EIC e+A science programme

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BROOKHAVEN
NATIONAL LABORATORY

10 week INT programme - Fall 2010

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Talks online

Application form

Exit report

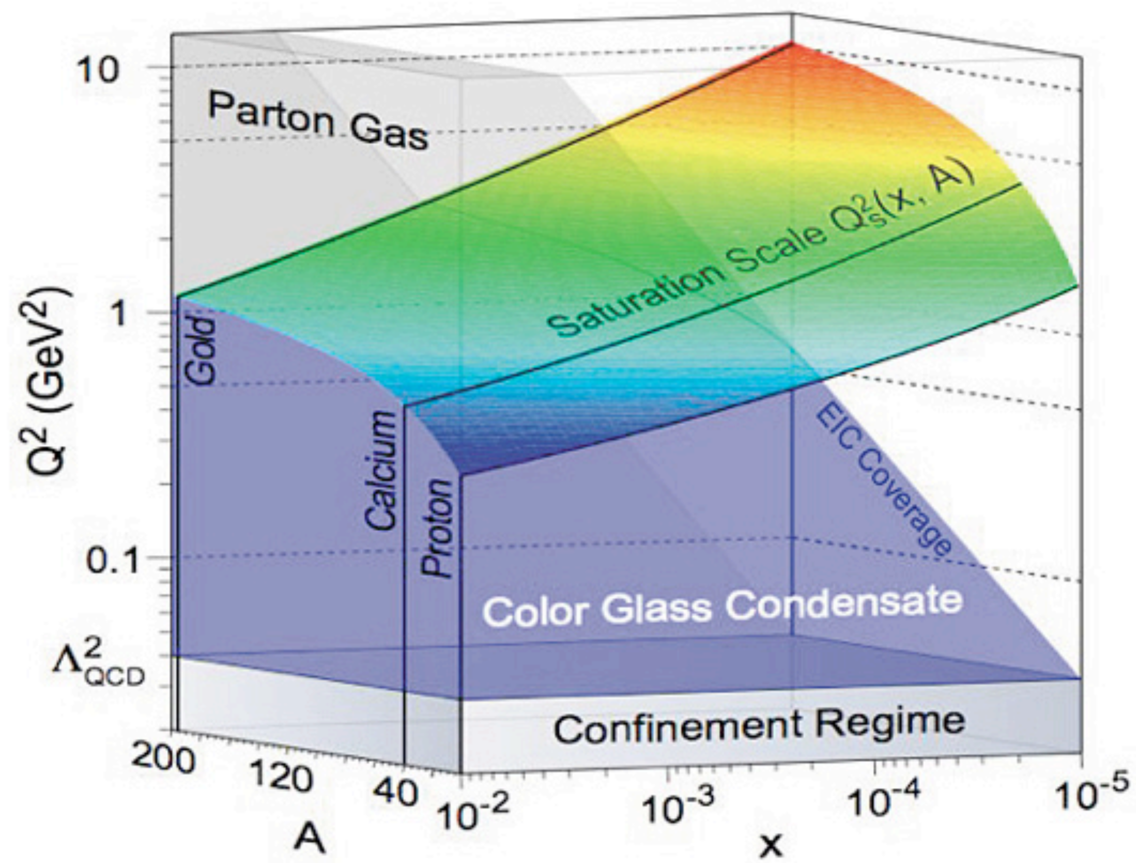
Friends of the INT

Obtain an INT preprint number

INT homepage

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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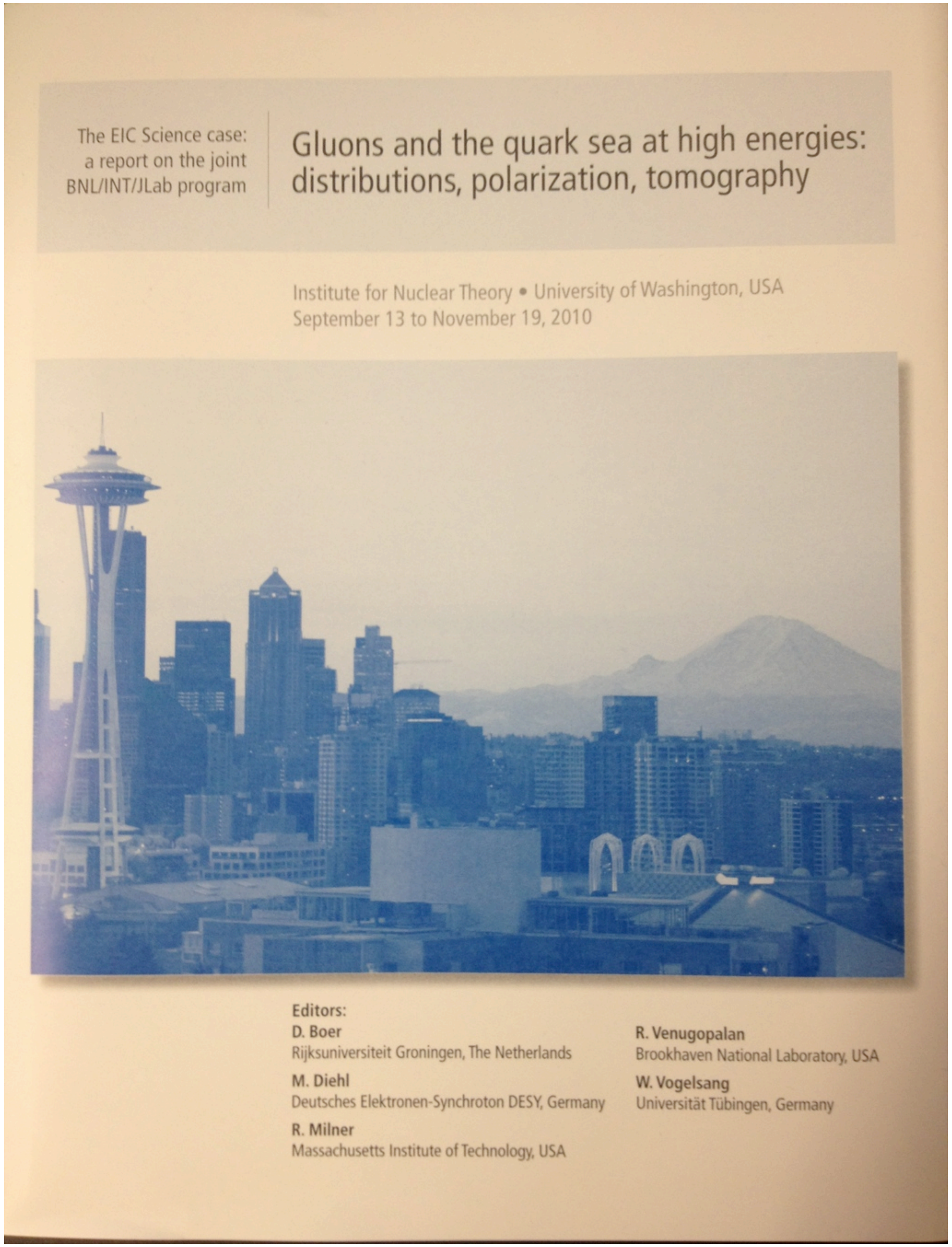
INT Writeup….



- ~ 6 months to write
  - ➡ 189 authors
  - ➡ 7 chapters, 550 pages
- arXiv:1108.1713

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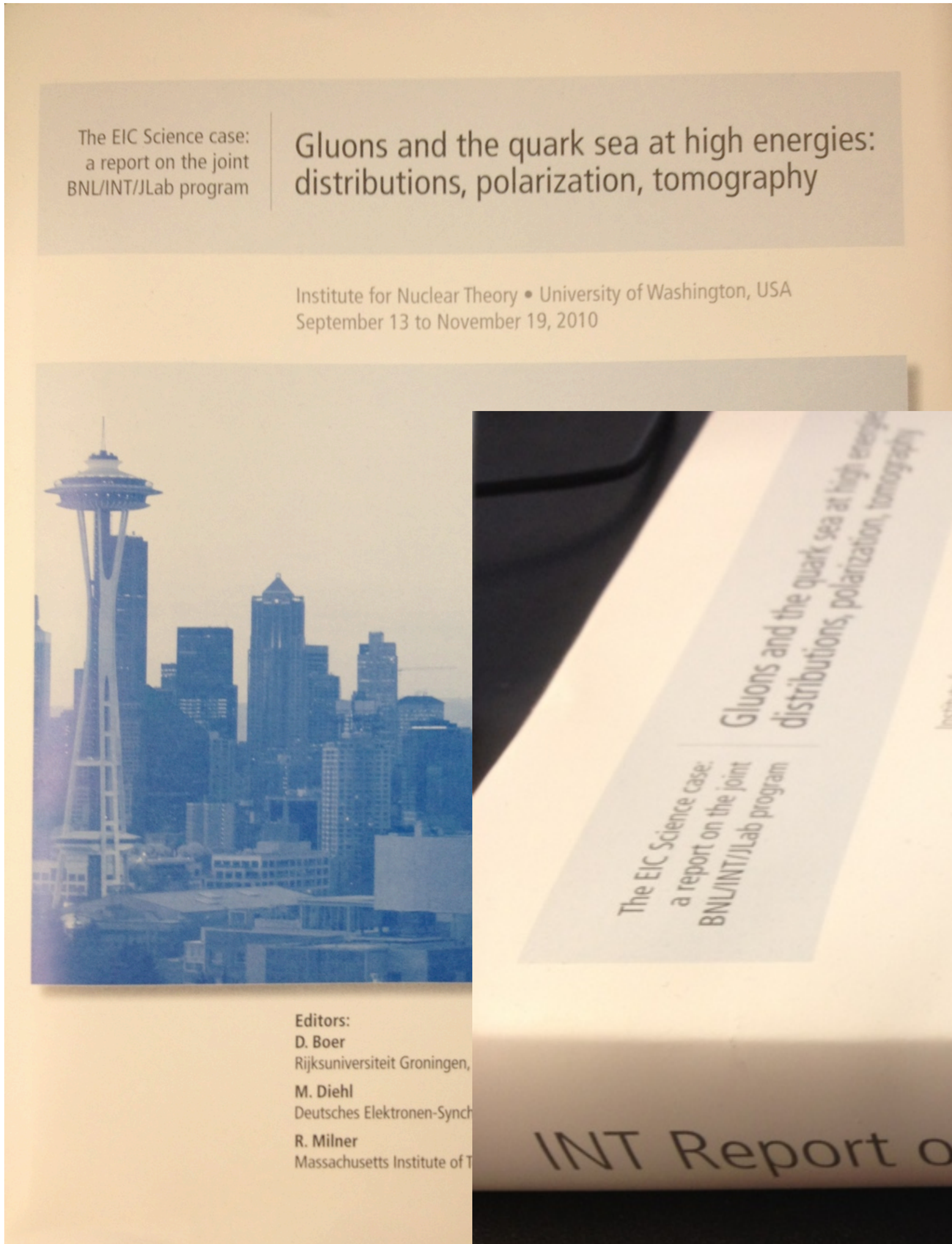
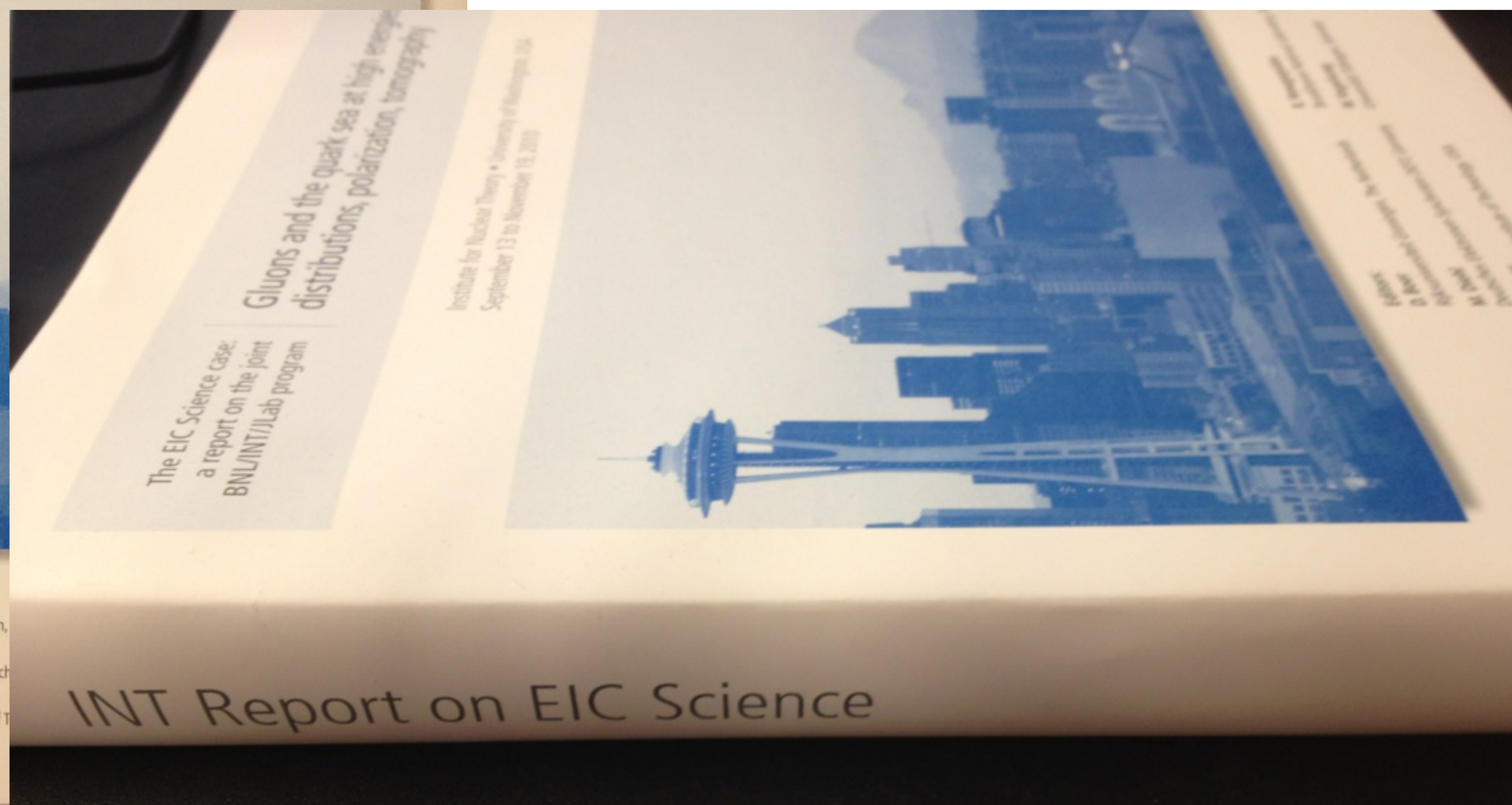
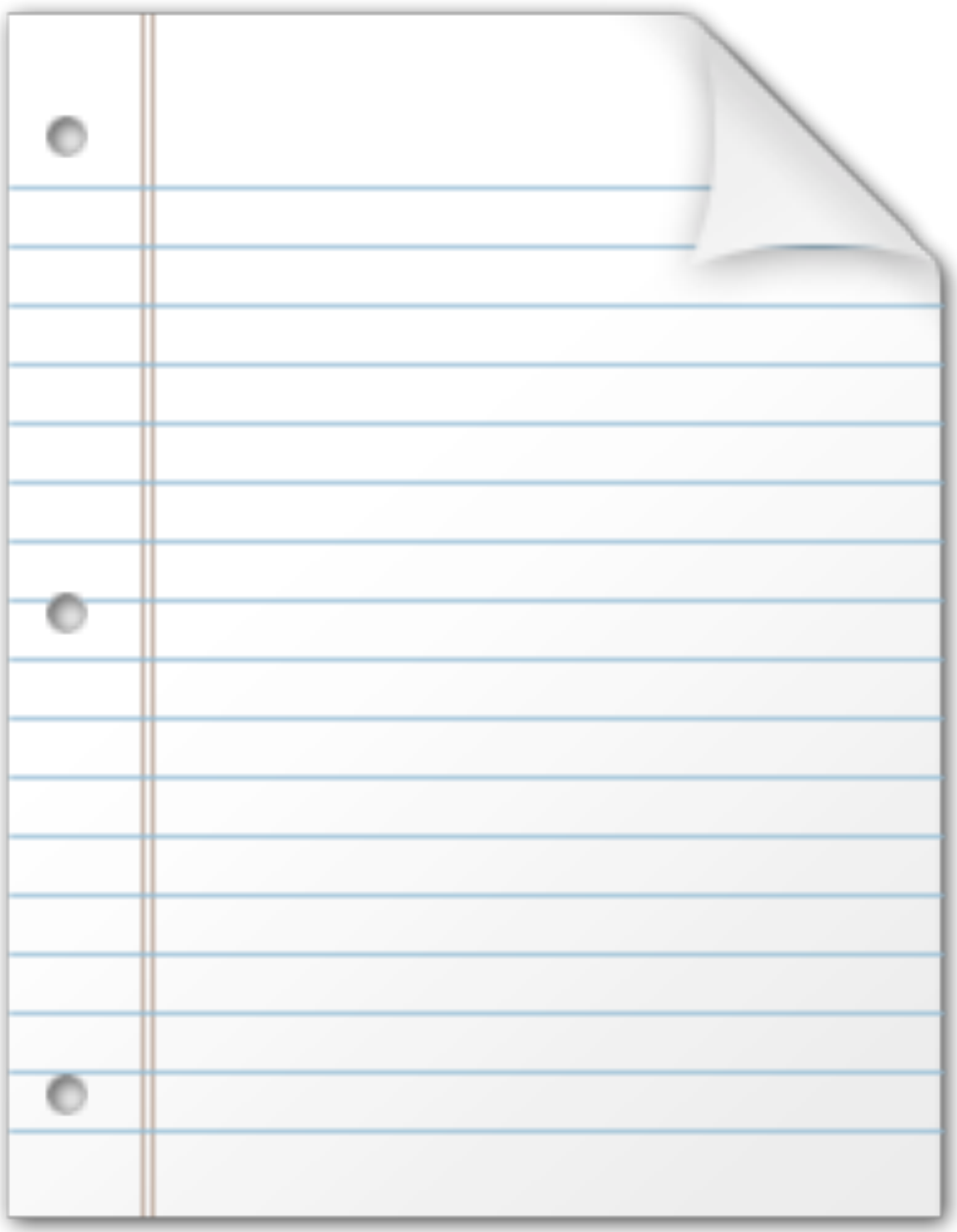




White Paper (almost complete?)



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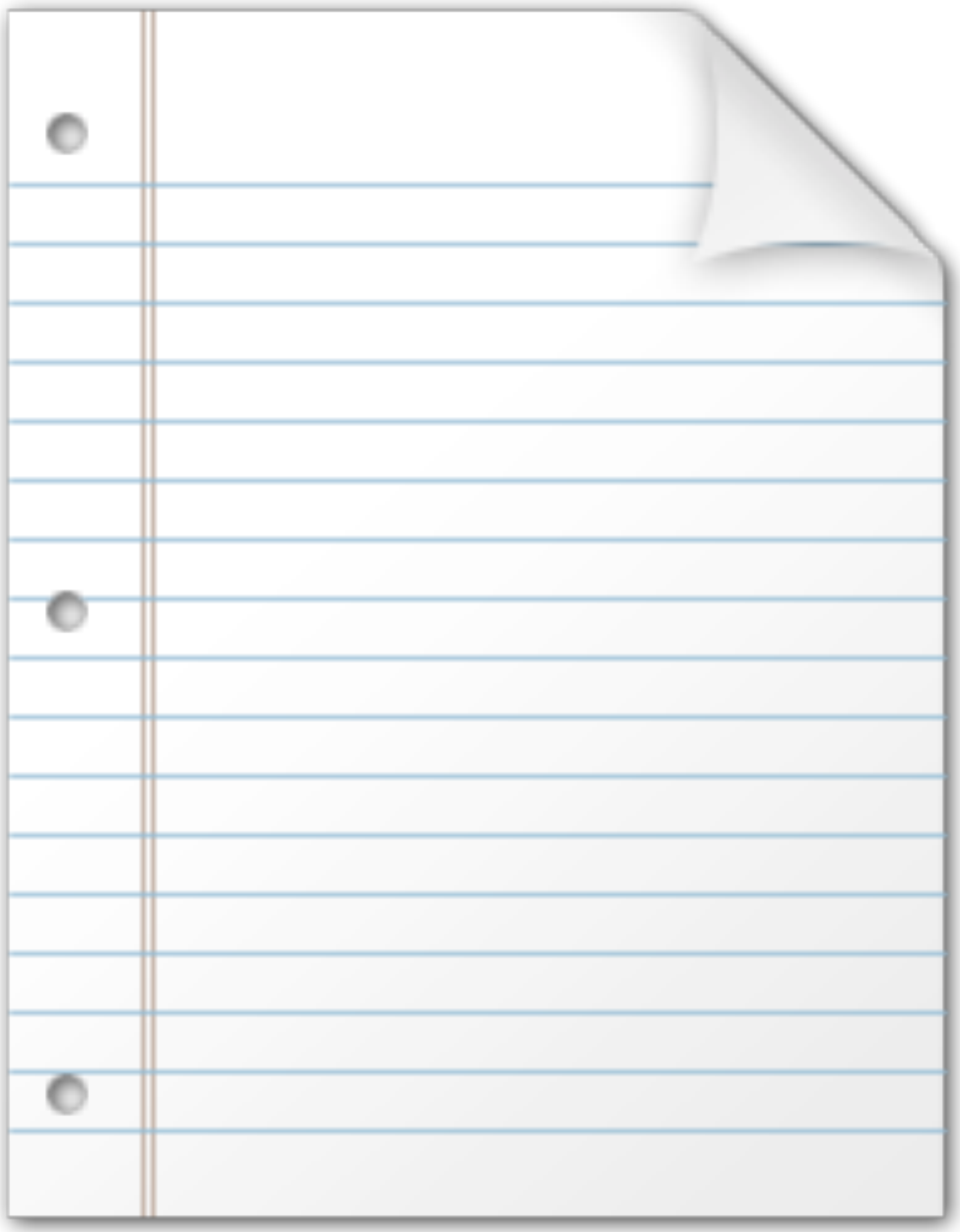
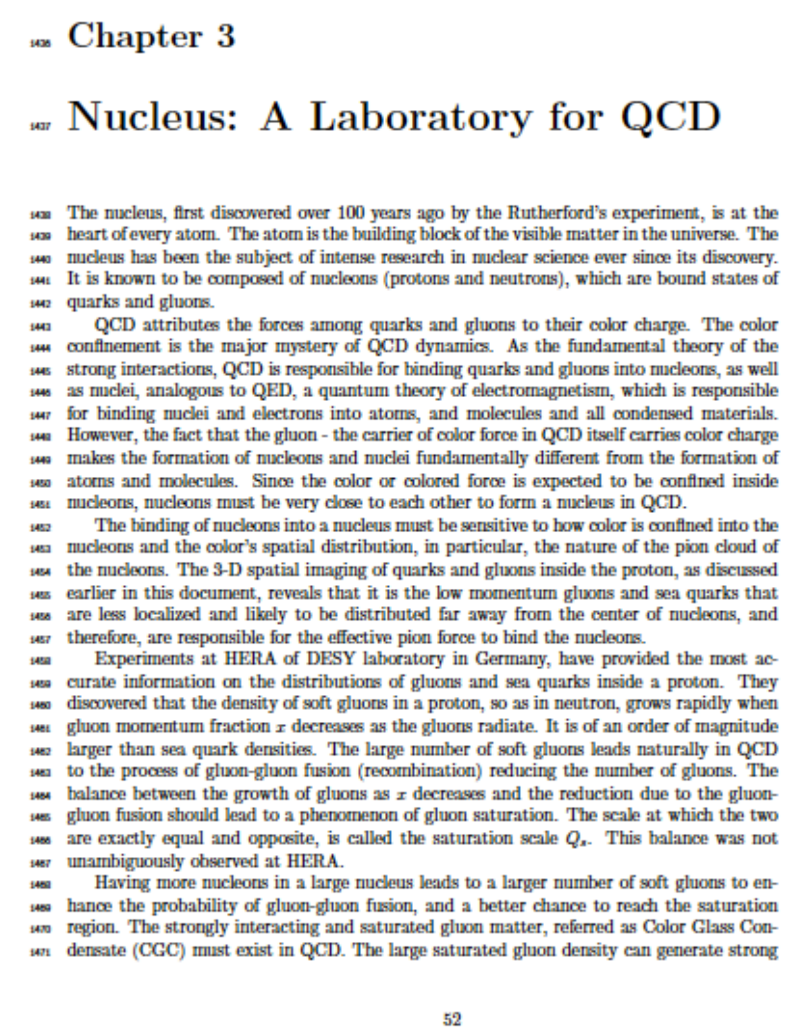




Chapter 3

Nucleus: A Laboratory for QCD

The nucleus, first discovered over 100 years ago by the Rutherford's experiment, is at the heart of every atom. The atom is the building block of the visible matter in the universe. The nucleus has been the subject of intense research in nuclear science ever since its discovery. It is known to be composed of nucleons (protons and neutrons), which are bound states of quarks and gluons.

QCD attributes the forces among quarks and gluons to their color charge. The color confinement is the major mystery of QCD dynamics. As the fundamental theory of the strong interactions, QCD is responsible for binding quarks and gluons into nucleons, as well as nuclei, analogous to QED, a quantum theory of electromagnetism, which is responsible for binding nuclei and electrons into atoms, and molecules and all condensed materials. However, the fact that the gluon - the carrier of color force in QCD itself carries color charge makes the formation of nucleons and nuclei fundamentally different from the formation of atoms and molecules. Since the color or colored force is expected to be confined inside nucleons, nucleons must be very close to each other to form a nucleus in QCD.

The binding of nucleons into a nucleus must be sensitive to how color is confined into the nucleons and the color's spatial distribution, in particular, the nature of the pion cloud of the nucleons. The 3-D spatial imaging of quarks and gluons inside the proton, as discussed earlier in this document, reveals that it is the low momentum gluons and sea quarks that are less localized and likely to be distributed far away from the center of nucleons, and therefore, are responsible for the effective pion force to bind the nucleons.

Experiments at HERA of DESY laboratory in Germany, have provided the most accurate information on the distributions of gluons and sea quarks inside a proton. They discovered that the density of soft gluons in a proton, so as in neutron, grows rapidly when gluon momentum fraction x decreases as the gluons radiate. It is of an order of magnitude larger than sea quark densities. The large number of soft gluons leads naturally in QCD to the process of gluon-gluon fusion (recombination) reducing the number of gluons. The balance between the growth of gluons as x decreases and the reduction due to the gluon-gluon fusion should lead to a phenomenon of gluon saturation. The scale at which the two are exactly equal and opposite, is called the saturation scale Q_s. This balance was not unambiguously observed at HERA.

Having more nucleons in a large nucleus leads to a larger number of soft gluons to enhance the probability of gluon-gluon fusion, and a better chance to reach the saturation region. The strongly interacting and saturated gluon matter, referred as Color Glass Condensate (CGC) must exist in QCD. The large saturated gluon density can generate strong

52

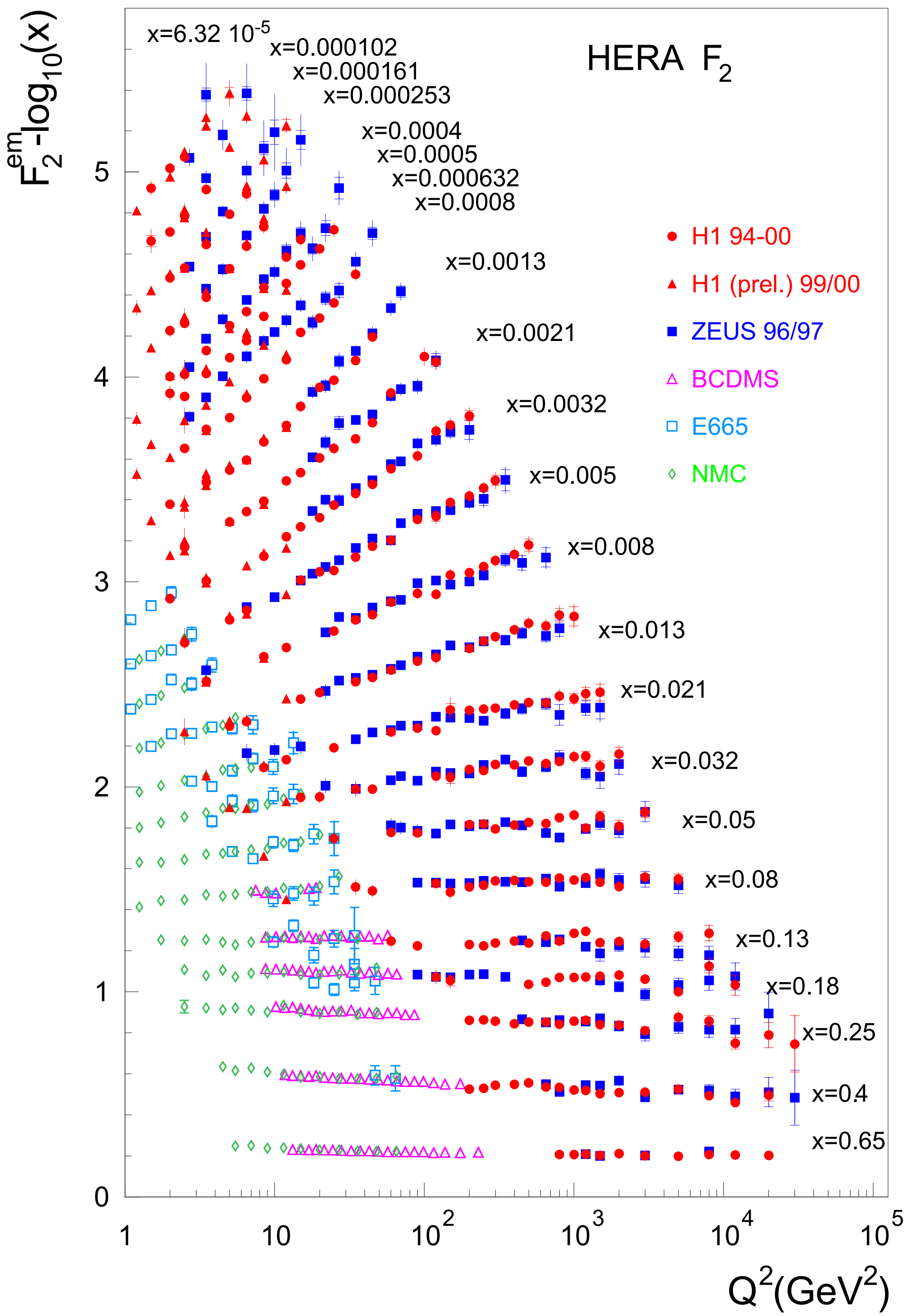
- Soon to be made public…
- ~ 120 pages

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 momentum distributions

gluon momentum distribution



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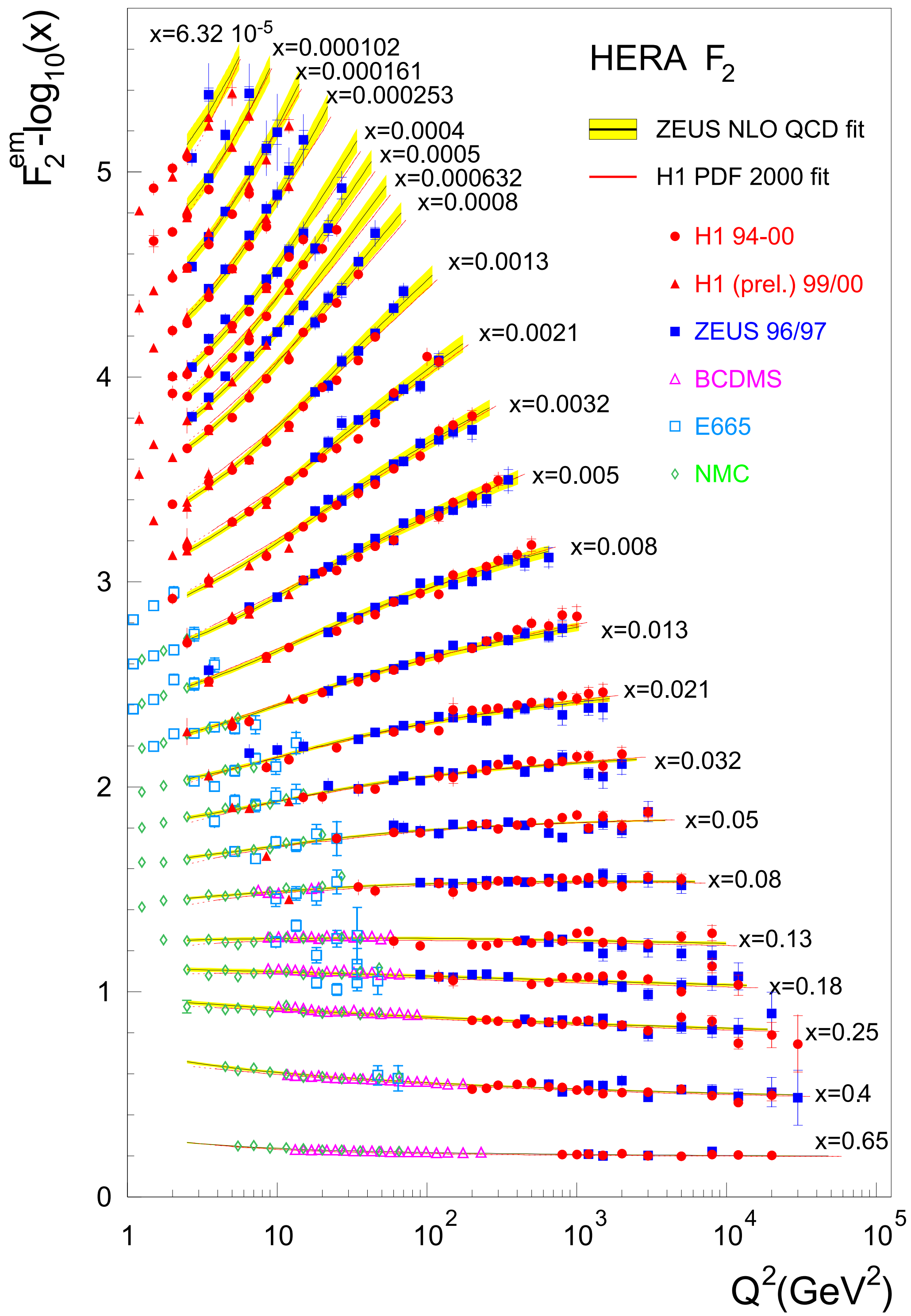

Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

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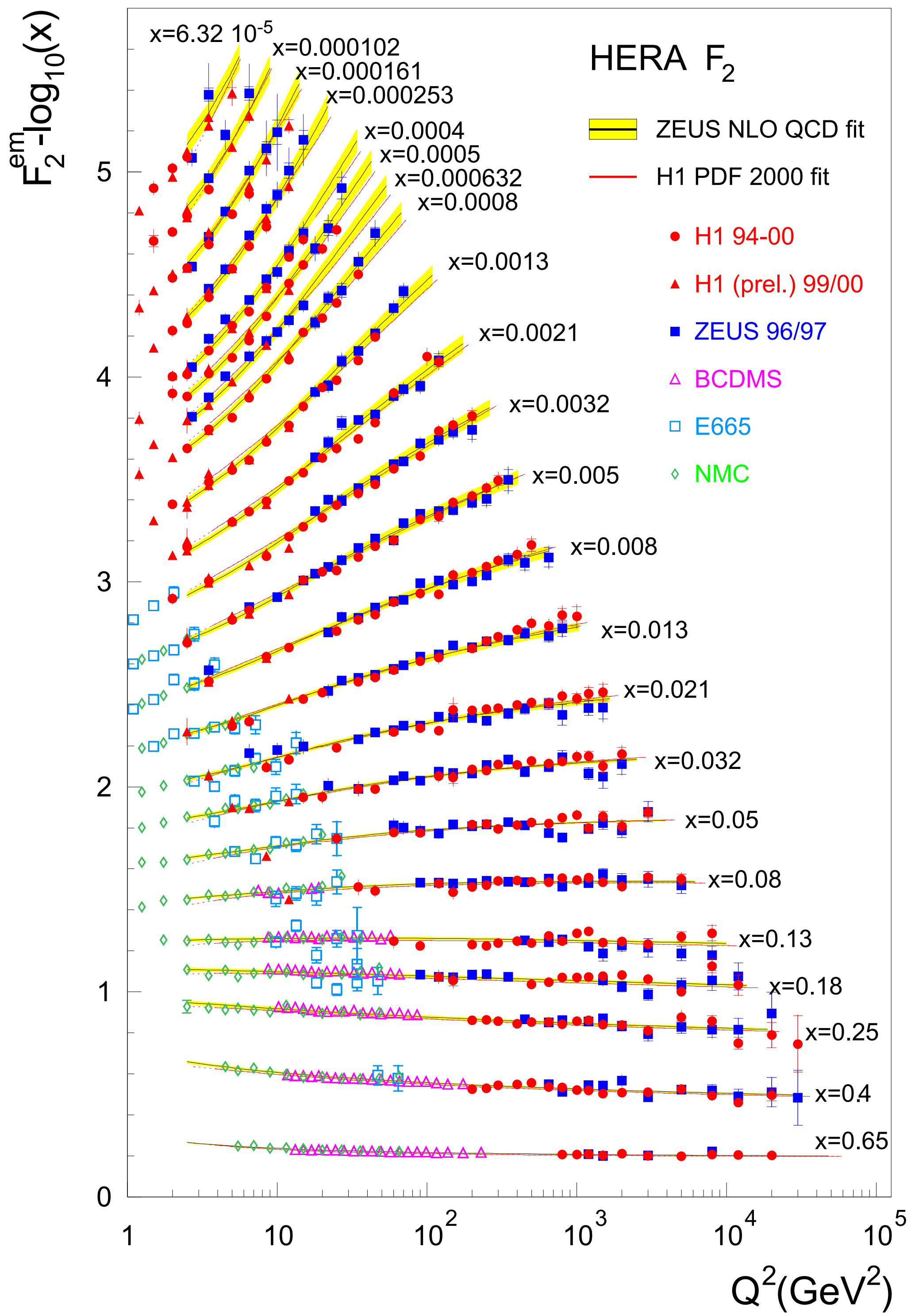
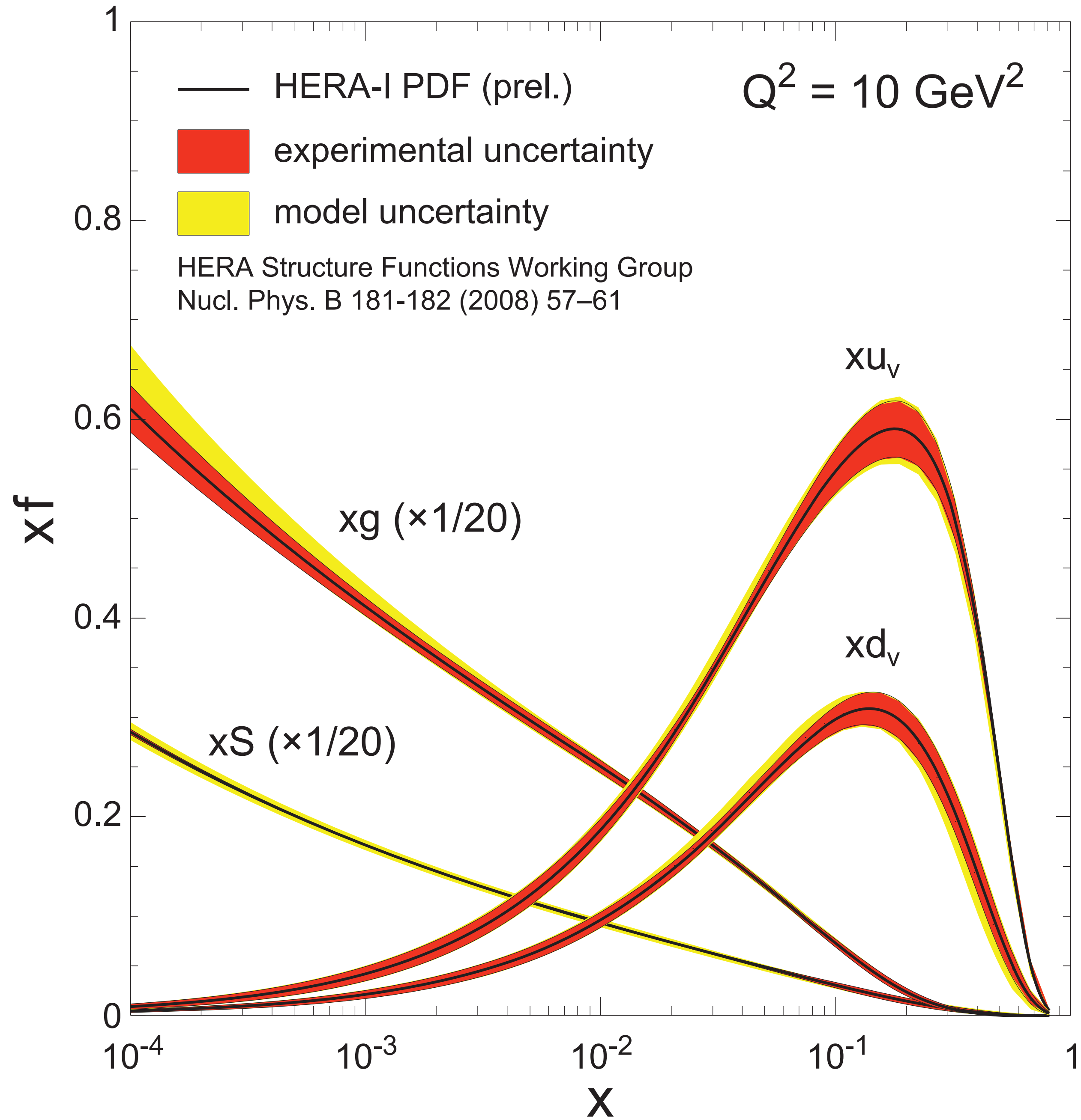


Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP

Evolution ⇒ $G(x,Q^2)$



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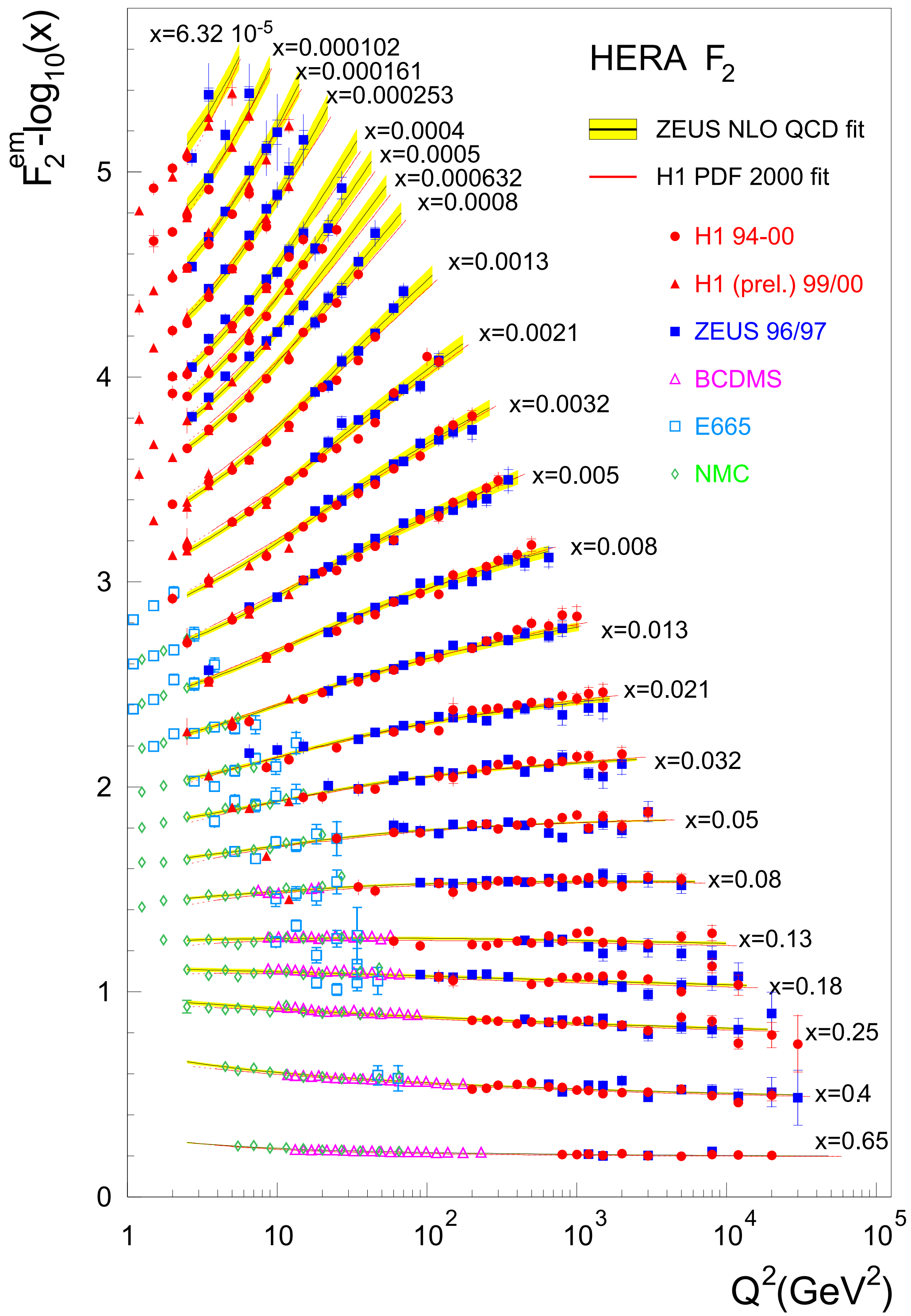

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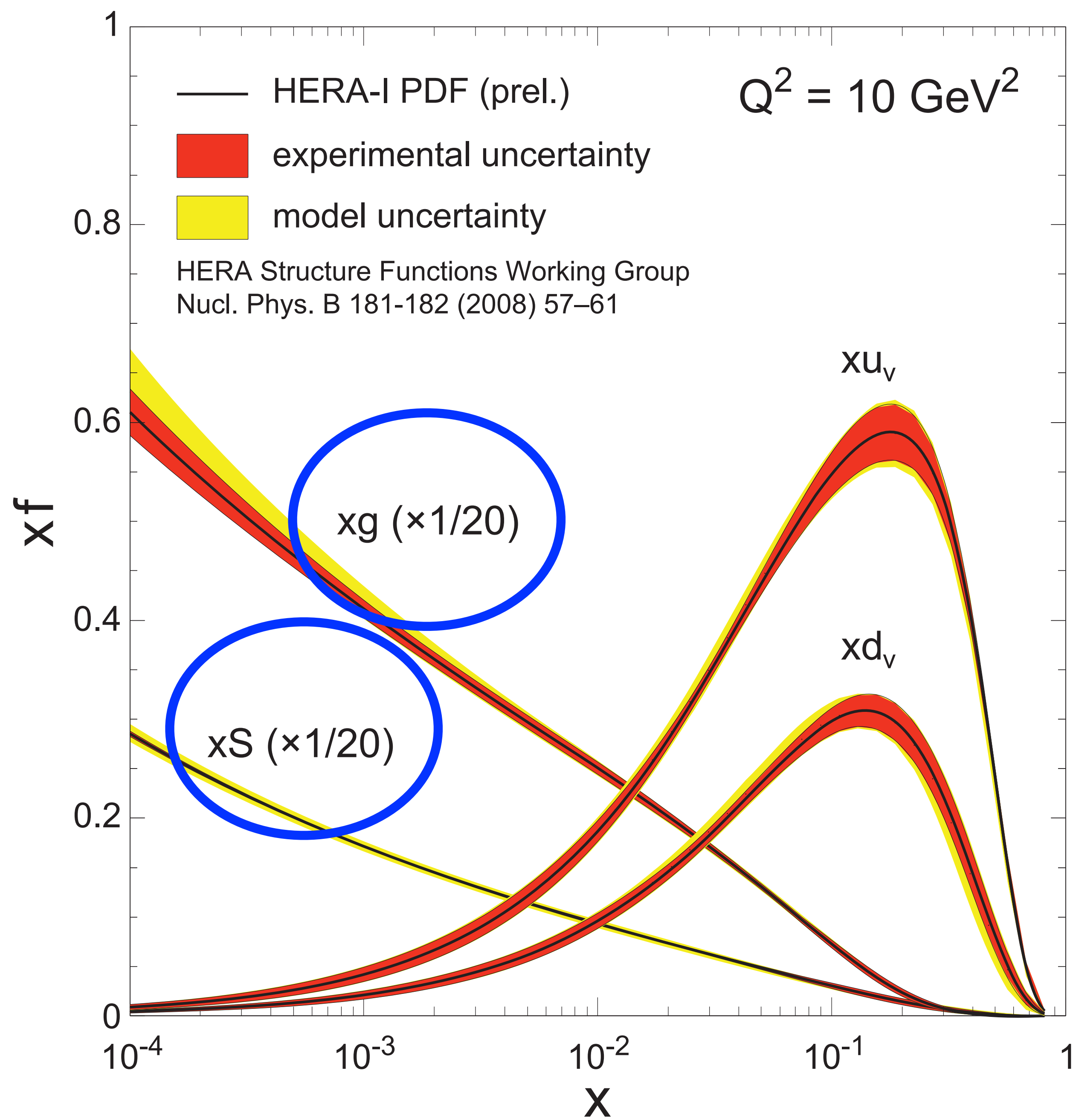

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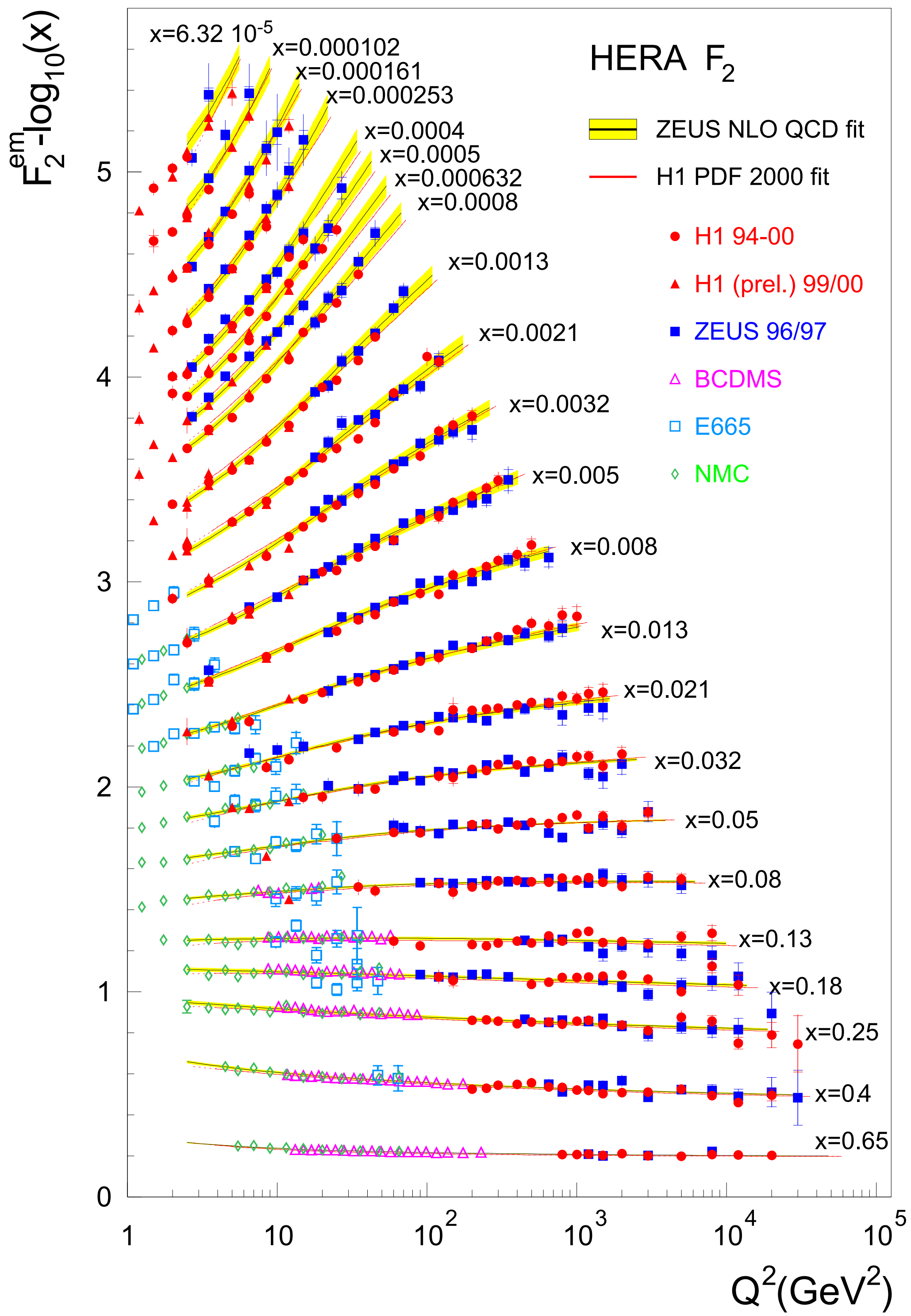

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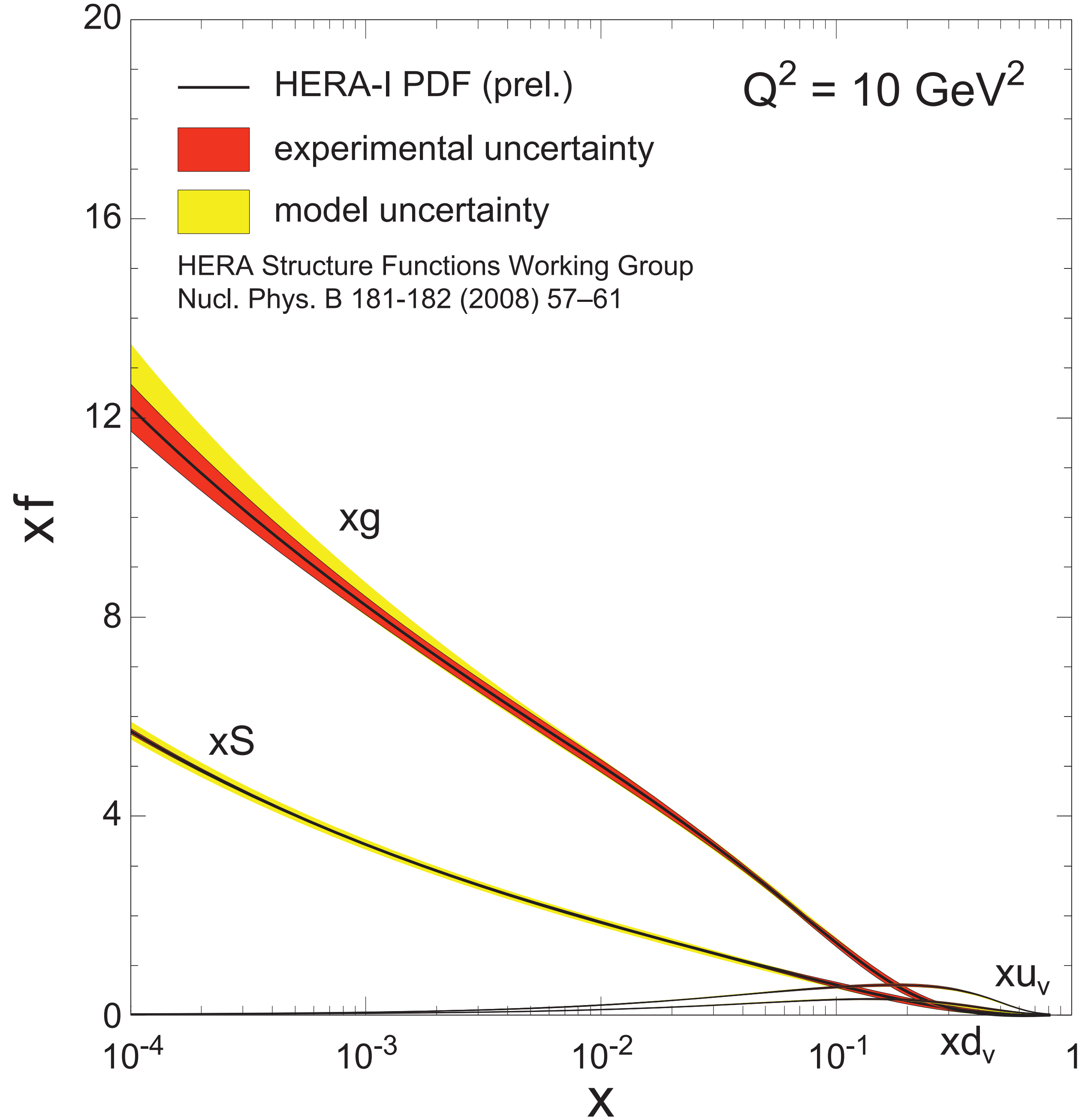
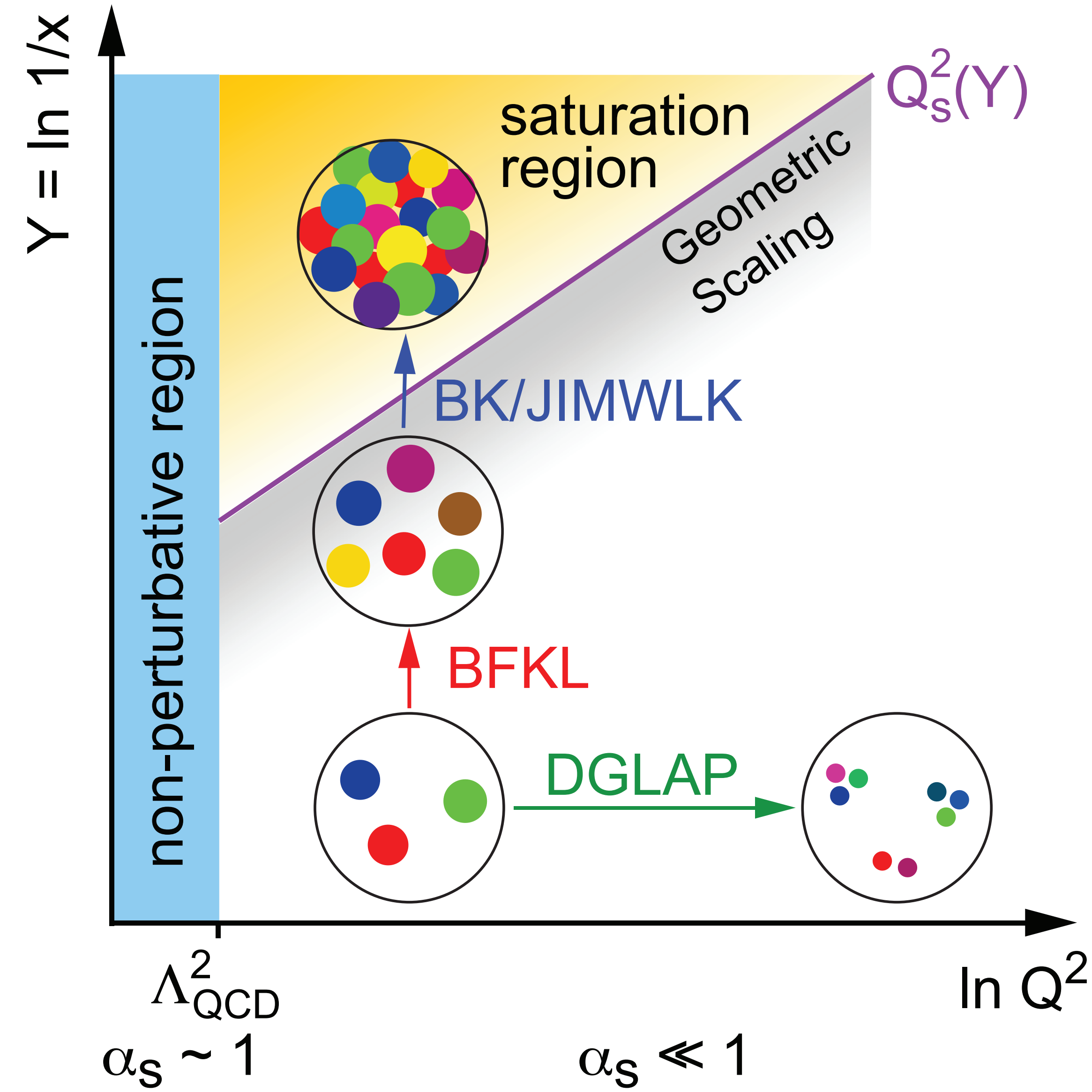
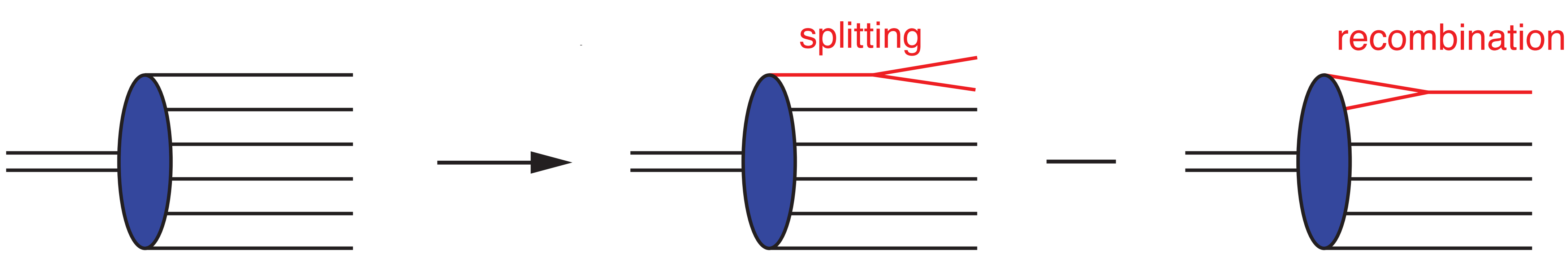


Saturation Scale, Q_s

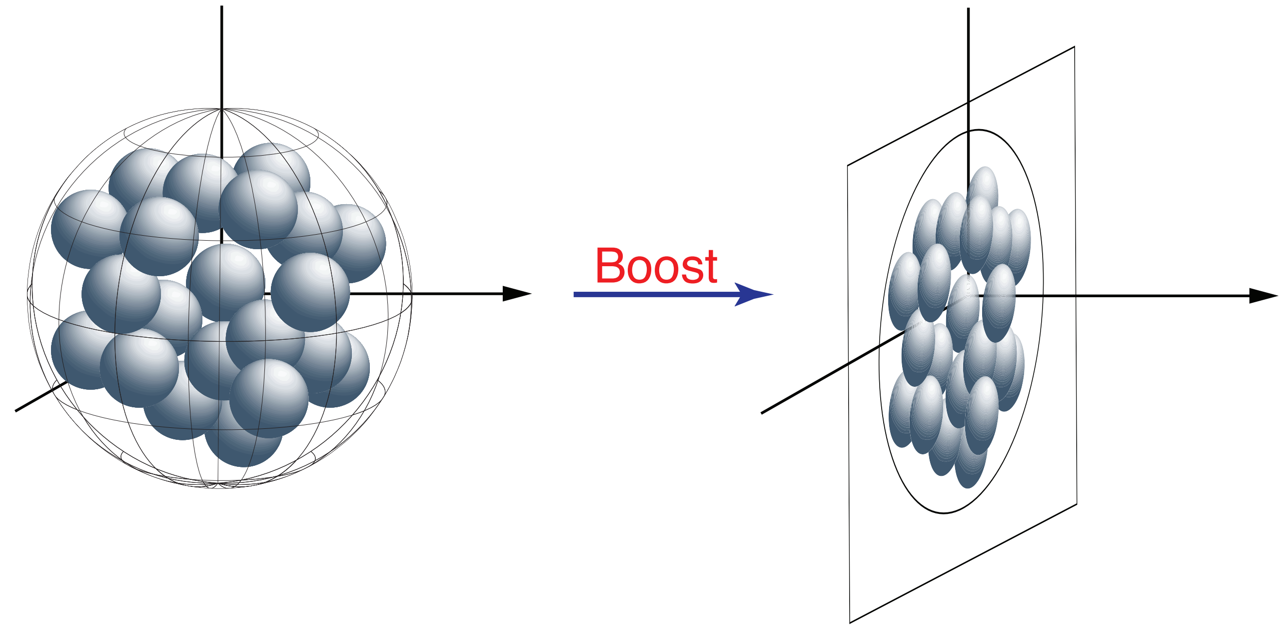
- As we go higher in energy (larger values of 1/x) we move away from the *linear BFKL* regime to the *non-linear BK/JIMWLK* realm
- Take advantage of the fact that gluons are self-interacting
  - ➡ Not only can we have gluon splitting, but also recombination
    - ‣ Tame the explosive growth of the gluon density in the nucleon observed from fitting HERA data





Nuclear “oomph” effect

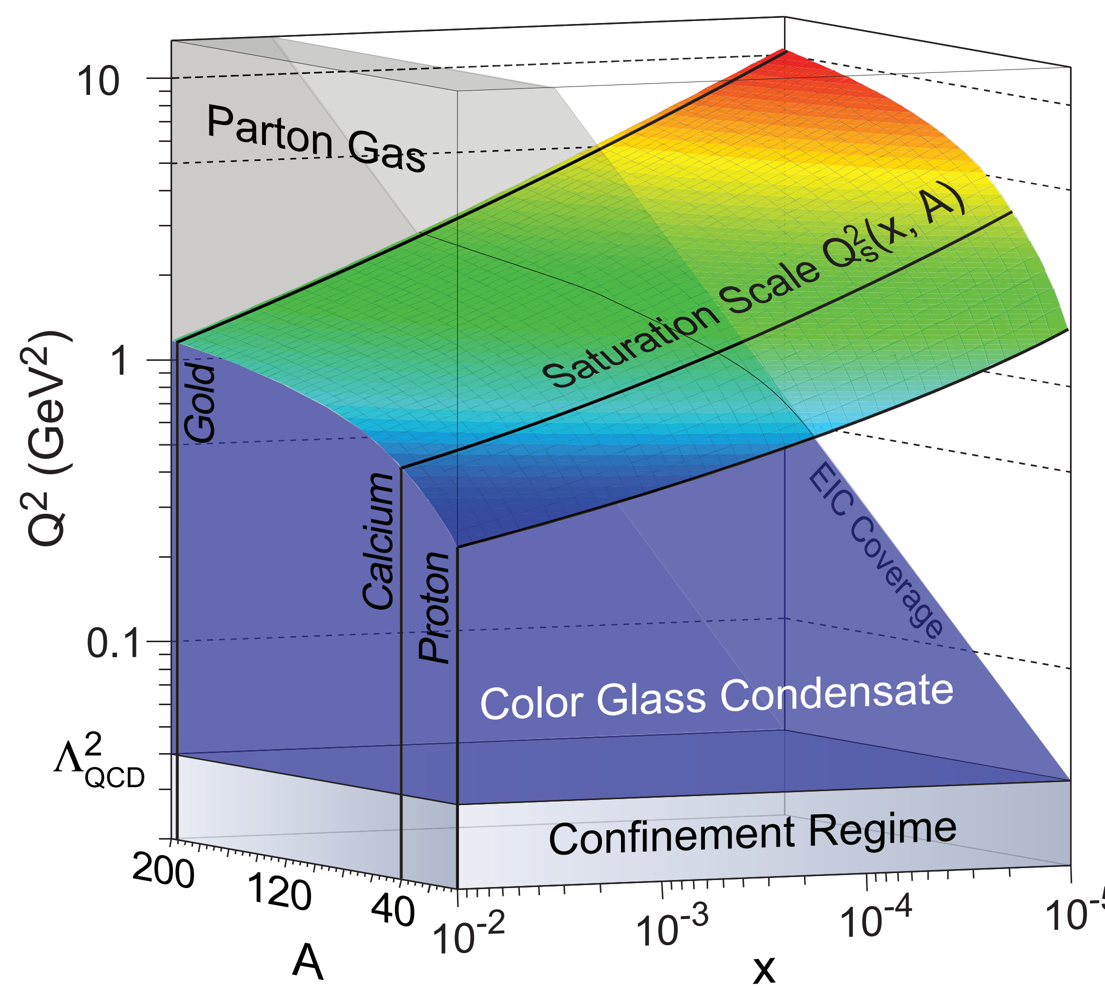
- When we accelerate out nucleus to high energy, we give it a Lorentz boost



- Incoming probe interacts coherently with all of the nucleons in the nucleus

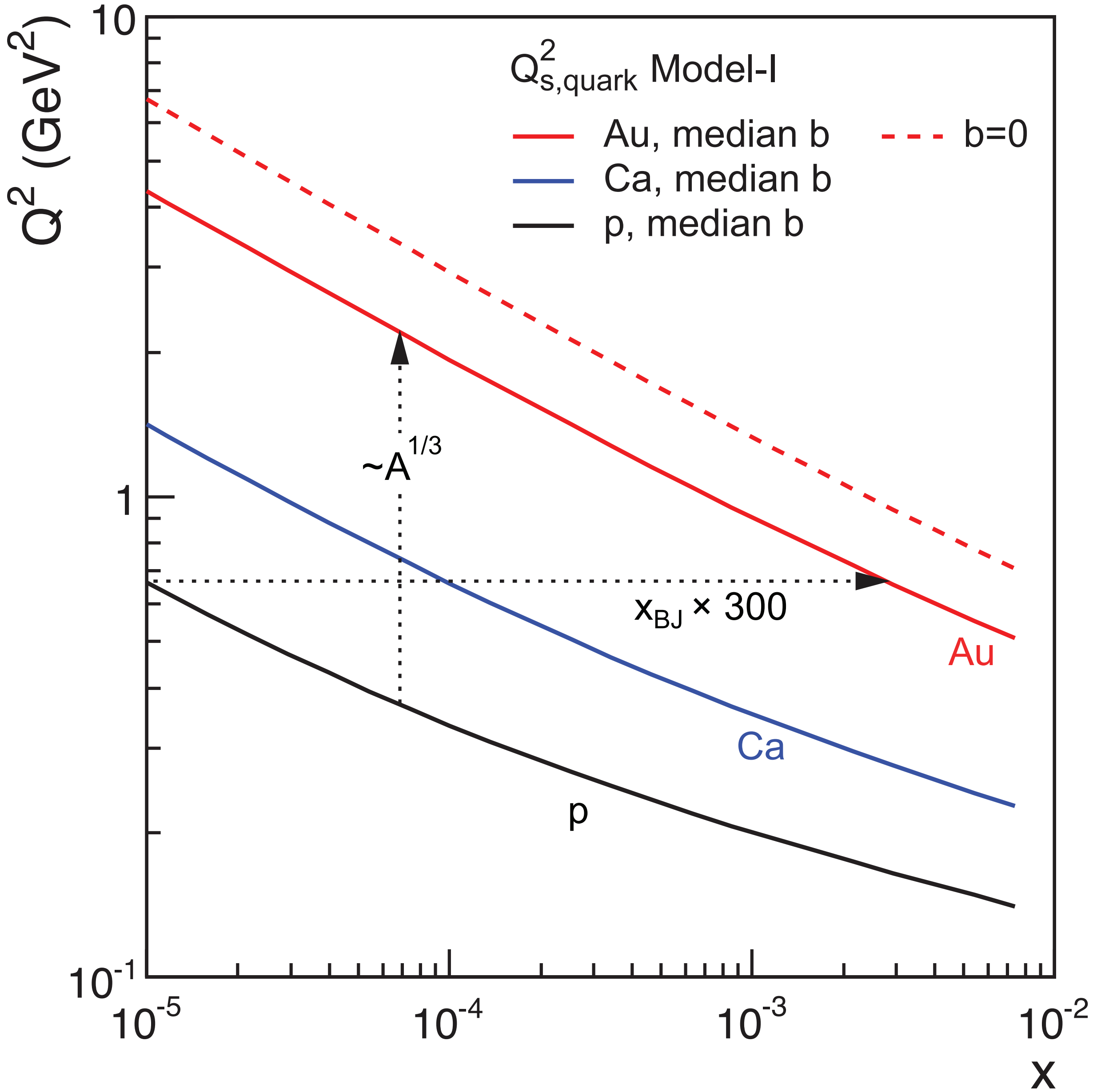
➡ Qs is given a boost simply by the geometry of the collision system

