Measuring the gluon distribution in nuclei at an Electron-Ion Collider

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BROOKHAVEN NATIONAL LABORATORY

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
September 13 to November 19, 2010

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arXiv:1108.1713

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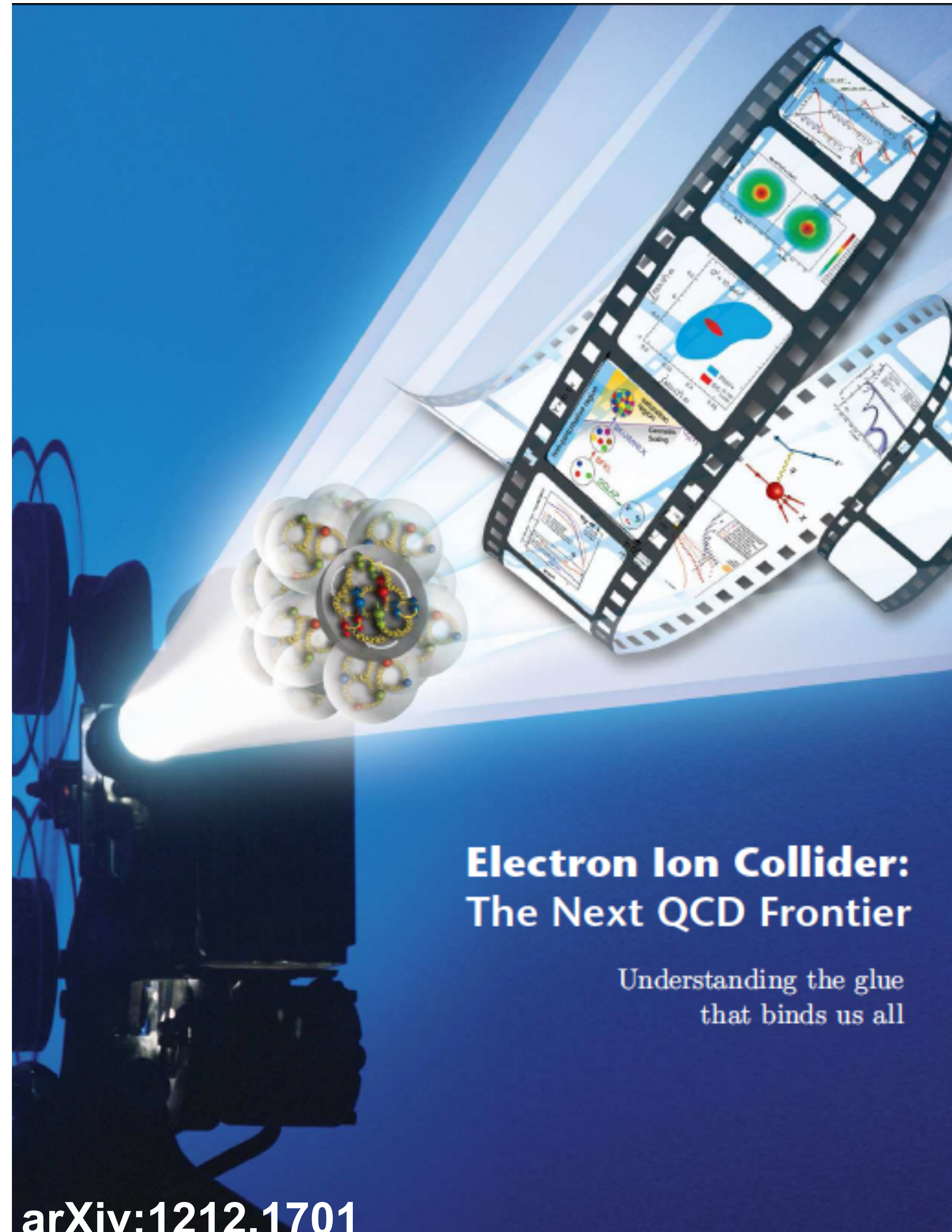


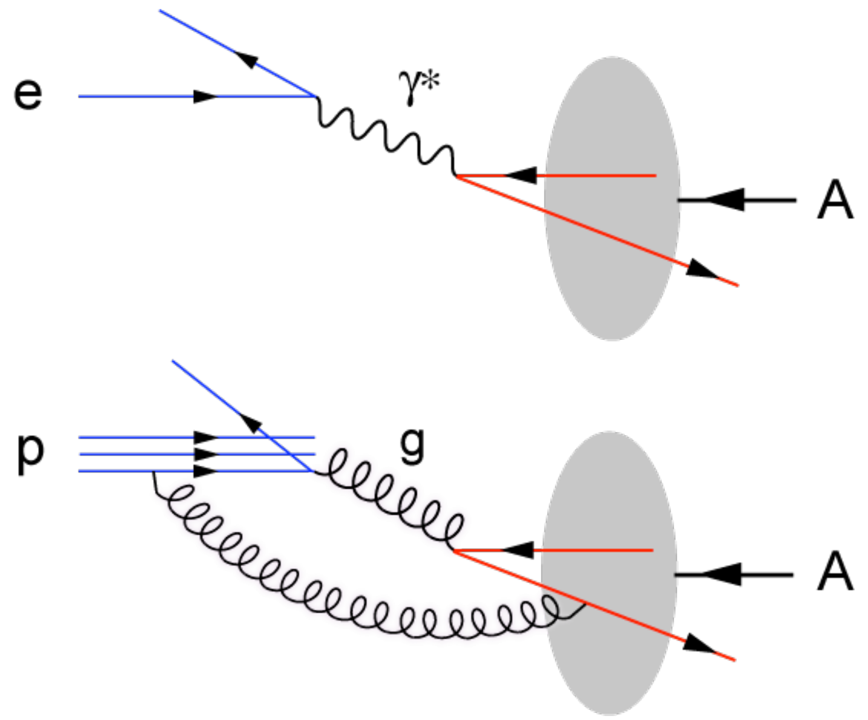
arXiv:1212.1701

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

- Issues:
  - ➡ 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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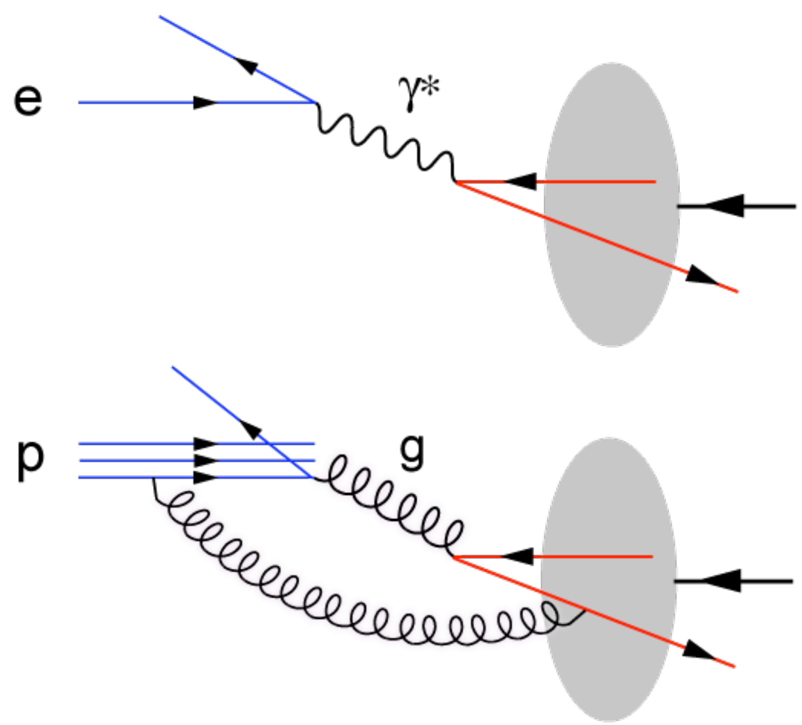

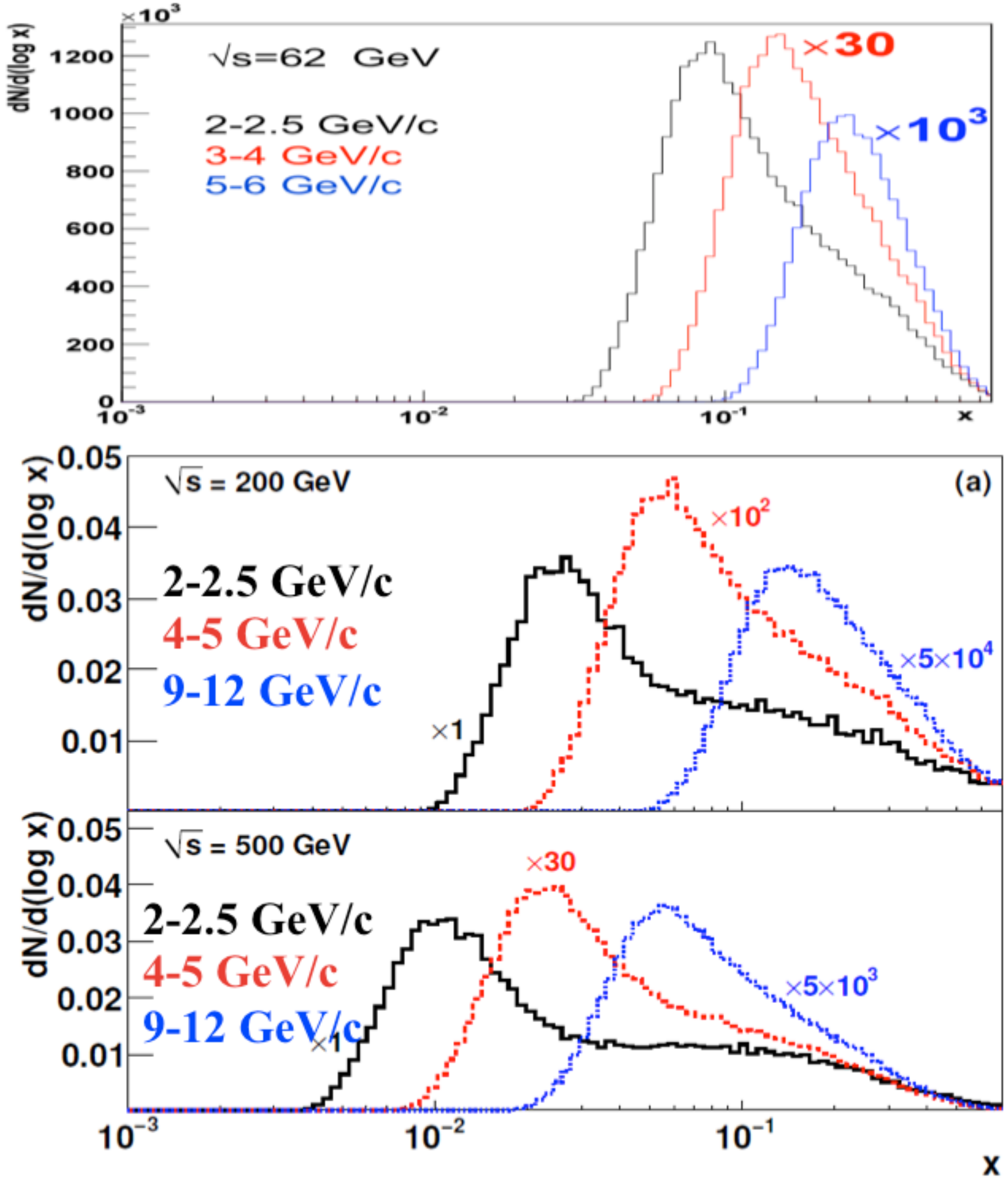

p_T - x correlation in p+p

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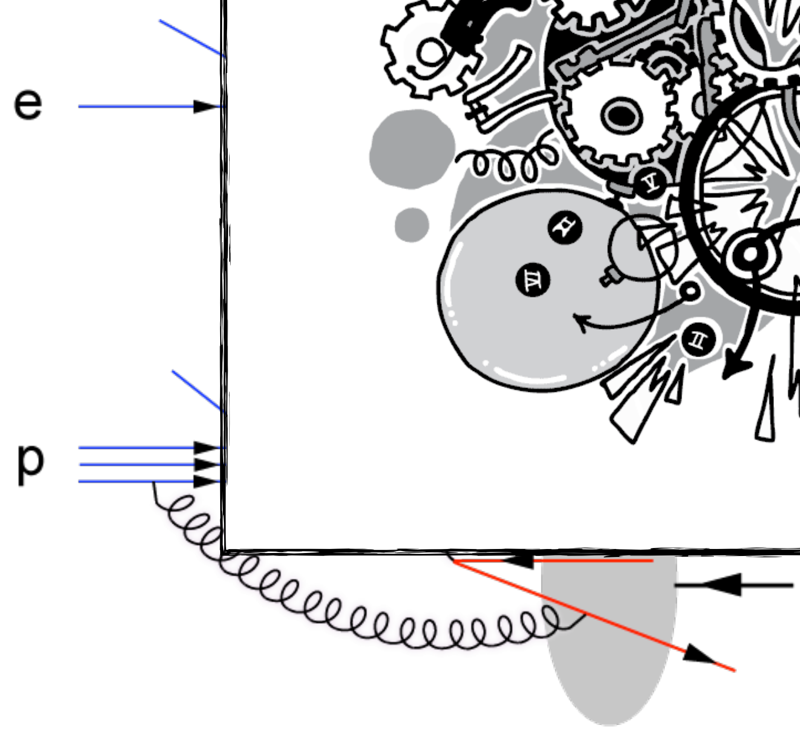
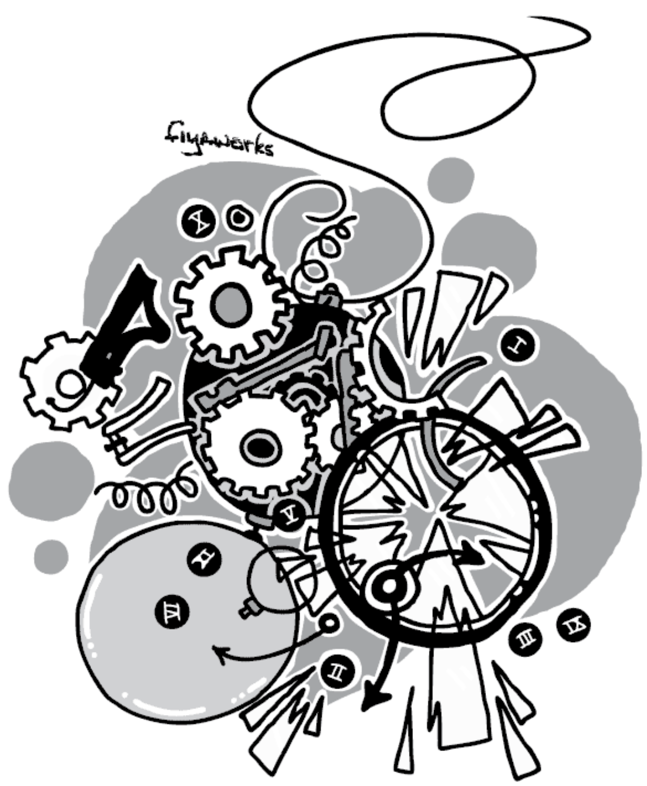
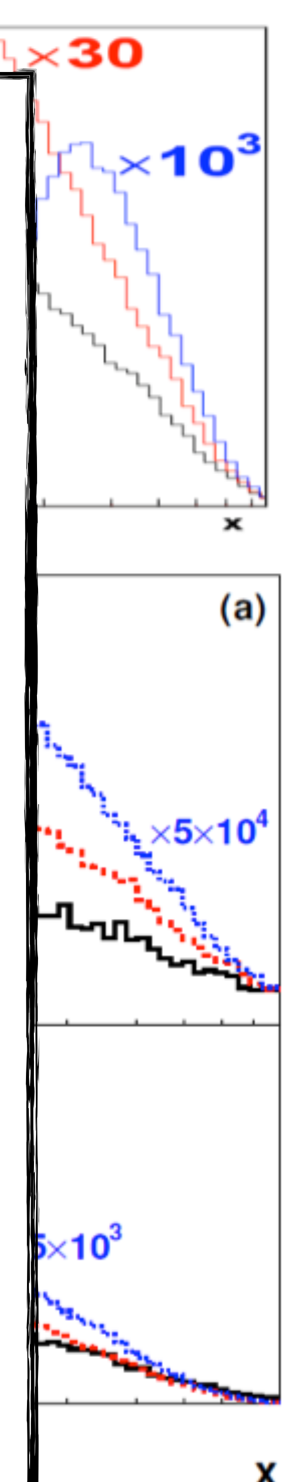


Scattering of protons on protons is like colliding Swiss watches to find out how they are built.

R. Feynman





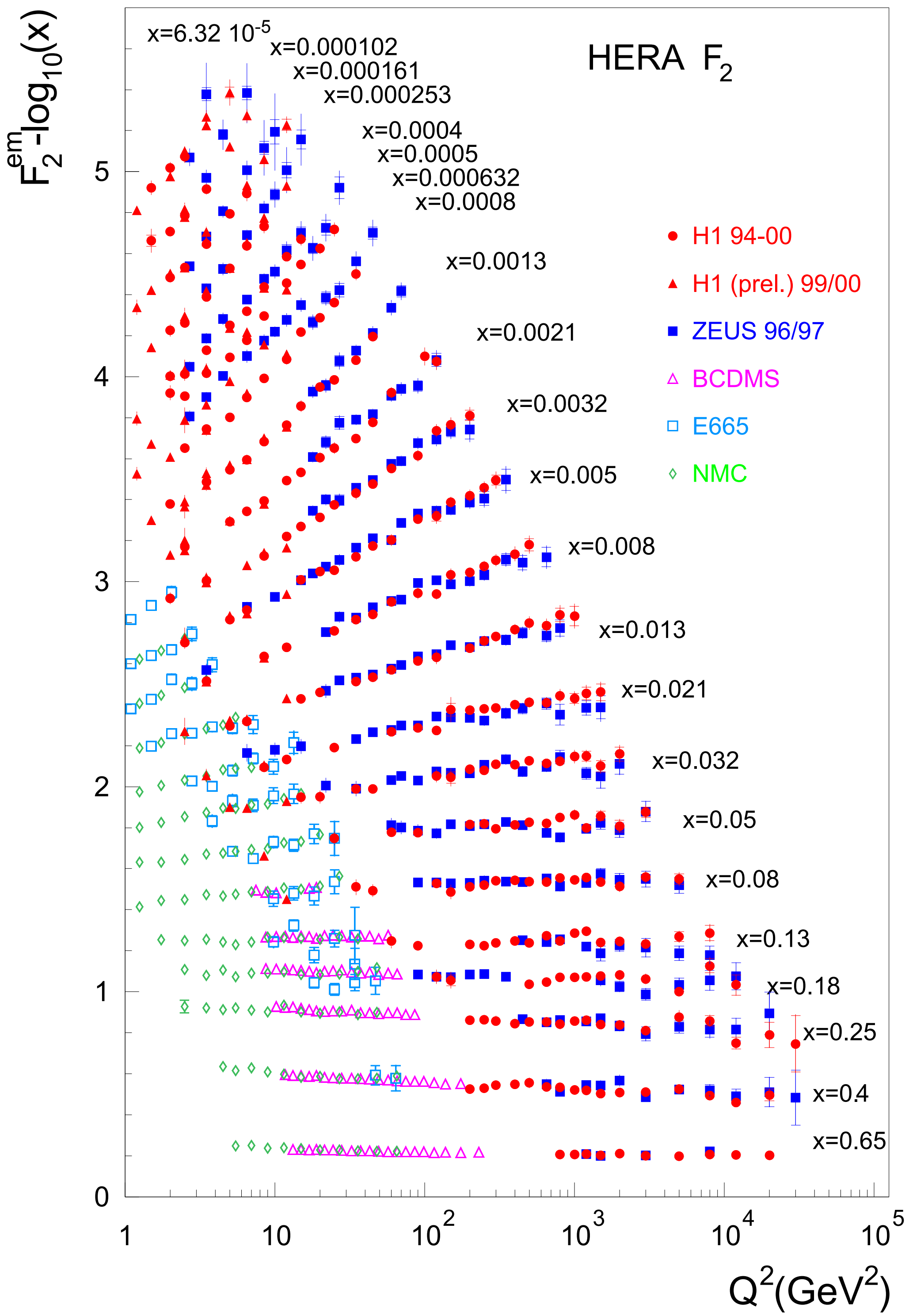
p_T - x correlation in p+p

What did we learn from e+p collisions at HERA?

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

quark+anti-quark momentum distributions

gluon momentum distribution



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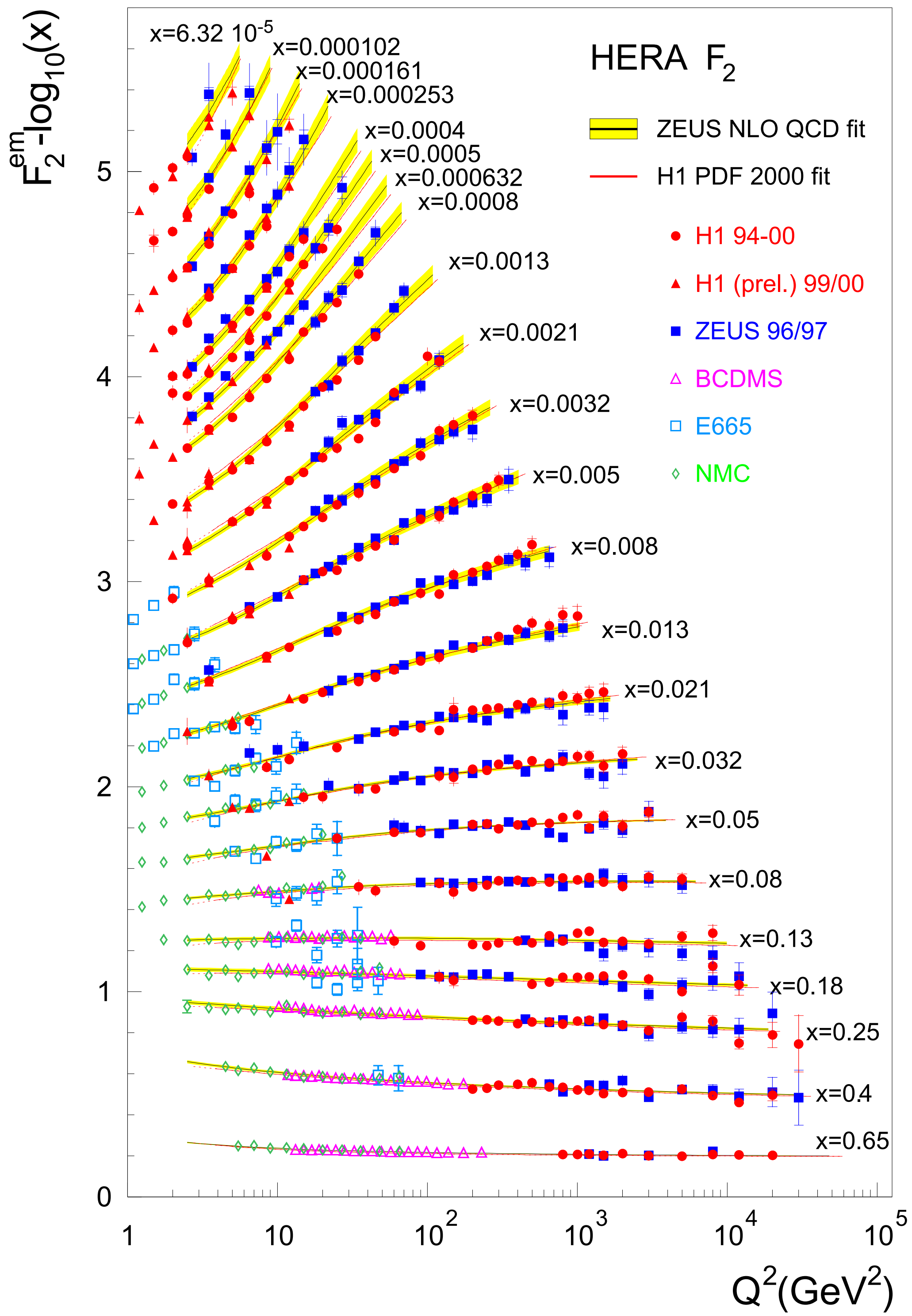

Scaling violation: *$dF_2/d\ln Q^2$* and linear DGLAP Evolution ⇒ *$G(x,Q^2)$*

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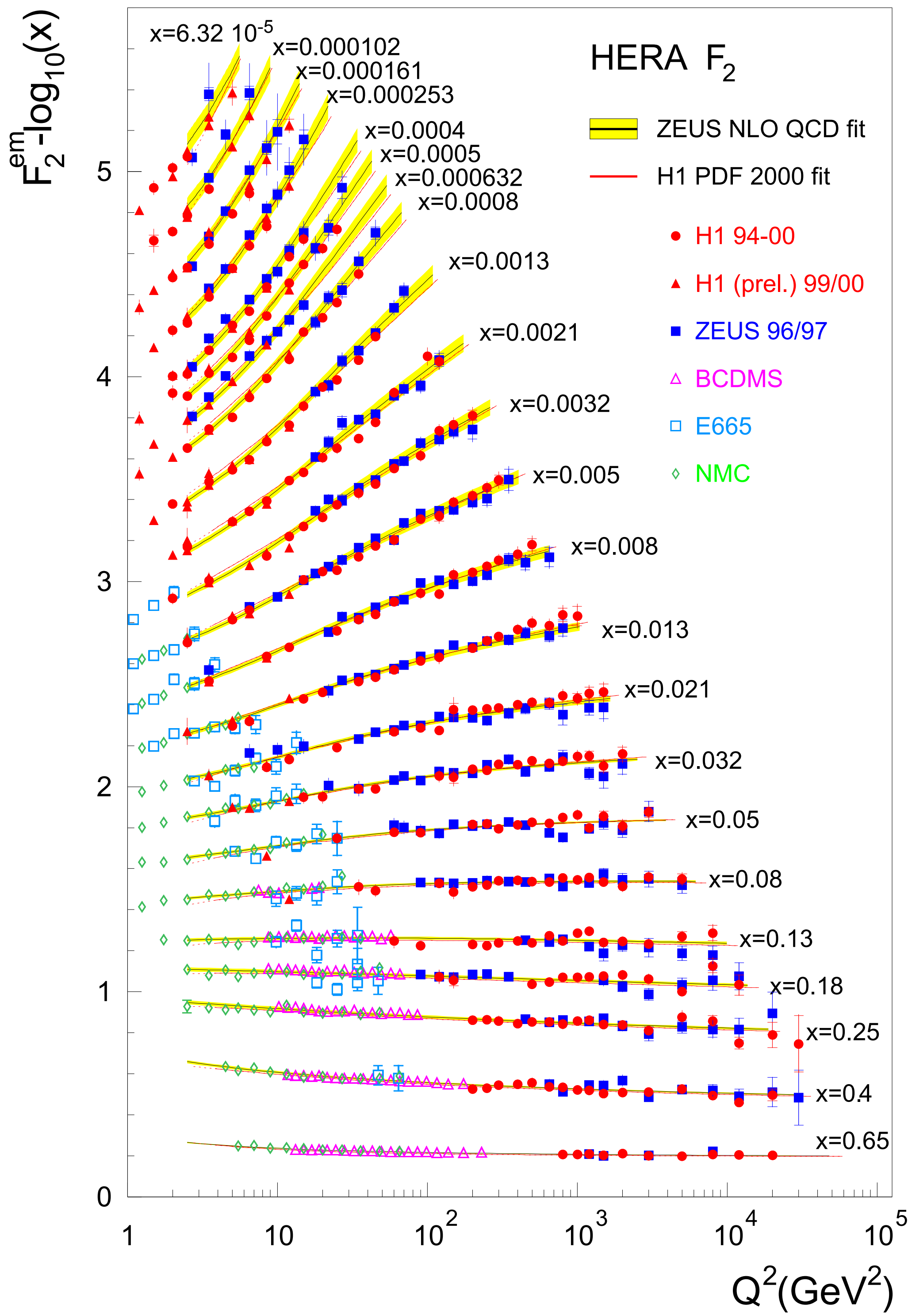

