Measuring the gluon distribution in nuclei 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

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arXiv:1108.1713

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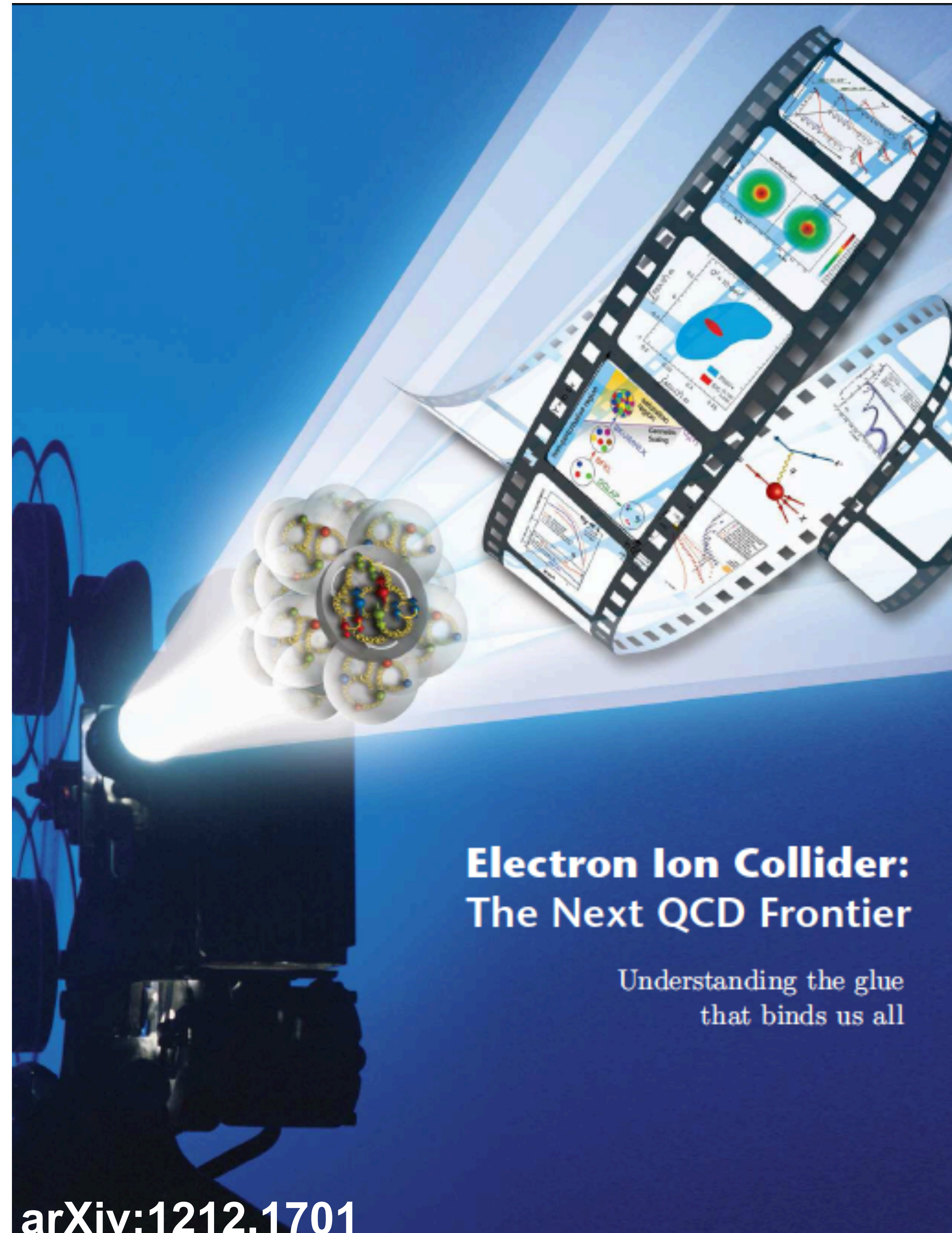
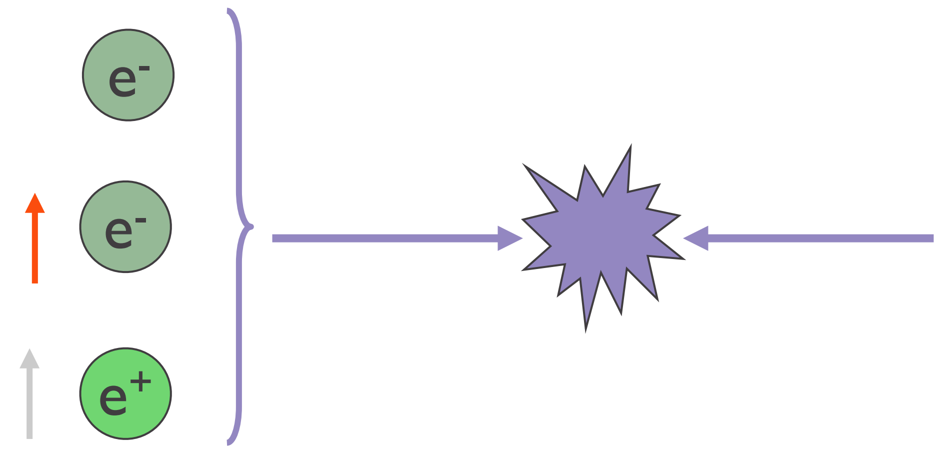


What is eRHIC?

Electron accelerator

(to be built)

Unpolarized and
polarized leptons
5-20 (30) GeV

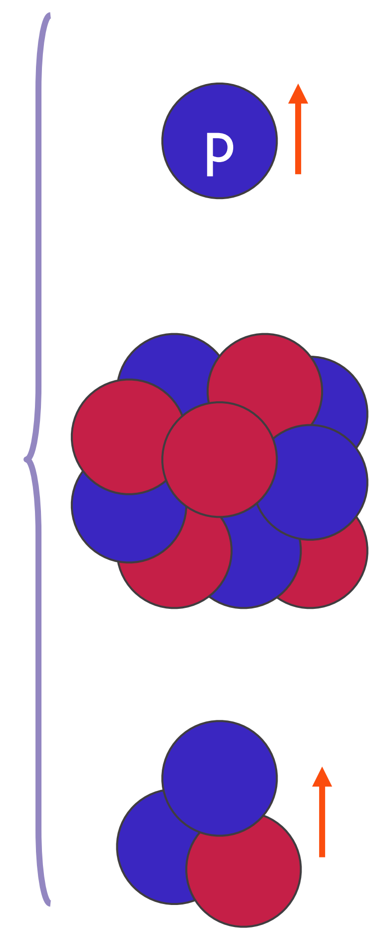


70% e- beam polarization goal

polarized positrons?

RHIC

Existing = $2B

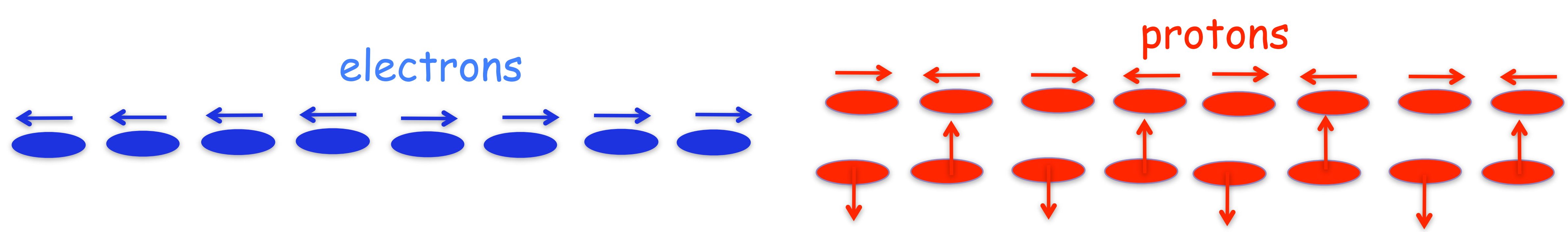


Polarized protons
50-250 GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

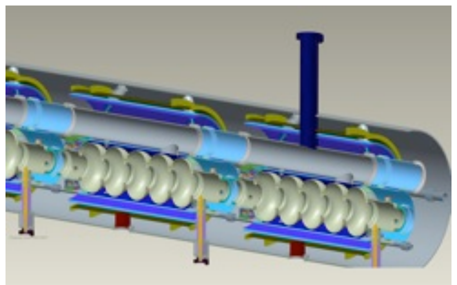
Polarized light ions He^3
166 GeV/u

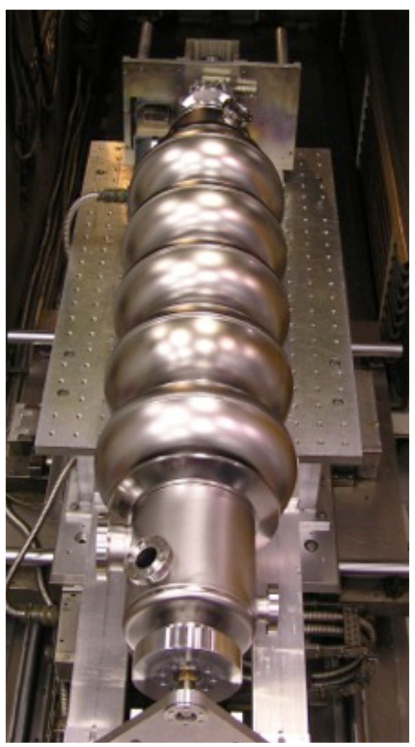
Center mass energy range: $\sqrt{s}$=30-200 GeV; L~100-1000xHera
longitudinal and transverse polarization for p/He^3 possible

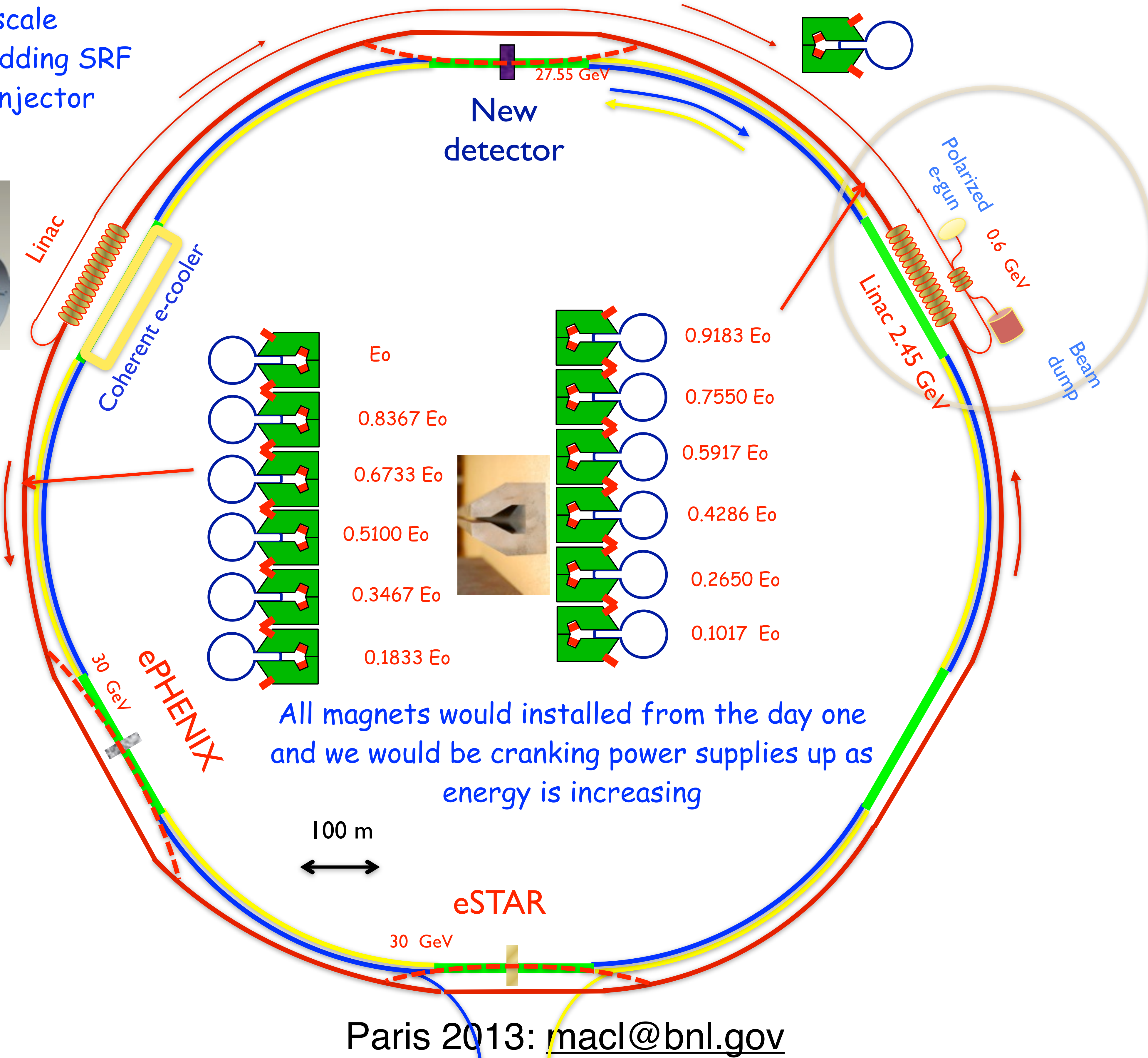


Staging of eRHIC: E_e: 5 to 30 GeV

All energies scale proportionally by adding SRF cavities to the injector





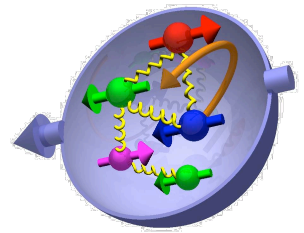


All magnets would installed from the day one and we would be cranking power supplies up as energy is increasing

E/Eo
0.0200
0.1017
0.1833
0.2650
0.3467
0.4283
0.5100
0.5917
0.6733
0.7550
0.8367
0.9183
1.0000

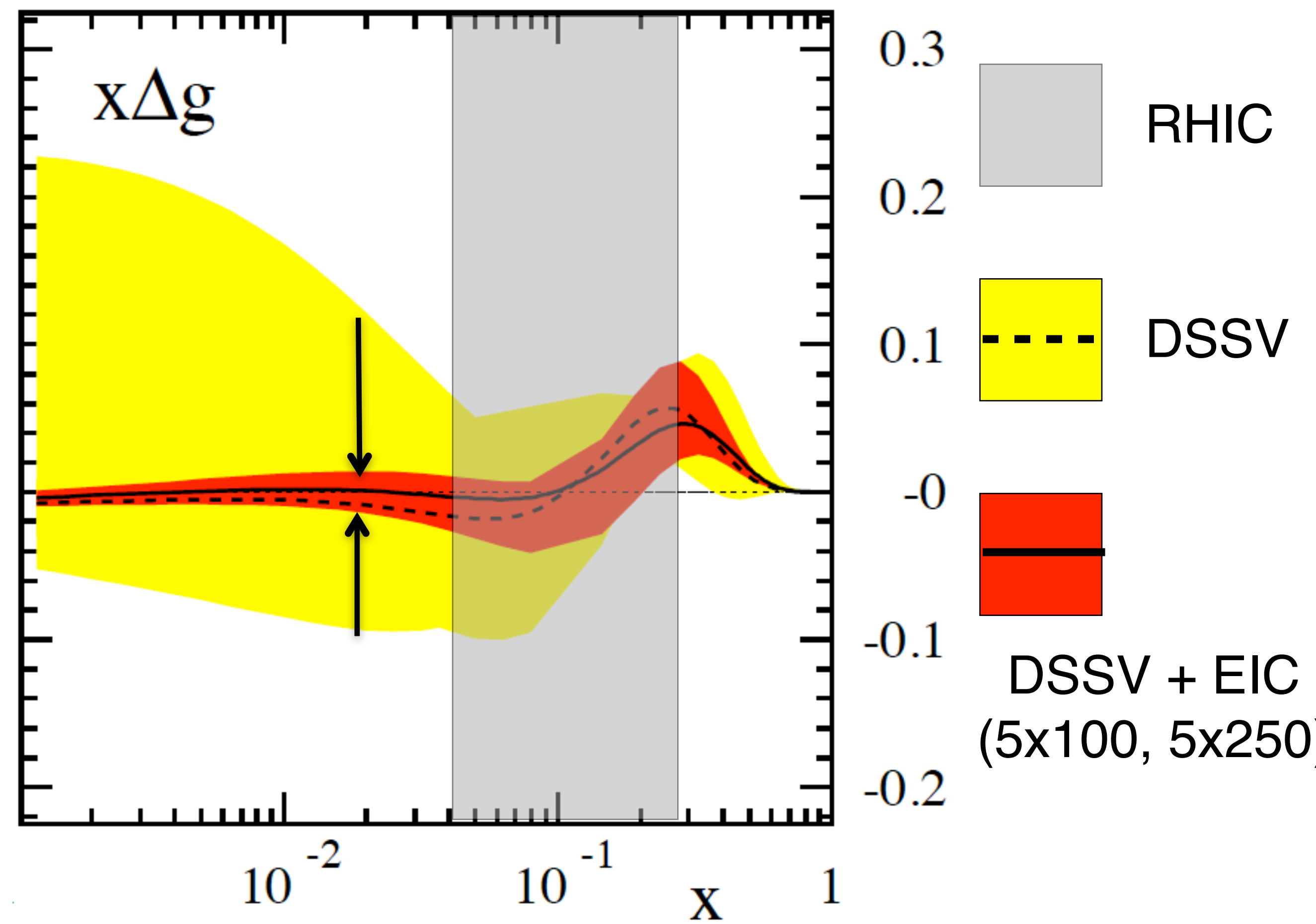
Most compelling physics questions

Spin physics

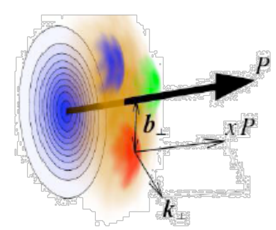


- What is the polarisation of gluons at small x where they dominate?
- What is the x-dependence and flavour decomposition of the polarised sea?

Determine quark and gluon contributions to the proton spin at last!!

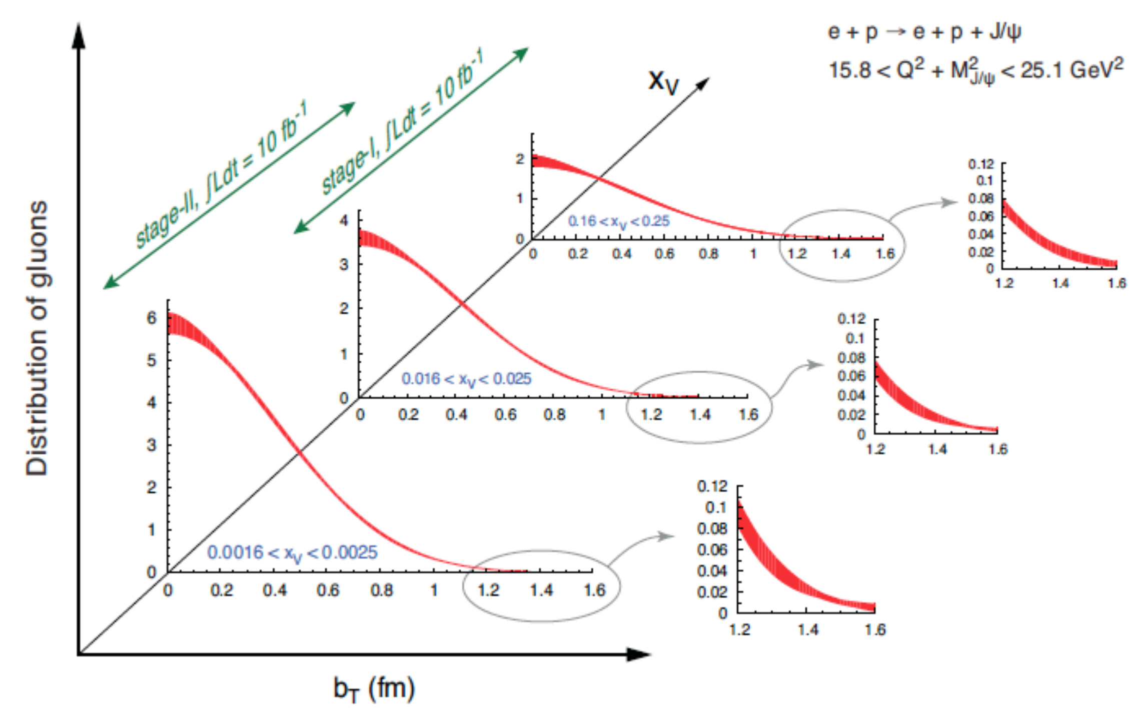


Imaging



- What is the spatial distribution of quarks/ gluons in nucleons AND nuclei?
- Understand deep aspects of gauge theories revealed by k_T dependent distributions

Possible window to orbital angular momentum



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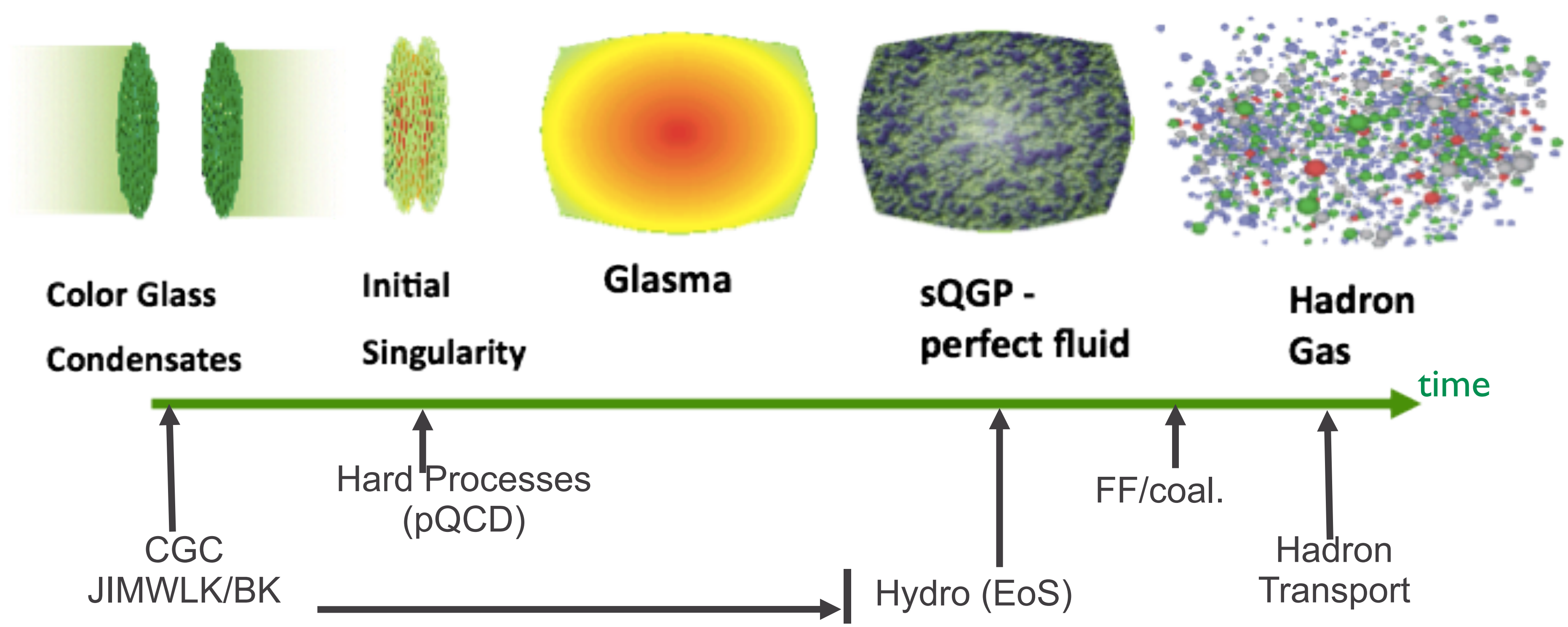
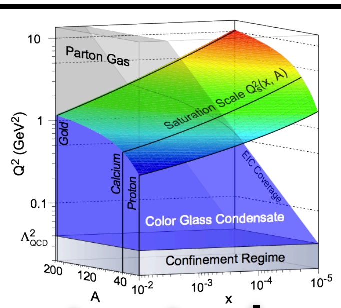
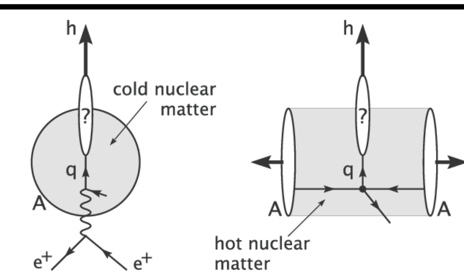




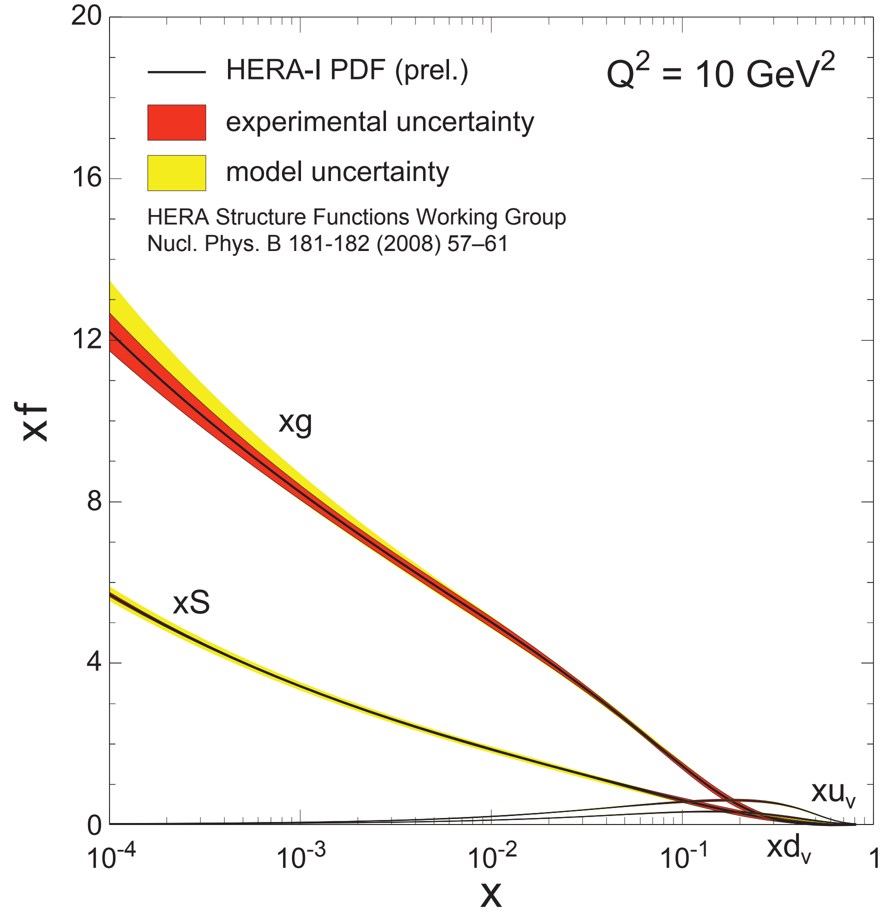
Strong Colour Fields and Hadronisation

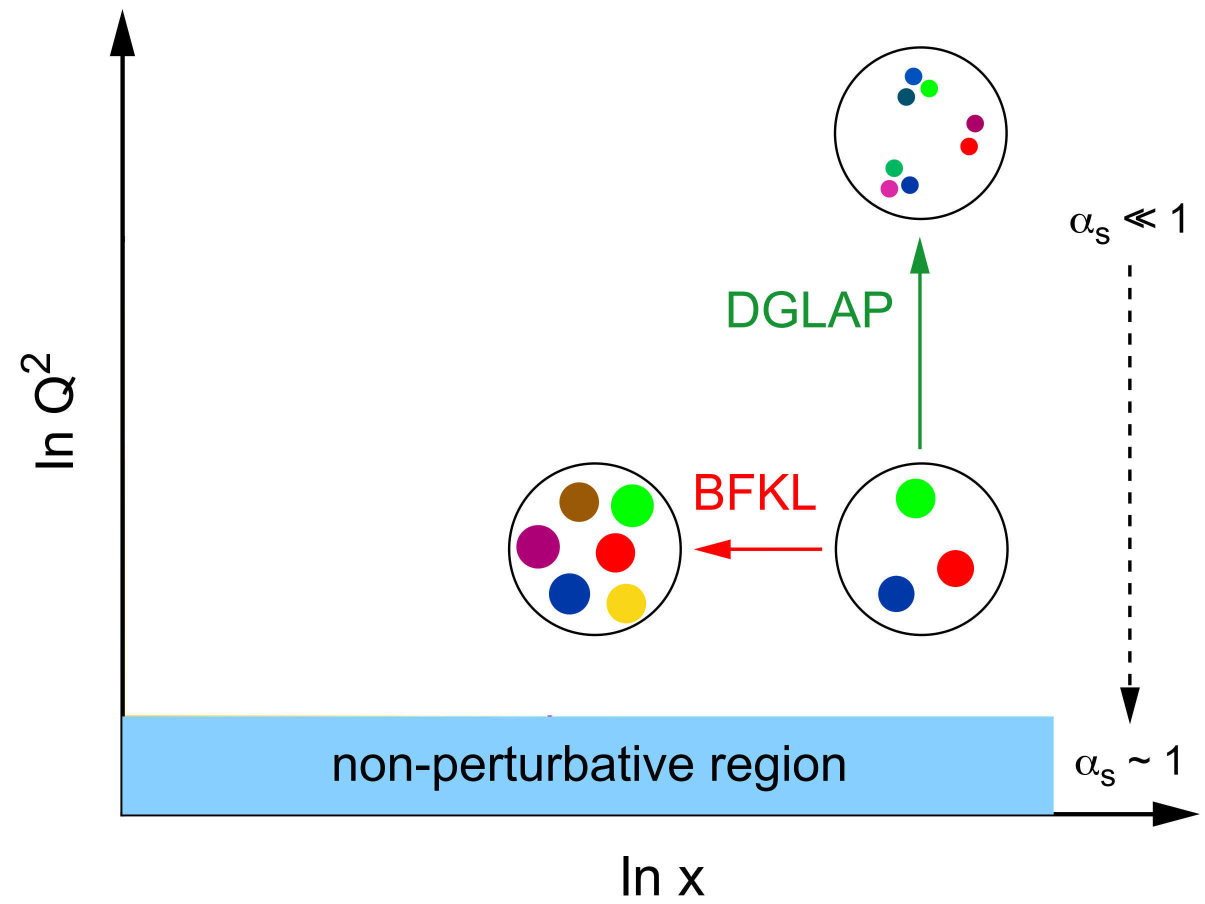


- Quantitatively probe the universality of strong colour fields in A+A, p+A and e+A
- Understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- What is the spatial distribution of quarks and gluons in nucleu and how much does it fluctuate?
- How do hard probes in e+A interact with the medium?

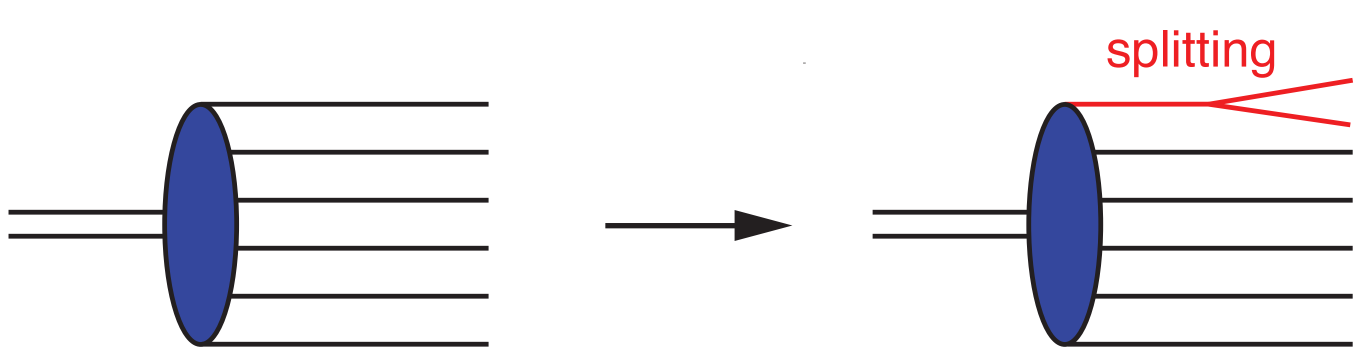
Currently have no experimental knowledge of gluons in nuclei at small x!!

