UPC 2023: International workshop on the physics of Ultra Peripheral Collisions
December 10-15, Playa del Carmen, Mexico

Photon-induced process to understand QCD
(Mainly from the point of view of experiments)

Guillermo Contreras

Czech Technical University in Prague

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The road towards QCD
81 years in a few minutes

Science is a conversation amongst people
that takes place through articles

We have arrived late to this conversation, so let's have a look at what people have been talking about in the past

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In order to understand a bit better what we will discuss during this week

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Homework: try to read at least one of the original papers in the next few pages

Photon-induced processes to understand the QCD structure of hadrons

Hadrons?

Photon-induced processes to understand the QCD structure of hadrons

Hadrons?

Photon-induced processes to understand the QCD structure of hadrons

structure?

QCD?

Hadrons?

Photon-induced processes to understand the QCD structure of hadrons

structure?

The first hadrons

Before we knew they were hadrons!

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1911: The discovery of nuclei (Rutherford)

Atoms have nuclei

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1935: A model for the nuclear force (Yukawa)

New force and new particle carrying the force

https://academic.oup.com/ptps/article/doi/10.1143/PTPS.1.1/1878532

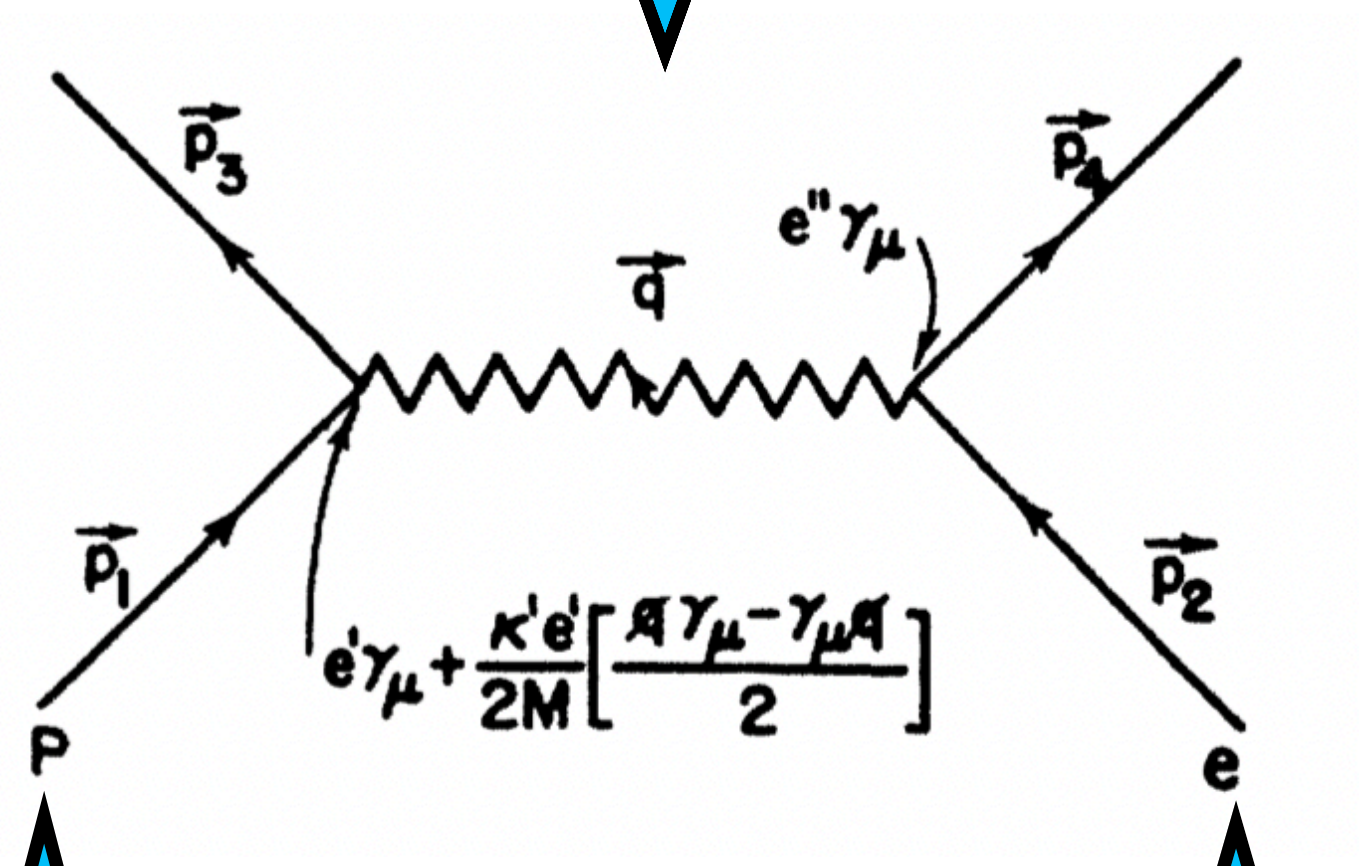
At this point in time, we have hadrons and a new force

Studying hadrons with light

1950: High energy ep elastic scattering (Rosenbluth)

https://journals.aps.org/pr/abstract/10.1103/PhysRev.79.615

Through the exchange of one photon



scatters off a proton

An electron

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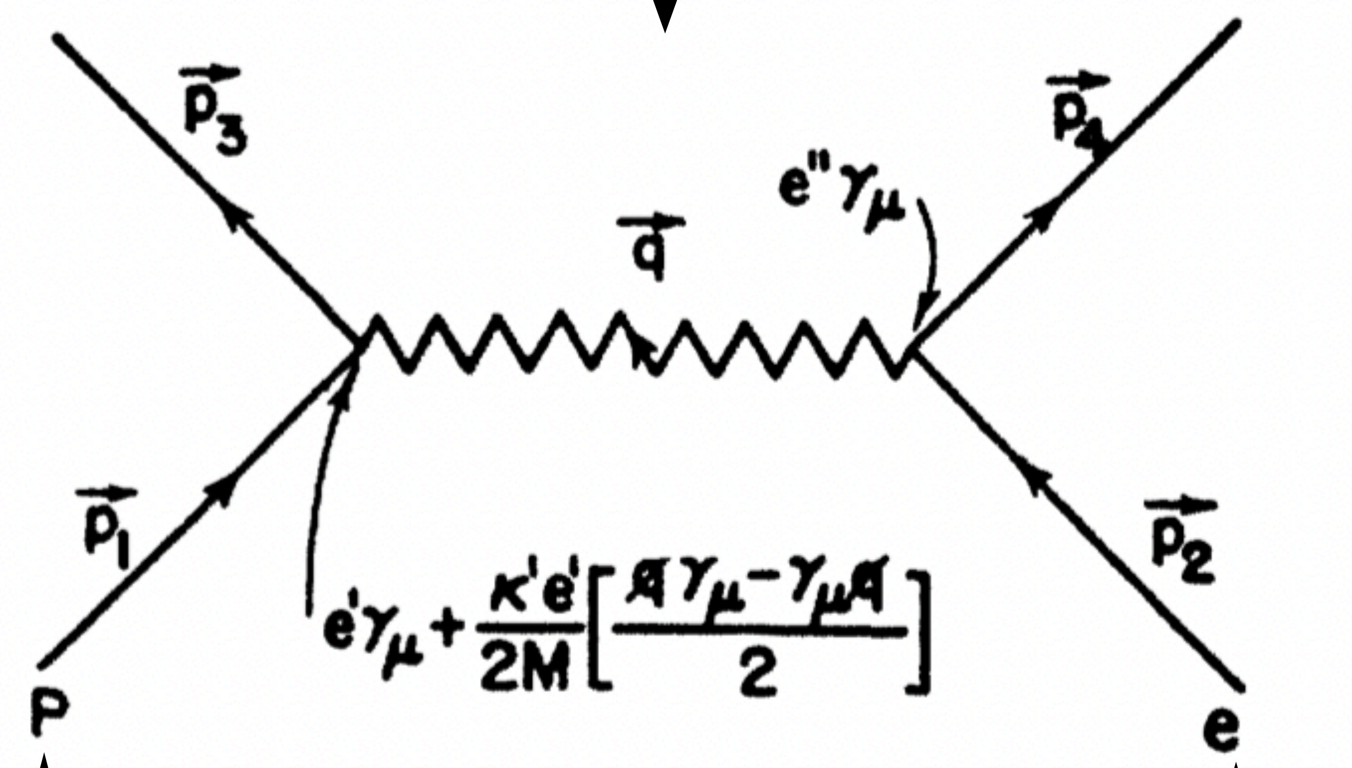

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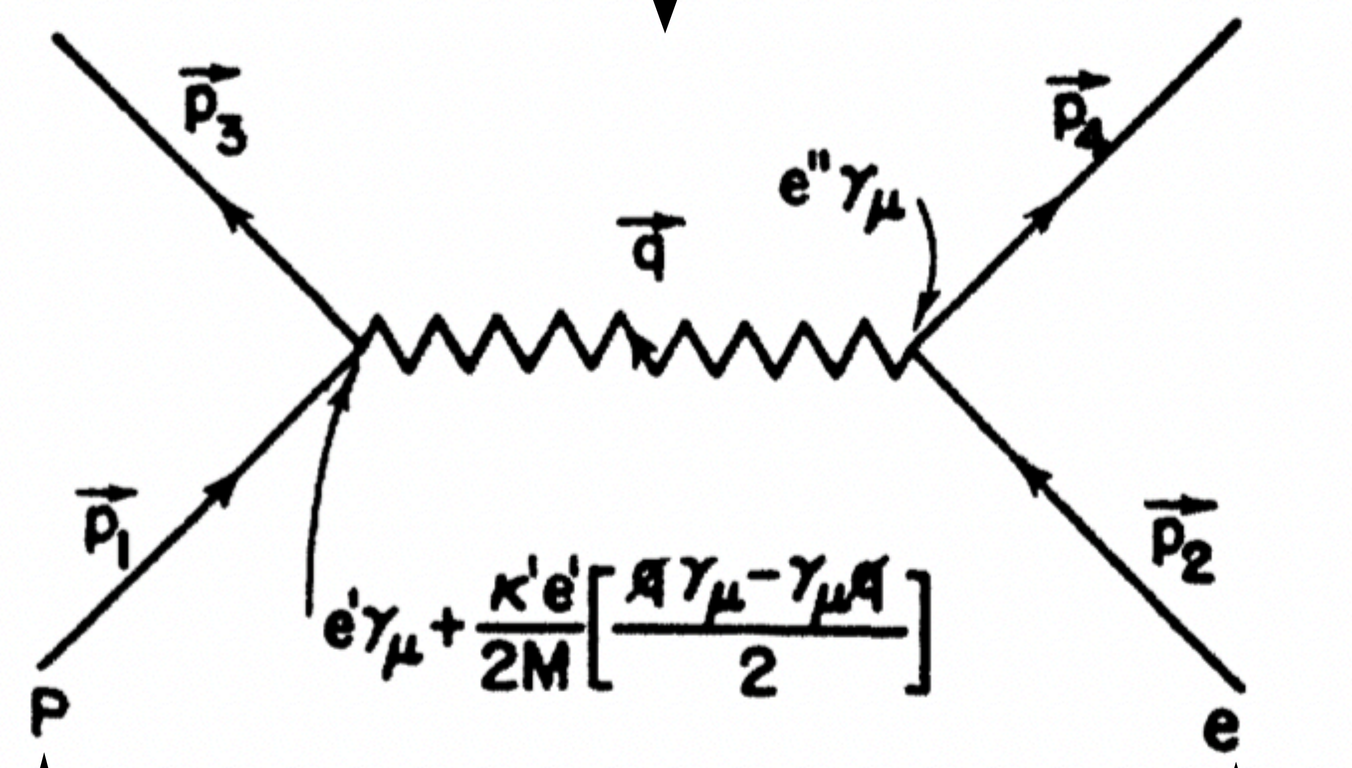

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Experiments to be performed with accelerators

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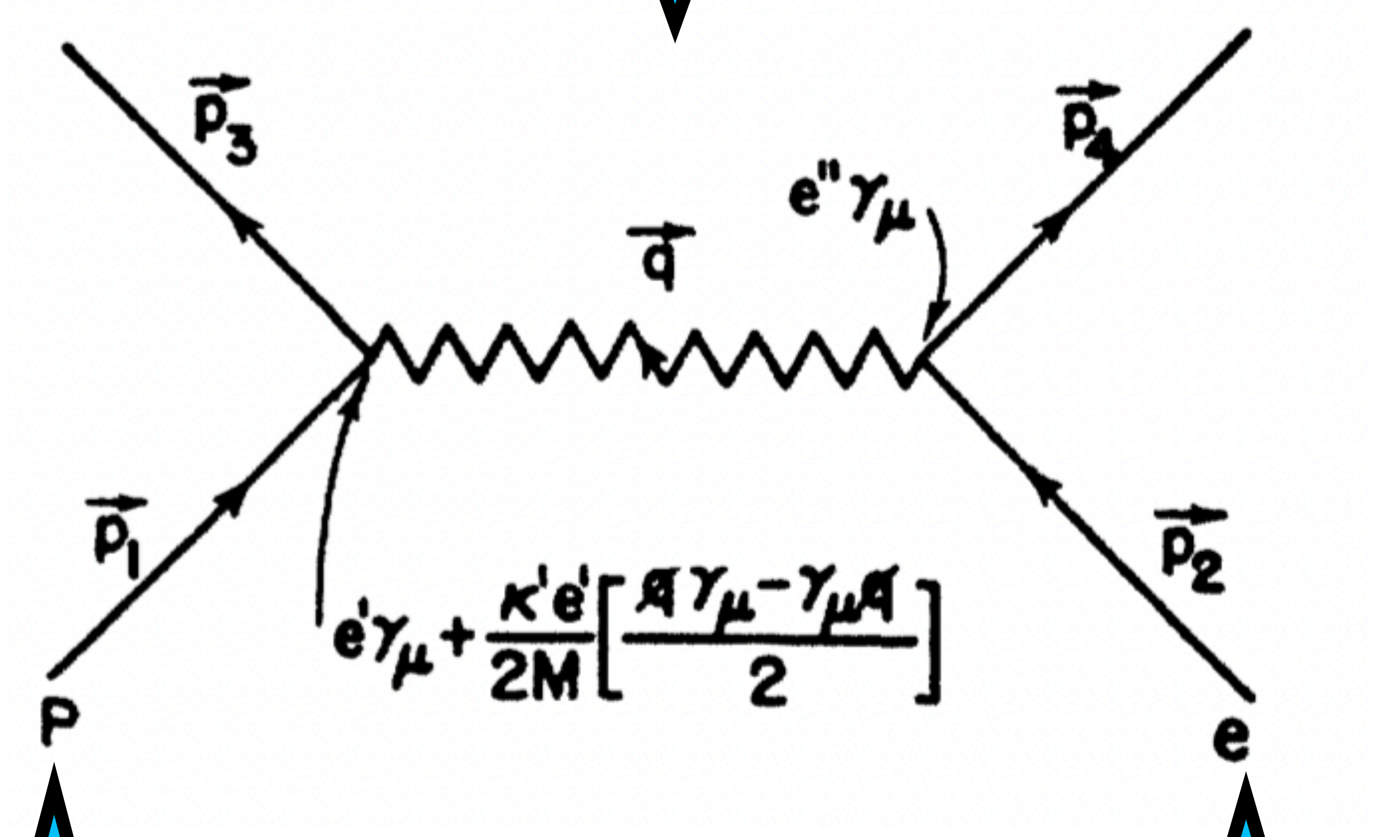

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An electron

Guillermo Contreras, CTU in Prague

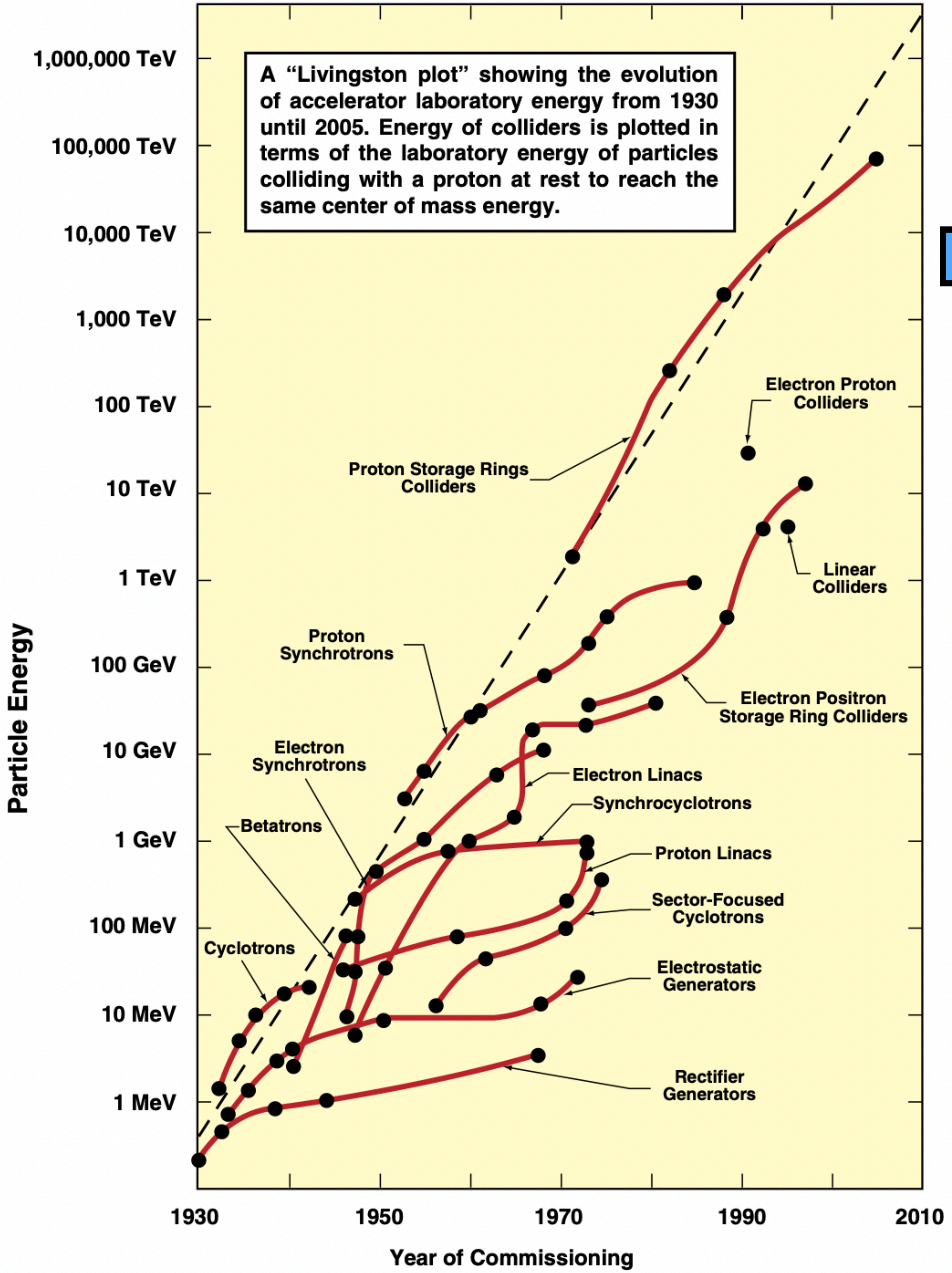
At this point in time, we have hadrons and a new force
and means to compute the scattering of an electron off a proton

At this point in time, we have hadrons and a new force
and means to compute the scattering of an electron off a proton

... and we also have accelerators ...

To study the proton, probes at high energies (small de Broglie wave length) are needed

Evolution of accelerators



Snowmass 2001 https://inspirehep.net/literature/572688

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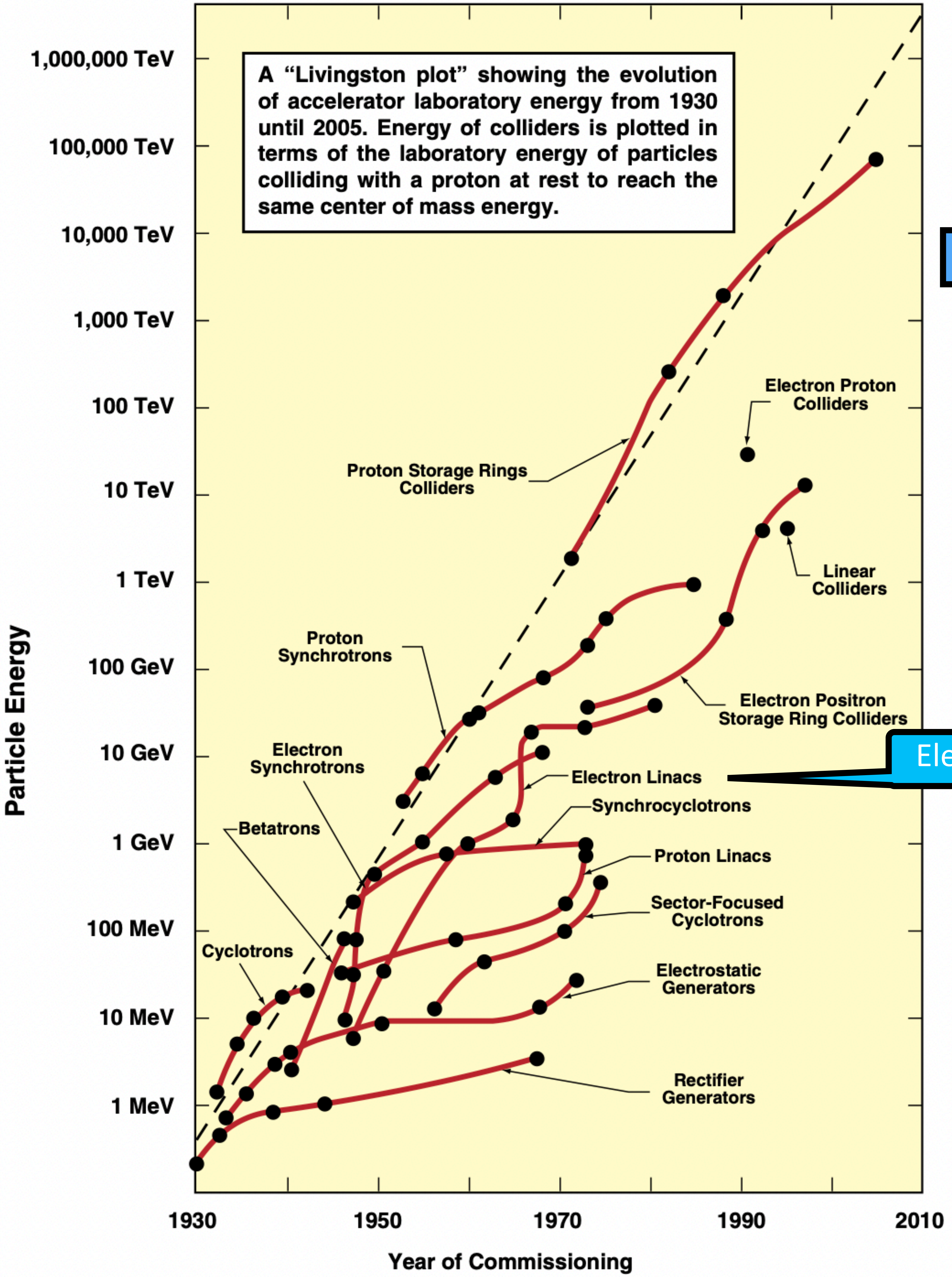

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Electron linear accelerators were used for the experiments discussed in the next slides

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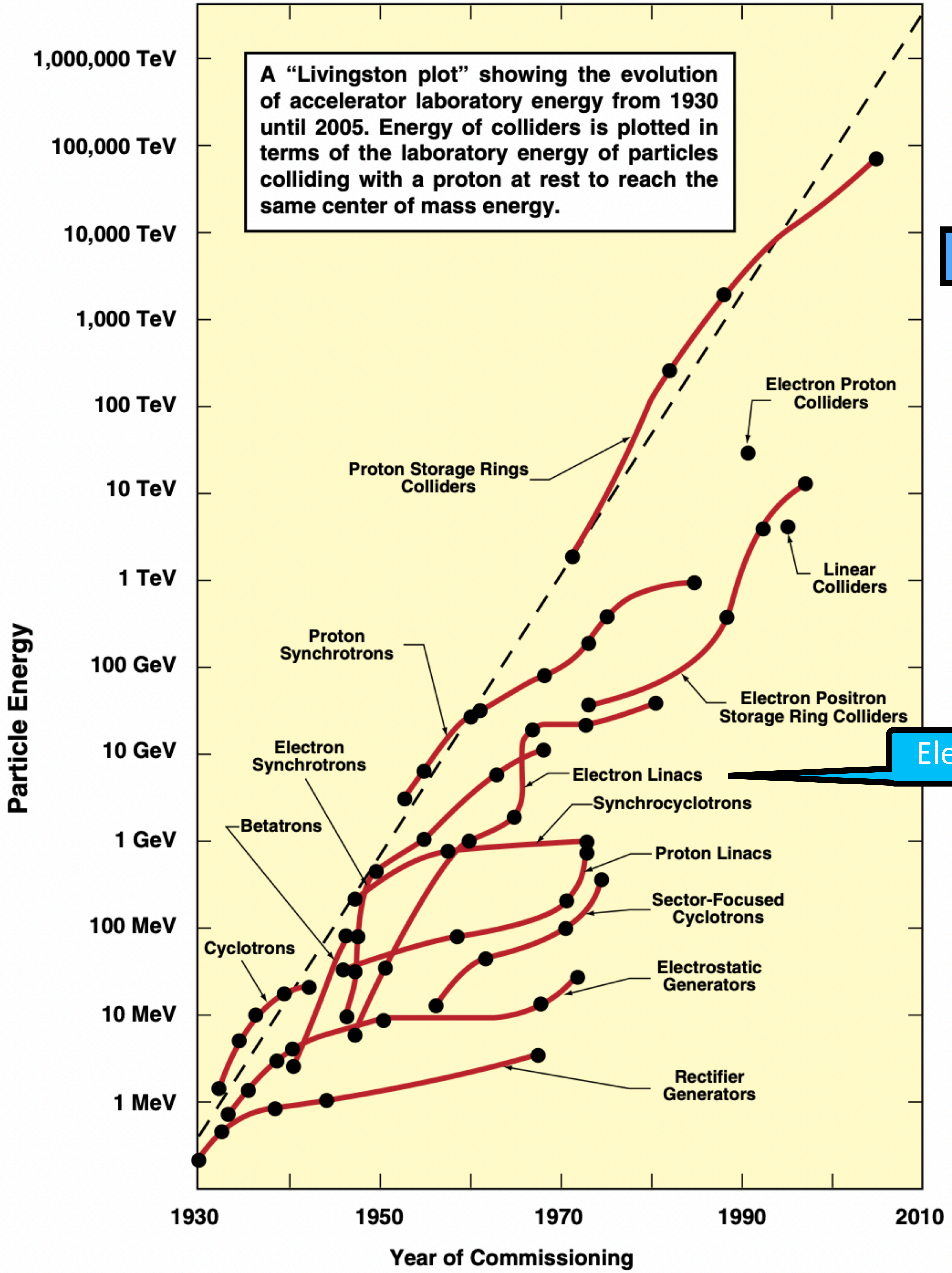

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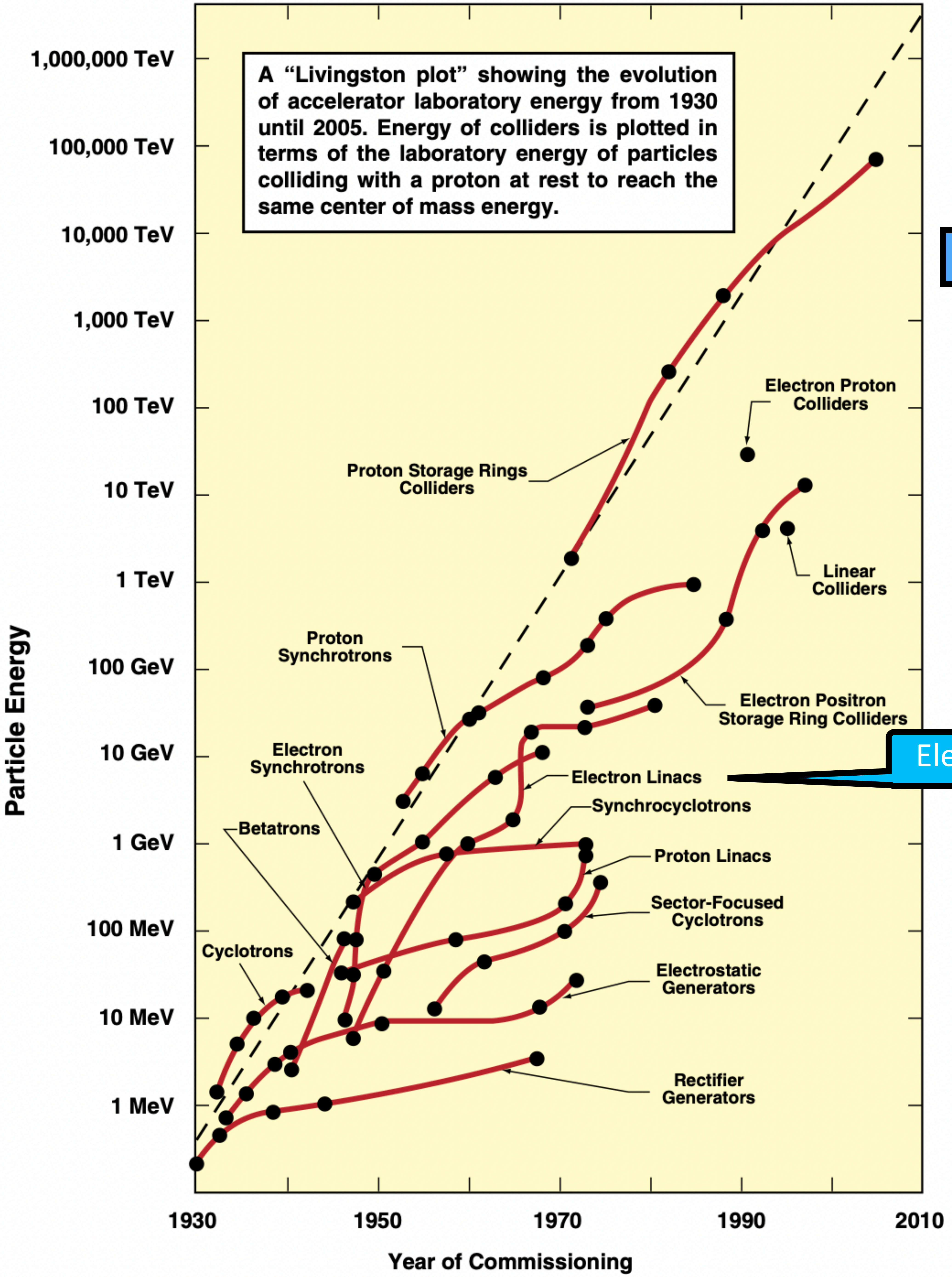

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1966: The two-mile accelerator
Electron beams of up to 20 GeV

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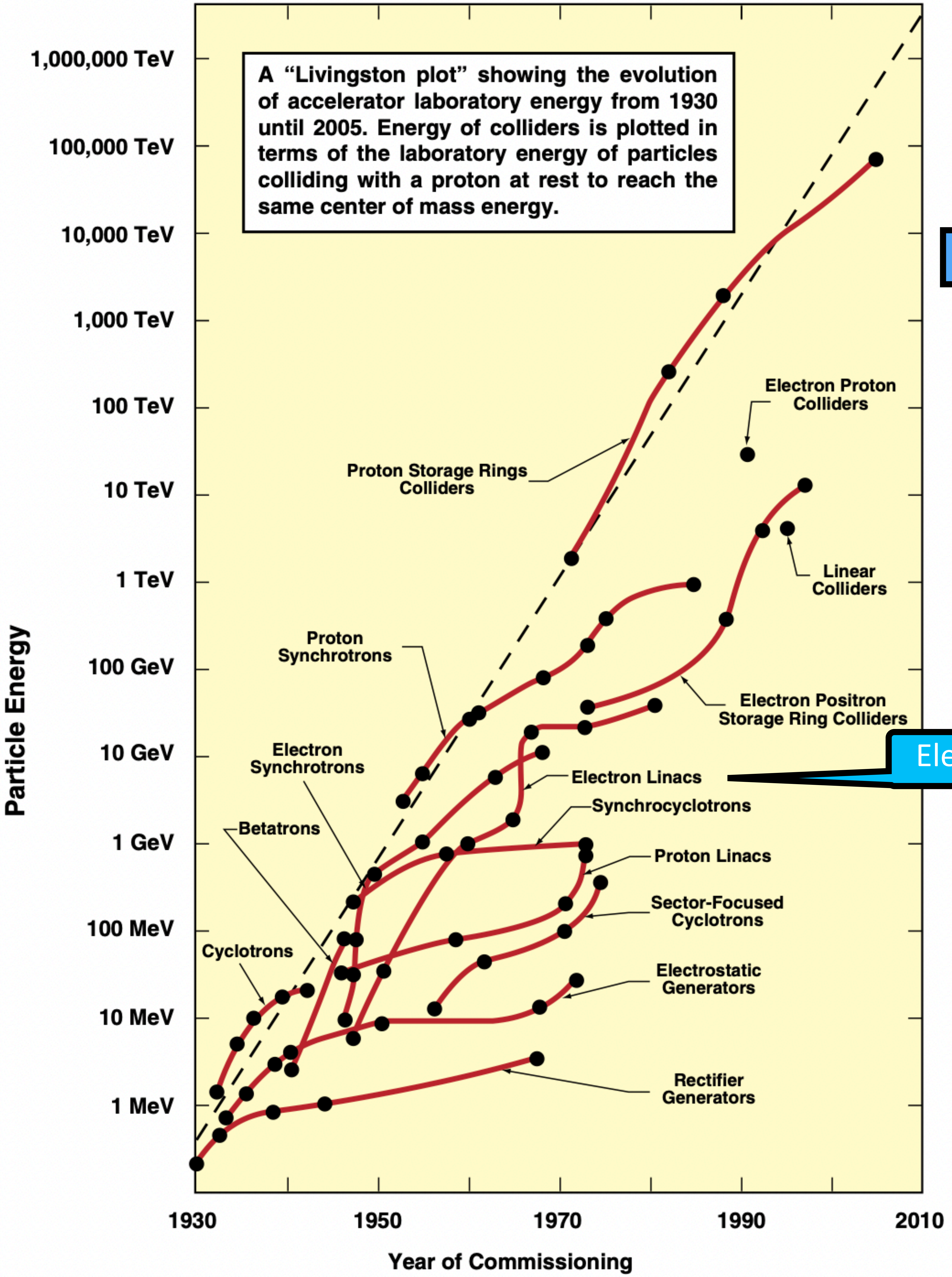

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Alpha particles from Ra reach less than 6 MeV

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Protons have structure

1955: Elastic scattering (Hofstadter and McAllister)

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Protons are not point like: RMS radius (0.74 ± 0.24) 10^{-13} cm

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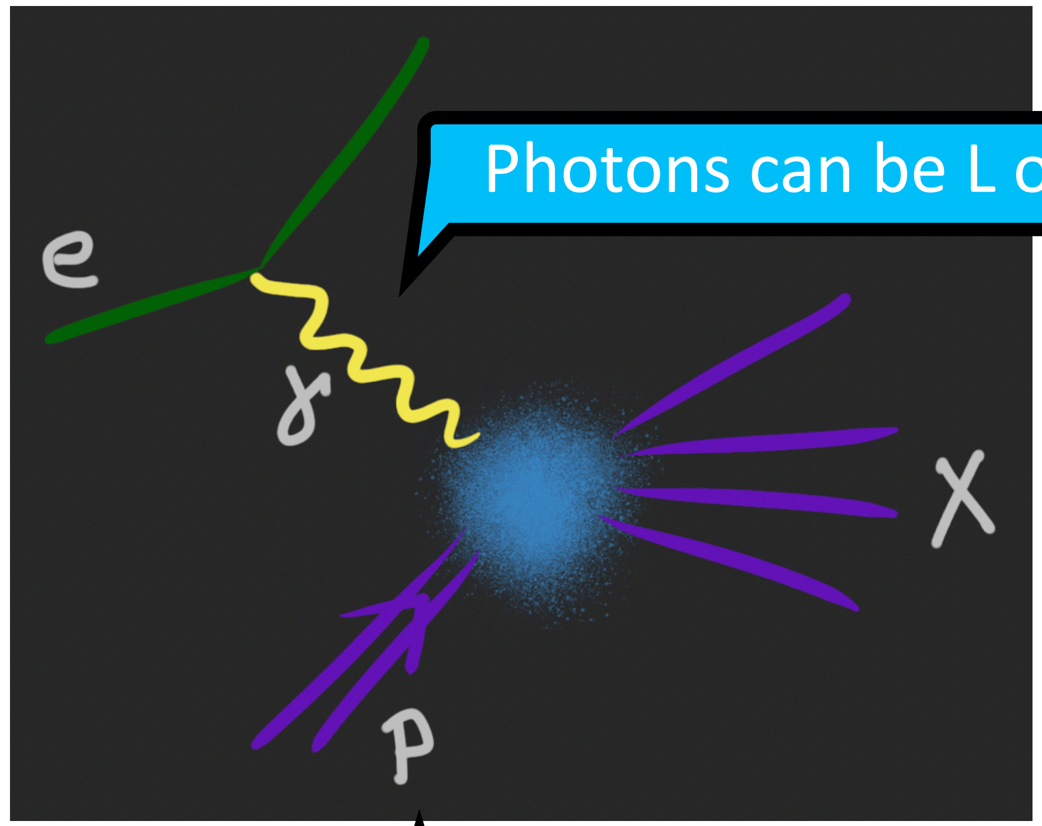

Photons can be L or T

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ICHEP 2024 in Prague :)

Proceedings from ICHEP68 in Wien

LOW q^2 ELECTRODYNAMICS, ELASTIC AND INELASTIC ELECTRON (AND MUON) SCATTERING

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No link for this one: I got it scanned thanks to the CERN Library :)

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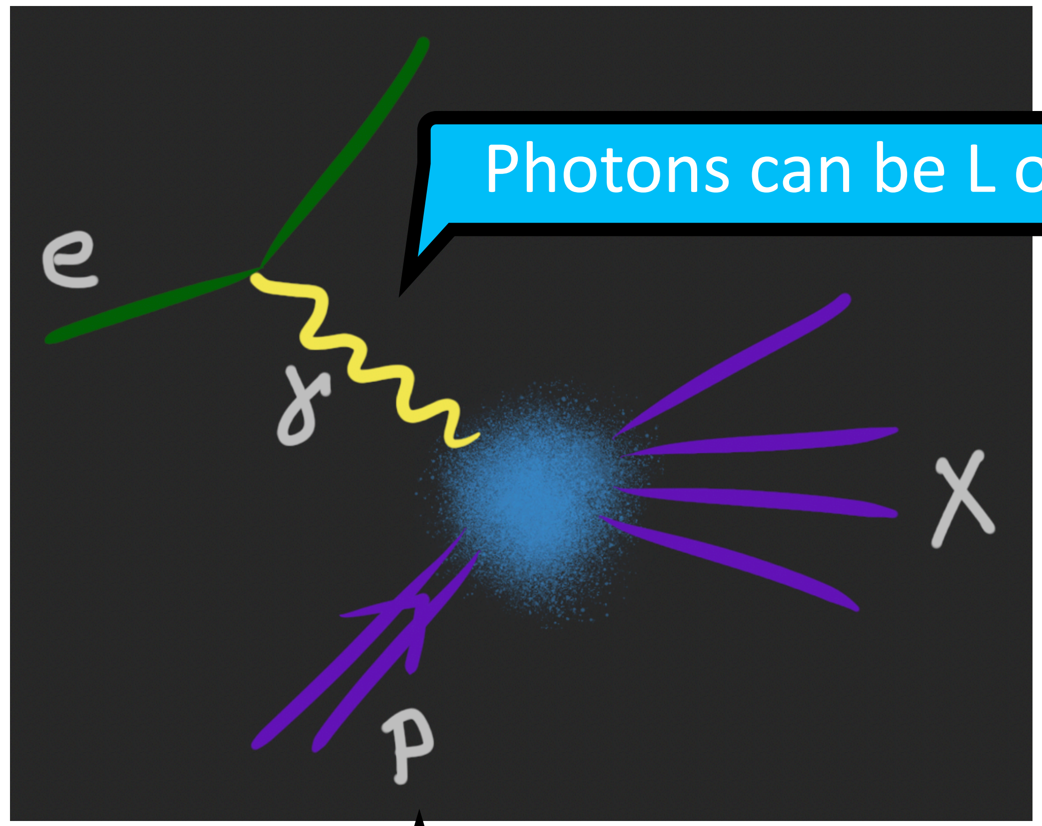

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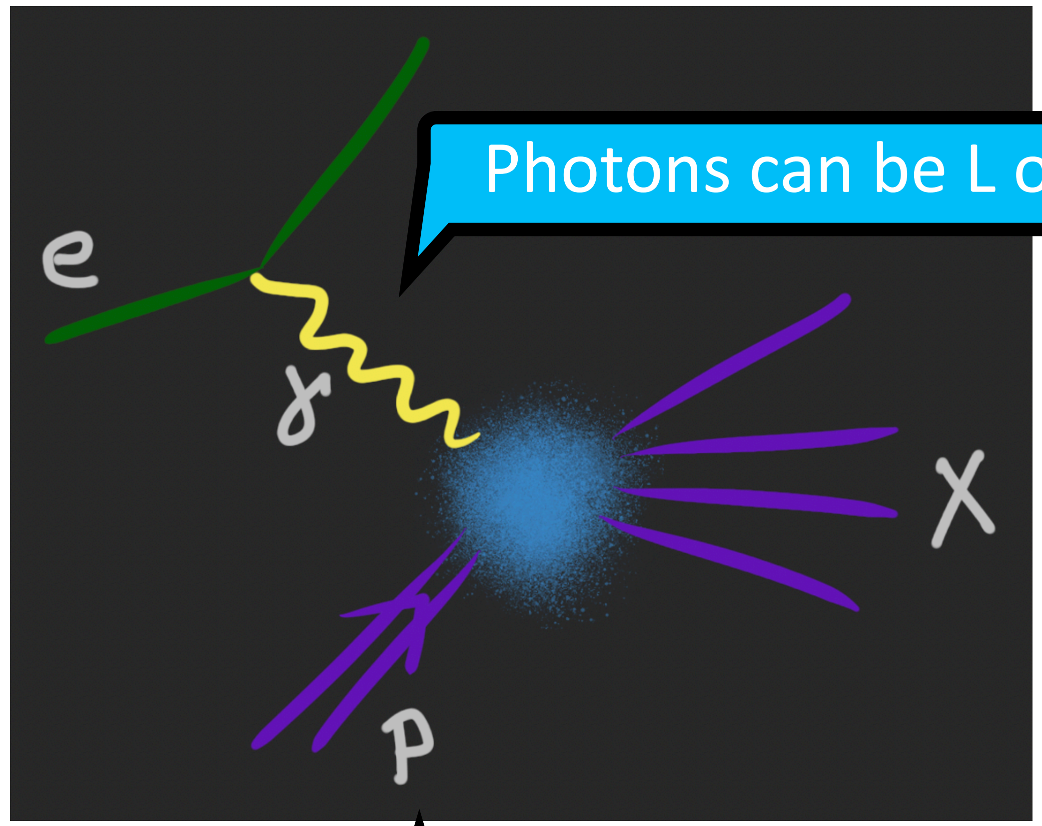

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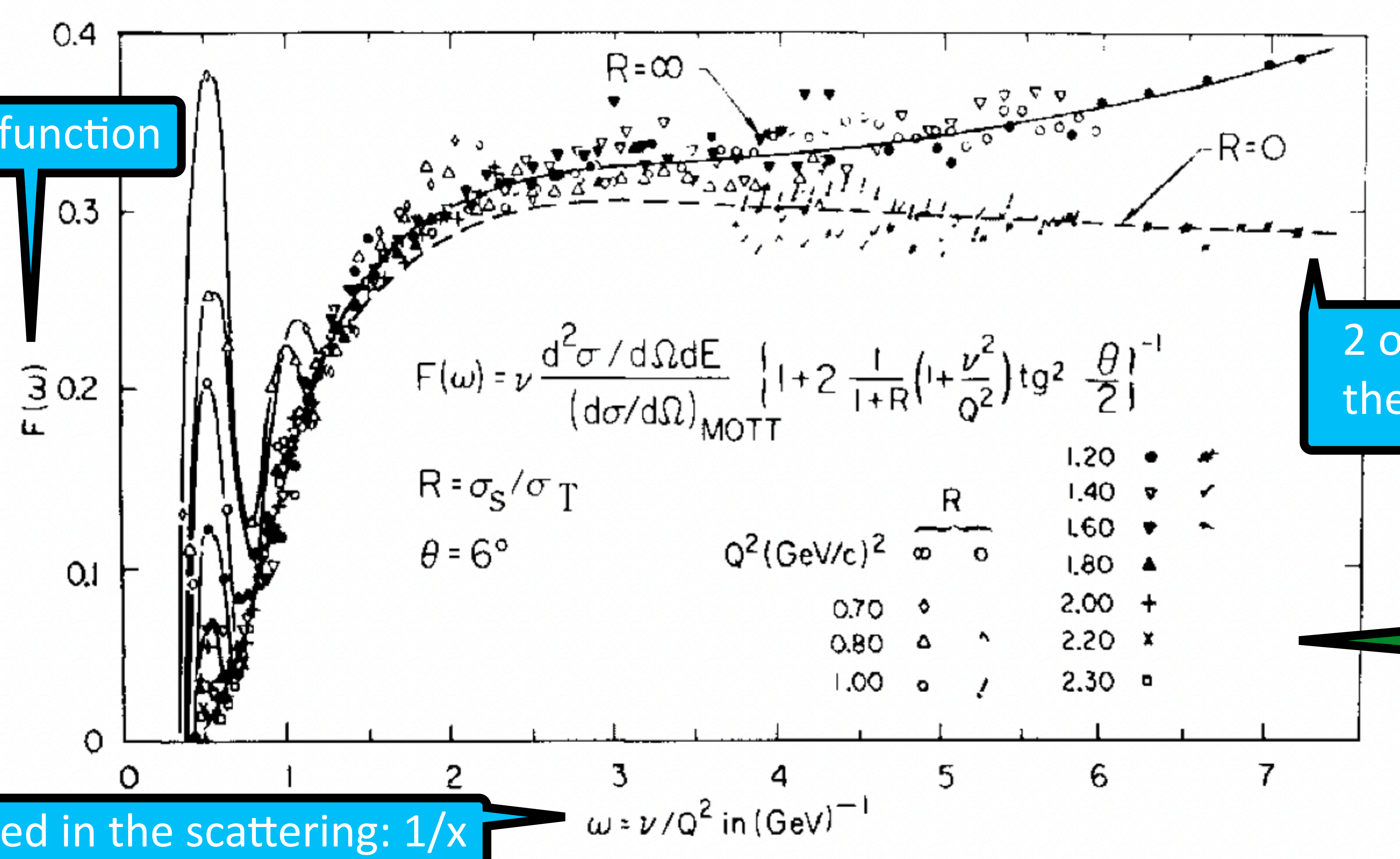
Protons have structure

Structure function



2 options on the behaviour of R: the ratio of L to T contributions

Different Q^2 values (virtuality/resolution of the photon)

Energy involved in the scattering: 1/x

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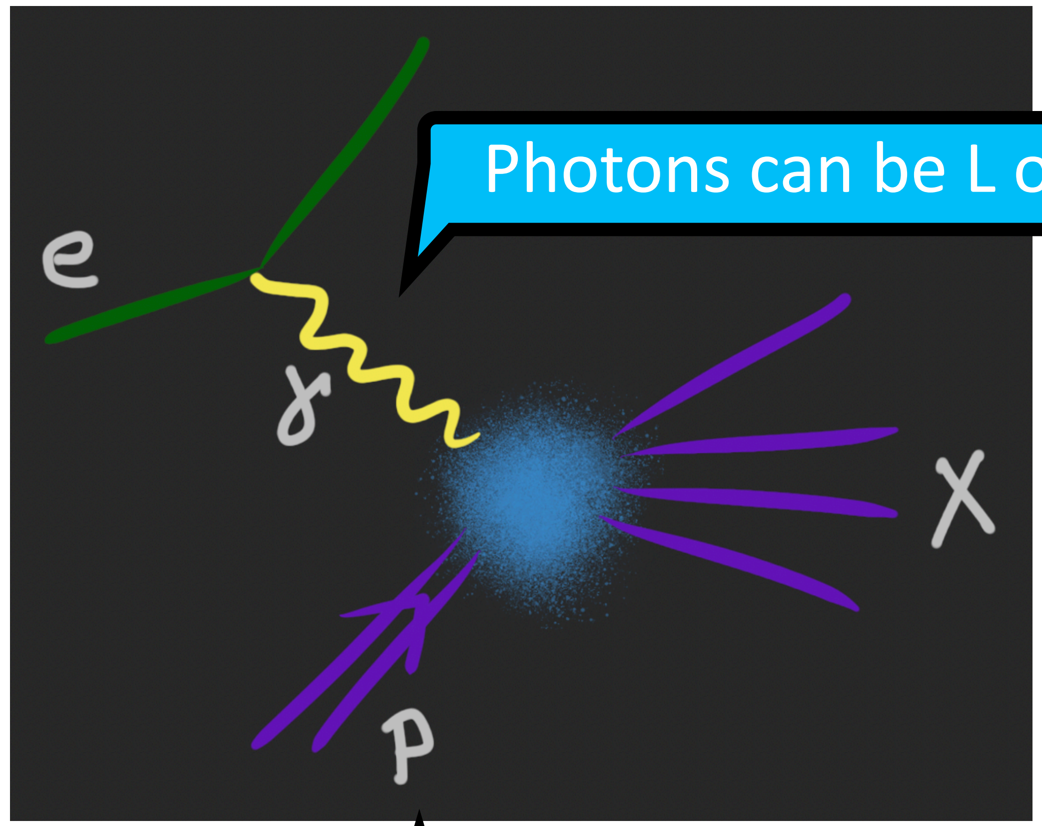

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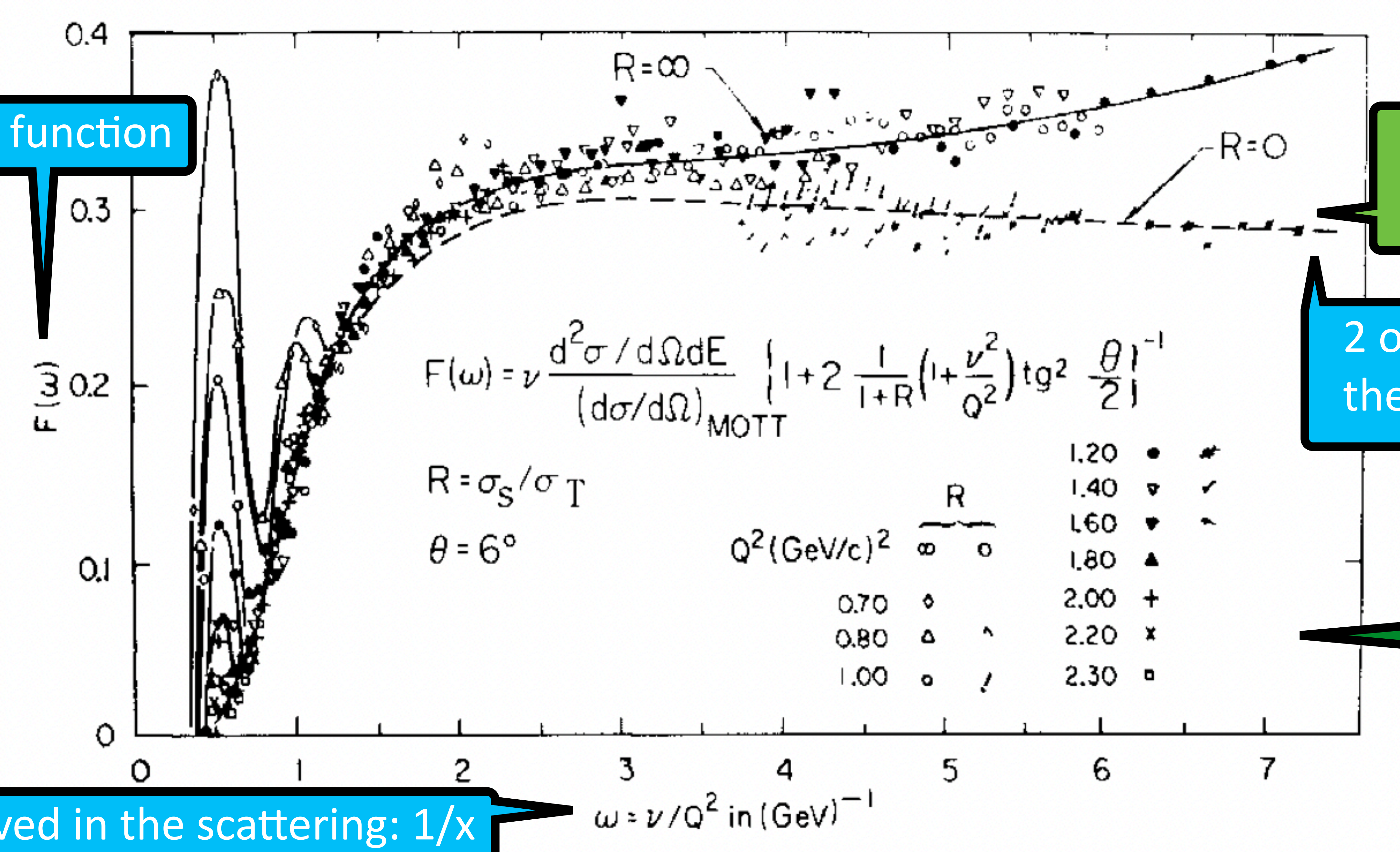

All symbols in the same line => no dependence on the photon virtuality!

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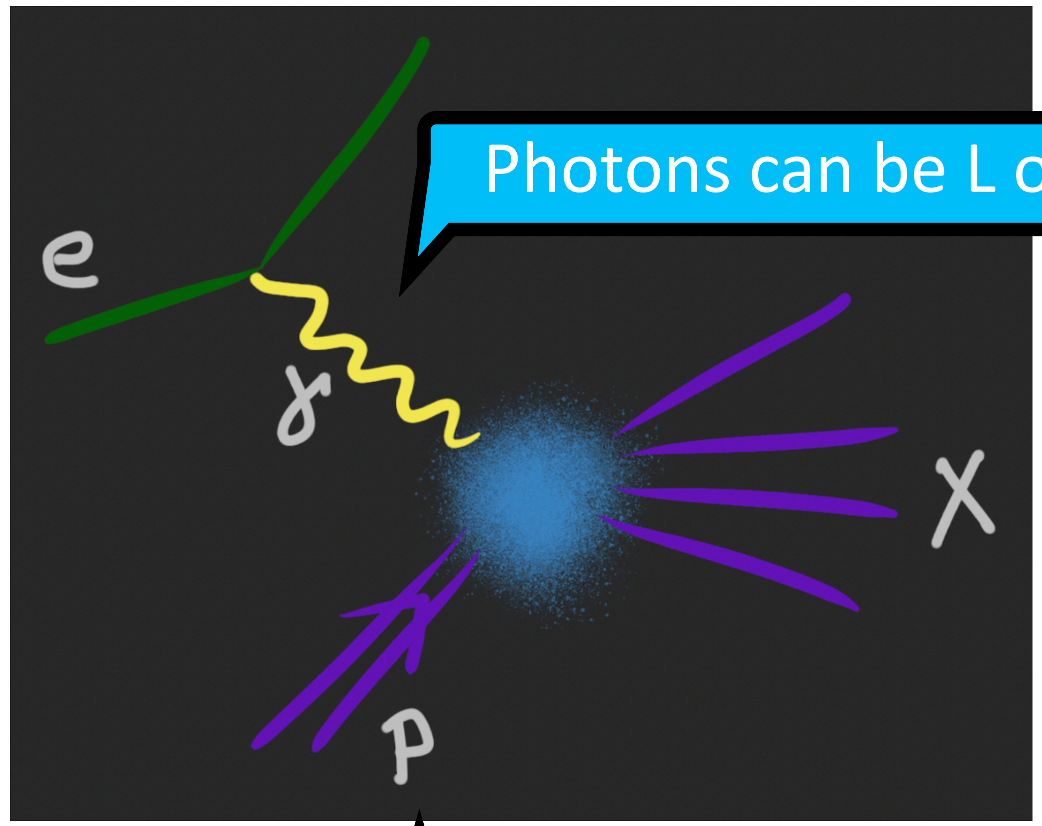

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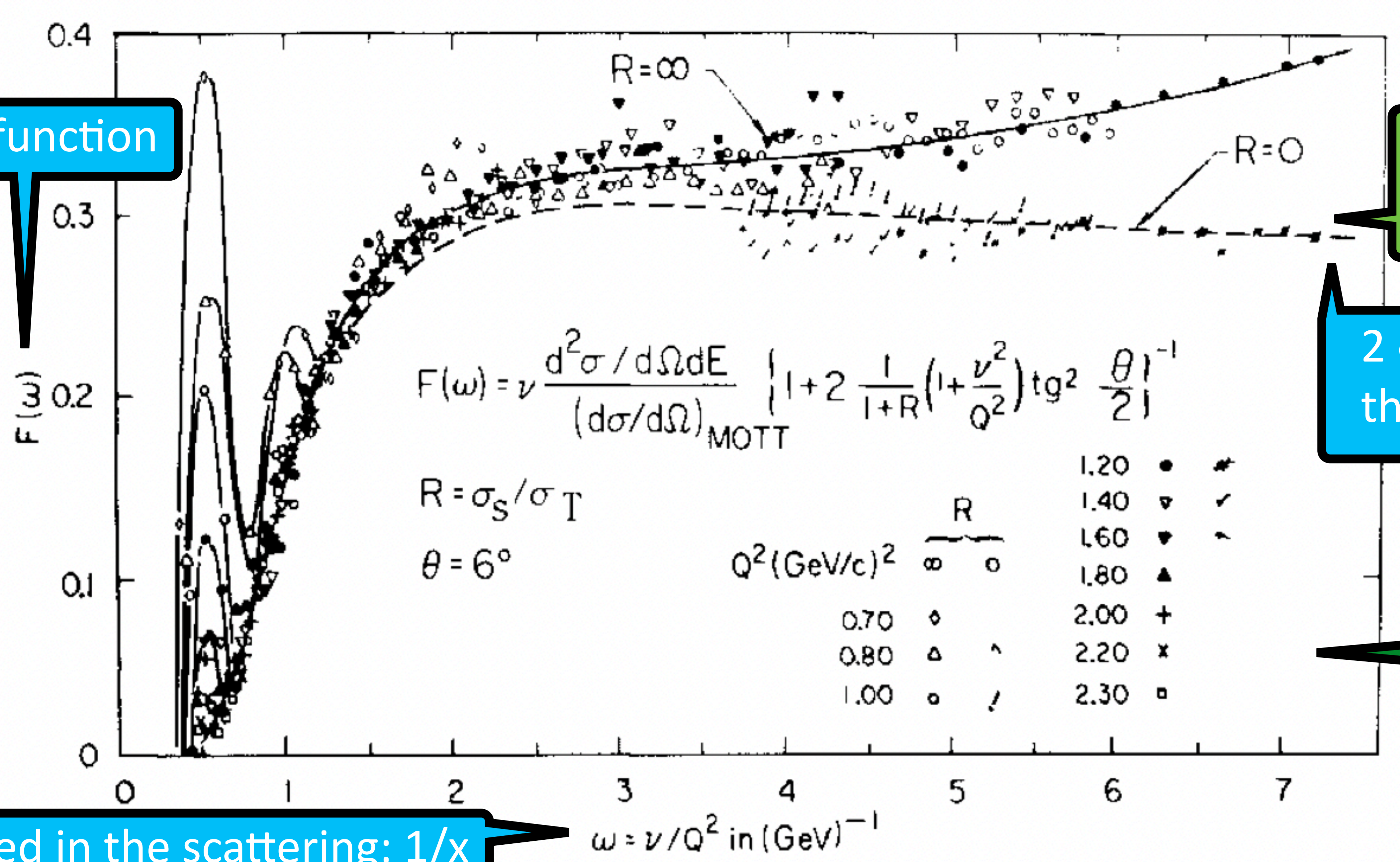
Bjorken scaling



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DIS and partons

point-like constituents

1969: Bjorken scaling

https://doi.org/10.1103/PhysRev.179.1547

1969: Feynman partons

No link for this one. It can be found via the CERN Library :)

1969: DIS in a parton picture (Bjorken and Paschos)

https://doi.org/10.1103/PhysRev.185.1975

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Picture only valid in the (proton) infinite-momentum frame

Partons are free during the interaction

Asymptotic freedom

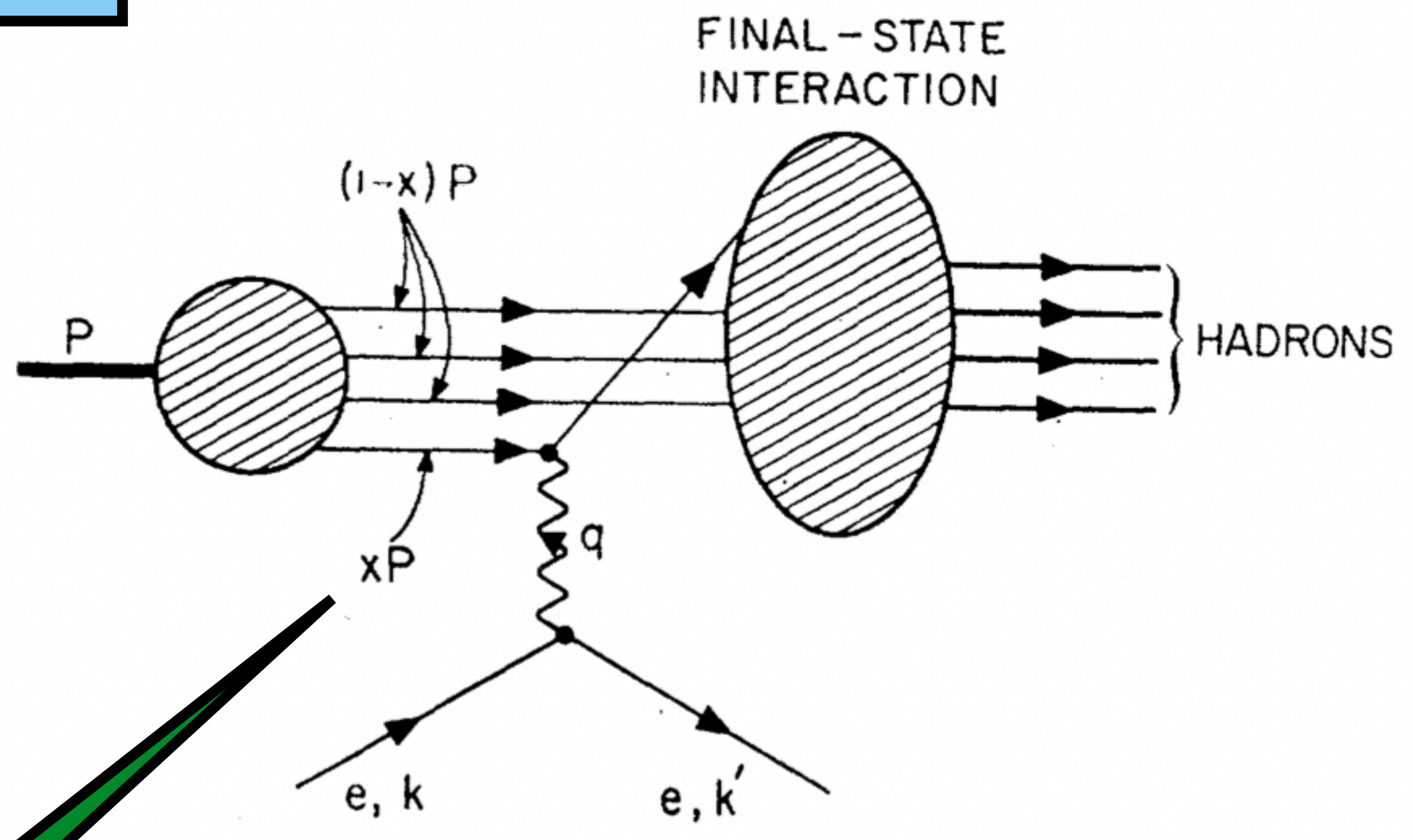

FIG. 1. Kinematics of lepton-nucleon scattering in the parton model.

Bjorken-x: fraction of the proton momentum carried by the struck parton

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https://doi.org/10.1103/PhysRev.185.1975

1969: Callen-Gross relation

https://doi.org/10.1103/PhysRevLett.22.156

1972: Partons have spin 1/2 (Miller et al)

https://doi.org/10.1103/PhysRevD.5.528

Picture only valid in the (proton) infinite-momentum frame

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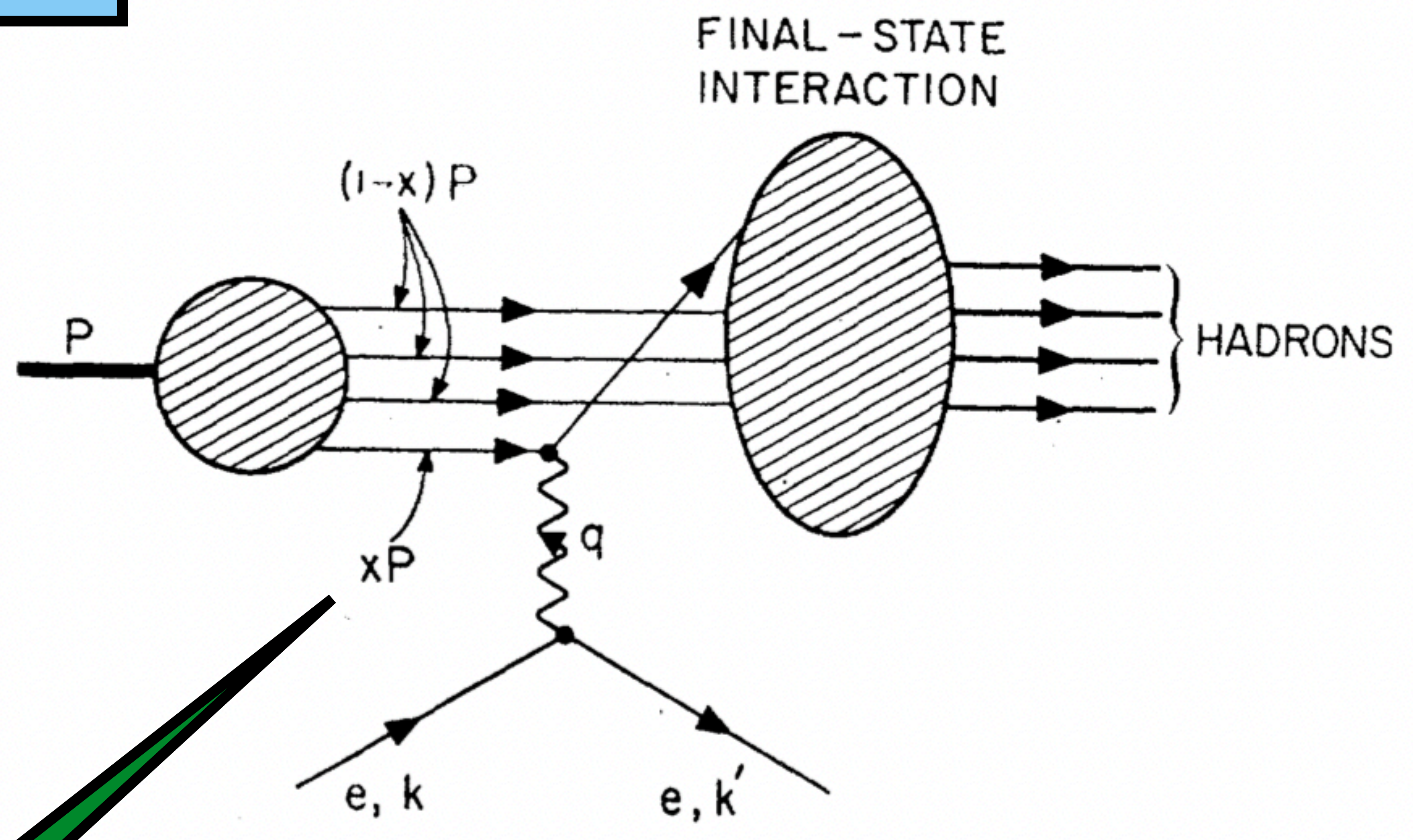

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Bjorken-x: fraction of the proton momentum carried by the struck parton

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How could there be 'free' constituents in the proton?

Needed to explain scaling

QCD

1973: Price of asymptotic freedom (Coleman, Gross)

No renormalizable field theory without non-Abelian gauge field can be asymptotically free

https://doi.org/10.1103/PhysRevLett.31.851

1973: Asymptotic freedom (Politzer, Gross and Wilczek)

Non-Abelian gauge field theories can be asymptotically free

https://doi.org/10.1103/PhysRevLett.30.1346

https://doi.org/10.1103/PhysRevLett.30.1343

1973: SU(3) color (Fritzsch, Gell-mann, Leutwyler)

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QCD

Charm to accept QCD

1964: Charm (Bjorken and Glashow)

https://doi.org/10.1016/0031-9163(64)90433-0

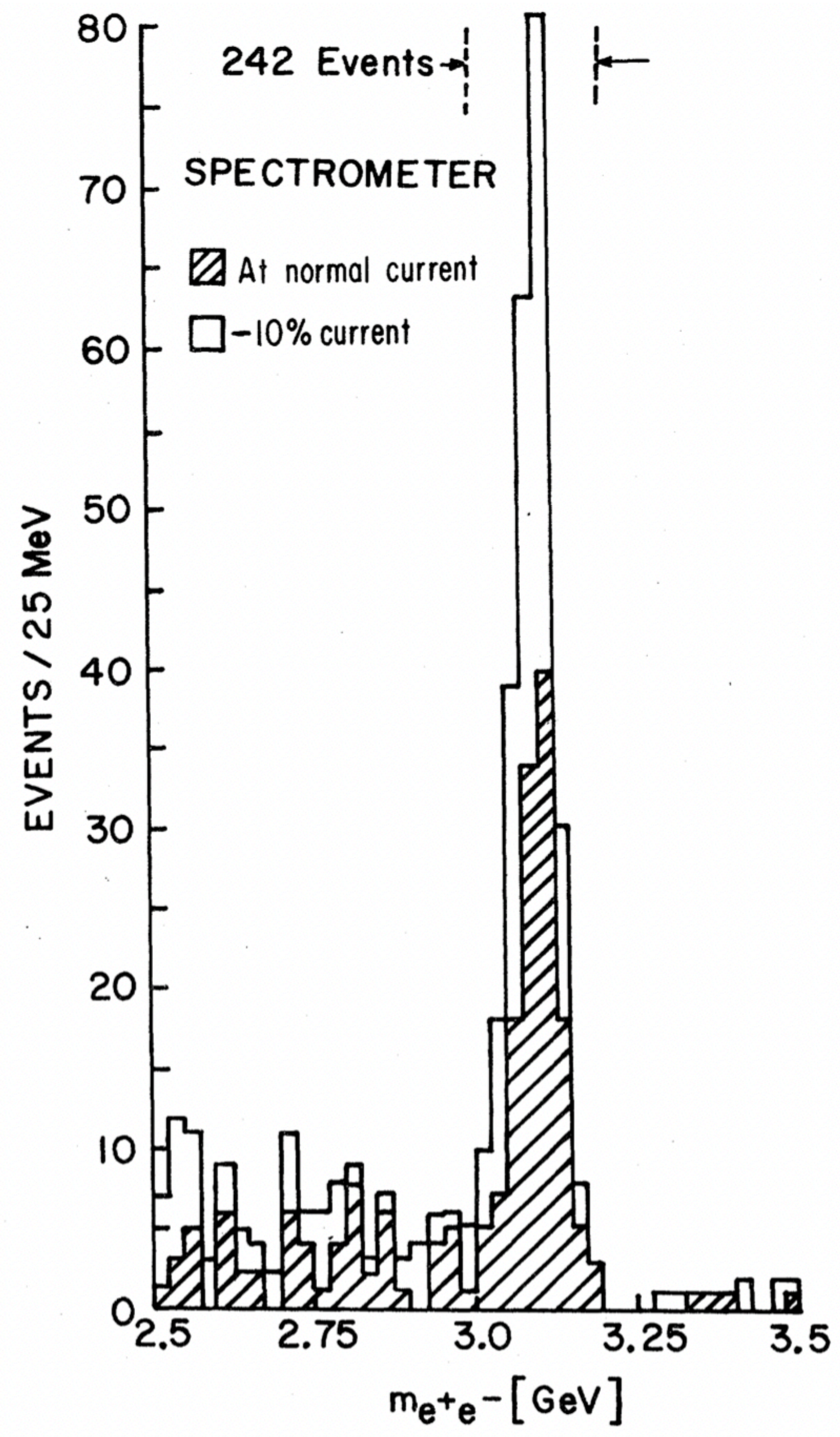
1974: charmonium (Appelquist, Politzer)

https://doi.org/10.1103/PhysRevLett.34.43

1974: J/ψ and the November revolution (Richter et al, Ting et al)

https://doi.org/10.1103/PhysRevLett.33.1406

https://doi.org/10.1103/PhysRevLett.33.1404



Nobel prize 1961

https://www.nobelprize.org/prizes/physics/1961/
https://www.nobelprize.org/uploads/2018/06/hofstadter-lecture.pdf

Nobel prize 1990

https://www.nobelprize.org/prizes/physics/1990/
https://www.nobelprize.org/uploads/2018/06/taylor-lecture.pdf
https://www.nobelprize.org/uploads/2018/06/kendall-lecture-1.pdf
https://www.nobelprize.org/uploads/2018/06/friedman-lecture.pdf

To be read in this order

Nobel prize 2004

https://www.nobelprize.org/prizes/physics/2004/
https://www.nobelprize.org/uploads/2018/06/gross-lecture.pdf

Nobel prize 1961

https://www.nobelprize.org/prizes/physics/1961/
https://www.nobelprize.org/uploads/2018/06/hofstadter-lecture.pdf

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https://www.nobelprize.org/prizes/physics/1990/
https://www.nobelprize.org/uploads/2018/06/taylor-lecture.pdf
https://www.nobelprize.org/uploads/2018/06/kendall-lecture-1.pdf
https://www.nobelprize.org/uploads/2018/06/friedman-lecture.pdf

To be read in this order

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https://www.nobelprize.org/prizes/physics/2004/
https://www.nobelprize.org/uploads/2018/06/gross-lecture.pdf

Homework: try to read at least the 1990 lectures

At this point in time, we have a theory to explain scaling
But QCD is a lot more than scaling ...

2

Establishing QCD:
Proton structure functions from HERA

Reminder: how do data tell us about QCD?

Deep-inelastic scattering: QED and Lorentz invariance

This is the cross section to be measured

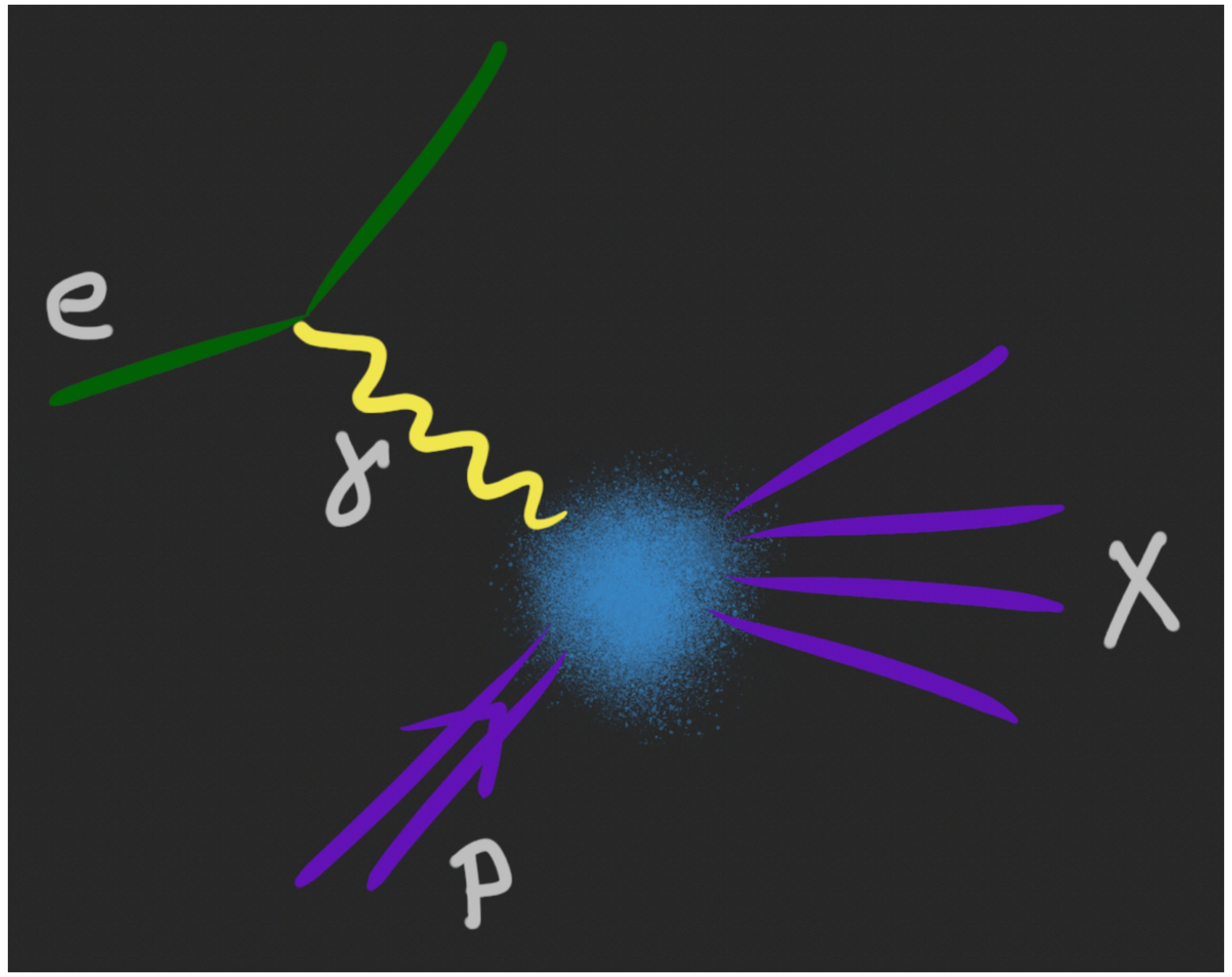
$$\frac{d\sigma^{ep}}{dx dQ^2}$$

Deep-inelastic scattering: QED and Lorentz invariance

This is the cross section to be measured

$$\frac{d\sigma^{ep}}{dx dQ^2} \sim \frac{1}{Q^4} L_{\mu\nu} W^{\mu\nu}$$

One photon exchange



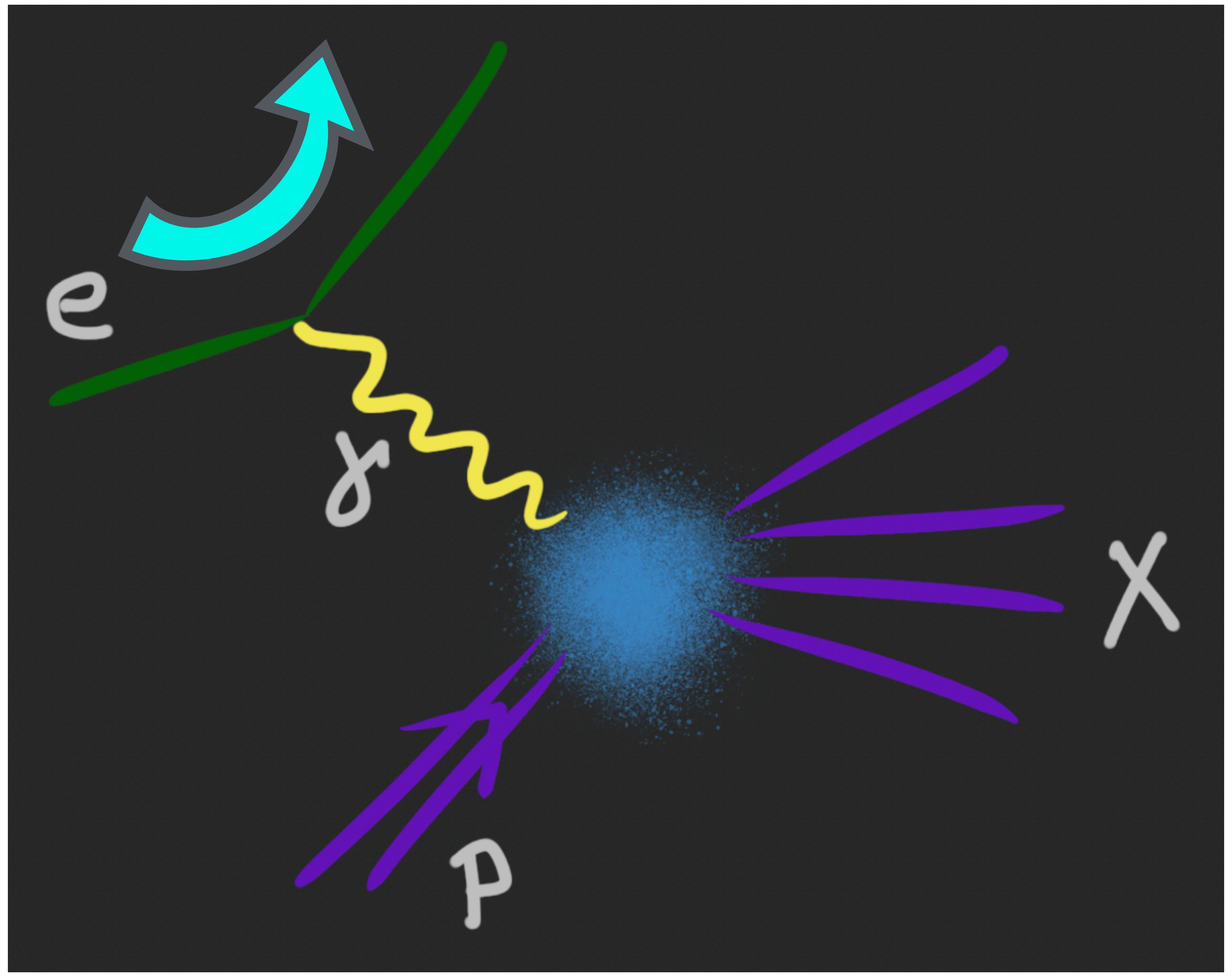
Deep-inelastic scattering: QED and Lorentz invariance

This is the cross section to be measured

The EM current gives rise to a tensor

$$\frac{d\sigma^{ep}}{dx dQ^2} \sim \frac{1}{Q^4} L_{\mu\nu} W^{\mu\nu}$$

One photon exchange



Deep-inelastic scattering: QED and Lorentz invariance

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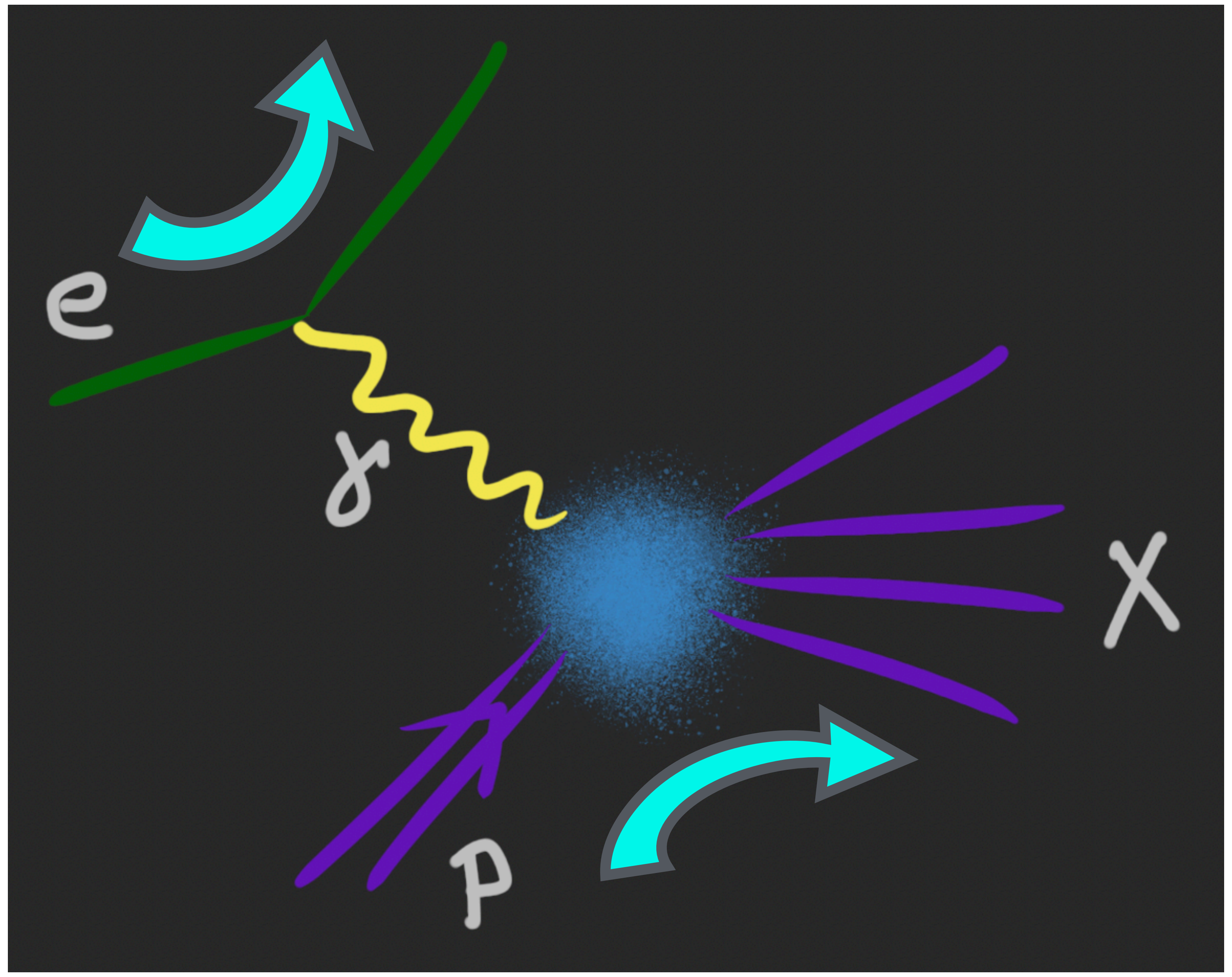

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Noting that:

- ✓ The lepton tensor is symmetric
- ✓ Photon exchange conserves parity
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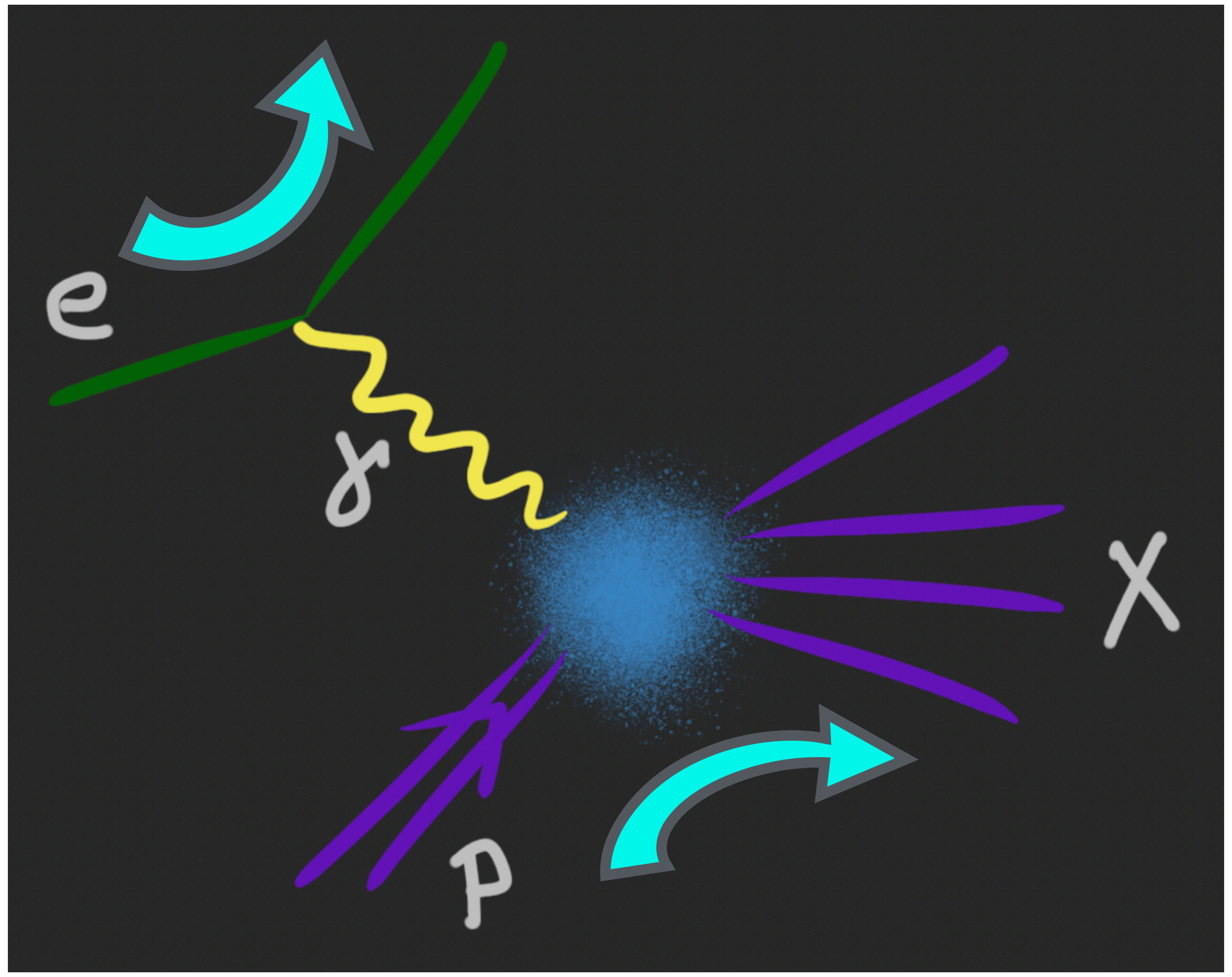
- ✓ Summing and averaging over spins

The most general tensor can be expressed as



$$W^{\mu\nu} = W_1 \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}) \right) + W_2 \frac{1}{M^2} \left(p^\mu - \frac{p \cdot q}{q^2} q^\mu \right) \left(p^\nu - \frac{p \cdot q}{q^2} q^\nu \right)$$

See e.g. Quarks & Leptons by Halzen and Martin

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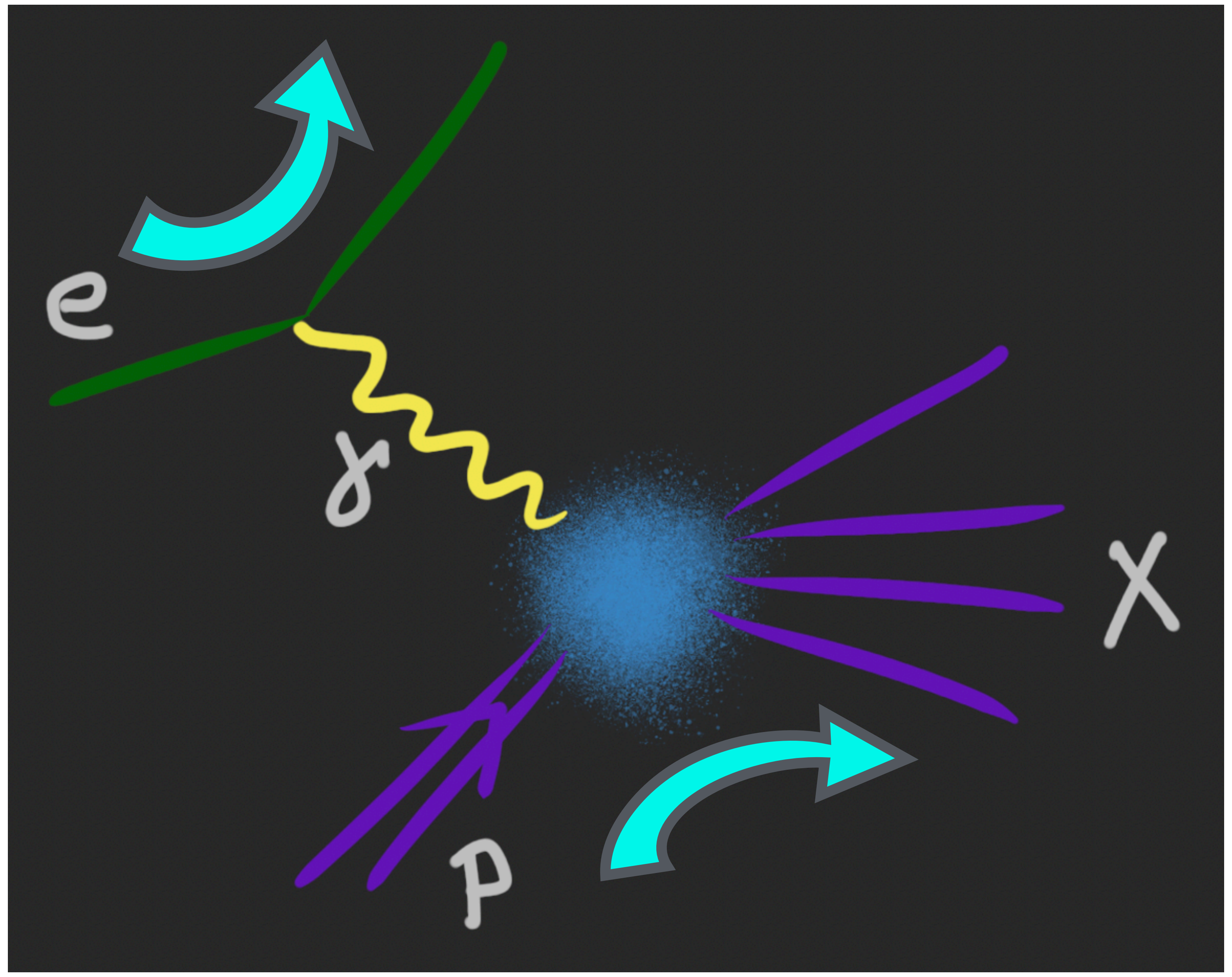

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For large photon virtualities and in a frame where the proton is moving infinitely fast

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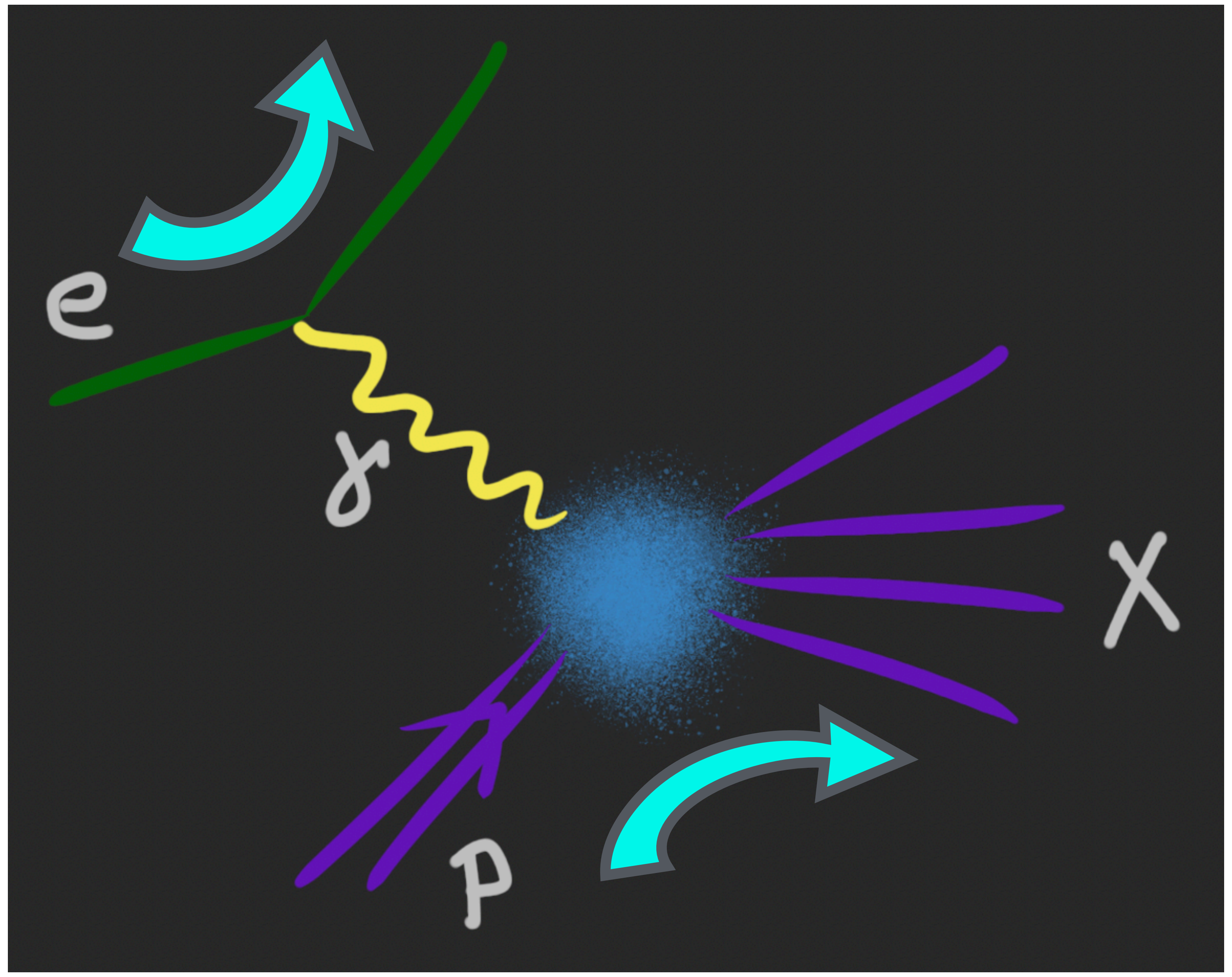

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If the constituents have spin one half

$$2xF_1(x) = F_2(x)$$

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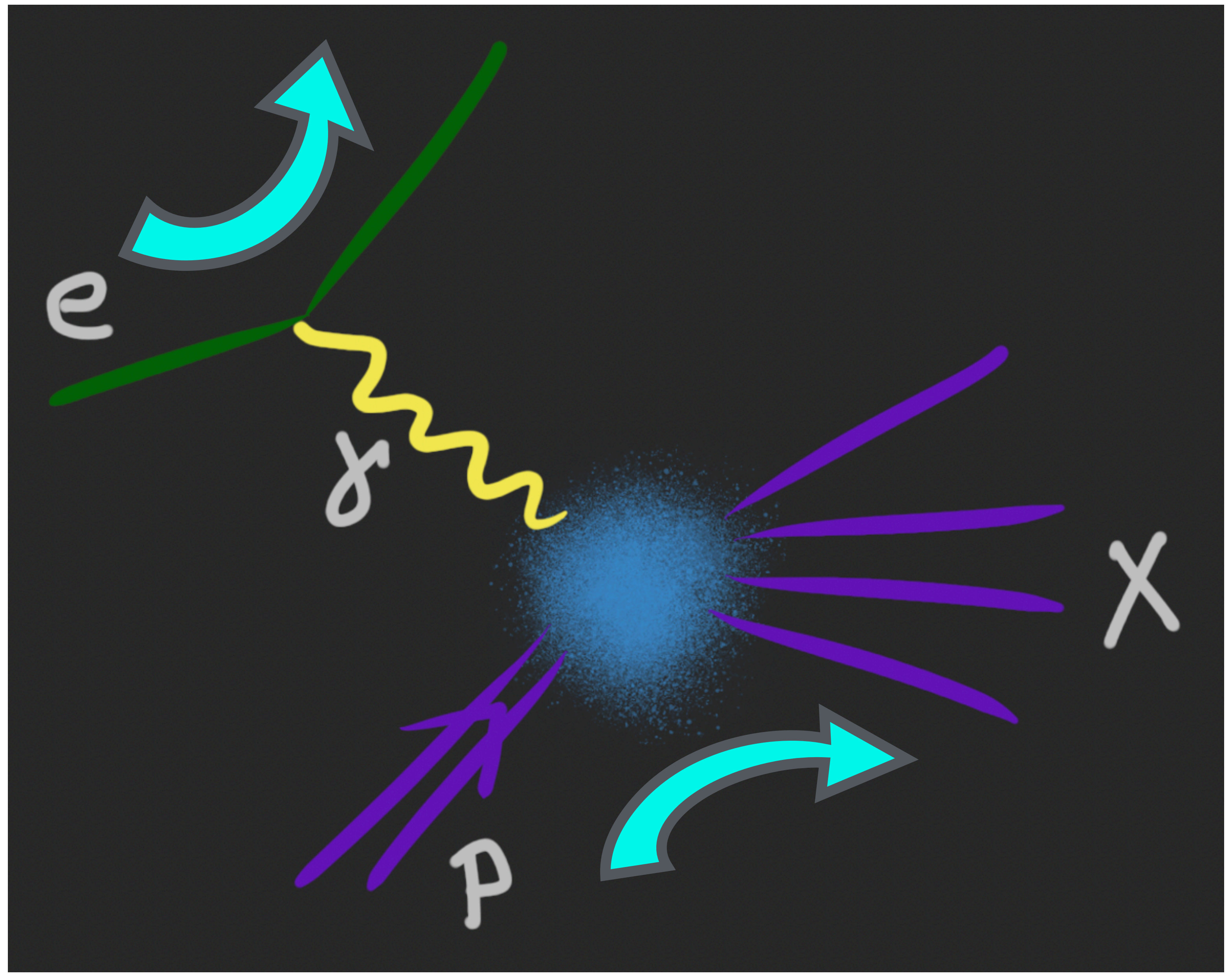

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Structure functions

If the constituents have spin one half

$$2xF_1(x) = F_2(x)$$

Note that up to this point there is no QCD involved

See e.g. Quarks & Leptons by Halzen and Martin

Deep inelastic scattering: quarks in the Bjorken limit

For large photon virtualities, thinking about point like constituents (partons), and in a frame where the proton is moving infinitely fast

If the constituents are free during the interaction

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QCD enters when we identify the partons with quarks

See e.g. Quarks & Leptons by Halzen and Martin

At this point in time we have a theory and an understanding how to learn about QCD from measurements
.... now, we need a new accelerator to perform the measurements and look deeper into the proton ...

To study the proton, probes at high energies (small de Broglie wave length) are needed

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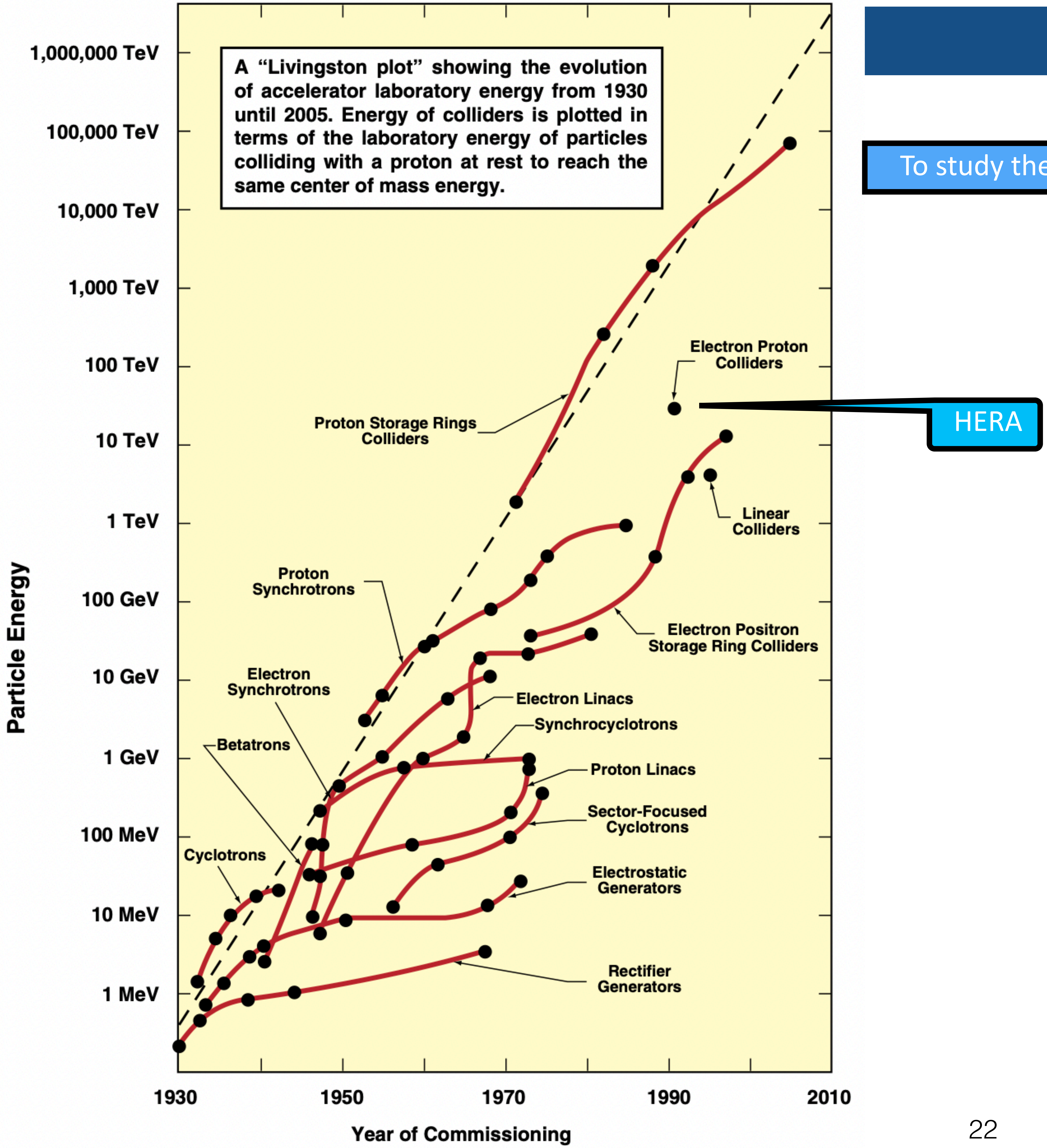
To study the inside of the proton, even larger energies are needed

What about ep accelerators?



Snowmass 2001 https://inspirehep.net/literature/572688

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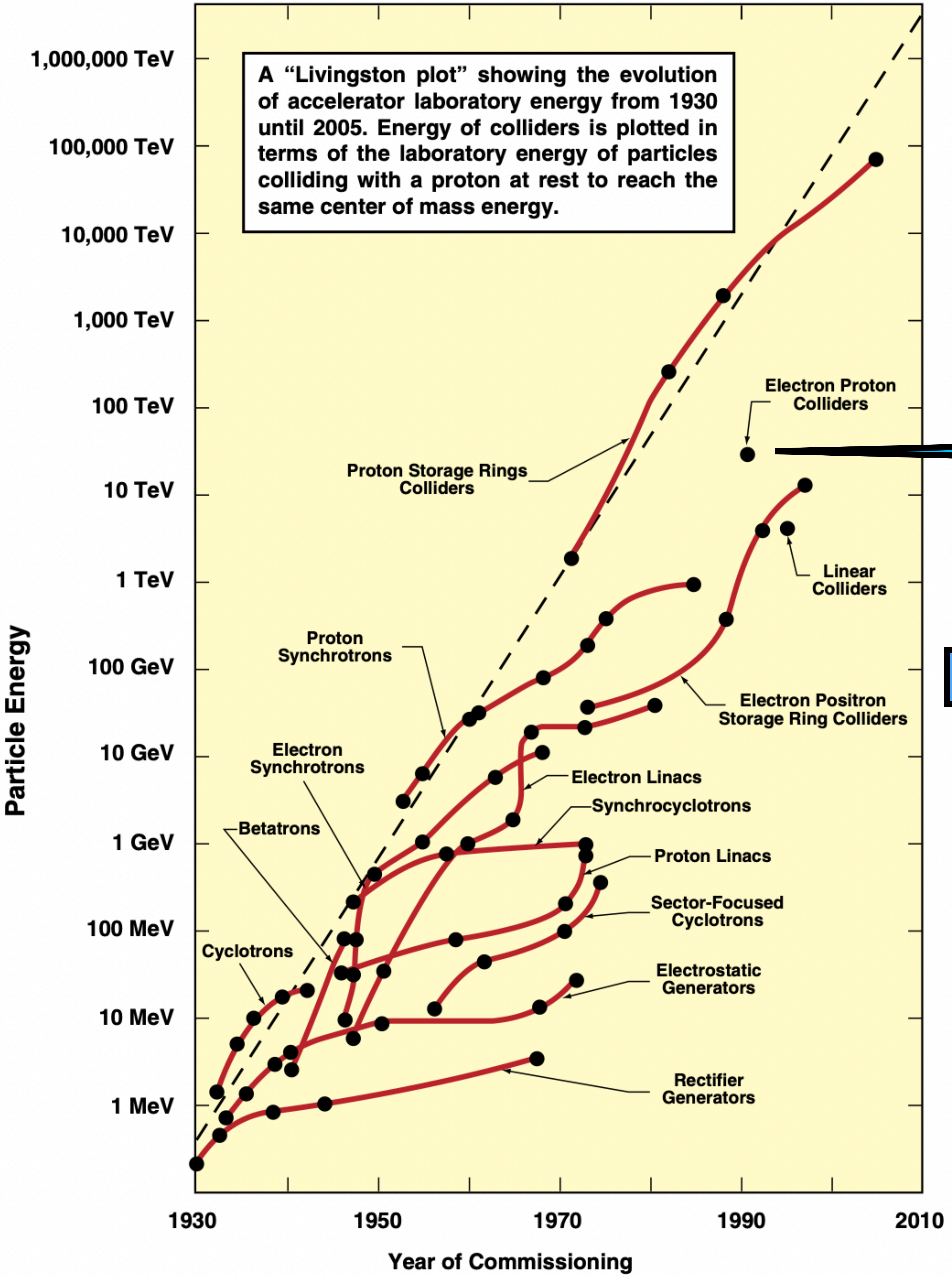

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HERA

To study the proton, probes at high energies (small de Broglie wave length) are needed

To study the inside of the proton, even larger energies are needed

Hopefully, we will add another ep collider in a few years when EIC enters operation

HERA

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Located at DESY in Hamburg
6.3 km of circumference
2 accelerators: protons and electrons or positrons

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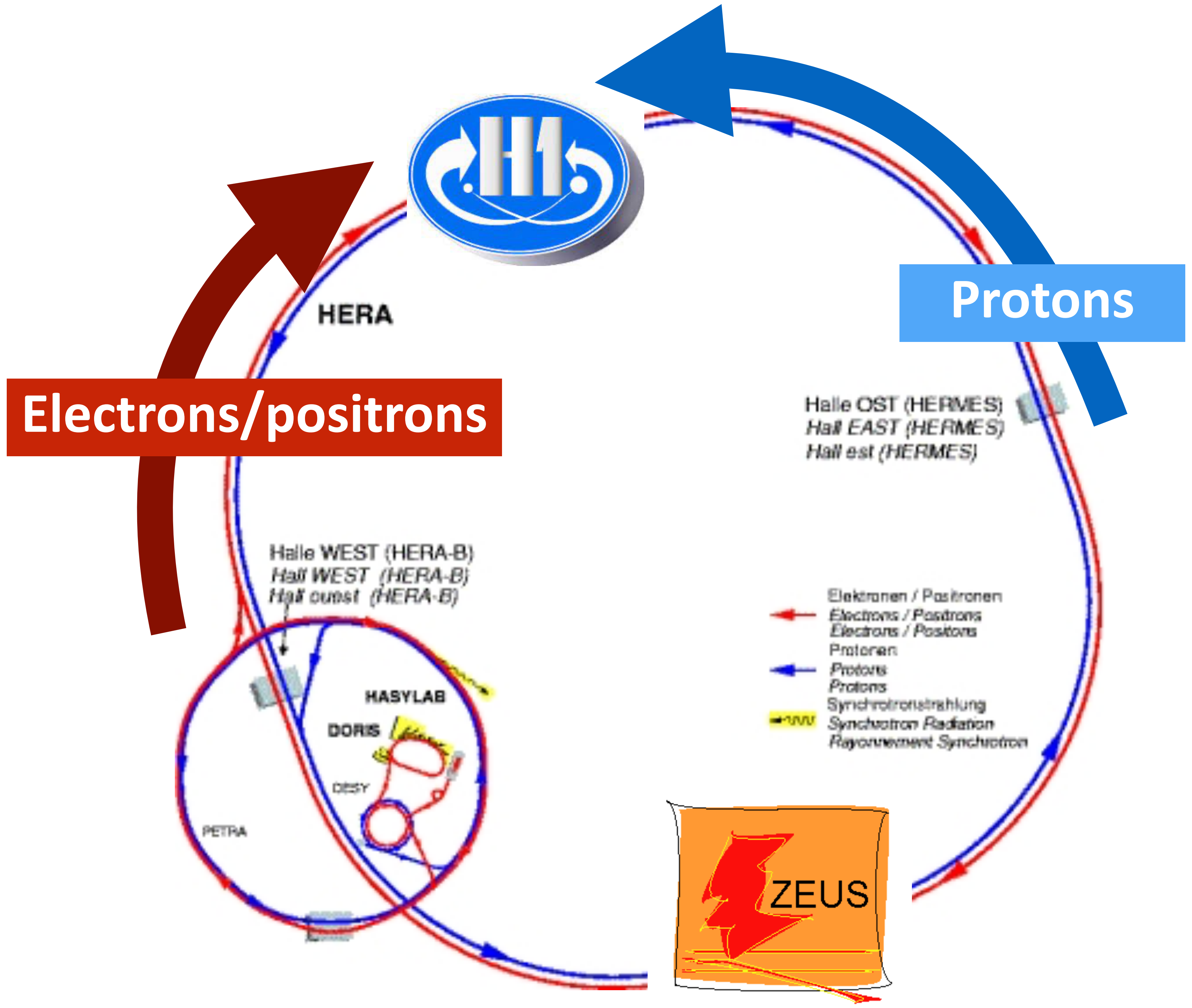
Two beam-target experiments, HERMES, HERA-B
Two collider experiments, H1 and ZEUS



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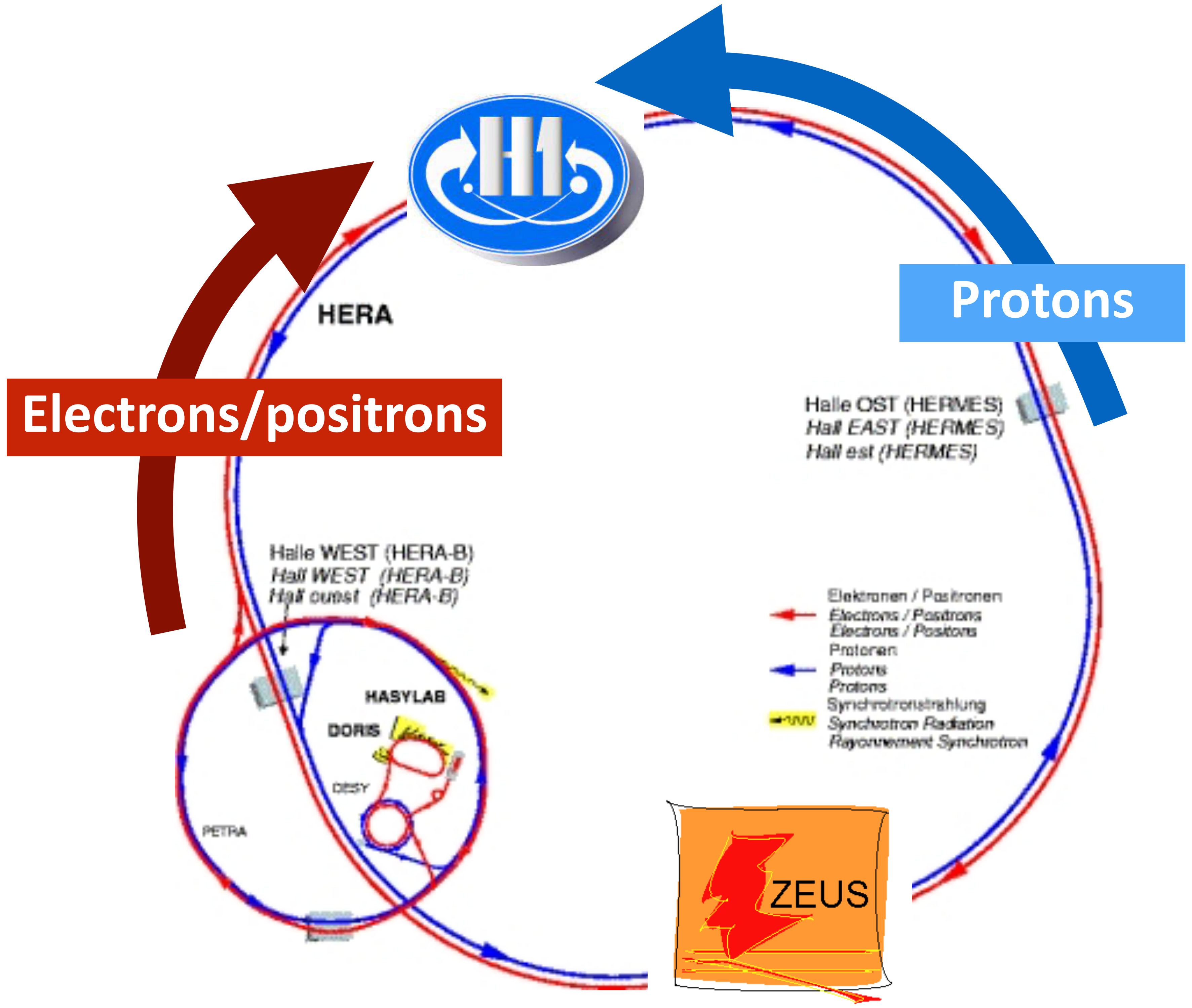
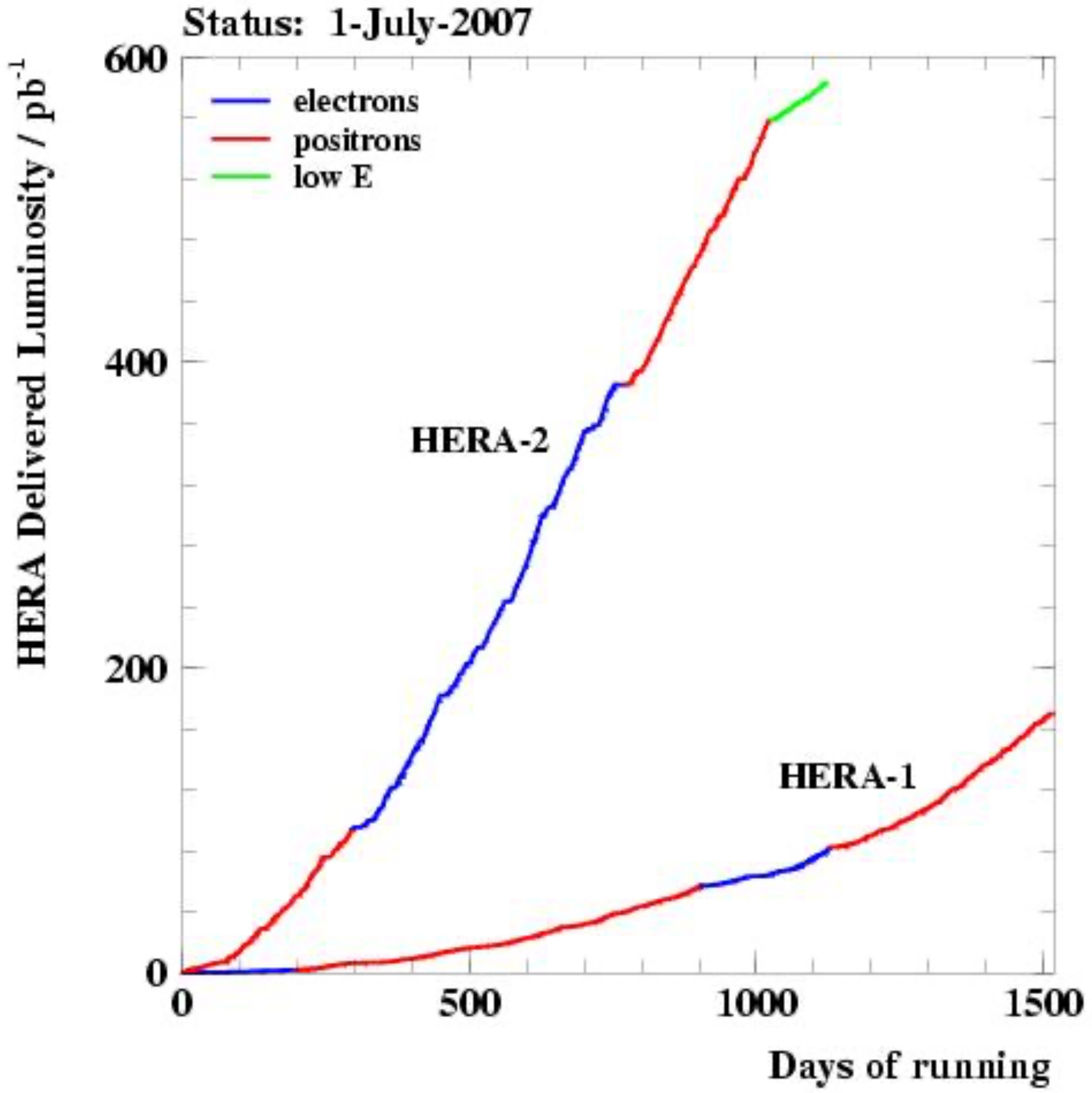


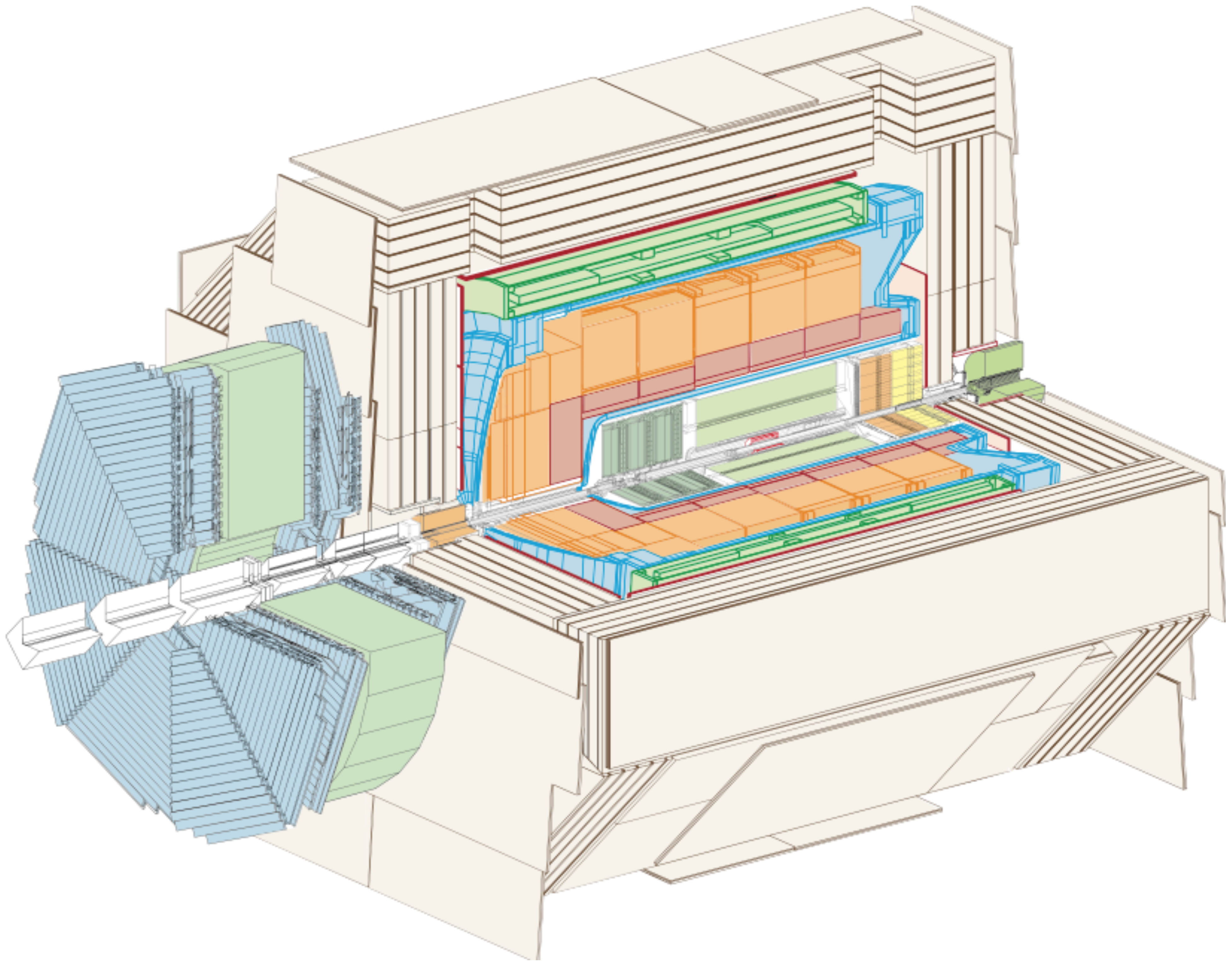
HERA-I, 1992–2000
e± beam 27.5 GeV, p beam 820 GeV (1992–1997)
p beam 920 GeV (1998–2000)

HERA-II, 2002–2007
e± longitudinally polarised, p beam 920 GeV
also p beam at 575 and 460 GeV



Guillermo Contreras, CTU in Prague

H1 detector: central detectors



Asymmetric detector

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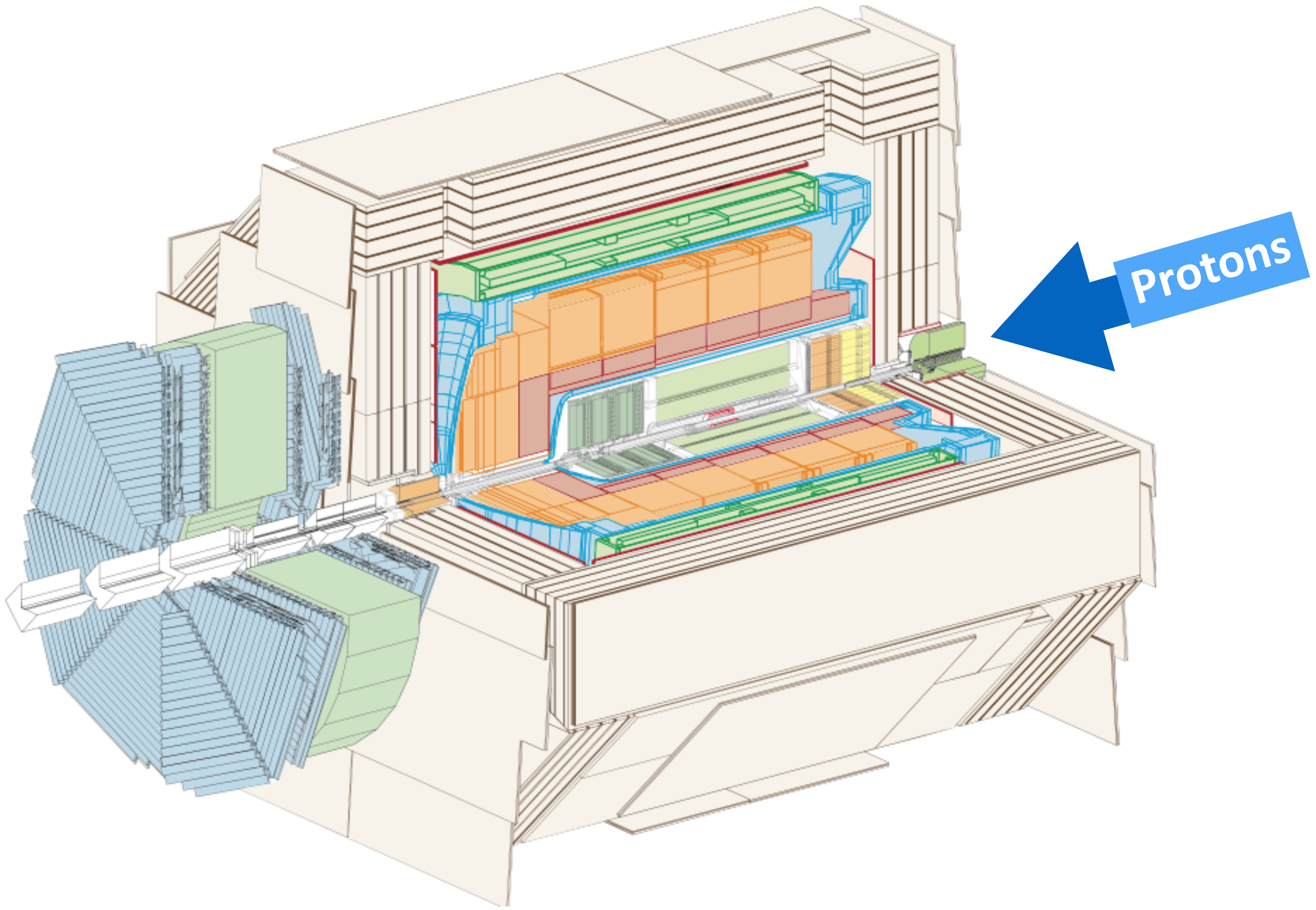

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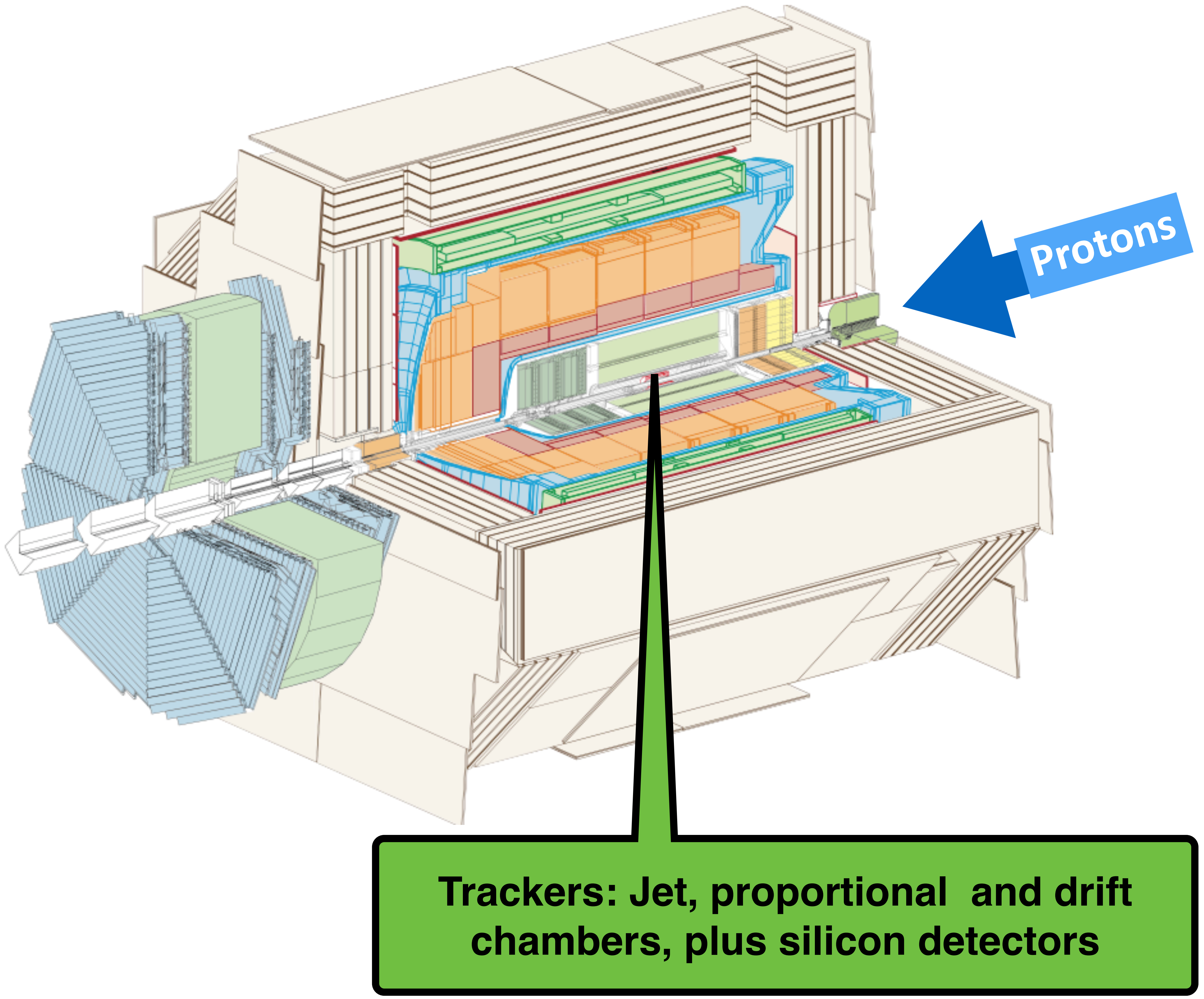

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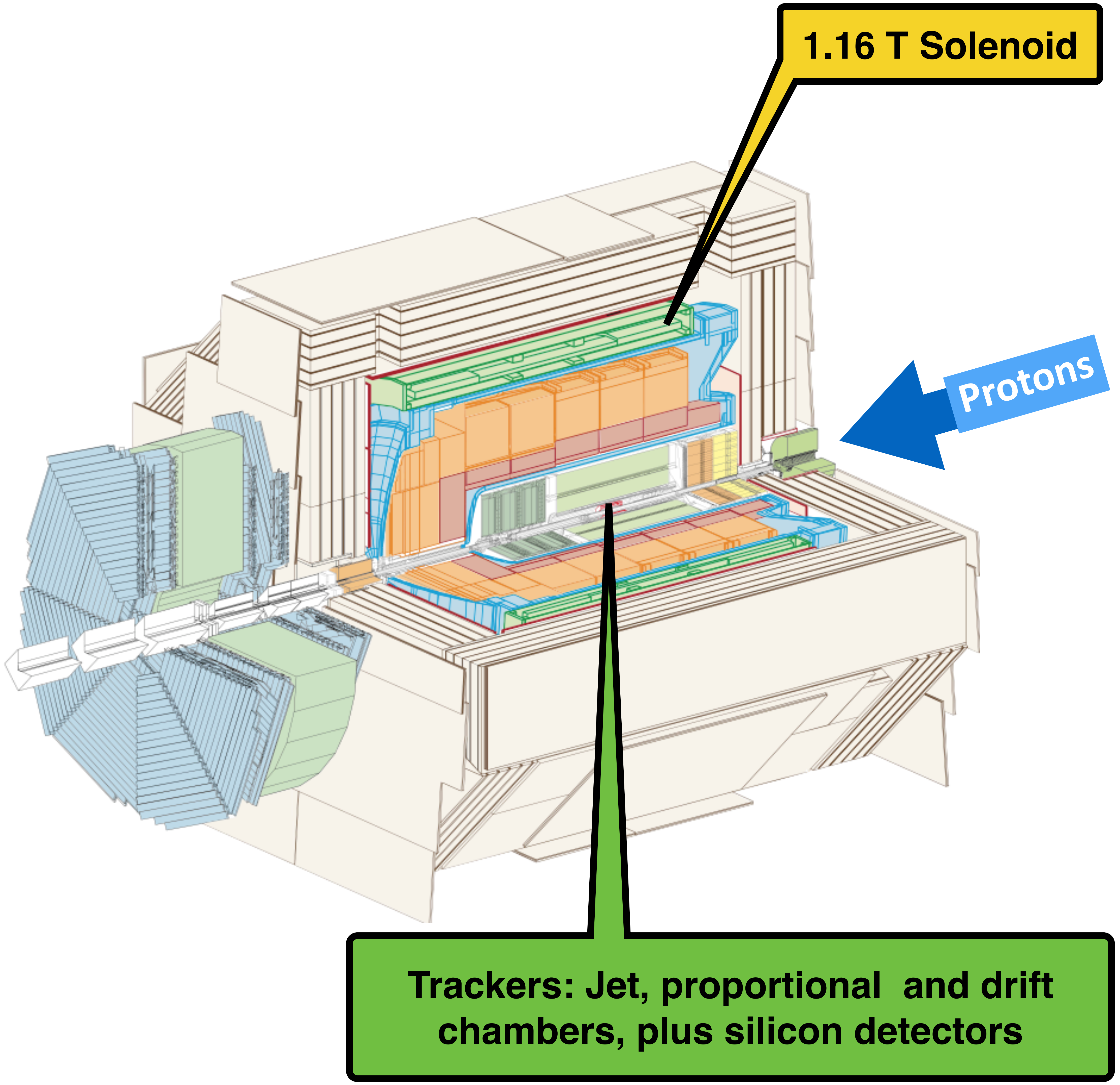

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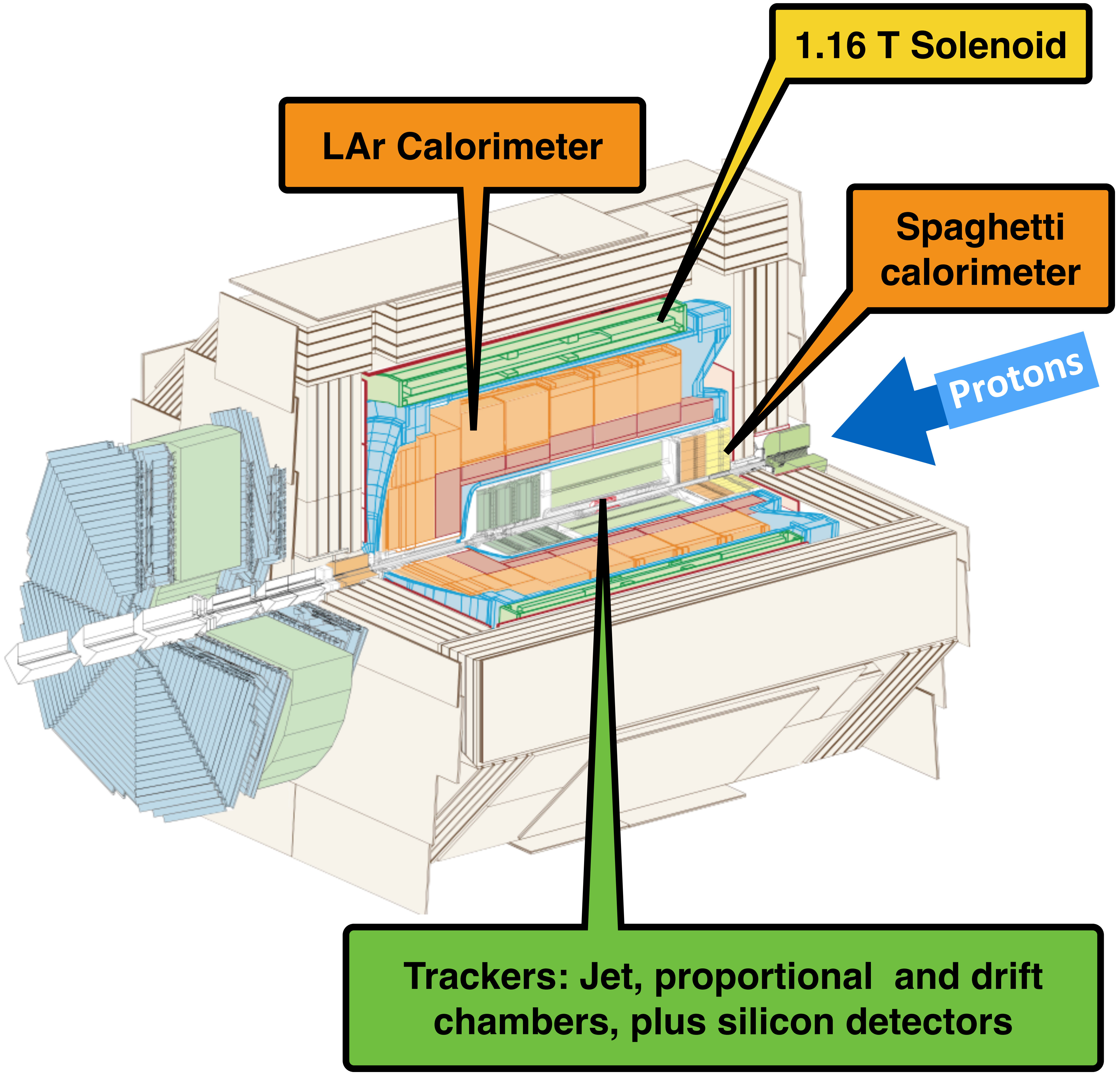

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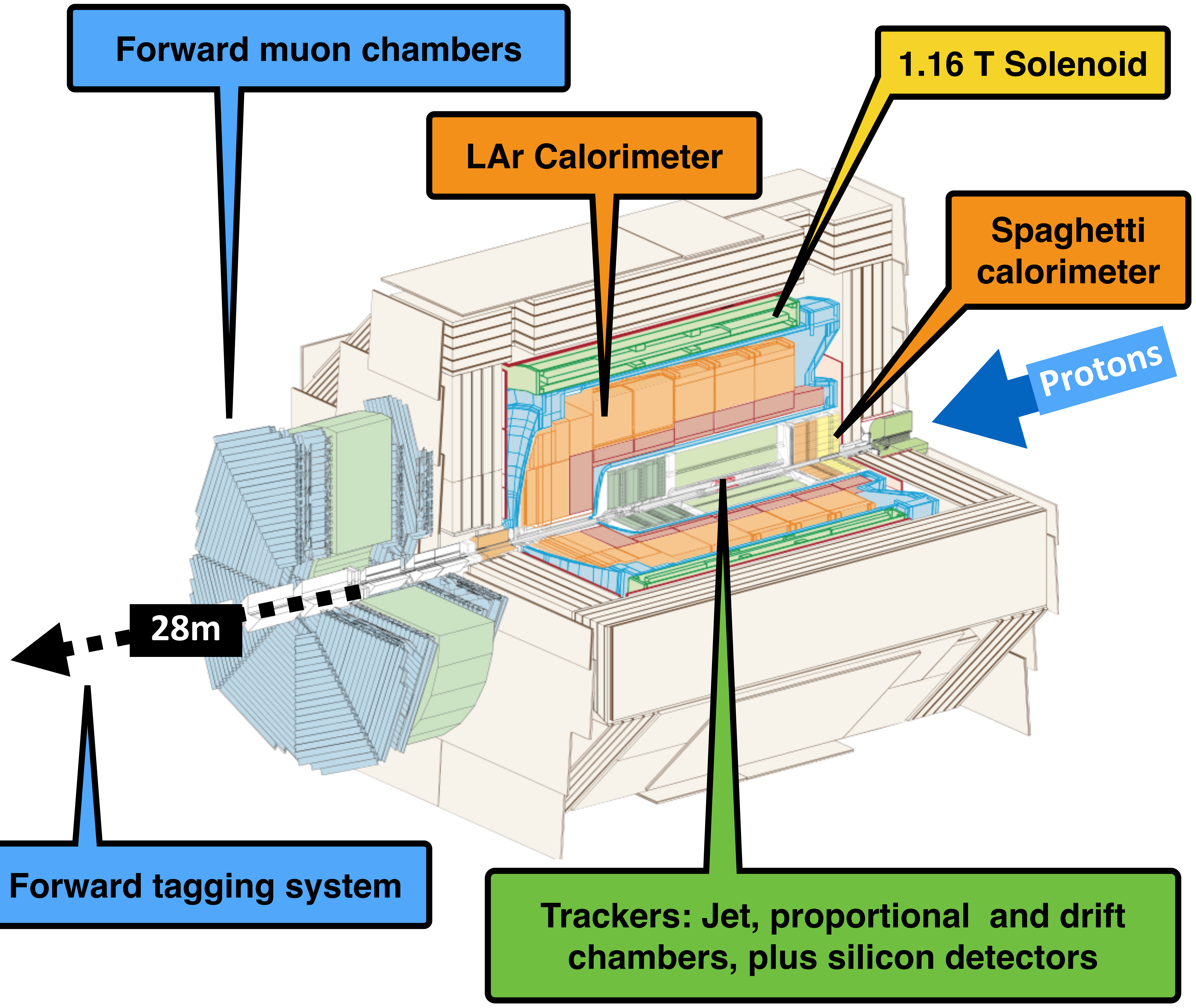

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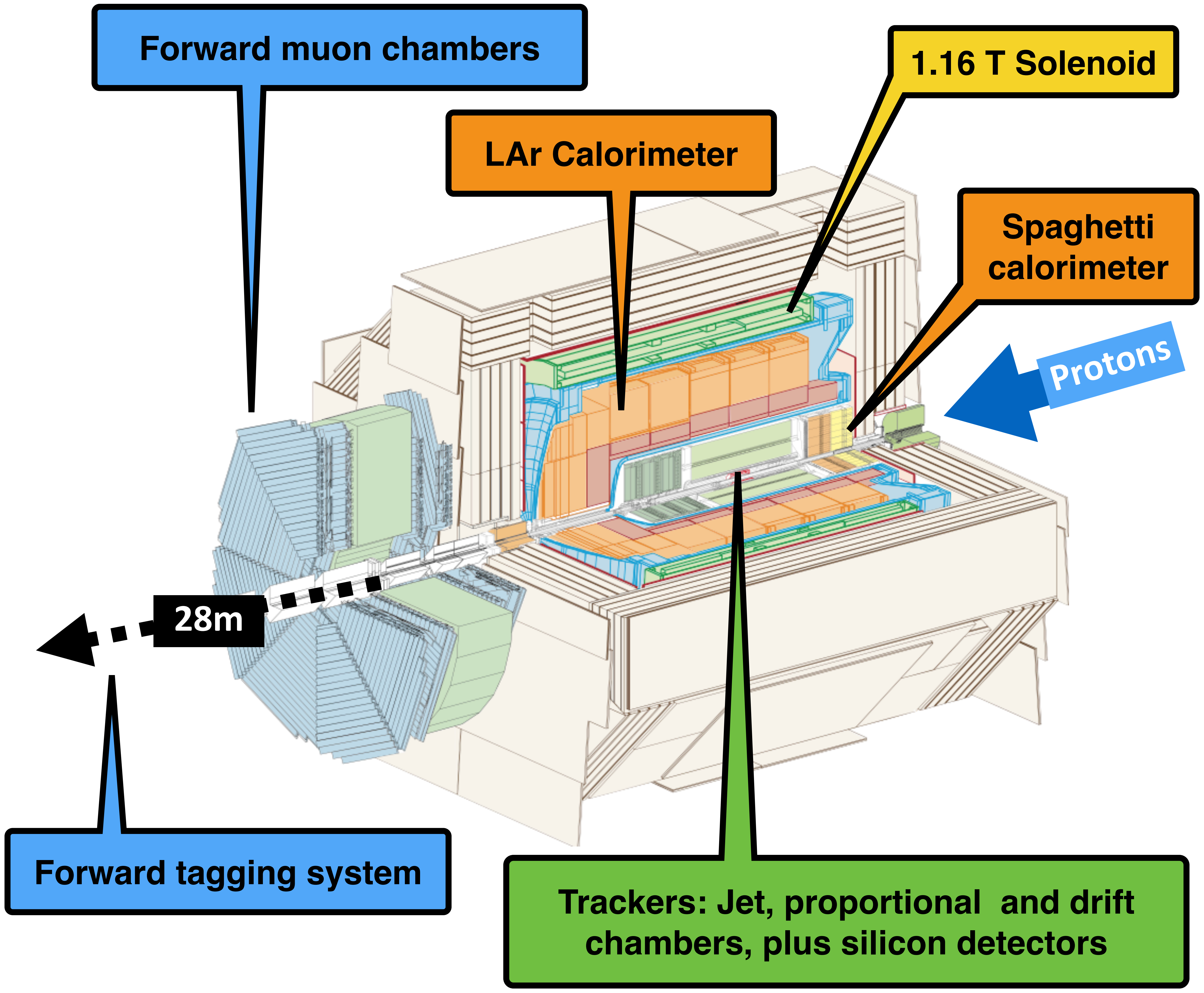

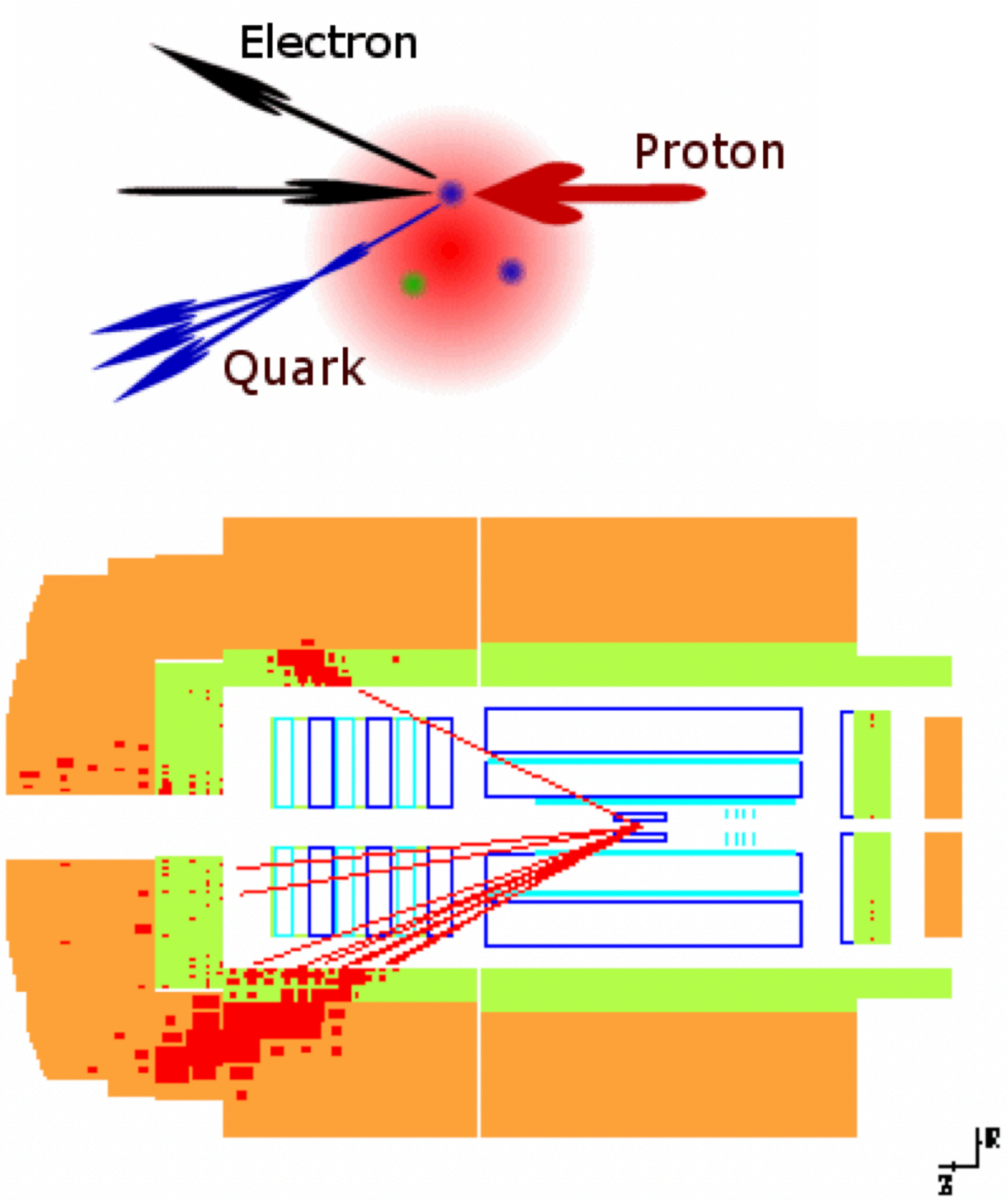

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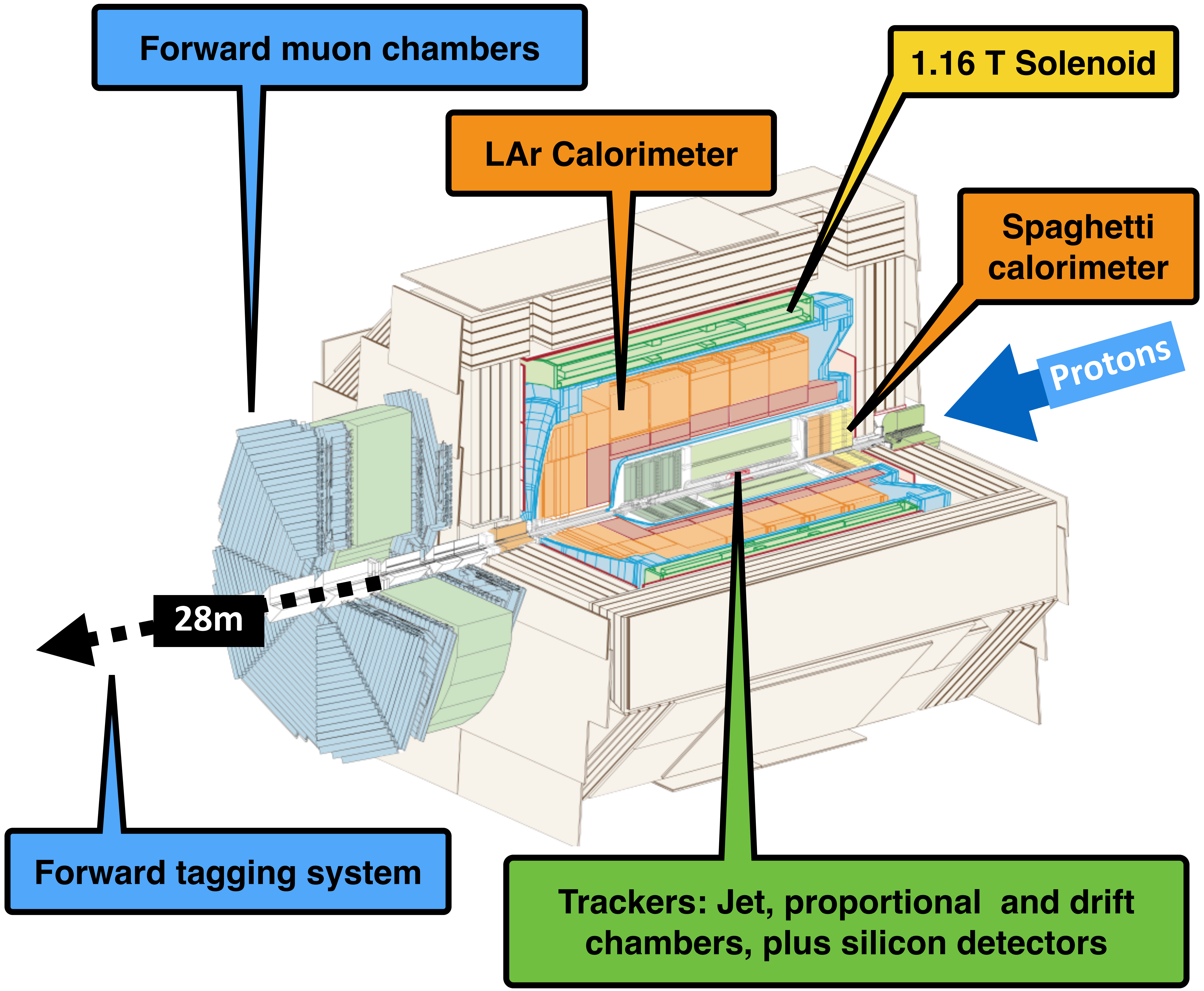
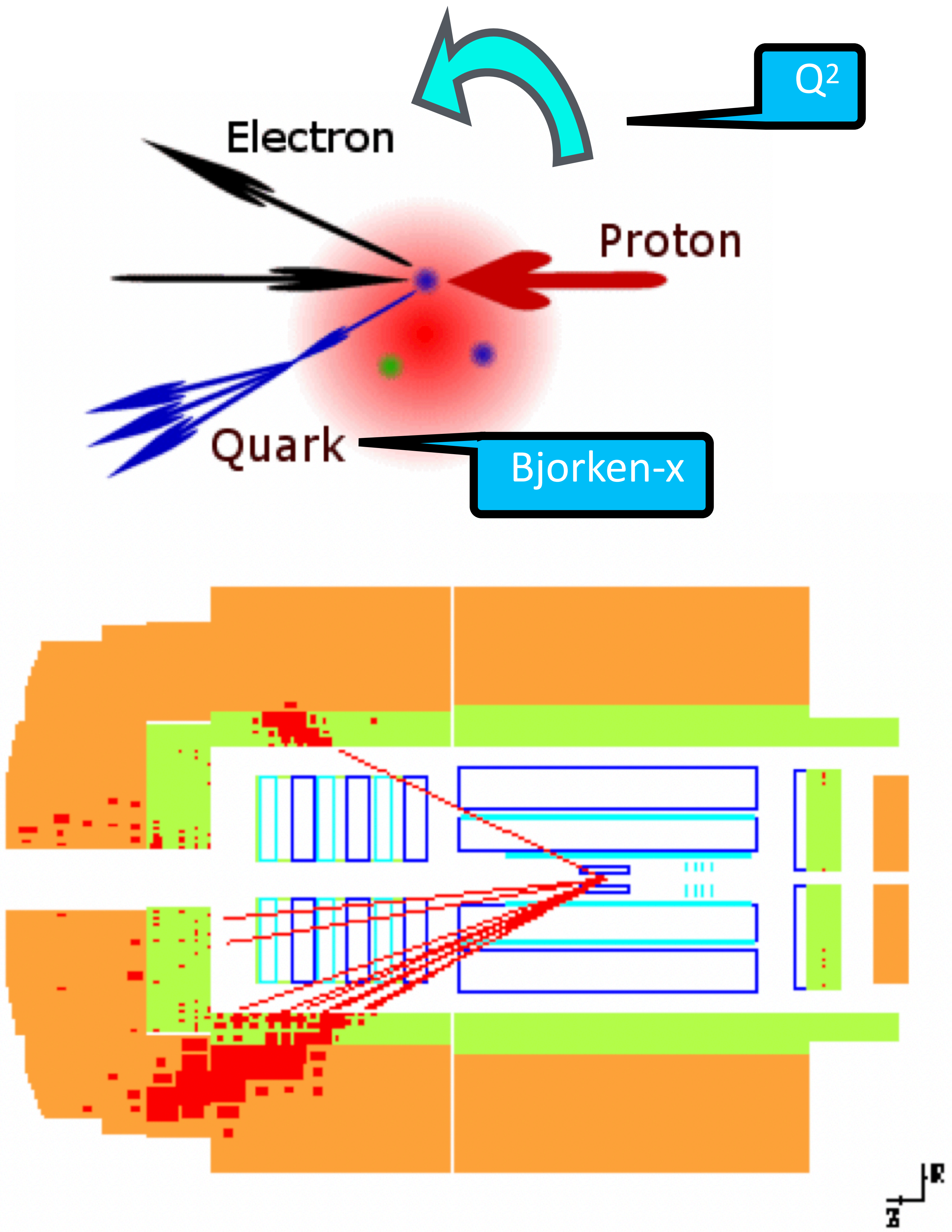
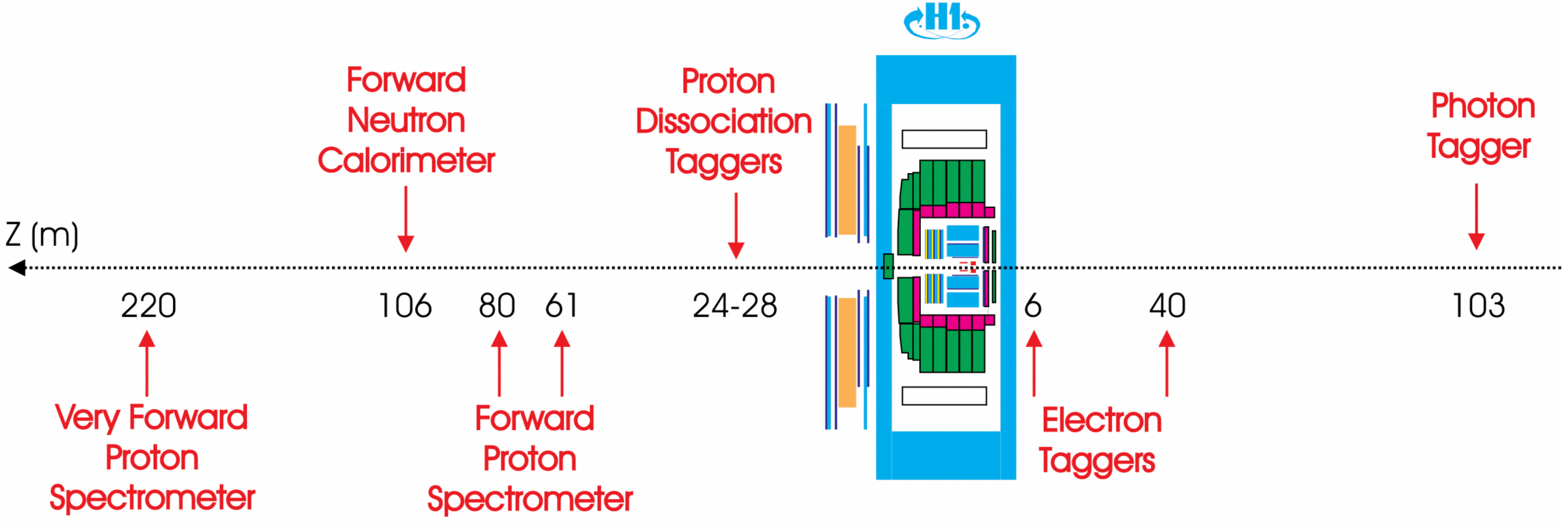




Asymmetric detector

H1 detector: forward detectors

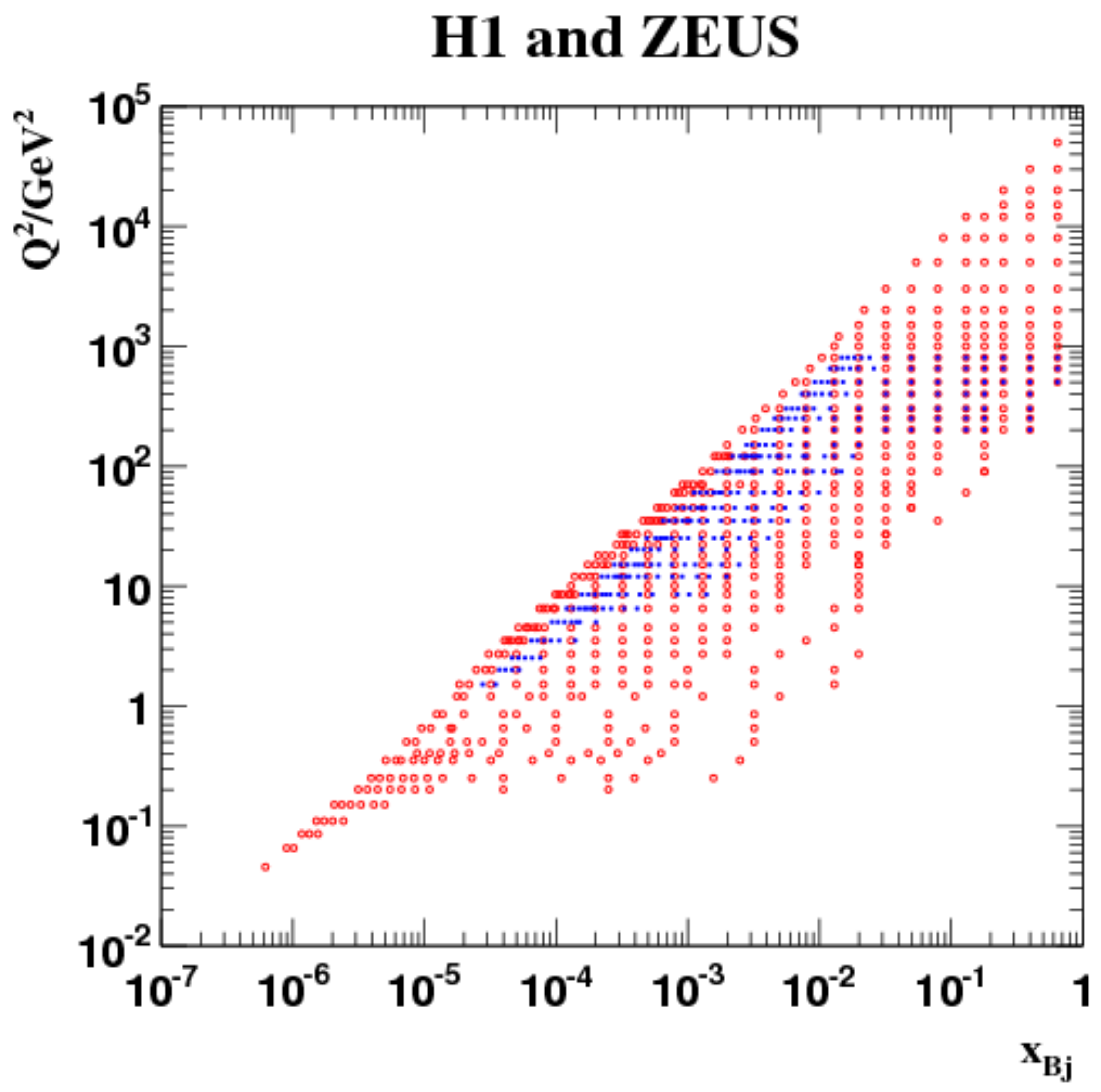


Tag diffractive processes

Luminosity (BH process) and phootoproduction

Newman, Wing, https://inspirehep.net/literature/1247974

HERA: Kinematic coverage



H1 and ZEUS, https://inspirehep.net/literature/1377206

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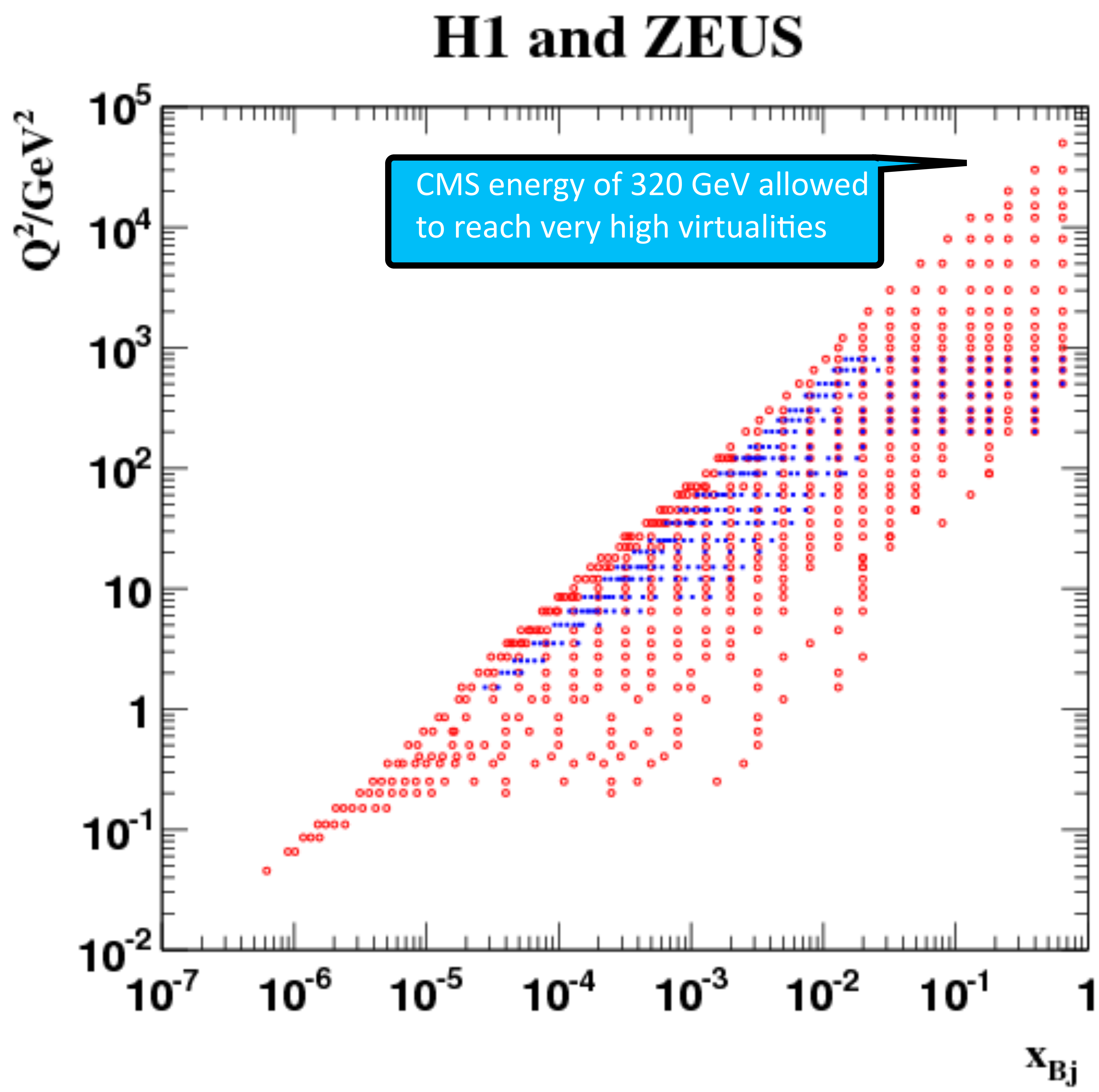

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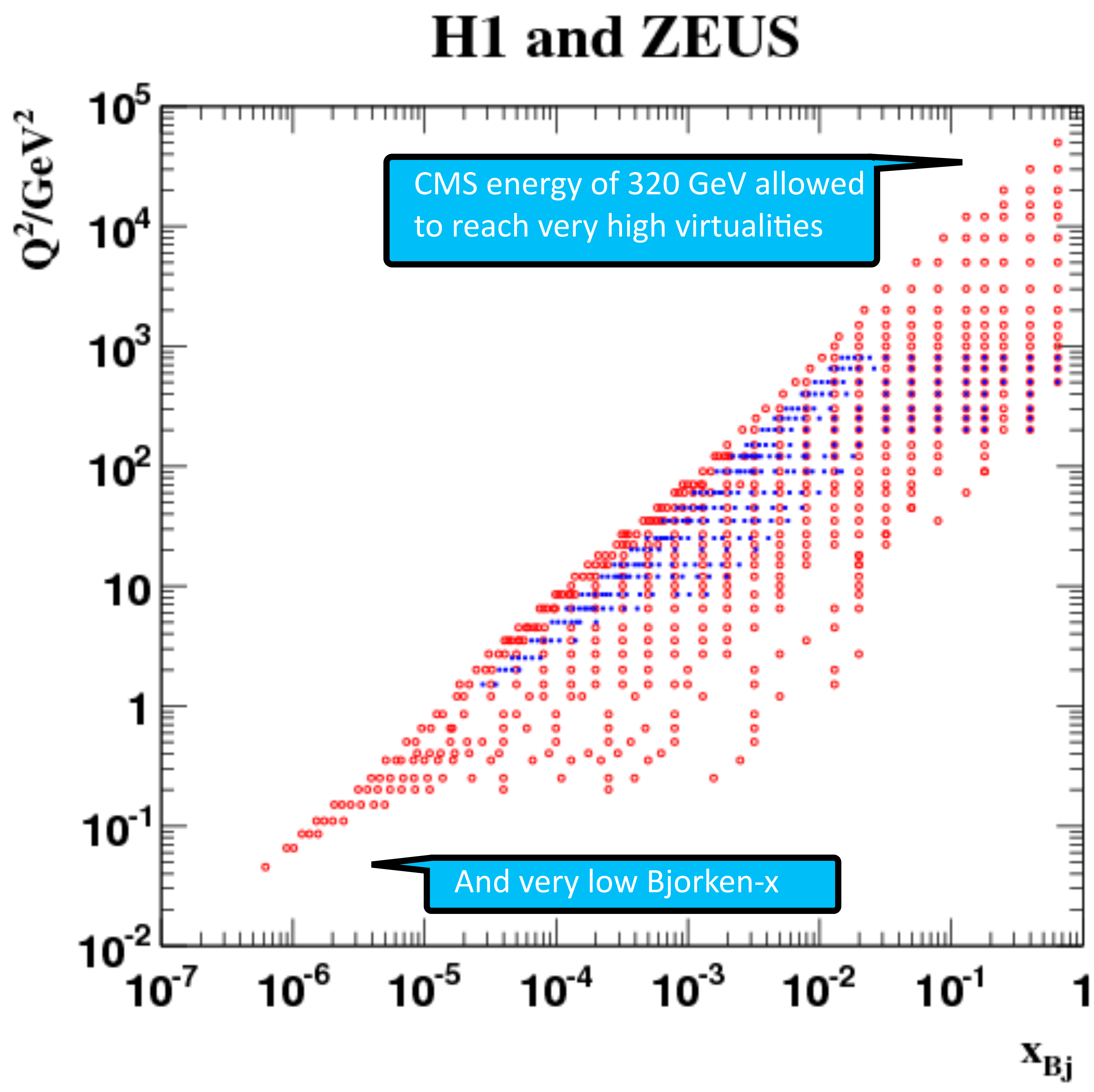

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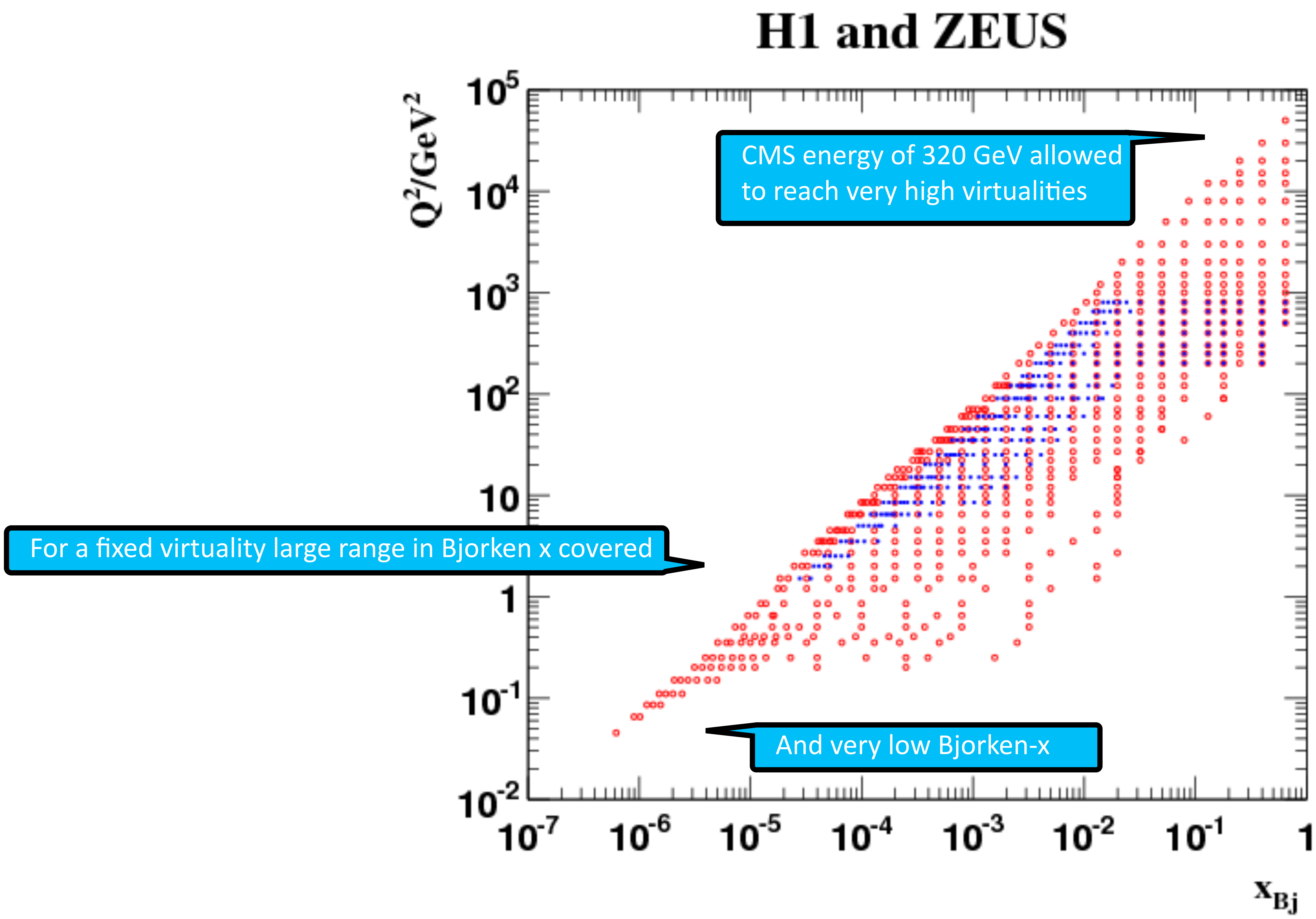

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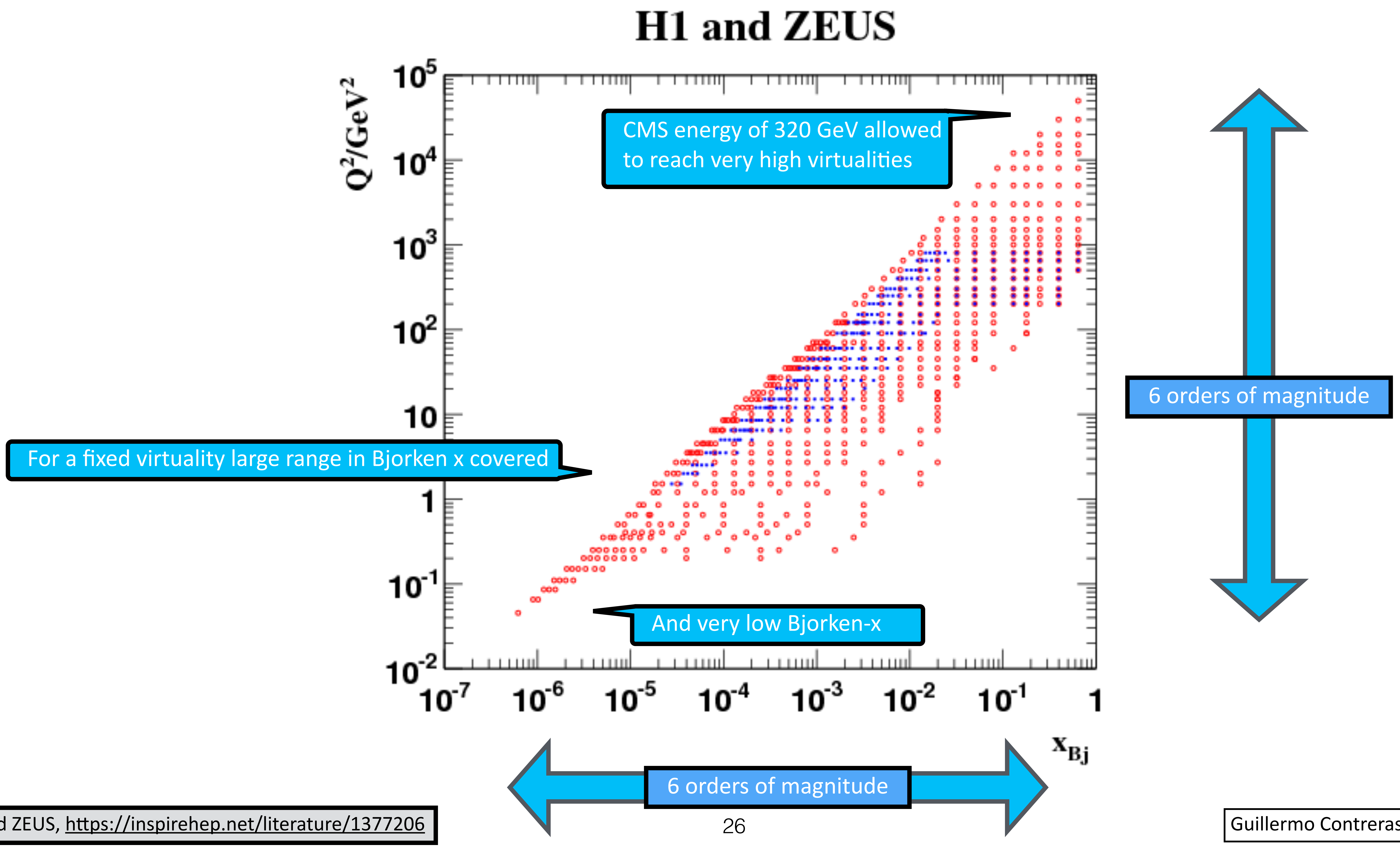
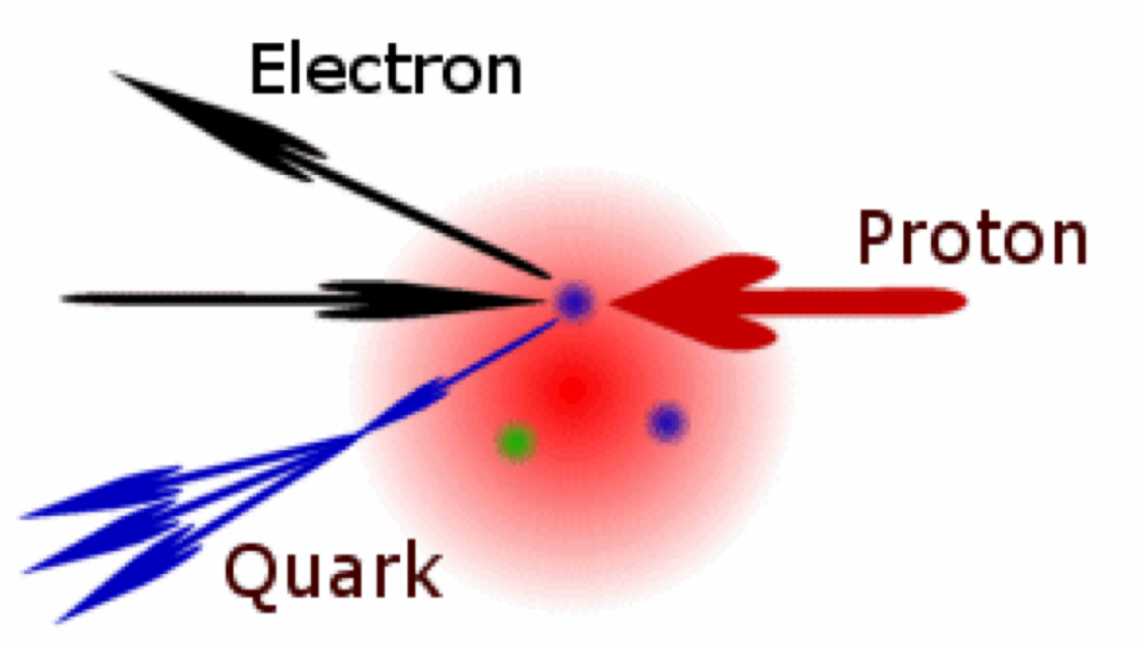


H1 and ZEUS, https://inspirehep.net/literature/1377206

At this point in time, we have an accelerator and detectors with a huge range in kinematics
and we know how to extract QCD information from the measurements.
Let's look at HERA data to extract the behaviour of quarks and gluons inside hadrons ...

