A detailed study of the nucleus at an Electron-Ion Collider

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U.S. DEPARTMENT OF ENERGY

Lots of work recently on the physics of e+A collisions

The EIC Science case:
a report on the joint
BNL/INT/JLab program

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

Institute for Nuclear Theory • University of Washington, USA
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arXiv:1108.1713

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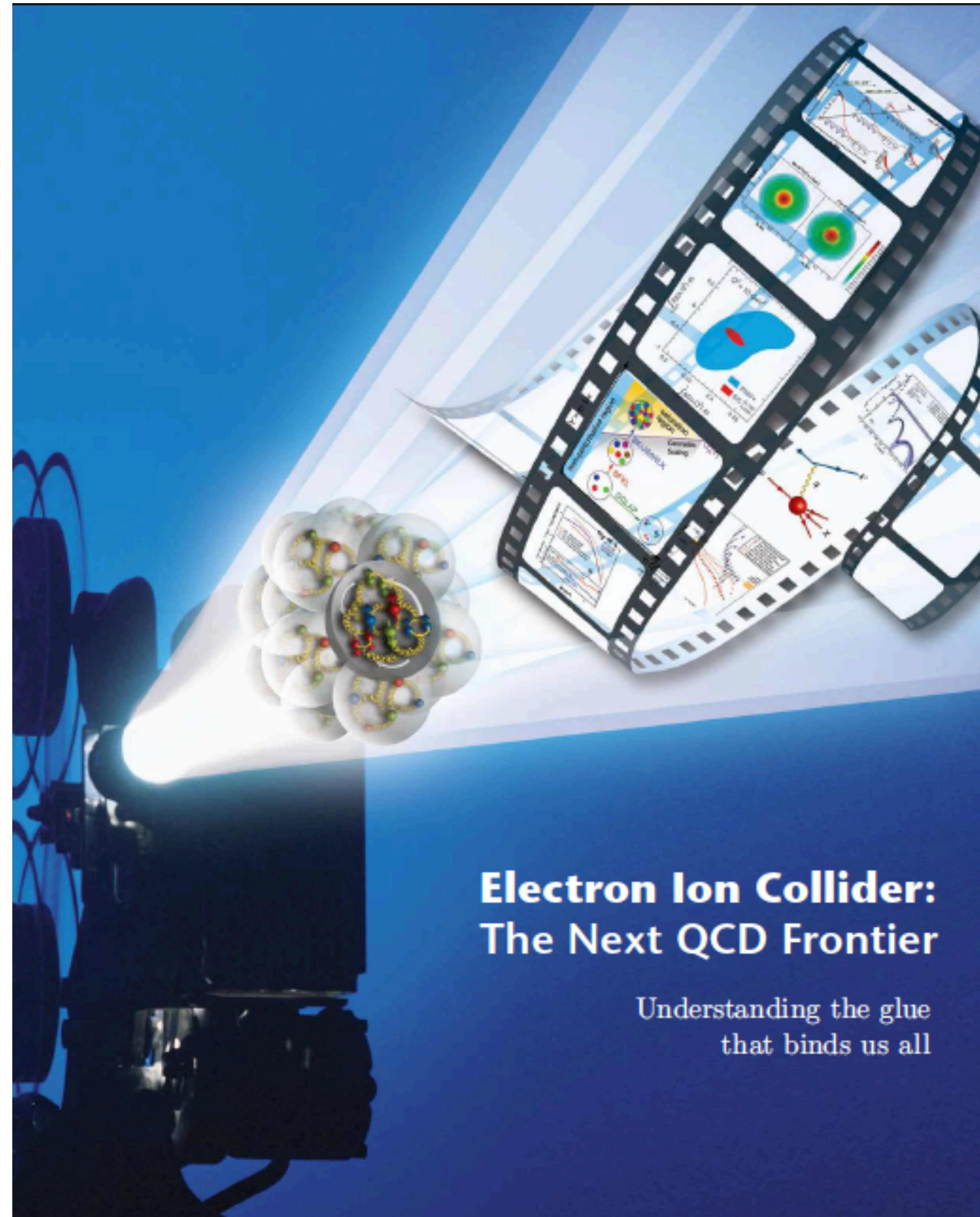

arXiv:1212.1701

Fundamental questions addressed via e+A collisions

- What is the role of strong gluon fields, parton saturation effects, and collective gluon excitations in nuclei?
  - ➡ Can we complete the discovery of the gluon saturation (CGC) regime, tantalising hints of which have been observed at HERA, RHIC and the LHC?
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    - ▸ Accomplishing the discovery of a new regime of QCD would have a profound impact on our understanding of strong interactions.
- Can we experimentally find evidence of non-linear QCD dynamics in high-energy scattering off nuclei?
  - ➡ One of the main predictions of saturation is the x-dependence of DIS cross-sections and structure functions is described by non-linear evolution equations.
    - ▸ Discovery of the saturation regime would not be complete without unambiguous experimental evidence in favour of these non-linear equations

Fundamental questions addressed via e+A collisions

- What is the momentum distribution of gluons and sea quarks in nuclei? What is the spatial distribution of gluons and sea quarks in nuclei?
  - ➡ The physics of multiple re-scatterings at larger-x, along with parton saturation (if found) would allow us to reconstruct the momentum and impact parameter distributions of gluons and sea quarks in nuclei.
    - ‣ At small-x, the transverse momentum distribution may allow us to identify the saturation scale, Q_s.

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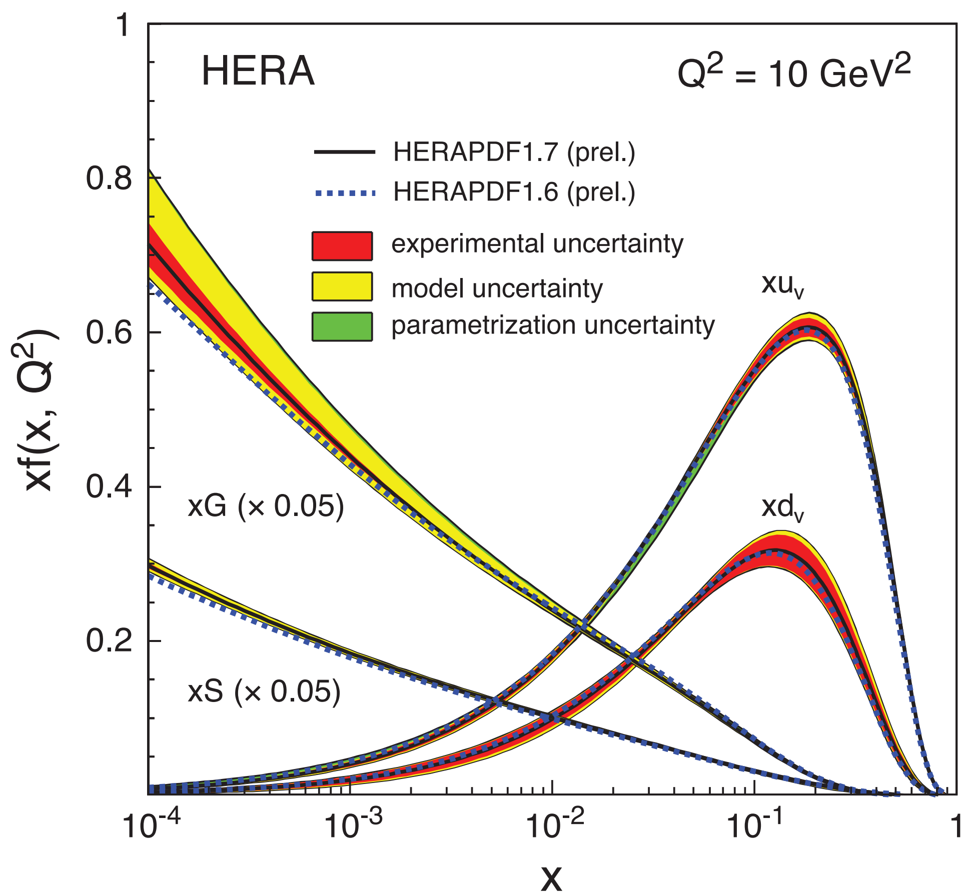
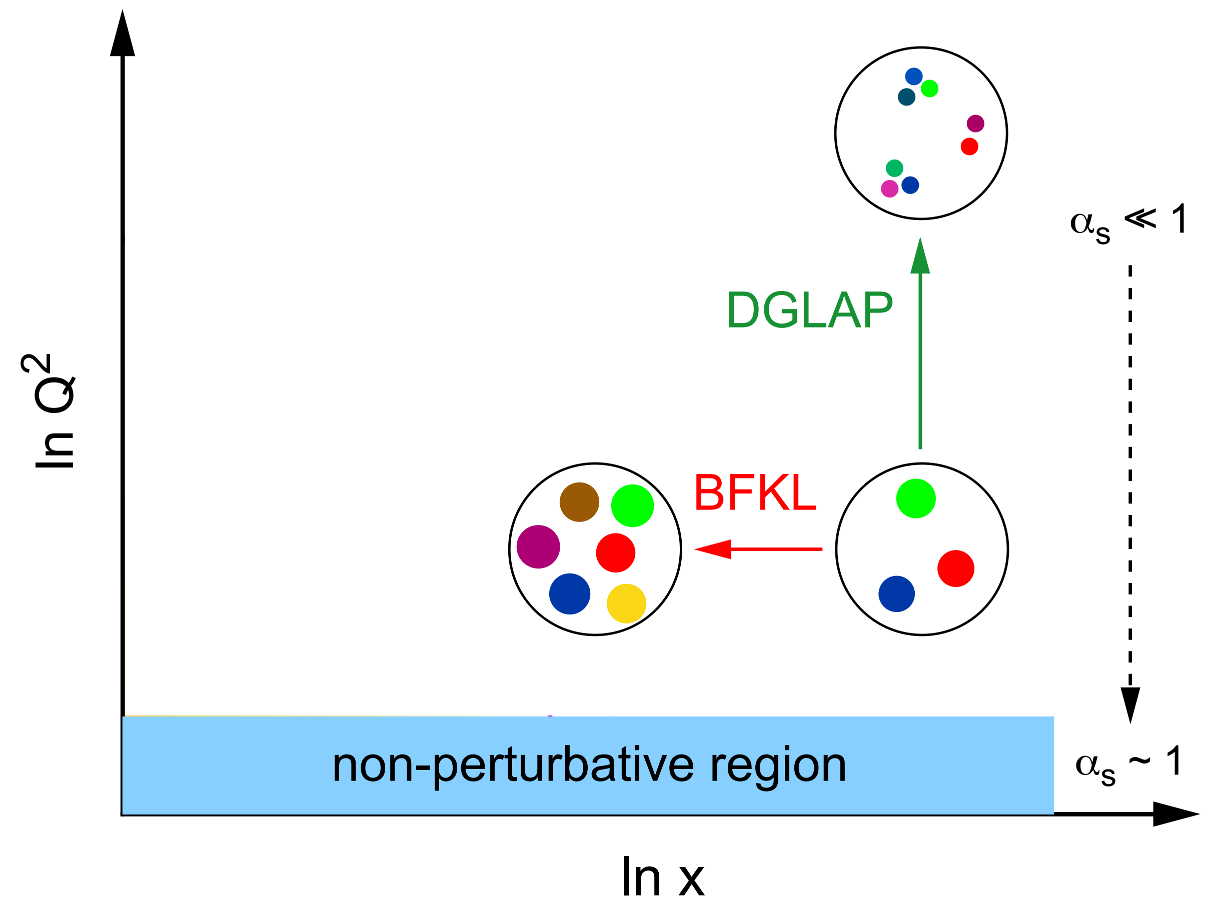
        - ‣ At small-x, the transverse momentum distribution may allow us to identify the saturation scale, Q_s.
- Are there strong colour (quark and gluon density) fluctuations inside a large nucleus? How does the nucleus respond to the propagation of a colour charge through it?
    - ➡ Our understanding of the spatial and momentum-space distributions of quarks and gluons would not be complete without understanding their fluctuations.
        - ‣ The typical size of colour fluctuations can be measured by sending a quark probe through the nucleus.
        - ‣ The conversion of the quark probe into a hadron my be affected by the nuclear environment, giving us a better understanding of the process.

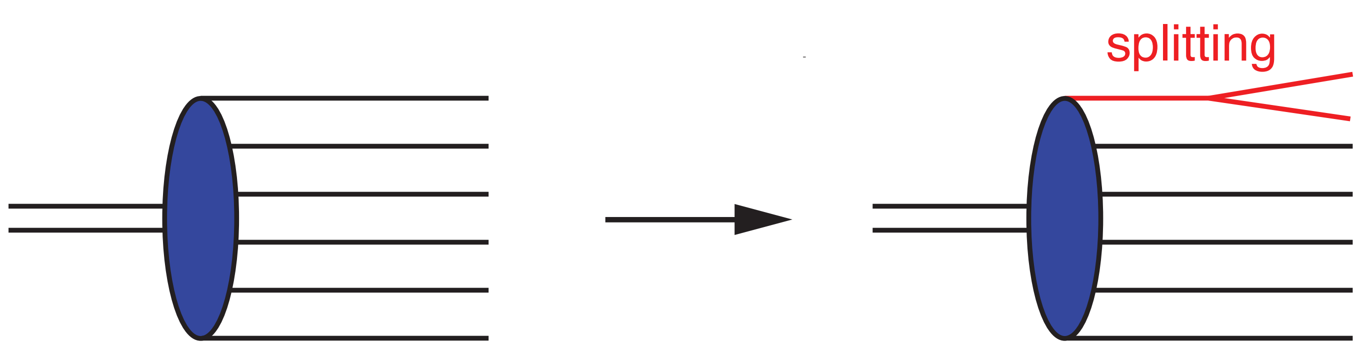
The structure of matter at small-x





- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)

➡ Rapid rise in gluons described naturally by linear pQCD evolution equations



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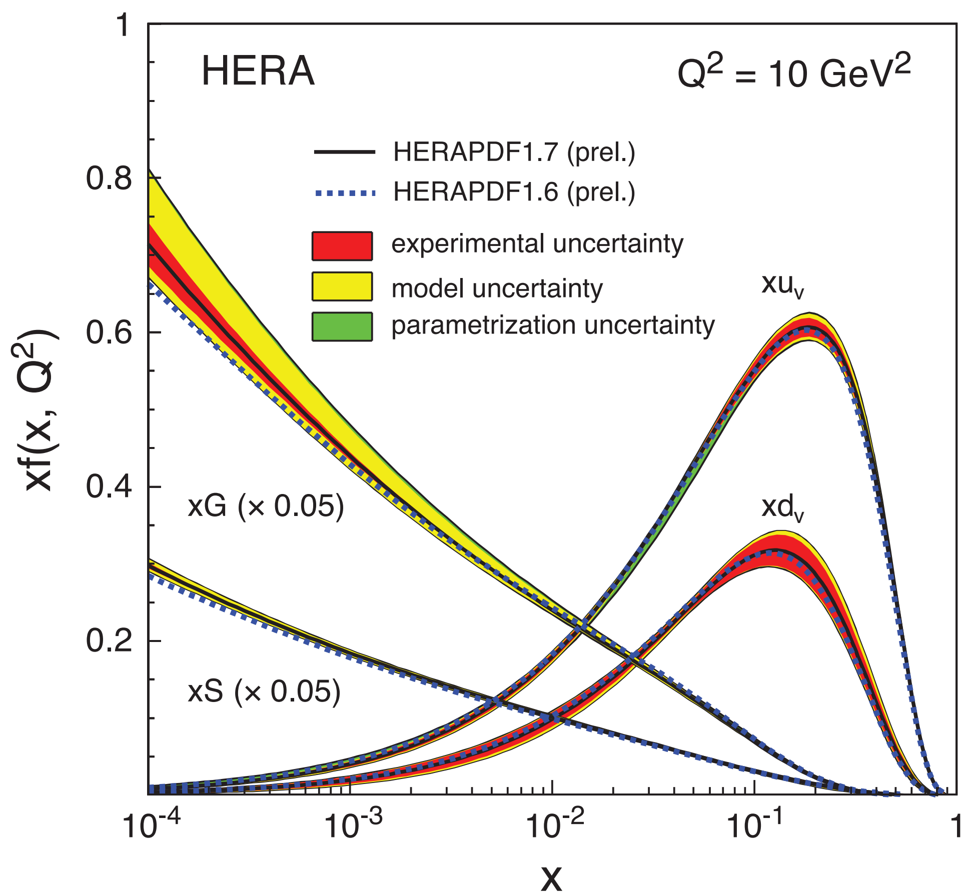
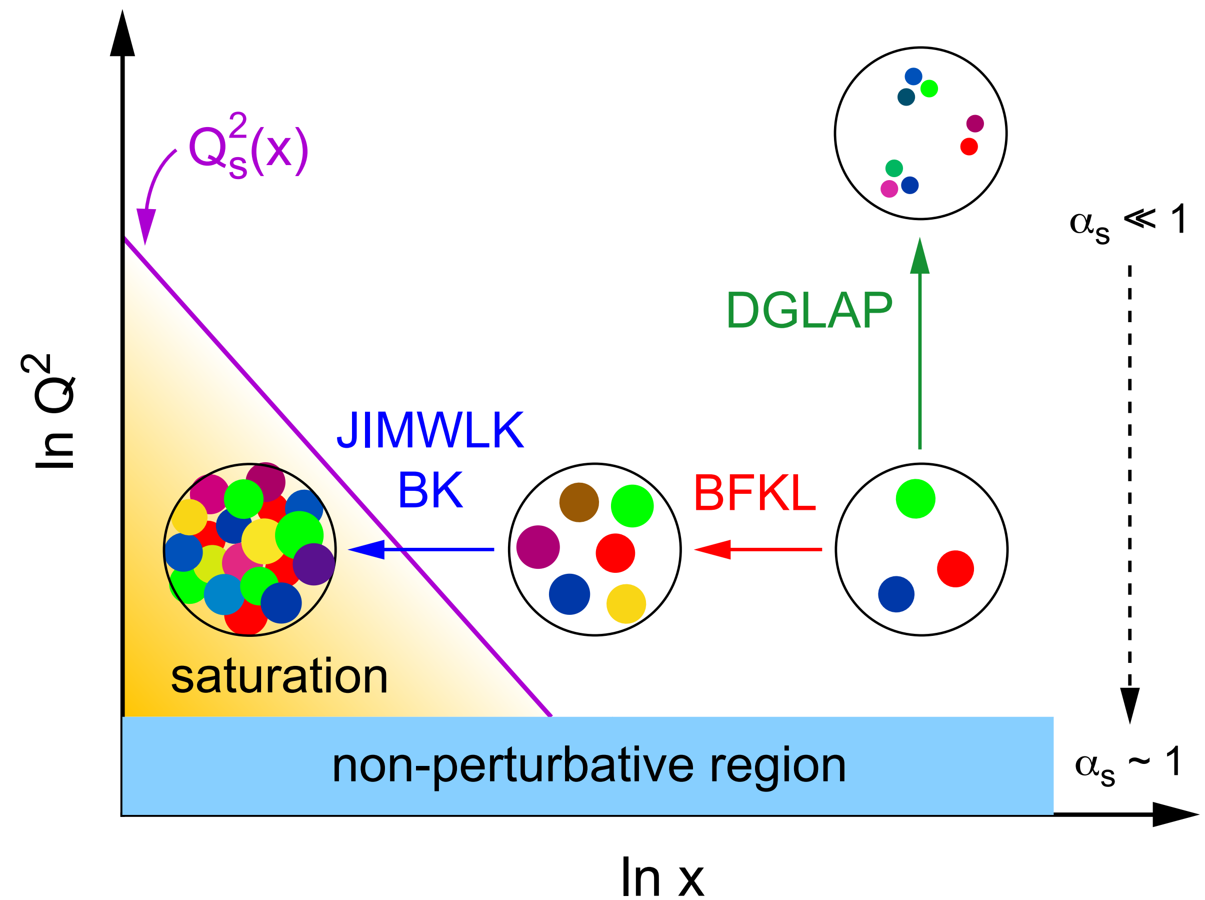
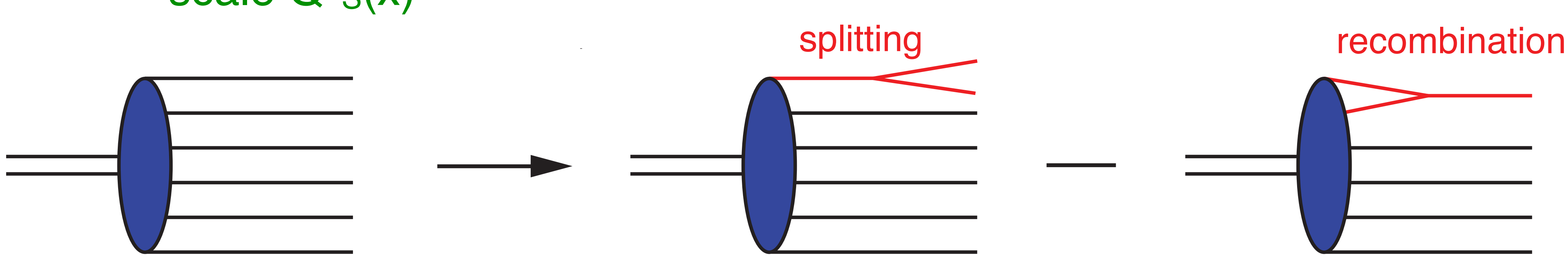


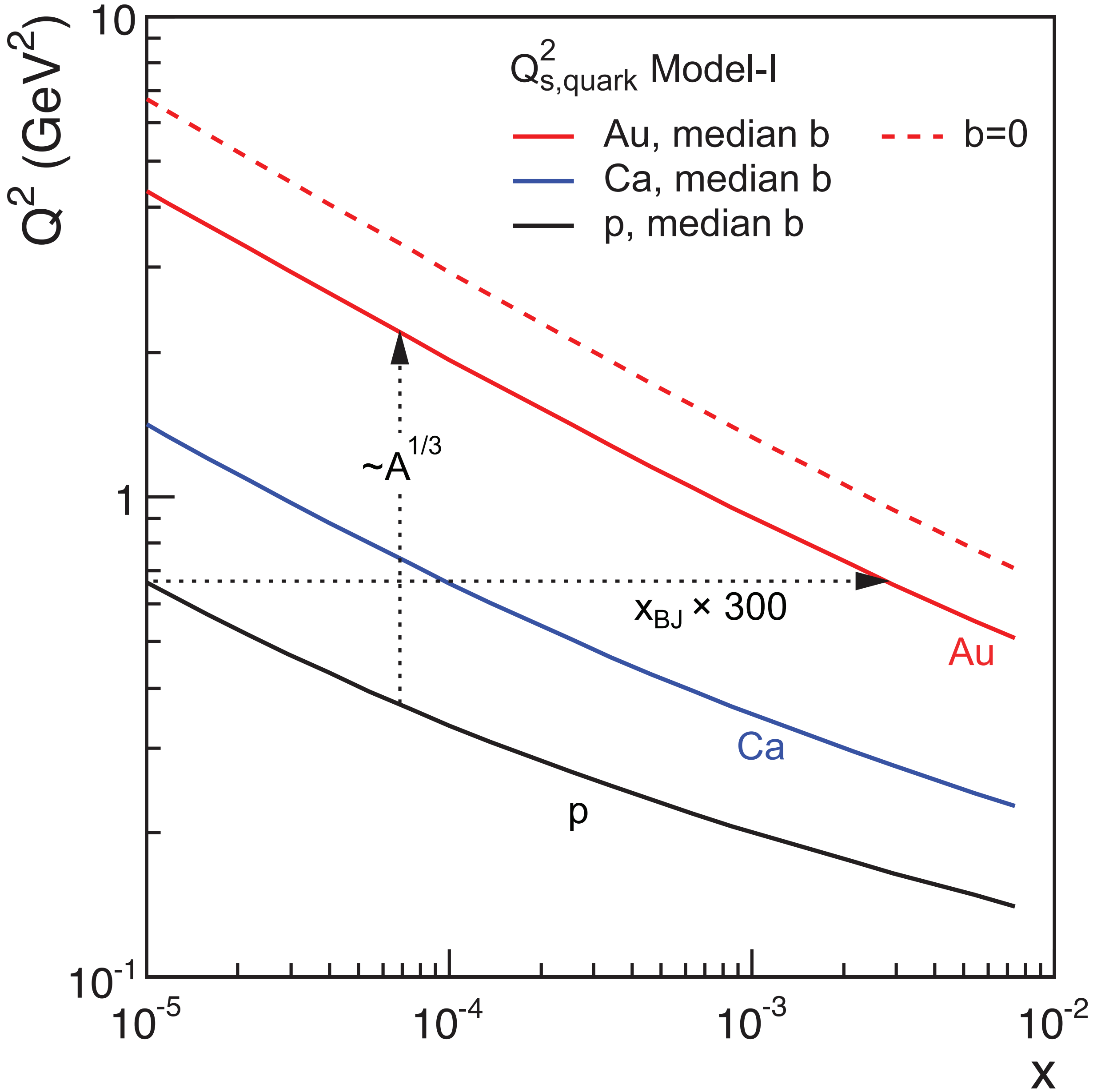


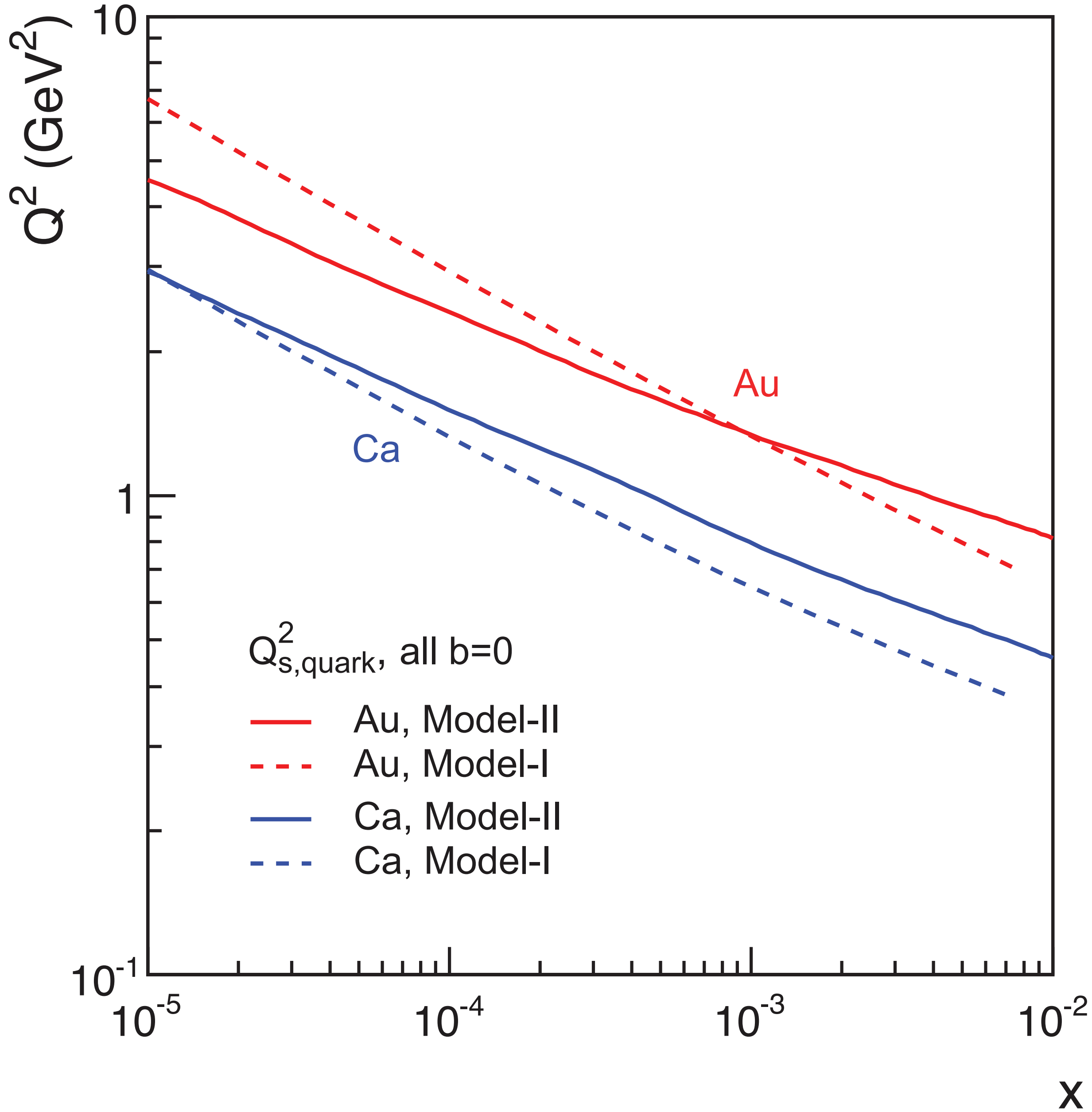
- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2{}_S(x)$