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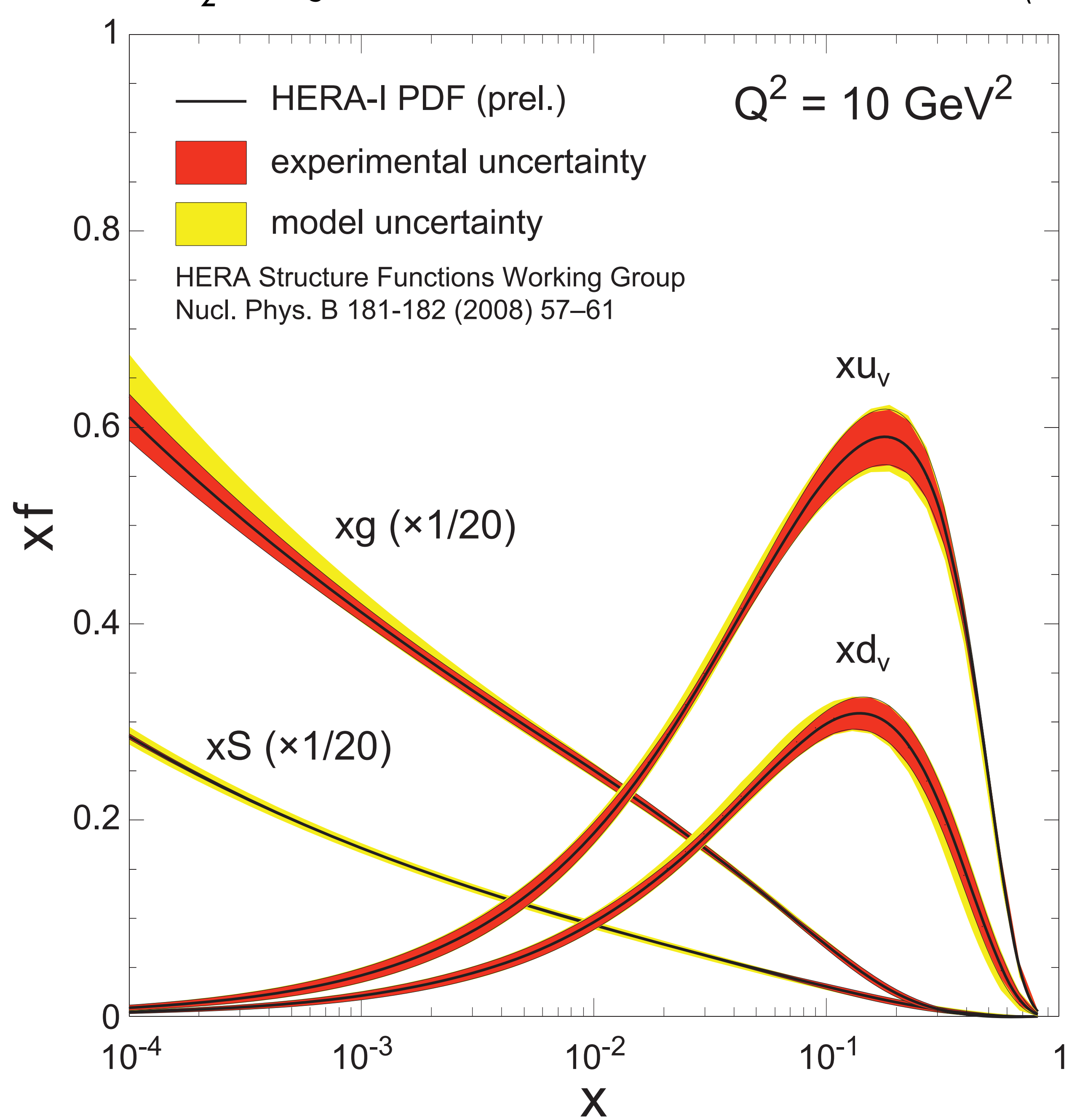

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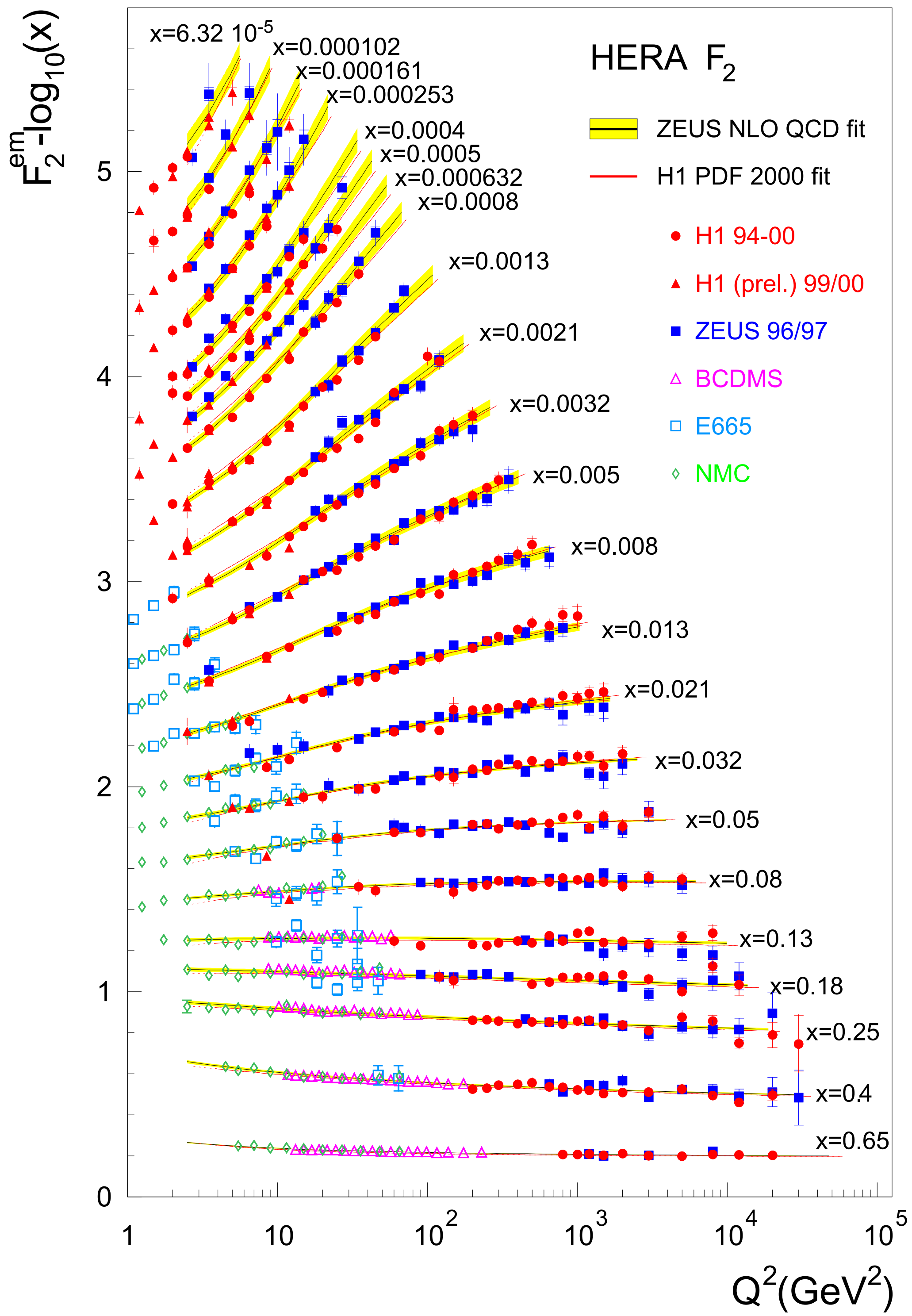

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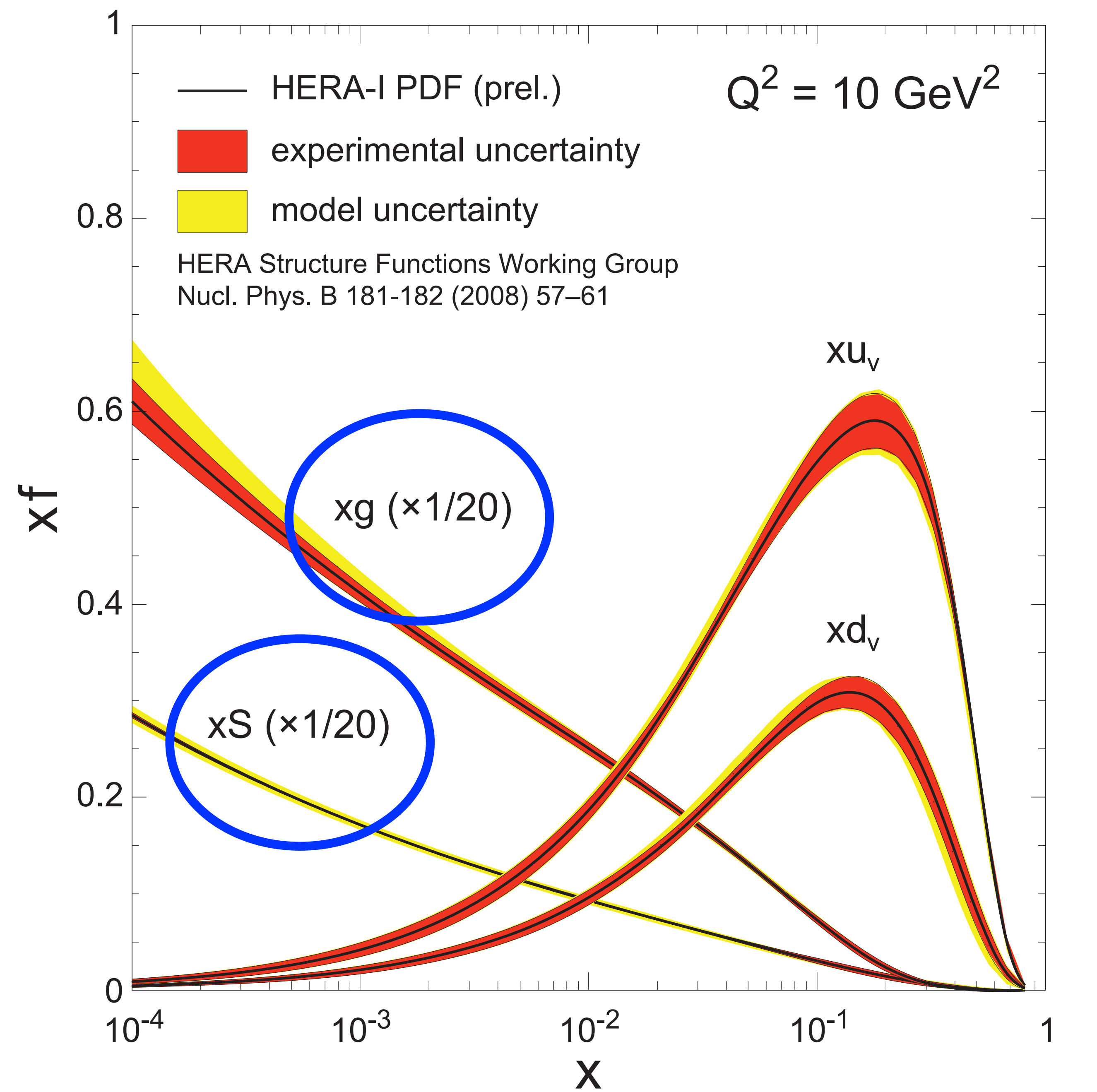

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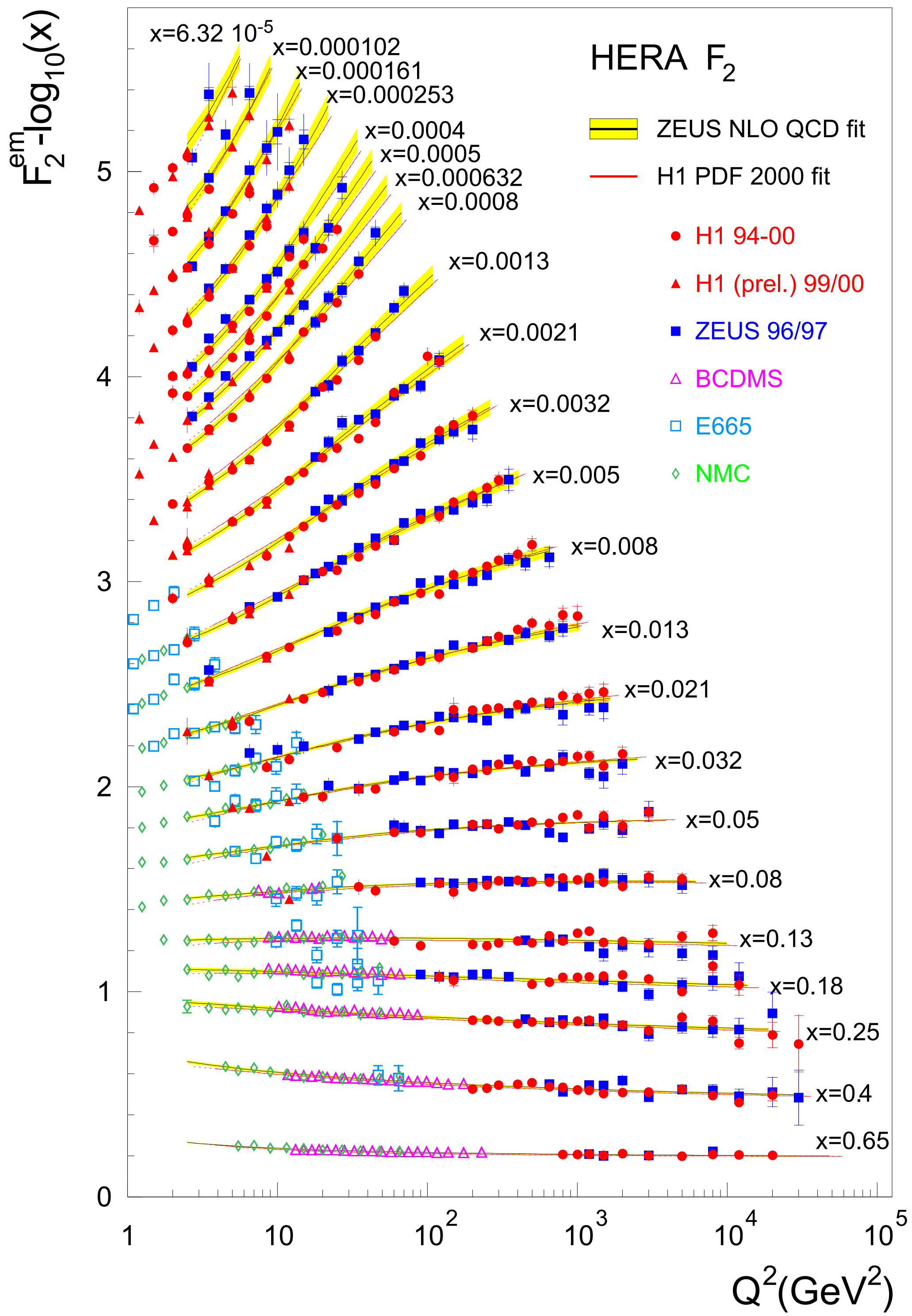

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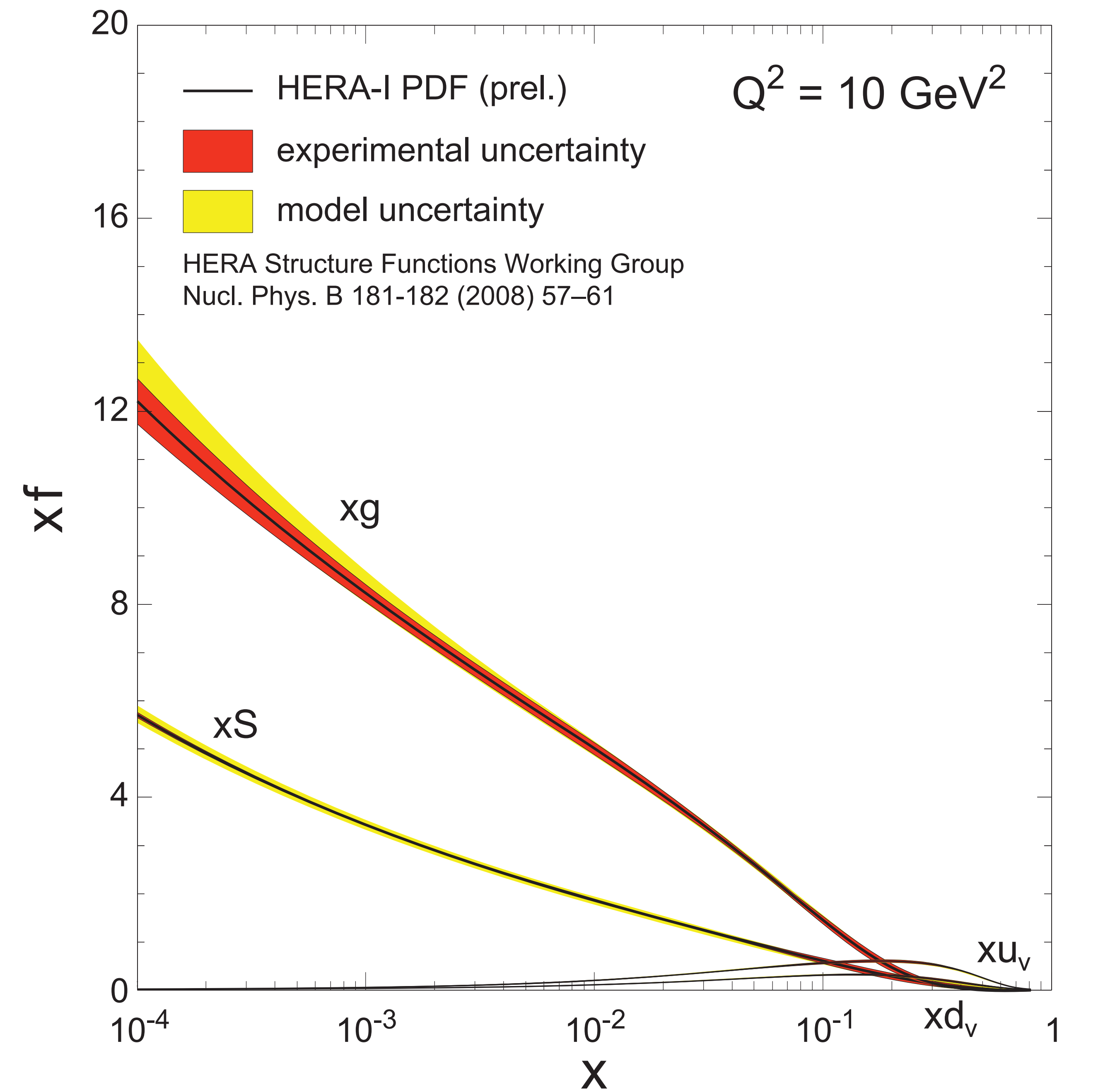

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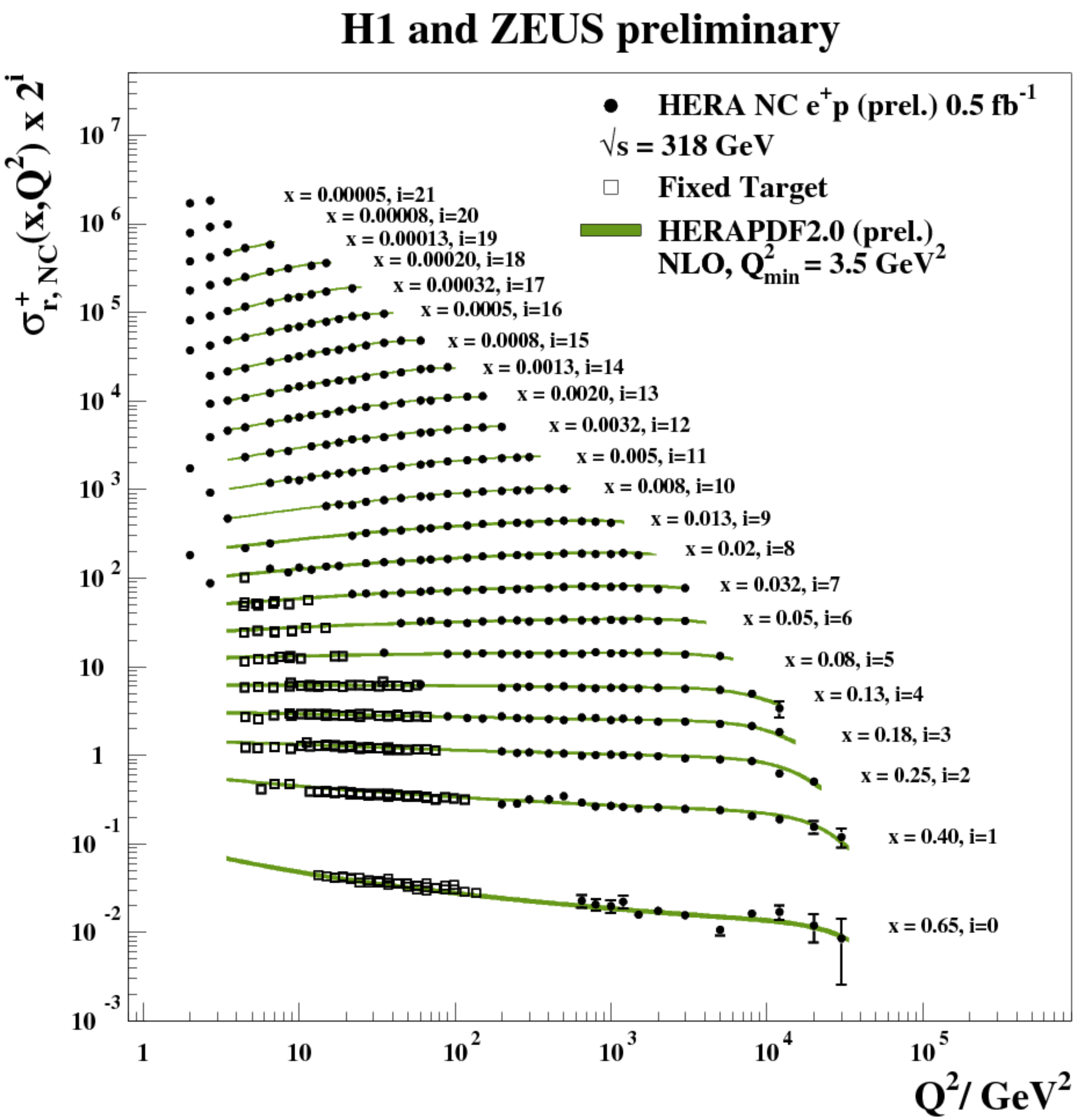