Reconstructing the kinematics

Kinematics could be determined using only the scattered electron



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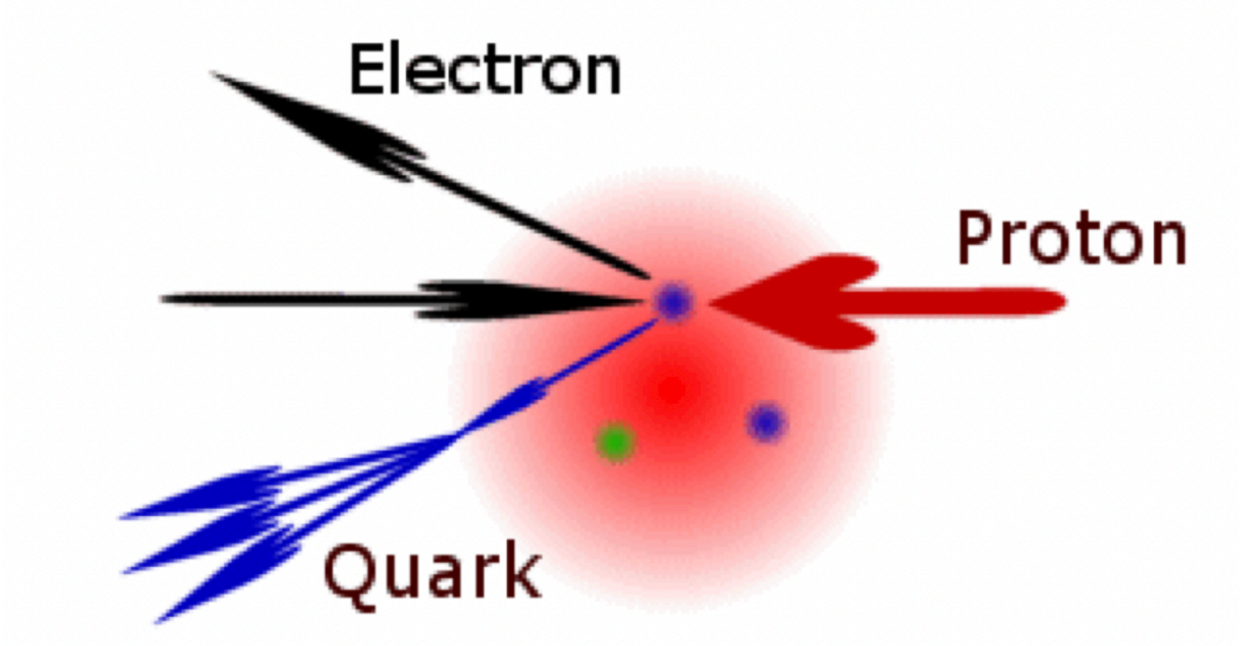

Or the final hadronic state

Guillermo Contreras, CTU in Prague

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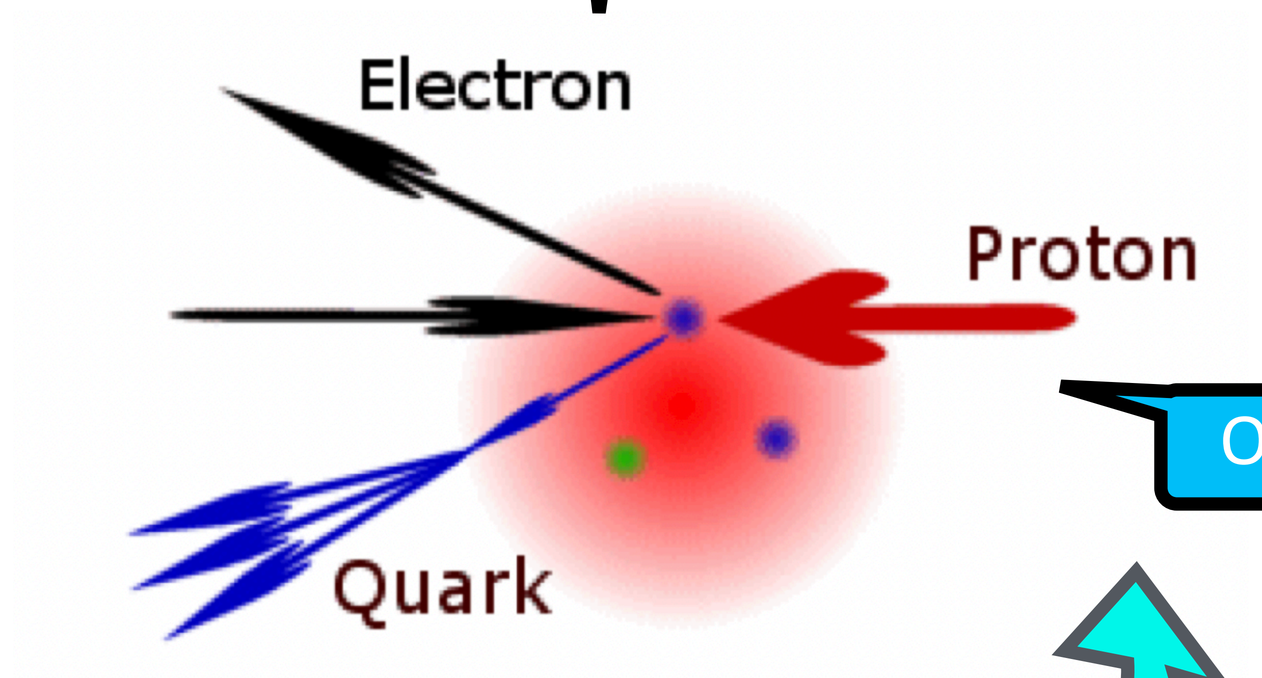

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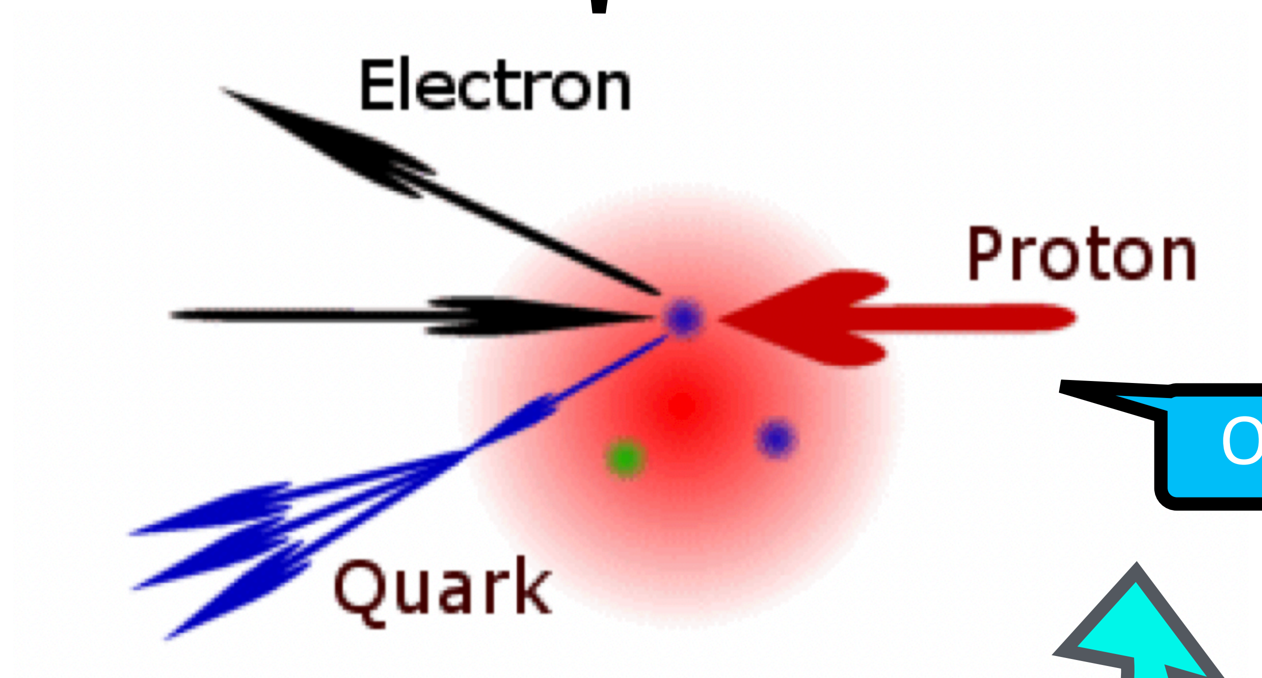
If beam energies are known ...



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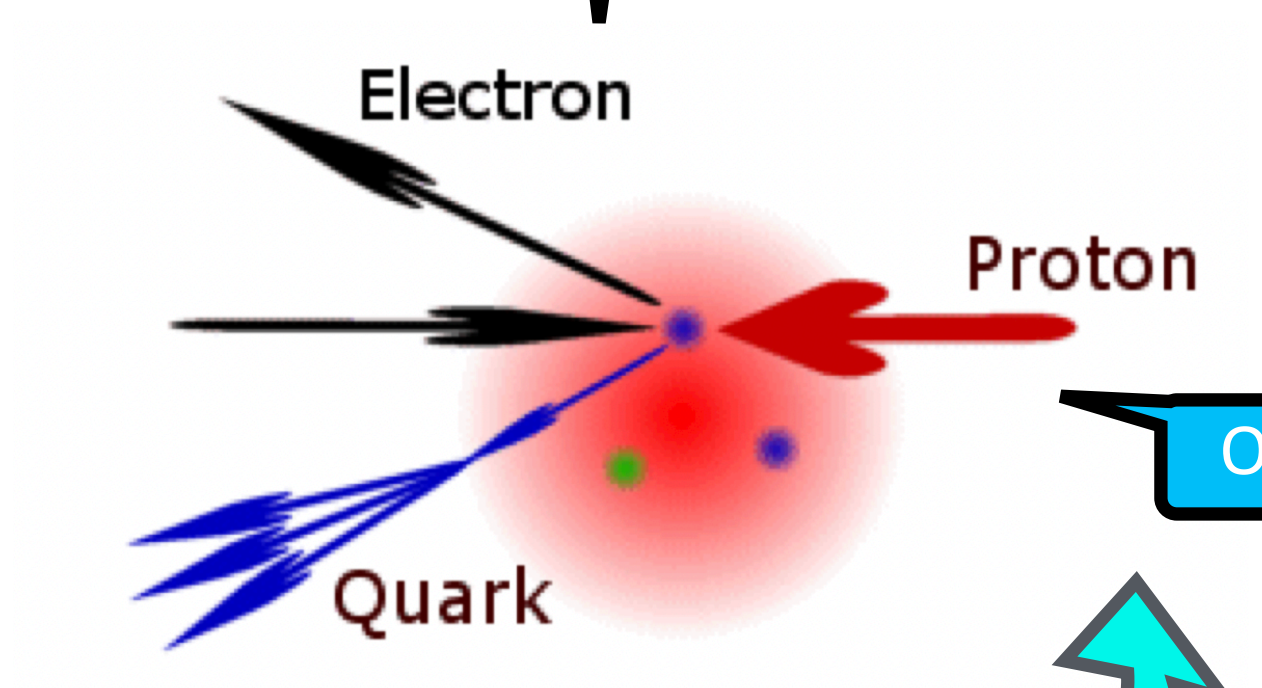

Or mixtures of both

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Not an exhaustive list

Method	y	Q^2	x
e	$1-\frac{E}{E^e}\sin^2\theta/2$	$4E^eE\cos^2\theta/2$	Q^2/ys
h	$\Sigma/2E^e$	$\frac{T^2}{1-y_h}$	Q^2/ys
m	y_h	Q_e^2	Q^2/ys
DA	$\frac{\tan\gamma/2}{\tan\gamma/2+\tan\theta/2}$	$4E^{e2}\frac{\cot\theta/2}{\tan\gamma/2+\tan\theta/2}$	Q^2/ys
Σ	$\frac{\Sigma}{\Sigma+E(1-\cos\theta)}$	$\frac{E^2\sin^2\theta}{1-y_\Sigma}$	Q^2/ys
I DA	y_{DA}	$E^2\tan\theta/2\frac{\tan\gamma/2+\tan\theta/2}{2\cot\theta/2+\tan\theta/2}$	$\frac{E}{E^p}\frac{\cot\gamma/2+\cot\theta/2}{\cot\theta/2+\tan\theta/2}$
I Σ	y_Σ	Q_Σ^2	$\frac{E}{E^p}\frac{\cos^2\theta/2}{y_\Sigma}$

Bassler, Bernardi, https://inspirehep.net/literature/381117

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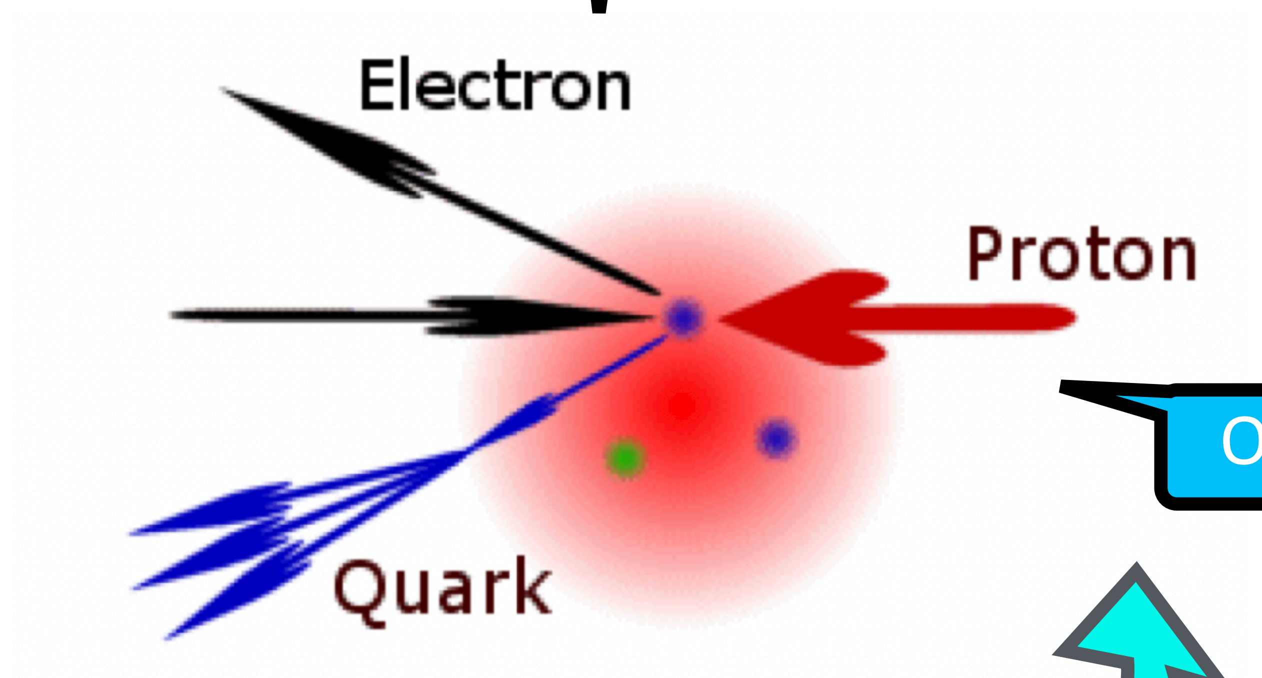

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Homework: deduce some of the formulas in the table

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IDA	y_{DA}	$E^2\tan\theta/2\frac{\tan\gamma/2+\tan\theta/2}{2\cot\theta/2+\tan\theta/2}$	$\frac{E}{E^p}\frac{\cot\gamma/2+\cot\theta/2}{\cot\theta/2+\tan\theta/2}$
IΣ	y_Σ	Q_Σ^2	$\frac{E}{E^p}\frac{\cos^2\theta/2}{y_\Sigma}$

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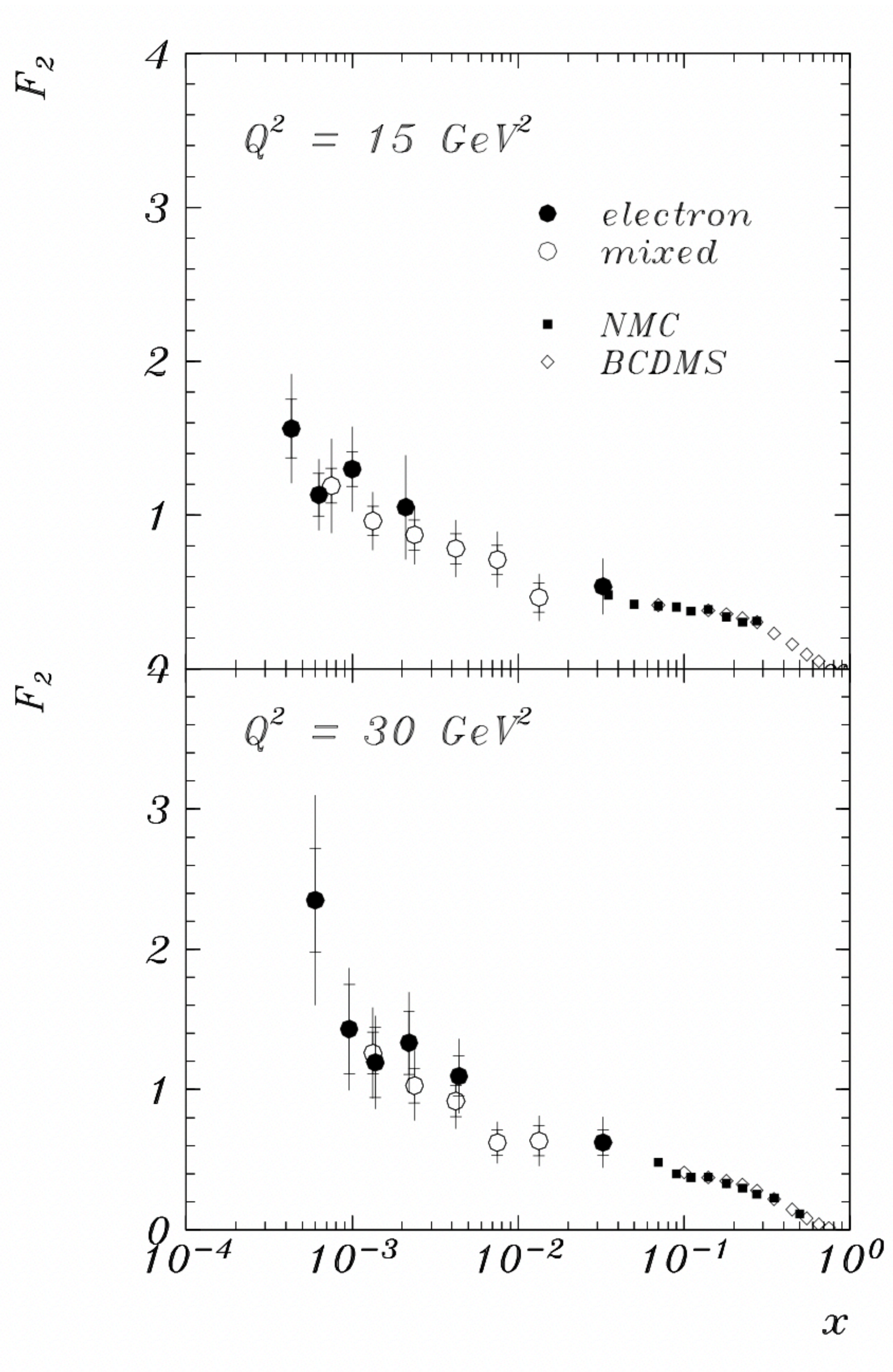
Most of the results shown here are from H1, just because I am more familiar with them. ZEUS produced similar results along the way.

The proton structure function with the first HERA data (1993)

H1, https://inspirehep.net/literature/357797



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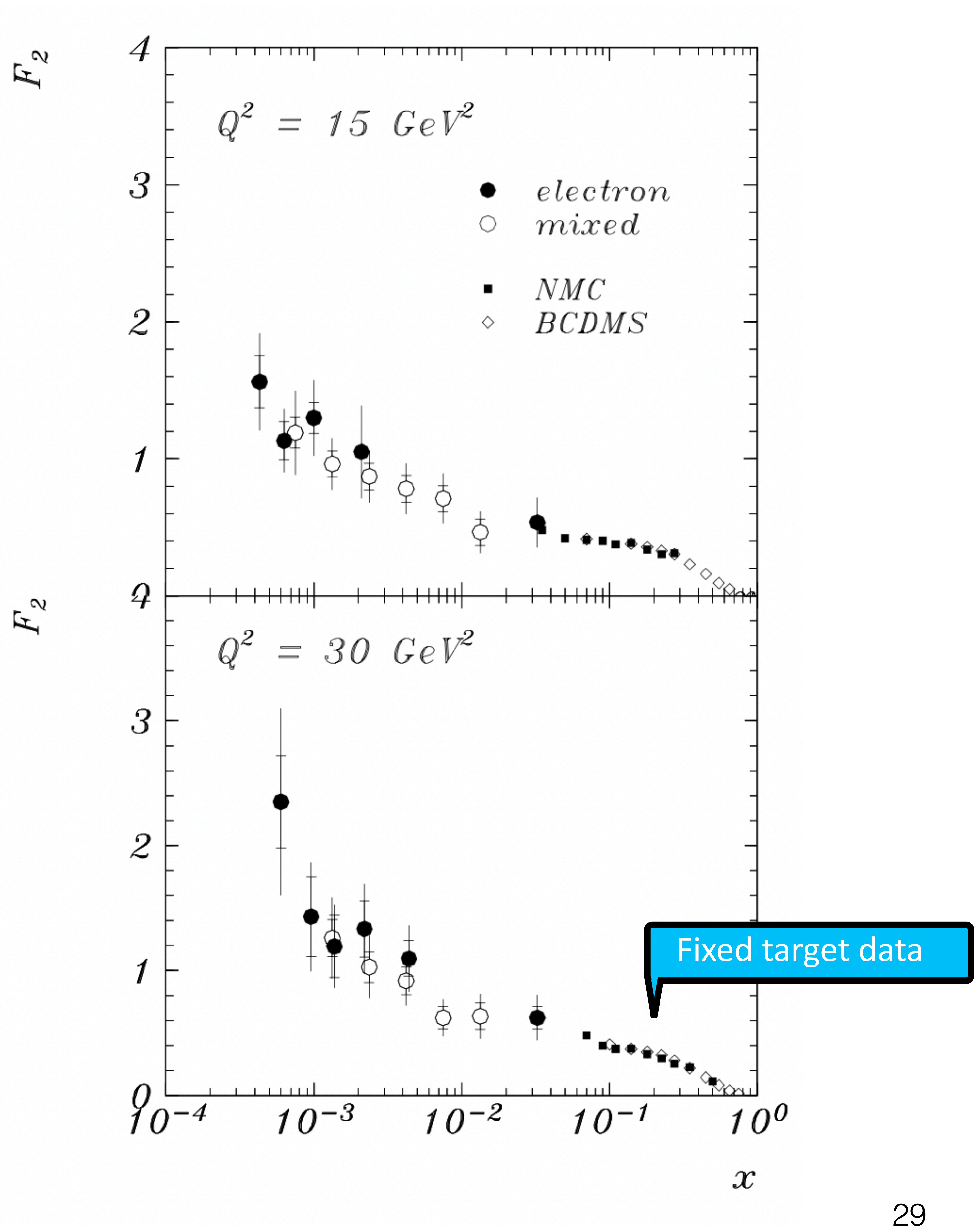

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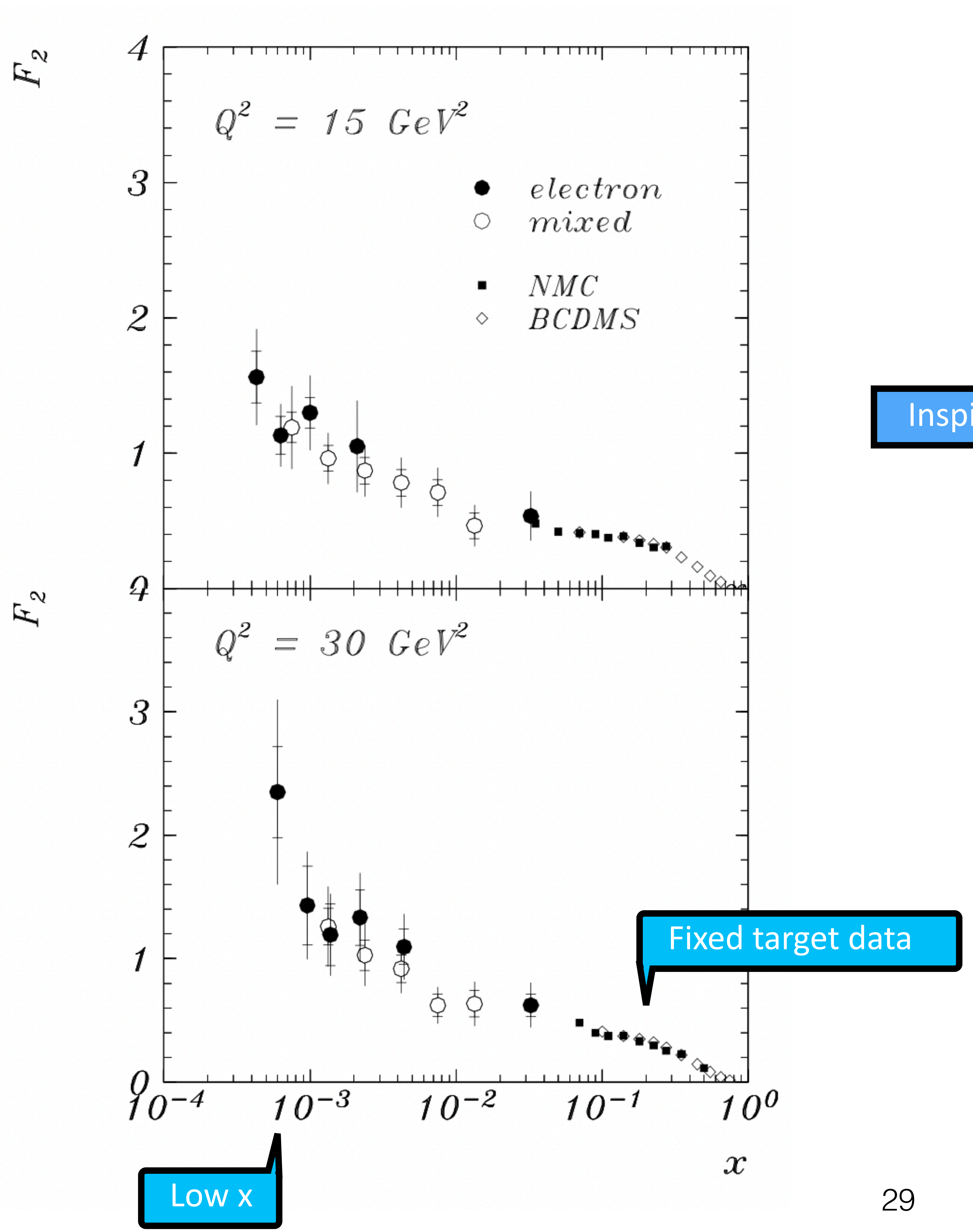

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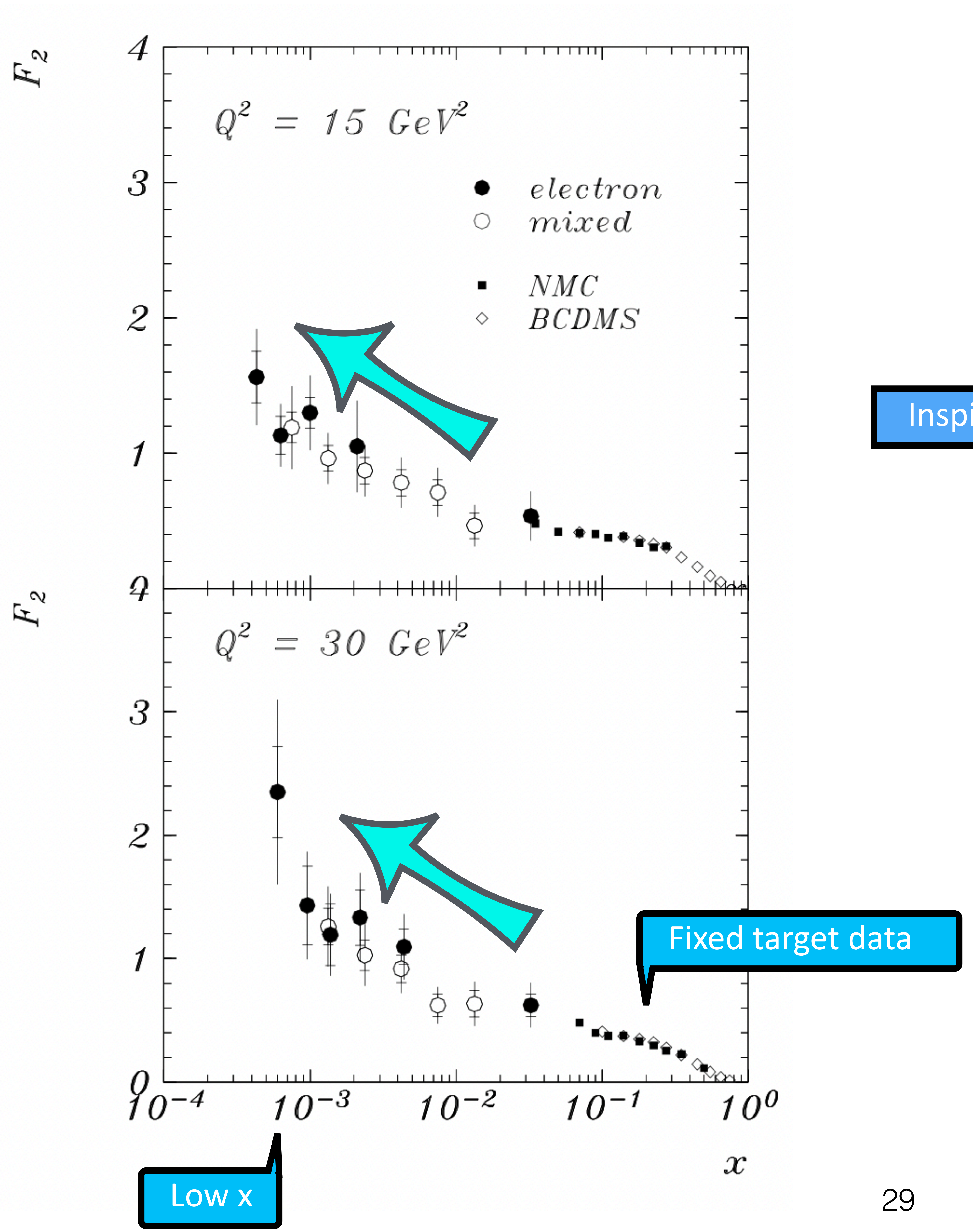

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F_2 raises with decreasing Bjorken-x

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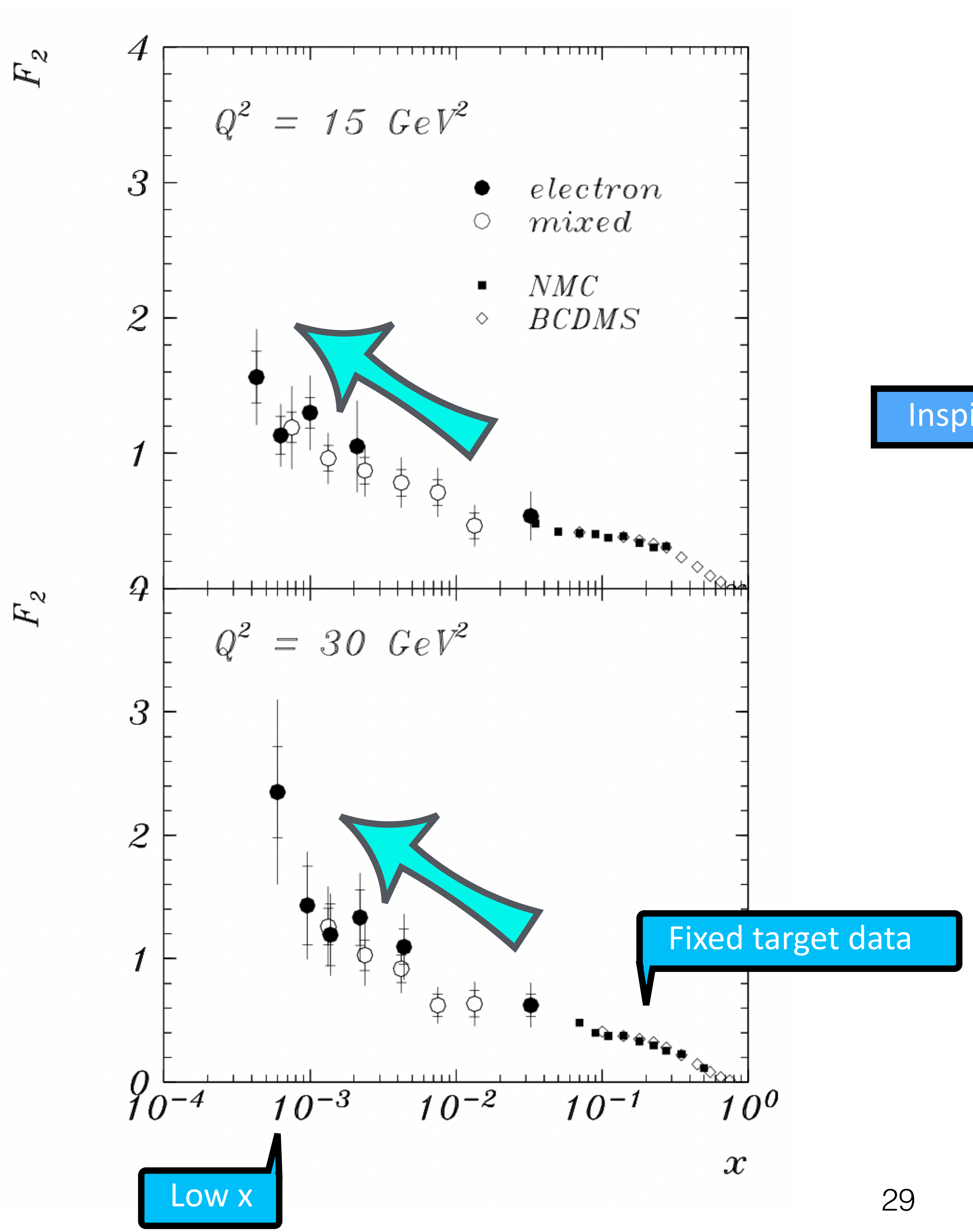
H1, https://inspirehep.net/literature/357797



Most of the results shown here are from H1, just because I am more familiar with them. ZEUS produced similar results along the way.

Inspite of the large statistical and systematical uncertainties, it is cleared that:

Data reach 2 orders of magnitude smaller Bjorken-x than fixed target experiments

F_2 raises with decreasing Bjorken-x

How does F_2 change with the photon virtuality?

The evolution of hadron structure is predicted within pQCD in the form of differential equations

Parenthesis: Altarelli-Parisi equations

1977: Evolution equations

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *
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Received 12 April 1977

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In this paper we show that an alternative derivation of all results of current interest for the Q^2 behaviour of deep inelastic structure functions is possible. In this approach all stages of the calculation refer to parton concepts and offer a very illuminating physical interpretation of the scaling violations. In our opinion the present approach, although less general, is remarkably simpler than the usual one since all relevant results can be derived in a direct way from the basic vertices of QCD, with no loop calculations being involved (the only exception is the lowest order expression for the running coupling constant which we do not rederive).

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$t \equiv \ln Q^2/Q_0^2$

$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[q^i(y,t)\,P_{qq}\left(\frac{x}{y}\right) + G(y,t)\,P_{qG}\left(\frac{x}{y}\right)\right],$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_{i=1}^{2f} q^i(y,t)\,P_{Gq}\left(\frac{x}{y}\right) + G(y,t)\,P_{GG}\left(\frac{x}{y}\right)\right].$$

Probability density per unit t, at order α, of finding a gluon inside a quark with a fraction x/y of the quark momentum

Density of gluons inside the proton in the infinite momentum frame

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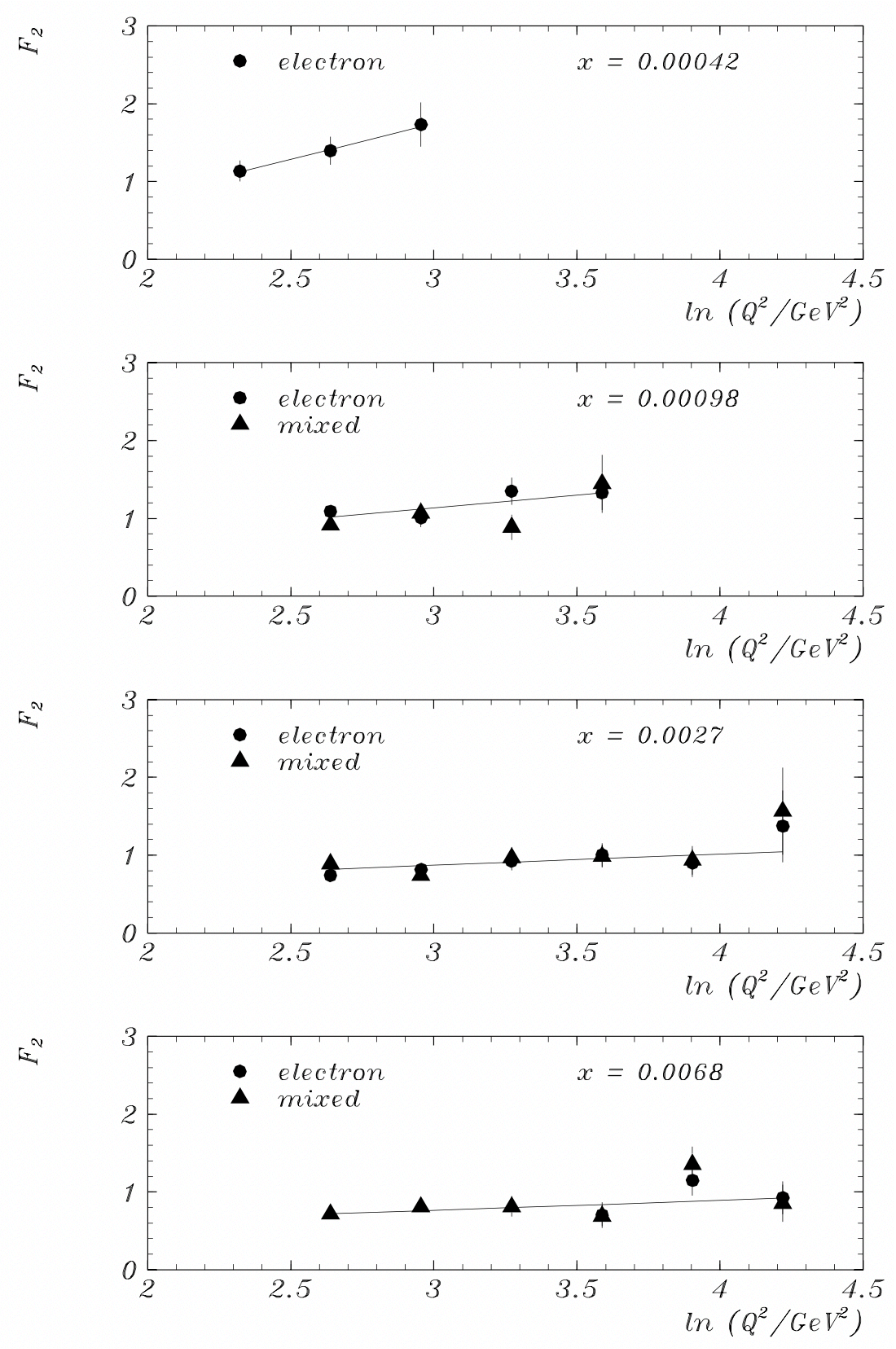
Scaling violations and the gluon in the proton (1994)

H1, https://inspirehep.net/literature/360235



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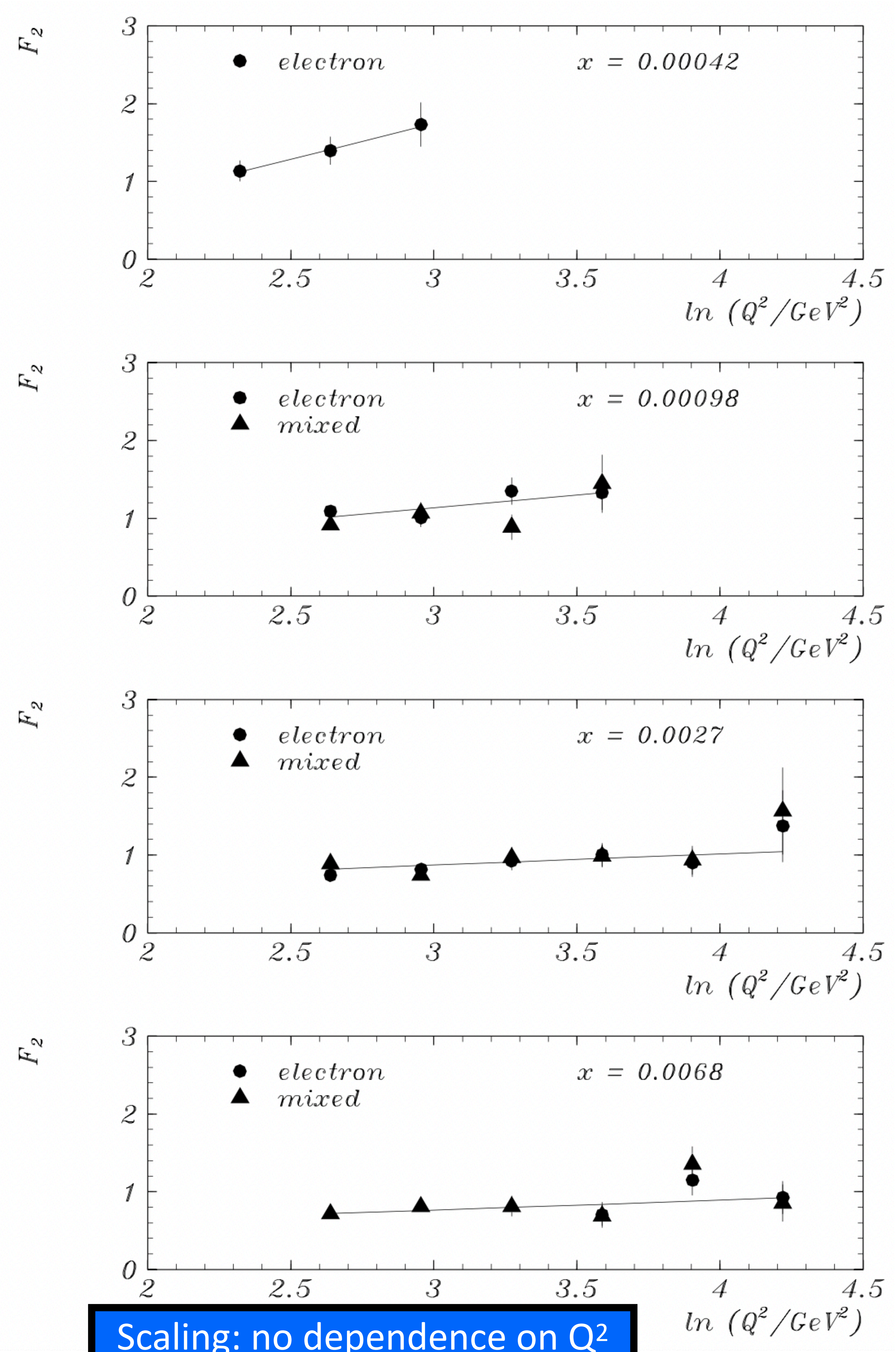

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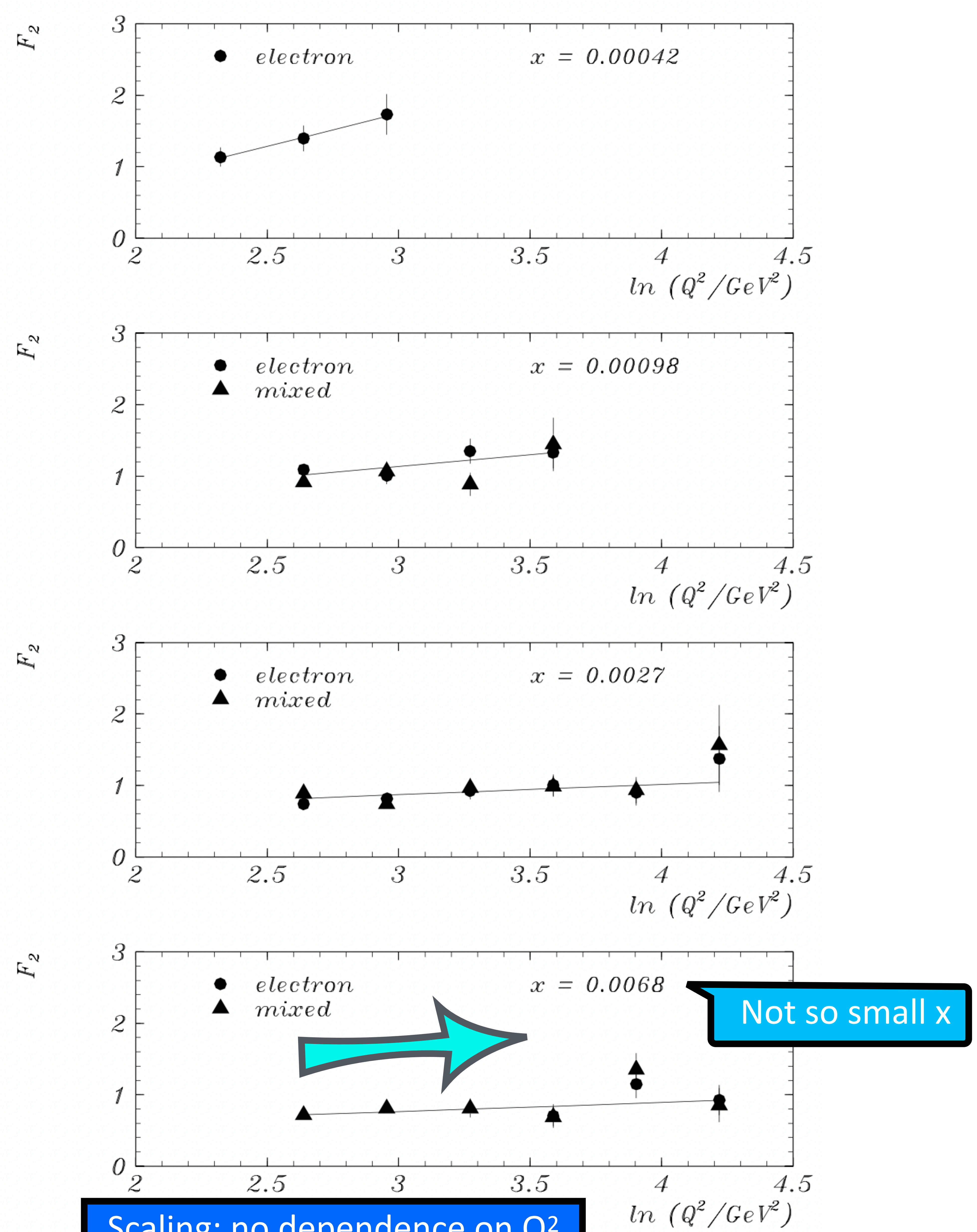

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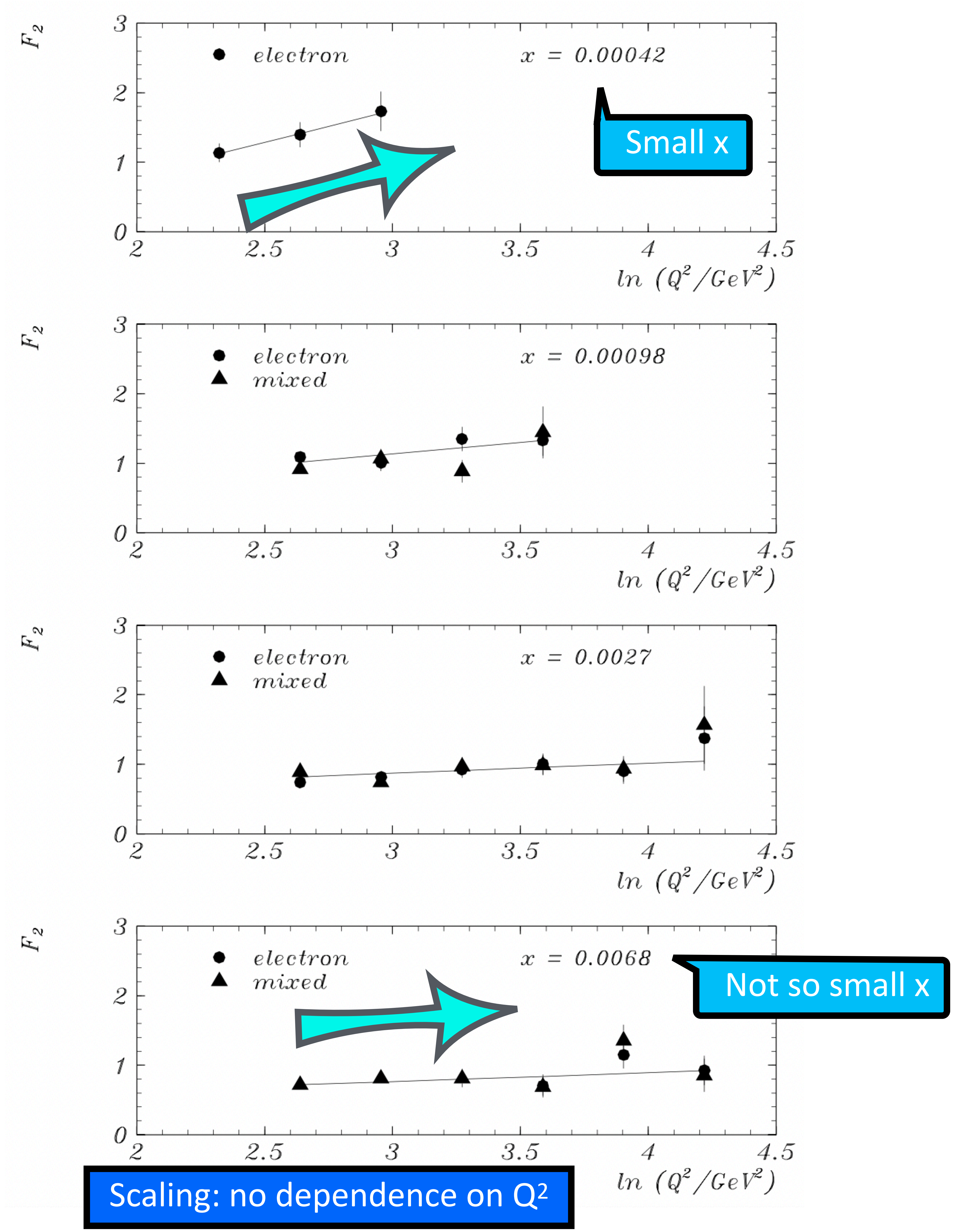

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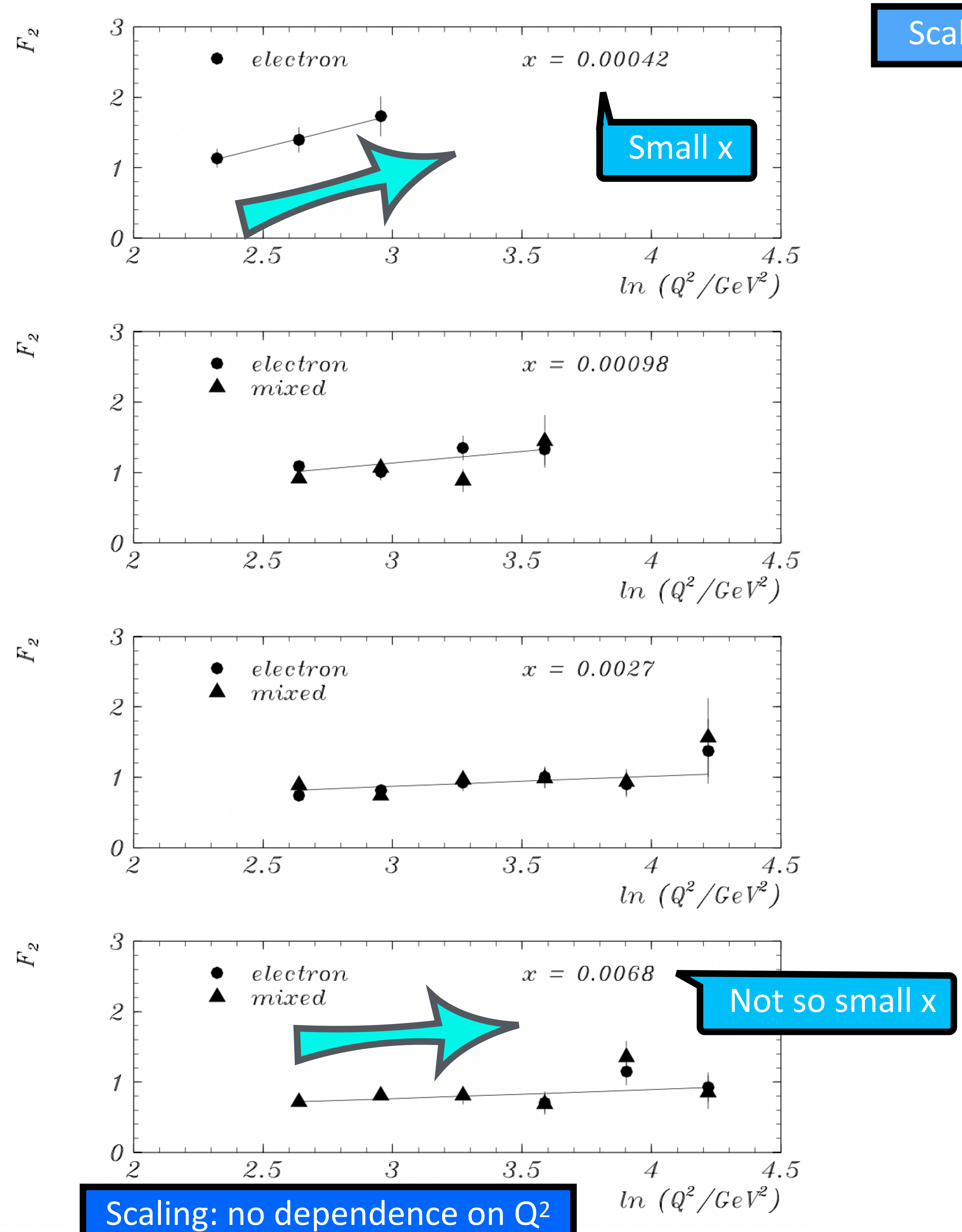

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Scaling violations logarithmic in virtuality

Violations more severe at small Bjorken x

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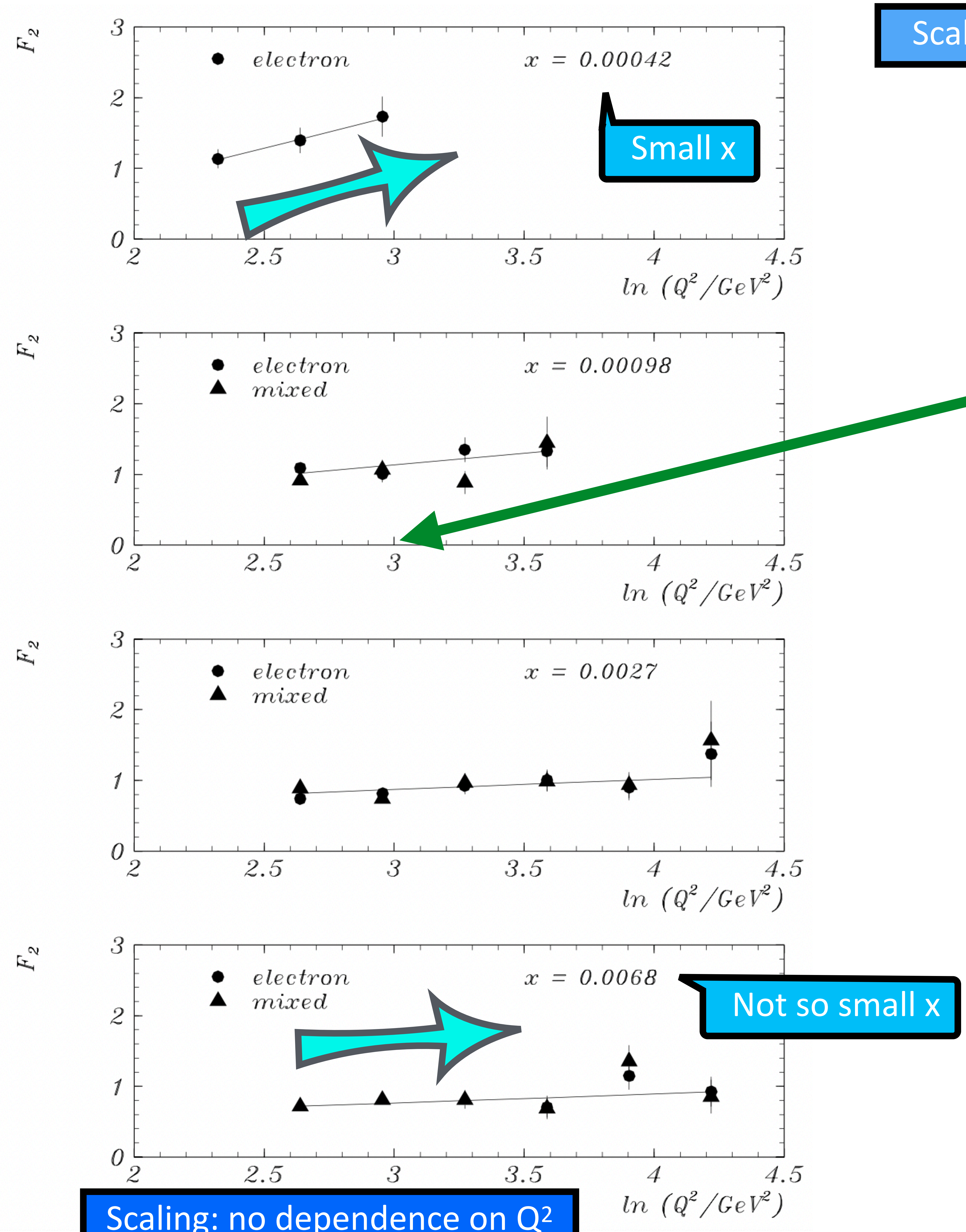

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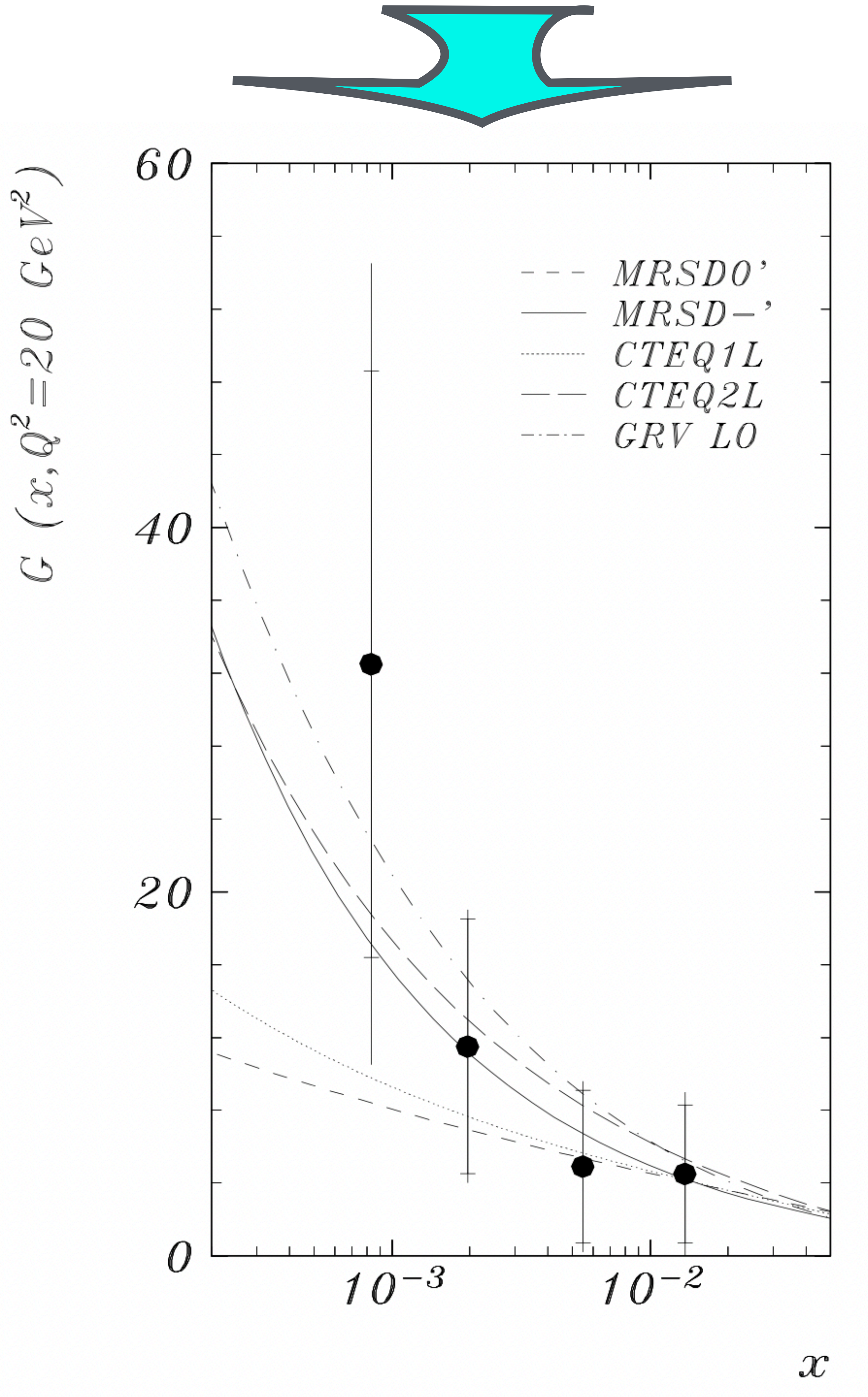

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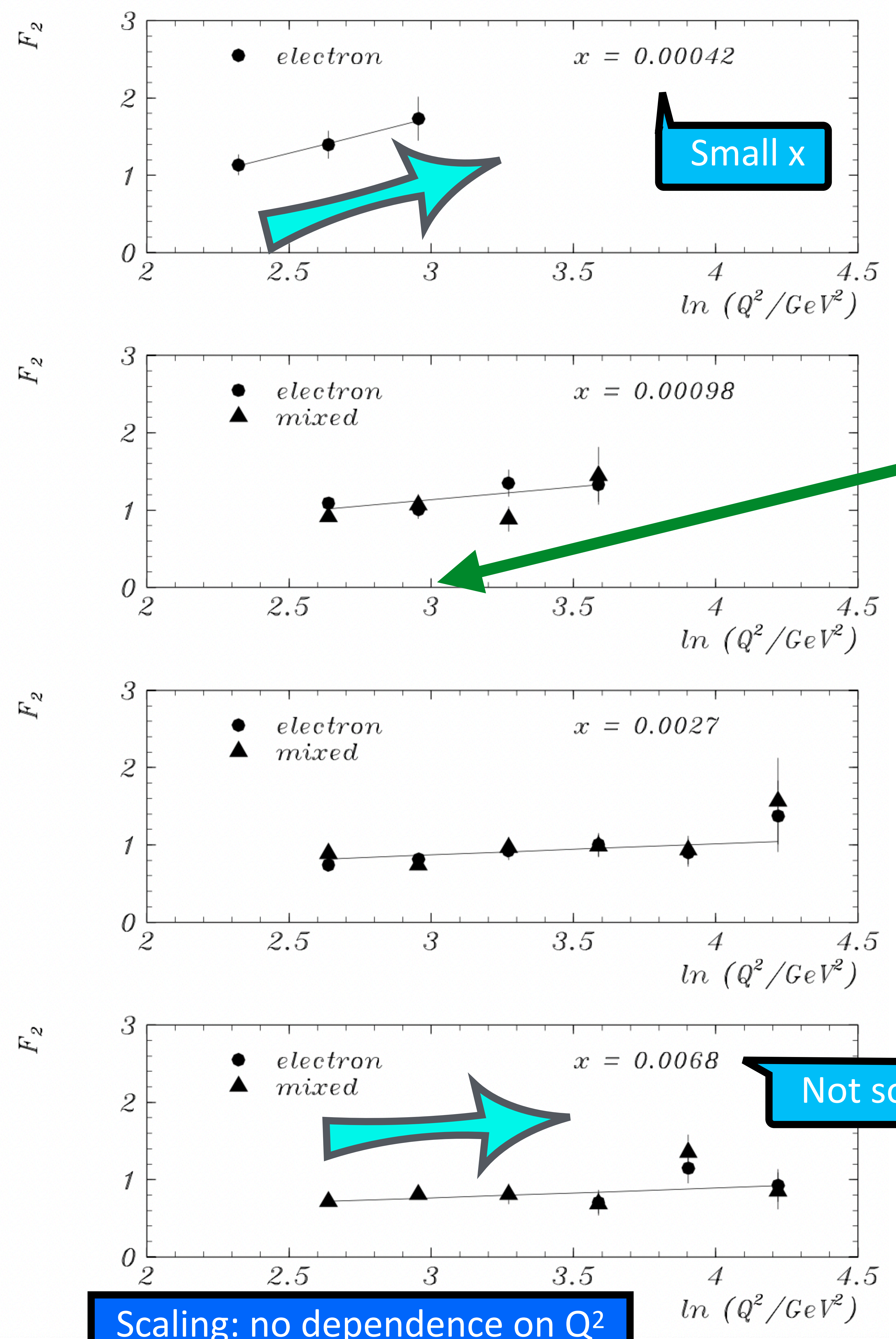

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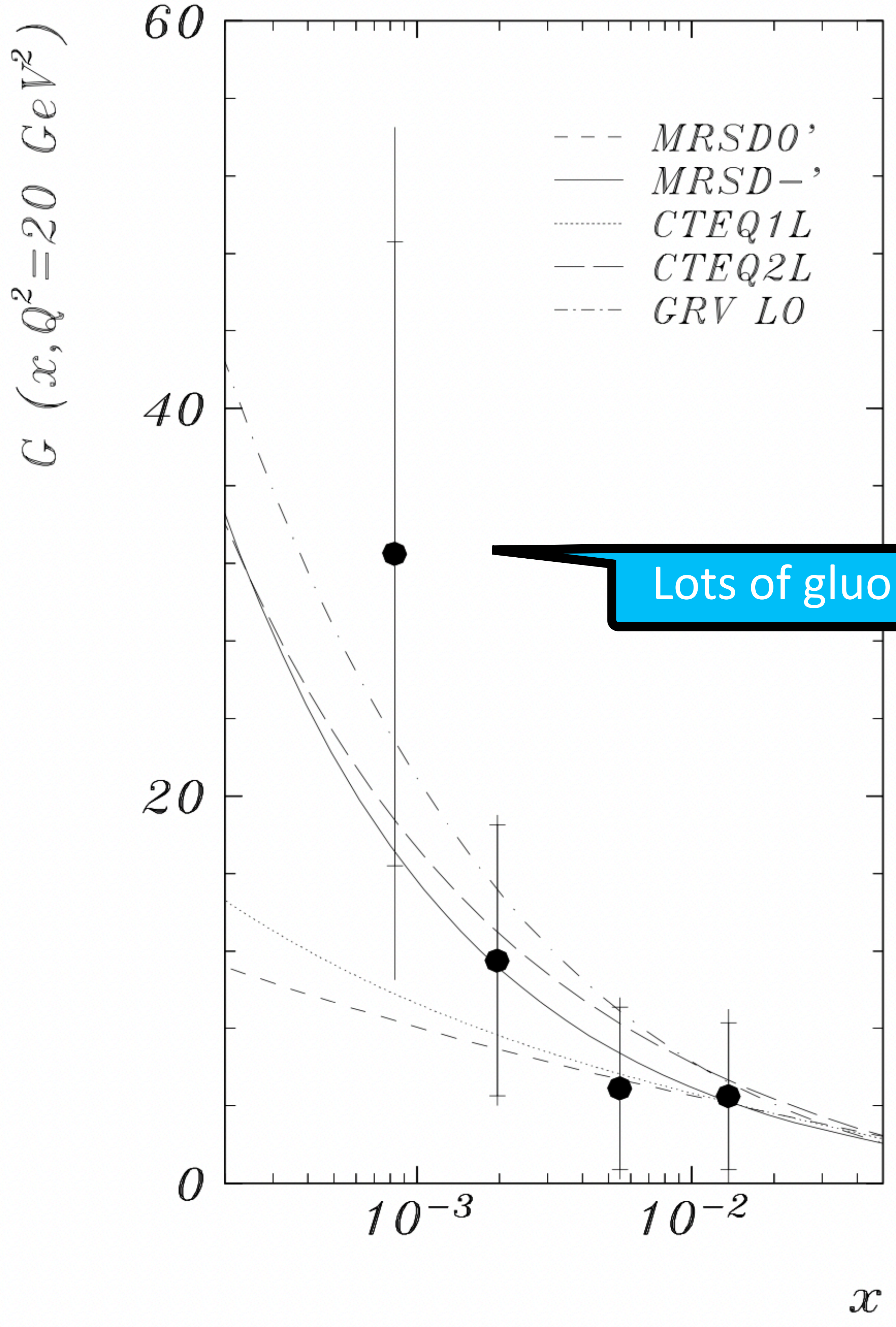

Photon-gluon fusion (1995)

Let's try to see the gluons directly!

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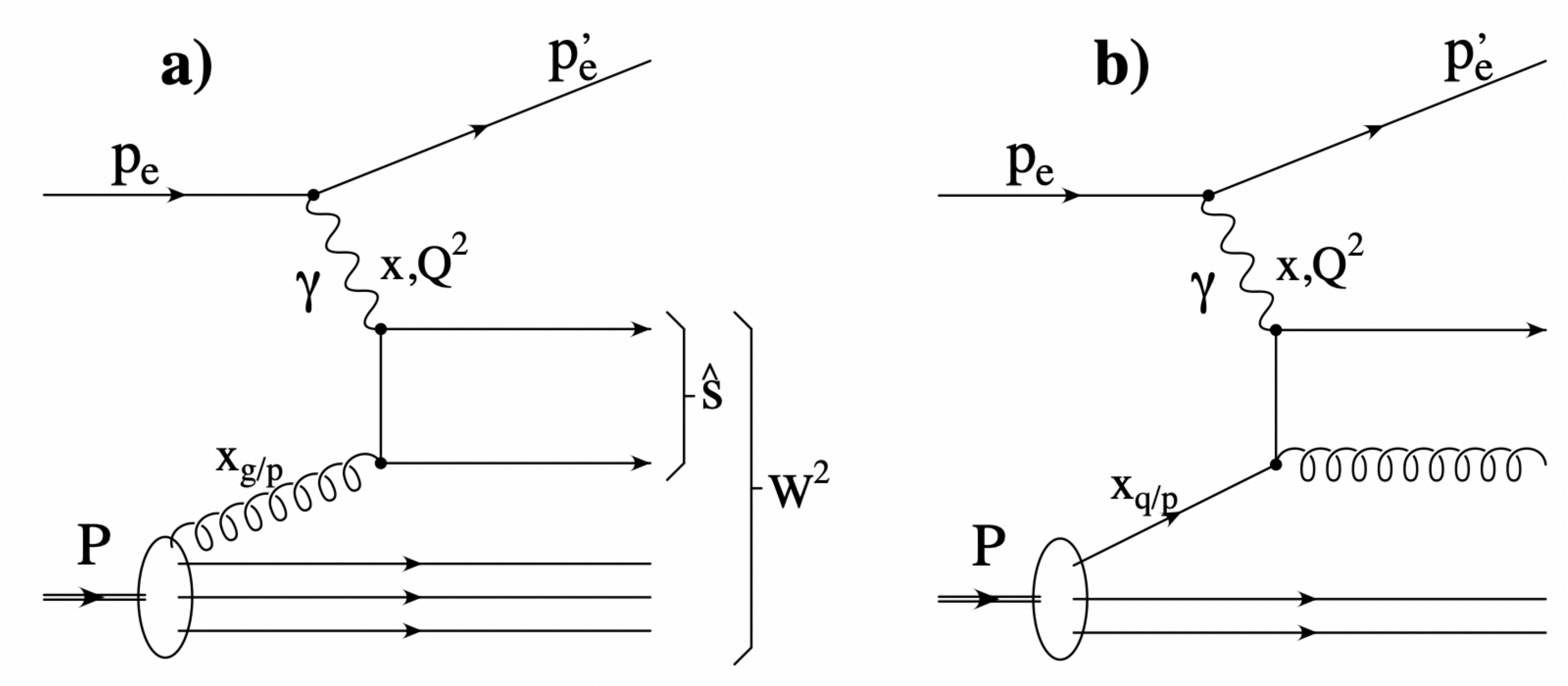
H1, https://inspirehep.net/literature/395643



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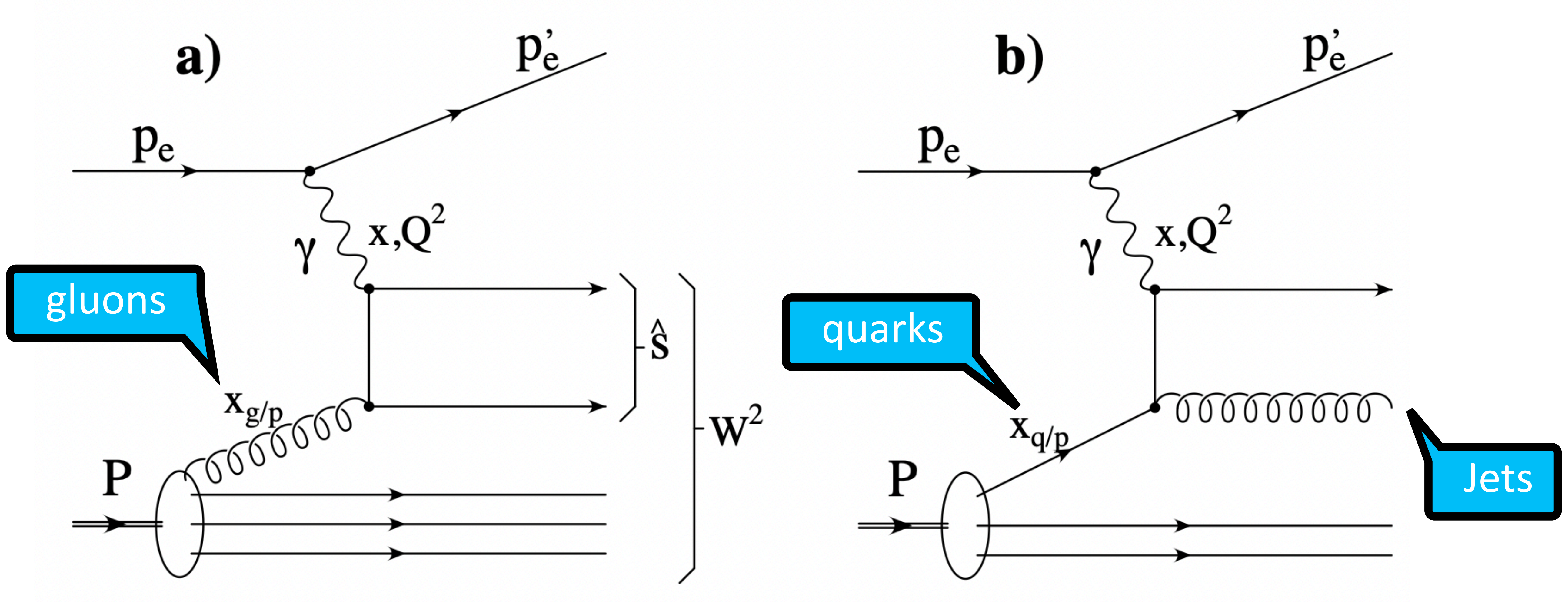

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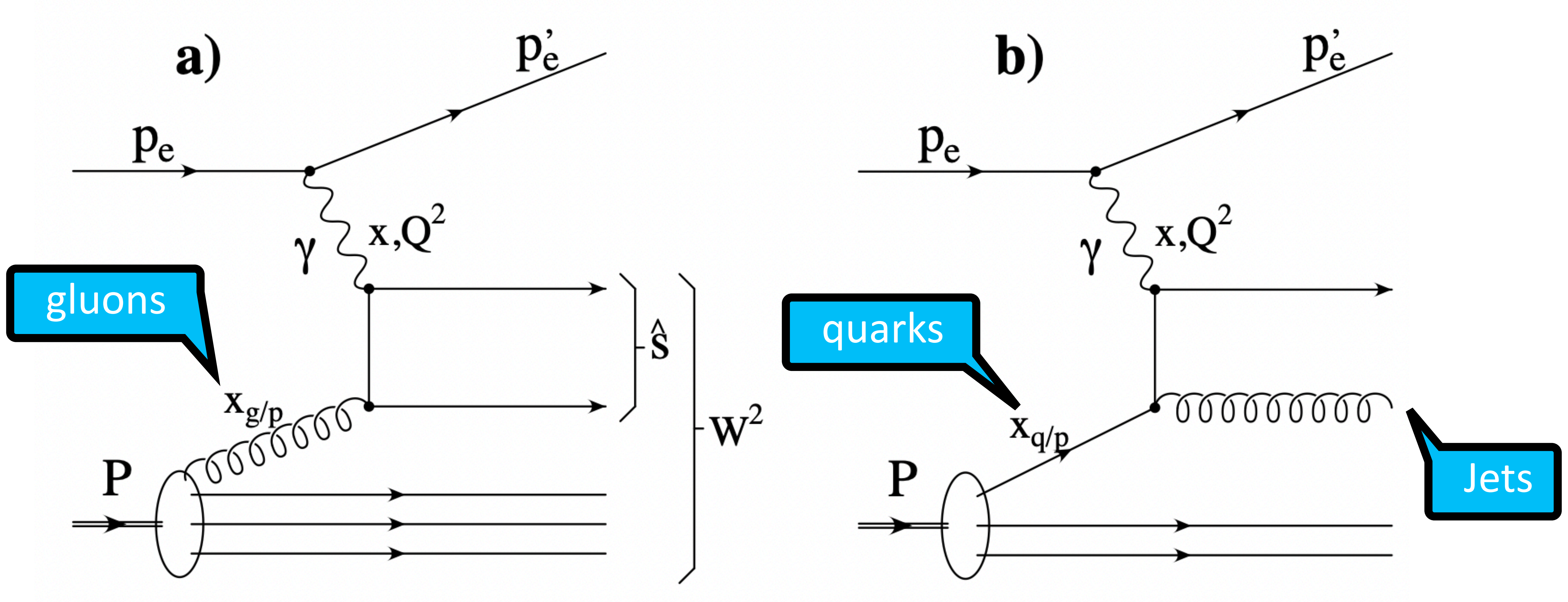

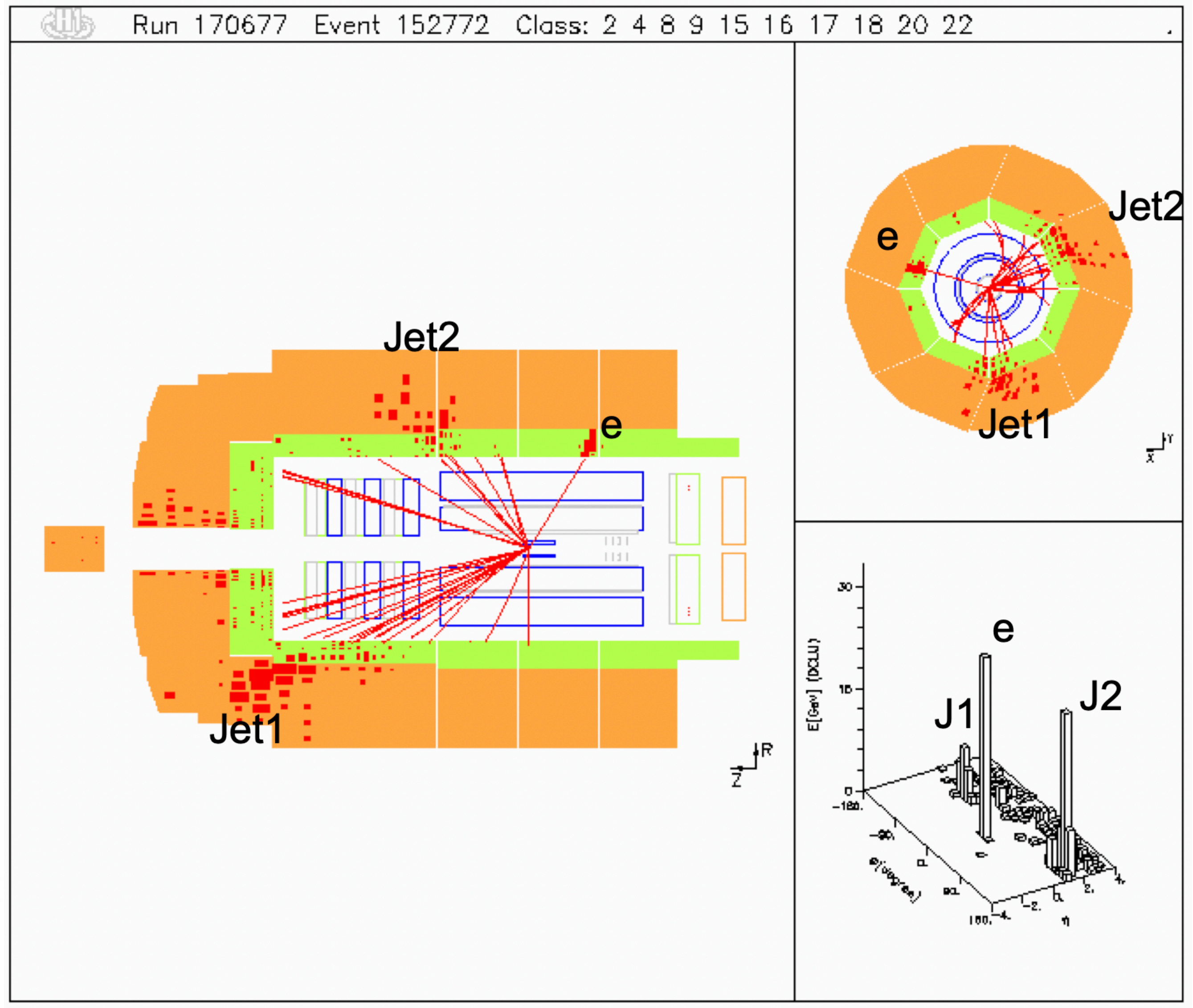

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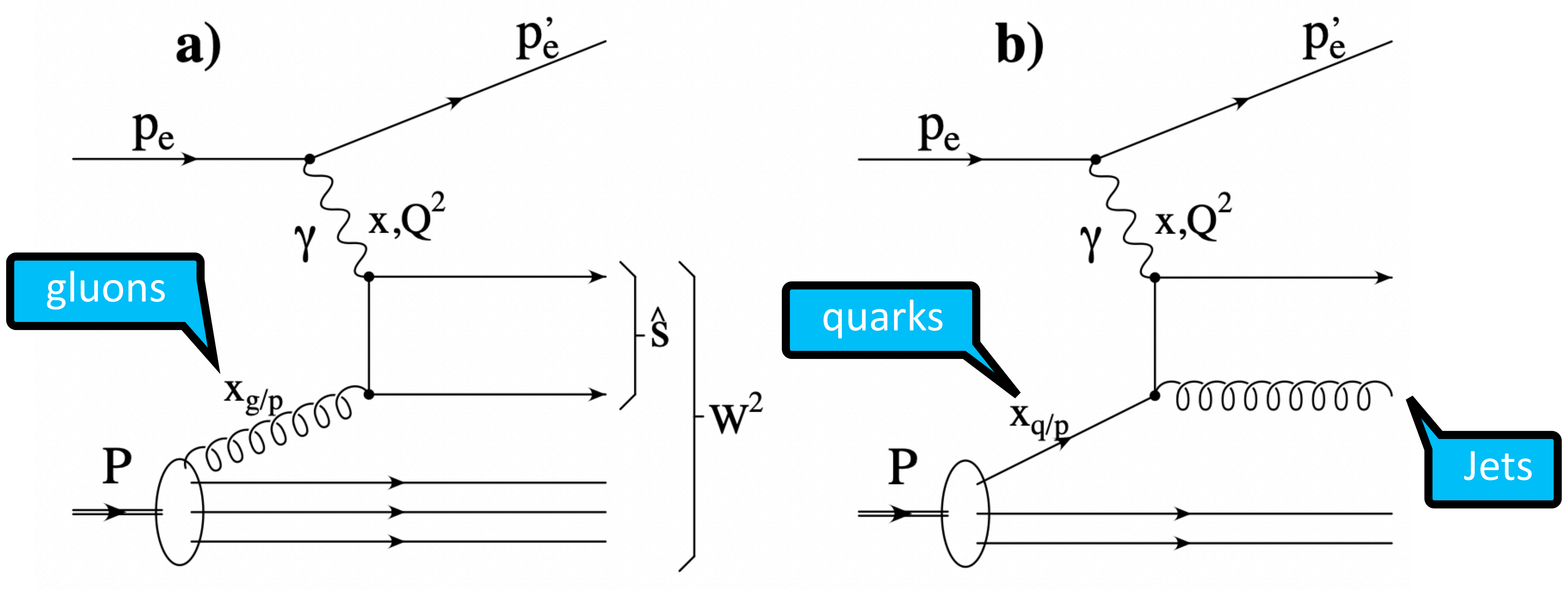

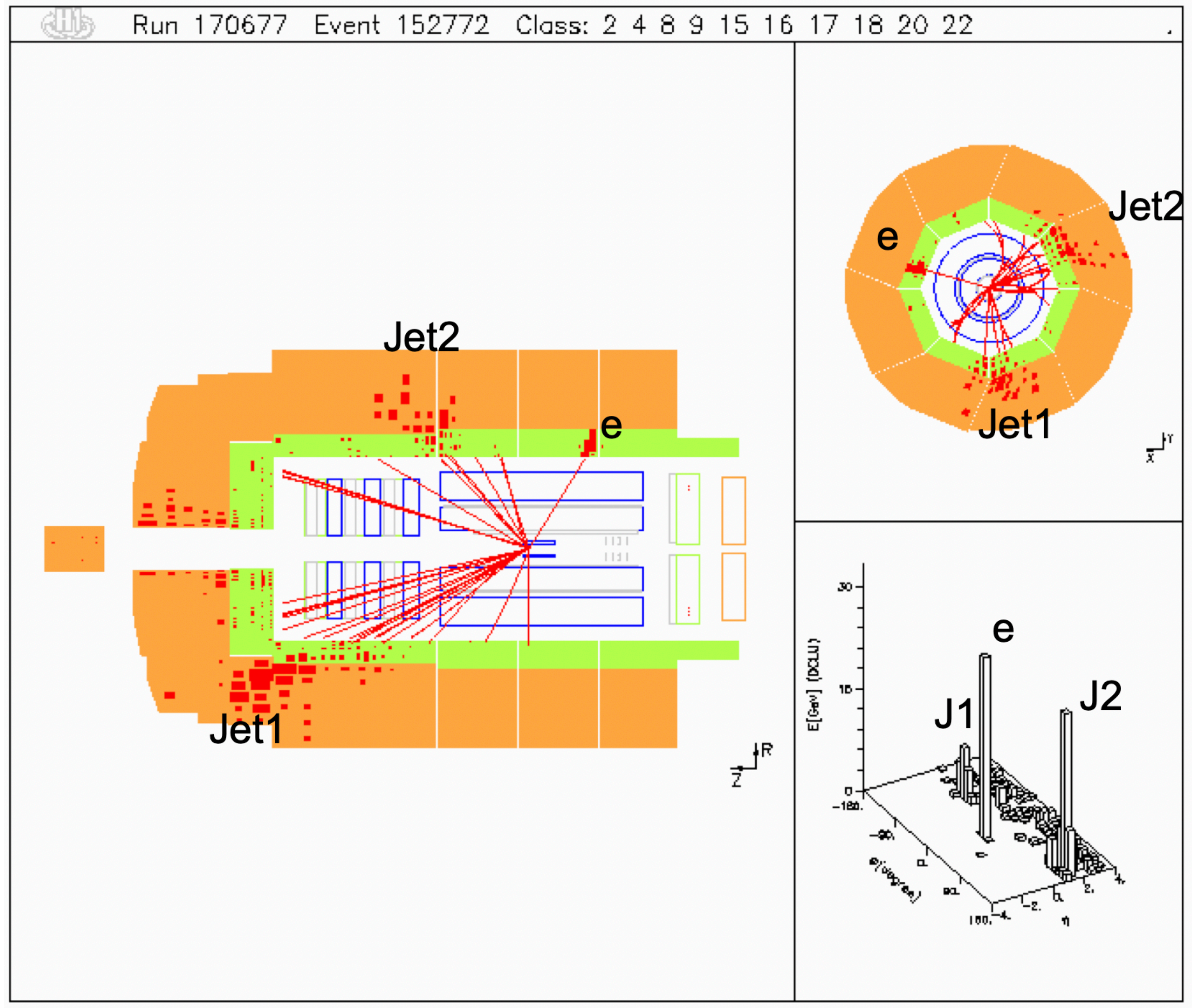

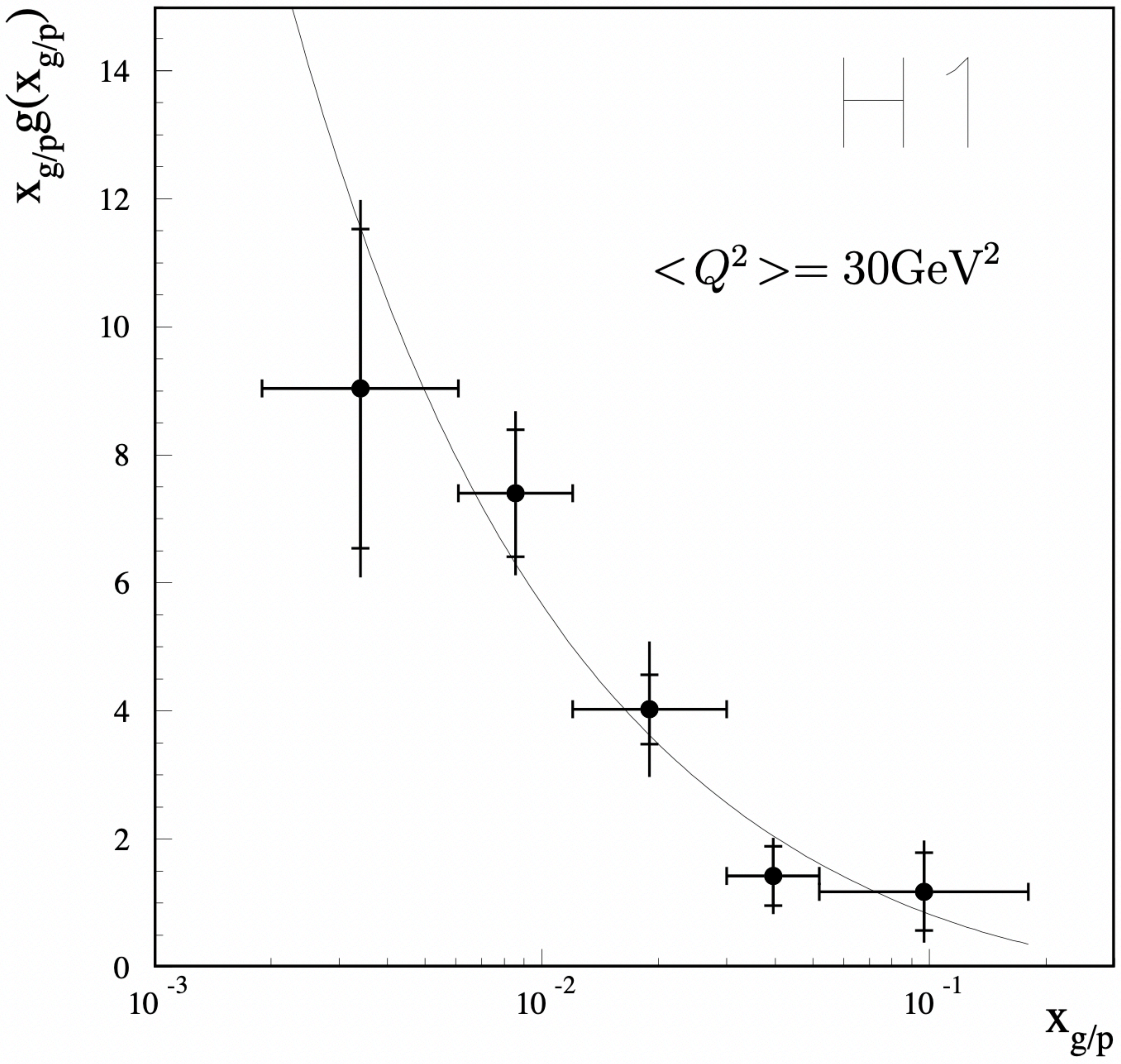

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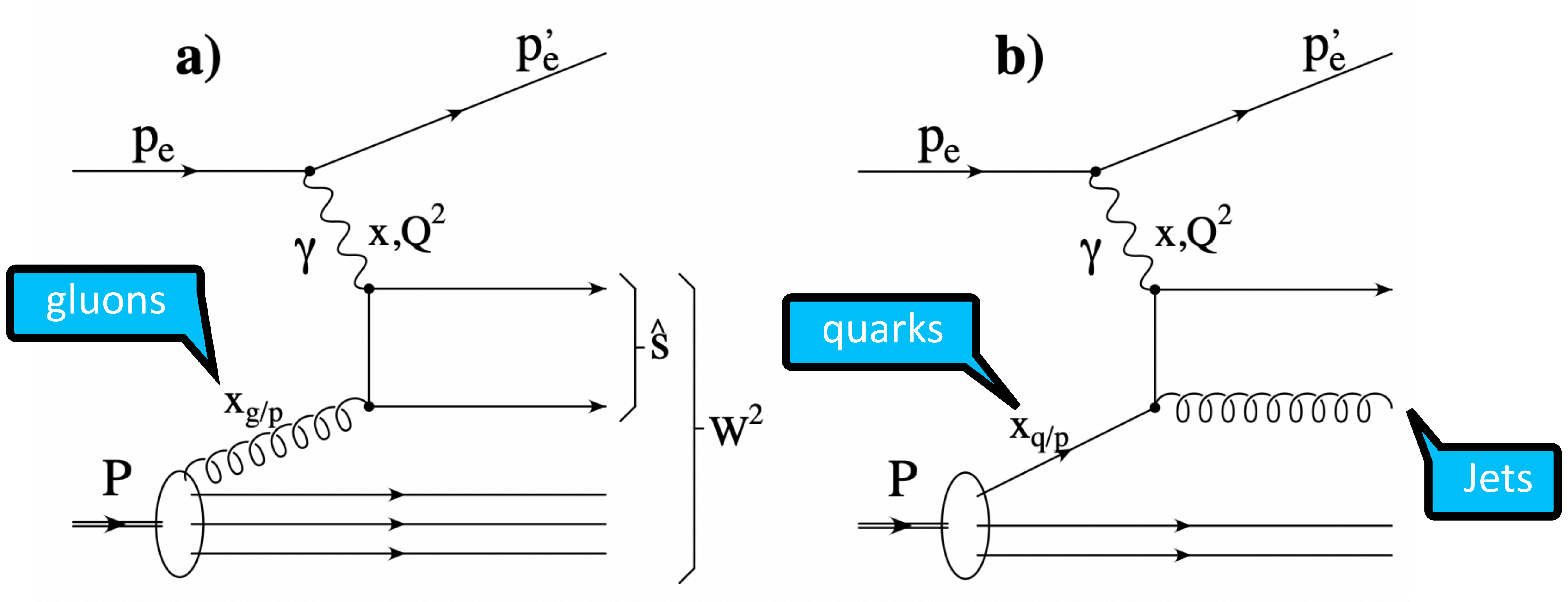

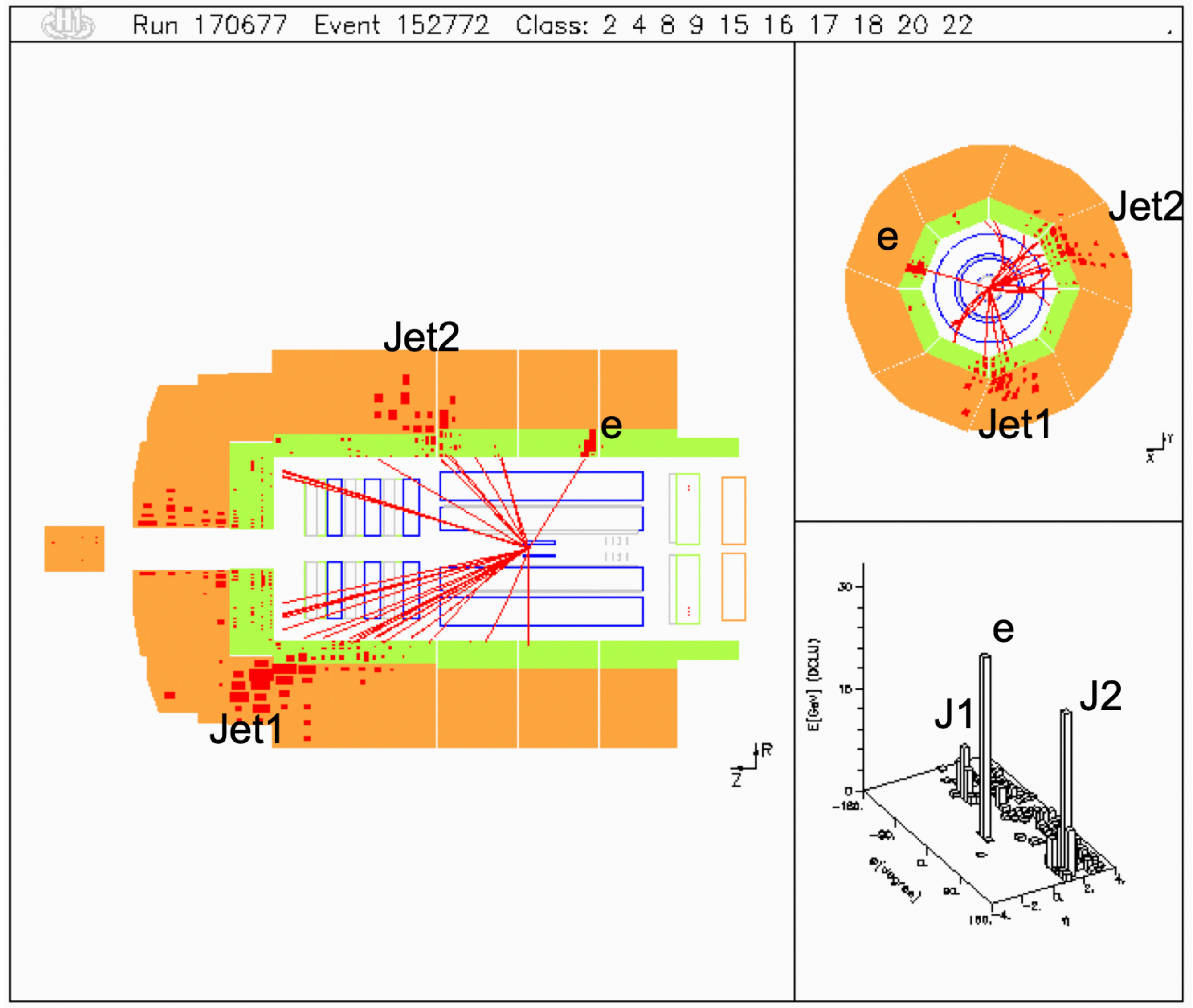

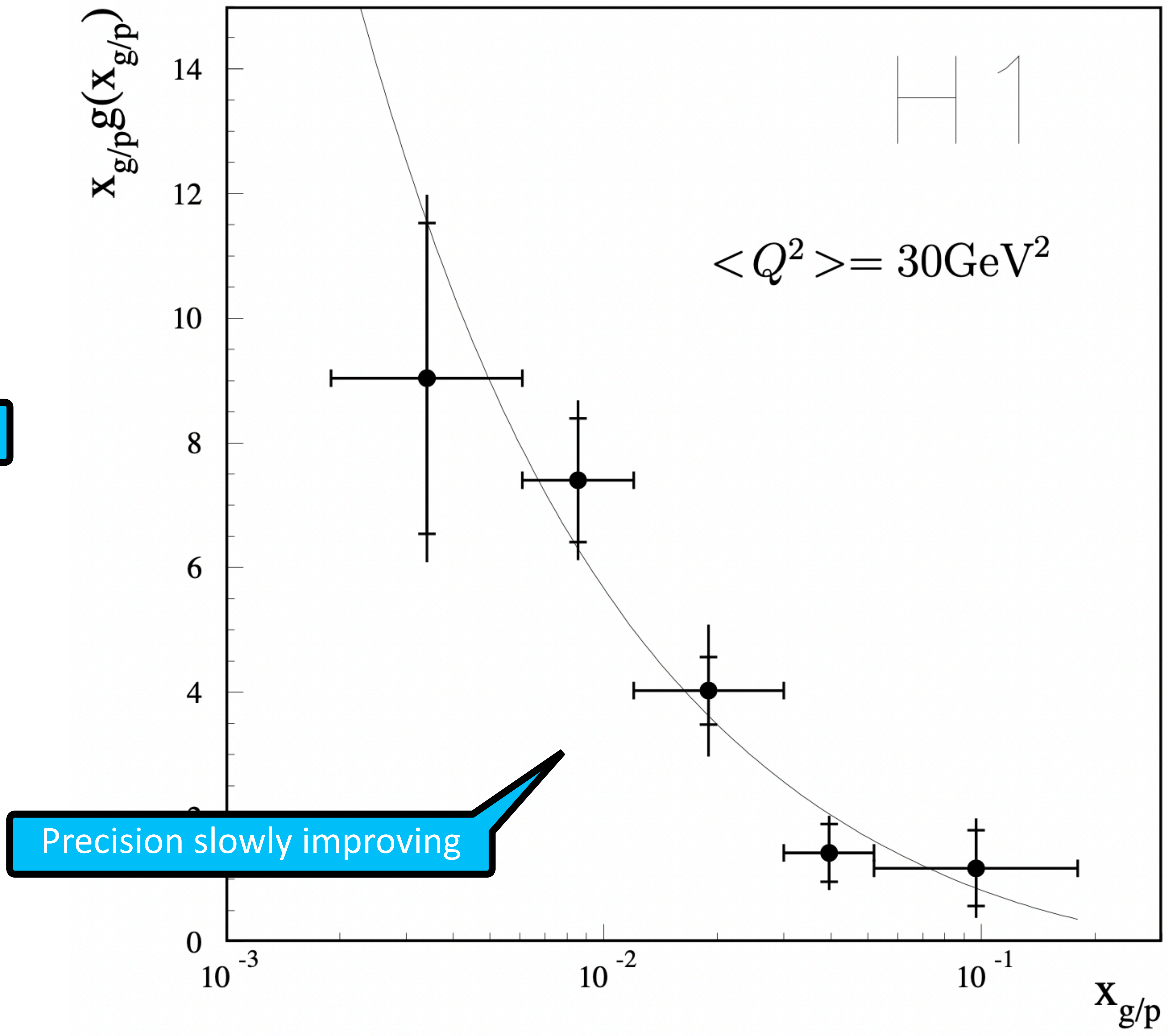

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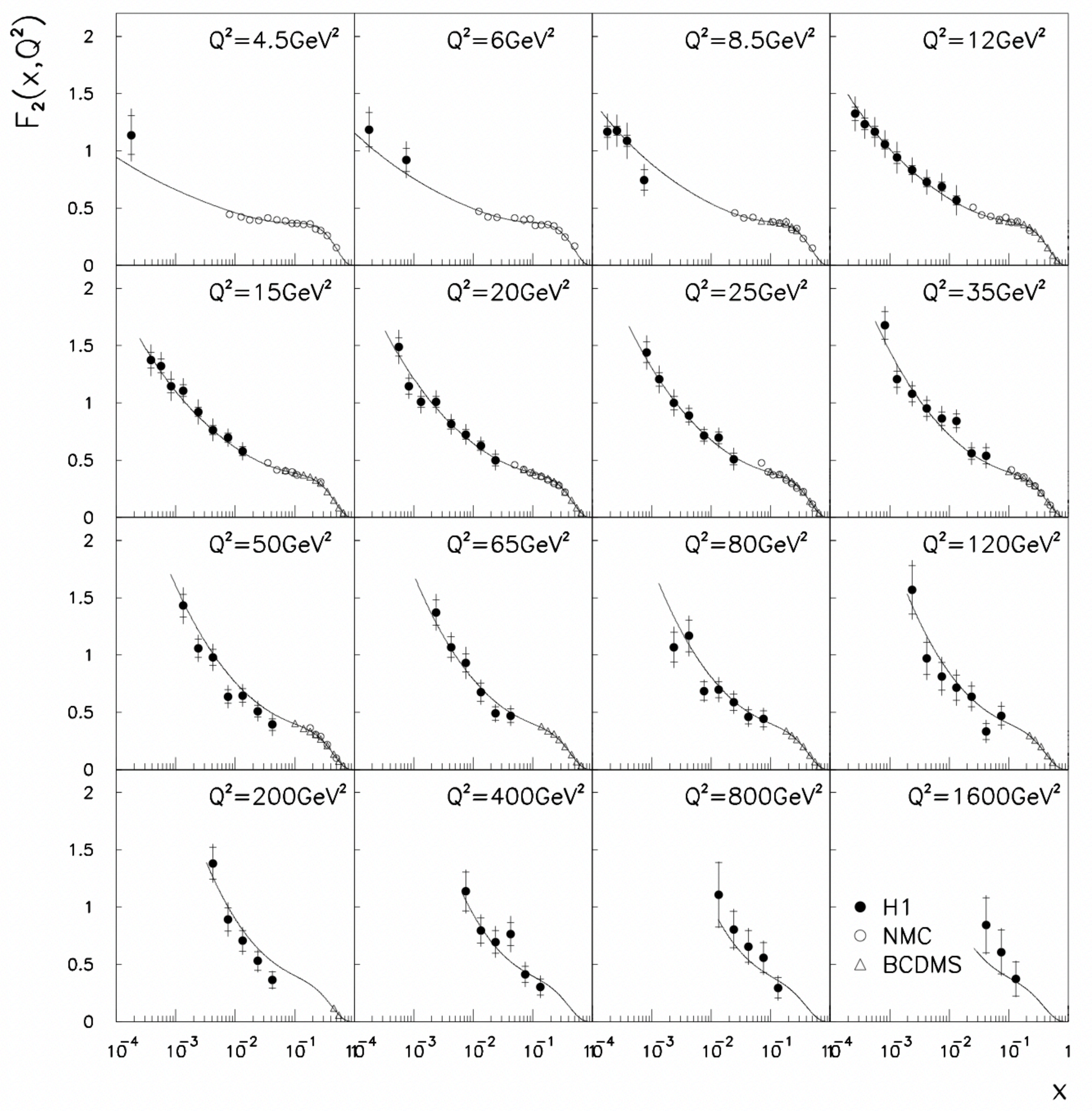
Back to inclusive measurements: early QCD fits (1995)

H1, https://inspirehep.net/literature/395814



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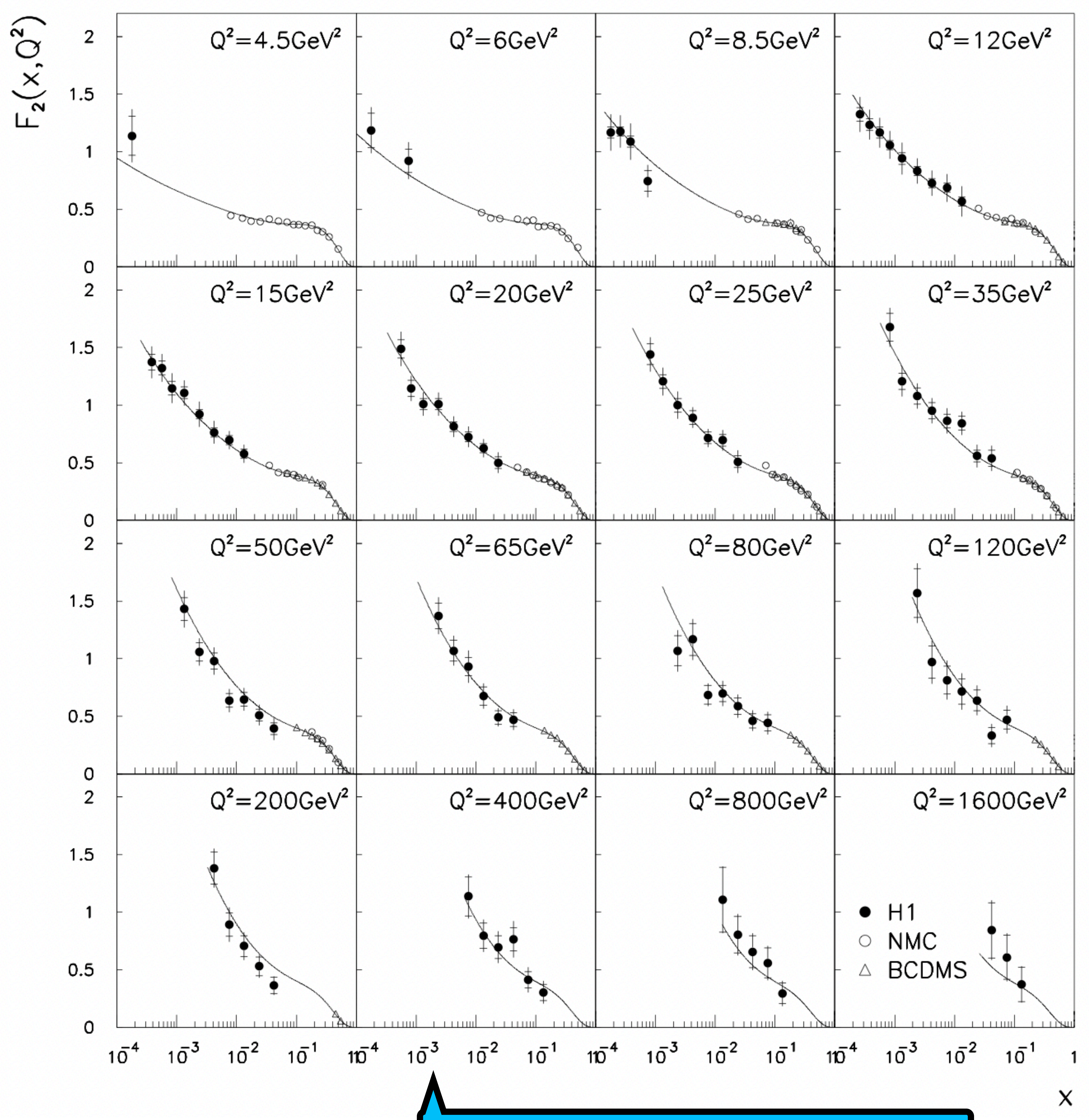

Uncertainties are getting smaller :)

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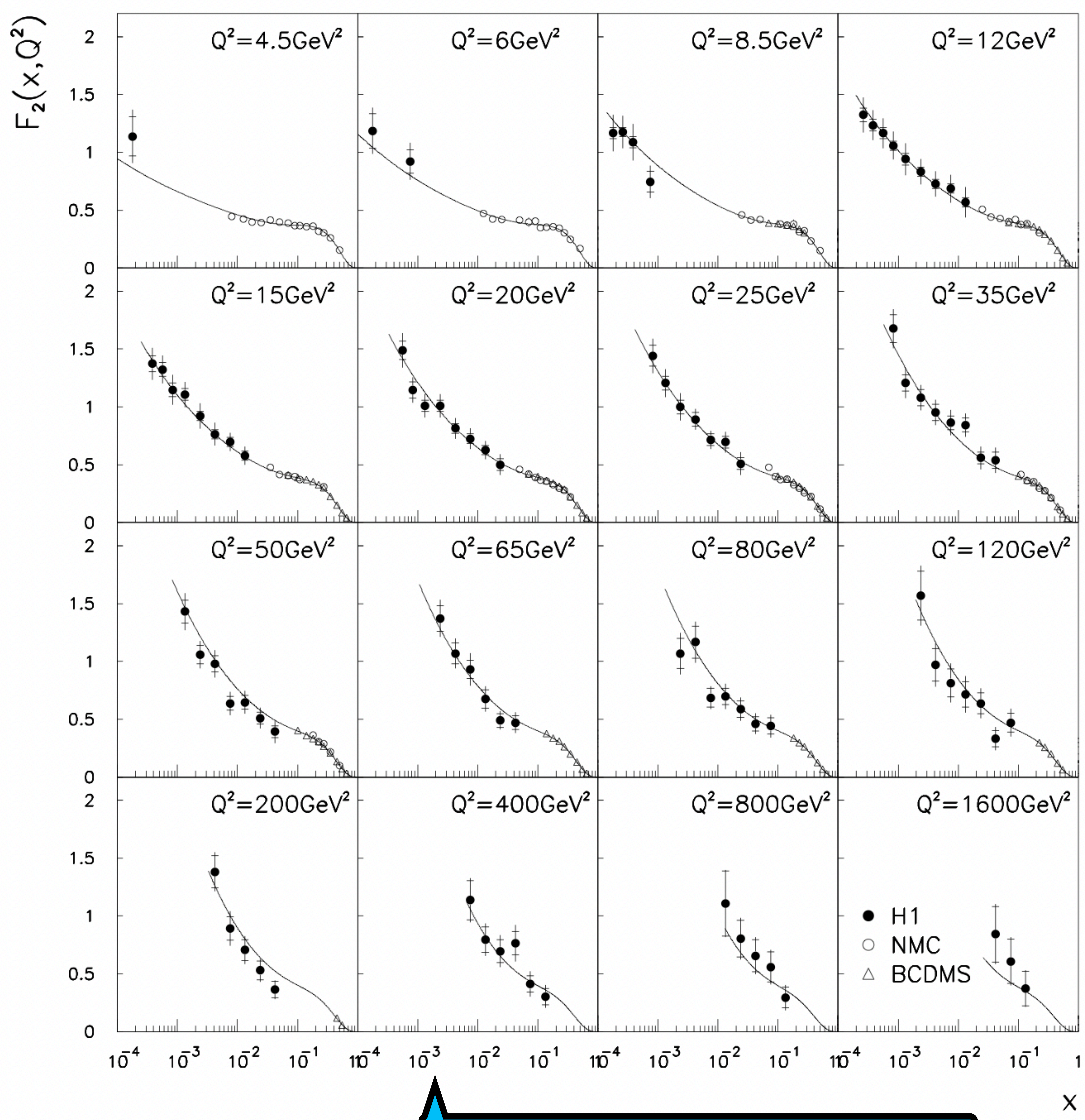

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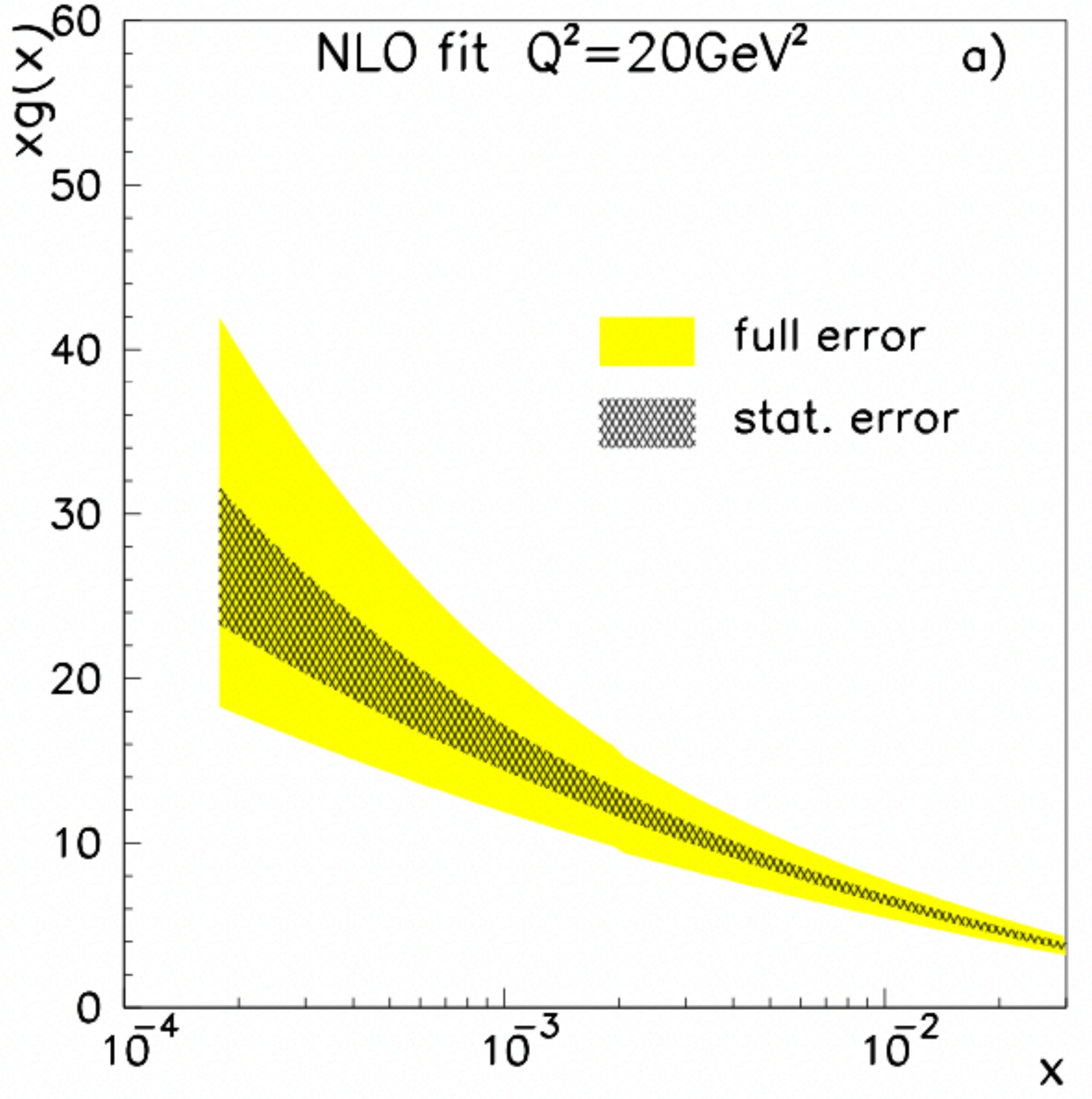
NLO fit



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The longitudinal srtucture function (1997)

Once the precision is good enough, one can use the fits to extract F_L

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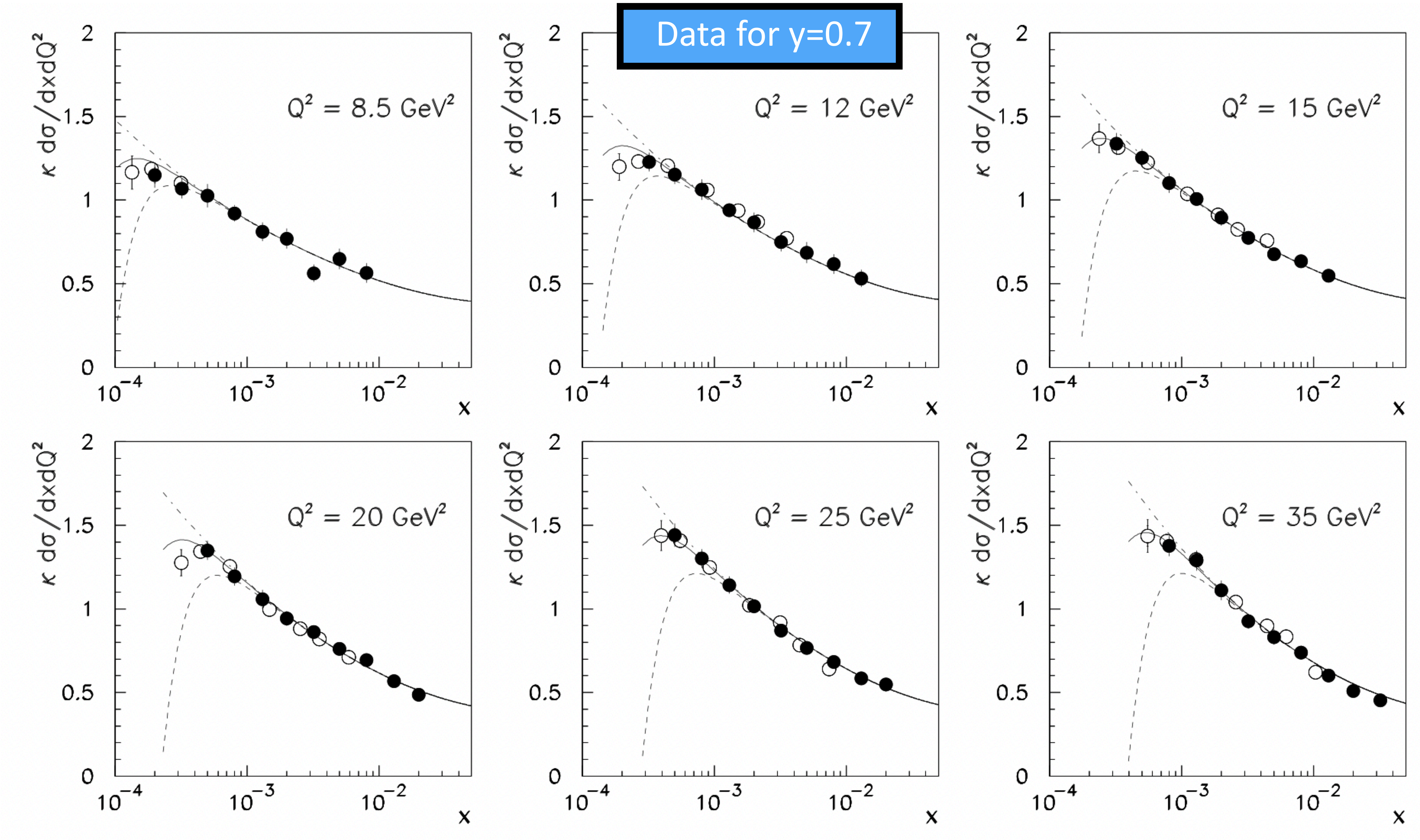
Data for y=0.7



H1, https://inspirehep.net/literature/426362

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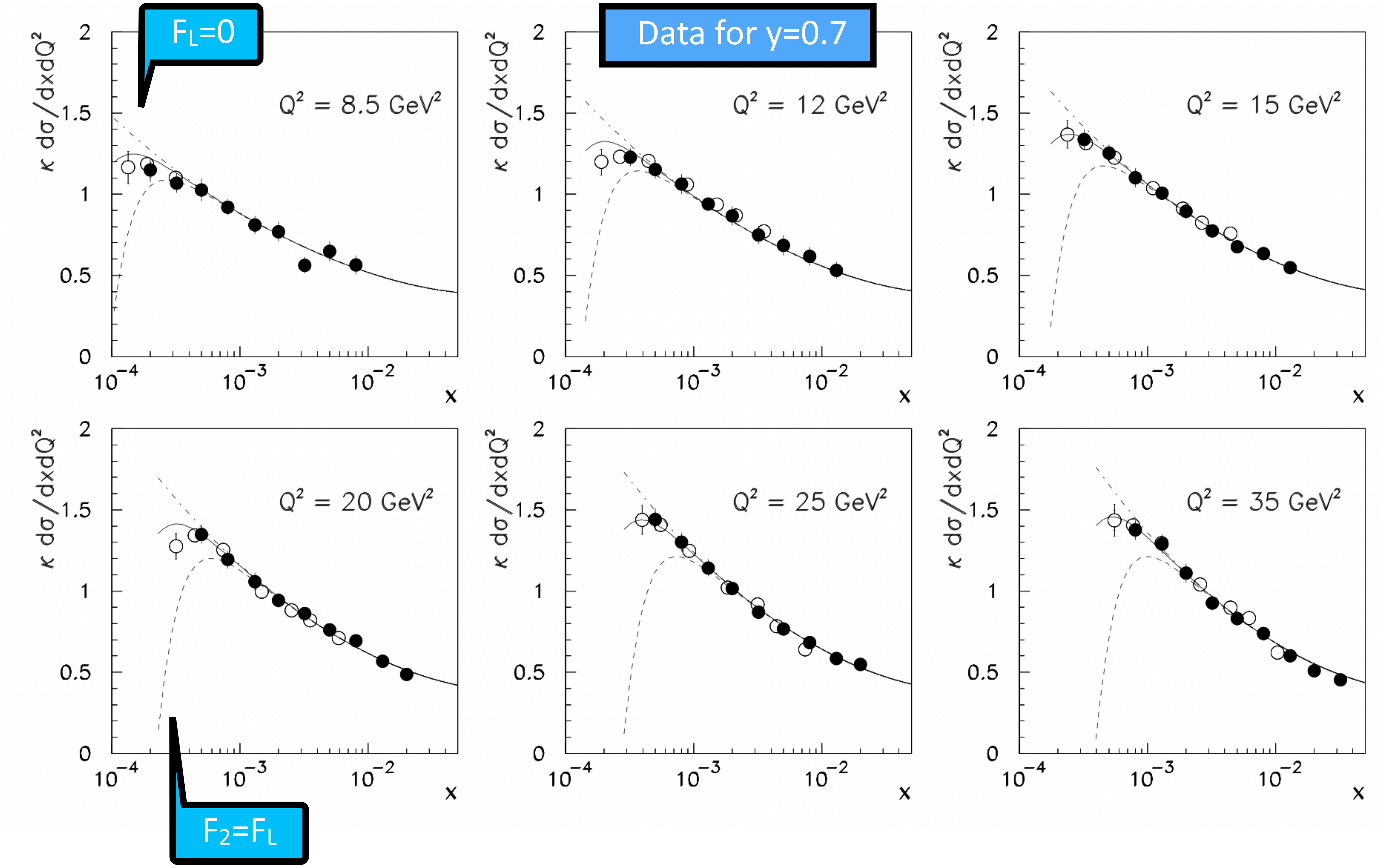

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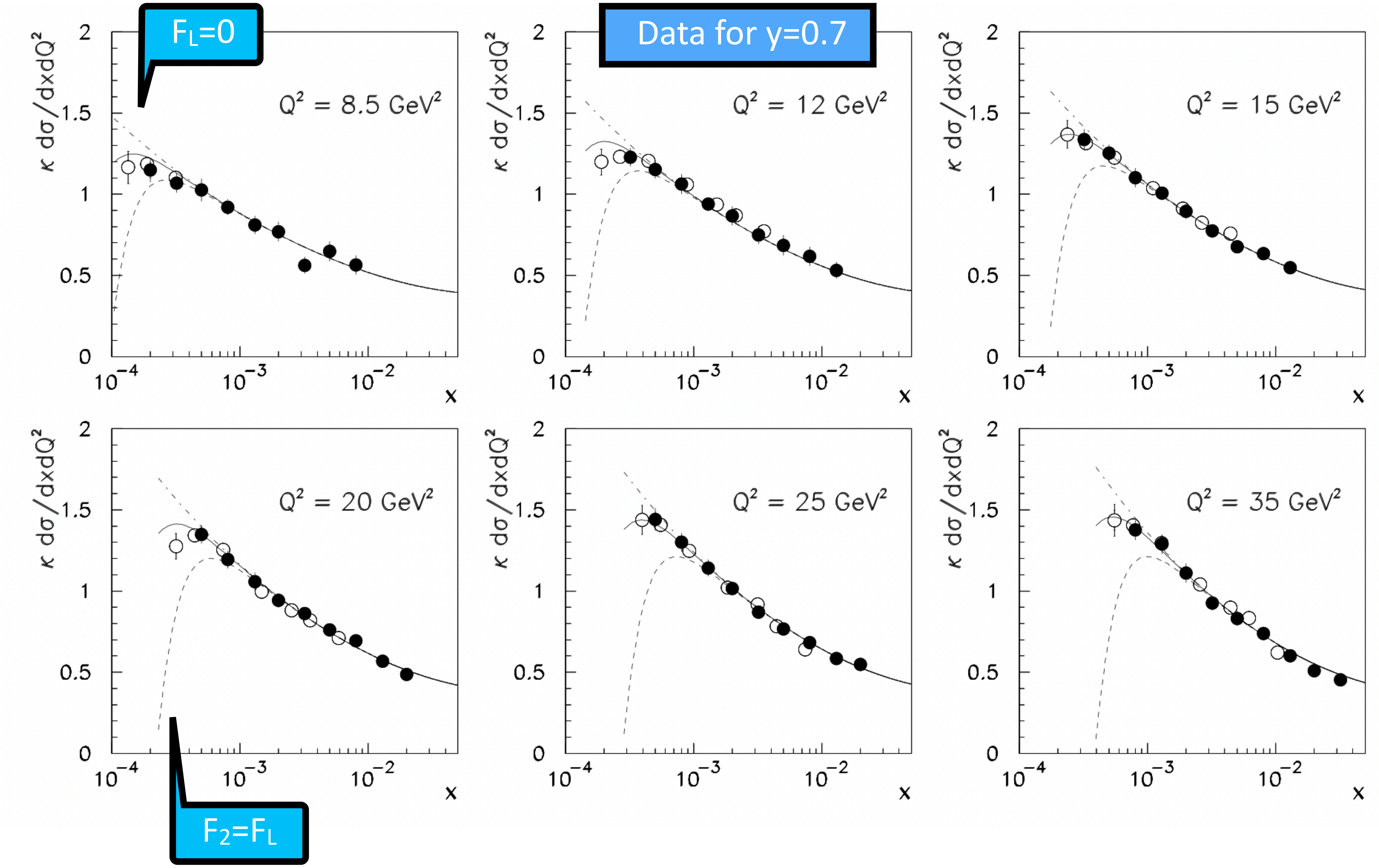
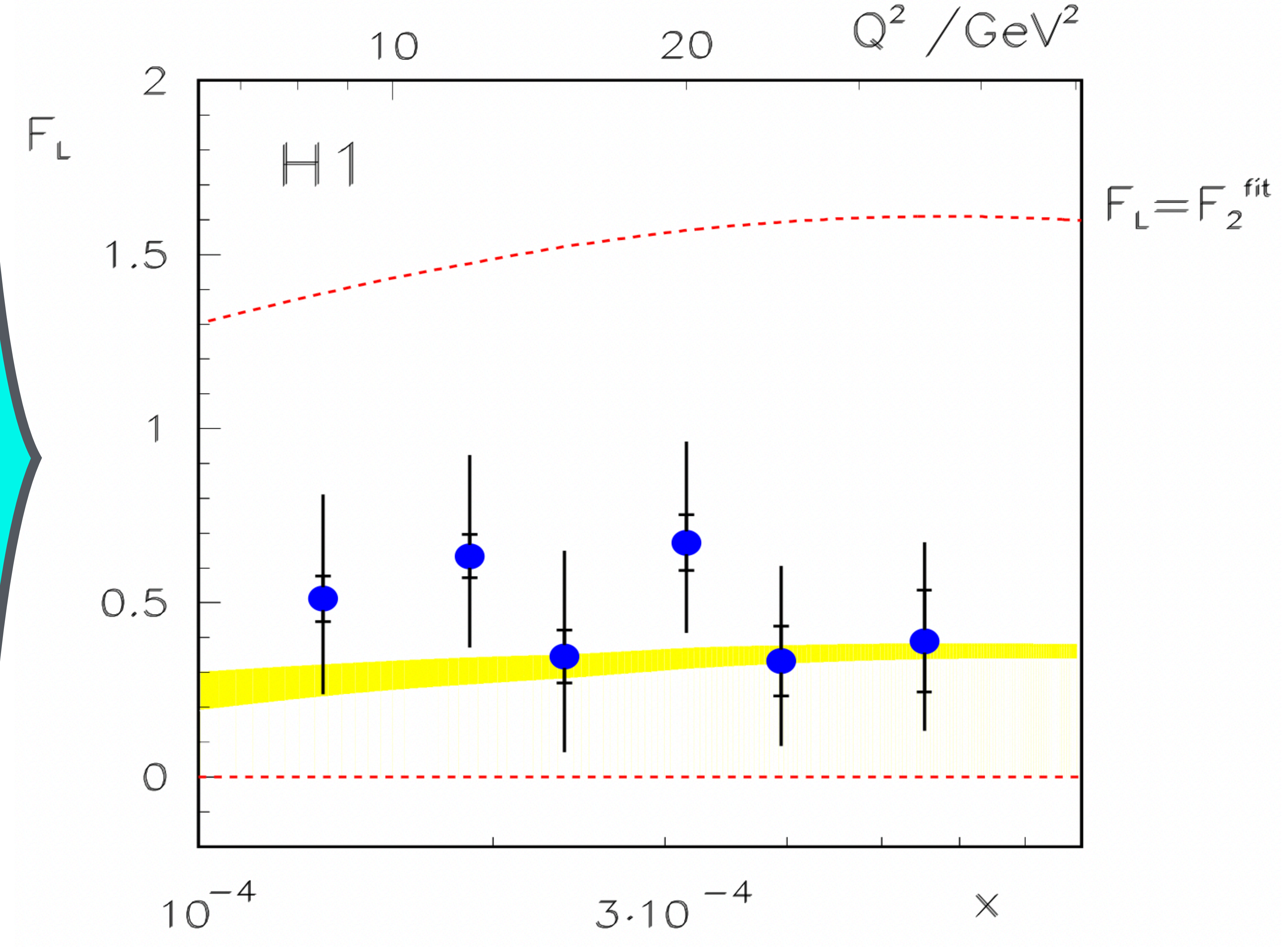


Measure F_2 at low y, use fits to get it at y=0.7 and get F_L



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Heavy-quark structure functions (2010)

Use the longer lifetime of heavy flavour hadrons and precise tracking from silicon detectors to select charm or beauty initiated events

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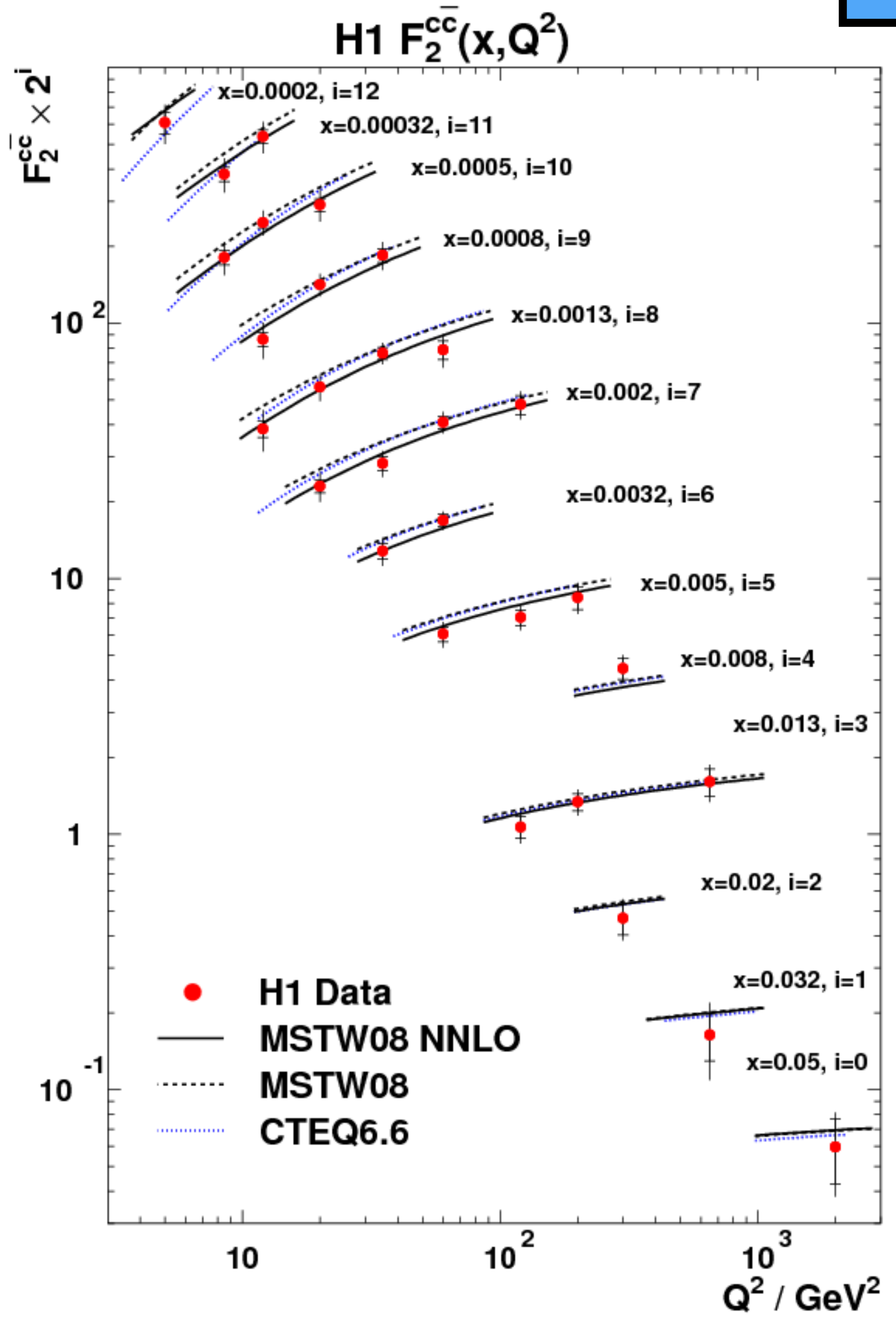

H1, https://inspirehep.net/literature/825811

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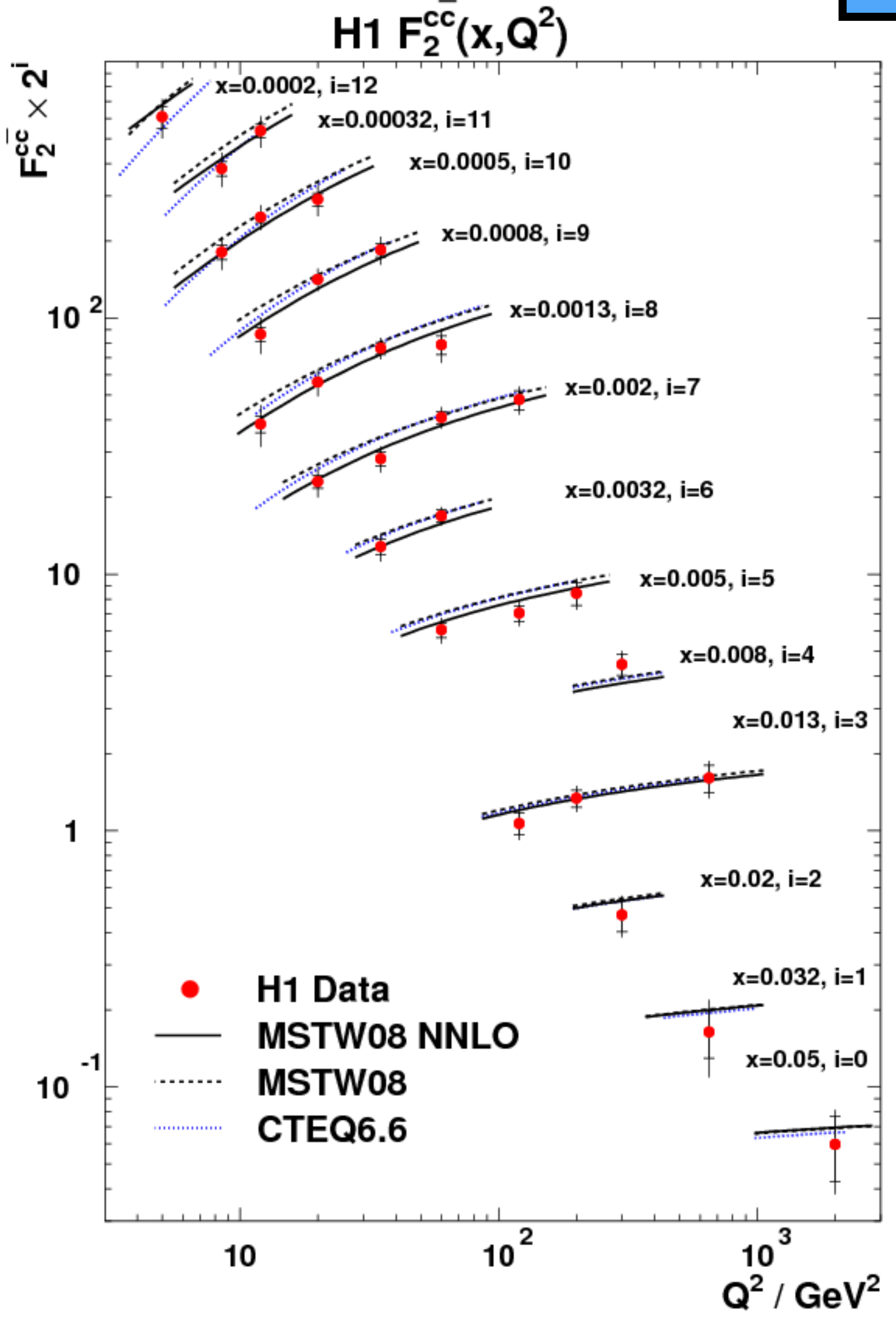

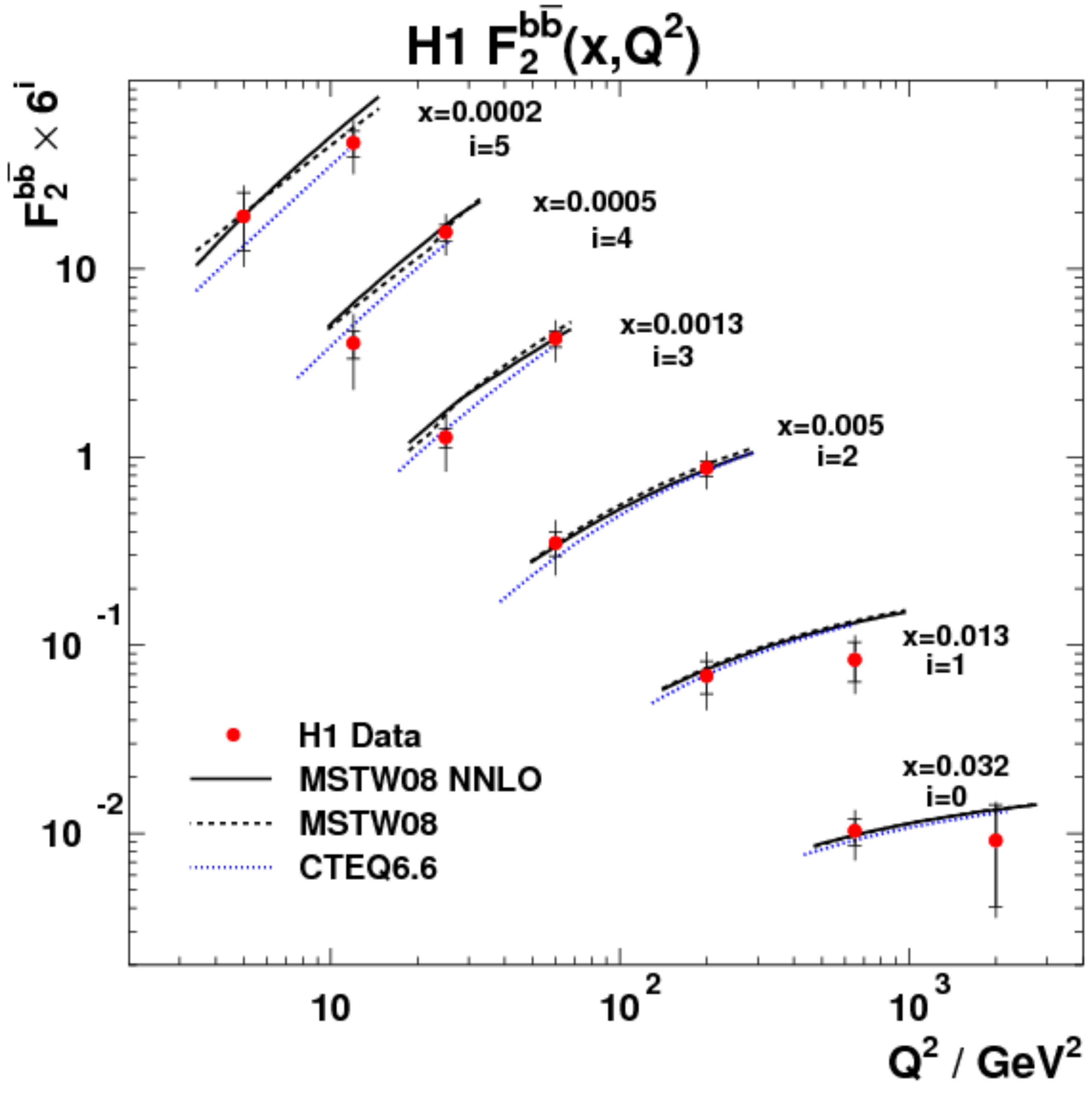

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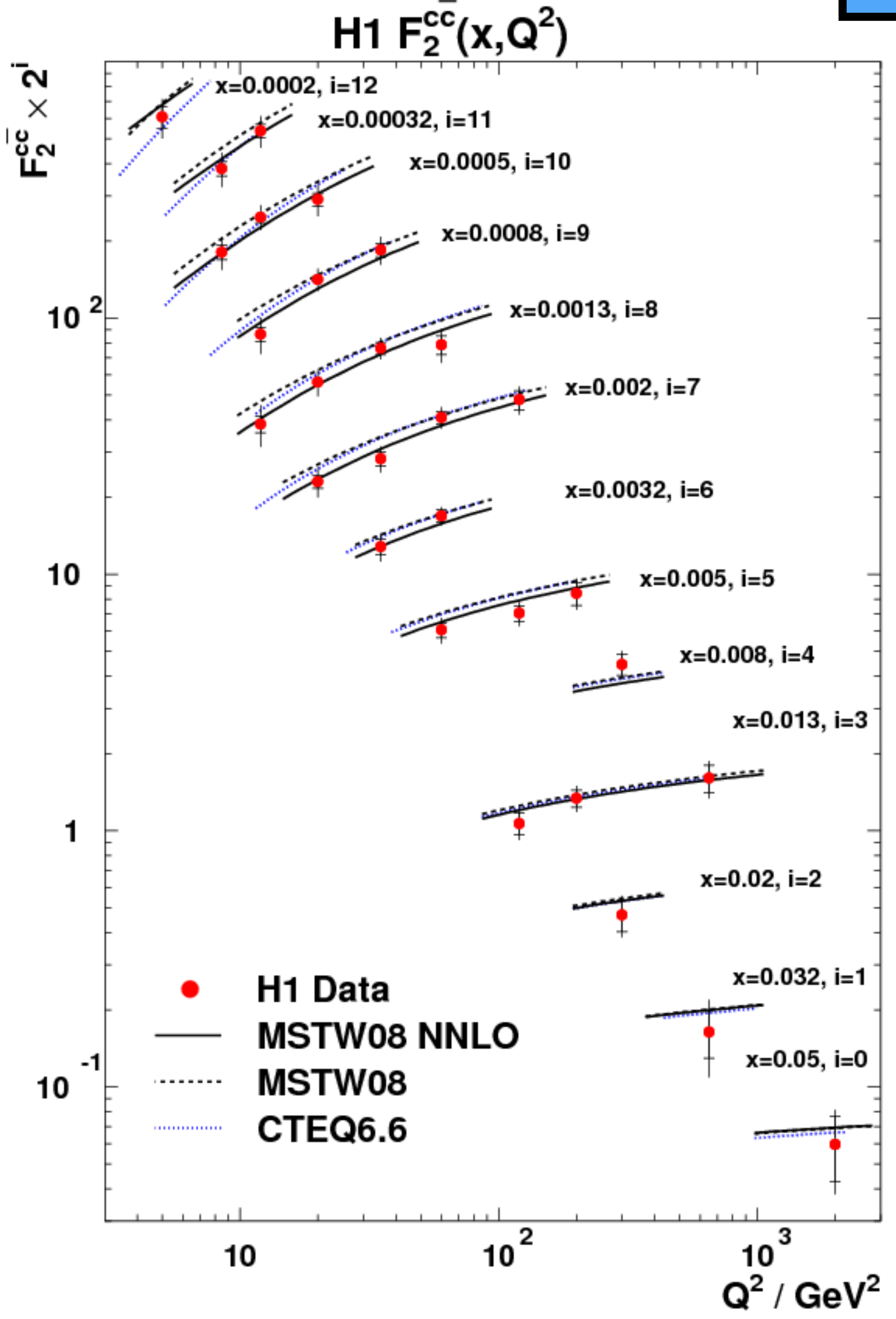
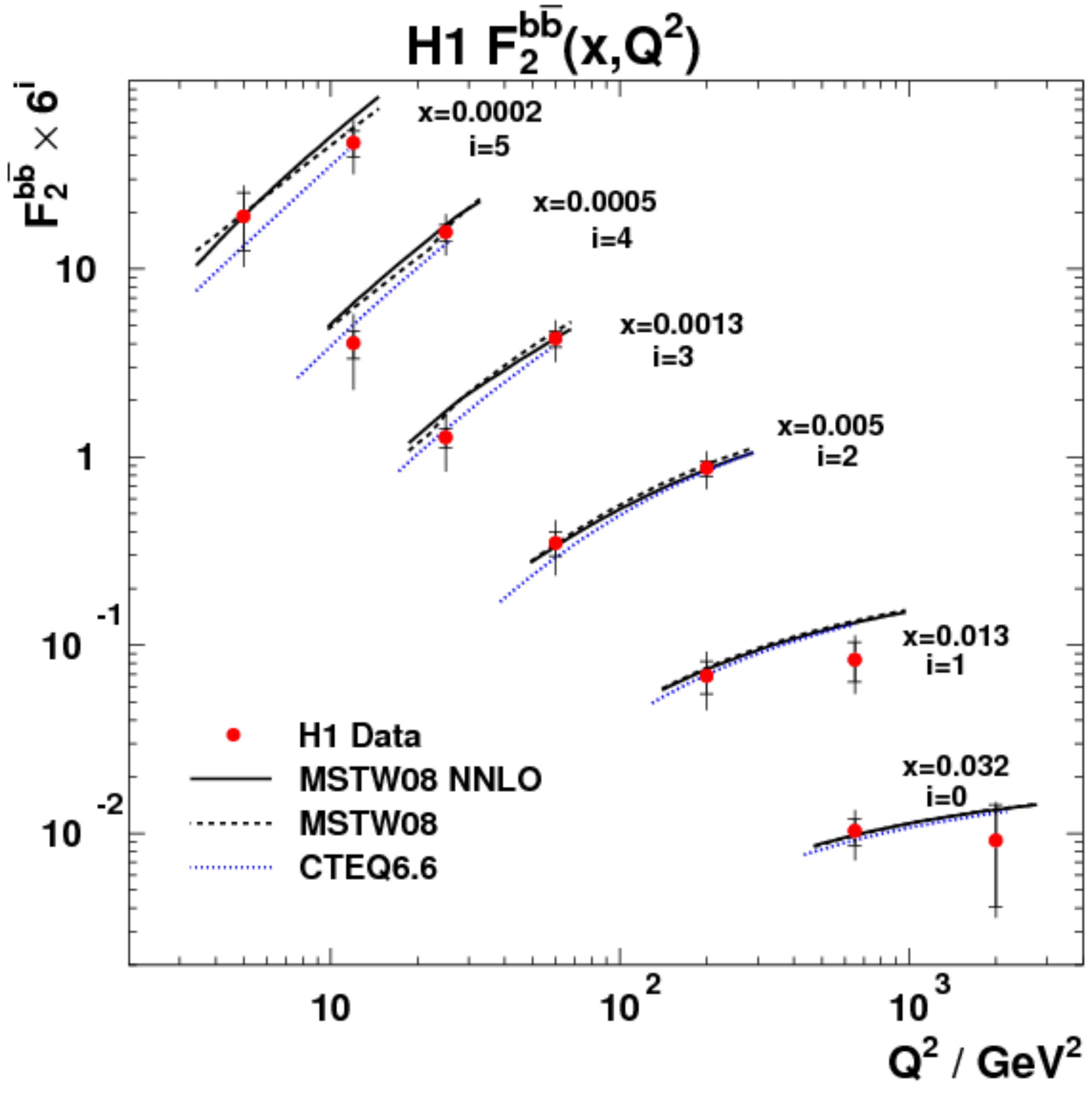
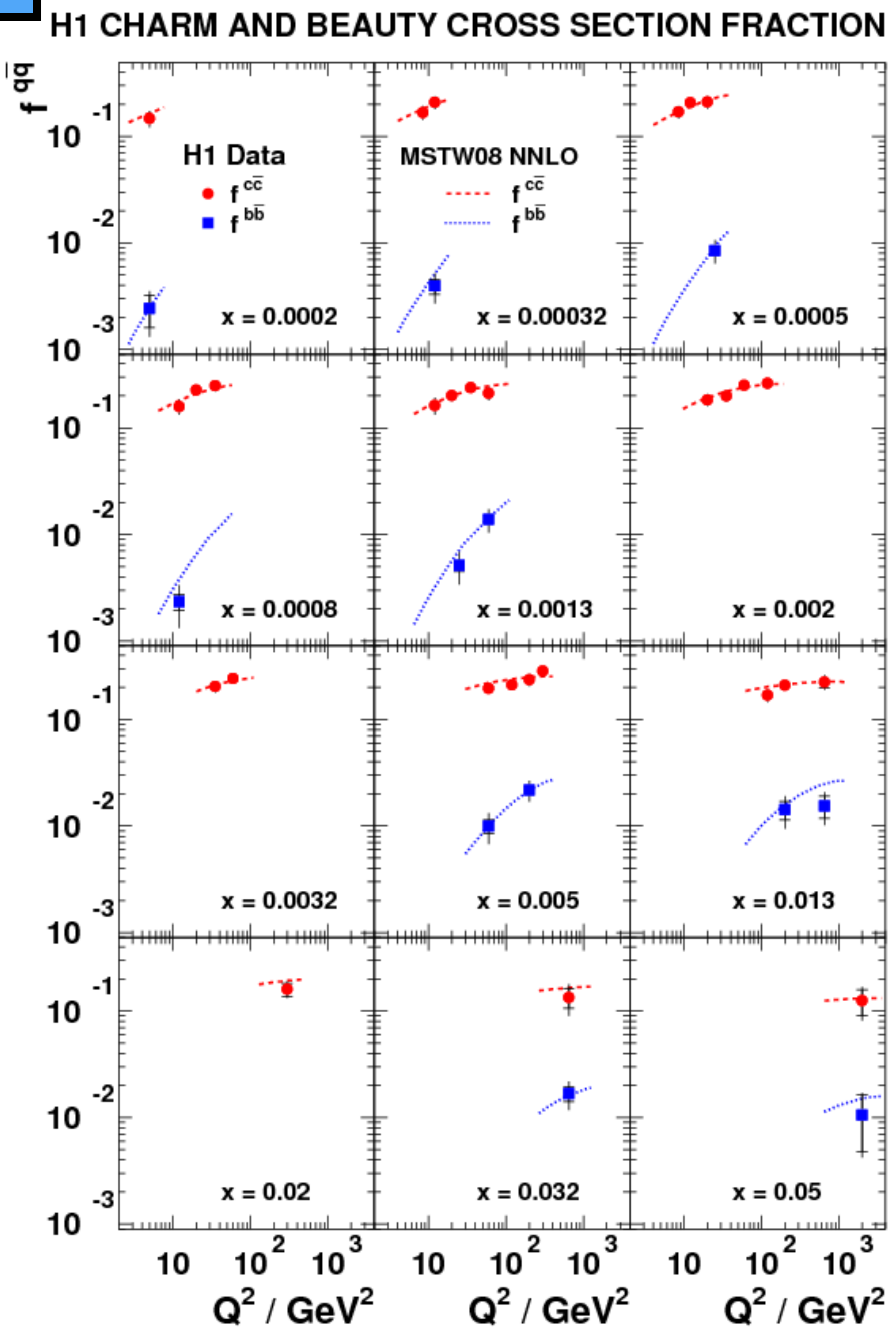
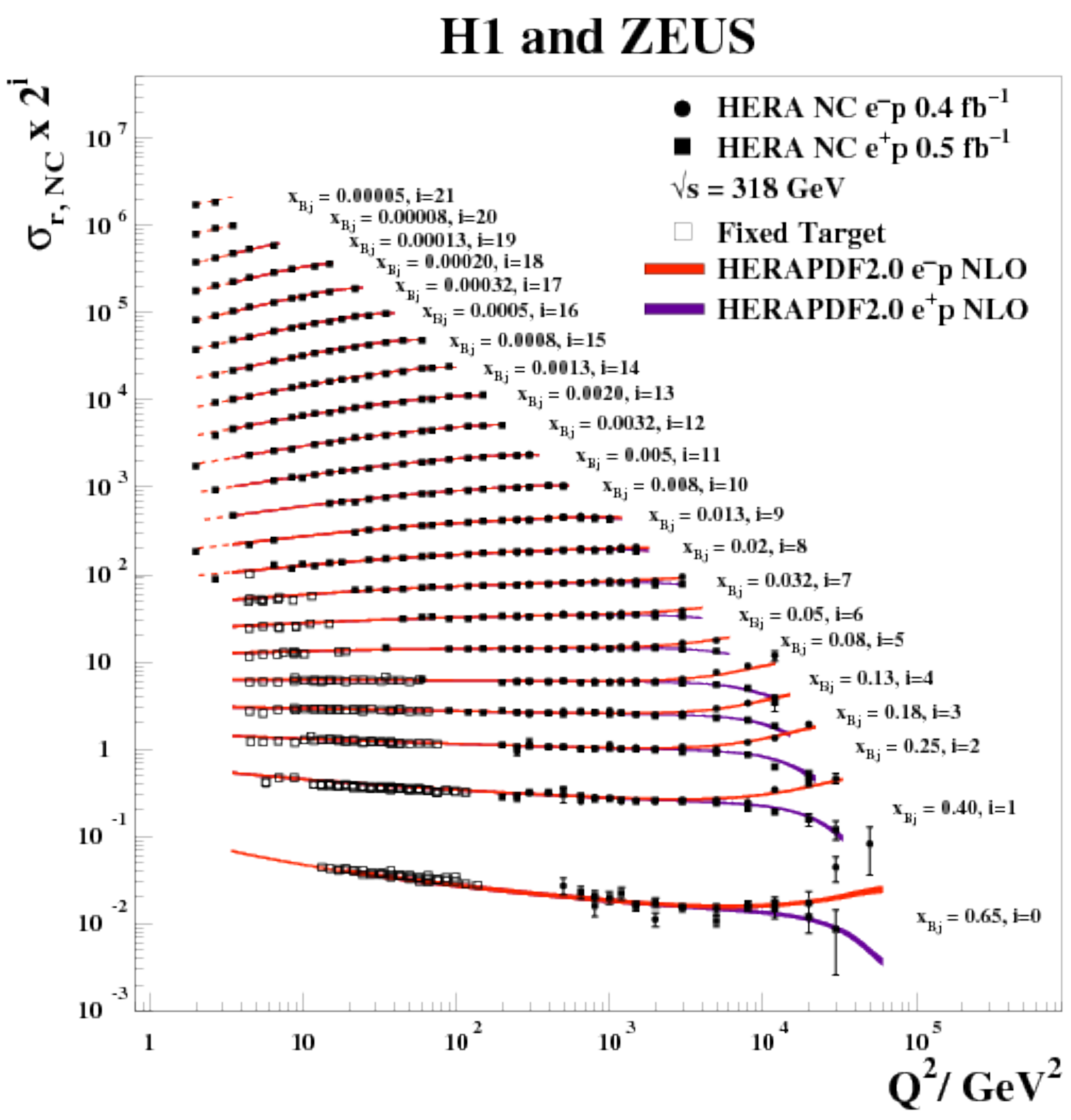






H1, https://inspirehep.net/literature/825811

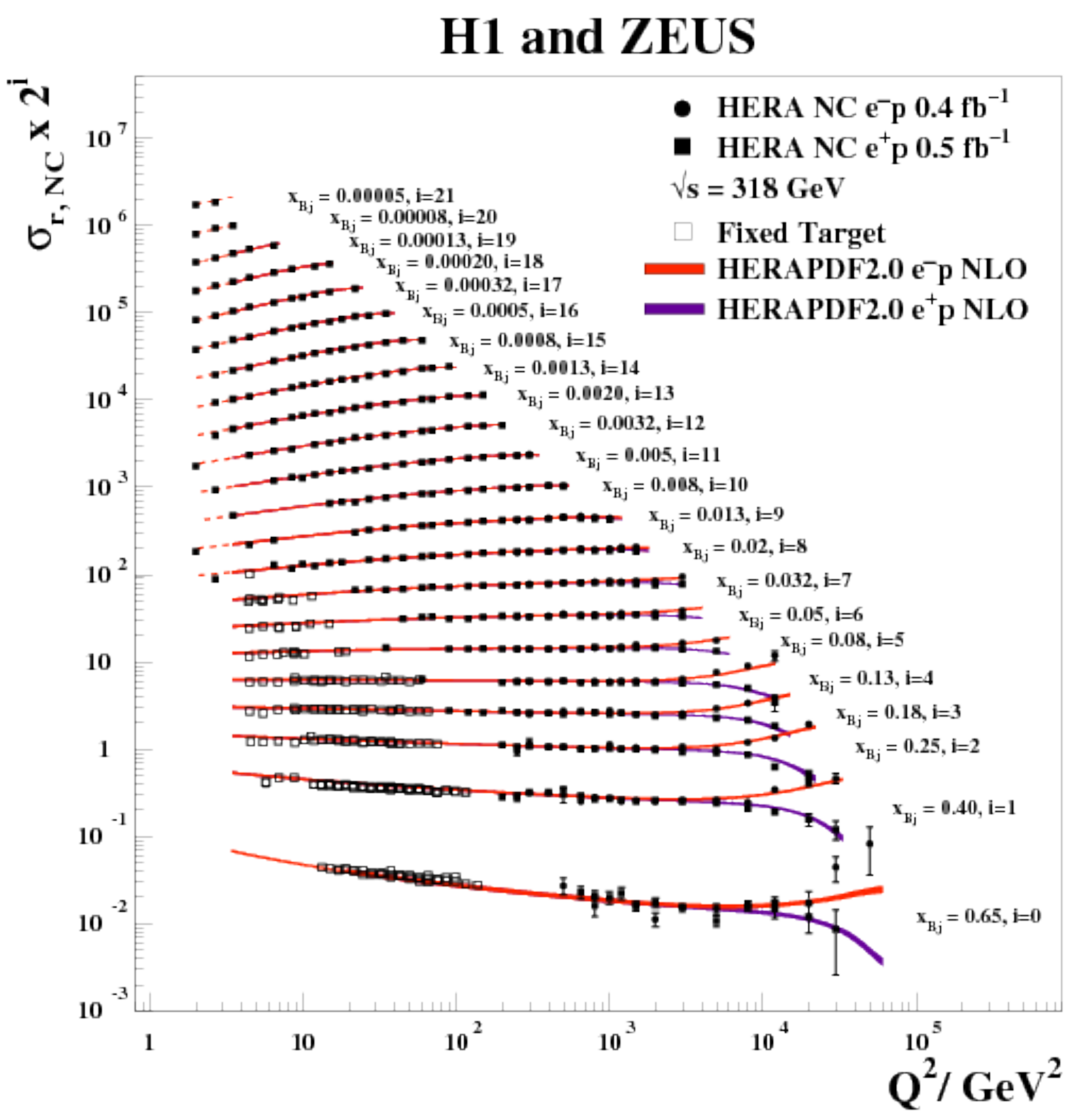
$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{NC}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2}\cdot\frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+}$$

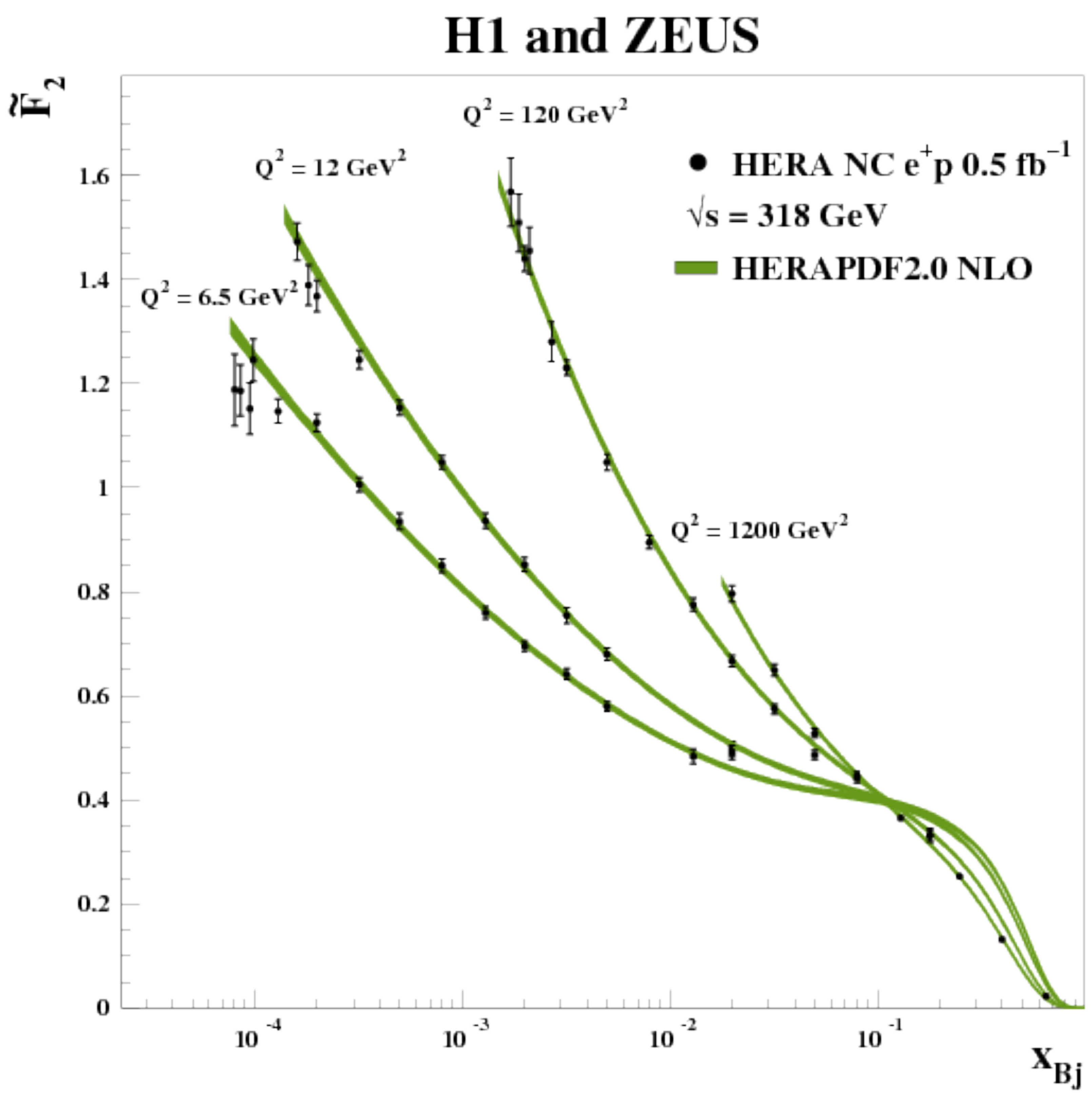


H1 and Zeus, https://inspirehep.net/literature/1377206

DIS data, state of the art (2015)

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^\pm p}_{\mathrm{NC}}}{dx_{\mathrm{Bj}}dQ^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L, \qquad \tilde{F}_2 = F_2 - \kappa_Z v_e \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2)\cdot F_2^Z$$





H1 and Zeus, https://inspirehep.net/literature/1377206

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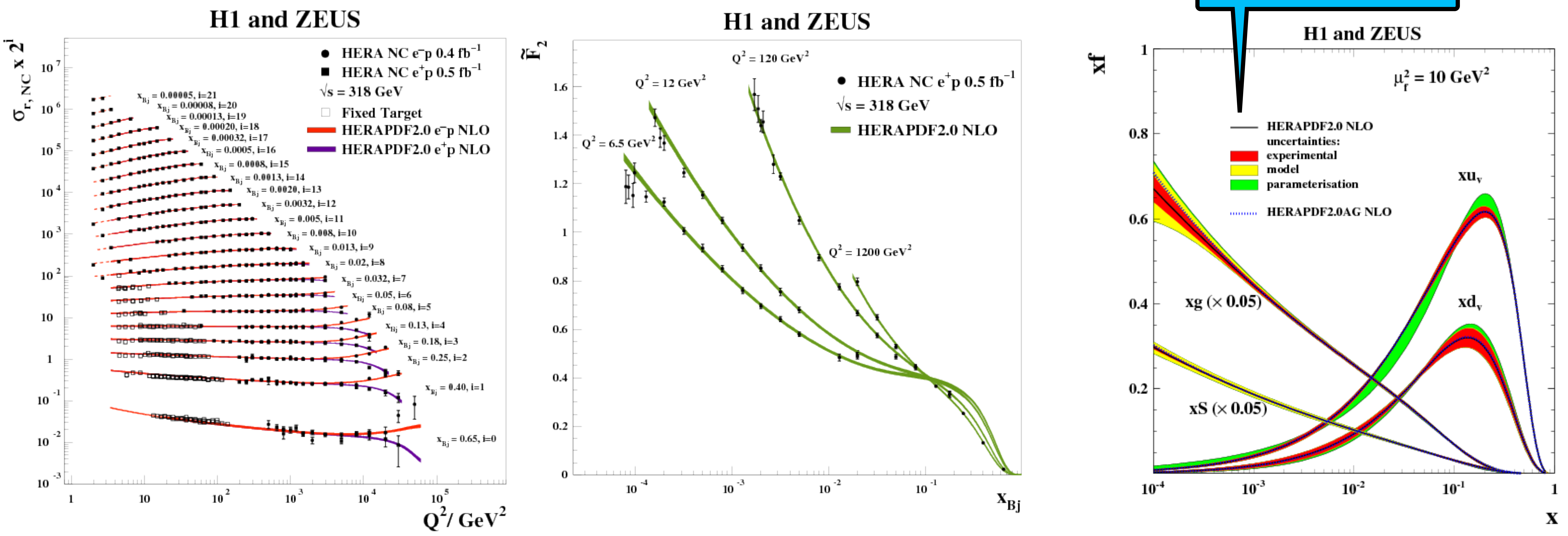
There also are NNLO fits



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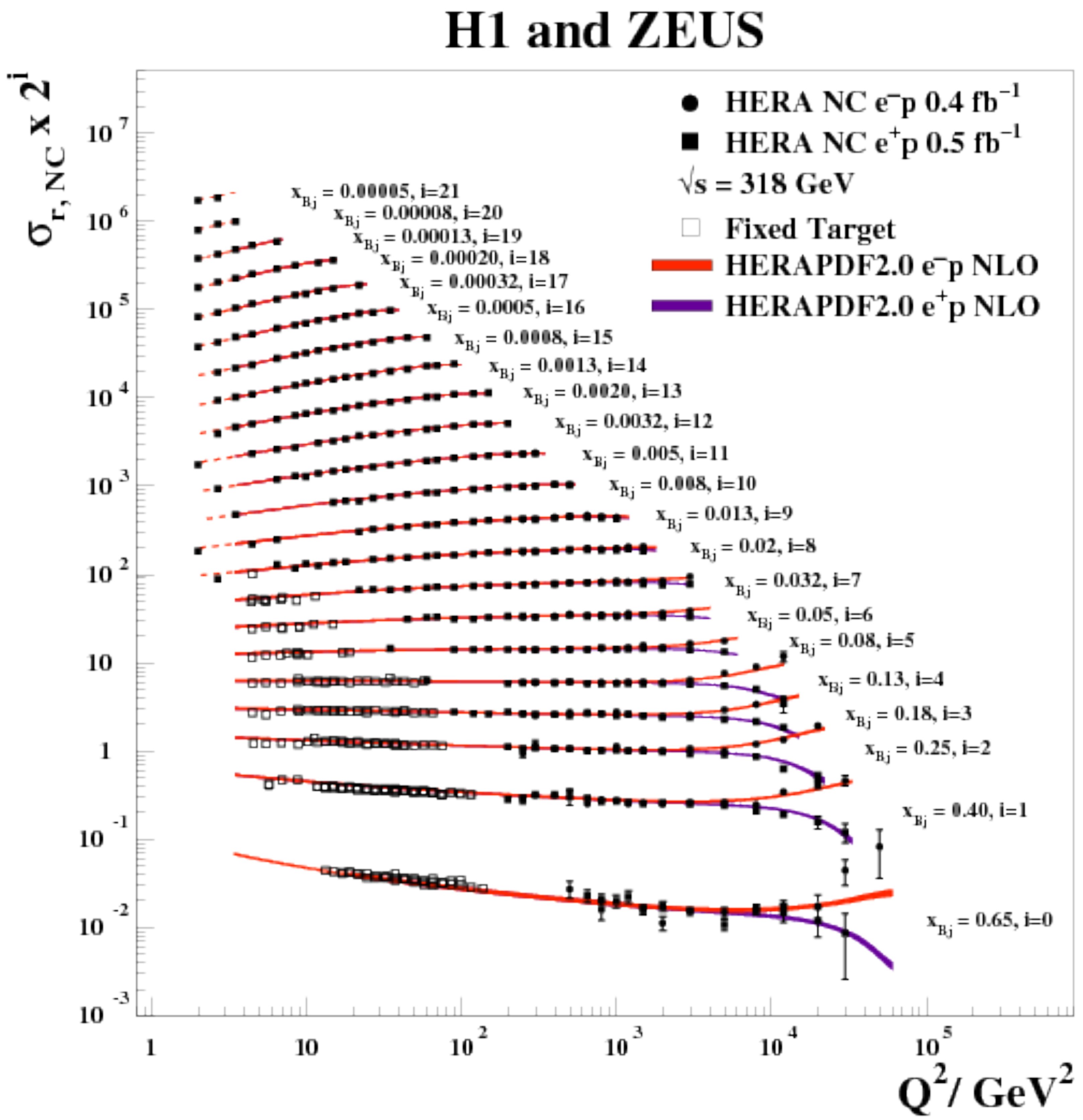

