Postscriptum: What are Leptoquarks?

Leptoquarks are hypothetical particles that carry both lepton (L) and baryon number (B). Their other quantum numbers, like spin, (fractional) electric charge and weak isospin vary among models. Leptoquarks are encountered in various extensions of the Standard Model, such as technicolor theories, theories of quark–lepton unification (e.g., Pati–Salam model), or GUTs based on SU(5), SO(10), E6, etc. Leptoquarks are currently searched for in experiments ATLAS and CMS at the Large Hadron Collider in CERN.

Table 94.1: Possible leptoquarks and their quantum numbers.

Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	$1/3$	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$
0	-2	$\bar{3}$	1	$4/3$	$\bar{d}^c_R e_R$
0	-2	$\bar{3}$	3	$1/3$	$\bar{q}^c_L \ell_L$
1	-2	$\bar{3}$	2	$5/6$	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$
0	0	3	2	$7/6$	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	$1/6$	$\bar{d}_R \ell_L$
1	0	3	1	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	$5/3$	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$

CERN-TH-97-195
hep-ph/9708437

HERA DATA AND LEPTOQUARKS IN SUPERSYMMETRY

G. Altarelli [a]

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I present a concise review of the possible evidence for new physics at HERA and of the recent work towards a theoretical interpretation of the signal. It is not clear yet if the excess observed at large Q^2 is a resonance or a continuum (this tells much about the quality of the signal). I discuss both possibilities. For the continuum case one considers either modifications of the quark structure functions or contact terms. In the case of a resonance, a leptoquark, the most attractive possibility that is being studied is in terms of s-quarks with R-parity violation. In writing this script I updated the available information to include the new data and the literature presented up to August 1, 1997.

Postscriptum: ISABELLE

No Stock

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ISABELLE

A Proposal for Construction
of a
Proton-Proton
Storage Accelerator Facility

May 1976

MASTER

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

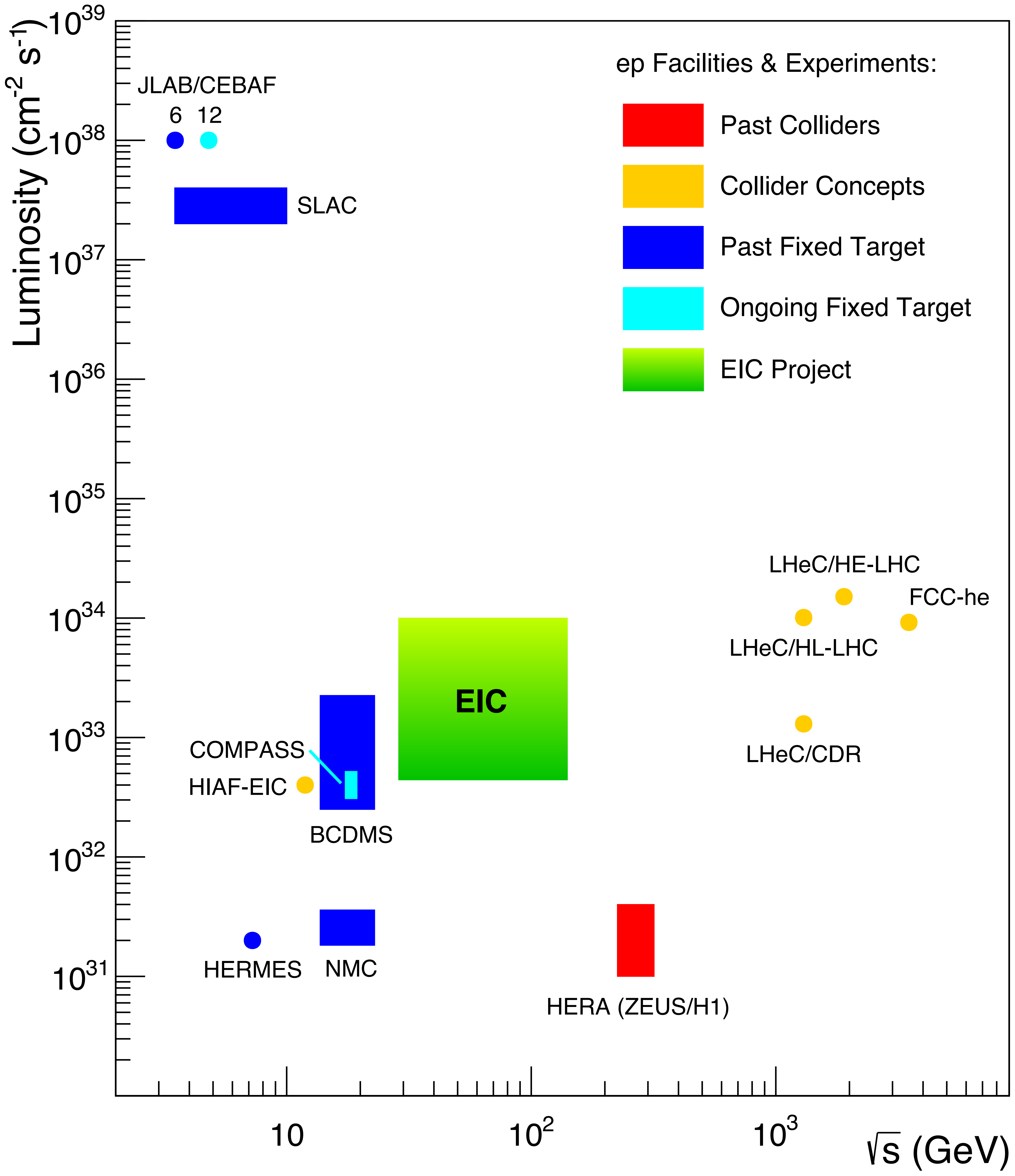
over the entire range. An overview of the physics potential of this machine is given, covering the production of charged and neutral intermediate vector bosons, the hadron production at high transverse momentum, searches for new, massive particles, and the energy dependence of the strong interactions. The

ISABELLE (also known later as Colliding Beam Accelerator, CBA) was a 200+200 GeV proton–proton colliding beam particle accelerator partially built by the US government at BNL.

New York politicians pushed through funding before development of magnet technology had been completed. Construction began in 1978. The following year a prototype SC magnet was successfully tested. In 1981, however, production models of magnets failed at less than the magnetic field intensity needed for operation.

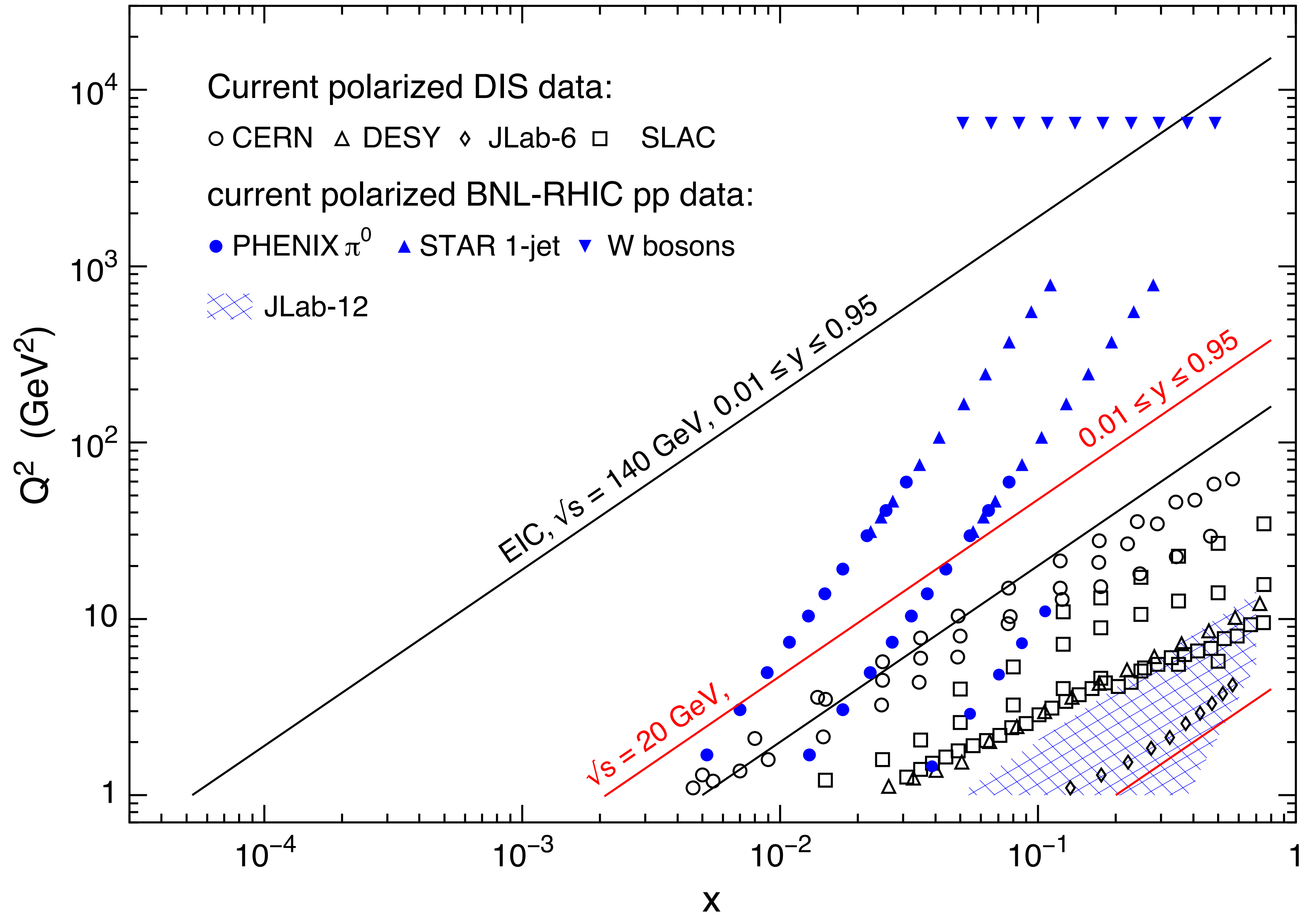
Delays in the project led to competitive evaluation against a proposal for a much larger machine, eventually called the Superconducting Supercollider, a proton-proton system aimed at 20+20 TeV; while developments in Europe at CERN, including discovery of the W and Z bosons, appeared to make ISABELLE redundant. In July, 1983, the U.S. Department of Energy cancelled the ISABELLE project after spending more than US$200 million on it.

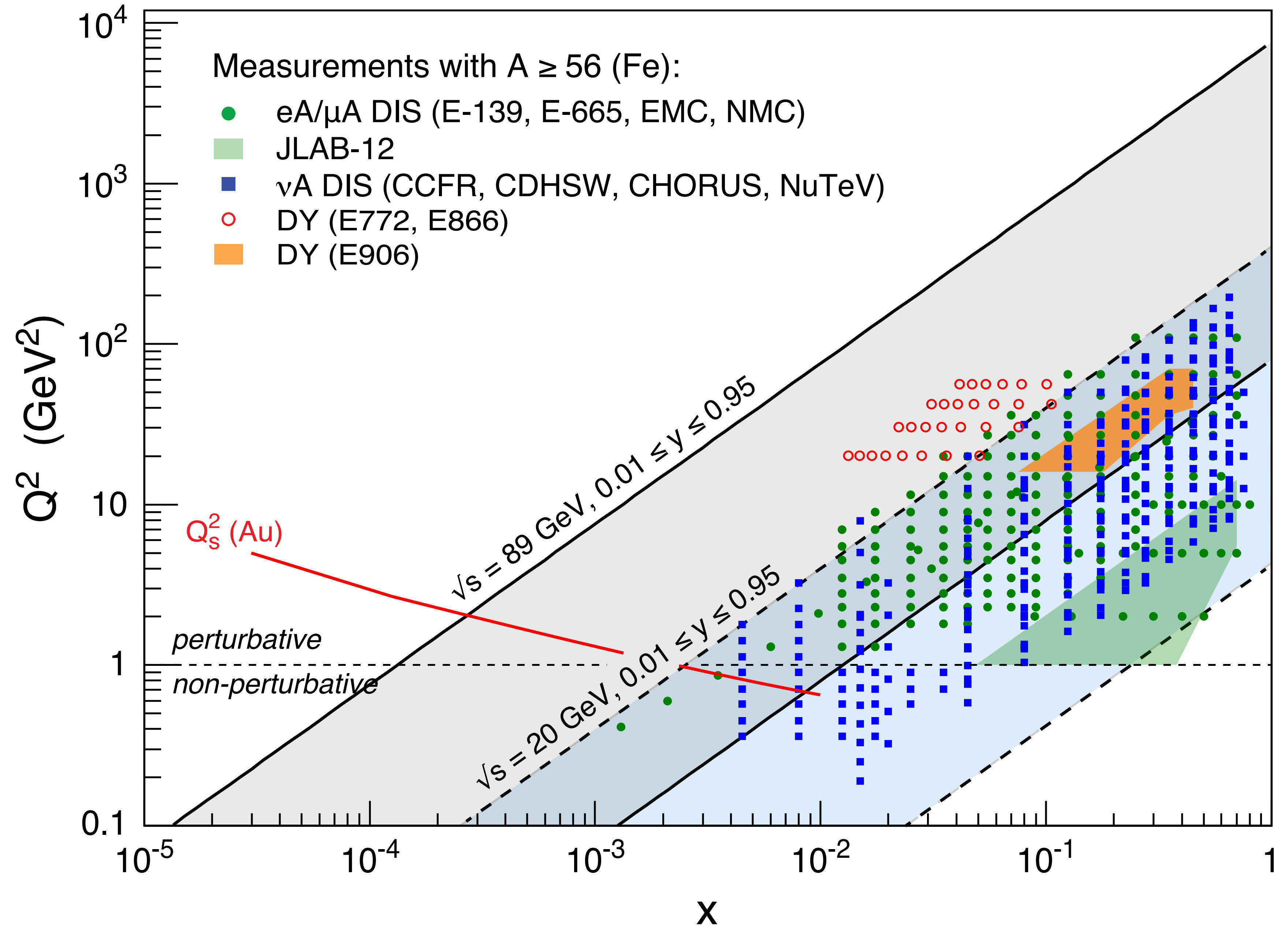
Landscape of DIS: The Uniqueness of EIC



- EIC cannot compete with e+p at HERA ($\sqrt{s}$ = 318 GeV)
- EIC's strength is polarized e↑+p↑ and e+A collisions
- Here the kinematic reach extends substantially compared to past (fixed target) coverage
  - Q^2×20, x/20 for e+A
  - Q^2×20, x/100 for polarized e↑+p↑

Landscape of DIS: The Uniqueness of EIC





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  - Q^2×20, x/20 for e+A
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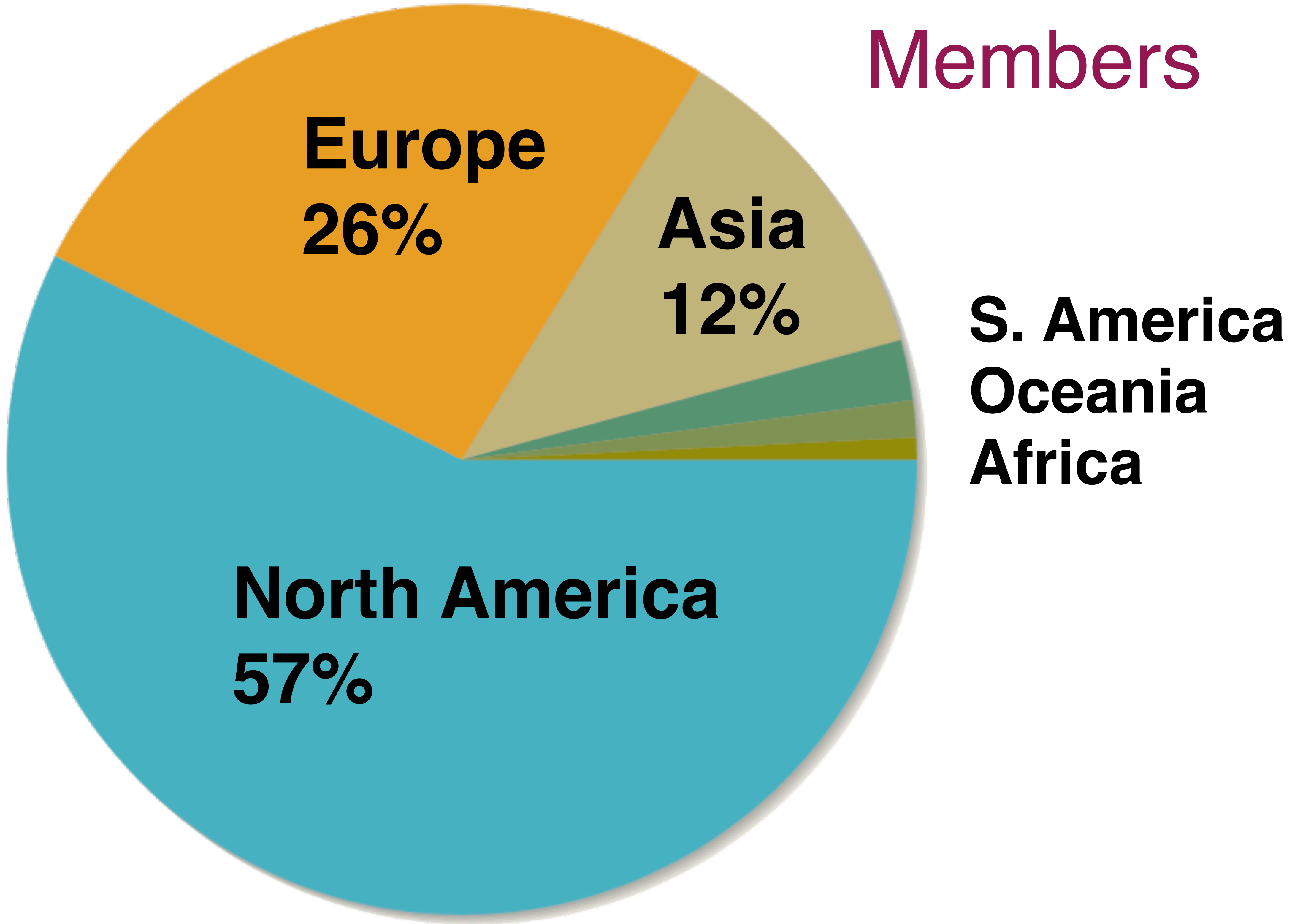
The EIC Community

The EIC User Group: http://eicug.org

- Formation of a formal EIC User Group in 2014/2015
- 1531 members, 295 institutions, 40 countries
- EIC Science Centers at JLab (EIC^2) and BNL/Stony Brook University (CFNS)



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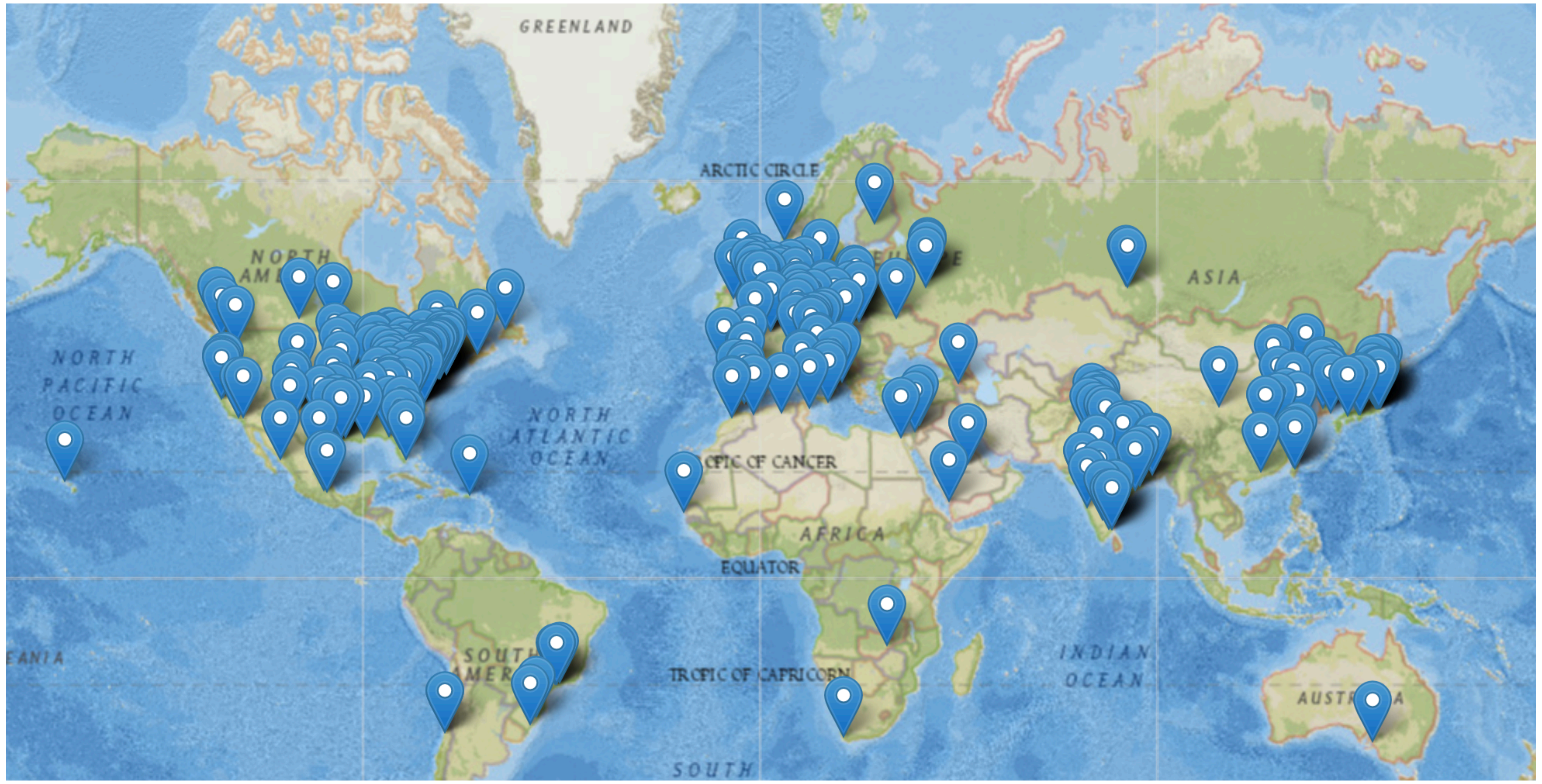
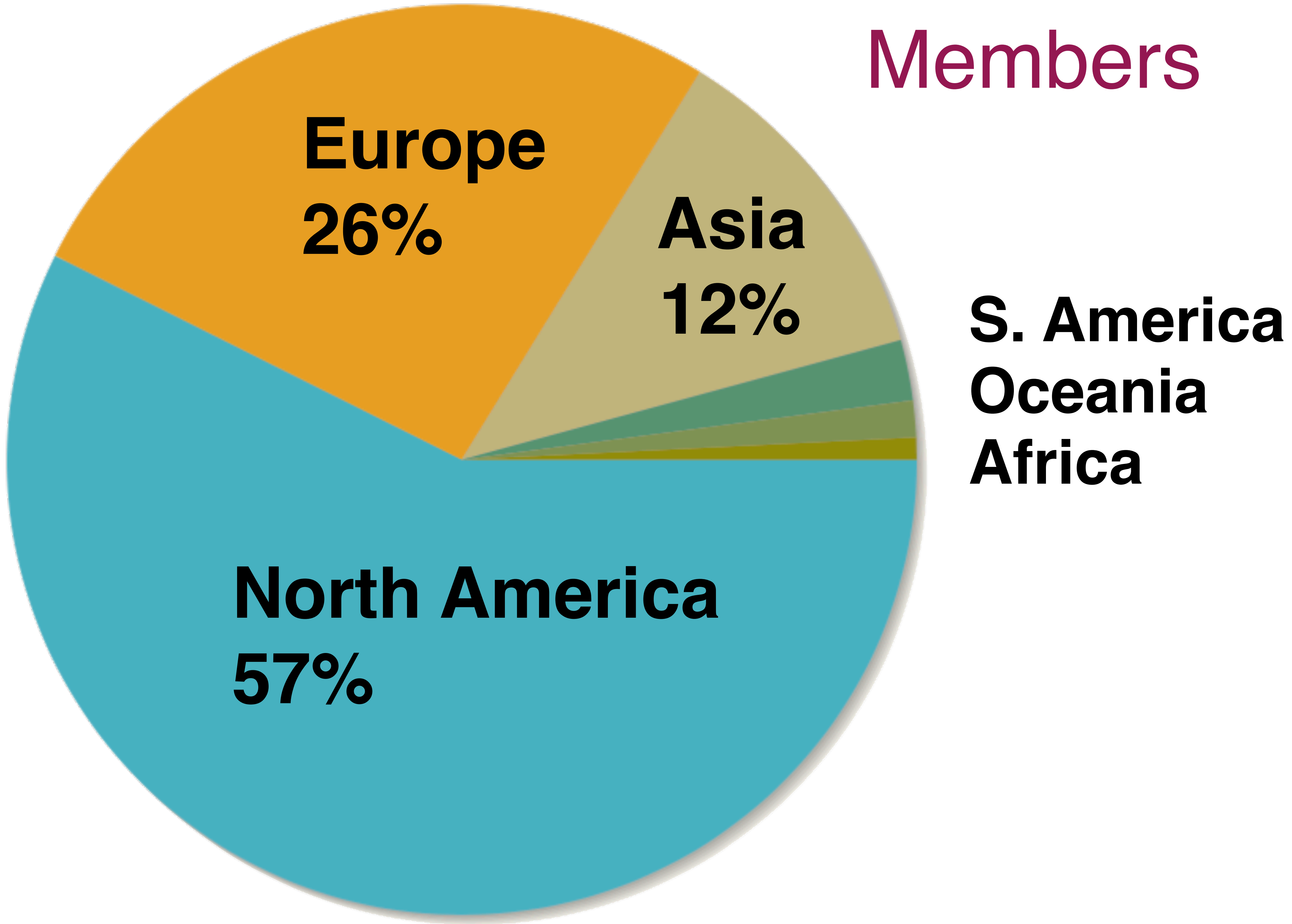




Interesting Comparison:
~25% US participants in LHC collaborations

Money - Lots of

Estimated Cost: $2-2.8B

- Main funding agent and owner of the EIC: DOE
- Many contributions (in-kind) from around the world
- International effort

How it Works

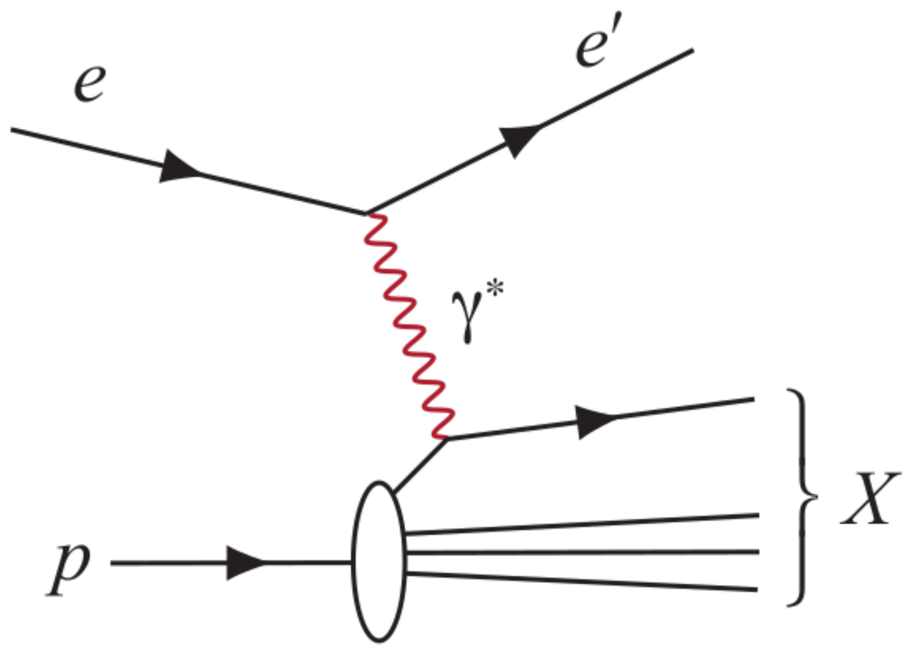
- DOE’s Order 413.3B outlines a series of staged project approvals, referred to as a “Critical Decision (CD)”
  - CD-0 – Approve Mission Need
  - CD-1 – Approve Alternative Selection and Cost Range
  - CD-2 – Approve Performance Baseline
  - CD-3 – Approve Start of Construction
  - CD-4 – Approve Start of Operations or Project Completion
  - Operation == Physics

The Path to Physics is plastered with reviews and reports

6. Examples of Key Measurements at an EIC

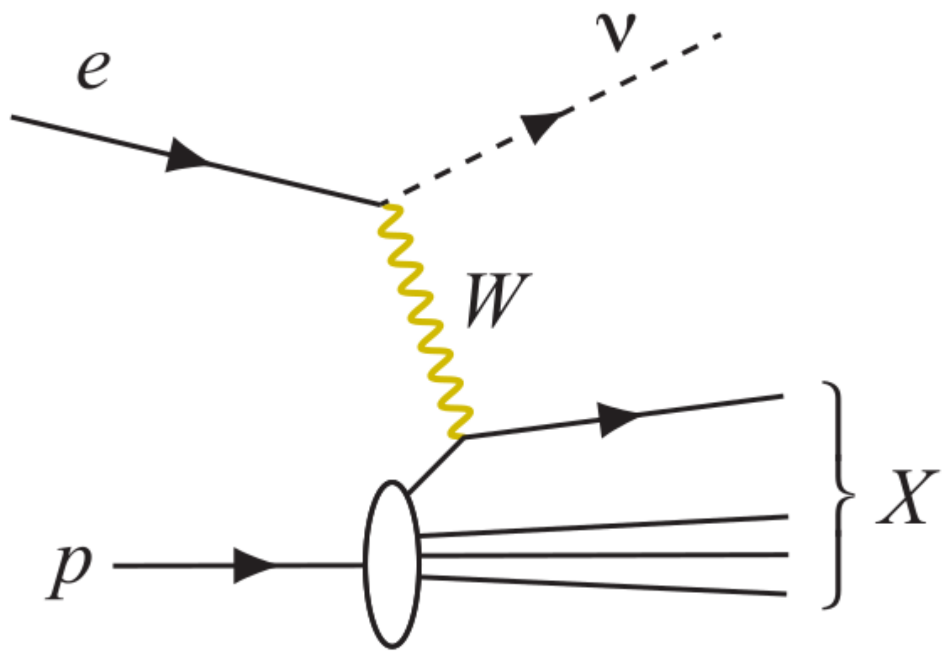
General: Category of Processes to Study

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)



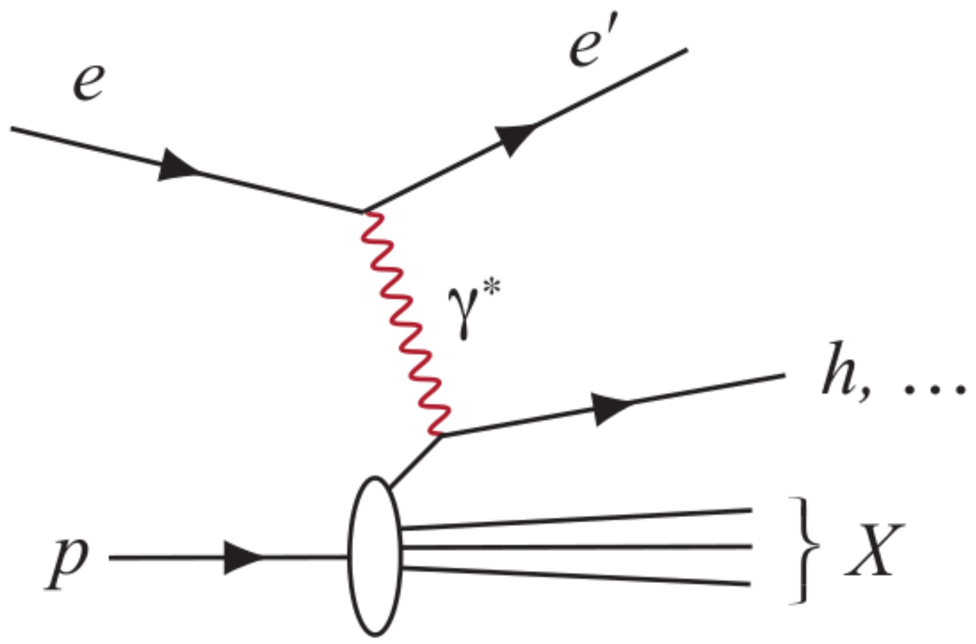
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



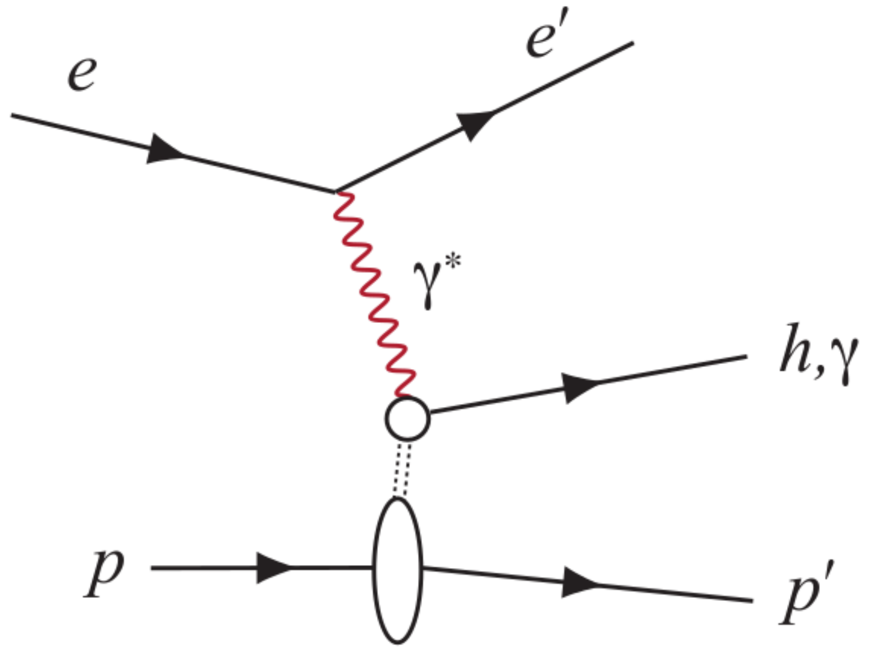
Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)



Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron



Deep Exclusive Processes

- Detection of all particles in event

Parton Distributions in nucleons and nuclei

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

6.1 Spin of the Proton

EIC: Longitudinal Spin of the Proton (I)

Determine the contribution of quarks and gluons to the proton spin need to measure spin-dependent structure function g_1 as function of x and Q^2 with longitudinal polarized beams:

Inclusive Measurement:
$e+p \to e'+X$

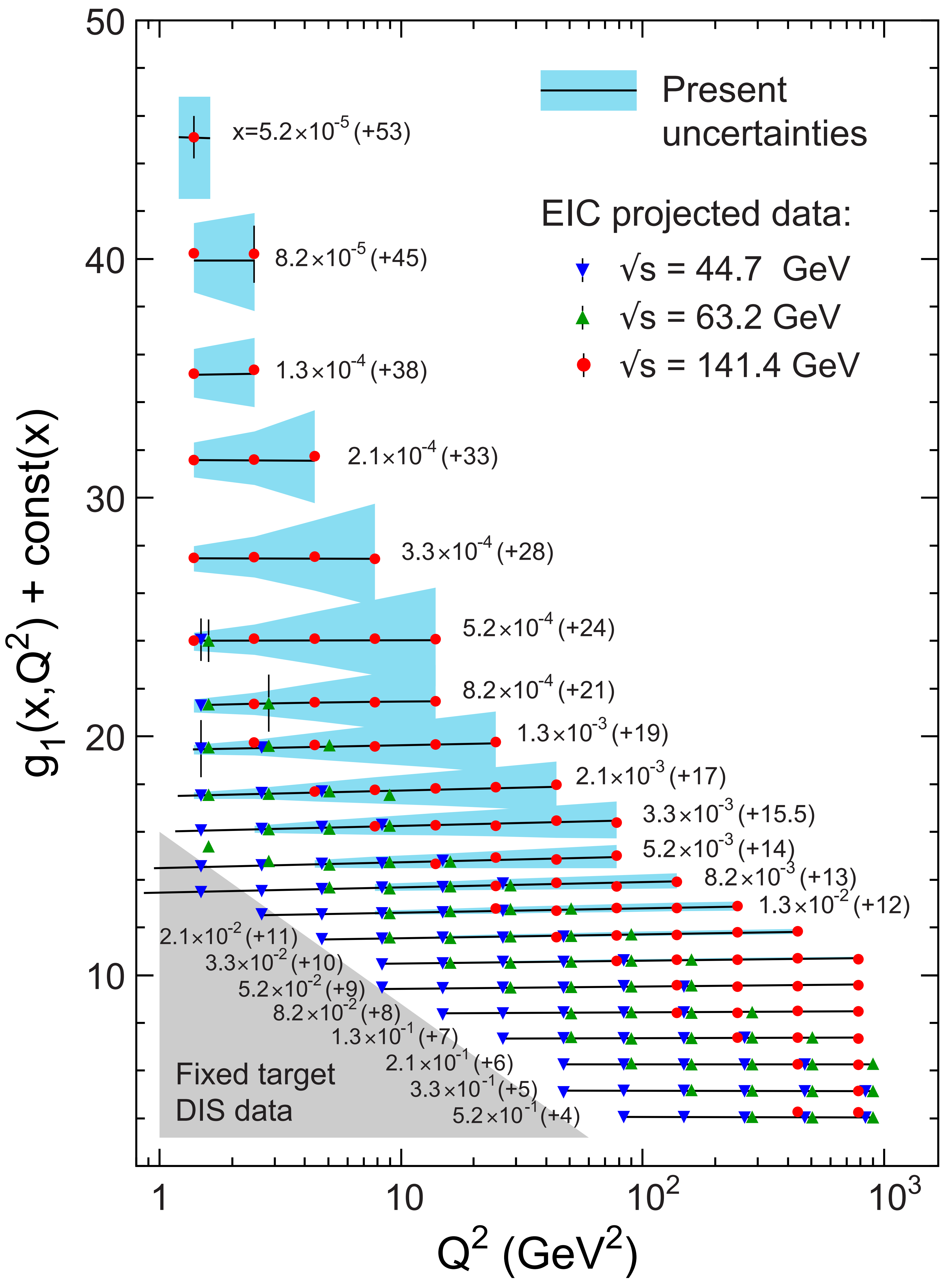
$$\frac{1}{2}\left[\frac{\mathrm{d}^2\sigma^{\rightleftarrows}}{\mathrm{d}x\,\mathrm{d}Q^2} - \frac{\mathrm{d}^2\sigma^{\rightrightarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$

Leading Order: $$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\,\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

$$\Delta\Sigma(Q^2) = \int_0^1 dx\;g_1(x,Q^2)$$ (Quark Spin)

Higher Order: $$\frac{dg_1}{d\log Q^2} \propto \Delta g(x,Q^2)$$ (Gluon Spin)

EIC: Longitudinal Spin of the Proton (II)



For $\int Ldt$ = 10 fb^{-1} and 70% polarization

Current knowledge (DSSV): uses strong theoretical constraints

EIC projections do not ⇒ test w/o assumptions

Recall Jaffe-Manohar sum rule:

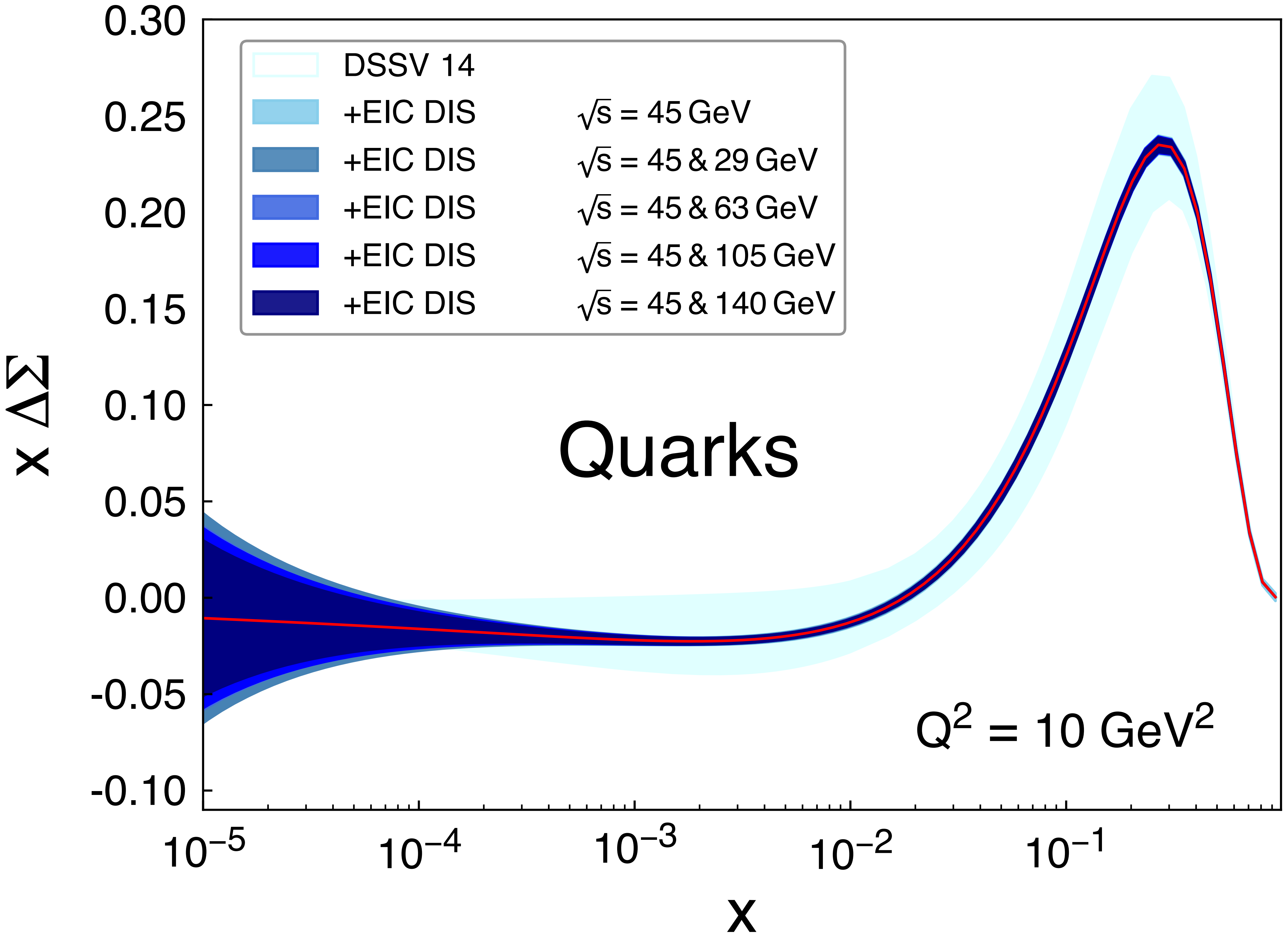
$$\frac{1}{2} = \frac{1}{2}\int_0^1 \mathrm{d}x \Delta\Sigma(x, Q^2) + \int_0^1 \mathrm{d}x \Delta g(x, Q^2) + \sum_q L_q + L_g$$

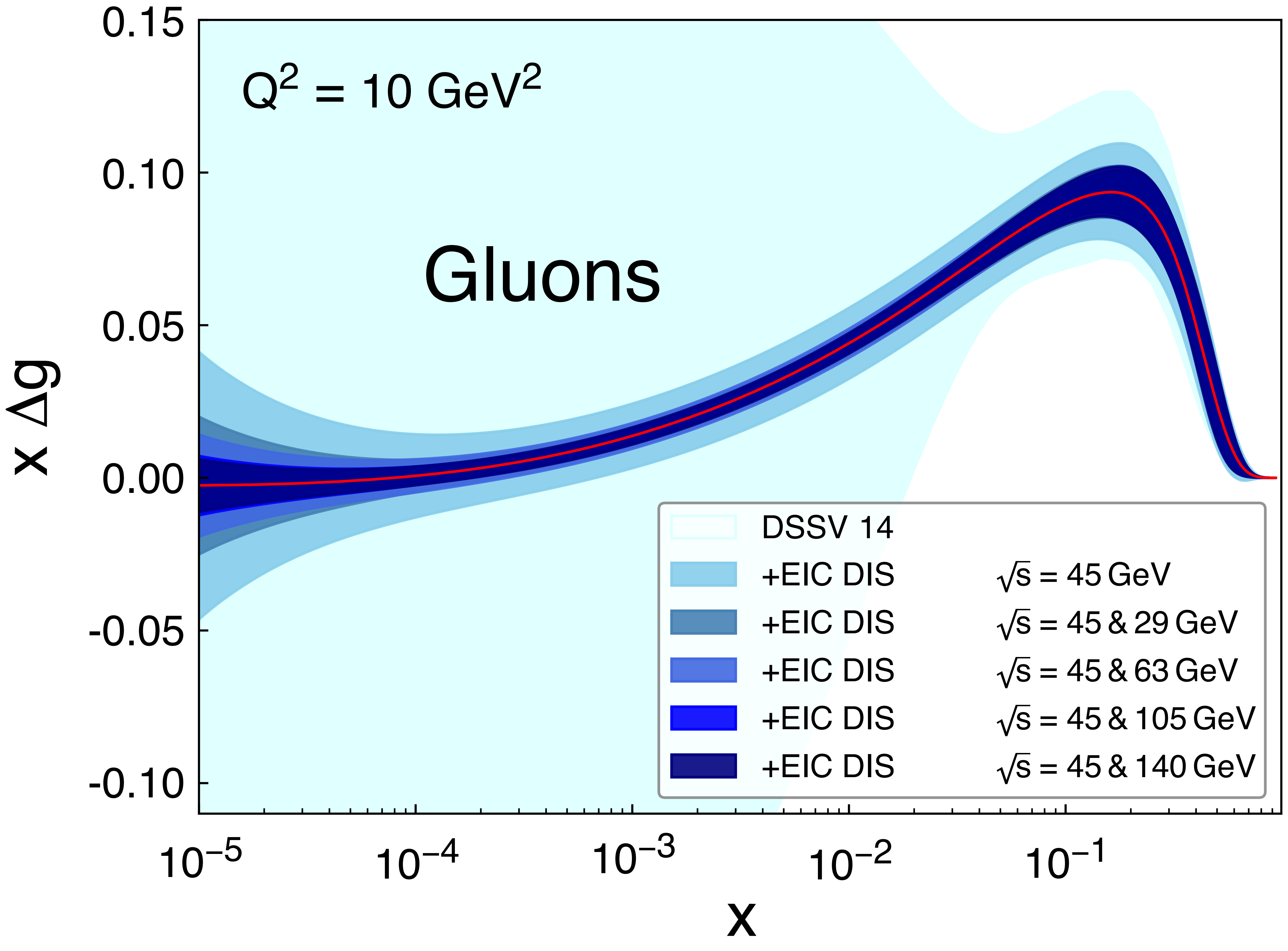
Don't know what x contribute!
Need to measure over wide range down to lowest x.