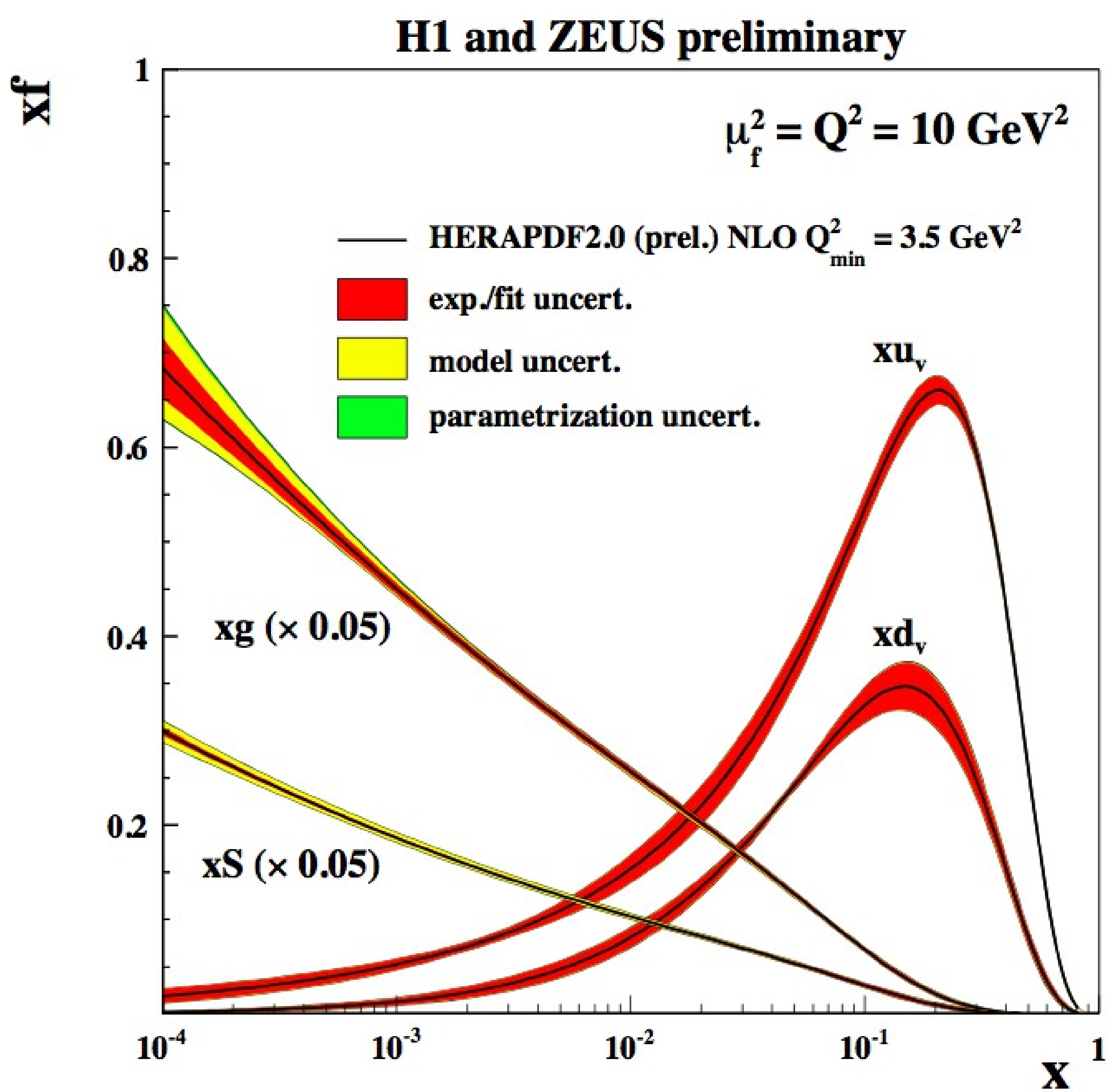

DIS 2014 - HERA Combined data

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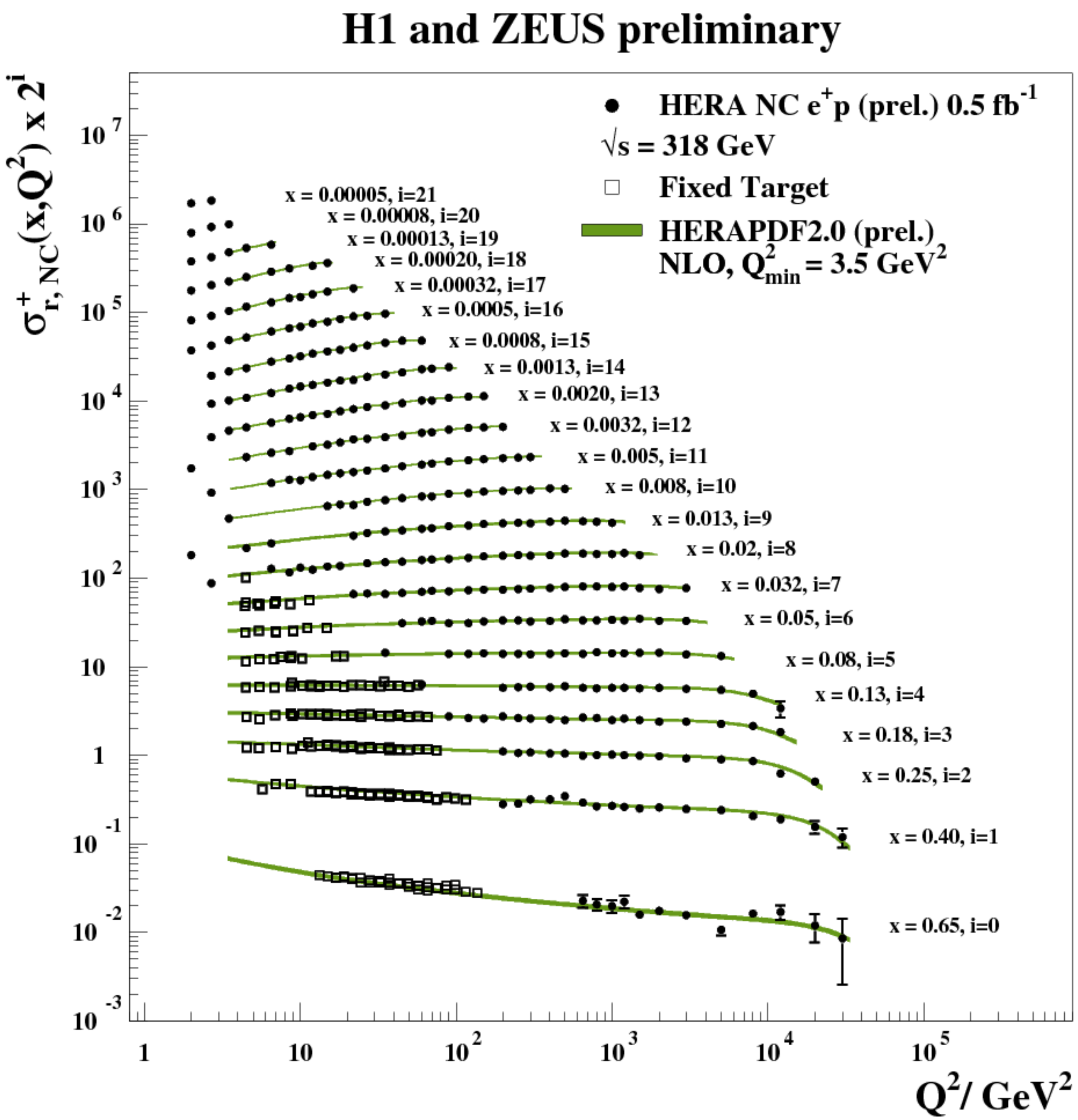
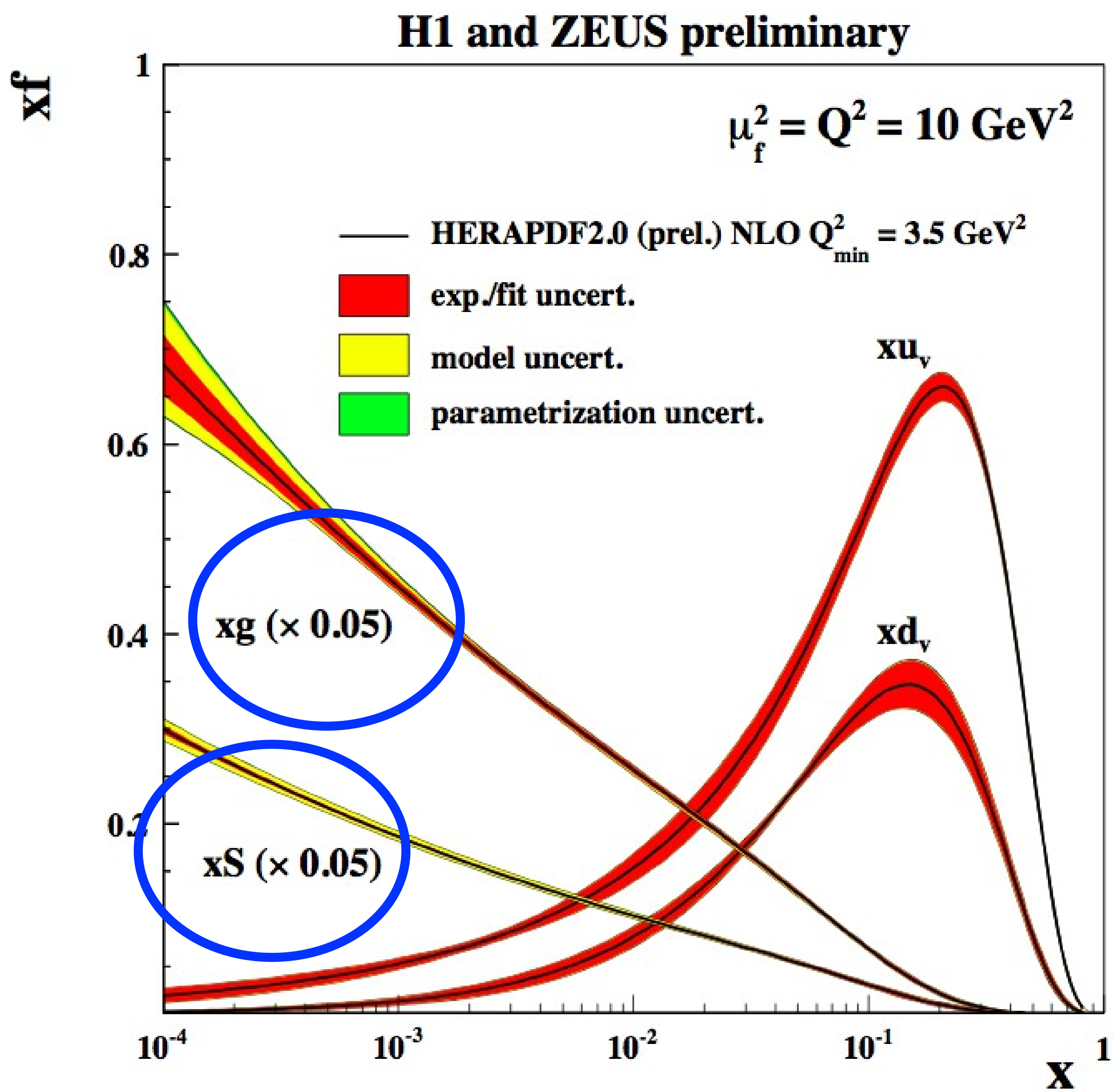
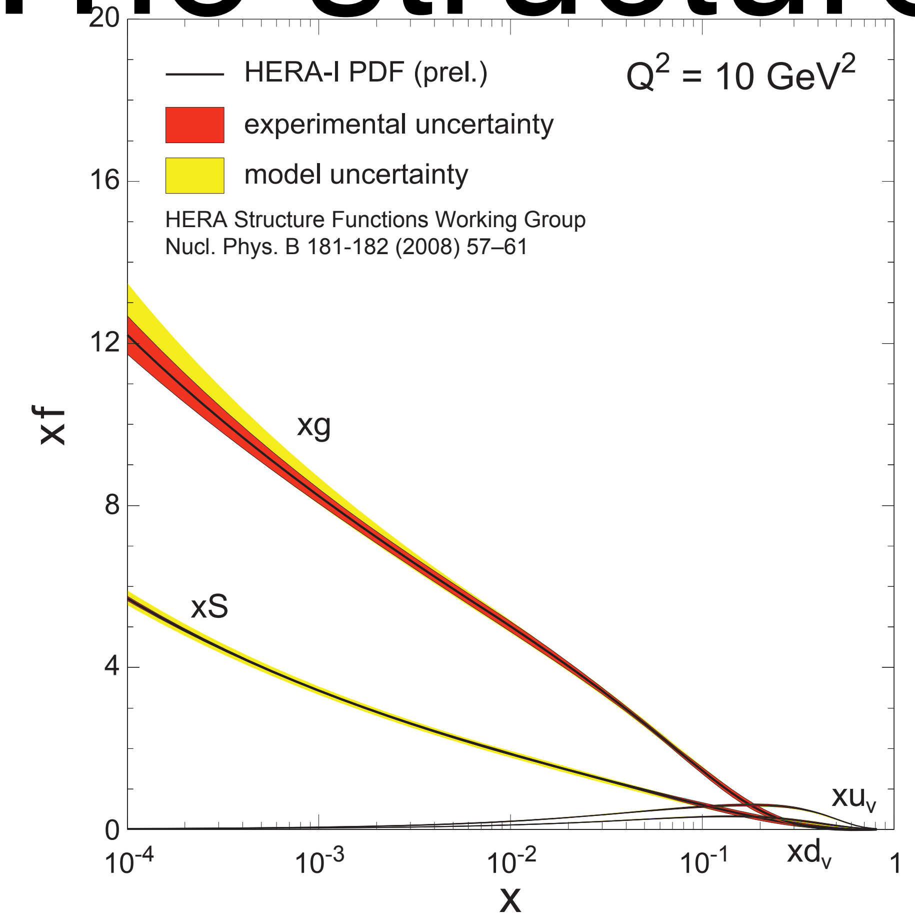
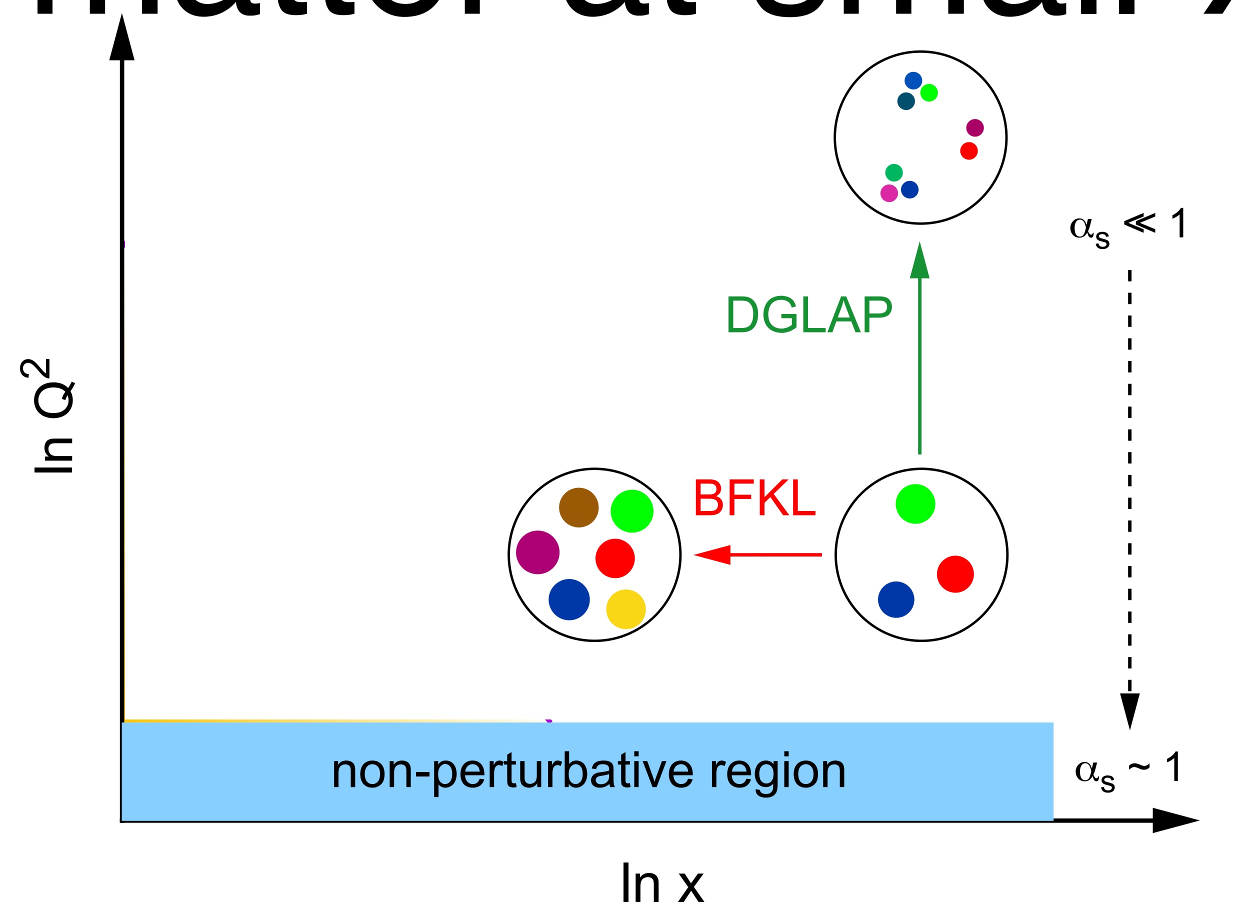




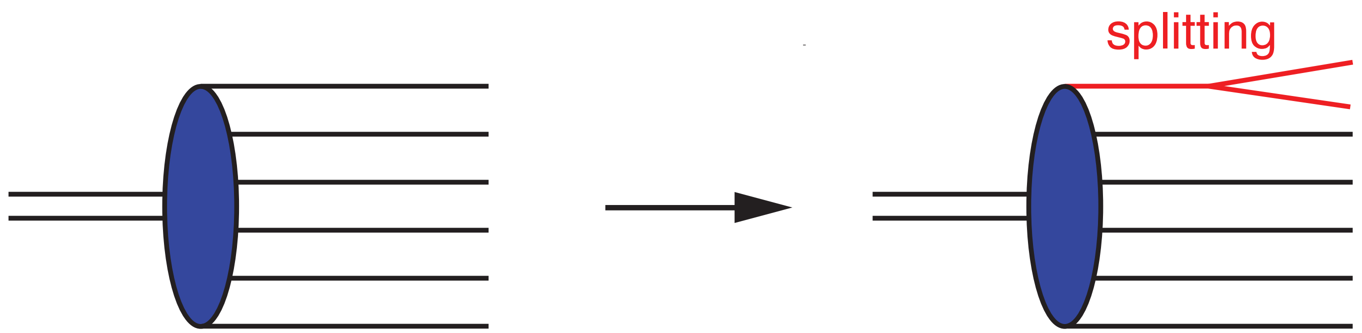
DIS 2014 - HERA Combined data

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
  - ➡ This rise cannot increase forever - limits on the cross-section



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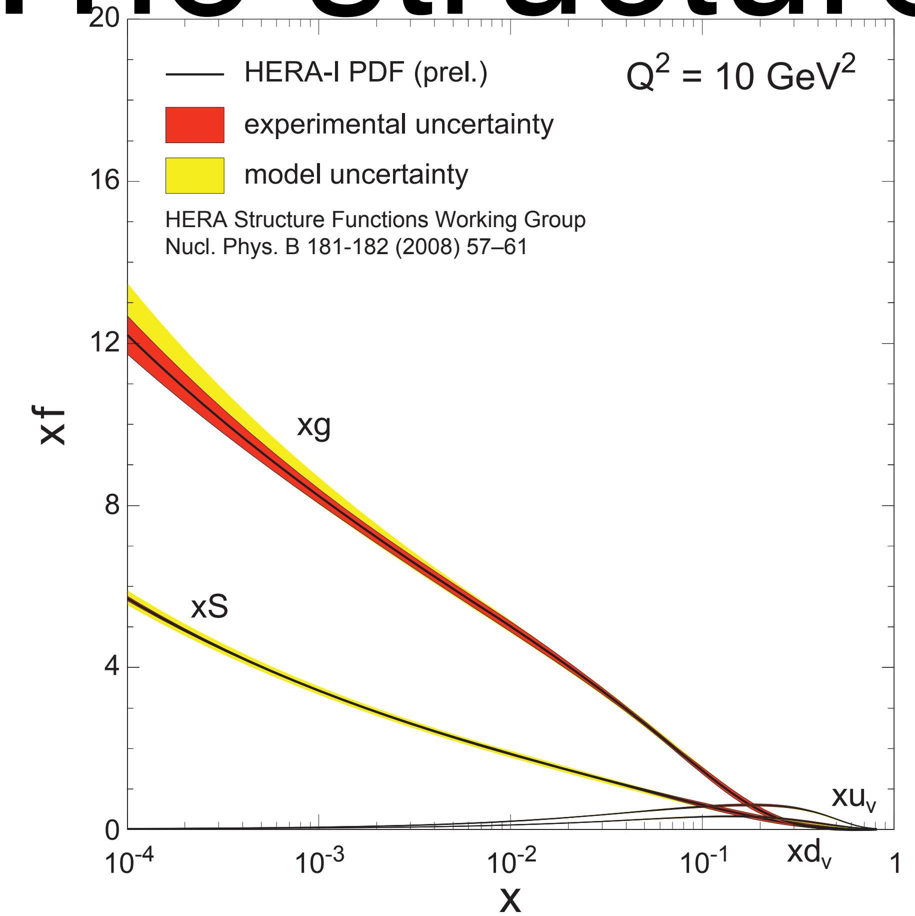
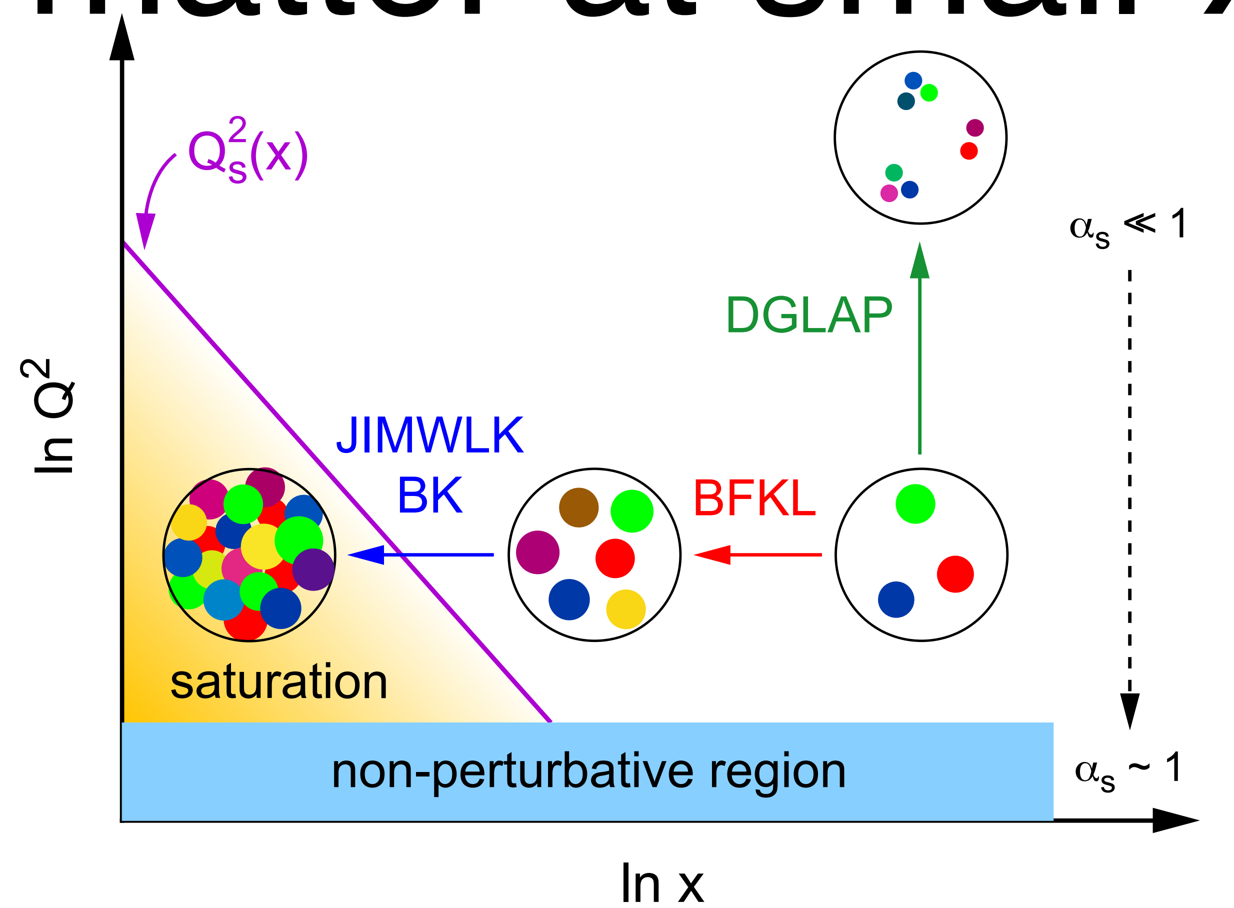
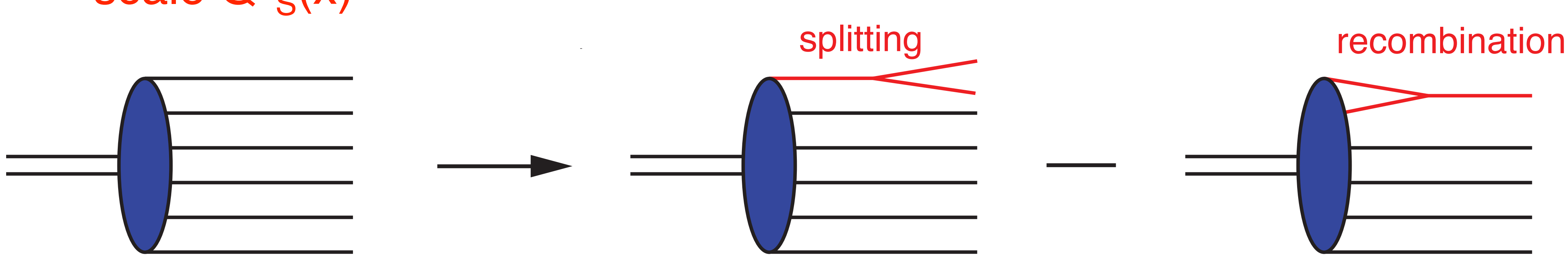




- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth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



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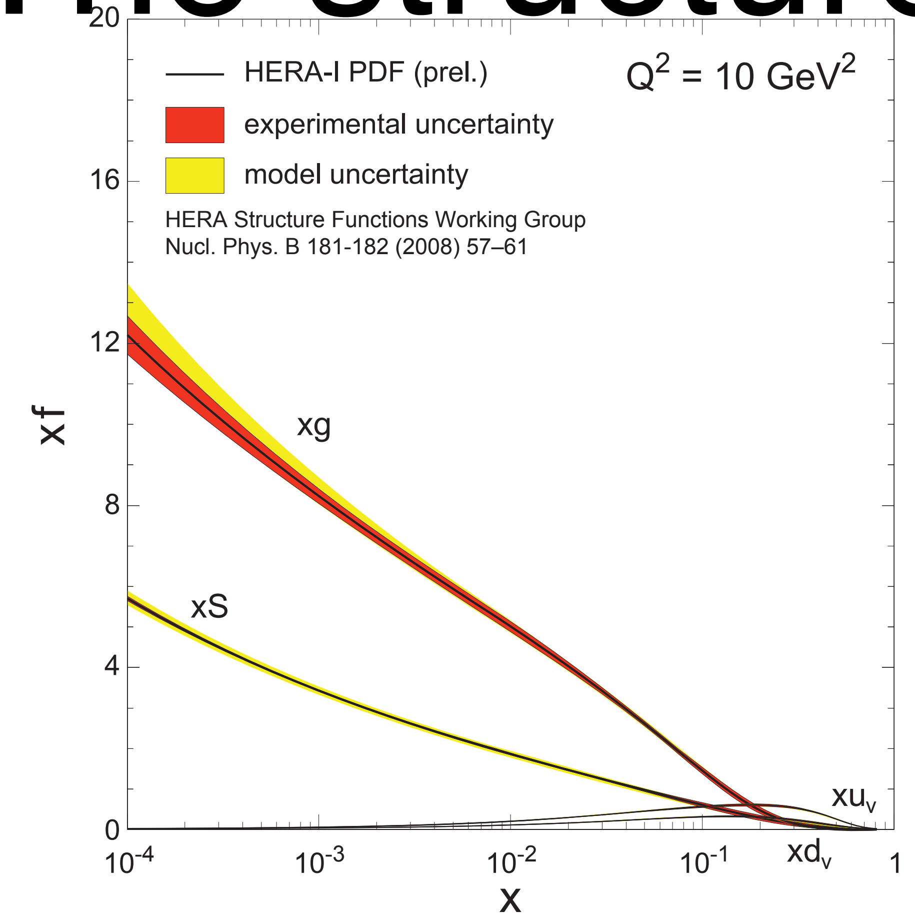
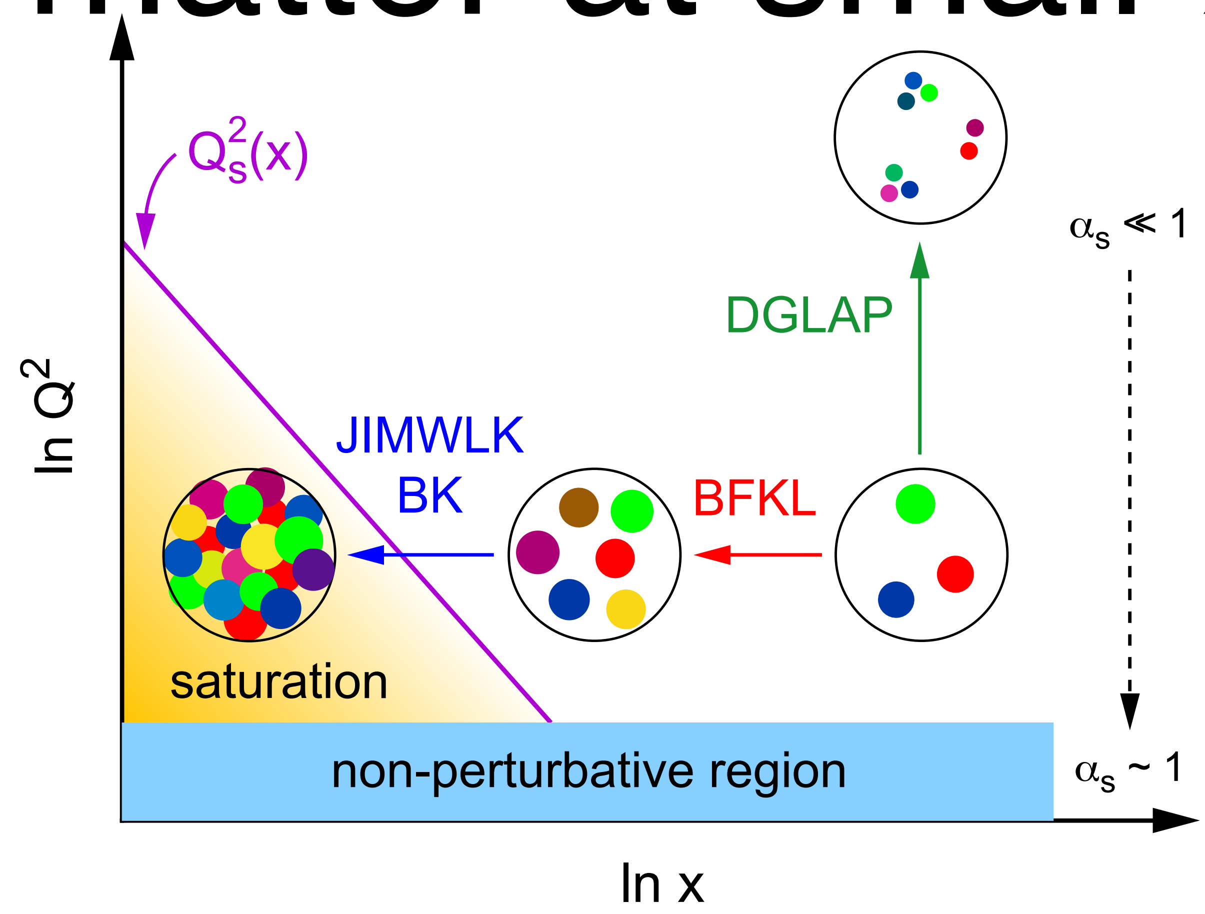