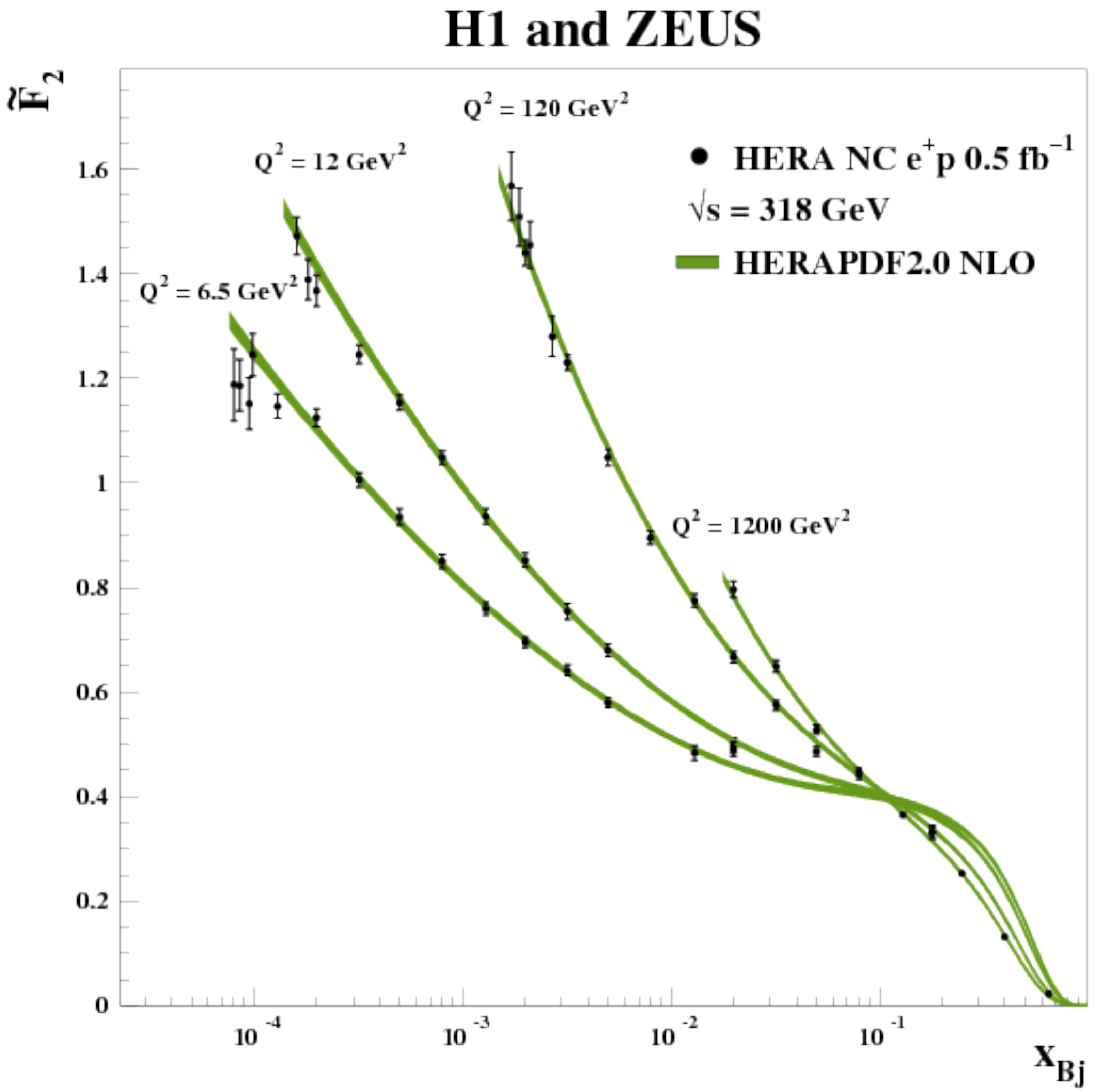

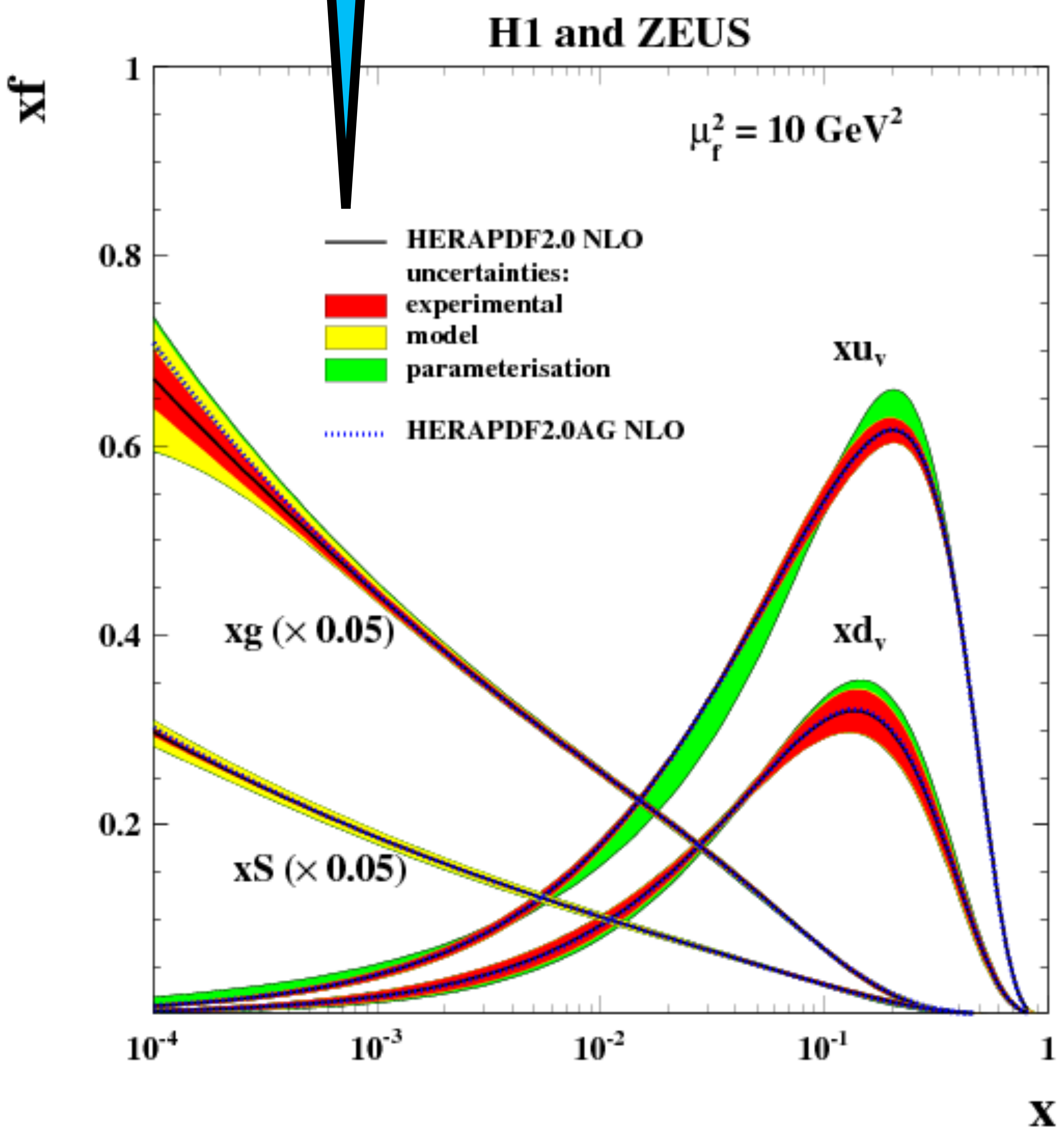

The QCD analysis of HERA data give us a deep and detailed view of the structure of the proton

We are interested in the high-energy limit of QCD

Reminder: small Bjorken-x corresponds to large interaction energy

At this point in time, HERA data show that the structure function grows fast as Bjorken-x decreases.
Let's look at data in more detail and from different perspectives

3

Exploring high-energy QCD:
Probing structure functions with colour dipoles at HERA

Growth of the cross section at fixed virtuality (2001)

In the BFKL approach, it is expected that the structure function at fixed virtuality grows as a power law

Fix the scale and
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https://inspirehep.net/literature/561805

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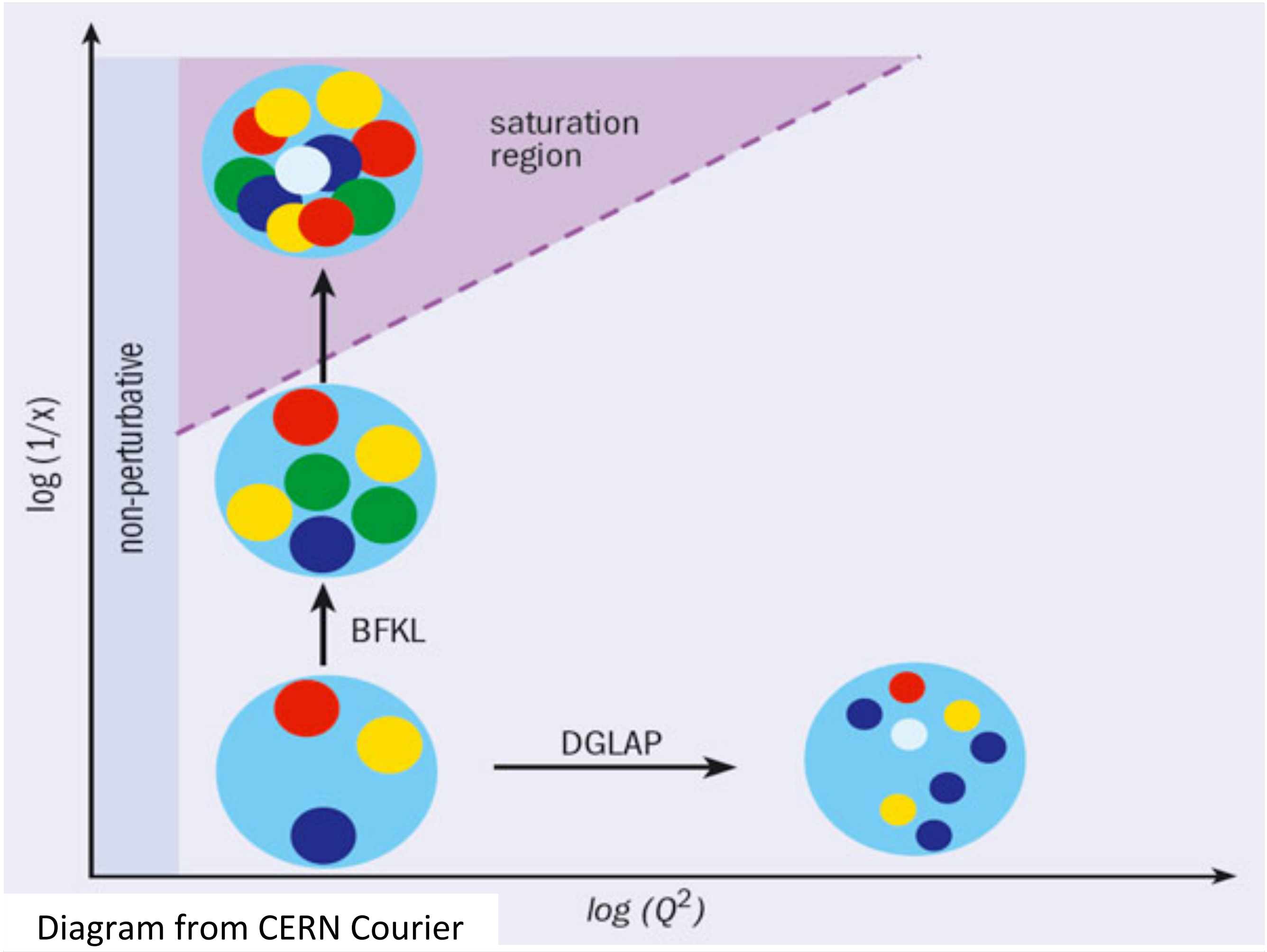

Diagram from CERN Courier

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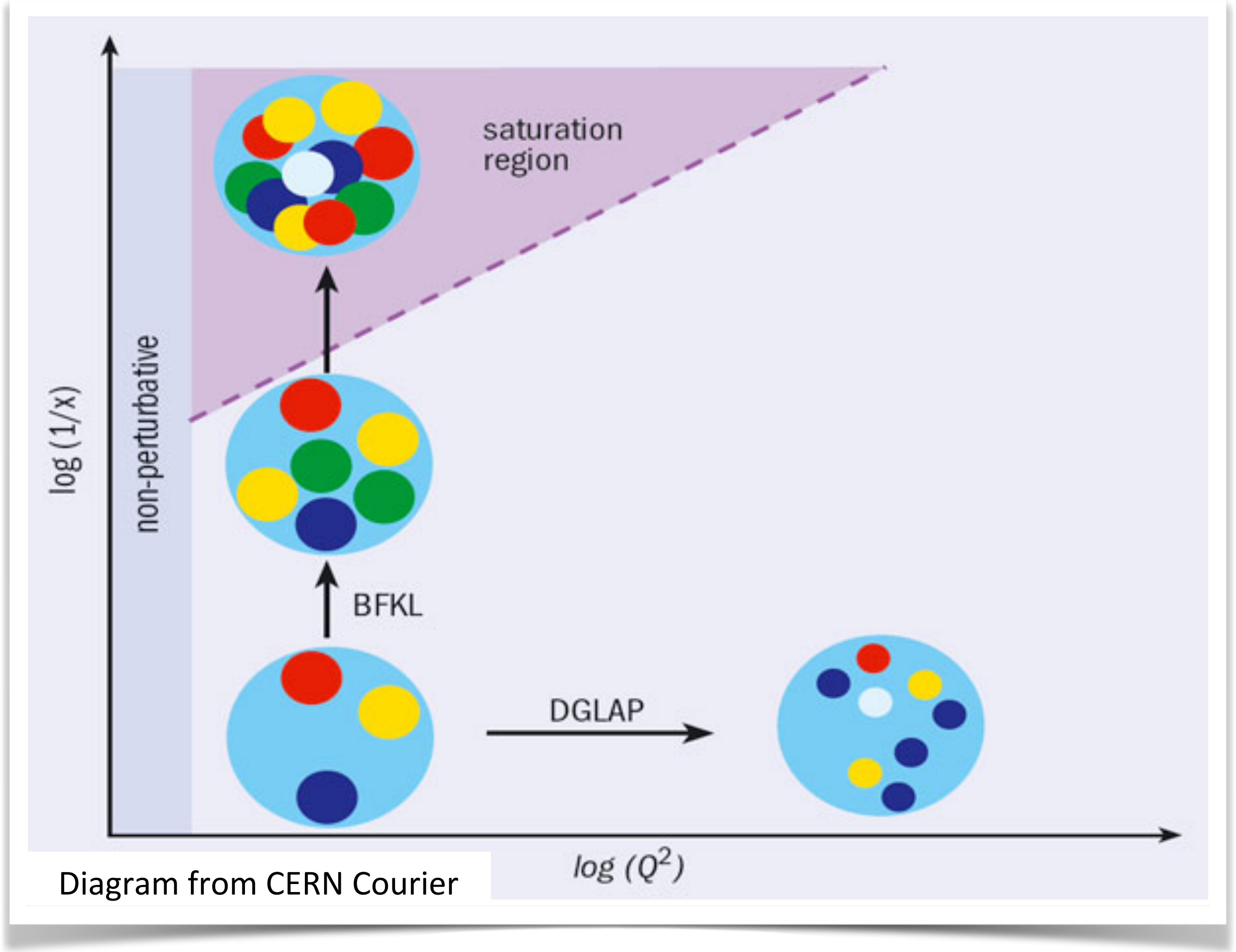

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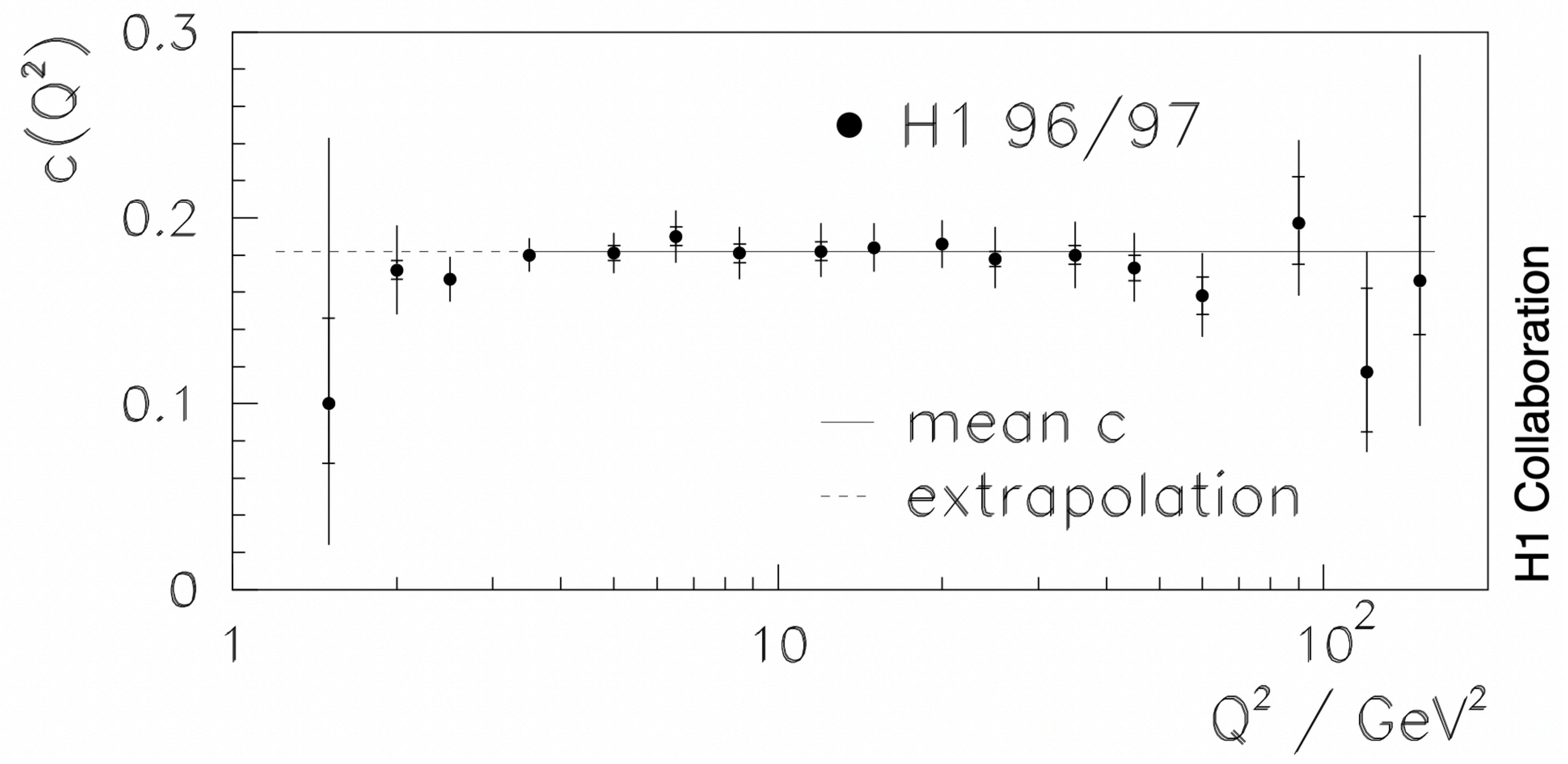

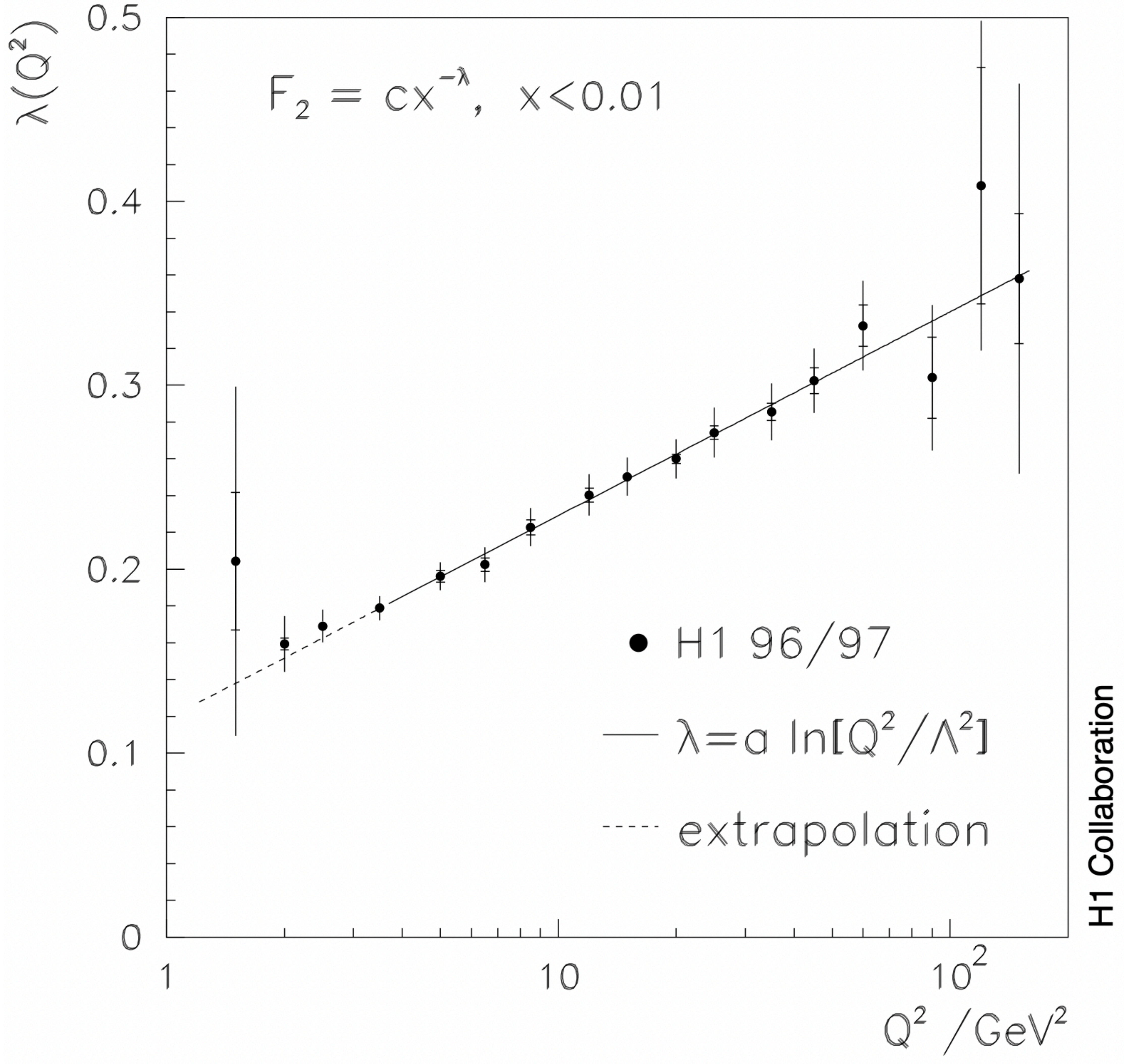

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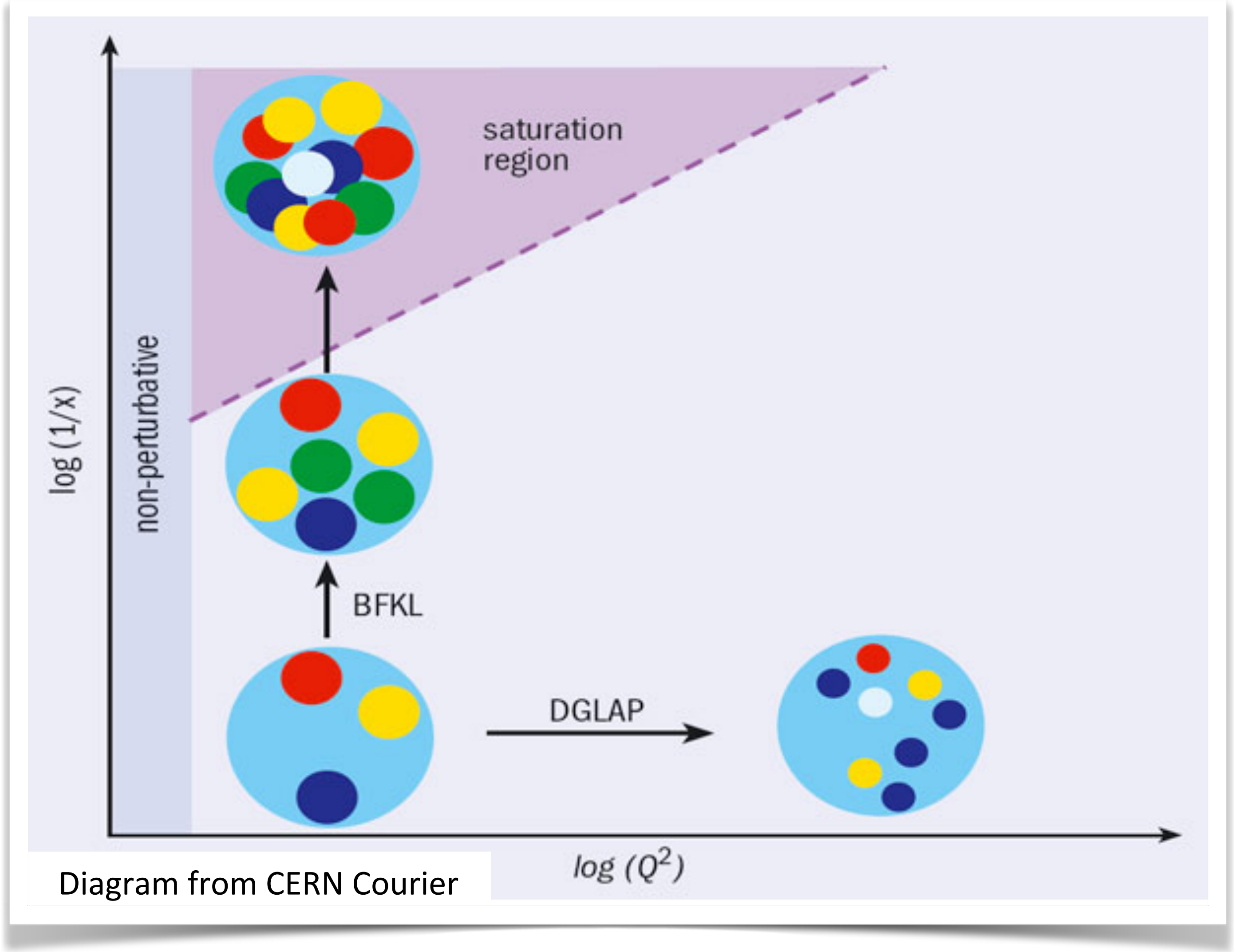

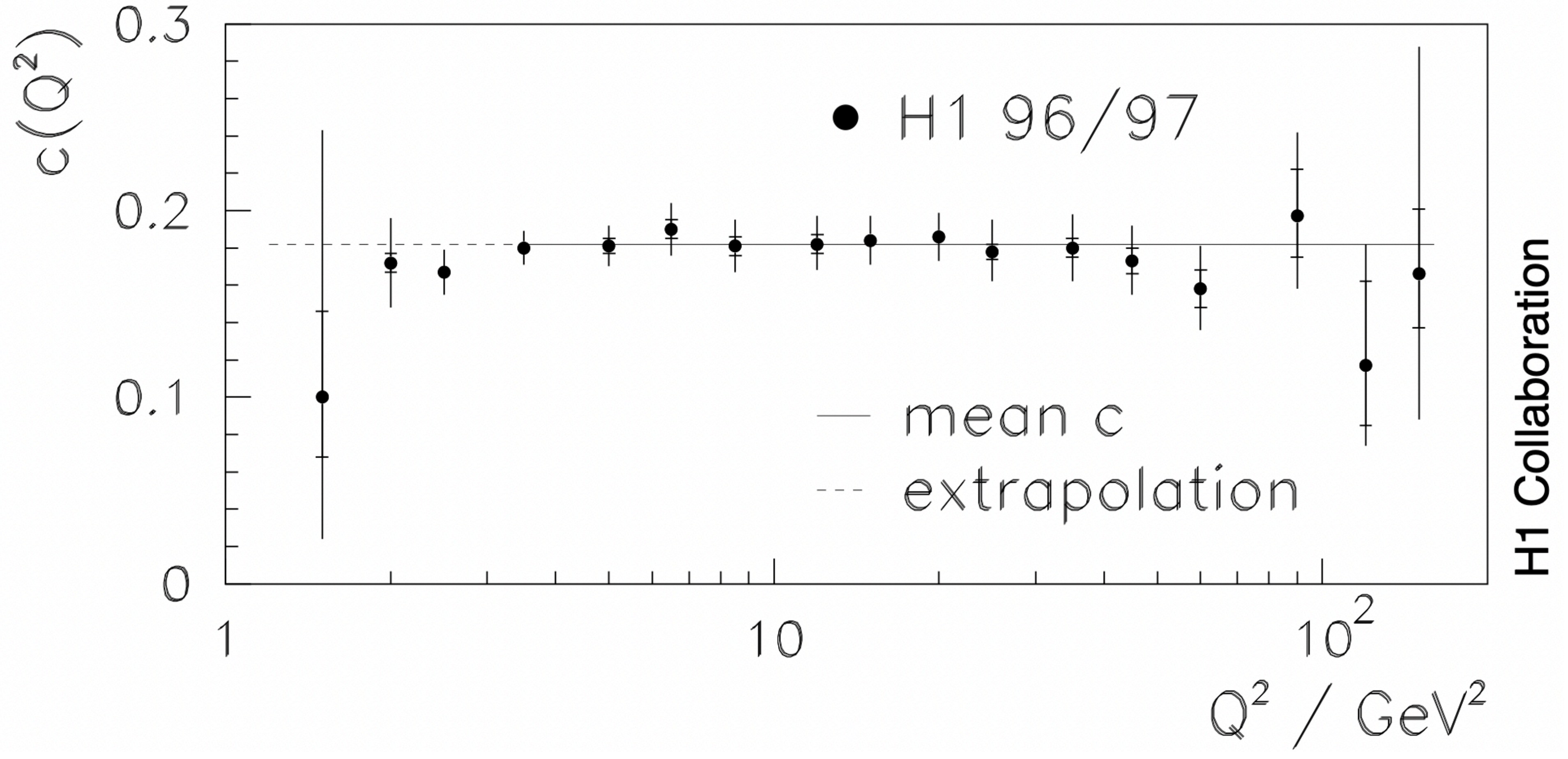

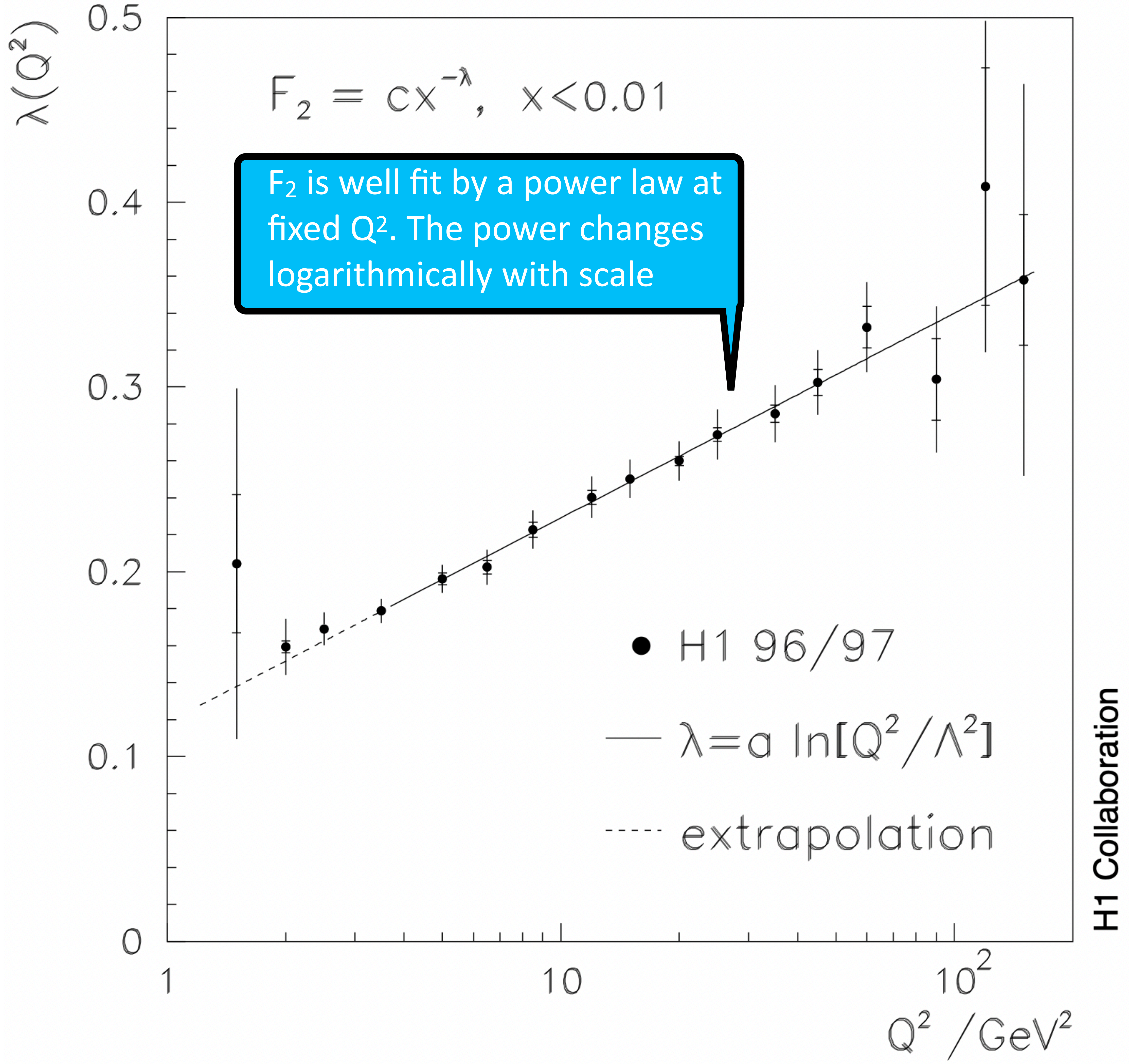

F_2 is well fit by a power law at fixed Q^2. The power changes logarithmically with scale

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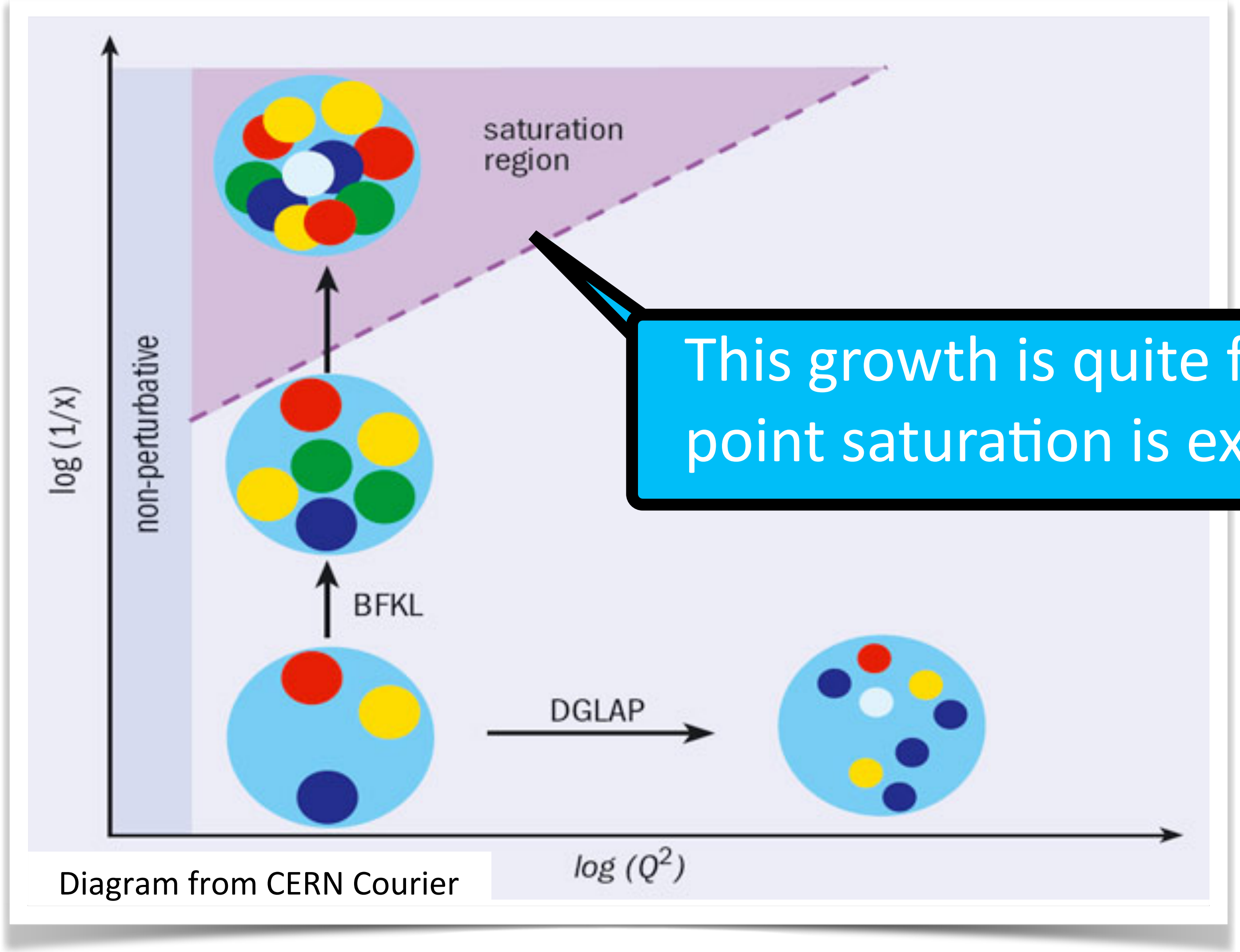

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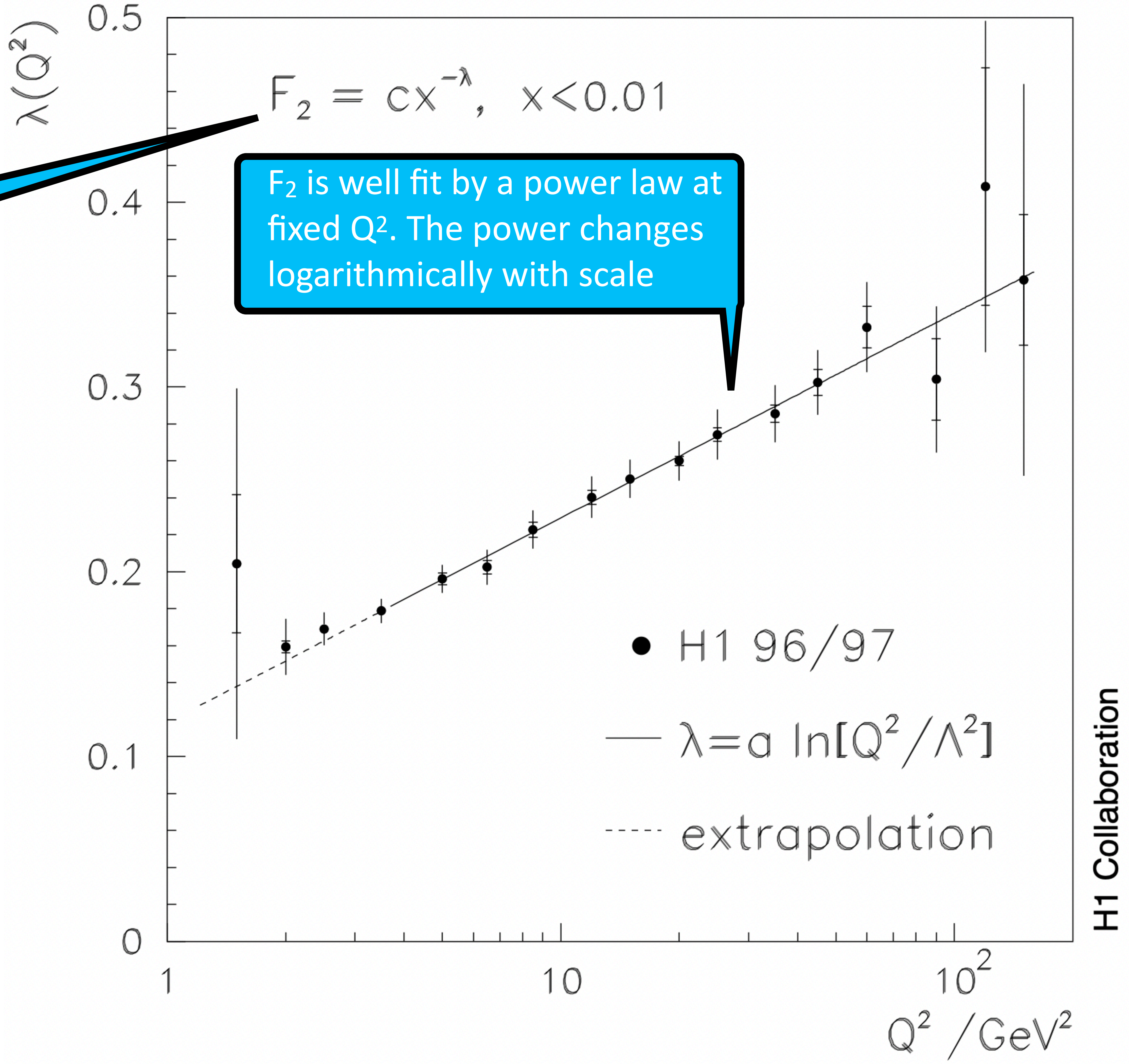
This growth is quite fast, at some point saturation is expected



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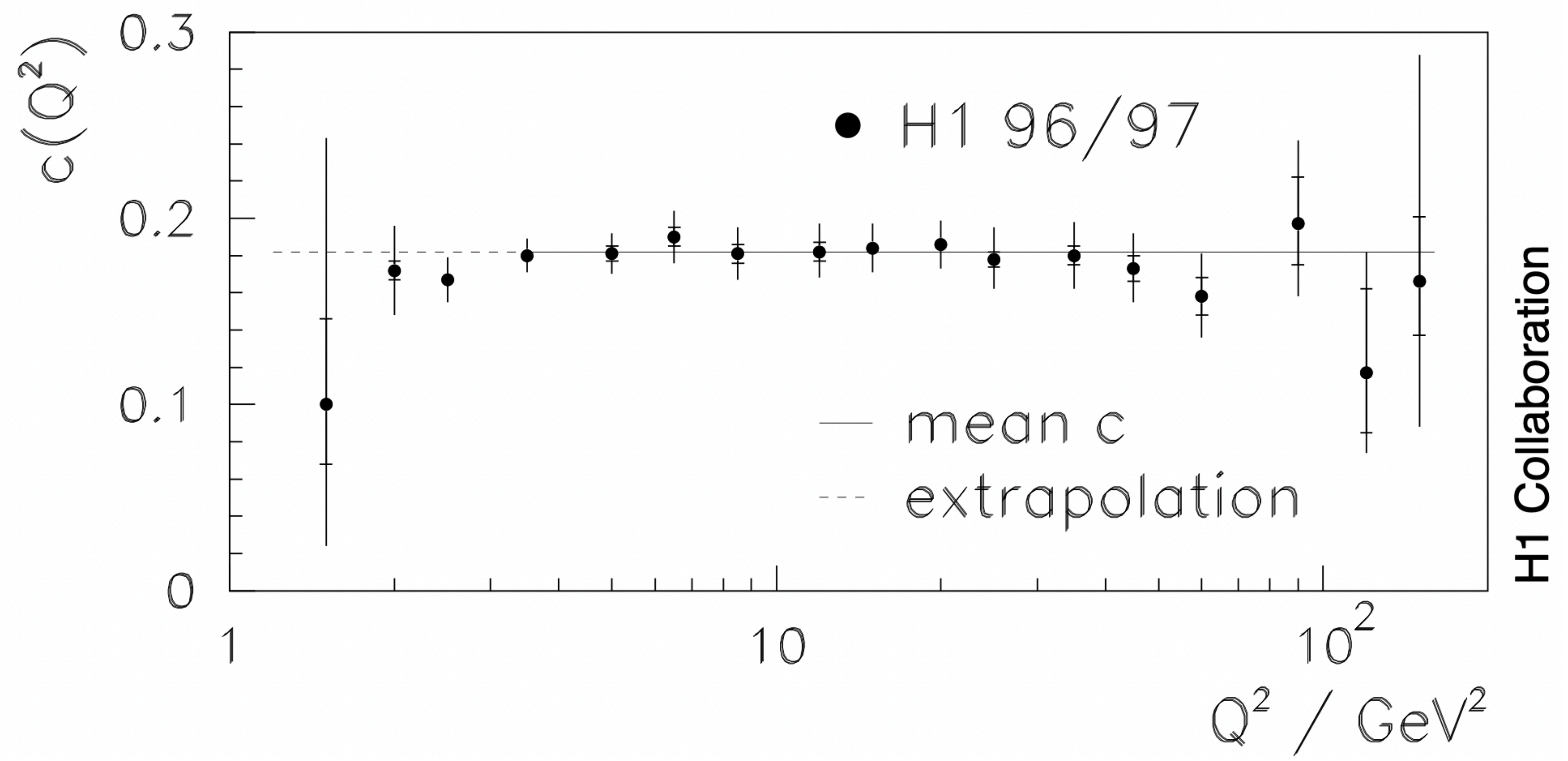

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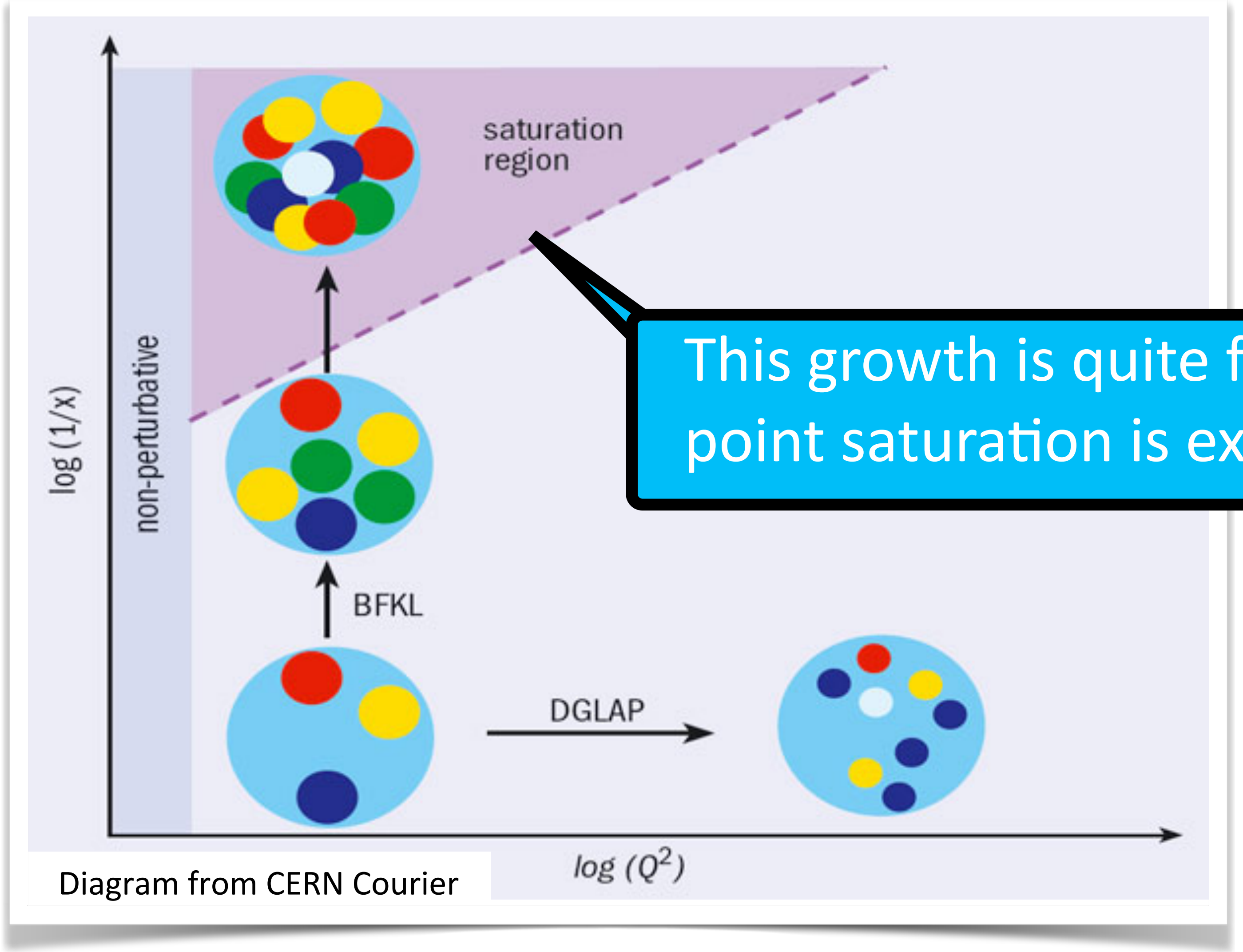

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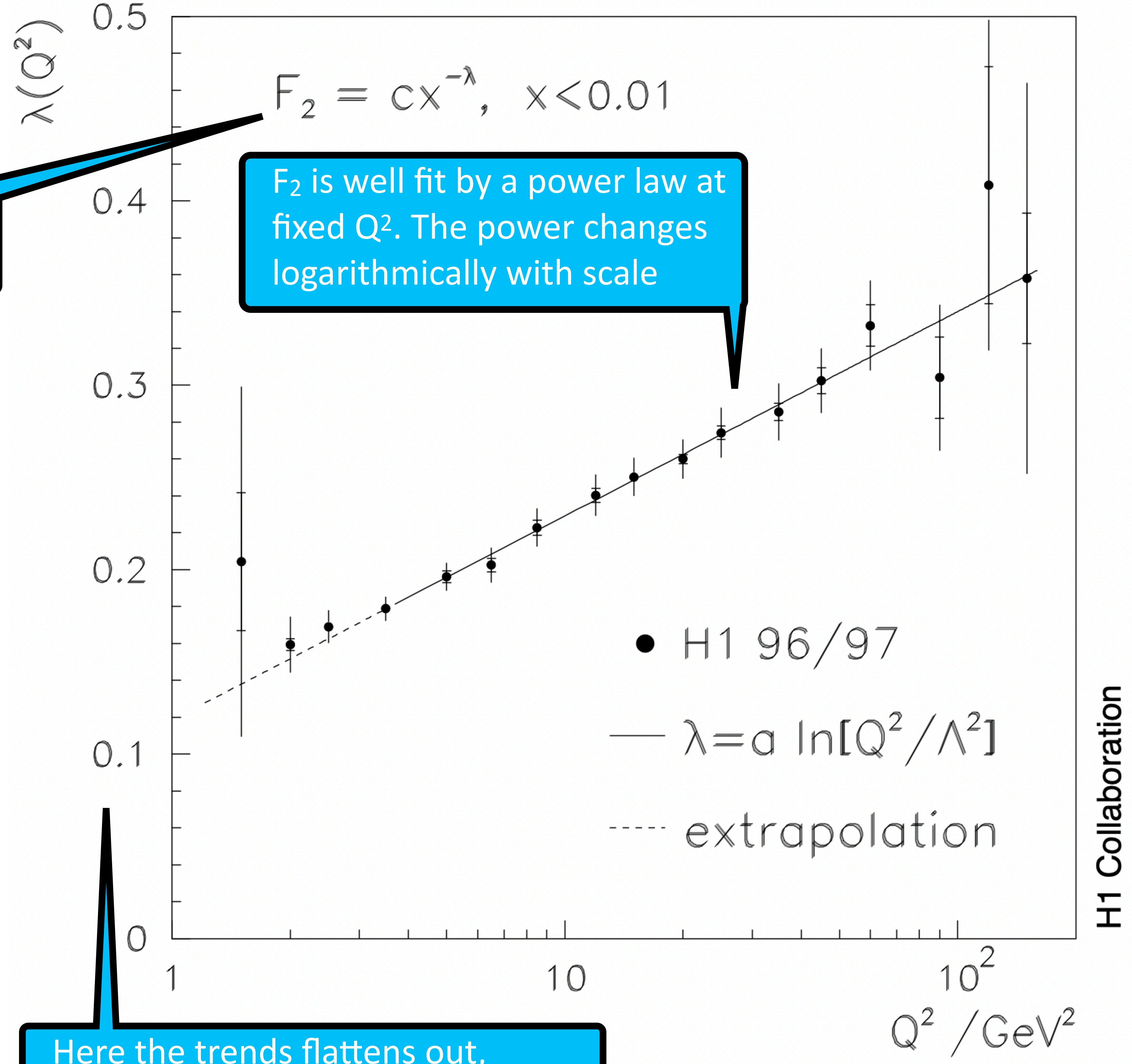

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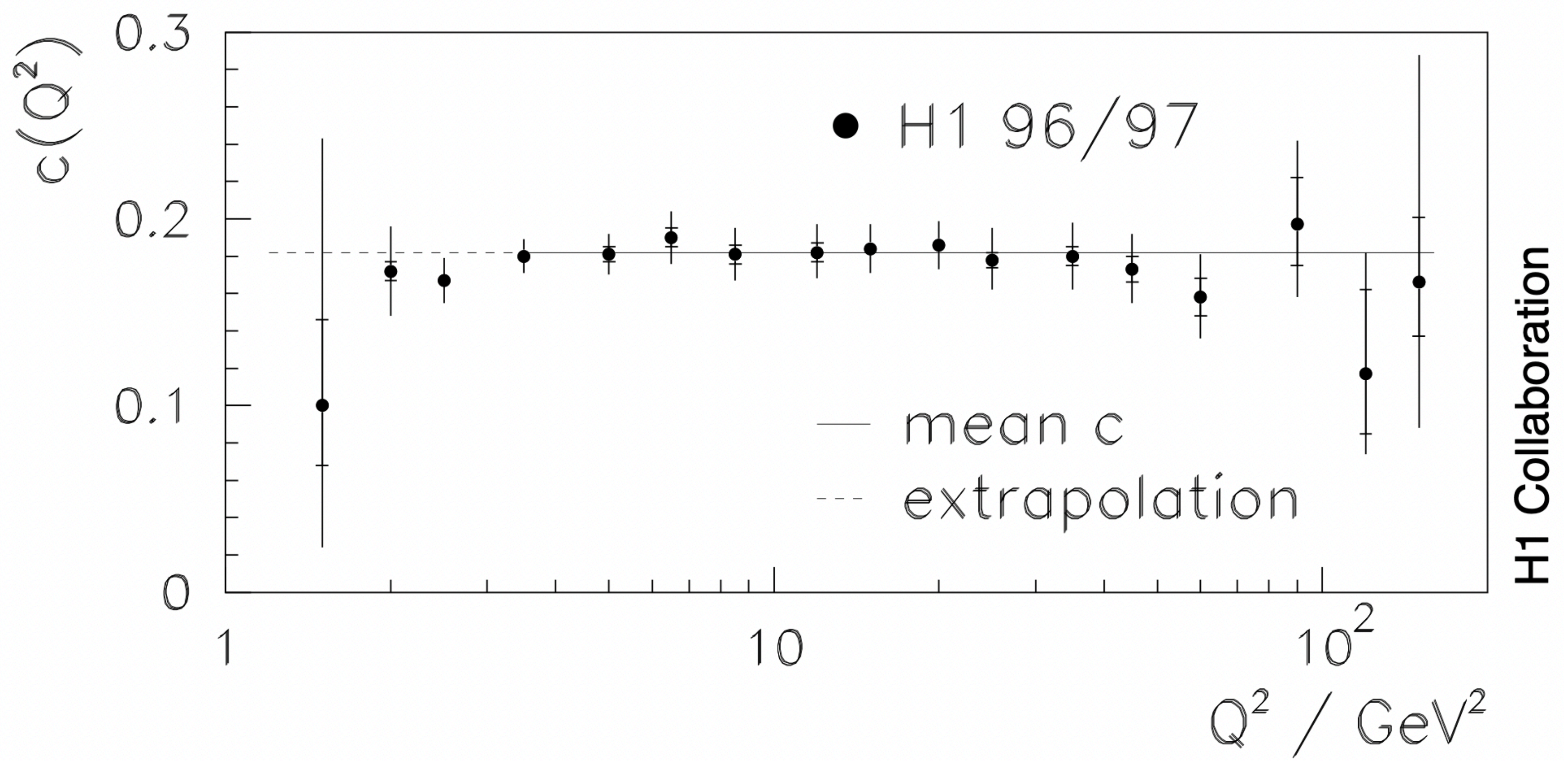

Here the trends flattens out, consistent with total cross sections

https://inspirehep.net/literature/561805

The determination of the onset of saturation is one of the prime tasks of experimental pQCD nowadays

Photo-production cross section (1997)

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4x}(2-2y+\frac{y^2}{1+R})F_2(x,Q^2) \;= \Gamma[\sigma_T(x,Q^2)+\epsilon(y)\sigma_L(x,Q^2)] \equiv \Gamma\sigma^{eff}_{\gamma^* p}(x,y,Q^2)$$

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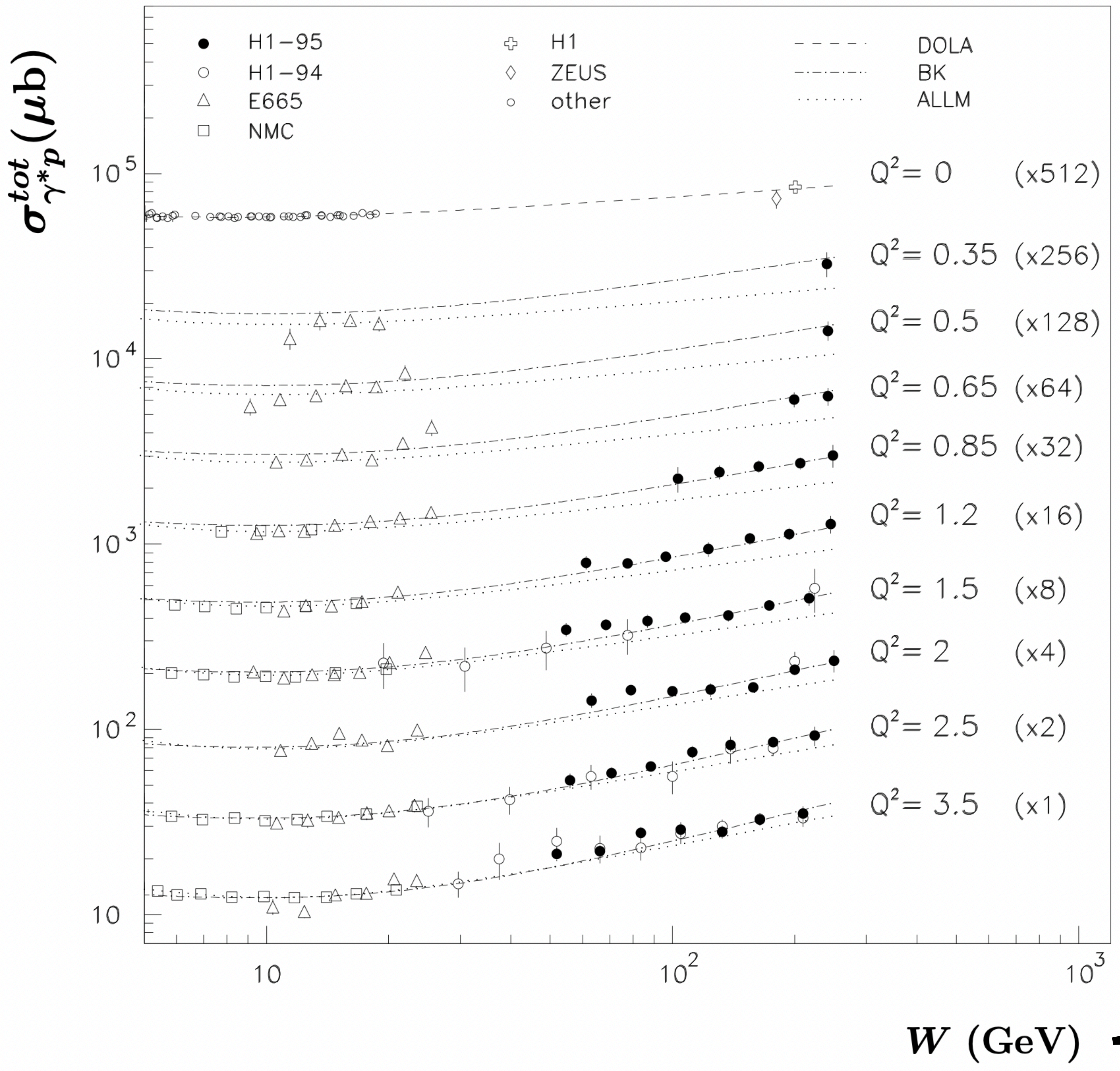

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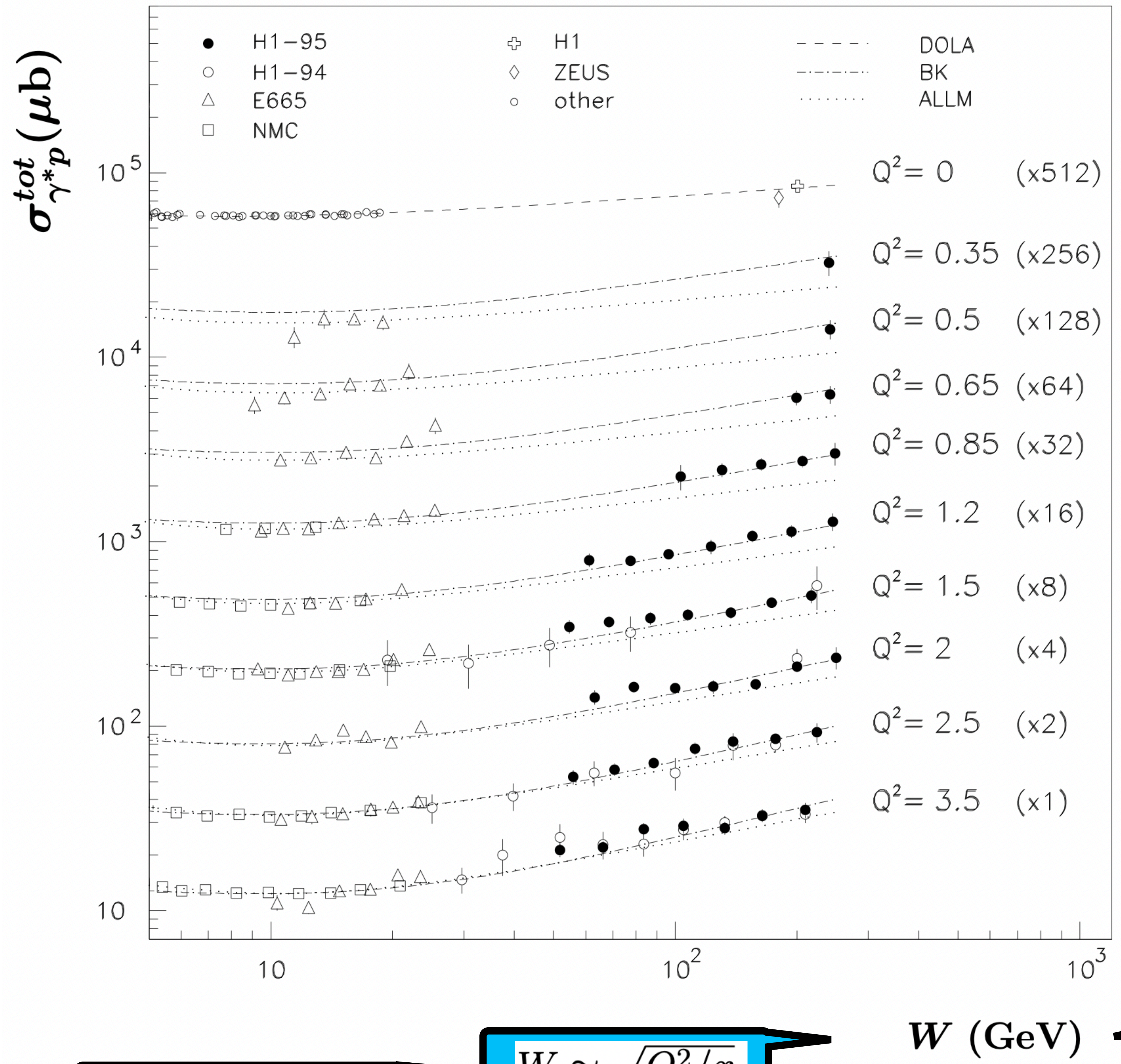

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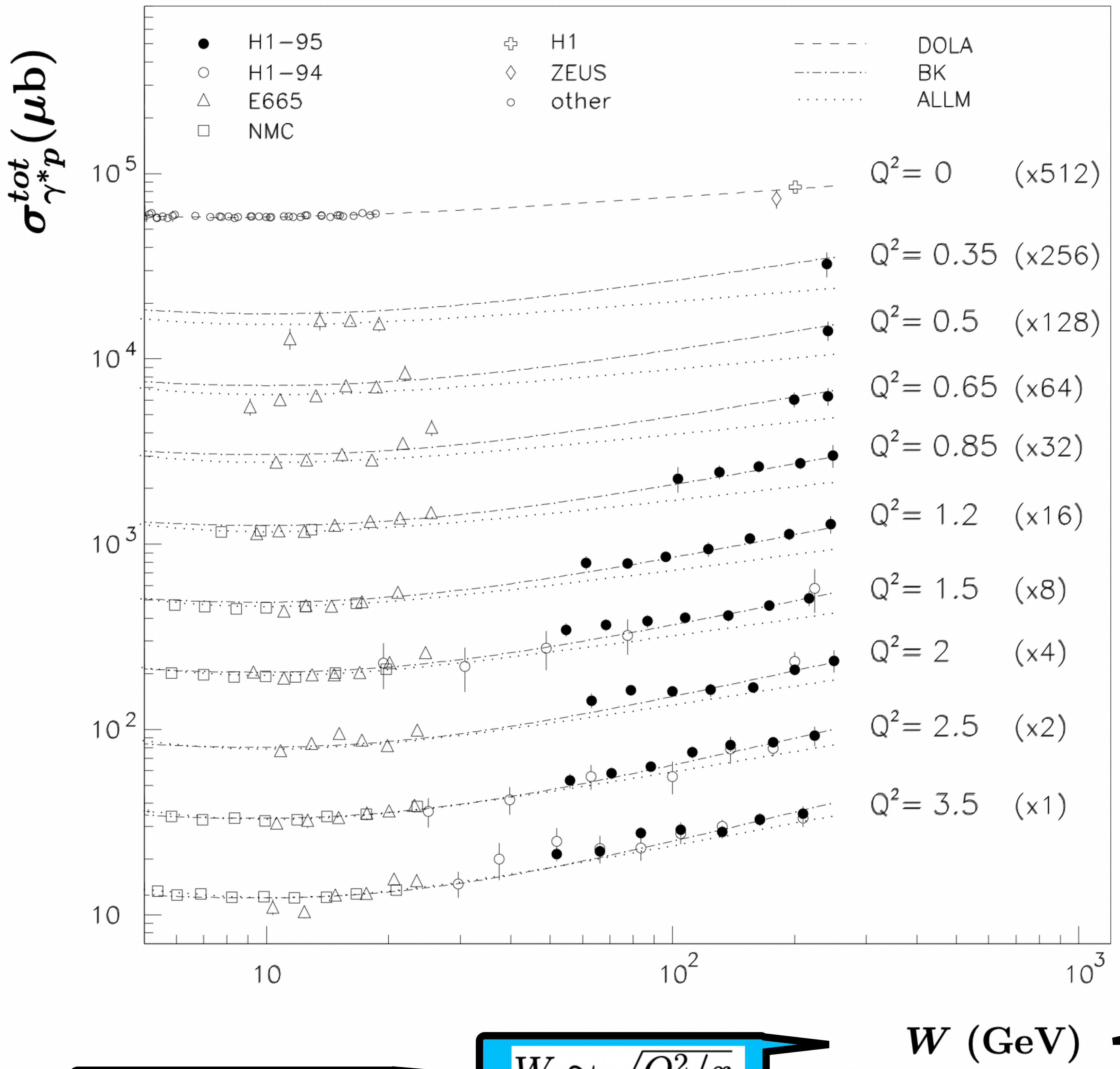

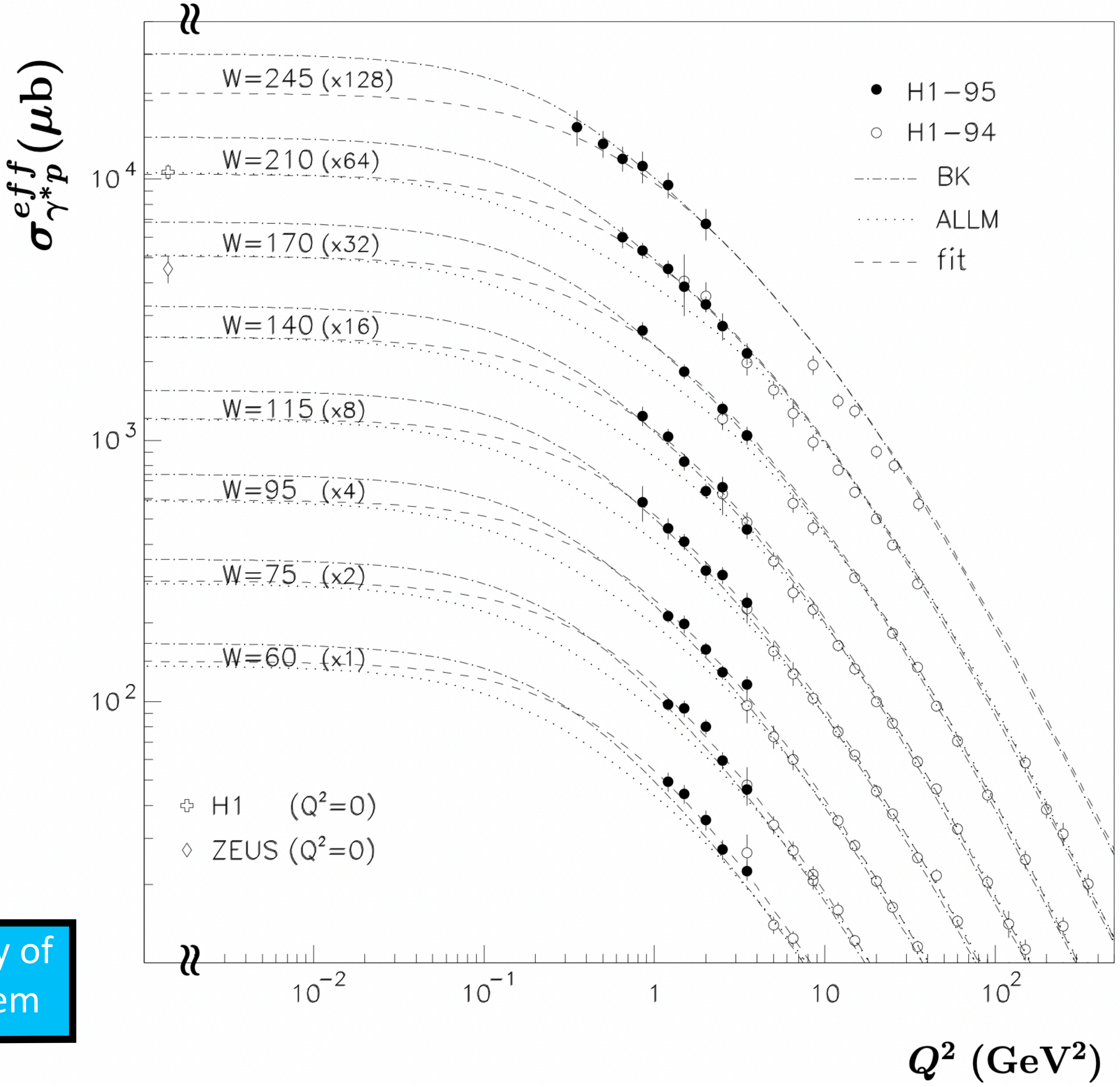

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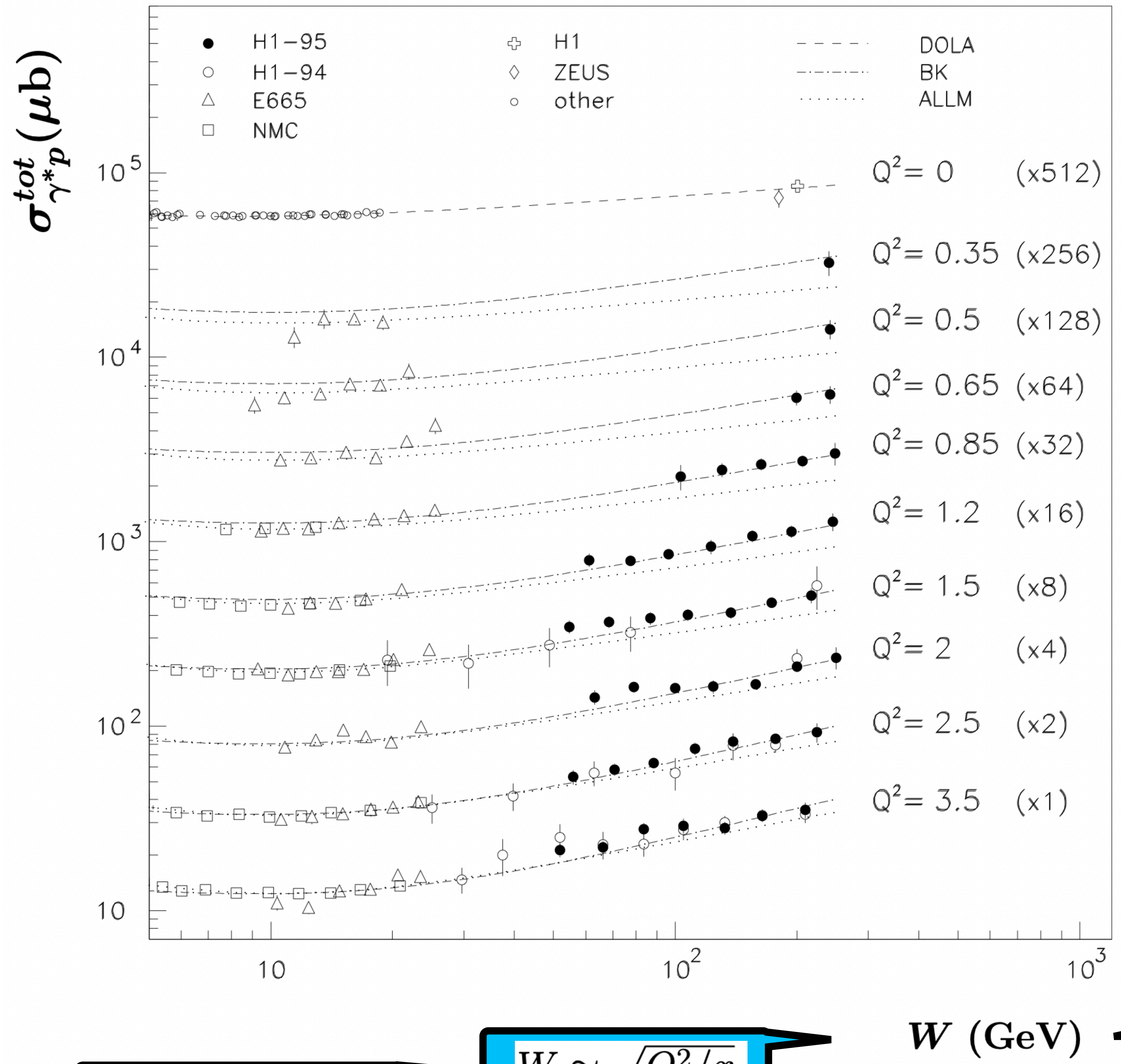

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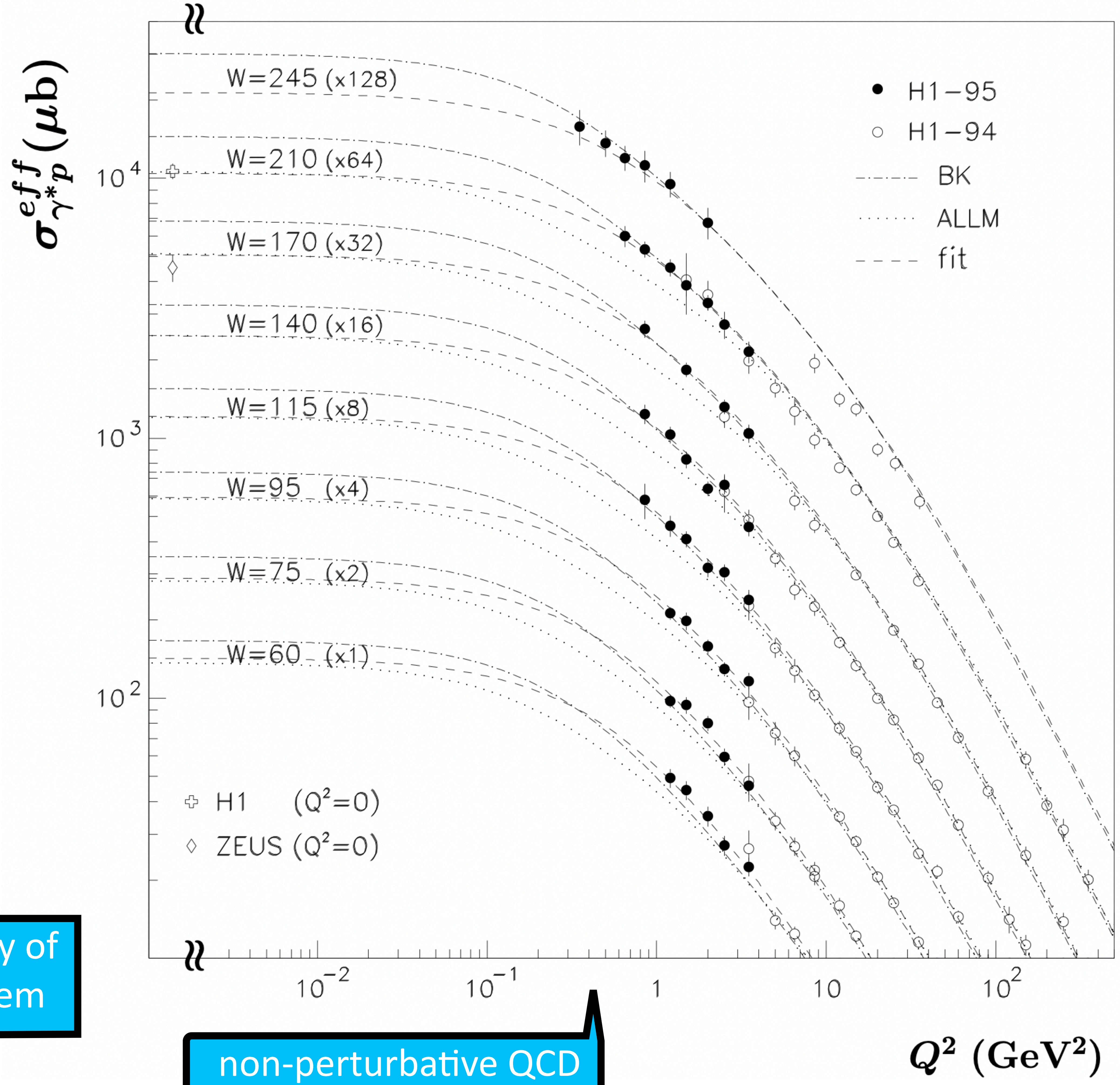

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This is a different type of saturation than the one mentioned in the previous page

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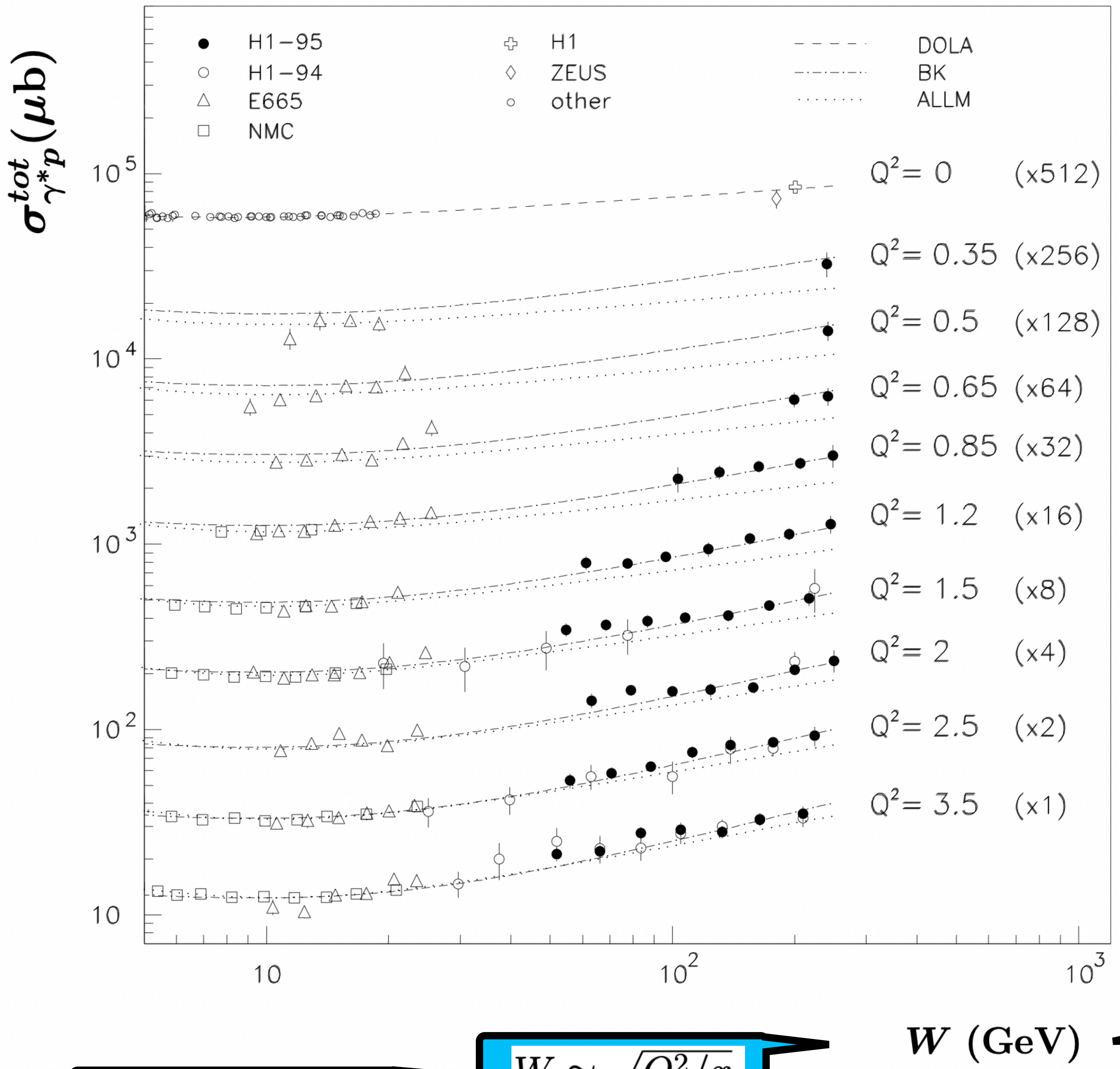

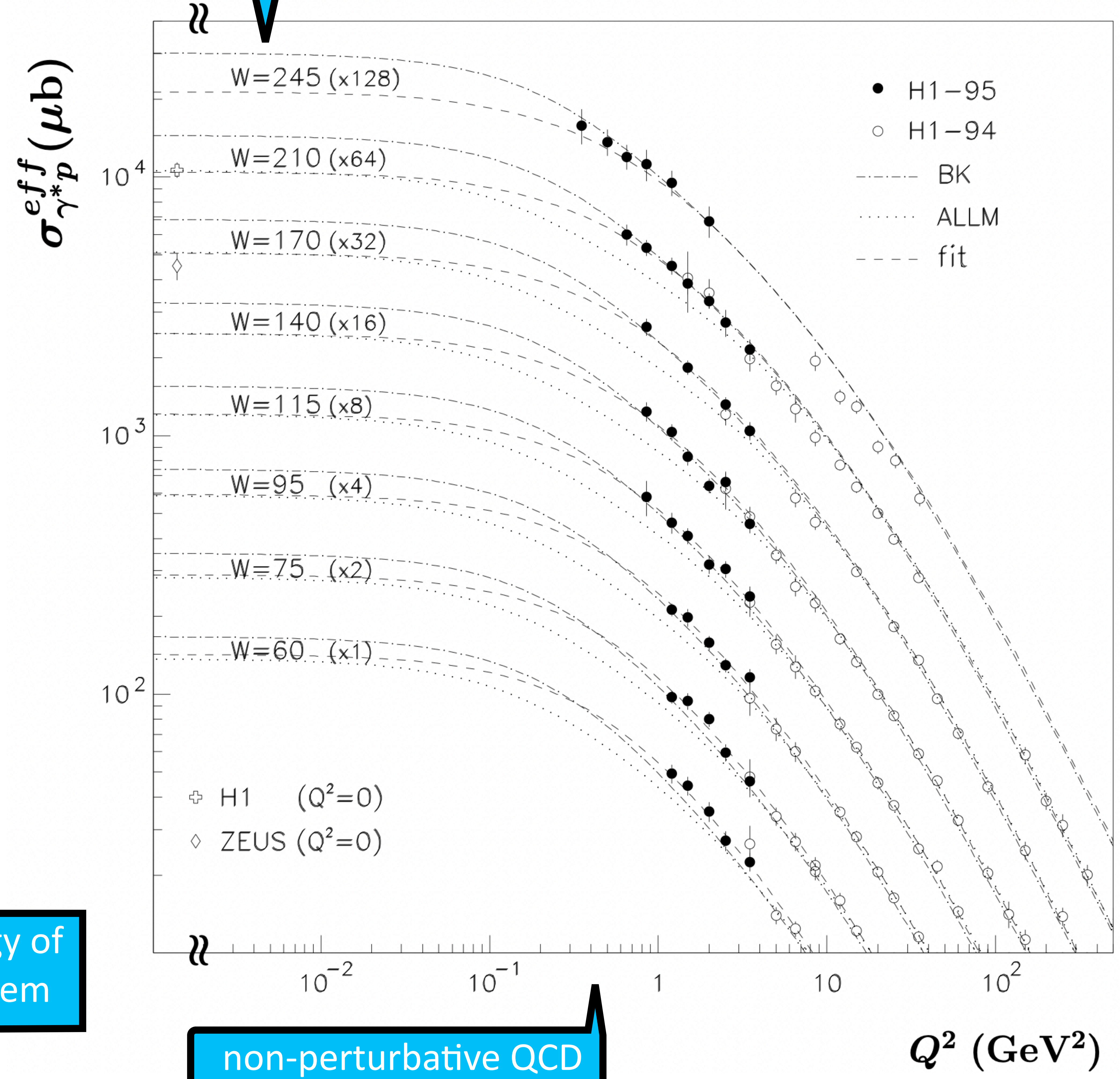

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The GBW (Golec-Biernart and Wüsthoff) model

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Homework: try to implement this model and reproduced the results in the next pages

1998: The GBW model. (1) A different reference frame

Up to now we have worked in the Bjorken limit, where the proton moves with infinite momentum

Golec-Biernat, Wüsthoff https://inspirehep.net/literature/473813

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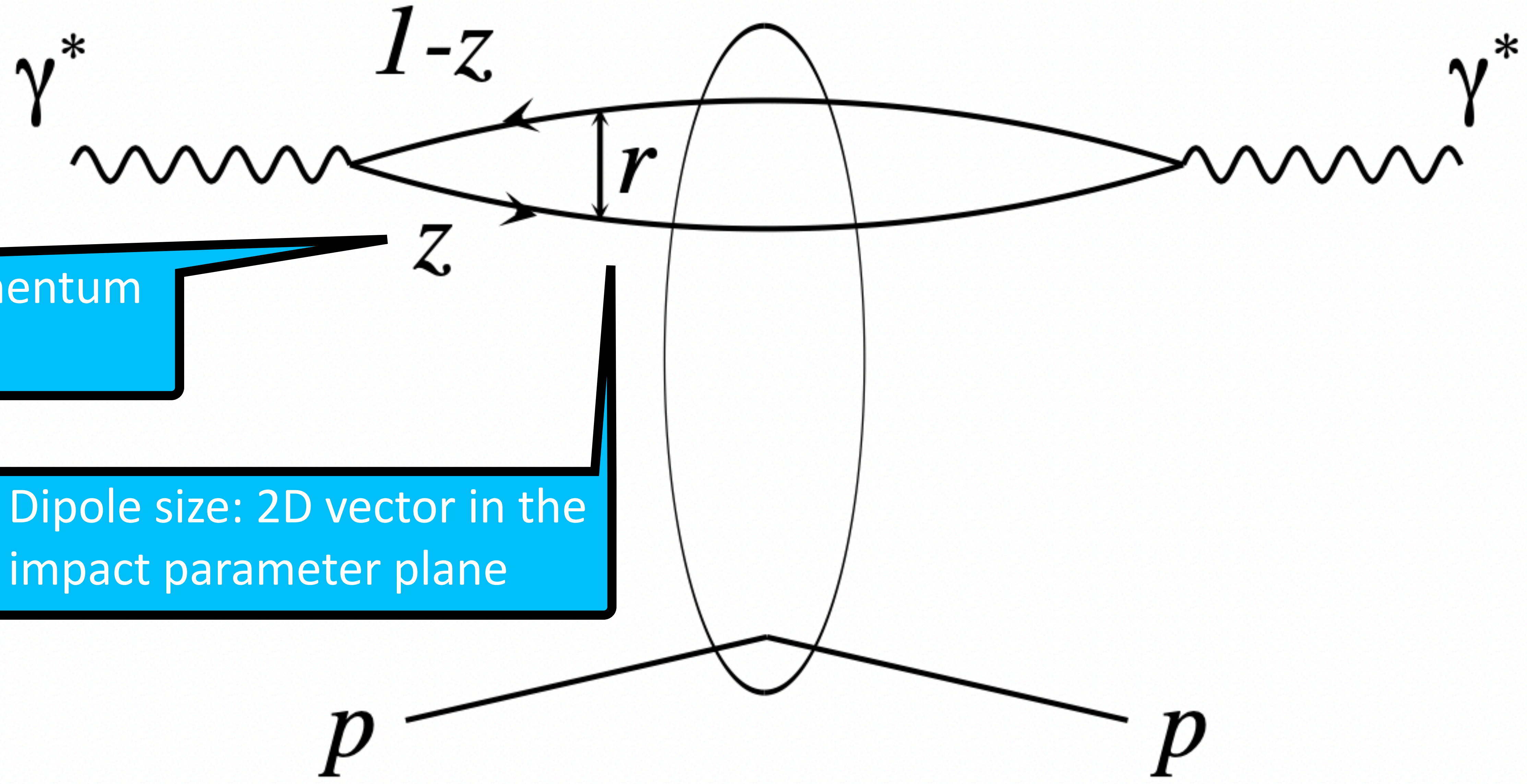

Fraction of the photon momentum carried by the quark

Dipole size: 2D vector in the impact parameter plane

1998: The GBW model. (2) Factorisation

In this frame the photo-production cross section factorises in a QED and a QCD part

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Wave function for the splitting of a photon into a quark-antiquark pair

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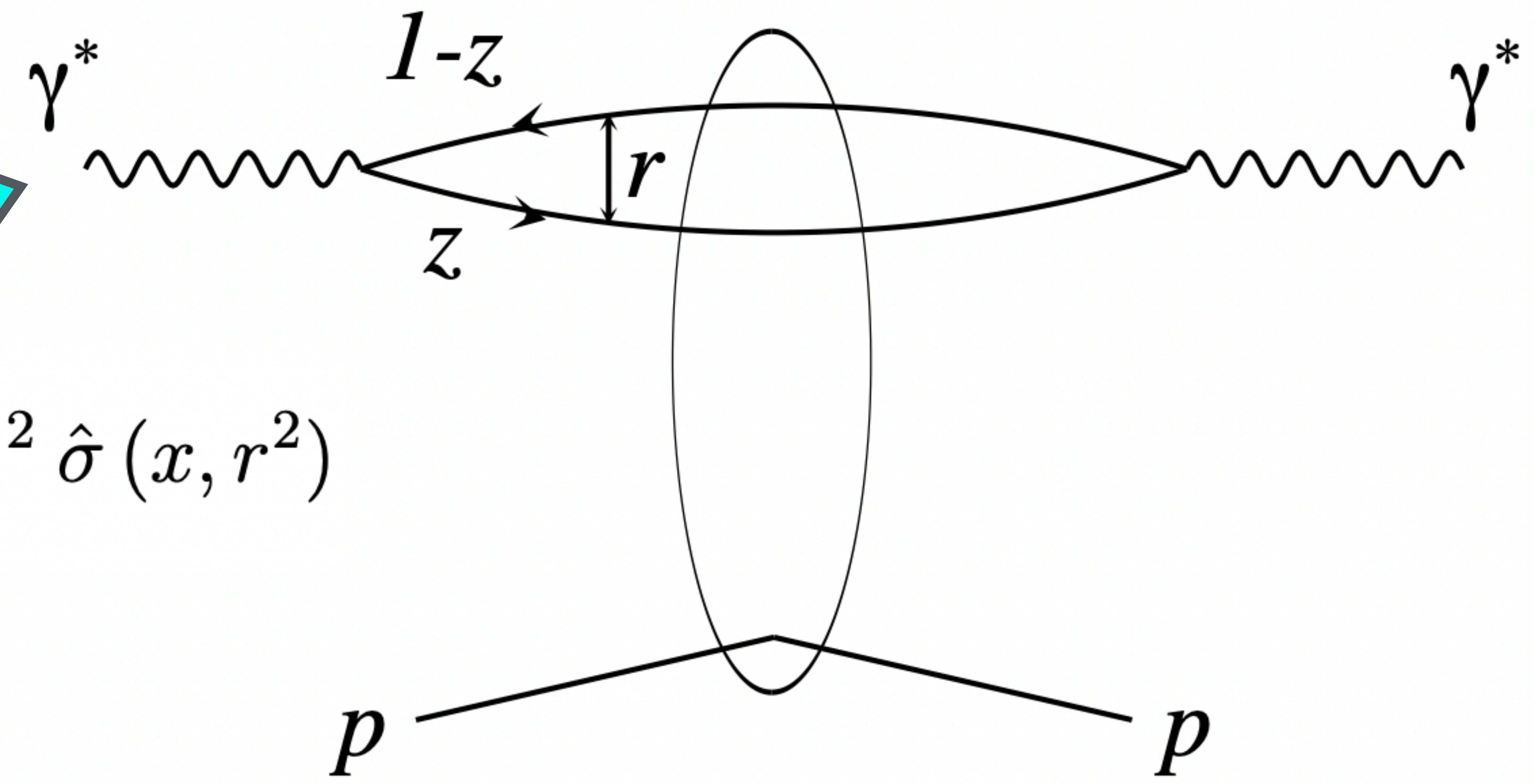

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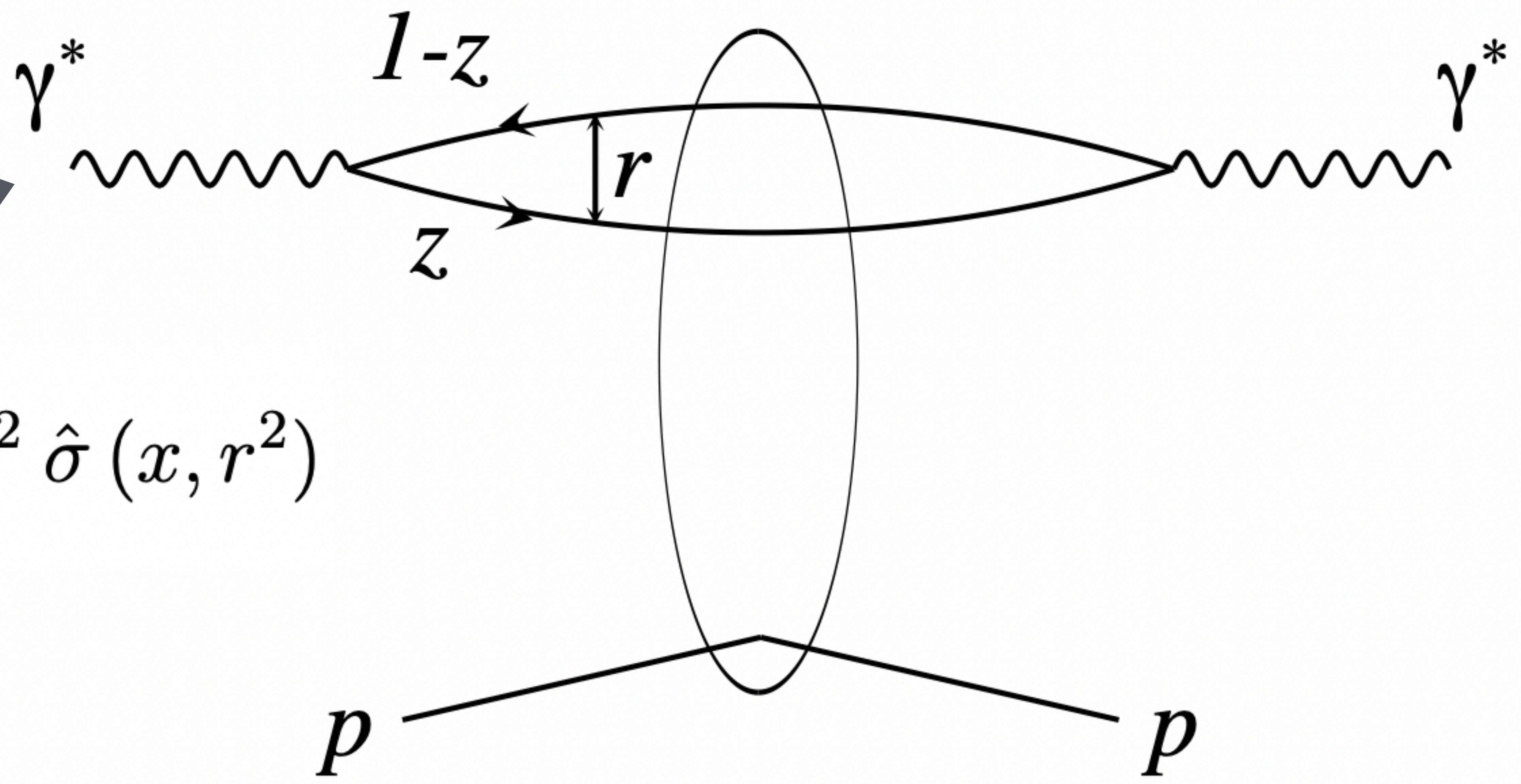

Computable in QED:

$$|\Psi_T(z,\mathbf{r})|^2 = \frac{6\,\alpha_{em}}{4\,\pi^2} \sum_f e_f^2 \left\{ [\, z^2 + (1-z)^2 \,]\, \epsilon^2 K_1^2(\epsilon r) + m_f^2 K_0^2(\epsilon r) \right\}$$

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Integrate over all dipole sizes and momentum configurations

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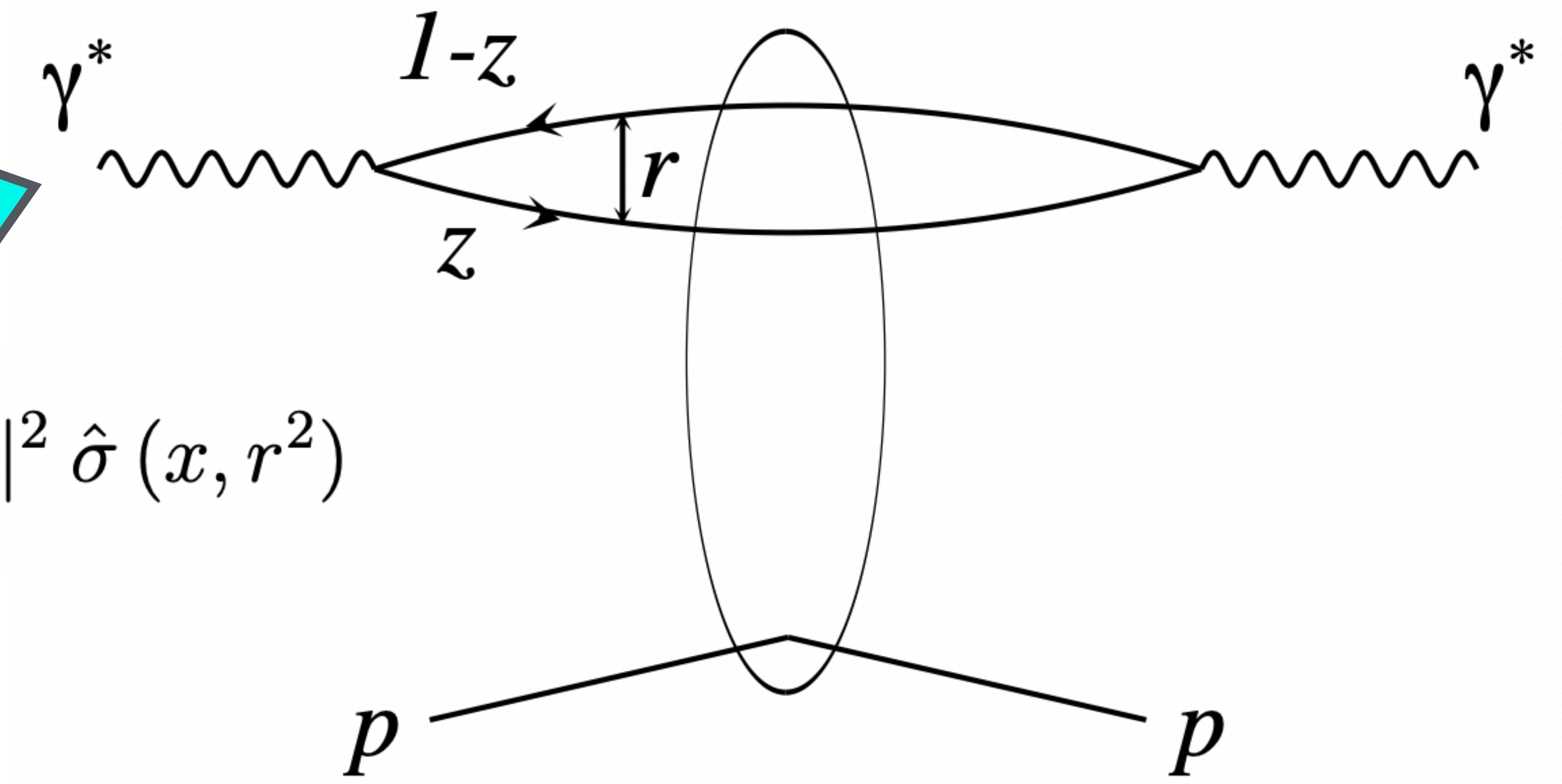

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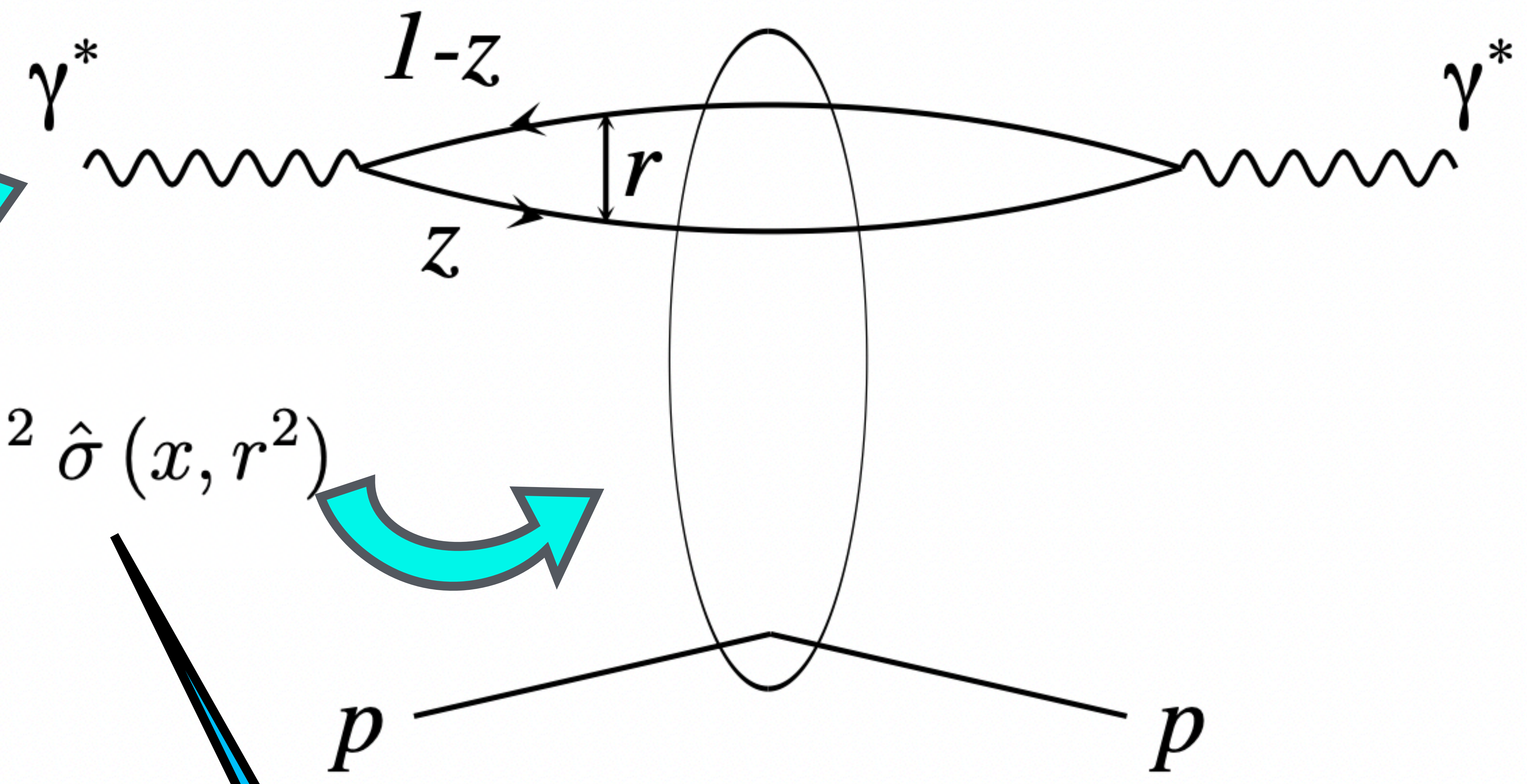

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Dipole cross section

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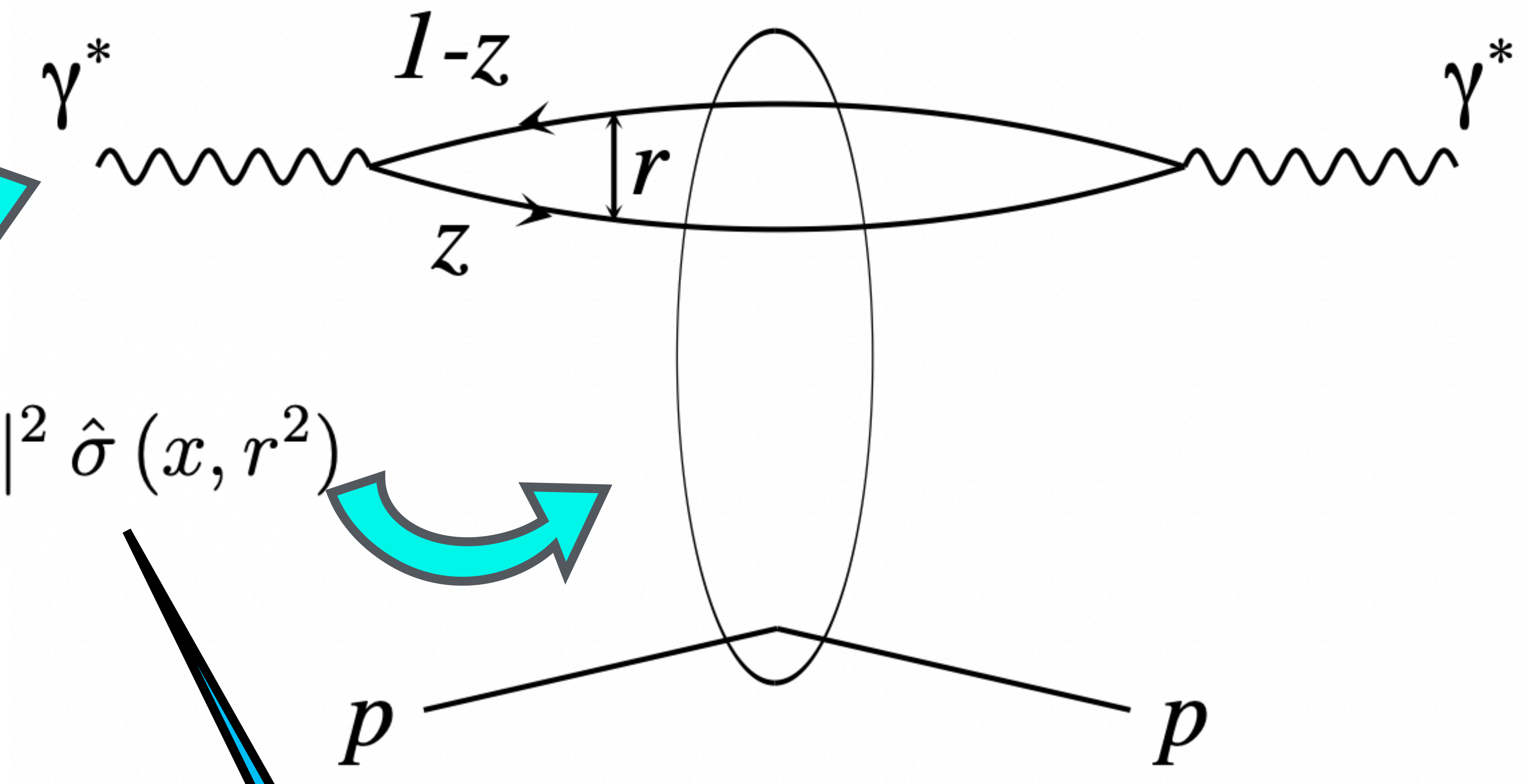

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QCD is here

Golec-Biernat, Wüsthoff https://inspirehep.net/literature/473813

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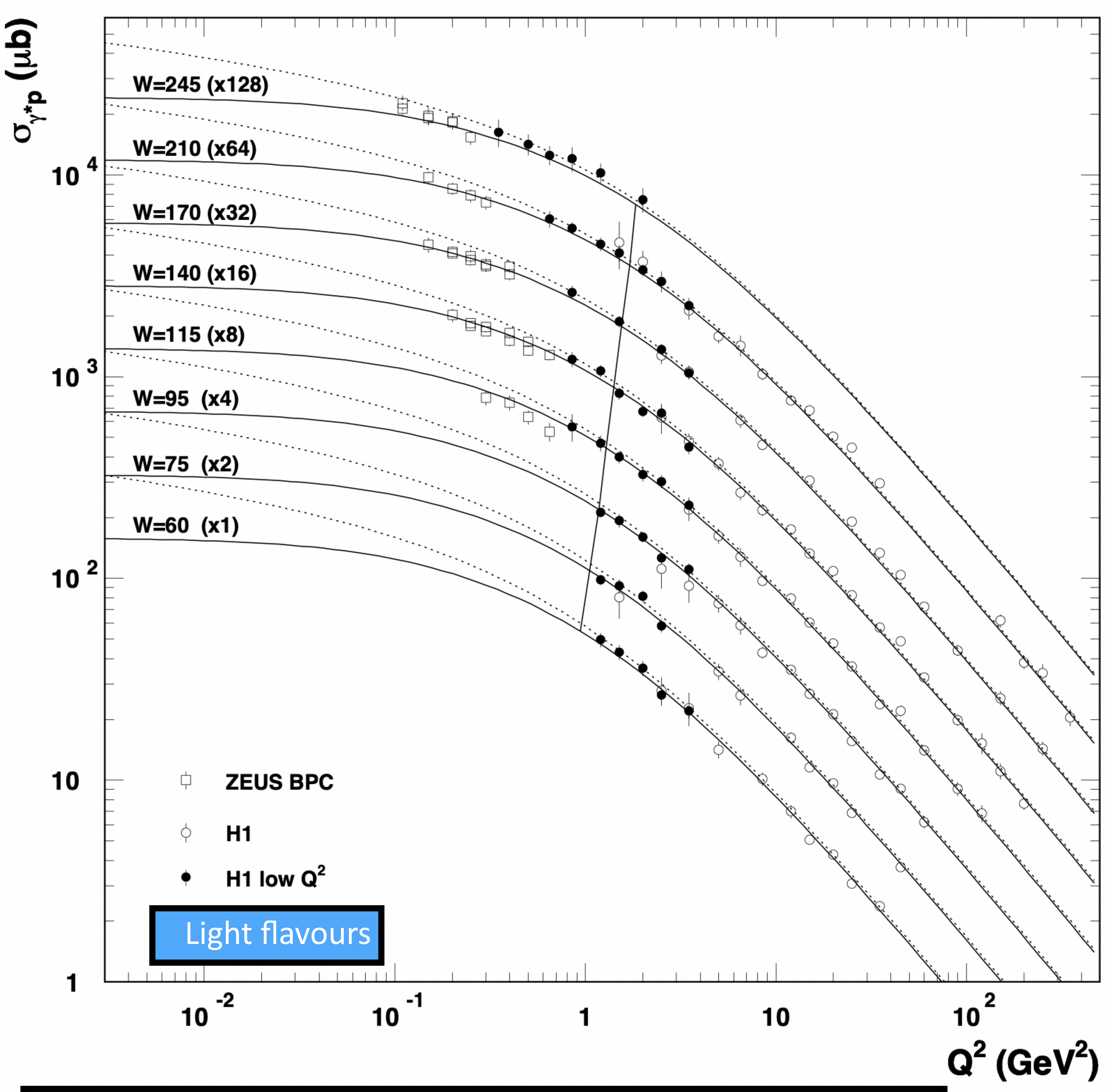
GBW define the critical line as:

$$R_0^2(x) = \frac{1}{Q^2}$$

1998: The GBW model. (4) Fit results



Golec-Biernat, Wüsthoff https://inspirehep.net/literature/473813

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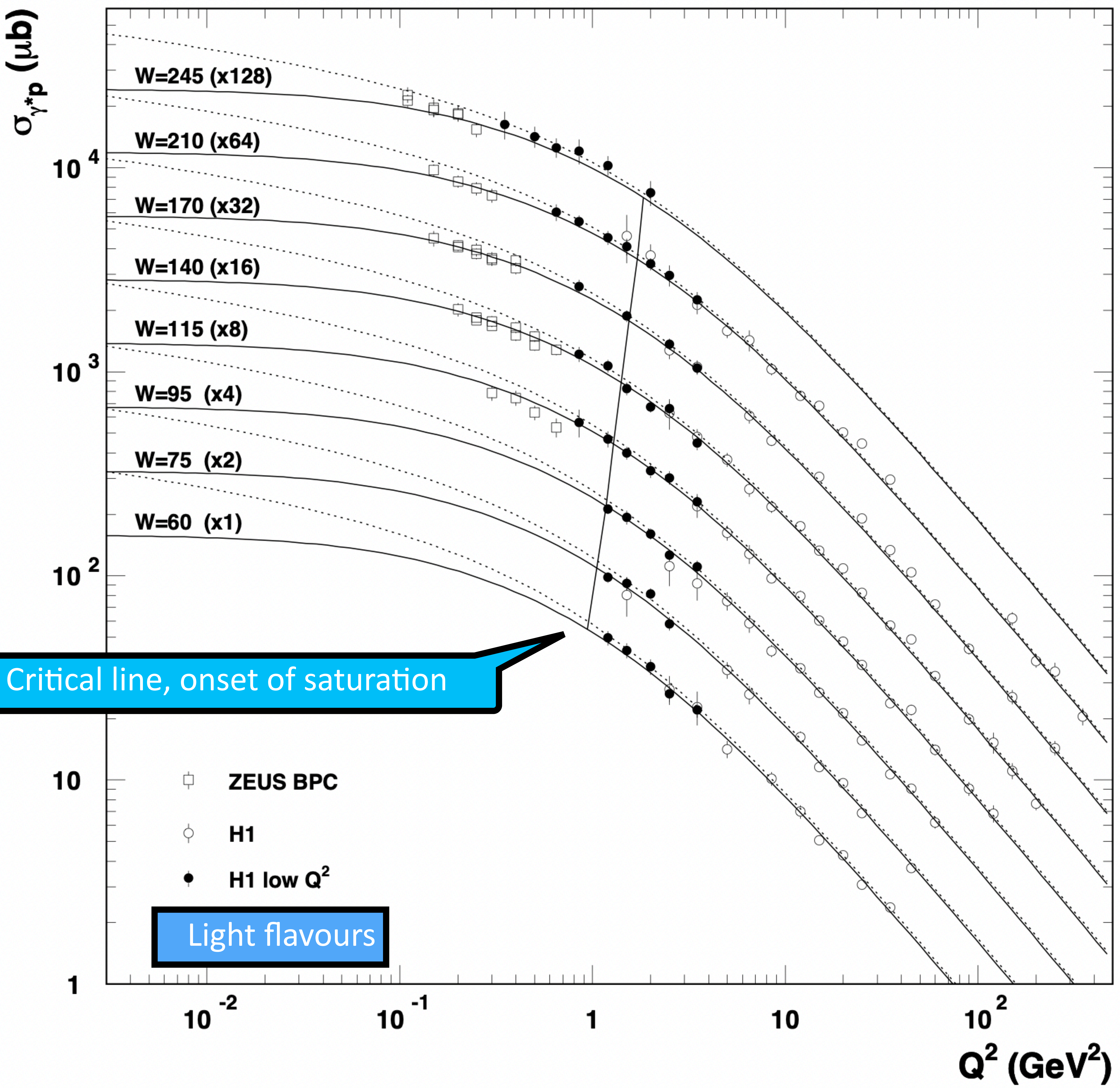

Critical line, onset of saturation

Light flavours

Golec-Biernat, Wüsthoff https://inspirehep.net/literature/473813

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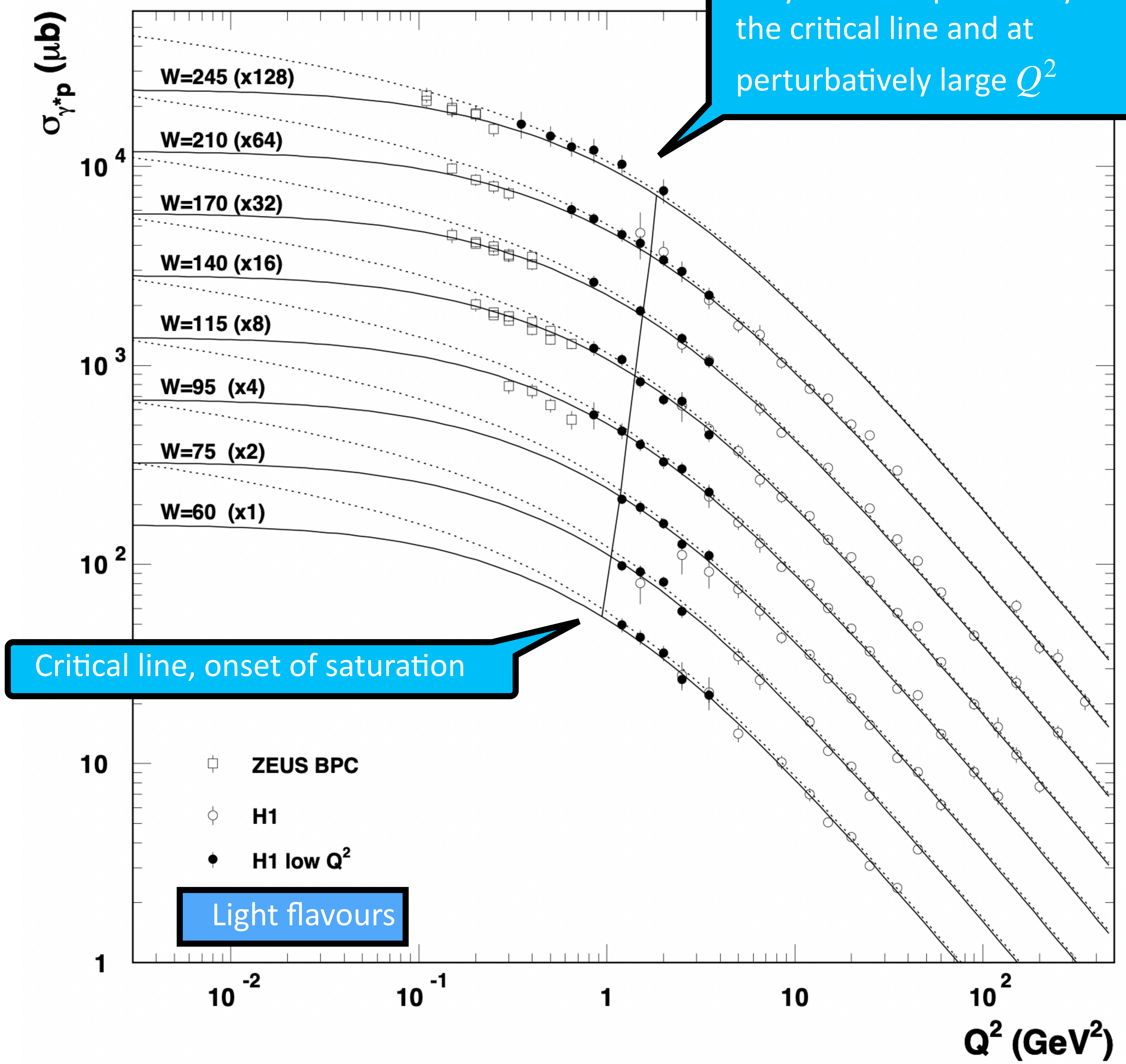

Very few data points beyond the critical line and at perturbatively large Q^2

Critical line, onset of saturation

Light flavours

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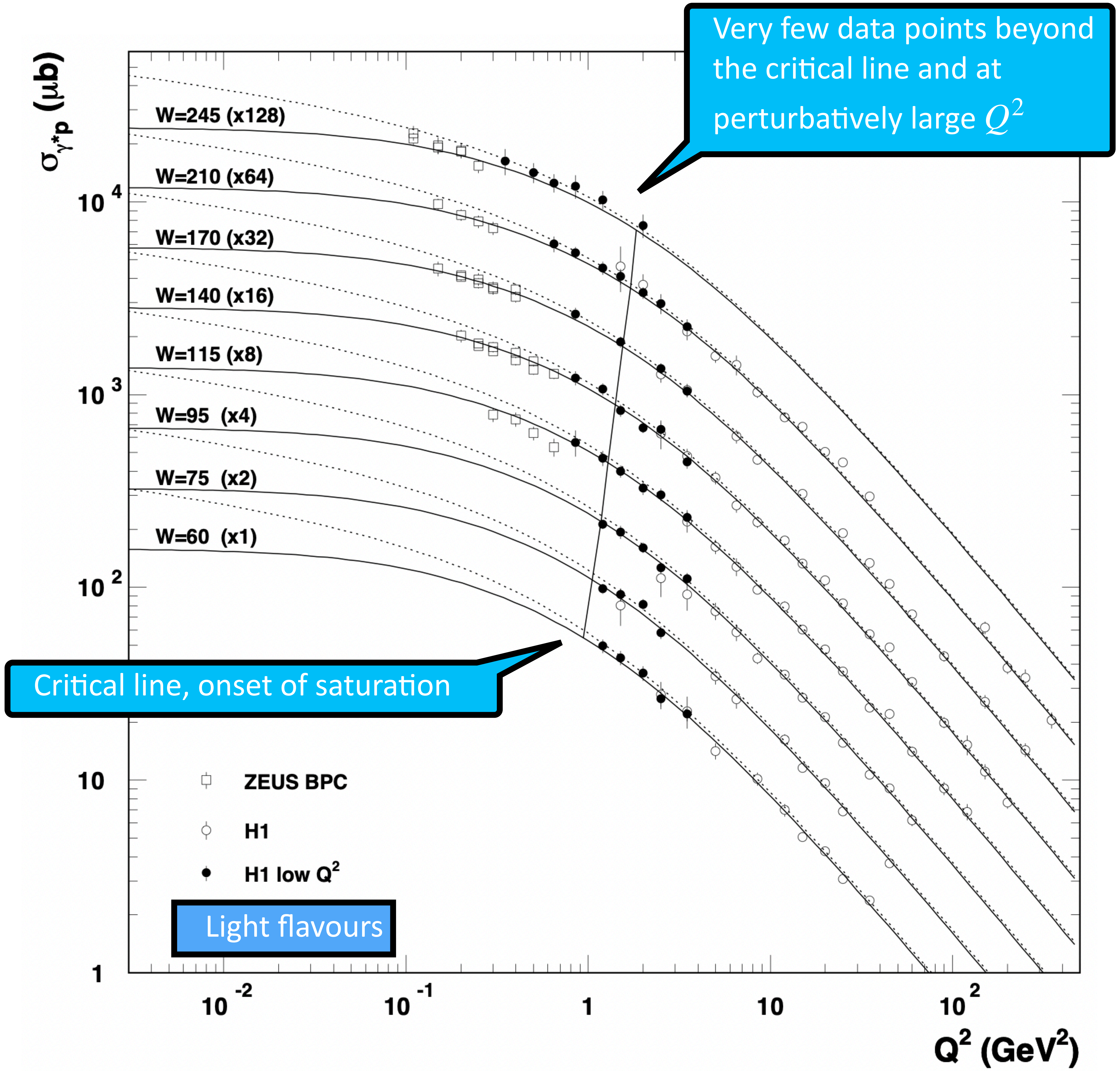

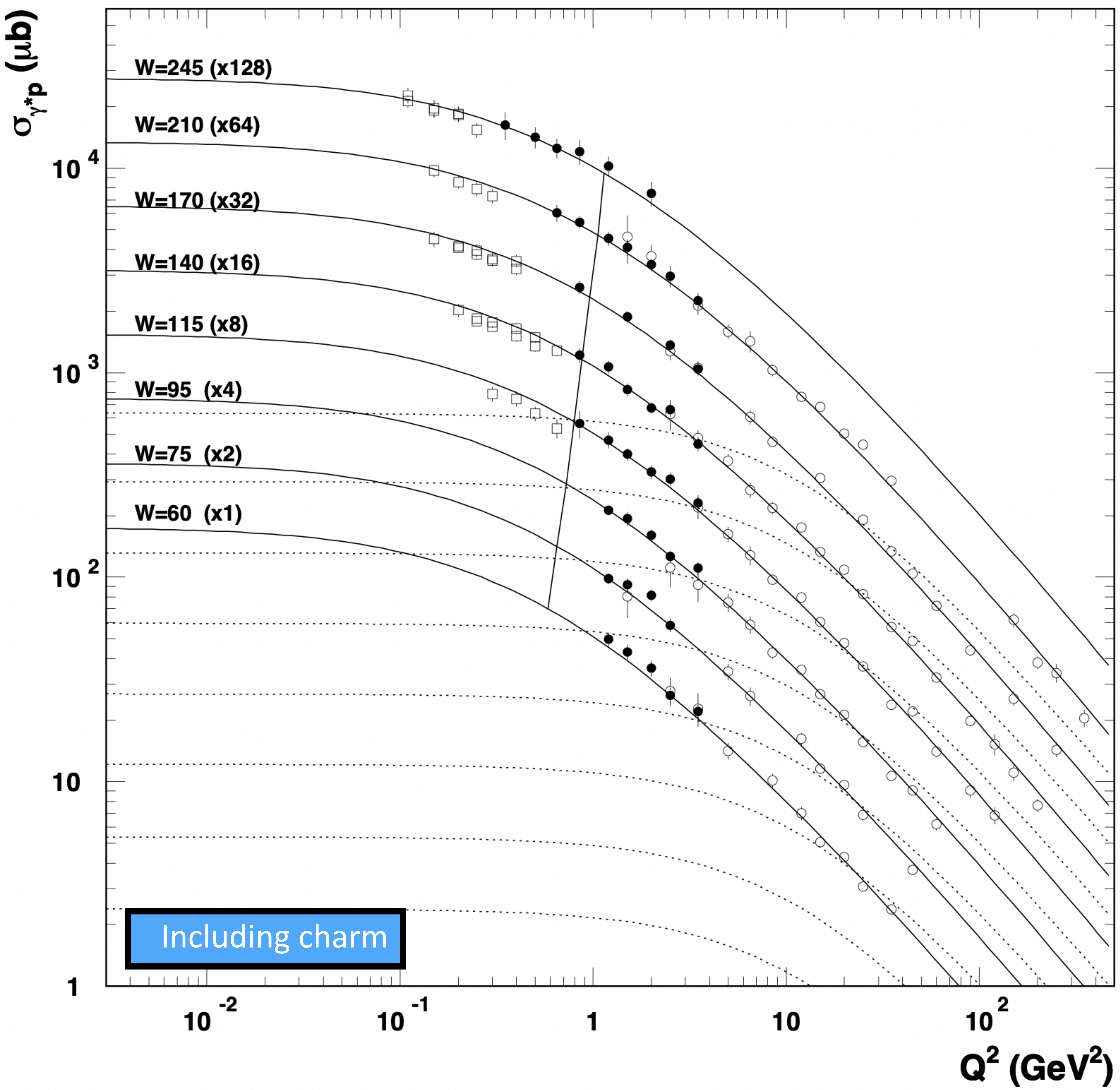

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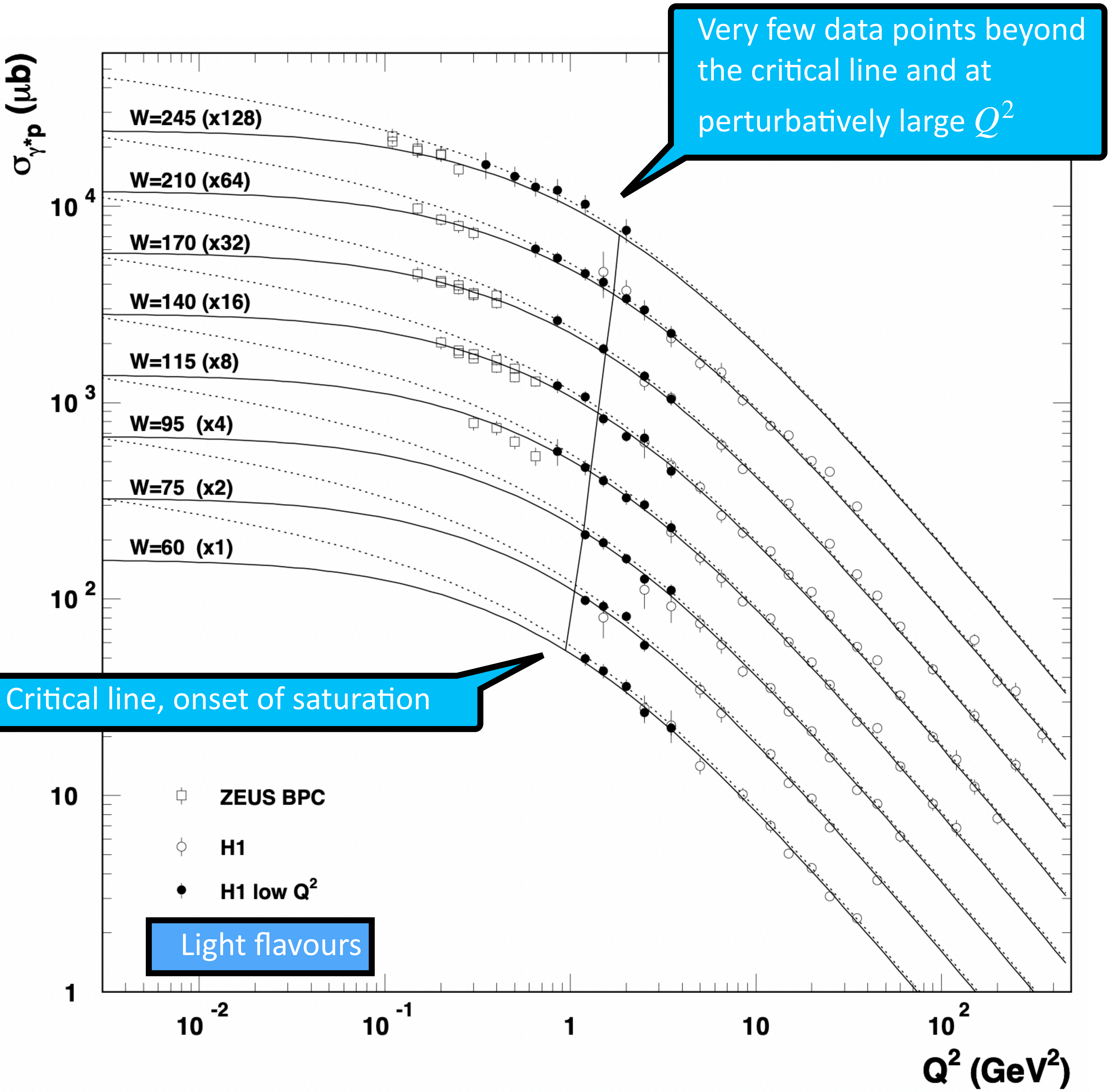

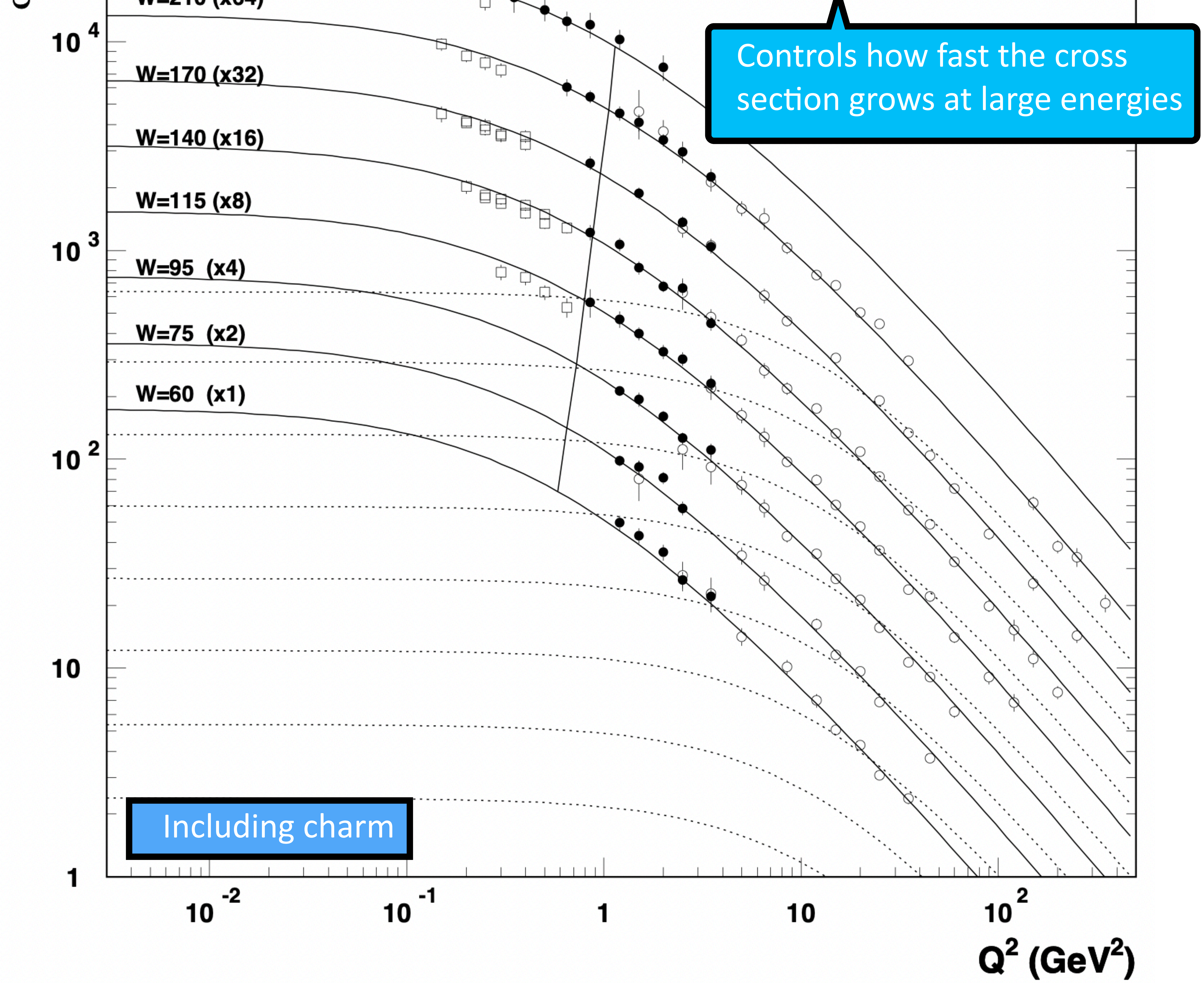

TABLE I. Fit results.

	σ_0 (mb)	λ	x_0	χ^2/(no.exp.po.)
No charm	23.03	0.288	3.04×10^{-4}	441/372=1.18
With charm	29.12	0.277	0.41×10^{-4}	558/372=1.50

Golec-Biernat, Wüsthoff https://inspirehep.net/literature/473813

The GBW model introduced a new scale
Can we use it?

Geometric scaling

2001: Geometric scaling. (1) The formalism

Abstract

We observe that the saturation model of deep inelastic scattering predicts a geometric scaling of the total $\gamma^* p$ cross section in the region of small Bjorken variable x. The geometric scaling in this case means that the cross section is a function of only one dimensionless variable $\tau = Q^2 R_0^2(x)$, where the function $R_0(x)$ decreases with decreasing x. We show that the experimental data from HERA in the region $x < 0.01$ confirm the expectations of this scaling over a very broad region of Q^2. We suggest that the geometric scaling is more general than the saturation model.

Stasto, Golec-Biernat, Kwiecinski, http://inspirehep.net/record/530453

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In the dipole picture

$$\sigma_{T,L}(x, Q^2) = \int d^2\mathbf{r} \int_0^1 dz\, |\Psi_{T,L}(r, z, Q^2)|^2 \hat{\sigma}(r, x)$$

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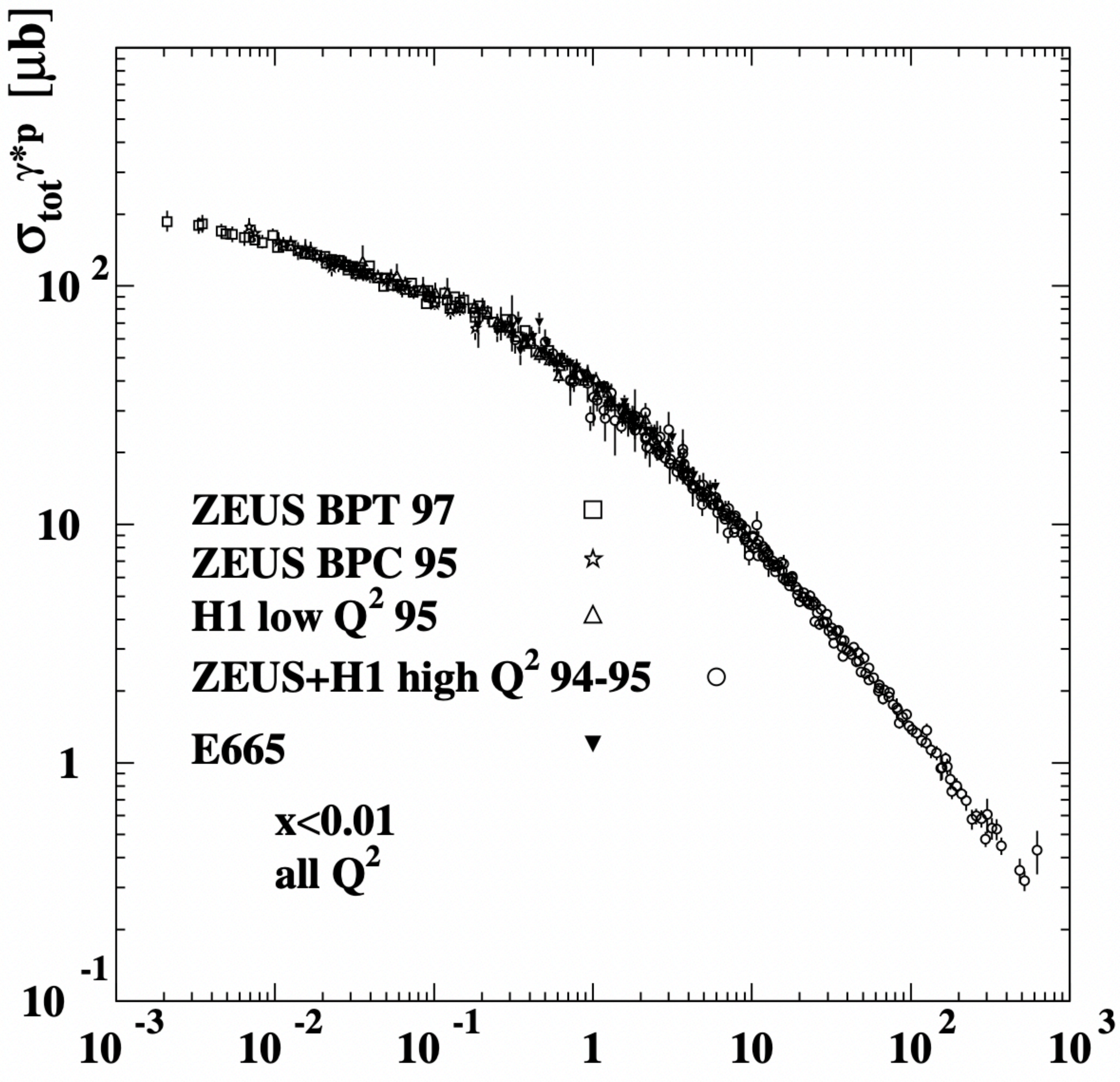
Really?

With the dimensionless variable $\tau = Q^2 R_0^2(x)$

2001: Geometric scaling. (2) Comparison with data

Stasto, Golec-Biernat, Kwiecinski, http://inspirehep.net/record/530453



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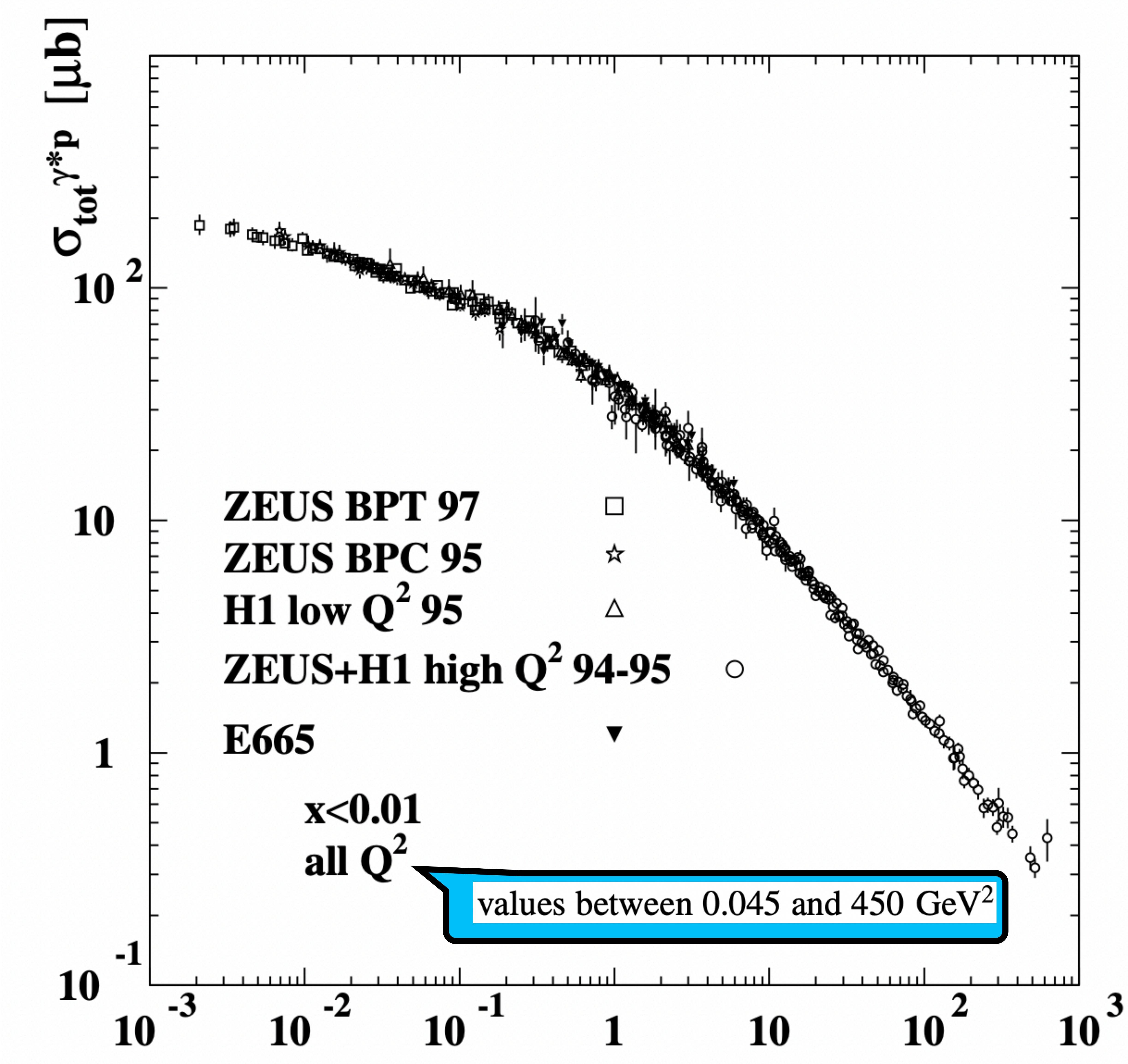

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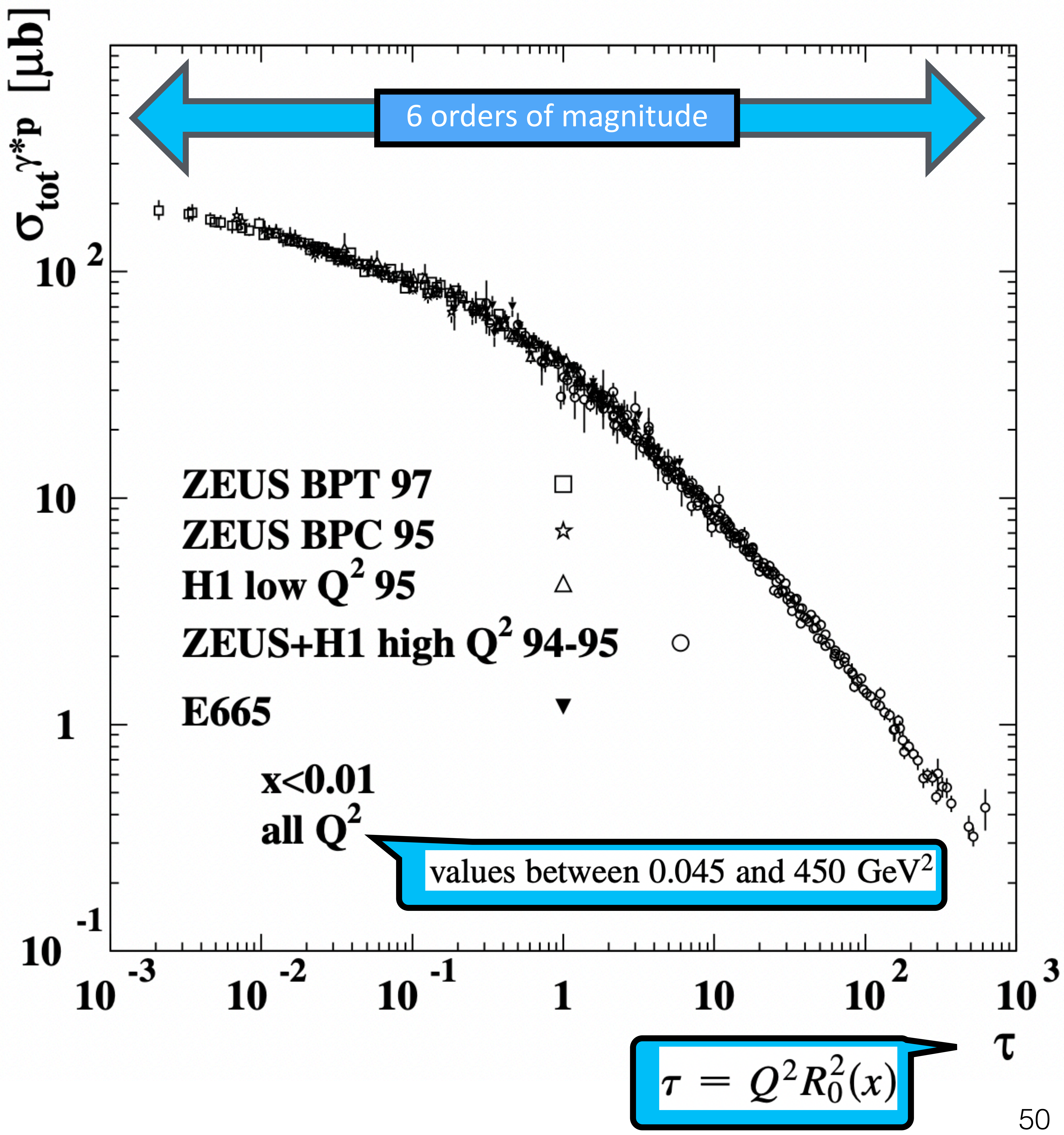

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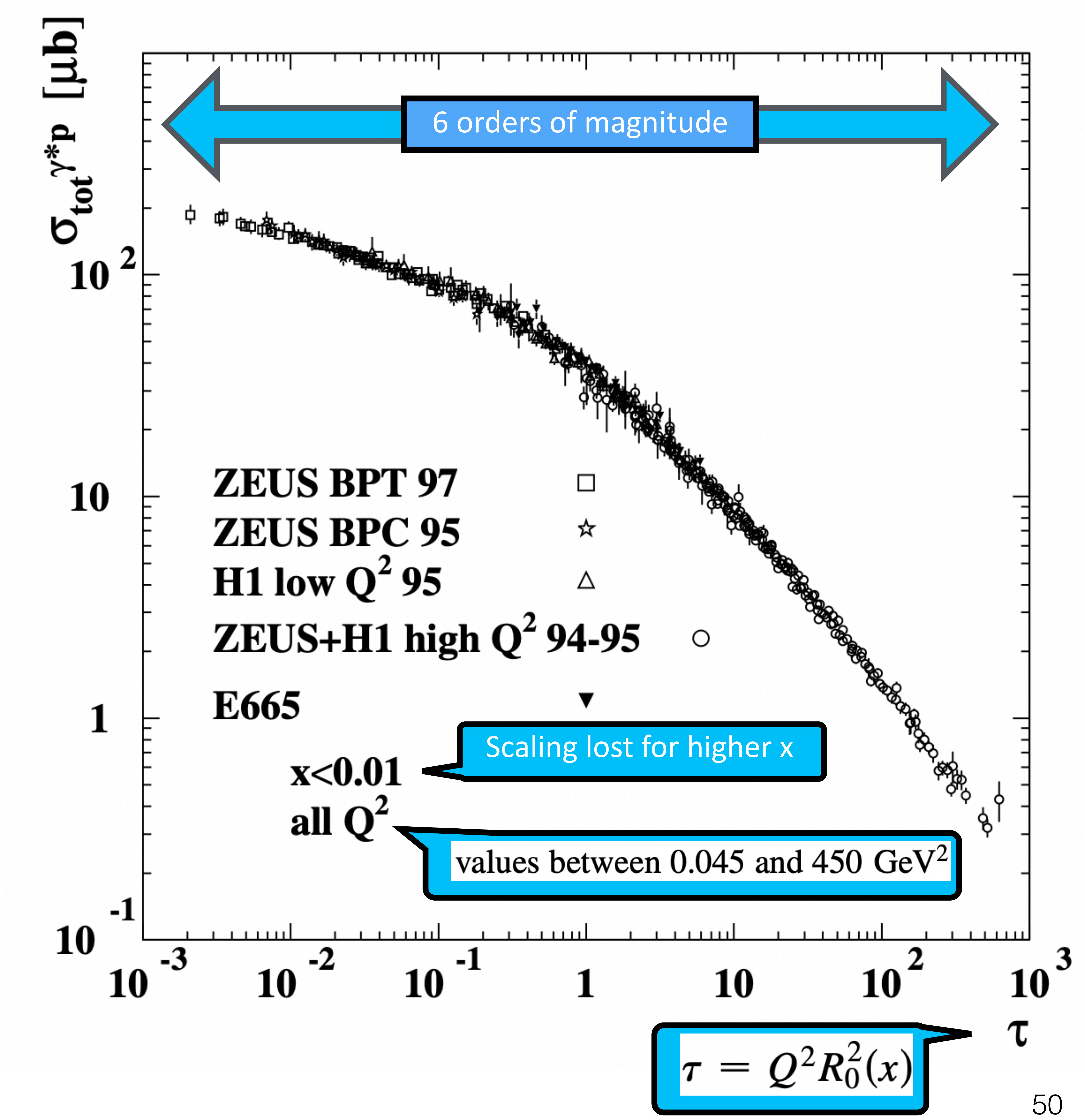

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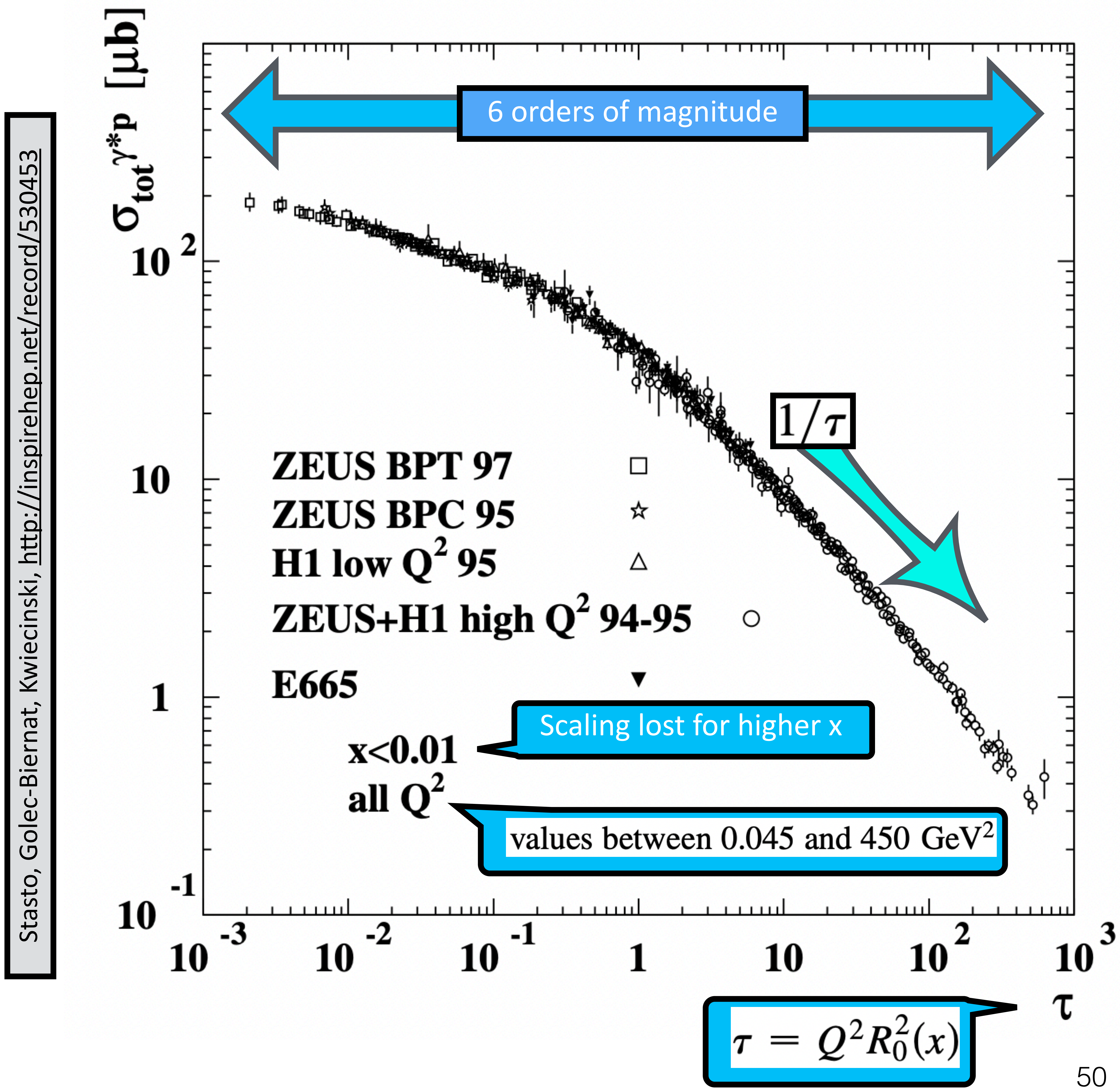

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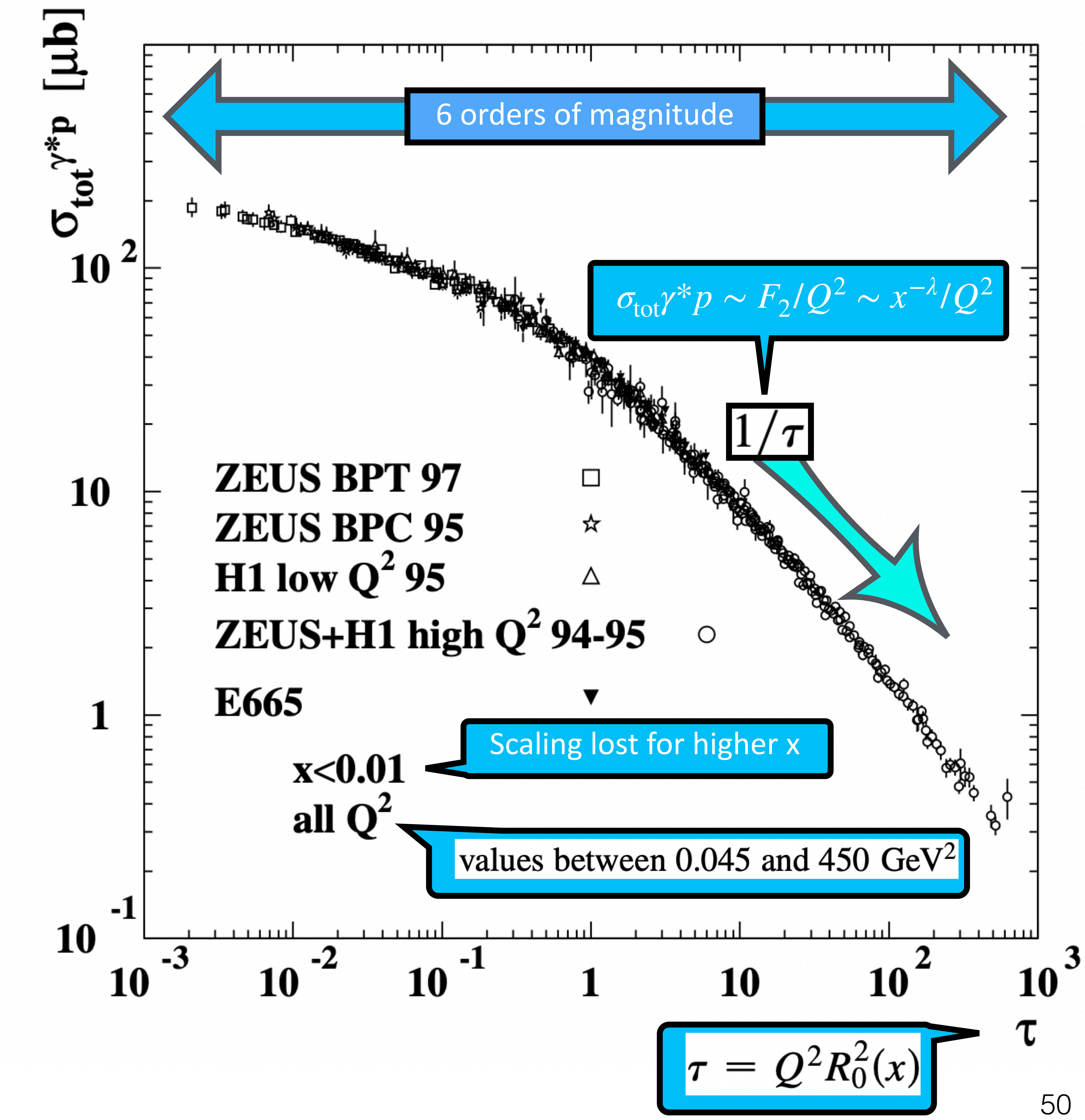

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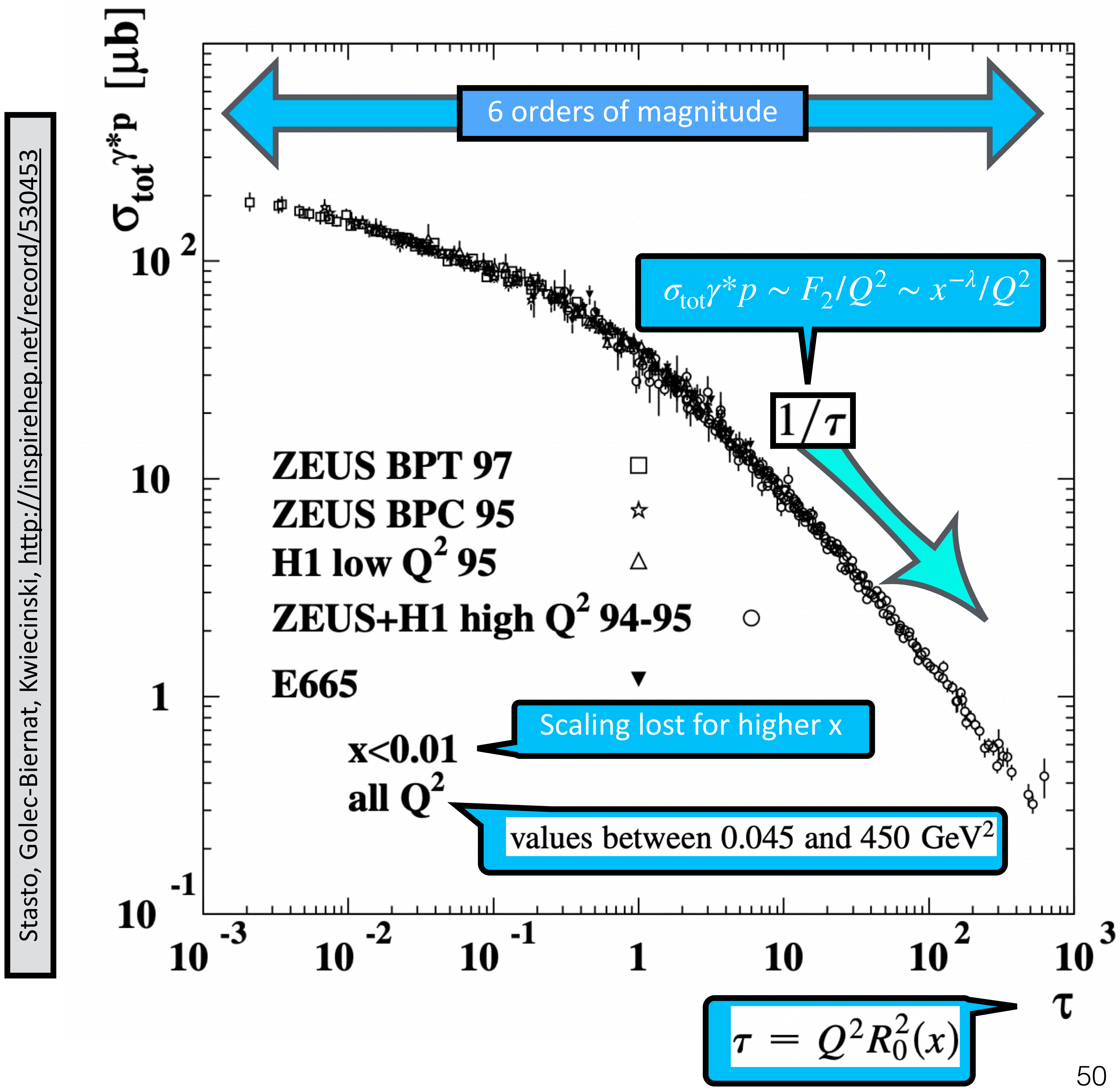

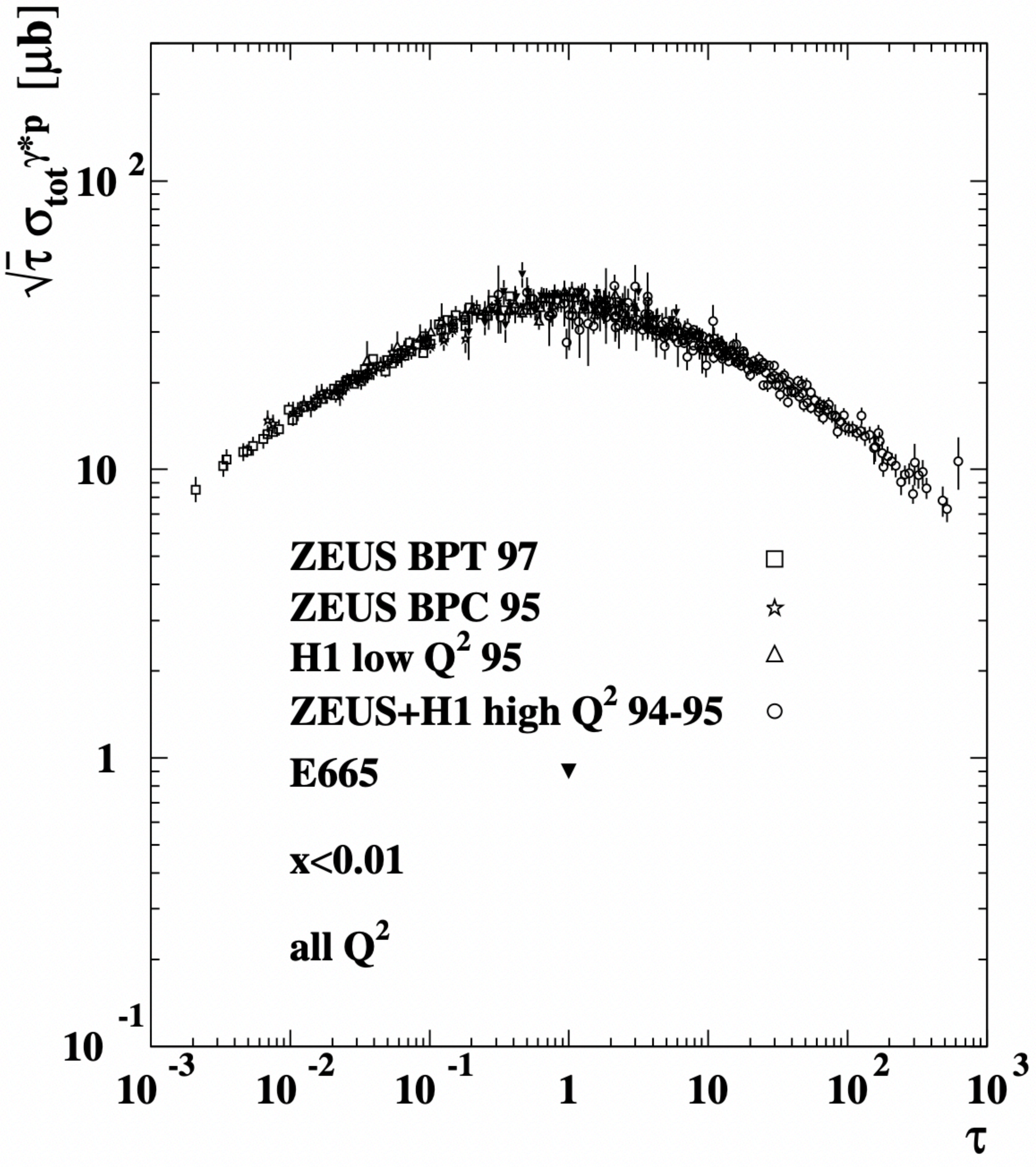

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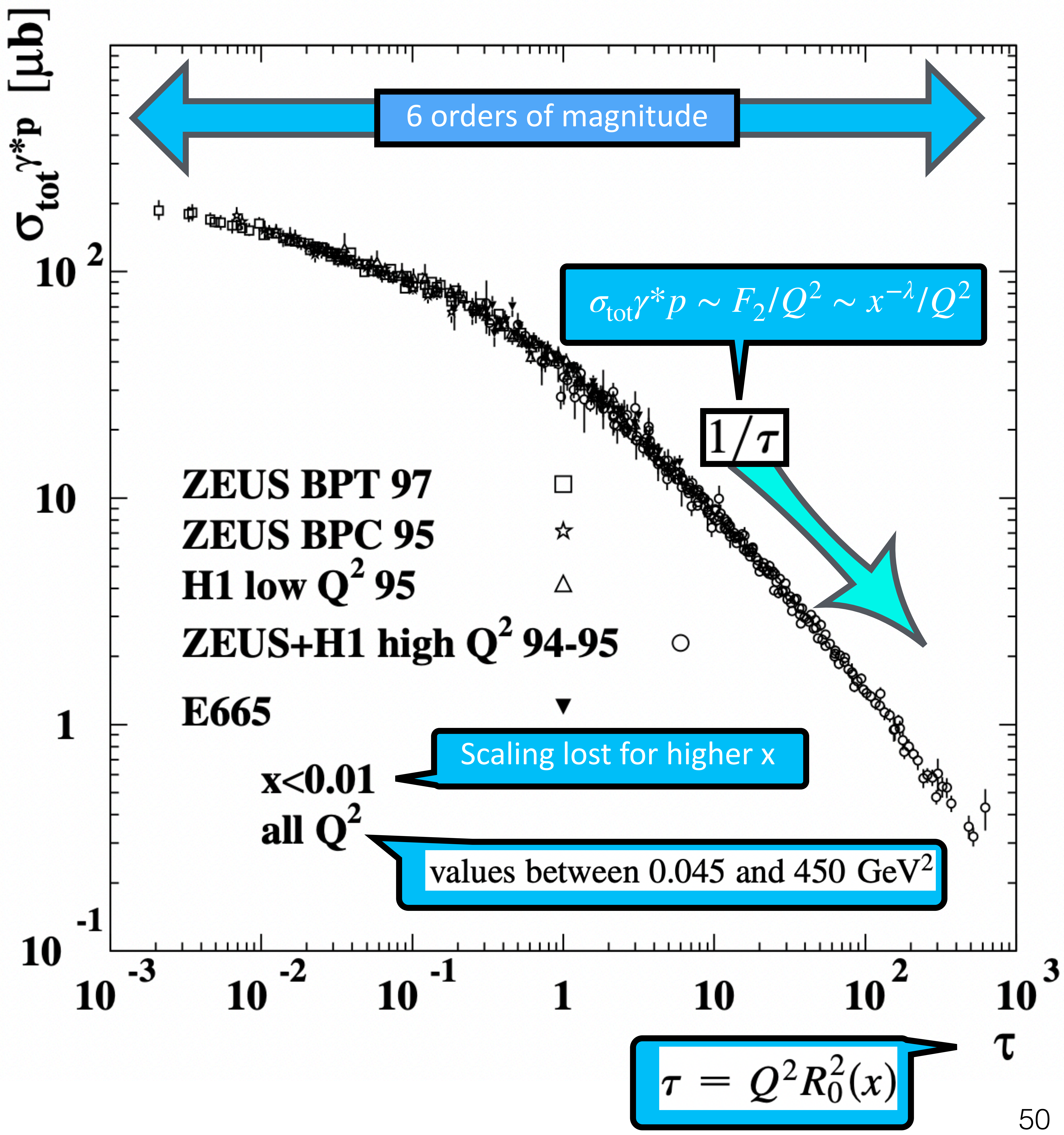

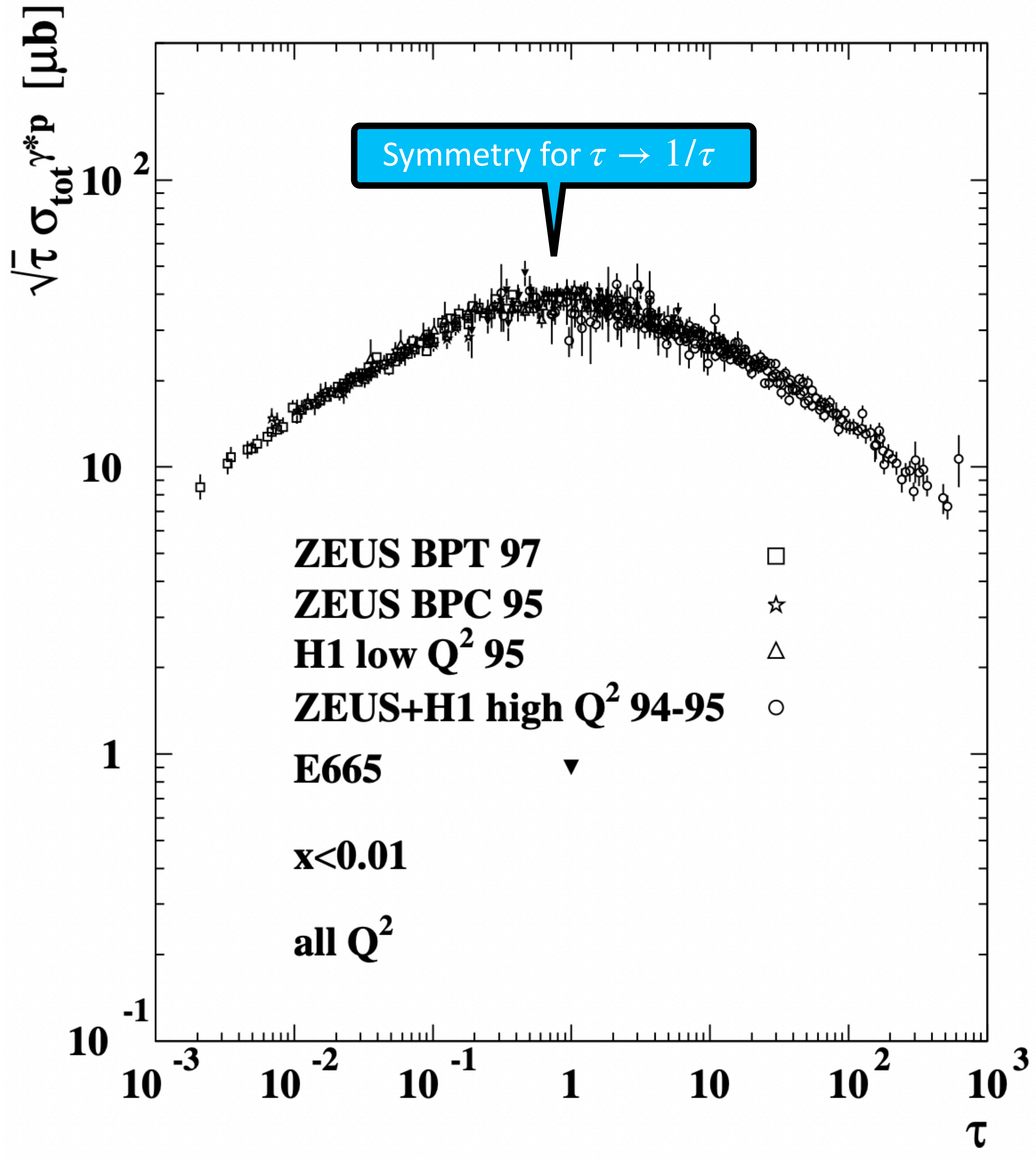

Up to now, we have mainly used inclusive observables to study high-energy QCD
(The exception was to look at two-jet events to 'see' the gluon directly)
Which observables are particularly sensitive to the gluon distribution at high energies?