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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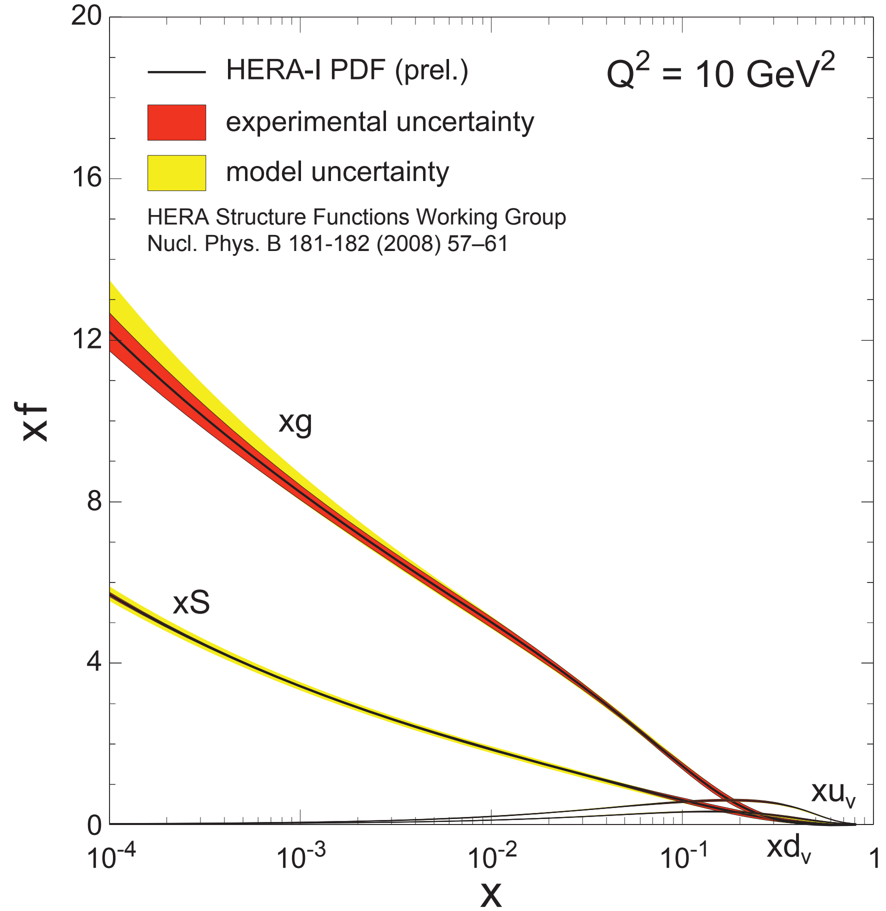

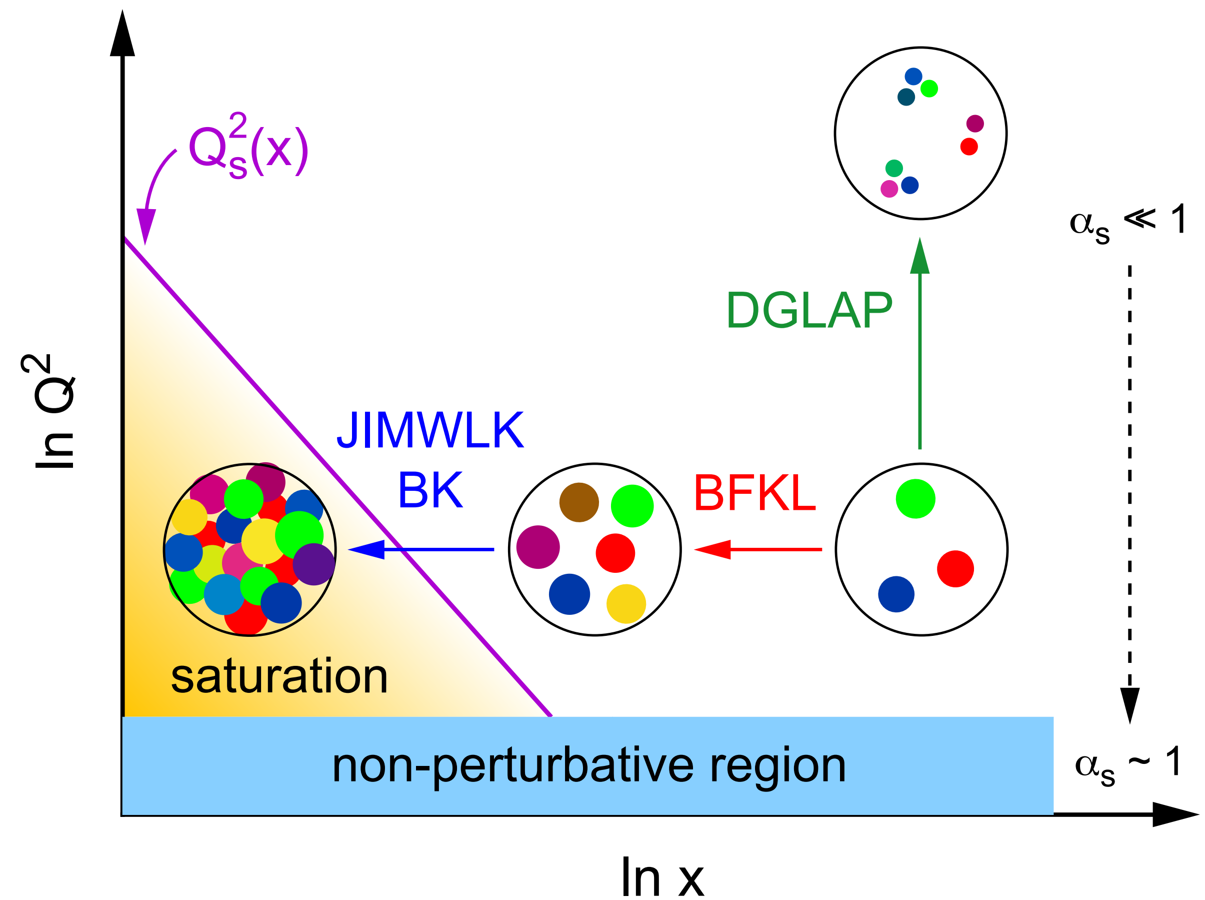

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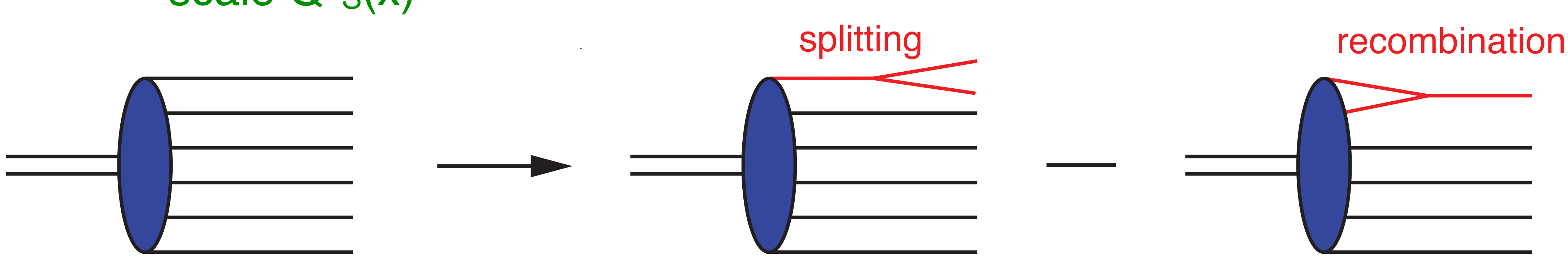
  - ➡ This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_S(x)$



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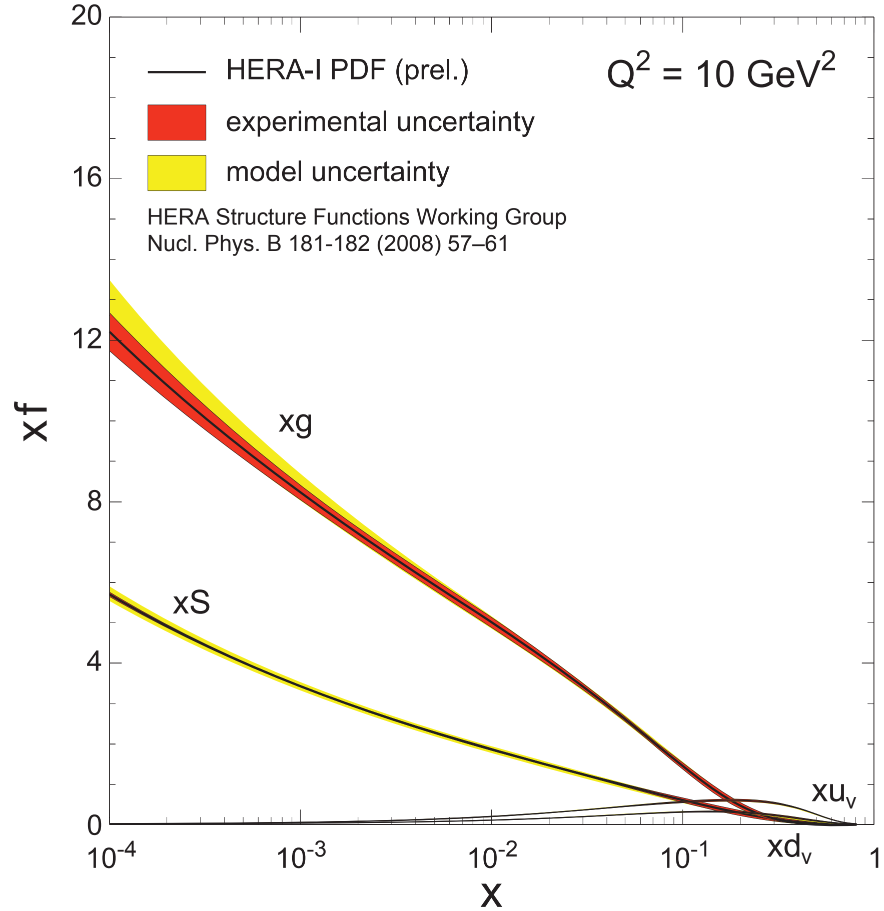

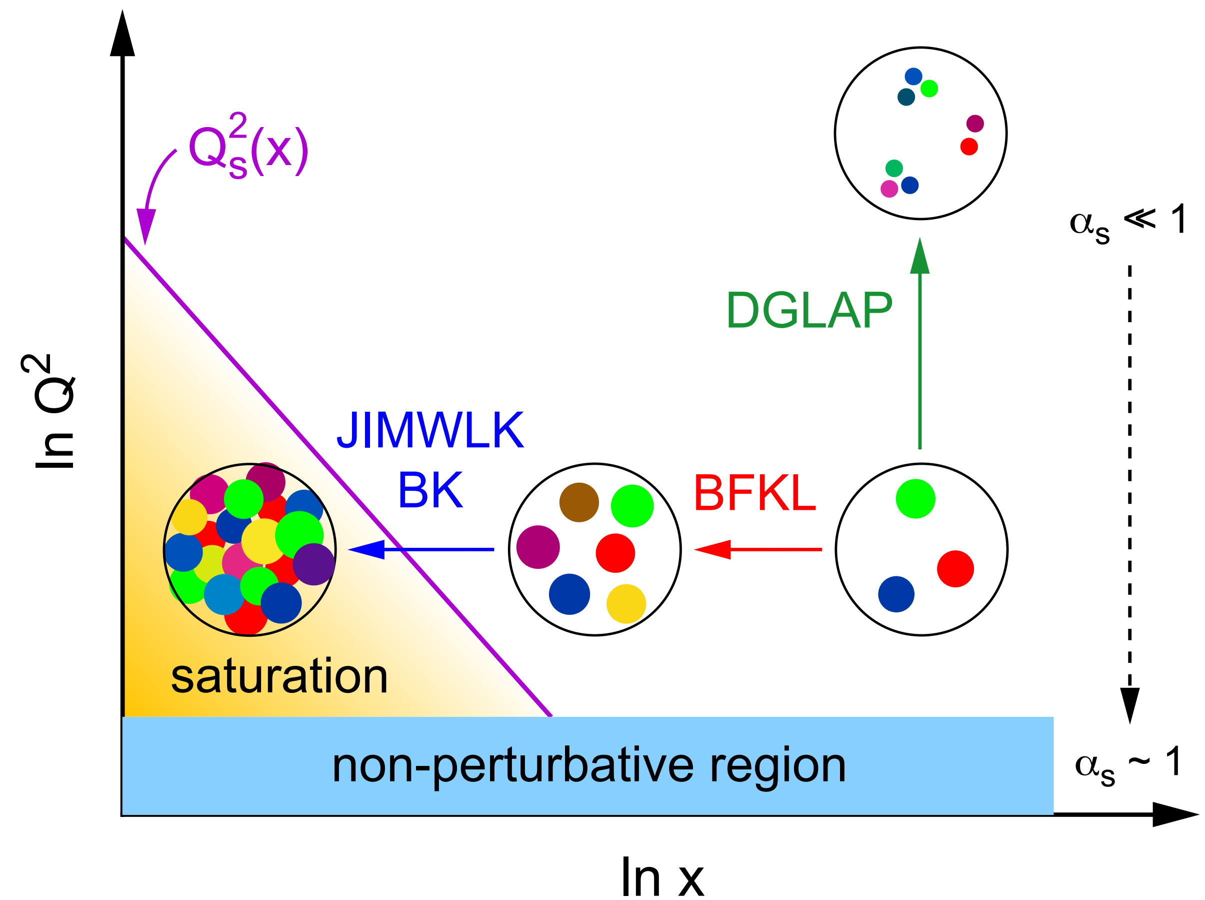

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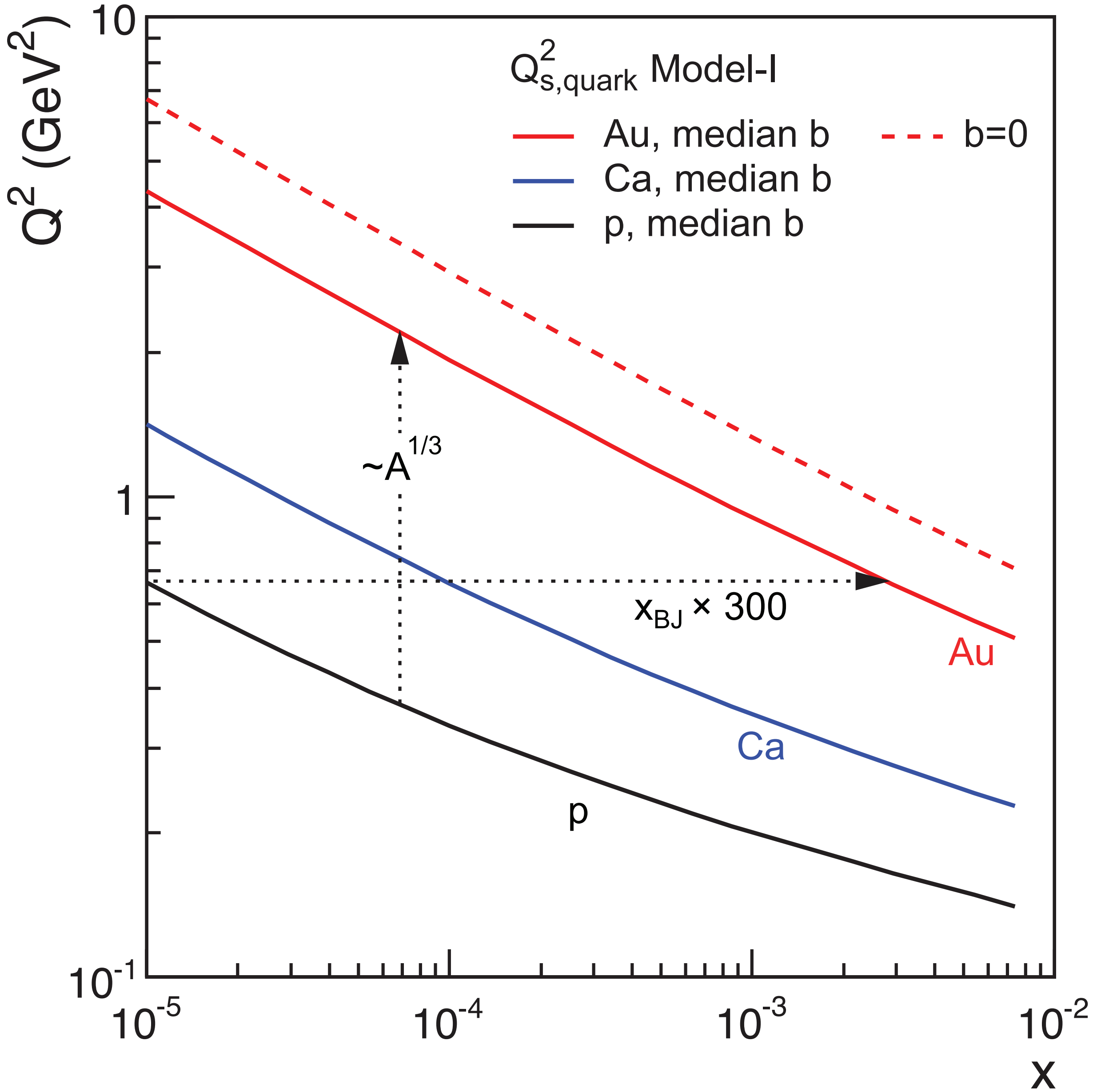
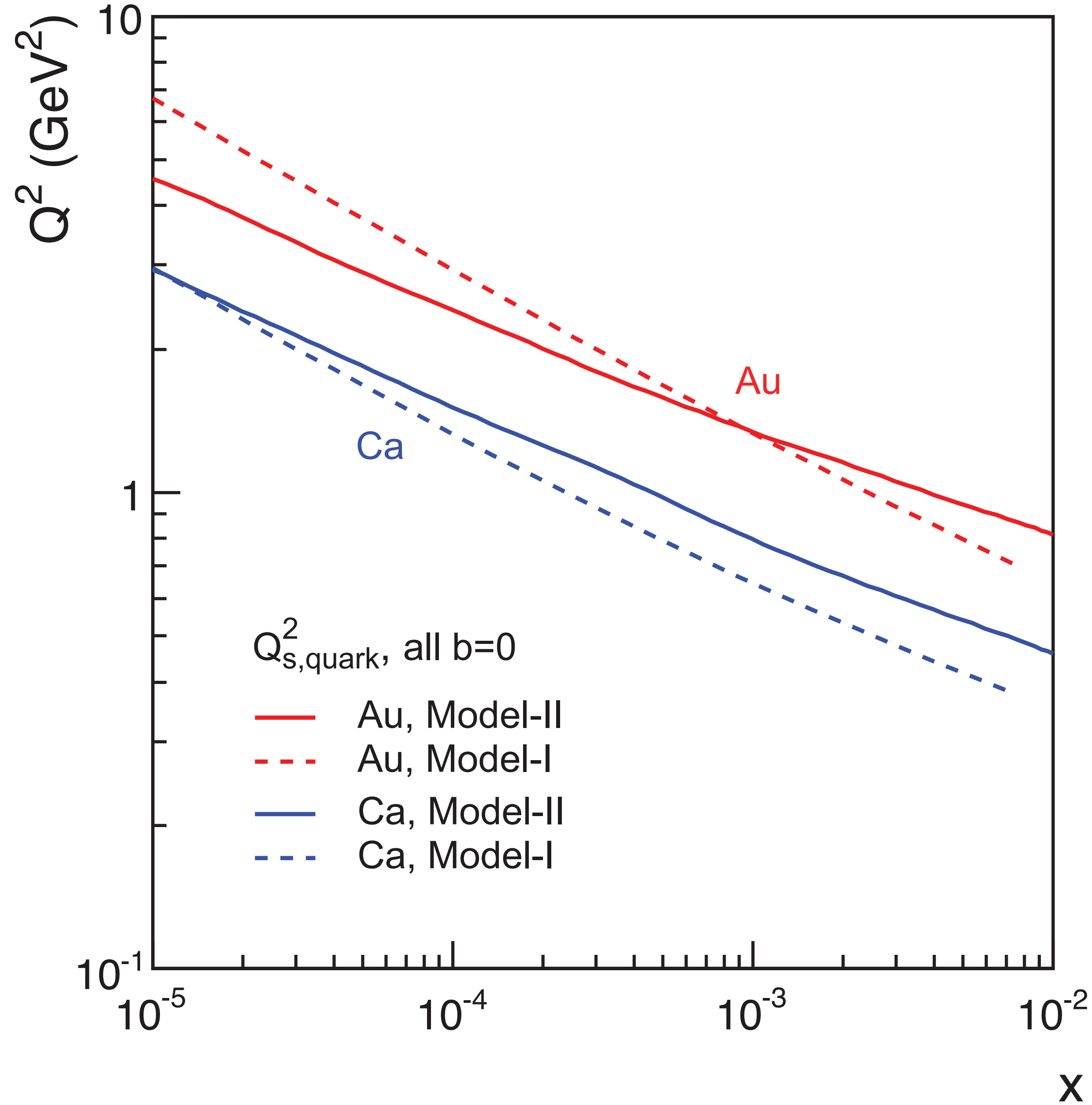
however - saturation in the gluon density is not observed in the gluon distribution at HERA -> too small an x

How can this be observed at eRHIC?

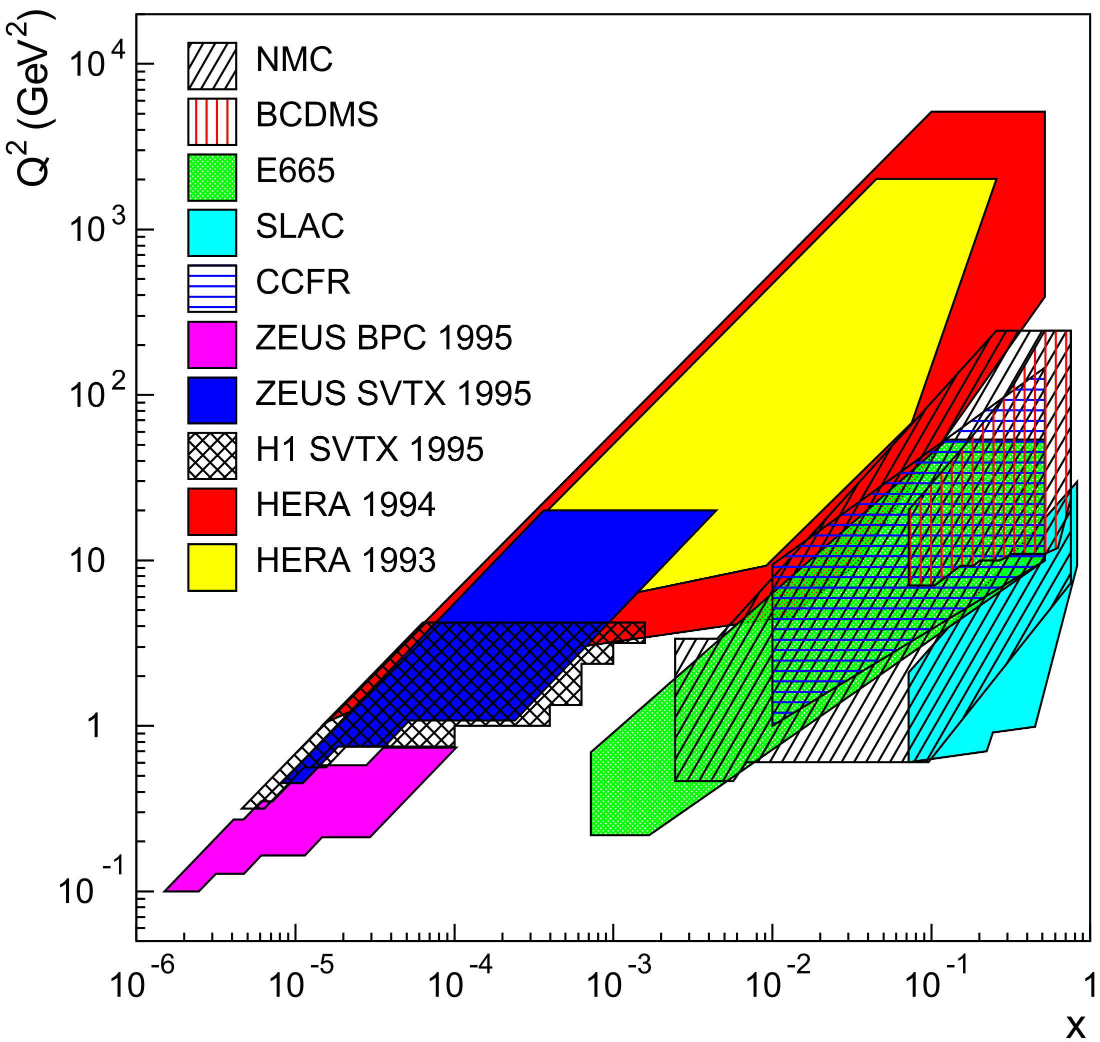
Nuclear "oomph" effect

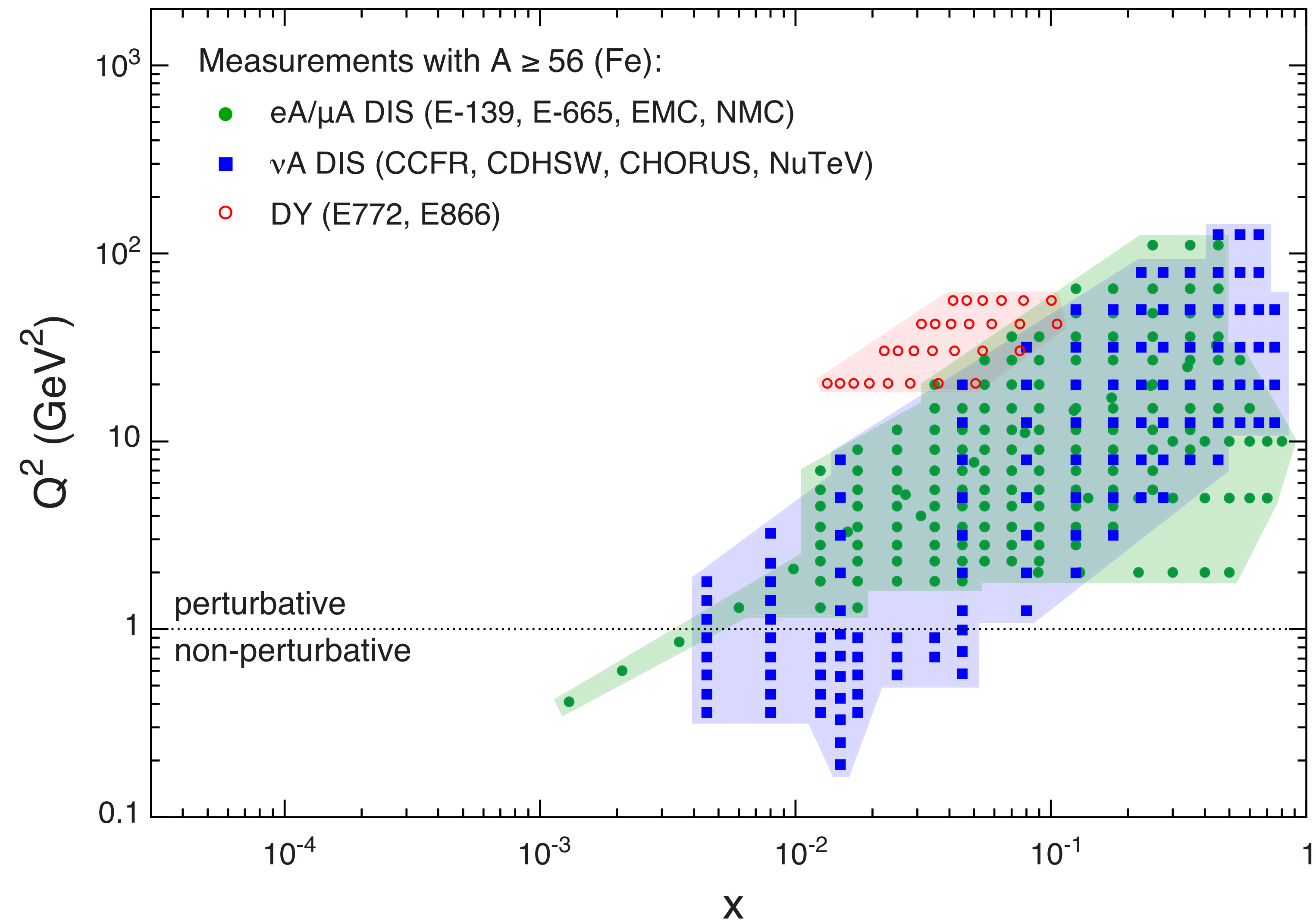
Pocket formula: $Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$





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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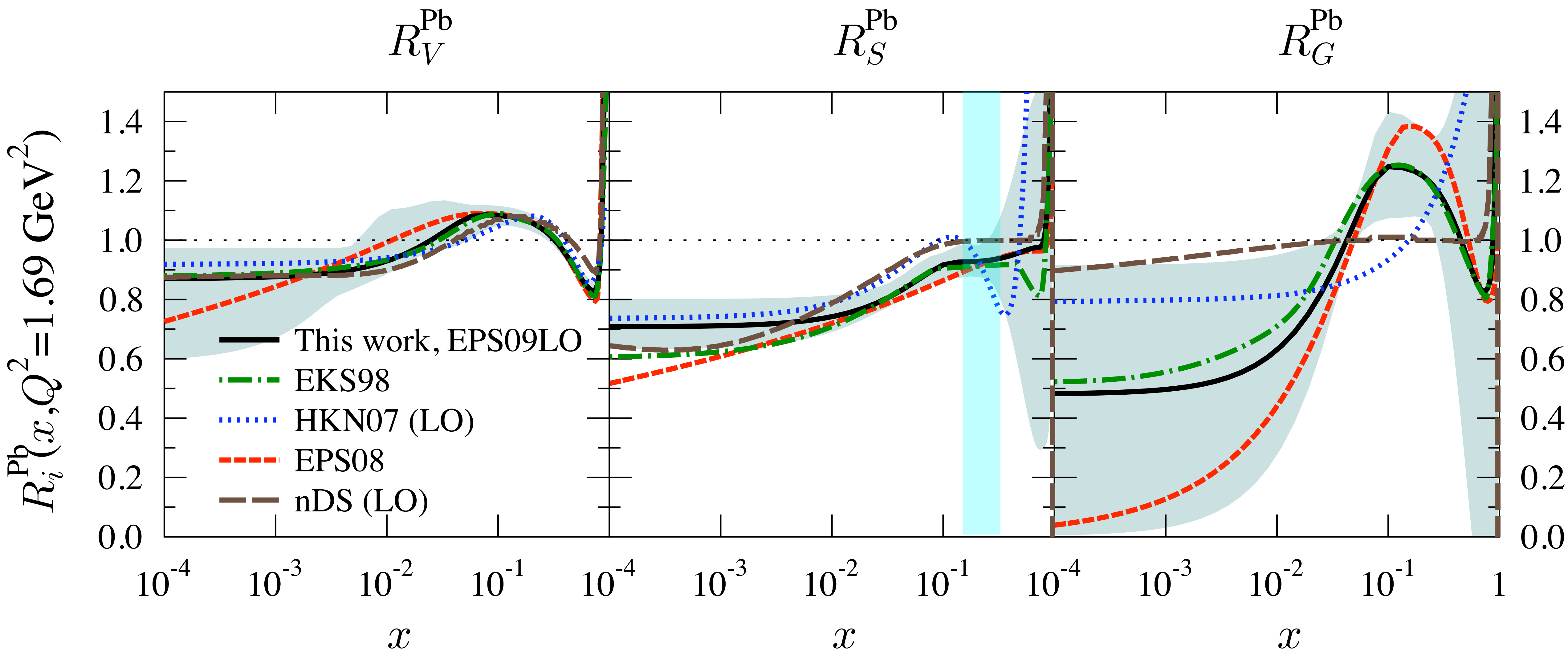

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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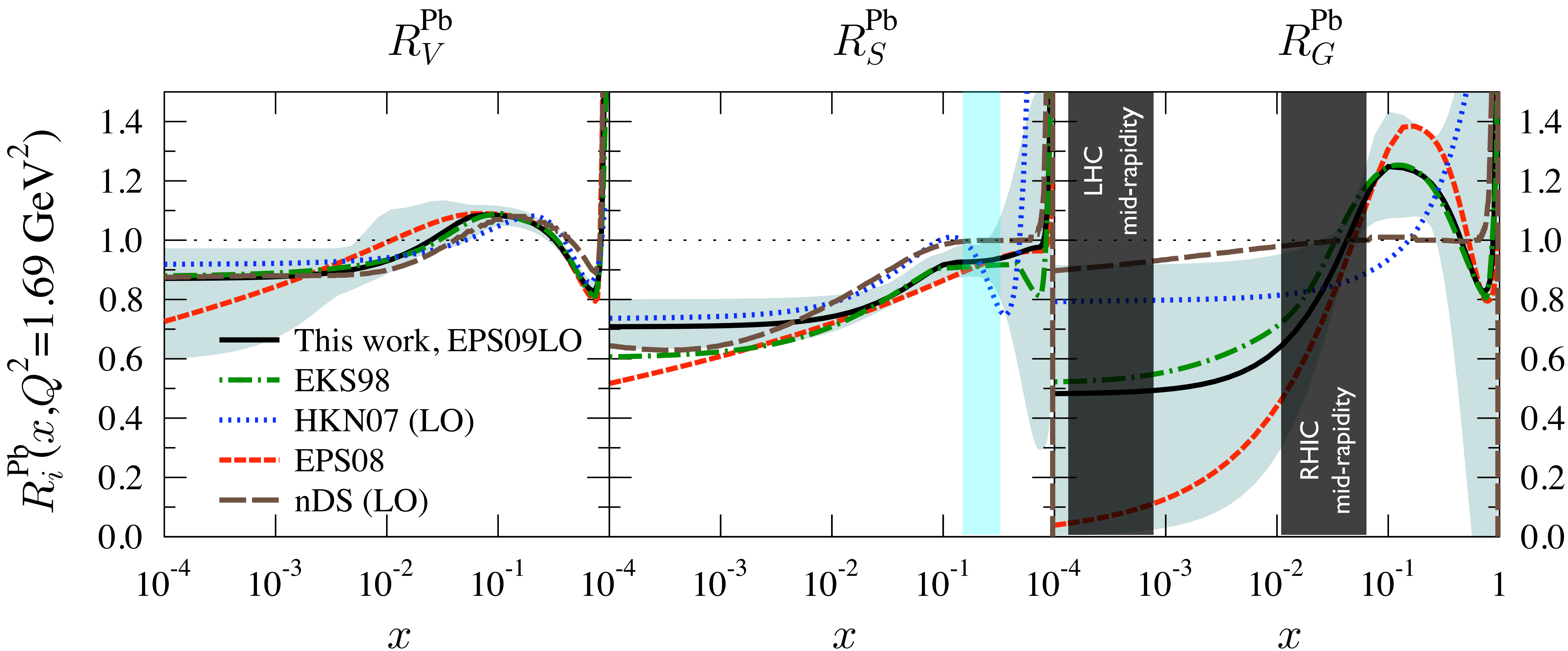

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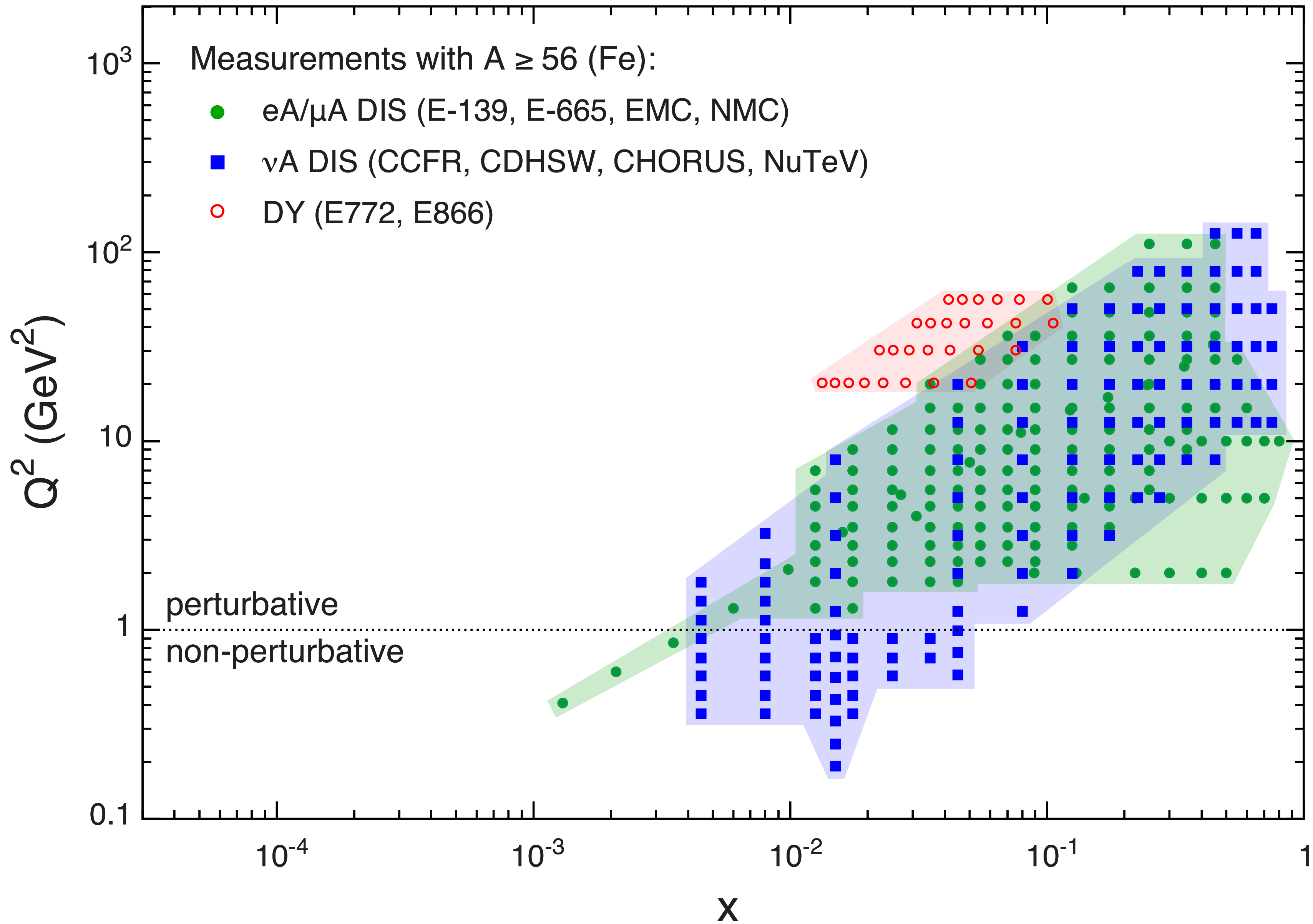
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

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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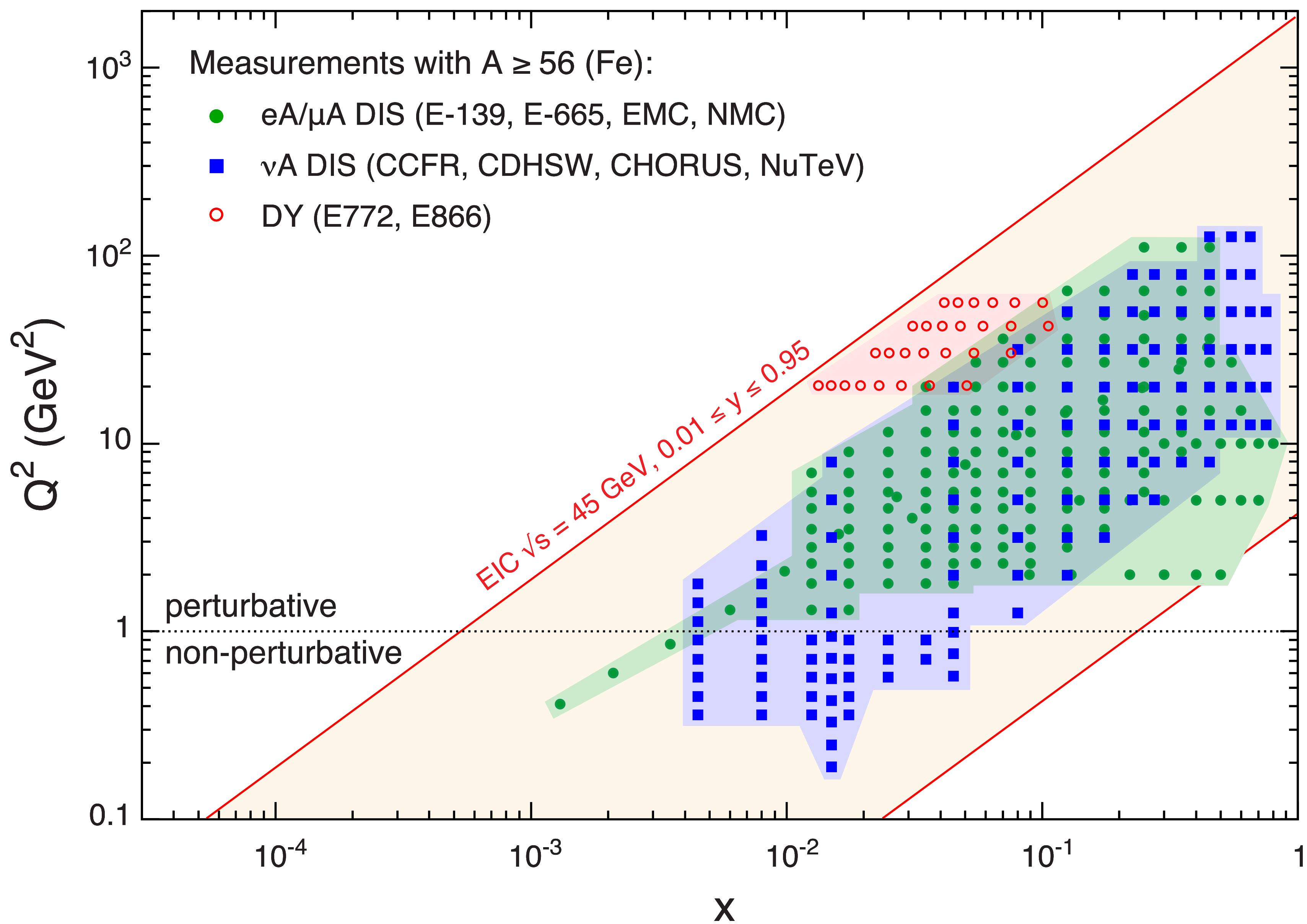