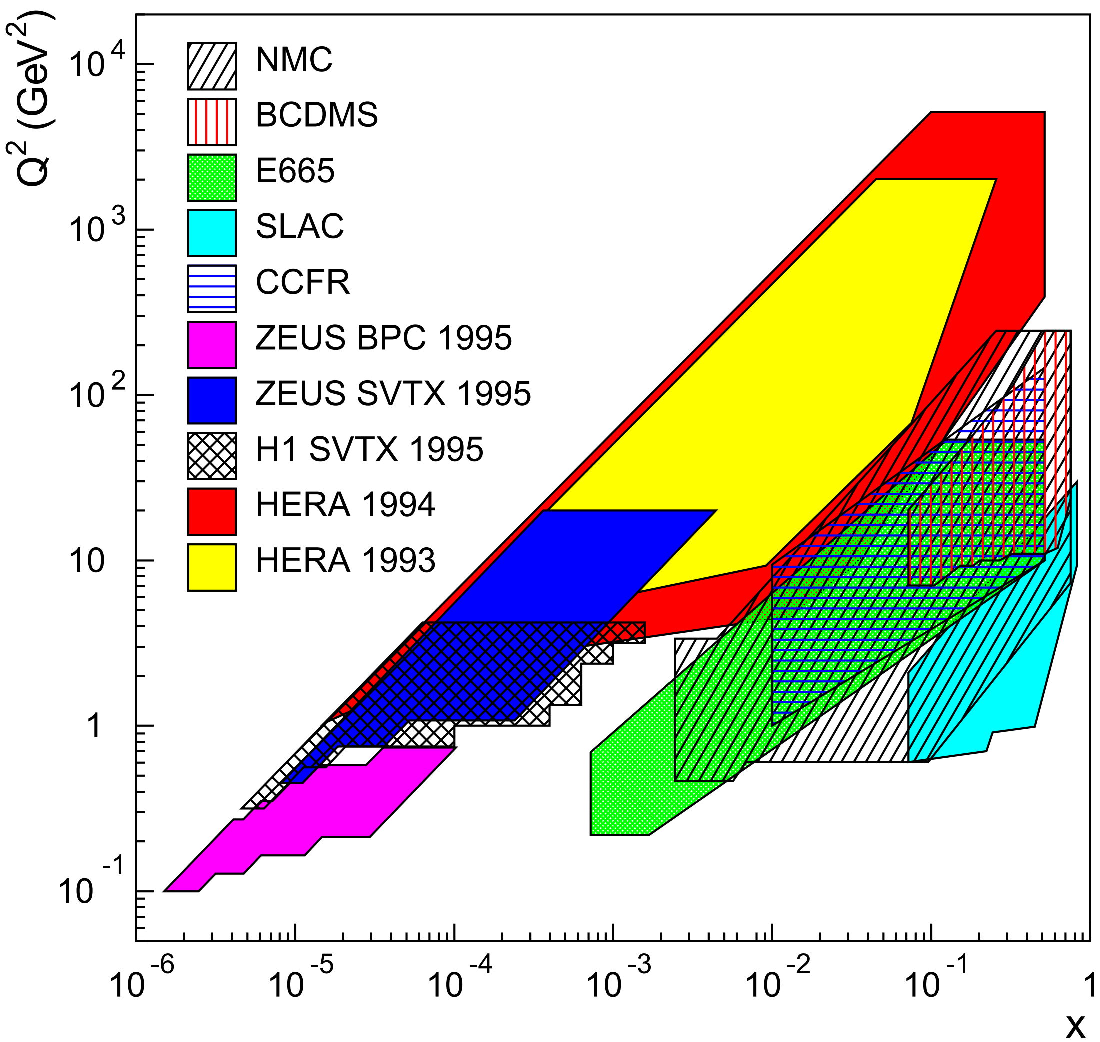
Nuclear "oomph" effect

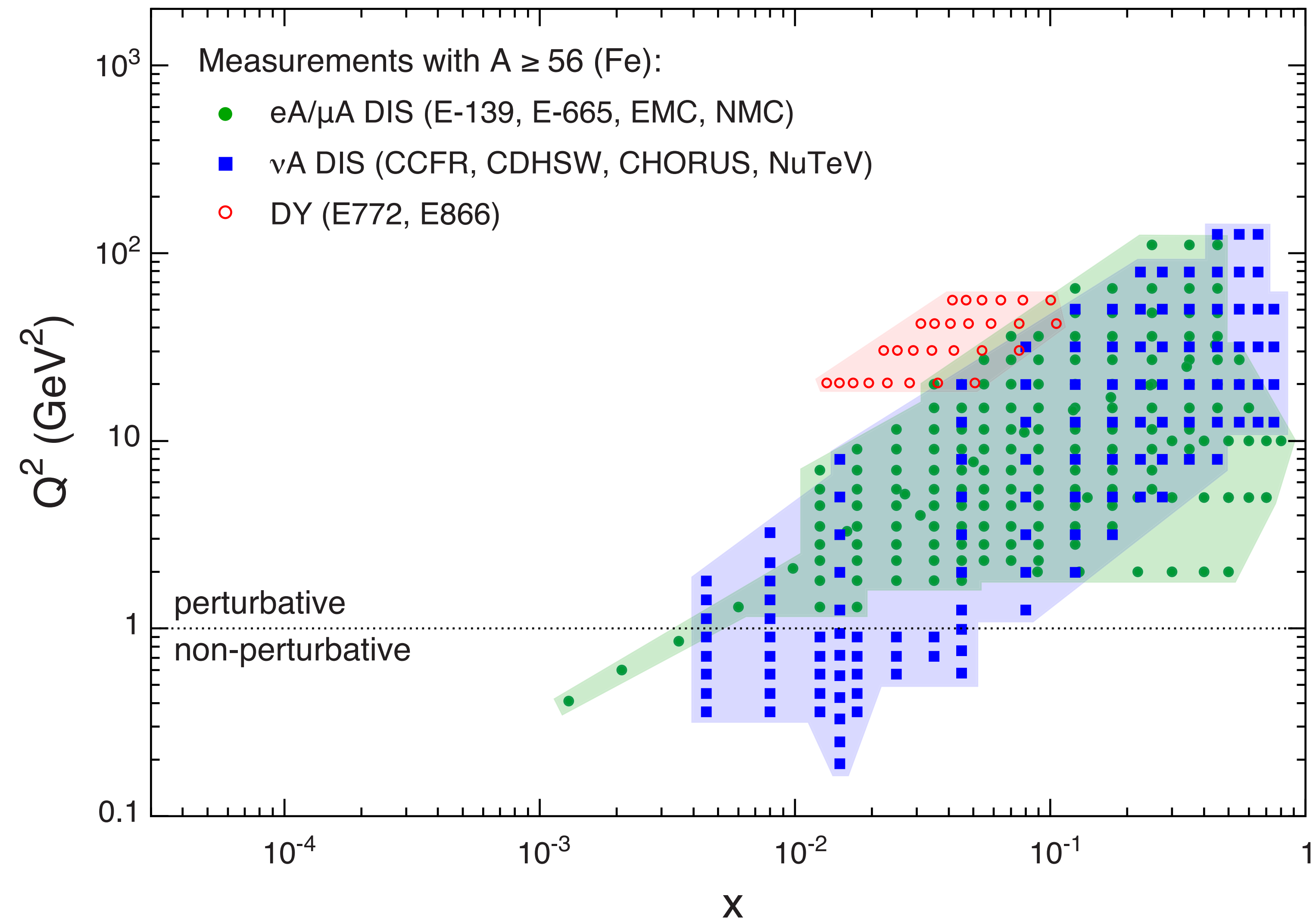
Pocket formula: $Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$





What do we know about the structure of nuclei?





- e+p data covers large part of phase space
  - ➡ low x and large Q^2
- e+A data only a small fraction of this (e+A was a fixed target programme at HERA)
  - ➡ high-medium x and low Q^2

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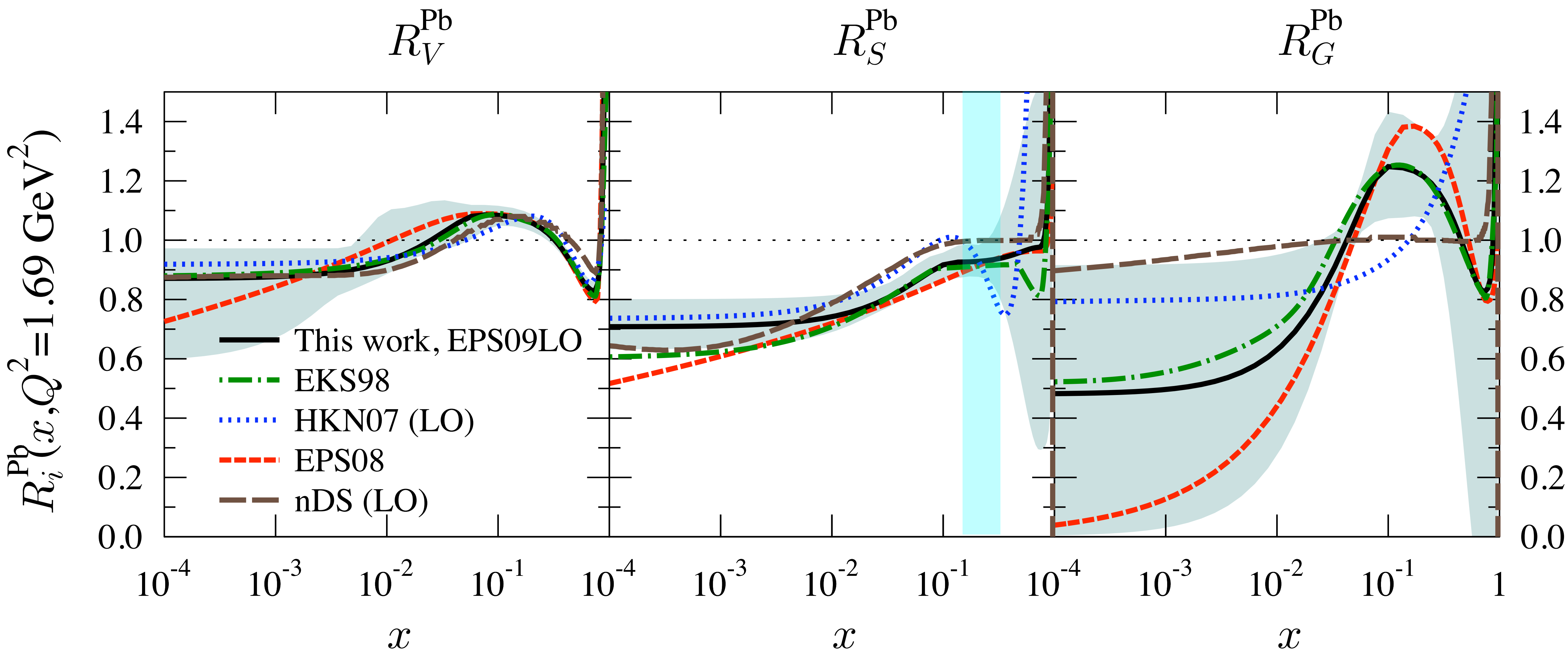

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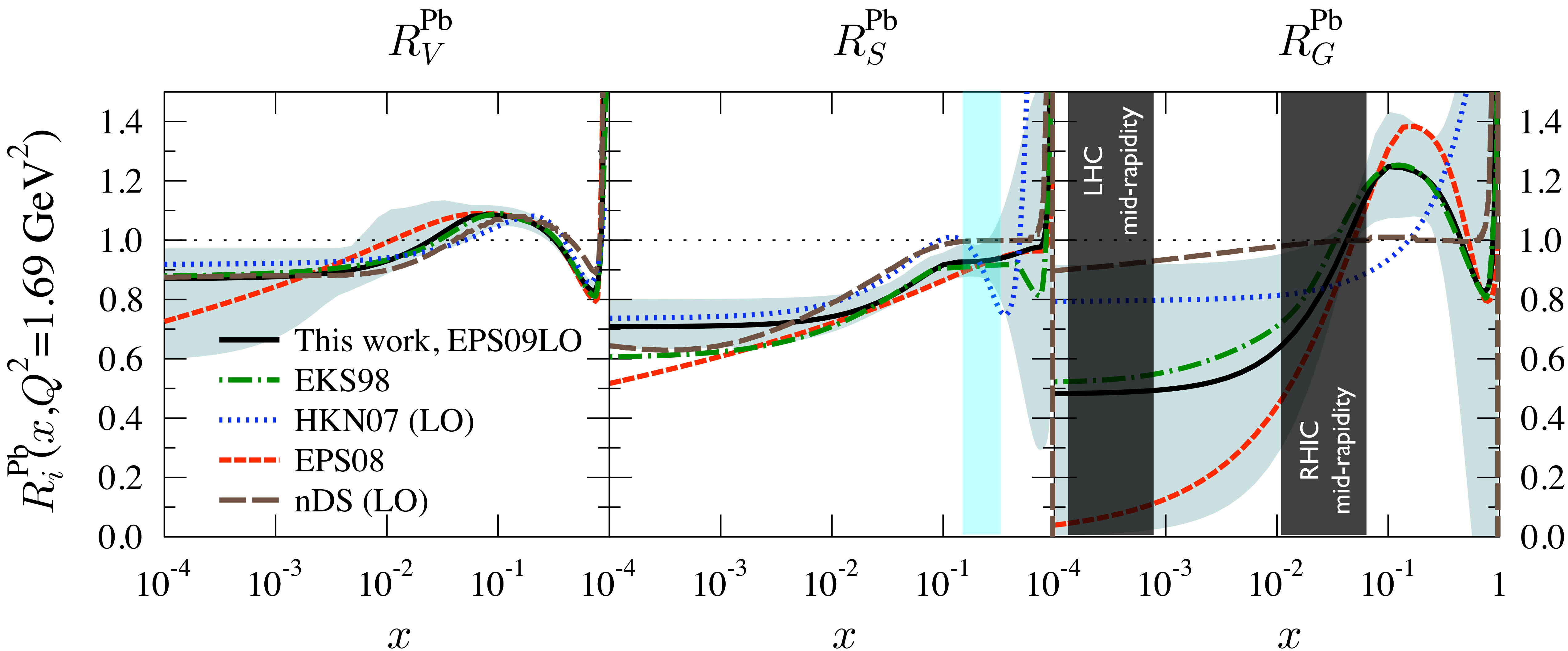

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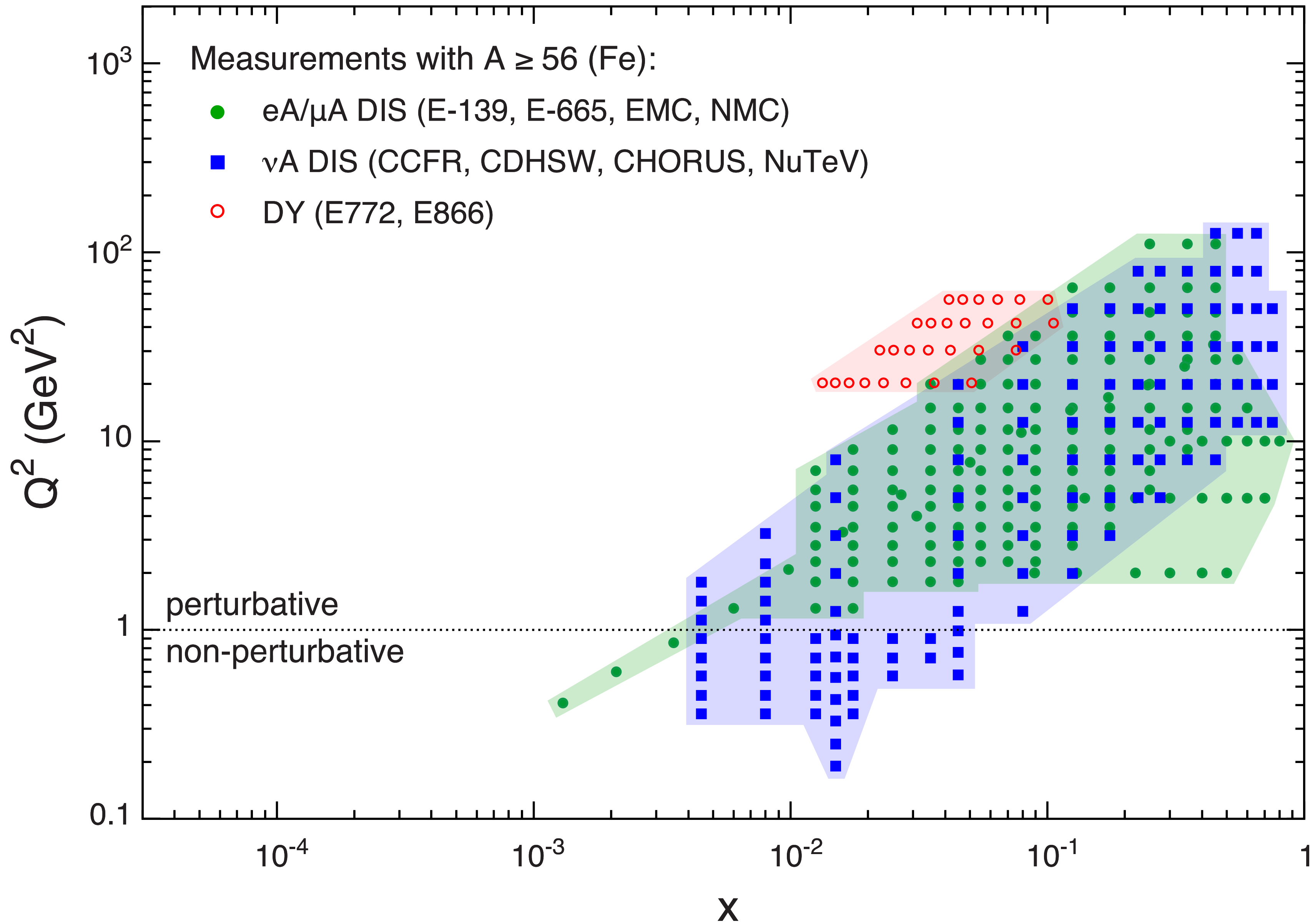
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

Phase-space coverage of e+A collisions for an EIC

- Existing data:
  - ➡ Low energy (fixed target)
  - ➡ Low statistics
  - ➡ Mainly light A
- EIC coverage:
  - ➡ Both “low energy” and “high energy” options extend the reach in x-Q^2 beyond current data
  - ➡ A coverage extended up to U
  - ➡ Saturation scale at moderate Q^2 can be investigated at the lowest x



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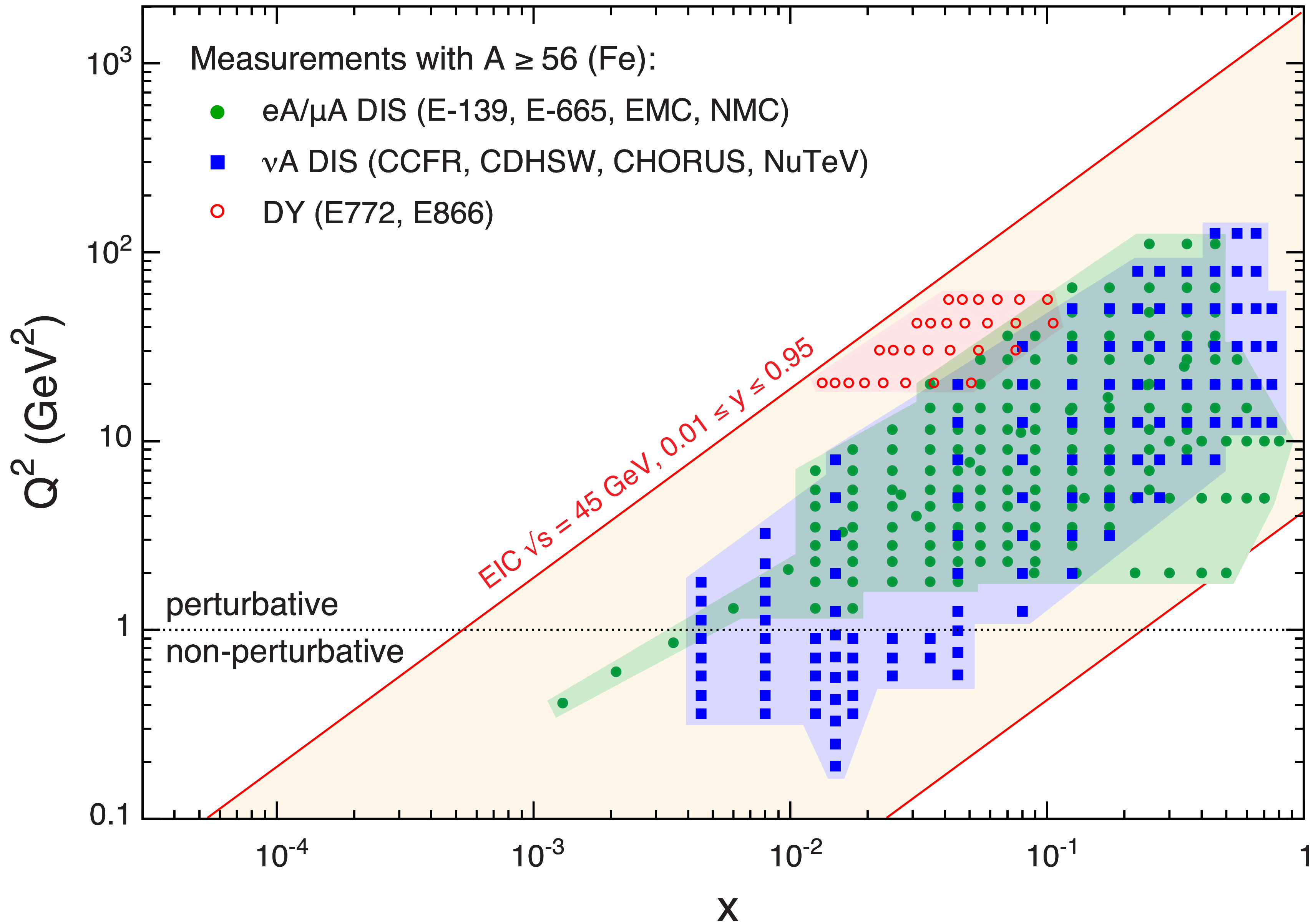

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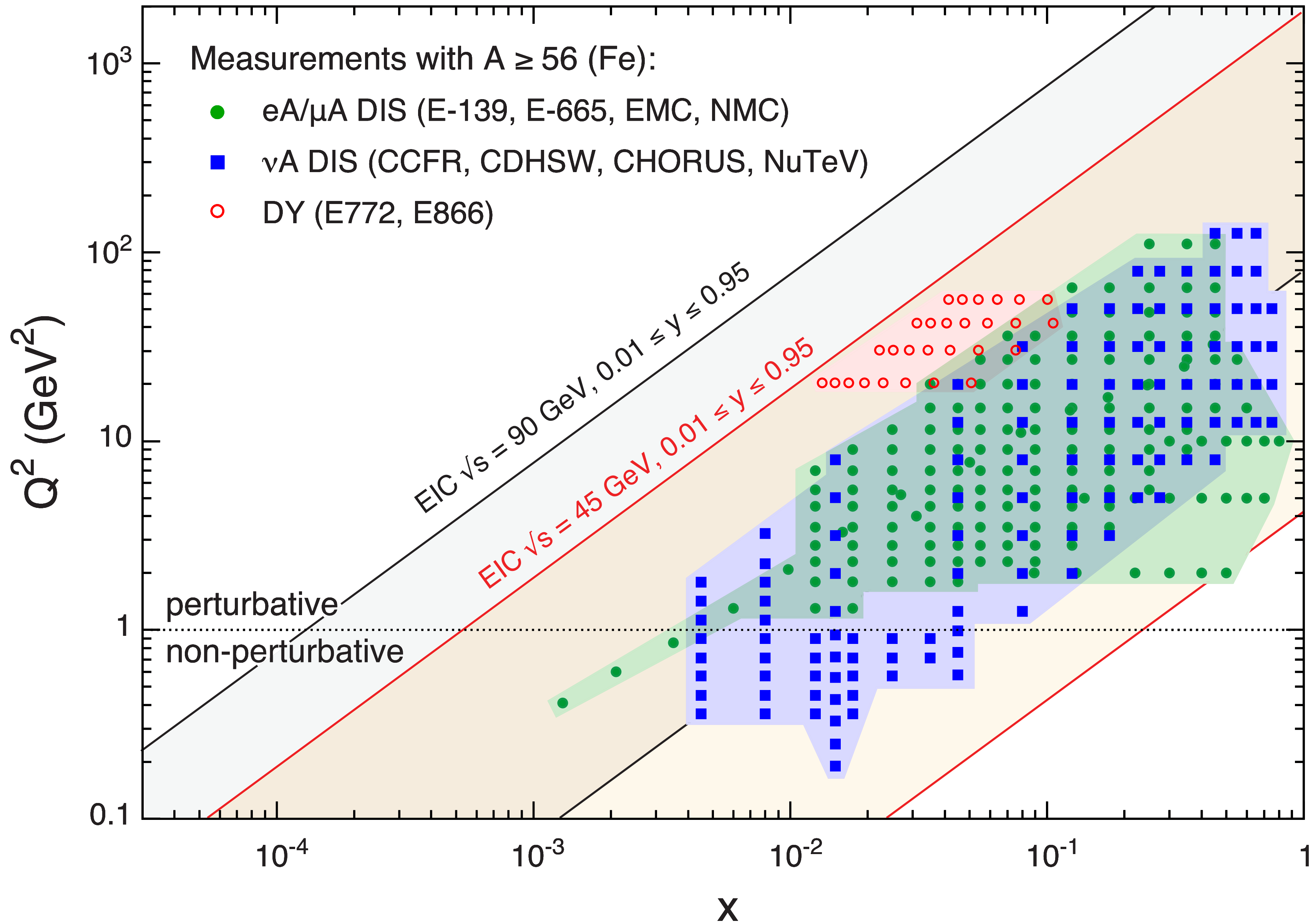

