

EIC e+A science programme

Matthew A. C. Lamont
Brookhaven National Lab



From the bestselling author of
A SHORT HISTORY OF TRACTORS IN UKRAINIAN and TWO CARAVANS



10 week INT programme - Fall 2010

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[Talks online](#)

[Application form](#)

[Exit report](#)

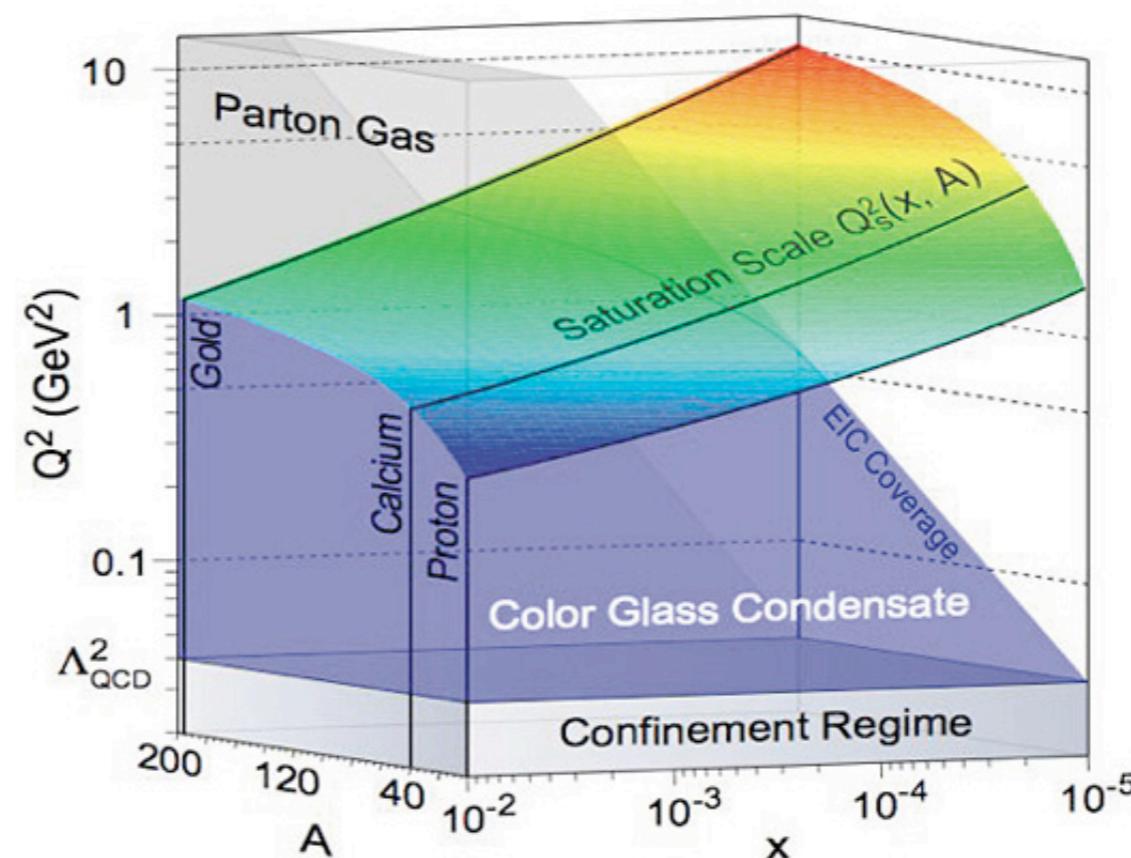
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Gluons and the quark sea at high energies: distributions, polarization, tomography

September 13 to November 19, 2010



This INT program will address open questions about the dynamics of gluons and sea quarks in the nucleon and in nuclei. Answers to these questions are crucial for a deeper understanding of hadron and nuclear structure in QCD at high energies. Many of them are relevant for understanding QCD final states at the LHC, which often provide a background for physics beyond the standard model. The topics addressed in this program have important ramifications for understanding the matter produced in heavy-ion collisions at RHIC and the LHC.

<http://www.int.washington.edu/PROGRAMS/10-3/>

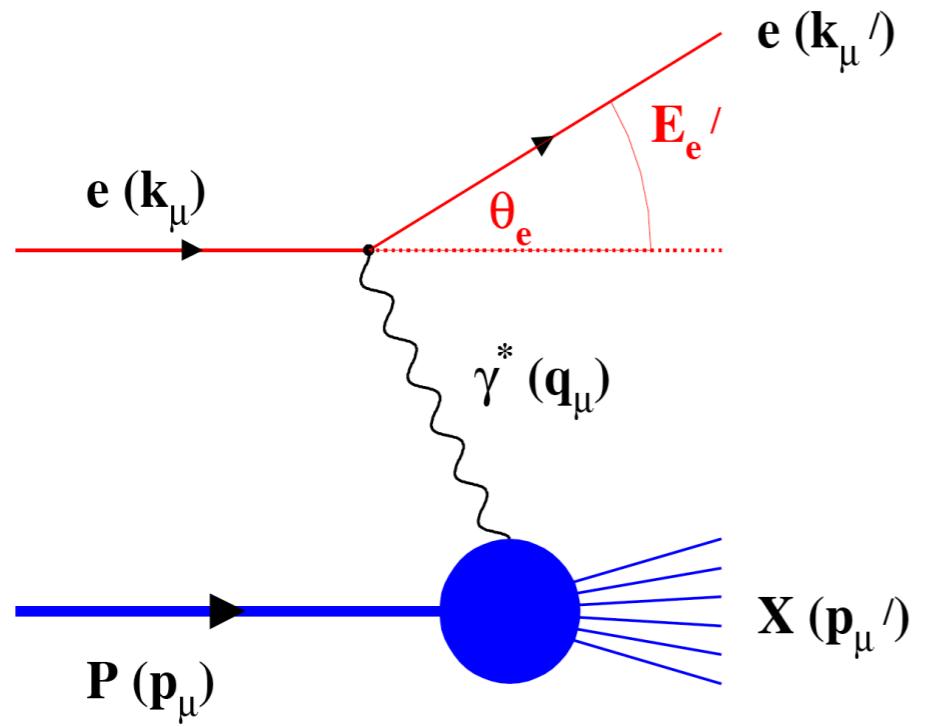
10 week INT programme - Fall 2010

week	dates	topics
1	13–17 Sept	Workshop on "Perturbative and Non-Perturbative Aspects of QCD at Collider Energies" Agenda
2	20–24 Sept	open conceptual issues: factorization and universality, spin and flavor structure, distributions and correlations Agenda
3–5	27 Sept – 15 Oct	small x, saturation, diffraction, nuclear effects; connections to p+A and A+A physics; fragmentation/hadronization in vacuum and in medium Agenda for week 3 Agenda for week 4 Agenda for week 5
6–7	18–29 Oct	parton densities (unpolarized and polarized), fragmentation functions, electroweak physics Agenda for week 6 Agenda for week 7
8–9	1–12 Nov	longitudinal and transverse nucleon structure; spin and orbital effects (GPDs, TMDs, and all that) Agenda for week 8 Agenda for week 9
10	16–19 Nov	Workshop on "The Science Case for an EIC" Agenda for week 10

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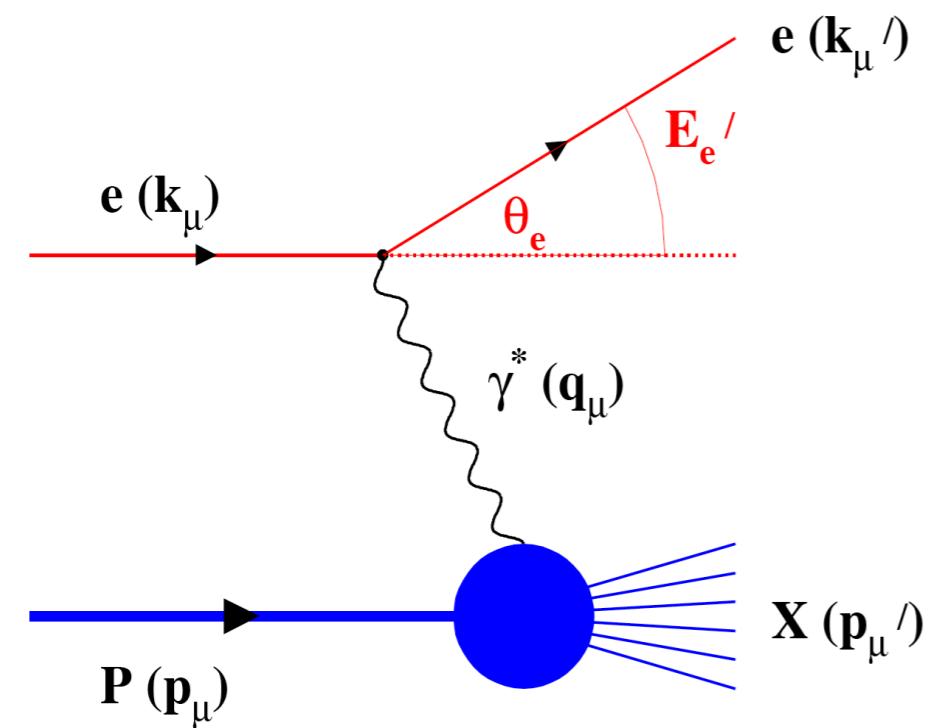
DIS Kinematics

$$e(k) + p(p) \rightarrow e(k') + X(p_x)$$



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$$e(k) + p(p) \rightarrow e(k') + X(p_x)$$



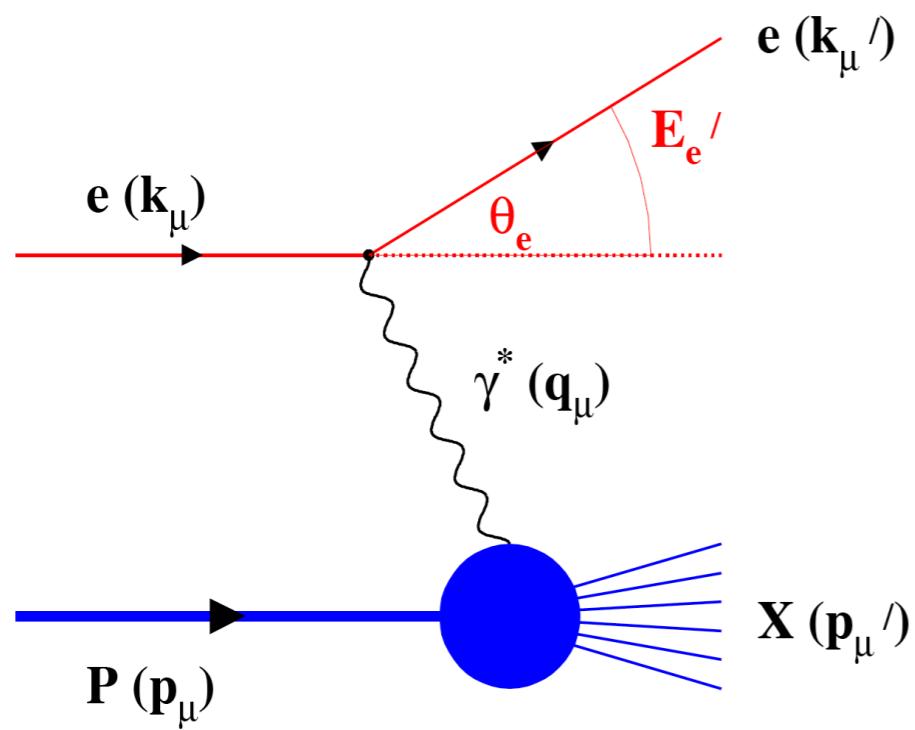
$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta_e}{2}\right)$$

Measure of
resolution
power or
"Virtuality"

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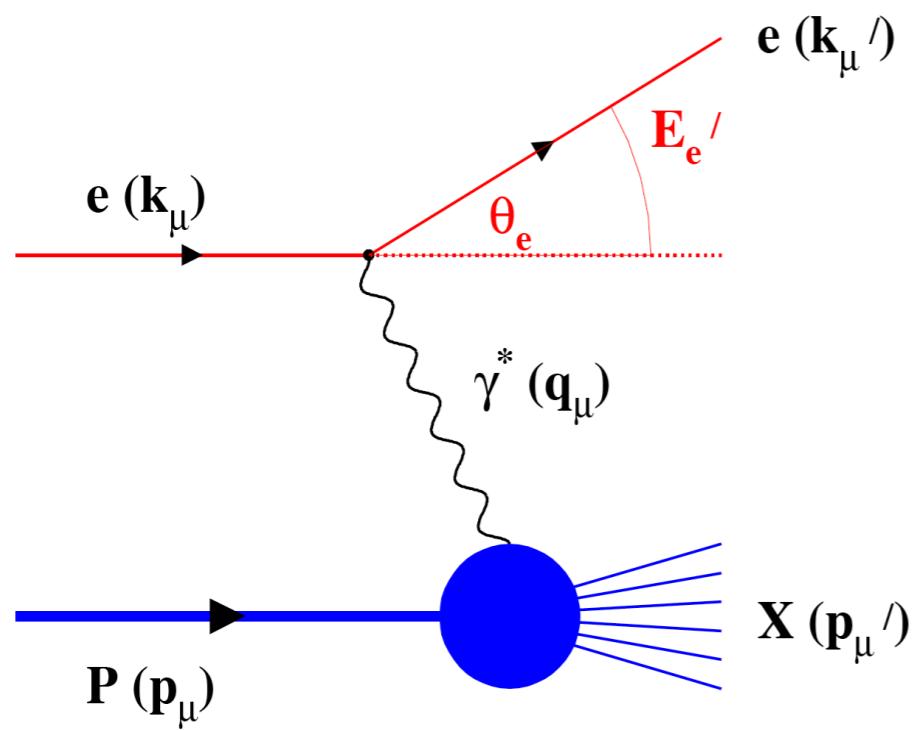
Measure of resolution power or "Virtuality"

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

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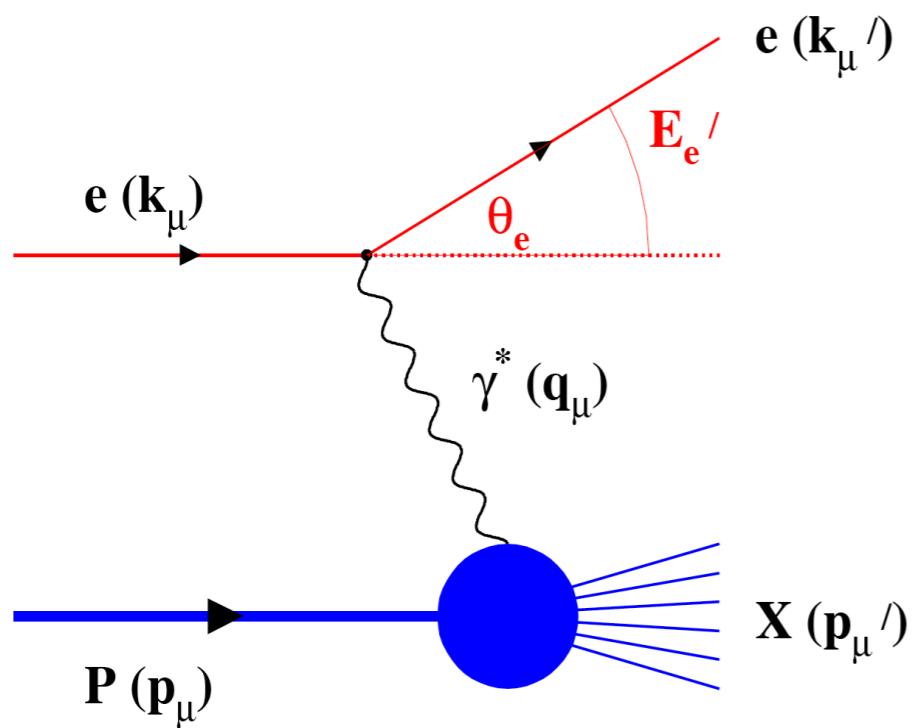
Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

DIS Kinematics

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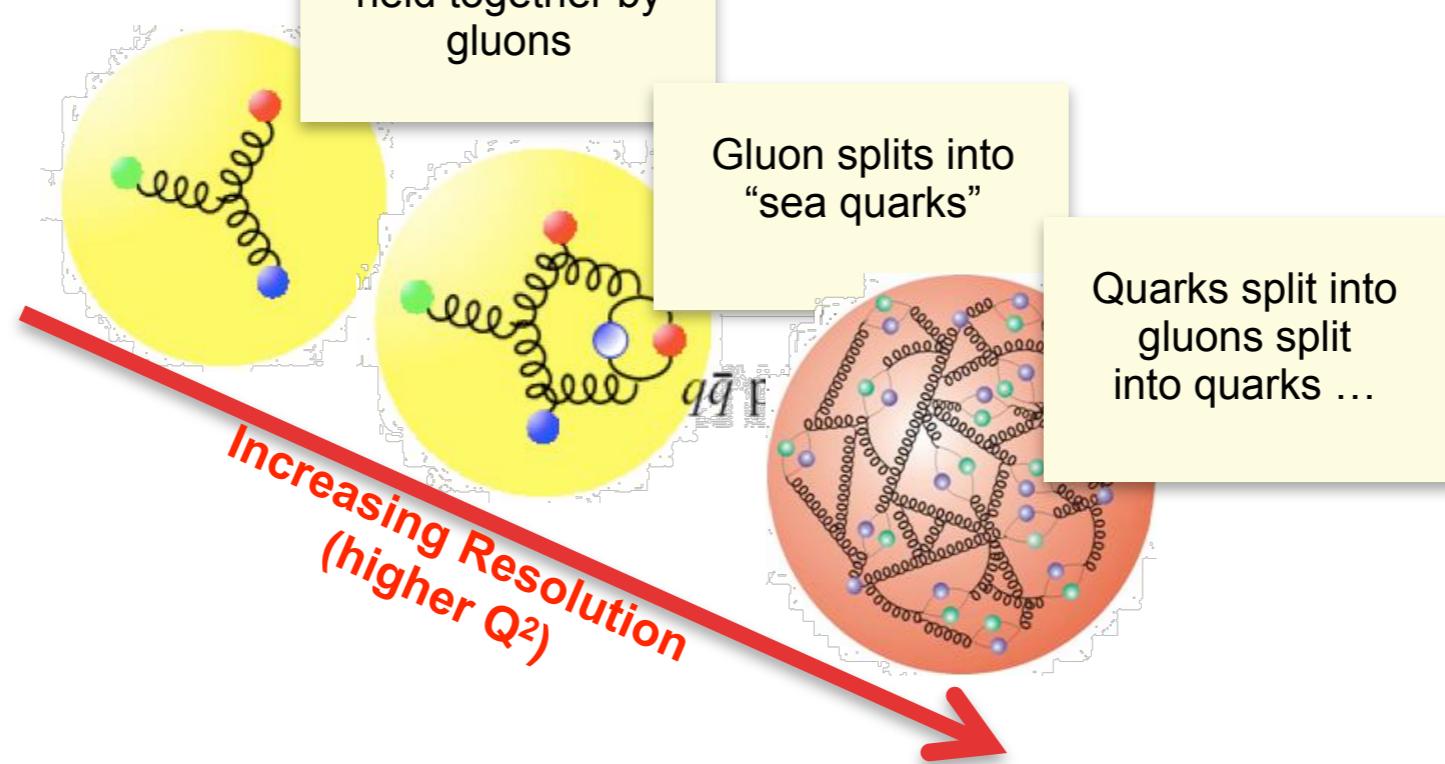
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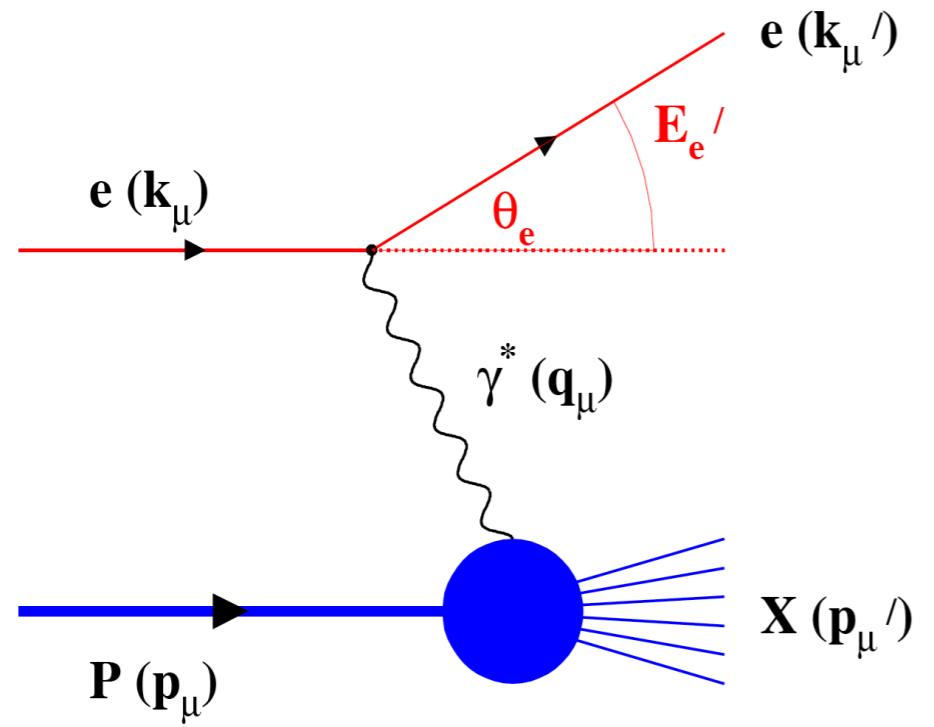
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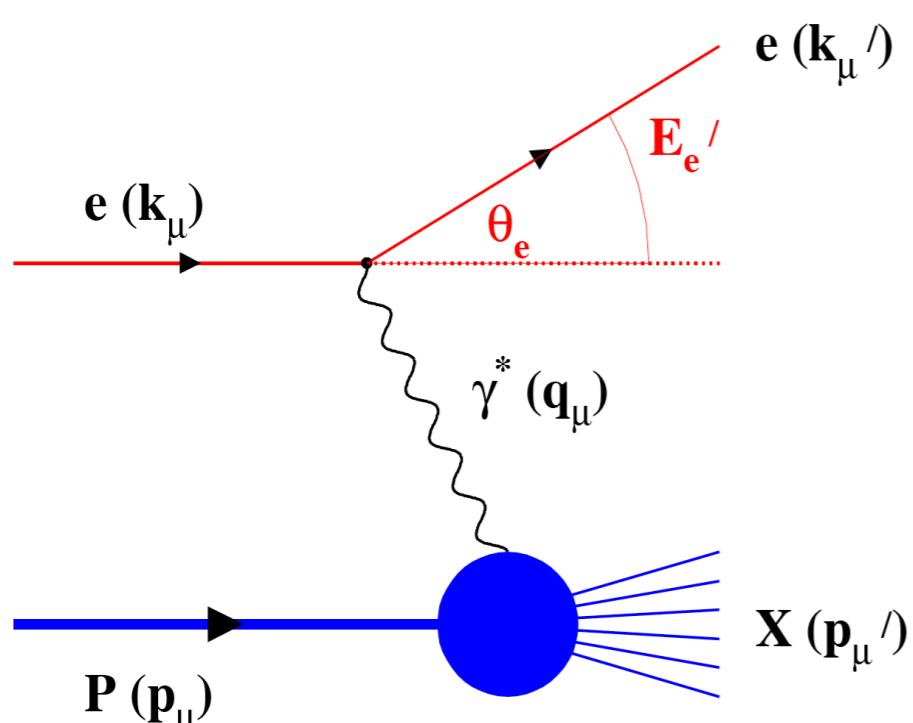
Diffractive Kinematics

$$e(k) + p(p) \rightarrow e(k') + X(p_x)$$

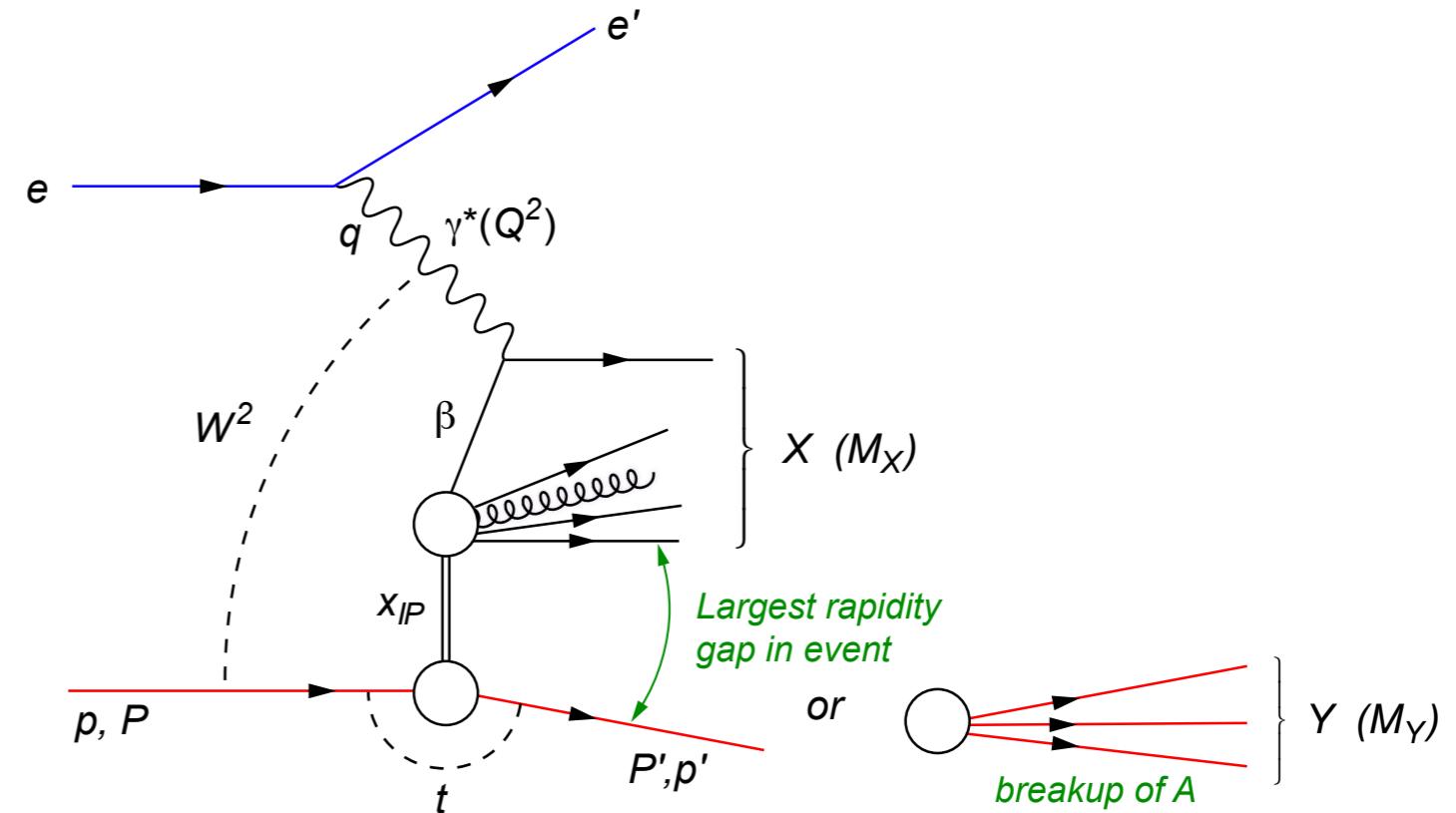


Diffractive Kinematics

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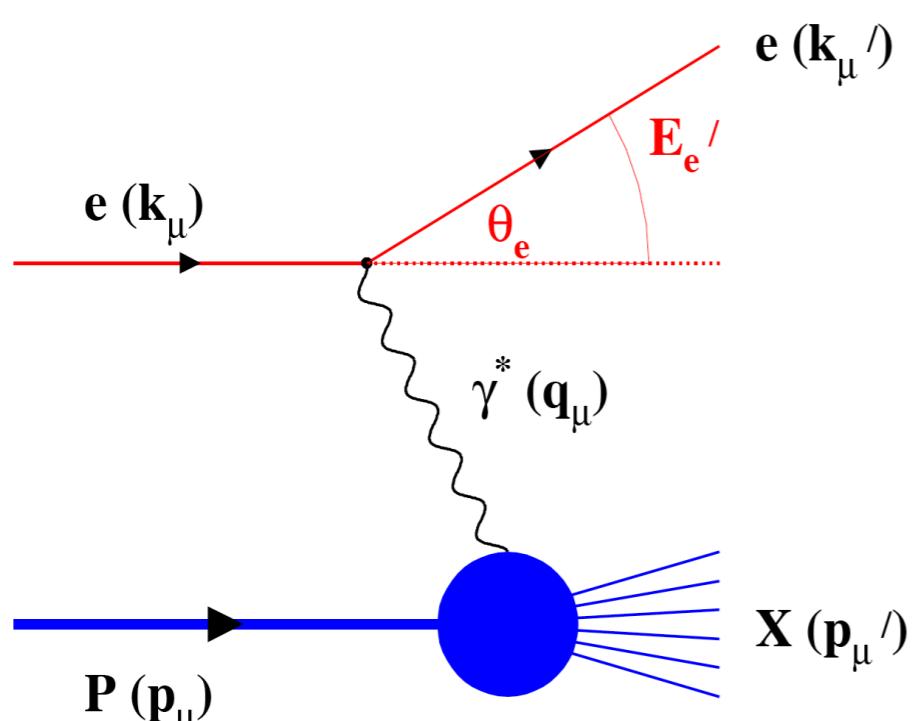


$$e(k) + p(p) \rightarrow e(k') + X(p_X) + Y(p_Y)$$

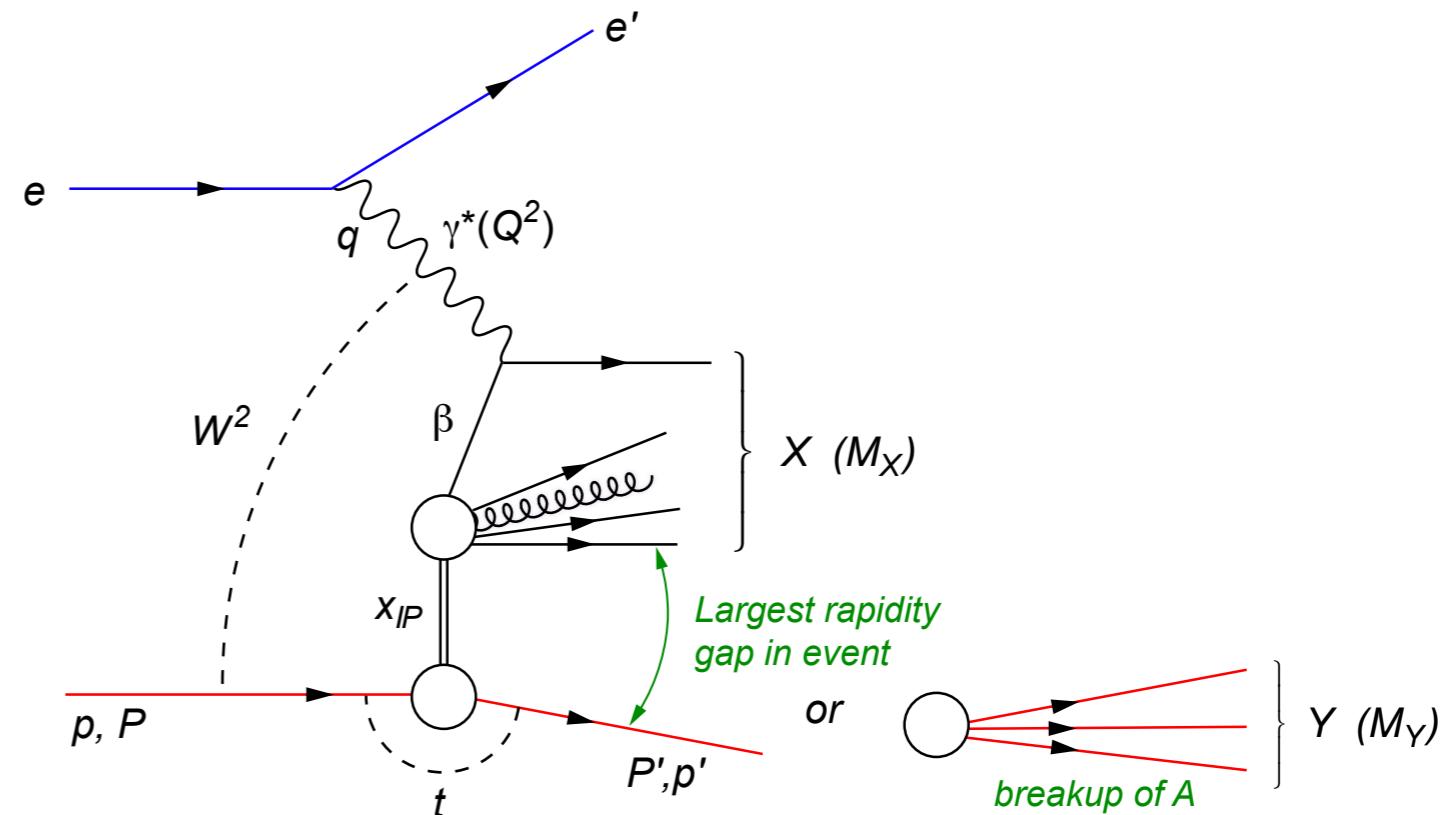


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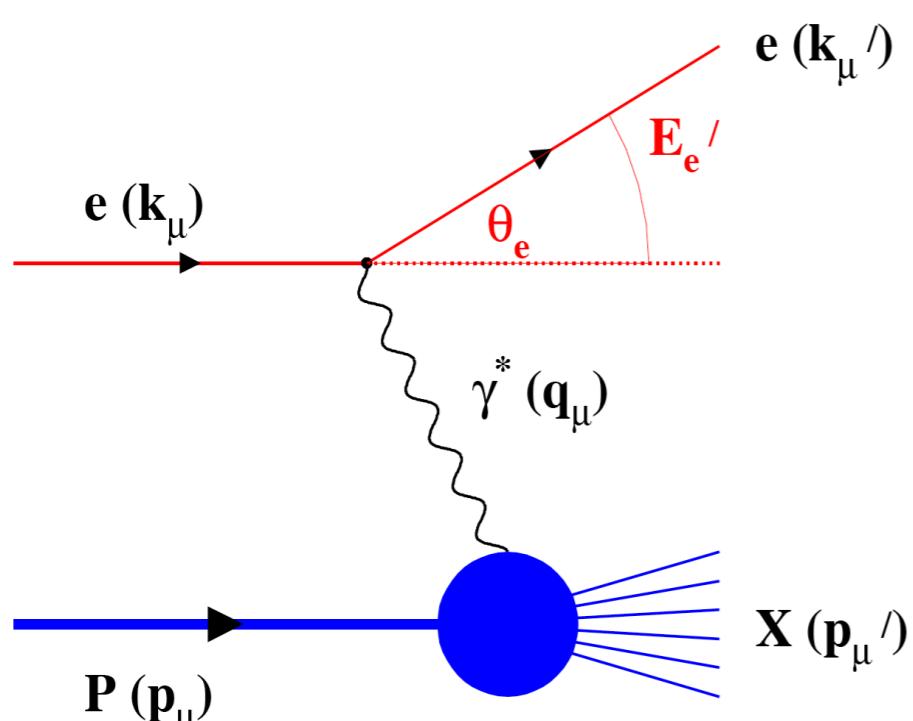


$$x_P = \frac{q \cdot (p - p_Y)}{q \cdot p}$$

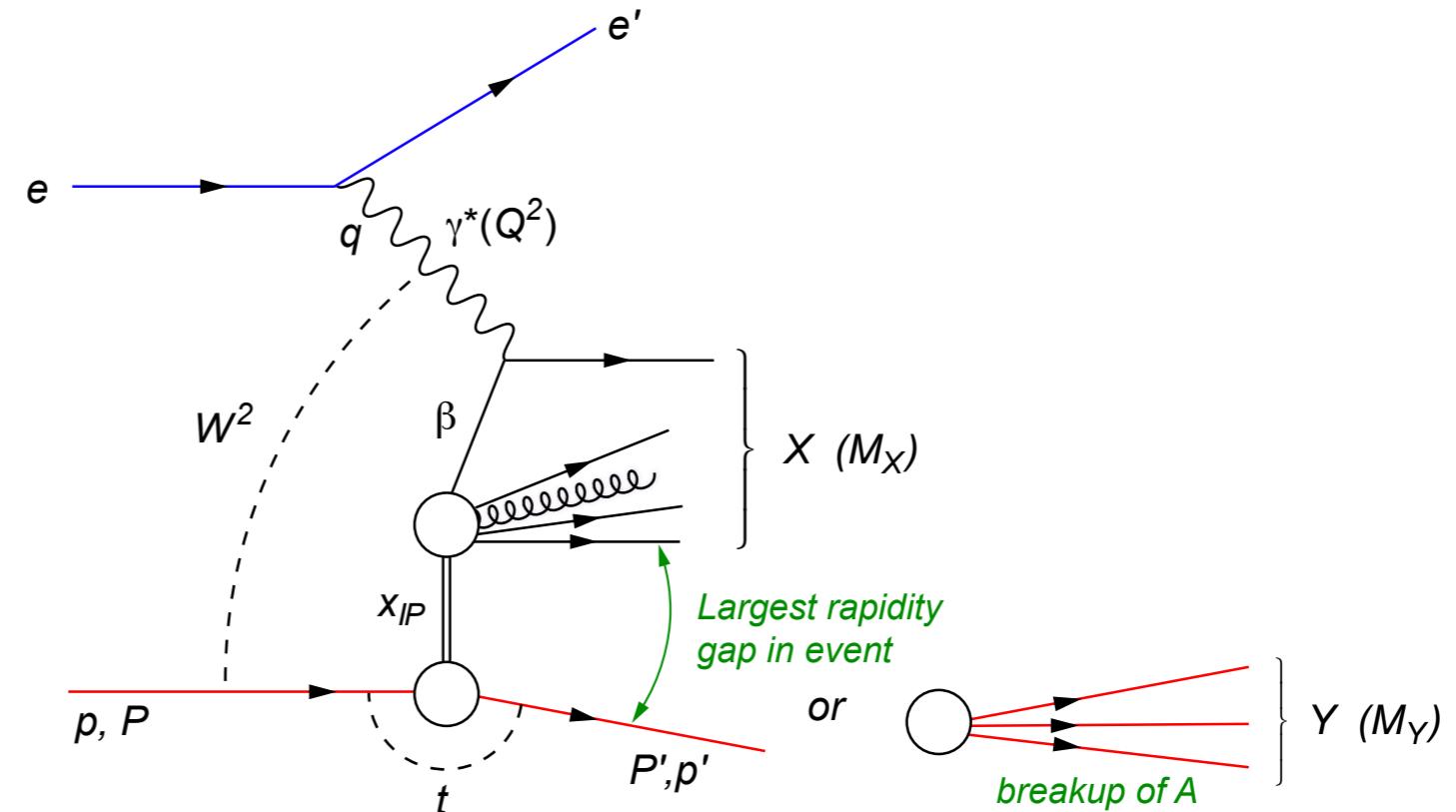
the momentum fraction of the proton carried by the pomeron

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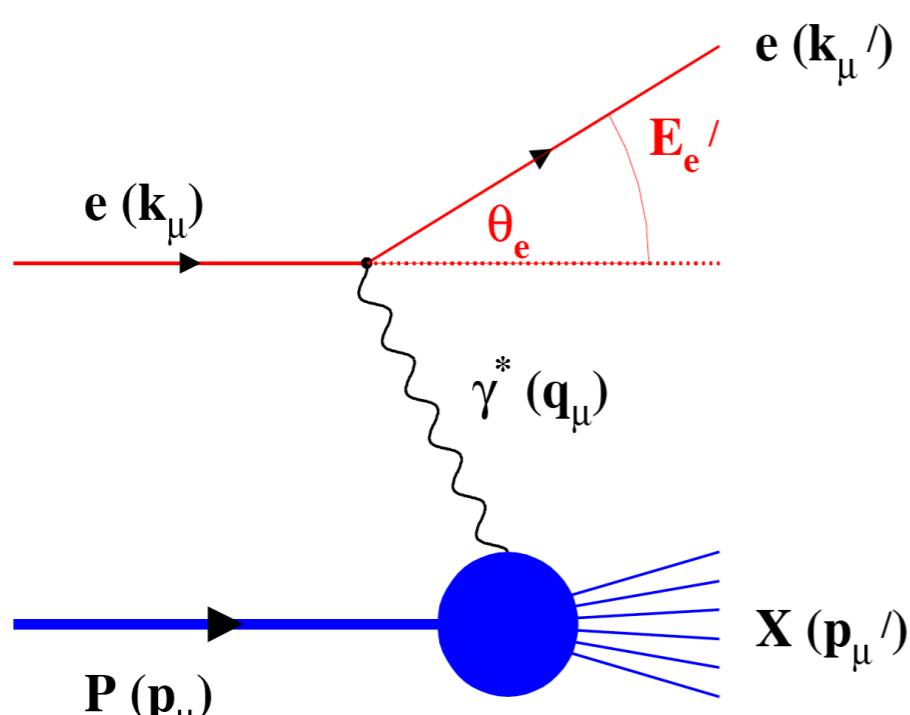
the momentum fraction of the proton carried by the pomeron

$$t = (p - p_Y)^2$$

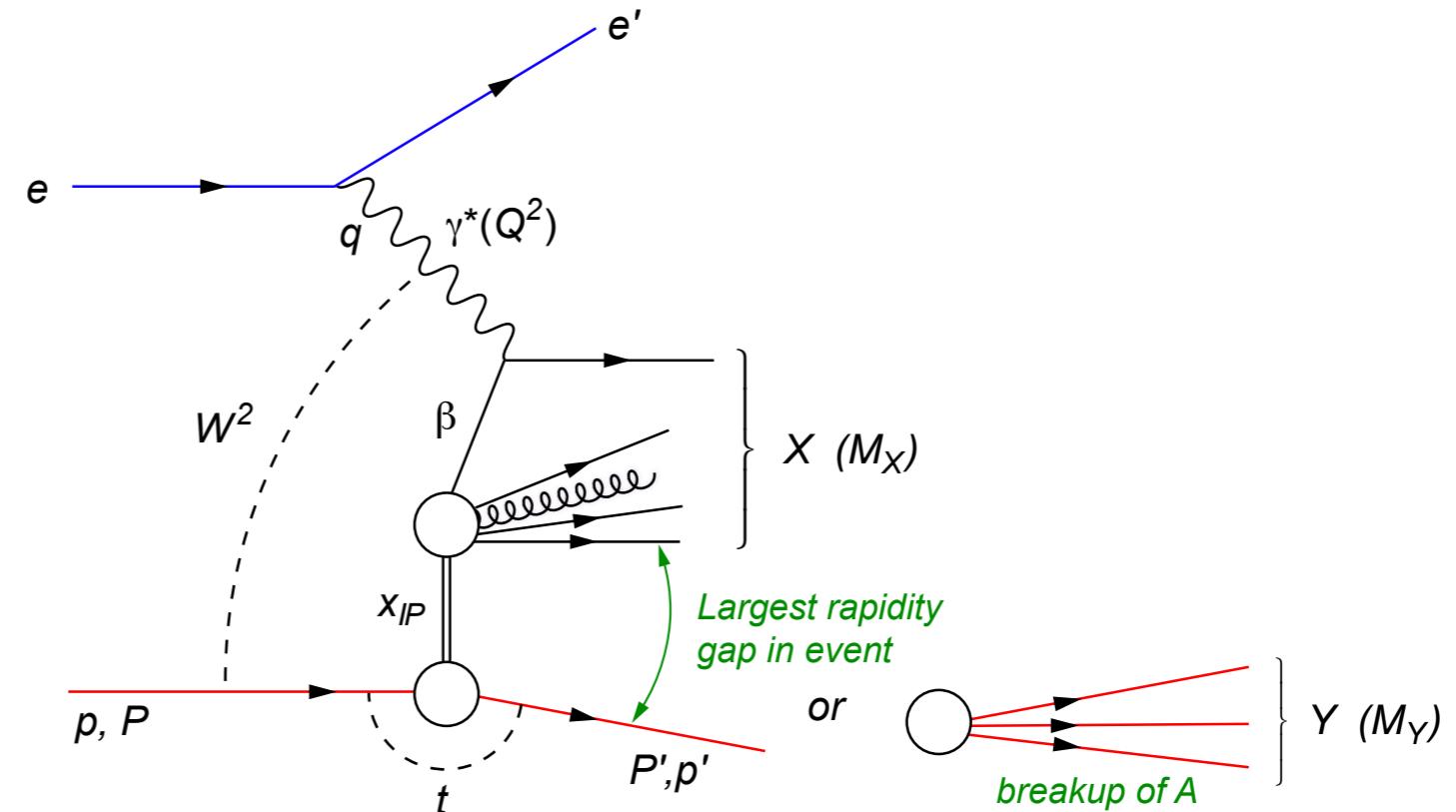
the momentum transfer at the proton vertex

Diffractive Kinematics

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$$x_{\mathbb{P}} = \frac{q \cdot (p - p_Y)}{q \cdot p}$$

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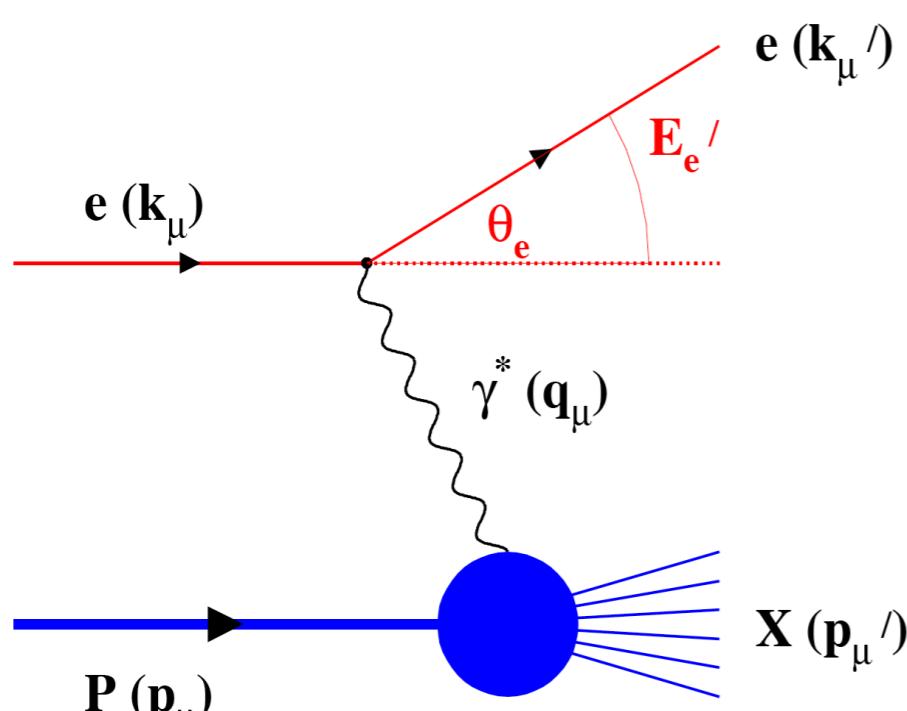
the momentum transfer at the proton vertex

$$\beta = \frac{-q^2}{q \cdot (p - p_Y)} = \frac{x}{x_{\mathbb{P}}}$$

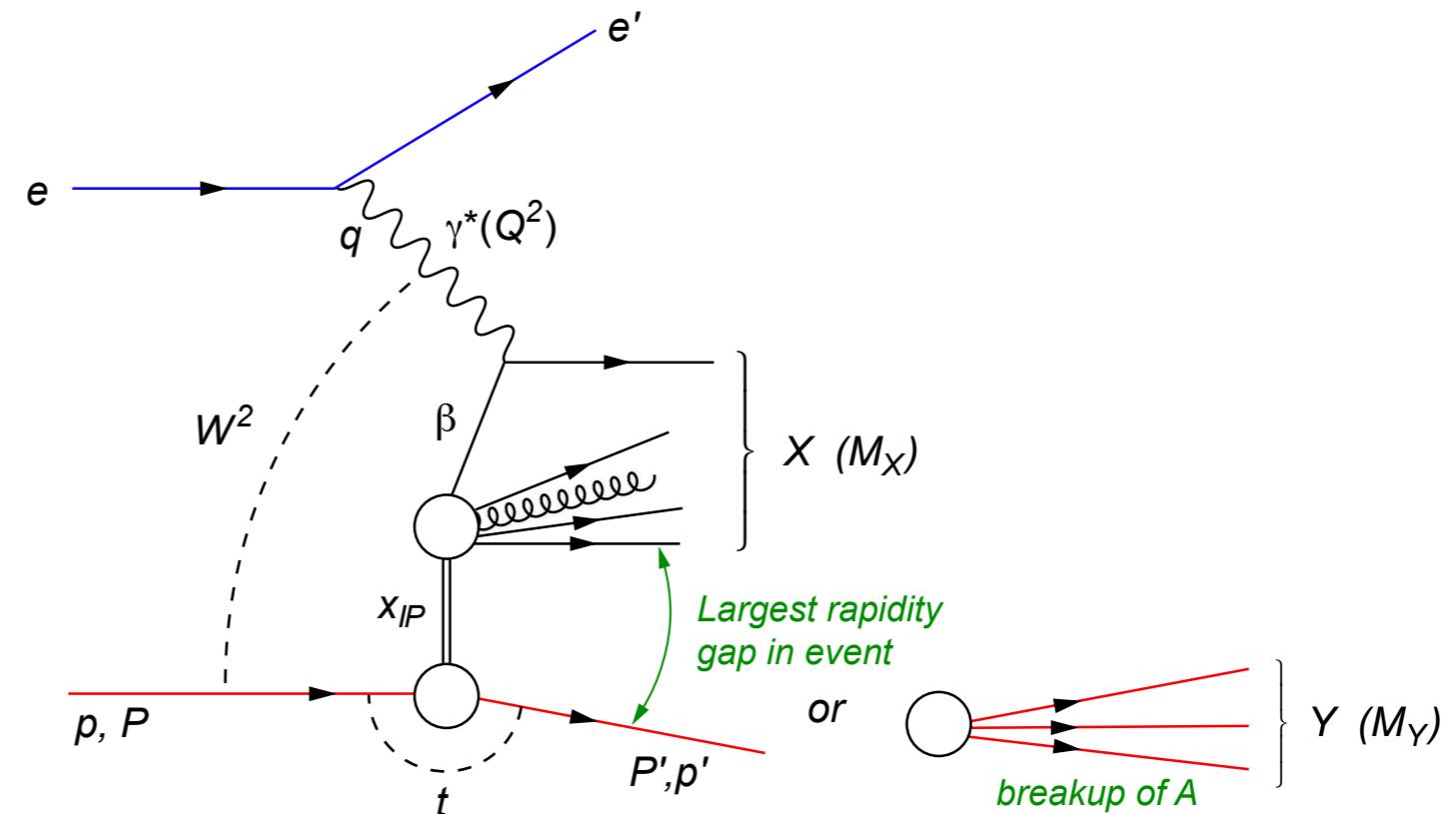
the momentum fraction of the pomeron carried by the interacting quark

Diffractive Kinematics

$$e(k) + p(p) \rightarrow e(k') + X(p_x)$$



$$e(k) + p(p) \rightarrow e(k') + X(p_x) + Y(p_y)$$



- HERA
 - 10-15% of all events were diffractive
- EIC
 - saturation models predict that 30-40% of all events will be diffractive

Measuring the glue via Structure Functions

$$\frac{d^2\sigma^{eA \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[\left(1 - y + \frac{y^2}{2}\right) F_2^A(x, Q^2) - \frac{y^2}{2} F_L^A(x, Q^2) \right]$$

**quark+anti-quark
momentum distributions**

**gluon momentum
distribution**



Measuring the glue via Structure Functions

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**quark+anti-quark
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**gluon momentum
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Reduced cross-section:

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

where:

$$Y^+ = 1 + (1 - y)^2$$

Measuring the glue via Structure Functions

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

**quark+anti-quark
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**gluon momentum
distribution**

The equation shows the difference between the quark+anti-quark momentum distributions (F_2^A) and the gluon momentum distribution (F_L^A) scaled by y^2/Y^+ . The text below the equation identifies these components.

Golden Measurements

Deliverables	Observables	What we learn	Stage-1	Stage-II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavours and charm; jets	rare probes and bottom; large-x gluons

Silver Measurements

Deliverables	Observables	What we learn	Stage-I	Stage-II
integrated gluon distributions	$F_{2,L}^c, F_{2,L}^D$	nuclear wave function; saturation, Q_s	difficult measurement / interpretation	saturation regime
flavour separated nuclear PDFs	charged current and γZ structure functions	EMC effect origin	full flavour separation for $10^{-2} < x < 1$	measure Q_s
k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large- x gluons
b-dependent gluons; gluon correlations	DVCS; diffractive vector mesons	interplay between small- x evolution and confinement	moderate x with light, heavy nuclei	smaller x , saturation

Integrated gluon distributions from inclusive structure functions

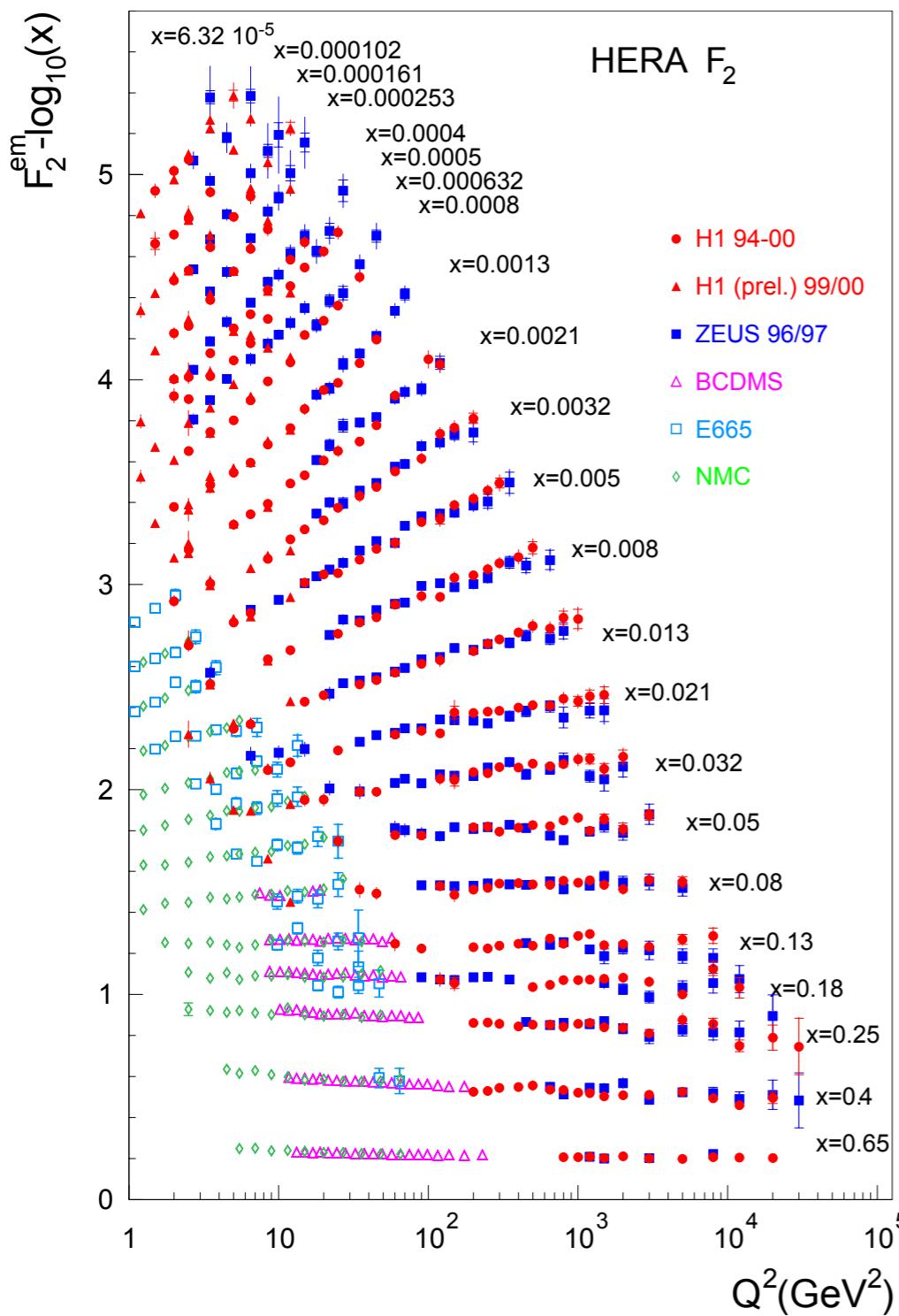
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integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
integrated gluon distributions	$F_{2,L}^c$, $F_{2,L}^D$	nuclear wave function; saturation, Q_s	difficult measurement / interpretation	saturation regime

charm diffractive

Measuring the glue via Structure Functions

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

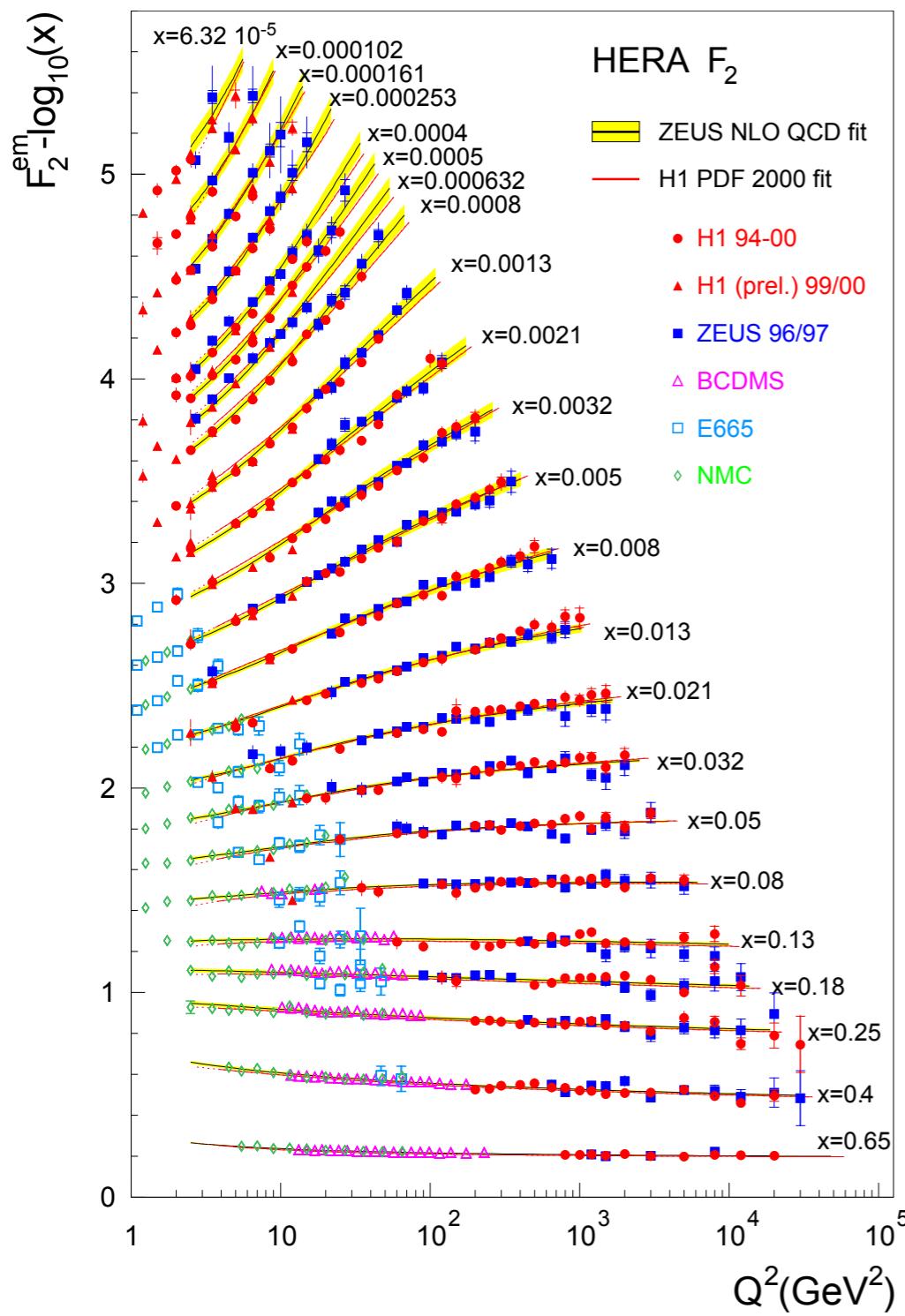


**quark+anti-quark
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**gluon momentum
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Measuring the glue via Structure Functions