4

Exploring high-energy QCD:
Diffractive vector meson production at HERA

Guillermo Contreras, CTU in Prague

At this point in time, we know that at small Bjorken-x the DIS cross section raises as a power law at high energies, we also know that this raise is driven by the gluon PDF.
We want now to concentrate in one process that is particularly sensitive to the gluon structure of hadrons

Diffractive vector meson photoproduction

Two experimentally important vector mesons

EVIDENCE FOR A π-π RESONANCE IN THE $I=1$, $J=1$ STATE*

A. R. Erwin, R. March, W. D. Walker, and E. West
Brookhaven National Laboratory, Upton, New York and University of Wisconsin, Madison, Wisconsin
(Received May 11, 1961)

https://inspirehep.net/literature/28197
https://inspirehep.net/literature/48851

The ρ(770)

- ✓ Discovered in 1961
- ✓ Decays mainly to ππ pairs
- ✓ Large width, strong interference with continuum

ON THE APPARENT SHIFT
OF THE RHO MESON MASS IN PHOTOPRODUCTION

P. SÖDING
II. Institüt für Exberimentalphysik der Universität Hamburg

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The J/ψ (mass 3.097 GeV/c²)
- ✓ Discovered in 1974 (November revolution)
- ✓ Useful decays into lepton pairs
- ✓ Very small width (clean signature)

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

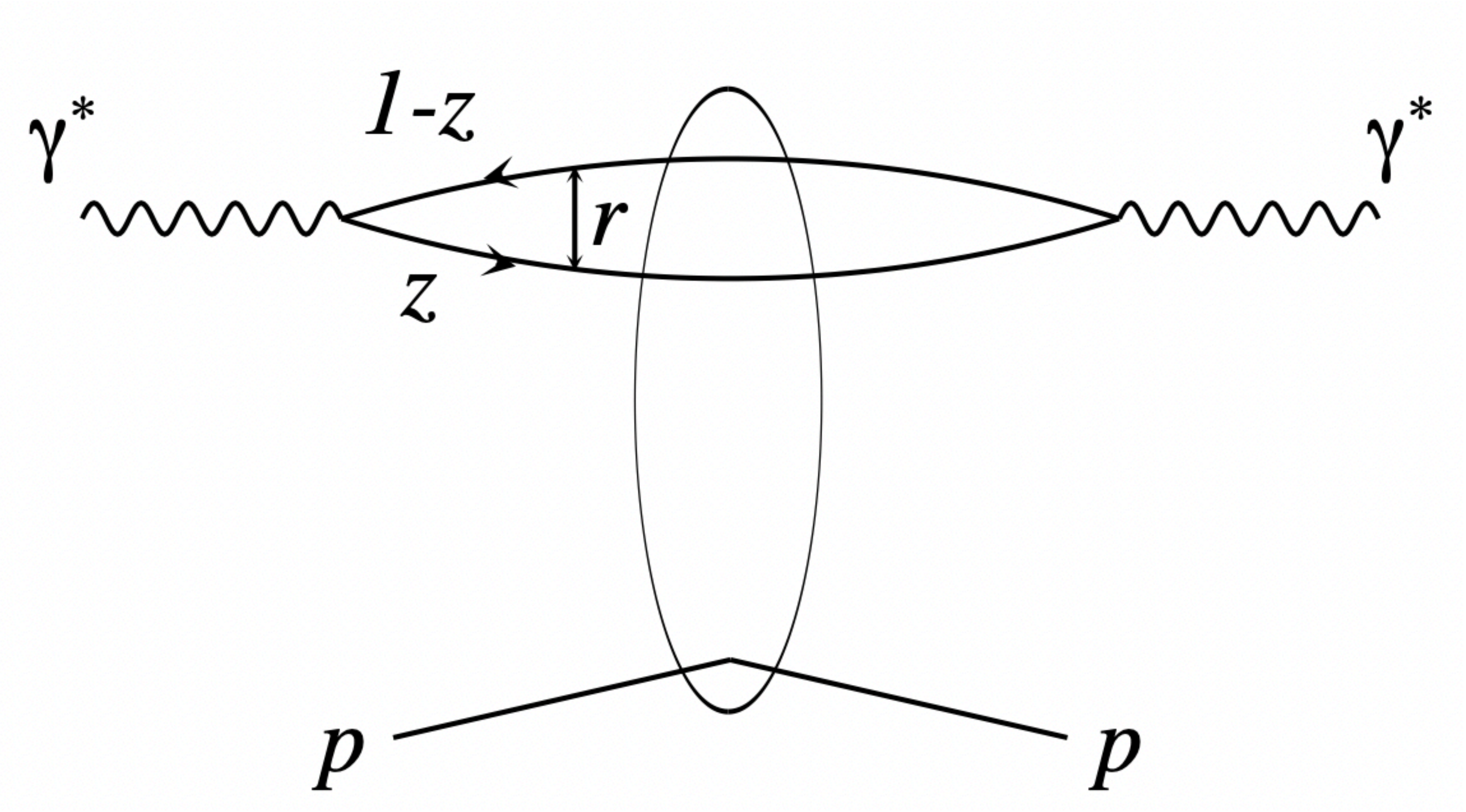
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

https://inspirehep.net/literature/90773
https://inspirehep.net/literature/91761

Diffractive vector meson production: a process close to DIS

A representation of the DIS cross section



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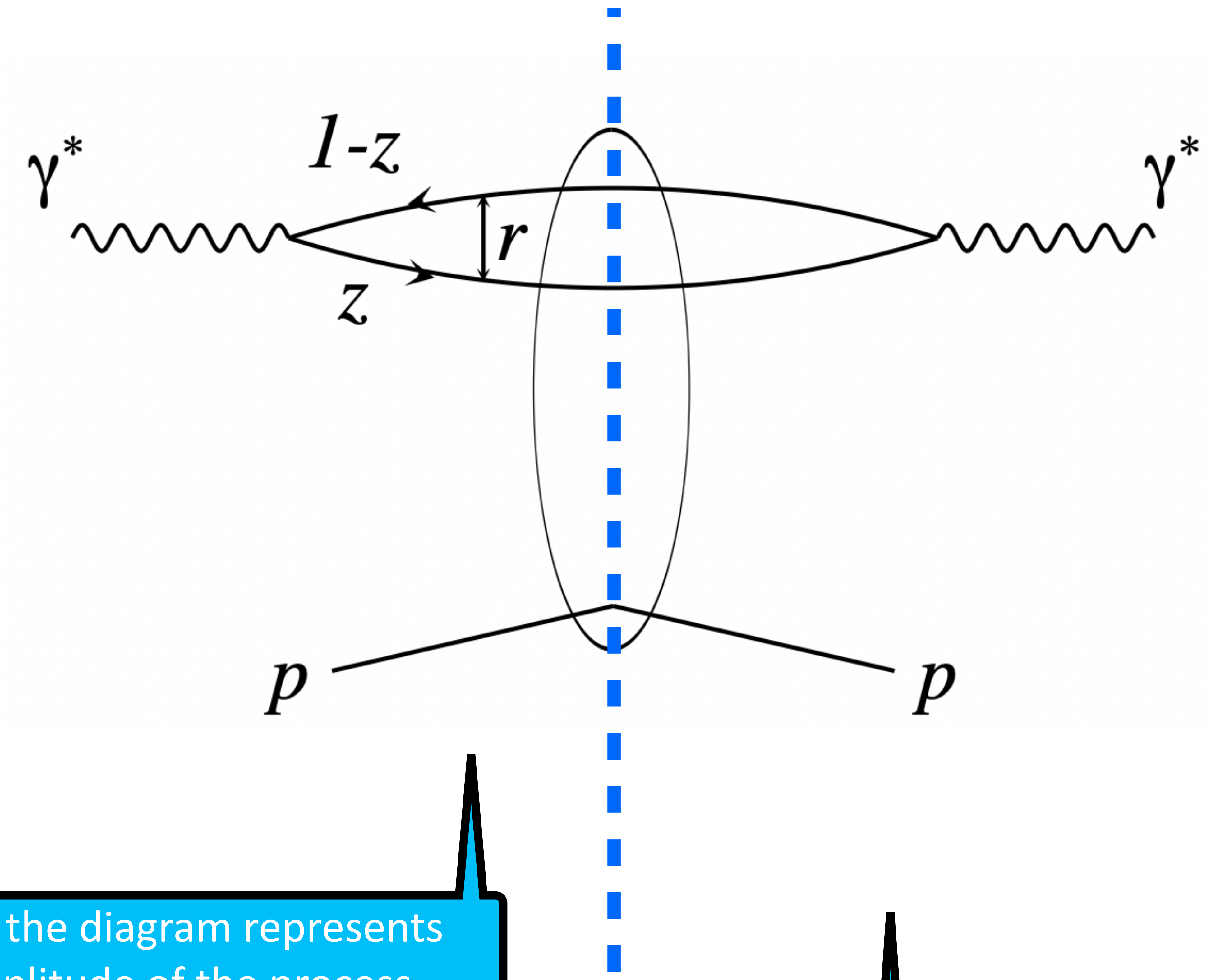


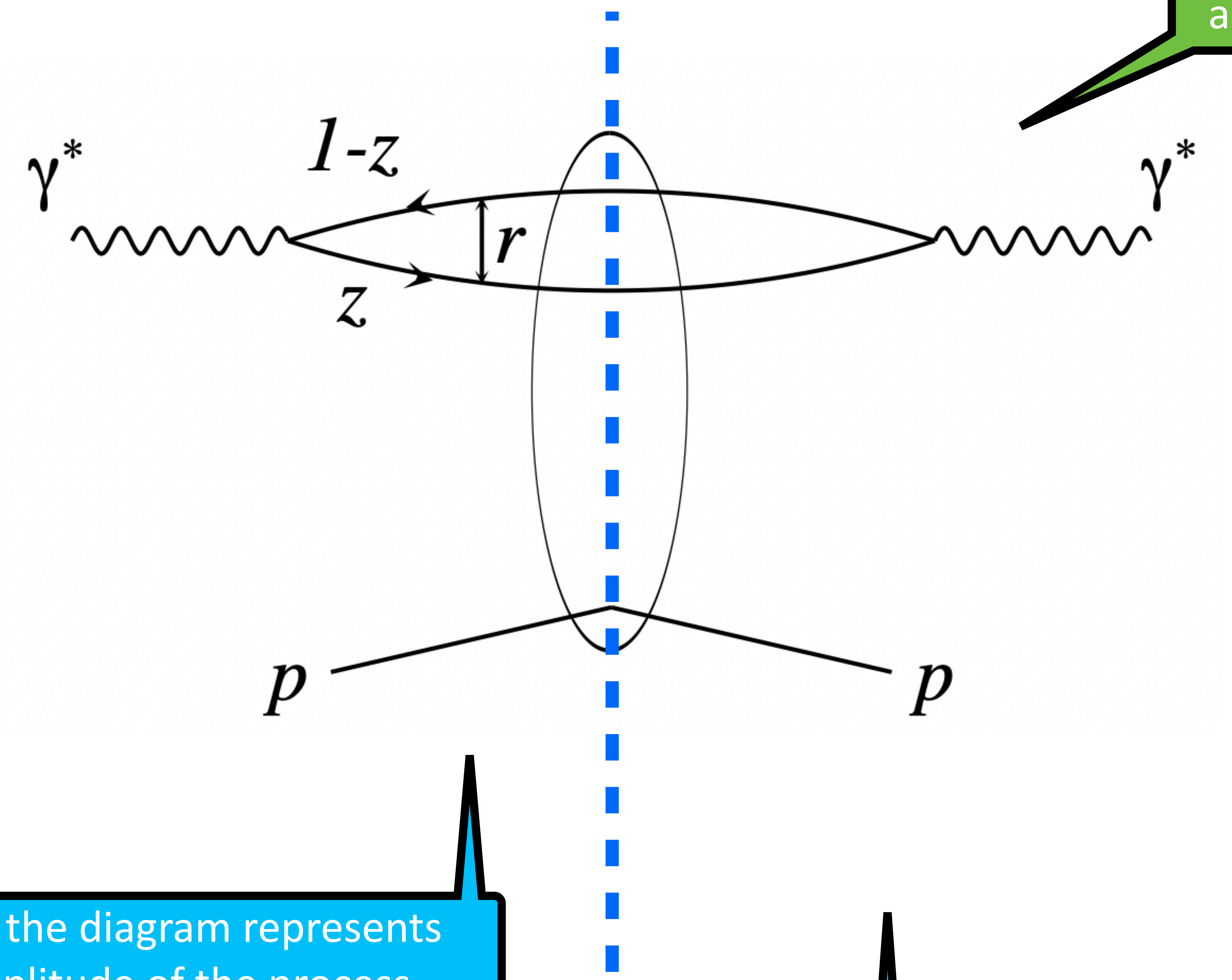
Half of the diagram represents the amplitude of the process

The other half the conjugate of the amplitude

Diffractive vector meson production: a process close to DIS

A representation of the DIS cross section

Now consider the full diagram to represent an amplitude, not a cross section ... then ...



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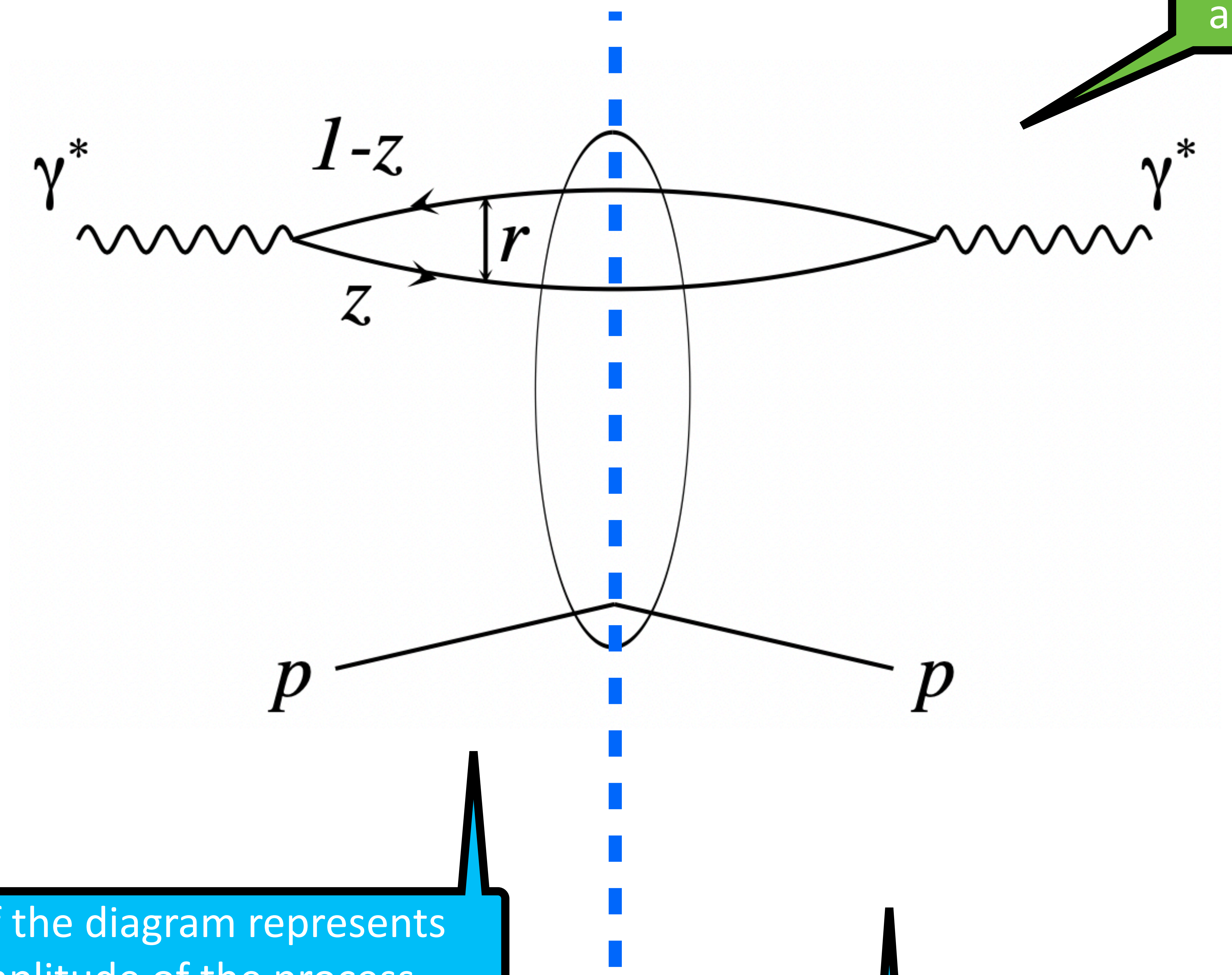
A representation of the DIS cross section



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... exchange the photon for another particle with the same quantum numbers, e. g. a vector meson

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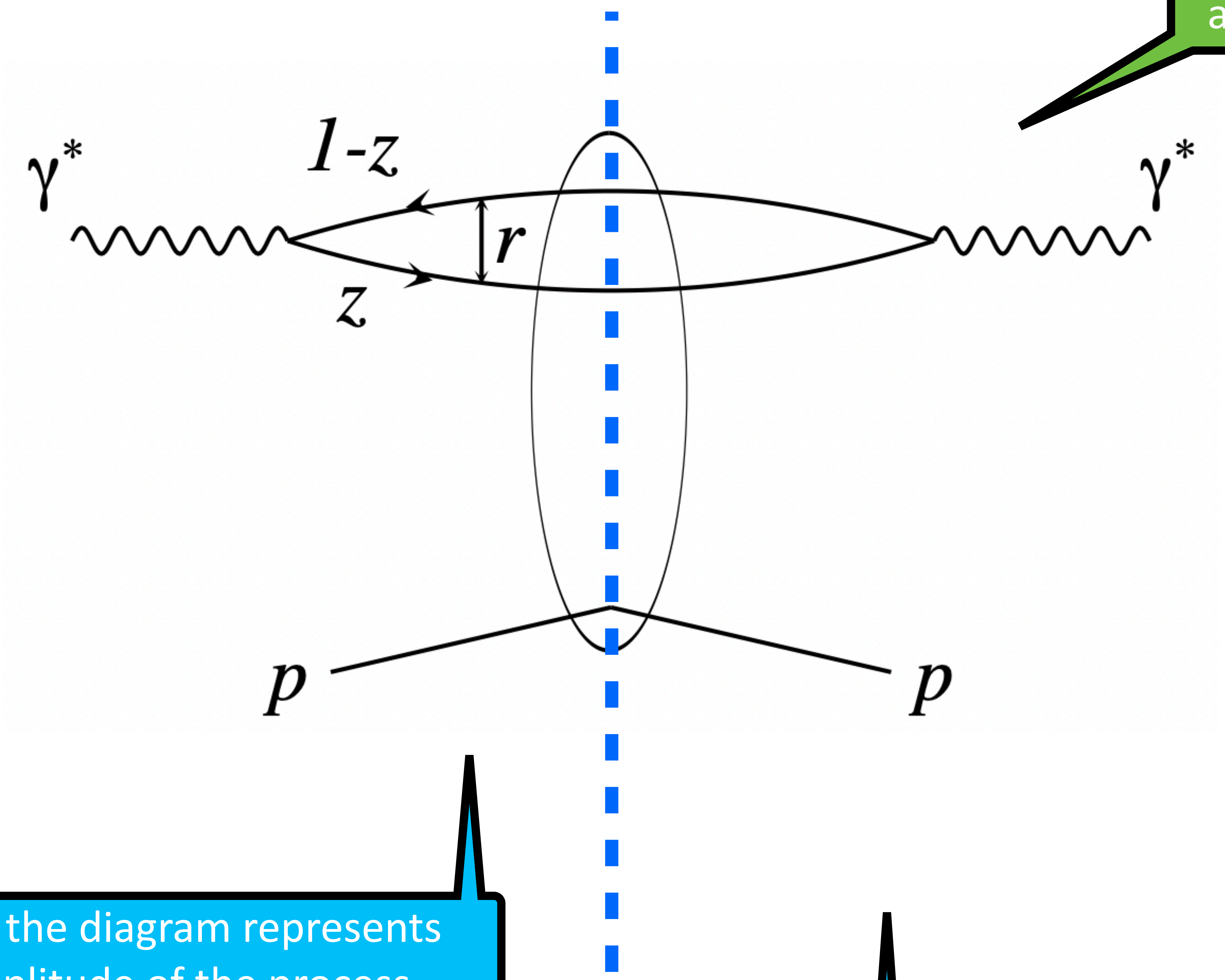

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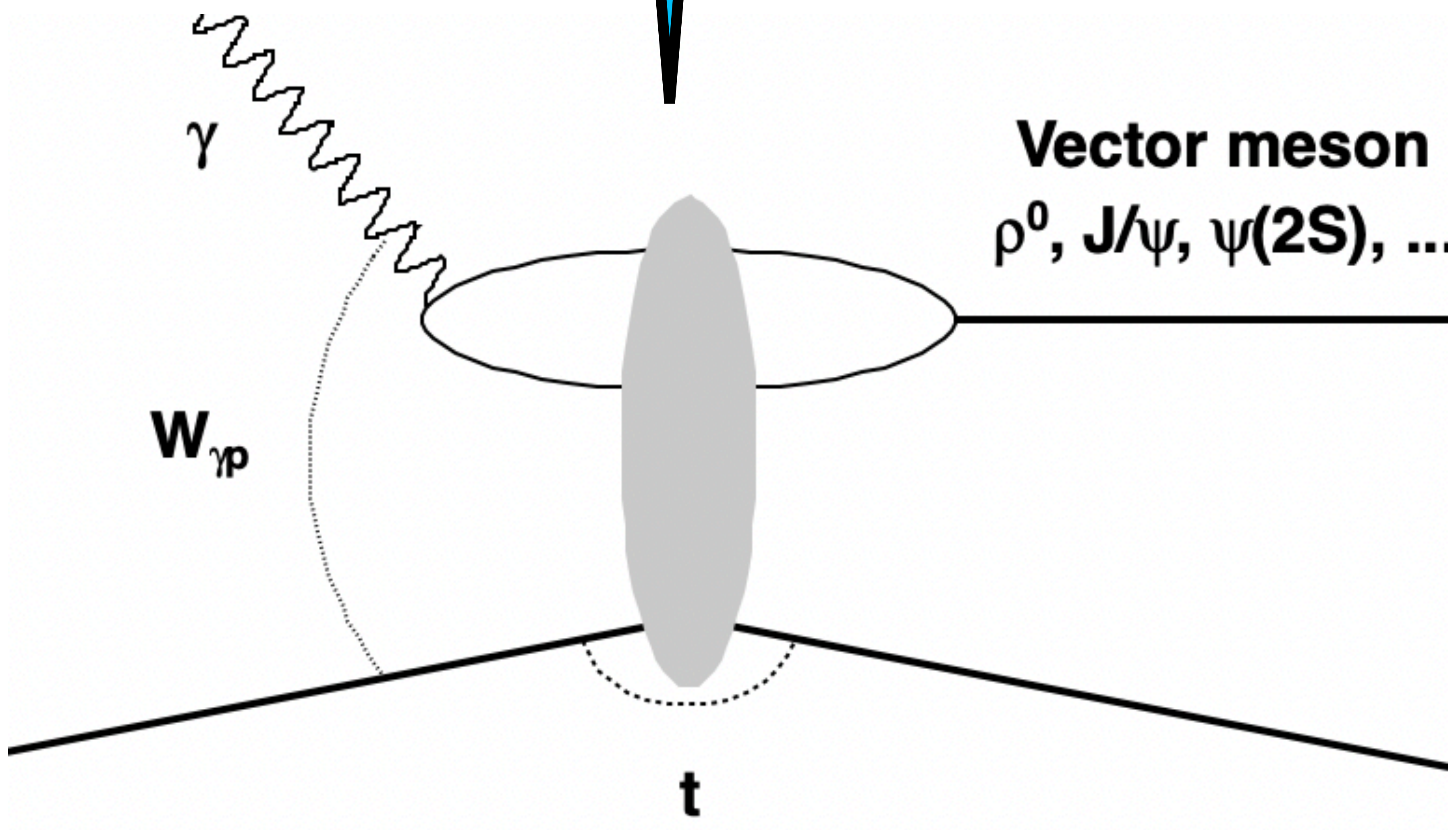
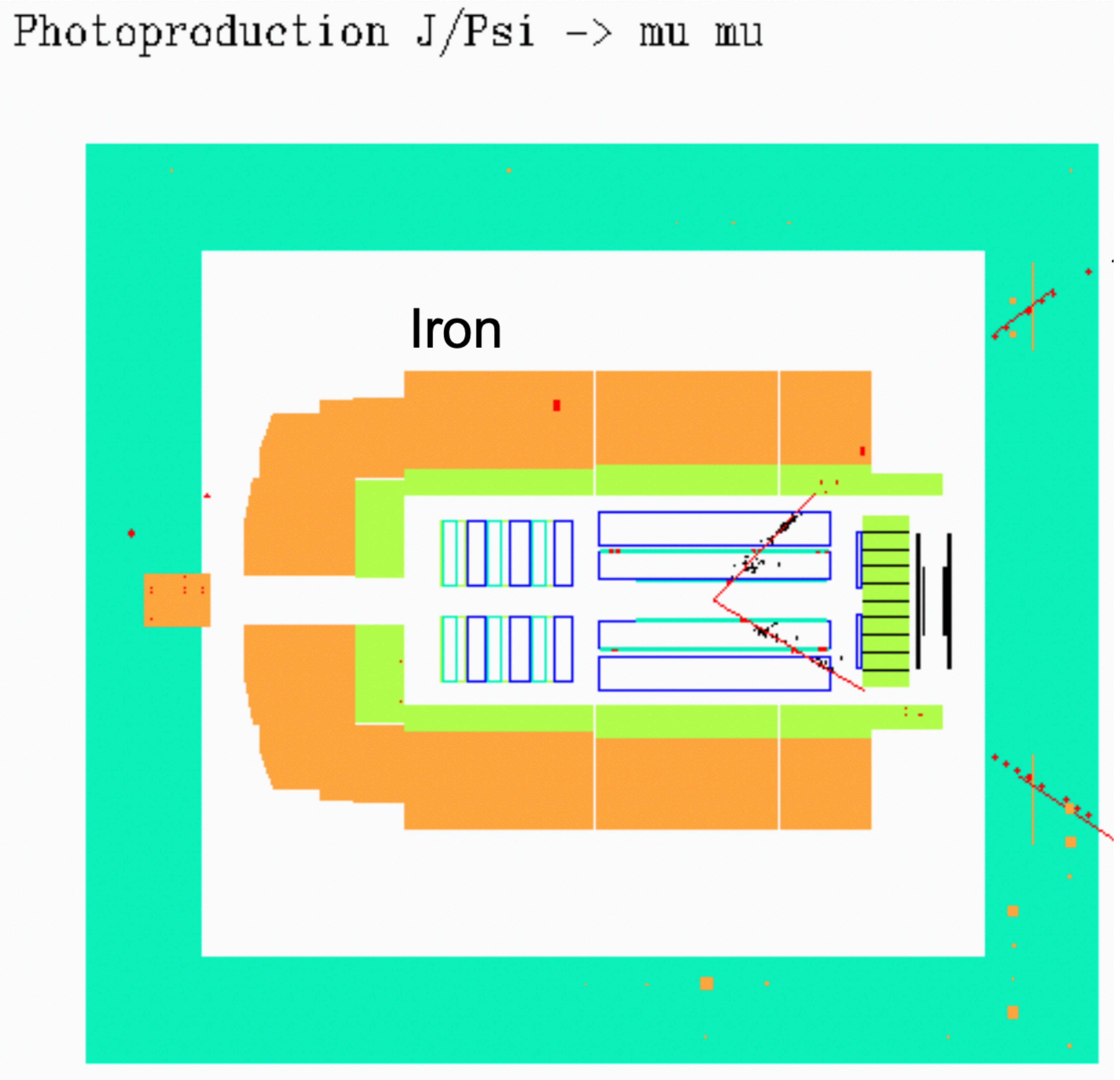
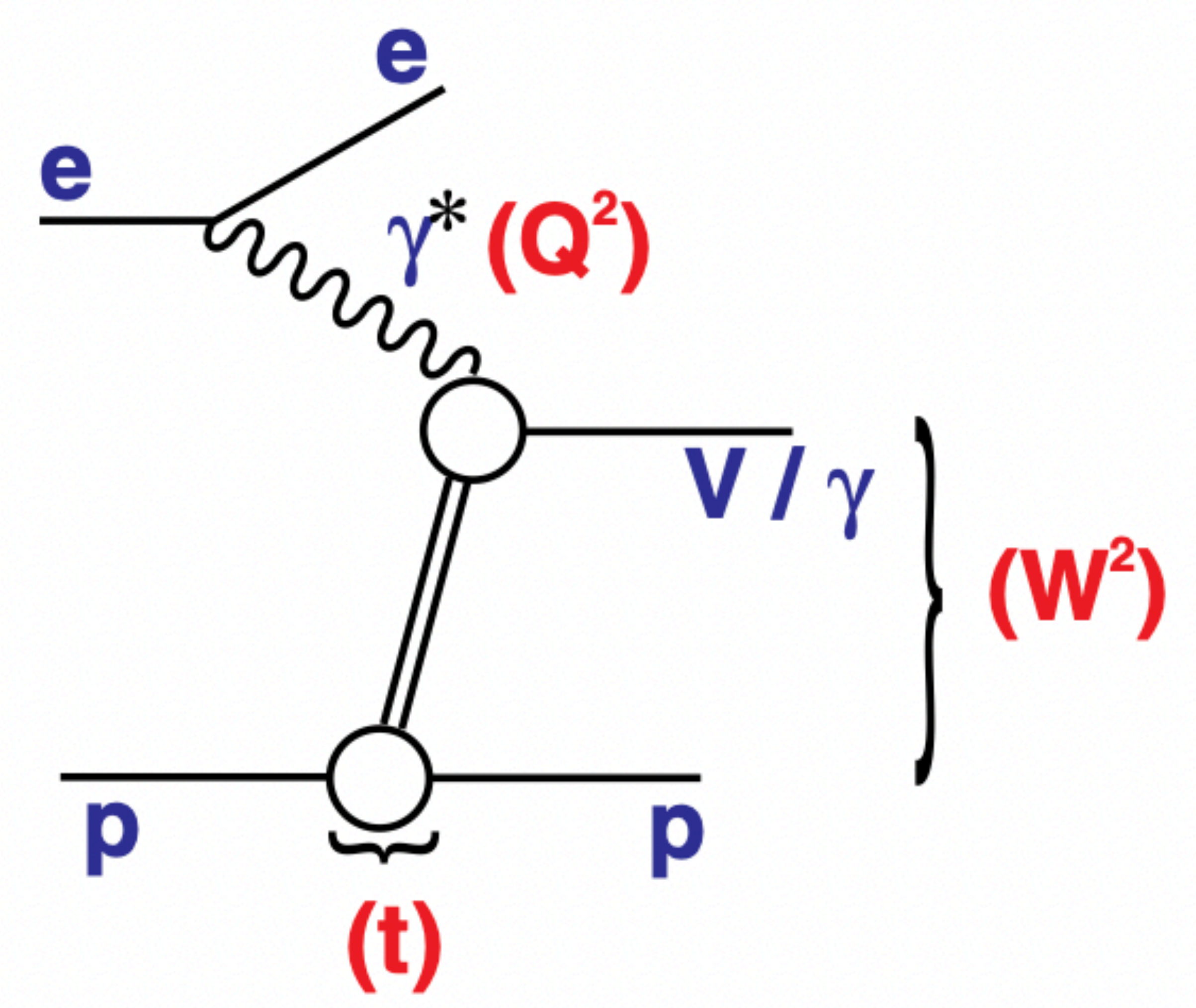
The other half the conjugate of the amplitude

This would be a diffractive process where the protons remains intact after the interaction



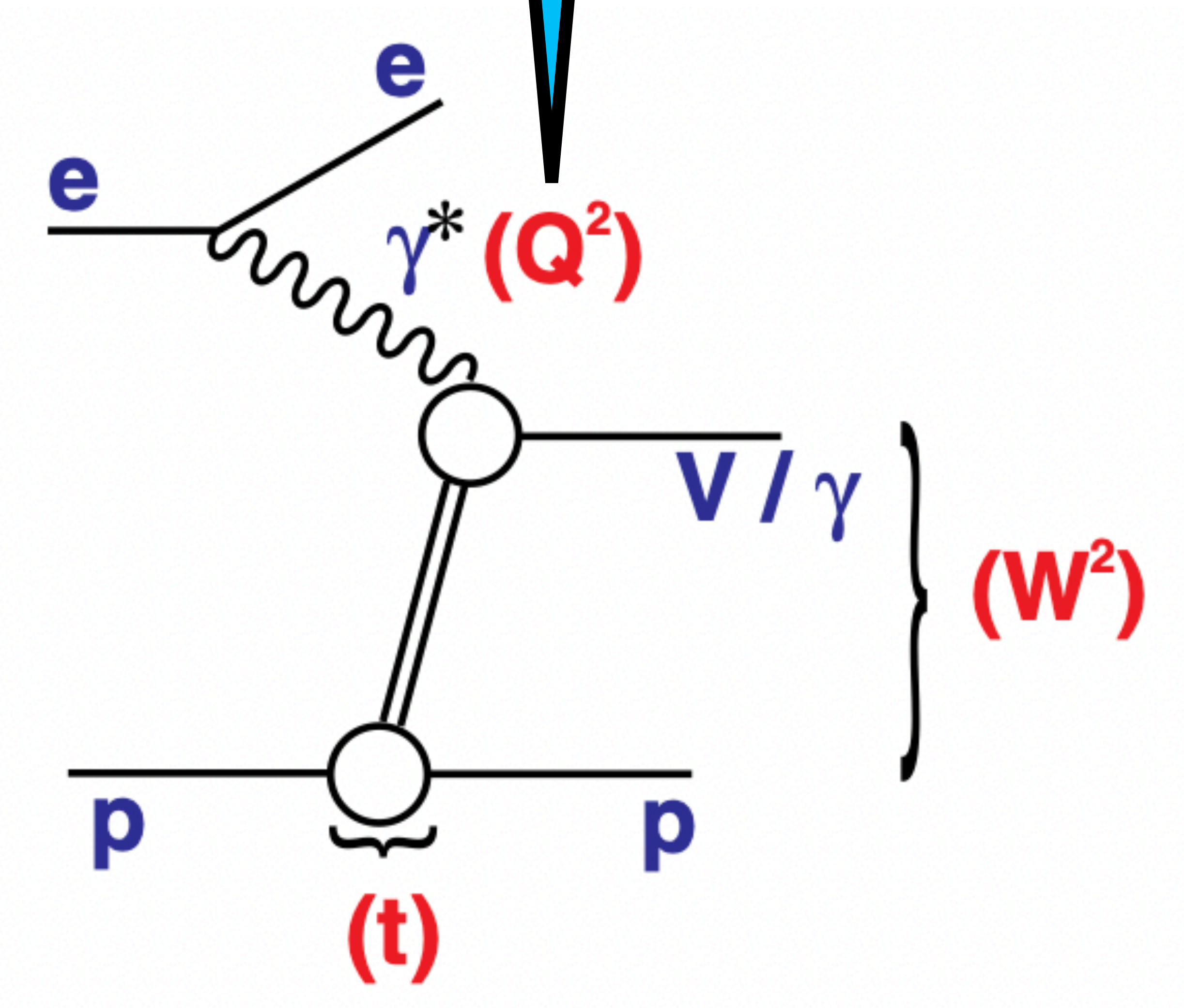

Photoproduction J/Psi -> mu mu
Iron



Newman, Wing, https://inspirehep.net/literature/1247974

Diffractive vector meson photoproduction

If virtuality small or zero: photoproduction, if perturbatively large, electroproduction



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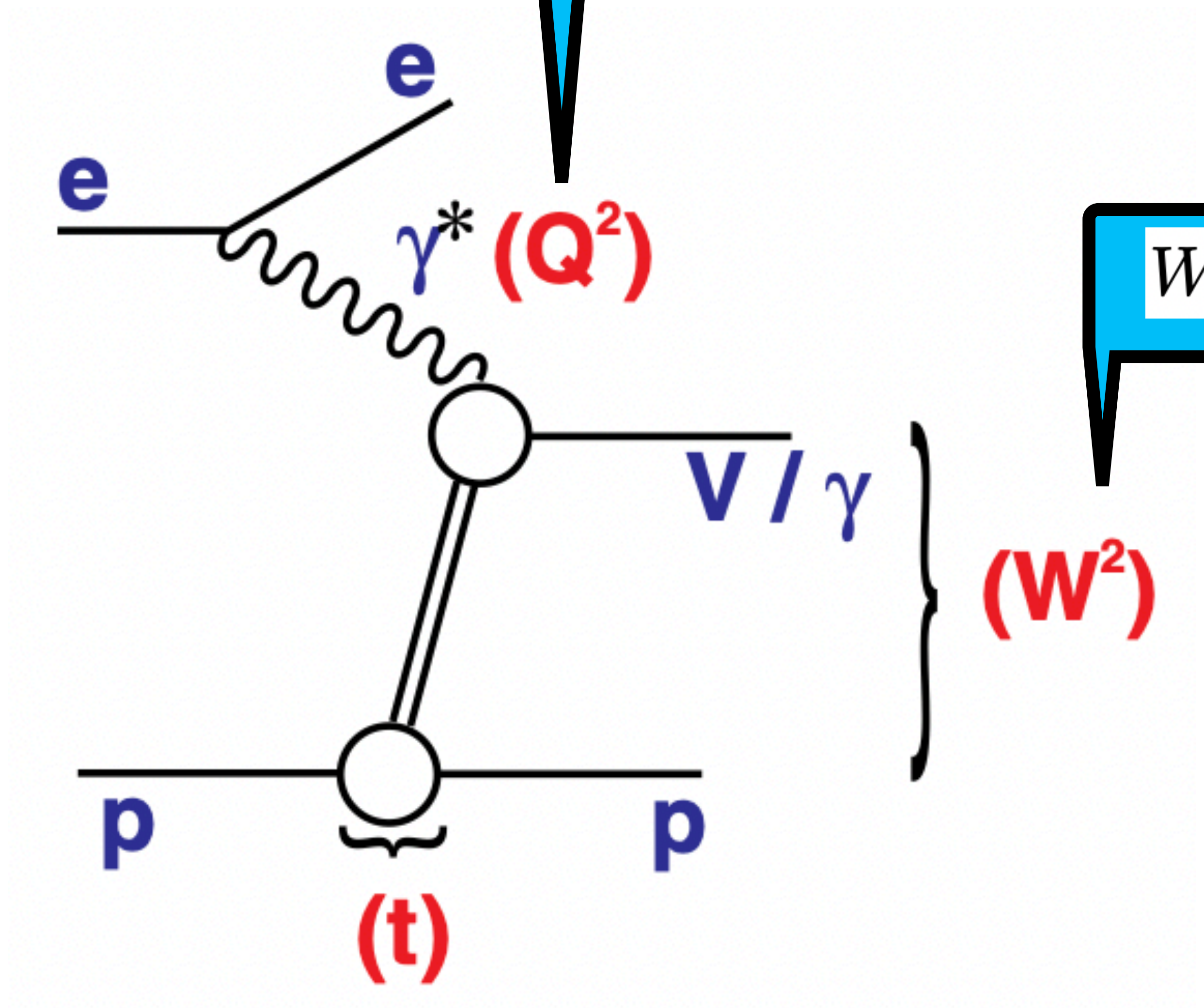
$W \simeq \sqrt{Q^2/x}.$



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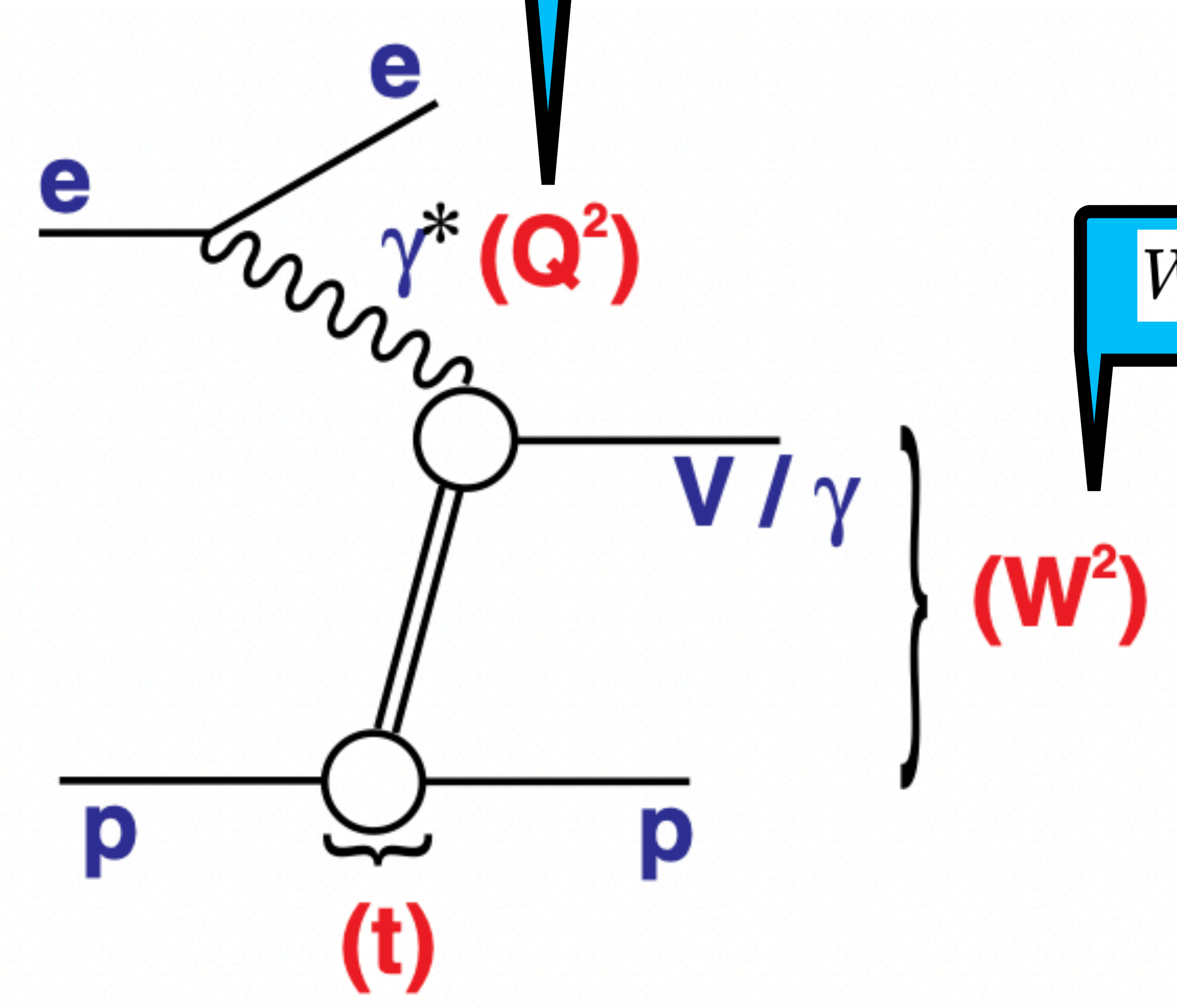

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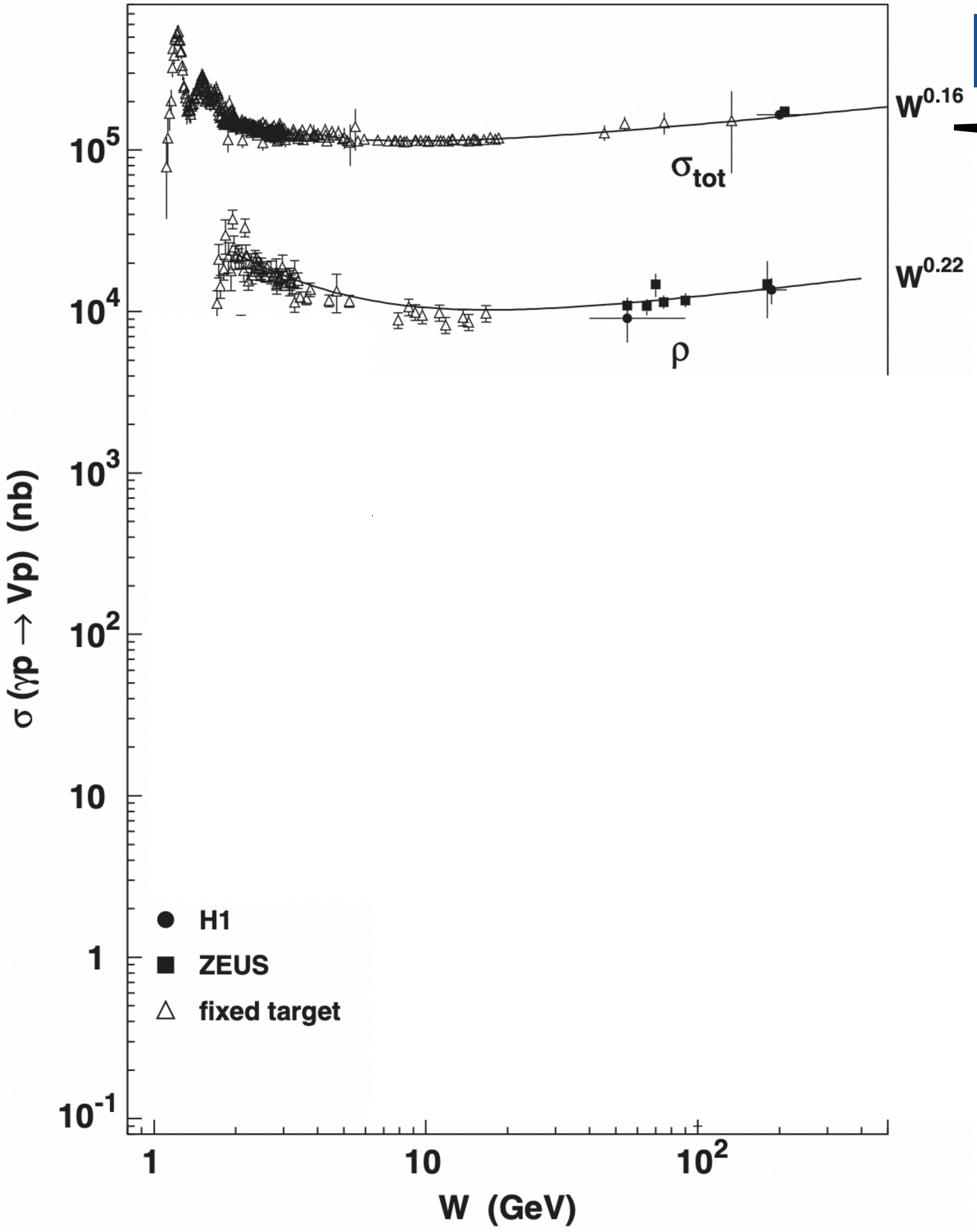
Related, through a Fourier transform, to the distribution of colour fields in the transverse plane

Newman, Wing, https://inspirehep.net/literature/1247974

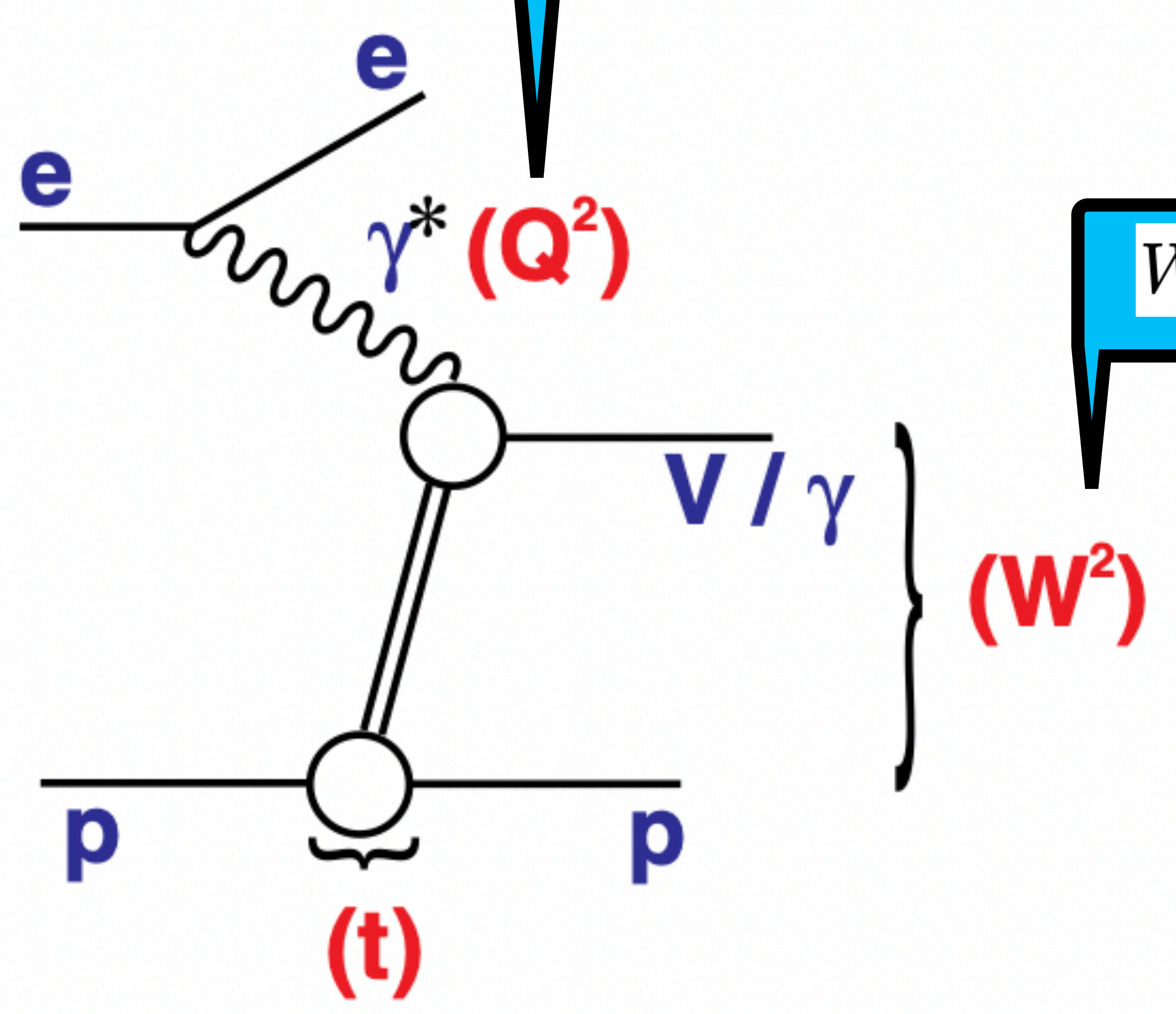
Diffractive vector meson photoproduction



Total photoproduction cross section

ρ(770) photoproduction cross section

If virtuality small or zero: photoproduction, if perturbatively large, electroproduction



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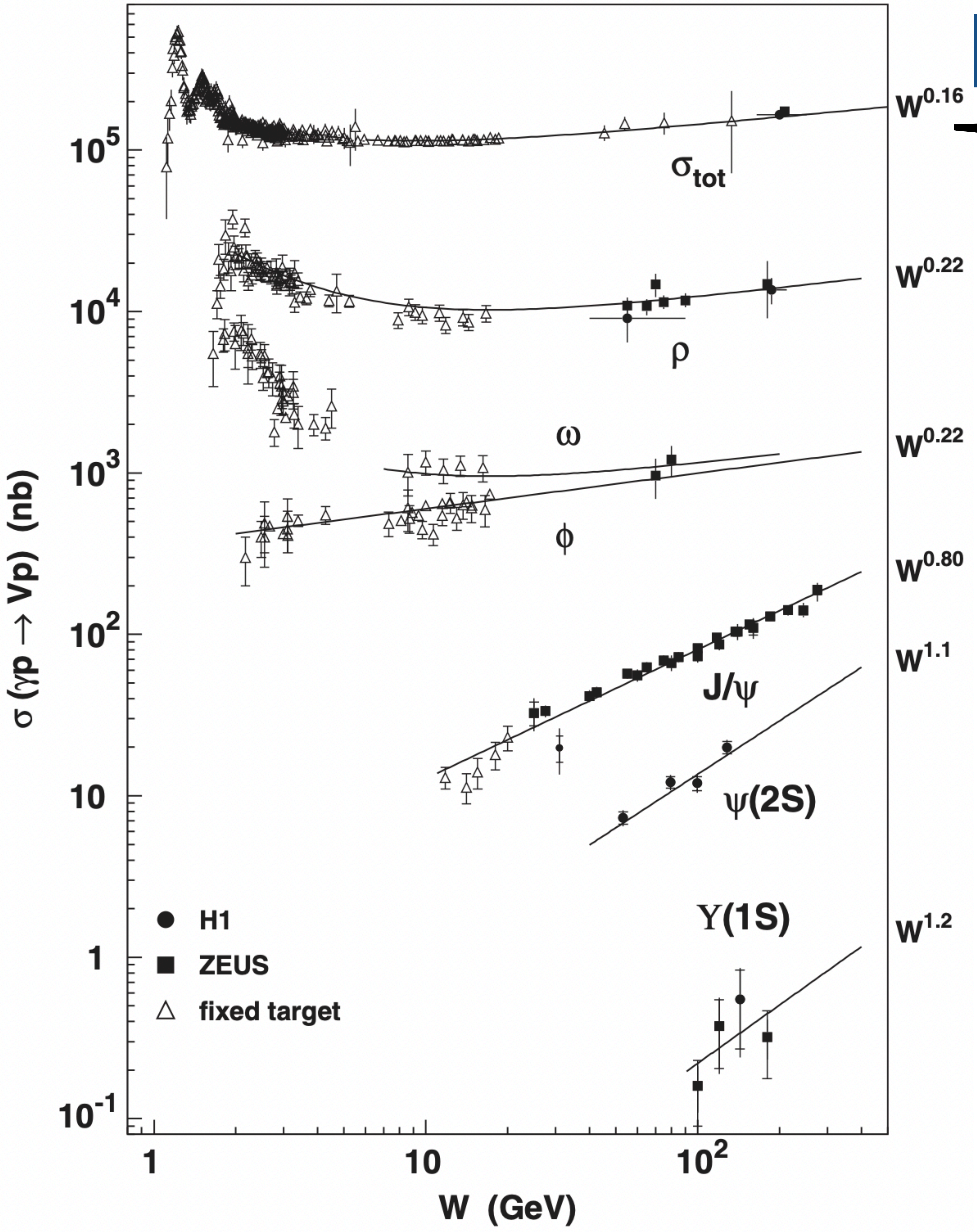

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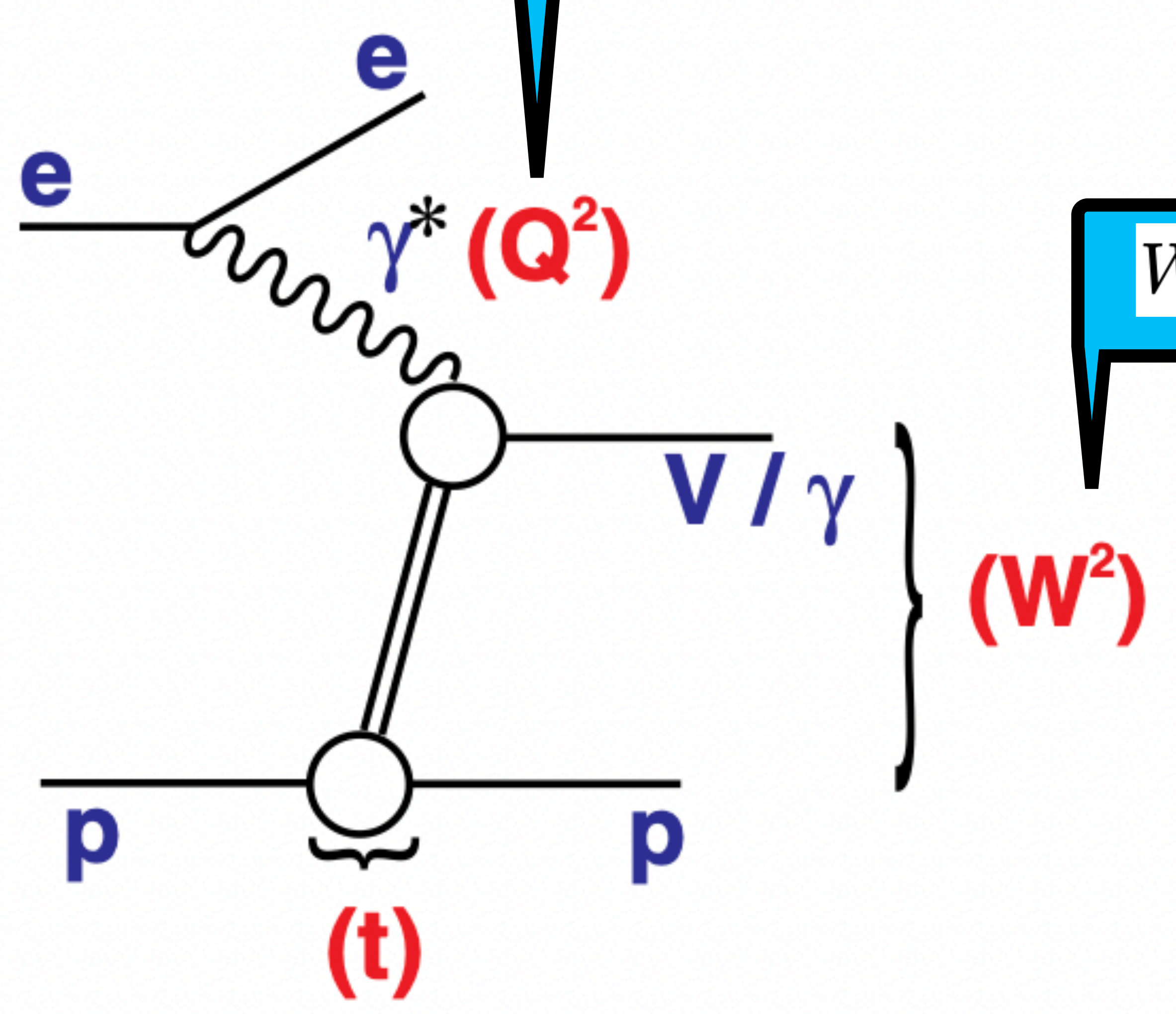

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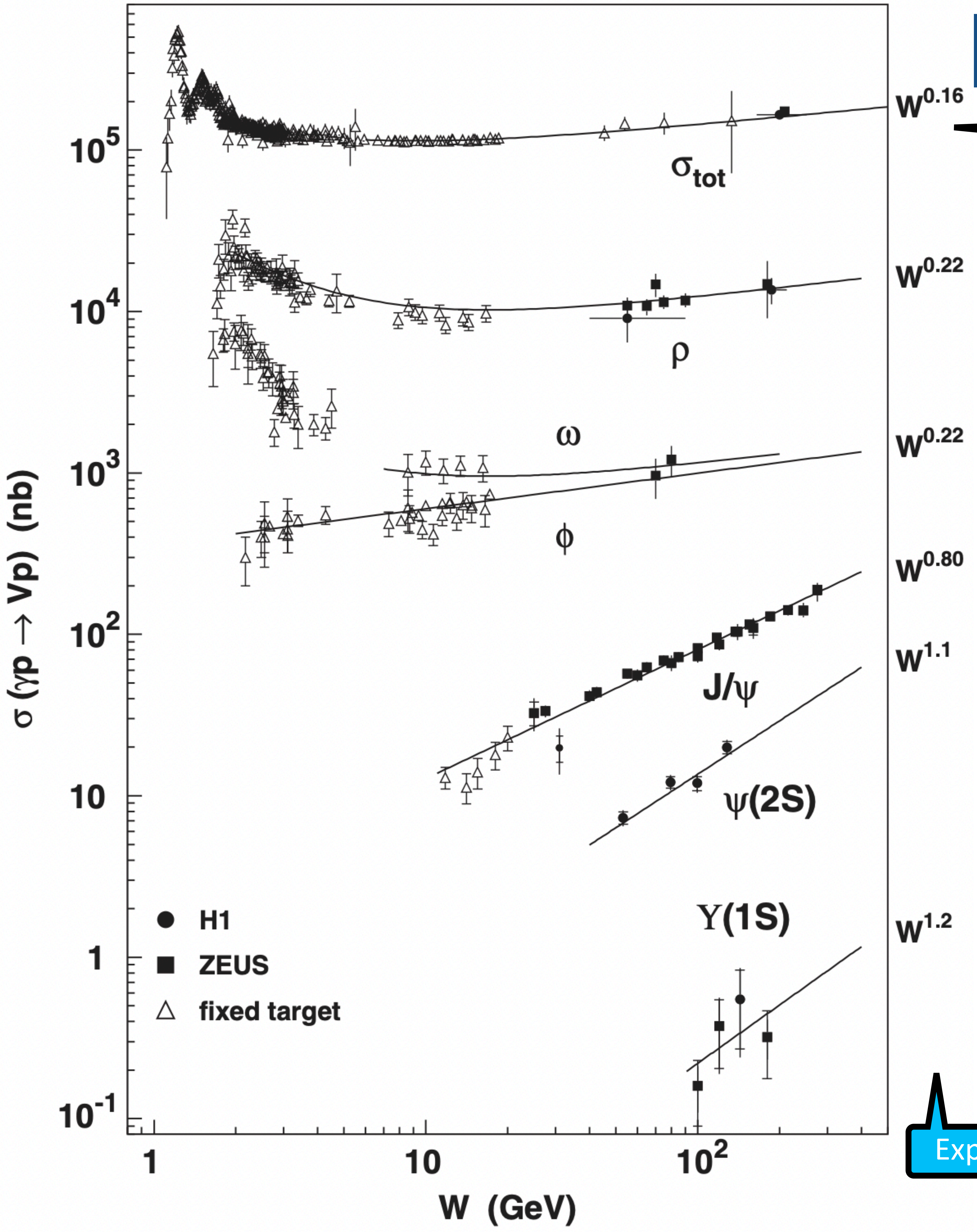

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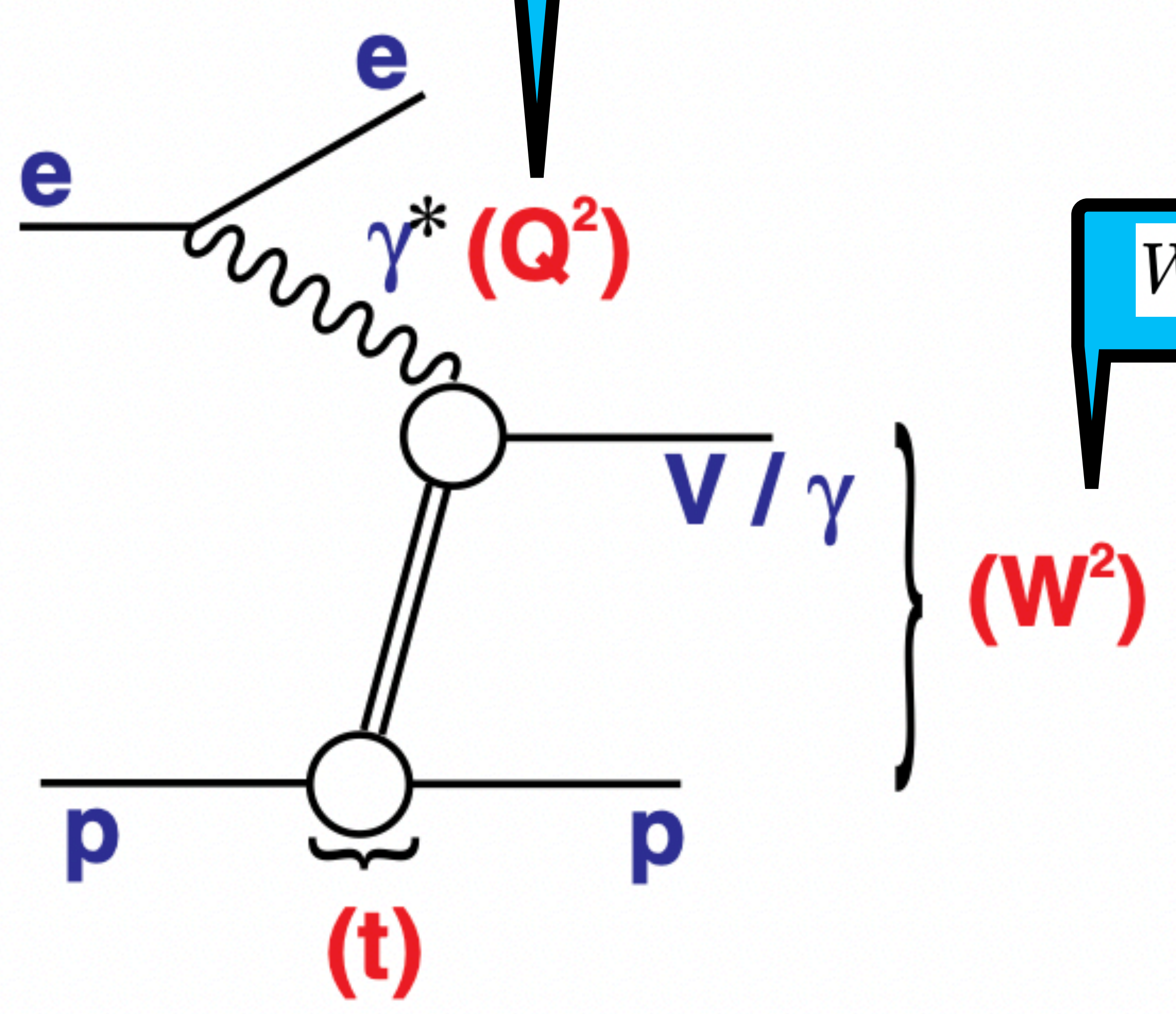
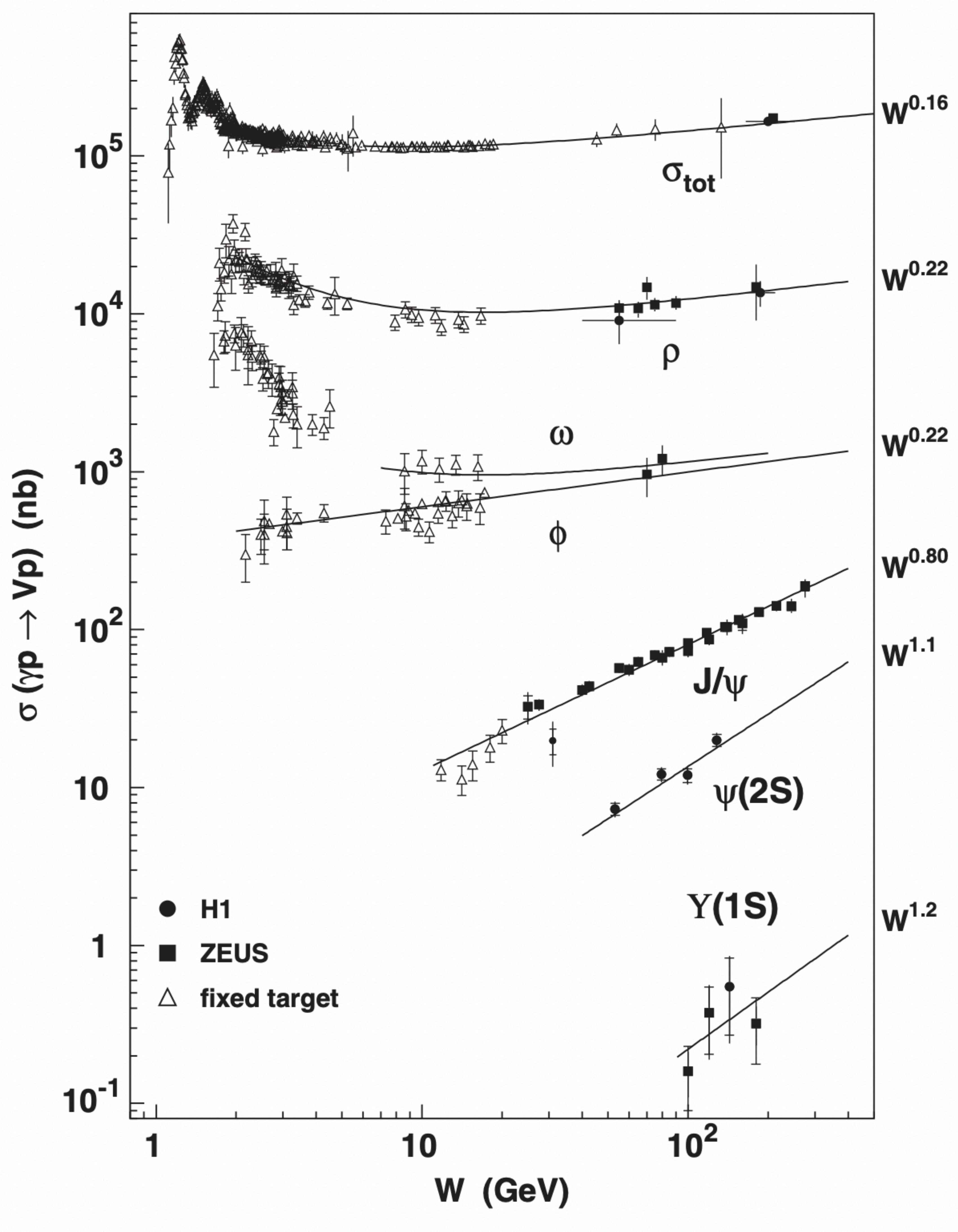


Related, through a Fourier transform, to the distribution of colour fields in the transverse plane

Exponent grows with the scale

Newman, Wing, https://inspirehep.net/literature/1247974

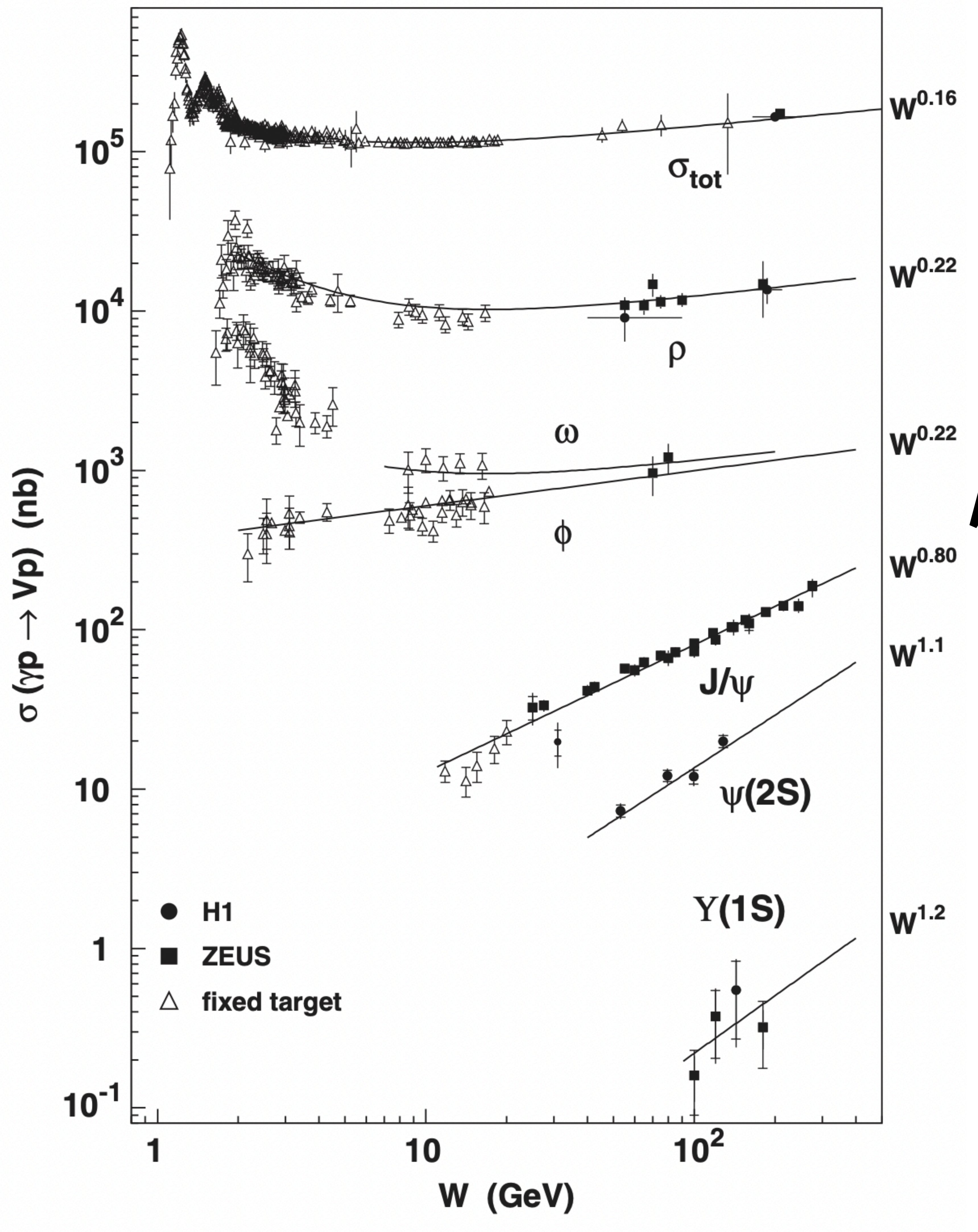
Sensitivity to the gluon



$\sigma \propto W^{\delta}$

Newman, Wing, https://inspirehep.net/literature/1247974

Sensitivity to the gluon



$\sigma \propto x^{-\delta/2}$

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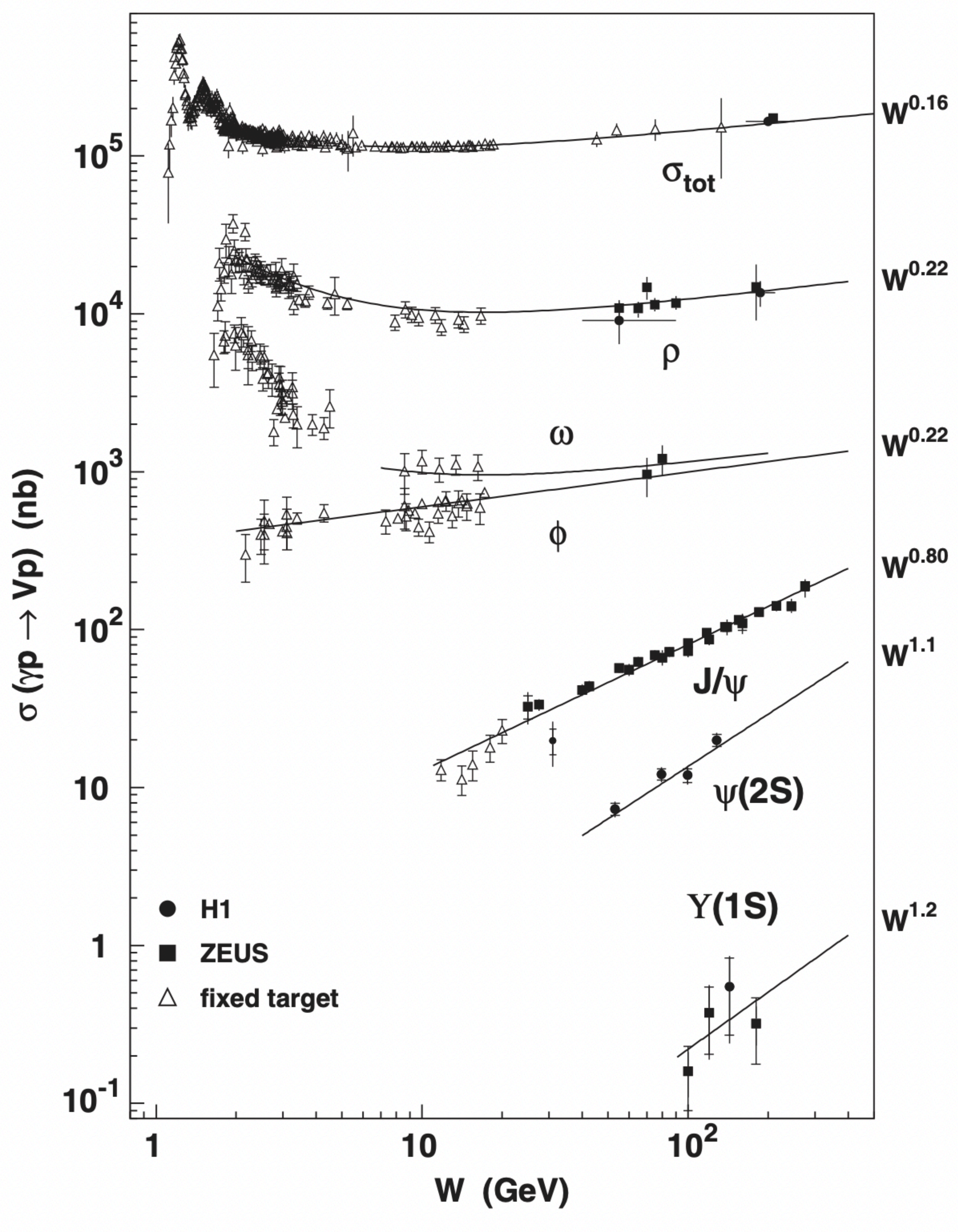

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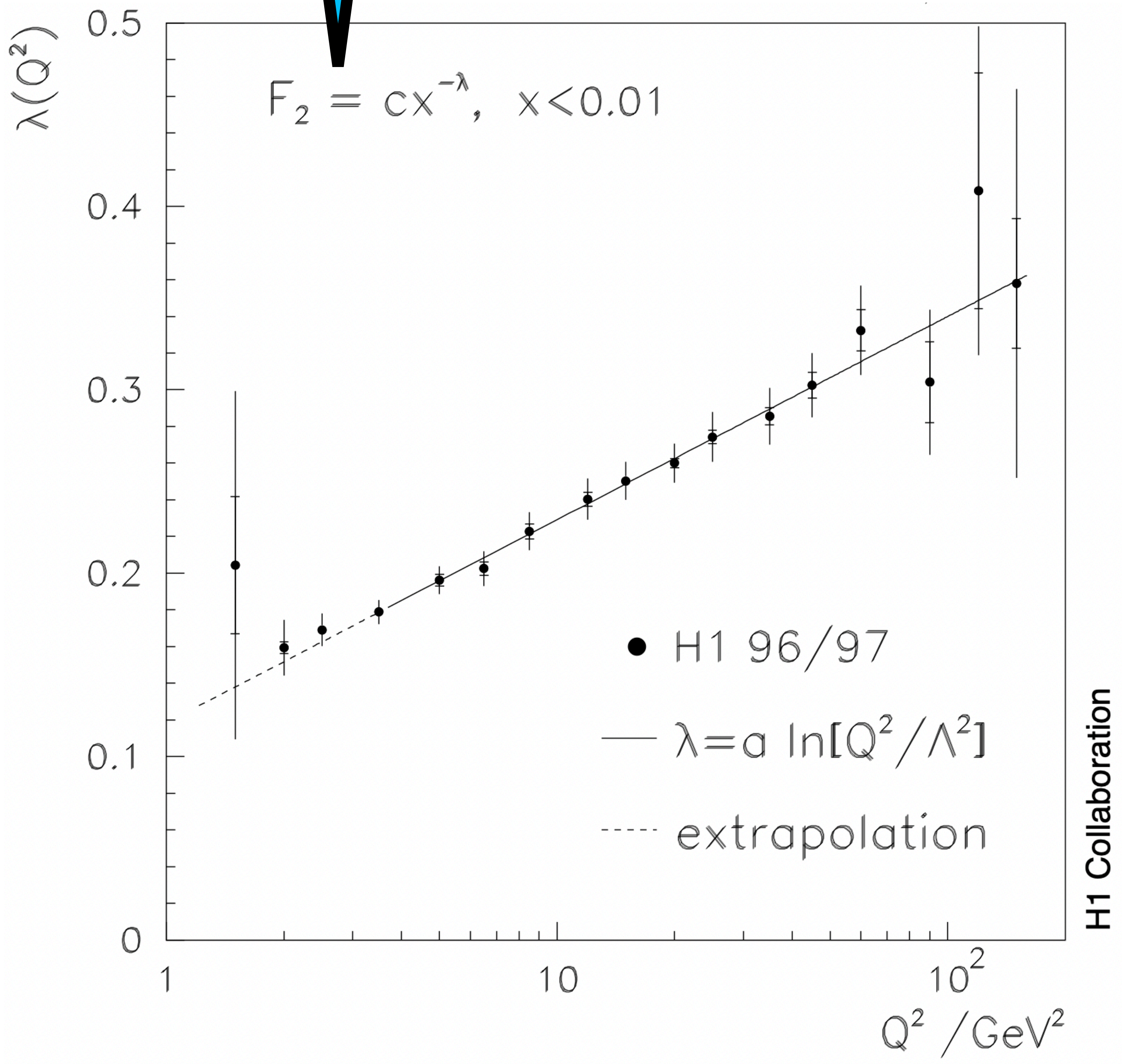
$F_2 \propto x^{-\lambda}$



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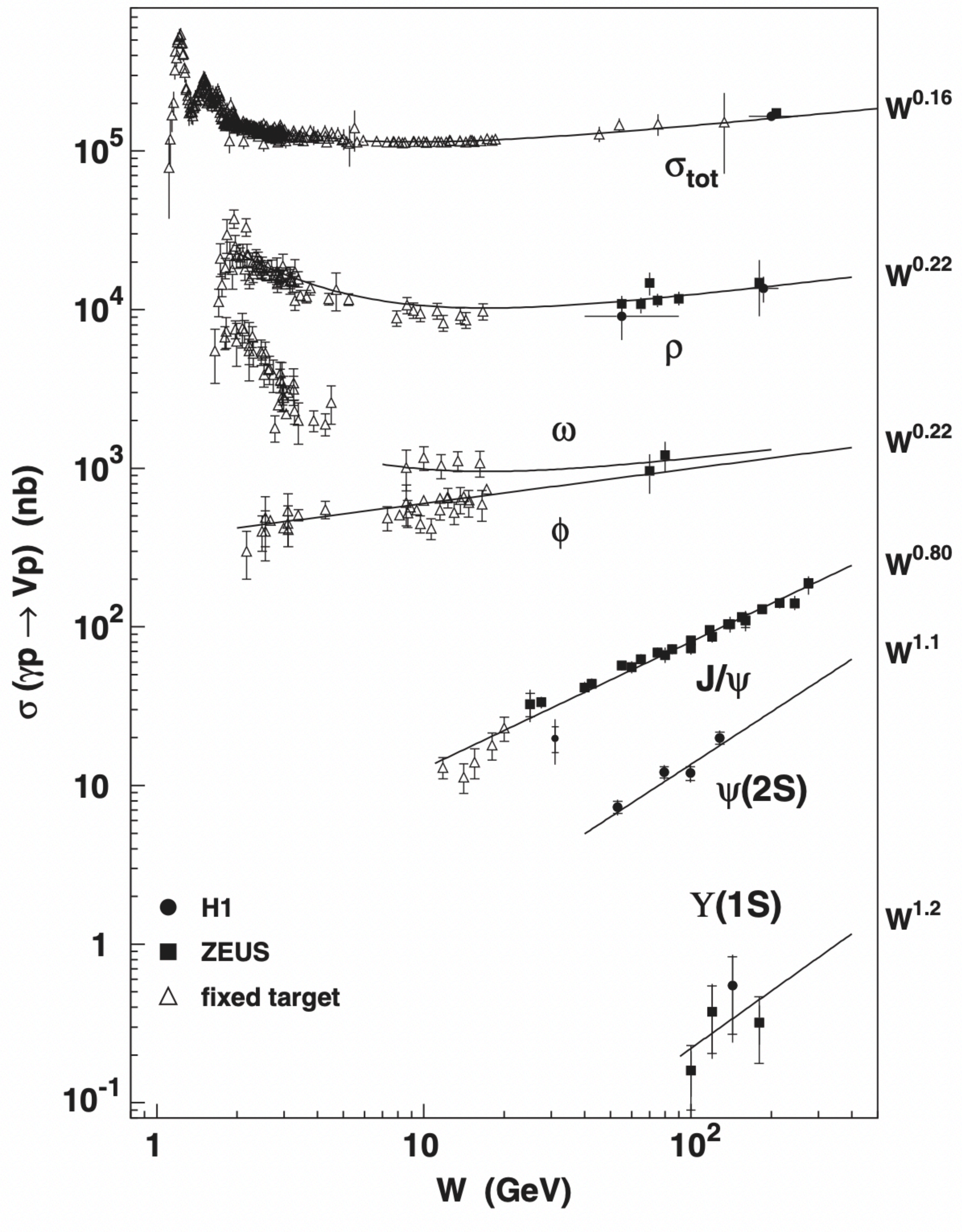
H1, https://inspirehep.net/literature/561805

Sensitivity to the gluon



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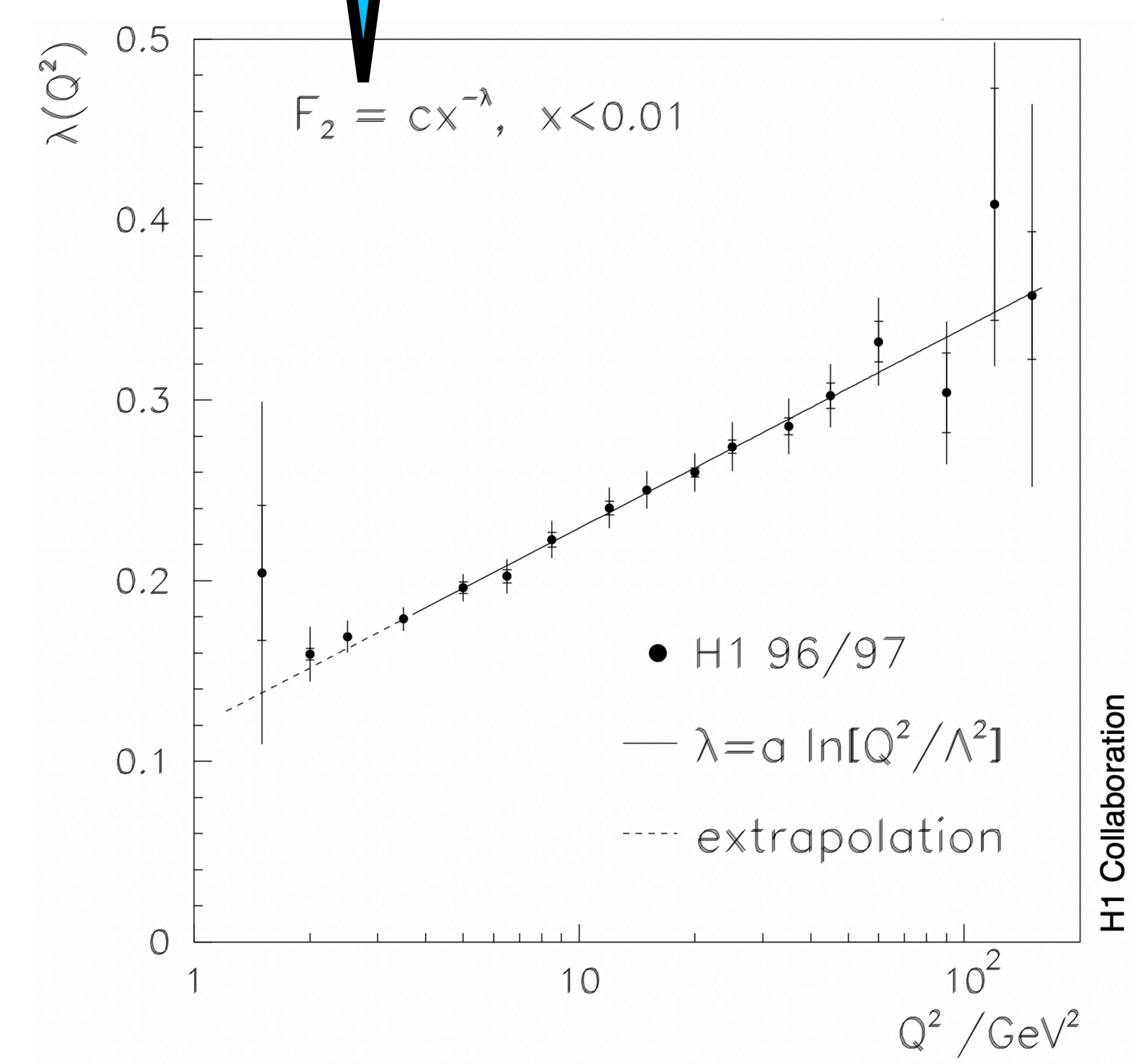
Raise of the gluon distribution

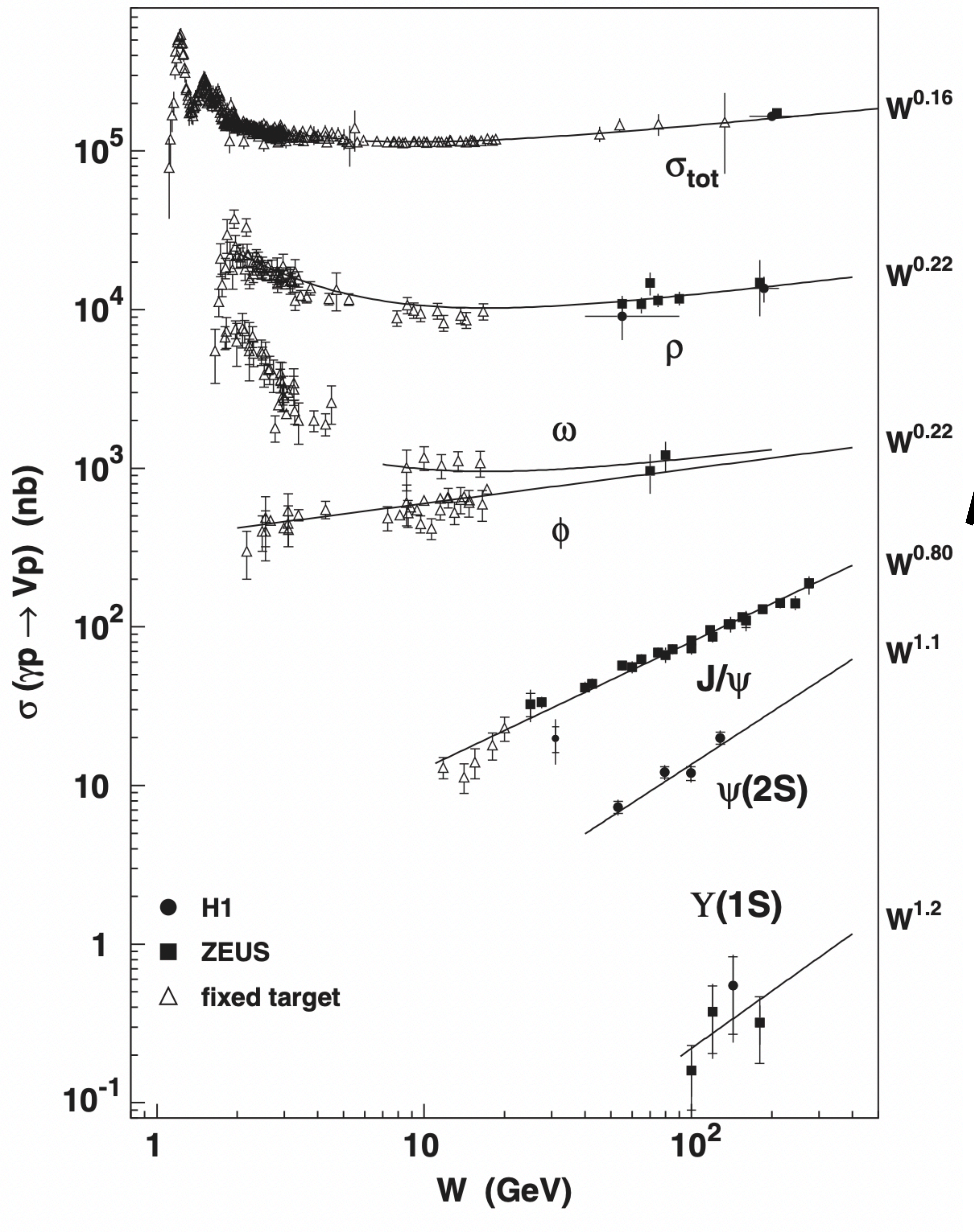
$F_2 \propto x^{-\lambda}$



H1, https://inspirehep.net/literature/561805

Guillermo Contreras, CTU in Prague

Sensitivity to the gluon



Newman, Wing, https://inspirehep.net/literature/1247974

$\sigma \propto W^{\delta}$

$\sigma \propto x^{-\delta/2}$

$4\lambda \approx \delta$

At the same scale: $Q^2 + M^2$

Raise of the gluon distribution

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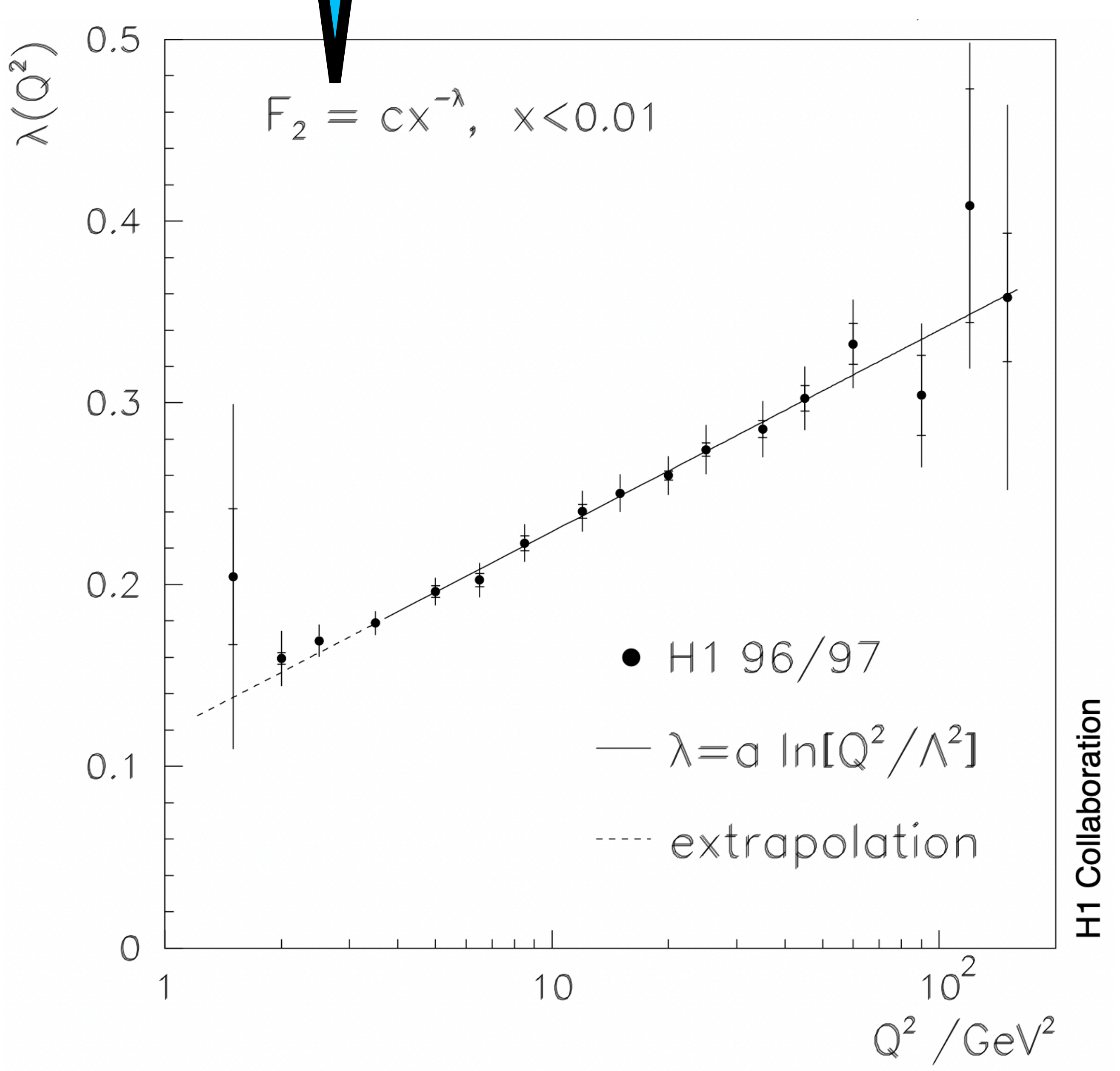

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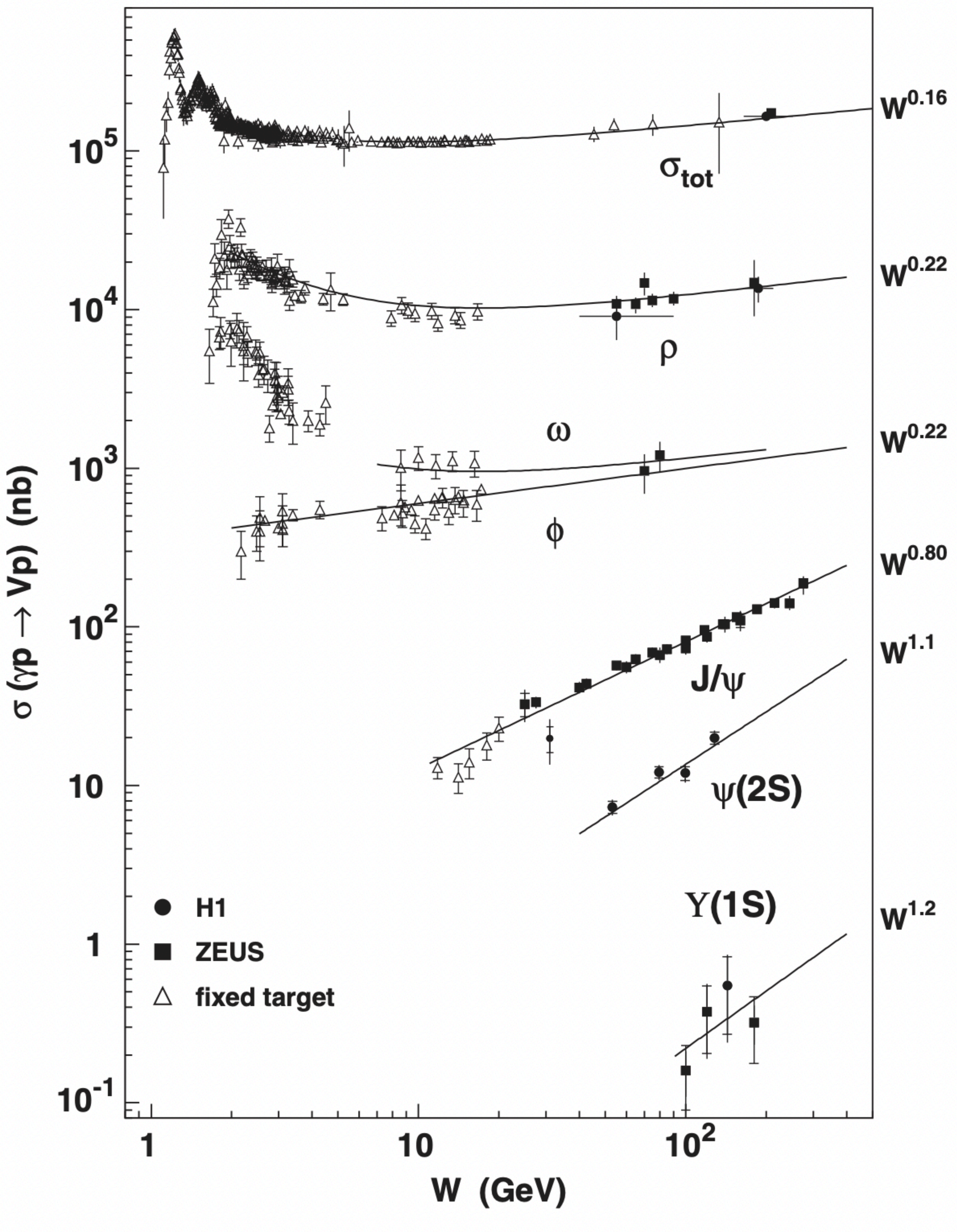
Sensitivity to the gluon



Newman, Wing, https://inspirehep.net/literature/1247974

$\sigma \propto W^{\delta}$

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Raises as the square of gluon distribution

At the same scale: $Q^2 + M^2$

$4\lambda \approx \delta$

Raise of the gluon distribution

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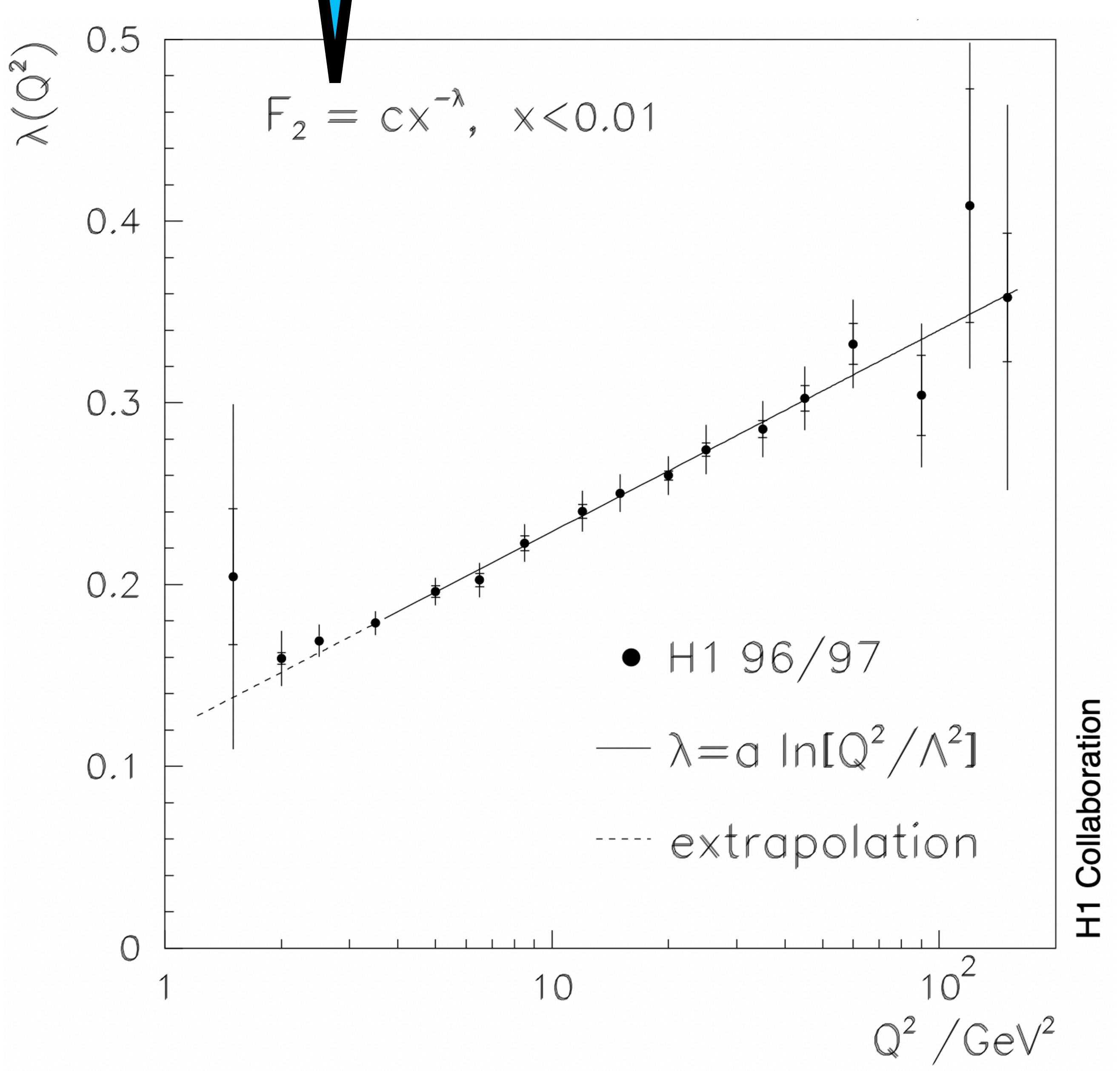

H1, https://inspirehep.net/literature/561805

1993: Diffractive vector meson production in LLA QCD

The process of J/Ψ electroproduction arouses interest due to two reasons. First, it can be calculated within the perturbative QCD and second, its cross section is proportional to the gluon structure function. So, it is a good way to study the gluon distribution inside a proton [1, 2].

Ryskin, https://inspirehep.net/literature/334350

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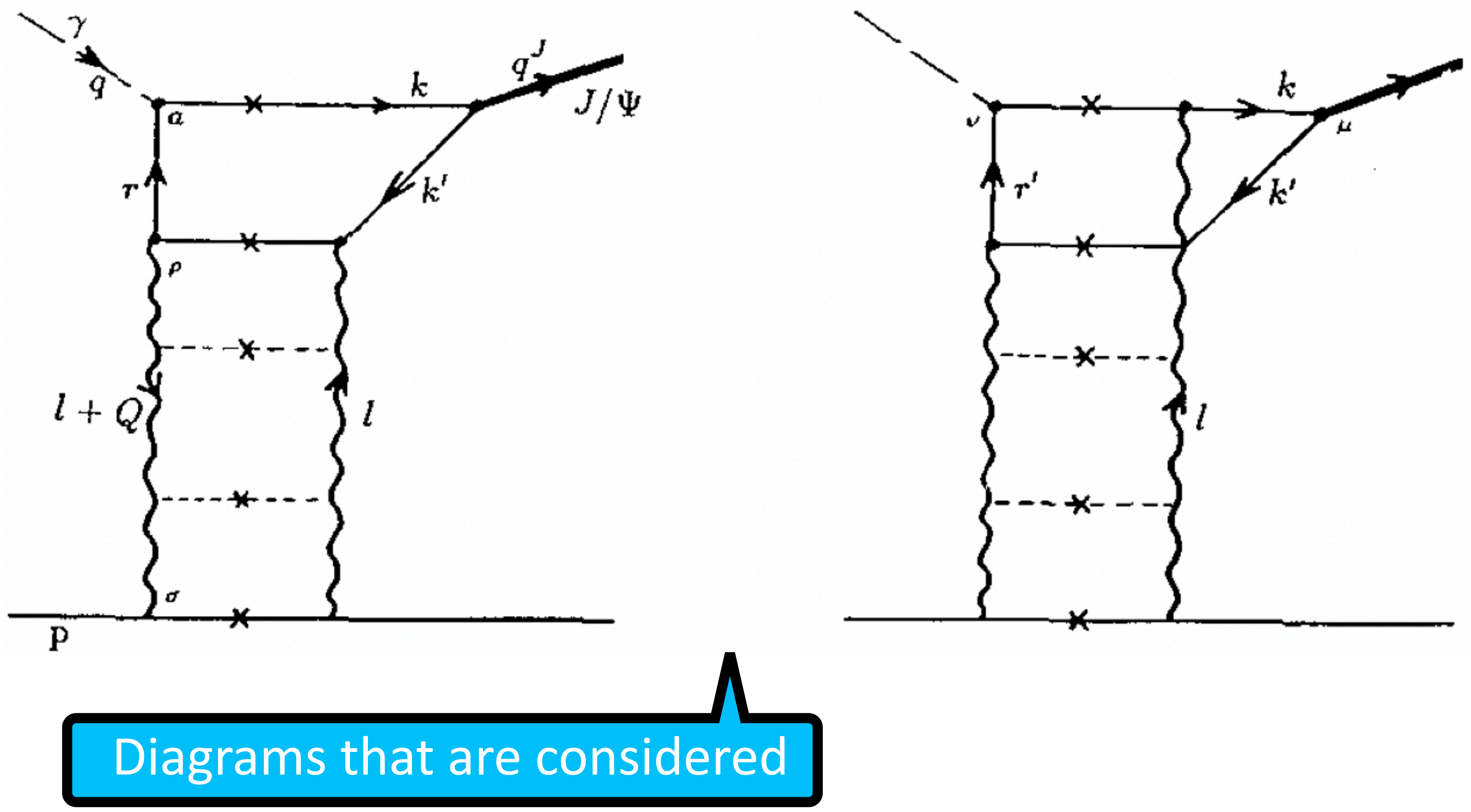

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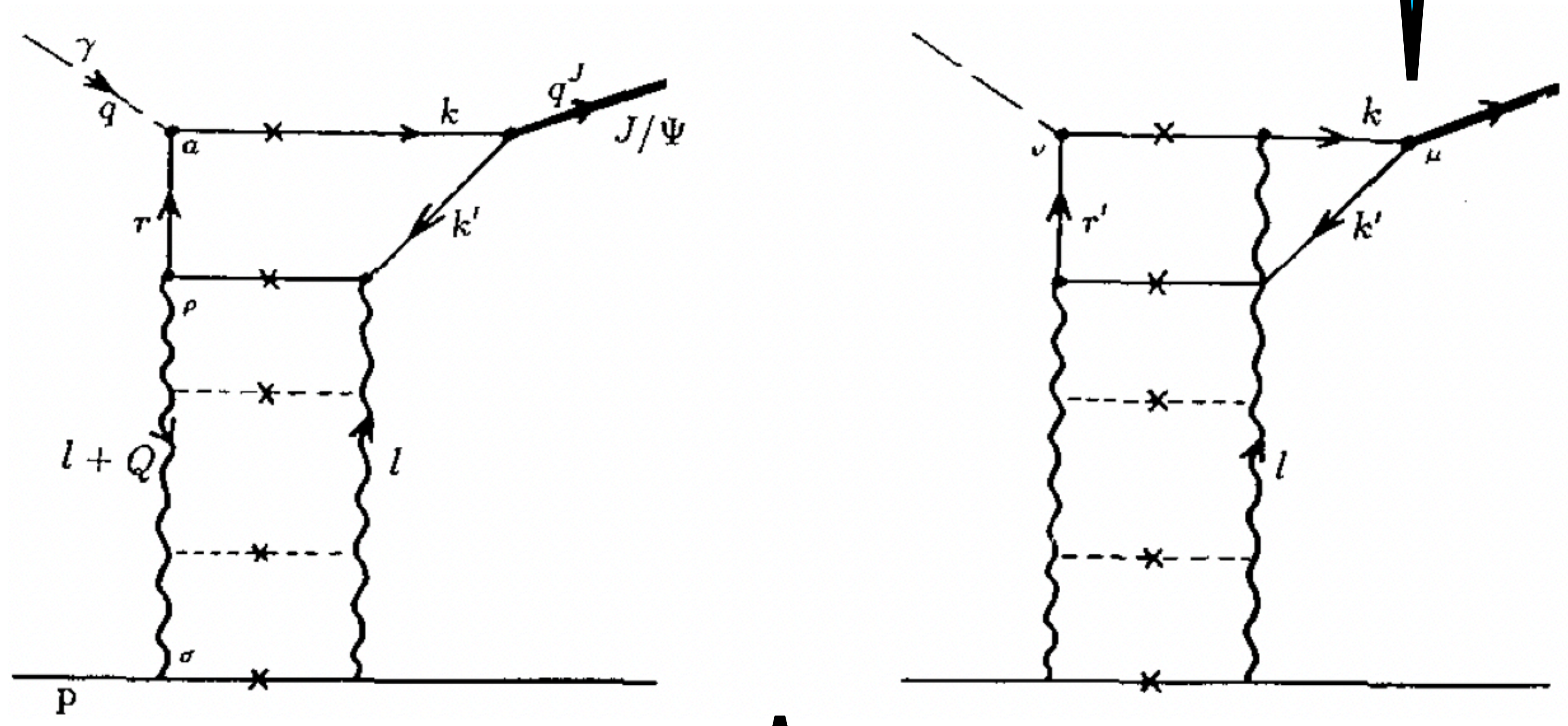
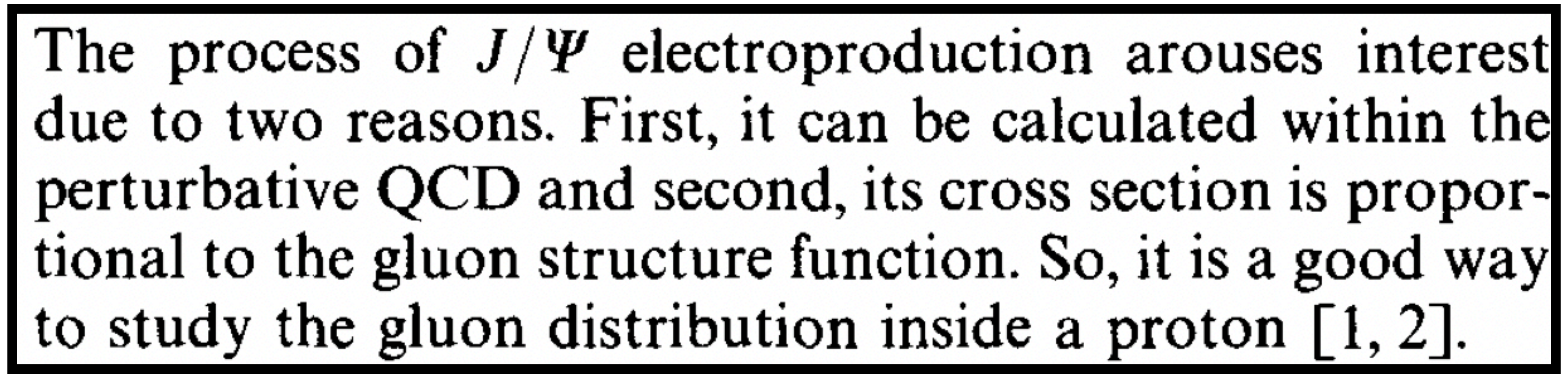
No detailed model of the wave function of the vector meson



Diagrams that are considered



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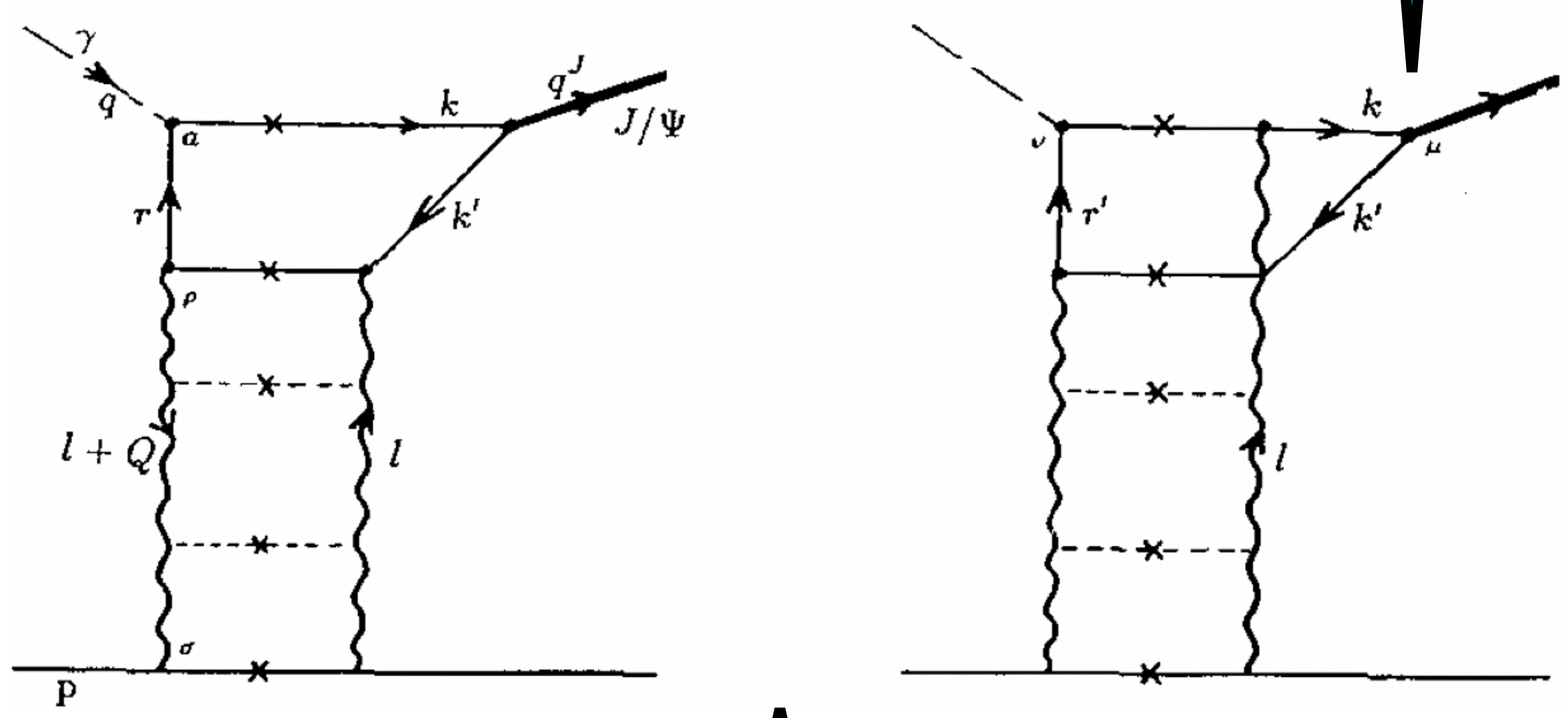

Diagrams that are considered

$$\frac{d\sigma^T(\gamma p \to J/\Psi + p)}{dt} = \frac{|M|^2}{16\pi s^2}$$

$$= [F_N^{2G}(t)]^2 \frac{\alpha_s^2 \Gamma_{ee}^J m_J^3}{3\alpha_{em}} \pi^3$$

$$\times \left[\bar{x} G(\bar{x}, \bar{q}^2) \frac{2\bar{q}^2 - |q_t^J|^2}{(2\bar{q}^2)^3} \right]^2 ,$$

Square of gluon distribution

The process of J/Ψ electroproduction arouses interest due to two reasons. First, it can be calculated within the perturbative QCD and second, its cross section is proportional to the gluon structure function. So, it is a good way to study the gluon distribution inside a proton [1, 2].

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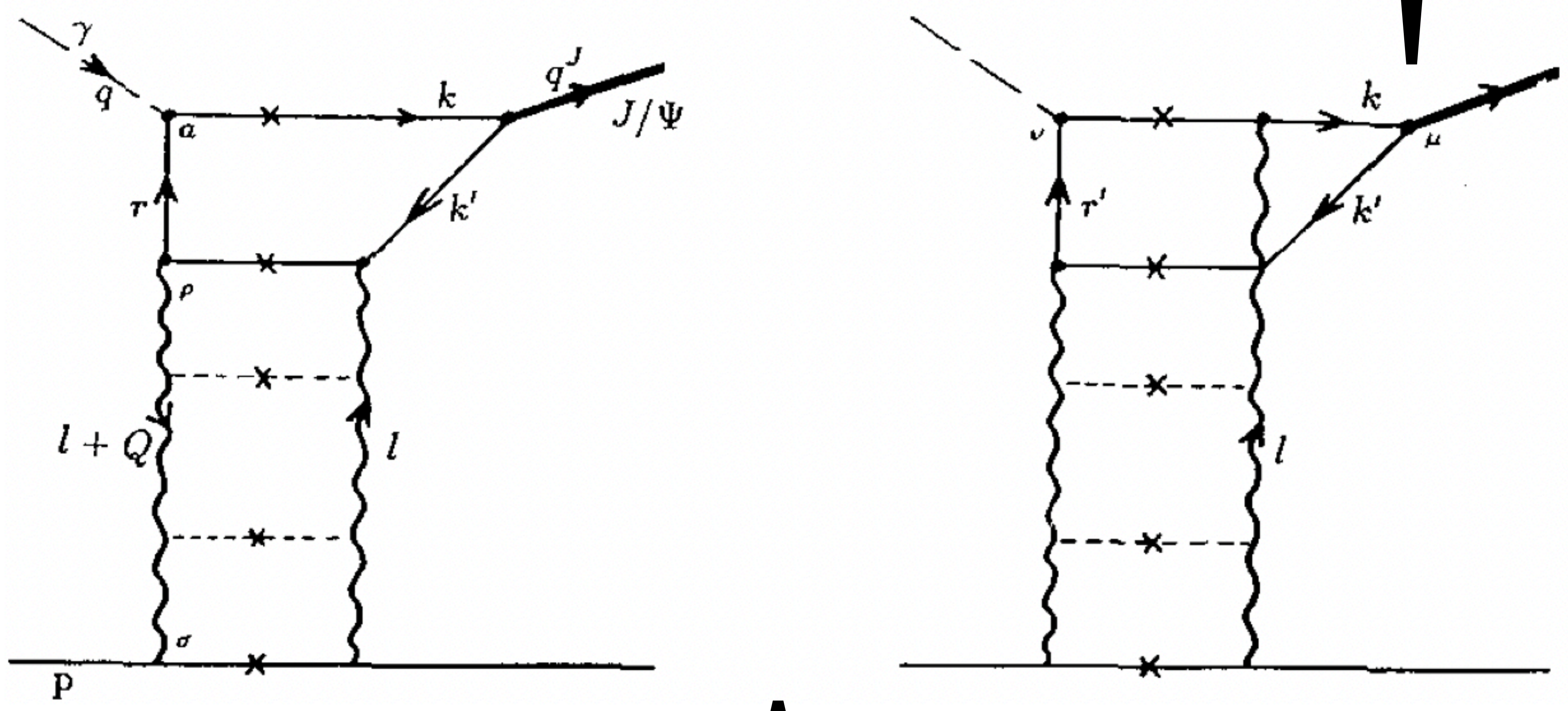

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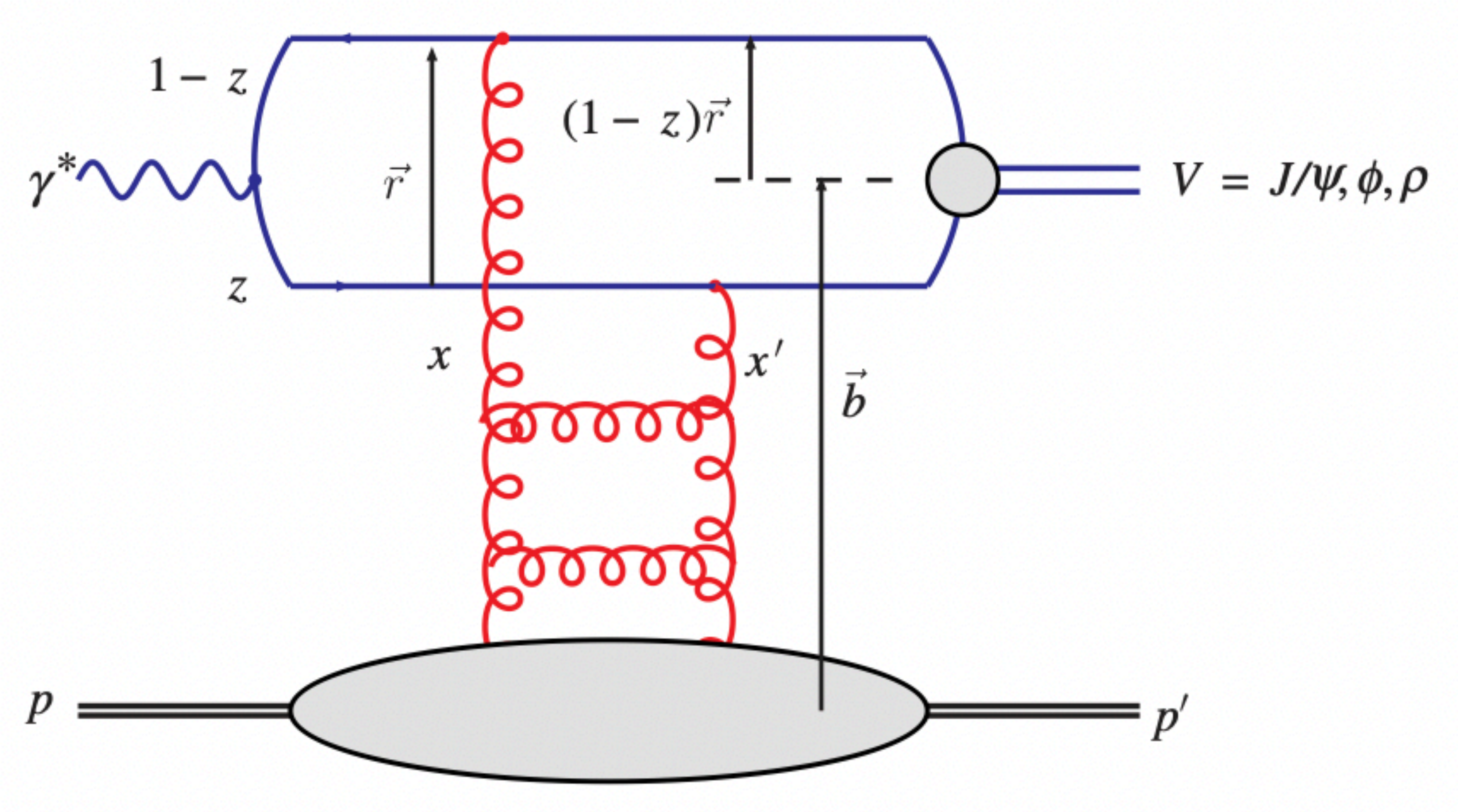
Thus, the diffractive J/Ψ production provides us with a good chance to find the real position of the saturation boundary and, hence, to answer this question.

Good process to study the approach to the saturation regime

Ryskin, https://inspirehep.net/literature/334350

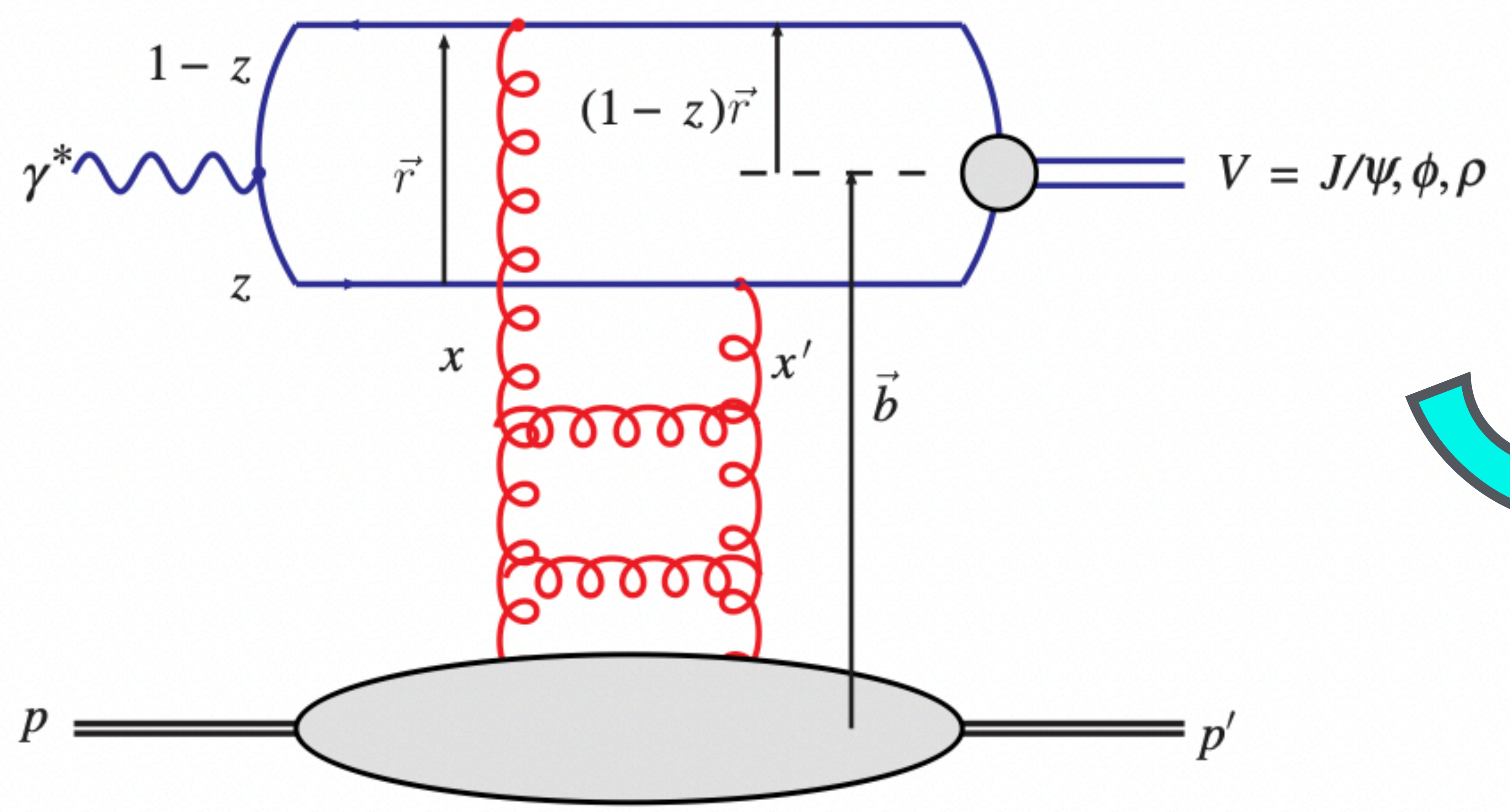
2006: Diffractive vector meson production in the dipole approach (1/5)

Formalism



Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

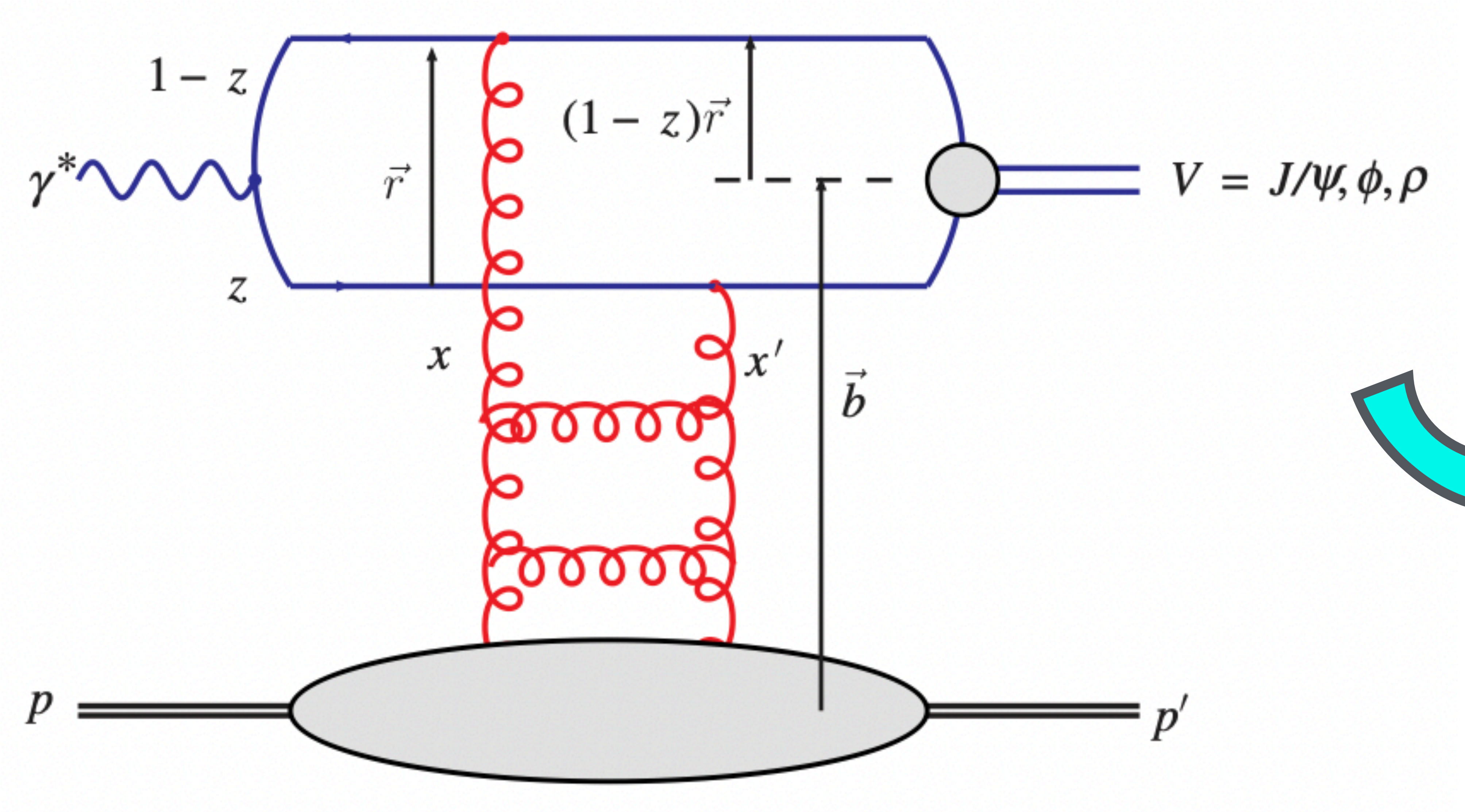
Formalism



$$\frac{d\sigma_{T,L}^{\gamma^* p\to Ep}}{dt} = \frac{1}{16\pi}|\mathcal{A}_{T,L}^{\gamma^* p\to Ep}|^2$$
$$= \frac{1}{16\pi}\left|\int d^2\boldsymbol{r}\int_0^1 \frac{dz}{4\pi} \times \int d^2\boldsymbol{b}(\Psi_E^*\Psi)_{T,L} e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}} \frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}}\right|^2.$$

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



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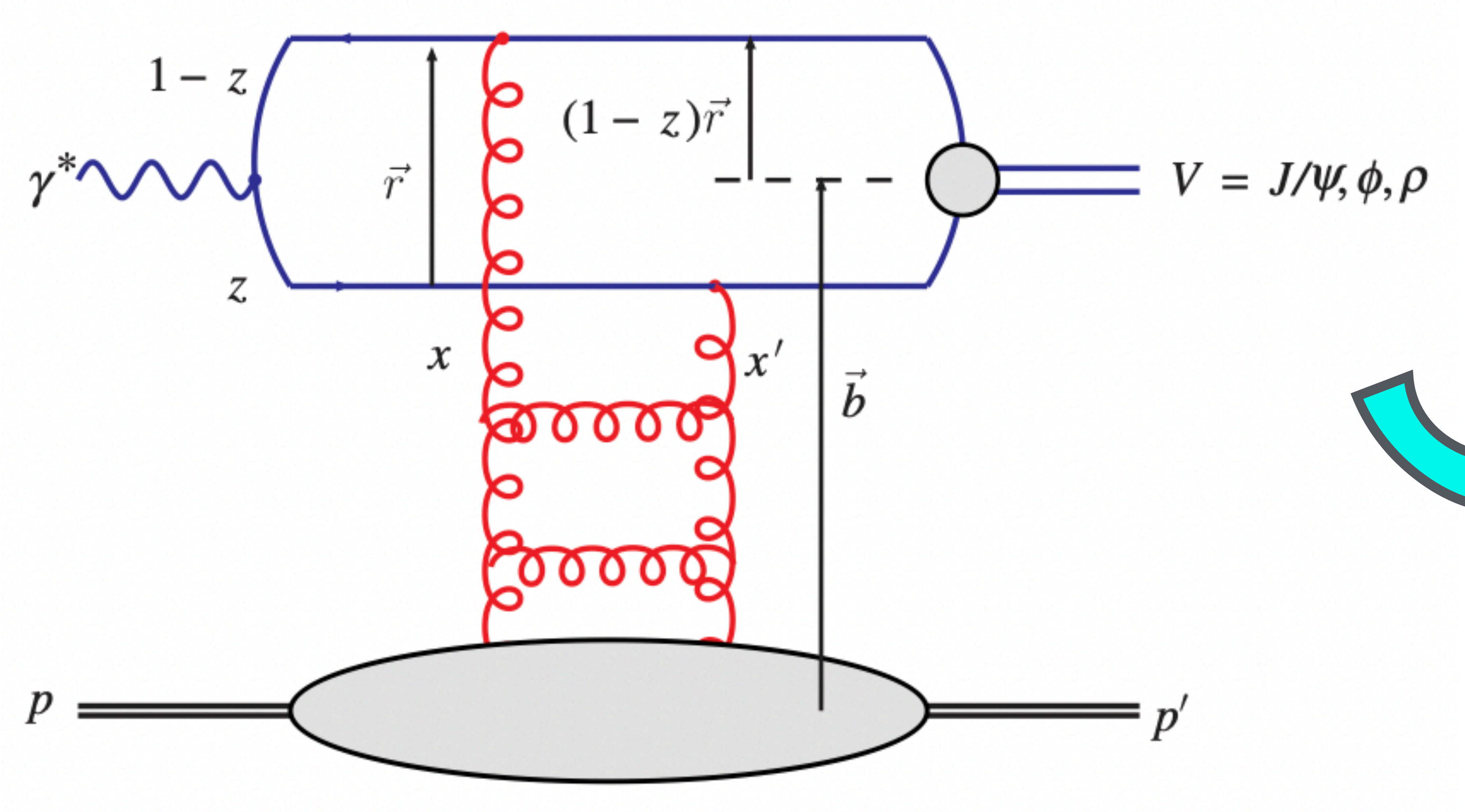
1 Forward wave functions

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



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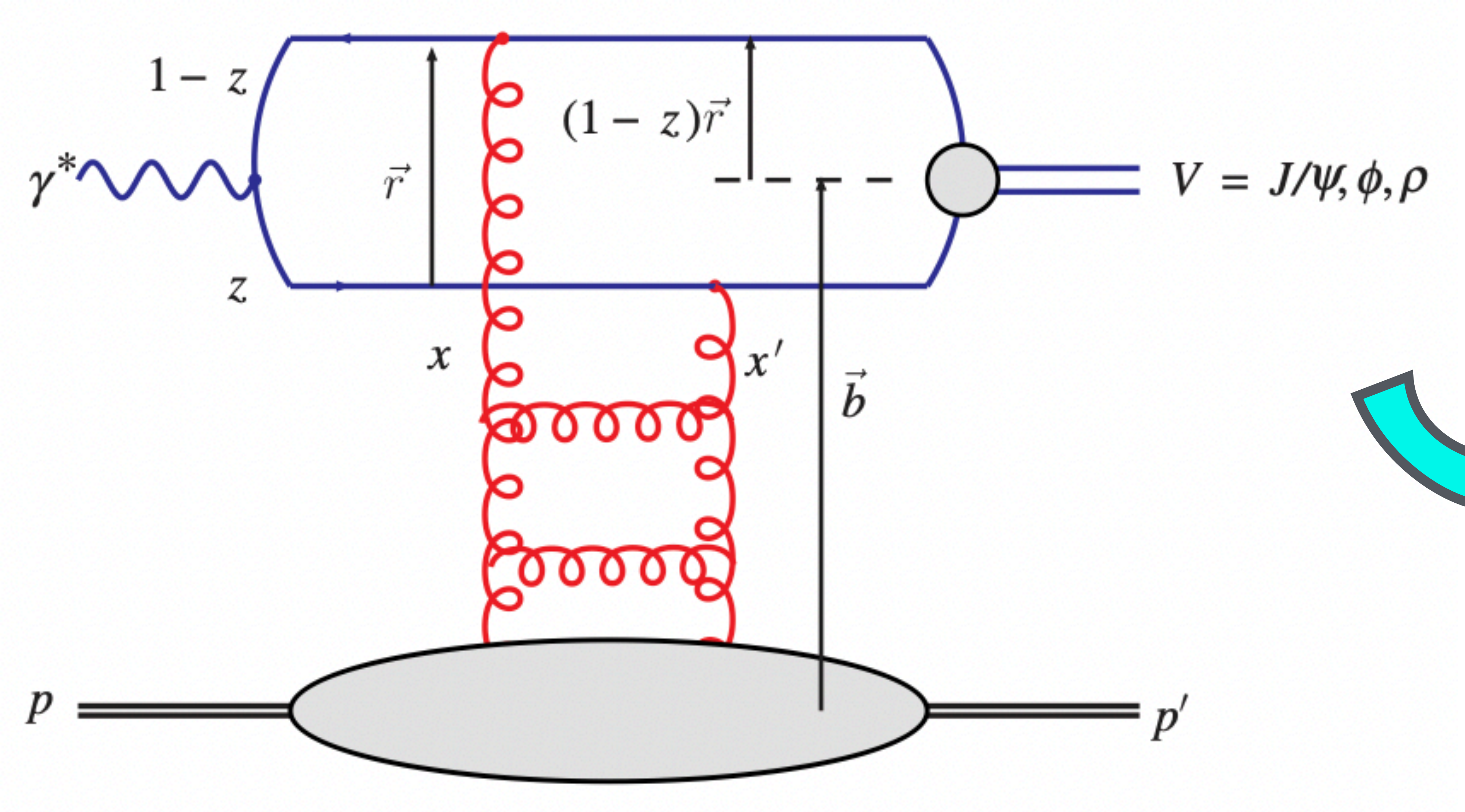
Forward wave functions

1

$\vec{\Delta}^2 = -t$

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



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Conjugate variable

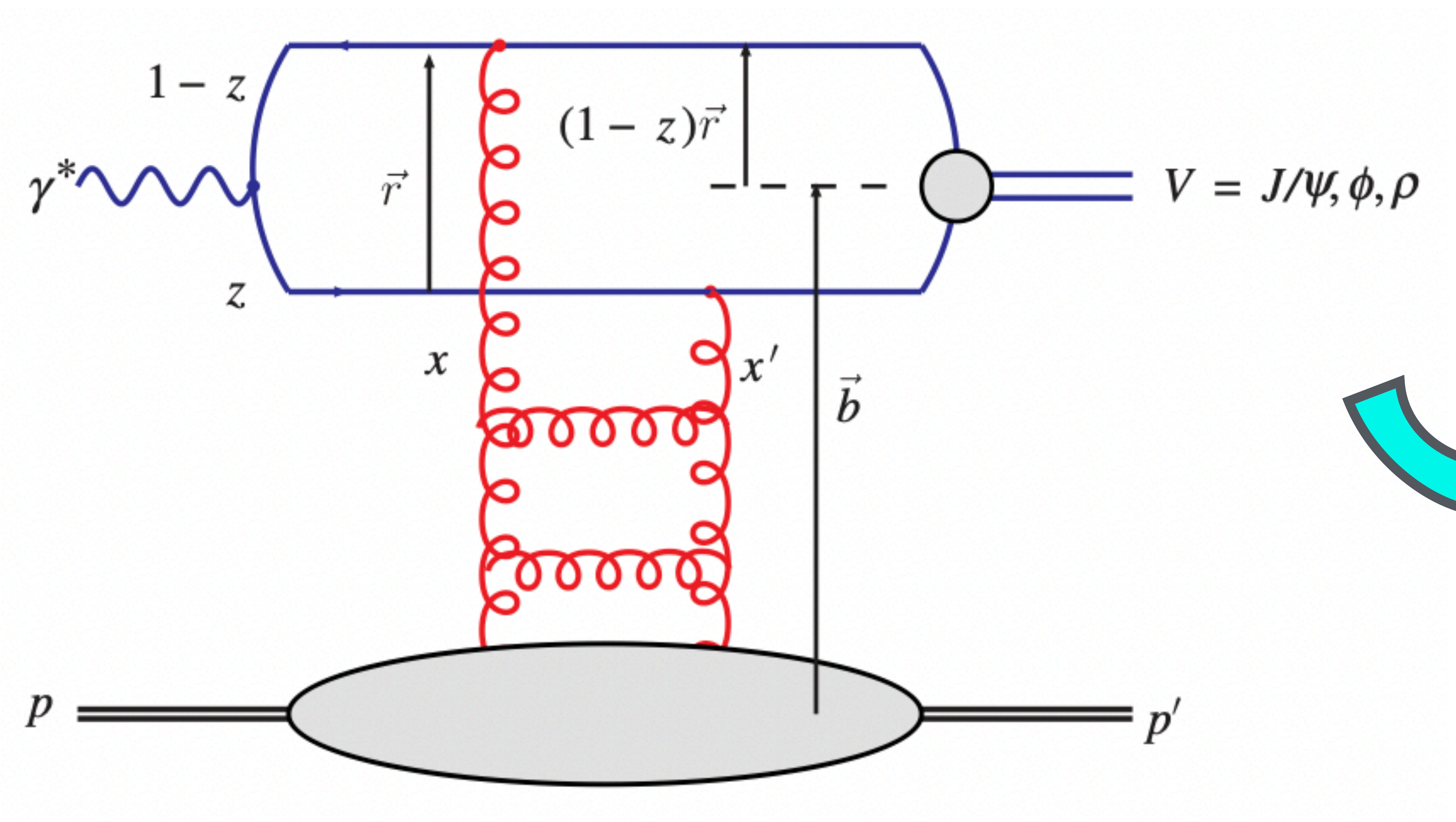
$\vec{\Delta}^2 = -t$

Forward wave functions

1

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



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Includes the effect of non-forward wave fundtions

Conjugate variable

$\vec{\Delta}^2 = -t$

Forward wave functions

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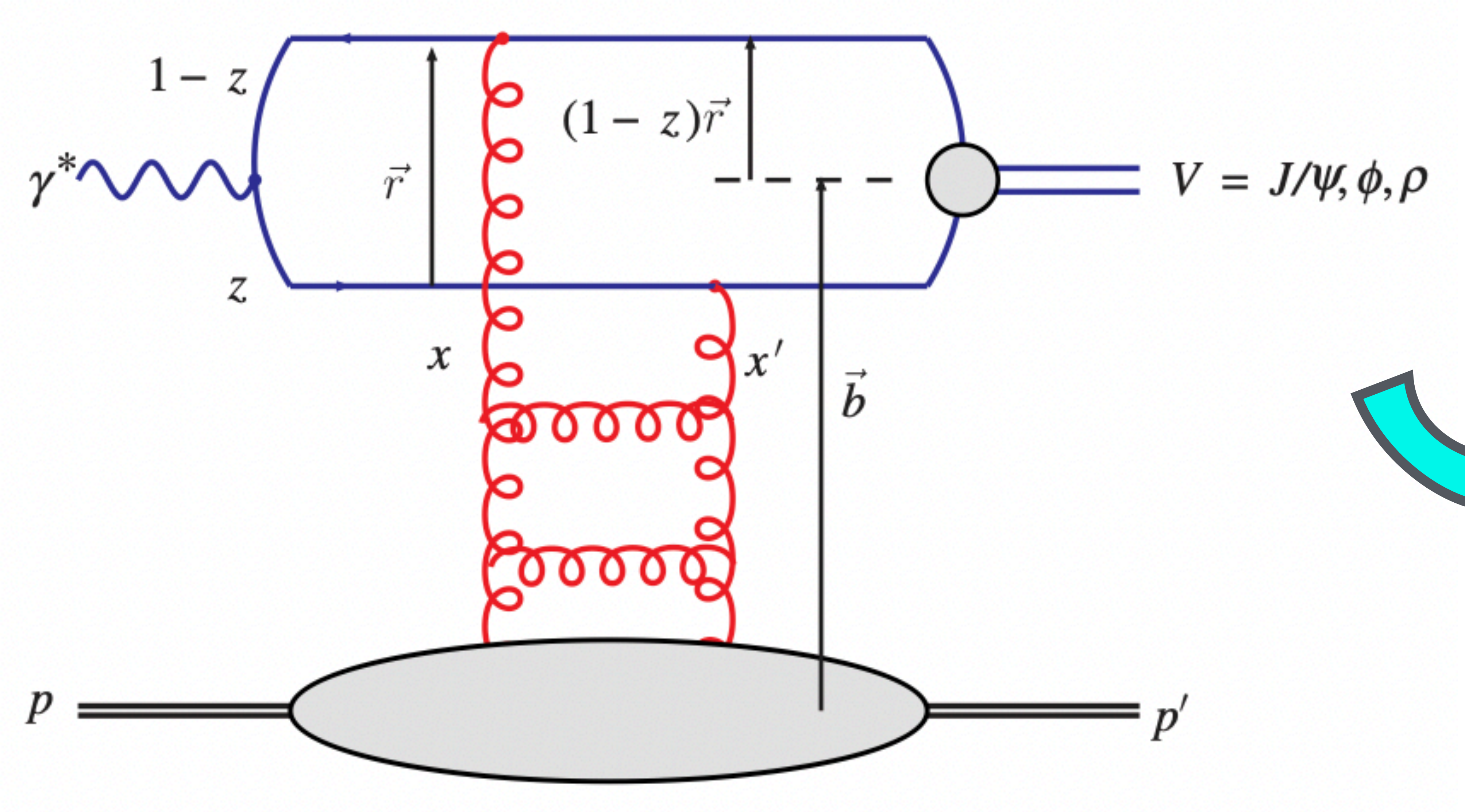
Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



Slightly different form use nowadays

$$(1-z) \rightarrow (\frac{1}{2} - z)$$

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Conjugate variable

Forward wave functions

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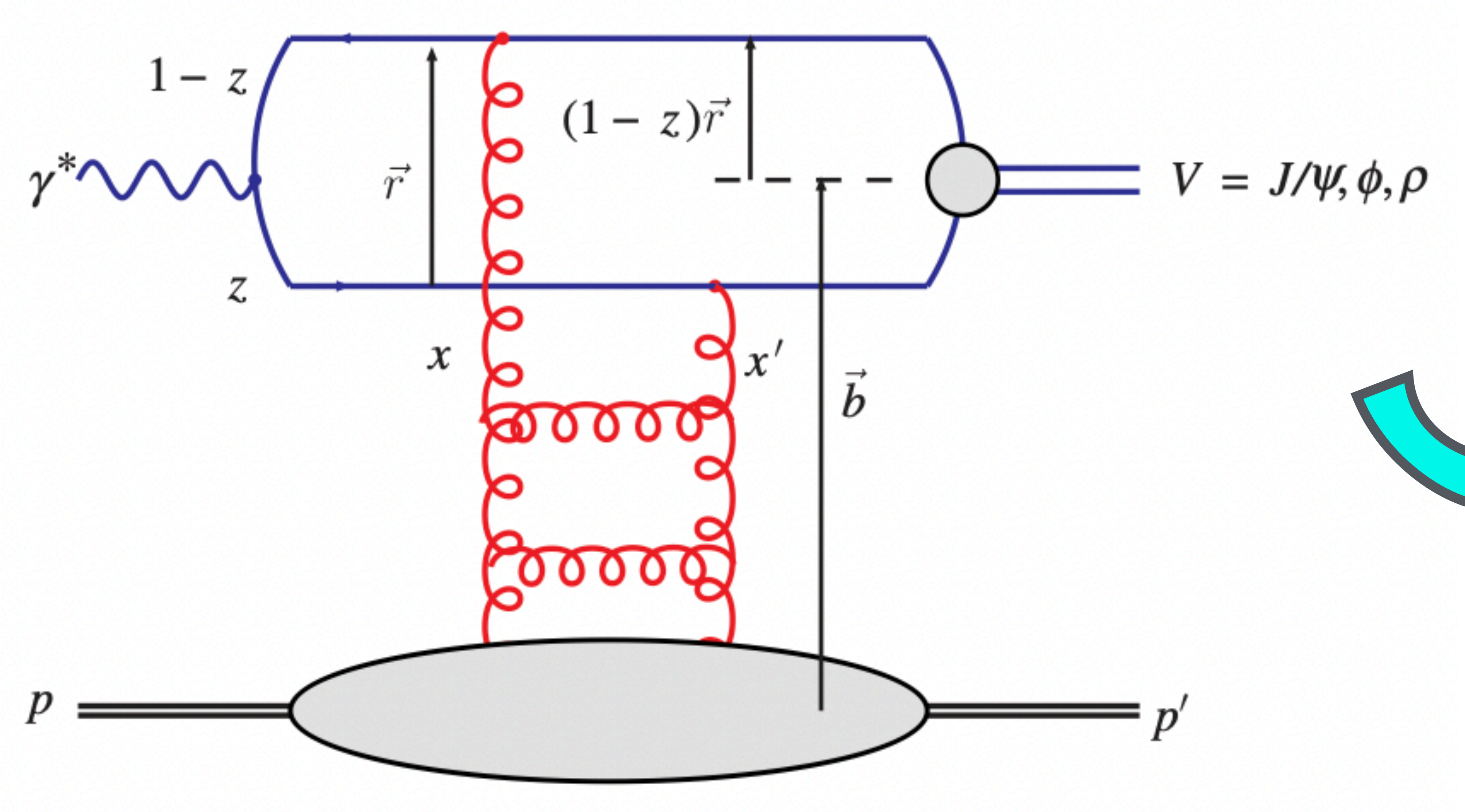
Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



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Slightly different form use nowadays $(1-z)\to(\frac{1}{2}-z)$

Includes the effect of non-forward wave fundtions

Conjugate variable

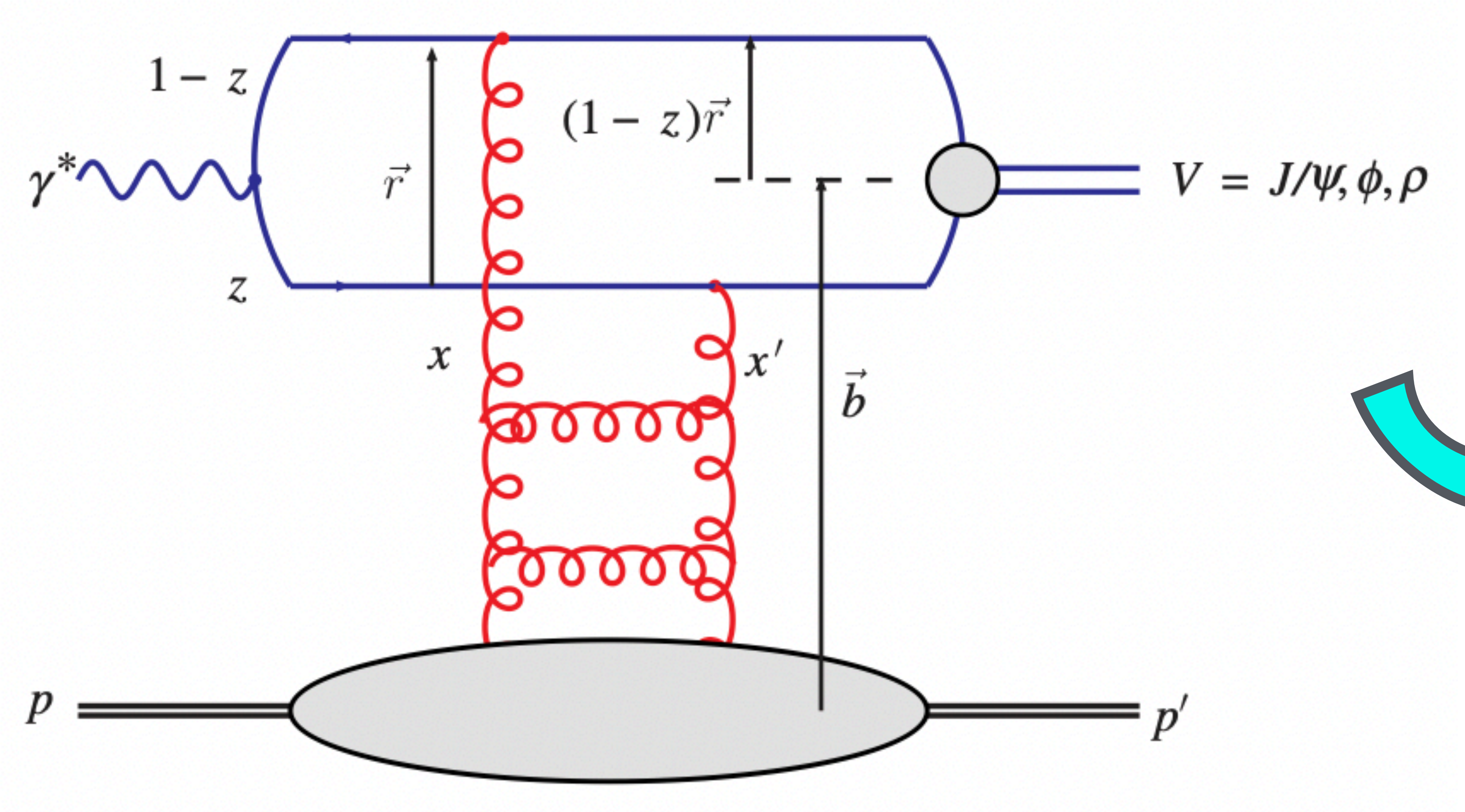
$\vec{\Delta}^2 = -t$

1 Forward wave functions

2 Dipole-target cross section assumes a real matrix element

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

Formalism



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Includes the effect of non-forward wave fundtions

Conjugate variable

$$\vec{\Delta}^2 = -t$$

1 Forward wave functions

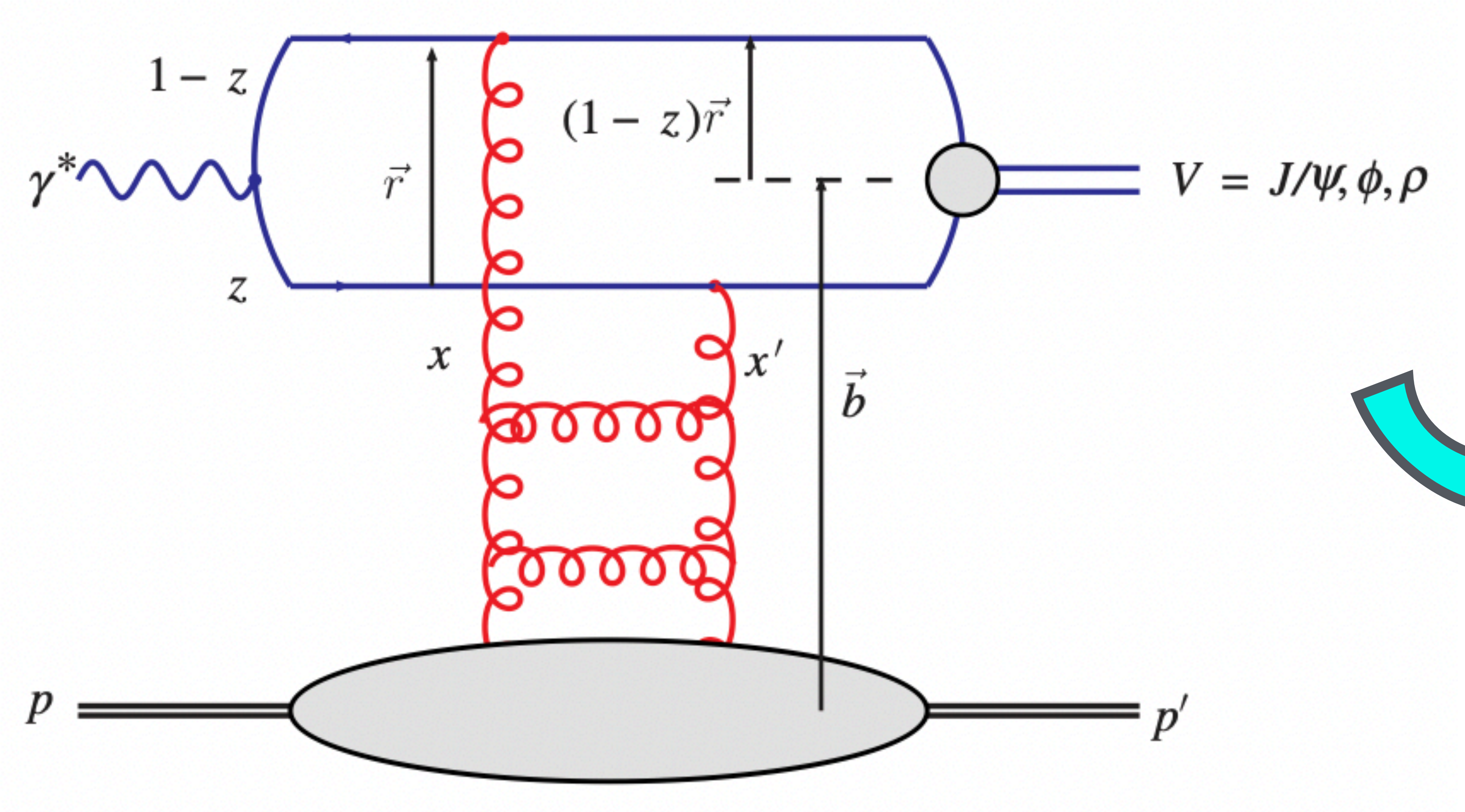
2 Dipole-target cross section assumes a real matrix element

Normally a correction is used to account for the fact that the matrix element may not be fully real

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (1/5)

Formalism



The fact that x and x' are not the same is taken into account with the so-called skewedness correction

Slightly different form use nowadays

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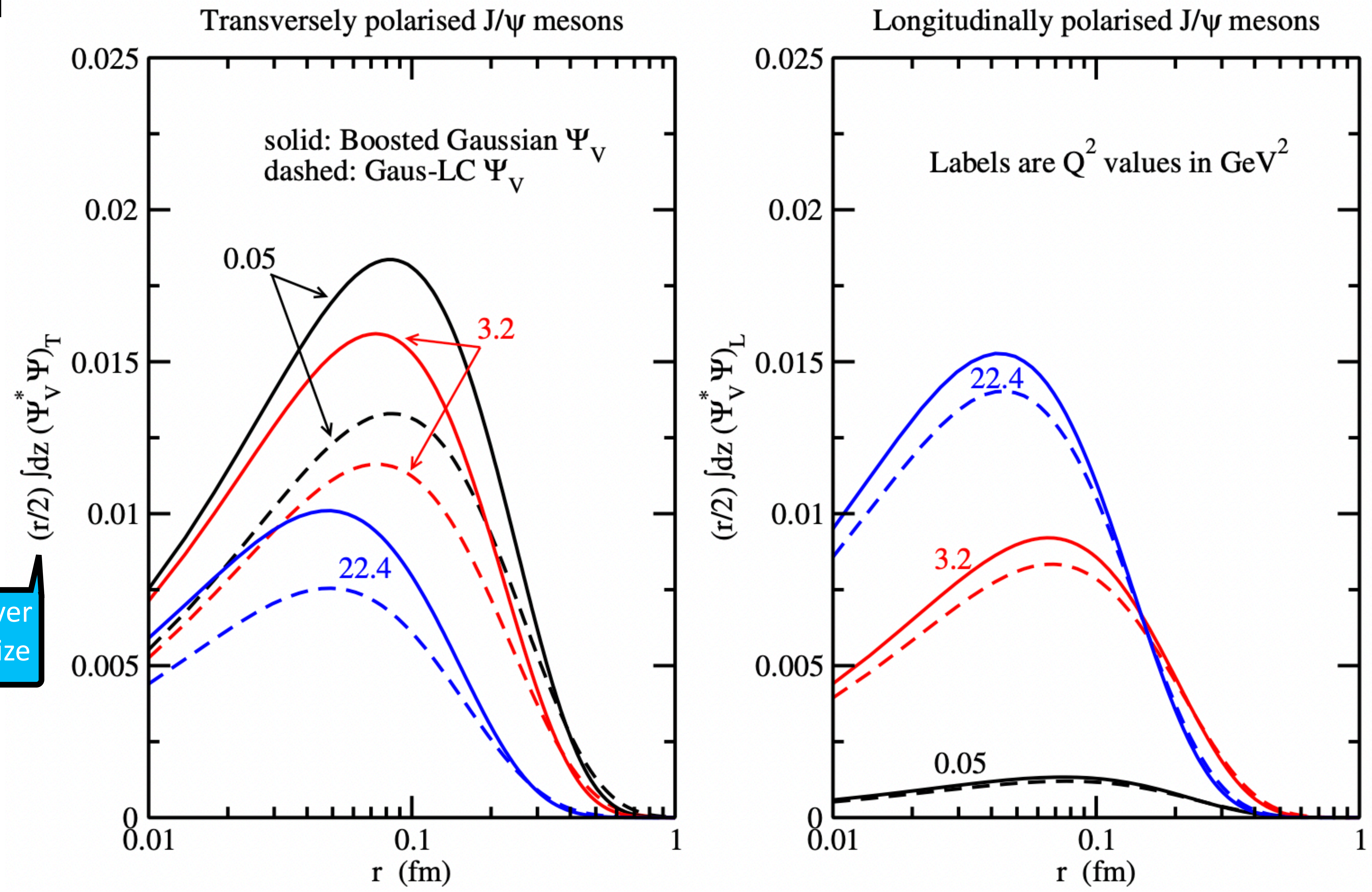
2006: Diffractive vector meson production in the dipole approach (2/5)

1 Forward wave functions



Forward wave functions, integrated over energy fraction and scaled by dipole size

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (2/5)

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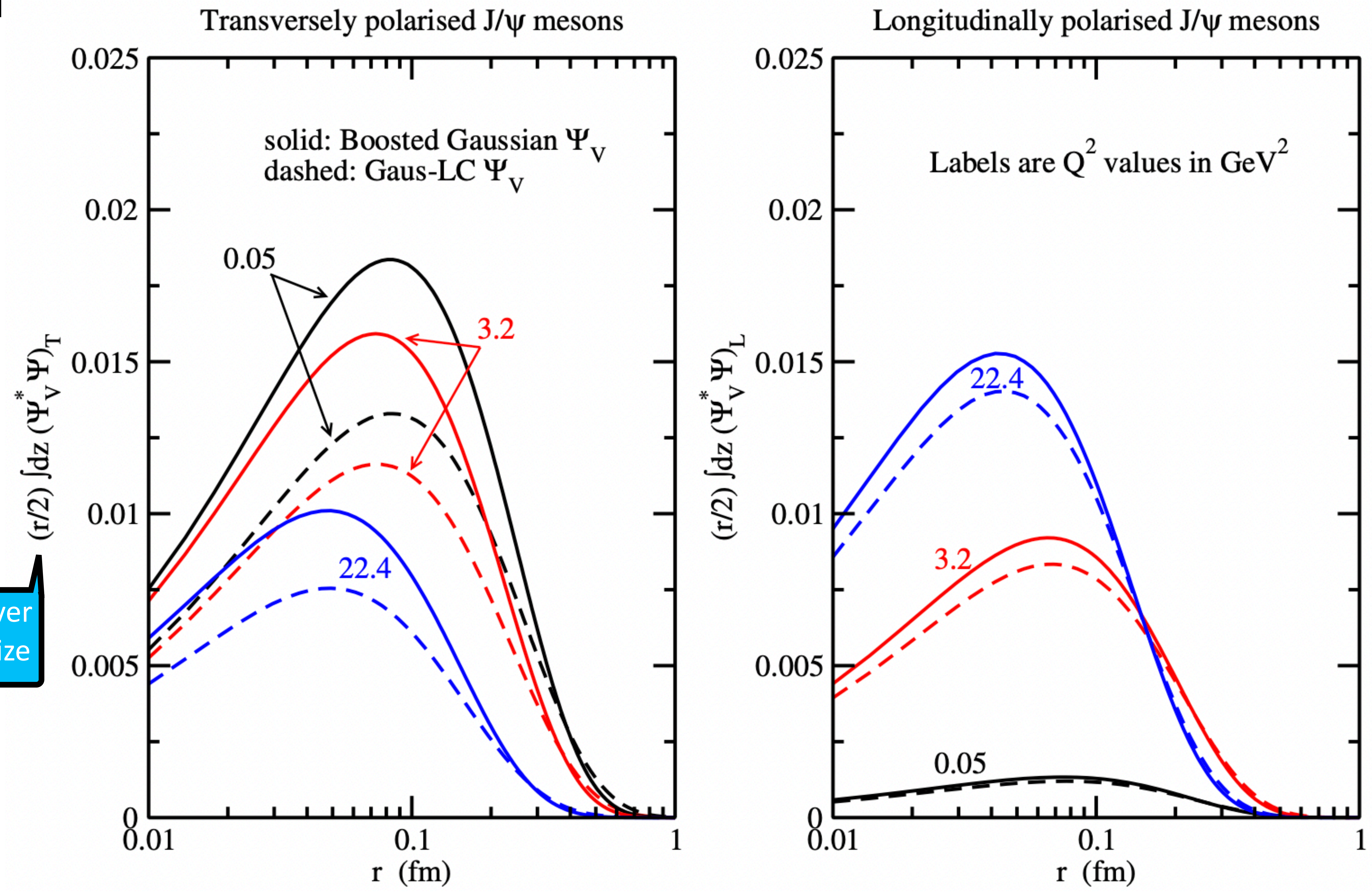

Forward wave functions, integrated over energy fraction and scaled by dipole size

$$\int d\vec{r} \rightarrow \int r dr d\phi$$

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (2/5)

1 Forward wave functions

The QED part is computable, but the vector meson part has to be modelled

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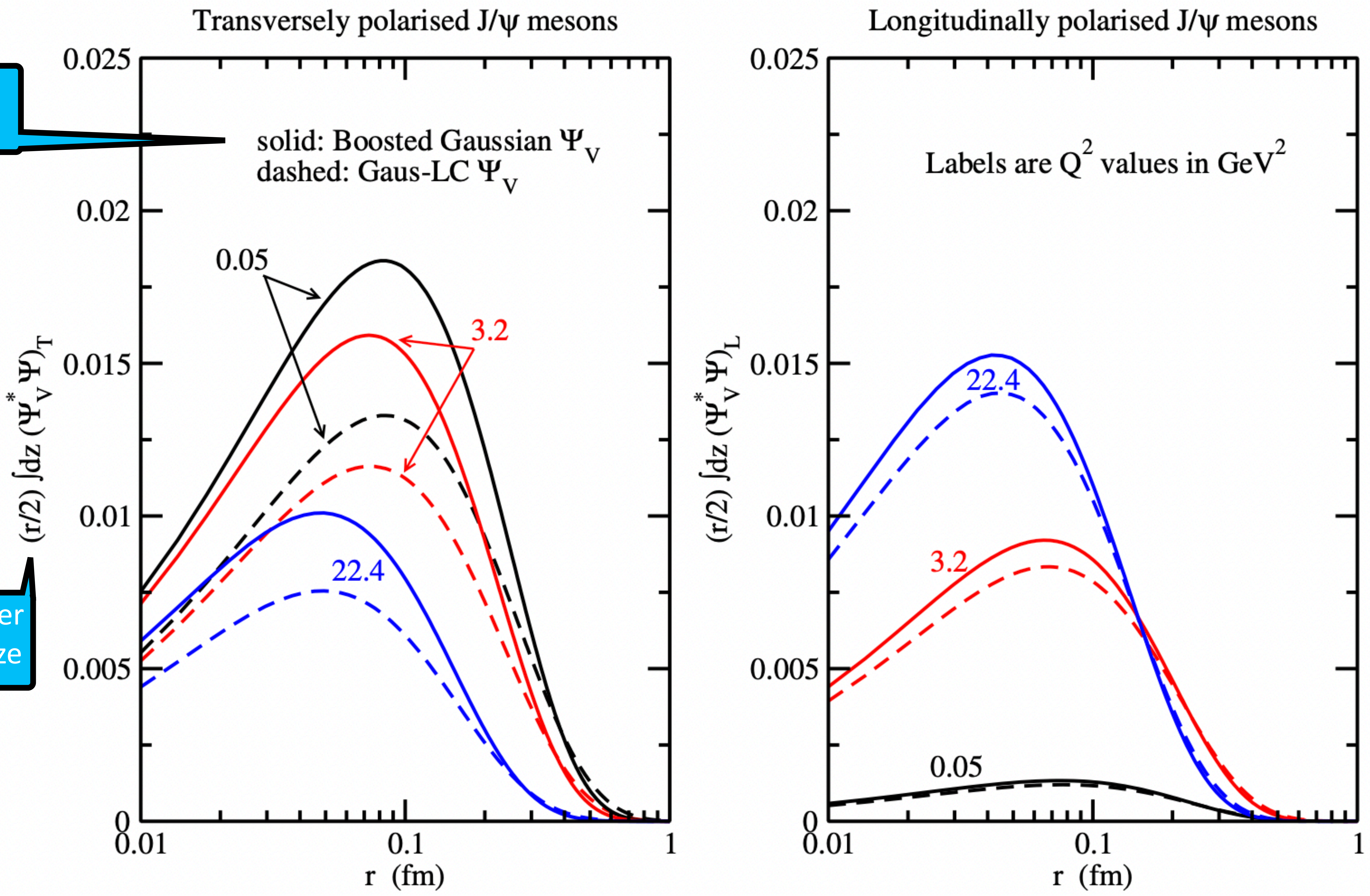

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2006: Diffractive vector meson production in the dipole approach (2/5)

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Modelling may have a strong influence in the normalisation.

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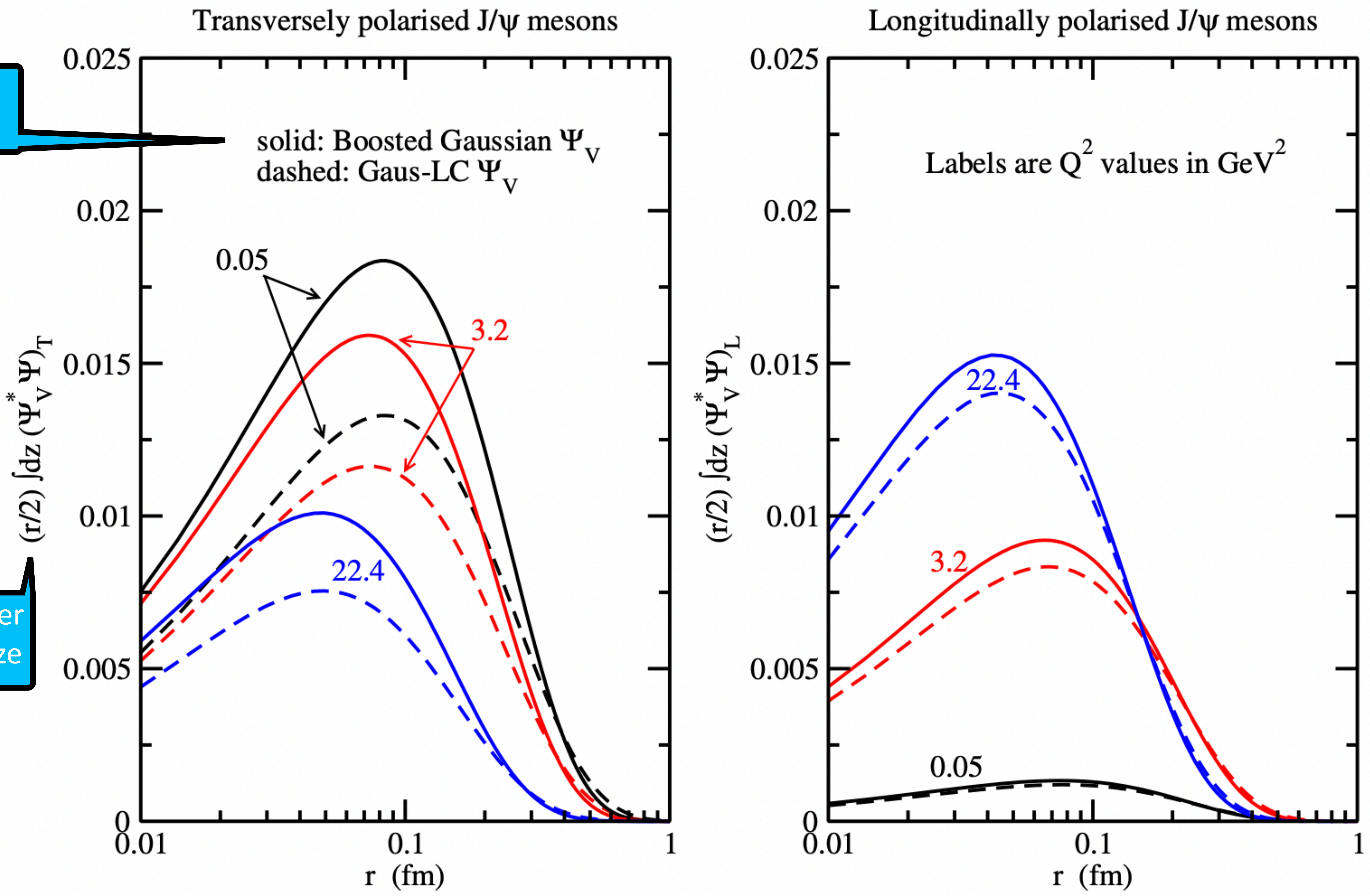

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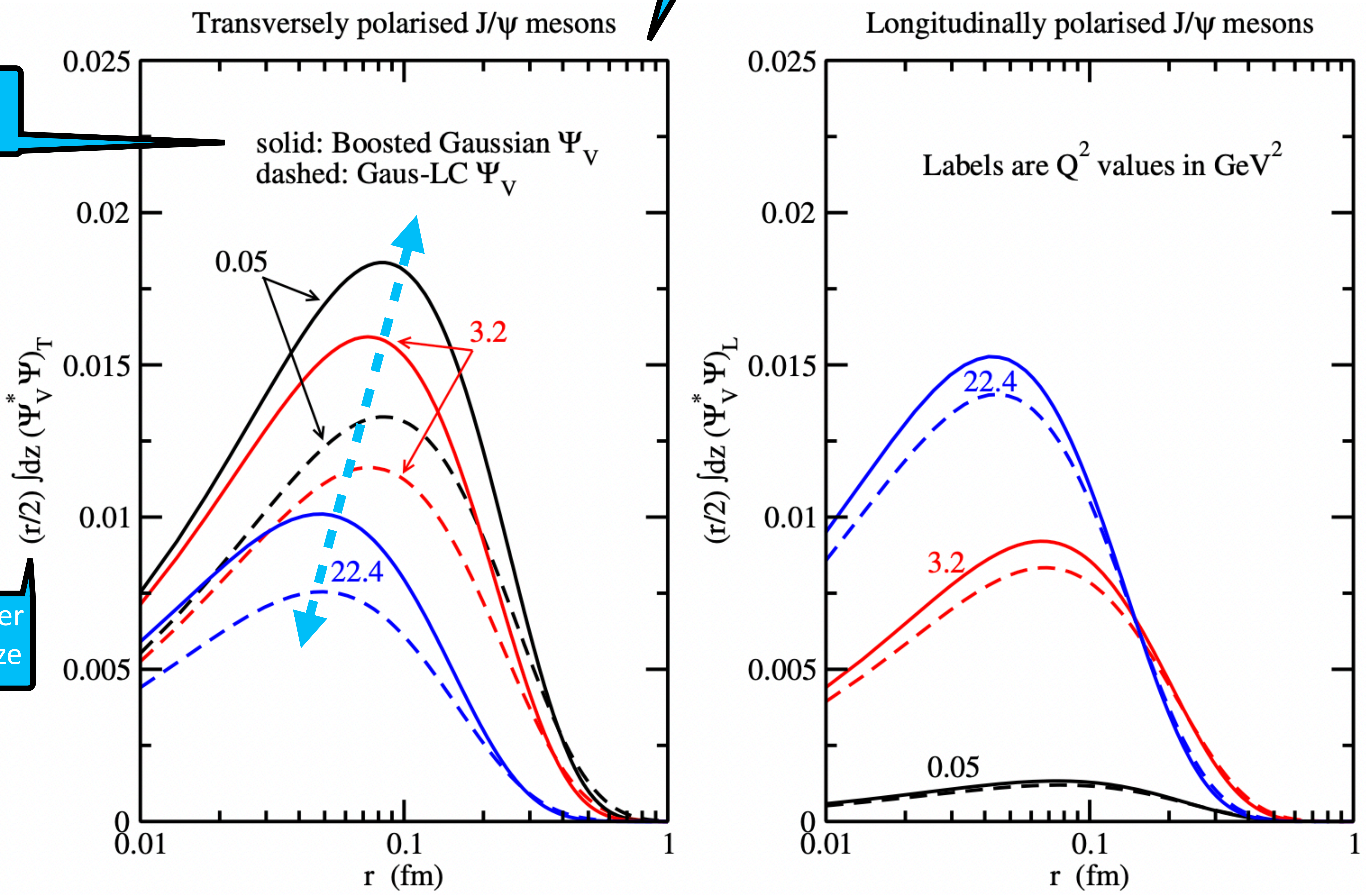
Position of the peak moves with virtuality selecting specific dipole sizes



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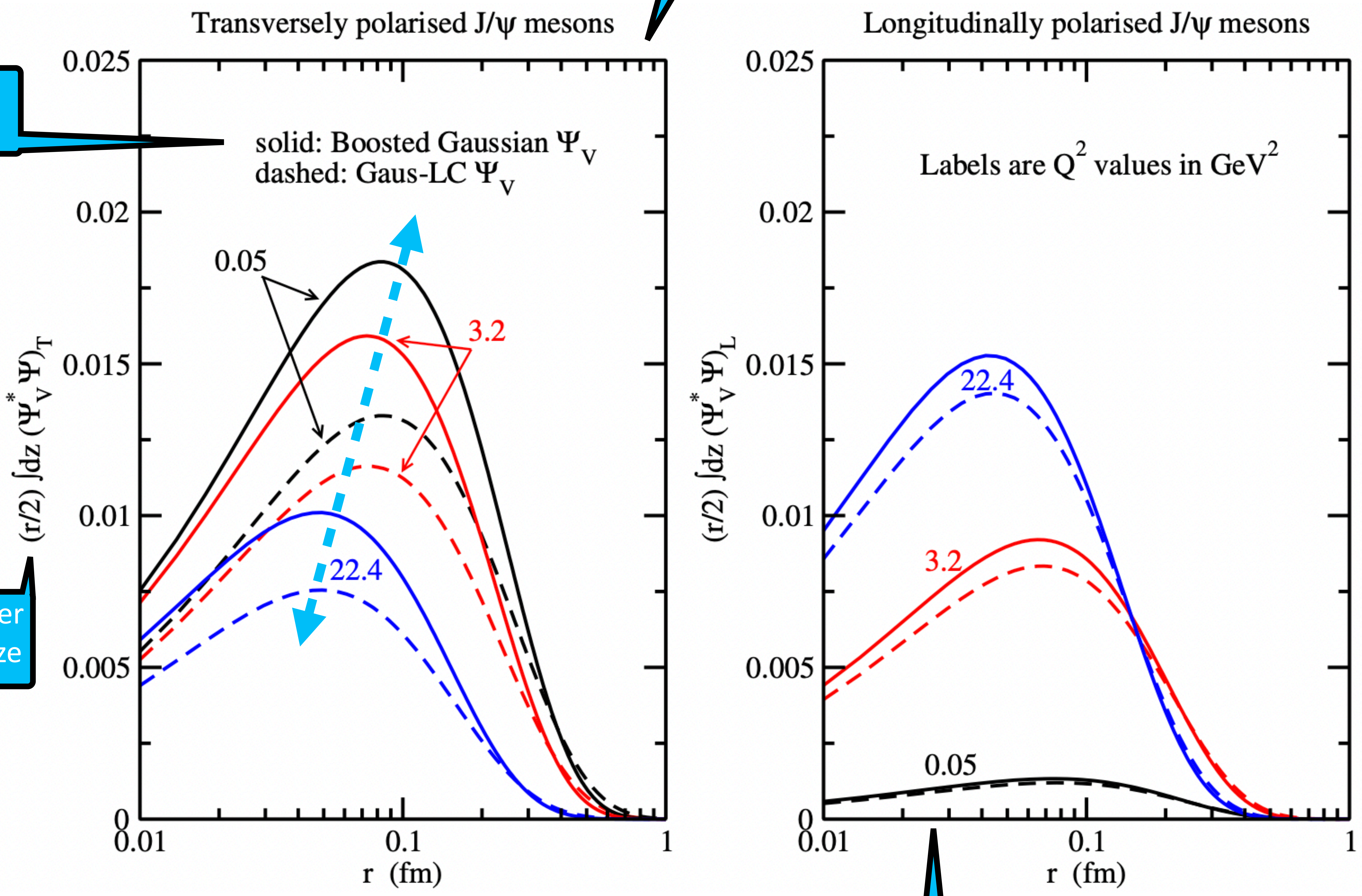

In (quasi-) photoproduction, almost no longitudinal

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (2/5)

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Modelling may have a strong influence in the normalisation.