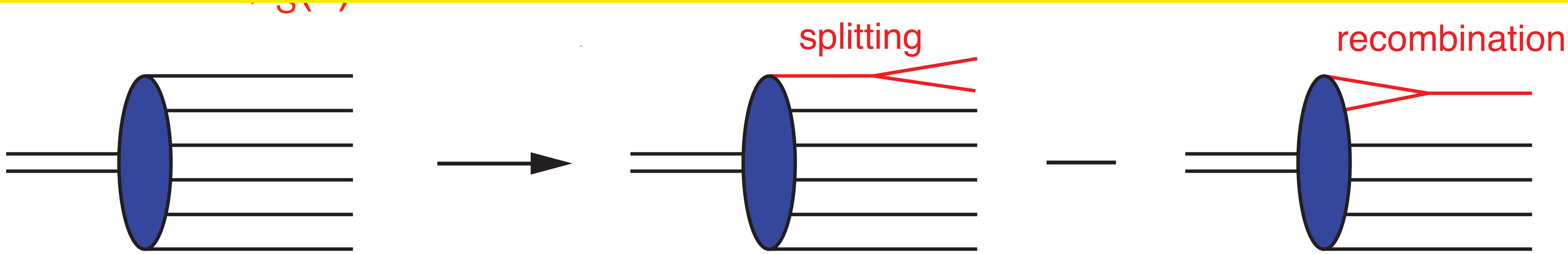


- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)

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

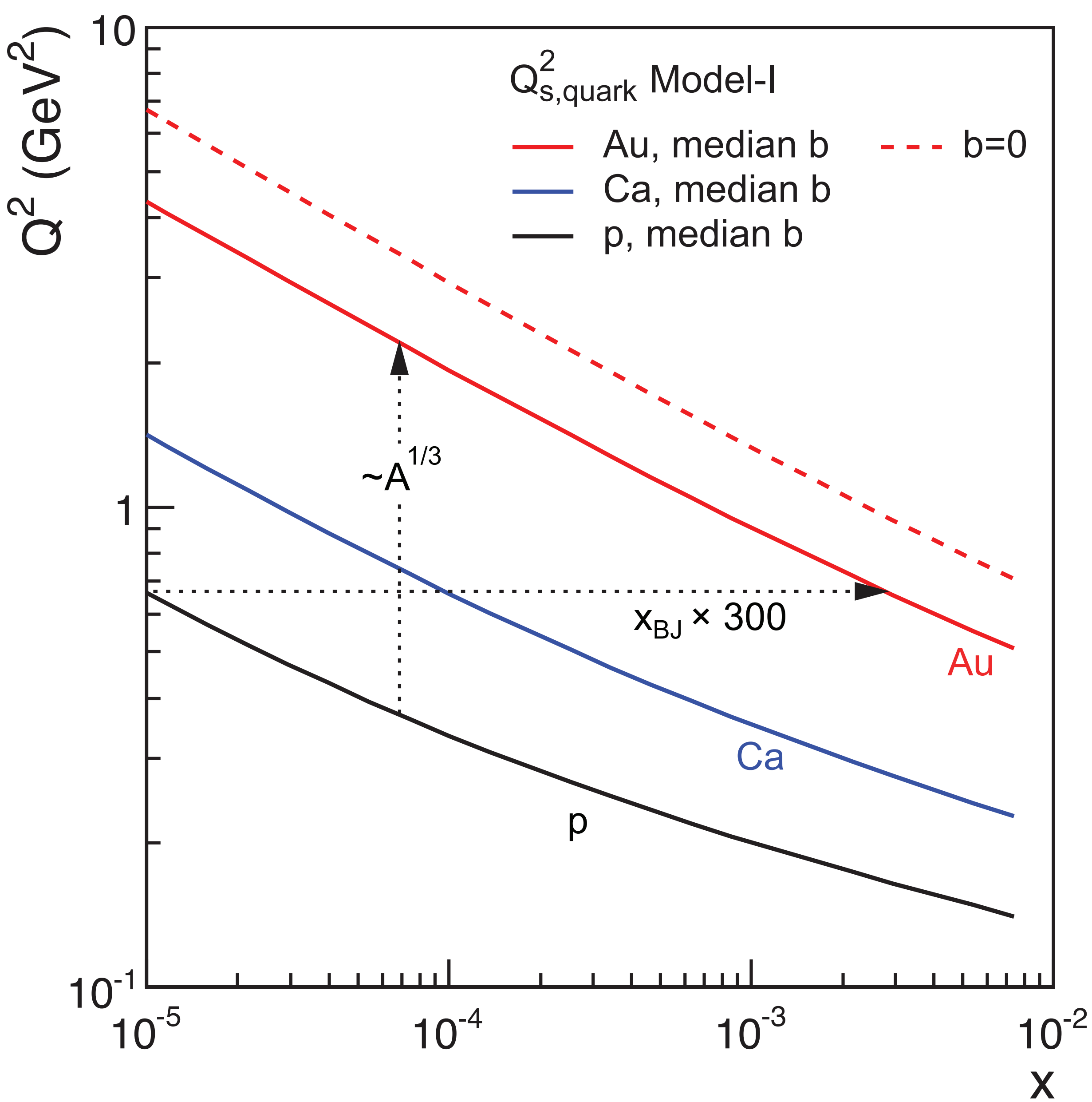
however - saturation in the gluon density is not observed in the gluon distribution at HERA -> too small an x

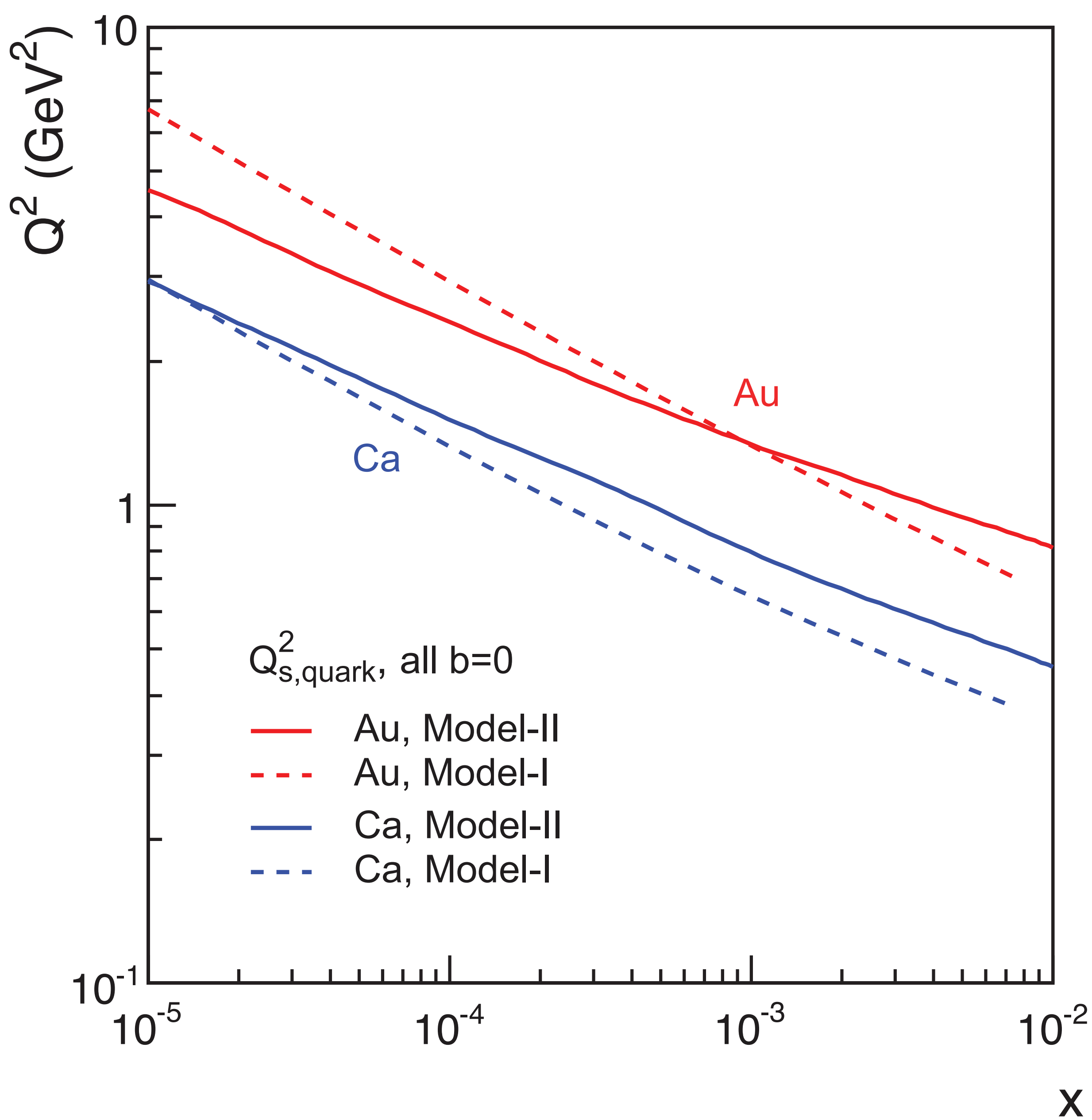
How can this be observed experimentally?



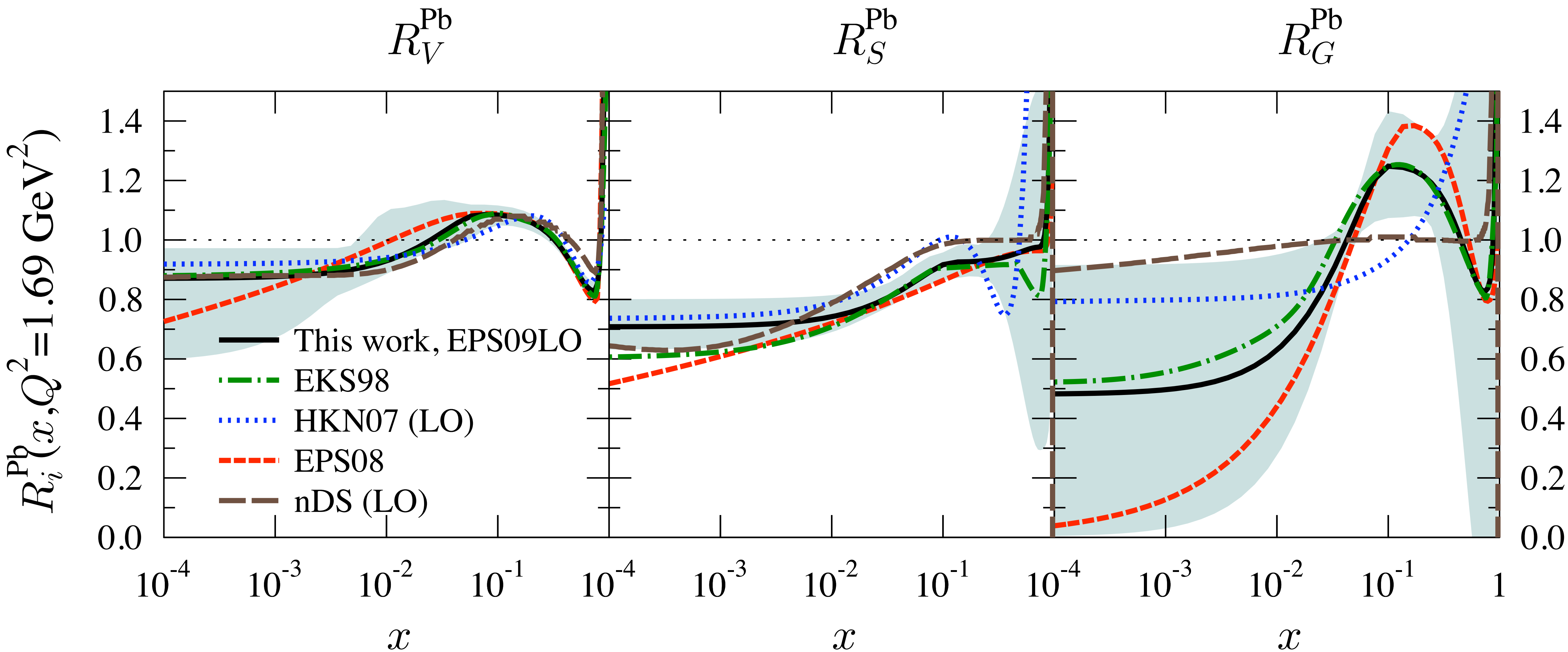
Nuclear "oomph" effect

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?



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

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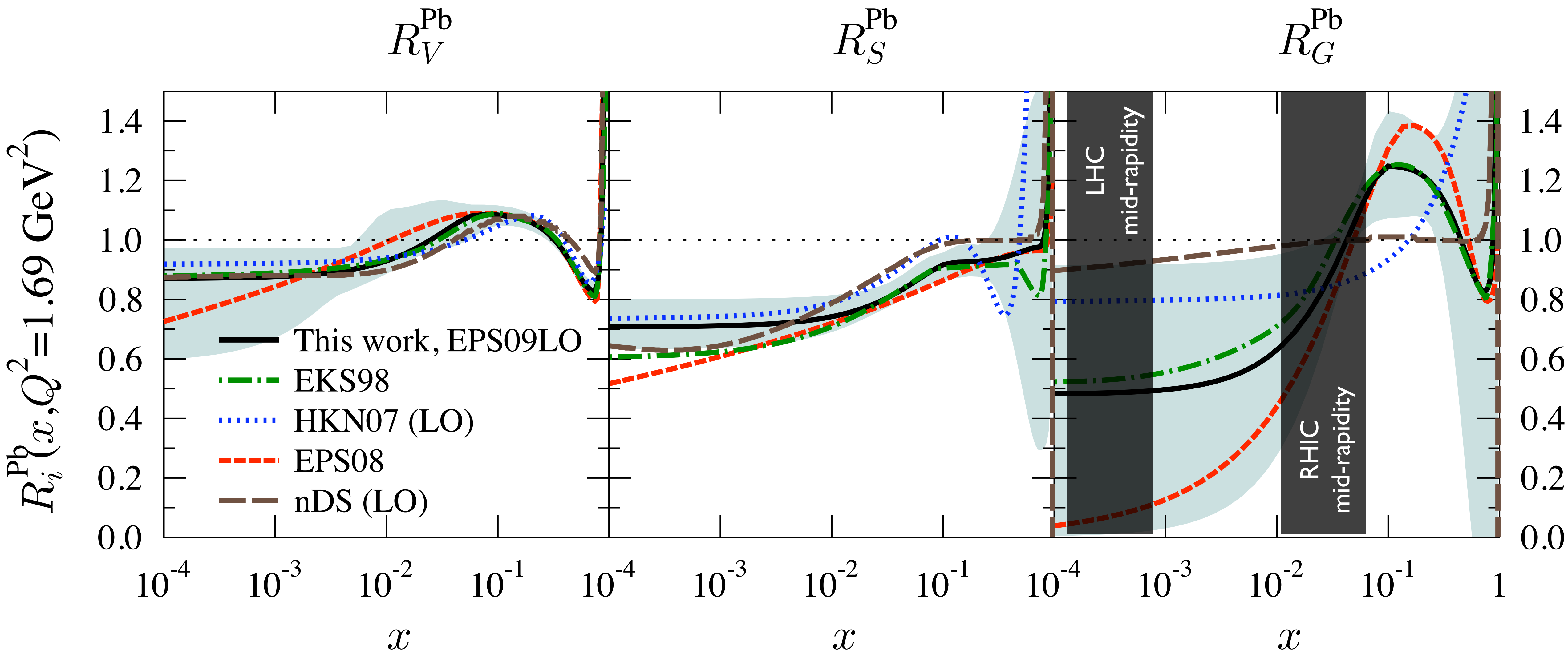

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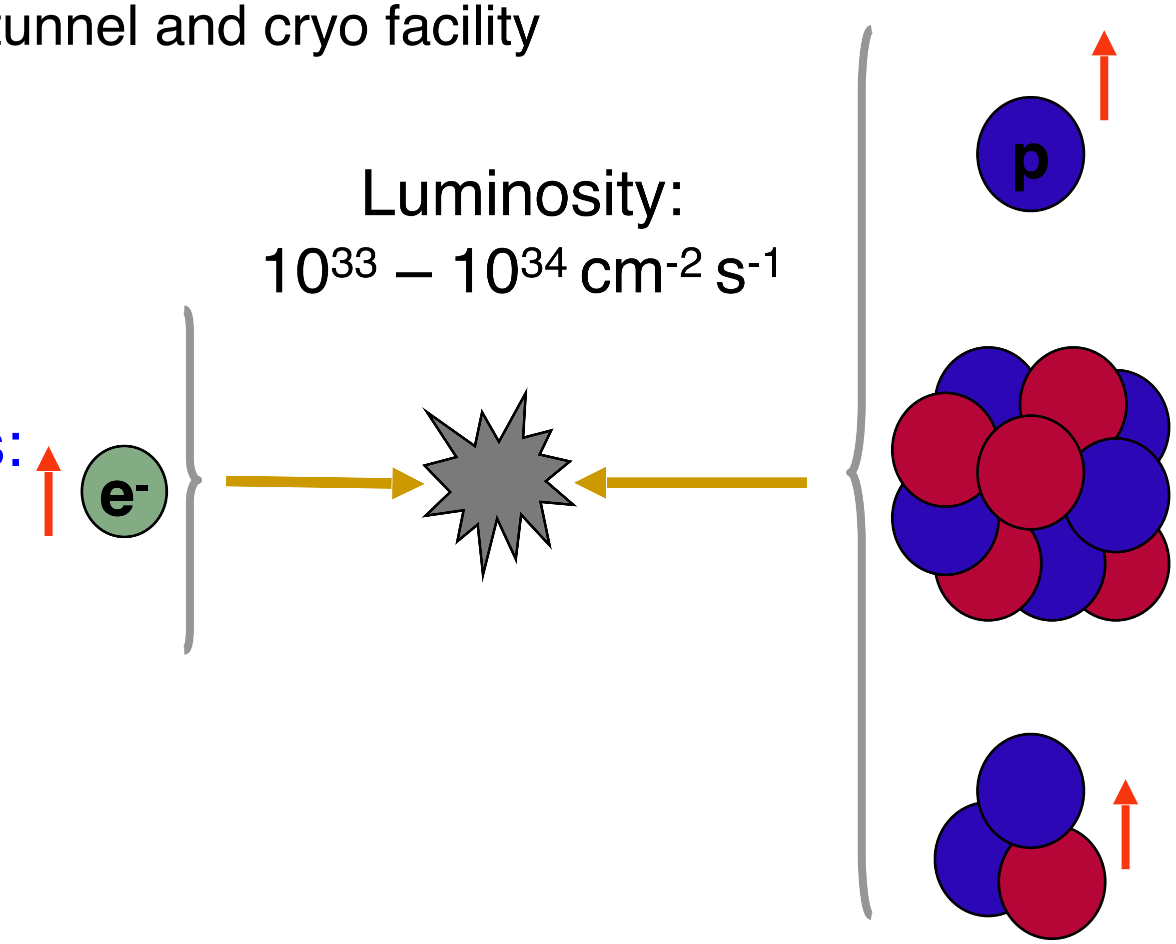
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel and cryo facility

Luminosity:
$10^{33} - 10^{34}$ cm^{-2} s^{-1}

80% polarized electrons:
6.6 – 21.2 GeV

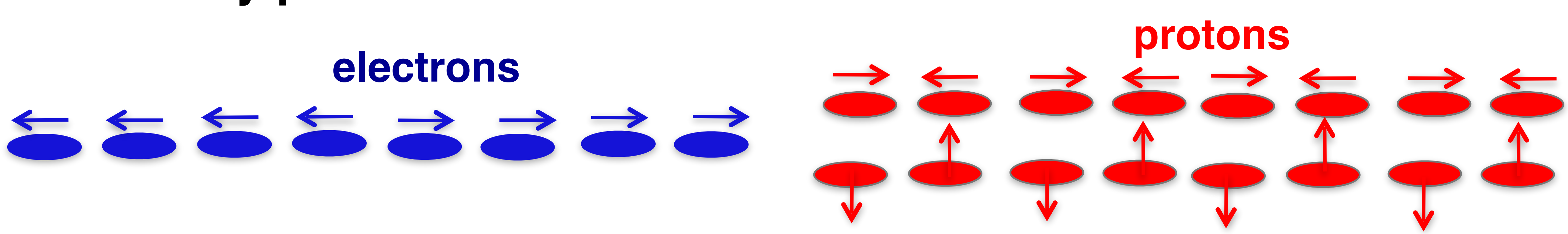


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

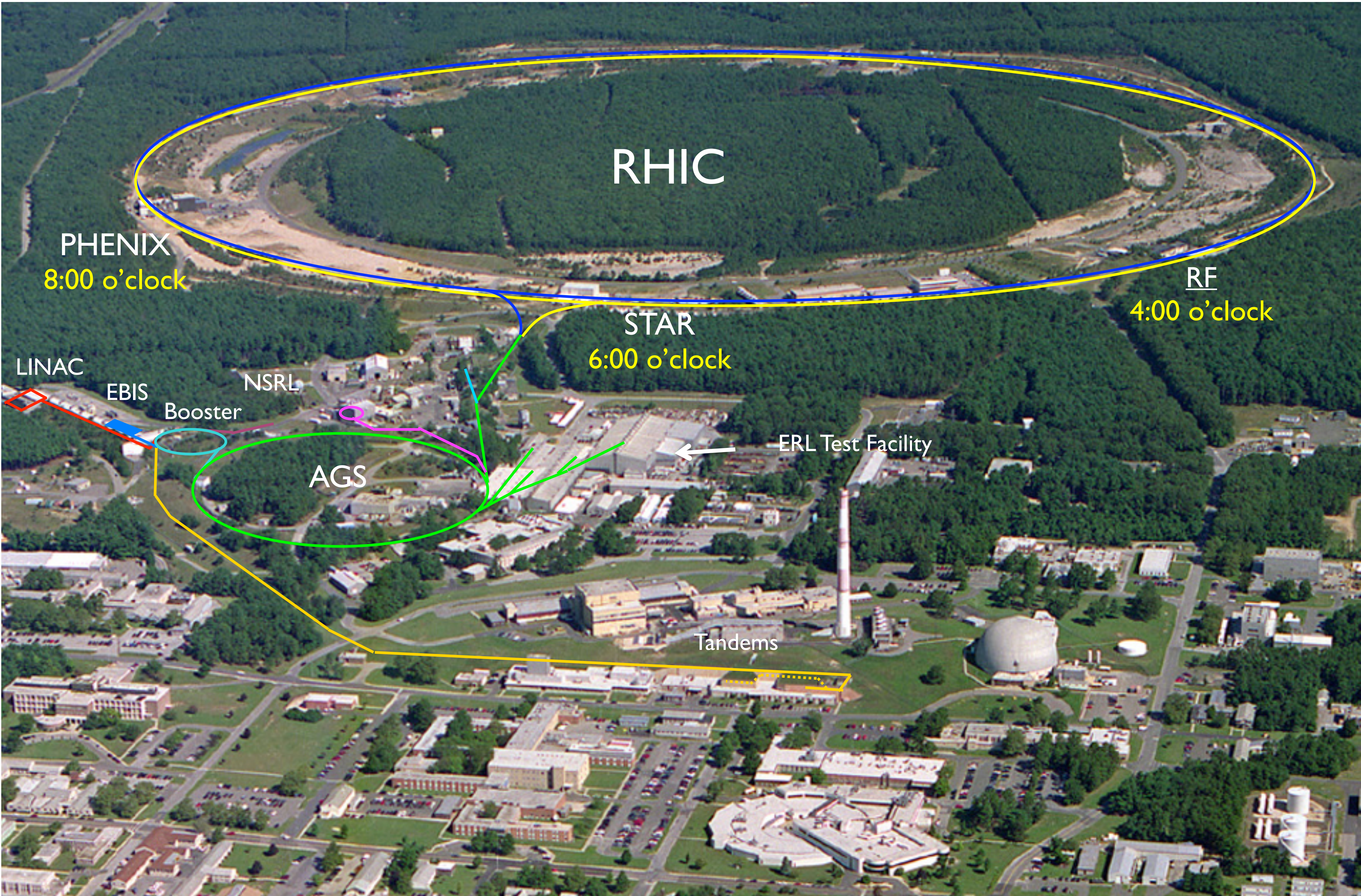
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

Center-of-mass energy range: 30 – 145 GeV
Any polarization direction in electron-hadron collisions