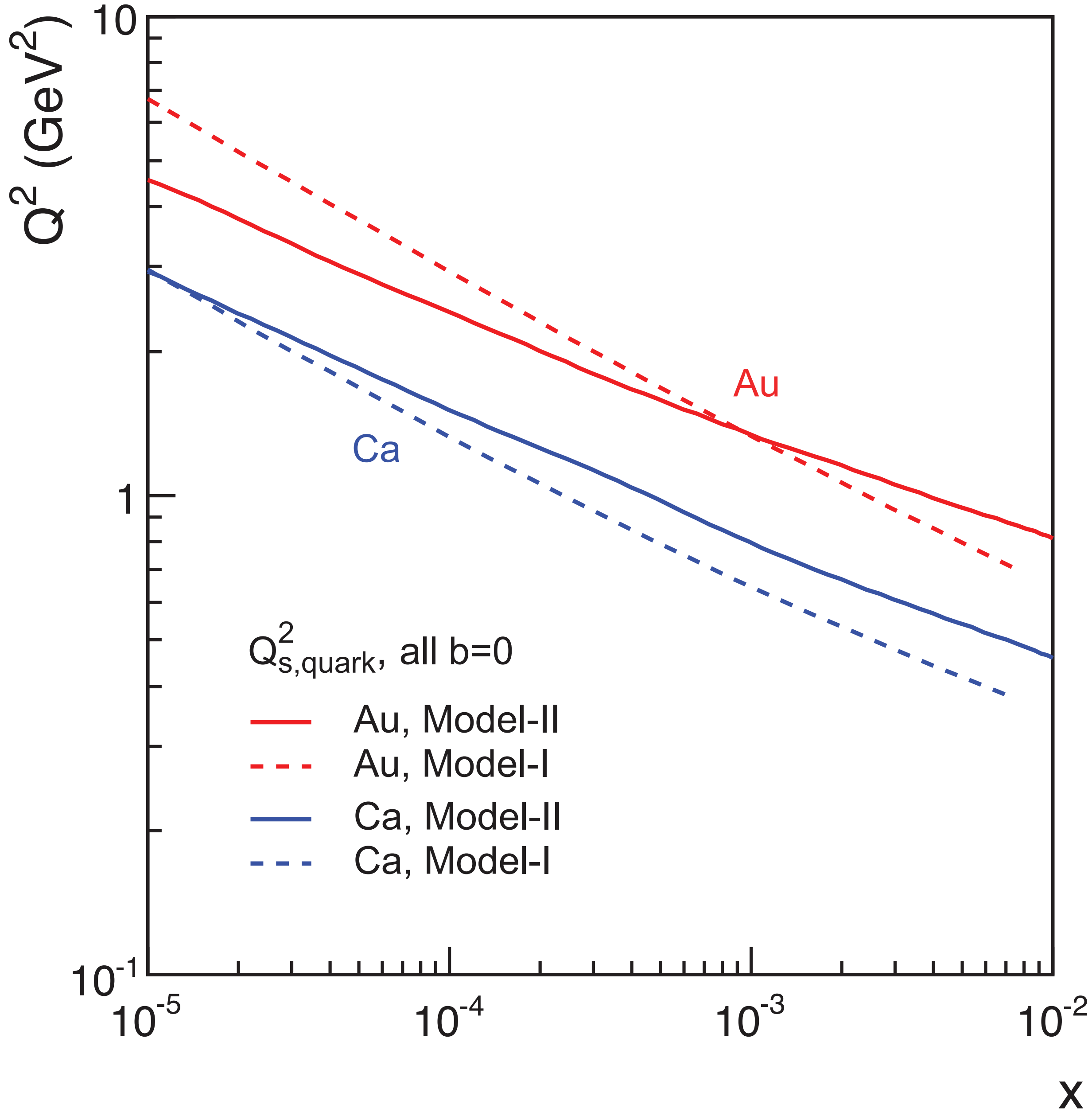
$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$$



Nuclear "oomph" effect

Pocket formula: $Q_s^2(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$





Fundamental questions which arise:

- What is the role of strong gluon fields, parton saturation effects and collective gluon excitations in scattering off nuclei?
  - ➡ tantalising hints of a saturated/CGC regime have been observed at HERA/RHIC/LHC
- Can we experimentally find the evidence of non-linear QCD evolution in high-energy scattering off nuclei?
  - ➡ x-dependence of DIS cross-sections and structure functions
  - ➡ The discovery of the saturation regime would not be complete without unambiguous evidence in favour of these non-linear equations

Fundamental questions which arise:

- What is the momentum and spatial distribution of gluons and sea quarks in nuclei?
  - ➡ Large-x: the physics of multiple scatterings at allows us to reconstruct the momentum and impact parameter distributions of gluons and sea quarks in nuclei
  - ➡ Small-x: momentum distribution may allow us to identify the saturation scale, Q_s
- Are there strong colour (quark and gluon density) fluctuations inside of a large nucleus? How does the nucleus respond to the propagation of a colour charge through it?
  - ➡ Need to understand fluctuations in order to fully understand the spatial and momentum distributions of sea quarks and gluons

Golden Measurements

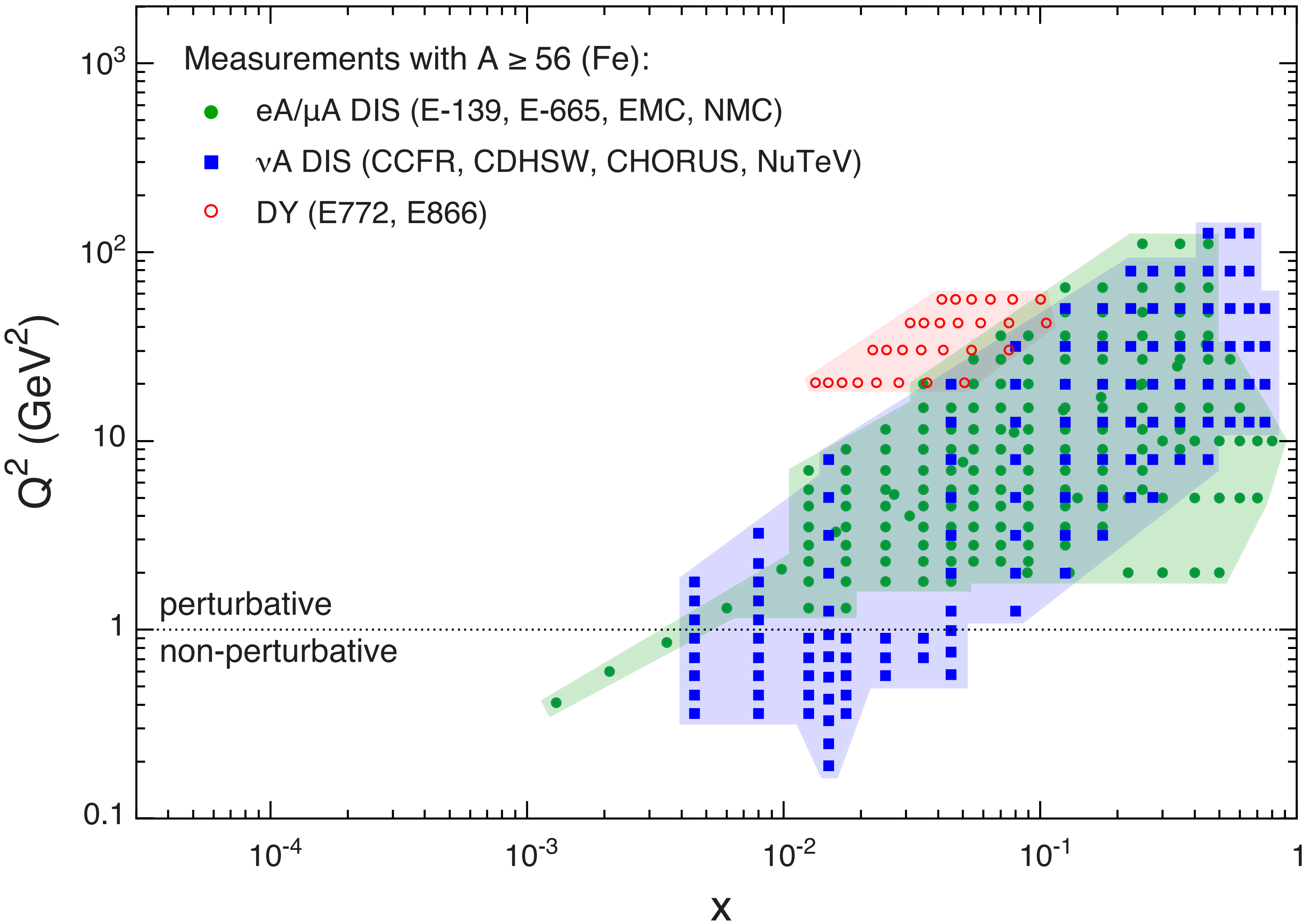
Deliverables	Observables	What we learn	Stage-1	Stage-II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	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	$F^{c}_{2,L}$, $F^{D}_{2,L}$	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

How do we try to answer these questions?

- Need to undertake nuclear DIS measurements at a new facility
  - ➡ Existing measurements with heavy ions are very sparse
  - ➡ A new accelerator (eRHIC) with a staged approach would address these questions in a new phase space



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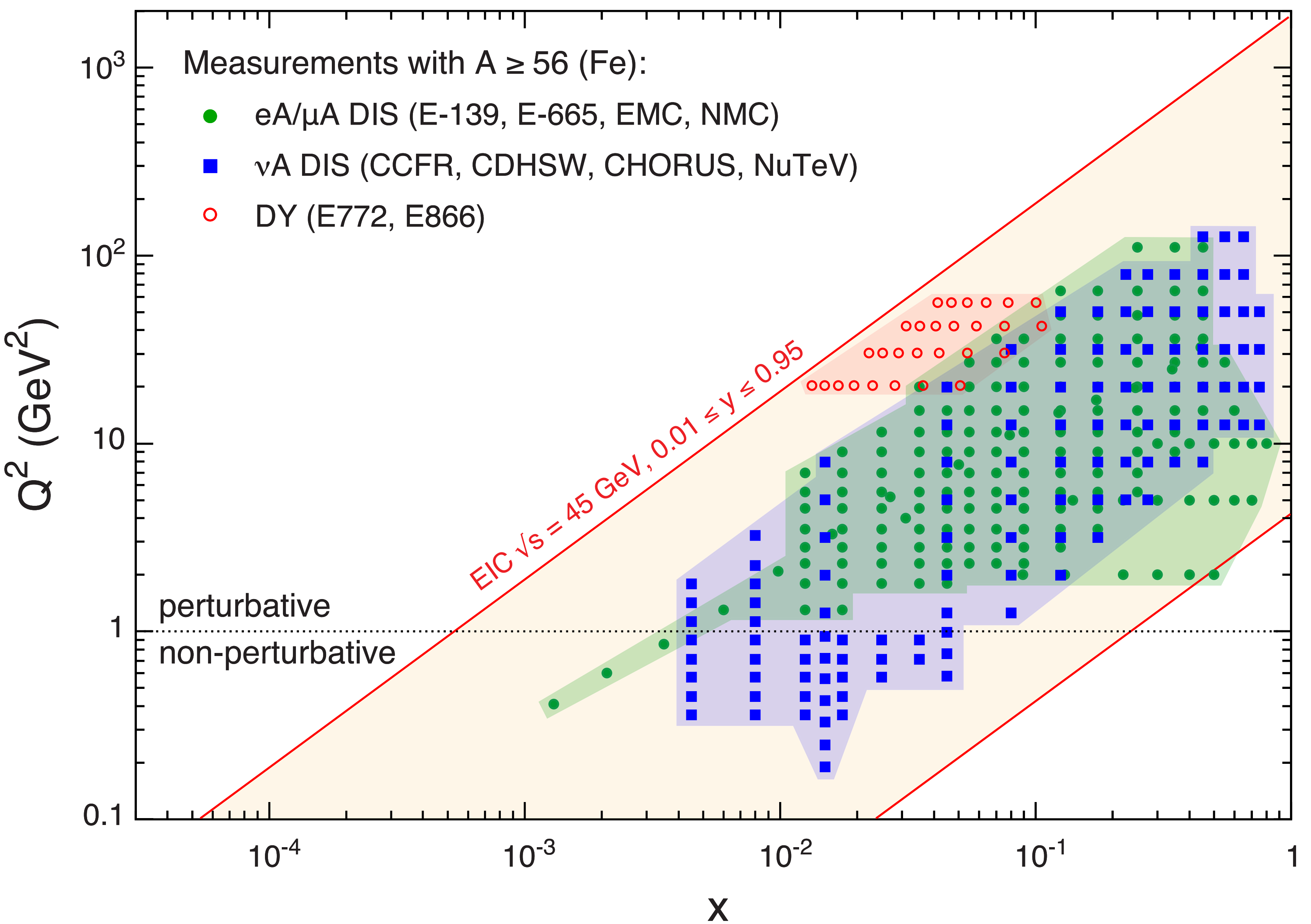

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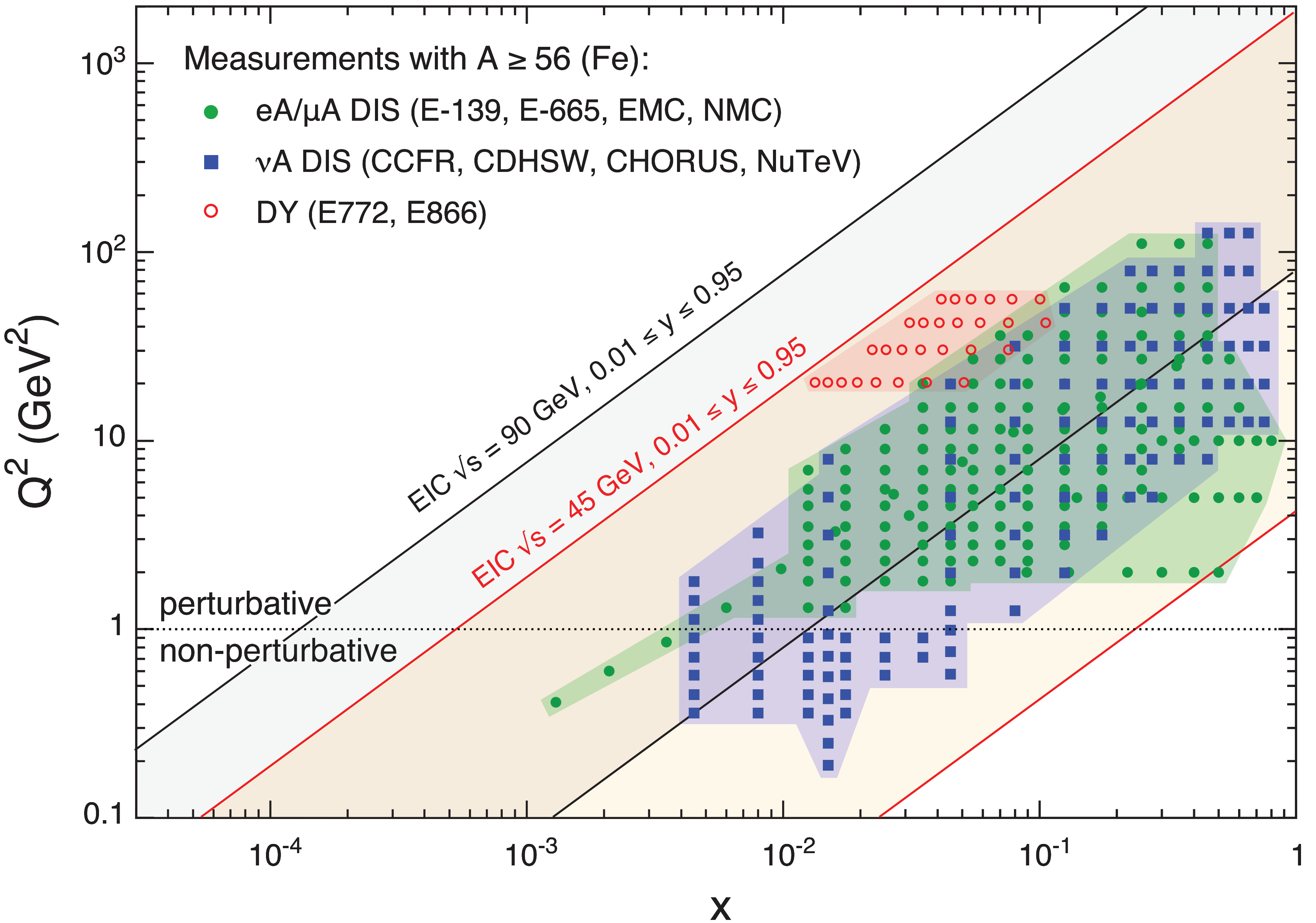

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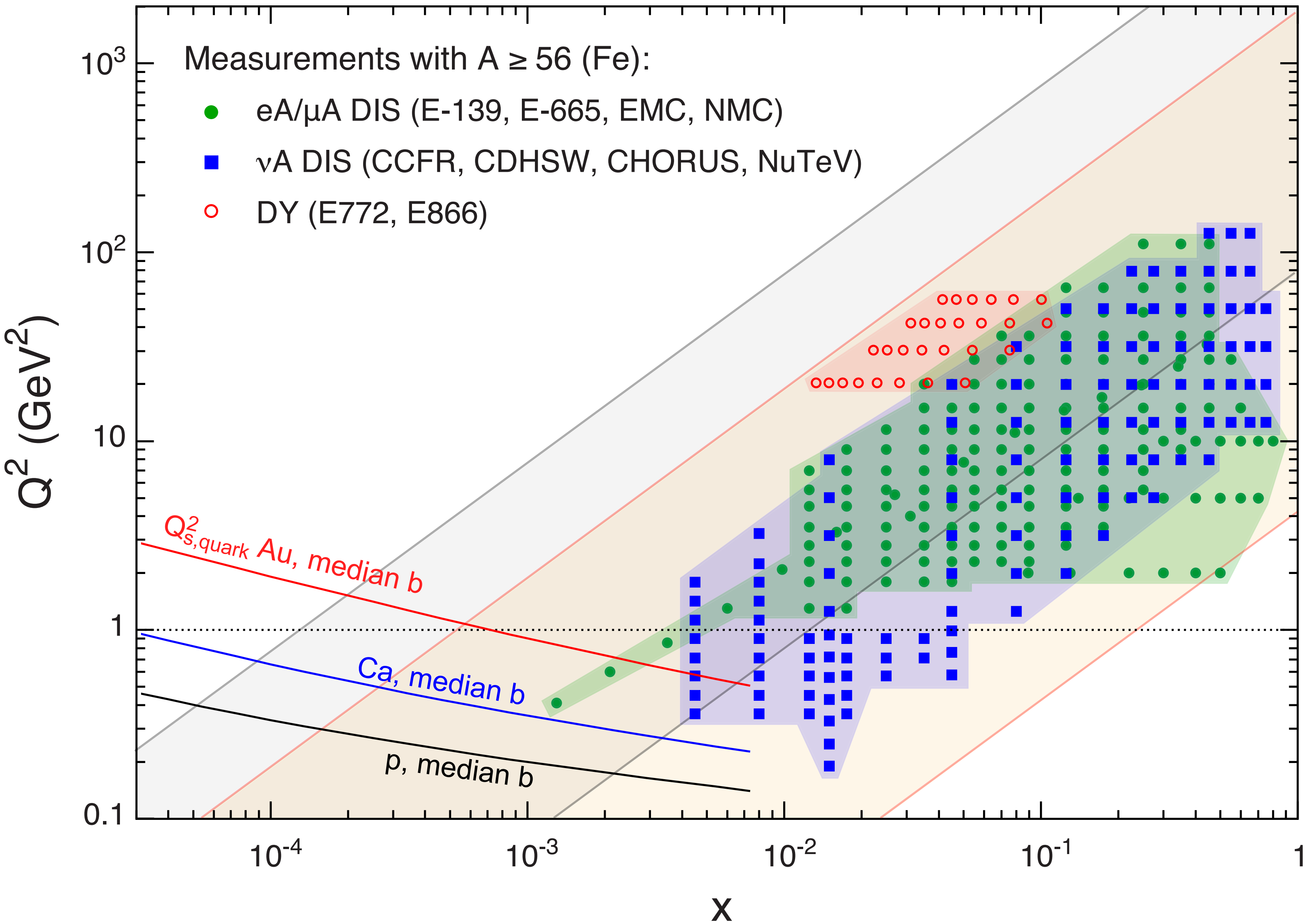

Integrated gluon distributions from inclusive structure functions

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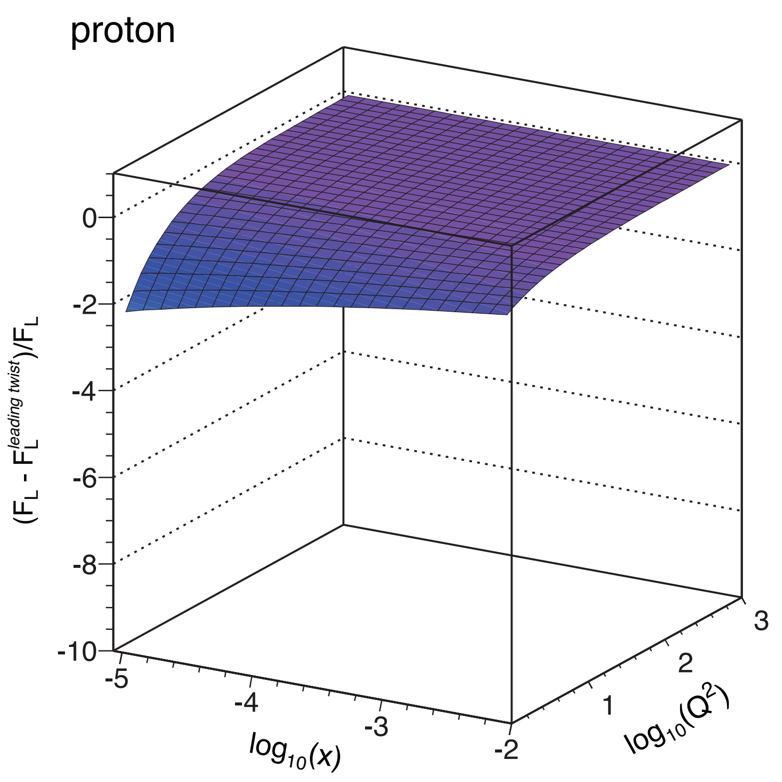
integrated gluon distributions	$F^c_{2,L}$, $F^D_{2,L}$	nuclear wave function; saturation, Q_s	difficult measurement / interpretation	saturation regime

charm

diffractive

The effects of higher-twist corrections on F_L

$$\frac{F_L - F_L^{leading\ twist}}{F_L}$$



- Plotting F_L-$F_L^{leading\ twist}/F_L$ coming out of saturation inspired GBW model
  - ➡ protons: little effect of leading twist corrections, only starting to come in at small-x and small Q2

The effects of higher-twist corrections on F_L

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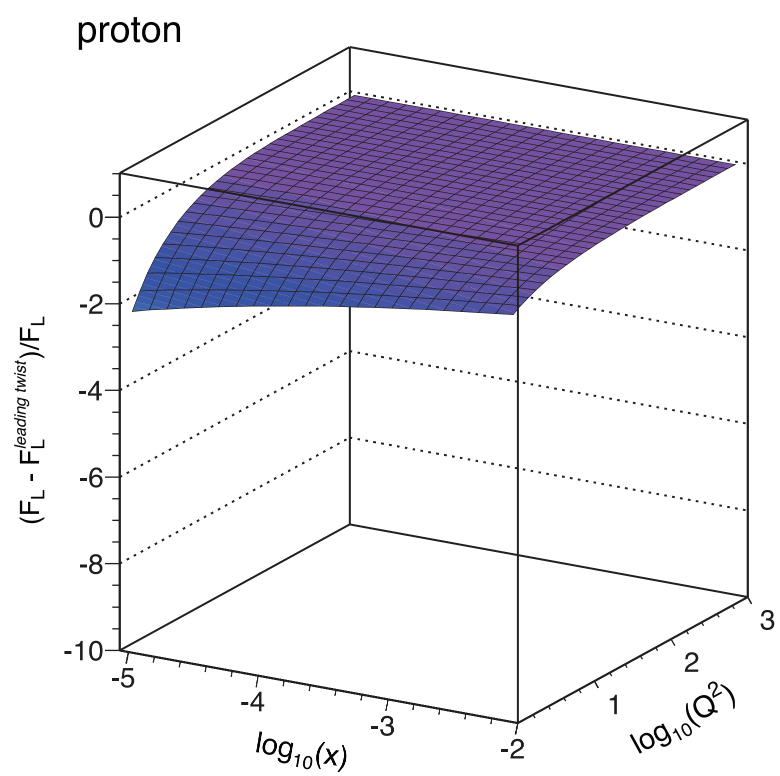

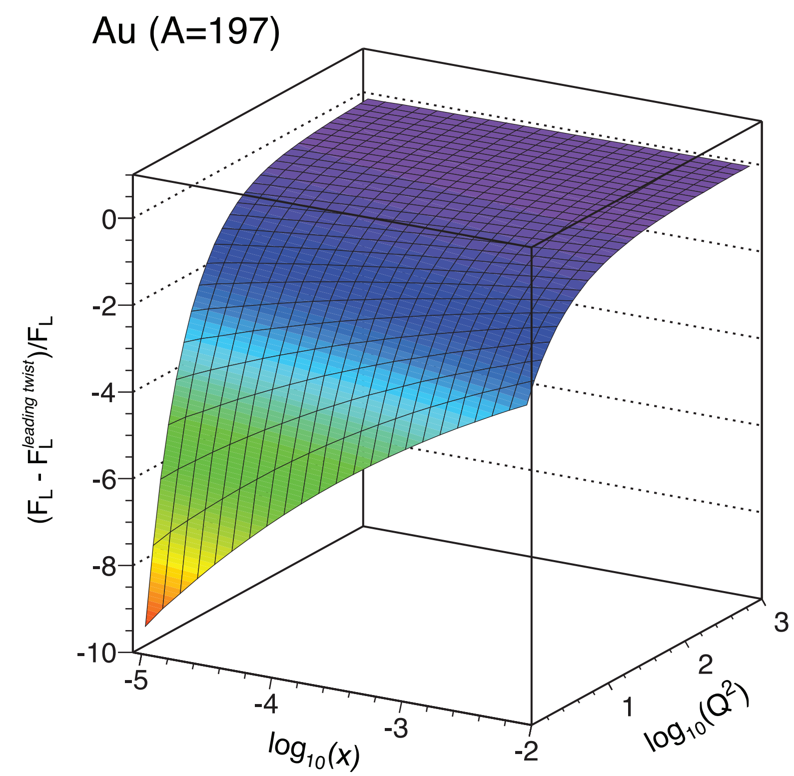

- Plotting F_L-$F_L^{leading\ twist}/F_L$ coming out of saturation inspired GBW model
  - ➡ protons: little effect of leading twist corrections, only starting to come in at small-x and small Q2
  - ➡ Au: much larger corrections coming from leading twist contributions
    - ‣ nuclear "oomph" effects well manifested in the F_L structure function

Measuring the gluons: extracting F_L

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

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- $F_L \sim \alpha_s \, xG(x,Q^2)$
    - ➡ $y = Q^2/xs$
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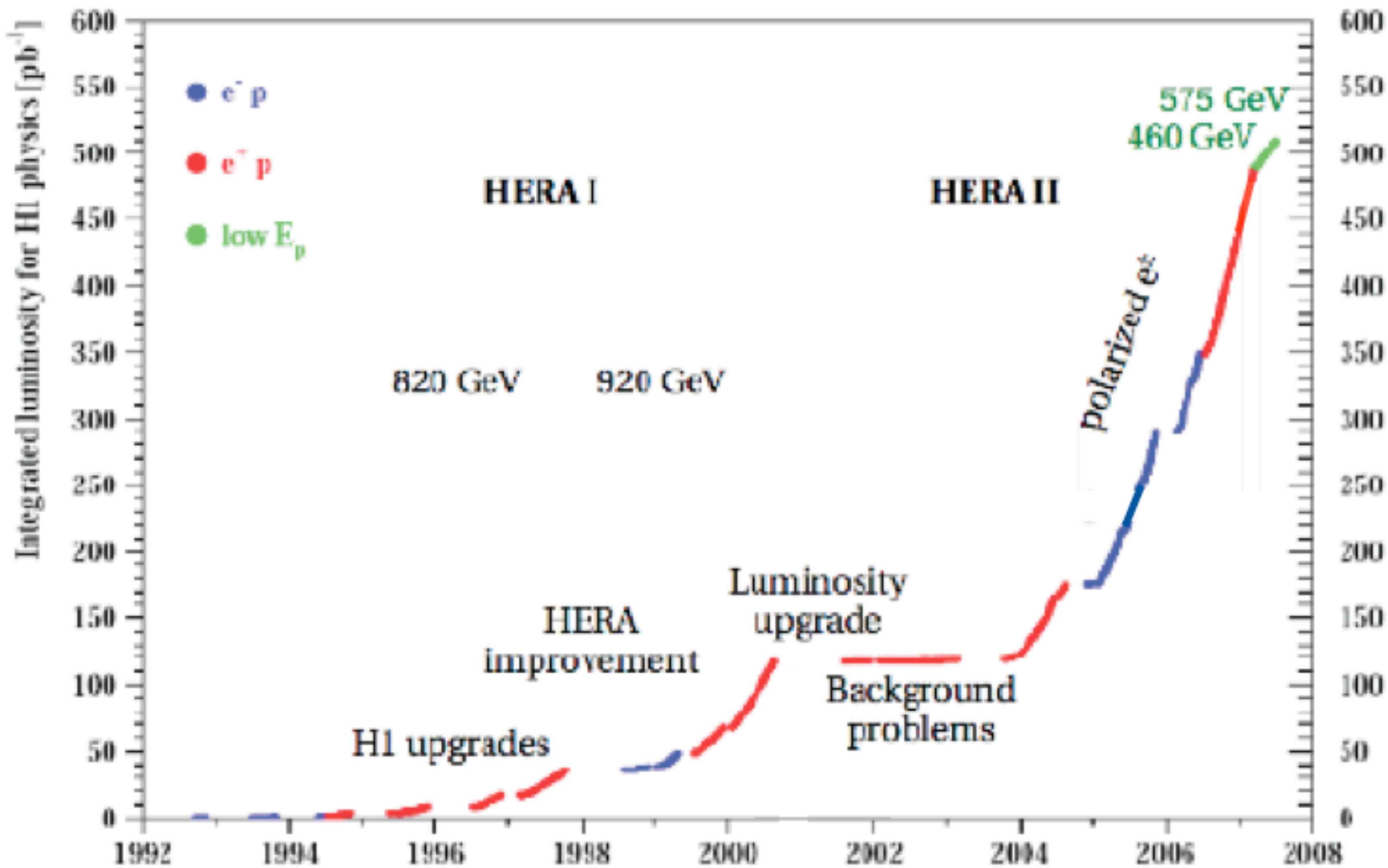
- 3 different proton energies run at HERA
  - ➡ 2 low-statistics runs
  - ➡ bad for F_L extraction



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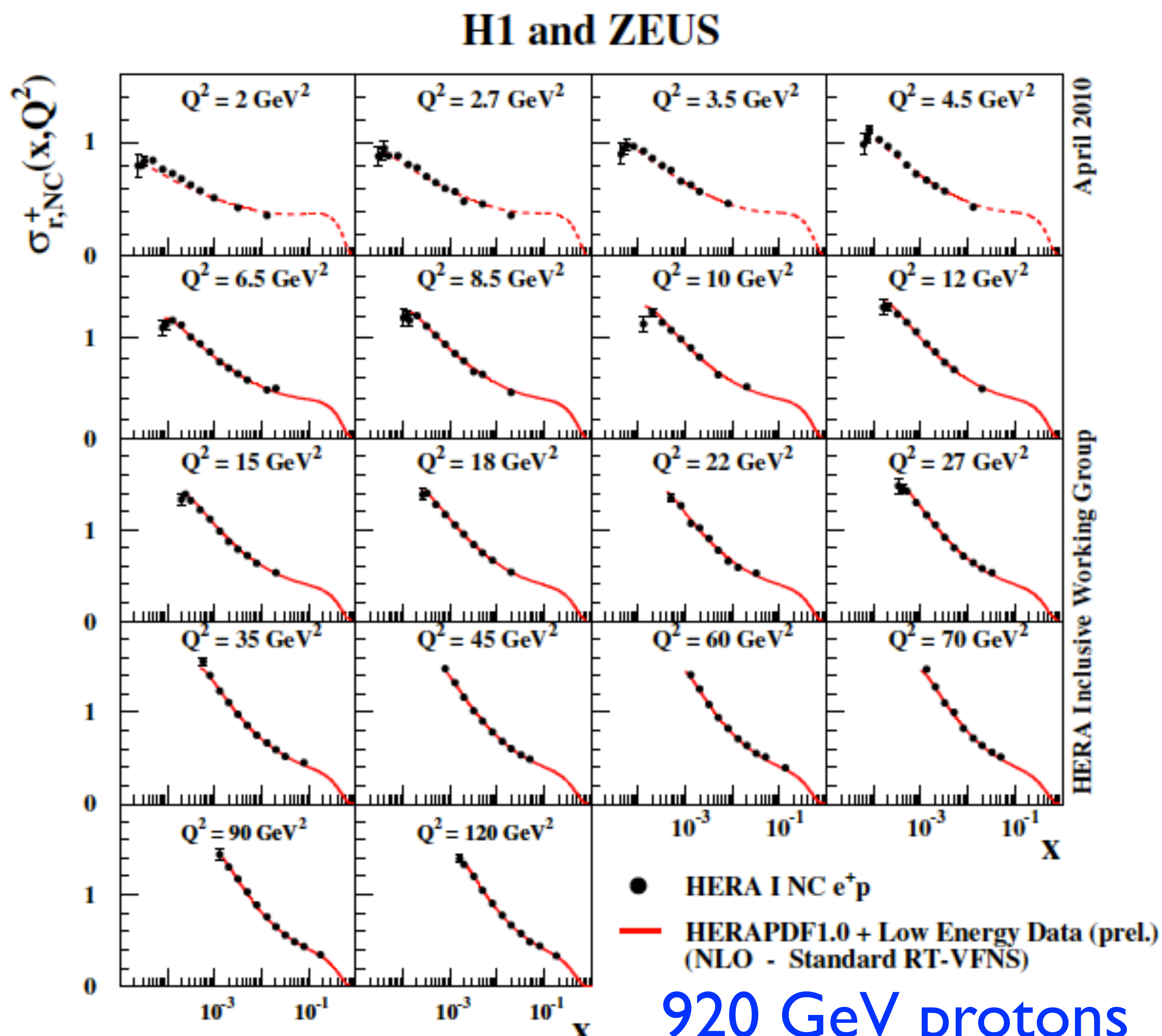