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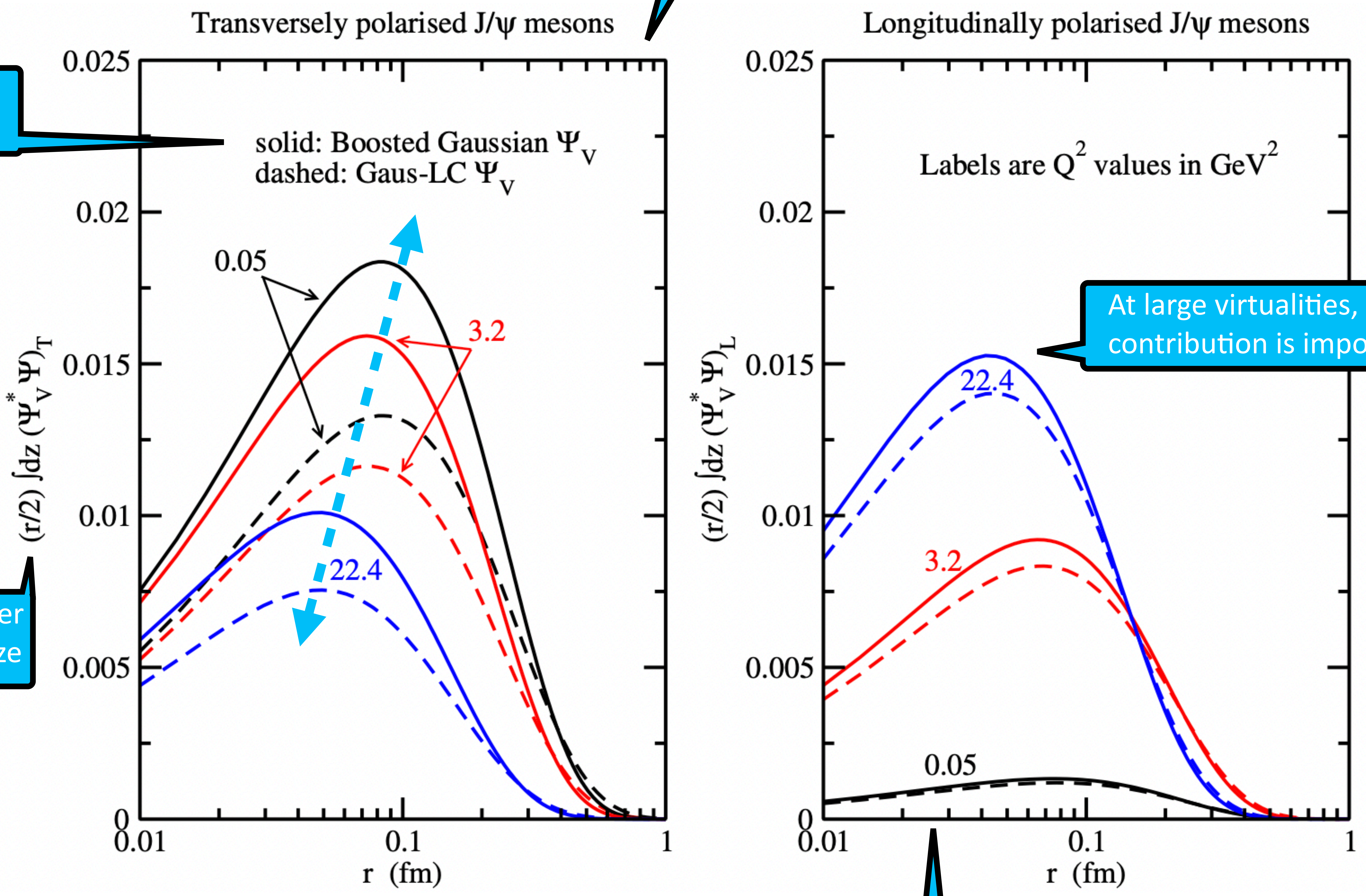

At large virtualities, the longitudinal contribution is important

In (quasi-) photoproduction, almost no longitudinal

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (3/5)

2 Dipole cross sections

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (3/5)

2 Dipole cross sections

GBW approach

$$\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}} \equiv 2[1 - \mathrm{Re}S(x, r, b)] \equiv 2\mathcal{N}(x, r, b)$$
$$= 2\mathcal{N}(x, r)\Theta(b_S - b),$$

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (3/5)

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$$= 2\mathcal{N}(x, r)\Theta(b_S - b),$$

Profile in impact parameter

$$\sigma_{q\bar{q}}(x, r) = \sigma_0 \mathcal{N}(x, r),$$

$$\sigma_0 \equiv 2\pi b_S^2$$

Related to the average square radius of the target in impact parameter

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (3/5)

2 Dipole cross sections

b-Sat approach

$$\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b)\right)\right].$$

GBW approach

$$\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}} \equiv 2[1 - \mathrm{Re}S(x, r, b)] \equiv 2\mathcal{N}(x, r, b)$$

$$= 2\mathcal{N}(x, r)\Theta(b_S - b),$$

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$$= 2 \times \begin{cases} \mathcal{N}_0\left(\frac{rQ_s}{2}\right)^{2(\gamma_s + (1/\kappa\lambda Y)\ln(2/rQ_s))} & : rQ_s \le 2 \\ 1 - e^{-A\ln^2(BrQ_s)} & : rQ_s > 2 \end{cases},$$

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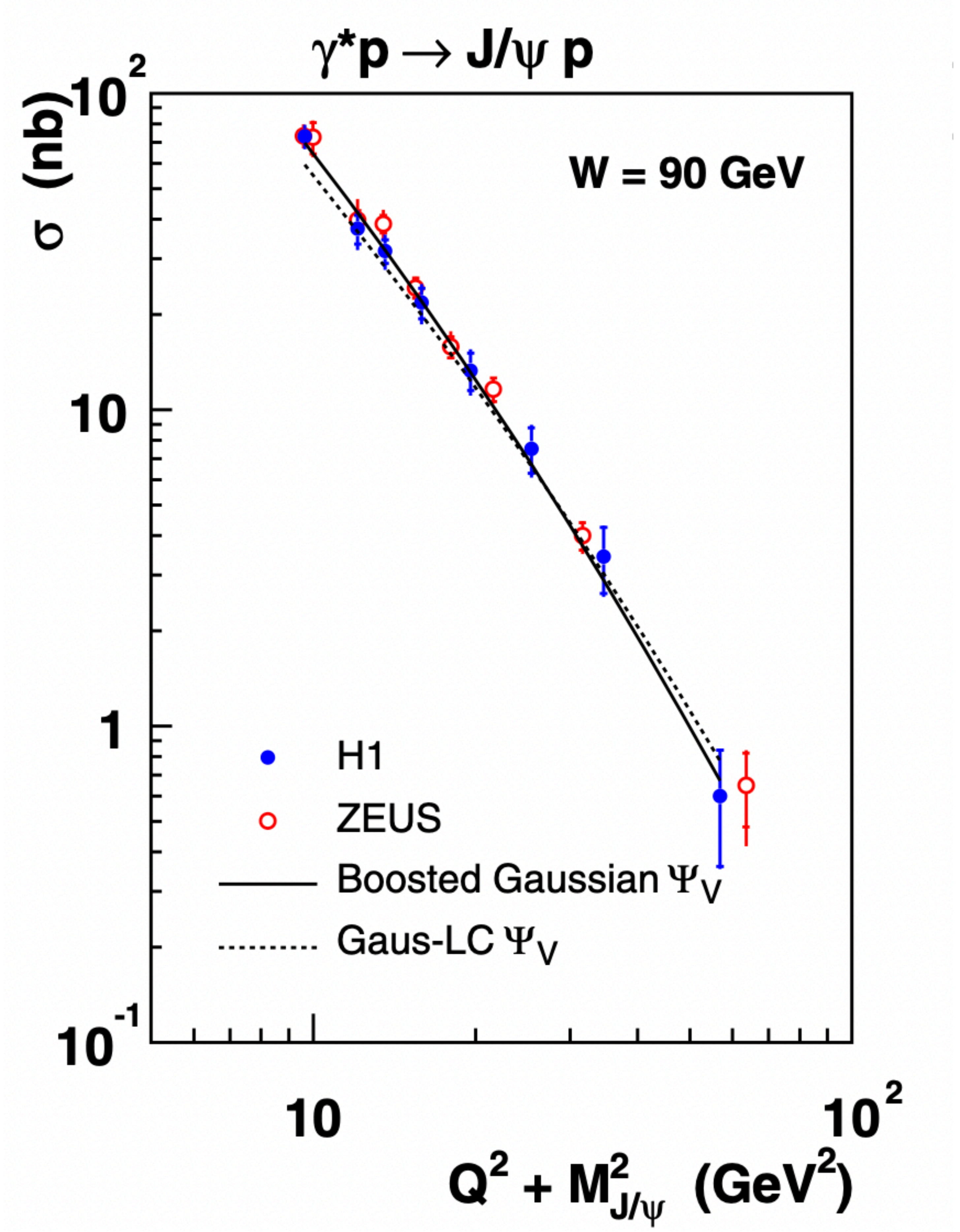
$$Q_s \equiv Q_s(x, b) = \left(\frac{x_0}{x}\right)^{\lambda/2}\left[\exp\left(-\frac{b^2}{2B_{CGC}}\right)\right]^{1/2\gamma_s}.$$

Profile in impact parameter

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (4/5)

Results



Cross section decreases with the scale

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (4/5)

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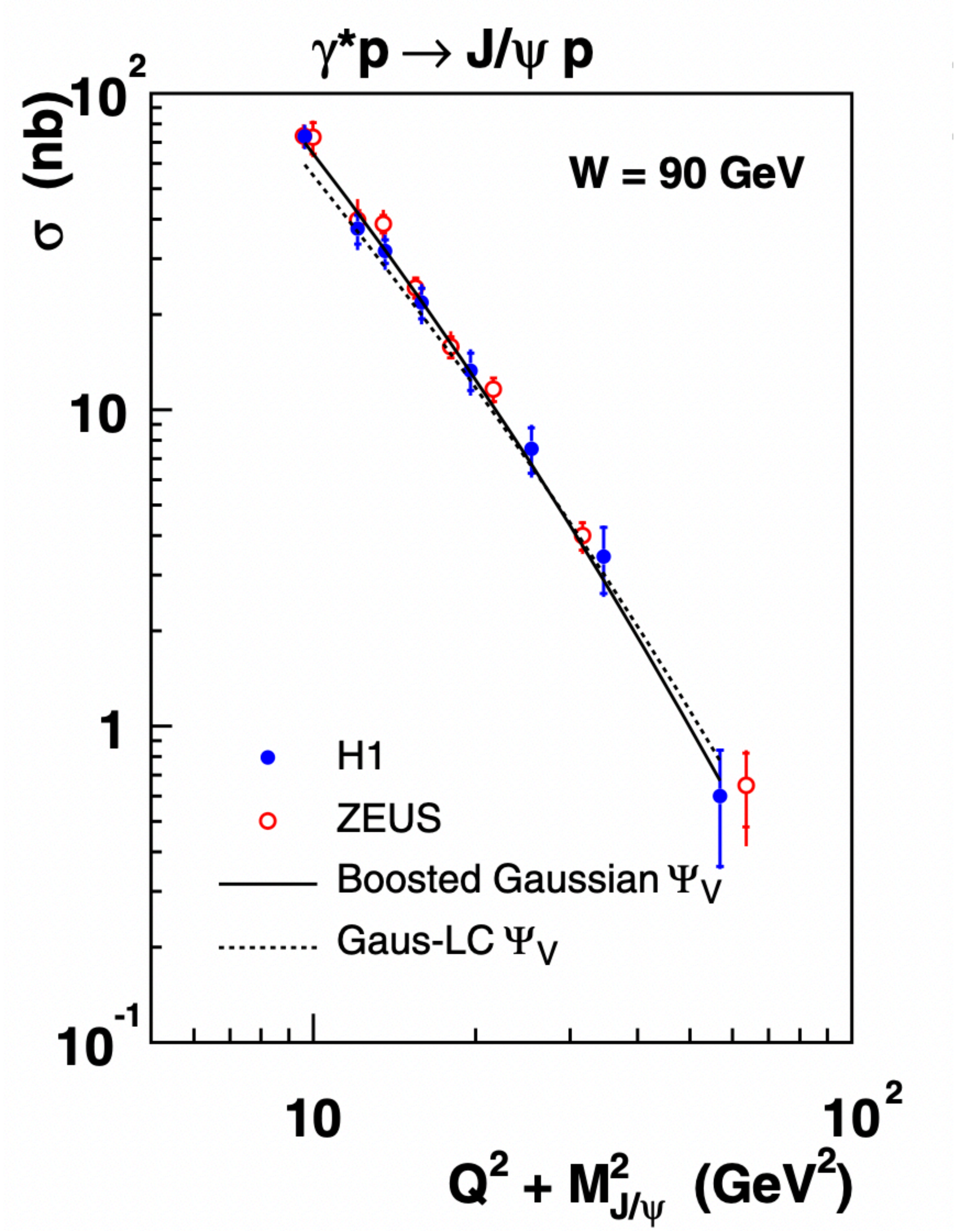

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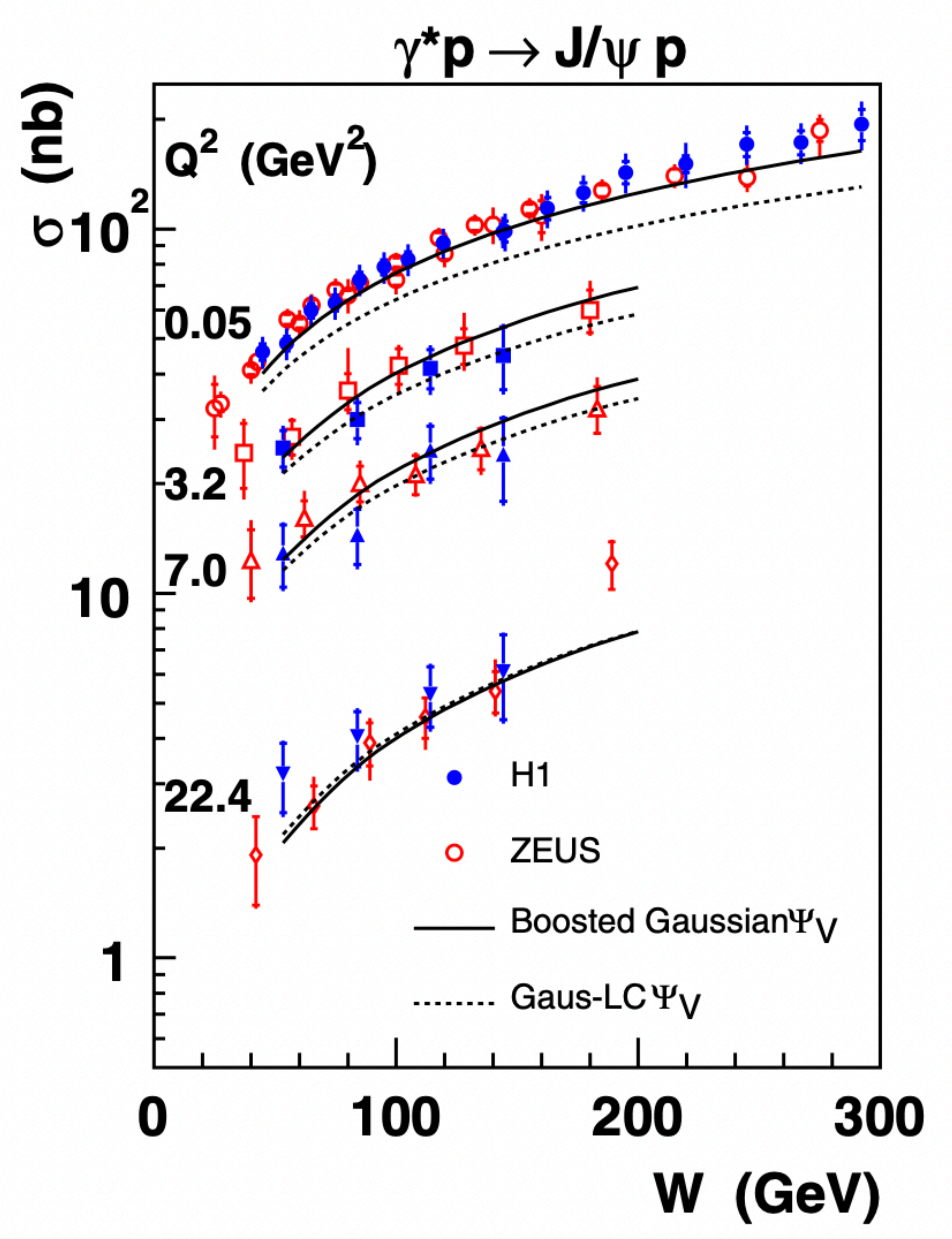

Cross section grows with energy for different virtualities

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

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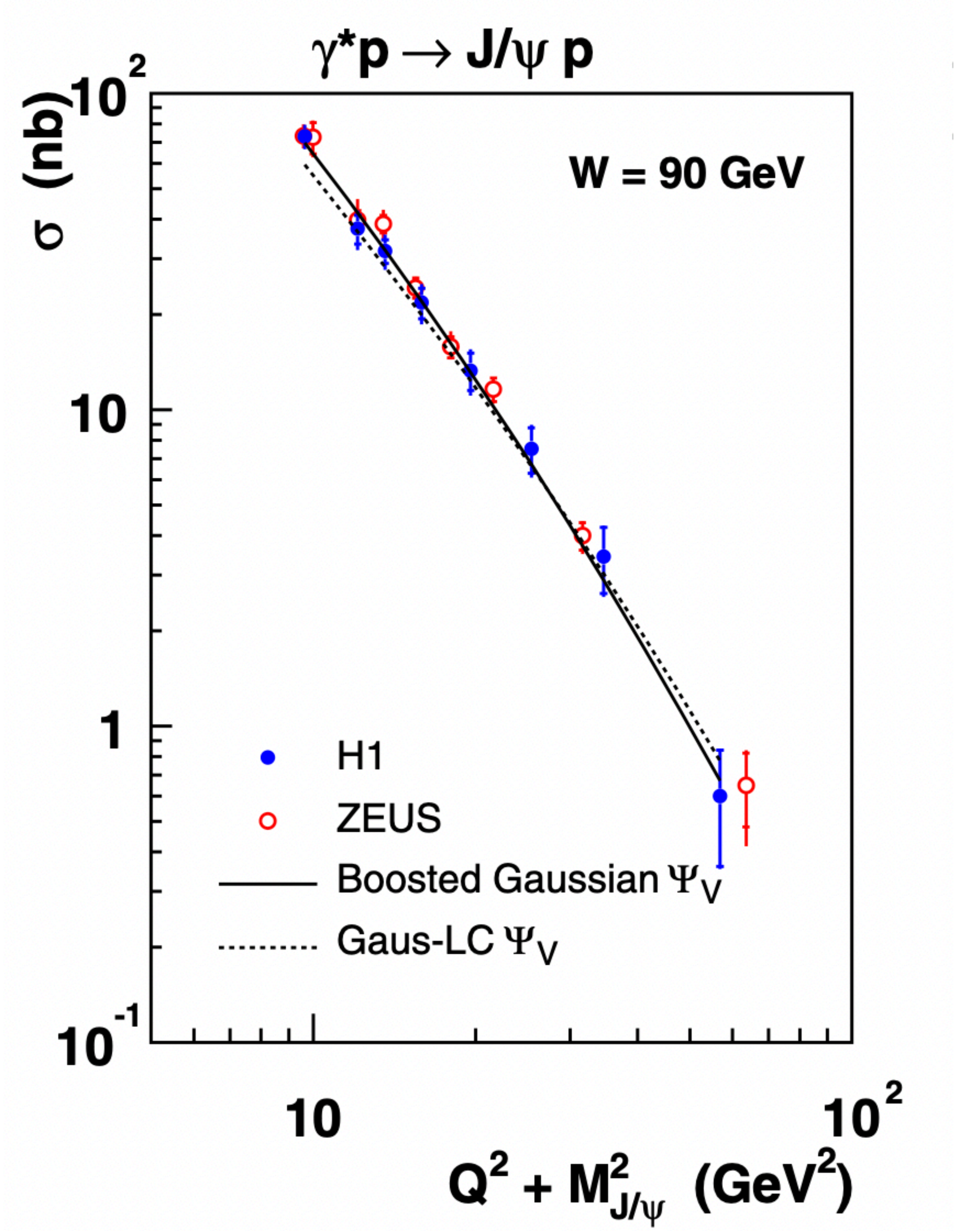

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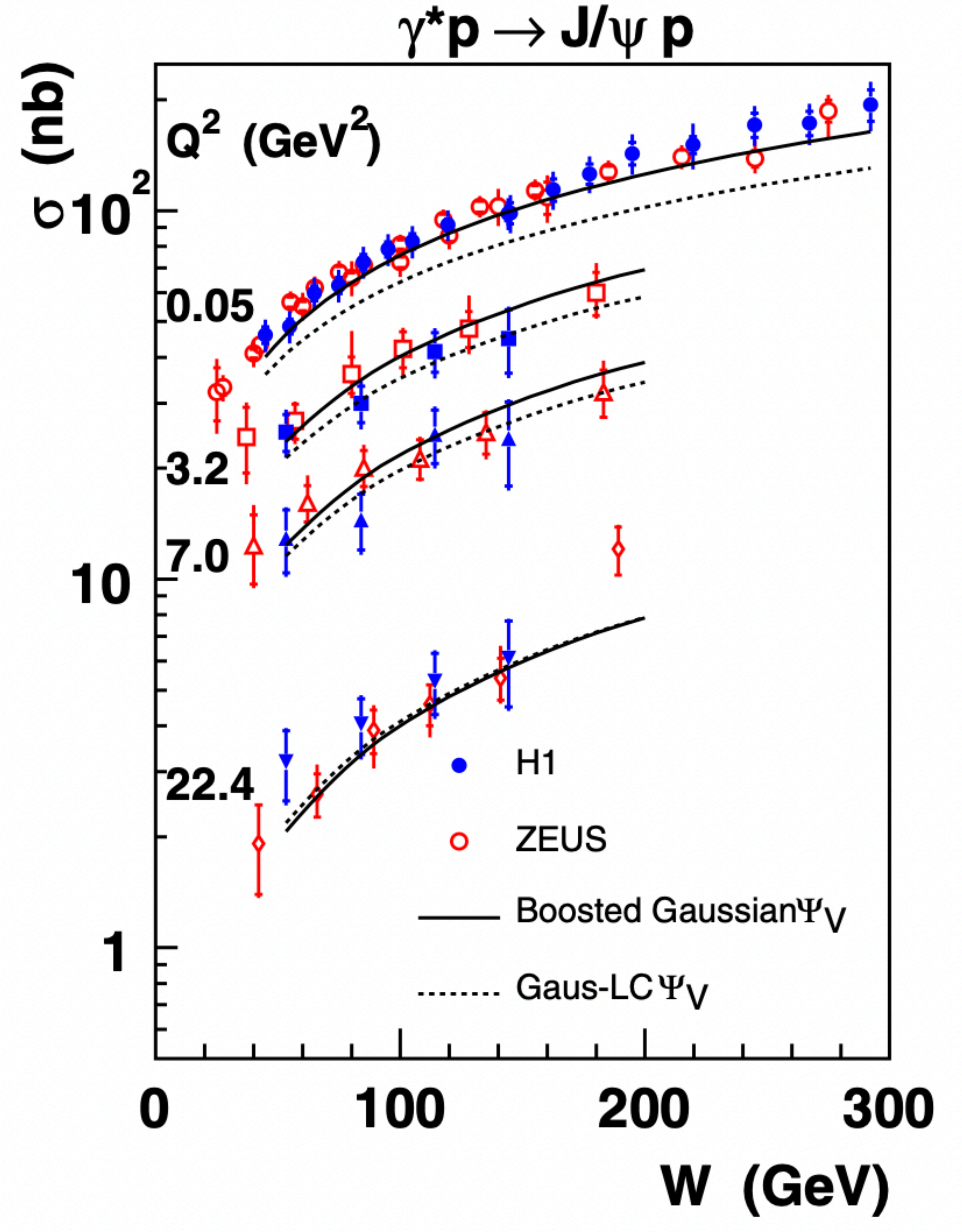

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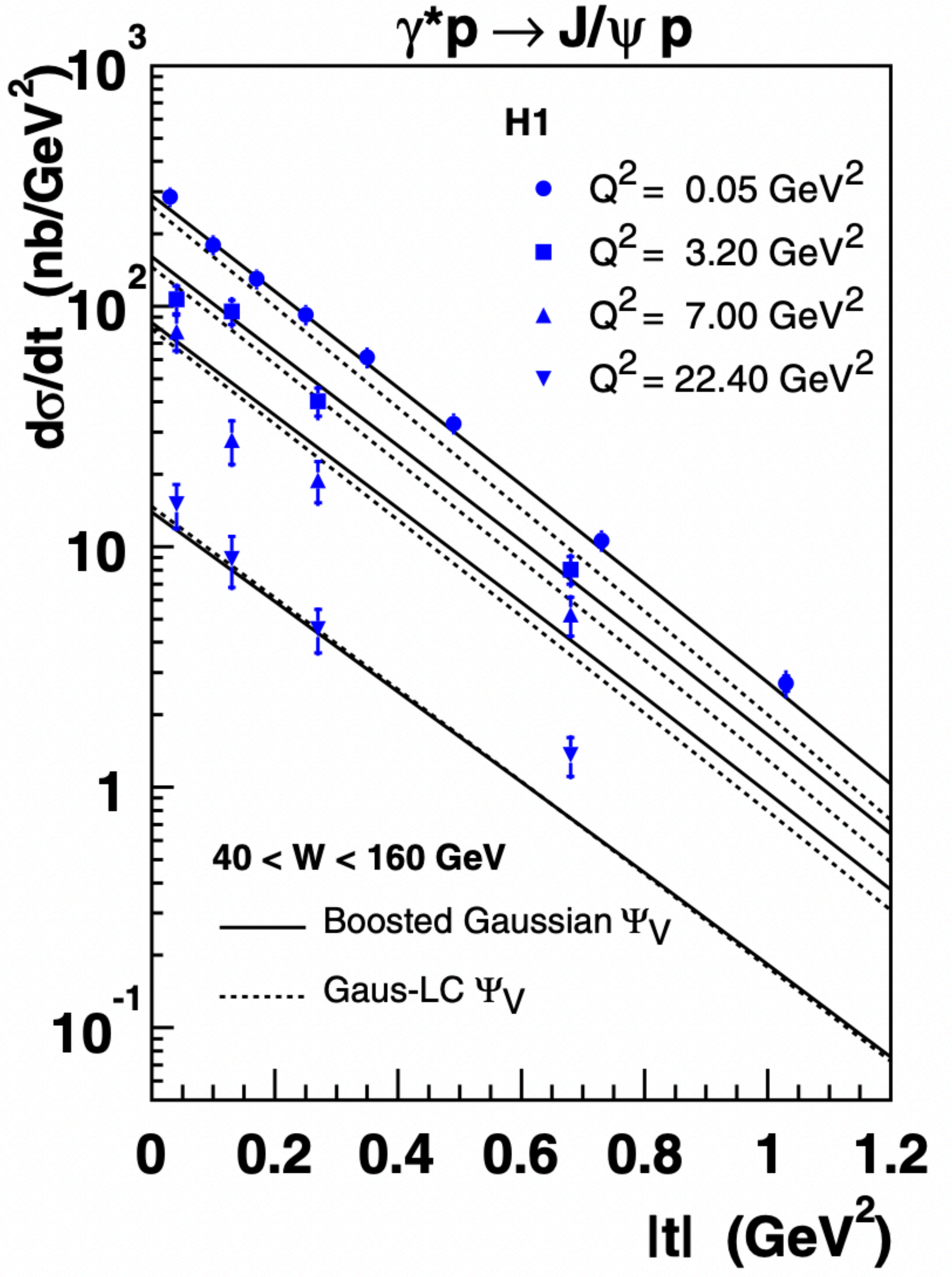
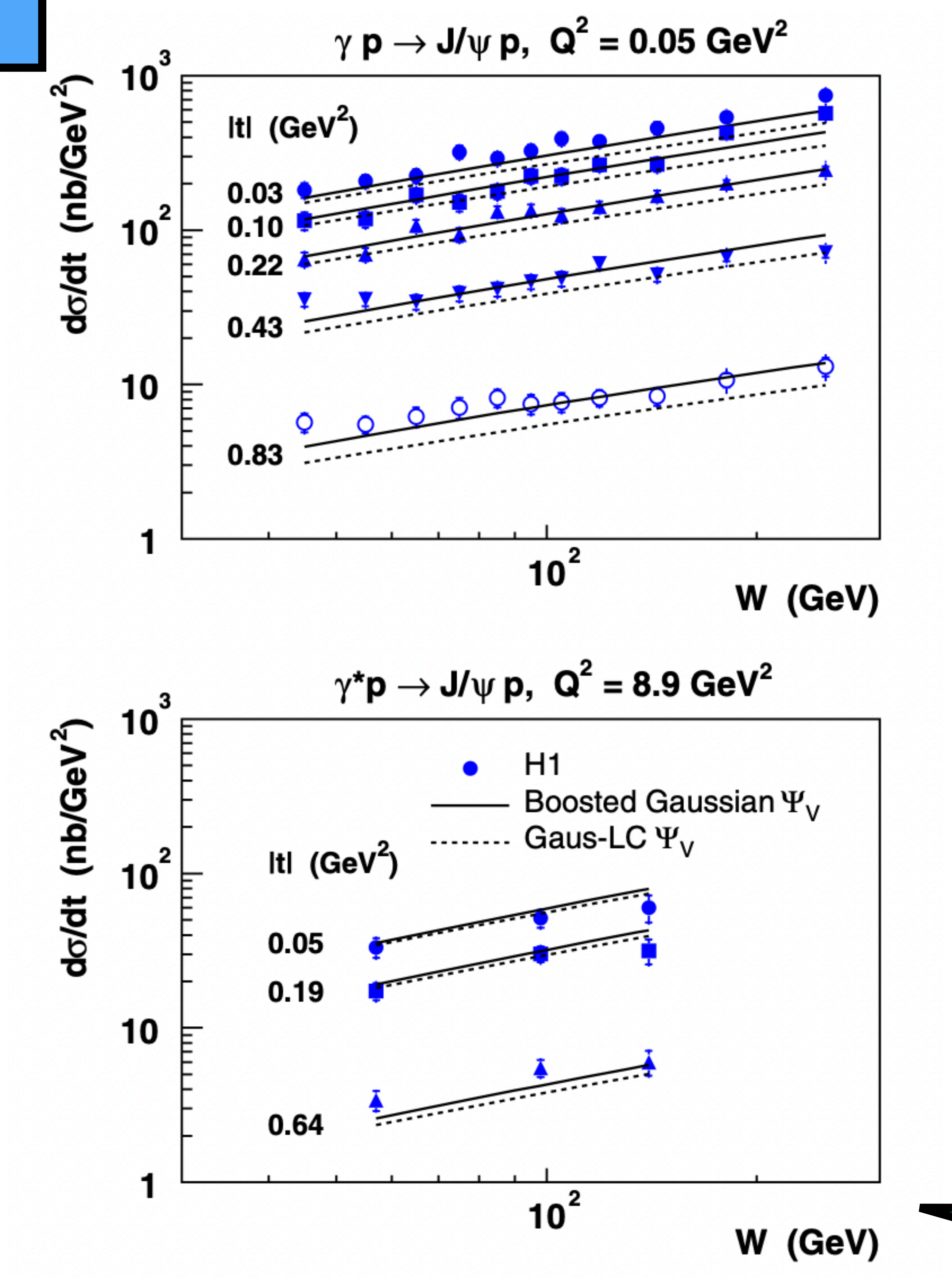


Consistent with Gaussian shape for different virtualities

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (5/5)

Results

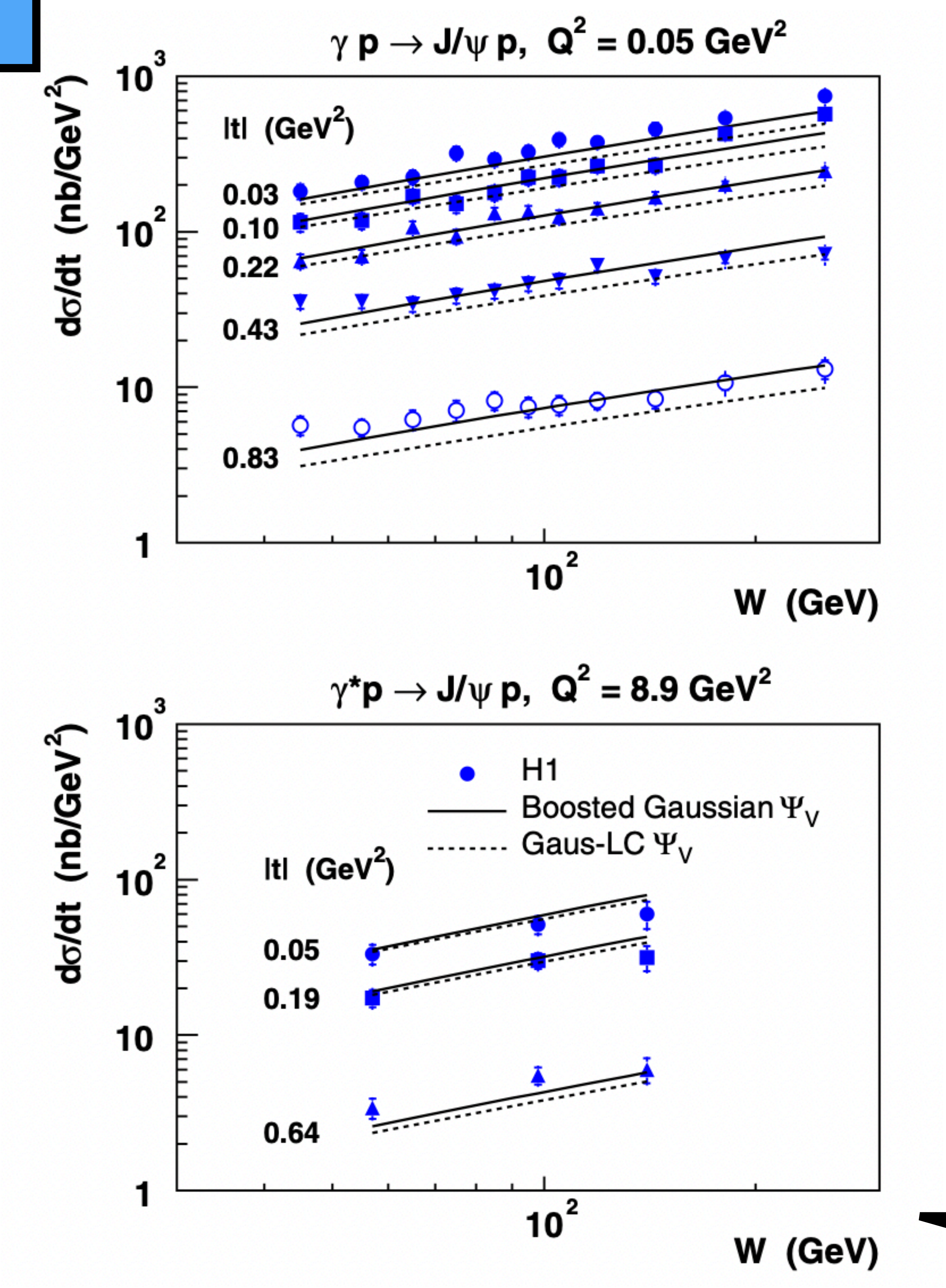


Cross section grows with energy for different momentum transfer

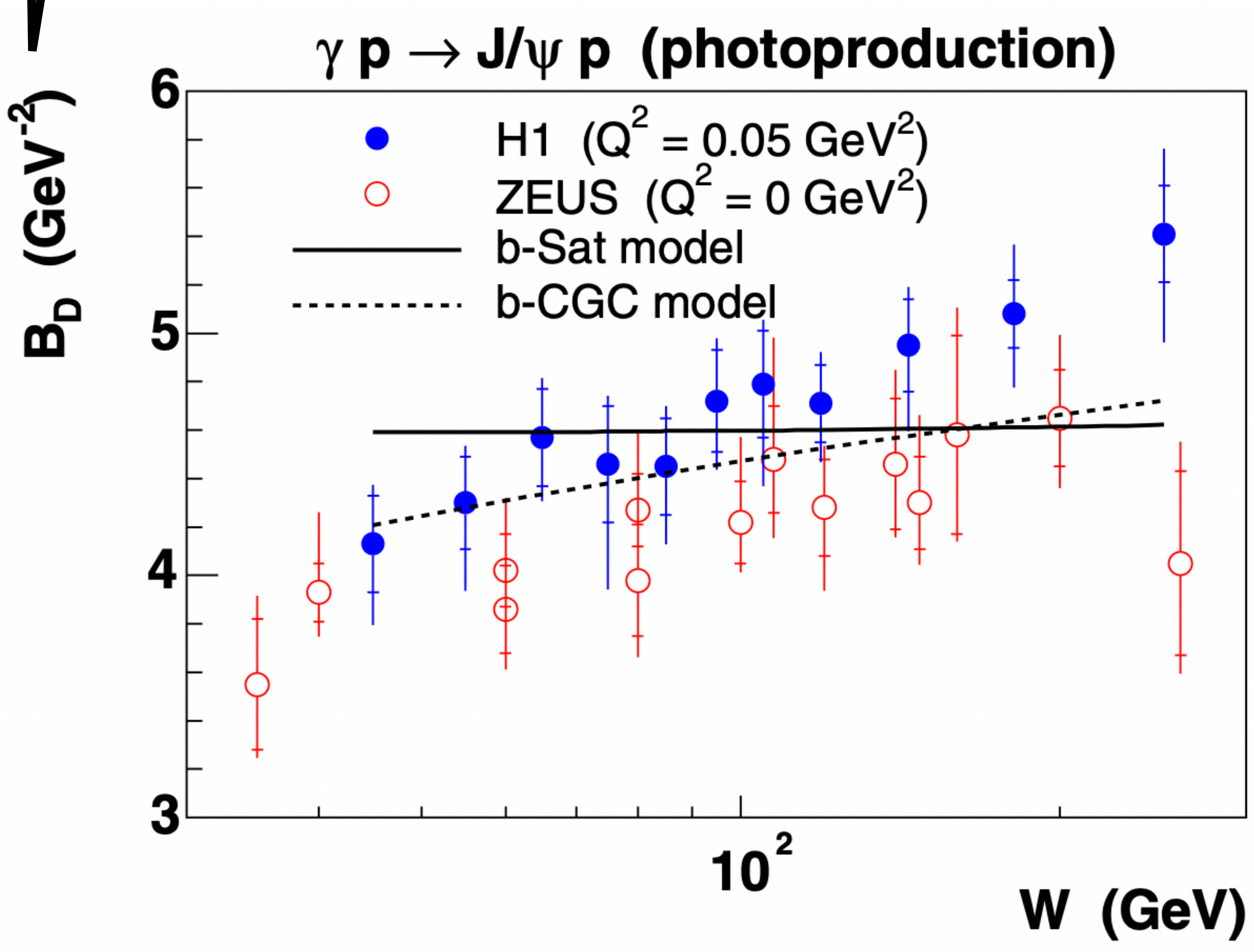
Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Diffractive vector meson production in the dipole approach (5/5)

Results



Gaussian profile grows with energy



Cross section grows with energy for different momentum transfer

Kowalski, Motyka, Watts https://inspirehep.net/literature/720153

2006: Geometric scaling for vector mesons

Reminder: Geometric scaling in DIS

$$\sigma_{\rm tot}^{\gamma^* p\to X}(x,Q^2) = \sigma_{\rm tot}^{\gamma^* p\to X}(\tau), \qquad \tau = Q^2/Q_s^2(x).$$

$$Q_s(x) = Q_0\left(\frac{x}{x_0}\right)^{-\lambda/2}, \qquad Q_0 \equiv 1\ \mathrm{GeV}$$

Marquet, Schoeffel, https://inspirehep.net/literature/718734

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Geometric scaling in diffractive VM production

$$\sigma_{\rm VM}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2) = \sigma_{\rm VM}^{\gamma^* p\to Vp}(\tau_V)$$

$$\tau_V = (Q^2 + M_V^2)/Q_s^2(x_{\mathbb{P}}).$$

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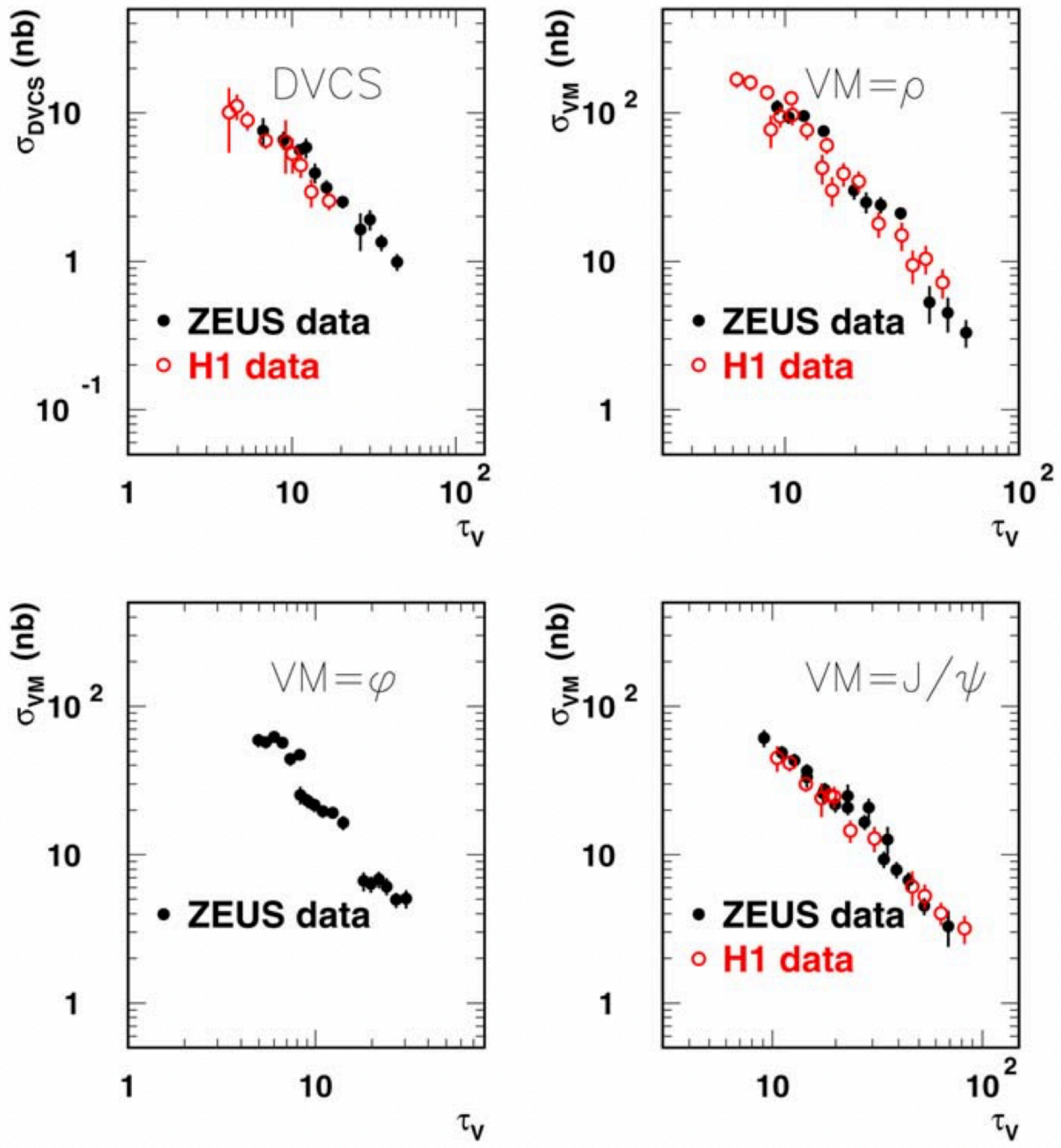

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Exclusive diffractive vector meson production is very sensitive to the gluon content of the proton
This process has been extensively studied at HERA as a function of:
Mass of the vector meson
Virtuality of the photon
CMS energy of the photon-proton system
Mandelstam-t
Polarisation structure (not shown)

What about dissociative production?

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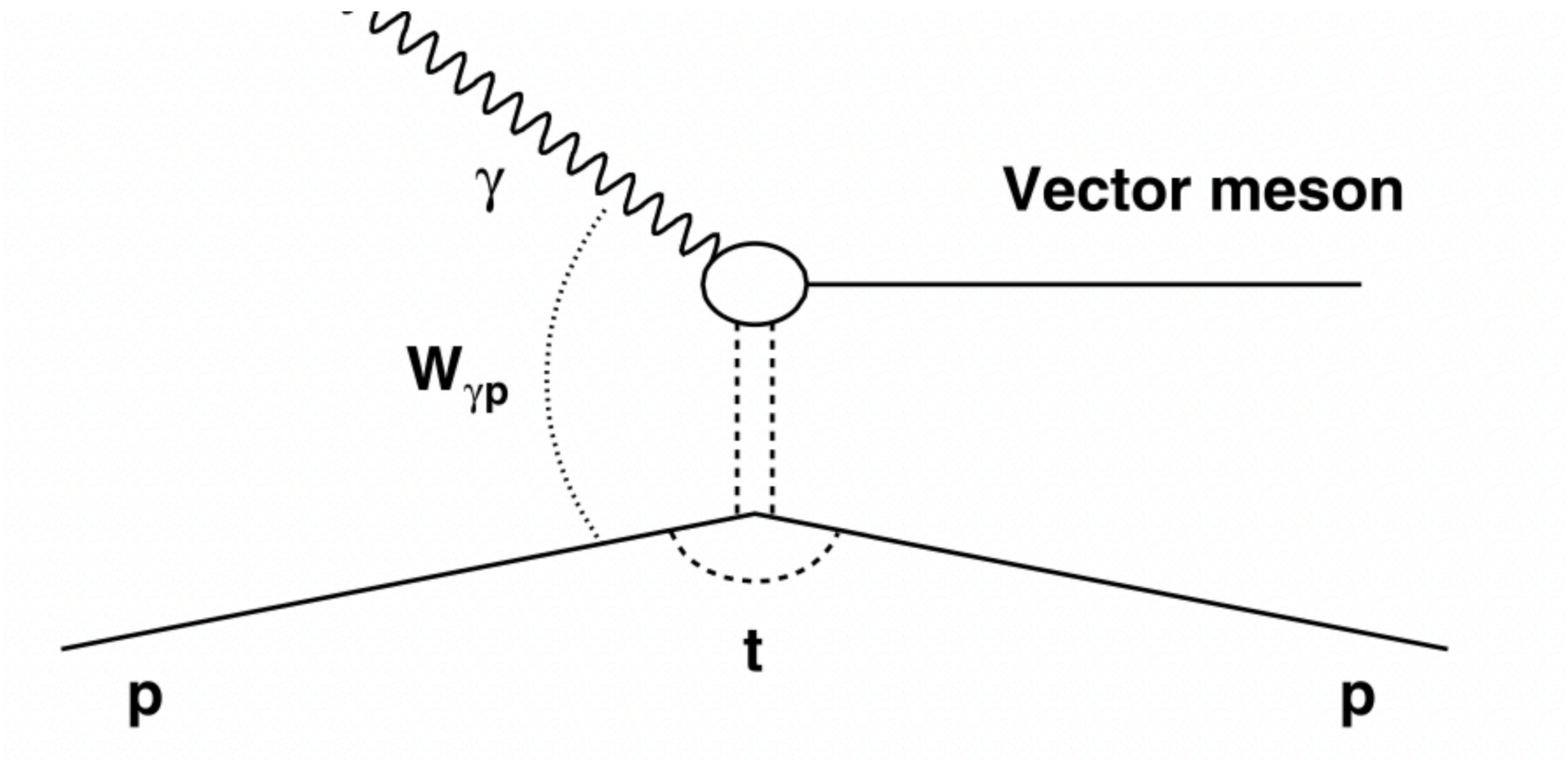
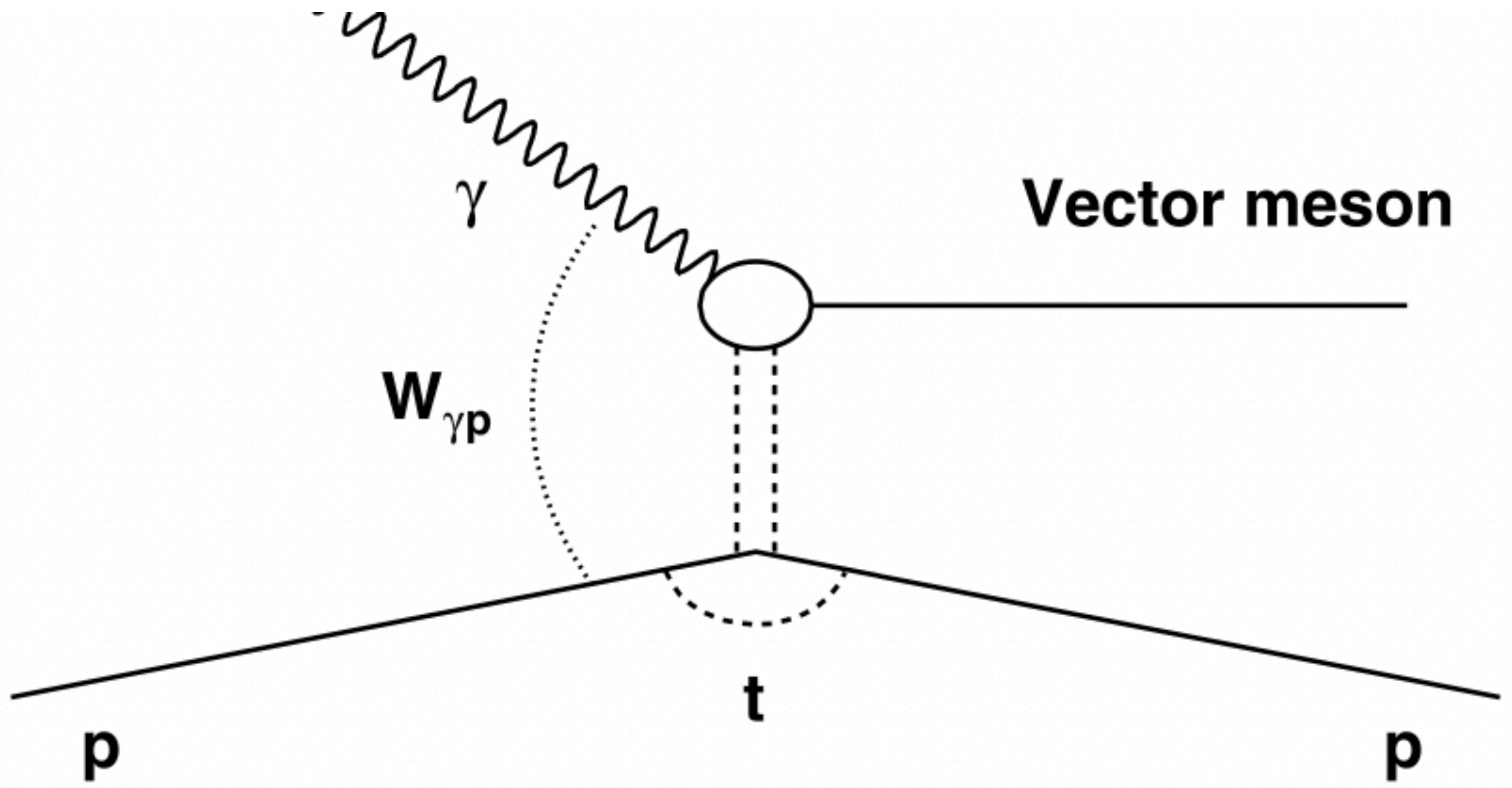
Dissociative vector meson production



Up to now, we have studied this process (called exclusive or coherent) where the proton survives the interaction

Dissociative vector meson production



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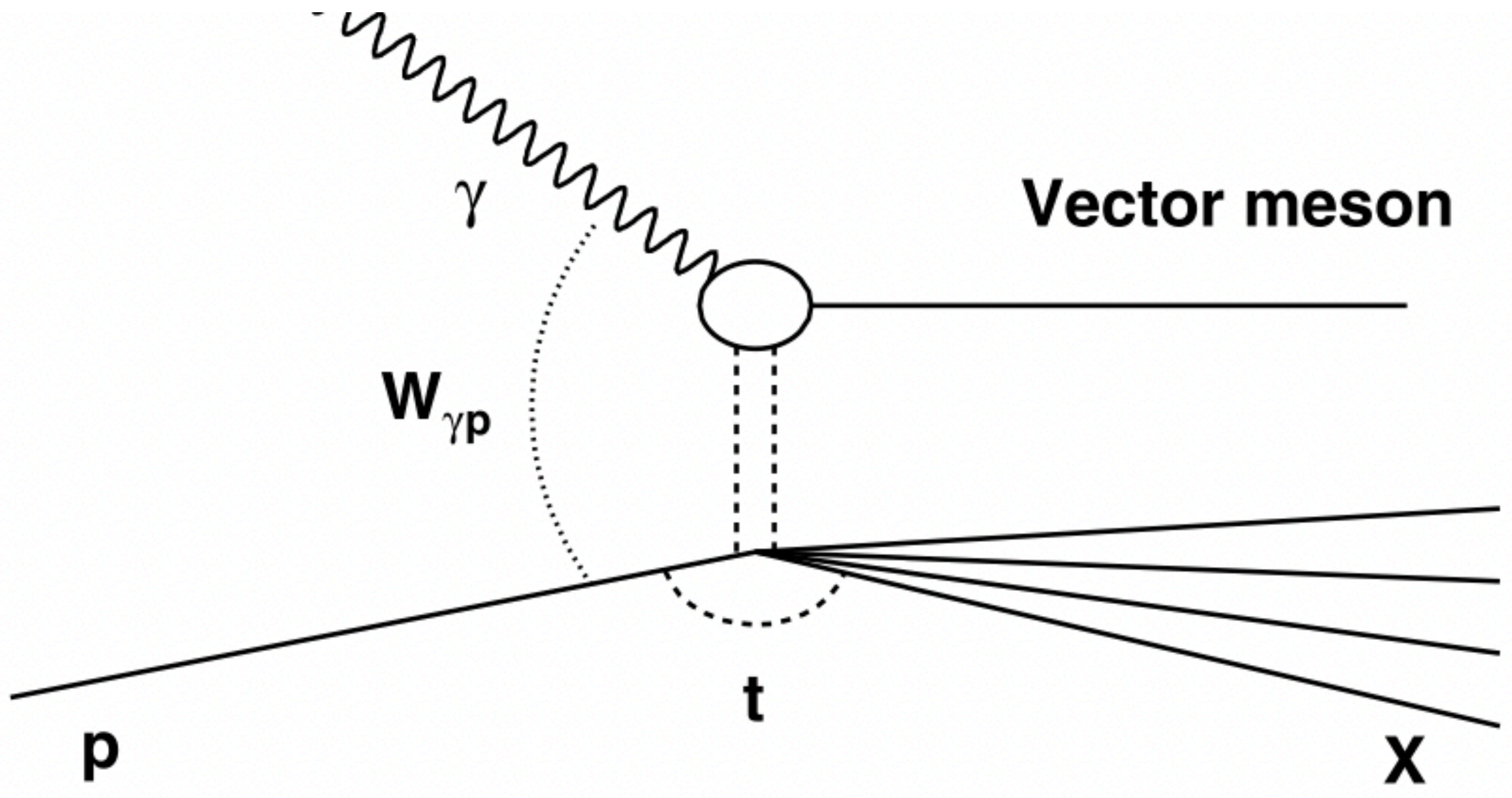
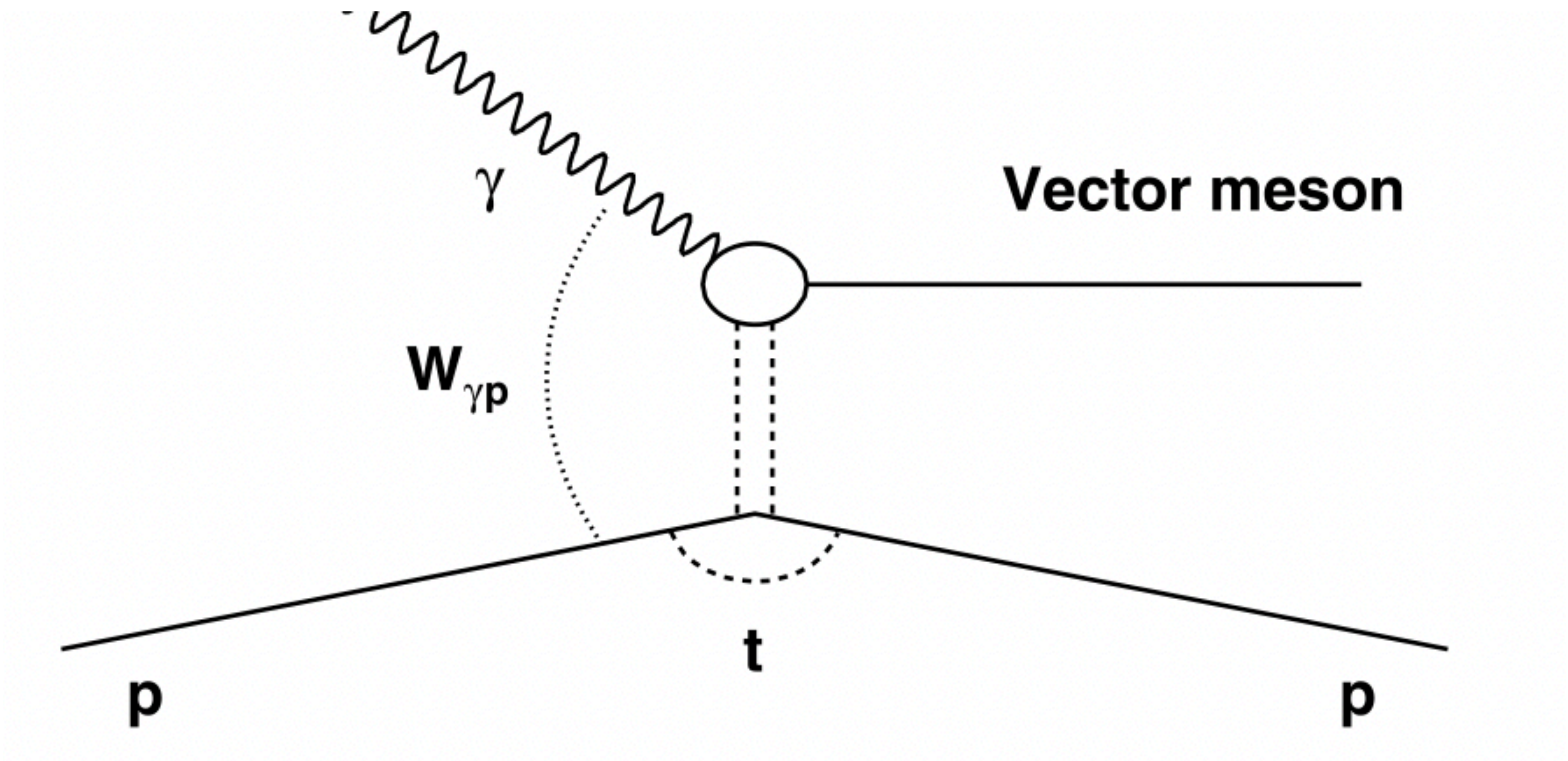


There is a similar process (called dissociation or incoherent), where the proton dissociates in a final state with the same quantum numbers as the proton

Dissociative vector meson production

Average over target configurations

$$\frac{d\sigma^{\gamma^* p \to J/\psi p}}{dt} = \frac{1}{16\pi} |\langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle|^2.$$



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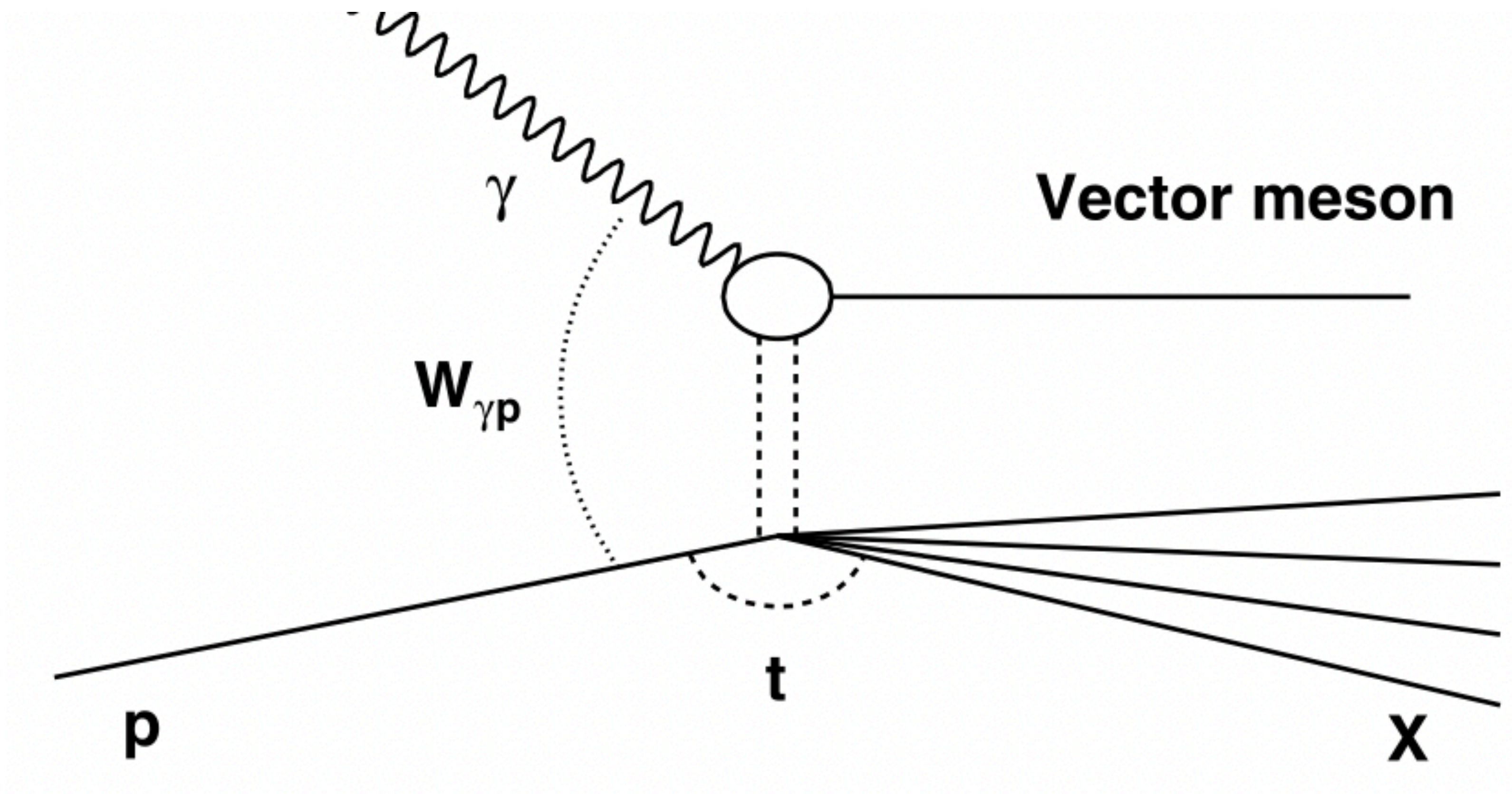

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Good, Walker, https://inspirehep.net/literature/9375
Miettinen, Pumplin, https://inspirehep.net/literature/9375
Mantysaari, Schenke, https://inspirehep.net/literature/1427435

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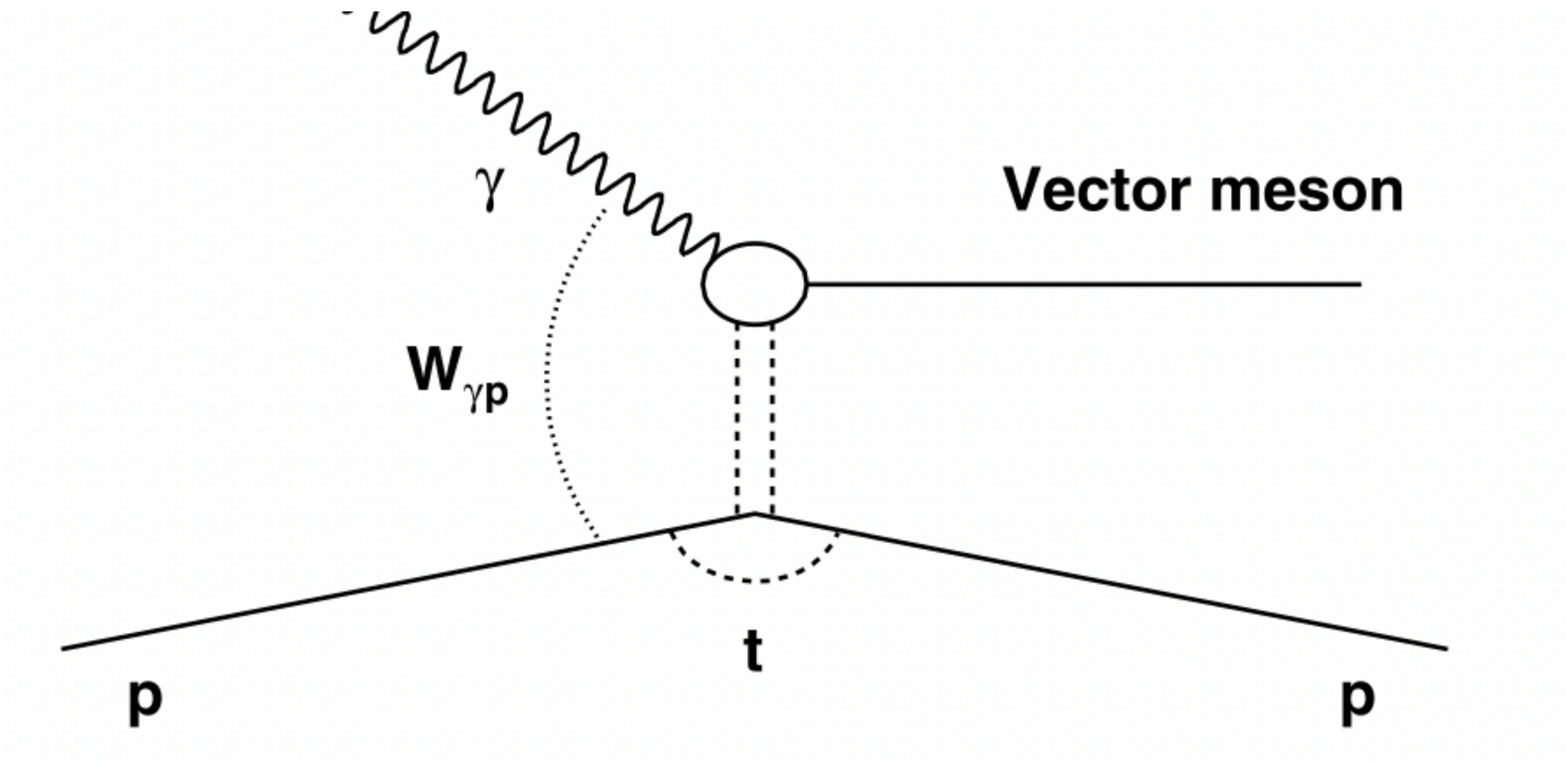

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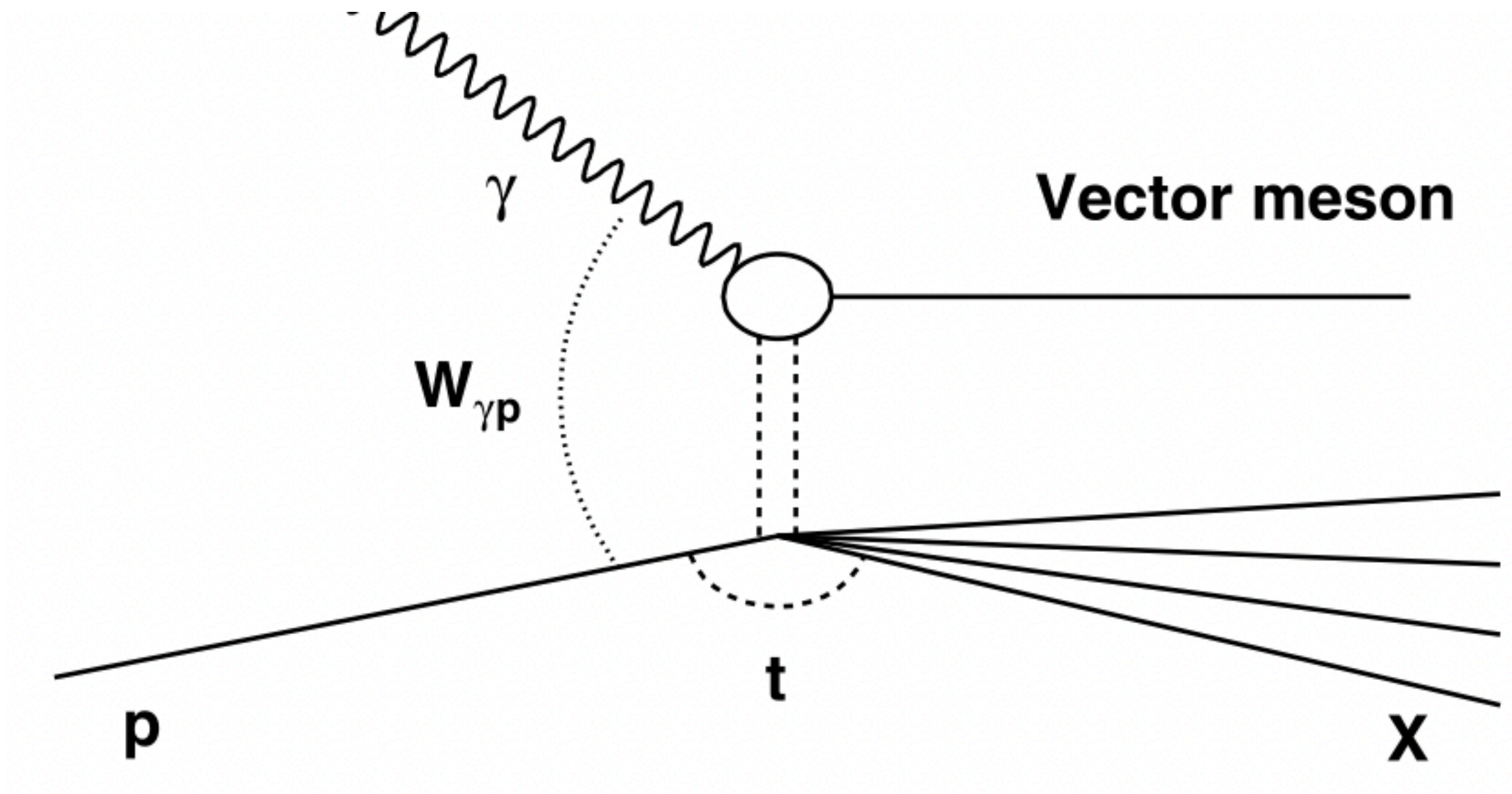

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Dissociative vector meson production

Words of caution

Klein, https://inspirehep.net/literature/2620130

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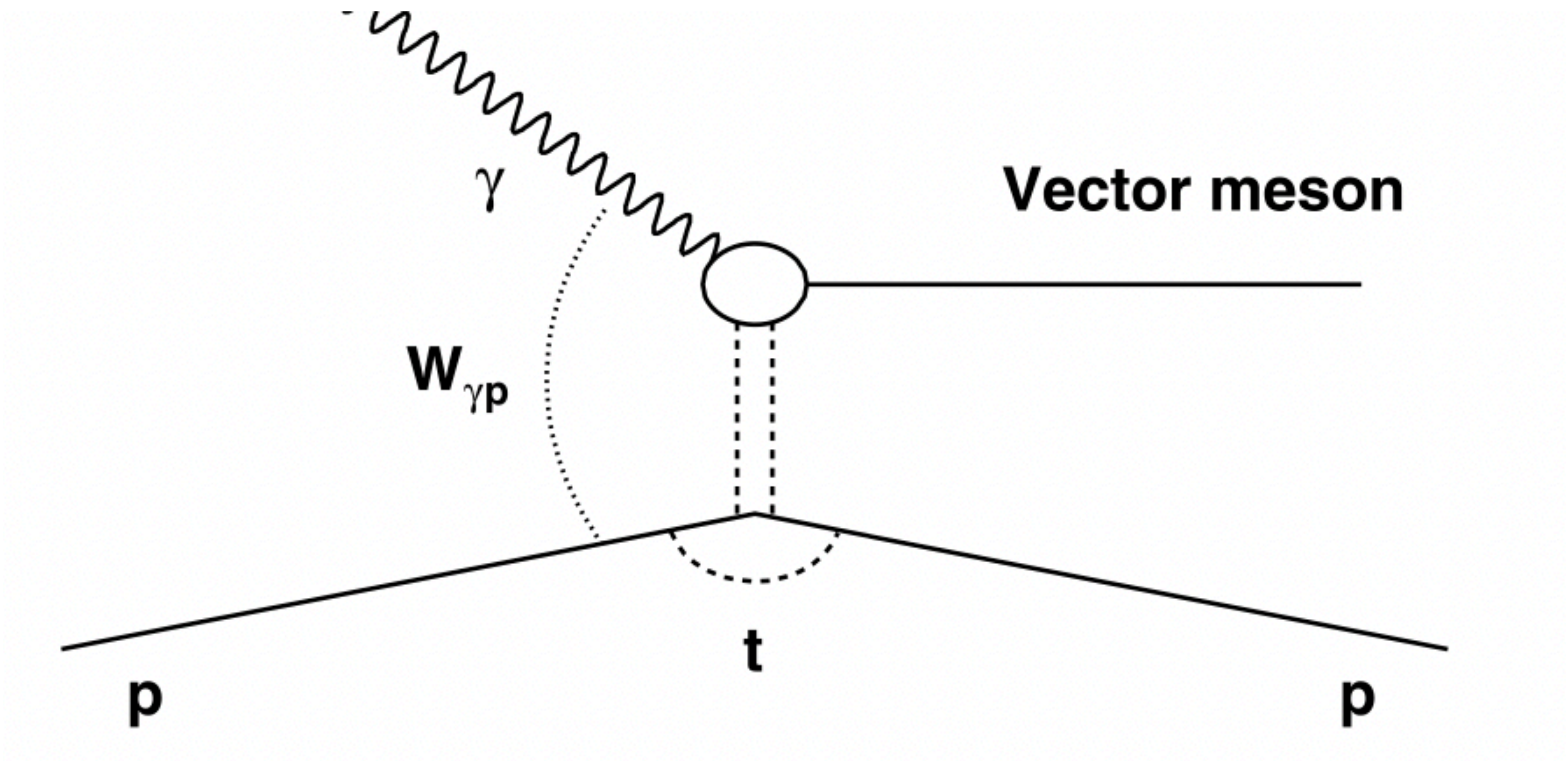

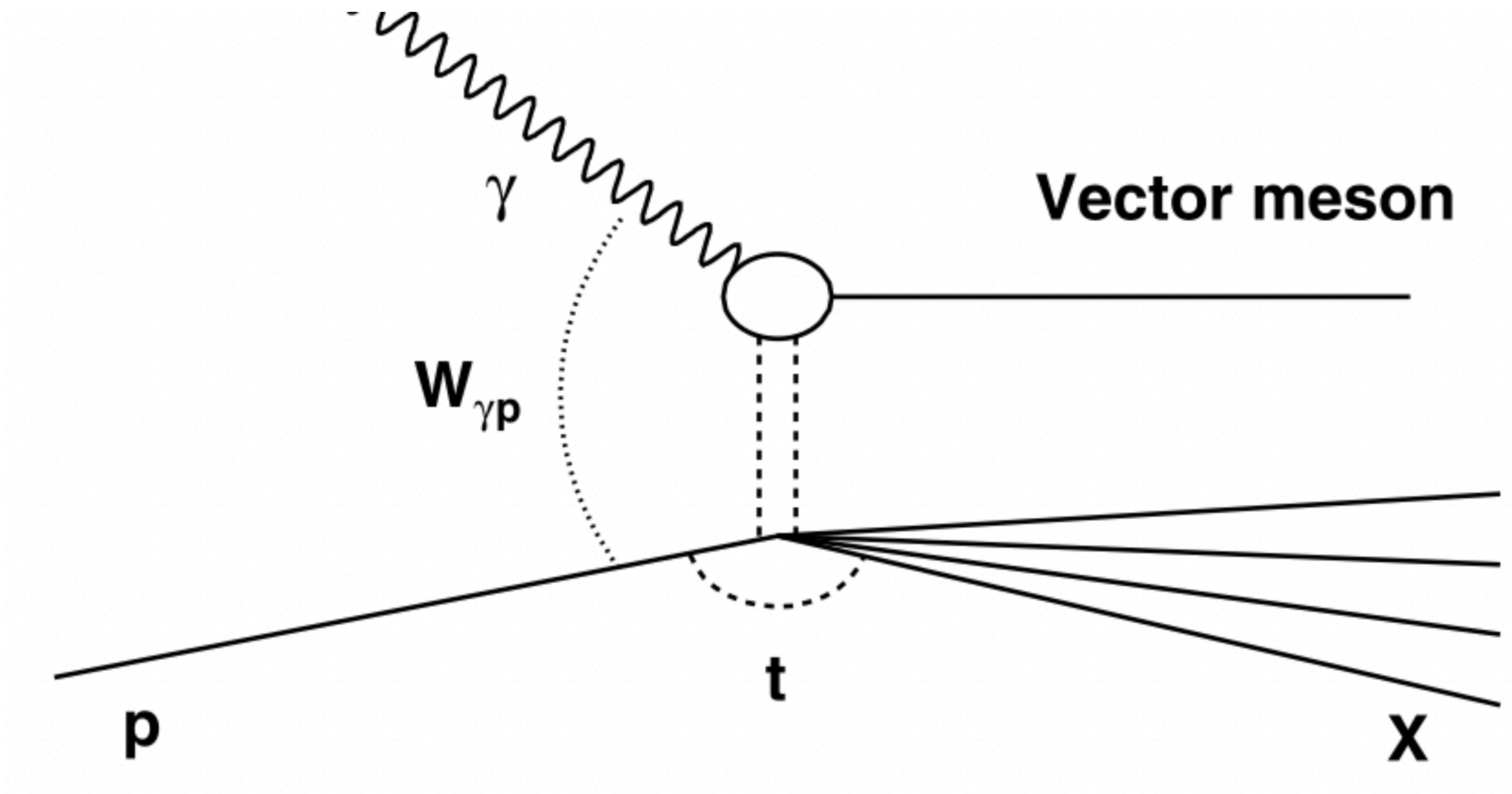

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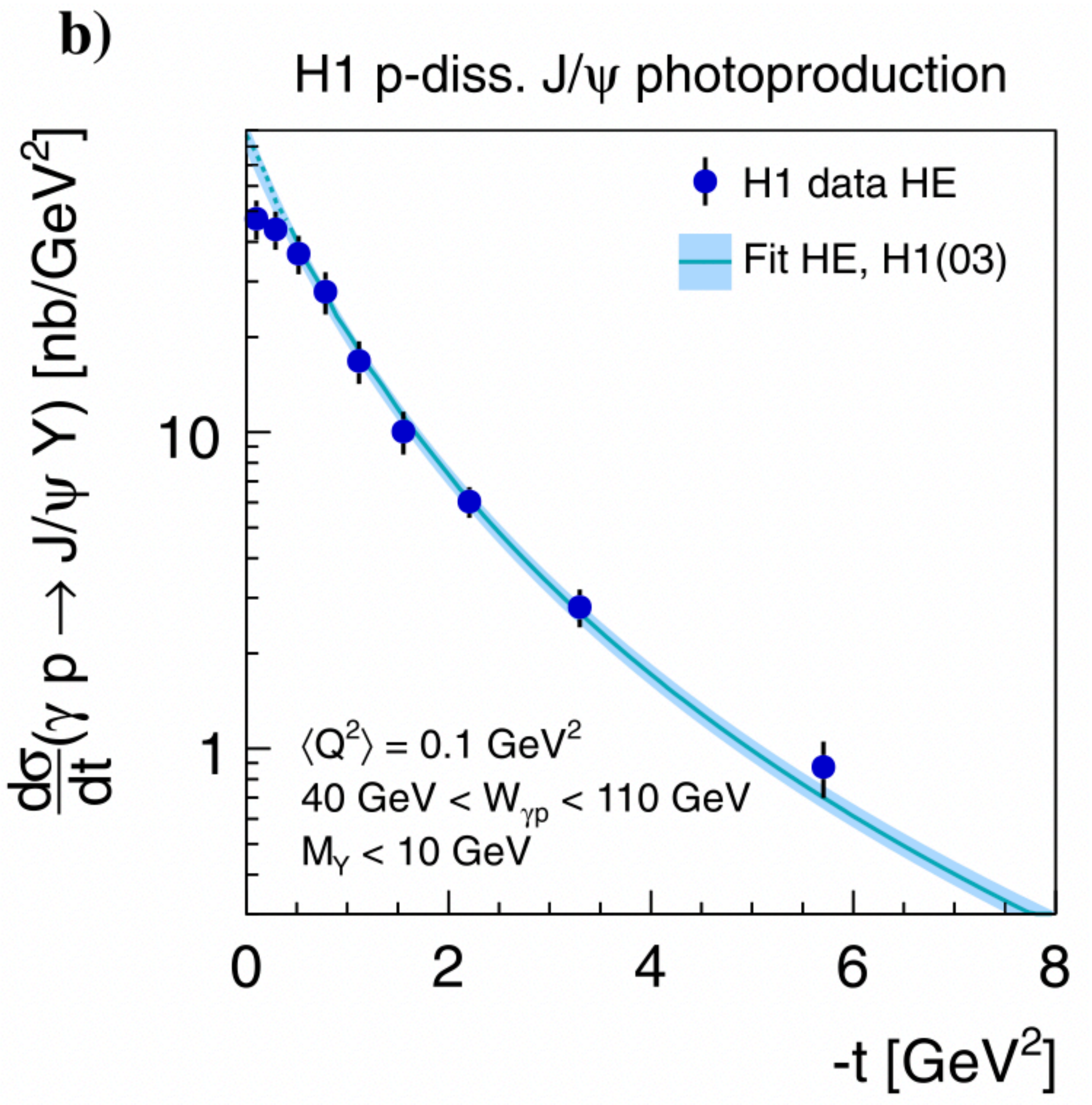
2013: Diffractive dissociative J/ψ photo production



H1, https://inspirehep.net/literature/1228913

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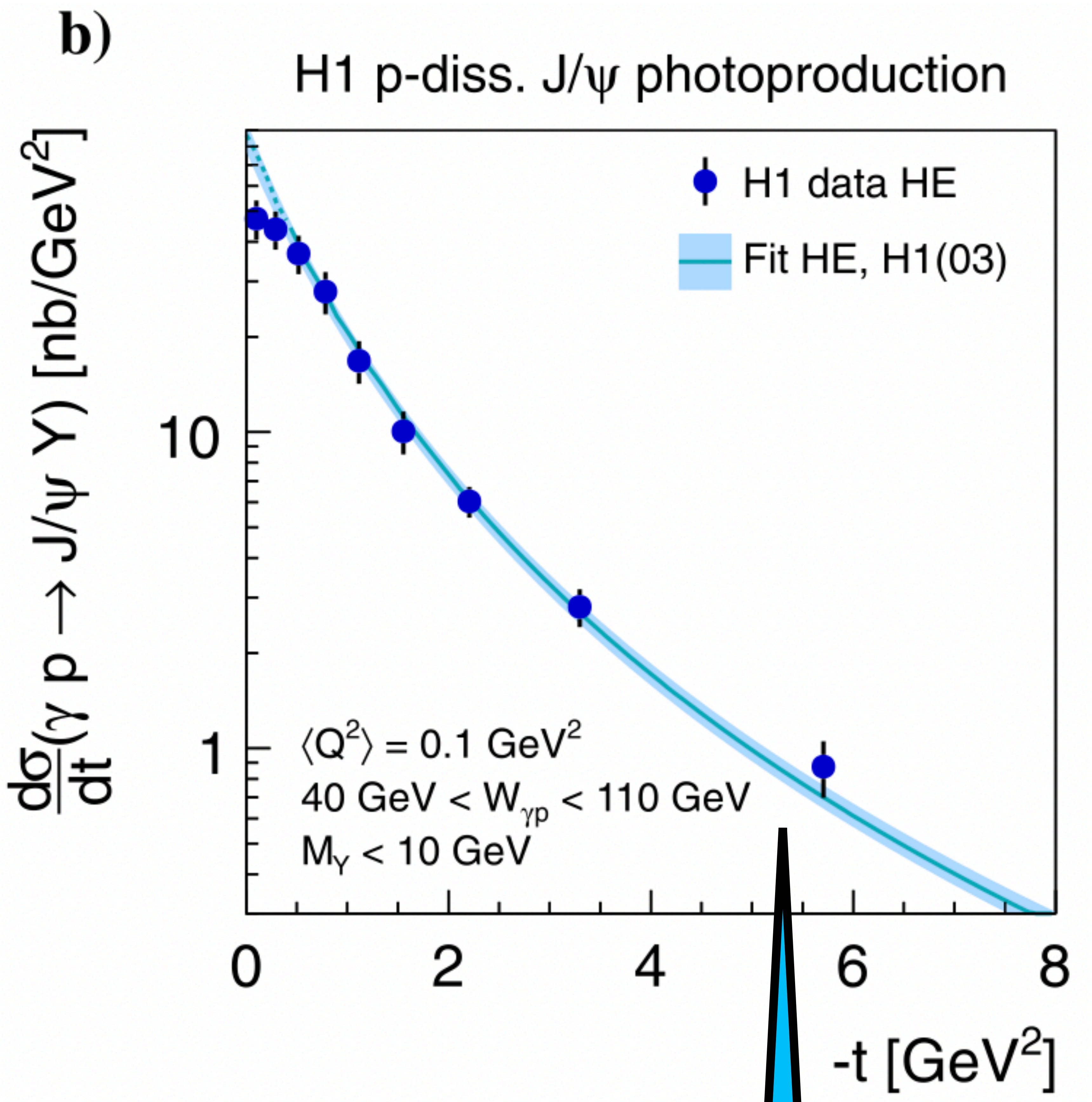

Fit:

$$d\sigma/dt = N_{pd}(1 + (b_{pd}/n)|t|)^{-n}$$

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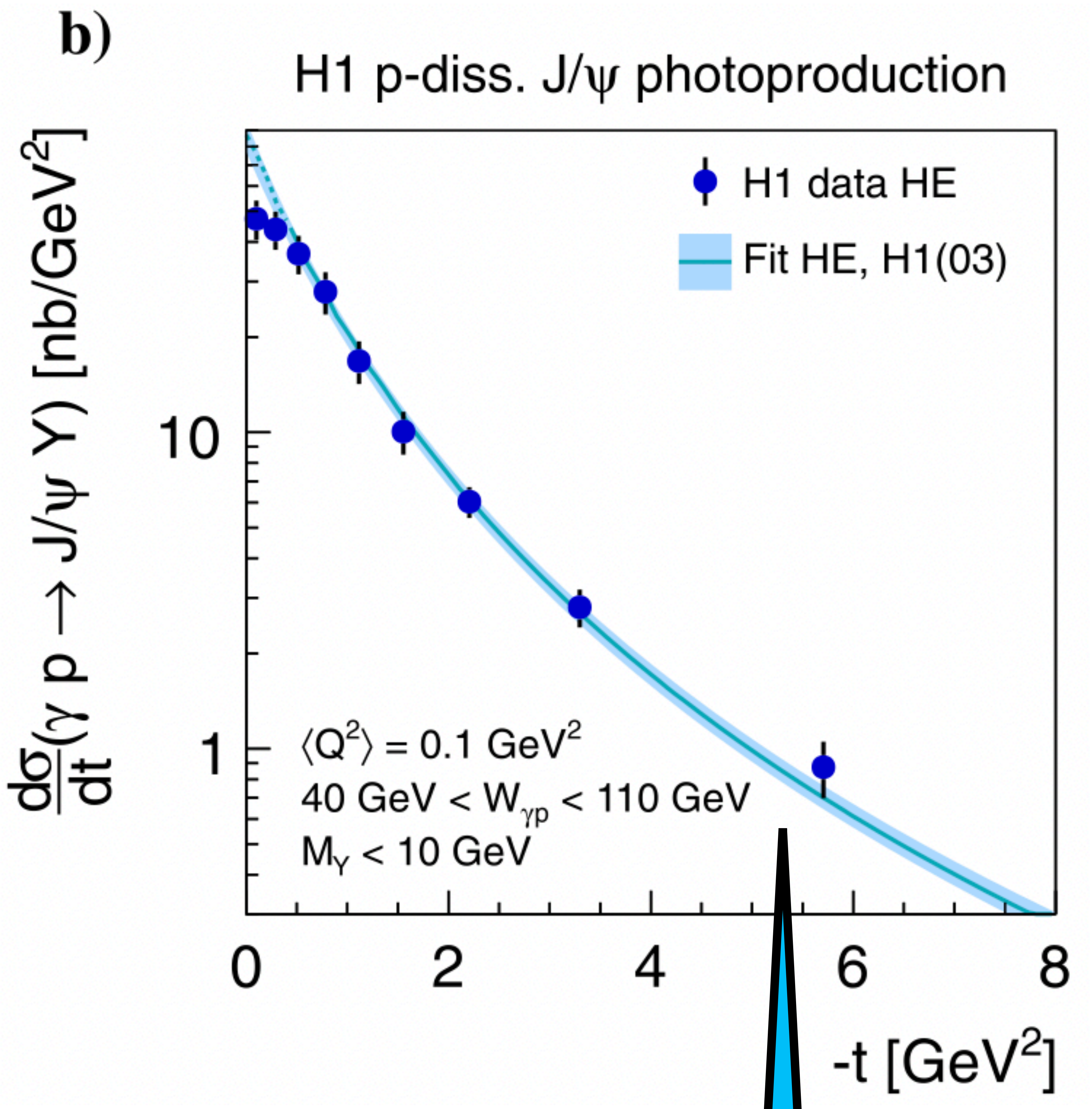

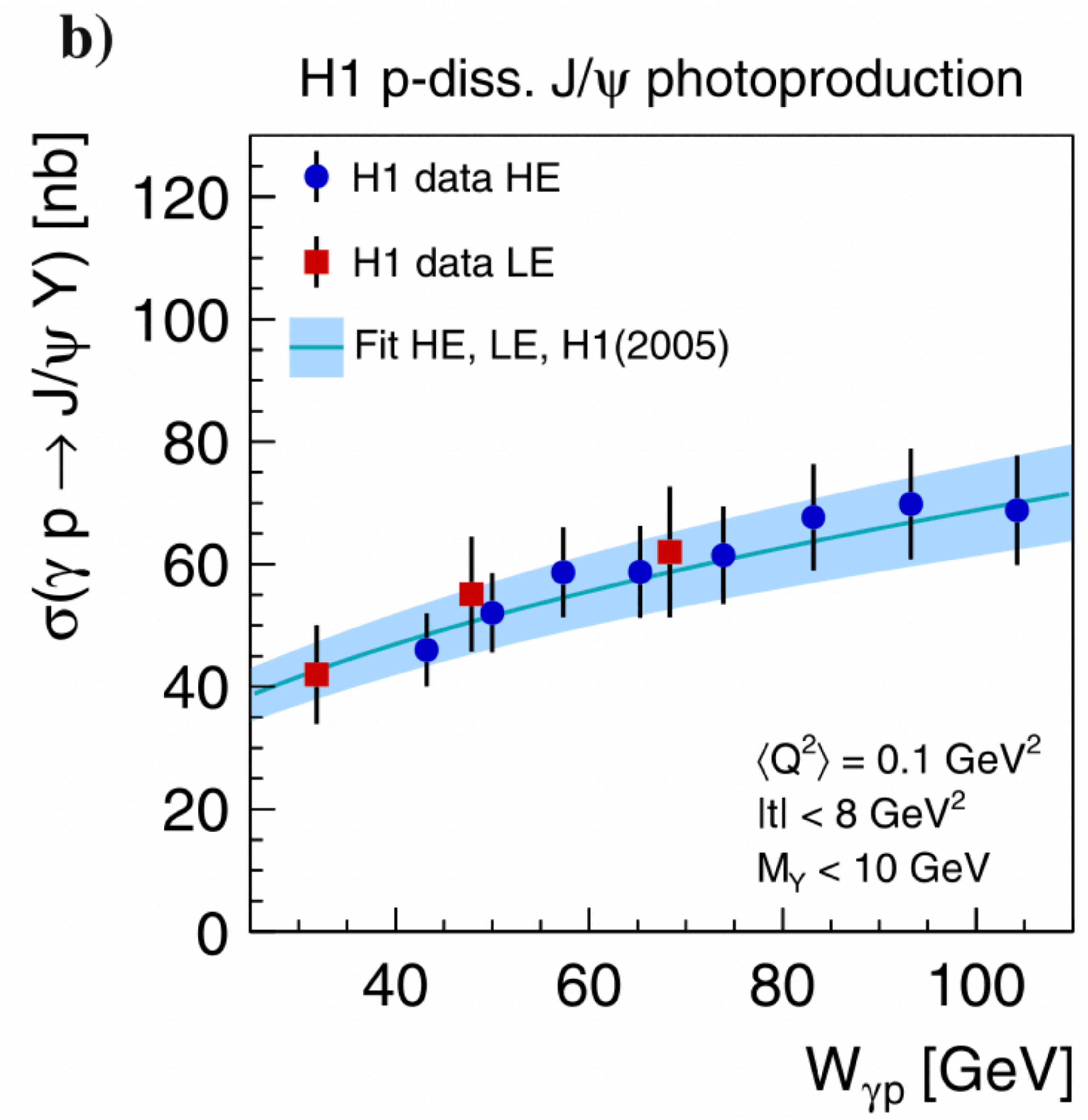

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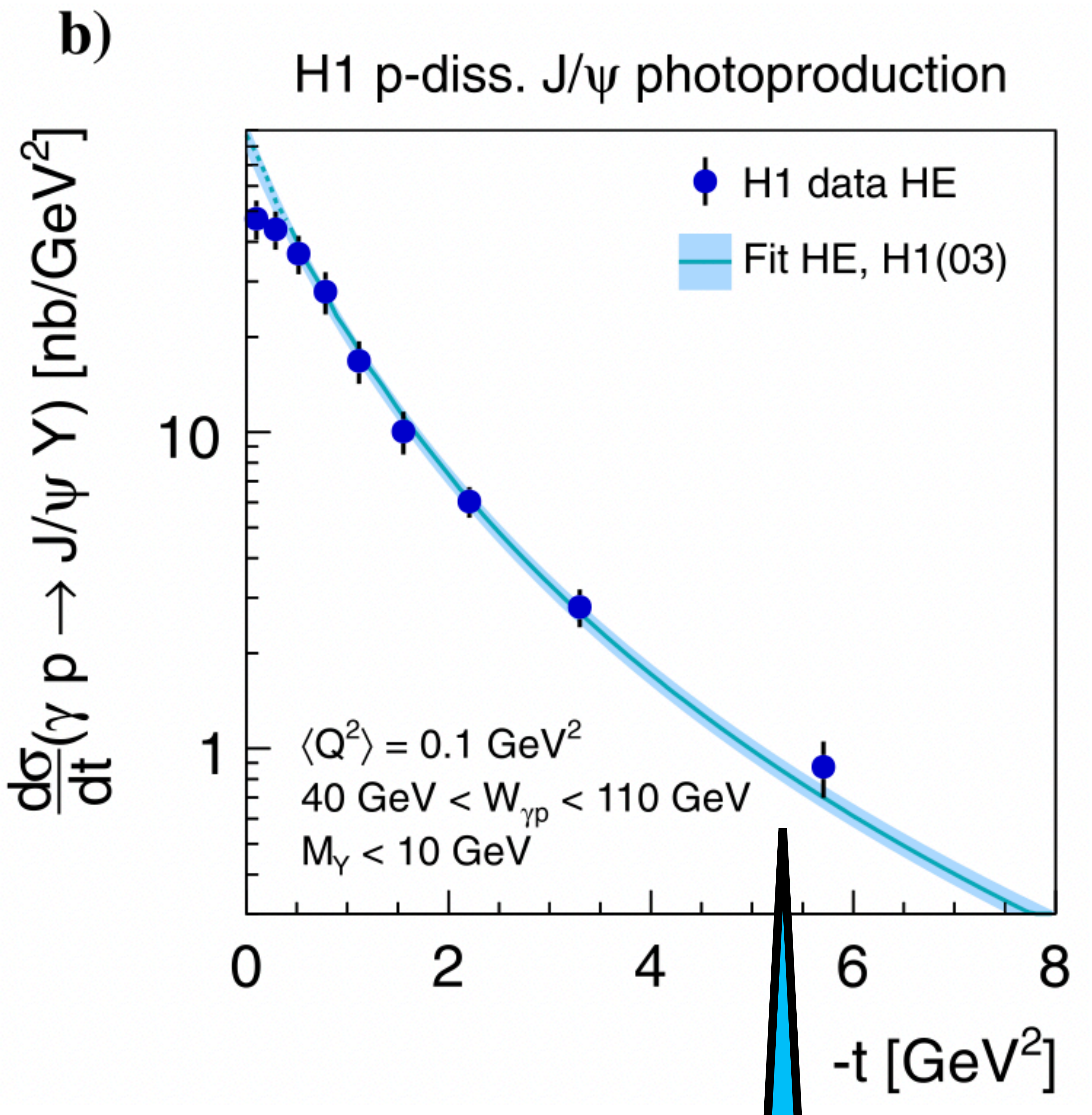

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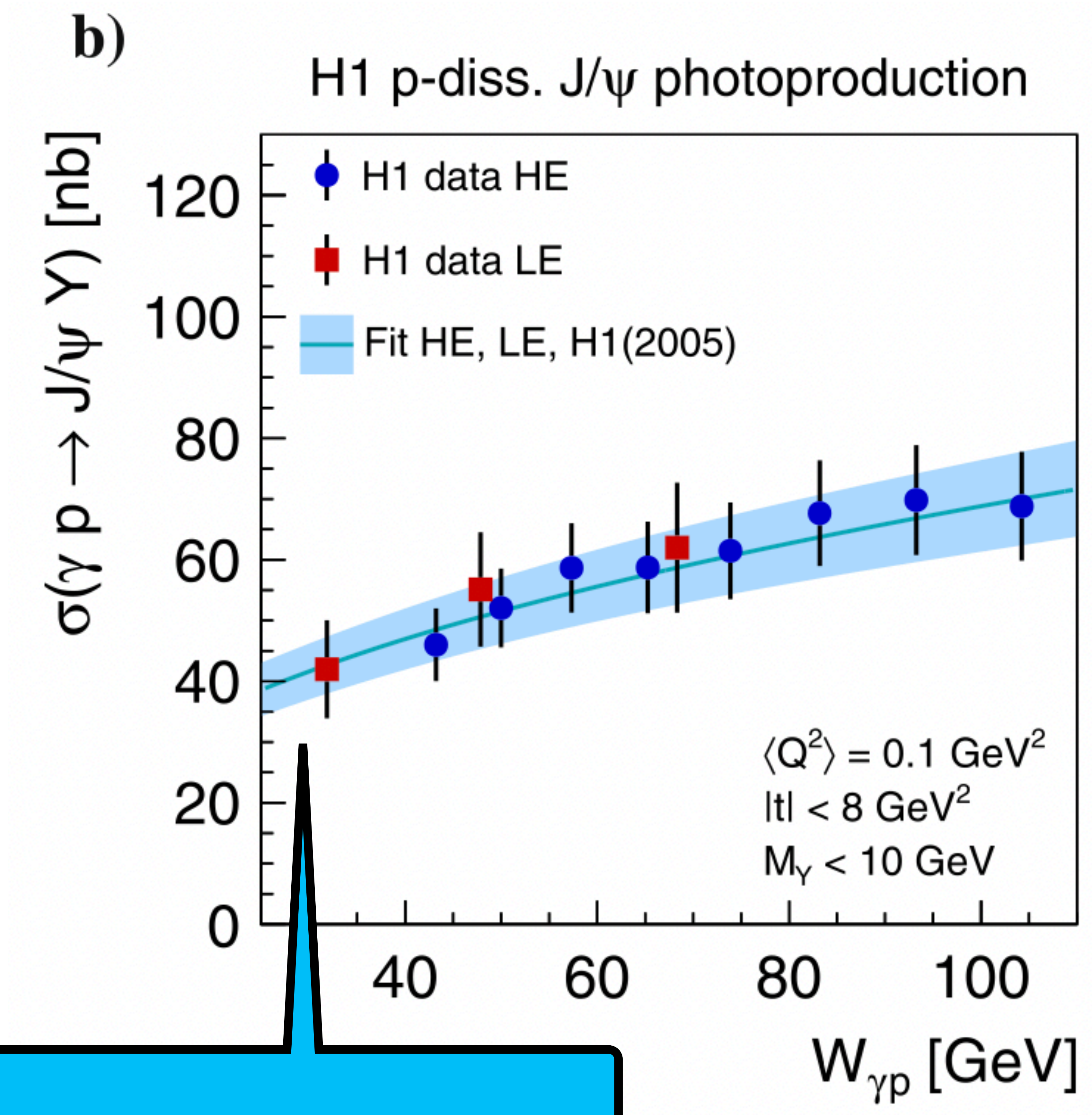

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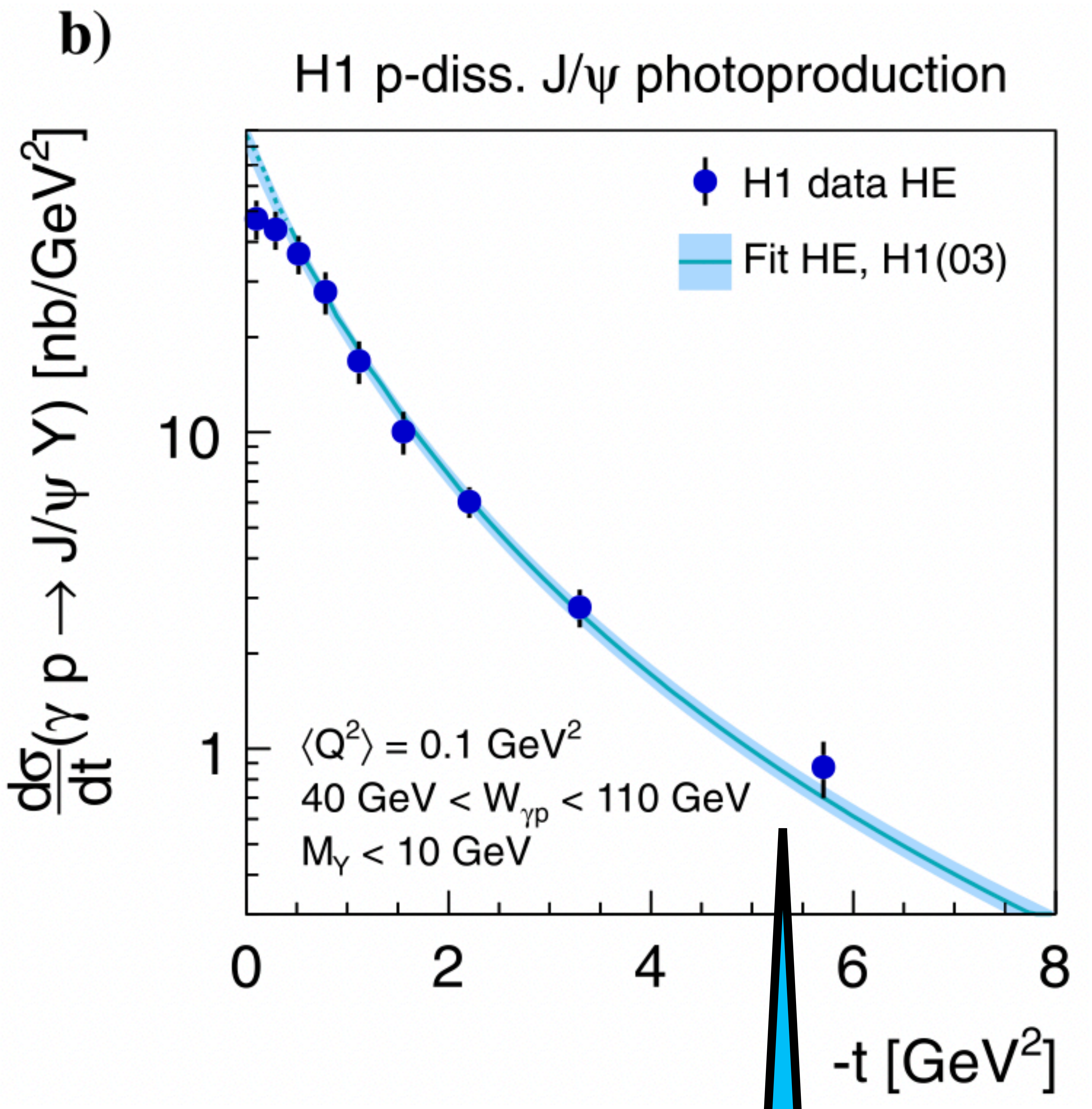

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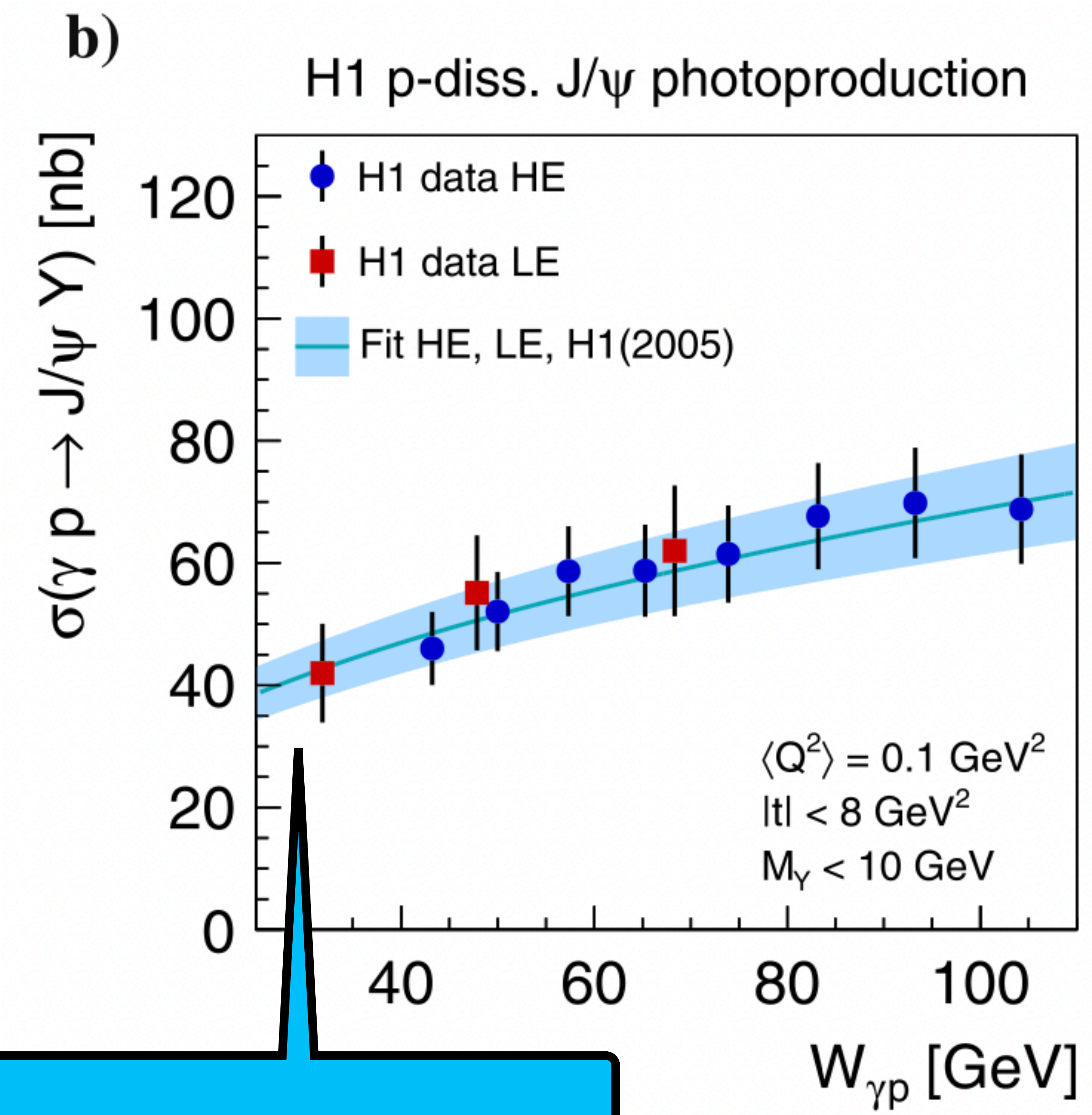


Fit:

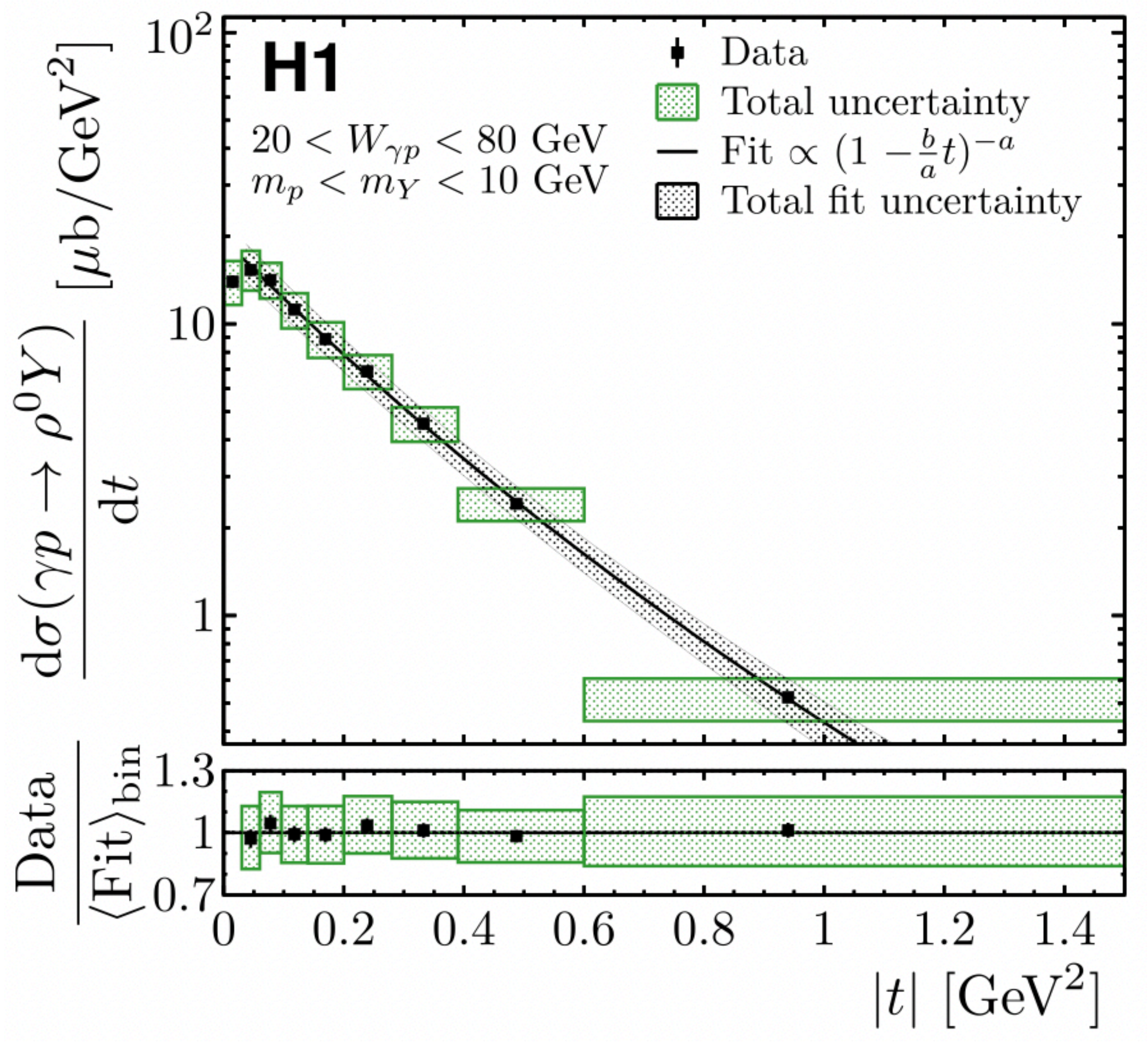
$$\sigma = N(W_{\gamma p}/W_{\gamma p,0})^{\delta}$$

δ=0.42±0.5

H1, https://inspirehep.net/literature/1228913

Guillermo Contreras, CTU in Prague

2020: Diffractive dissociative ρ photo production



H1, https://inspirehep.net/literature/1798511

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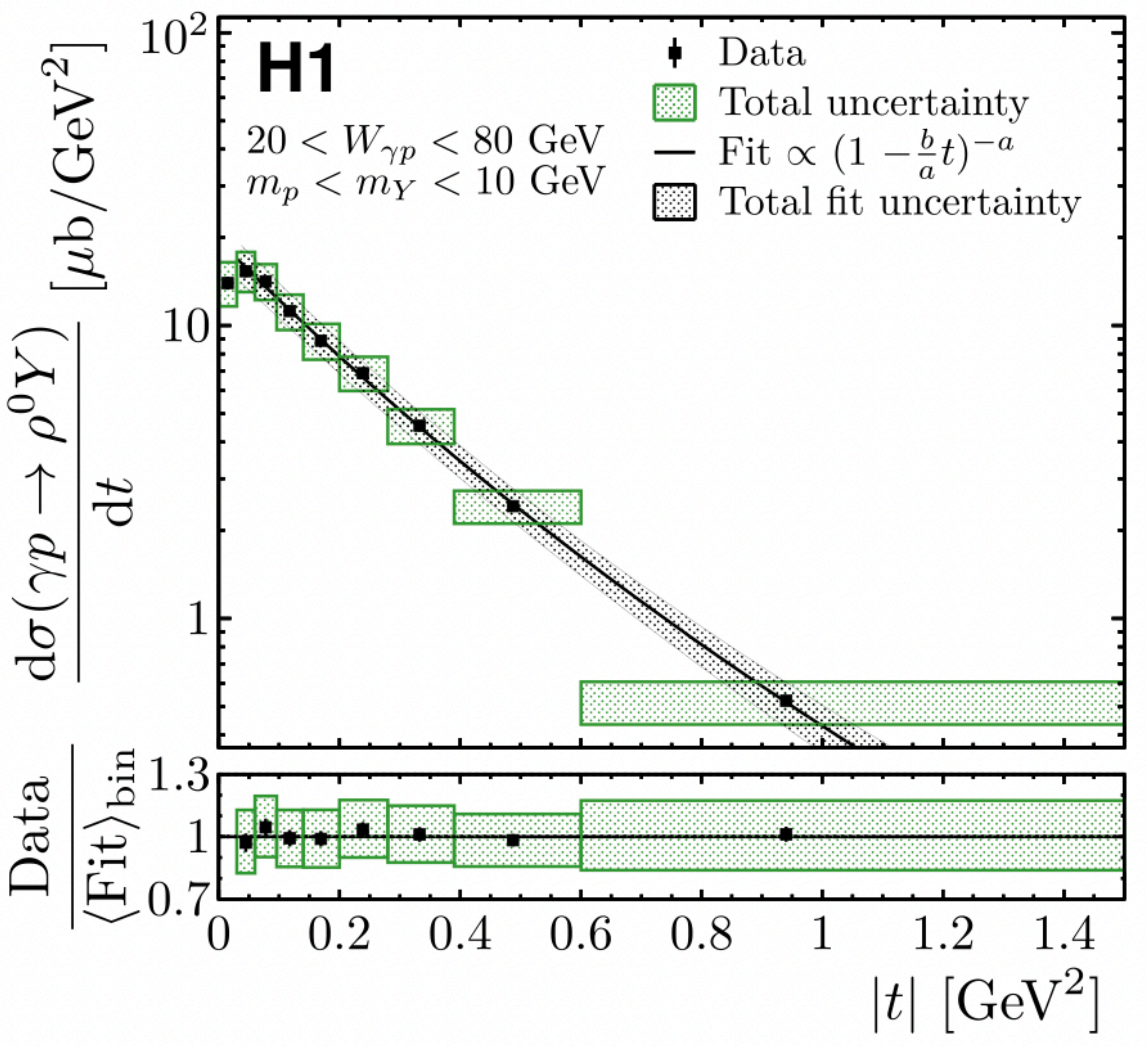
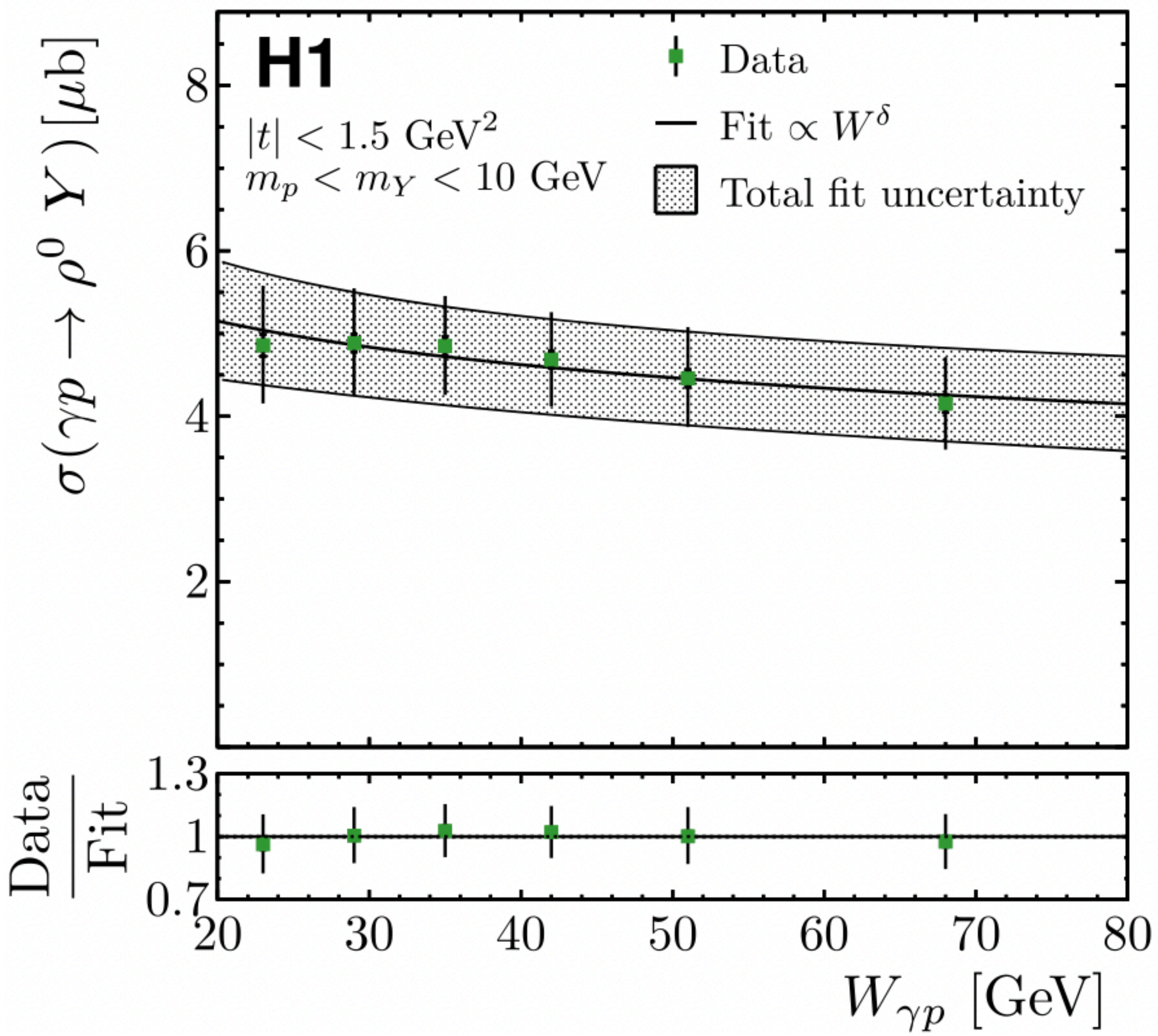
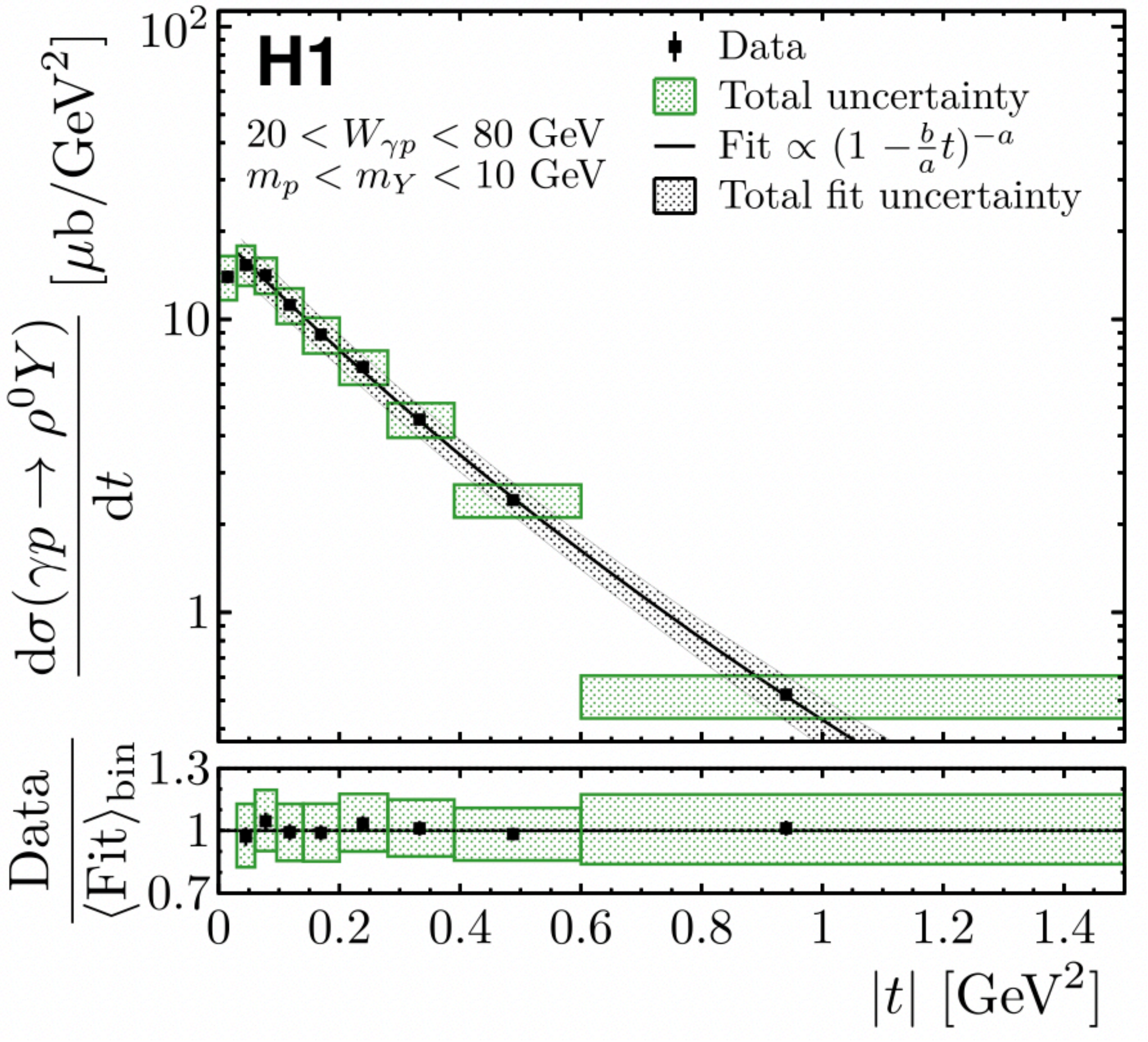


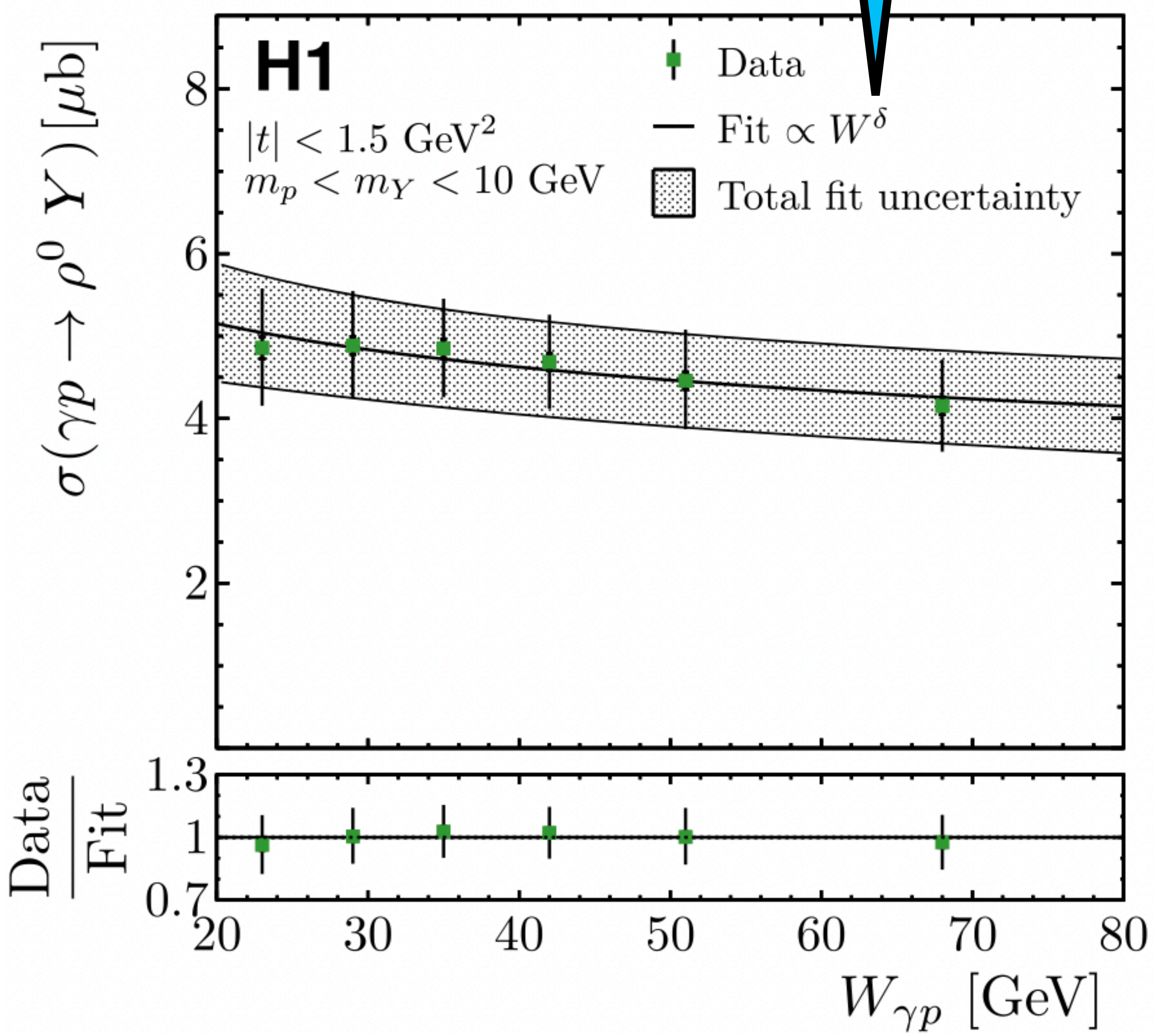


H1, https://inspirehep.net/literature/1798511

2020: Diffractive dissociative ρ photo production

$\delta = -0.156 \pm 0.026^{+0.081}_{-0:079}$





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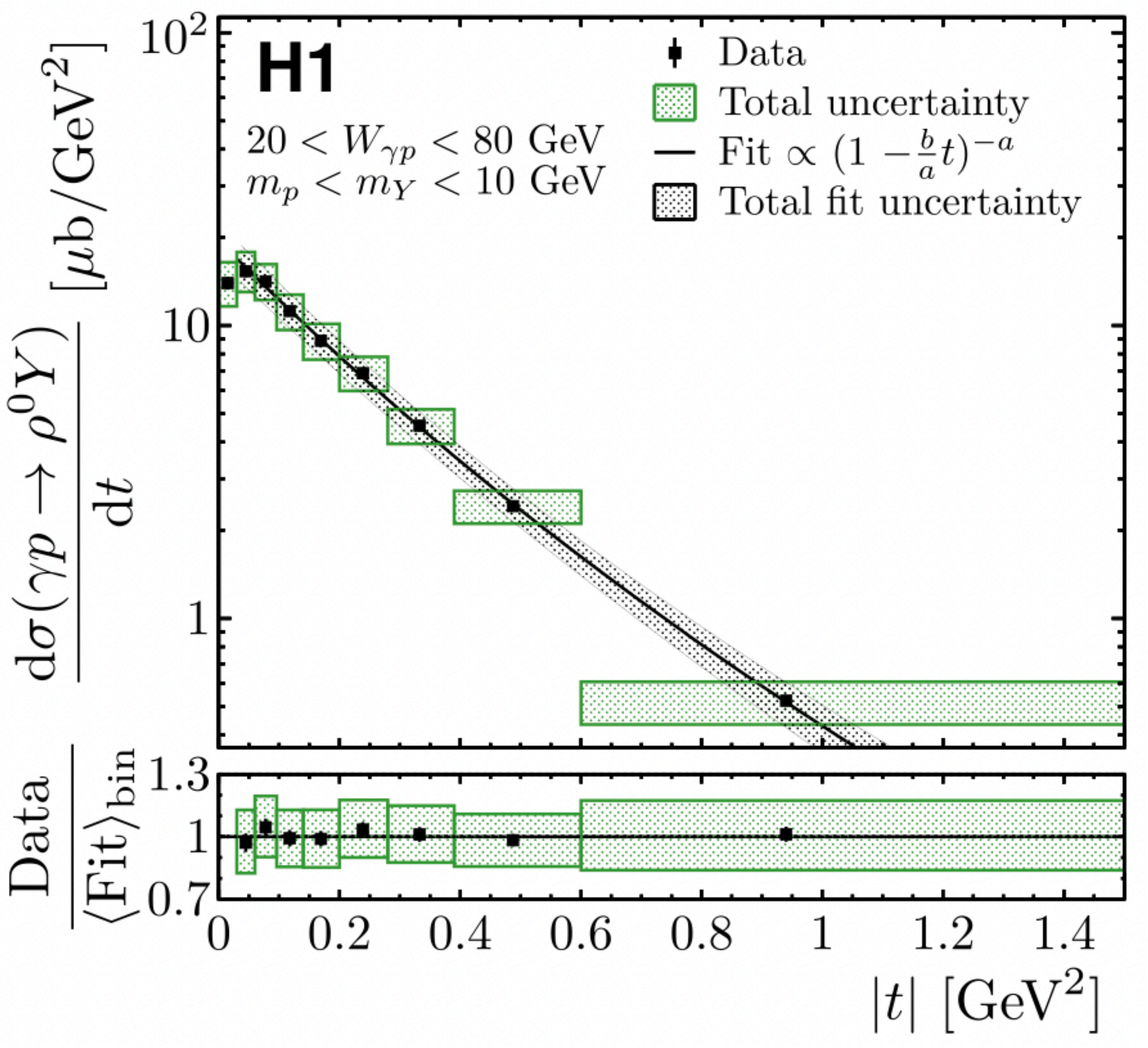

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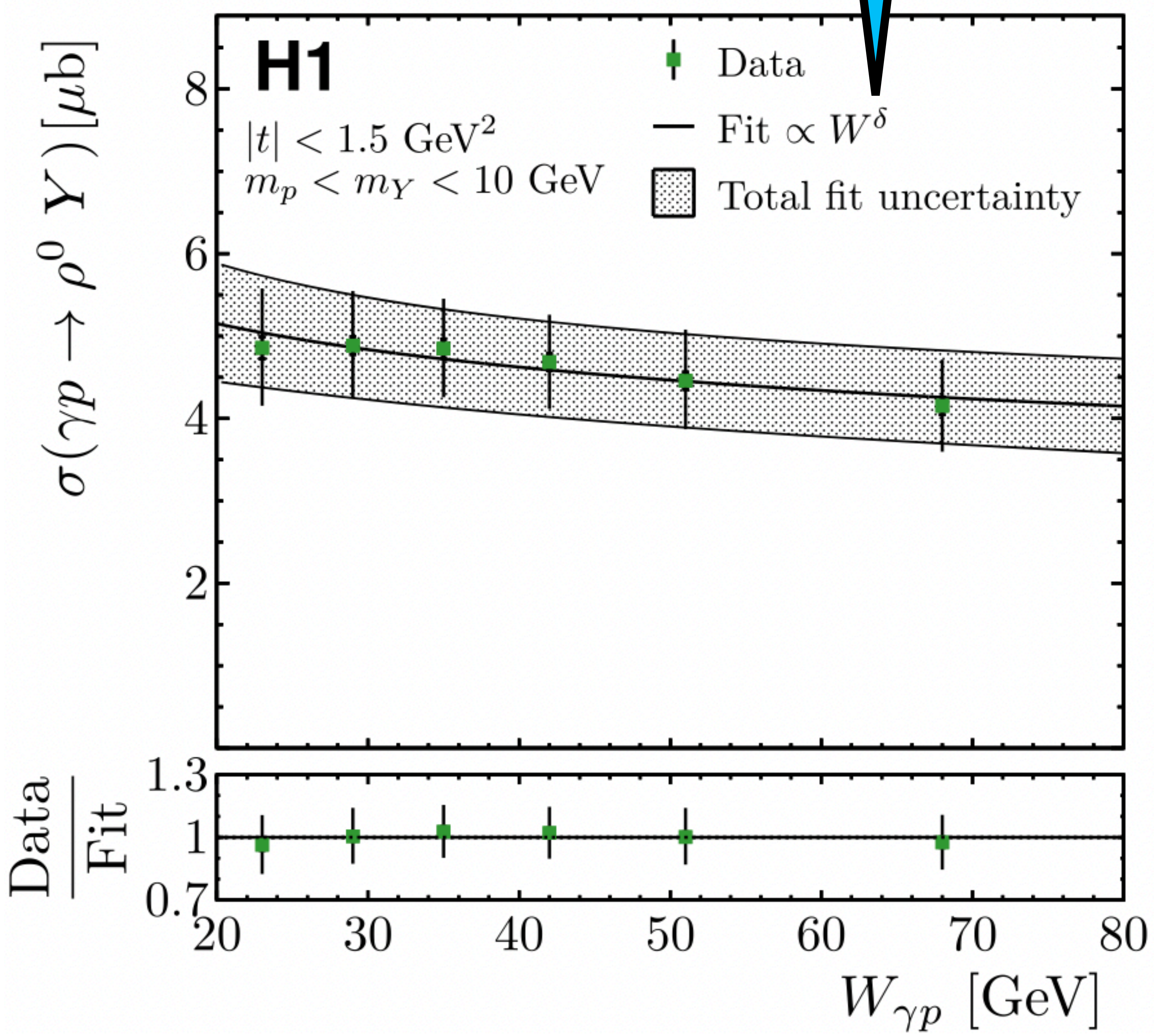

The cross section decreases!
How can this be interpreted?

H1, https://inspirehep.net/literature/1798511

2016: Fluctuations in the proton

In the Good-Walker approach, the dissociative cross section is related to the variance over configurations

$$\frac{d\sigma^{\gamma^* N \to J/\psi N^*}}{dt} = \frac{1}{16\pi}\left(\langle|A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})|^2\rangle - |\langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\rangle|^2\right)$$

Mantysaari, Schenke, https://inspirehep.net/literature/1427435

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Use a profile function that varies event-by-event

$$T_p(\mathbf{b}) \to \frac{1}{N_q}\sum_{i=1}^{N_q} T_q(\mathbf{b} - \mathbf{b}_i)$$

Mantysaari, Schenke, https://inspirehep.net/literature/1427435

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$$\frac{d\sigma^{\gamma^* N \to J/\psi N^*}}{dt} = \frac{1}{16\pi}\left(\langle|A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})|^2\rangle - |\langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta})\rangle|^2\right)$$

Use a profile function that varies event-by-event

$$T_p(\mathbf{b}) \to \frac{1}{N_q}\sum_{i=1}^{N_q} T_q(\mathbf{b} - \mathbf{b}_i)$$

Fixed number of "quarks" in the proton (3)

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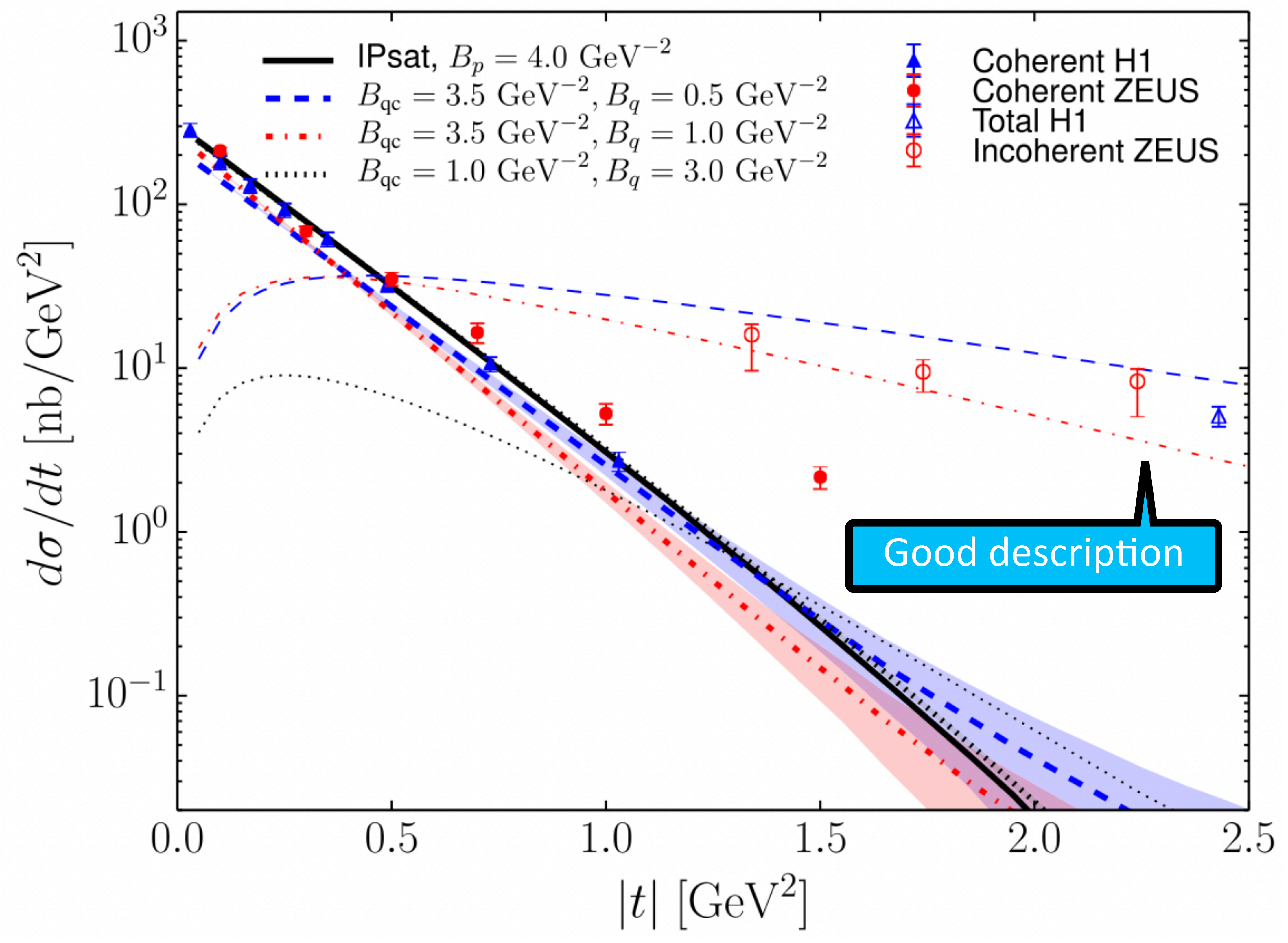

Good description

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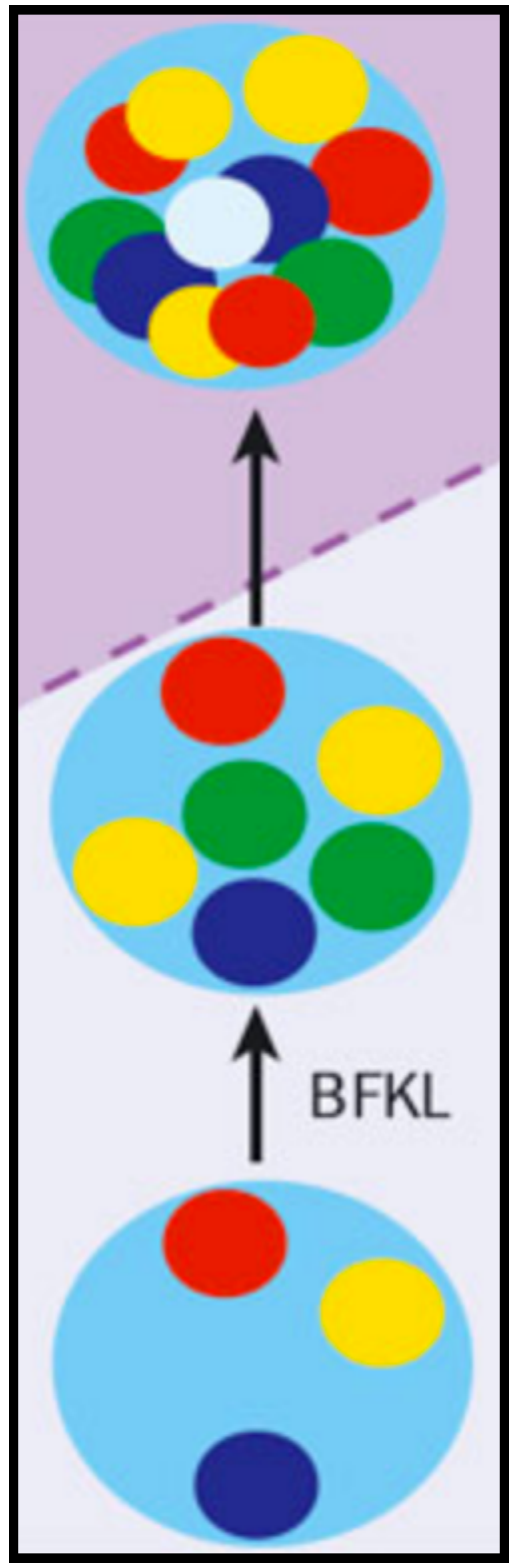
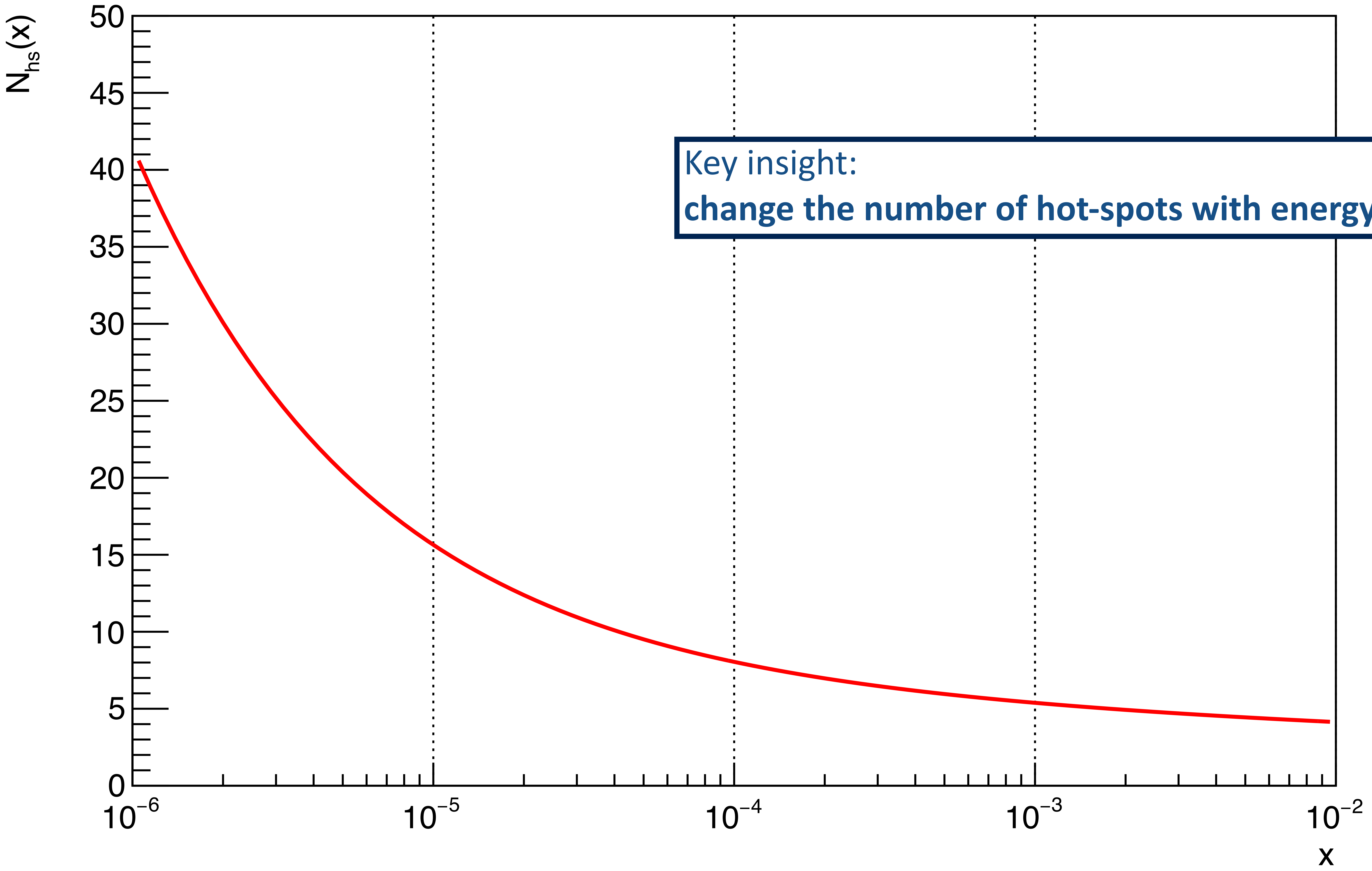
Energy-dependent hot-spot model (1/2)





Key insight:
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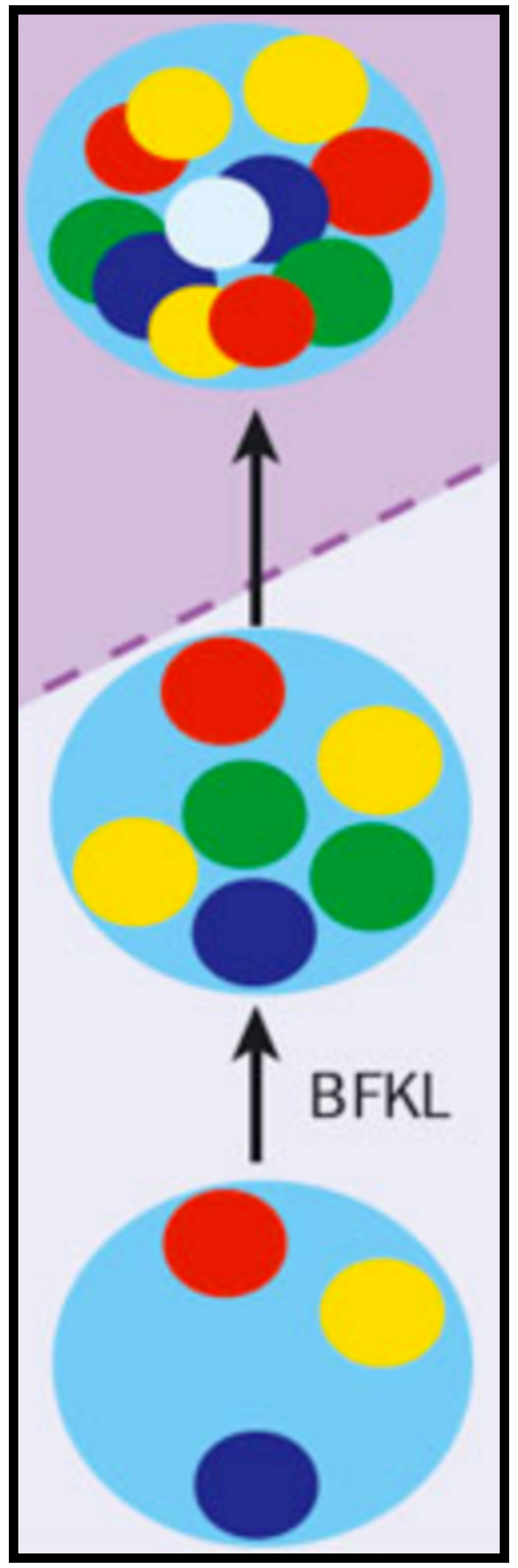

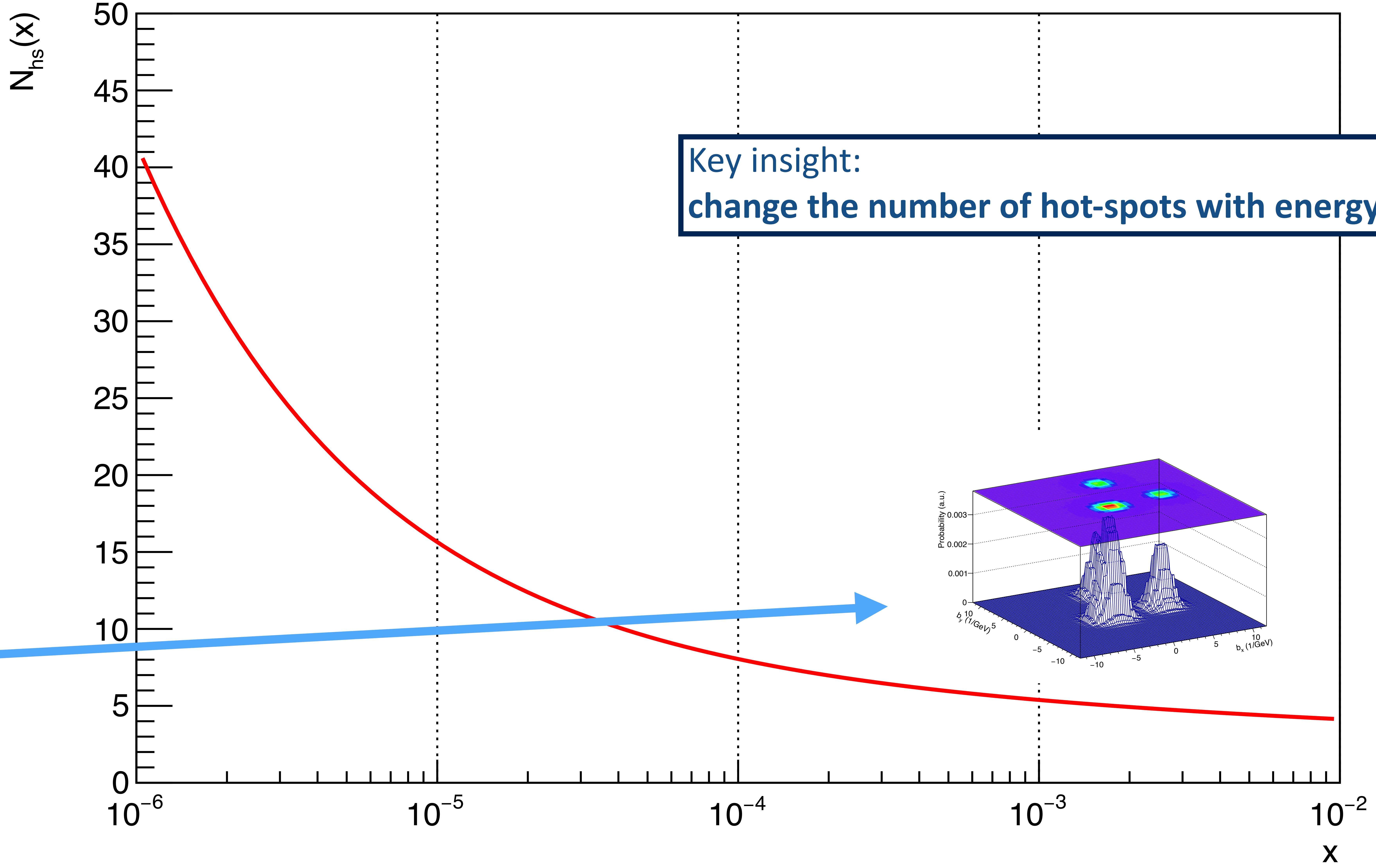

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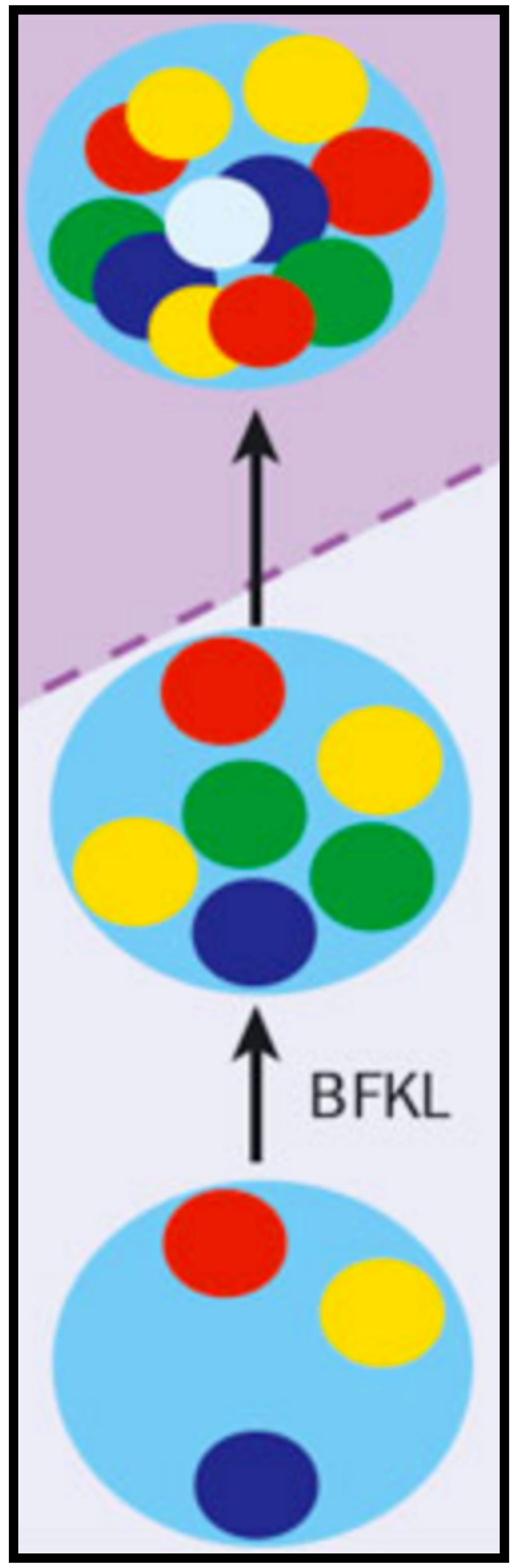

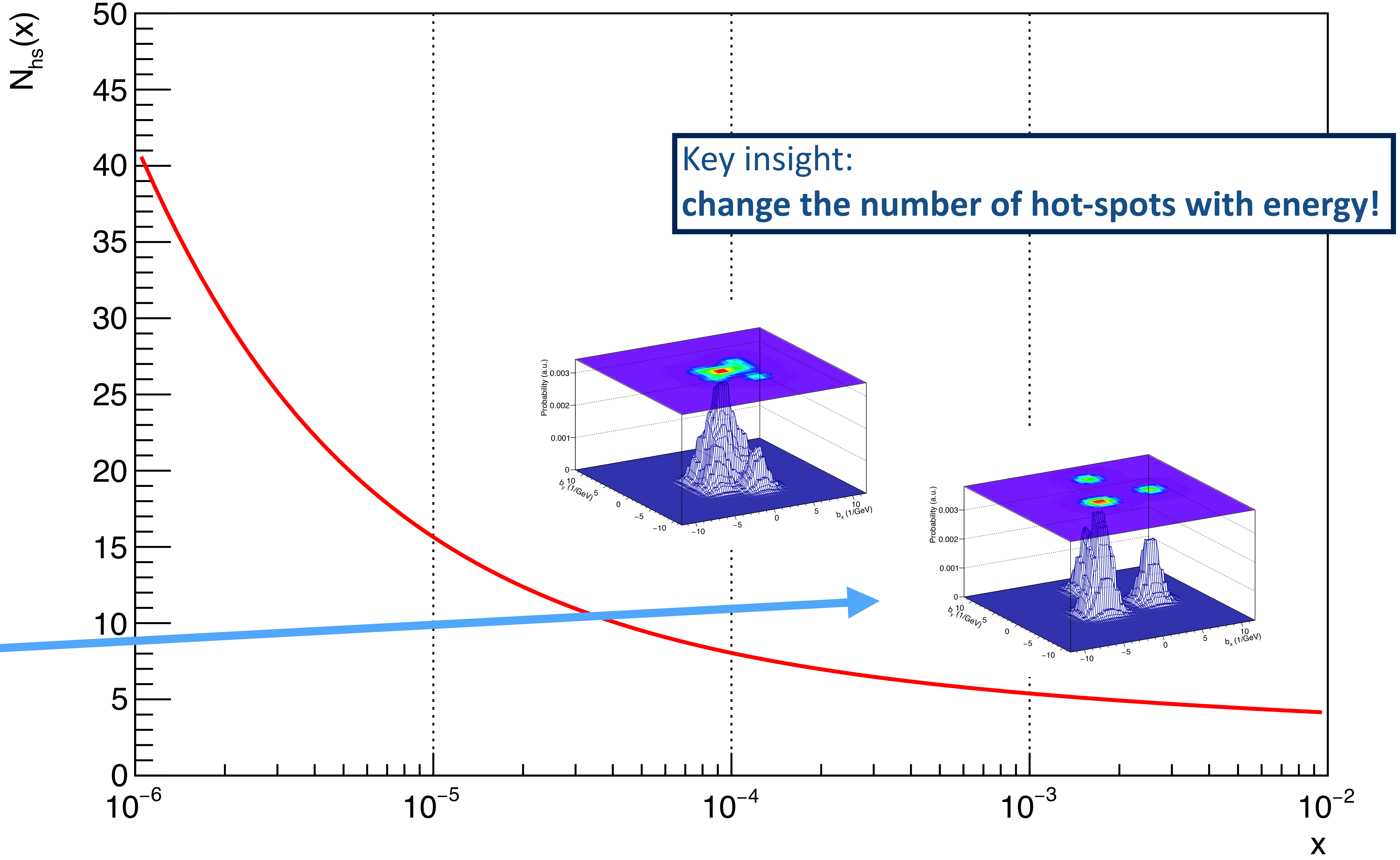

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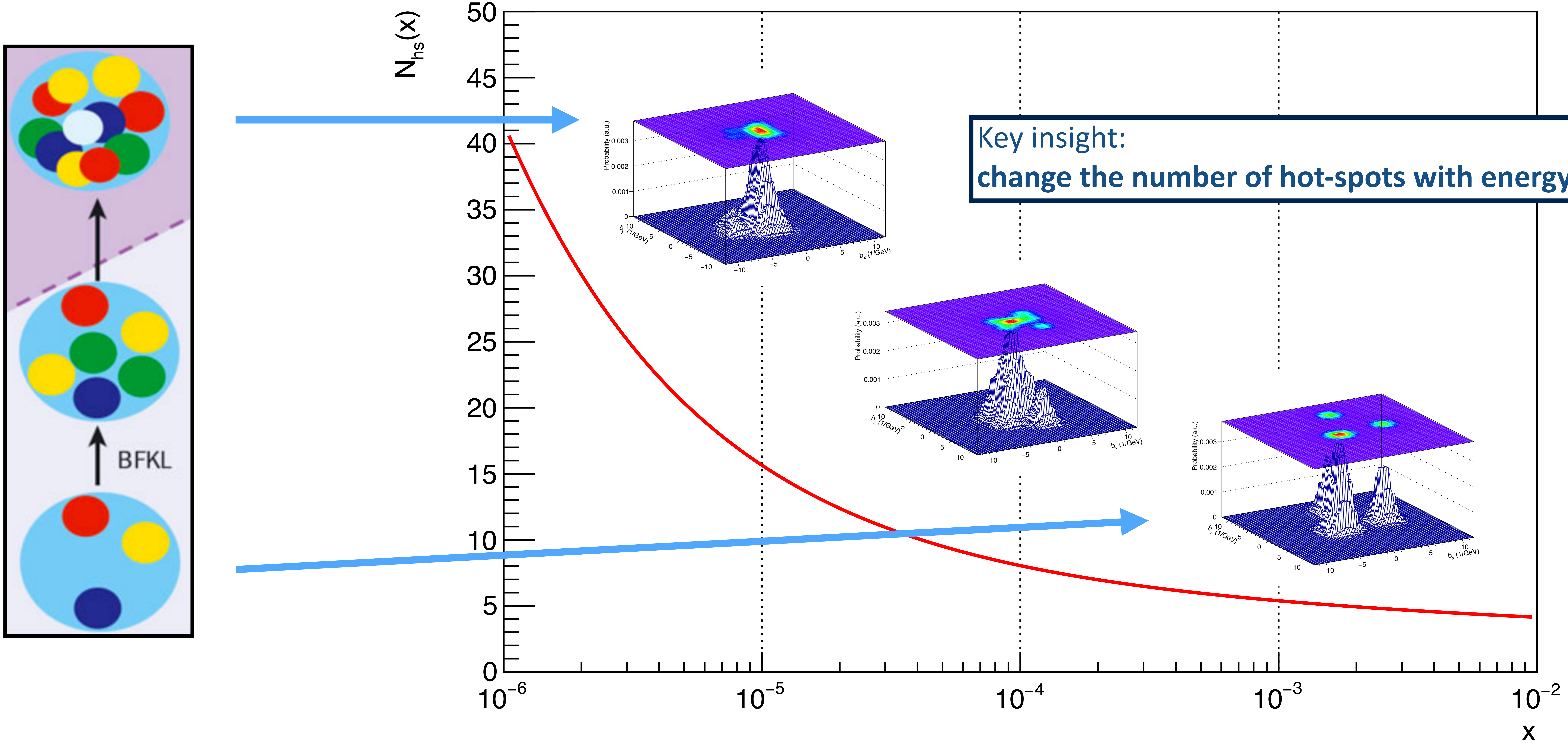

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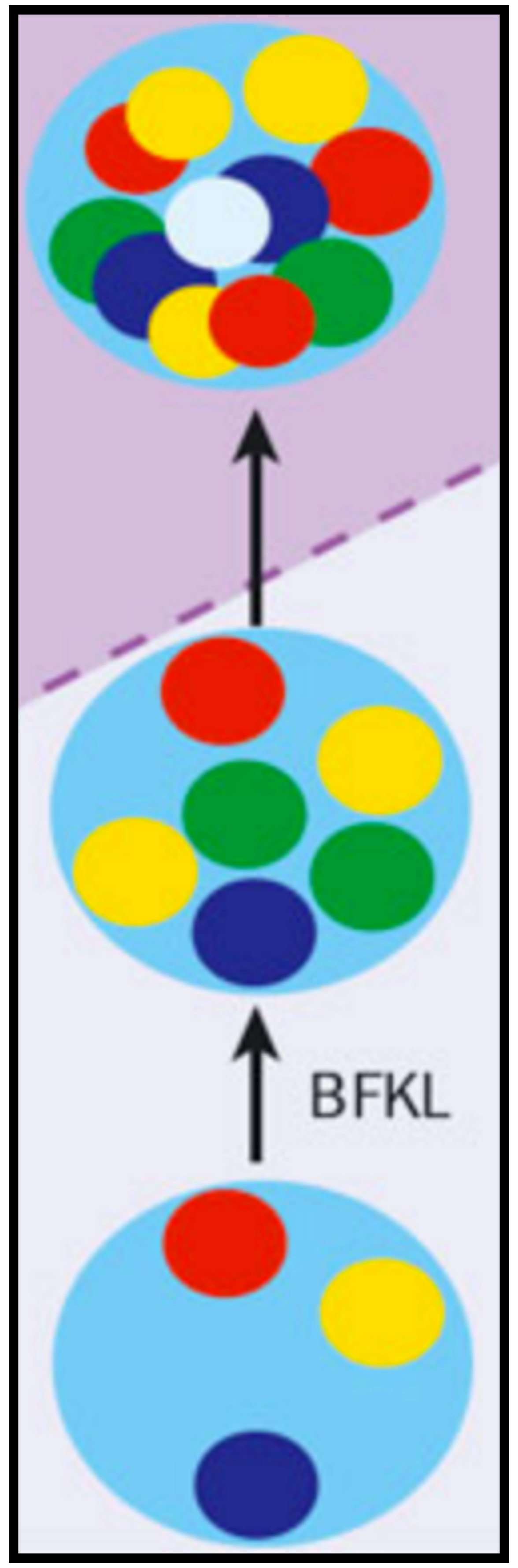

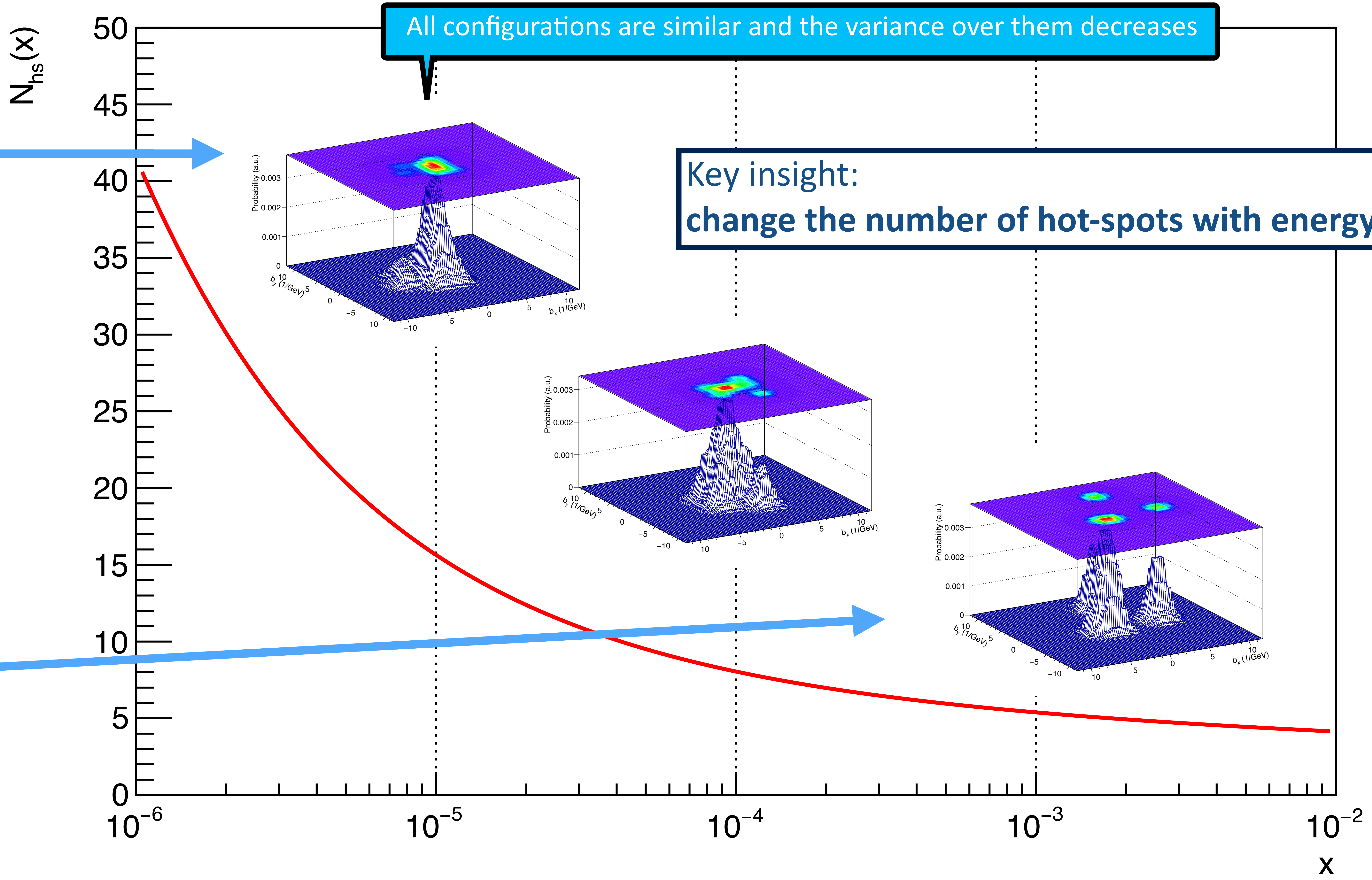

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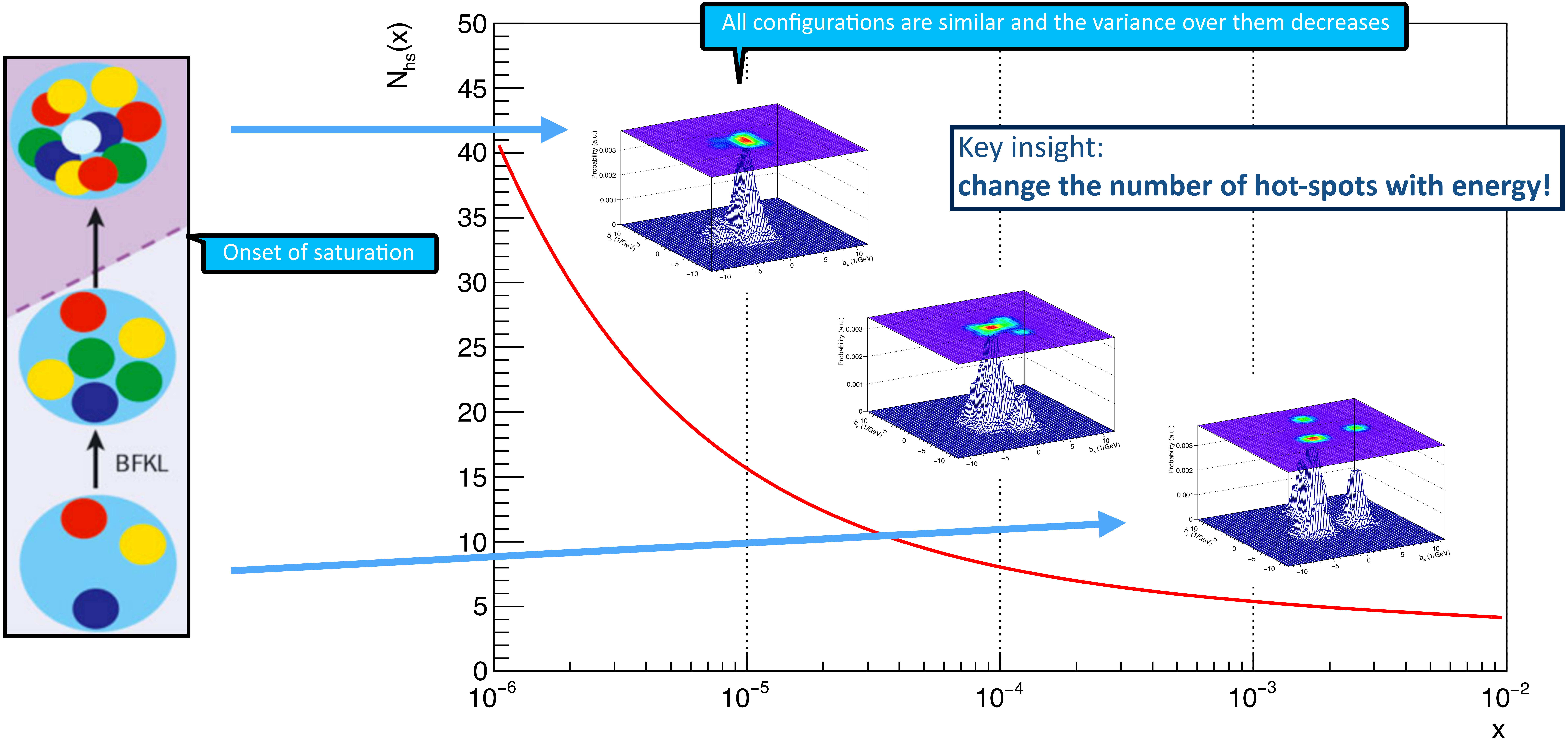

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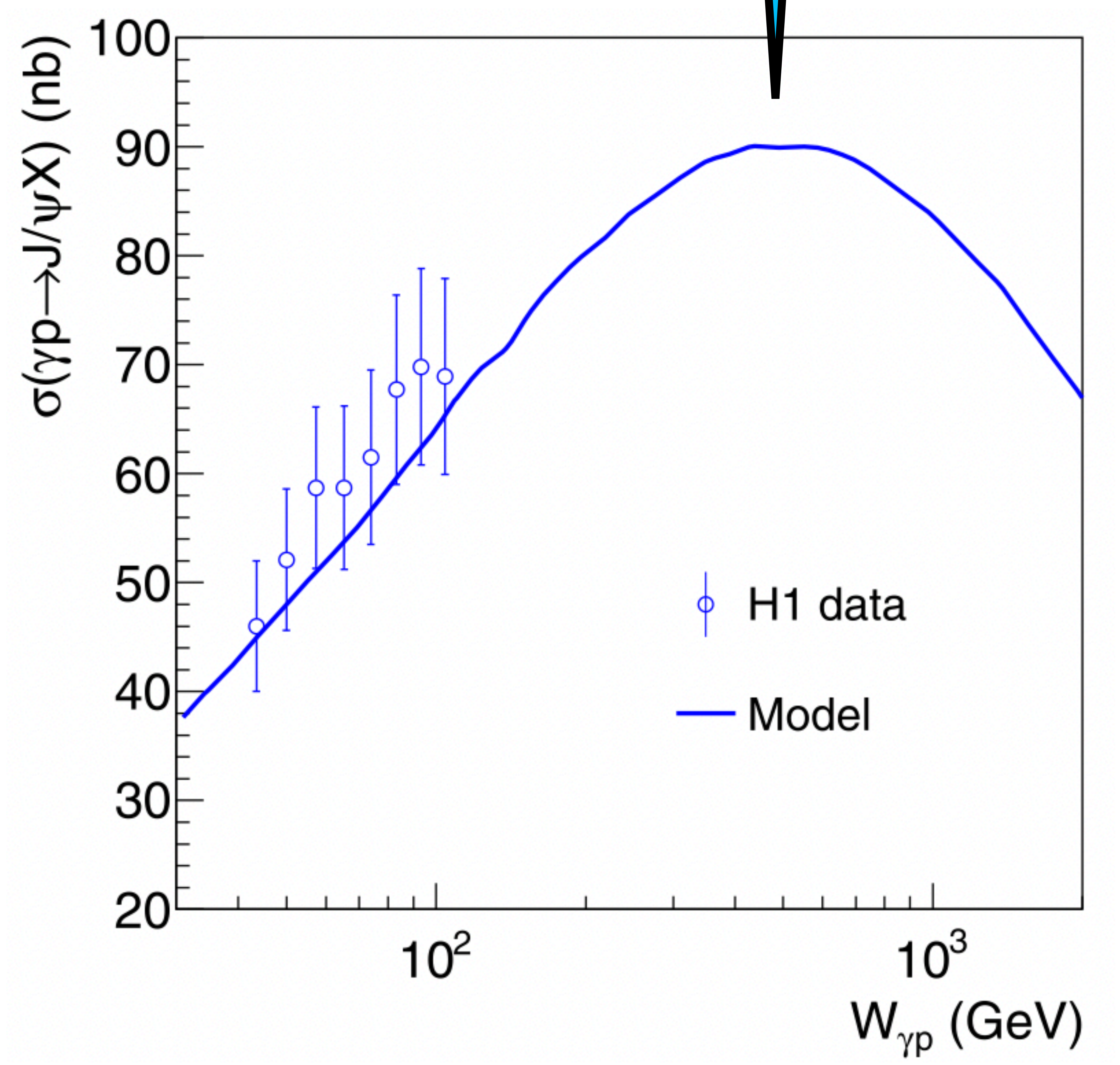
Energy-dependent hot-spot model (2/2)

In this model the onset of saturation is here



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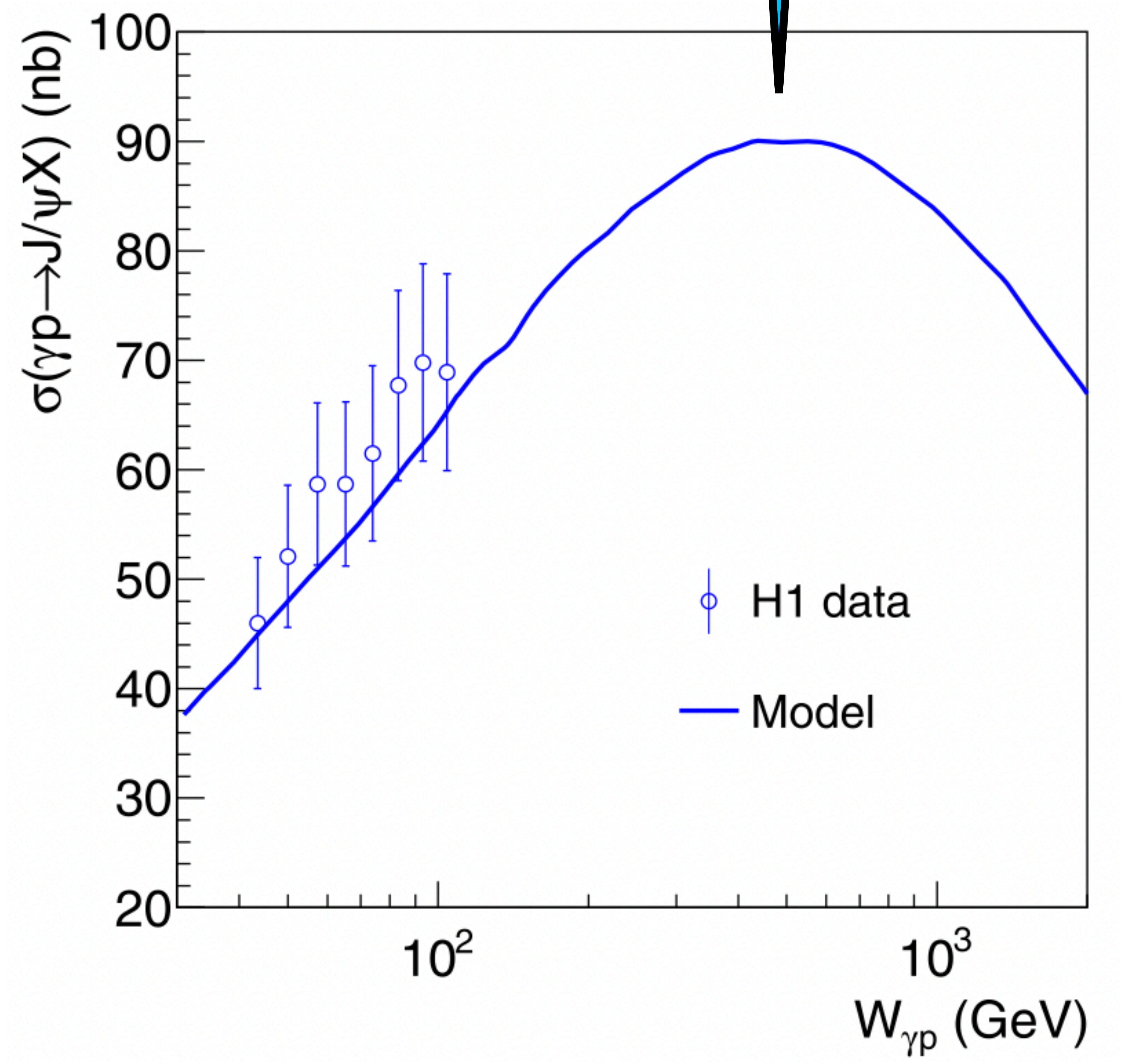

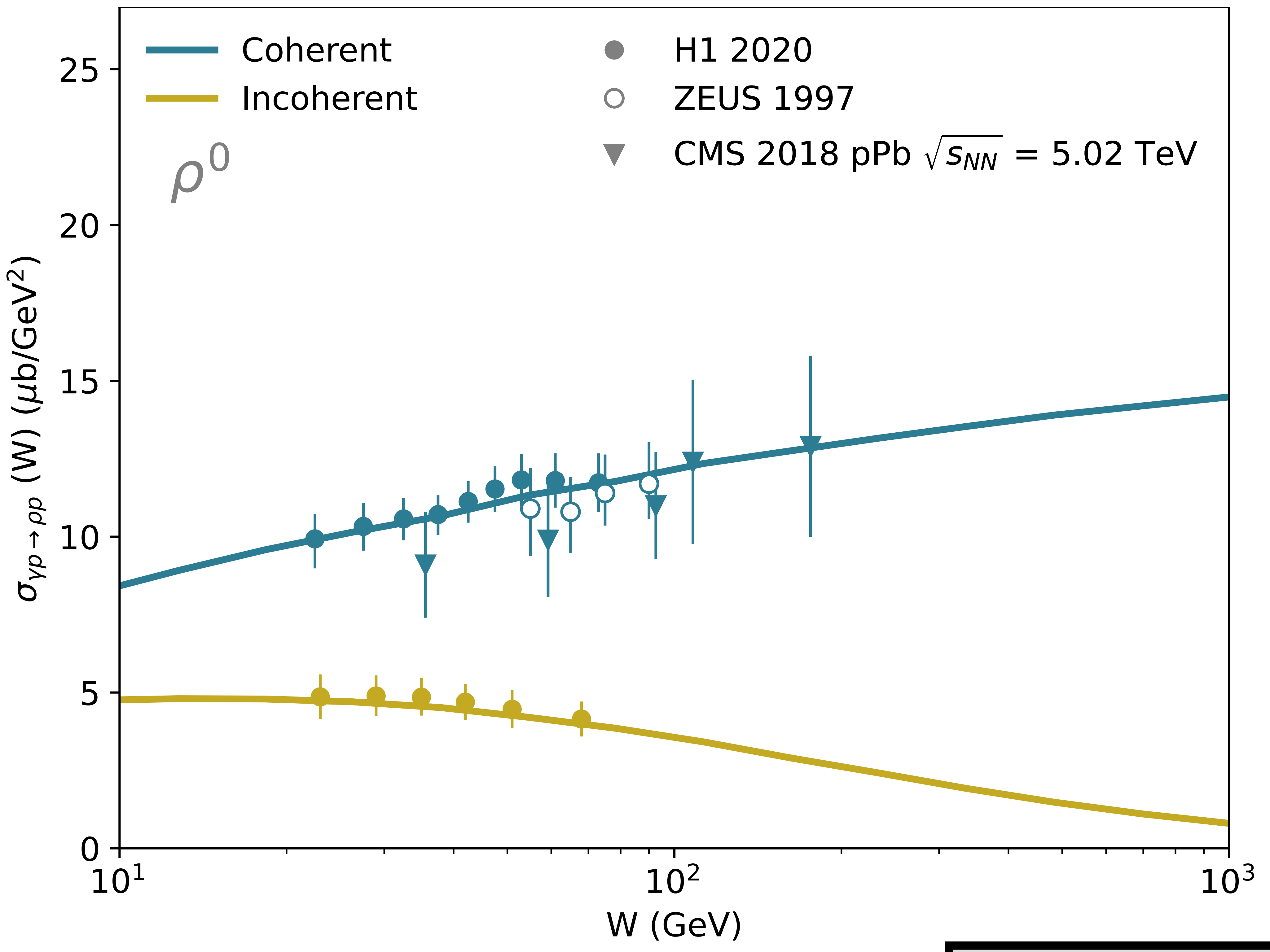

Cepila et al, arXiv 2312.#####

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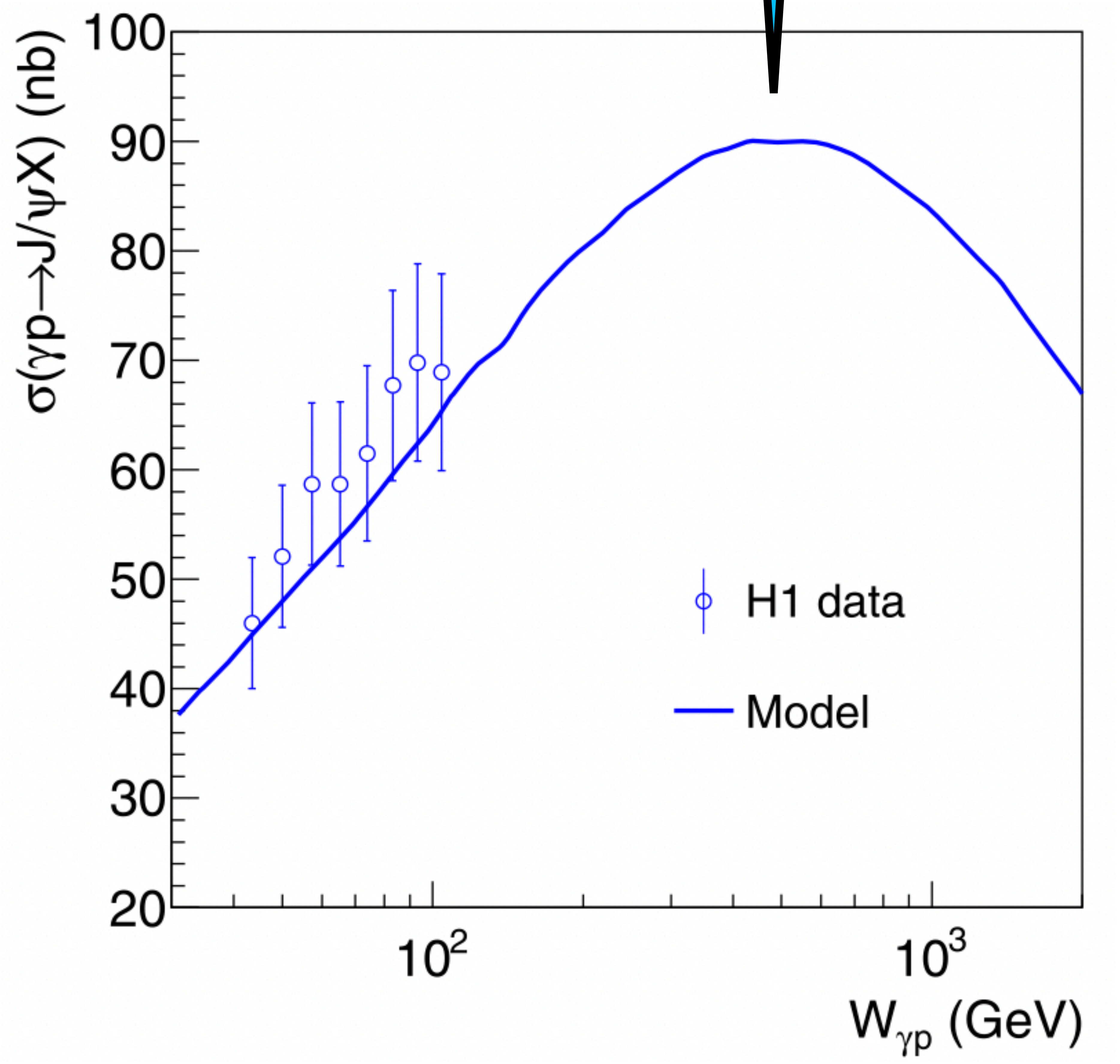

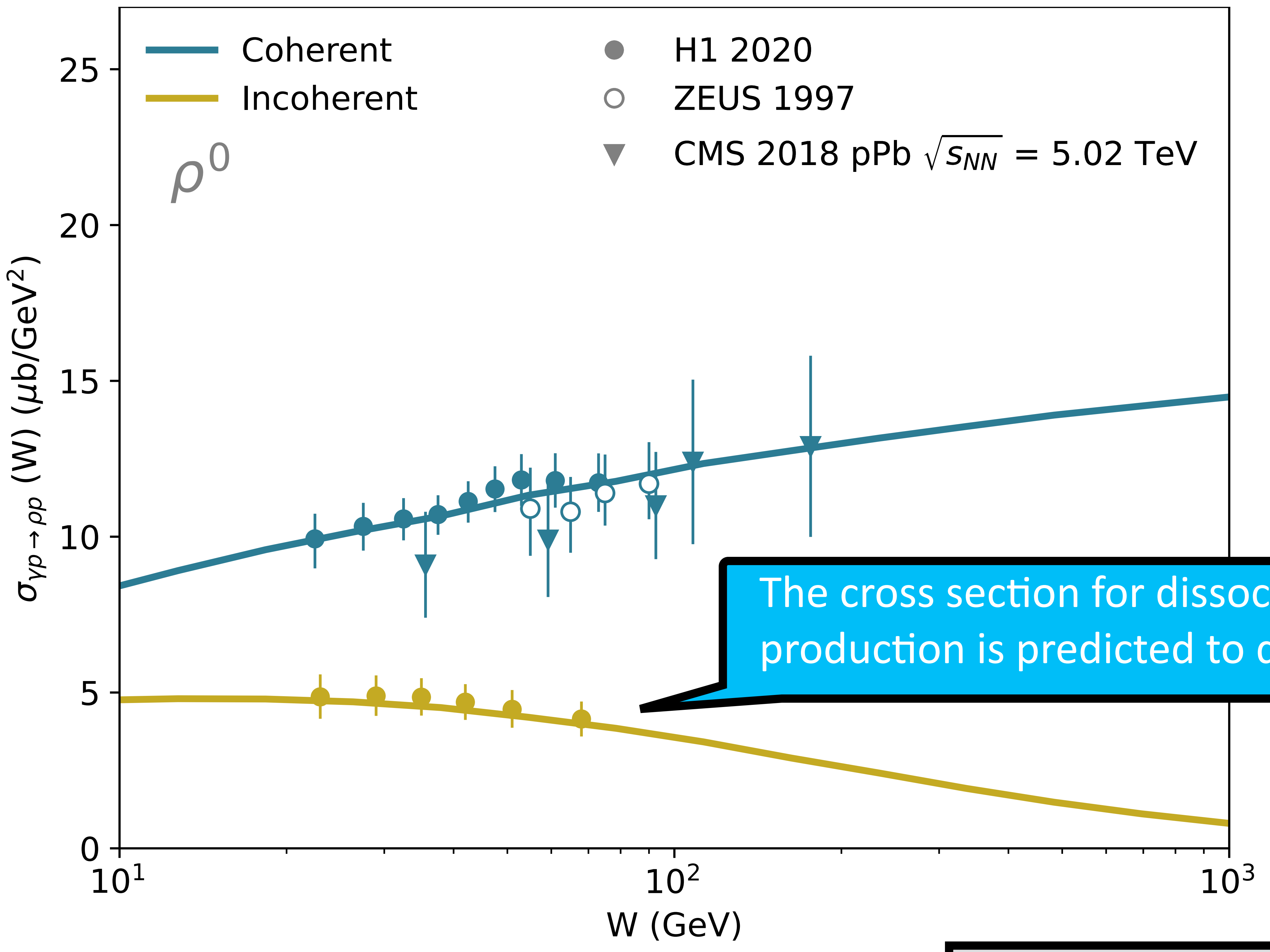

The cross section for dissociative ρ photo-production is predicted to decrease

Cepila et al, arXiv 2312.#####

Cepila, JGC, Tapia Takaki, https://inspirehep.net/literature/1484177

Dissociative ρ photoproduction offers some tantalising results ....
But the ρ mass-scale is low, so the application of perturbative ideas to interpret data is in question
The J/ψ dissociative cross section is still growing at HERA energies,
Where and how can we study this type of processes at even higher energies?

