XXVII International Workshop on Deep-Inelastic Scattering and Related Subjects
8-12 April 2019
Torino, Italy

Some recent results related to low-x and forward physics

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Czech Technical University in Prague

April 8, 2019, Torino

Disclaimers

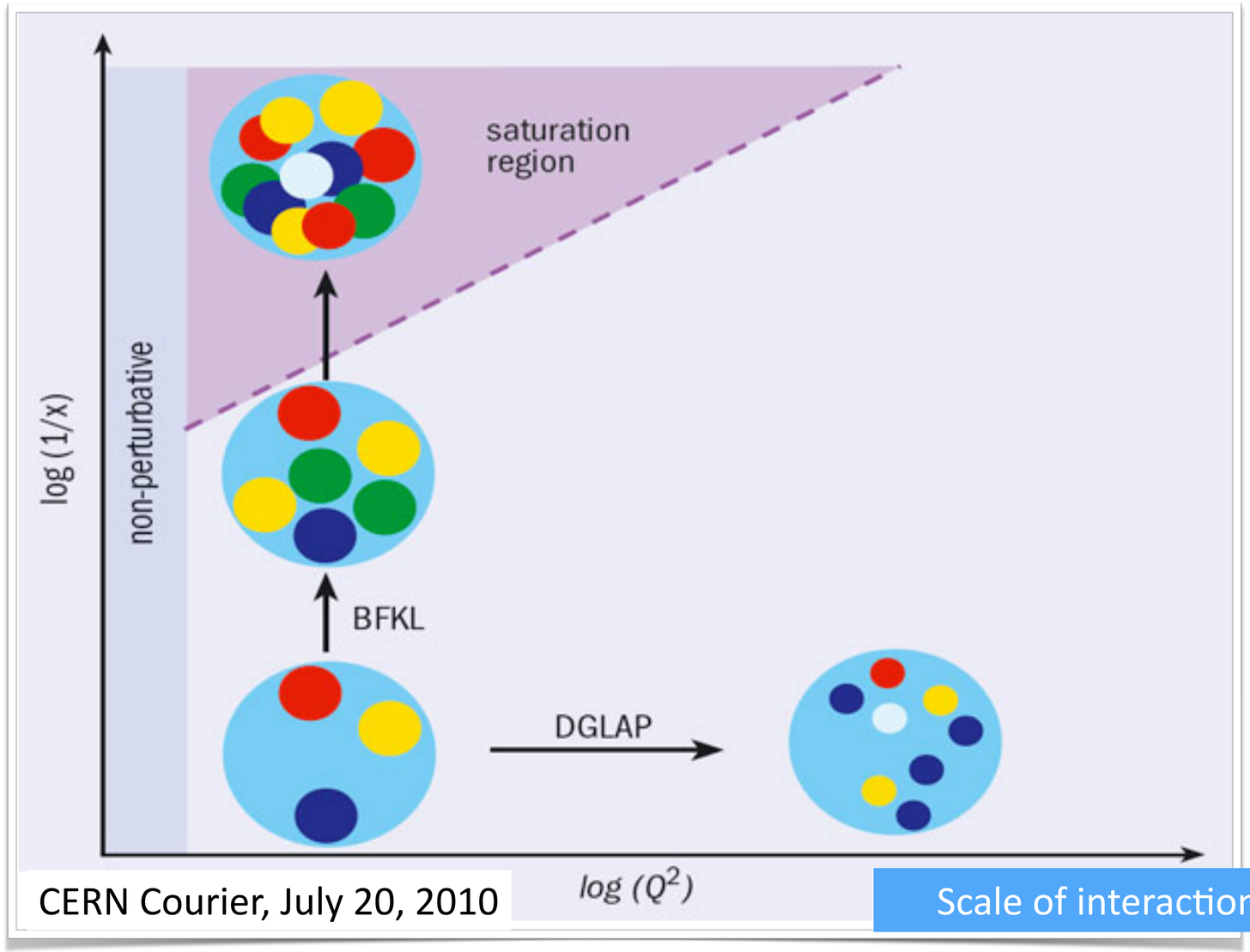
Selection of content based on:

- My ignorance of other topics.
- Not presented before in plenary talks in the few previous DIS meetings.
- Of potential interest to the DIS community.

Apologies to the many nice results that I do not cover.

The structure of nuclei at low x

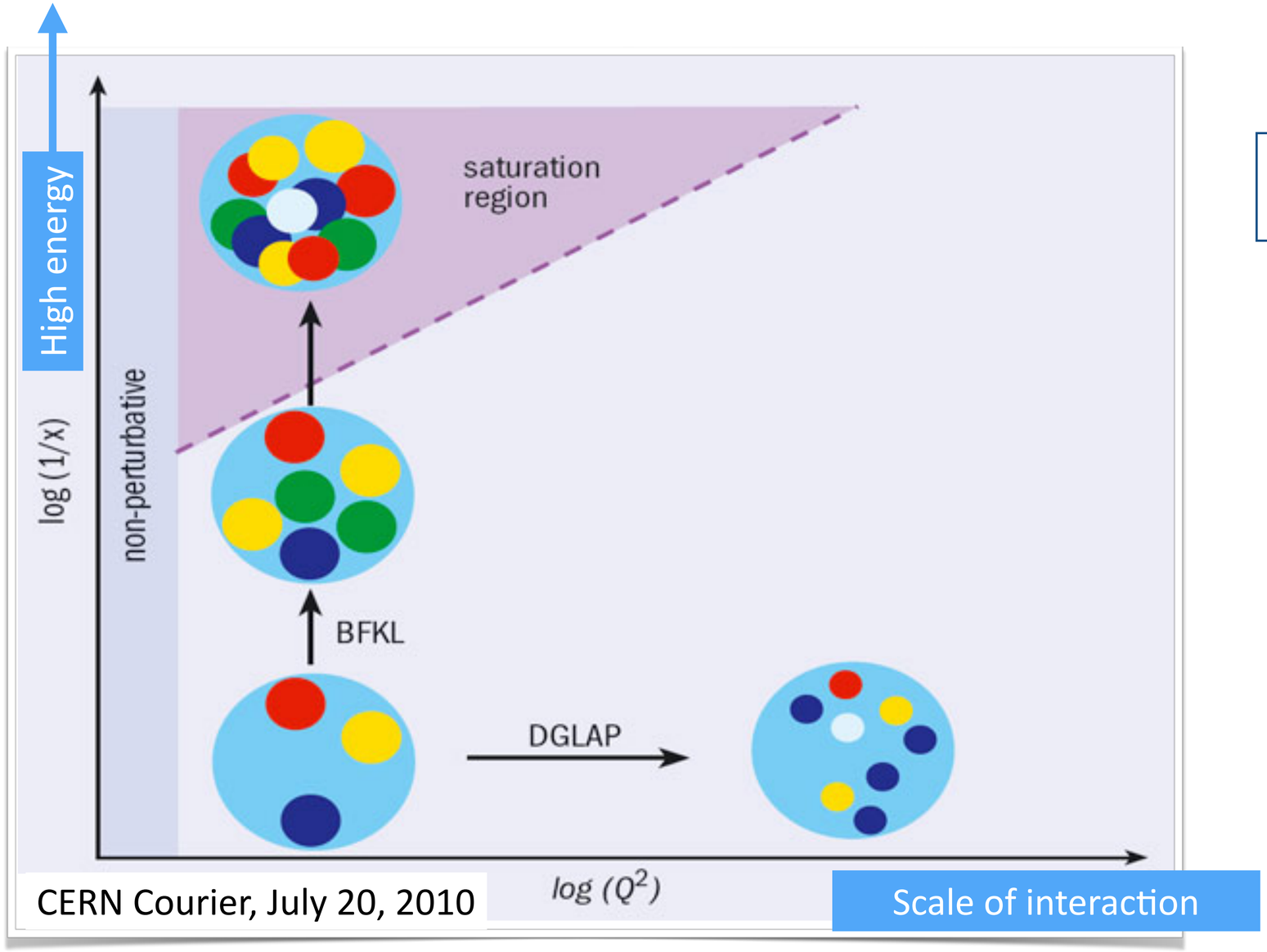
Low-x and the structure of hadrons



CERN Courier, July 20, 2010

Scale of interaction

Low-x and the structure of hadrons



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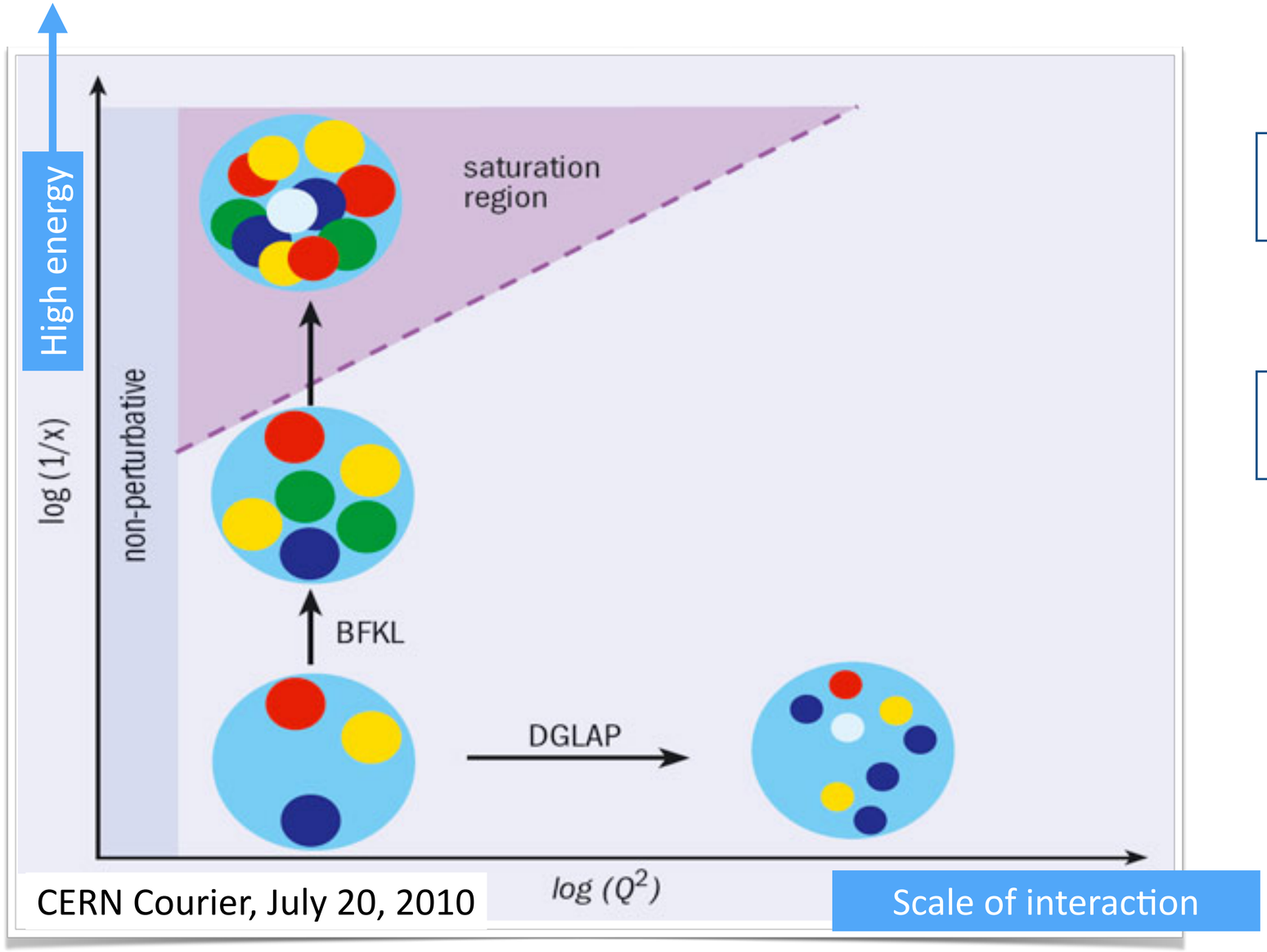
The high-energy limit of pQCD corresponds to the low x limit.

Low-x and the structure of hadrons



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In this limit, the structure of hadrons is expected to reach the saturation region.

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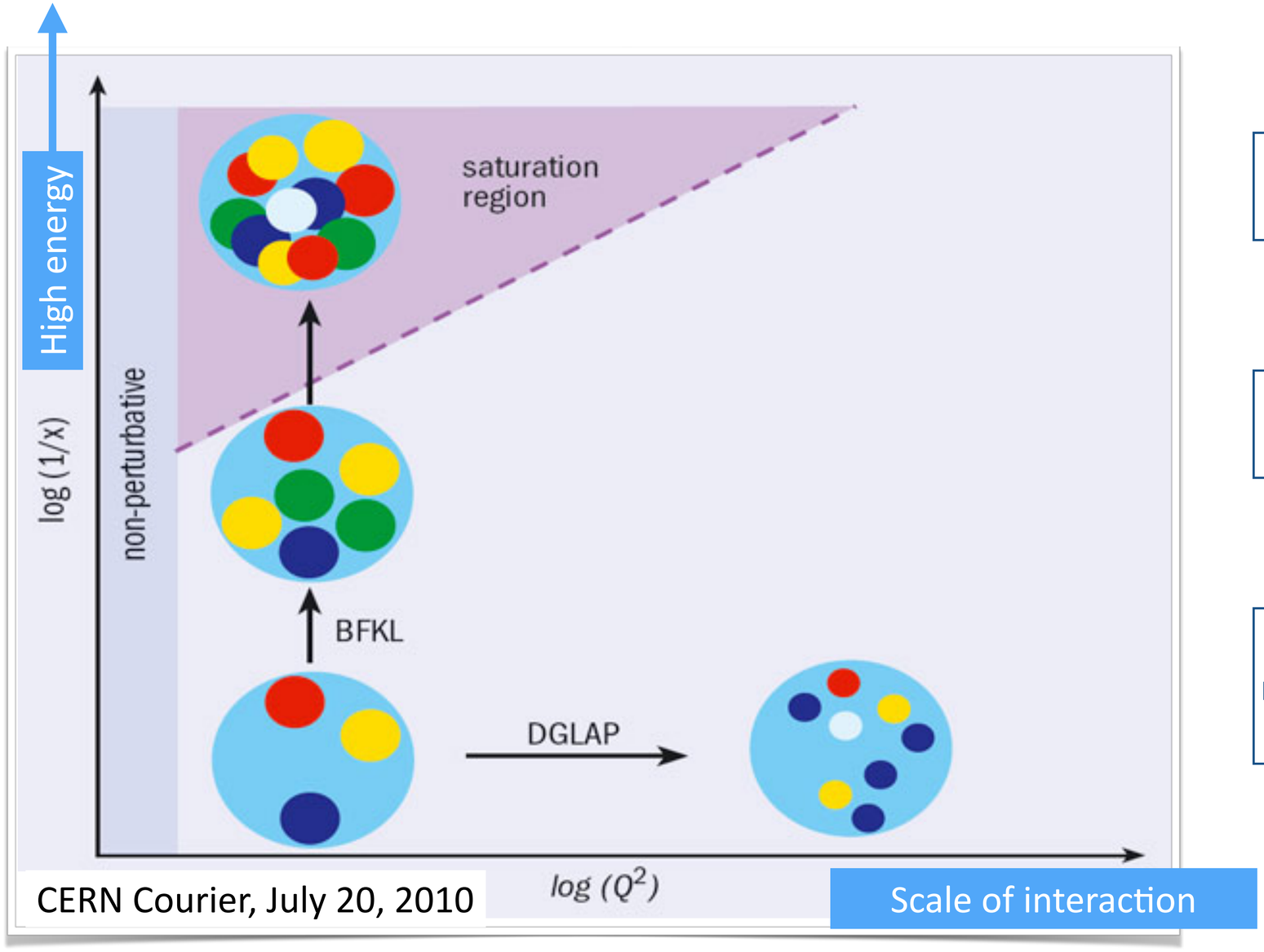

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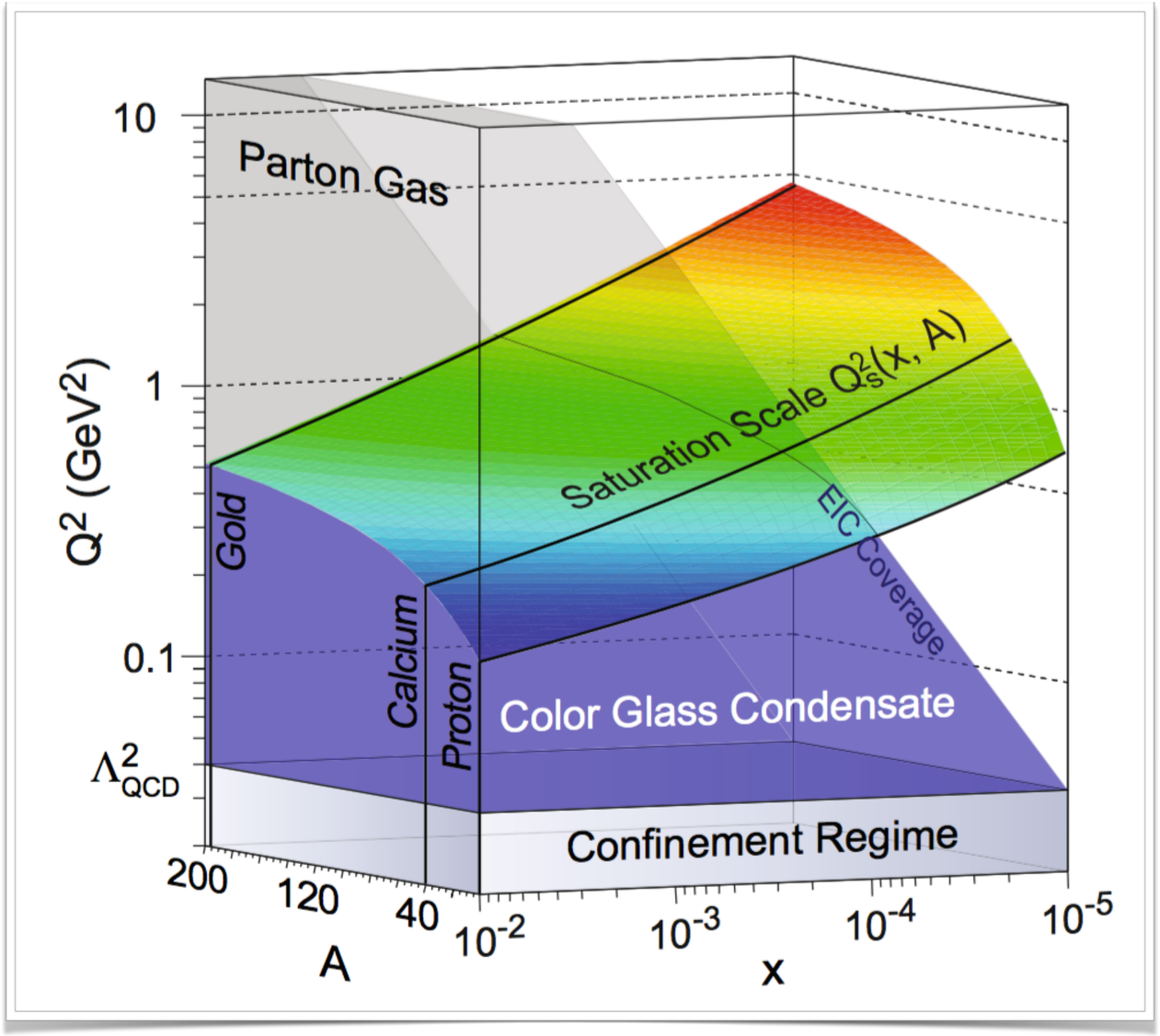
In this limit, the structure of hadrons is expected to reach the saturation region.

One of the most interesting questions nowadays in pQCD is the precise location of the saturation region.

Low x and nuclear targets

Accardi et al, EPJA 52 (2016) 268



The boundary between the dilute and saturated regimes is expected to appear at larger x in nuclei than in nucleons.

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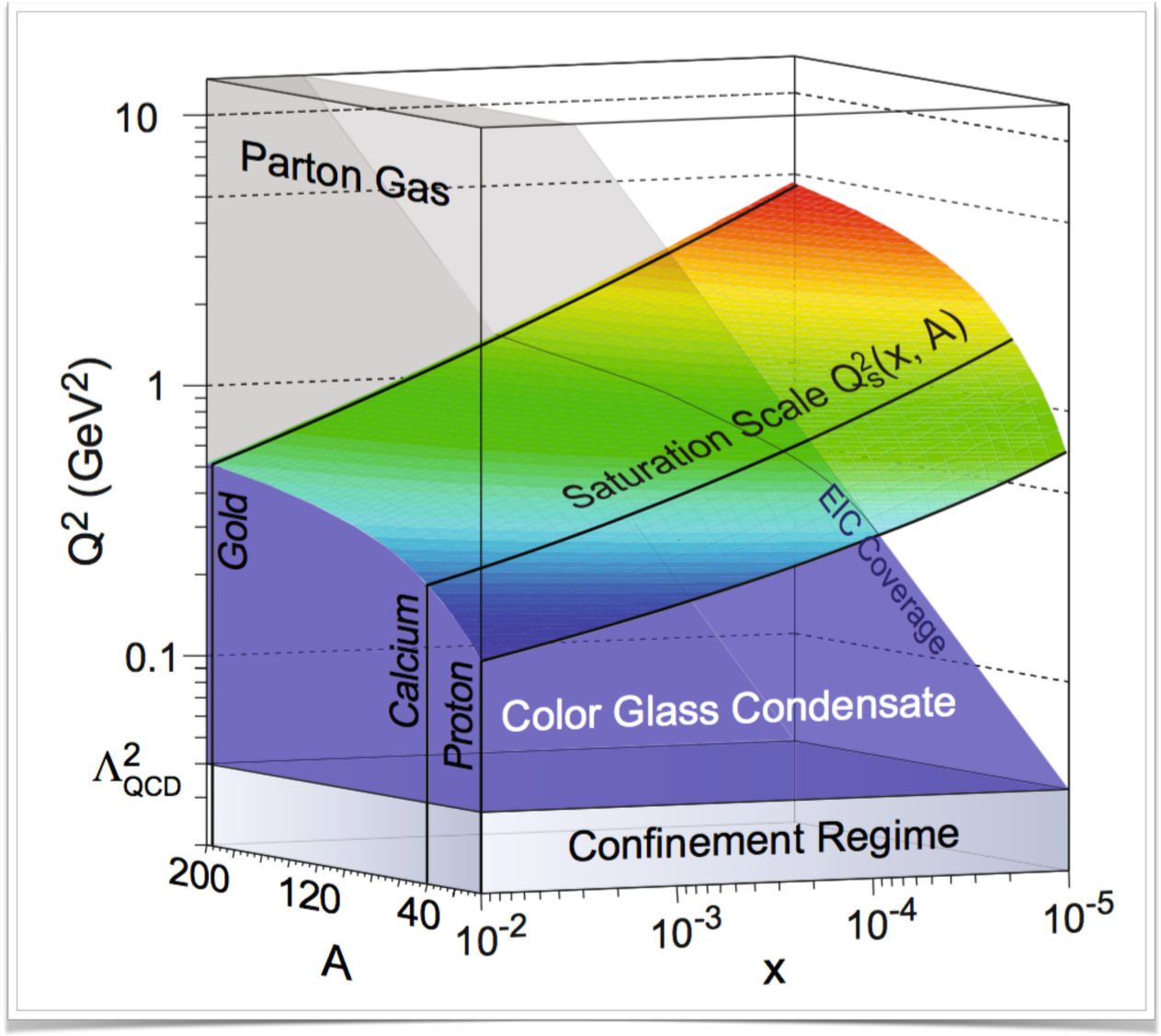

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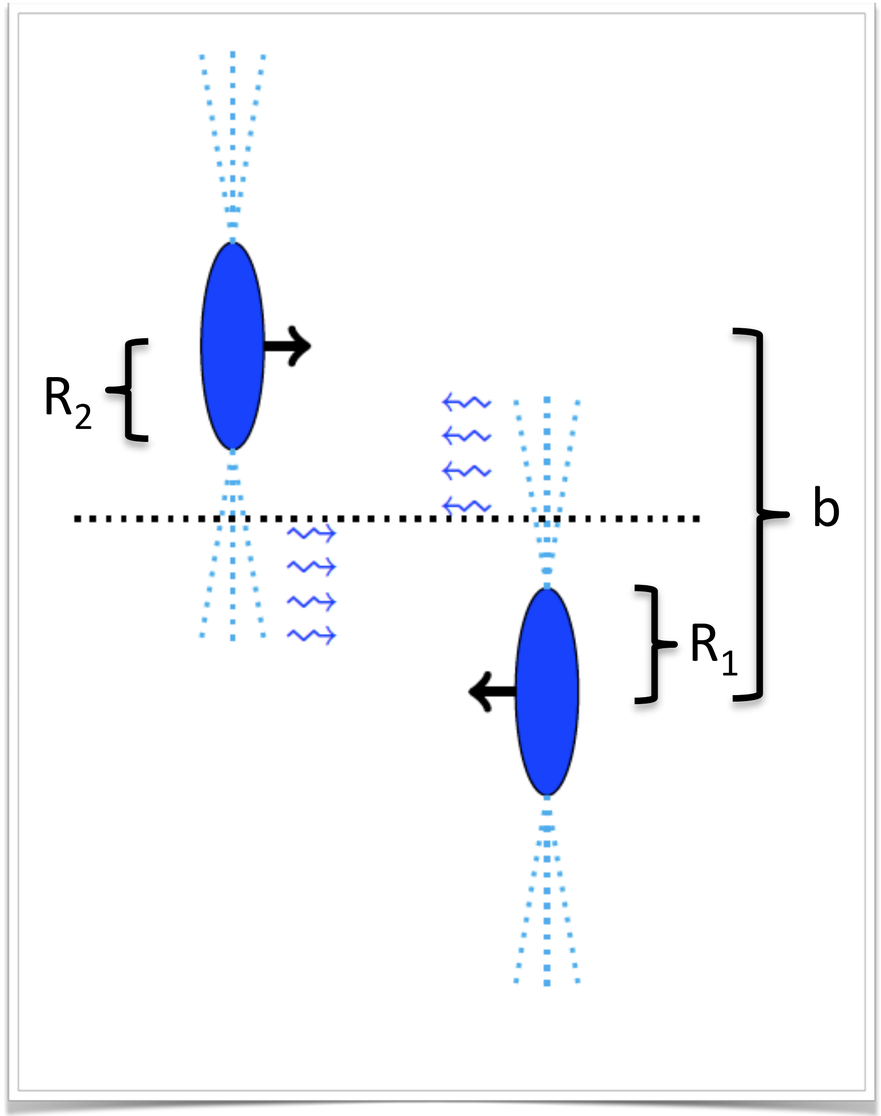
How can we study the evolution of the pQCD structure of nuclear targets?
Today: RHIC and LHC.
Tomorrow: EIC.

RHIC and LHC: our current photon-hadron colliders



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There are two potential sources, correspondingly two potential targets.

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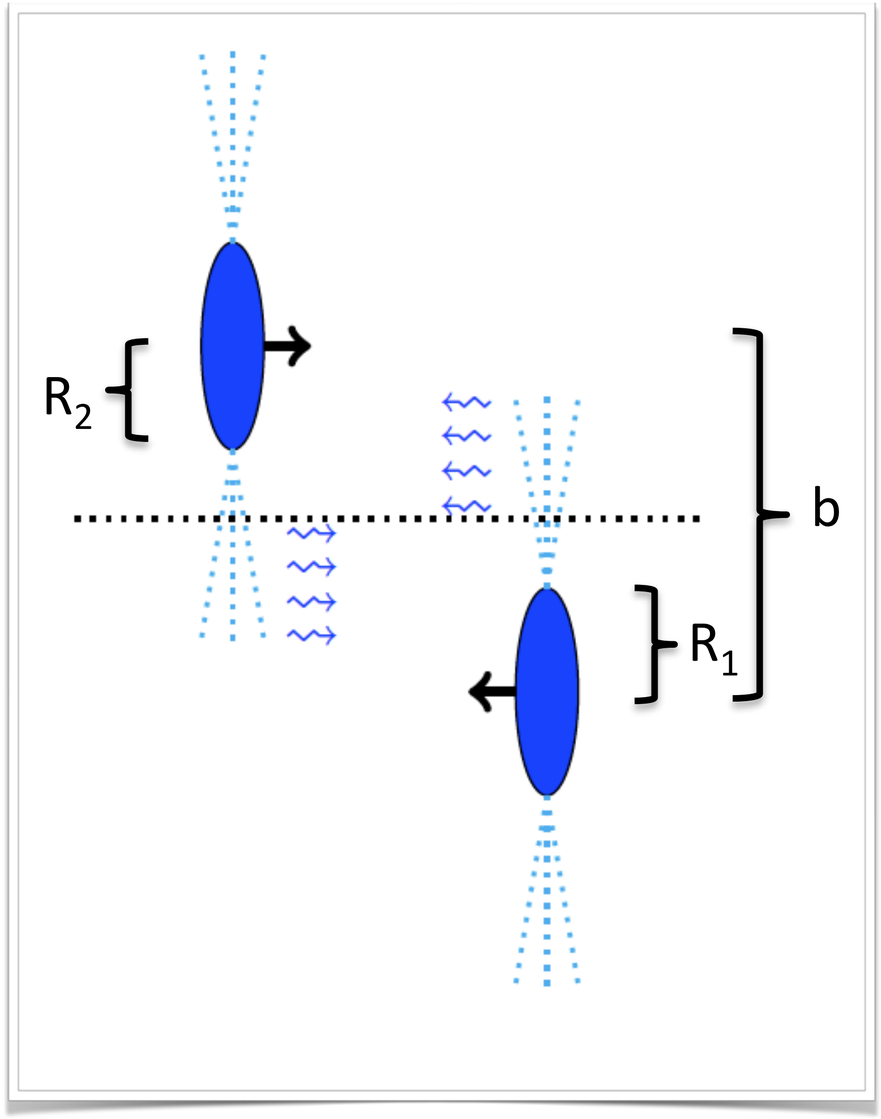

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The photons are coherently emitted by the source and its virtuality is restricted by the radius of the emitting particle:
Virtuality of photons from Pb: $Q^2 \approx (30\ \text{MeV})^2$.

The intensity of the photon beam is proportional to Z^2.
Heavy nuclei are intense sources of quasi-real photons!

The max energy of the photons in the lab system is determined by the boost of the emitting particle:
Large photon energies are possible at RHIC and at LHC!

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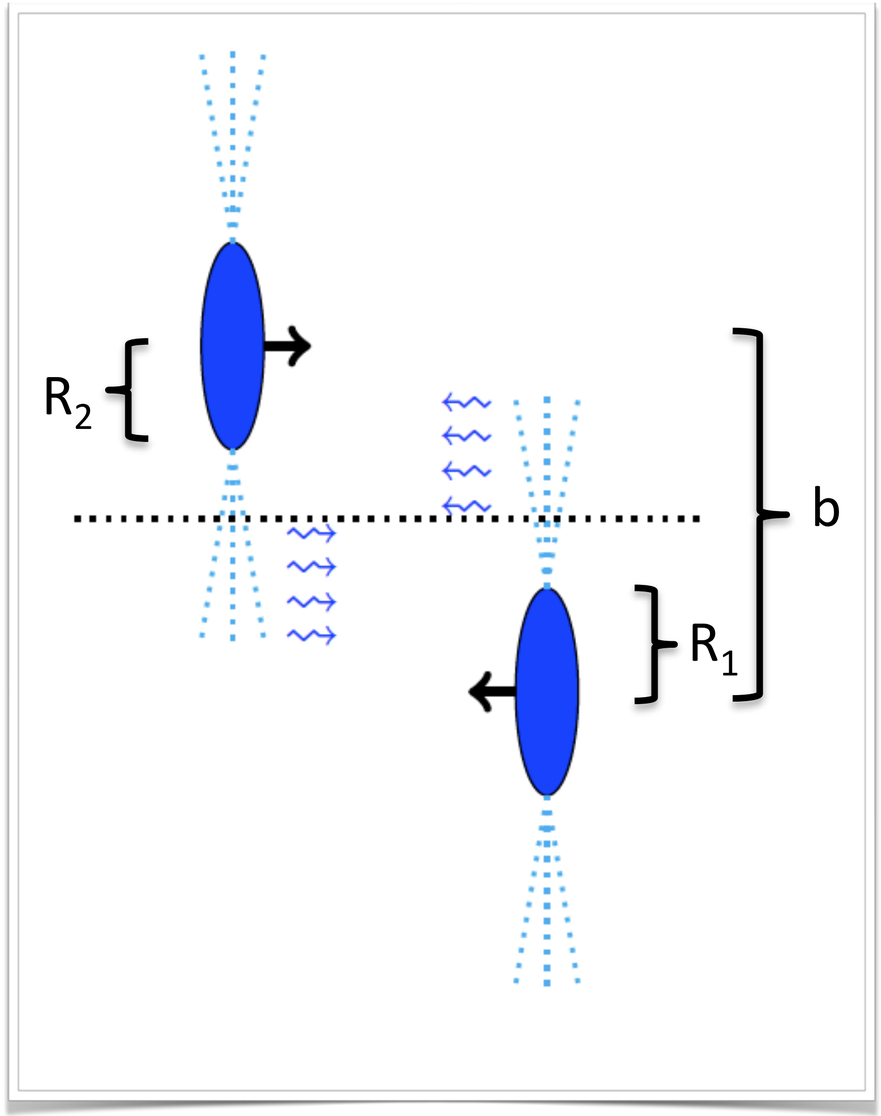

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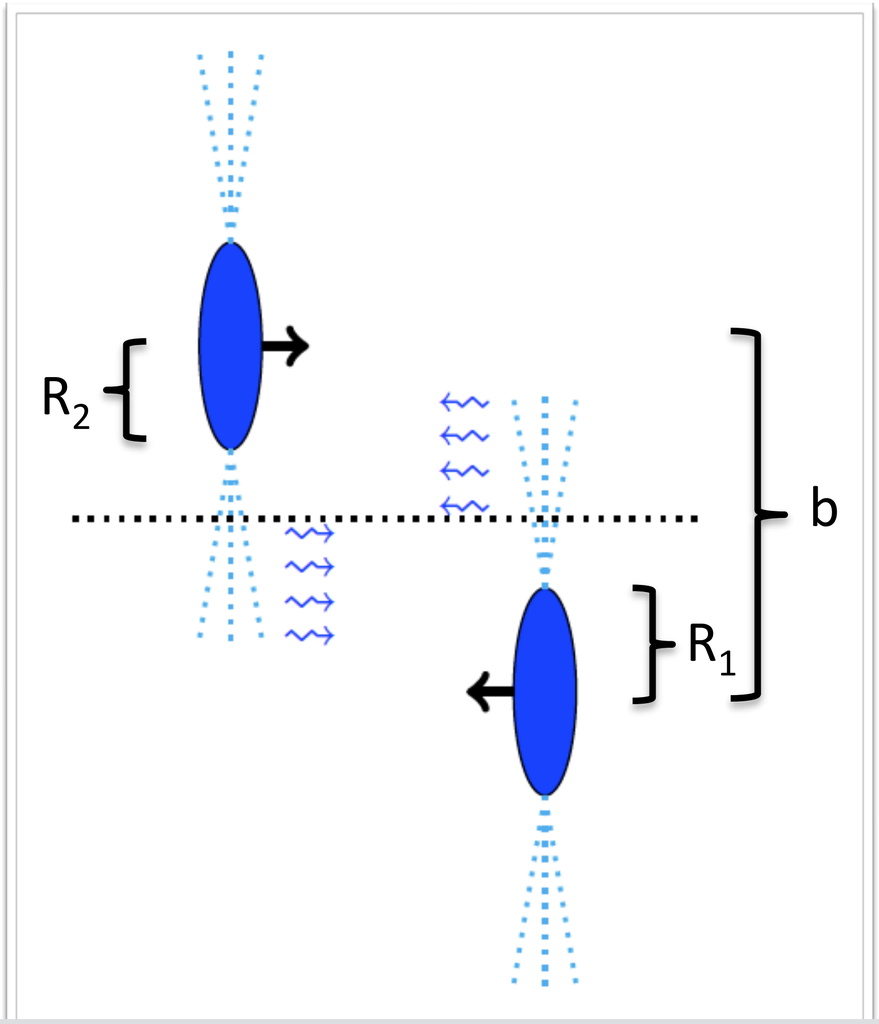

For $b>R_1+R_2$ only photon induced processes remain.
These are called ultra-peripheral collisions (UPC).