DSSV = D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang

EIC: Longitudinal Spin of the Proton (III)

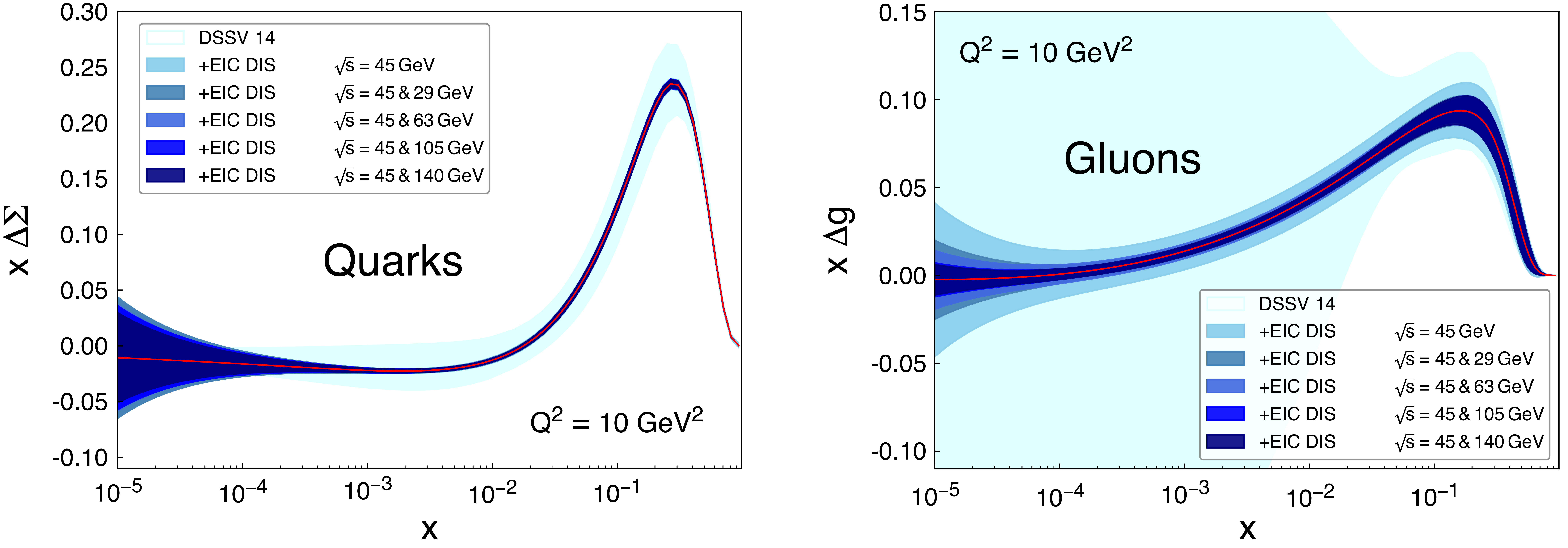
Using the simulated $g_1(x,Q^2)$ pseudo-data the following constrains on quark and gluon spin emerge:





EIC: Longitudinal Spin of the Proton (III)

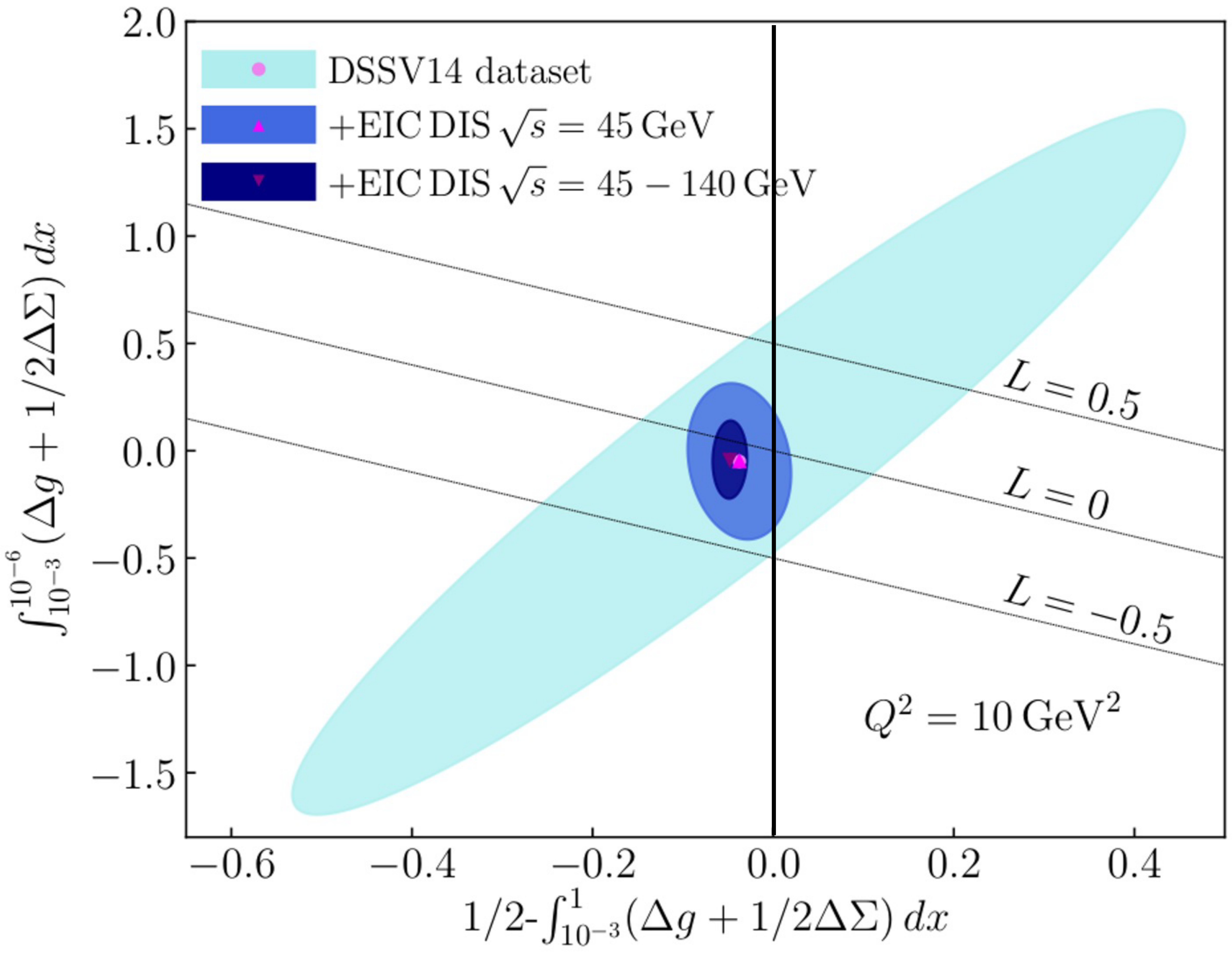
Using the simulated $g_1(x,Q^2)$ pseudo-data the following constrains on quark and gluon spin emerge:



Combining information on ΔΣ and Δg constrains angular momentum

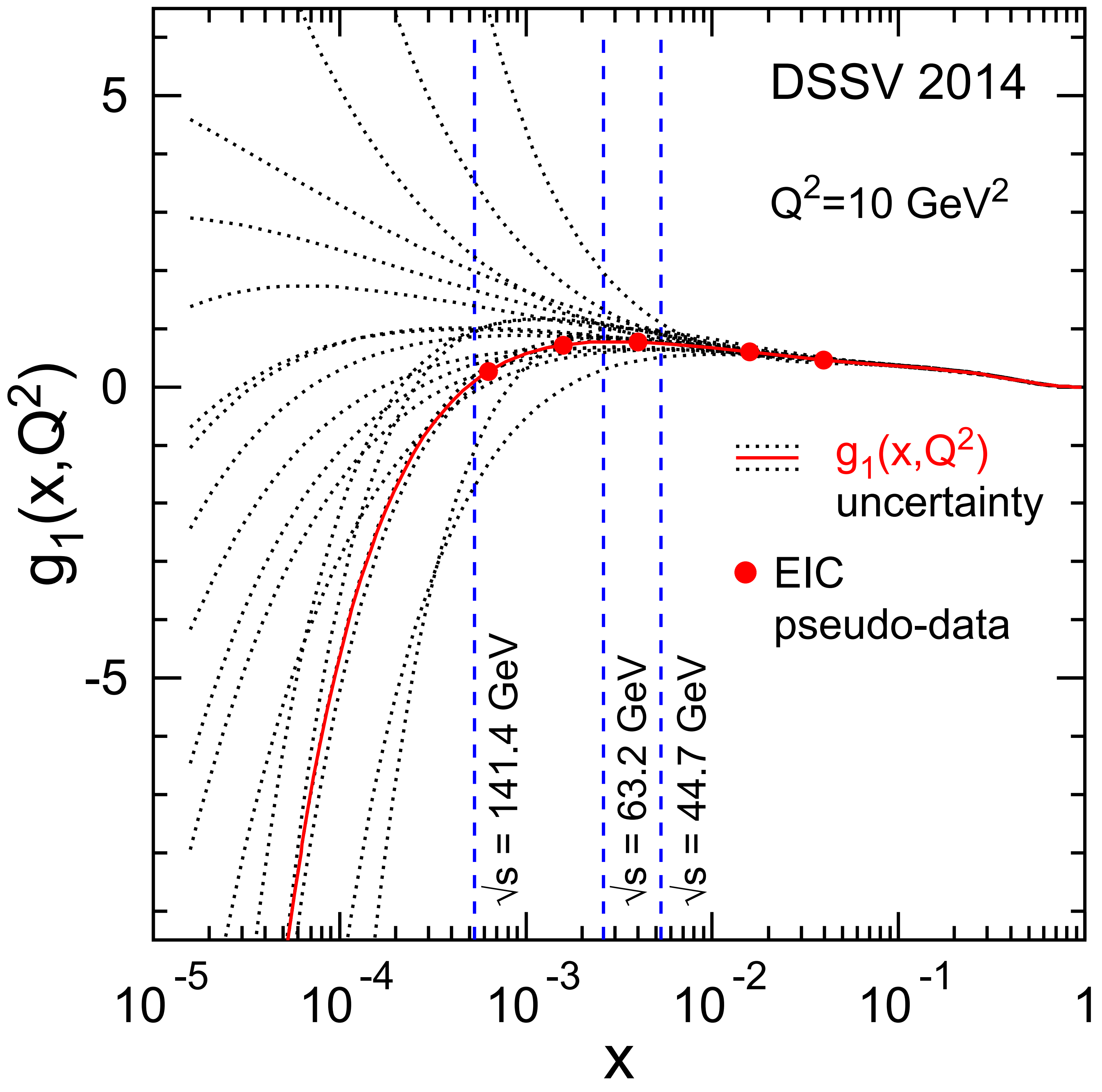
EIC: Longitudinal Spin of the Proton (IV)

Spin contribution from partons with x =(10^{-6}–10^{-3})

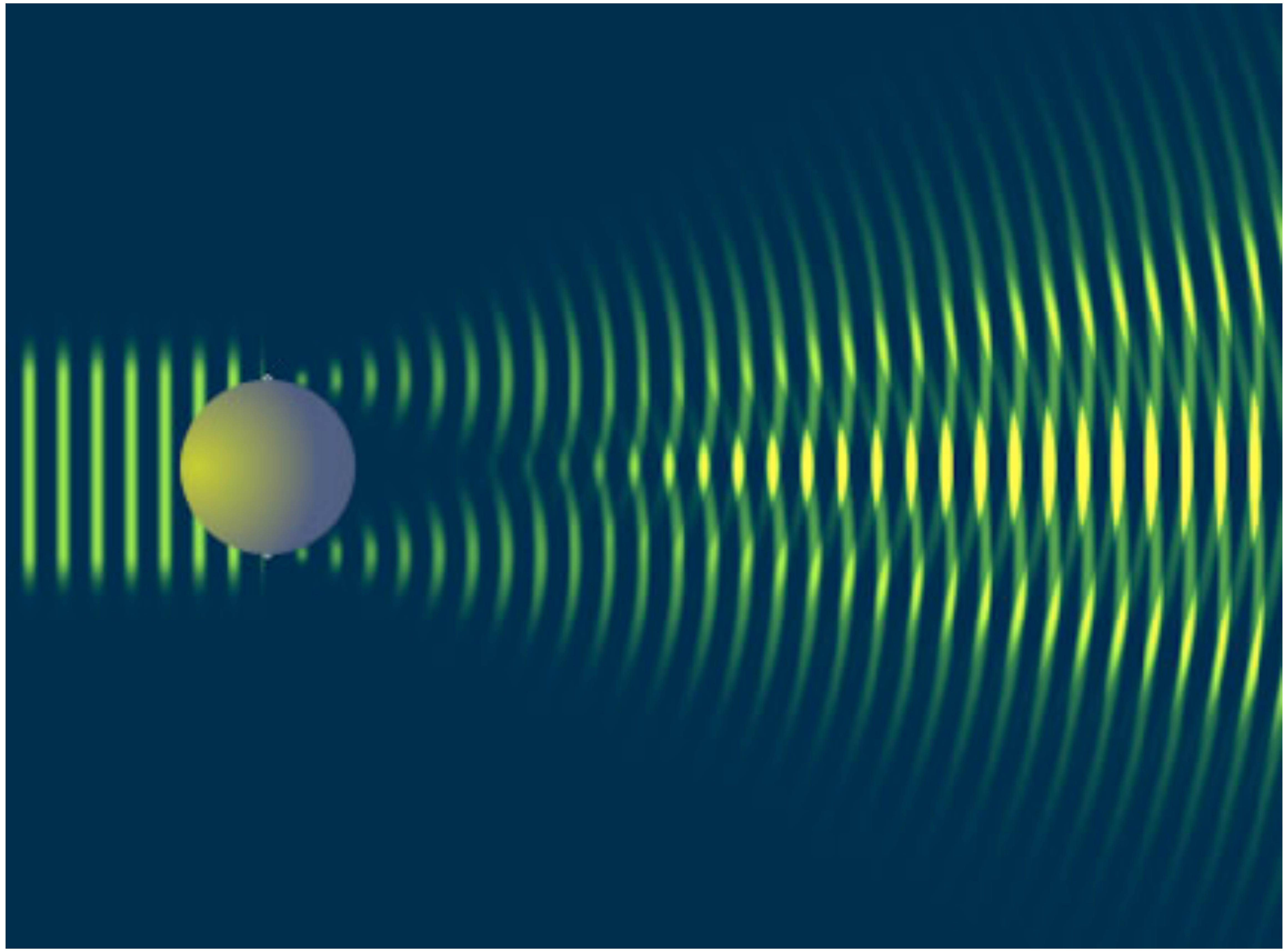


Room left for potential OAM contributions to the proton spin from partons with x > 0.001

Constraining spin of the sea-quarks and gluons at low-x is important but requires high √s

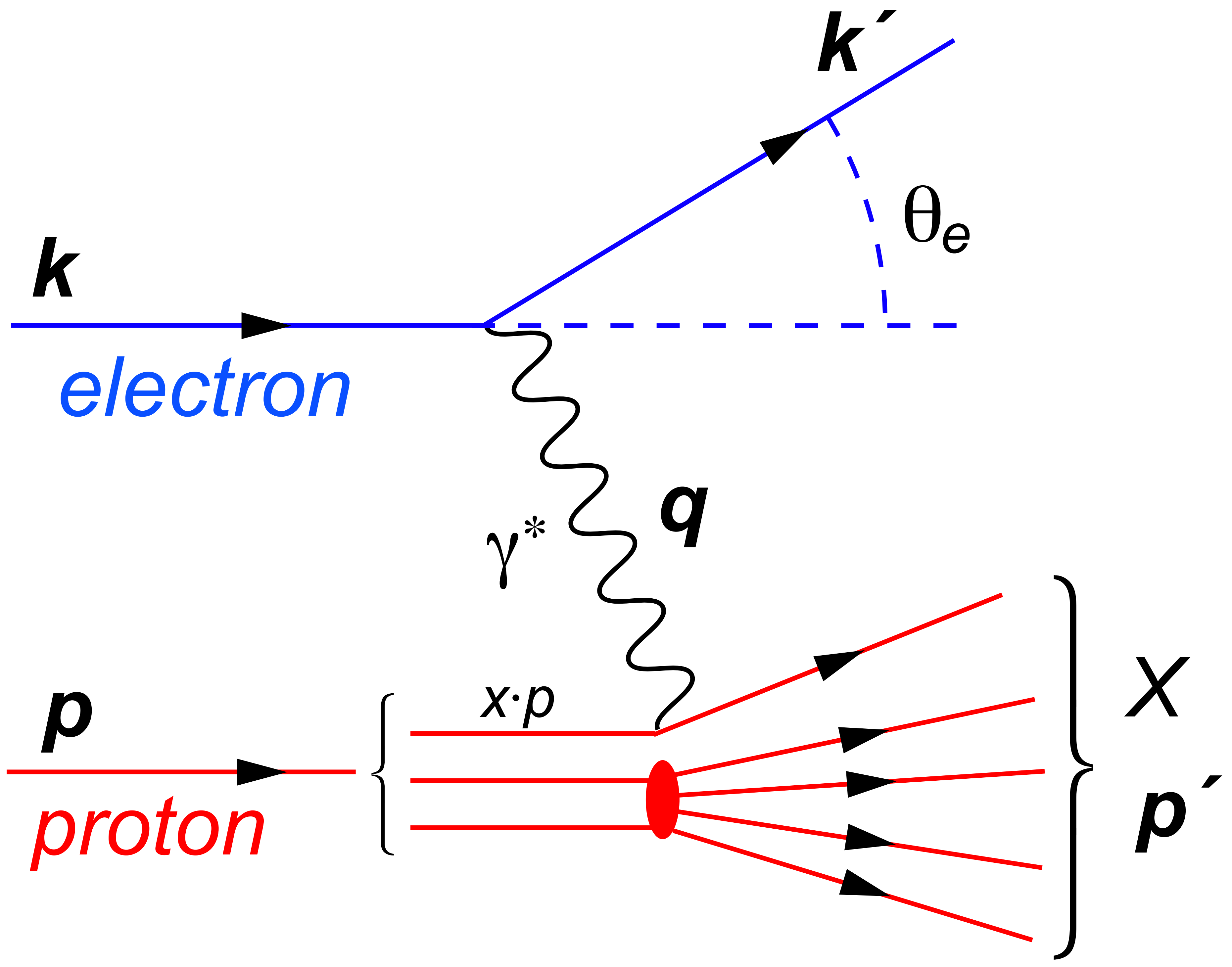


6.2 Diffractive Physics



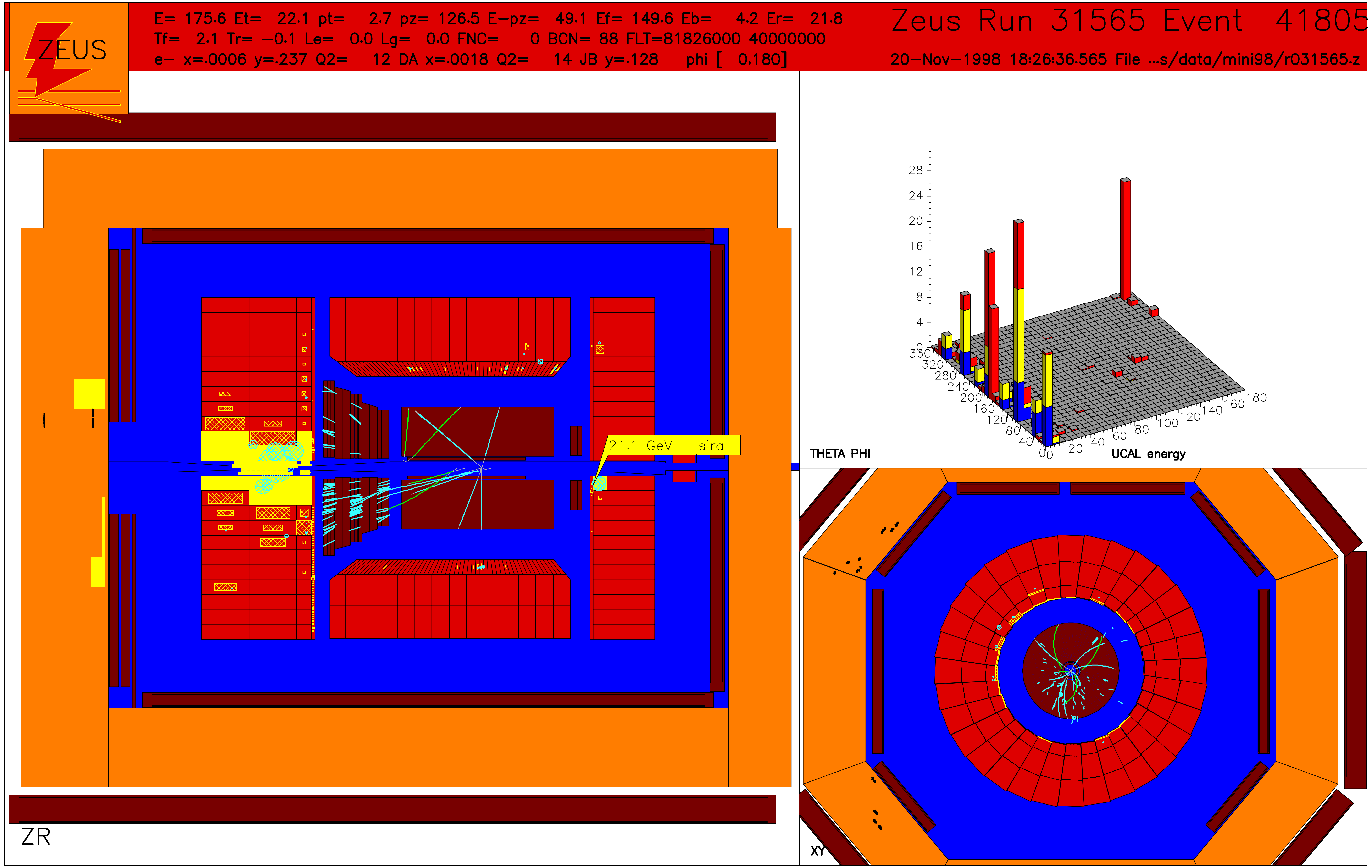
Hard Diffraction: What is It?

A DIS event (theoretical view)



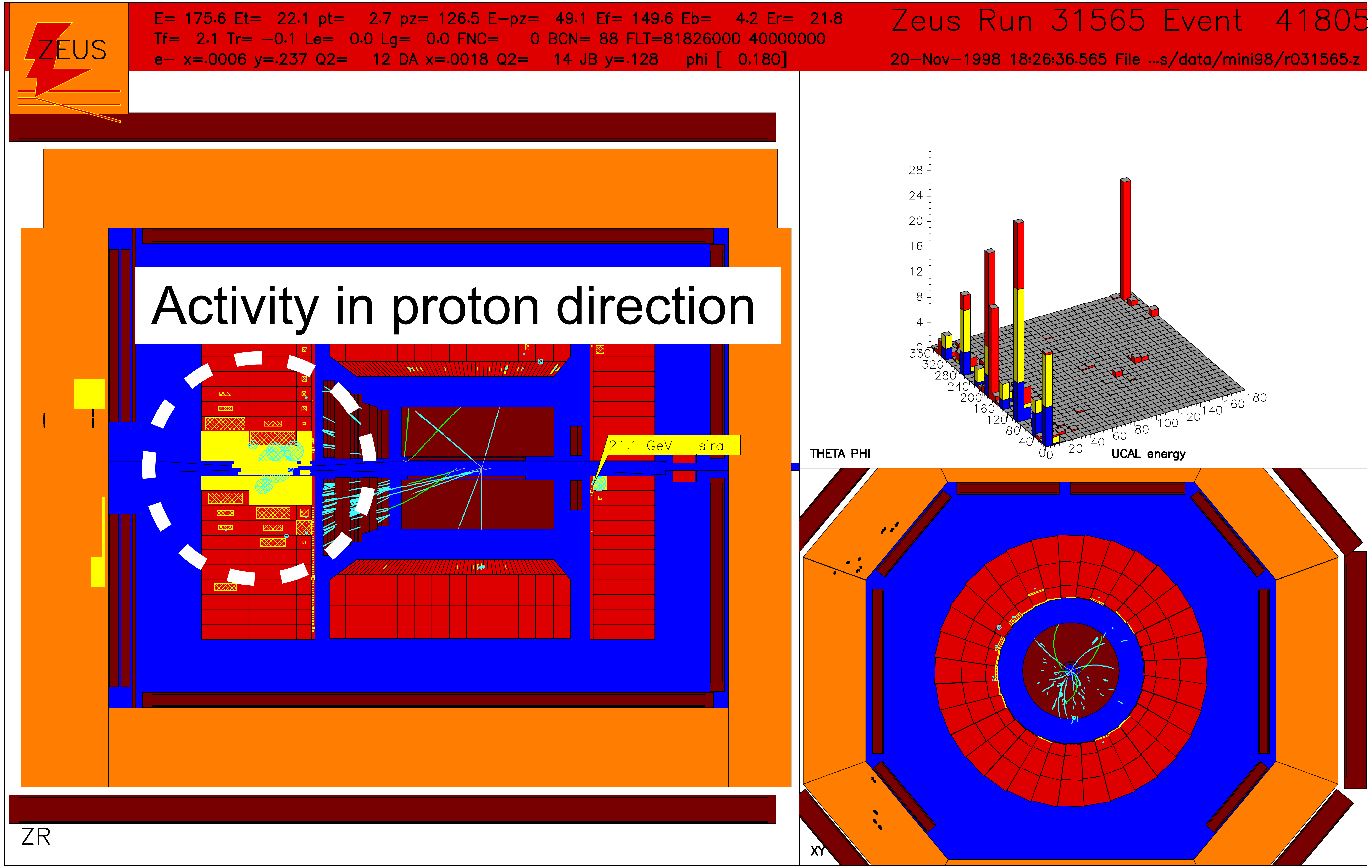
Hard Diffraction: What is It?

A DIS event (experimental view)

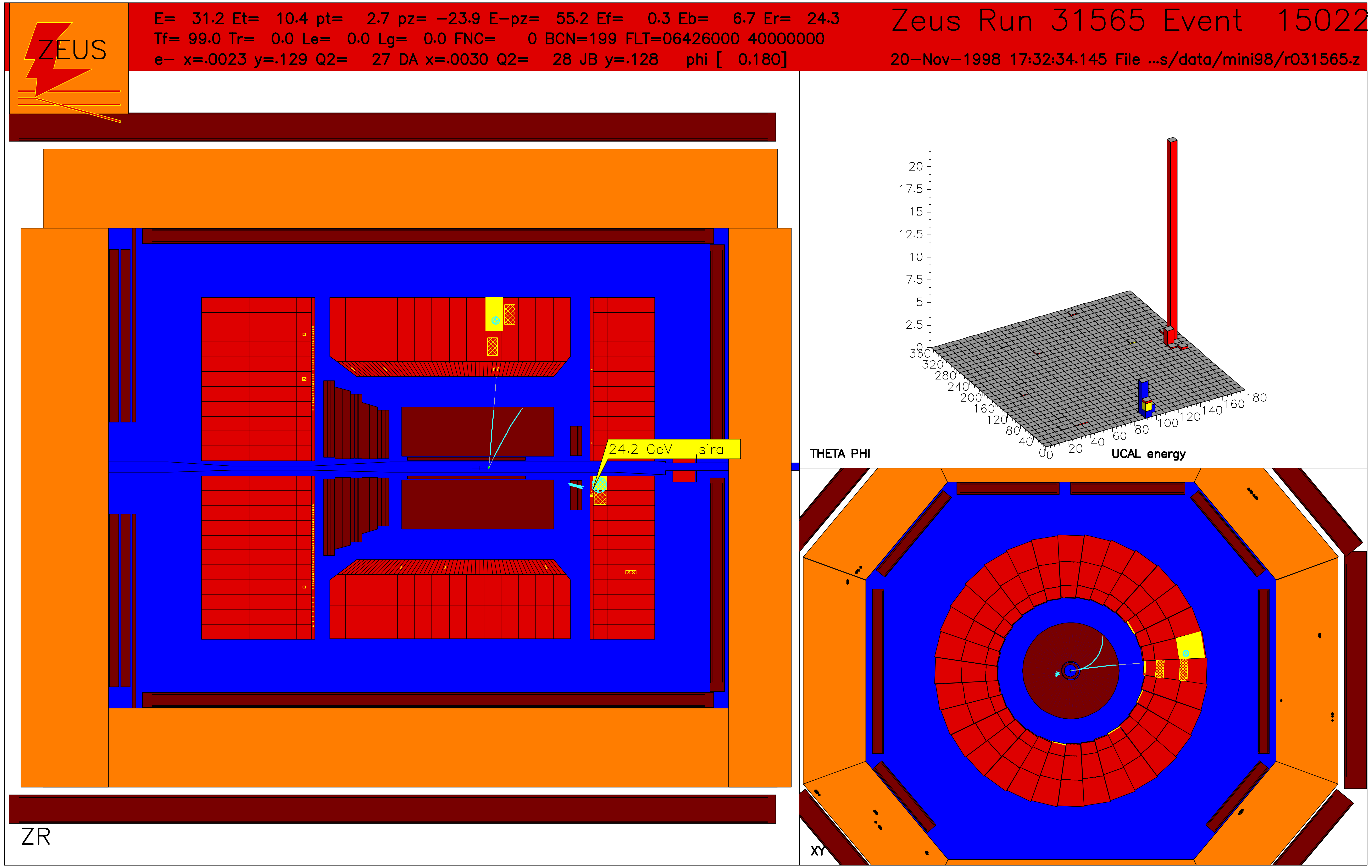


Hard Diffraction: What is It?

A DIS event (experimental view)

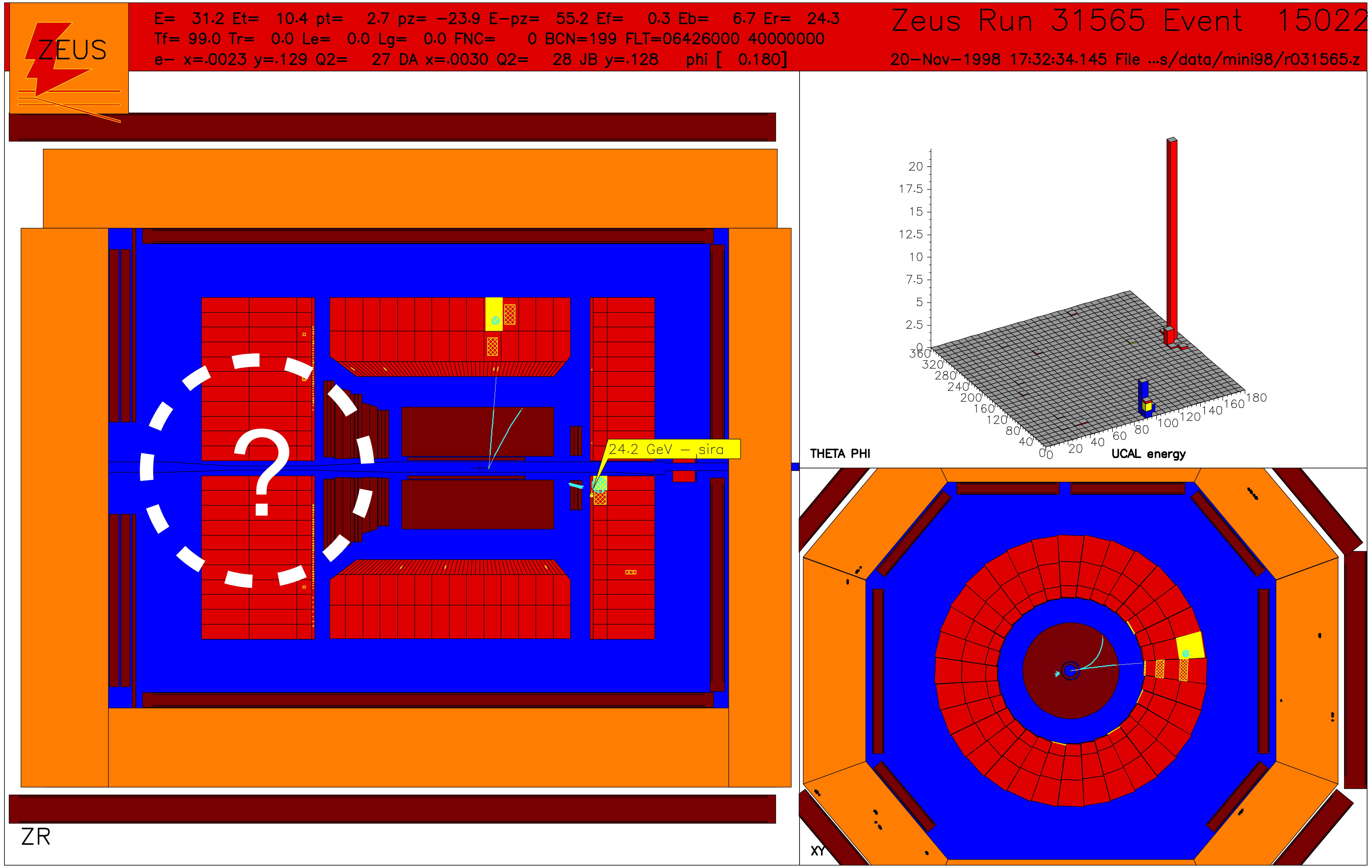


Hard Diffraction: What is It?



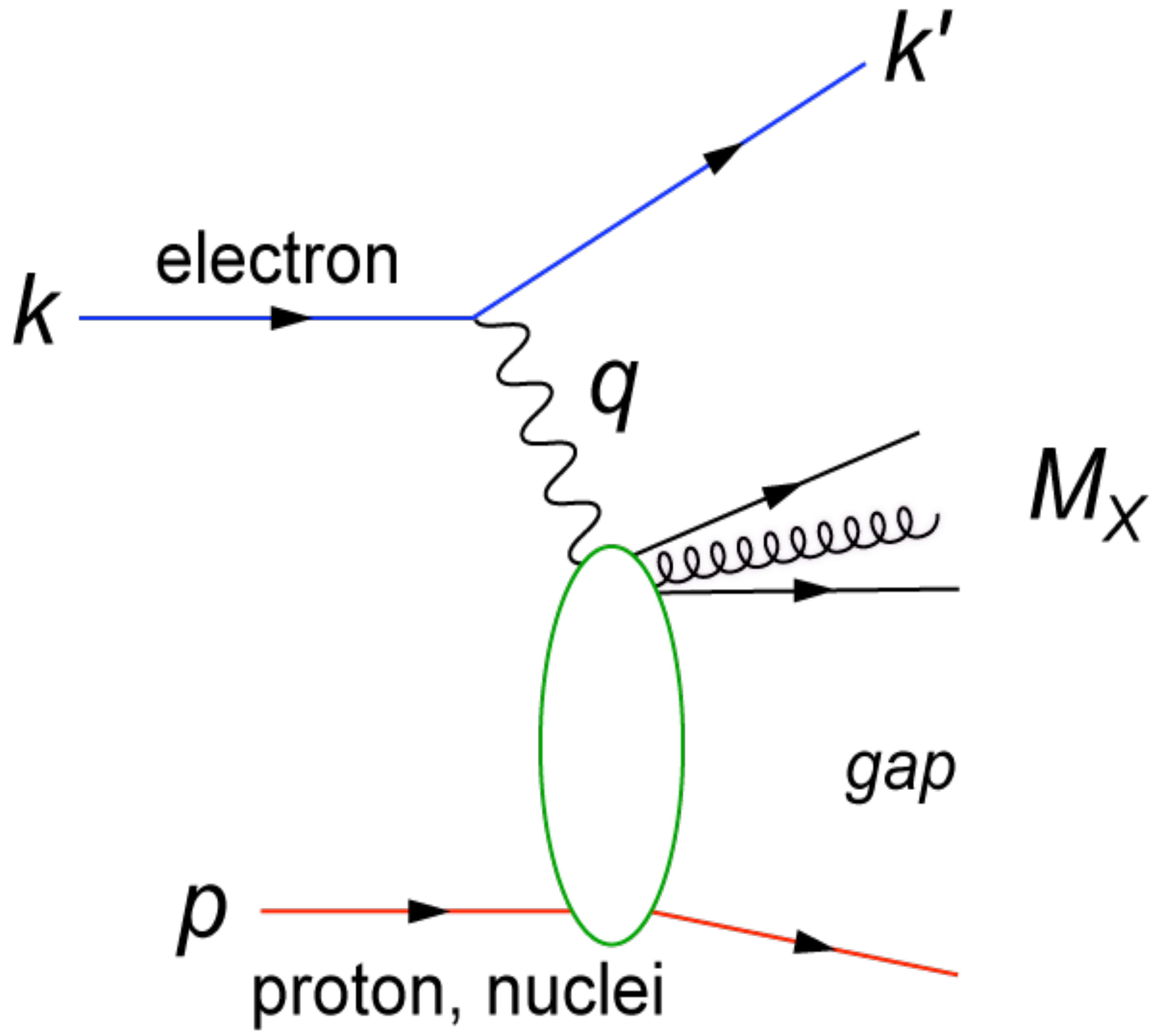
Hard Diffraction: What is It?

A diffractive event (experimental view)



Hard Diffraction: What is It?