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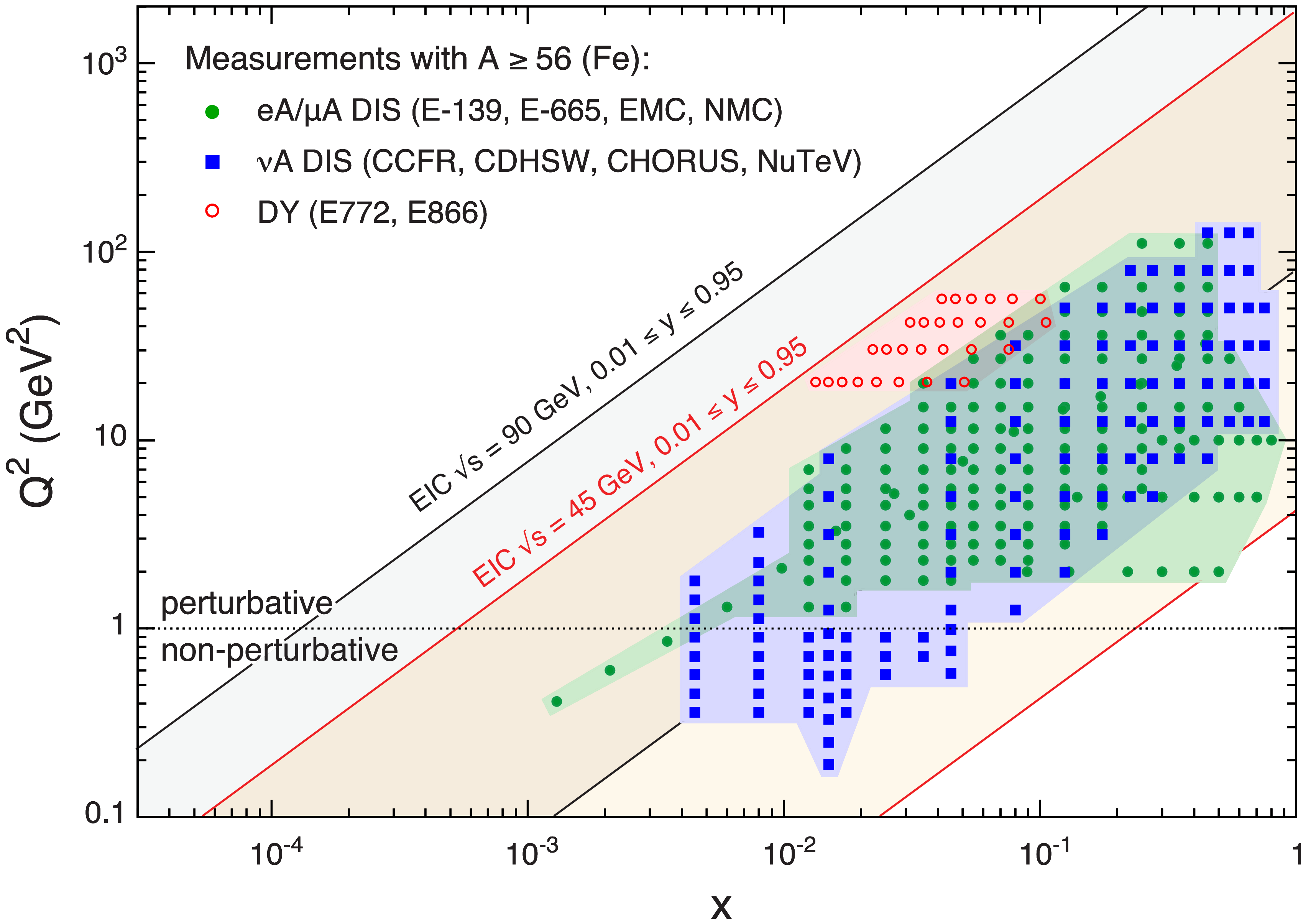

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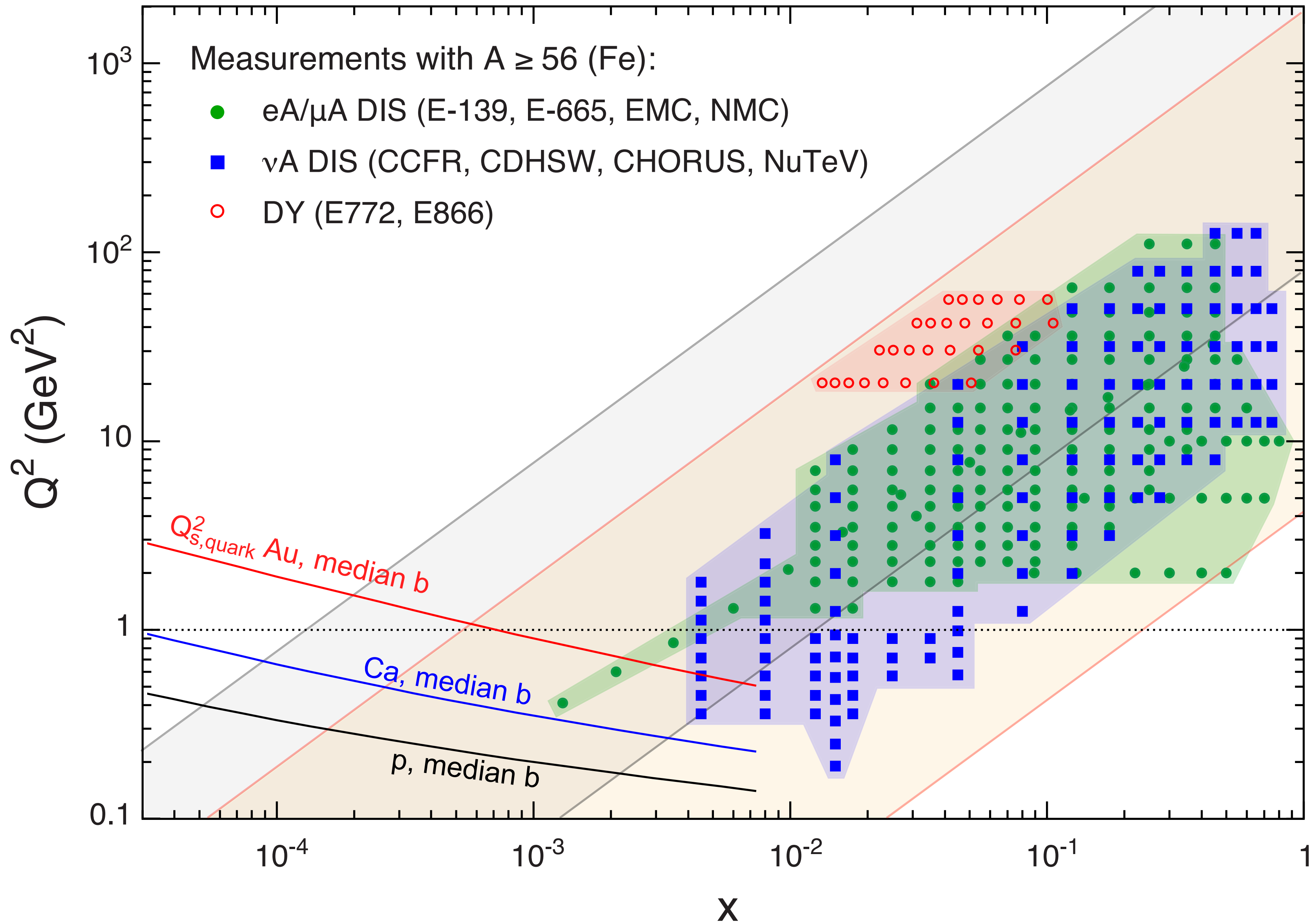
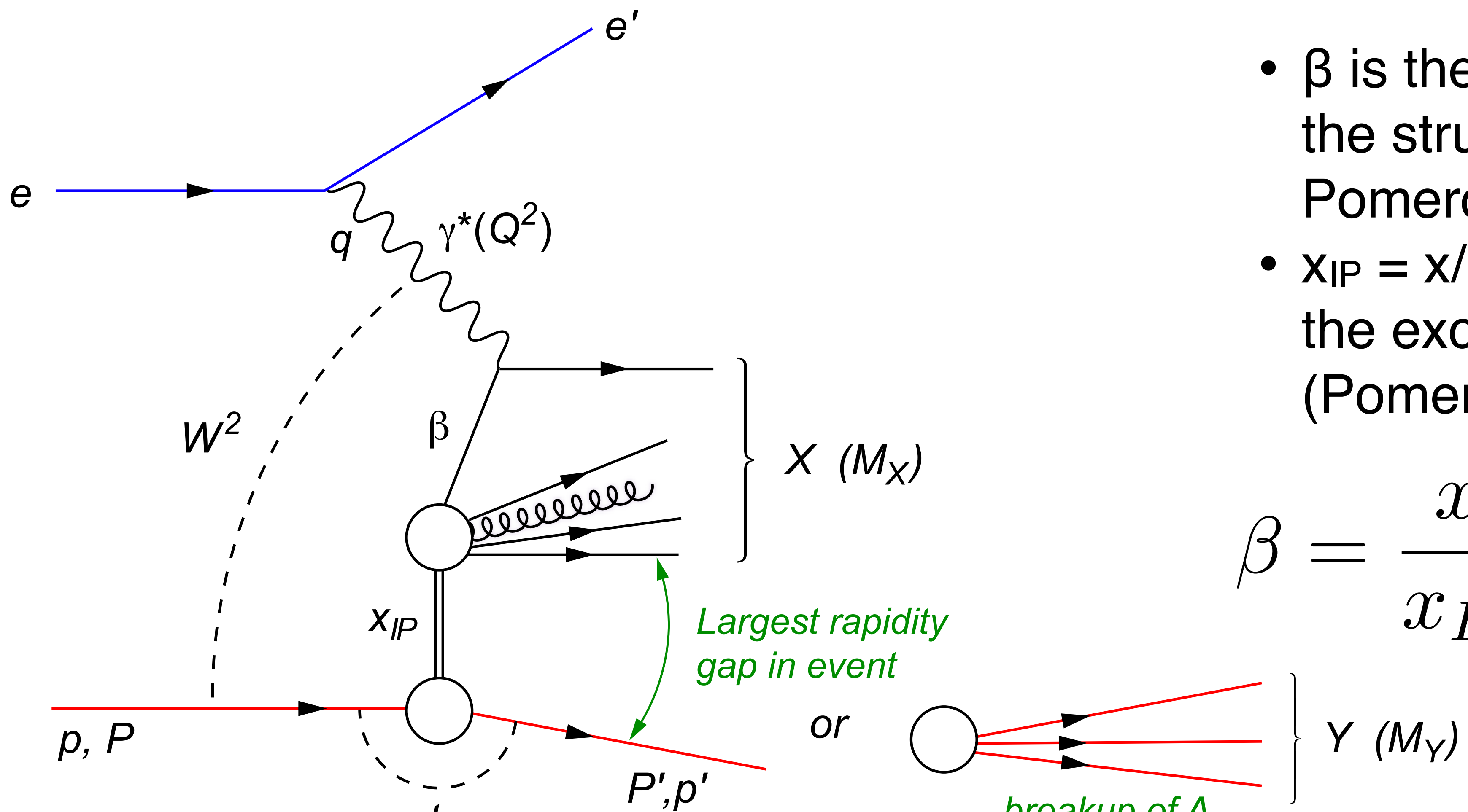


Exclusive processes in e+A - diffraction



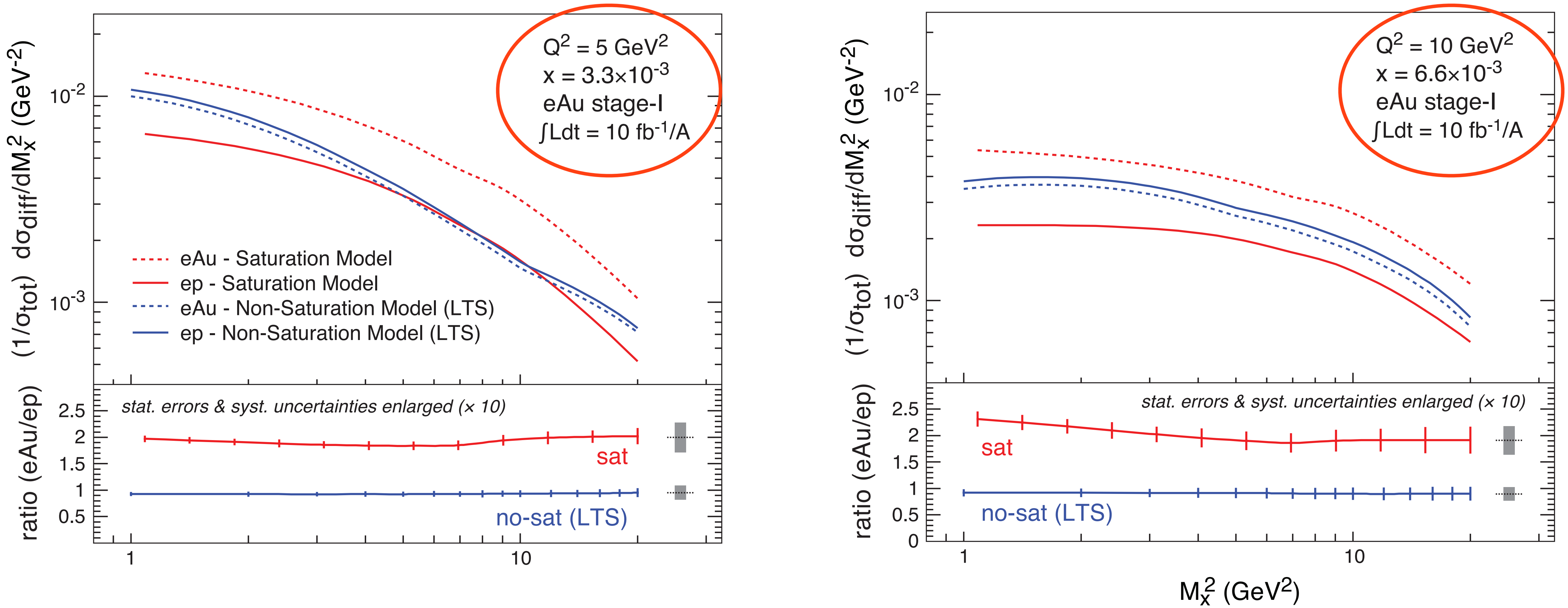
$$t = (p - p')^2$$

- 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

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

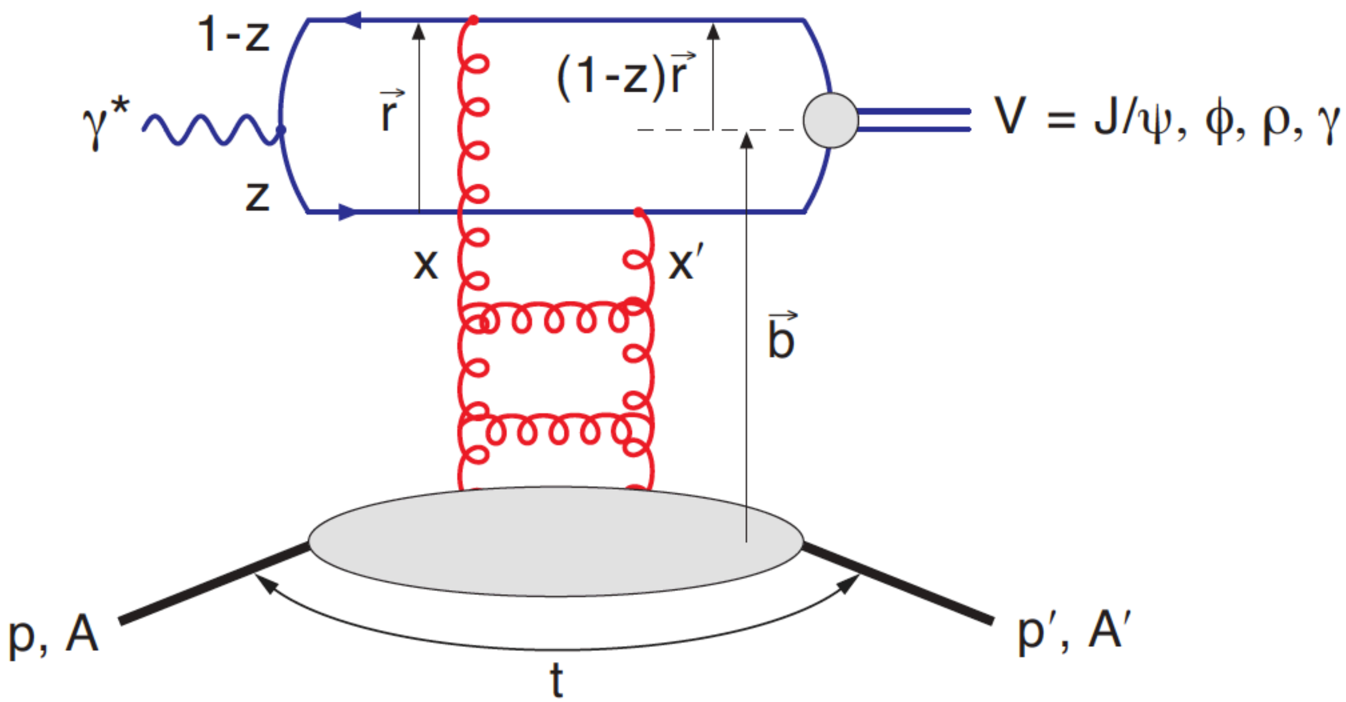
- **Diffraction in e+p:**
  - ➡ HERA: 15% of all events are diffractive
- **Diffraction in e+A:**
  - ➡ Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - ➡ Coherent diffraction (nuclei intact)
  - ➡ Incoherent diffraction: breakup into nucleons (nucleons intact)

Day 1: Diffractive Cross-sections

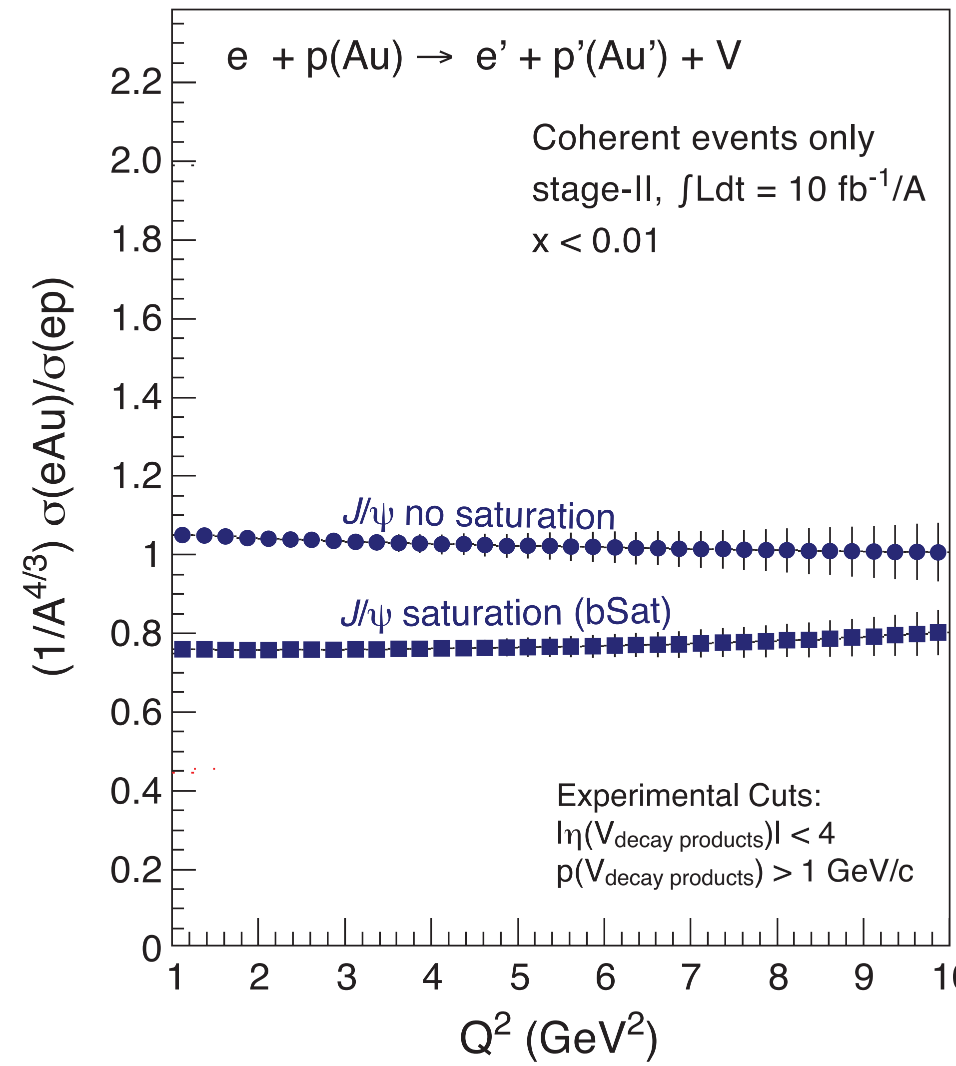


- Ratio of diffractive-to-total cross-section drastically different between saturation (Marquet) and non-saturation (Frankfurt, Guzey, Strikman) models
- Expected experimental error bars (simulated for 10 fb^{-1} of data for a low-energy eRHIC) can distinguish between the two scenarios

Exclusive vector meson production

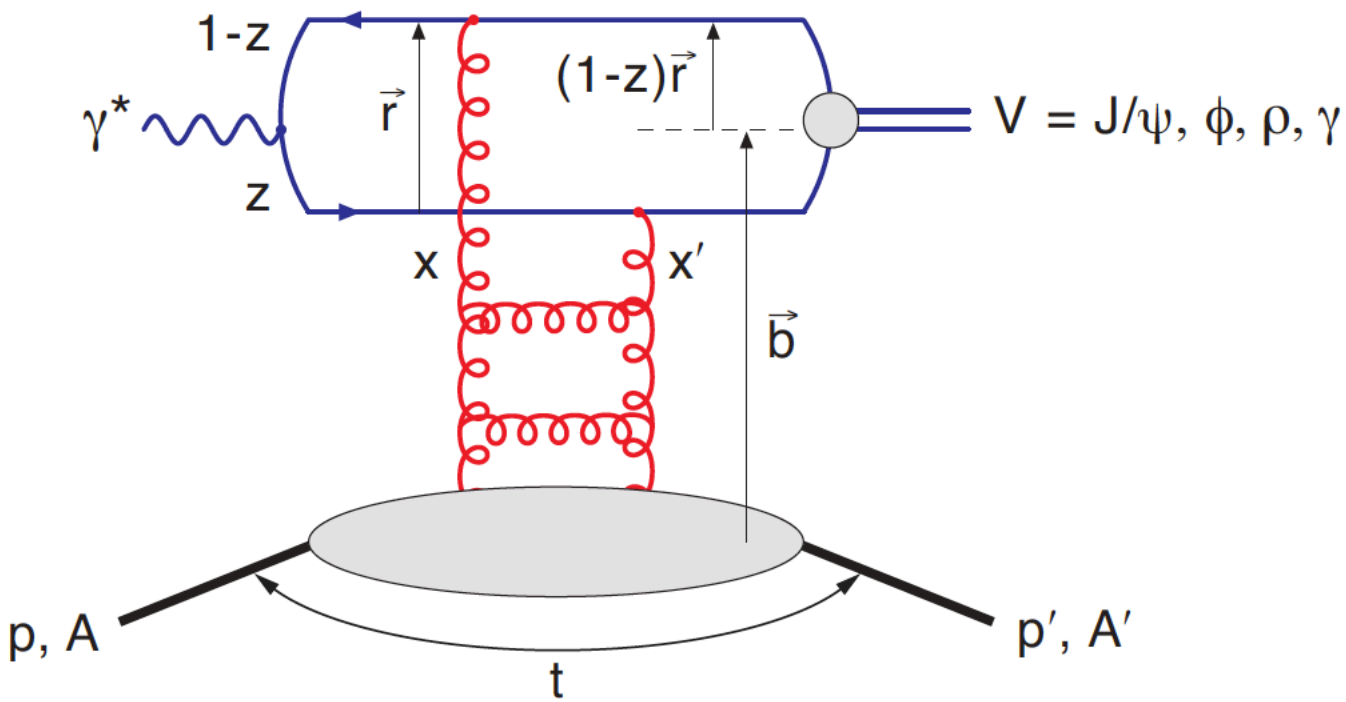


$$d\sigma \propto g(x)^2$$



- 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

Exclusive vector meson production



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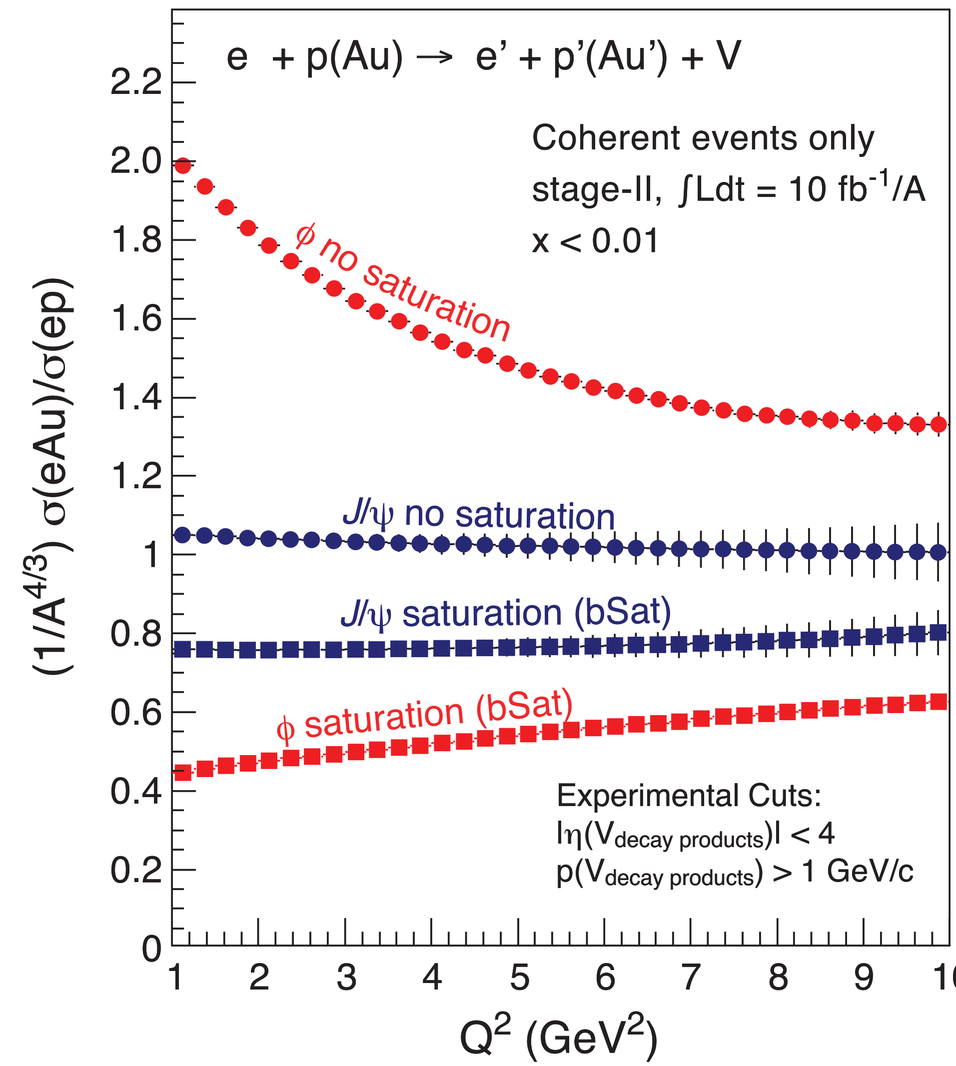
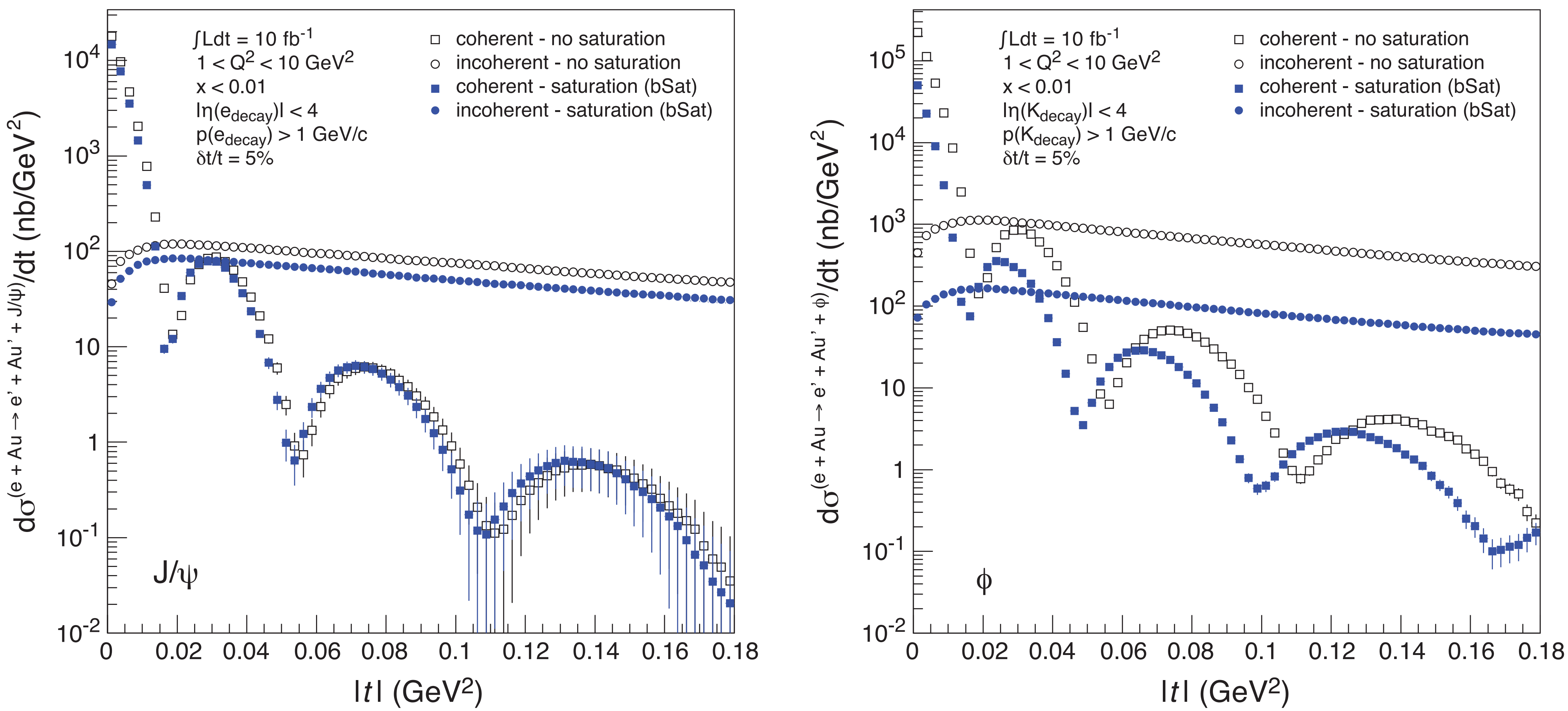


- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference
  - ➡ wave function for ϕ is larger and hence more sensitive to saturation effects

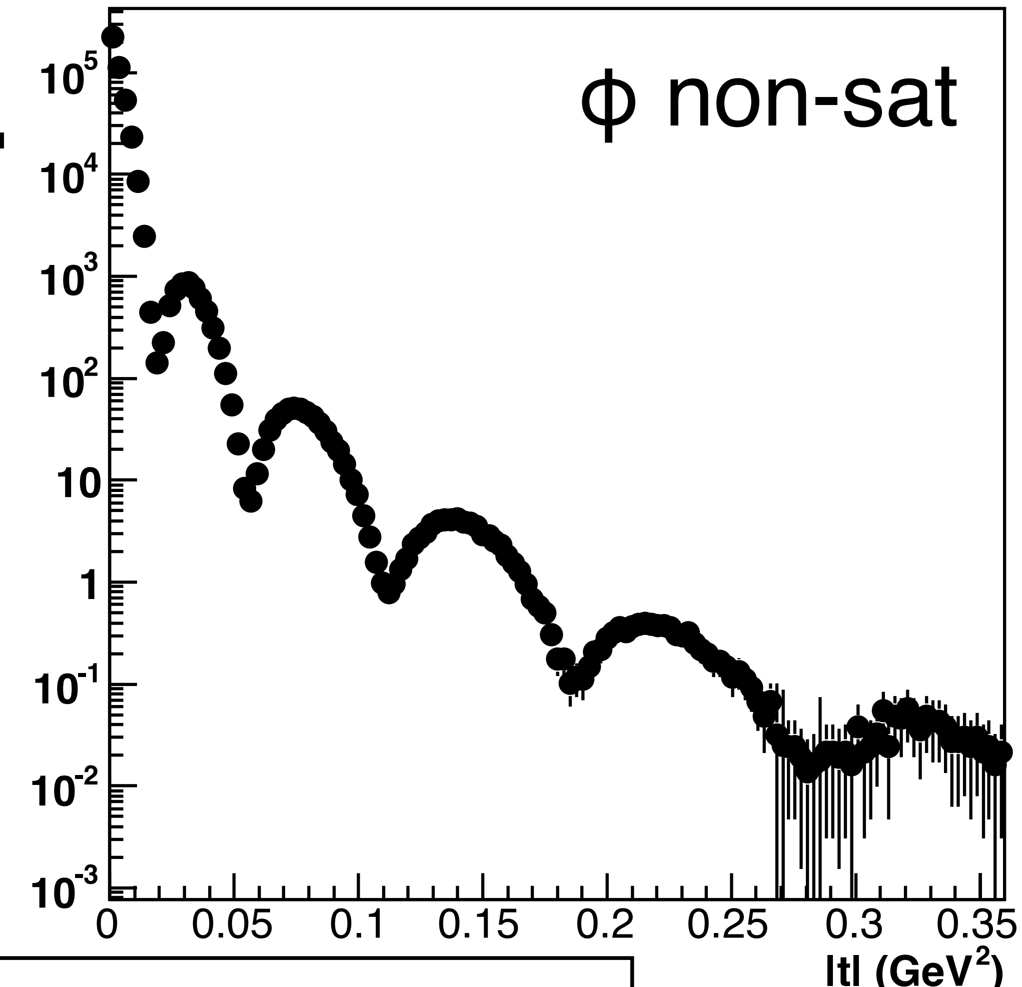
Exclusive Vector Meson Production in e+A



- 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

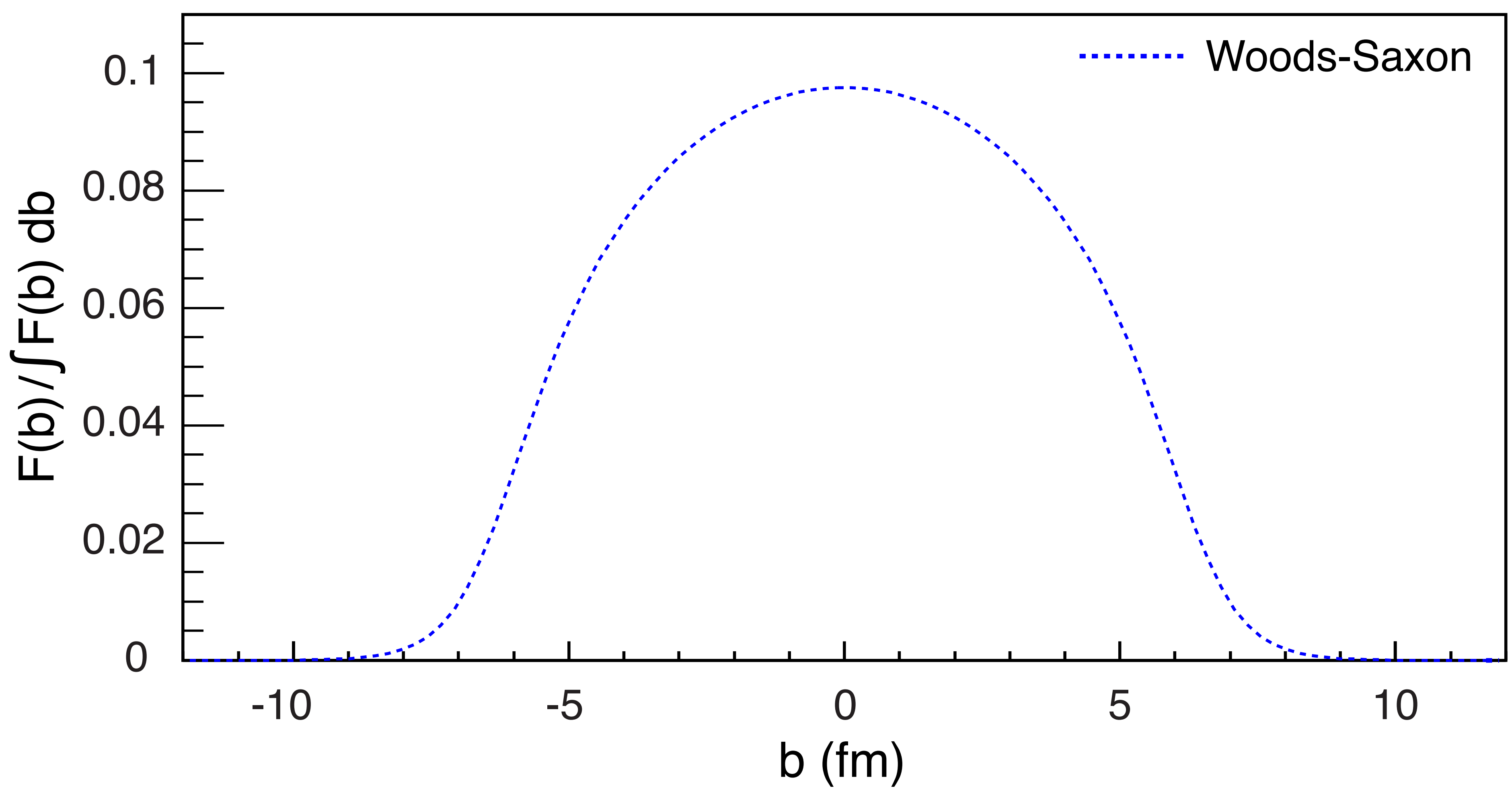
Finding the source...