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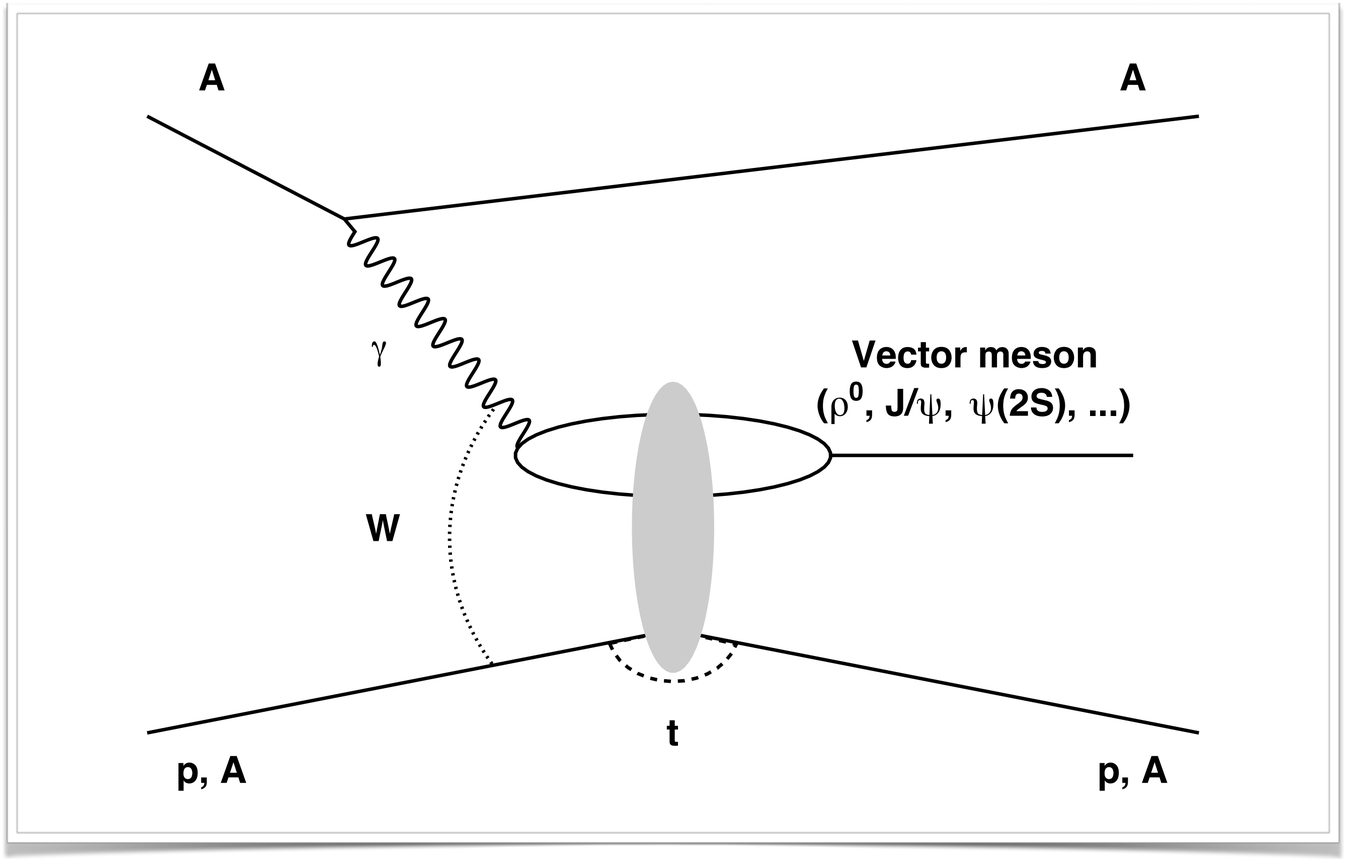
Exclusive photoproduction of vector mesons

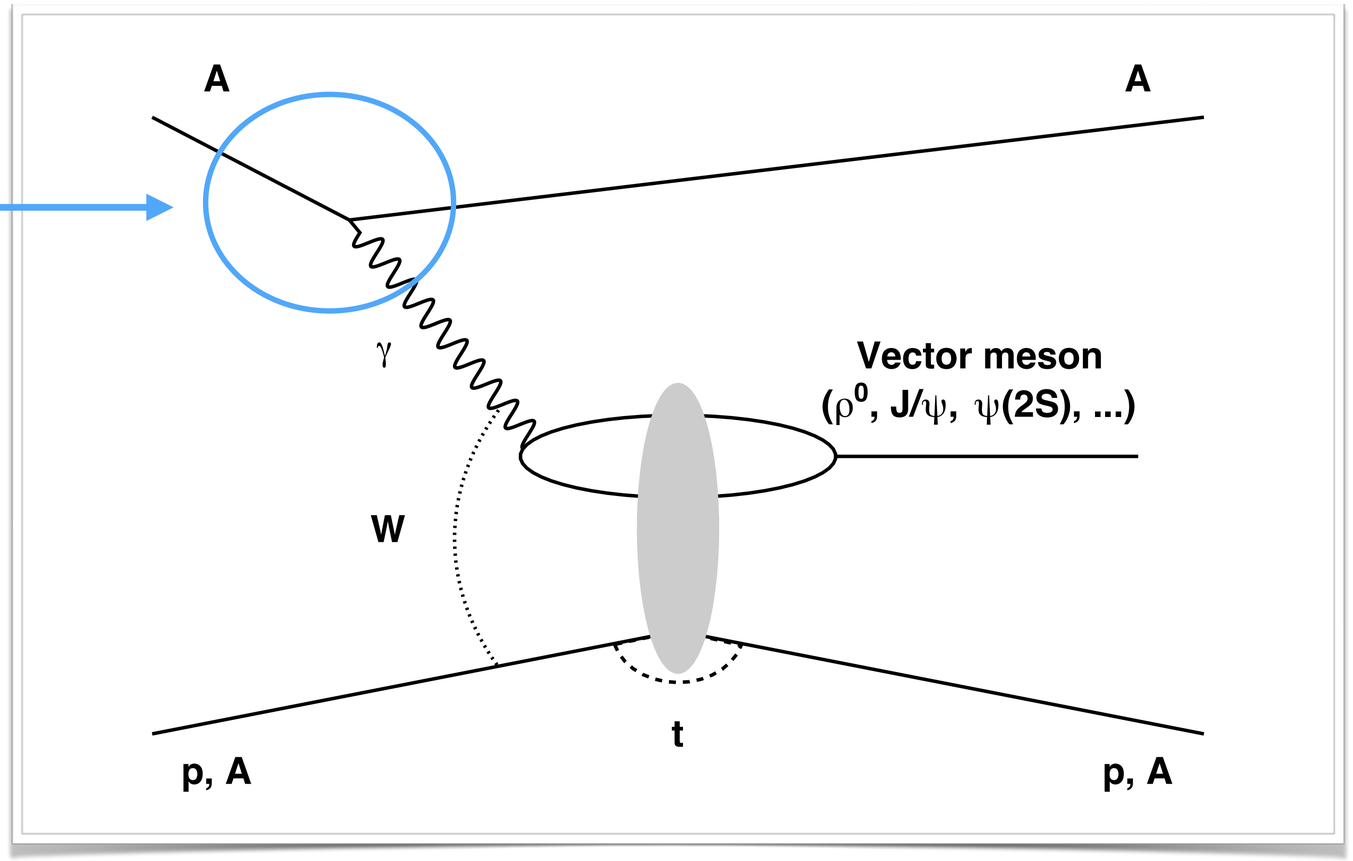


Exclusive photoproduction of vector mesons

The process can be factorised in two parts:

- Emission of the photon.

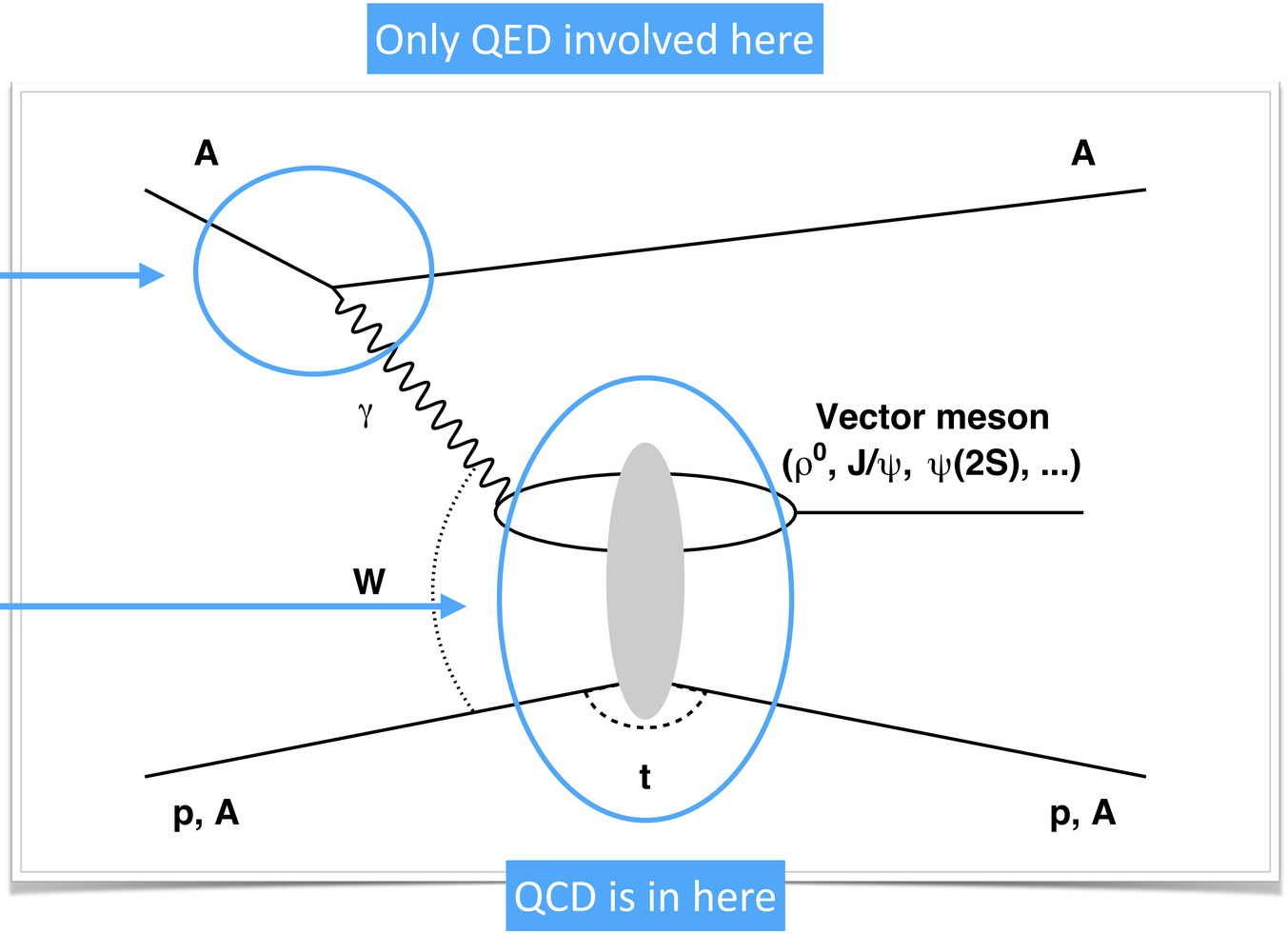
Only QED involved here



Exclusive photoproduction of vector mesons

The process can be factorised in two parts:

- Emission of the photon.
- Interaction of the photon with the target.



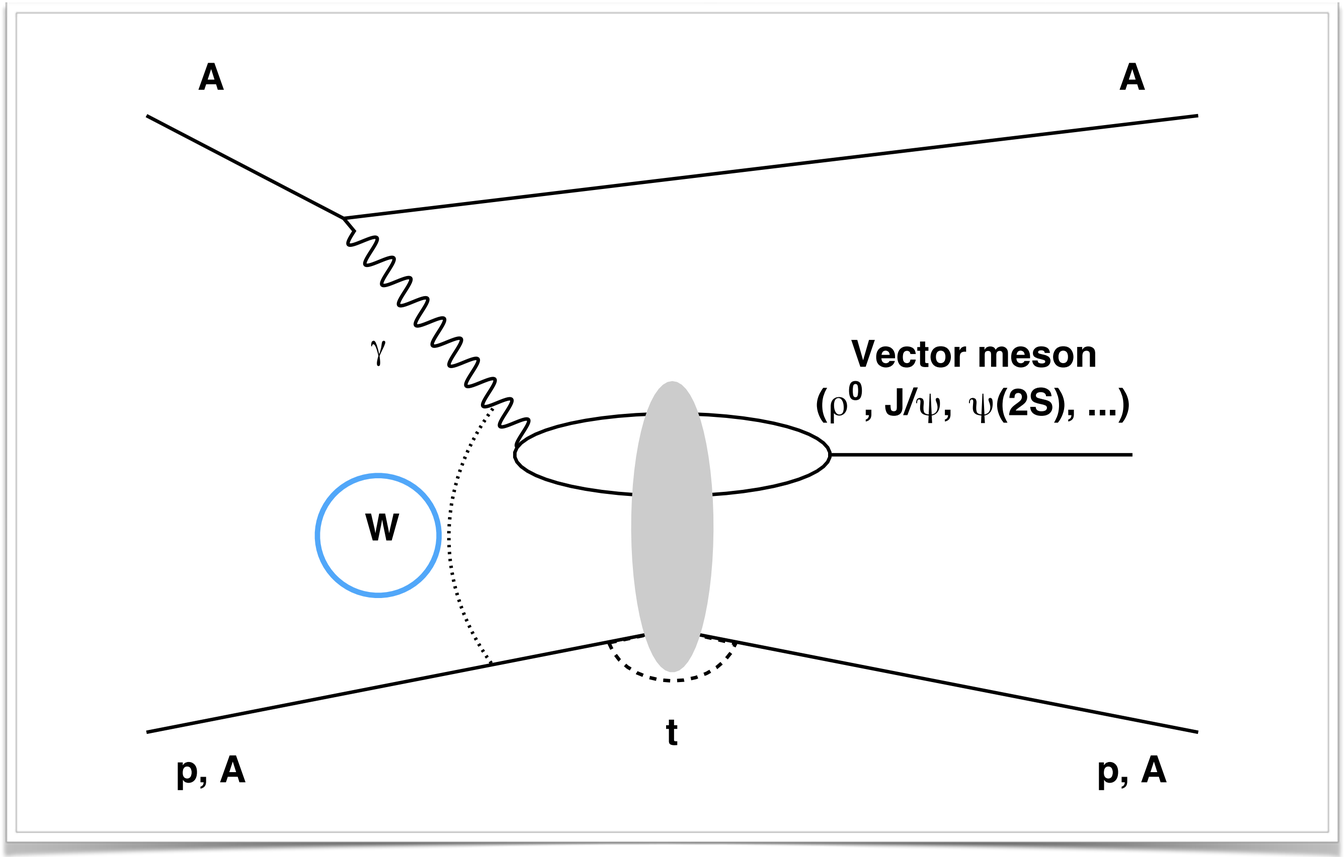
Kinematics: energy and rapidity

Centre-of-mass energy of the photon-target system:

$$W = \sqrt{2\omega 2E_{\text{beam}}}$$

where

- E_{beam} is the energy of the incoming beam and
- ω is the photon energy.



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$$2\omega = M\exp(-y)$$

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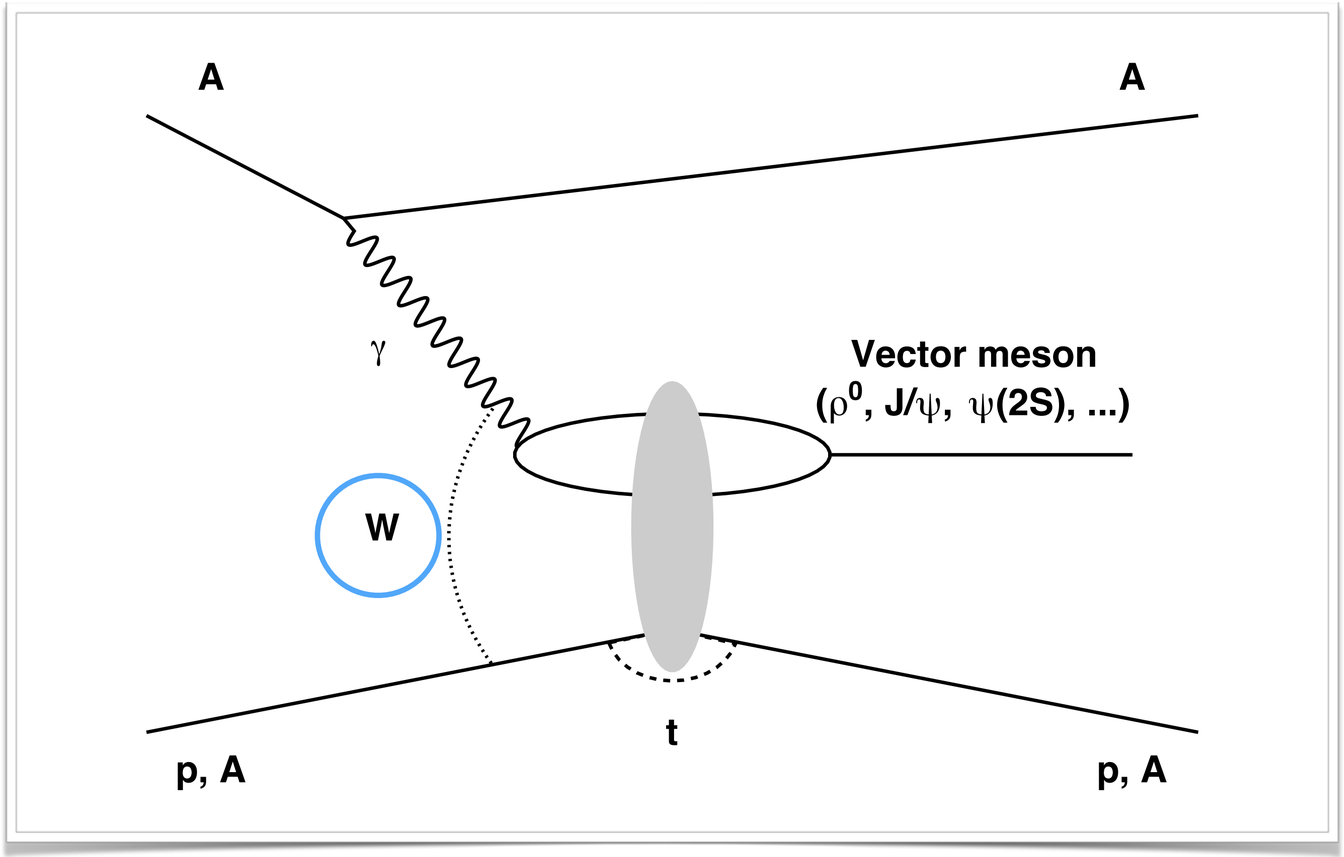
- y is the rapidity of the vector meson measured in the laboratory frame **with respect to the direction of the target** and
- M is the mass of the vector meson.



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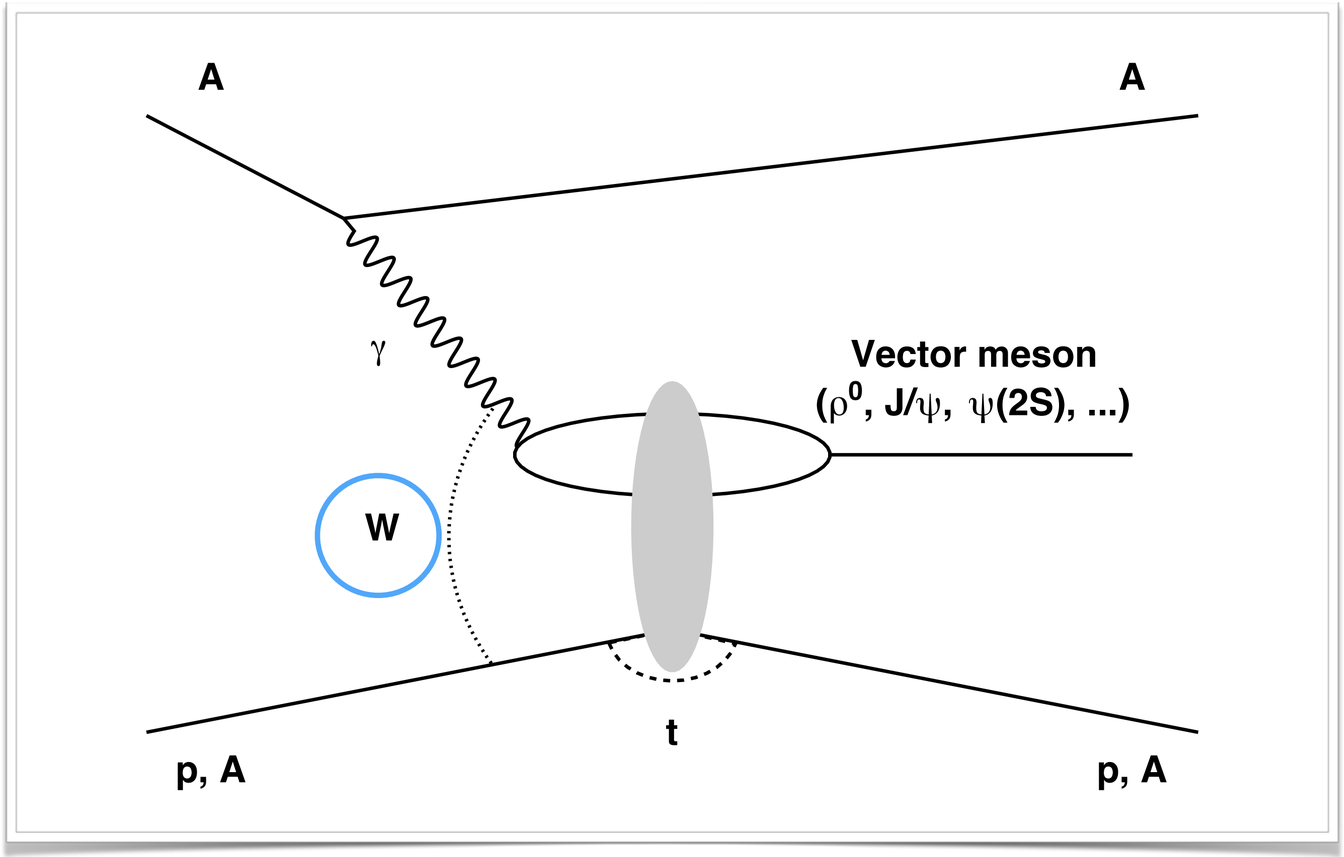
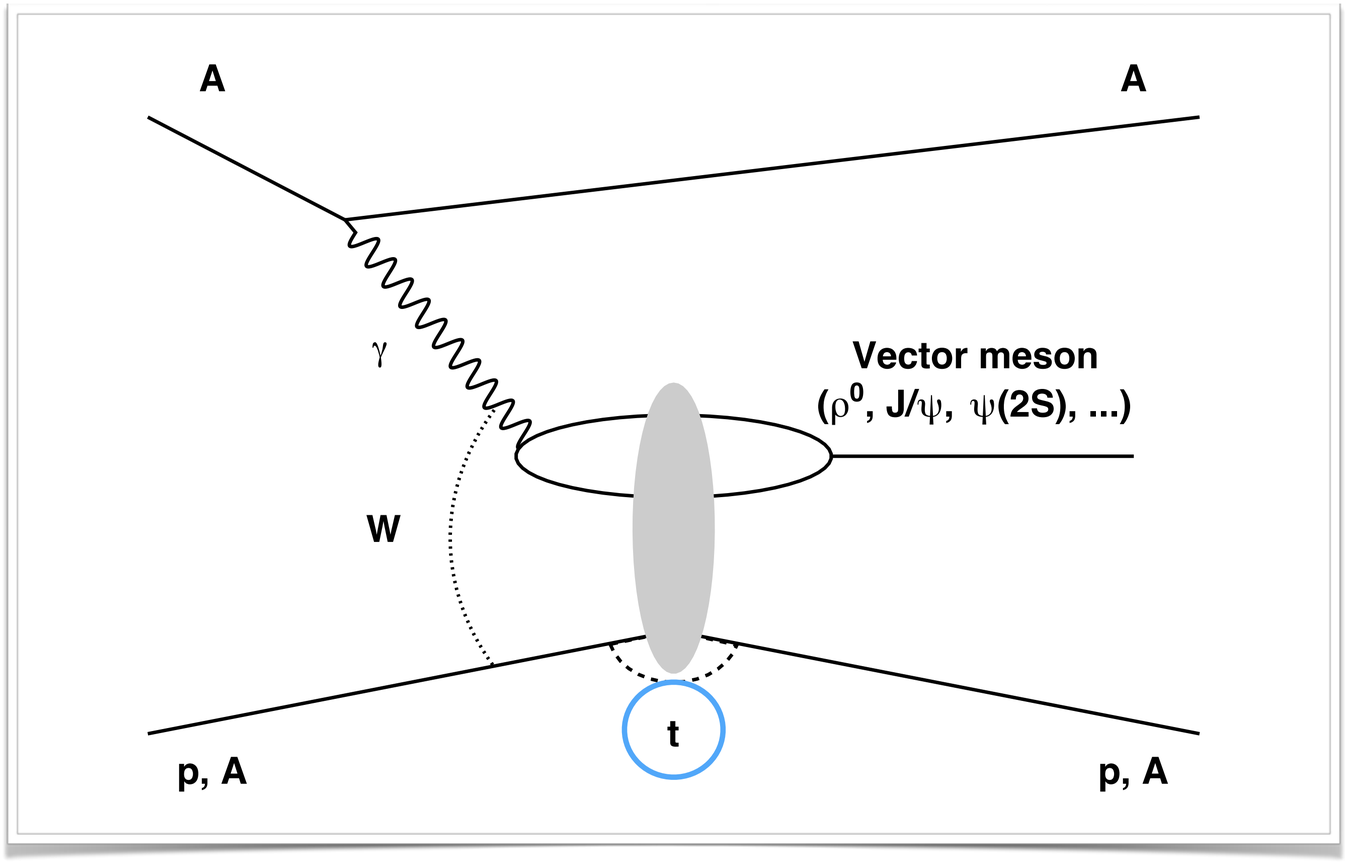


The rapidity of the vector meson determines the centre-of-mass energy of the photon-target interaction

Kinematics: transverse momentum

The square of the momentum transferred in the proton vertex -t is related to the transverse momentum of the J/ψ:

$$-t \approx p_{\perp}^{2}$$



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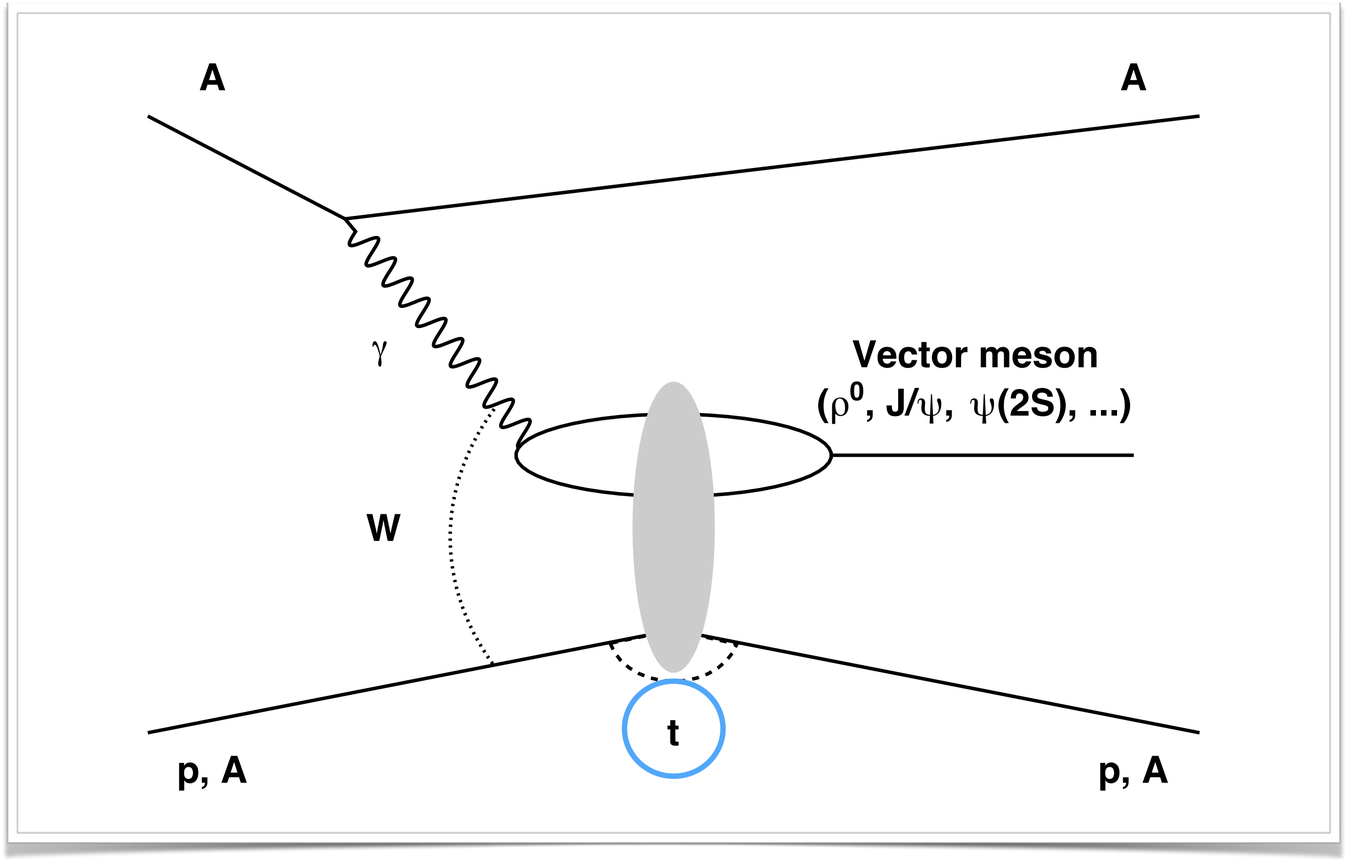
The -t distribution is determined by the **nuclear form factor**, which gives, through a Fourier transform, the distribution of of gluons, in the transverse plane.



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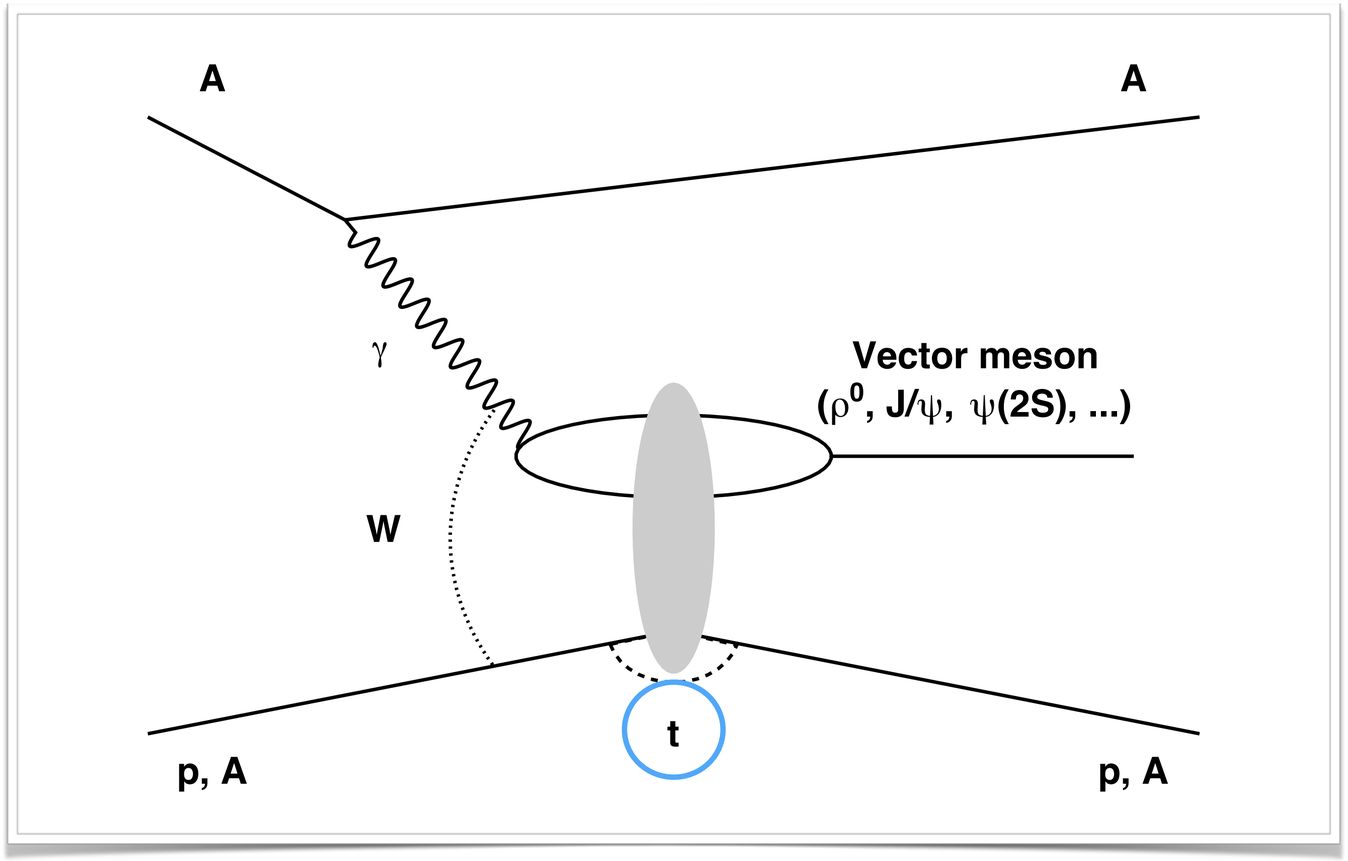
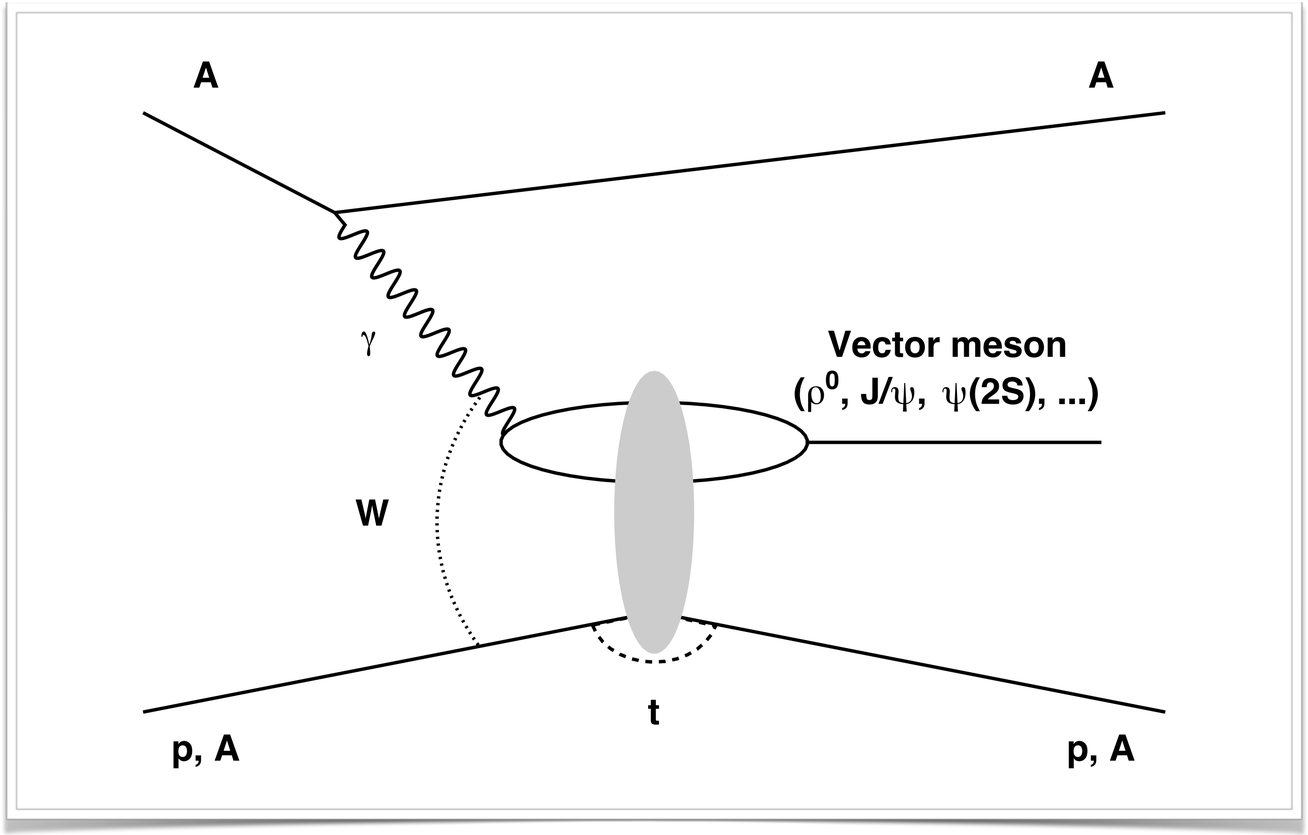


The -t dependence of vector meson production determines the transverse distribution of matter in the target!