*** It is possible to increase RHIC ring energy by 10%**

From RHIC to eRHIC



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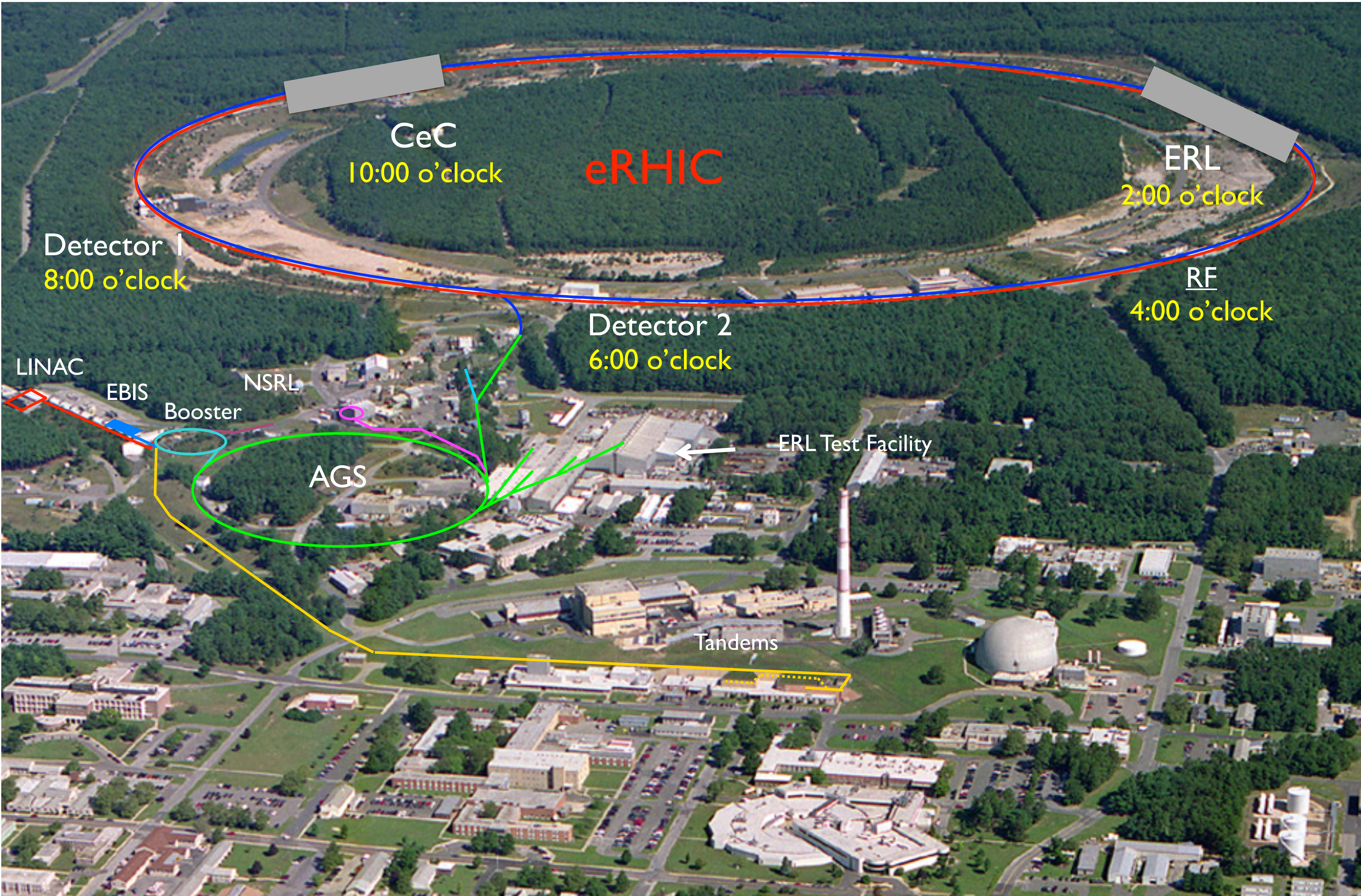
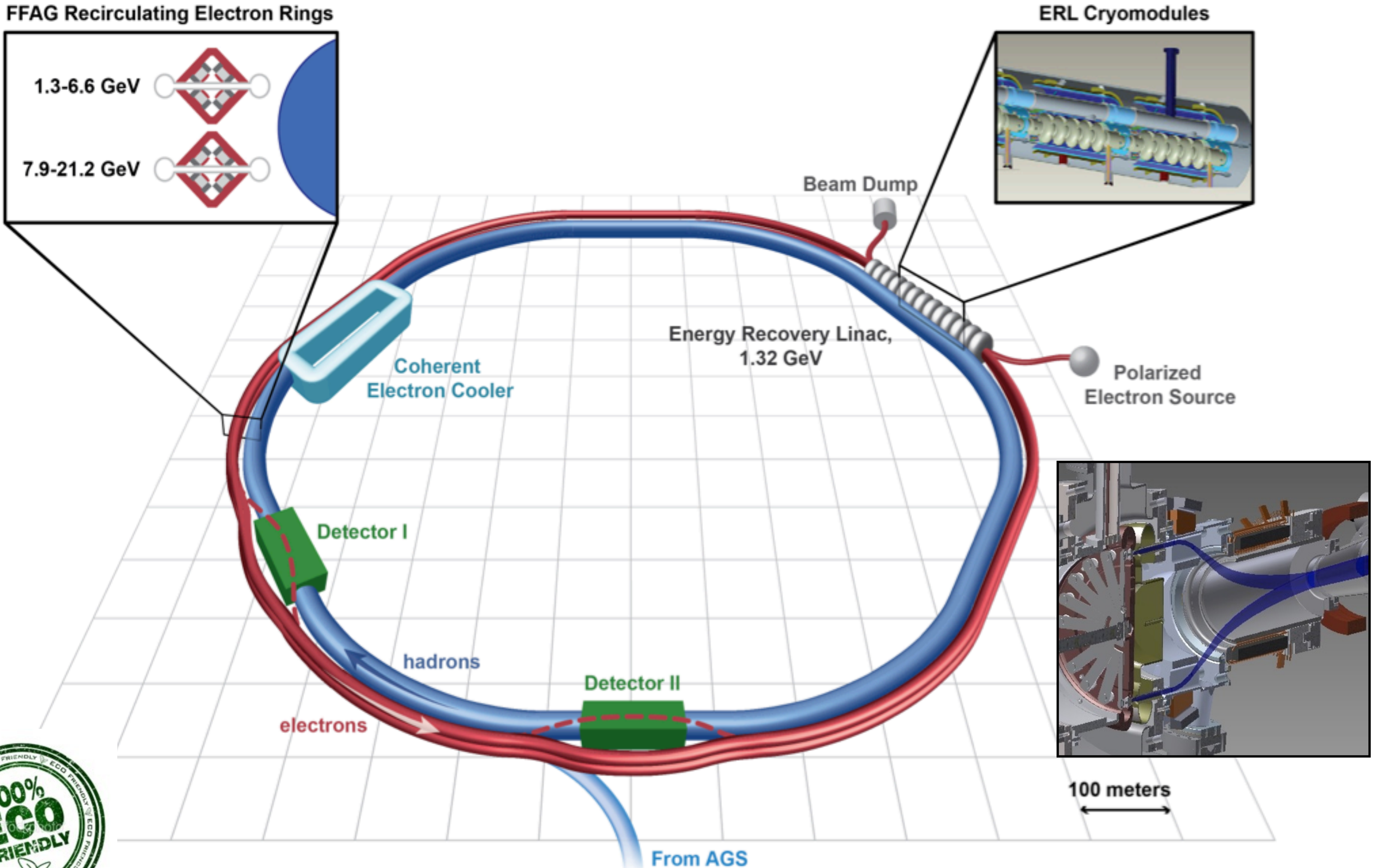
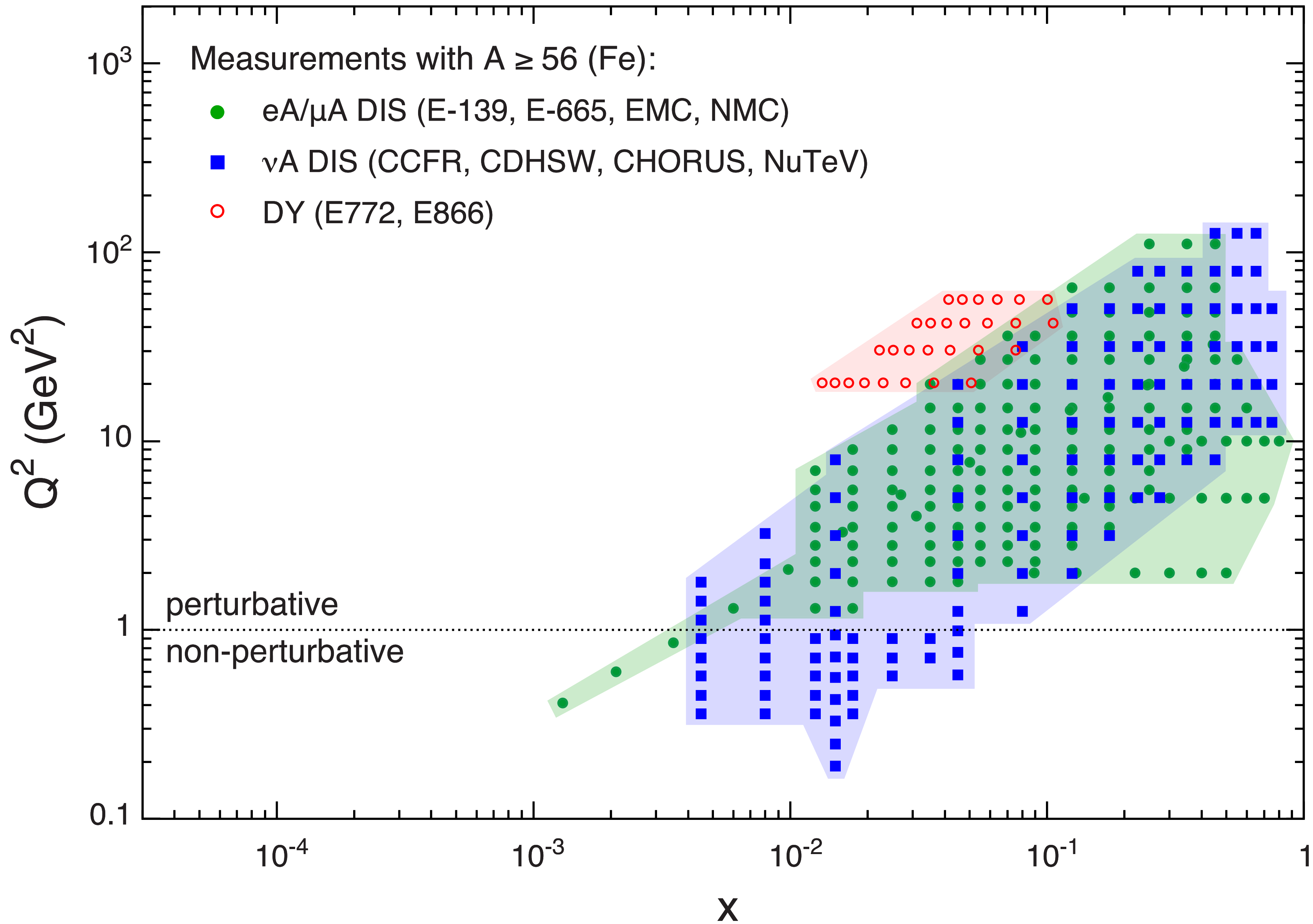


eRHIC design with E_e = 21.2 GeV



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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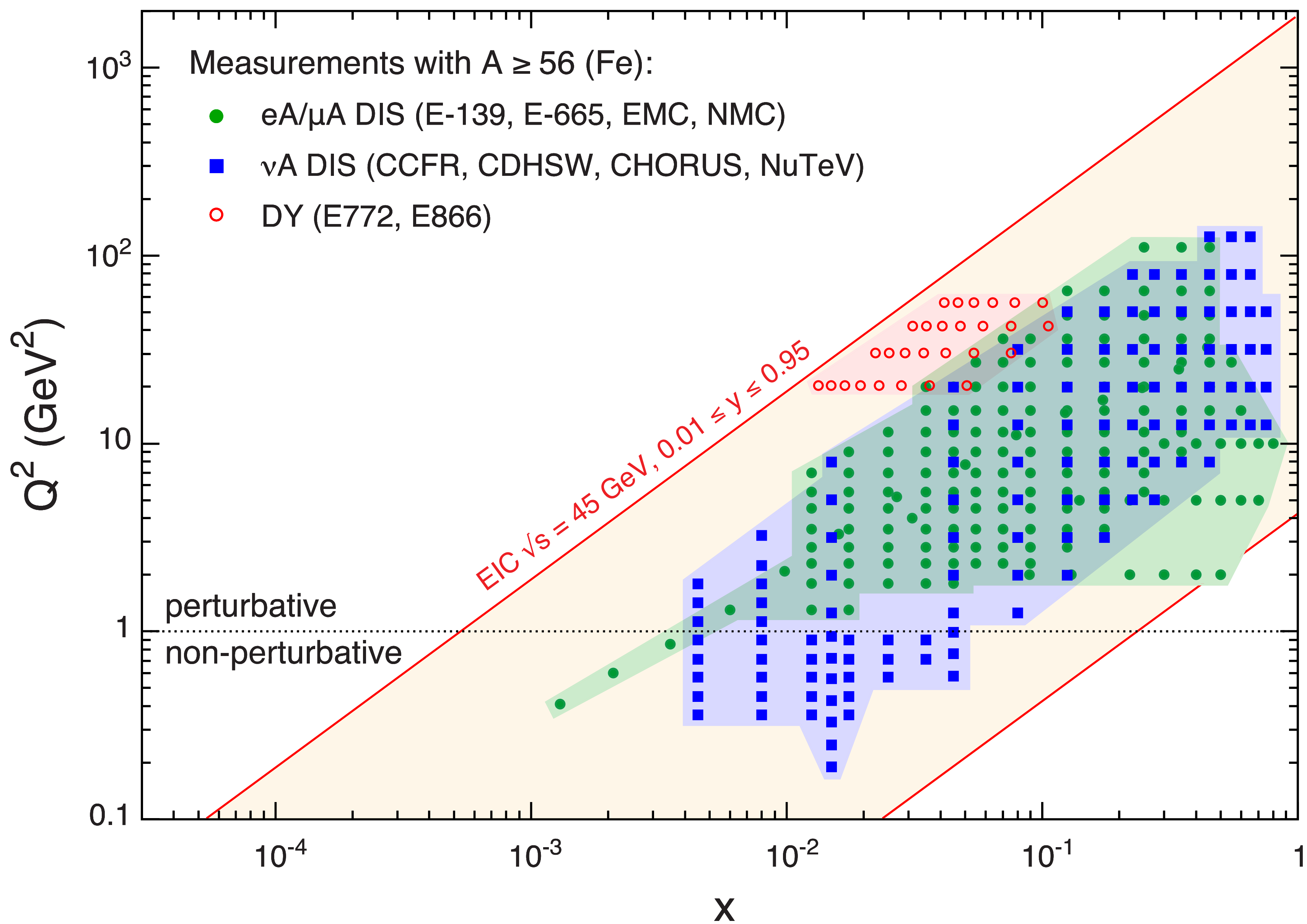

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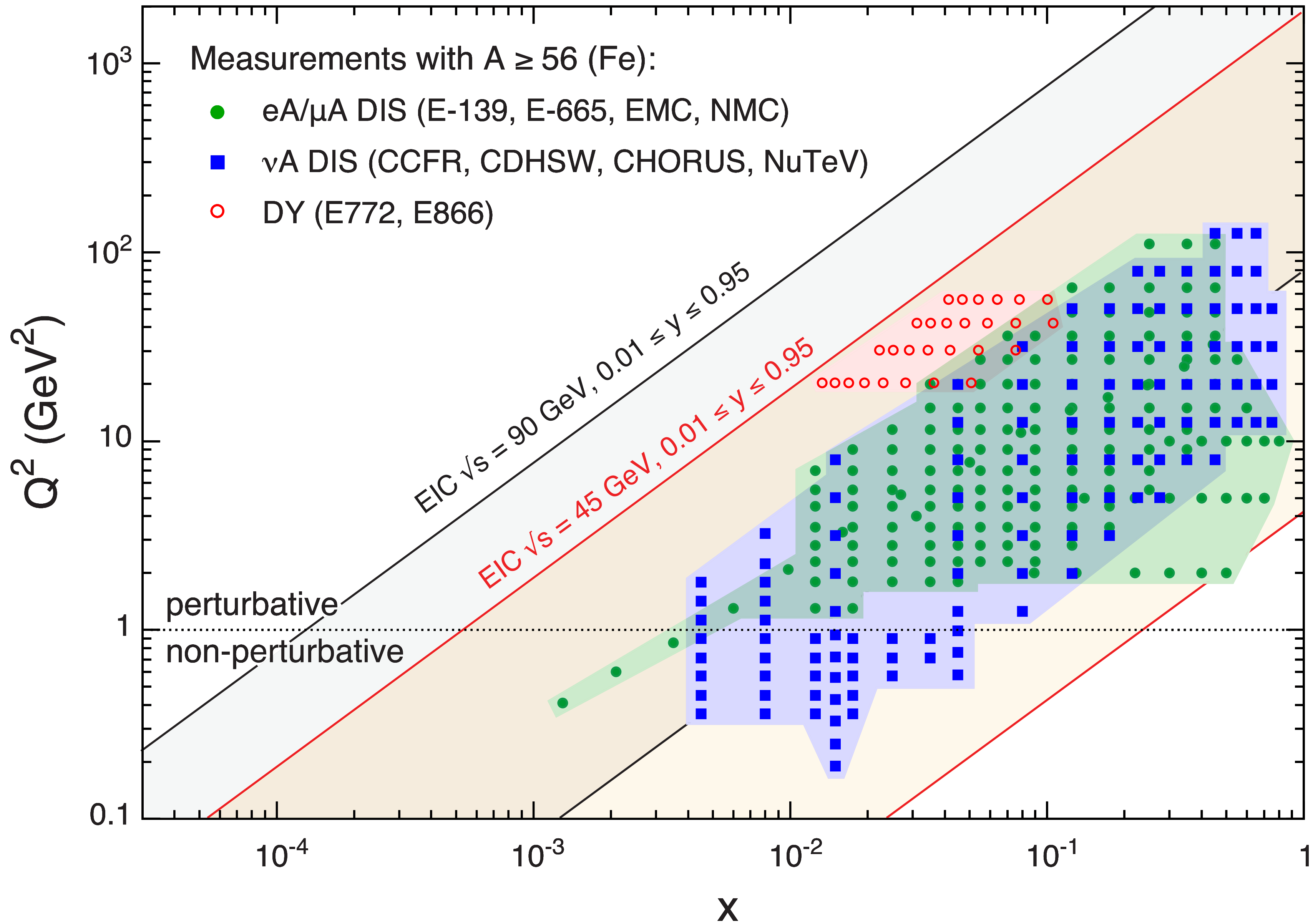

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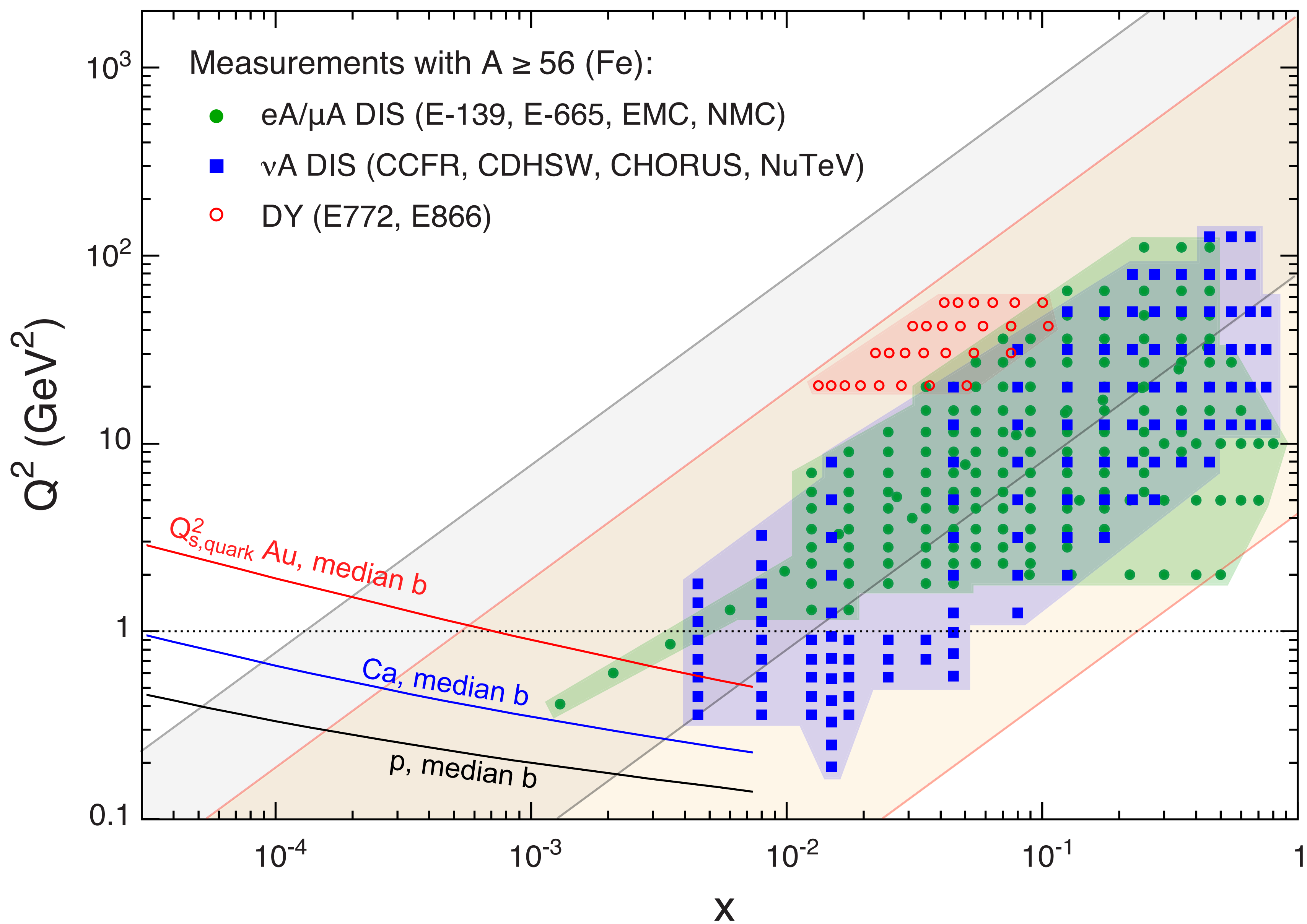

Saturation effects in the proton and nucleus

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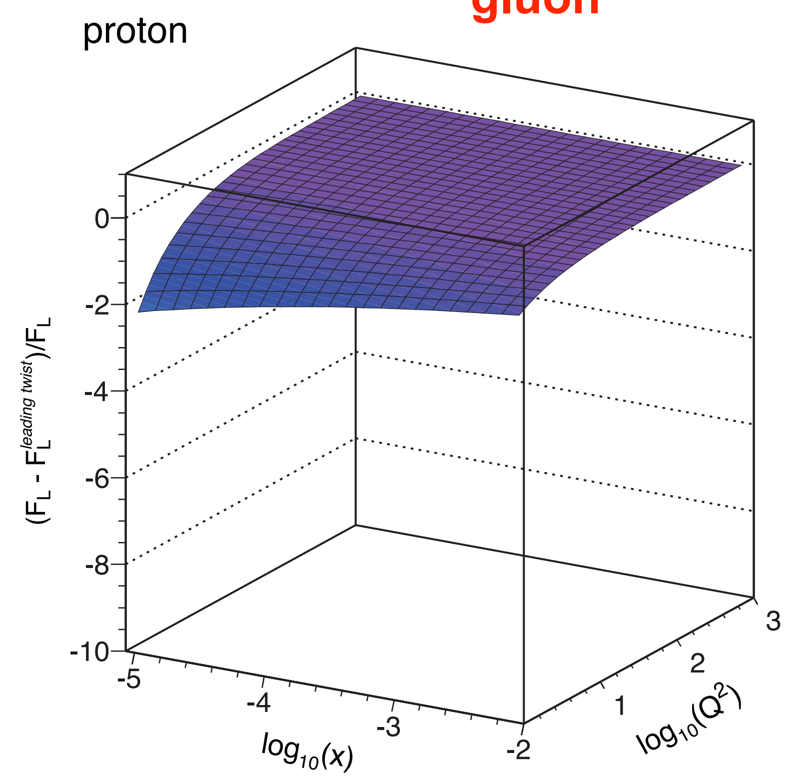
quark+anti-quark (F_2) **gluon** (F_L)

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
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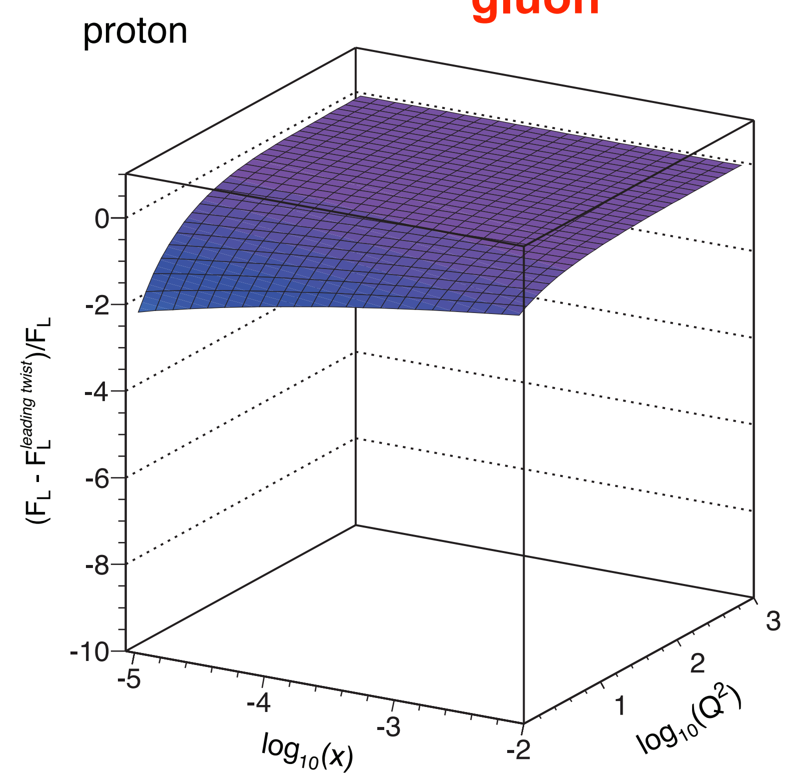