- 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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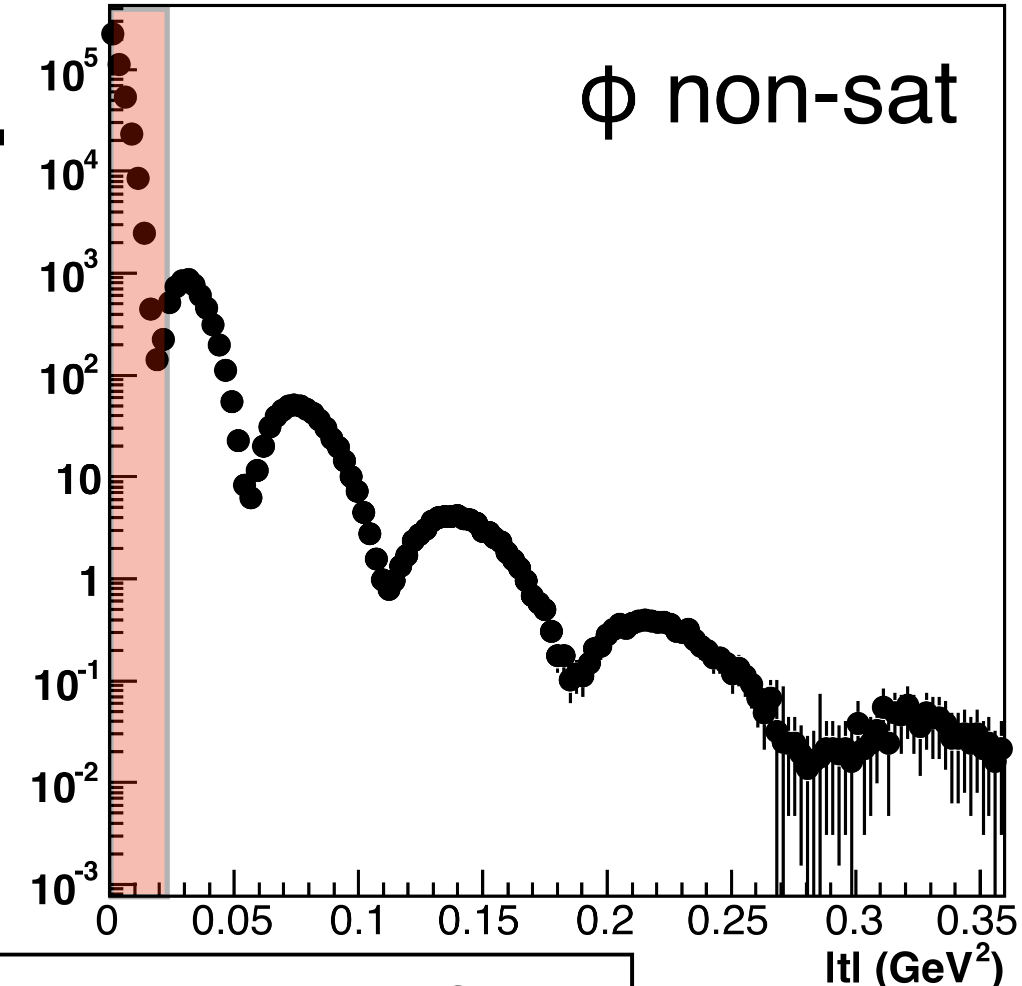

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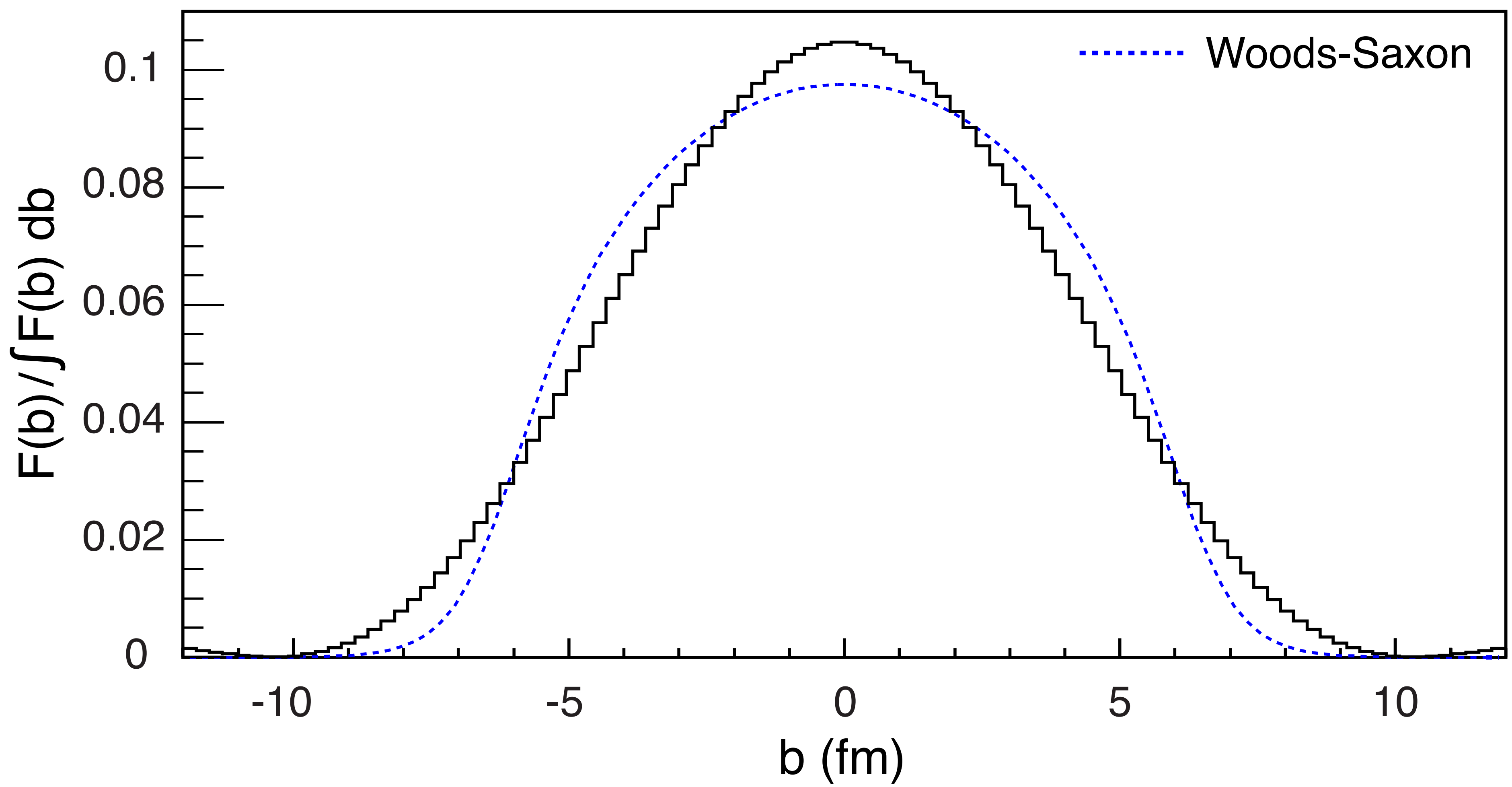

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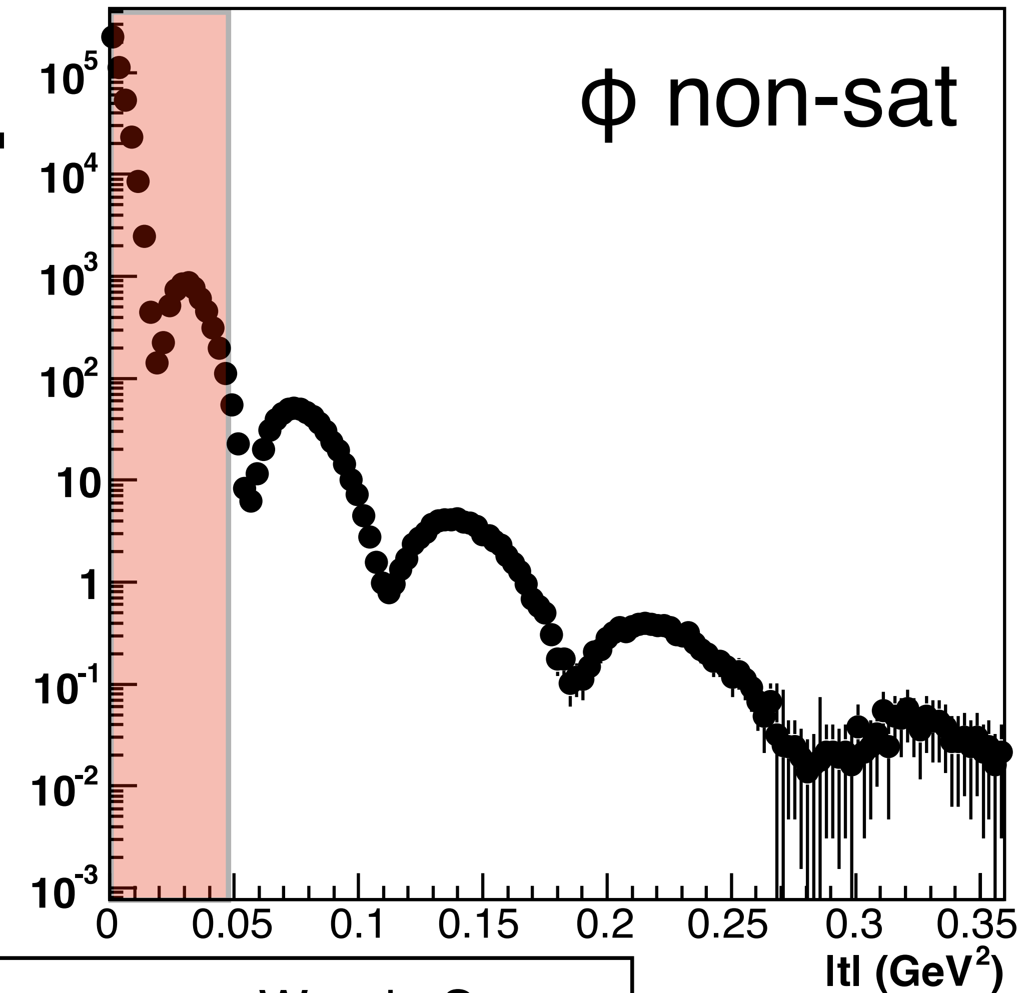

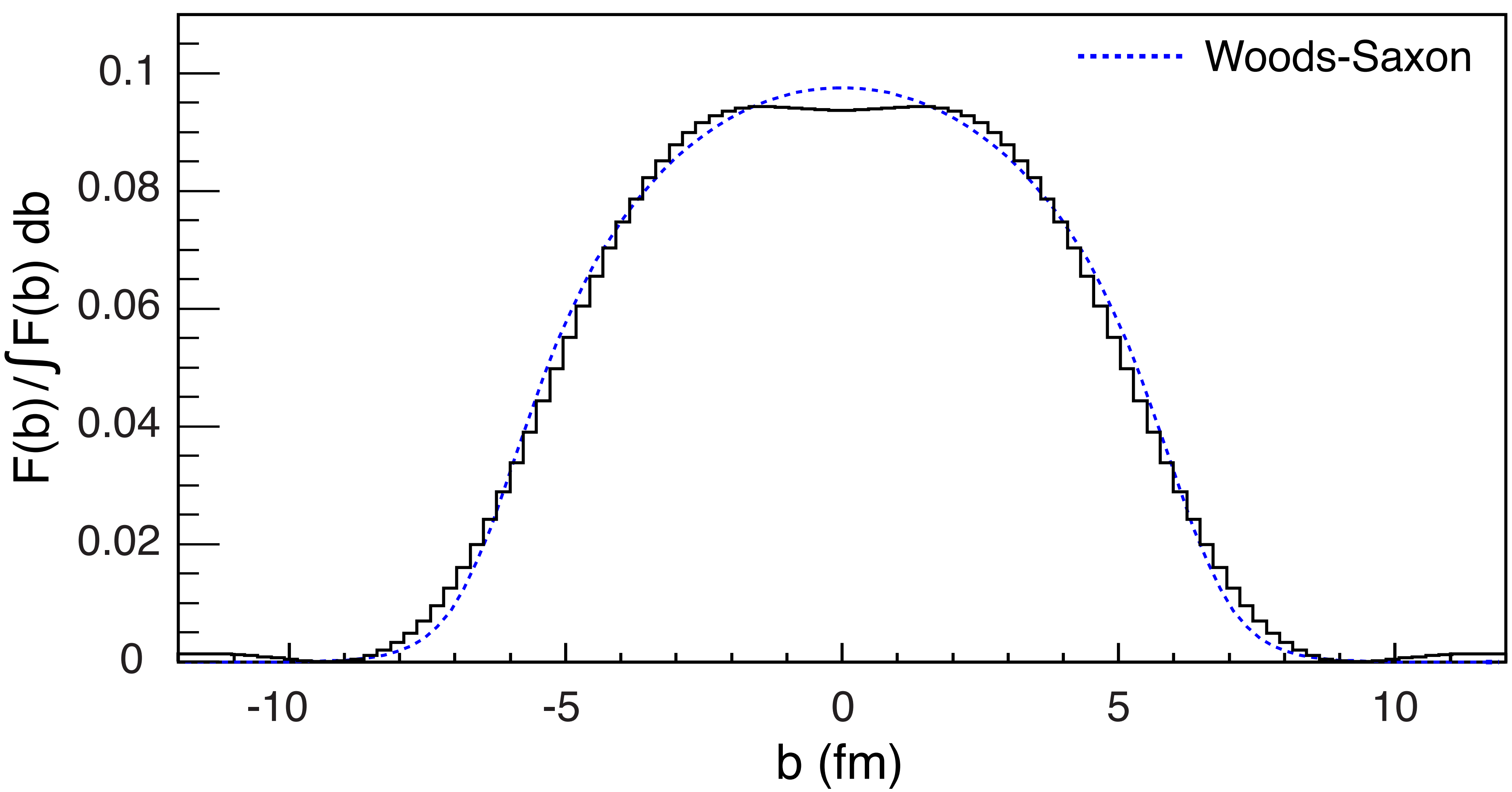

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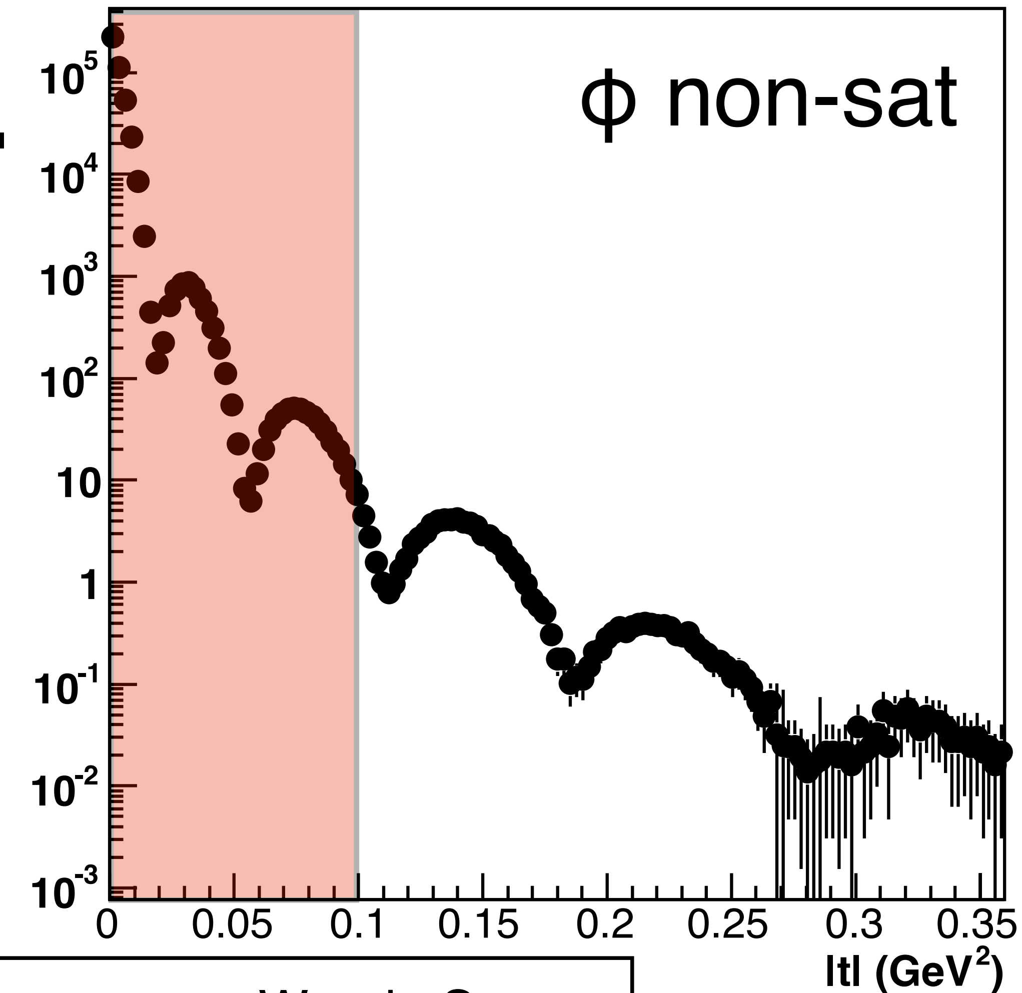

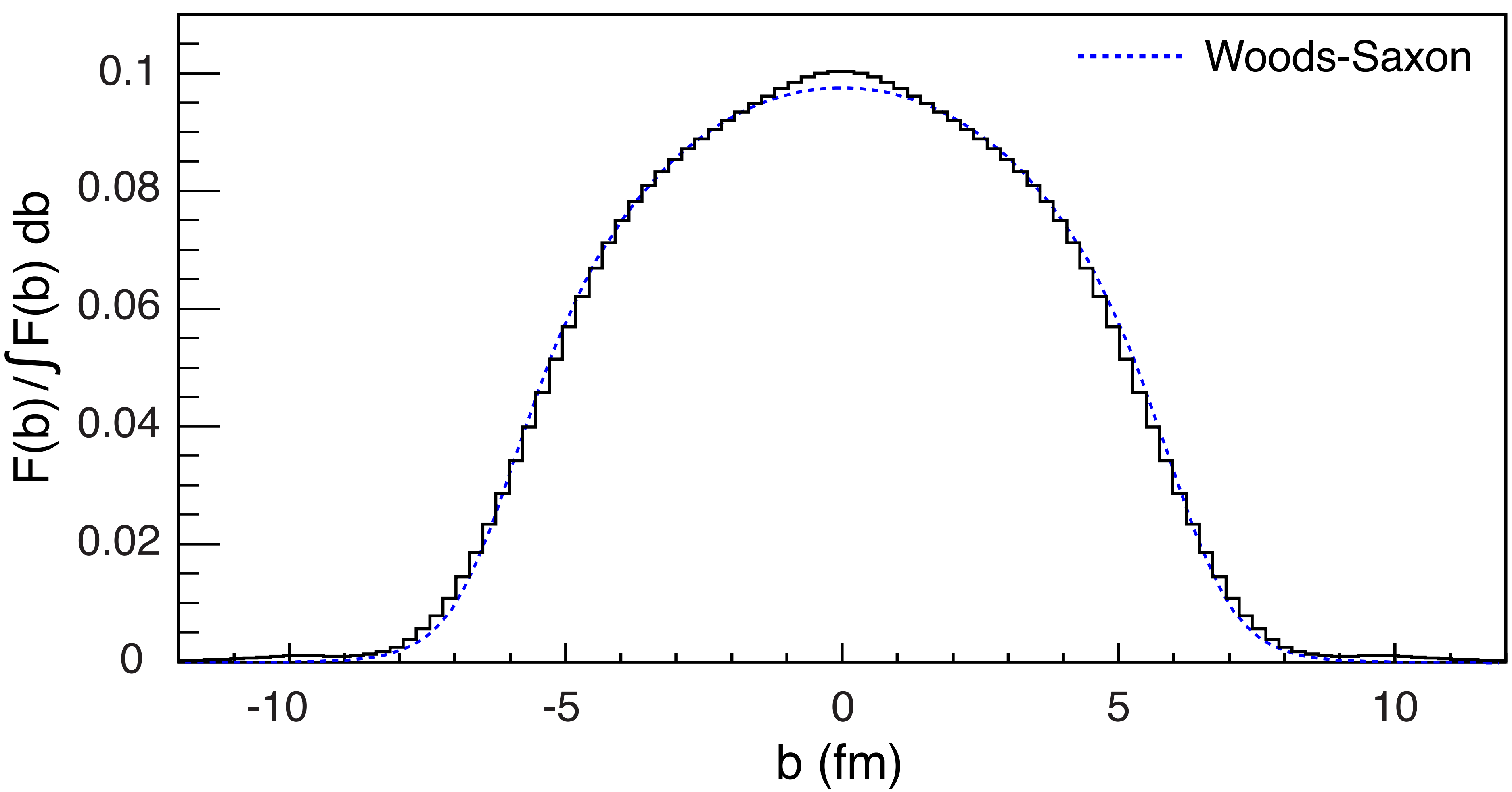

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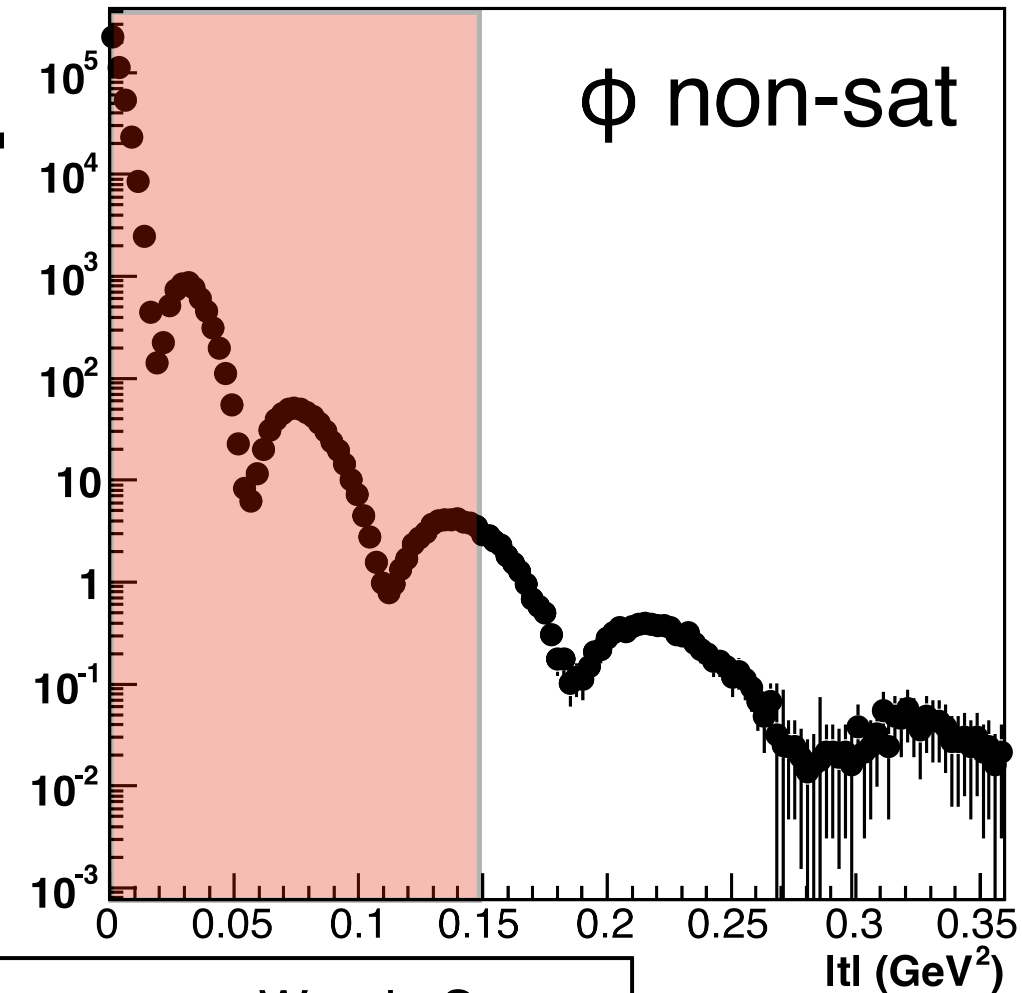

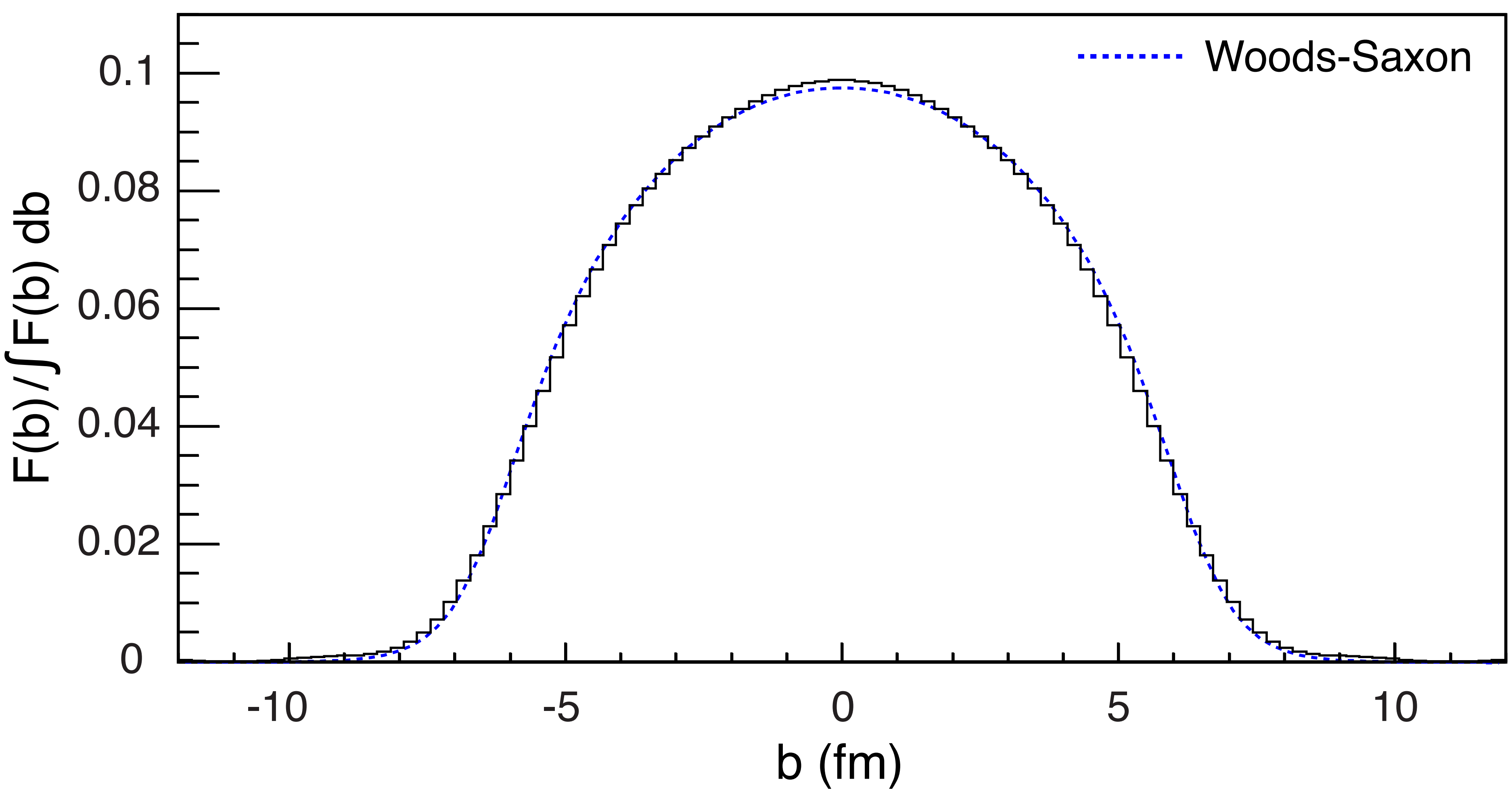

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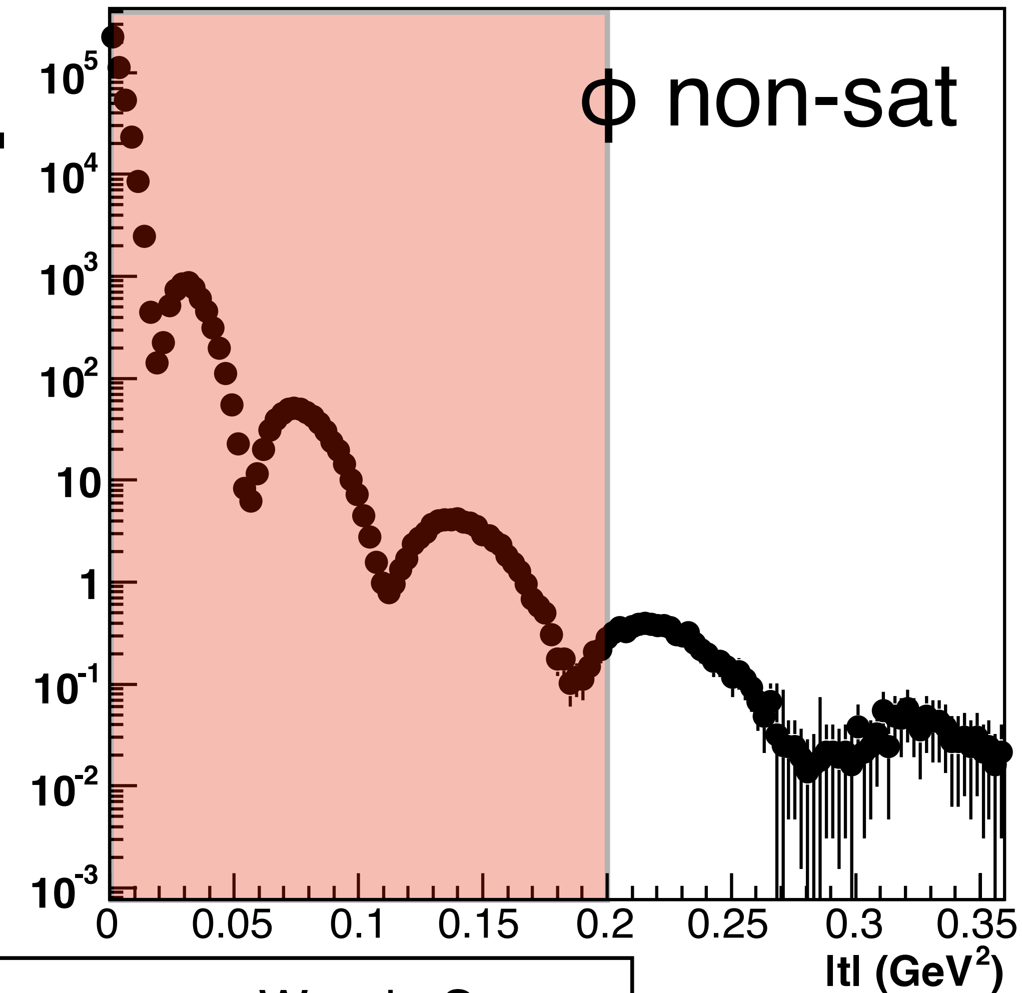
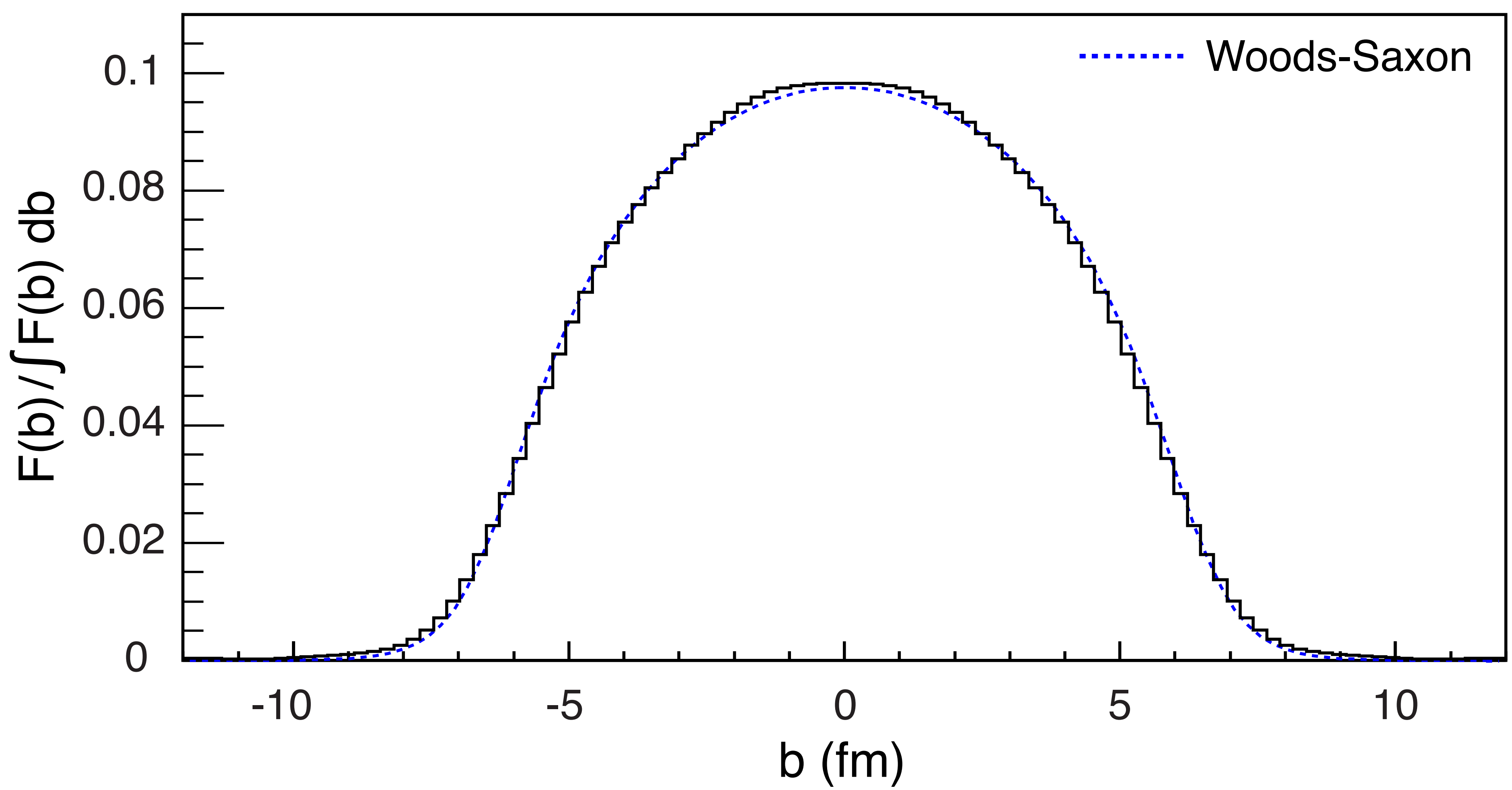
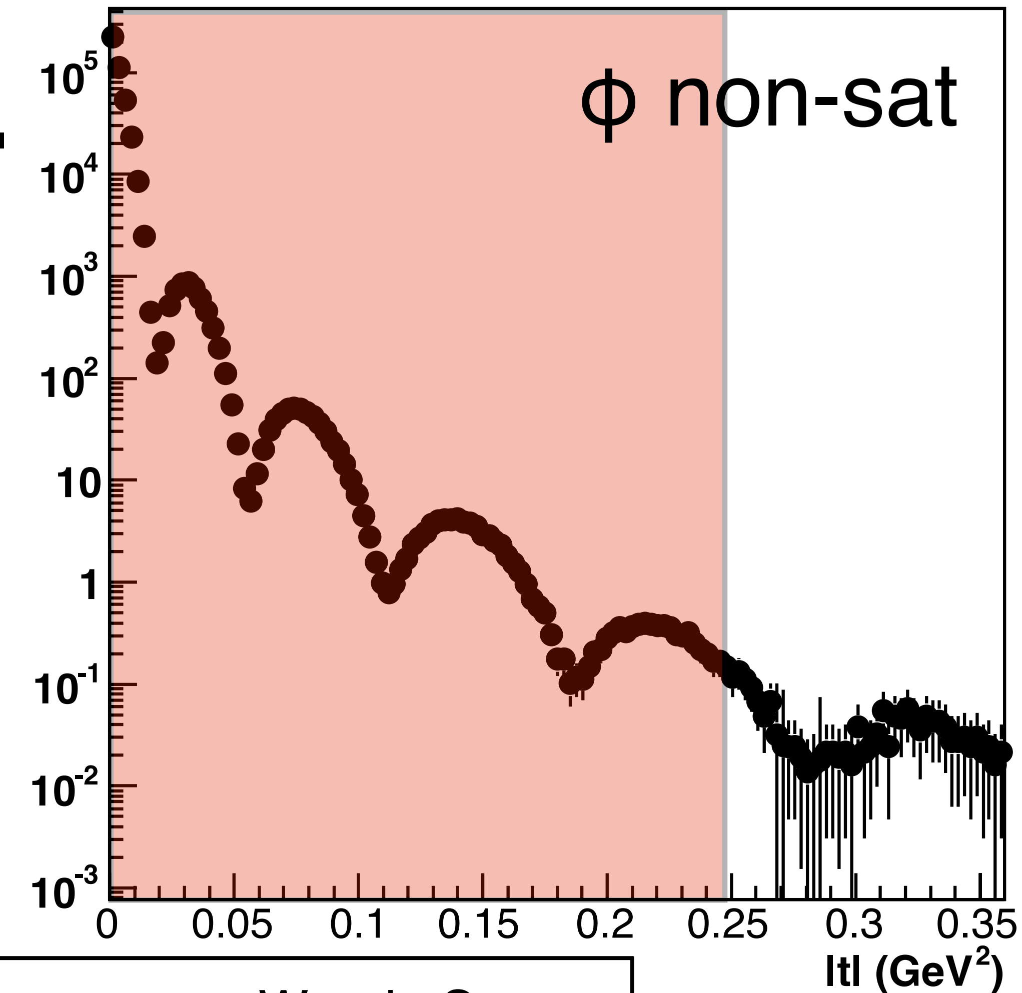




Finding the source...