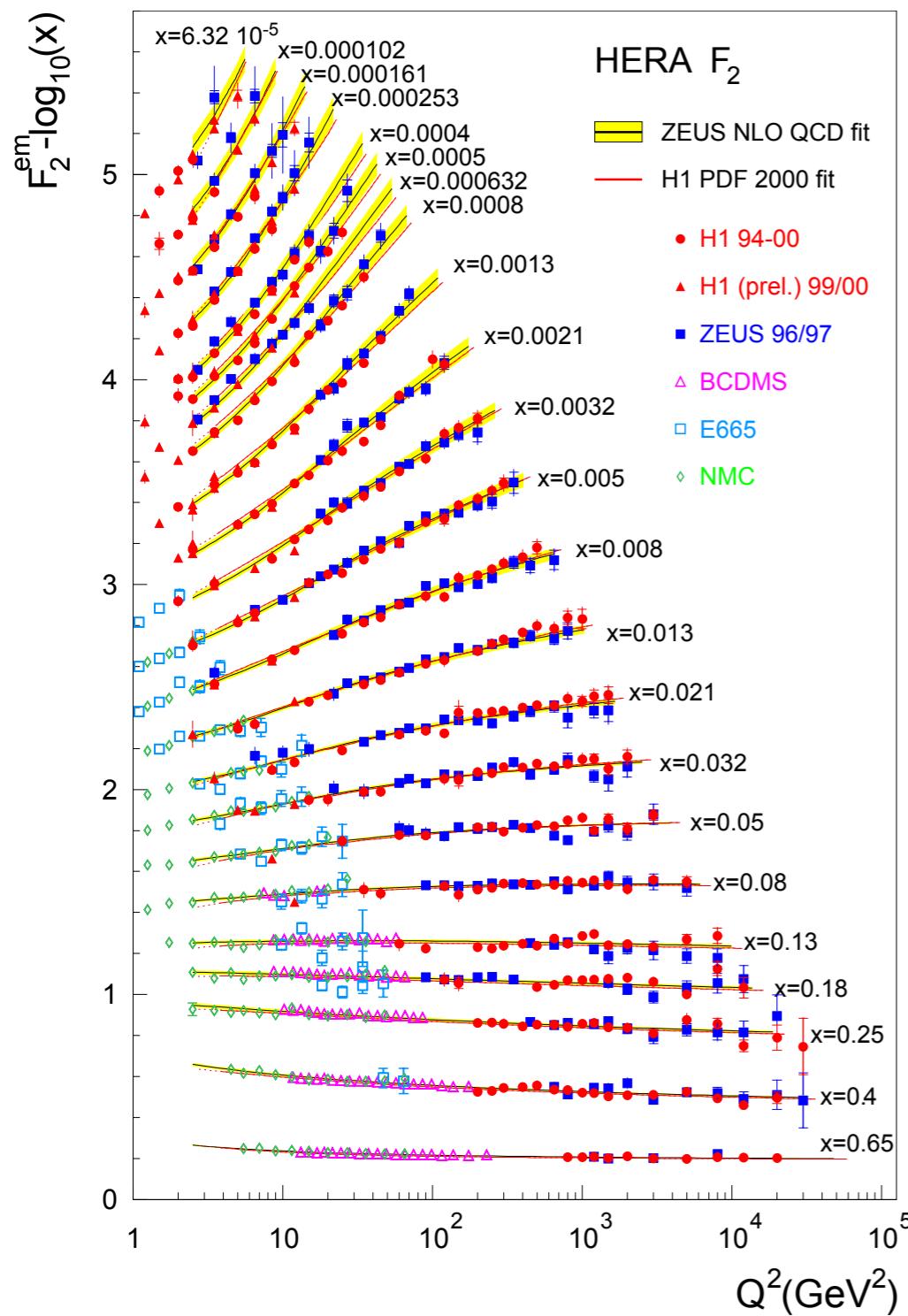
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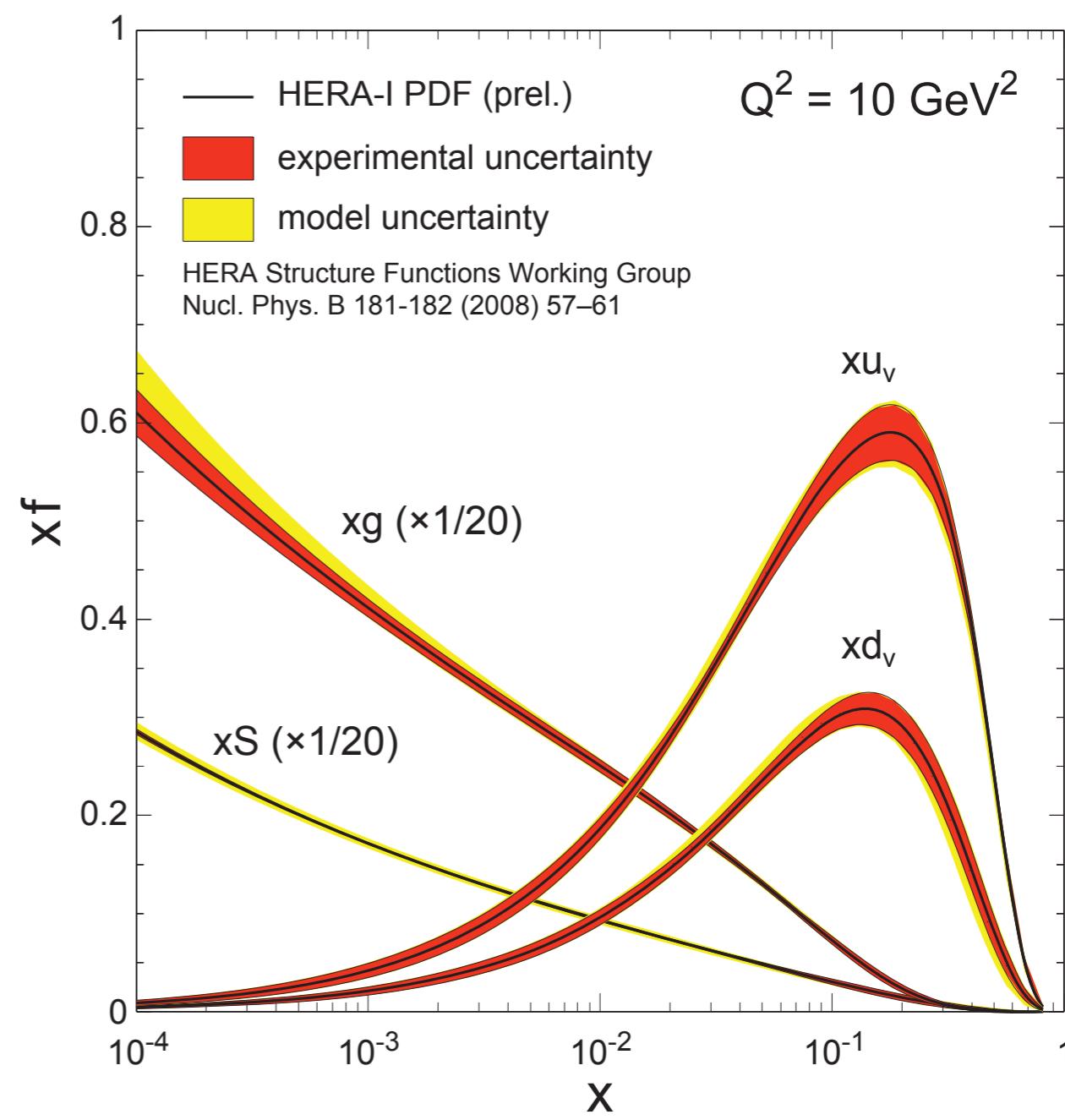
Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP
Evolution $\Rightarrow G(x, Q^2)$

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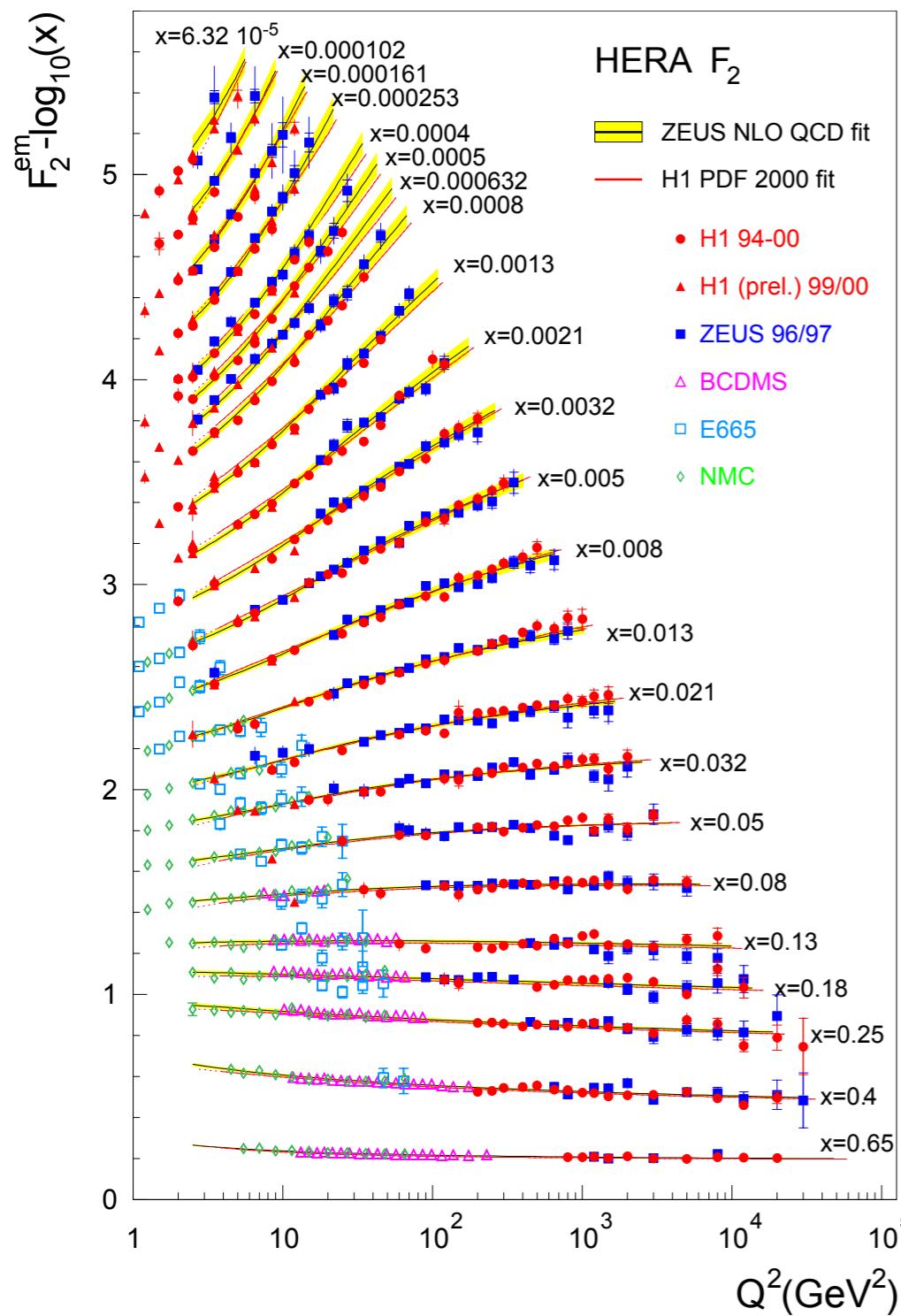


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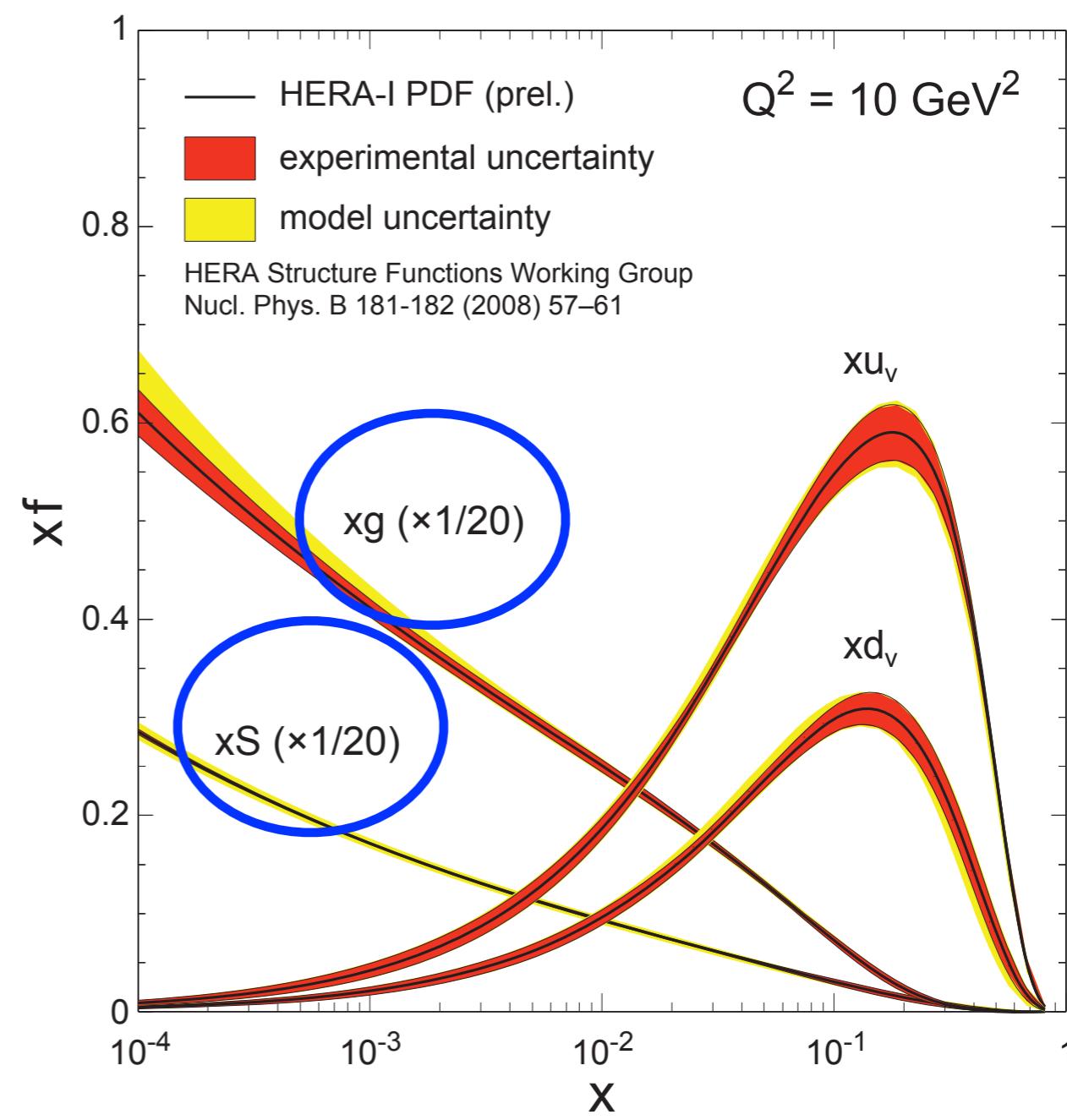


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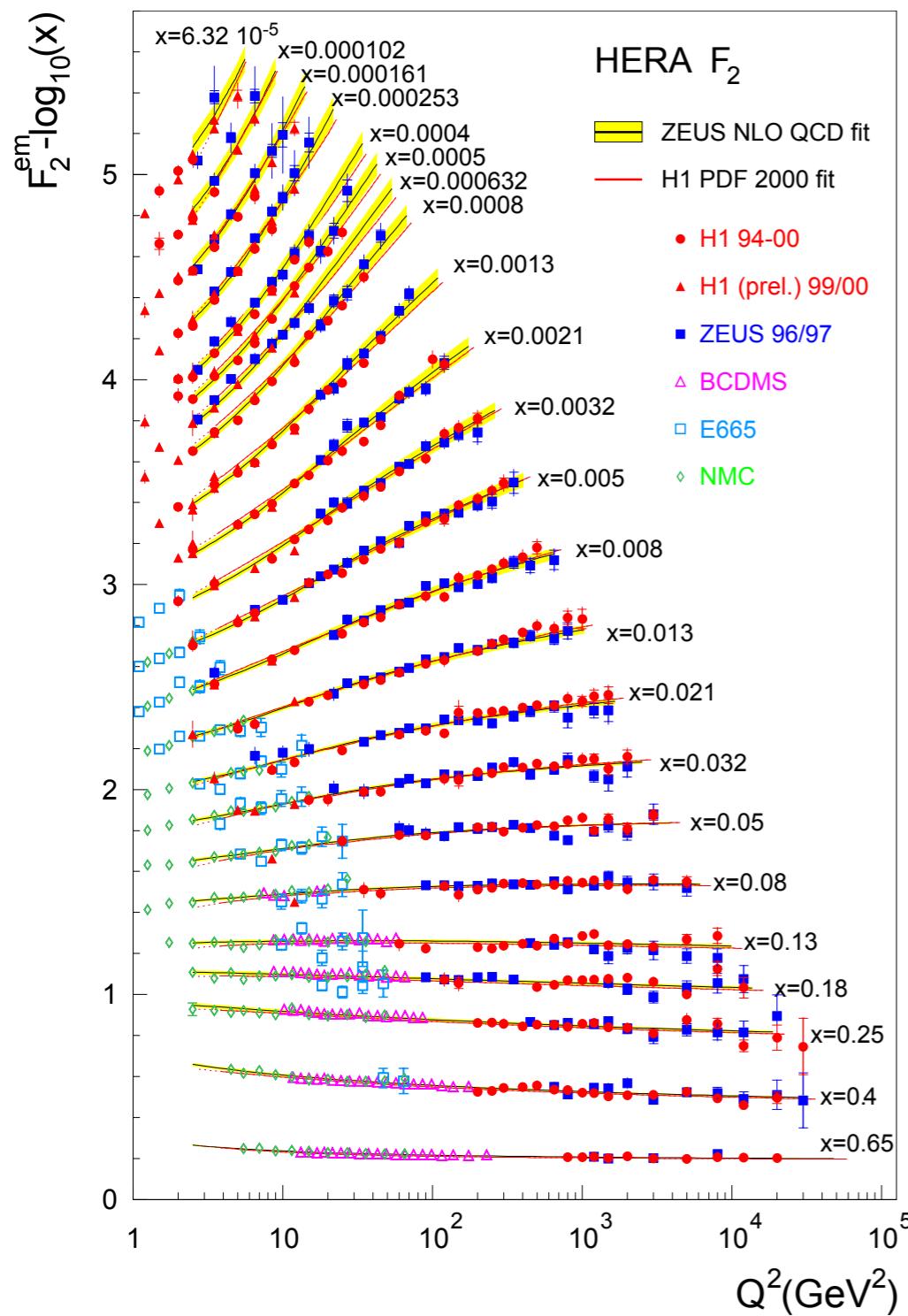


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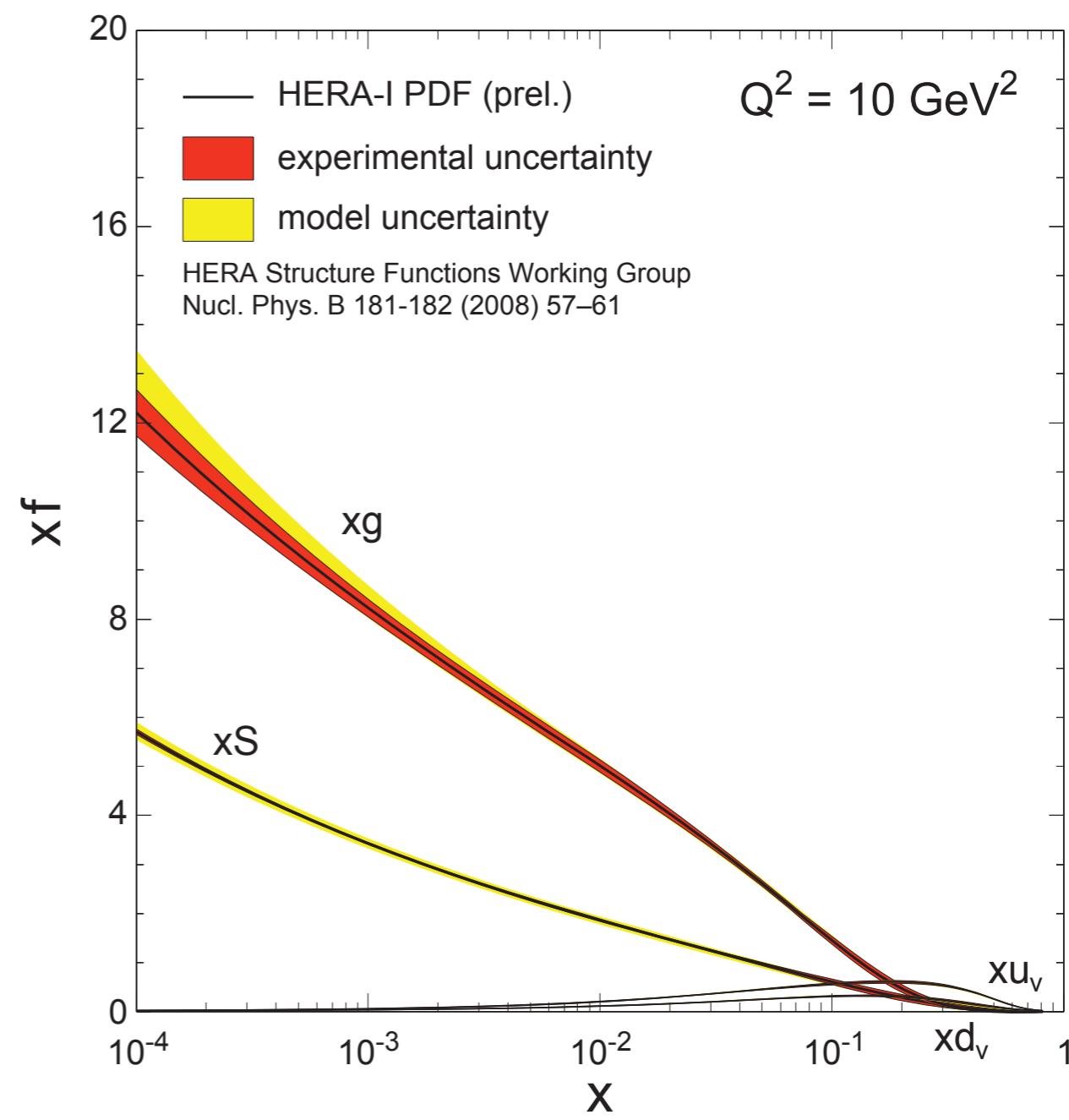


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Measuring the gluons: extracting F_L

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

Measuring the gluons: extracting F_L

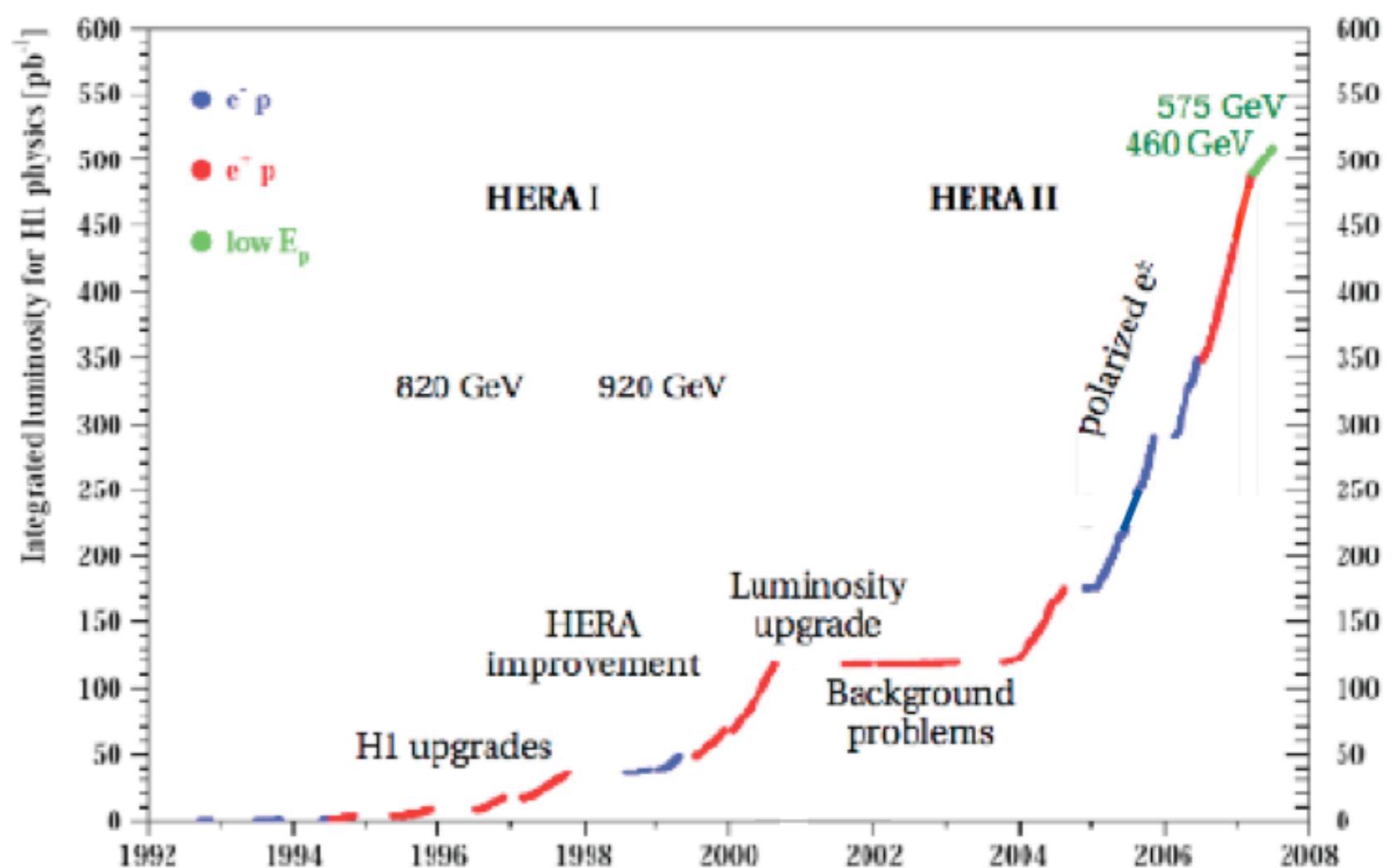
$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

- $F_L \sim \alpha_s x G(x, Q^2)$
 - $y = Q^2/x s$
 - require an energy scan to extract F_L

Measuring the gluons: extracting F_L

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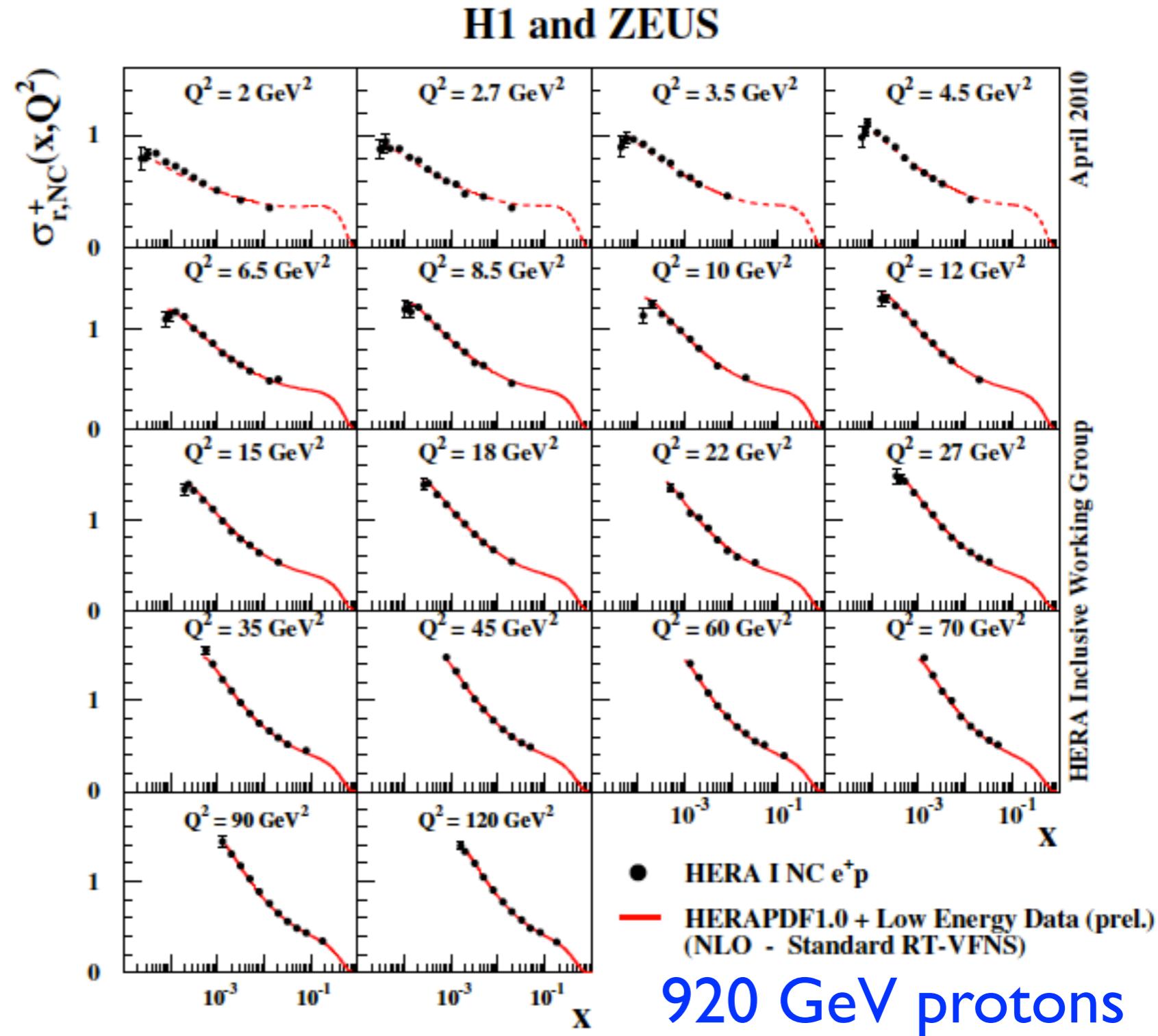
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- 3 different proton energies run at HERA
 - 2 low-statistics runs
 - bad for F_L extraction



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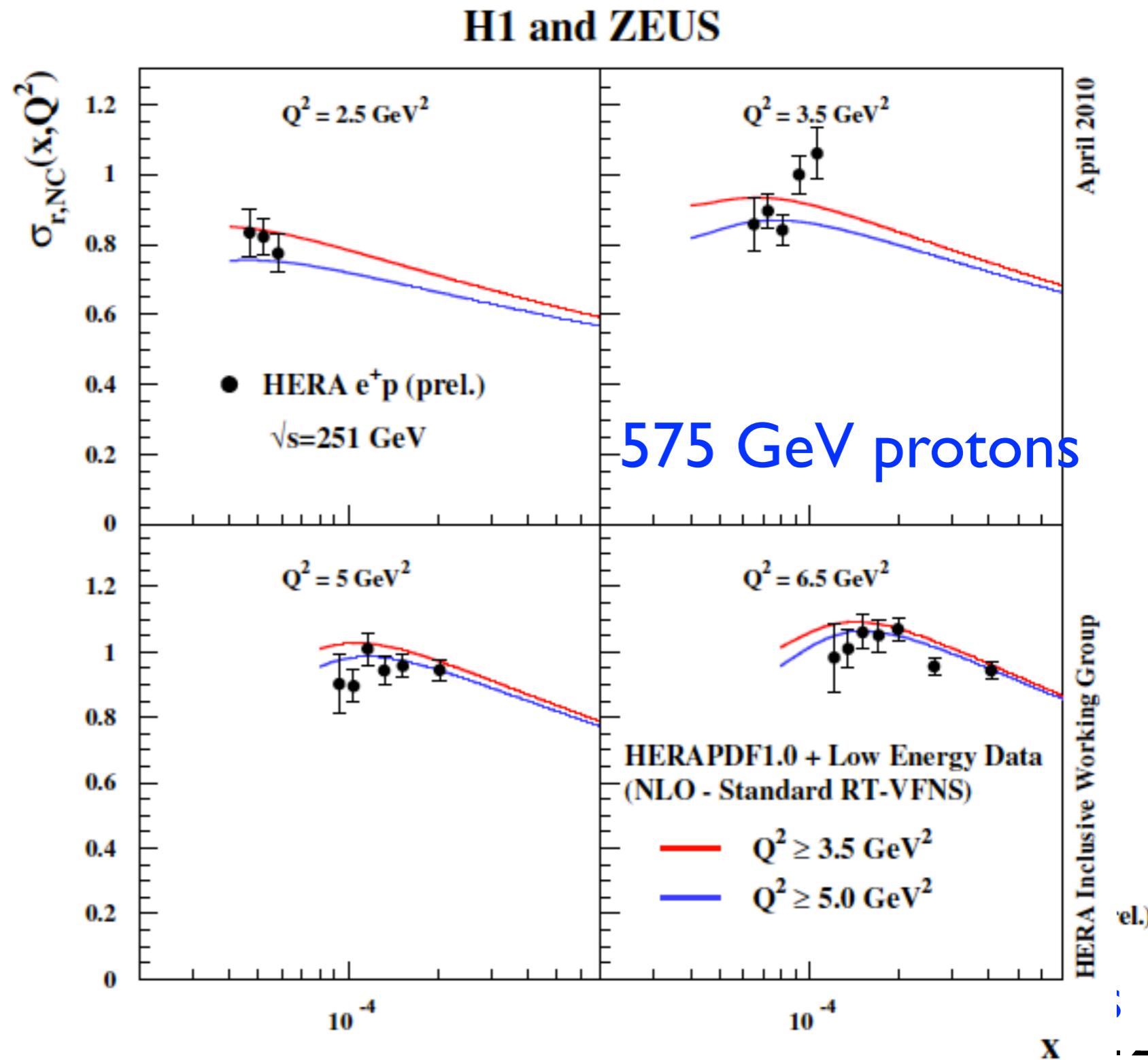
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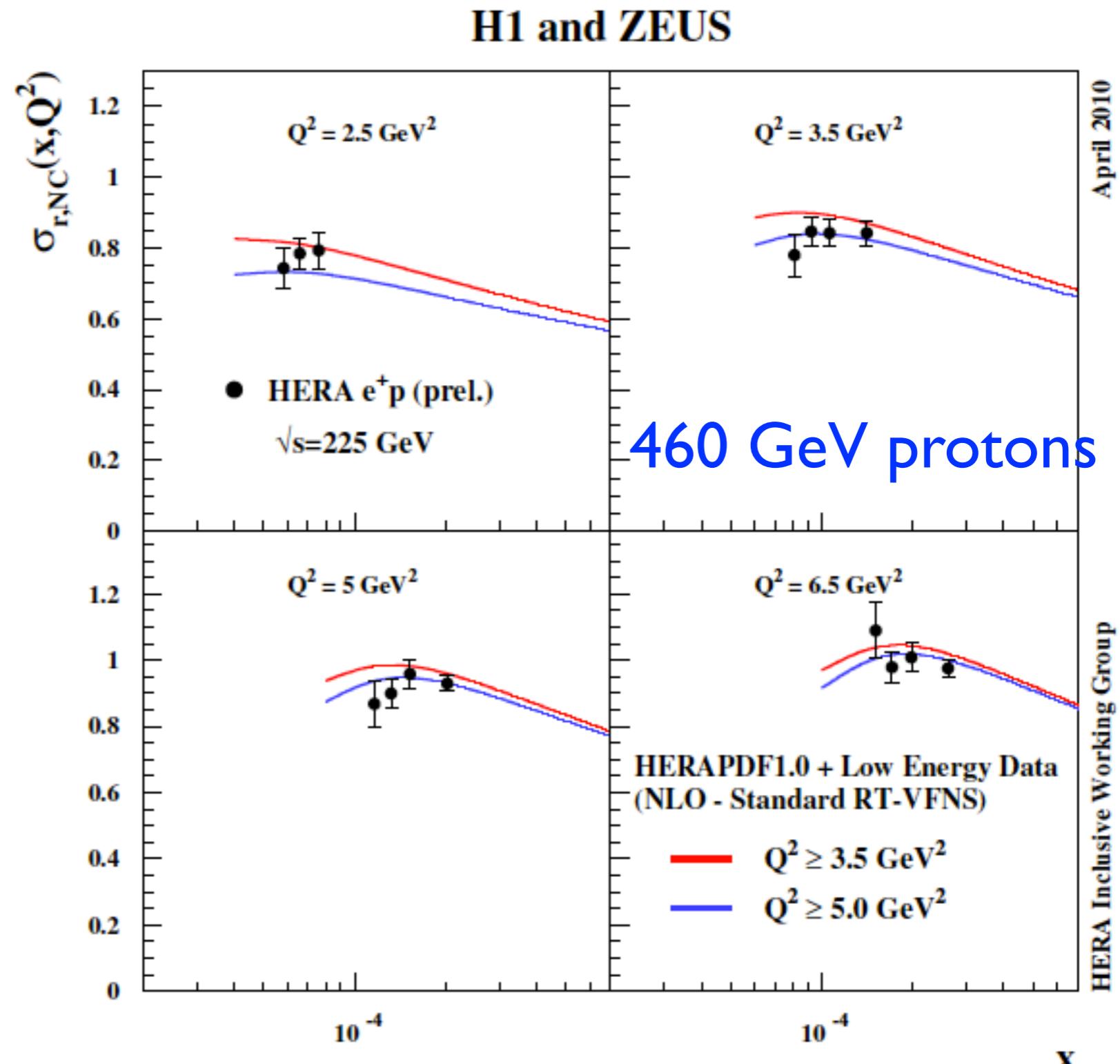
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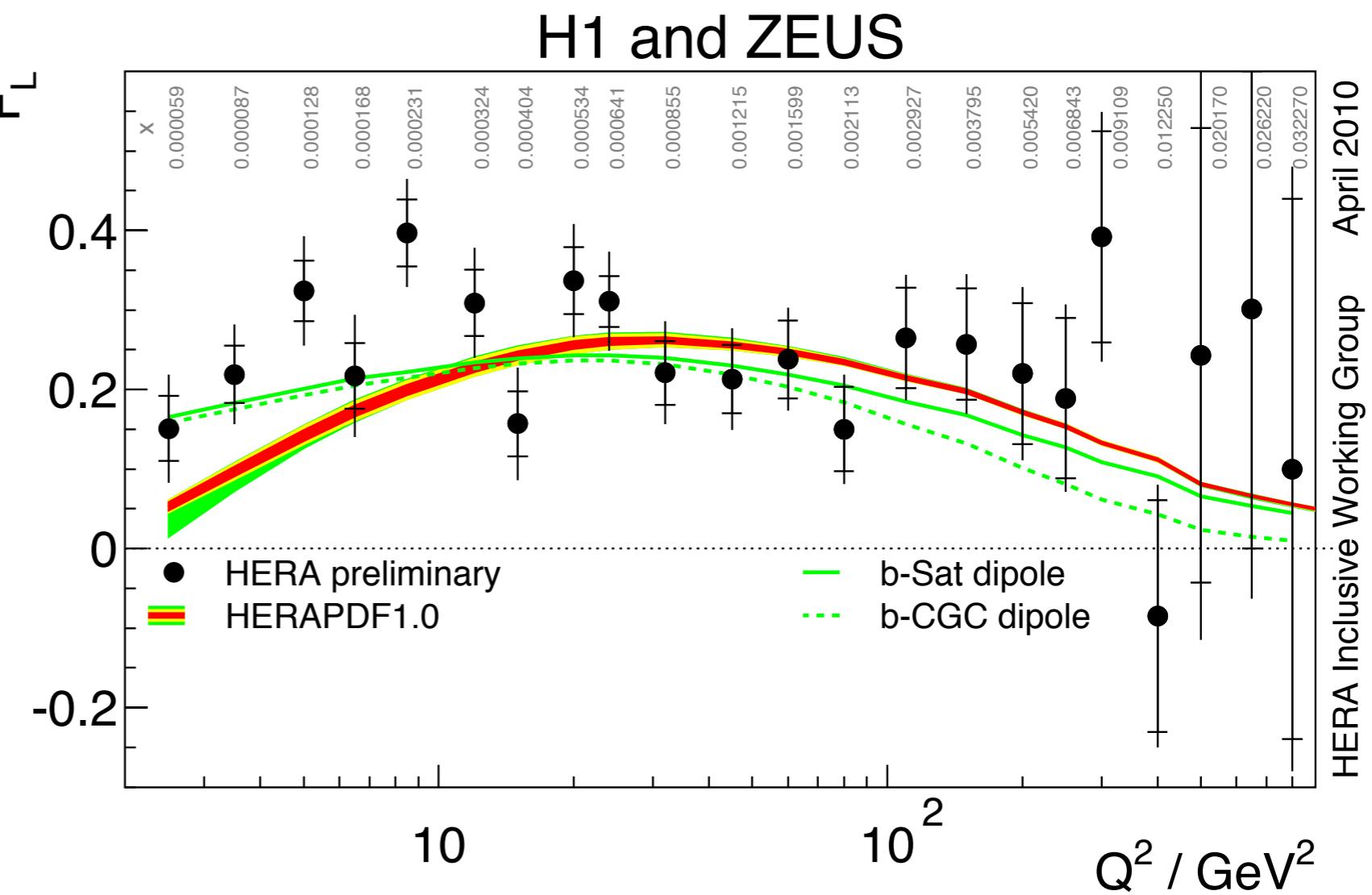
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Feasibility study:

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y_+} F_L^A(x, Q^2)$$

Strategies:

slope of y^2/Y_+ for different s at fixed x & Q^2

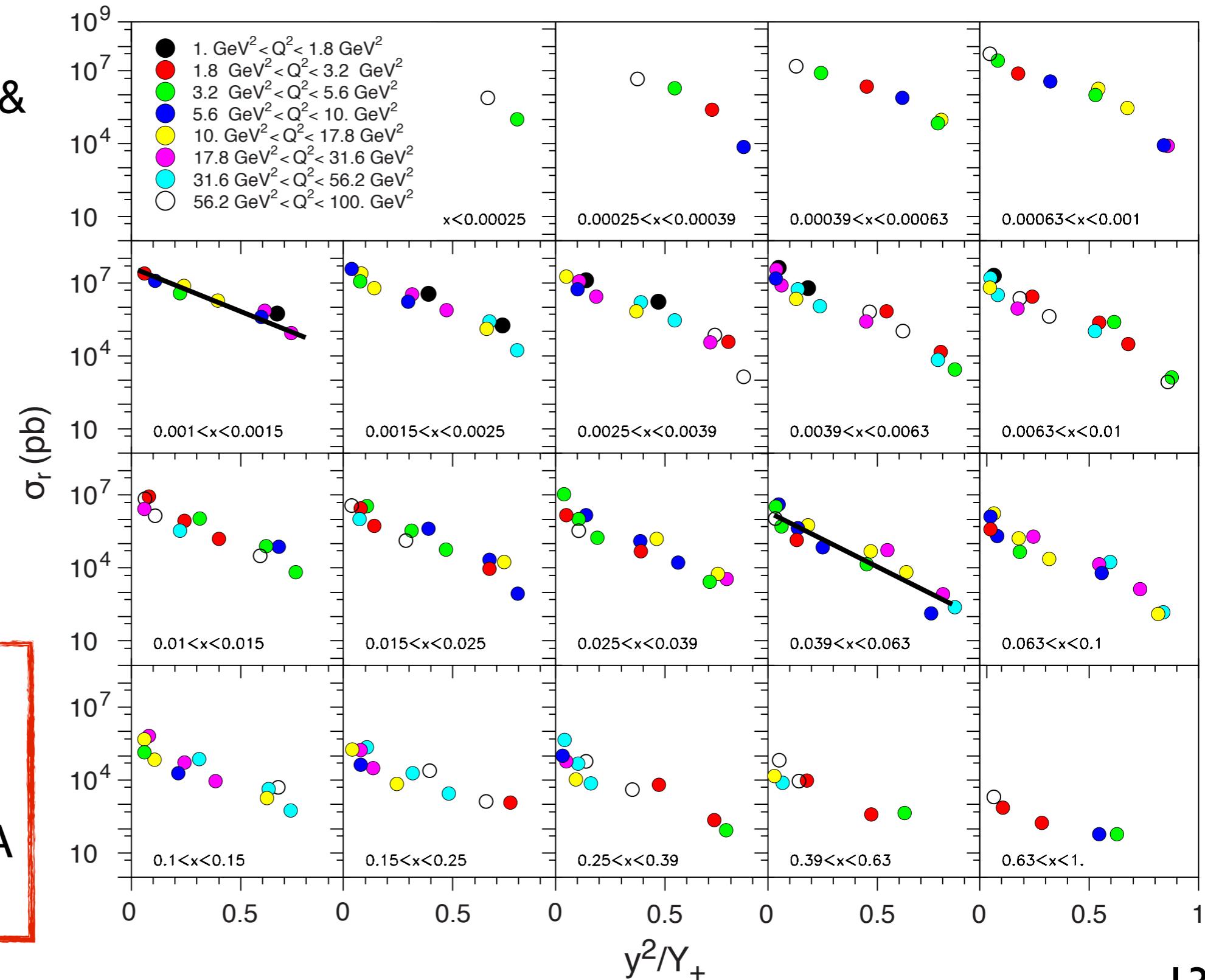
e+p: 1st stage

5x50 - 5x325
running combined
4 weeks/each
(50% eff)

stat. error shown
and negligible

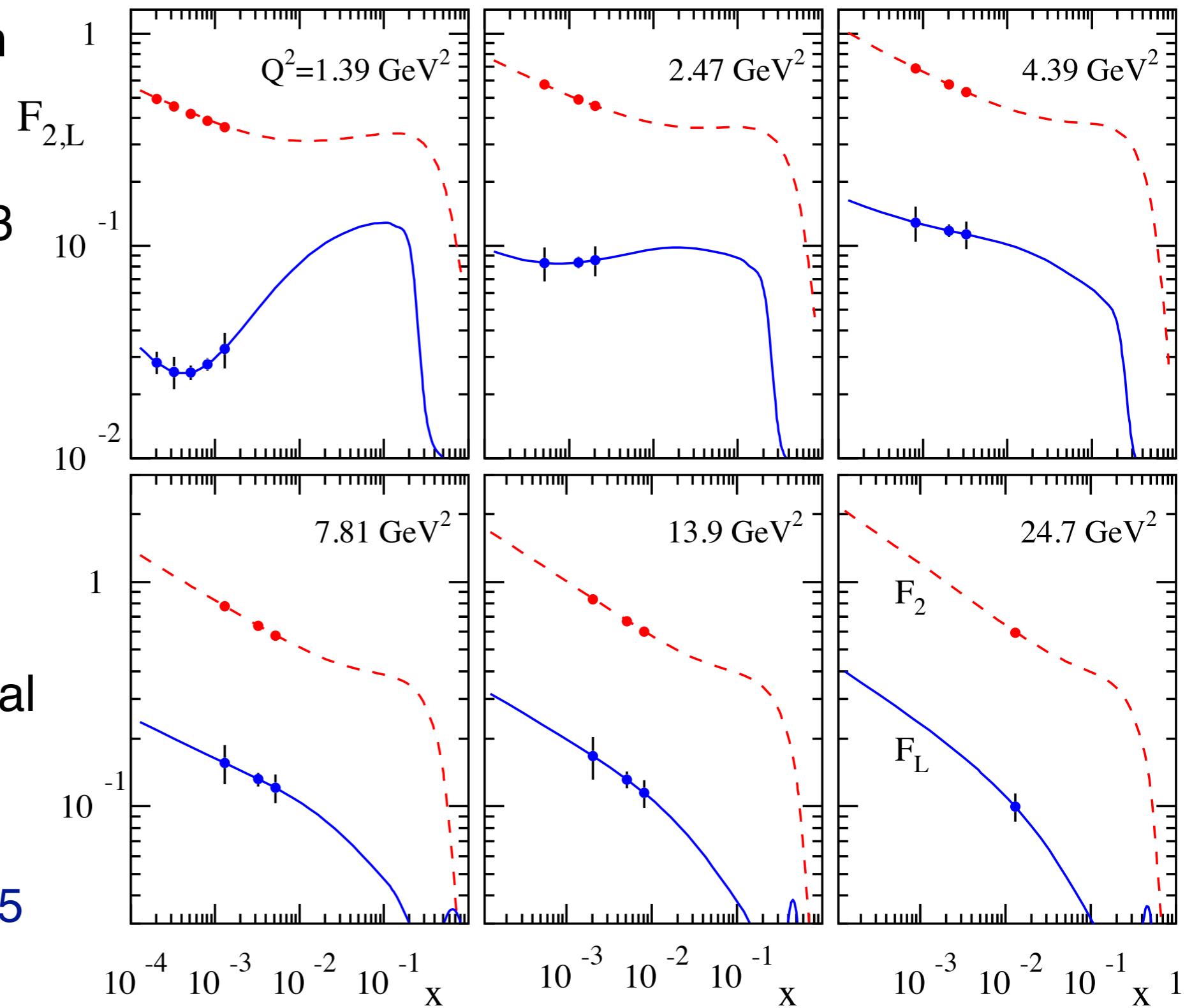
To Do:

refine method &
test how well we
can extract F_L in e+A
collisions



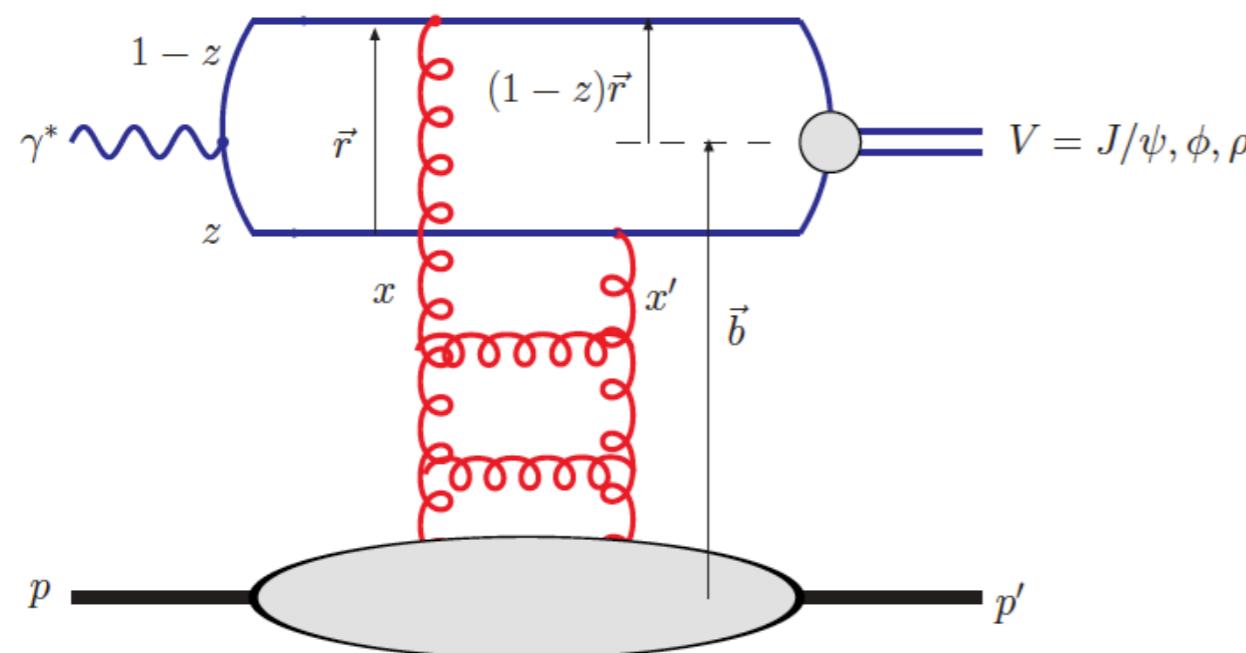
Extracting F_2 and F_L at the EIC

- $F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 eRHIC energies
 - 5+100 GeV
 - 5+250 GeV
 - 5+325 GeV
- Data, with errors, added to theoretical expectations from ABKM09 PDF set
 - valid for $Q^2 > 2.5$ GeV^2



Getting a “Feel” for Non-Linear QCD

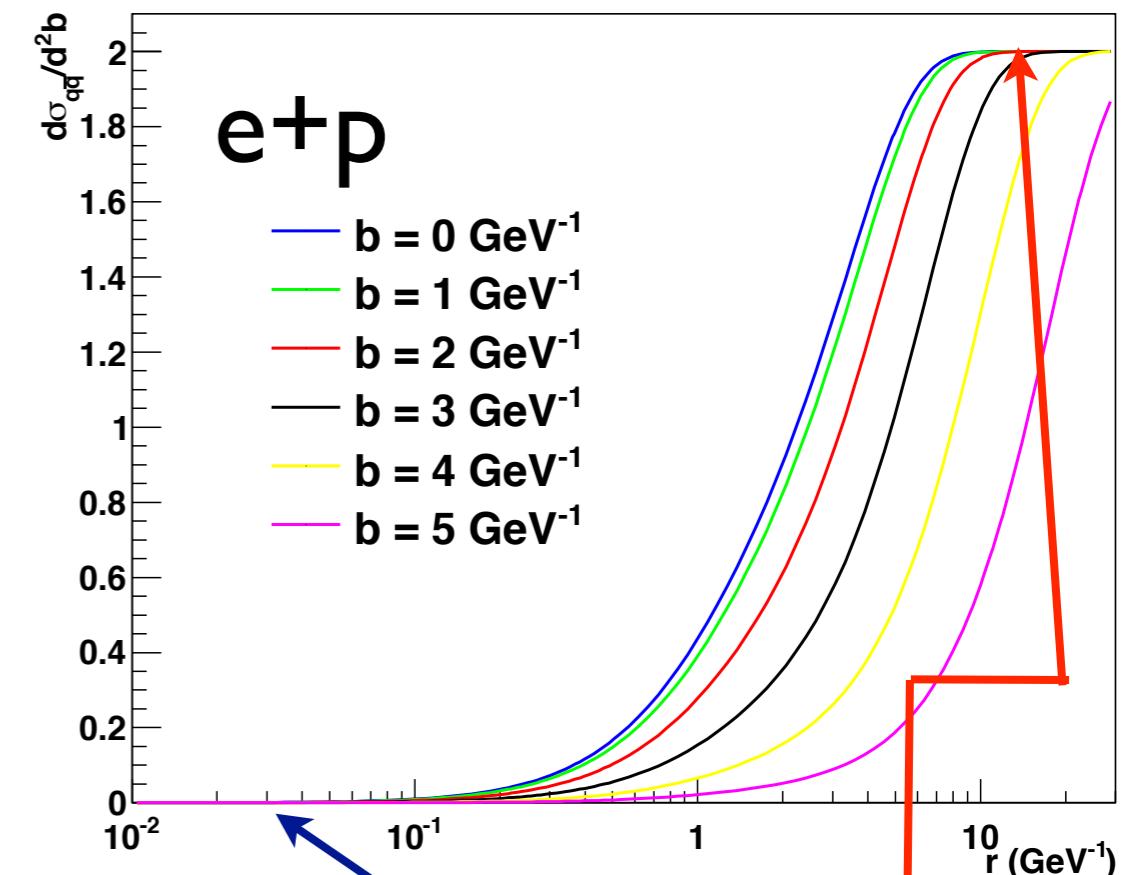
Dipole Model: $\frac{d\sigma_{q\bar{q}}}{d^2b} = 2\mathcal{N}(x, r, b)$



$$\mathcal{N}(x, r, b) = 1 - \exp \left(-r^2 \frac{\pi^2}{2N_c} \alpha_s(\mu^2) x G(x, \mu^2) T(b) \right)$$

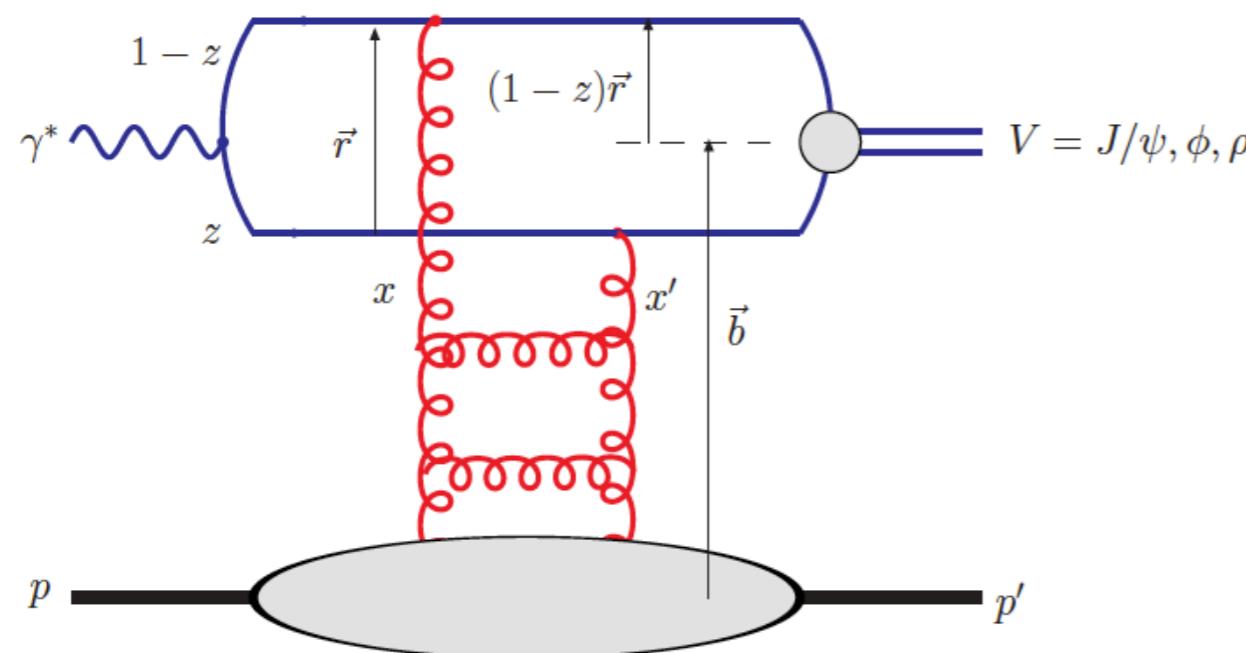
\mathcal{N} = Dipole Scattering Amplitude

0 dilute system, linear QCD
| saturated, non-linear regime



Getting a “Feel” for Non-Linear QCD

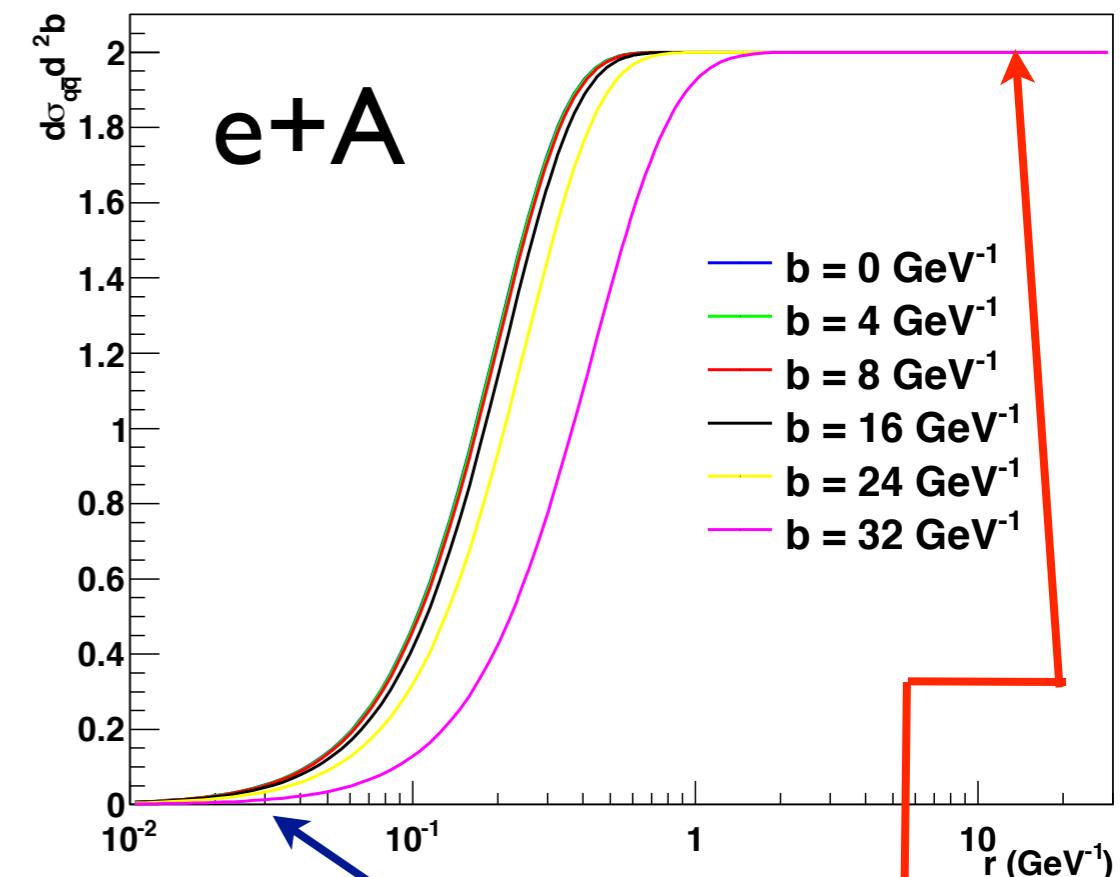
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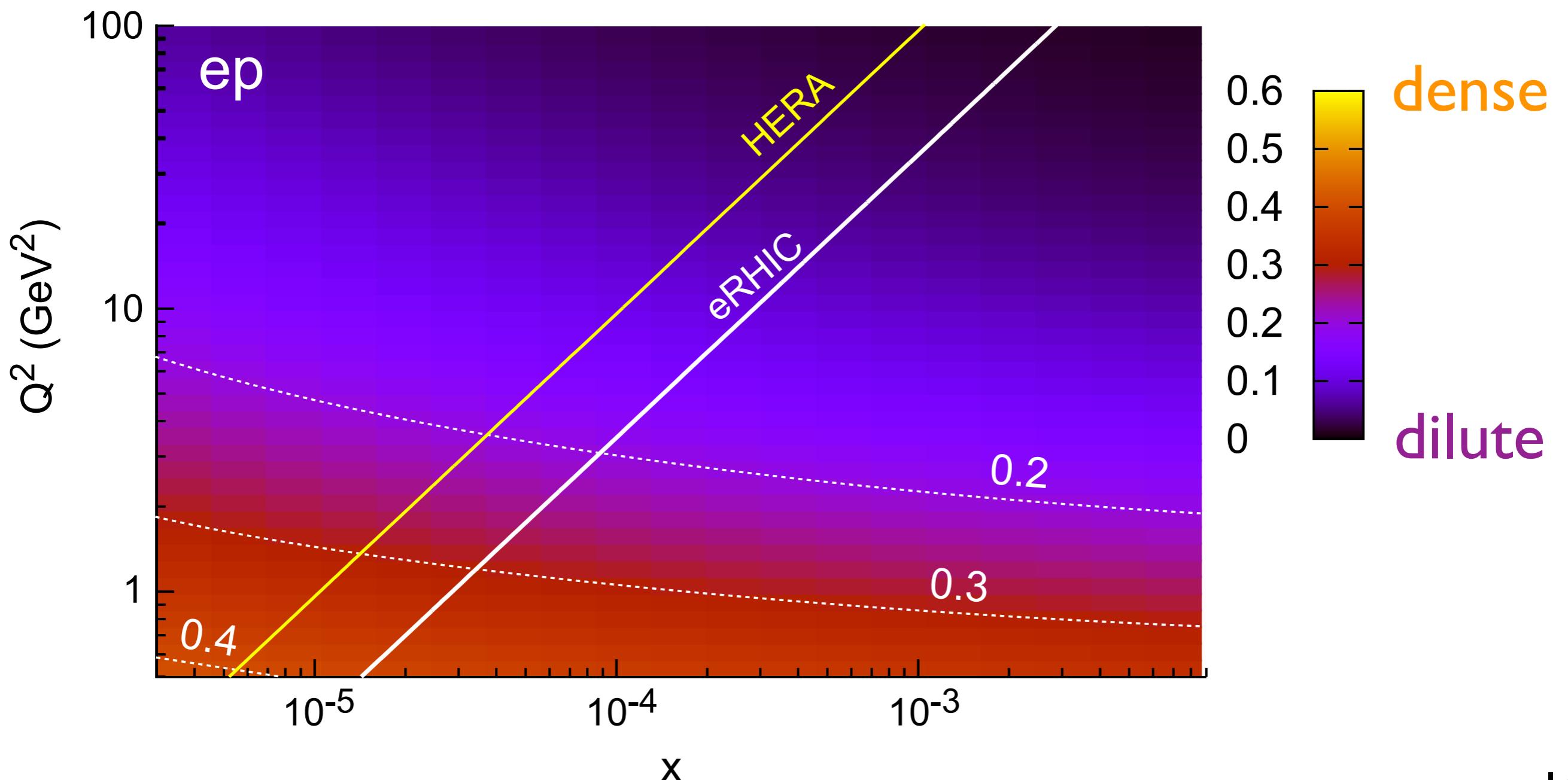