A diffractive event (theoretical view)

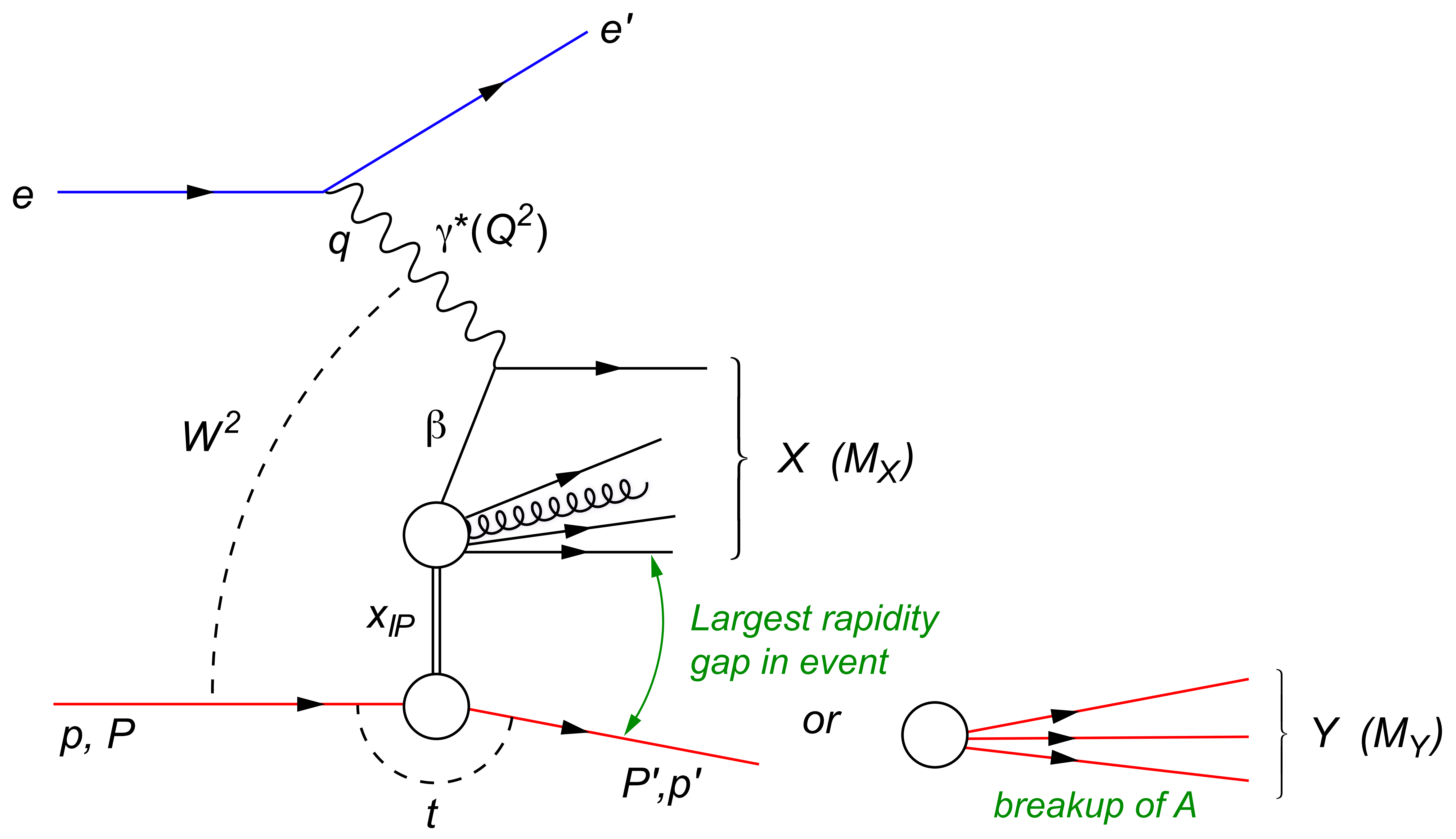


- HERA: large fraction of diffractive events (15% of total DIS rate)

Diffraction for the 21st Century

Diffractive physics will be a major component of the e+A program at an EIC

HERA: $\sigma_{diff}/\sigma_{tot}$ ~ 14%



coherent
p/A stays intact

incoherent
p/A breaks up

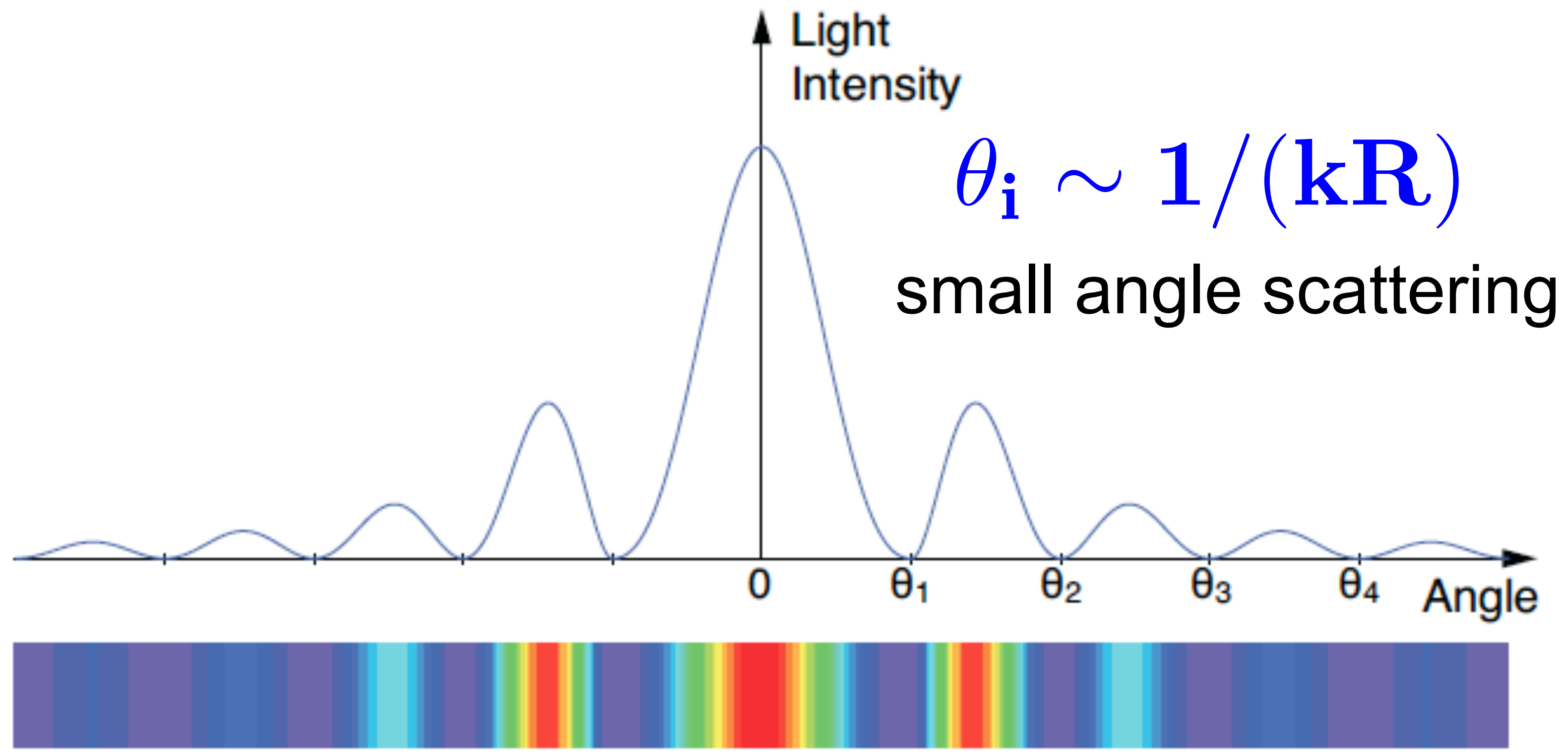
- Diffractive event characterized by large rapidity gap mediated by color neutral exchange (e.g. 2 or more gluons) aka Pomeron

t: momentum transfer squared (**p-p'**)^2
M$_X$: mass of diffractive final-state

Why Is Diffraction So Important for an EIC?

Recall: diffractive pattern in optics

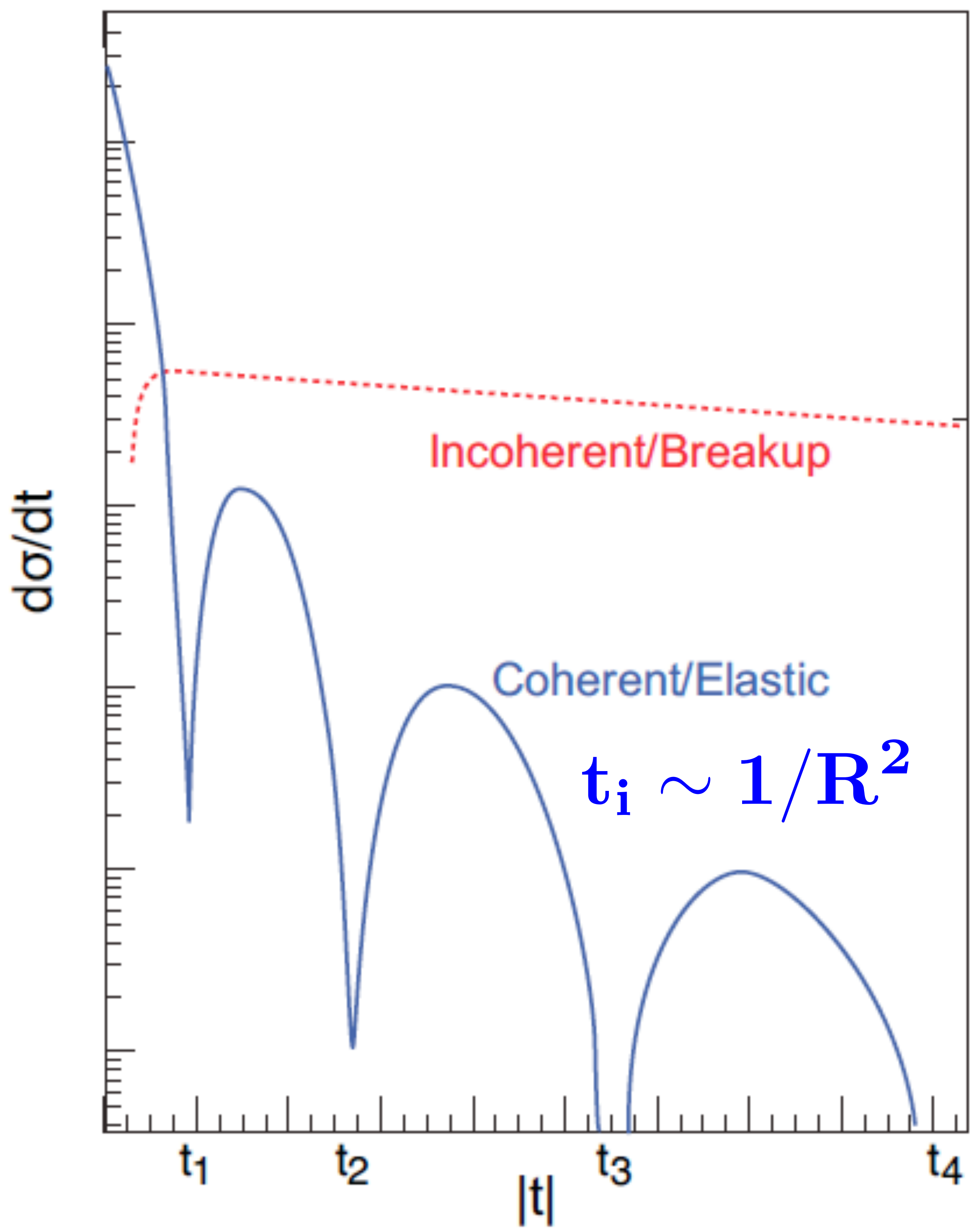
Position of minima θ_i related to size R of screen



Similarly: in coherent (elastic) scattering dσ/dt resembles diffractive pattern where $|t| \approx k^2\theta^2$

Crucial differences:

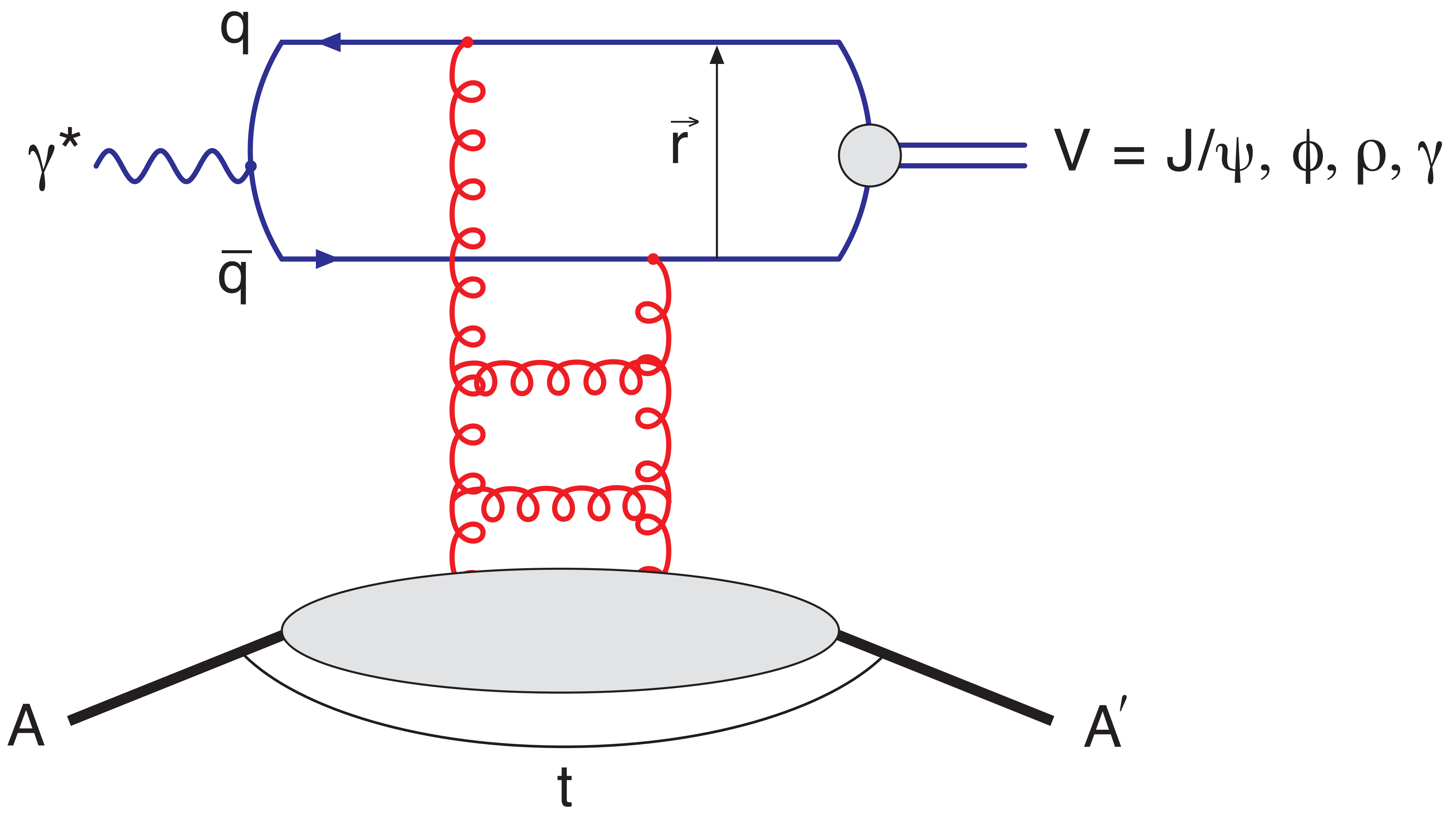
- target not always “black disc”
  - sensitivity to “size” of probe / onset of black disc limit
- incoherent (inelastic) contribution



Exclusive Diffractive Vector Meson

- *t* can be measured in e+p with a forward spectrometer measuring the scattered p
- in e+A this is not possible. A’ stays in the beam pipe.
- Only process where this is possible is exclusive VM production.

$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$



High Sensitivity to $g(x,Q^2)$

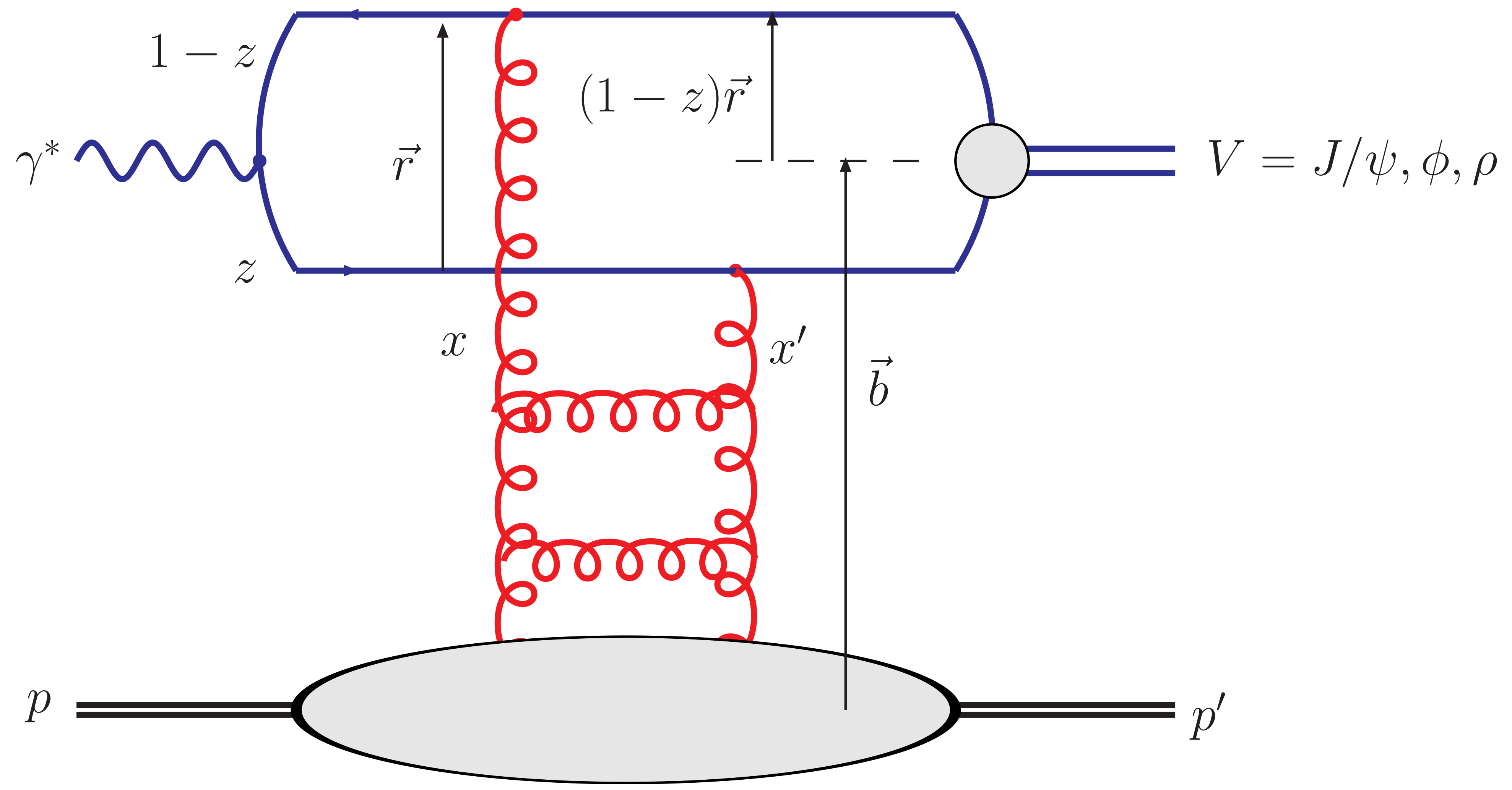
Diffraction is most precise probe of non-linear dynamics in QCD

Example: Exclusive diffractive production of a vector meson

$$\gamma^* p \rightarrow V p'$$
$$\gamma^* A \rightarrow V A'$$

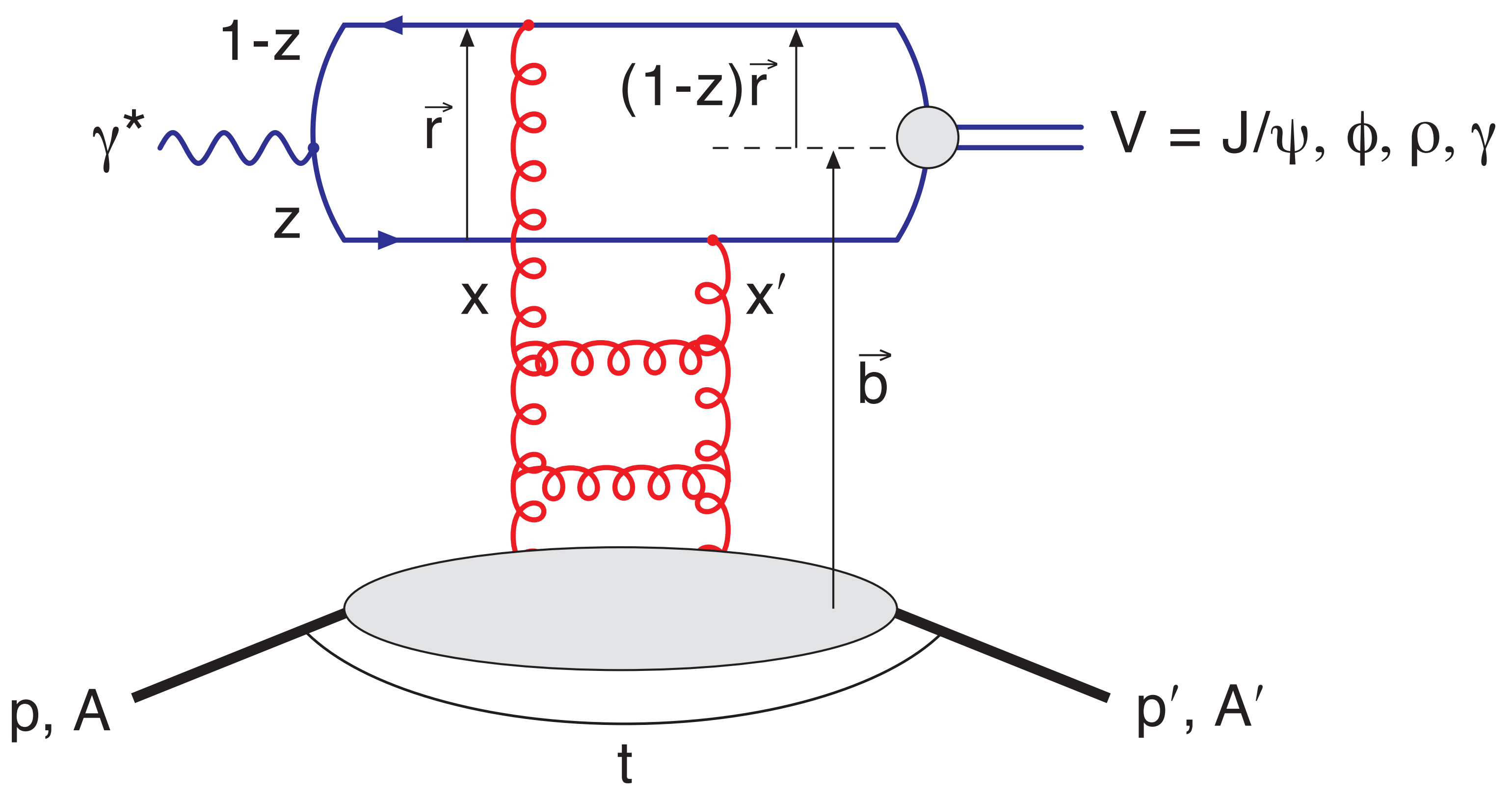
$$\mathbf{d}\sigma \sim [\mathbf{g}(\mathbf{x})]^{\mathbf{2}}$$

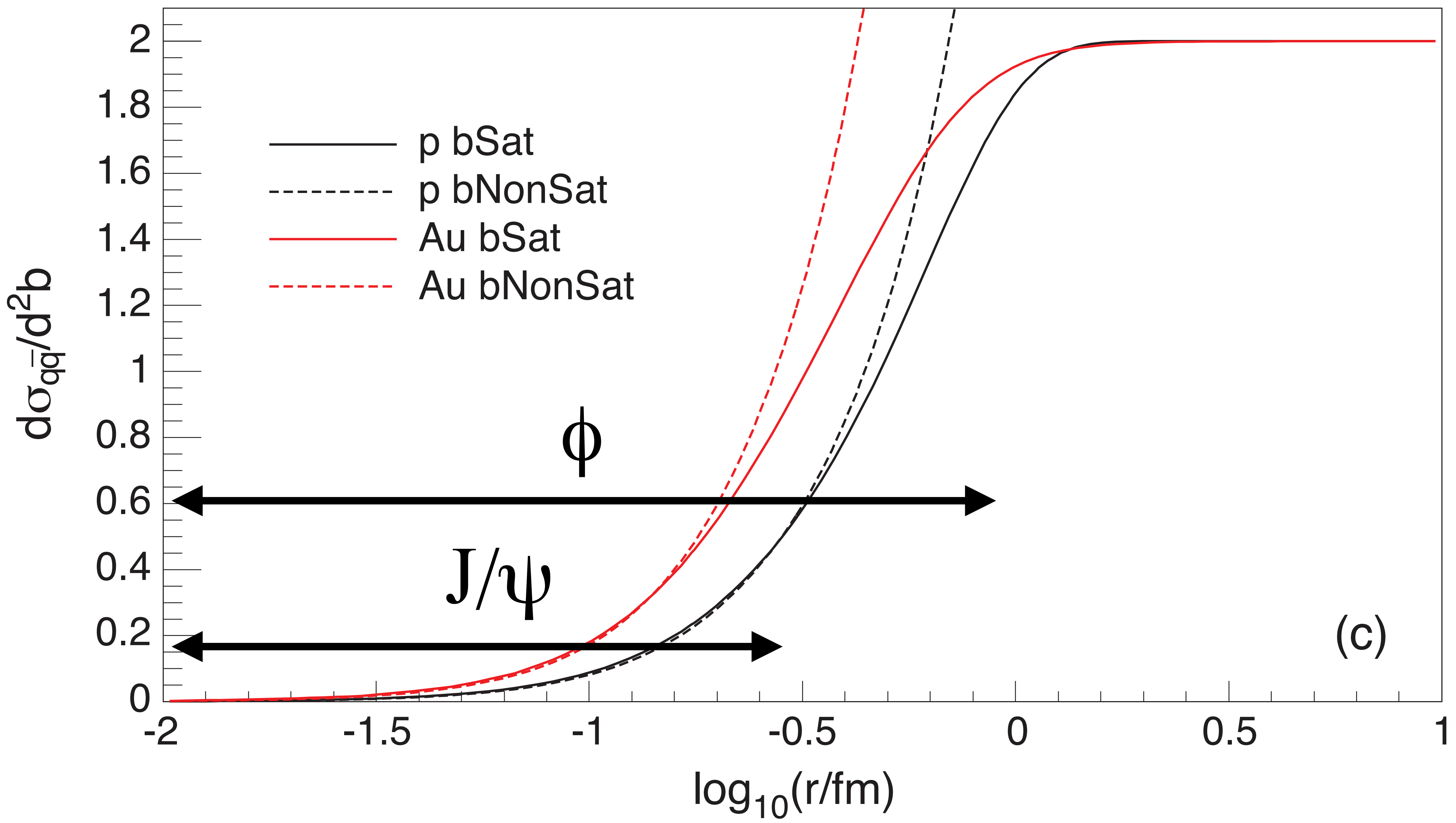
Dipole Model



- High sensitivity to gluon density: $\sigma \sim [g(x,Q^2)]^2$ due to color-neutral exchange

Warning - Warning - J/ψ has issues

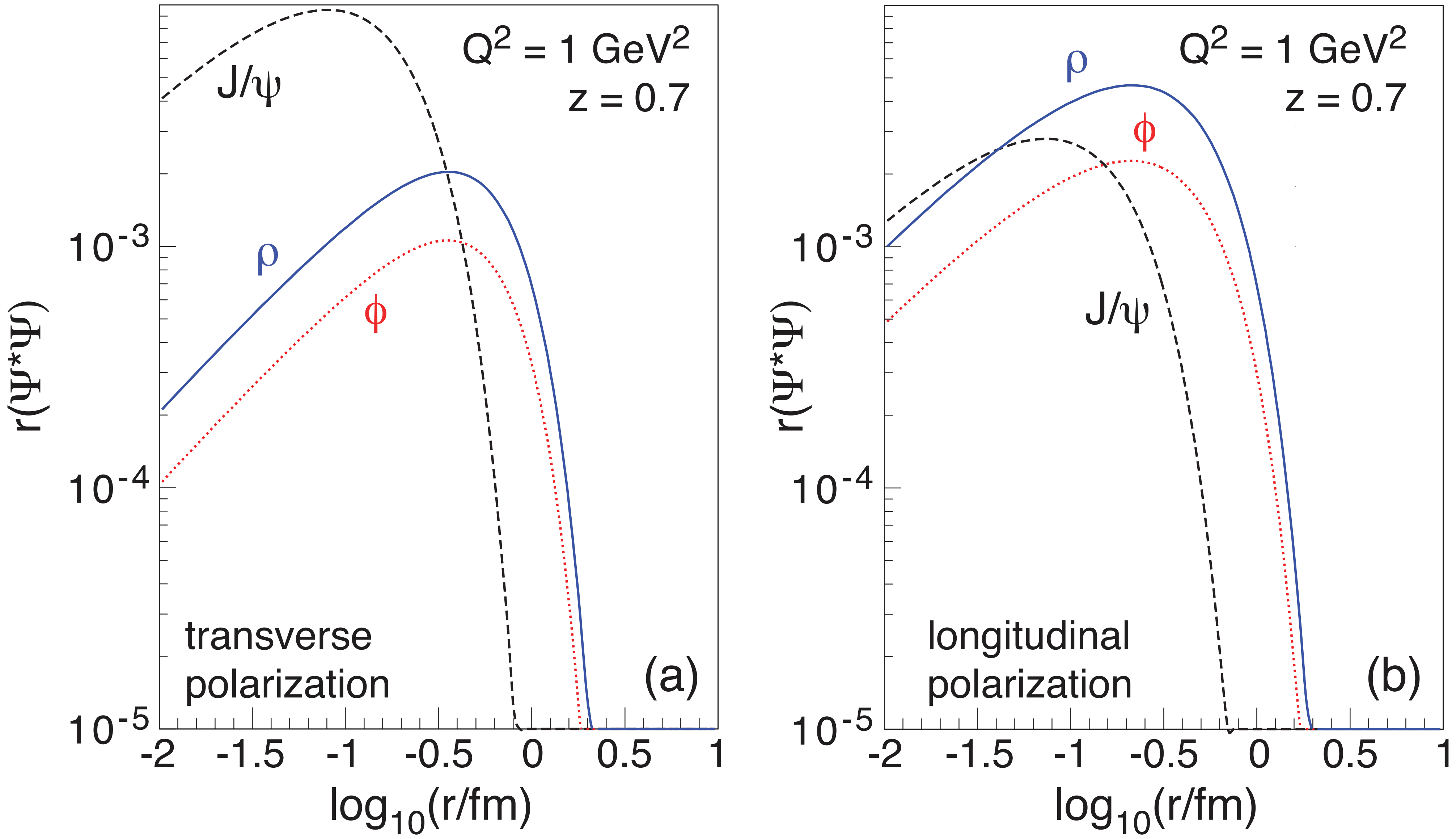




Wave overlap function $\Psi^*\Psi$ falls steeply for large dipole radii

- J/ψ not sensitive to saturation.
- Need to look at ϕ, or ρ that "see" more of the dipole amplitude

$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x, Q, \Delta) = i \int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^* \Psi)(r, z) \times 2\pi r J_0([1-z] r\Delta) e^{-i\mathbf{b}\cdot\Delta} \frac{\mathrm{d}\sigma_{q\bar{q}}^{(p)}}{\mathrm{d}^2\mathbf{b}}(x, r, \mathbf{b})$$

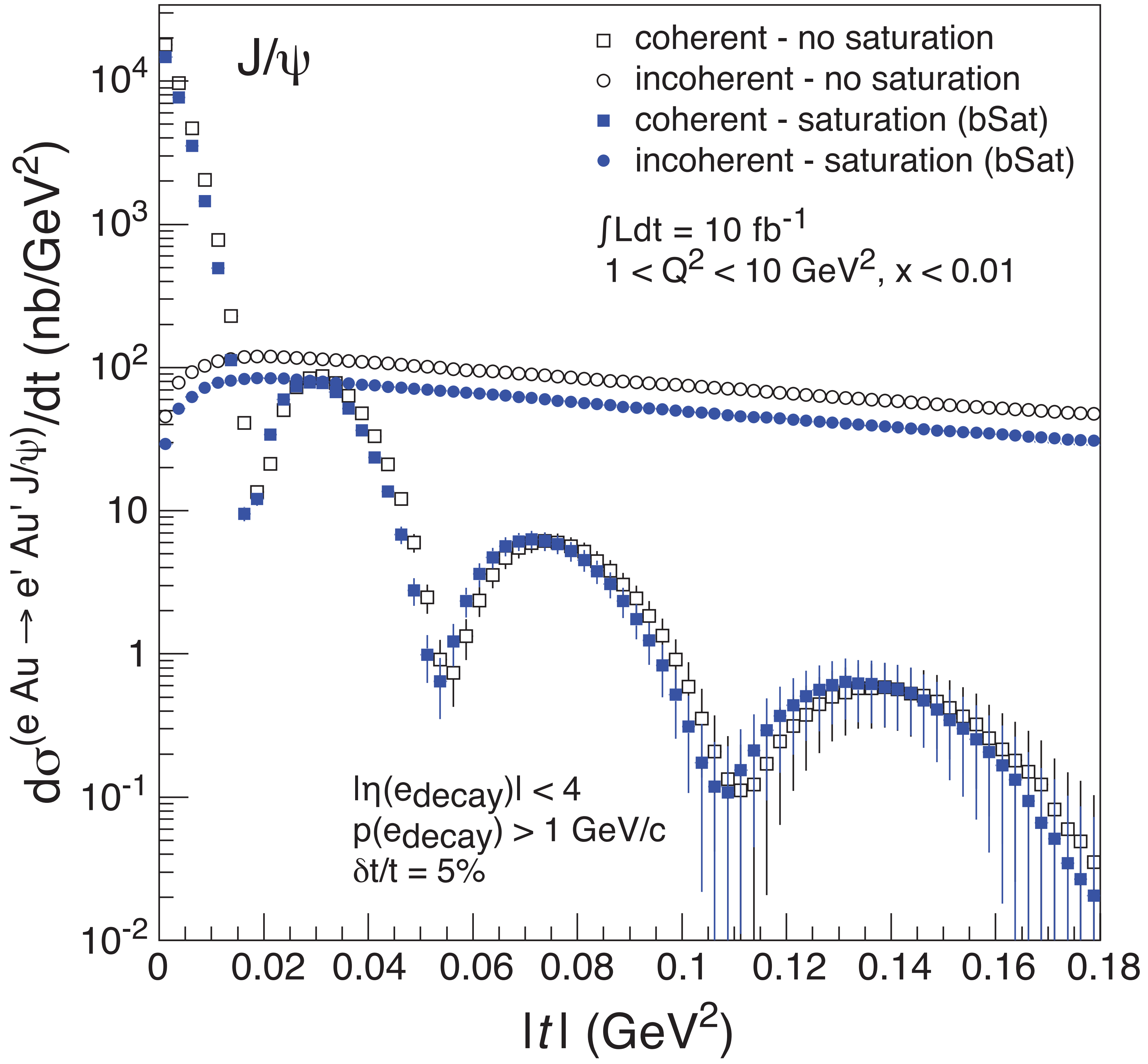


Toll and TU,
PRC 87 (2013) 024913

Spatial Gluon Distribution from dσ/dt

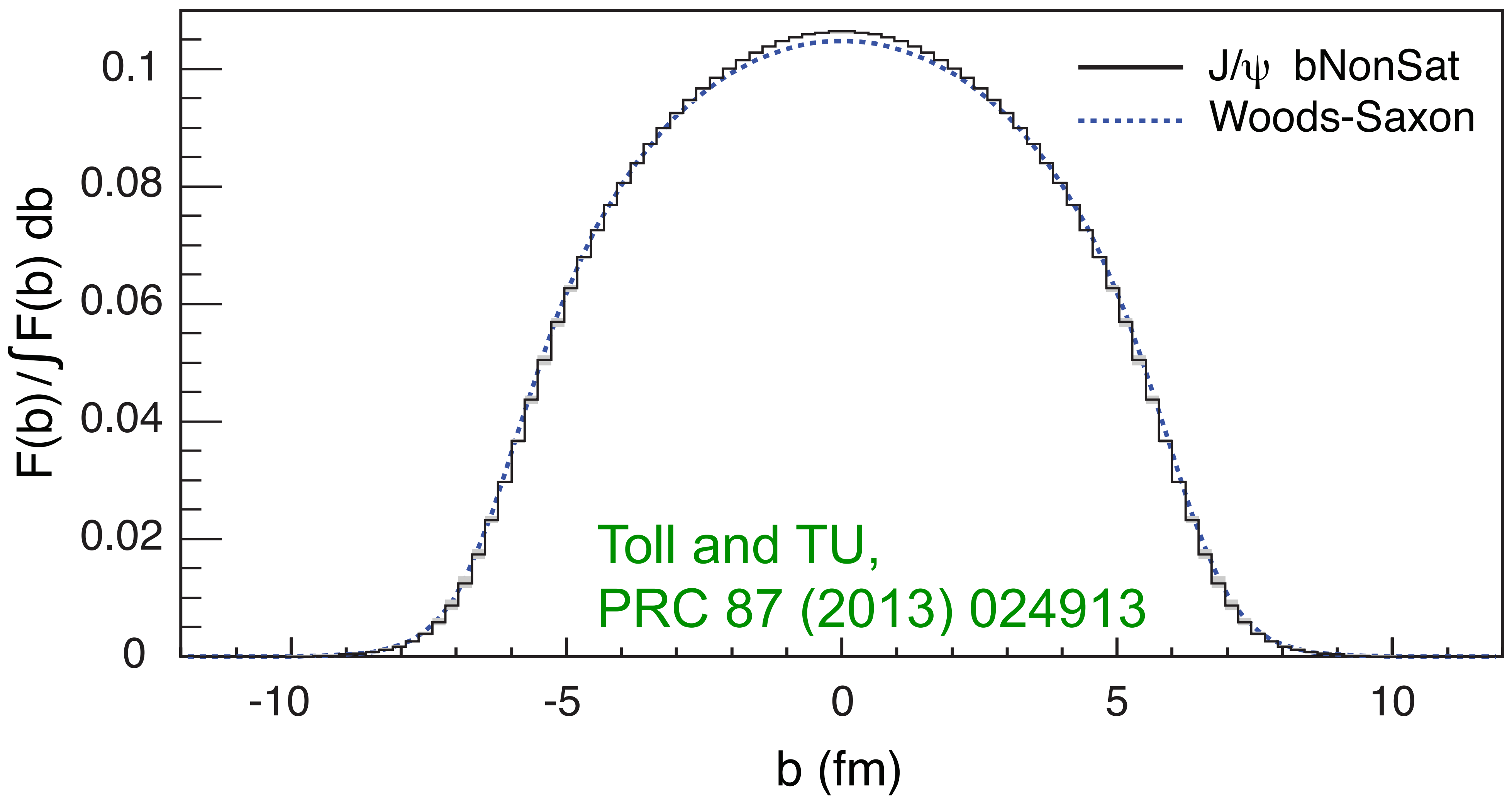
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi$

- Momentum transfer $t = |\mathbf{p}_{Au} - \mathbf{p}_{Au'}|^2$ conjugate to b_T



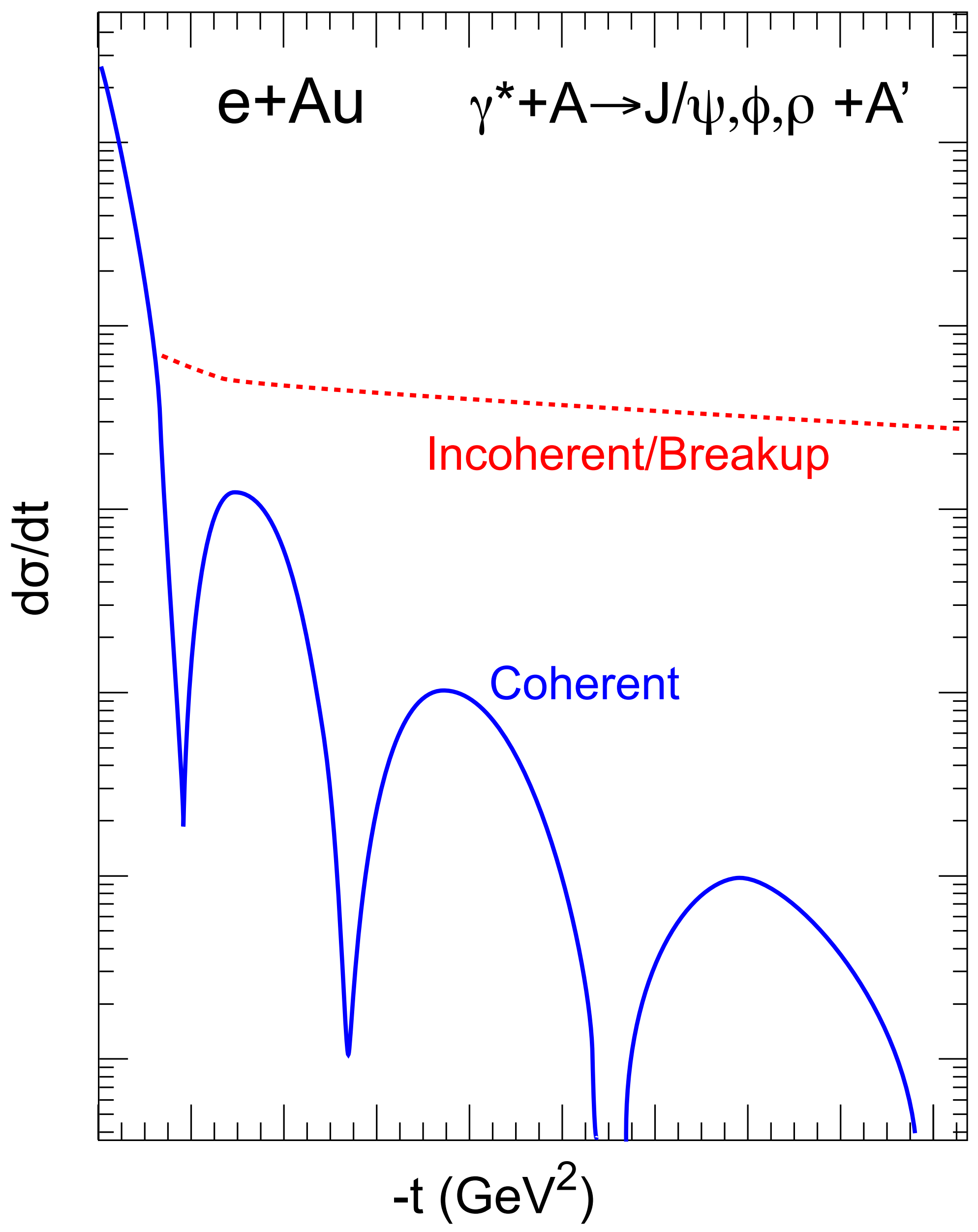
$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$



- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough

Importance of Incoherent Diffraction



Nucleus dissociates: $f \neq i$

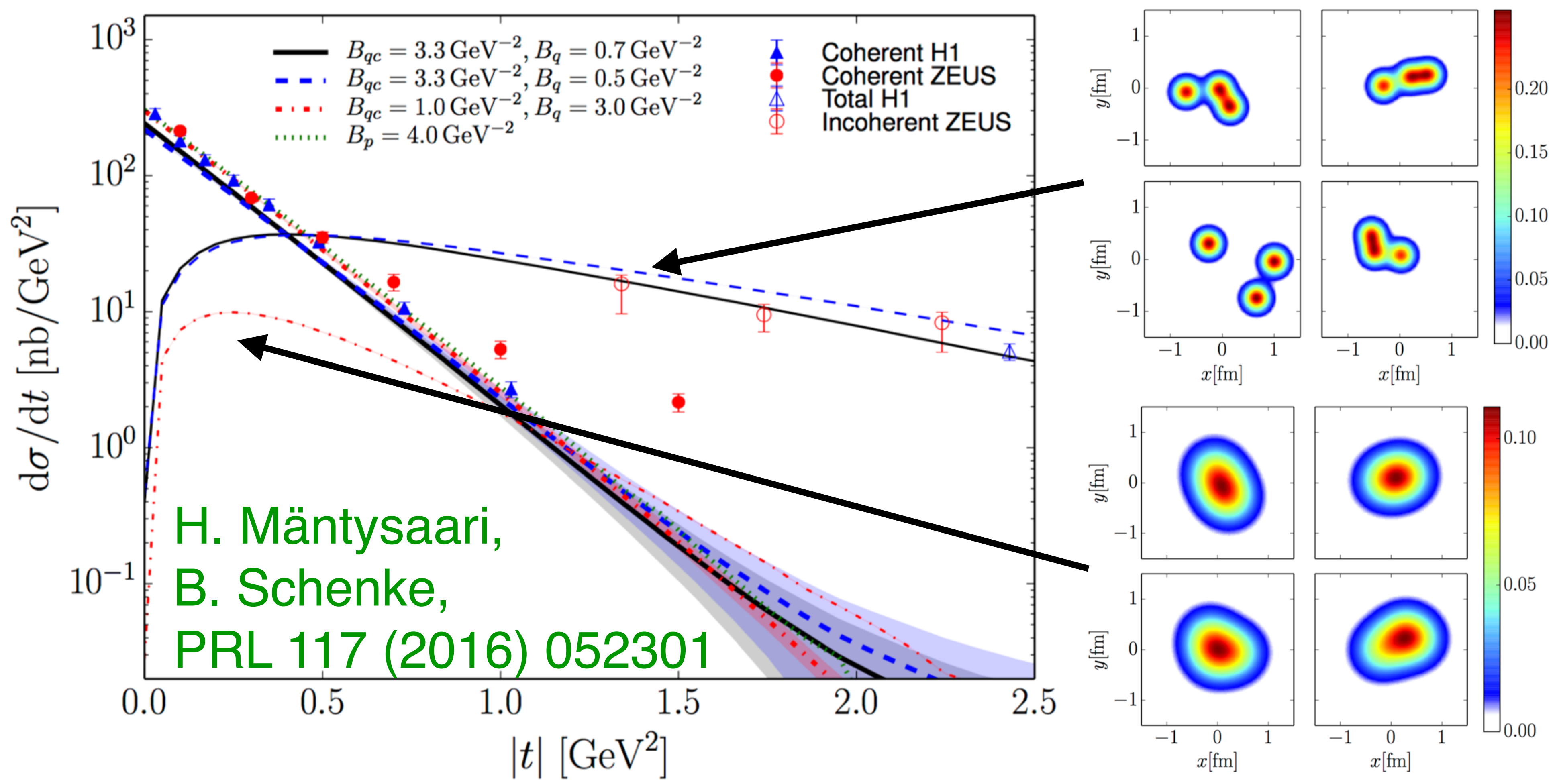
$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle \langle f|\mathcal{A}|i\rangle$$

$$= \langle |\mathcal{A}|^2 \rangle - \langle |\mathcal{A}| \rangle^2$$

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi} \langle |\mathcal{A}|^2 \rangle \qquad \frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} \langle |\mathcal{A}| \rangle^2$$

- Incoherent CS is the variance of the amplitude ⇒ measure of fluctuation of the source $G(x, Q^2, b)$ at scale ~1/t
- Note: Variance disappears in black disk limit! Clear saturation signature.