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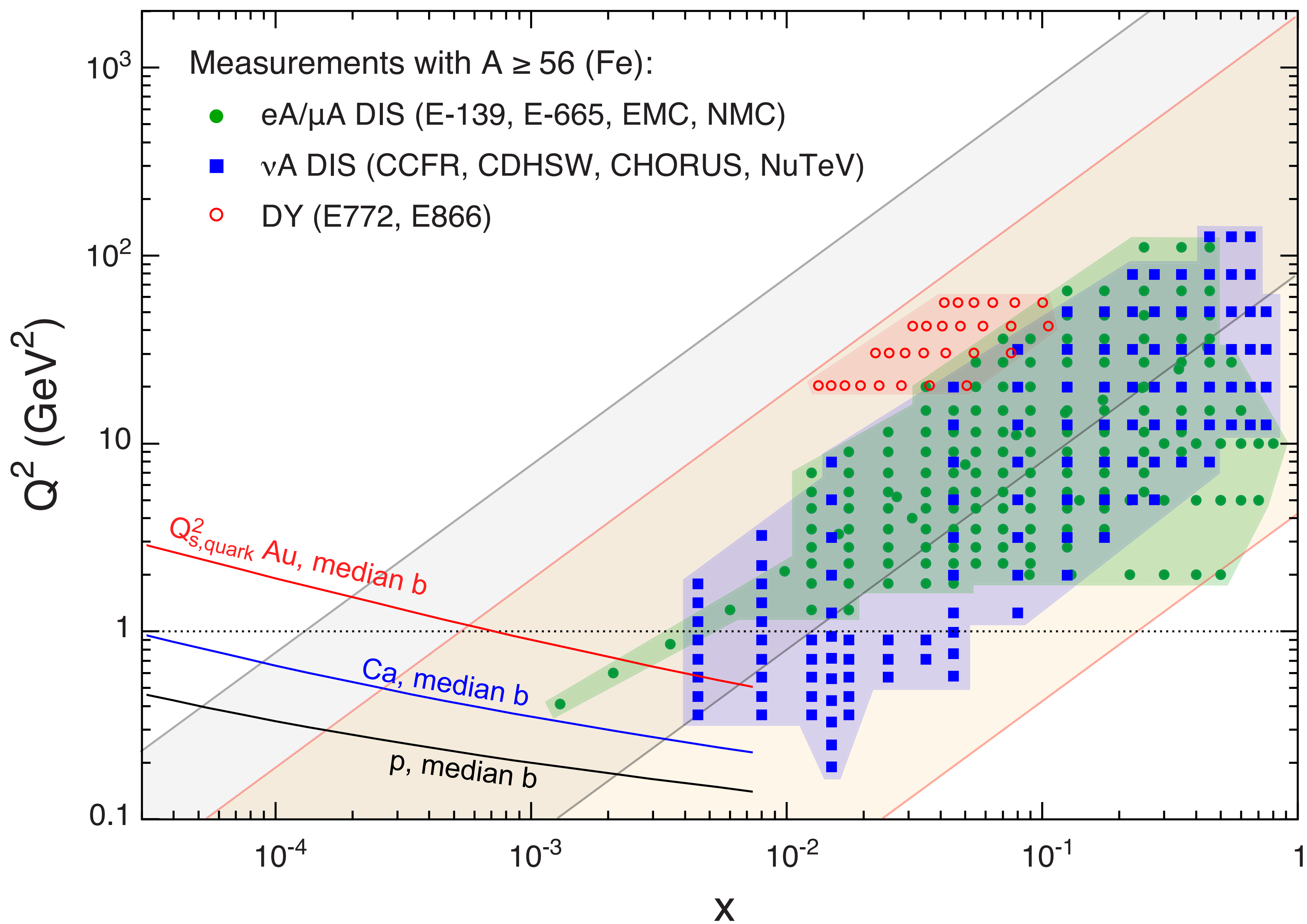


Saturation effects in the proton and nucleus

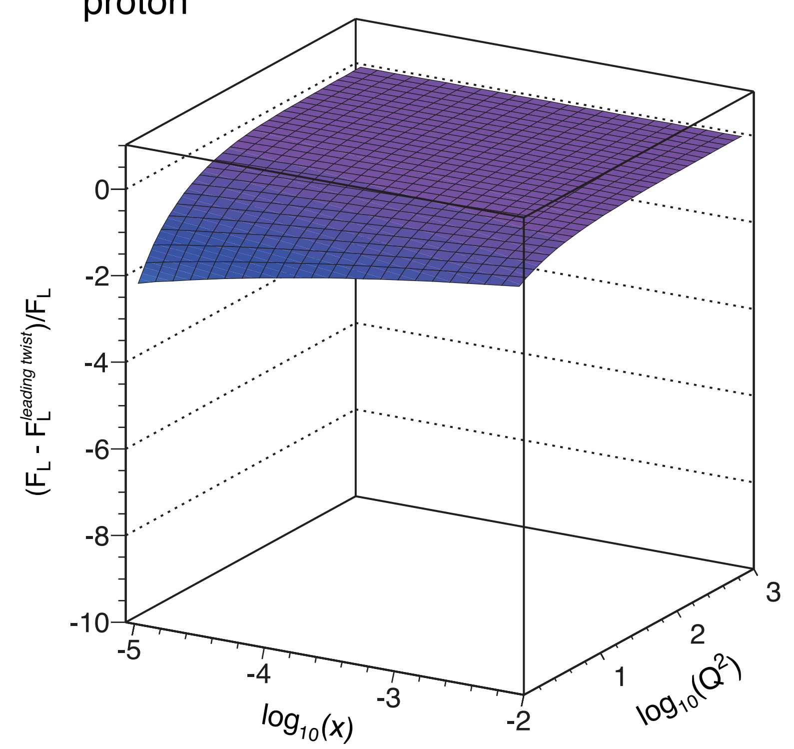
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark (F_2)

gluon (F_L)

Measure of non-linear effects in the F_L structure function

Dipole model (J. Bartels *et al.*)



- Plotting this distribution coming out of saturation inspired GBW model
    - ➡ p: small effect only starting to come in at small-x and small Q^2

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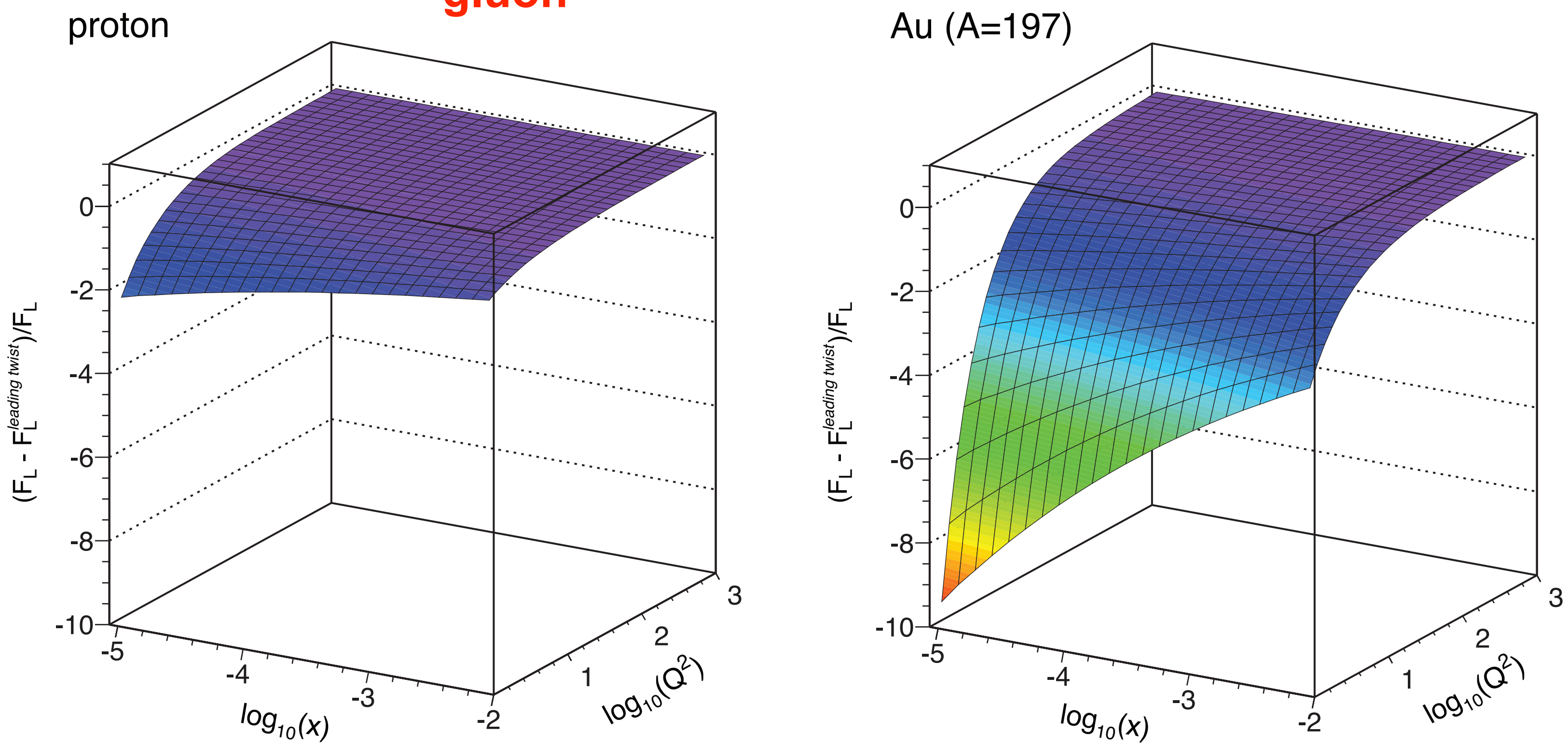

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    - ▸ nuclear "oomph" effects well manifested in the F_L structure function

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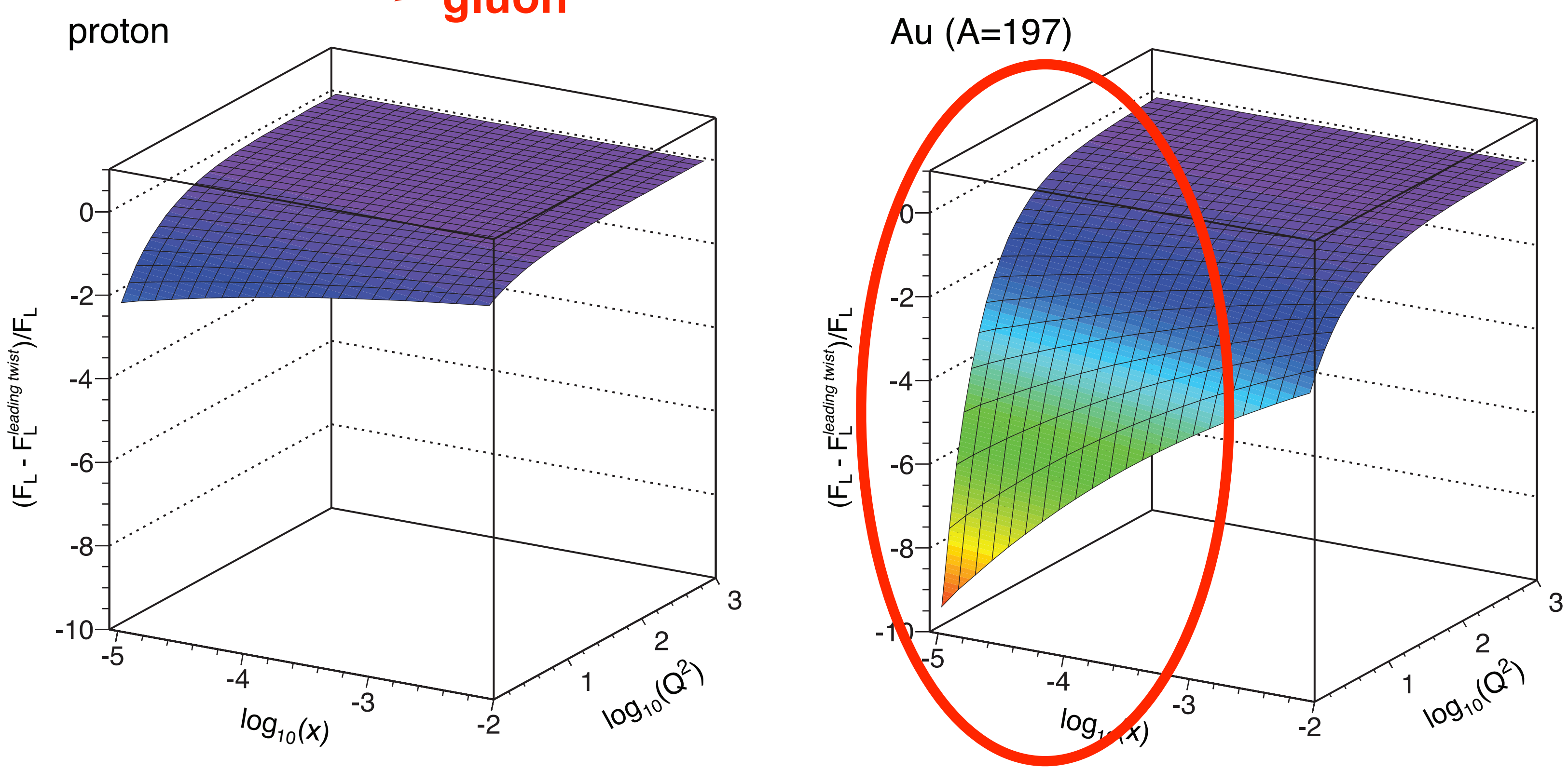

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Feasibility study: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$

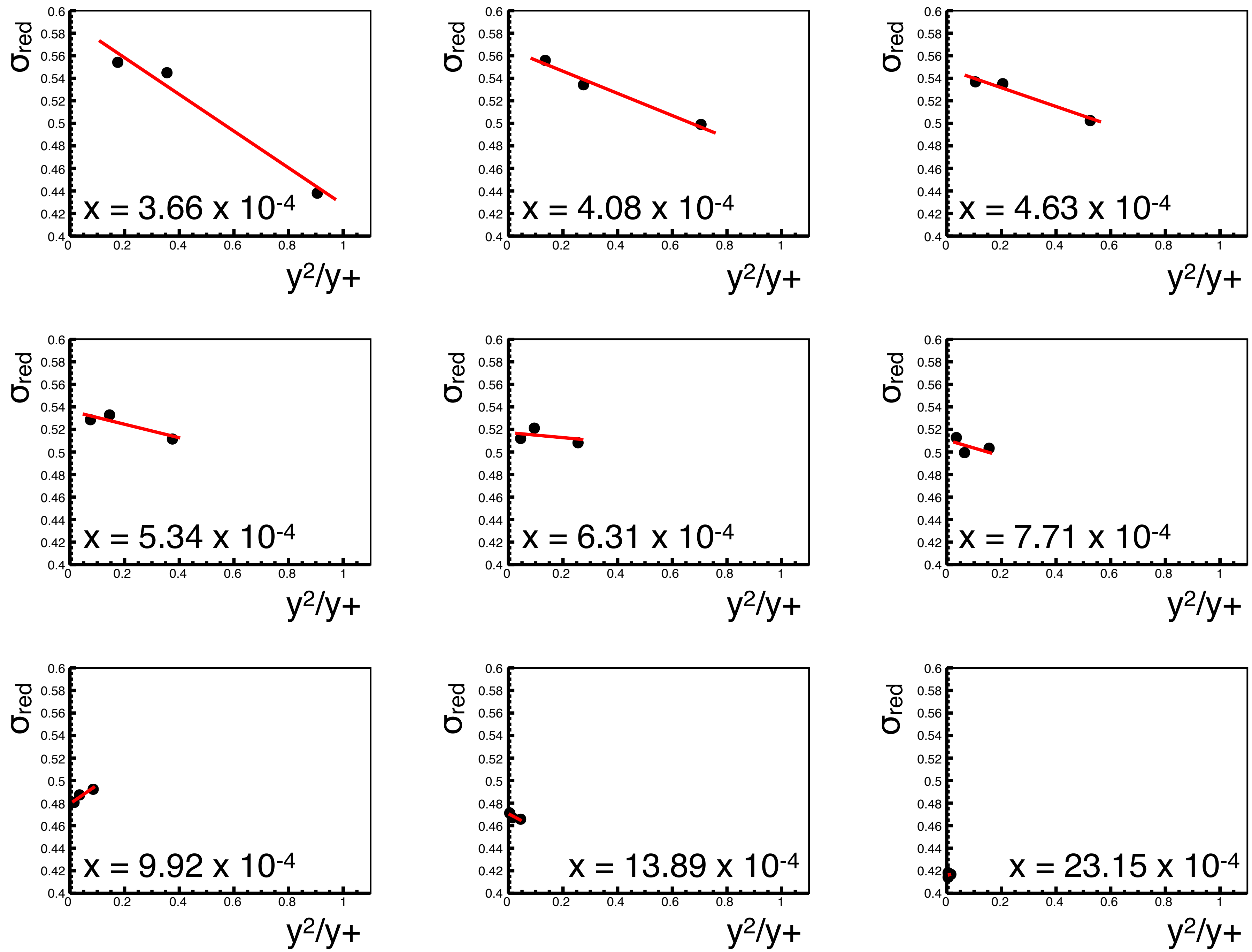
Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+Au:
20x50 - A∫Ldt = 2 fb^{-1}
20x75 - A∫Ldt = 4 fb^{-1}
20x100 - A∫Ldt = 4 fb^{-1}
running combined
~6 months total running (50% eff)

statistical errors are swamped by the 3% systematic errors

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

Q^2 = 1.389 GeV^2



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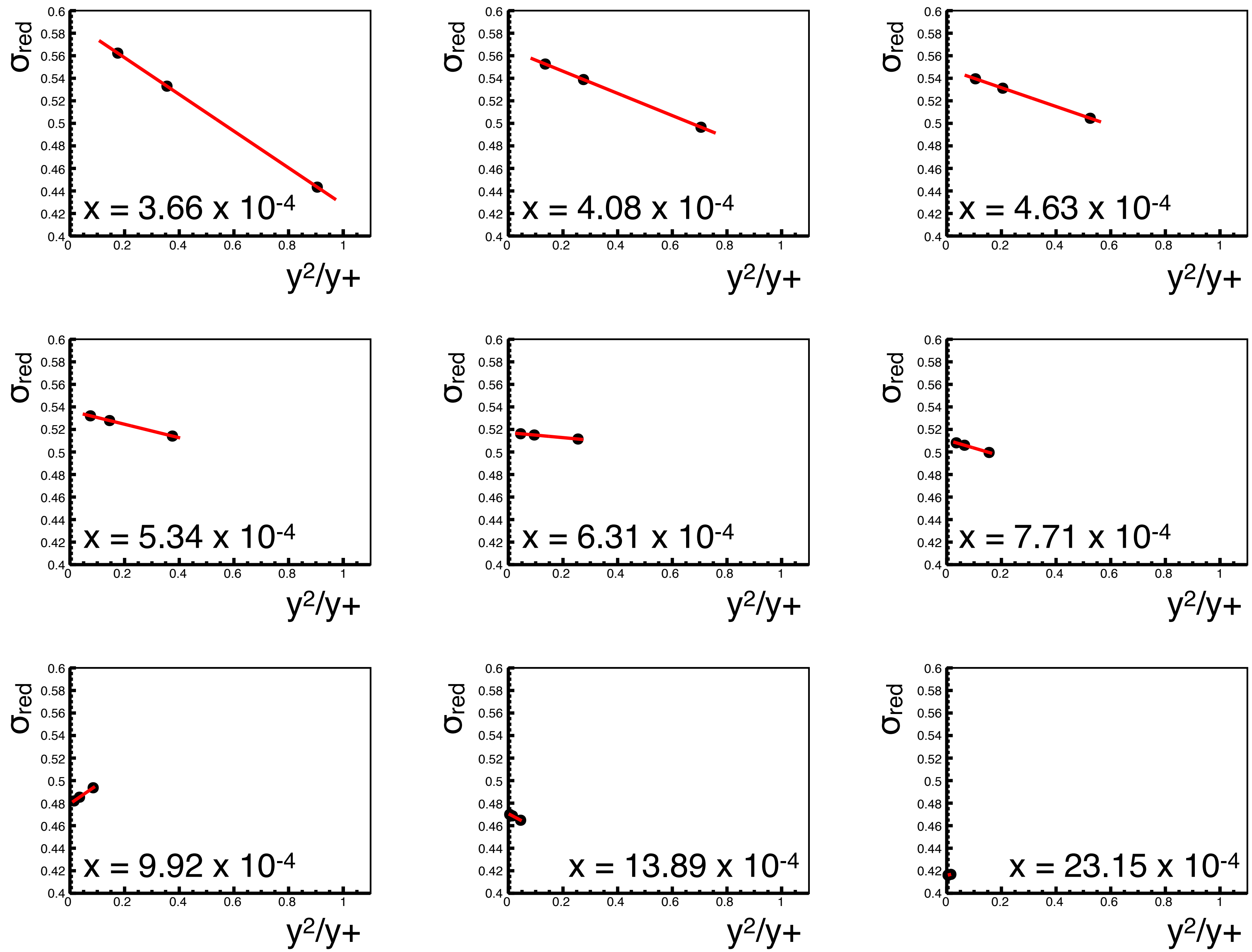

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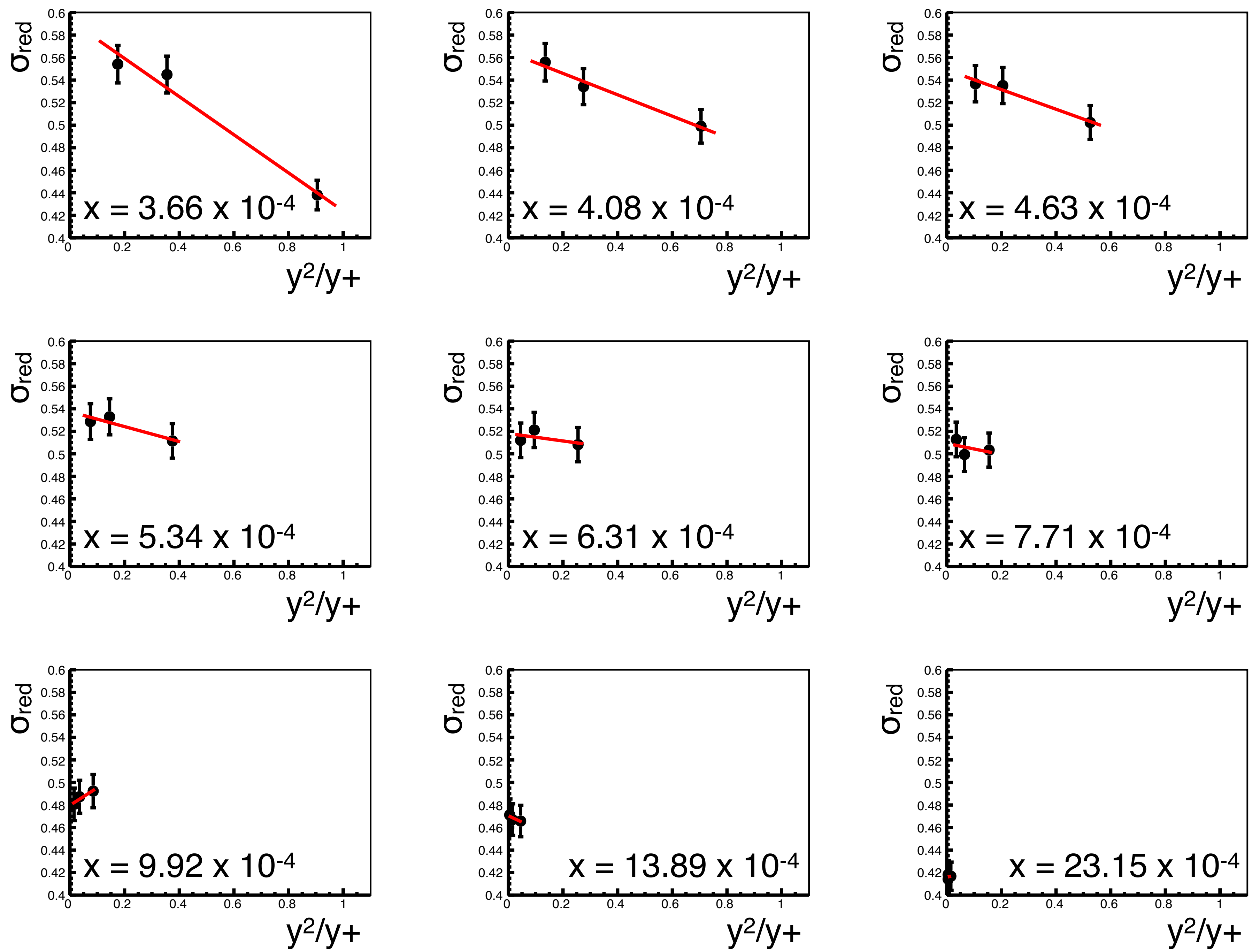

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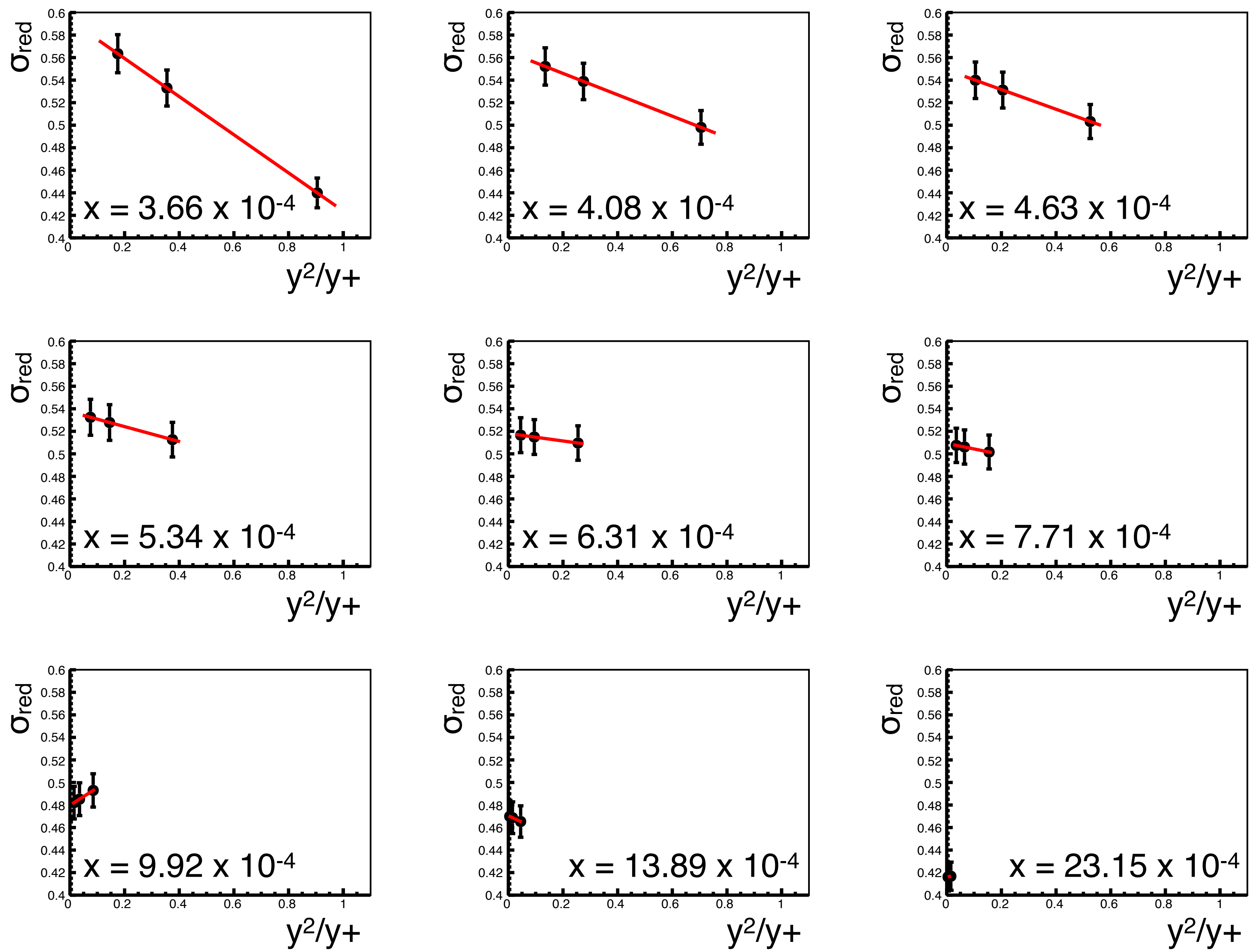