Getting a “Feel” for Non-Linear QCD

To assess typical values of \mathcal{N} calculate average:

$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b d^2r dz [\psi^* \psi]_{2,L} \mathcal{N}^2}{\int d^2b d^2r dz [\psi^* \psi]_{2,L} \mathcal{N}}$$

$$\langle \mathcal{N} \rangle_2 \rightarrow F_2$$
$$\langle \mathcal{N} \rangle_L \rightarrow F_L$$

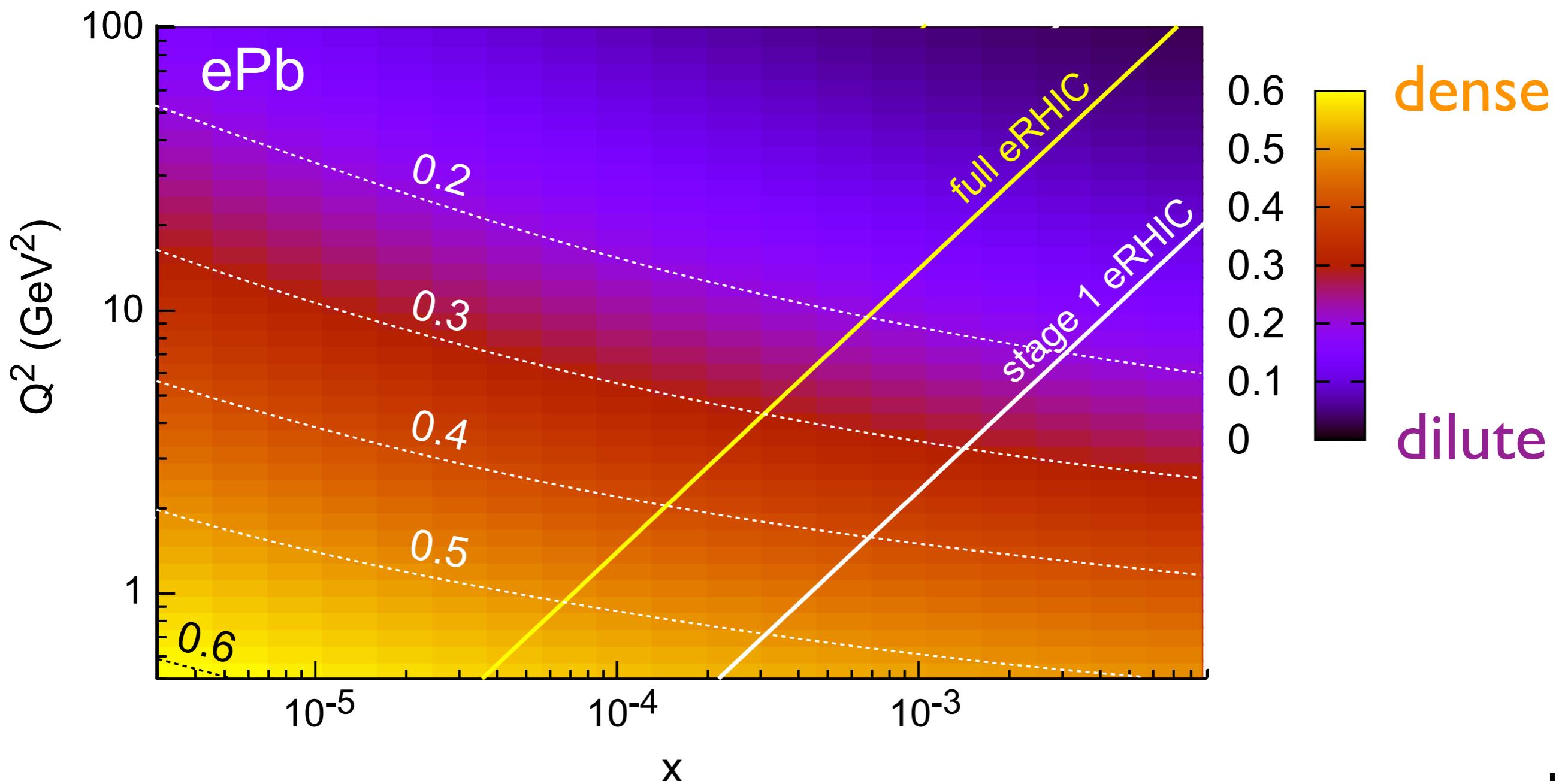


Getting a “Feel” for Non-Linear QCD

To assess typical values of \mathcal{N} calculate average:

$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b d^2r dz [\psi^* \psi]_{2,L} \mathcal{N}^2}{\int d^2b d^2r dz [\psi^* \psi]_{2,L} \mathcal{N}}$$

$$\langle \mathcal{N} \rangle_2 \rightarrow F_2$$
$$\langle \mathcal{N} \rangle_L \rightarrow F_L$$



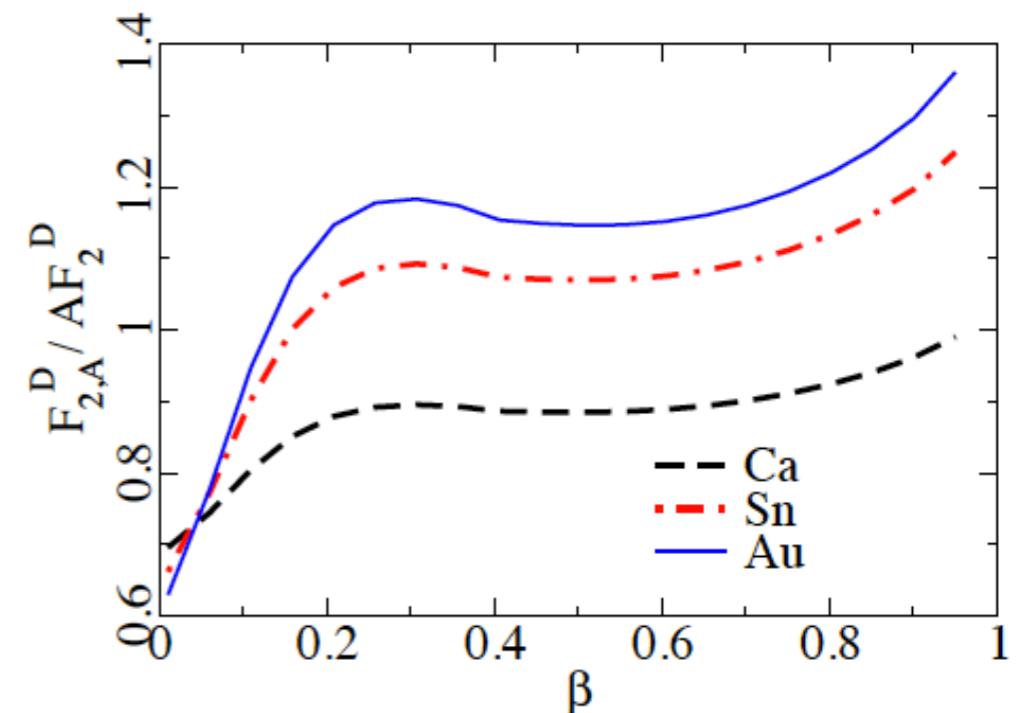
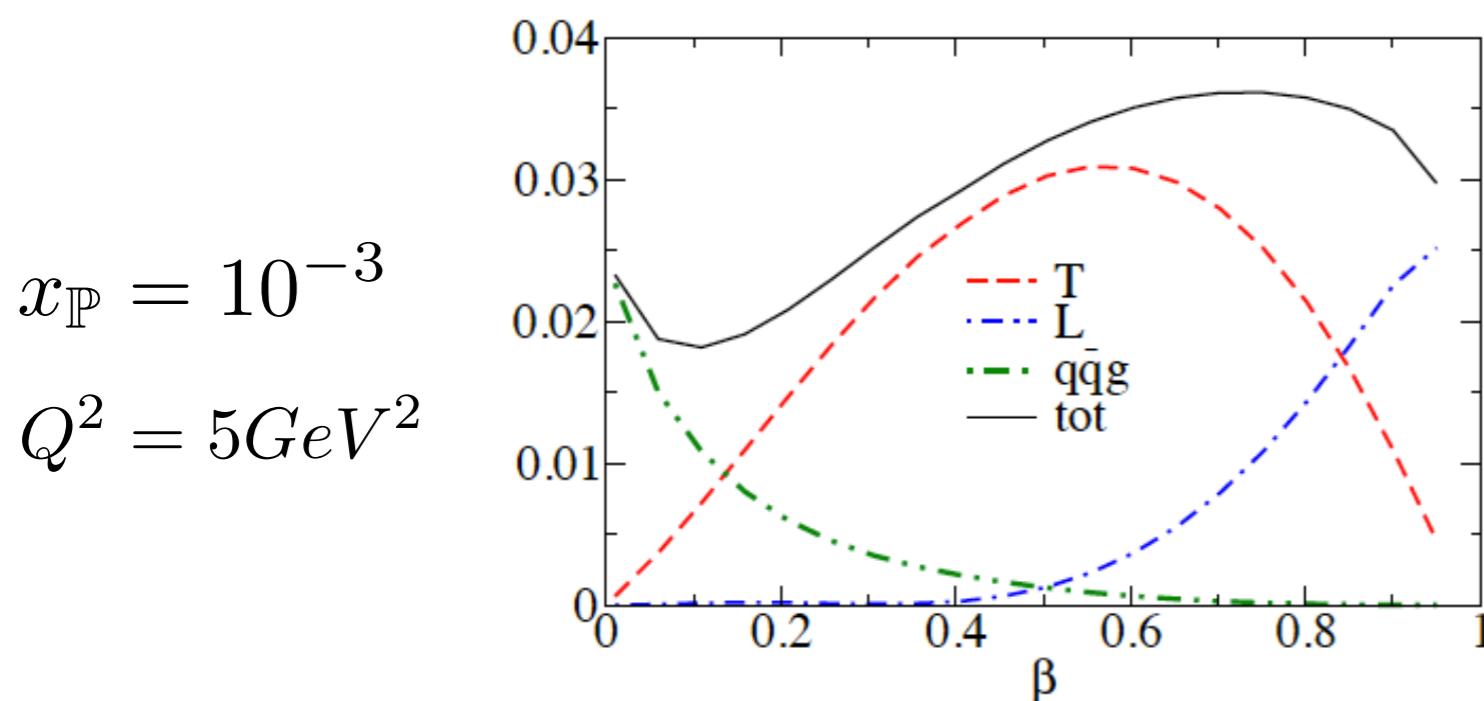
Charm and diffractive structure functions, $F_{2,L}^D$, $F_{2,L}^c$

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 - Less sensitive to non-linear effects
- $F_{2,L}^D$ is also sensitive to the gluon distribution
 - Differences between linear and non-linear models appear at higher Q^2 than for F_2 (8 GeV^2 vs 2 GeV^2)
 - More experimentally challenging measurement than F_2

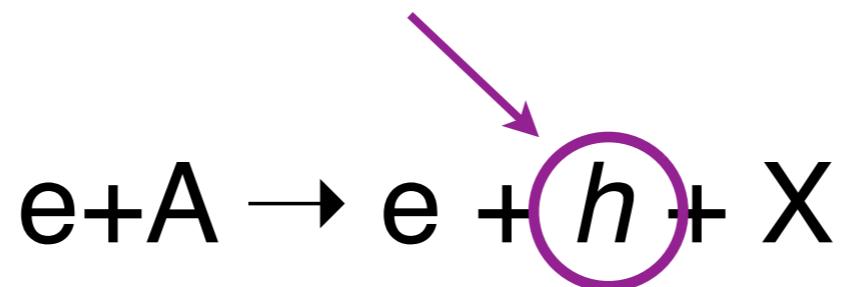


k_T dependent gluons, gluon correlations from
di-hadron correlations, SIDIS (semi-inclusive DIS)

k_T dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)

Deliverables	Observables	What we learn	Stage-I	Stage-II

Direct link between p_T of produced hadron and that of the small- x gluon



k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large- x gluons
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k_T dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)



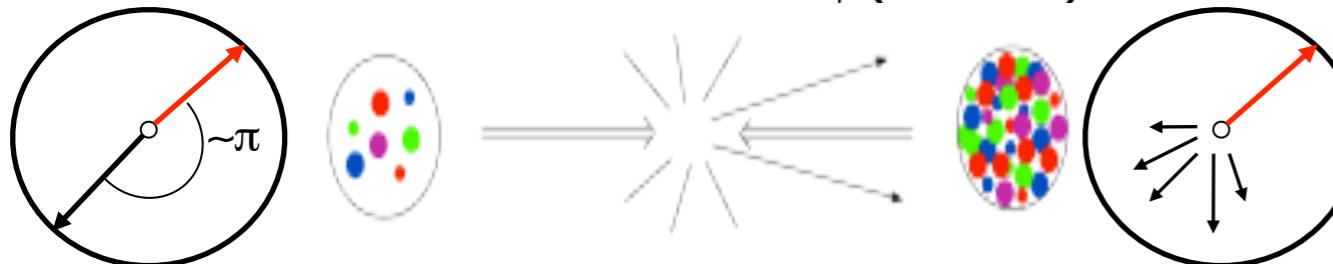
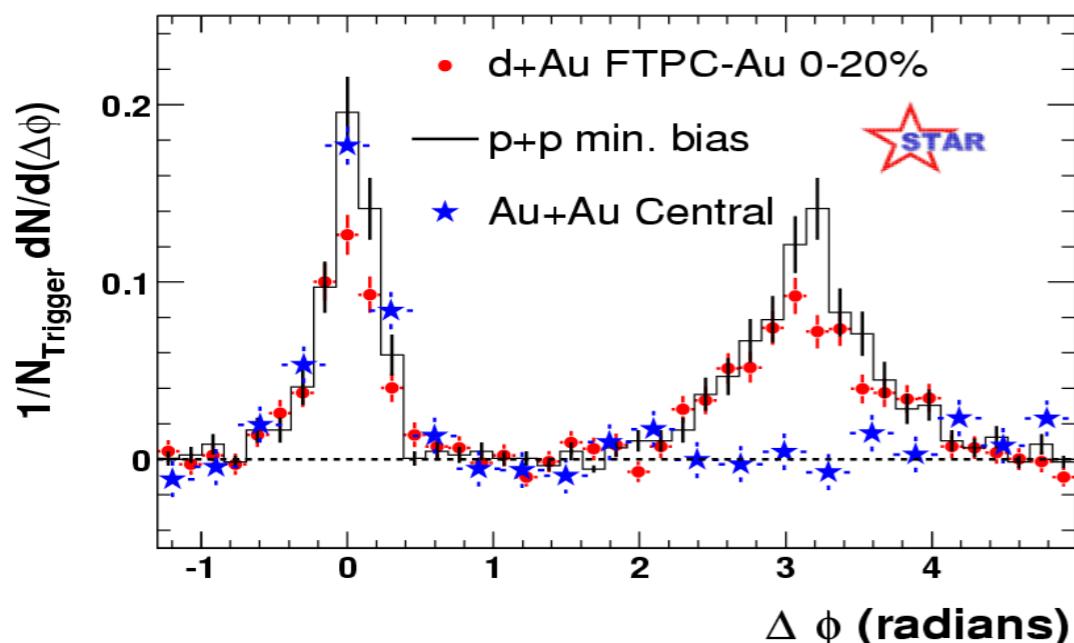
Deliverables	Observables	What we learn	Stage-I	Stage-II
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s



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di-hadron angular correlations in d+A

comparisons between $d+Au \rightarrow h_1 h_2 X$ (or $p+Au \rightarrow h_1 h_2 X$) and $p+p \rightarrow h_1 h_2 X$



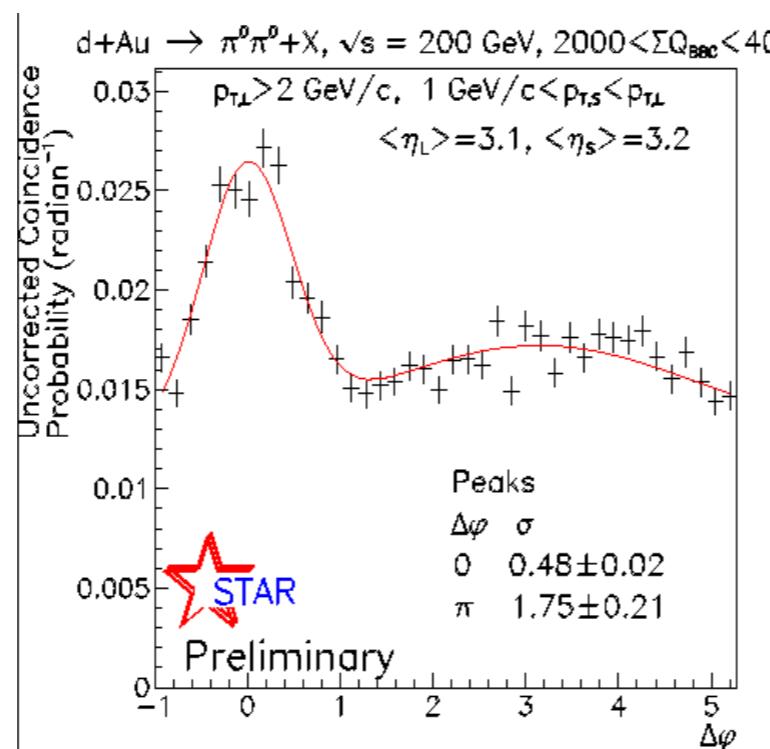
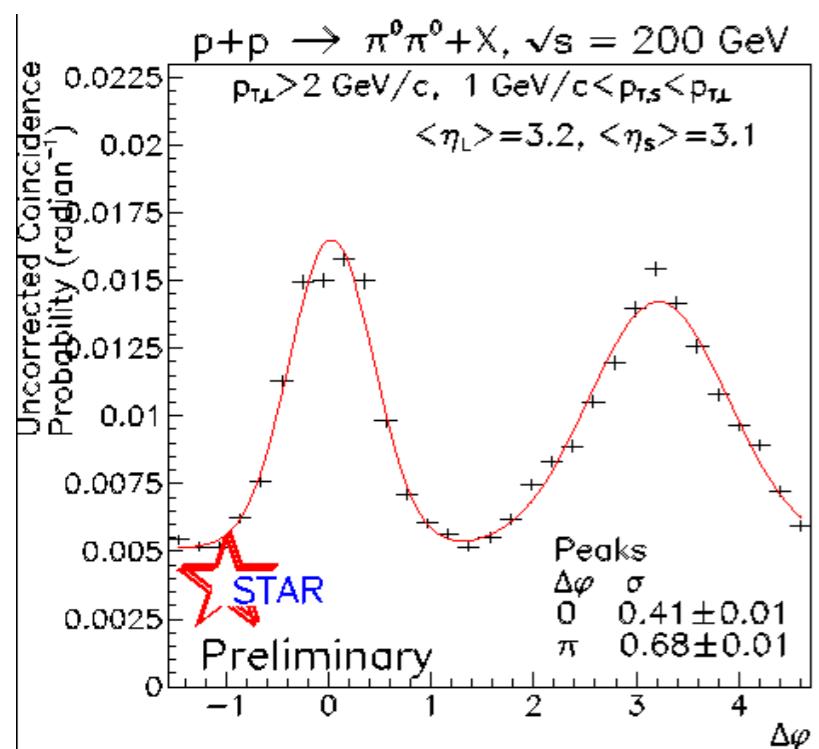
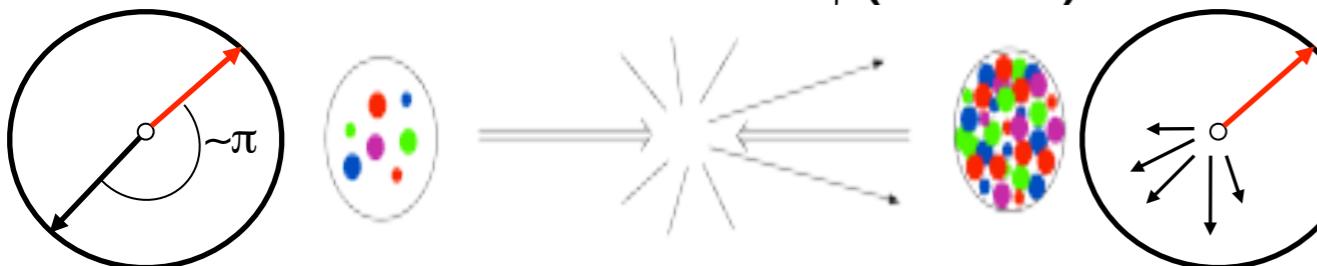
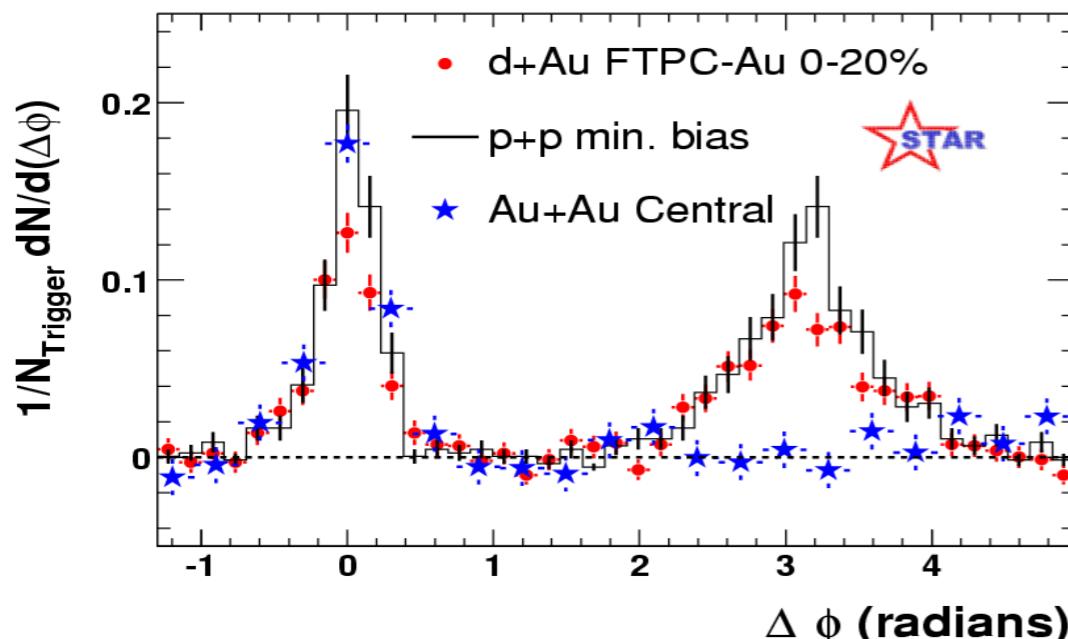
- At $y=0$, suppression of away-side jet is observed in $A+A$ collisions
- No suppression in $p+p$ or $d+A$

$$\rightarrow x \sim 10^{-2}$$

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} \ll 1$$

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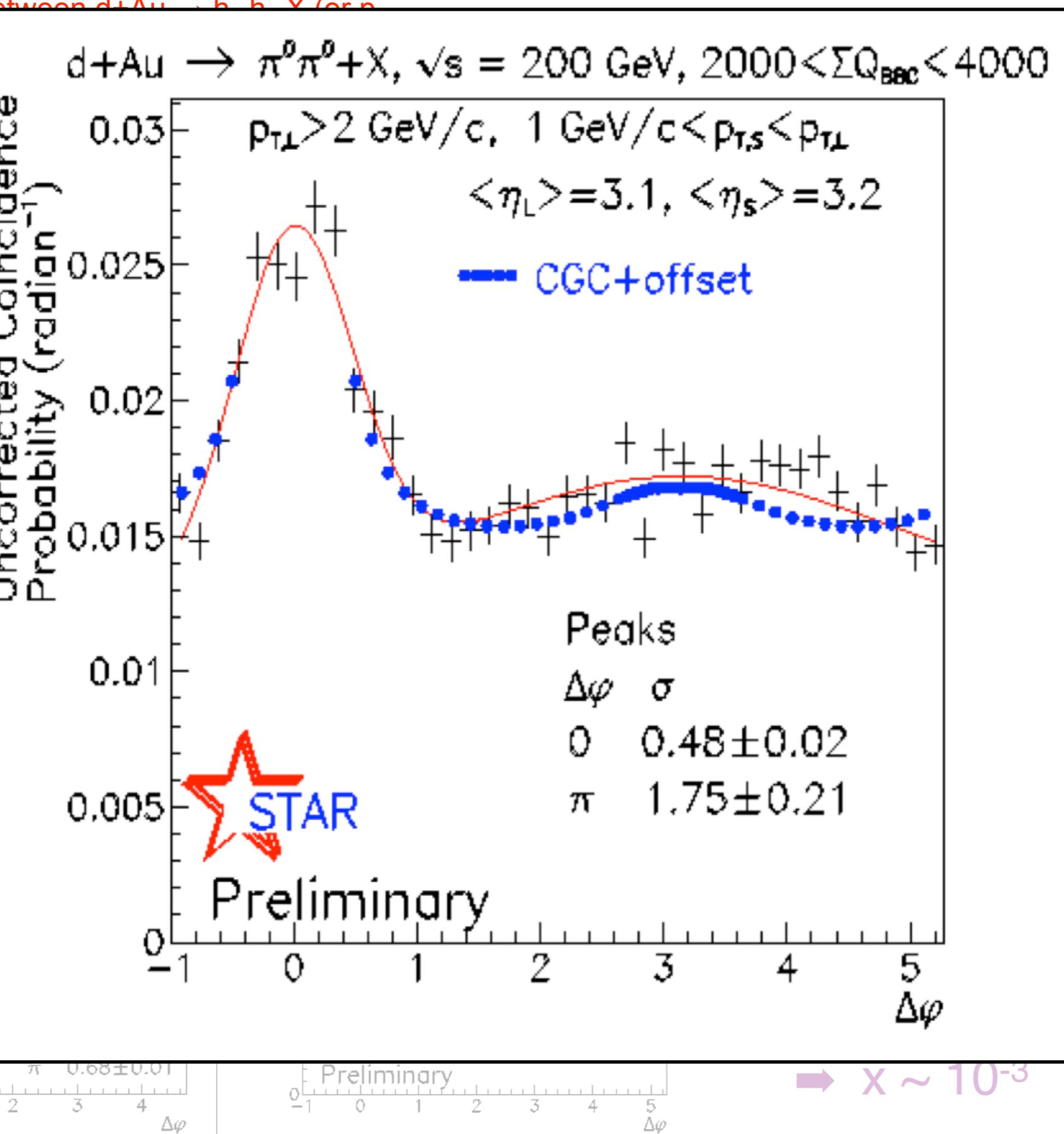
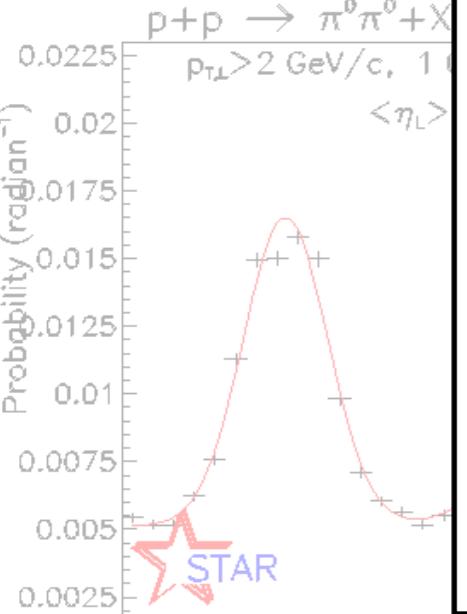
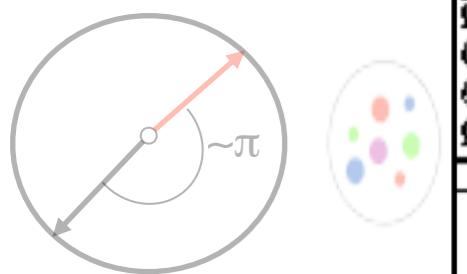
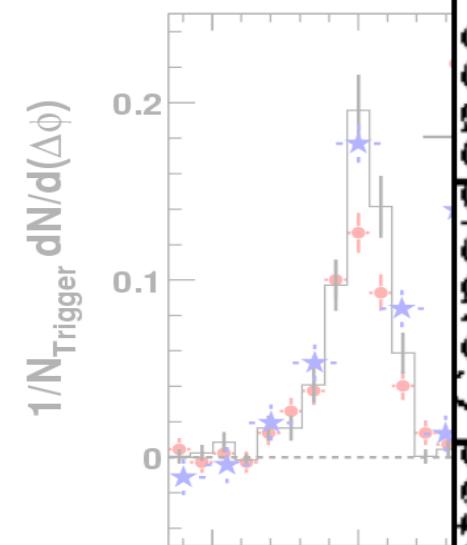
- However, at forward rapidities ($y \sim 3.1$), an away-side suppression is observed in $d+Au$
- Away-side peak also much wider in $d+Au$ compared to $p+p$

$$\rightarrow x \sim 10^{-3}$$

di-hadron angular correlations in d+A

comparisons between d+Au → h₁ h₂ ×/or

+Au → h₁ h₂



of away-
in A+A

+p or d+A

$+ k_2 e^{-y_2}$
 $\sqrt{s} \ll 1$

forward
(3.1), an
oppression is
+Au

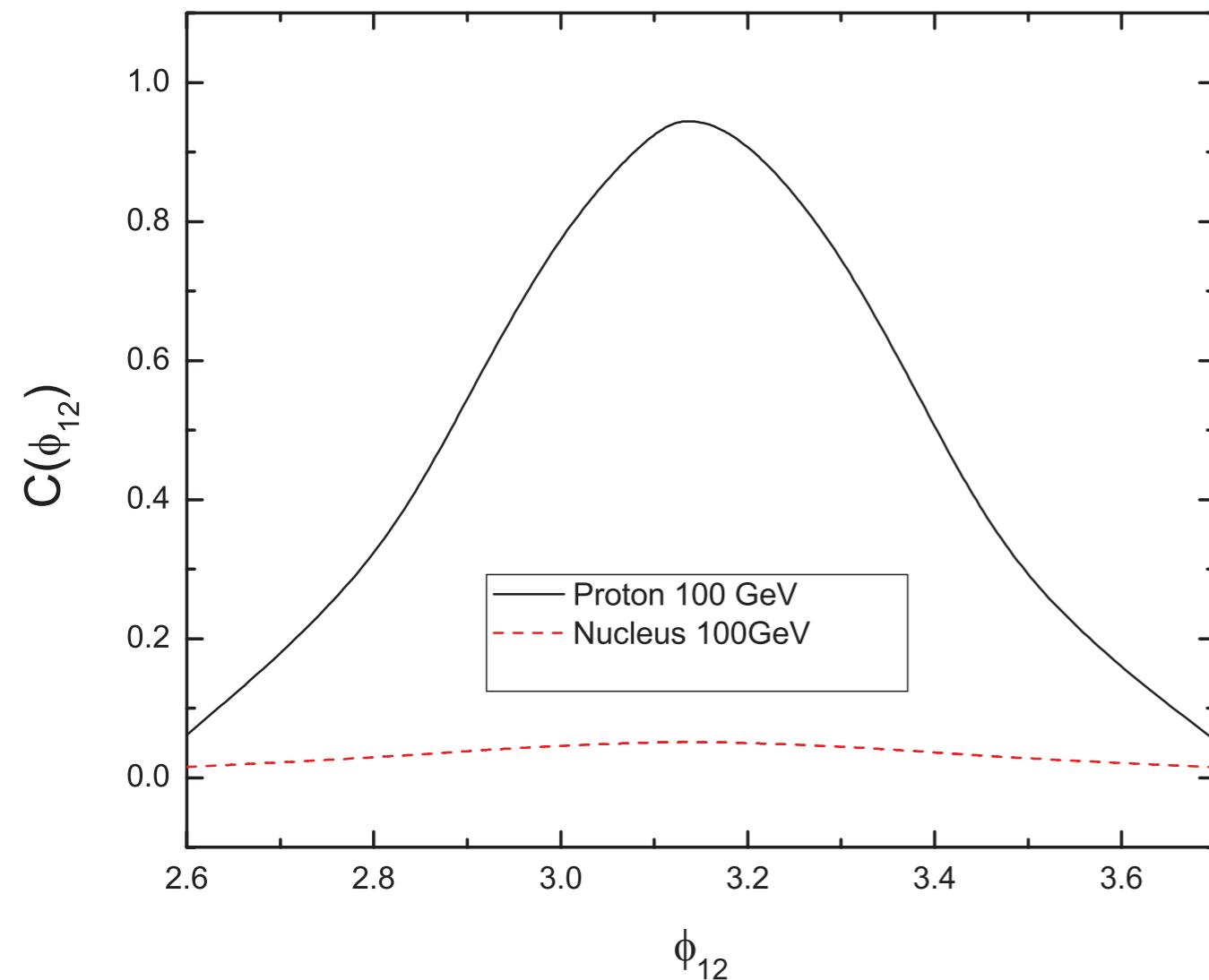
peak also

d+Au

+p

di-hadron correlations in e+A

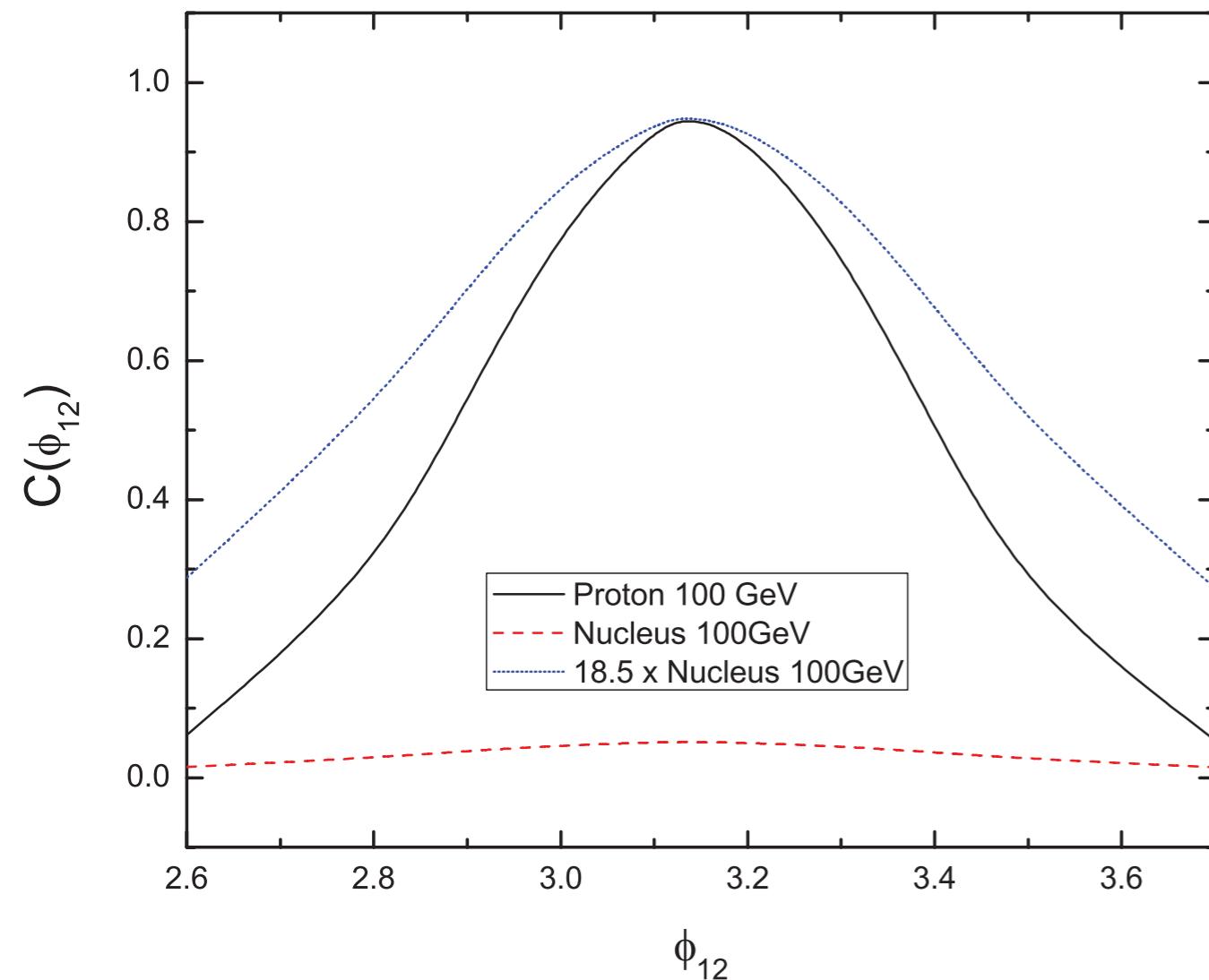
Never been measured - we expect to see the same effect in e+A as in d+A



- At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations
 - The non-linear evolution of multi-gluon distributions is different from that of single-gluon distributions and it is **equally important** that we understand it
- The d+Au RHIC data is therefore subject to many uncertainties
 - these correlations in e+A can help to constrain them better

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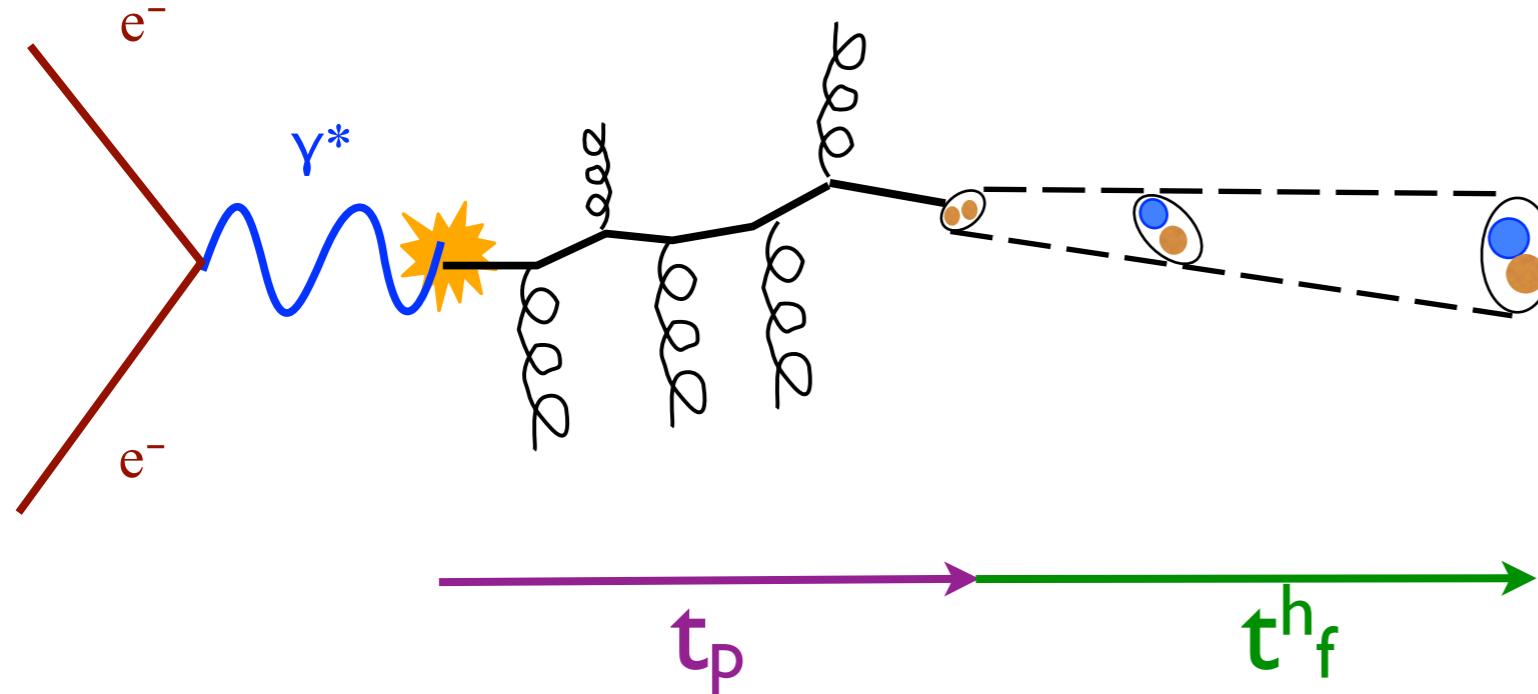
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transport coefficients in cold nuclear matter
from large-x semi-inclusive DIS and jets

Transport coefficients in cold nuclear matter

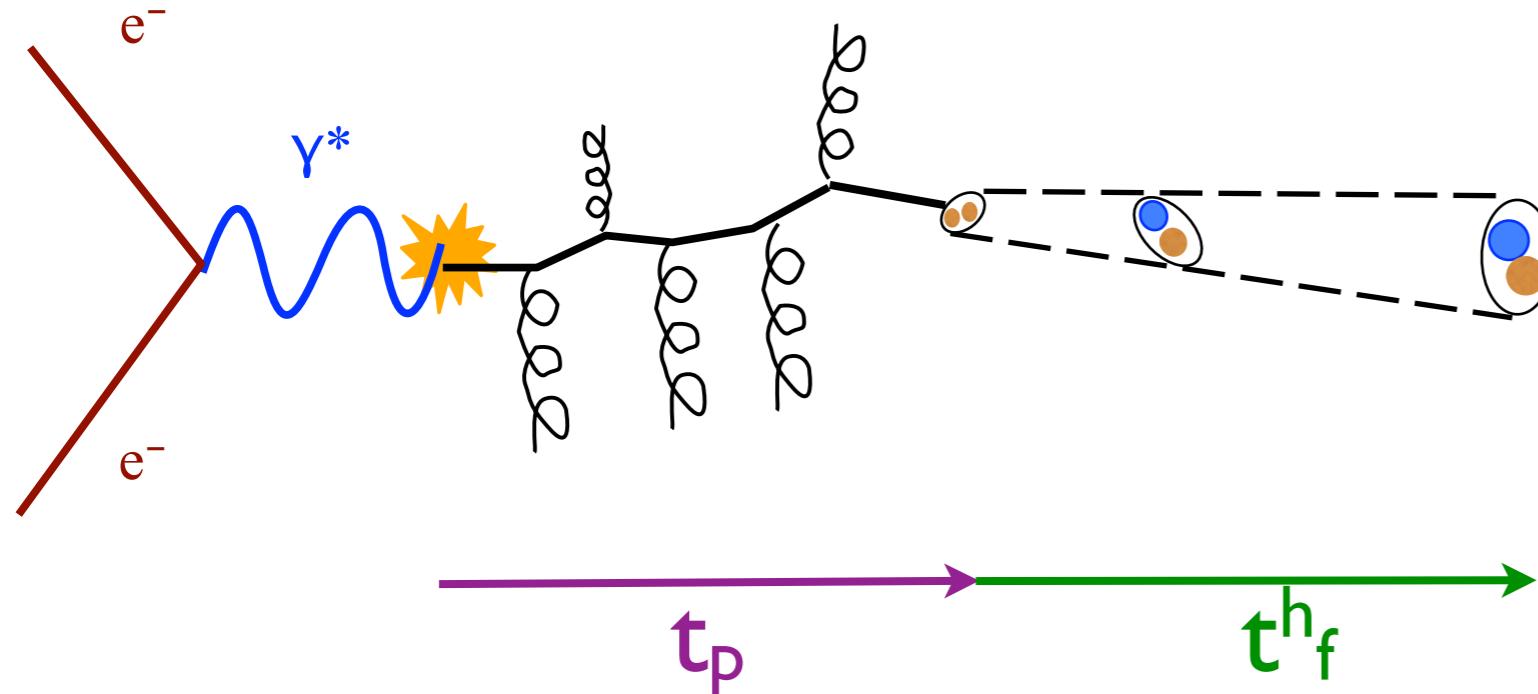
Deliverables	Observables	What we learn	Stage-I	Stage-II
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavours and charm; jets	rare probes and bottom; large-x gluons

Jets and hadronization



- t_p - production time of propagating quark
- t_{h_f} - hadron formation time

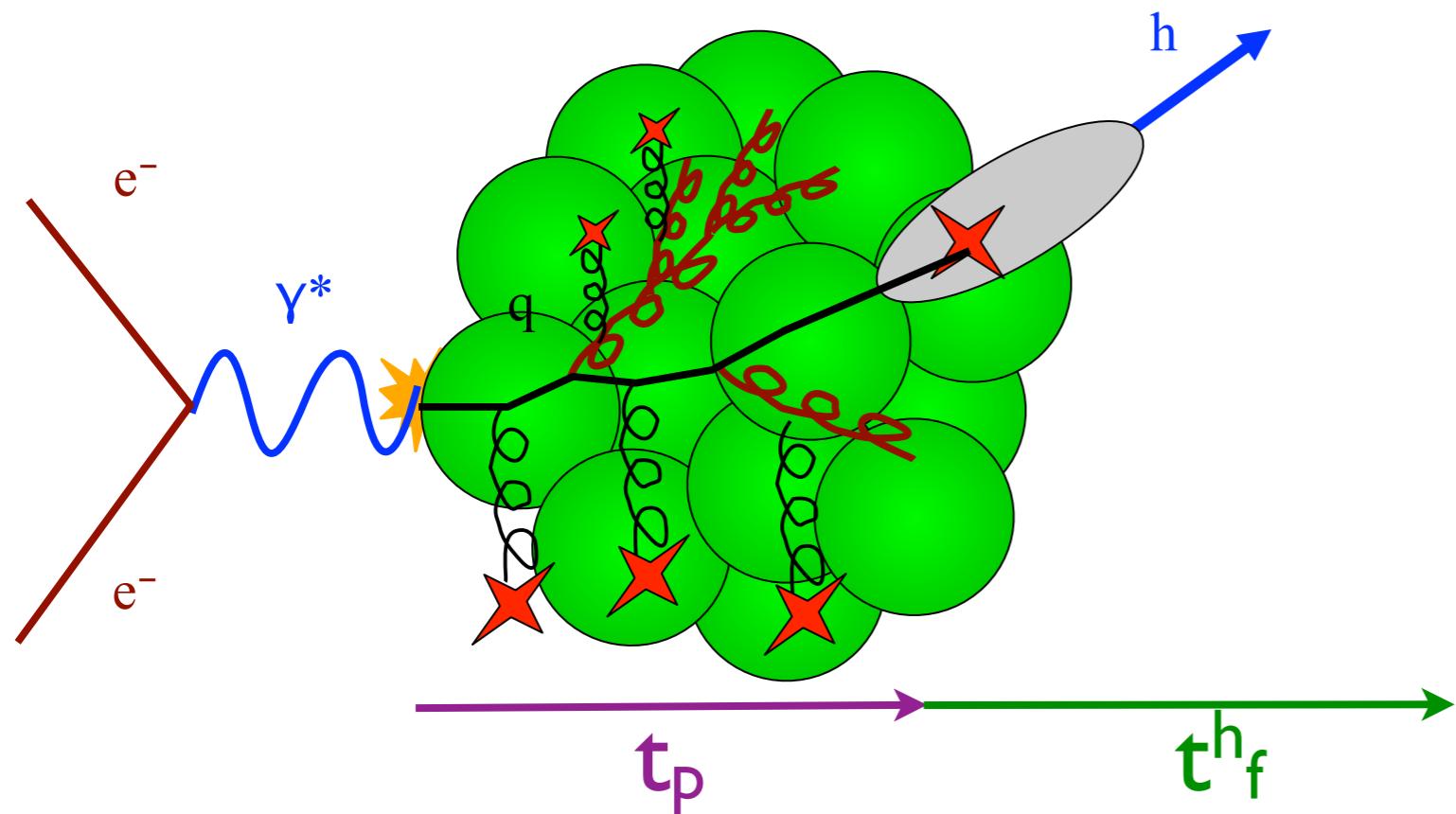
Jets and hadronization



What happens if
we add a nuclear
medium?

- t_p - production time of propagating quark
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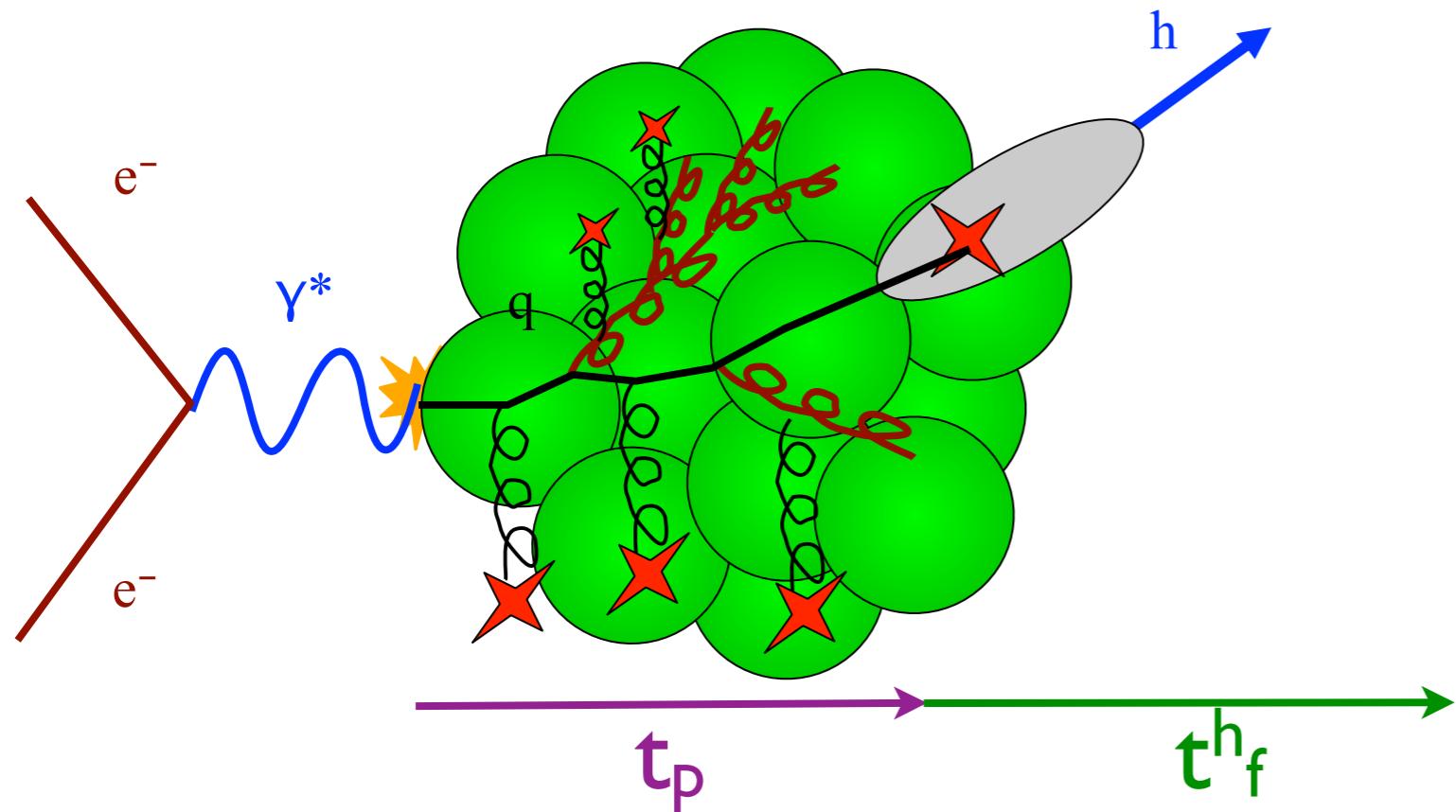
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Jets and hadronization



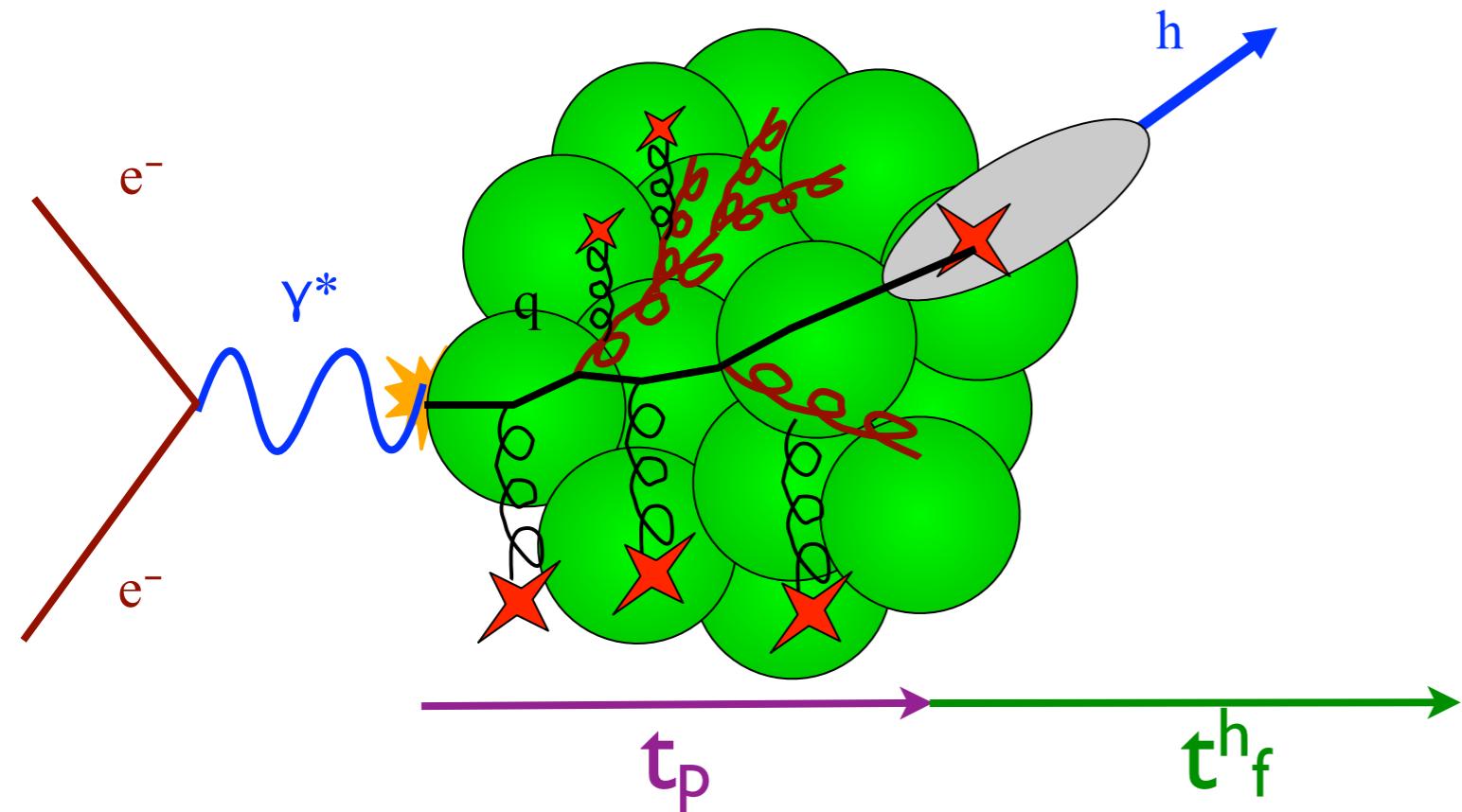
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Jets and hadronization



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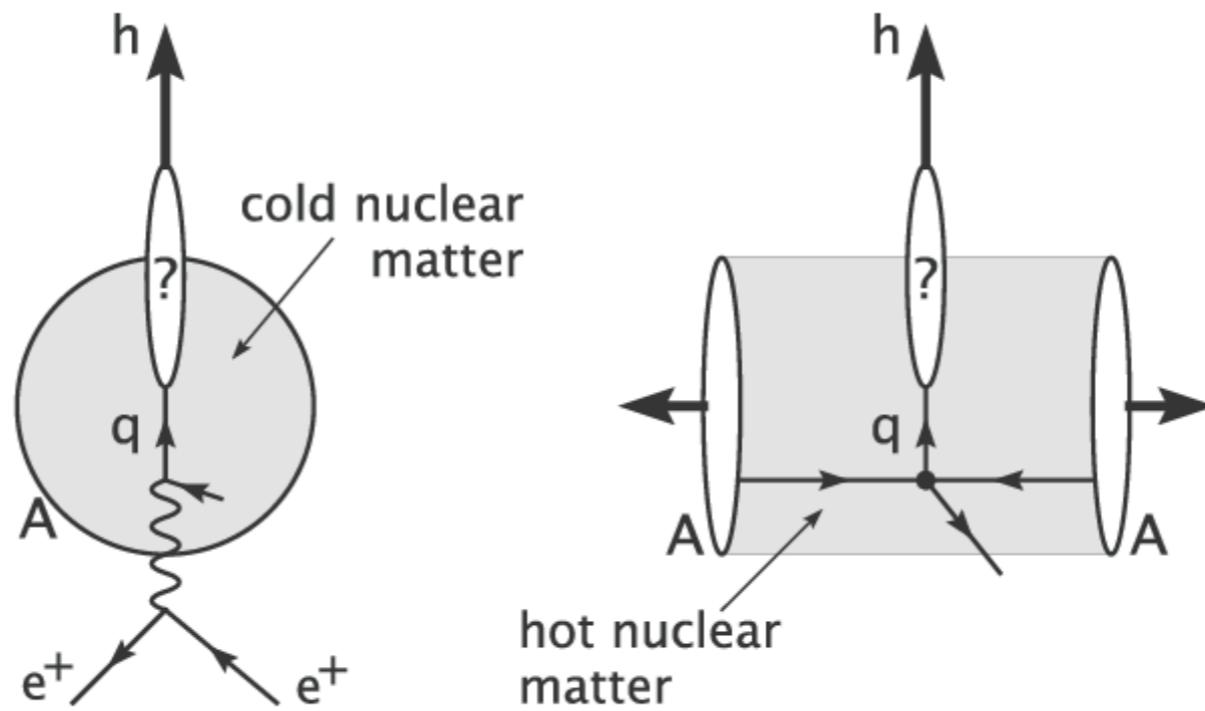
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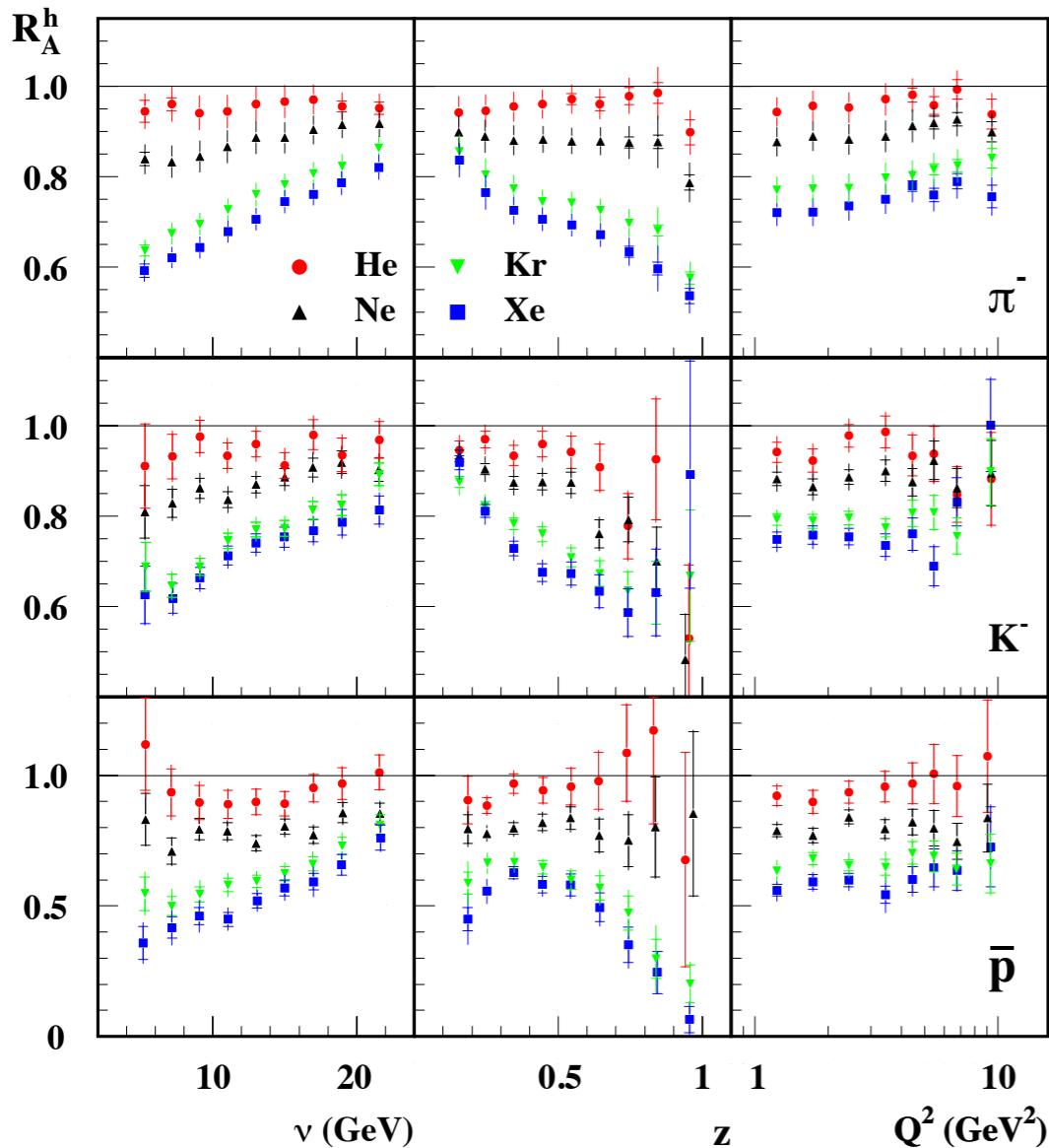
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How can the EIC contribute?