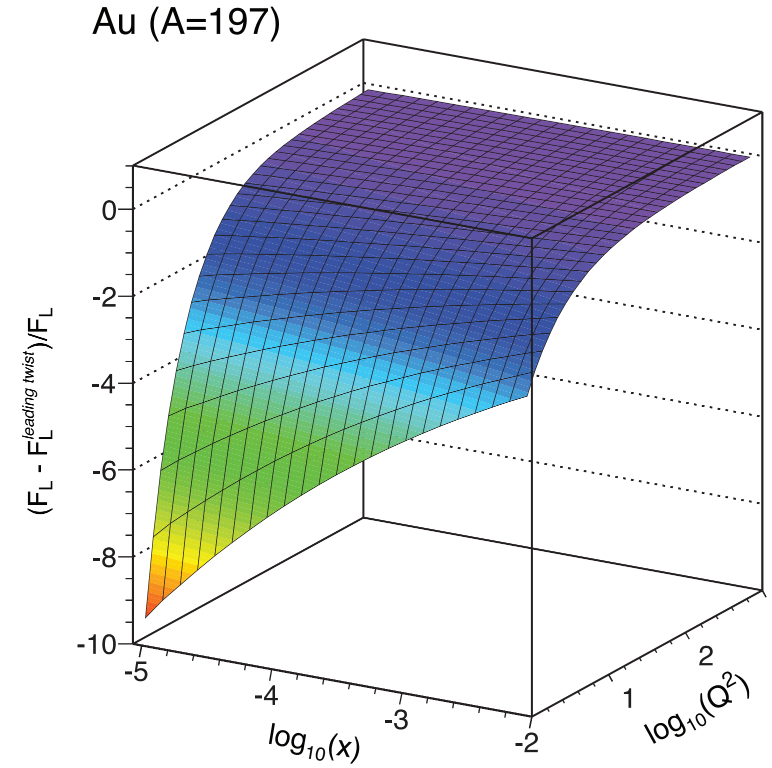

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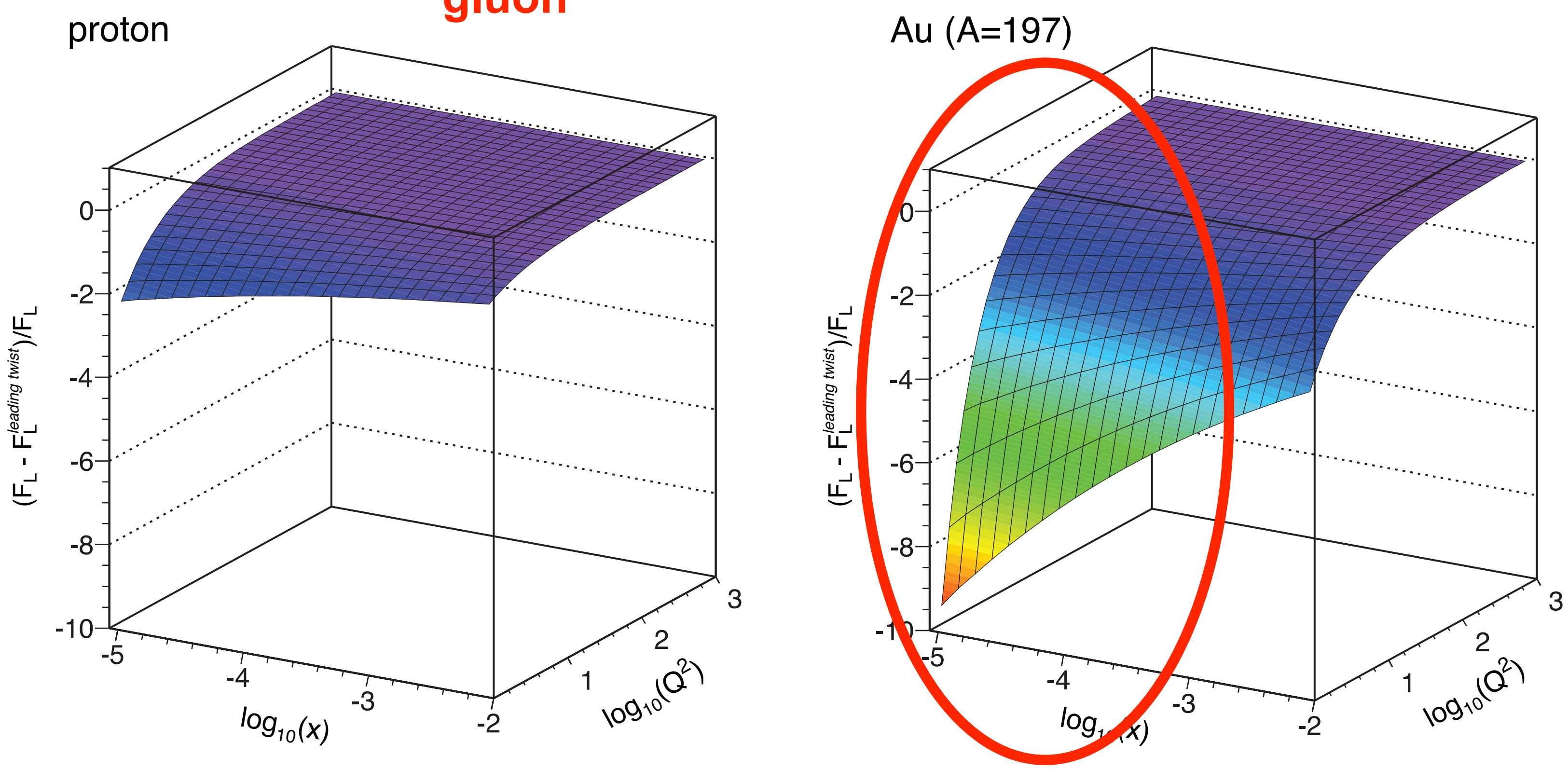

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A precision measurement of the F_2^A nuclear structure function

- Method:
  - ➡ Generate 10^7 e+A events with pythia 6.4, using EPS09 as input PDFs
  - ➡ Calculate σ_{red} as a function of (x,Q^2)
  - ➡ Calculate $F_2^A(x,Q^2)$ using a parameterisation of $R(x,Q^2)$ a la HERMES
    - Taken from A. Airapetian et al, JHEP 05 (2011) 126
  - ➡ Method has the advantage that the full range in (x,Q^2) can be utilised

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha_{em}^2}{Q^4}\frac{F_2(x,Q^2)}{x}\left[1 - y - \frac{Q^2}{4E^2} + \frac{y^2 + Q^2/E^2}{2[1+R(x,Q^2)]}\right]$$

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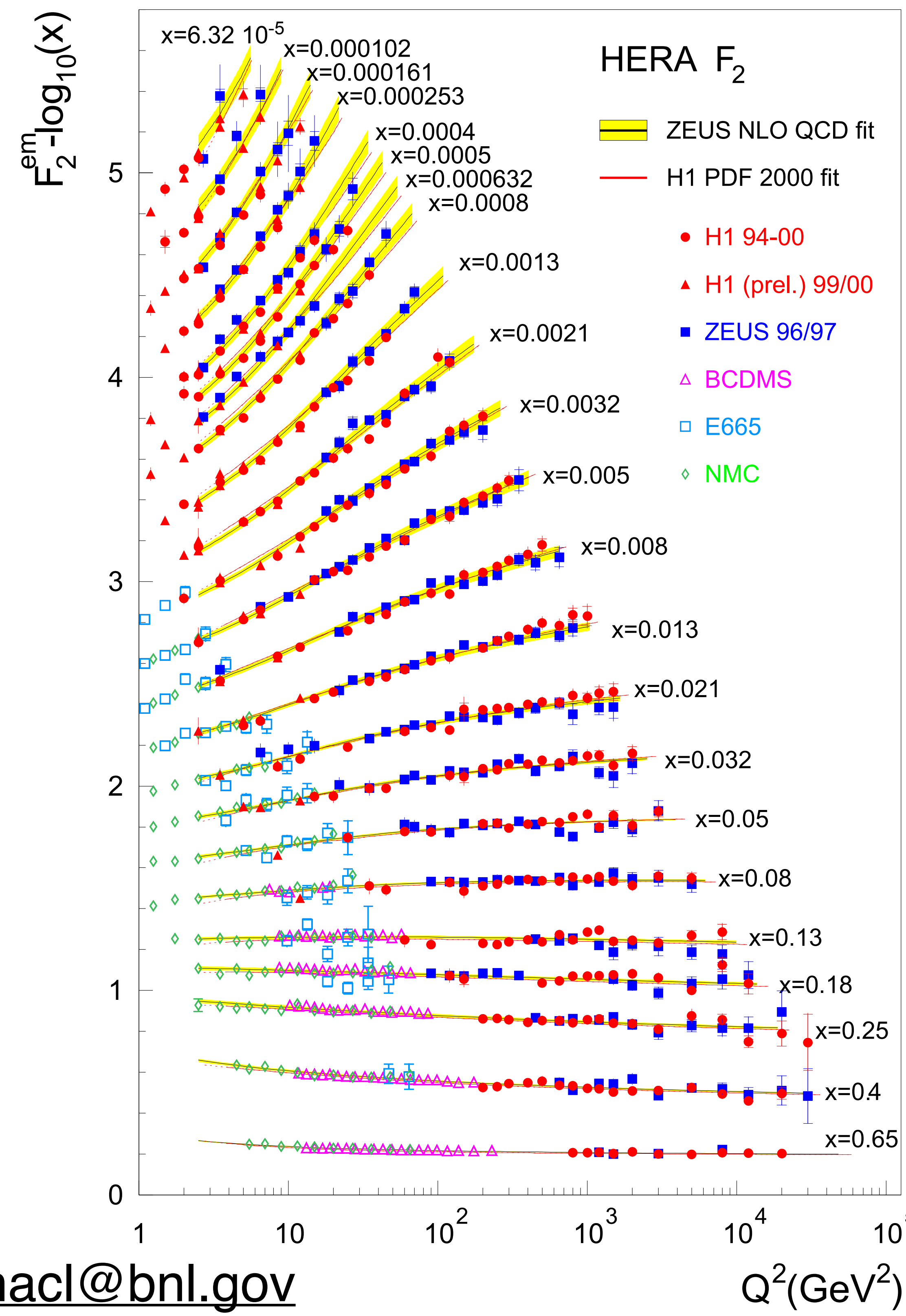
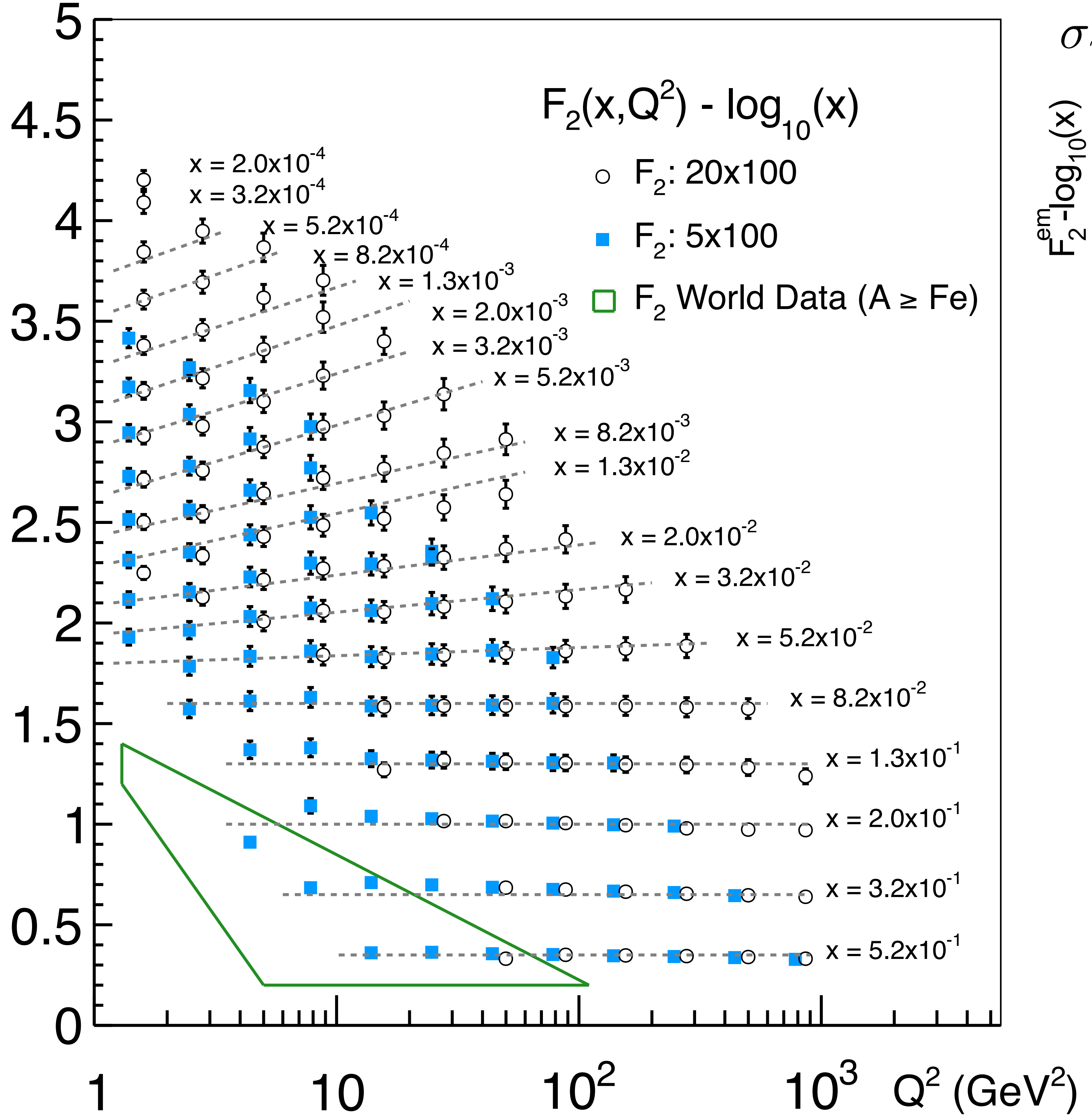
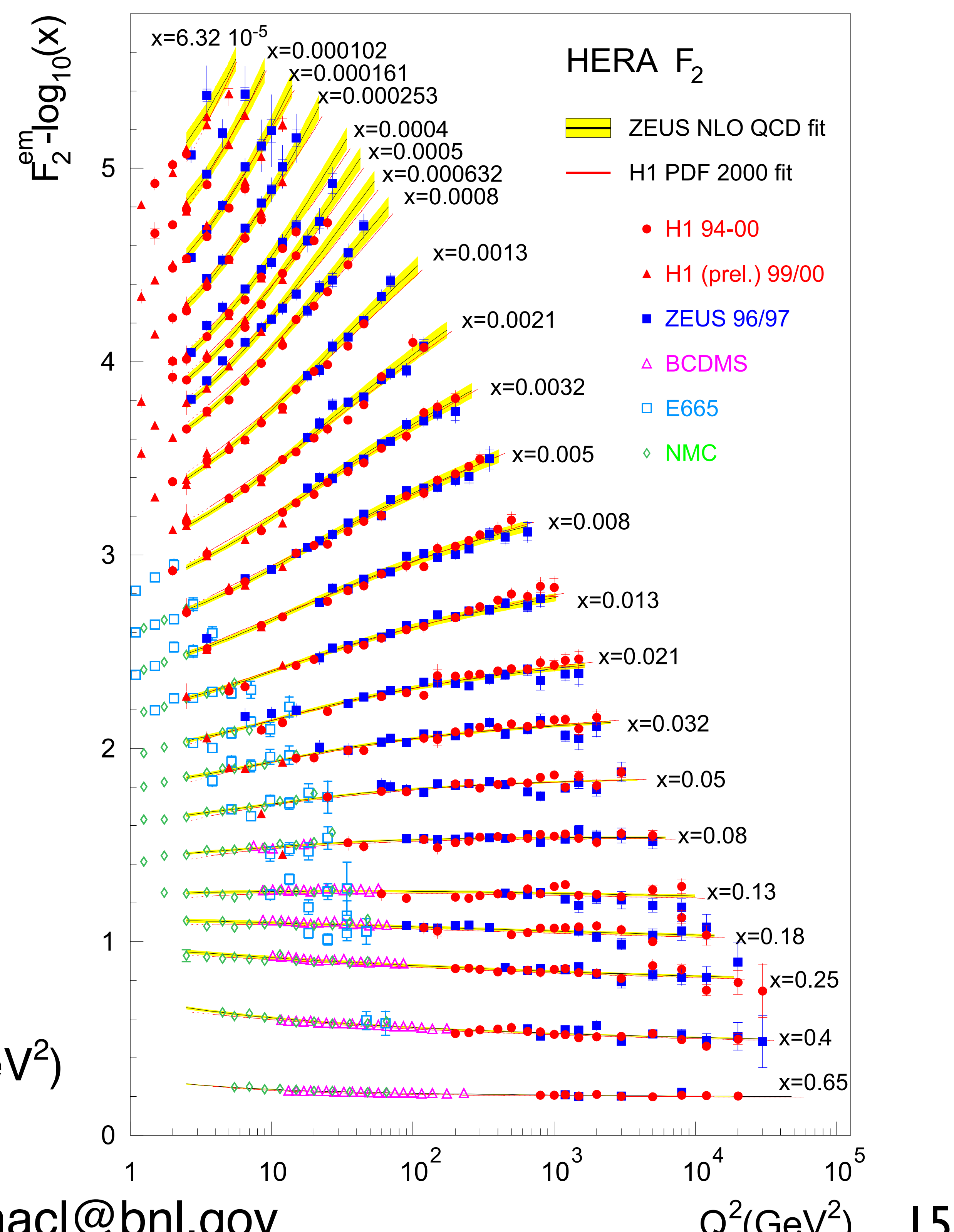


3% systematic errors added in quadrature

A precision measurement of the F_2^A nuclear structure function



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



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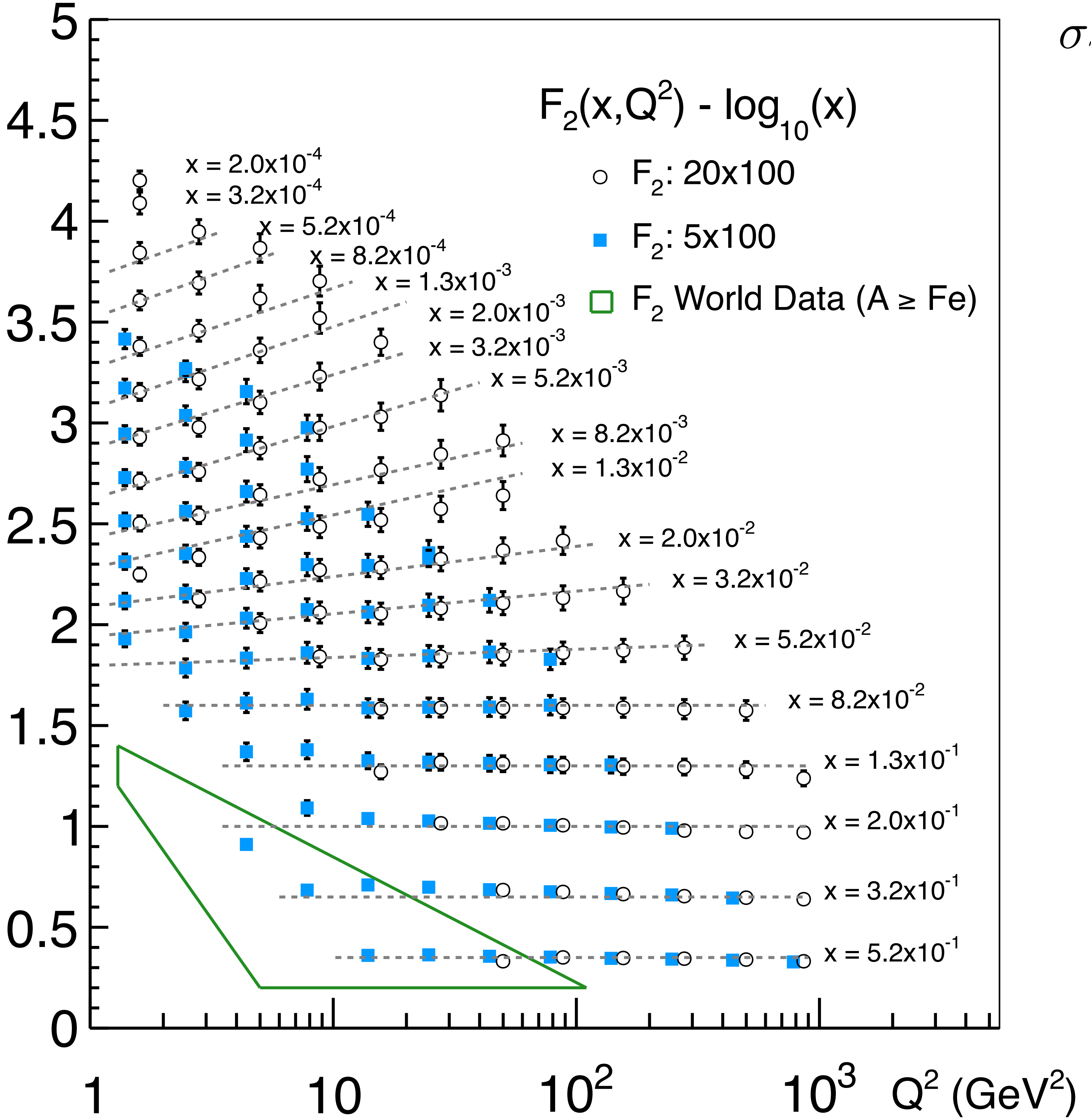

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$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$$

- F_2^{Au} as a function of x and Q^2
- Same scaling employed as the HERA plot
- Scaling violation observed at low (x,Q^2)

➡Need to go to higher energies to observe the scaling

- Difficult to see at low energies
- Smaller effect than in protons due to suppression of gluons

- Entering a new region of phase-space not previously explored in nuclei
- Dominated by systematic uncertainties

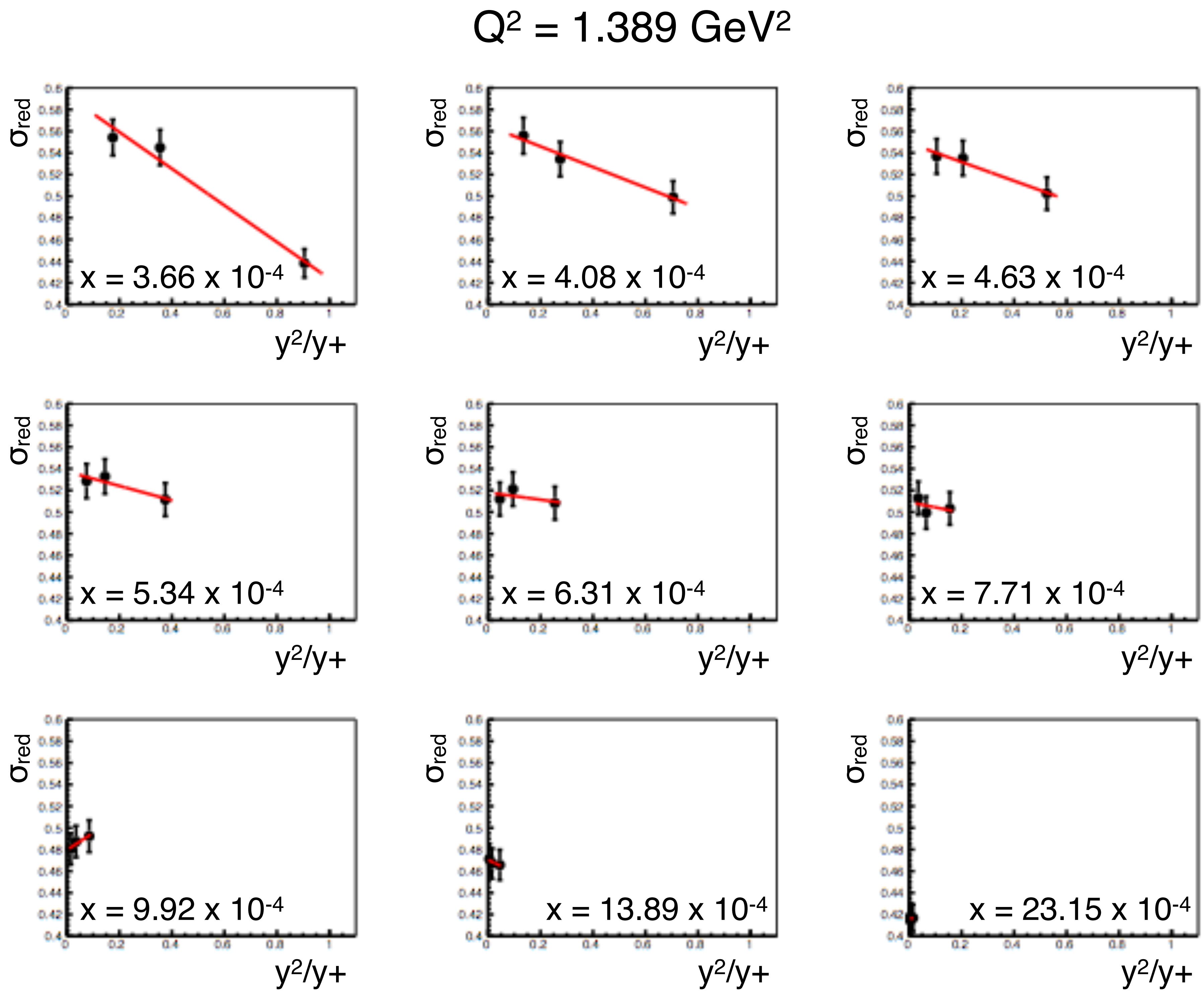
Feasibility study of F_L^A: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+} F_L^A(x,Q^2)$

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

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

Need a good lever arm in $y^2/y+$ in order to have a good fit. Not all bins are used because of this

Require $\Delta y^2/y+ > 0.1$ to have a meaningful fit.