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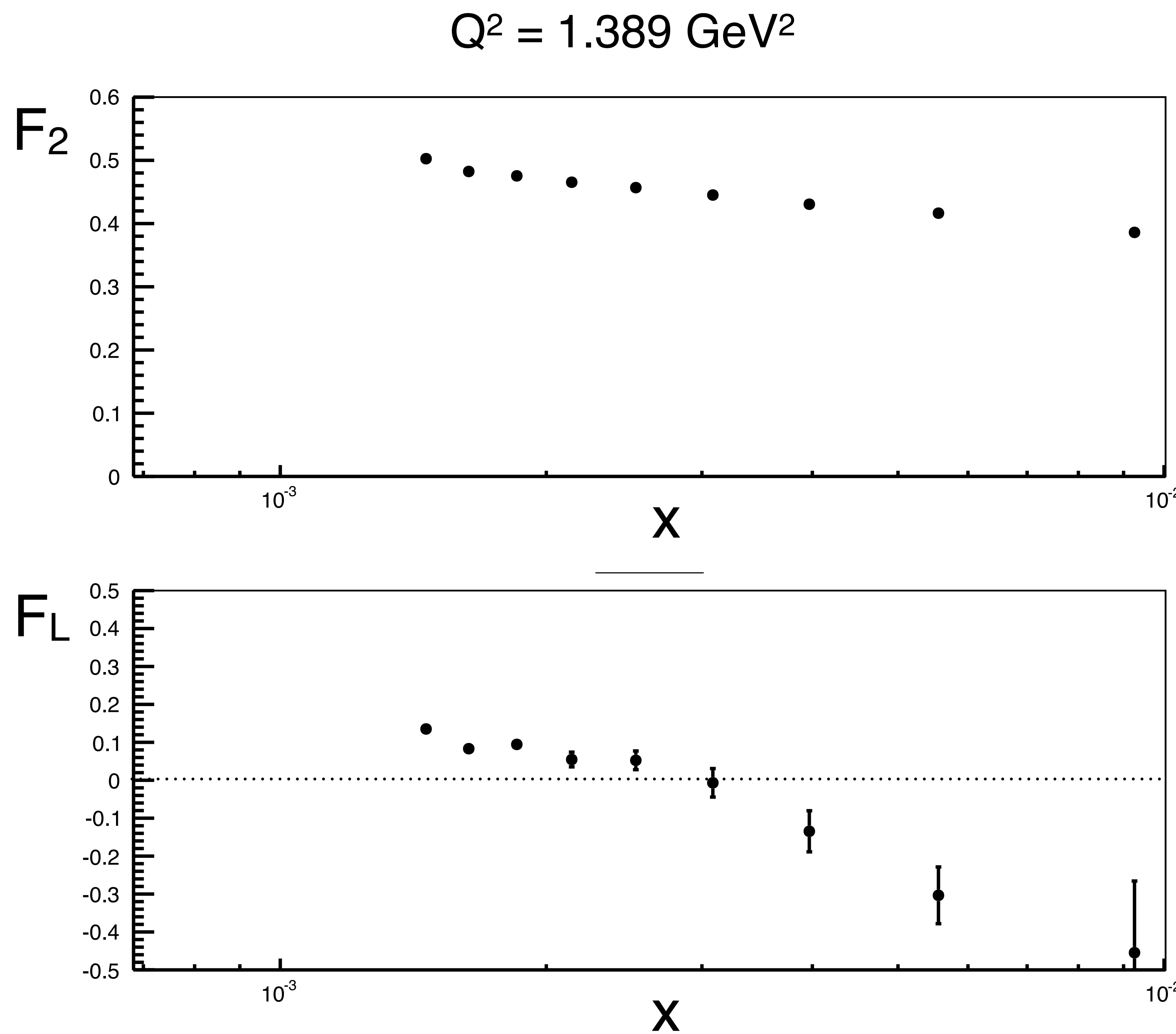

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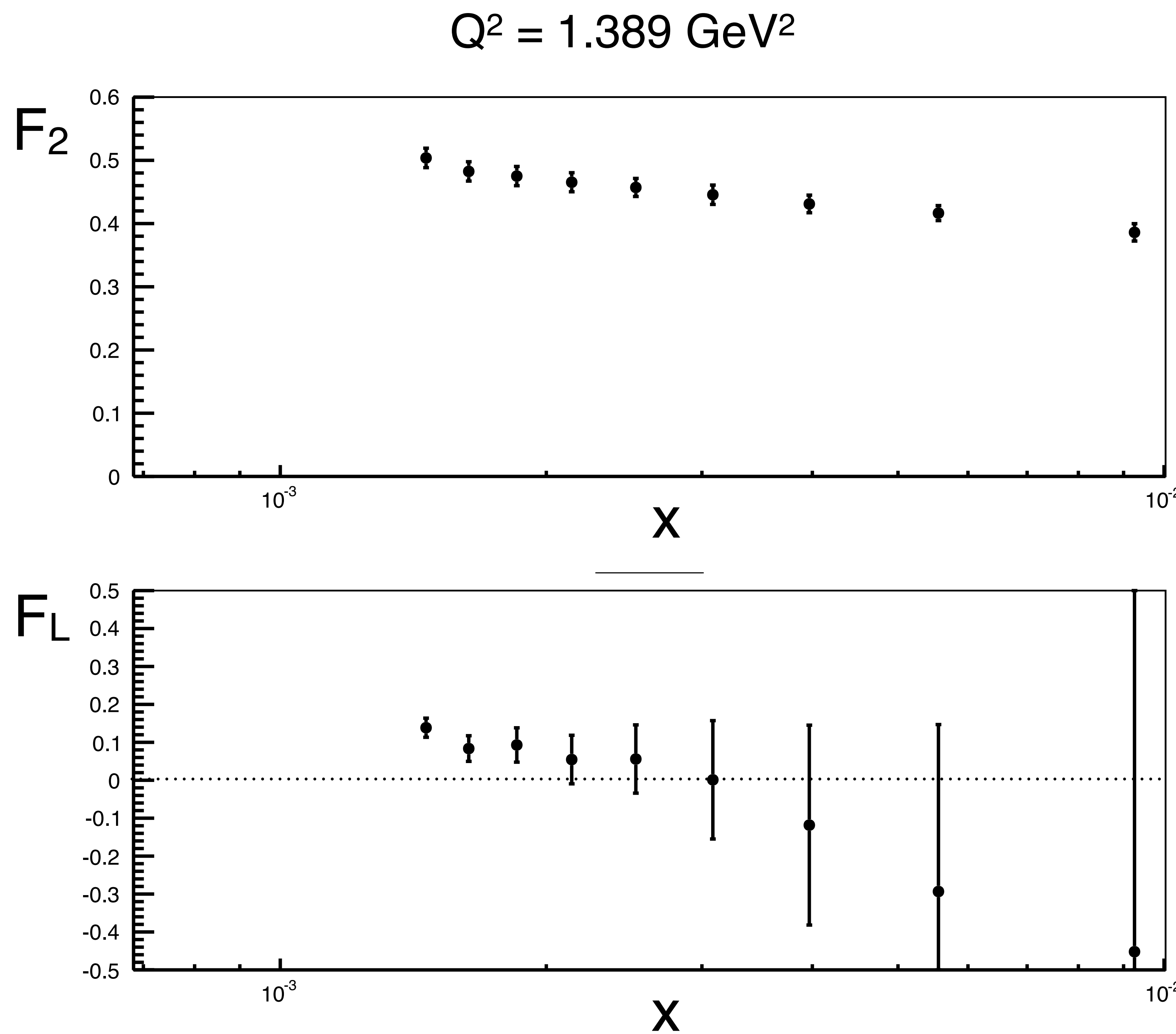

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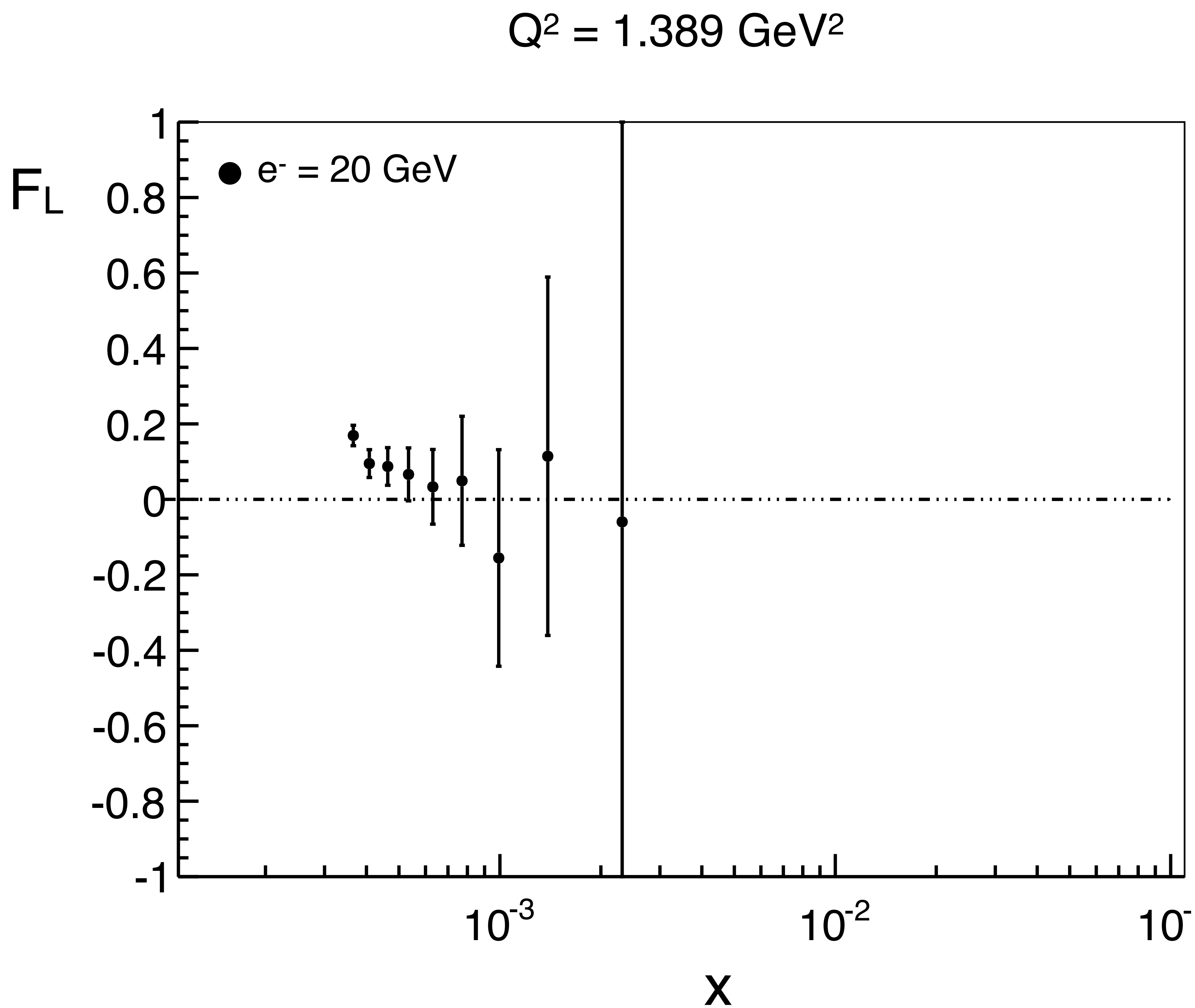

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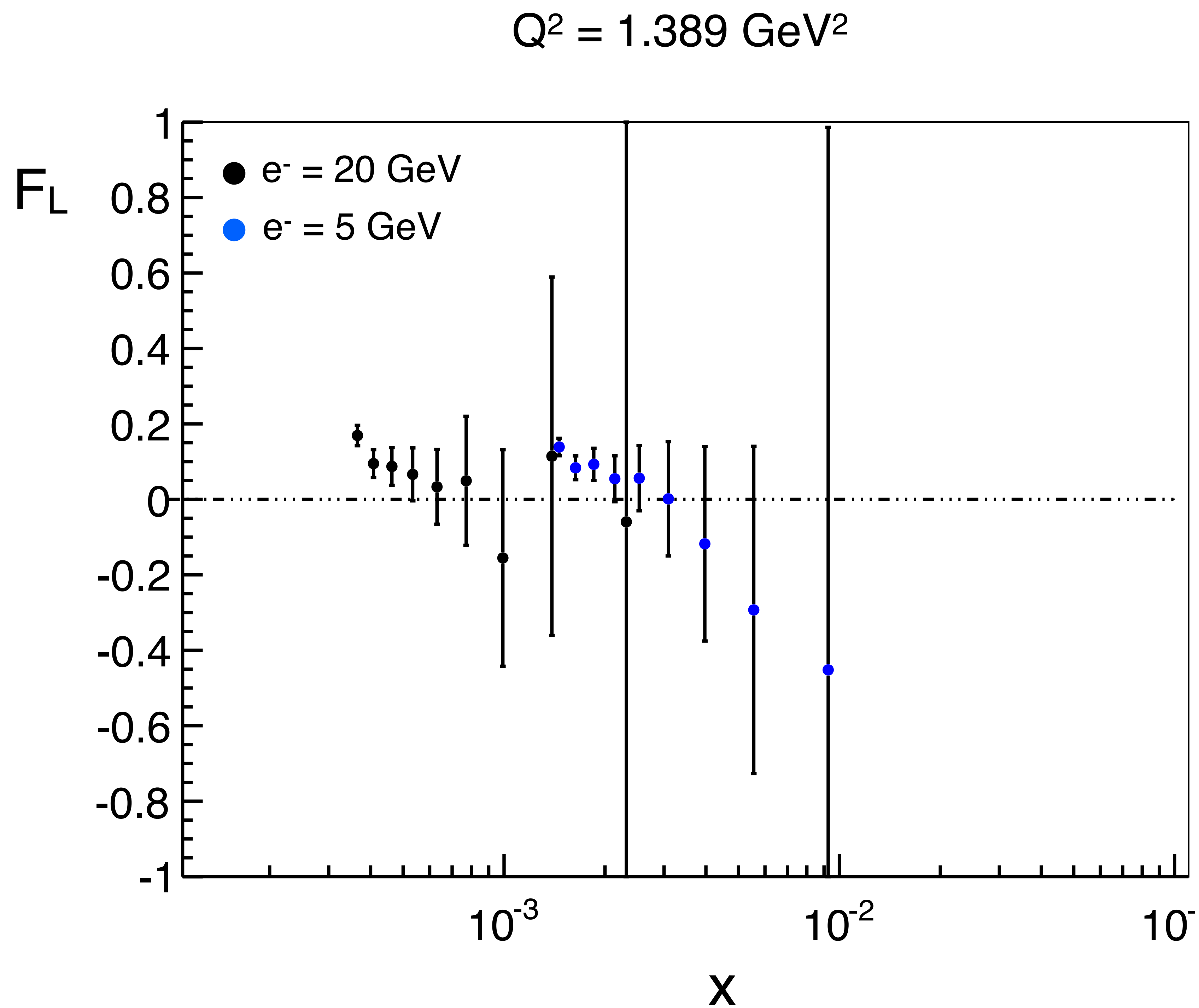

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e+Au: 1st stage
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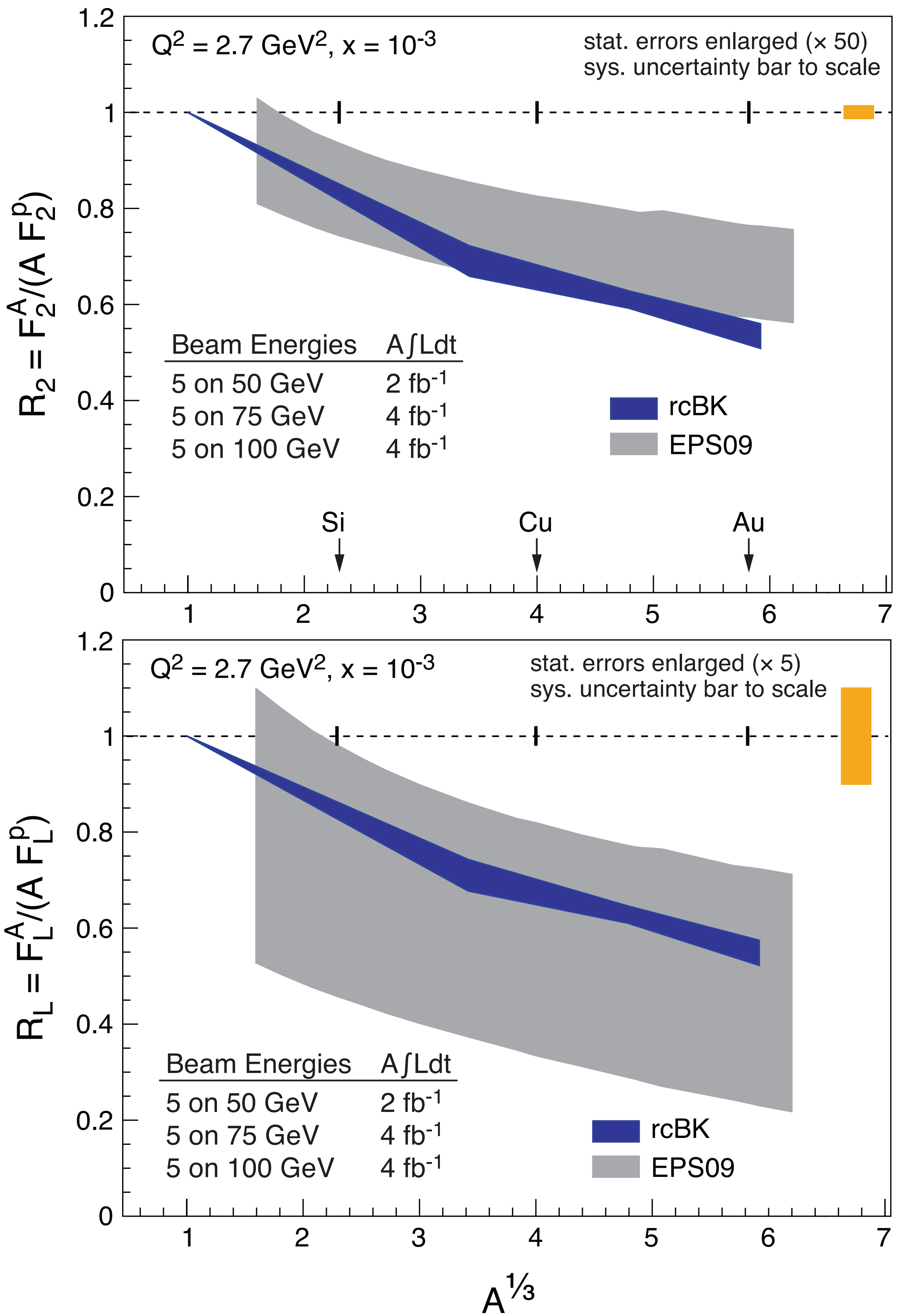
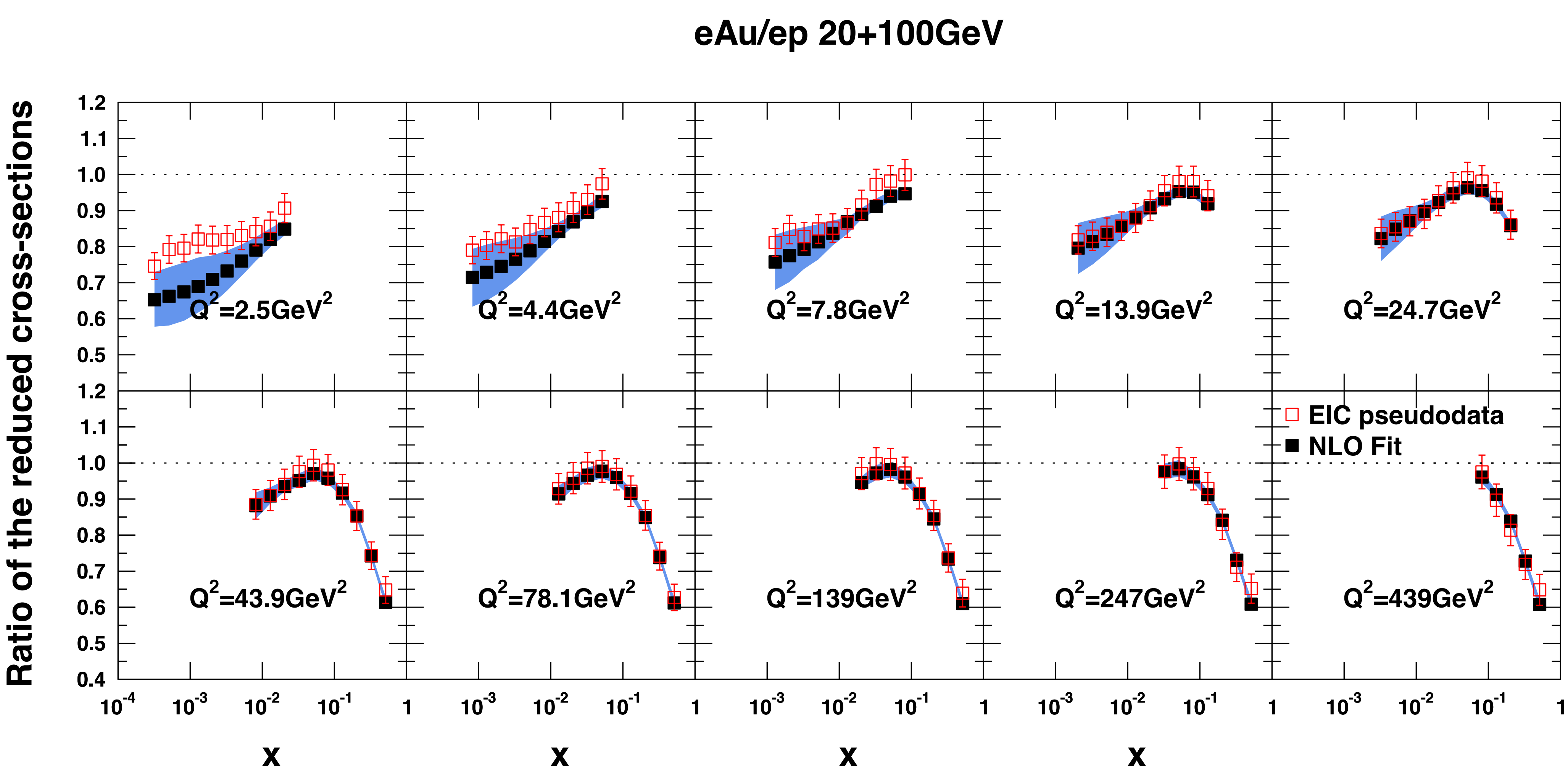


Work in progress… (H. Paukkunen)

- Take the generated Pseudo-data and include it in a global fit
  - ➡ Only 20x100 and 5x100 included in these plots
    - ▸ More data will constrain this further
    - ▸ c.f. Hannu's talk on Tuesday for LHeC data



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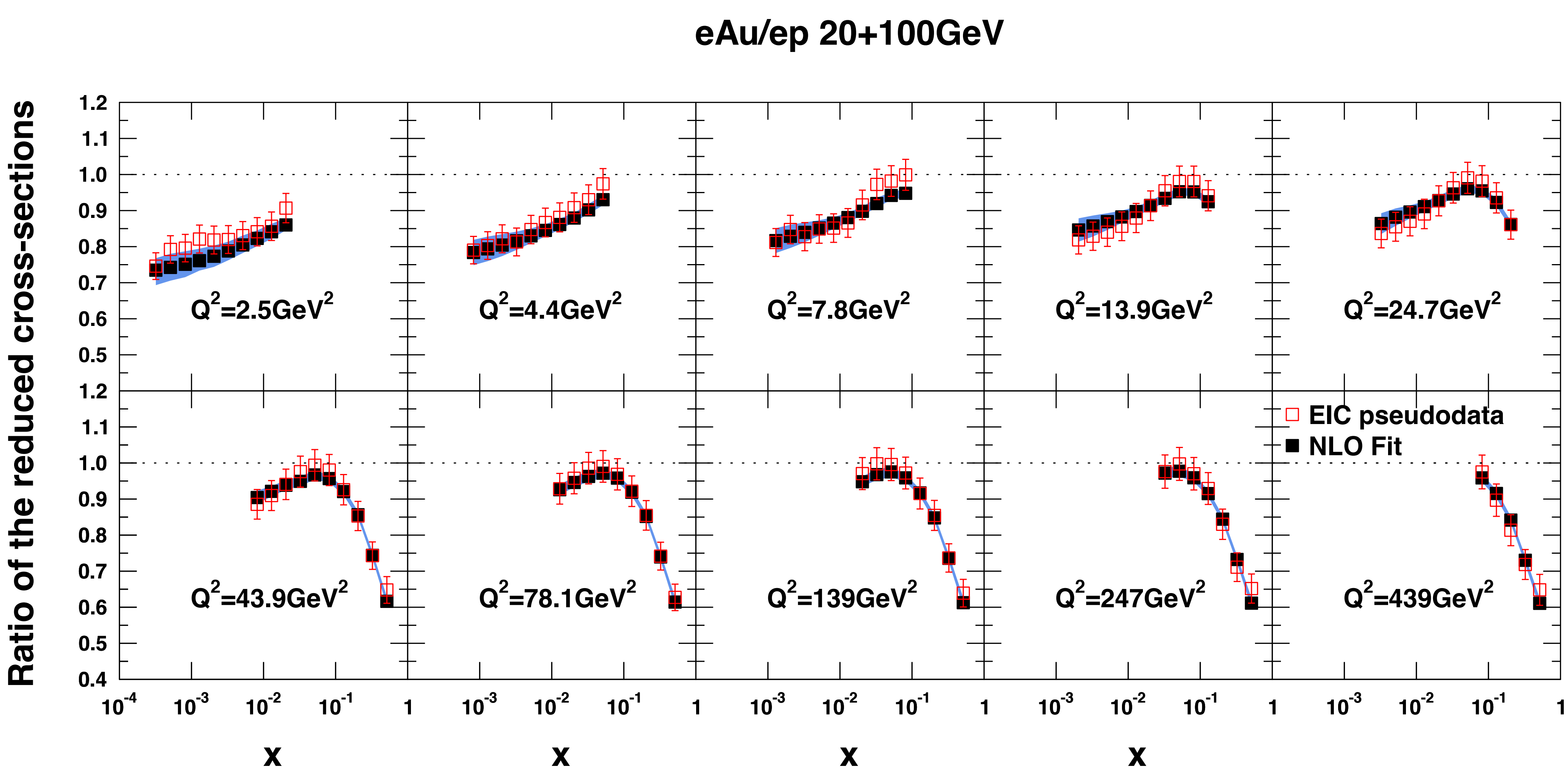