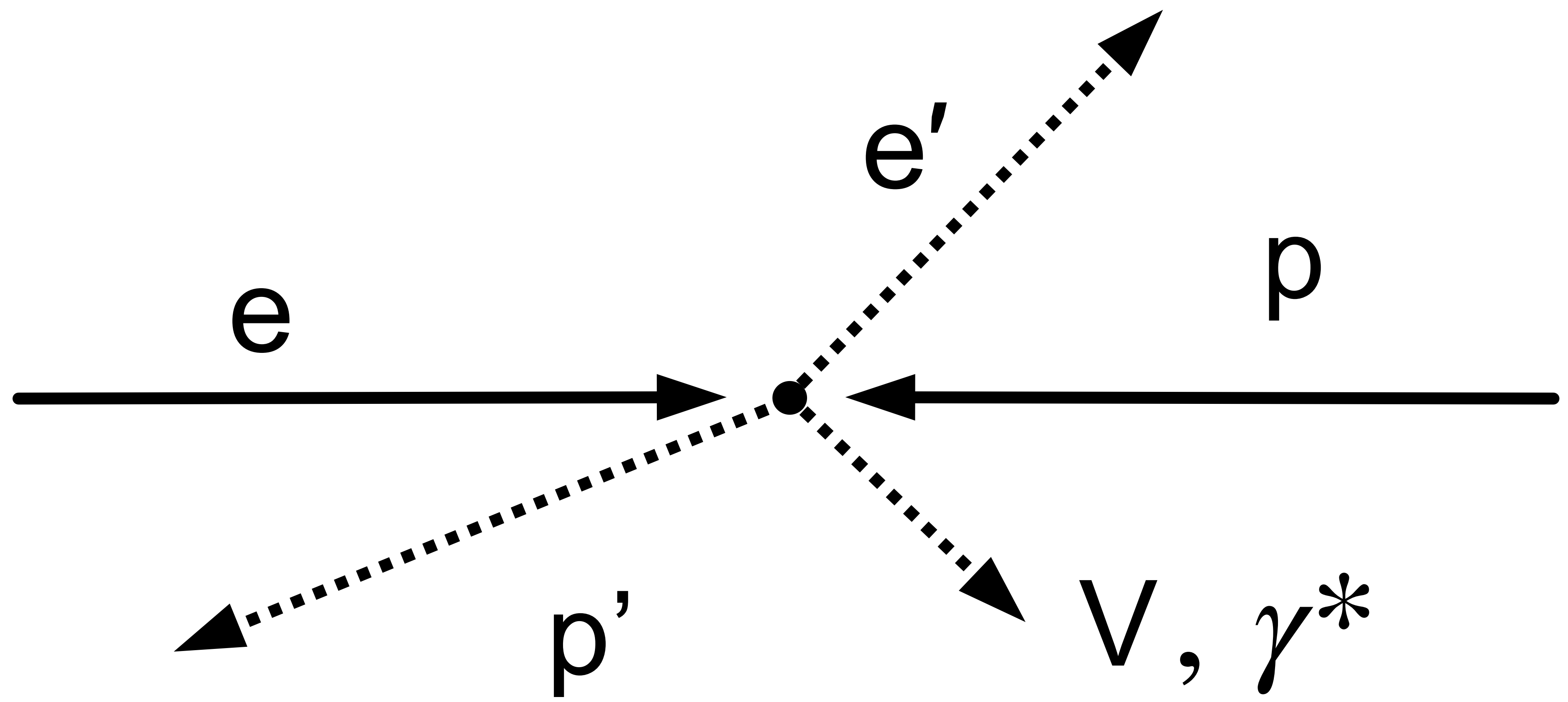
Example from ep:



Question: How to Measure t?

In e+p we can use the original definition of *t*:

$$t = (p - p')^2$$



p is known (beam) and p’ is measured by forwards proton spectrometers (Roman Pots etc)

How well that ultimately works in terms of σ_t / t one has to see.

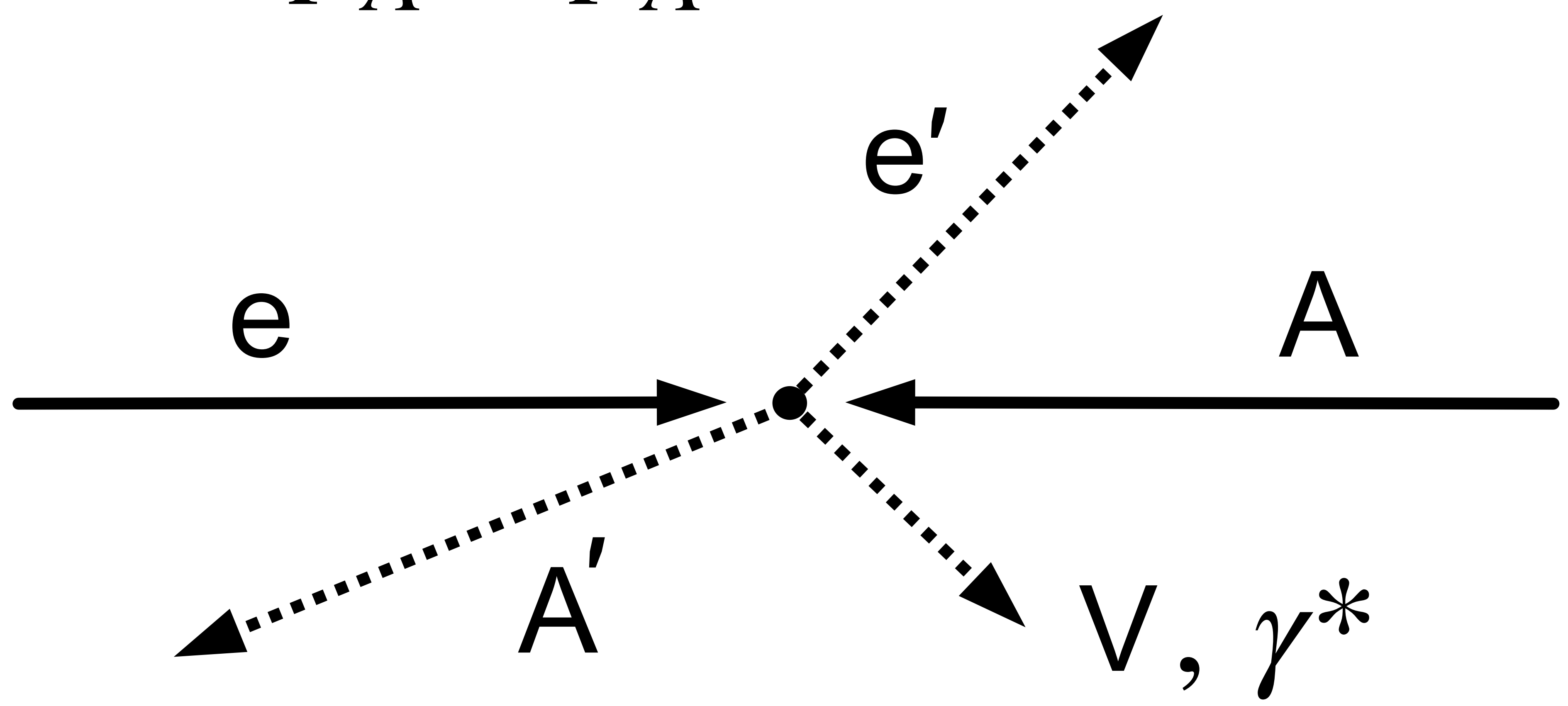
In any case alternative methods should be considered either to improve the precision or for systematic cross-checks.

Question: How to Measure t in e+A?

In e+A we *cannot* measure $p_{A'}$:

- coherent: *t* kick not big enough to get heavy ions out of the beam envelope
- incoherent: unlikely we can measure all fragments and reconstruct the whole ion and its momentum.

$$t = (p_A - p_{A'})^2$$



In general *t* cannot be measured w/o knowing $p_{A'}$ *except* in exclusive vector meson production:

$$e + A \to e' + A' + V$$

since 4-momenta from e, A, e' and V are known

Exact Way (Method E)

One can directly calculate *t* as:

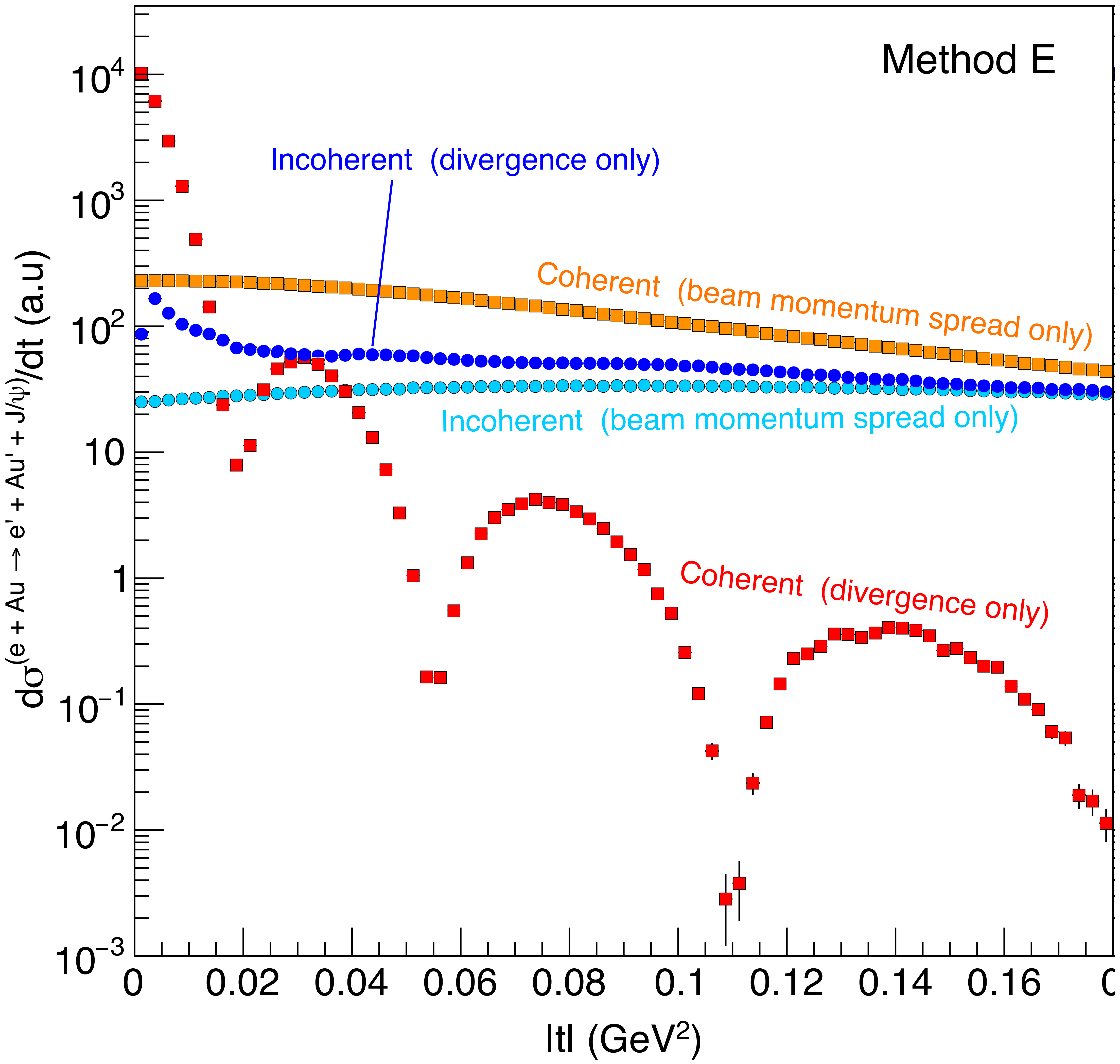
$$t = (p_A - p_{A'})^2 = (p_V + p_{e'} - p_e)^2$$

we call this method E (exact)

- In absence of any distortions (e.g. MC) this method delivers the true *t*
- BUT: Sensitivity to beam effects
  - Beam divergence affects little: σ_t/t ~ 6% to 0.5%
  - Beam momentum spread is devastating: σ_t/t ~ 15000% to 103%

Method E

Effect on $d\sigma/dt$:



$$t = (p_V + p_{e'} - p_e)^2$$

Why does it fail:

Have to subtract large incoming and large outgoing momenta to get the "longitudinal part" of *t*. So a small error/smearing/inaccuracy in these has enormous effect on *t*

Method A

Approximate method:

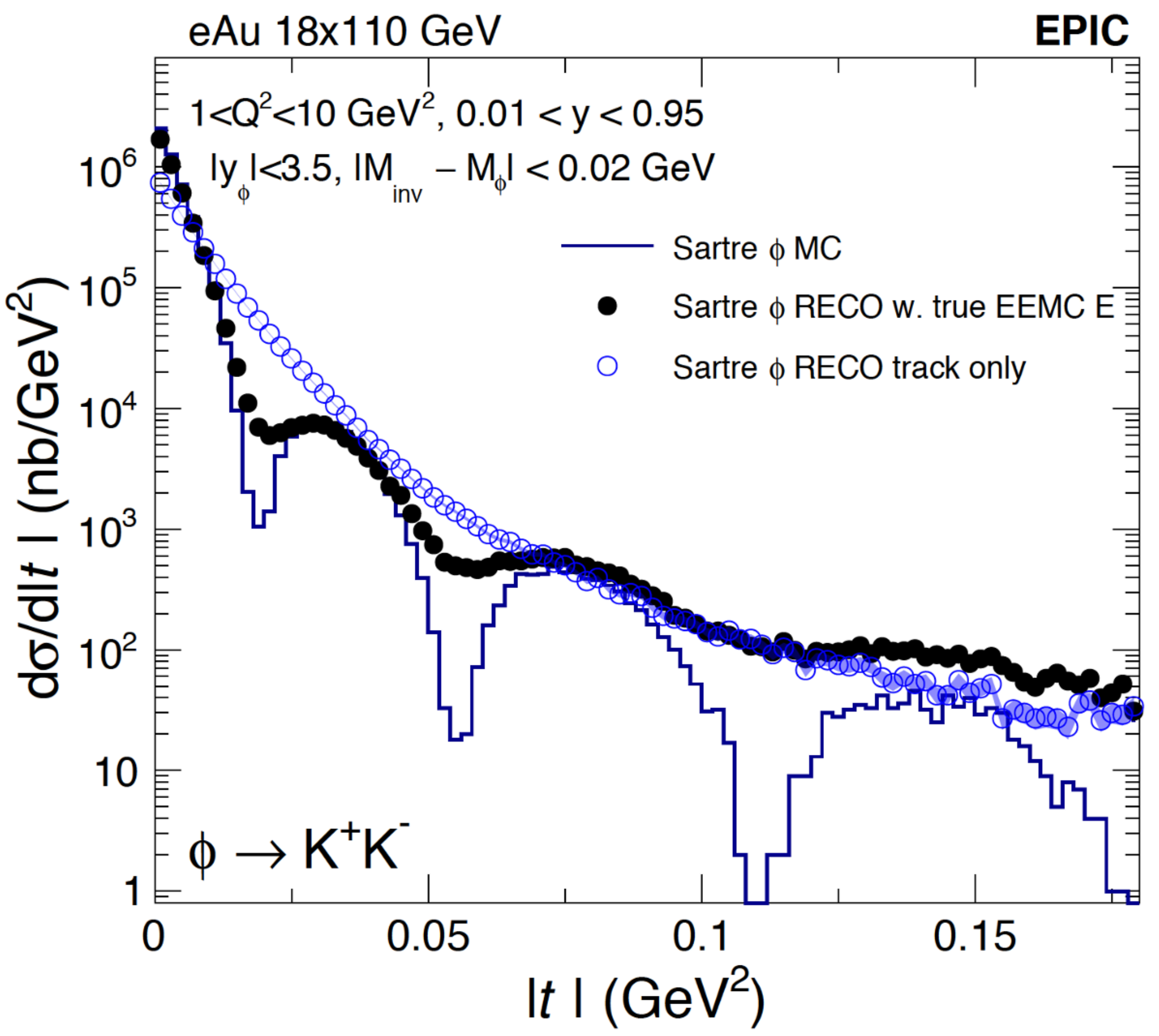
Rely only on the transverse momenta of the vector meson and the scattered electron ignoring all longitudinal momenta. Therefore beam momentum fluctuations do not enter the calculations. This method was extensively used at HERA in diffractive vector meson studies.

$$t = \left[\vec{p}_T(e') + \vec{p}_T(V)\right]^2$$

- This formula is valid only for small t and small Q^2. It also performs better for lighter vector mesons such as ϕ and ρ. In what follows we refer to this method as method A.
- There is a improved method (L from Lappi) that is an extension and a huge improvement overcoming some of the shortcomings.

Massive Disappointment

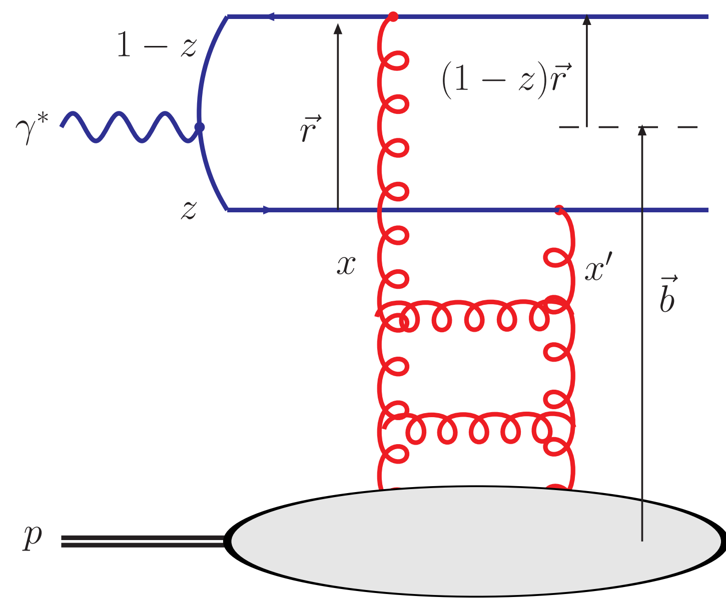
- It turns that with using realistic detector simulations the killer is the measuring the p_T of the scattered electron with the required precision.
- This measurement was one of the key diffractive plots but it seems out of reach
- We can:
  - change the kinematic where to measure e' reducing x reach
  - measure p directly with light ions losing Qs oomph
  - think harder and longer …



There are Others Measurements …

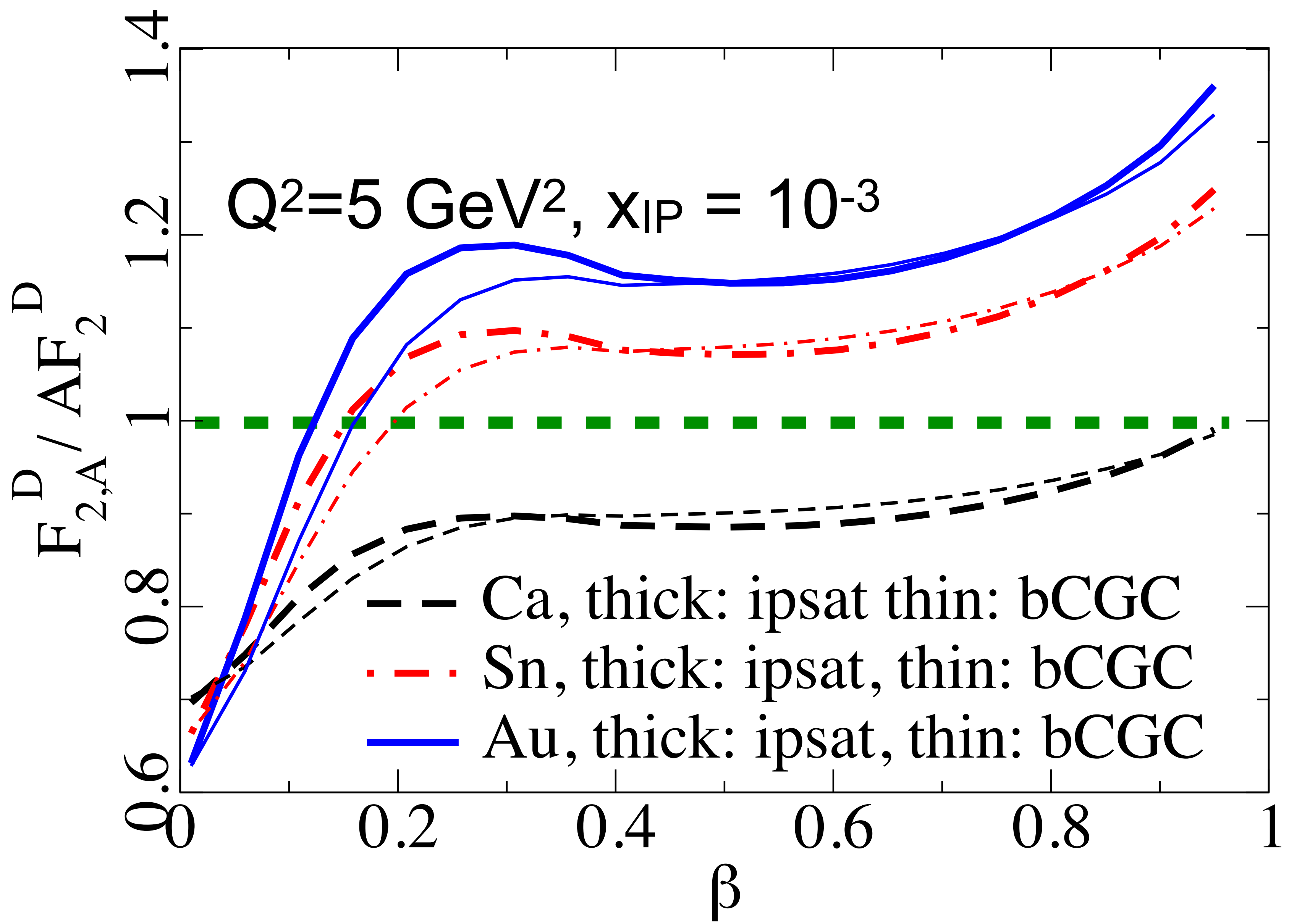
Diffractive over Total Cross-Section

- Saturation models (CGC) predict up to $\sigma_{diff}/\sigma_{tot}$ ~ 25% in eA (Hera in ep ~15%)
- Enhanced at large β, i.e. small M_X^2
  - β = momentum fraction of the struck parton with respect to the Pomeron

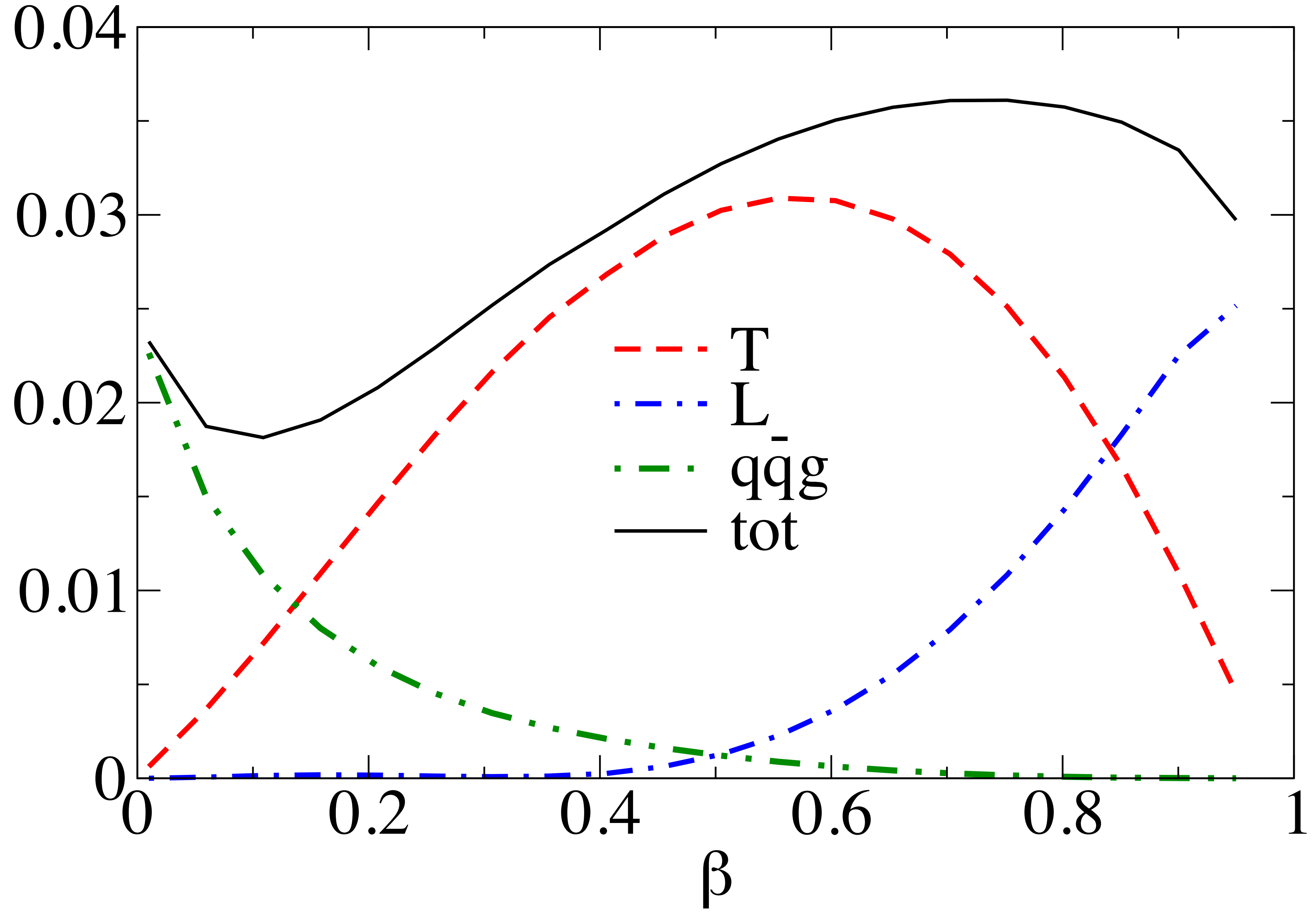


$$\beta \approx \frac{Q^2}{Q^2 + M_X^2} \qquad x = \beta\, x_{I\!P}$$

$$\text{Rapidity Gap} : \approx \ln \beta / x$$



contributions to the proton diffractive structure function



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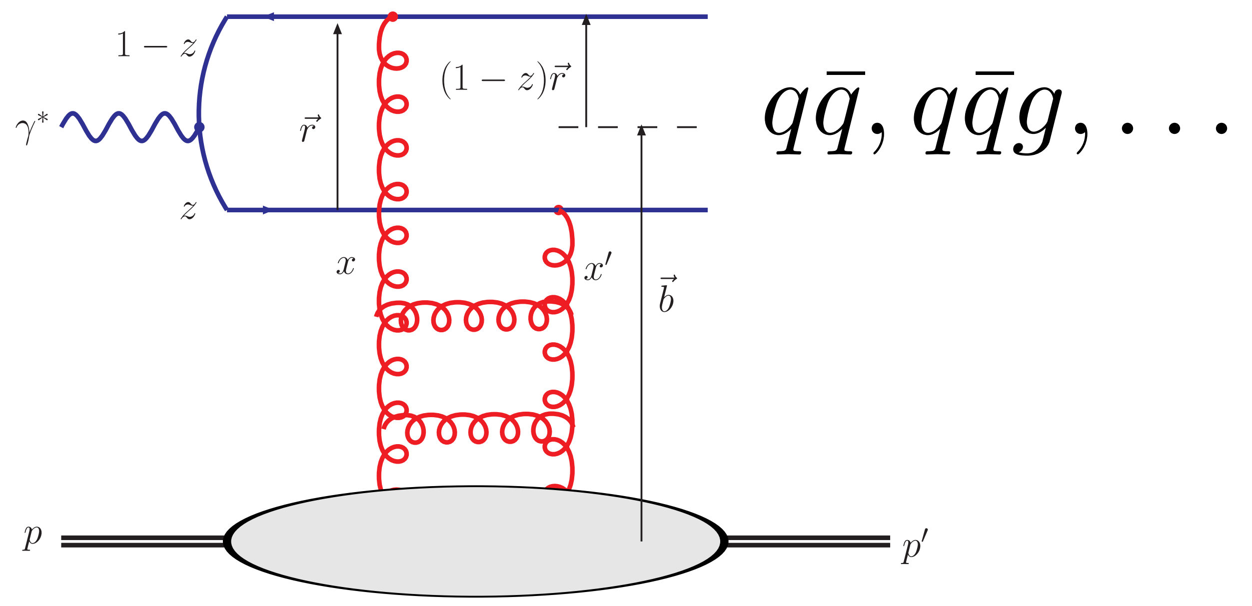

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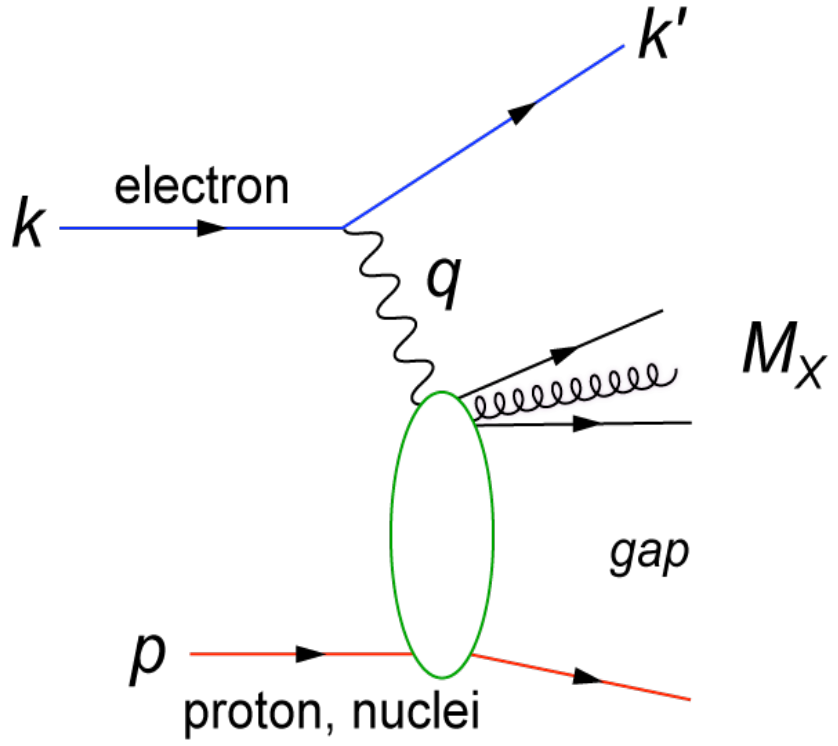

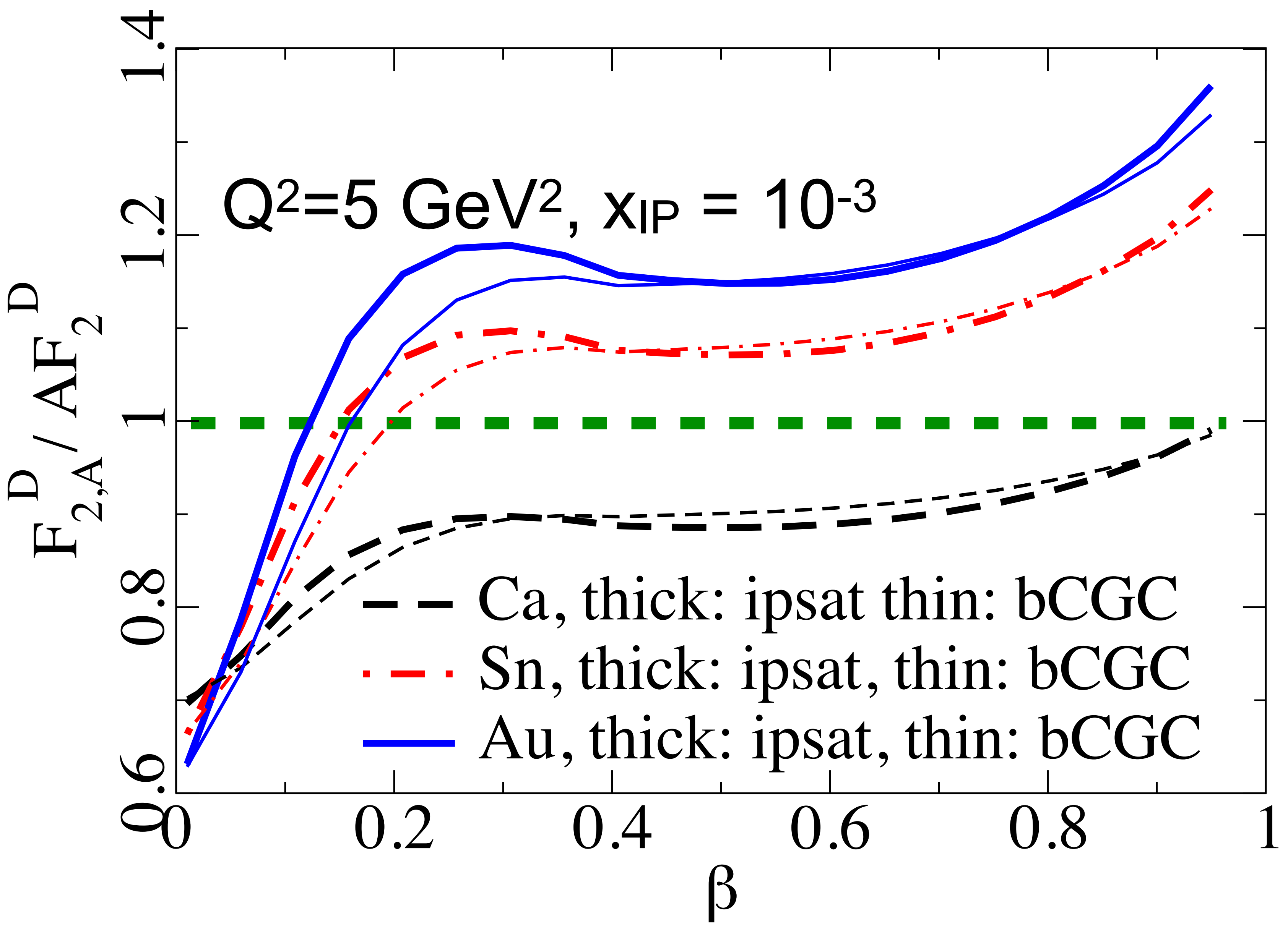

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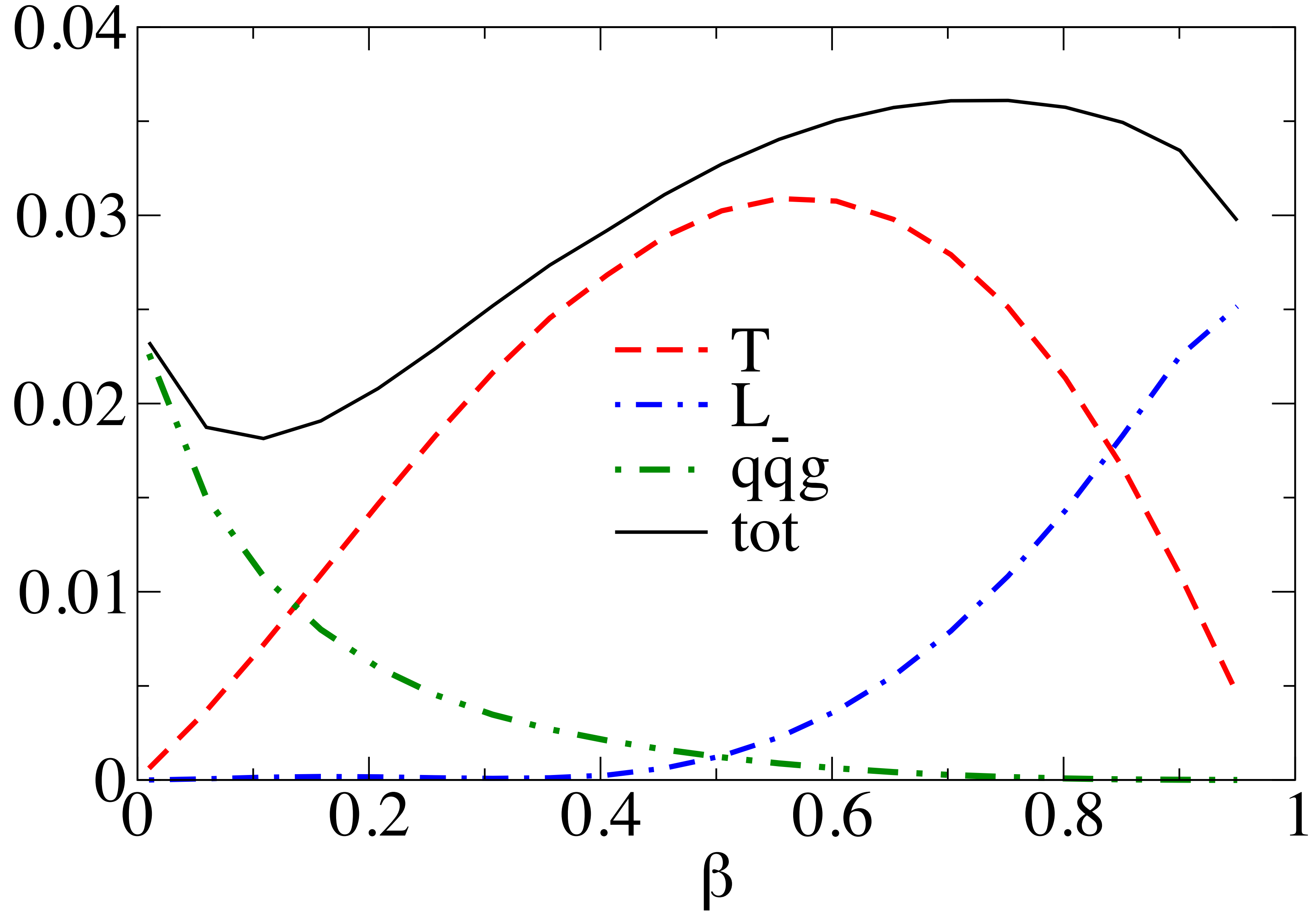
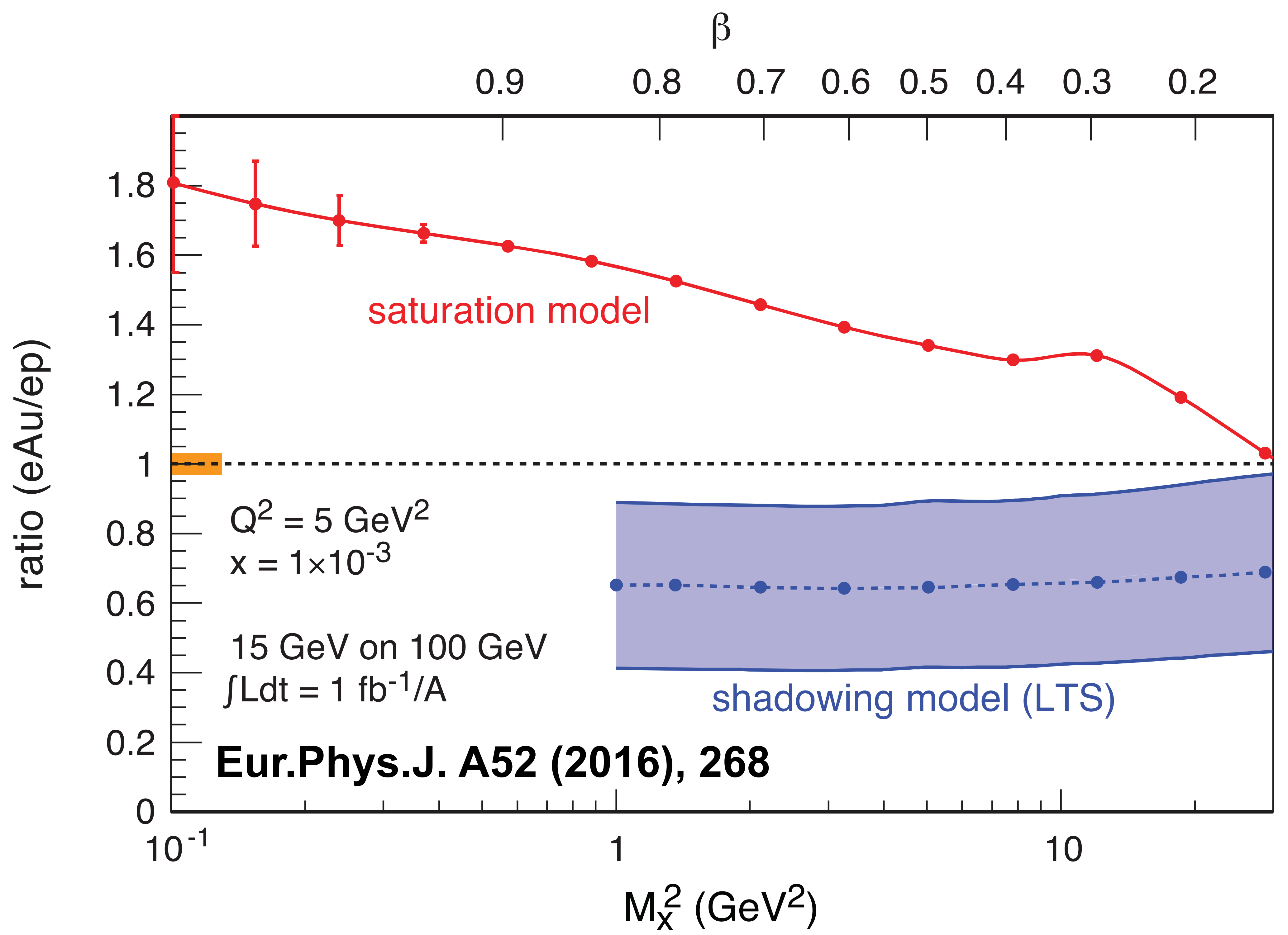




- Studies using diffractive event generator Sartre based on Dipole model.
- Ratio *enhanced* for small M_X and *suppressed* for large M_X
- Standard QCD predicts no M_X dependence and a moderate suppression due to shadowing.