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Where and how can we study this type of processes at even higher energies?

Enter RHIC and the LHC where we can study photon-induced processes off nuclei

5

Understanding the photon flux in collisions of heavy ions

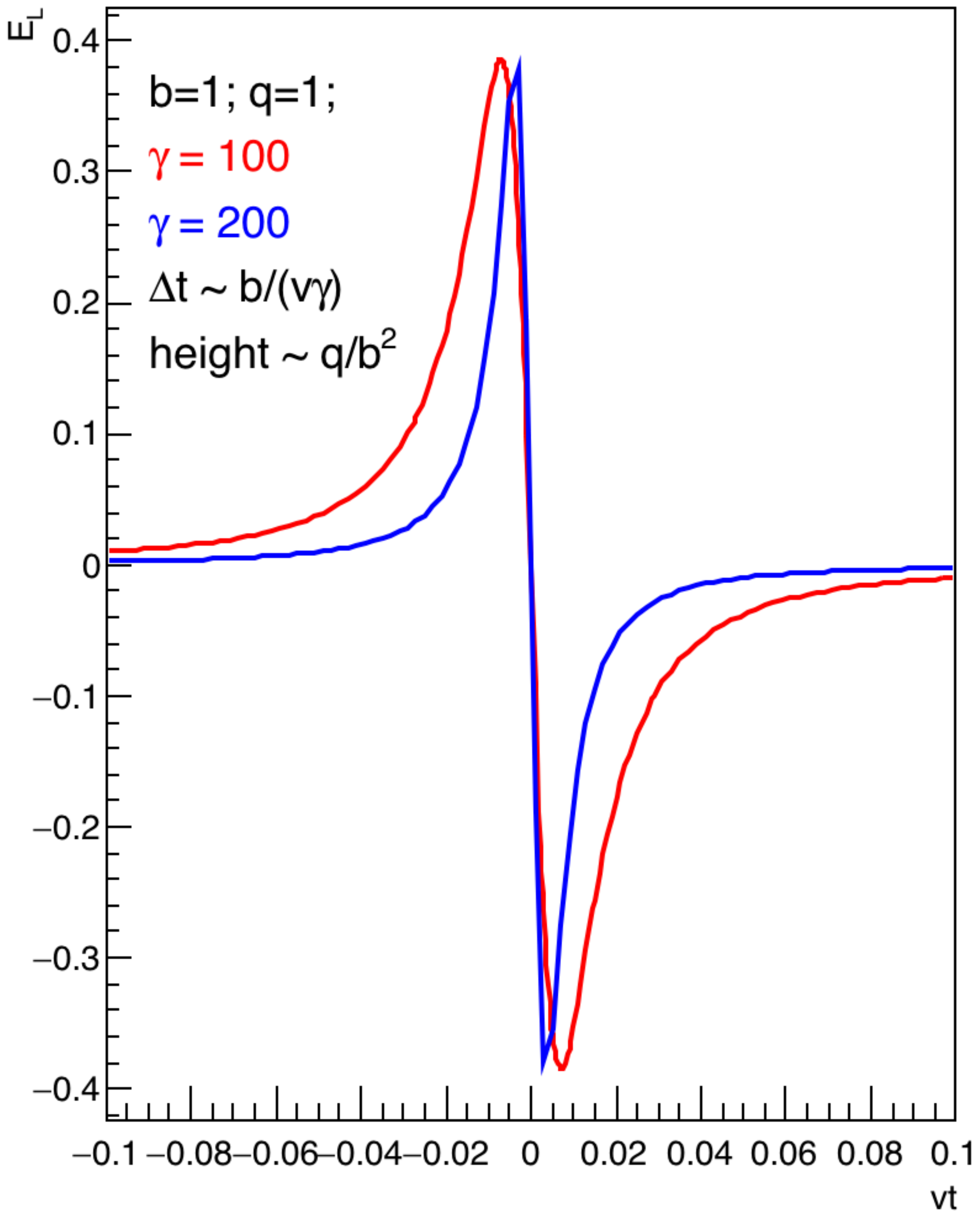
proportional to Z^2

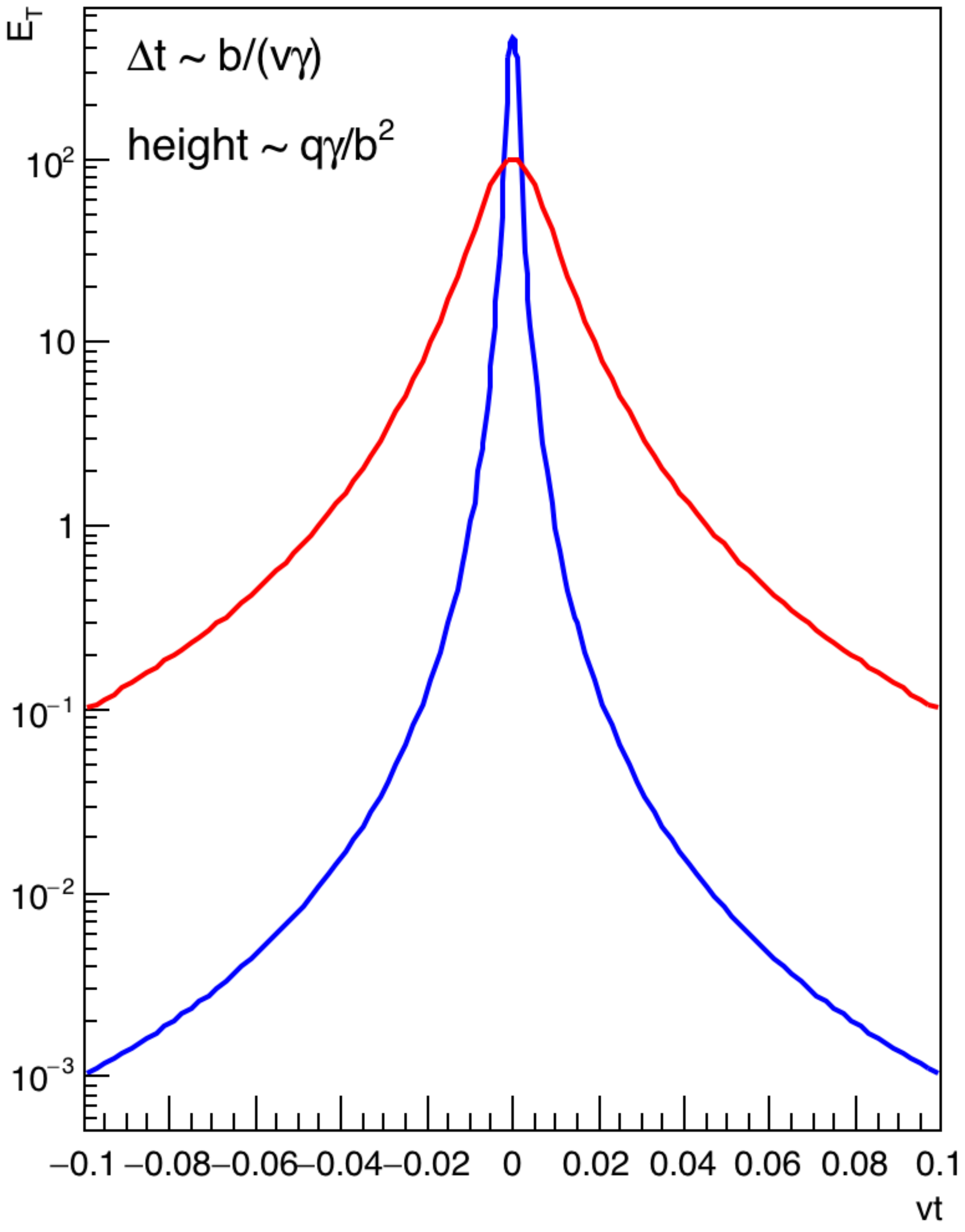
Heavy ions have intense electromagnetic fields that can be used to study photon-induced interactions

The photon flux: field of a point charge

The photon flux: field of a point charge

Take the electric field of the particle at rest and boost it to the collider frame





The photon flux: field of a point charge

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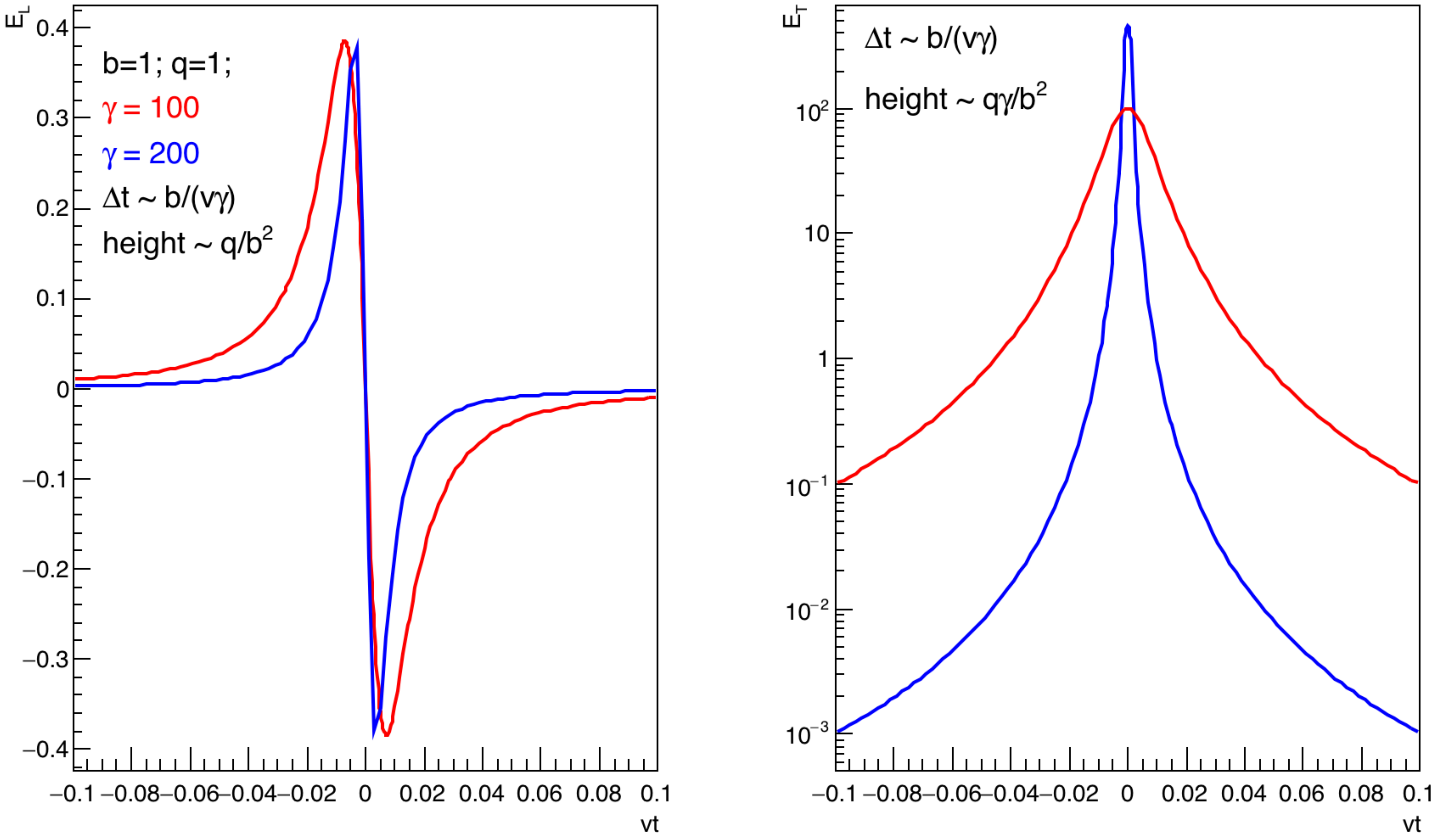
Longitudinal component



Guillermo Contreras, CTU in Prague

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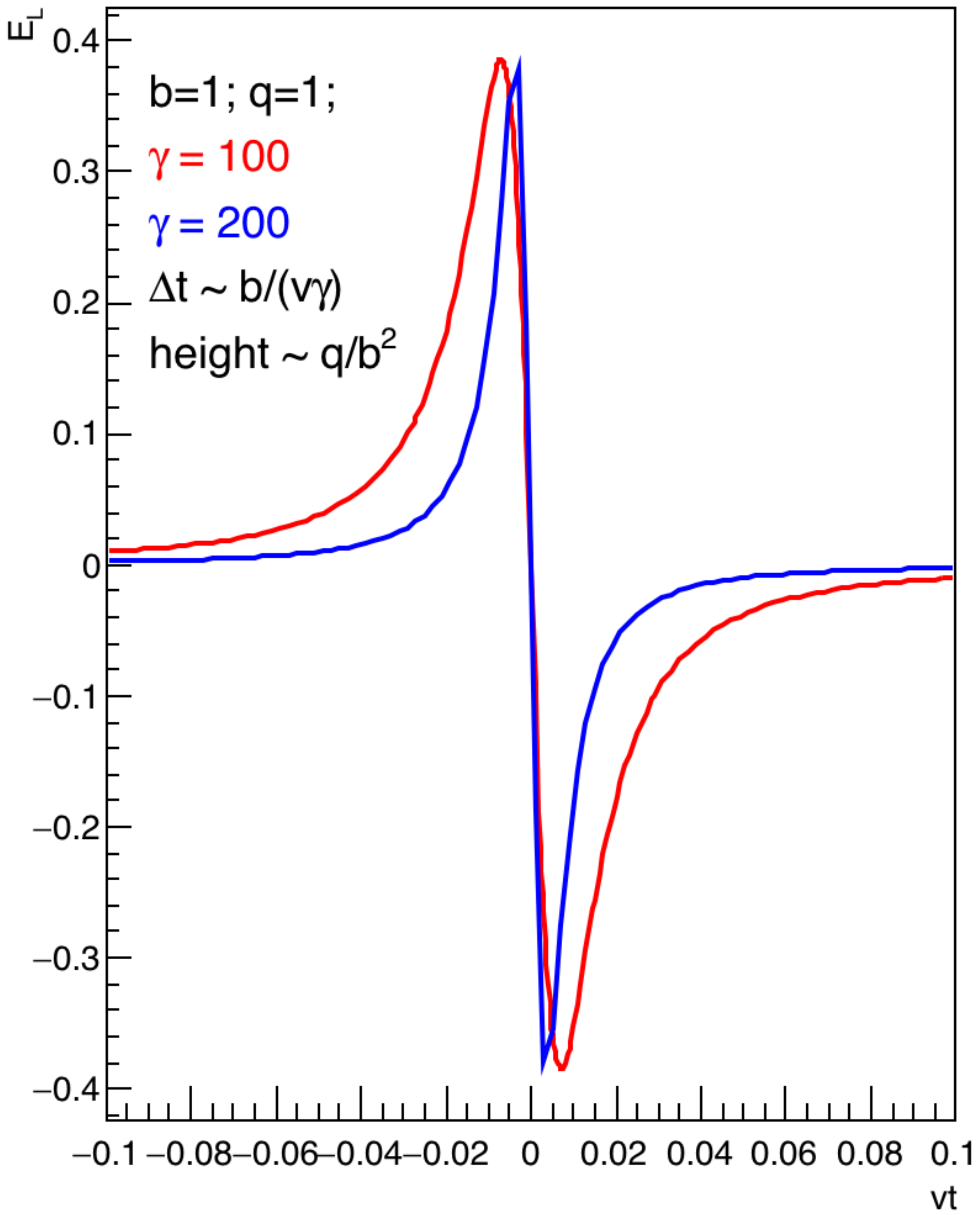
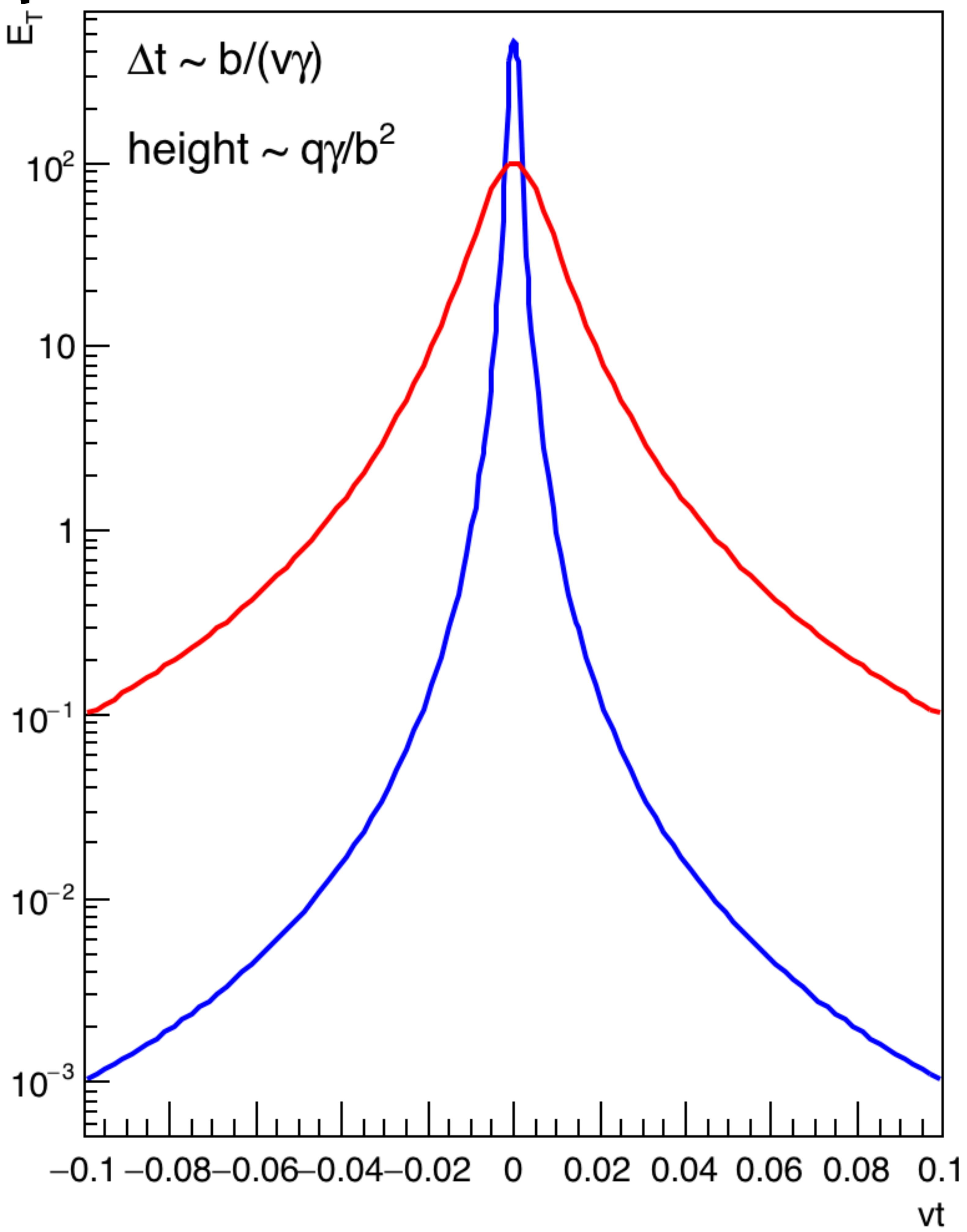


Transverse component



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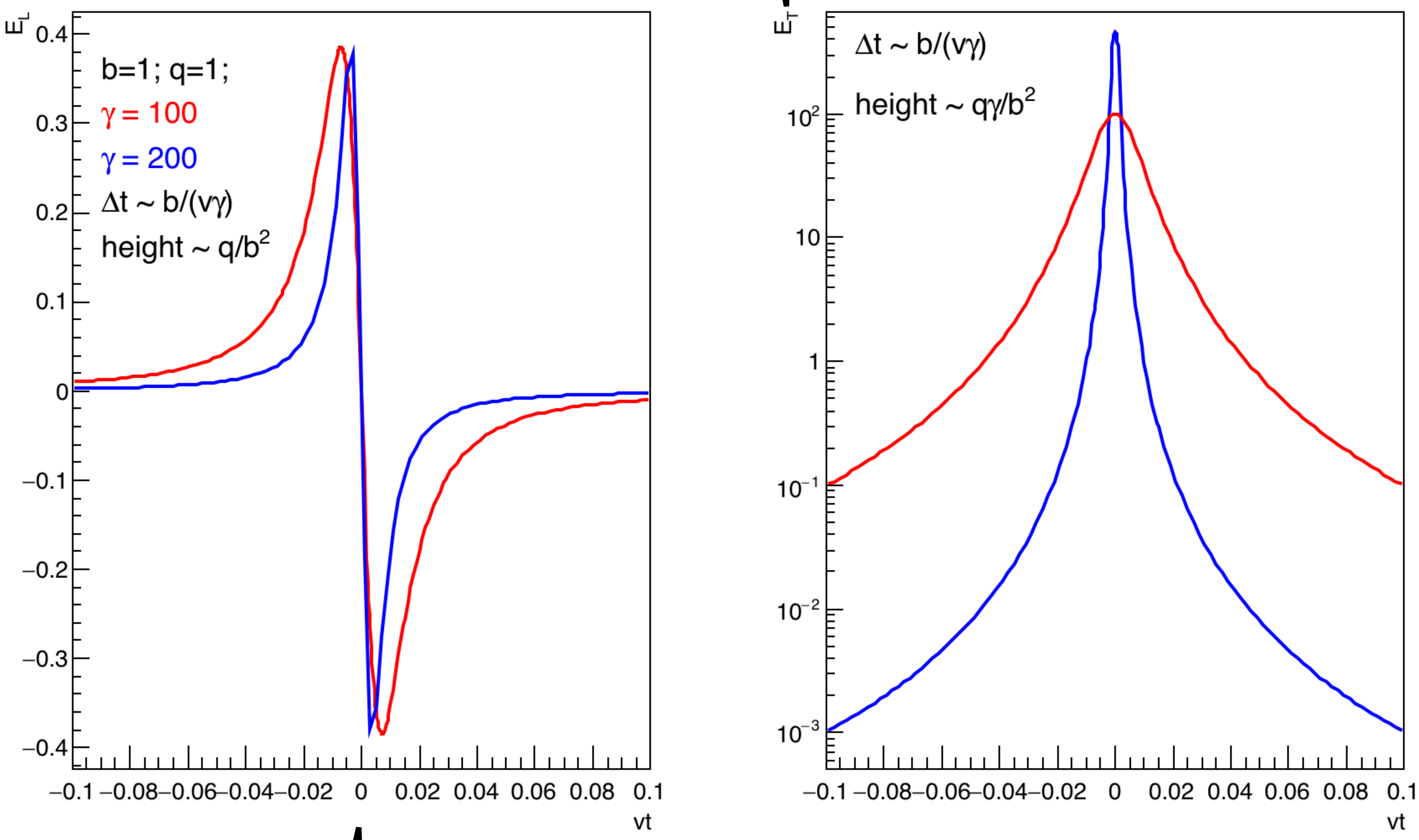

Observation point

Guillermo Contreras, CTU in Prague

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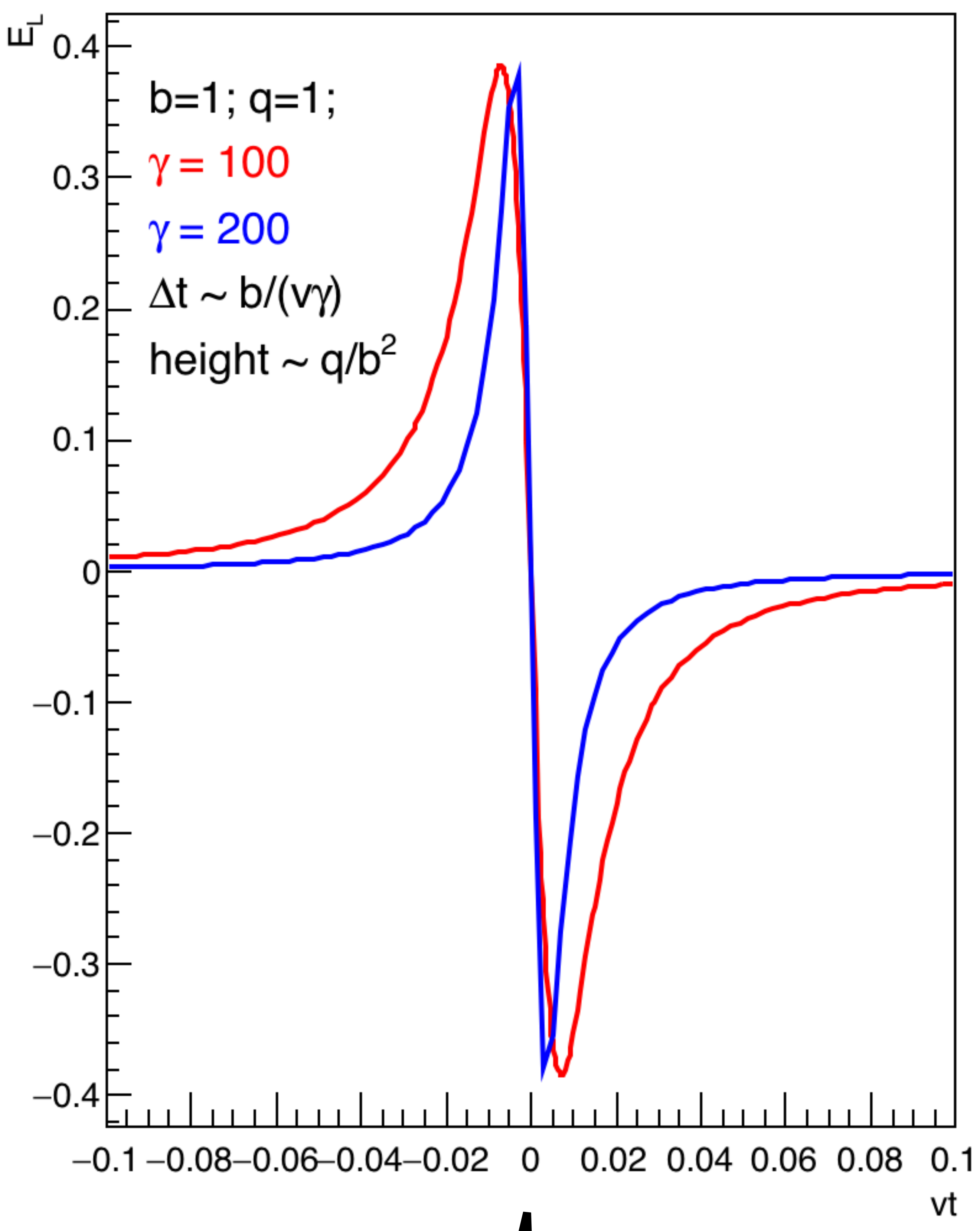

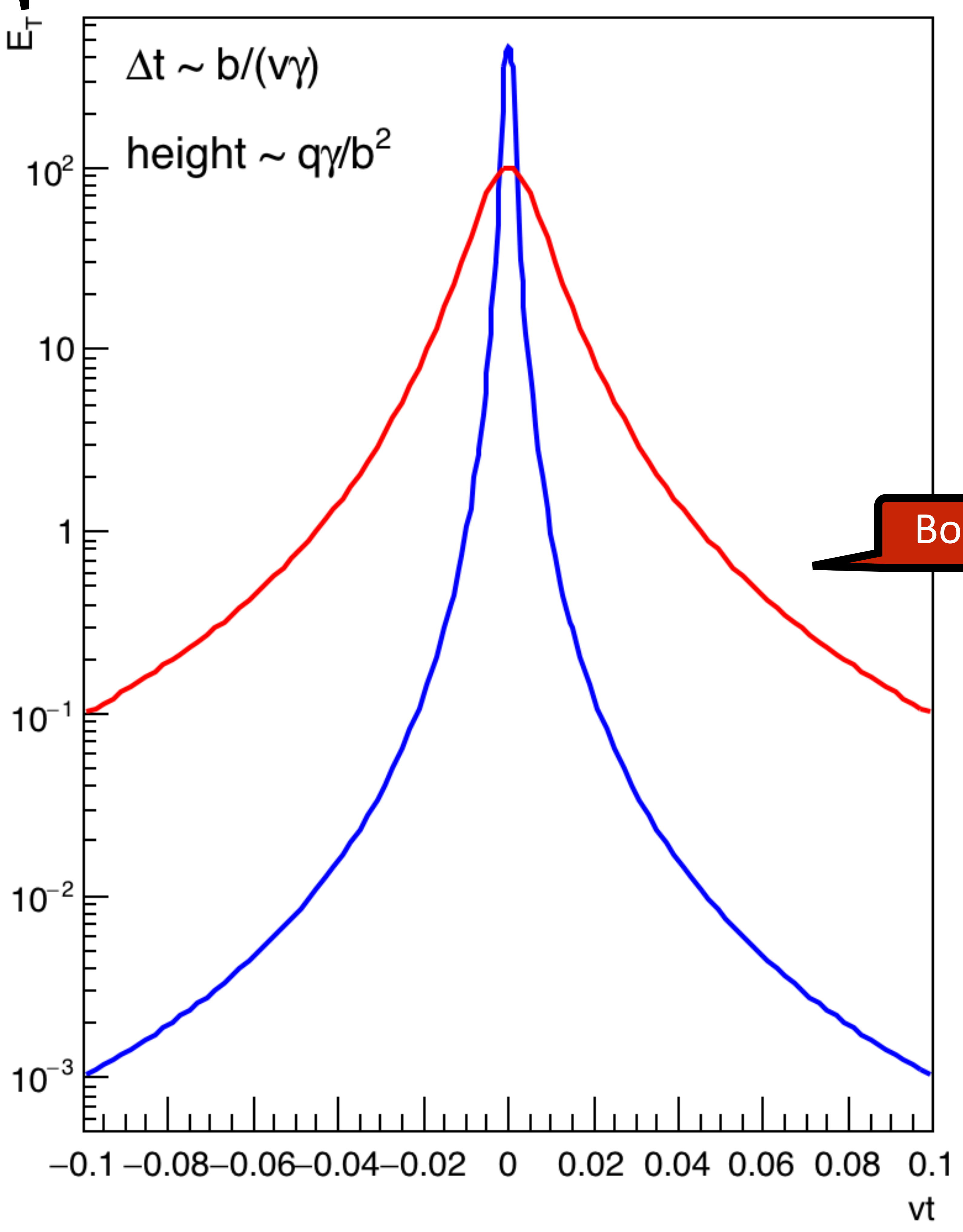

Boost = 100

Observation point

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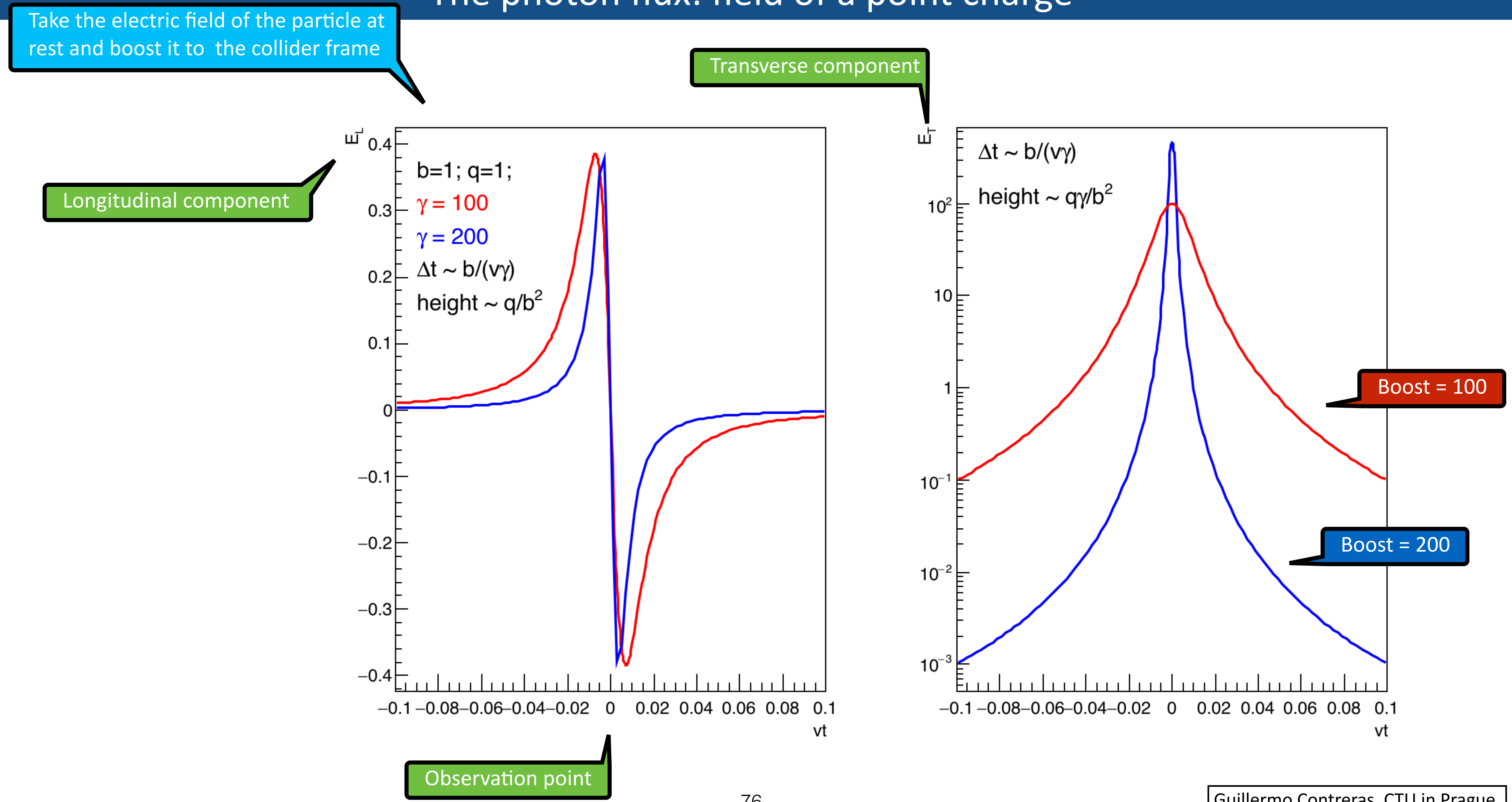

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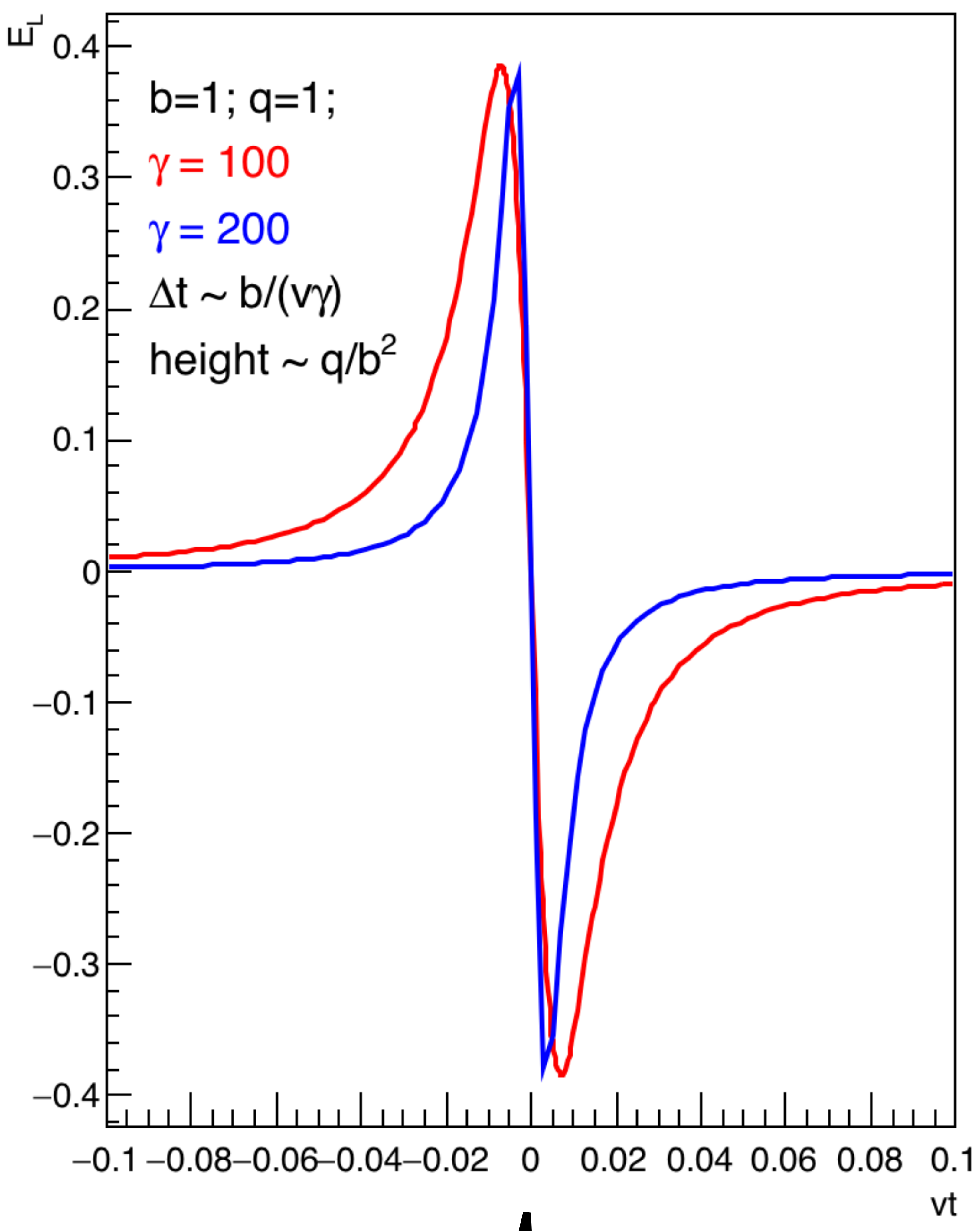
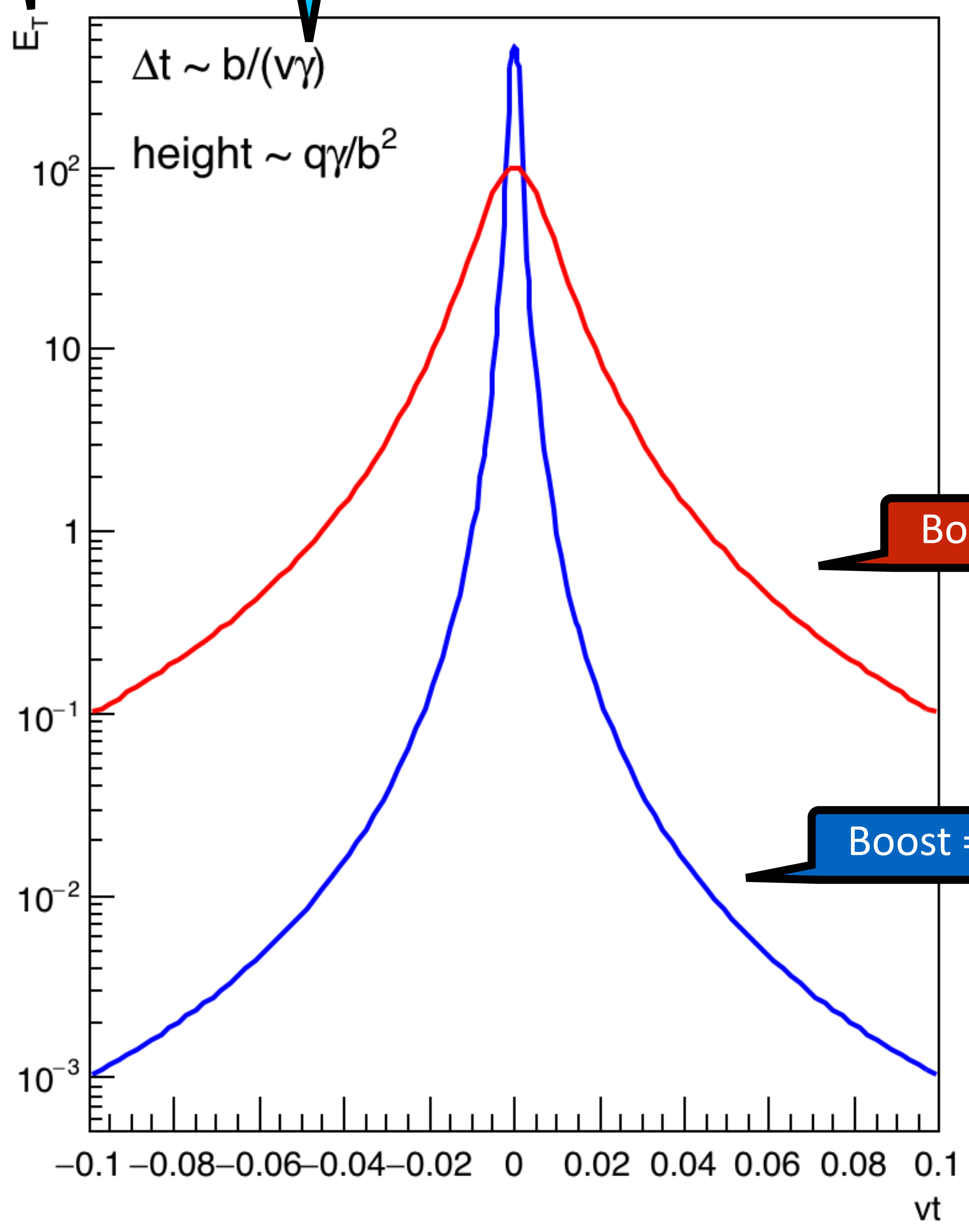
Take the electric field of the particle at rest and boost it to the collider frame

Longitudinal component

Transverse component

Narrowness and height driven by boost factor





Boost = 100

Boost = 200

Observation point

The photon flux: field of a point charge

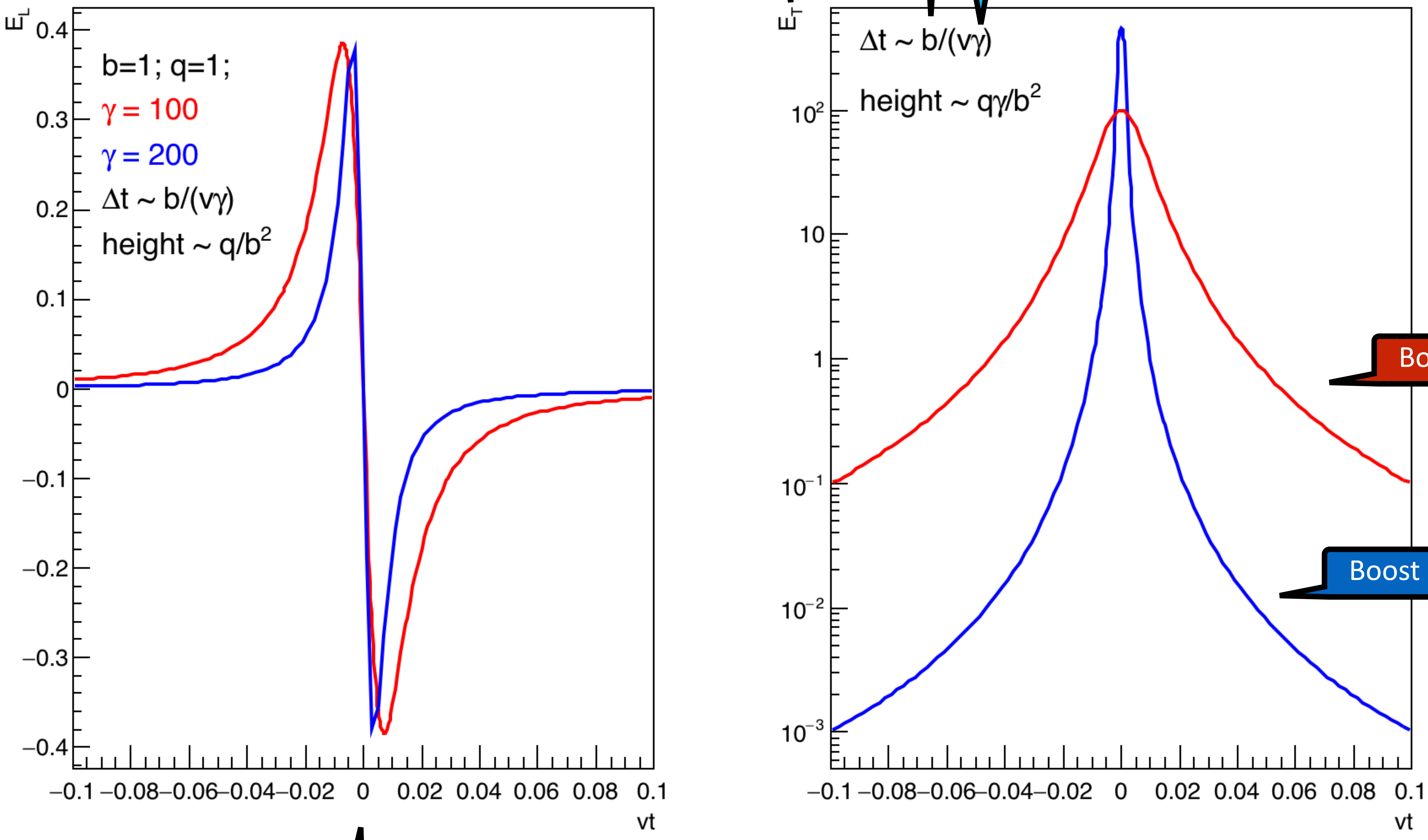
Take the electric field of the particle at rest and boost it to the collider frame

Longitudinal component

Transverse component

... and distance from the charge

Narrowness and height driven by boost factor



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The photon flux: Fourier transform for the field of a point charge

Take the square of the Fourier transform of the electric field into frequency space

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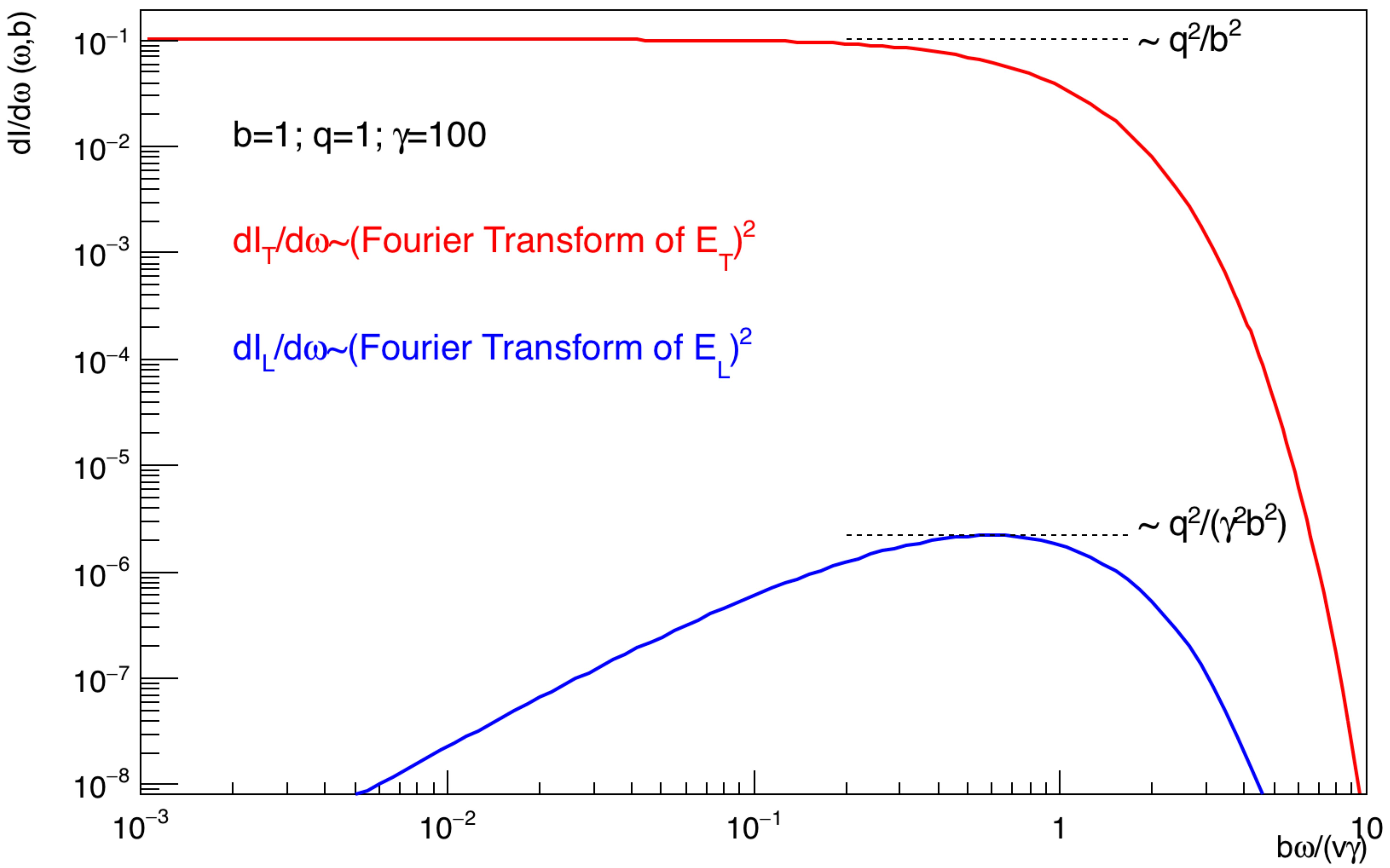

frequency

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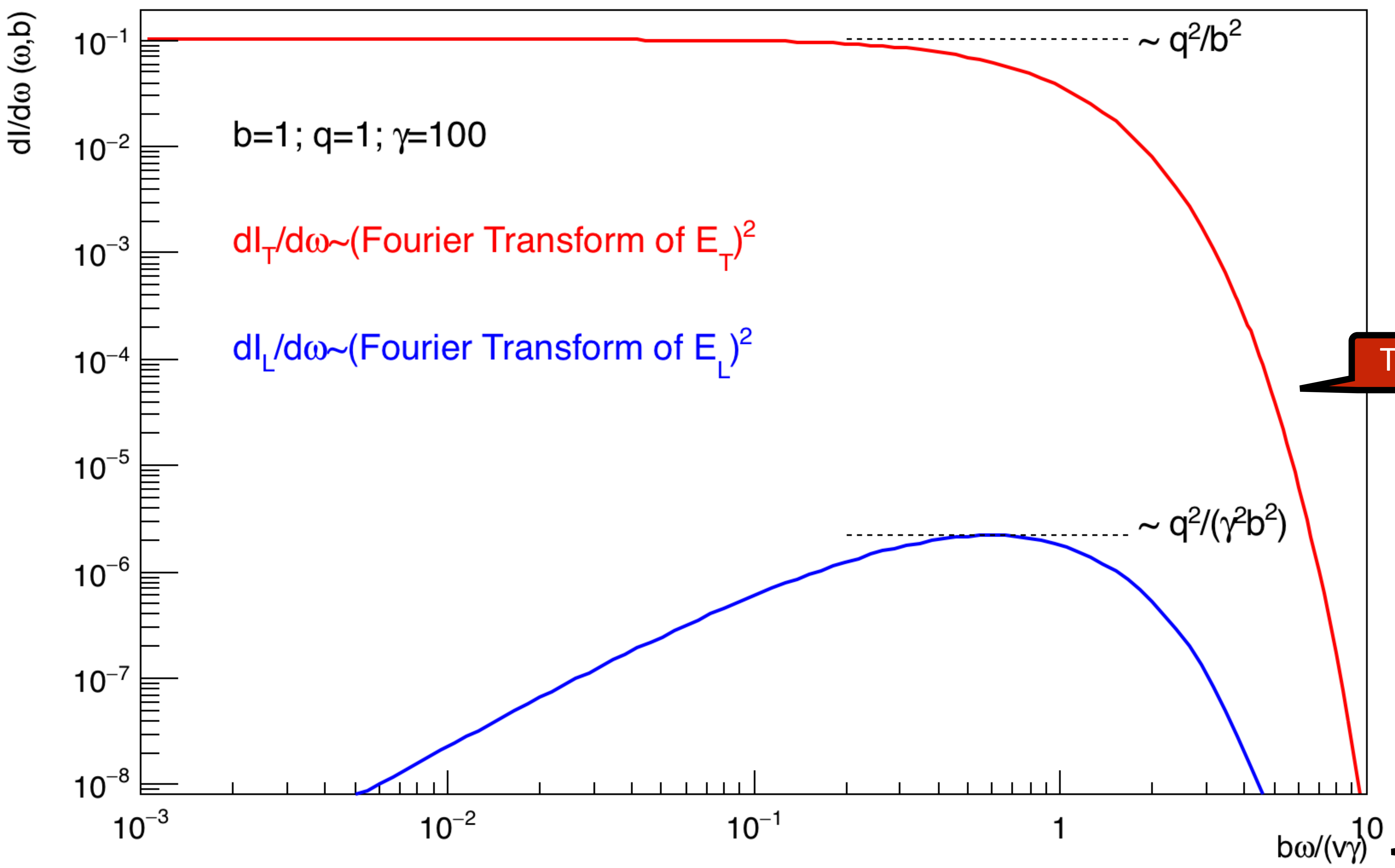

Transverse

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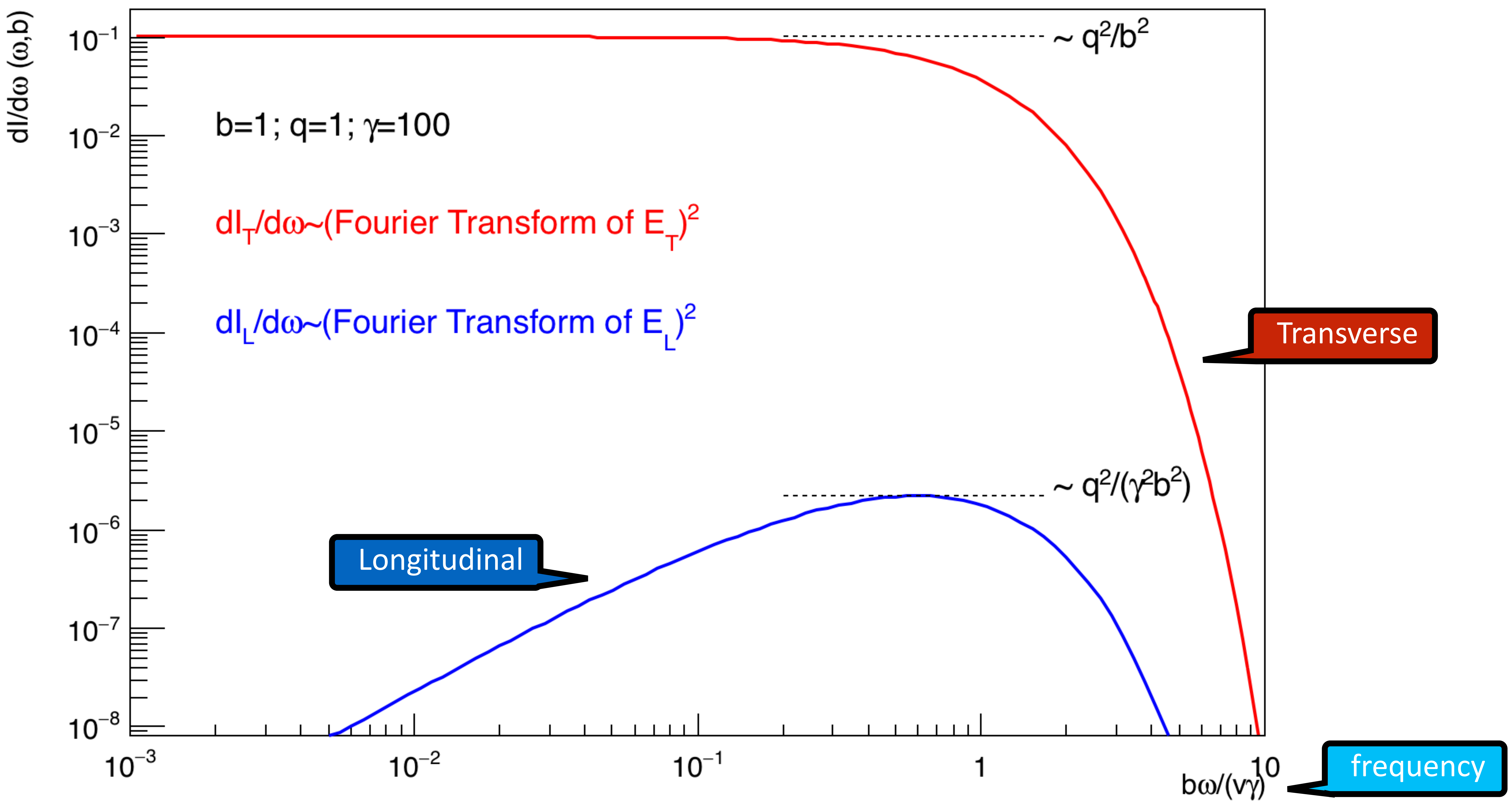

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The photon flux: Fourier transform for the field of a point charge

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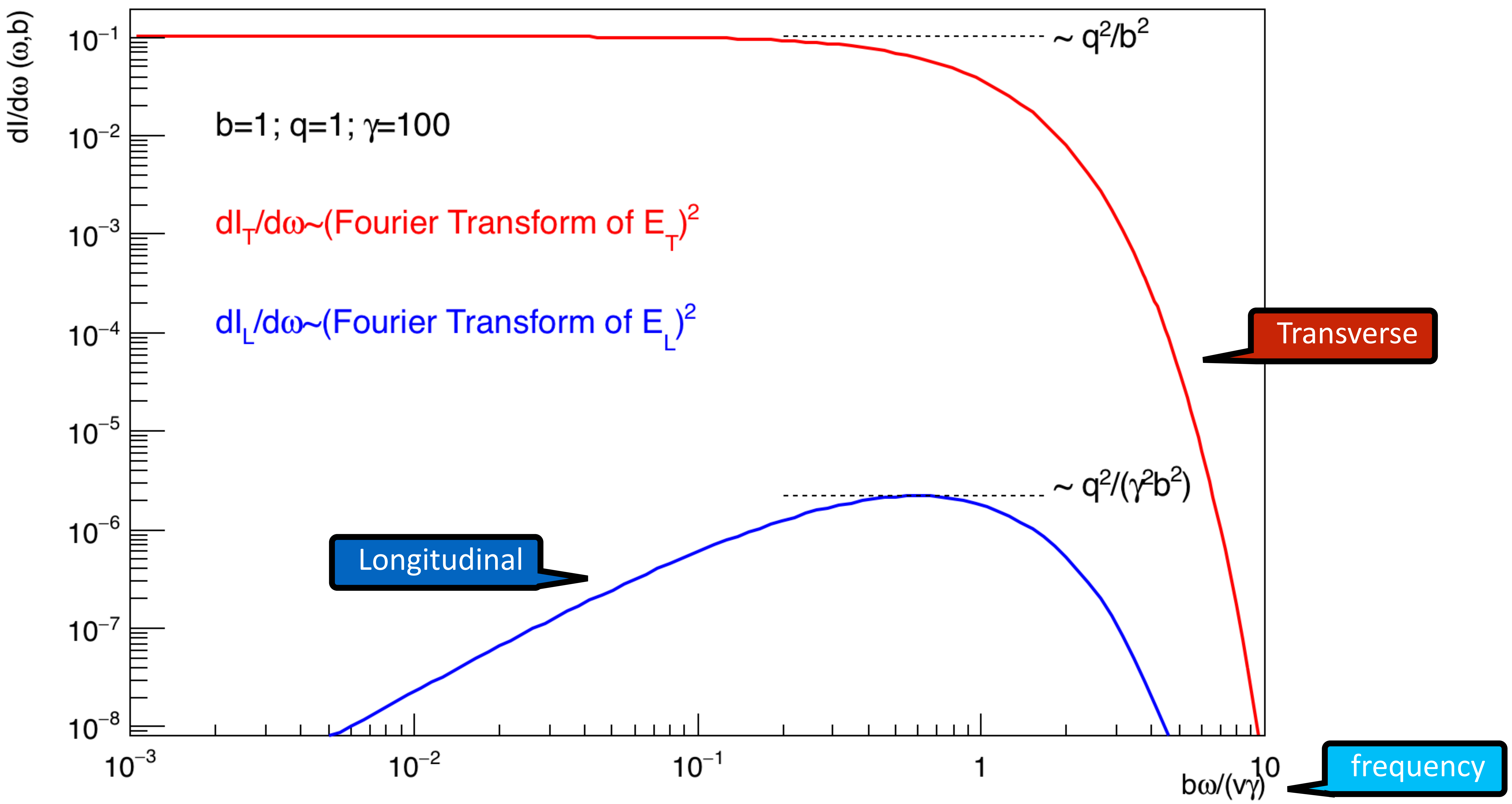
Flat behaviour due to the Dirac-delta-like shape of the field



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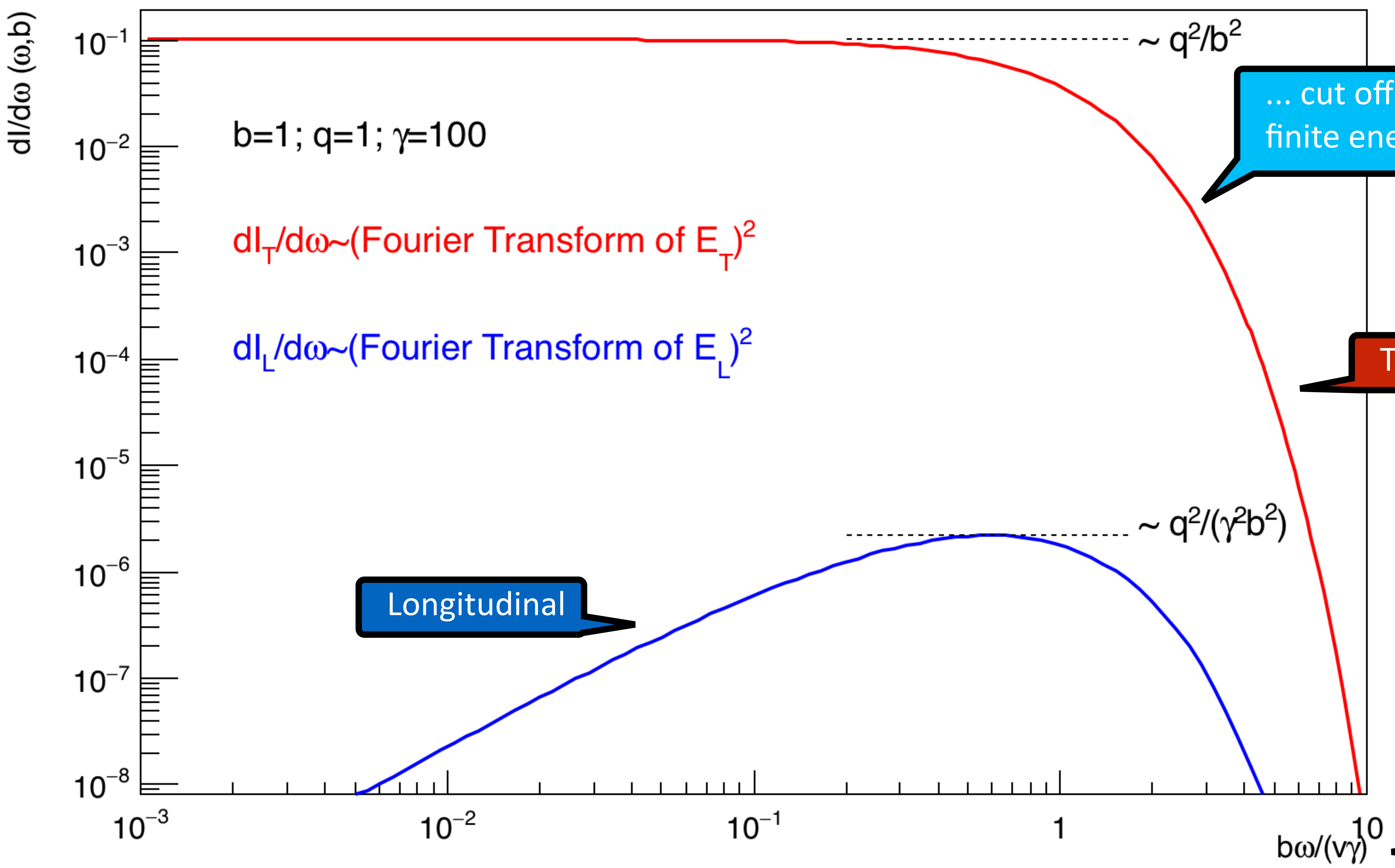

... cut off at large frequencies due to the finite energy (the pulse is not a Dirac delta)

Transverse

Longitudinal

frequency

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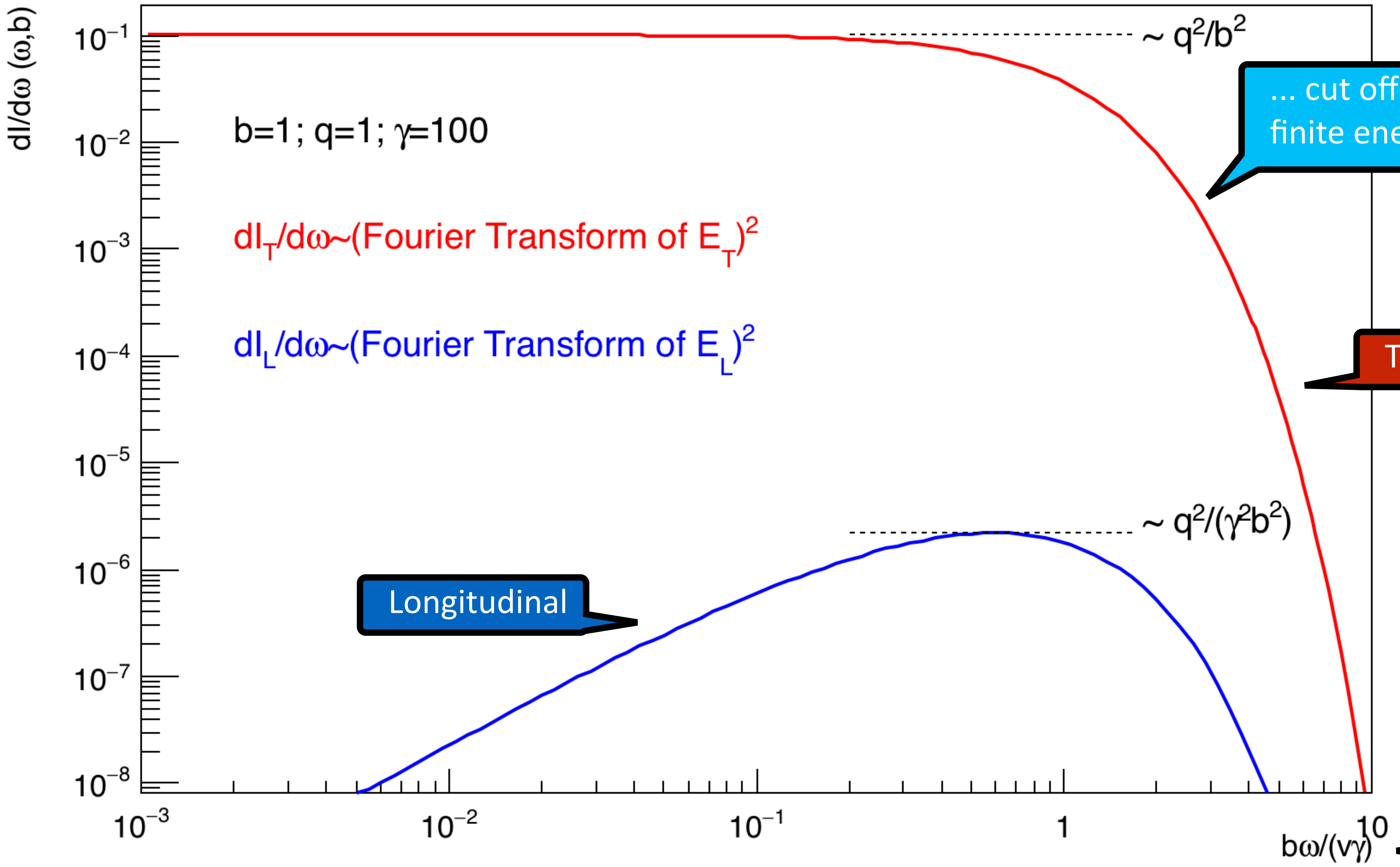

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frequency

This intensity is interpreted as the number of photons with a given energy and at a given transverse distance from the charge.

The photon flux: a bit more general approach

$$n(k, \vec{x}_\perp) = \frac{Z^2 \alpha_{\rm QED}}{\pi^2 k} \left| \int_0^\infty dk_\perp k_\perp^2 \frac{F(k_\perp^2 + (k/\gamma)^2}{k_\perp^2 + (k/\gamma)^2} J_1(x_\perp k_\perp) \right|^2$$

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The number of photons
(known as the photon flux)

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Energy of photon

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Energy of photon

Distance from the centre of the charged particle

The photon flux: a bit more general approach

The number of photons (known as the photon flux)

Particle charge

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Energy of photon

boost

Distance from the centre of the charged particle

The photon flux: a bit more general approach

The number of photons (known as the photon flux)

Particle charge

Form factor

$$n(k,\vec{x}_\perp) = \frac{Z^2\alpha_{\mathrm{QED}}}{\pi^2 k}\left|\int_0^\infty dk_\perp k_\perp^2 \frac{F(k_\perp^2+(k/\gamma)^2)}{k_\perp^2+(k/\gamma)^2} J_1(x_\perp k_\perp)\right|^2$$

Energy of photon

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The number of photons (known as the photon flux)

Energy of photon

Distance from the centre of the charged particle

Particle charge

Form factor

Point charge

Fourier-Bessel transform of a Woods-Saxon distribution

boost

The photon flux: a bit more general approach

STARlight https://inspirehep.net/literature/1475495

STARlight: convolution of a Yukawa potential and a hard sphere

Point charge

Fourier-Bessel transform of a Woods-Saxon distribution

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Particle charge

Form factor

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Energy of photon

boost

Distance from the centre of the charged particle

Form factor of a point charge

Form factor

$$F_{pc}(q) = 1$$

Integral can be done analytically

$$n_{pc}(k, \vec{x}_\perp) = \frac{Z^2 \alpha_{\rm QED} k}{\pi^2 \gamma^2} K_1^2(k x_\perp / \gamma)$$

Other form factors

Used in STARlight

$$F_{hsY}(q) = \frac{4\pi d_0}{Aq^3}\left[\sin(qR_A) - qR_A\cos(qR_A)\right]\left(\frac{1}{1+a^2q^2}\right)$$

Other form factors

Used in STARlight

$$F_{hsY}(q) = \frac{4\pi d_0}{Aq^3}\left[\sin(qR_A) - qR_A\cos(qR_A)\right]\left(\frac{1}{1+a^2q^2}\right)$$

$$F_{WS}(q) = \frac{4\pi}{qA}\int \rho(r)\sin(rq)r dr$$

Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{1+\exp(\frac{r-r_A}{z})}$$

Other form factors

Form factor

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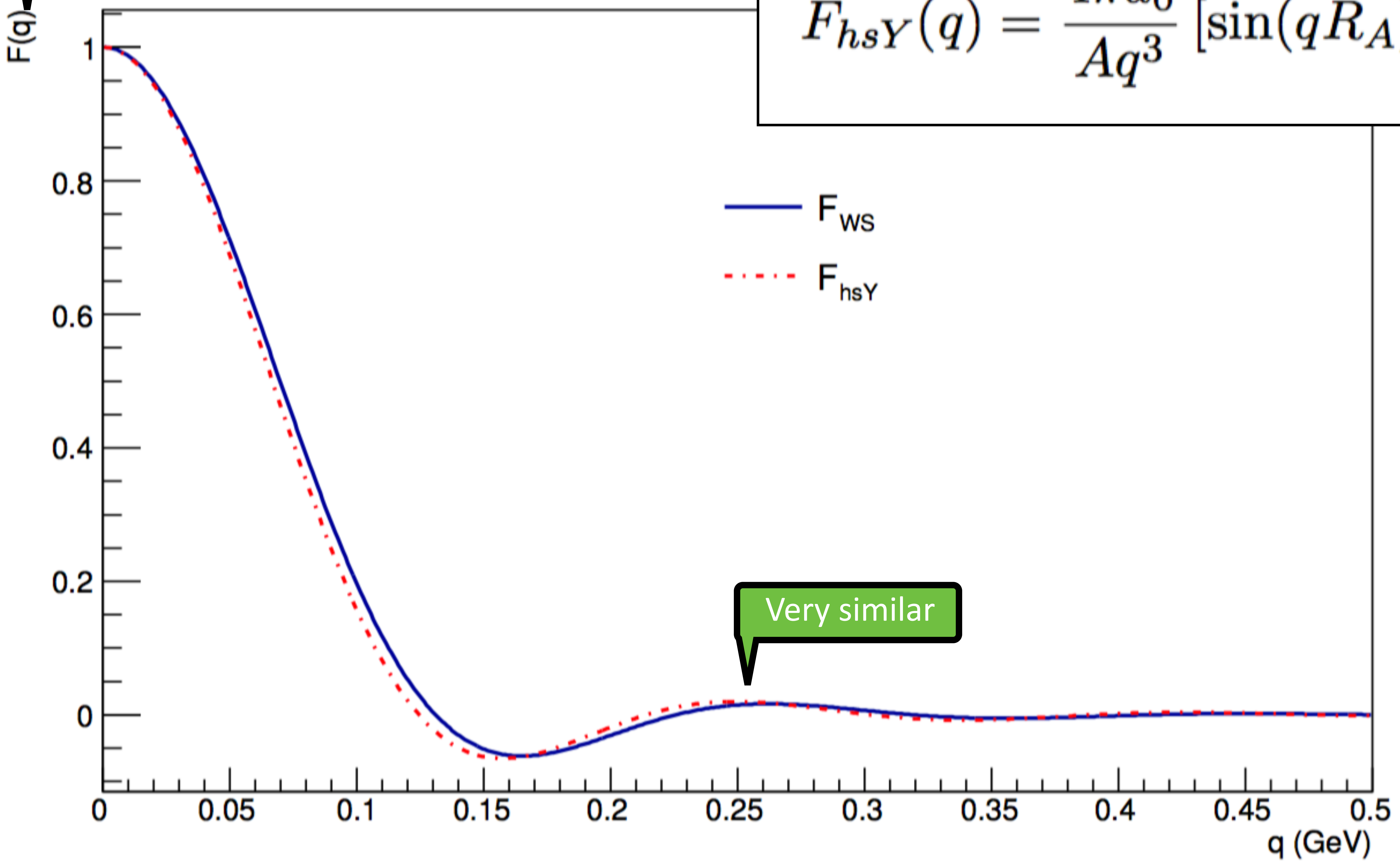

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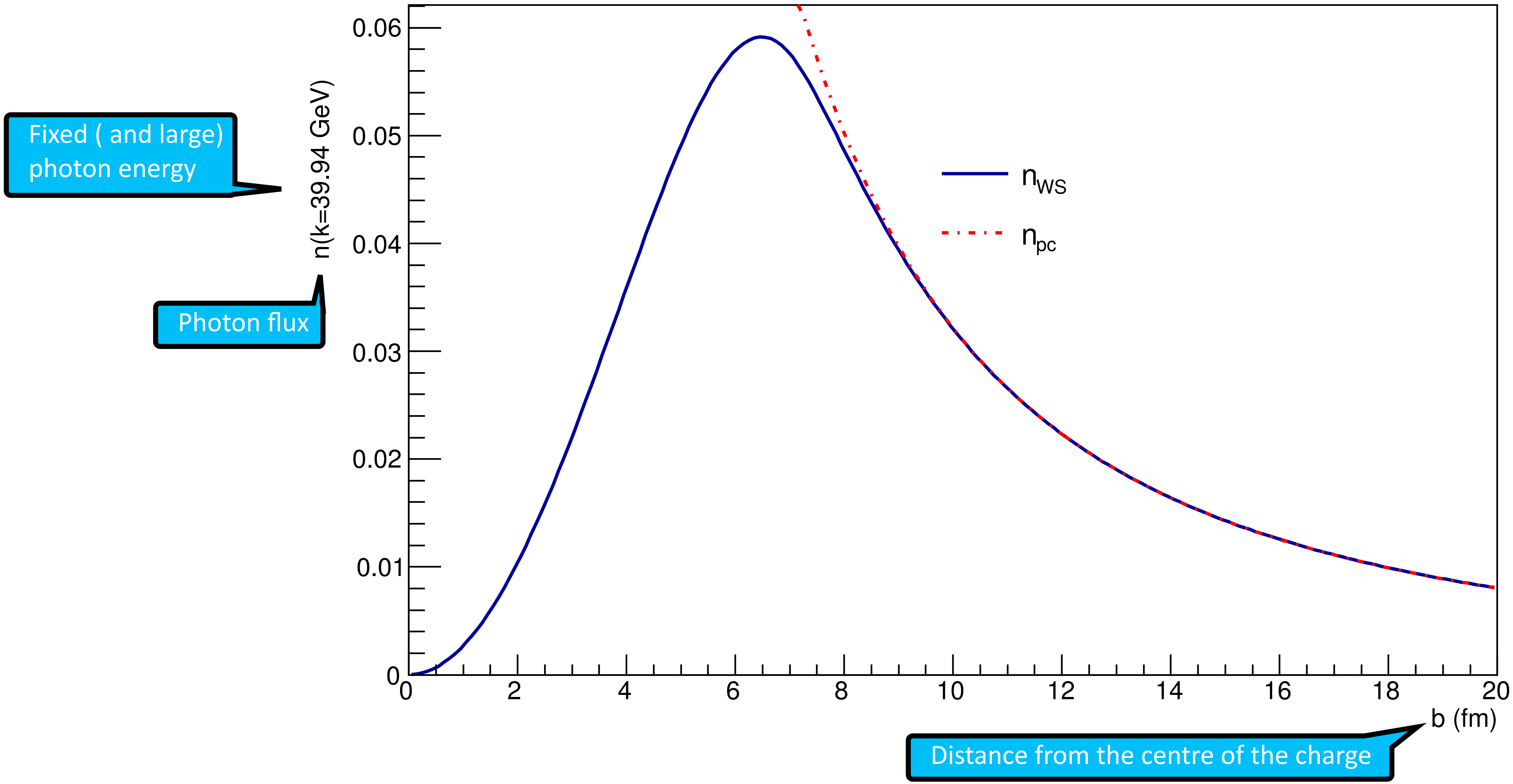
Magnitude of the transferred momentum

JGC, Phys.Rev. C96 (2017) 015203

Comparing fluxes

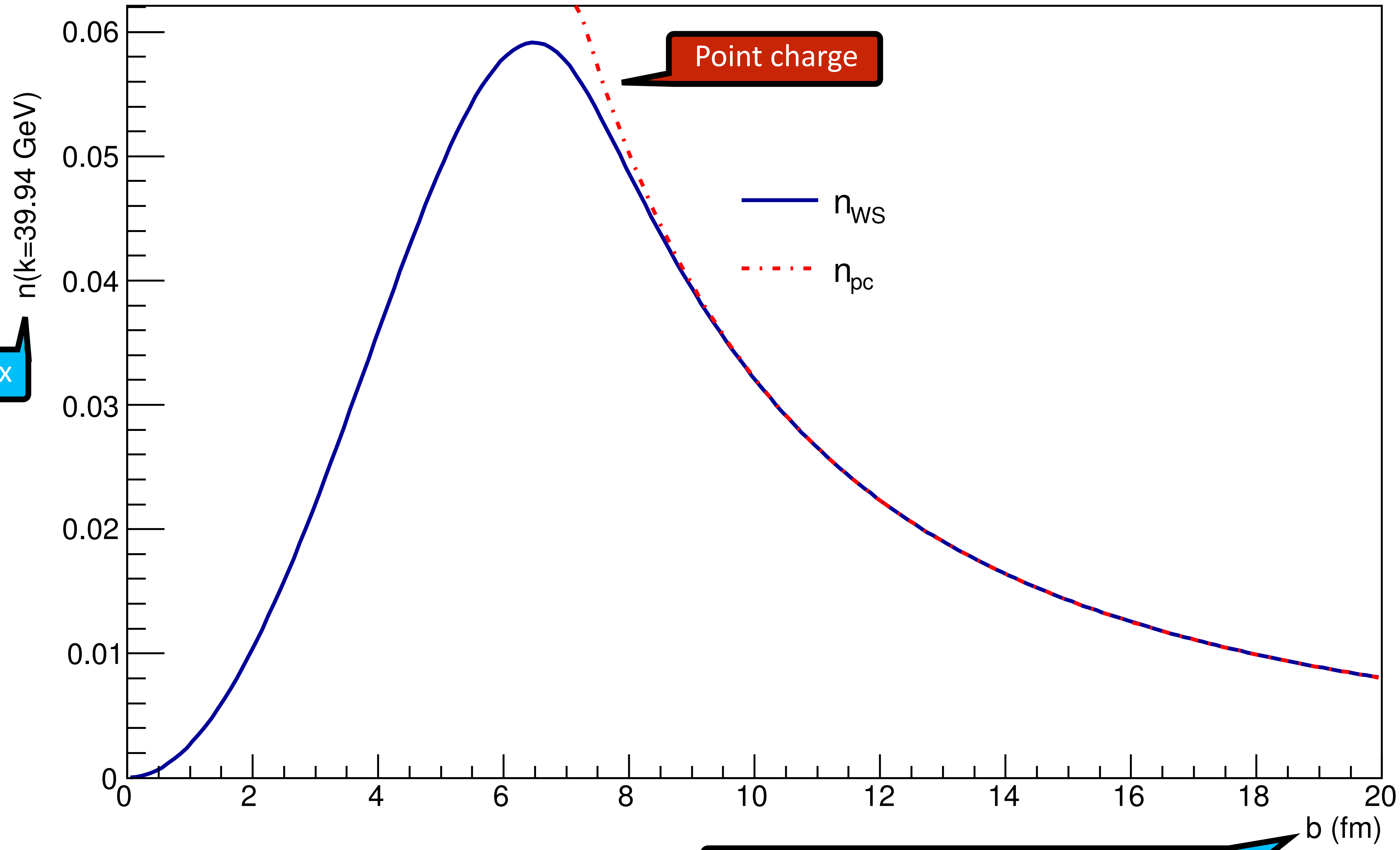


JGC, Phys.Rev. C96 (2017) 015203

Comparing fluxes

Fixed (and large) photon energy

Photon flux

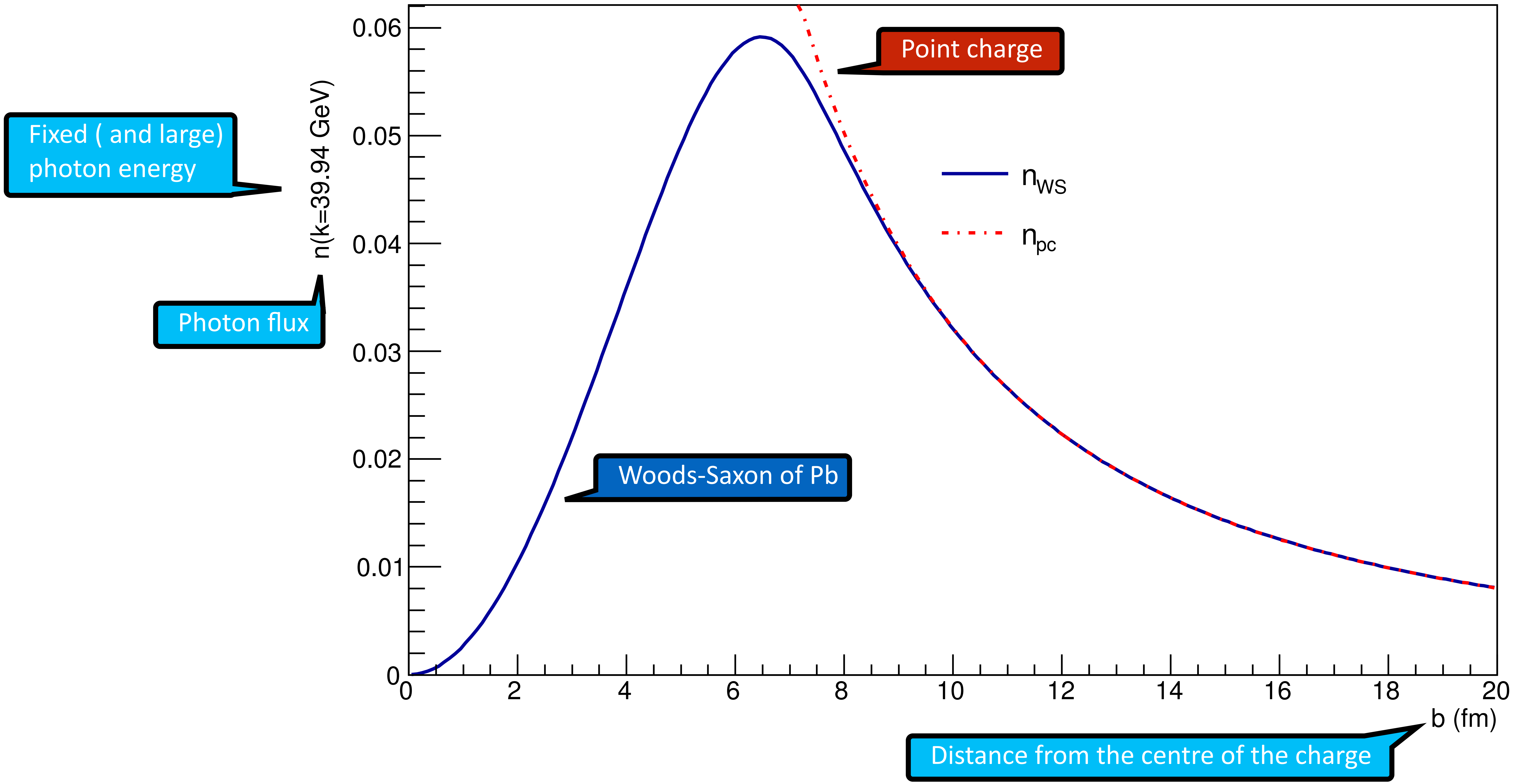


Point charge

Distance from the centre of the charge

JGC, Phys.Rev. C96 (2017) 015203

Comparing fluxes



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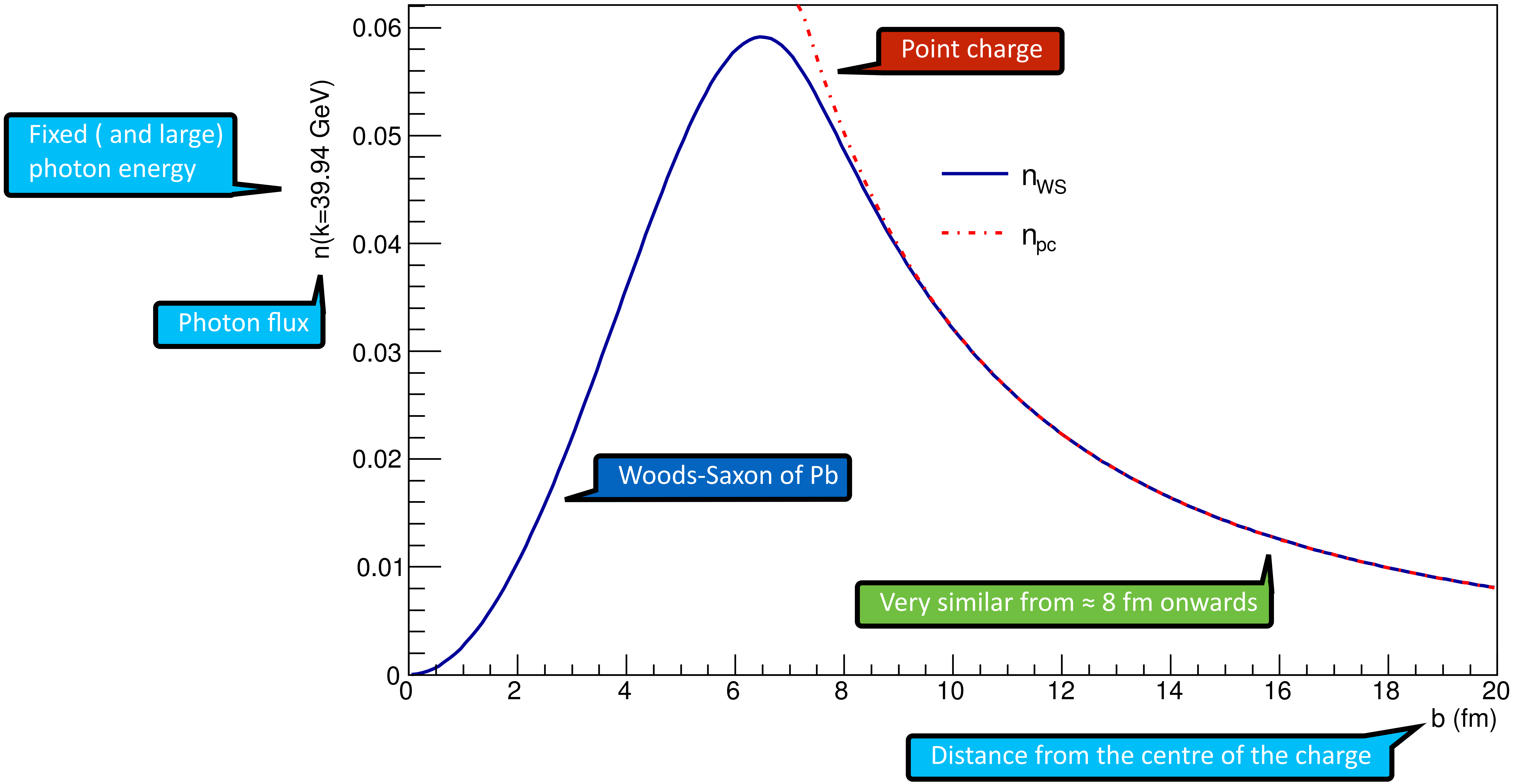
Comparing fluxes



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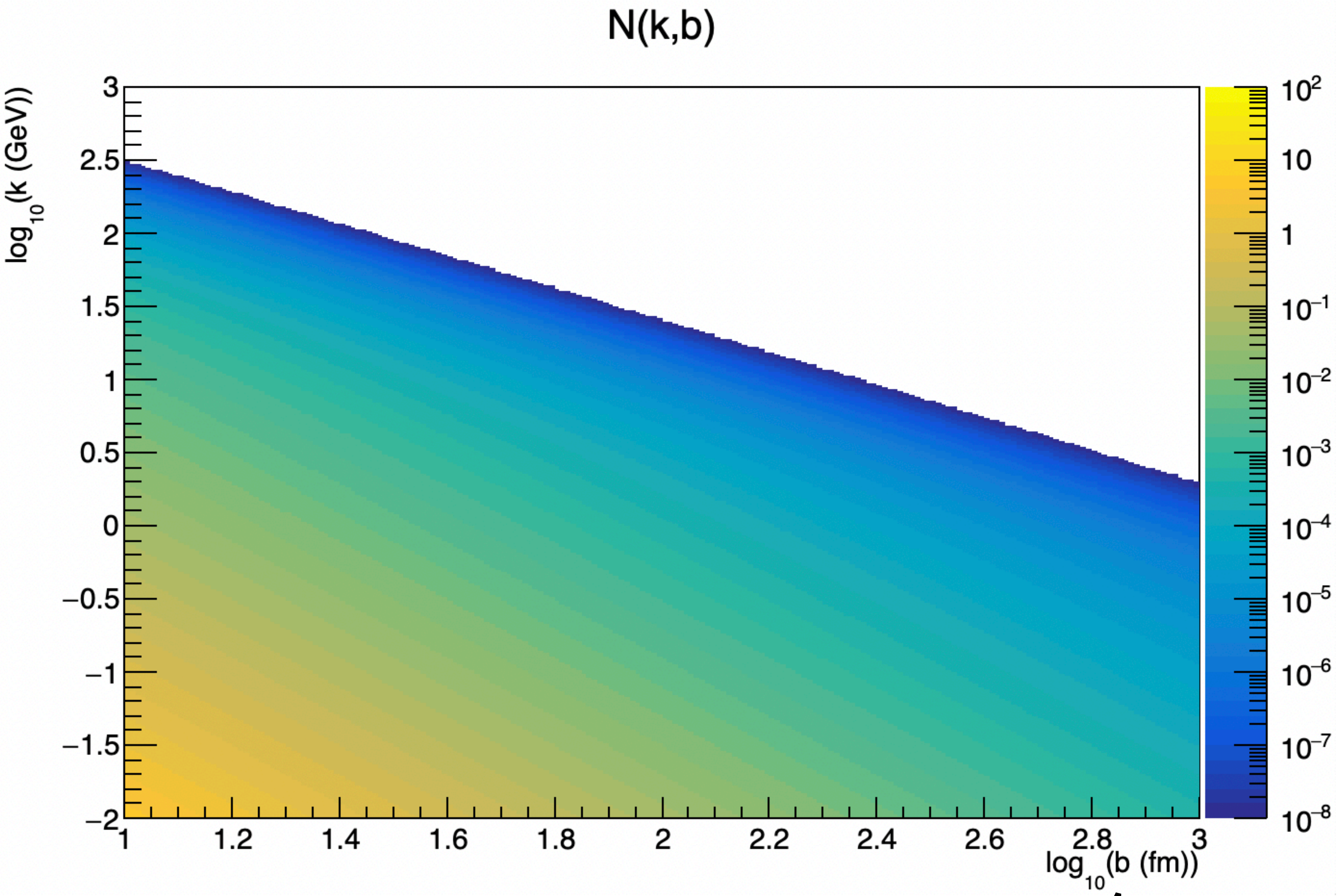
Photon flux of a point charge

Photon energy

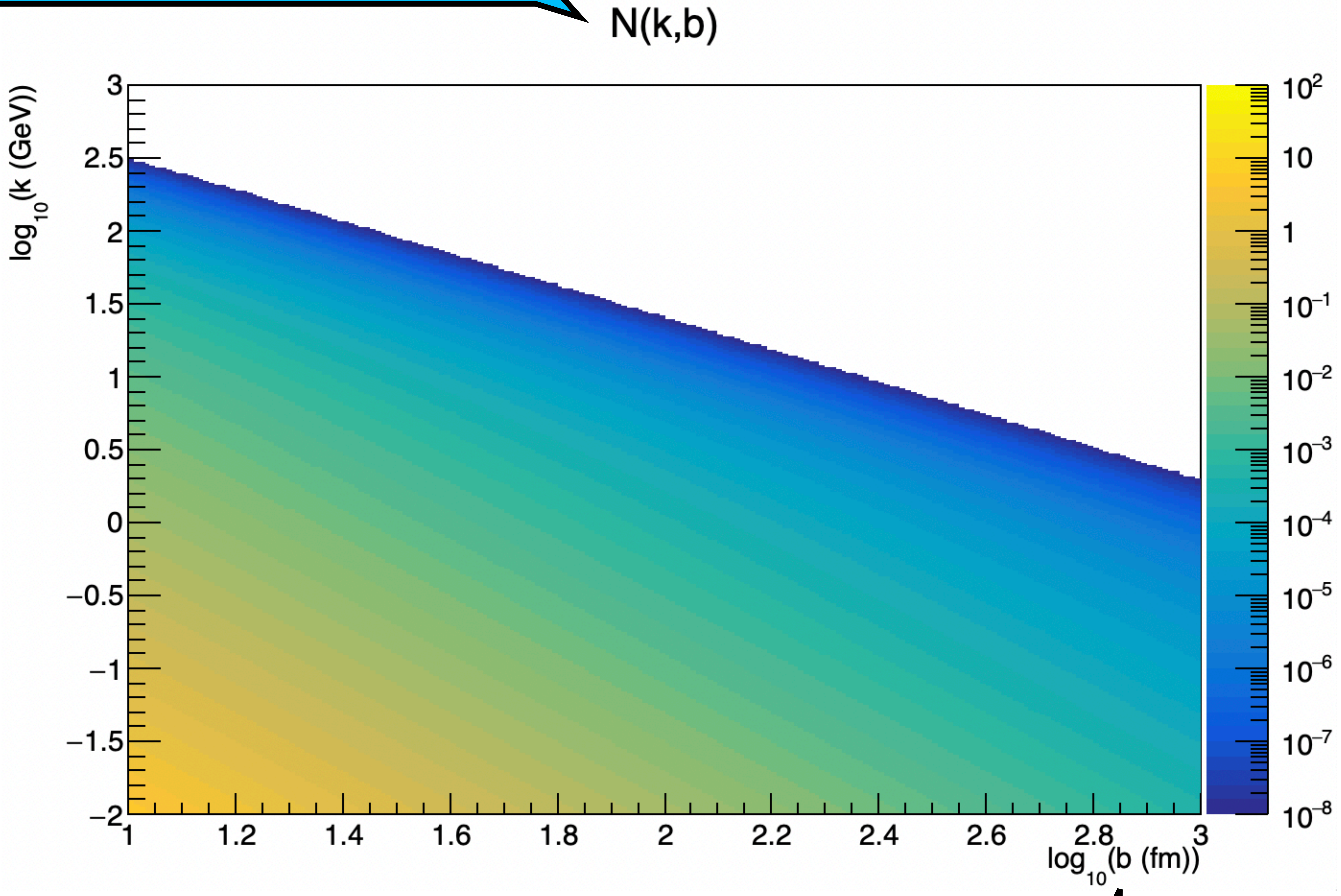


Distance from the centre of the charge

Photon flux of a point charge

Using LHC relevant parameters and ranges for k and b

Photon energy



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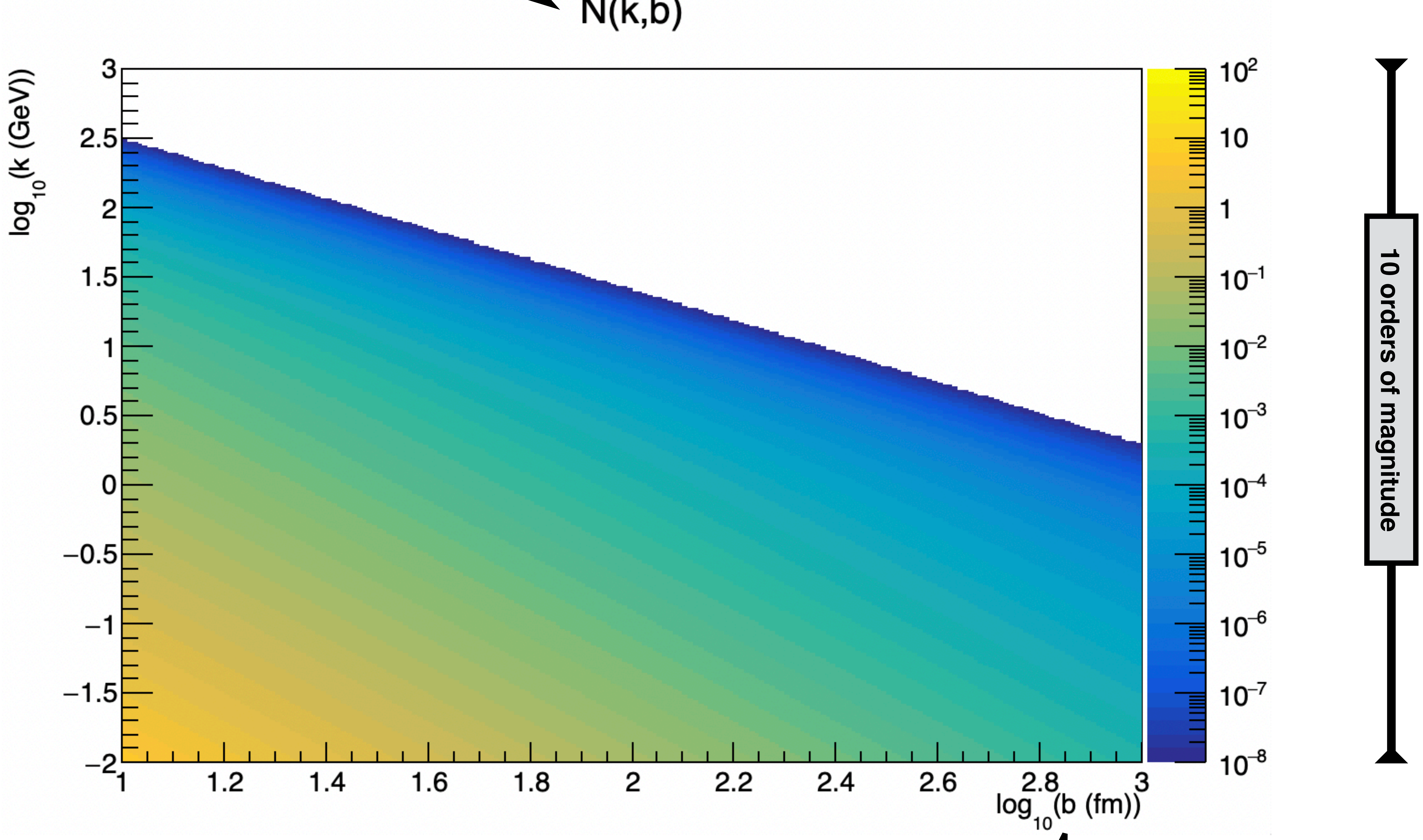

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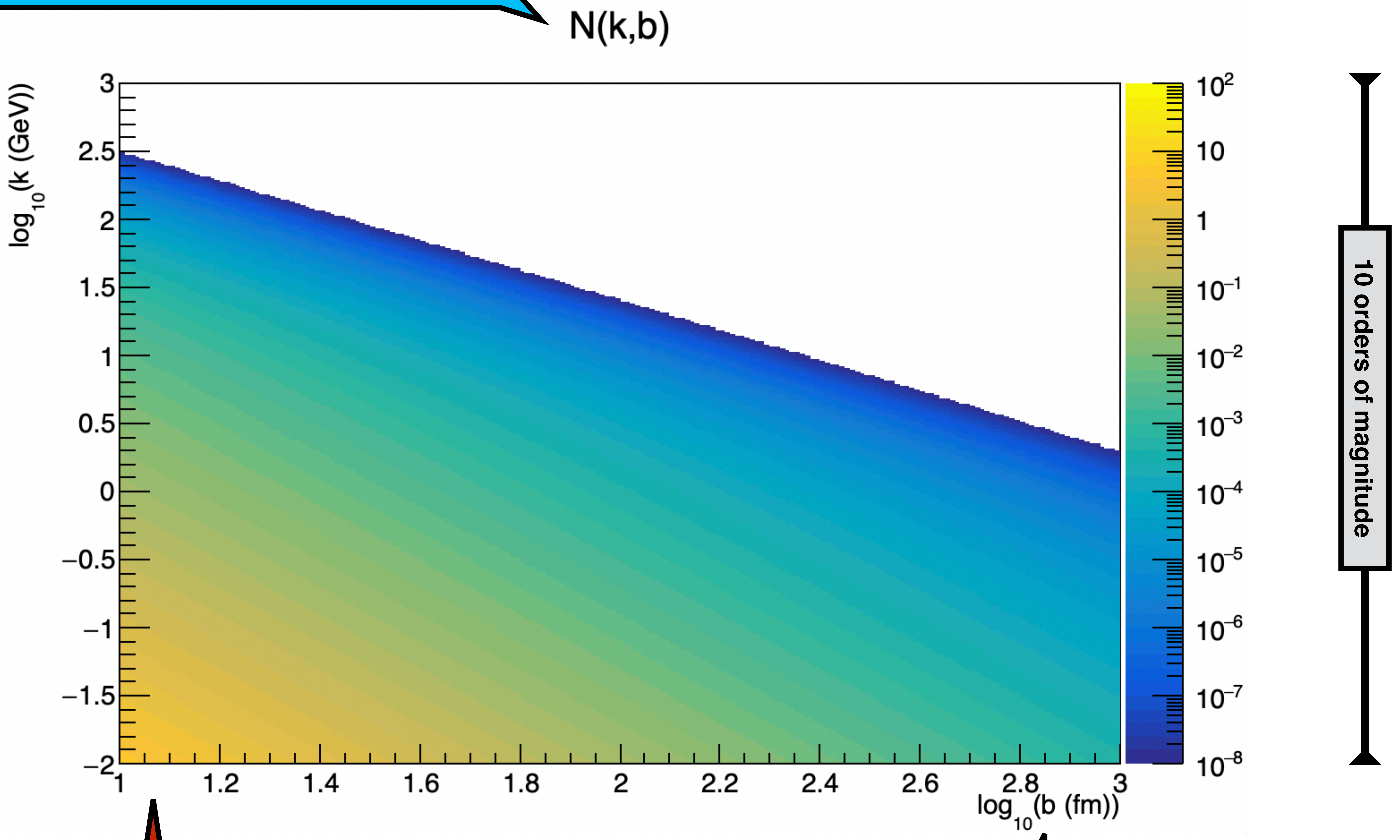


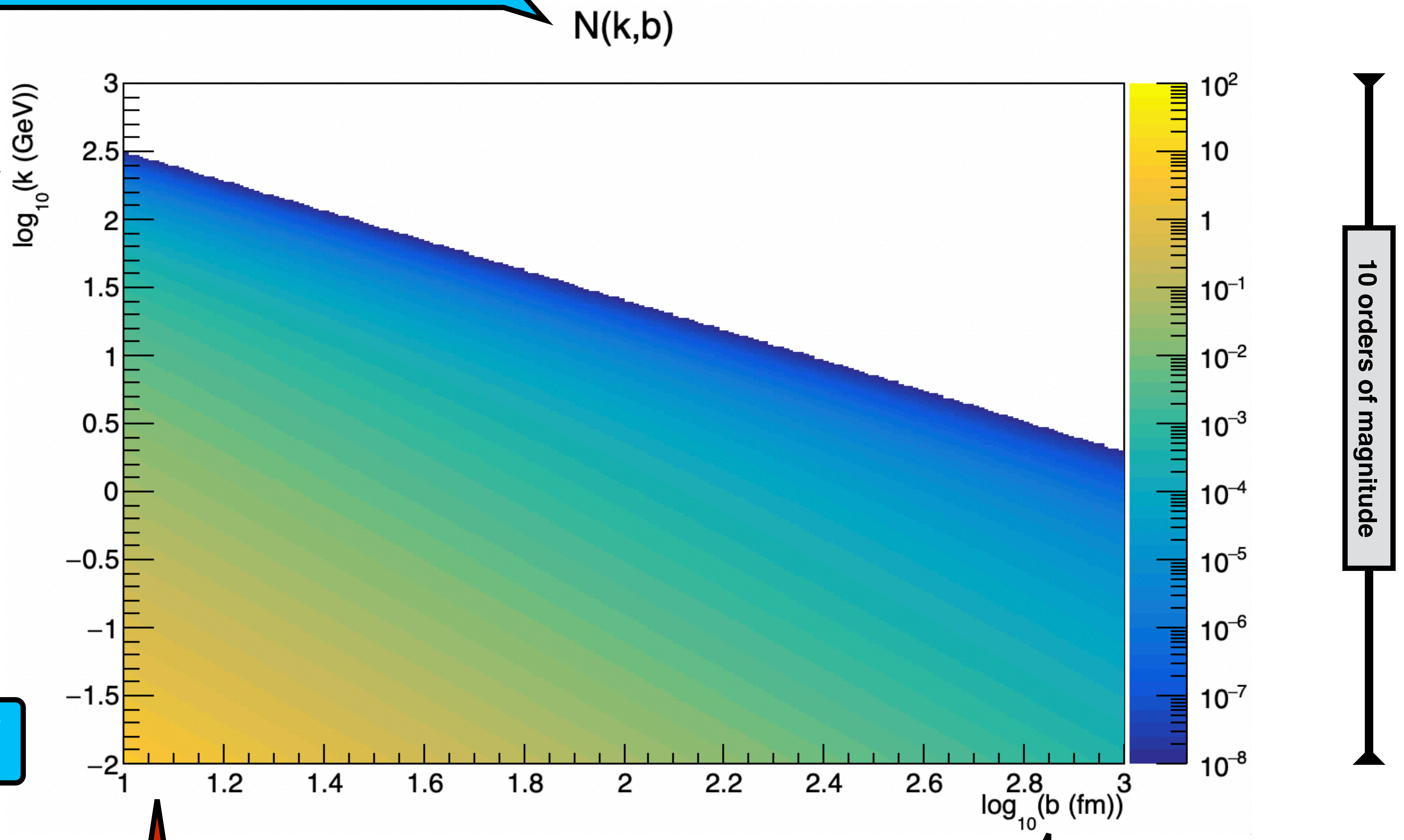
Large photon energies are more probable at small distances

Distance from the centre of the charge

Photon flux of a point charge

Using LHC relevant parameters and ranges for k and b

Photon energy



Different final states sample different parts of this plot

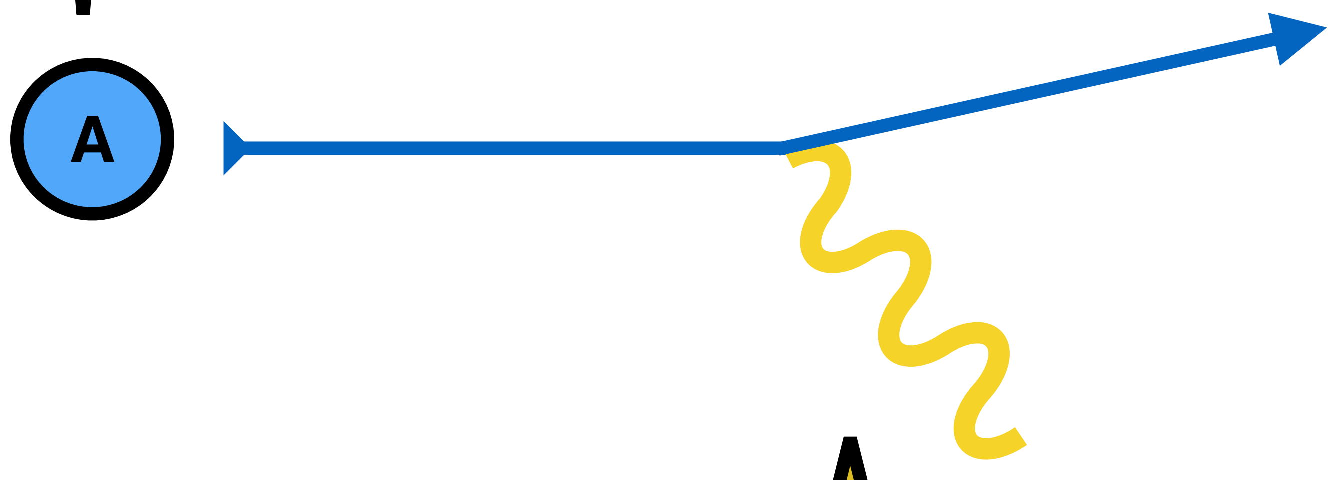
Large photon energies are more probable at small distances

Distance from the centre of the charge

Now that we have the photons, what can we do with them?

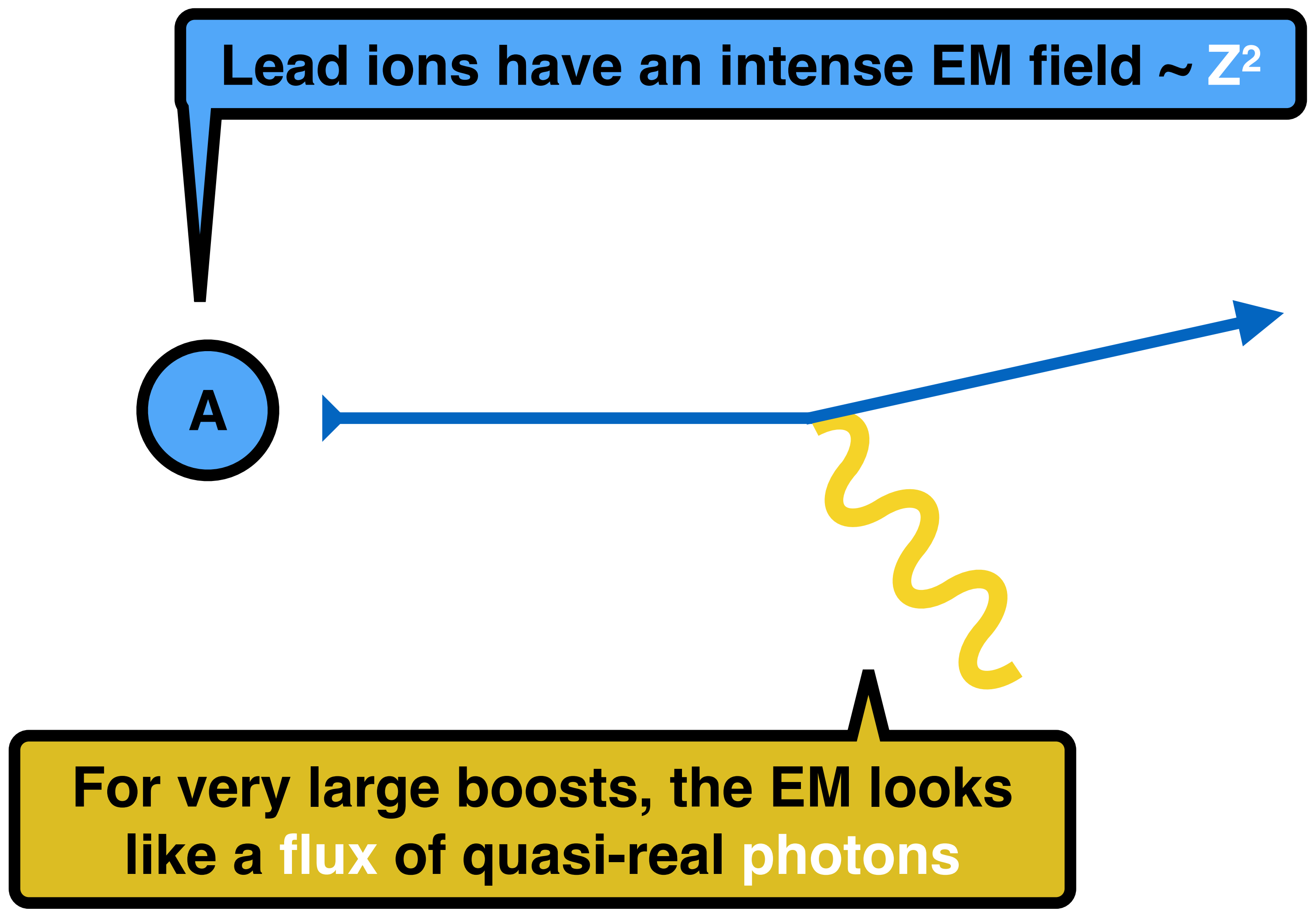
Photons at the ion colliders: examples of what can be done

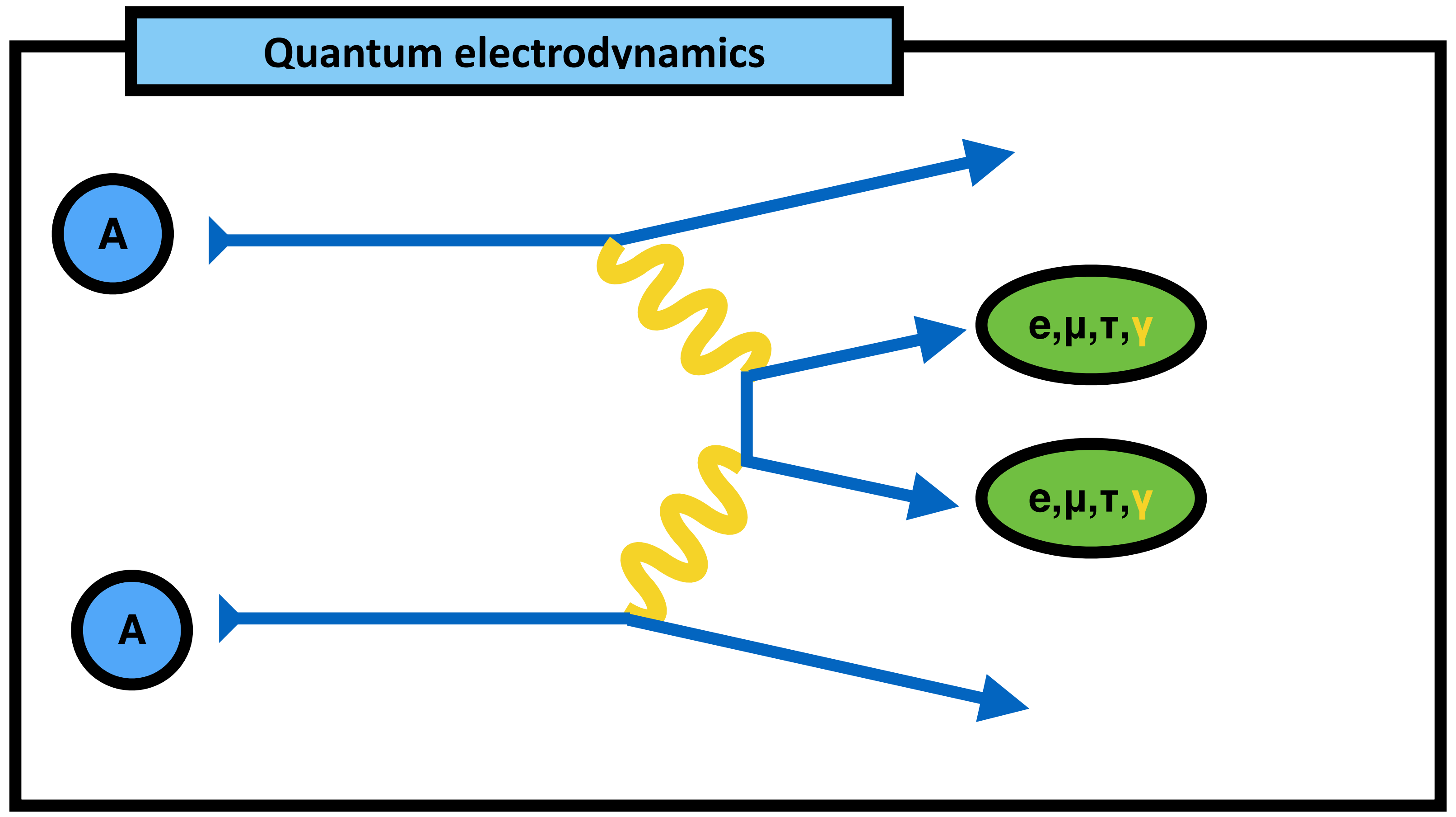
Lead ions have an intense EM field ~ Z^2



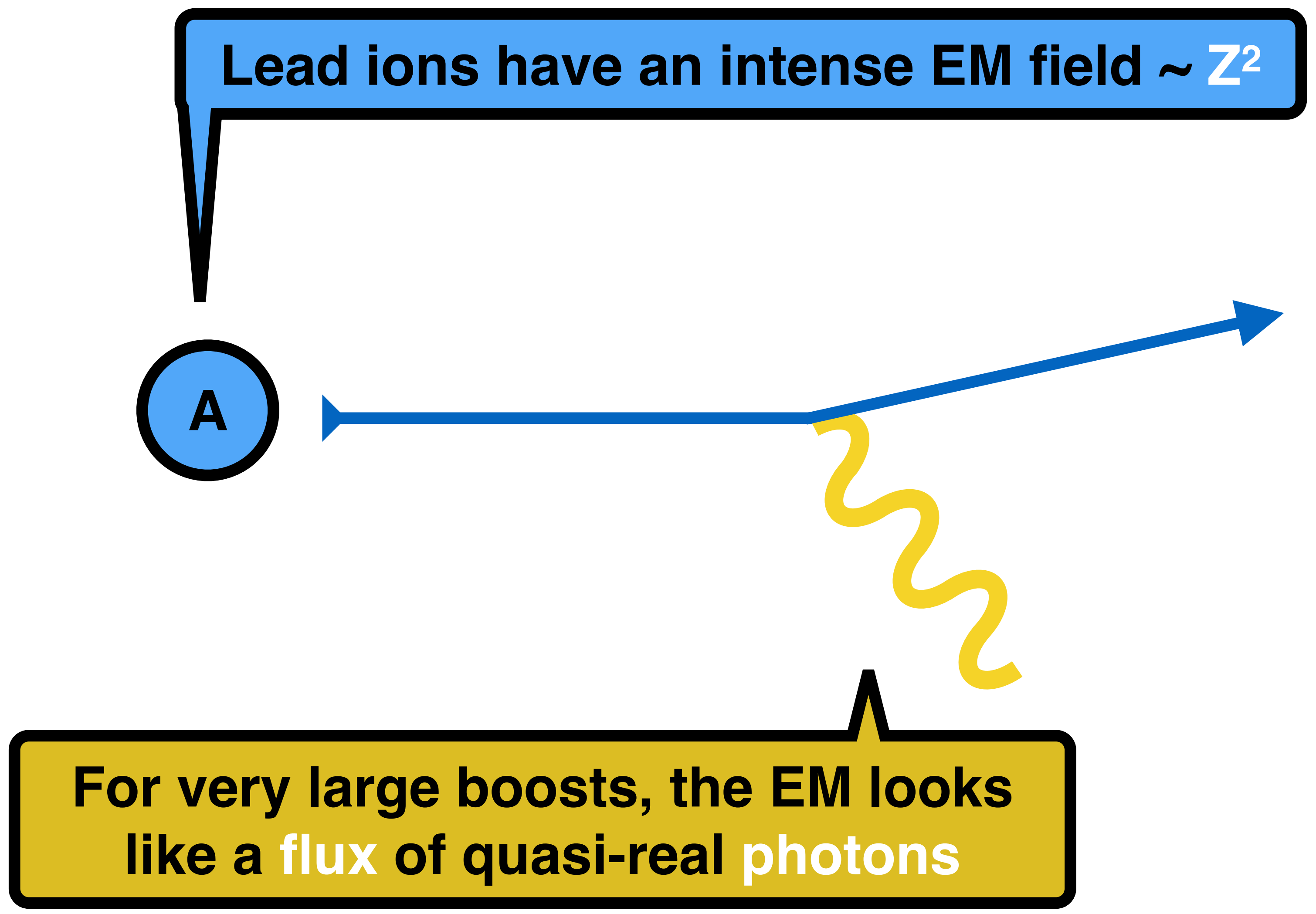
For very large boosts, the EM looks like a flux of quasi-real photons

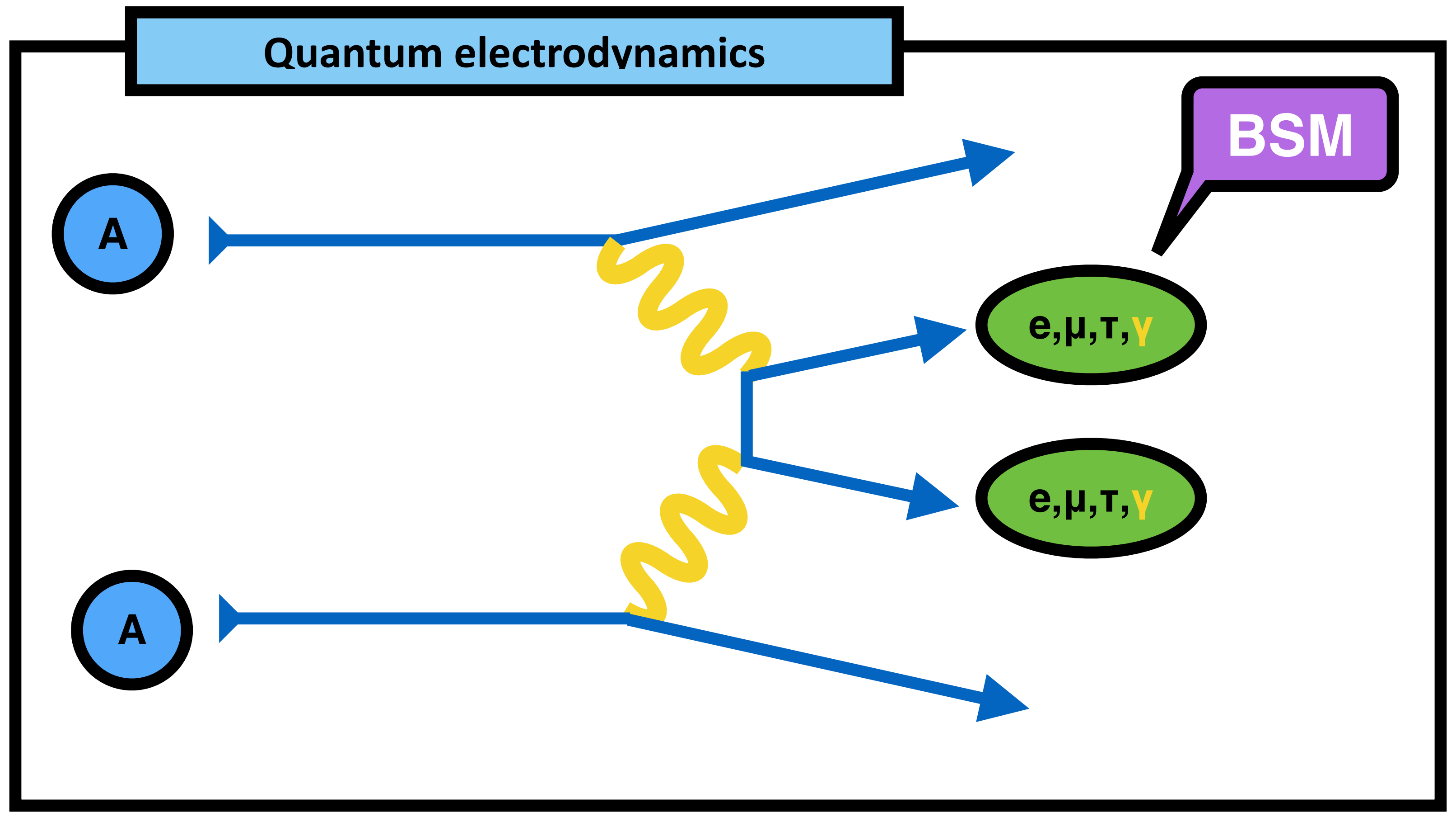
Photons at the ion colliders: examples of what can be done



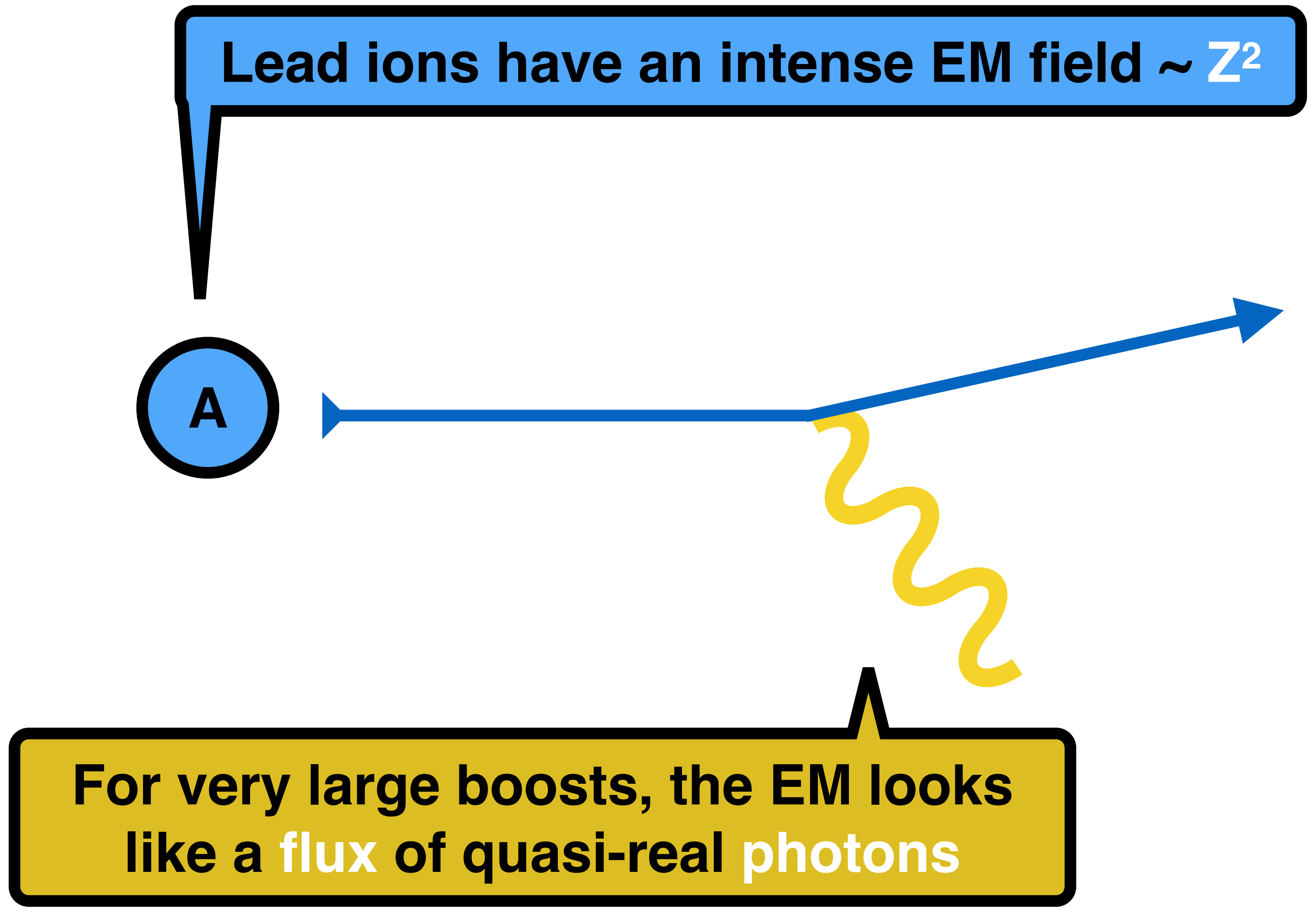


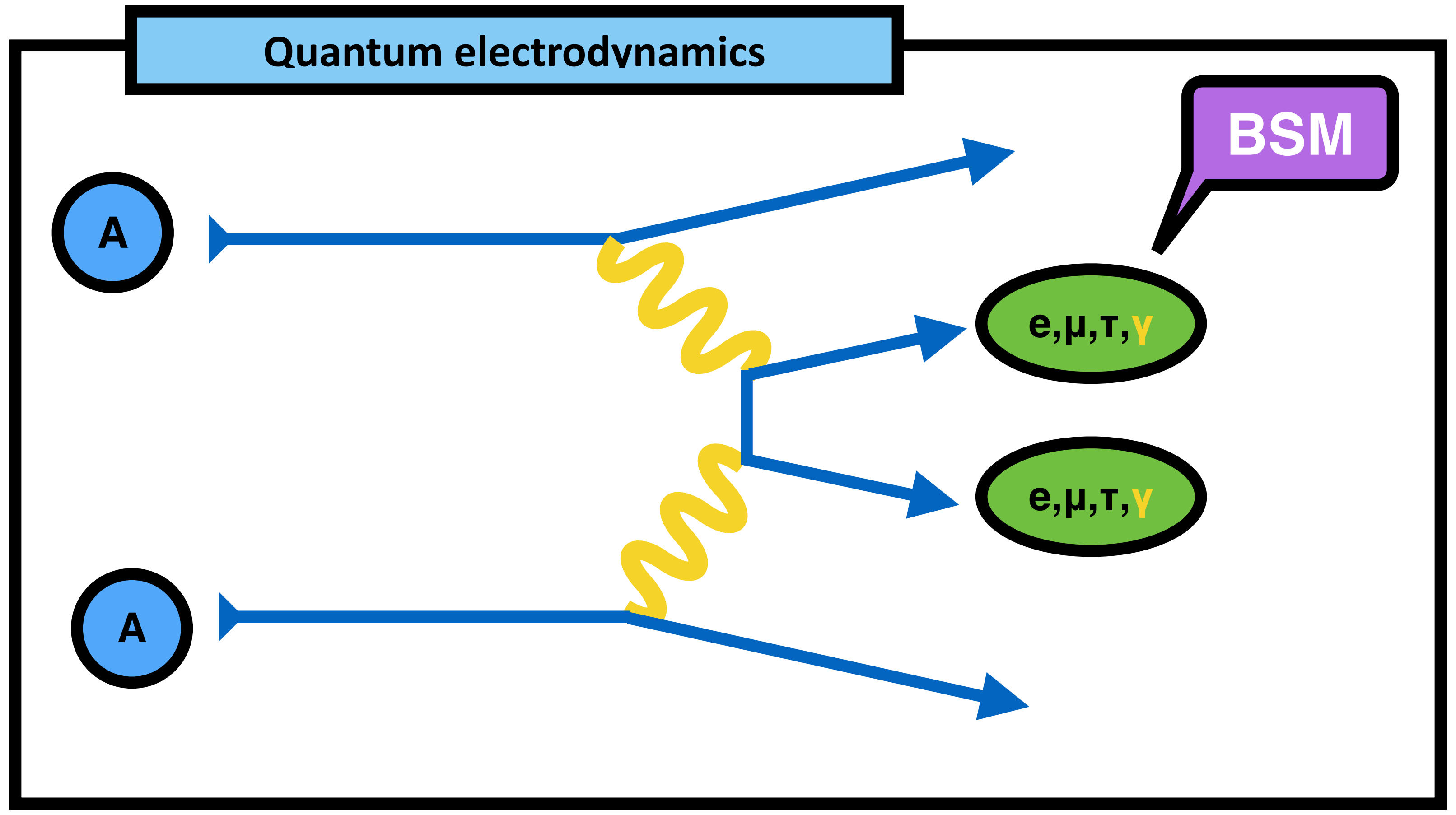
Photons at the ion colliders: examples of what can be done

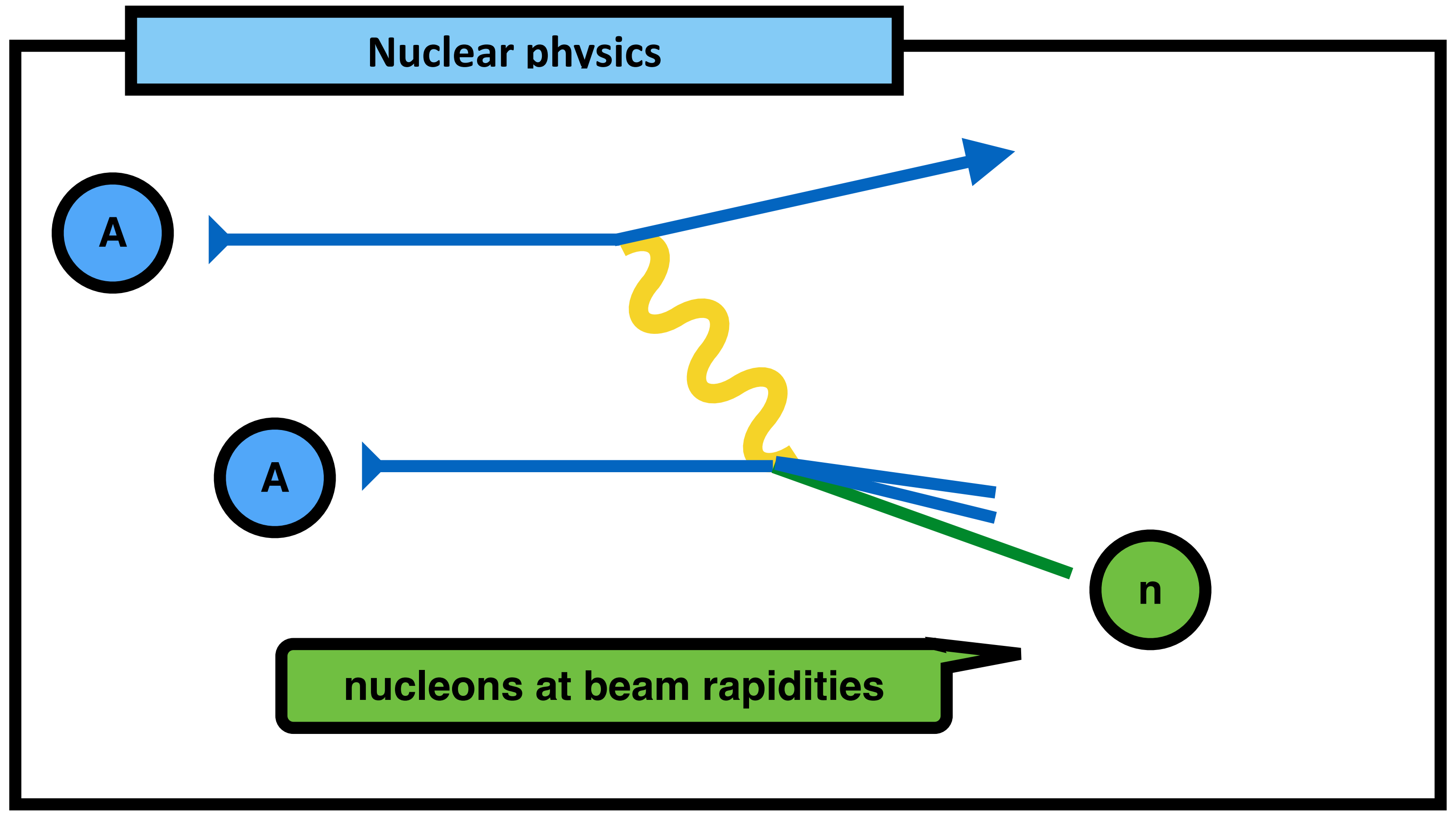




Photons at the ion colliders: examples of what can be done







Photons at the ion colliders: examples of what can be done

Photons at the ion colliders: examples of what can be done

Photons at the ion colliders: examples of what can be done

Finding these processes in hadron colliders requires specific search techniques tailored to the environment and the available detectors

How to find photon-induced interactions in hadron colliders (1/4)

For inclusive observables one has to use ultra-peripheral collisions (UPC)

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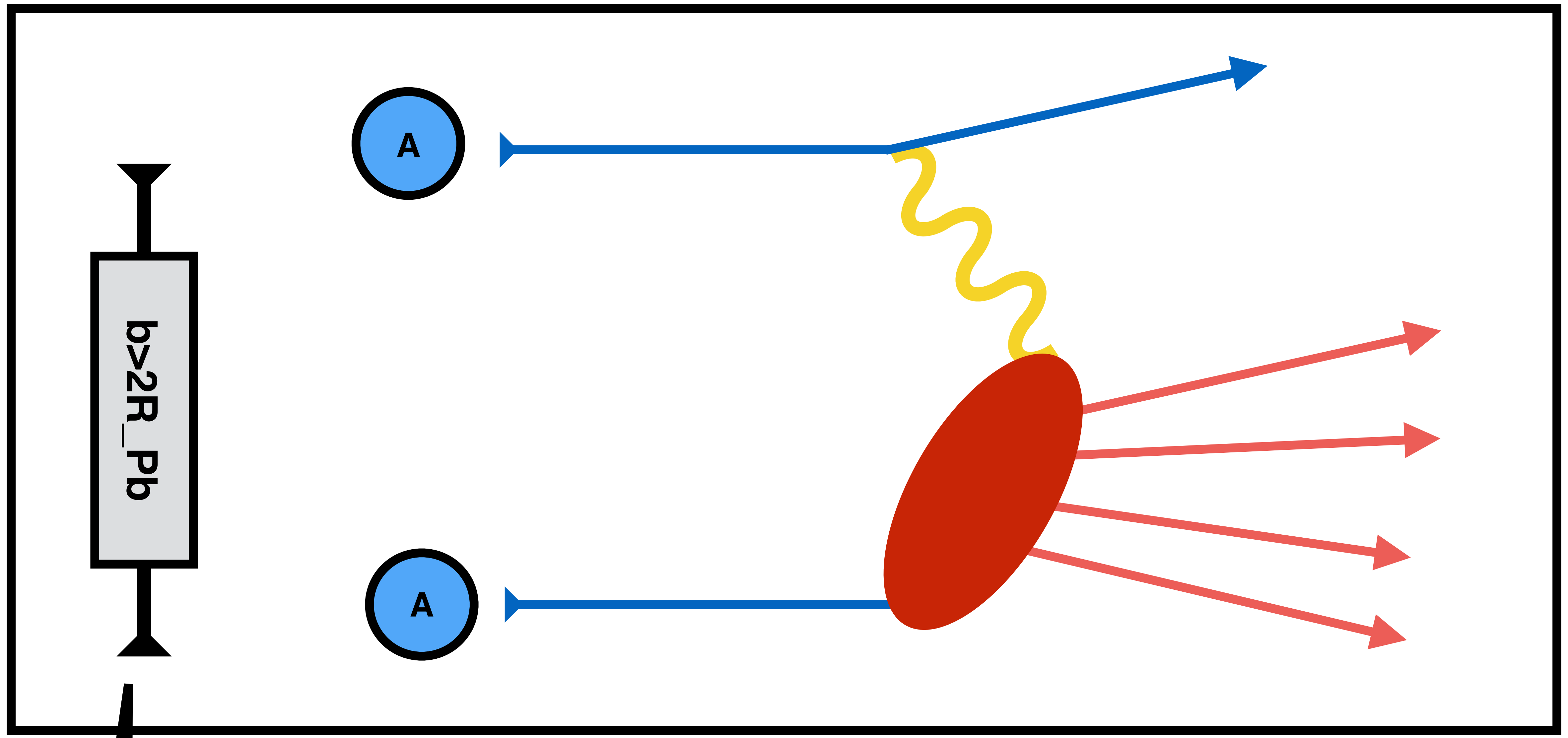

Choose interactions at large impact parameters

How to find photon-induced interactions in hadron colliders (1/4)

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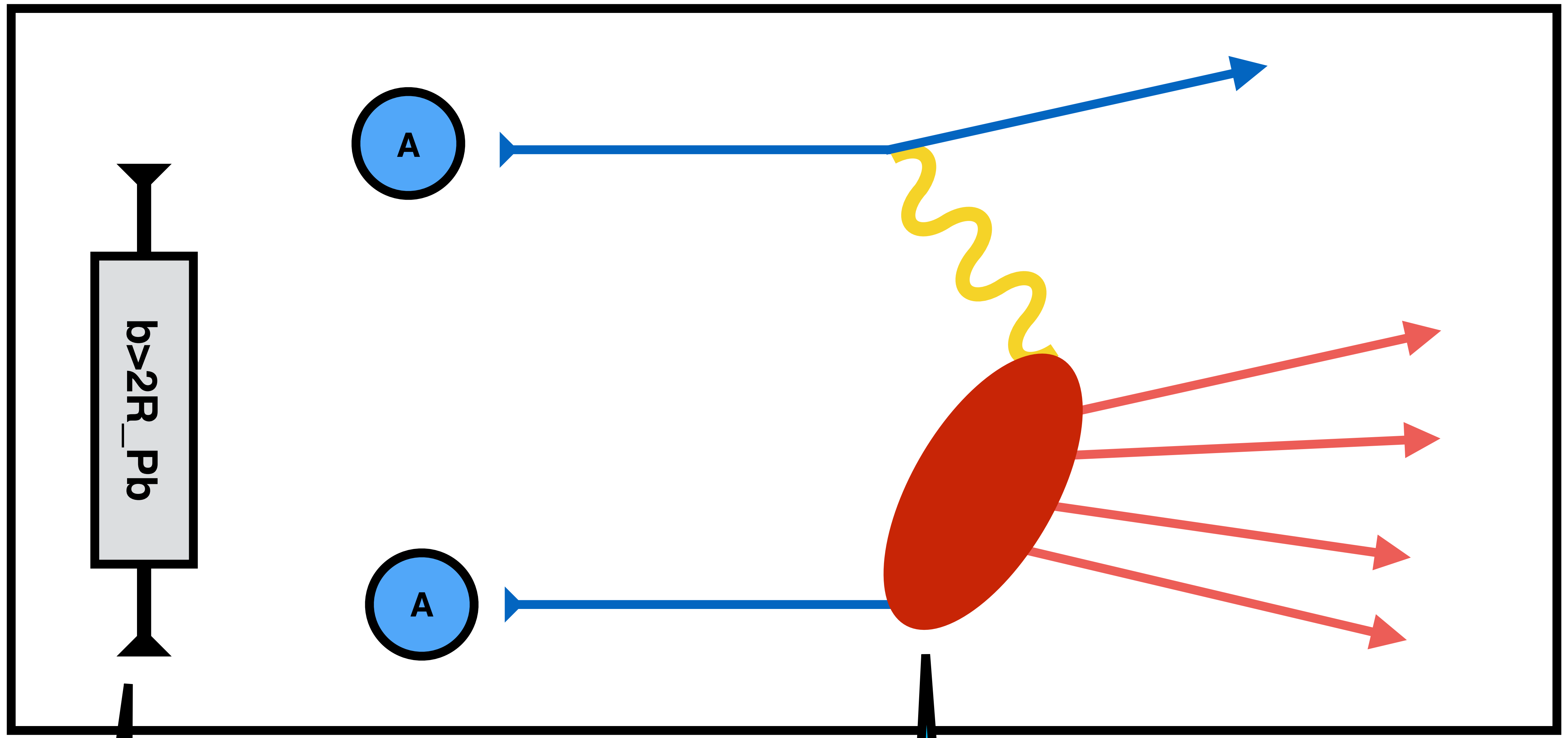

Choose interactions at large impact parameters

The range of QCD interactions is O(1 fm), so at these large distances only photon induced interactions will remain

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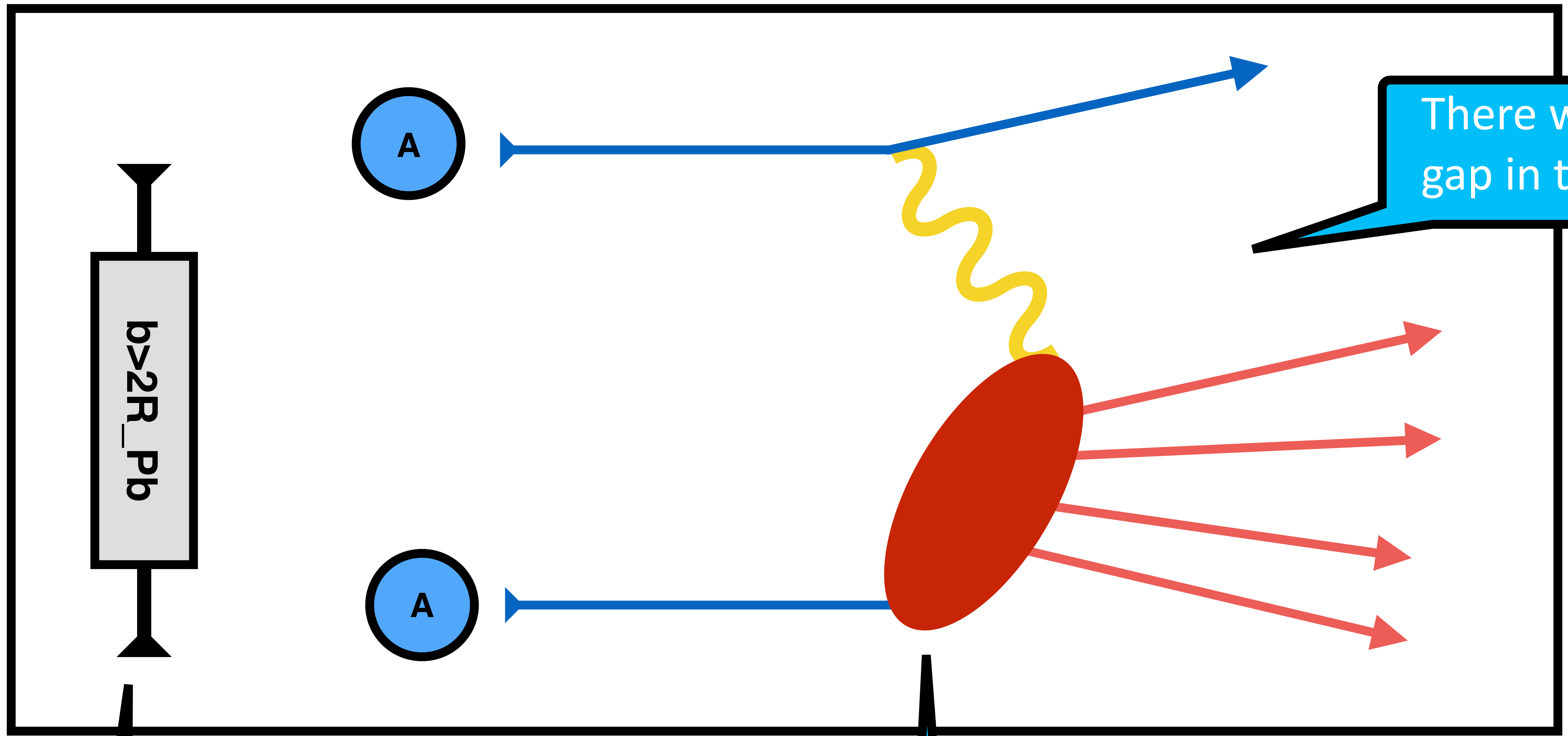

There will be a large rapidity gap in the photon side

Choose interactions at large impact parameters

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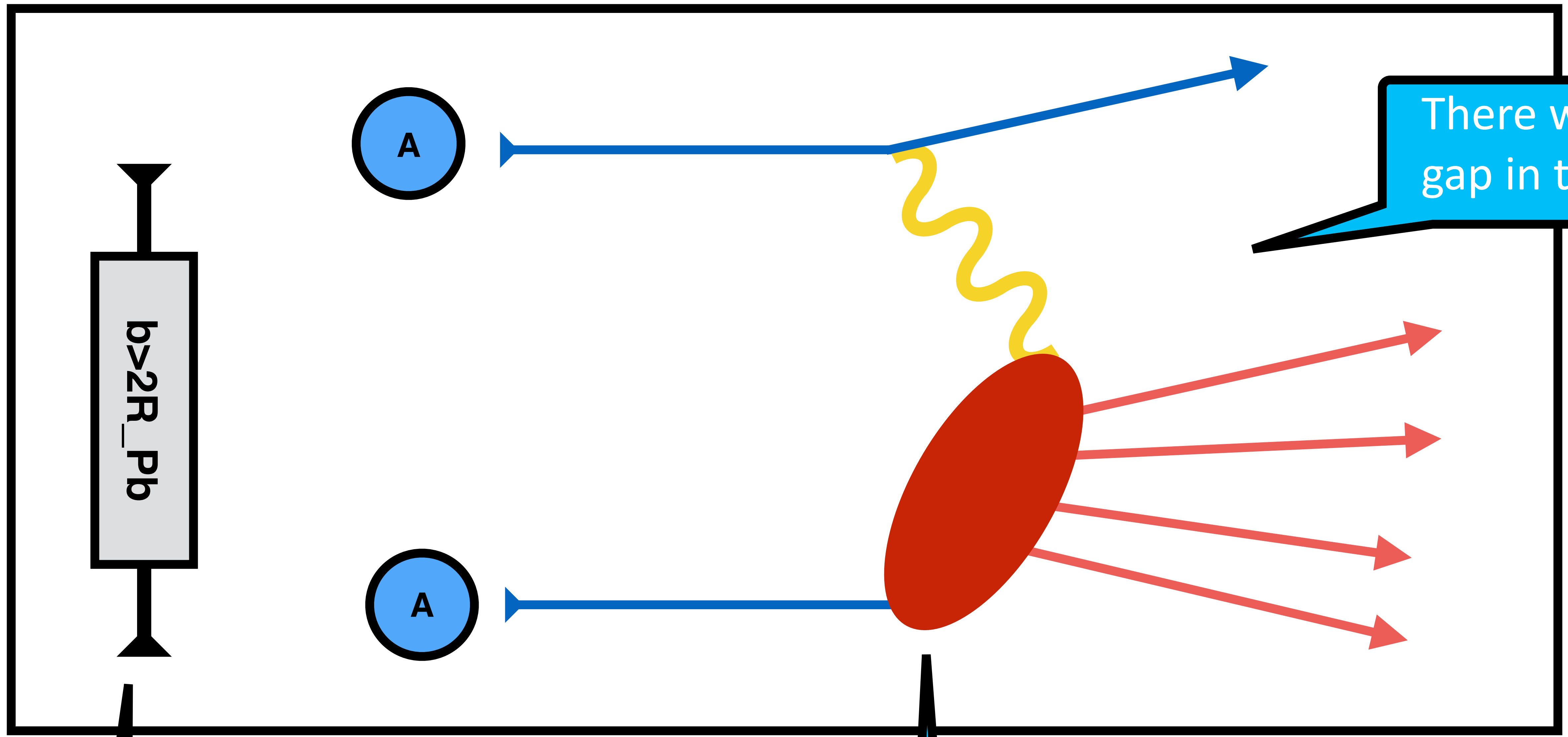
Guillermo Contreras, CTU in Prague

How to find photon-induced interactions in hadron colliders (1/4)

For inclusive observables one has to use ultra-peripheral collisions (UPC)

Signature: Look for a large rapidity gap in one side of the detector



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How to find photon-induced interactions in hadron colliders (2/4)

For exclusive diffractive observables, one can use peripheral collisions

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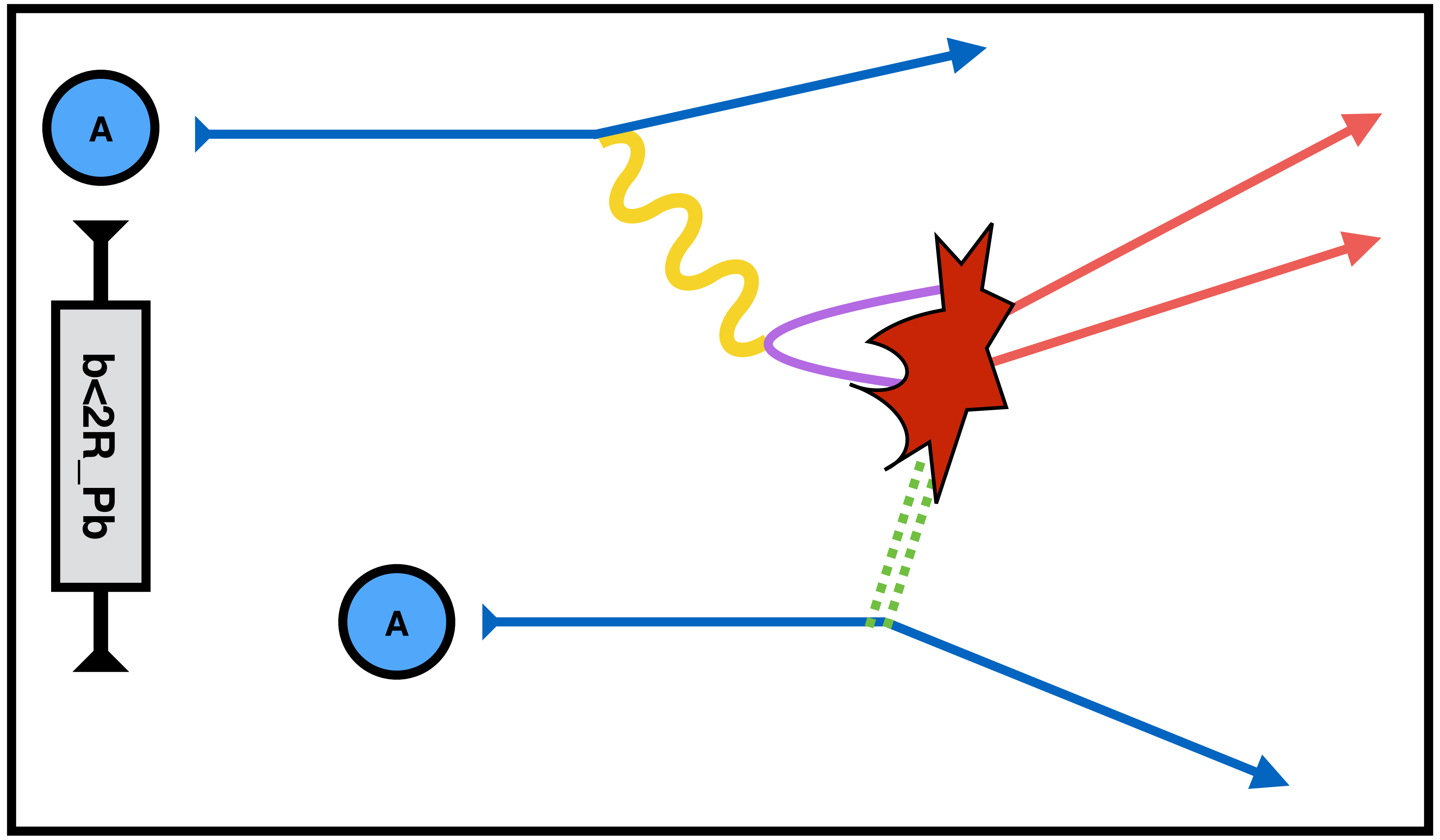

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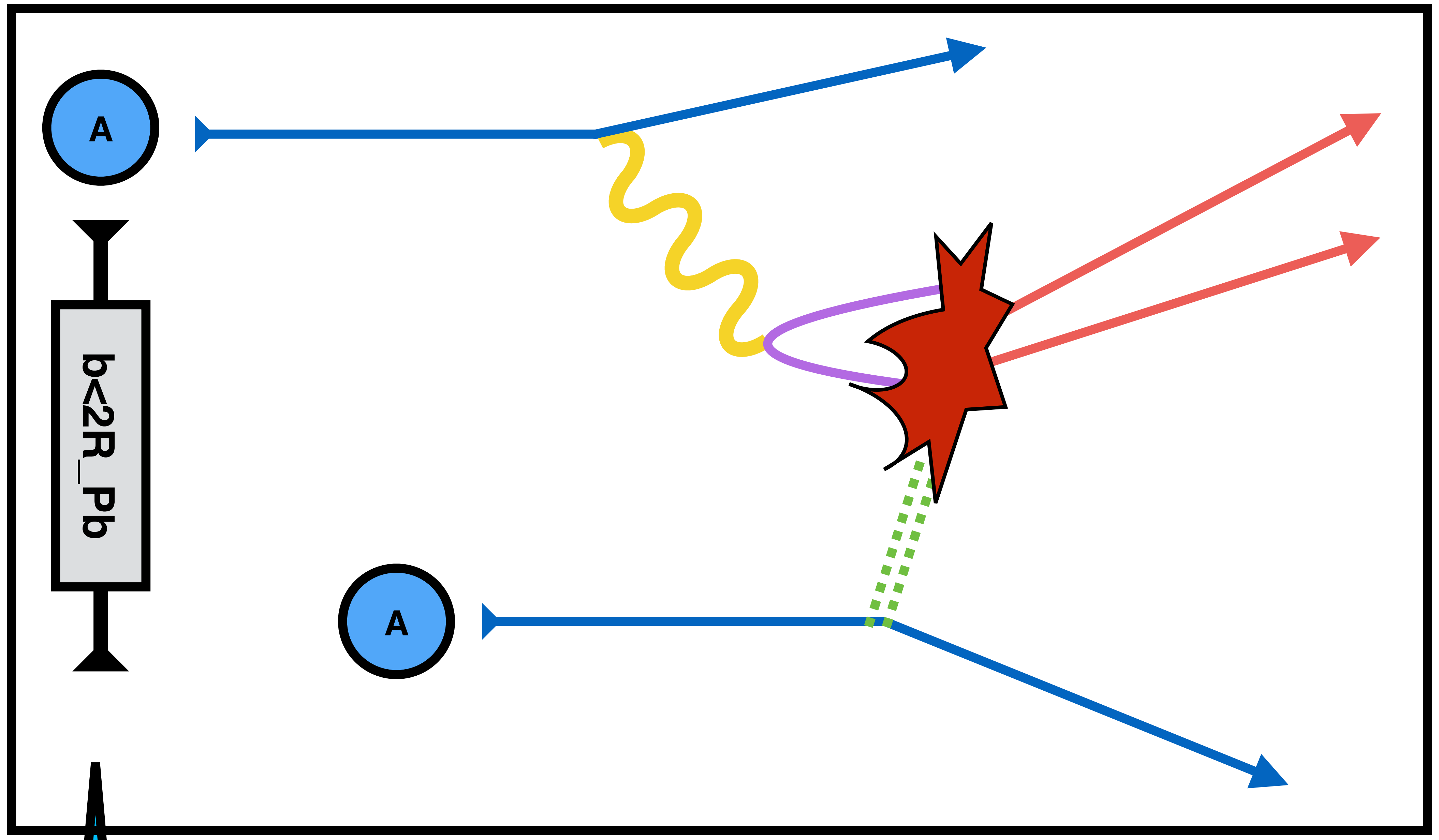


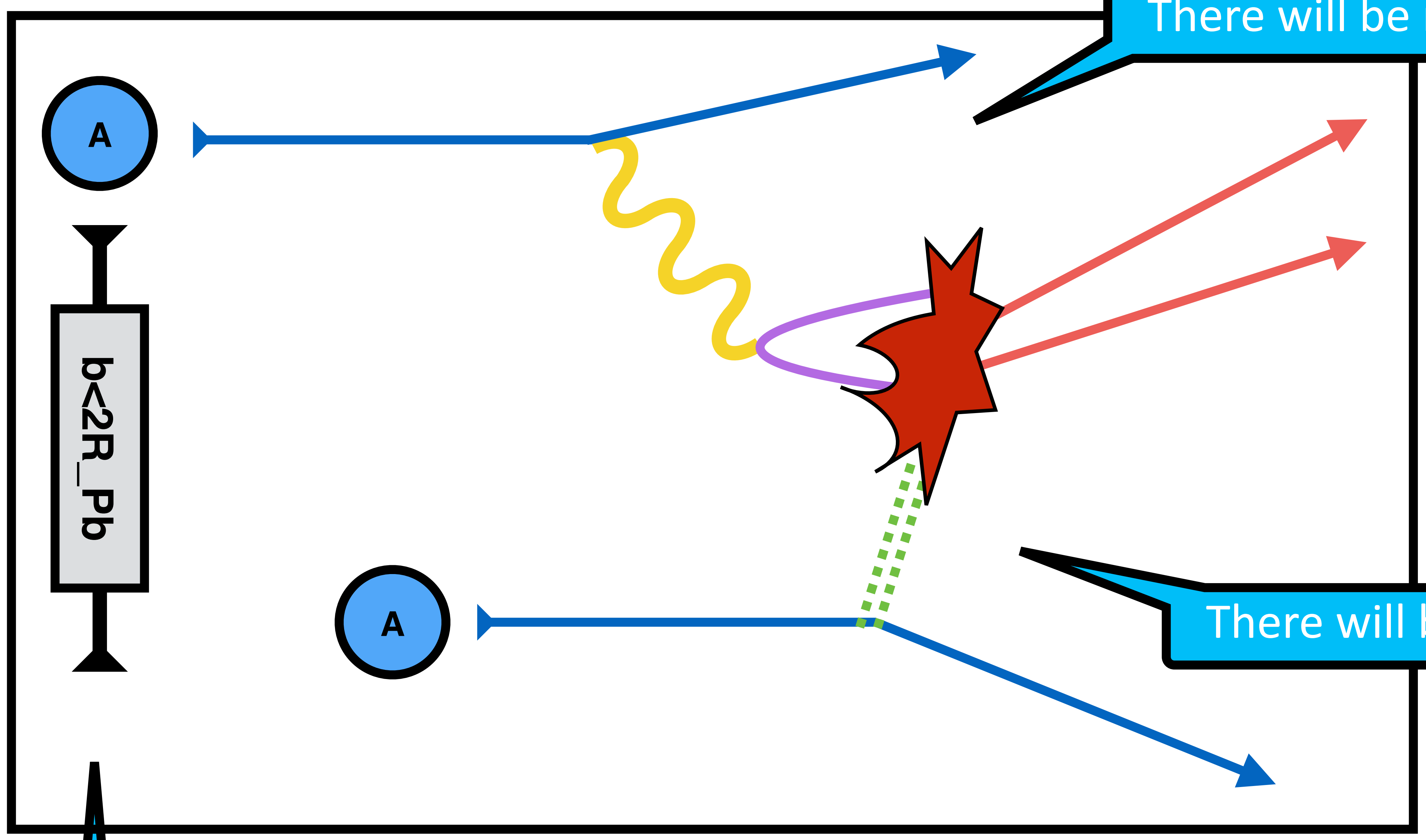
For peripheral collisions the photon-induced process will overlap with hadronic inelastic interactions

Guillermo Contreras, CTU in Prague

How to find photon-induced interactions in hadron colliders (2/4)

For exclusive diffractive observables, one can use peripheral collisions

There will be no rapidity gaps



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How to find photon-induced interactions in hadron colliders (2/4)

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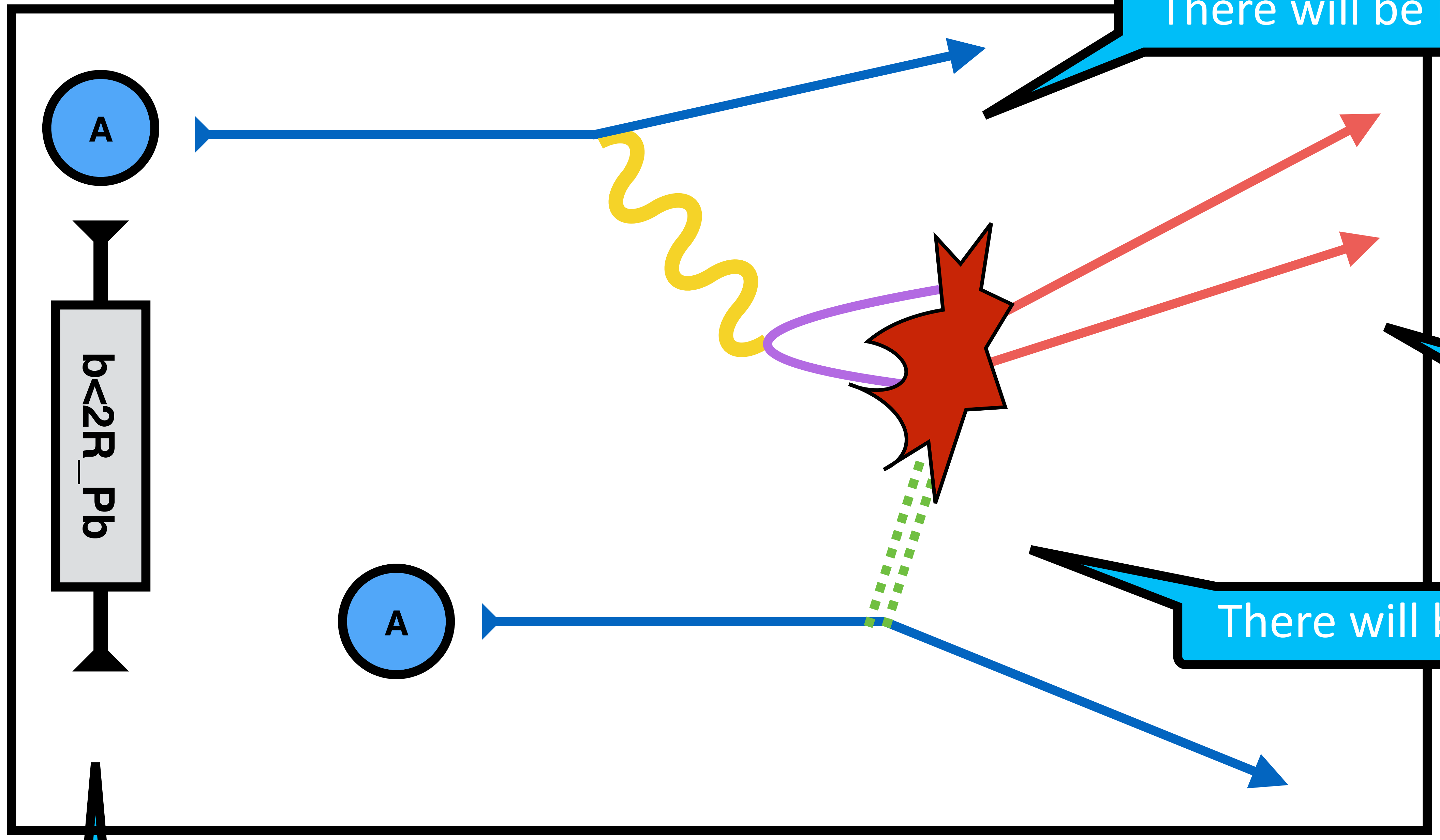