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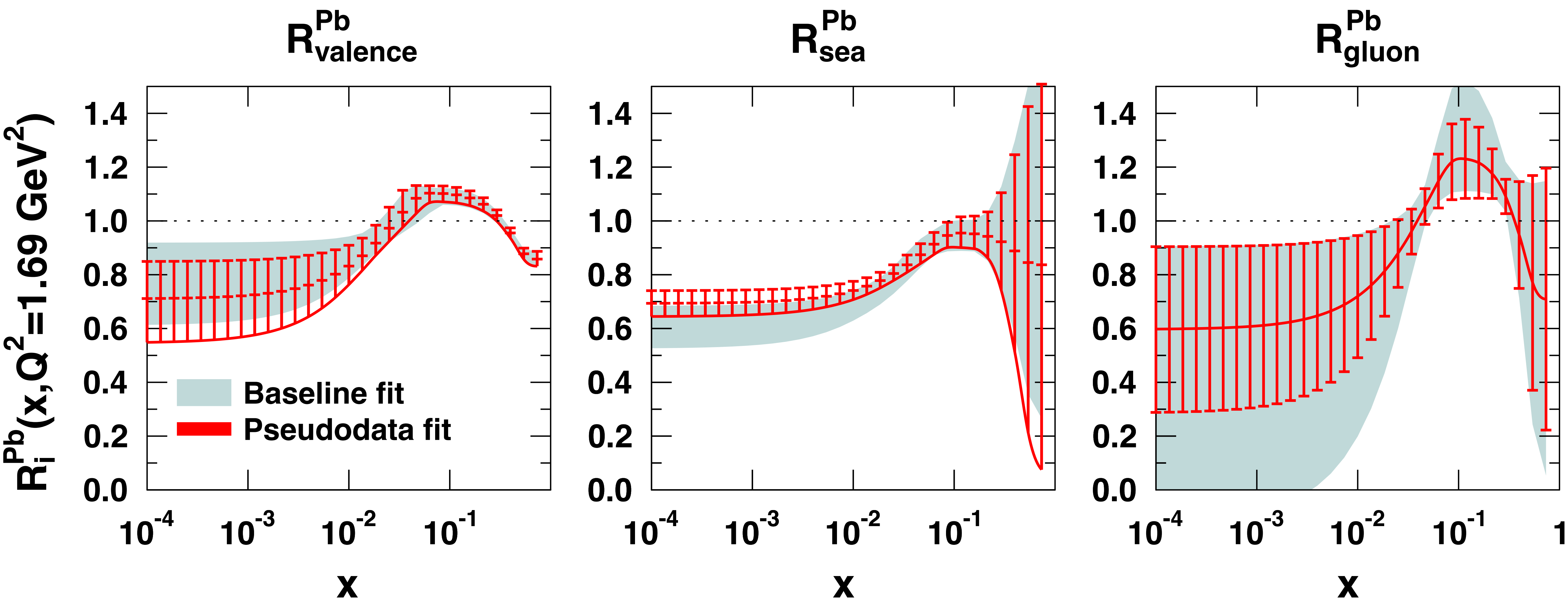
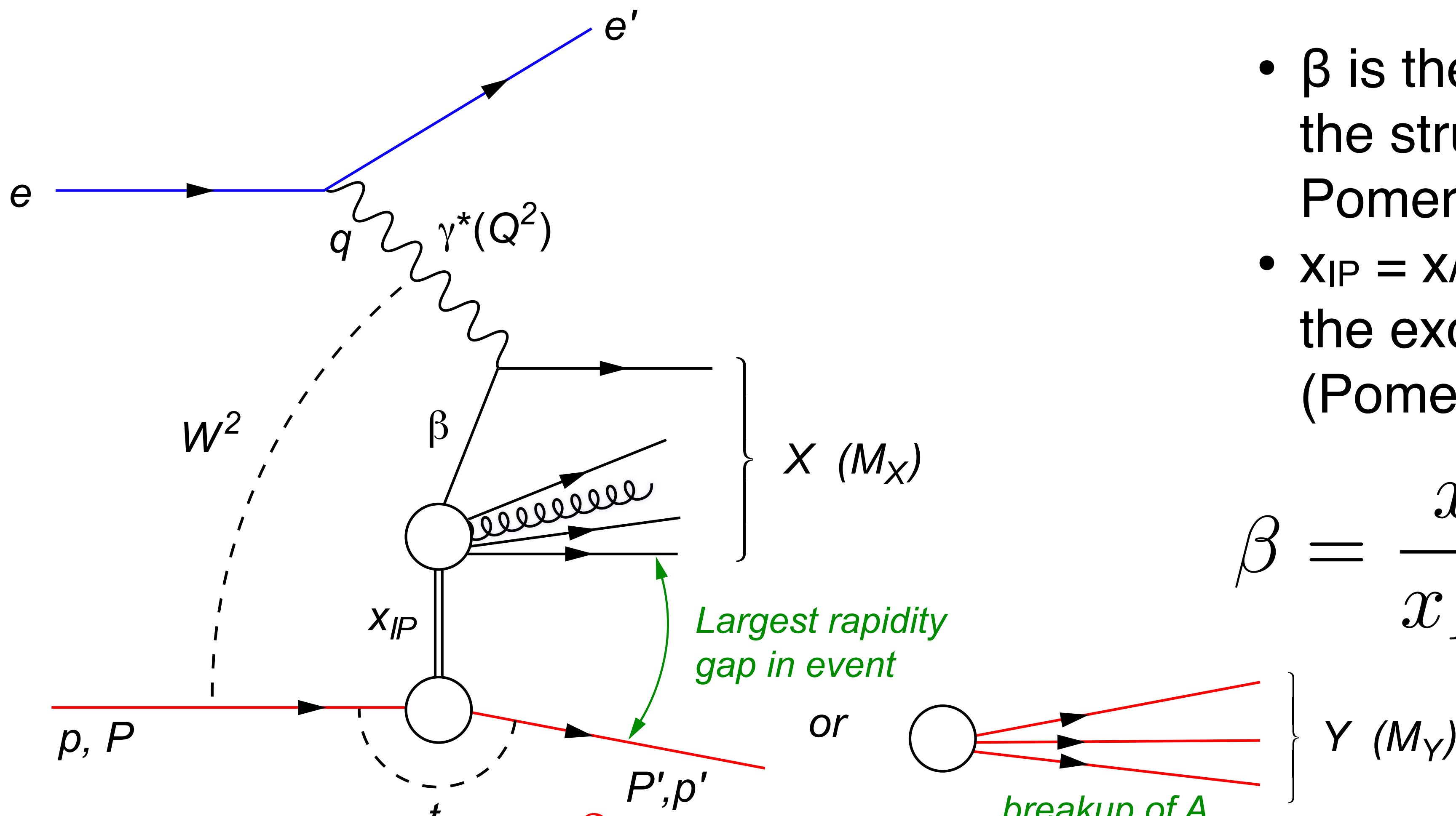


Exclusive processes in e+A - diffraction



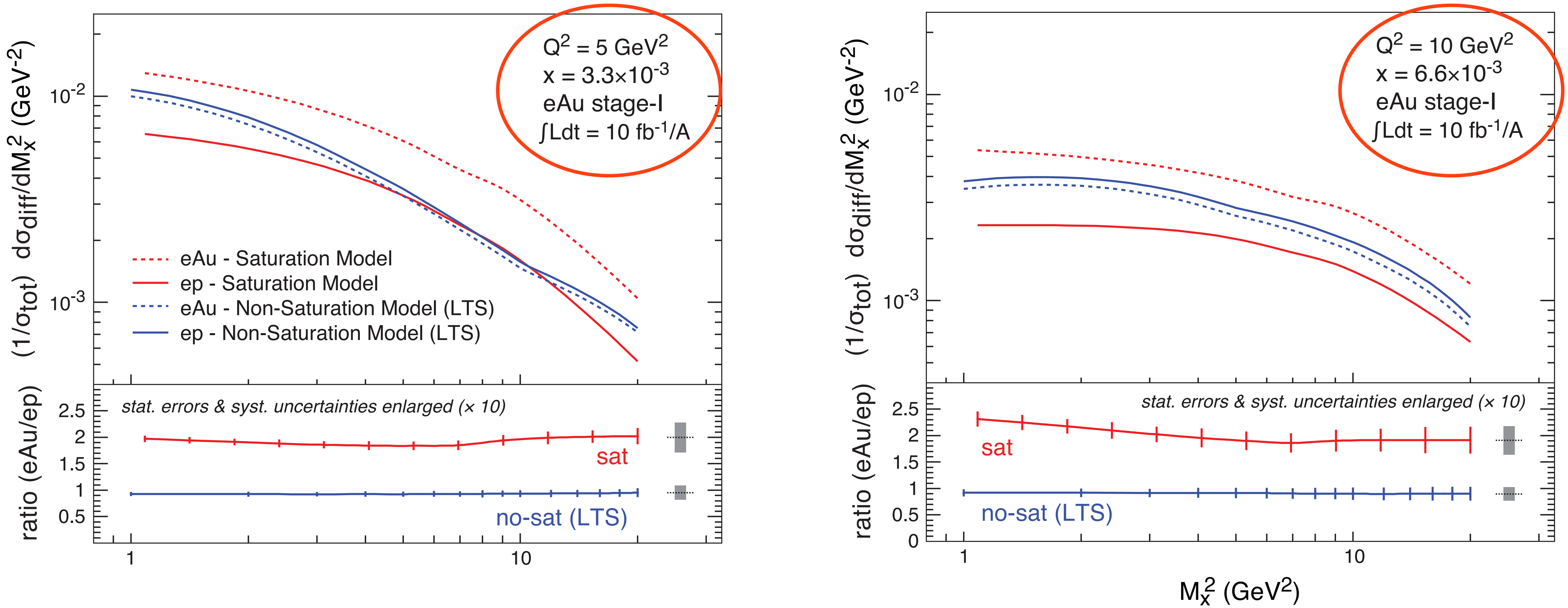
$$t = (p - p')^2$$

- 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

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

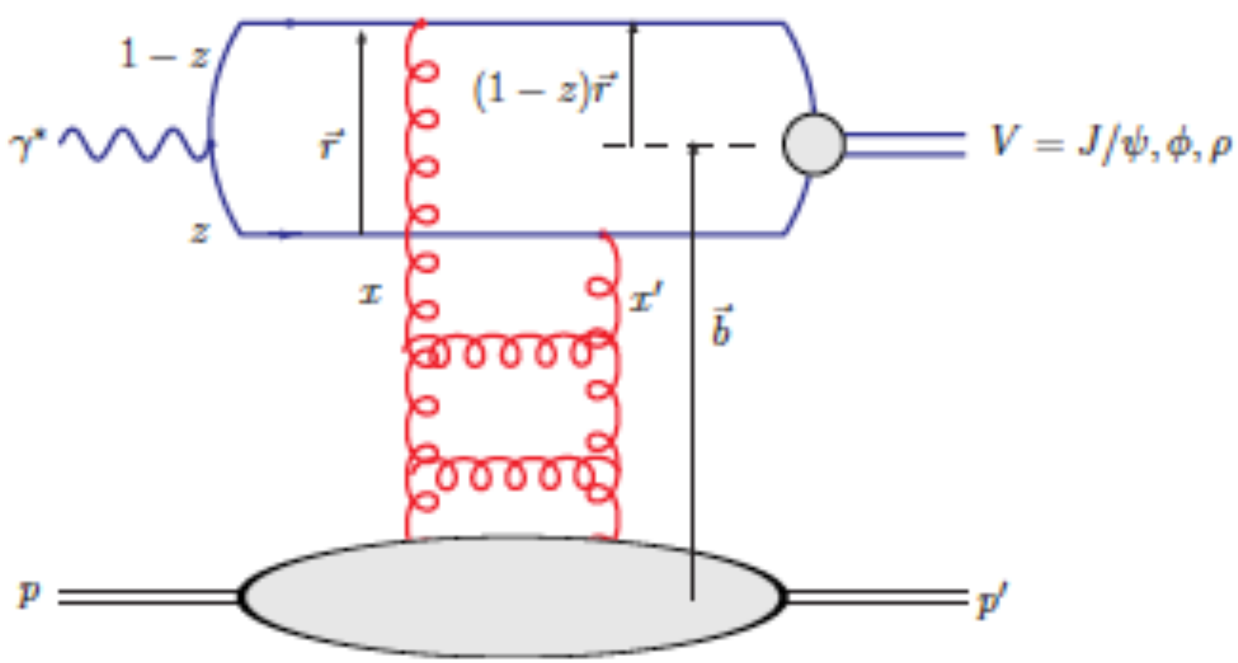
- Diffraction in e+p:
  - ➡ HERA: 15% of all events are diffractive
- Diffraction in e+A:
  - ➡ Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - ➡ Coherent diffraction (nuclei intact)
  - ➡ Incoherent diffraction: breakup into nucleons (nucleons intact)

Day 1: Diffractive Cross-sections

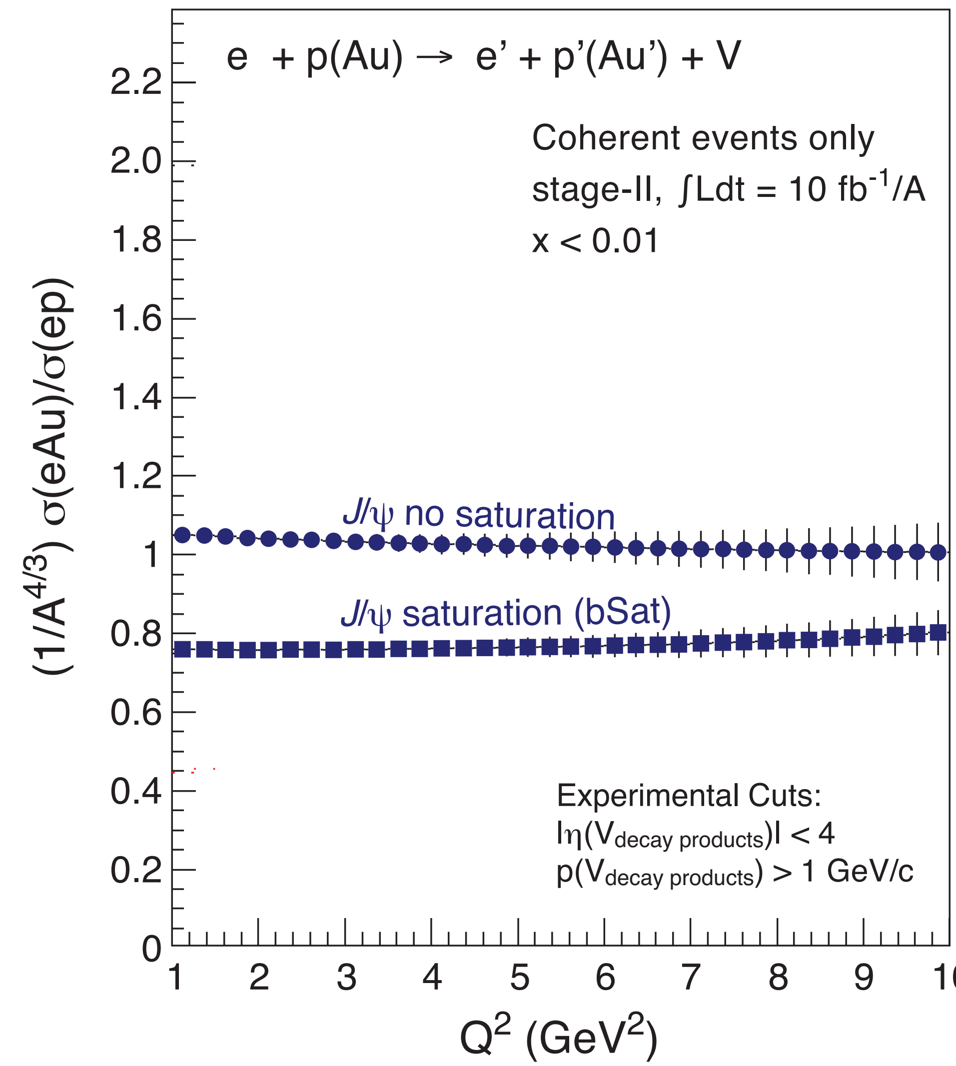


- Ratio of diffractive-to-total cross-section drastically different between saturation (Marquet) and non-saturation (Frankfurt, Guzey, Strikman) models
- Expected experimental error bars (simulated for 10 fb^{-1} of data for a low-energy eRHIC) can distinguish between the two scenarios

Exclusive vector meson production



$$d\sigma \propto g(x)^2$$



- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation

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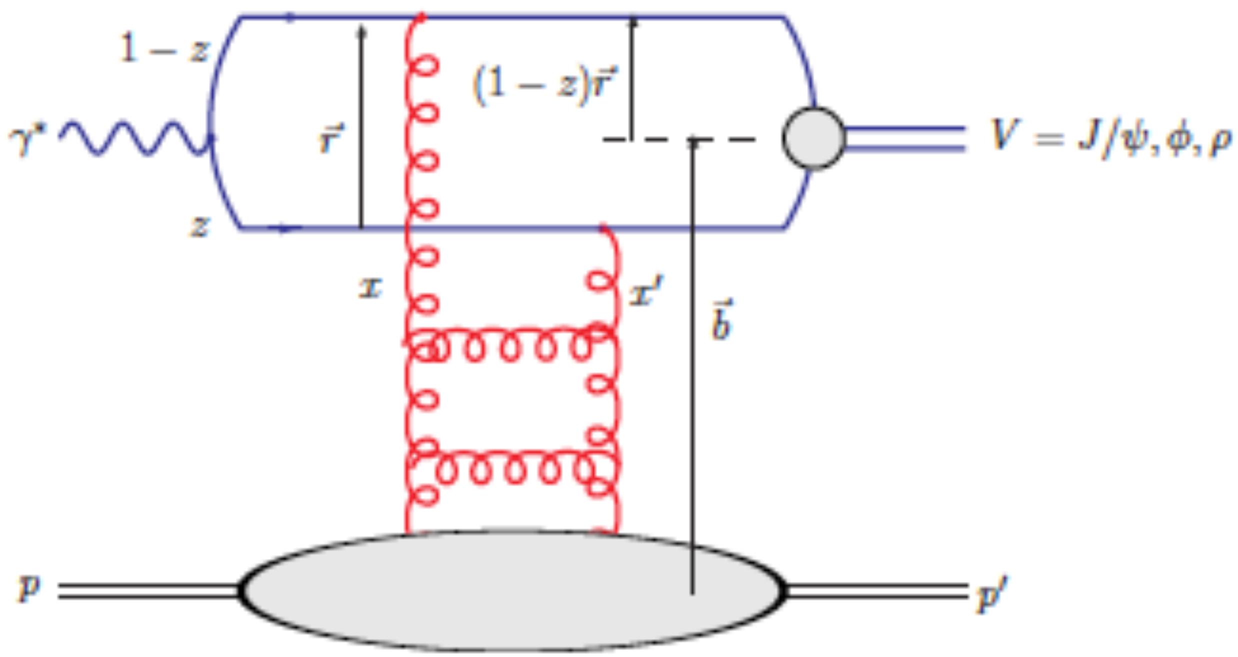

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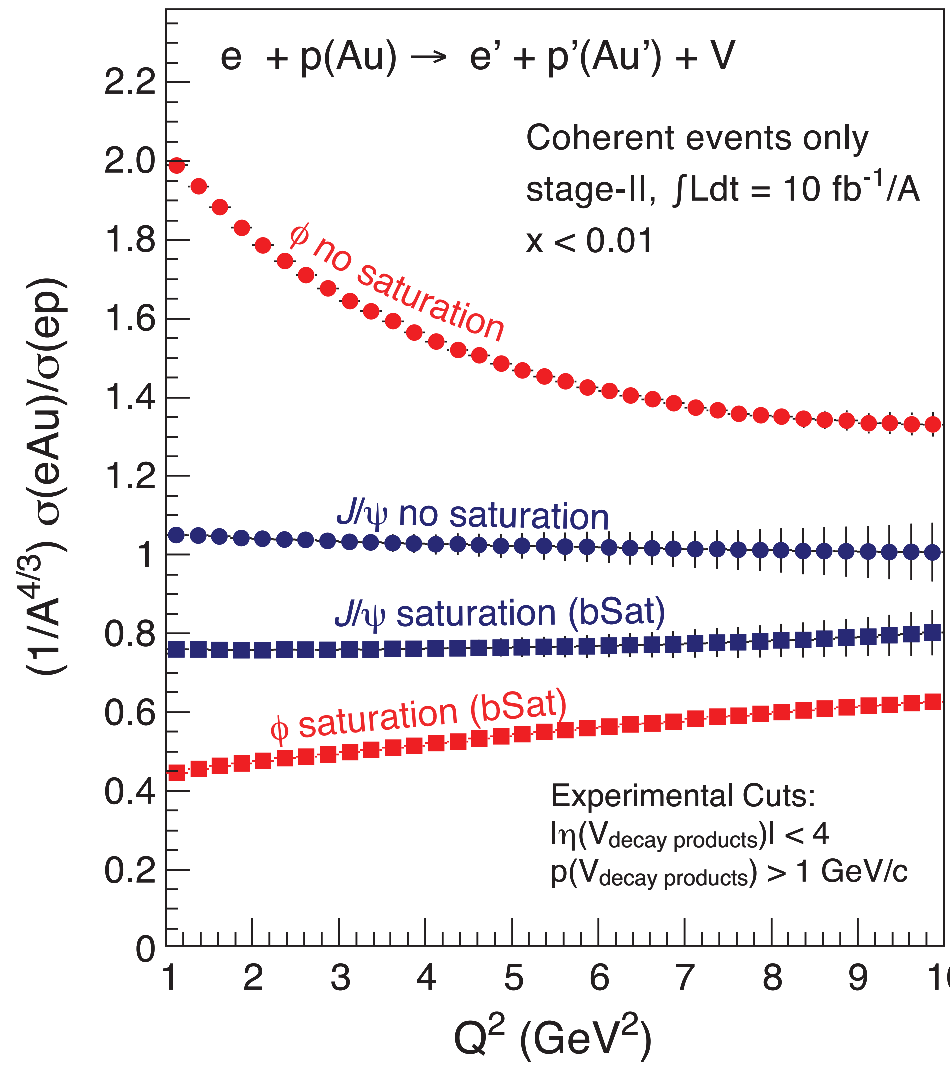
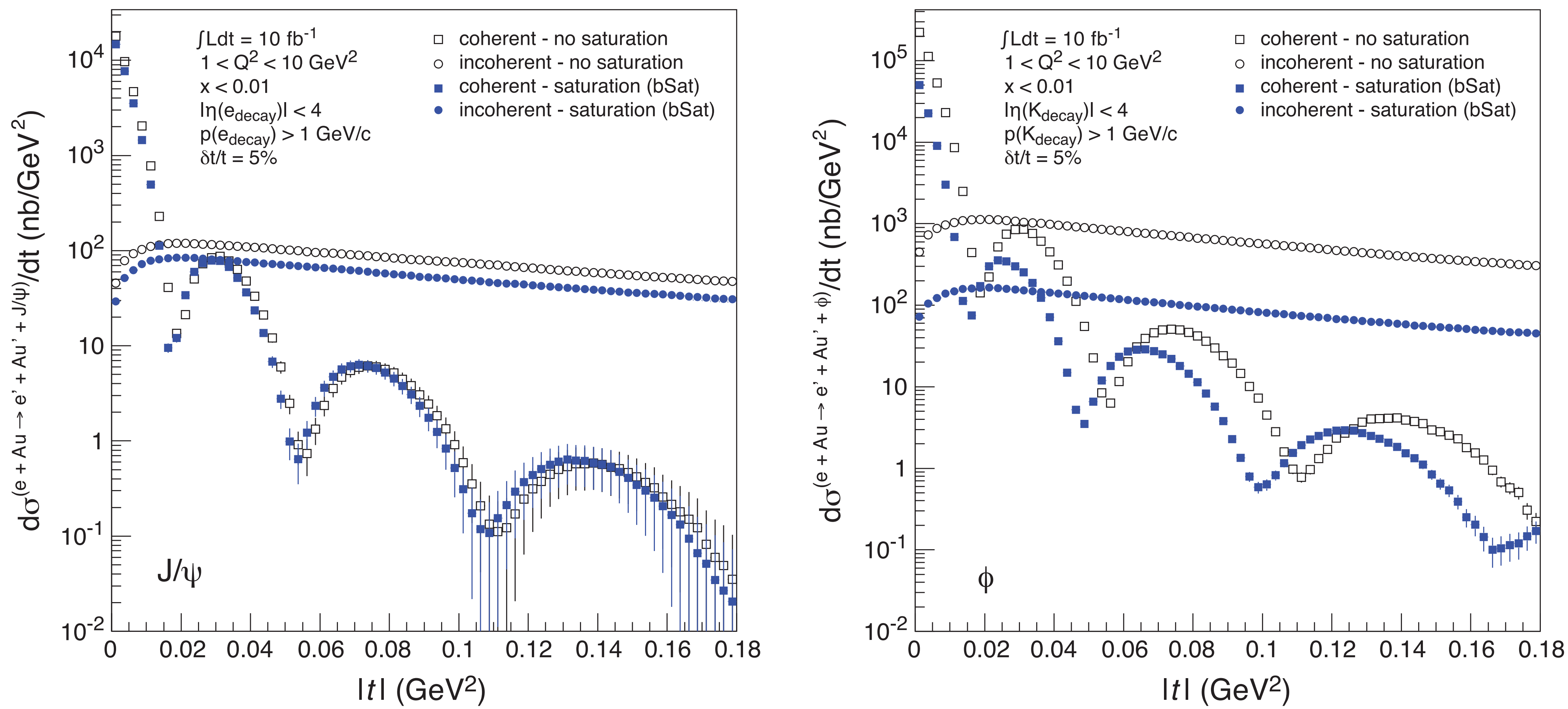


- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference
  - ➡ wave function for ϕ is larger and hence more sensitive to saturation effects

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

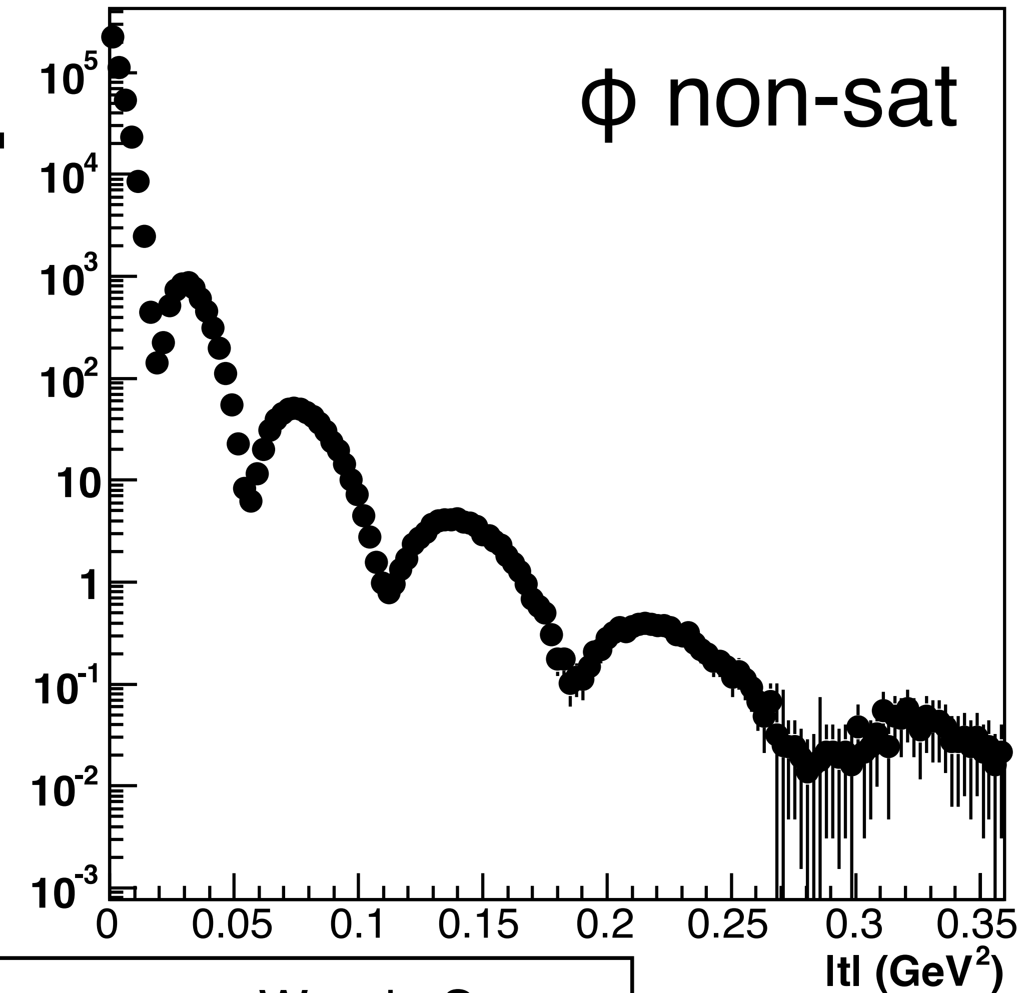
- ▸ unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- ▸ rapidity gap with absence of break-up fragments sufficient to identify coherent events