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



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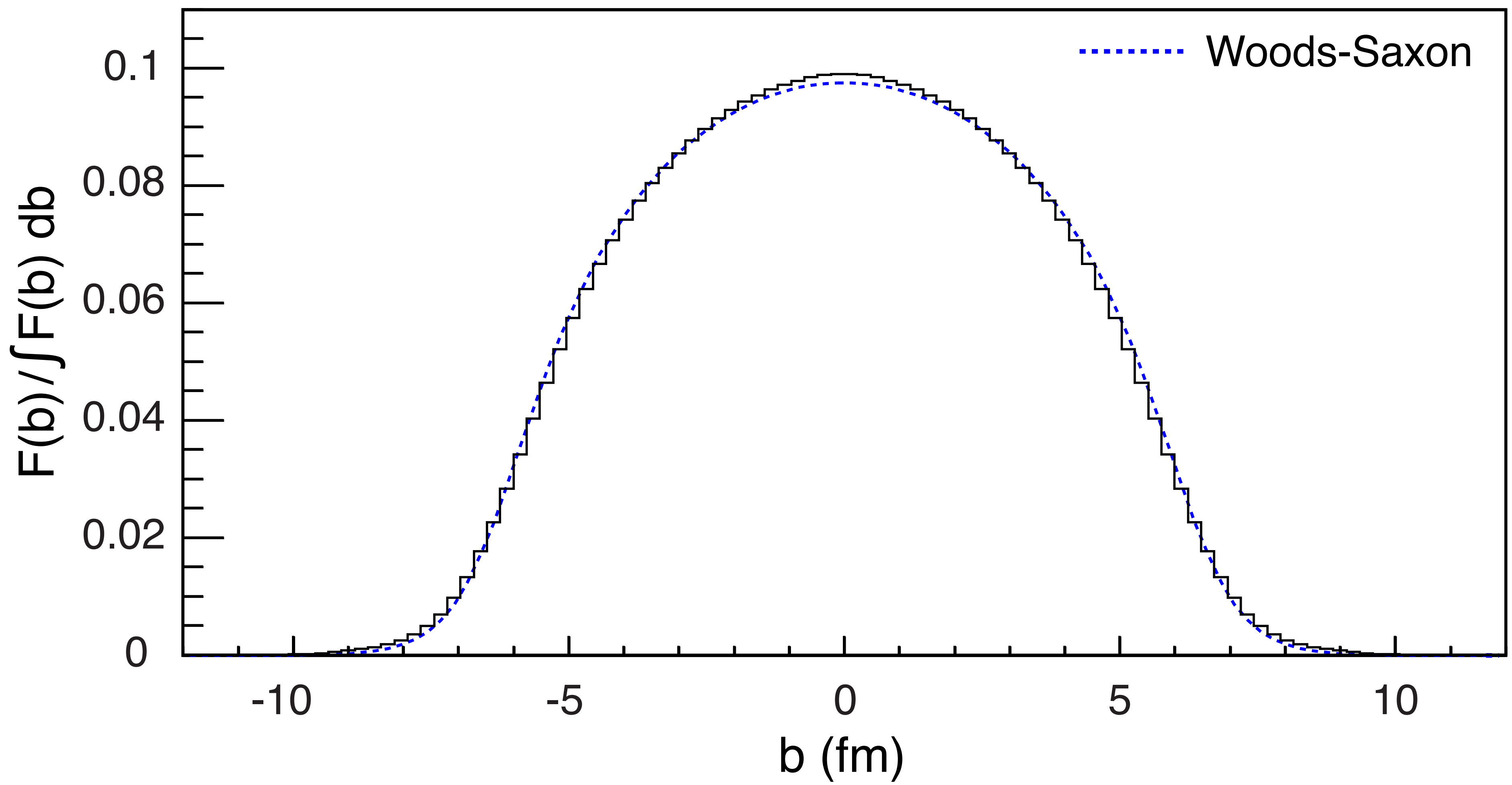

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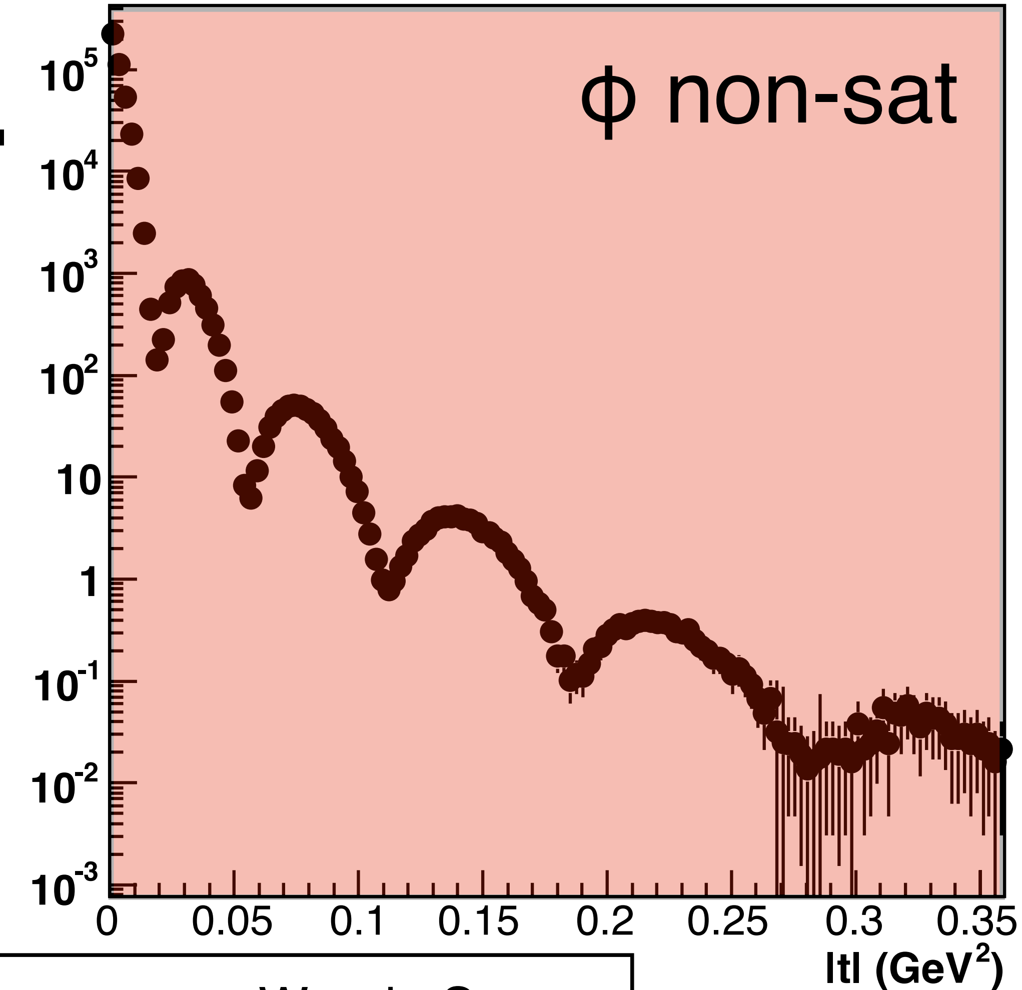
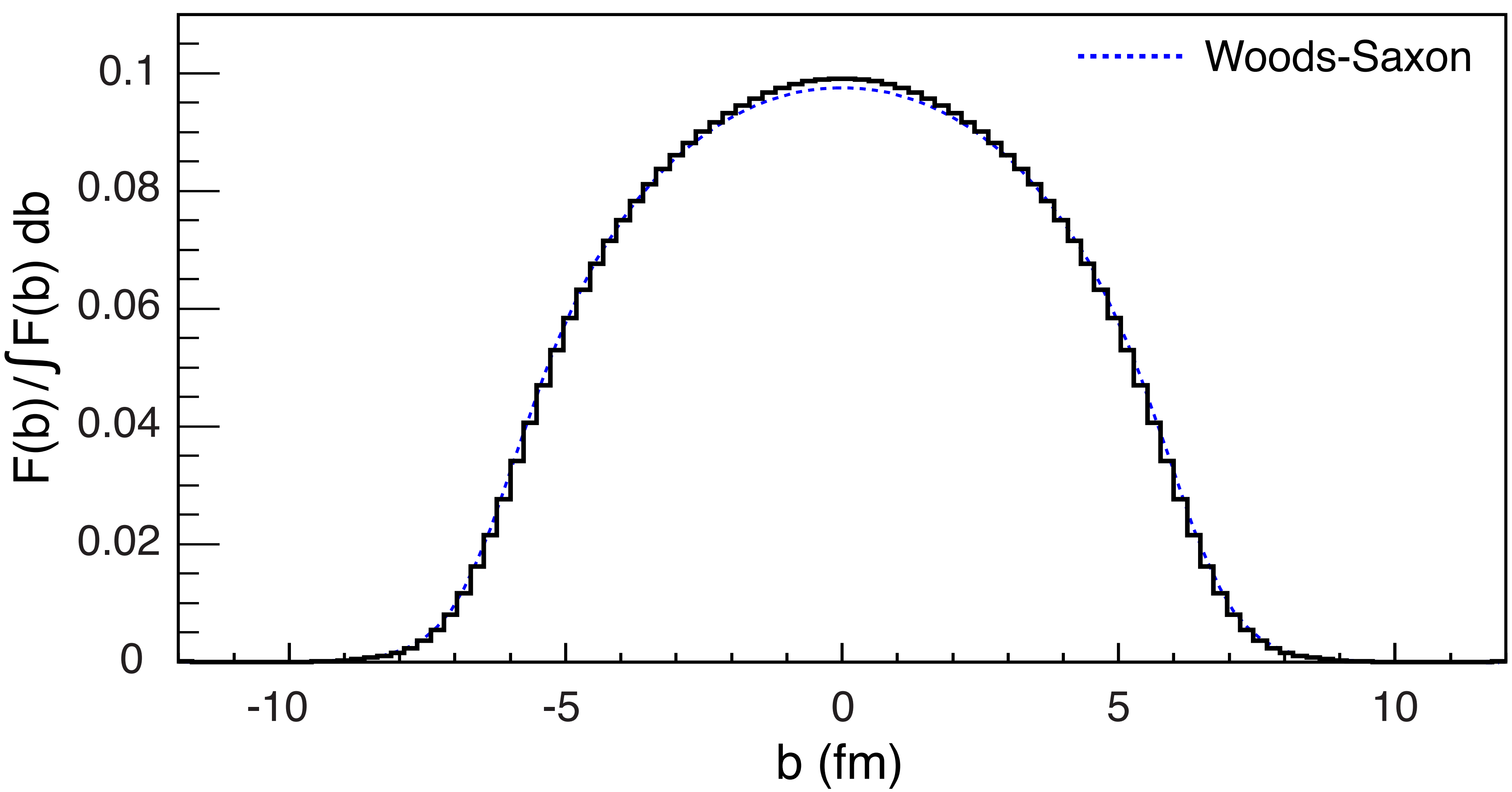
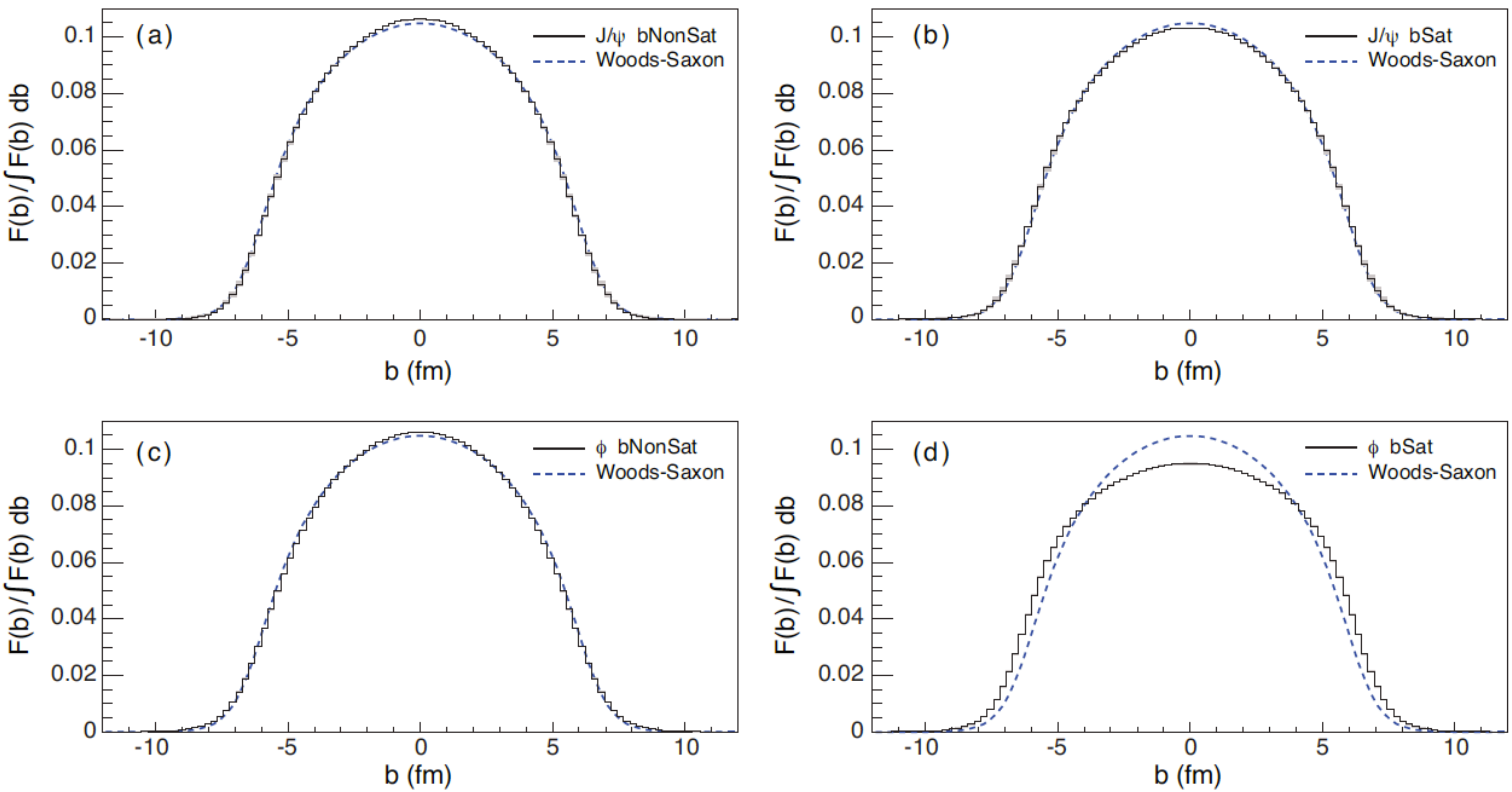




Finding the source...

- J/ψ shows little difference for both saturated and non-saturated modes.
- ϕ shows a significant difference



Summary and Conclusions

- Understanding the role of gluons in nuclei is crucial to understanding RHIC and LHC results
- 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
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entire science programme is uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

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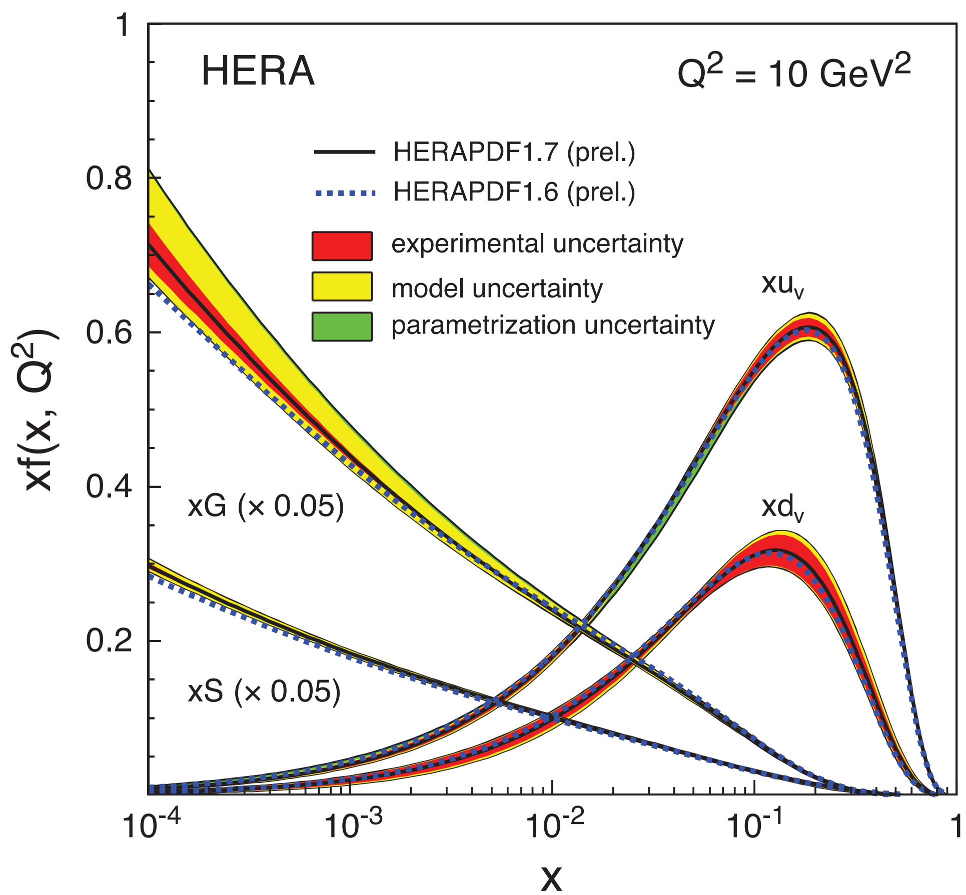
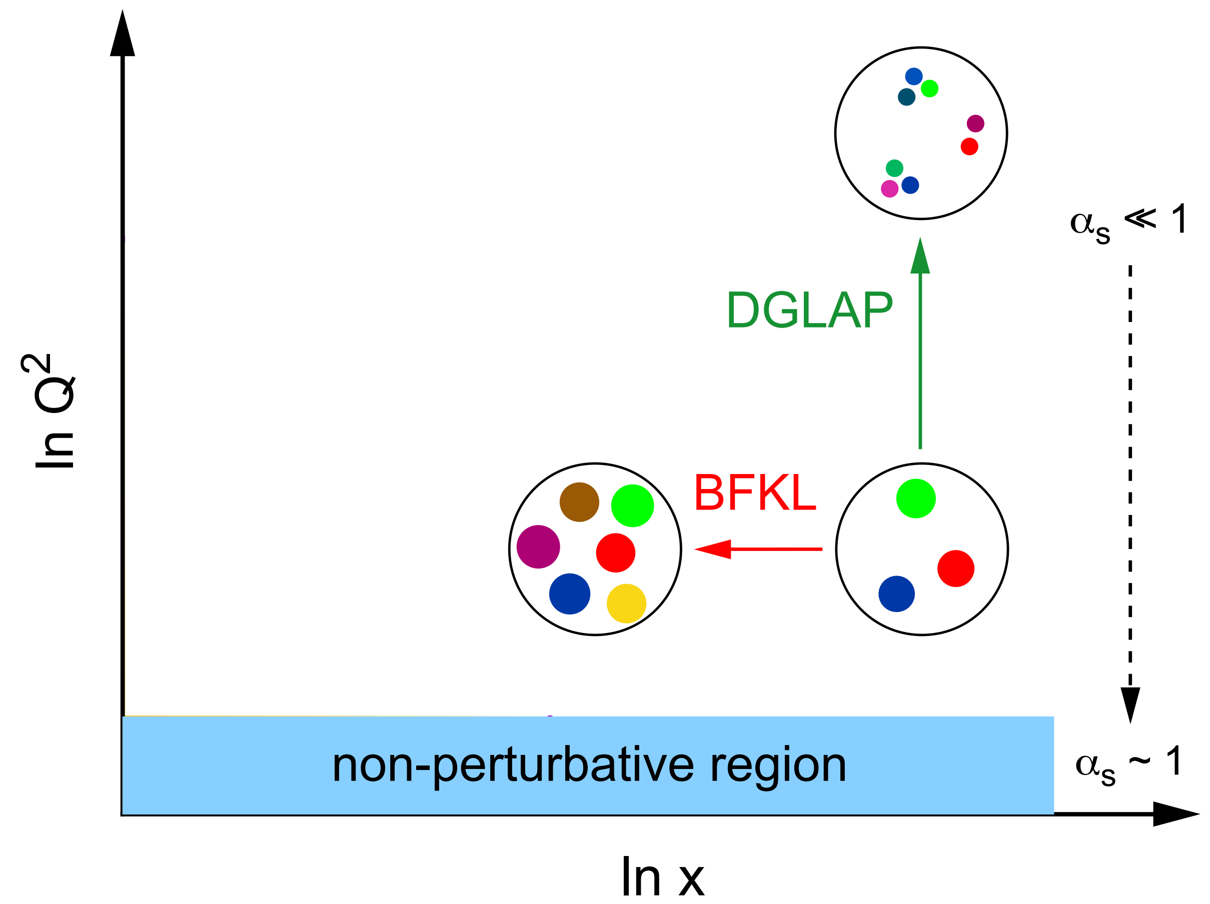
BACKUP

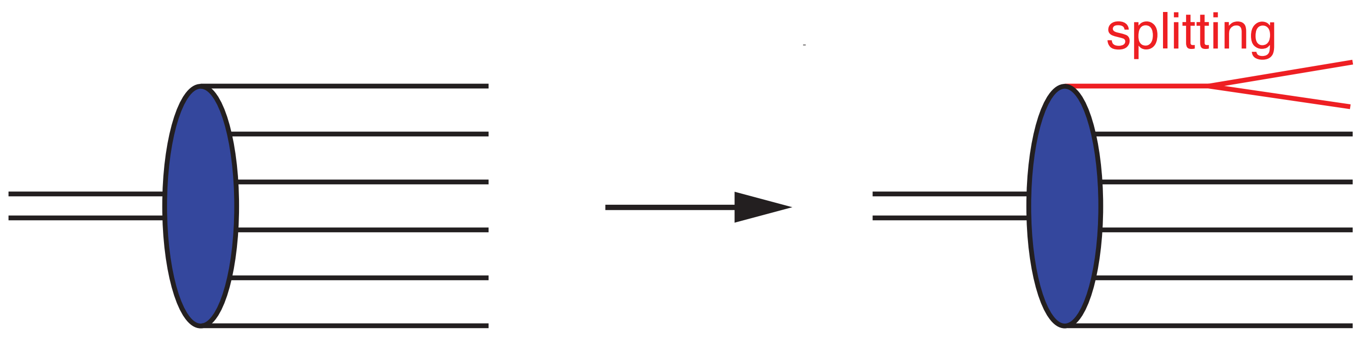
The structure of matter at small-x





- 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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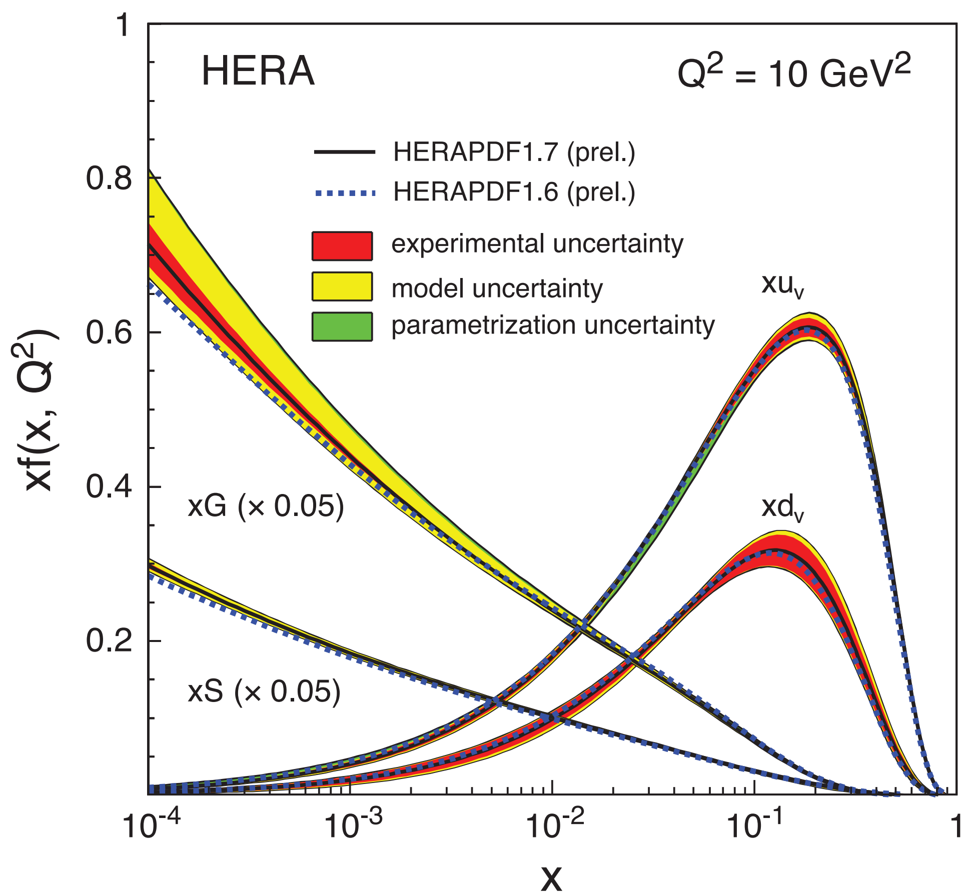
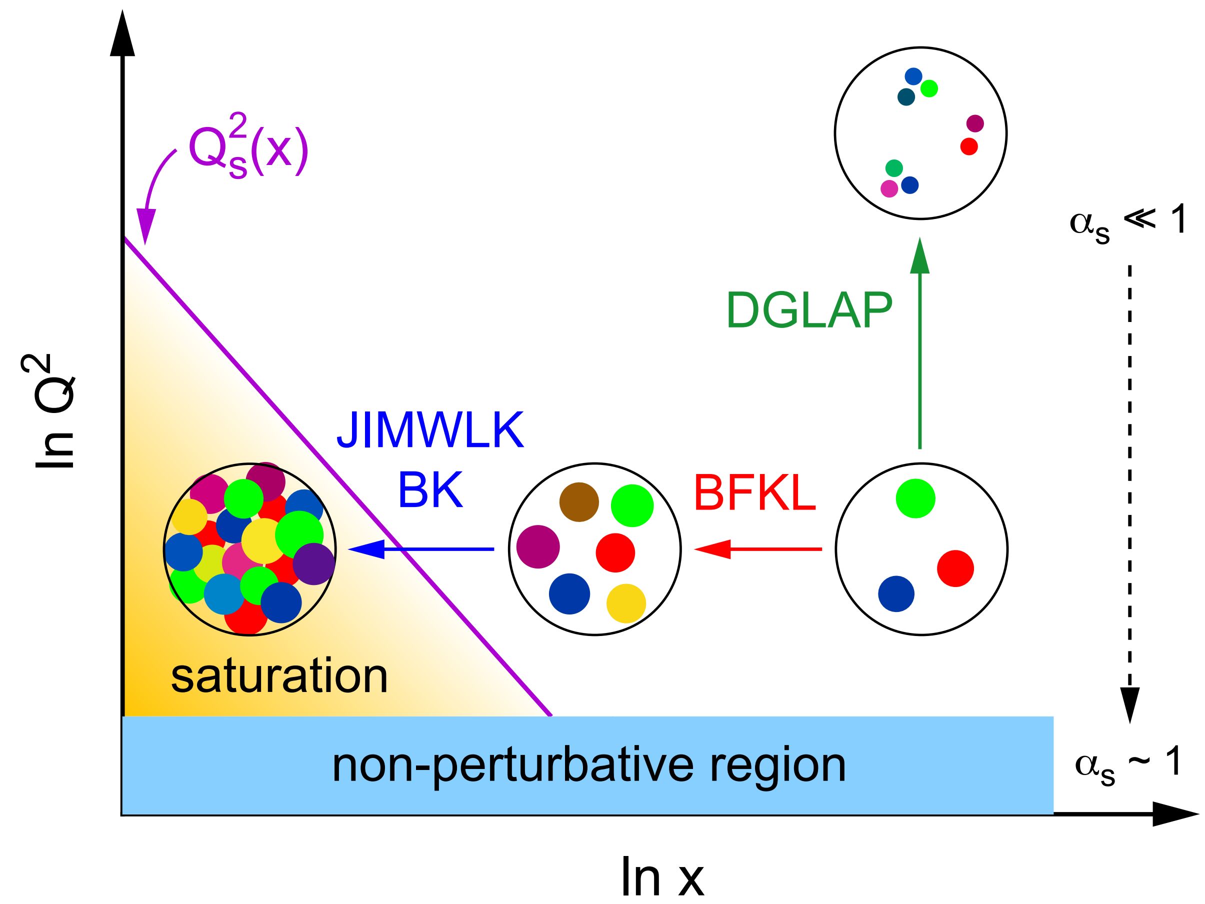
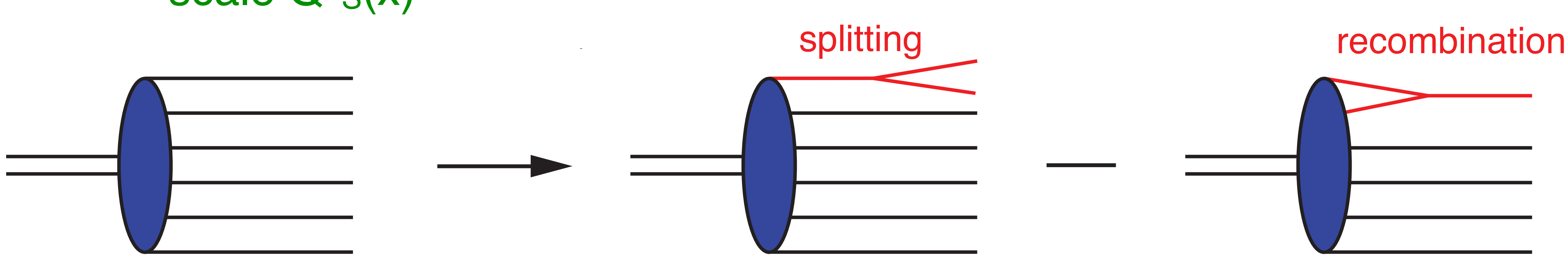




- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth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

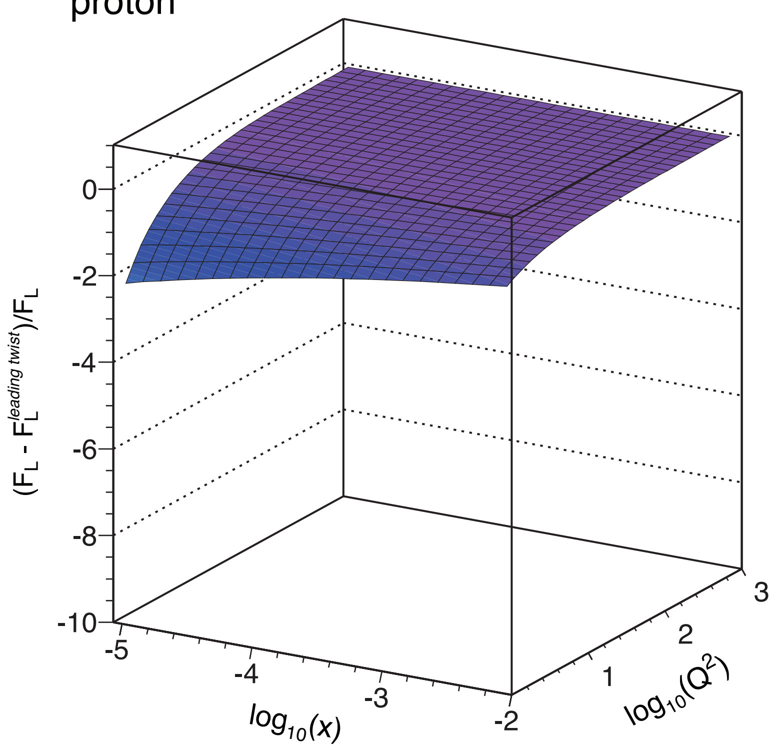


Saturation effects in the proton and nucleus

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

quark+anti-quark

gluon



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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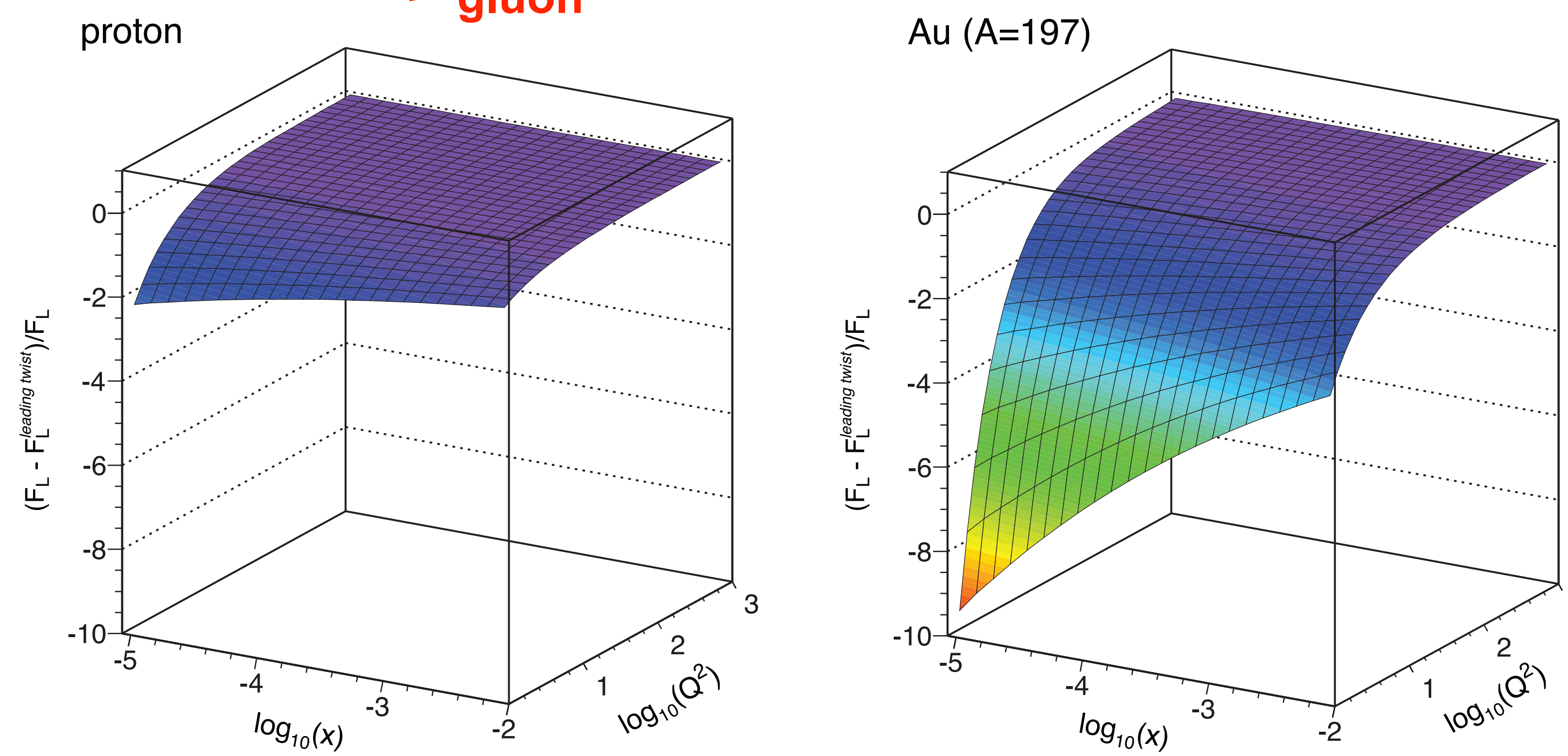