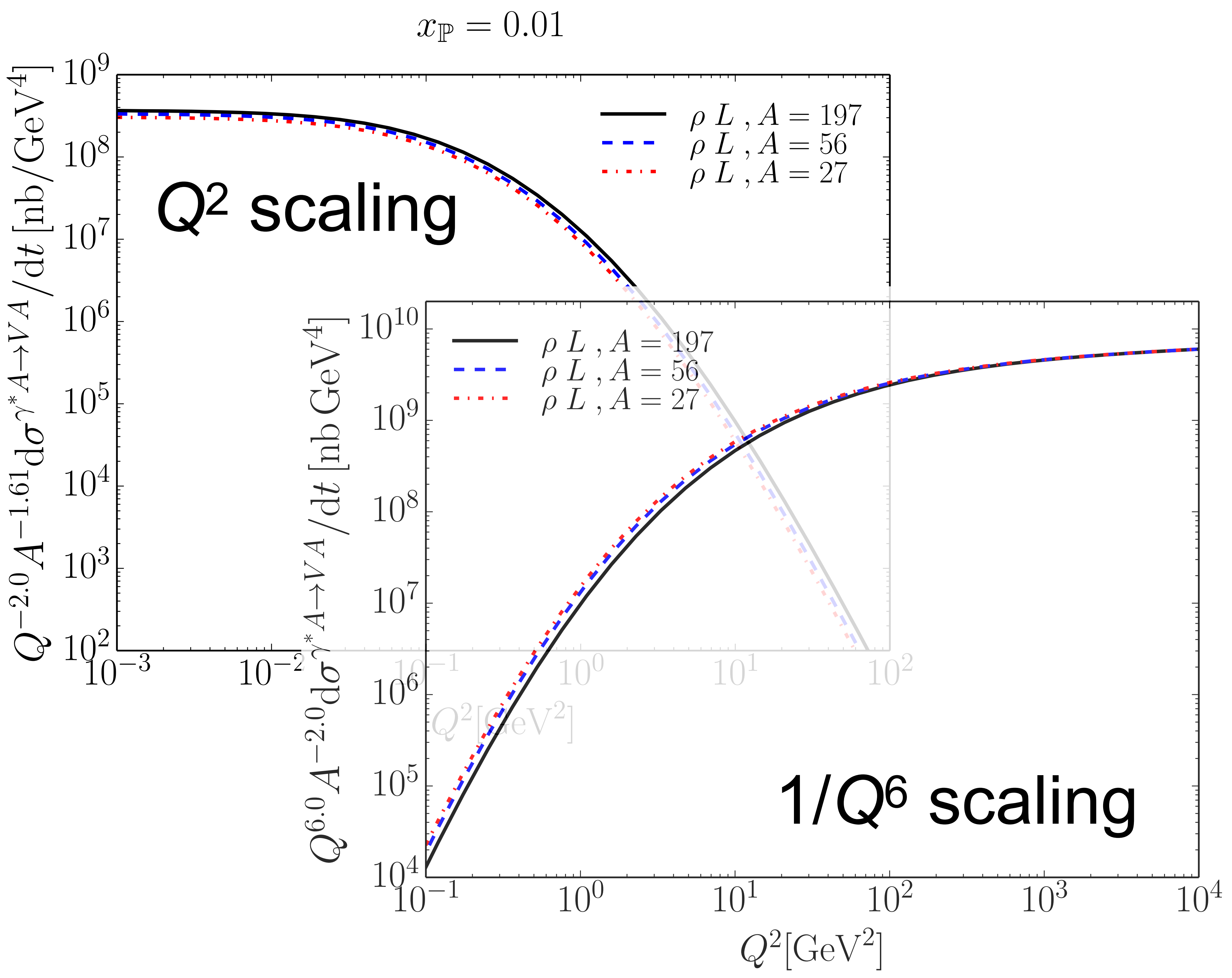
Simple Day 1 Measurement:
Ratio of cross-sections

$$\frac{\sigma_{diff}/\sigma_{total}\ (eA)}{\sigma_{diff}/\sigma_{total}\ (ep)}$$

Unambiguous signature for reaching the saturation limit

Key Measurement: $\sigma_{diffractive}/\sigma_{total}$

- Saturation models predict very special and strong dependencies in A and Q^2 that are different above and below Q^2_S



- $Q^2 > Q^2_S$
  - $\sigma \sim 1/Q^6$
  - $\sigma(t=0) \sim A^2$
  - $\sigma \sim A^{4/3}$
- $Q^2 < Q^2_S$
  - $\sigma \sim Q^2$
  - $\sigma(t=0) \sim A^{4/3} \leftrightarrow A^{5/3}$
  - $\sigma \sim A^{2/3} \leftrightarrow A$

- Non-Saturation scenarios do not show this behavior making A, Q^2 dependencies a key measurement

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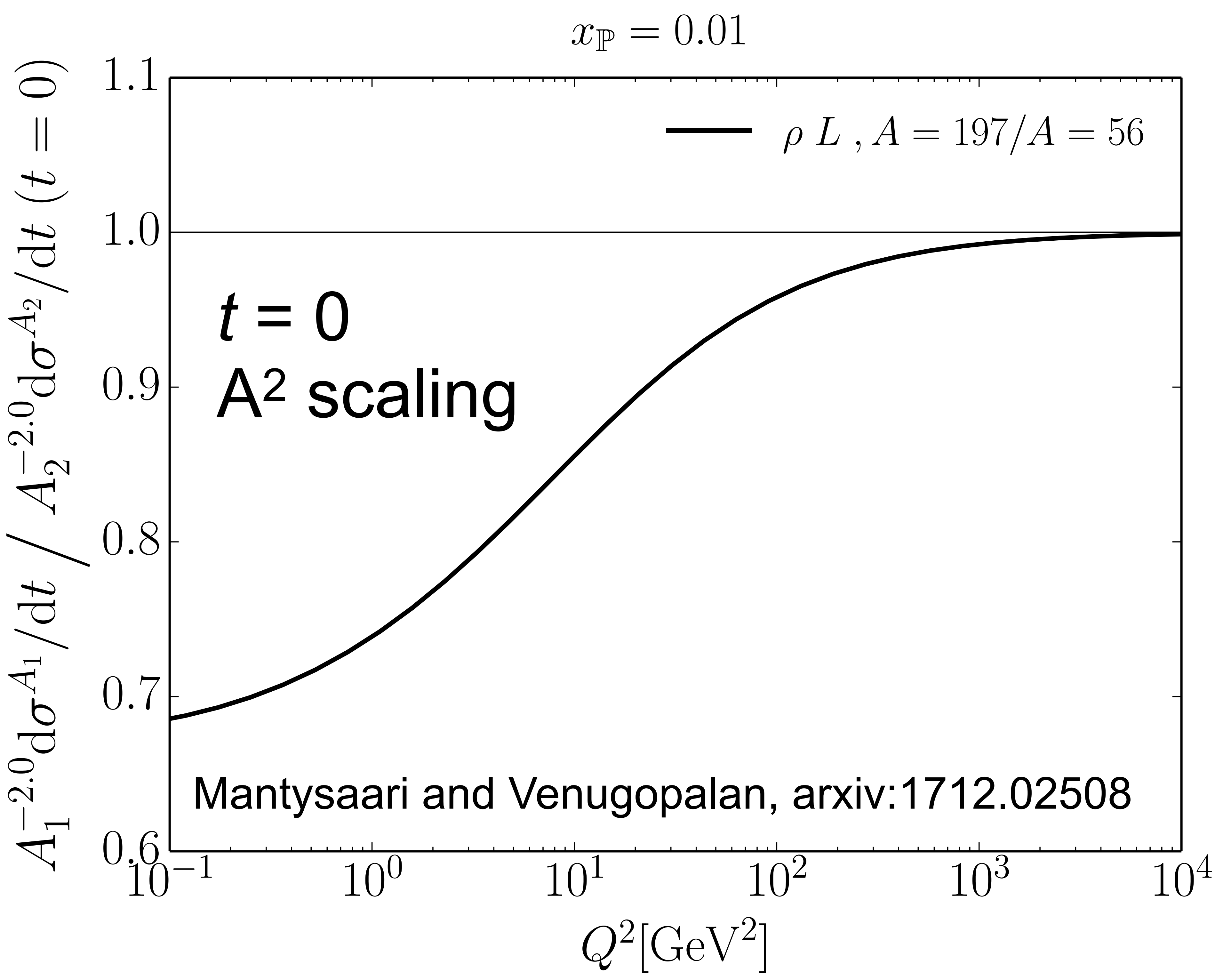

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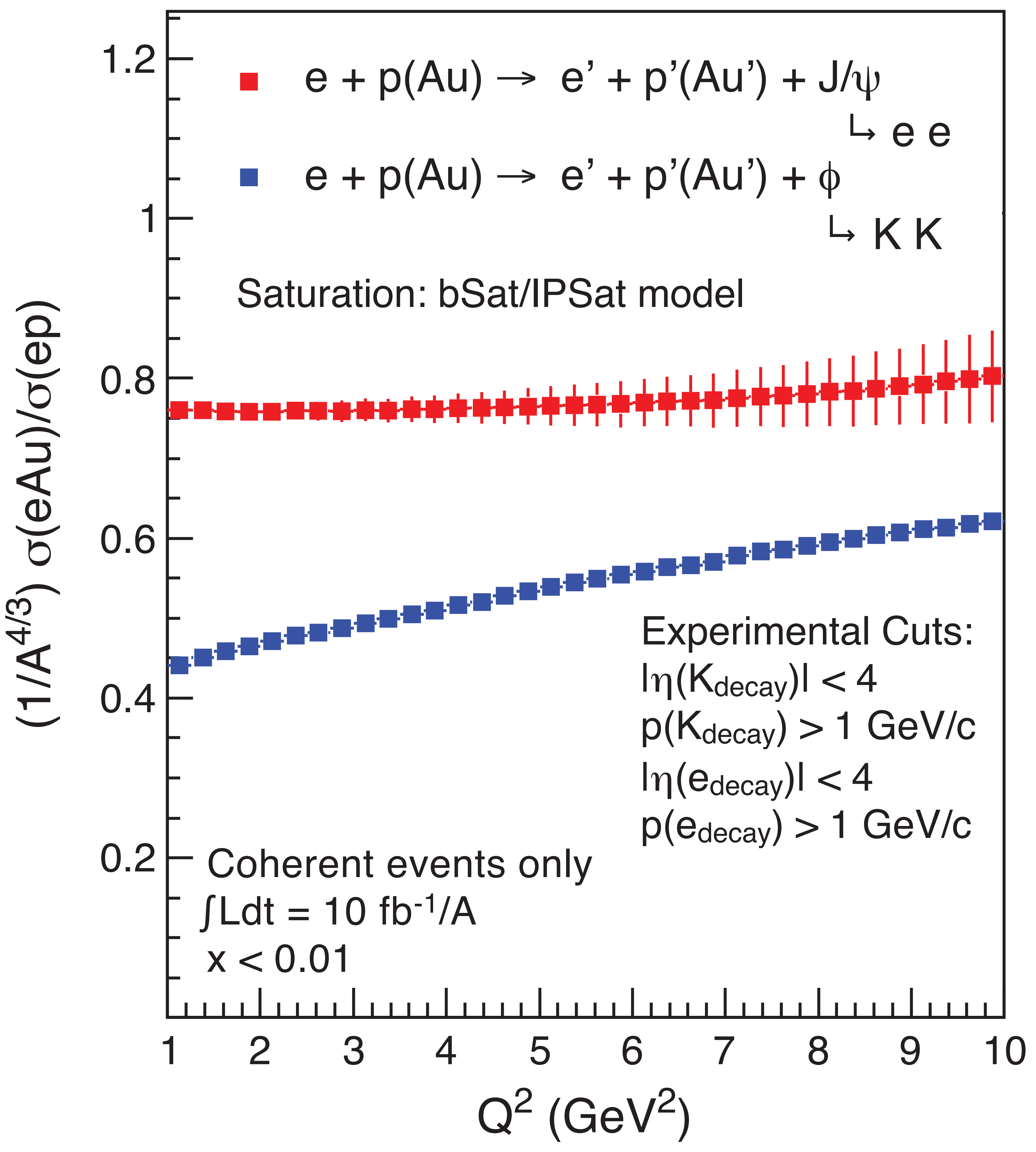
Exclusive Diffractive Vector Meson Production



Full simulations using Sartre event generator based on IPSat (aka bSat) model

- Suppression larger for φ than for J/ψ as expected
- Straightforward measurement for early days of an EIC

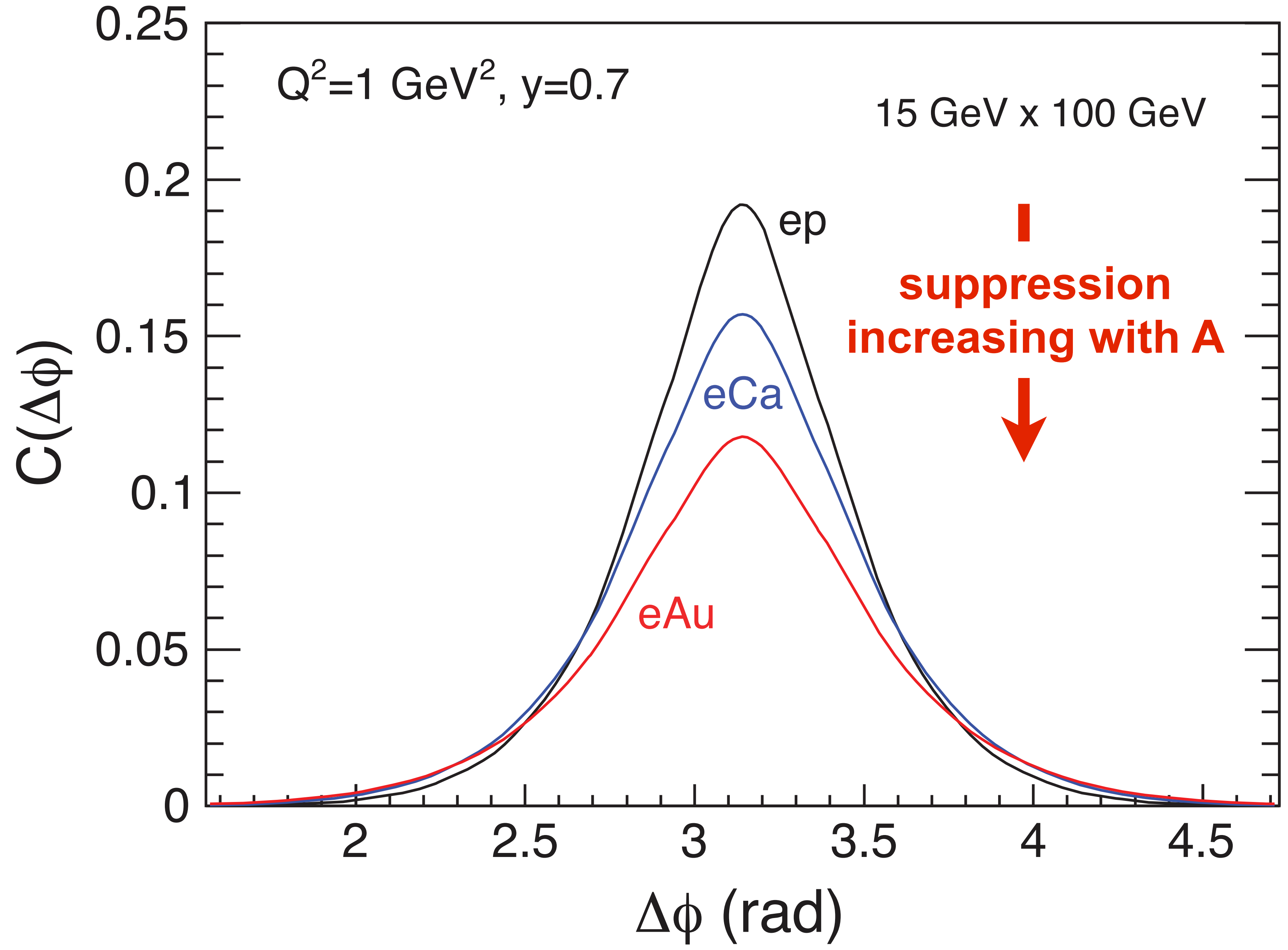
Note: $A^{4/3}$ scaling strictly only valid at large Q^2

6.3 Dihadron Correlations

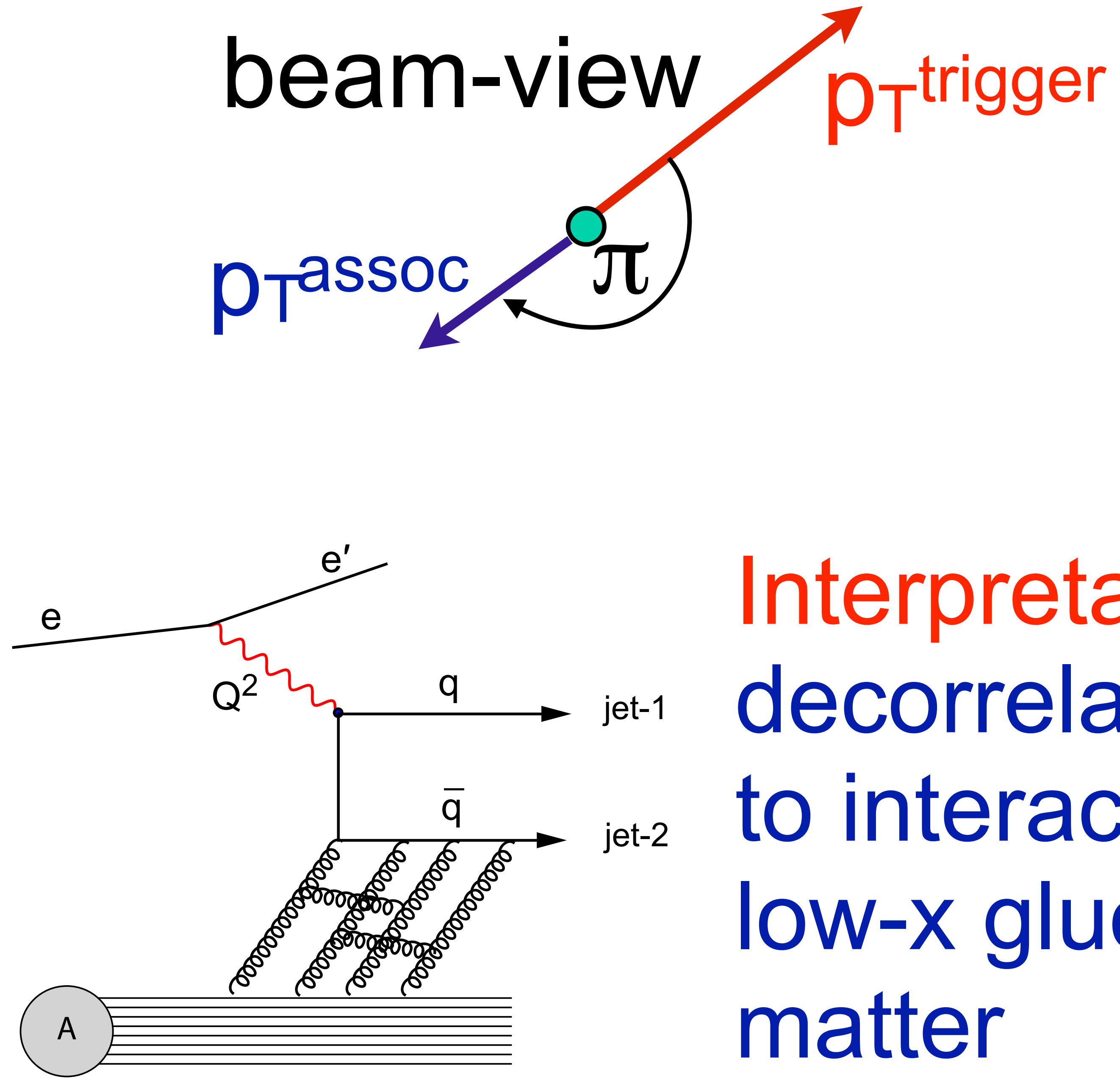
Dihadron Correlations

Dihadron correlation as a probe to saturation.

Saturation models predict suppression of away-side peak



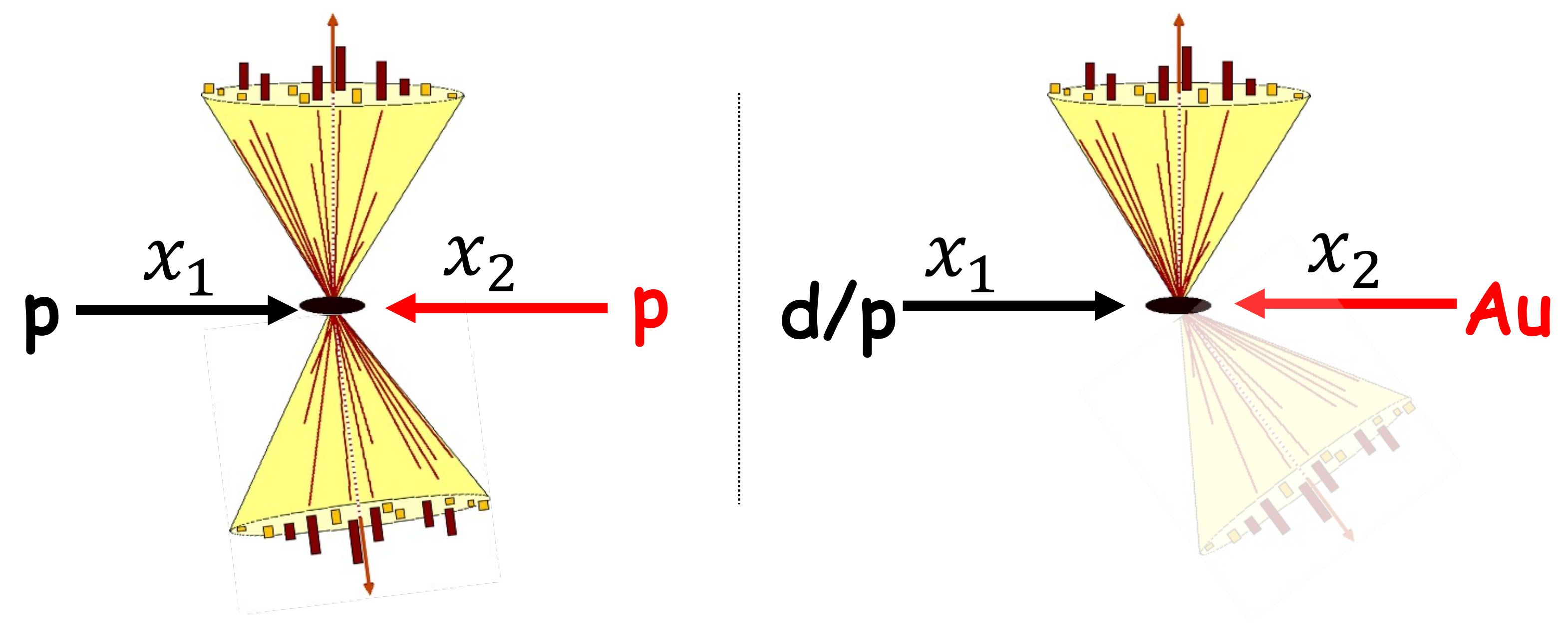
Experimental Simple Measurement



Interpretation:
decorrelation due to interaction with low-x gluonic matter

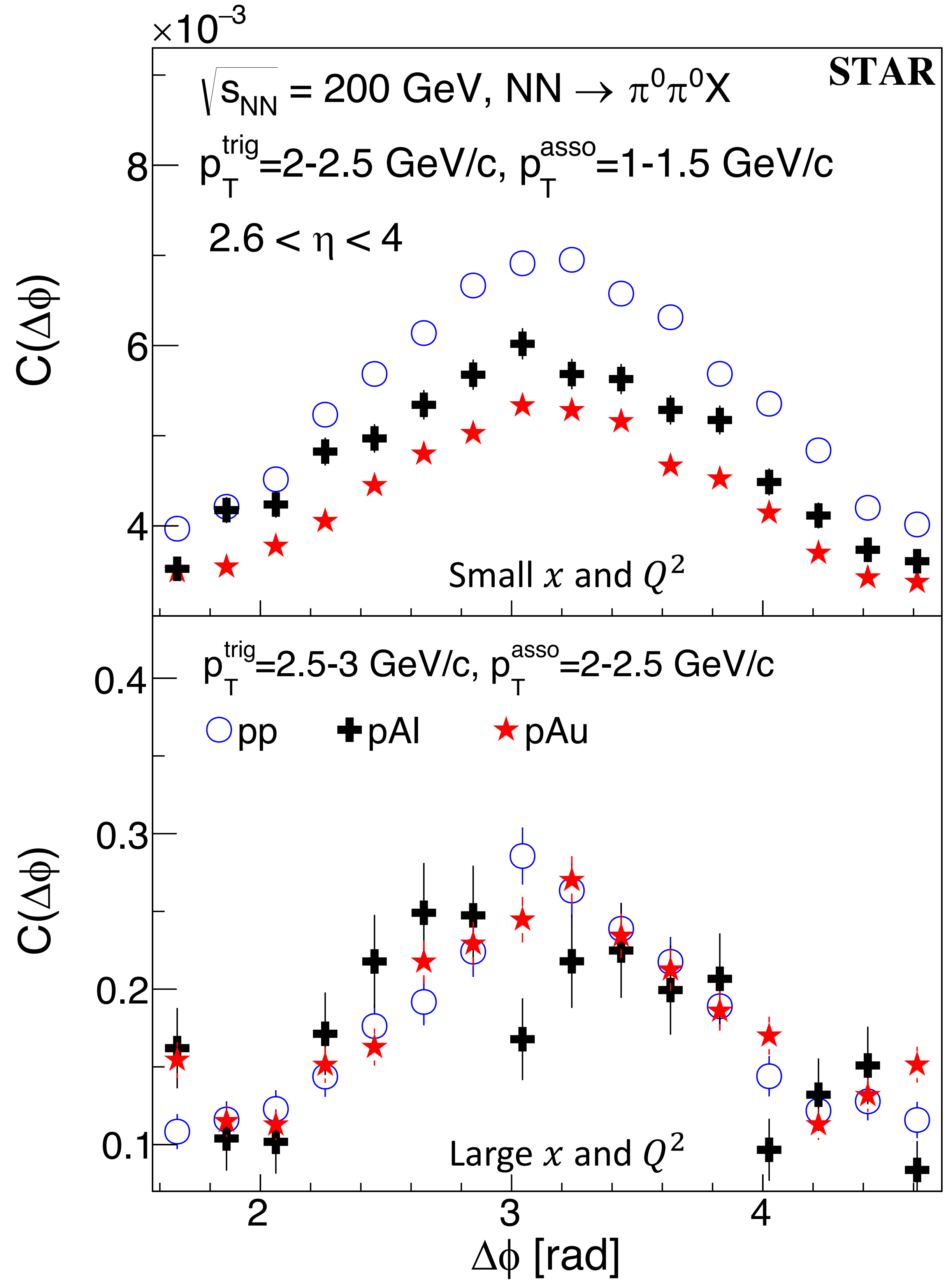
- Predicted [C. Marquet, 09] as important hint of saturation
- Robust calculations available (Albacete, Dominguez, Lappi, Marquet, Stasto, Xiao) including Sudakov resummation in dijet processes

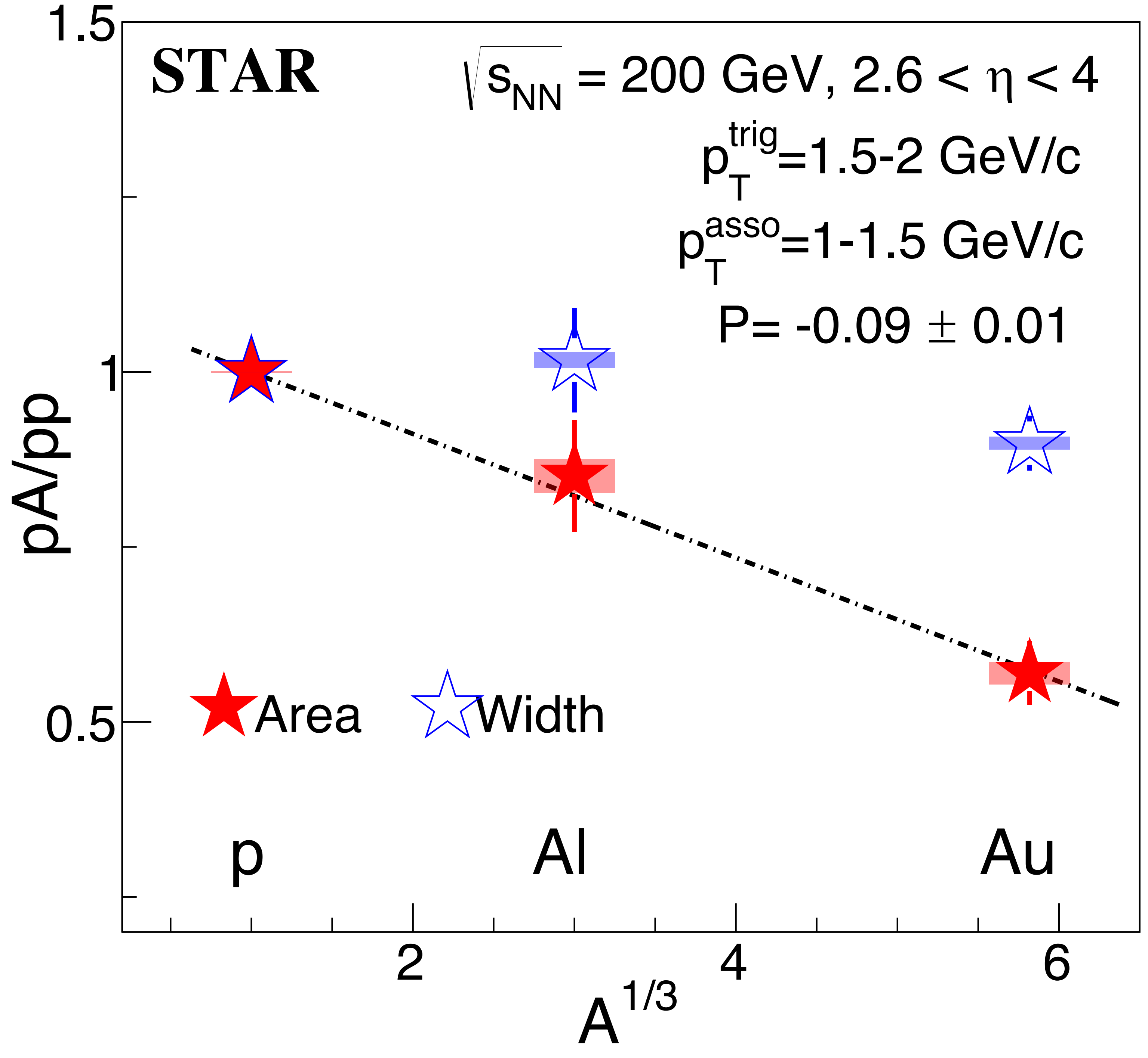
Reminder: Dihadrons at RHIC



p: non-saturated

Au: saturated

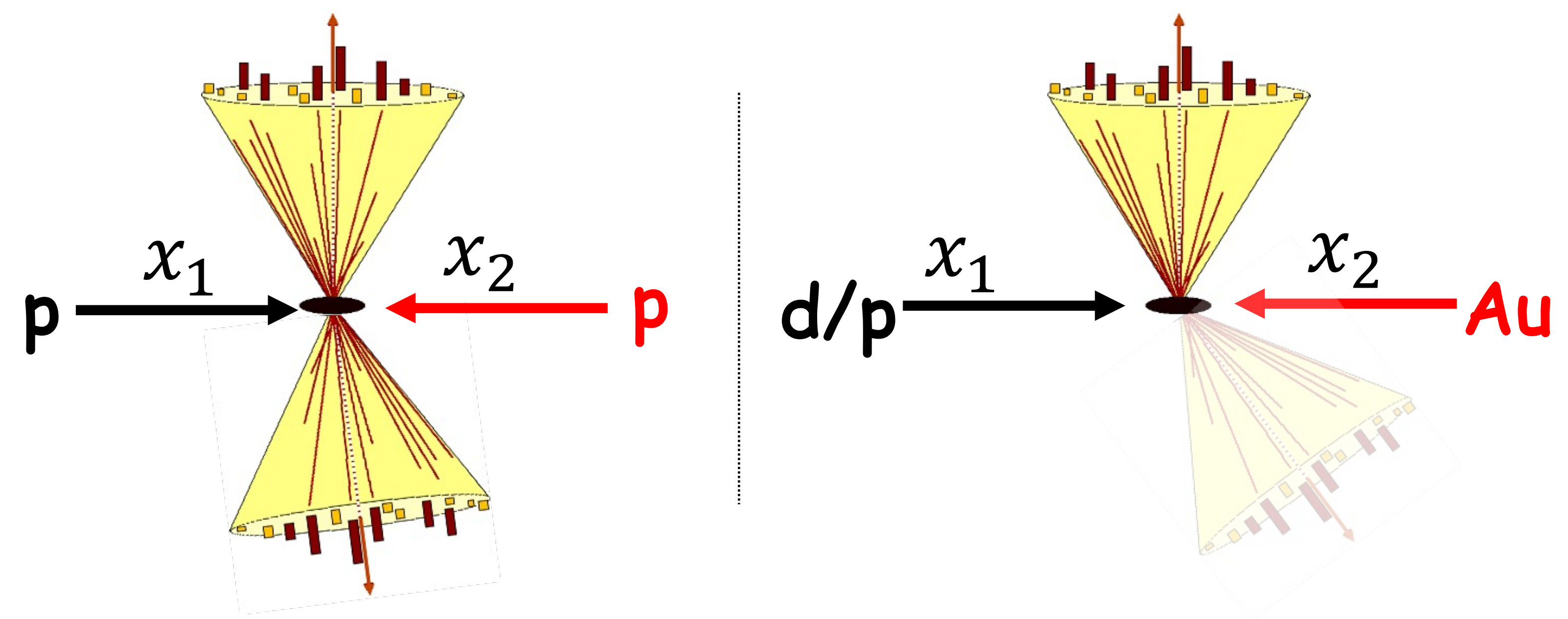




- Experiments: suppression dependence on A and p_T observed at STAR
- Suppression exists at low p_T not high p_T.
- In a fixed $x - Q^2$ region, suppression is dominantly affected by various A
  - Suppression depends linearly on $A^{1/3}$
- No broadening is observed

STAR, PRL 129, 092501 (2022)

Reminder: Dihadrons at RHIC



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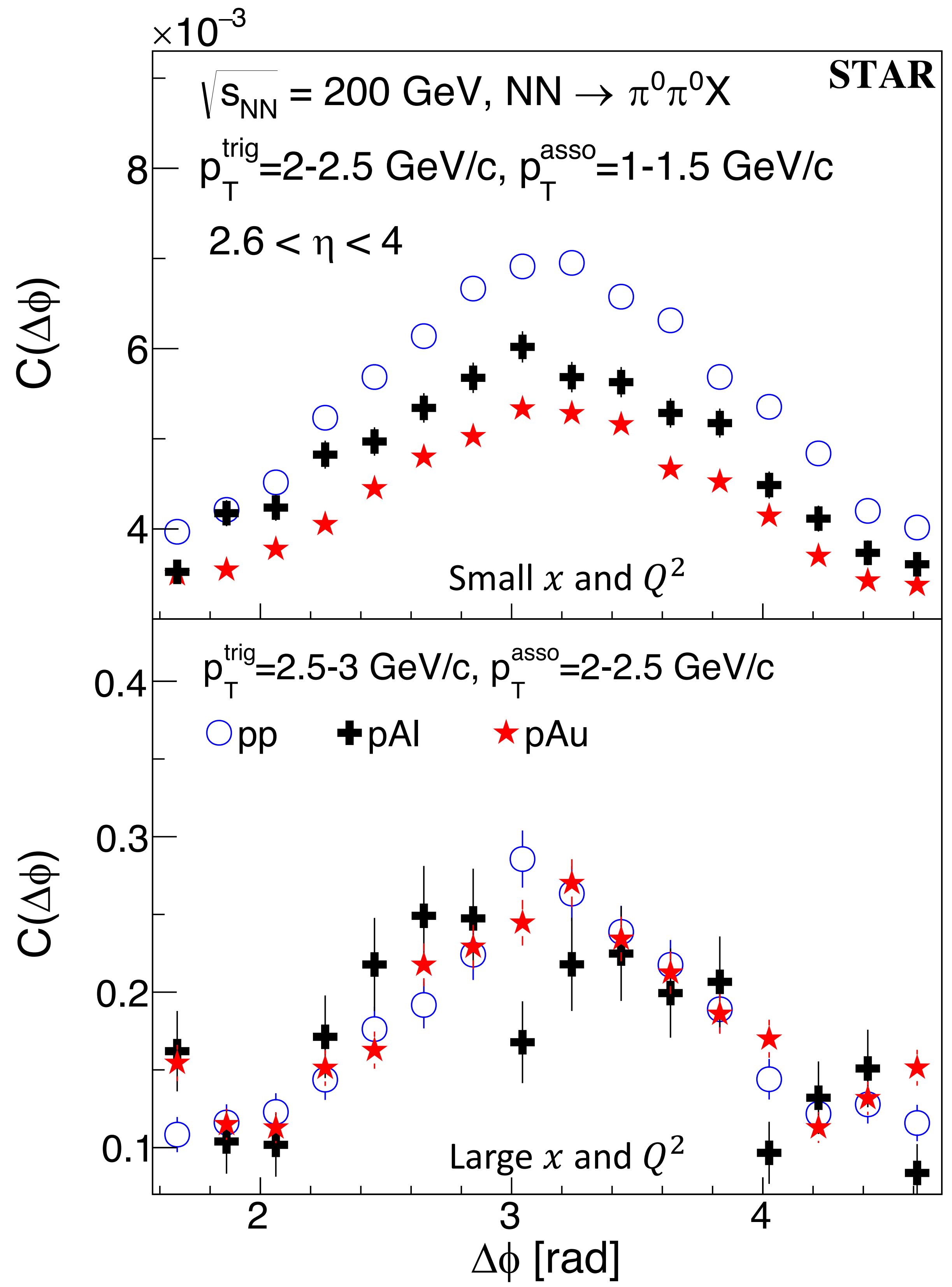