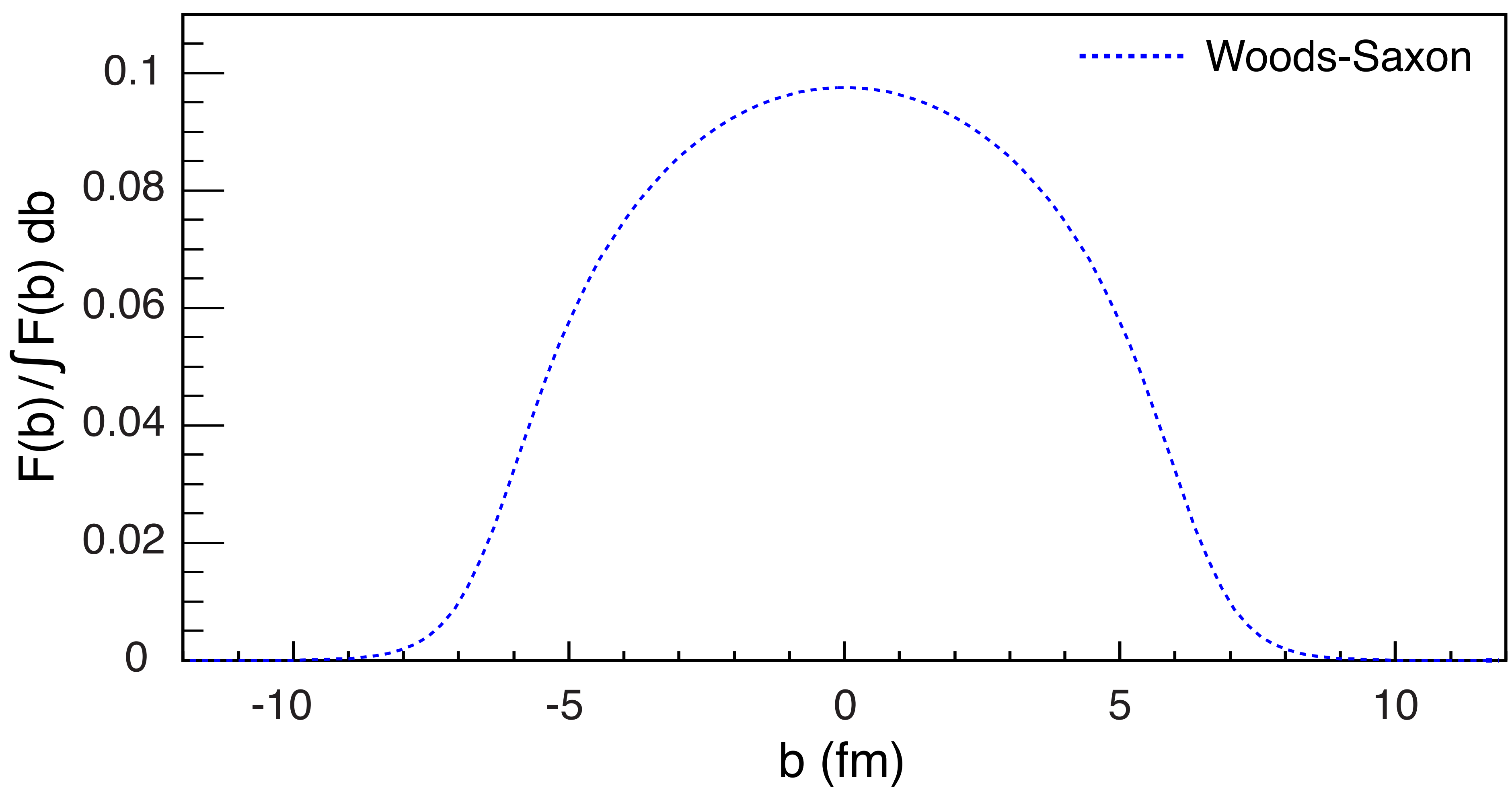
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

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

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





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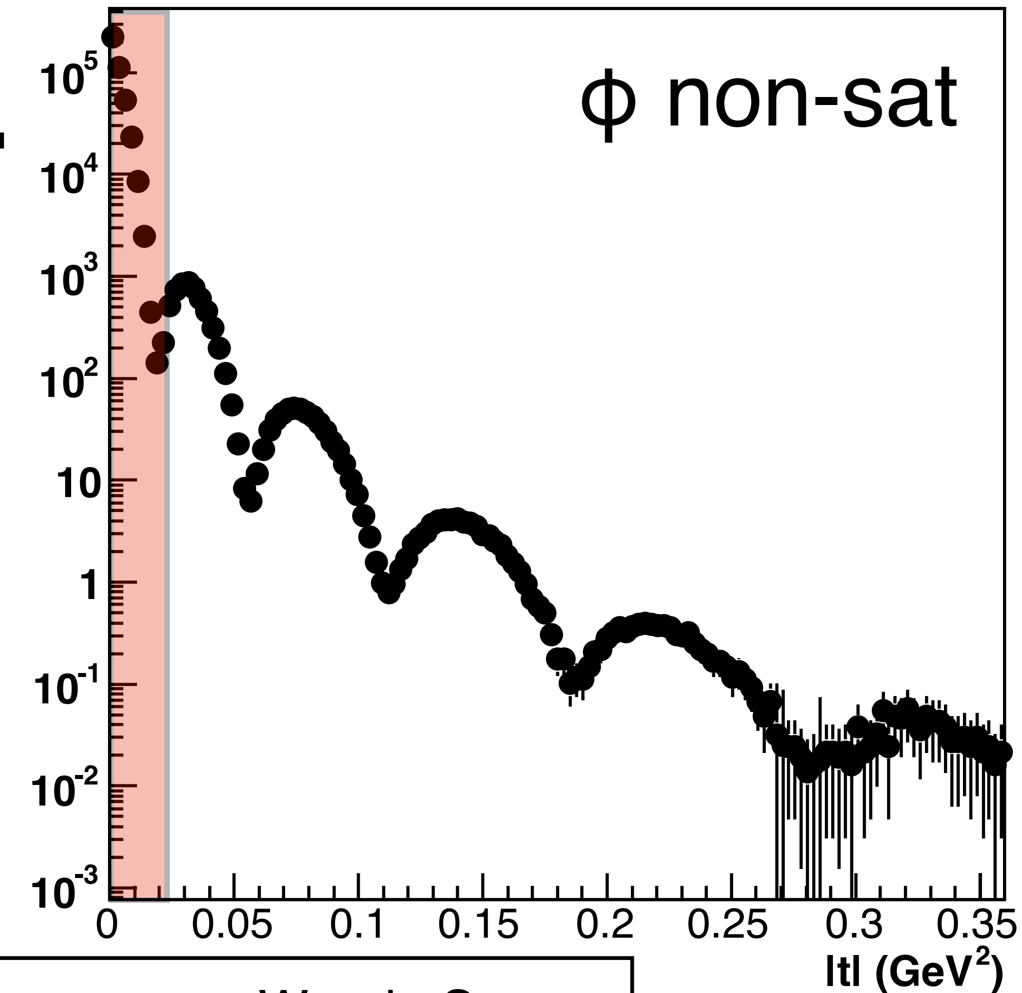

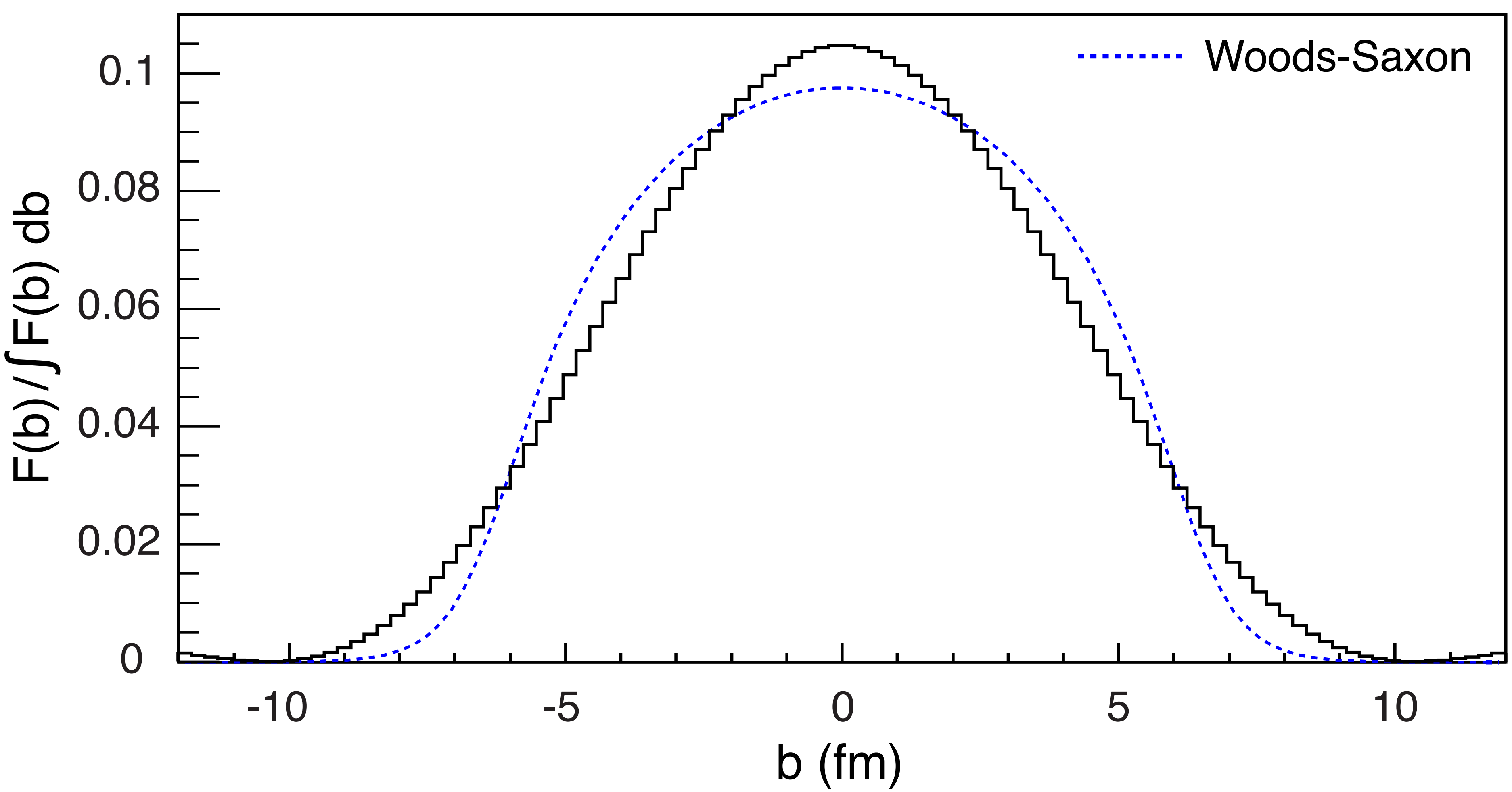

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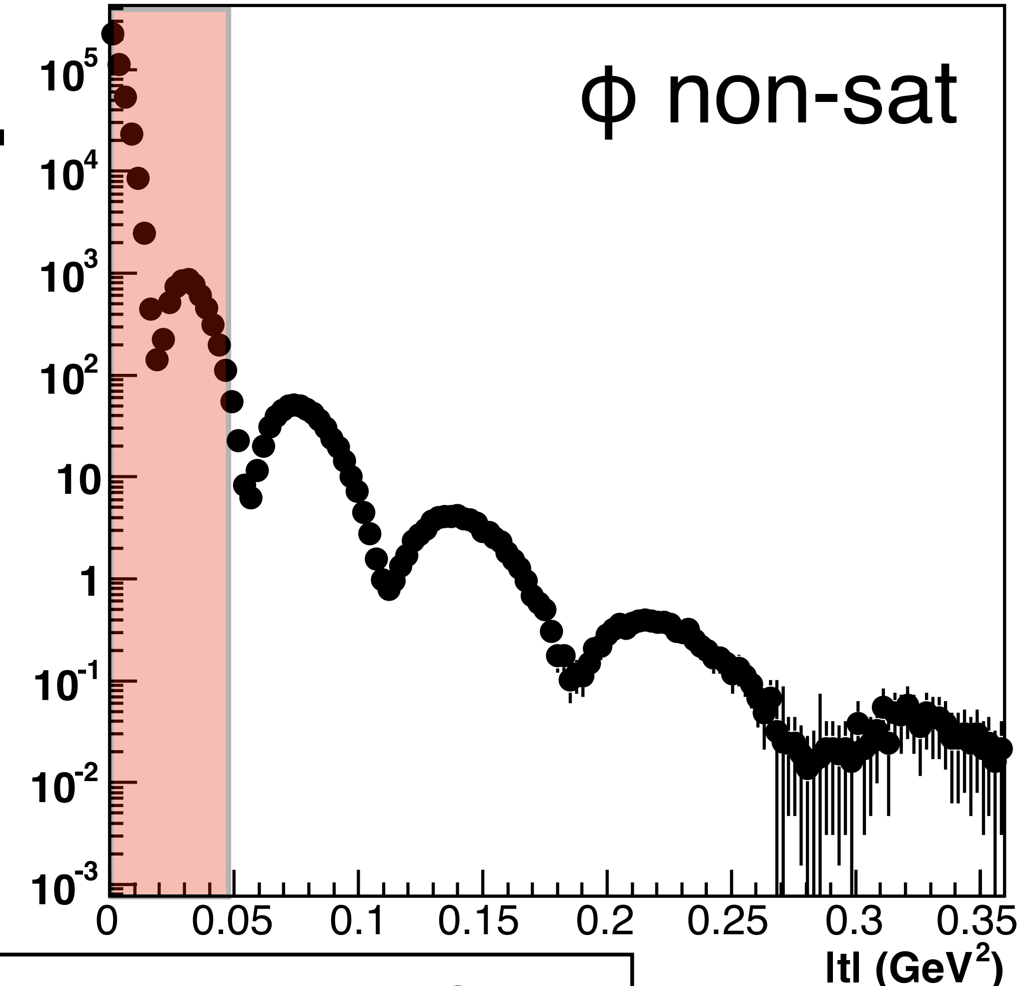

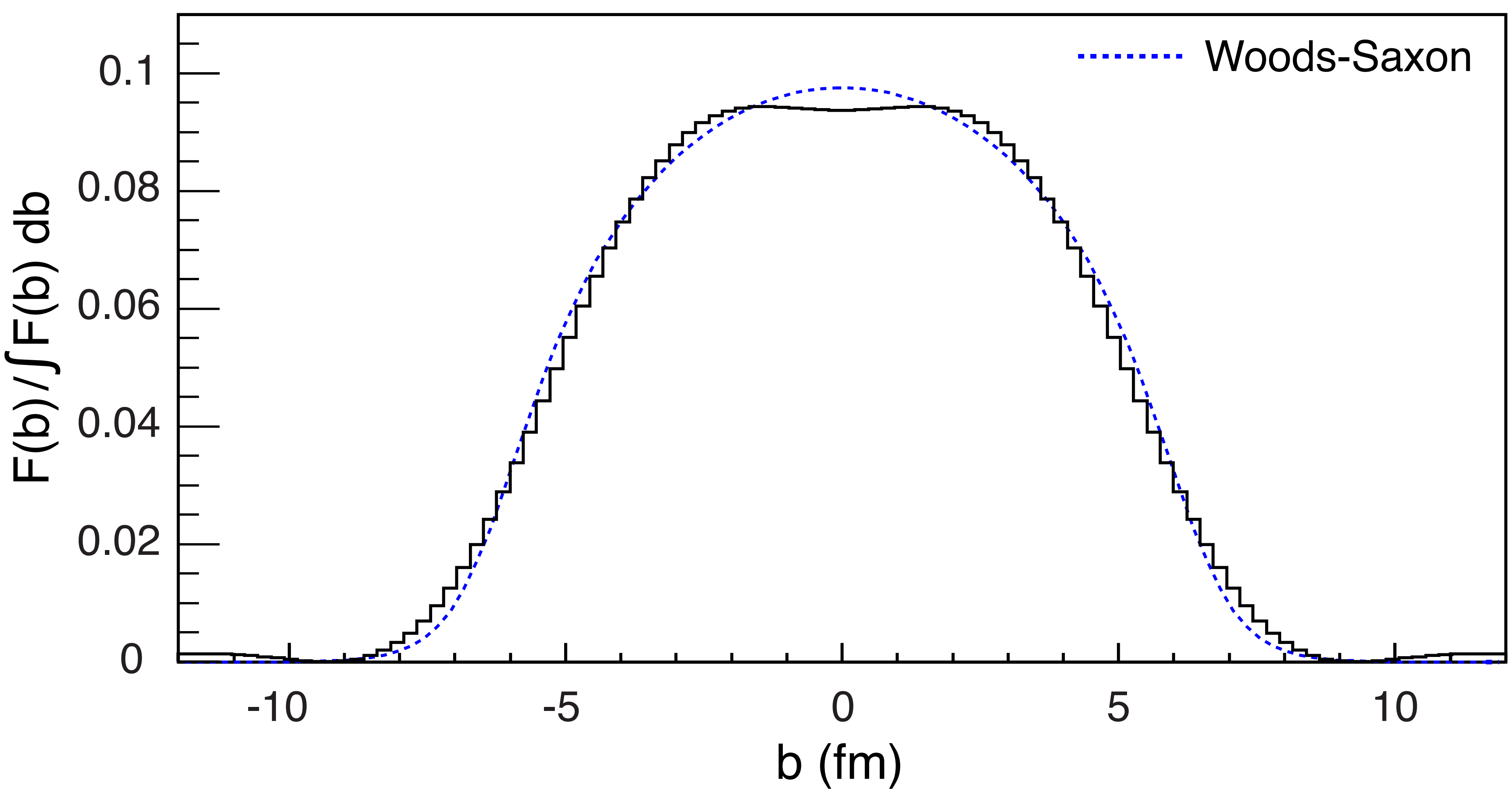

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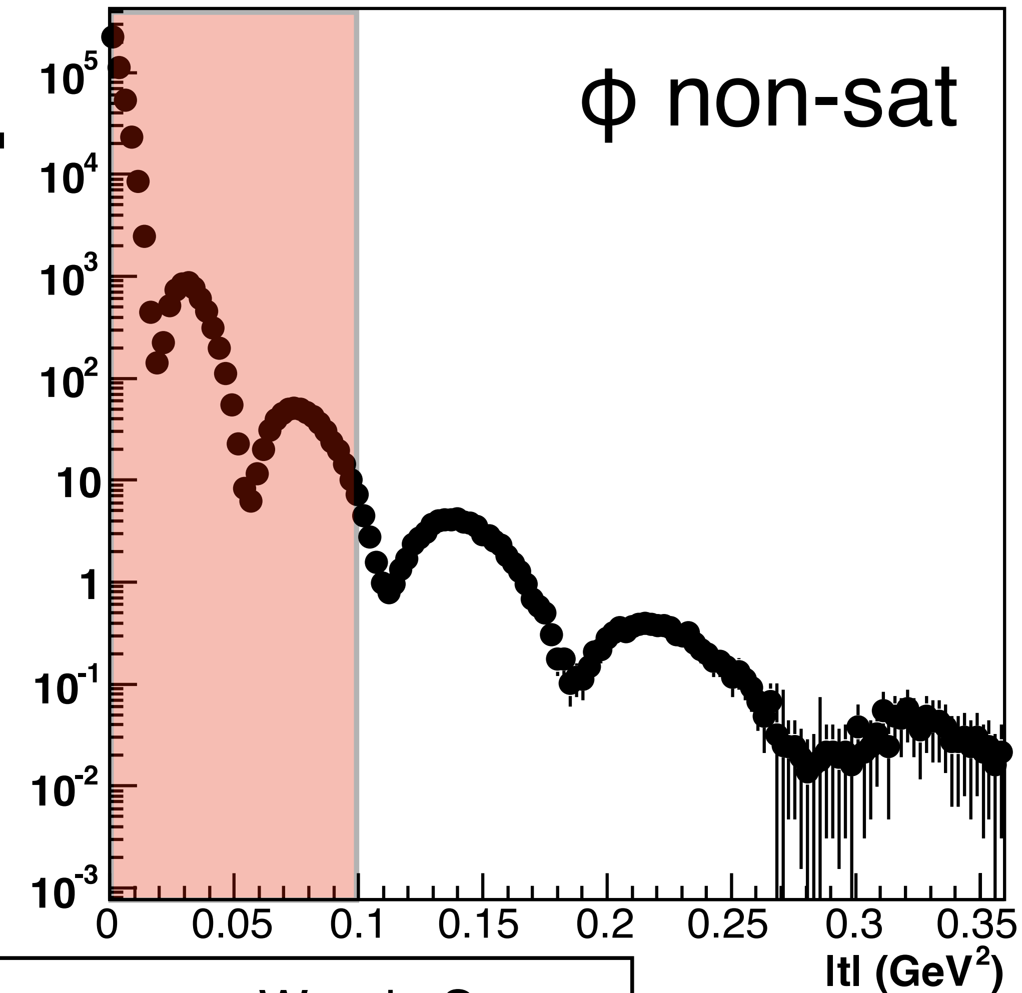

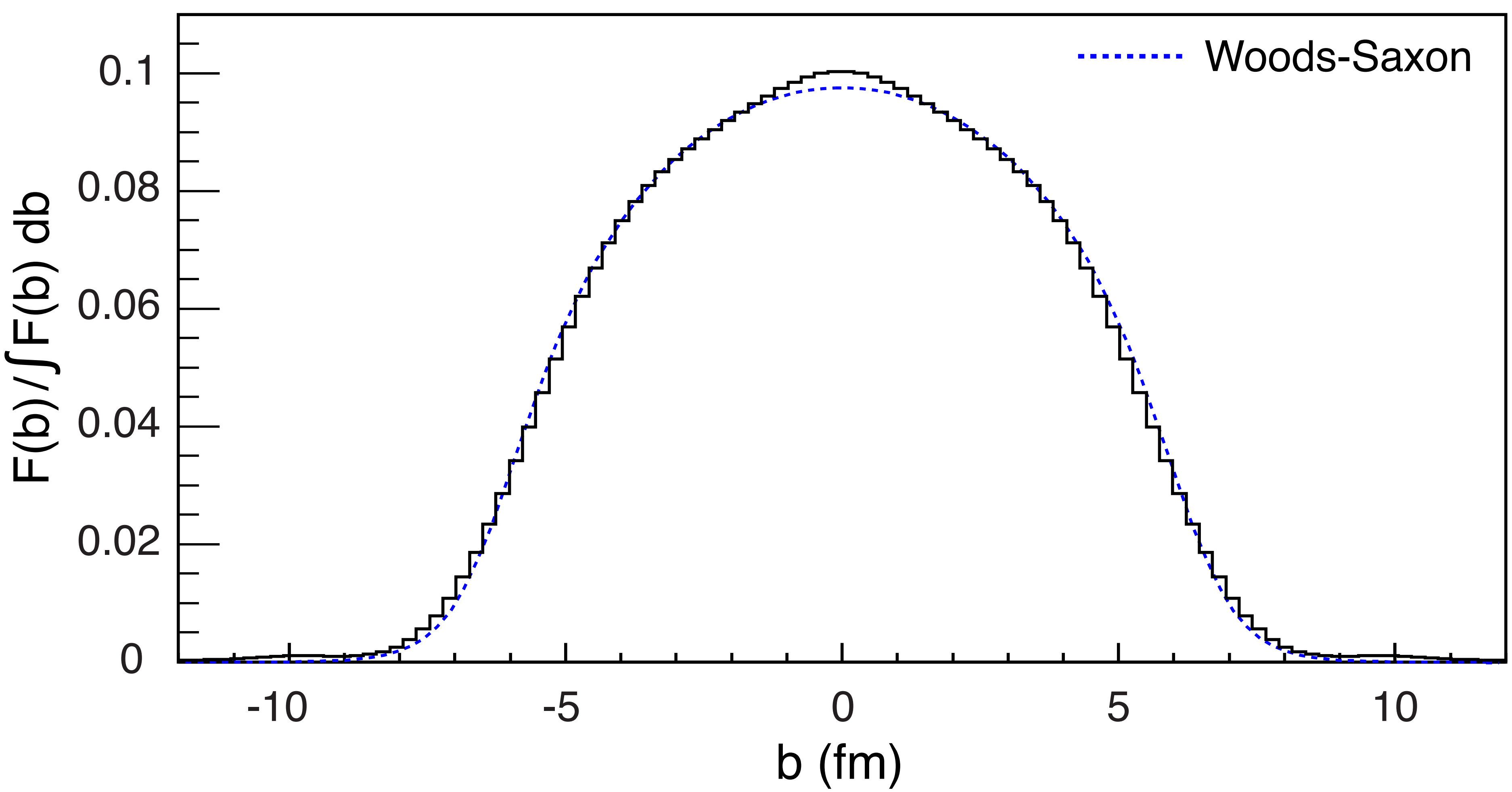

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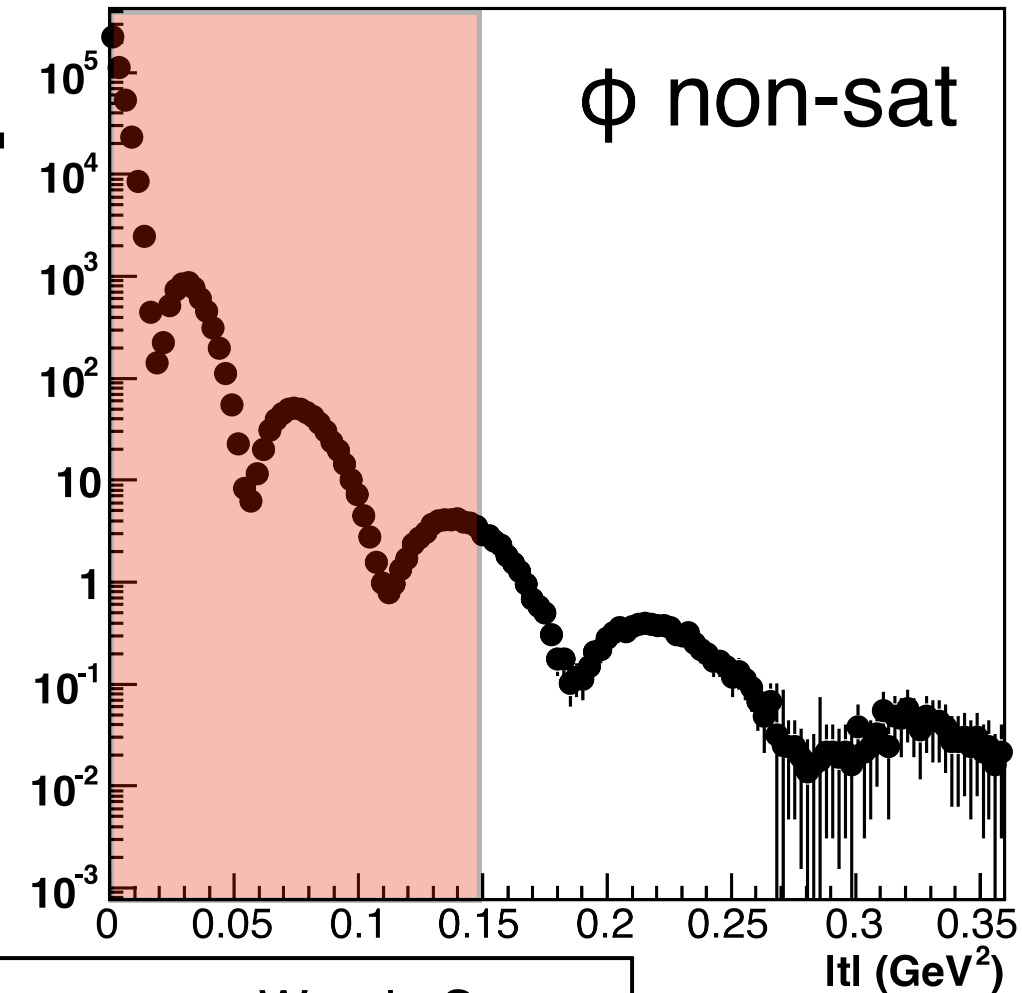