920 GeV protons

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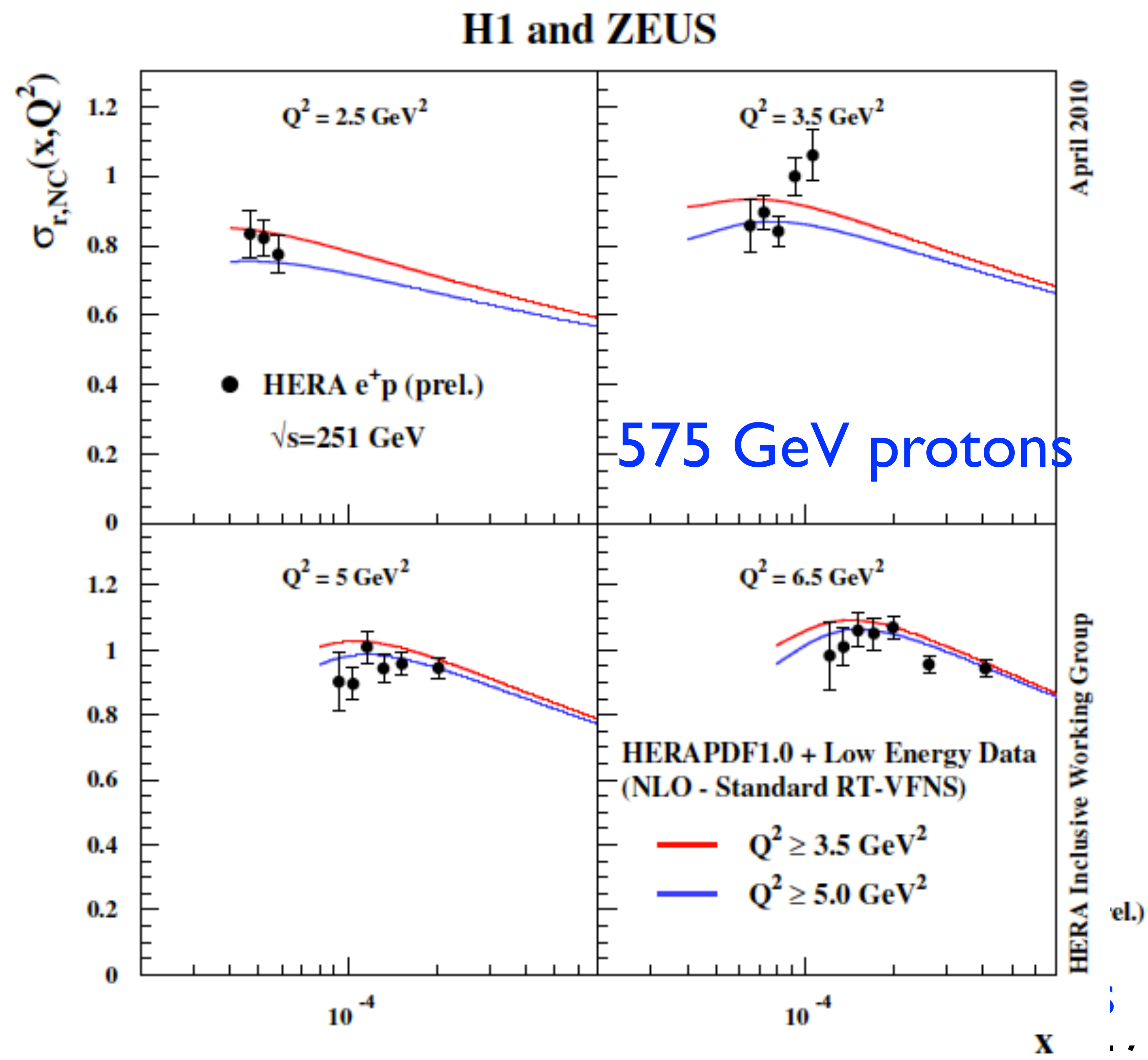

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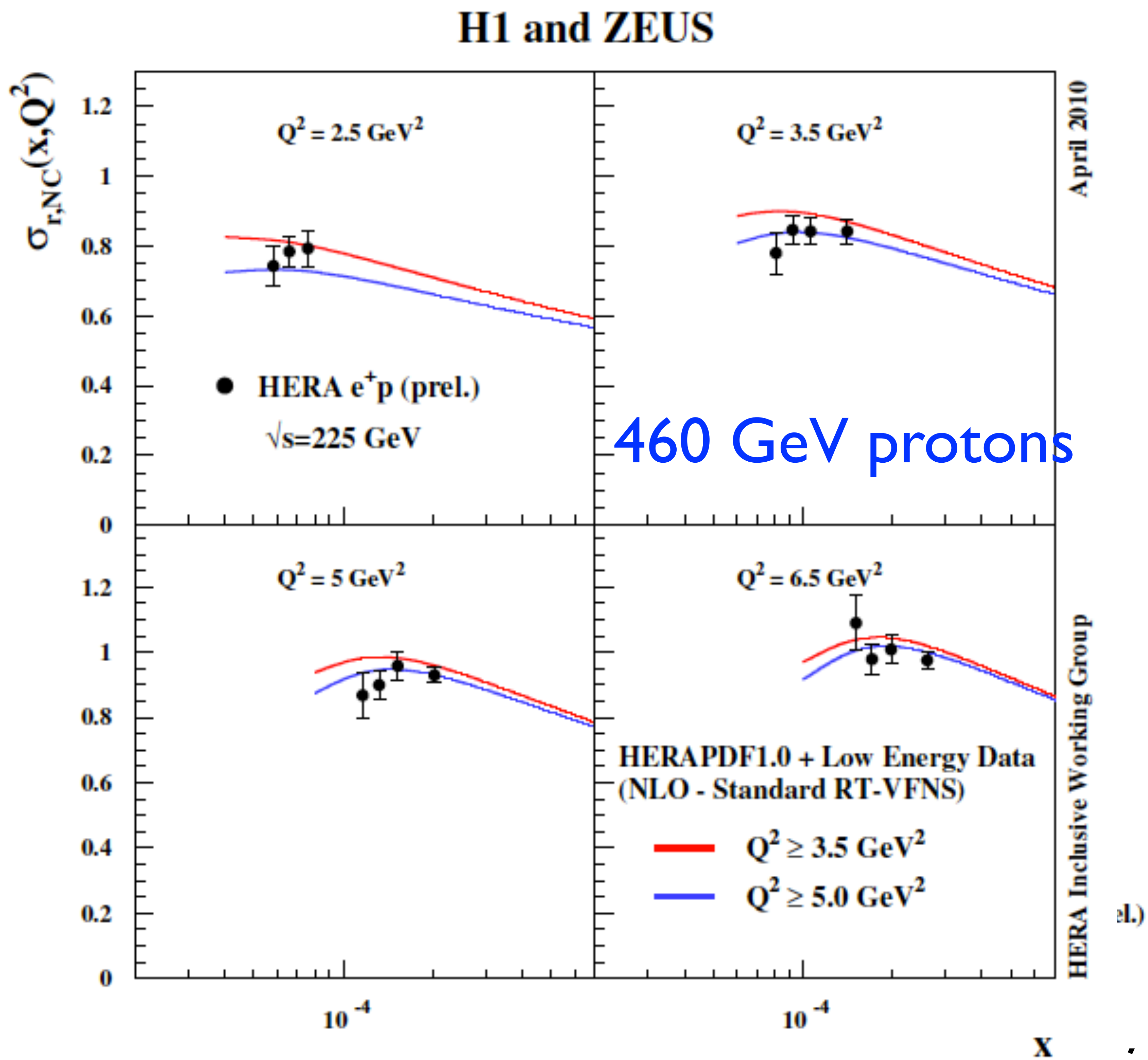

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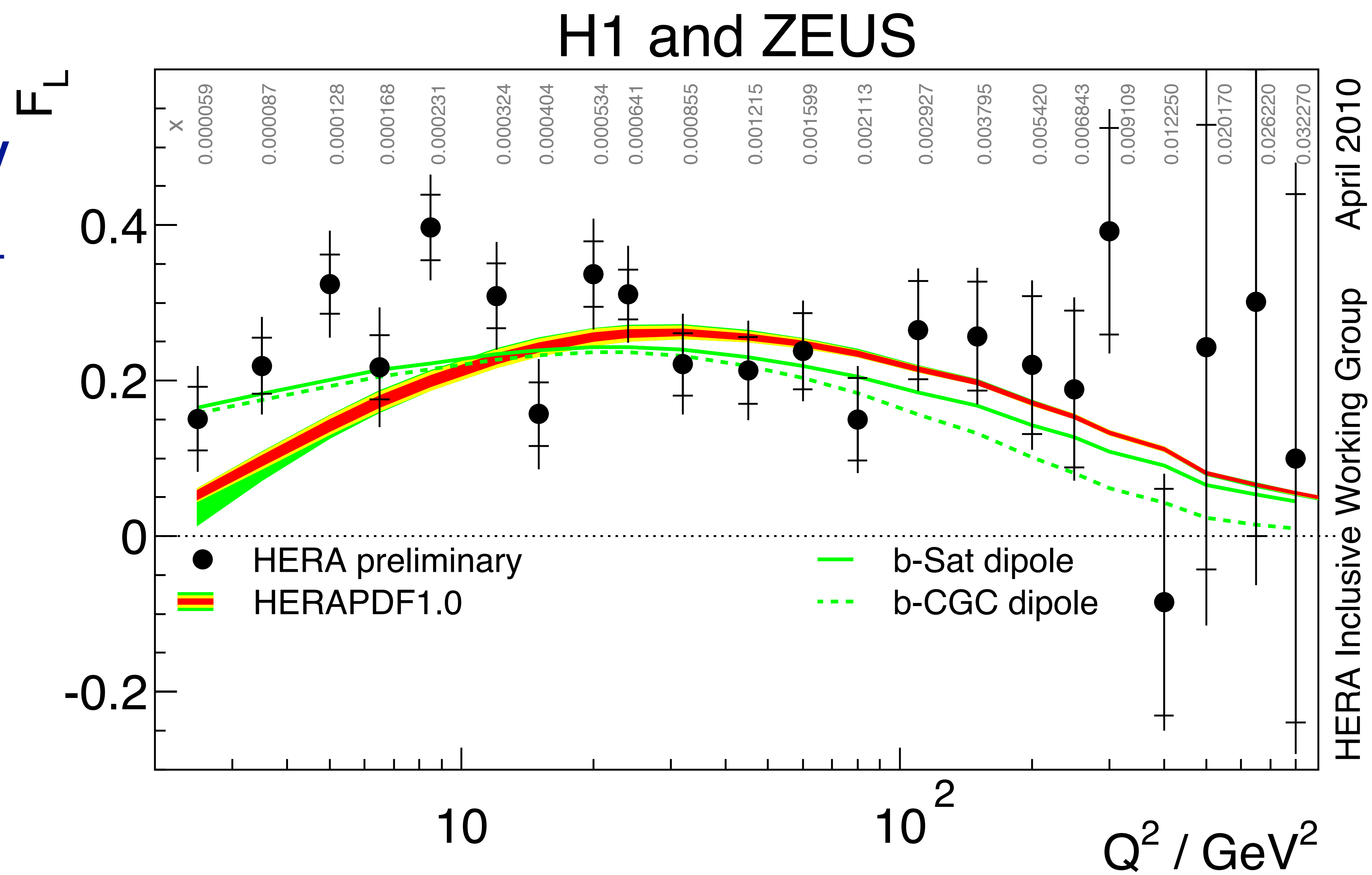


Feasibility study: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+} F_L^A(x,Q^2)$

Strategies:

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

e+p: 1st stage

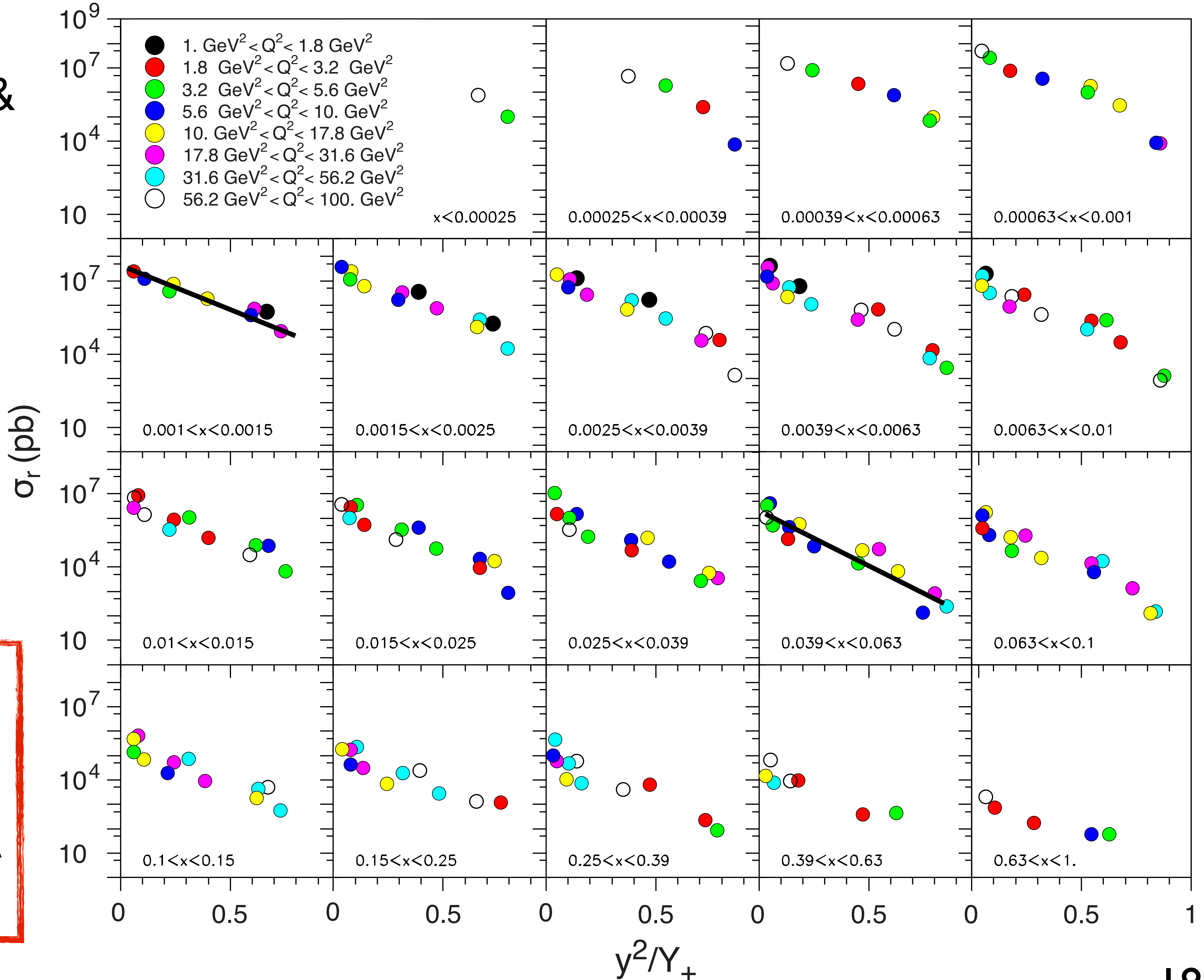
5x50 - 5x325

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

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Strategies:

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

e+Au: 1st stage

5x50 - $A\int Ldt = 2\ fb^{-1}$

5x75 - $A\int Ldt = 4\ fb^{-1}$

5x100 - $A\int Ldt = 4\ fb^{-1}$

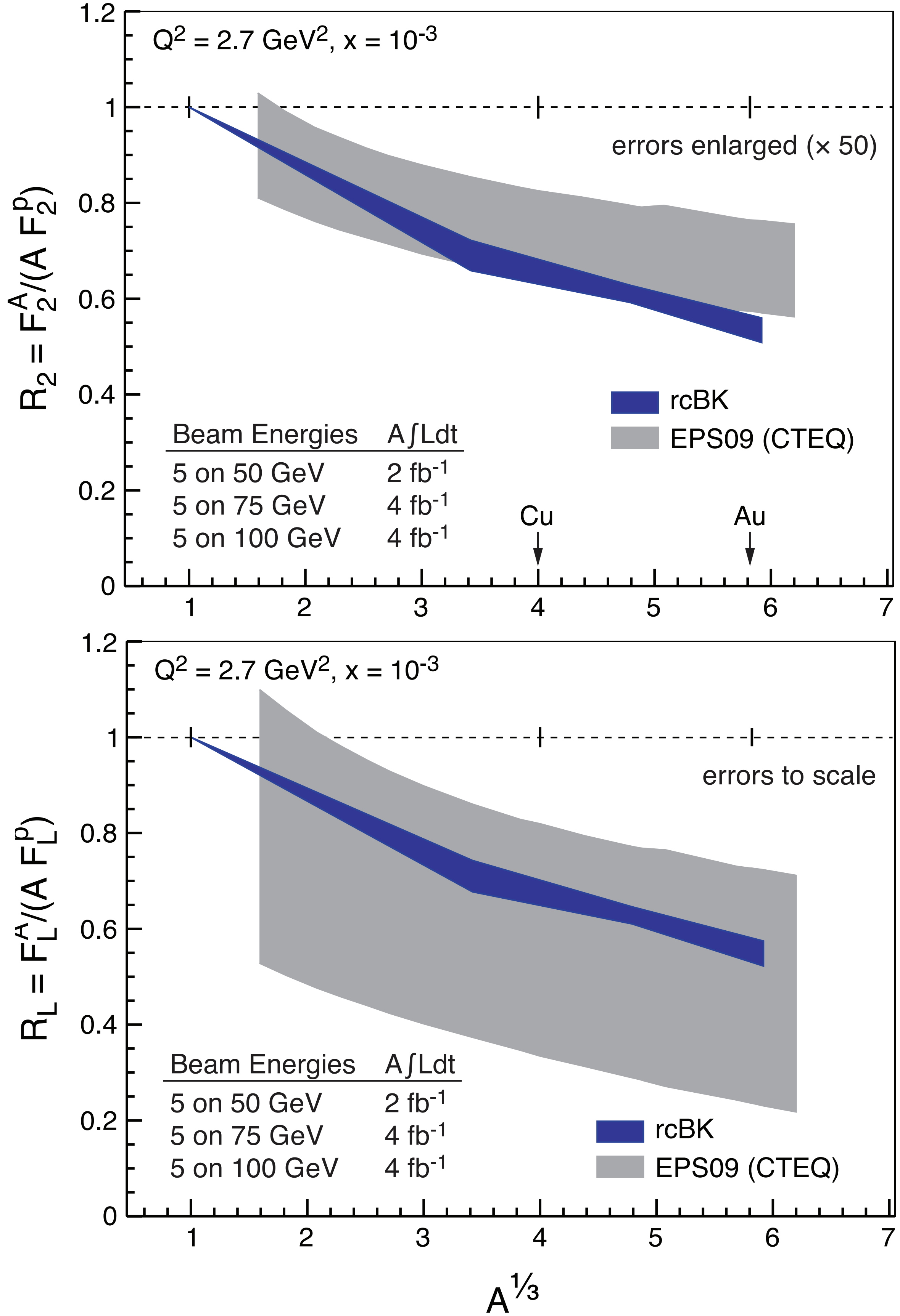
running combined

4 weeks/each

(50% eff)

statistical errors only are shown

Will be dominated by systematics, but would need a full detector simulation in order to estimate them



Charm and diffractive structure functions, $F^D_{2,L}$, $F^c_{2,L}$

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- $F^c_{2,L}$ give more direct access to the gluon distribution than the inclusive F_2 structure function
  - ➡ Due to the high charm mass, they probe higher values of x
    - ‣ Less sensitive to non-linear effects
  - ➡ QCD calculations with non-zero m_c are scheme dependent
    - ‣ Can absorb non-linear signals if not handled correctly

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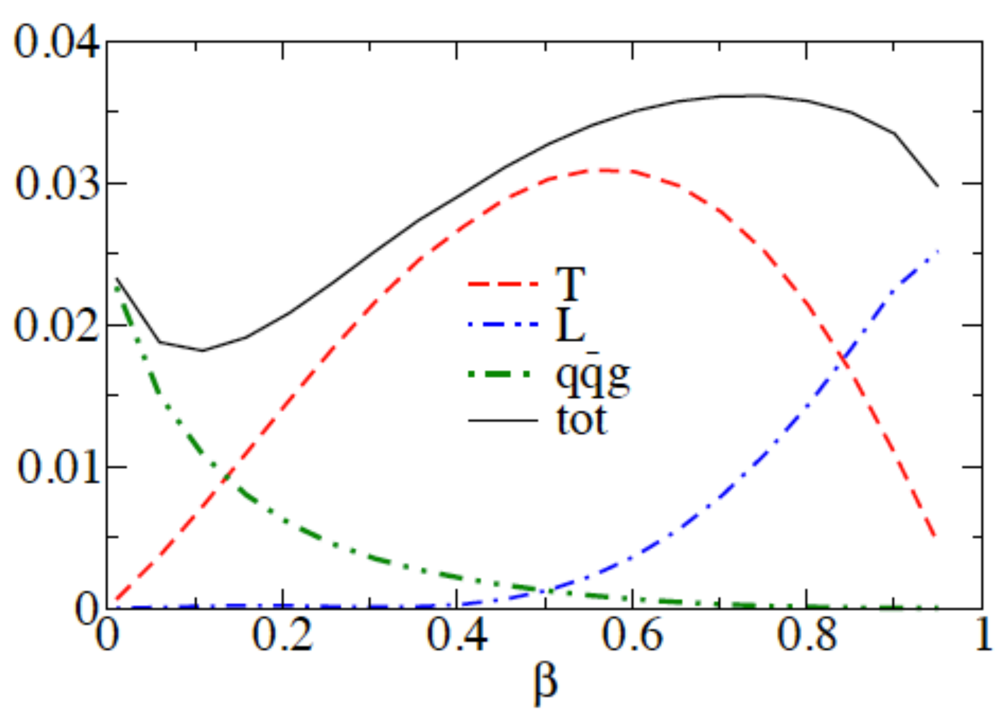
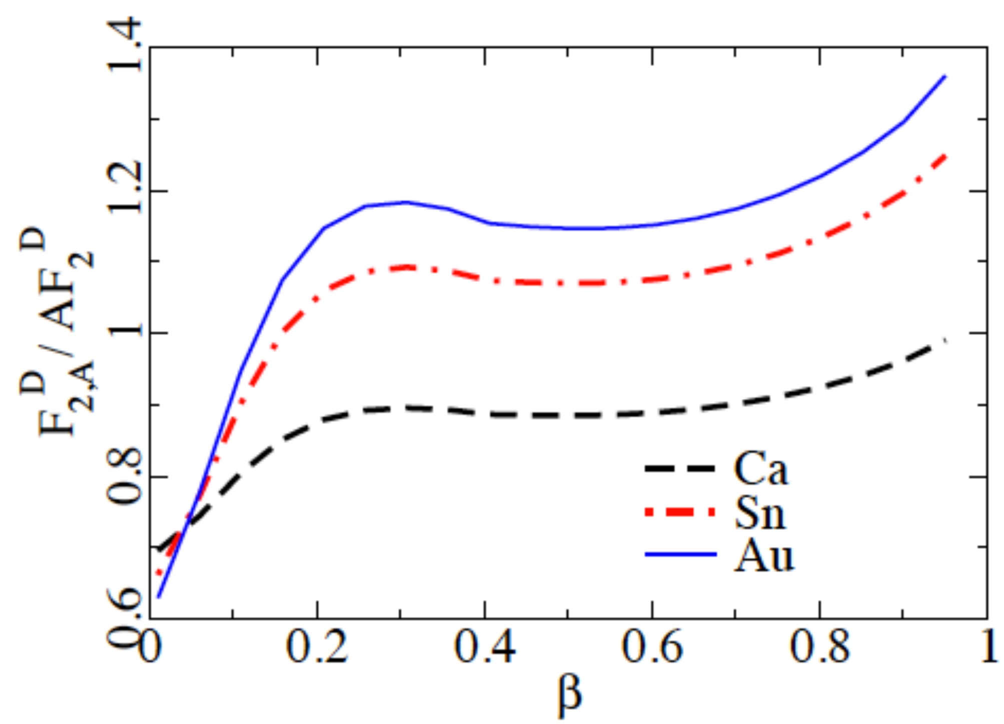
- $F^D_{2,L}$ is also sensitive to the gluon distribution
  - ➡ Differences between linear and non-linear models appear at higher Q^2 than for F_2 (8 GeV^2 vs 2 GeV^2)
    - ‣ More experimentally challenging measurement than F_2

$$x_{\mathbb{P}} = 10^{-3}$$

$$Q^2 = 5GeV^2$$





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
k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large-x gluons

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

$$e+A \rightarrow e + h + X$$

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

$$e+A \rightarrow e + h_1 + h_2 + X$$

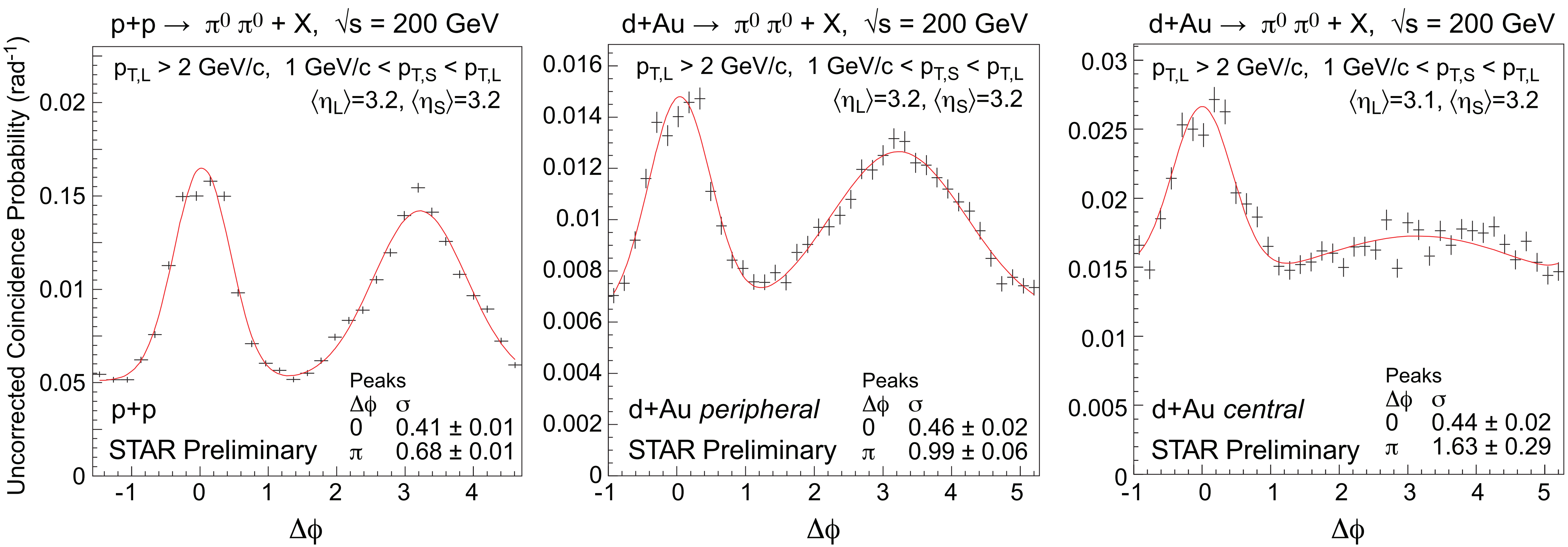
Deliverables	Observables	What we learn	Stage-I	Stage-II
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s

$$e+A \rightarrow e + h + X$$

k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large-x gluons

di-hadron Correlations

- For details of these measurements, please refer to Liang Zheng’s talk yesterday morning
- Plots come from his MC development as discussed yesterday



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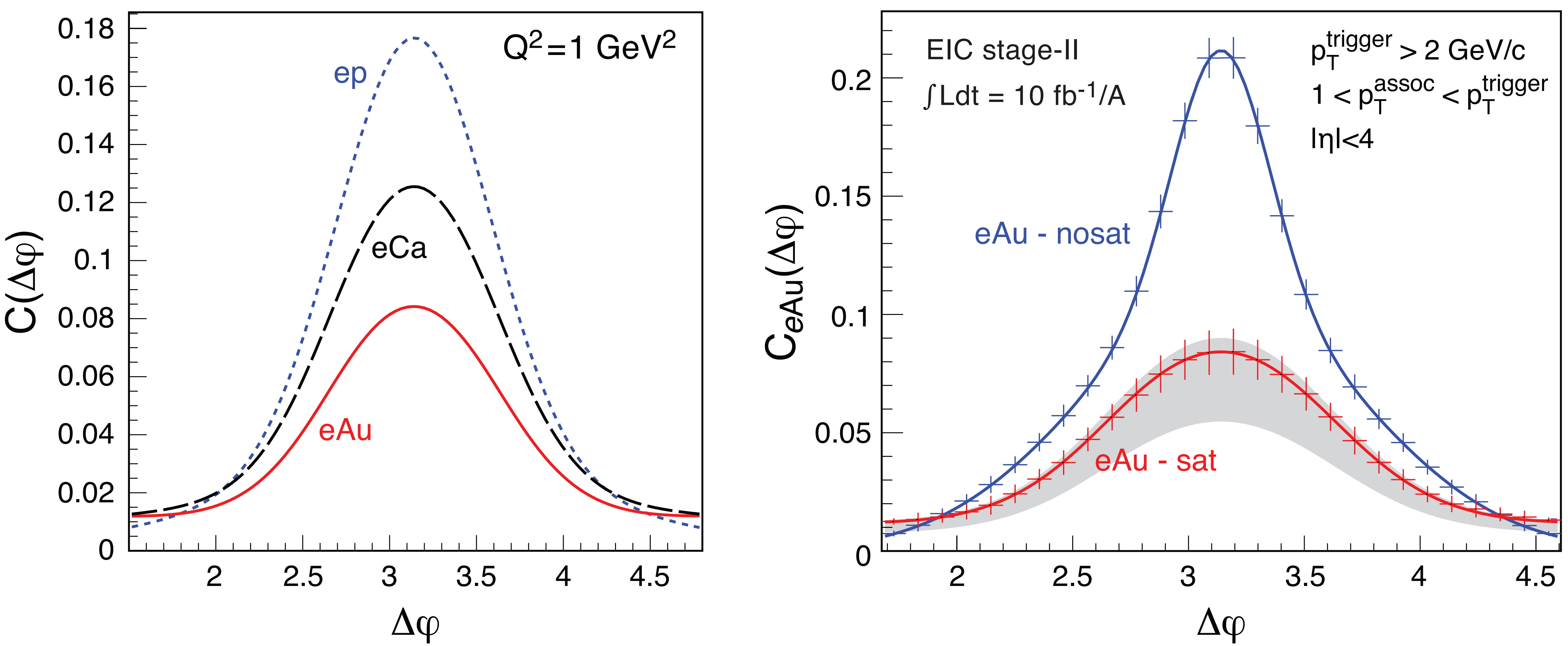

Saturation model prediction courtesy of Bo-wen, Feng ...