HERMES:

$$E_e = 27 \text{ GeV} \rightarrow \sqrt{s} = 7.2 \text{ GeV}$$

$$E_h = 2\text{-}15 \text{ GeV}$$



v = virtual photon energy

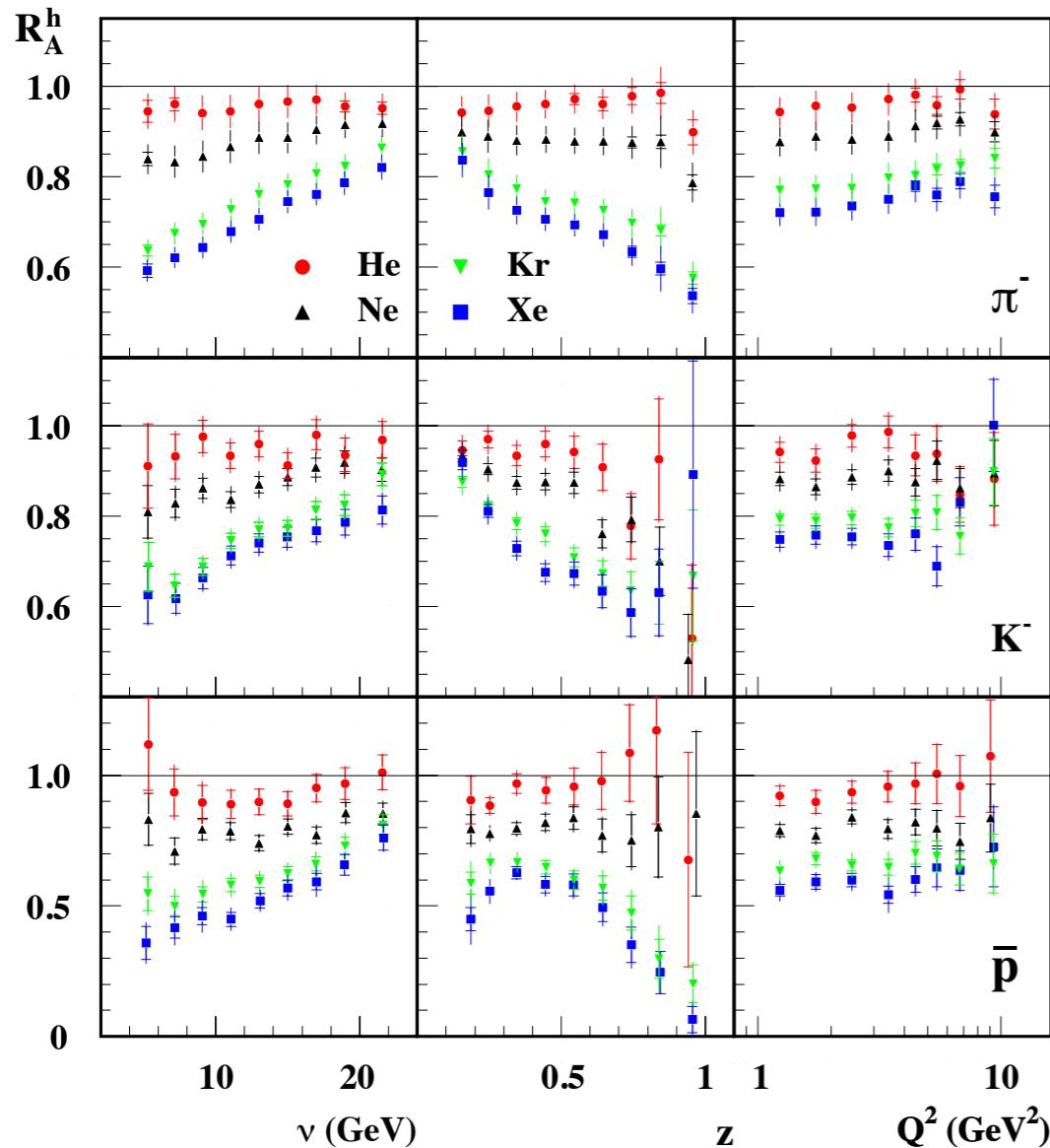
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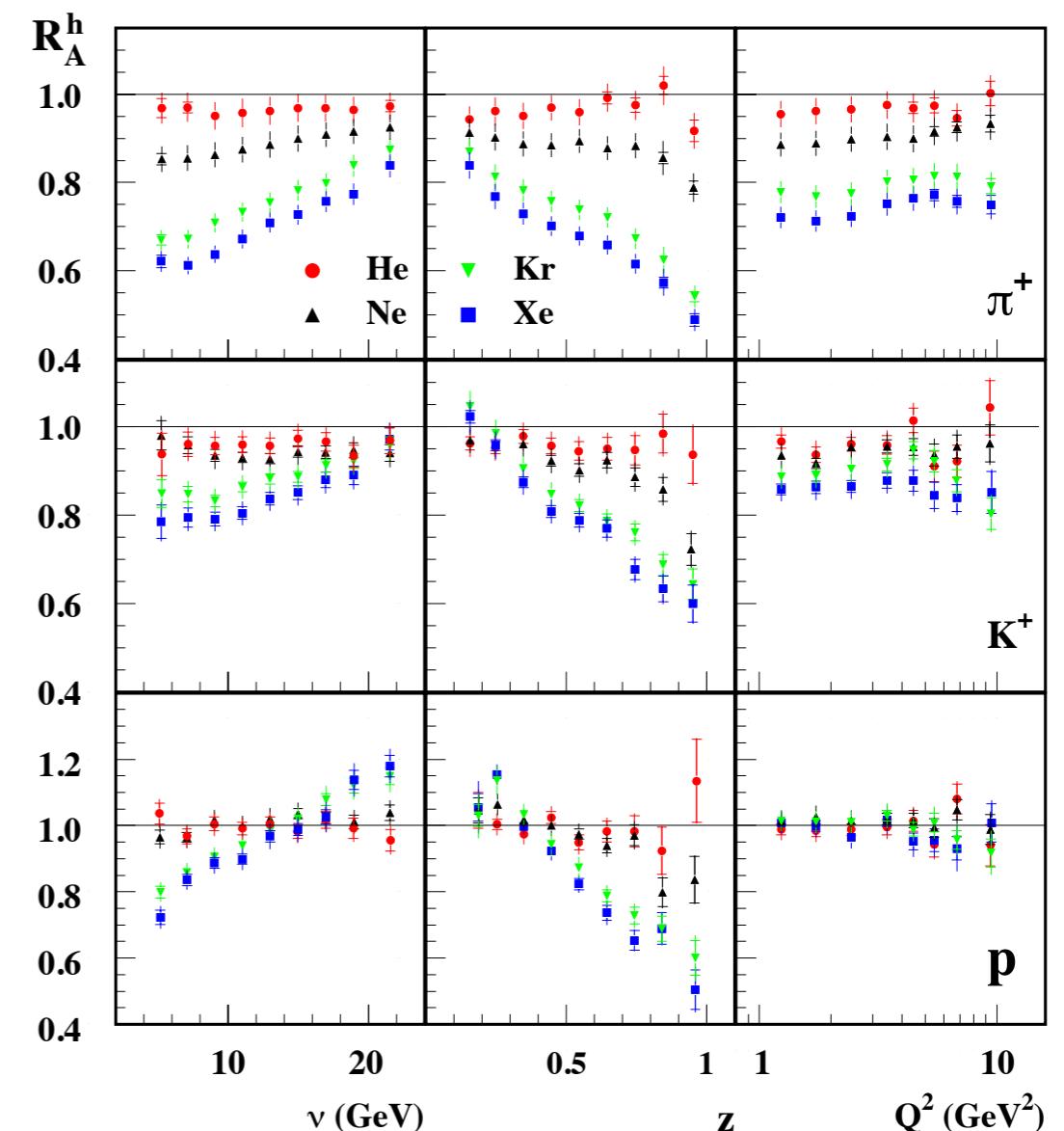
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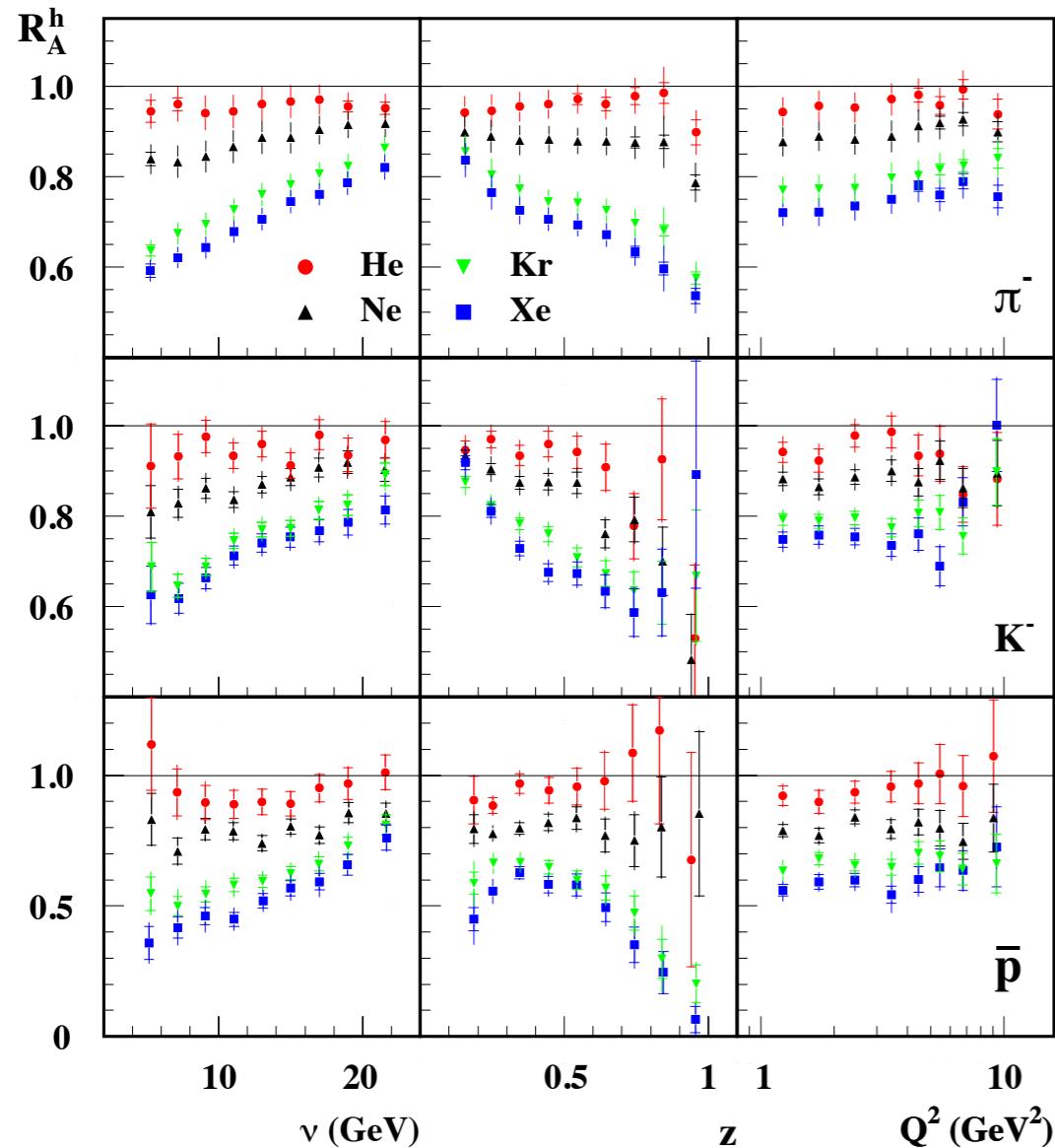


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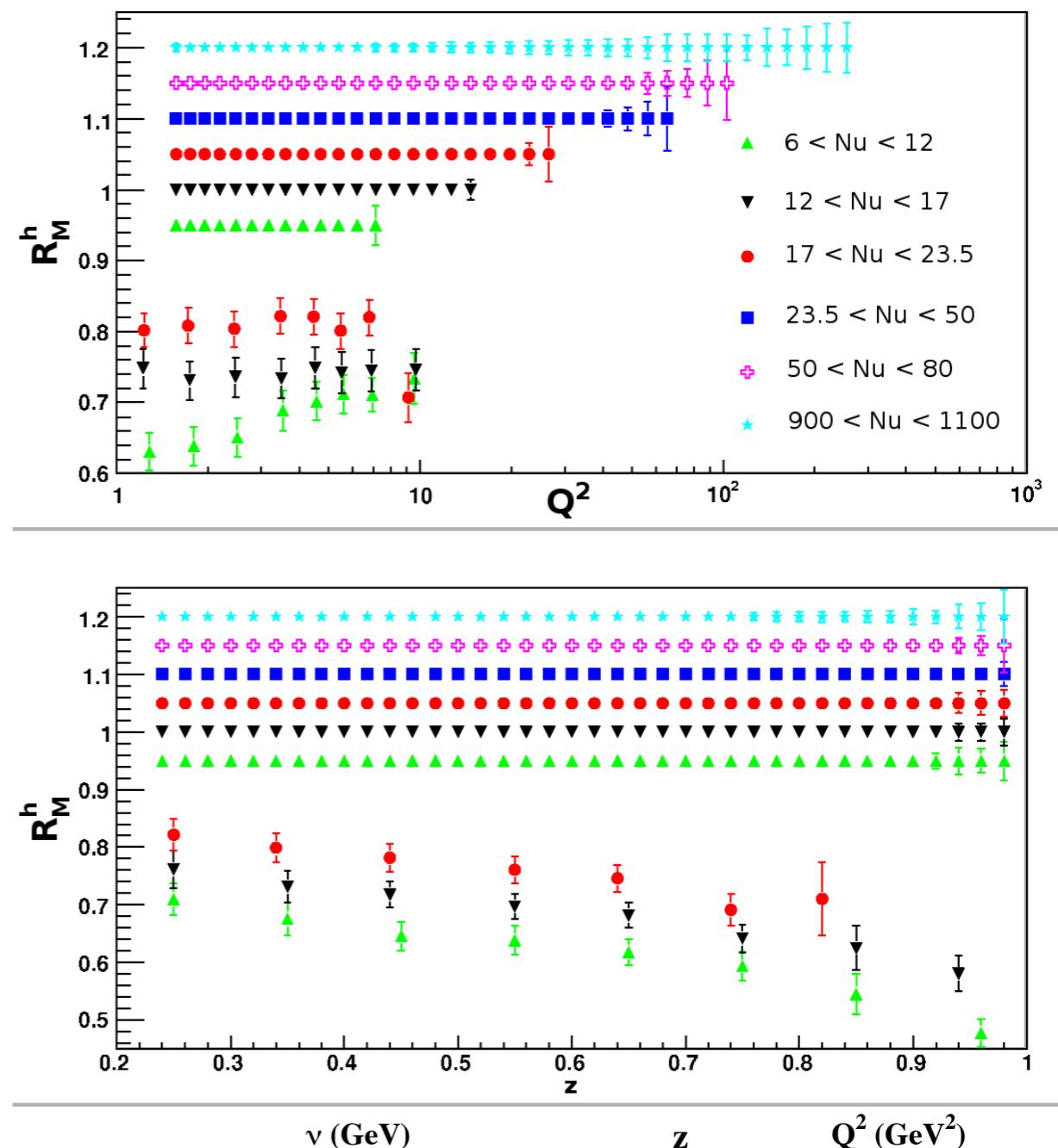


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EIC:

light hadrons:



large v range \rightarrow boost

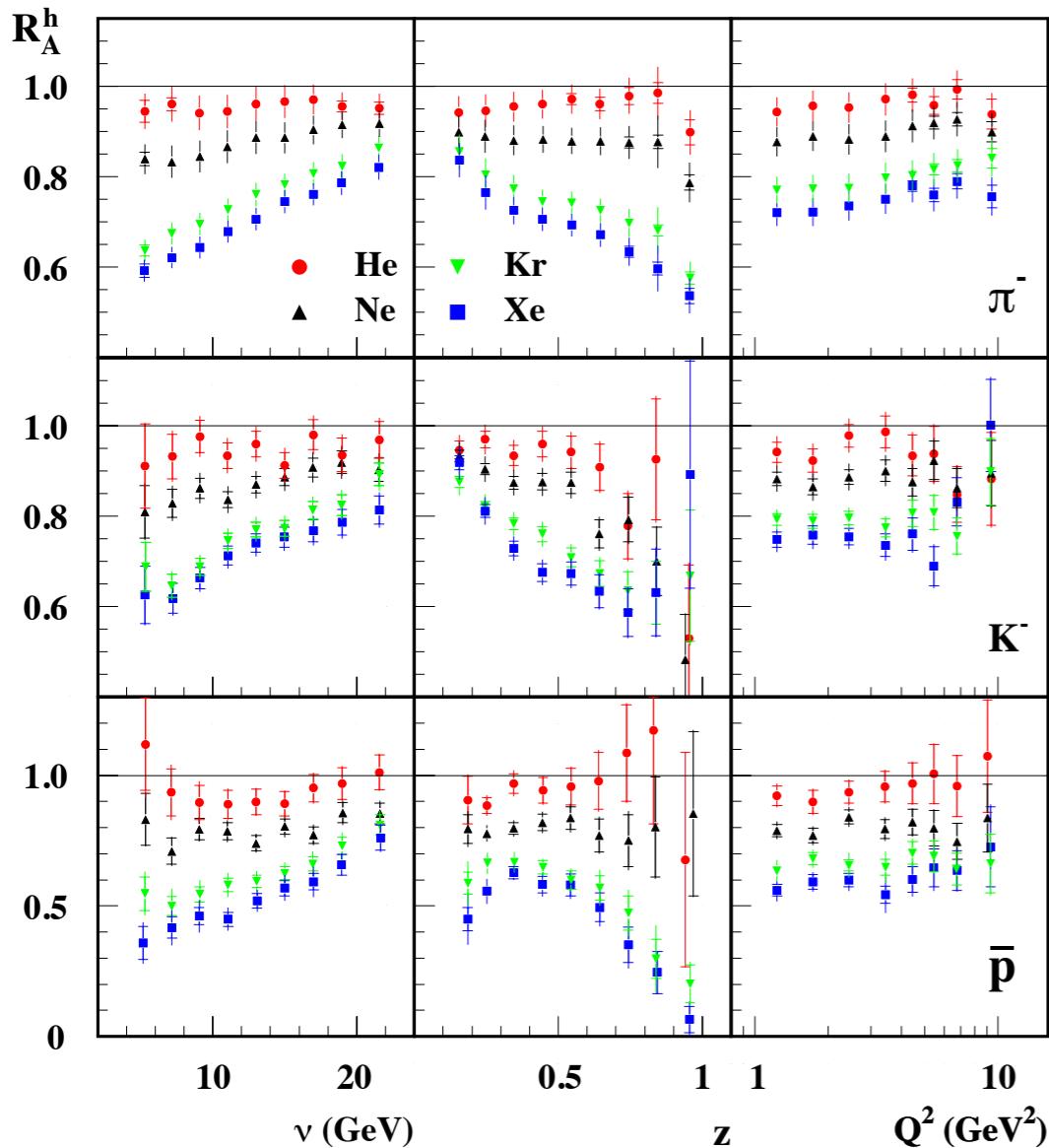
hadronization in and out of nucleus 25

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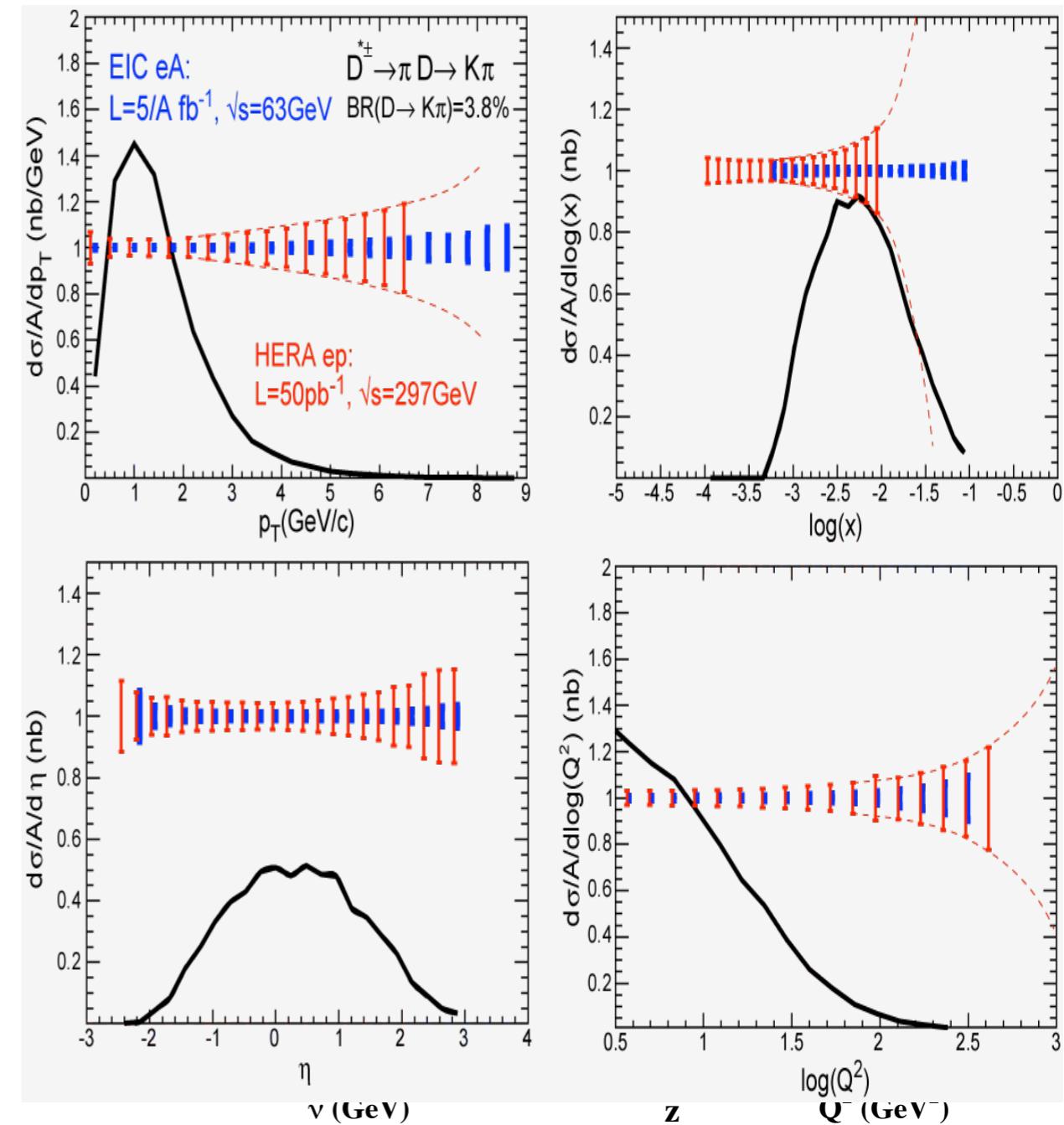
$$E_h = 2-15 \text{ GeV}$$



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EIC:

charm hadrons:



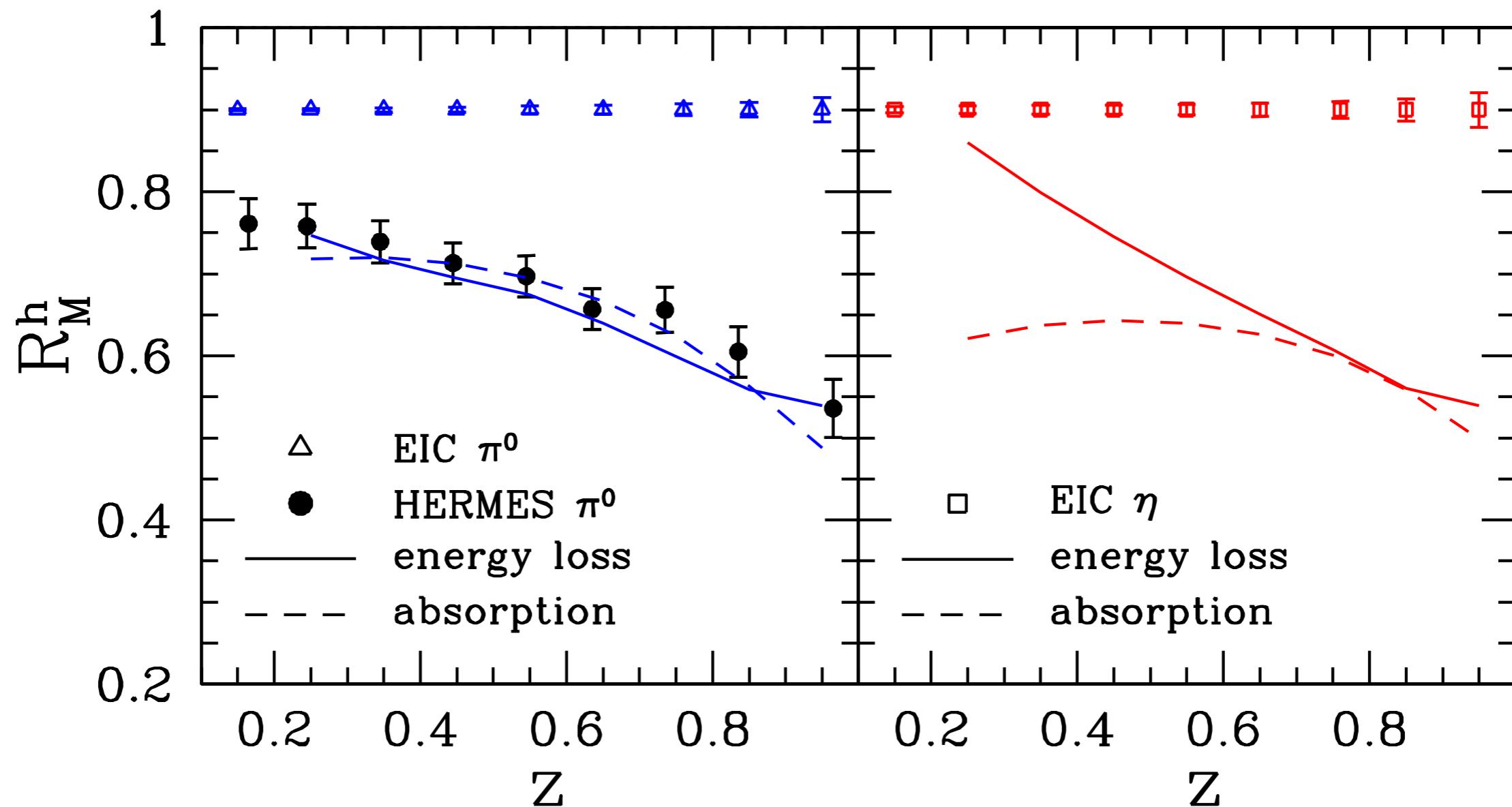
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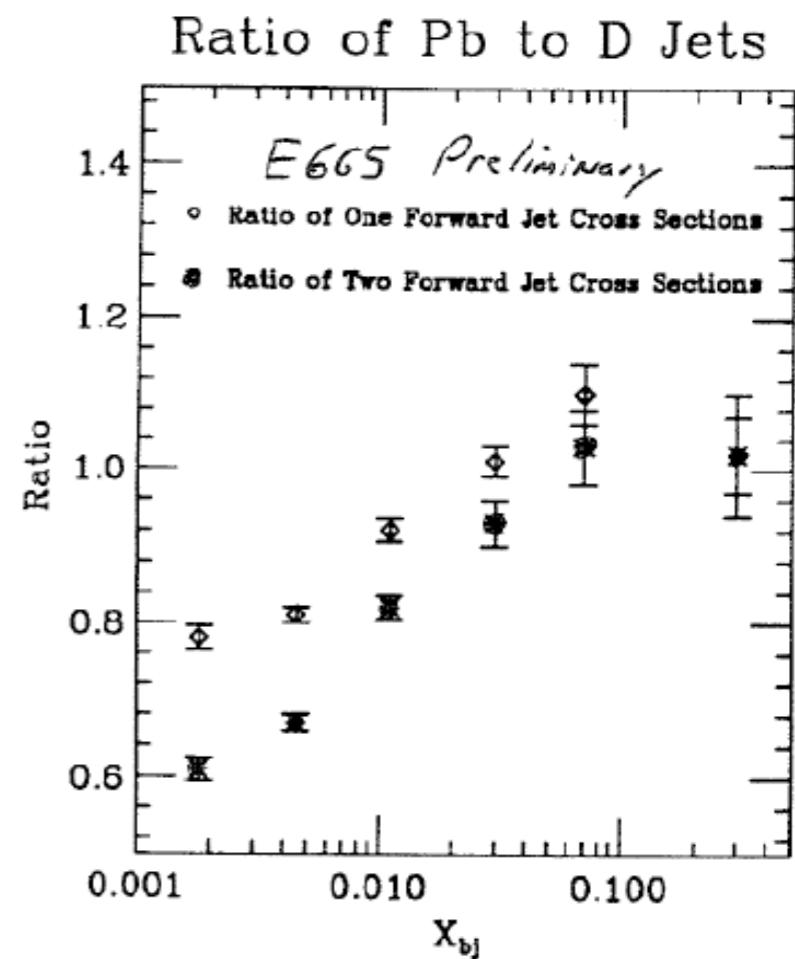
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Jets at an EIC

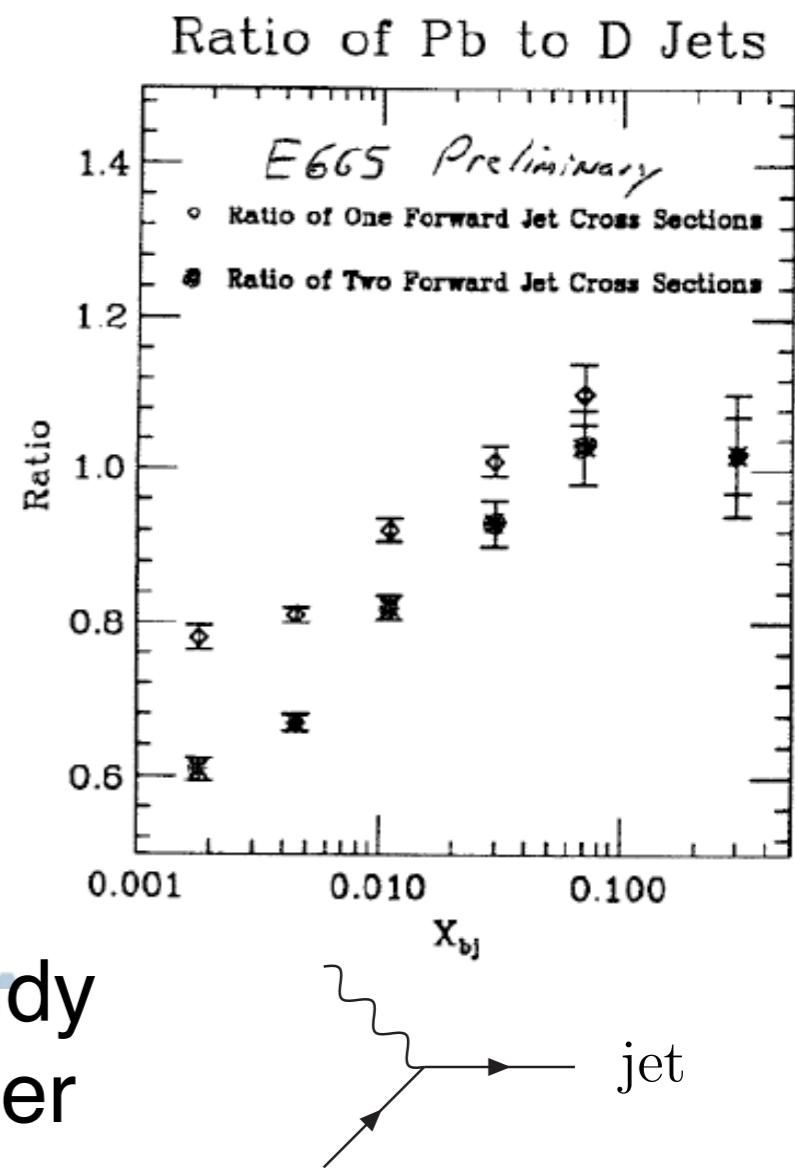
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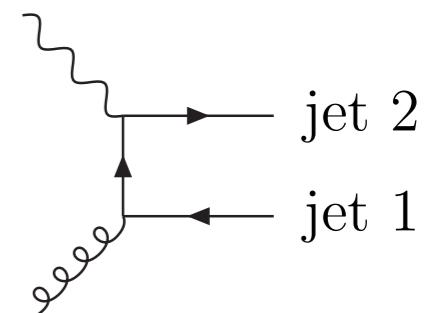
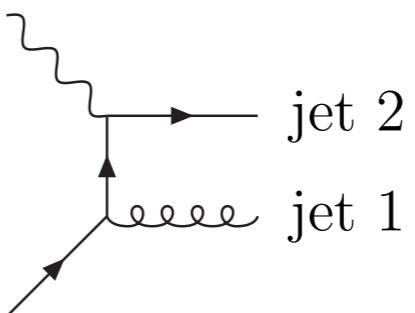
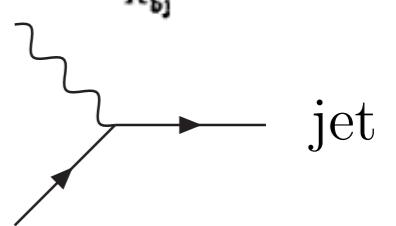
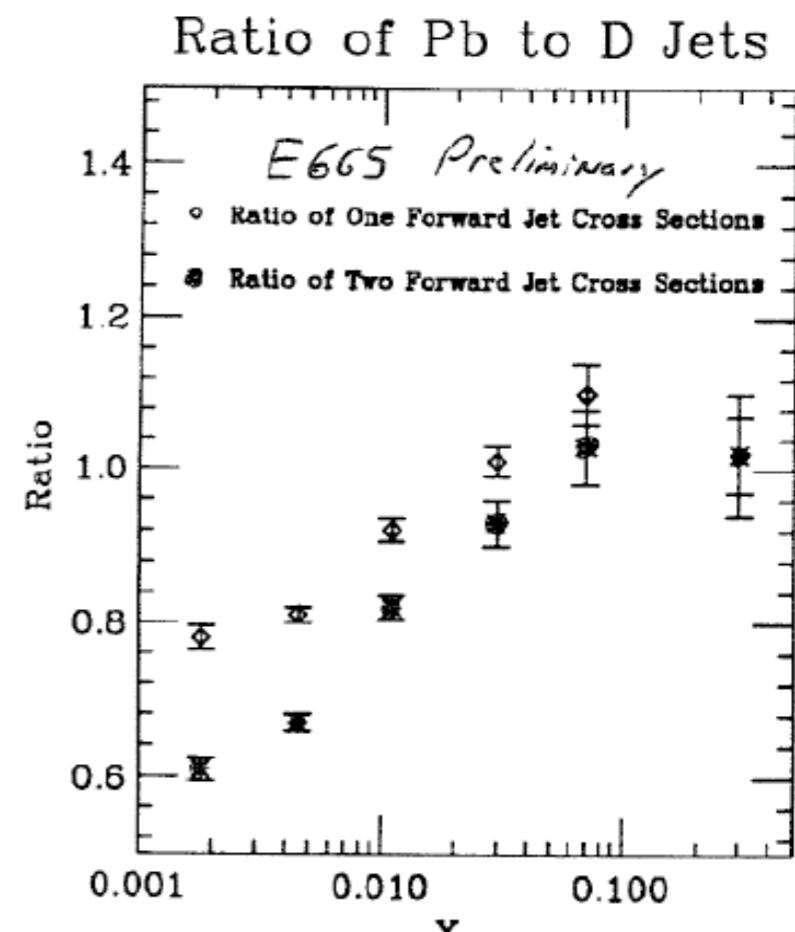
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$$\frac{d^2\sigma_{2+1}}{dxdQ^2} = A_q(x, Q^2)q^A(x, Q^2) + A_g(x, Q^2)g_A(x, Q^2)$$

2+1 jets → sensitive to nuclear gluons



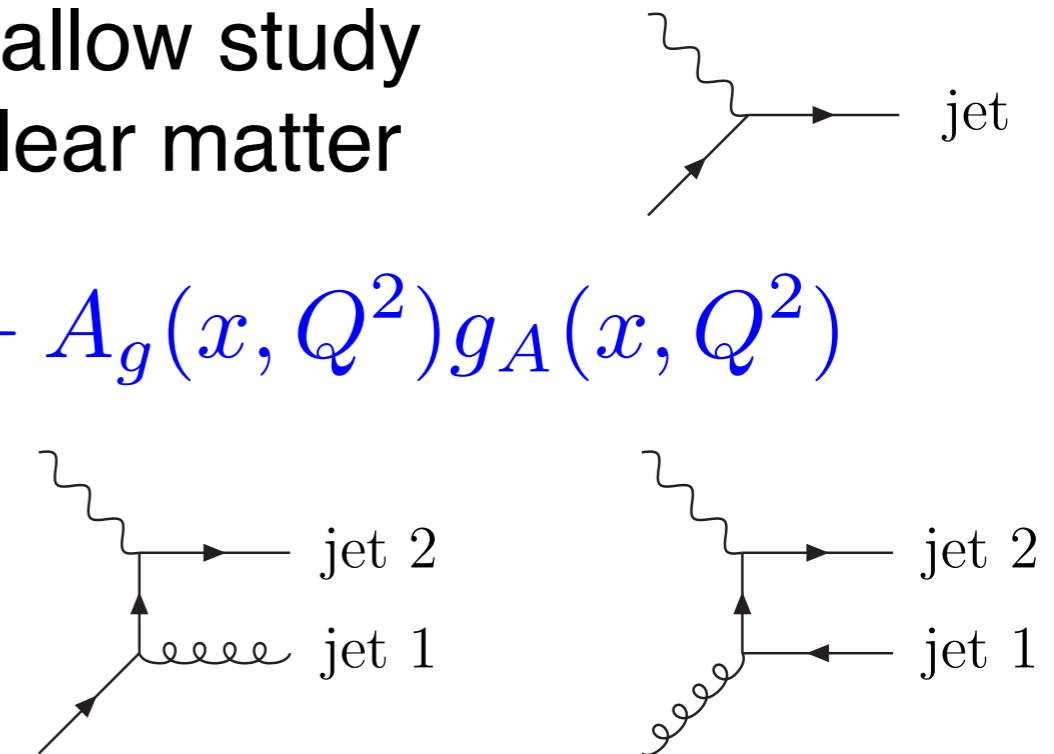
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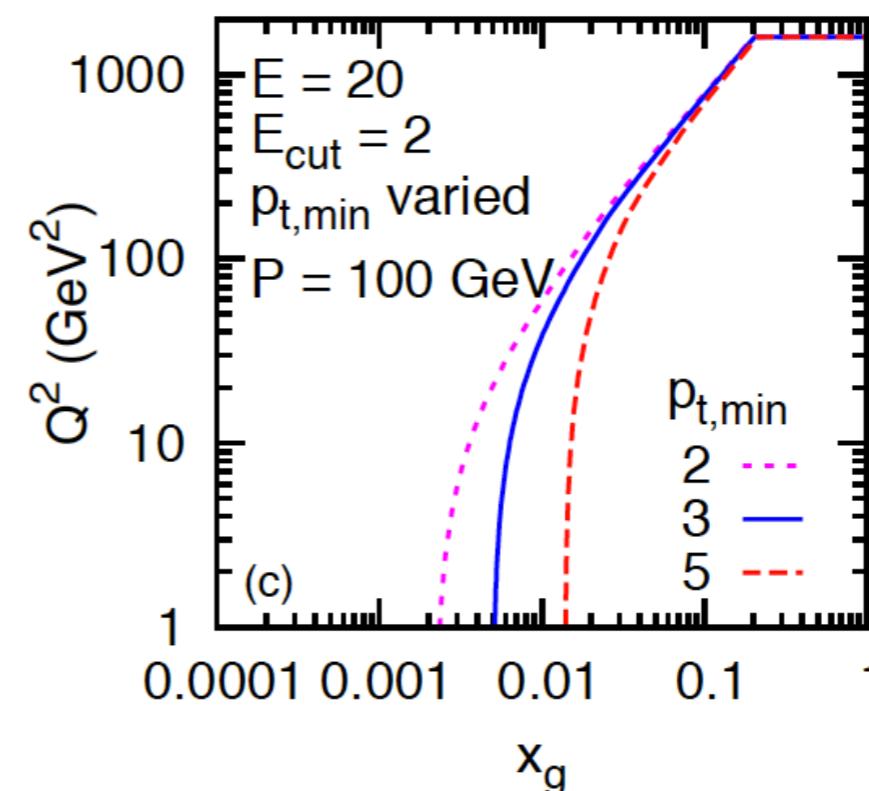
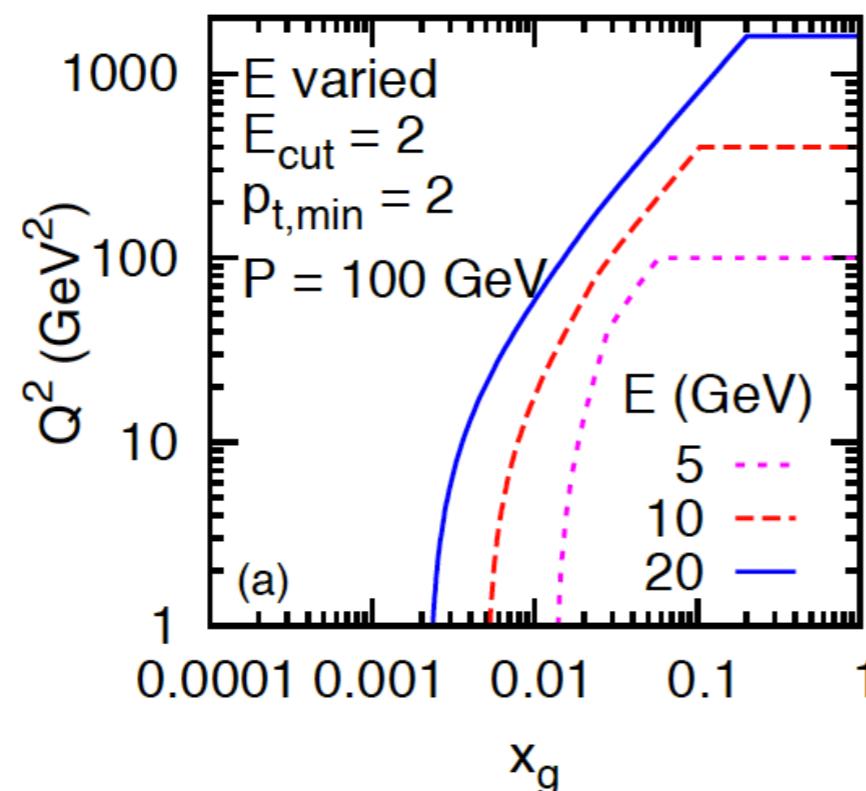
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b dependent gluons, gluon correlations from DVCS and diffractive vector meson production

Silver Measurements

Deliverables	Observables	What we learn	Stage-I	Stage-II
b-dependent gluons; gluon correlations	DVCS; diffractive vector mesons	interplay between small-x evolution and confinement	moderate x with light, heavy nuclei	smaller x, saturation

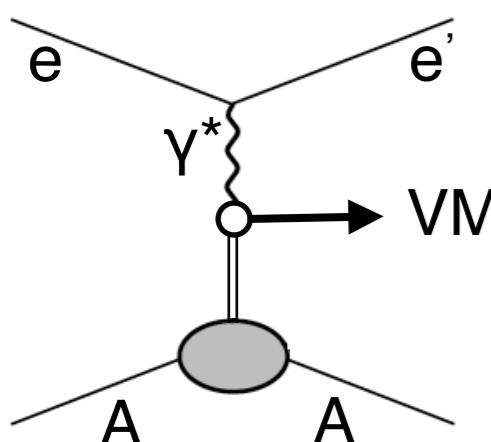
b-dependent gluons from DVCS and DVMP

- Transverse position distribution of gluons can be determined from Deeply Virtual Compton Scattering (DVCS: $e+A \rightarrow e+\gamma+A$) and Diffractive Vector Meson Production (DVMP: $e+A \rightarrow e+VM+A$)
 - Proportional to the square of the gluon distribution!!
- Coherent diffraction (intact nuclear target)
 - transverse distribution of gluon density
- Incoherent diffraction (dissociated nuclear target)
 - transverse gluon correlations in addition

b -dependent gluons from DVCS and DVMP

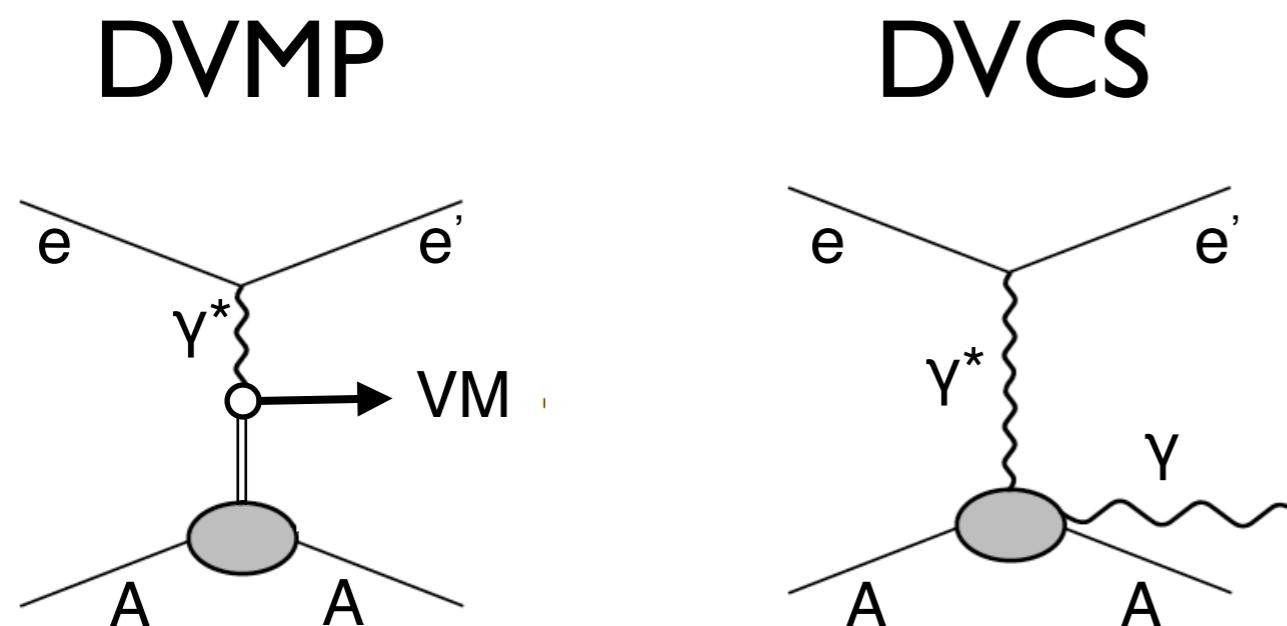
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DVMP



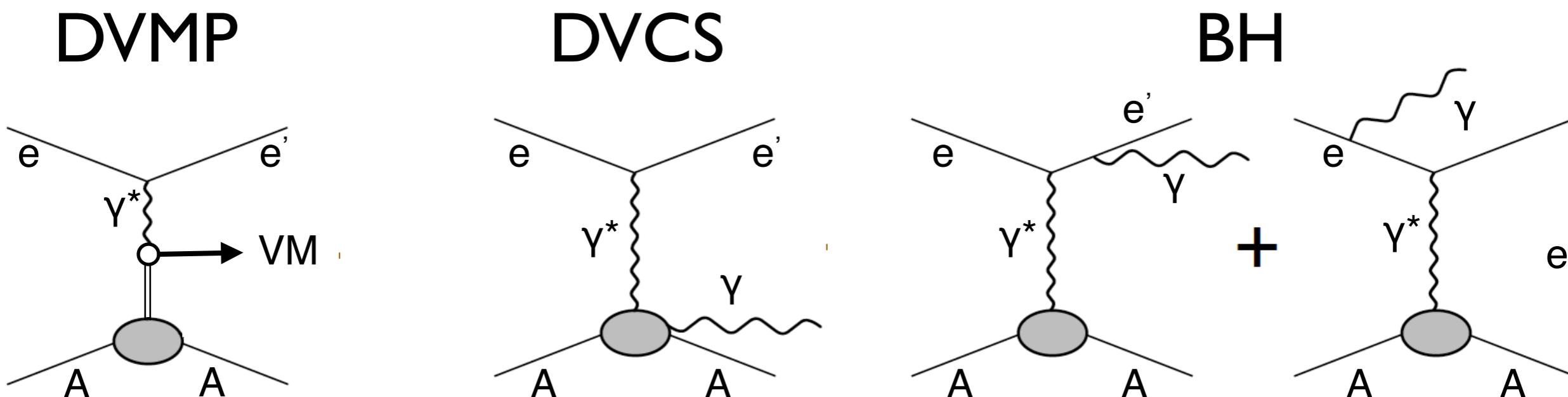
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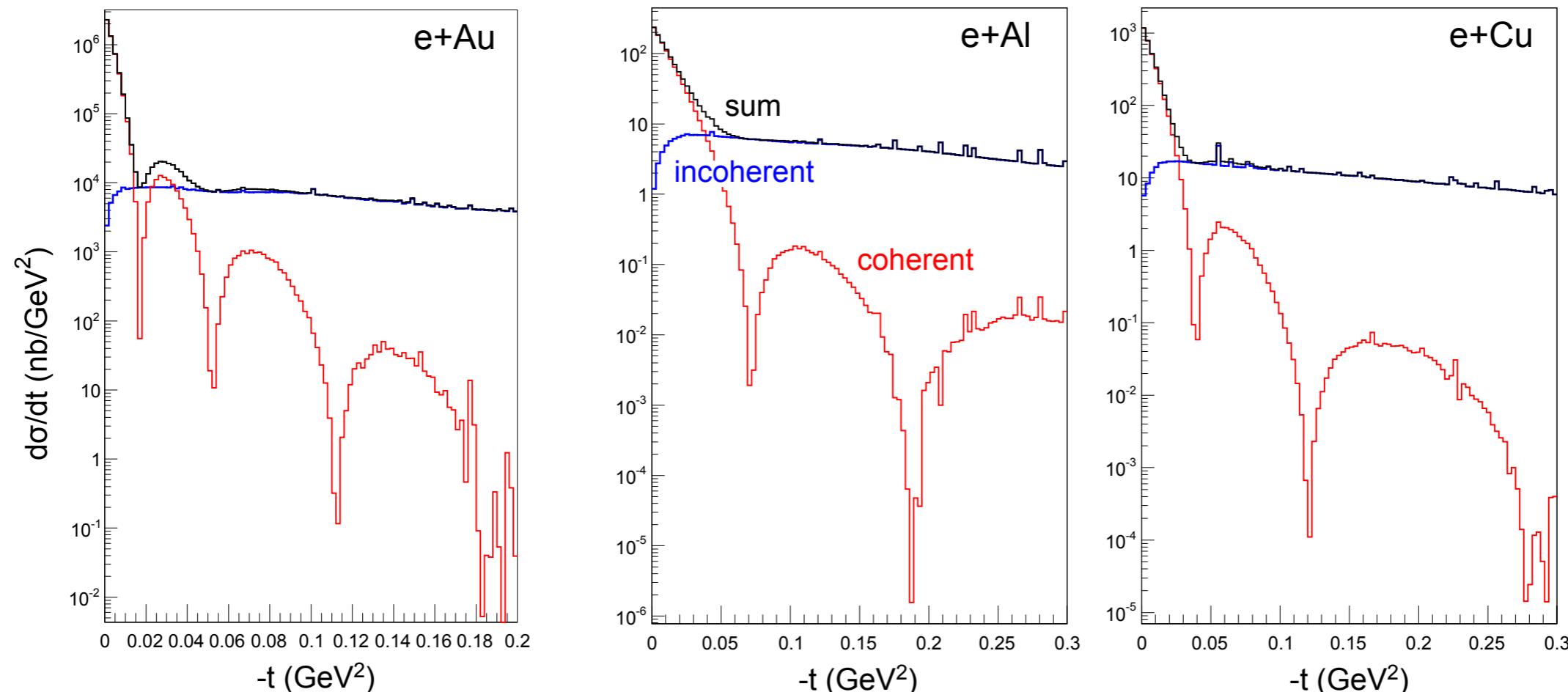
DVCS and Bethe-Heitler interference terms become difficult to distinguish experimentally

Exclusive Vector Meson Production in e+A

- Many event generators exist for e+p collisions
 - Pythia (v6), LEPTO, PEPSI, RAPGAP....
- Dearth of event generators for e+A collisions
 - DPMJET-III
- Work at BNL (T. Toll, T. Ullrich) to write an e+A generator (SARTRE)
 - Comparison of saturation vs non-saturation scenarios
 - First case study is that of exclusive diffractive J/ ψ production

Exclusive Vector Meson Production in e+A

e+A → e+J/ψ+A'



- Low- t : coherent diffraction dominates - **gluon density**
- High- t : incoherent diffraction dominates - **gluon correlations**
 - For smaller nuclei, transition between coherent and incoherent is pushed out to higher $|t|$
 - Need good breakup detection efficiency to discriminate between the two scenarios

Summary and Conclusions

- The **e+A physics programme** at an **EIC** will give us an unprecedented opportunity to study gluons in nuclei
- **Low-x:** Measure the properties of gluons where saturation is the dominant governing phenomena
- **Higher-x:** Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization
- Understanding the role of gluons in nuclei is crucial to understanding RHIC (and LHC) heavy-ion results

Good headway can be made on these measurements already
with a stage-I eRHIC ($E_e = 5 \text{ GeV}$)

- The INT programme in the Fall of 2010 allowed us to formulate the observables in terms of golden and silver measurements
 - A detailed write-up of the whole programme (encompassing both e+A and e+p) will be published shortly

with thanks

- Fellow INT workshop convenors: A. Accardi, C. Marquet
- BNL EIC science task-force: E. Aschenauer, T. Burton, R. Debbe, J. Dunlop, S. Fazio, W. Guryan, J-H. Lee, T. Toll, T. Ullrich
- Friendly theorists: M. Diehl, F. Gelis, W. Horowitz, T. Lappi, M. Stratmann, R. Venugopalan
- Summer students: W. Foreman, A. Kirleis, M. Savastio, P. Schnatz, O. Vail
- C-AD group: J. Beebe-Wang, V. Litvinenko, V. Ptitsyn, D. Trobojevic

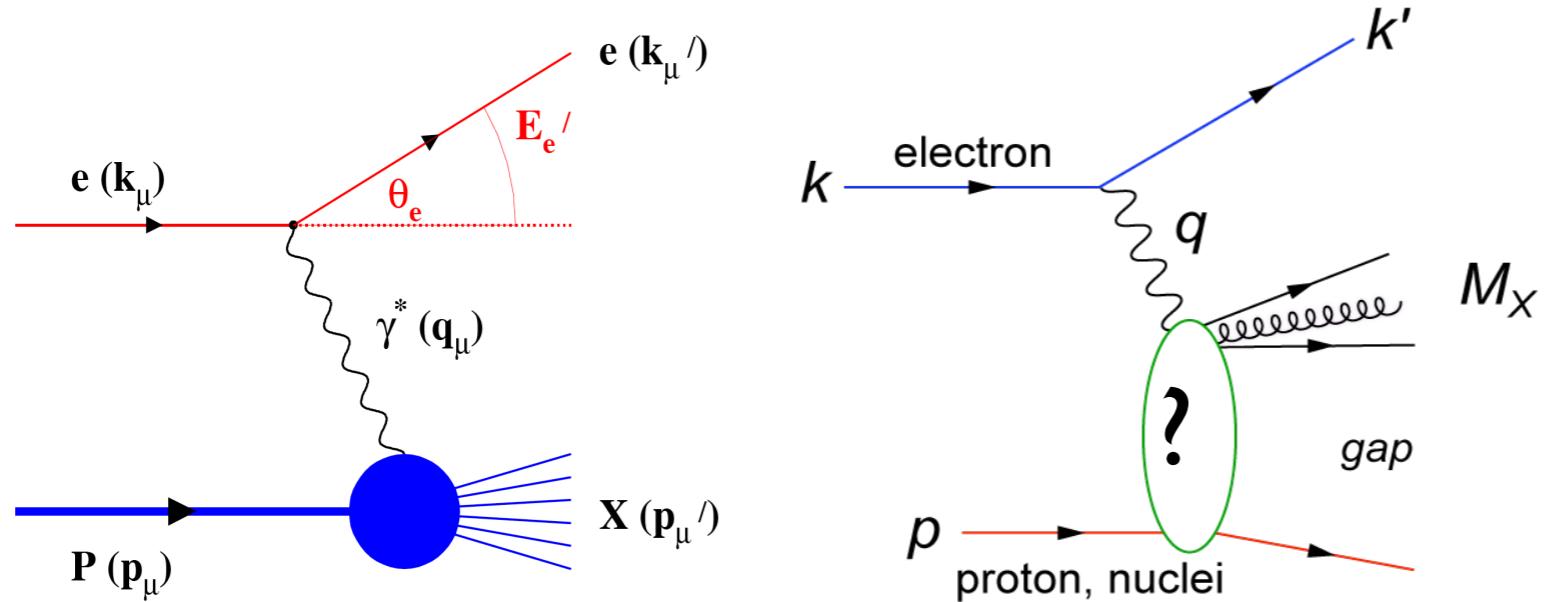
BACKUP SLIDES

e+A Golden Science Matrix

Primary new science deliverables	What we hope to fundamentally learn	Basic measurements	Typical required precision	Special requirements on accelerator/detector	What can be done in phase I	Alternatives in absence of an EIC	Gain/Loss compared with other relevant facilities	Comments
integrated nuclear gluon distribution	The nuclear wave function throughout x-Q ² plane	F_L, F_2, F_L^c, F_2^c	What HERA reached for F_2 with combined data	displaced vertex detector for charm	stage I: large-x & large-Q ² need full EIC, for F_L and F_2^c	p+A at LHC (not as precise though) & LHeC	First experiment with good x, Q ² & A range	This is fundamental input for A+A collisions
k_T dependence of gluon distribution and correlations	The non-linear QCD evolution - Q_s	SIDIS & di-hadron correlations with light and heavy flavours		Need low-pt particle ID	SIDIS for sure TBD: saturation signal in di-hadron p_T imbalance	1) p+A at RHIC/LHC, although e+A needed to check universality 2) LHeC	Cleaner than p+A: reduced background	
b dependence of gluon distribution and correlations	Interplay between small-x evolution and confinement	Diffractive VM production and DVCS, coherent and incoherent parts	50 MeV resolution on momentum transfer	hermetic detector with 4pi coverage low-t: need to detect nuclear break-up	Moderate x with light and heavy nuclei	LHeC	Never been measured before	Initial conditions for HI collisions – eccentricity fluctuations

Role of colour-neutral (Pomeron) excitations

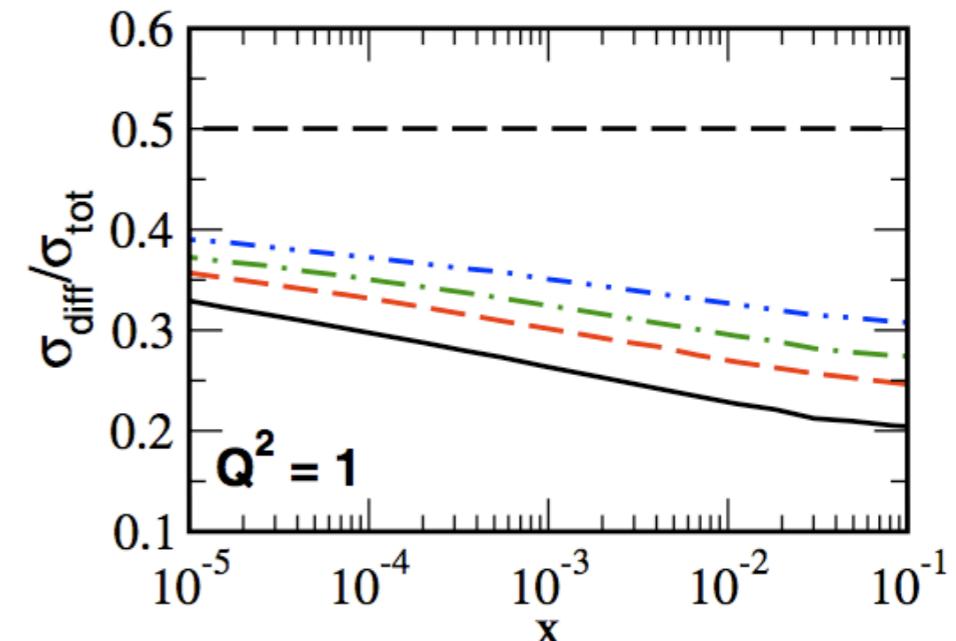
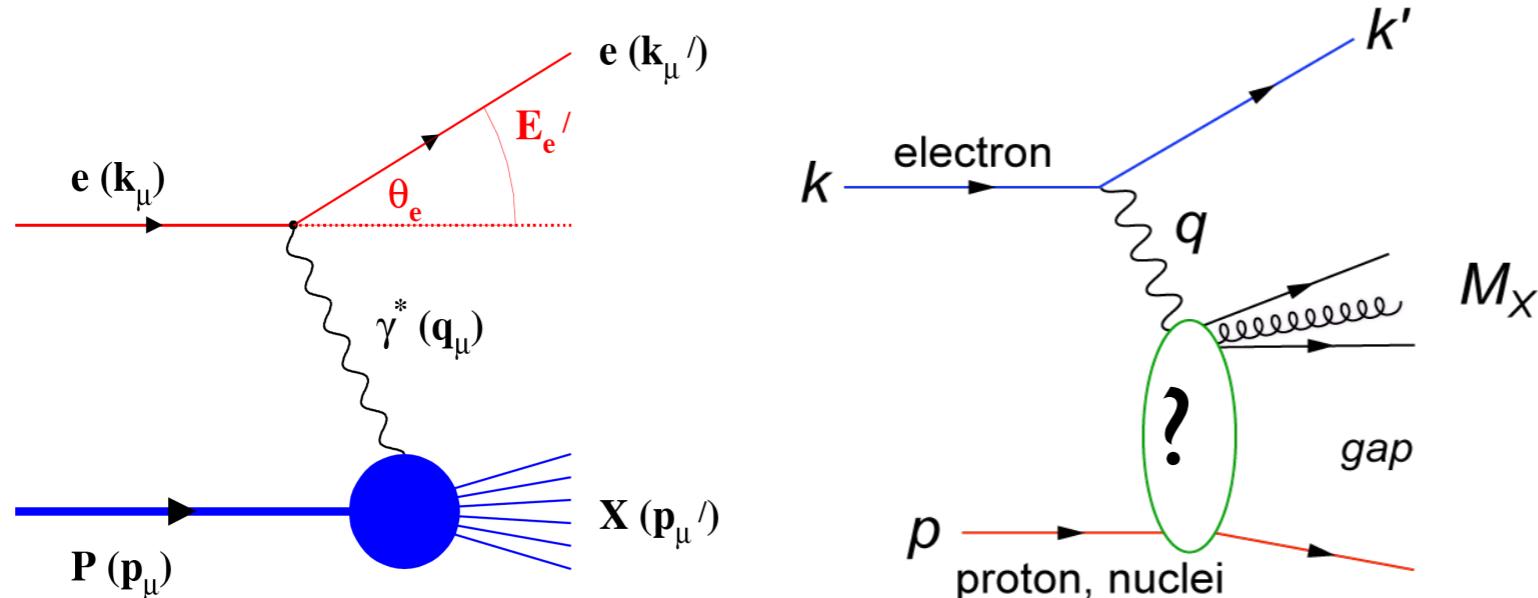
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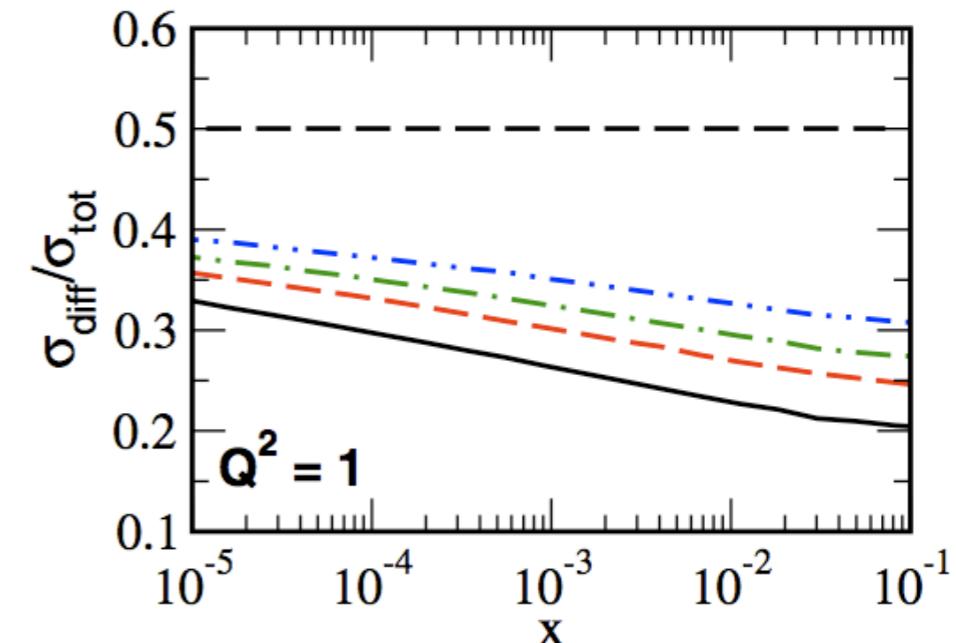
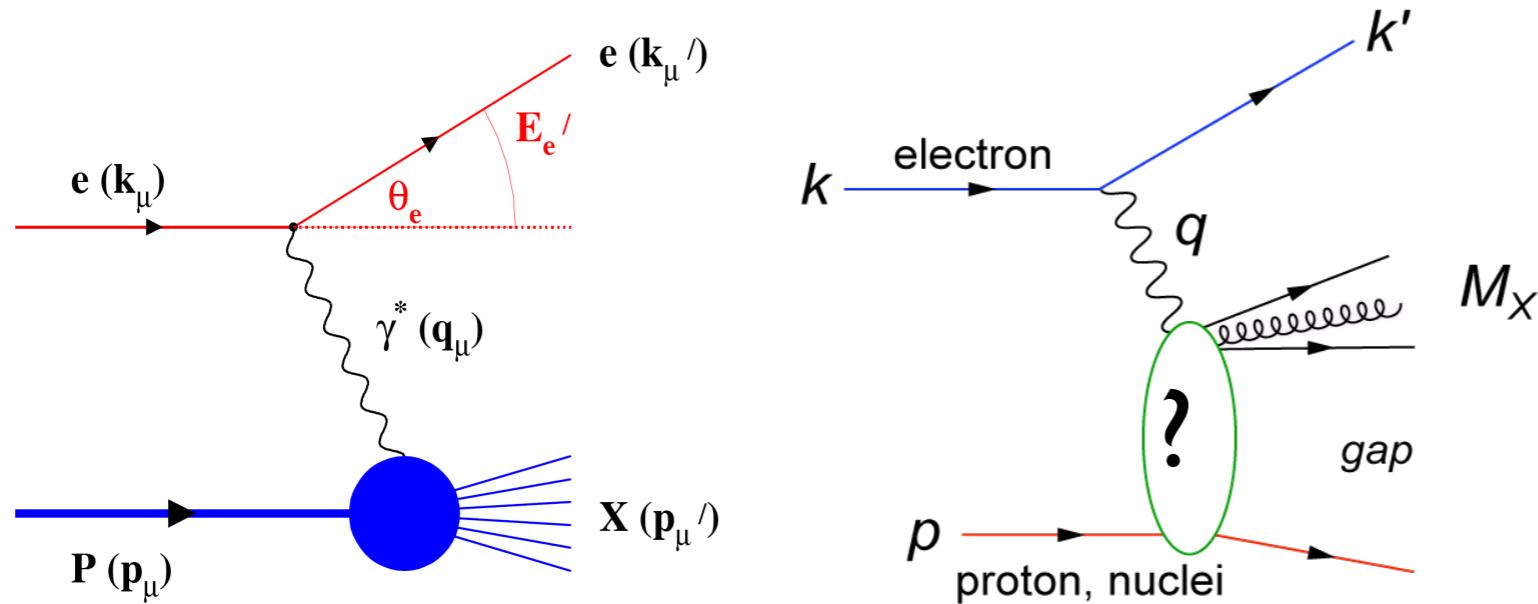