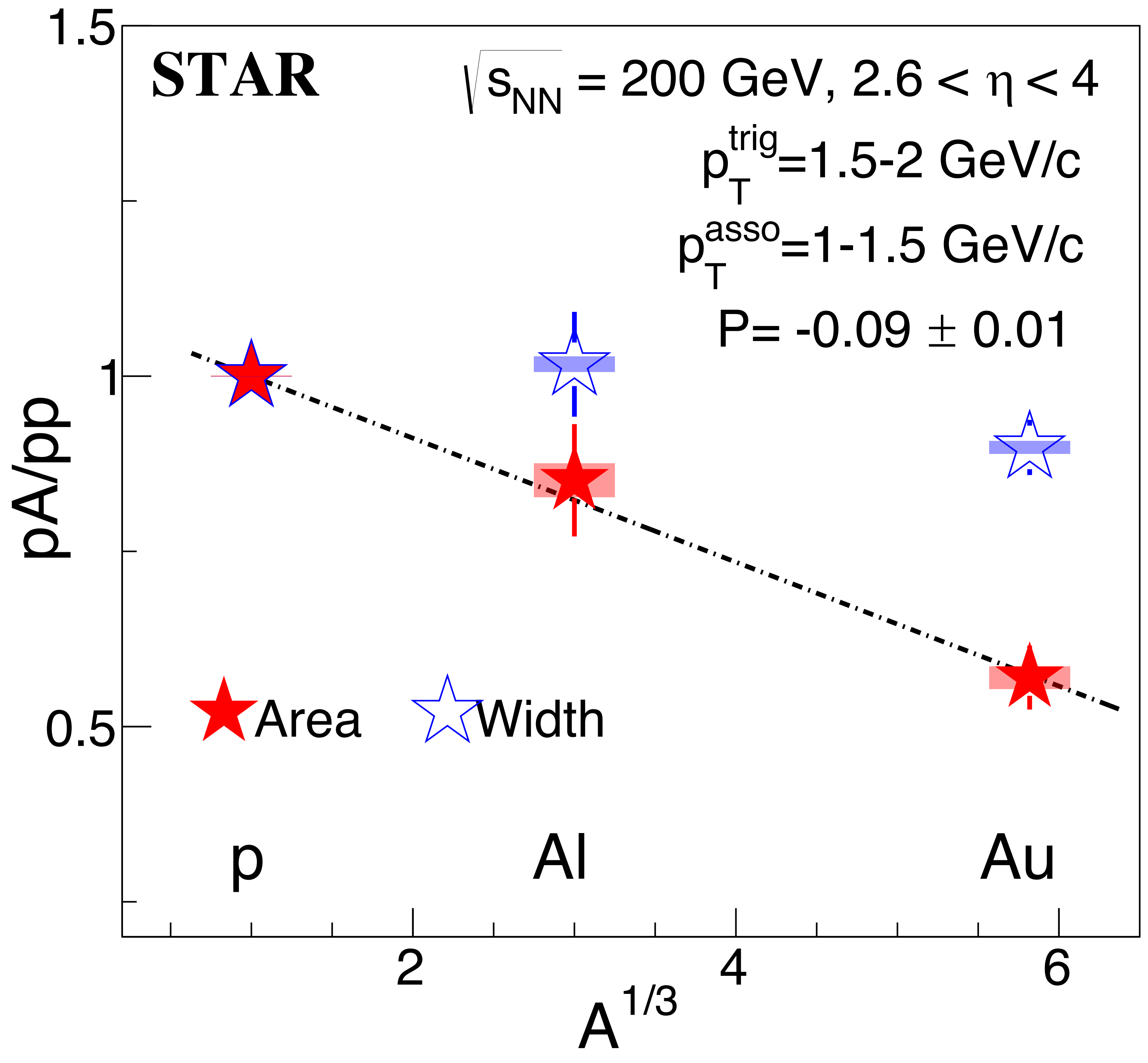

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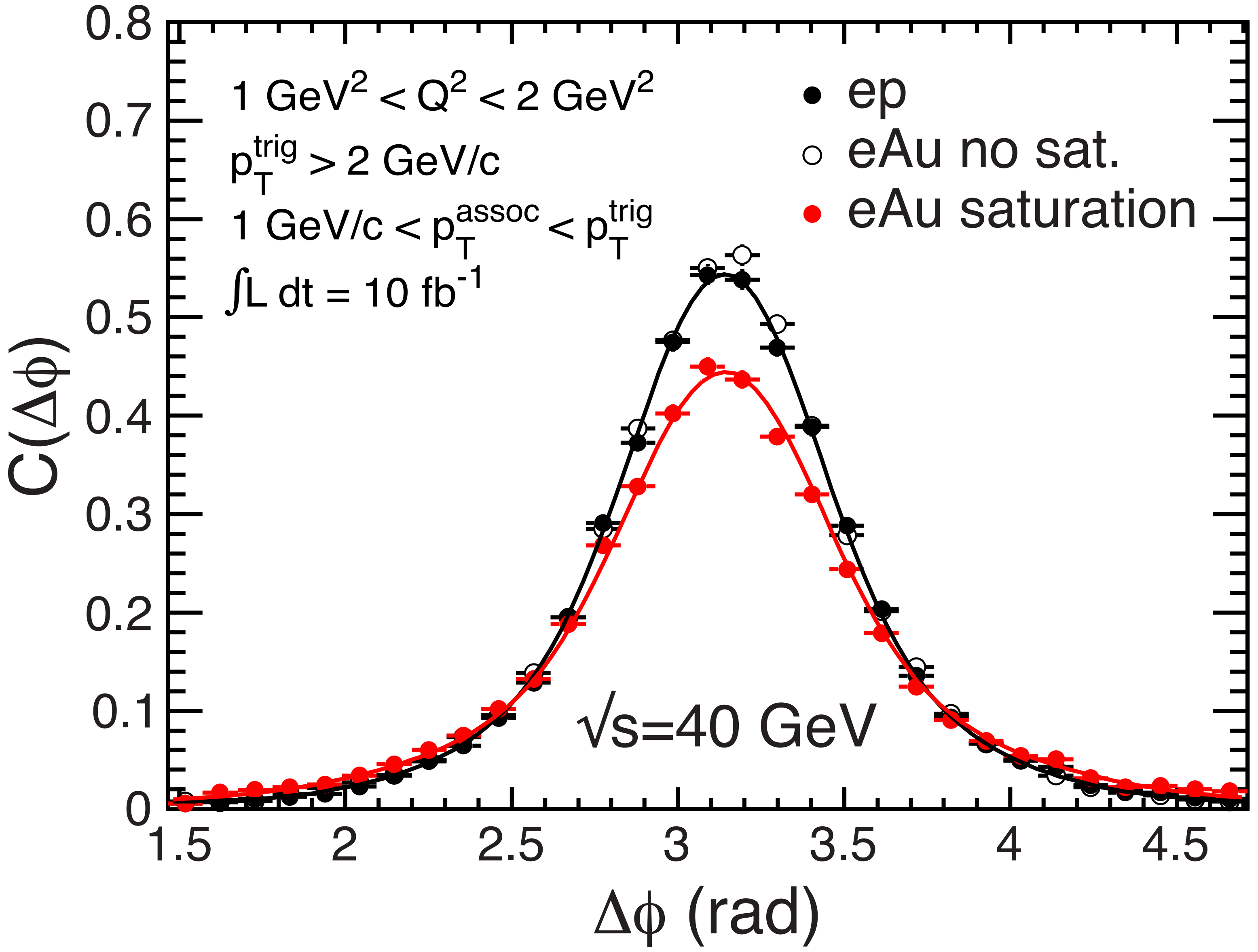
  - Suppression depends linearly on $A^{1/3}$
- No broadening is observed

- Cannot assure that effect has initial state contributions in p/d+A
- Large background, no access to process kinematics

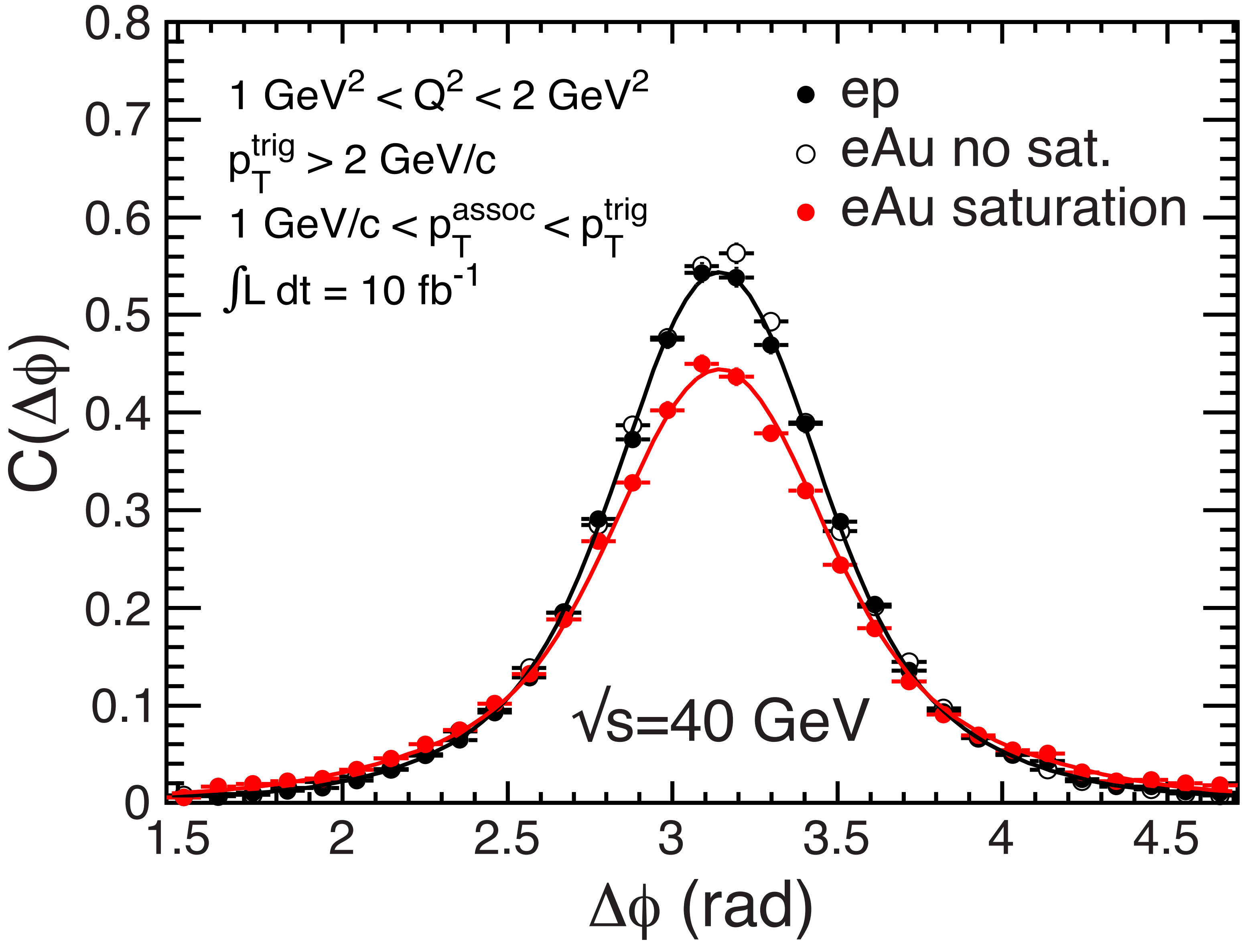
⇒ e+A

STAR, PRL 129, 092501 (2022)

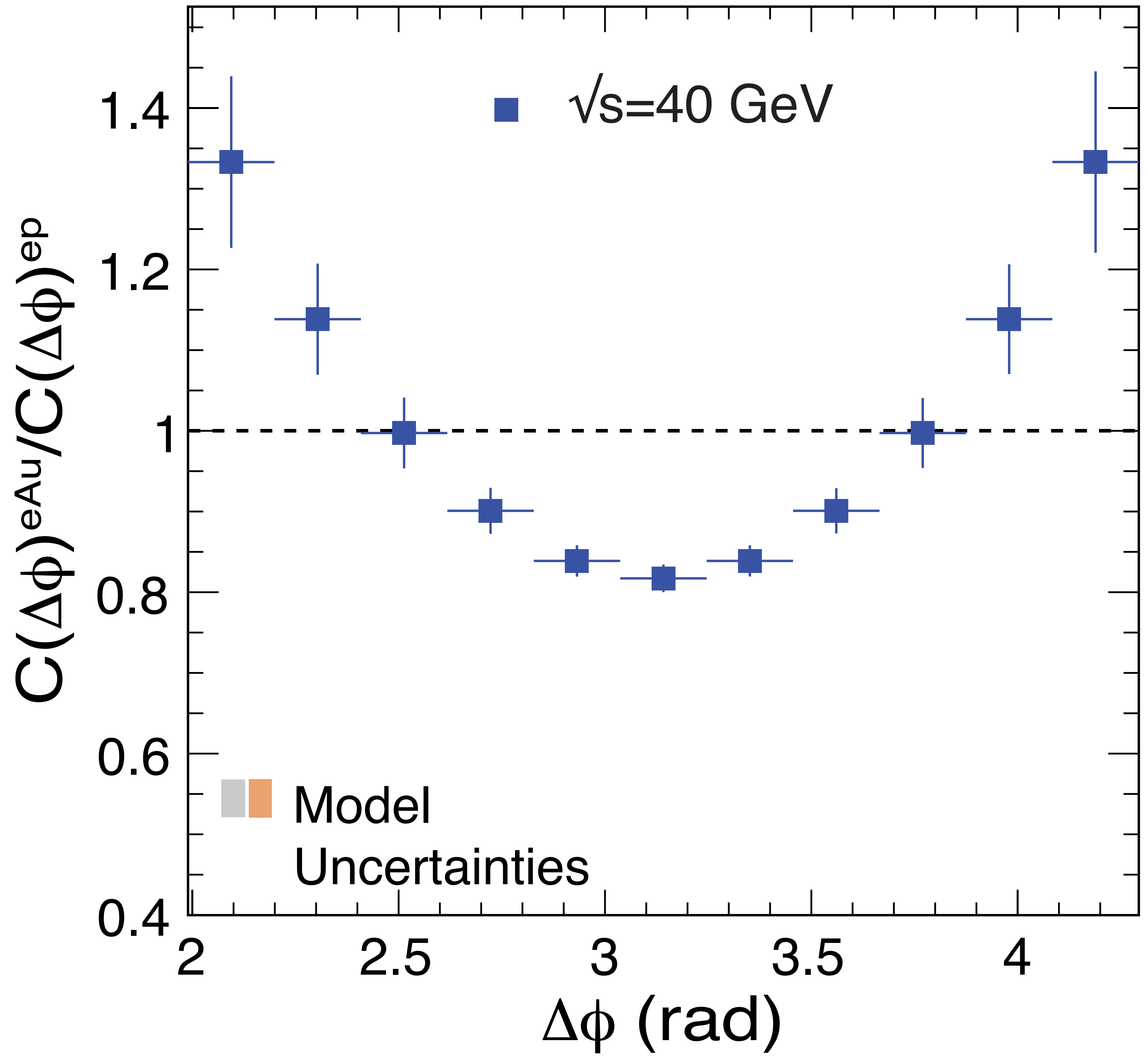
EIC Simulation Results: Dihadrons



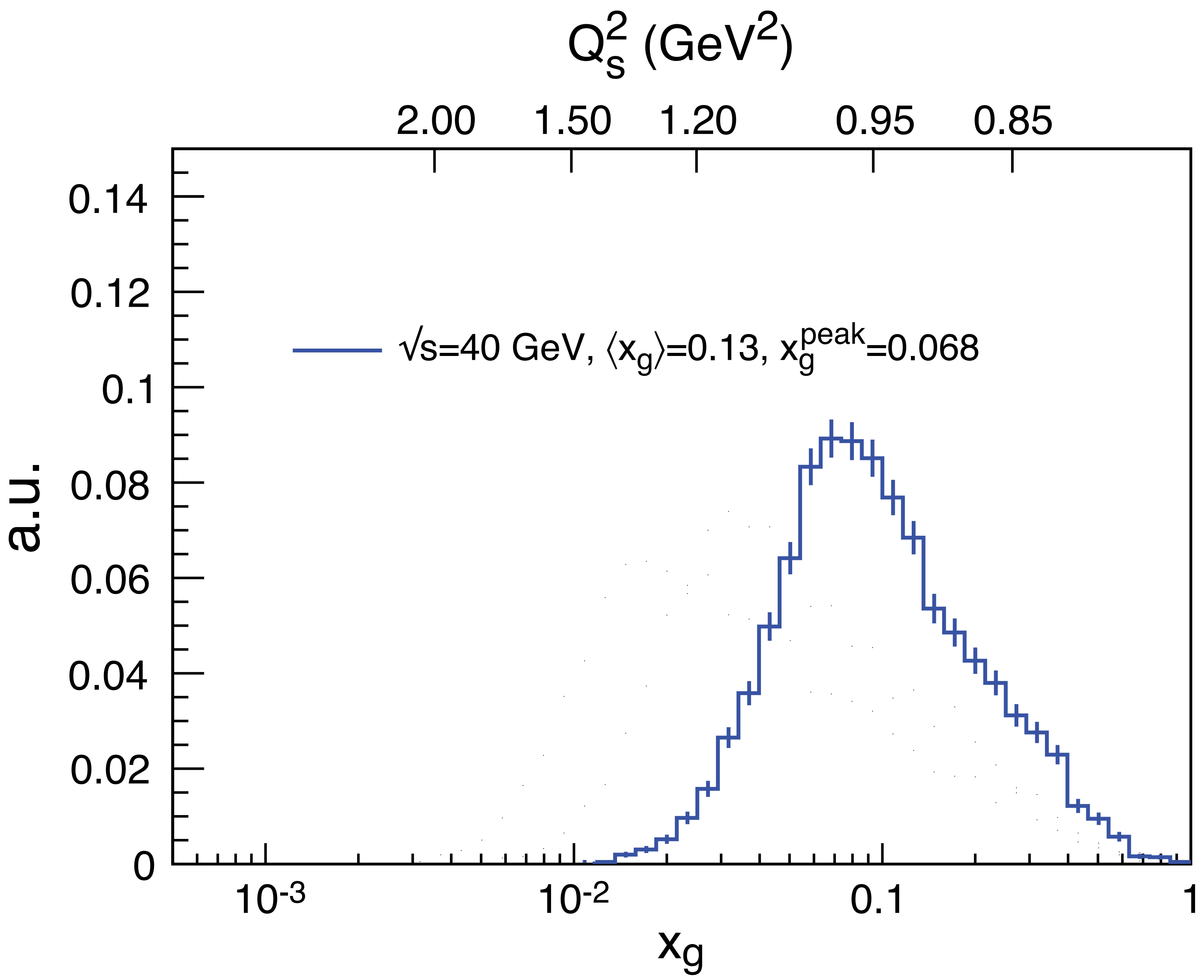
EIC Simulation Results: Dihadrons



Ratio



Zheng et al., PRD89 (2014) 074037;
BNL-114111-2017, arXiv:1708.01527



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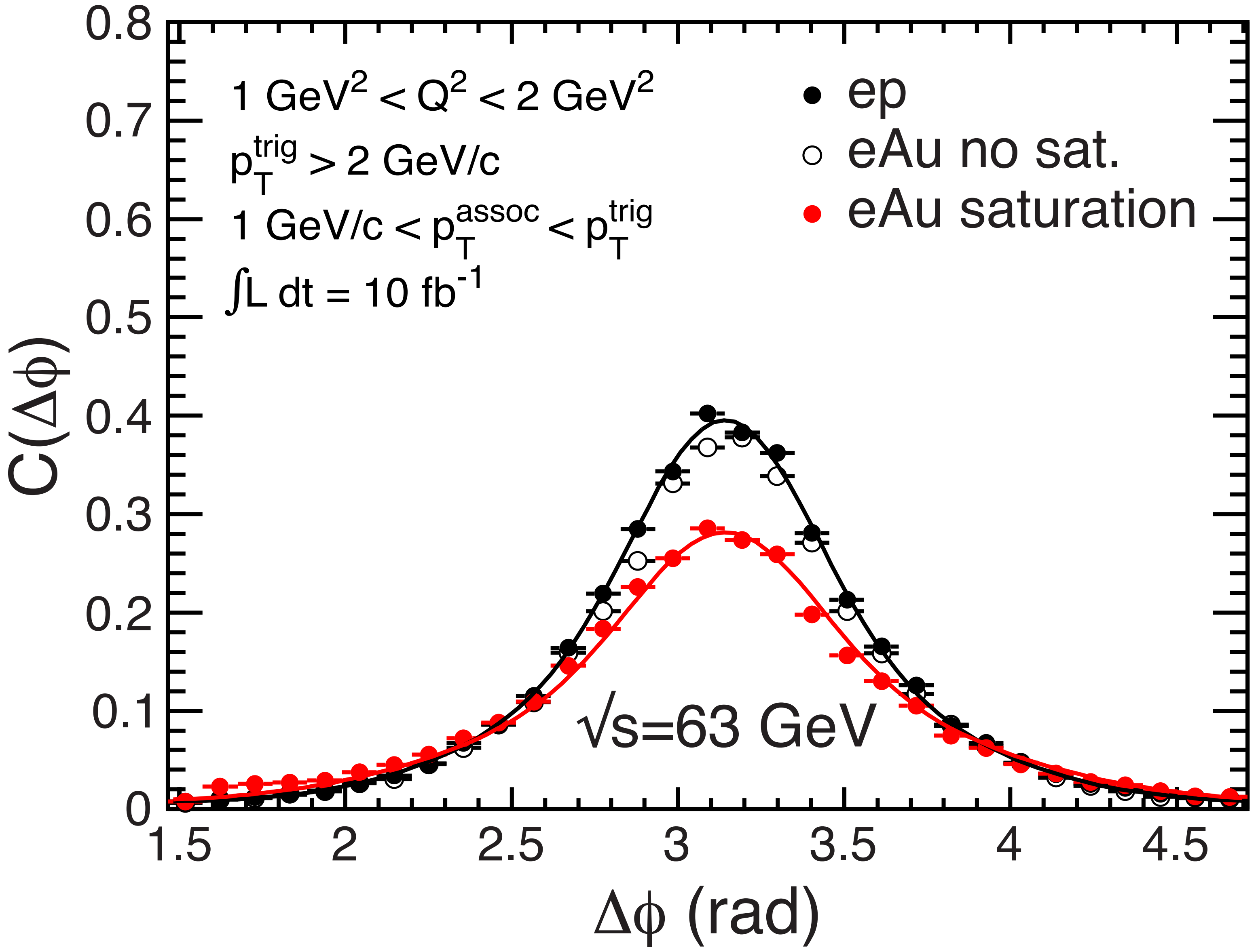
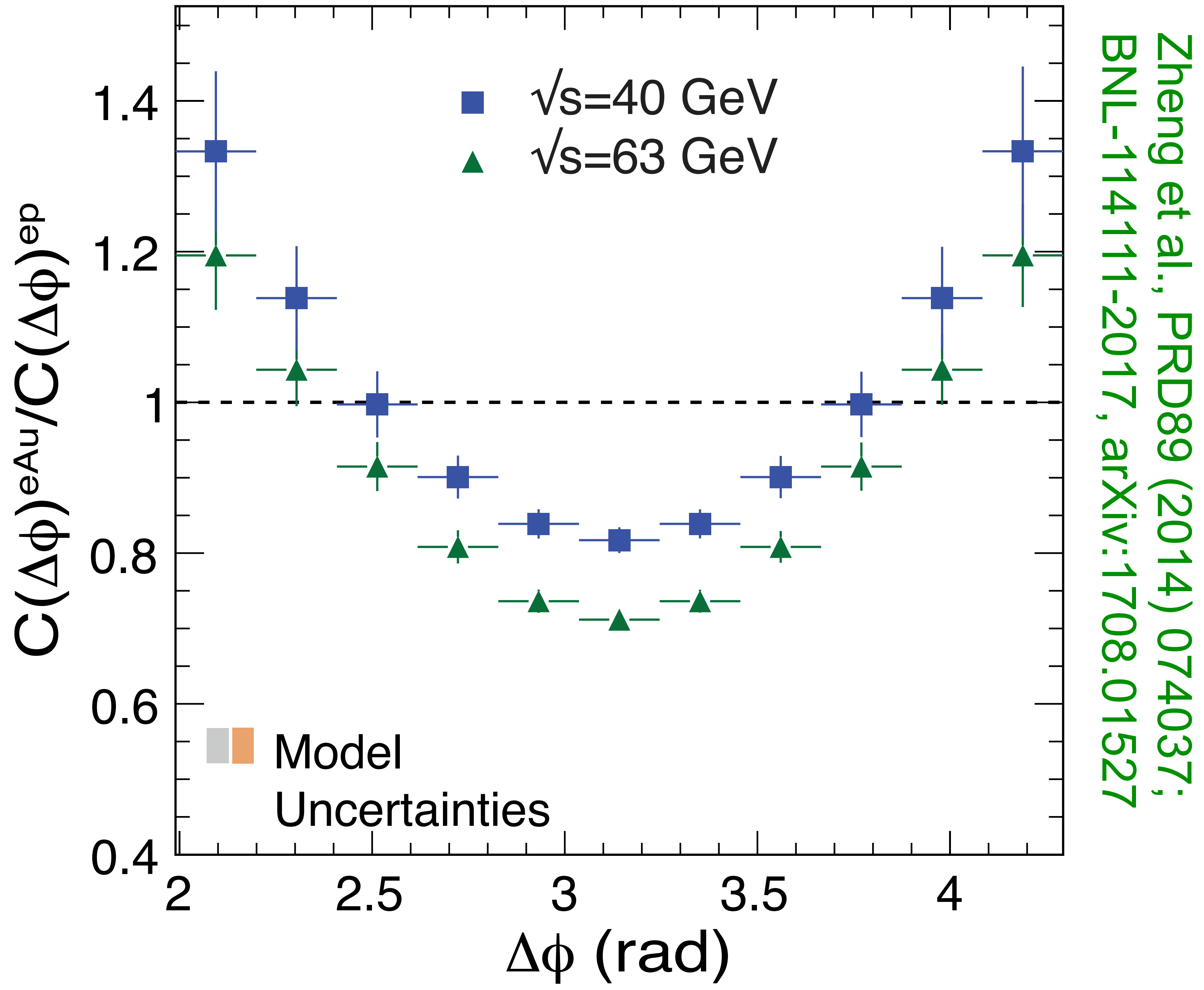
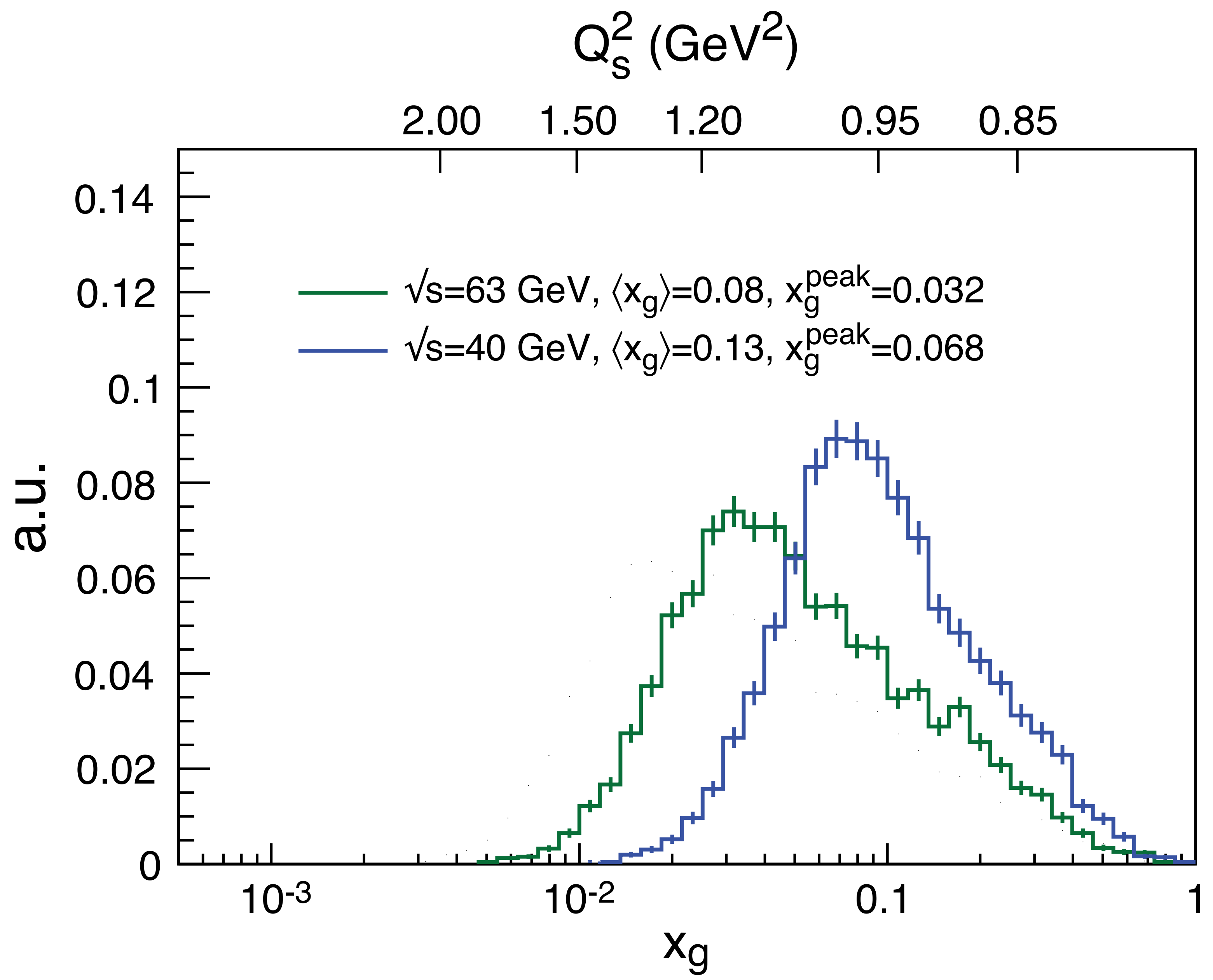


Ratio





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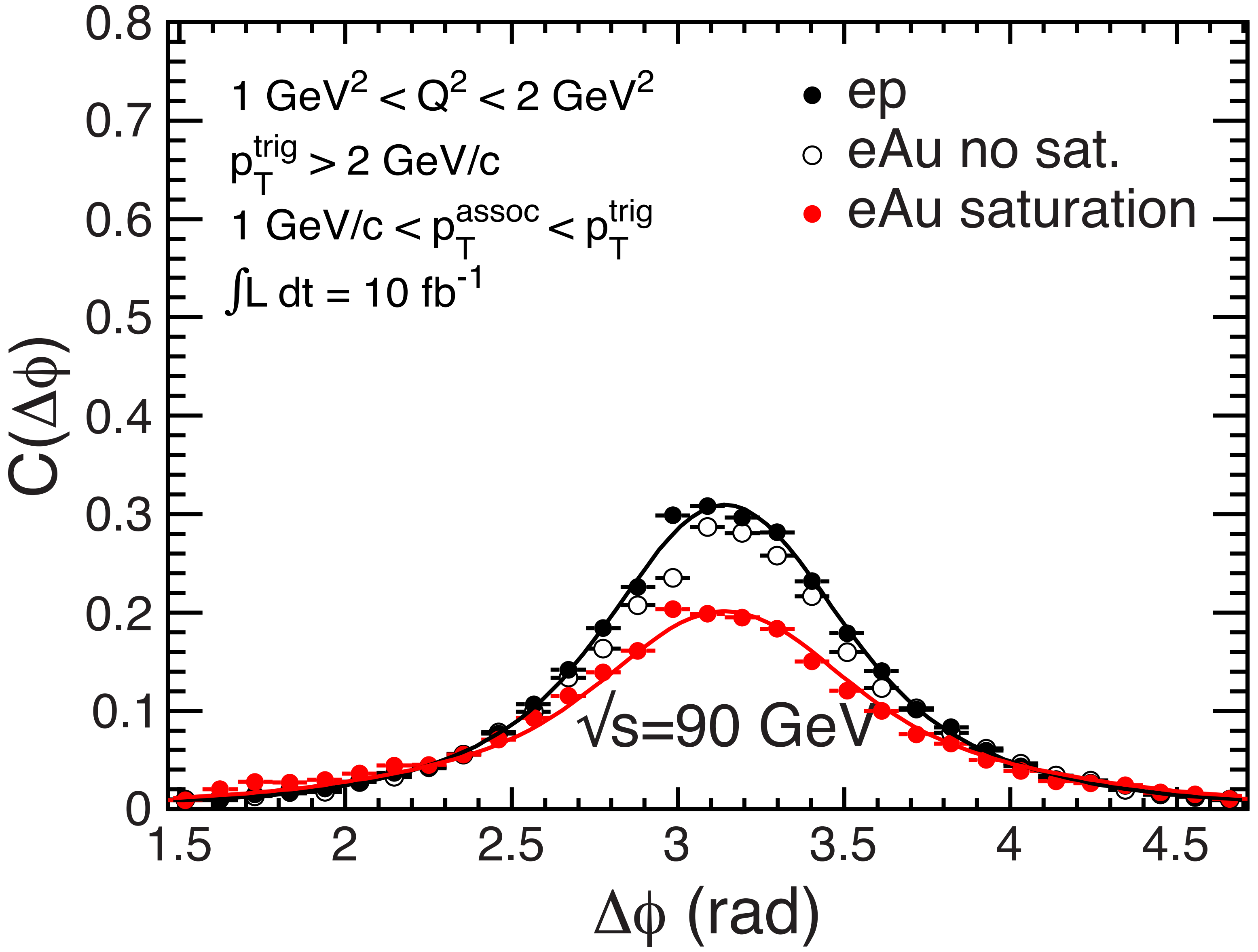
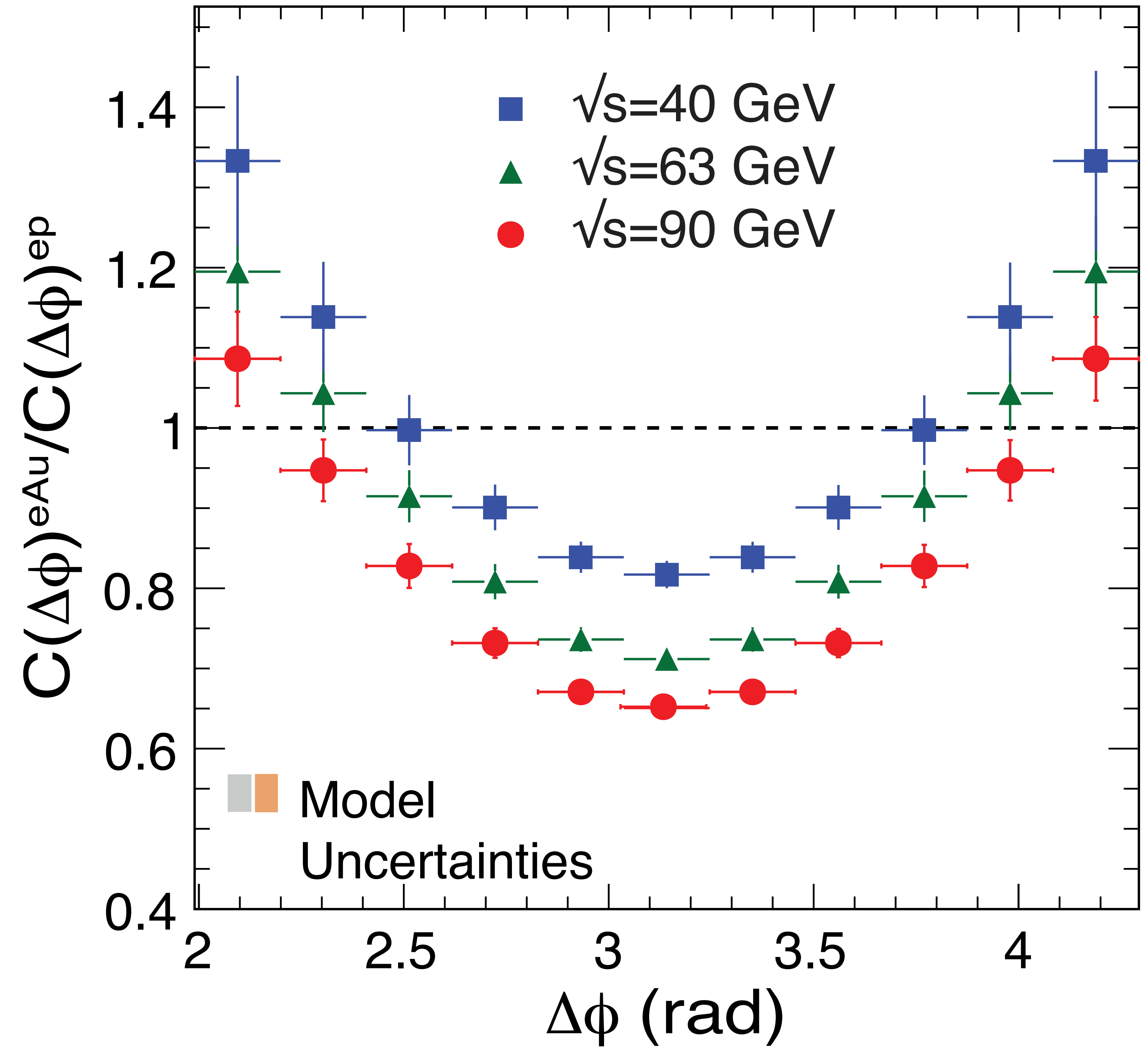


Ratio



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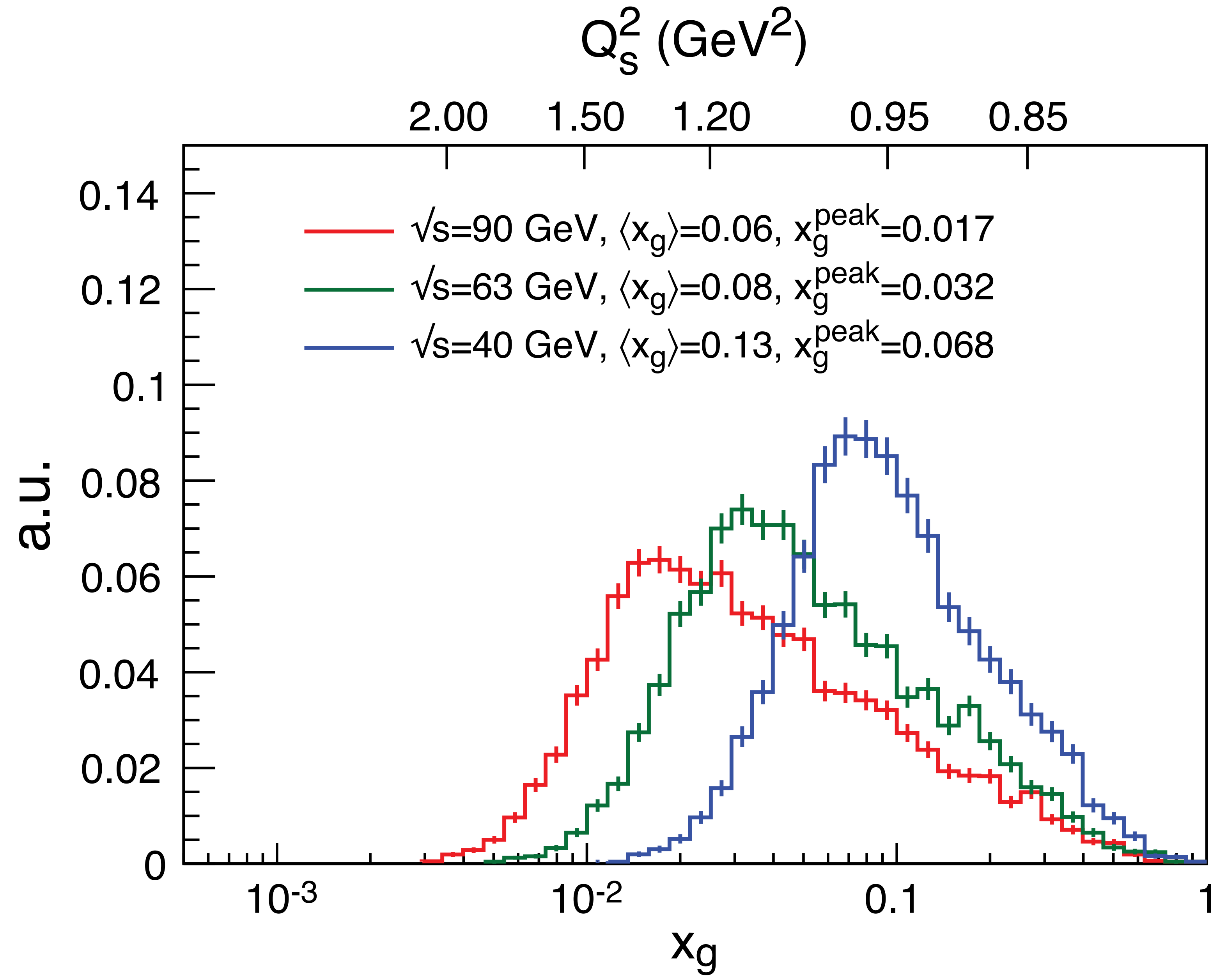
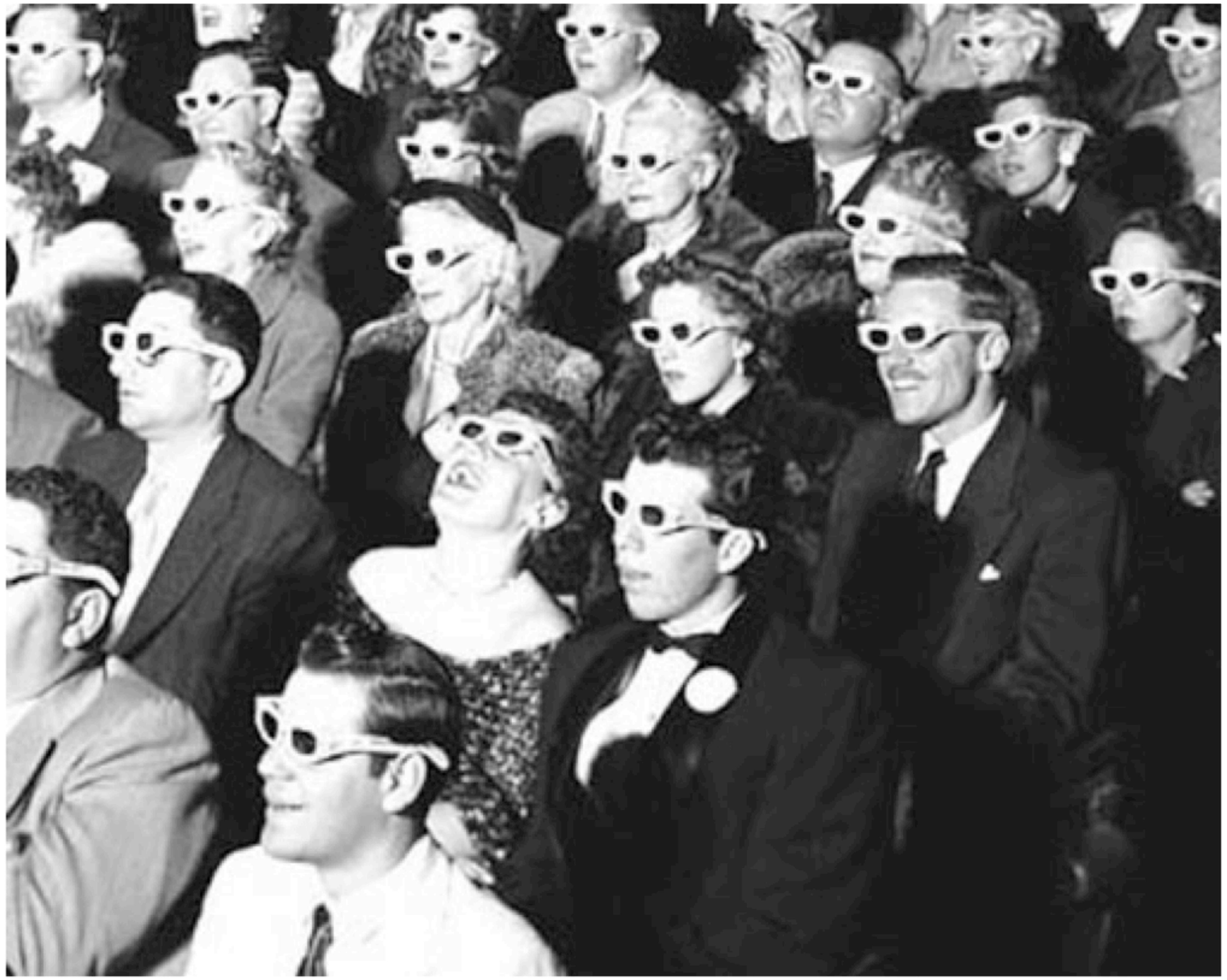