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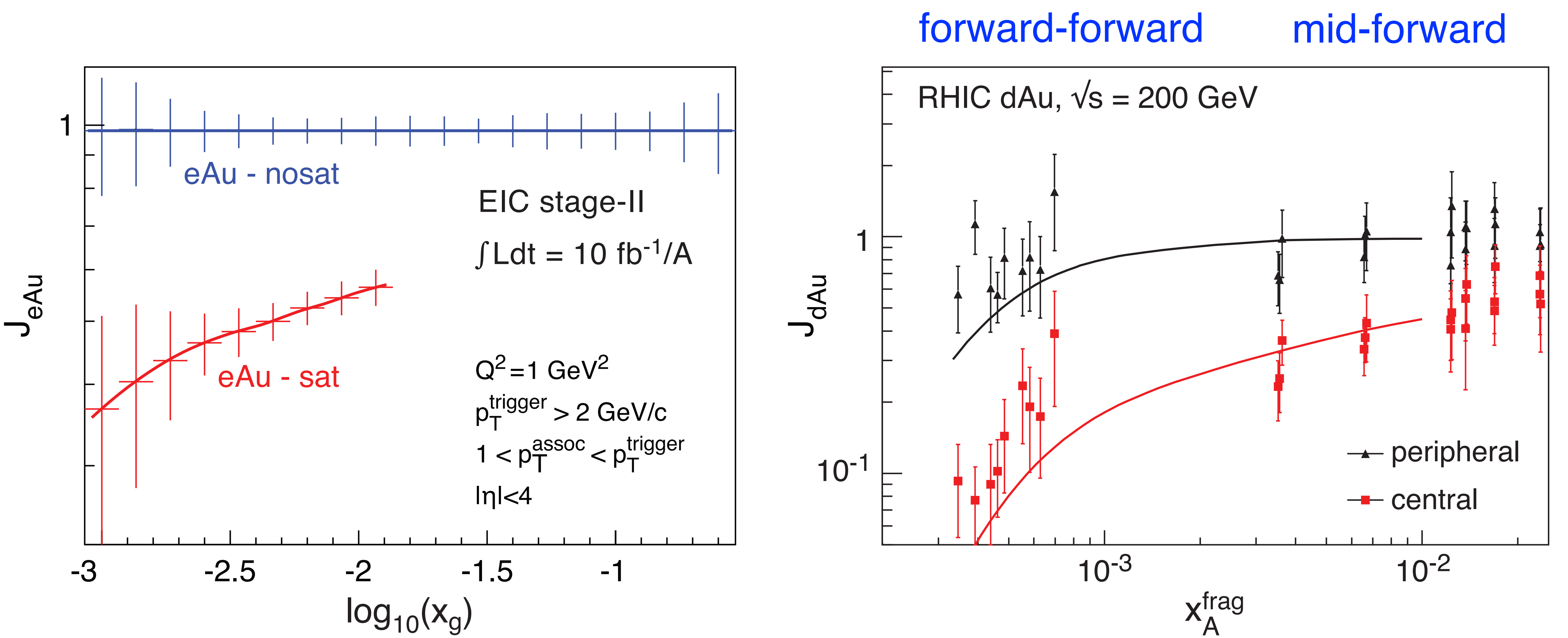

J_{eAu} - relative yield of di-hadrons produced in *e*Au compared to *ep* collisions

Note that x_A^{frag} is not an exact value - curves come from saturation model

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

Diffractive Vector Meson Production

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 → e+γ+A) and Diffractive Vector Meson Production (DVMP: e+A → 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

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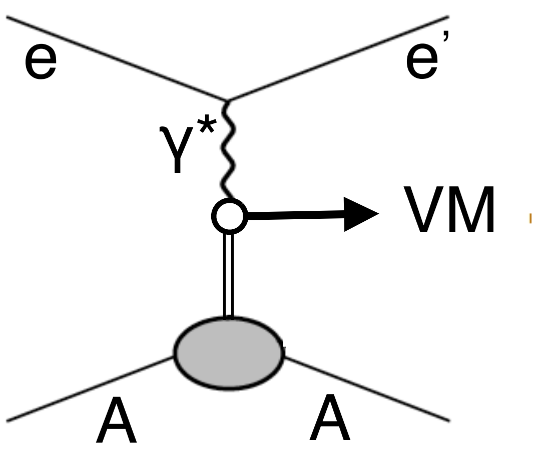
DVMP



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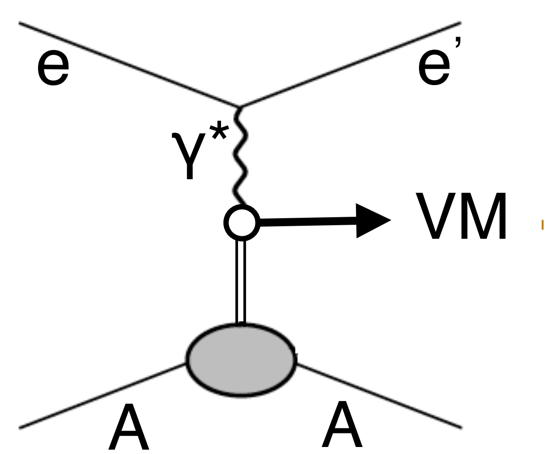
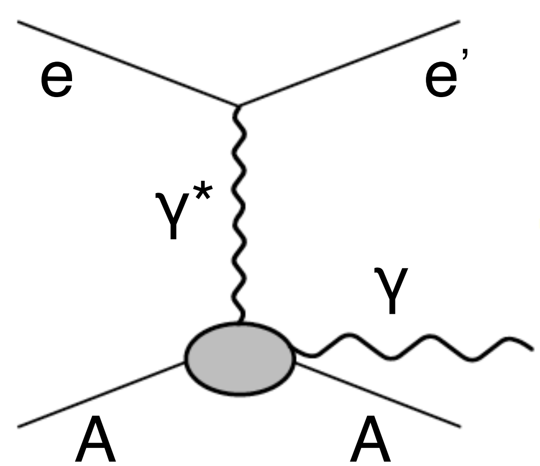


DVCS



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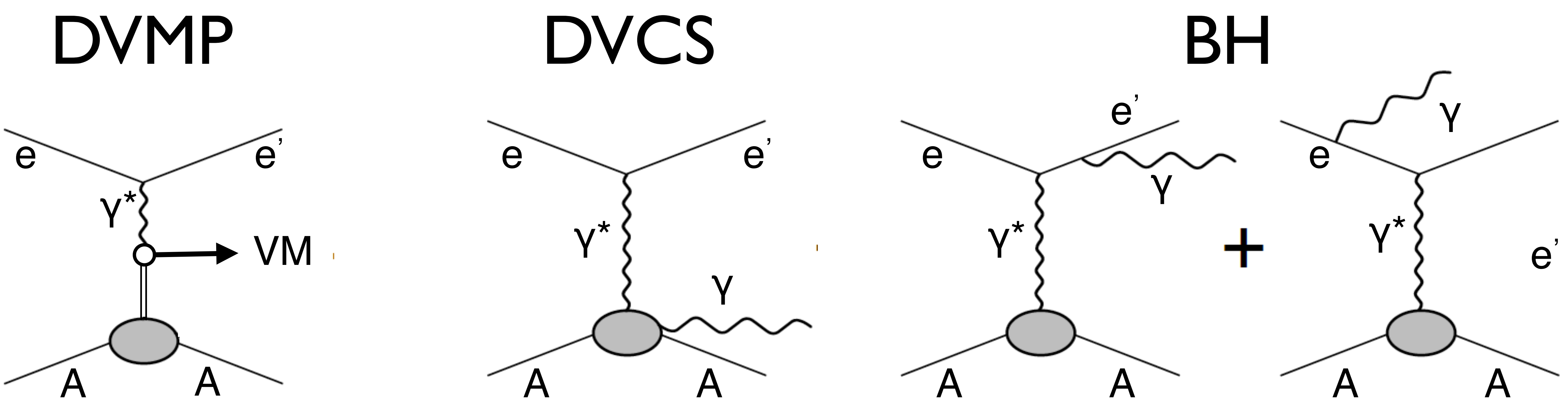
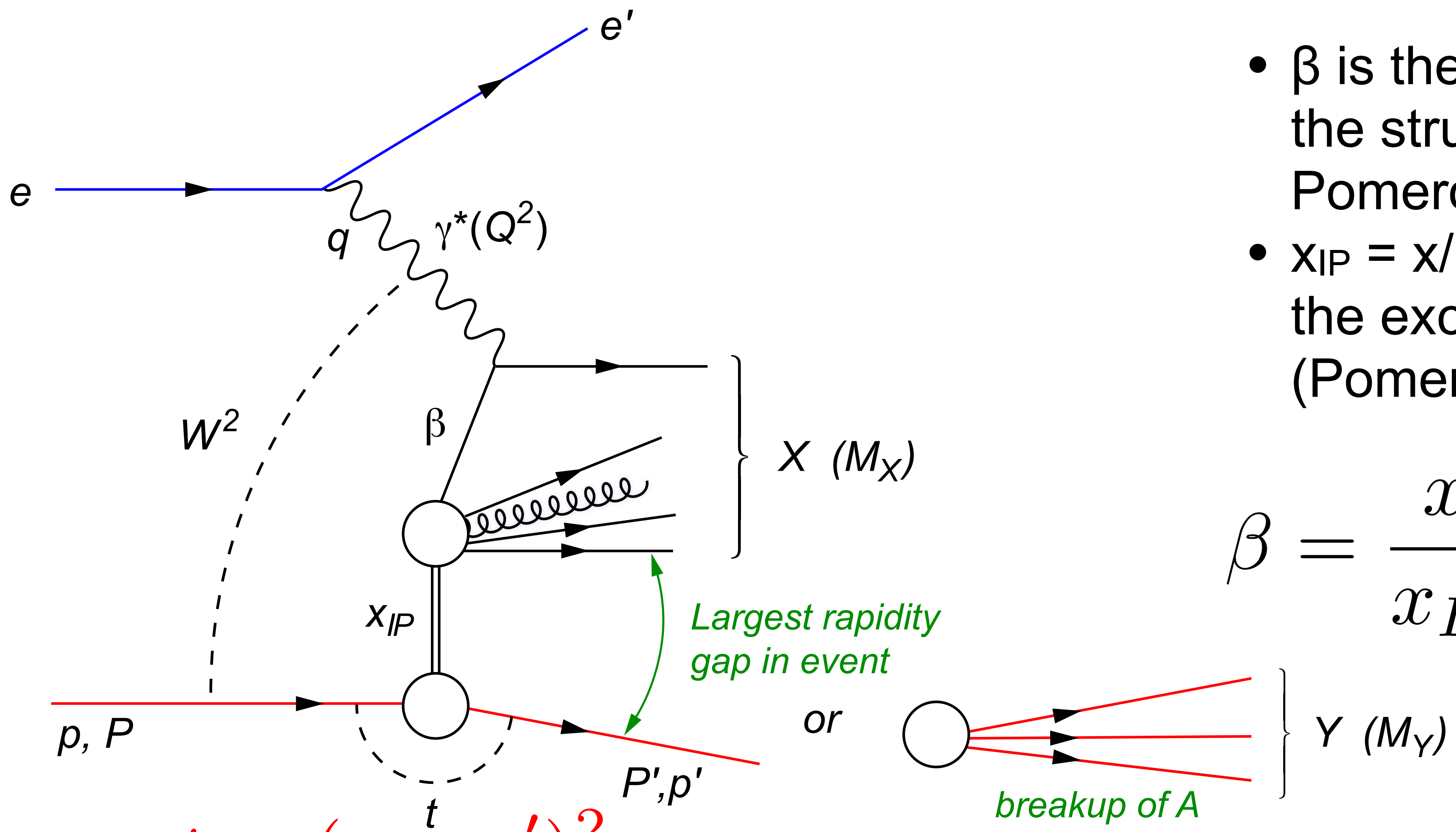


DVCS and Bethe-Heitler interference terms become difficult to distinguish experimentally

Hard Diffraction



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

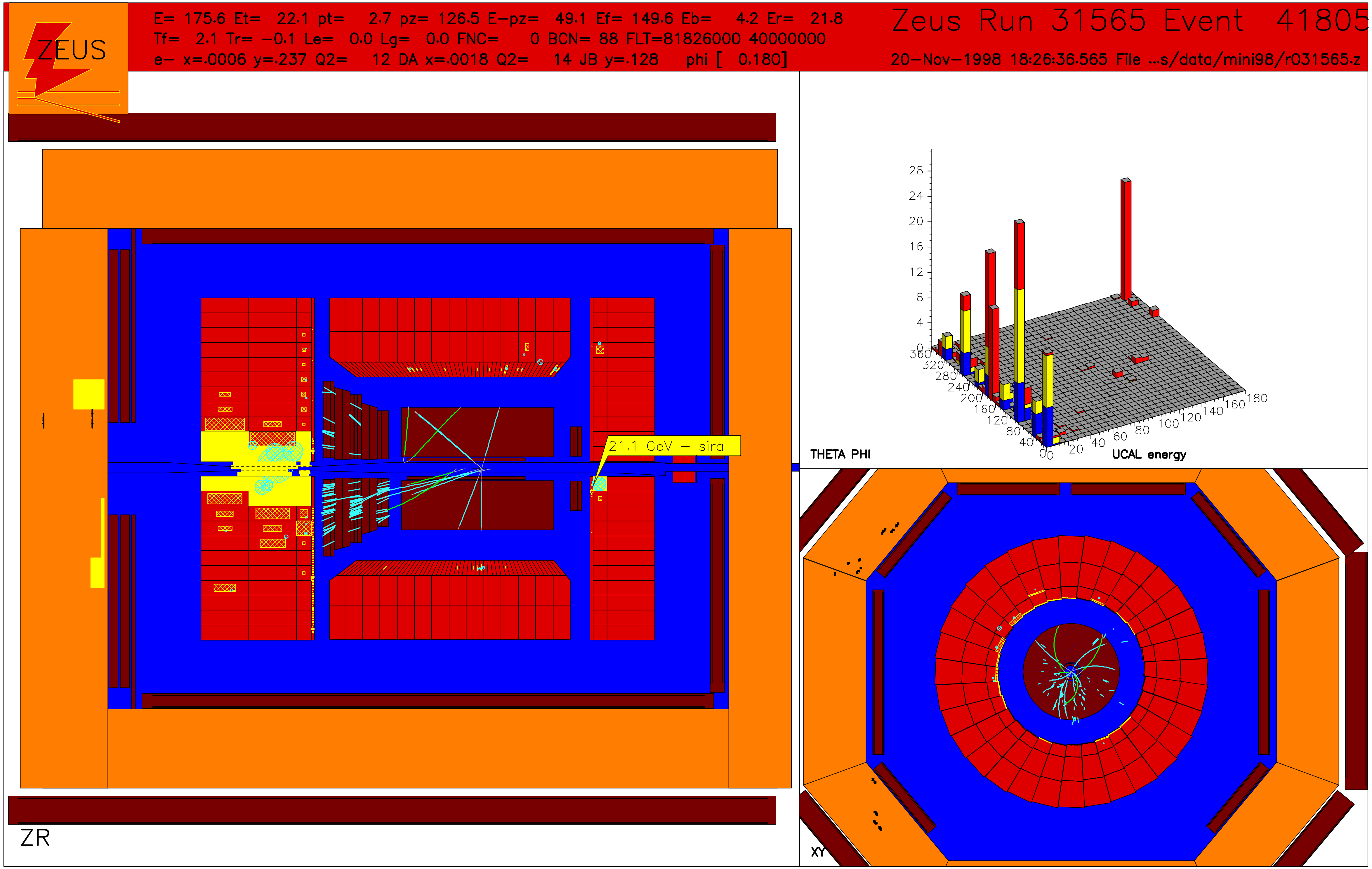
- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- **Diffraction in e+p:**
  - HERA: 15% of all events are diffractive
- **Diffraction in e+A:**
  - Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - Coherent diffraction (nuclei intact)
  - Incoherent diffraction: breakup into nucleons (nucleons intact)

Visualising Diffractive events

A DIS event (experimental view)



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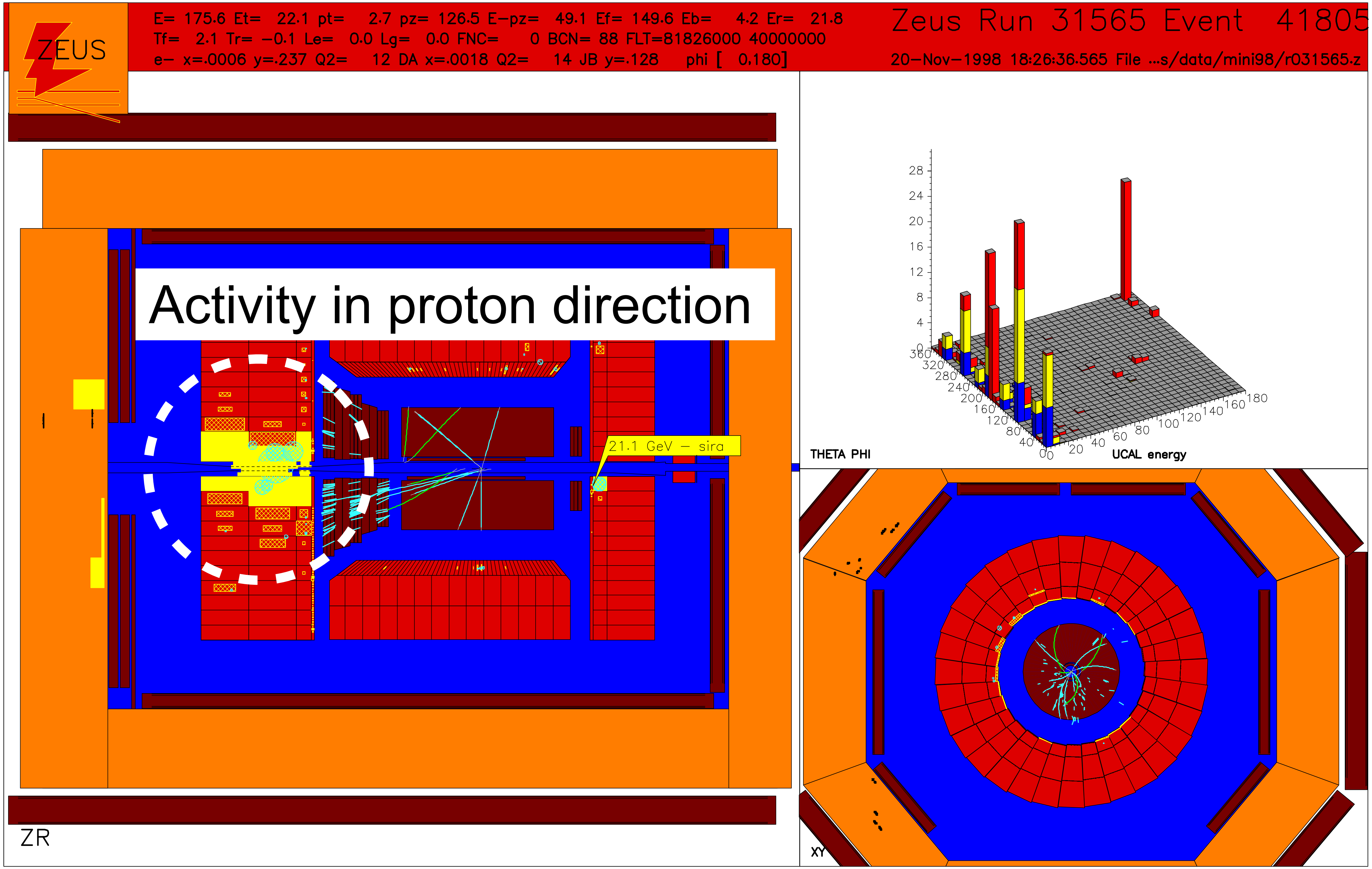
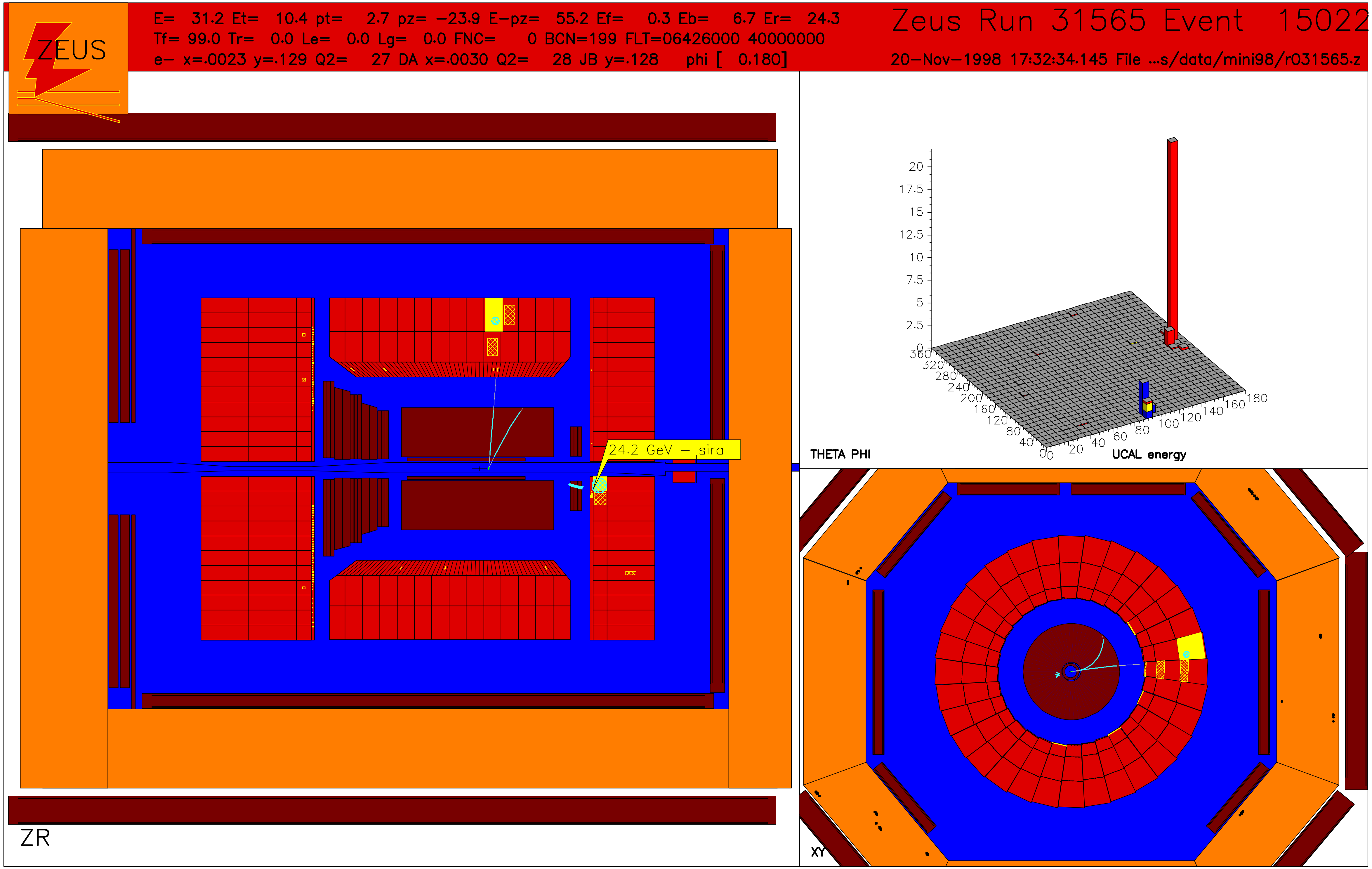


Visualising Diffractive events



Visualising Diffractive events

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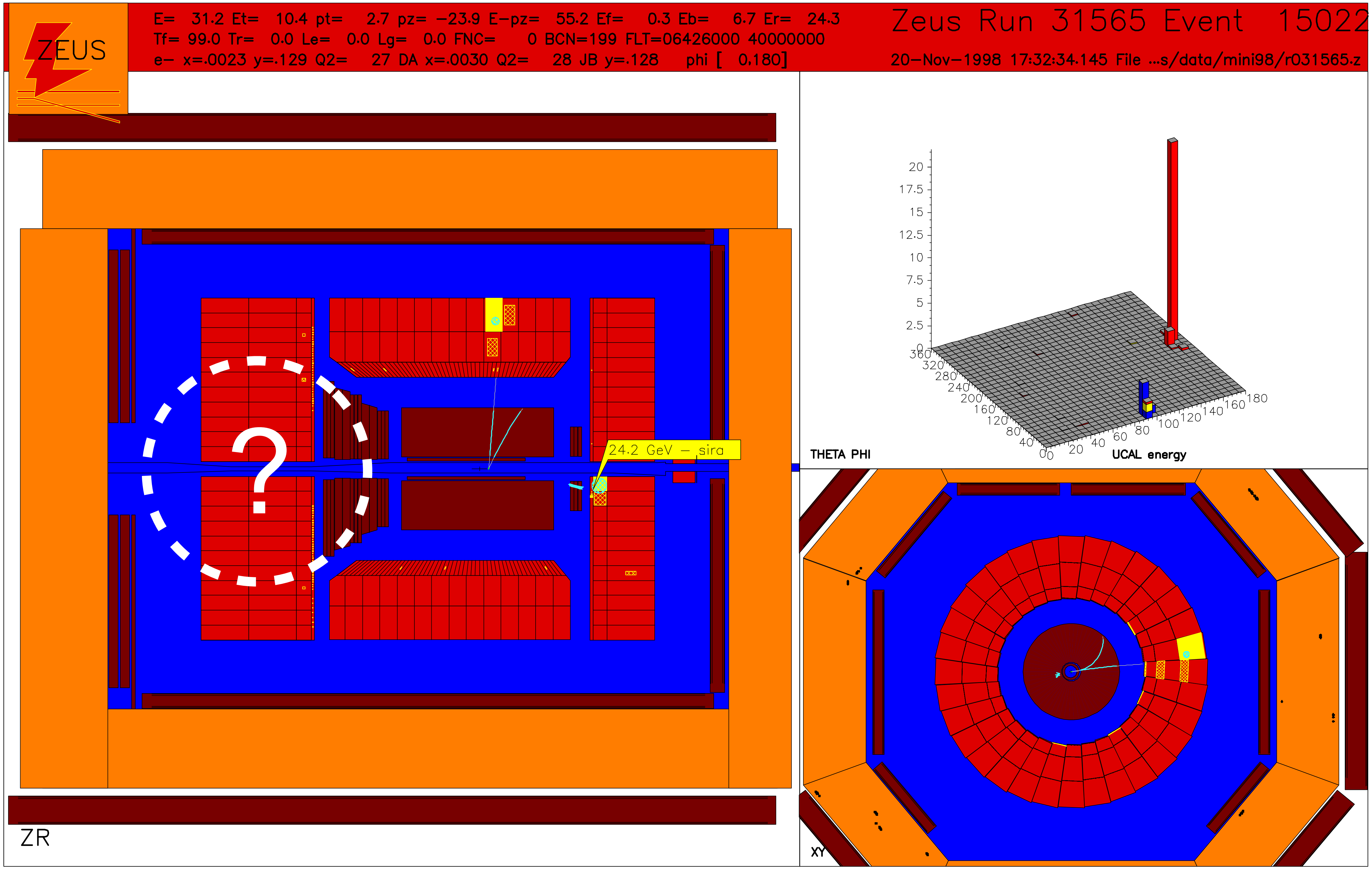
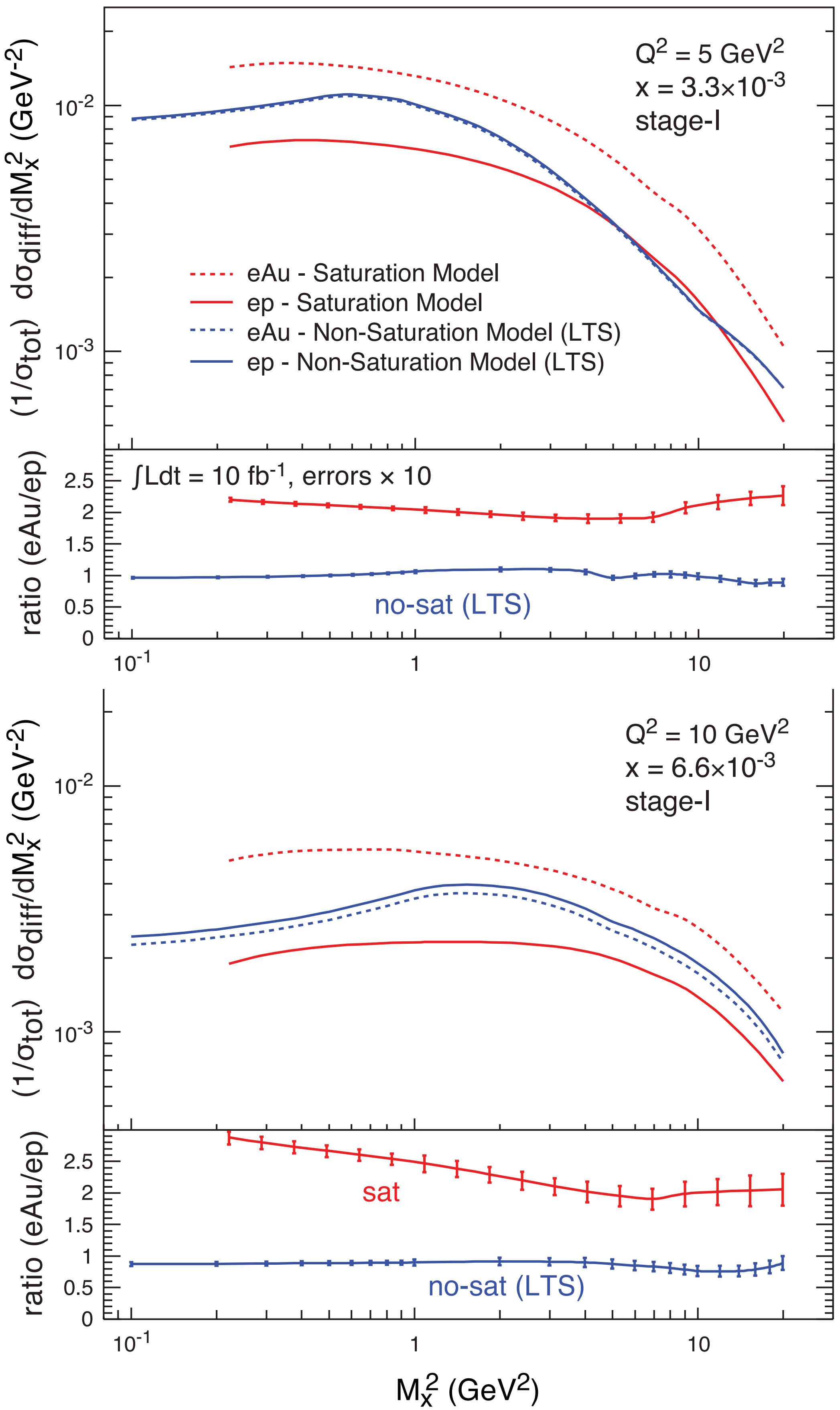


Diffractive cross-sections: Saturation vs Non-Sat

- Ratio of diffractive to total cross-sections between saturation model (Marquet) and Leading-Twist Shadowing (Guzey, Strickman).
  - ➡ Very little difference for LTS between e+p and e+Au, independent of Q^2
  - ➡ For saturation model, e+Au ~ 2*e+p, again independent of Q^2
  - ➡ Simulated error bars (10 fb^{-1}) can easily distinguish between these two scenarios
    - Note that the statistical errors are scaled on the plot so they are visible!

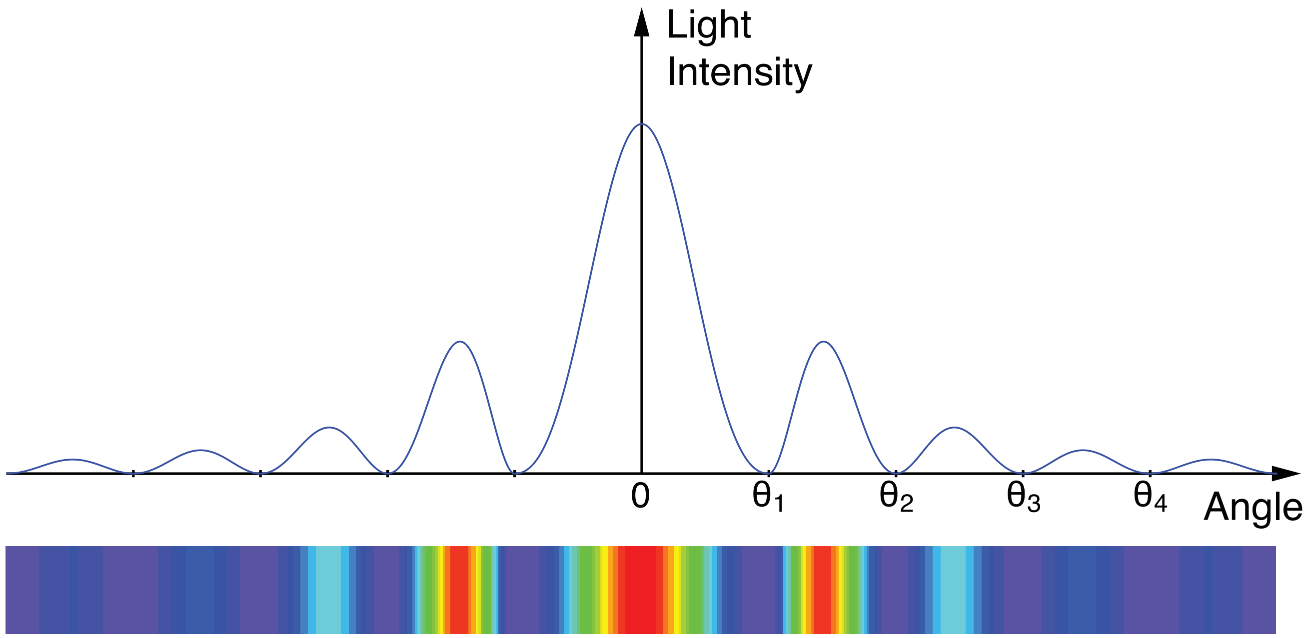


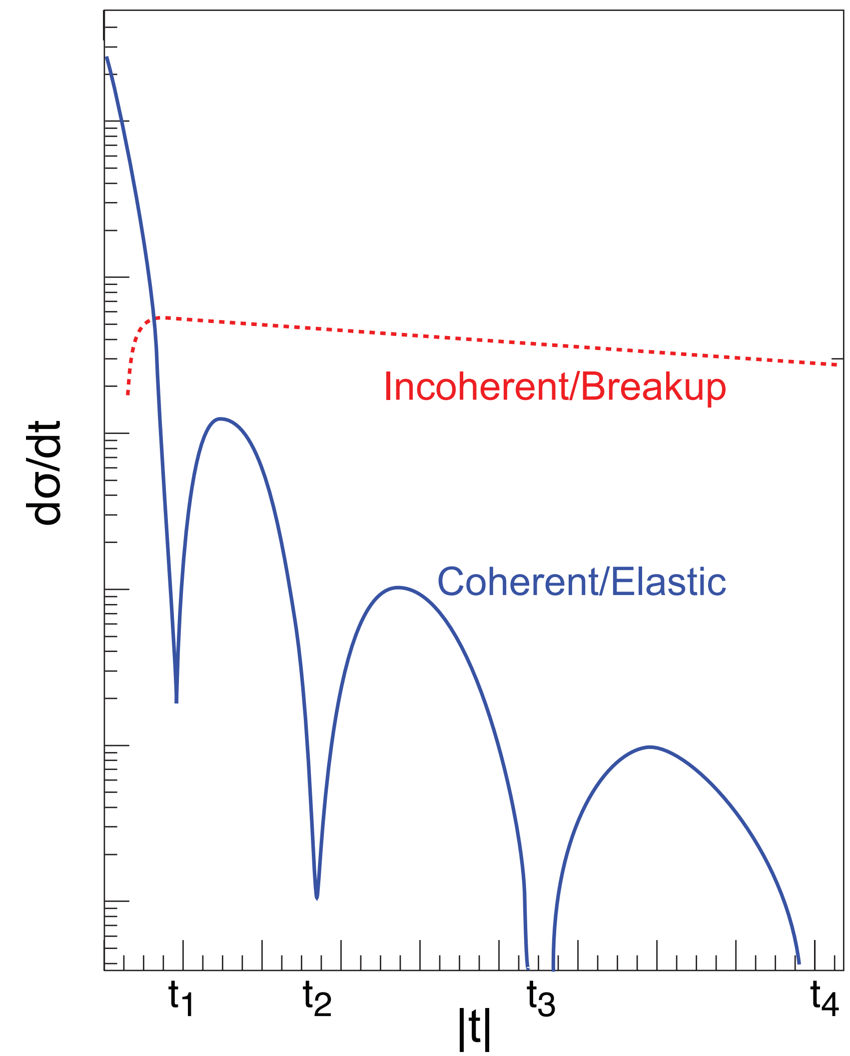
Exclusive Vector Meson Production in e+A

- 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’