Exclusive photoproduction of vector mesons: experimental point of view



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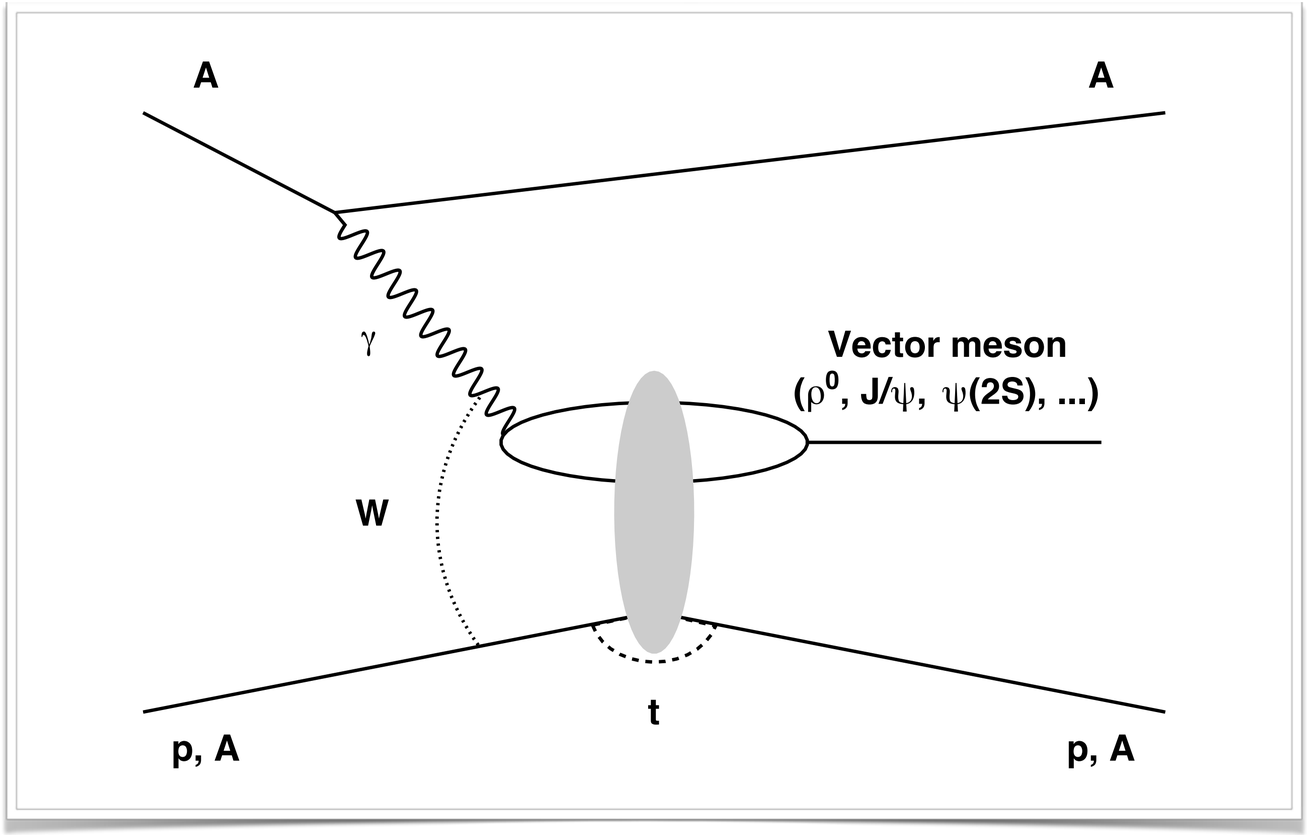

Very clean experimental signature:

- Vector mesons with low transverse momentum.
  (Few tens of MeV/c for nuclear targets.)
- Nothing else in the detector.
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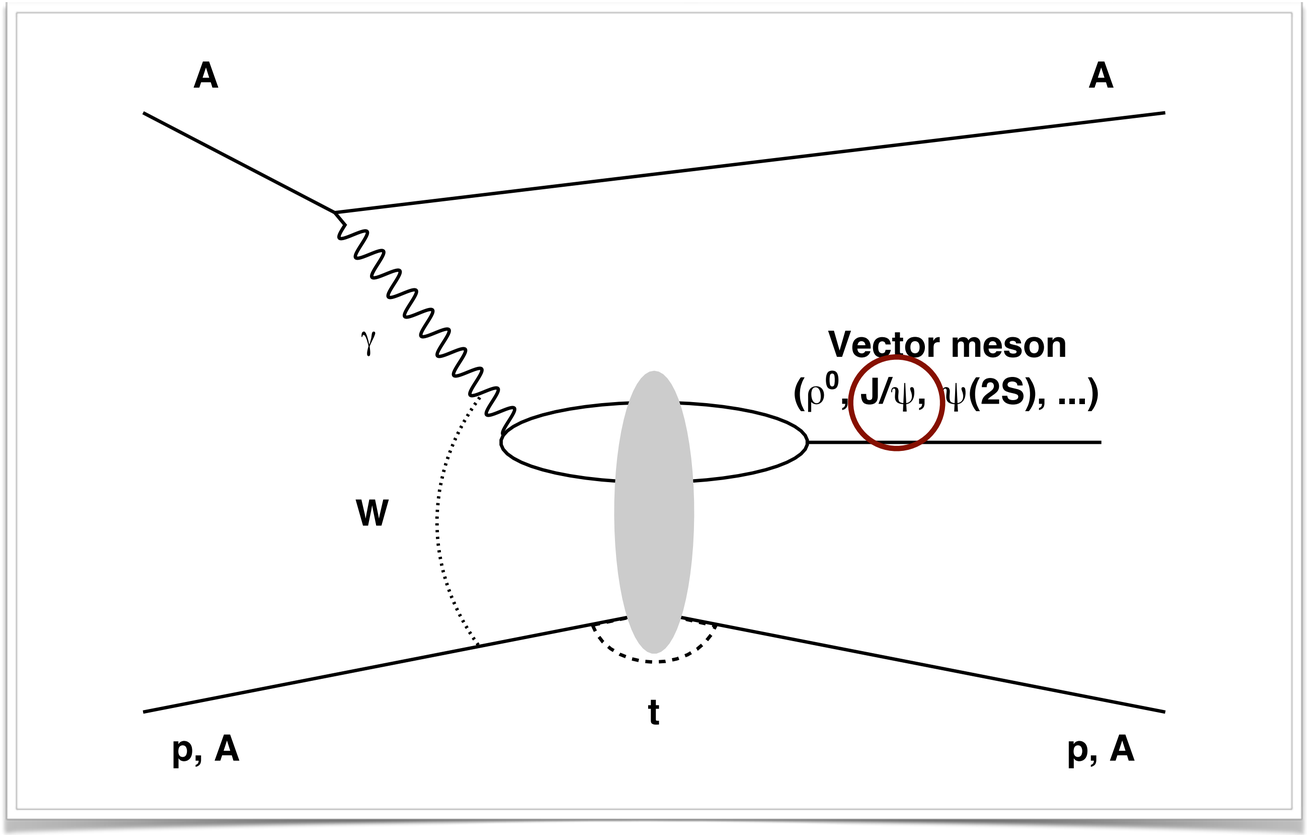

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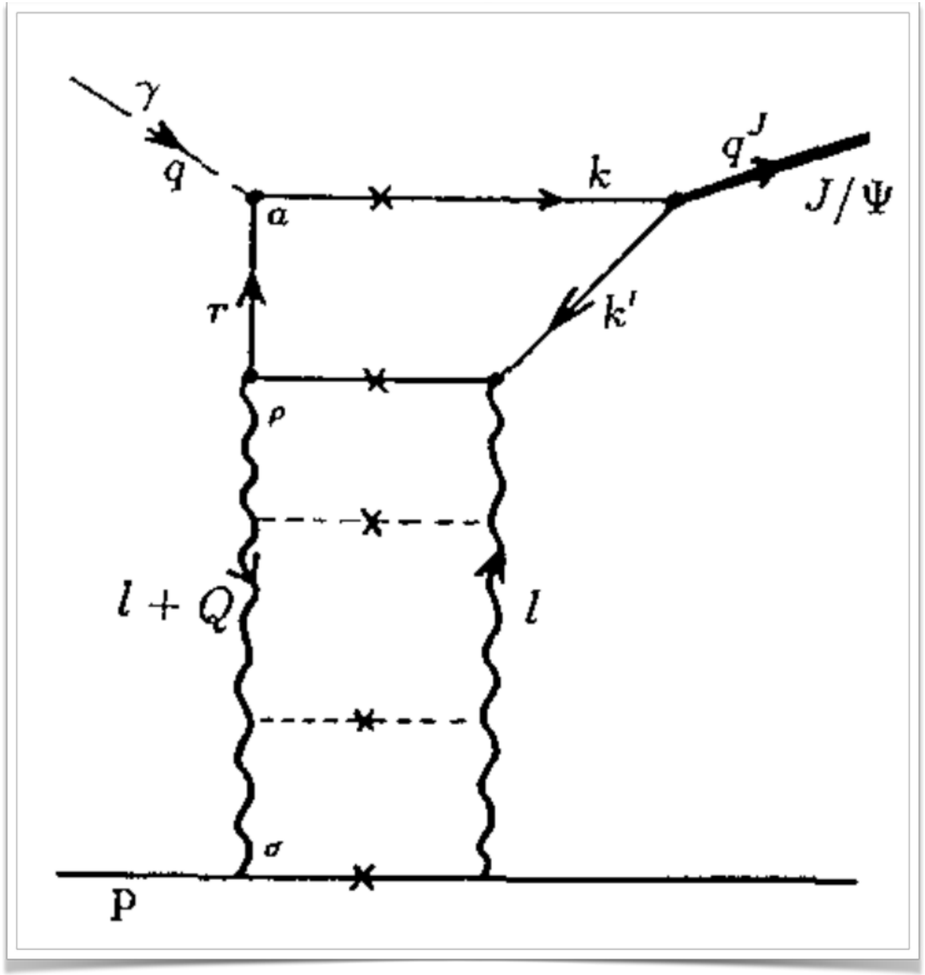
J/ψ

- Small width and leptonic decays with a large BR.
- Large mass of the charm quark allows for pQCD.

Exclusive photoproduction of vector mesons: pQCD point of view

Ryskin: Z. Phys. C 57, 89-92 (1993)



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

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

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

Cross section depends on the square of the gluon distribution
(Amplitude computed in the leading-log approximation of pQCD.)

The amplitude in the dipole picture

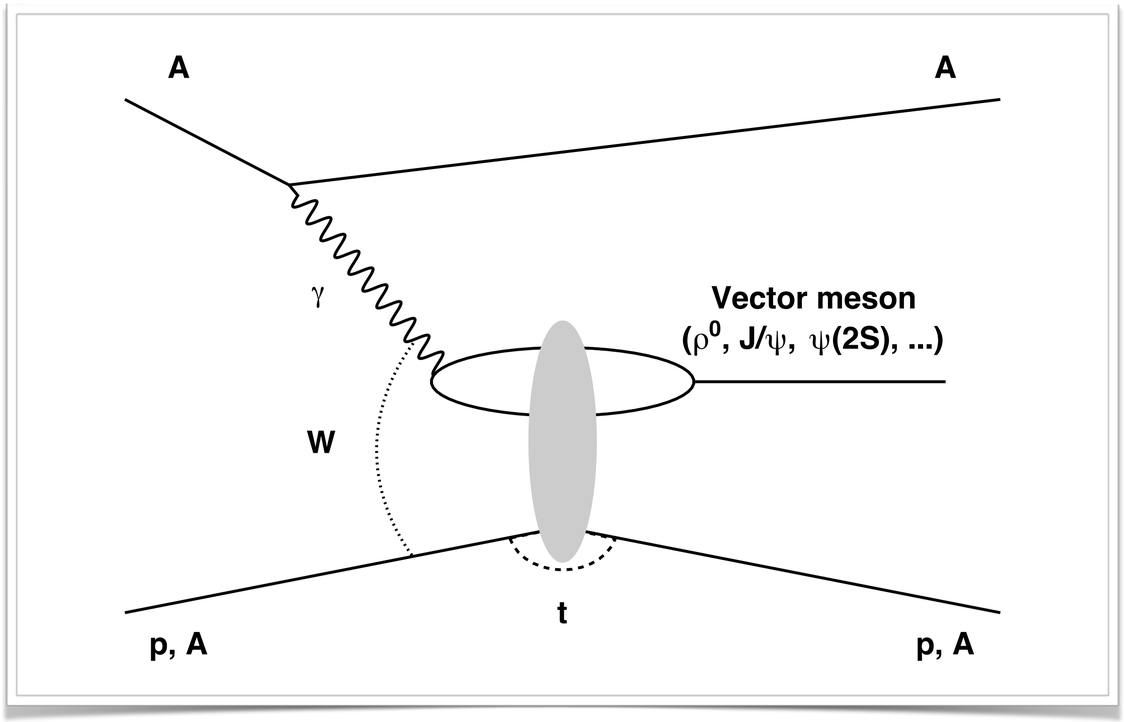
Δ^2=-t

Dipole size

Quark energy fraction

Impact parameter

$$A(x,Q^2,\vec{\Delta})_{T,L} = i\int d\vec{r}\int_0^1 \frac{dz}{4\pi}(\Psi^*\Psi_{\rm V})_{T,L}\int d\vec{b}\, e^{-i(\vec{b}-(1-z)\vec{r})\cdot\vec{\Delta}}\frac{d\sigma_{\rm dip}}{d\vec{b}}$$



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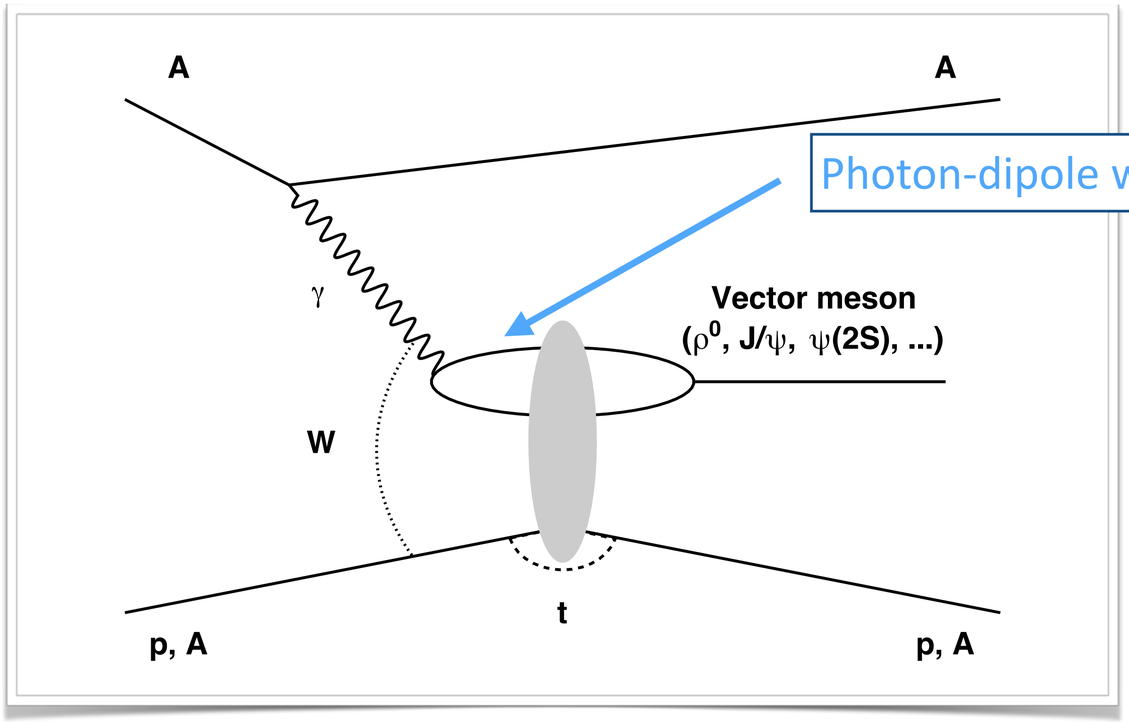
Photon-dipole wave function



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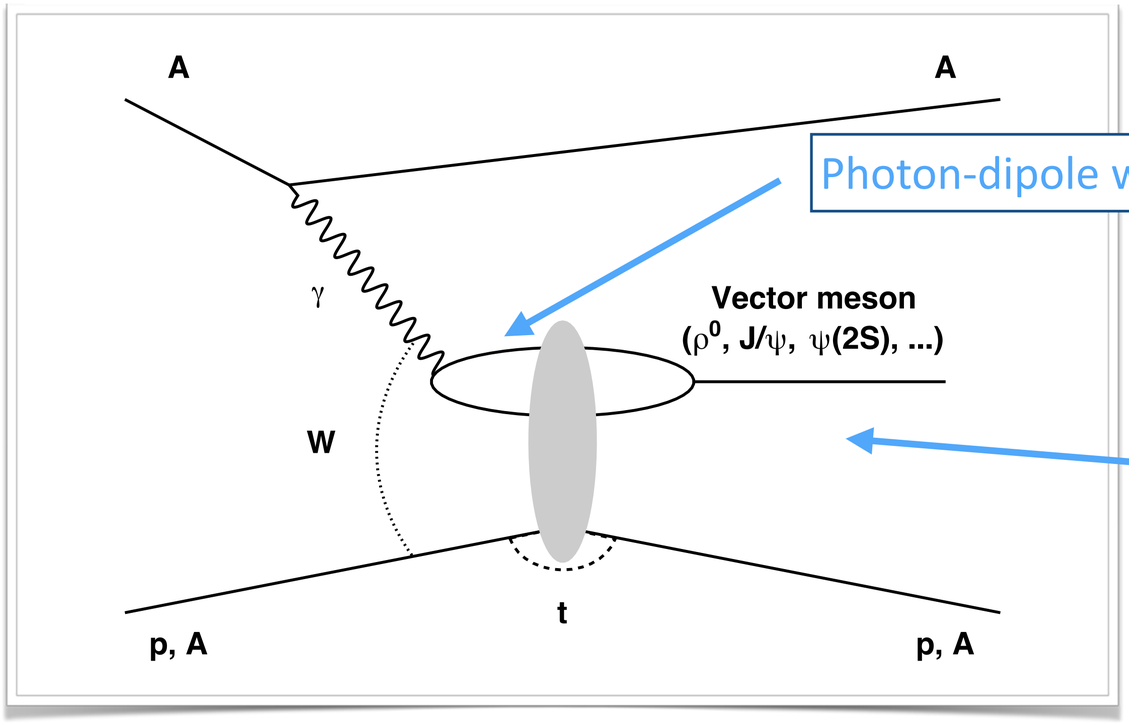

Photon-dipole wave function

Vector meson wave function

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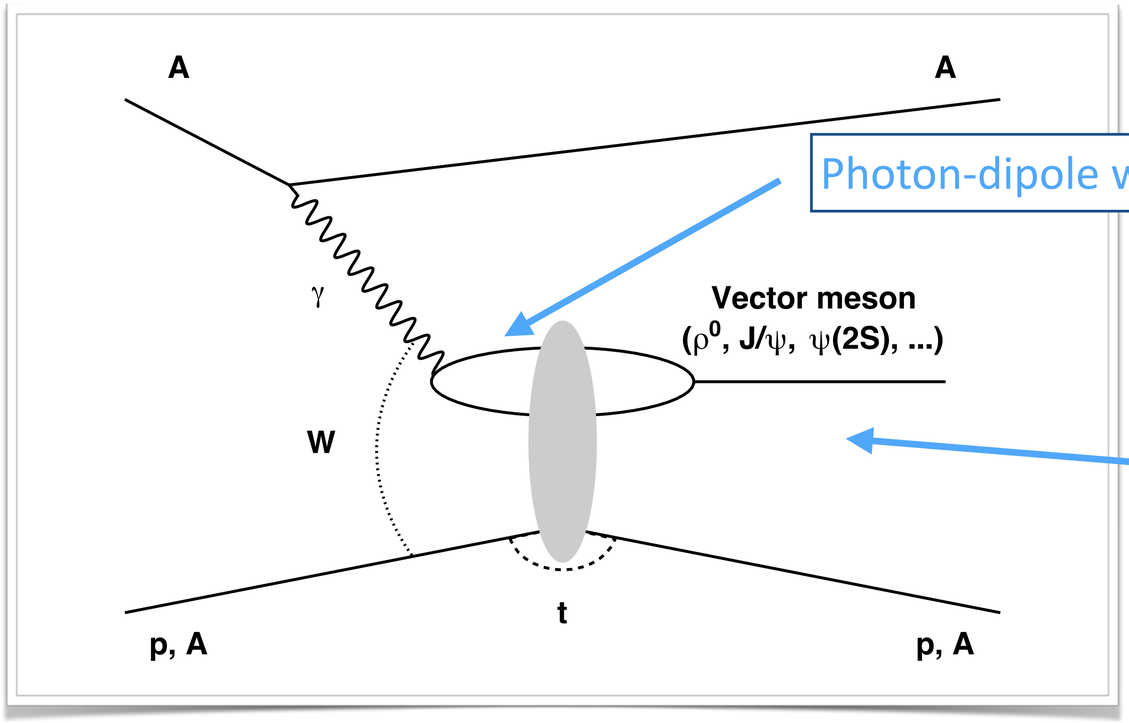

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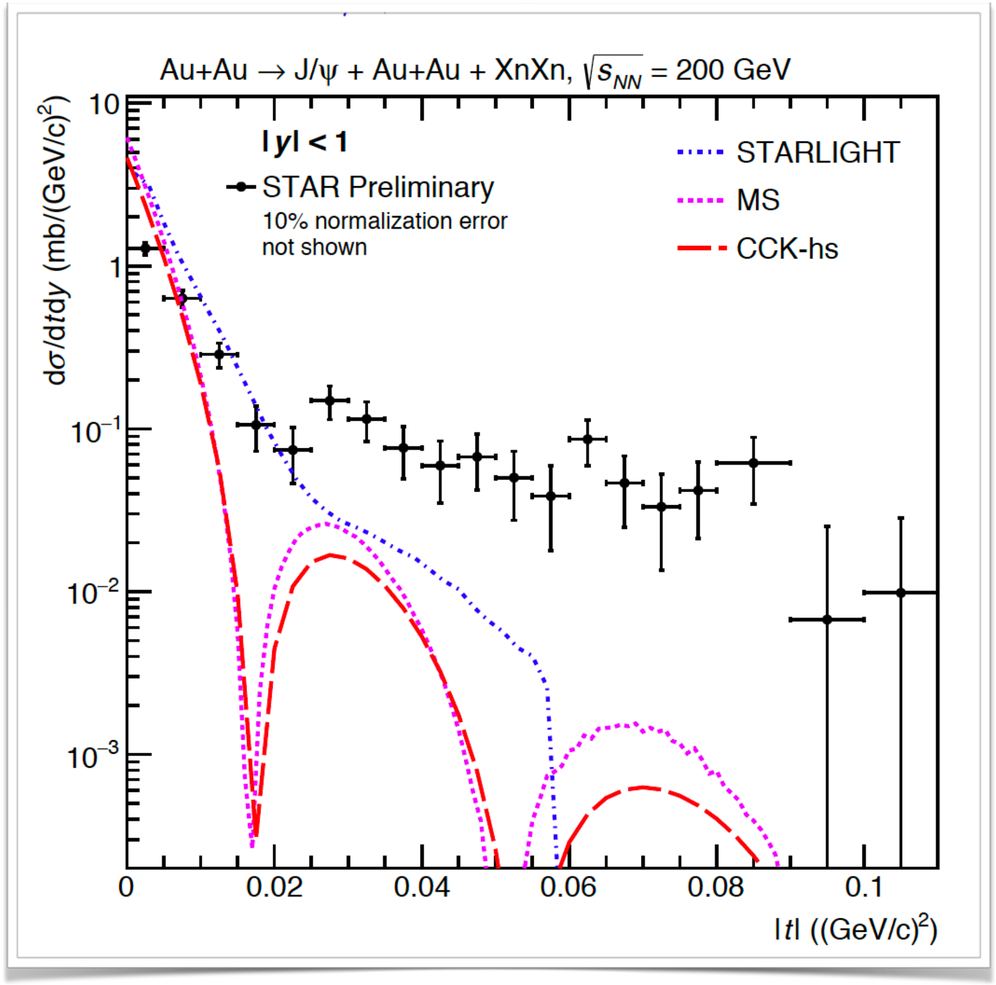
Dipole-Target cross section
pQCD physics gets here!

News from RHIC: coherent J/ψ photoproduction in UPC



Data from Au-Au UPC @ 200 GeV.

Measurement at mid-rapidity:
$W_{\gamma Au} \approx 25$ GeV.

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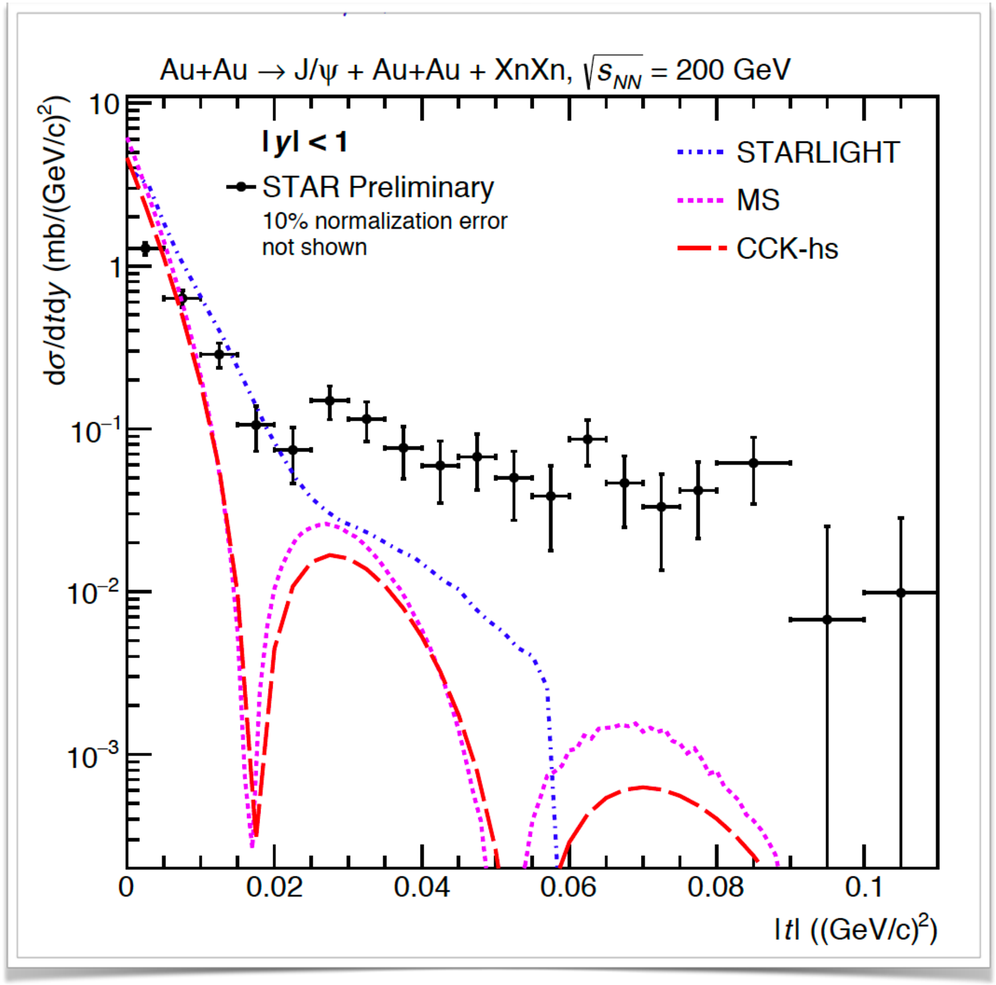

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MS: color dipole model + IPsat.
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Slope milder than dipole-based models
A hint of diffraction minimum.

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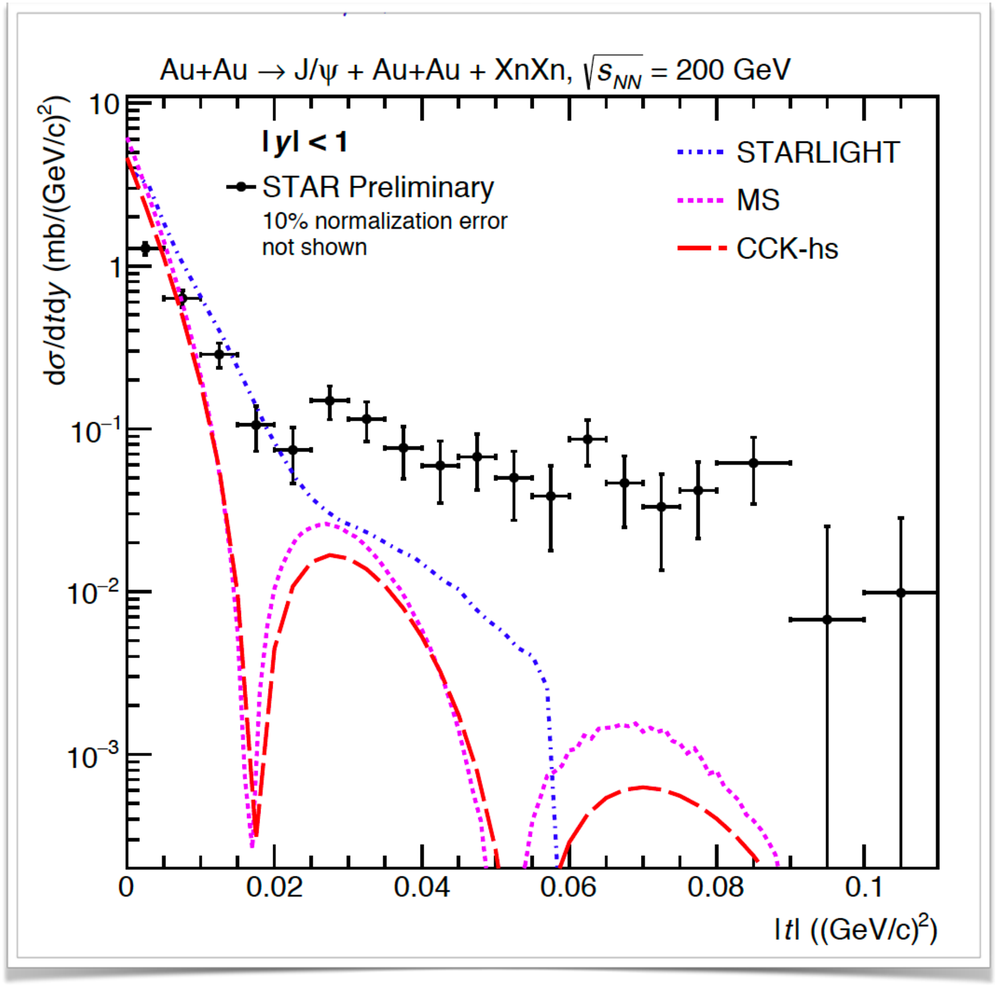

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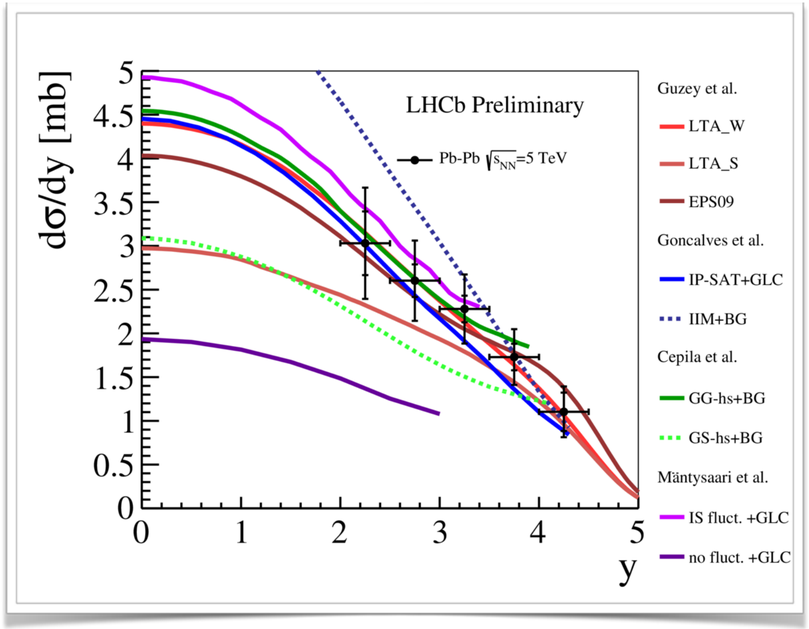
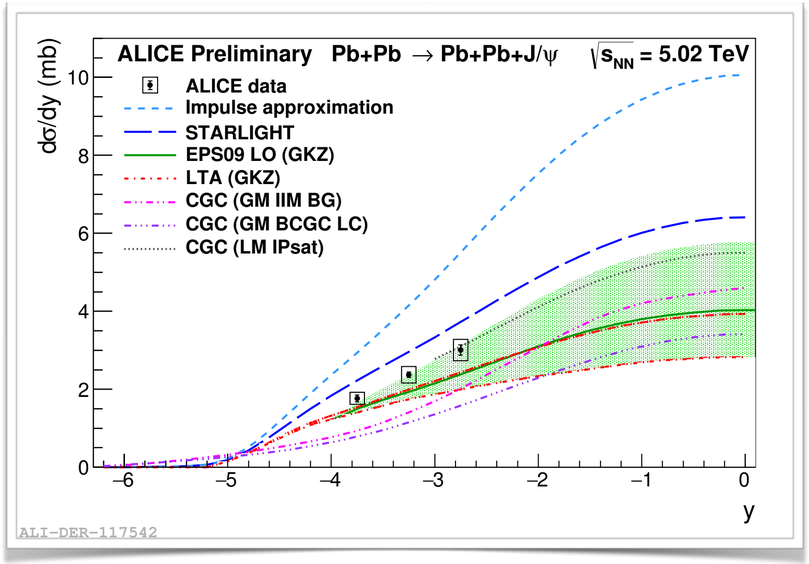
Wednesday in the WG2 session

Coherent J/ψ photoproduction in ultra-peripheral collisions at STAR, Jaroslav Adam.

News from the LHC: coherent J/ψ photoproduction in UPC





Data from Pb-Pb UPC @ 5020 GeV
Measurements by LHCb and ALICE.

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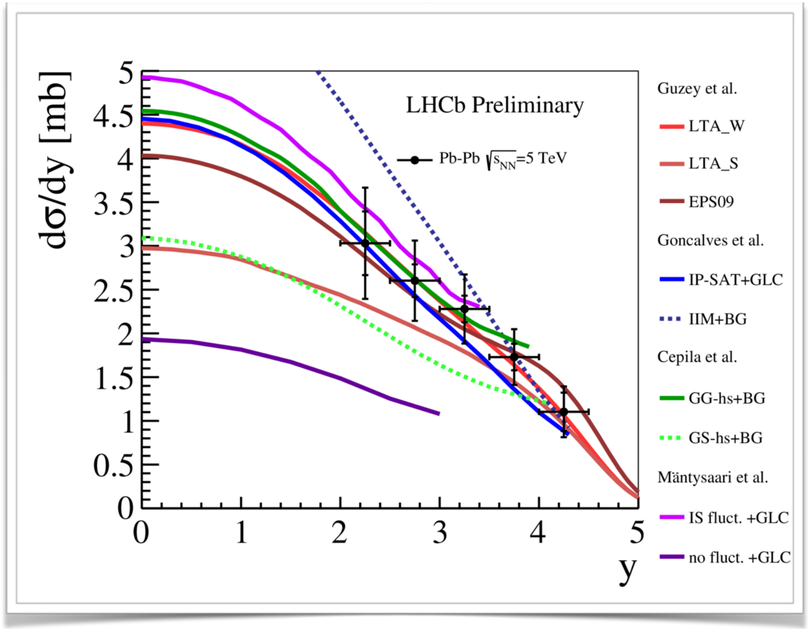

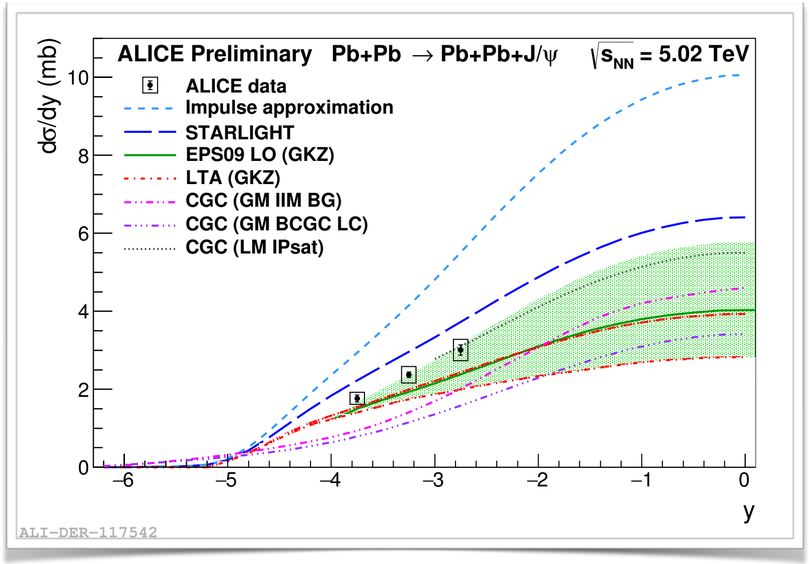

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Others: variations on the dipole model computation.

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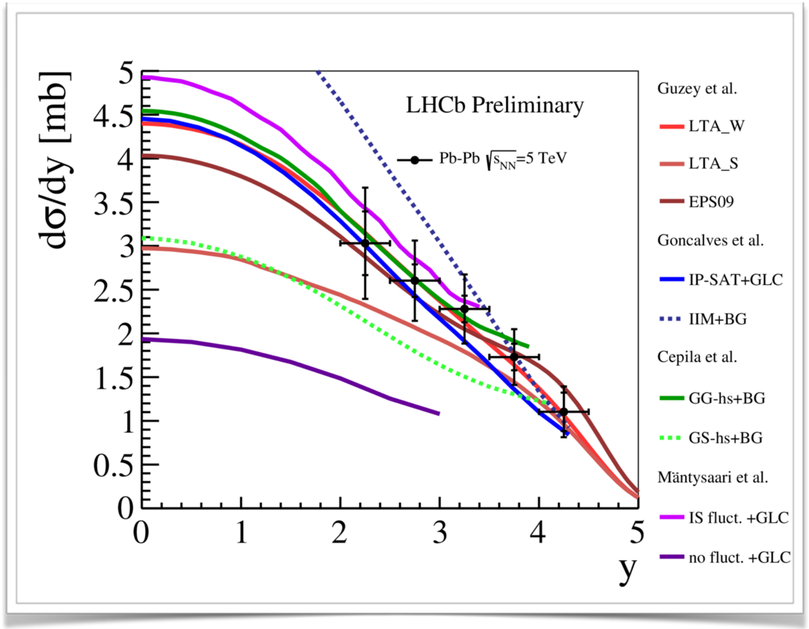

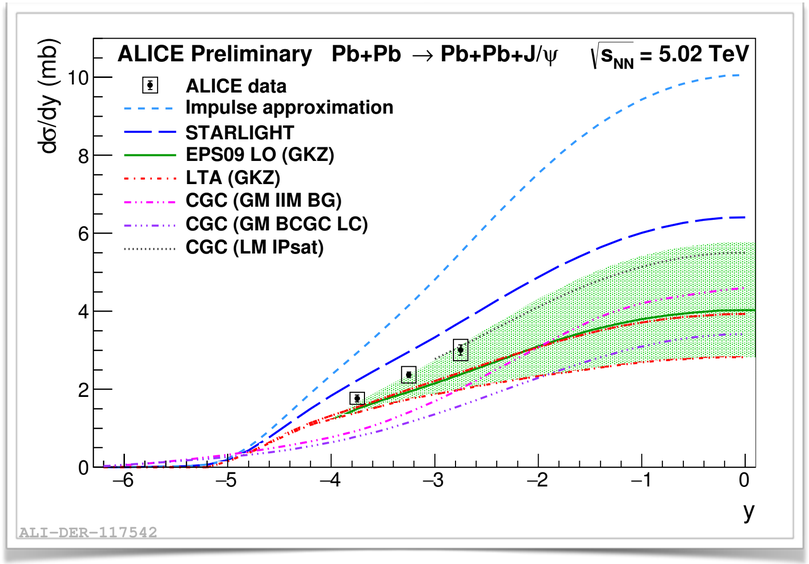

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There are **shadowing** effects!
Data is sensitive to variations in models.