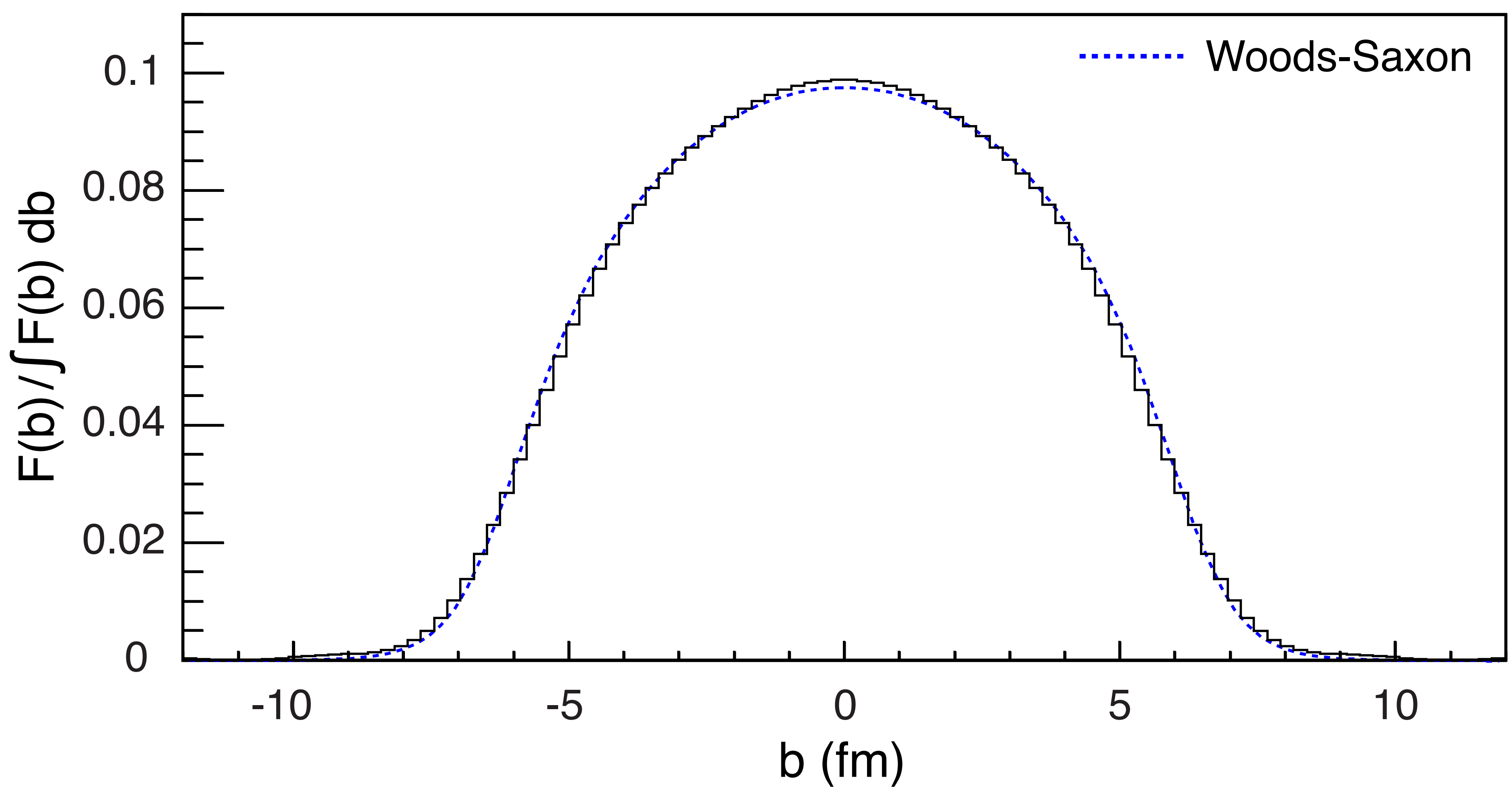

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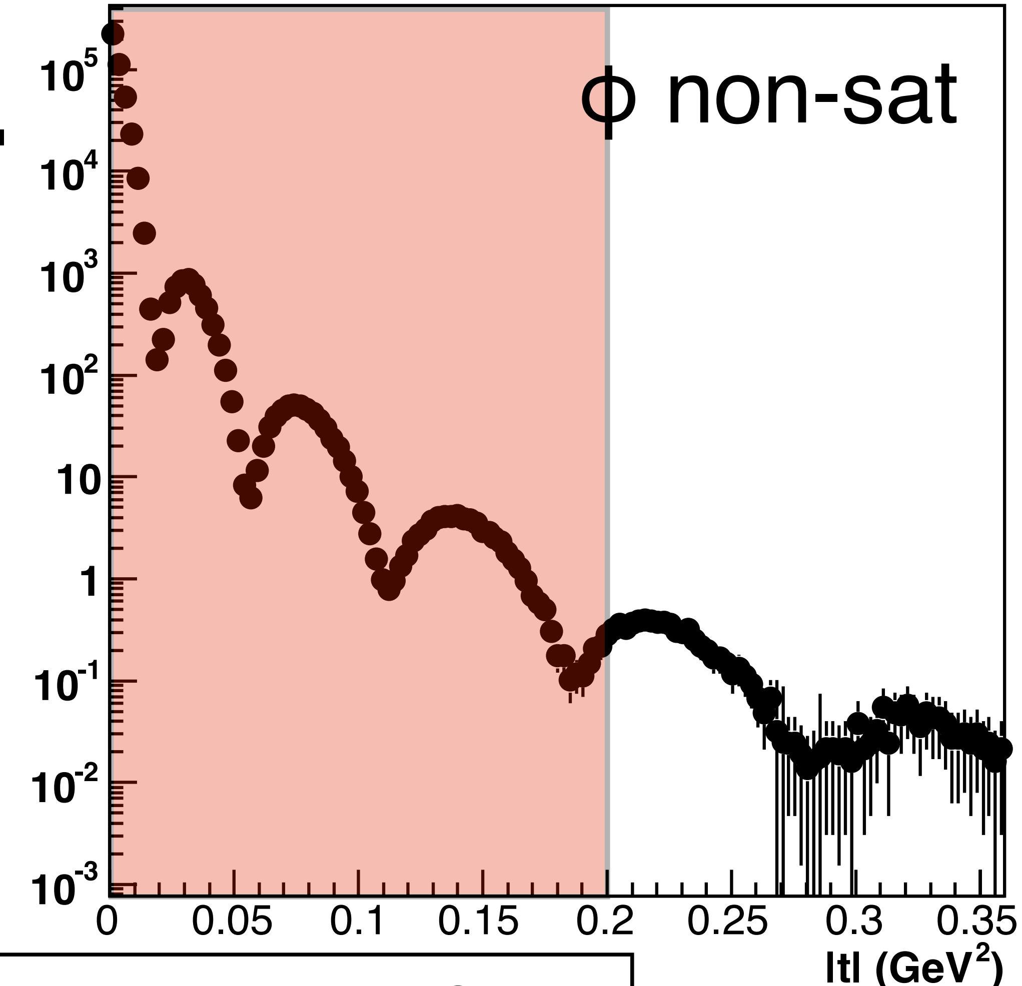

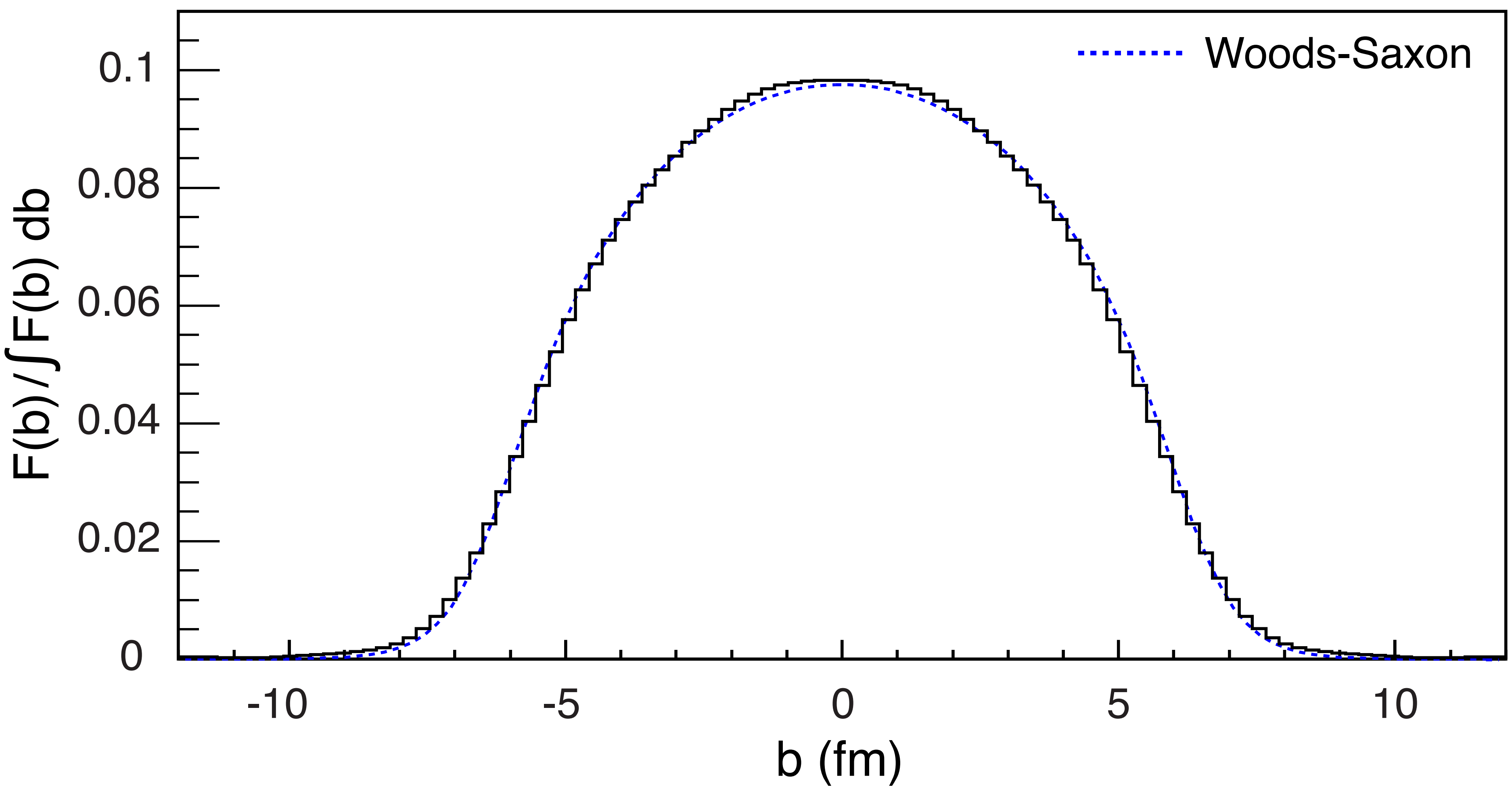

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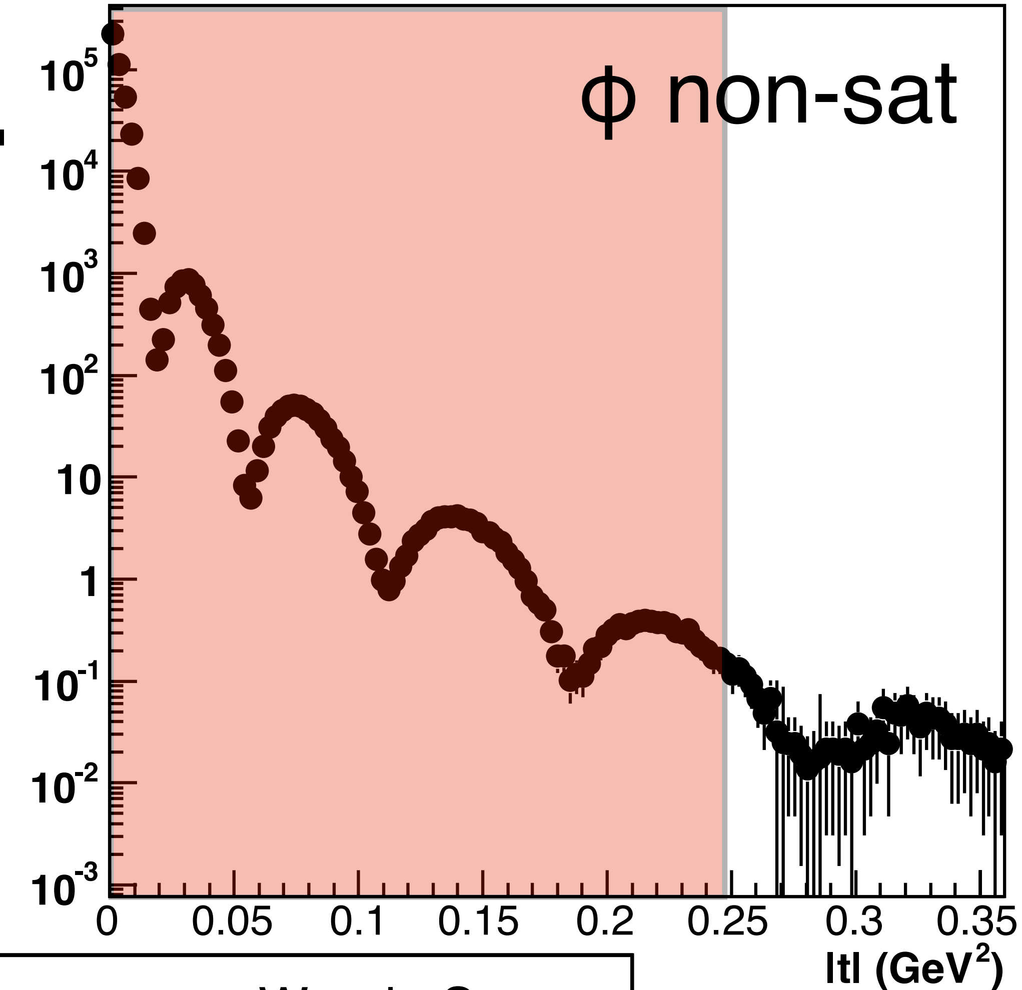

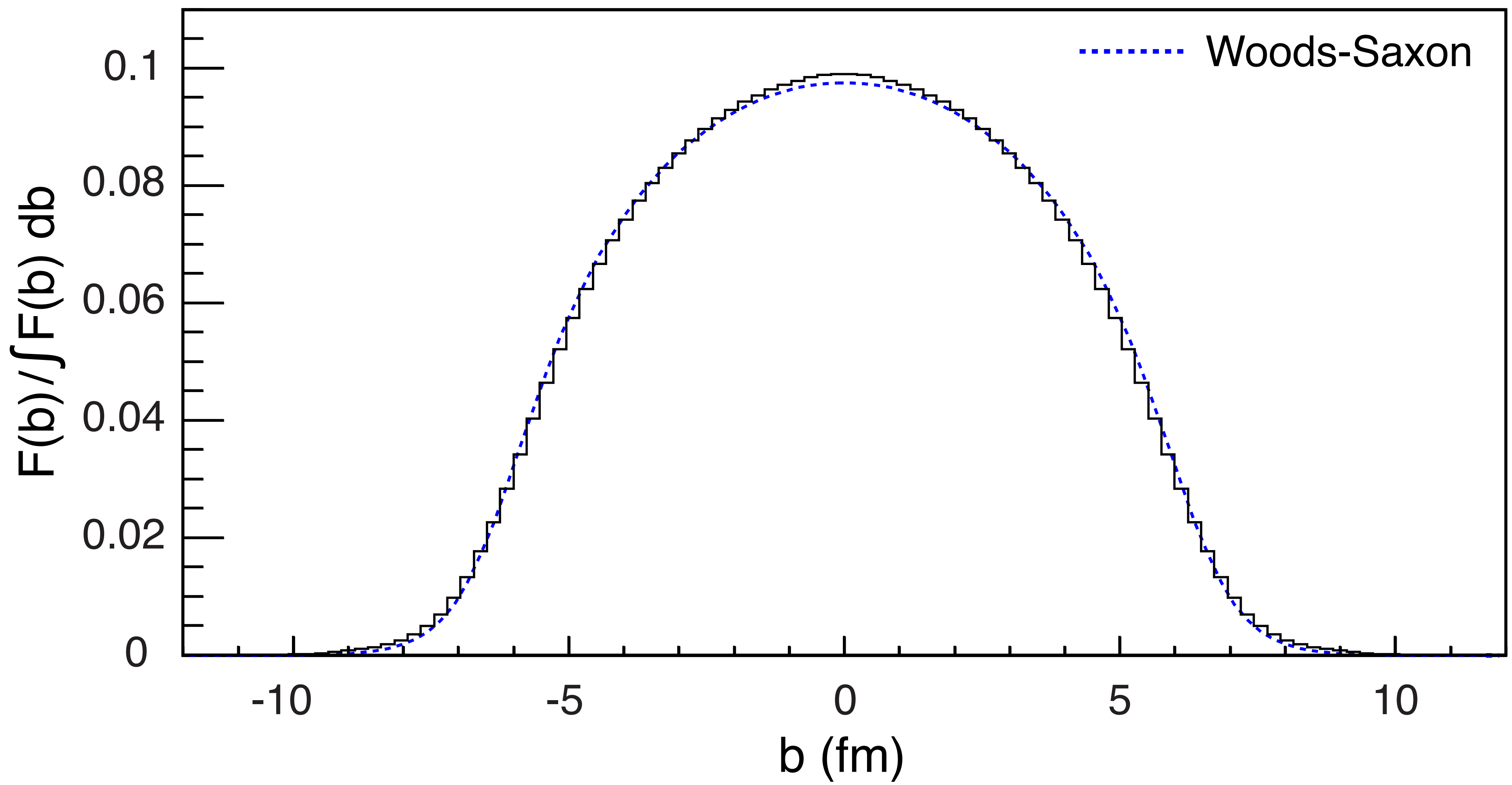

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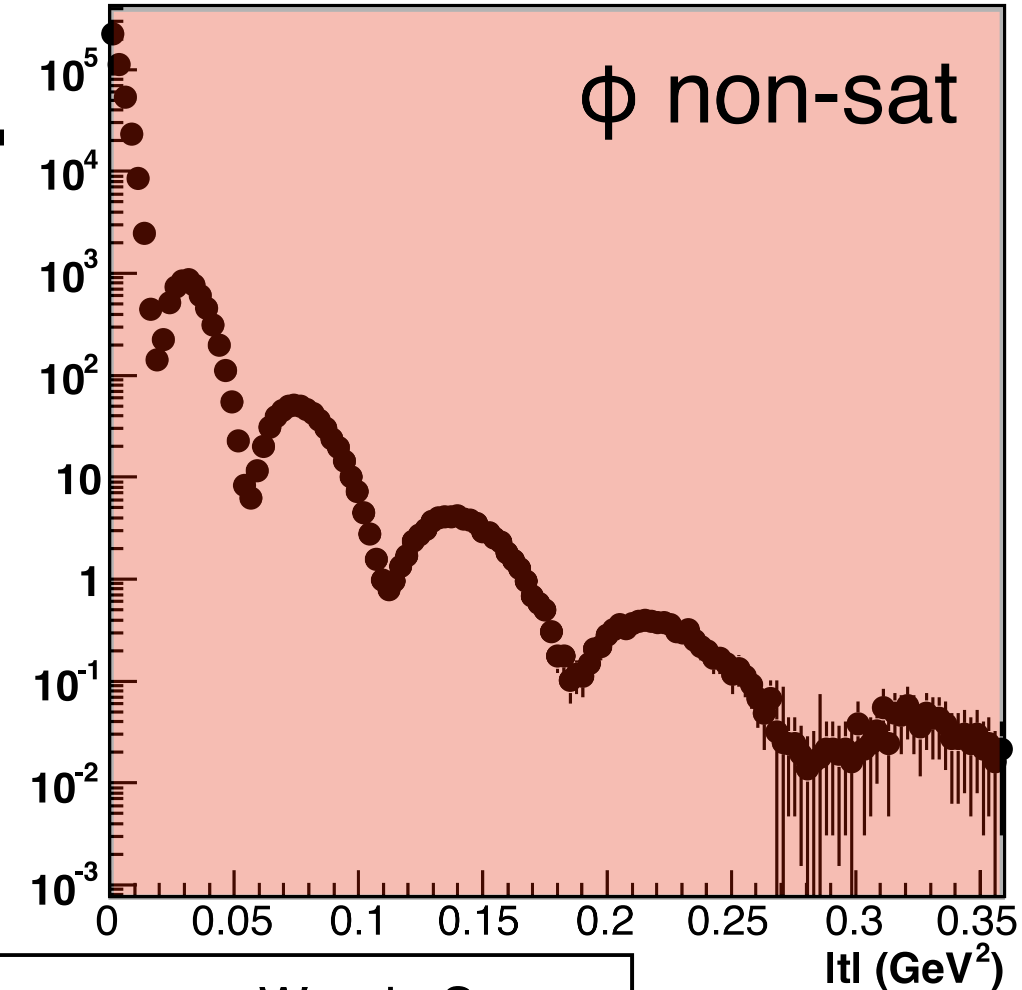
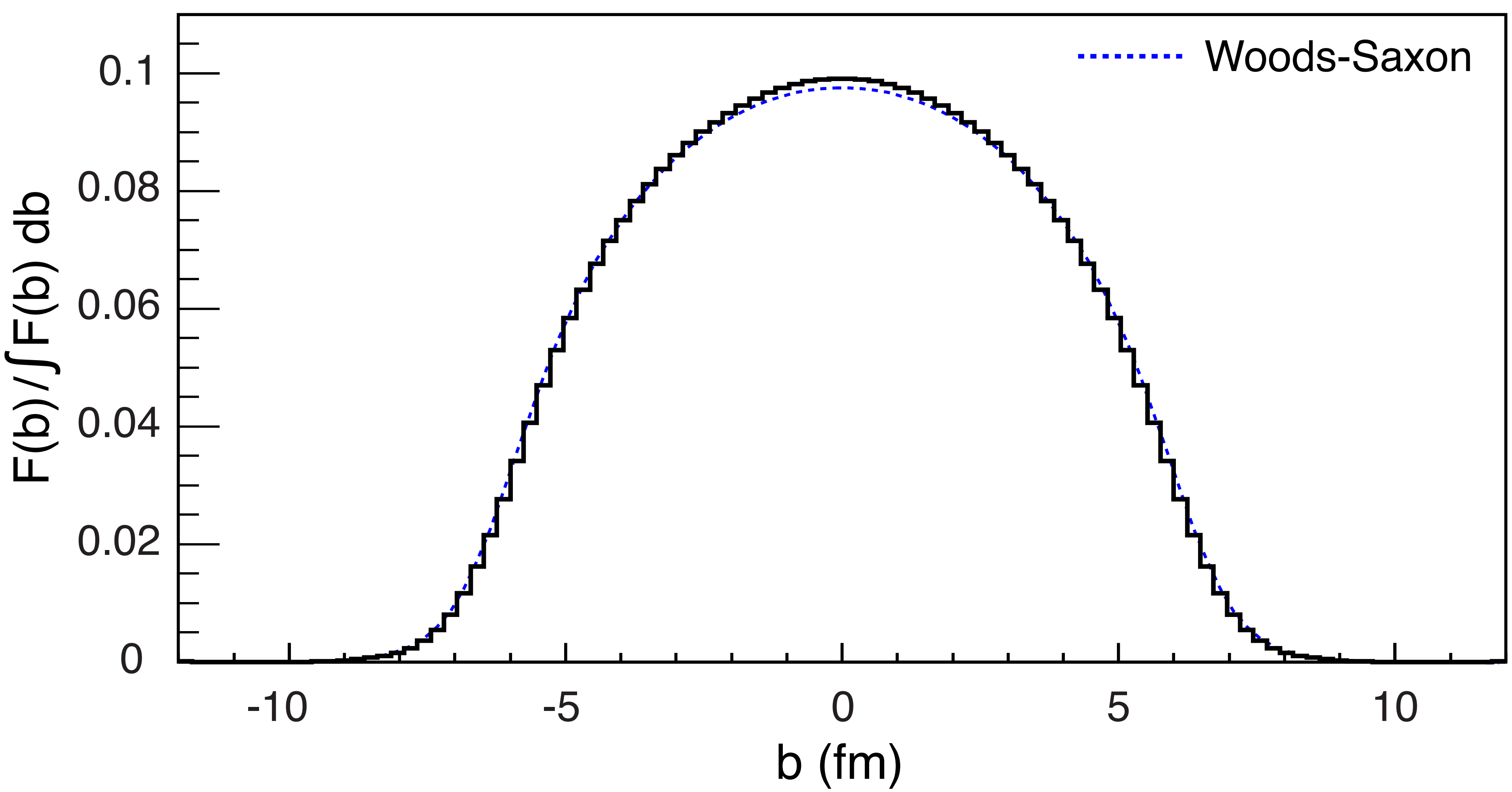
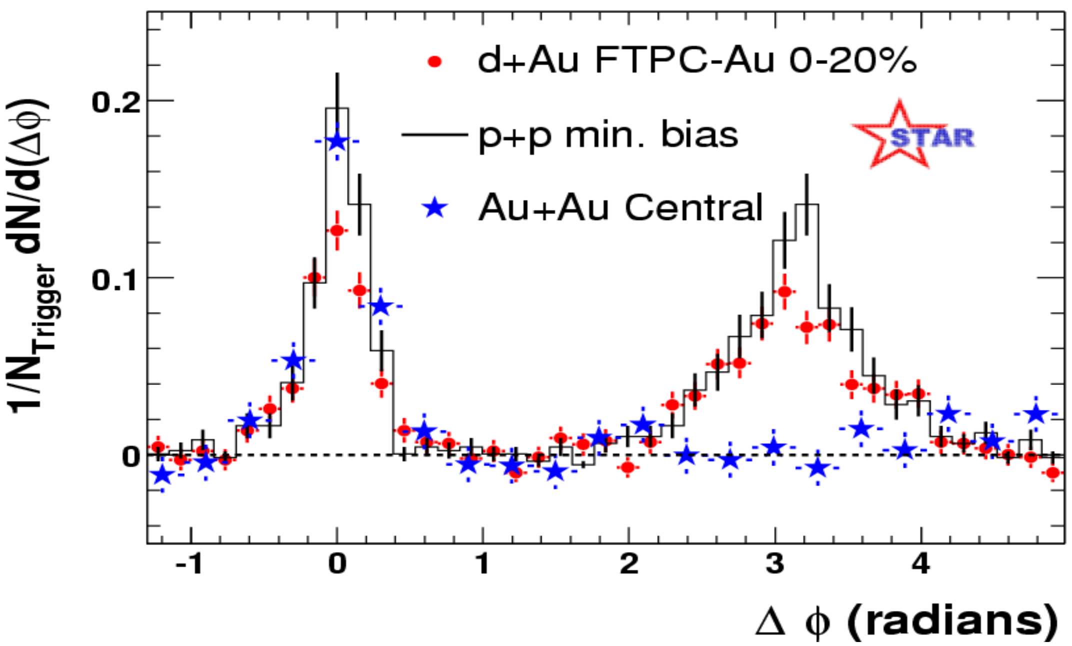
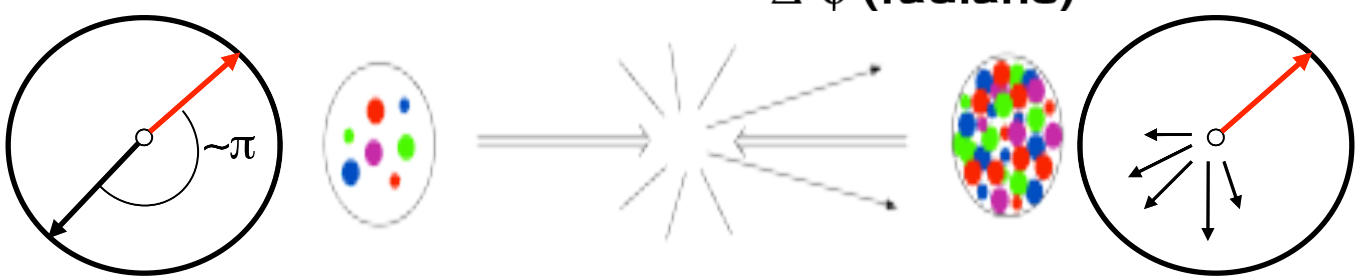




di-hadron correlations in d+A

comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → 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