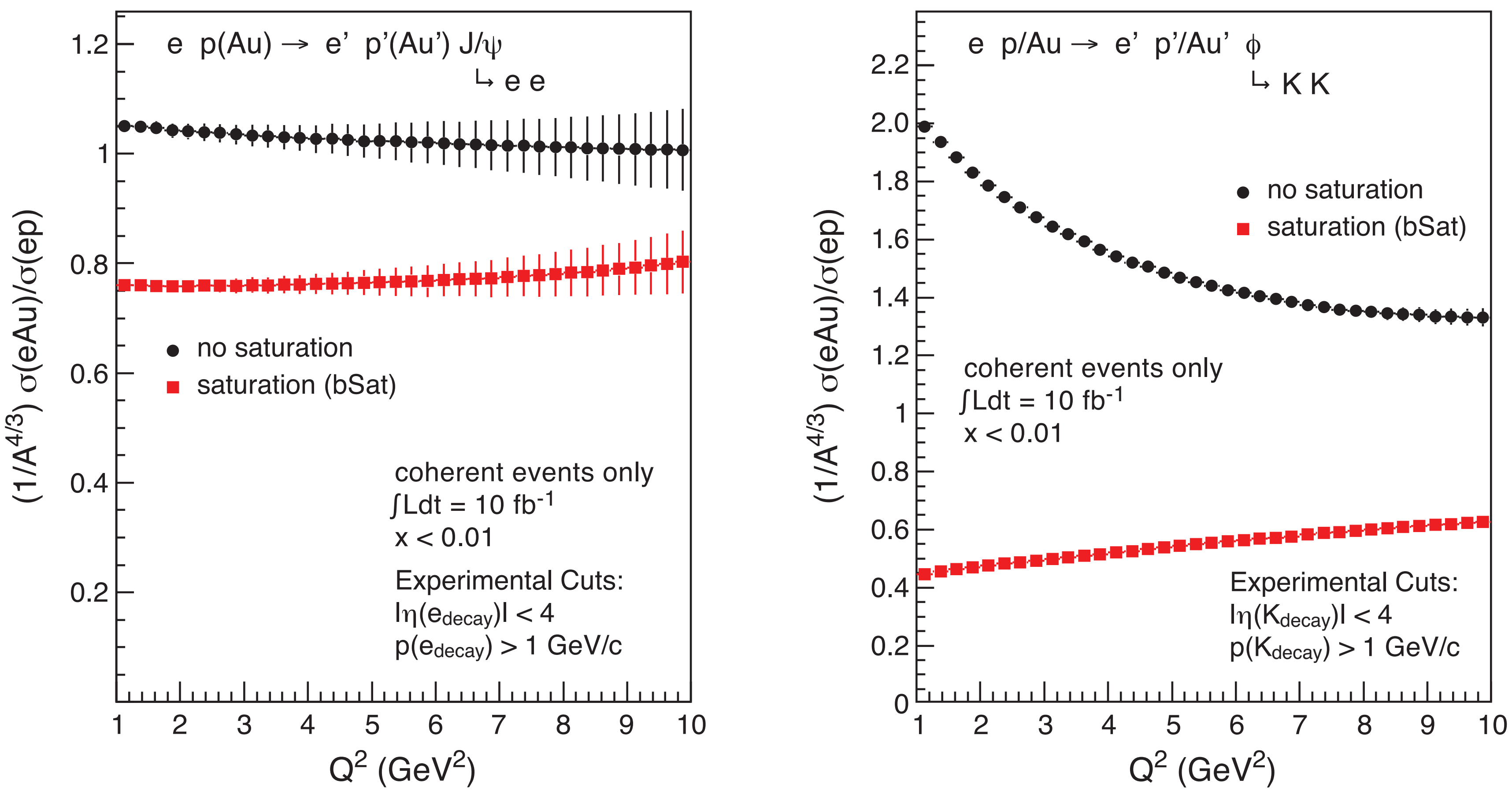




- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations
- Just like in optics - the positions of the diffractive minima are related to the size of the obstacle

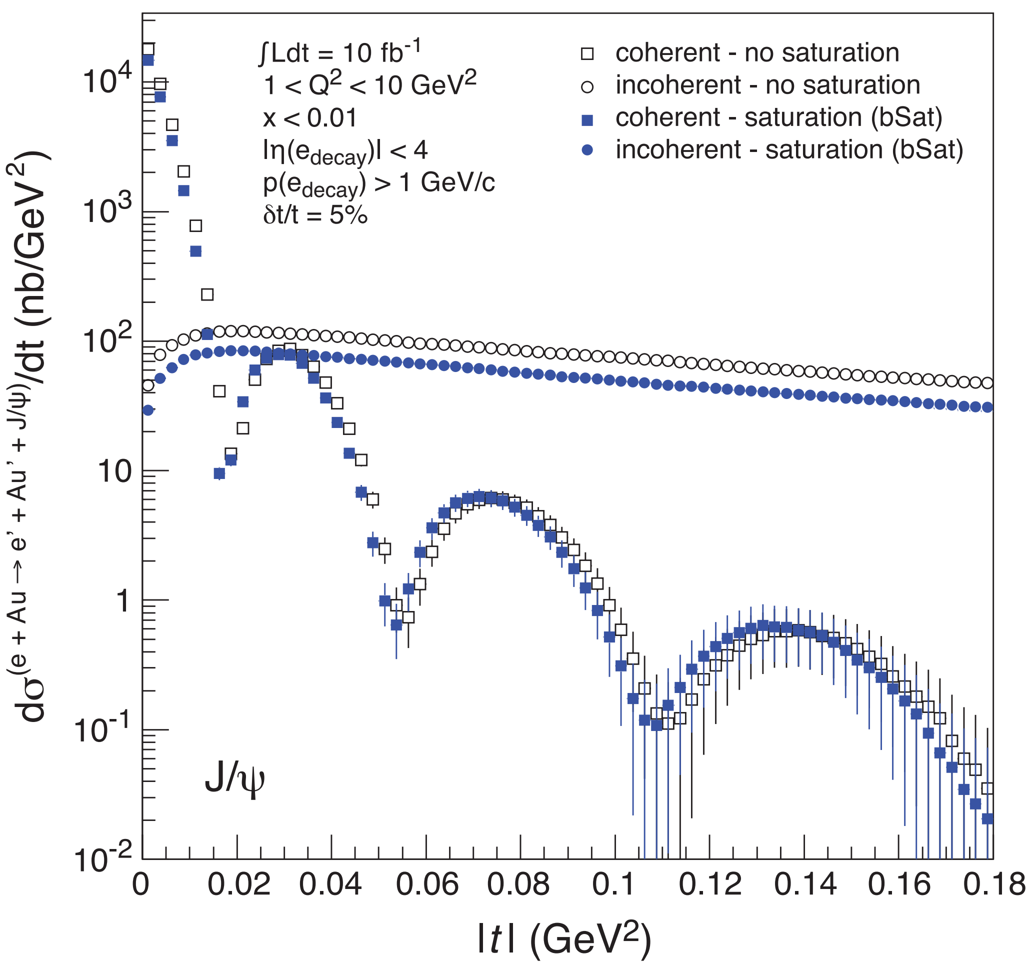
  ➡ $\theta_i \sim 1/(kR)$

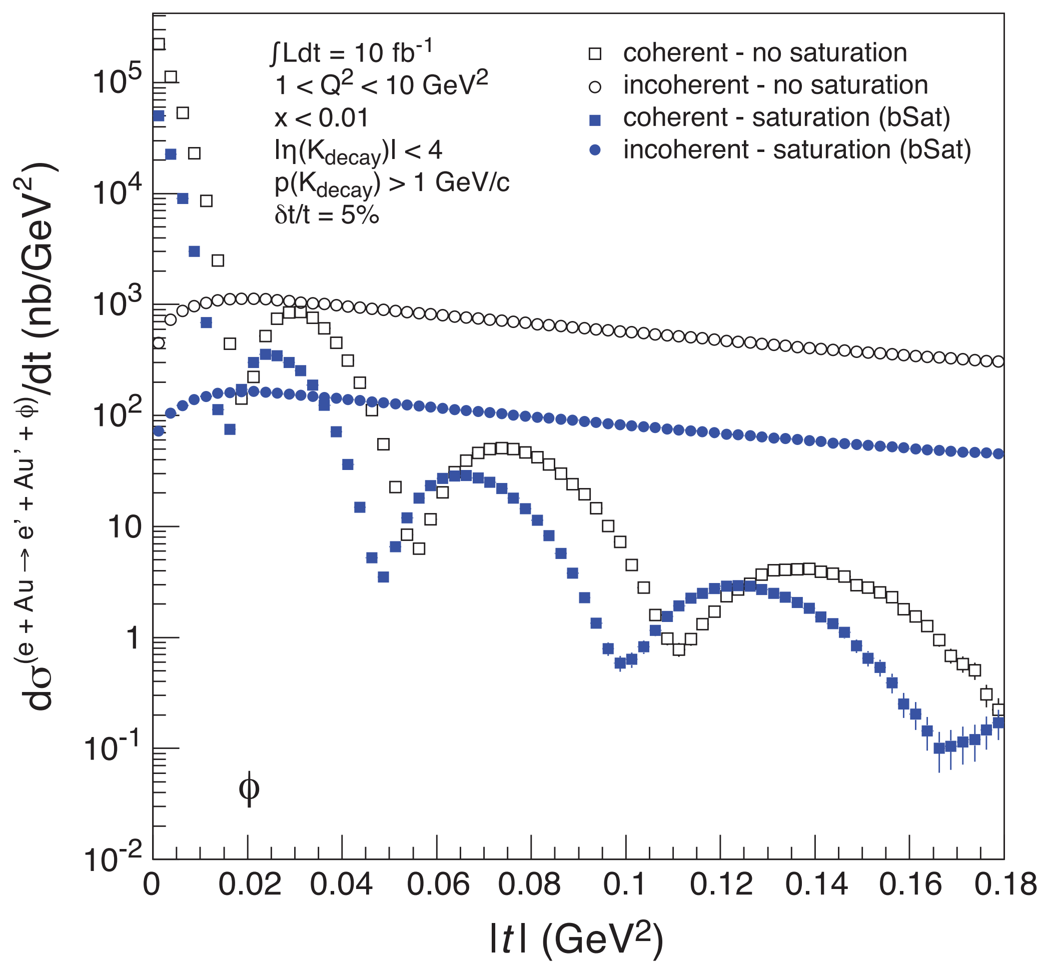
Exclusive Vector Meson Production in e+A



- Diffraction with final state VM - plots from Sartre event generator
  - ➡ Clean - only one new final state particle generated
  - ➡ Unambiguously identified via the presence of a rapidity gap
  - ➡ J/ψ less sensitive to saturation effects that phi
    - expected as ϕ has larger wave function

Exclusive Vector Meson Production in e+A





- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations

➡ Need good breakup detection efficiency to discriminate between the two scenarios

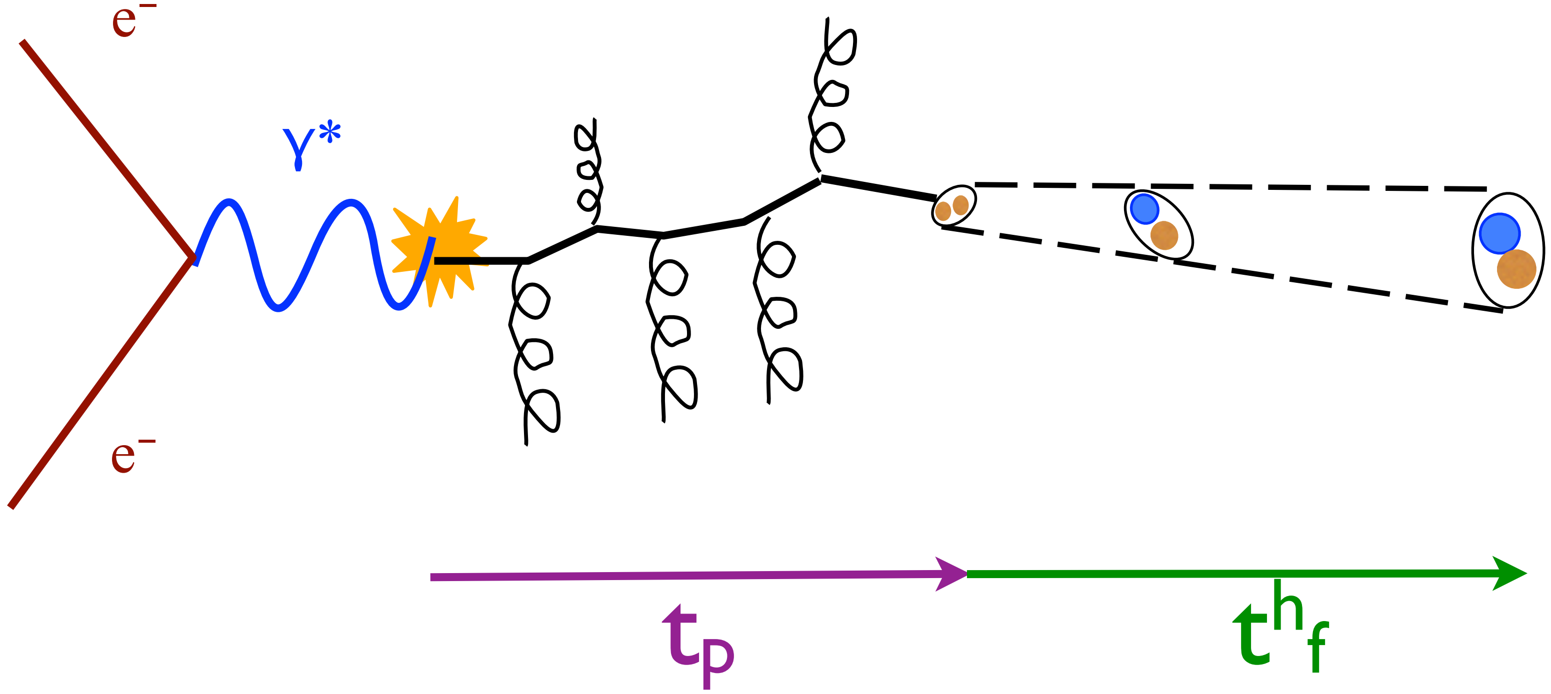
- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

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

Transport coefficients in cold nuclear matter

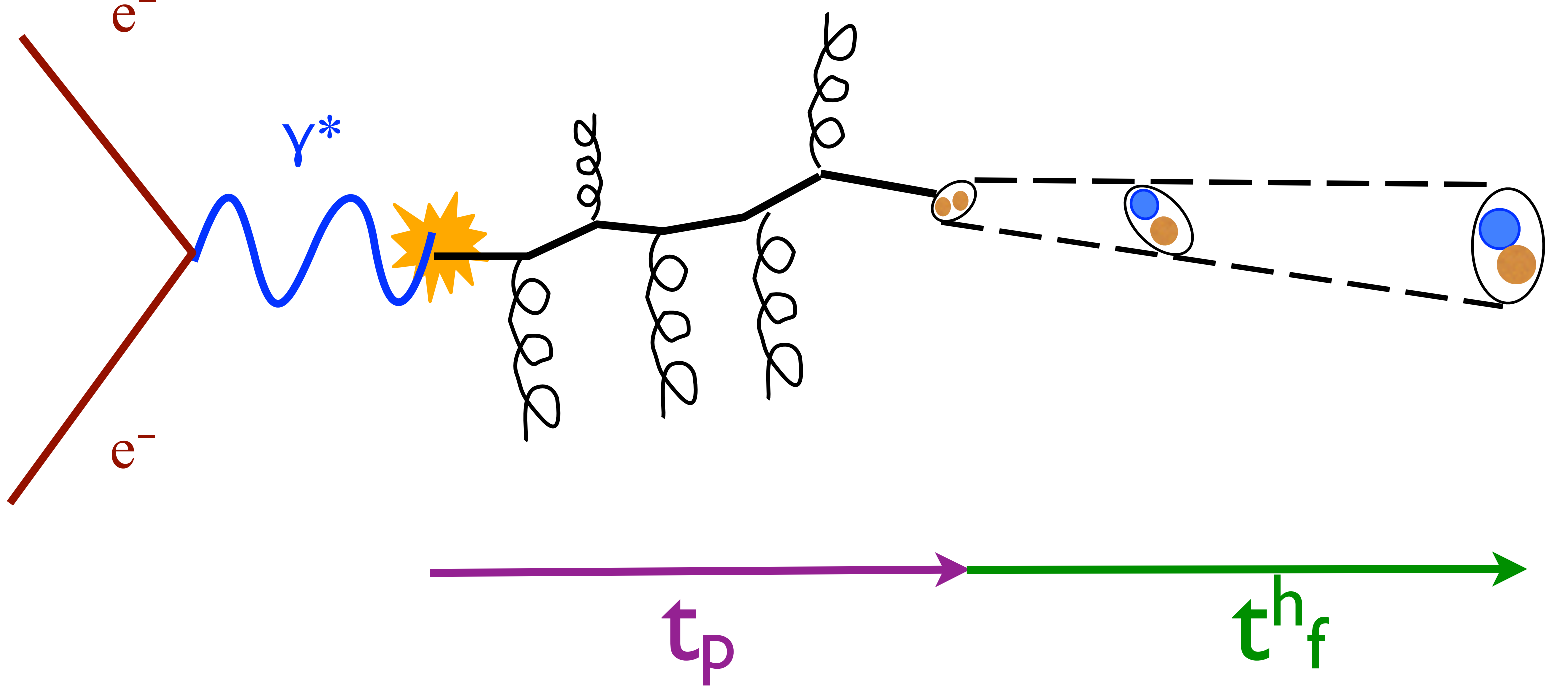
Deliverables	Observables	What we learn	Stage-I	Stage-II
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavours and charm; jets	rare probes and bottom; large-x gluons

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?

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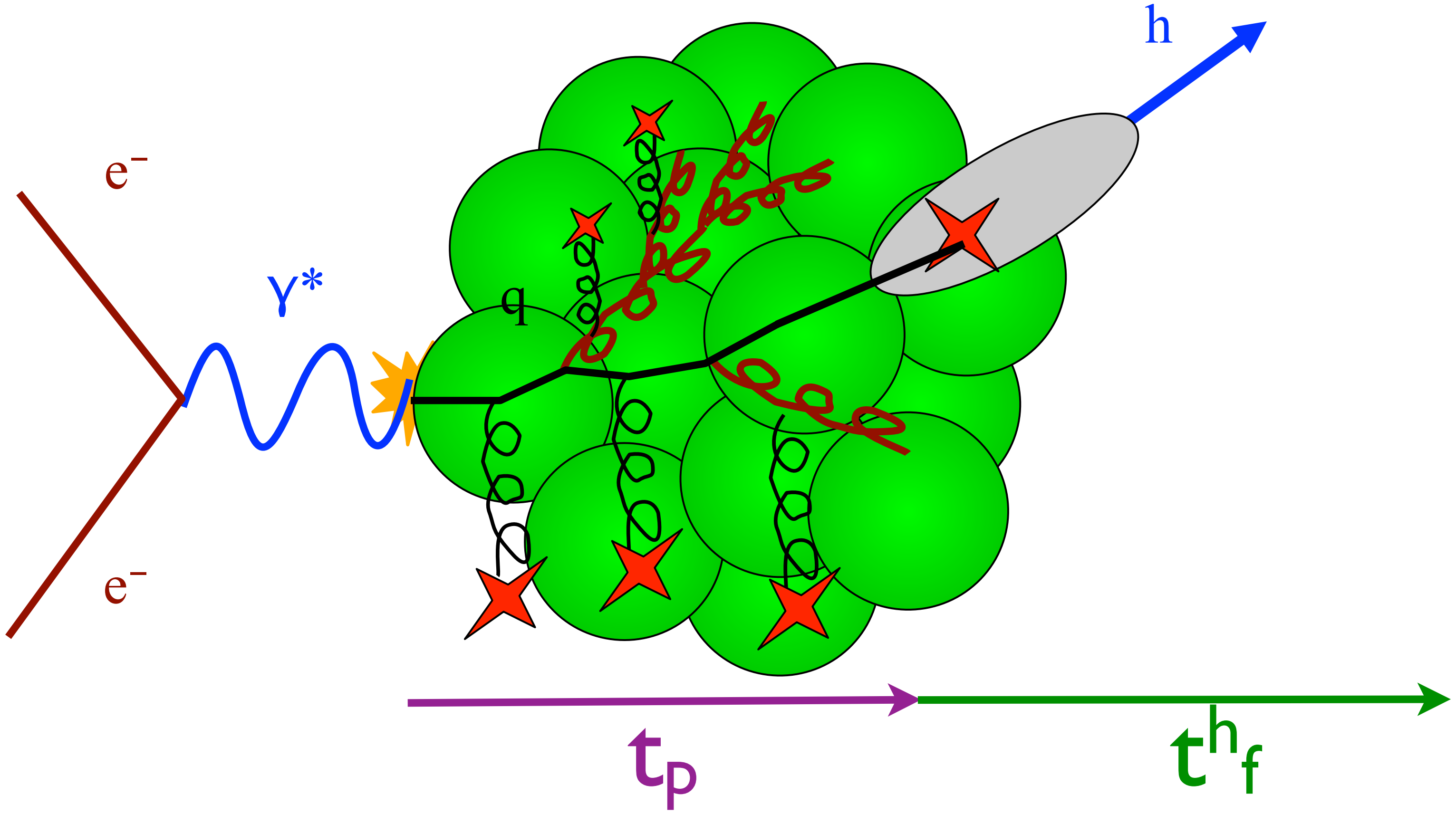
Jets and hadronization



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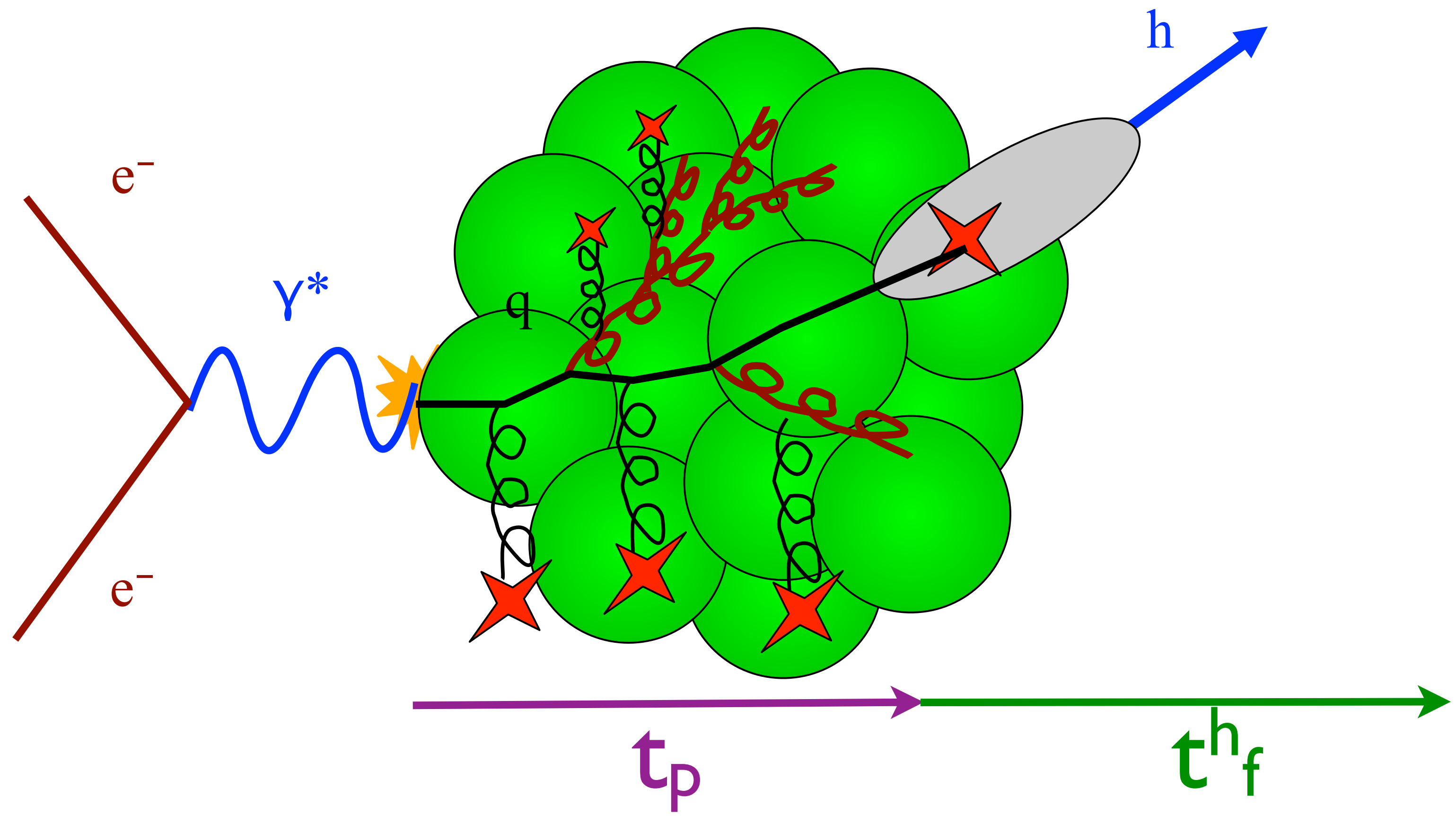

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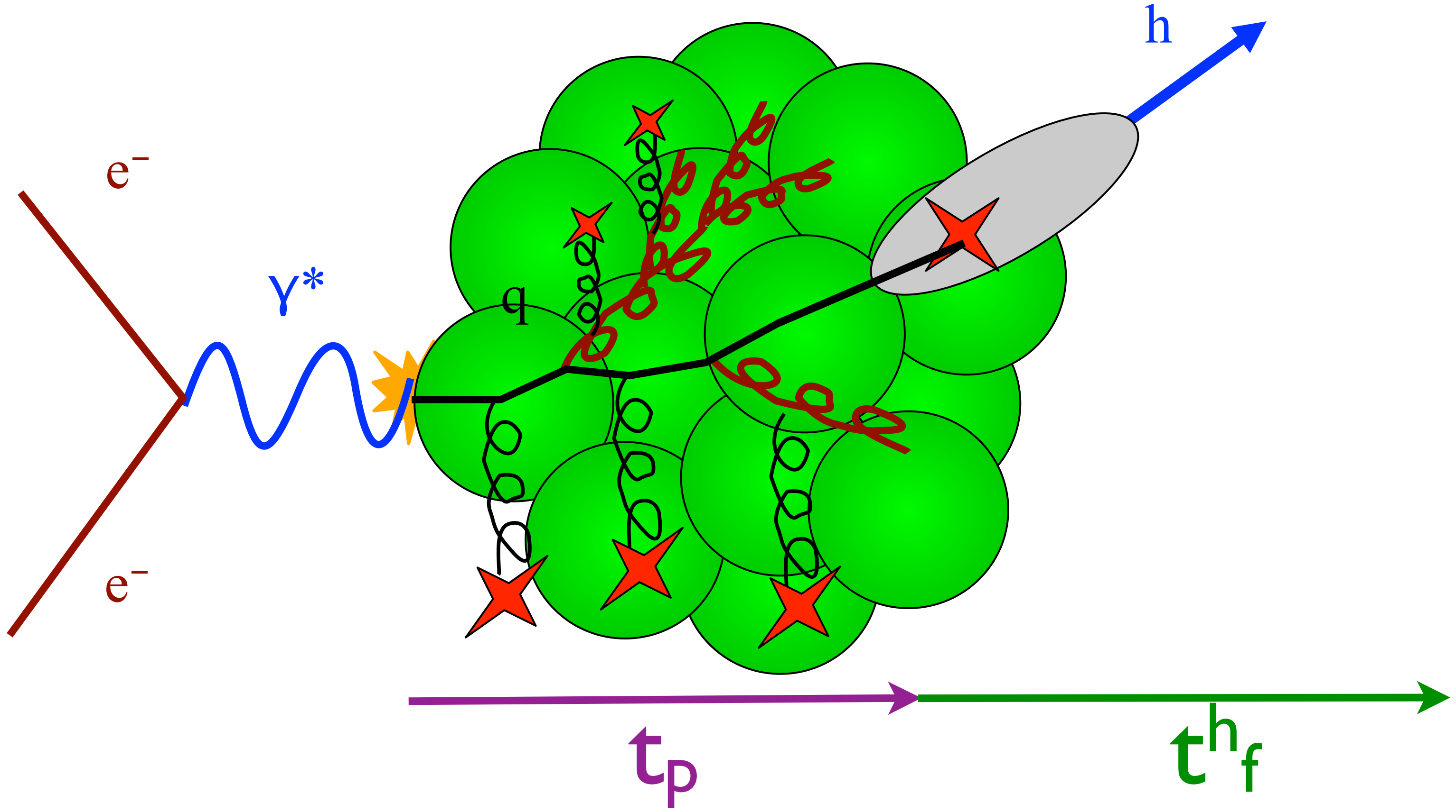

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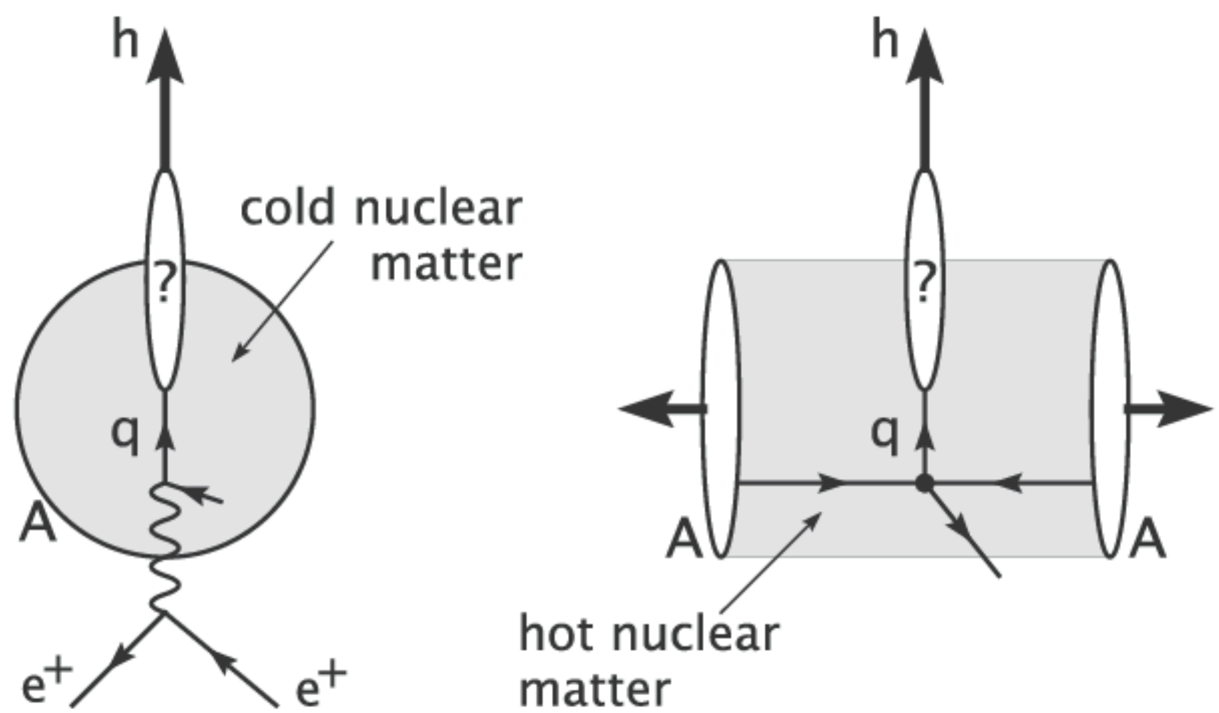

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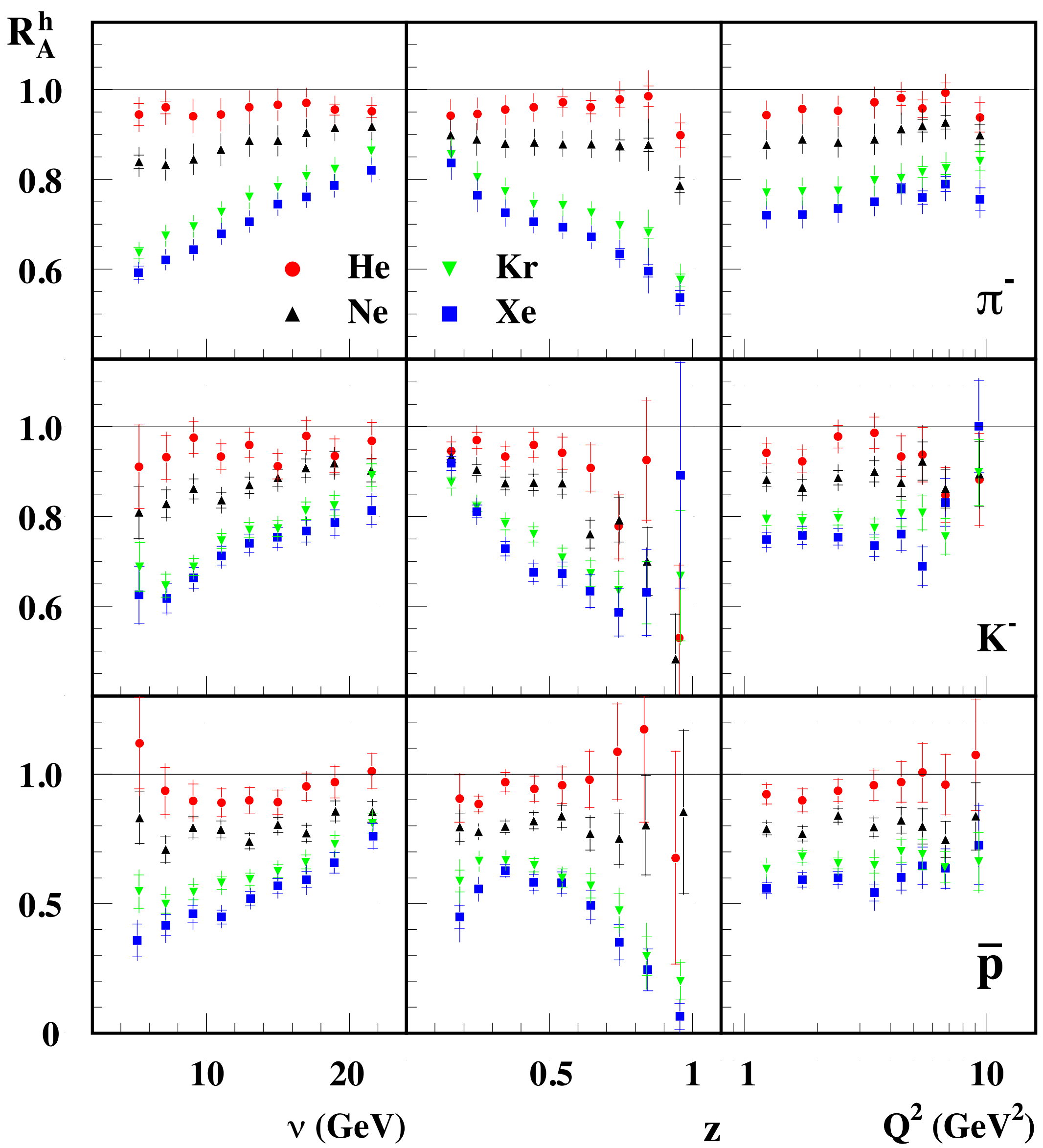
How can the EIC contribute?