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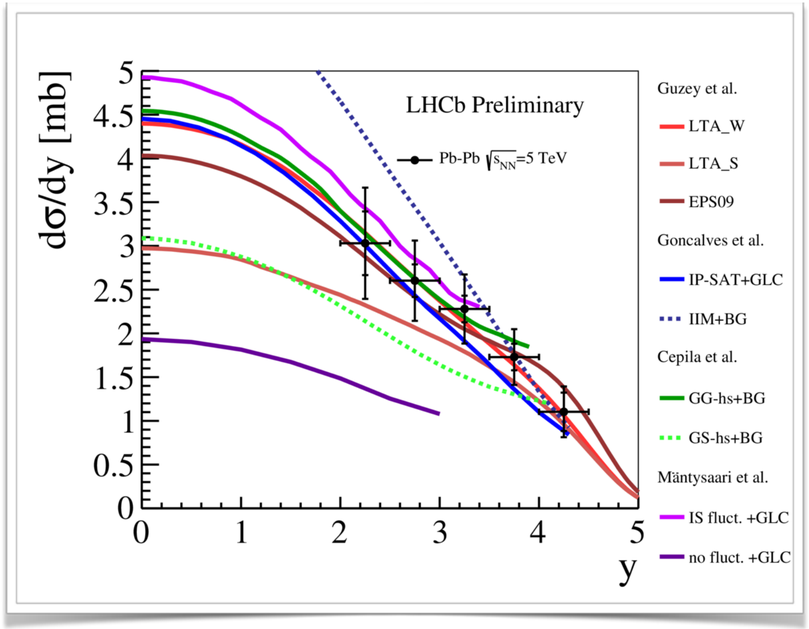

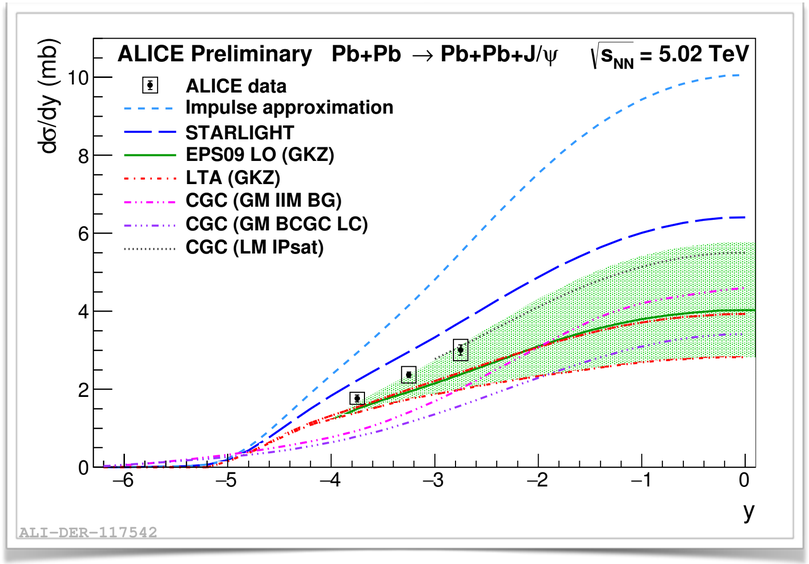

Data from Pb-Pb UPC @ 5020 GeV
Measurements by LHCb and ALICE.

Impulse Approximation: no nuclear effects.
LTA: leading twist approximation.
Others: variations on the dipole model computation.

There are **shadowing** effects!
Data is sensitive to variations in models.

Wednesday in the WG2 session

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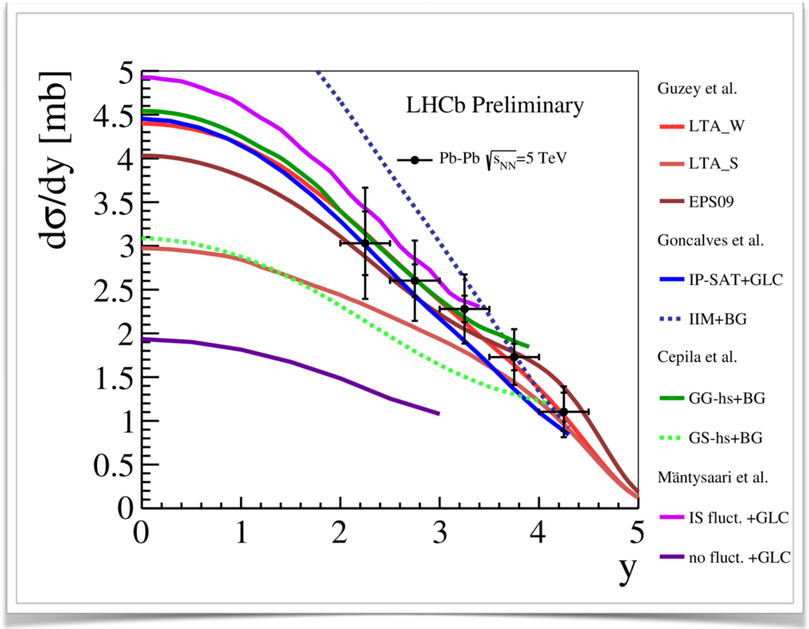

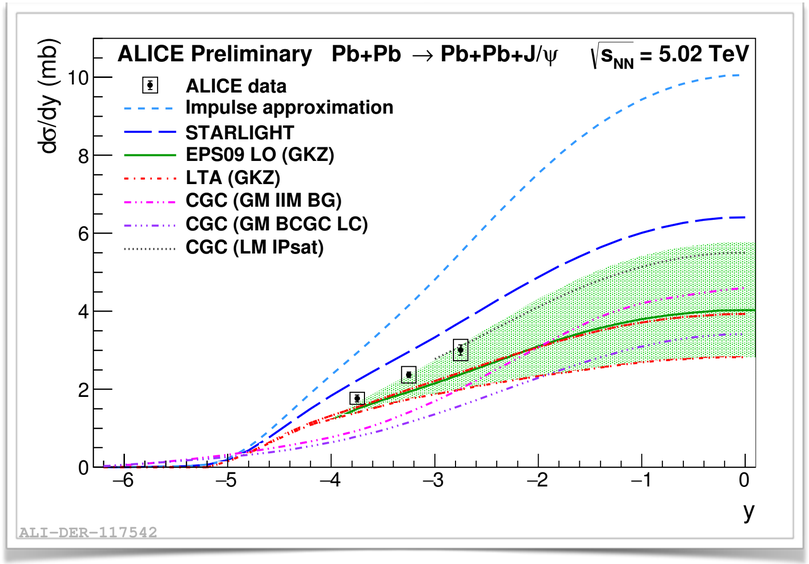

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What is the value of $W_{\gamma Pb}$?

Wednesday in the WG2 session

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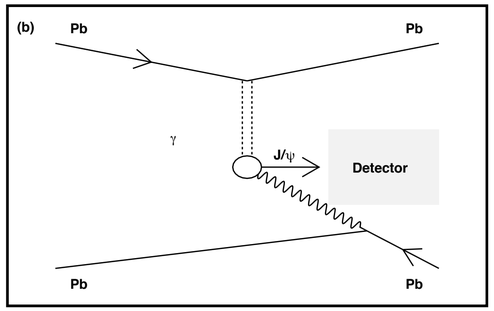
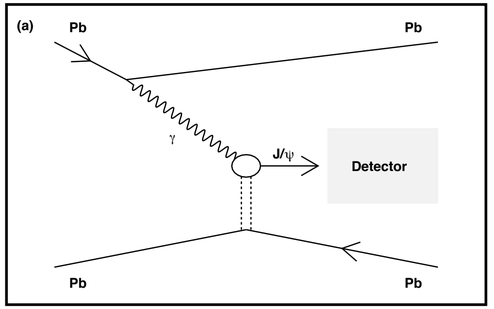
The UPC and γPb cross section





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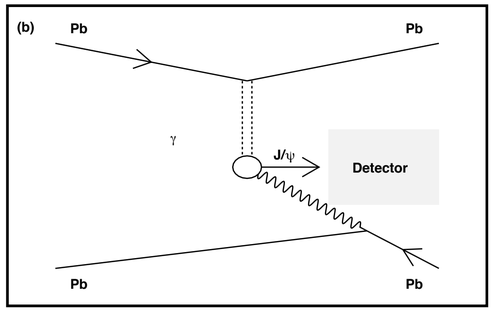

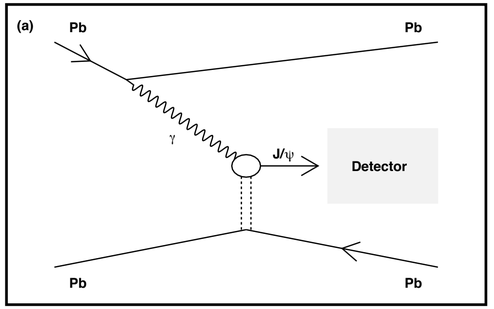

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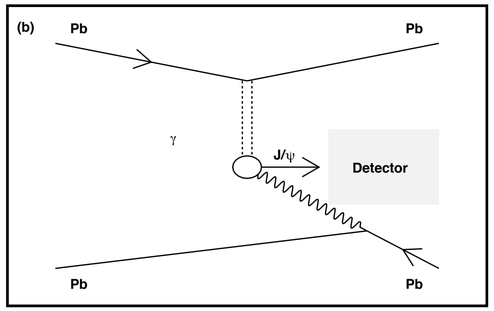

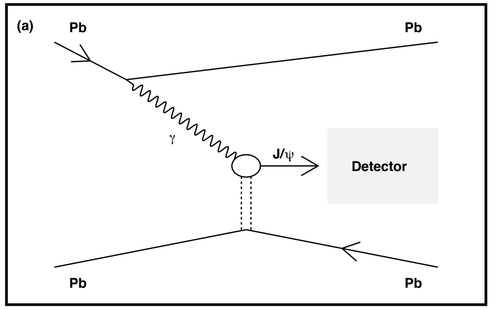

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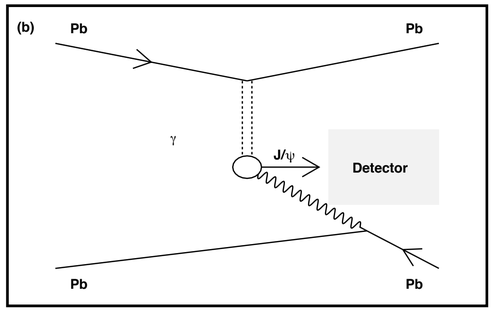

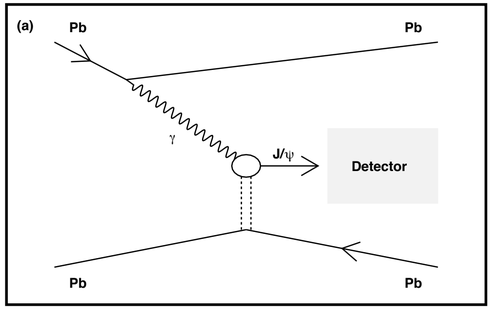

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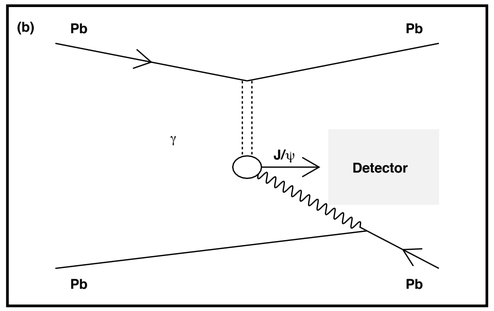

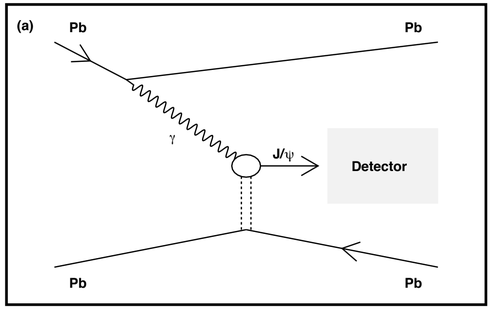

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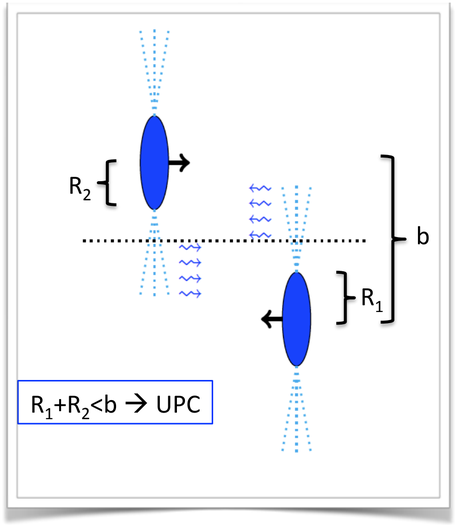
- At y=0 both UPC terms are equal.
- In pPb UPC one term is much larger than the other.
- In PbPb collisions we need to perform **the measurement at the same rapidity but at different impact parameters** in order to disentangle both contributions.

Coherent photoproduction in peripheral collisions @ 2.76 TeV



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… but the incoming nuclei will break.

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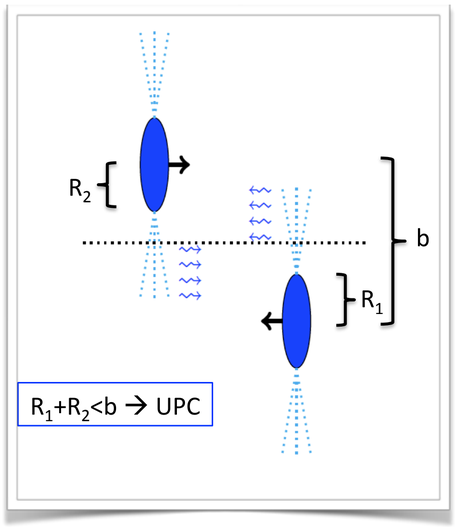

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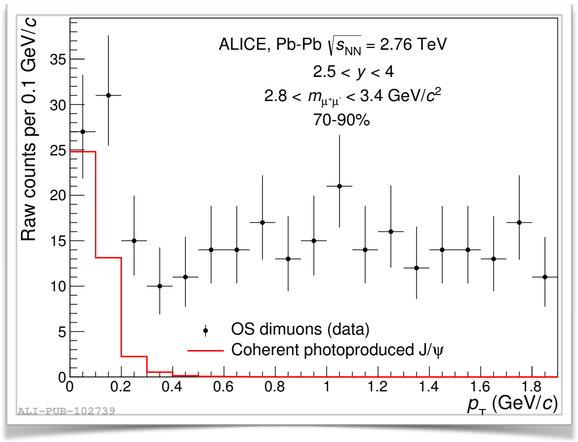
ALICE: Phys.Rev.Lett. 116 (2016) 222301



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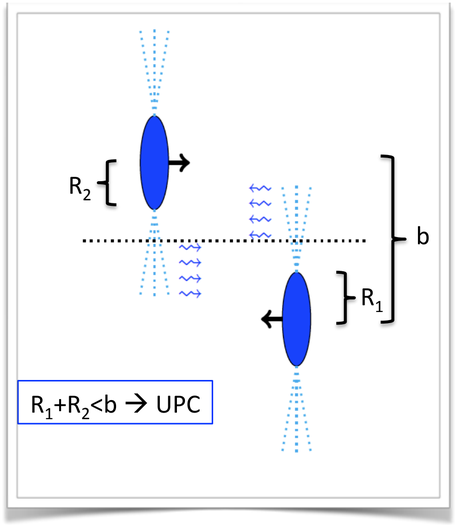

$R_1+R_2<b \rightarrow$ UPC

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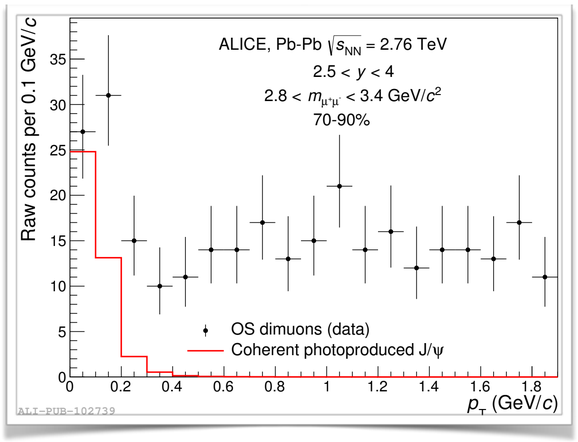

Cent. (%)	$d\sigma^{coh}_{J/\psi}/dy$ (μb)
0–10	< 318
10–30	< 290
30–50	$73 \pm 44^{+26}_{-27} \pm 10$
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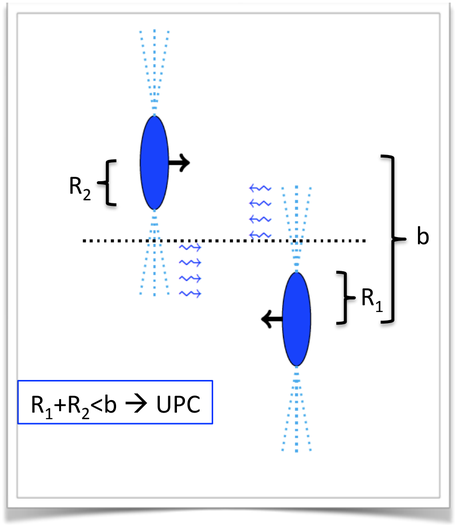

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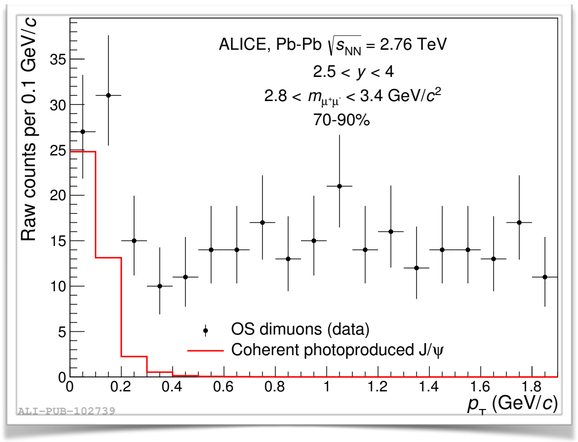

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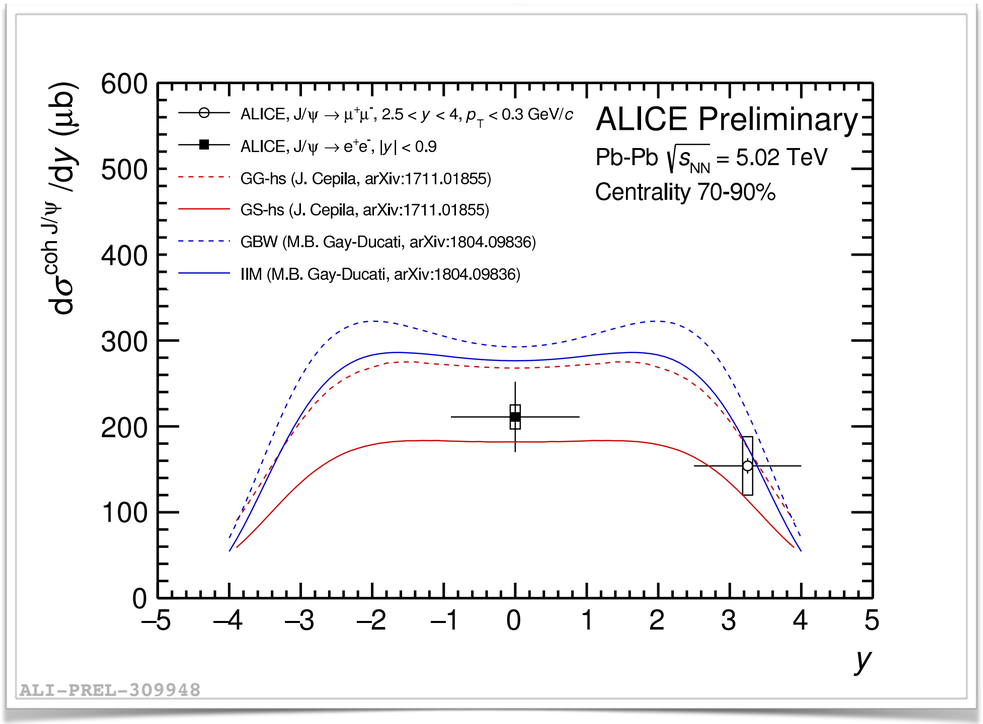

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Photonuclear cross section extracted from ALICE data

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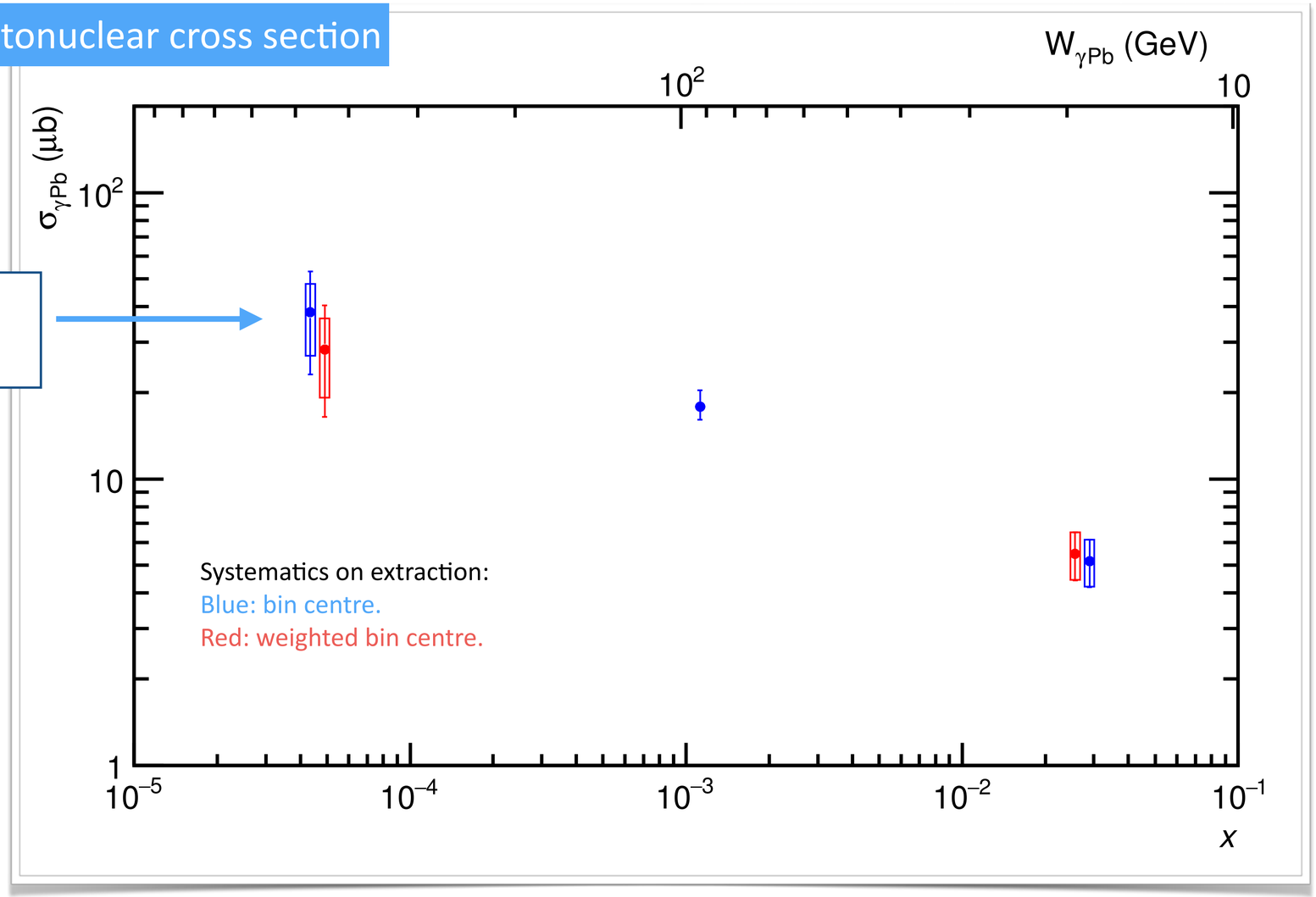

$W_{\gamma Pb}$ up to 470 GeV, x down to 4×10^{-5} !

$$x = \left(\frac{M}{W}\right)^2$$

JGC, Phys.Rev. C96 (2017) no.1, 015203

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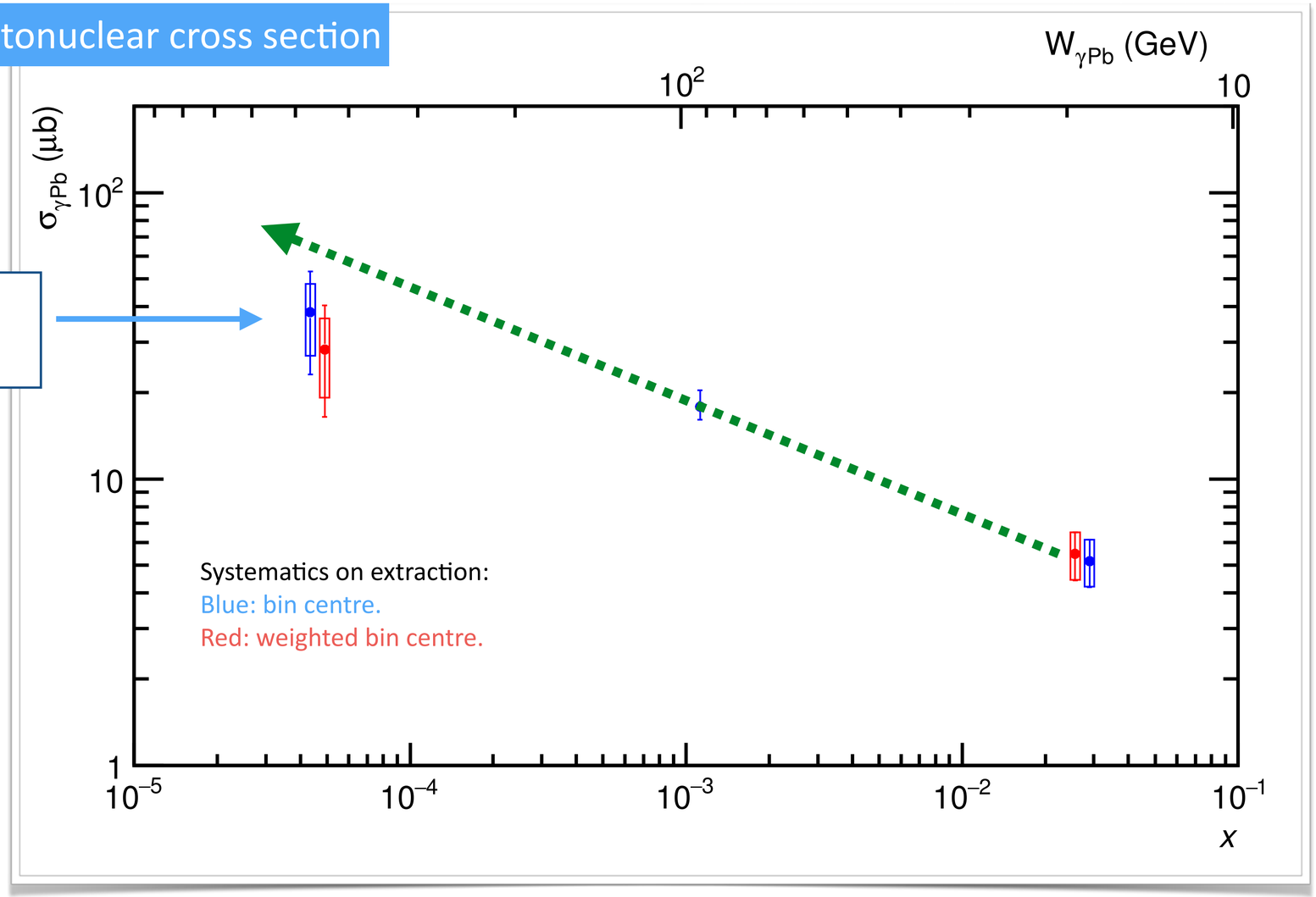

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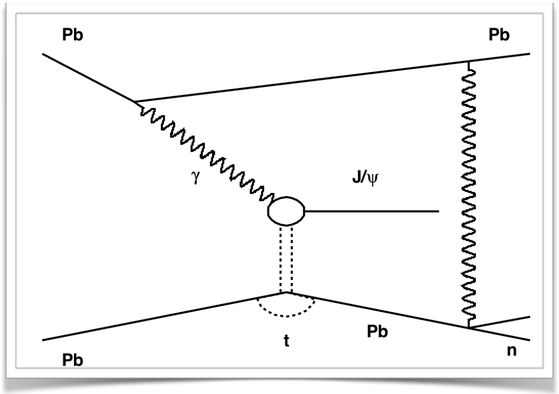
Second option: use forward neutrons!

Independent soft electromagnetic interactions between the nuclei excite them; upon de-excitation they **emit neutrons** in the forward direction



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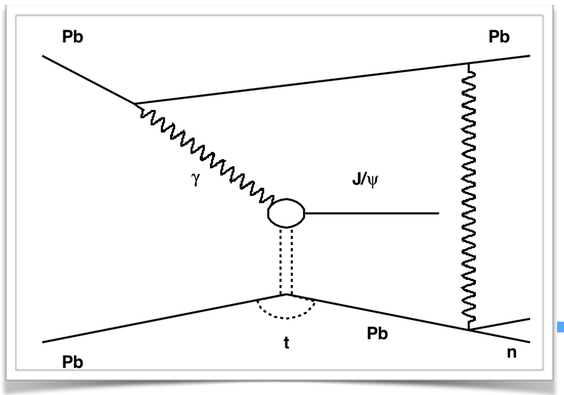

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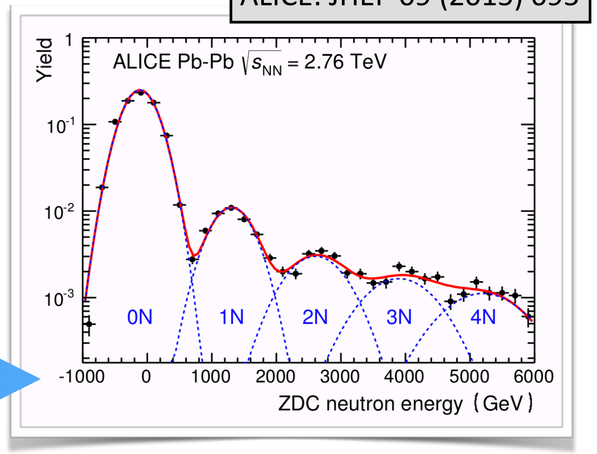

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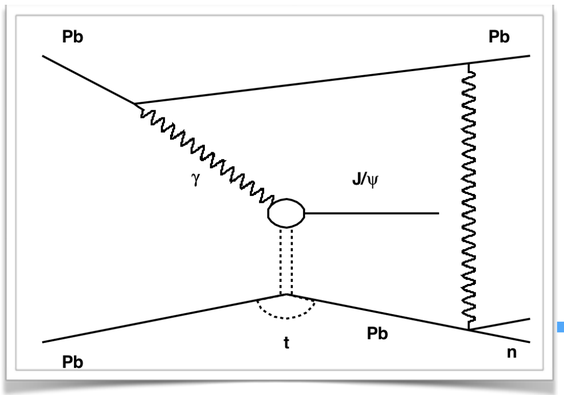

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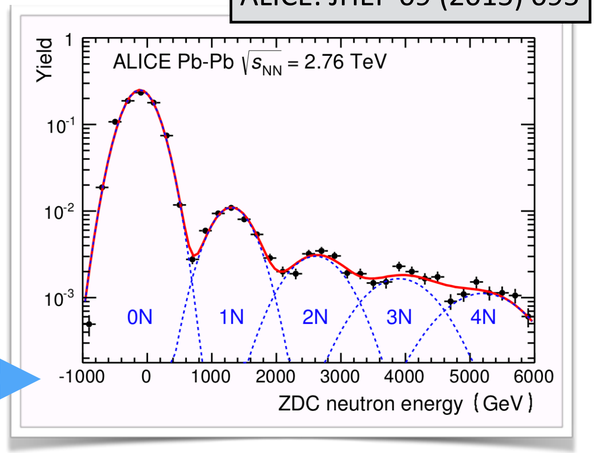

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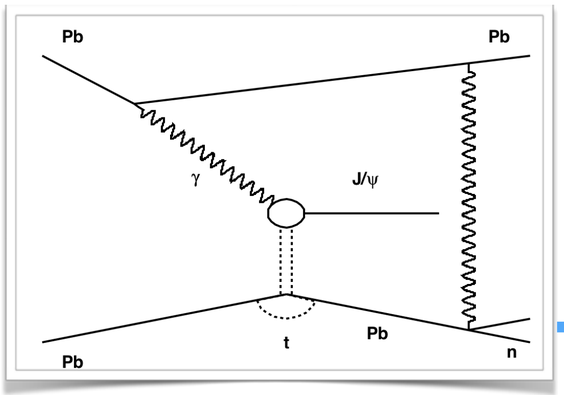

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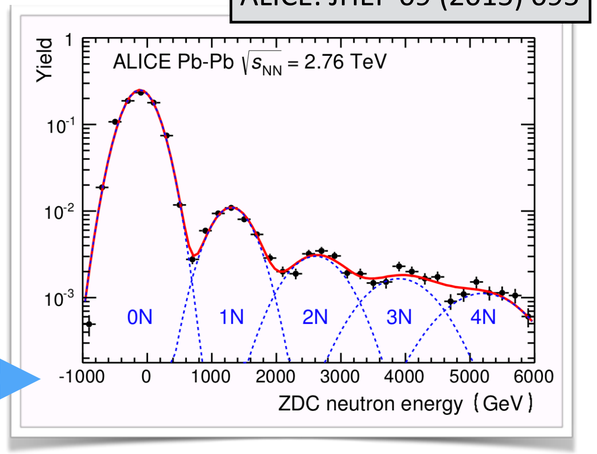

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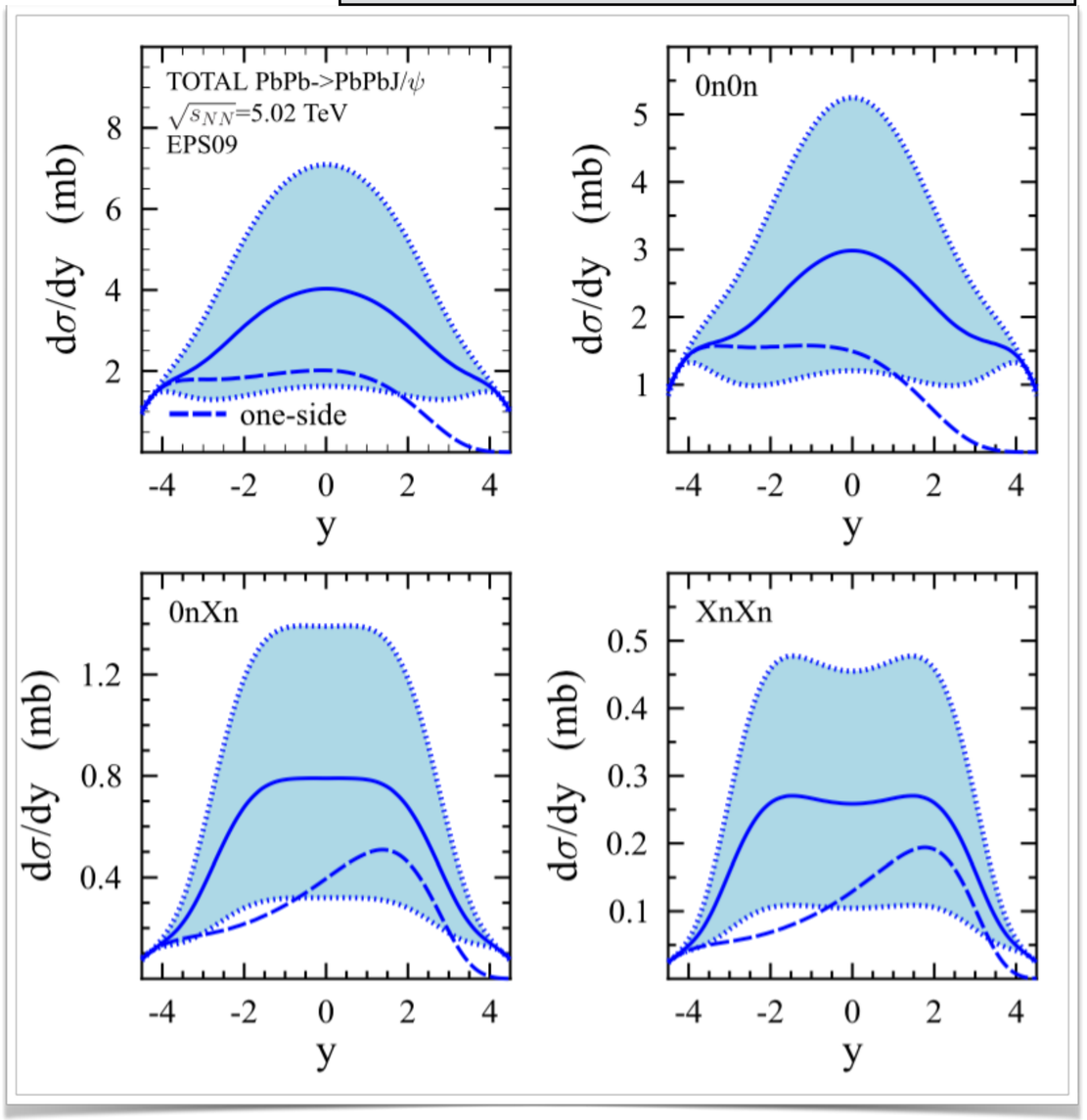
Guzay, Kryshen, Zhalov PRC 93 (2016)055206



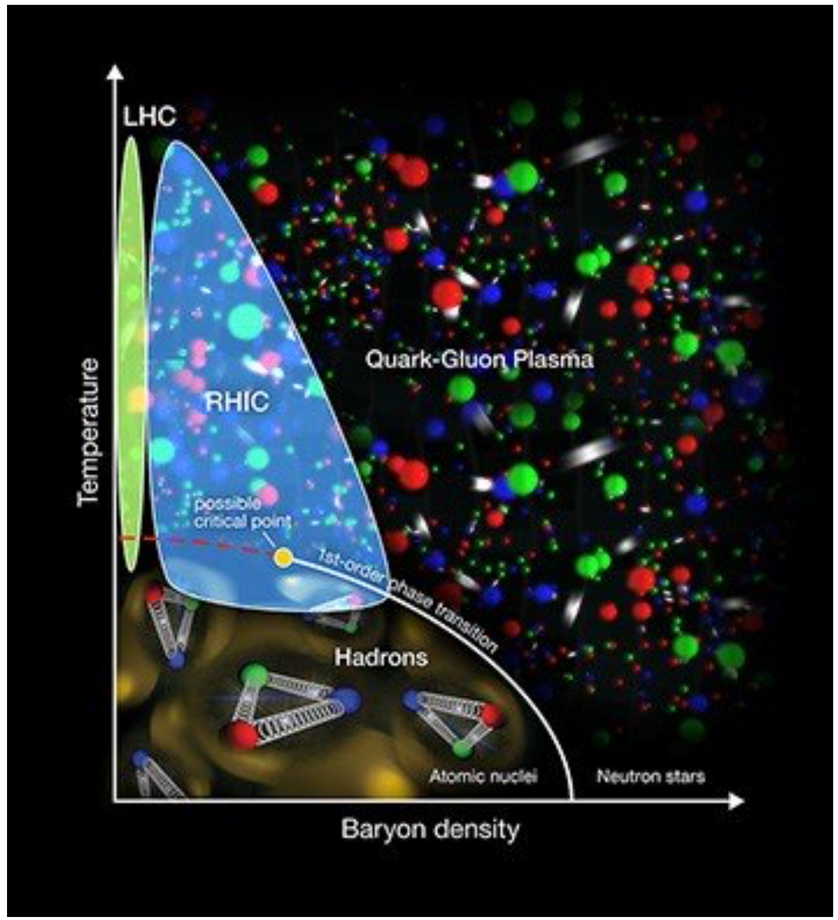
(a parenthesis)

Photon induced processes as a potential probe of QGP

The quark-gluon plasma and where to find it

QCD is richer than just hadrons.
It has a rich phase space with different states of matter.