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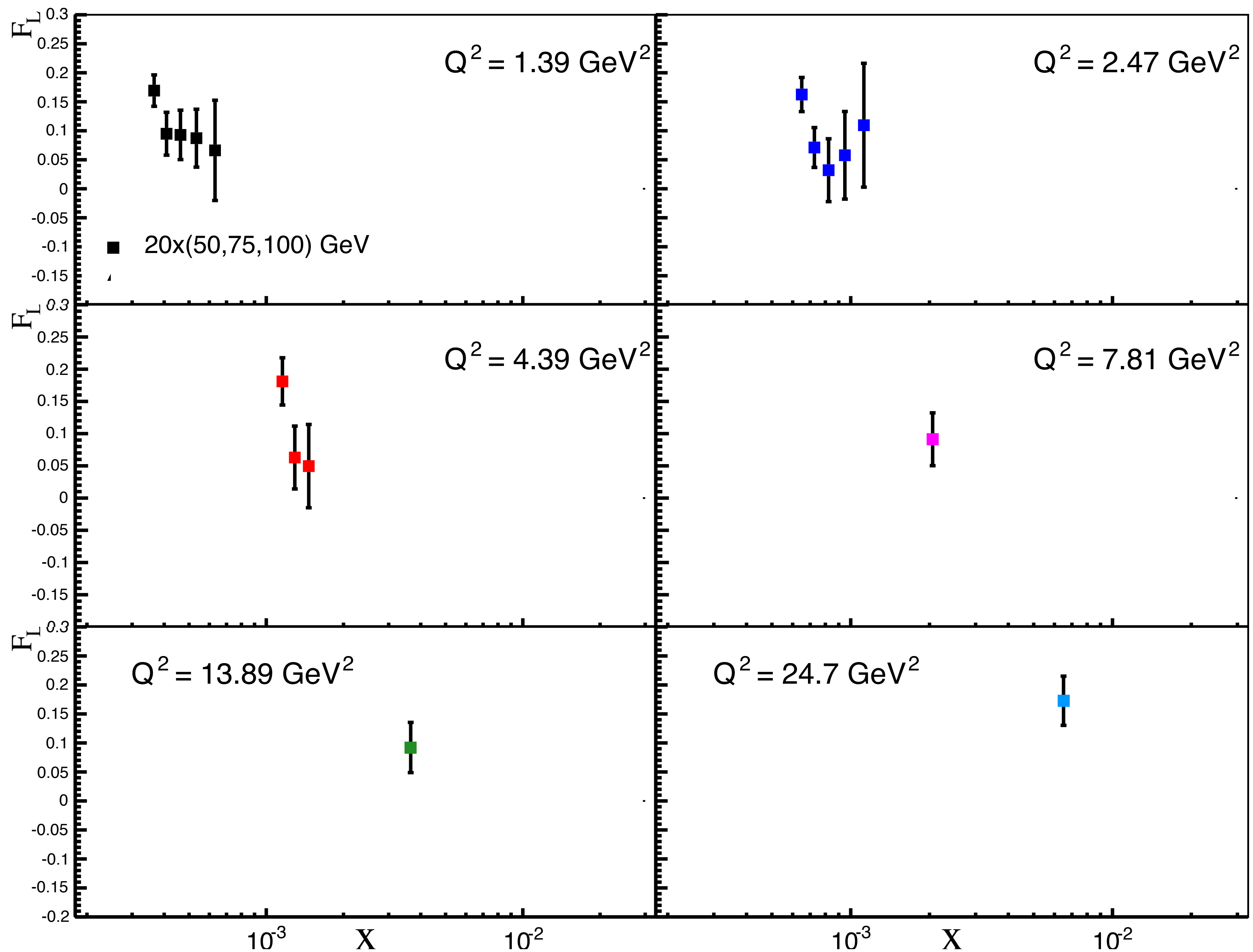

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5x50 - $A\int Ldt$ = 2 fb^{-1}
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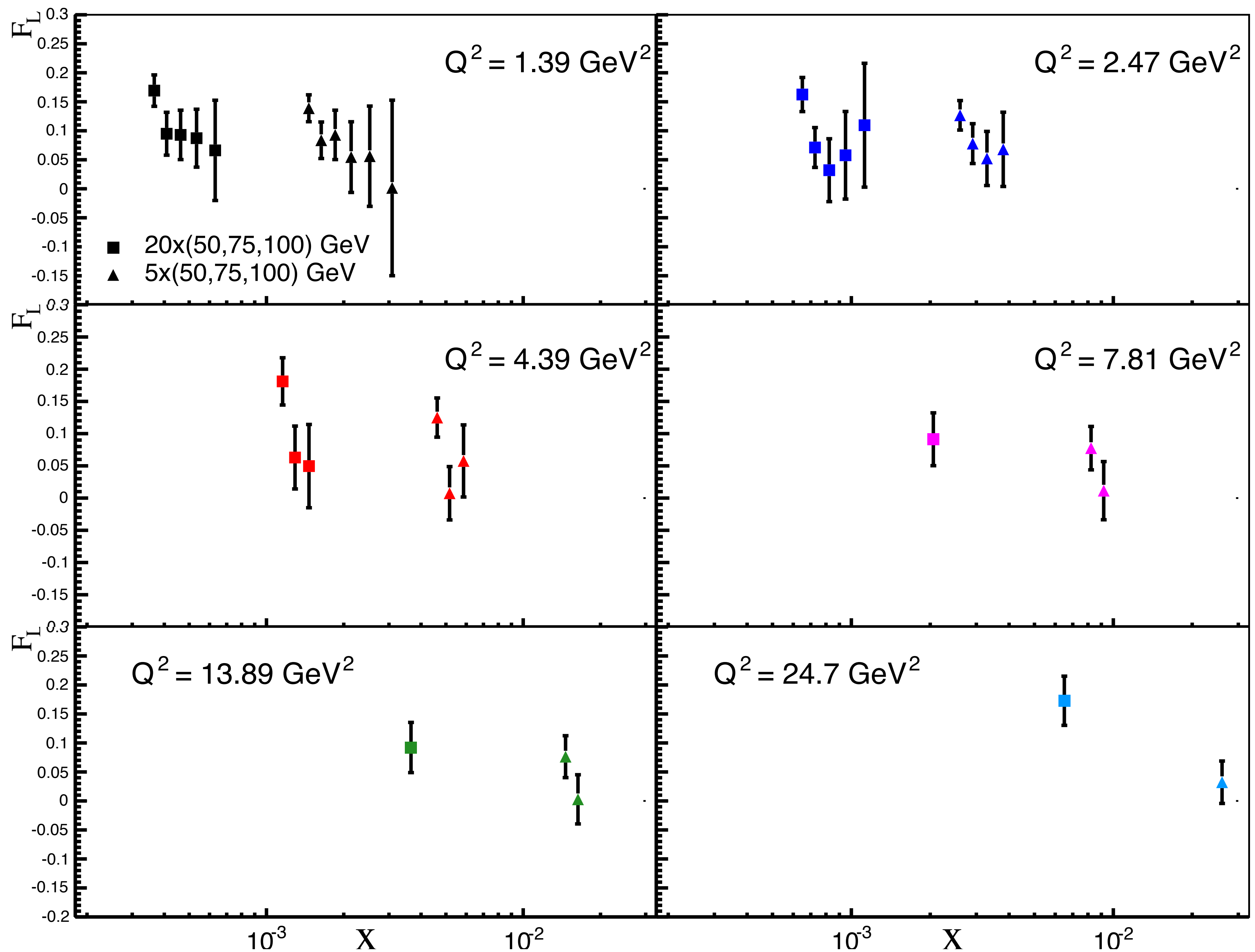
Uncertainties now become increasingly important

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



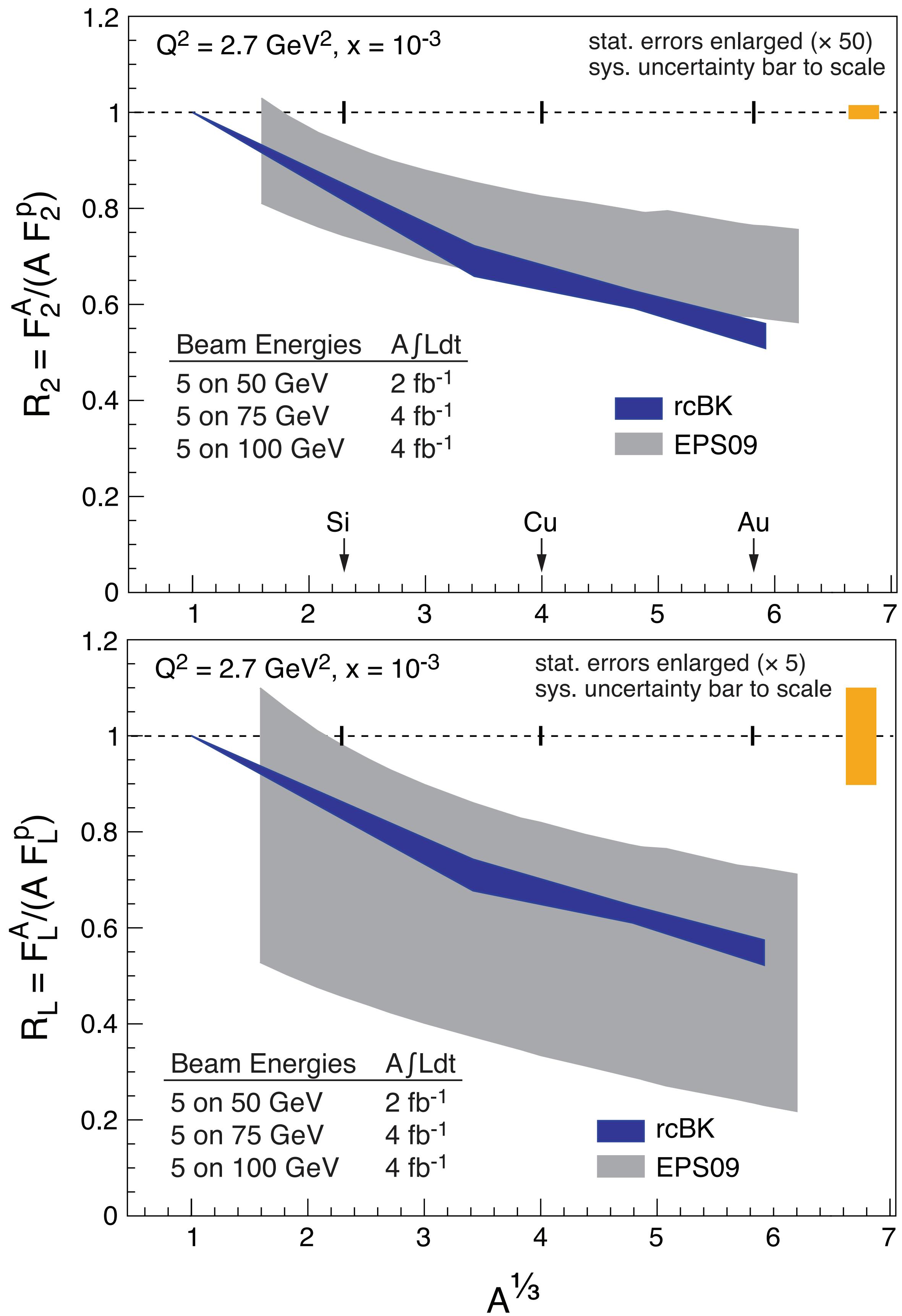
Comparison to theory: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+} F_L^A(x,Q^2)$

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

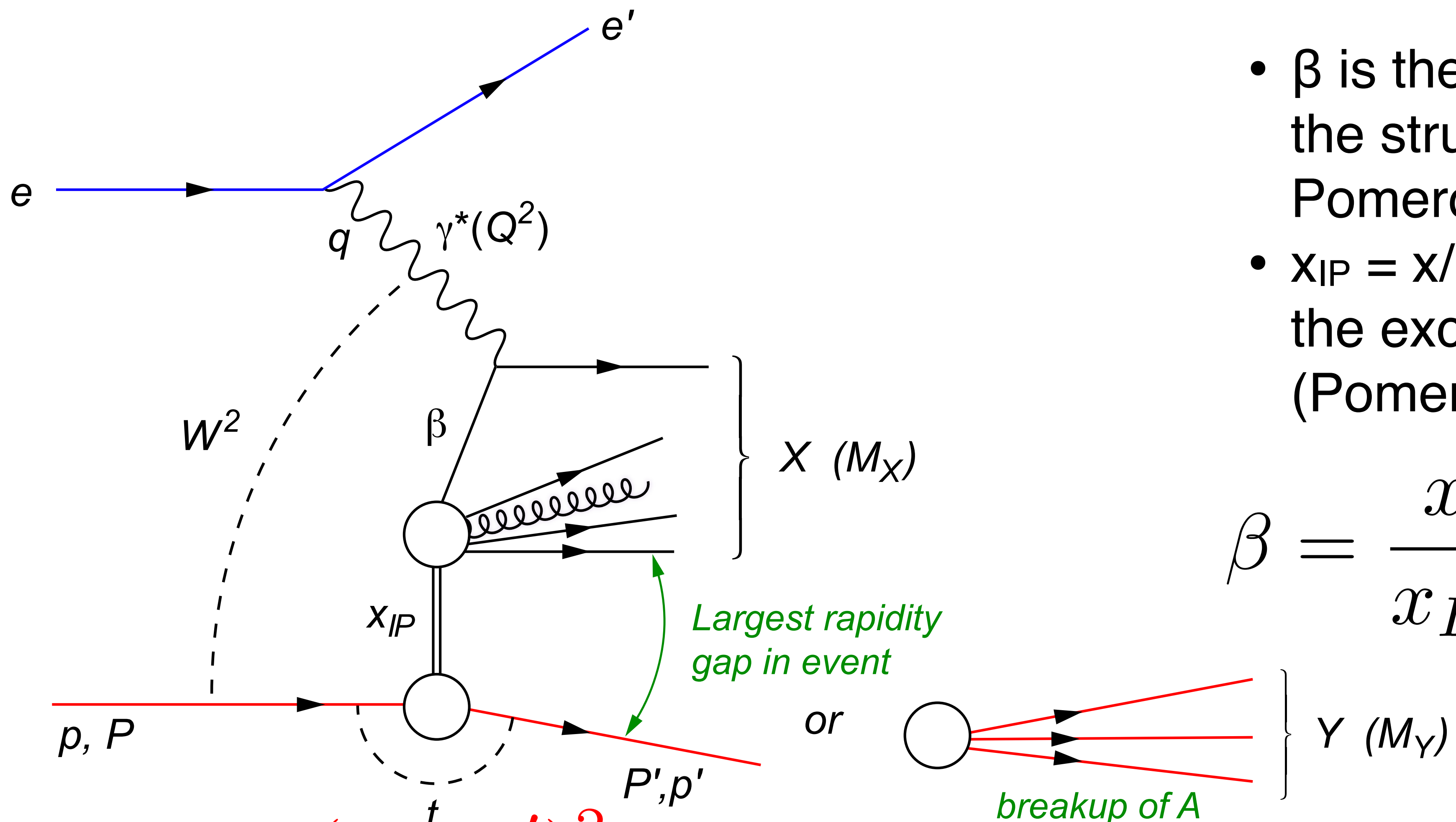
e+Au: 1st stage
5x50 - A∫Ldt = 2 fb^{-1}
5x75 - A∫Ldt = 4 fb^{-1}
5x100 - A∫Ldt = 4 fb^{-1}
running combined
~6 months total running (50% eff)

statistical errors are swamped by the 1% systematic errors

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



Exclusive processes in e+A - diffraction



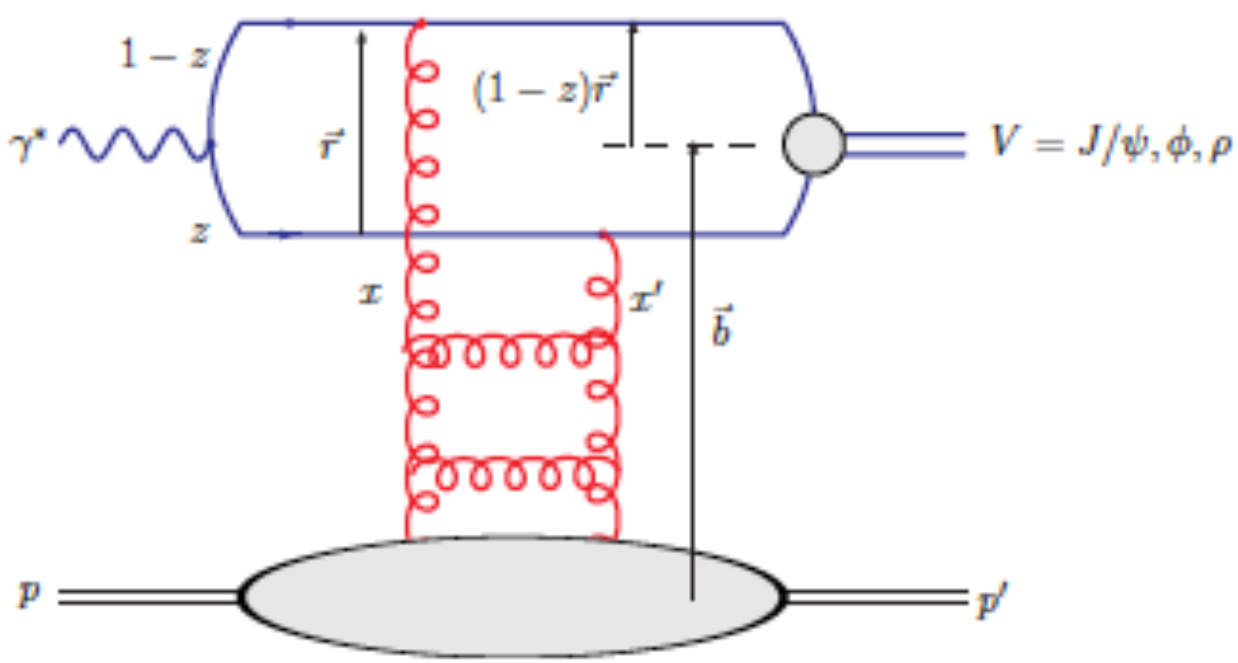
$$t = (p - p')^2$$

- 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

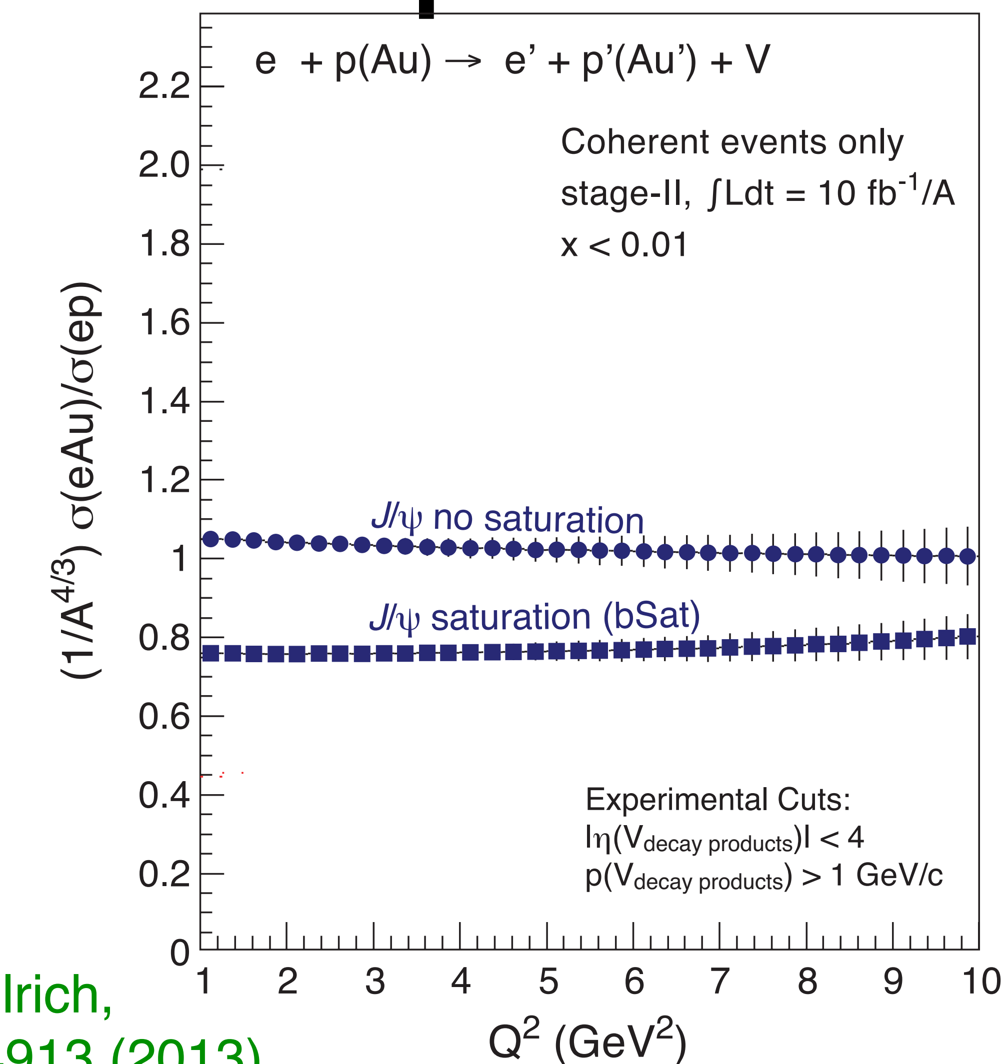
$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- **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)

Exclusive vector meson production



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



Sartre: Toll, Ullrich,
Phys.Rev. C87, 024913 (2013)

- 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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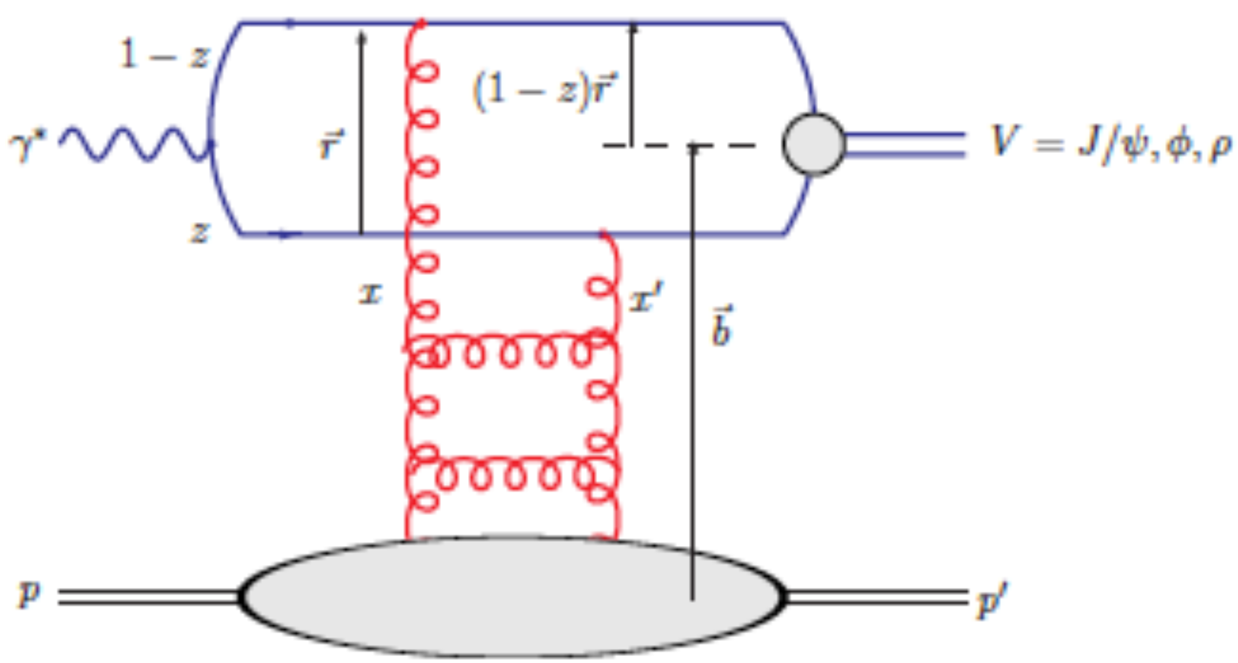

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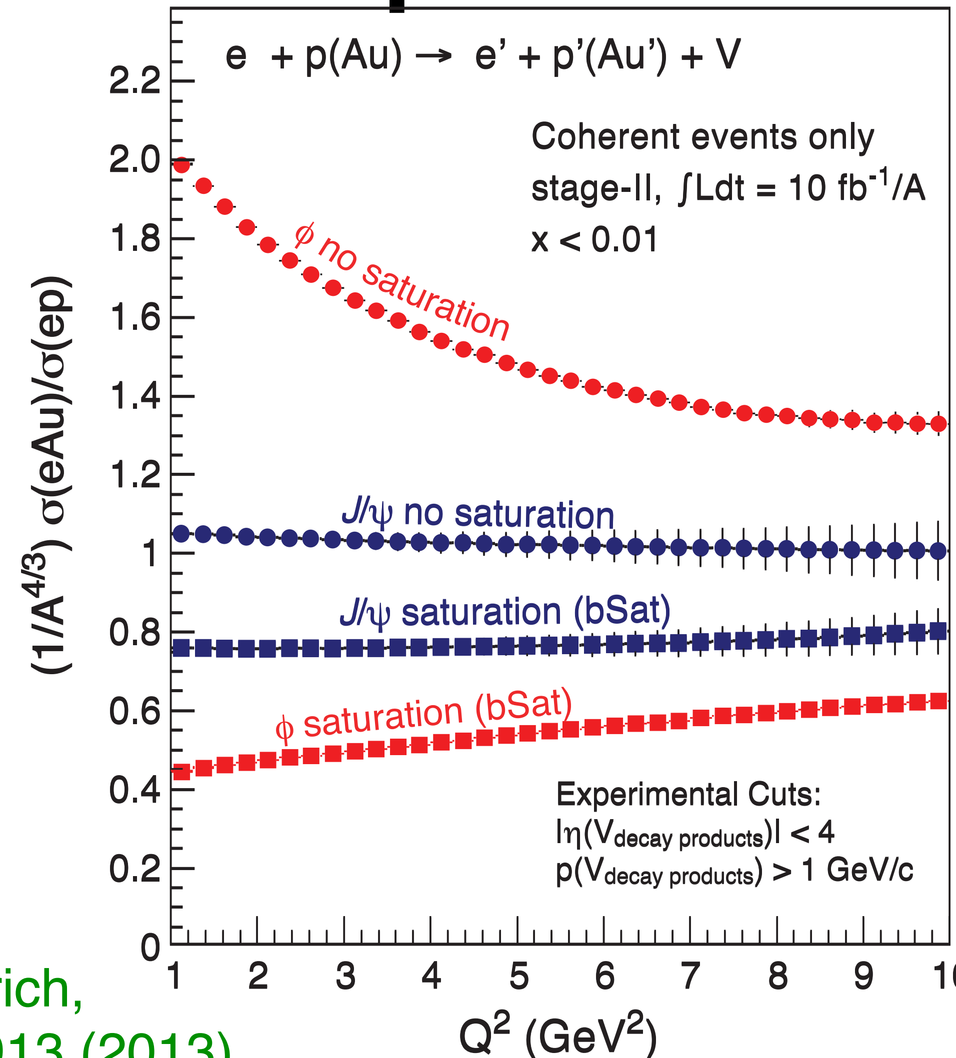

Sartre: Toll, Ullrich,
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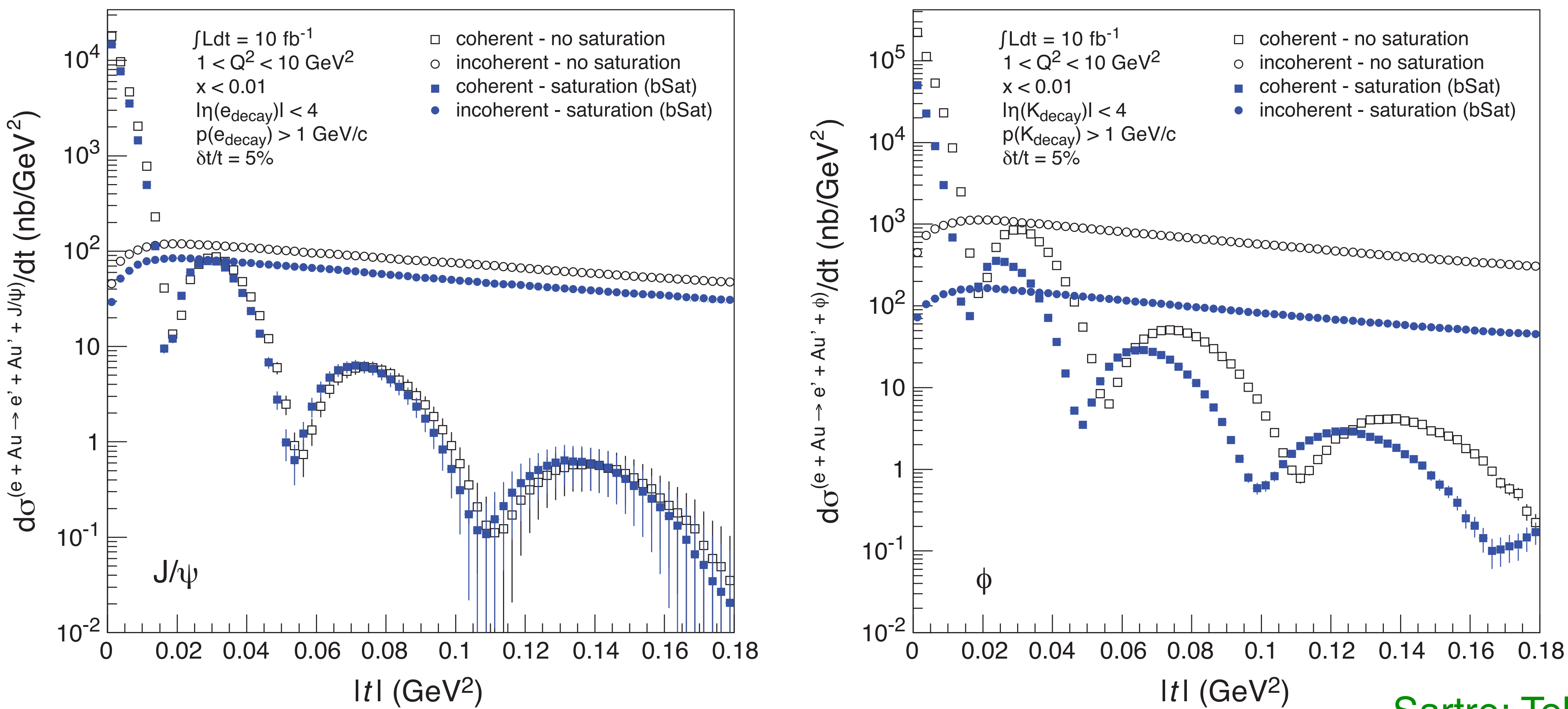
- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference
  - ➡ wave function for ϕ is larger and hence more sensitive to saturation effects