➡ x ~ 10^{-2}

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

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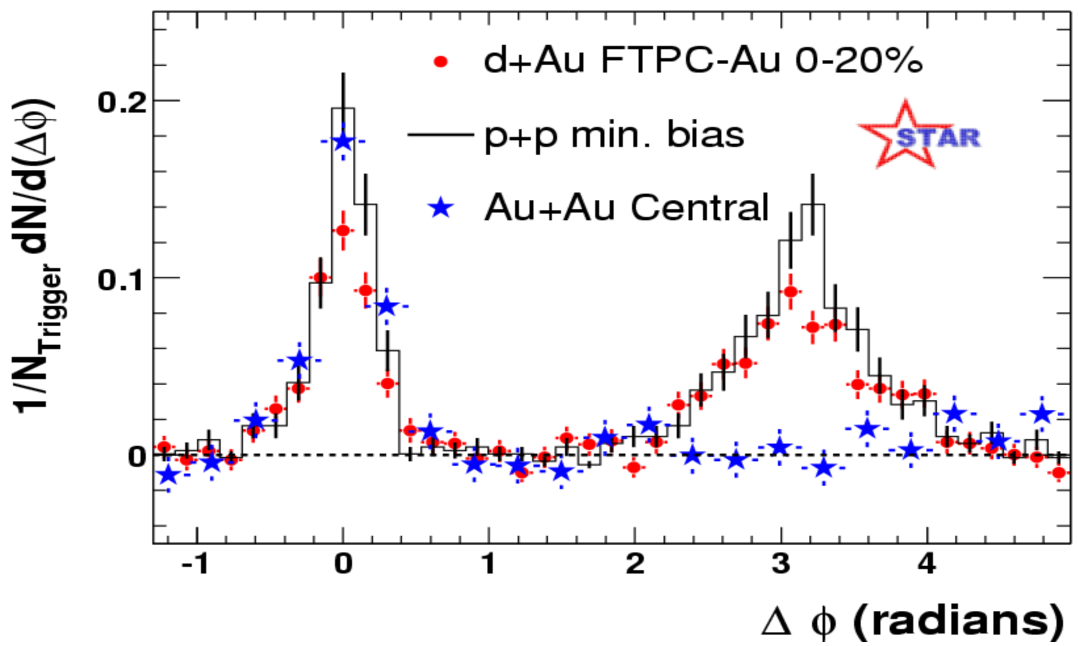

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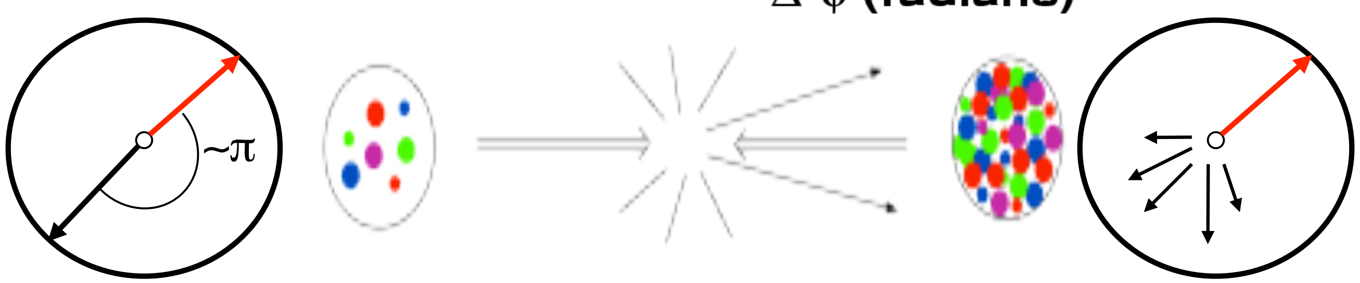
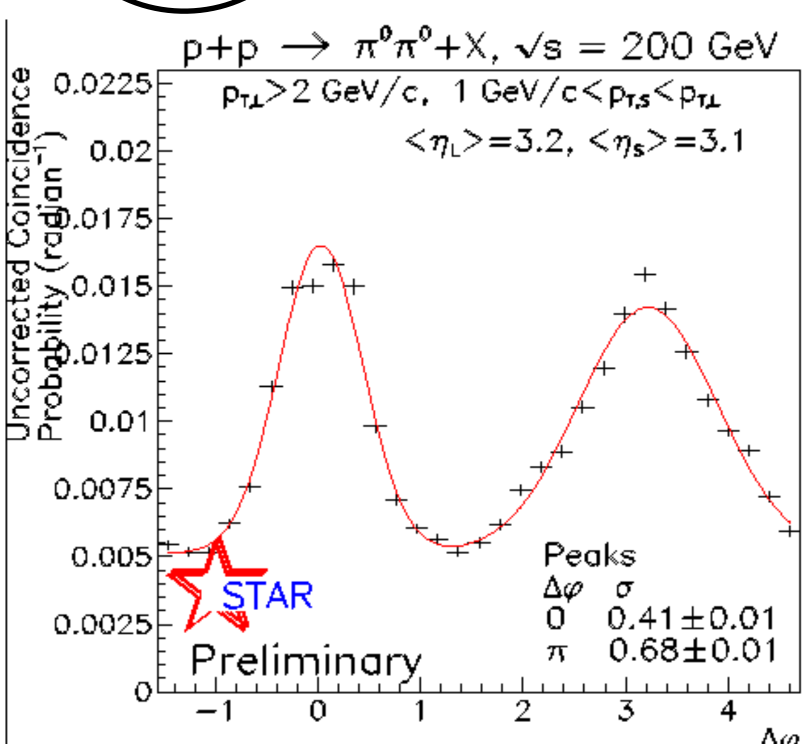
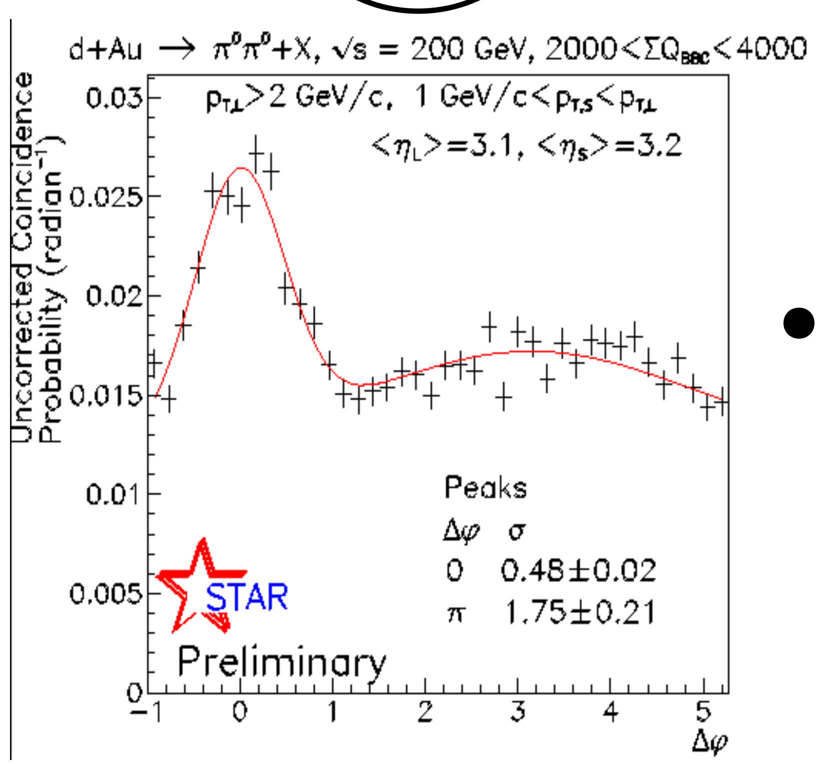


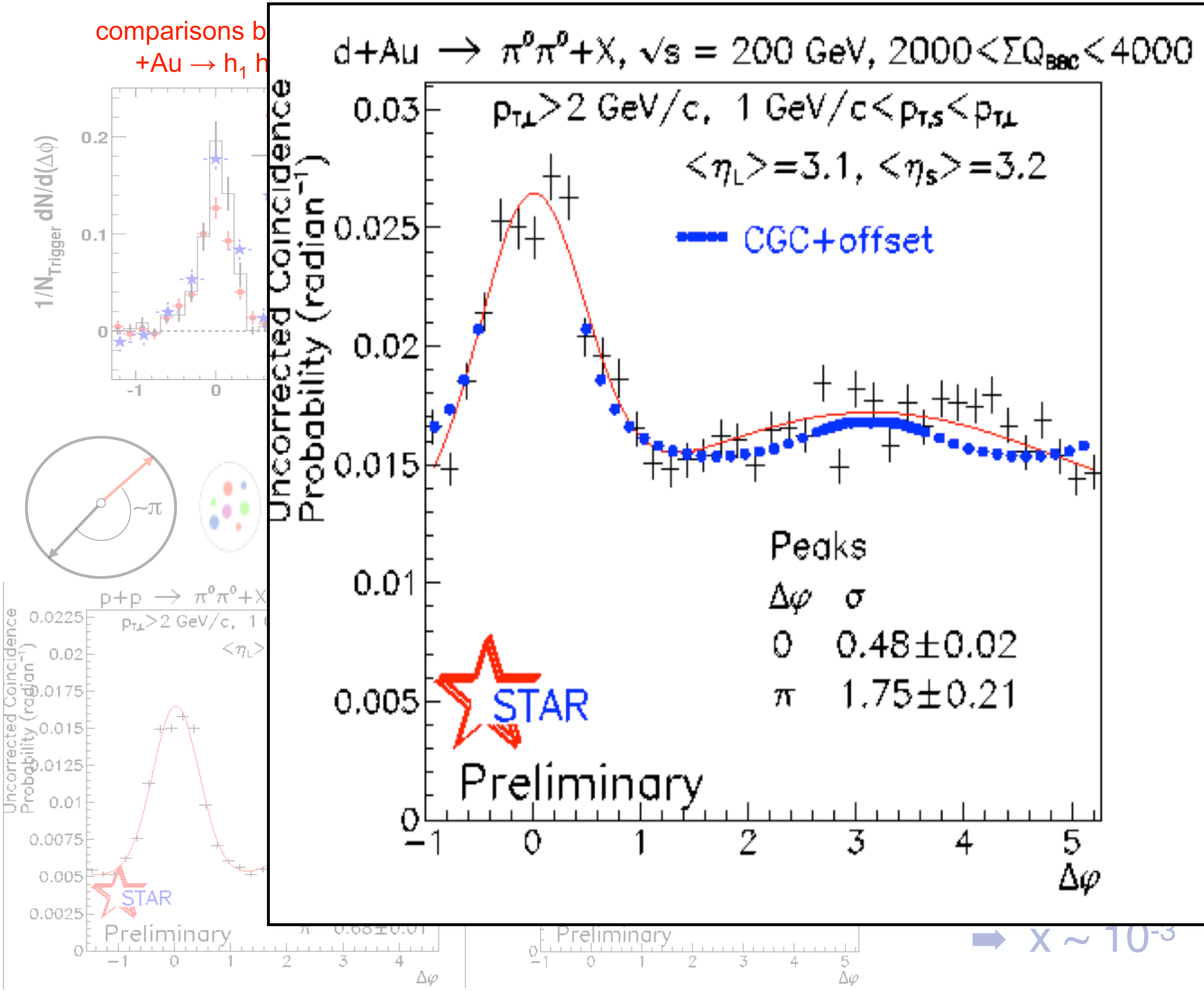




- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

➡ x ~ 10^{-3}

di-hadron correlations in d+A



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p+p or d+A

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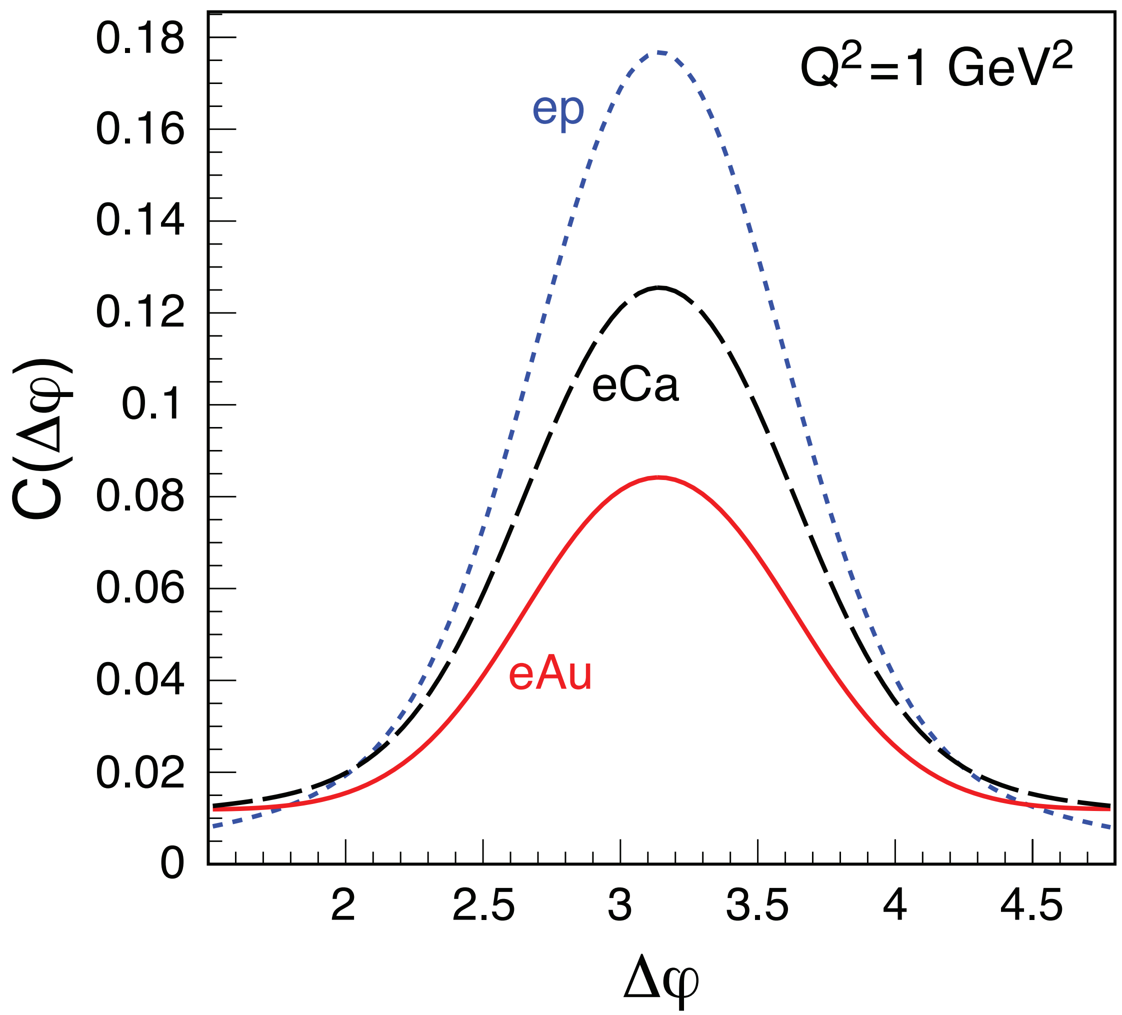
➡ $x \sim 10^{-3}$

di-hadron correlations in e+A

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



Dominguez, Xiao and Yuan (2012)

- 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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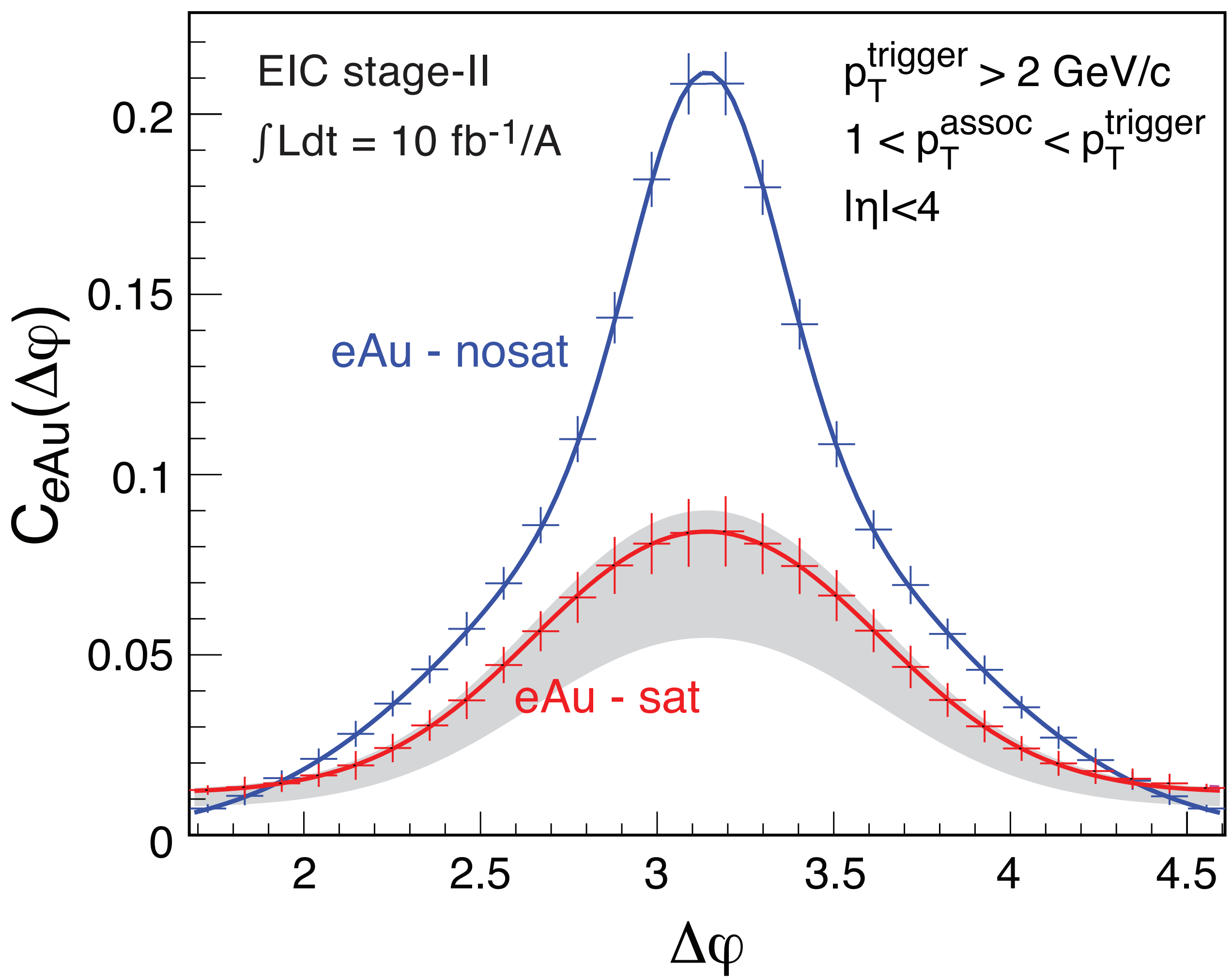

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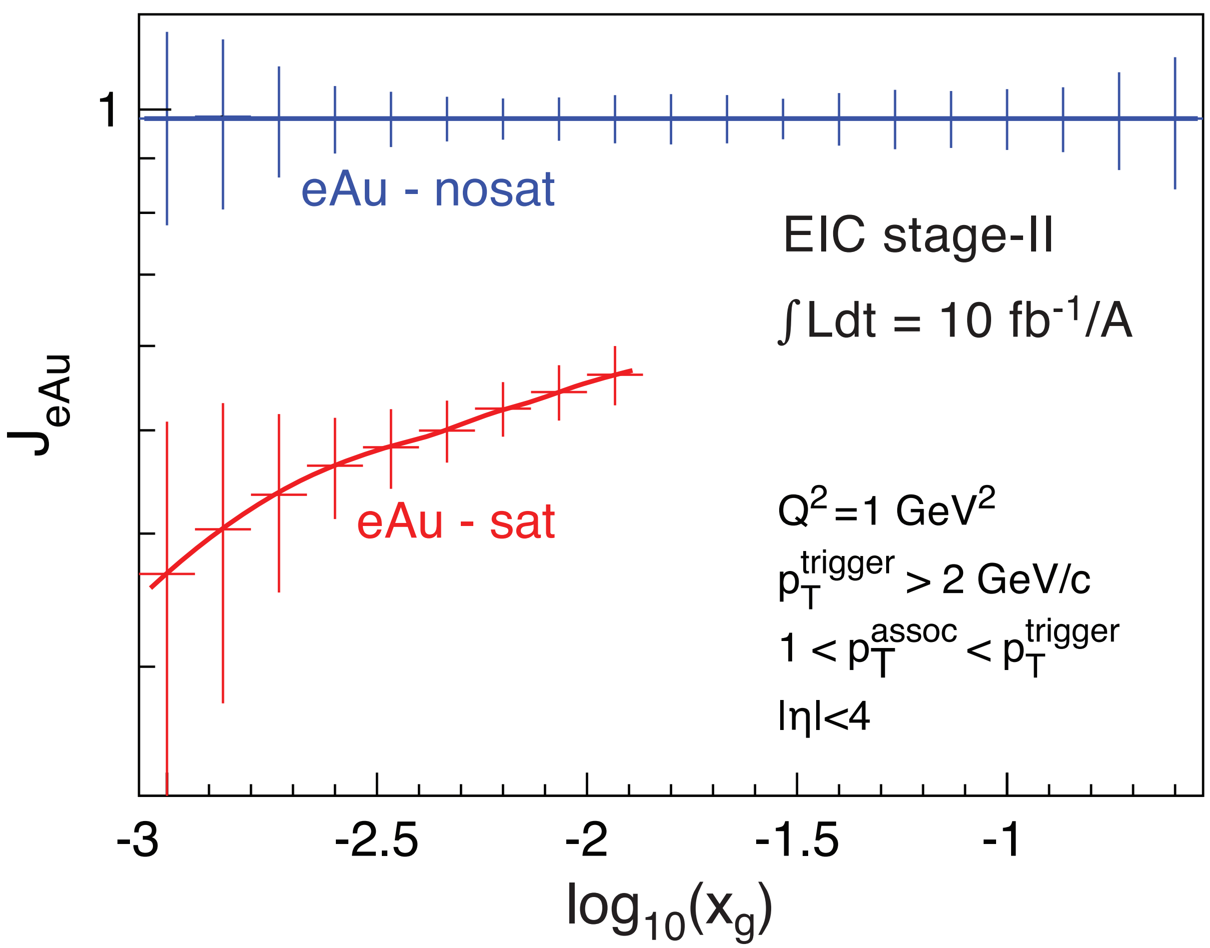
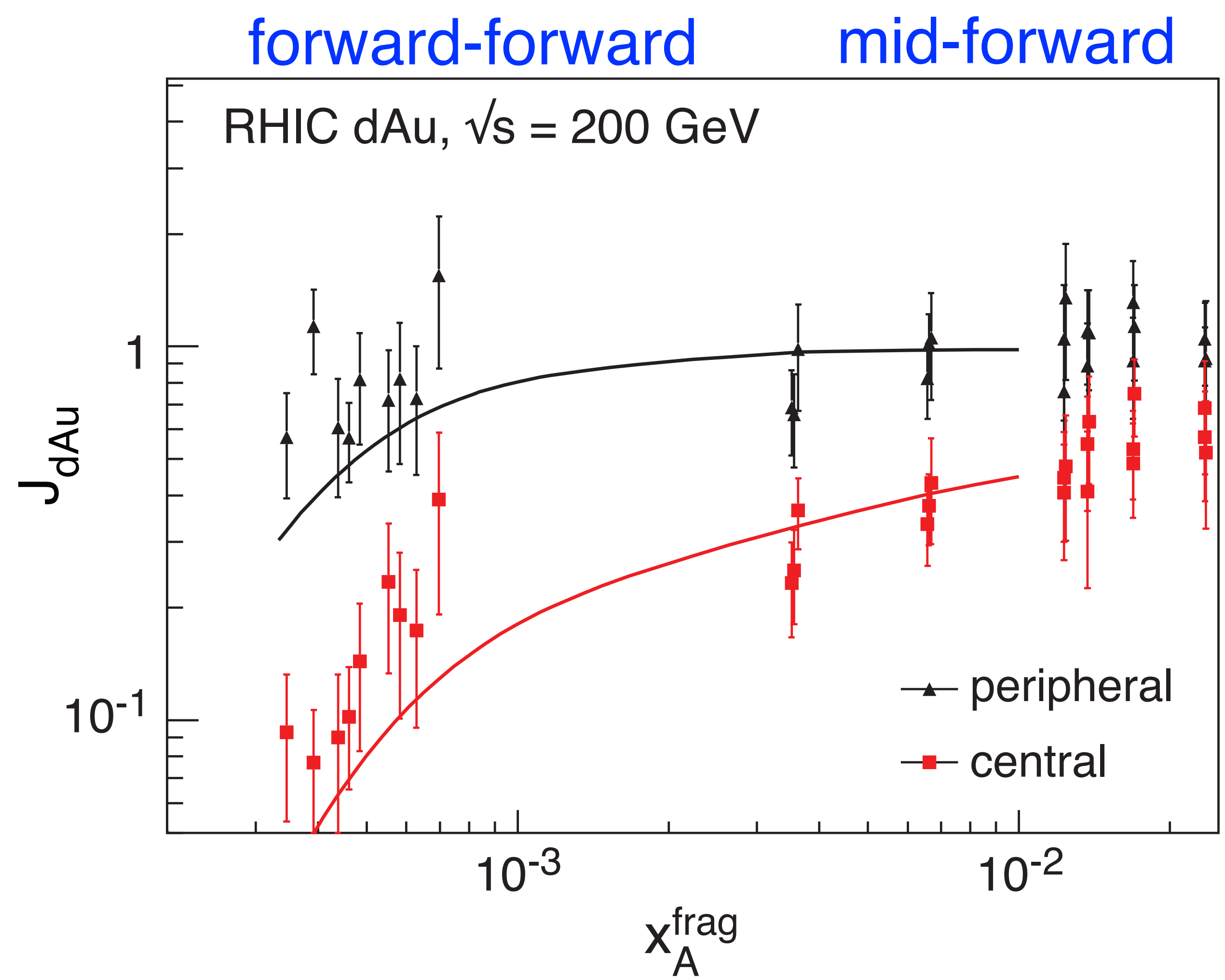
di-hadron Correlations - relative yields

- PHENIX measured J_{dAu} - relative yield of di-hadrons produced in d+Au compared to p+p collisions
  - ➡ Suppression in central events compared to peripheral as a function of x_A^{frag}
    - Curves come from saturation model
- Can perform the same measurement in e+A collisions





A. Adare et al., Phys. Rev. Lett. 107, 172301 (2011)

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 low-energy EIC (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: 1108.1713
  - ➡ An EIC White Paper (not just e+A), expounding on the INT programme has just been released to the community ArXiv: 1212.1701