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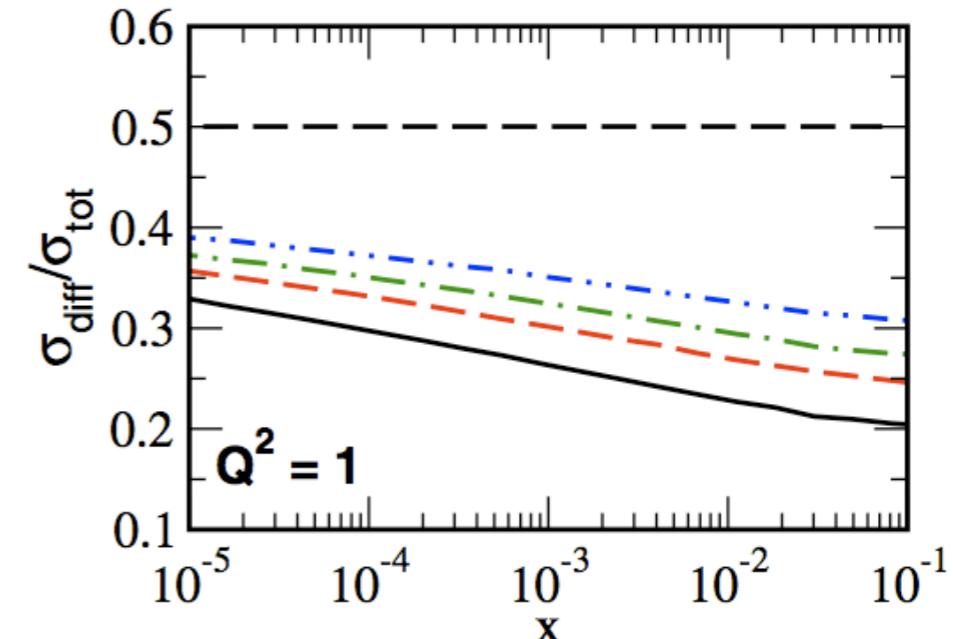
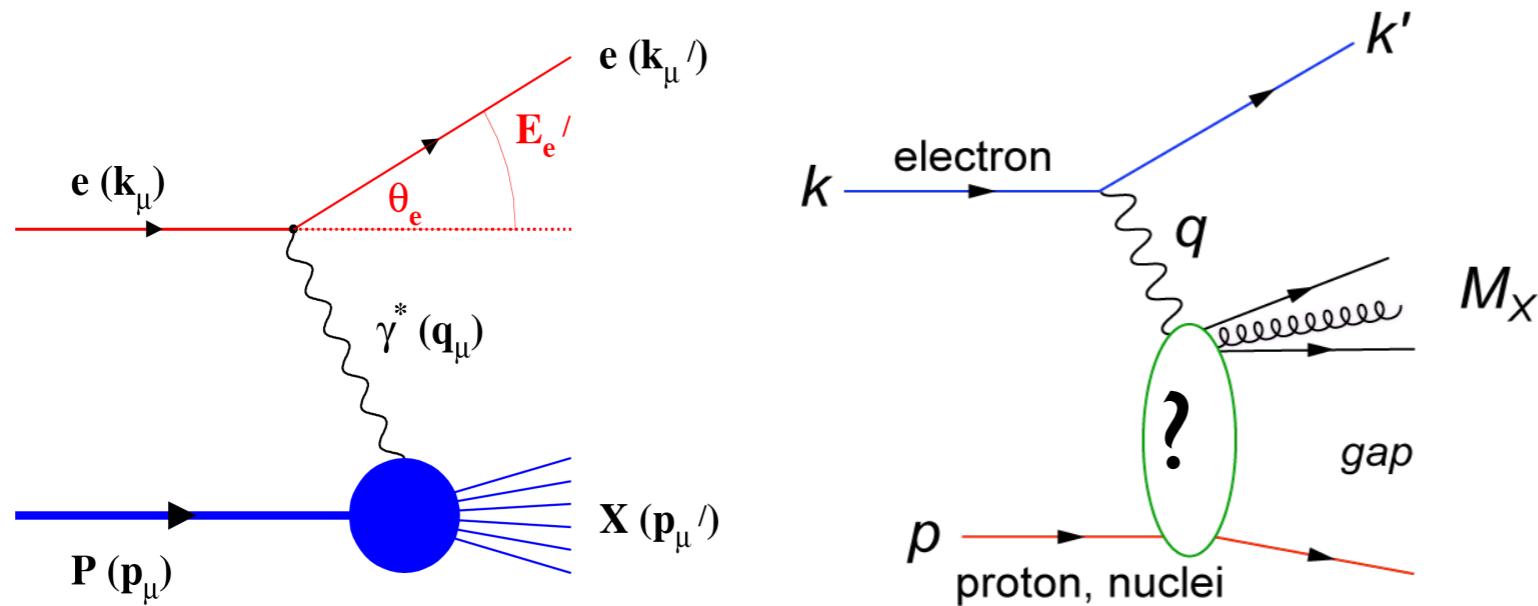
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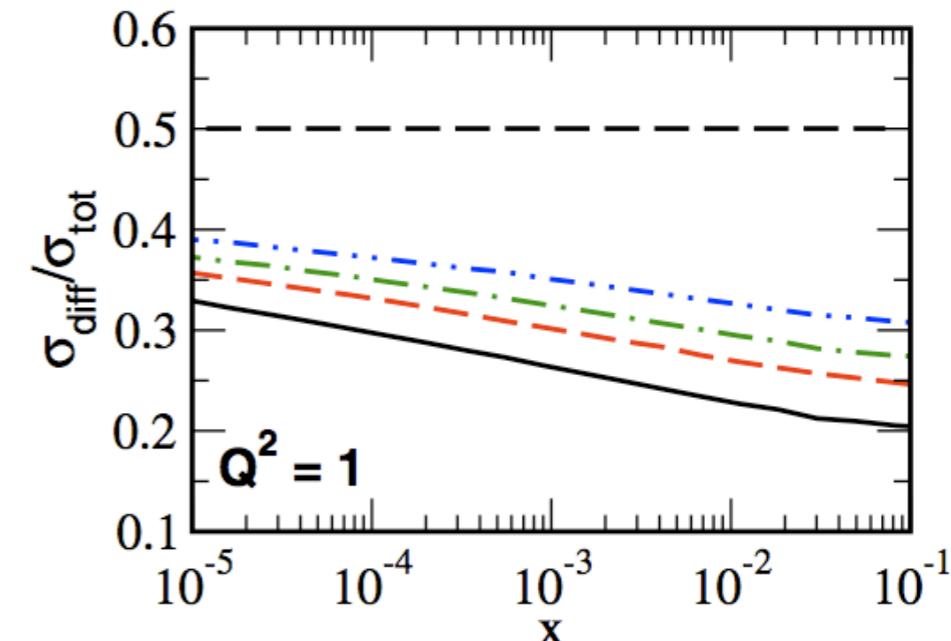
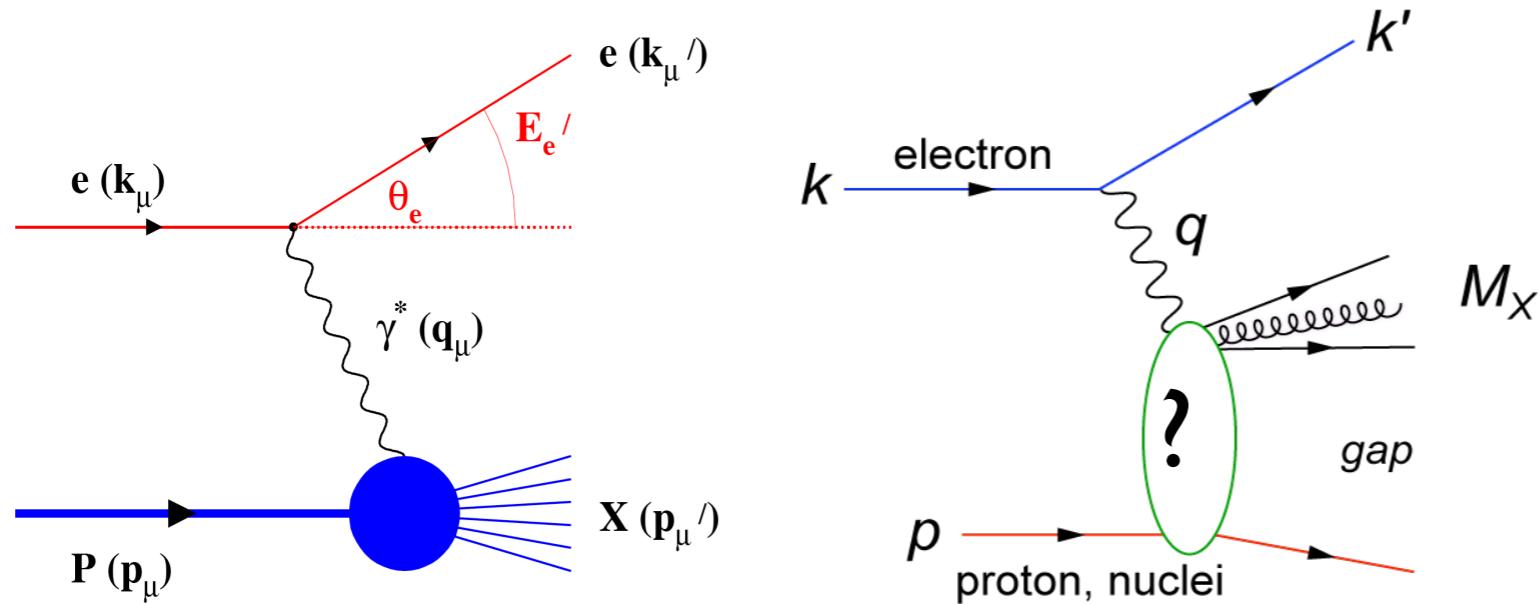
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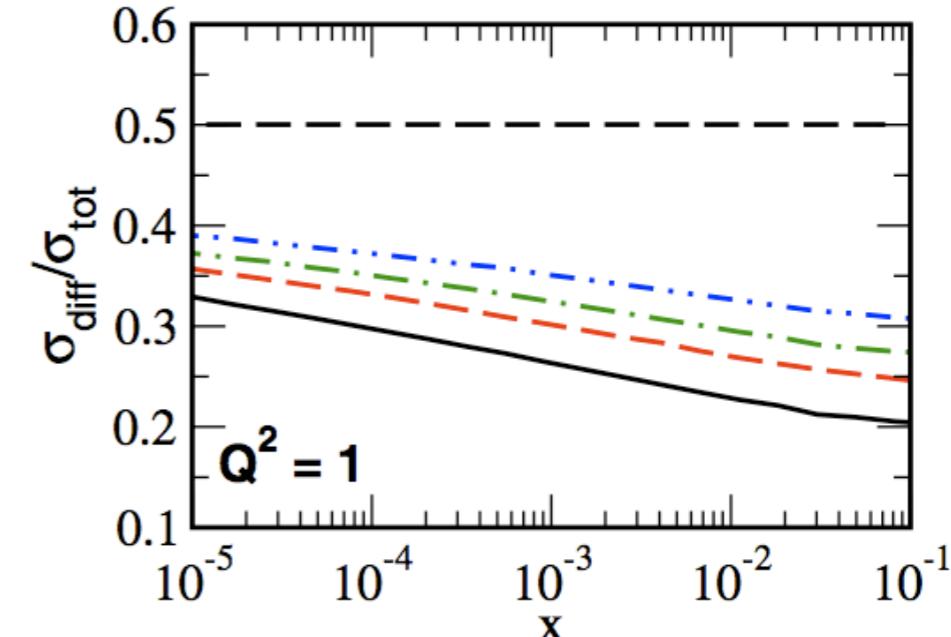
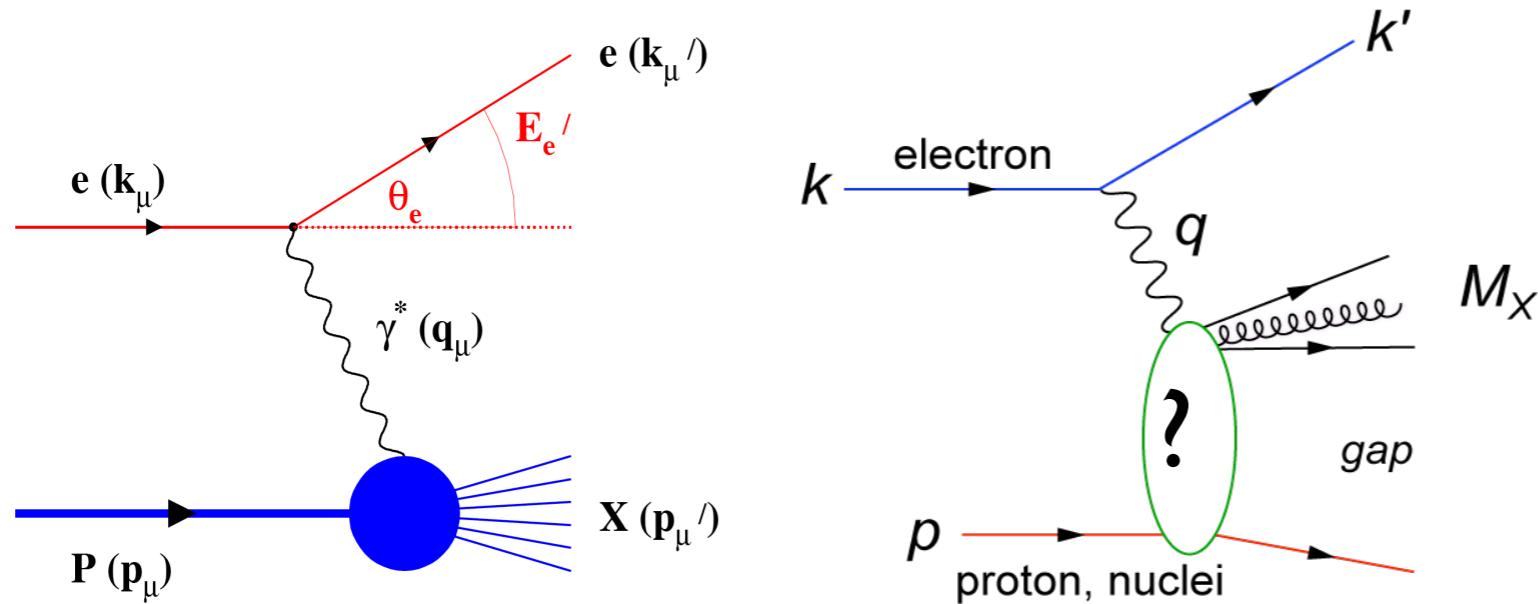
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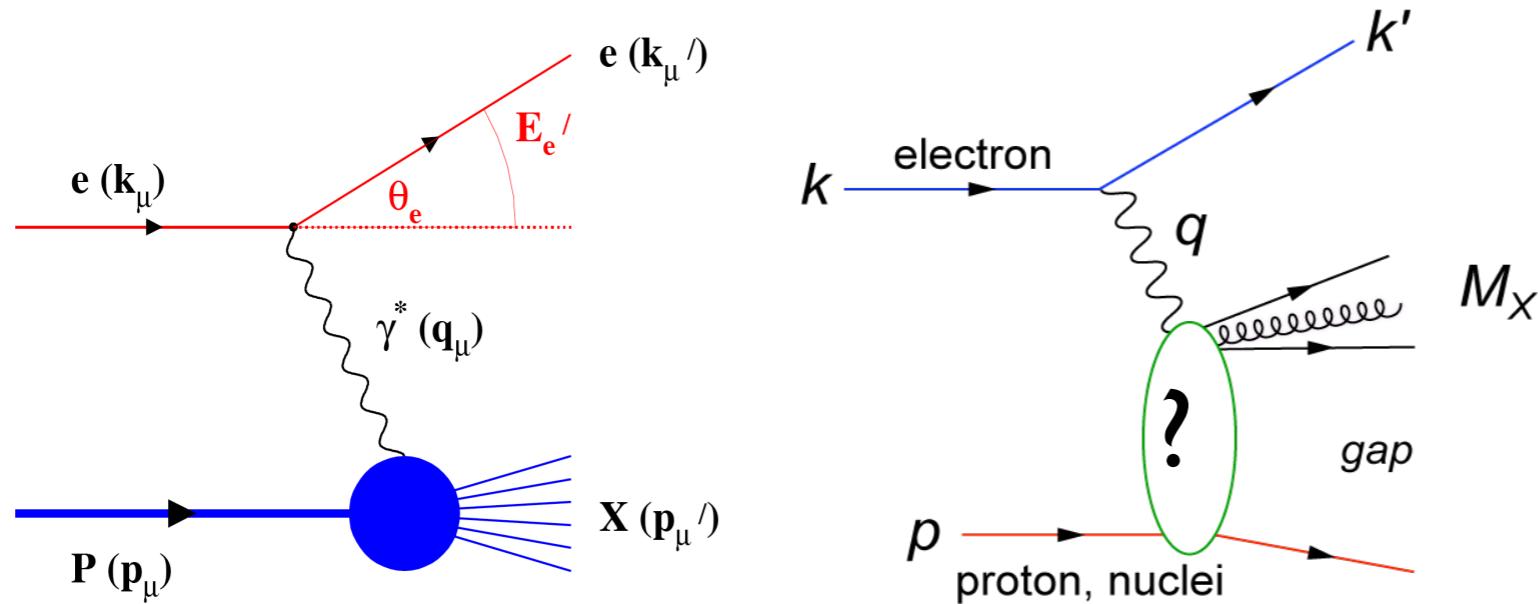
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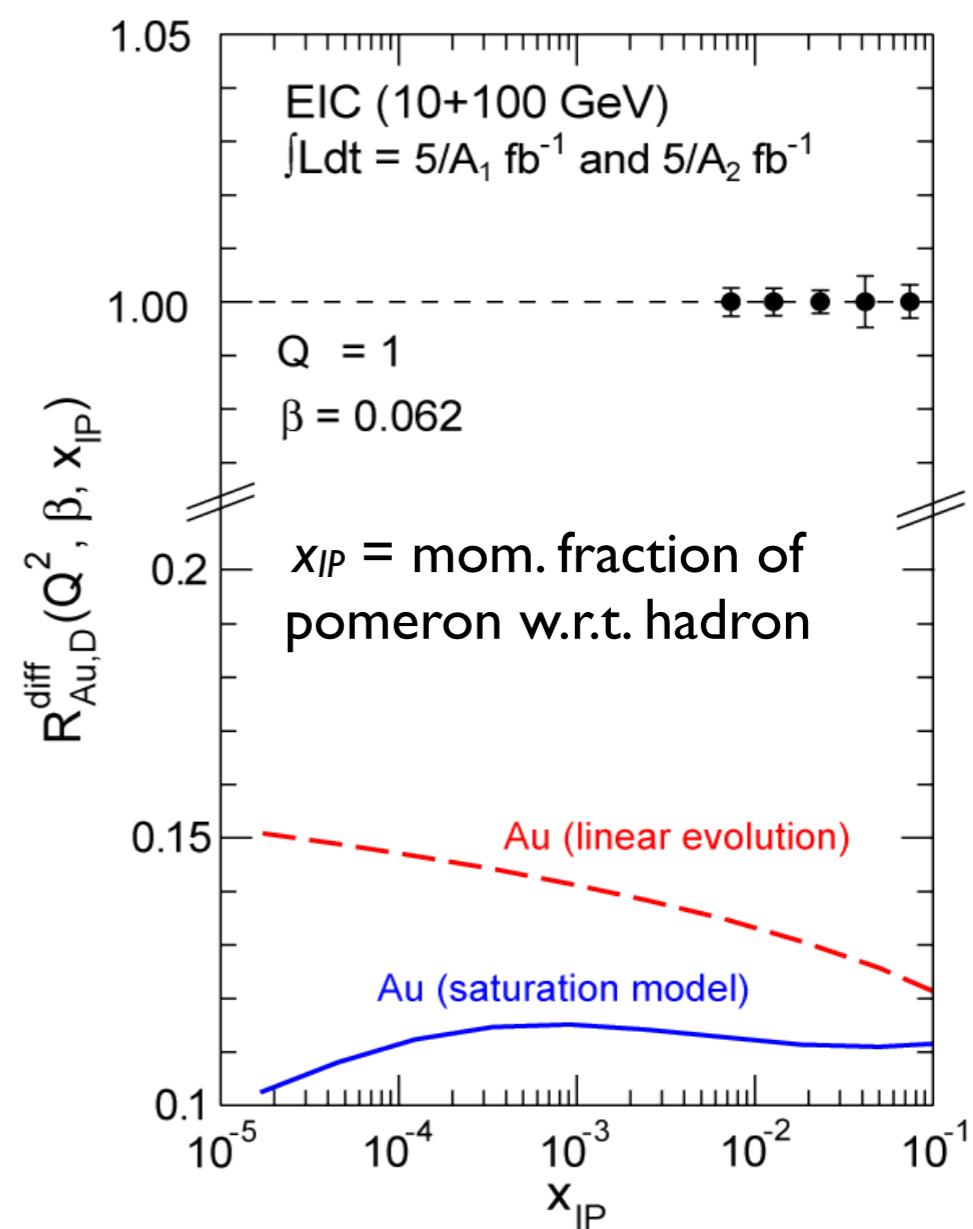
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Distinguish between **linear evolution** and **saturation models**

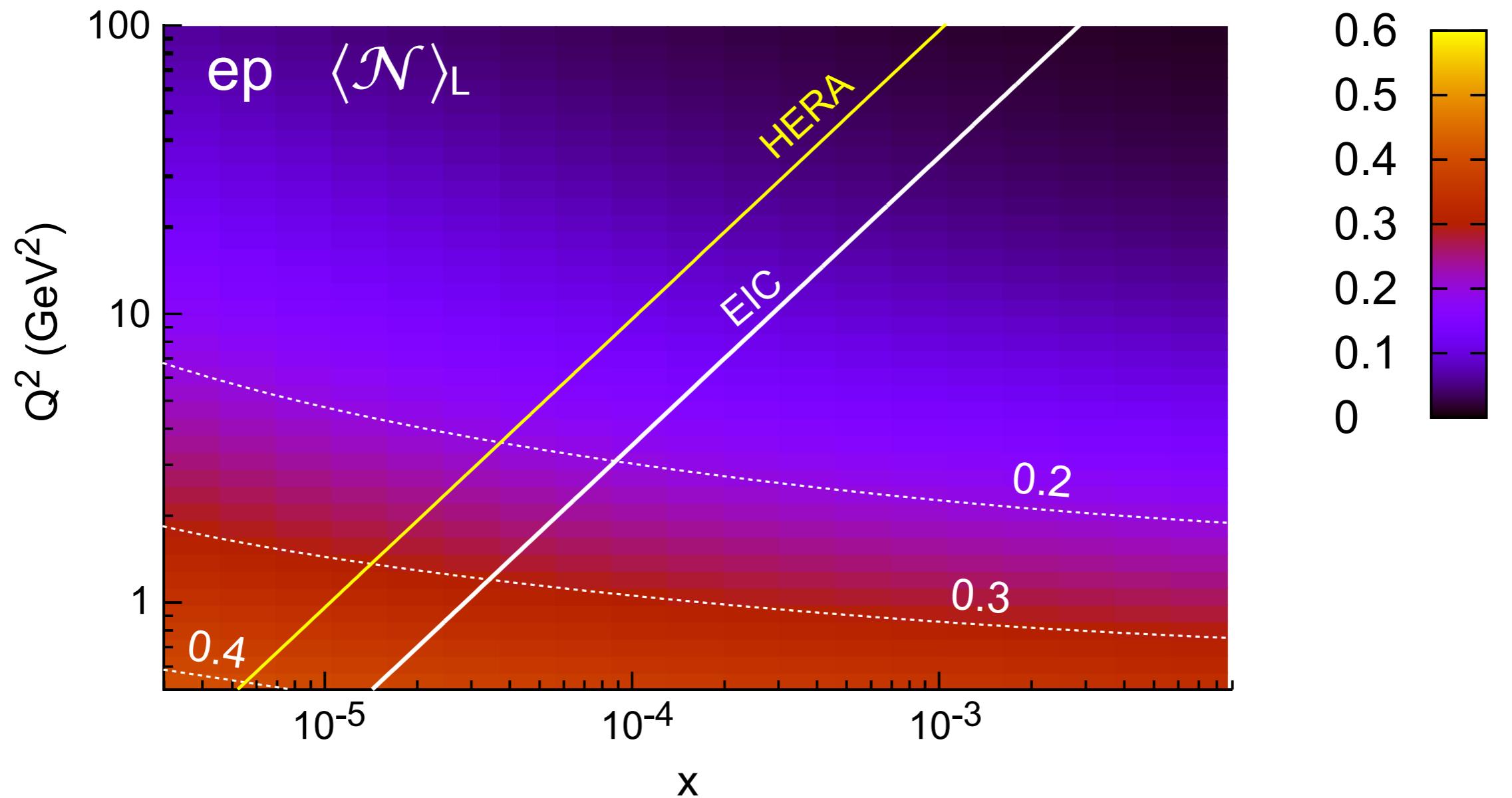


Getting a “Feel” for Non-Linear QCD

To assess typical values of \mathcal{N} calculate average:

$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b d^2r dz [\psi^* \psi]_{2,L} \mathcal{N}^2}{\int d^2b d^2r dz [\psi^* \psi]_{2,L} \mathcal{N}}$$

$$\begin{aligned}\langle \mathcal{N} \rangle_2 &\rightarrow F_2 \\ \langle \mathcal{N} \rangle_L &\rightarrow F_L\end{aligned}$$

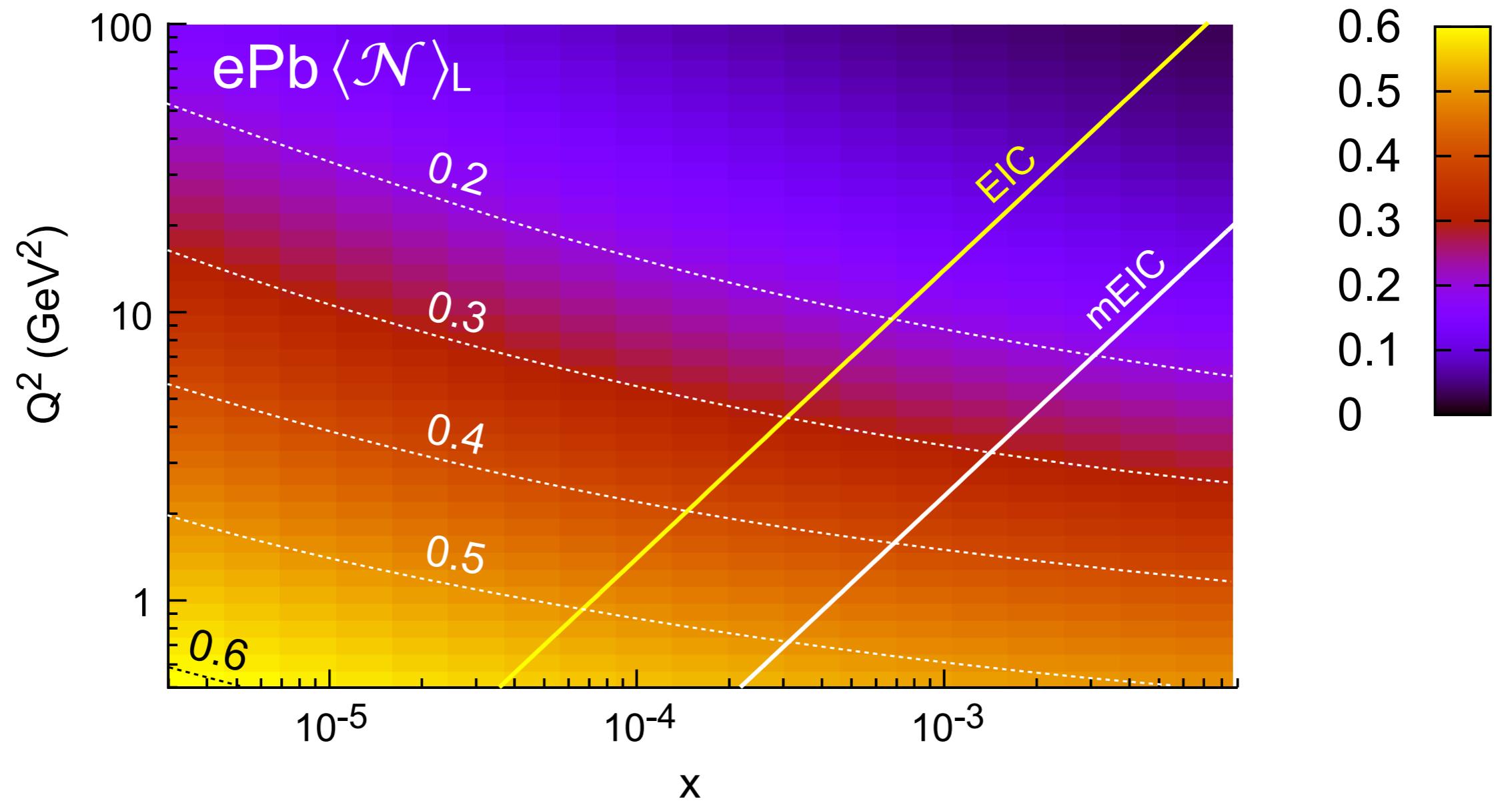


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$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

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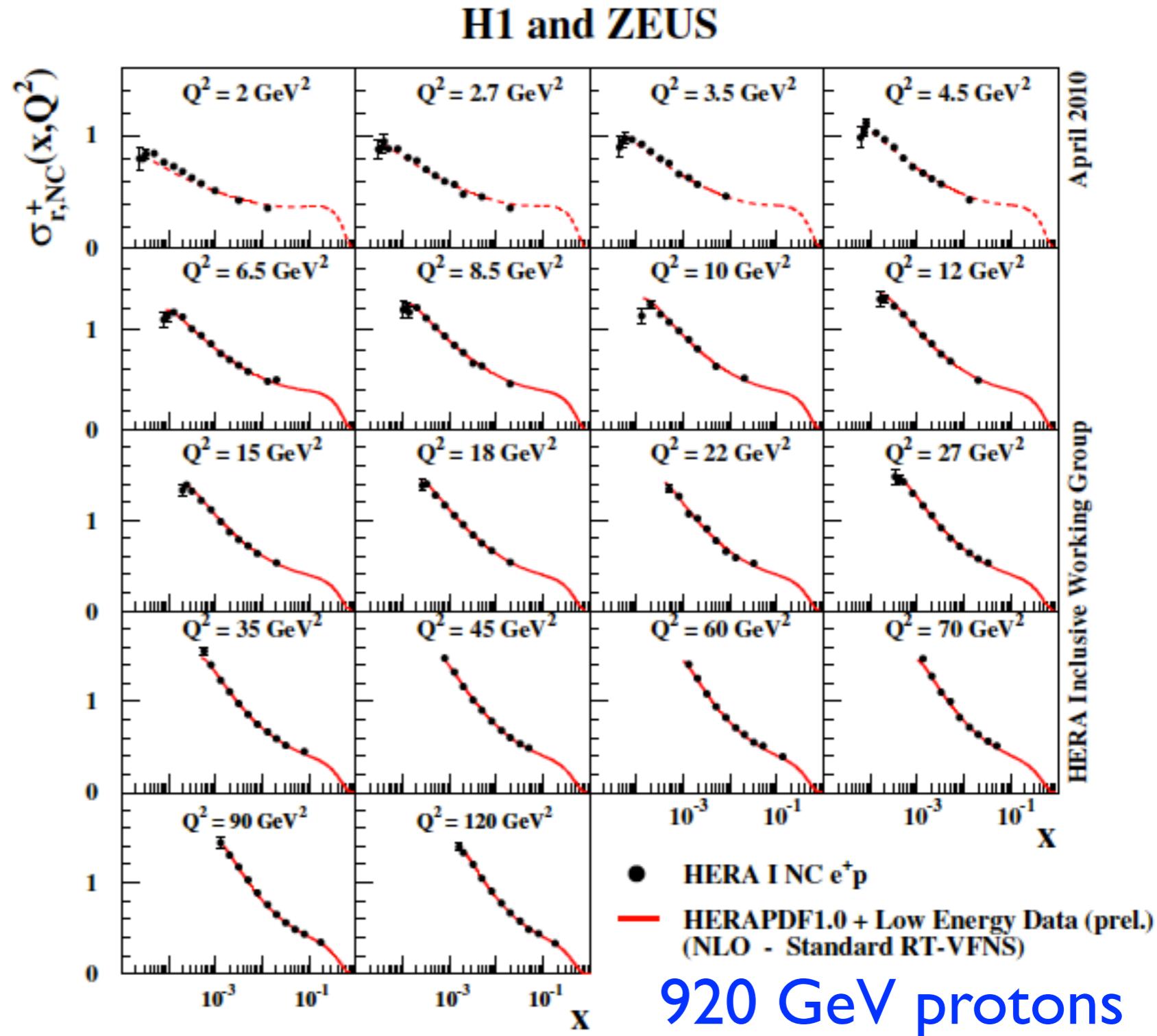
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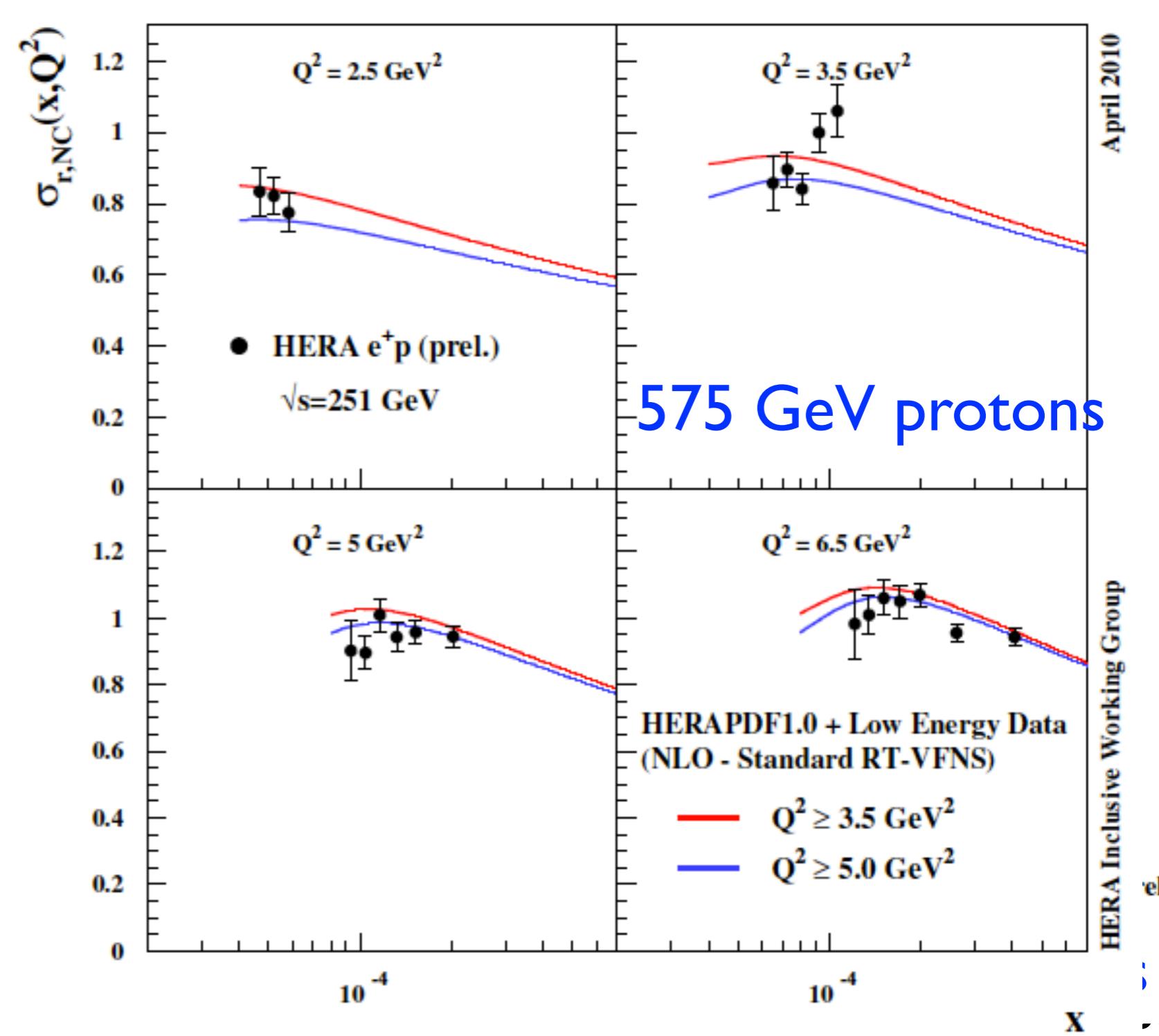


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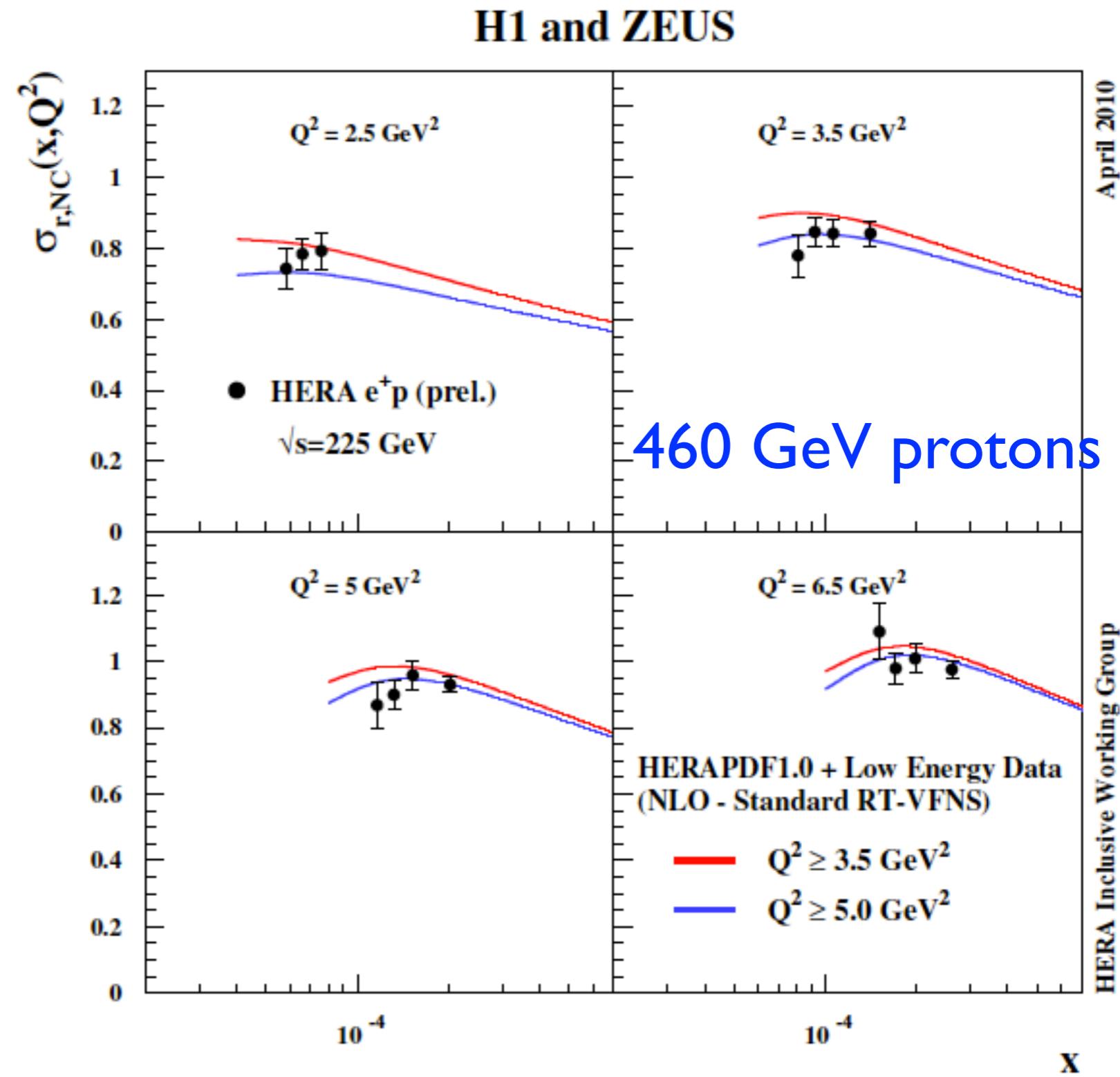
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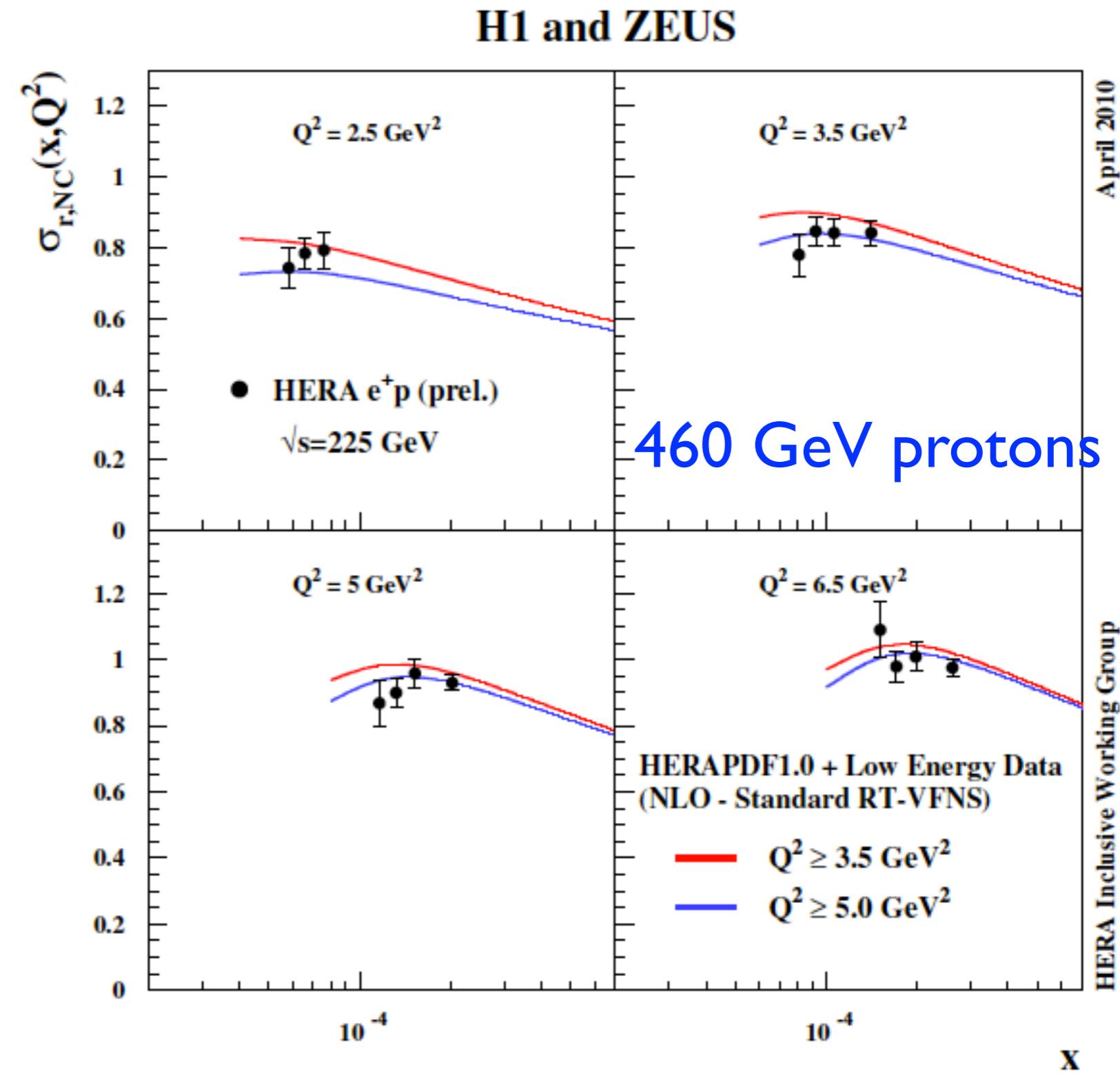
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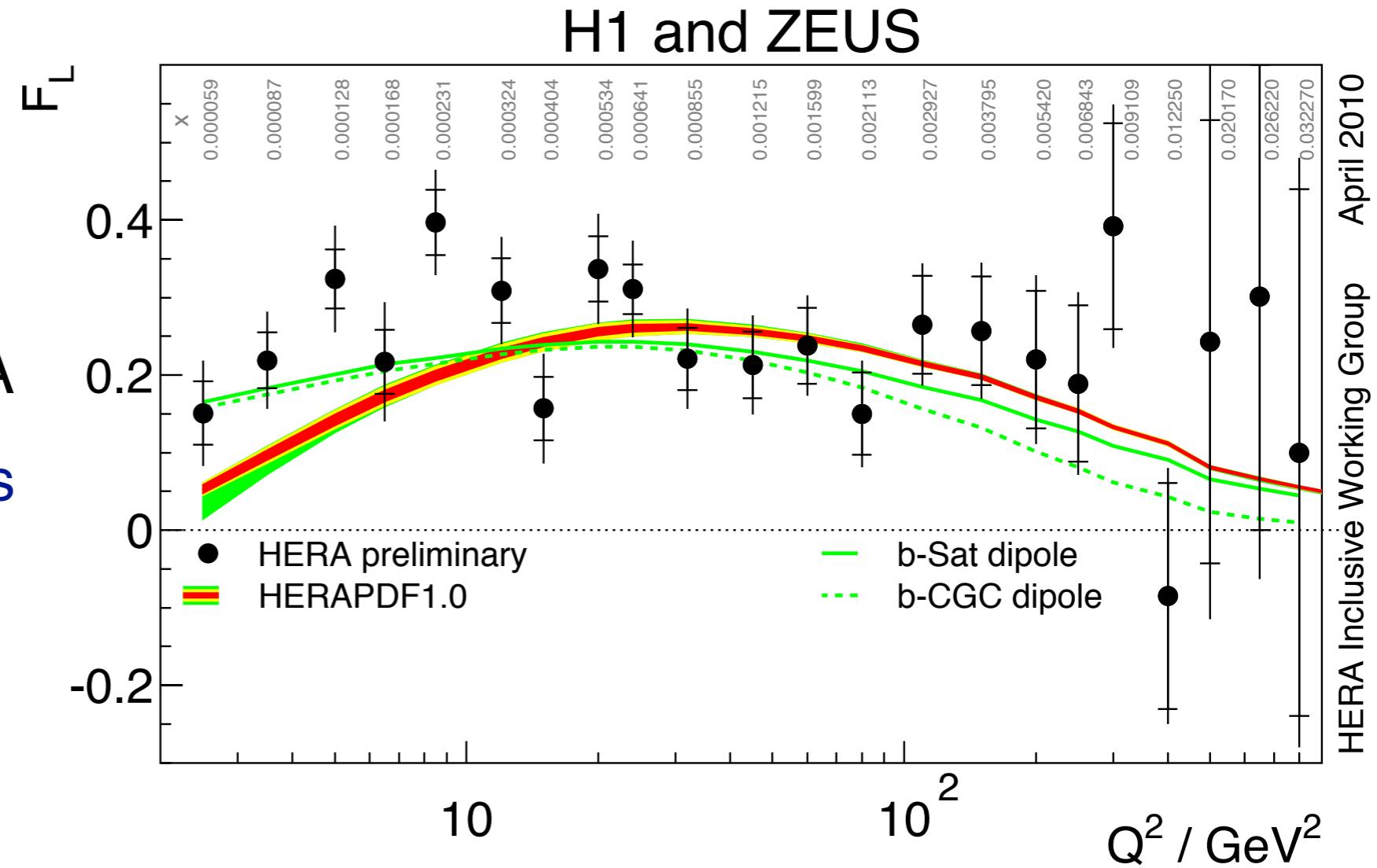
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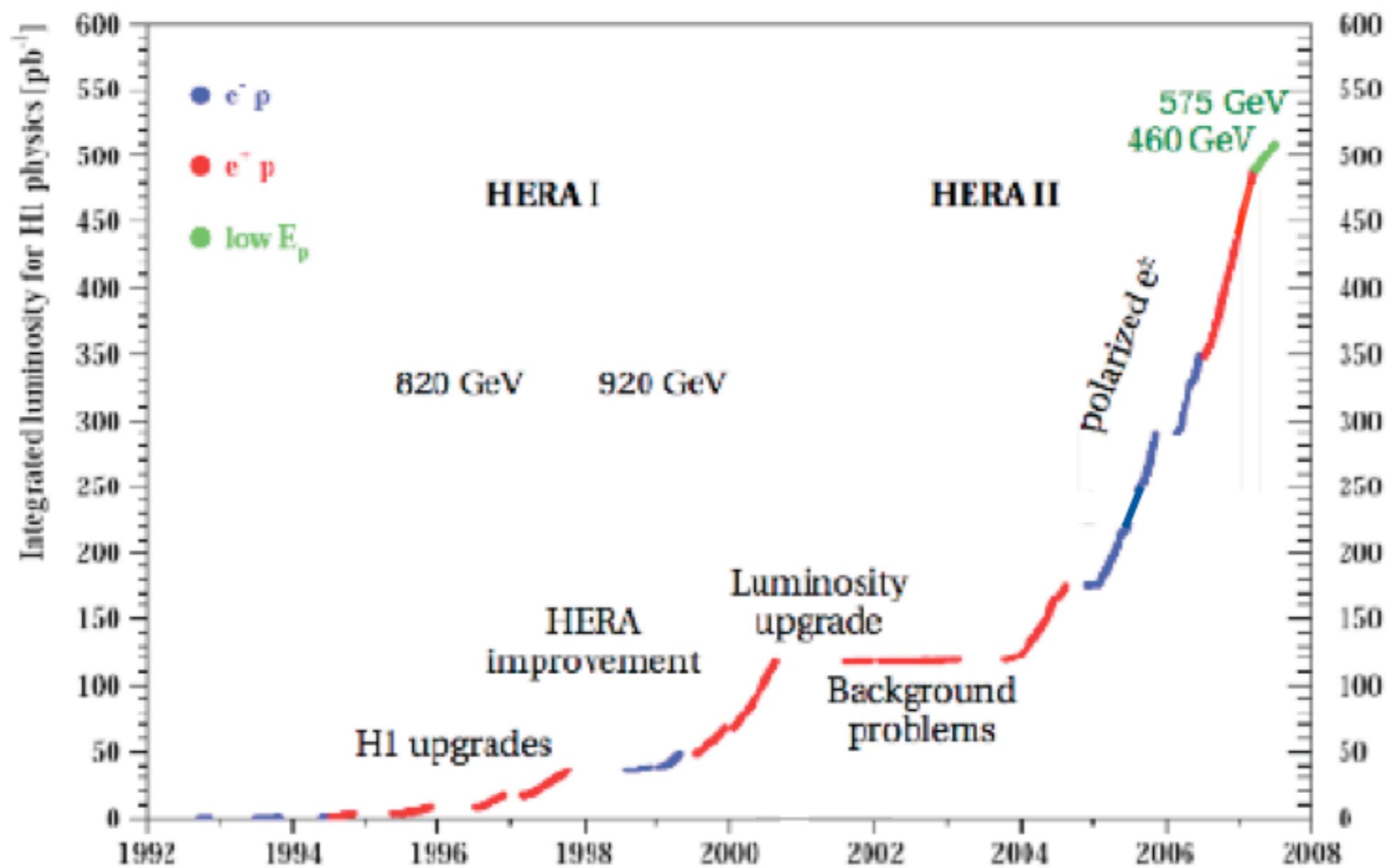


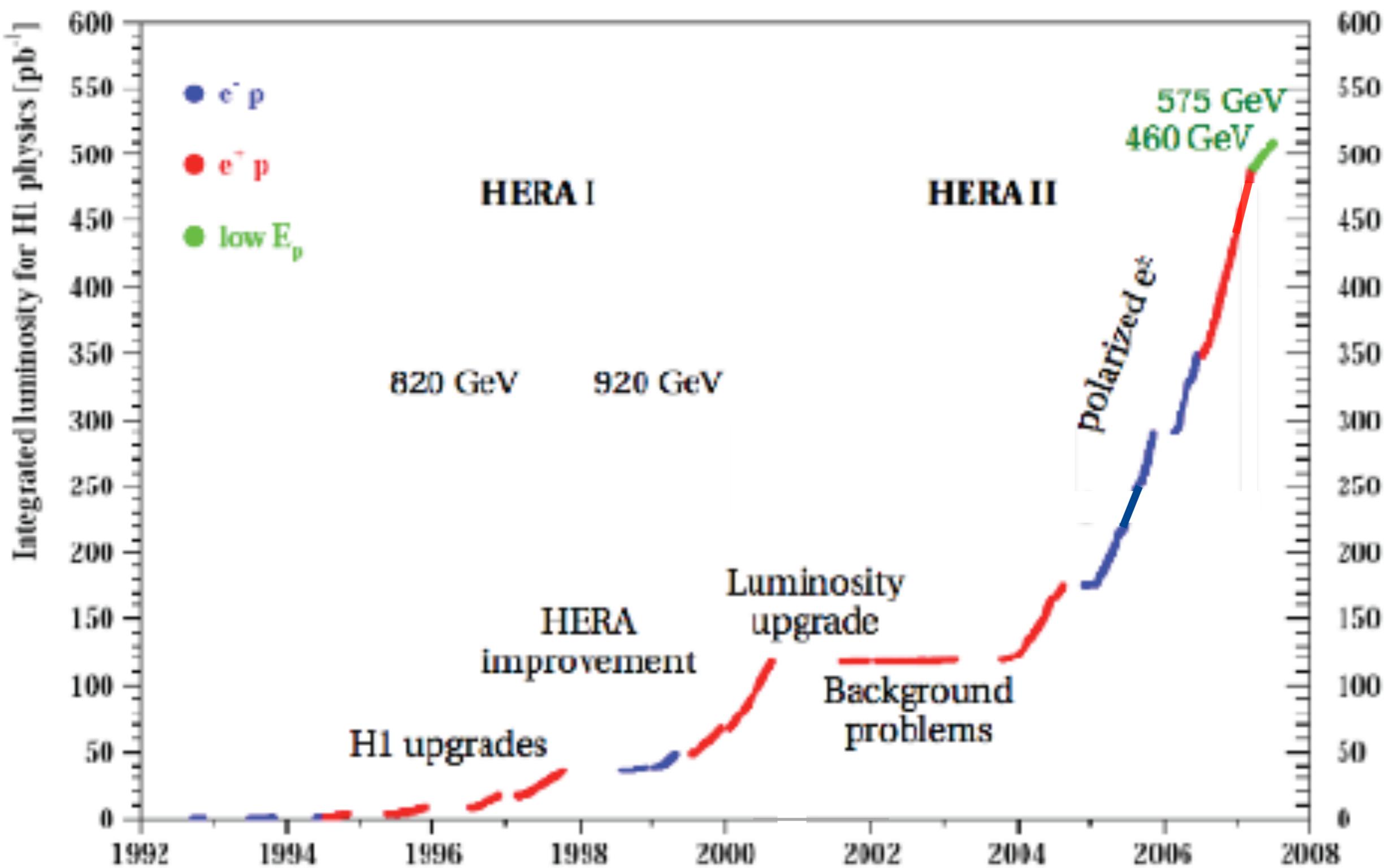
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- Note that non-linear fits describe the data better at the lowest x