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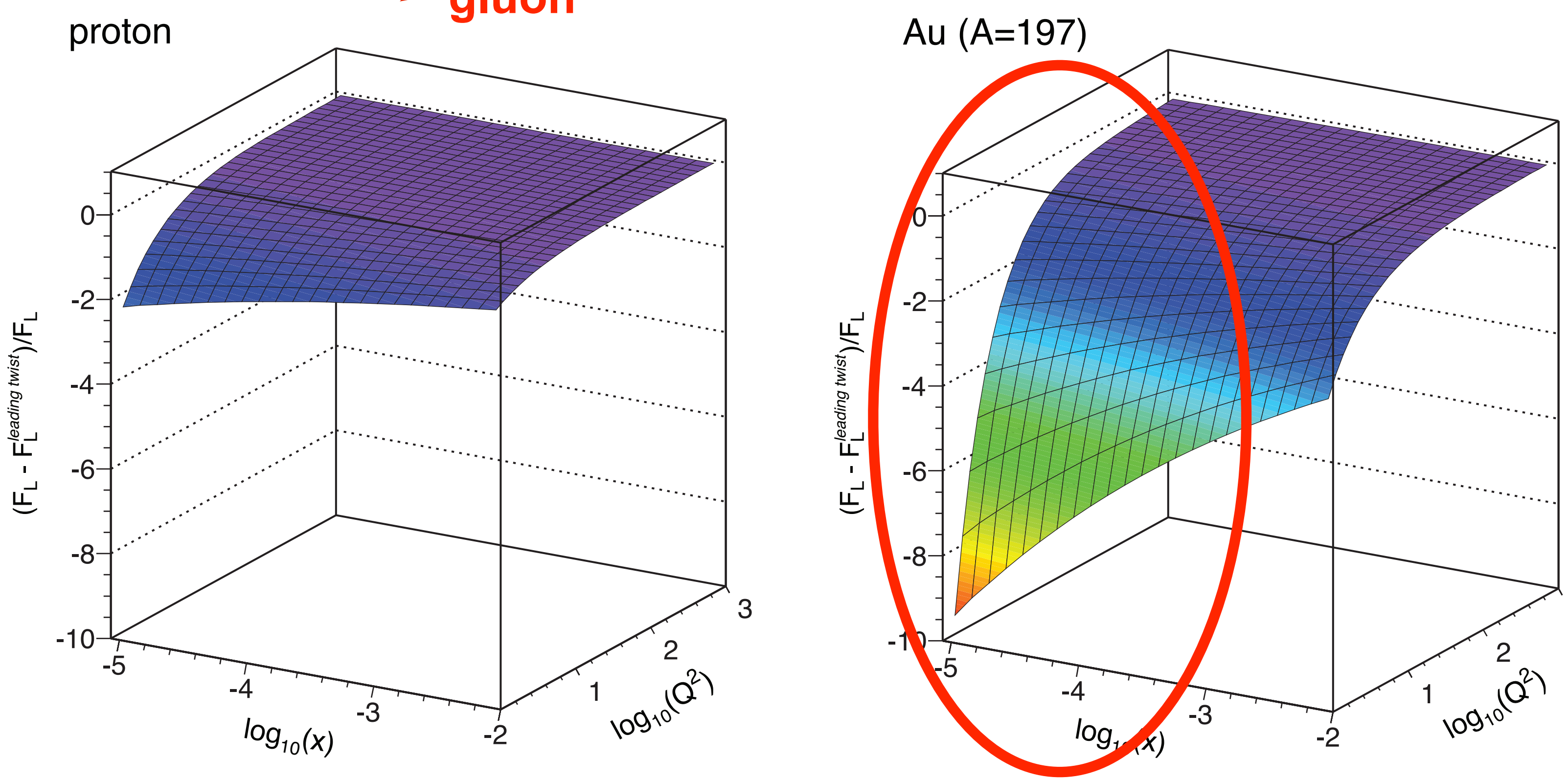

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Strategies:

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

e+Au:

20x50 - A∫Ldt = 2 fb^{-1}

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20x100 - A∫Ldt = 4 fb^{-1}

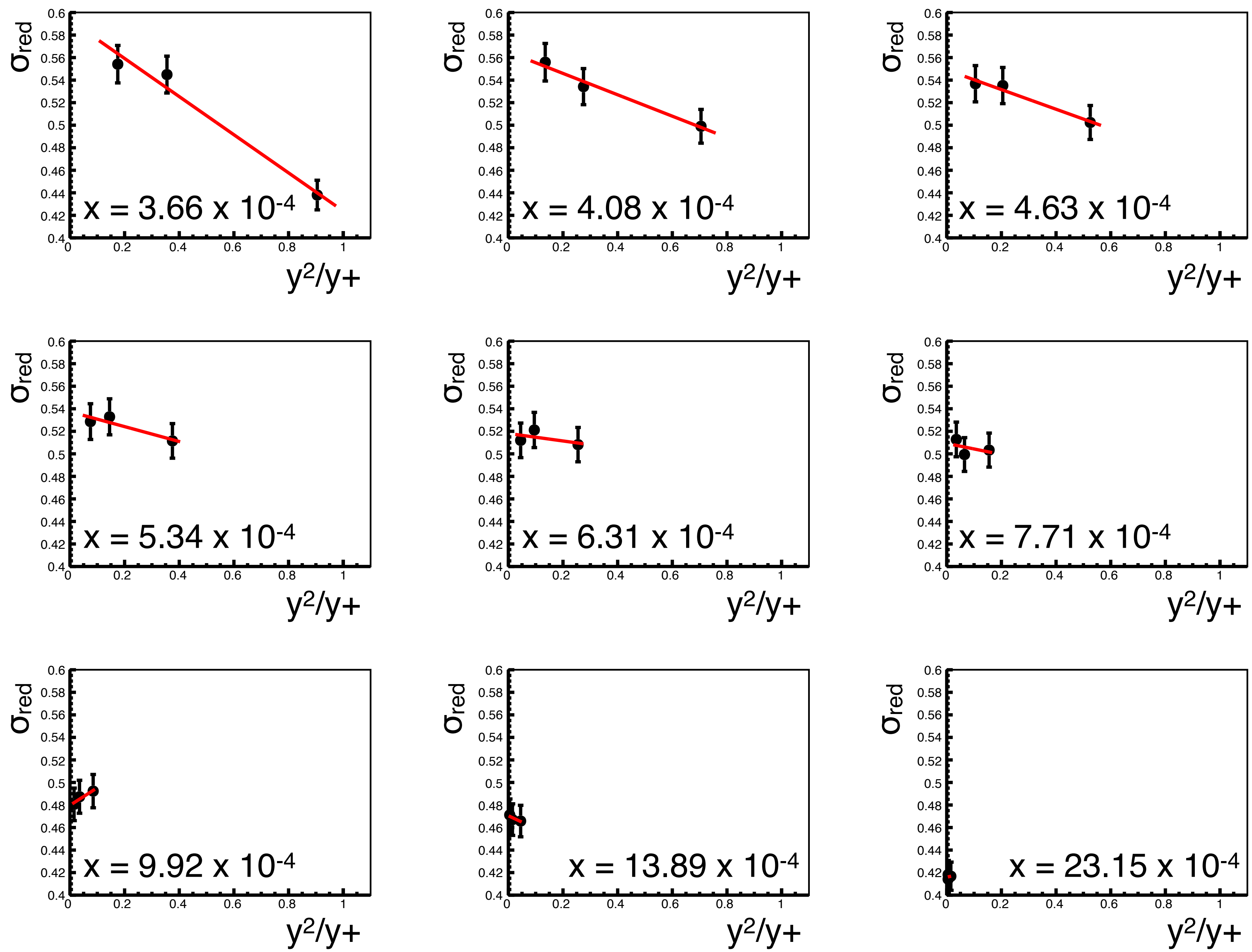
running combined

~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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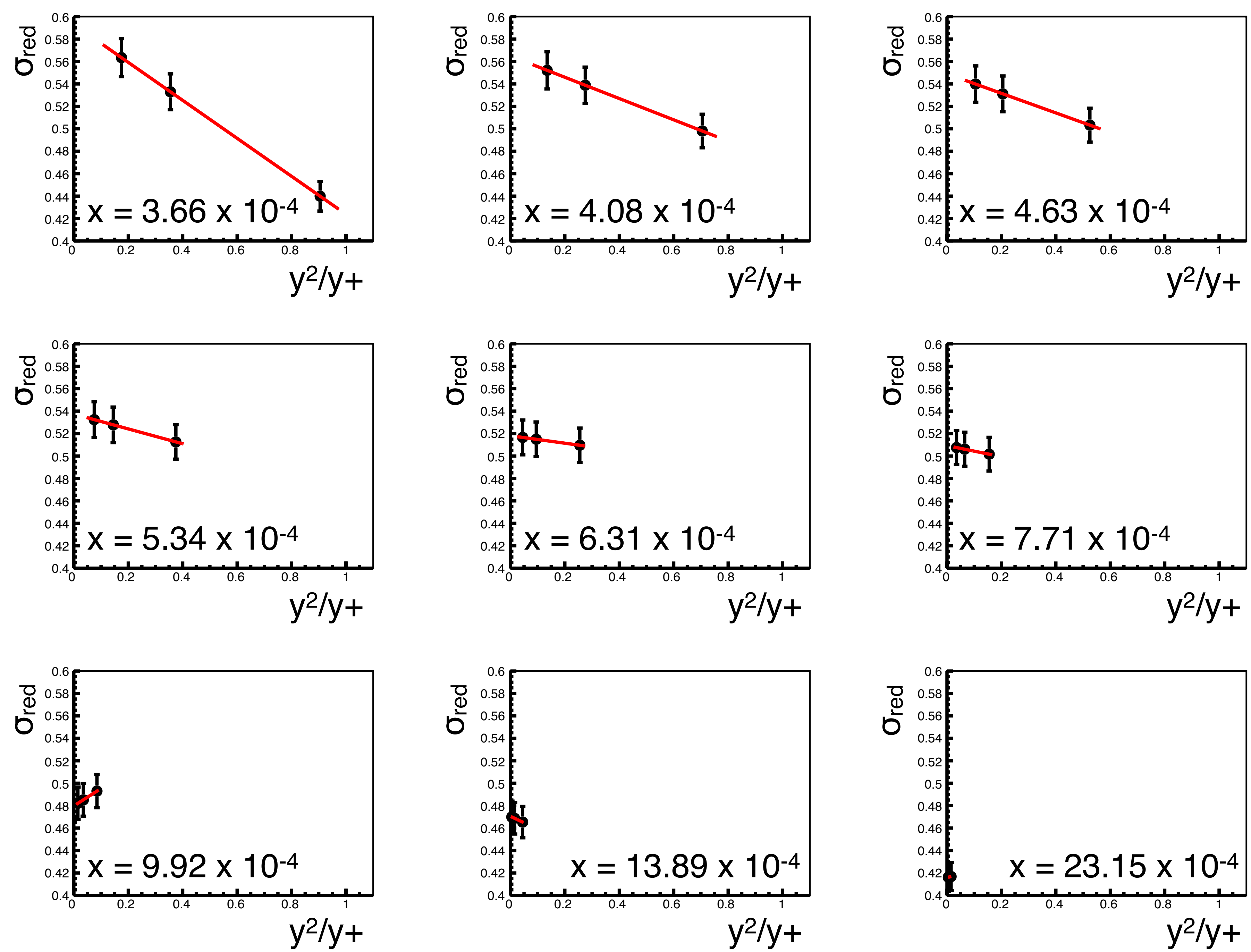

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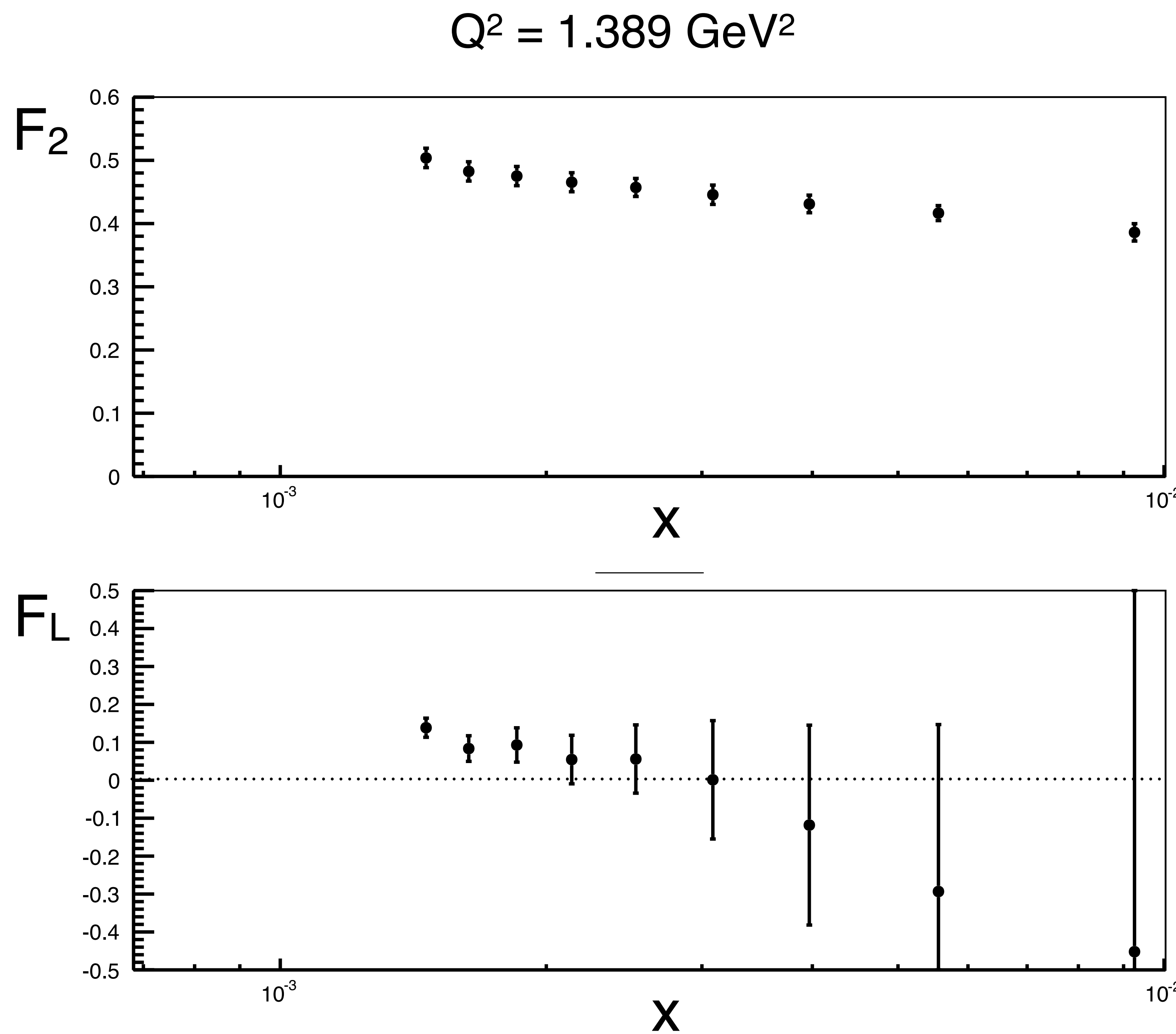

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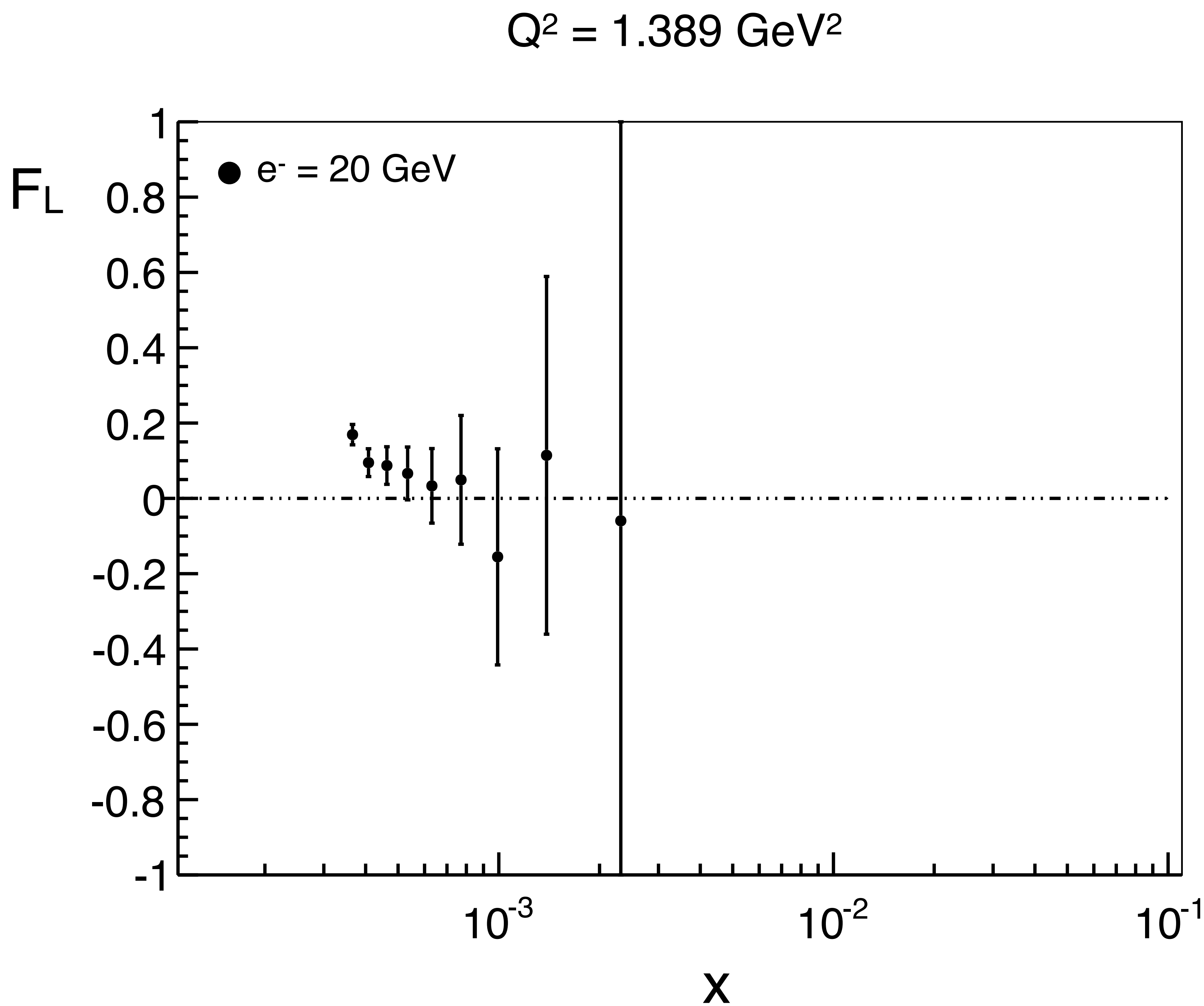

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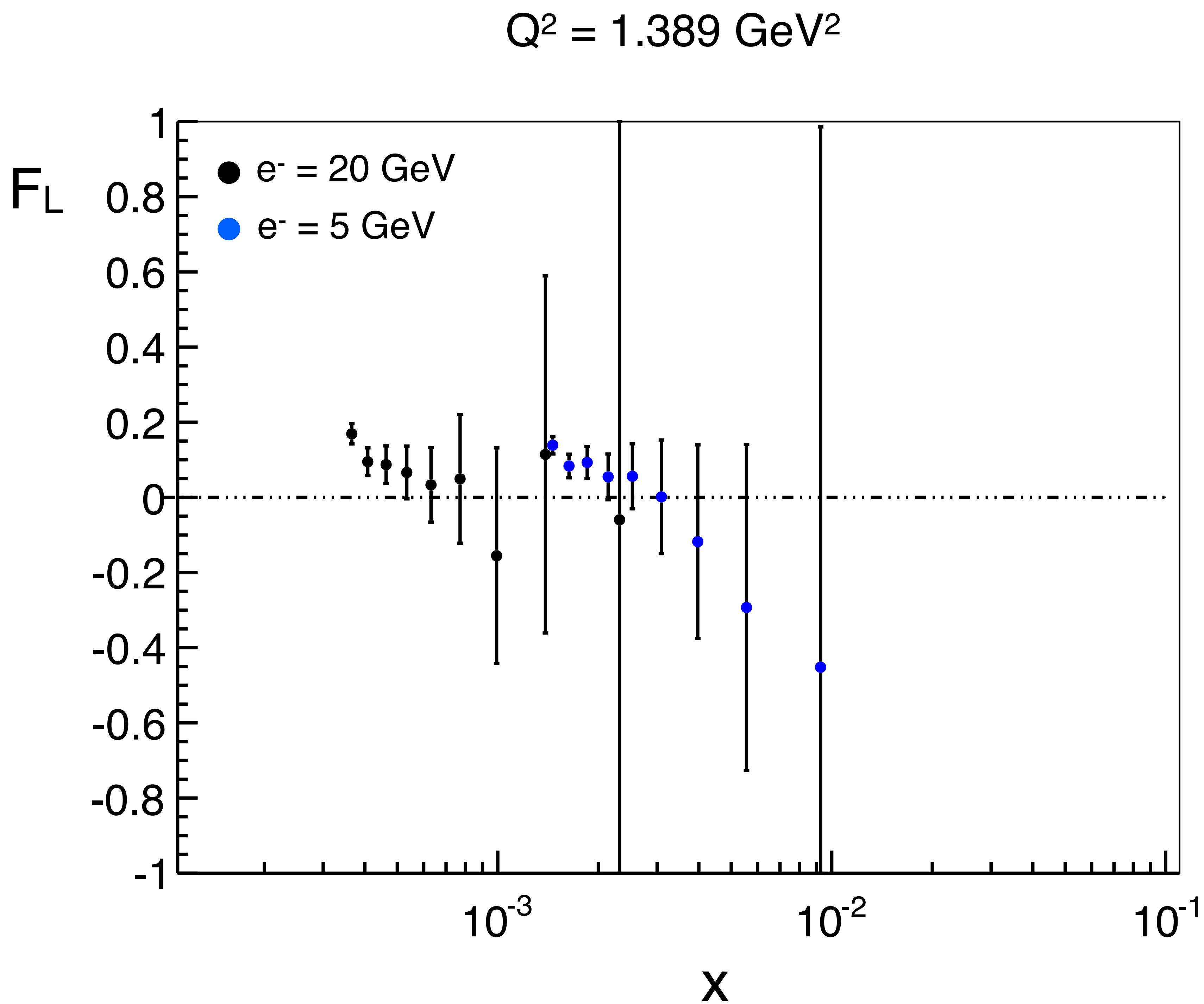

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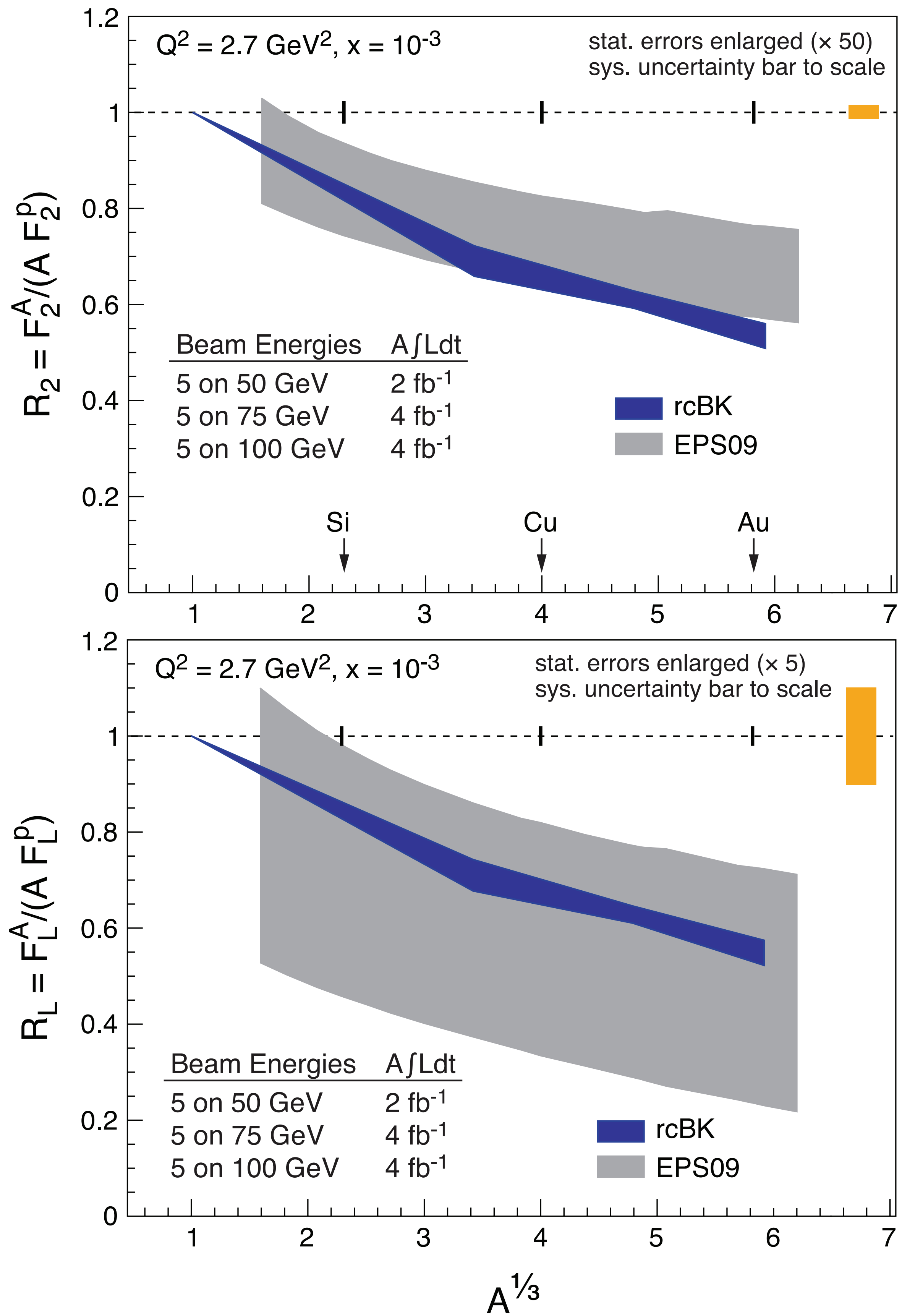

Constraining the gluon distributions with EPS09

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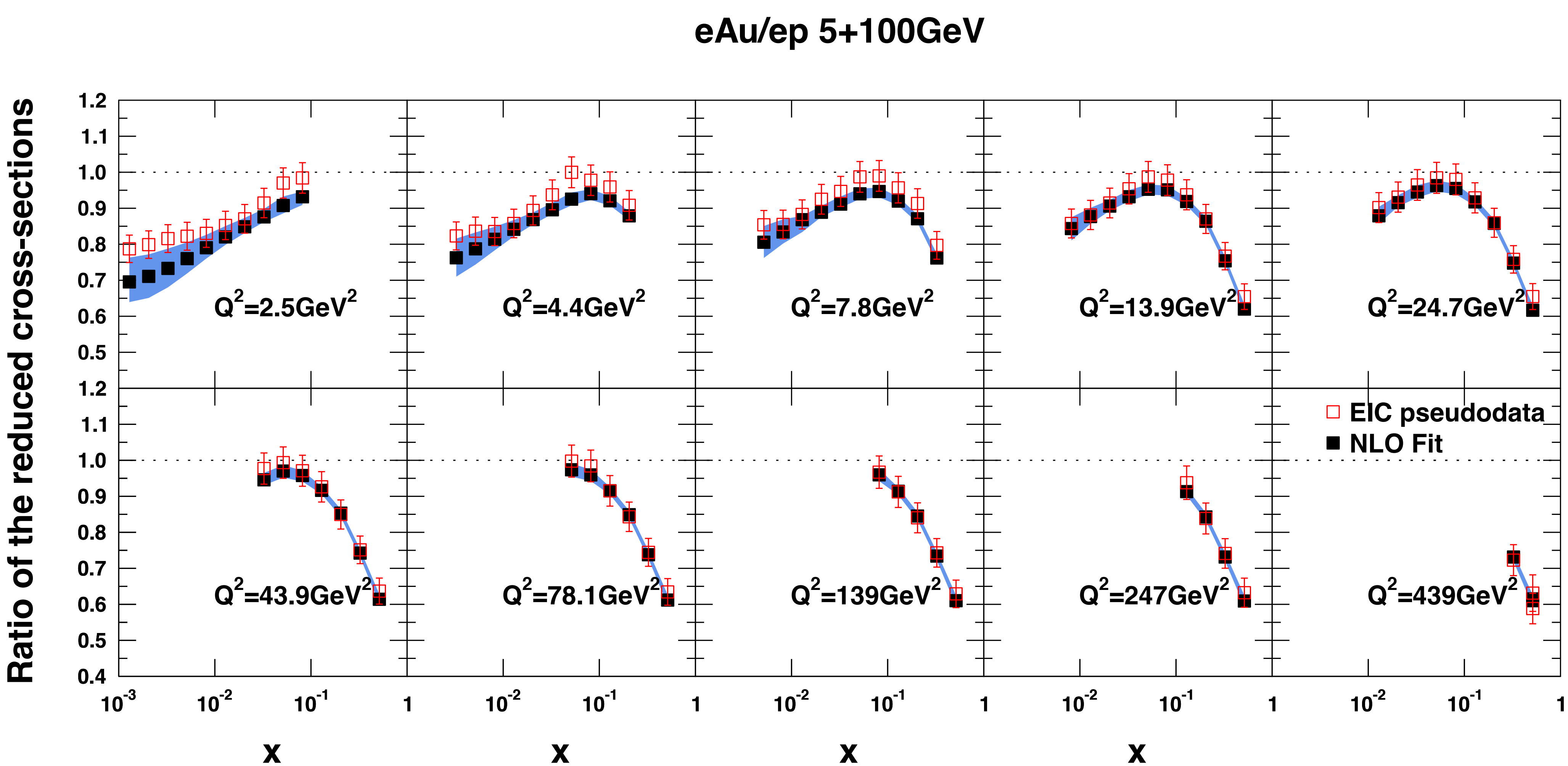

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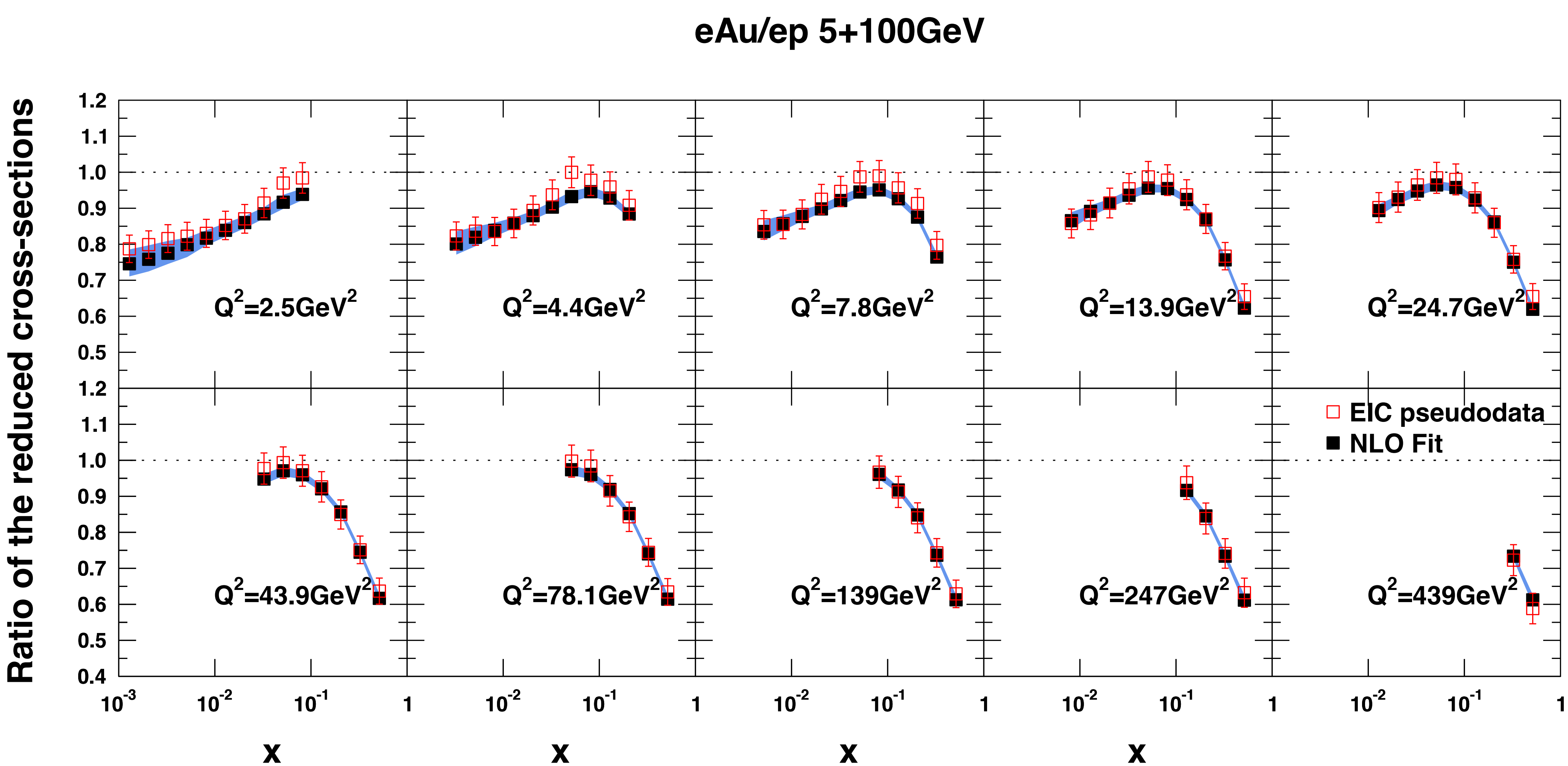

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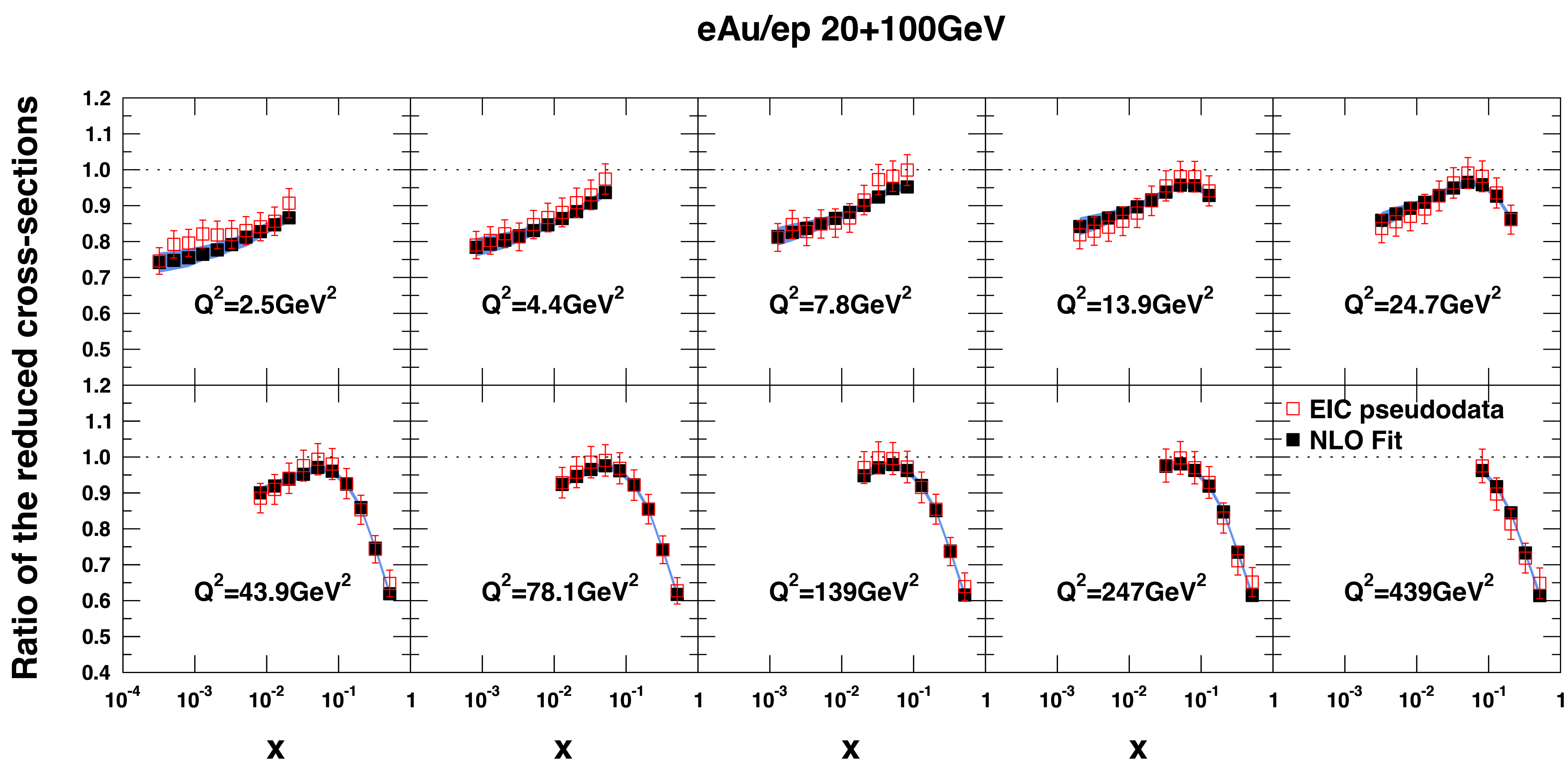