The quark-gluon plasma and where to find it



Credit: Brookhaven National Laboratory

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The study of the quark-gluon plasma (QGP) and its properties is one of the main topics of research at RHIC and LHC where such a state of matter is created in head-on (so called ‘central’) collisions of heavy nuclei.

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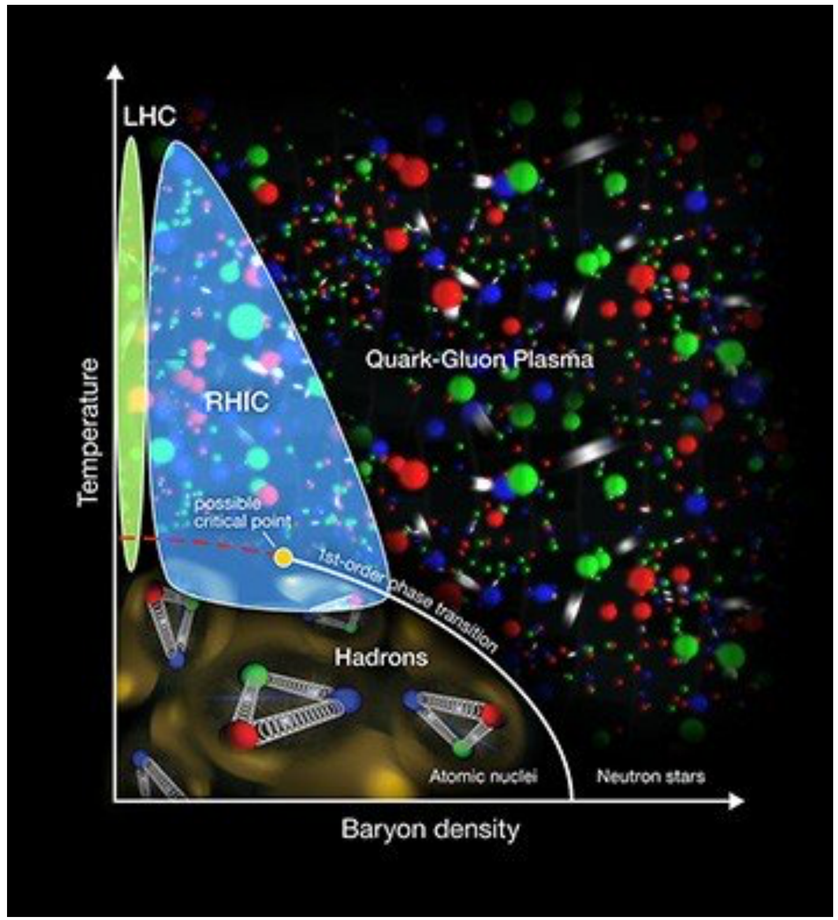

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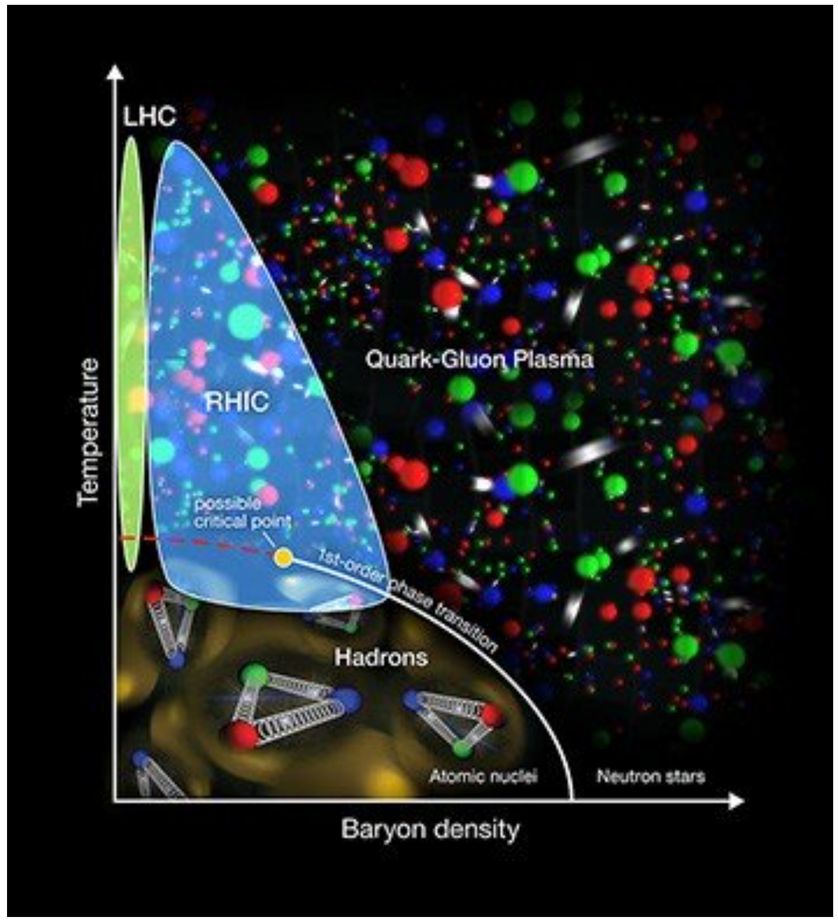

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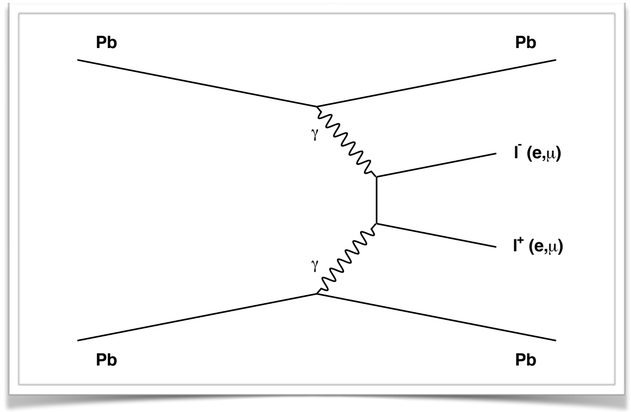
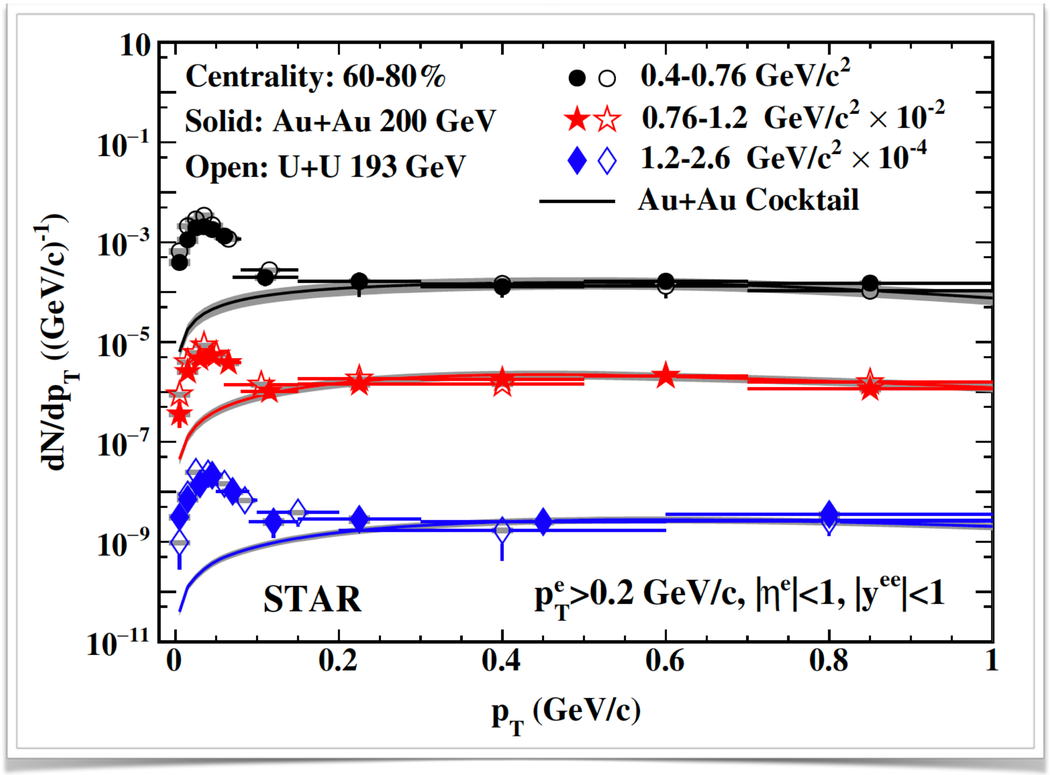
Can we use photon-induced processes to study the QGP?



News from RHIC: electron-positron pair production in Au-Au and U-U collisions

STAR, PRL 121 (2018) 132301



Different colors: different masses.
Line: expectations from hadronic collisions.
Clear excess at low transverse momentum.

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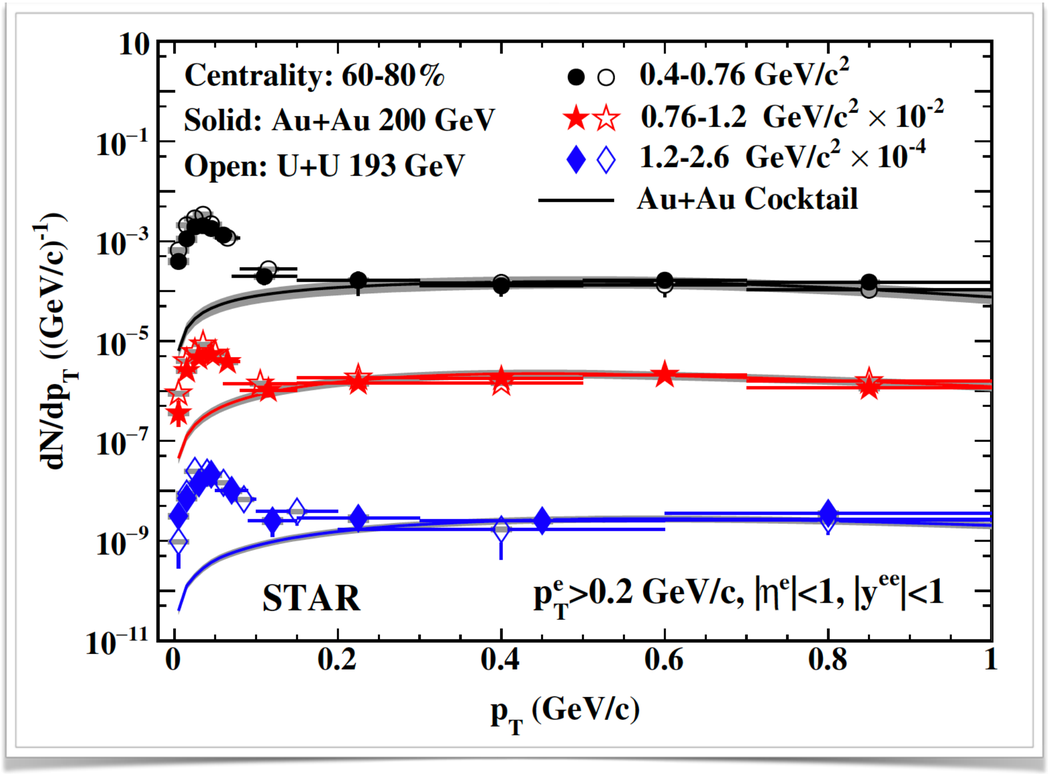

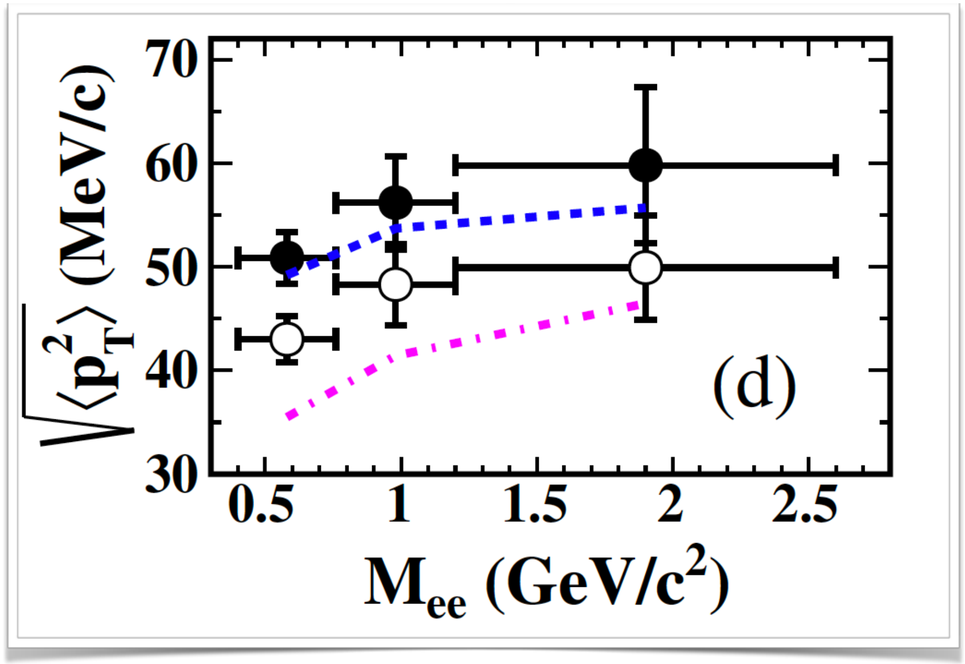

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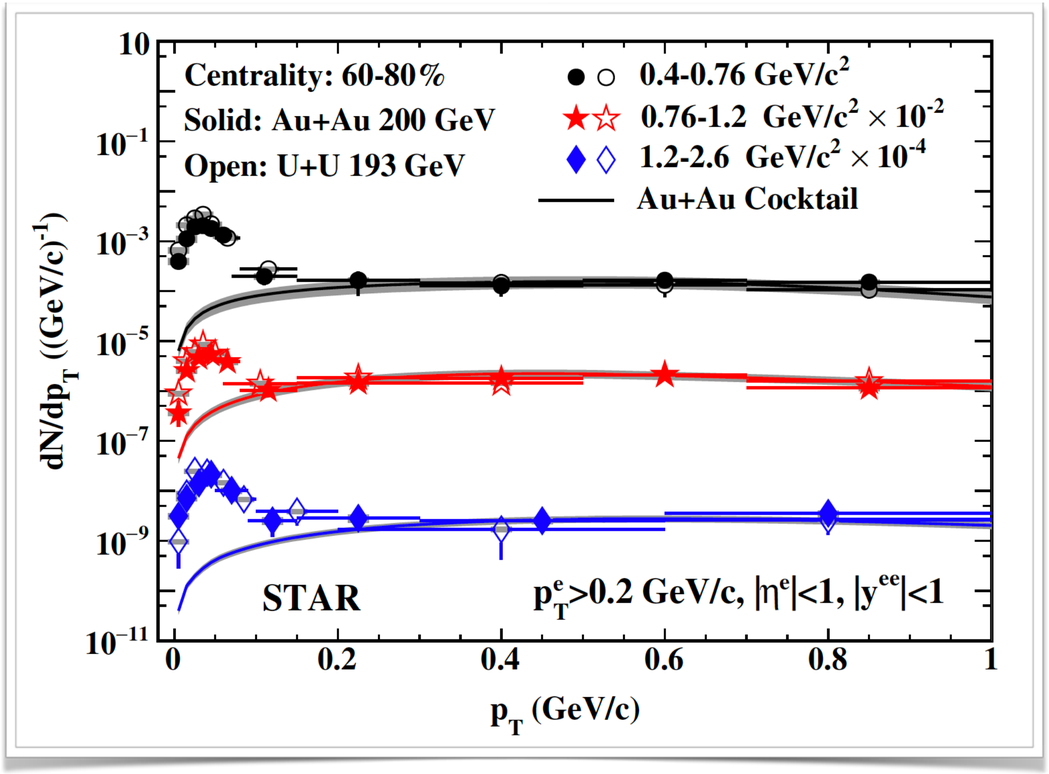

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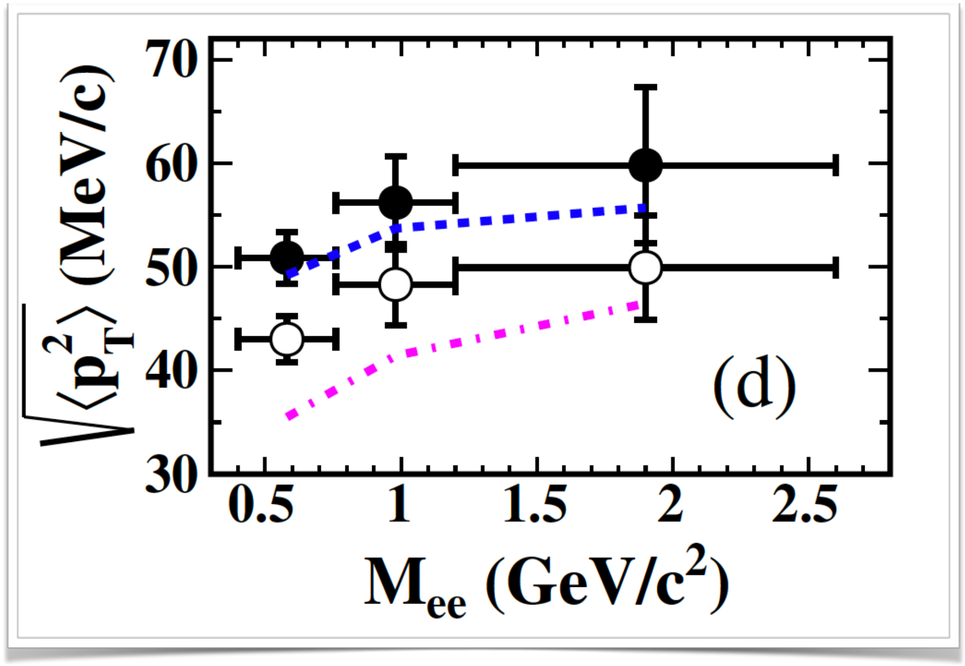

Magenta: 'standard' γγ contributions.
Blue: Magnetic field of 10^{14} T !
(Zha et al, PLB 781 (2018) 182)

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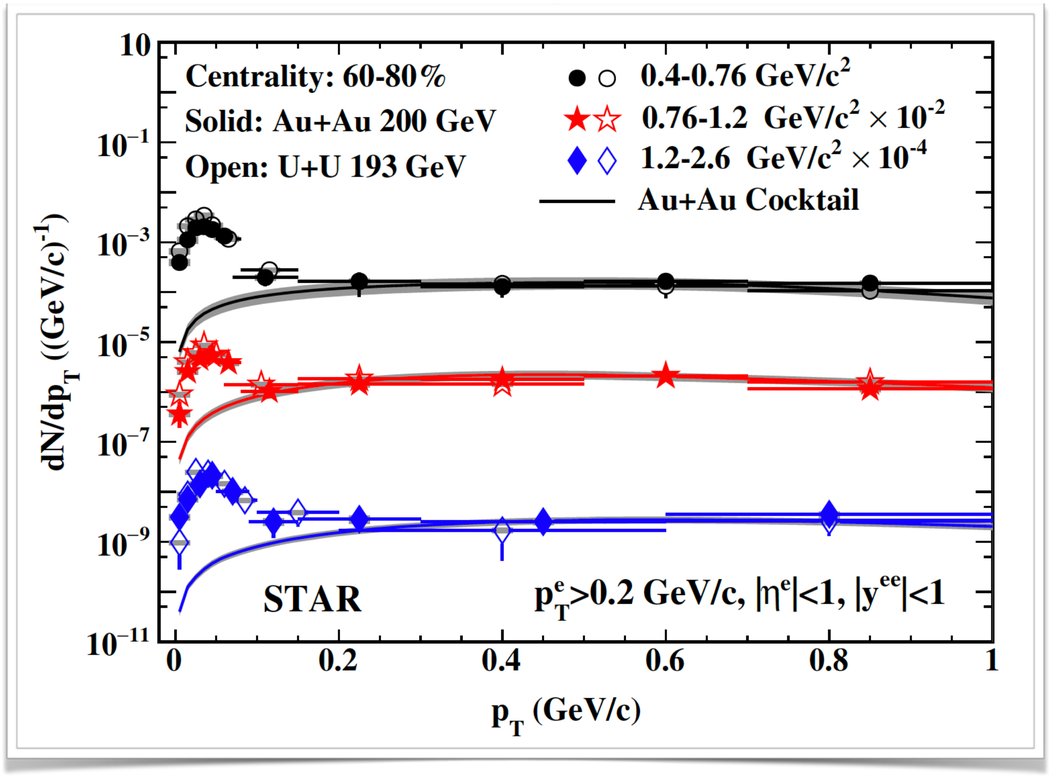

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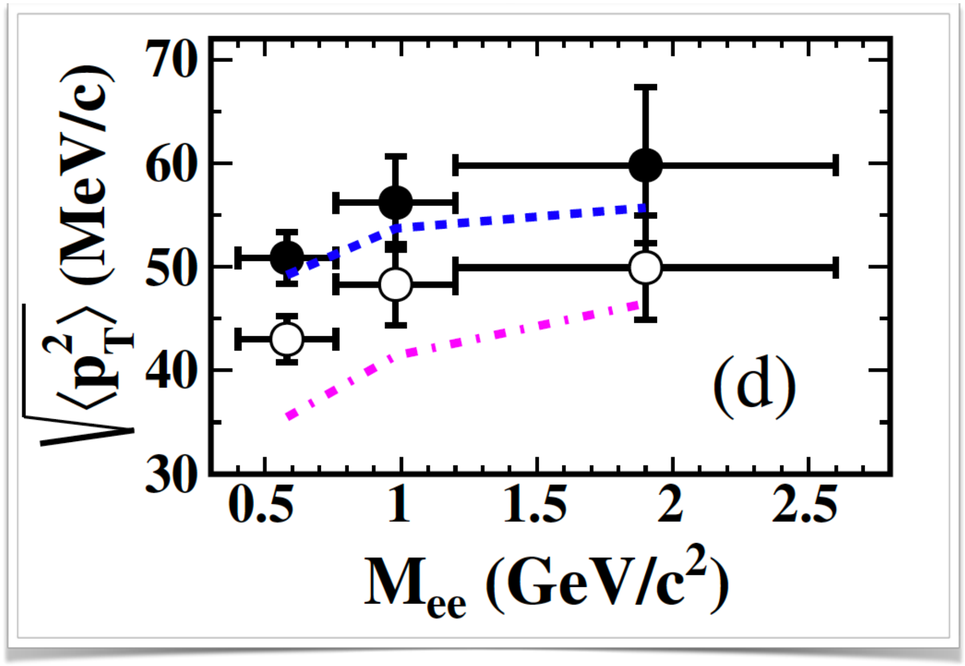

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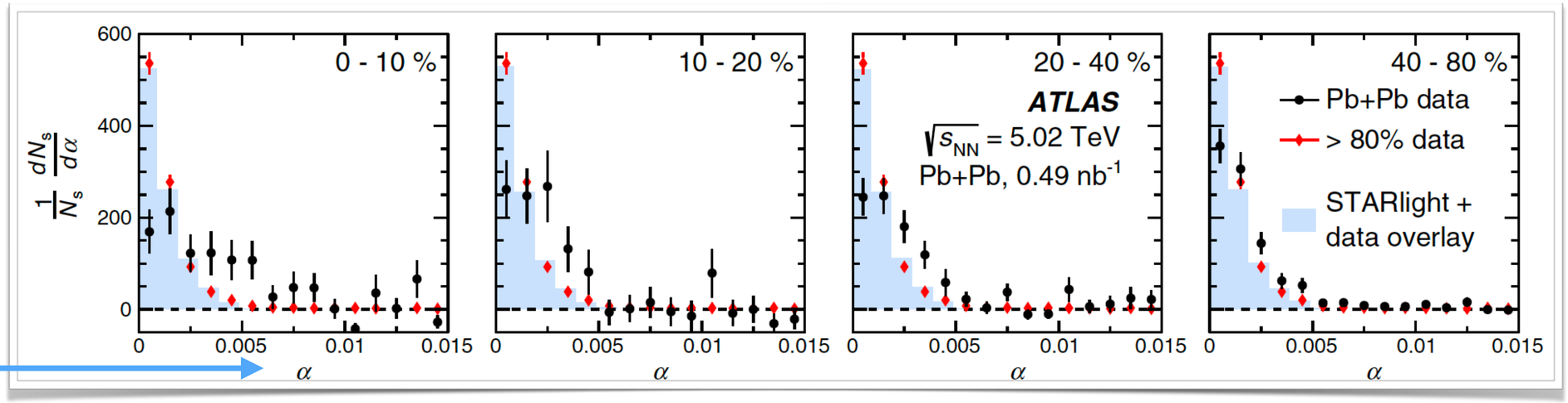
But other explanations are available:
Kłusek-Gawenda et al, PLB790 (2019) 339.
Zha et al, arXiv 1812.02820.

News from the LHC: muon-pair producrtion

ATLAS, PRL 121 (2018) 212301

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$



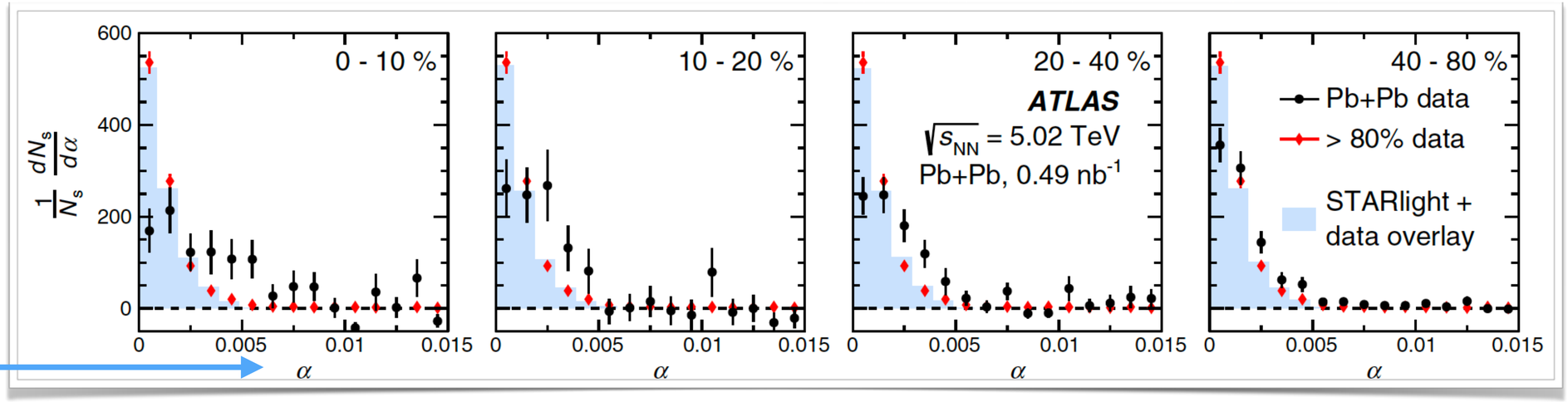
Peripheral collisions consistent with γγ→ μμ.

Shape changes with centrality.

News from the LHC: muon-pair producrtion

ATLAS, PRL 121 (2018) 212301

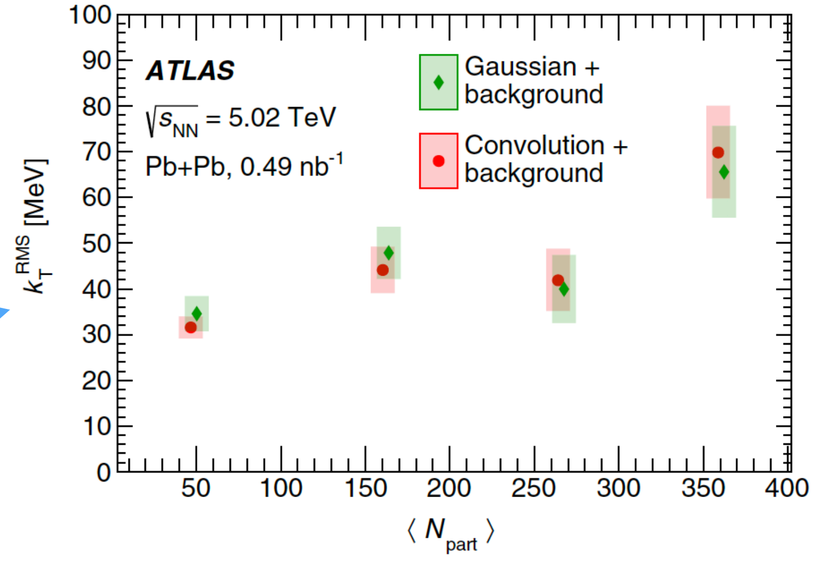
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$



Peripheral collisions consistent with γγ→ μμ.
Shape changes with centrality.

Assuming that the broadening of the α distributions results from a physical process that transfers a *small* amount of transverse momentum, $|\vec{k}_T| \ll p_T^{\pm}$, to each muon then the variance of the α distribution can be approximated as

$$\langle \alpha^2 \rangle = \langle \alpha^2 \rangle_0 + \frac{1}{\pi^2} \frac{\langle \vec{k}_T^2 \rangle}{\langle p_{T\,avg}^2 \rangle}, \qquad (1)$$

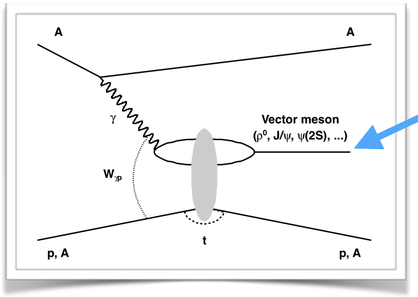


Increase in kT due to re-scattering in QGP?

The structure of protons at small x

News about wave functions

$$A(x, Q^2, \vec{\Delta})_{T,L} = i \int d\vec{r} \int_0^1 \frac{dz}{4\pi} (\Psi^* \Psi_{\rm V})_{T,L} \int d\vec{b}\, e^{-i(\vec{b}-(1-z)\vec{r})\cdot\vec{\Delta}} \frac{d\sigma_{\rm dip}}{d\vec{b}}$$



Vector meson wave function

News about wave functions

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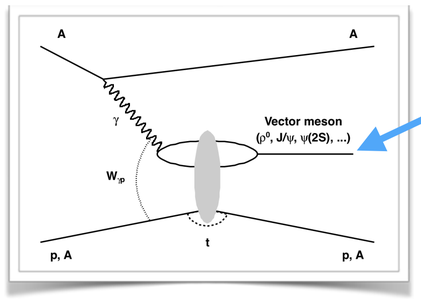
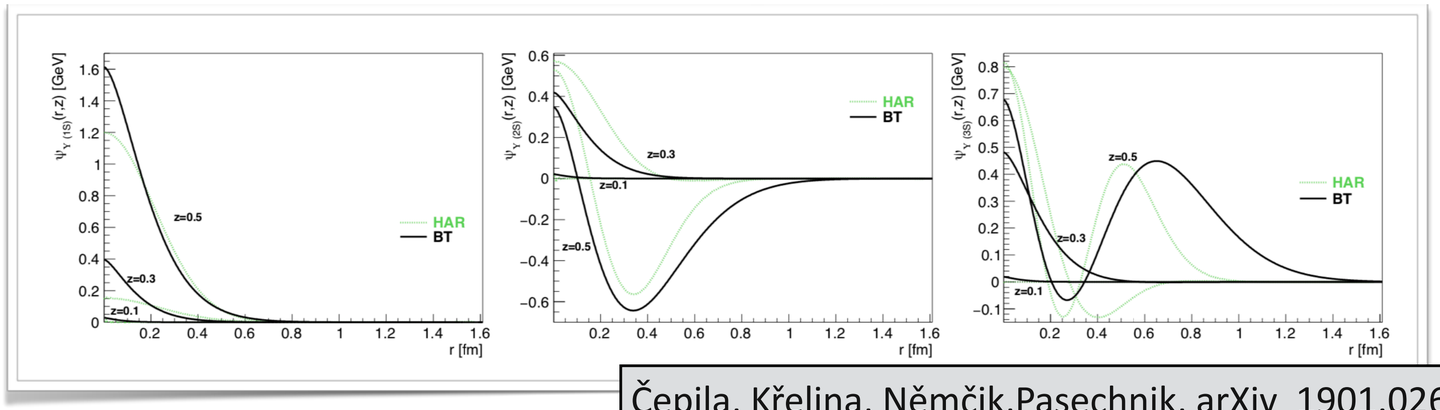
Wave functions with a spacial and a spin part

Spacial part from solution of Schrödinger equation with different potentials



Vector meson wave function



Čepila, Křelina, Němčik,Pasechnik, arXiv 1901.02664

News about wave functions

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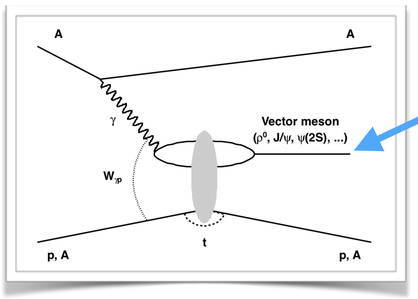

Vector meson wave function

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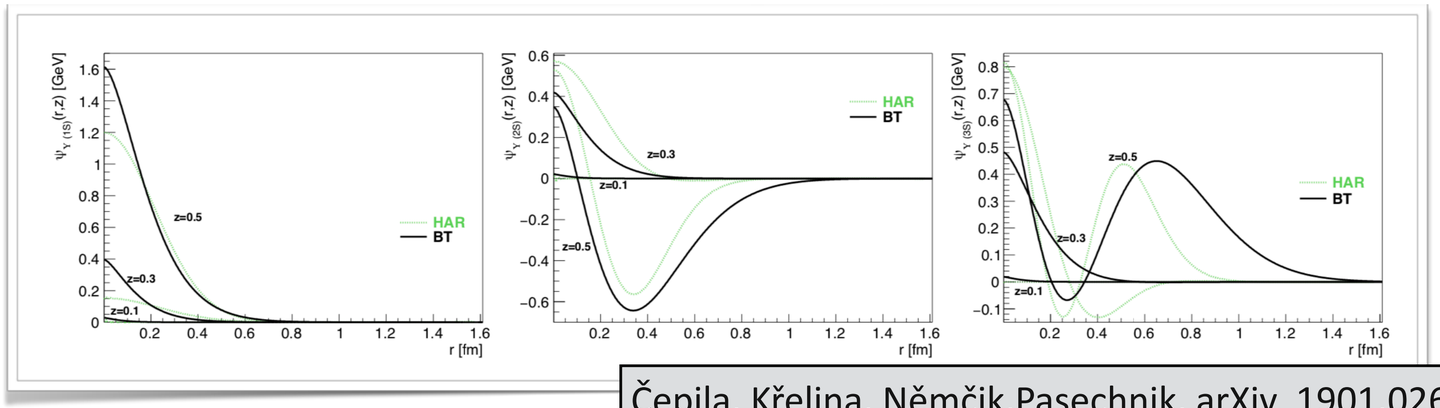
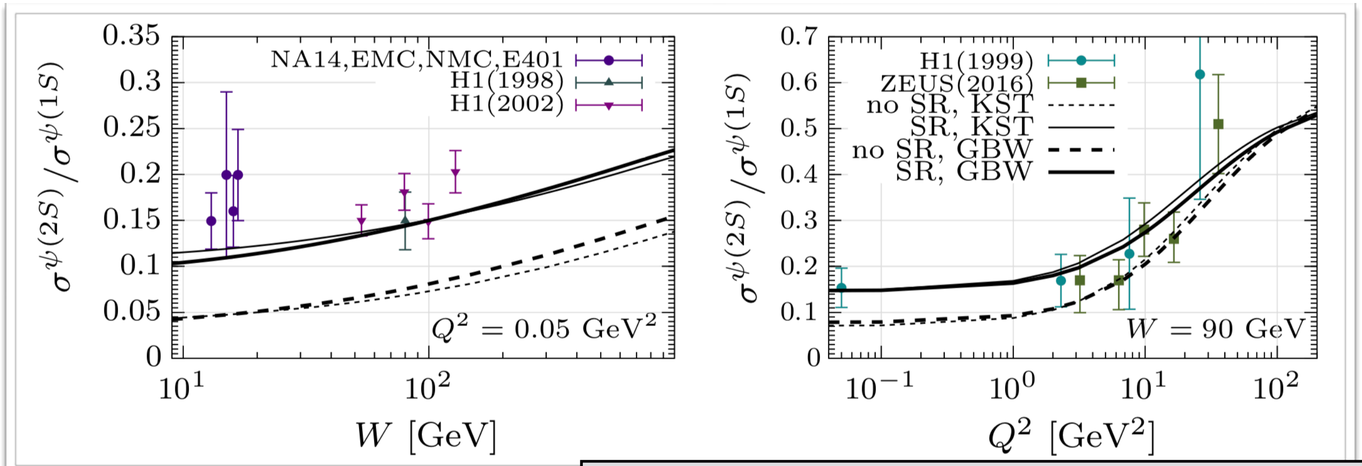


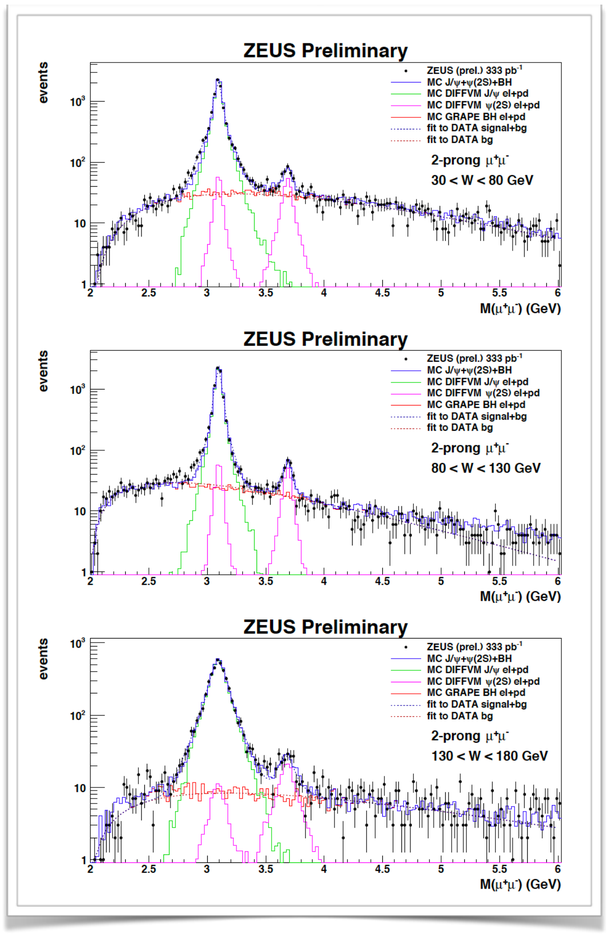
Čepila, Křelina, Němčik,Pasechnik, arXiv 1901.02664

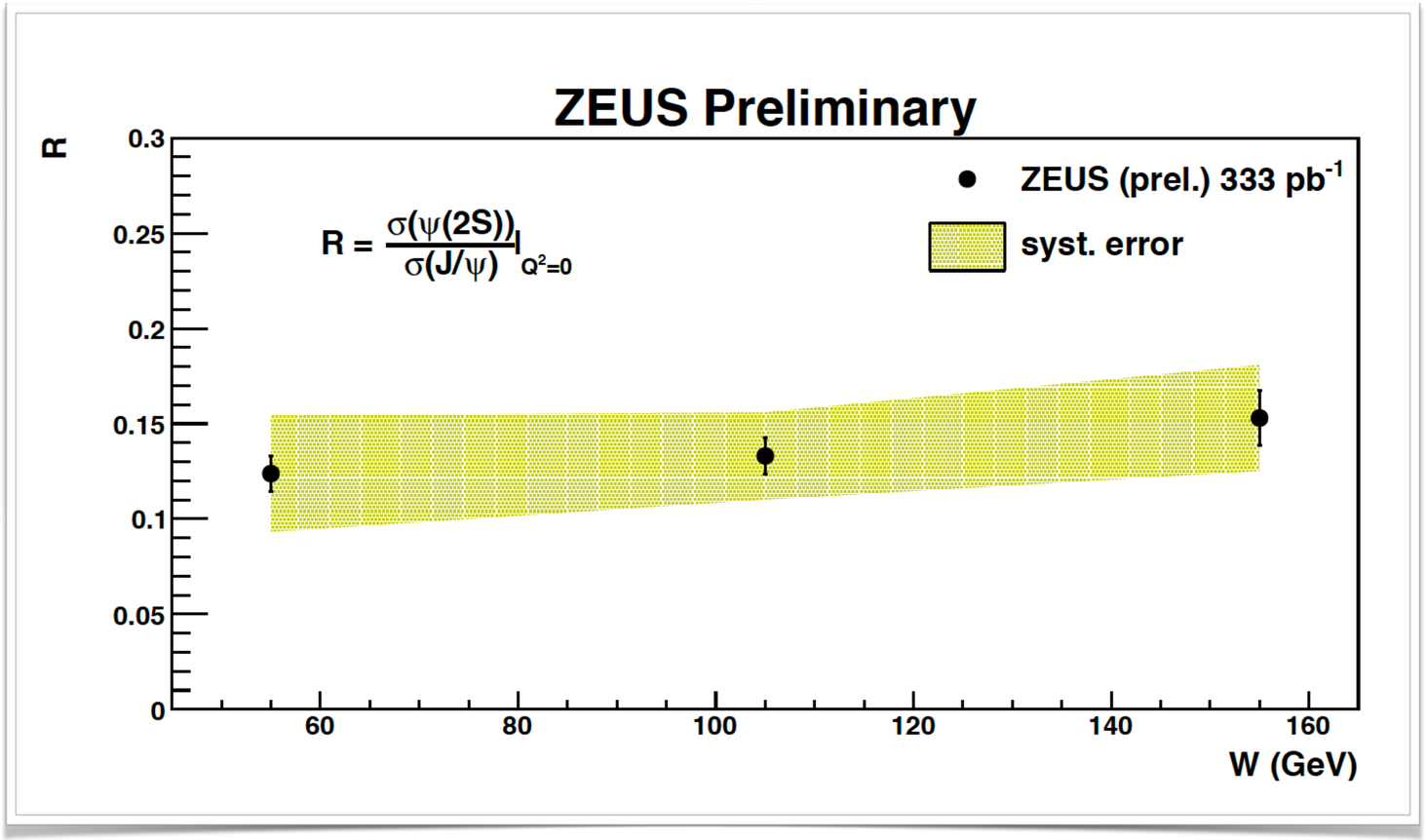
Inclusion of spin rotation effects have a large effect on 2S states due to a nodal structure of the corresponding wave functions.