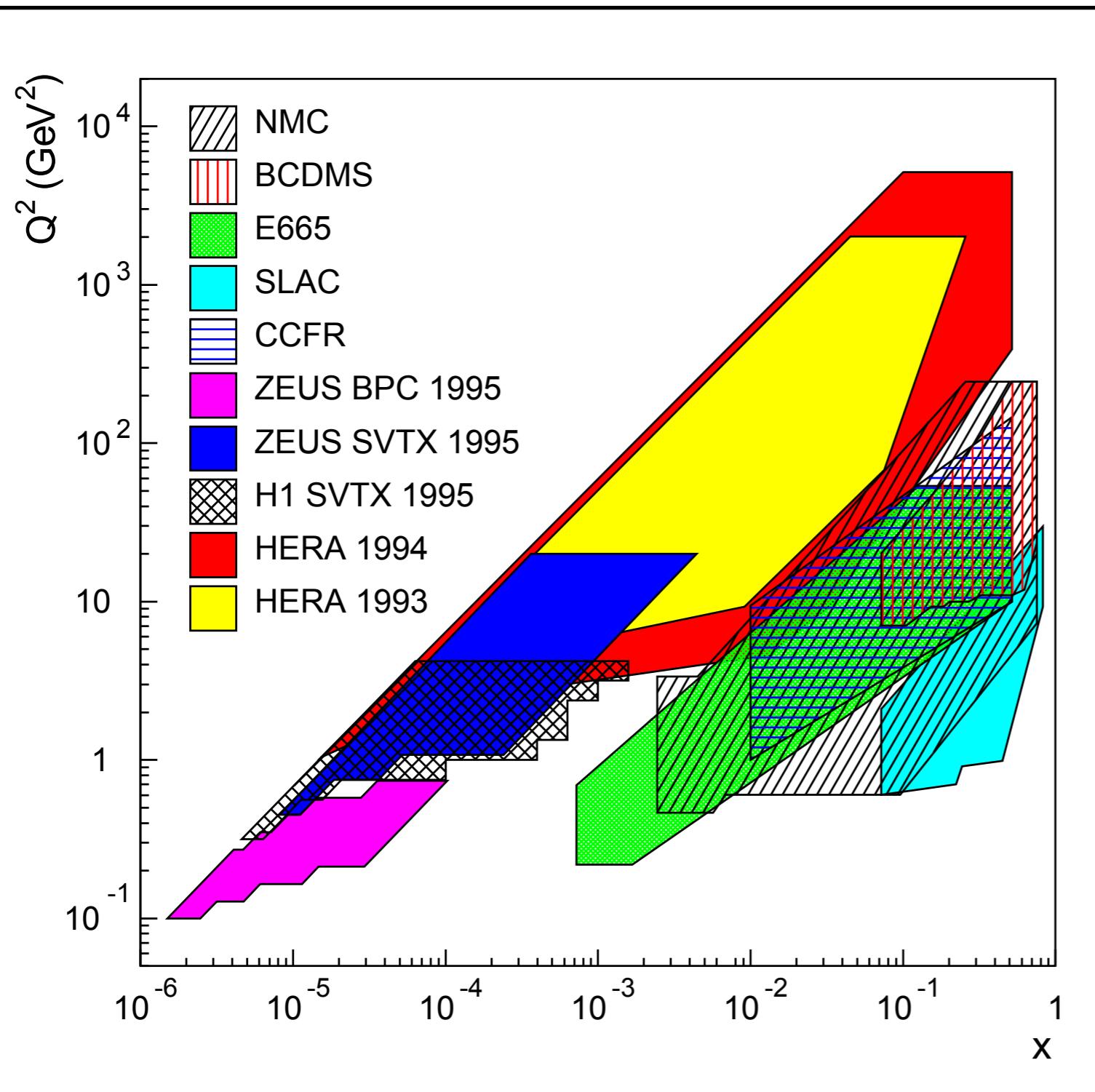






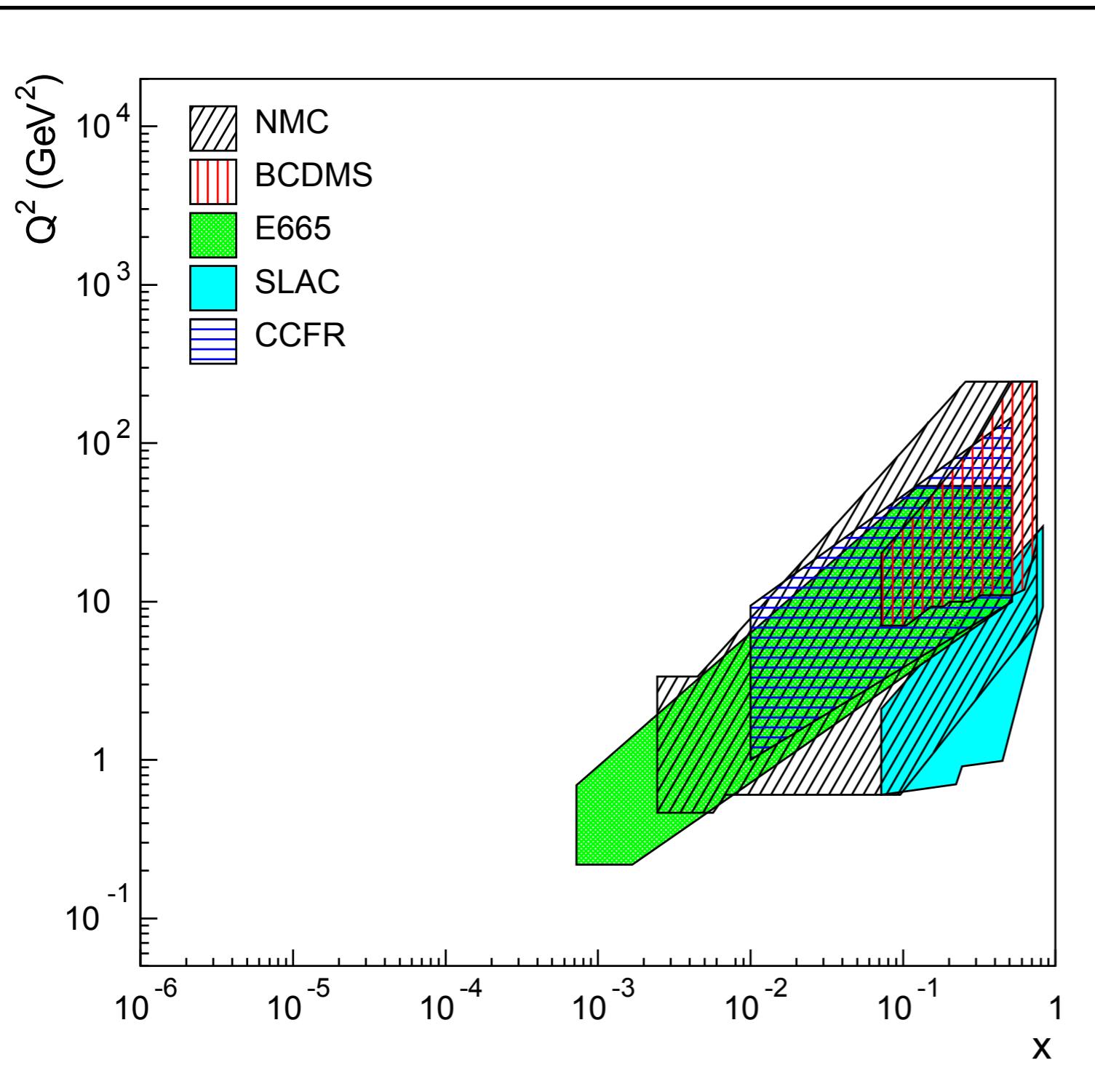
INTRO SLIDES

Requirements for an Electron-Ion Collider



Well mapped in $e+p$

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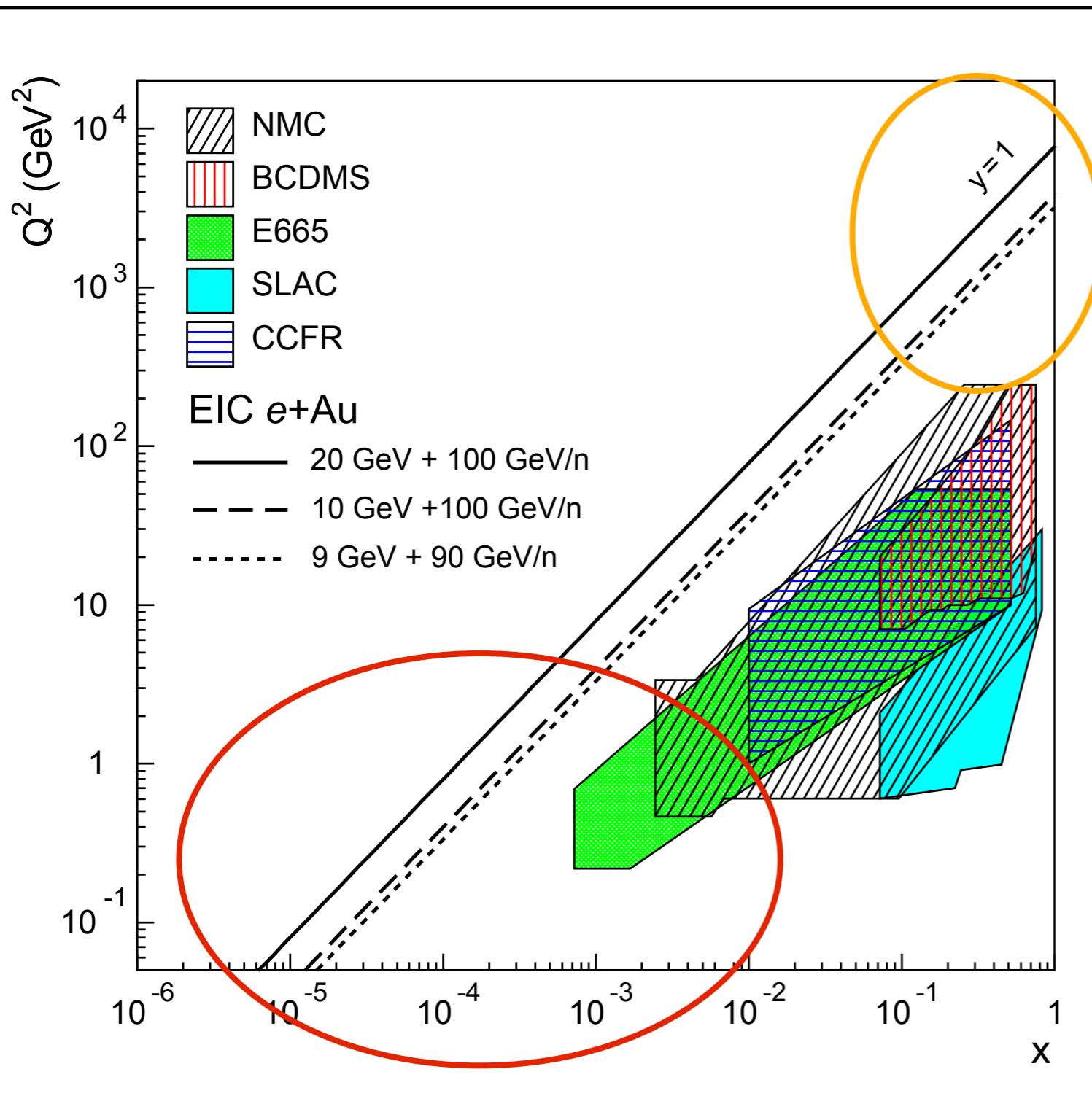


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- many with small A
- low statistics

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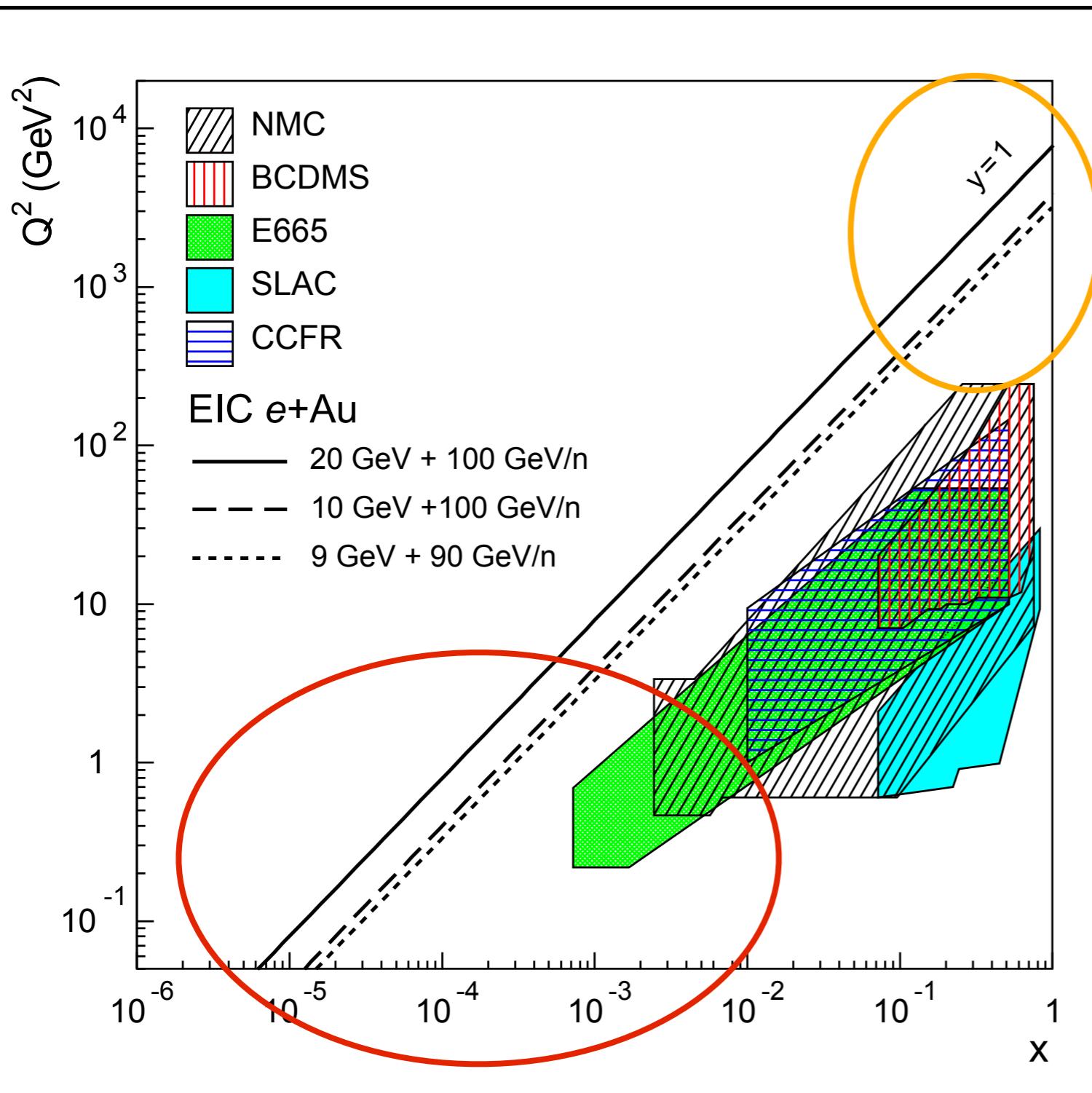
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Electron Ion Collider:

- $\mathcal{L}(\text{EIC}) > 100 \times \mathcal{L}(\text{HERA})$
- Electrons
 - $E_e = 3 - 30 \text{ GeV}$
 - polarized
- Hadron Beams
 - $E_A = 130 \text{ GeV}$
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 - $A = p \rightarrow U$
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Requirements for an Electron-Ion Collider



Terra incognita: small- x , $Q \leq Q_s$
high- x , large Q^2

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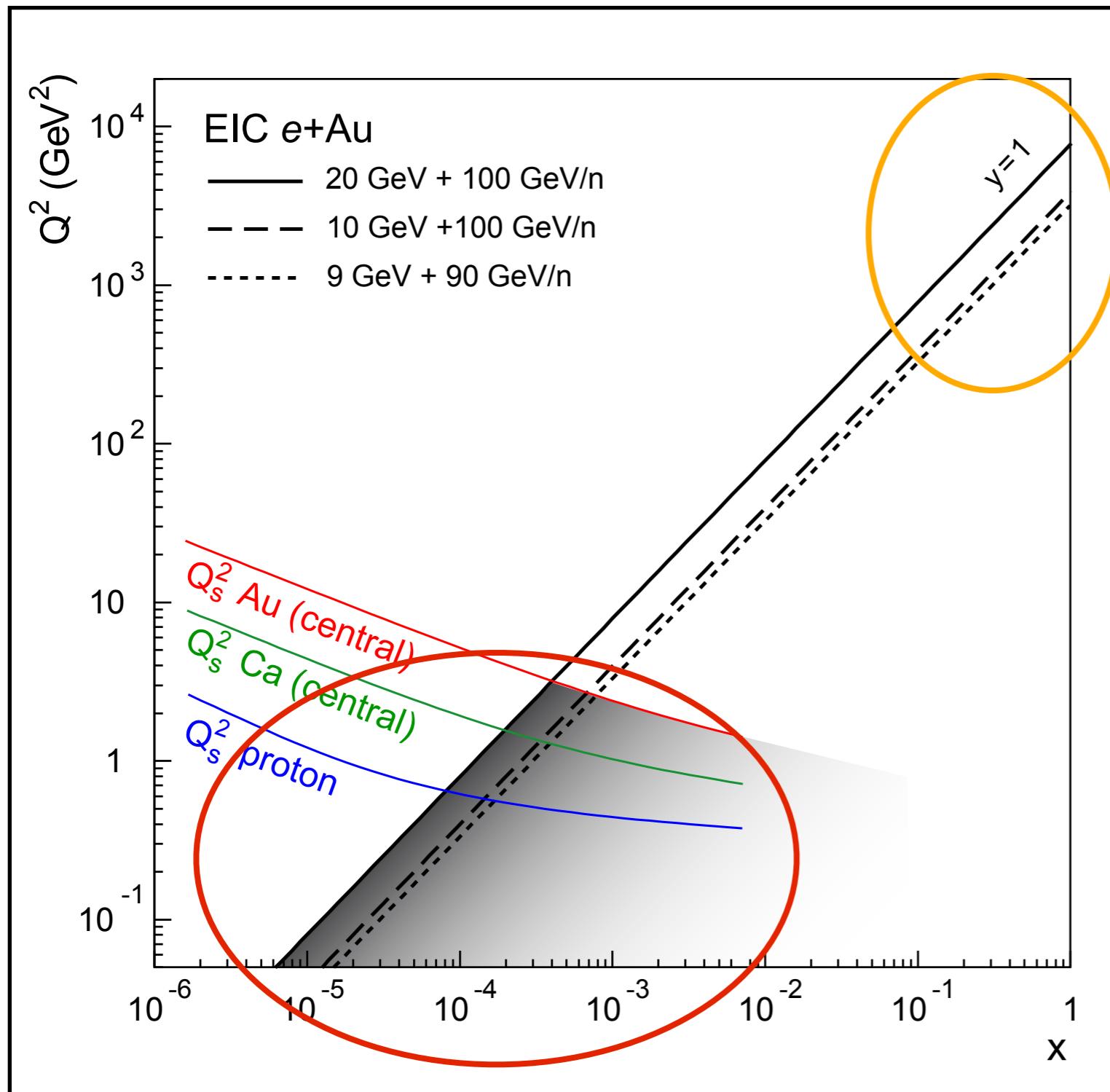
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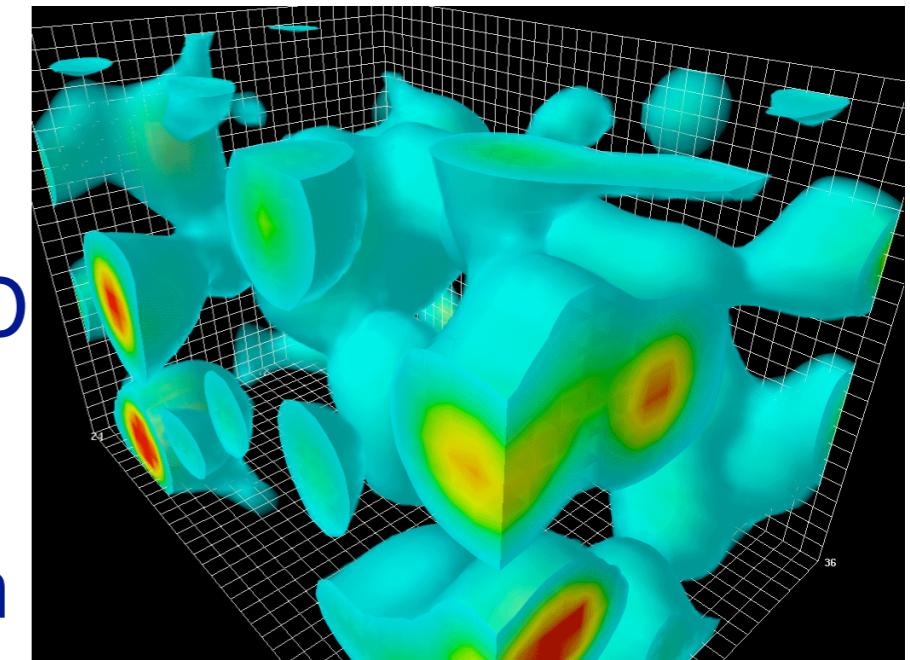
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What do we know about gluons?

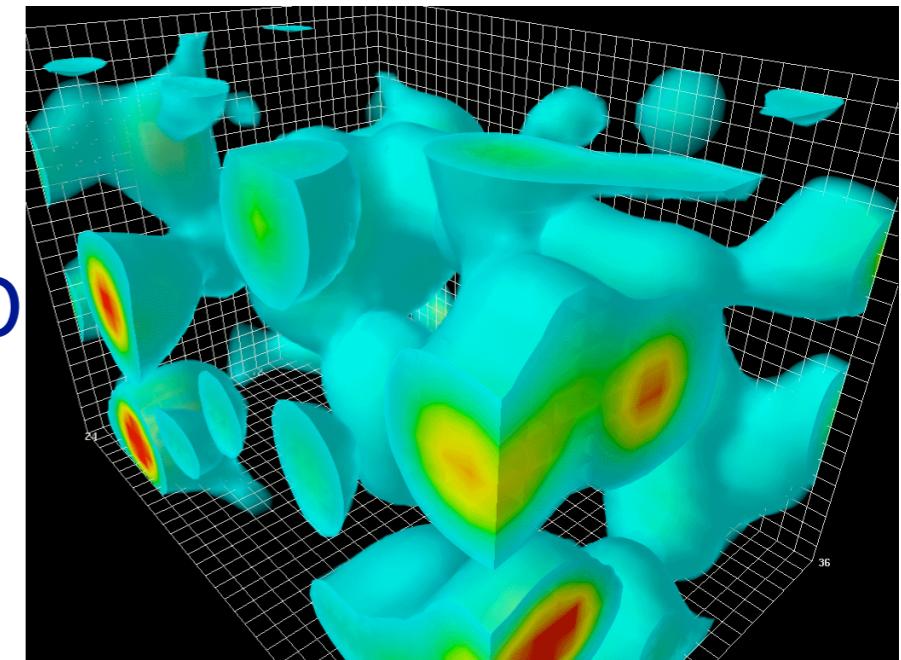
- **Gluons:**
 - Mediators of the strong interaction
 - Determine essential features of QCD
 - ▶ Asymptotic freedom from gluon loops
 - Dominate structure of QCD vacuum



Action (~energy) density fluctuations of gluon-fields in QCD vacuum ($2.4 \times 2.4 \times 3.6$ fm) (Derek Leinweber)

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- Hard to “see” glue in the low-energy world

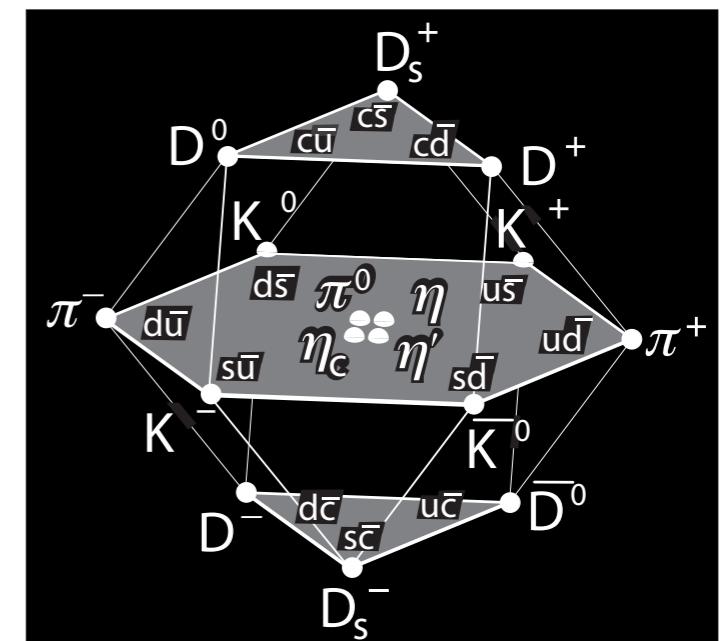
→ Gluon degrees of freedom “missing” in hadronic spectrum

▶ Constituent Quark Picture?

→ From DIS:

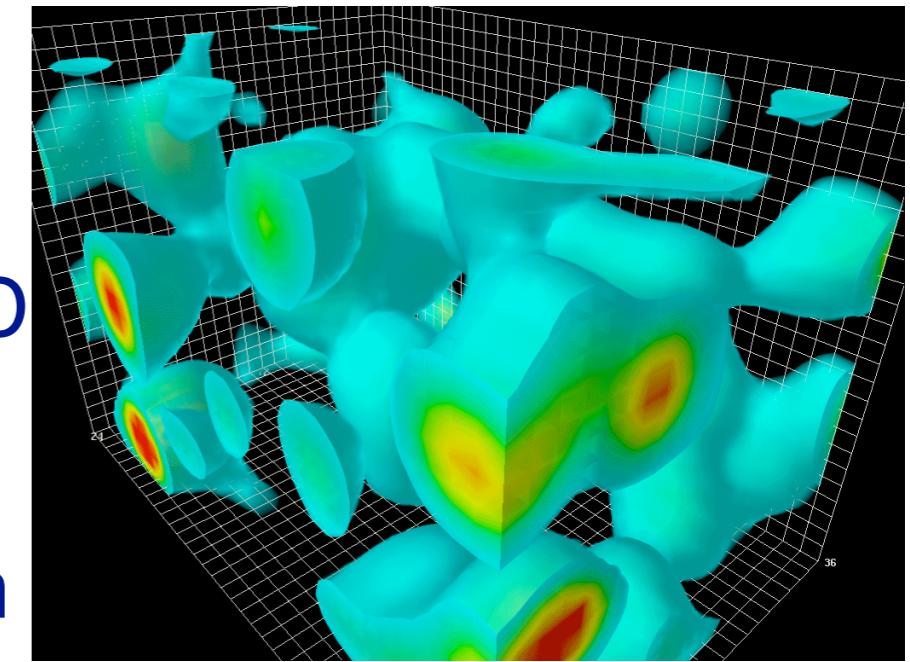
- Drive the structure of baryonic matter already at medium-x

★ Crucial players at RHIC and LHC



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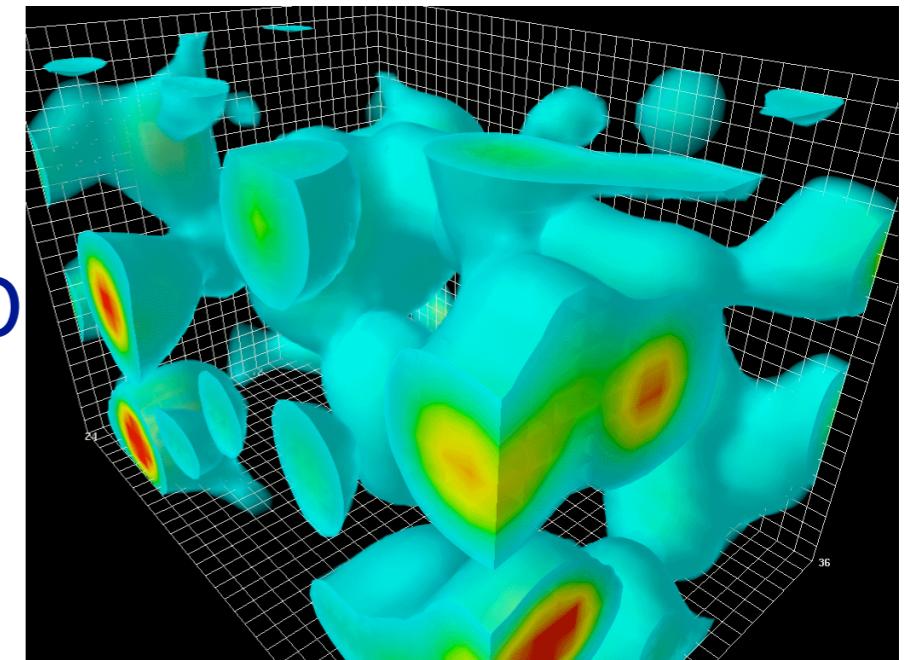


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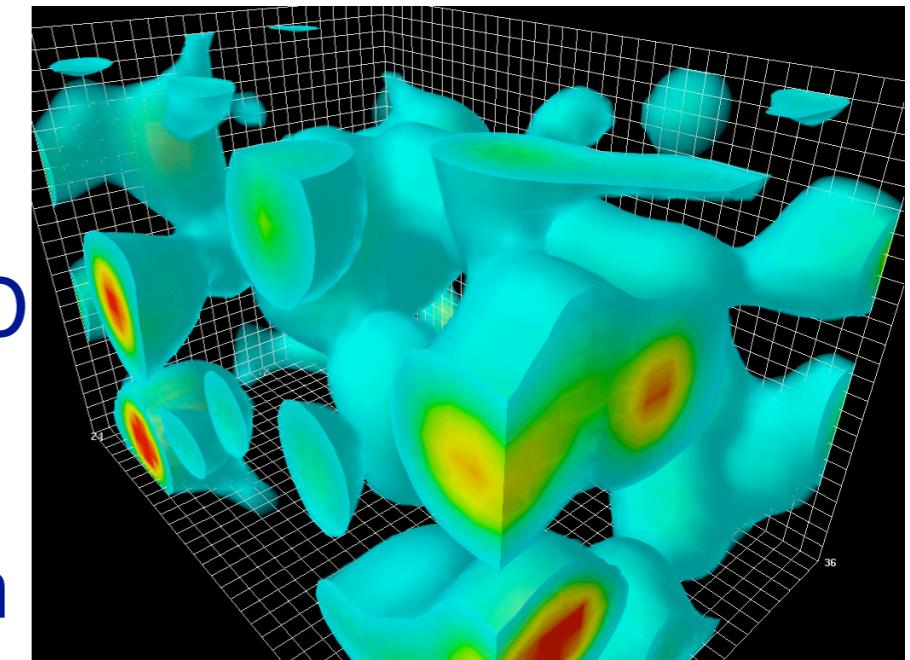
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- What is the **spatial** and **momentum** distribution of gluons in nuclei/nucleons?
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- What role do the **gluons** play in the **spin structure** of the nucleon?

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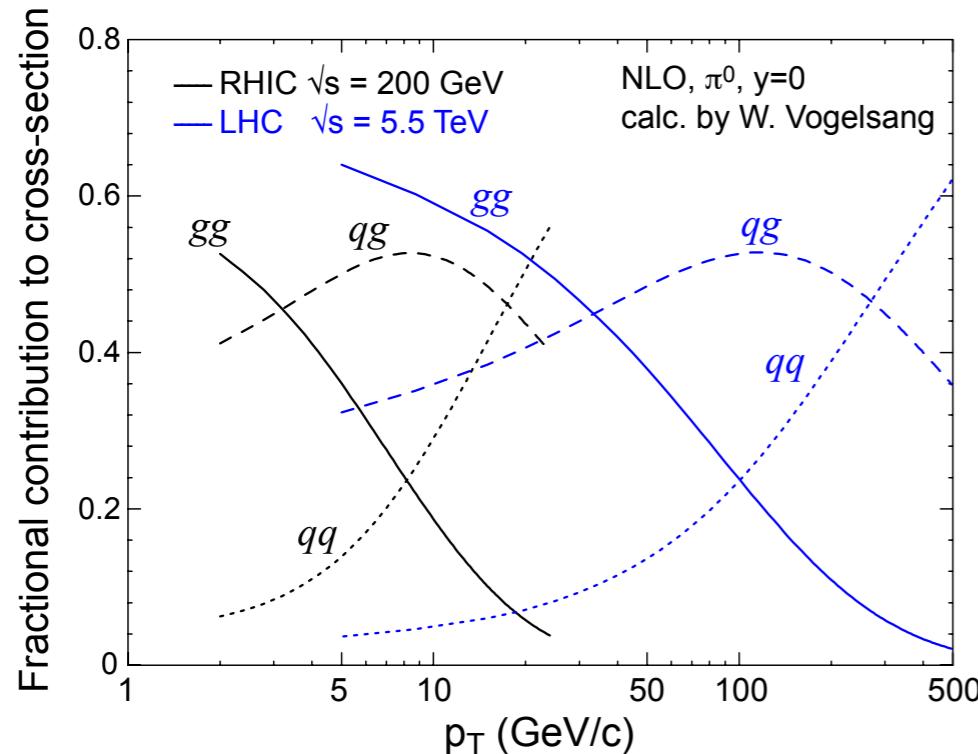
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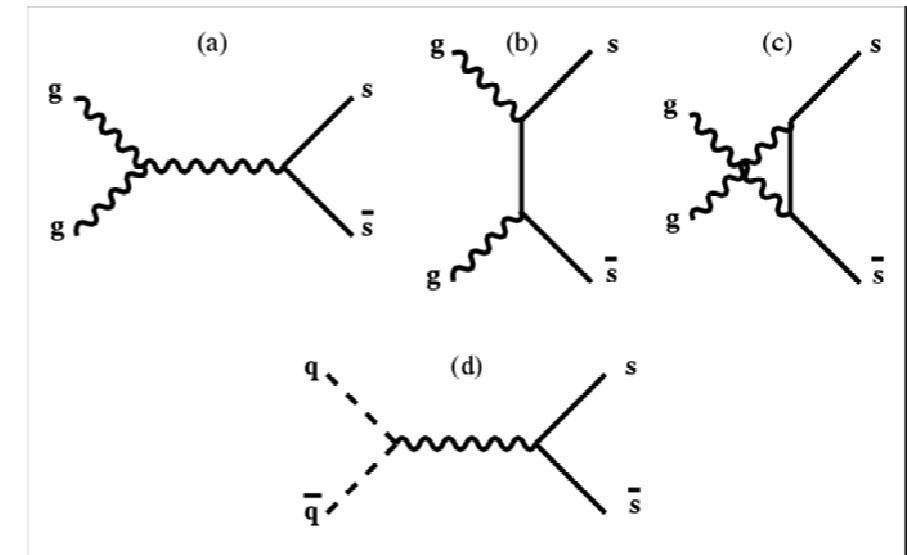
How do we get to the answers?

The role of gluons in hadronic collisions

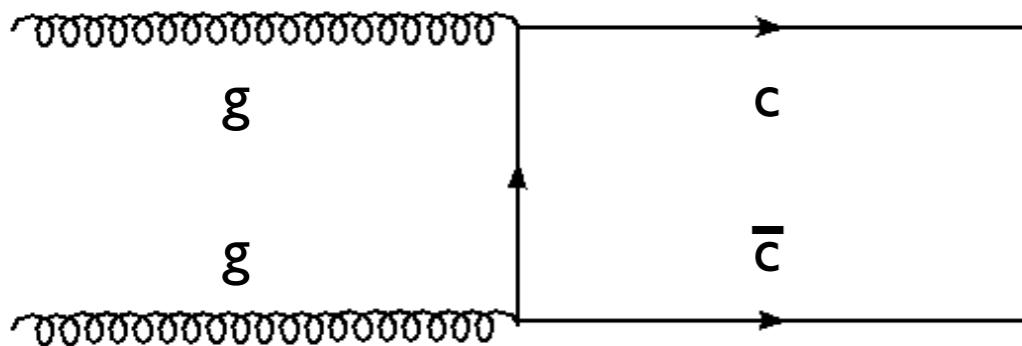
Jets (π^0 production)



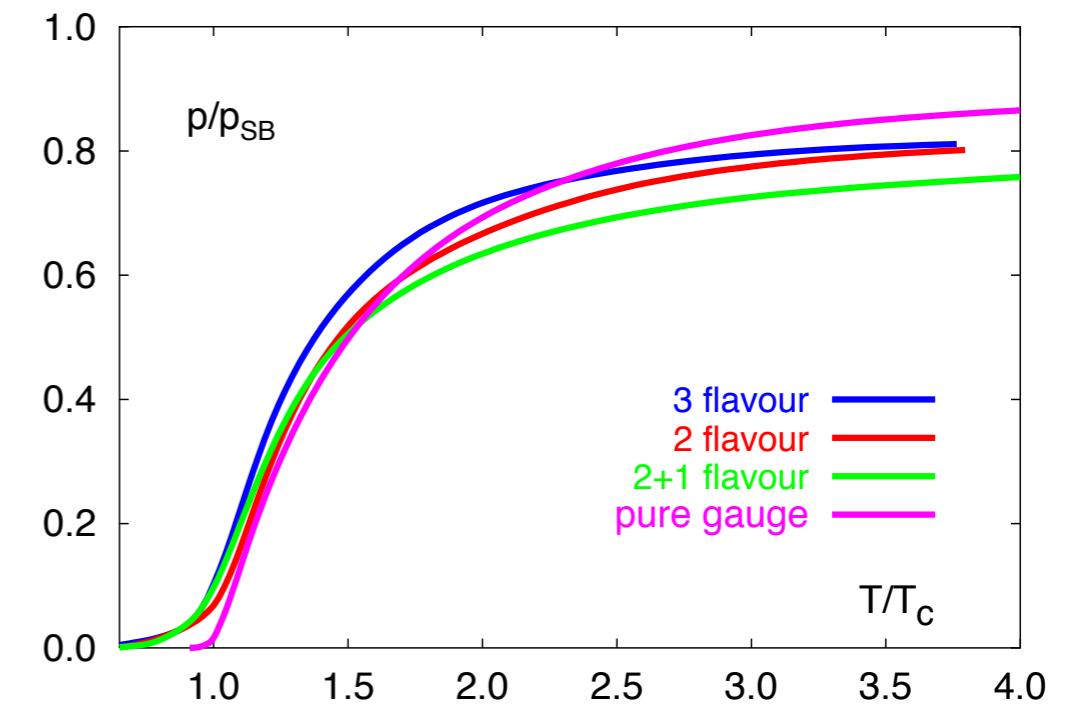
Strangeness Production



Heavy Flavour Production

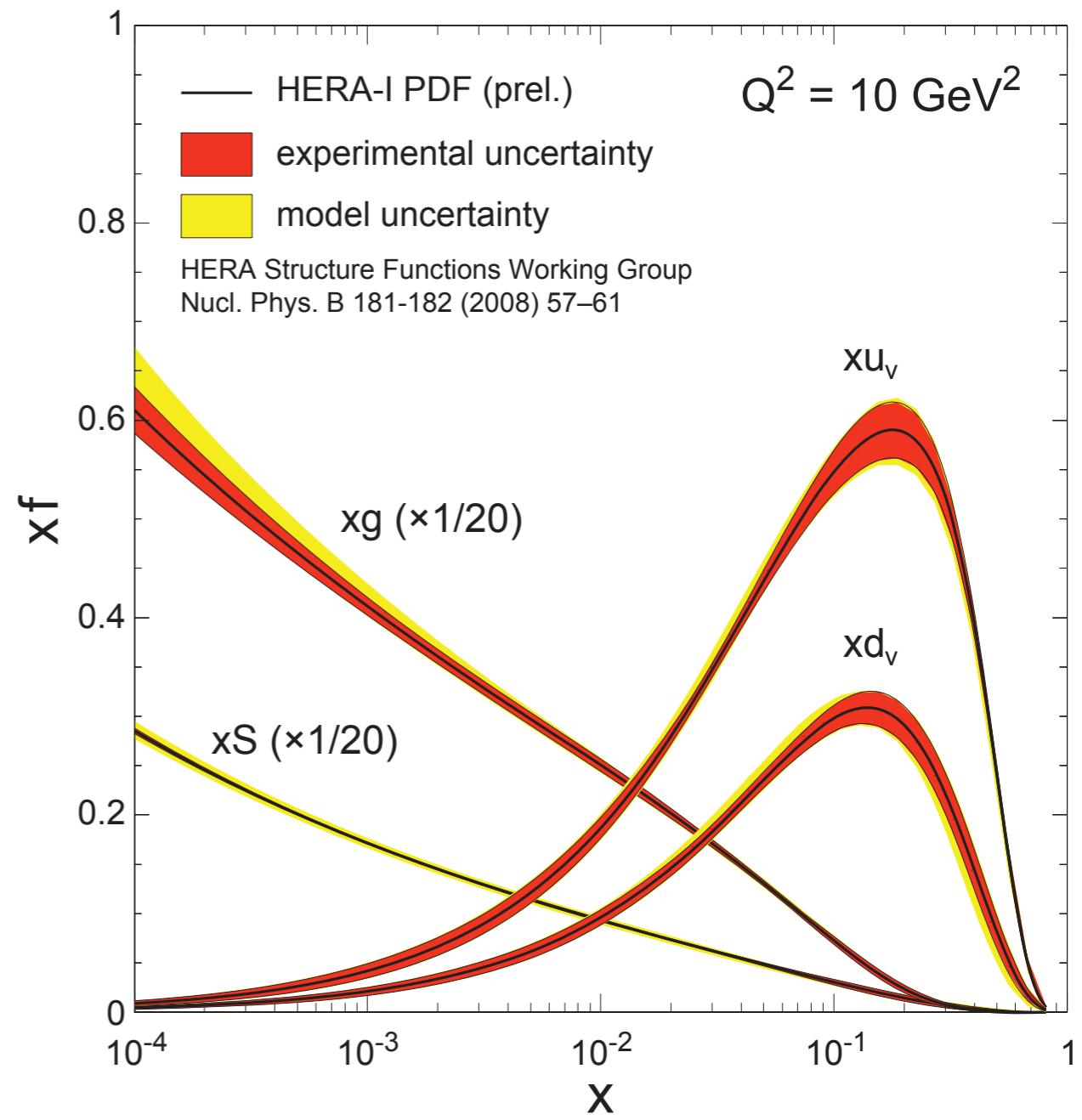


Lattice Gauge Theory

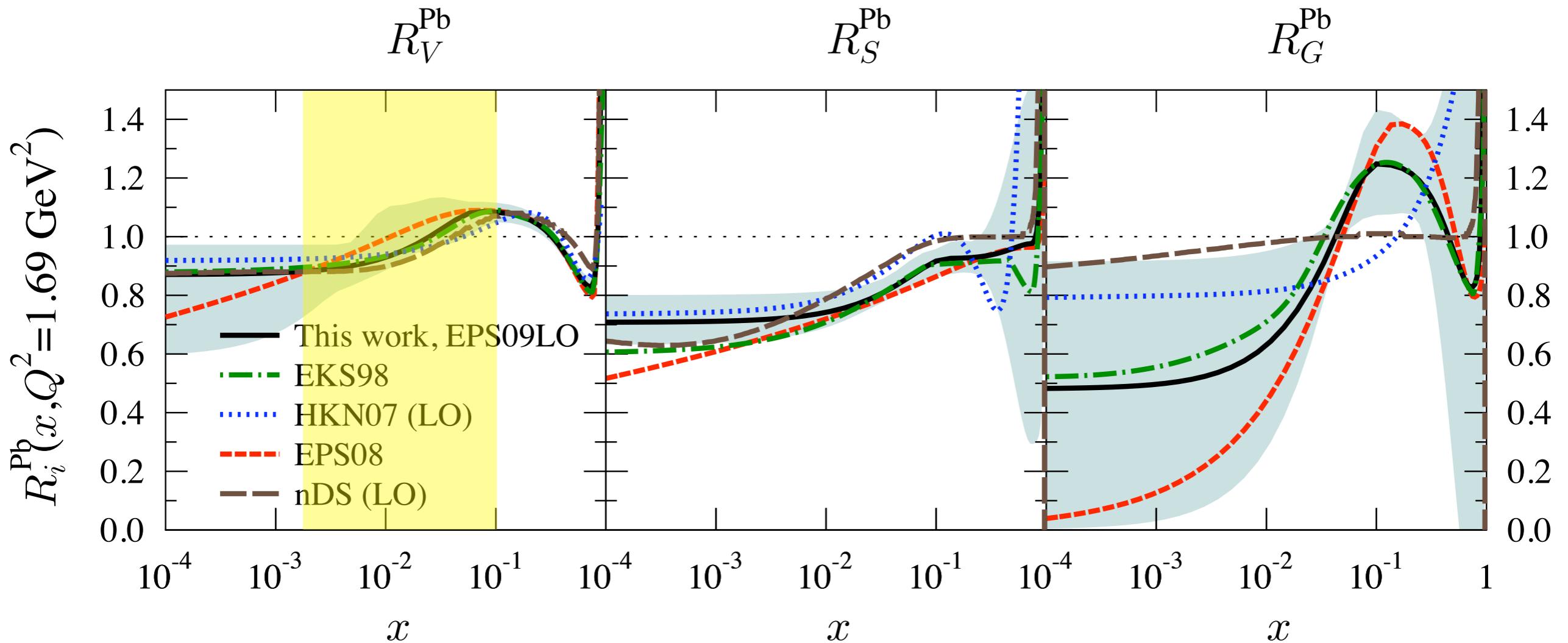


How well do we know gluon distributions in nucleons?

- HERA: e+p collisions:
 - 27.6 GeV (e^-) on
 - 920 GeV p
- Wealth of data allows a high-statistics extraction of valence quark, sea quark and gluon densities as a function of x_{Bj}
 - Gluons and sea quarks dominate over valence quarks at smaller values of x_{Bj}
- Small experimental and model uncertainties

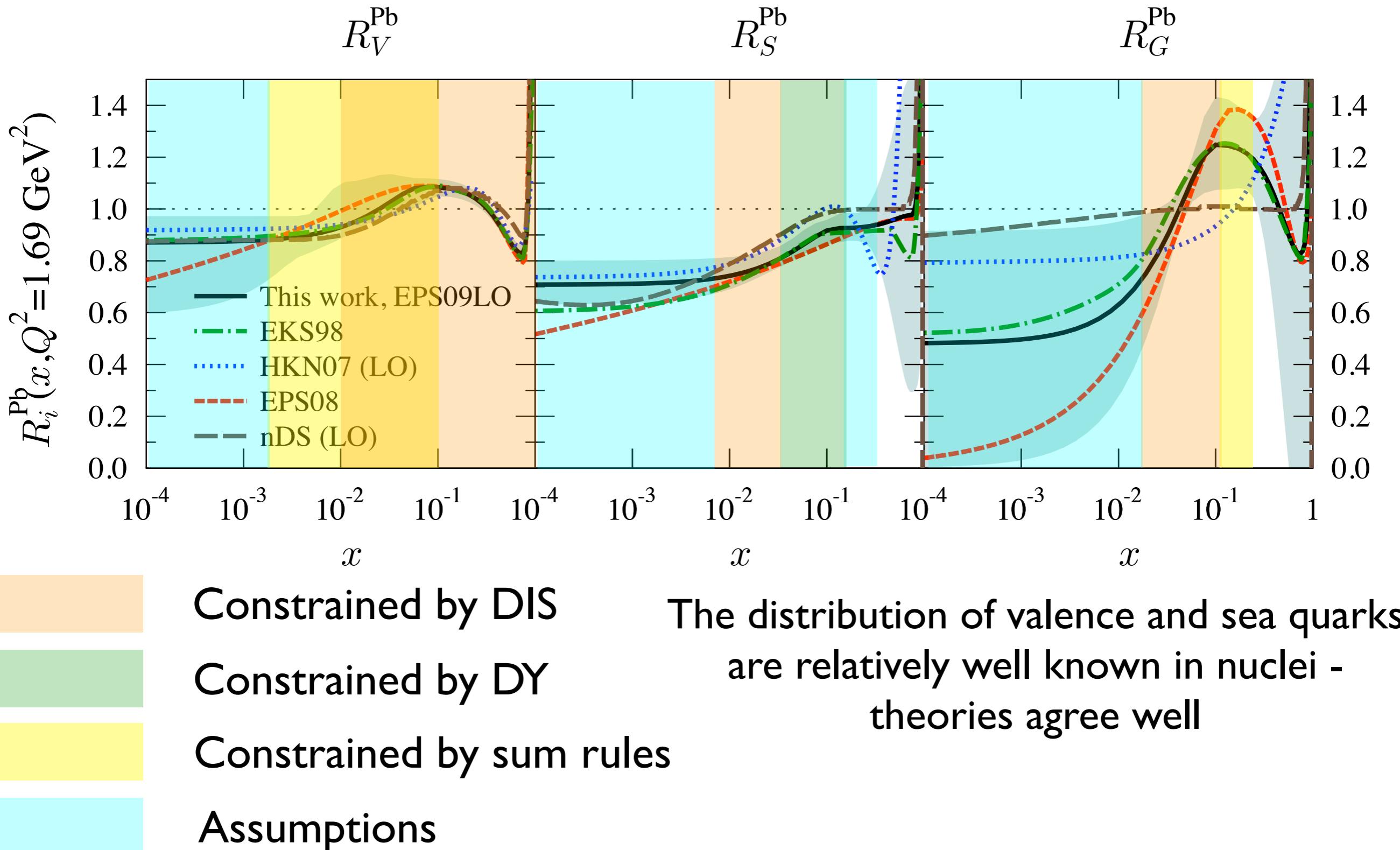


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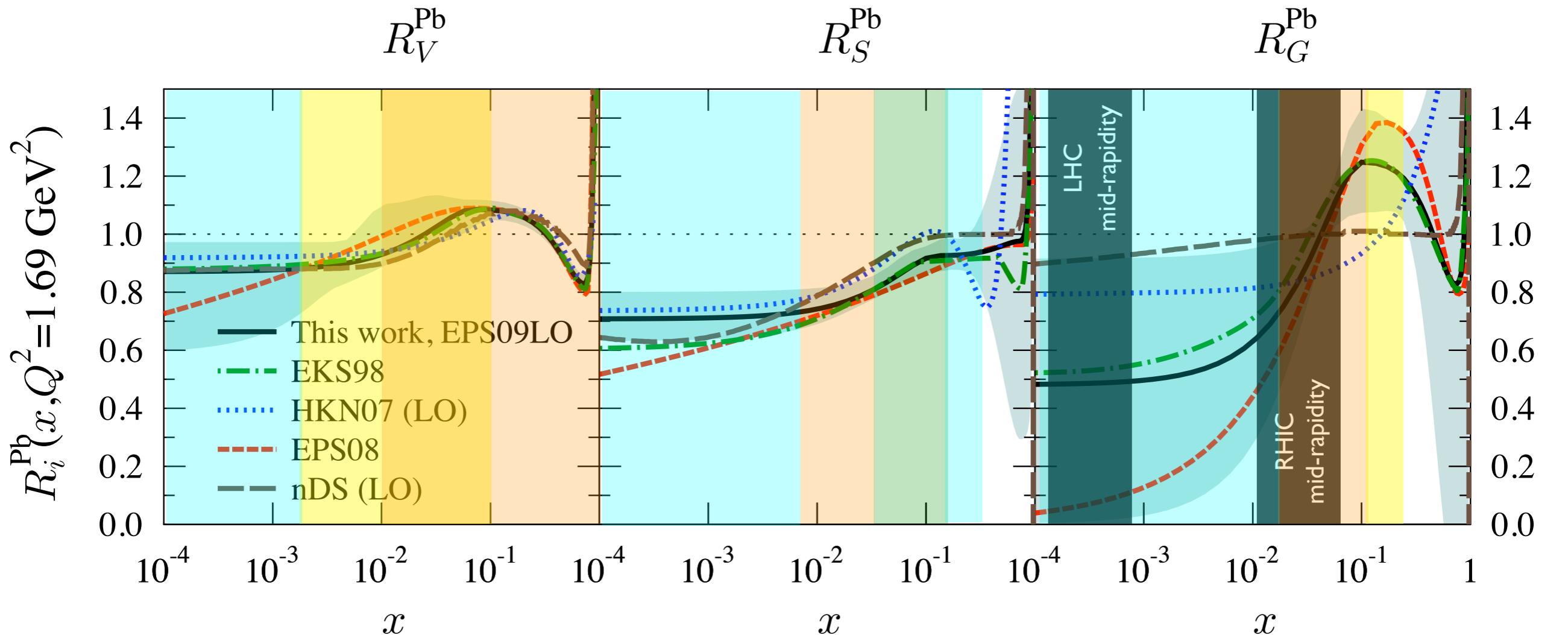


The distribution of valence and sea quarks
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What about gluons in nuclei?



Constrained by DIS

Constrained by DY

Constrained by sum rules

Assumptions

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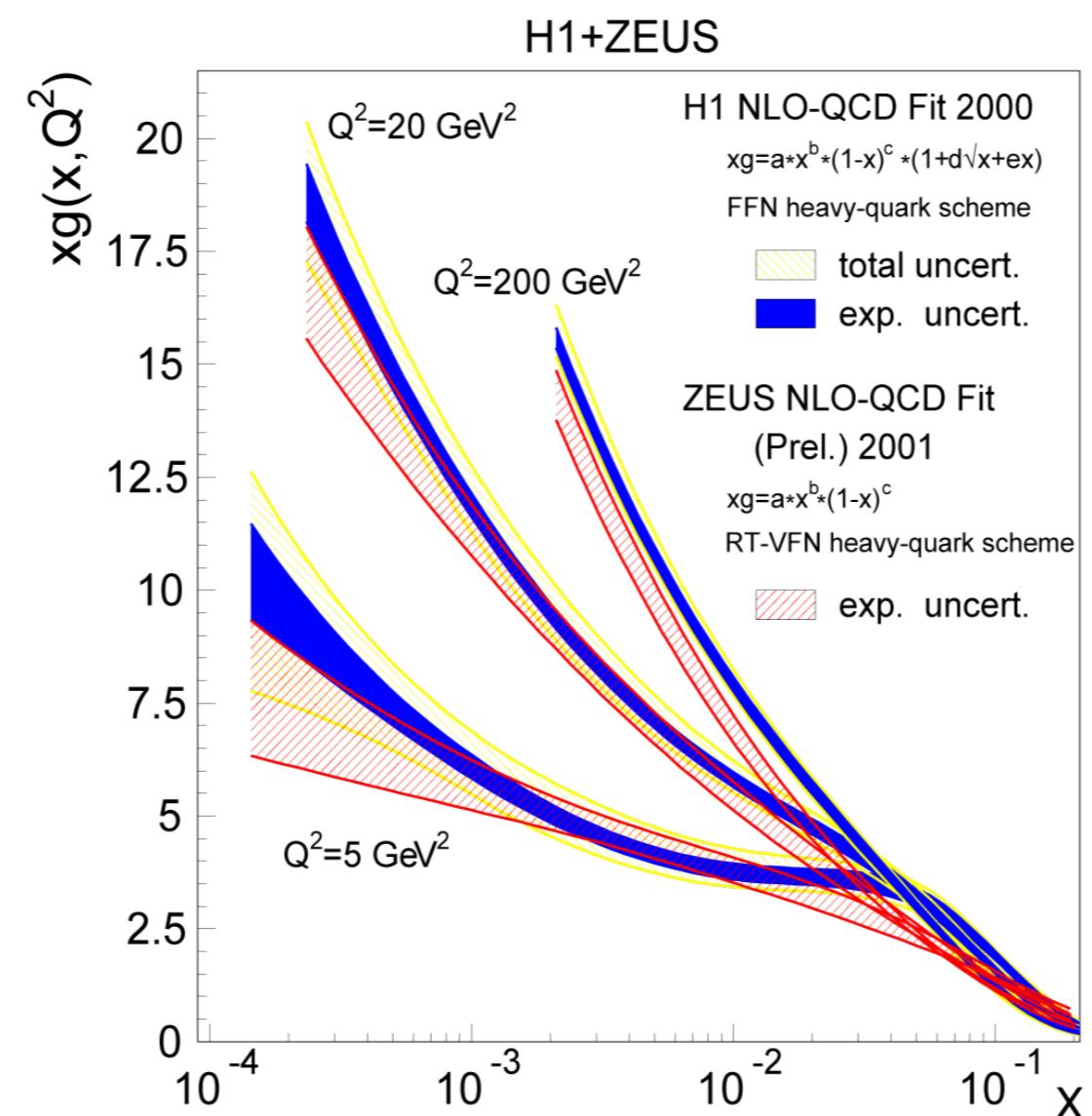
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

The problem with our current understanding

- Using the Linear DGLAP evolution model:
 - Linear evolution has a built-in high-energy “catastrophe”
 - xG has rapid rise with decreasing x (and increasing Q^2) ⇒ violation of Froissart unitarity bound

$$\sigma_{tot} = \frac{\pi}{m_\pi^2} (\ln s)^2$$

- ▶ Must have saturation to tame the growth



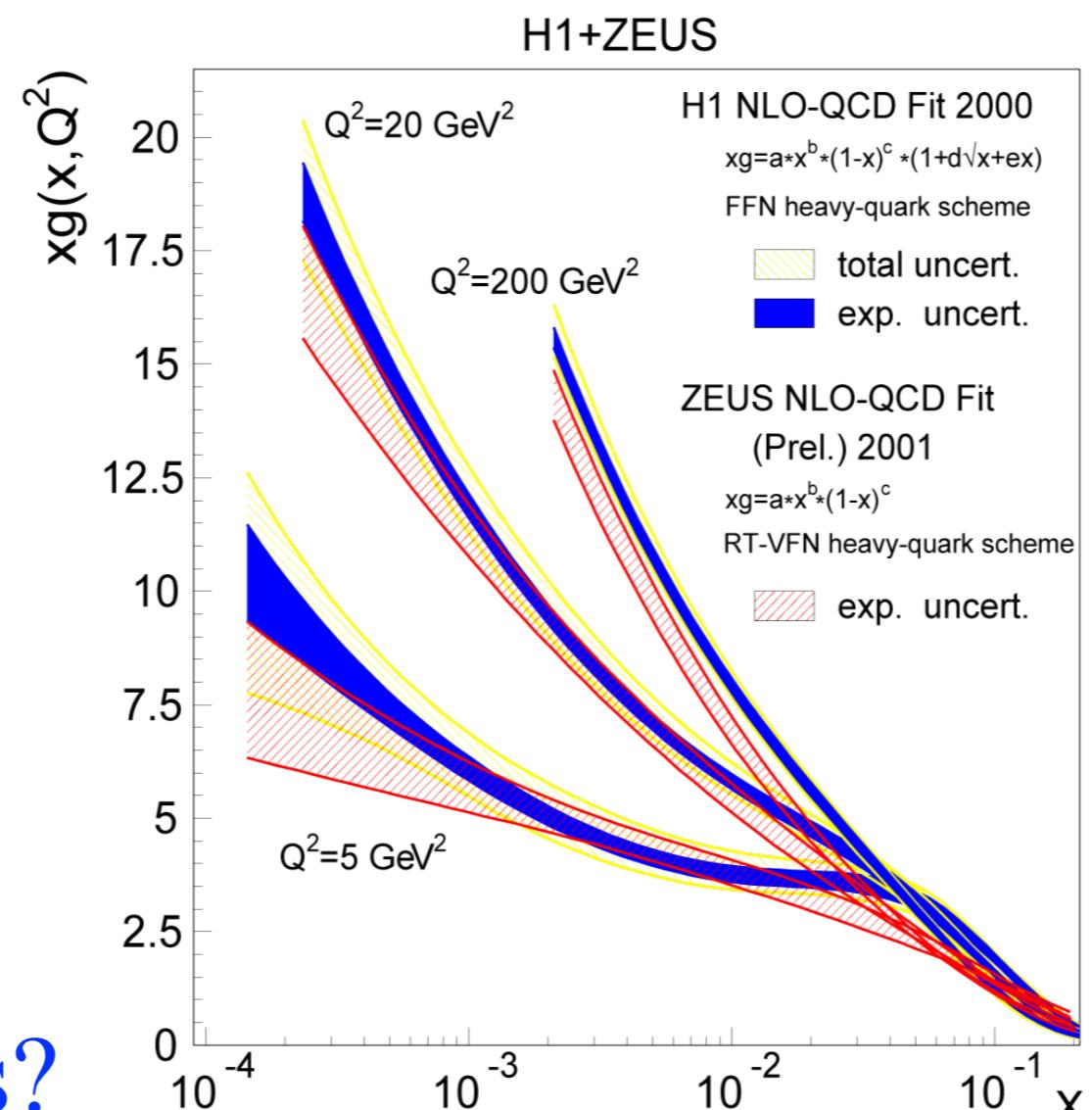
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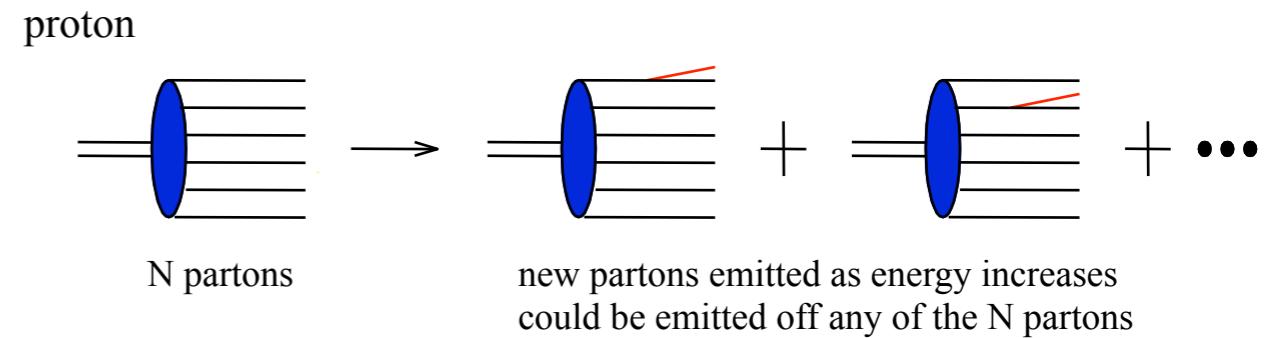
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What's the underlying dynamics?