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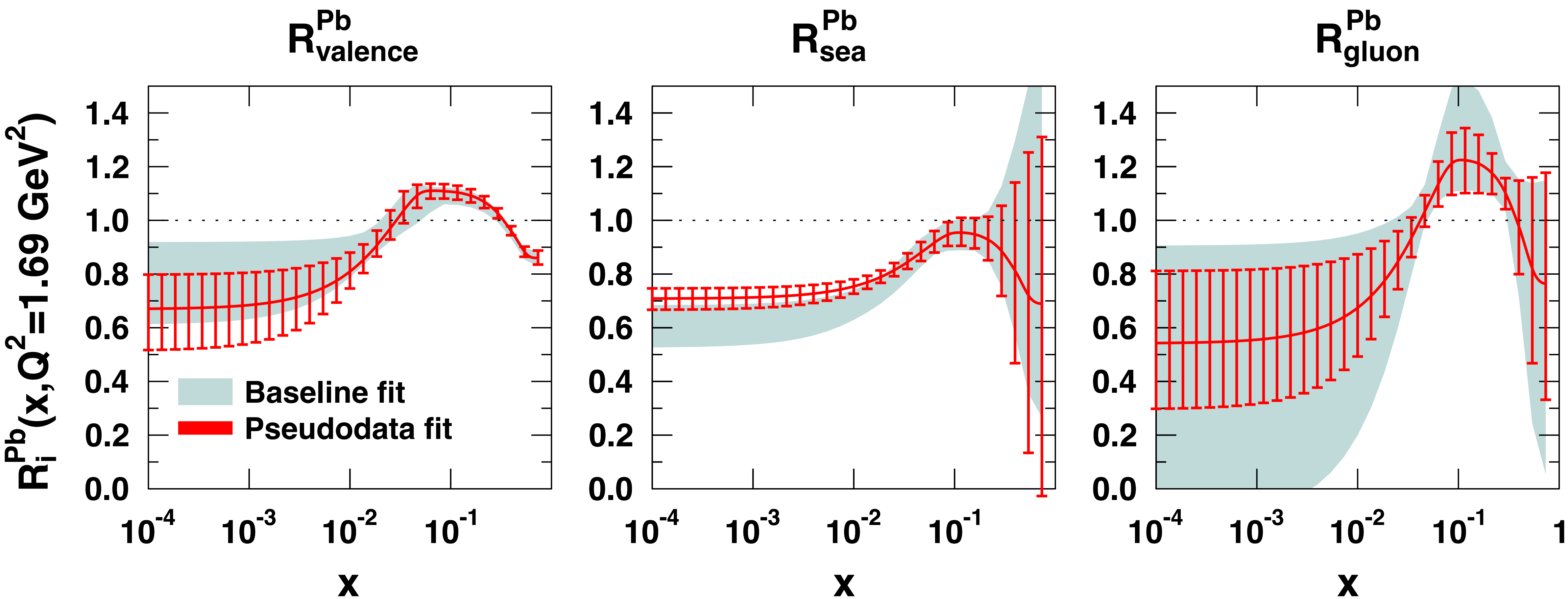

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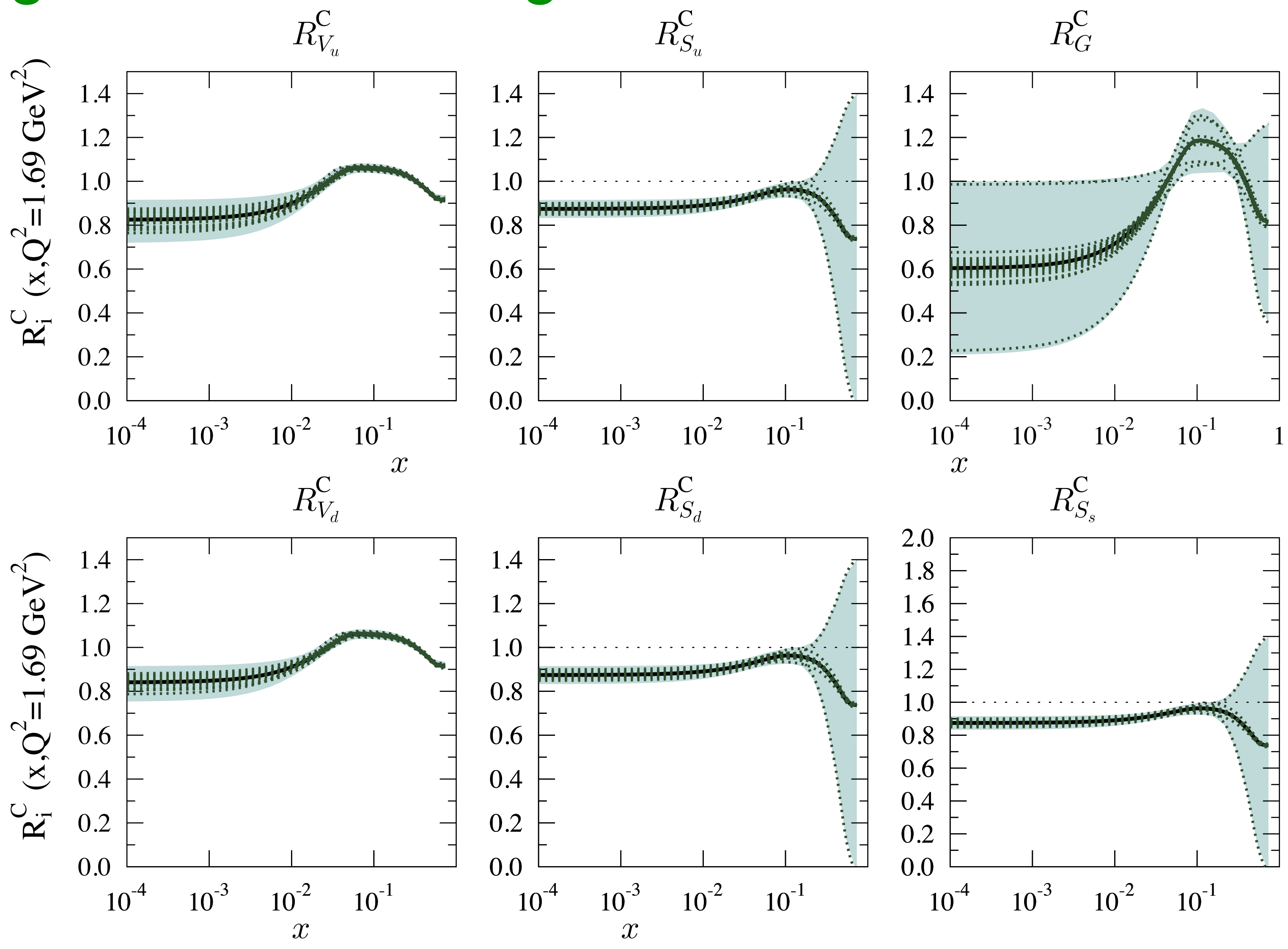
    - ▸ e.g. Carbon has large uncertainties associated with it



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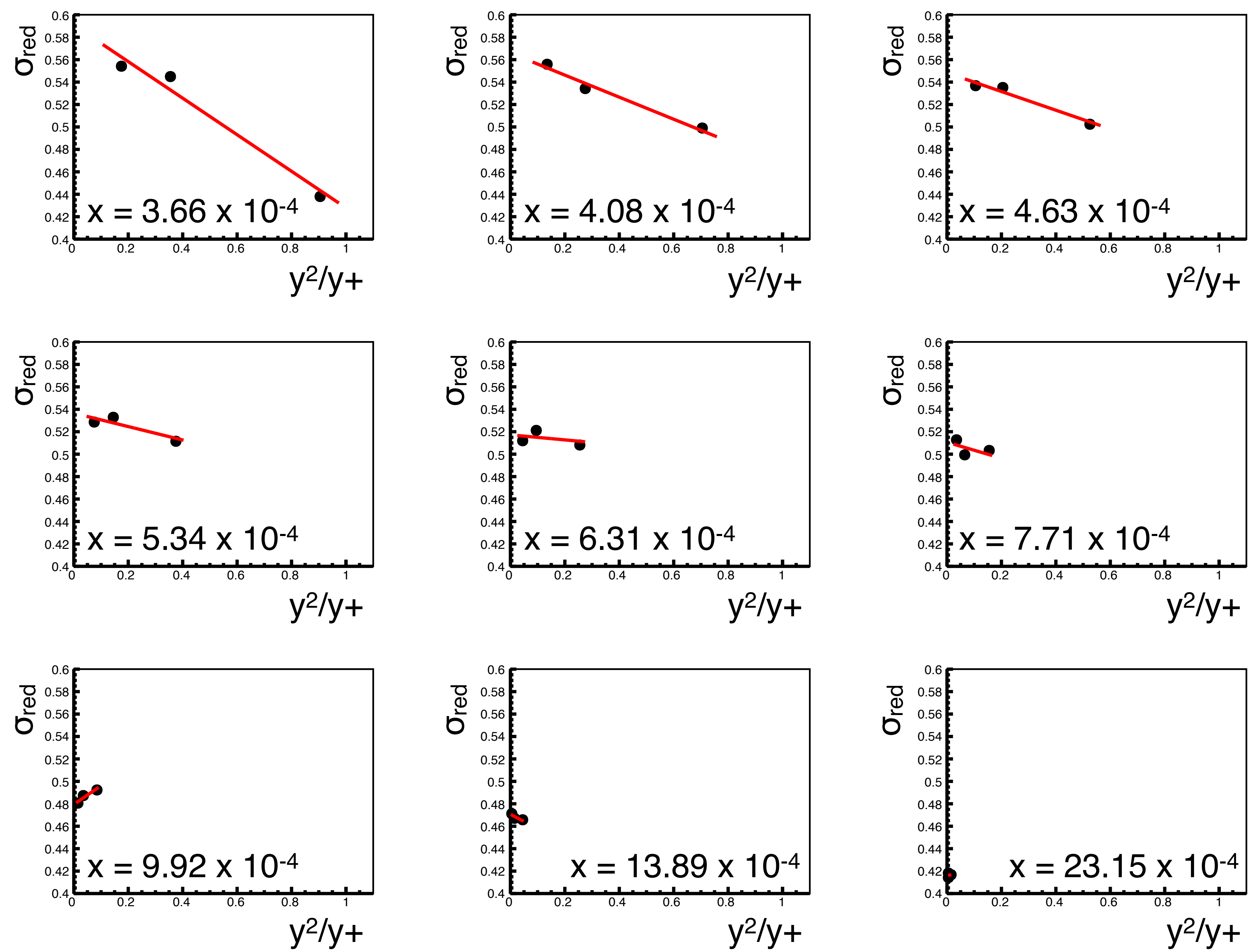

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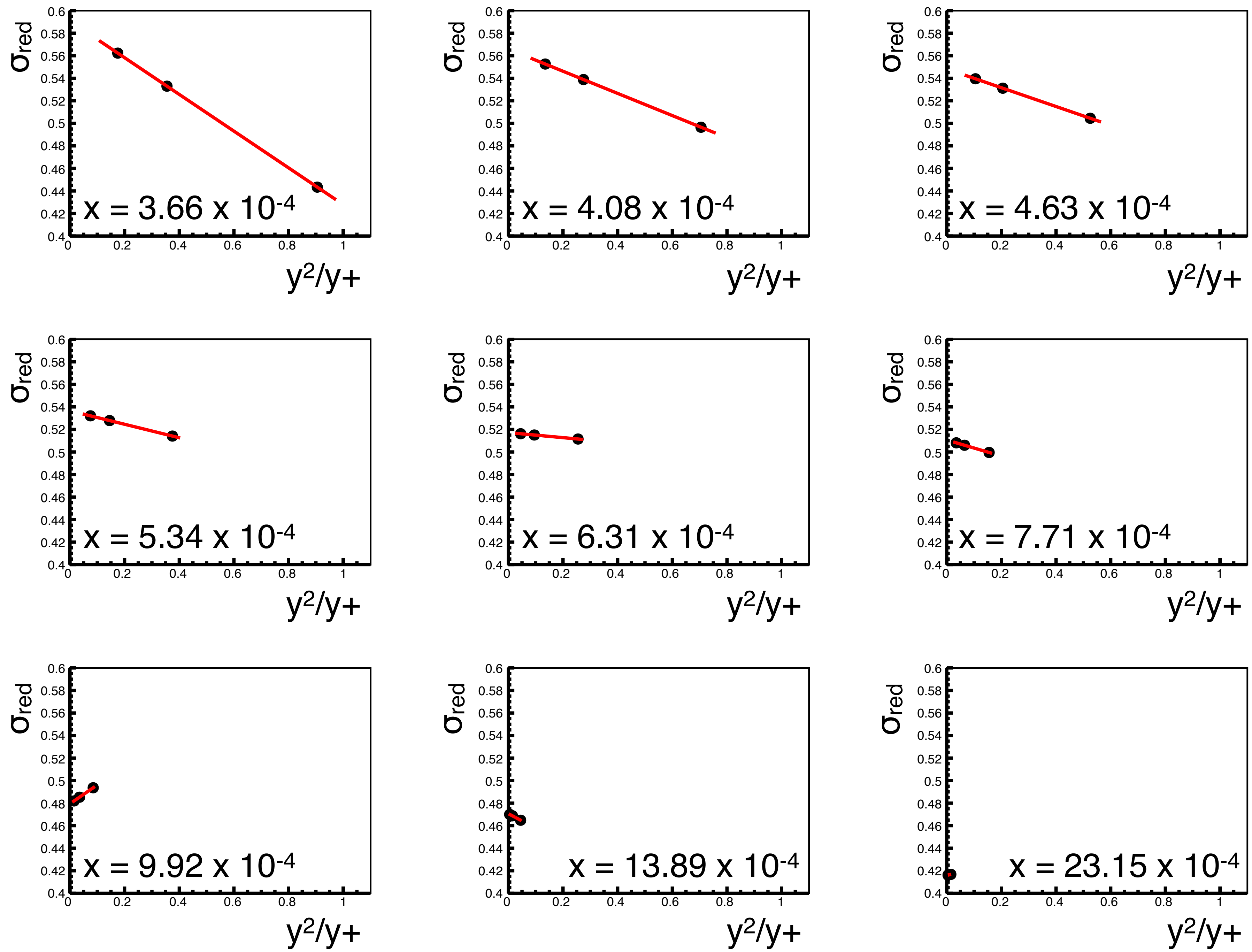

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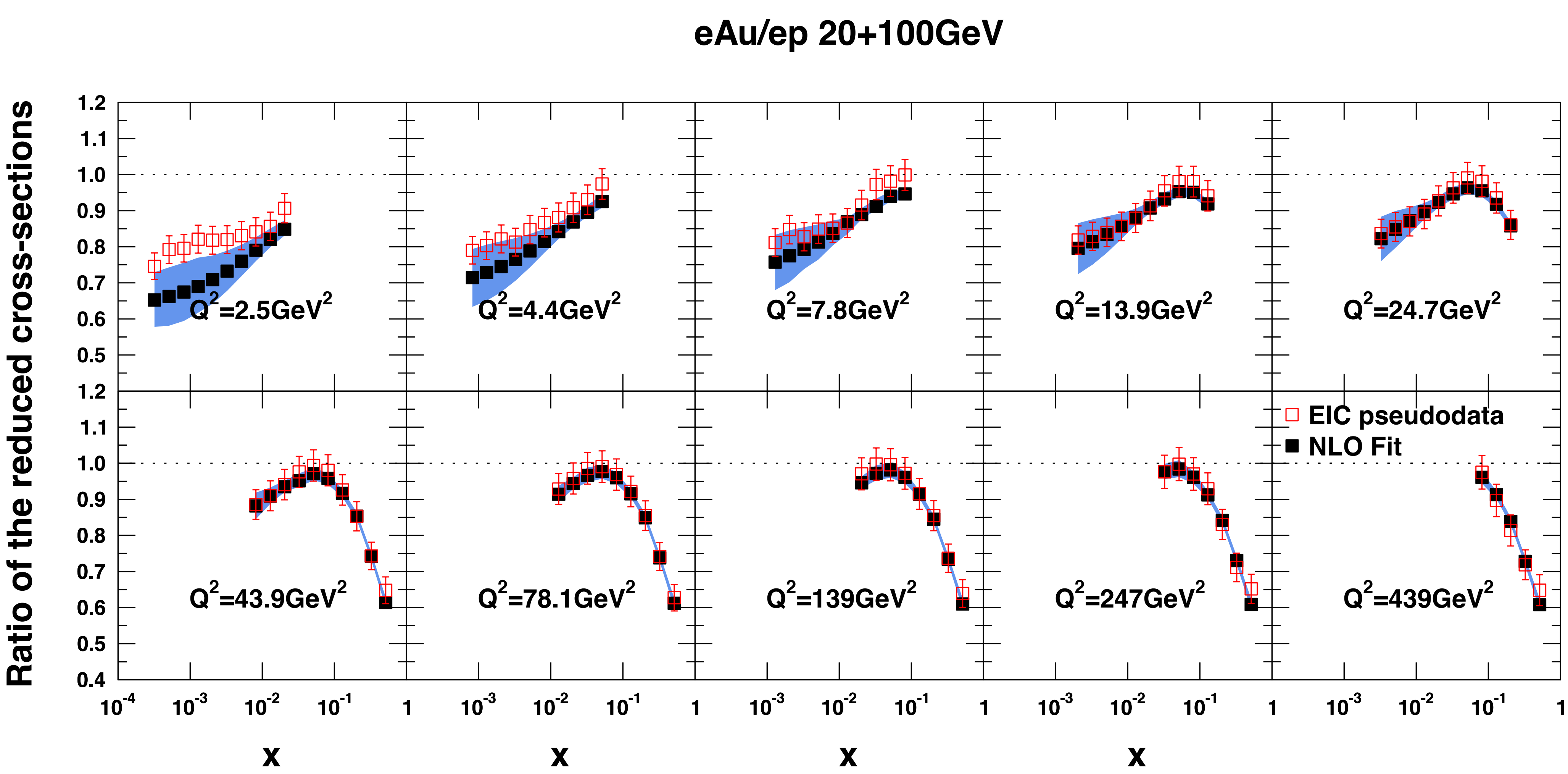

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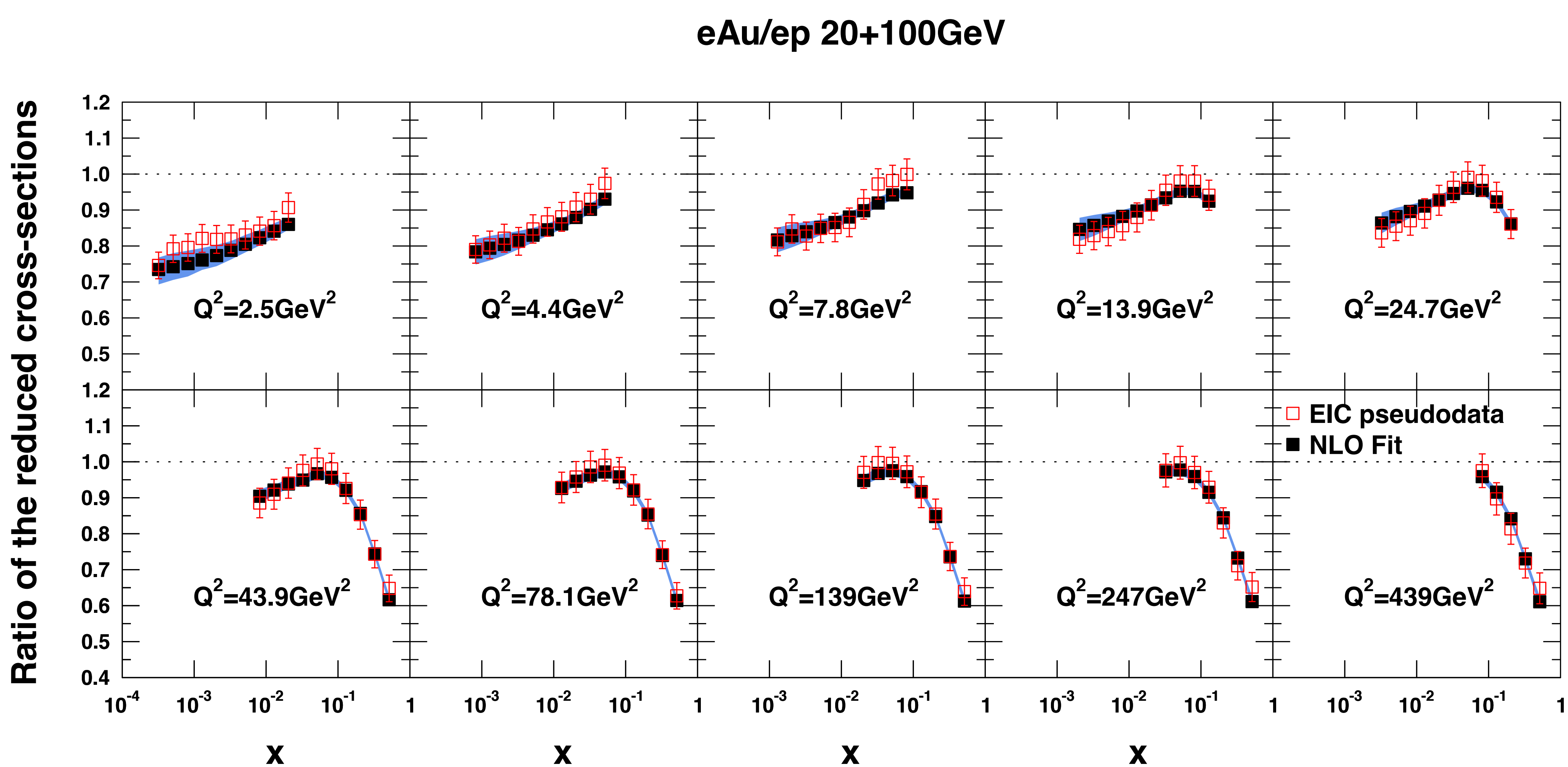

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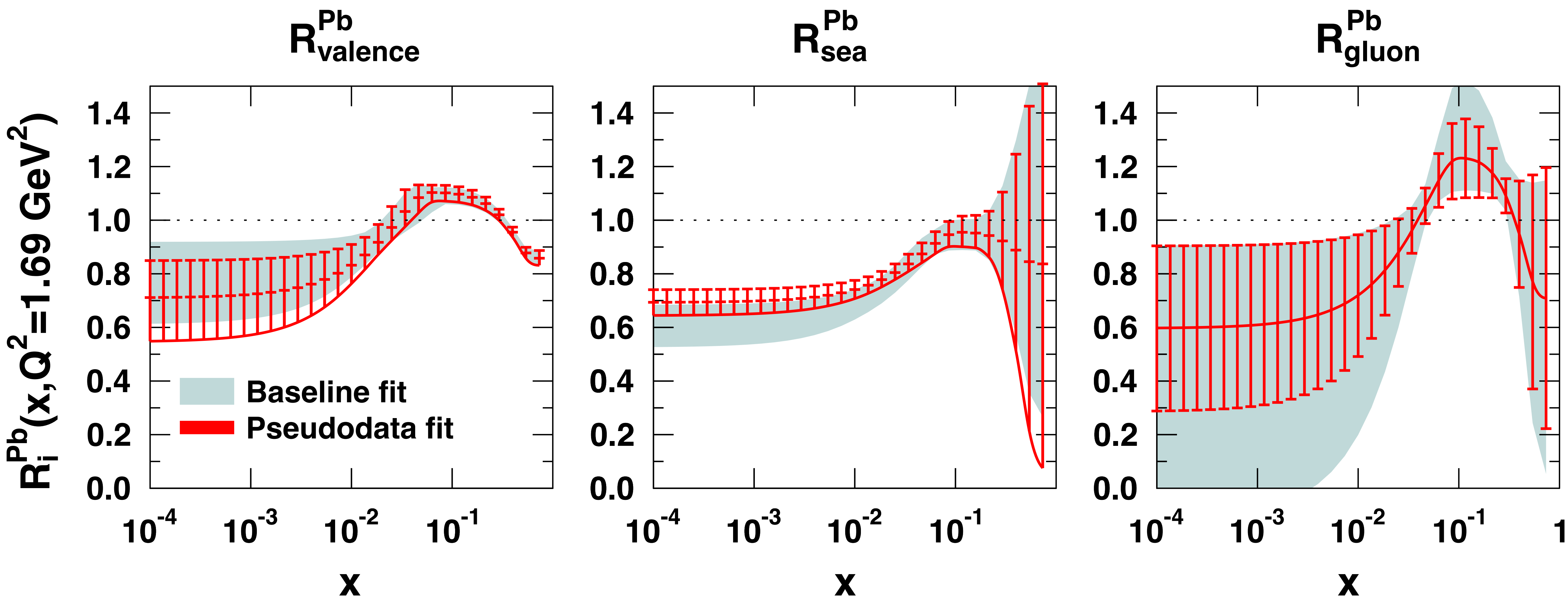

Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality
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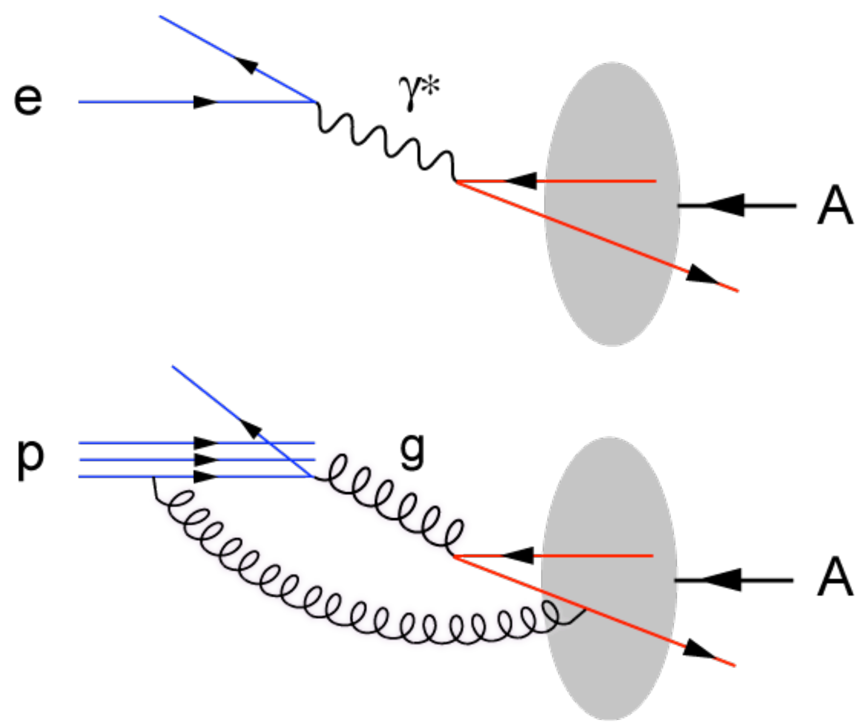
  - ➡ p+A combines initial and final state effects
  - ➡ multiple colour interactions in p+A
  - ➡ p+A lacks the direct access to x, Q^2



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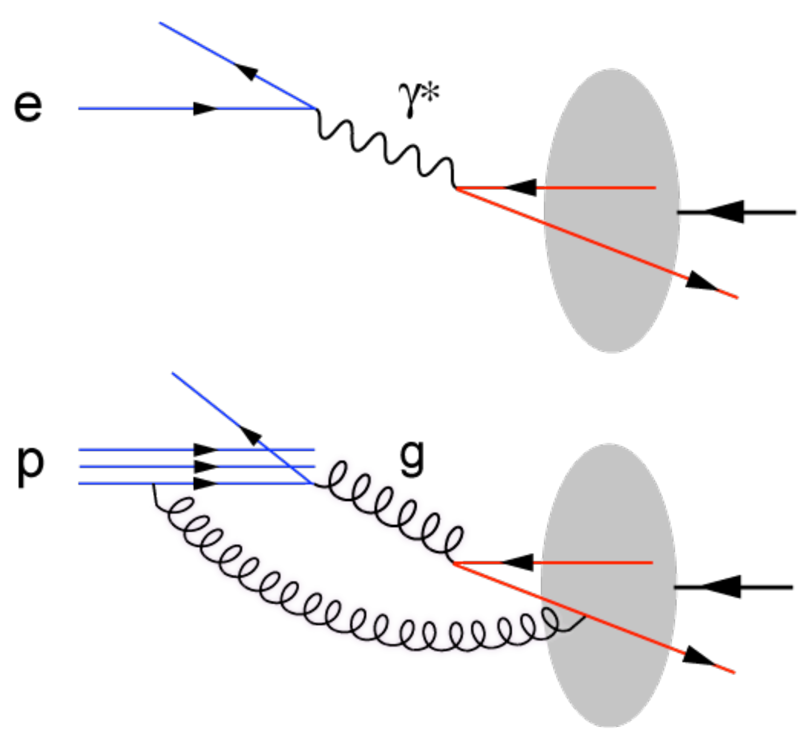

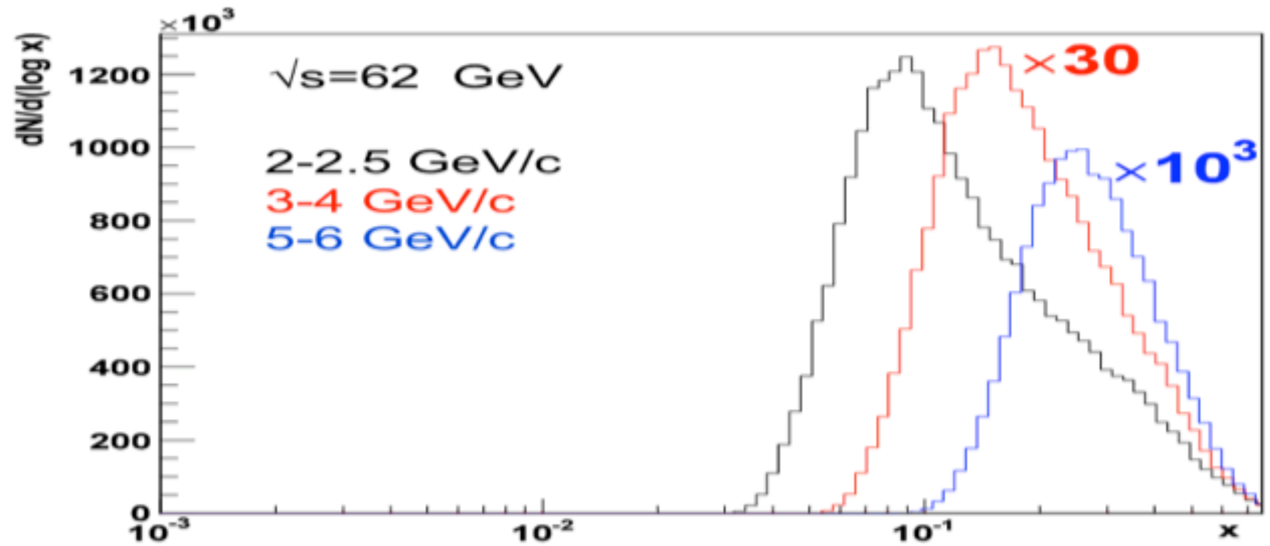

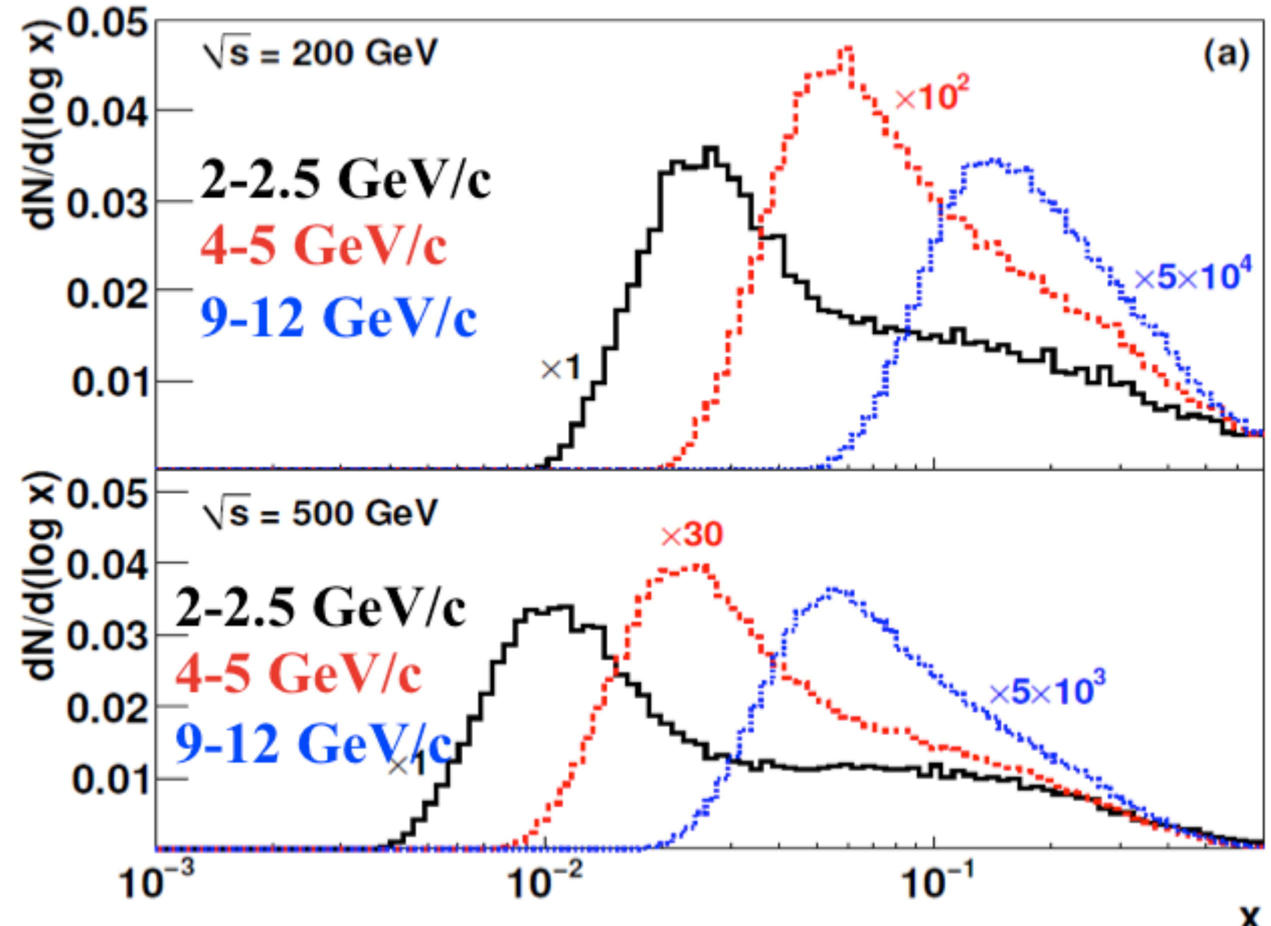

p_T - x correlation in p+p

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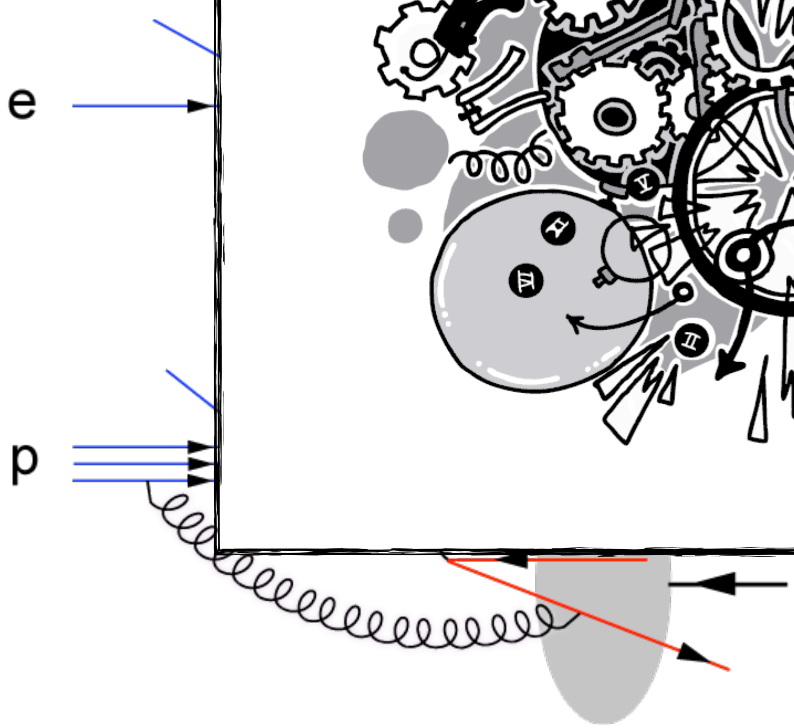
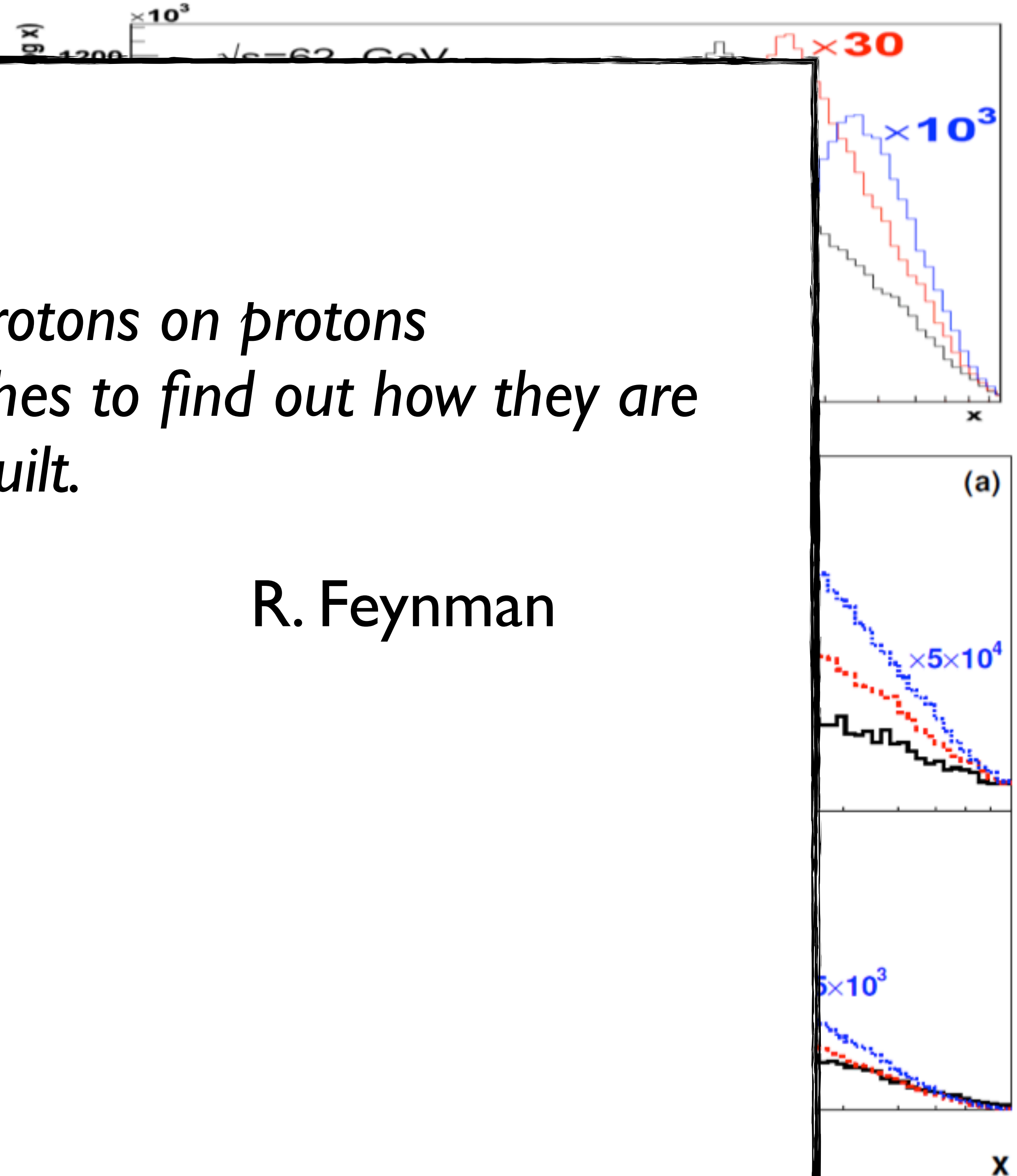
  - ➡ p+A lac