- Clear saturation signature
  - Allows us to extract the spatial multi-gluon correlations
- Similar Dijet Correlations
  - Unique measurement of WW Gluon Distributions (nTMDs)

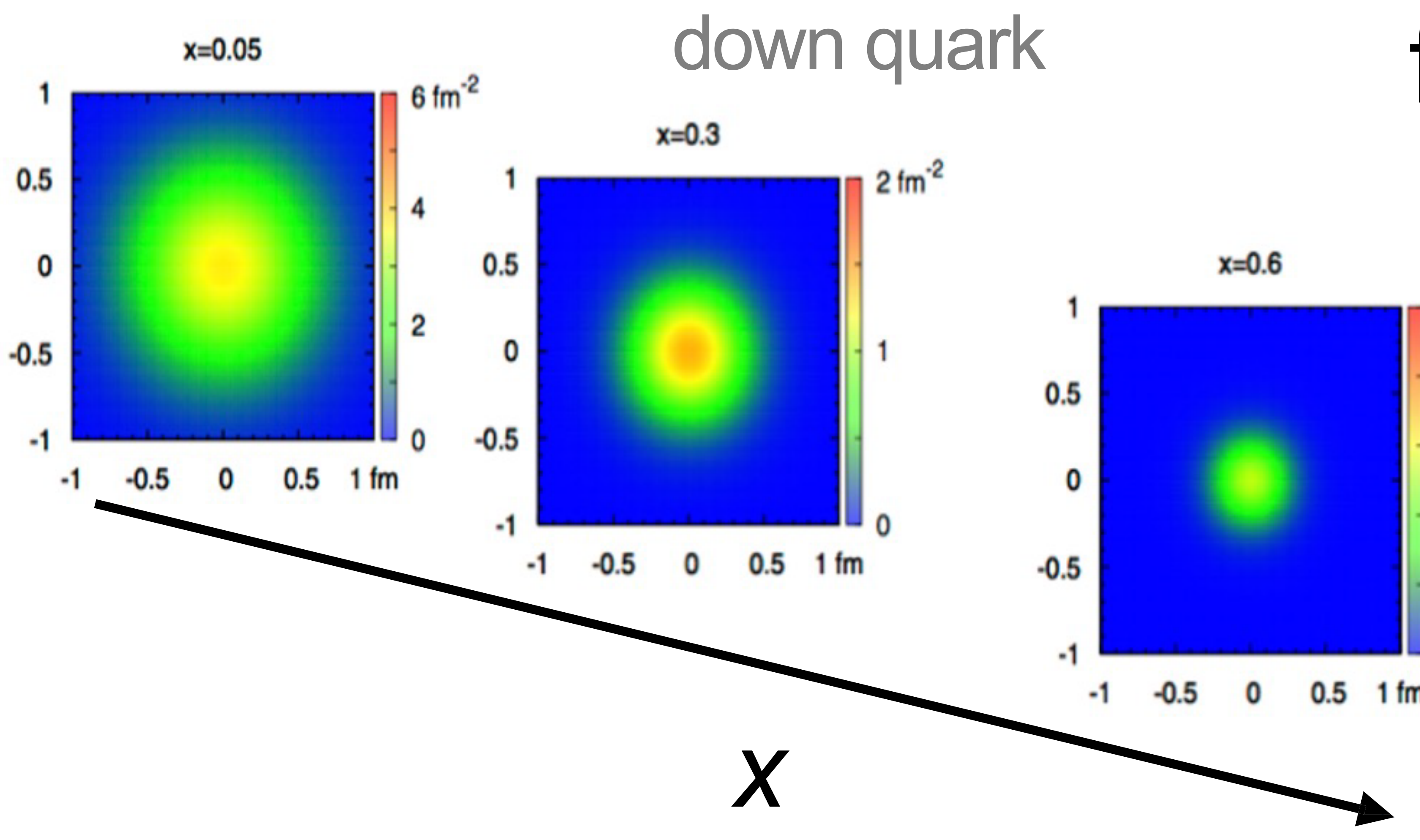
6.4 Imaging



3-D Imaging of Quarks and Gluons

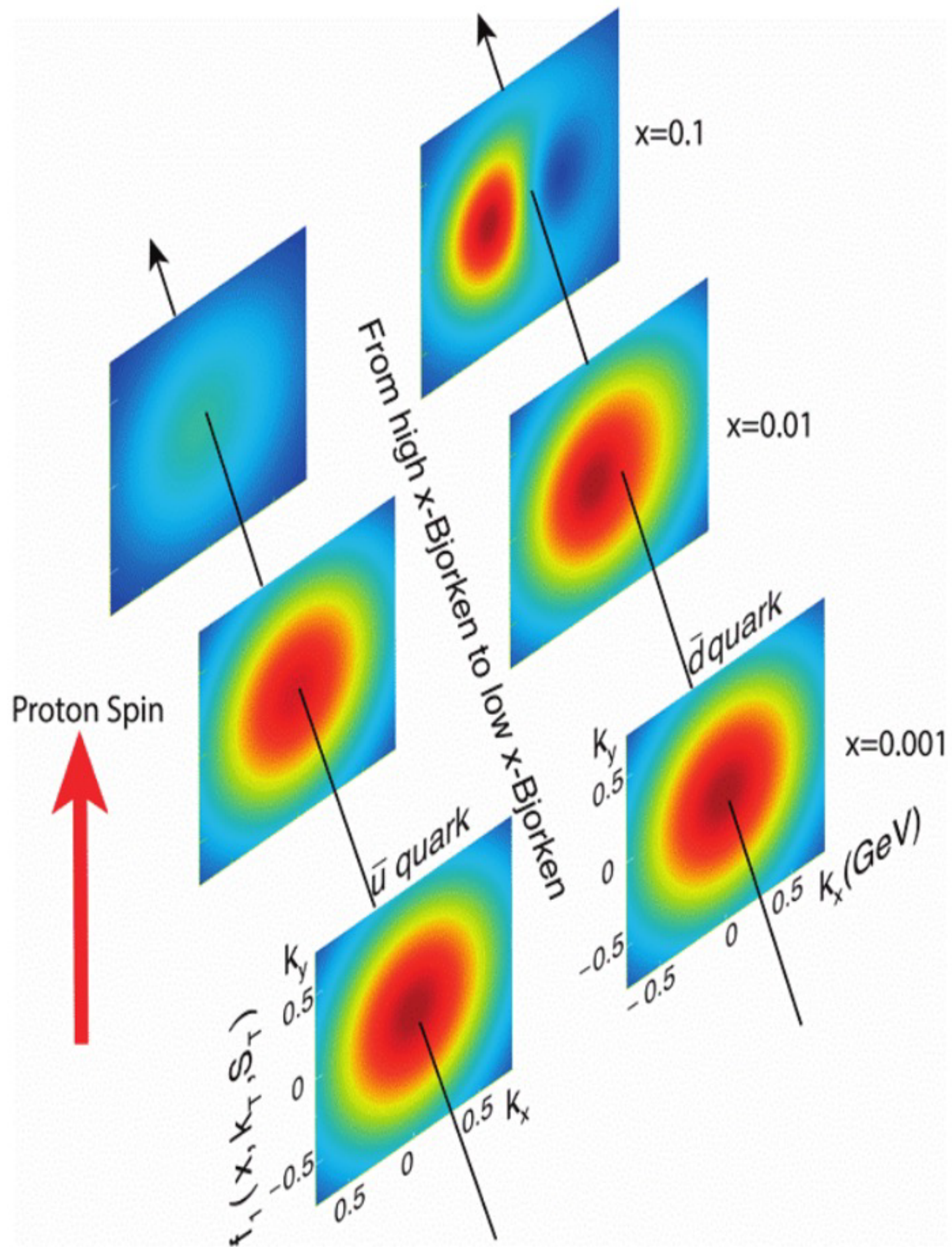
Imaging is big part of EIC program:

- Luminosity and energy hungry ➟ multi-year (decade) program



$f(x,b_T)$

- Momentum space, TMDs
  - semi-inclusive DIS
  - access to e.g., spin-orbit correlations
  - spin-dependent 3D momentum space images

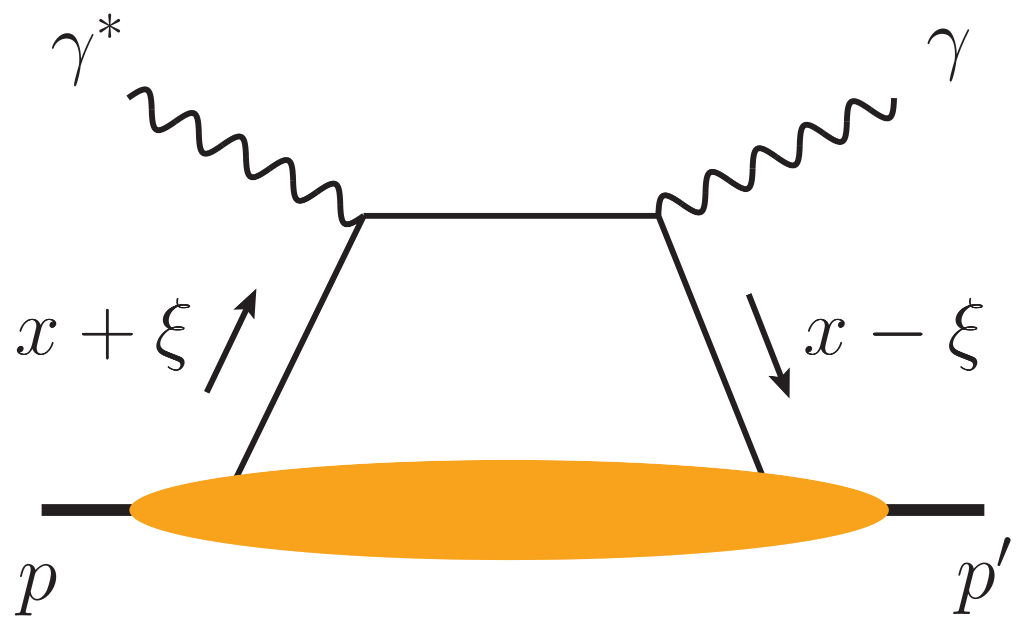


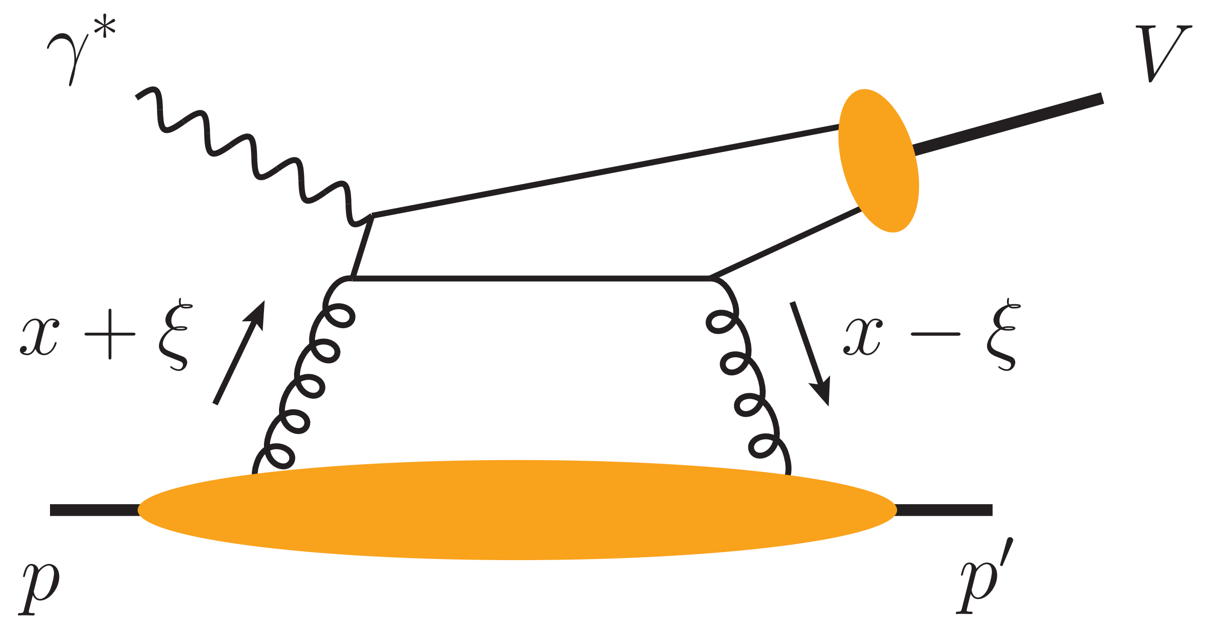
$f(x,k_T)$

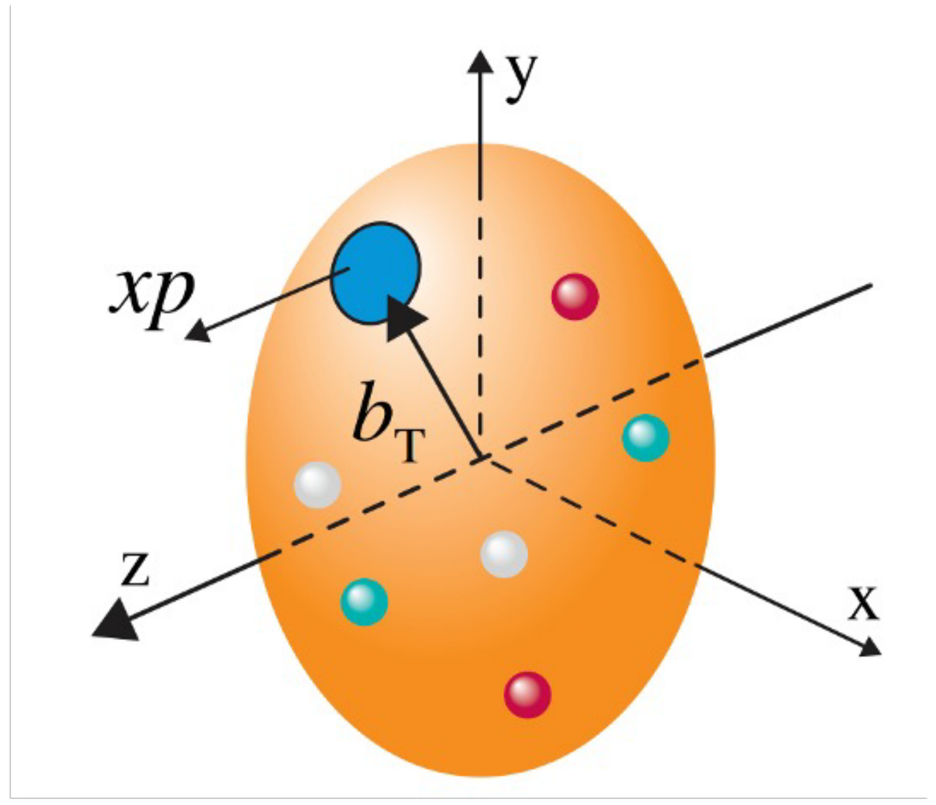
- Coordinate space, GPDs
  - exclusive measurements
    - DVCS
    - diffractive vector meson production
  - spin-dependent 2+1D coordinate space images from exclusive scattering

Accessing GPDs in exclusive processes (I)

Spatial imaging of quarks and gluons via exclusive reactions where the nucleon is left intact in the final state





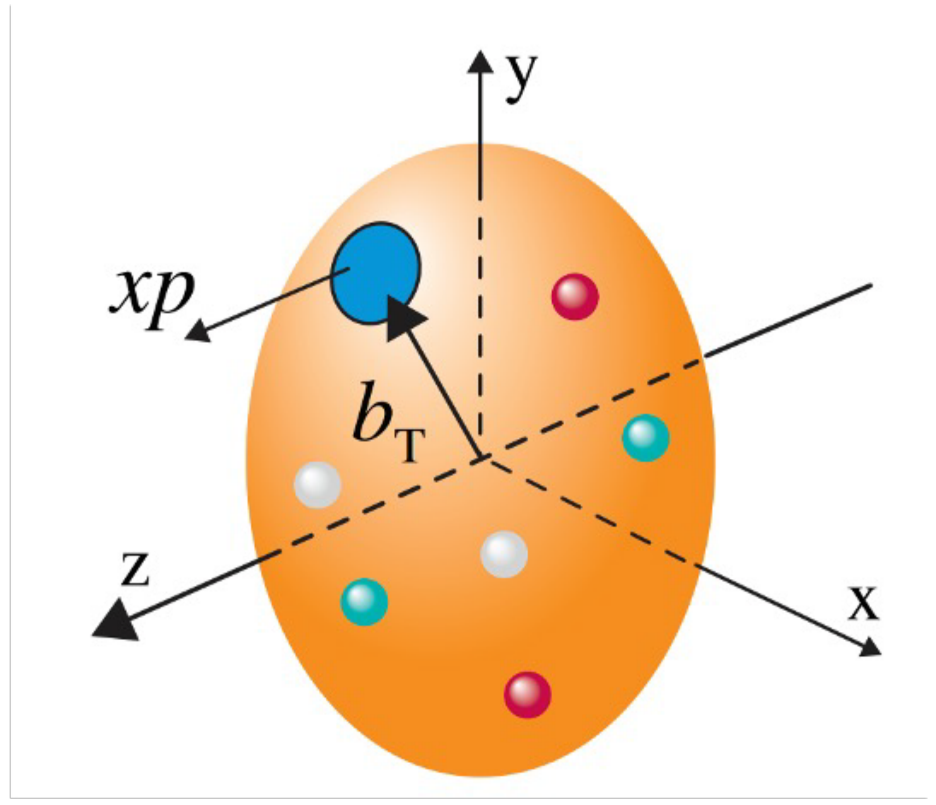


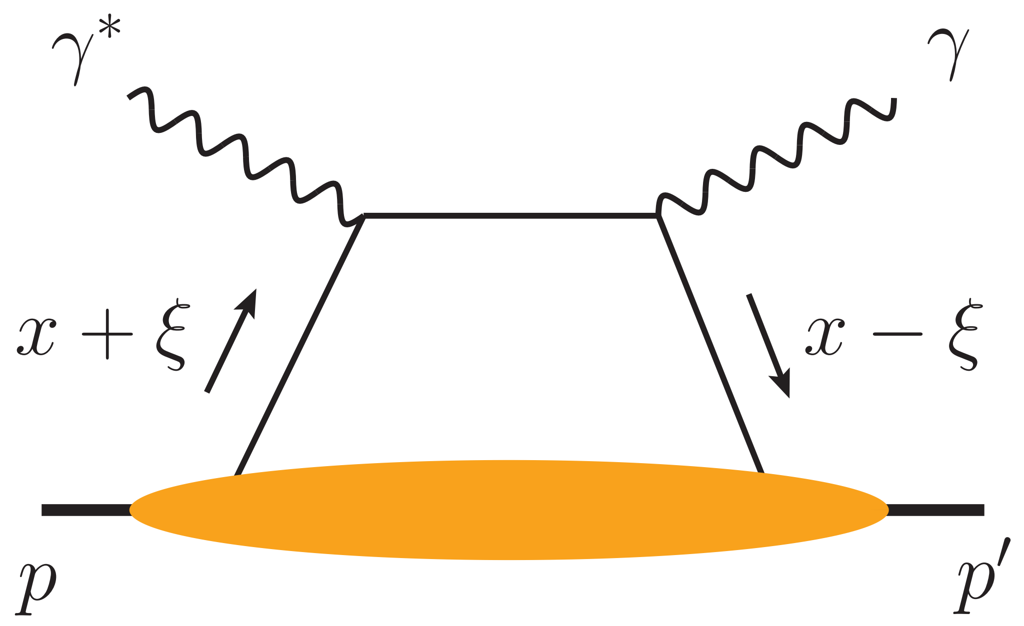
- Real photon (DVCS):
  - Very clean experimental signature
  - No VM wave-function uncertainty
  - Hard scale provided by Q^2
  - Access to the whole set of GPDs
  - Sensitive to both quarks and gluons [via Q^2 dependence of cross-section (scaling violation)]

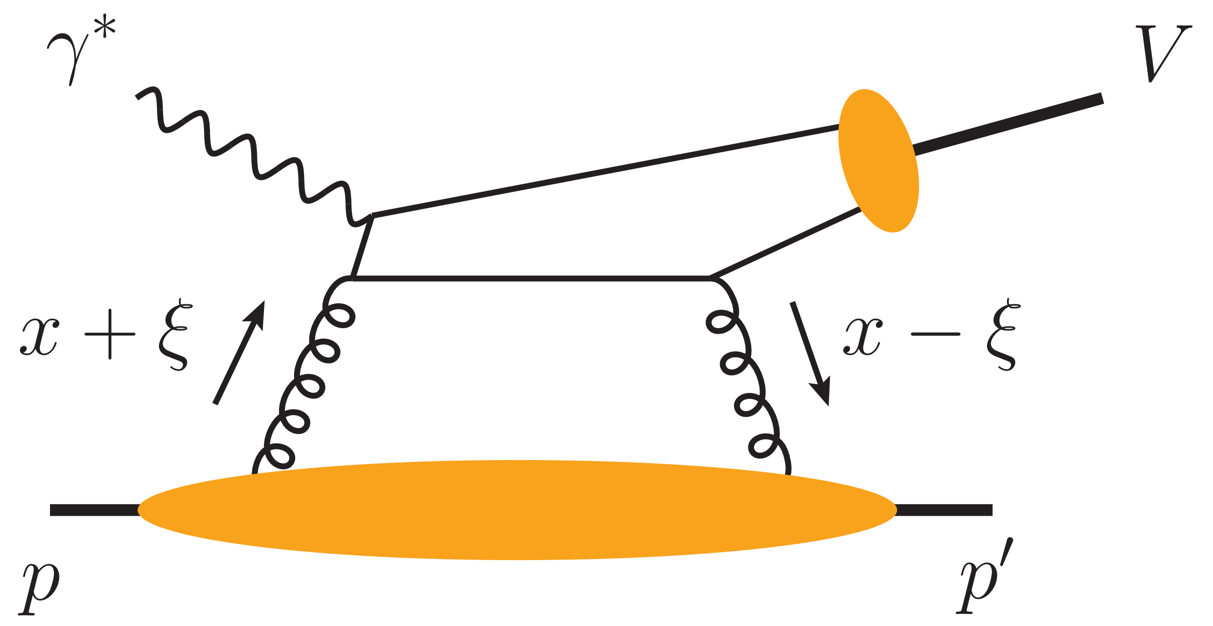
- Hard Exclusive Meson Production (HEMP):
  - Uncertainty of wave function
  - Hard scale provided by $Q^2 + M^2$
  - $J/\psi, \Upsilon$ ➟ direct access to gluons, $c\bar{c}, b\bar{b}$ pairs produced via $q(g) - g$ fusion
  - Light VMs ➟ quark-flavor separation
  - Pseudoscalars ➟ helicity-flip GPDs

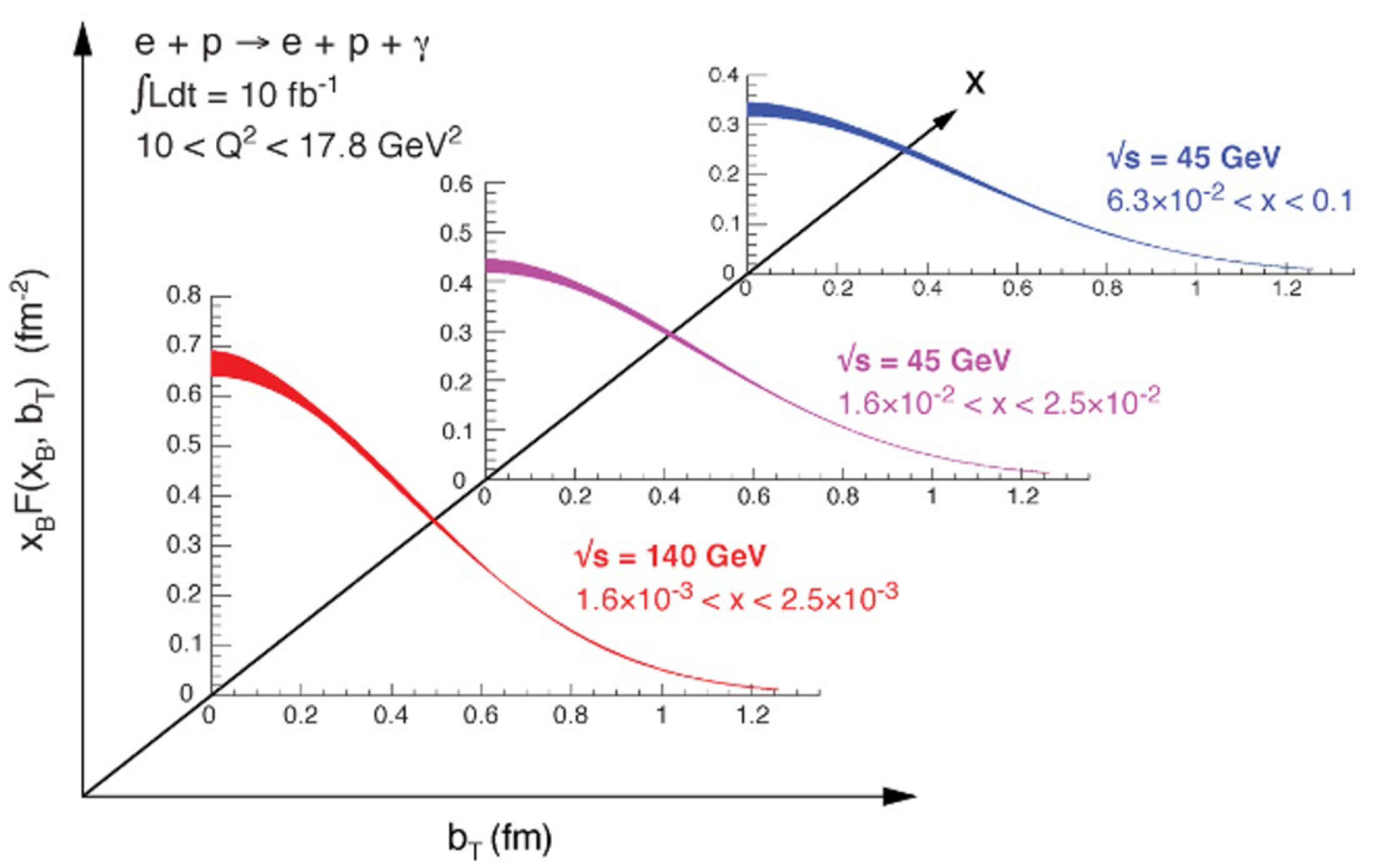
Accessing GPDs in exclusive processes (I)

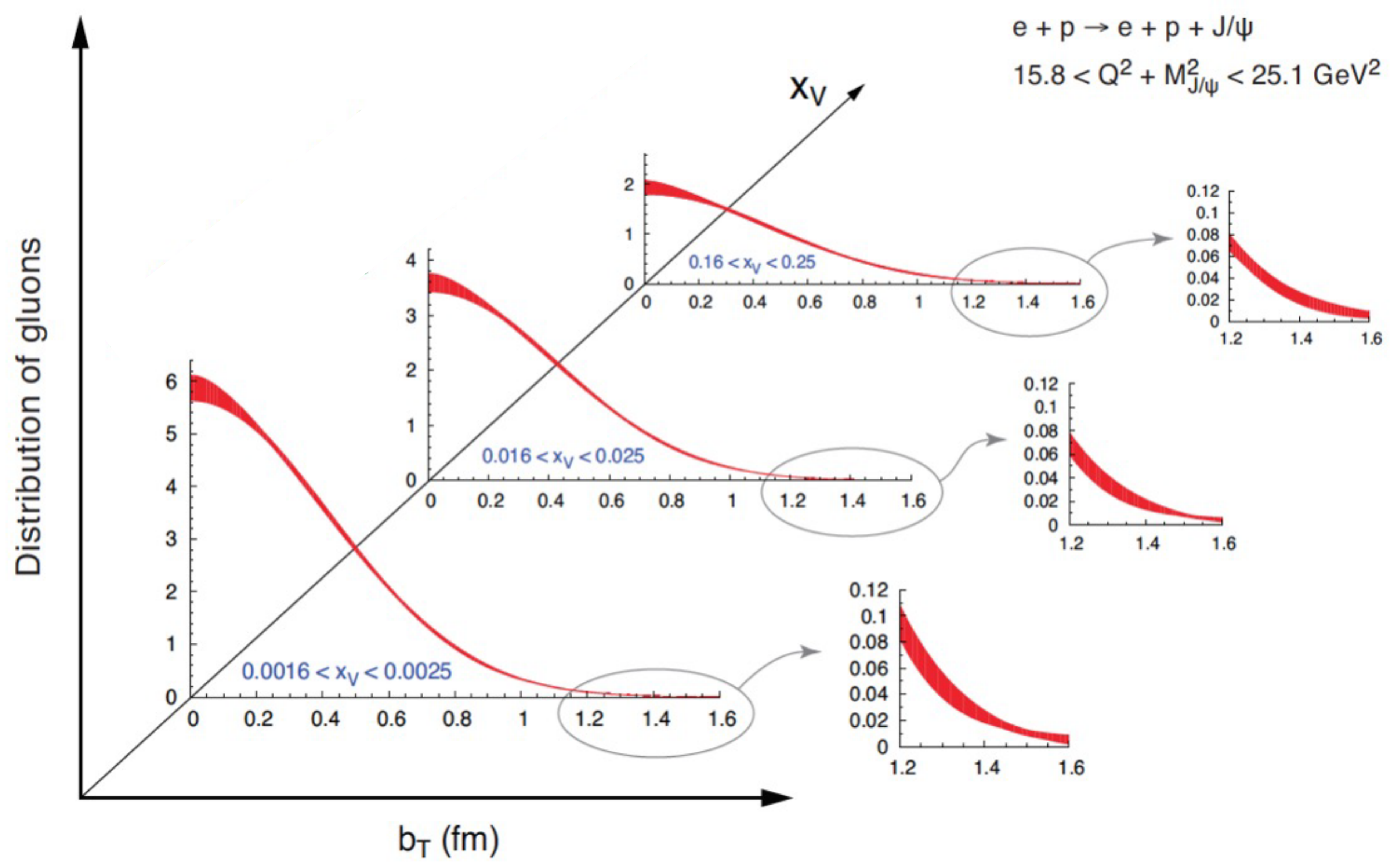
Spatial imaging of quarks and gluons via exclusive reactions where the nucleon is left intact in the final state



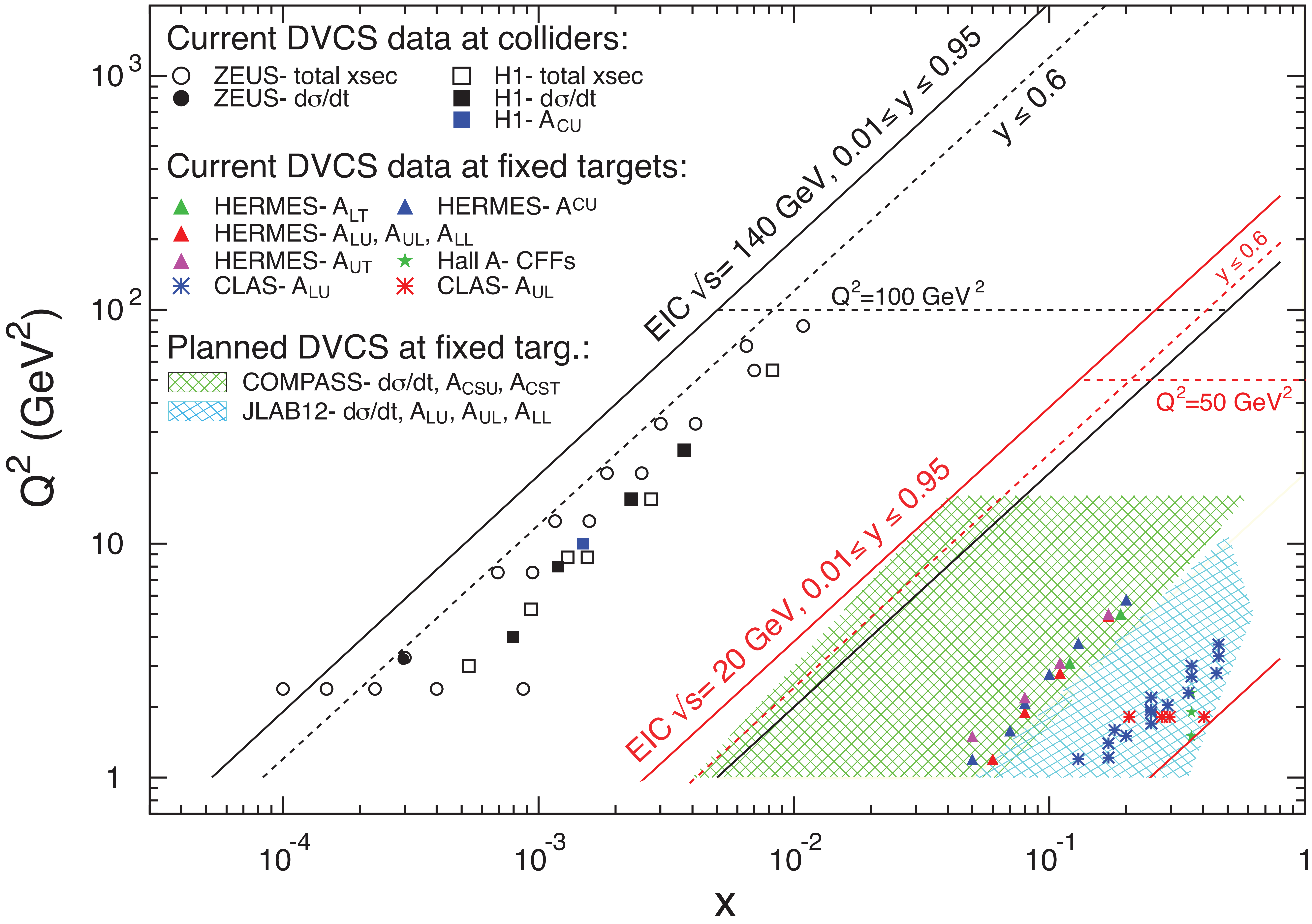






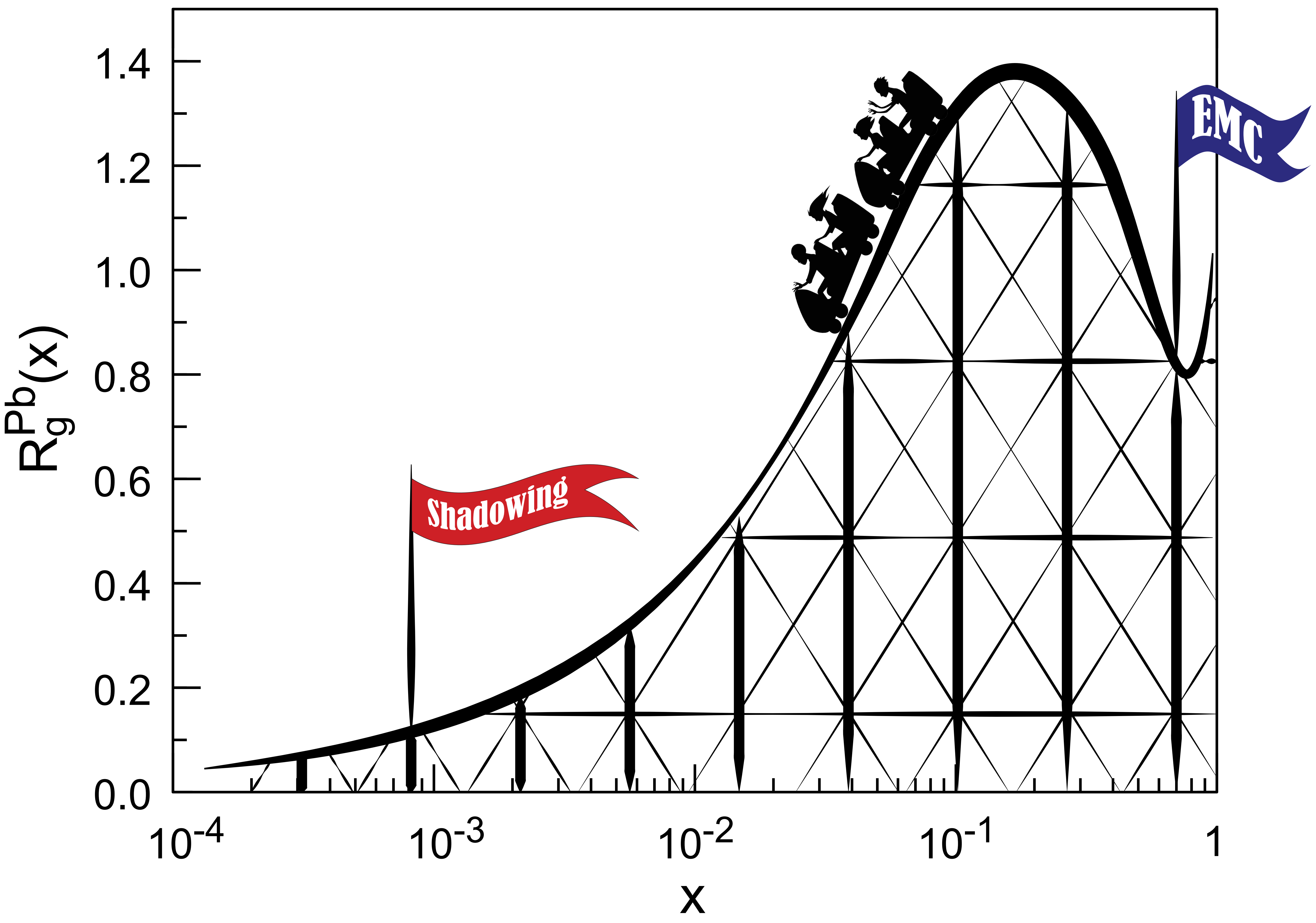


Accessing GPDs in exclusive processes (II)



Only possible at EIC:
from valence quark region, deep into the sea!