Non-linear QCD - Saturation

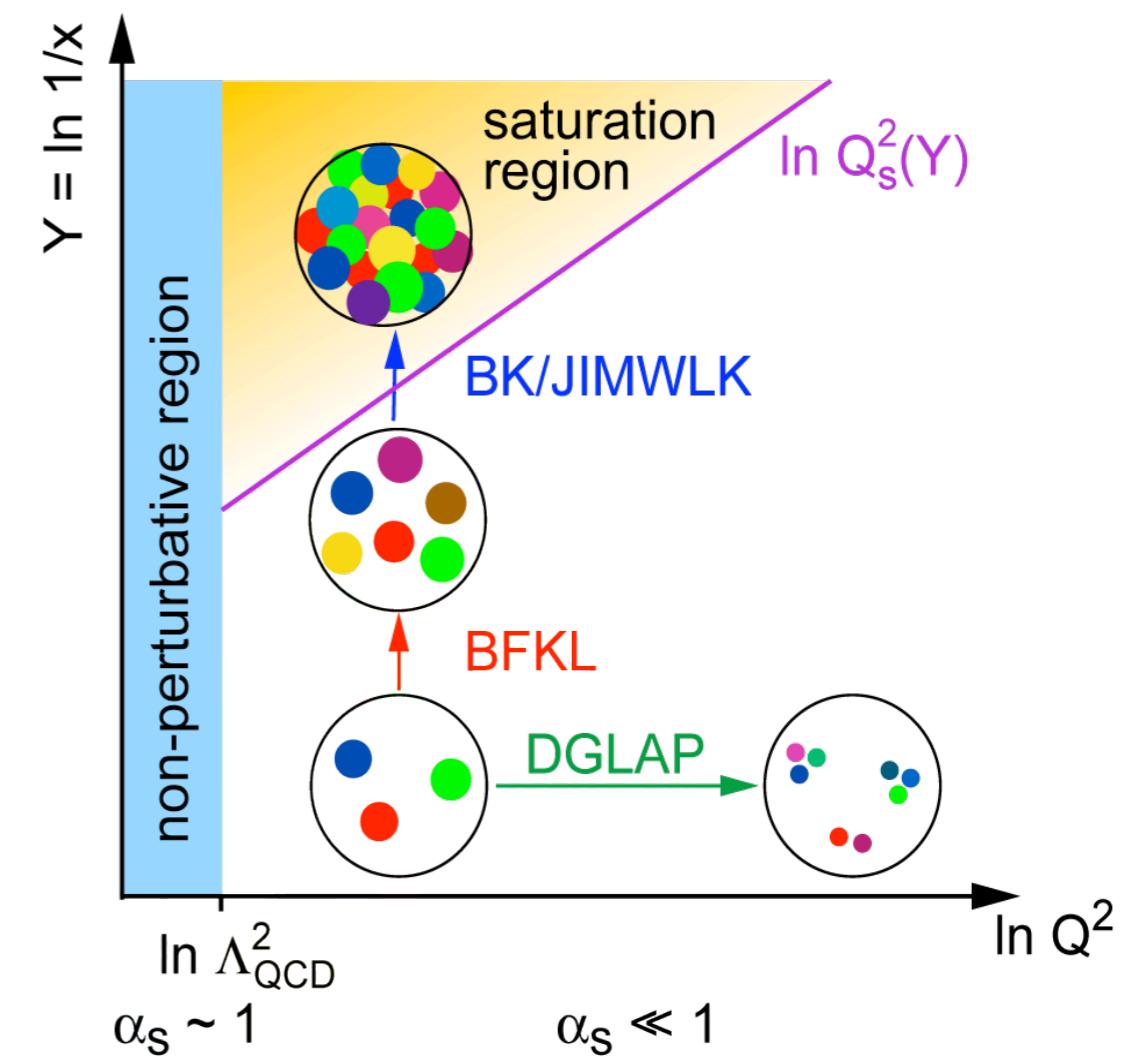
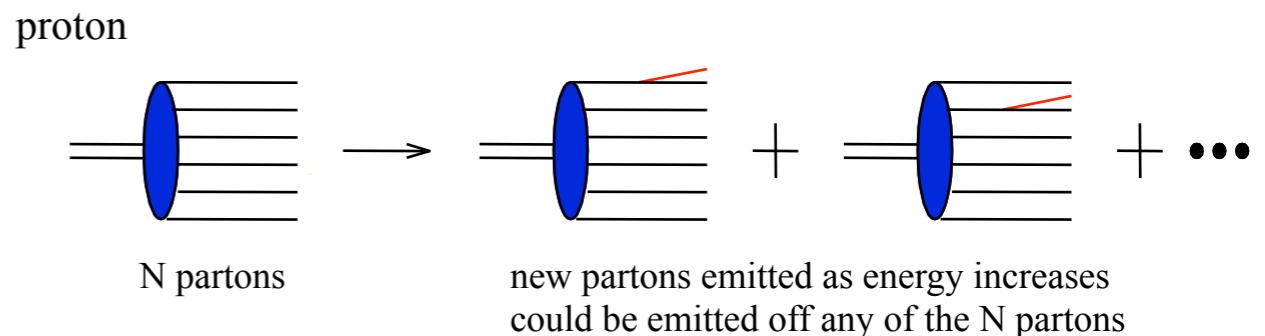


Non-linear QCD - Saturation

- **BFKL:** evolution in x

→ linear

- ▶ explosion in colour field at low- x



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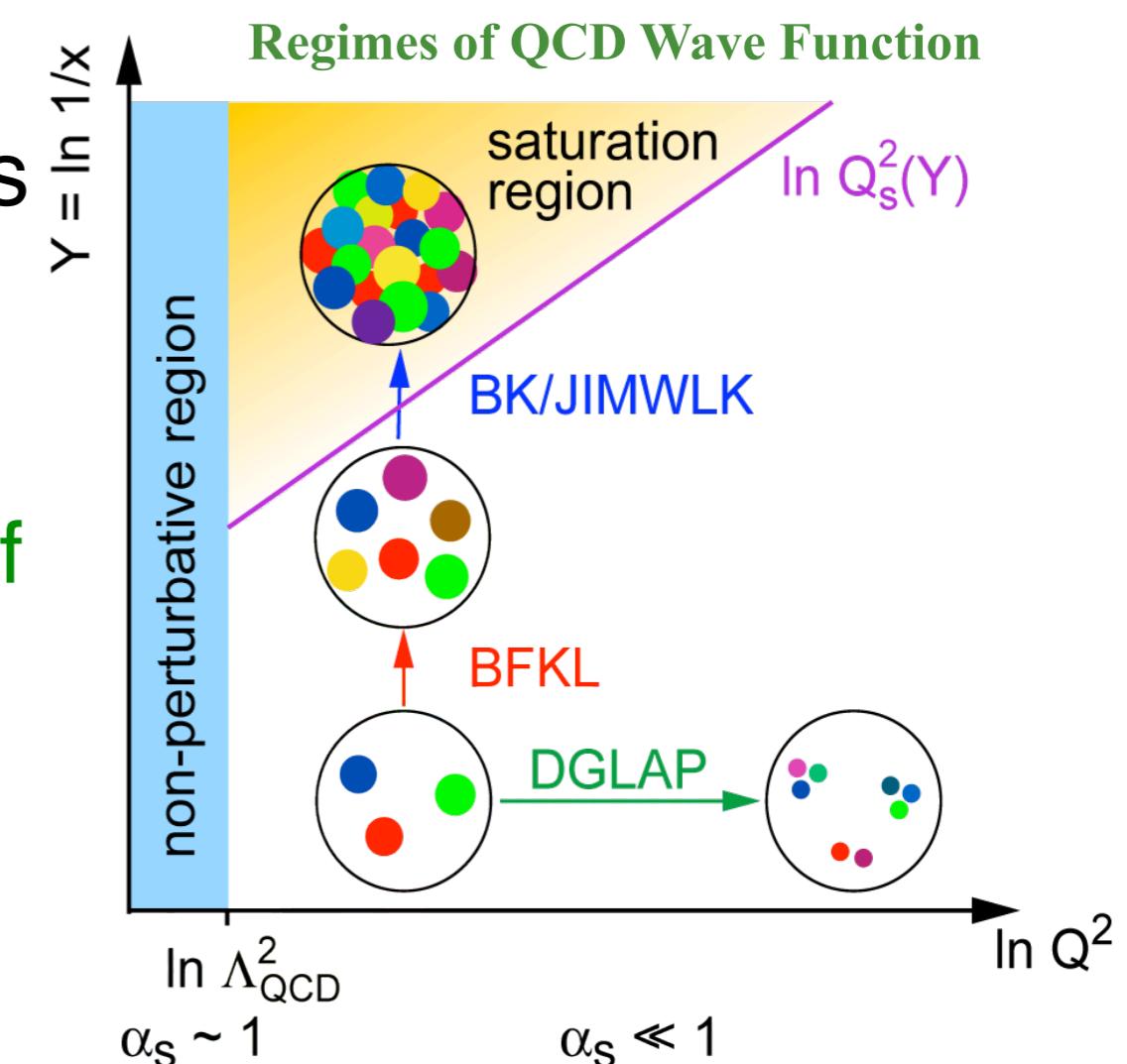
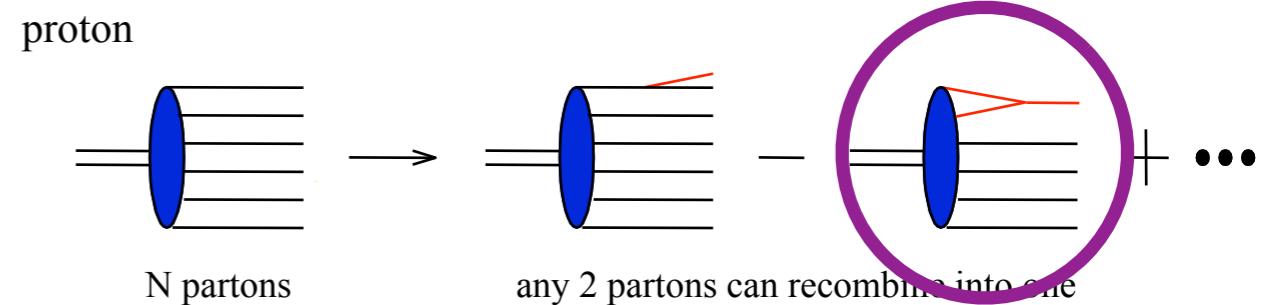
► explosion in colour field at low- x

- Non-linear **BK/JIMWLK** equations

→ non-linearity \Rightarrow saturation

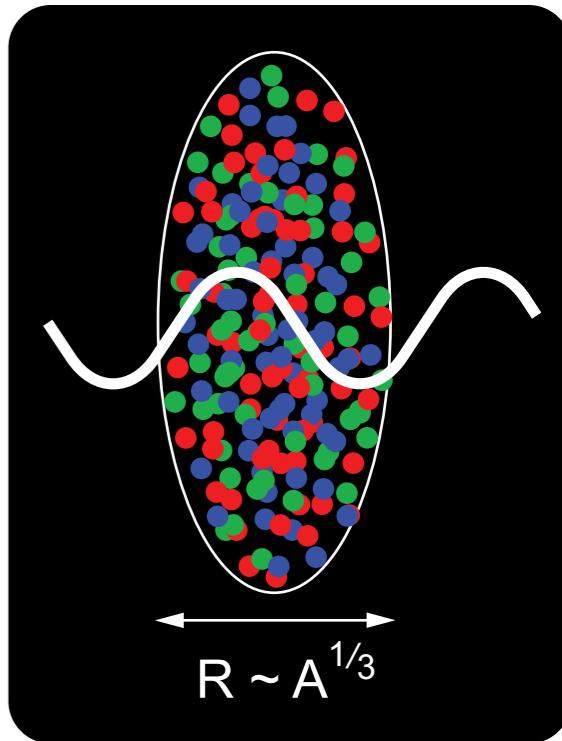
► Allows for the recombination of gluons in a dense gluonic medium

→ characterised by the saturation scale, $Q_s(x, A)$



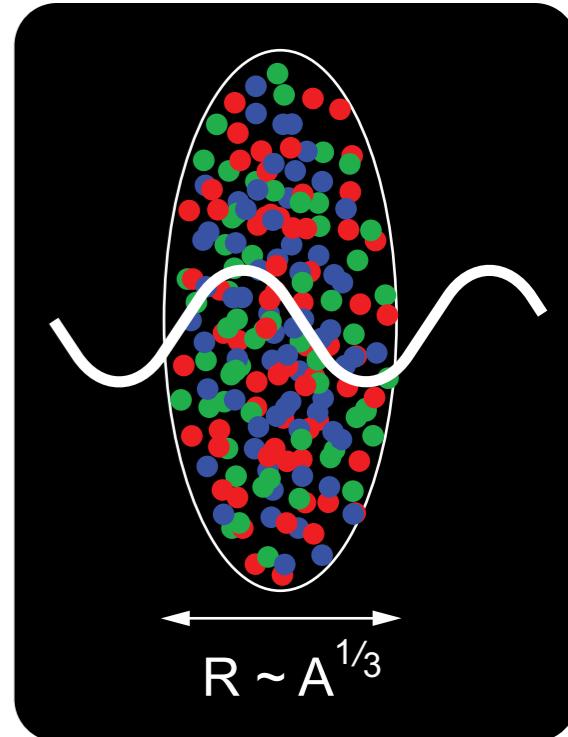
The Nuclear “Oomph Factor”

- Enhancing Saturation effects:
 - Probes interact over distances $L \sim (2m_n x)^{-1}$
 - For probes where $L > 2R_A (\sim A^{1/3})$ cannot distinguish between nucleons in front or back of the nucleus.
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Simple geometric considerations lead to:

$$Q_s^2 \propto \frac{\alpha_s x G(x, Q_s^2)}{\pi R_A^2}$$

HERA: $xG \propto \frac{1}{x^{1/3}}$

A dependence: $xG_A \propto A$

Nuclear “Oomph” Factor:

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x} \right)^{1/3}$$

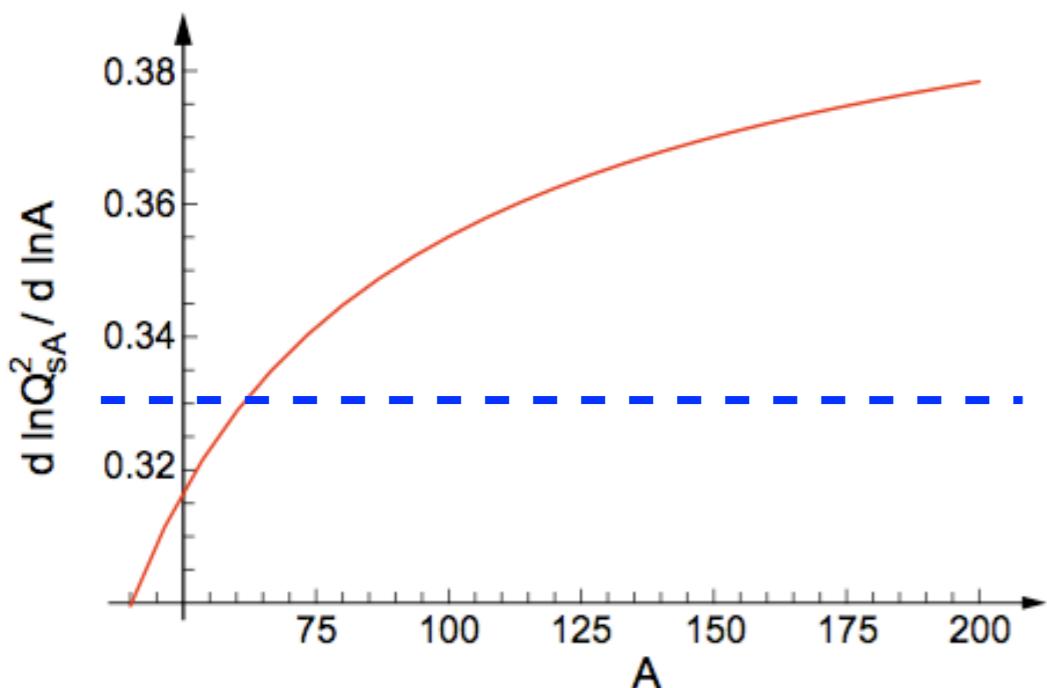
Enhancement of Q_s with A : \Rightarrow non-linear QCD regime

reached at significantly lower energy in $e+A$ than in $e+p$

The Nuclear “Oomph Factor”

More sophisticated analyses
⇒ confirm (exceed) pocket
formula for high A

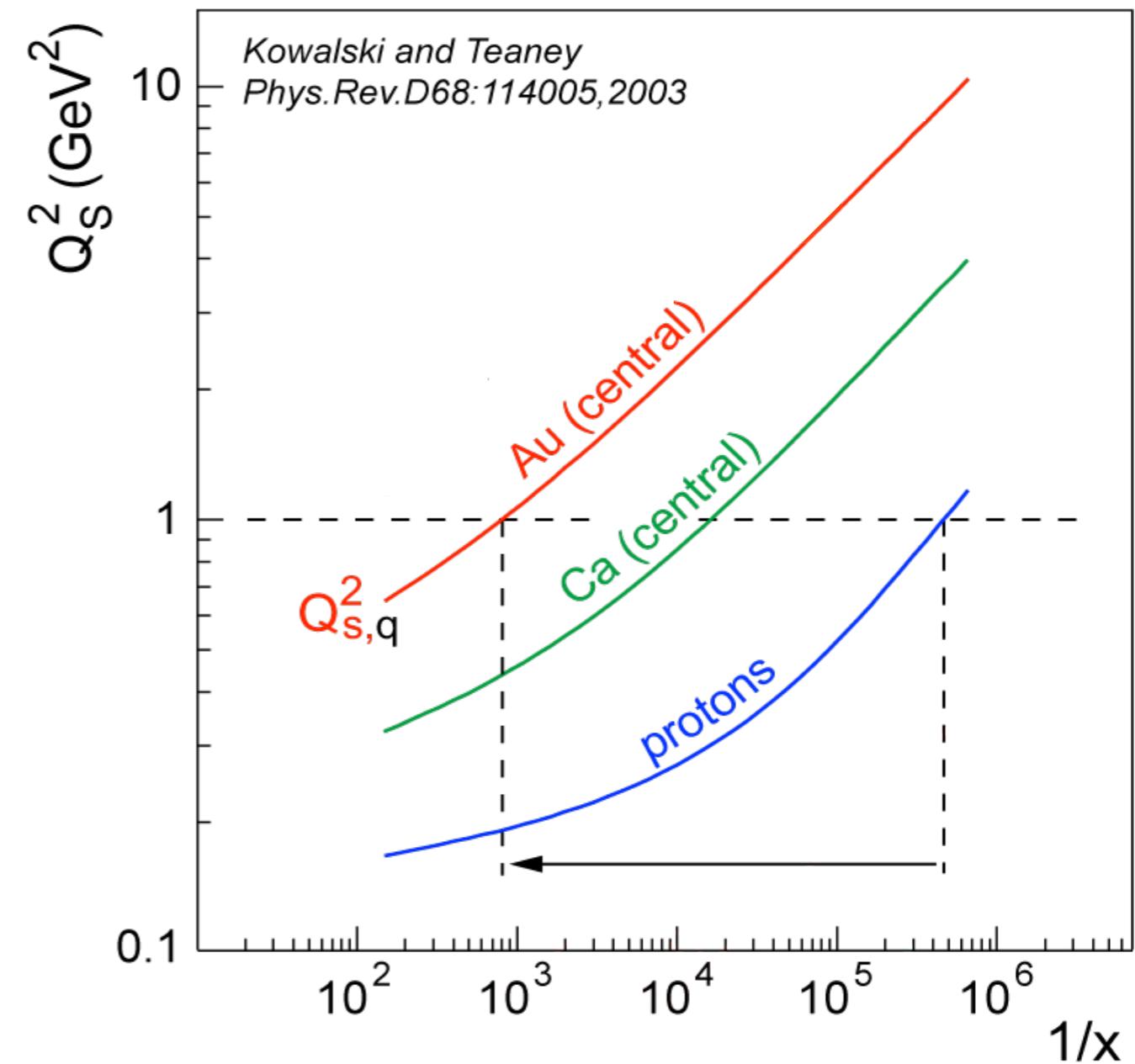
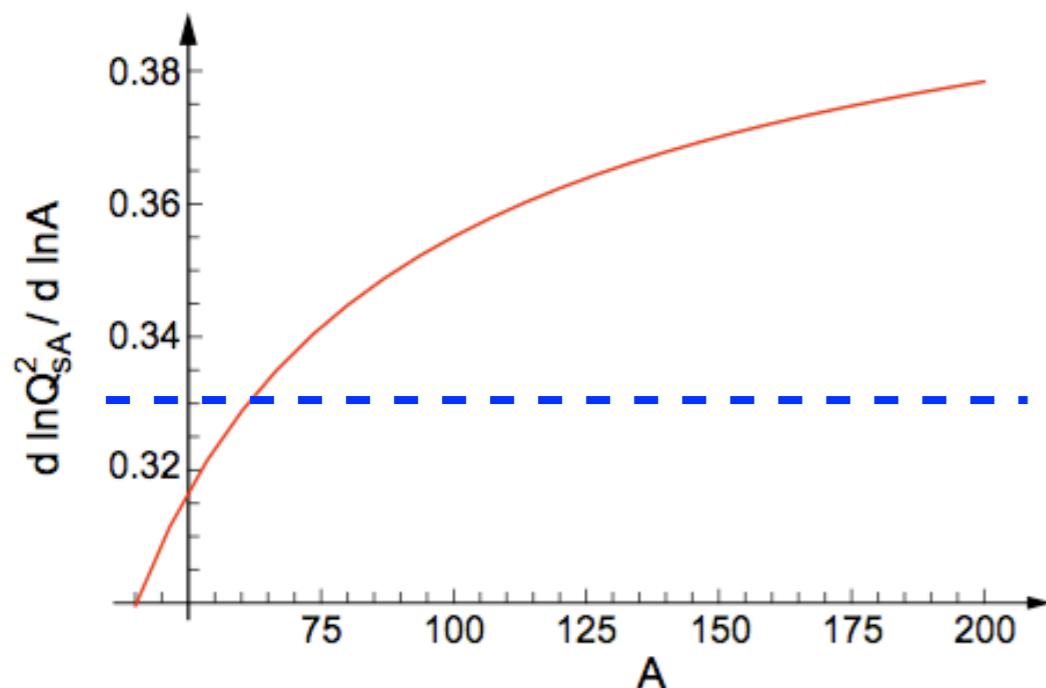
e.g. Kowalski, Lappi and Venugopalan,
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The Nuclear “Oomph Factor”

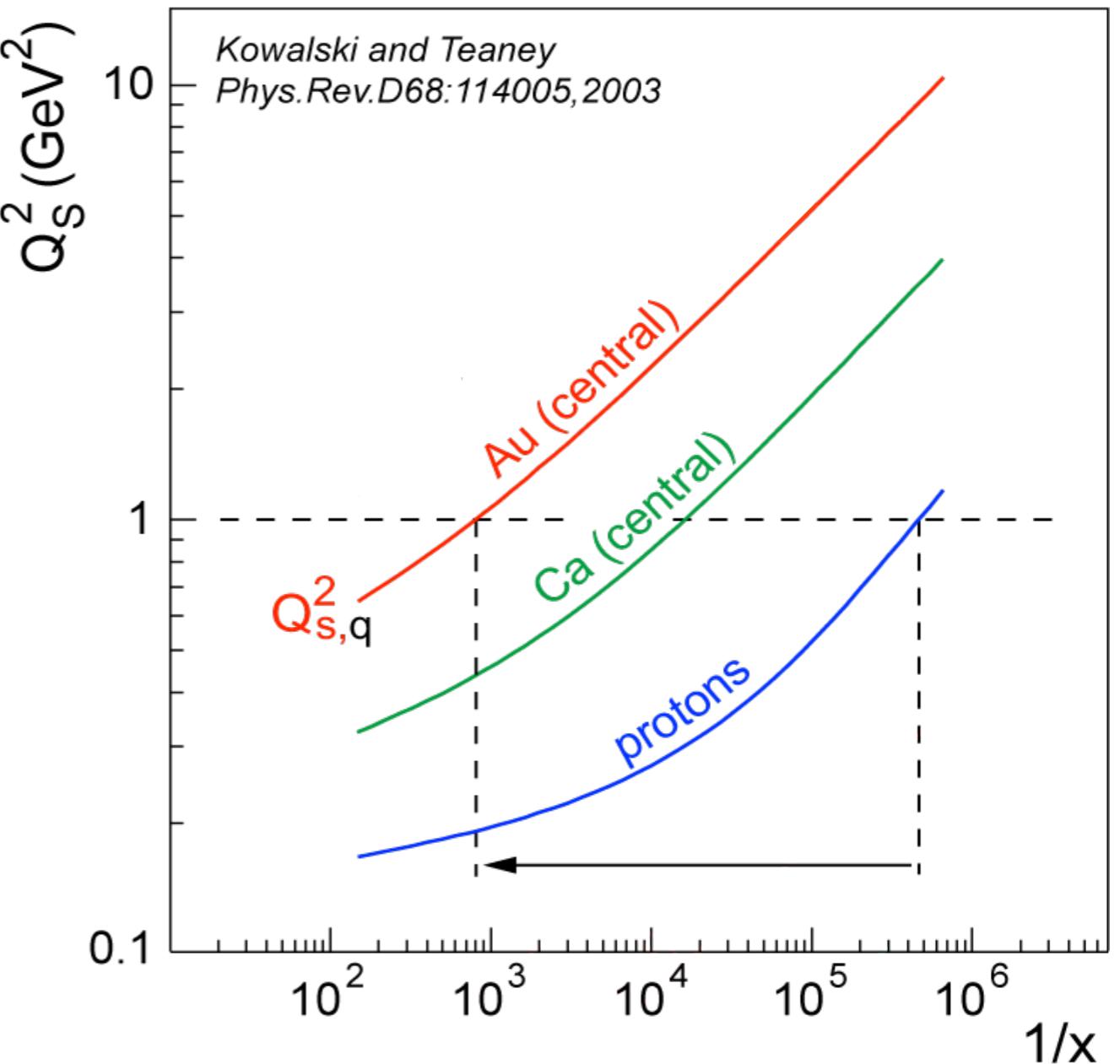
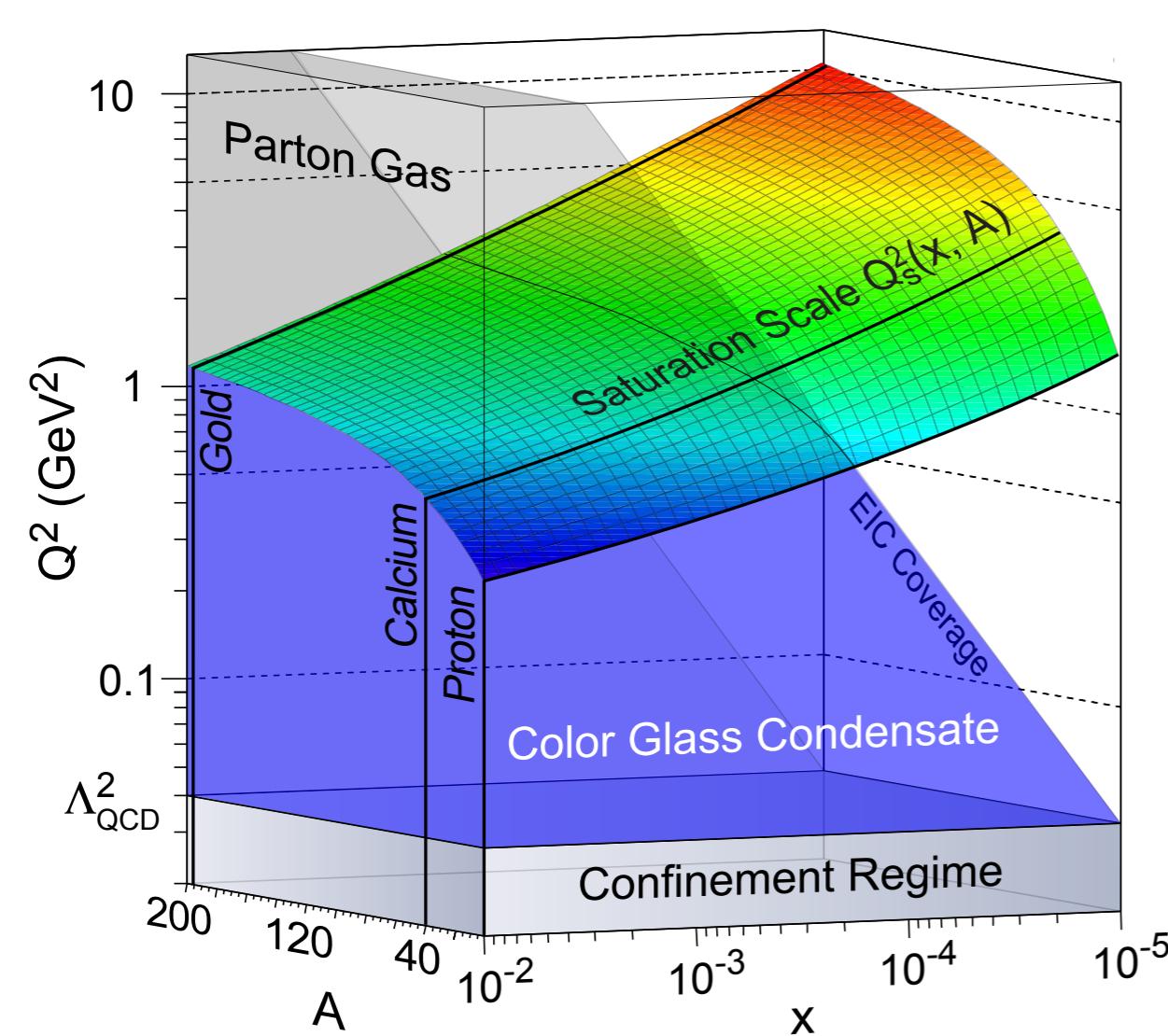
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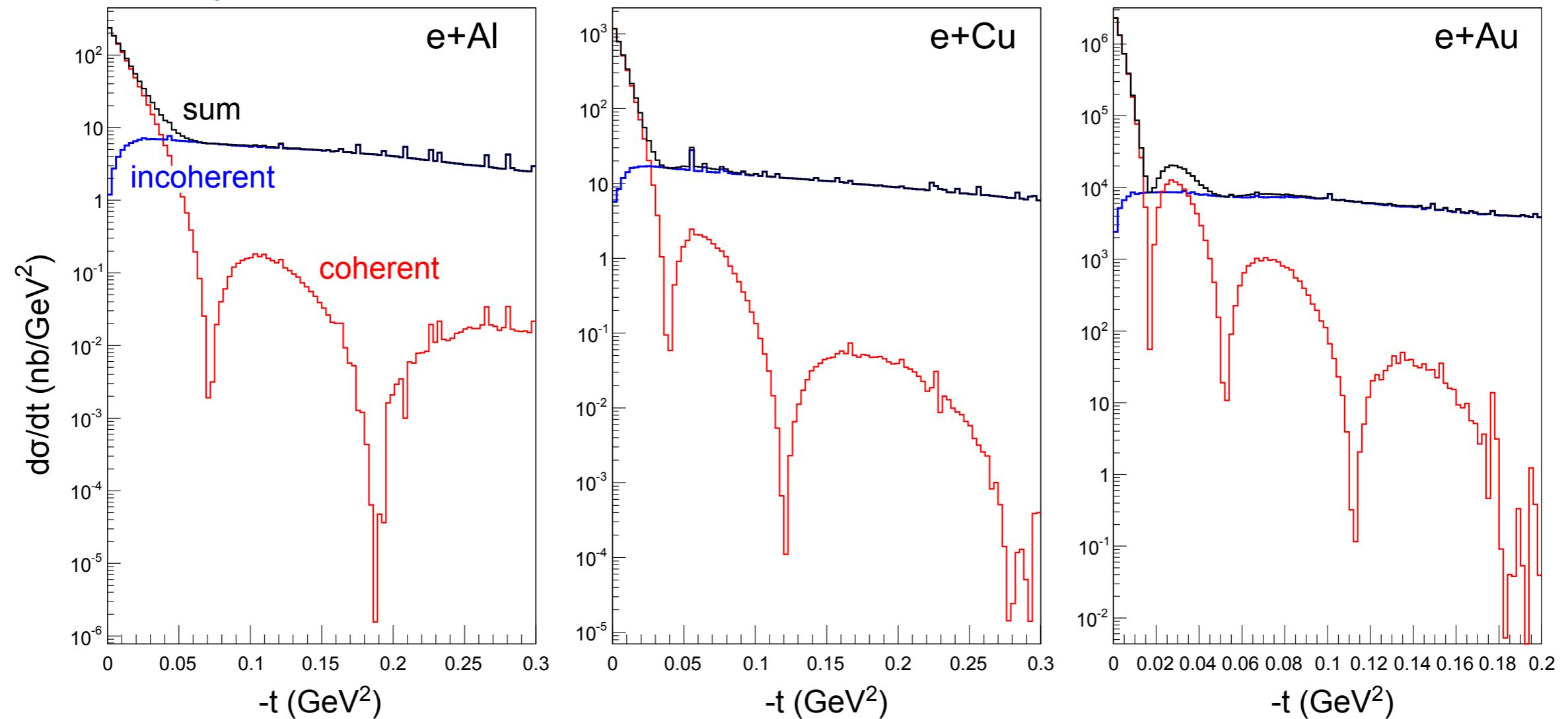
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 $\sim 10-100 \times e+A$ to get to same Q^2_s

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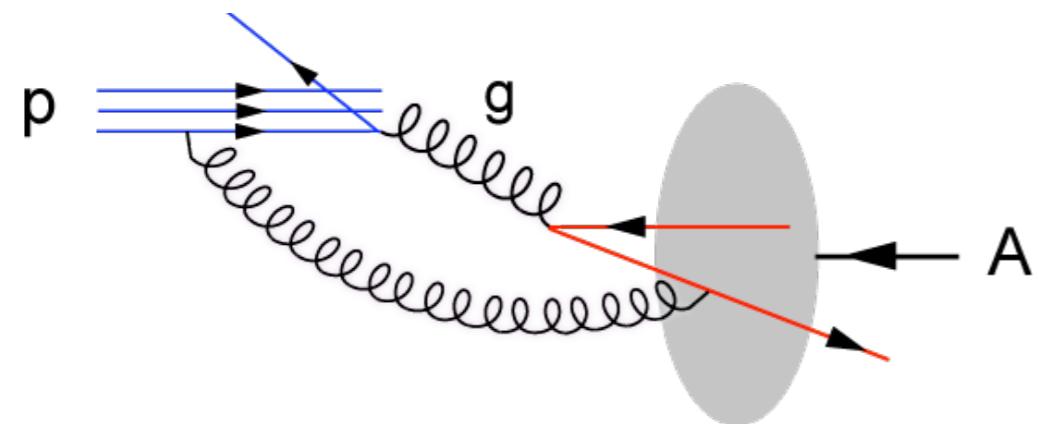
Diffraction in e+A



- Diffractive cross-section $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ in e+A predicted to be ~25-40%
- Process most sensitive to $xG(x, Q^2)$
- Rich physics program on momentum & spatial gluon distribution
- Coherent vs Incoherent: requires detection of breakup with $\sim 1-10^{-4}$ efficiency

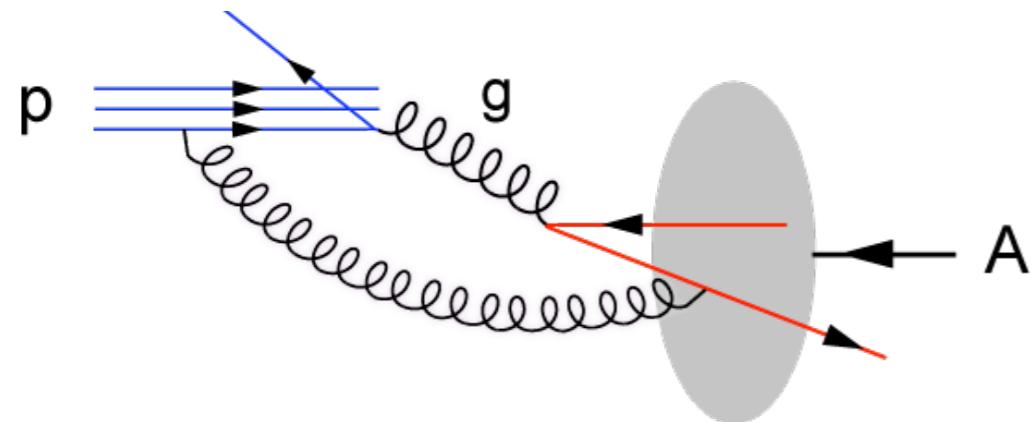
Never done at a collider!

How do we measure Glue ?



How do we measure Glue ?

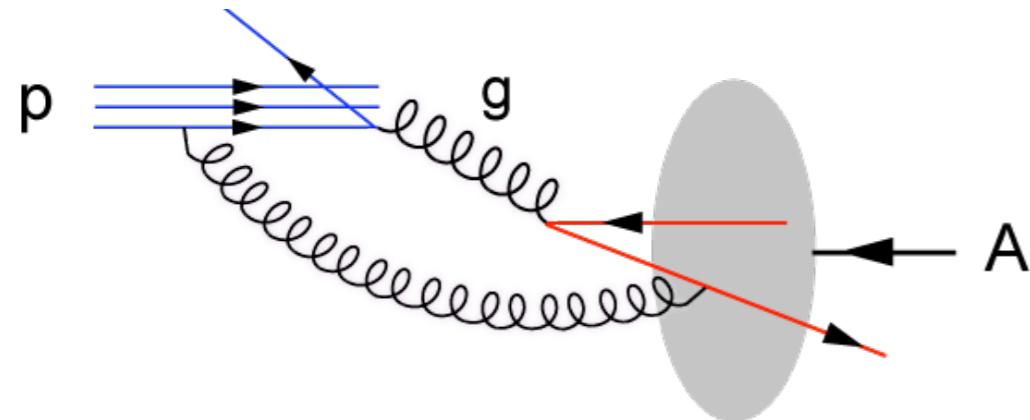
- Hadron-Hadron



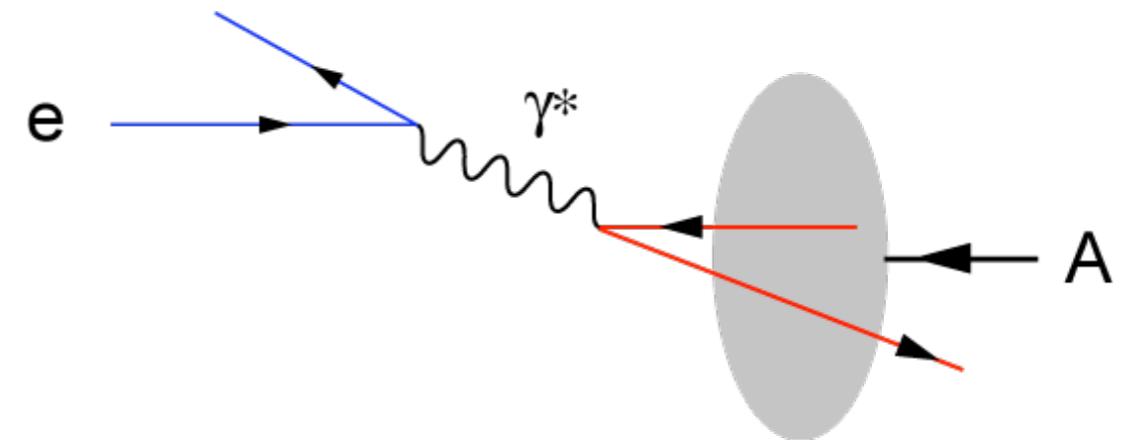
- Probe/Target interaction directly via gluons
- Lacks the direct access to collision kinematics

How do we measure Glue ?

- Hadron-Hadron



- Electron-Hadron (DIS)

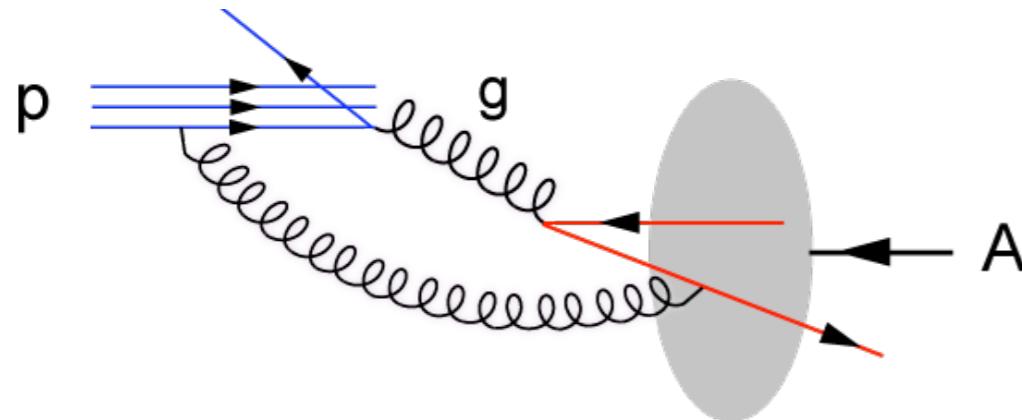


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- ★ Explore QCD & Hadron Structure
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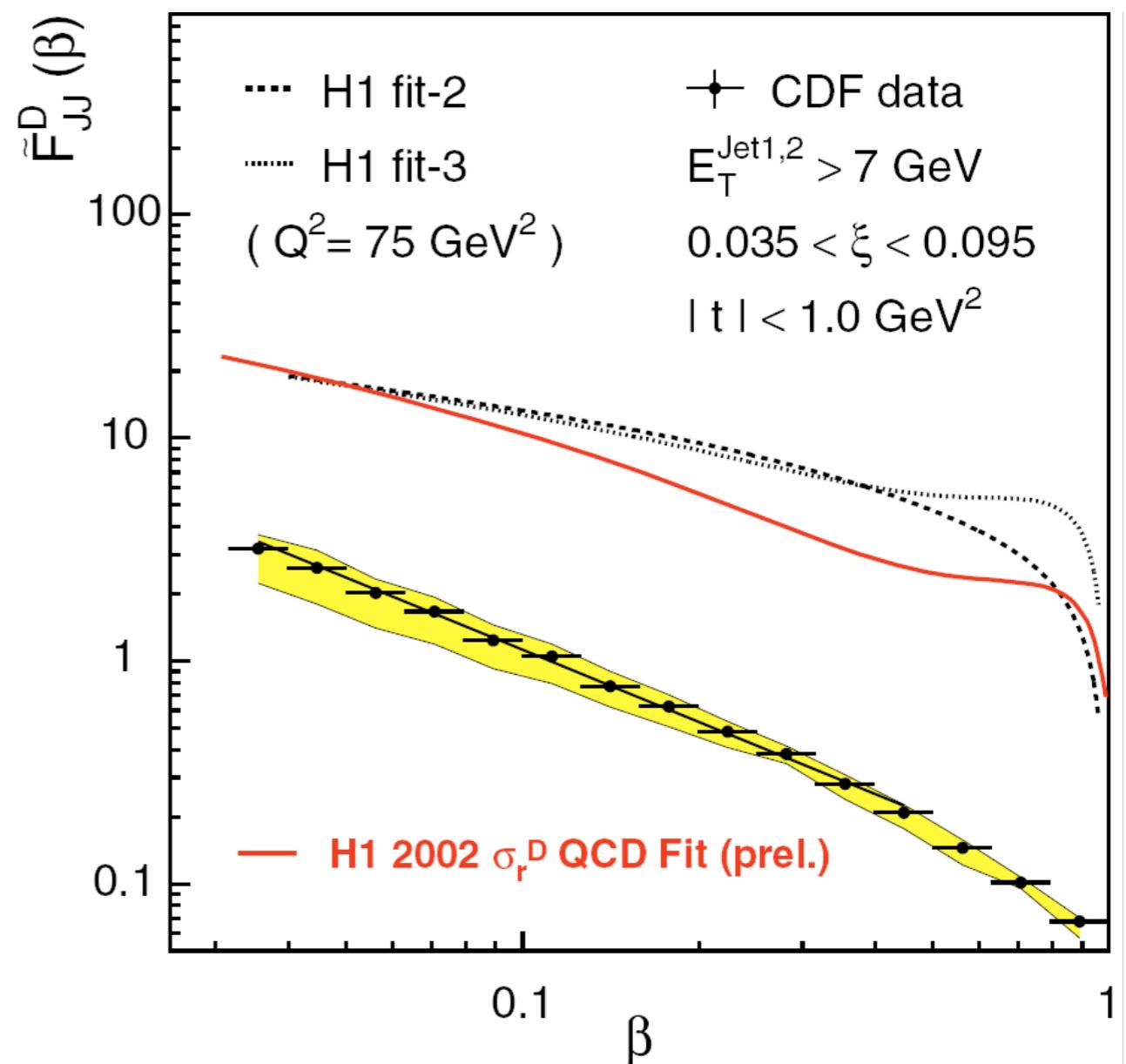
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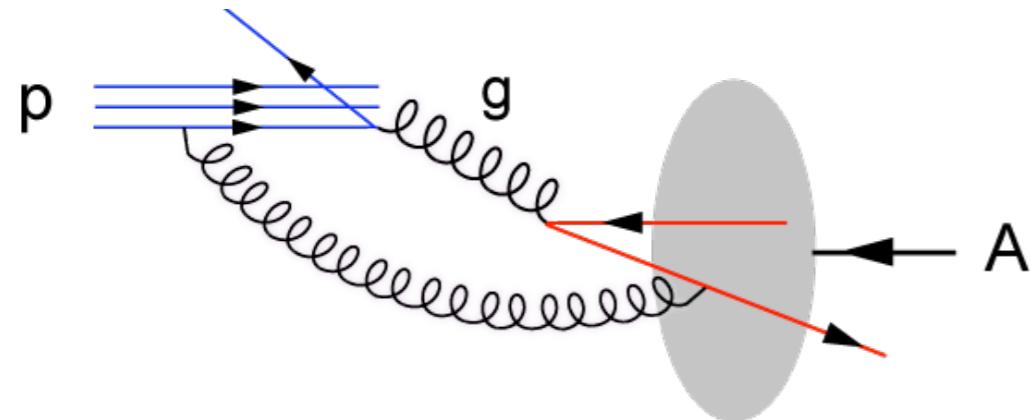
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- Lacks the direct access to collision kinematics
- Interactions with other partons modifies nuclear wave function

F. Schilling, hep-ex/0209001

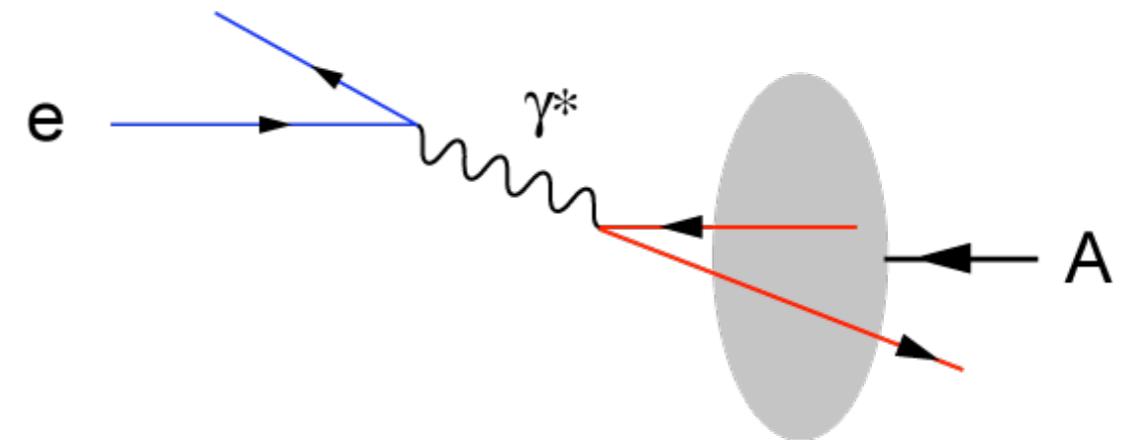


How do we measure Glue ?

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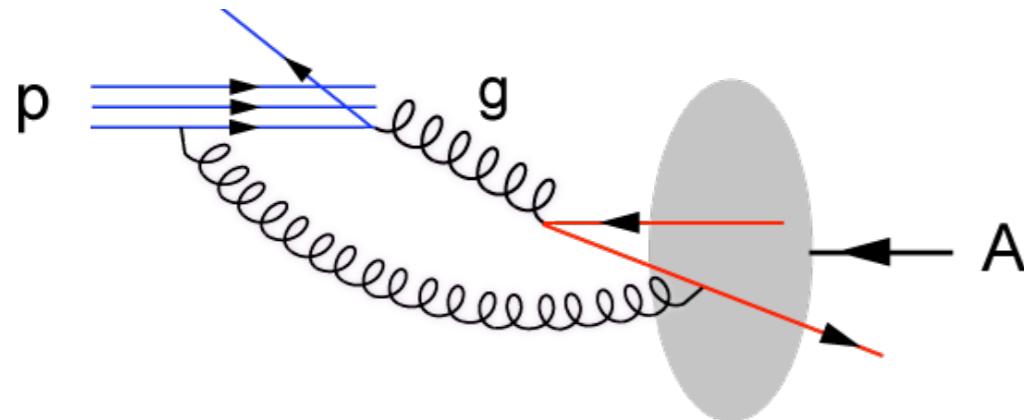


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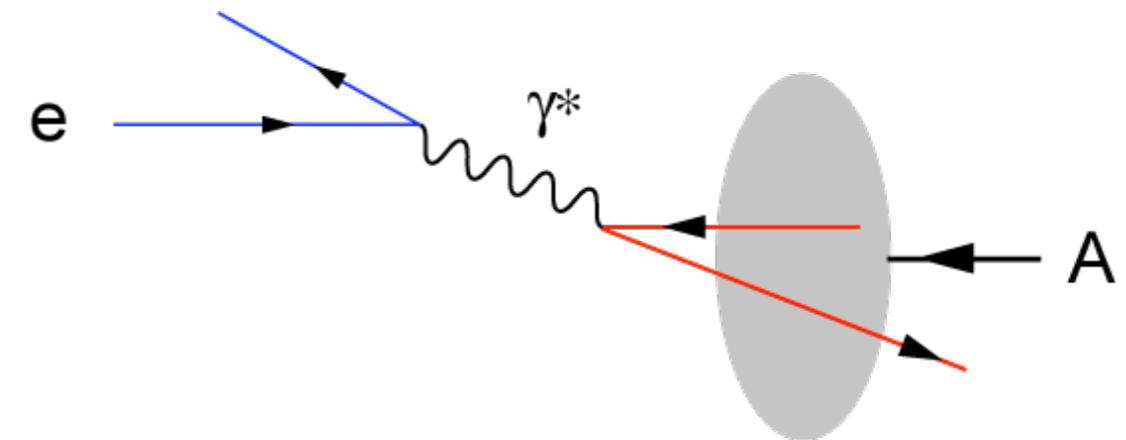
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Both are **complementary** and provide excellent information on properties of gluons in the nuclear wave functions

Precision measurements \Rightarrow DIS

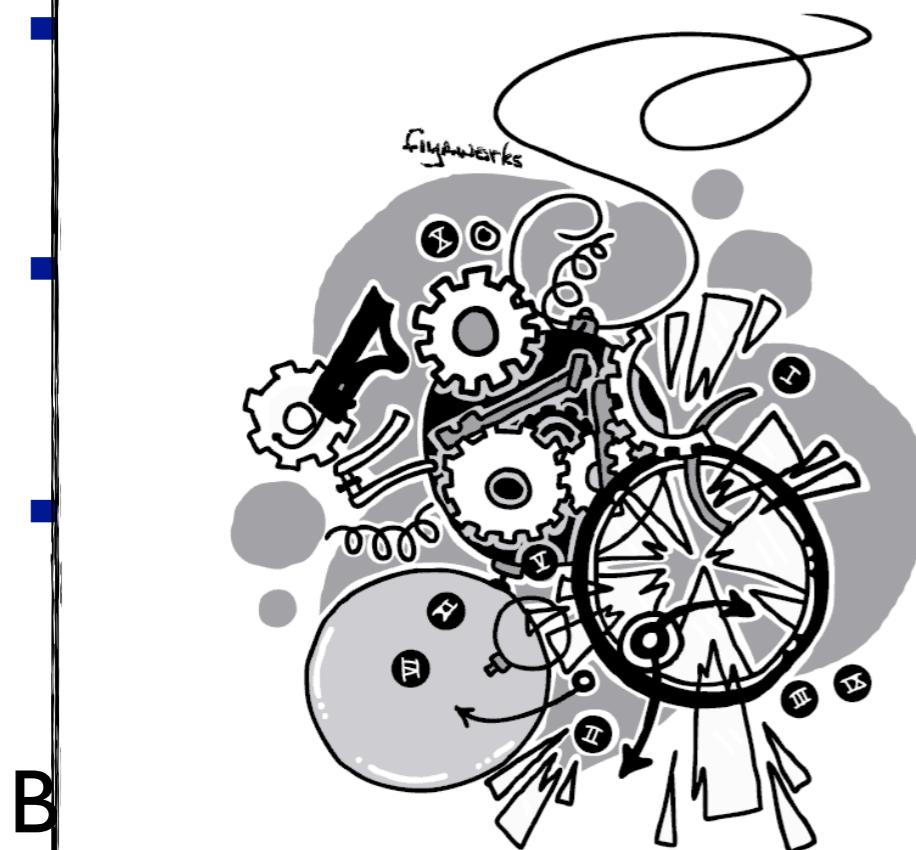
How do we measure Glue ?

- H

p

*Scattering of hadrons on hadrons
is like colliding Swiss watches to find out how
they are build.*

R. Feynman



B

A

gh

n

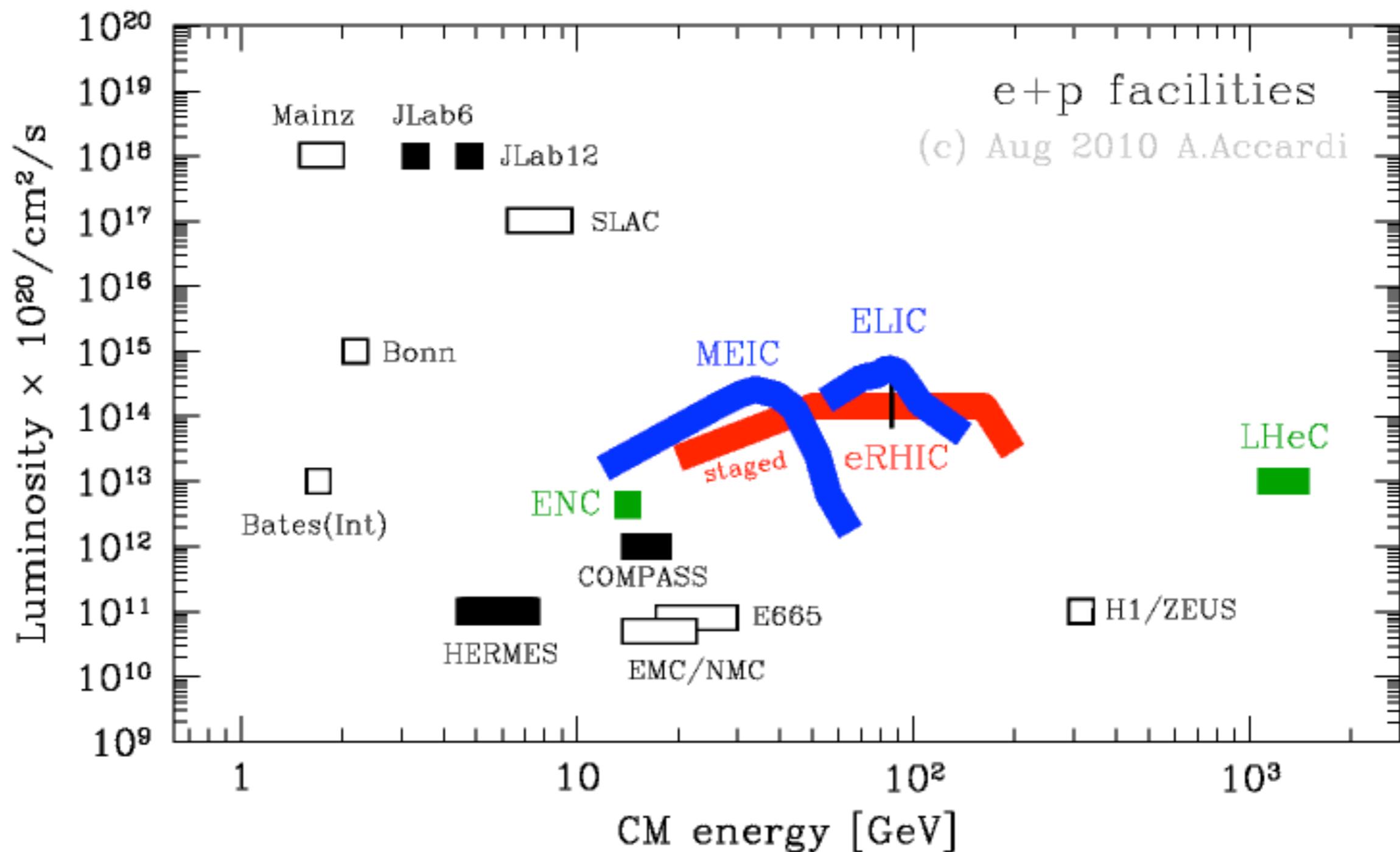
Precision measurements \Rightarrow DIS

Luminosity vs Energy comparison

- A comparison plot showing luminosities vs energy for existing and proposed e+p facilities.
- Both a staged eRHIC and a JLab design are shown for reference.

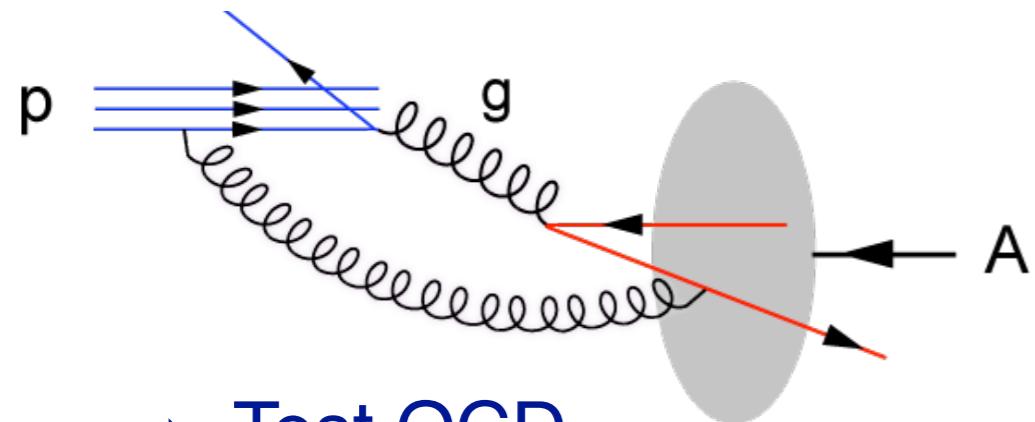
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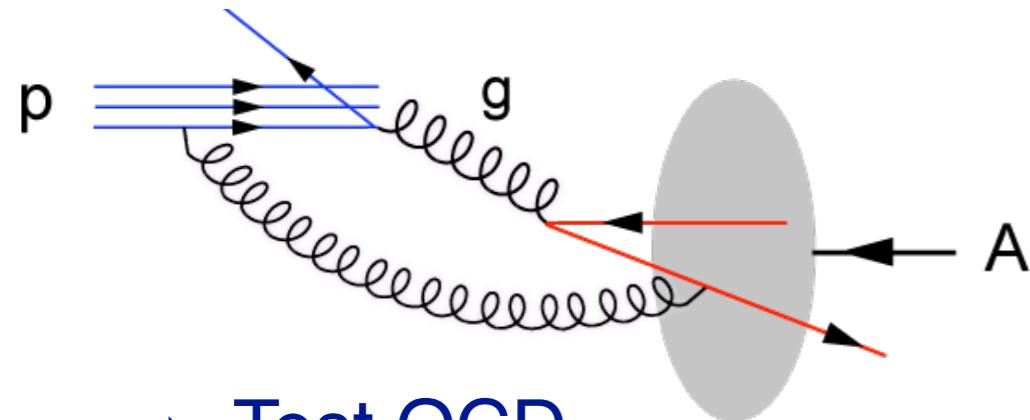
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- Test QCD
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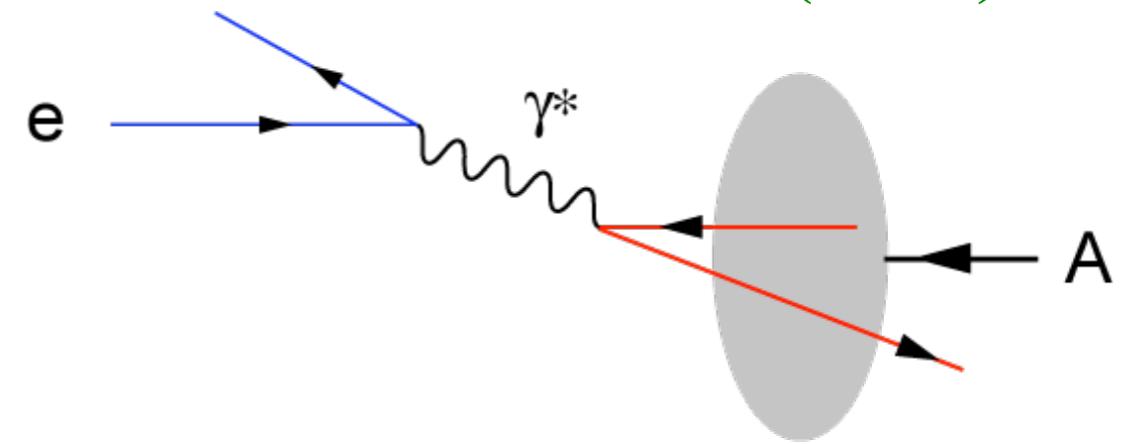
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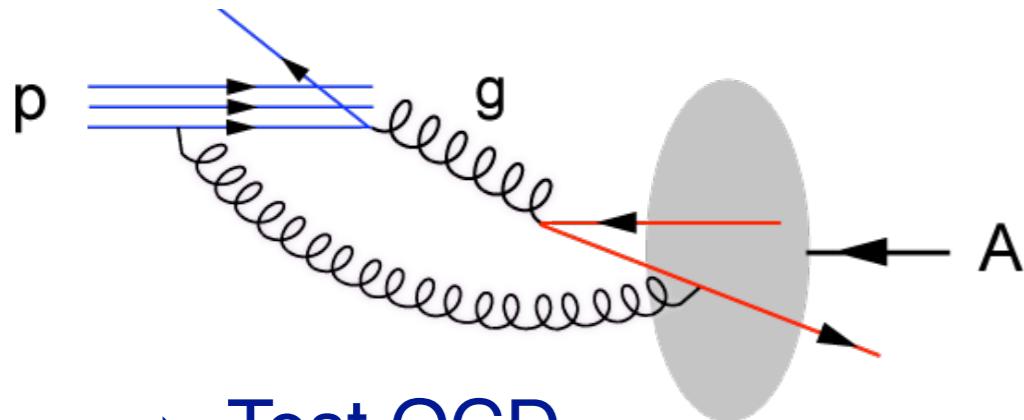
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How do we measure Glue ?