HERMES:

E_e = 27 GeV → $\sqrt{s}$ = 7.2 GeV

E_h = 2-15 GeV



ν = virtual photon energy

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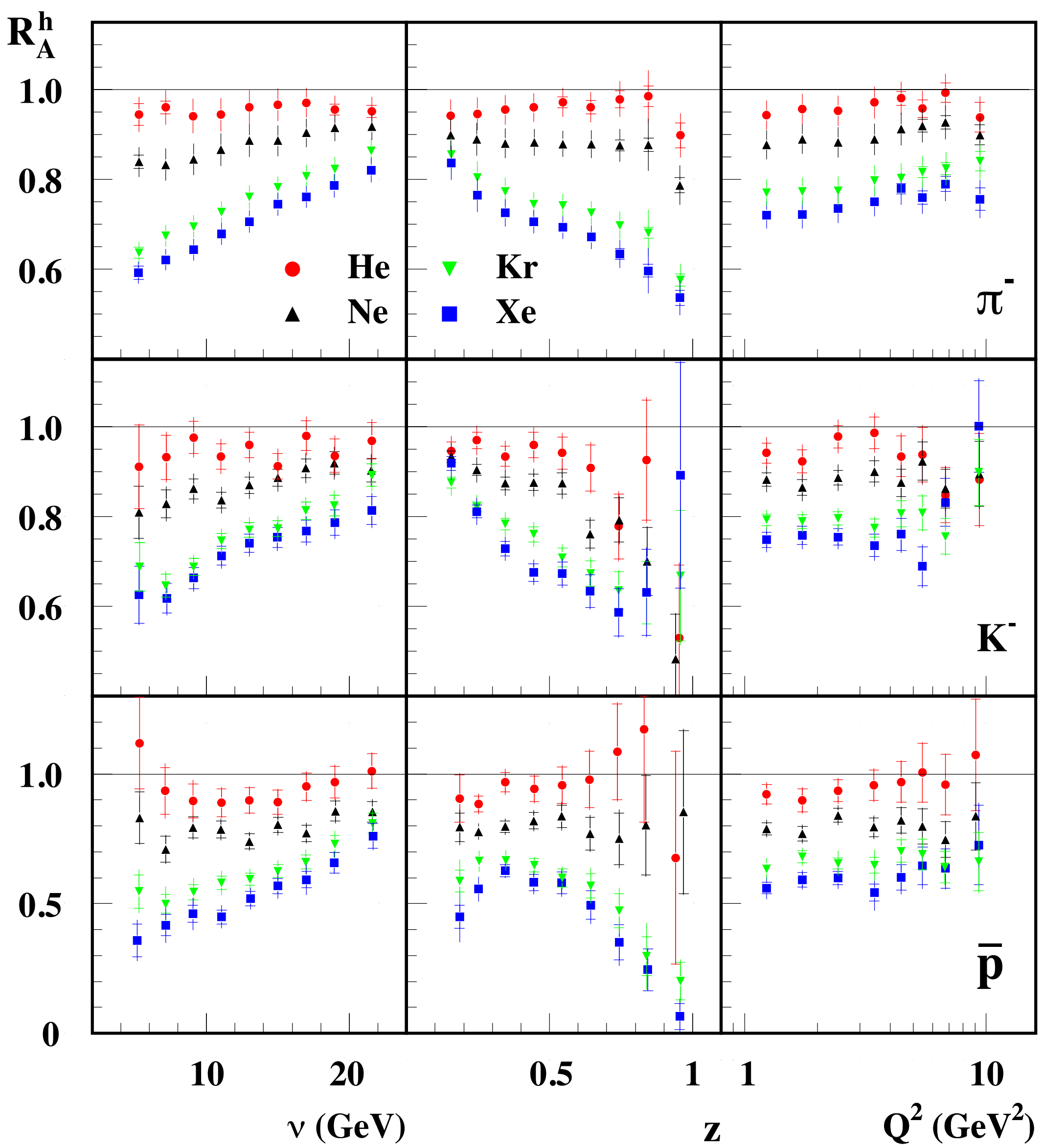

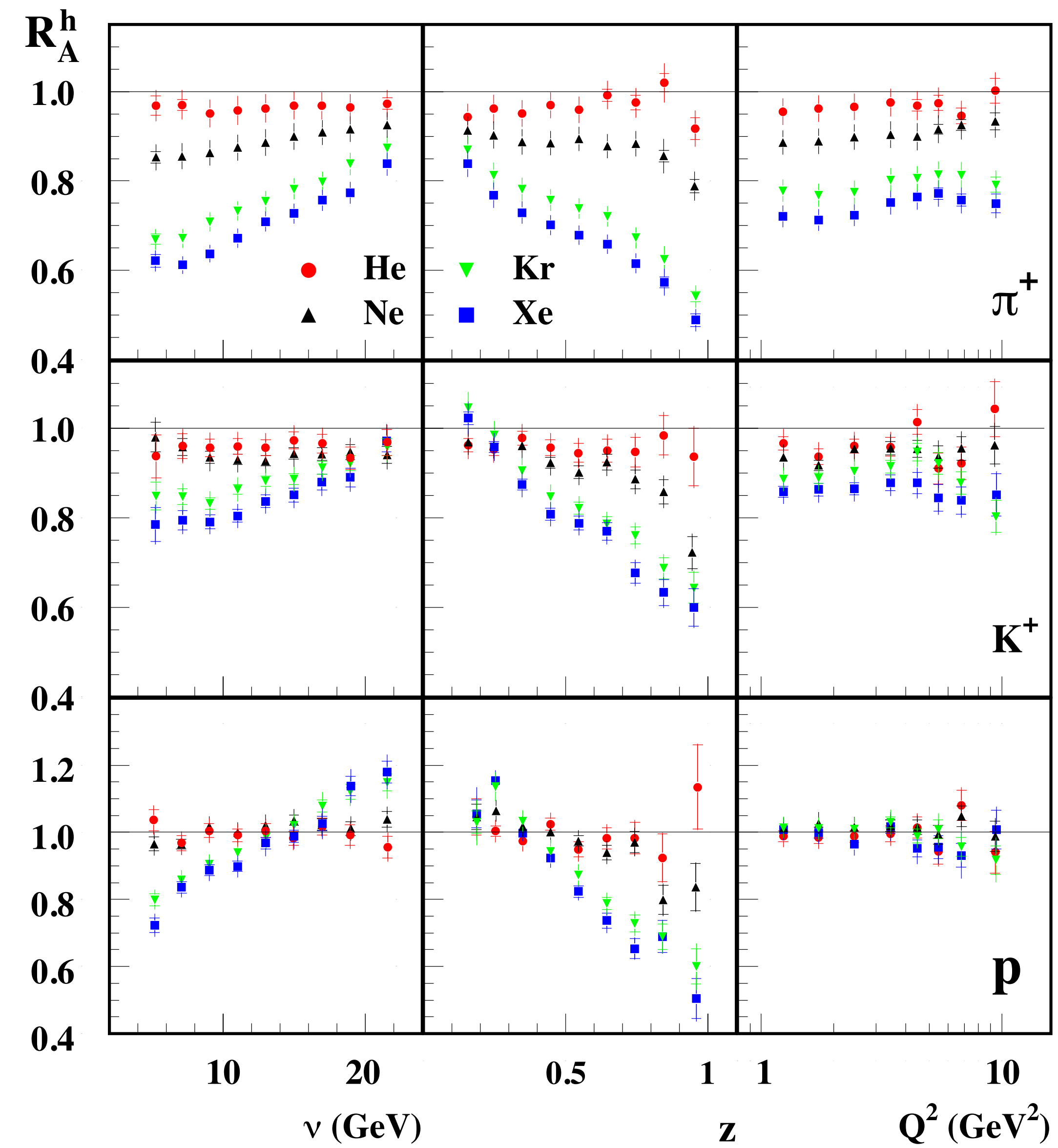

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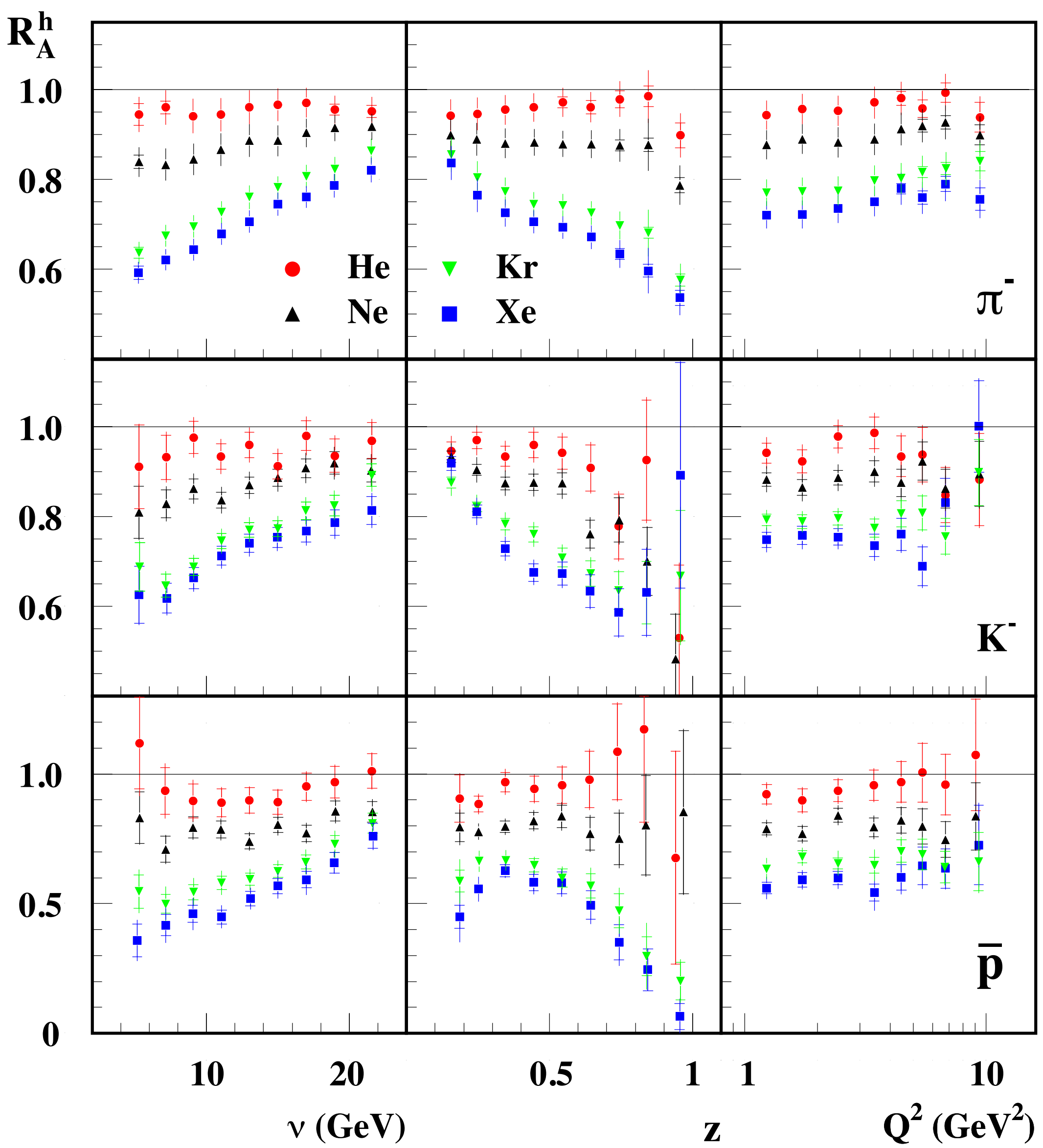
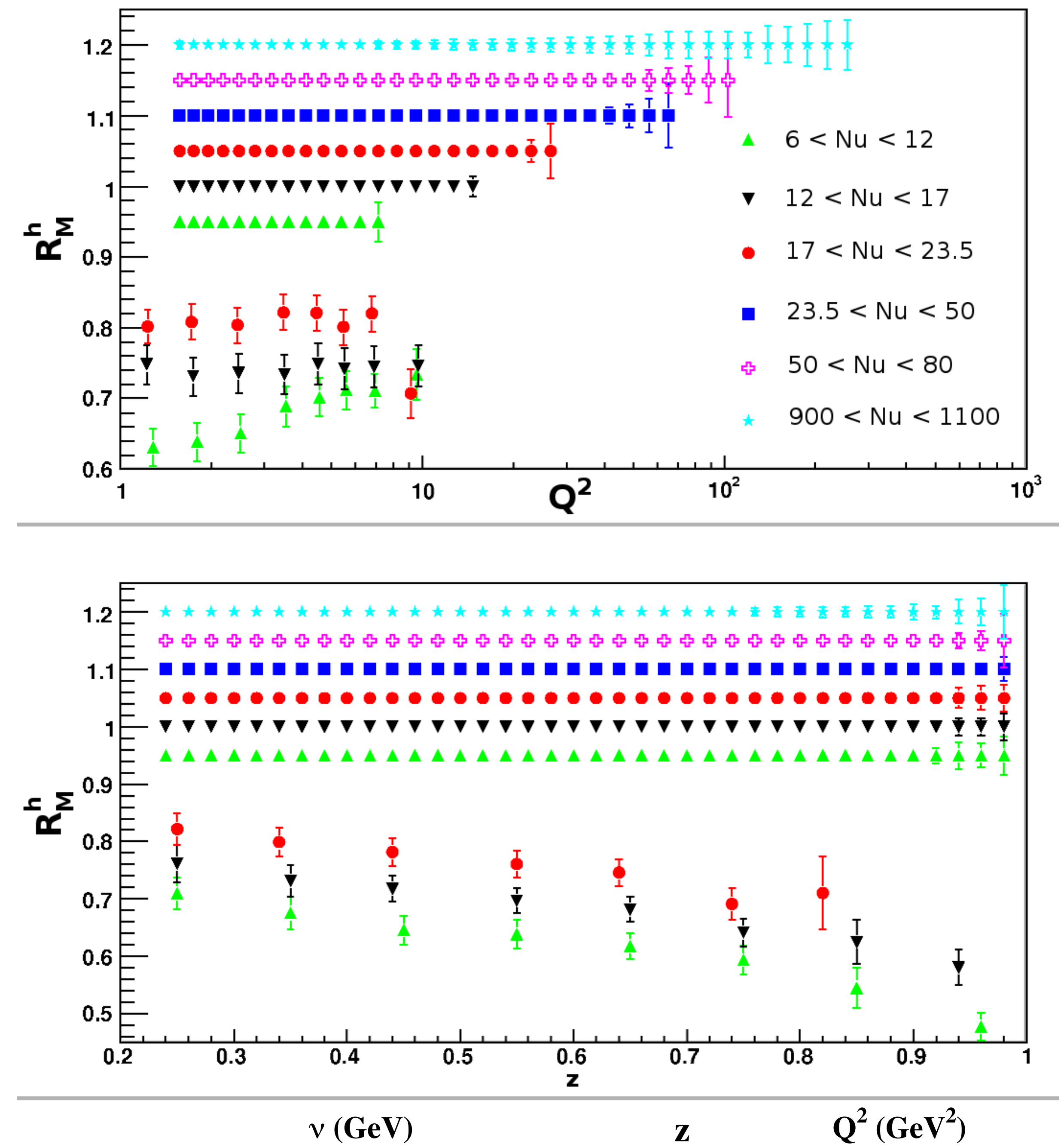


EIC:

light hadrons:



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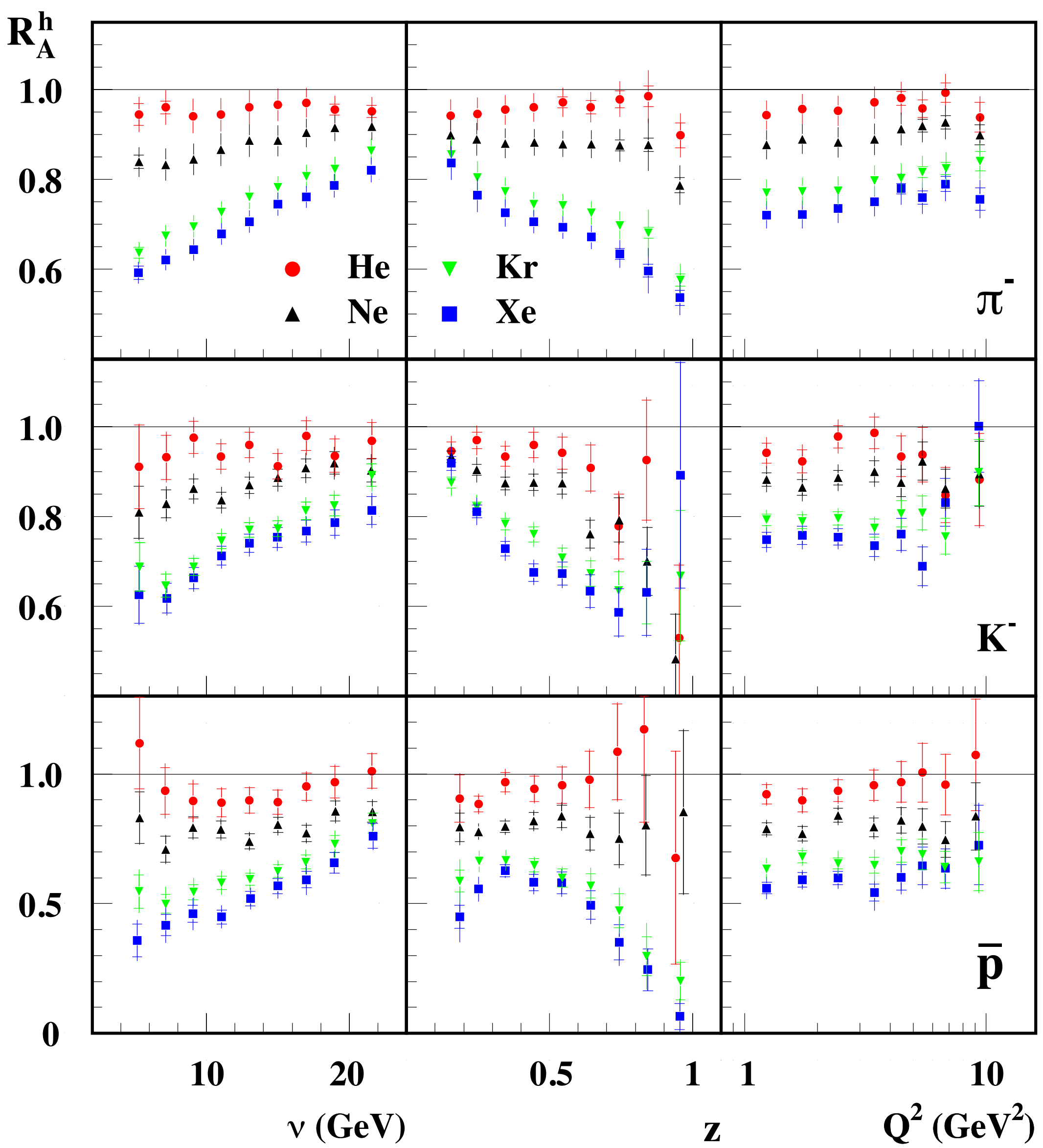
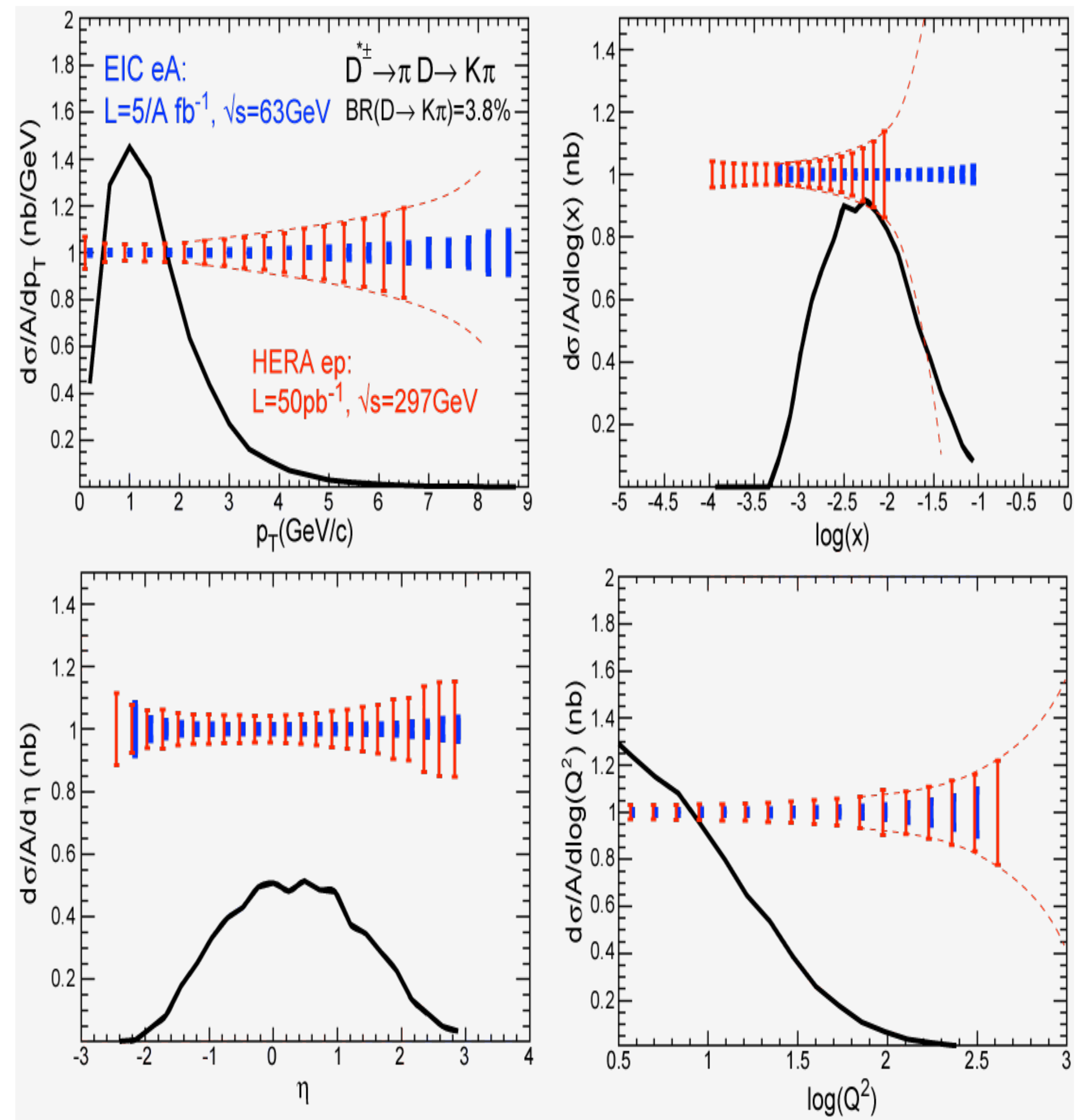


EIC:

charm hadrons:



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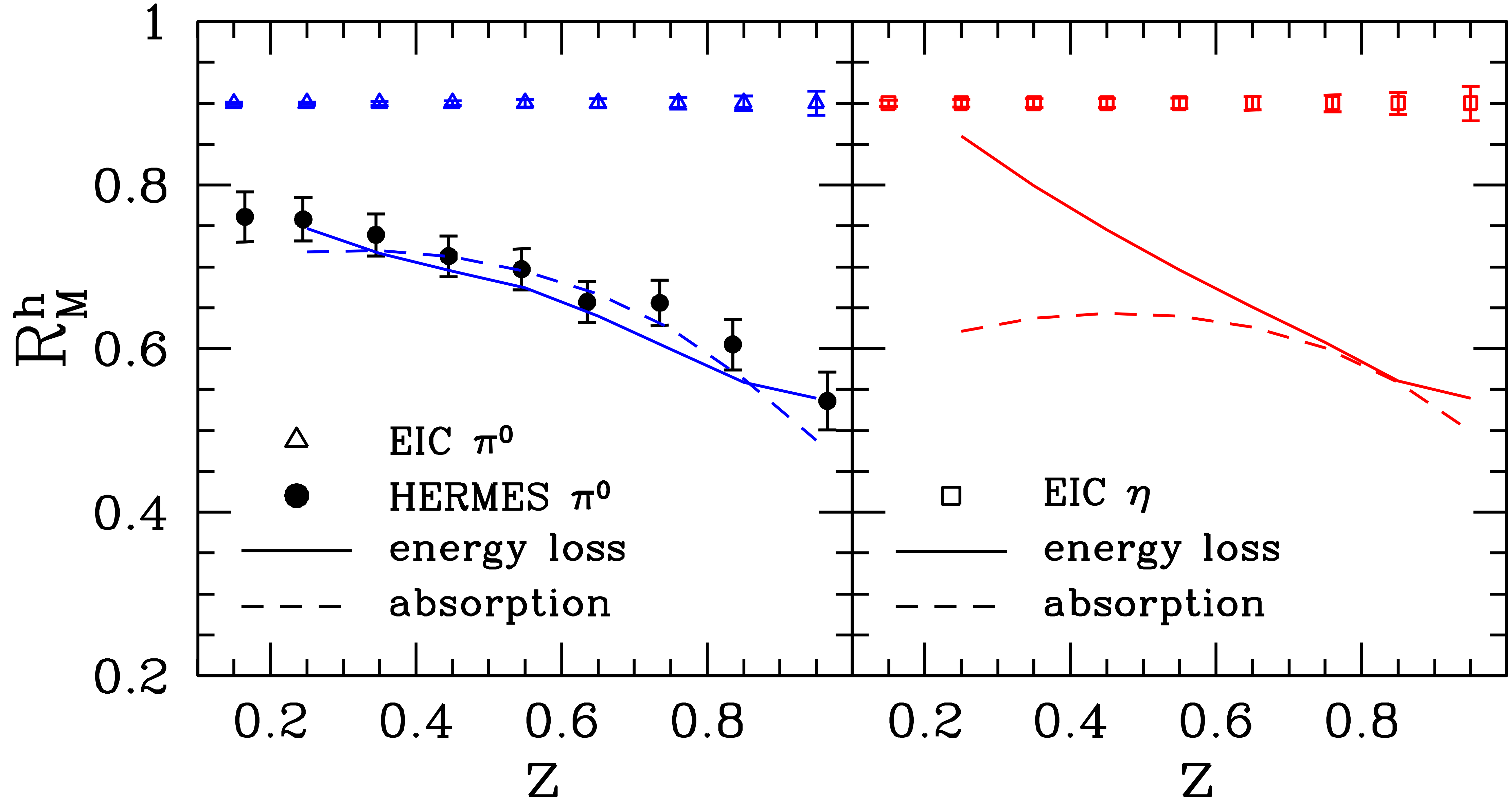

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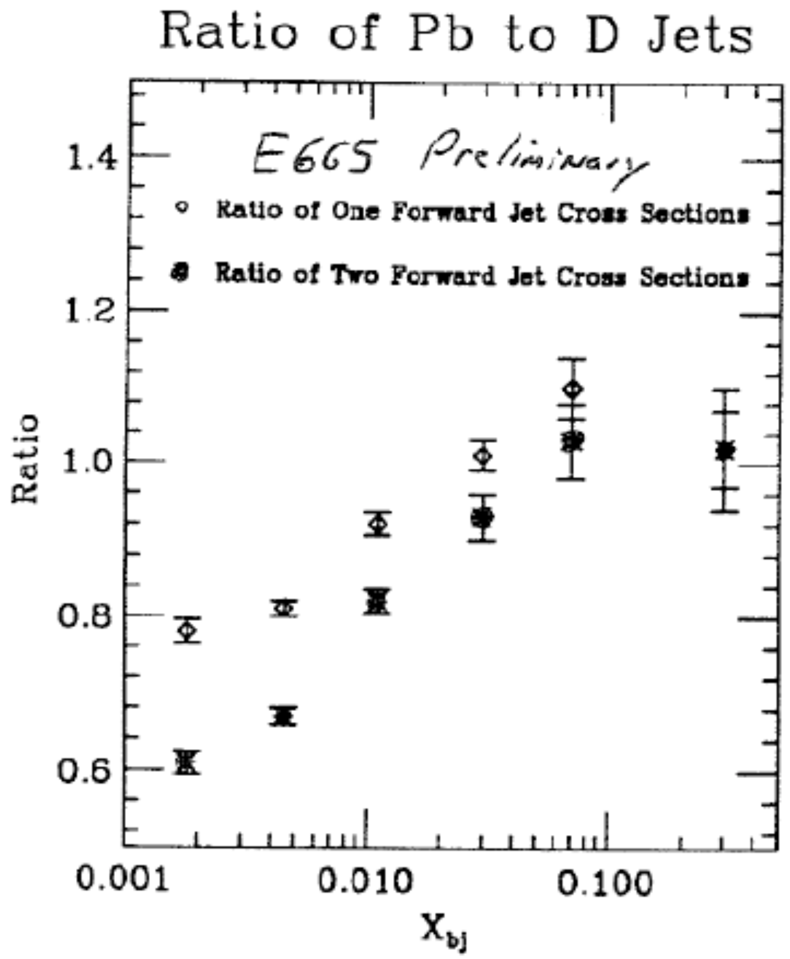
Jets at an EIC

- E665 at FNAL have measured jets in μ+A at $\sqrt{s} \sim 30$ GeV
  - ➡ Feasible to start a jet programme in phase 1
  - ➡ caveat that collider kinematics are different to fixed target



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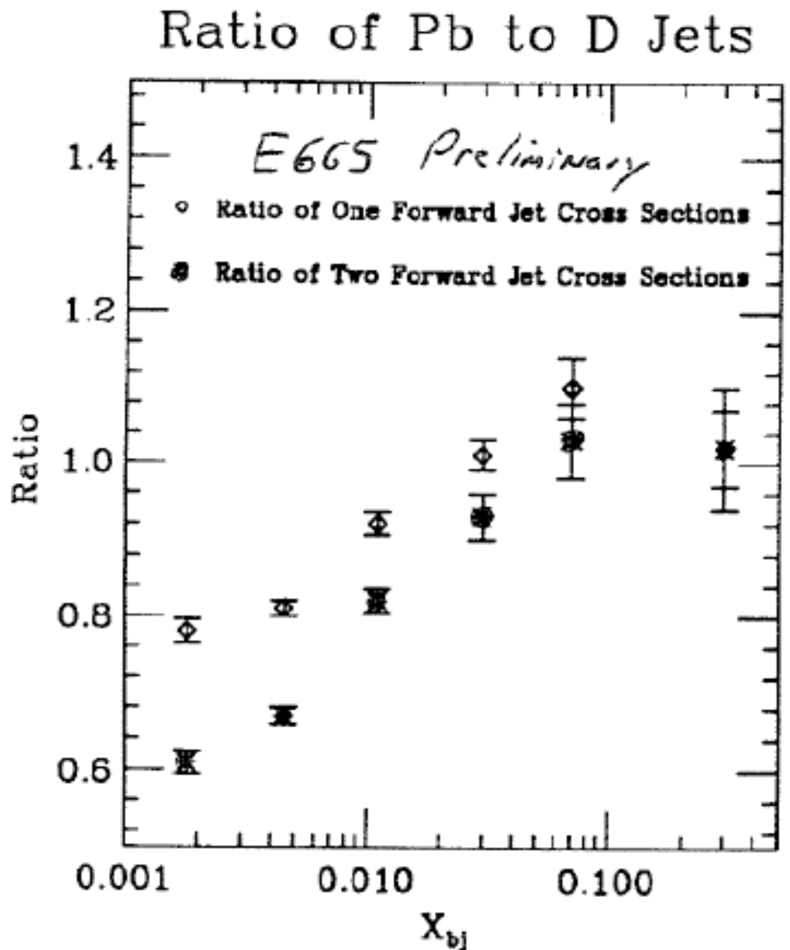
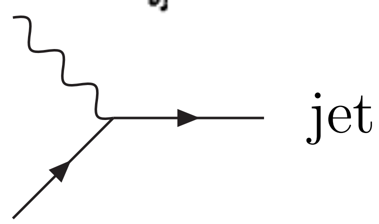


1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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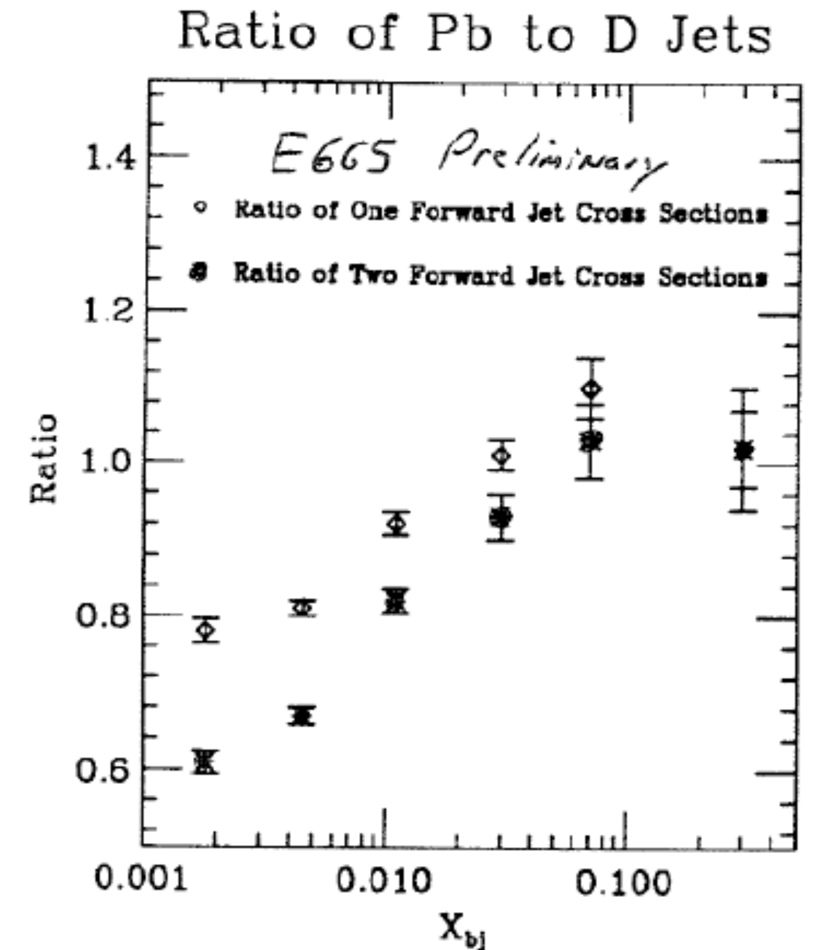