6.5. Structure Functions and PDFs

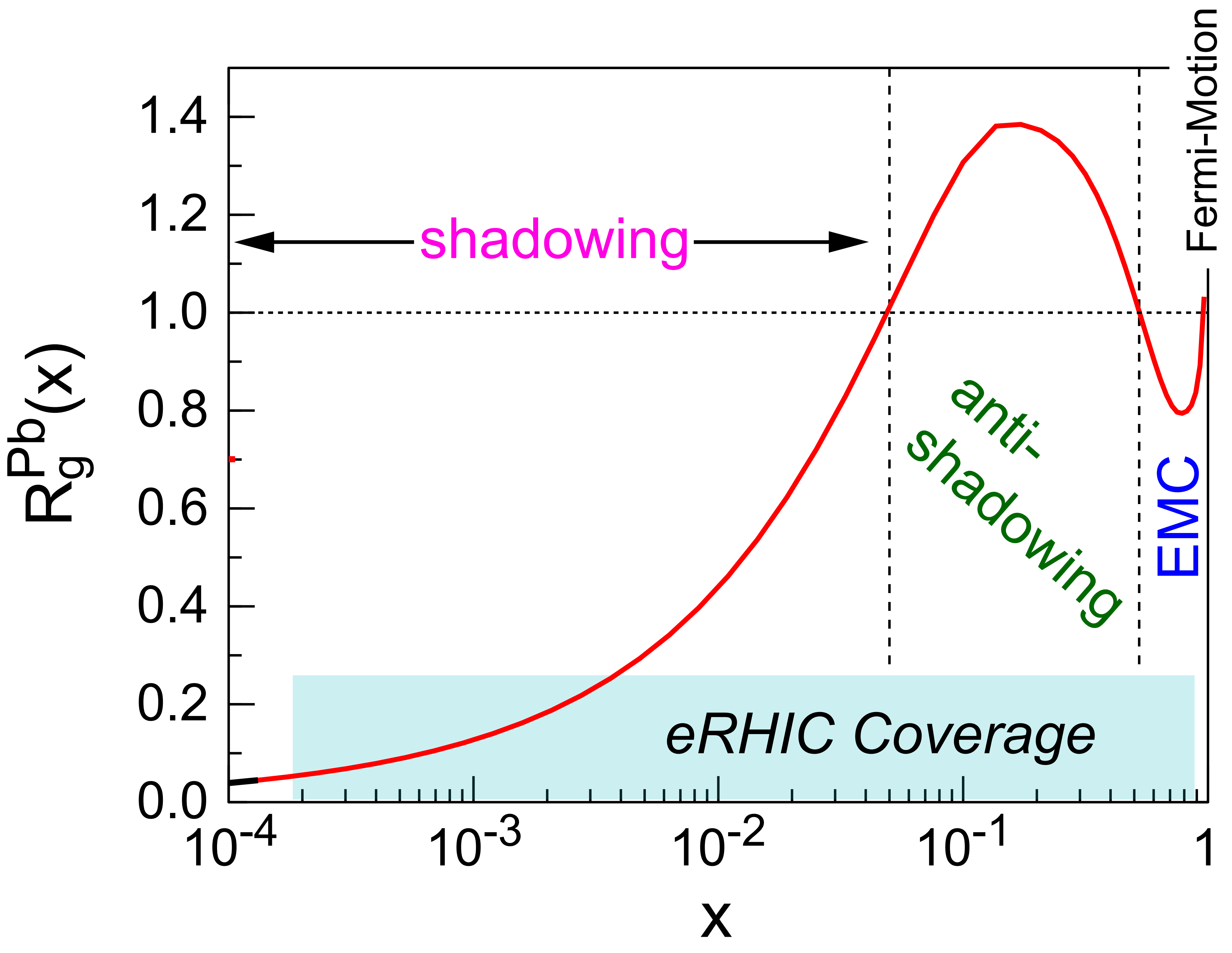


Nuclear PDFs (nPDFs)

Goal: Describe initial state of nuclei

For nuclei typically formulated as ration of structure fct A/p

$$R^A_{i=g,u,d,...}(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$



3 distinguished regions:
- shadowing
- anti-shadowing
- EMC effect region

none is understood

nPDFs are of interest in their own right but are also important for other fields (Heavy-Ions, Cosmic Rays etc)

PDFs

What is Needed:

- Good data
  - Best: F_2 (ep), σ_R, jets, Drell-Yan (pp)
  - Bad: Hadrons
- pQCD Calculation of the processes
  - LO, NLO, NNLO
- QCD Evolution Equations
  - DGLAP: Evolution in Q^2 (small to large) at fixed x (integro-differential equations)
  - BFKL: Evolution in x at fixed Q^2

PDFs

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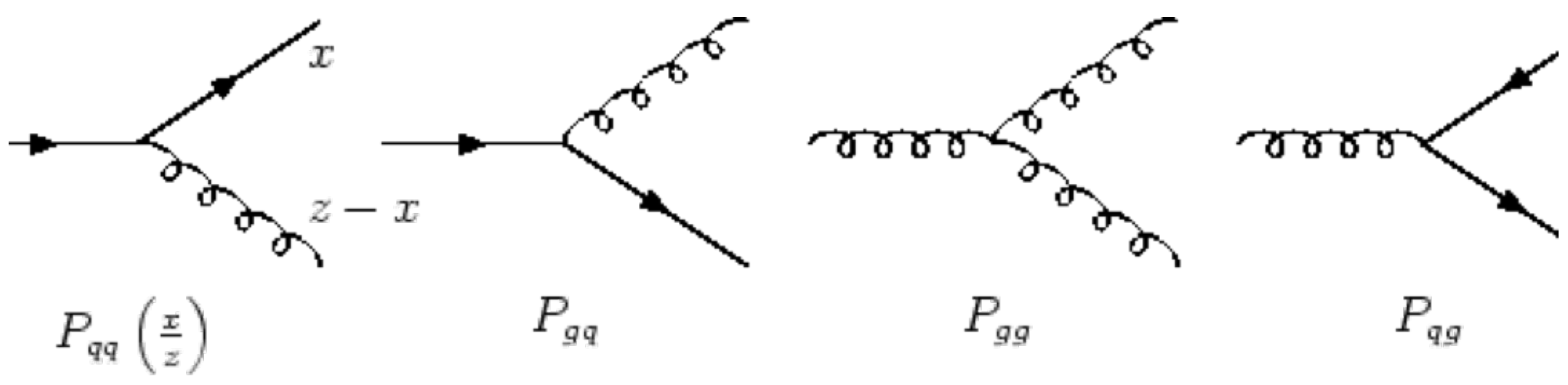
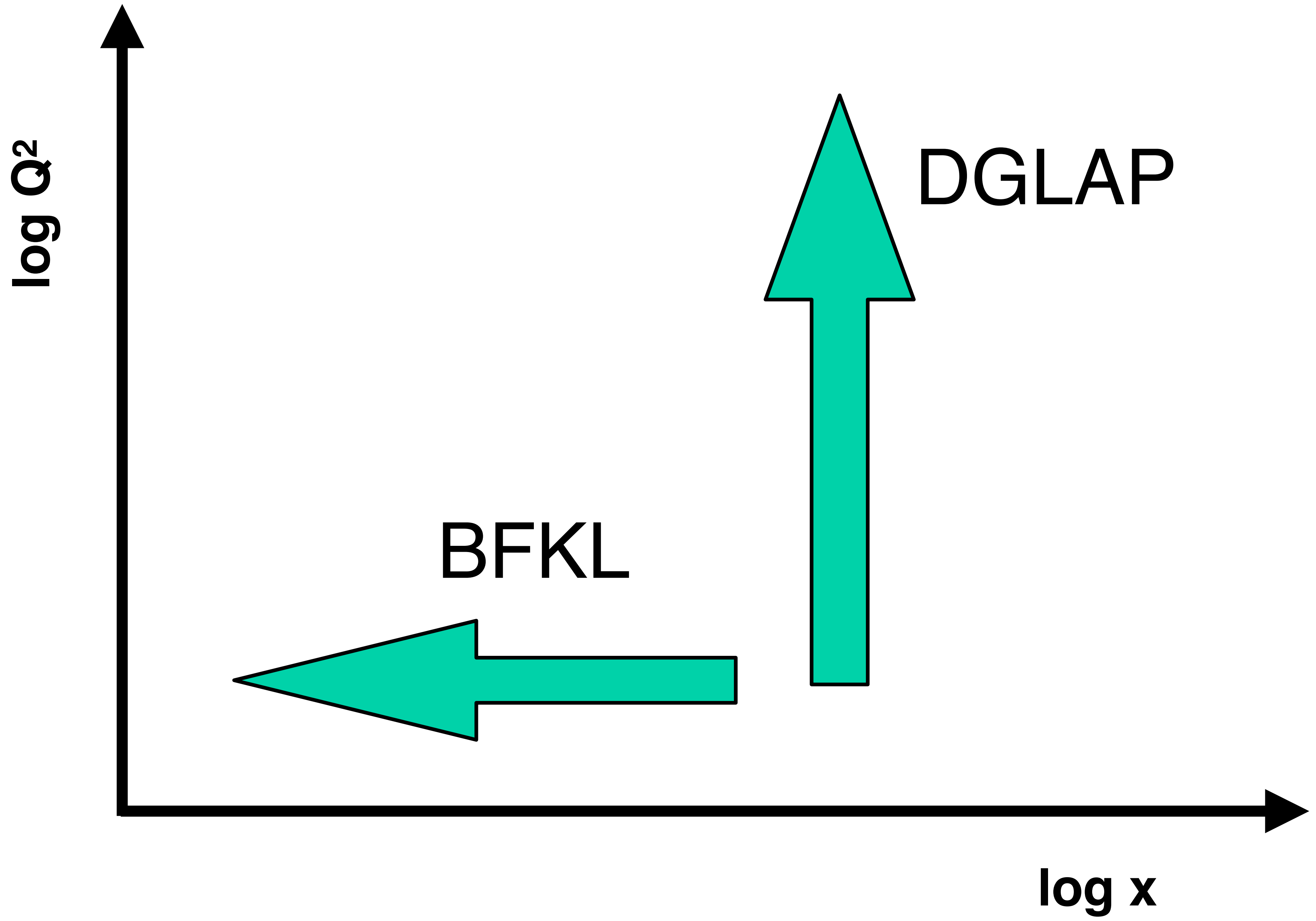
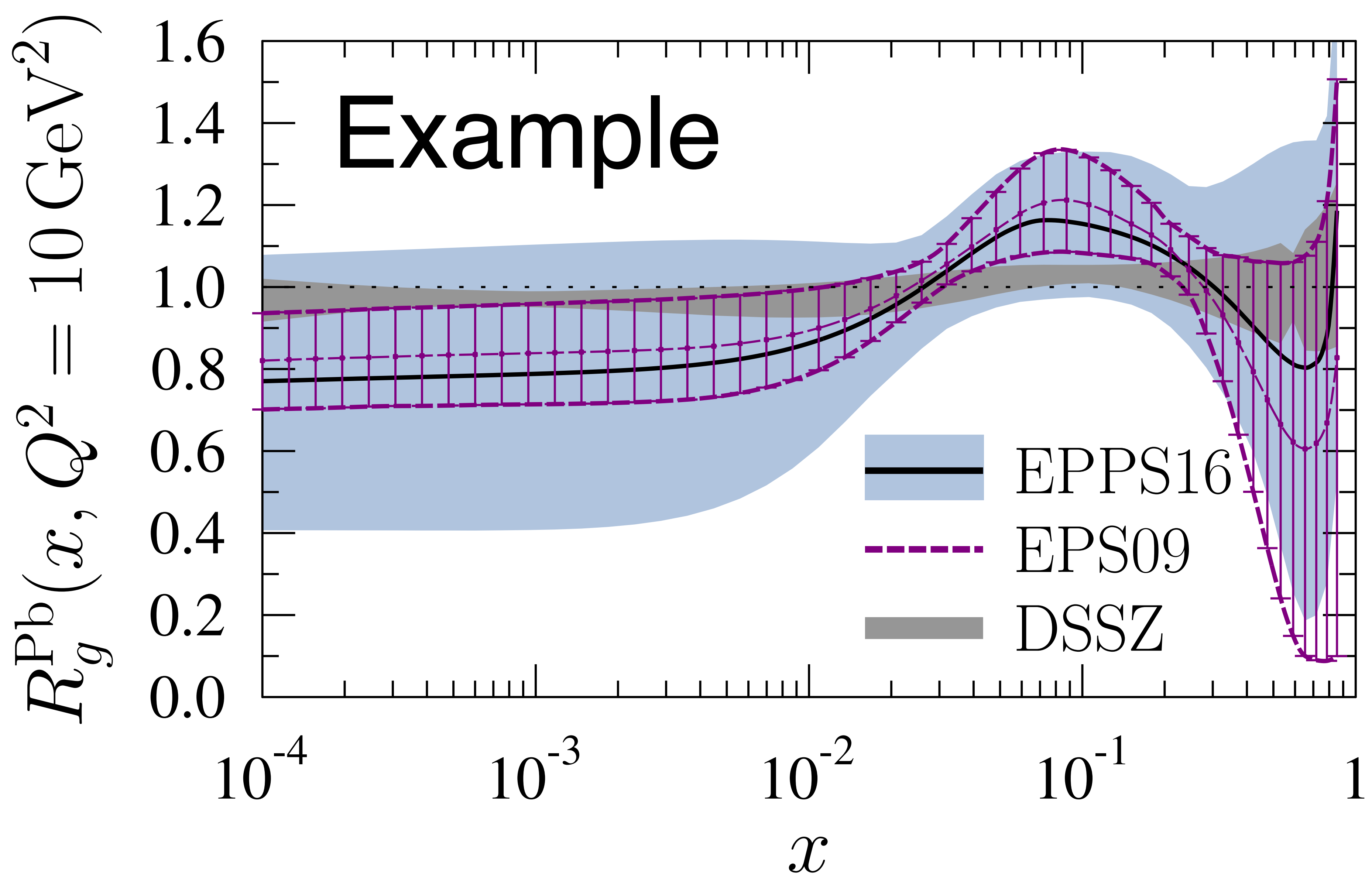


Figure 1.1: *The processes related to the lowest order QCD splitting functions. Each splitting function $P_{p'p}(x/z)$ gives the probability that a parton of type p converts into a parton of type p', carrying fraction x/z of the momentum of parton p*



Nuclear PDFs

nPDFs less well known due to lack of data



Theory/models have to be able to describe the structure functions and their evolution

- DGLAP:
  - predicts Q^2 but not A and x dependence
- Saturation models (JIMWLK):
  - predict A and x dependence but not Q^2
- Need: large Q^2 lever-arm for fixed *x*, A-scan

nPDF fits typically performed on reduced cross-section

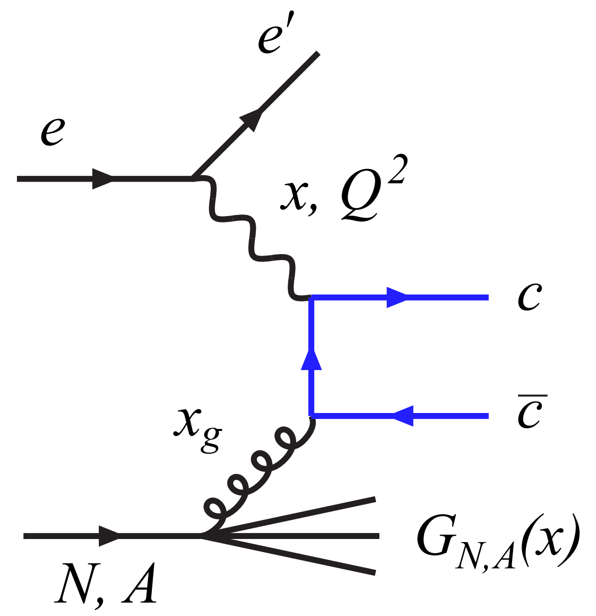
$$\sigma_{\mathrm{red}}(x,Q^2) = F_2(x,Q^2) - \left(\frac{y^2}{1+(1-y)^2}\right) F_L(x,Q^2)$$

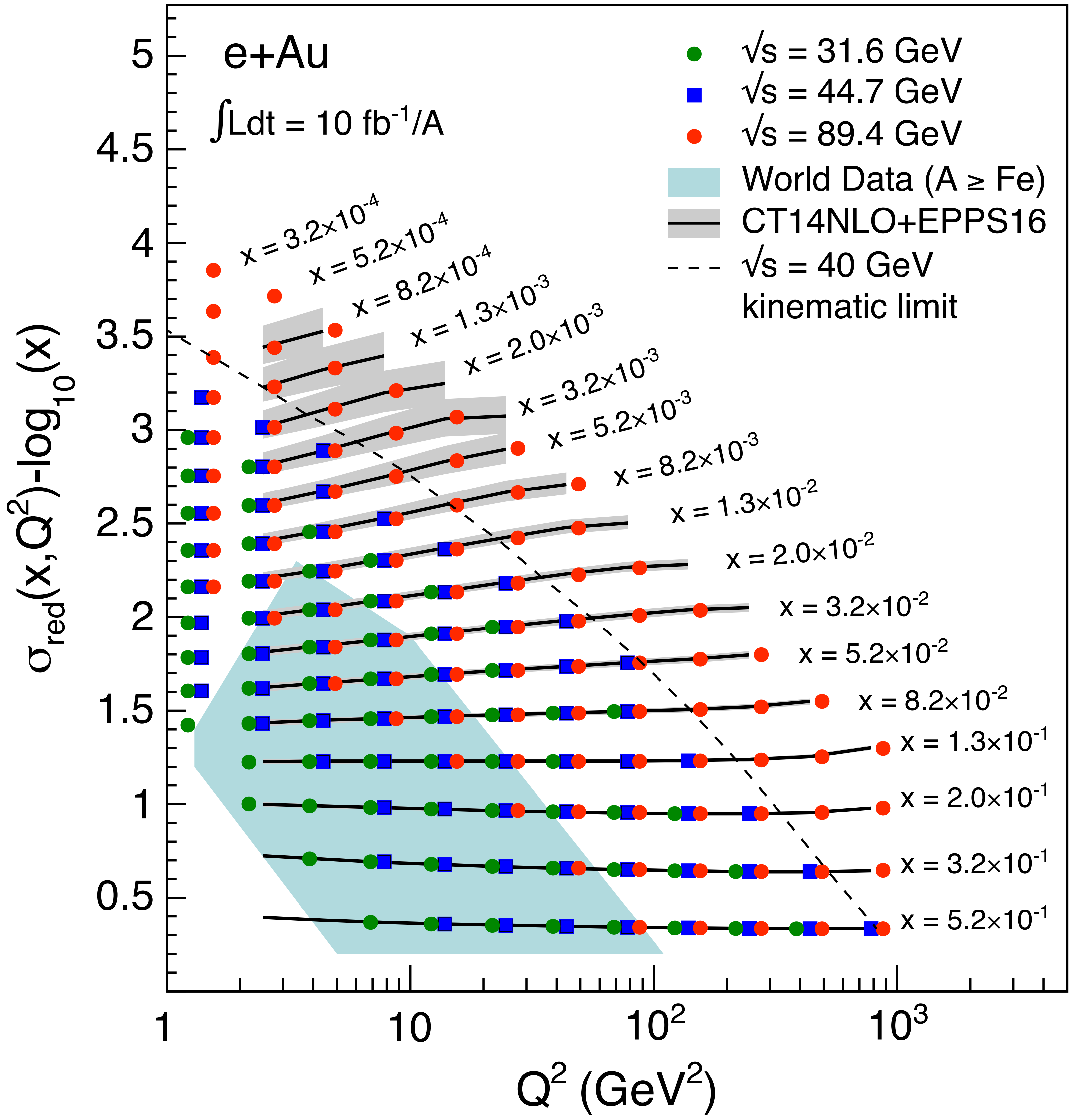
e+A: Aim at extending our knowledge on structure functions into the realm where gluon saturation (higher twist) effects emerge $\Rightarrow$ different evolution (JIMWLK)

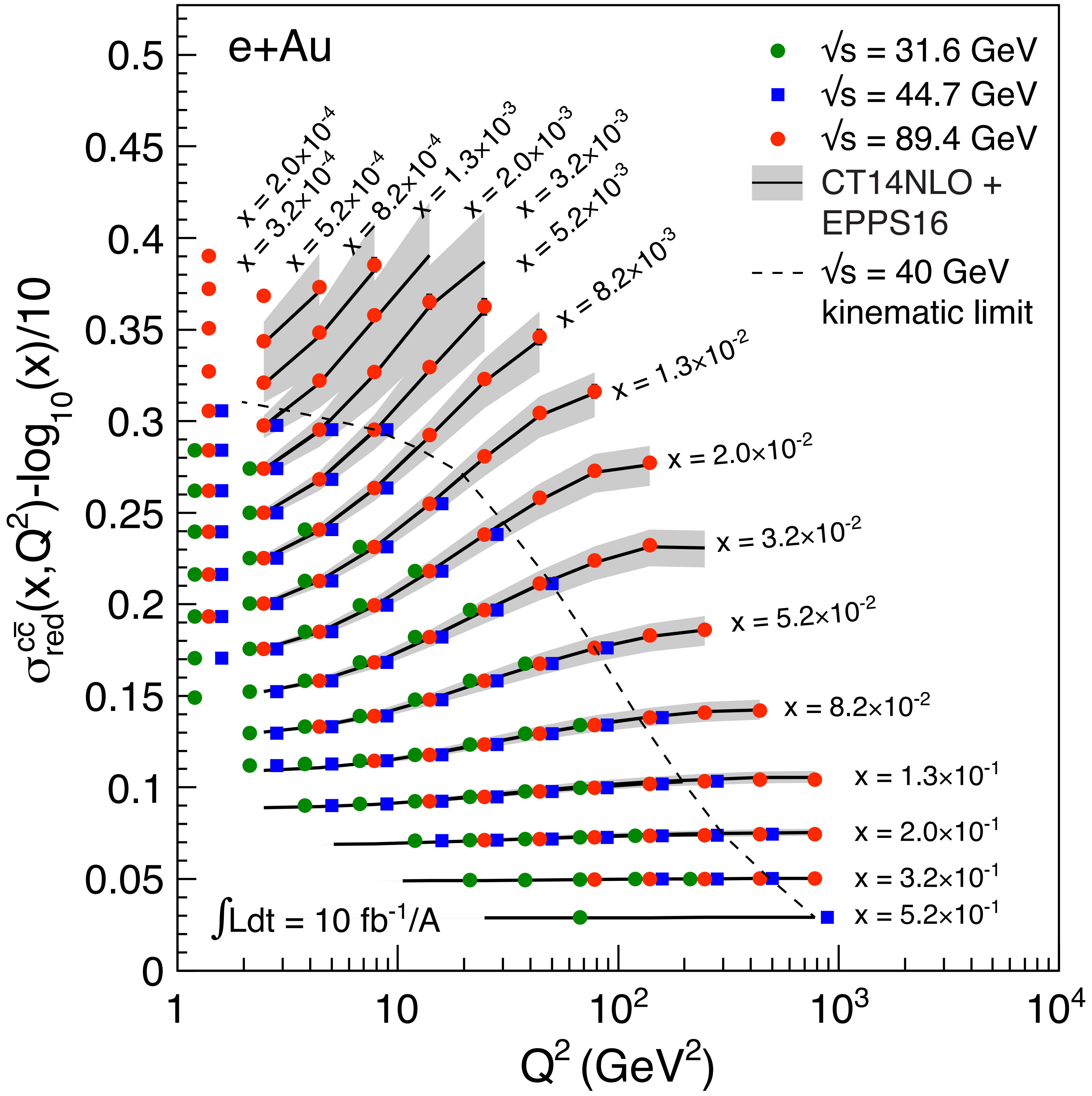
EIC: Structure Functions in eA

EIC pseudo-data

- F_L, F_2, σ_{red}, F_2^{cc} values from EPPS16
- Errors (sys and stat.) from simulations for $\int Ldt = 10\ fb^{-1}/A$



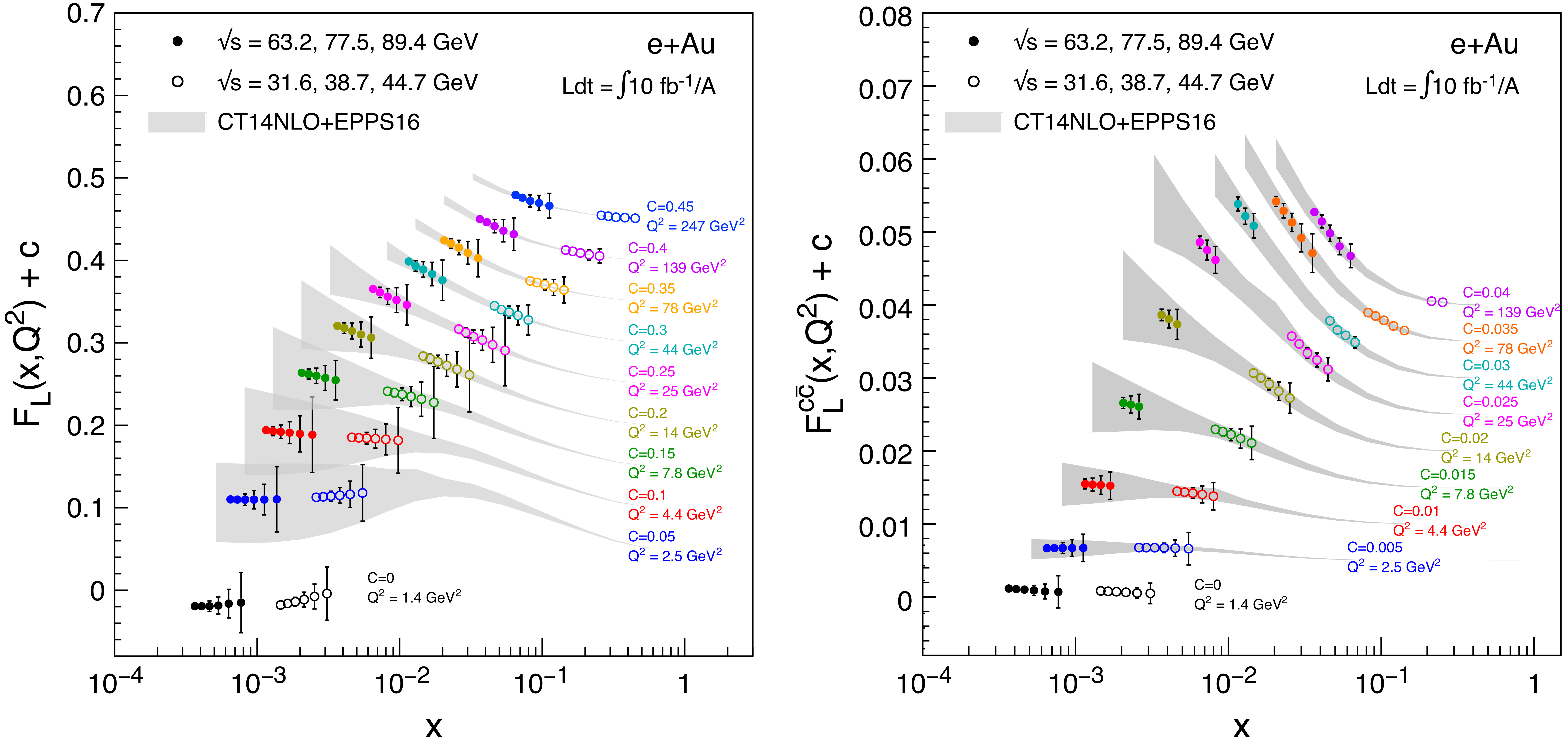




arXiv:1708.01527, 1708.05654

EIC: F_L Structure Function

- F_L probes glue more directly
- F_L is small and requires running at different √s and thus has larger systemic uncertainties than F_2

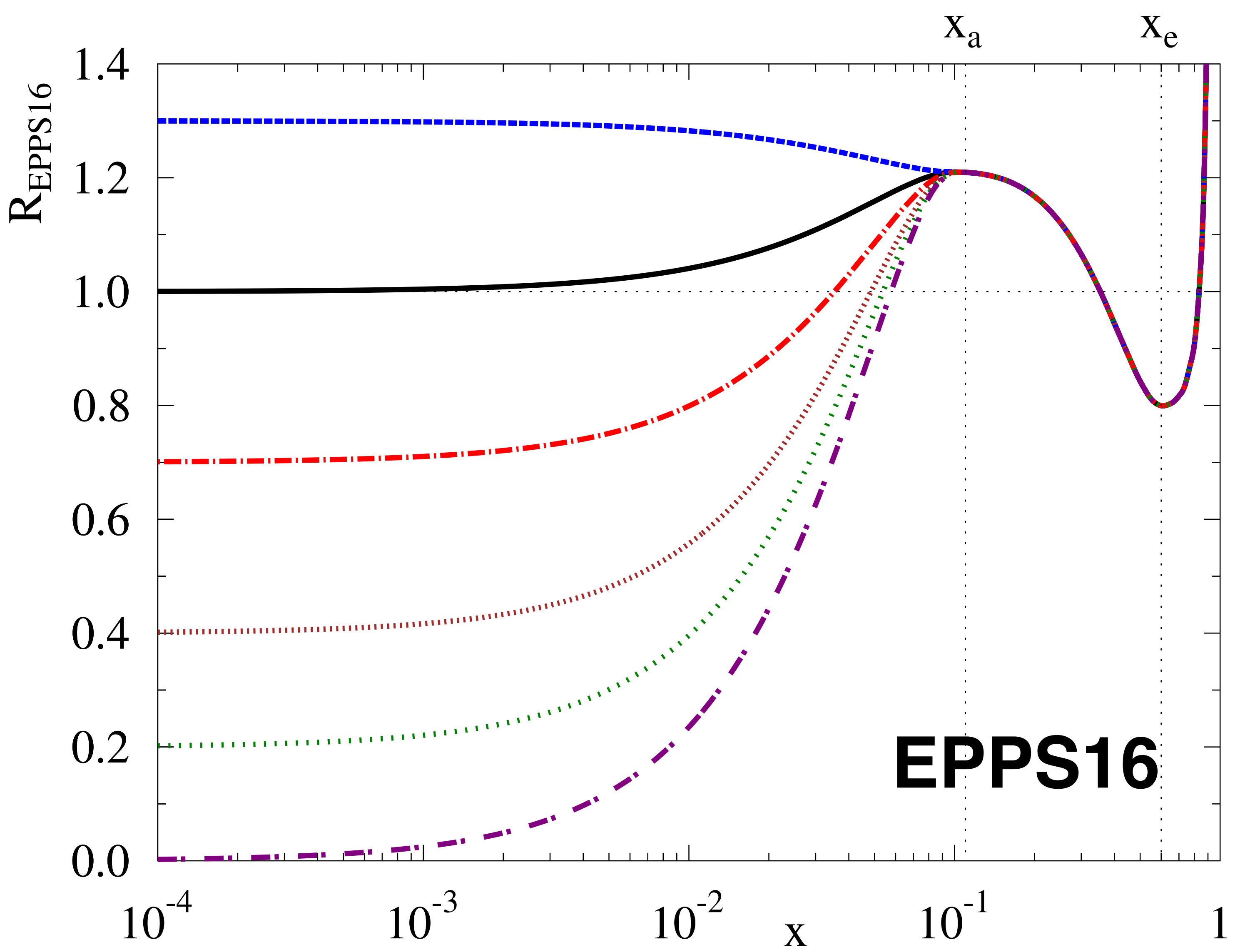


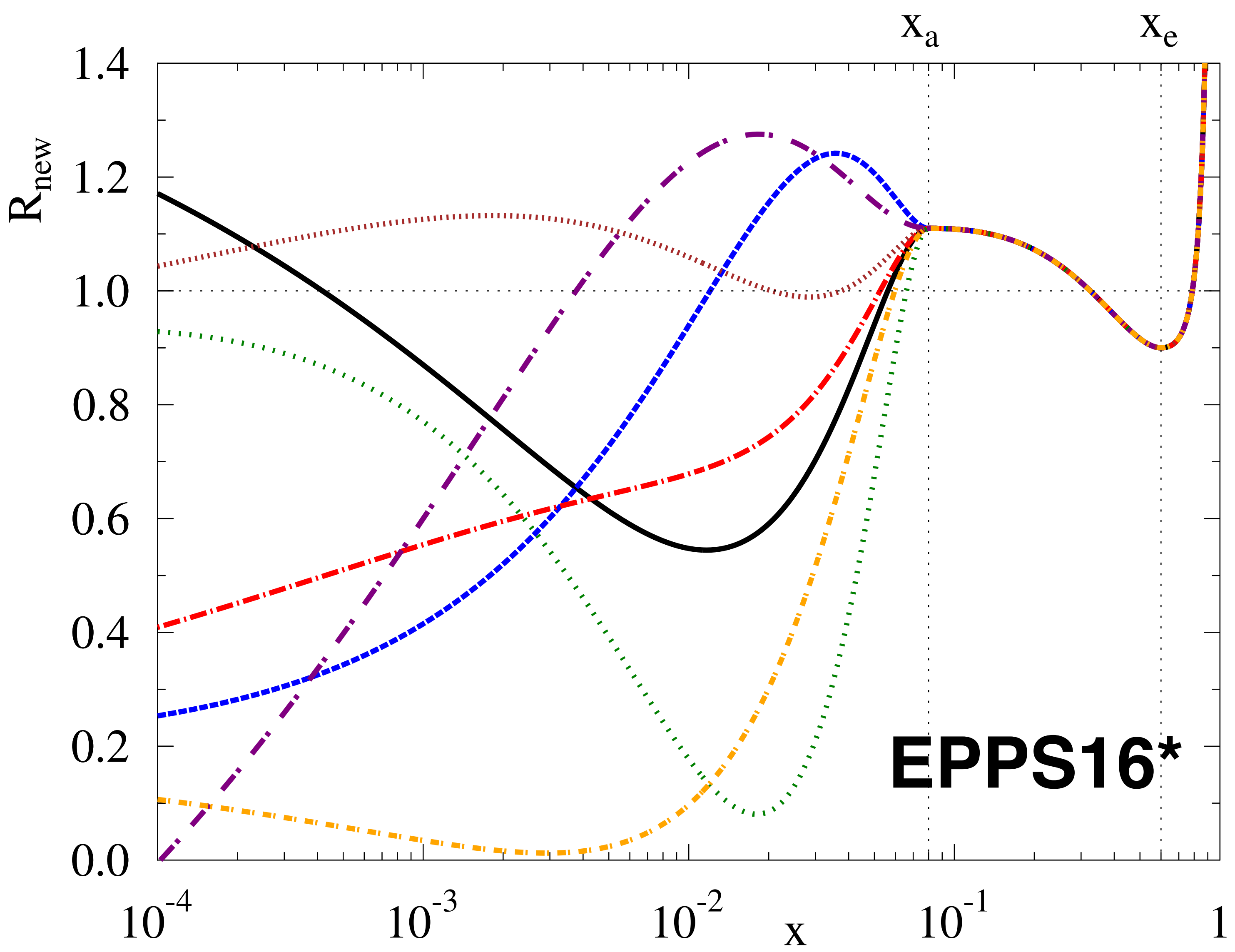
- Dramatic improvements with EIC at highest energy

The Problem of Estimating nPDF Constraints

Methods:

- Use σ_{red} (includes F_2 and F_L (F_3)) pseudo data
- Re-weighting EPPS16
  - EPPS16 is a bit stiff at low-x, over-constraints at low-x
- EPPS16* (arXiv:1708.05654, Hannu Paukkunen)
  - more flexible form cures EPPS16 problem (low-x bias)
  - might underestimate impact?

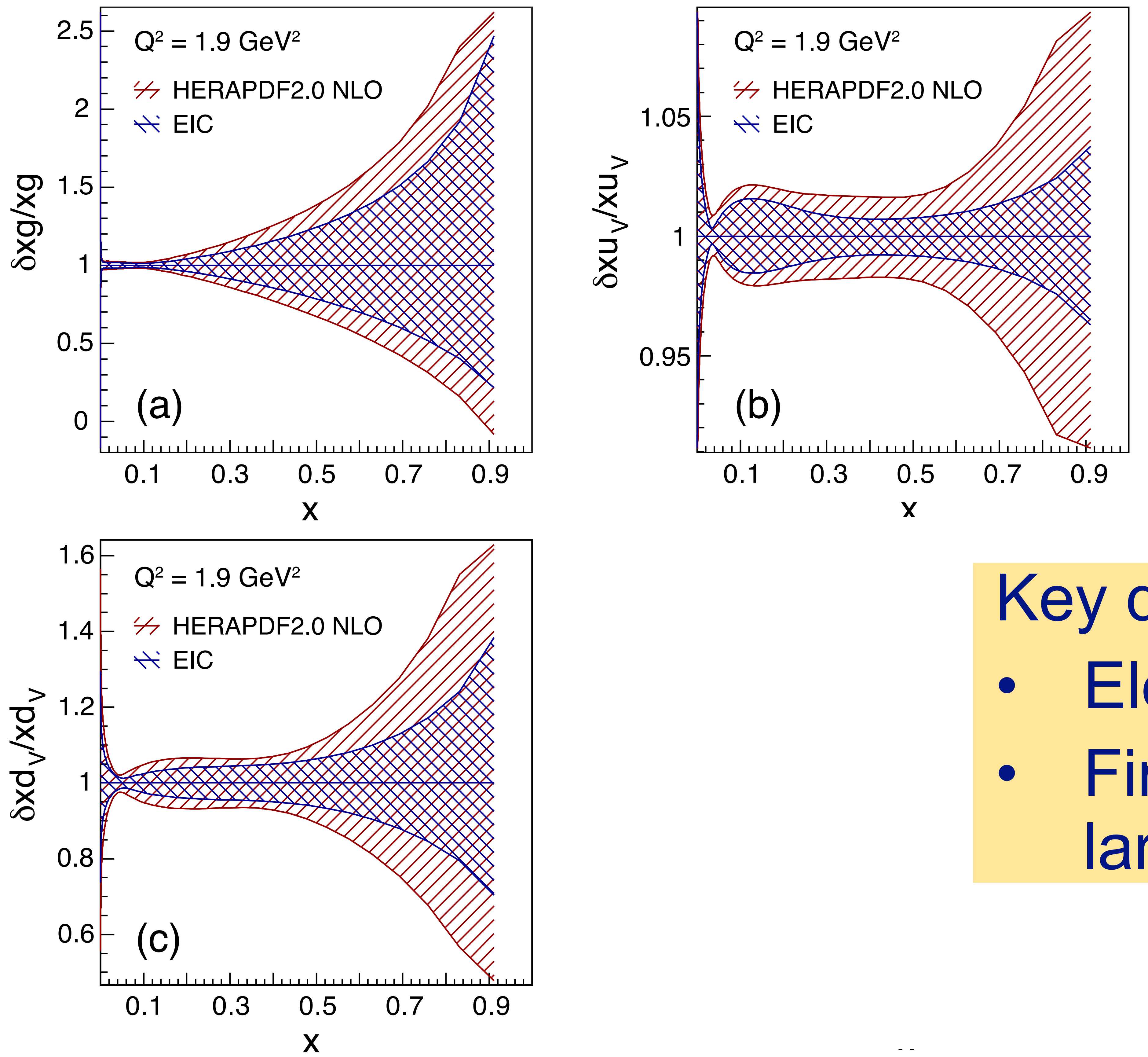




EIC's Impact on PDFs and nPDFs

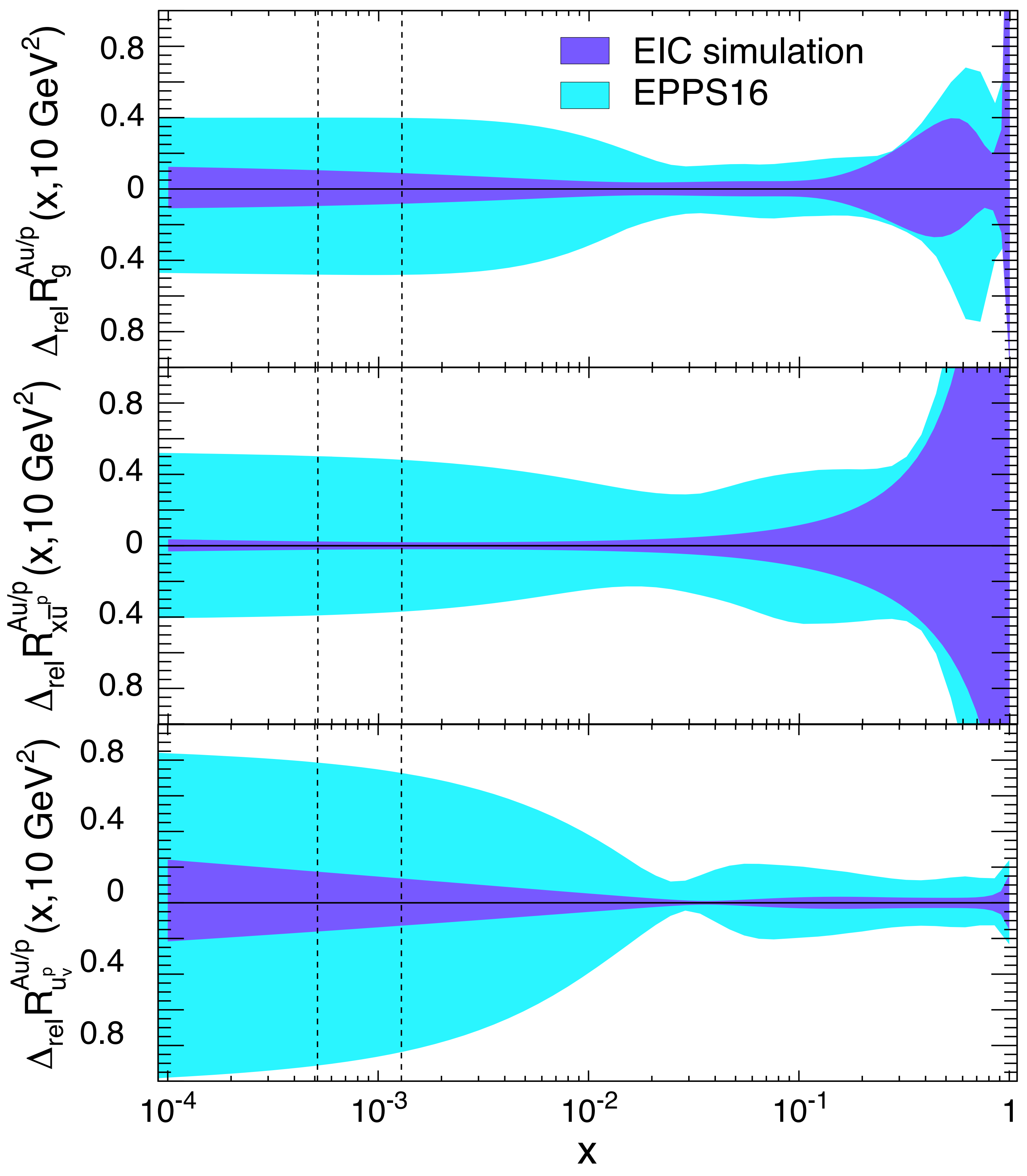
e+p:

EIC constrains the high-x region of both gluons and flavor-separated u and d valence quarks



e+A:

The EIC provides a factor ~10 larger reach in Q^2 and at low-x compared to available data



Key detector performance:

- Electron ID
- Fine *y* resolution over large phase space

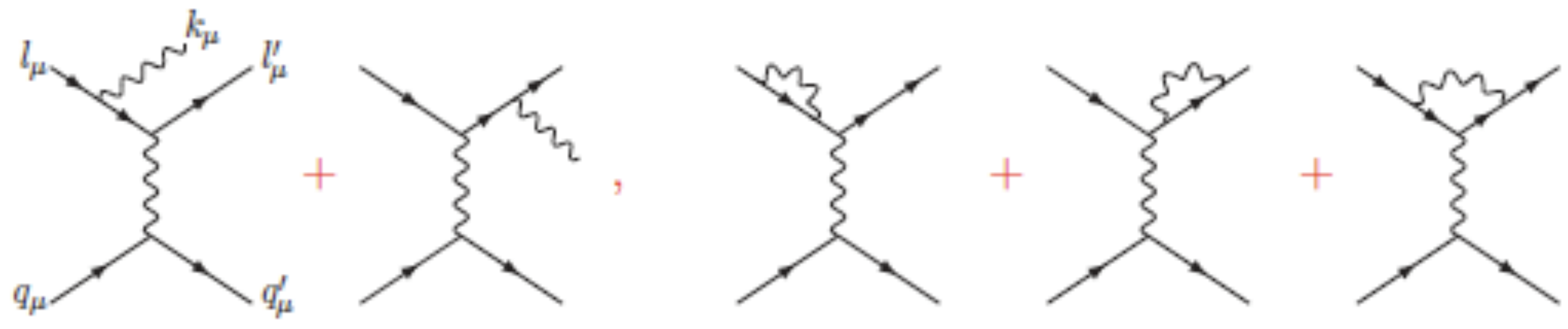
There's Always a Party Pooper …

Radiative "Correction"

- Emission of real photons experimentally often not distinguished from non-radiative processes: soft photons, collinear photons
- Studies underway (ignored in EIC WP)

Feynman diagrams for leptonic radiation at $O(\alpha)$ (NC)

for *eq* scattering:



$$F_n^{\text{obs}}(x, Q^2) = \int \mathrm{d}\tilde{x}\mathrm{d}\tilde{Q}^2 R_n(x, Q^2; \tilde{x}, \tilde{Q}^2) F_n^{\text{true}}(\tilde{x}, \tilde{Q}^2)$$

- Expect strong dependence on experimental prescriptions for measuring kinematic variables
  - leptonic variables: measure E and θ of scattered lepton ⇒ x and Q^2
  - hadronic variables: measure E, θ from hadronic final state ⇒ $\tilde{x}$ and $\tilde{Q}^2$
  - mixed variables: combine information from leptonic and hadronic final state
- Need MC to unfold, kinematic cuts can limit effect
- Detect radiated photon?

There's Always a Party Pooper …

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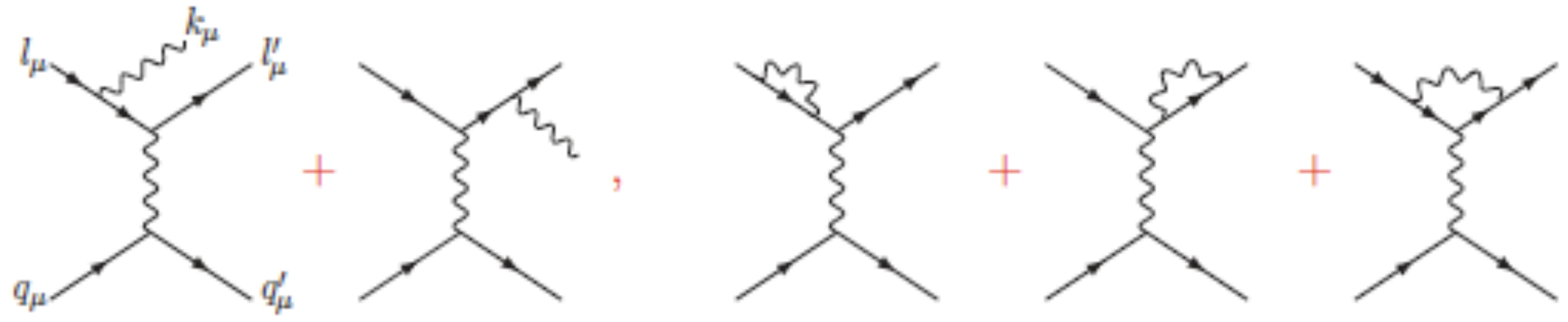

$$F_n^{\text{obs}}(x, Q^2) = \int \mathrm{d}\tilde{x}\,\mathrm{d}\tilde{Q}^2 R_n(x, Q^2; \tilde{x}, \tilde{Q}^2) F_n^{\text{true}}(\tilde{x}, \tilde{Q}^2)$$

$$Rcorr = \frac{\sigma_{red}\left(O(\alpha)\right)}{\sigma_{red}\left(born\right)} - 1$$