Čepila, Křelina, Němčik,Pasechnik, EPJC79 (2019) 154

News from HERA: ψ' to J/ψ ratio in photoproduction

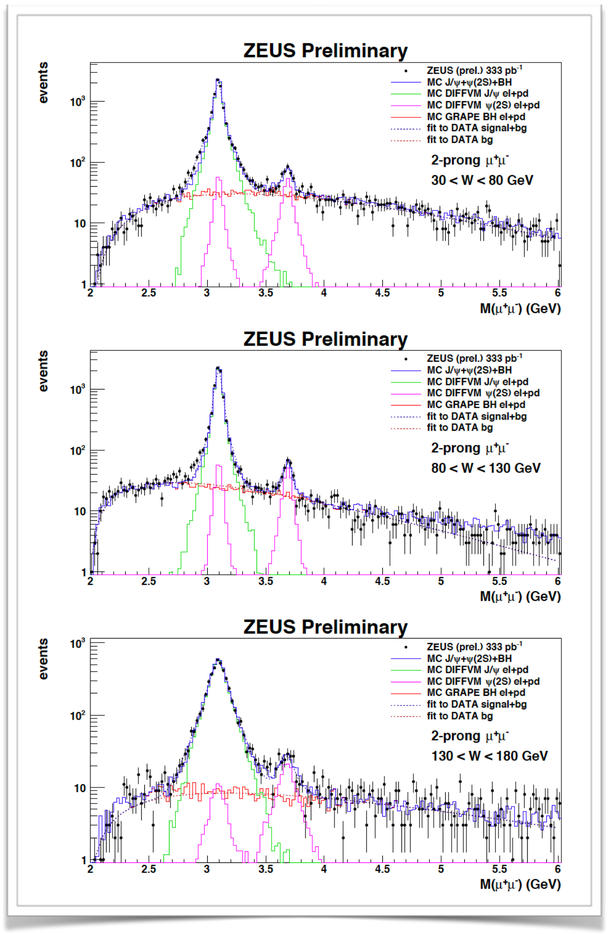


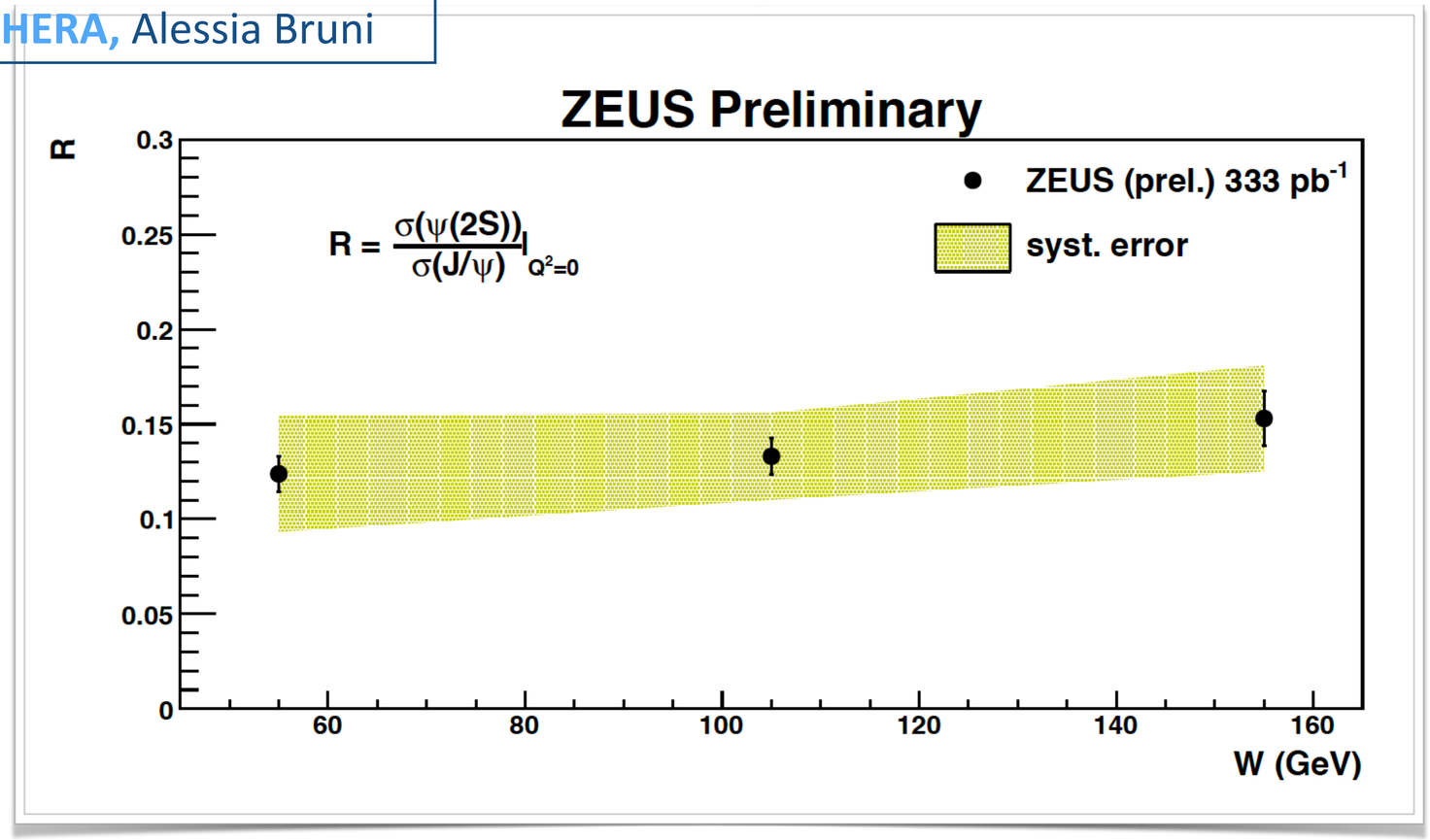


News from HERA: ψ' to J/ψ ratio in photoproduction

Wednesday in the WG2 session

Measurement of the Psi(2S) to J/Psi cross section ratio in photoproduction with the ZEUS detector at HERA, Alessia Bruni





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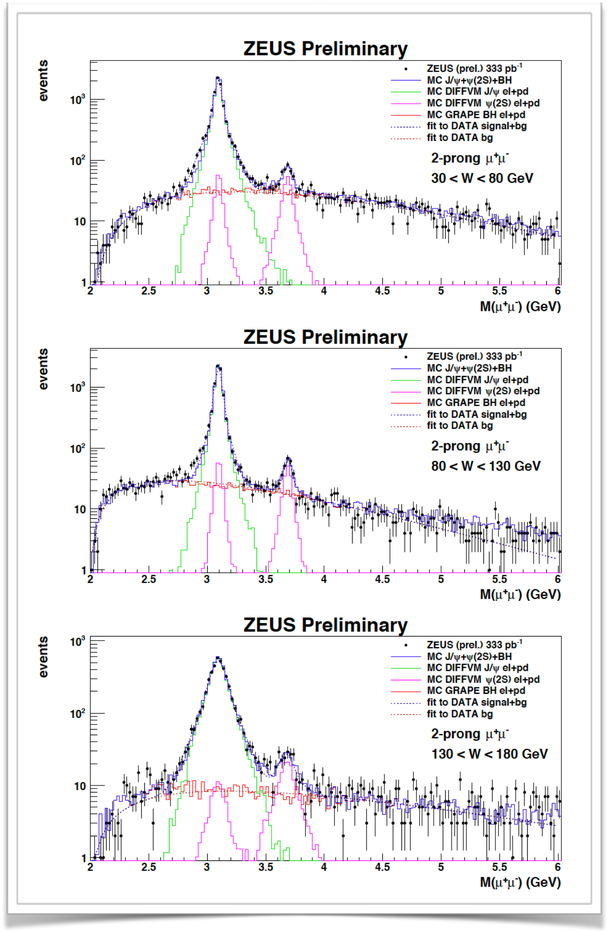
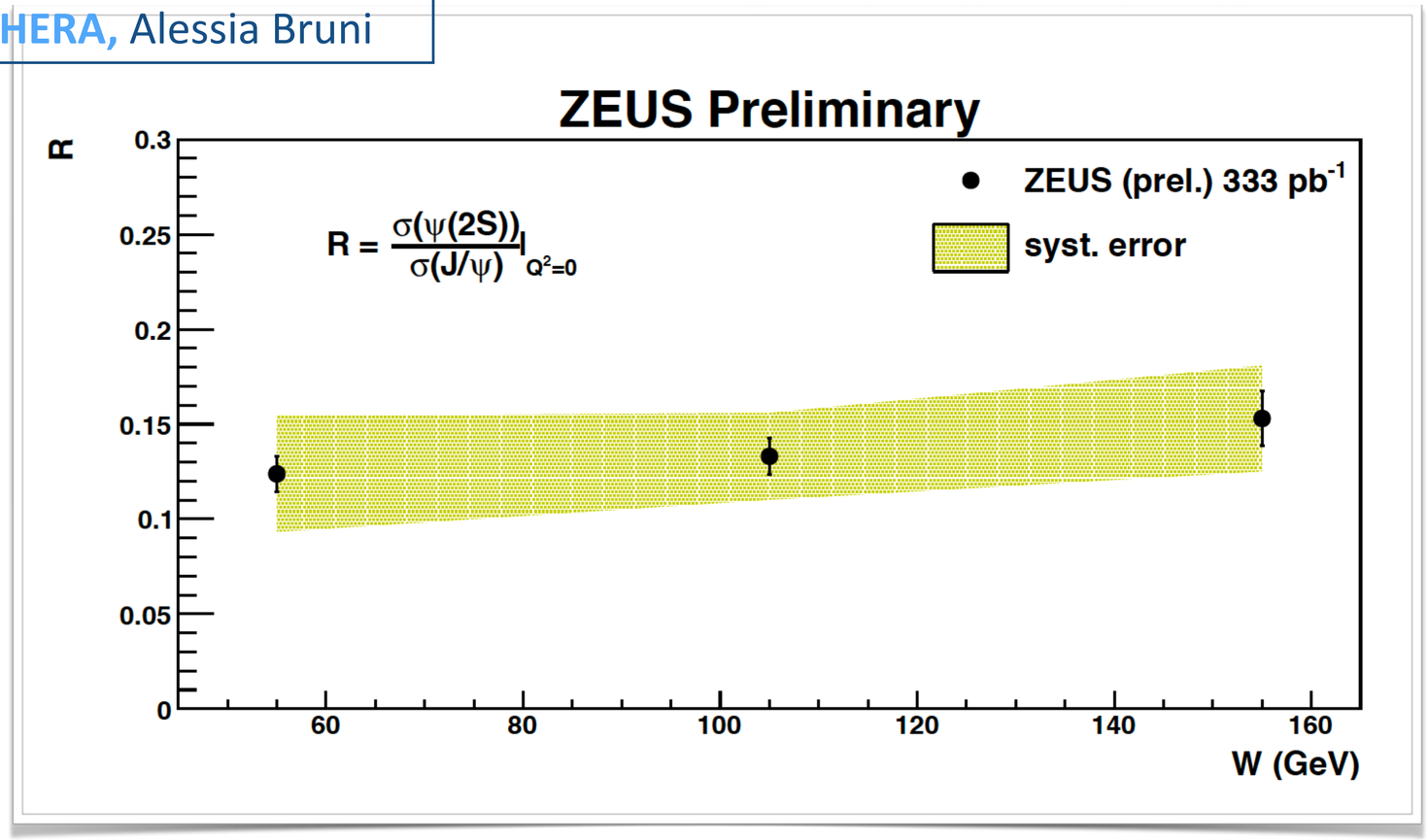


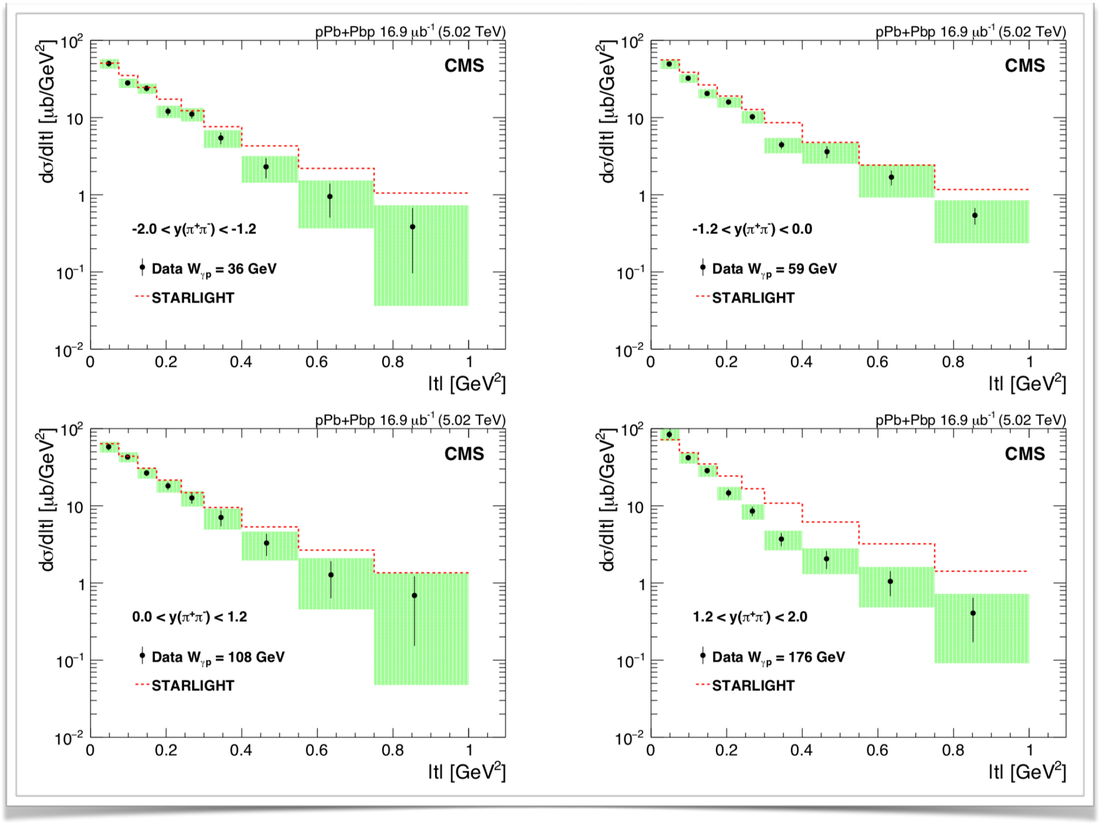


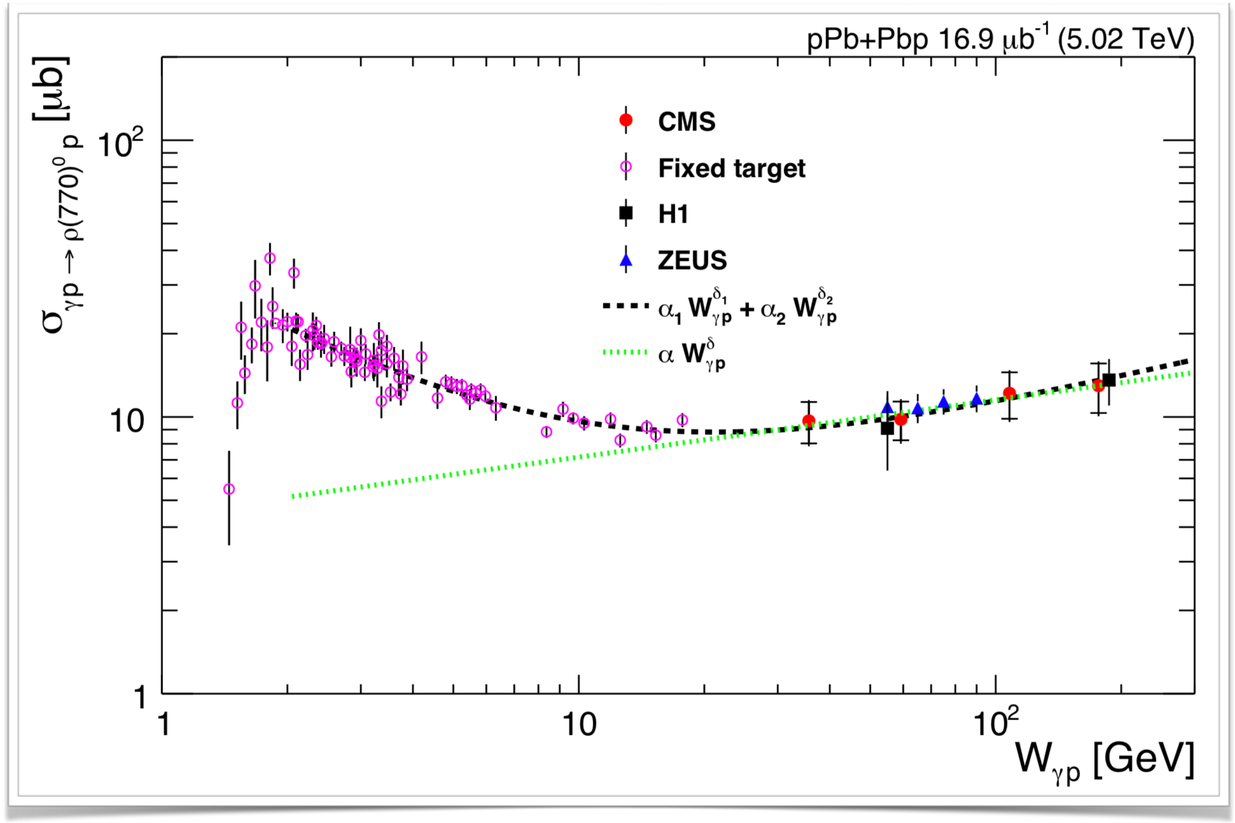
Wednesday in the WG2 session

Soft QCD and Central Exclusive Production at LHCb, Kucharczyk, Marcin

News from the LHC: ρ photoproduction off protons

CMS arXiv:1902.01339





Measurements of the |t| and energy dependence of this process!

News from the LHC: ρ photoproduction off protons

Wednesday in the WG2 session

Recent CMS results on exclusive processes Bylinkin Aleksandr

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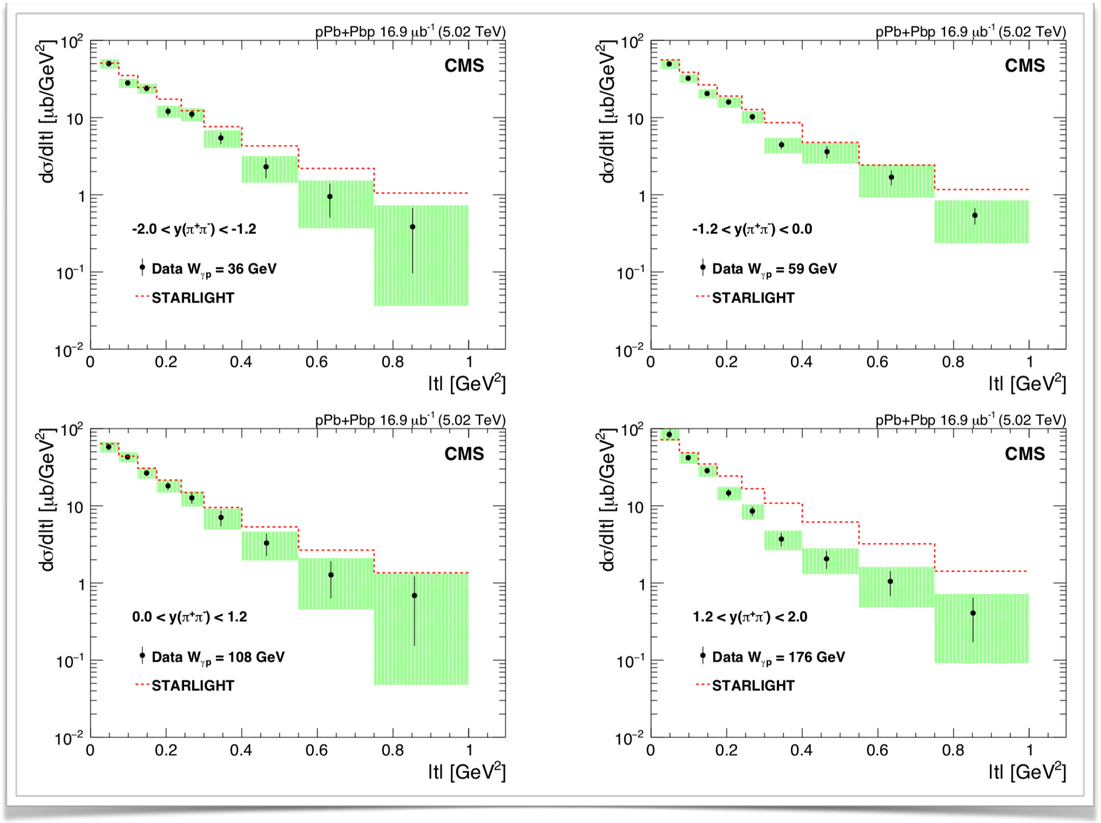

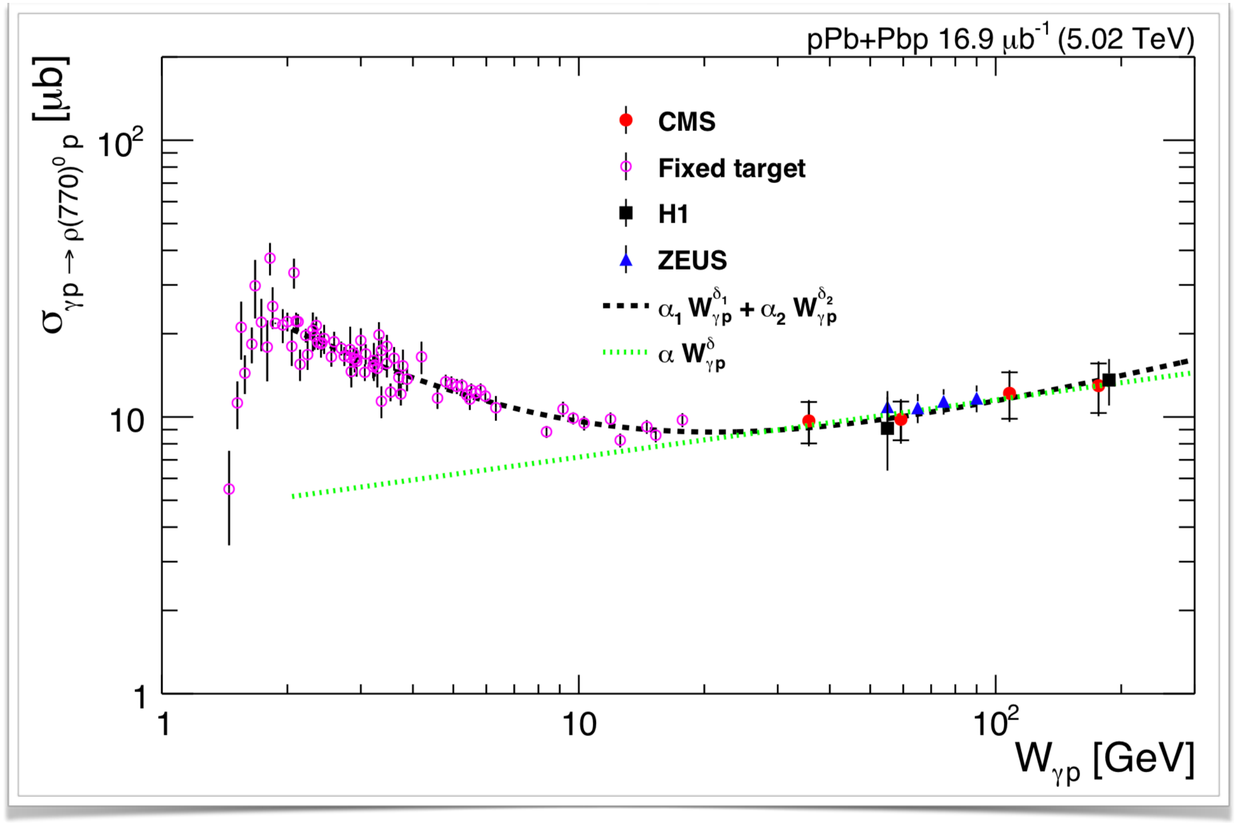

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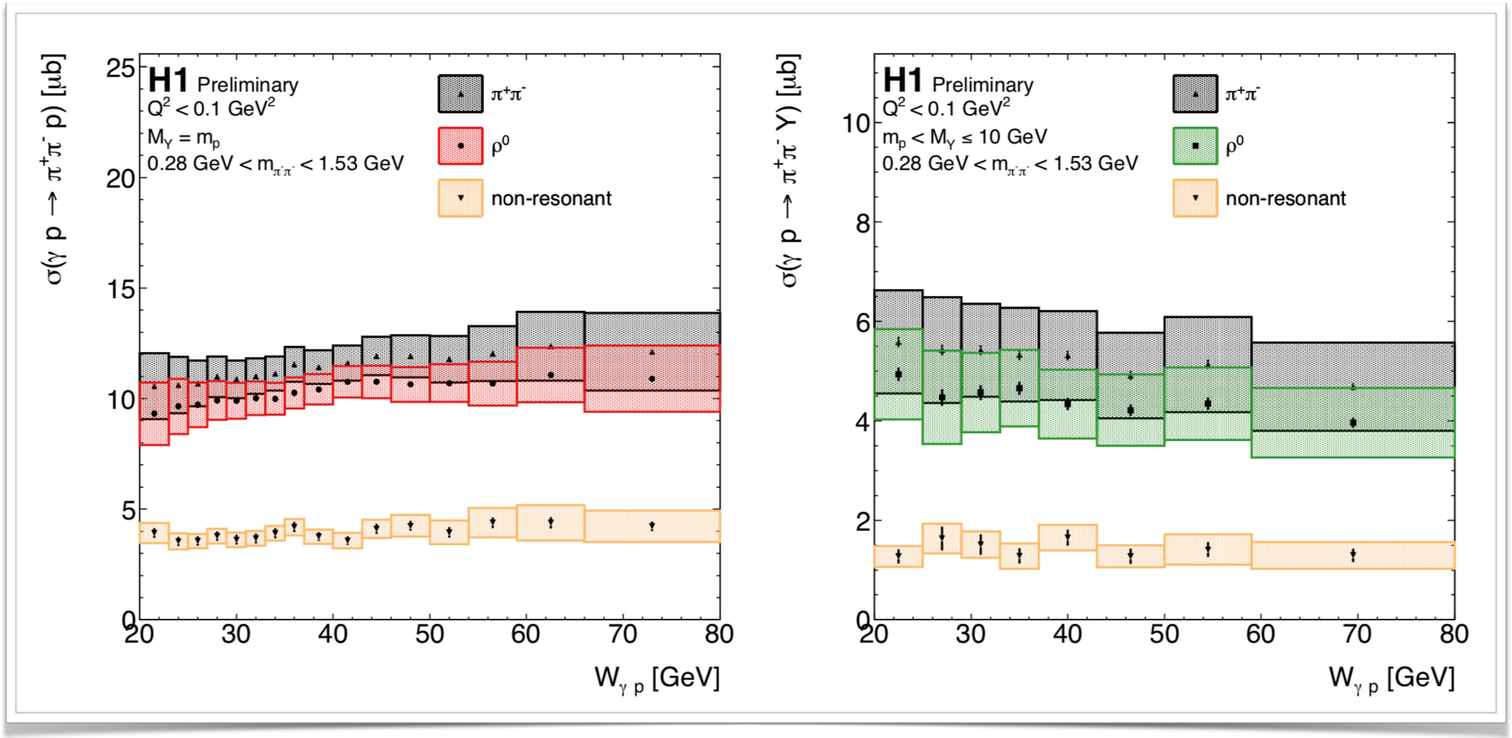
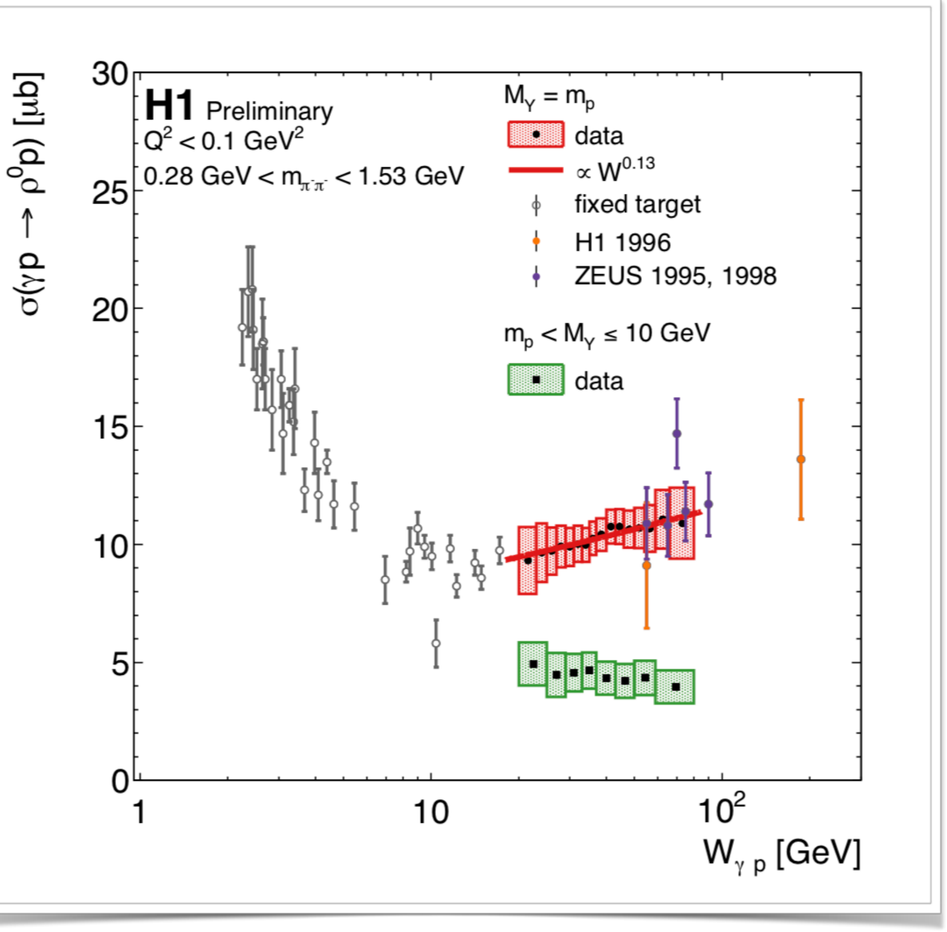
http://www-h1.desy.de/publications/htmlsplit/H1prelim-18-012.long.html





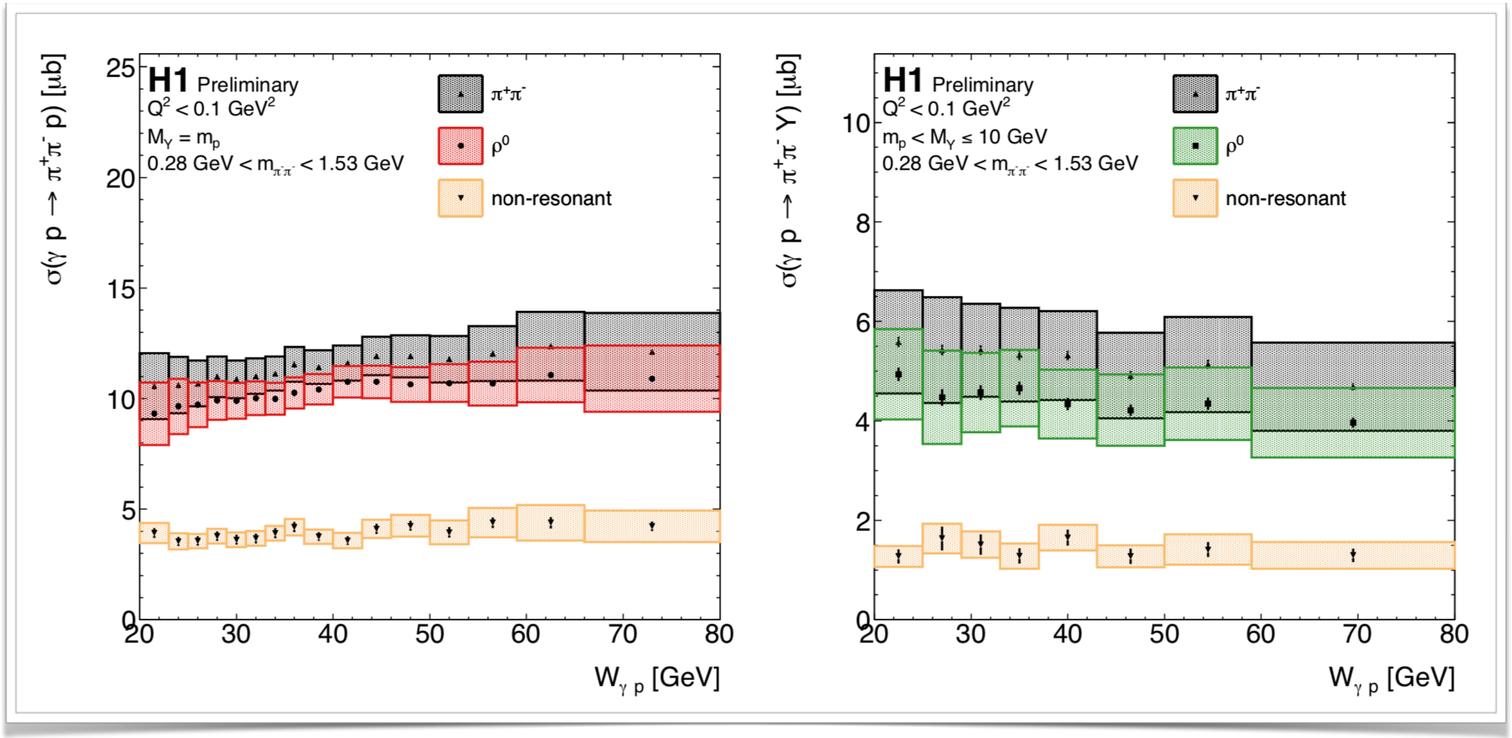
Measurement of exclusive and **dissociative** cross sections!