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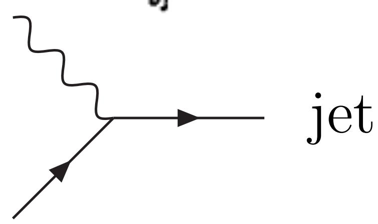
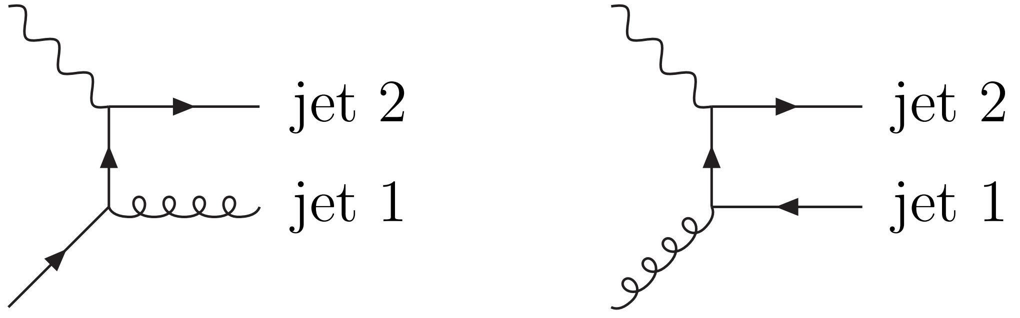


$$\frac{d^2\sigma_{2+1}}{dxdQ^2} = A_q(x,Q^2)q^A(x,Q^2) + A_g(x,Q^2)g_A(x,Q^2)$$

2+1 jets→ sensitive to nuclear gluons



By measuring 1+1 jets, can extract information on gluons

Jets at an EIC

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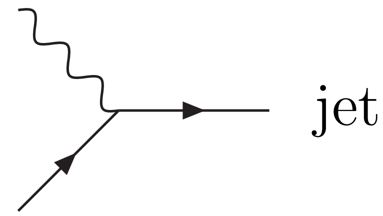
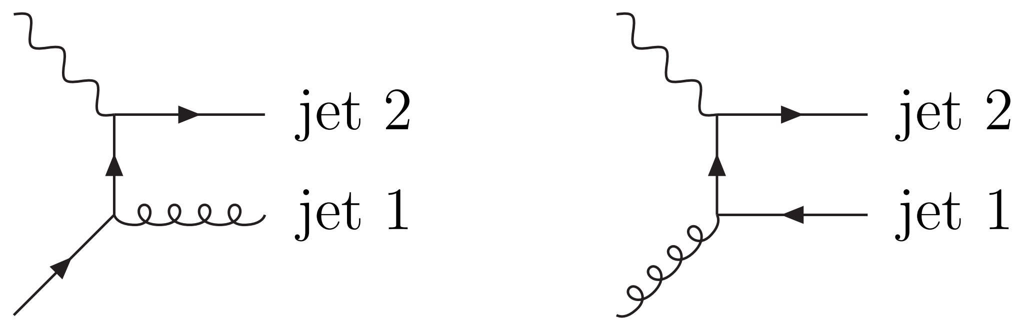
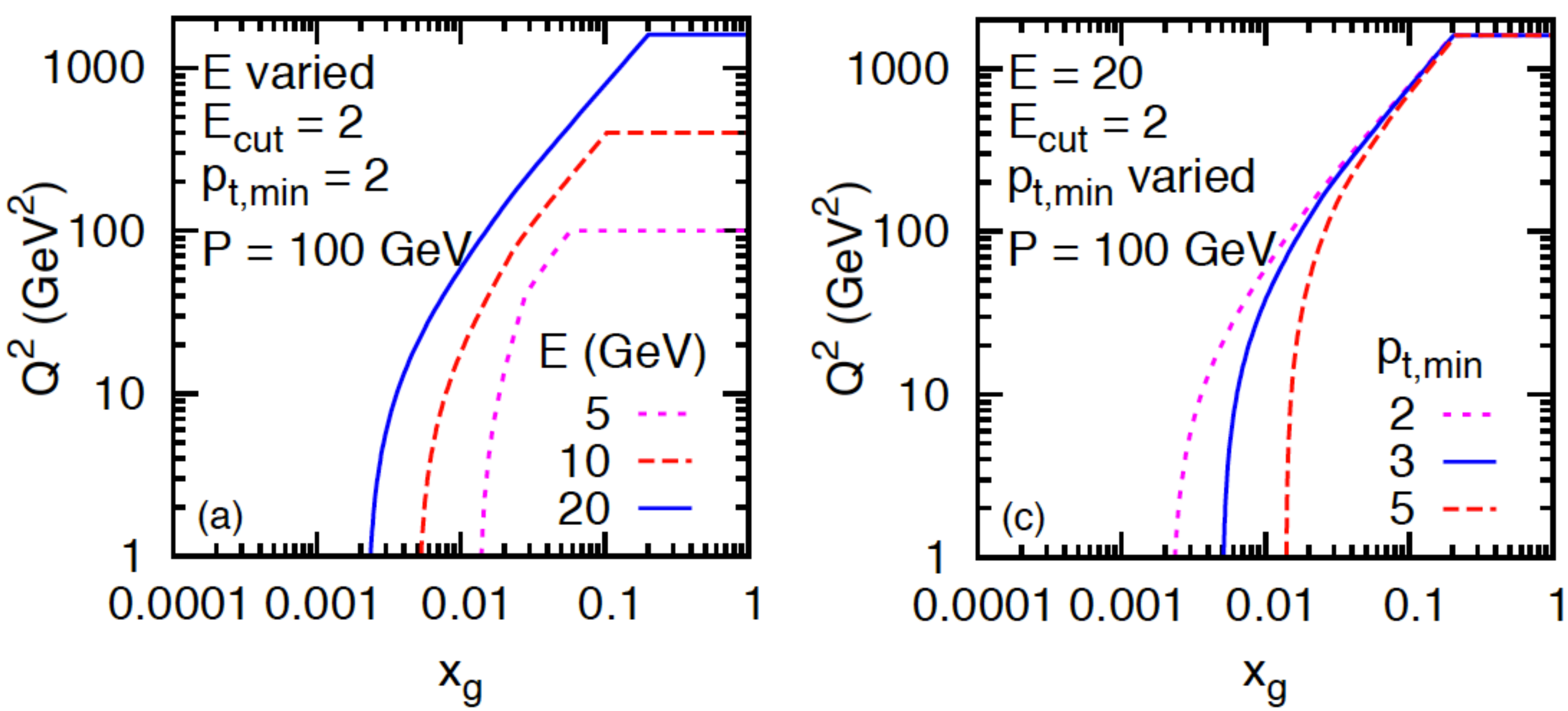


$$\frac{d^2\sigma_{2+1}}{dx dQ^2} = A_q(x,Q^2)q^A(x,Q^2) + A_g(x,Q^2)g_A(x,Q^2)$$

2+1 jets→ sensitive to nuclear gluons



By measuring 1+1 jets, can extract information on gluons



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

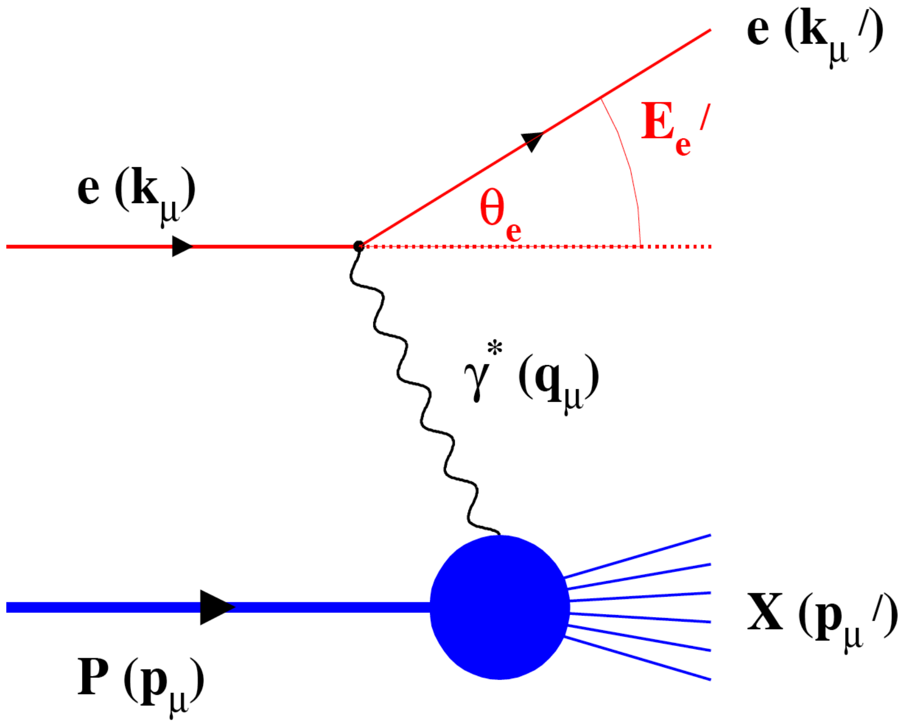
Good headway can be made on these measurements already with a stage-I eRHIC (E_e = 5 GeV)

- 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 is on the ArXiV
  - ➡ An EIC White Paper (not just e+A) will be released to the community shortly

BACKUP

DIS Kinematics

e(k) + p(p) → e(k') +X(p_X)



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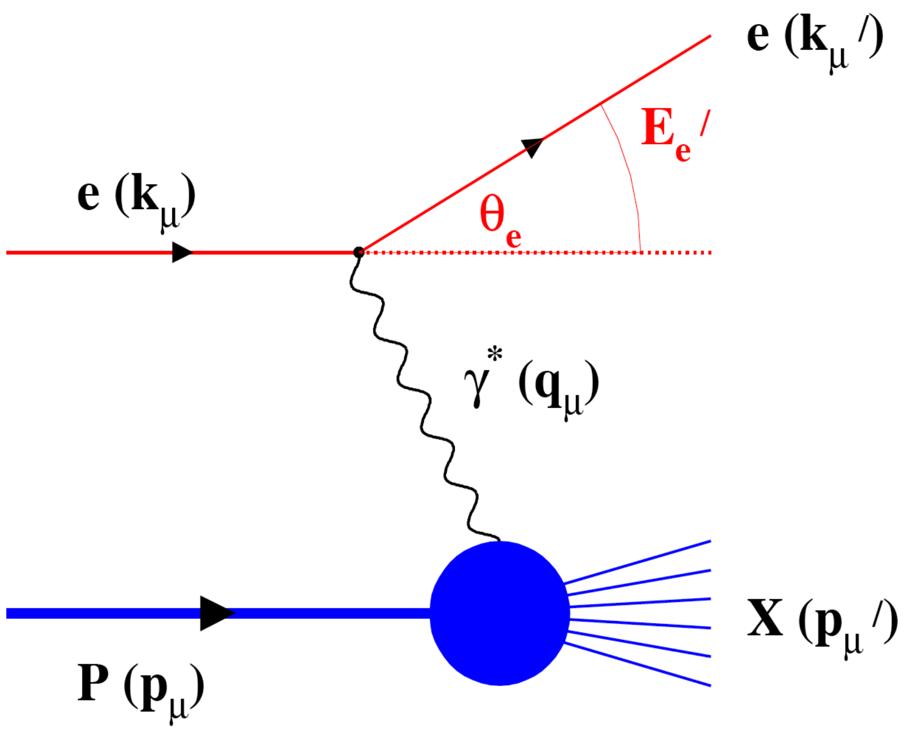


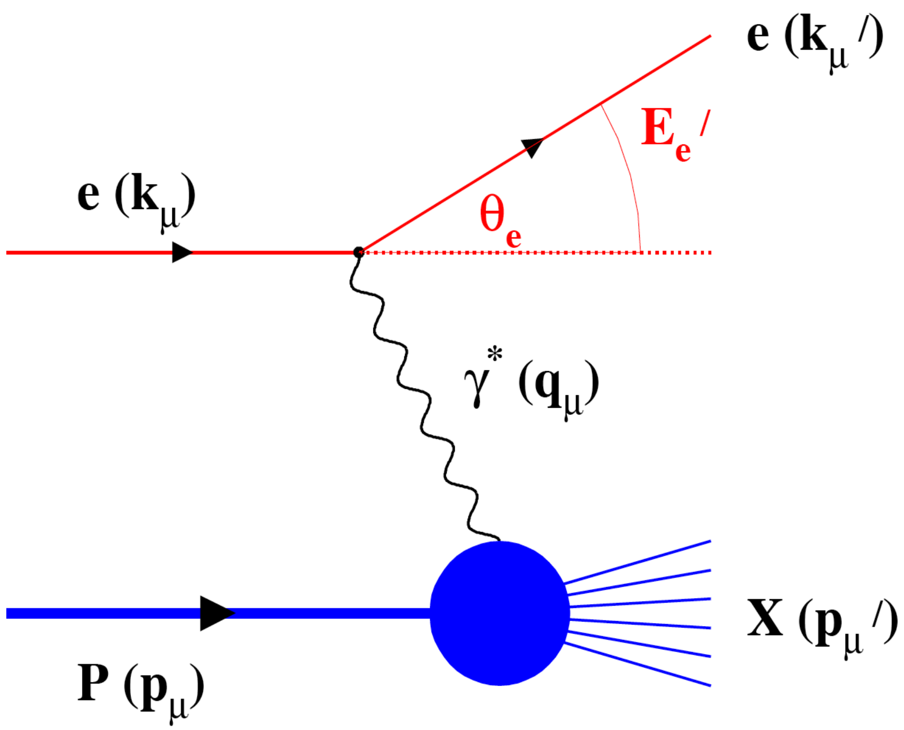
$$Q^2 = -q^2 = -(k_\mu - k_\mu^{'})^2$$

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

Measure of resolution power or "Virtuality"

DIS Kinematics

e(k) + p(p) → e(k') +X(px)



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Measure of resolution power or "Virtuality"

$$y = \frac{pq}{pk} = 1 - \frac{E_{e'}}{E_e} cos^2(\frac{\theta_e^{'}}{2})$$

Measure of inelasticity

DIS Kinematics

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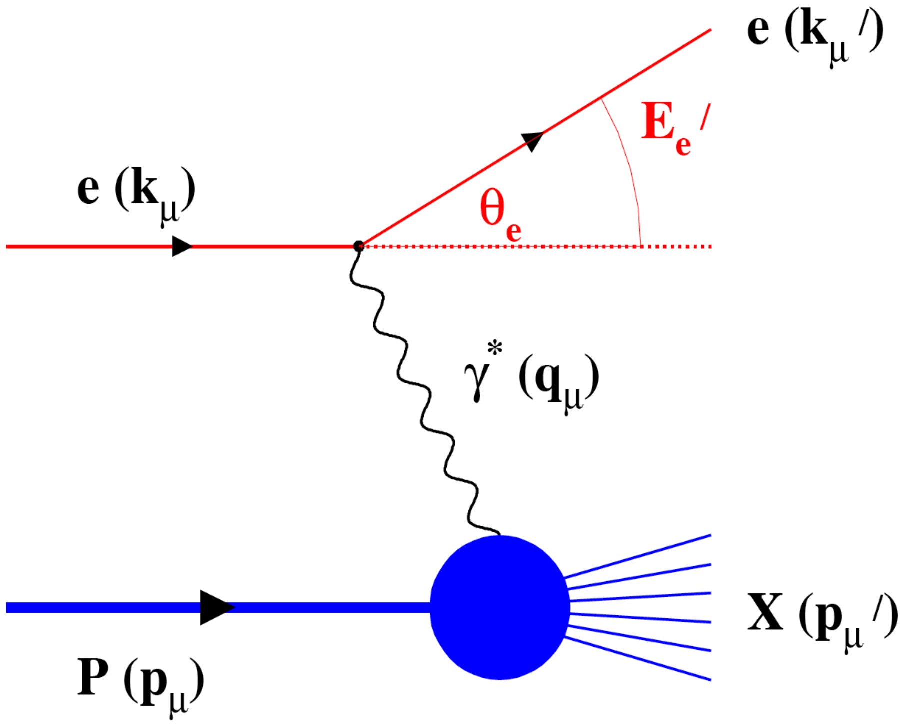

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Measure of inelasticity

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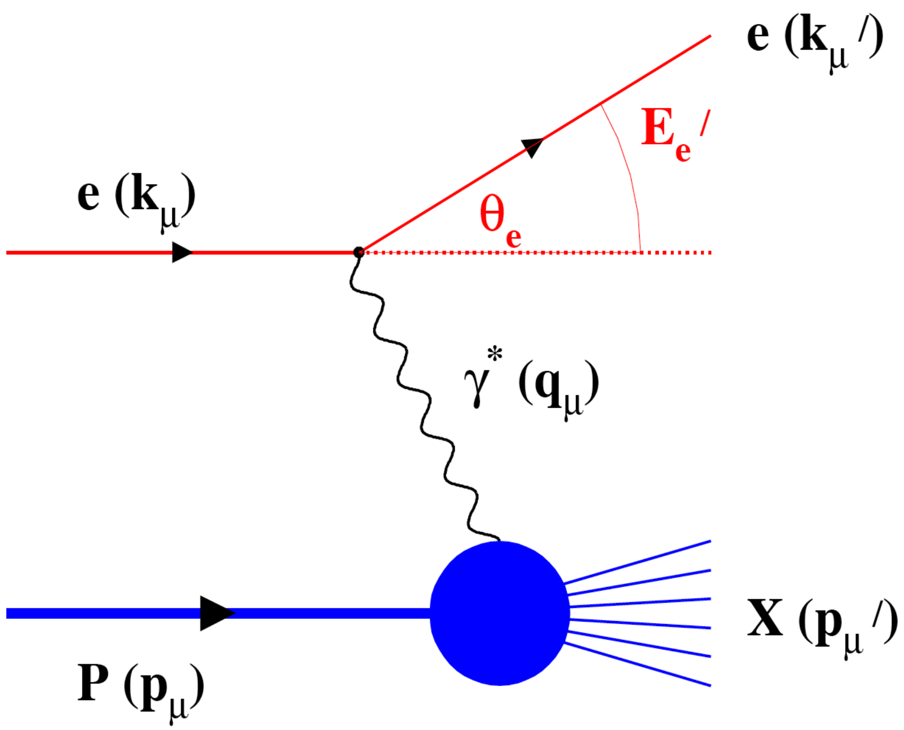
Measure of momentum fraction of struck quark

DIS Kinematics

e(k) + p(p) → e(k') +X(px)



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

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

Measure of resolution power or "Virtuality"

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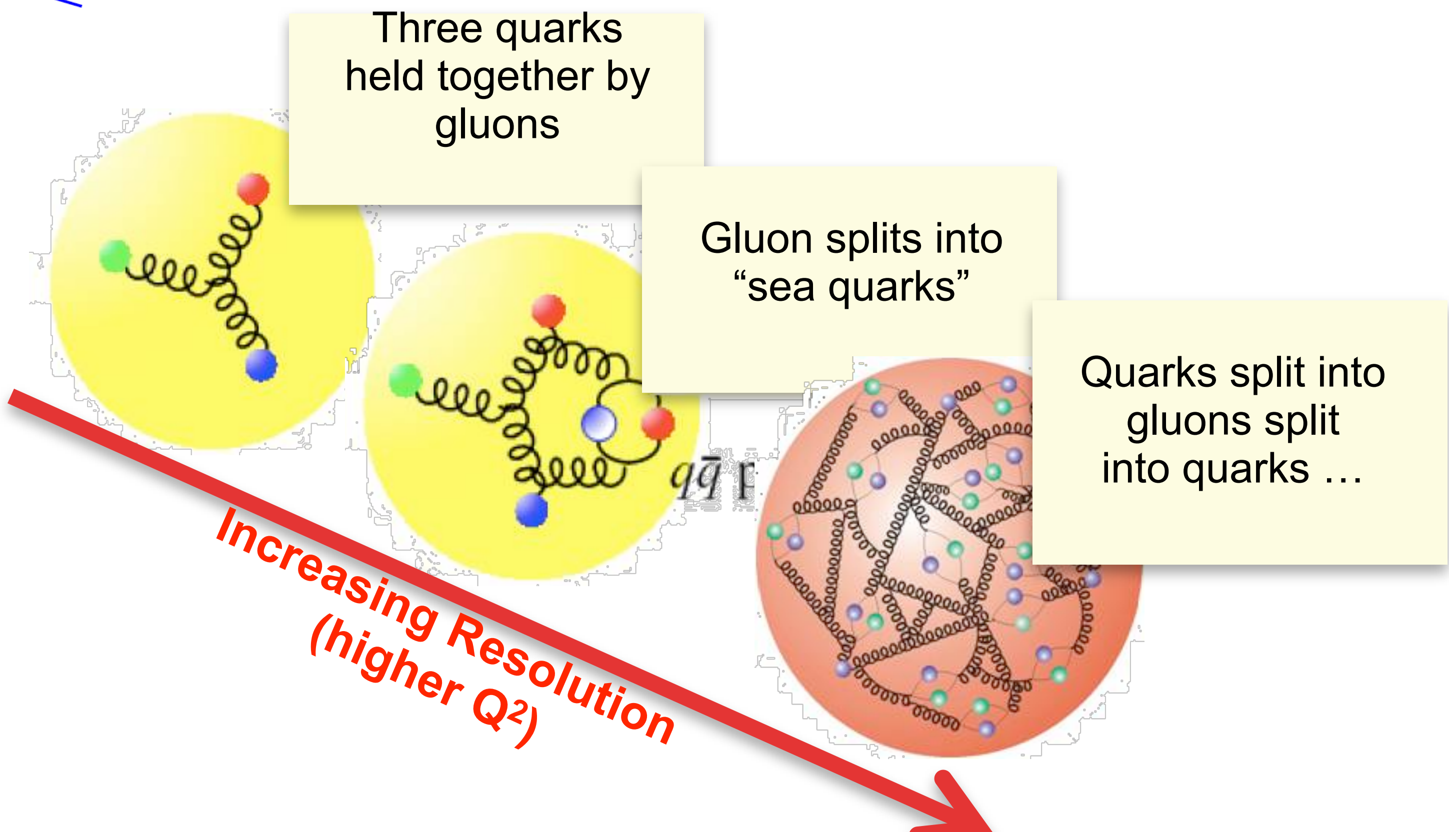
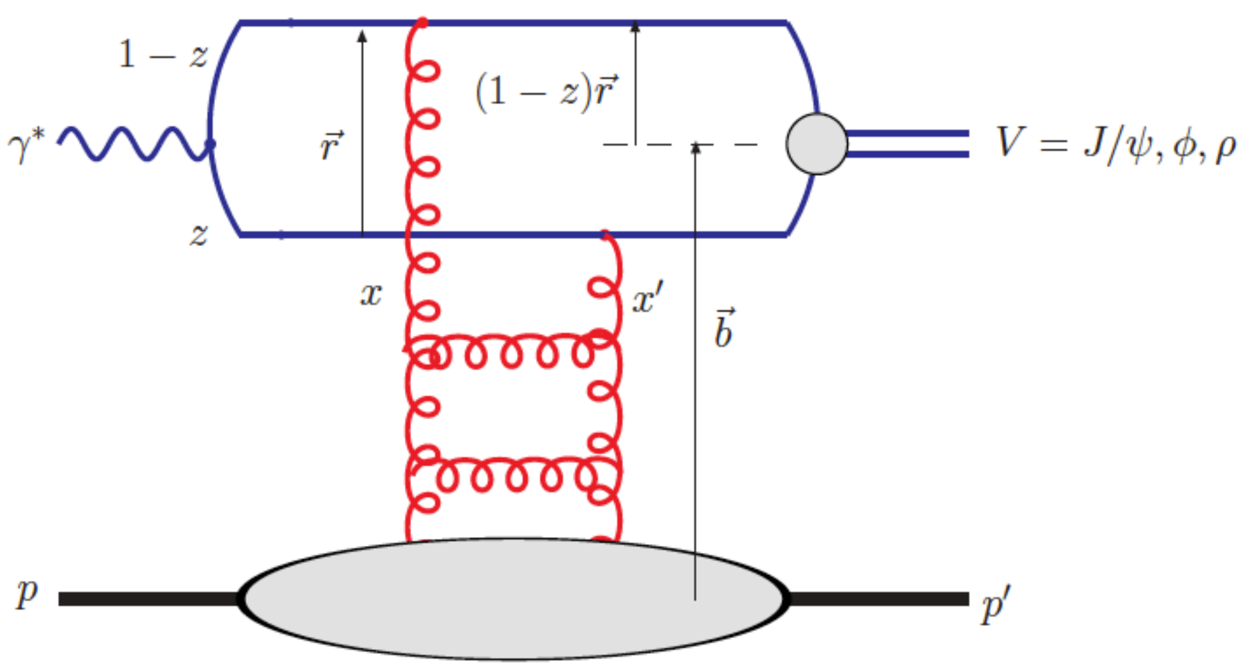
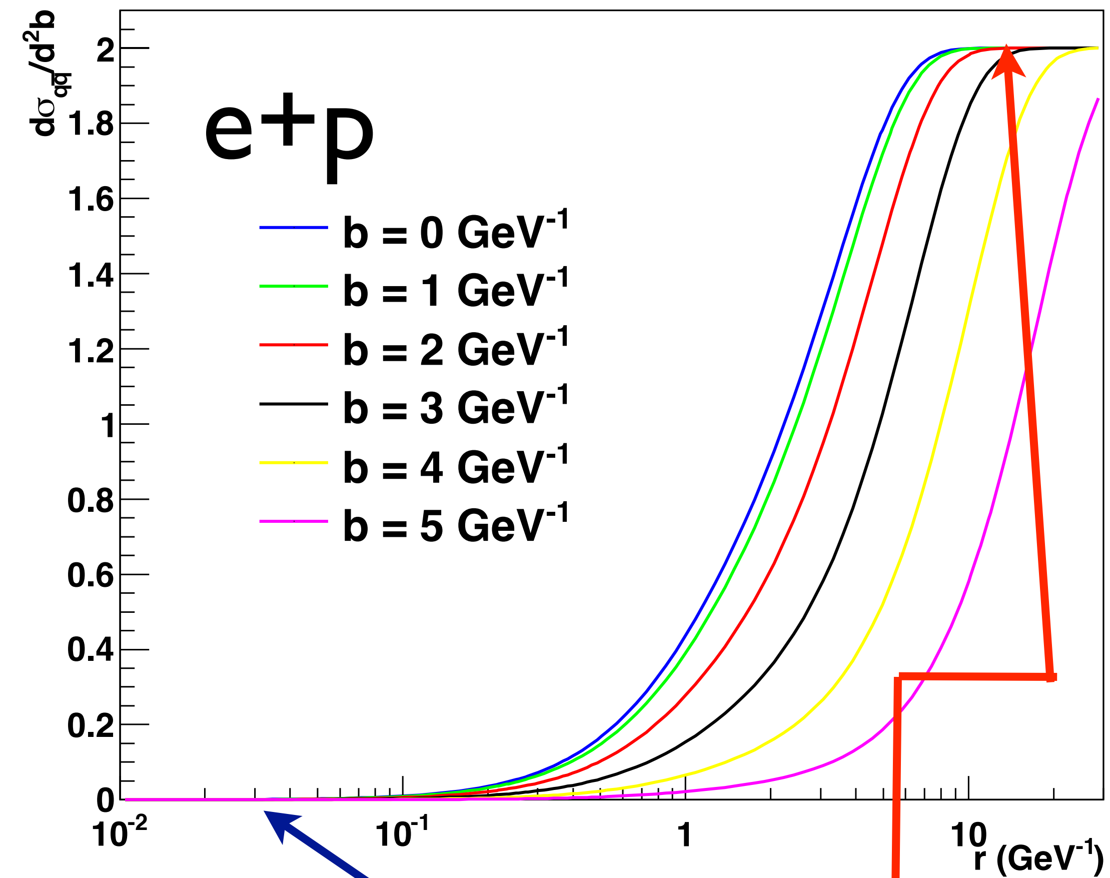


Getting a "Feel" for Non-Linear QCD

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

1 saturated, non-linear regime

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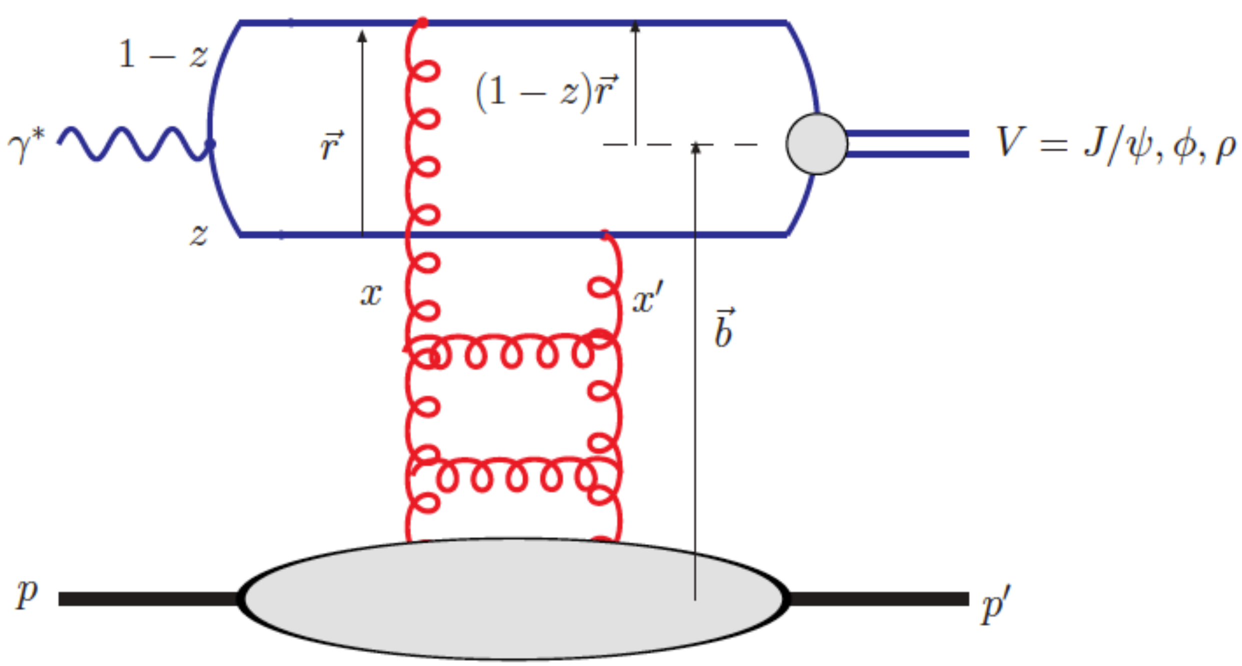

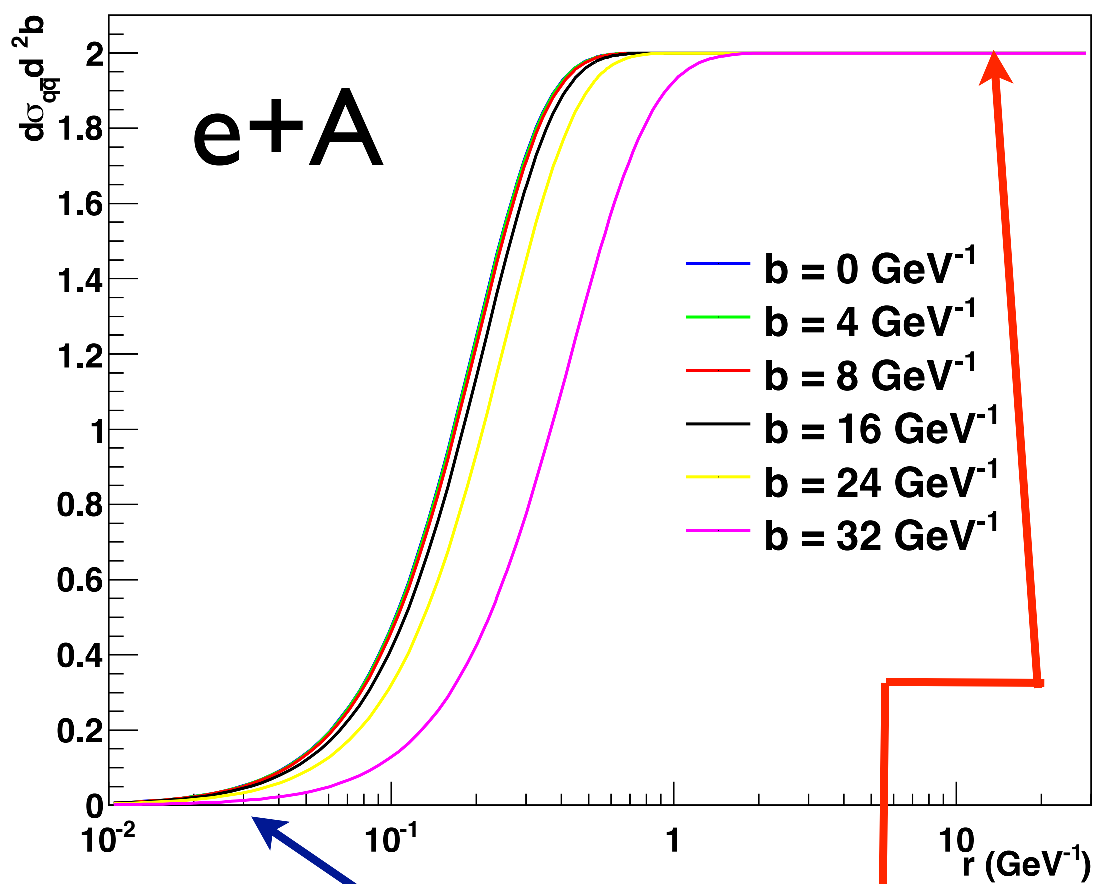

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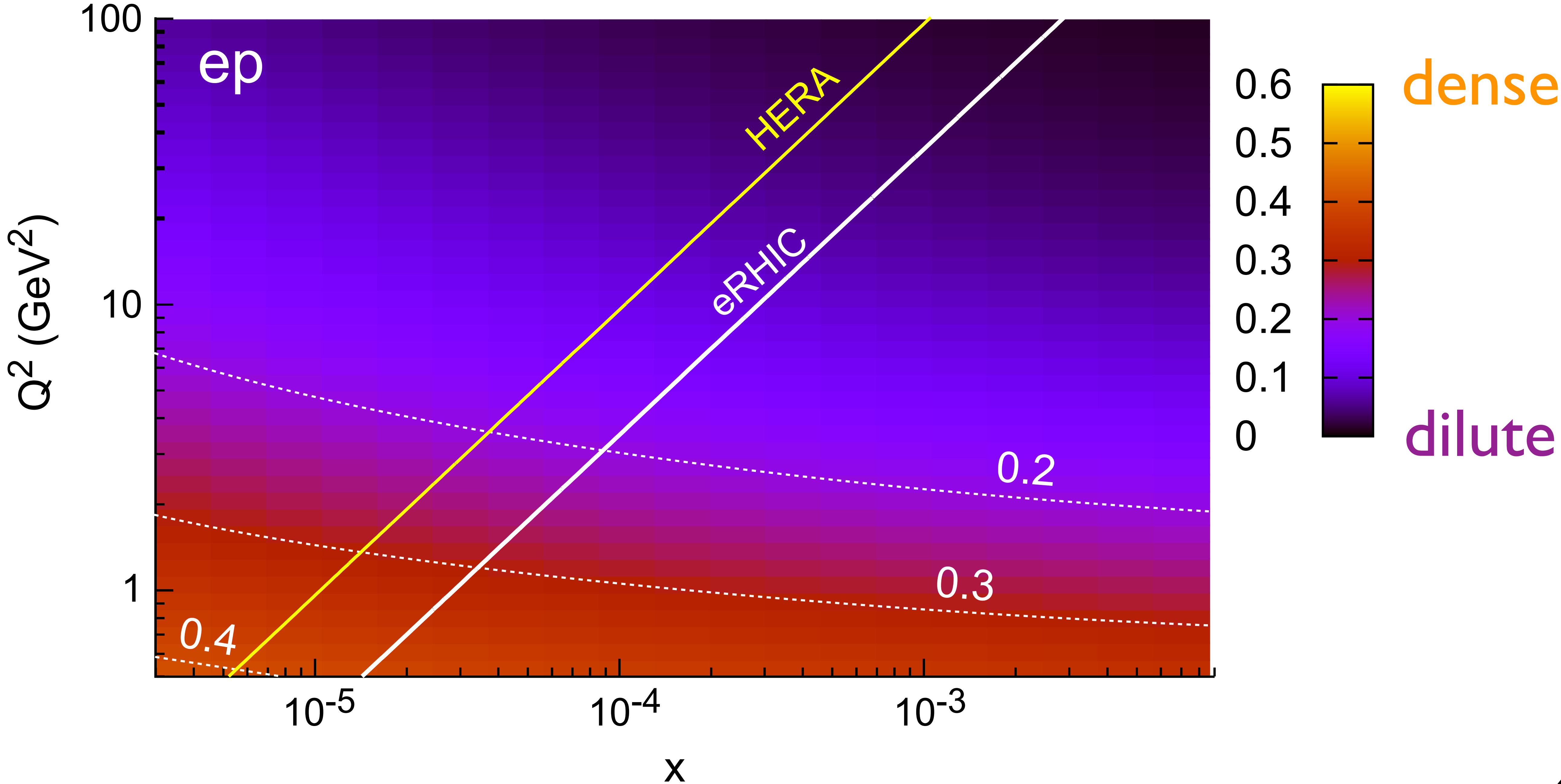
Getting a "Feel" for Non-Linear QCD

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

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

$\langle \mathcal{N} \rangle_2 \longrightarrow F_2$

$\langle \mathcal{N} \rangle_L \longrightarrow F_L$



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