For exclusive states in diffraction, the total transverse momentum is very small

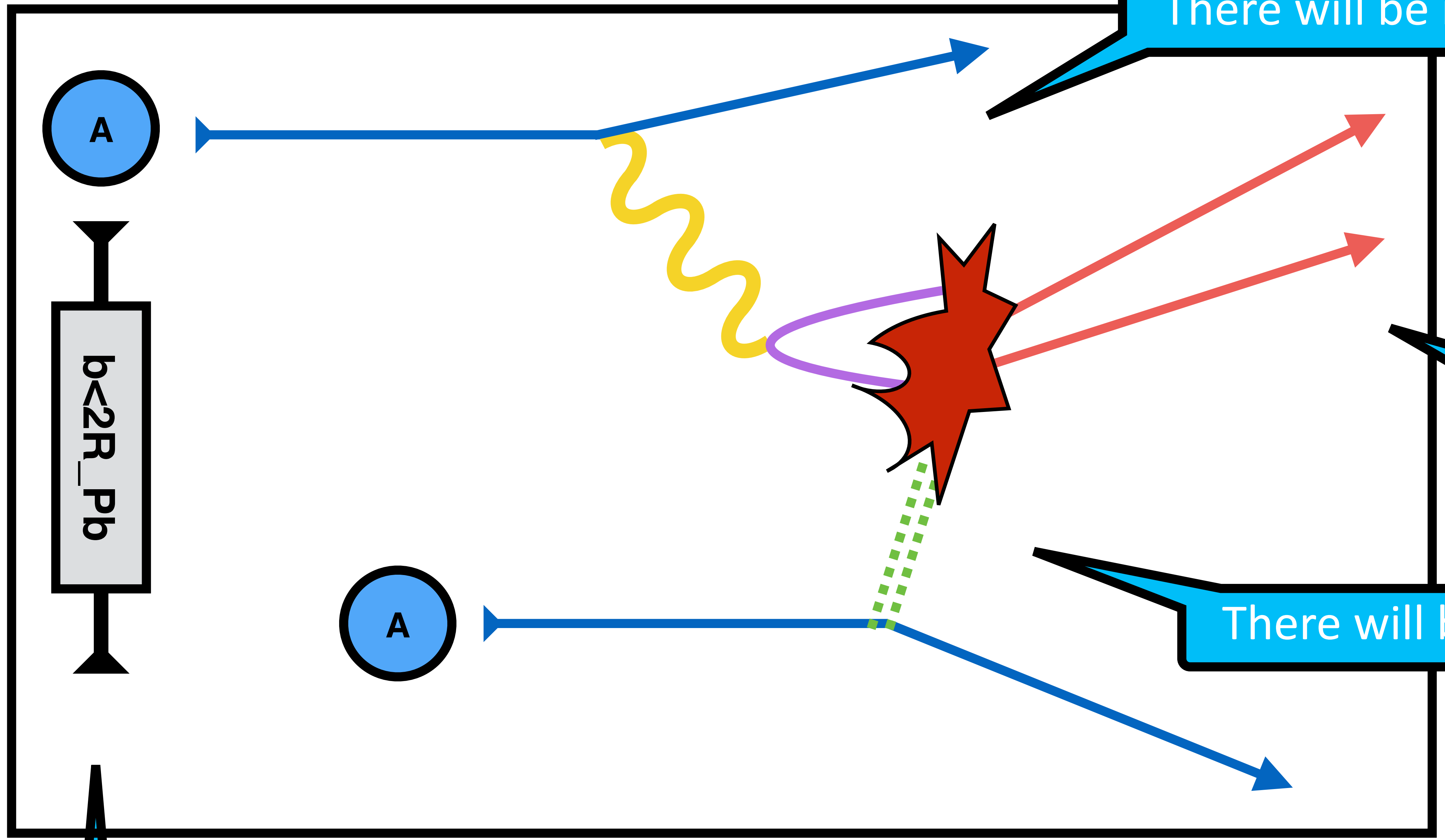
There will be no rapidity gaps

For peripheral collisions the photon-induced process will overlap with hadronic inelastic interactions

How to find photon-induced interactions in hadron colliders (2/4)

For exclusive diffractive observables, one can use peripheral collisions

Signature: Look for a low pT final state (eg. a dijet or a vector meson)



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How to find photon-induced interactions in hadron colliders (3/4)

For exclusive diffractive observables, one can also use UPC

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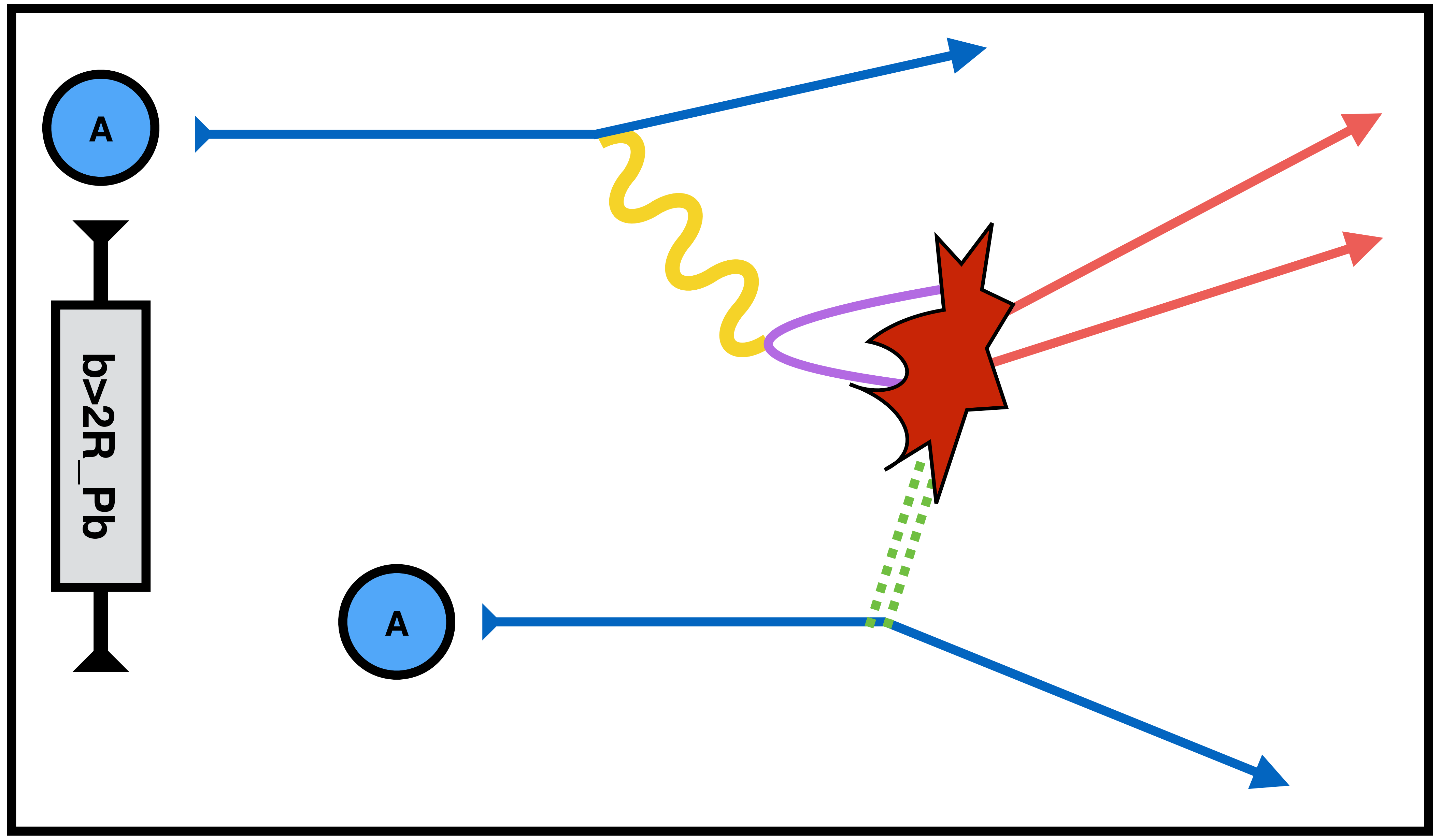

How to find photon-induced interactions in hadron colliders (3/4)

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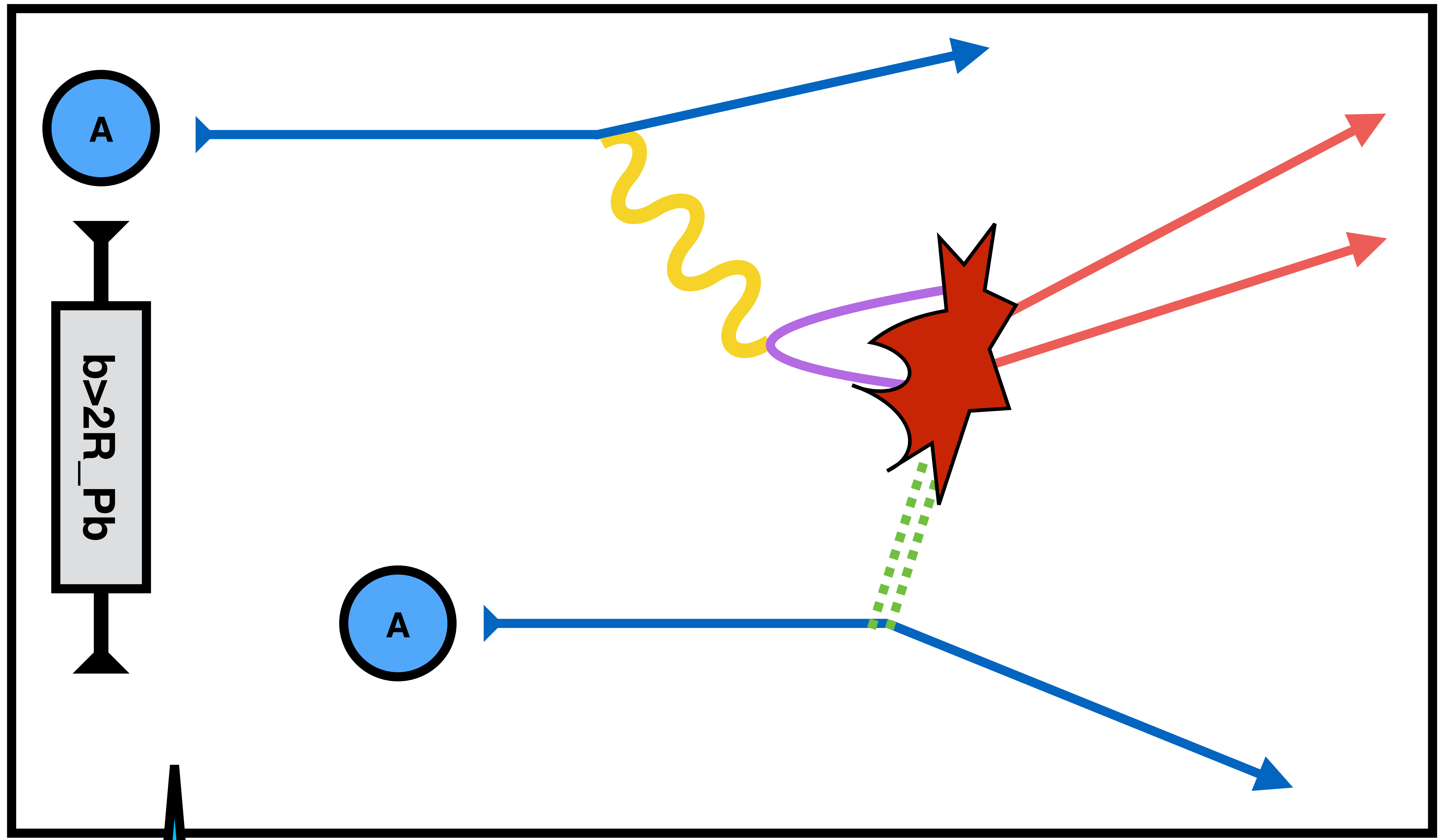


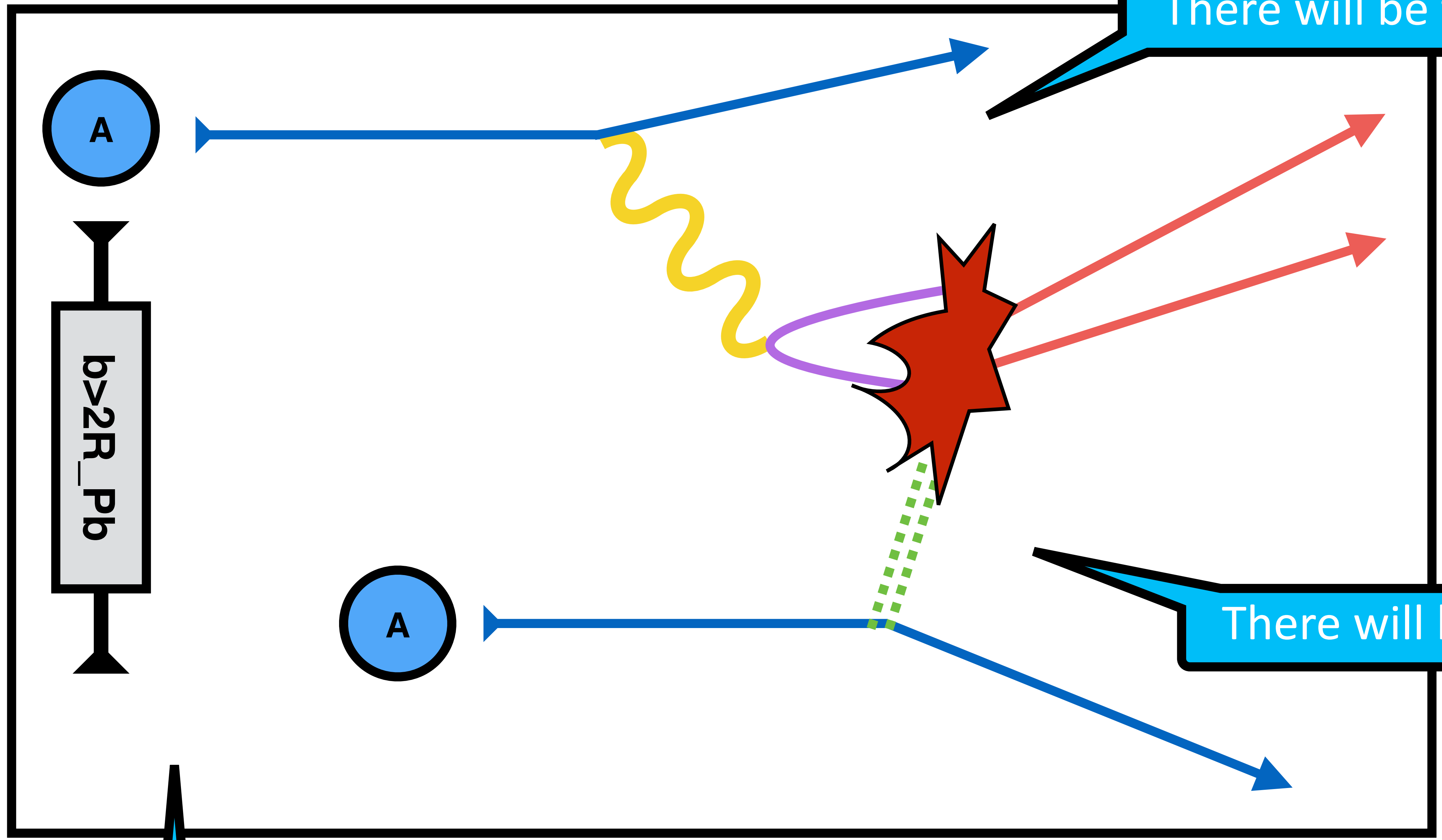
For UPC the photon-induced process there is no overlap of the incoming hadrons within the range of QCD

Guillermo Contreras, CTU in Prague

How to find photon-induced interactions in hadron colliders (3/4)

For exclusive diffractive observables, one can also use UPC

There will be two rapidity gaps



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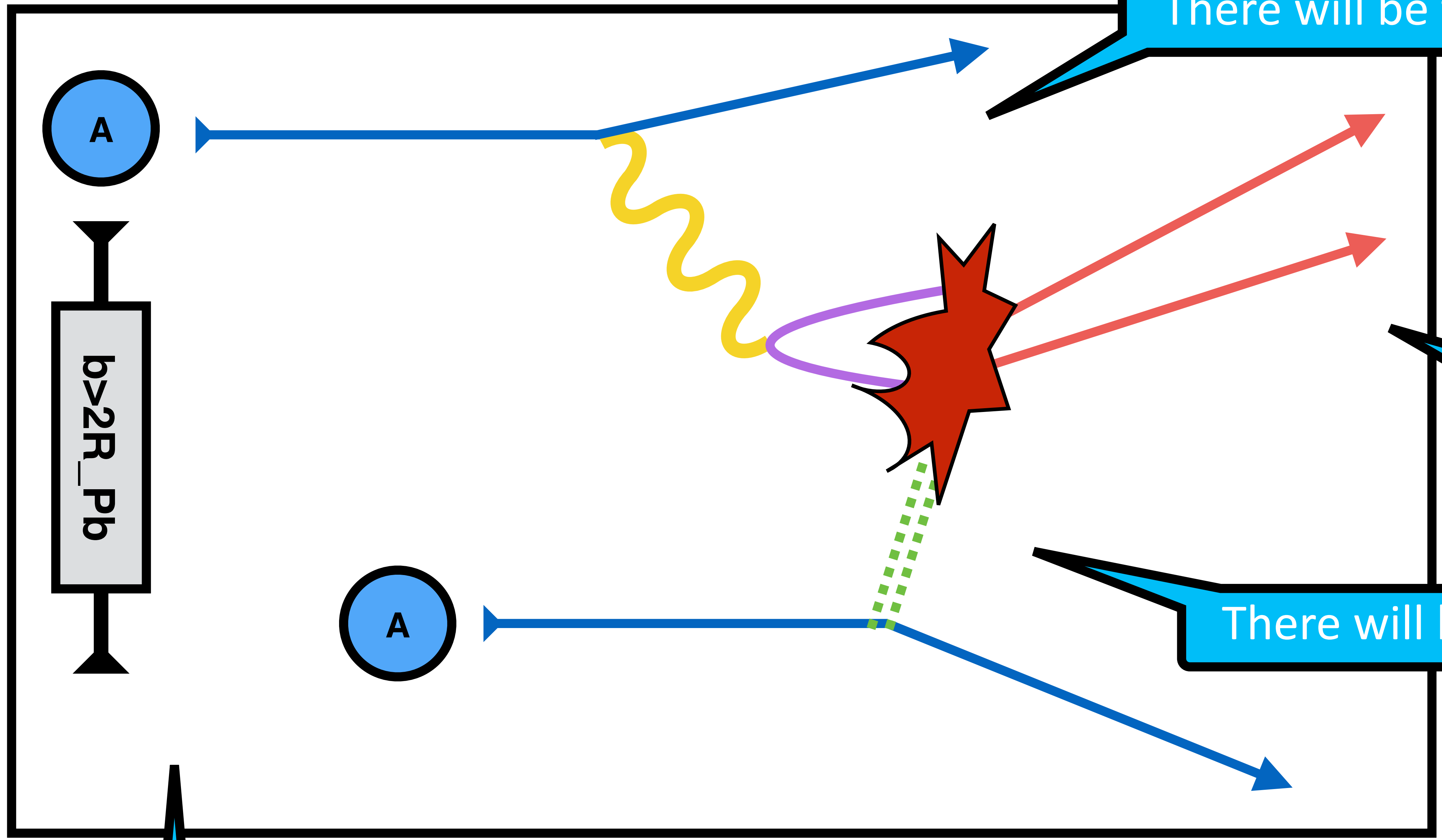

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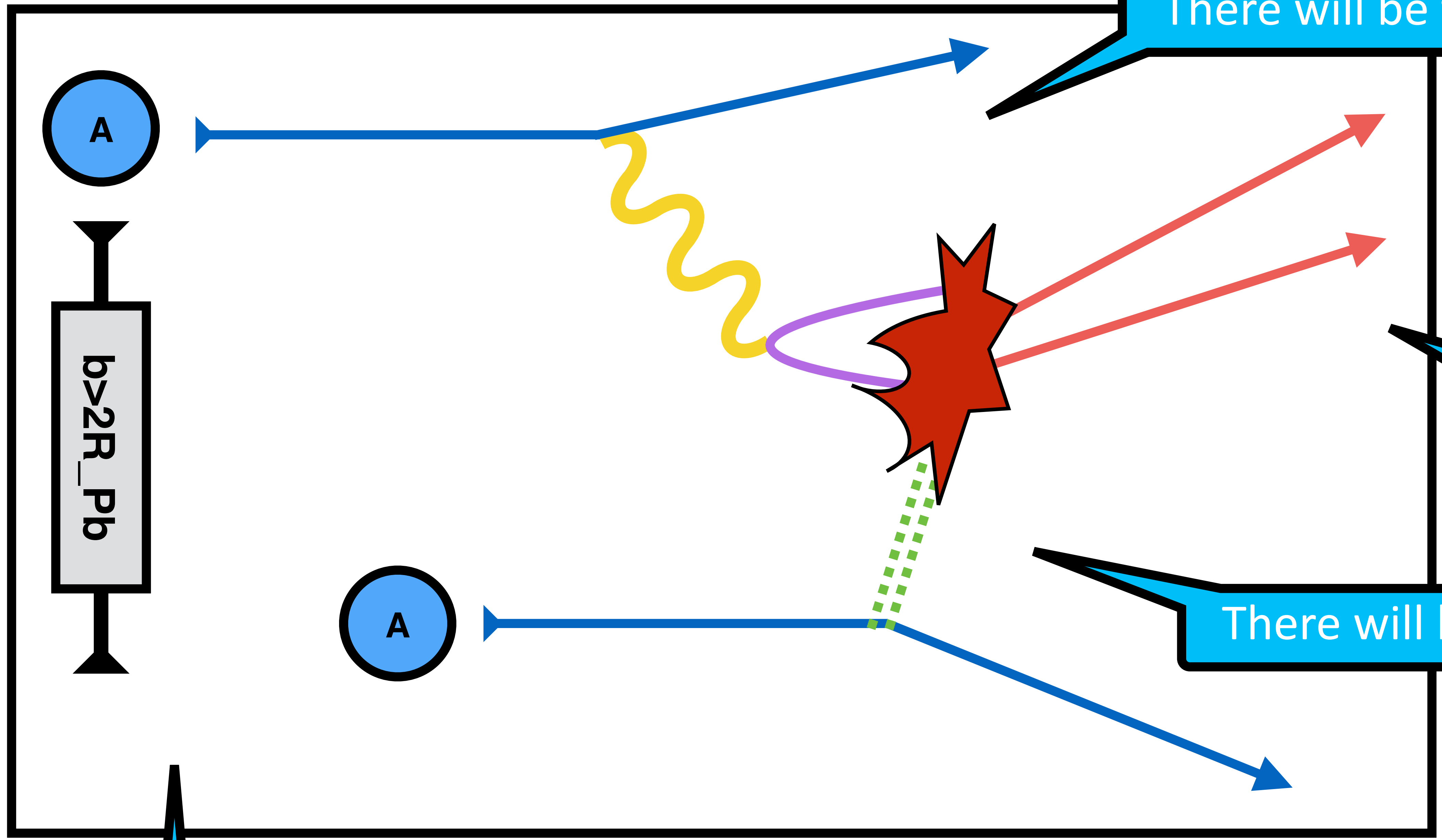
How to find photon-induced interactions in hadron colliders (3/4)

For exclusive diffractive observables, one can also use UPC

Signature: Look for a low pT final state (eg. a dijet or a vector meson) in an otherwise empty detector



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Imposing conditions to select events may select a subset of the total flux
Let's look at two variations of the flux formalism to account for this effect:
Selecting UPC coherent processes
Selecting EMD processes

The photon flux in coherent UPC according to STARlight

Use a Glauber description of the target to ensure the absence of hadronic inelastic collisions

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Use a Glauber description of the target to ensure the absence of hadronic inelastic collisions

$$n^U(y) = k\int_0^\infty db 2\pi b P_{NH}(b)\int_0^{r_A}\frac{rdr}{\pi r_A^2}\int_0^{2\pi}d\phi n(k, b + r\cos(\phi))$$

Flux

Details in: JGC, Phys.Rev. C96 (2017) 015203

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Use a Glauber description of the target to ensure the absence of hadronic inelastic collisions

Photon energy

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Photon energy

Flux

impact parameter

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Photon energy

Flux

Position in the target

impact parameter

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Photon energy

Flux

Position in the target

Average over all possible positions in the target

impact parameter

Details in: JGC, Phys.Rev. C96 (2017) 015203

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Rapidity of the final state

$$k = \frac{M}{2}e^y$$

Average over all possible positions in the target

Flux

impact parameter

Position in the target

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Rapidity of the final state

$$k = \frac{M}{2} e^y$$

Probability of no inelastic hadronic interactions at this impact parameter

Average over all possible positions in the target

Flux

impact parameter

Position in the target

Details in: JGC, Phys.Rev. C96 (2017) 015203

The photon flux in coherent UPC according to STARlight

Use a Glauber description of the target to ensure the absence of hadronic inelastic collisions

In a Poissonian model

$$P_{NH}(b) = \exp(-T_{AA}\sigma_{NN})$$

Photon energy

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cross section of a nucleon-nucleon inelastic hadronic interaction

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Flux

impact parameter

Position in the target

Details in: JGC, Phys.Rev. C96 (2017) 015203

The photon flux in coherent UPC according to STARlight

Use a Glauber description of the target to ensure the absence of hadronic inelastic collisions

Nucleus-nucleus interaction probability

$$T_{AA}(|\vec{b}|) = \int d^2\vec{r}\, T_A(\vec{r})T_A(\vec{r}-\vec{b})$$

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Average over all possible positions in the target

Flux

impact parameter

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Photon energy

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Flux

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Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{1+\exp(\frac{r-r_A}{z})}$$

In a Poissonian model

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Average over all possible positions in the target

Flux

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Position in the target

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Rapidity of the final state

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Probability of no inelastic hadronic interactions at this impact parameter

Average over all possible positions in the target

Flux

Position in the target

impact parameter

Homework: try to implement these formulas

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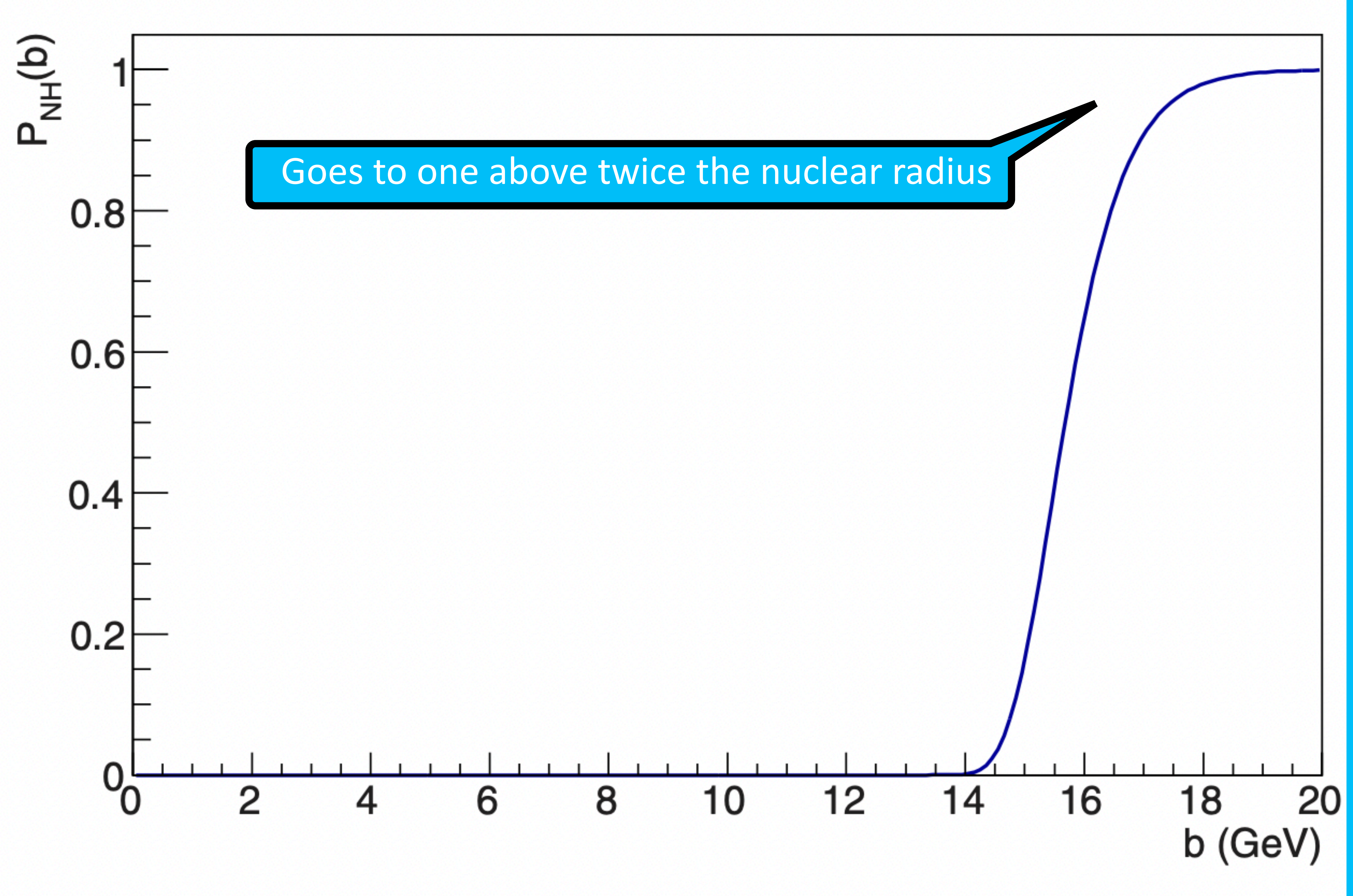
Probability of no inelastic hadronic interaction

Probability of no hadronic inelastic interaction for Pb-Pb collisions



$$n^U(y) = k \int_0^\infty db 2\pi b P_{NH}(b) \int_0^{r_A} \frac{rdr}{\pi r_A^2} \int_0^{2\pi} d\phi n(k, b + r\cos(\phi))$$

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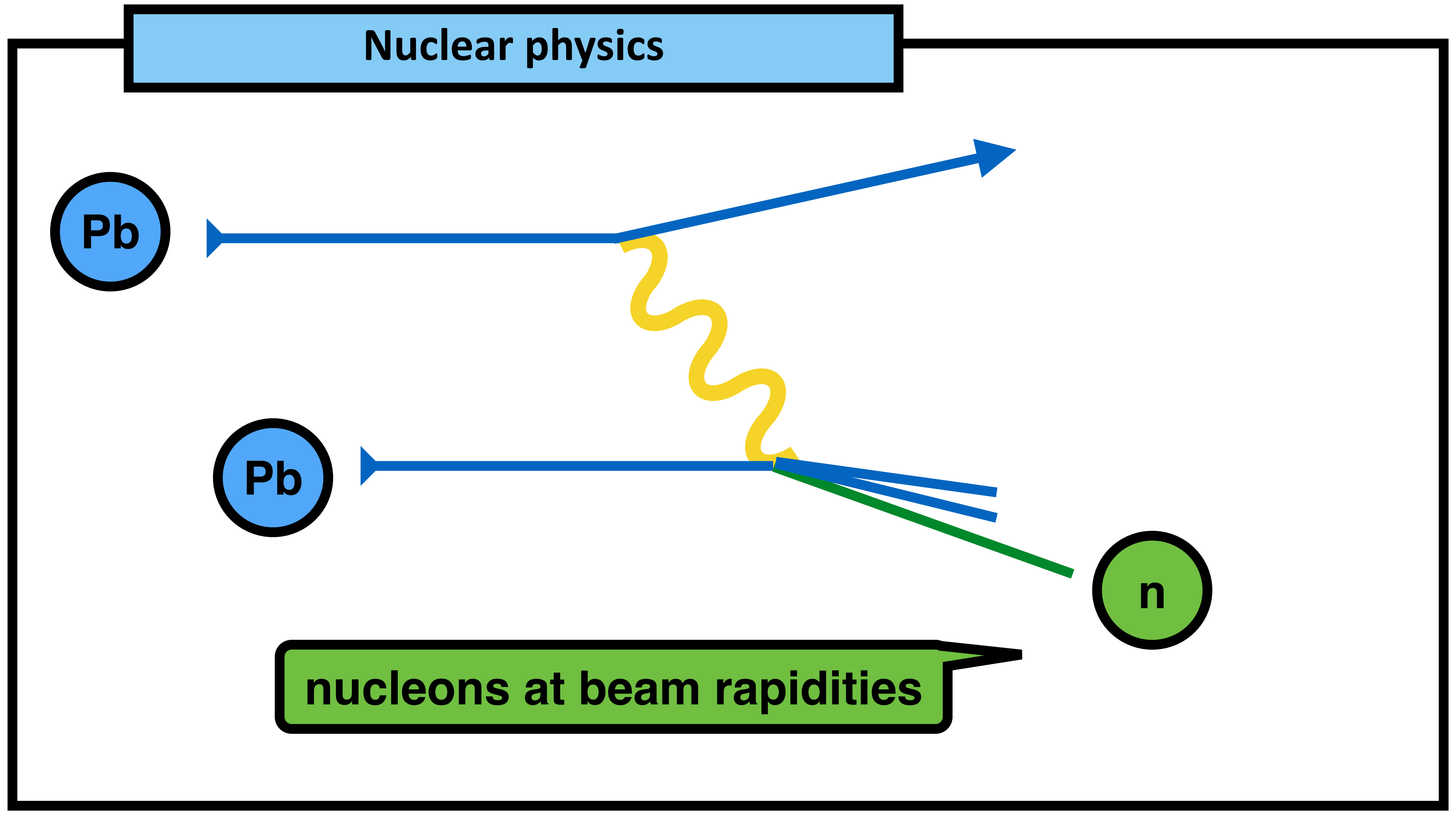
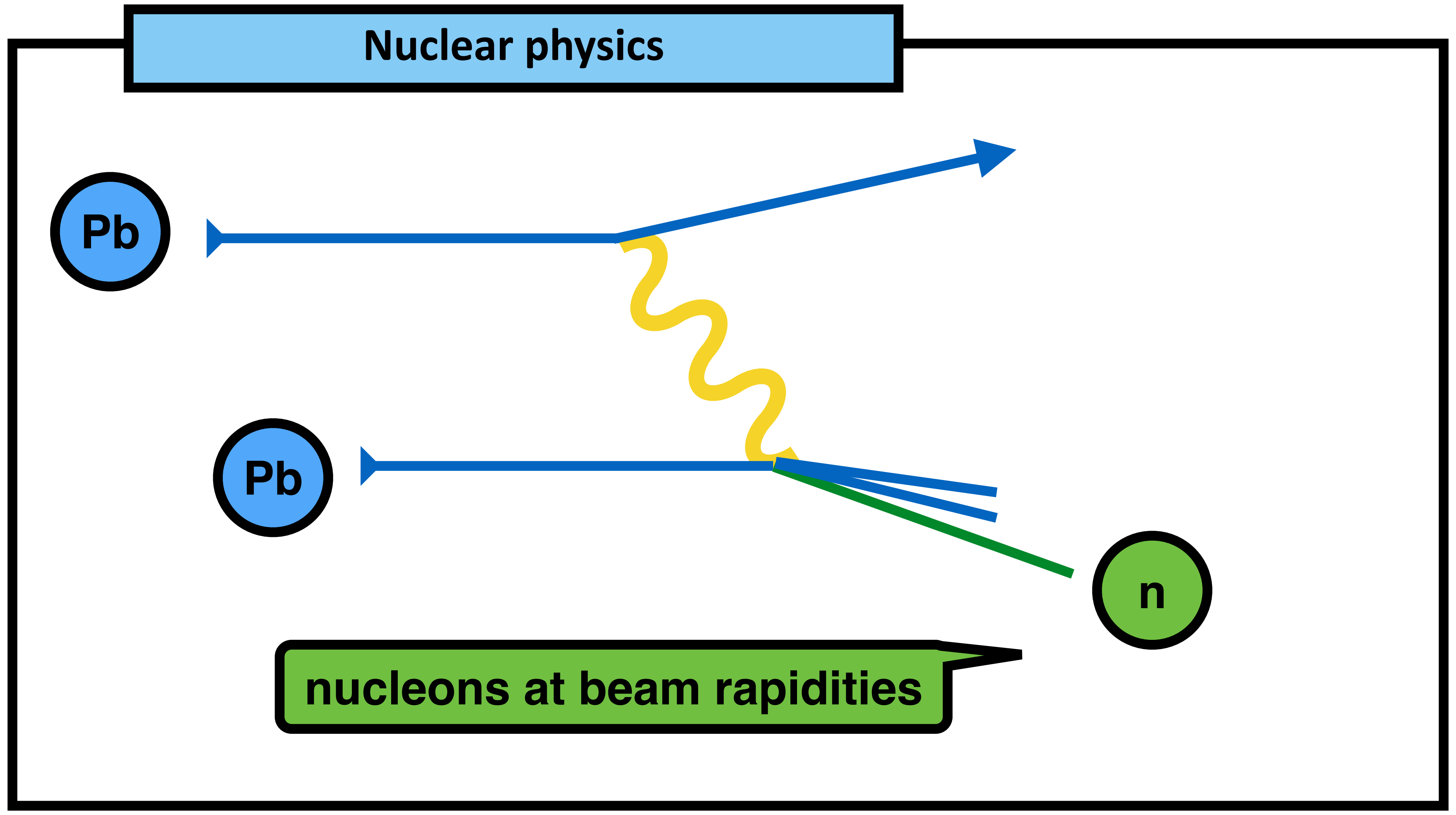
Electromagnetic dissociation (EMD)



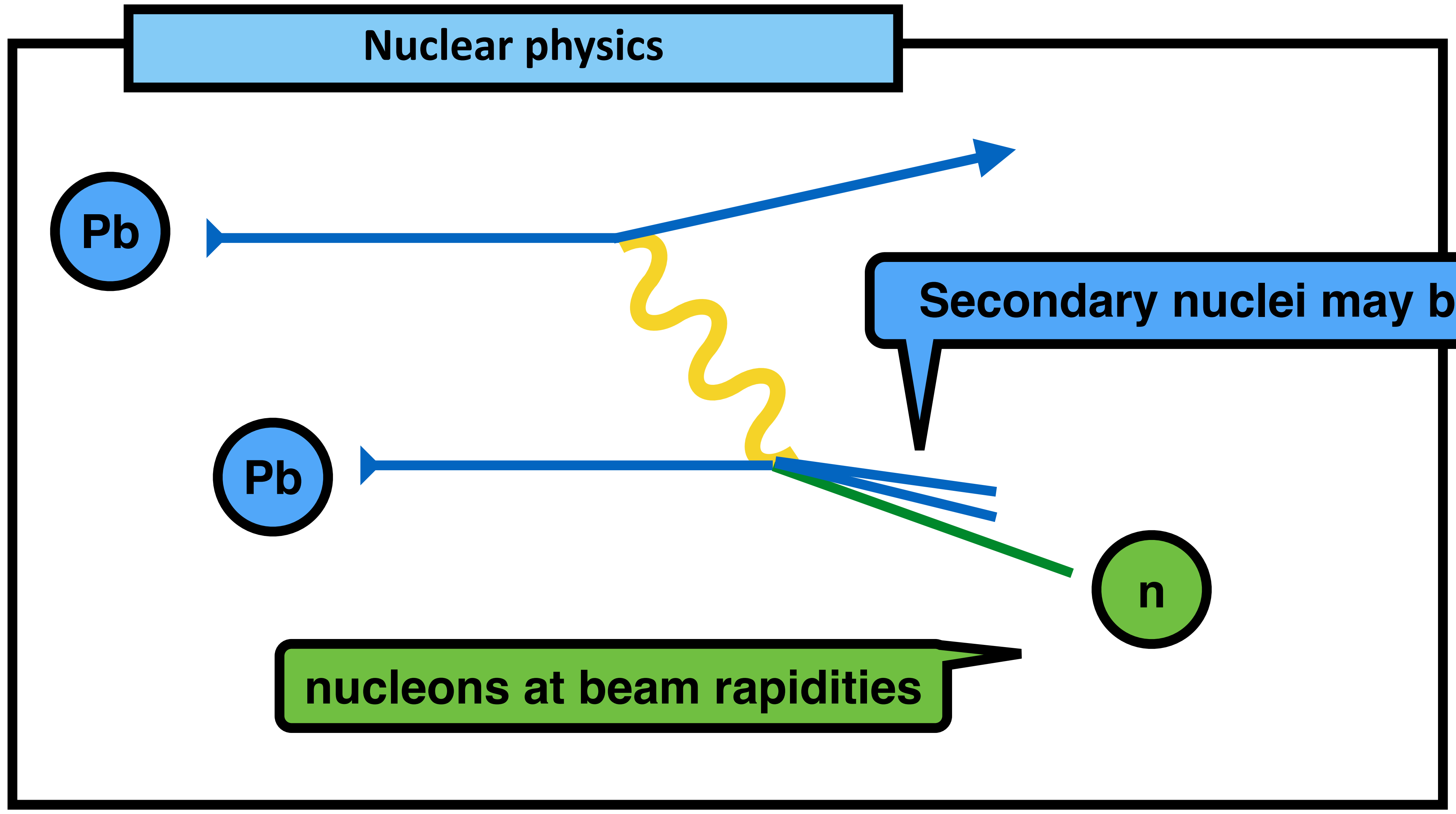
Electromagnetic dissociation (EMD)

This process limits the beam lifetime in heavy-ion colliders



Electromagnetic dissociation (EMD)

This process limits the beam lifetime in heavy-ion colliders



Secondary nuclei may be a hazard to LHC/FCC superconducting magnets

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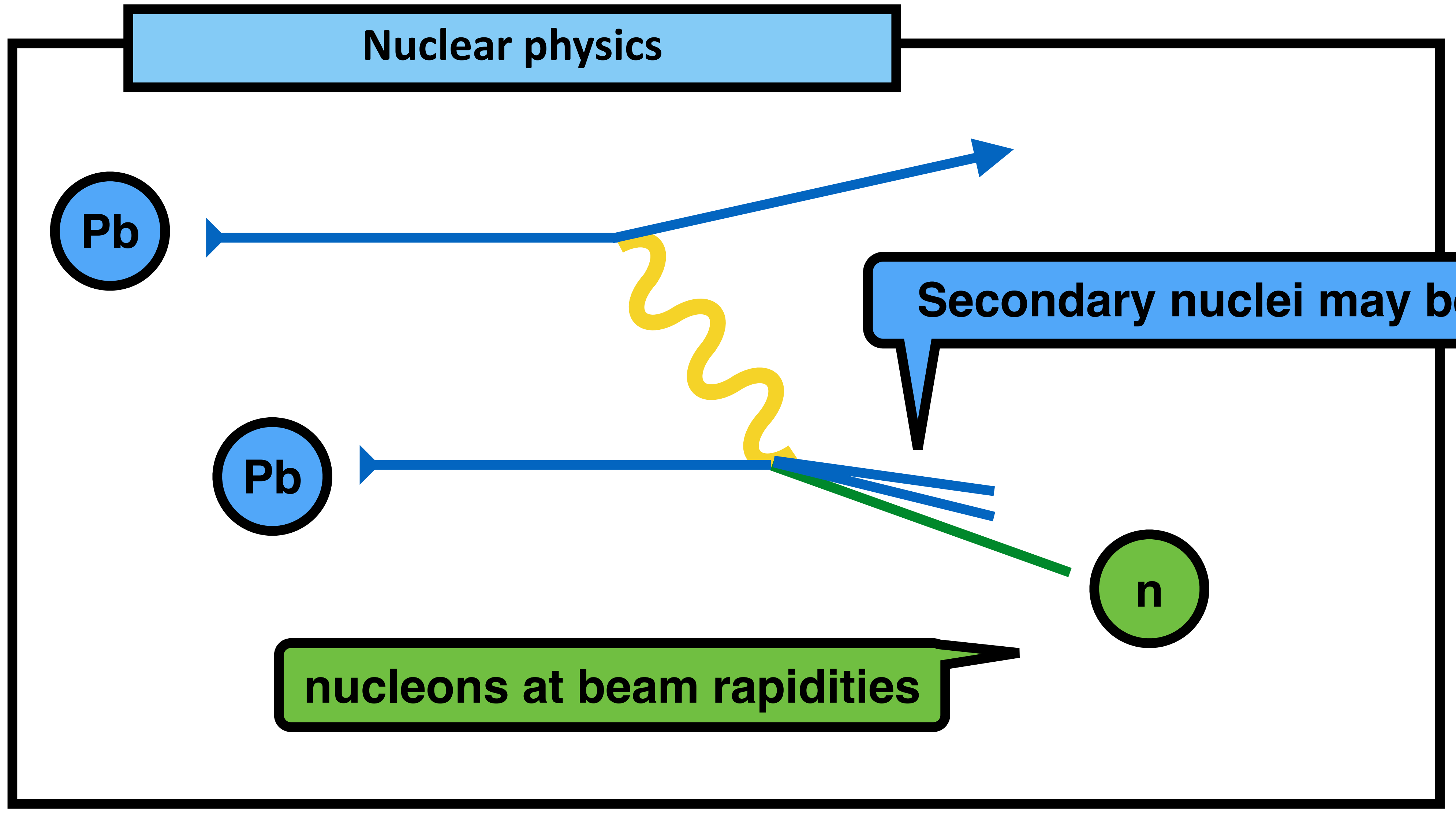

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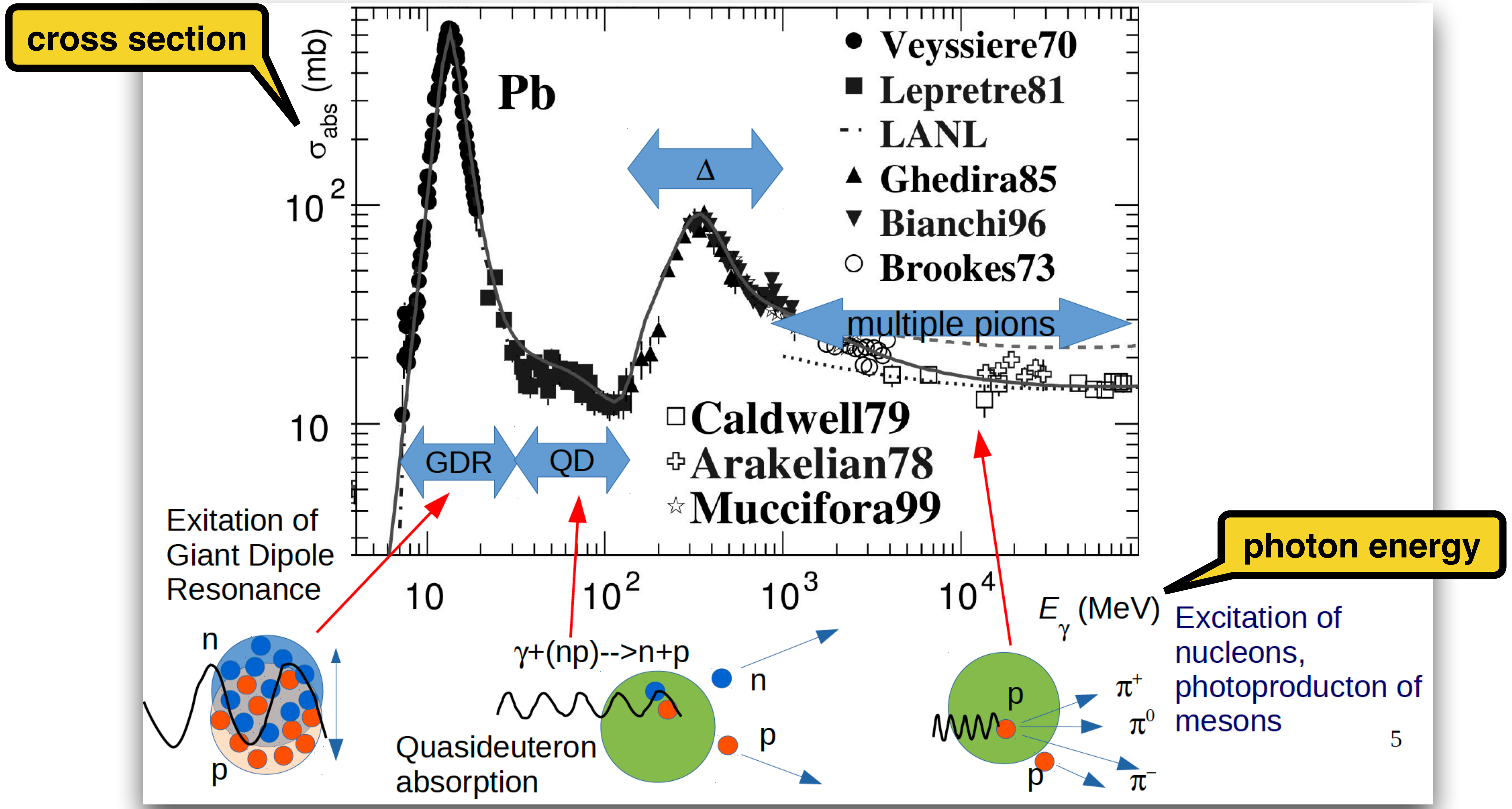
Slide from Igor Pshenichnov



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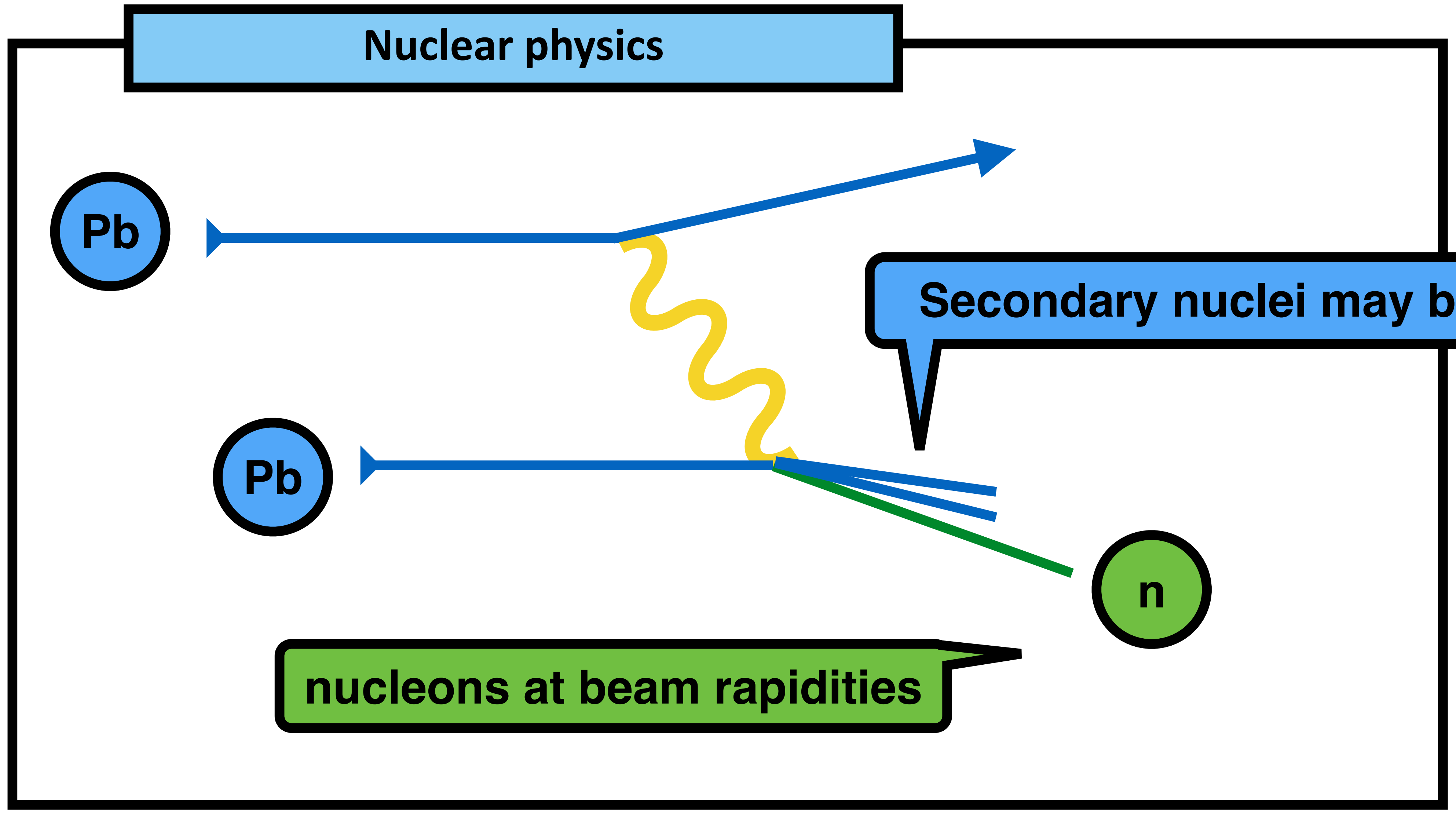

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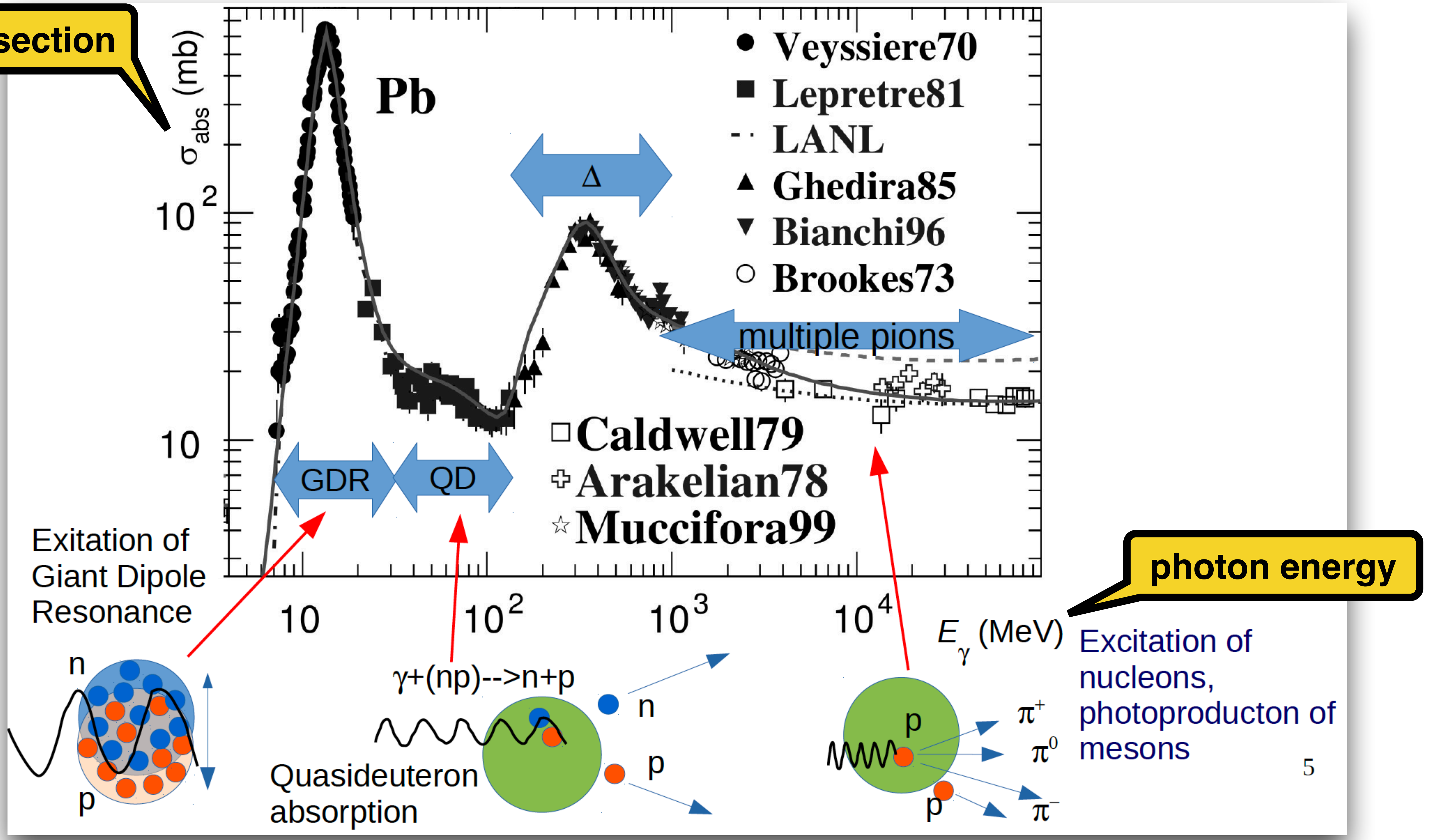

At larger photon energies, charged particles are produced: may affect the efficiency of vetos at forward rapidities

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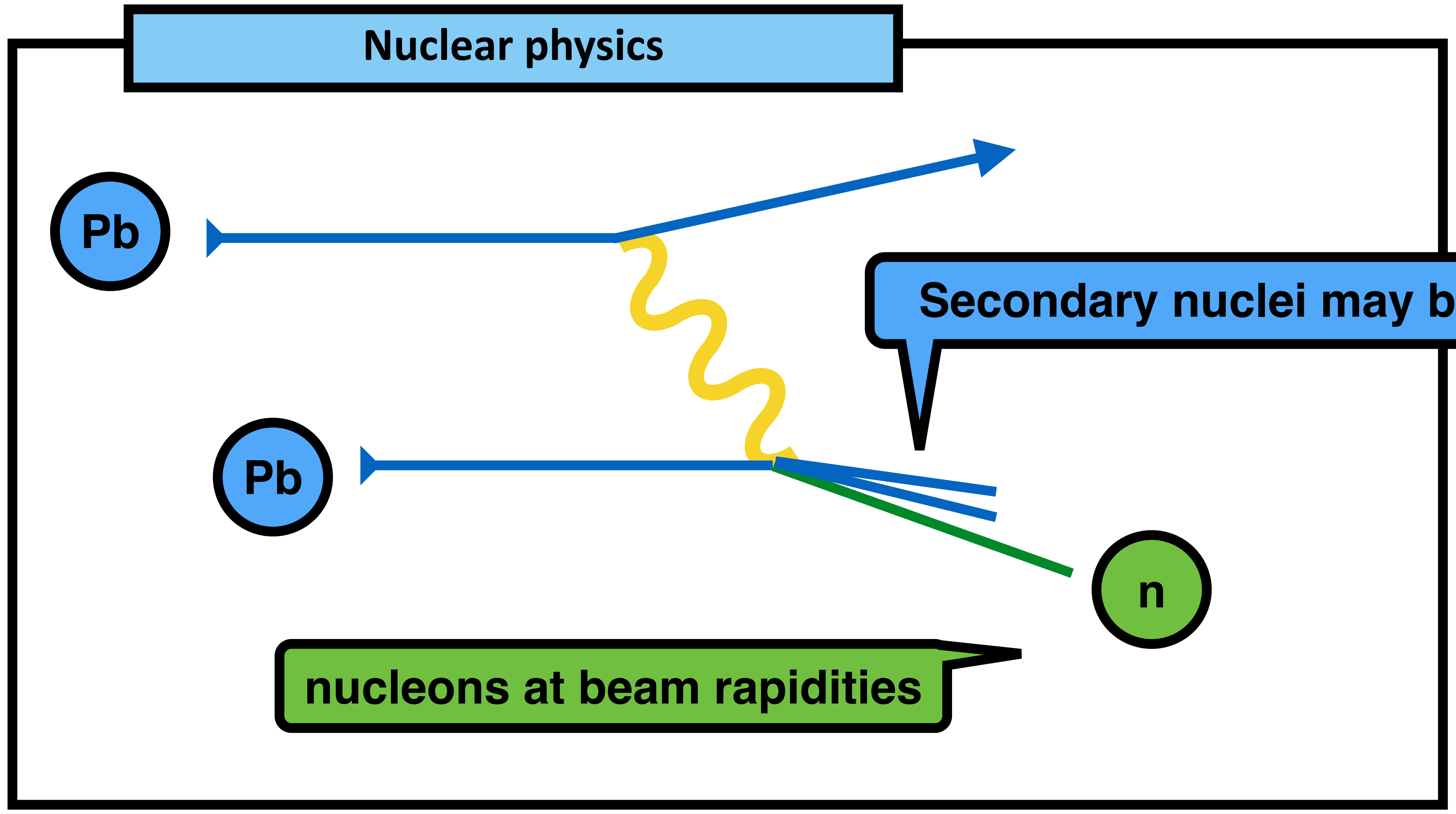

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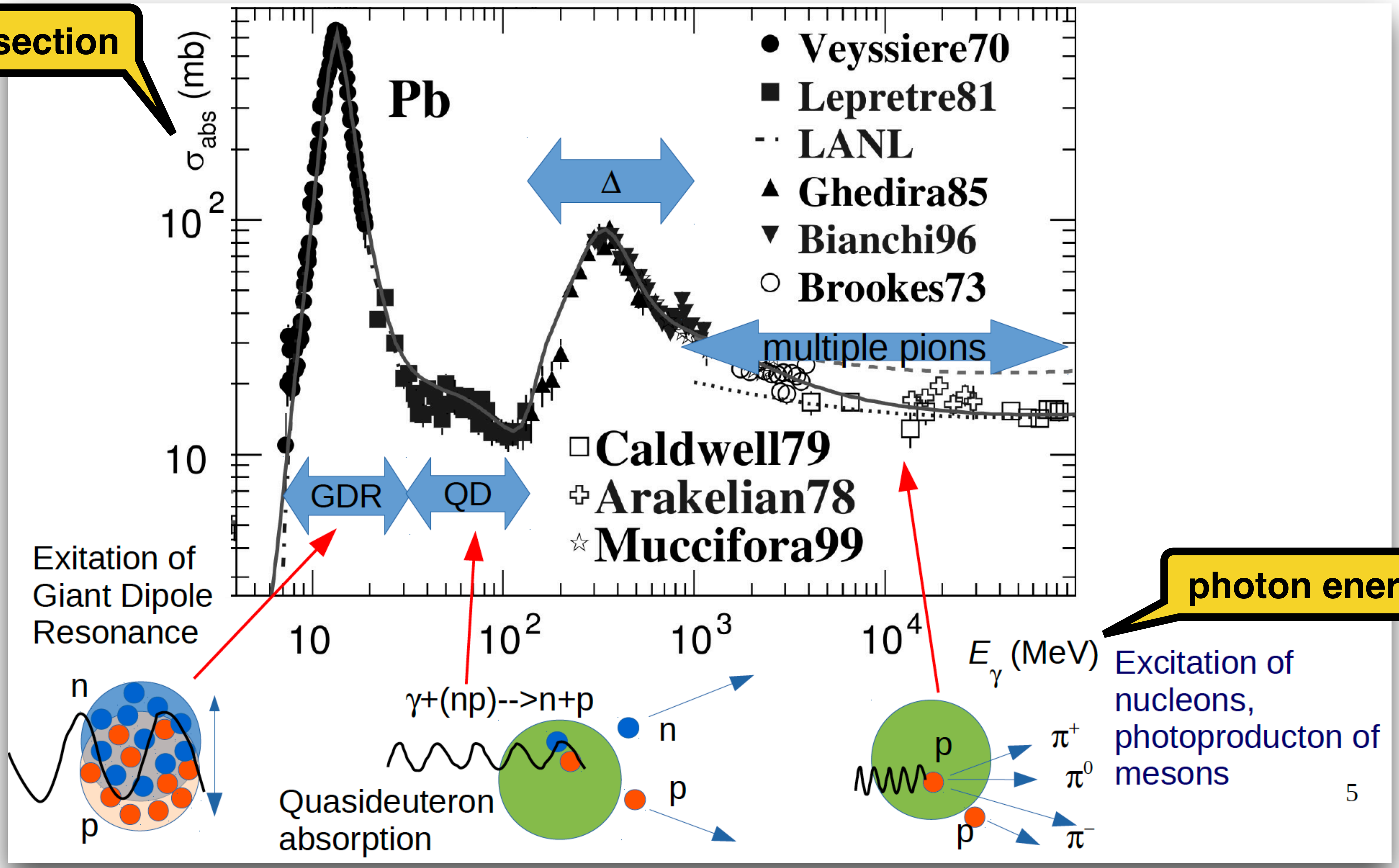
$\mathcal{O}(10)$ MeVs (in target rest frame) needed to excite the GDP



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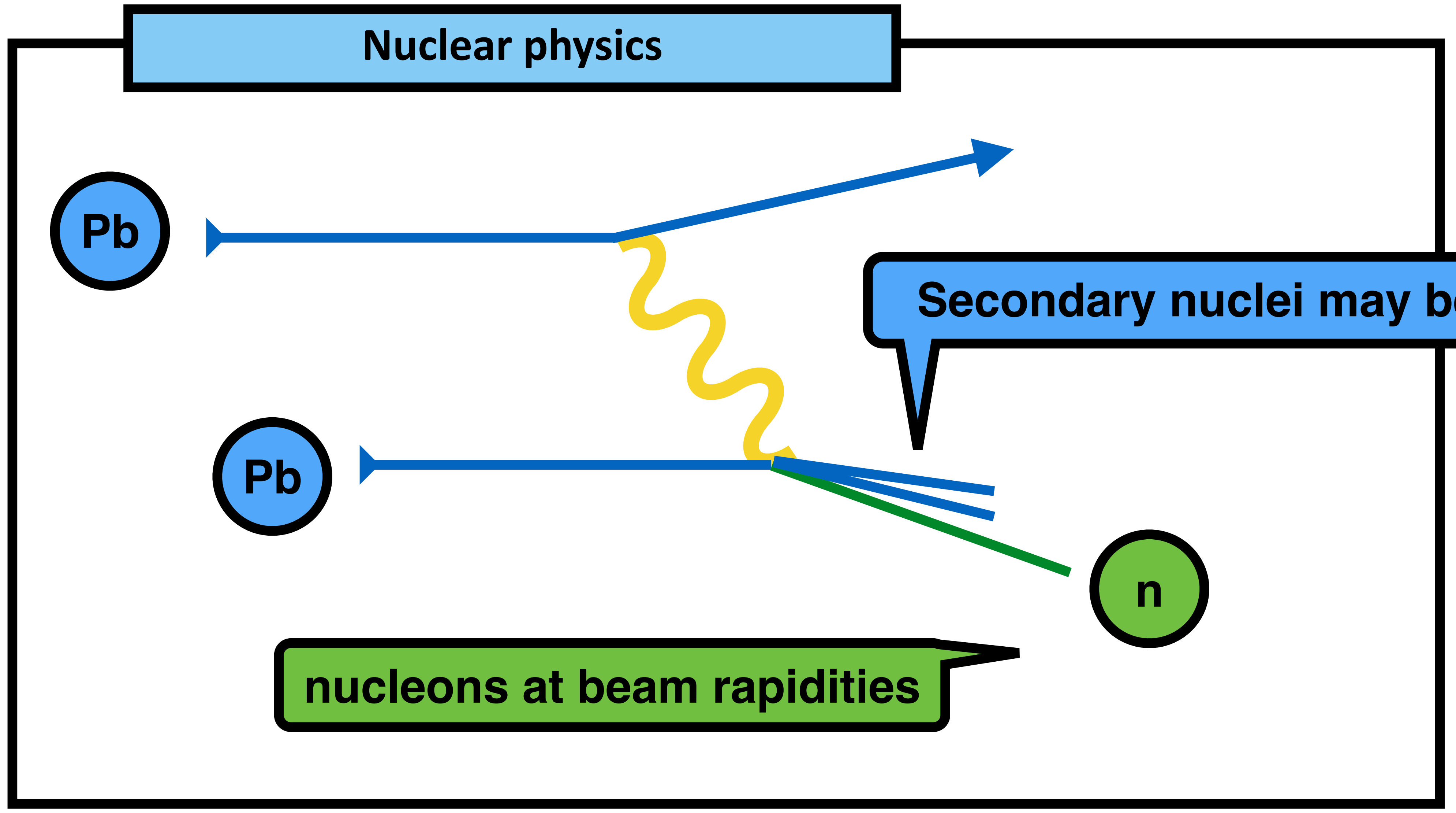

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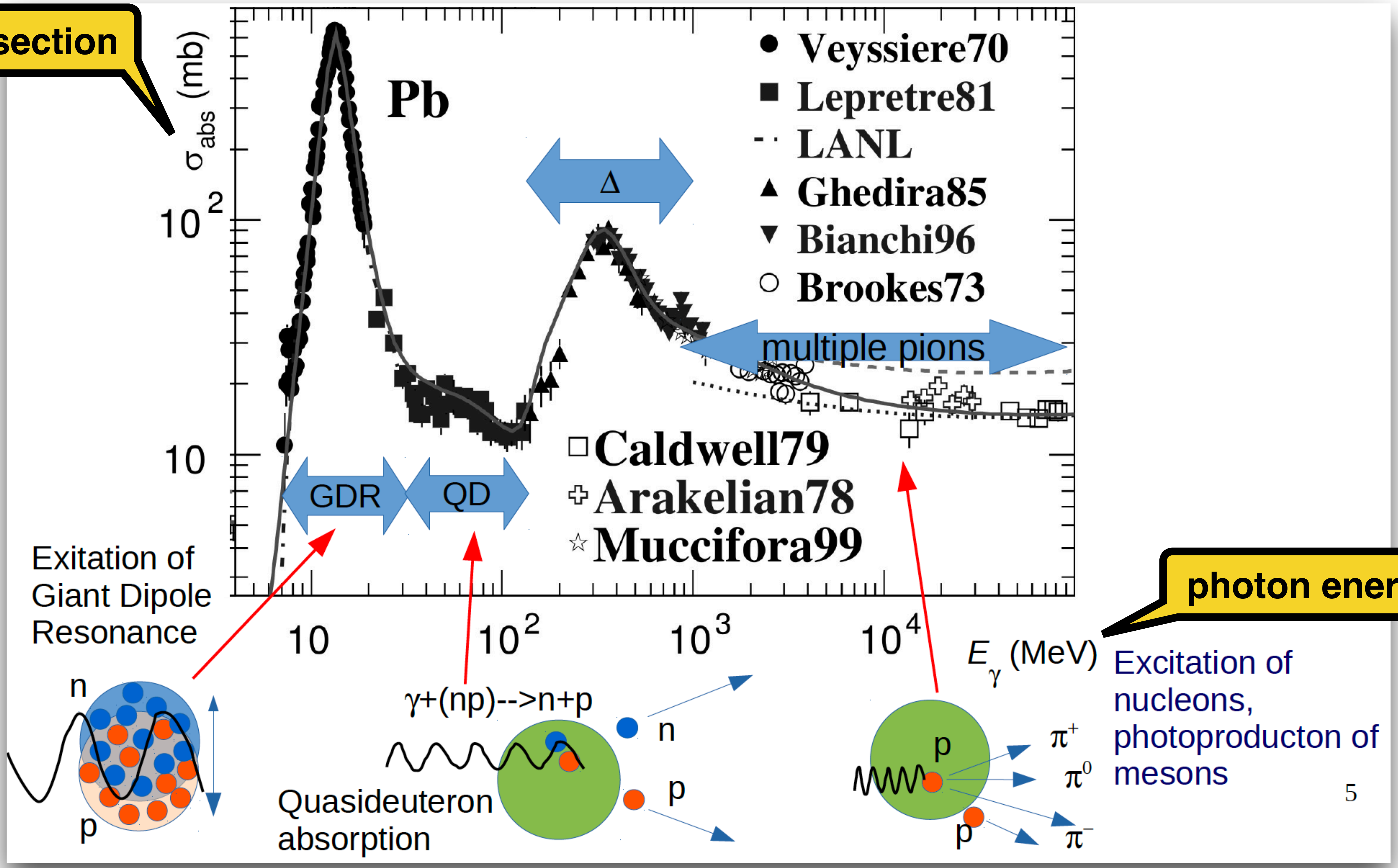
cross section



photon energy

$\mathcal{O}(10)$ MeVs (in target rest frame) needed to excite the GDP

This process can be used to select small impact parameters

At larger photon energies, charged particles are produced: may affect the efficiency of vetos at forward rapidities

Flux including EMD in nOOn

Use data to describe the neutron emission in EMD processes to tag different impact-parameter ranges

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$$P_{ij}(b) = P_i(b) \times P_j(b).$$

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Two one-neutron or one two-neutron emission

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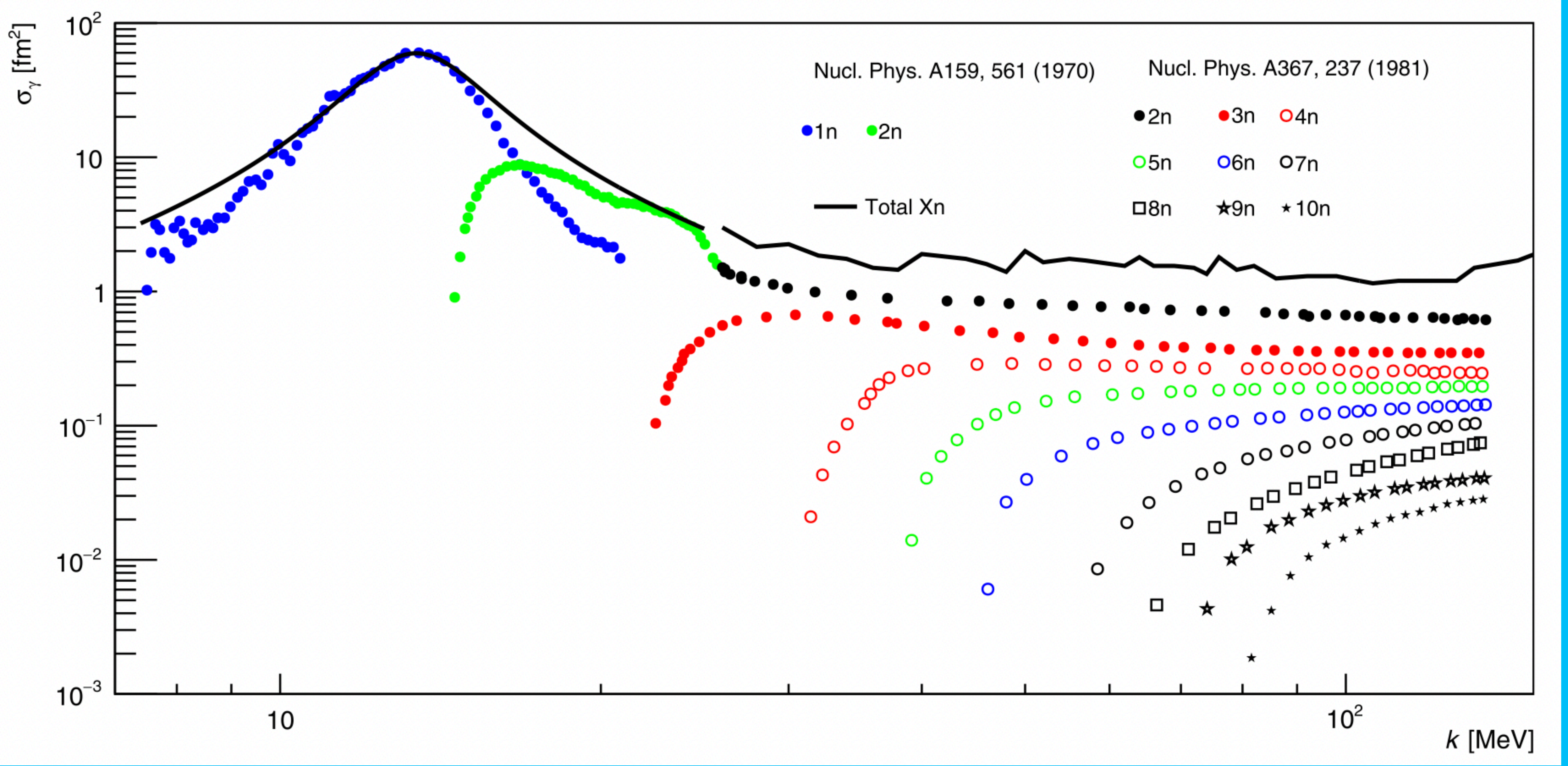
Formalism fit to EMD data sets, e. g.



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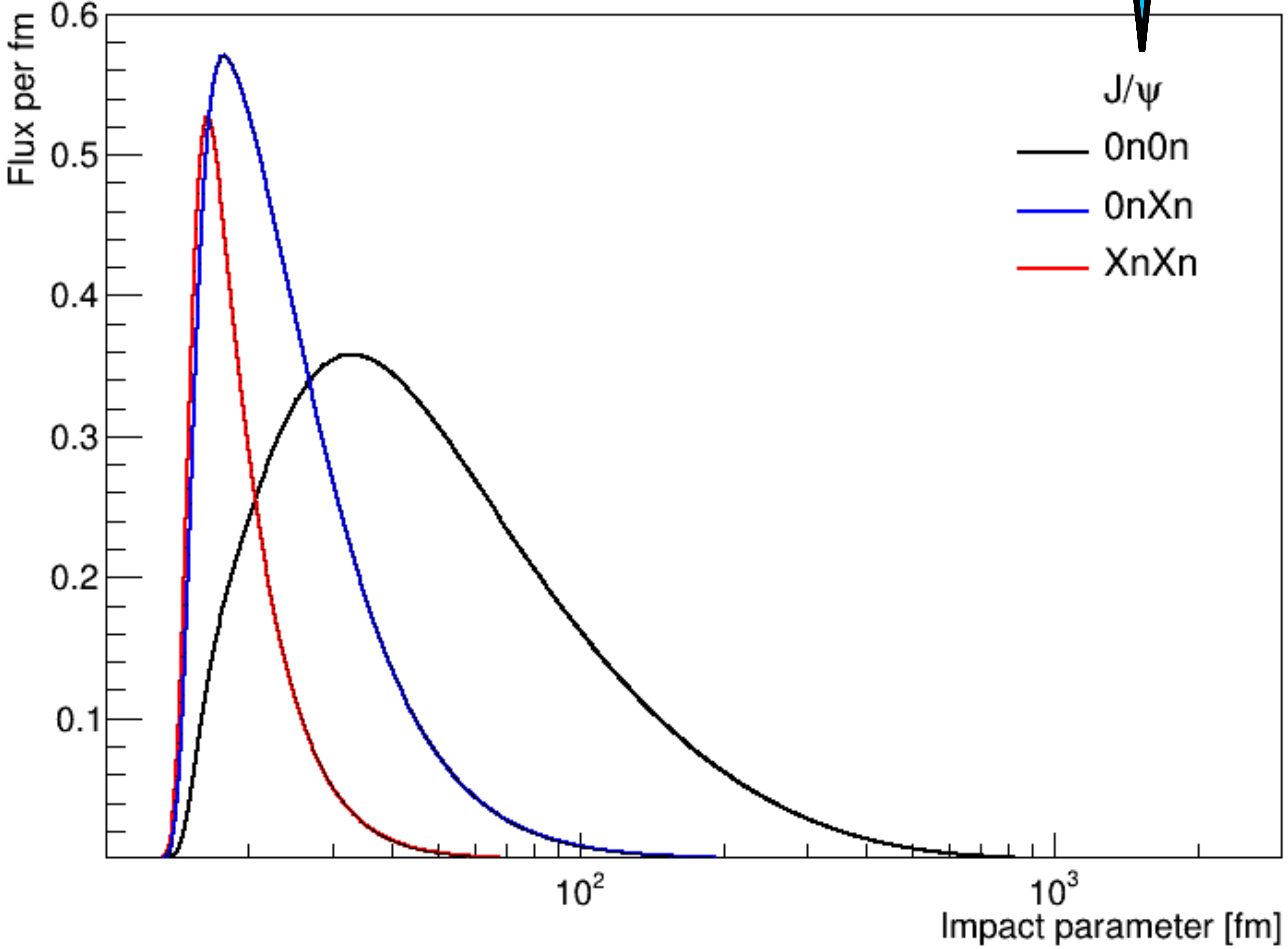
Example of impact-parameter dependence of the flux

J/ψ in the LHC at midrapidity



Plot made with nOOn, provided by Michal Broz

Guillermo Contreras, CTU in Prague

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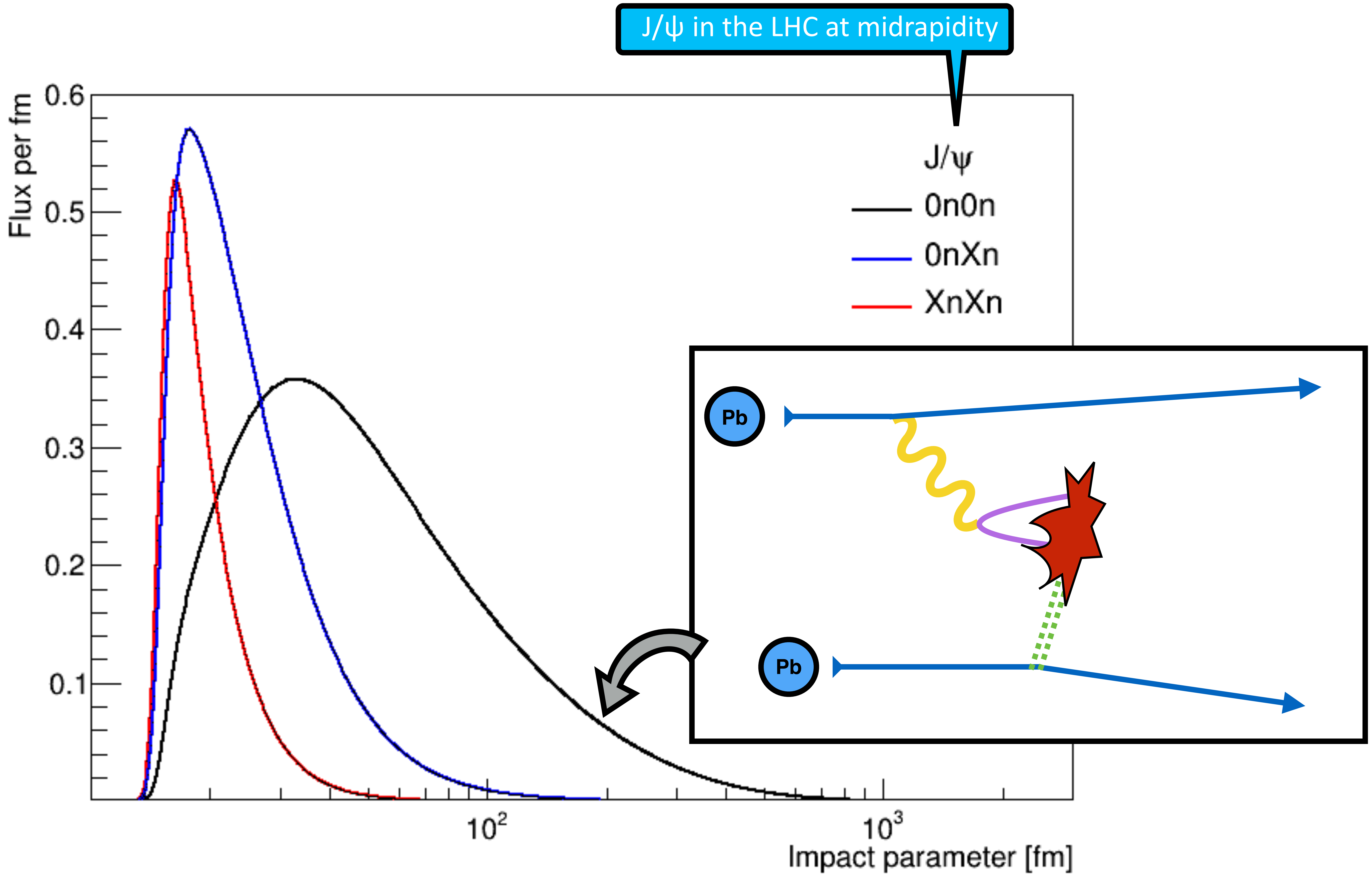

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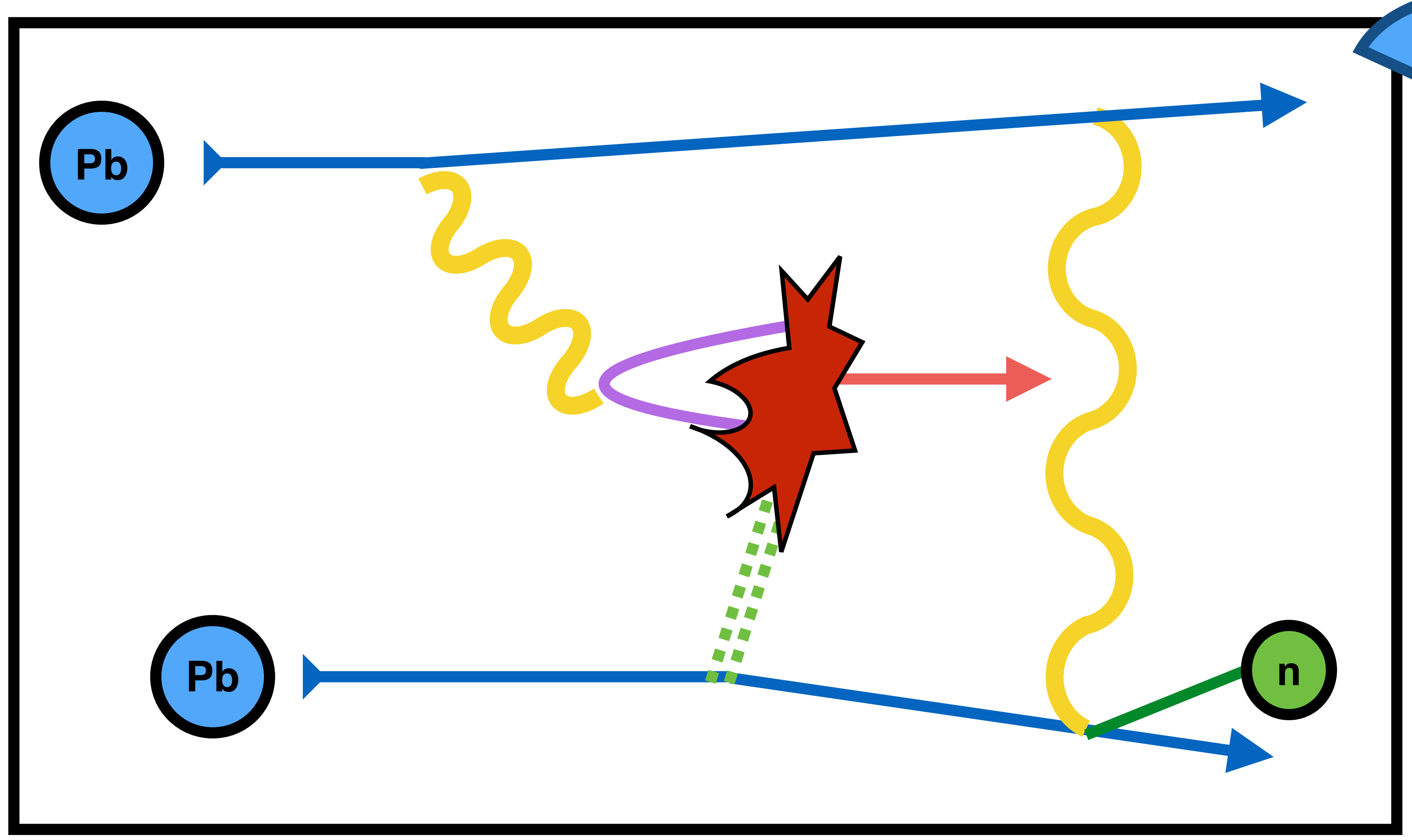

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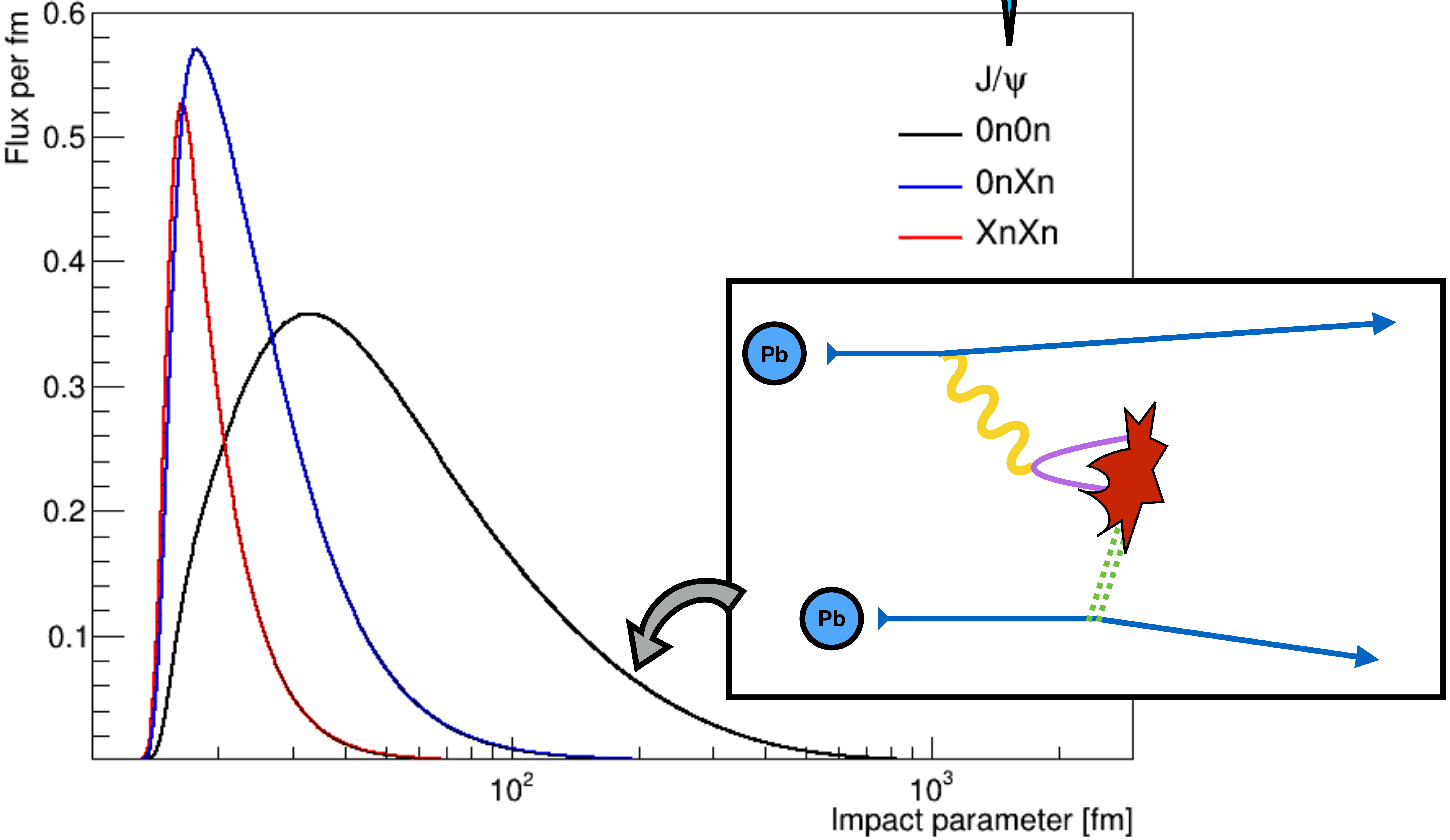

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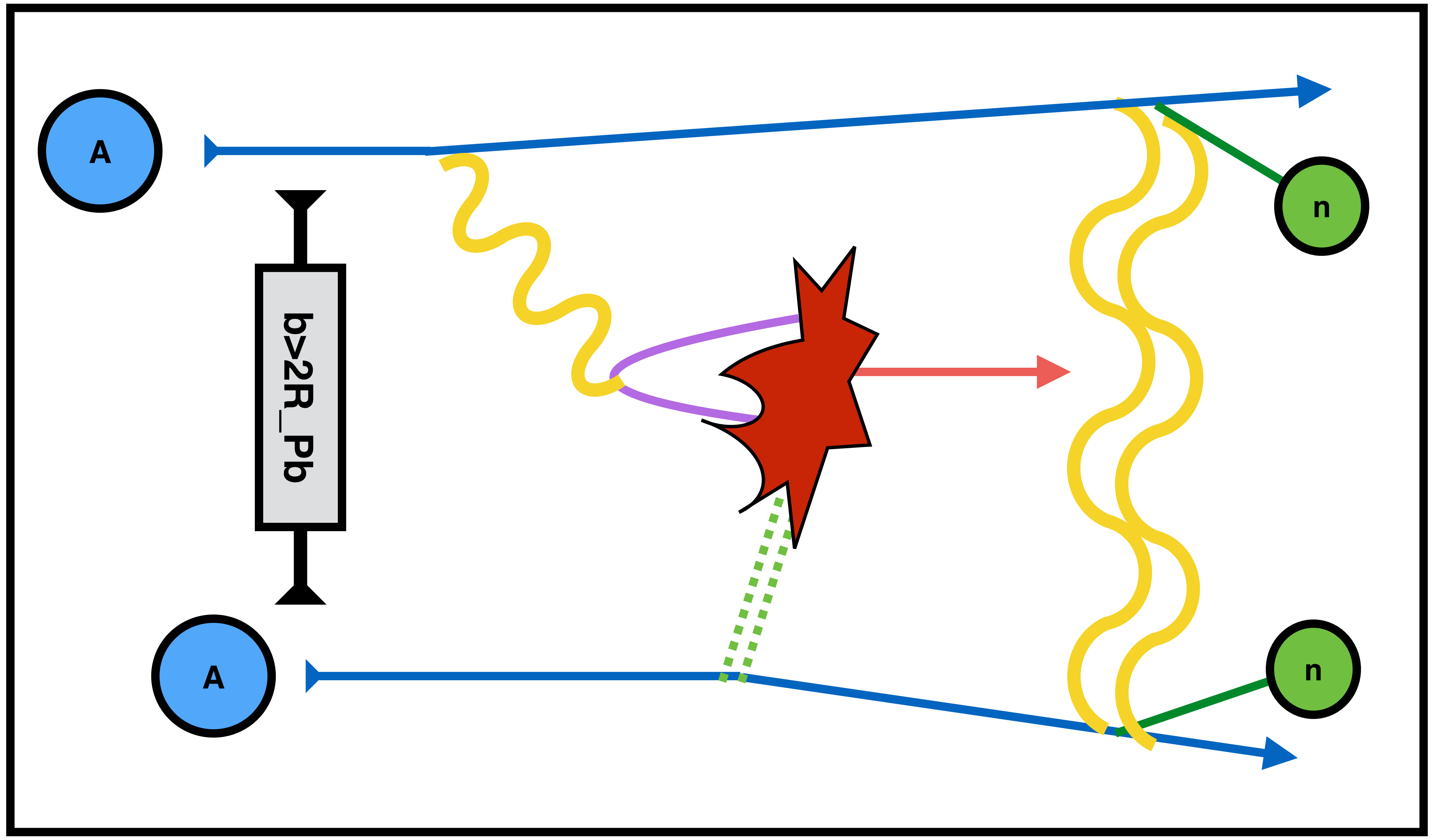
How to find photon-induced interactions in hadron colliders (4/4)

Sometimes, for exclusive diffractive observables in UPC an overlap with EMD is required in the trigger



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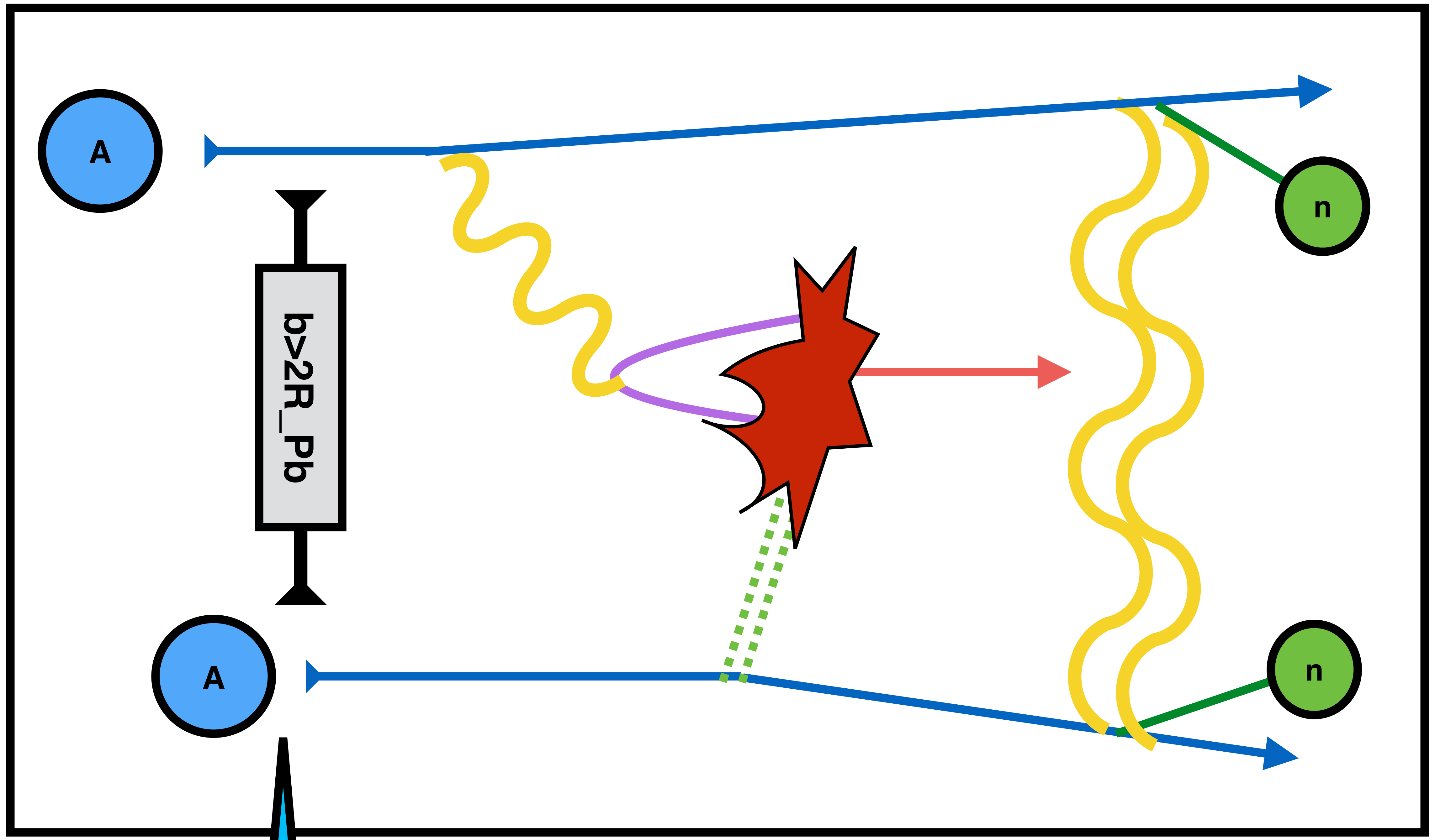

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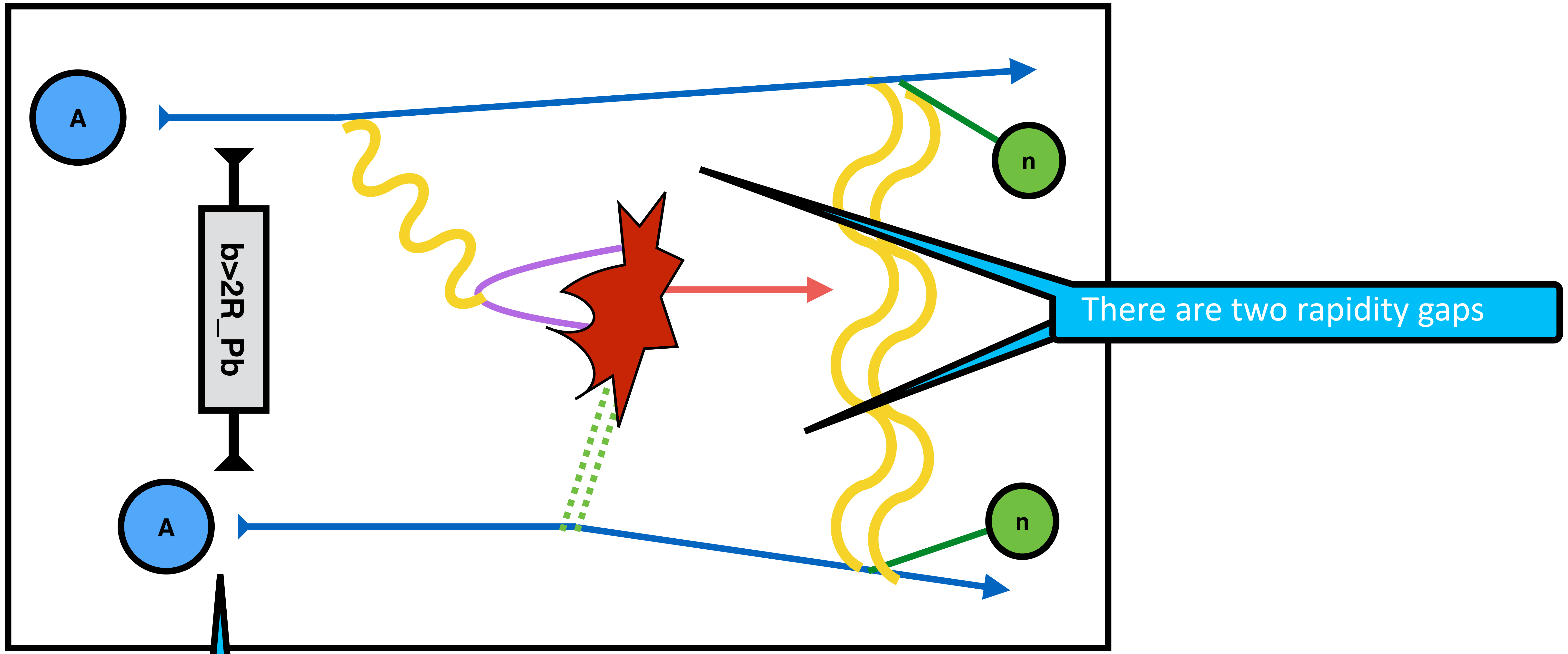

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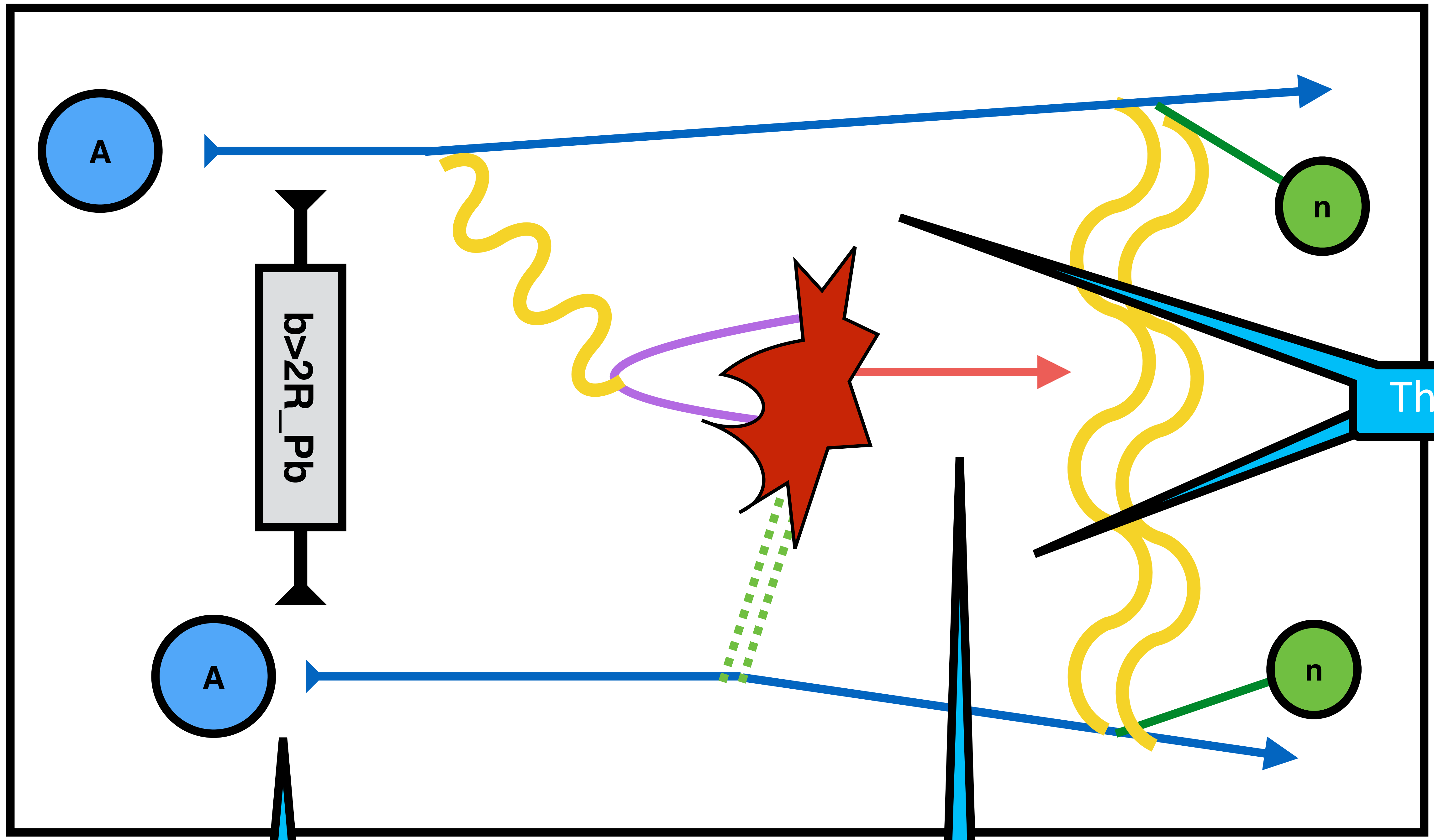

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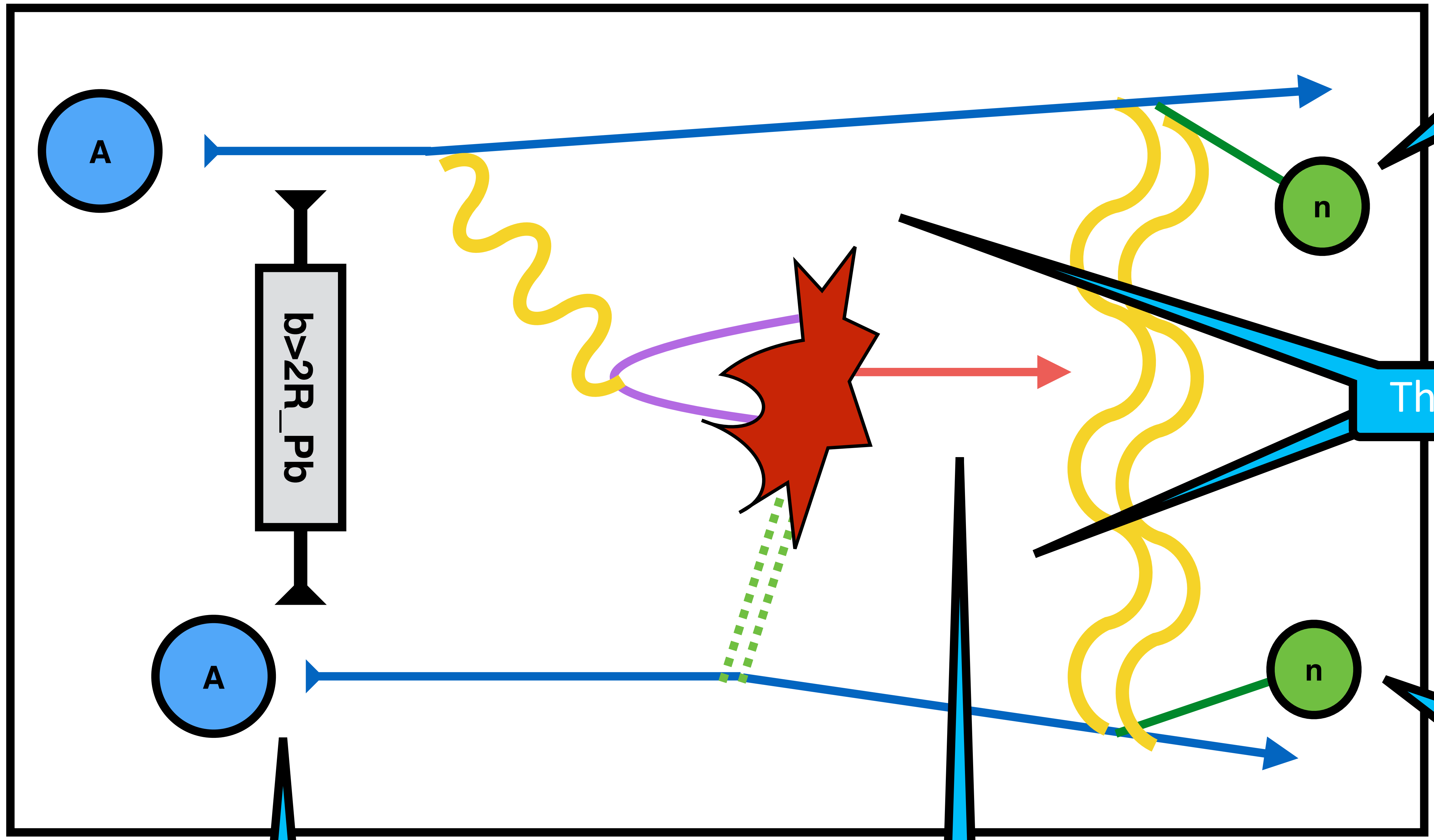

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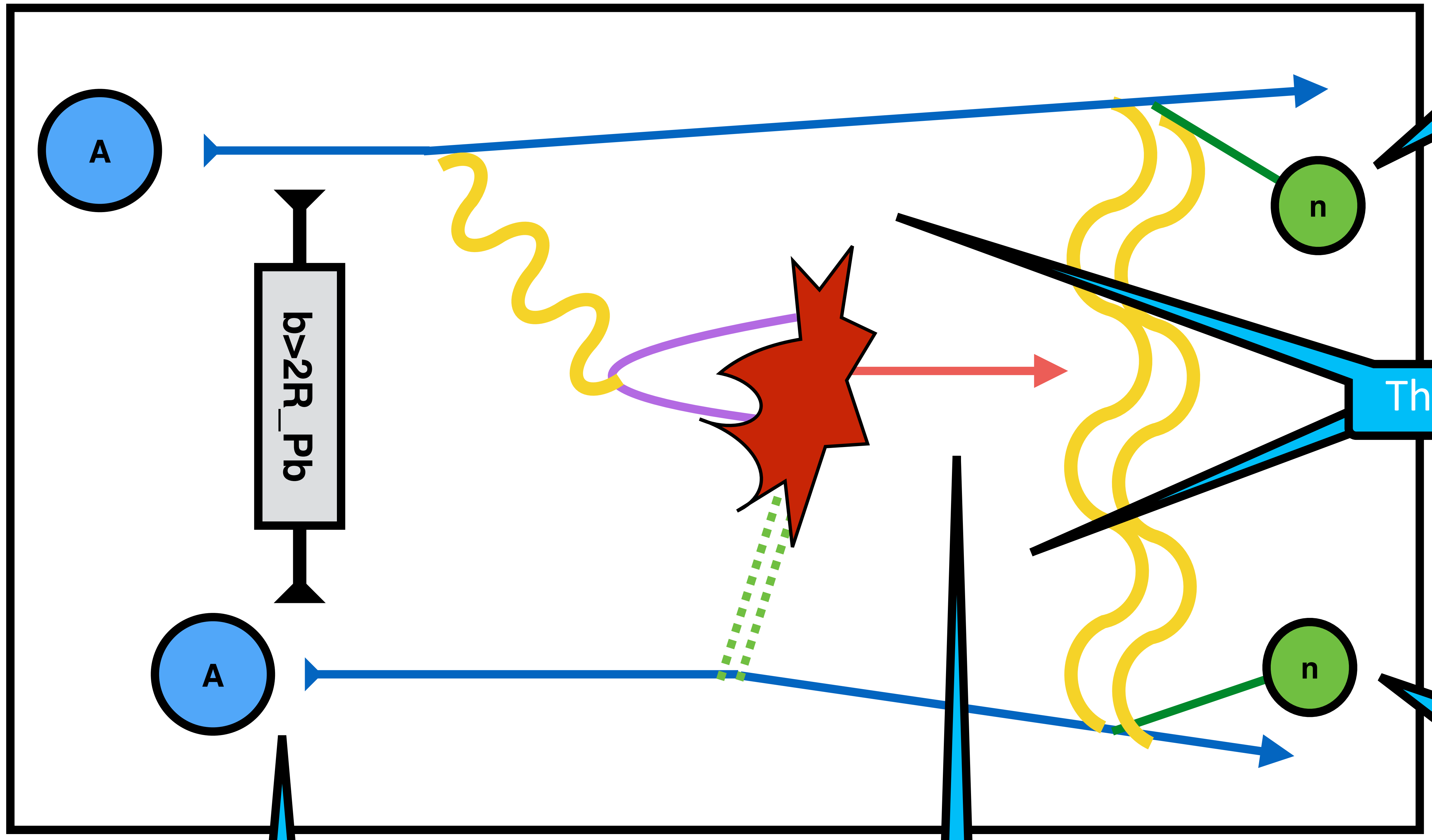
Signature: Look for a low pT final state and neutrons at zero-degrees in an otherwise empty detector



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The formalism to obtain the photon flux should be adapted to described the different types of photon induced processes

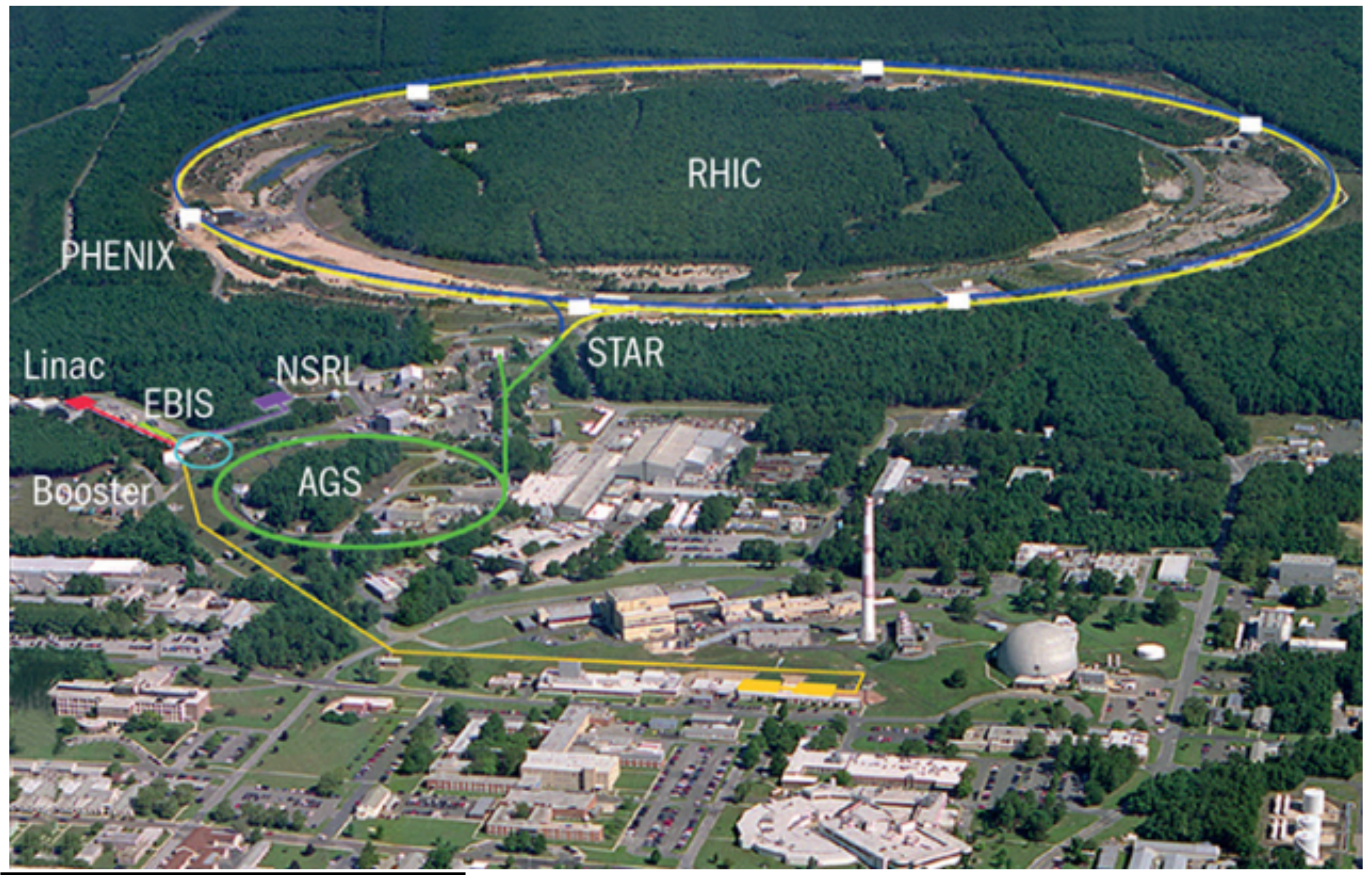
6

Exploring high-energy QCD with nuclei at RHIC and LHC

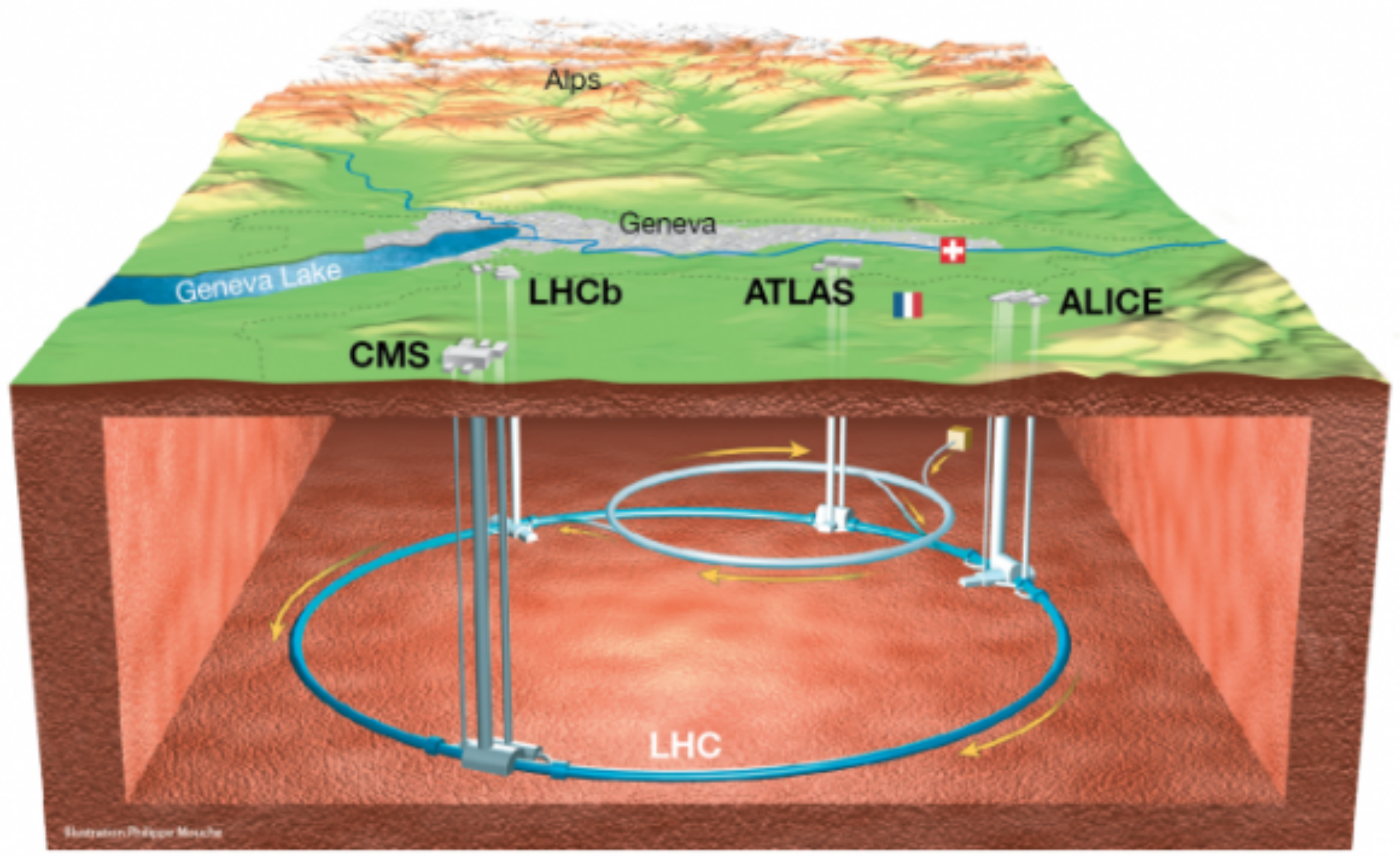
Heavy ions have more gluons and in a denser environment than protons which makes them ideal candidates to search for saturation effects

But other effects, like shadowing may complicate the search

RHIC and the LHC



Credit: BNL



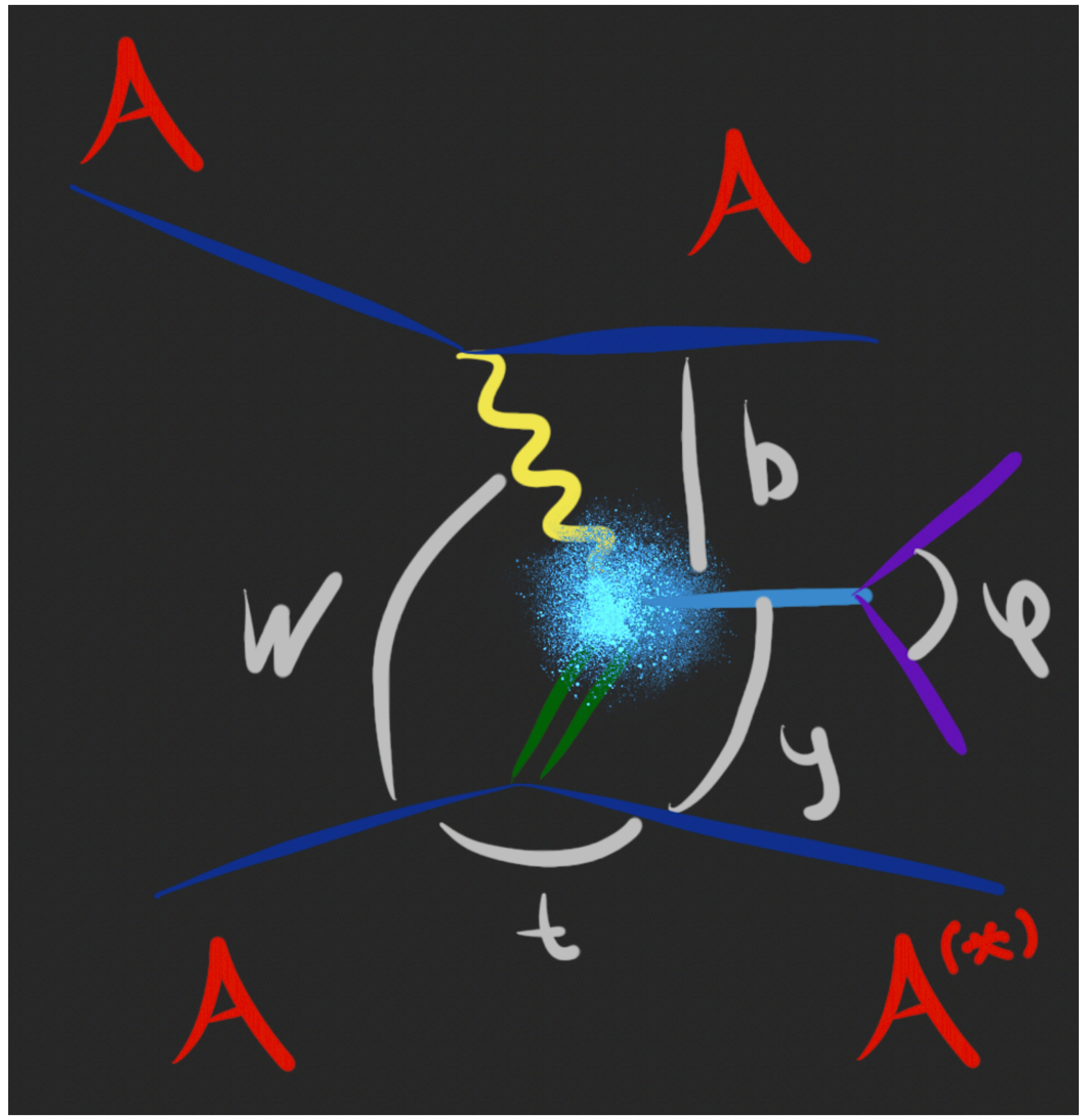
Credit: CERN

Relativistic heavy ion collider (RHIC)
Located in USA
3834 m of circumference
Operating since 2000
2 independent beams
Can accelerate different ions
Reaches collisions at 200 GeV (per NN) for AuAu

Both facilities have a very rich heavy-ion program

Large hadron collider (LHC)
Located in Europe
27 km of circumference
Operating since 2010
Has reached collisions at 5.36 TeV (per NN) for PbPb

There are many results, so I will concentrate on the possibilities offered by diffractive vector meson production
I will review only a few results, you will hear a lot more about this during the conference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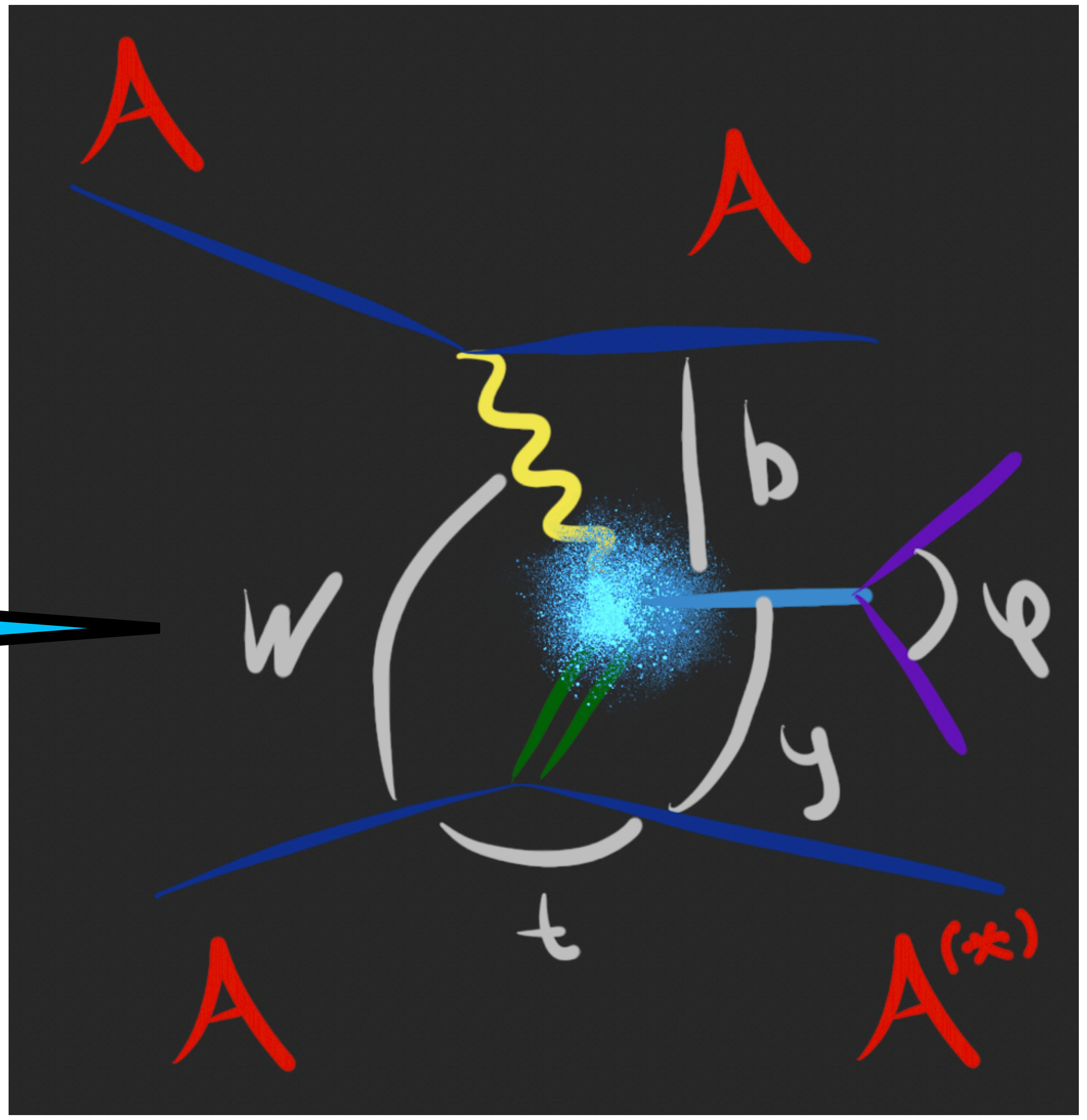
Diffractive vector meson photoproduction: a Swiss army knife for QCD (1/2)

The energy dependence, gives the Bjorken-x evolution of the target



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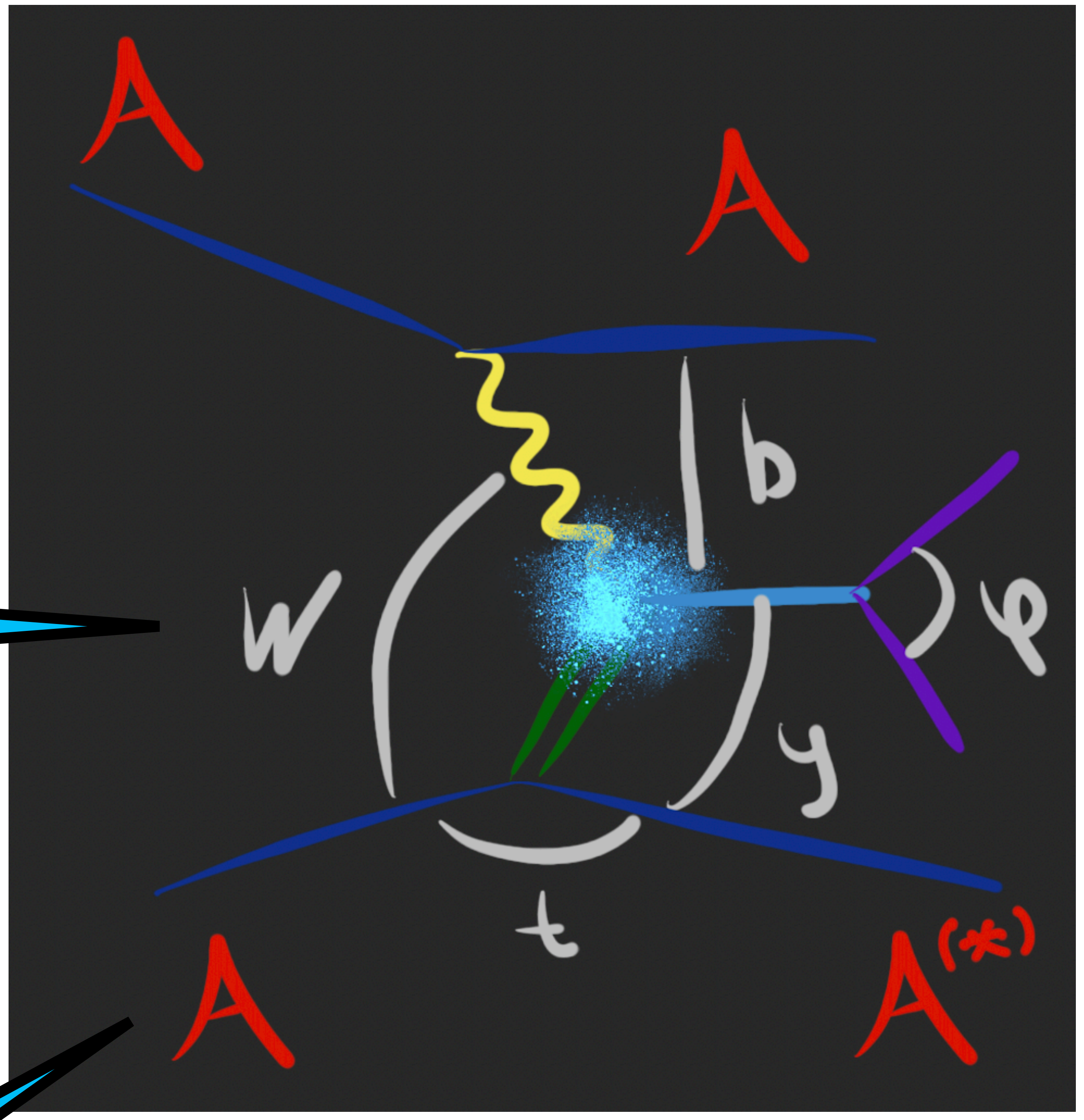

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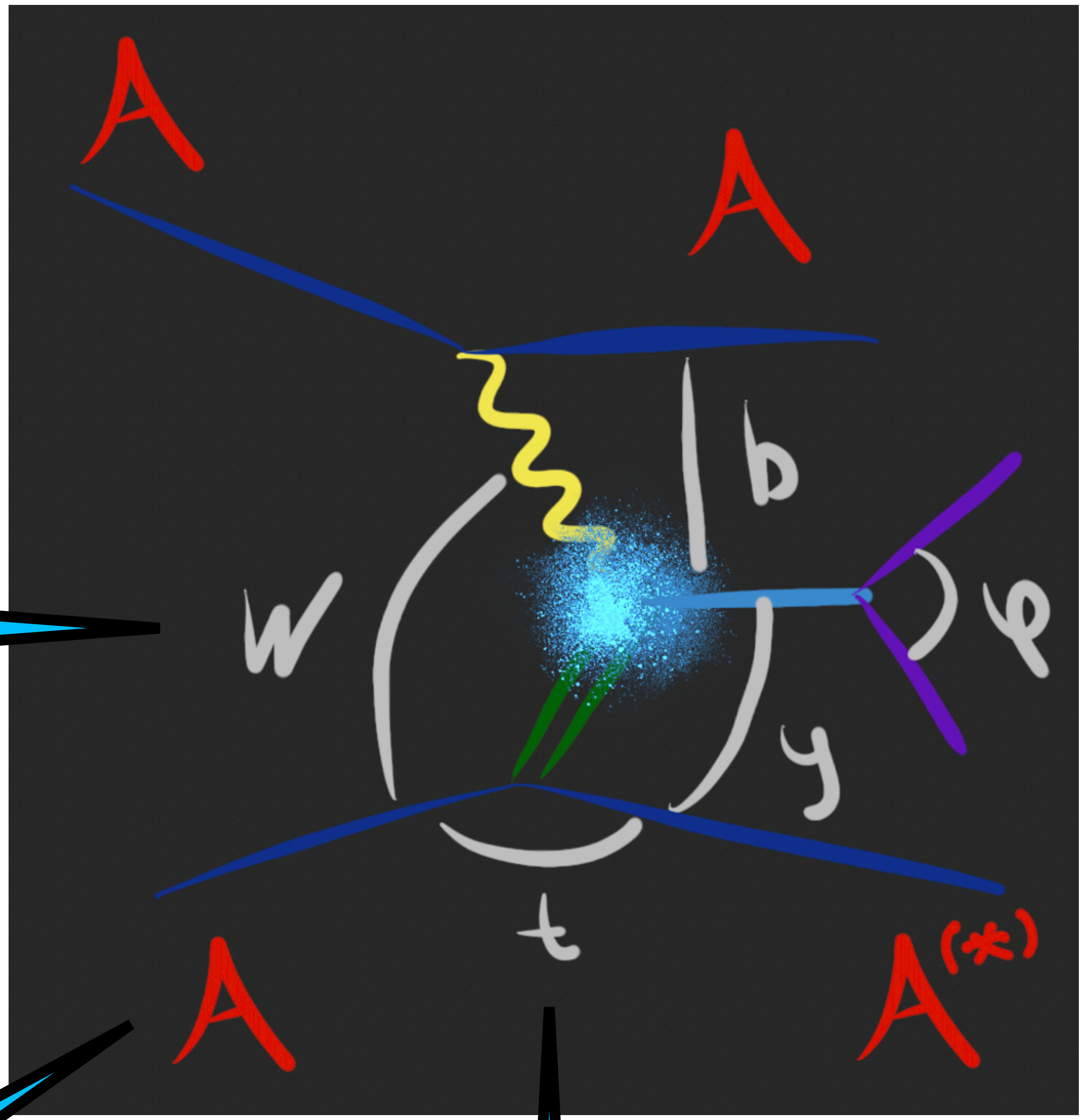

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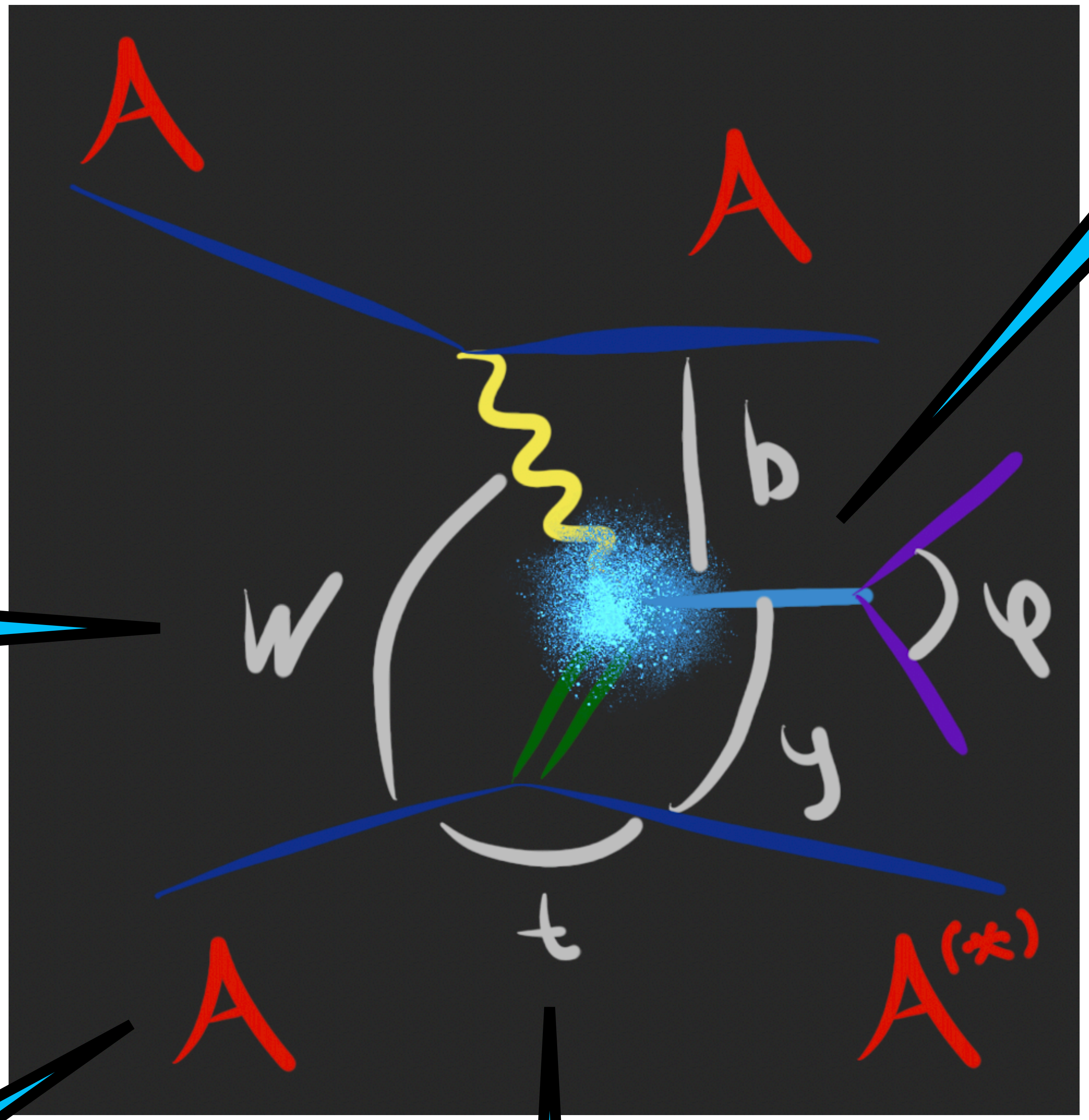

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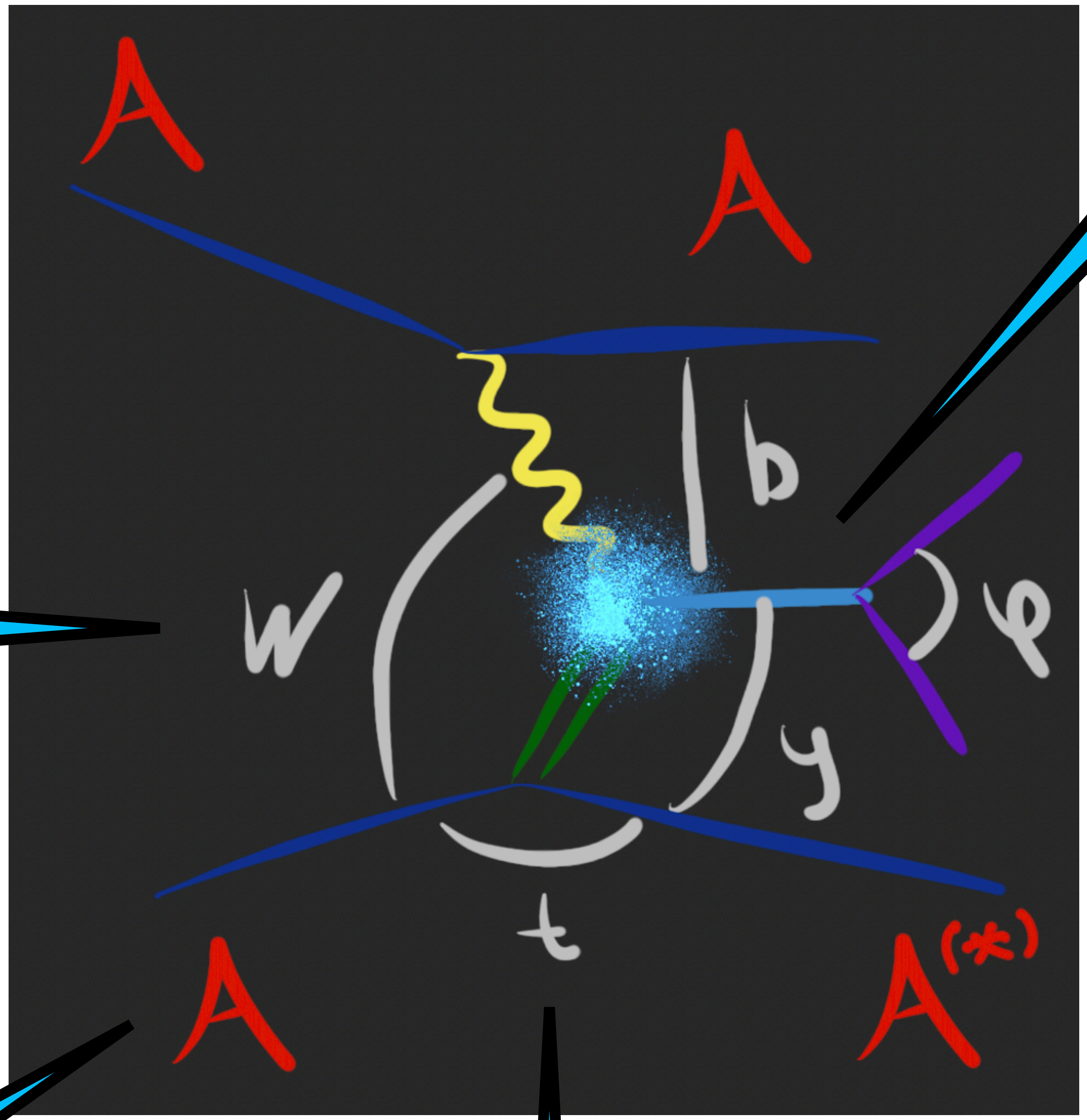

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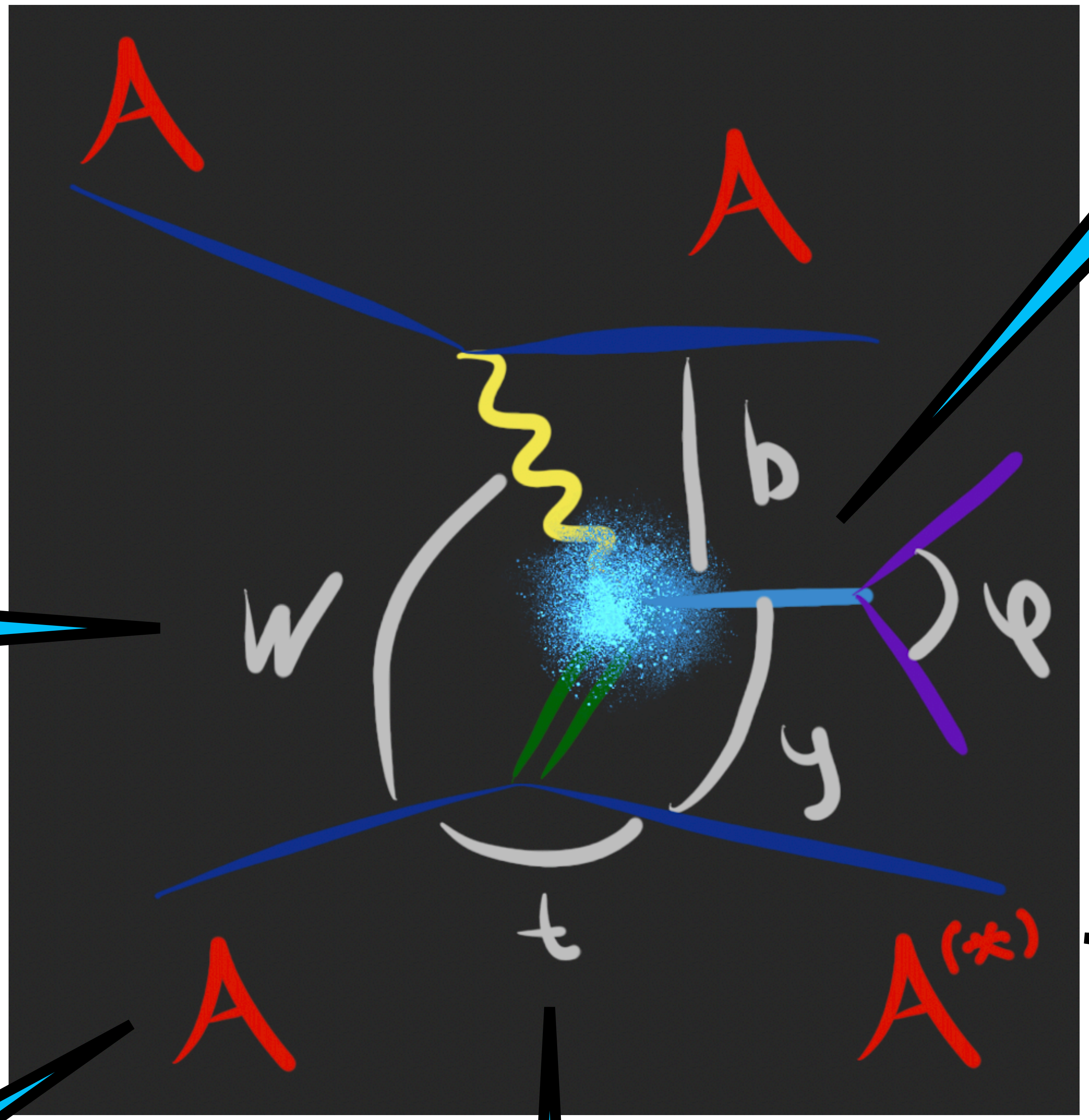

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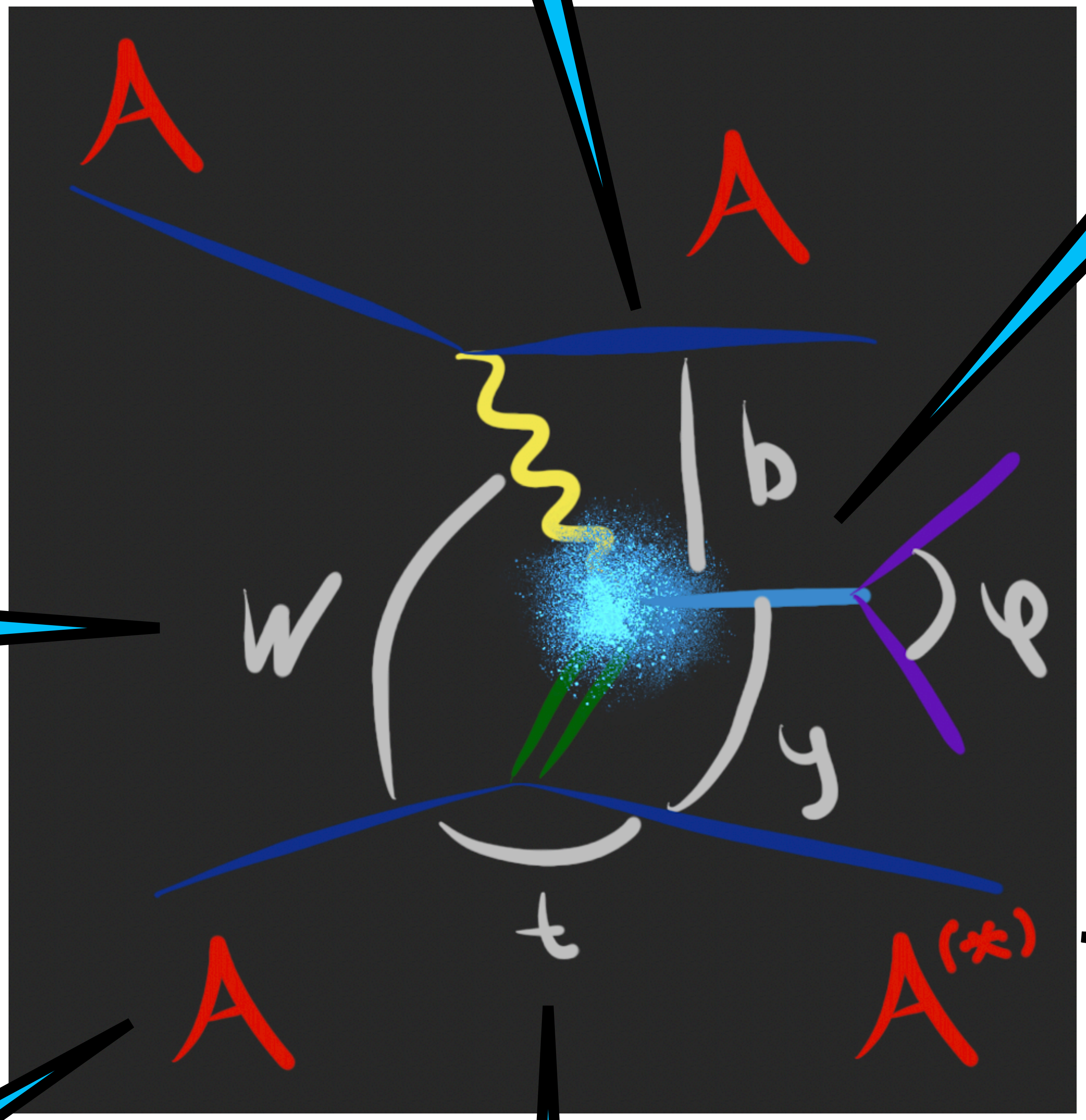

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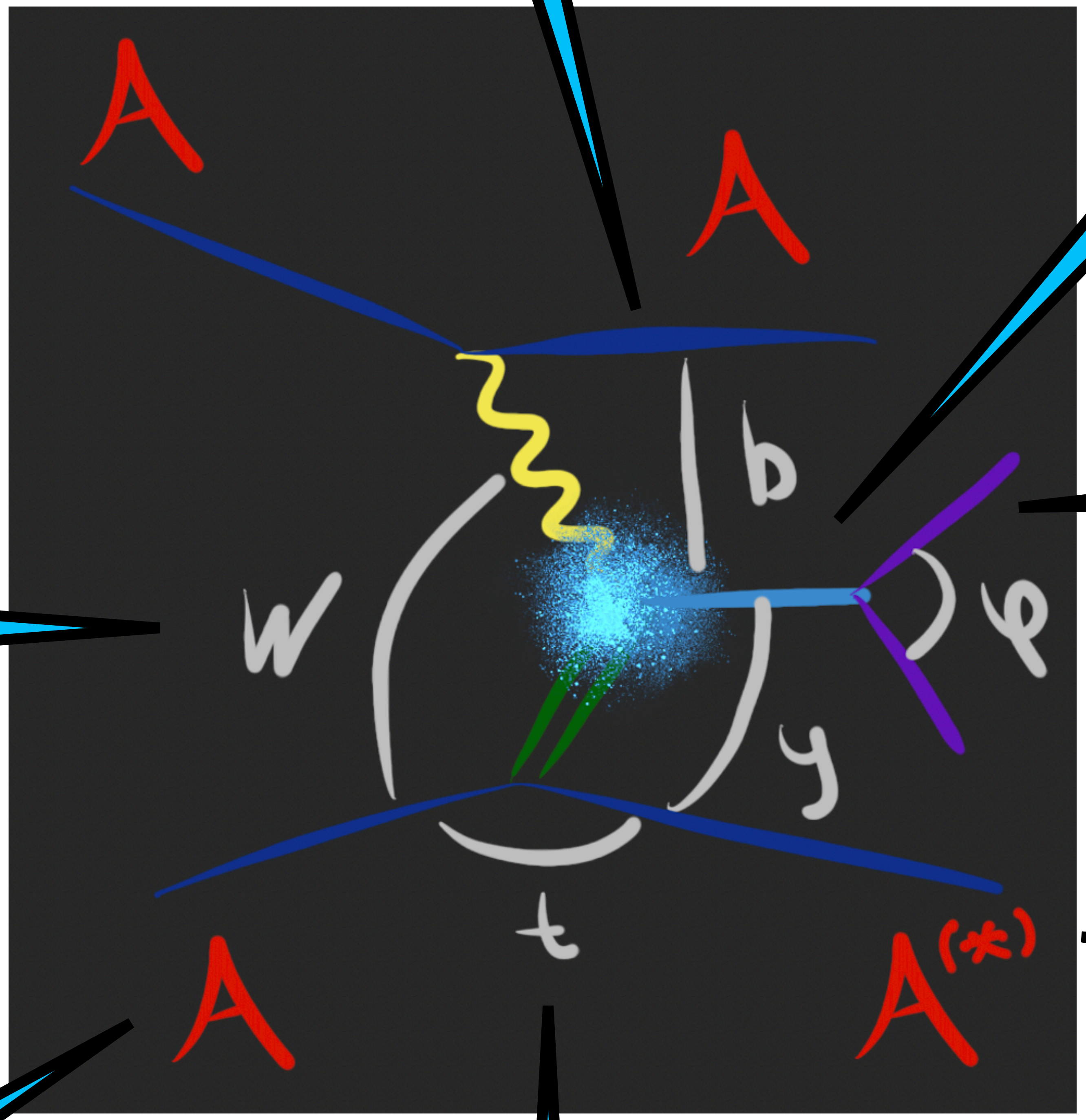

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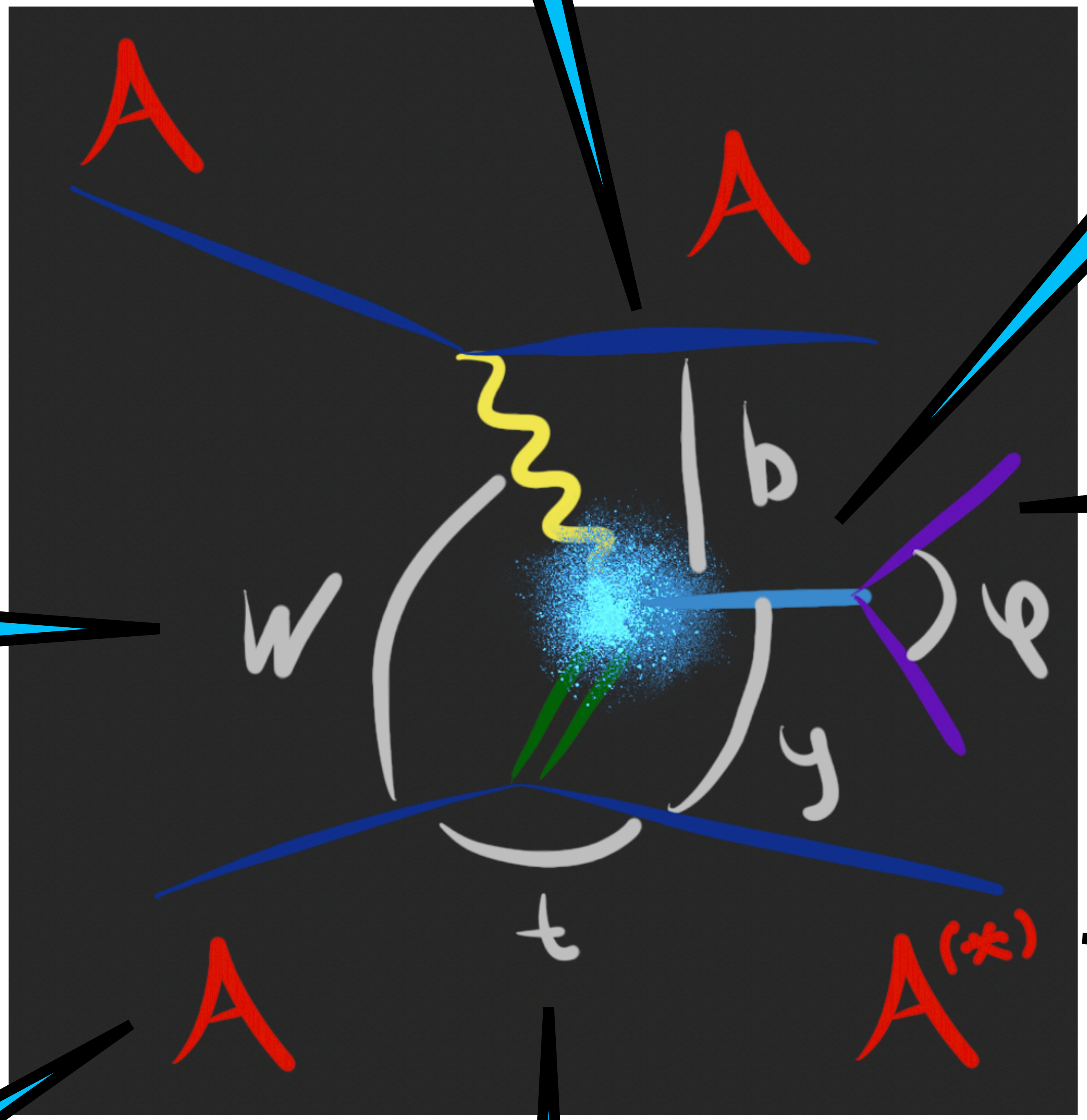

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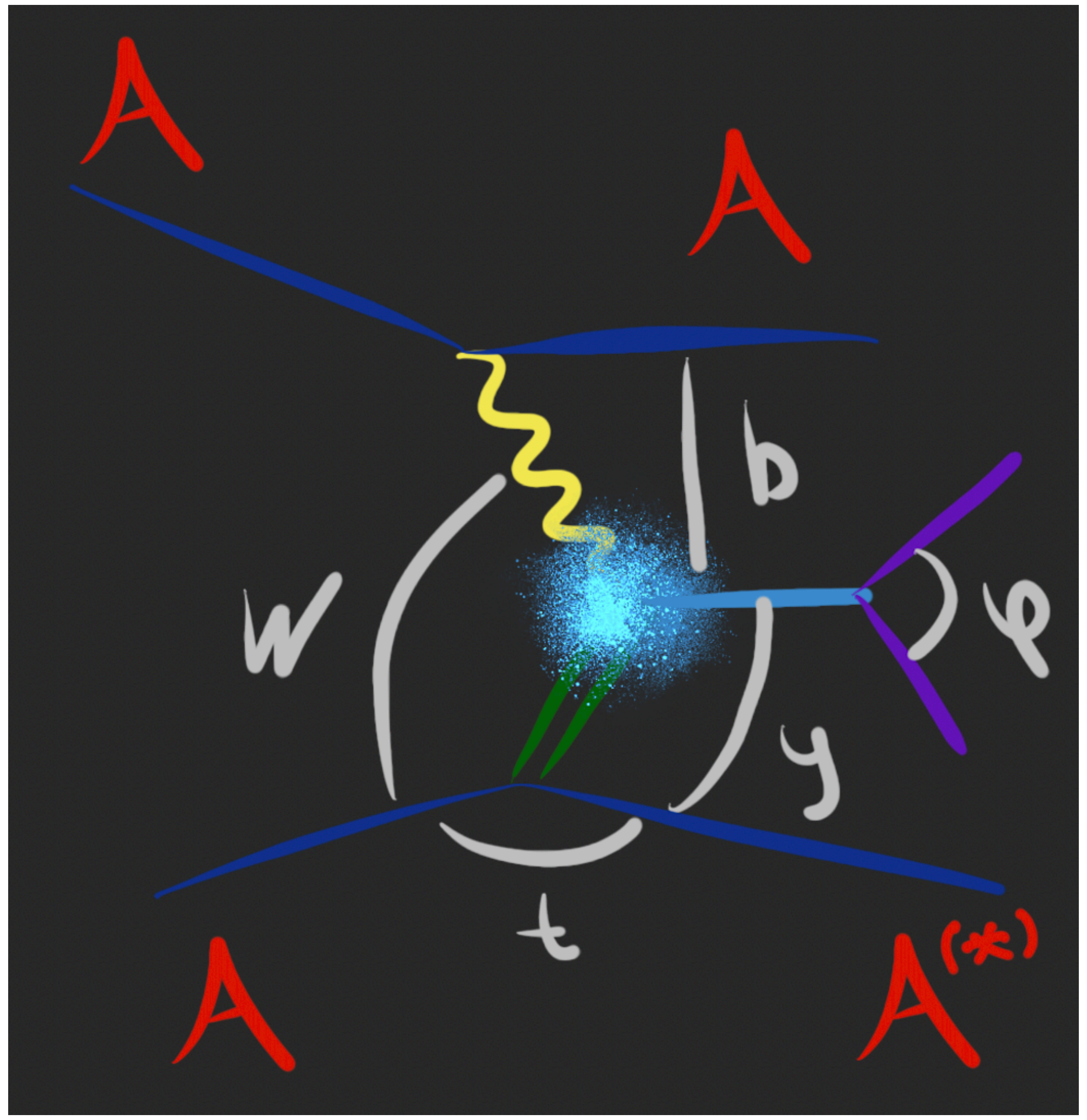
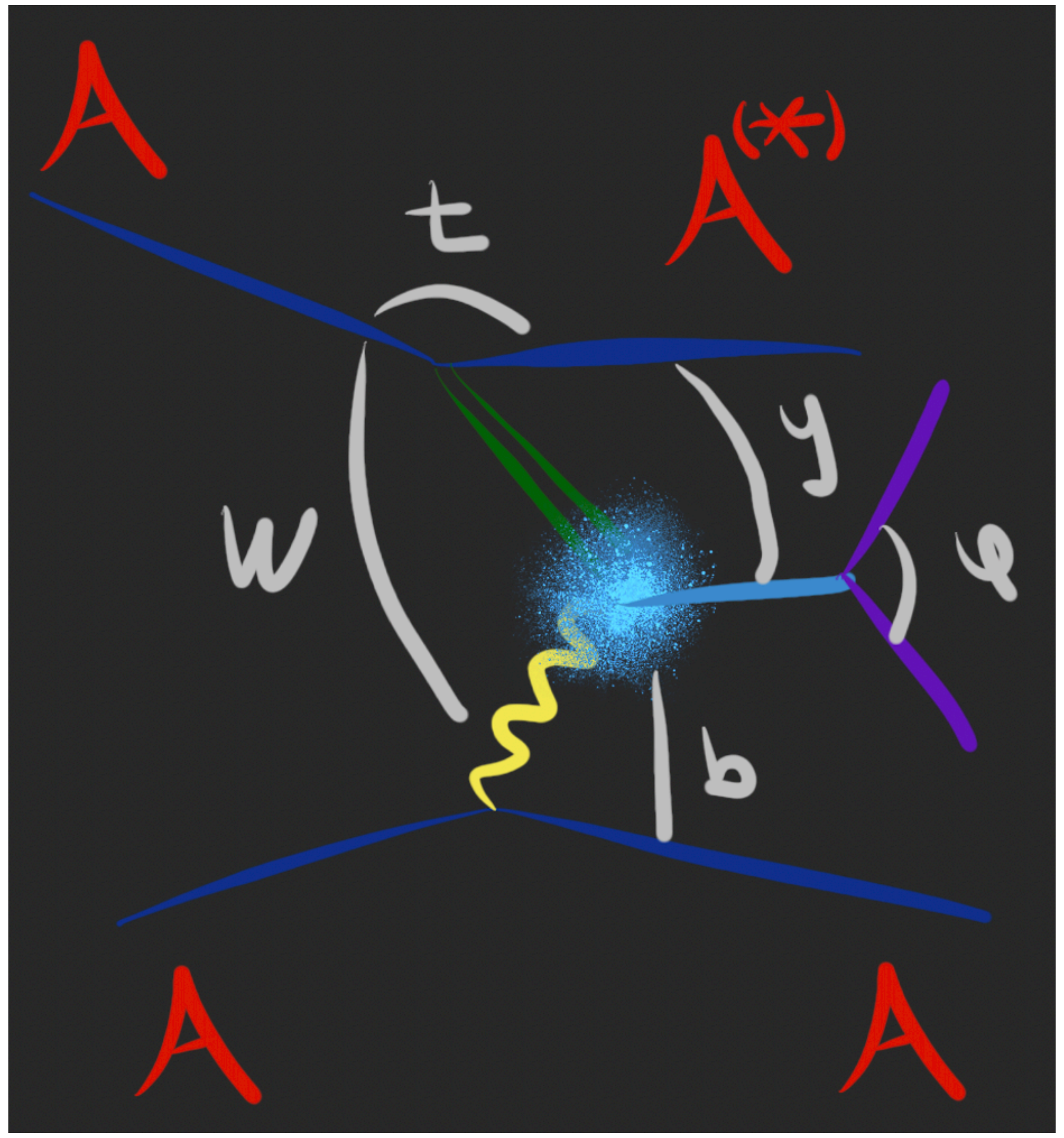
All of these observables have been measure at RHIC+LHC 😊

The presence of two competing amplitudes allows for the study of QM interference effects at new scales





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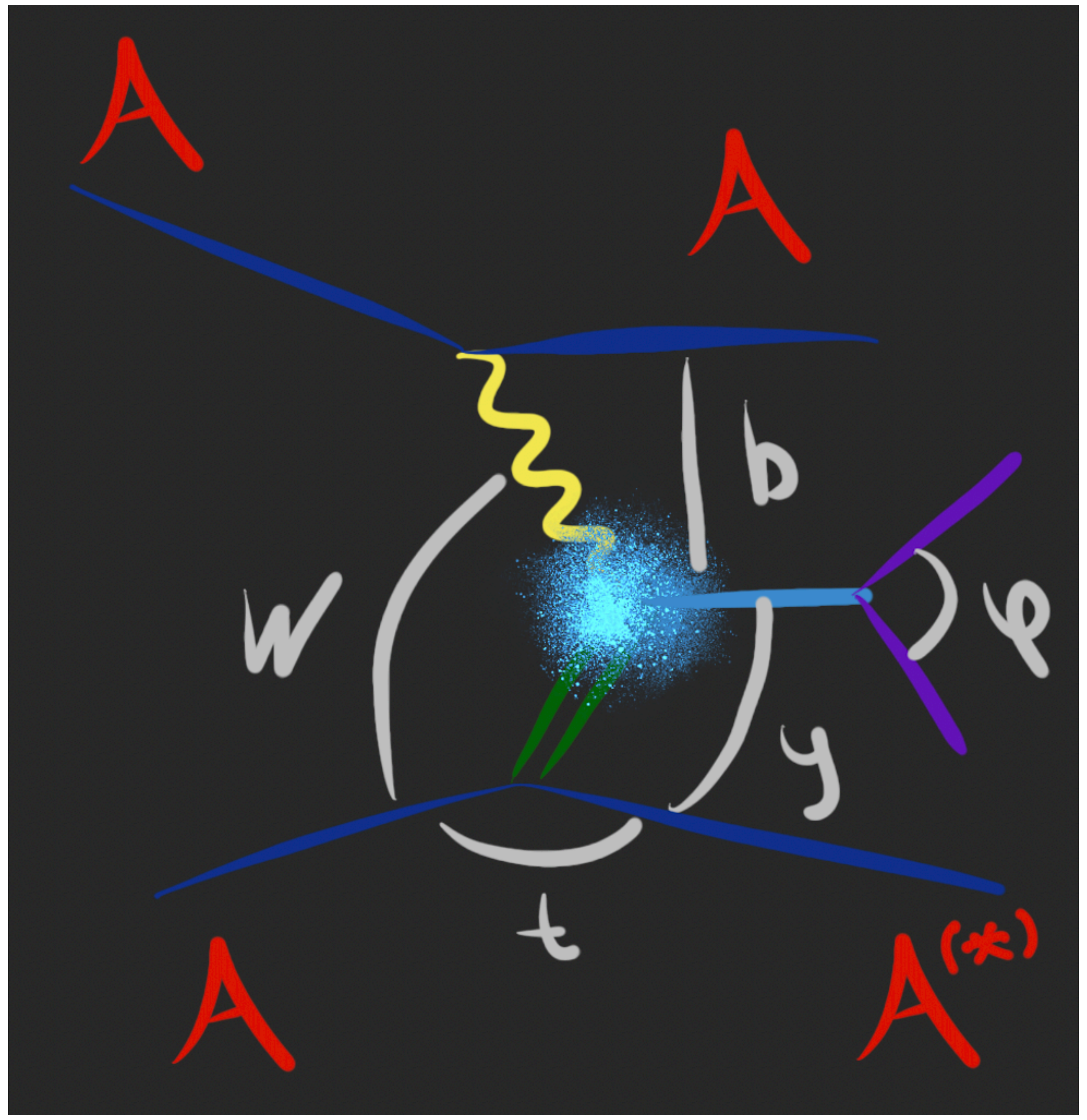

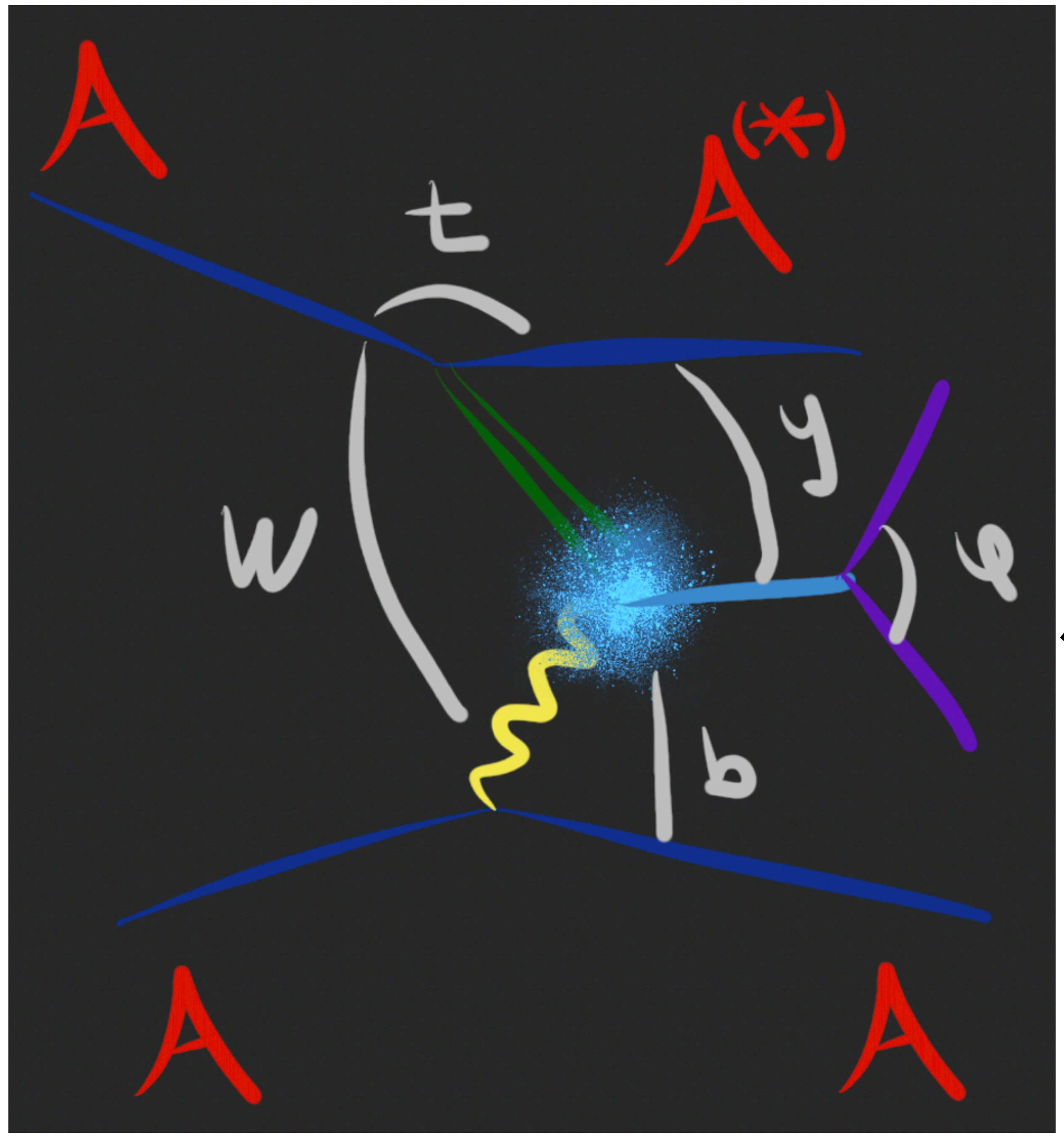

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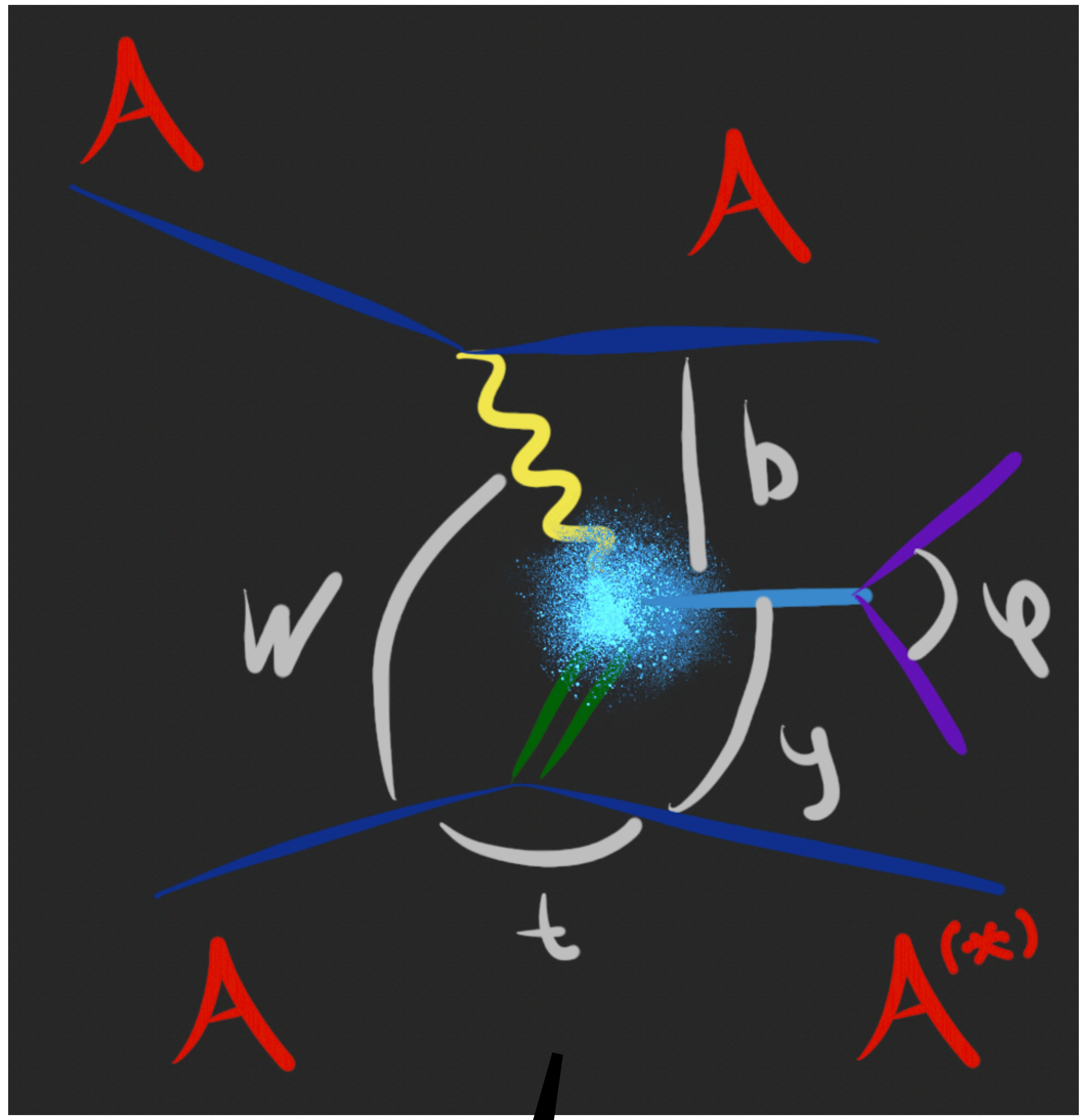

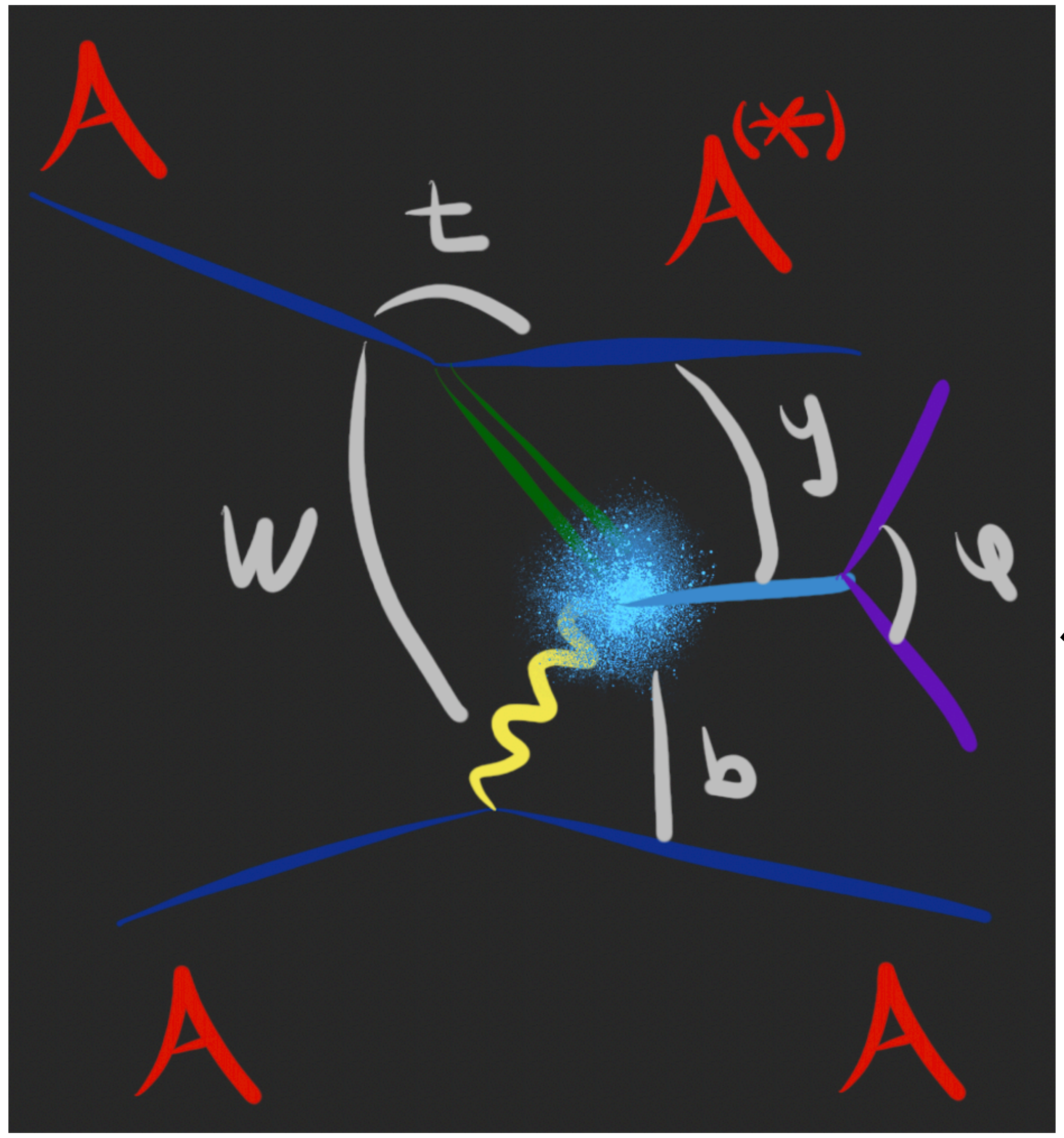

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The effects are more important at small |t| where the interference is destructive