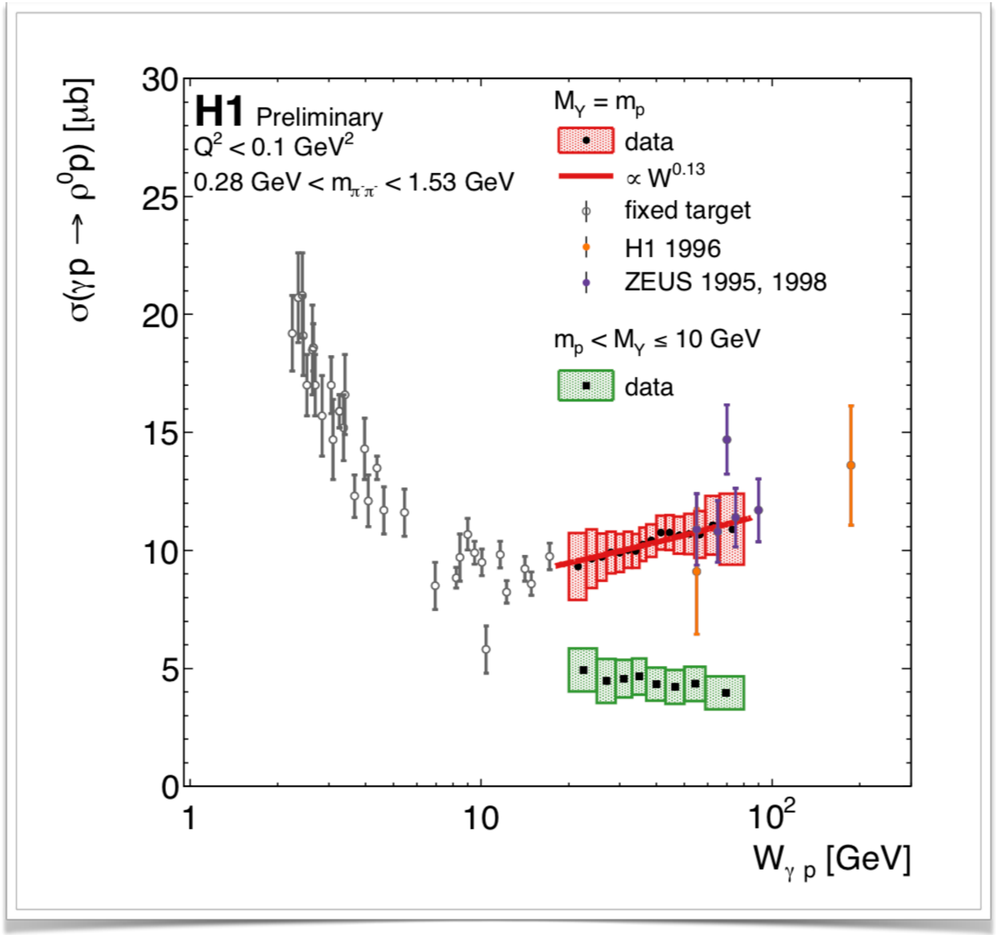
News from HERA: ρ photoproduction off protons

Wednesday in the WG2 session

Exclusive $\rho(770)$ photoproduction at HERA, Arthur Bolz.

http://www-h1.desy.de/publications/htmlsplit/H1prelim-18-012.long.html





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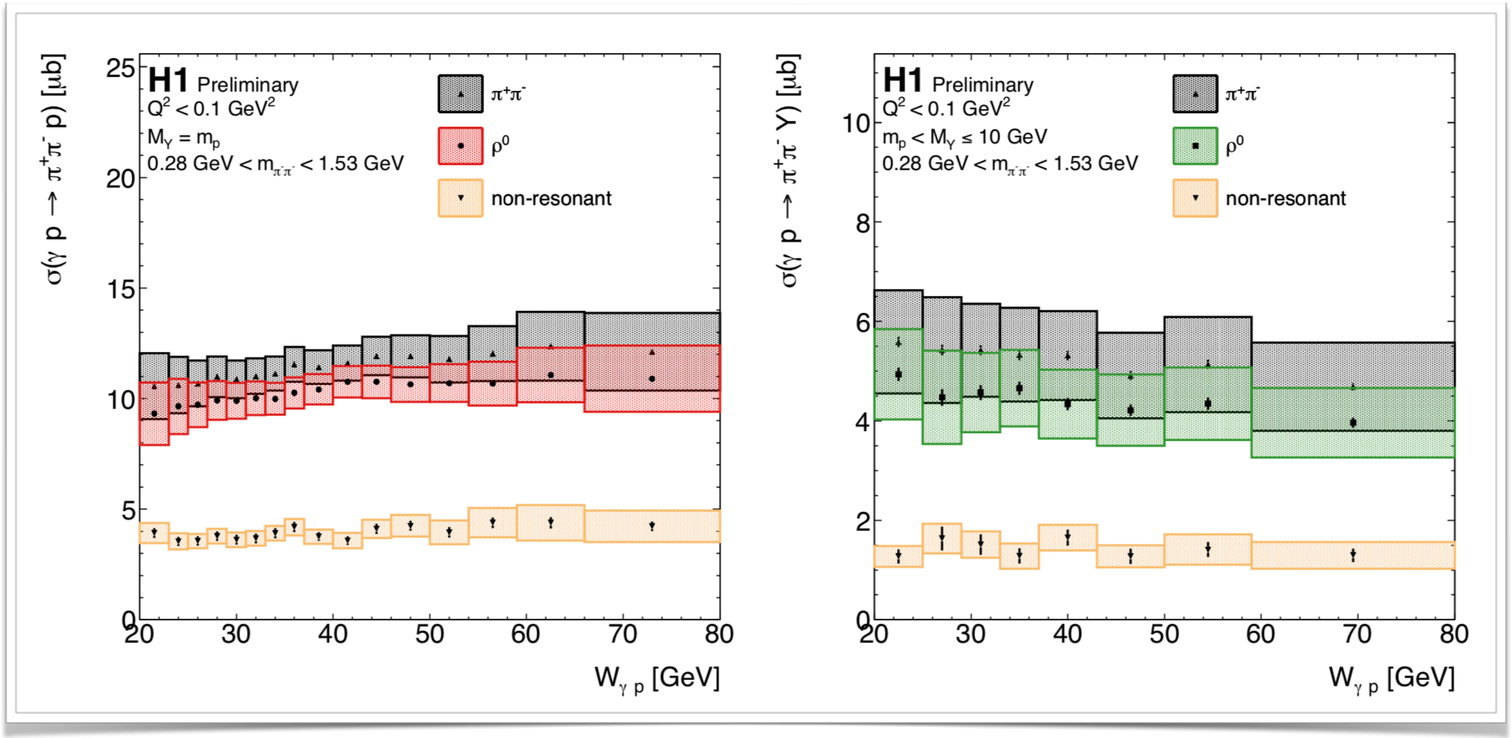
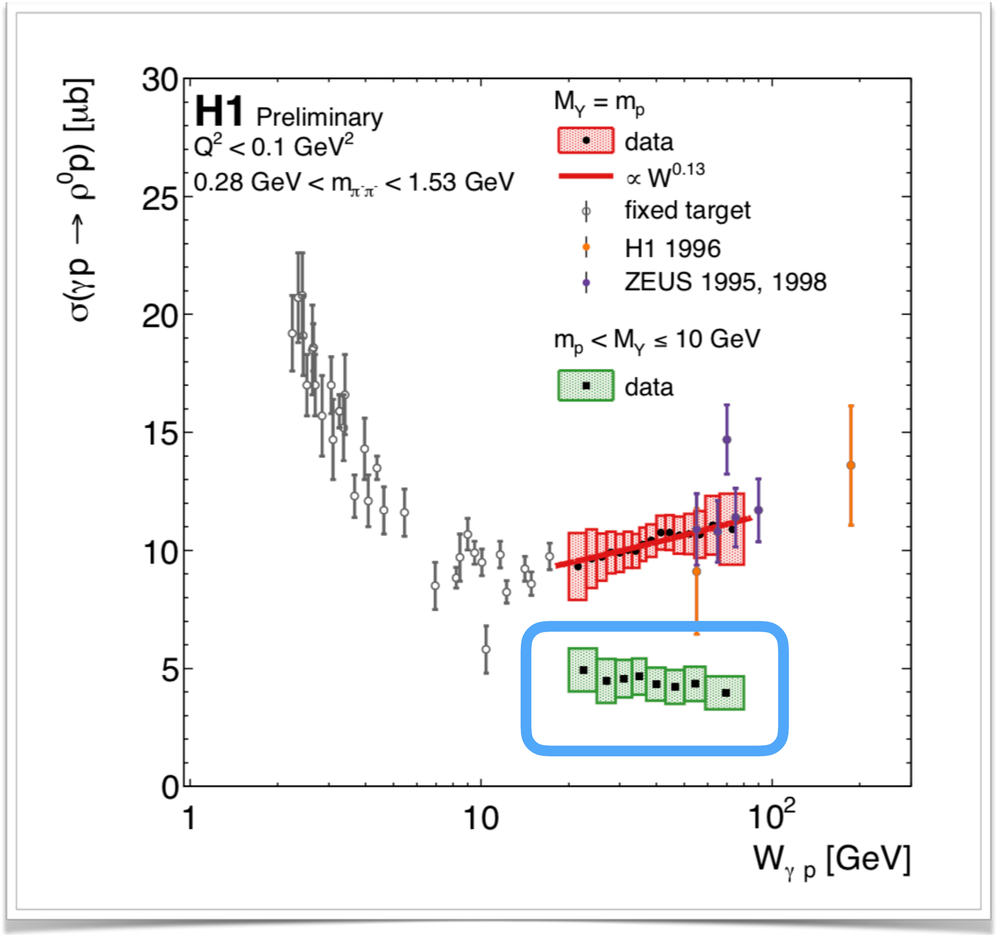
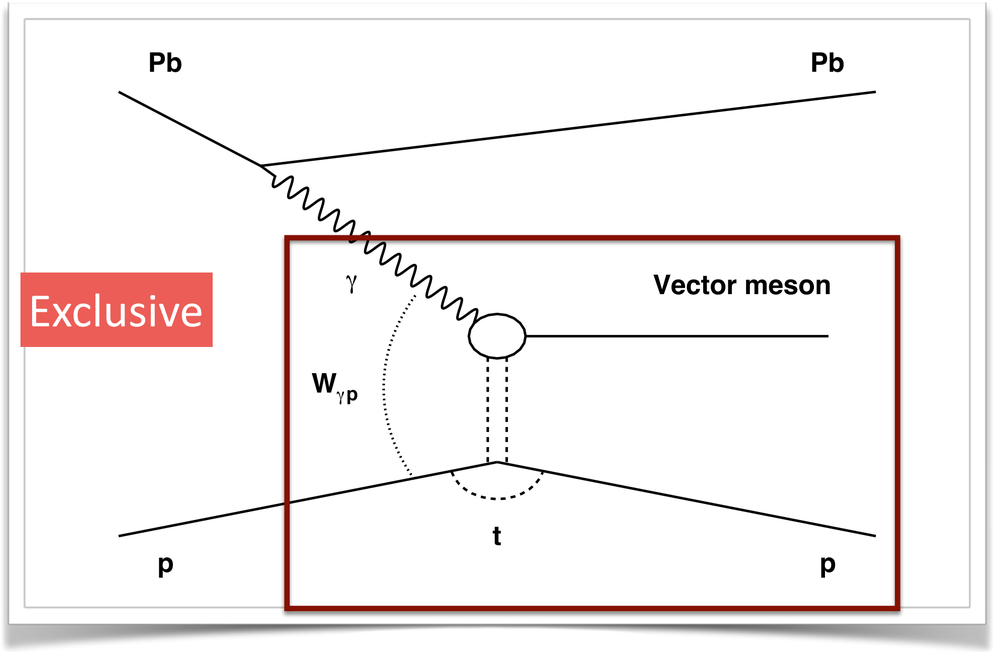




Measurement of exclusive and **dissociative** cross sections!

Dissociation: a new window to saturation at future EIC?

Exclusive and dissociative vector meson production in a Good-Walker approach



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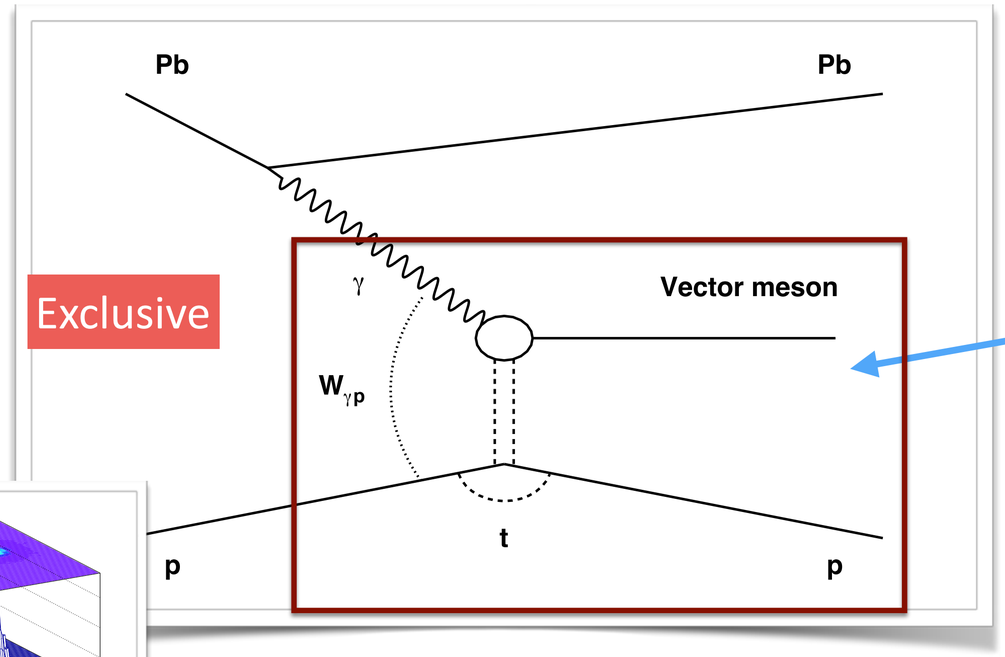

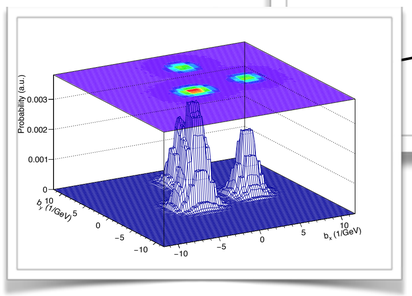

$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi p)}{dt} = \frac{R_g^2}{16\pi}\left|\left\langle A(x, Q^2, \vec{\Delta})\right\rangle\right|^2$$

Average over configurations

Good,Walker , PR 120 (1960) 1857

Miettinen, Pumplin, PRD18 (1978) 1696

Mantysaari, Schenke, PRL 117 (2016) 052301

Exclusive and dissociative vector meson production in a Good-Walker approach

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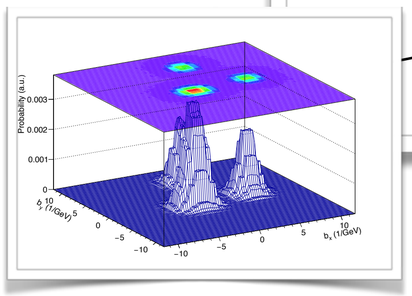

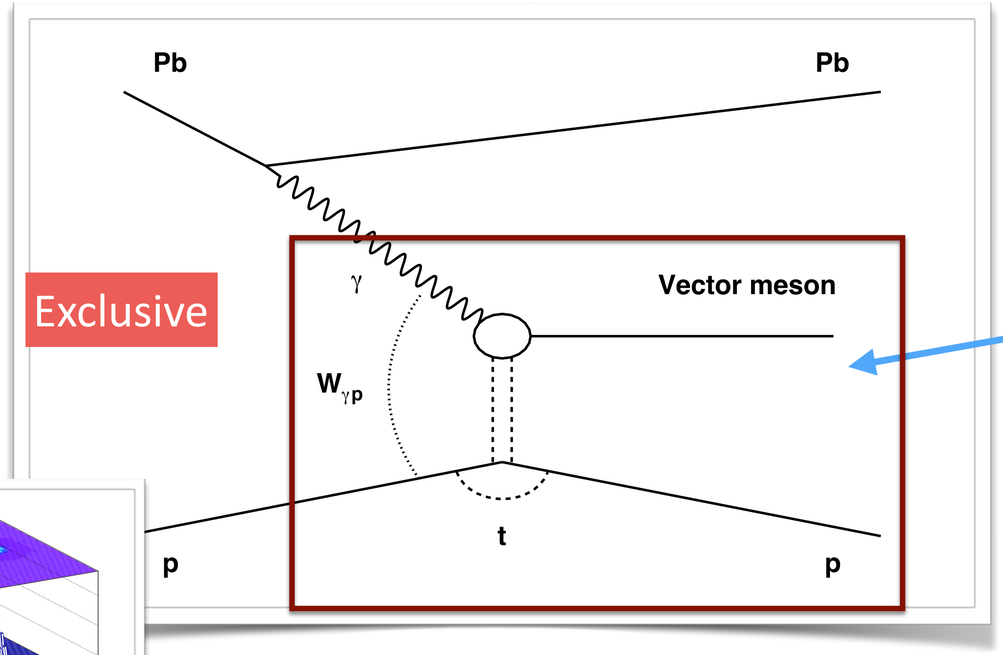

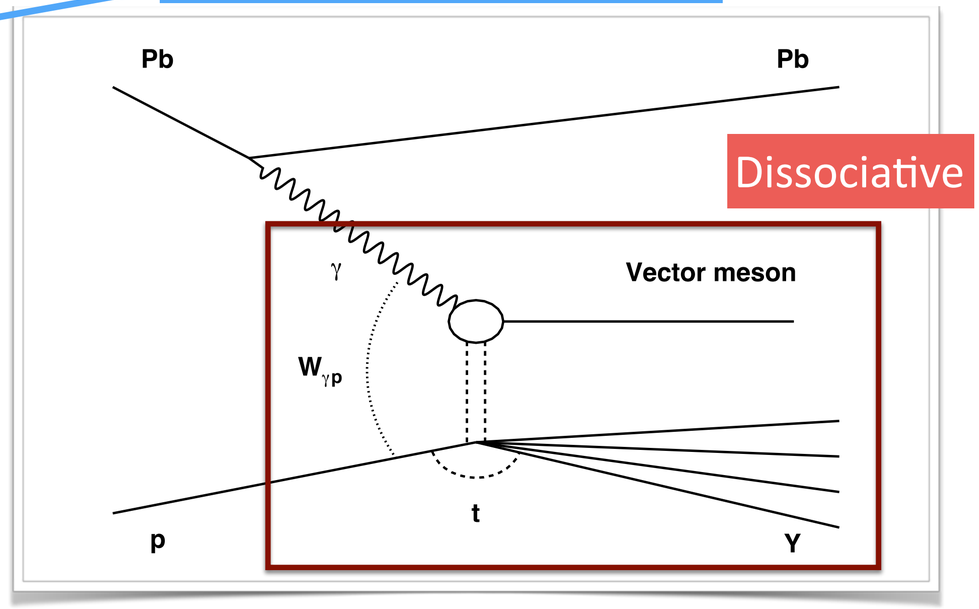

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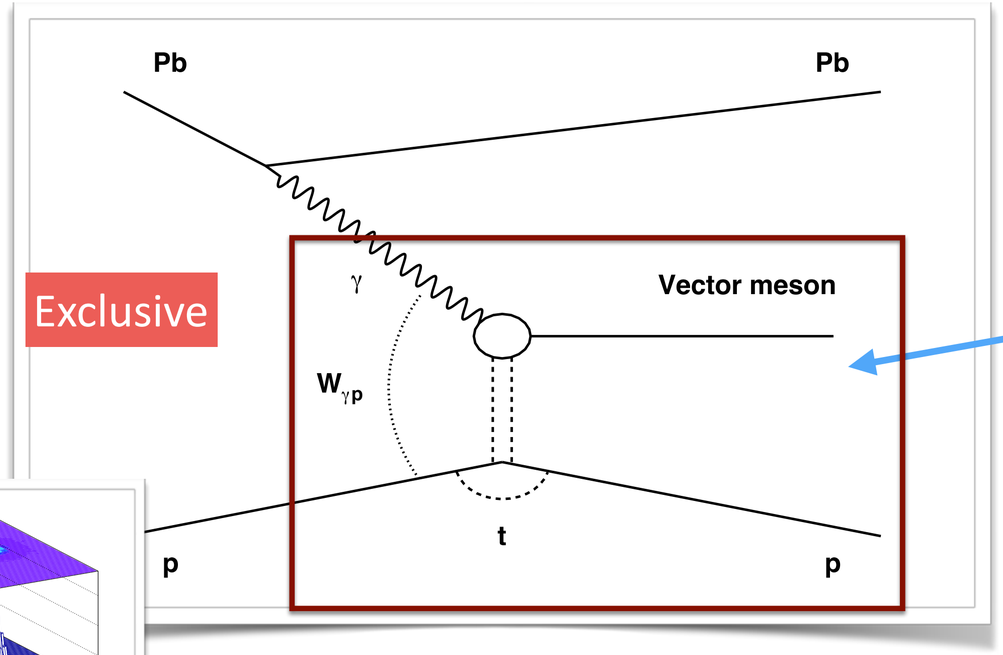
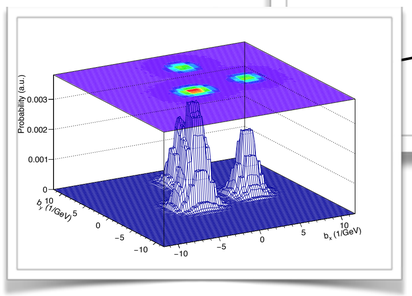
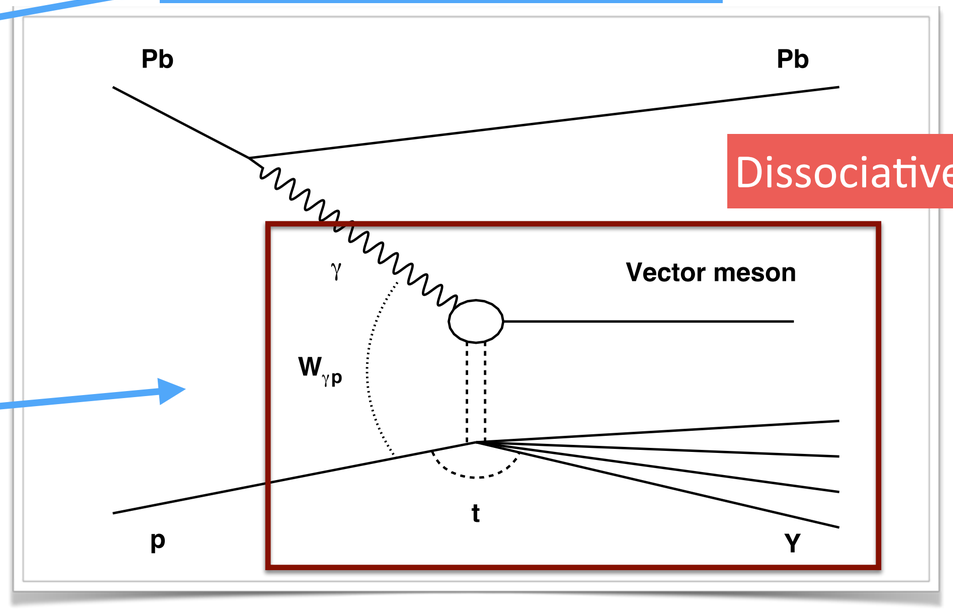
Exclusive





Dissociative



Variance over configurations

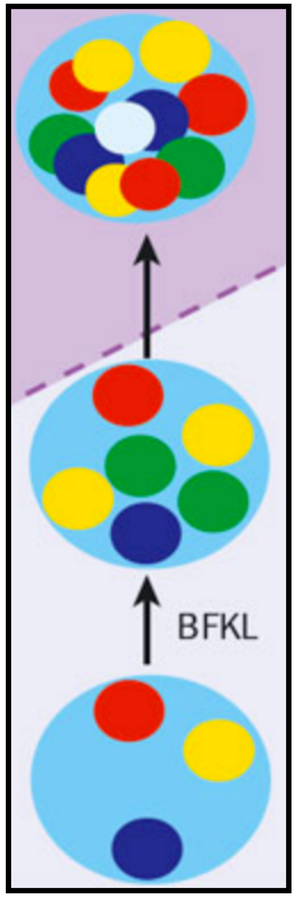
$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

Good,Walker , PR 120 (1960) 1857

Miettinen, Pumplin, PRD18 (1978) 1696

Mantysaari, Schenke, PRL 117 (2016) 052301

Energy-dependent hot spot model



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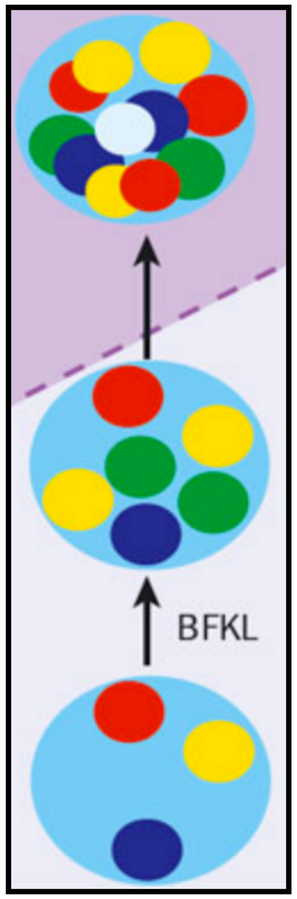
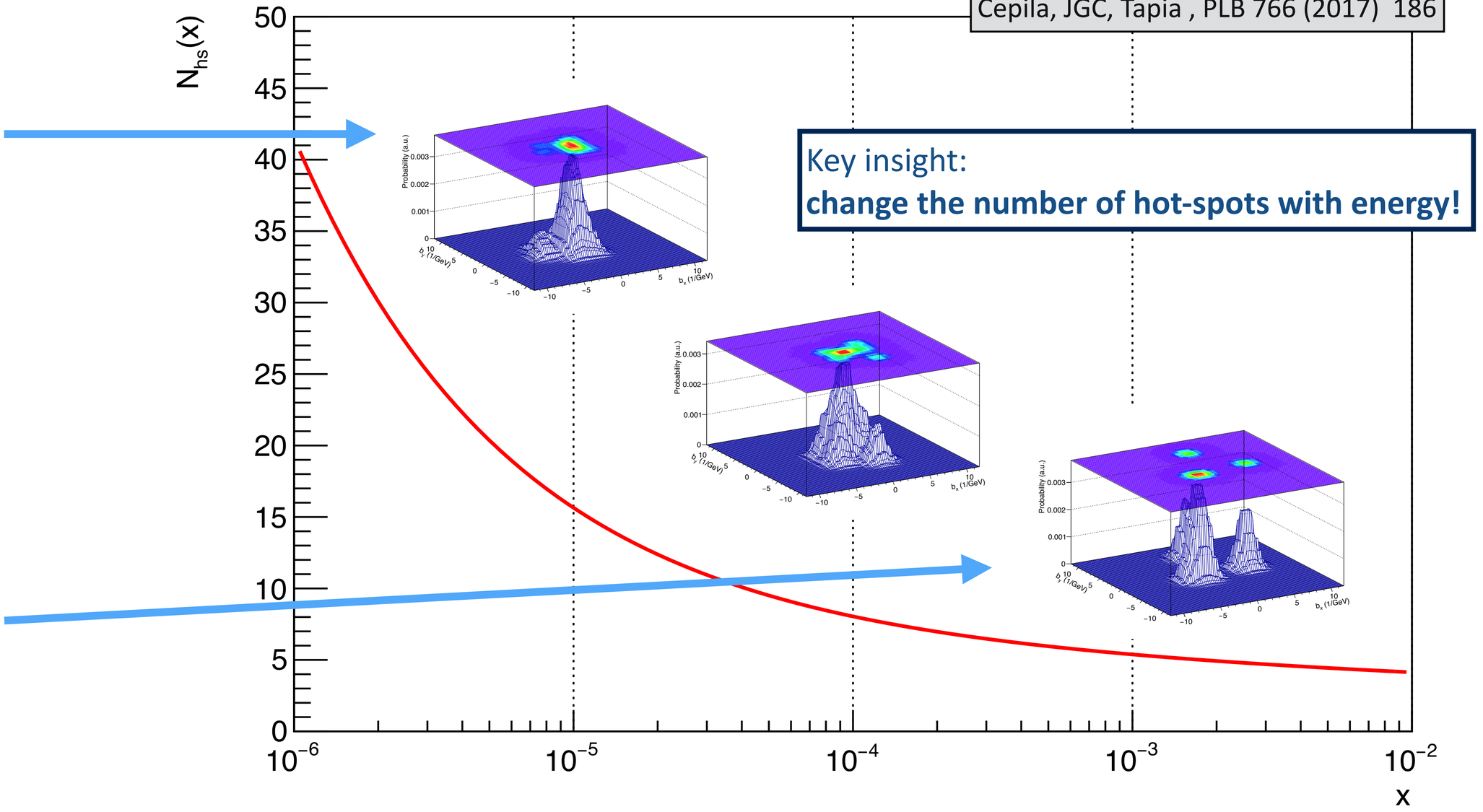


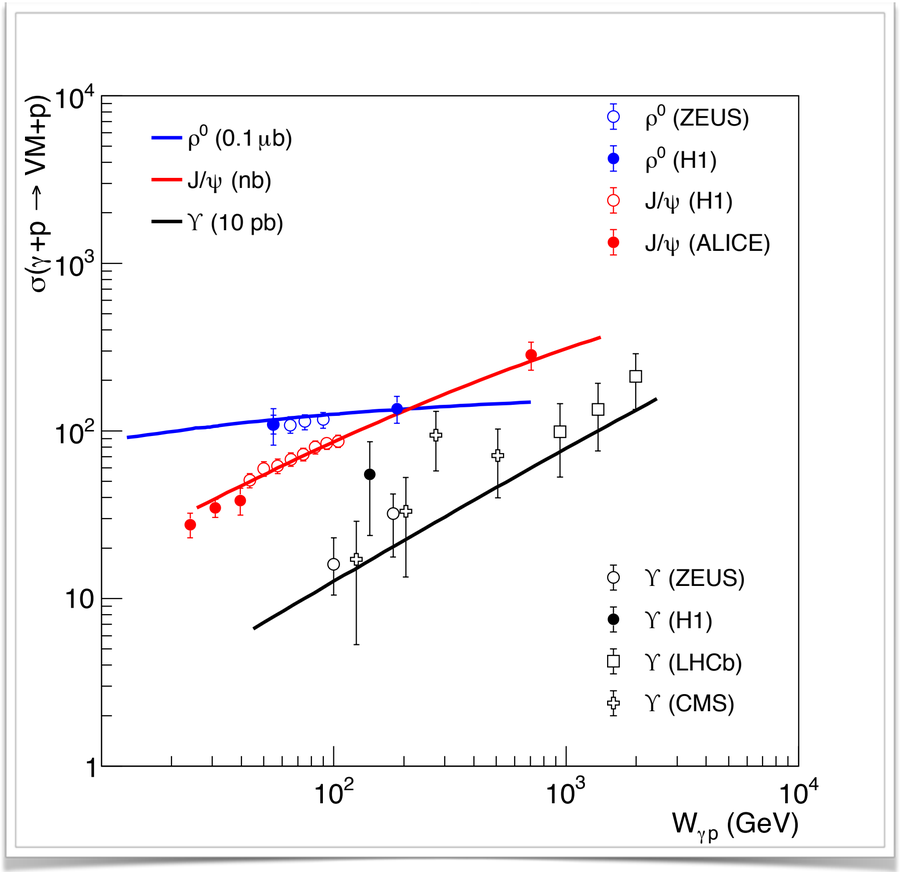
Čepila, JGC, Tapia , PLB 766 (2017) 186

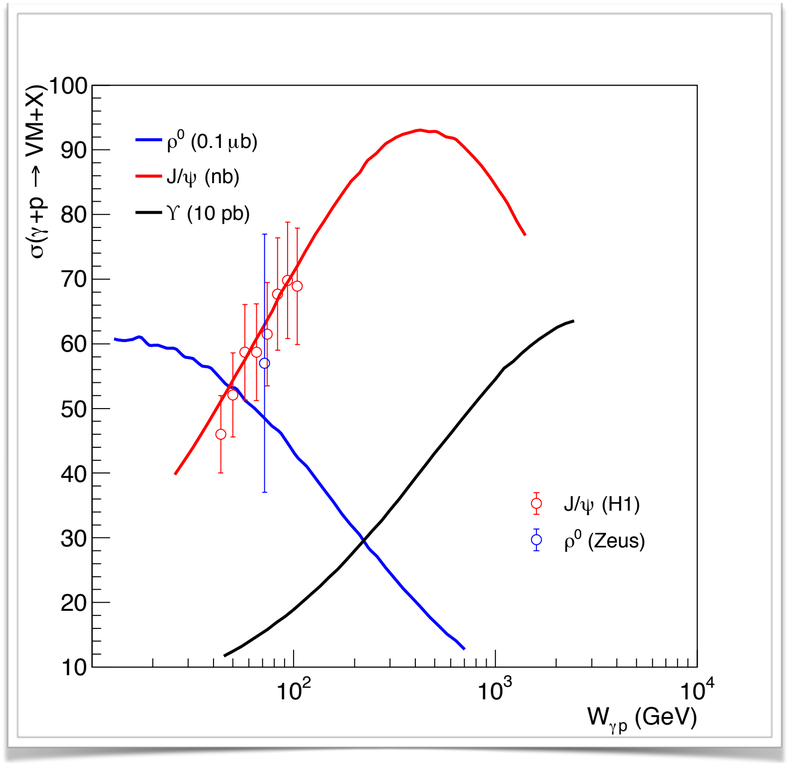


Key insight:
change the number of hot-spots with energy!

Prediction for the energy dependence of dissociative production

Čepila, JGC, Krelina, Tapia NPB934 (2018) 330

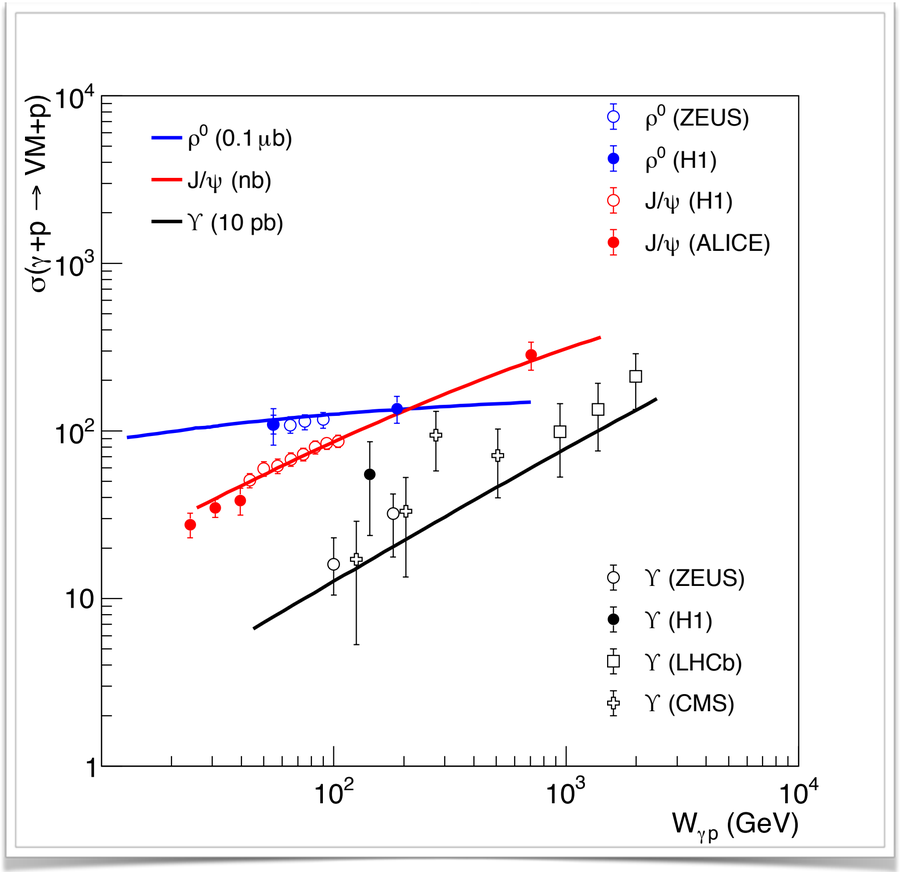


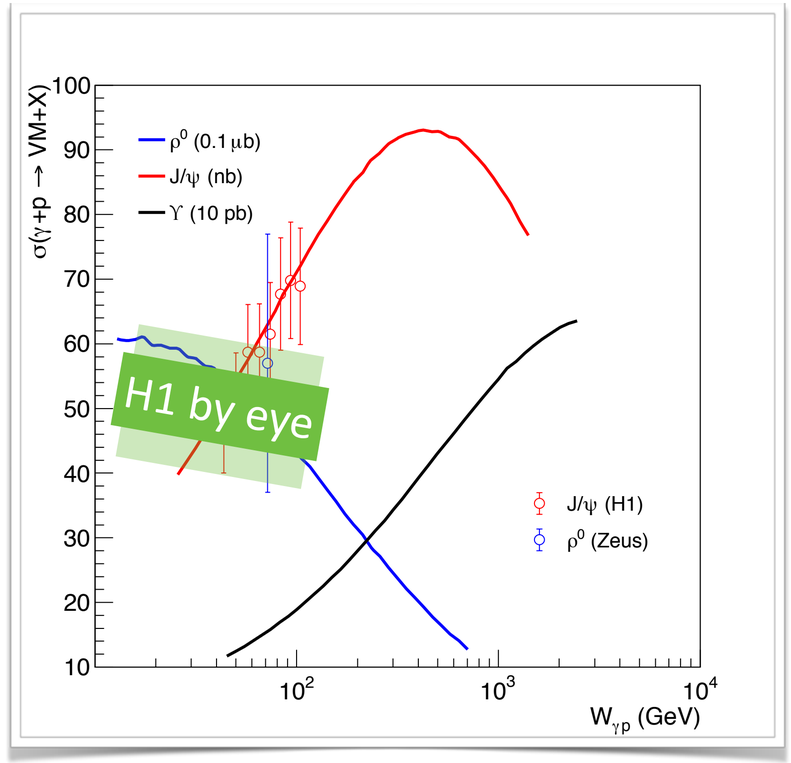


Correct description of available data.