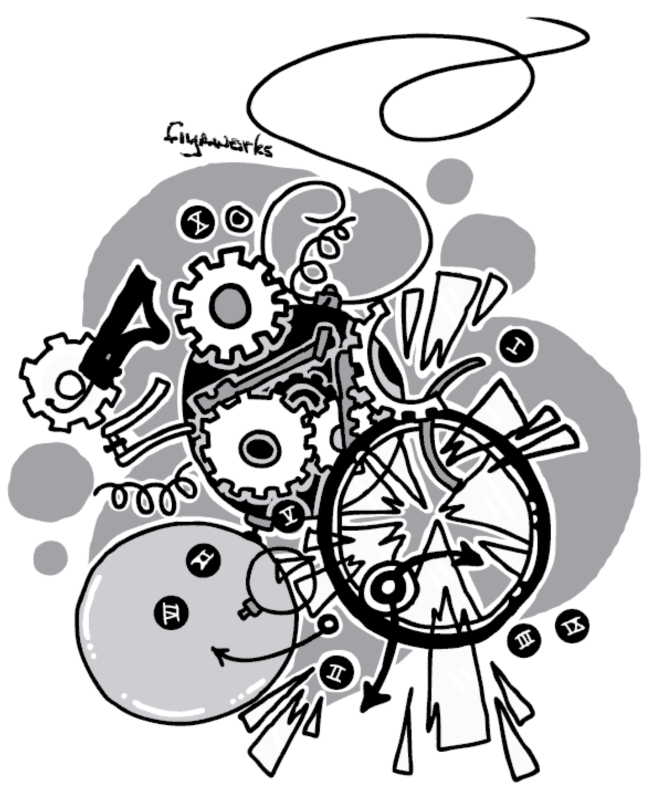




p_T - x correlation in p+p

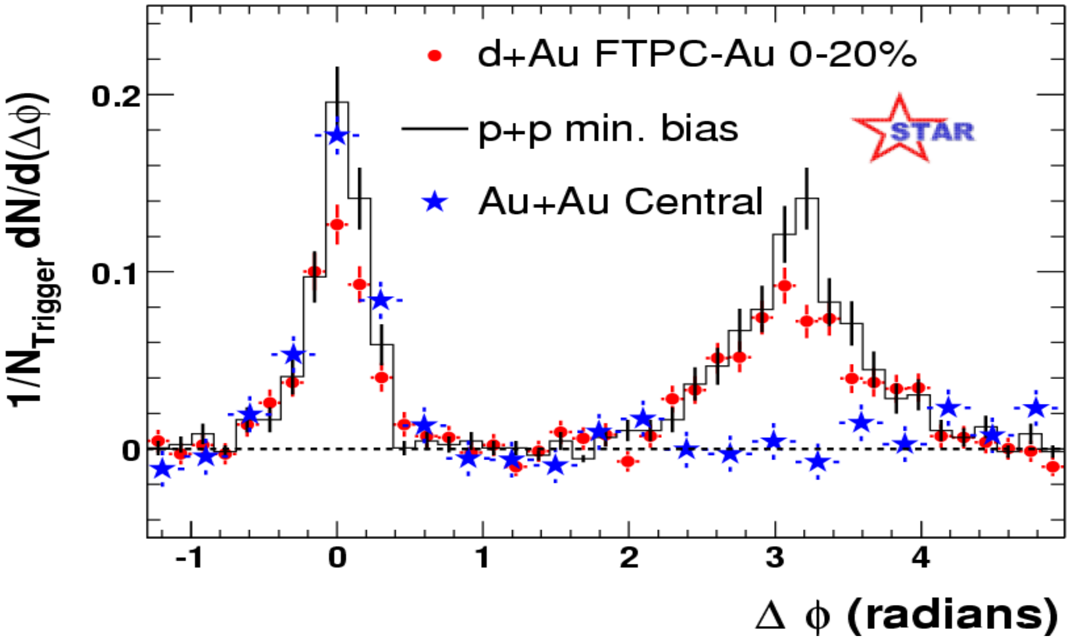
Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.

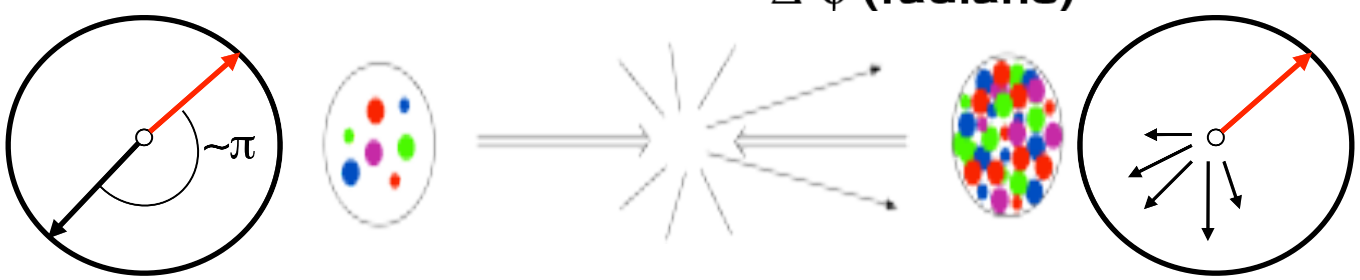
R. Feynman



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}

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

di-hadron correlations in d+A

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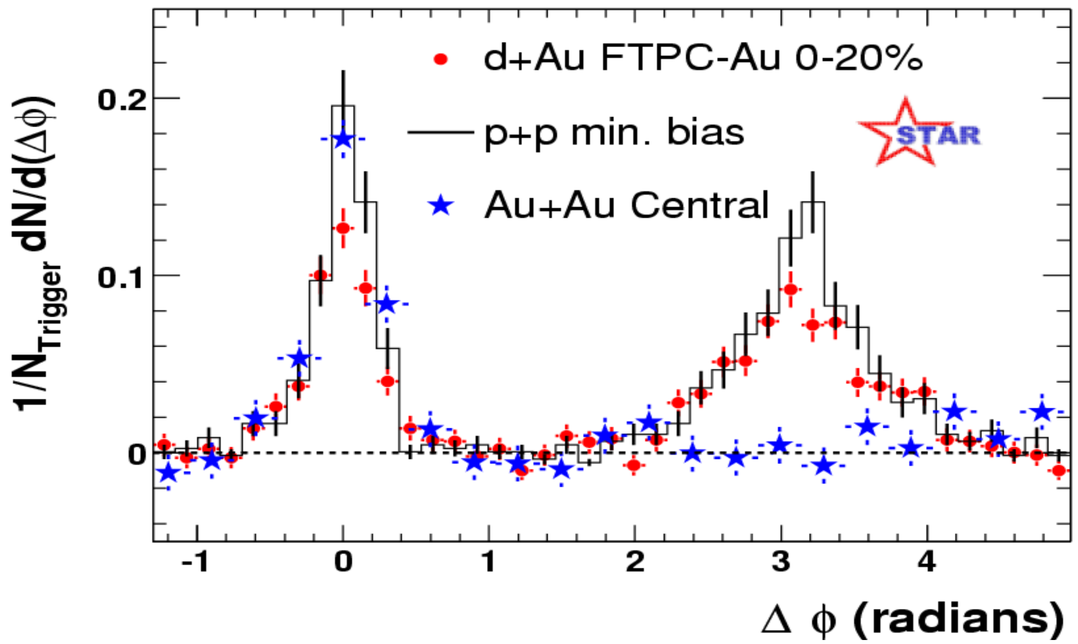

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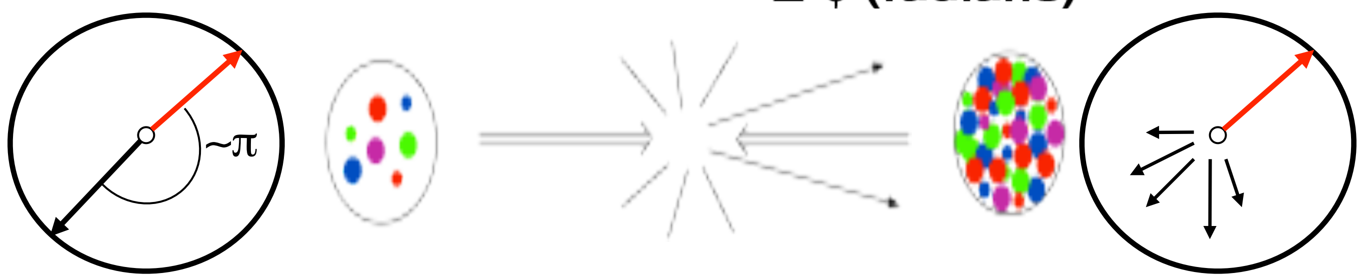
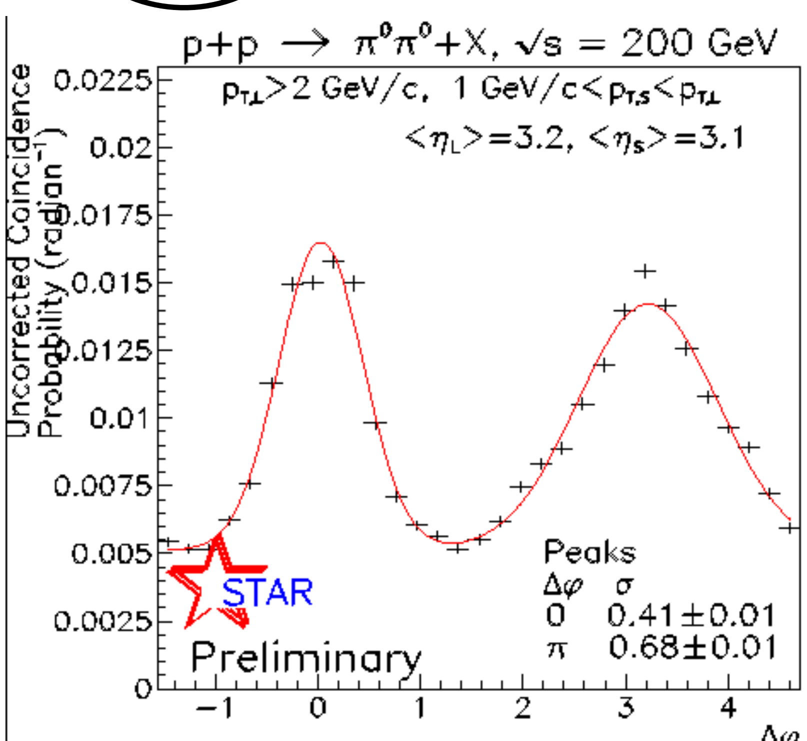
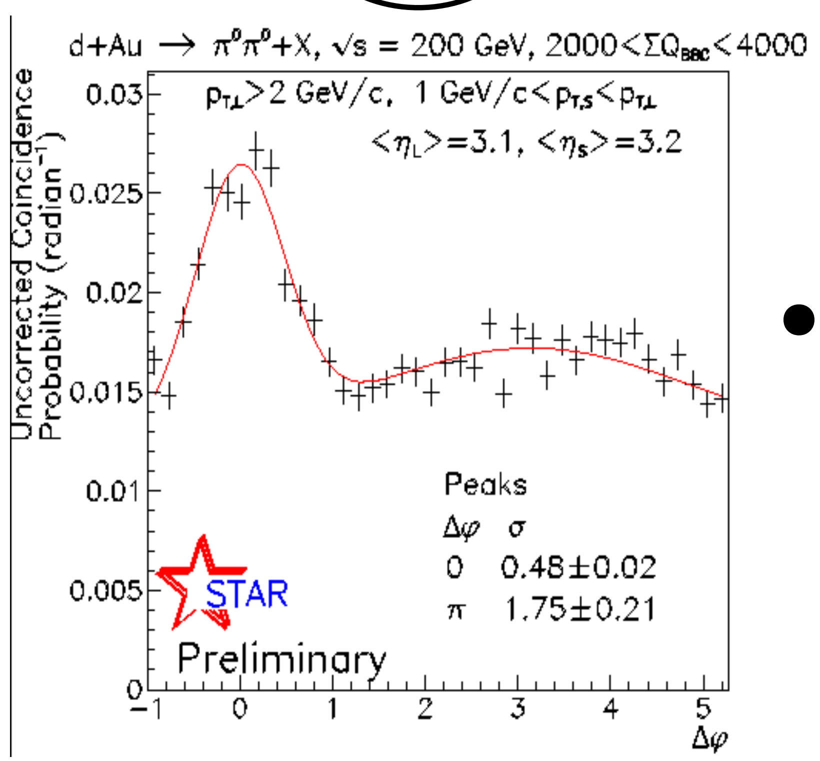




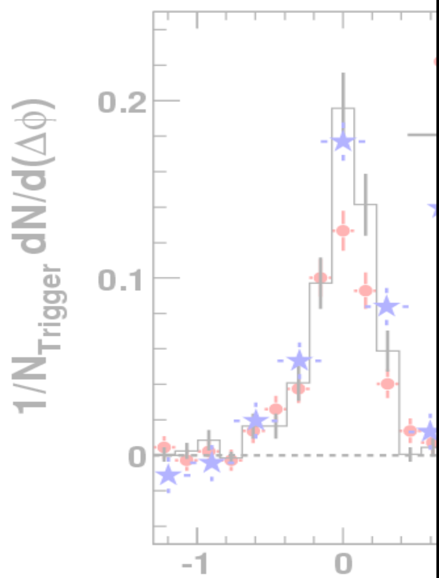


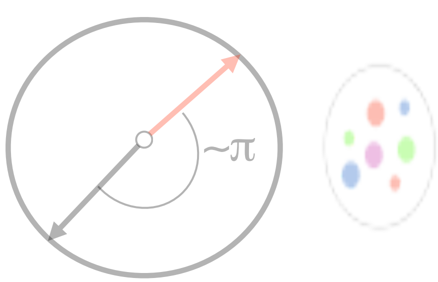
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

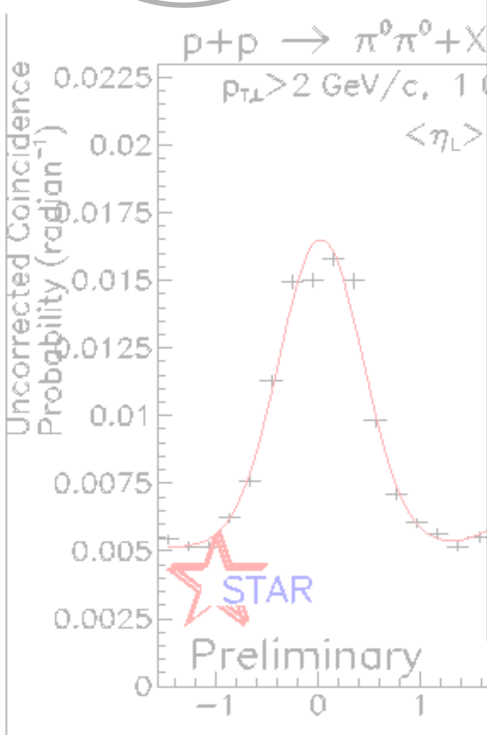
➡ x ~ 10^{-3}

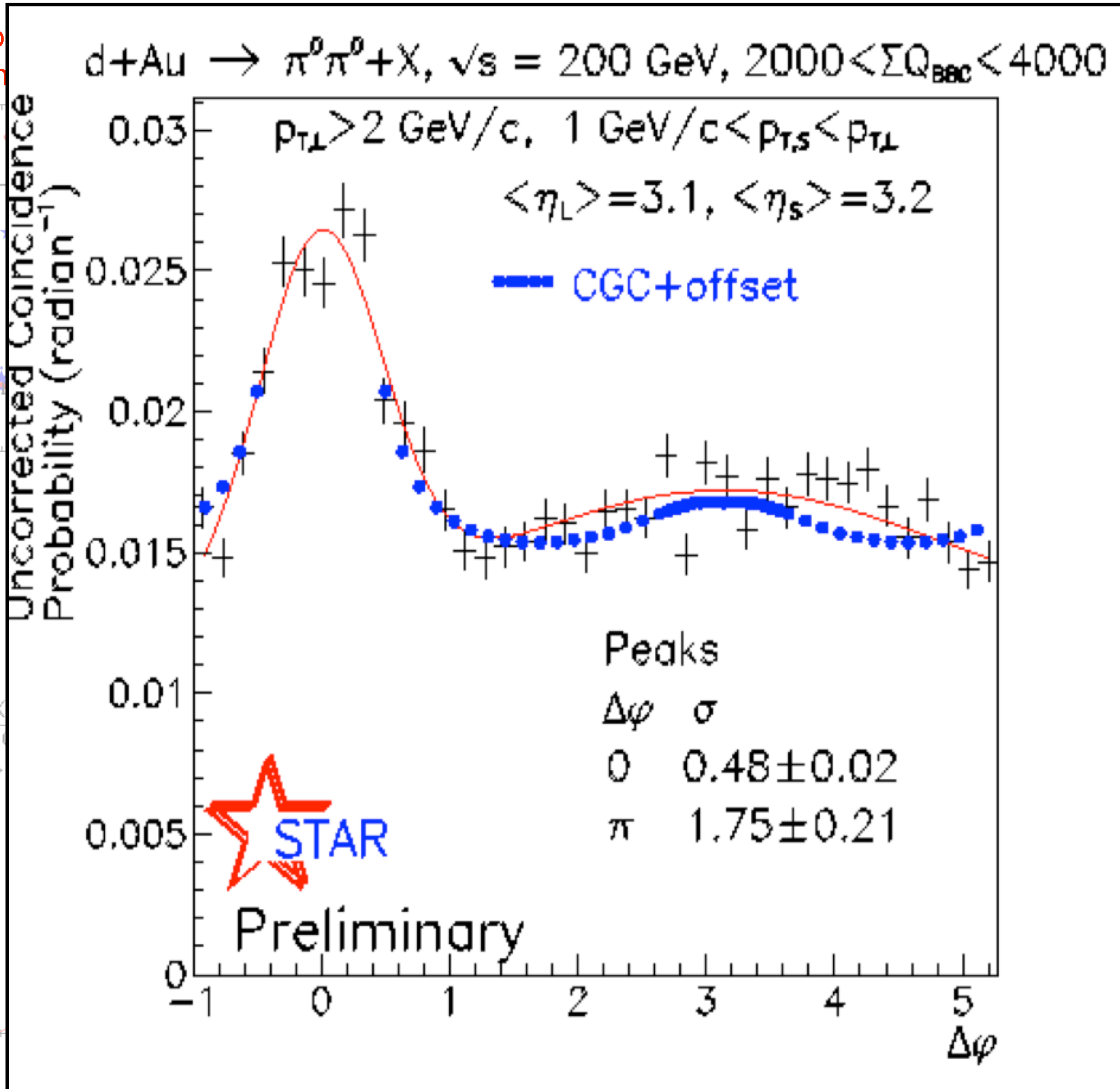
di-hadron correlations in d+A

comparisons b
+Au → h_1 h









of away-
in A+A

p+p or d+A

$+ k_2 e^{-y_2}$

$\sqrt{s}$ <<1

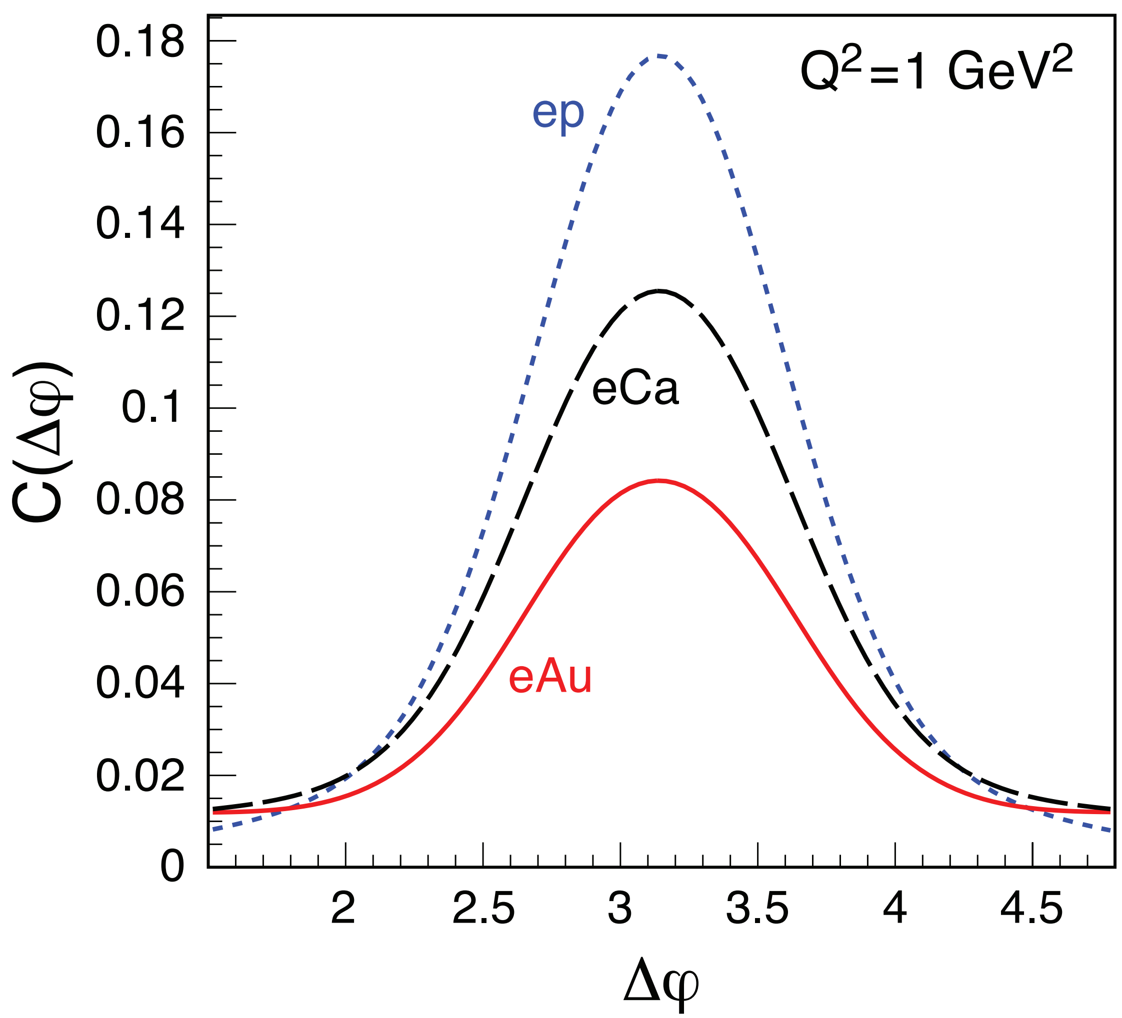
orward
3.1), an
ppression is
+Au

ak also
d+Au
p+p

➡ $x \sim 10^{-3}$

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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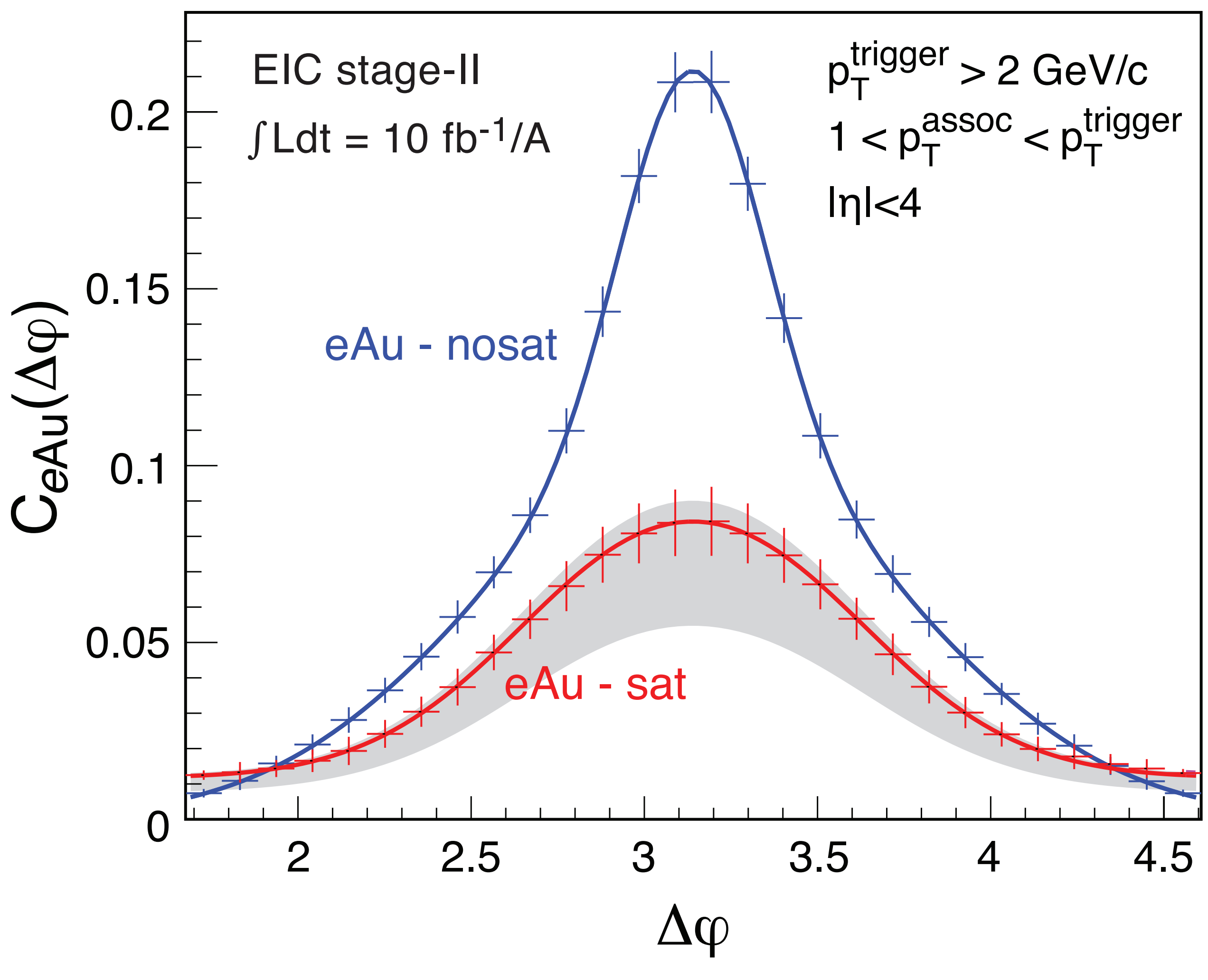

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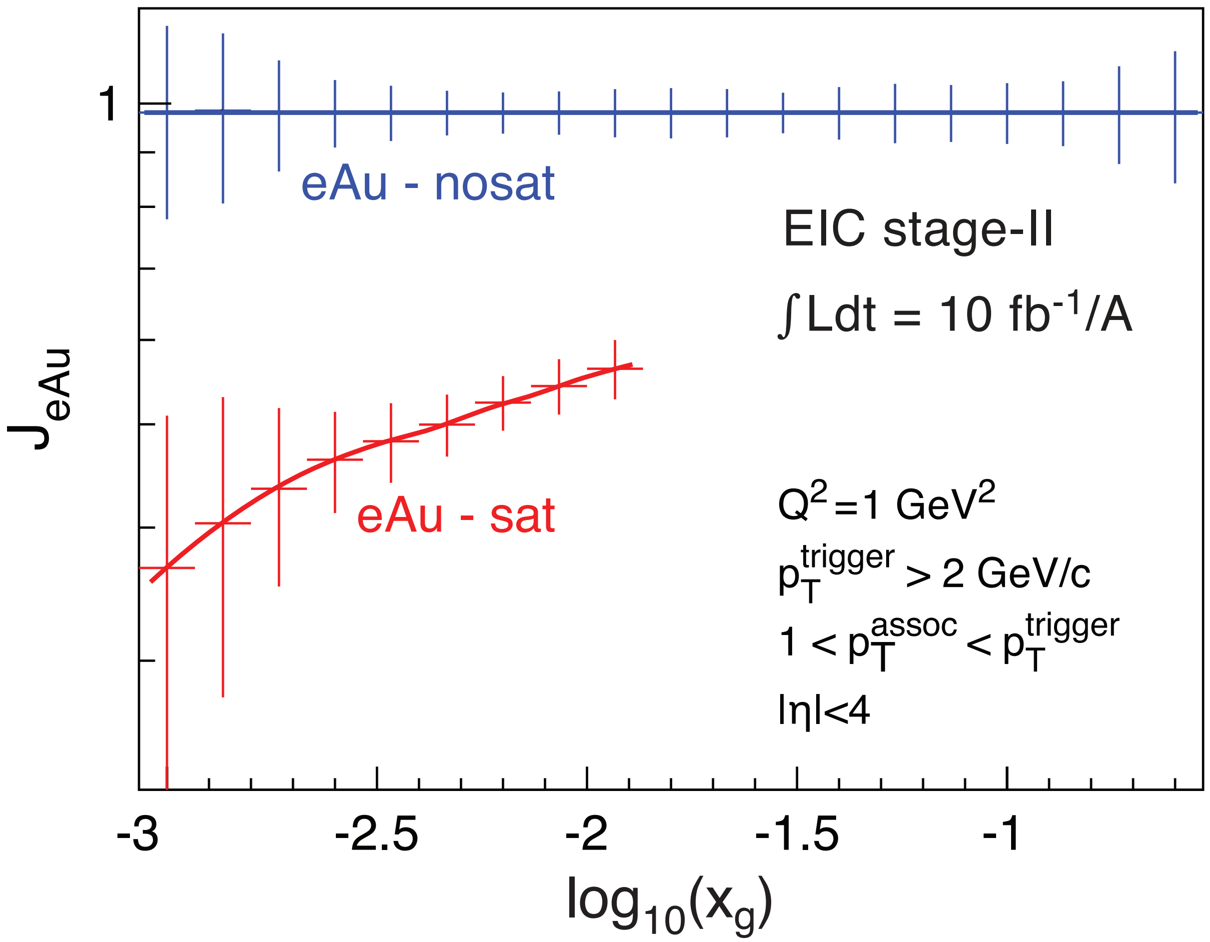
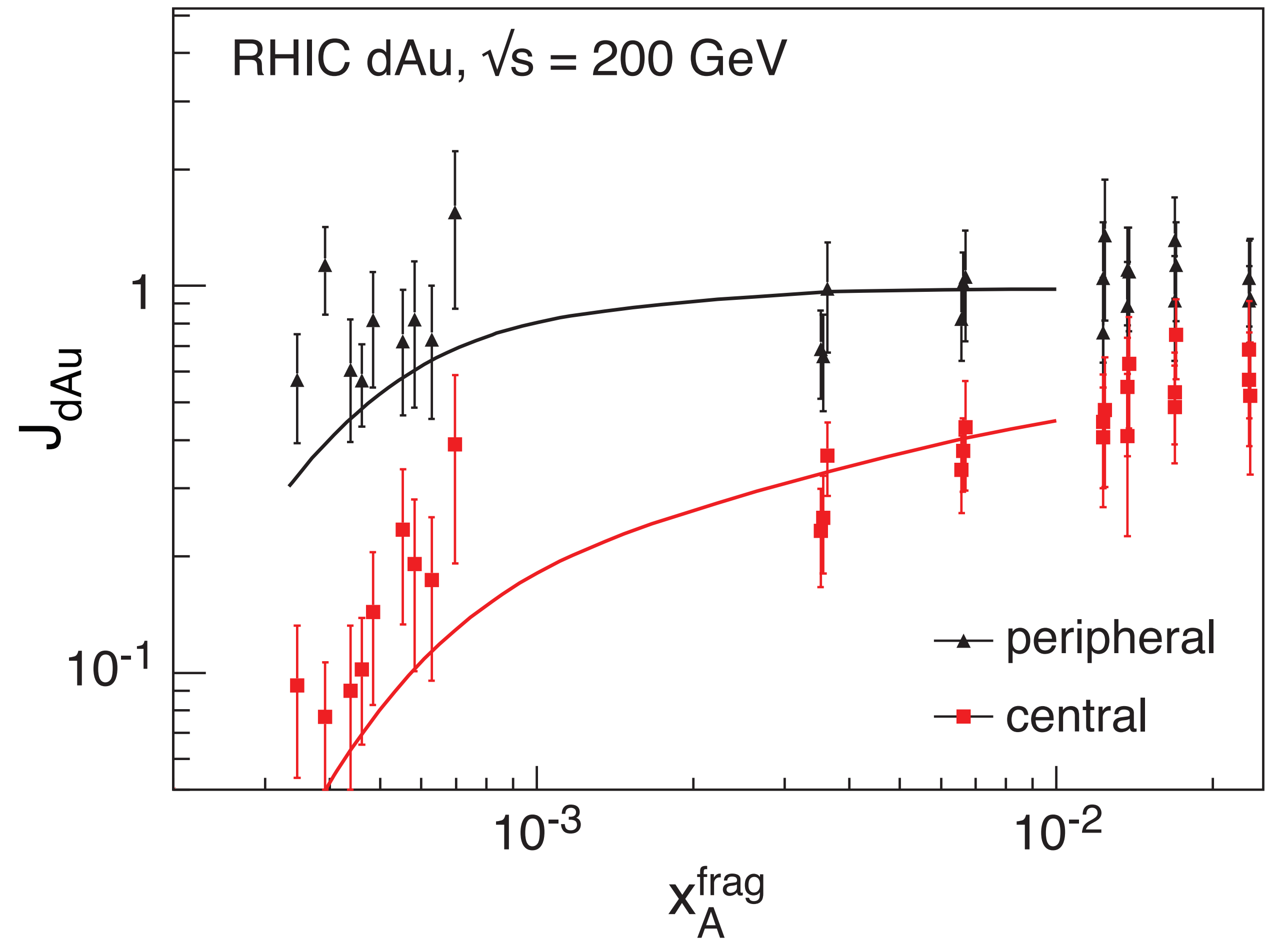
di-hadron Correlations - relative yields

- 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



forward-forward mid-forward



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