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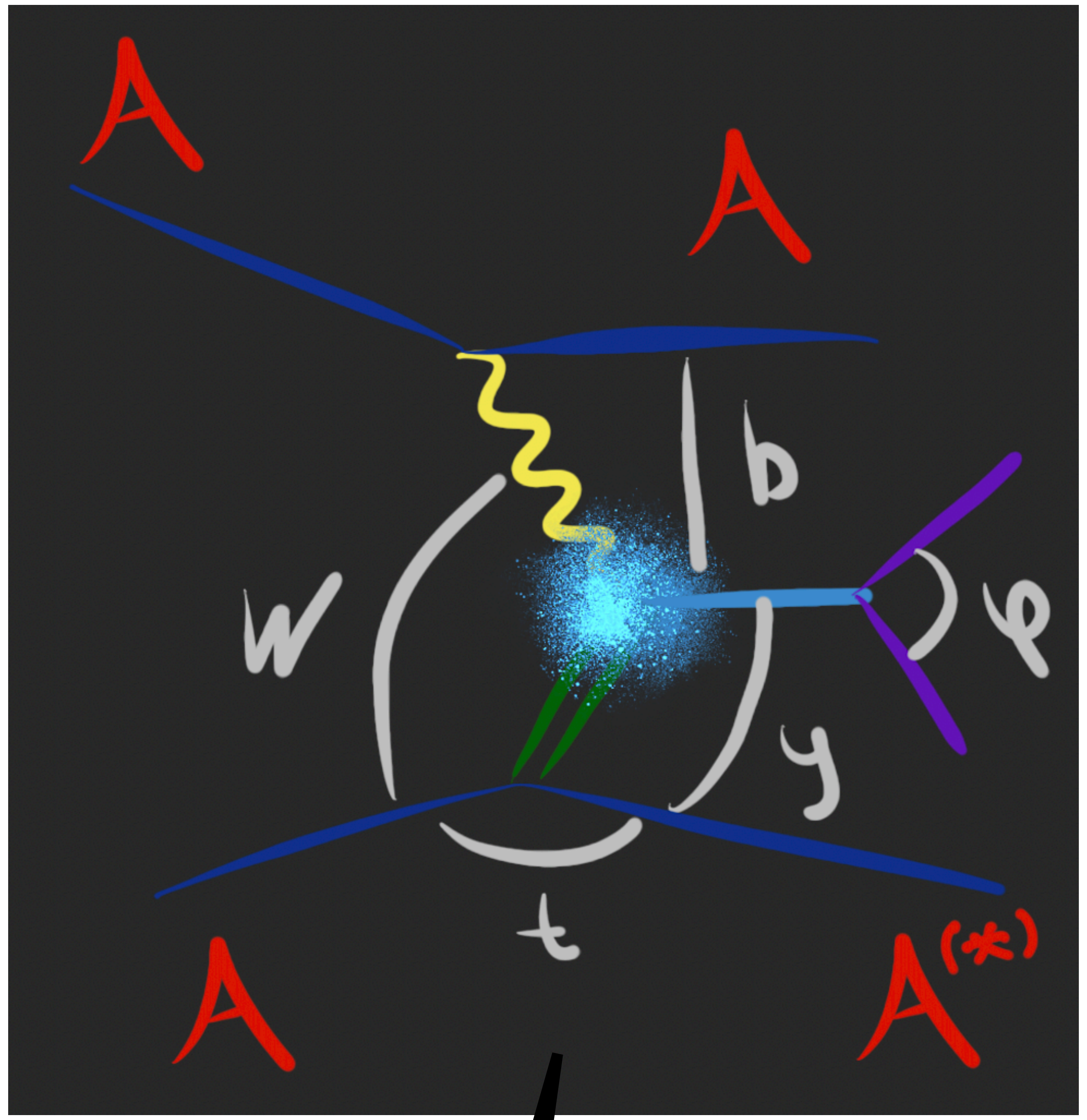

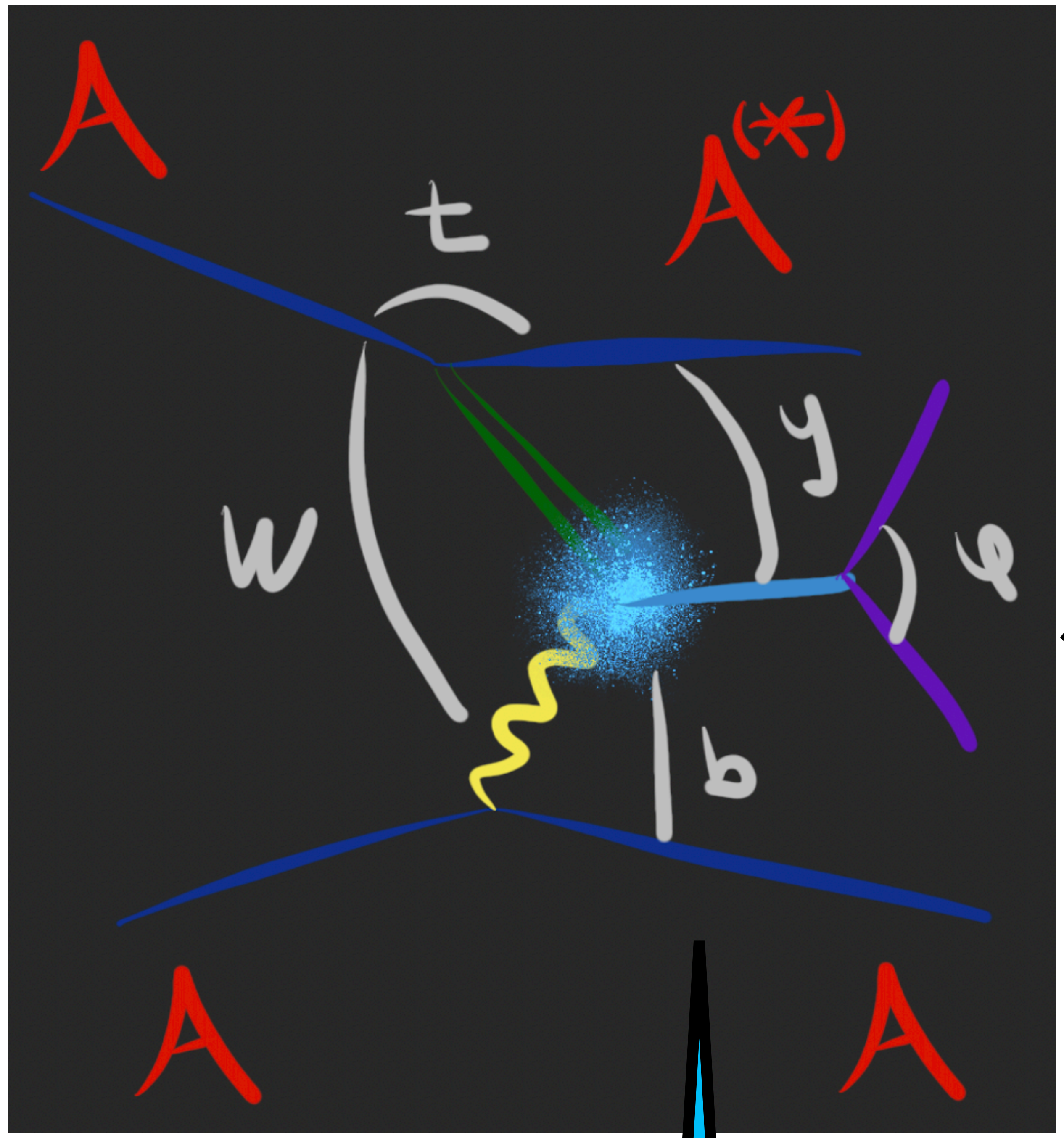

The effects are more important at small |t| where the interference is destructive

Interference depends on the impact parameter

The interference produces new angular correlations

Guillermo Contreras, CTU in Prague

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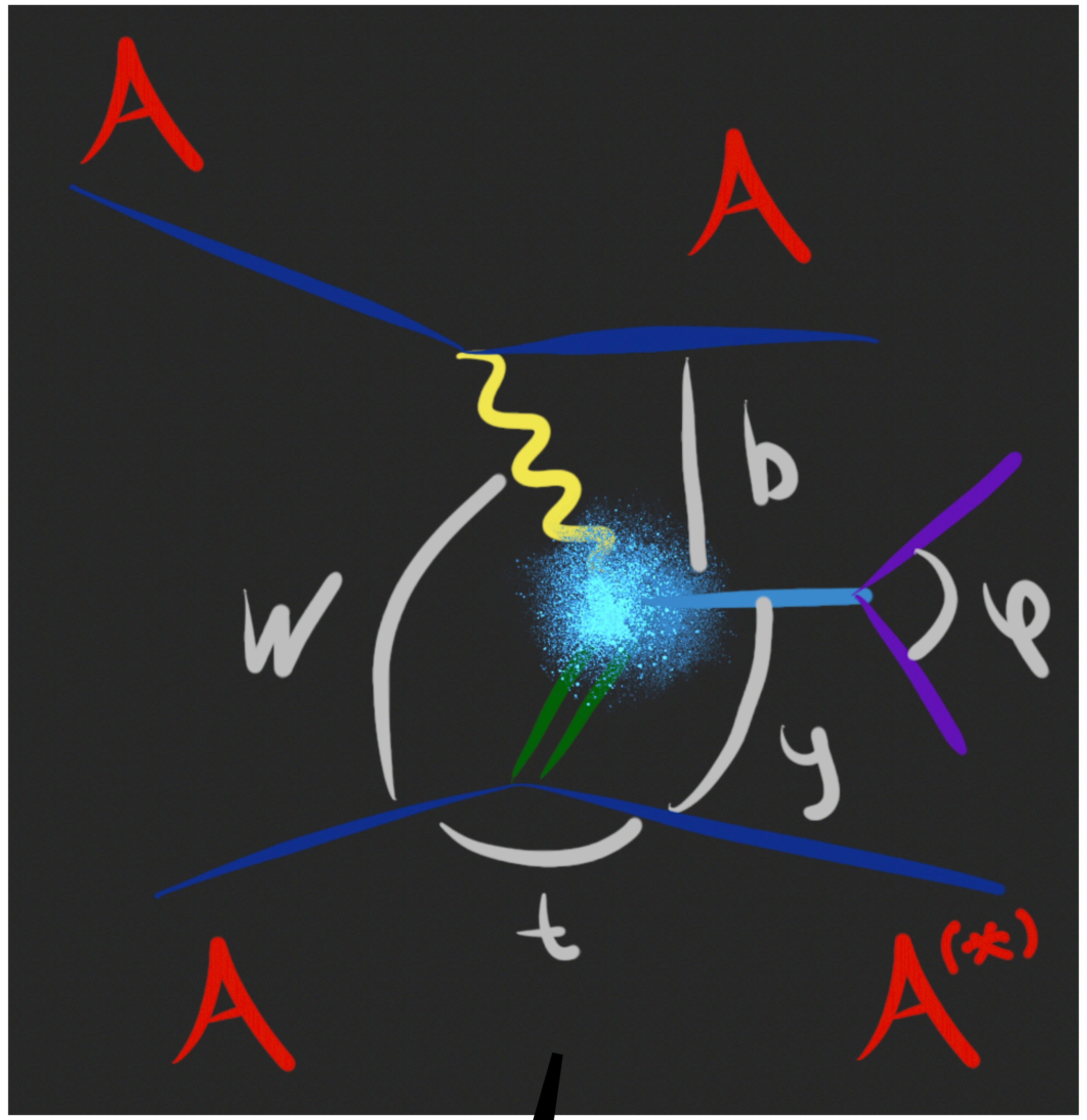

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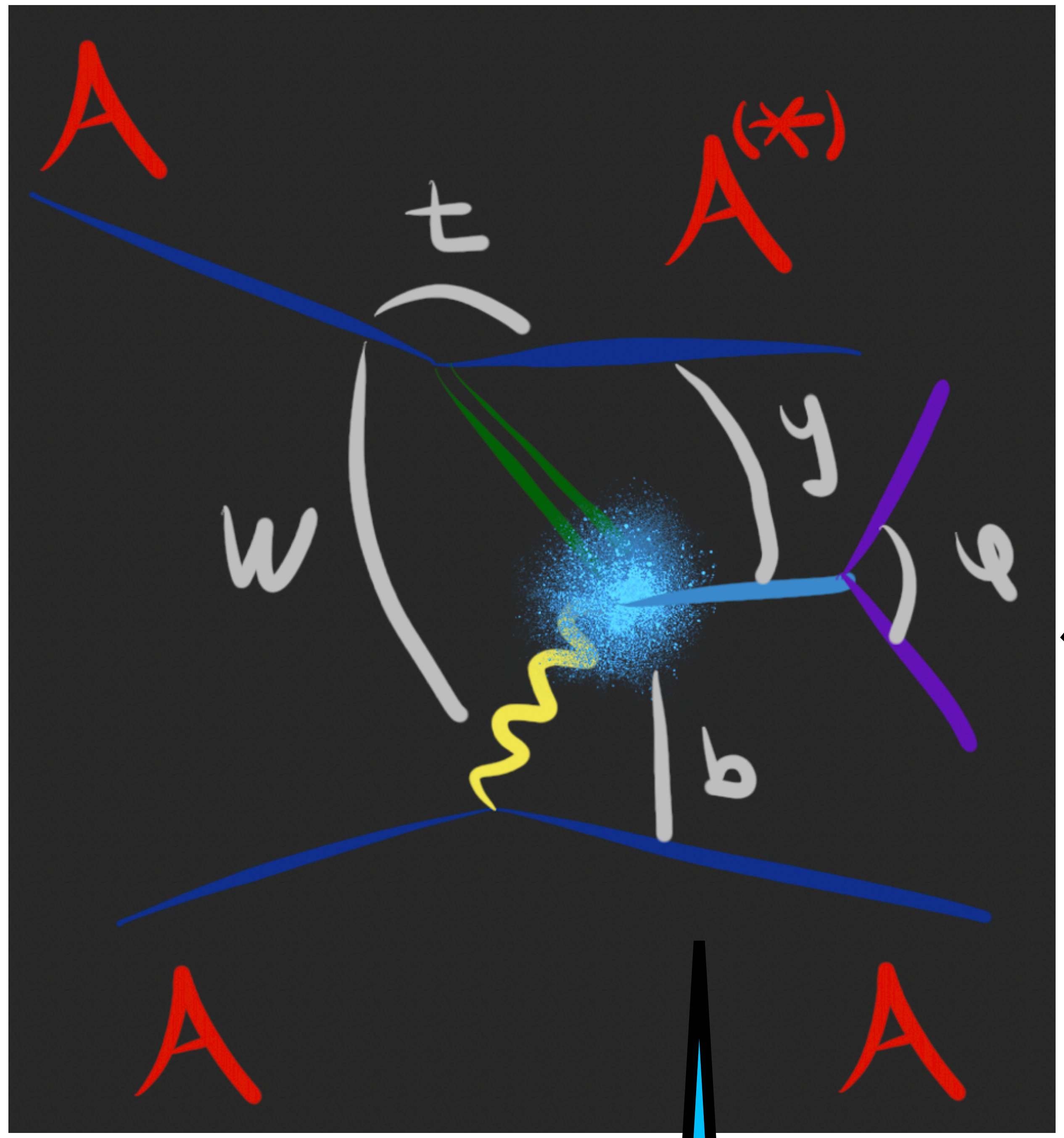

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Also these effects been measured at RHIC+LHC

As an example, I discuss here a few results that I think will not be discussed in detail during the conference

Energy dependence of coherent ρ^0 production: the first look (2002)

First observation of the process at RHIC by the STAR collaboration

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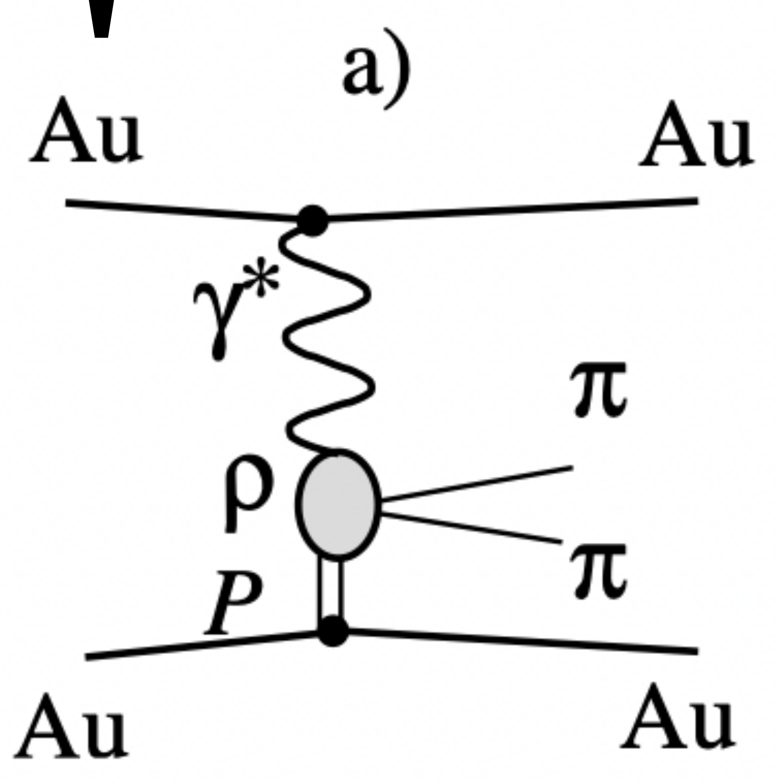

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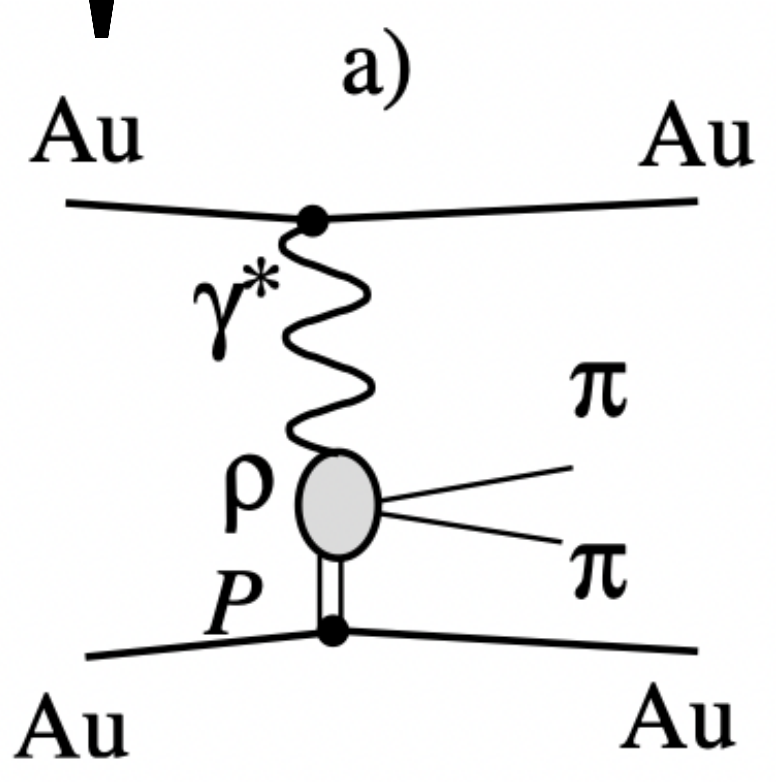
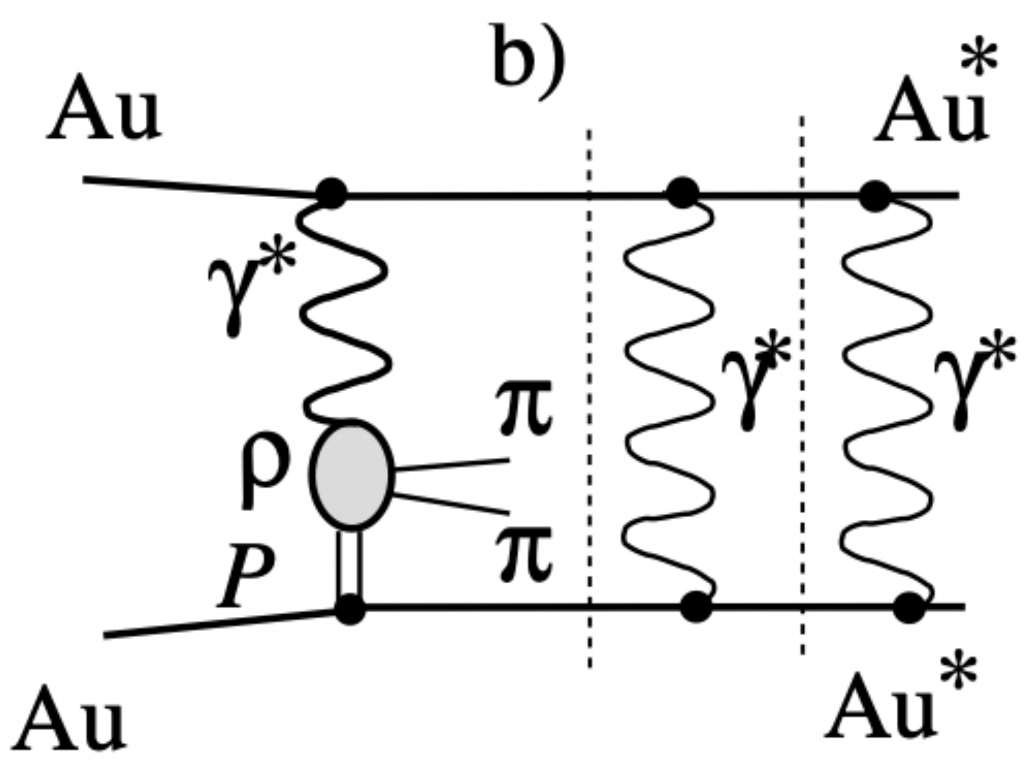


Triggering utilises EMD



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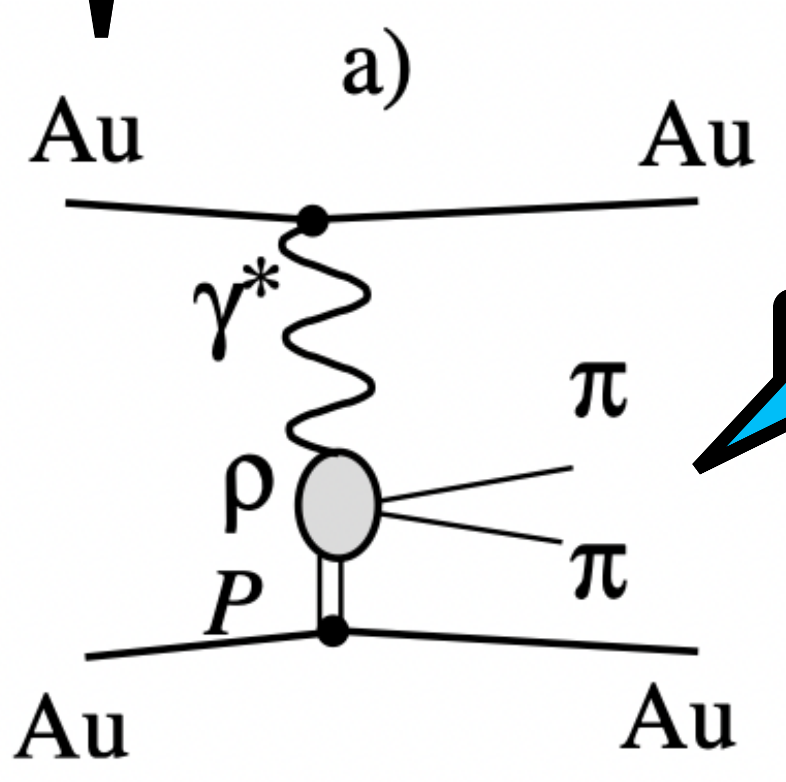

Decay to ππ almost 100% of the time

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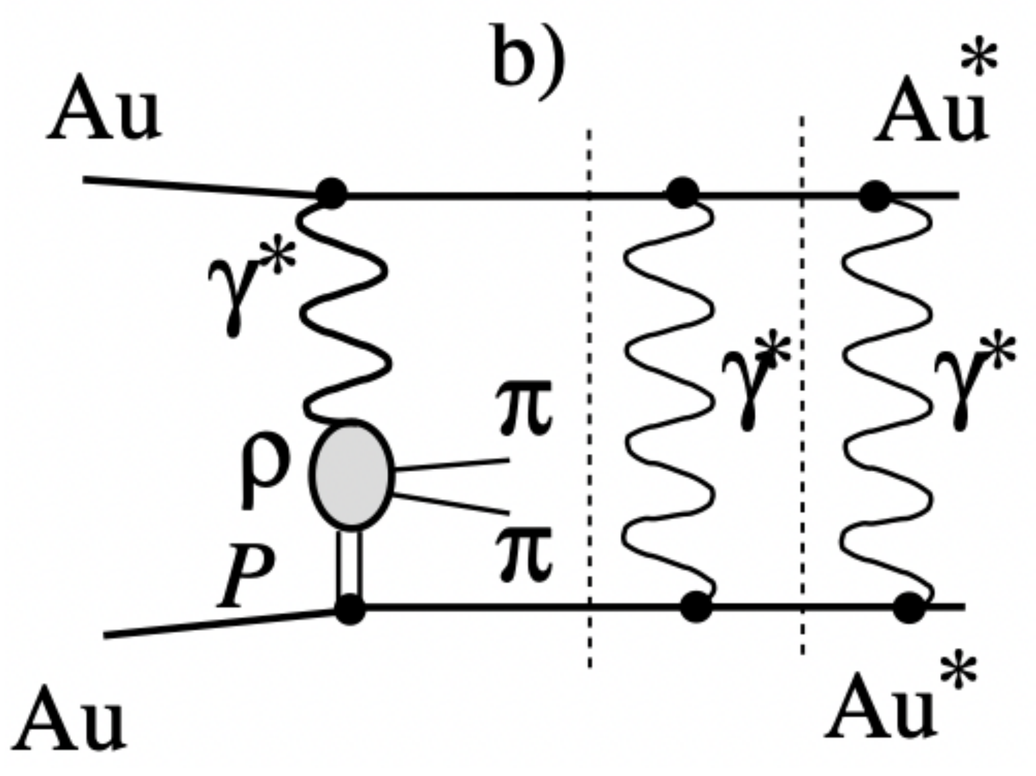

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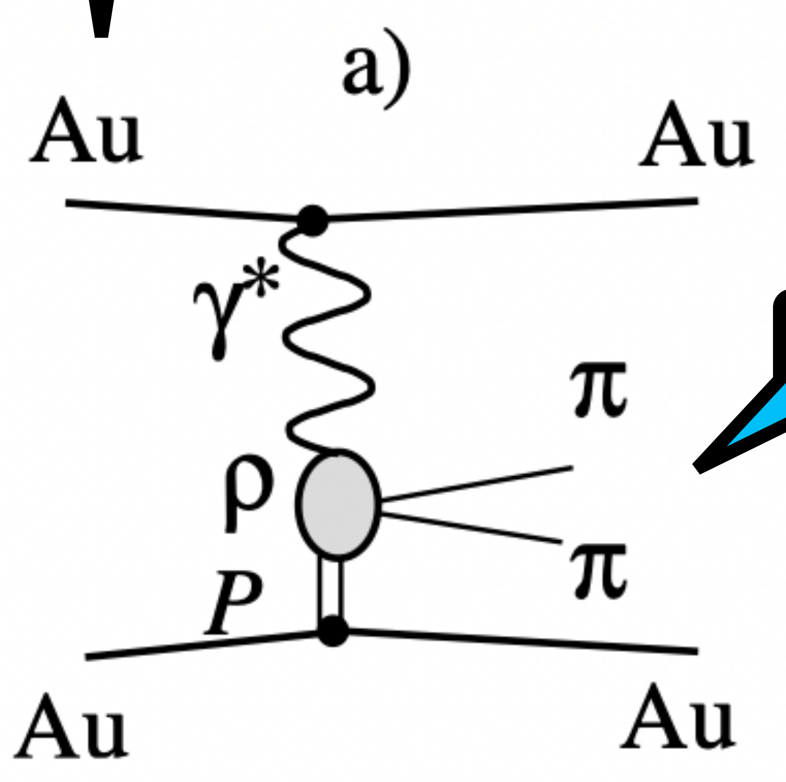

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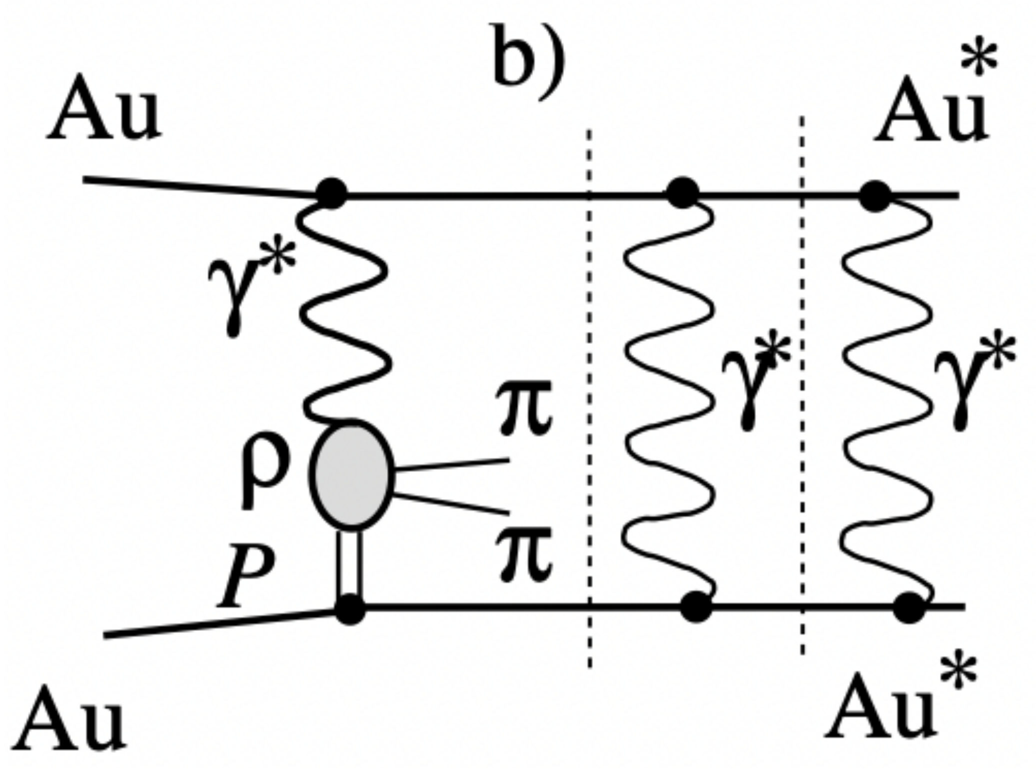
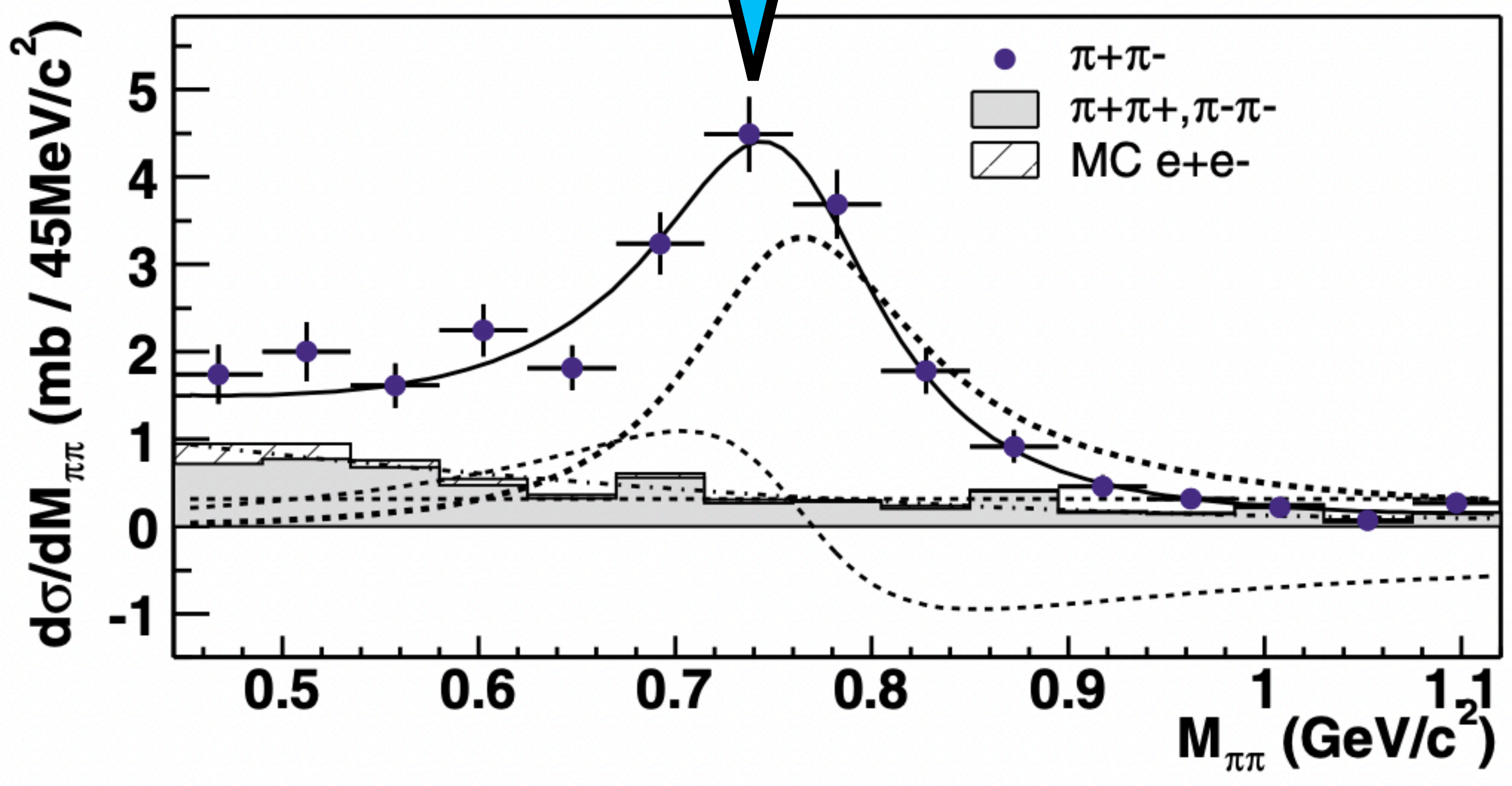


Broad resonance: need models to take into account continuum production



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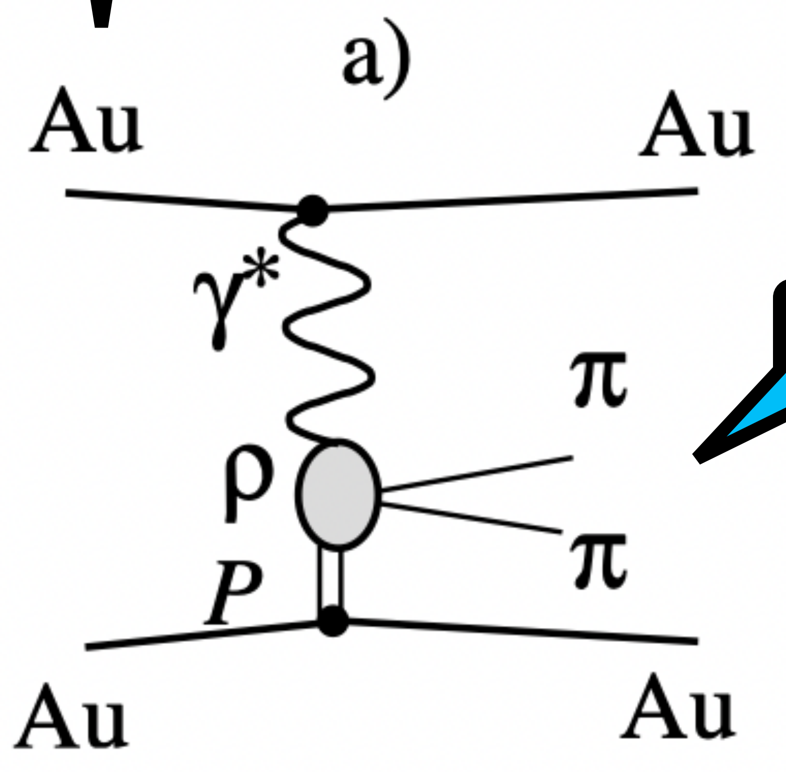

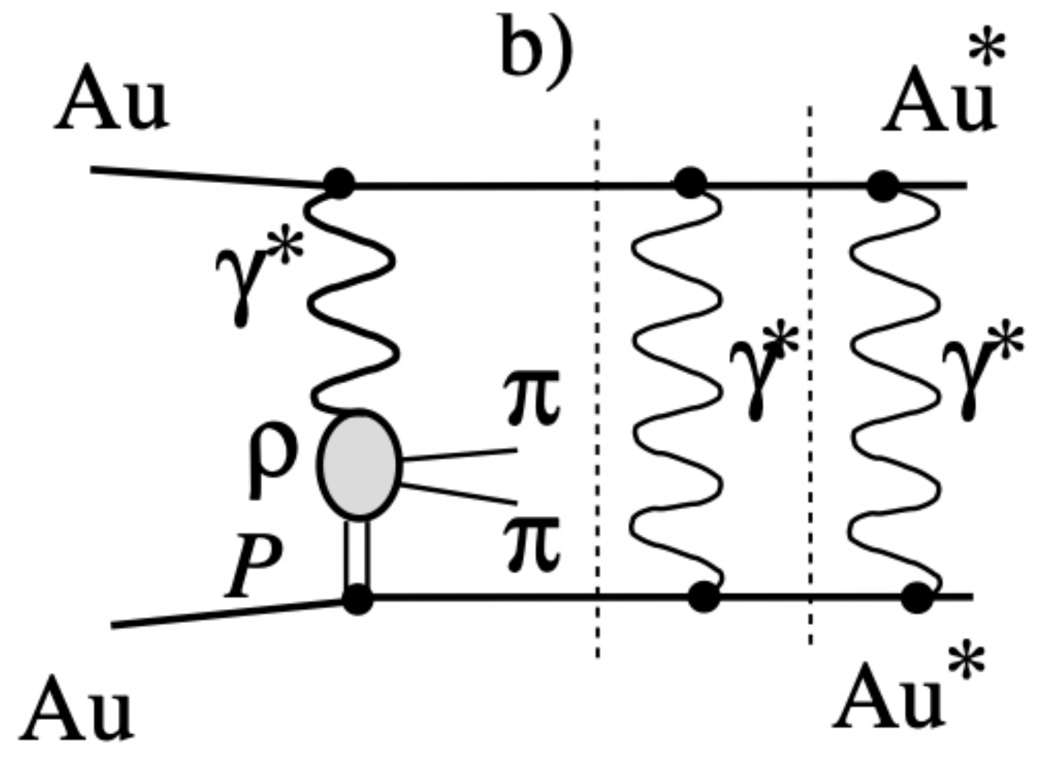

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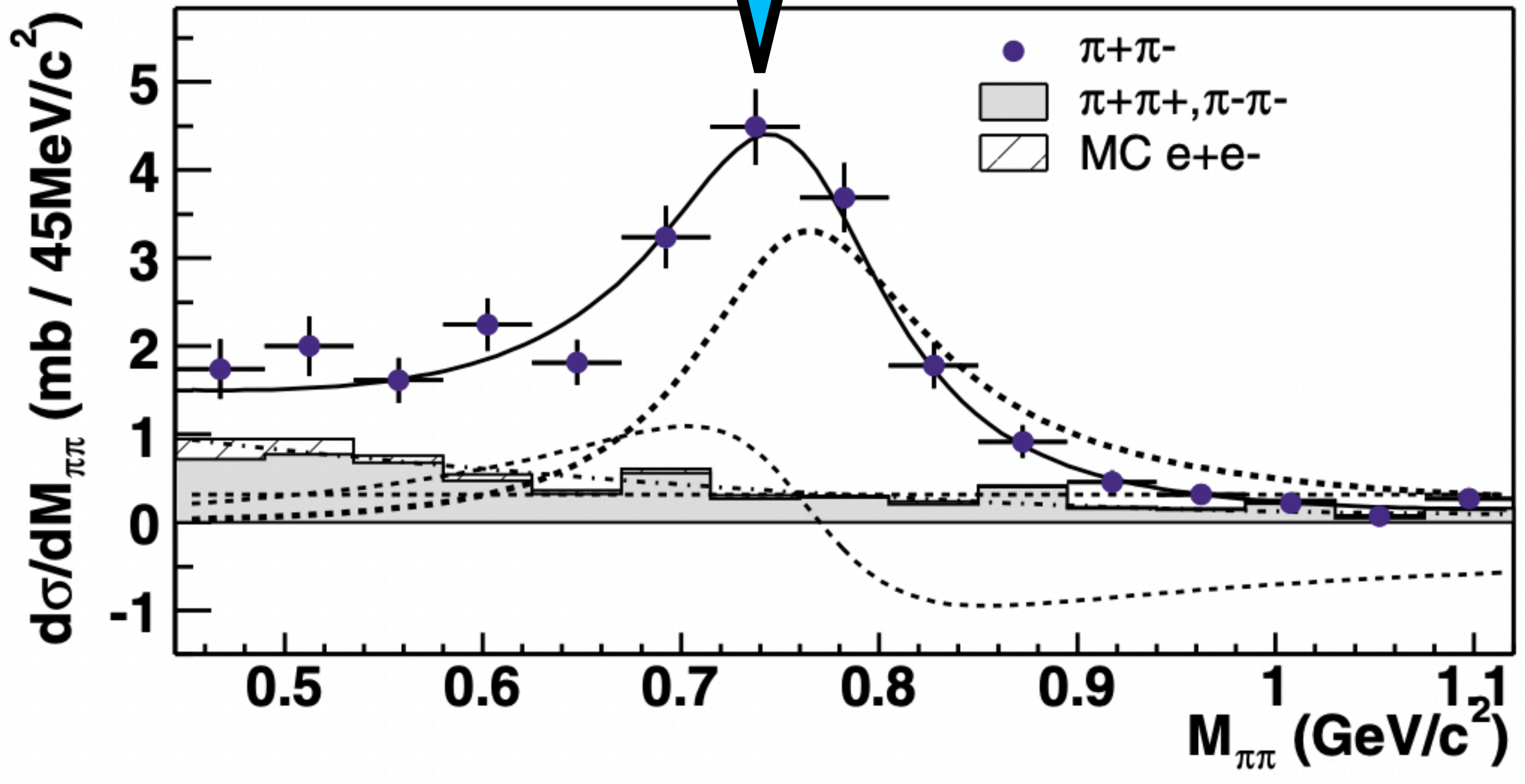

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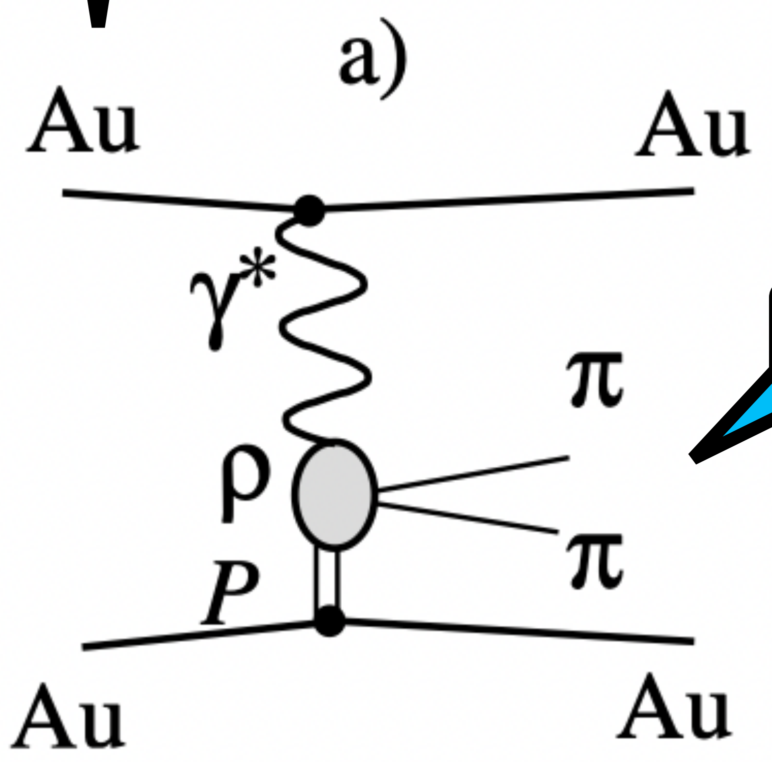

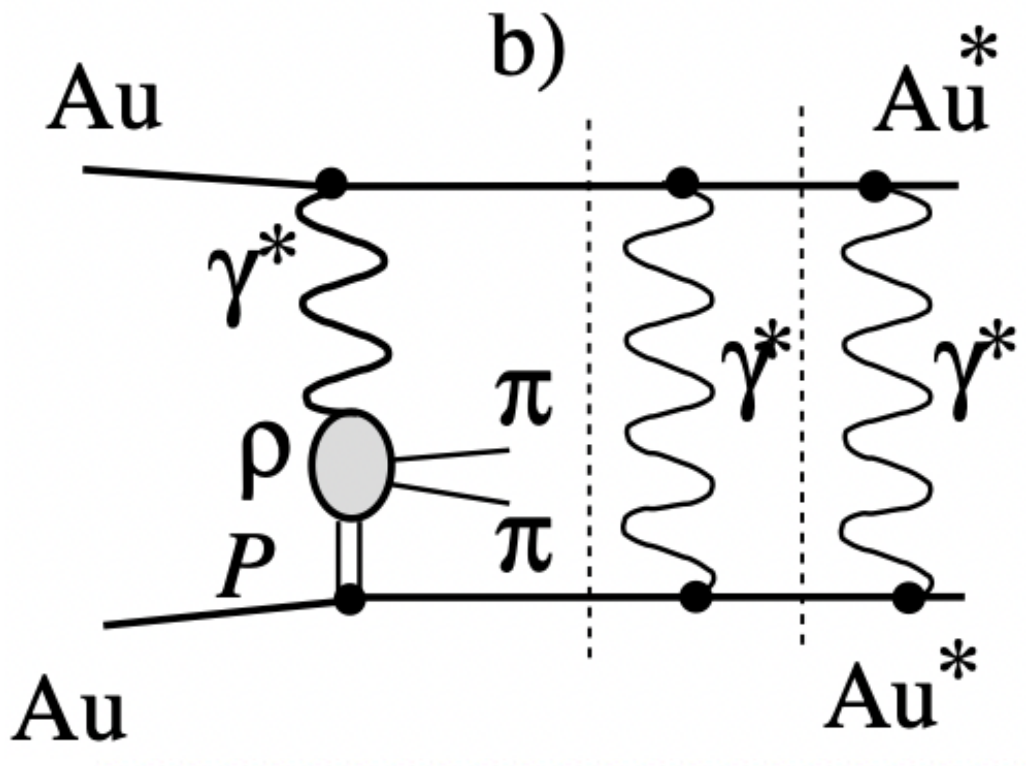

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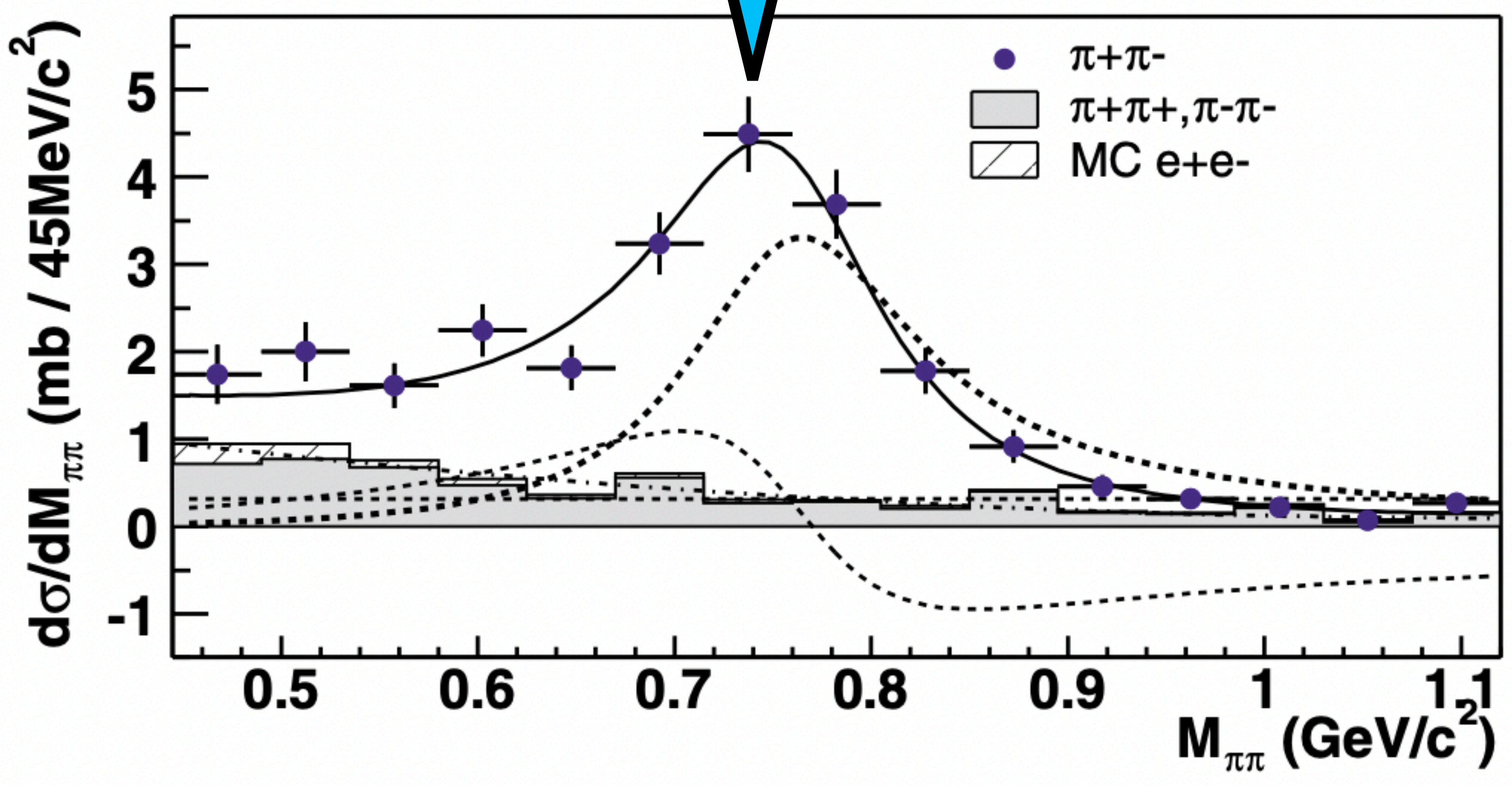

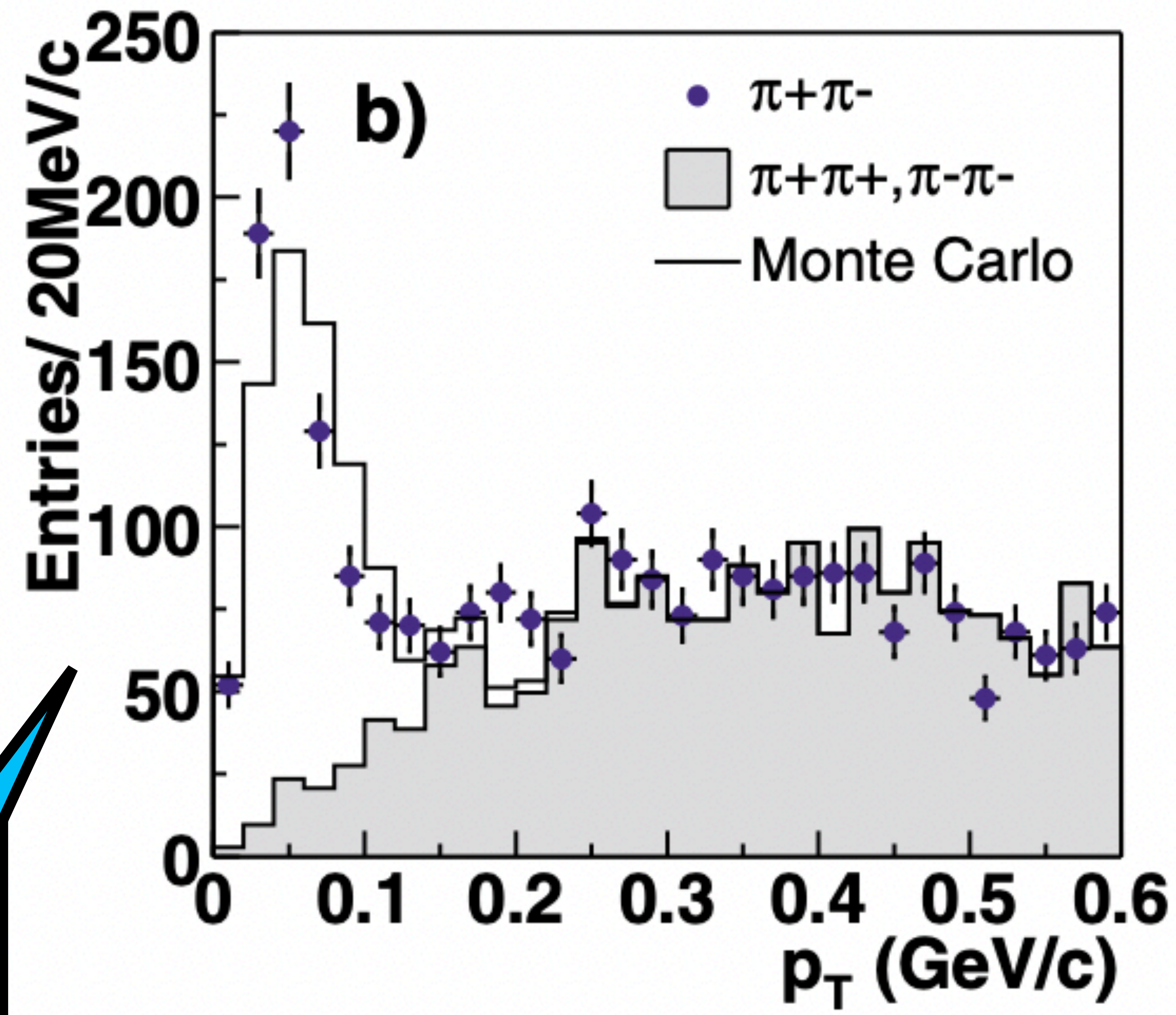

Typical shape of the transverse momentum distribution (below 0.1 GeV/c)

STAR (2002) http://inspirehep.net/record/588142?ln=en

Energy dependence of coherent ρ^0 production: the most precise look

Coherent production in 2017: AuAu at 200 GeV per NN

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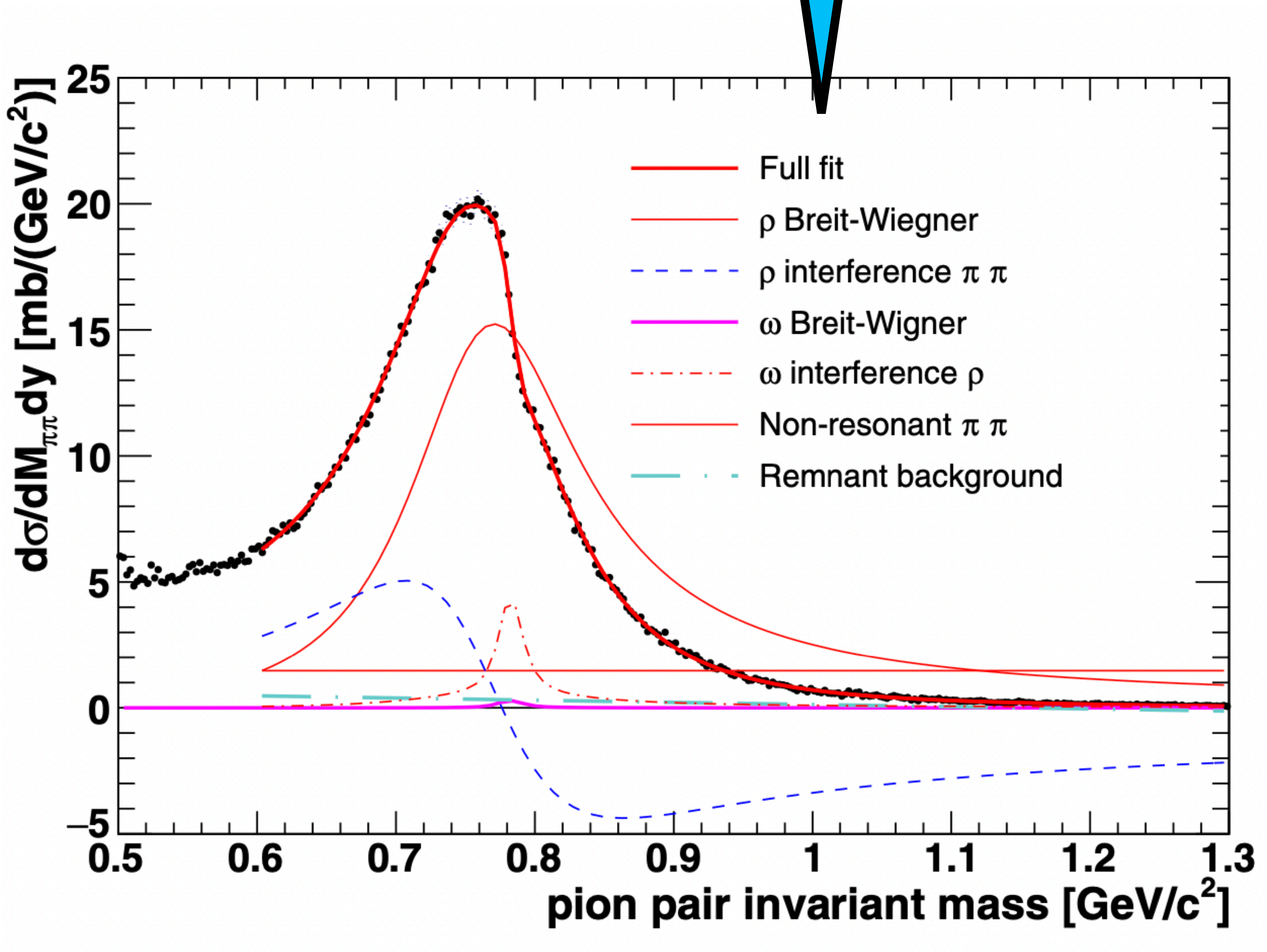

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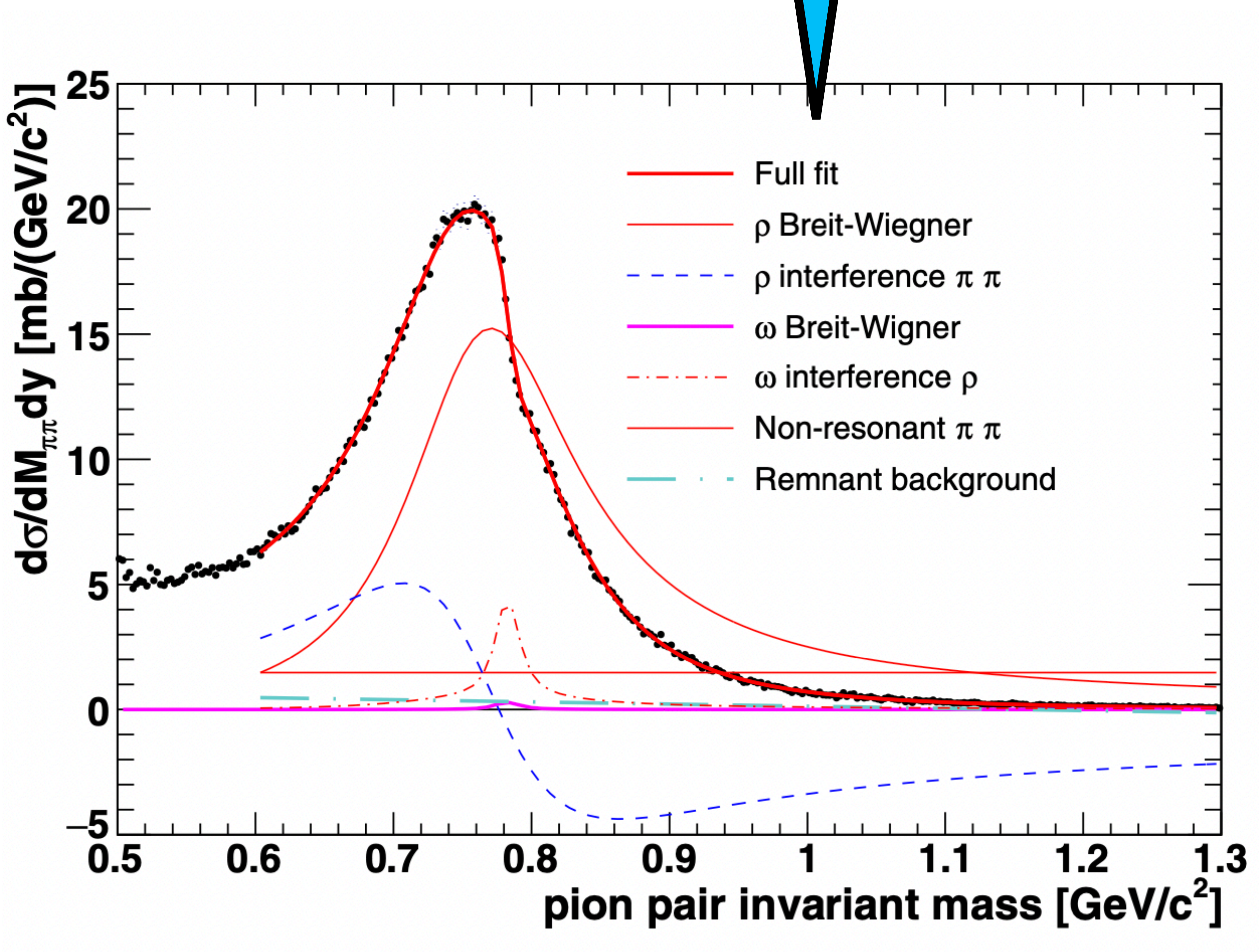
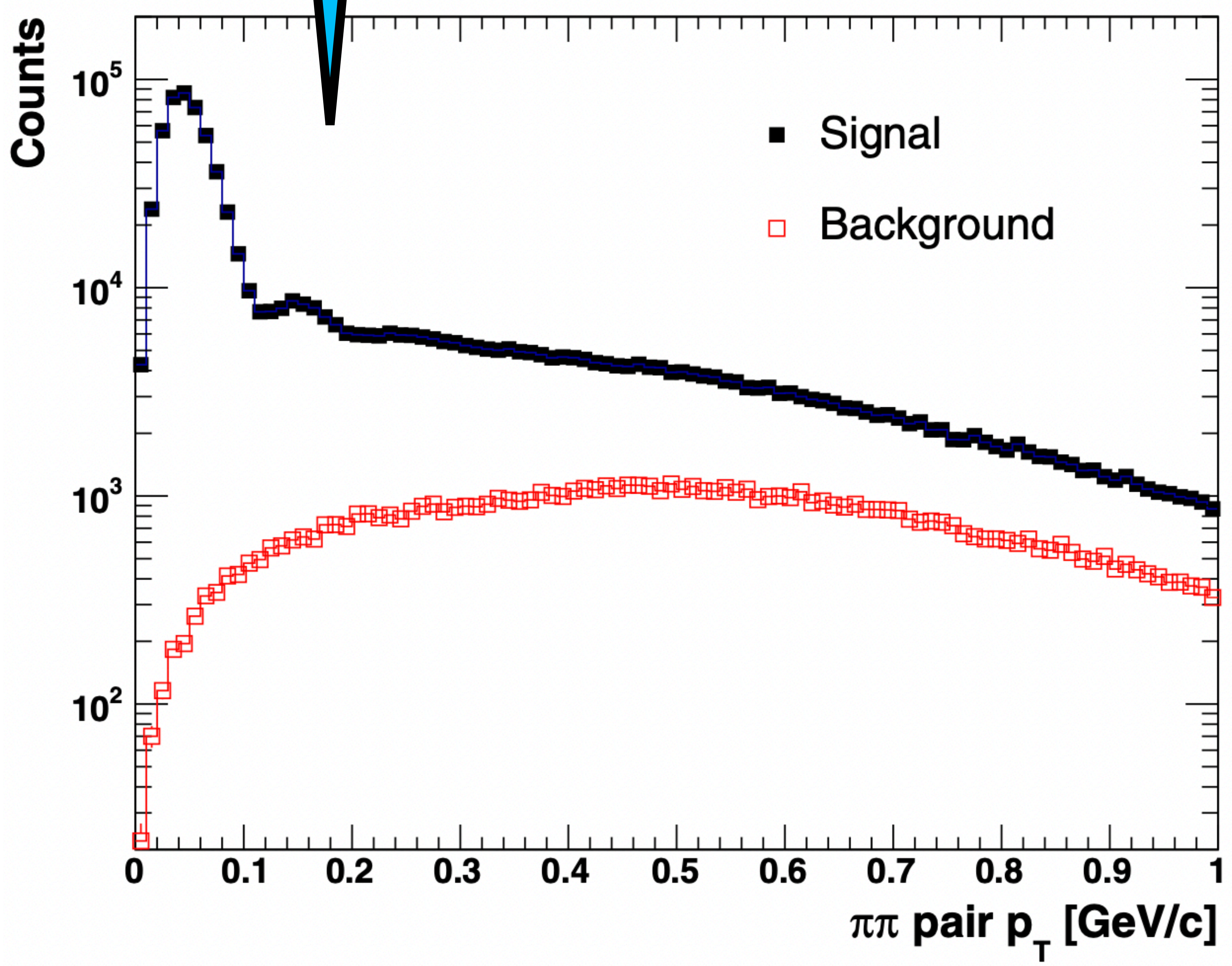


Second diffraction peak visible!



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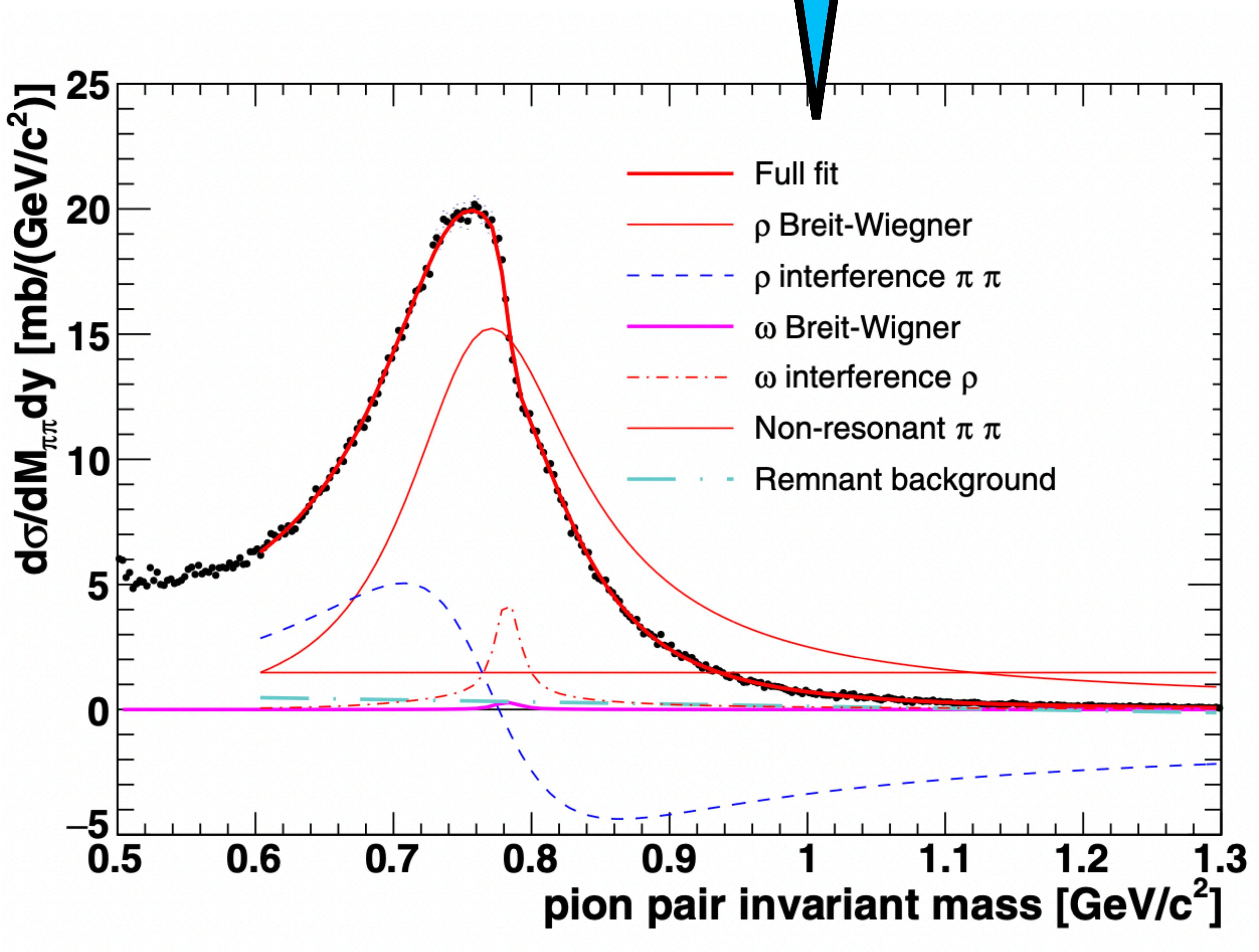

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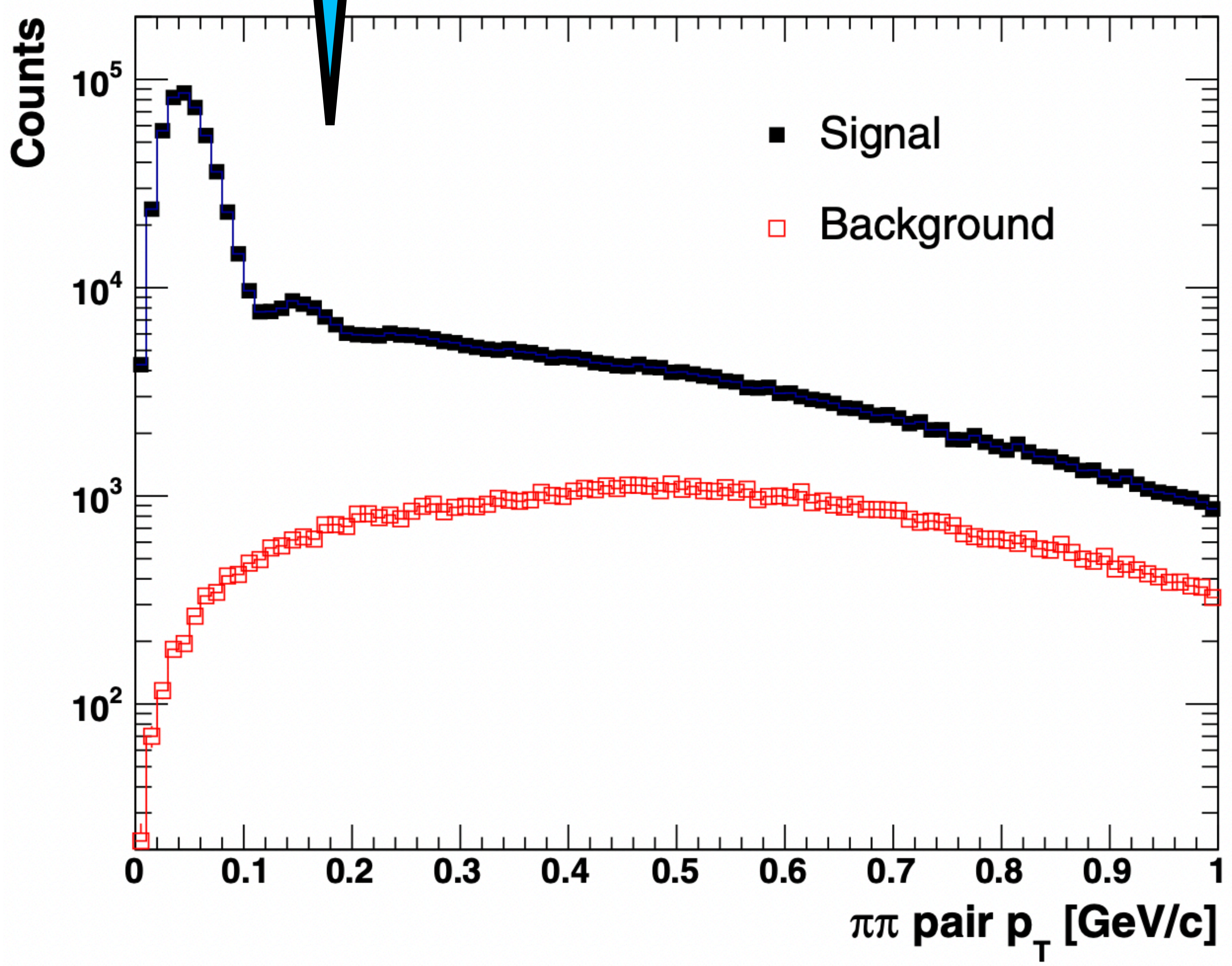

Other measurements available at 62.4 GeV per NN

Energy dependence of coherent ρ^0 production: PbPb in ALICE

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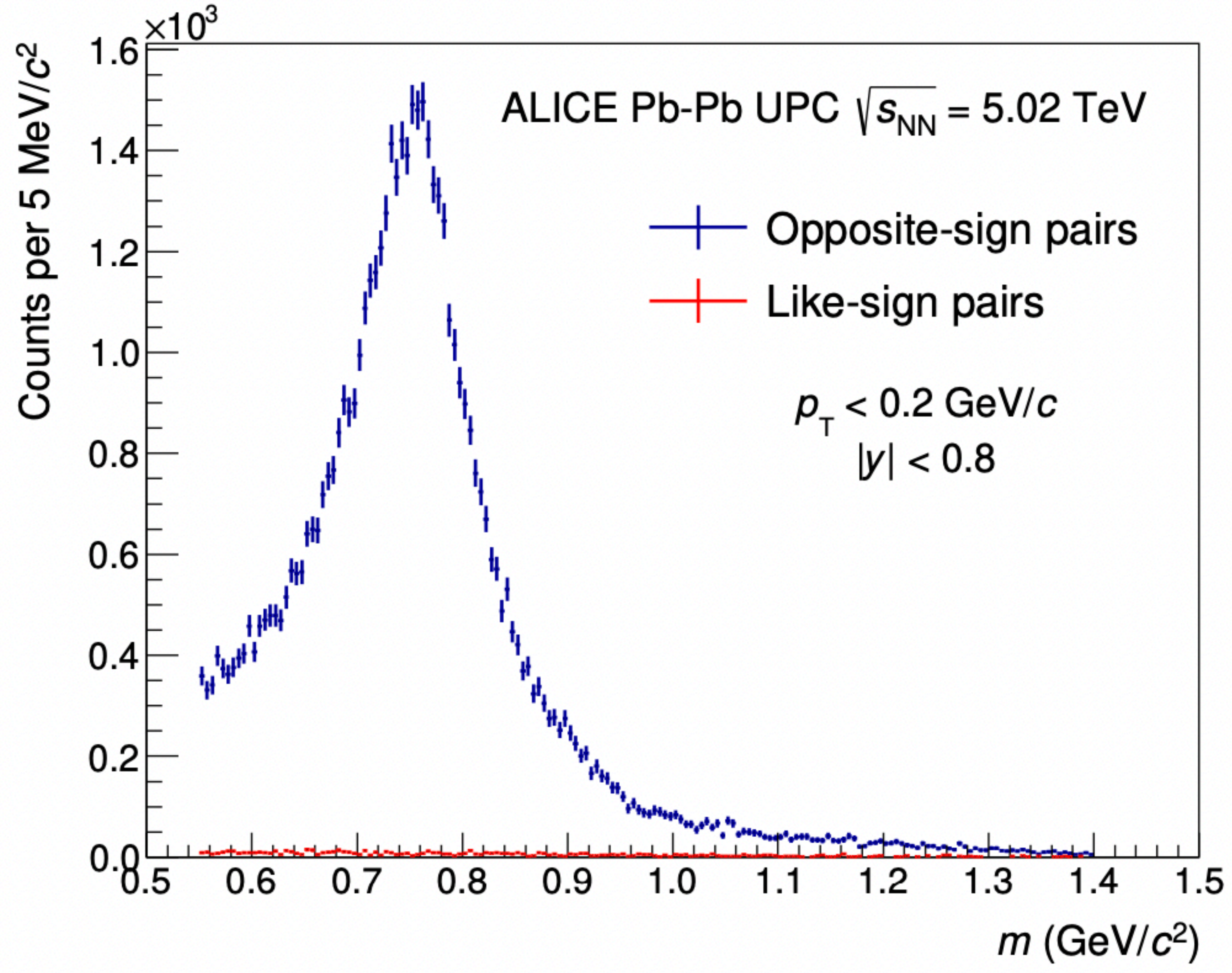

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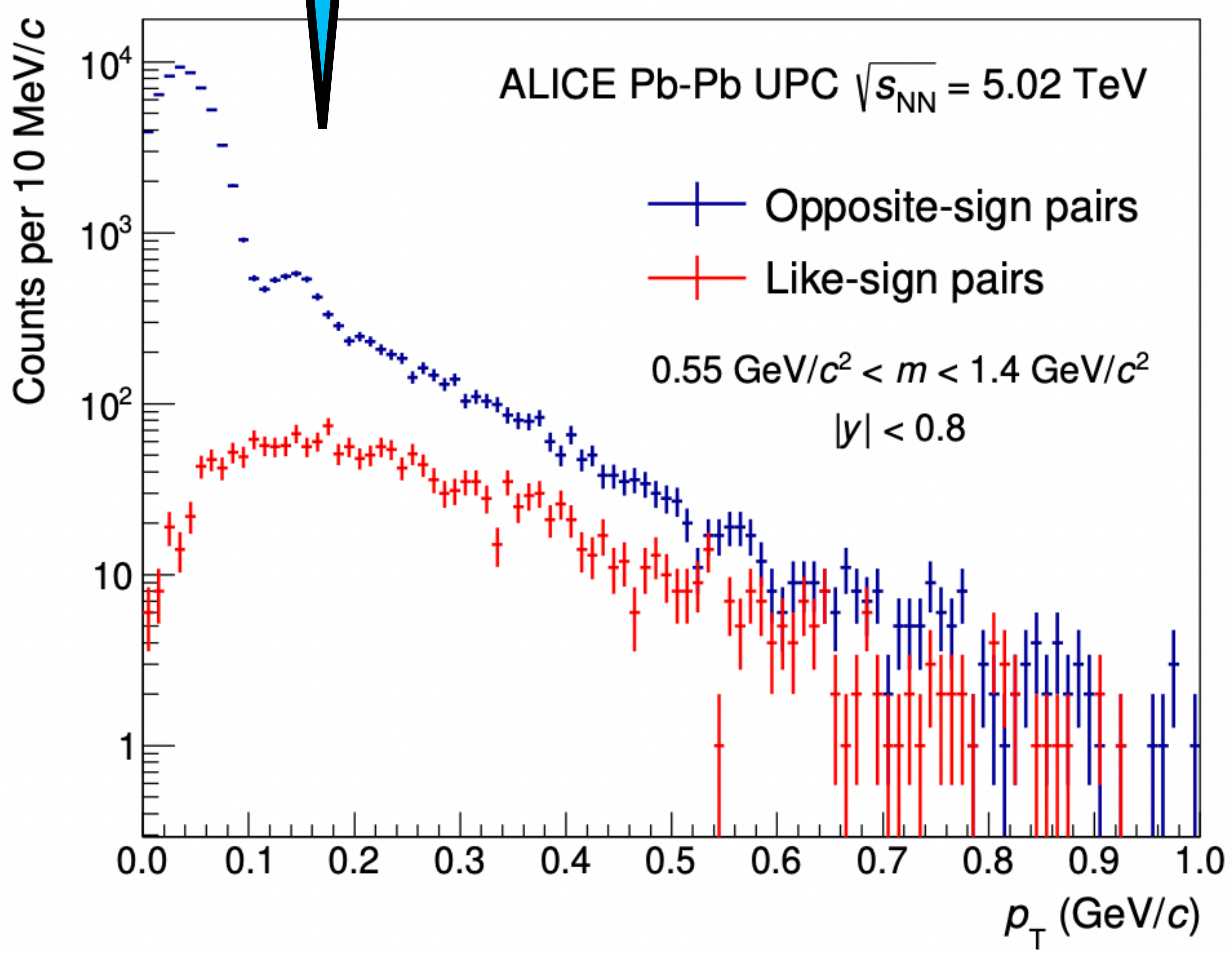

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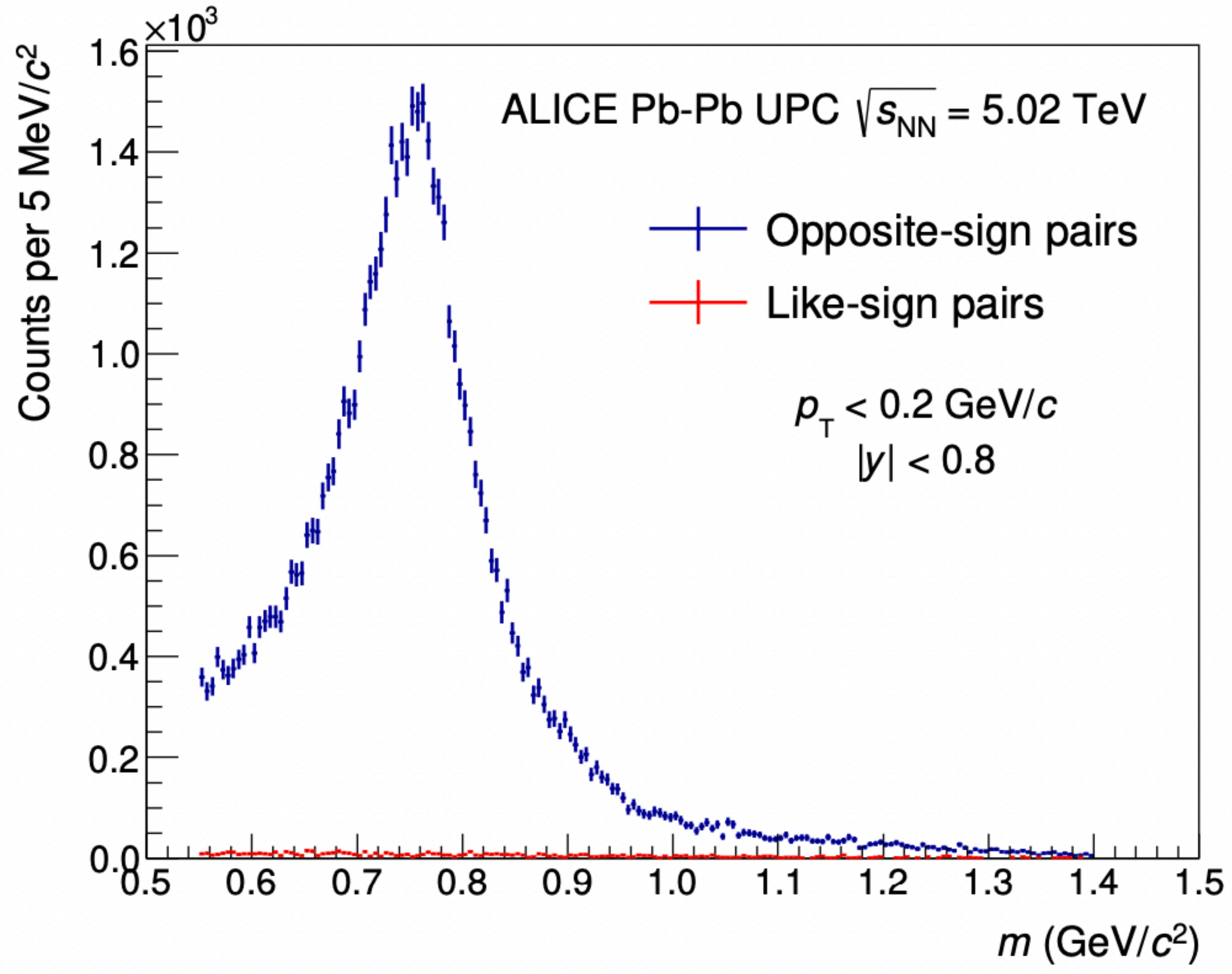

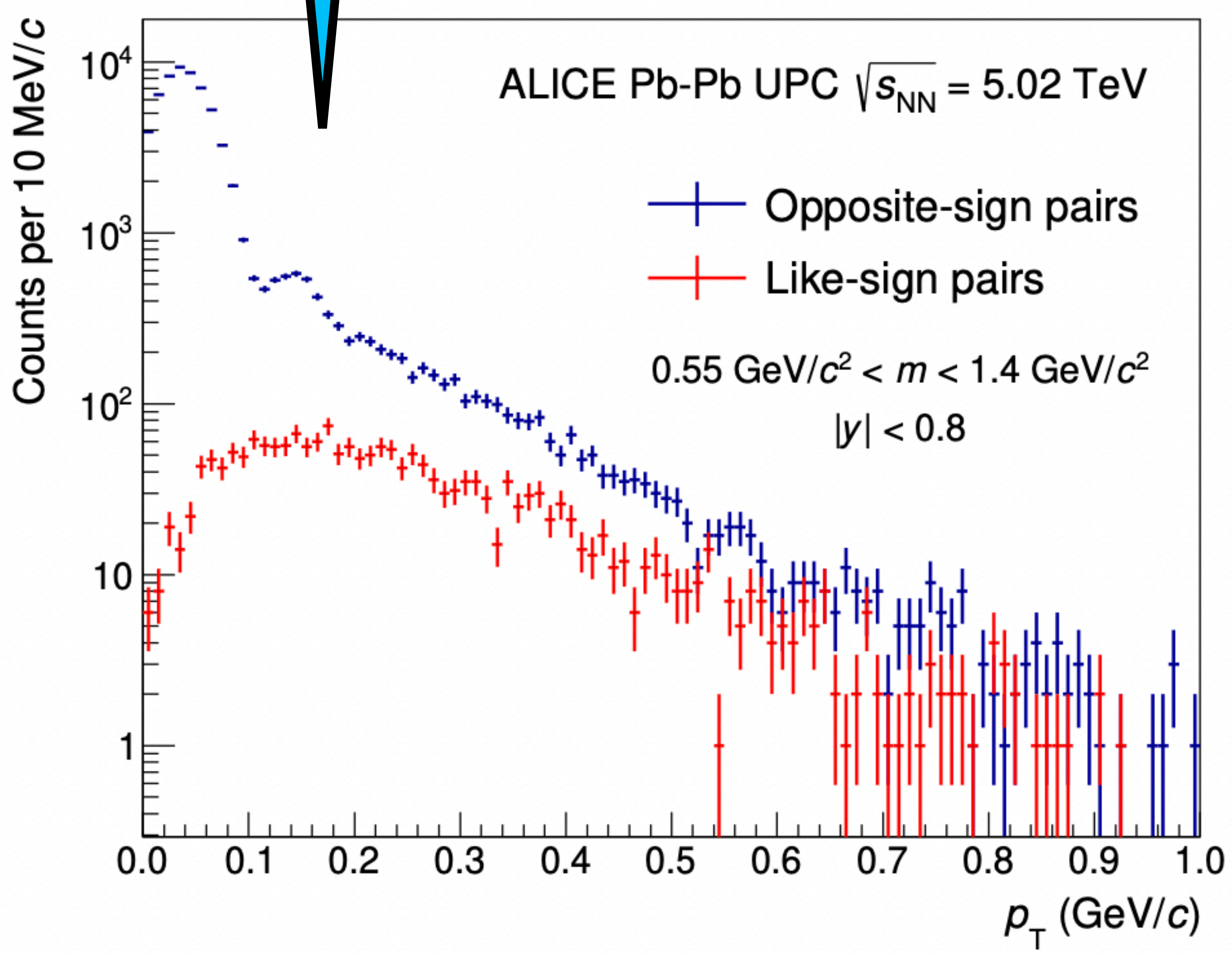

Trigger on tracks and vetoes, measuring in EMD classes to test our knowledge of the photon flux

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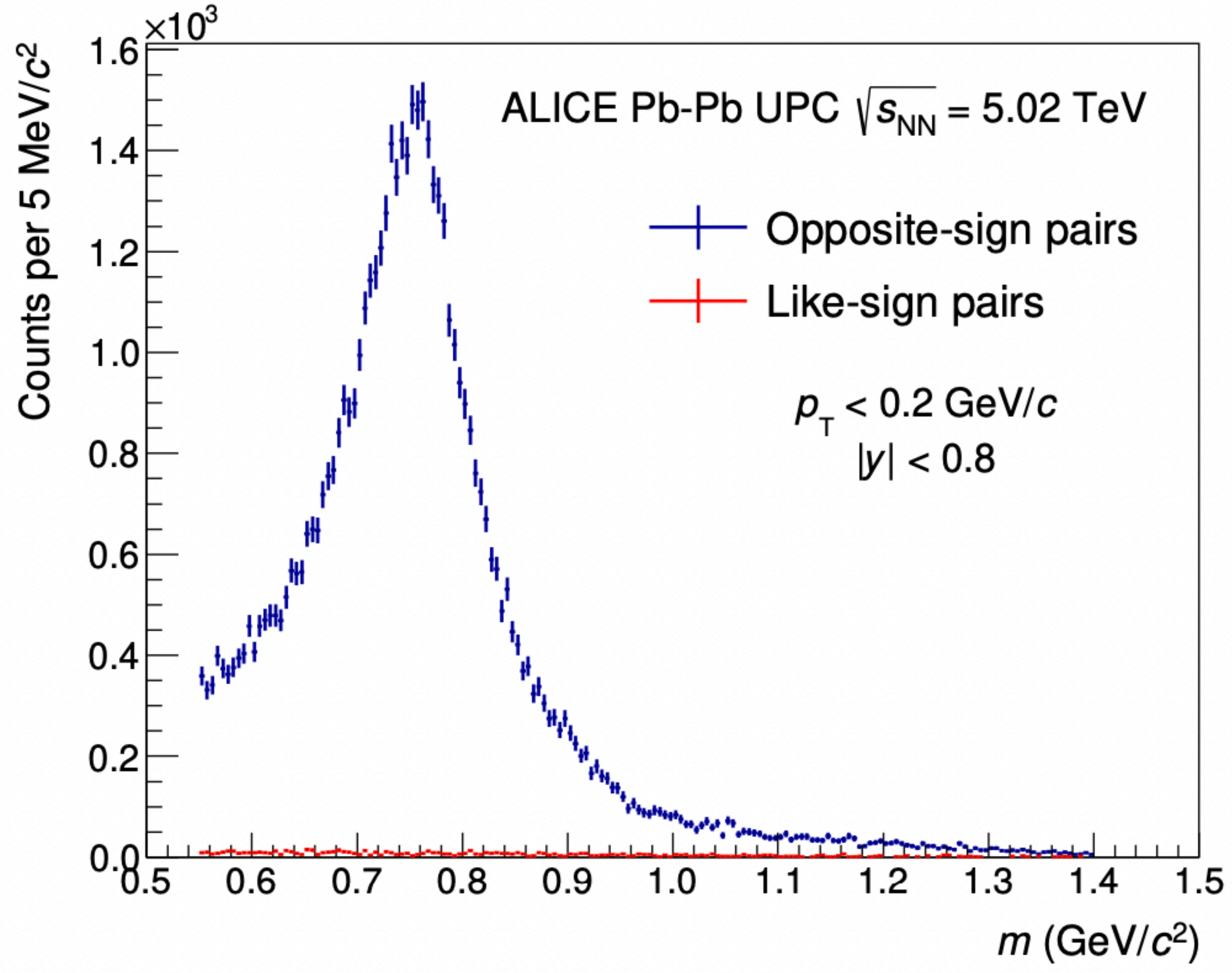

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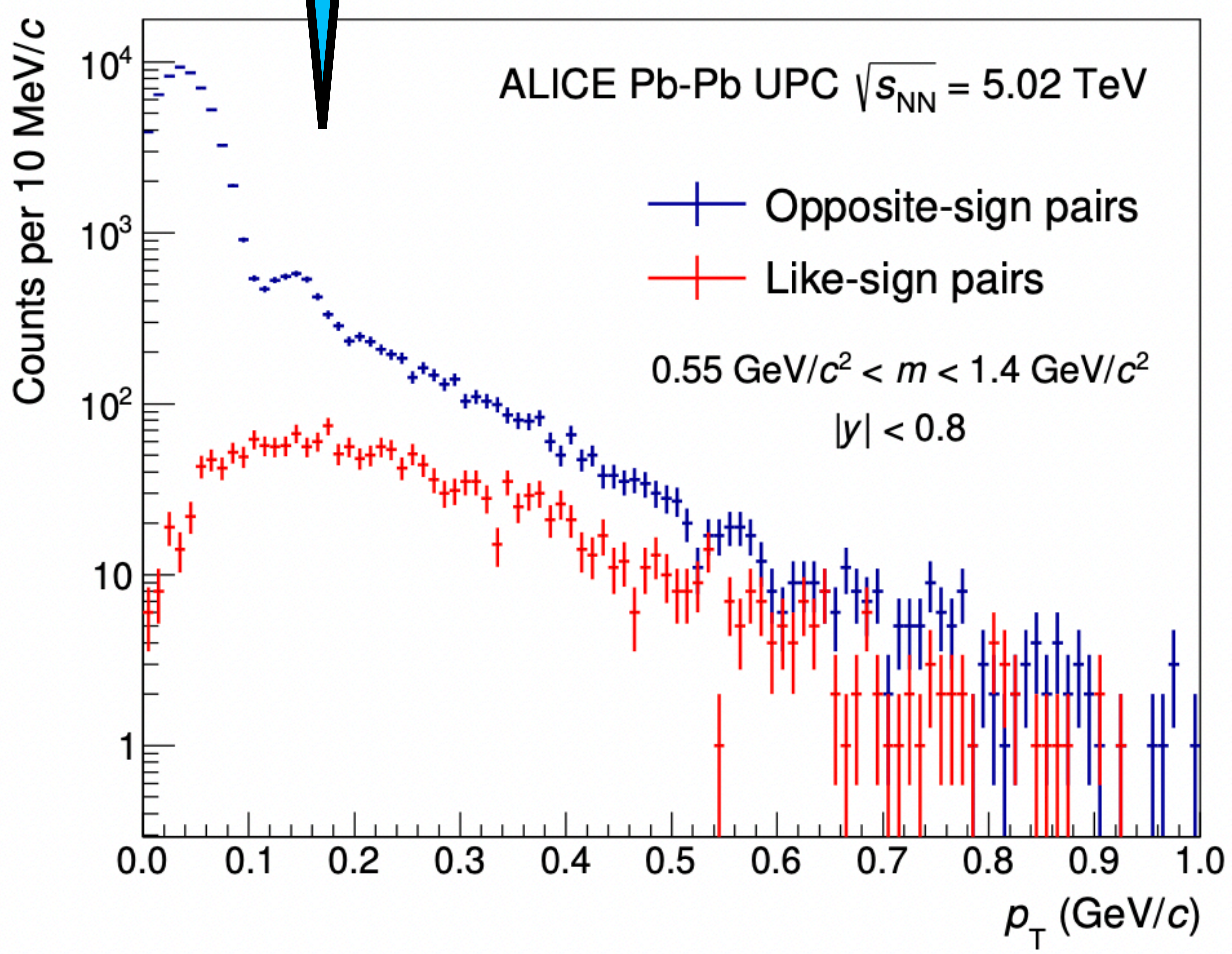

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Other measurements available at 2.76 TeV per NN

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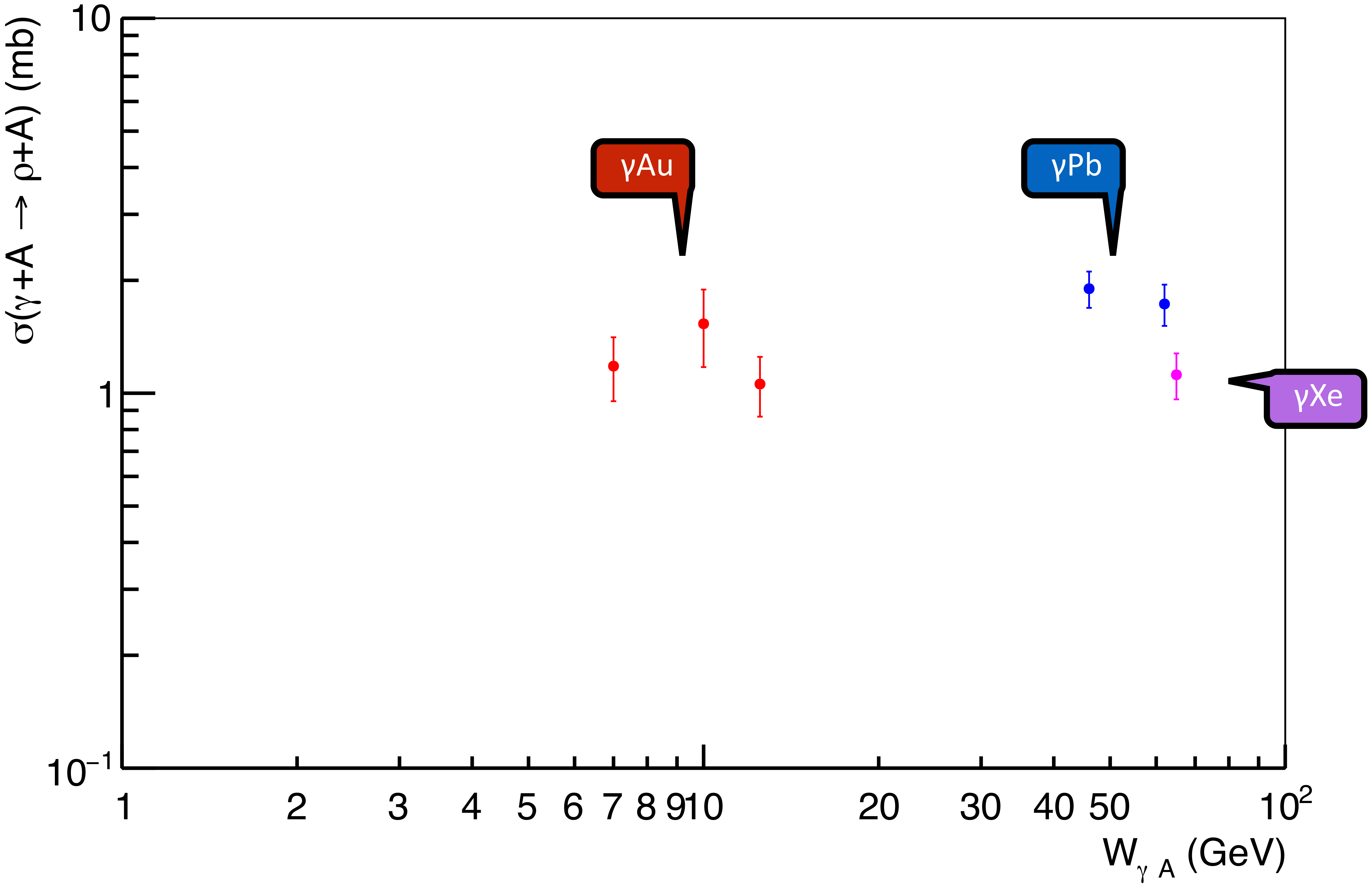

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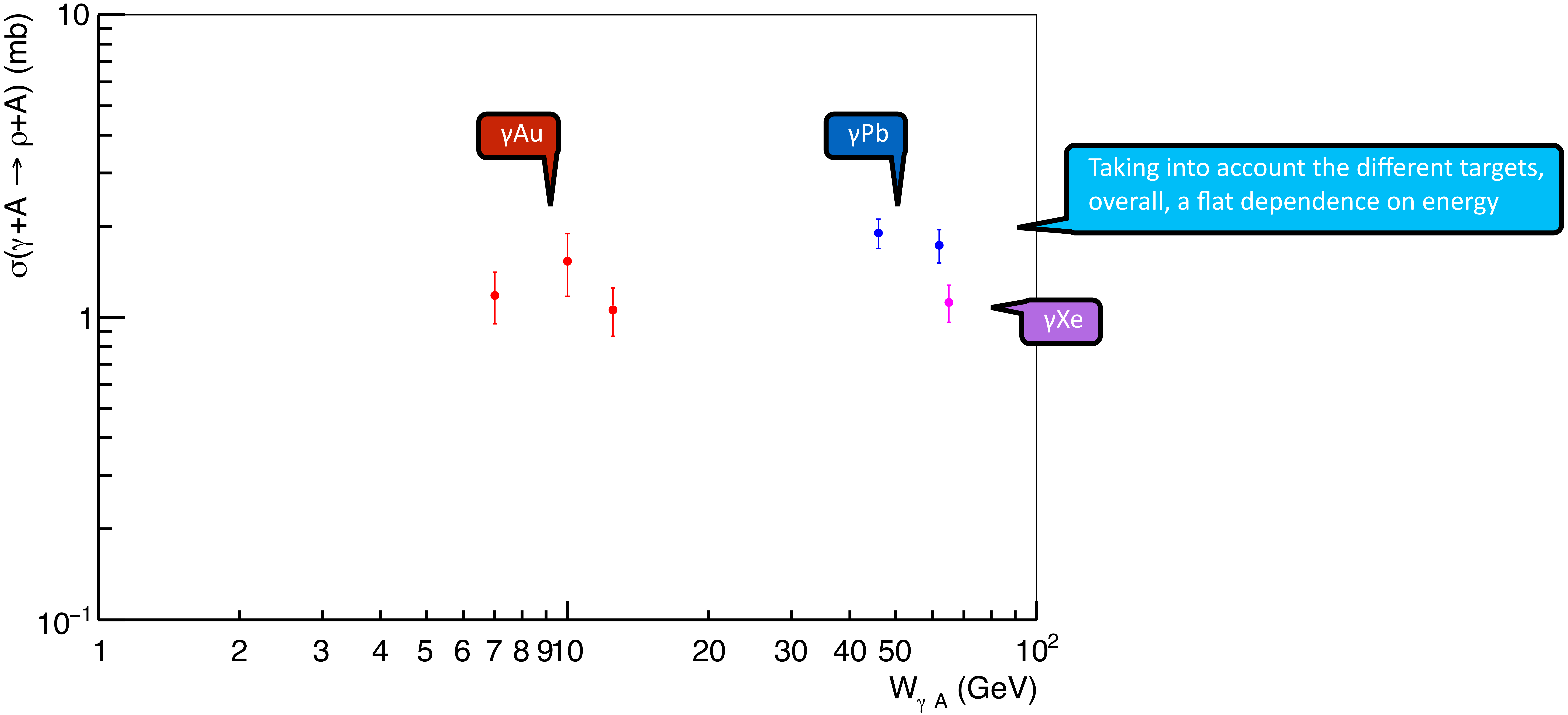

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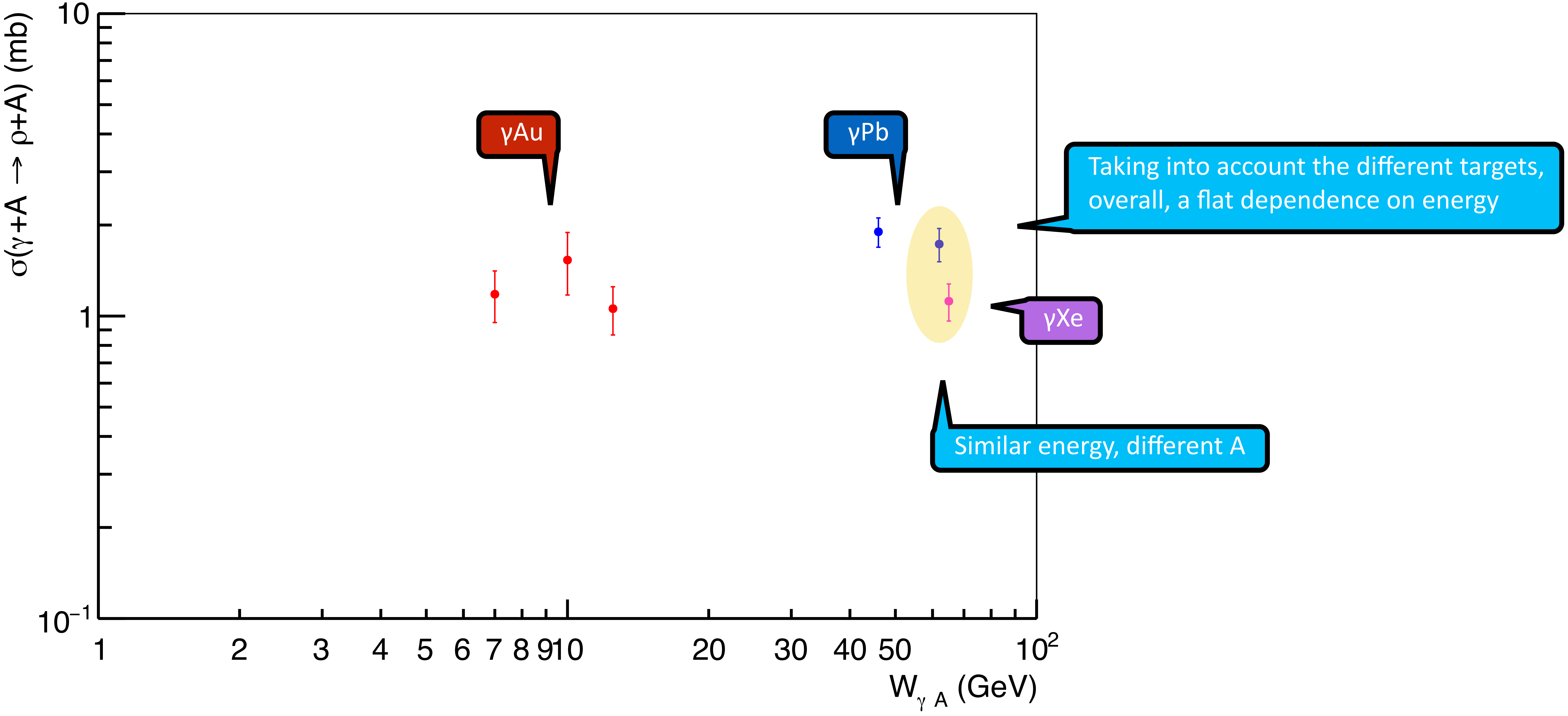
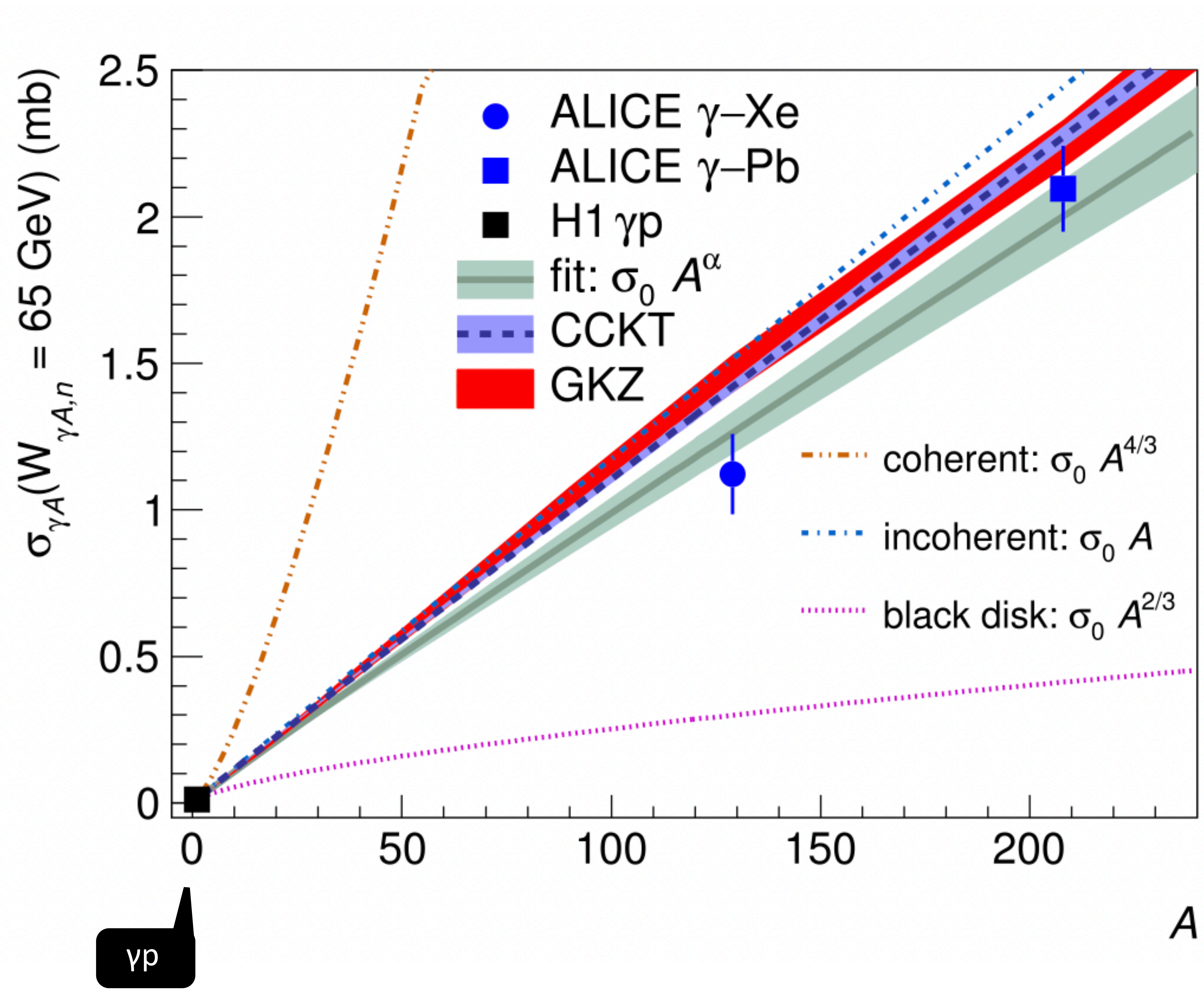


A dependence of coherent ρ⁰ production at high energies



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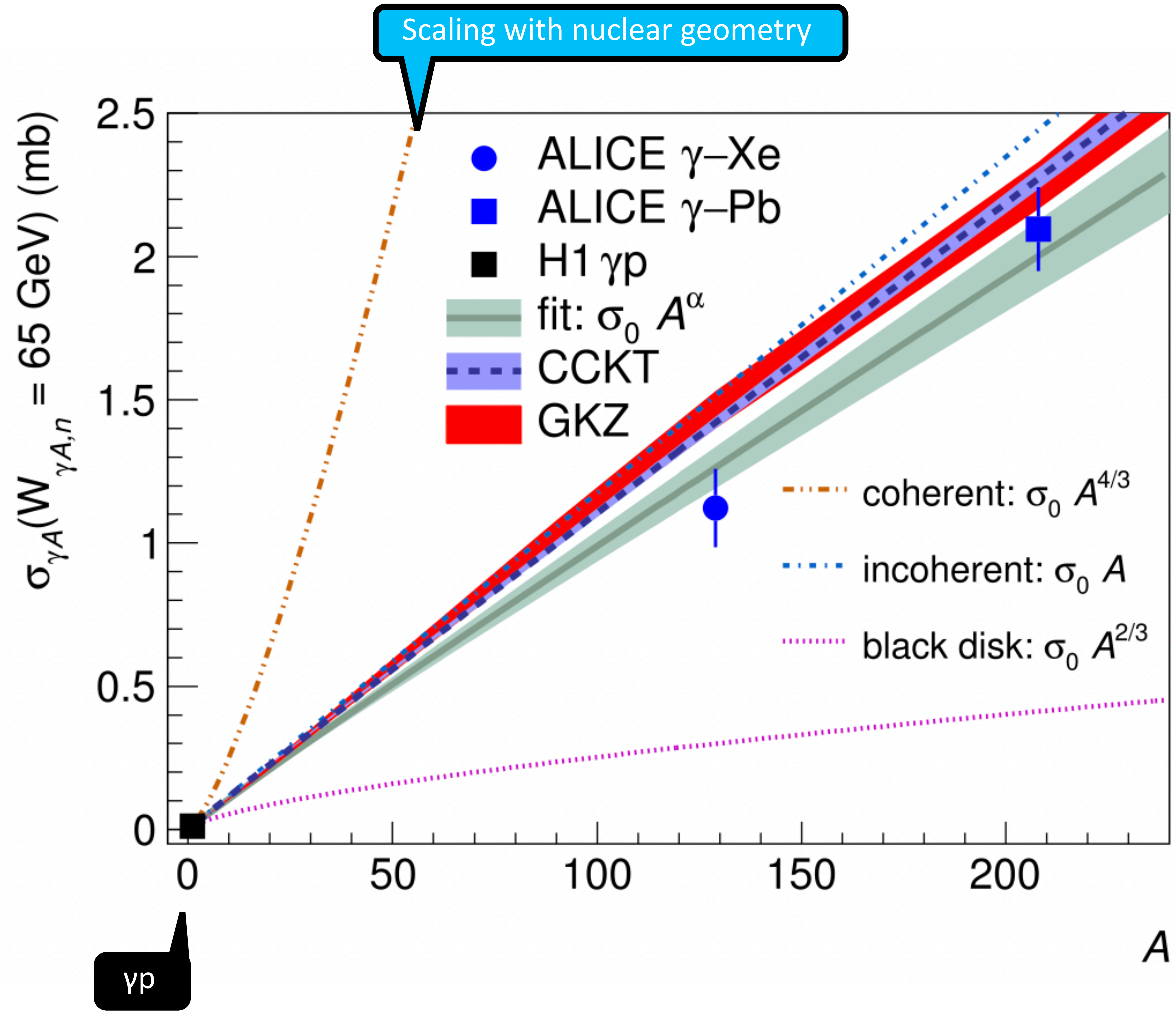

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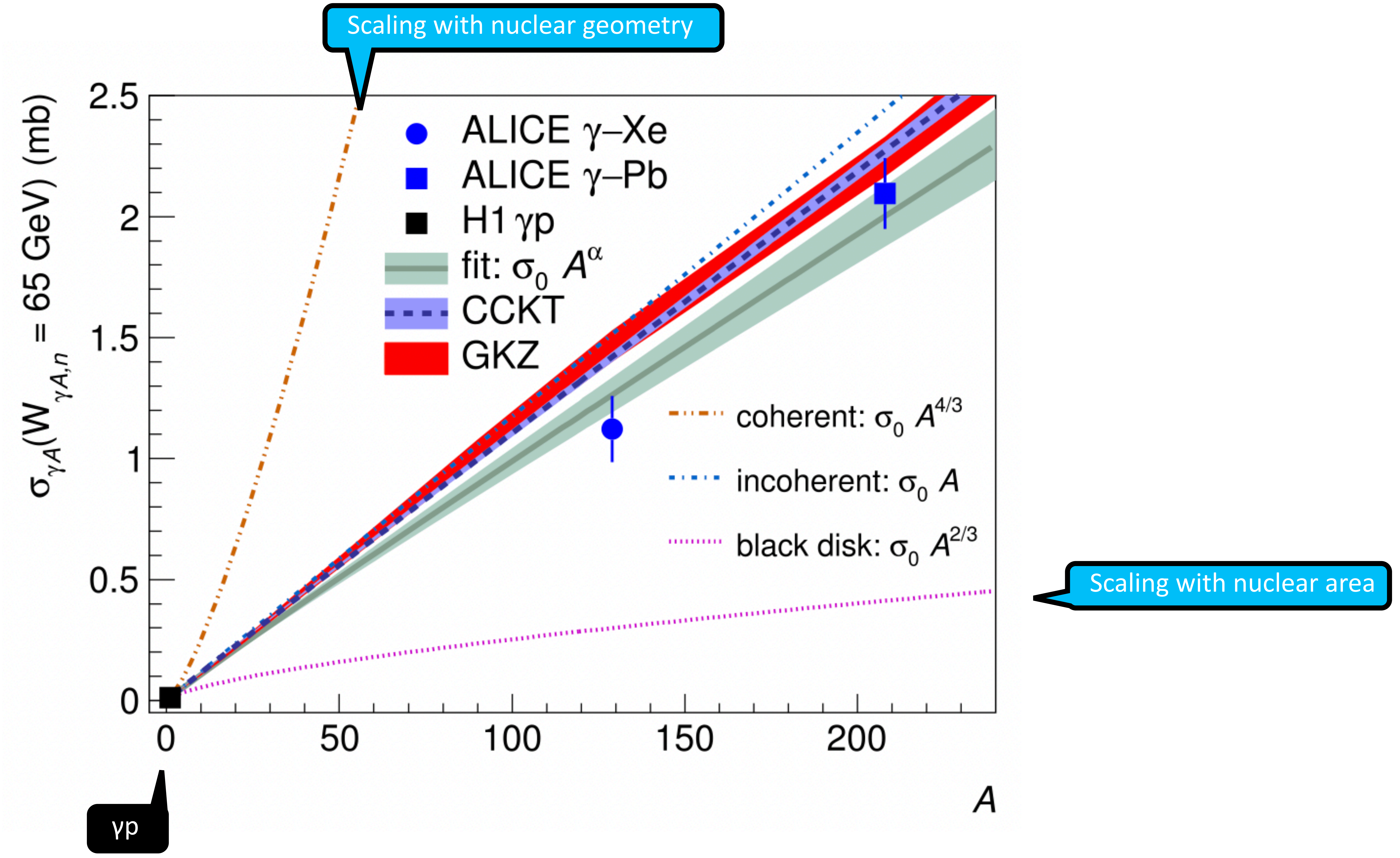

ALICE (2021) https://inspirehep.net/literature/1839719

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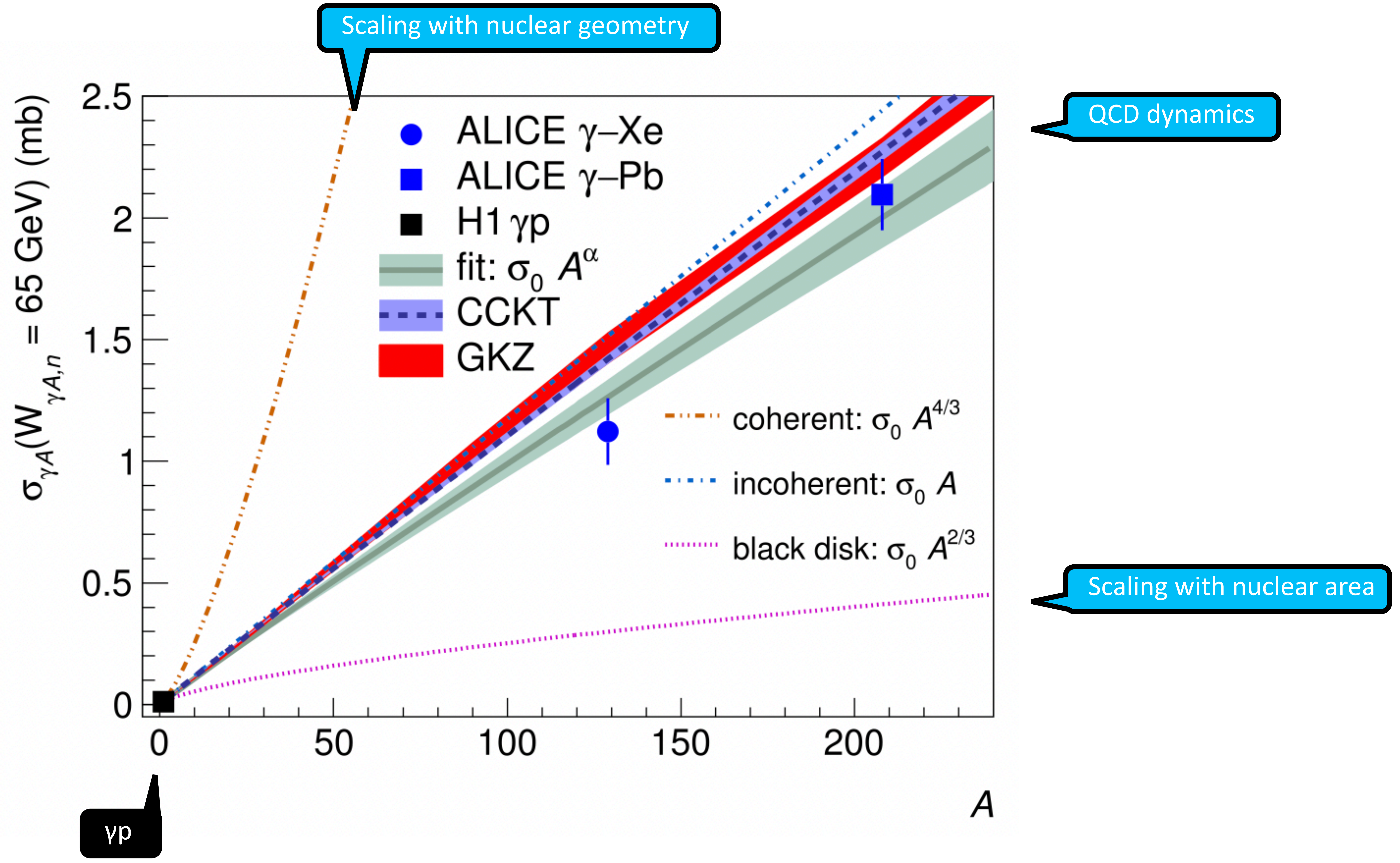
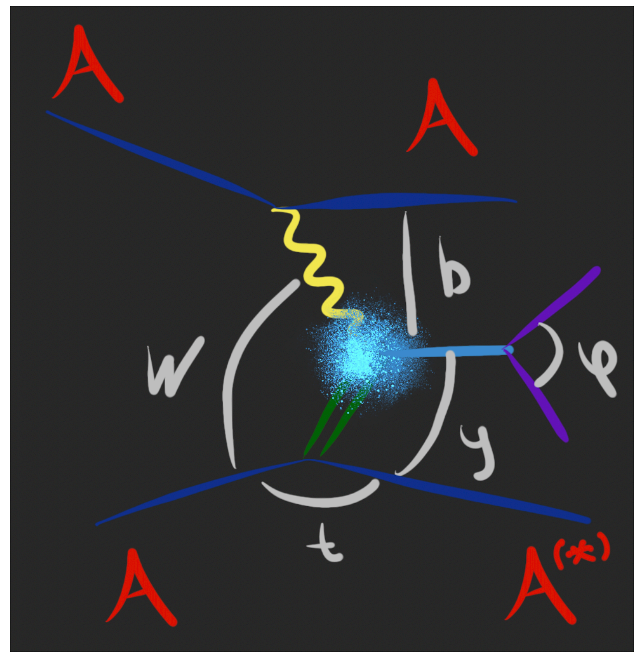


Interference effects in coherent ρ⁰ production: t dependence



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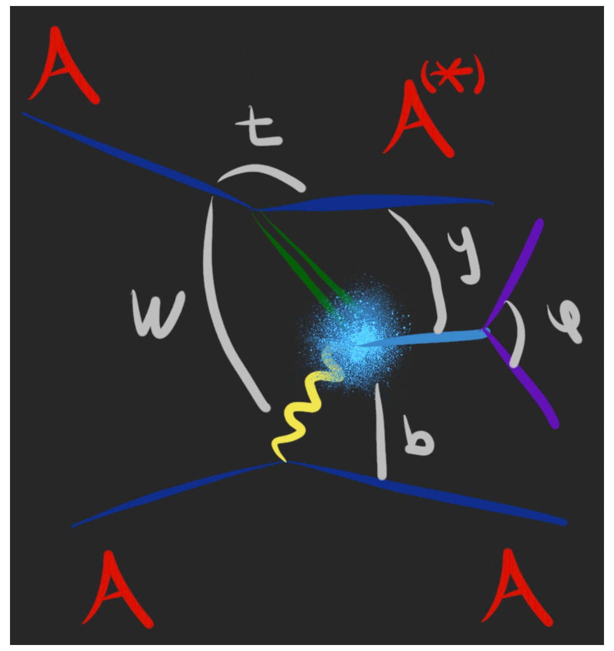

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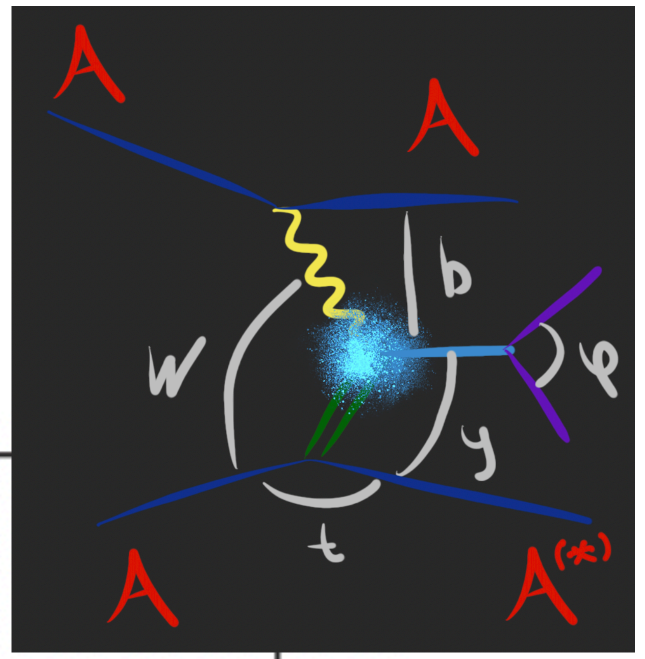

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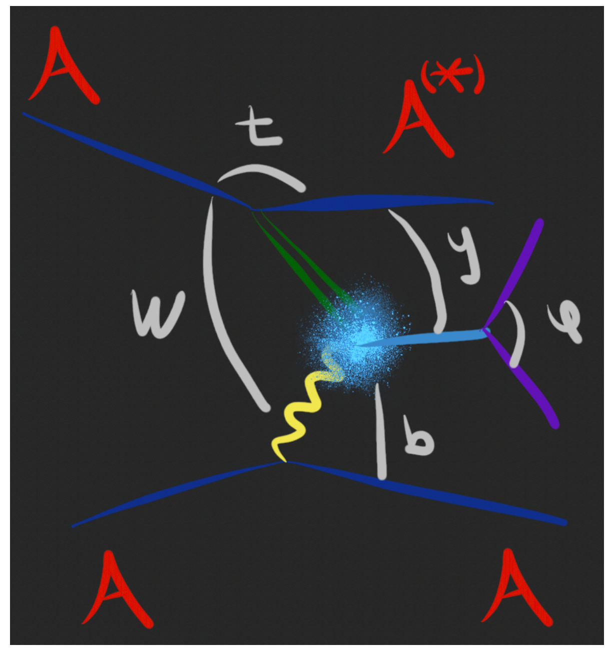

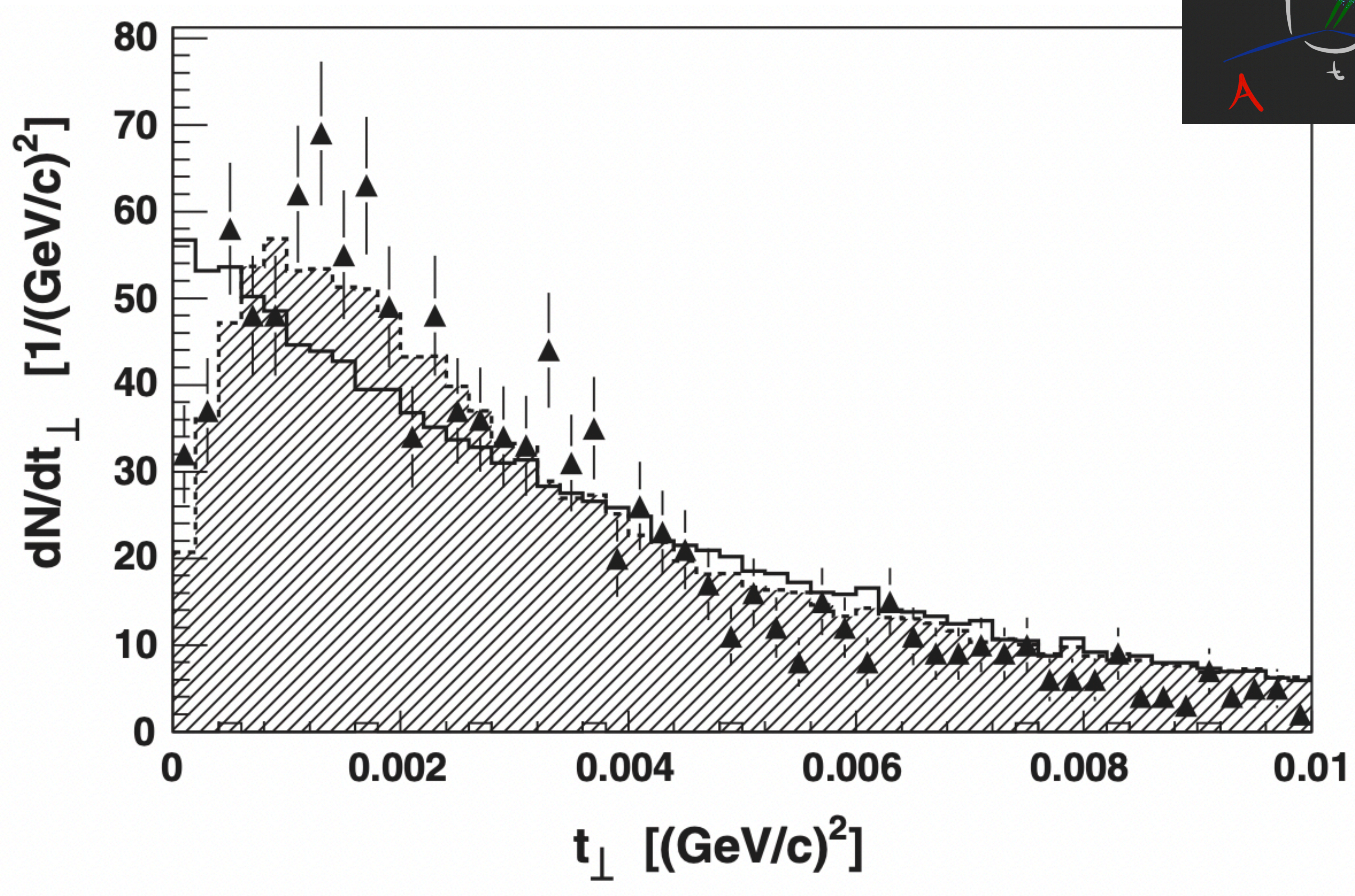

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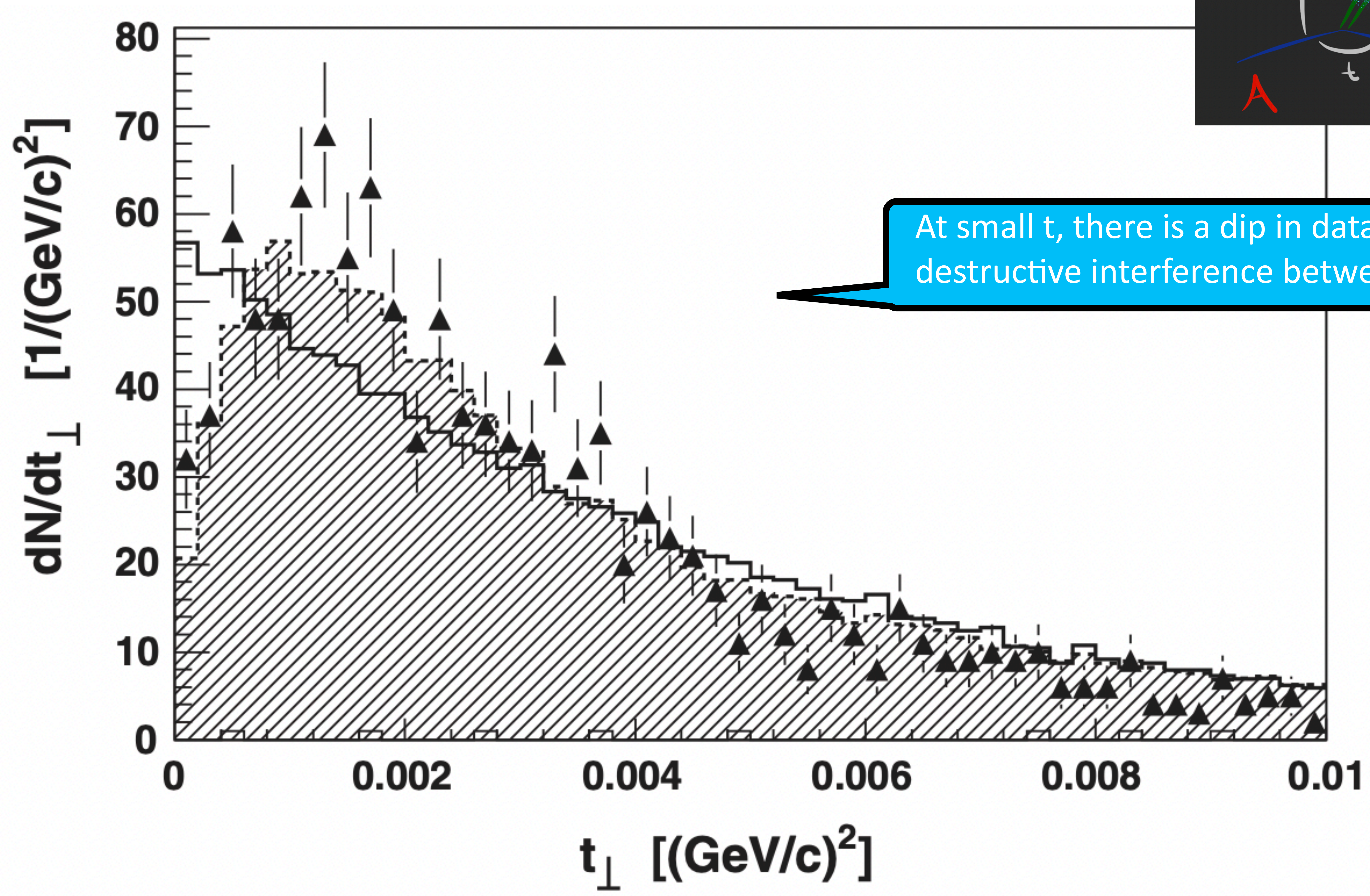

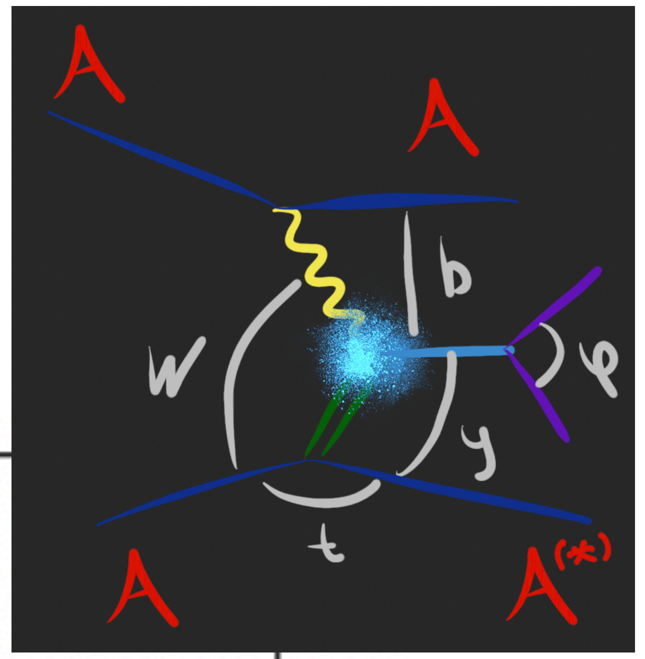

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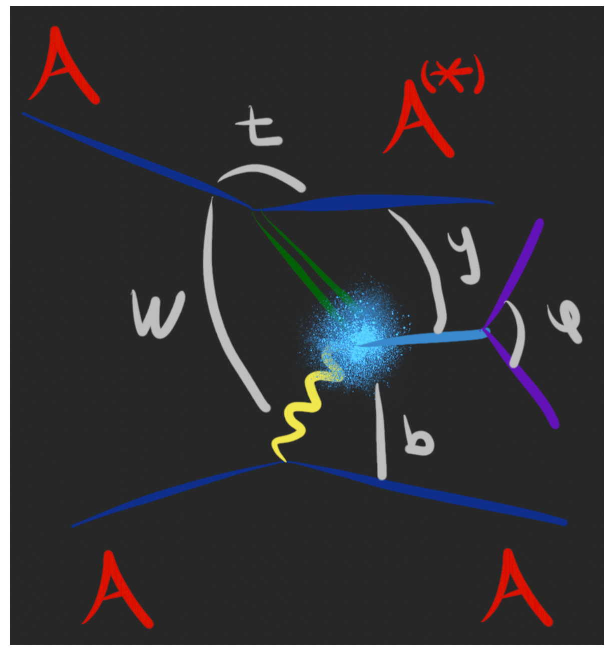

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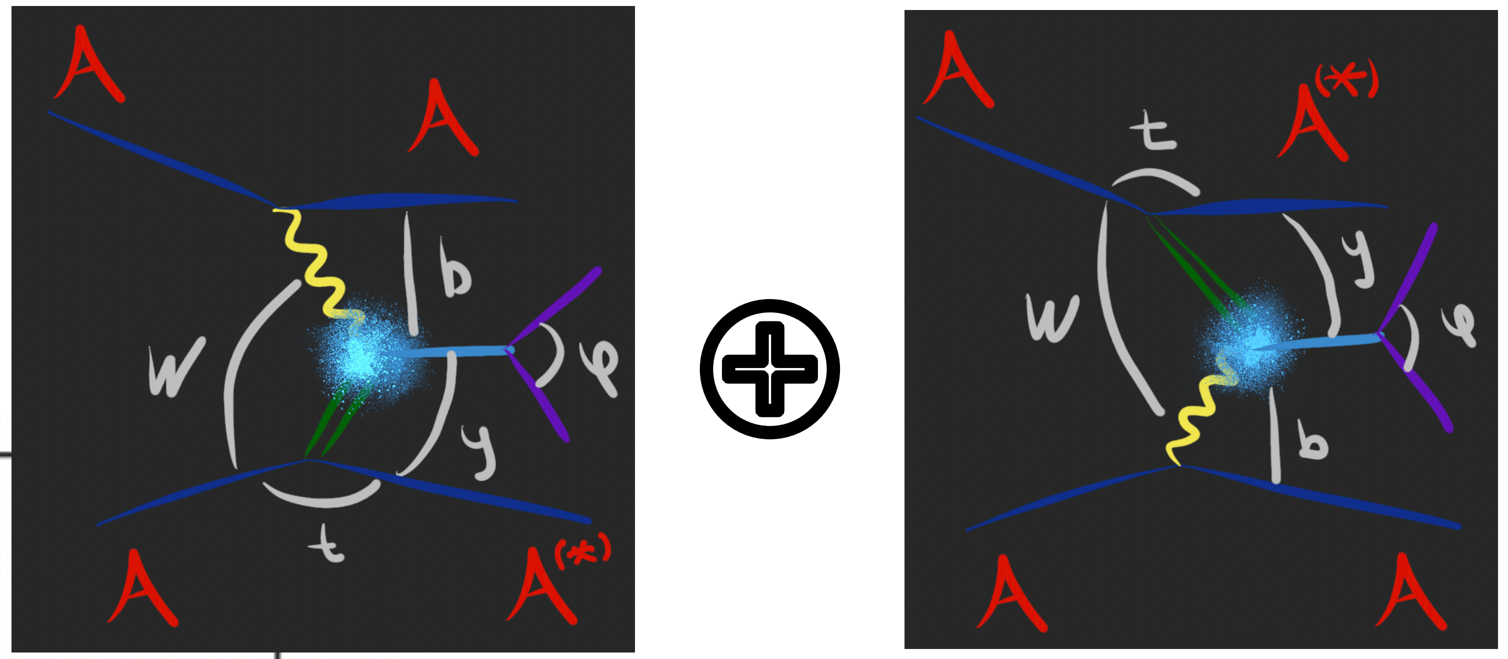

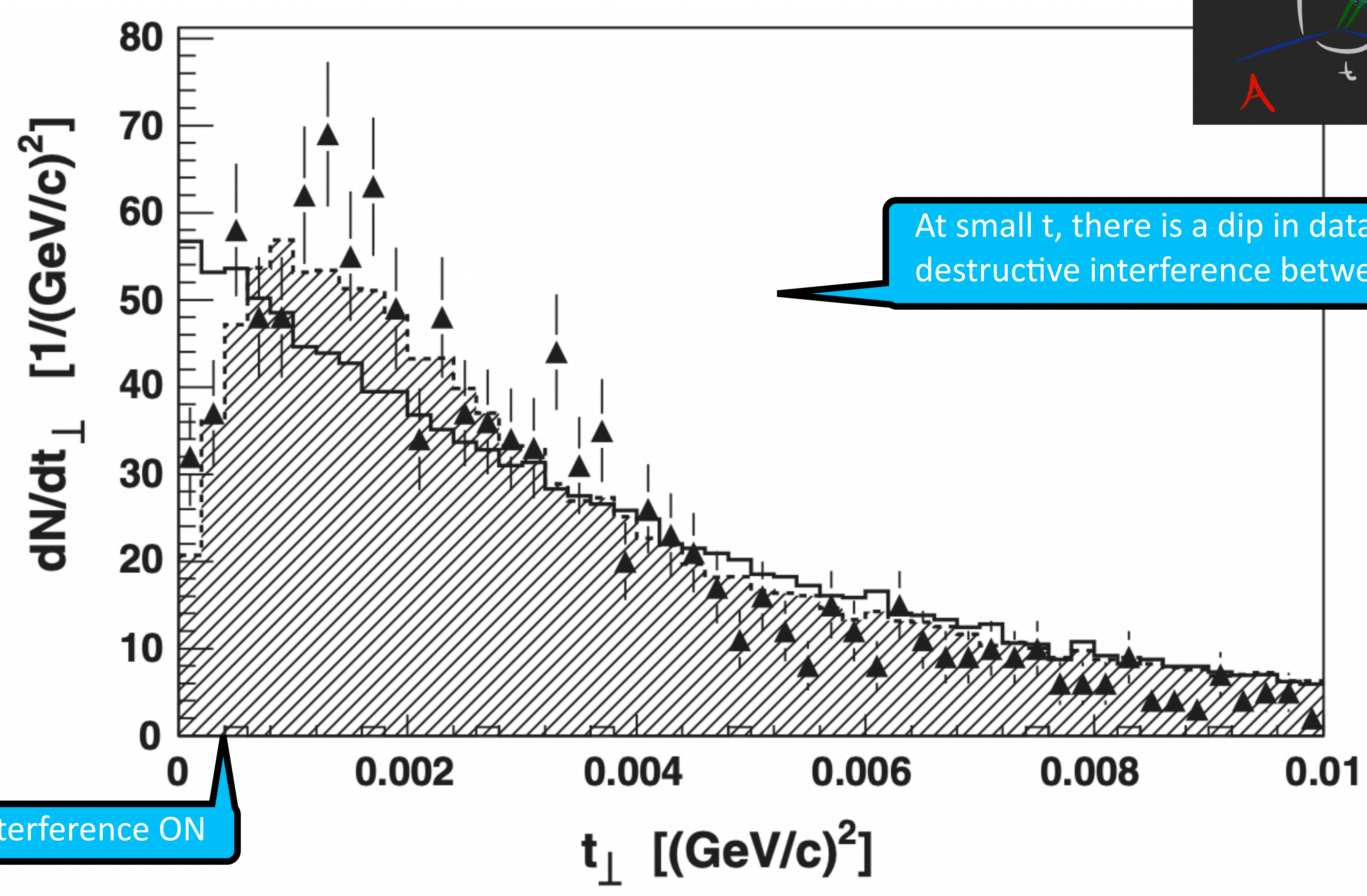

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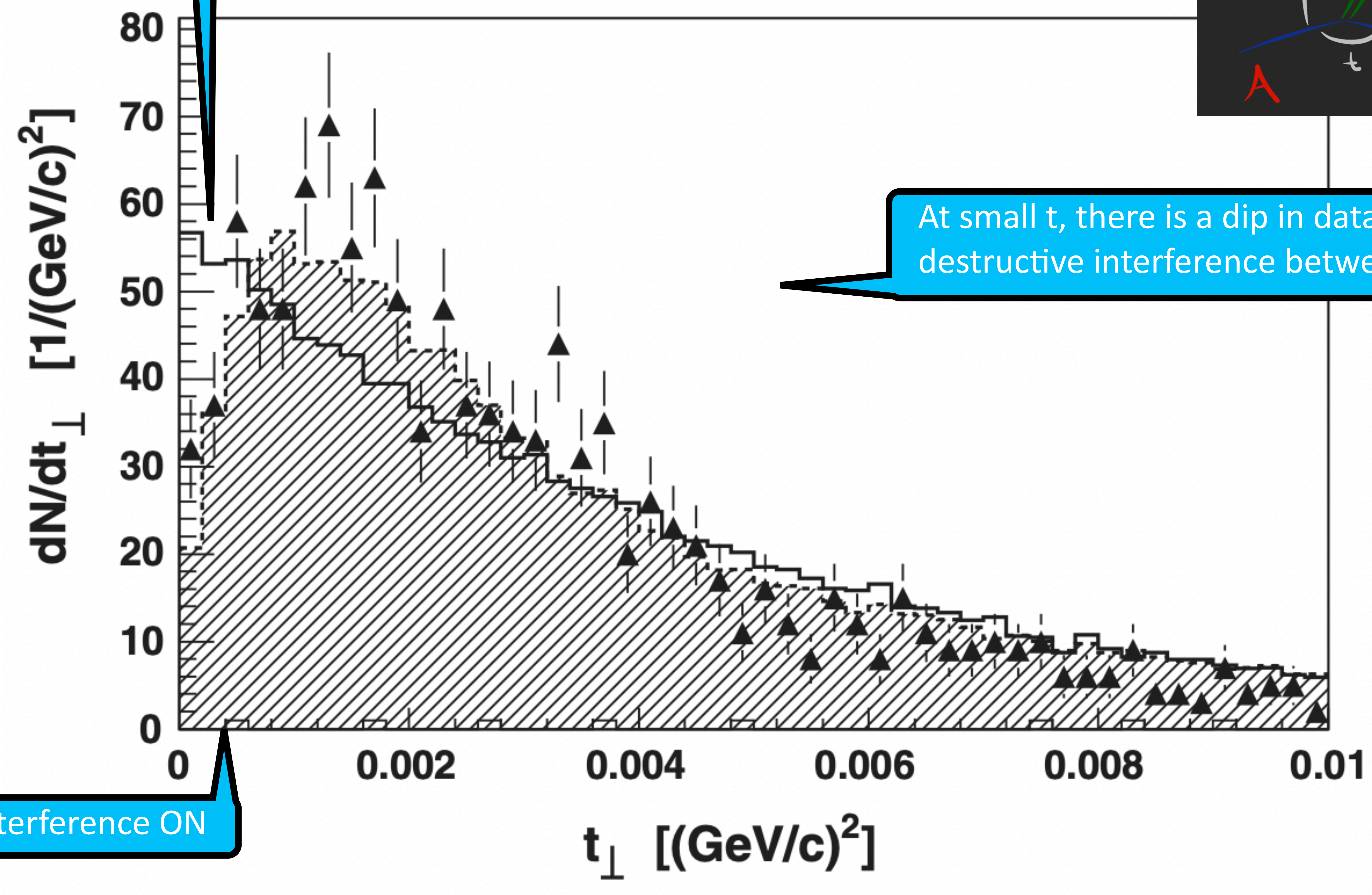

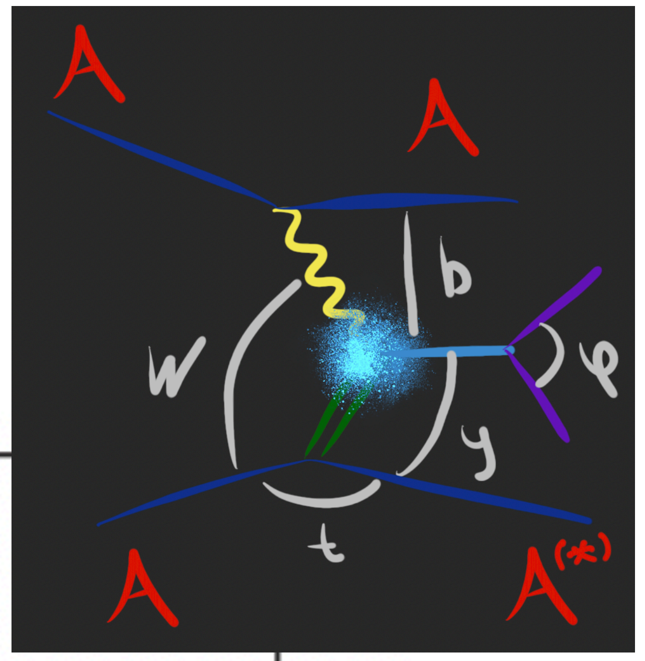

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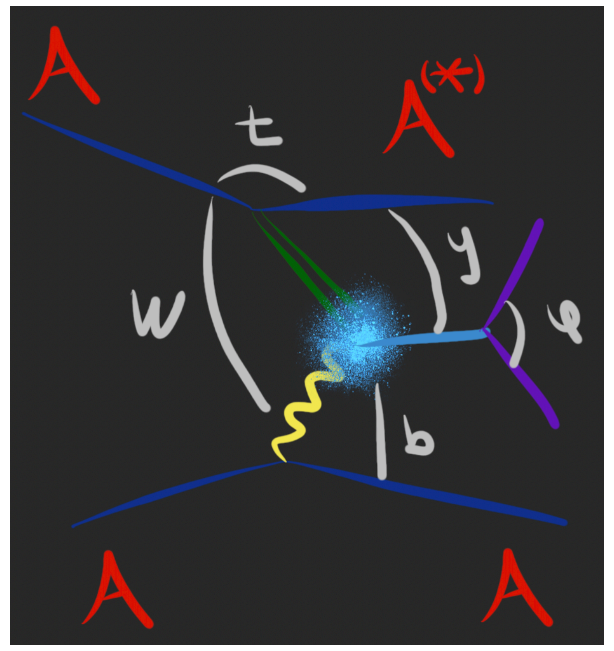

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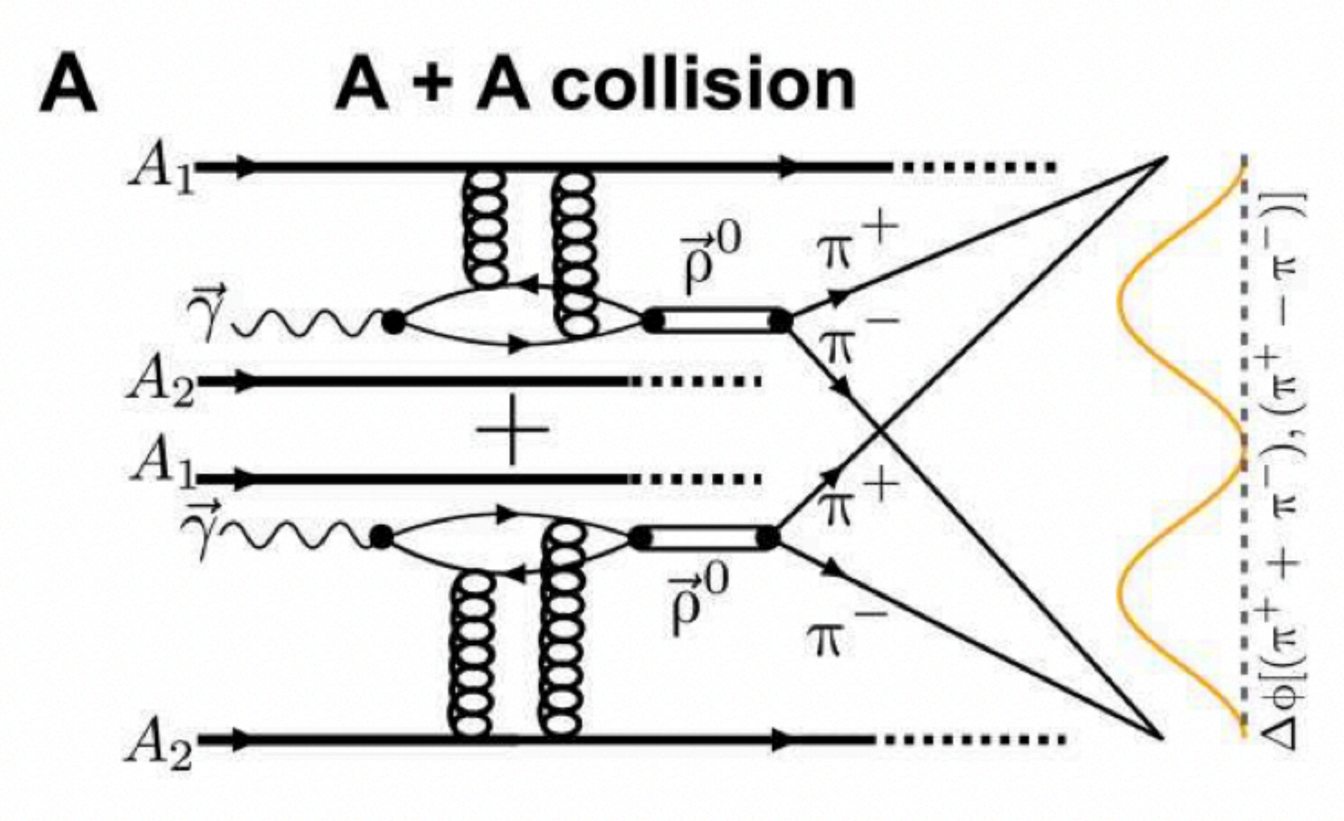
Interference effects in coherent ρ⁰ production: azimuthal asymmetries at RHIC



The interference between the amplitudes modifies the azimuthal correlations of the decay products

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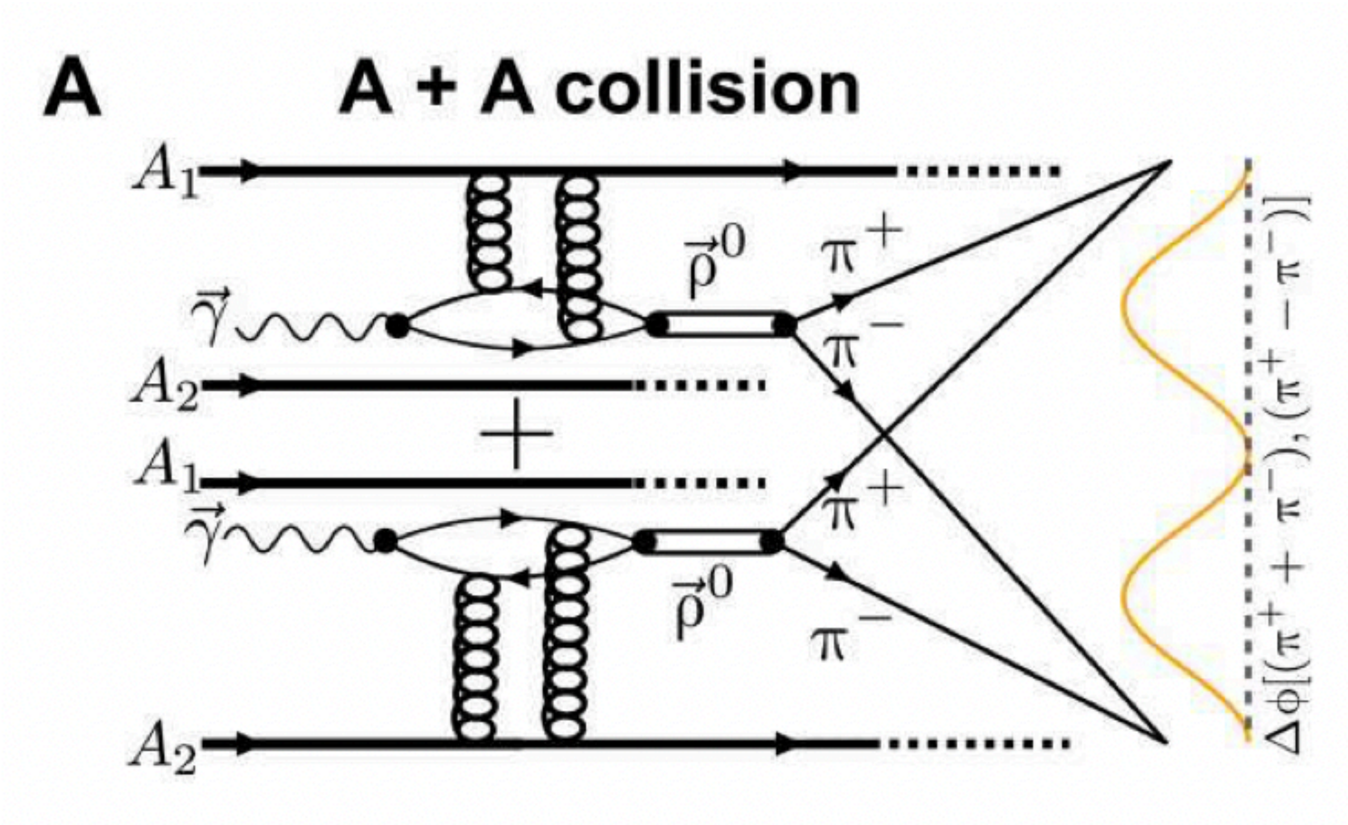

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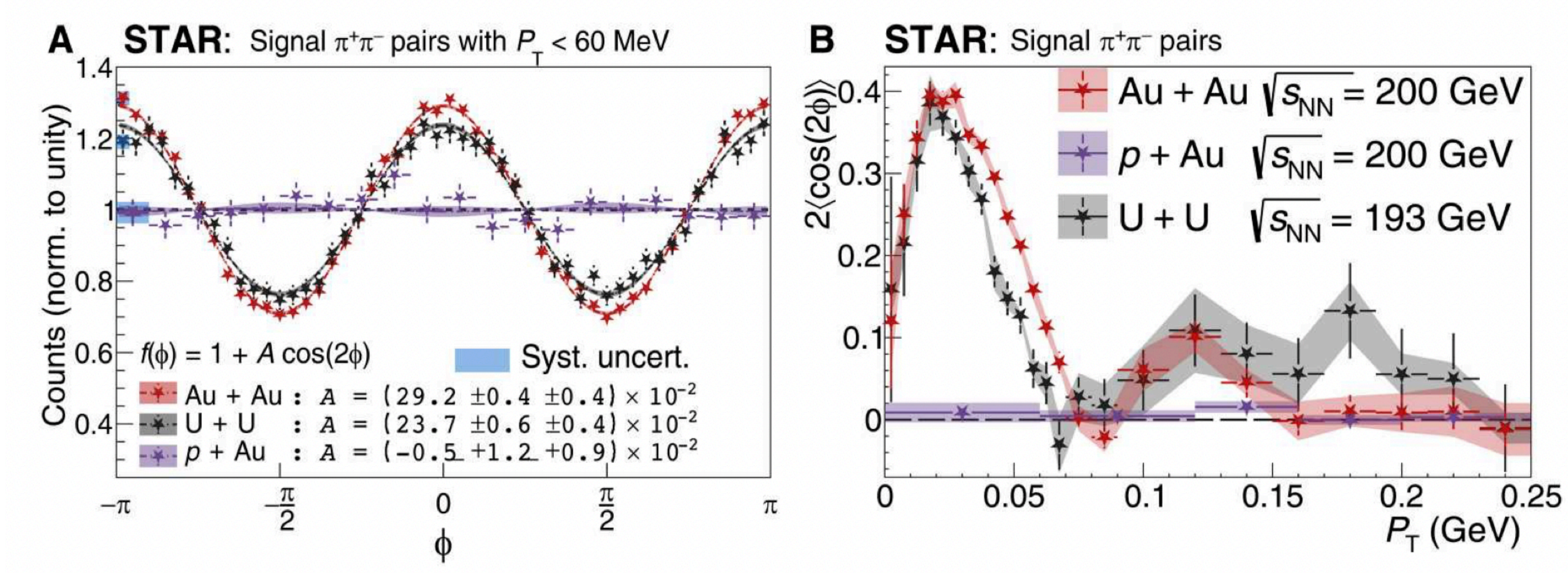
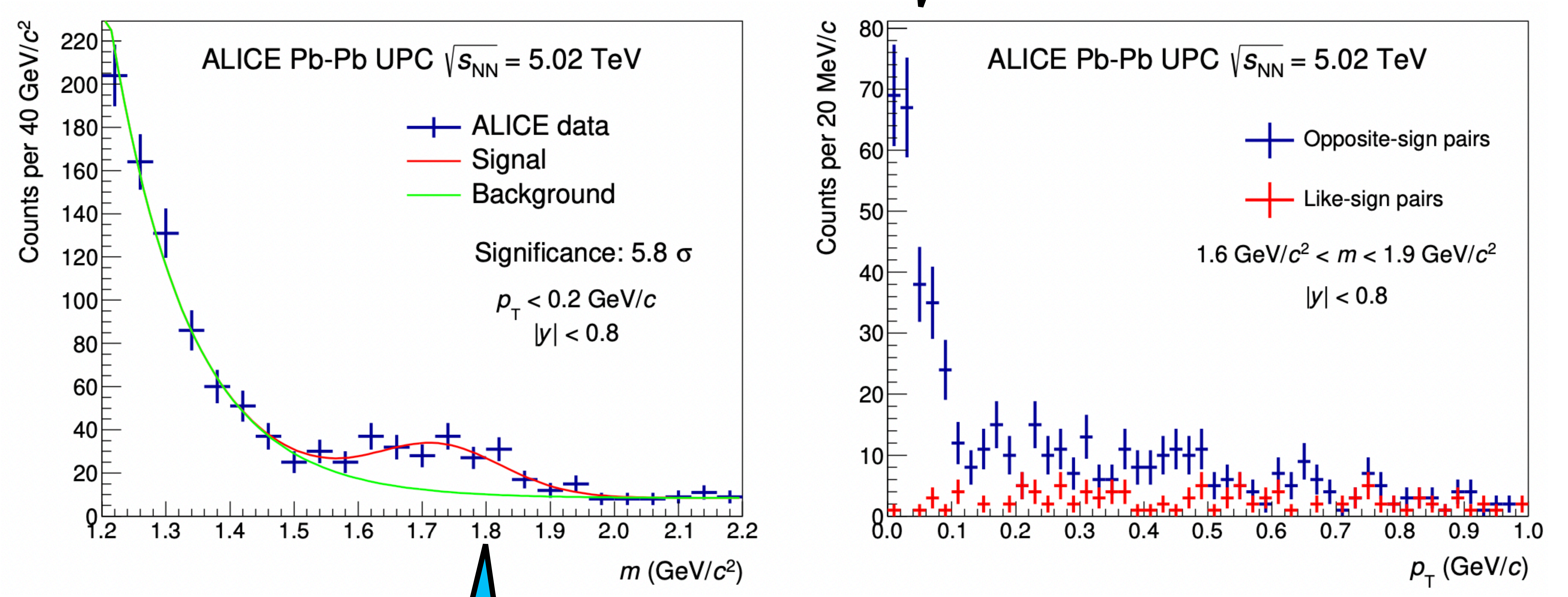


STAR (2023) https://inspirehep.net/literature/2062296

New (?) resonances in coherent ππ production

Transverse momentum distribution typical of coherent processes



Bump in the invariance mass distribution of pion pairs

ALICE (2020) https://inspirehep.net/literature/1782227

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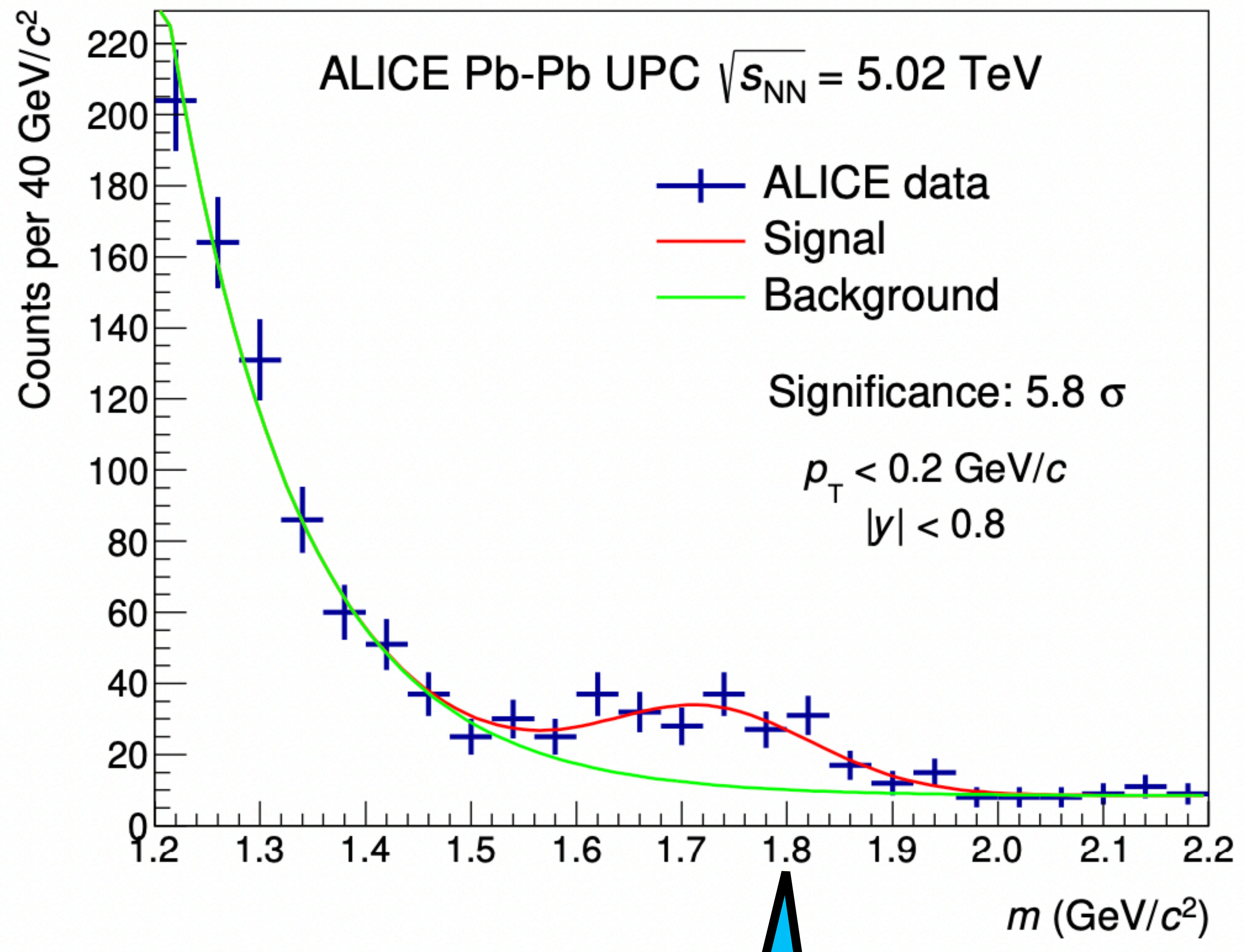

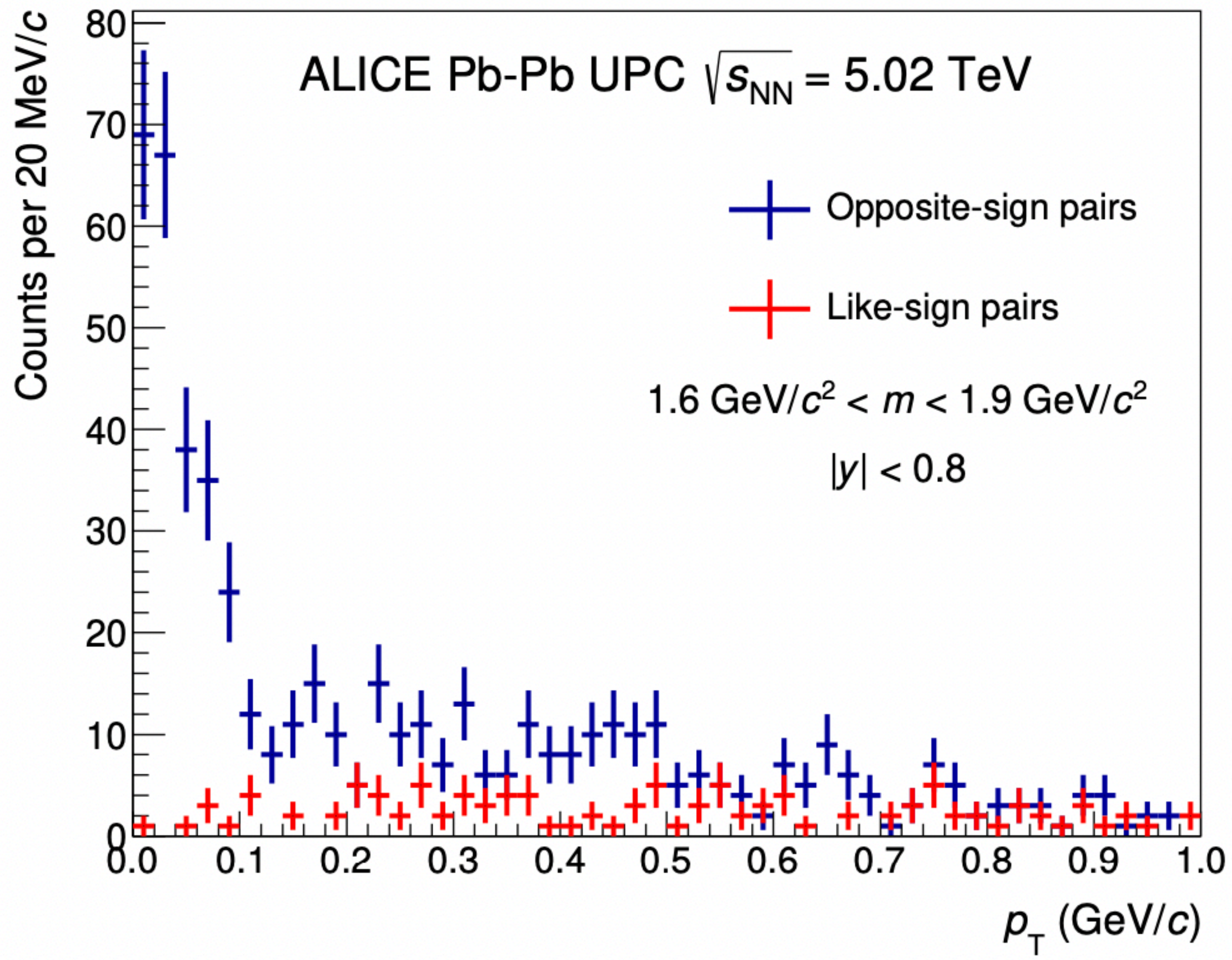

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Similar structures seen by H1, ZEUS, STAR

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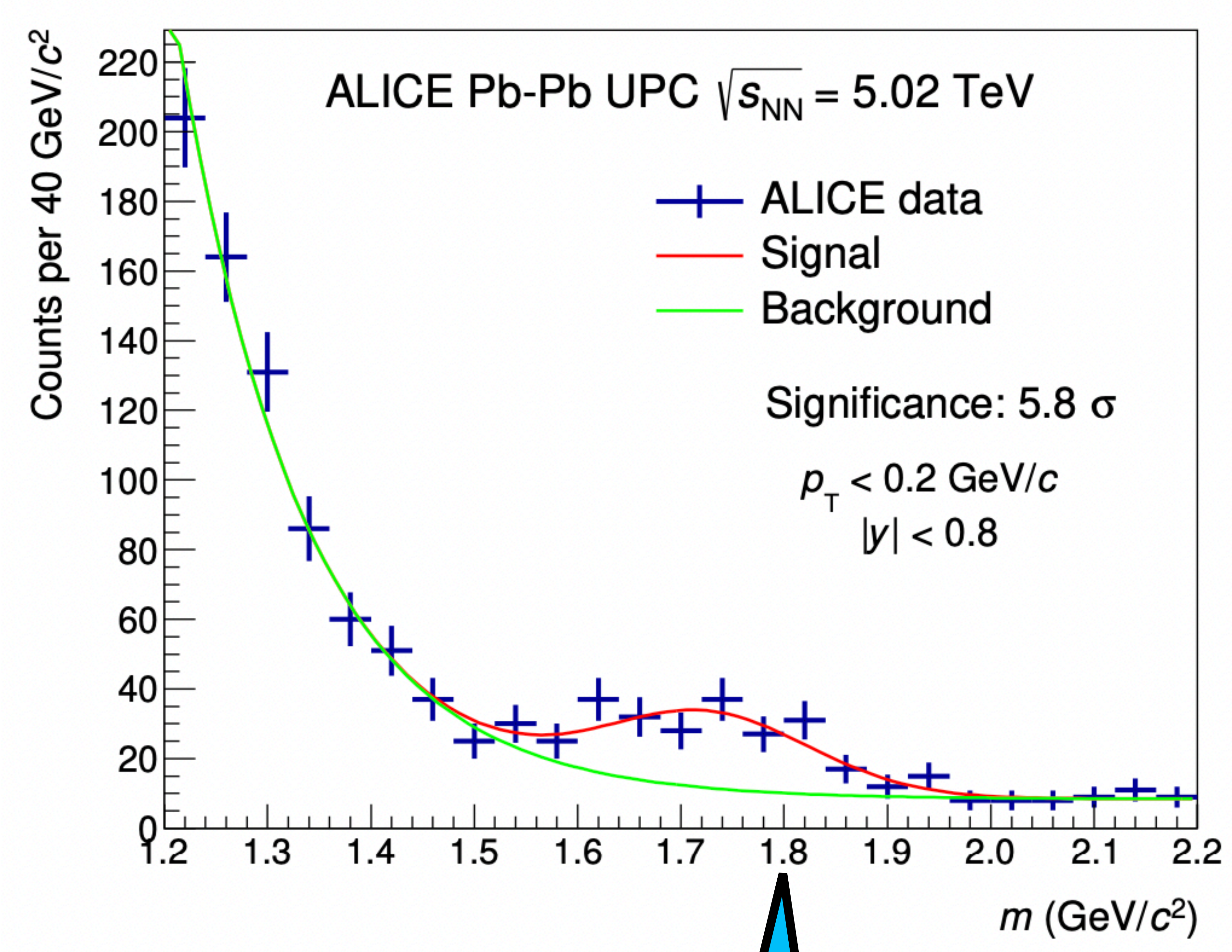

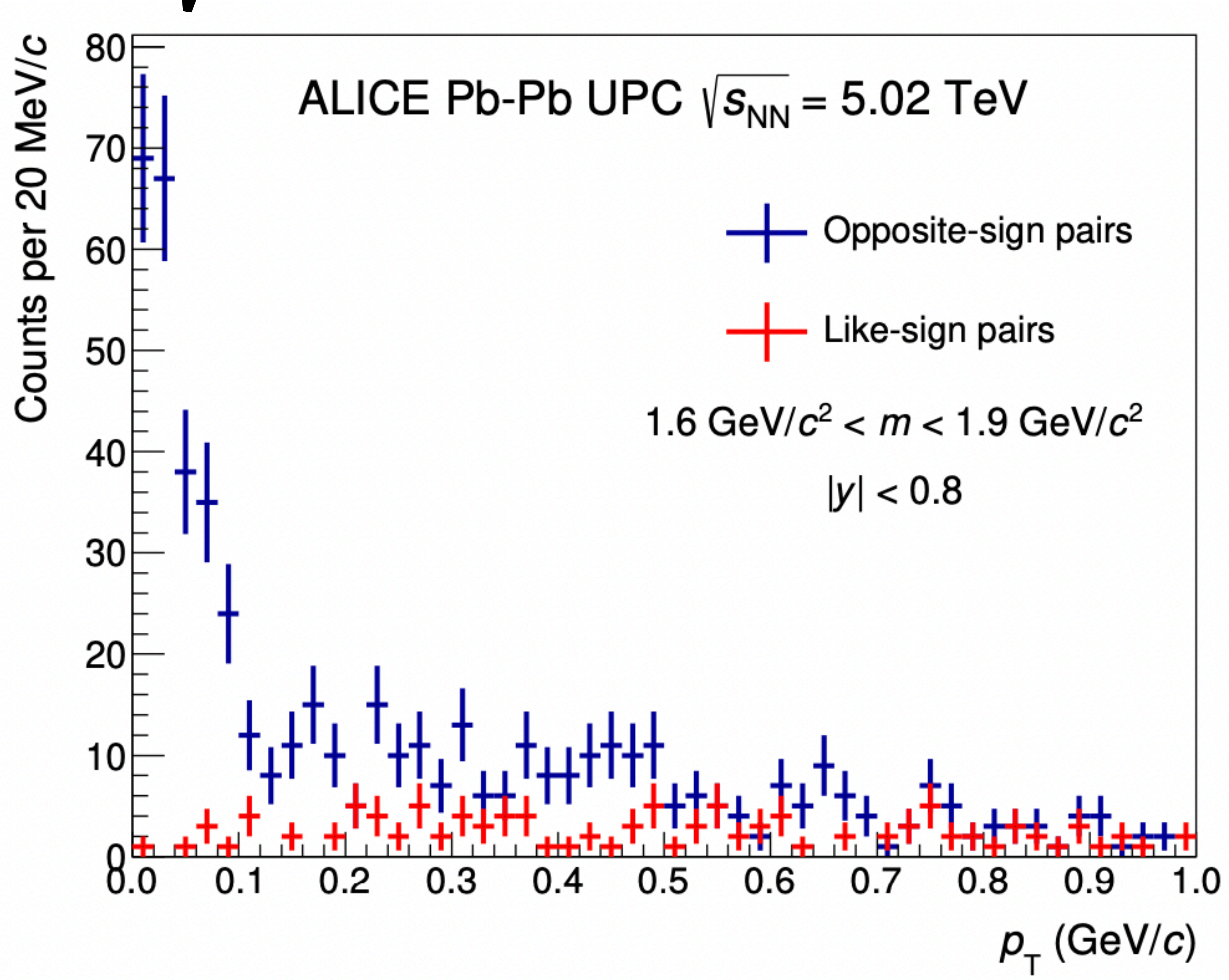

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The large improvement in luminosity in Run 3 may reveal more of these structures and allow for the determination of their properties

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what was done before to use photon-induced processes to study QCD
and what we are doing now at RHIC and LHC

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what was done before to use photon-induced processes to study QCD
and what we are doing now at RHIC and LHC

And you will learn a lot about this during the week

Homework:

Enjoy the meeting!