Prediction for the energy dependence of dissociative production

Čepila, JGC, Krelina, Tapia NPB934 (2018) 330





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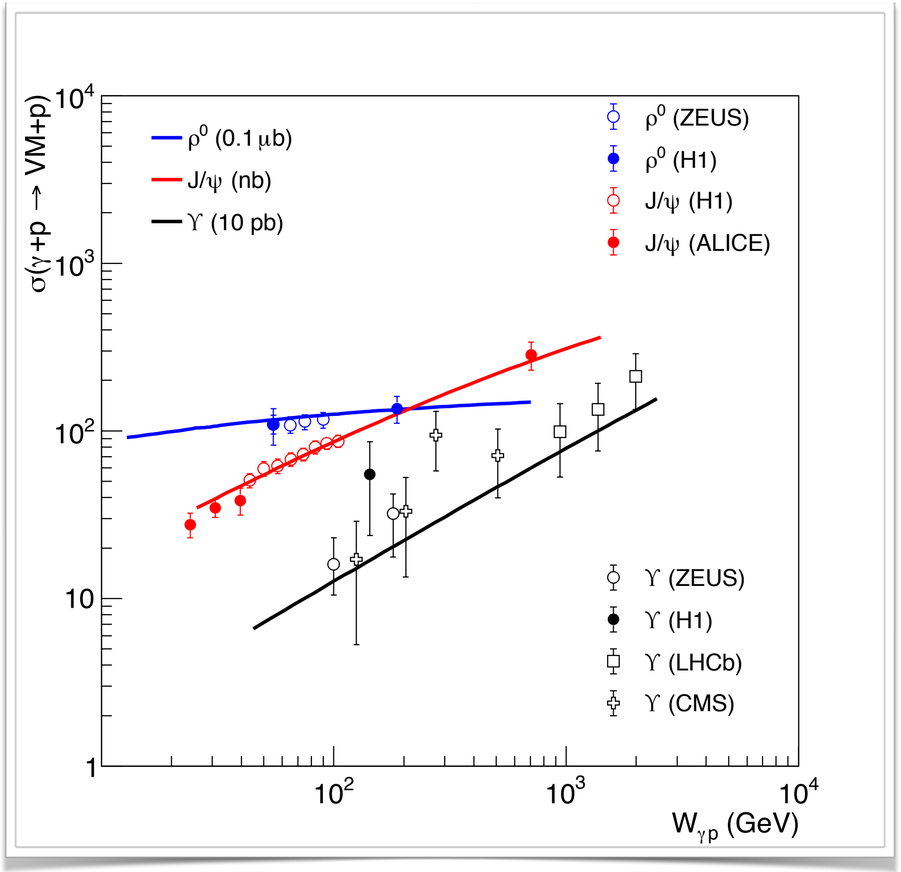

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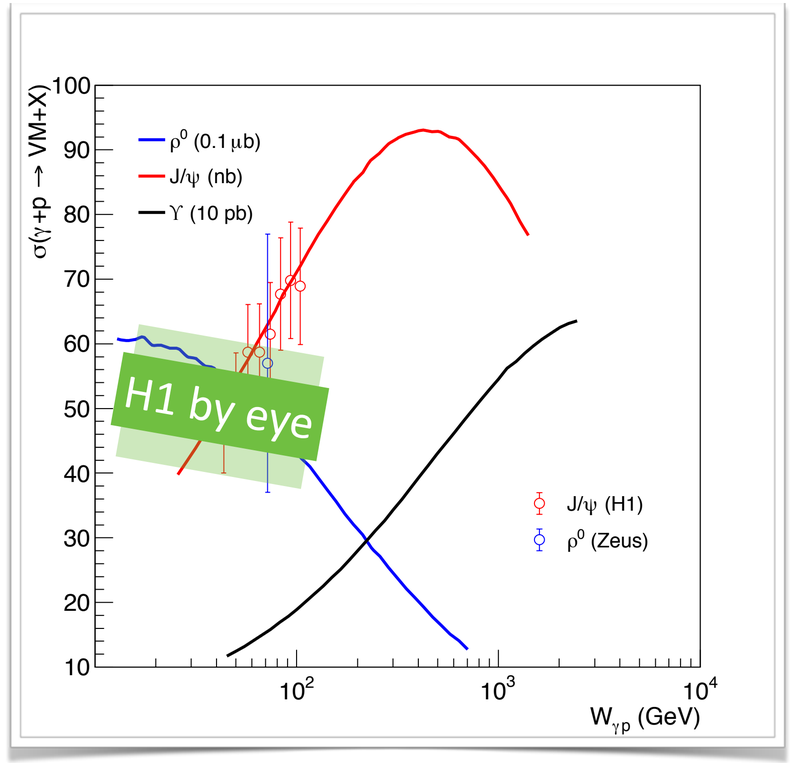
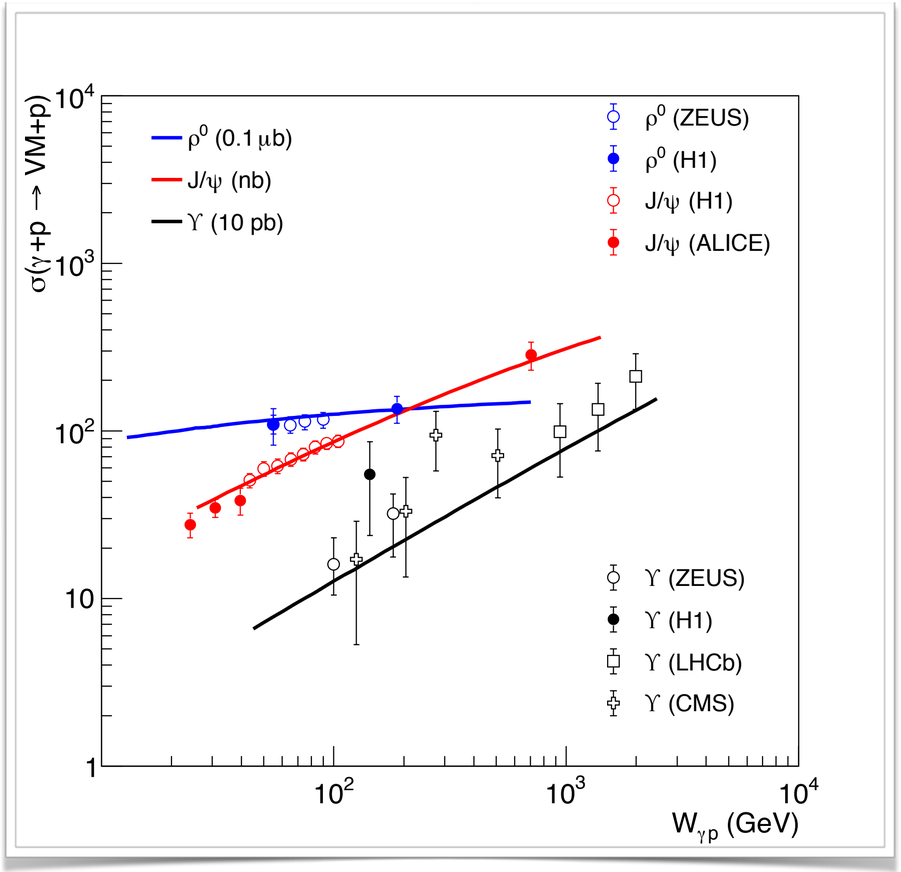


Behaviour of dissociative cross section depends on the **mass** of the vector meson.

Prediction for the energy dependence of dissociative production

Čepila, JGC, Krelina, Tapia NPB934 (2018) 330



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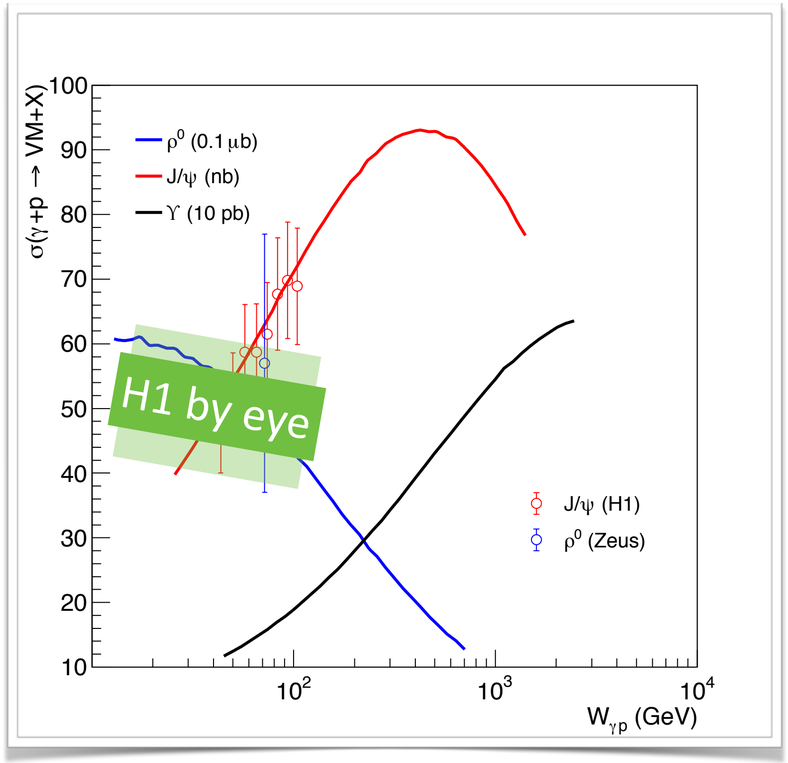
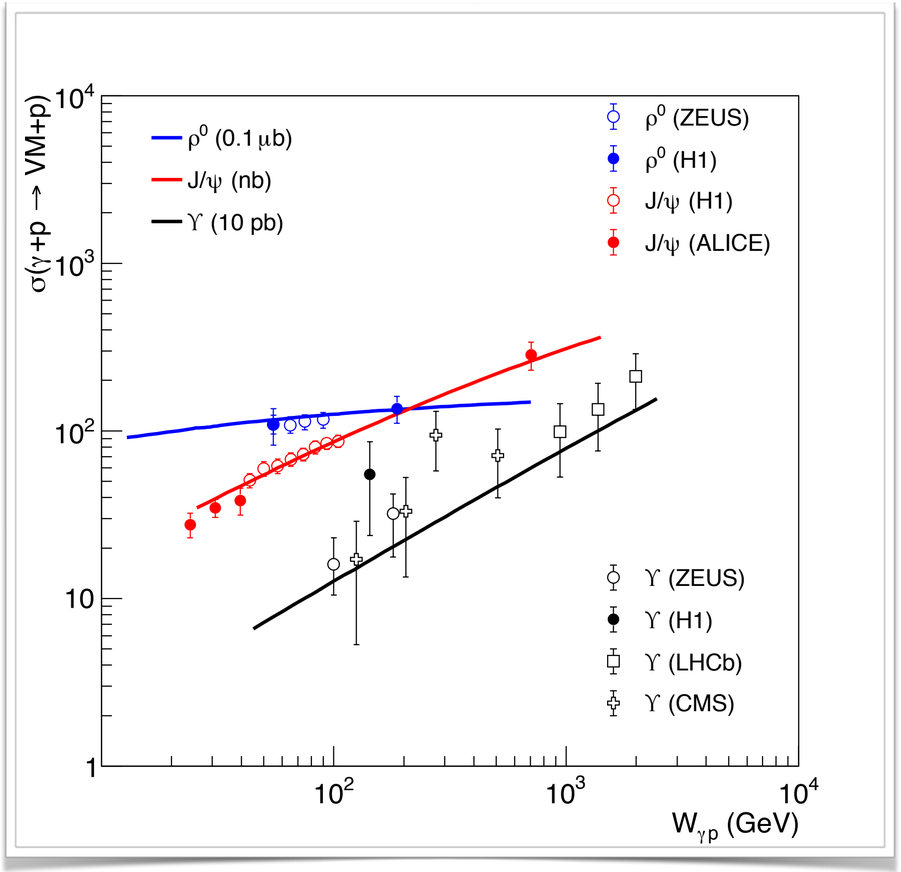


Behaviour of dissociative cross section depends on the **mass** of the vector meson.

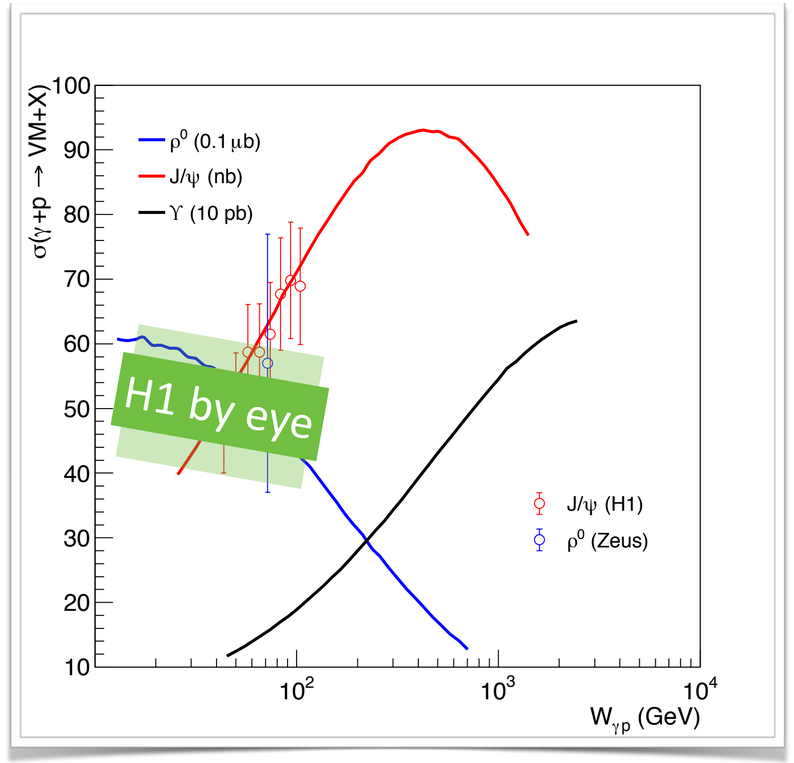
Decrease of the cross section, means smaller variance.
All targets look the same: **saturation in transverse plane.**

Prediction for the energy dependence of dissociative production

Čepila, JGC, Krelina, Tapia NPB934 (2018) 330



Correct description of available data.



Behaviour of dissociative cross section depends on the **mass** of the vector meson.

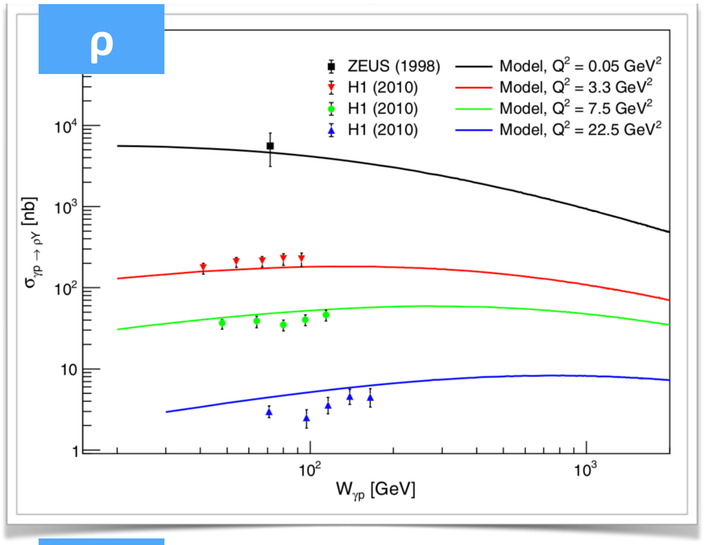
Decrease of the cross section, means smaller variance.
All targets look the same: **saturation in transverse plane.**

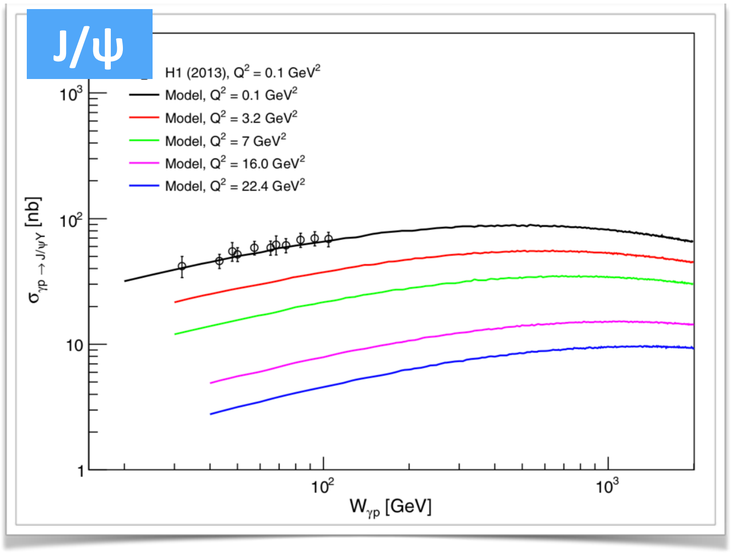
Saturation effects kick in at the position of the maximum

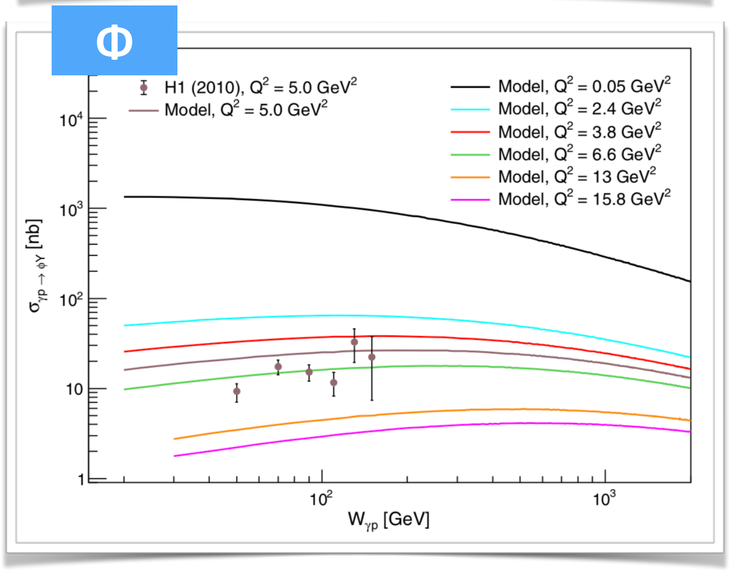
Dissociative electroproduction of vector mesons: new window to saturation?

Bendová, Čepila, JGC, PRD99 (2019) 034025

Different colours, different Q^2 values.







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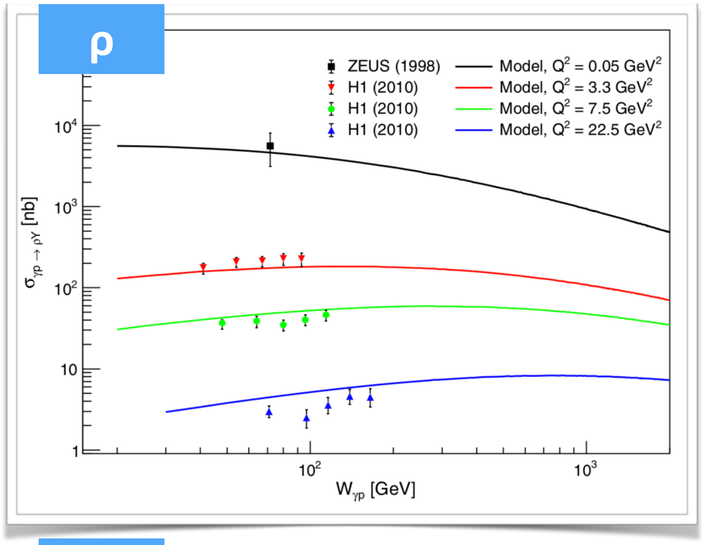

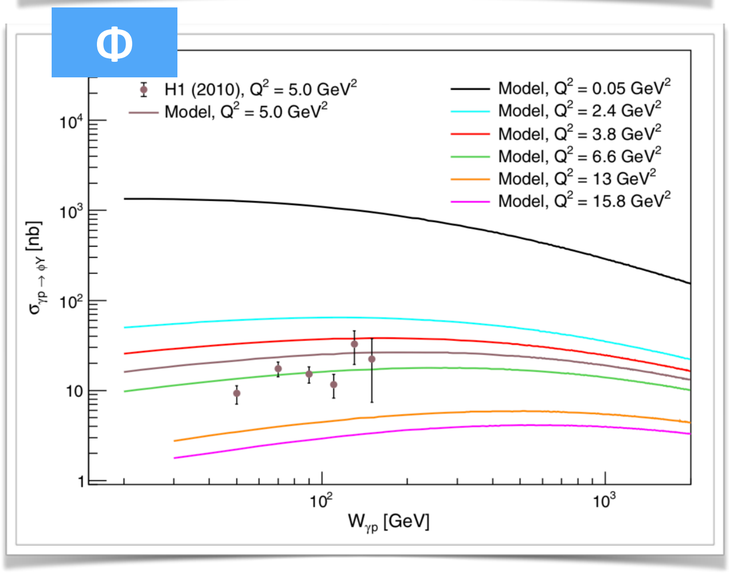

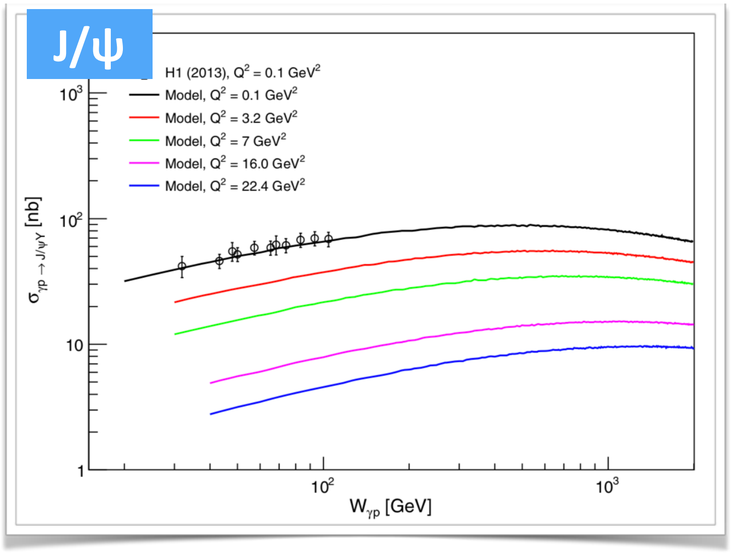

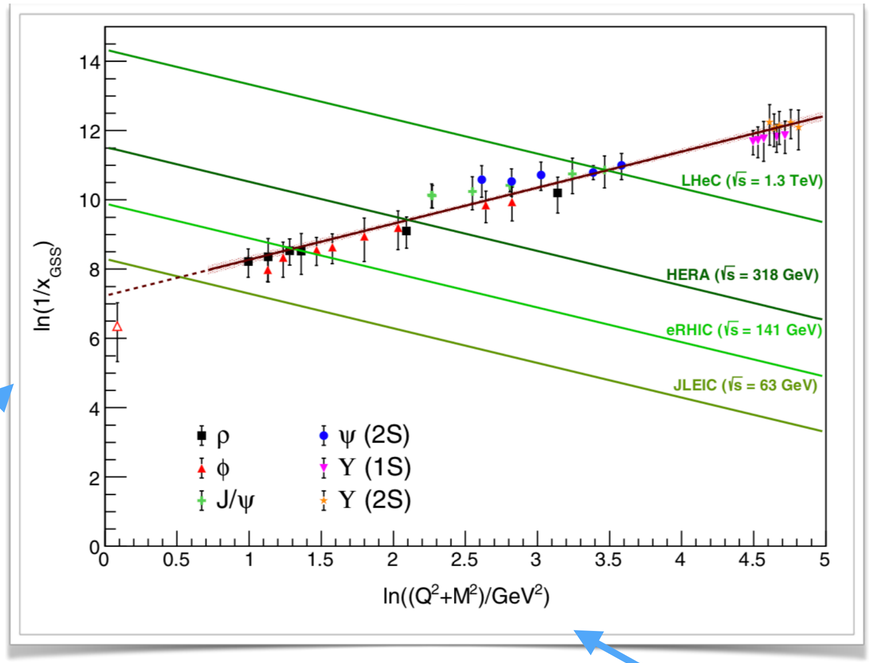

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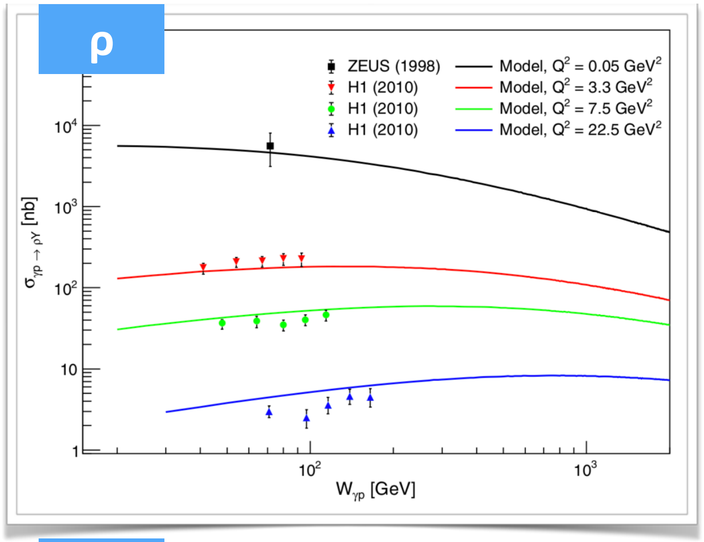

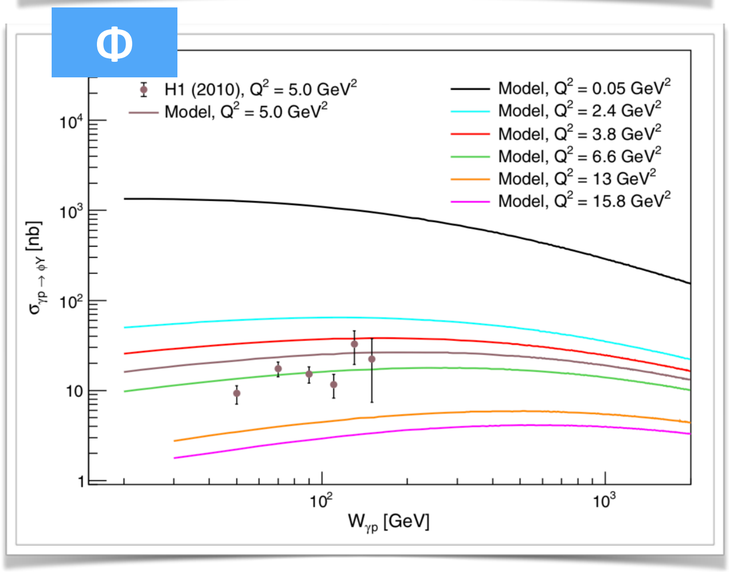

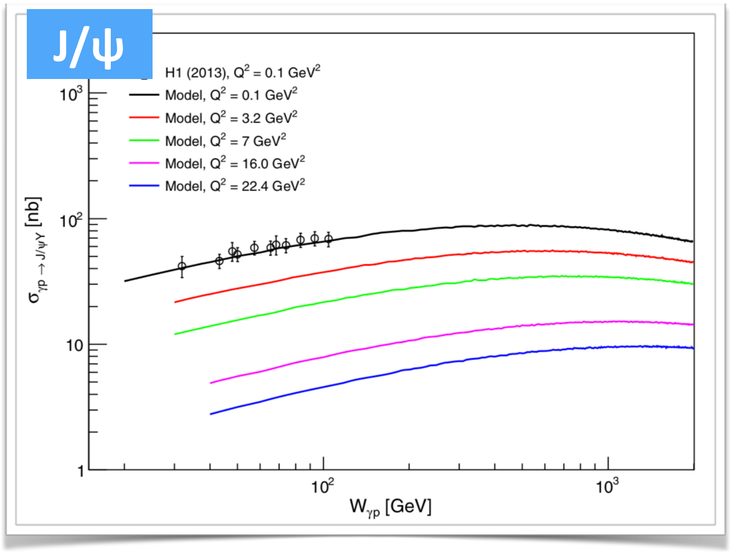

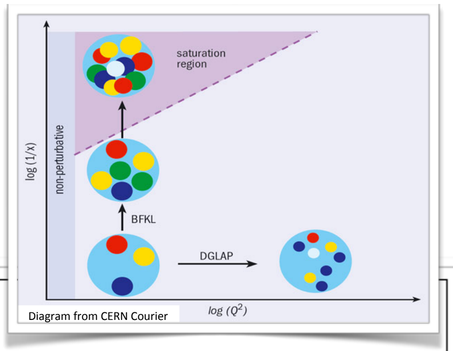

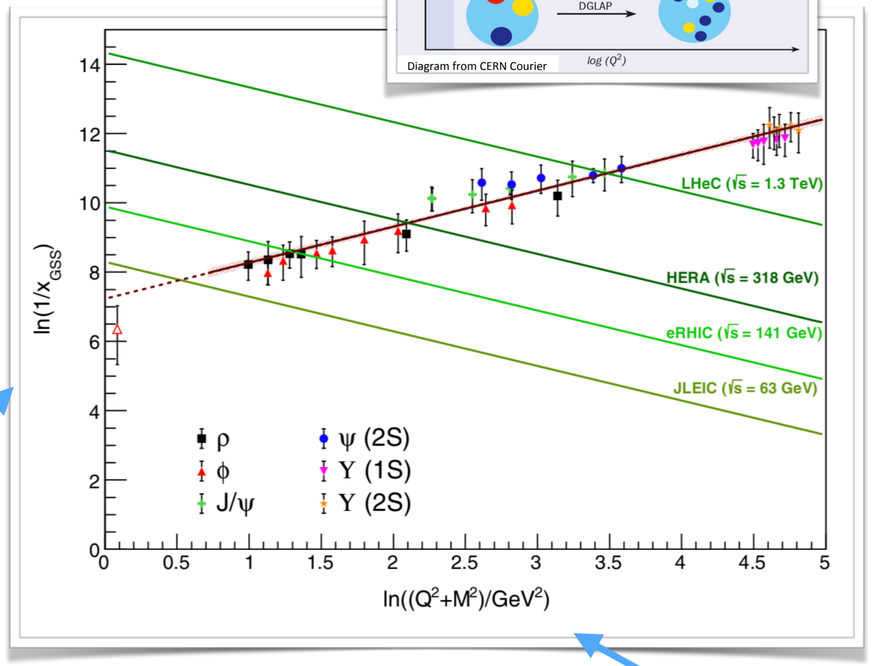

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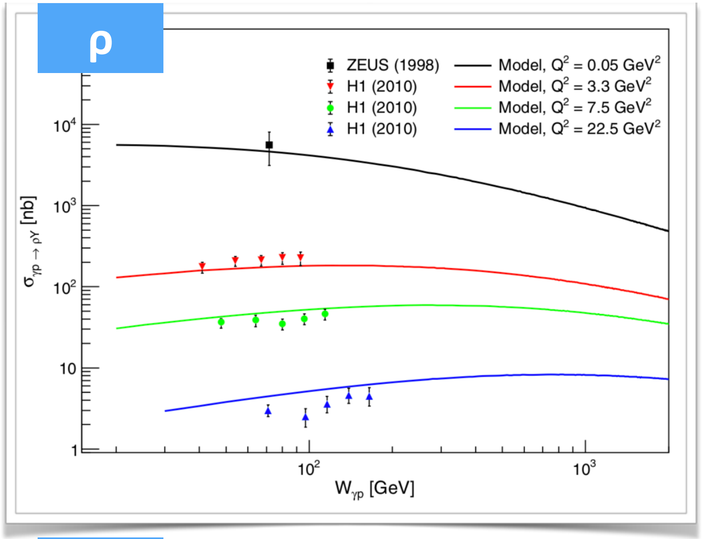

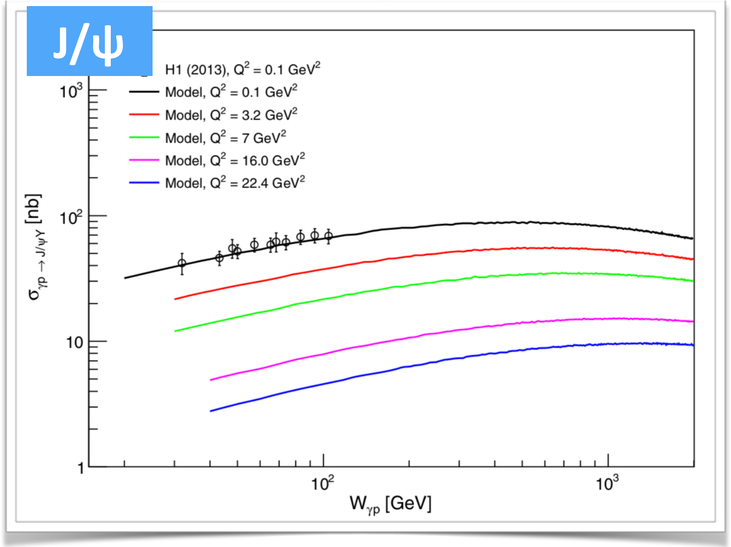

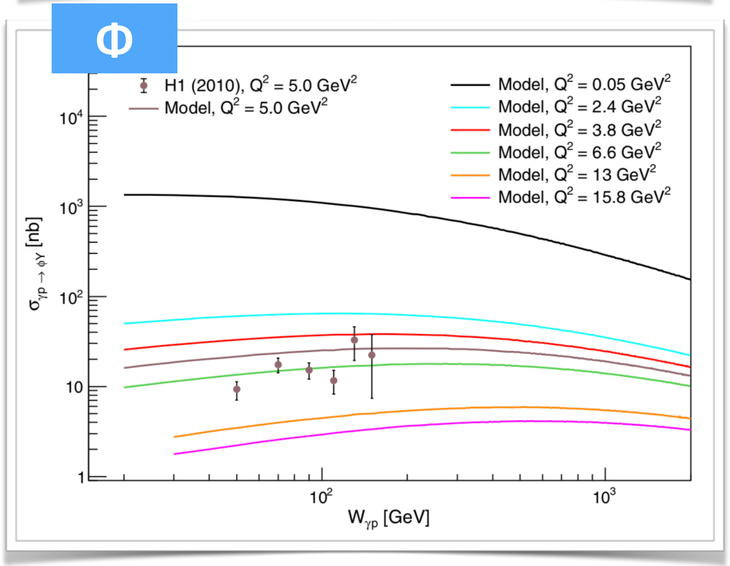

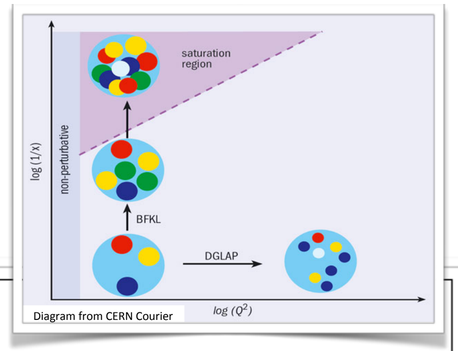

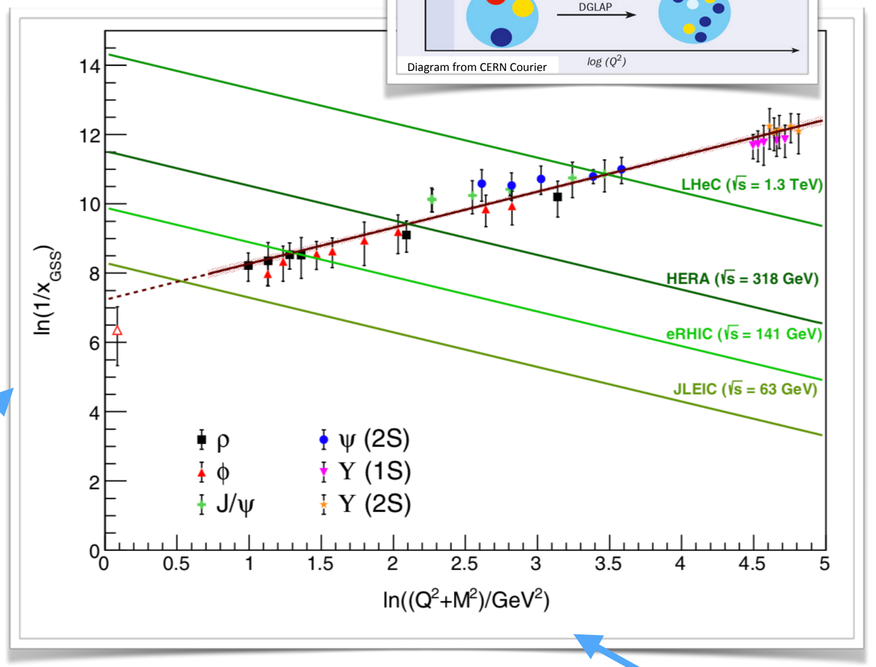

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It will be possible to open this window to saturation at the EIC!

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Enjoy DIS2019!