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→ Test QCD

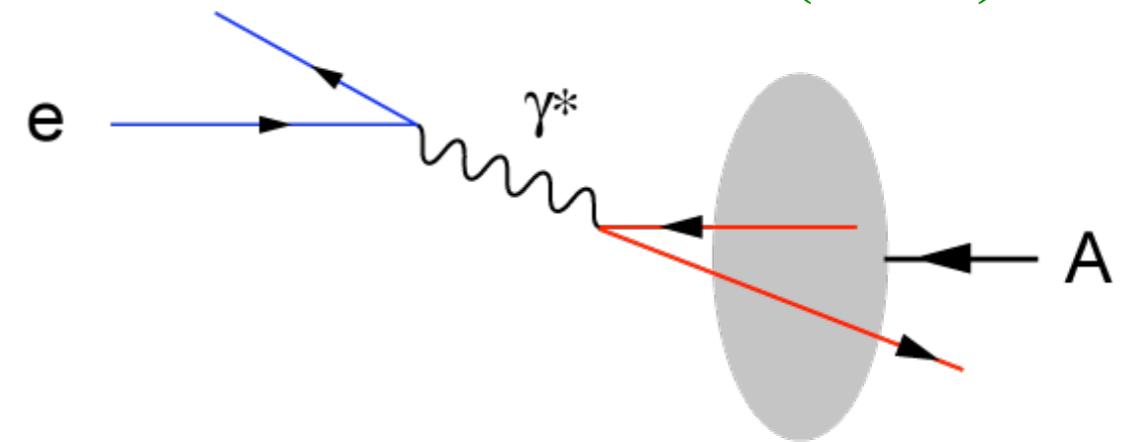
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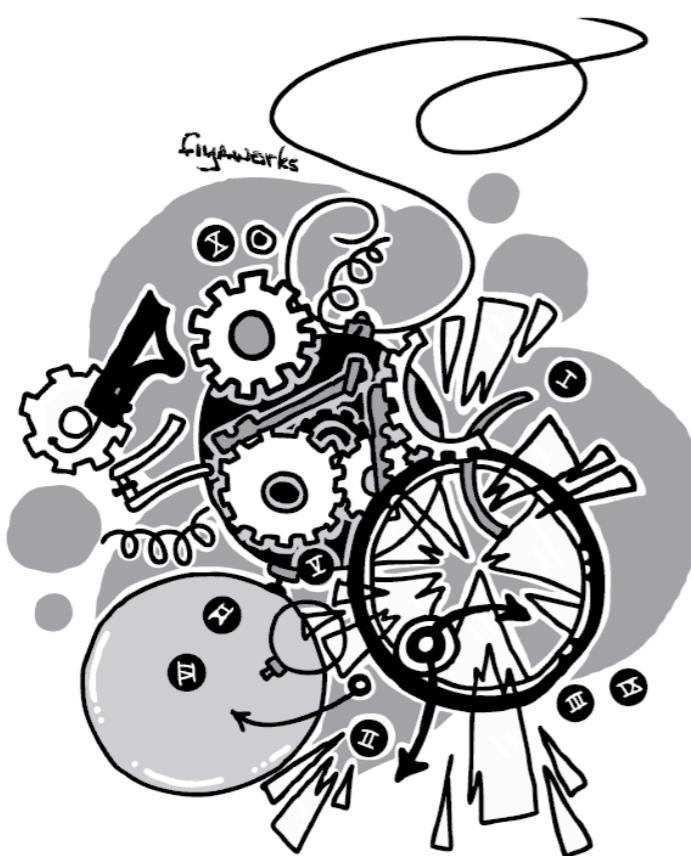
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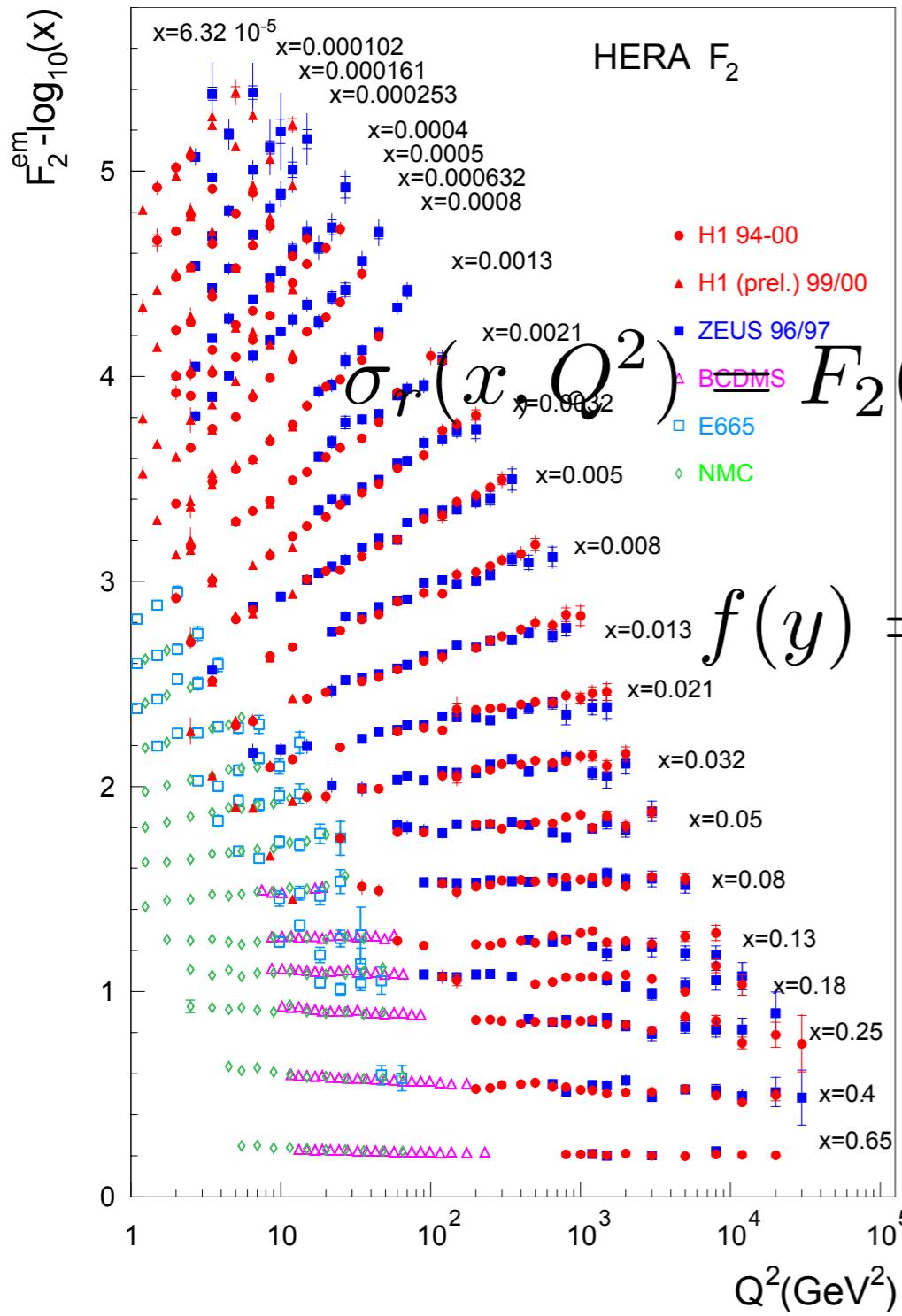
R. Feynman



Precision measurements \Rightarrow DIS

Measuring the glue via Structure Functions

$$\frac{d^2\sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$



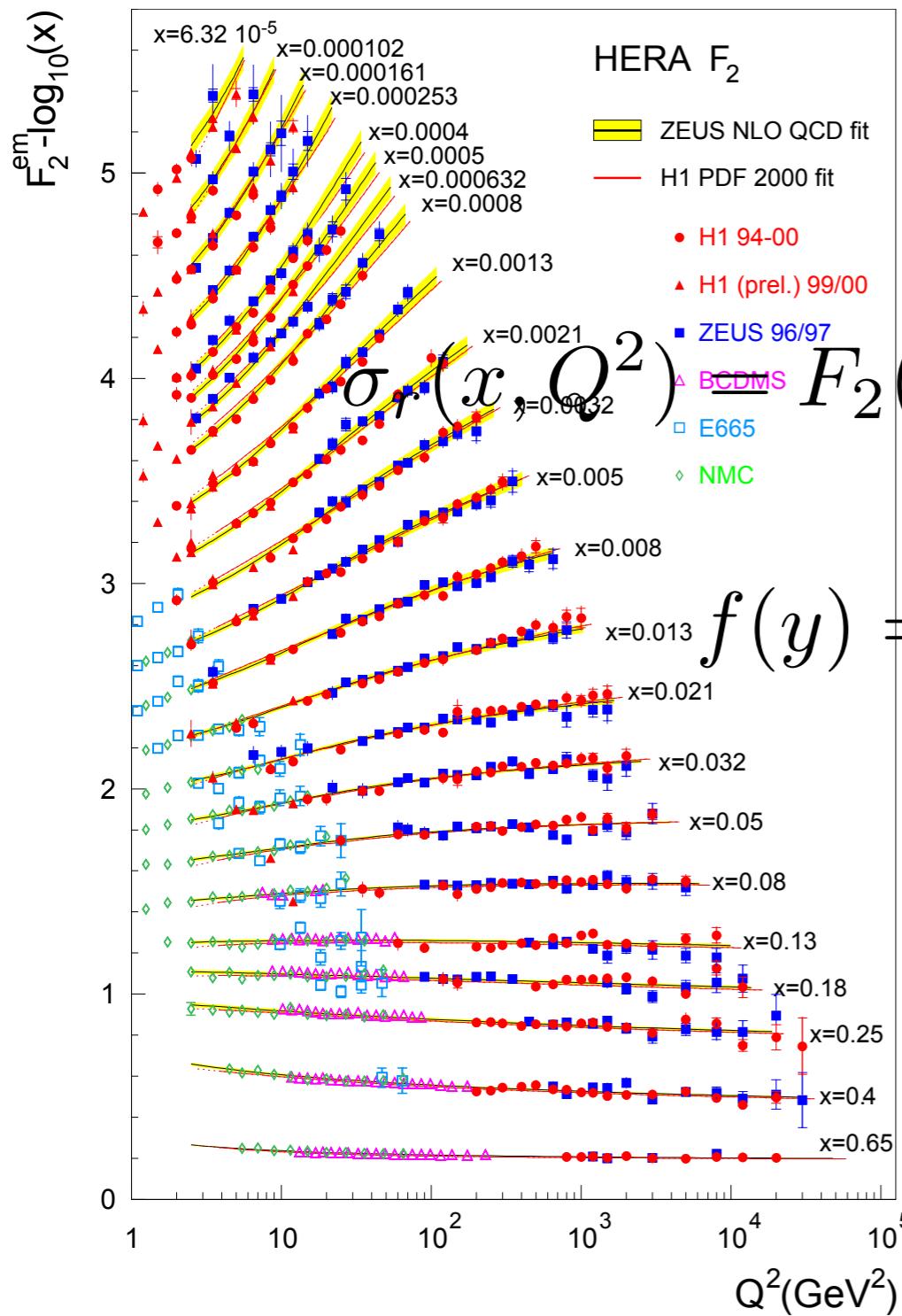
**quark+anti-quark
momentum distributions**

**gluon momentum
distribution**

$$f(y) = \frac{y}{1 + (1 - y)^2}$$

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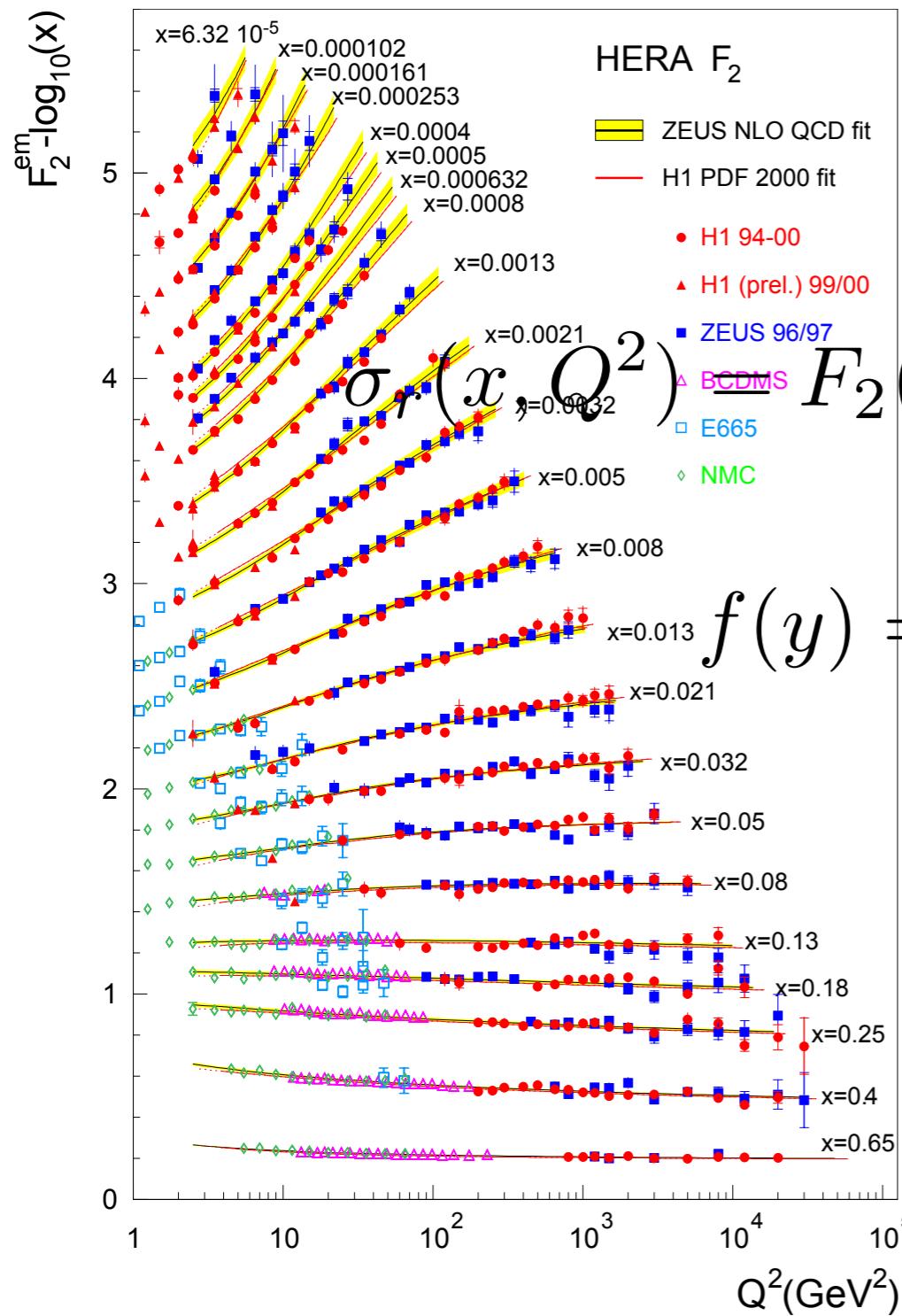
Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP
Evolution $\Rightarrow G(x, Q^2)$

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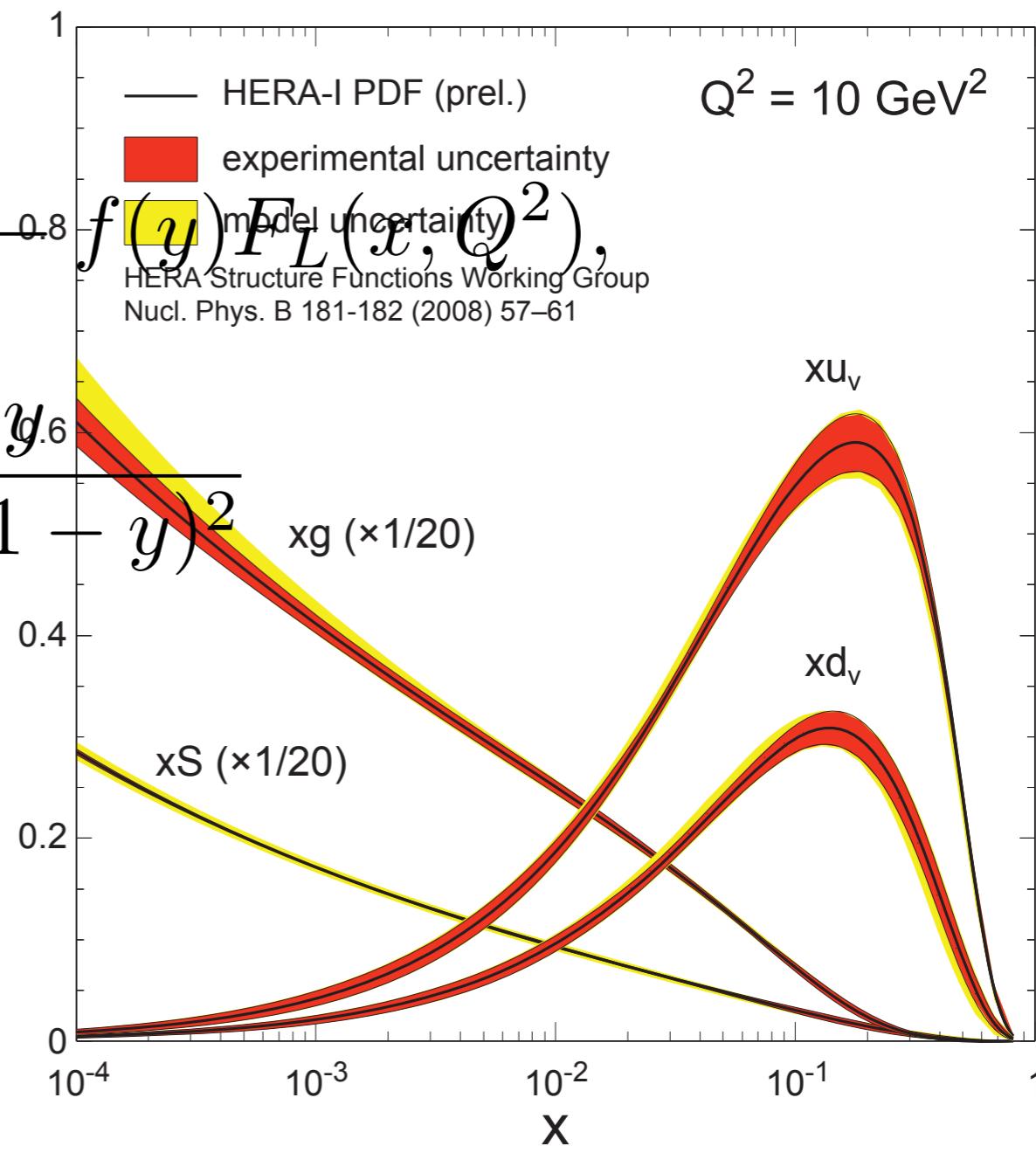
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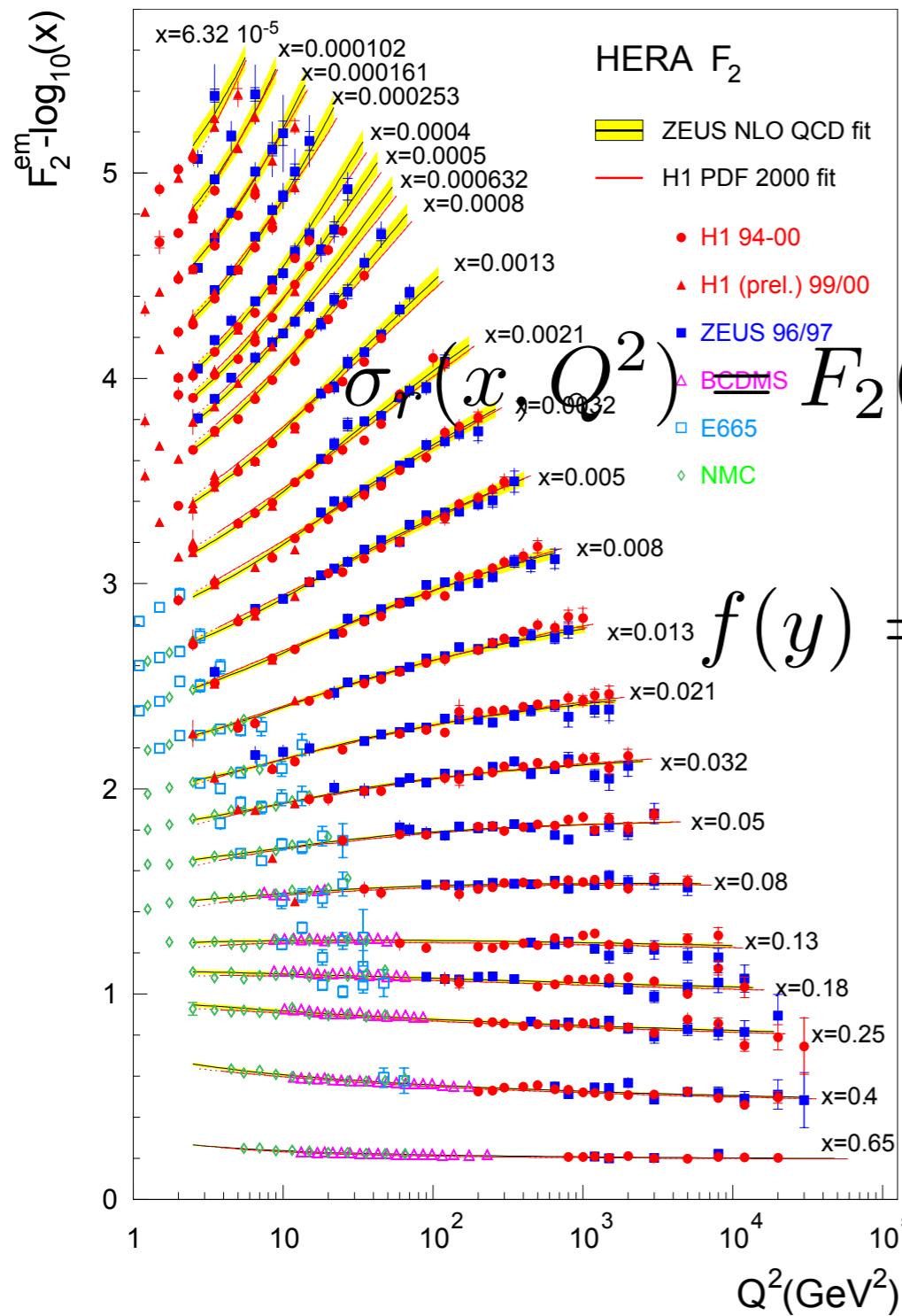


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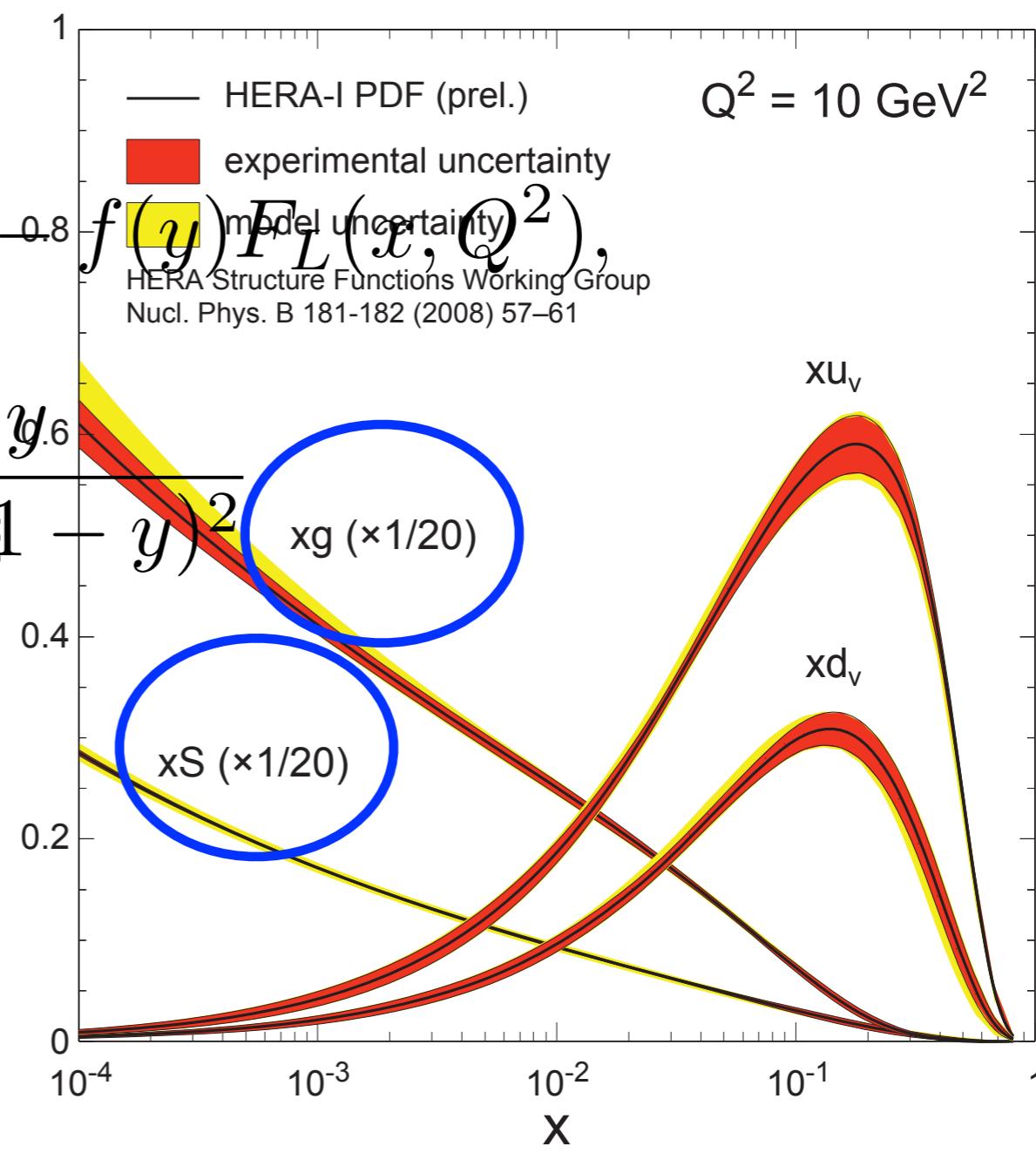


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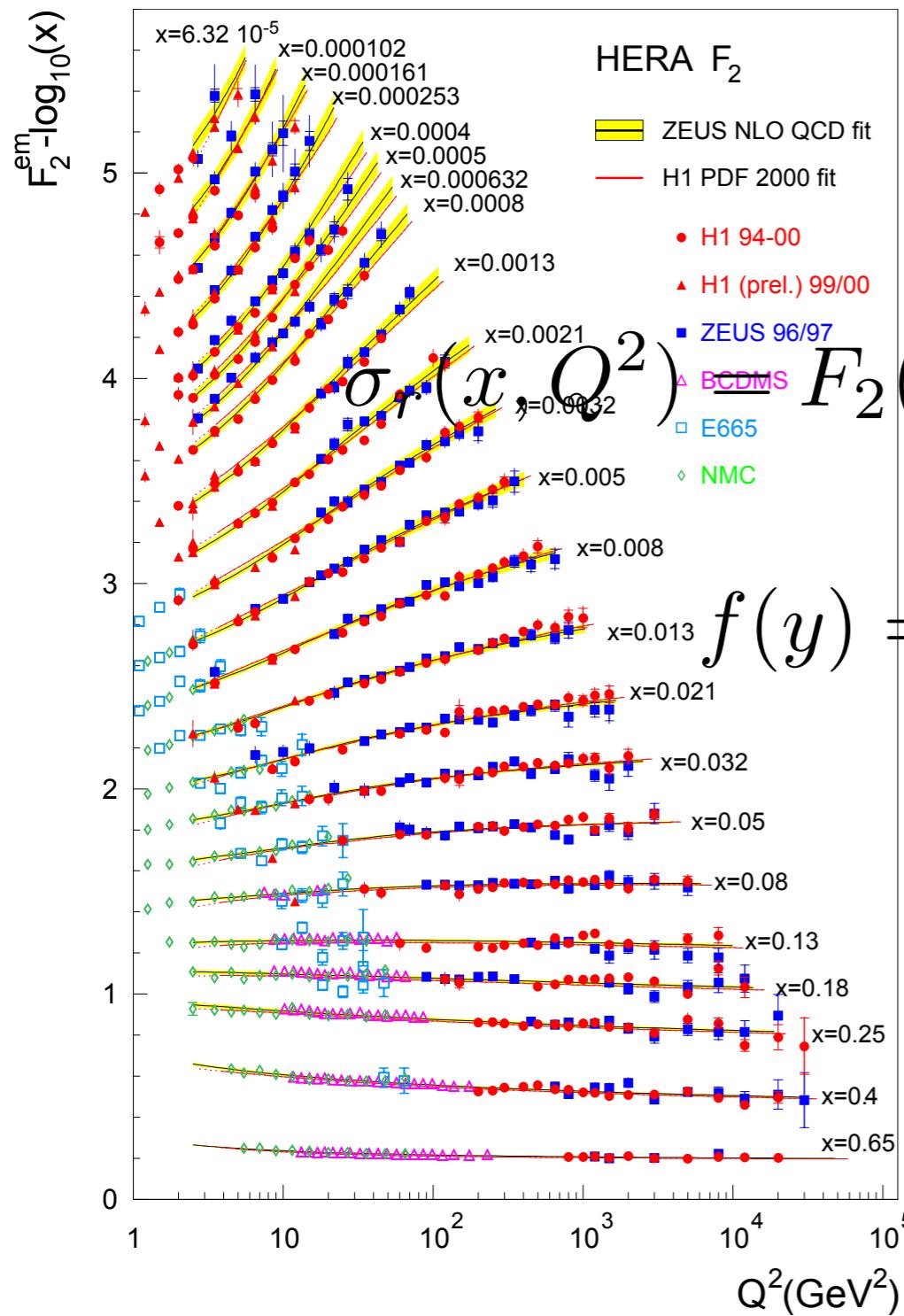


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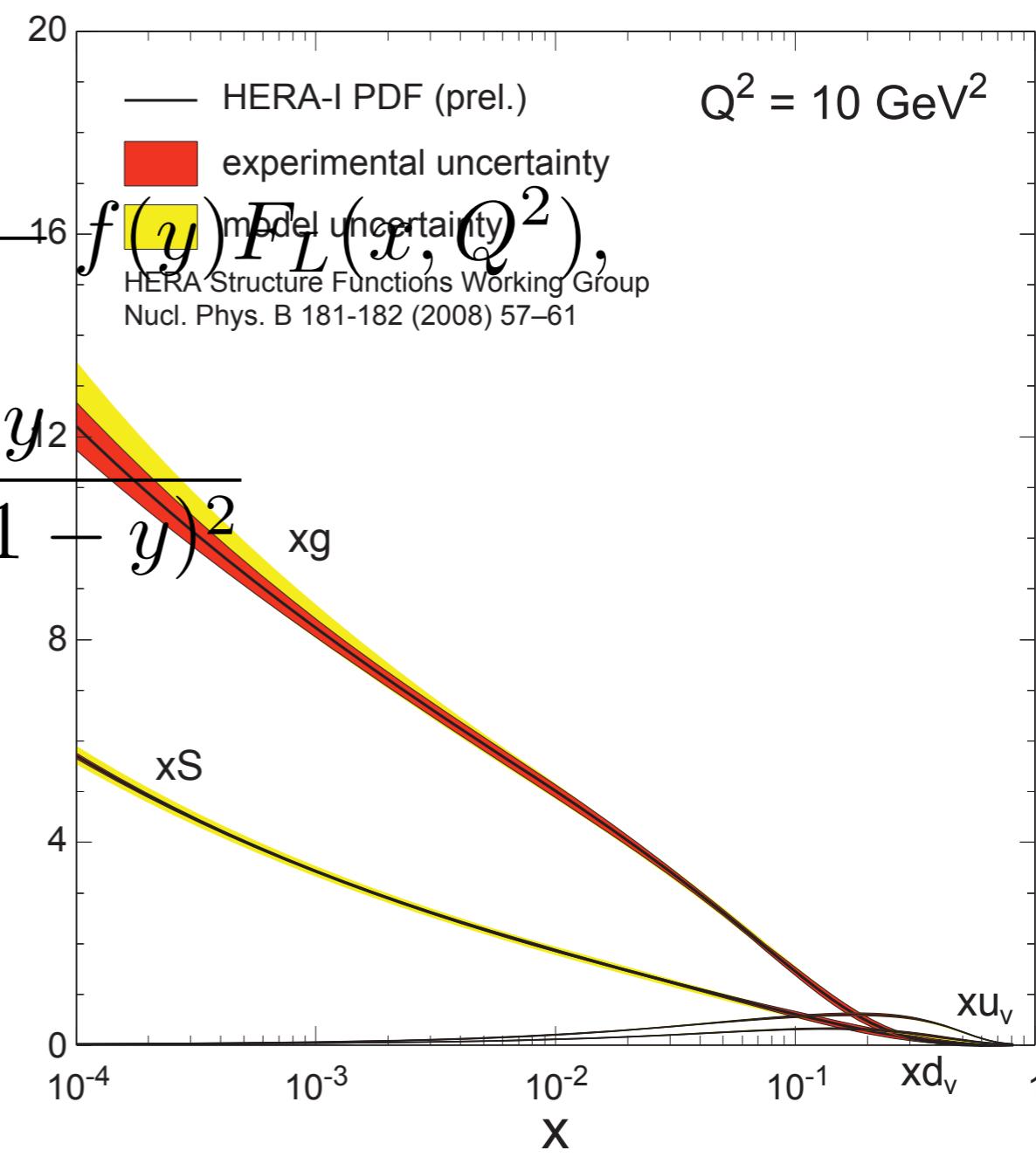


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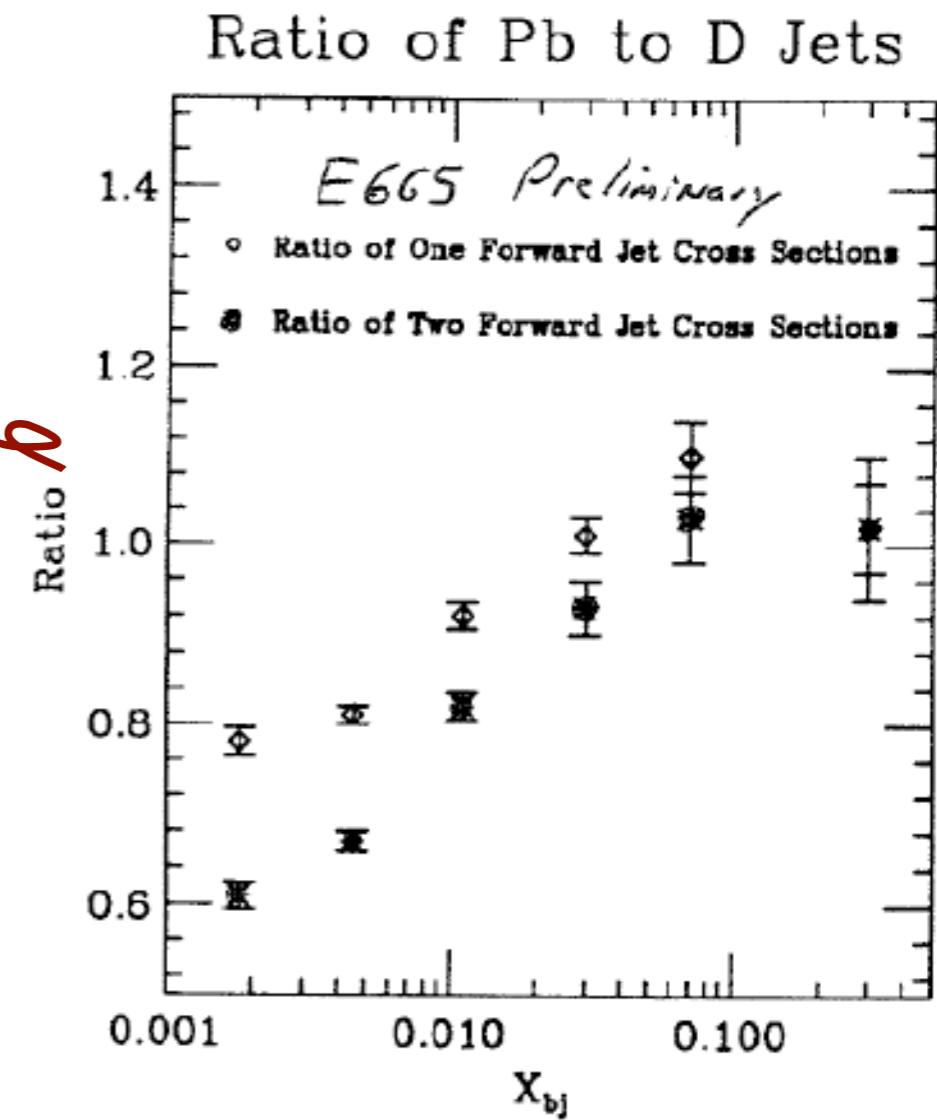
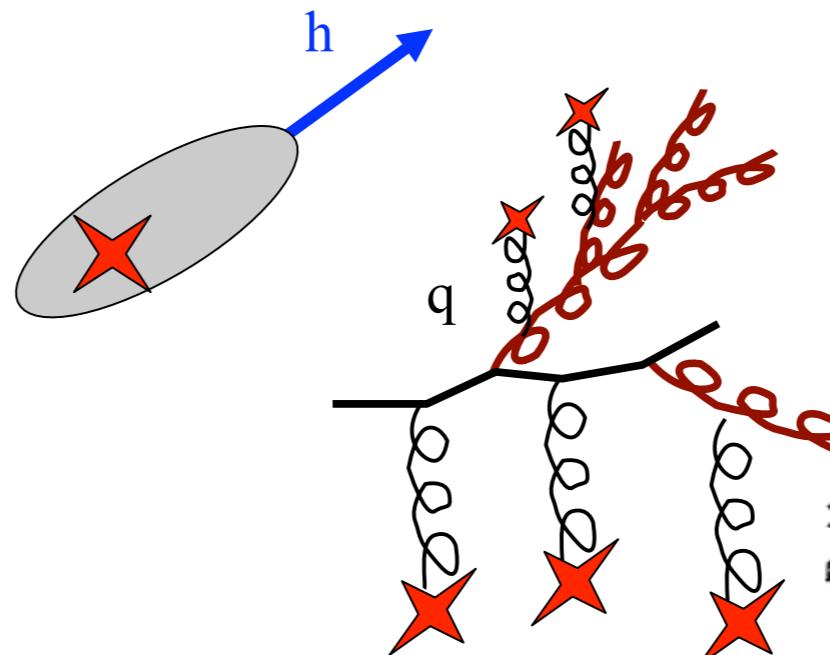
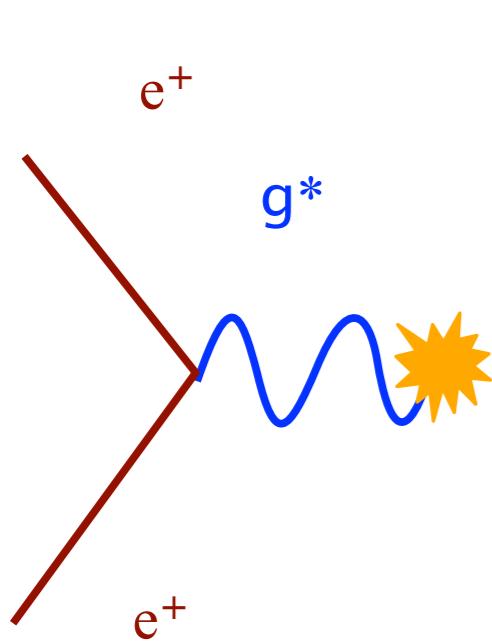
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Jets and hadronization

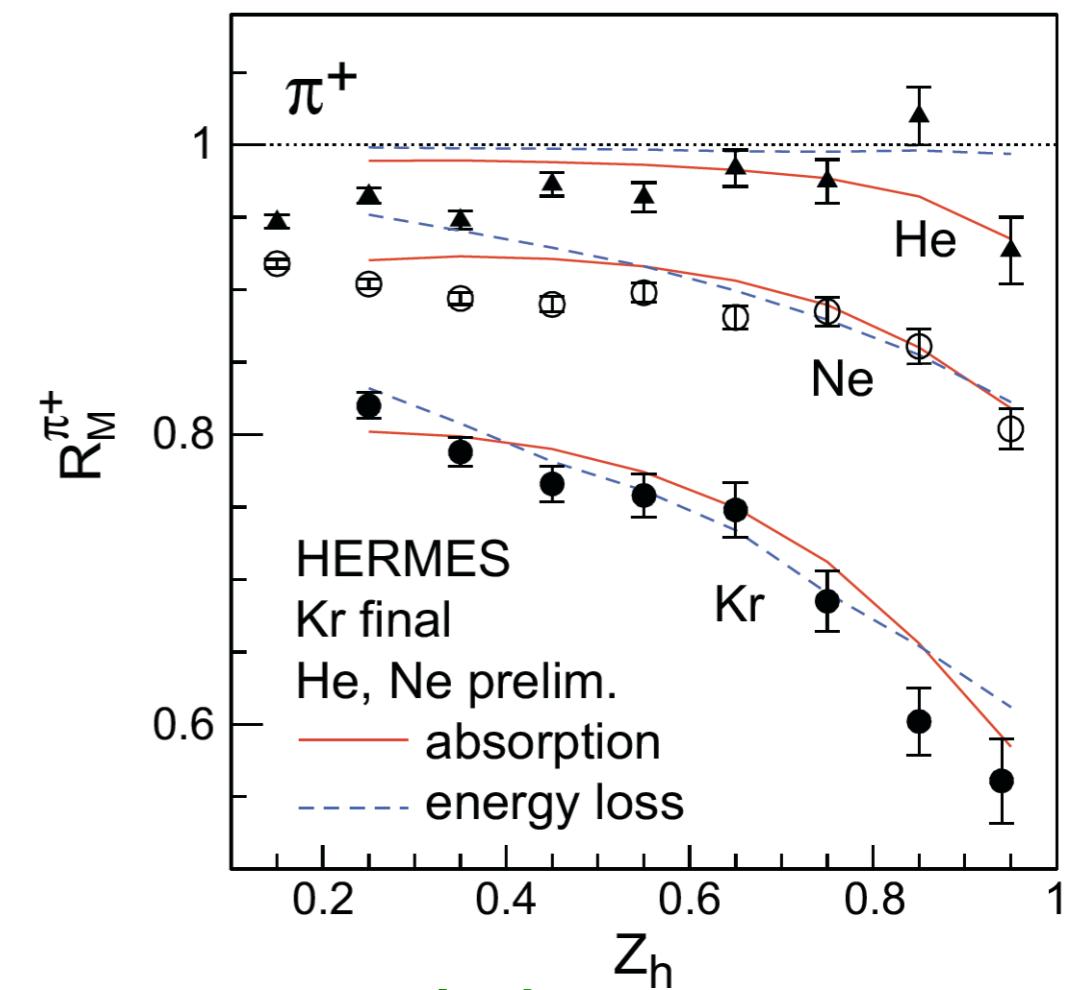
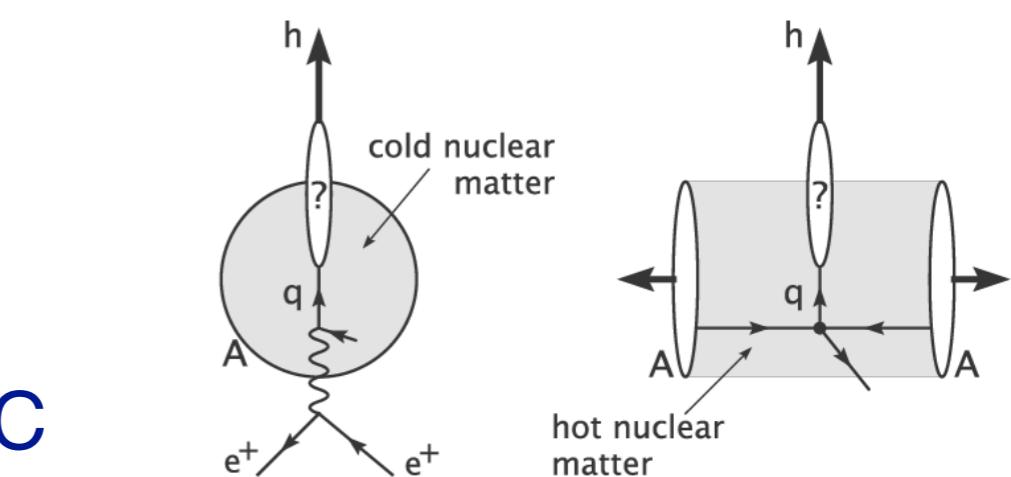
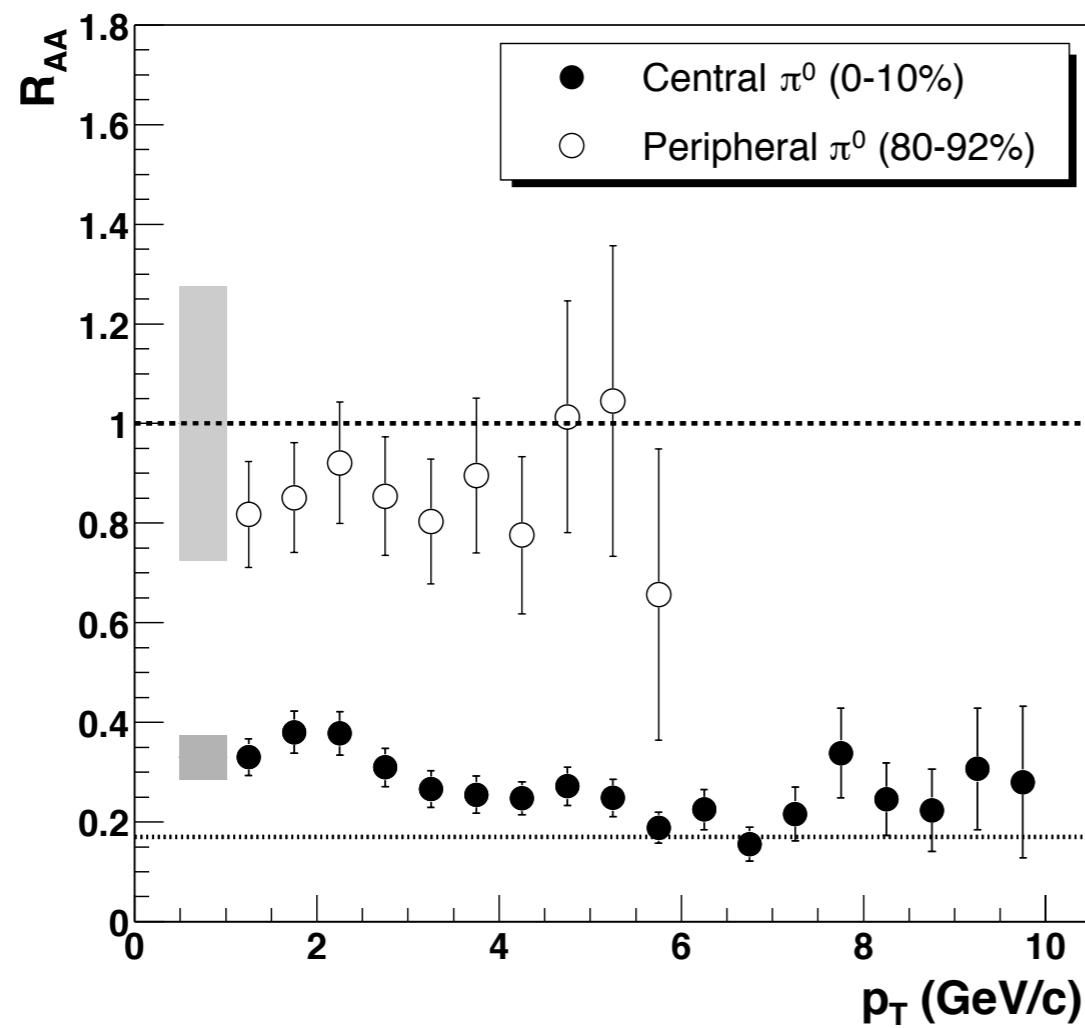


- Use coloured probes to study soft nuclear glue
 - a “large- x ” probe of small- x gluons
- Use nuclei to study parton propagation and fragmentation
 - parton showers, quark-to-hadron transition
- Ideal program for phase-1 EIC

Interaction of fast probes with gluonic medium

- nDIS:
 - Clean measurement in ‘cold’ nuclear matter
 - Suppression of high- p_T hadrons analogous to, but weaker than at RHIC

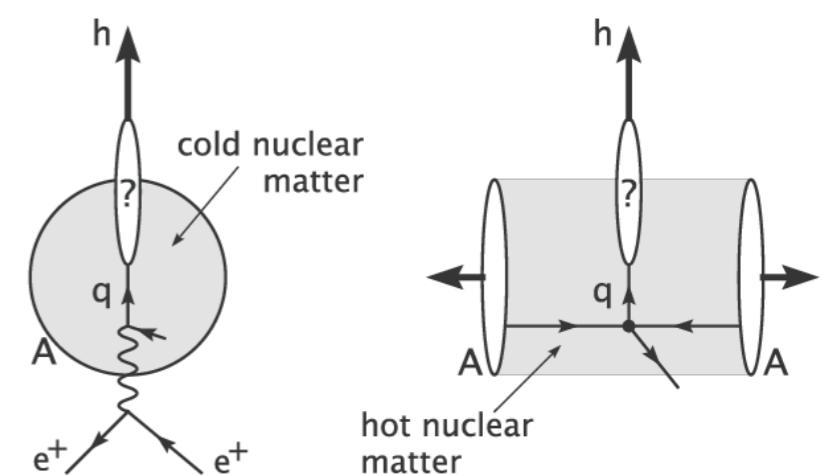
PHENIX expt: Phys.Rev.Lett.91:072301 (2003)



v = virtual photon energy
 $Z_h = E_h/v$

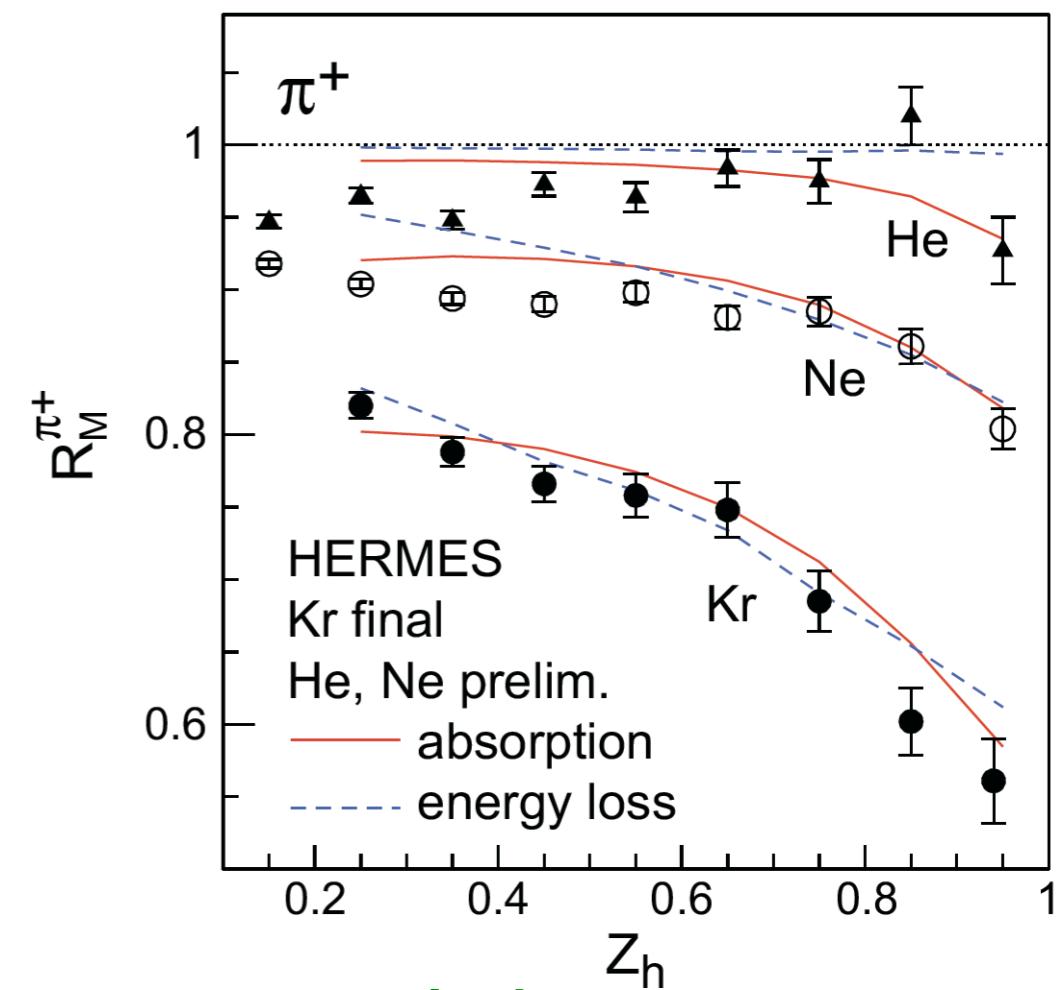
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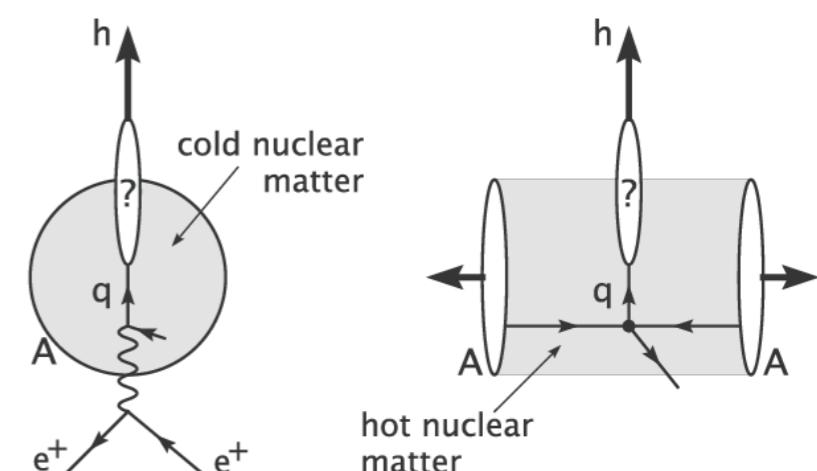
Parton energy loss vs. (pre)hadron absorption



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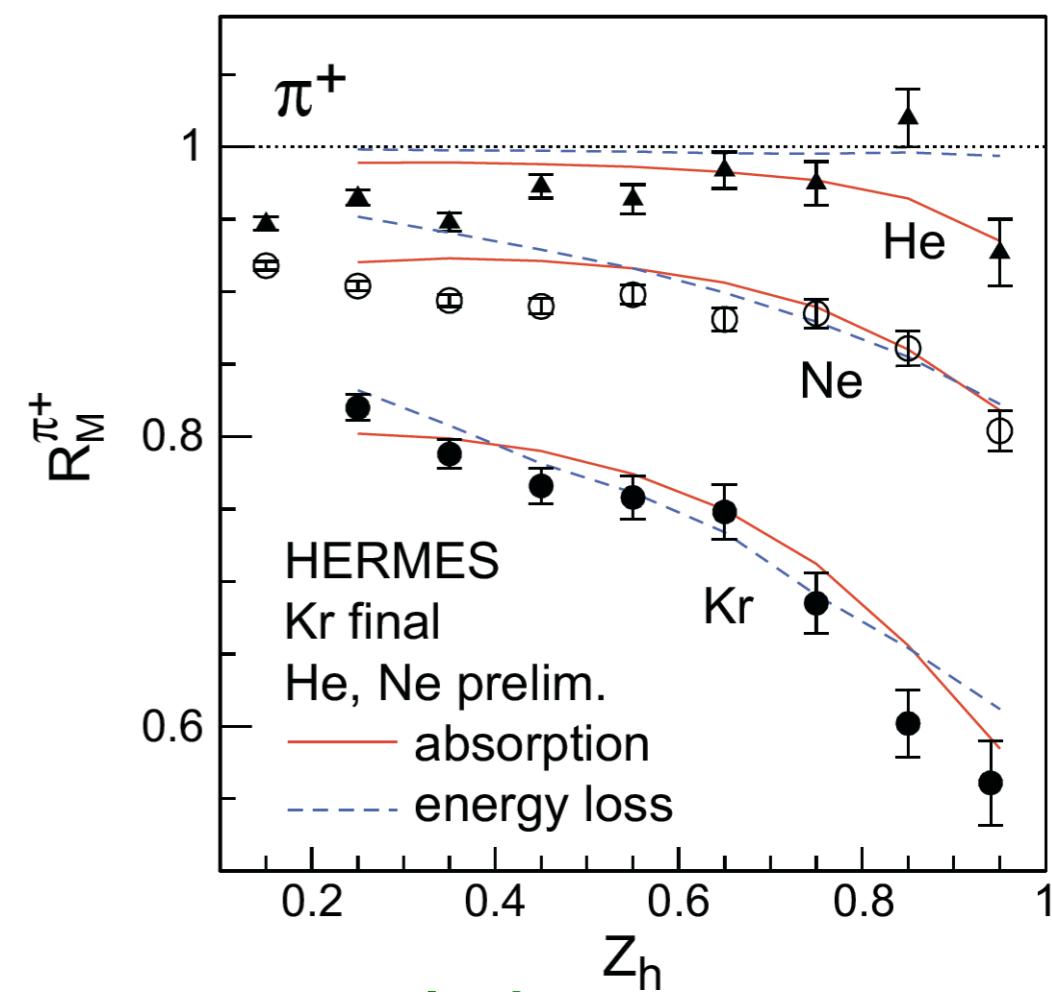
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Parton energy loss vs. (pre)hadron absorption

Energy transfer in lab rest frame:

EIC: $10 < \nu < 1600$ GeV

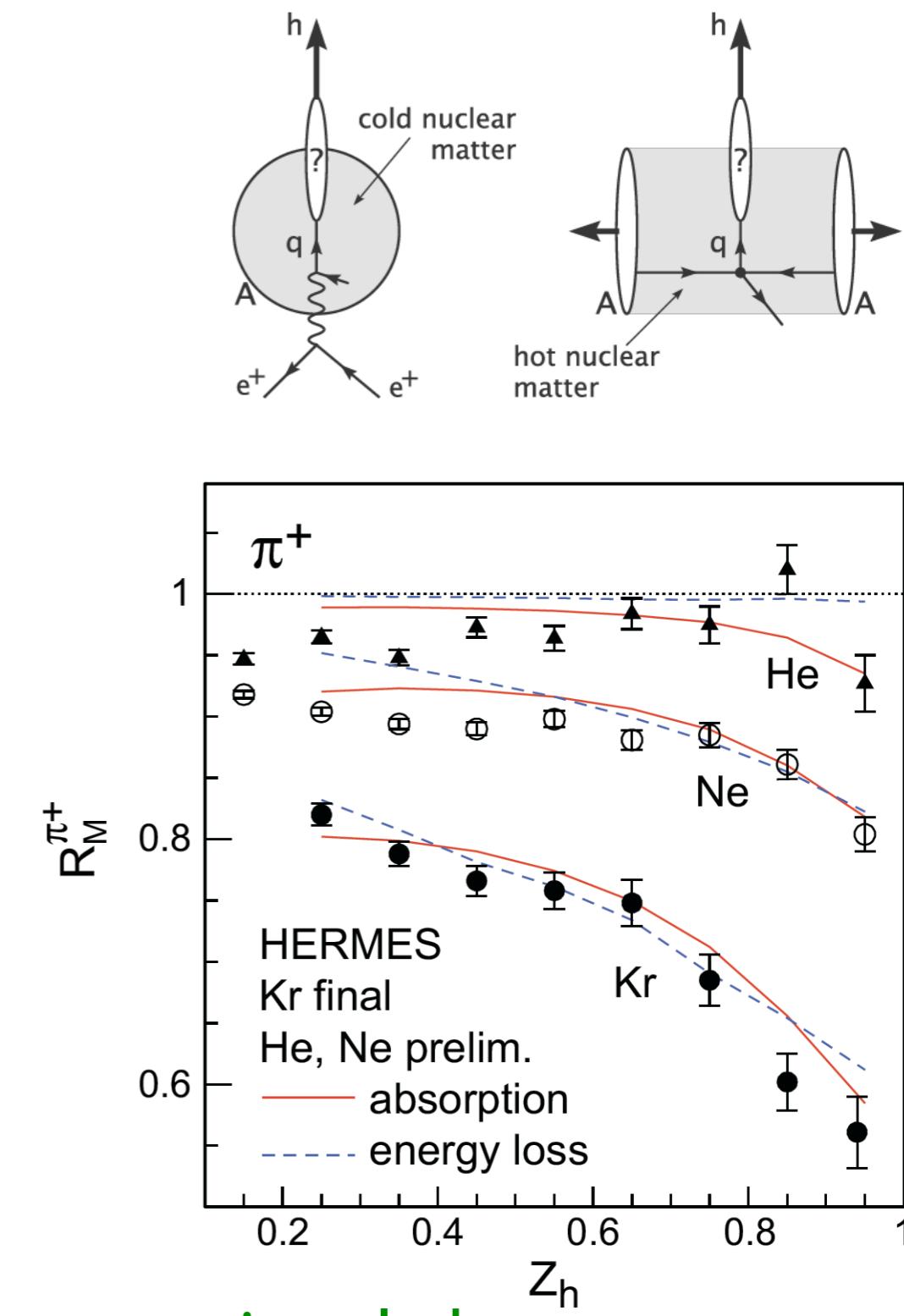
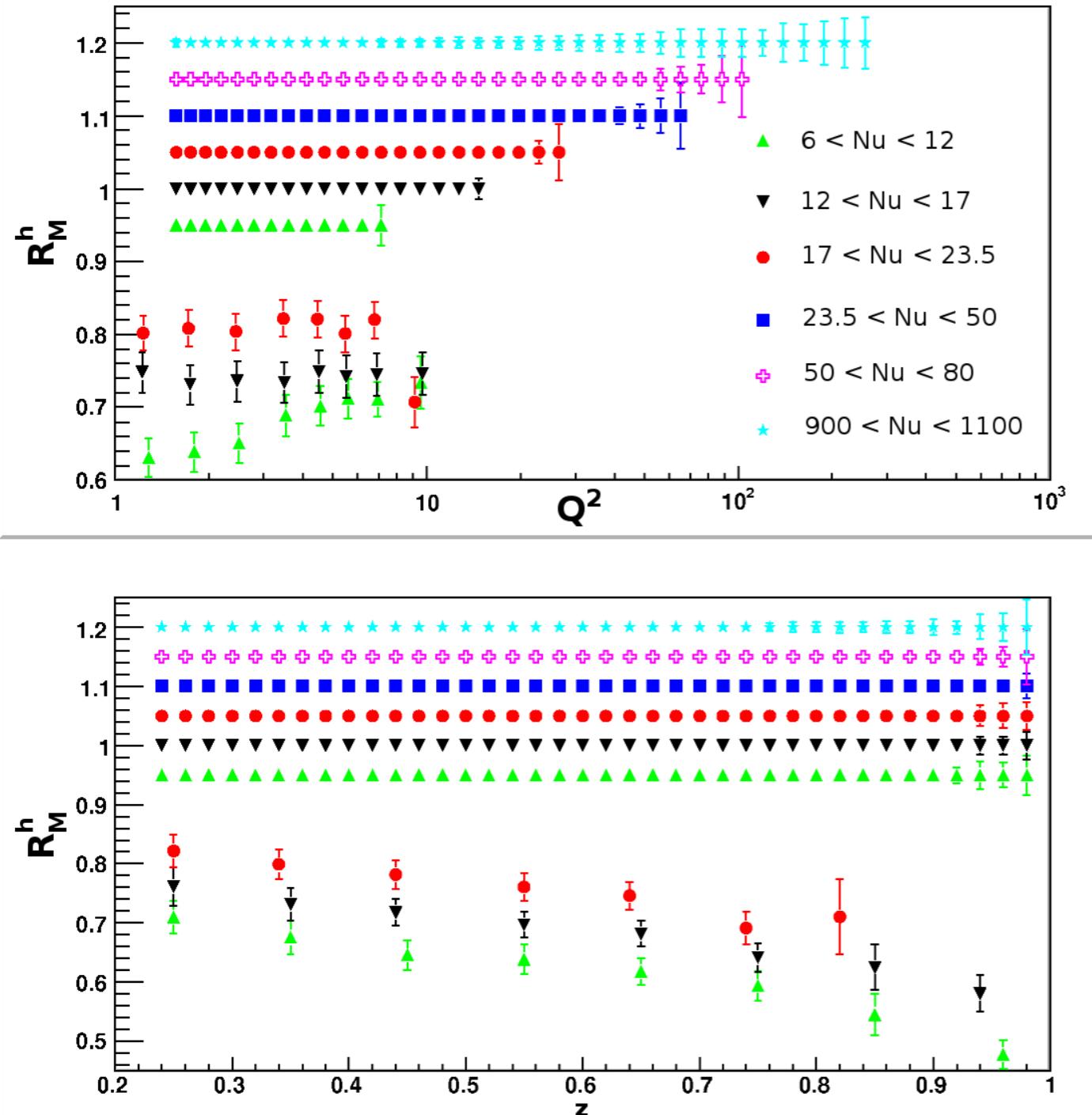
HERMES: 2-25 GeV



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Interaction of fast probes with gluonic medium



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Multiplicity Ratio