Exclusive Vector Meson Production in e+A



Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

- 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

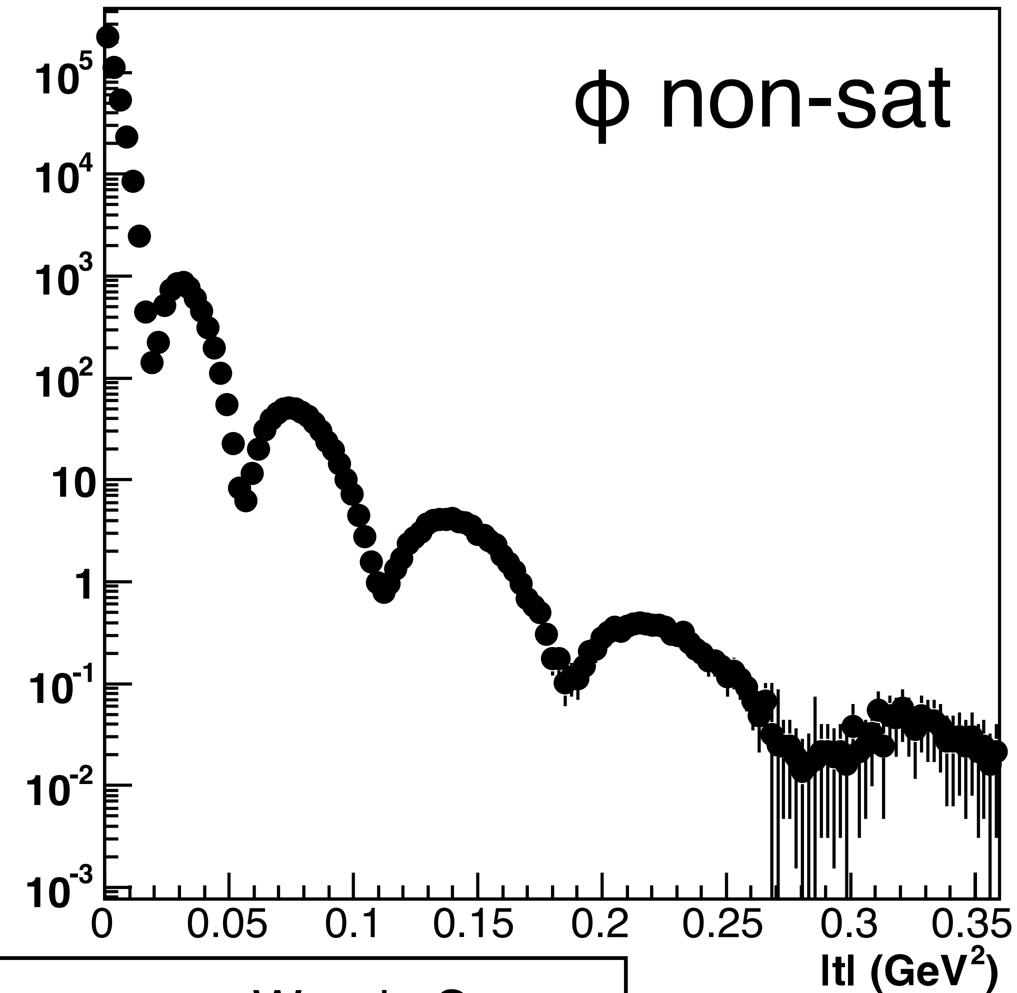
- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

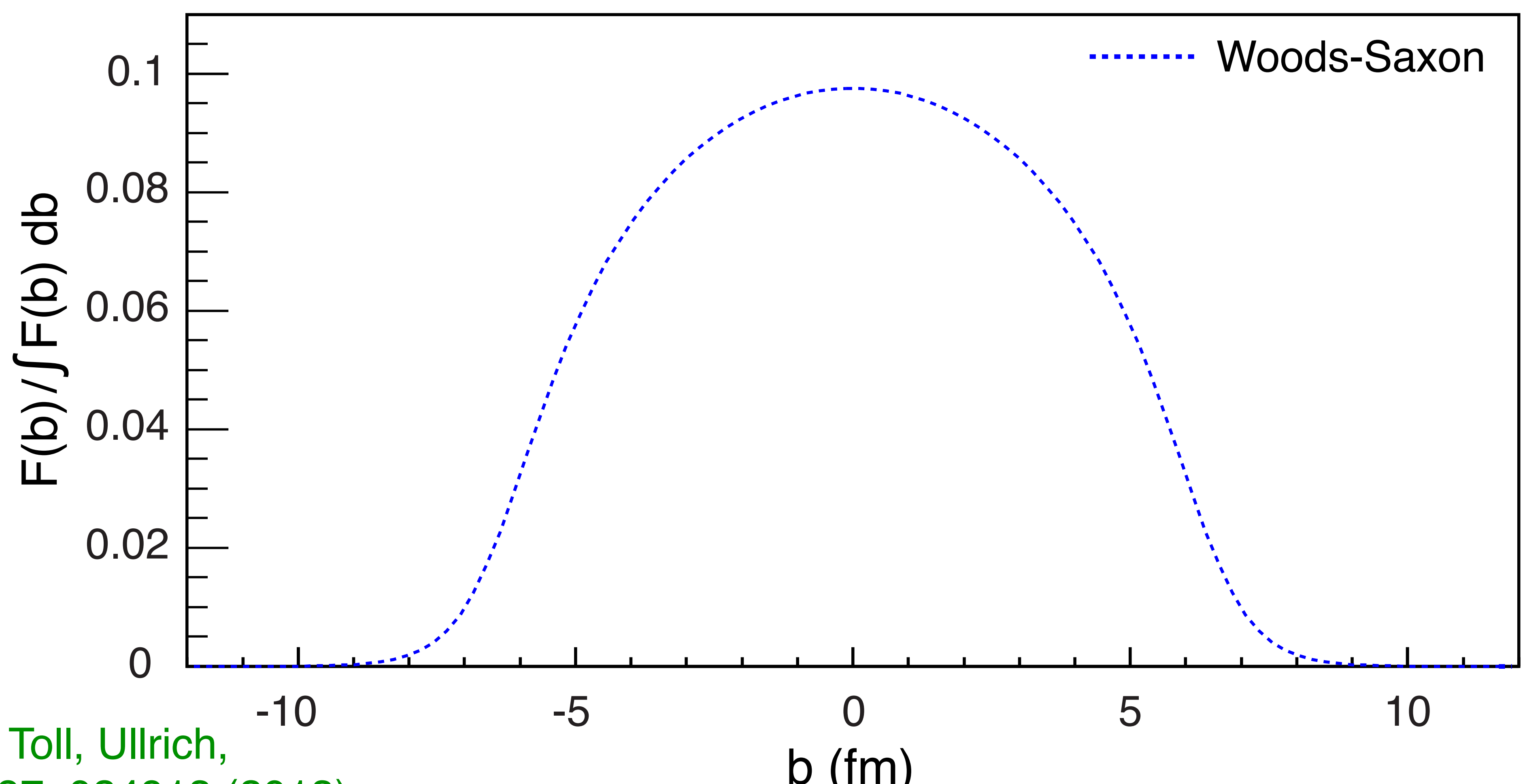
Finding the source...

- 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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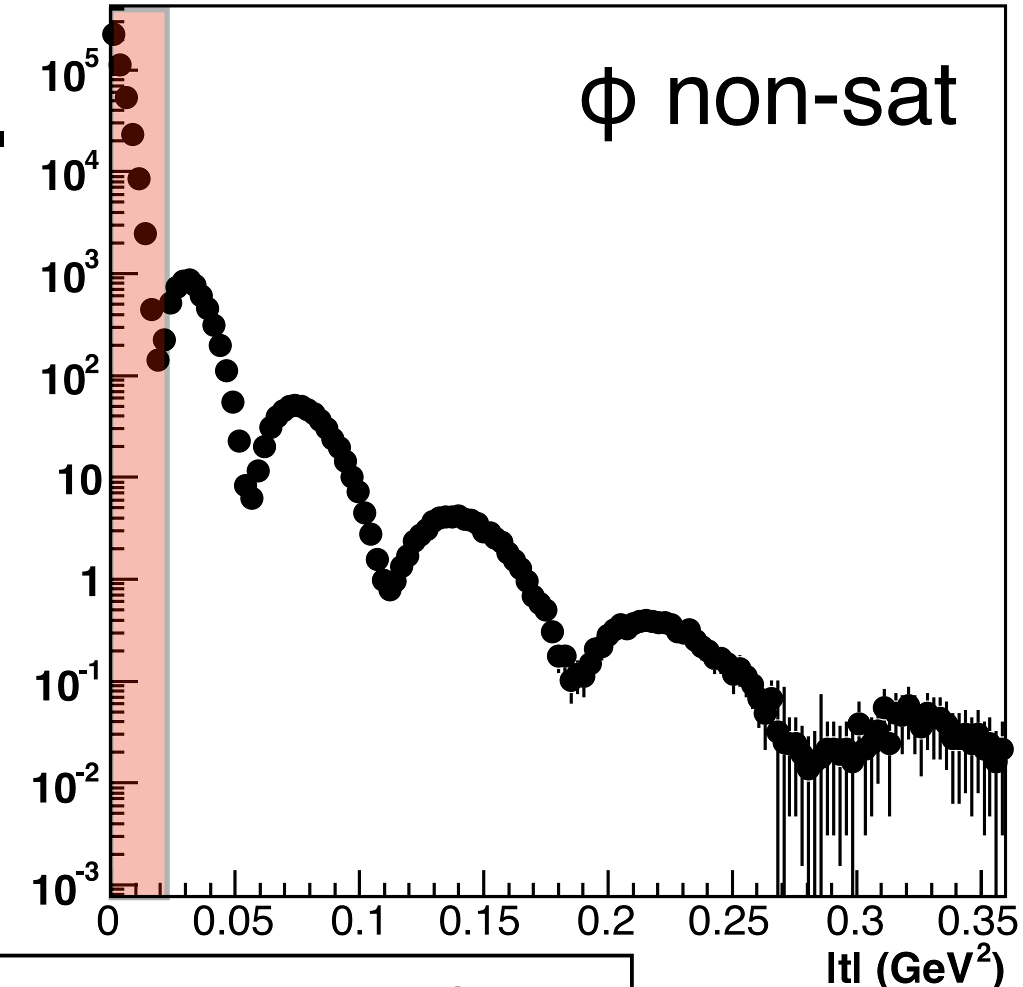

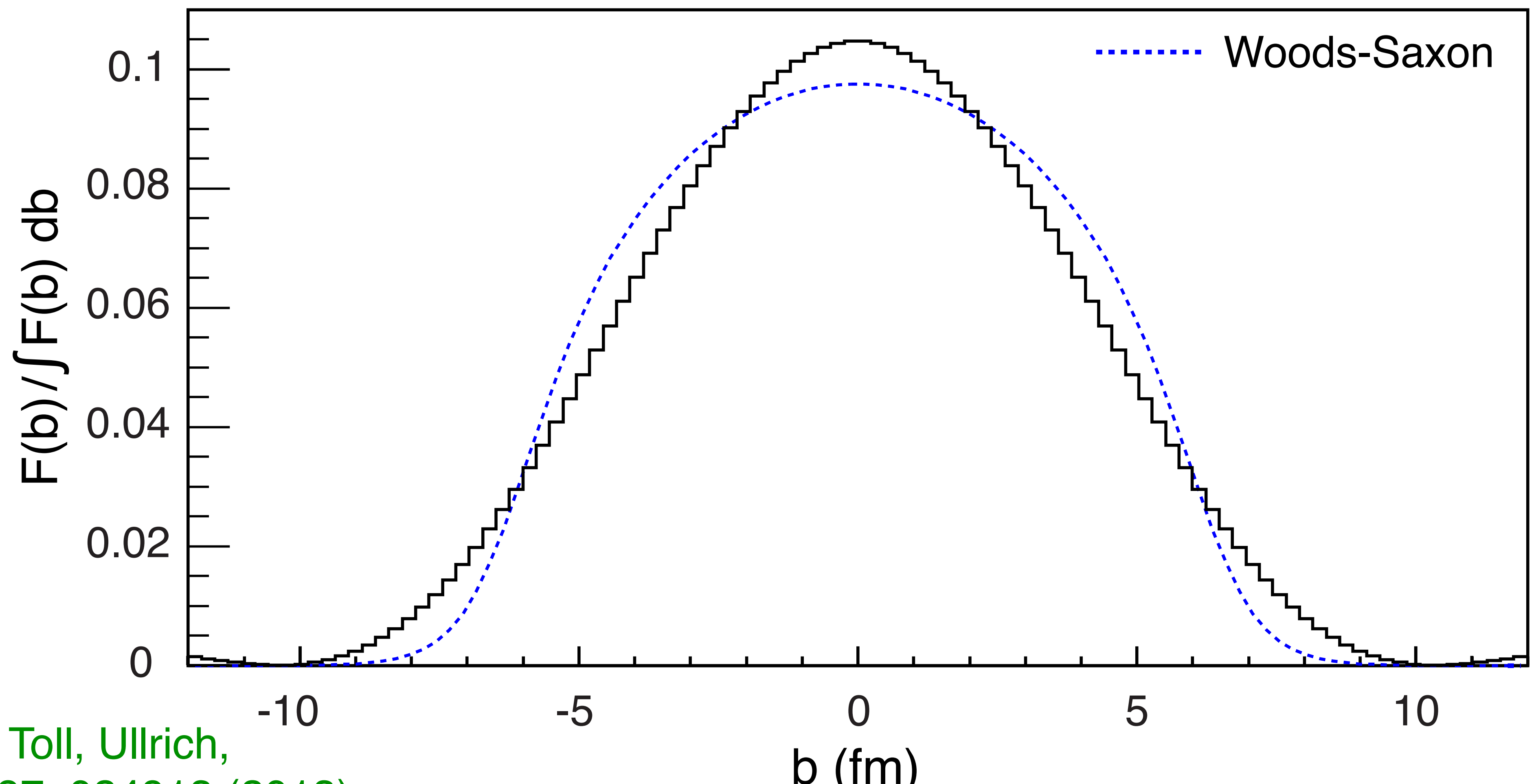

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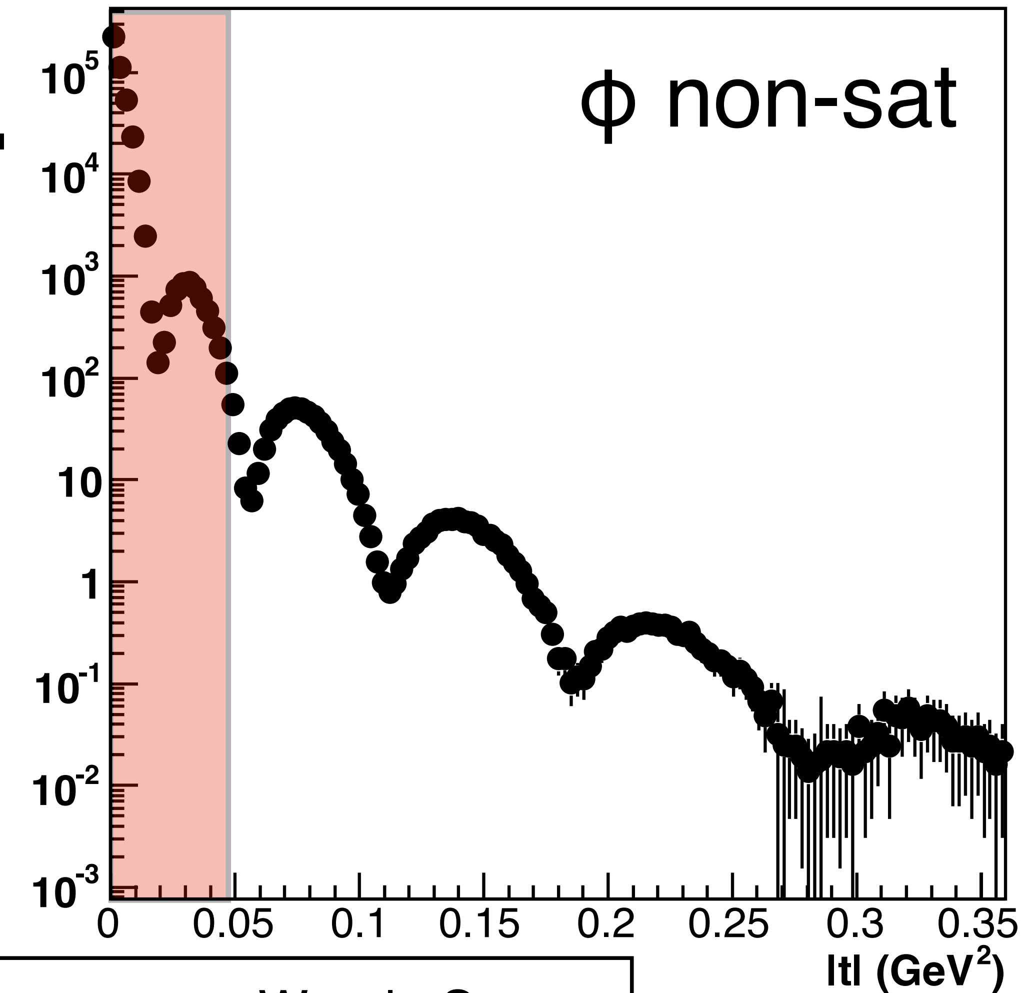

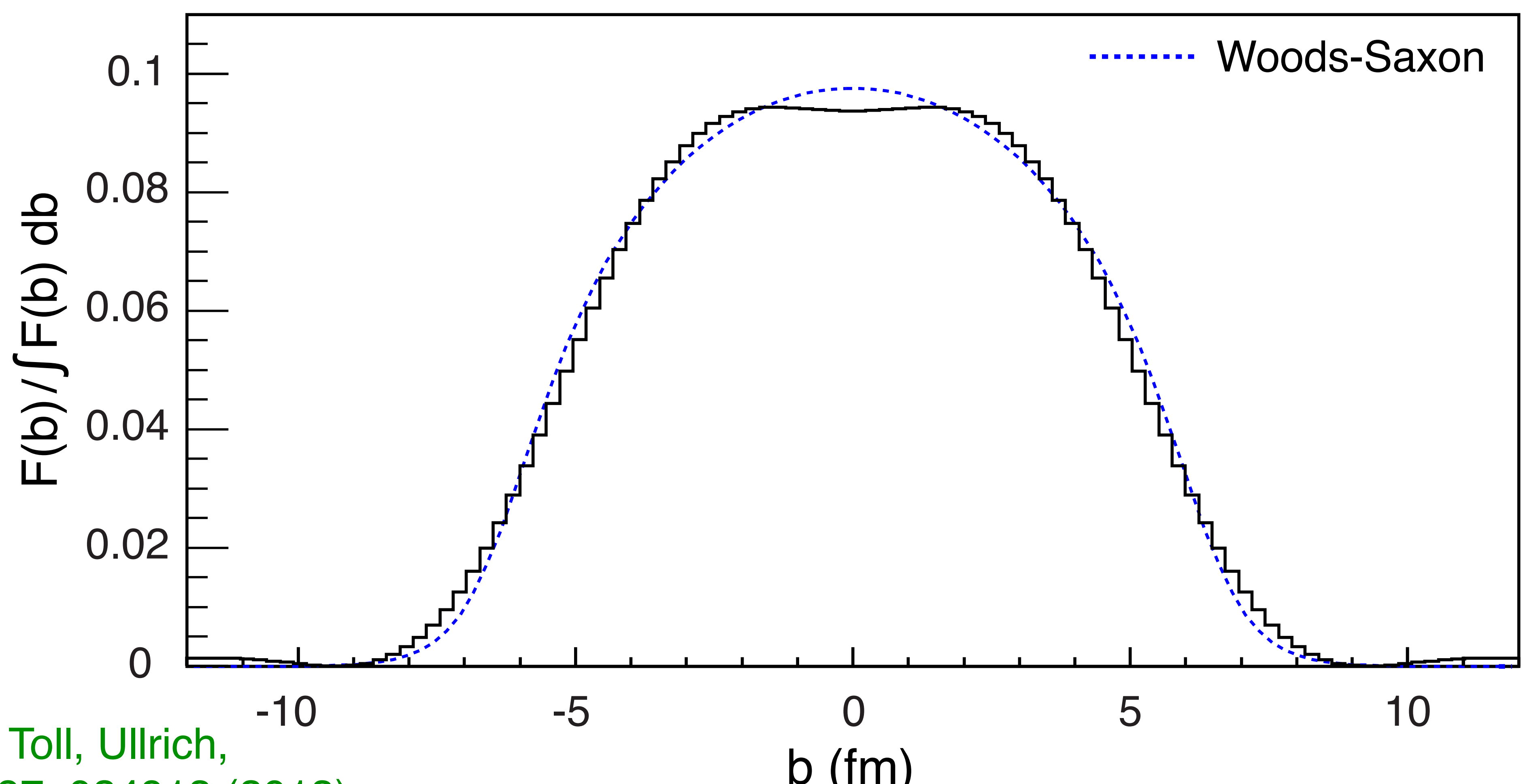

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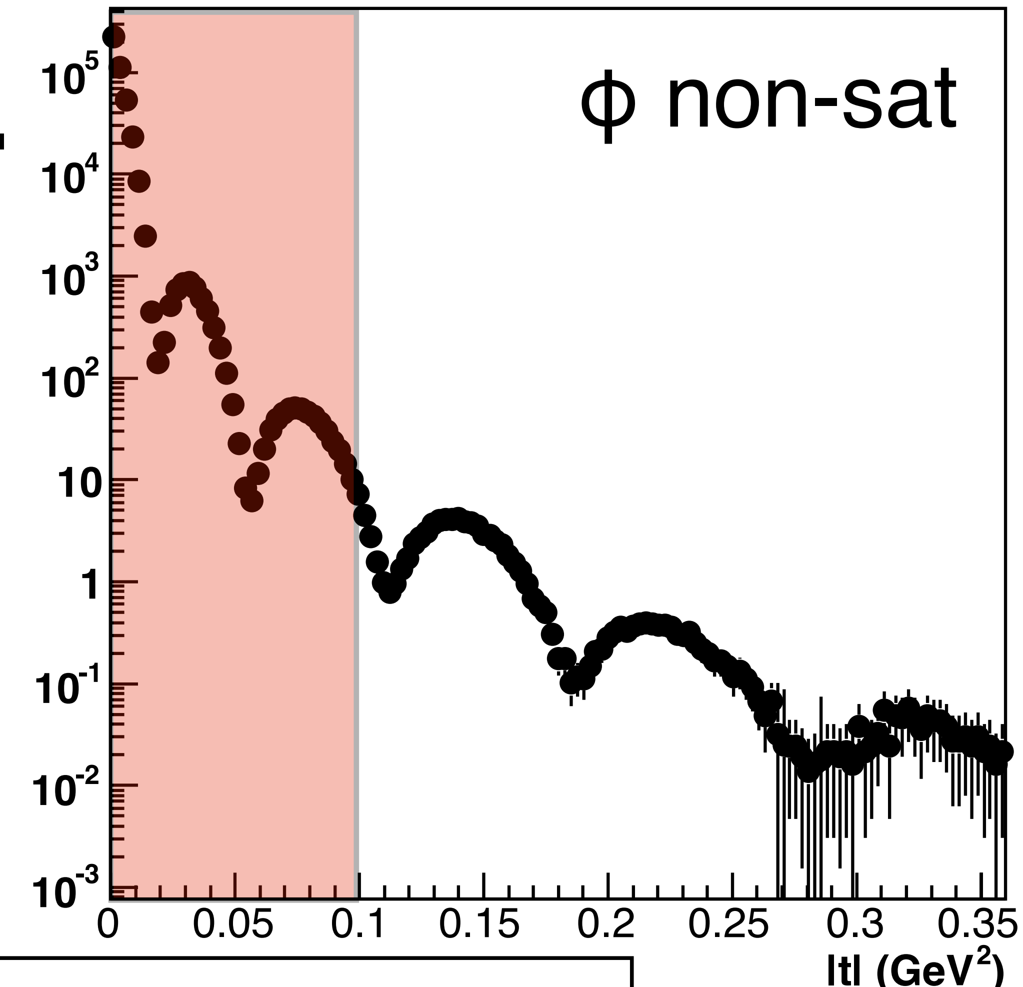

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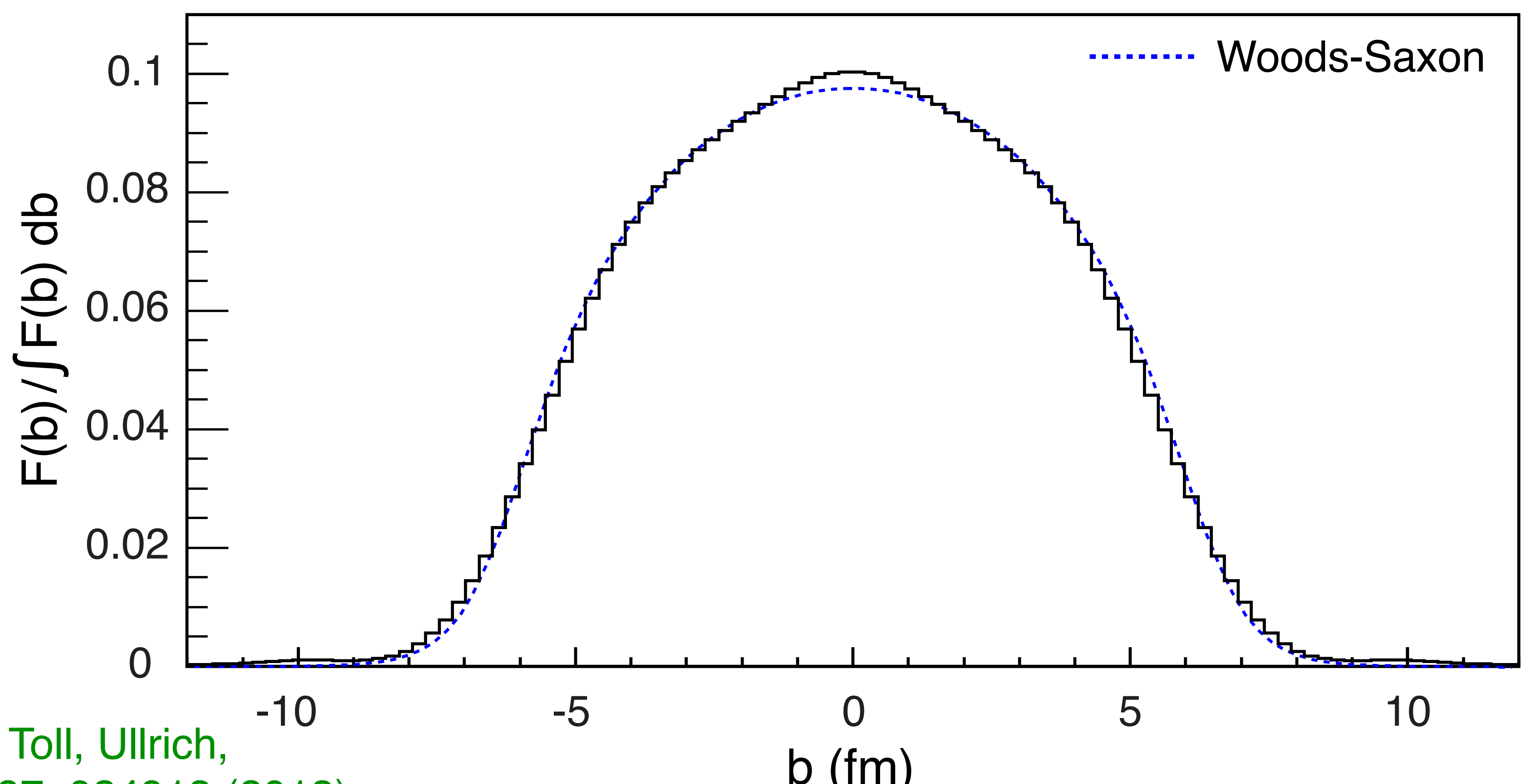

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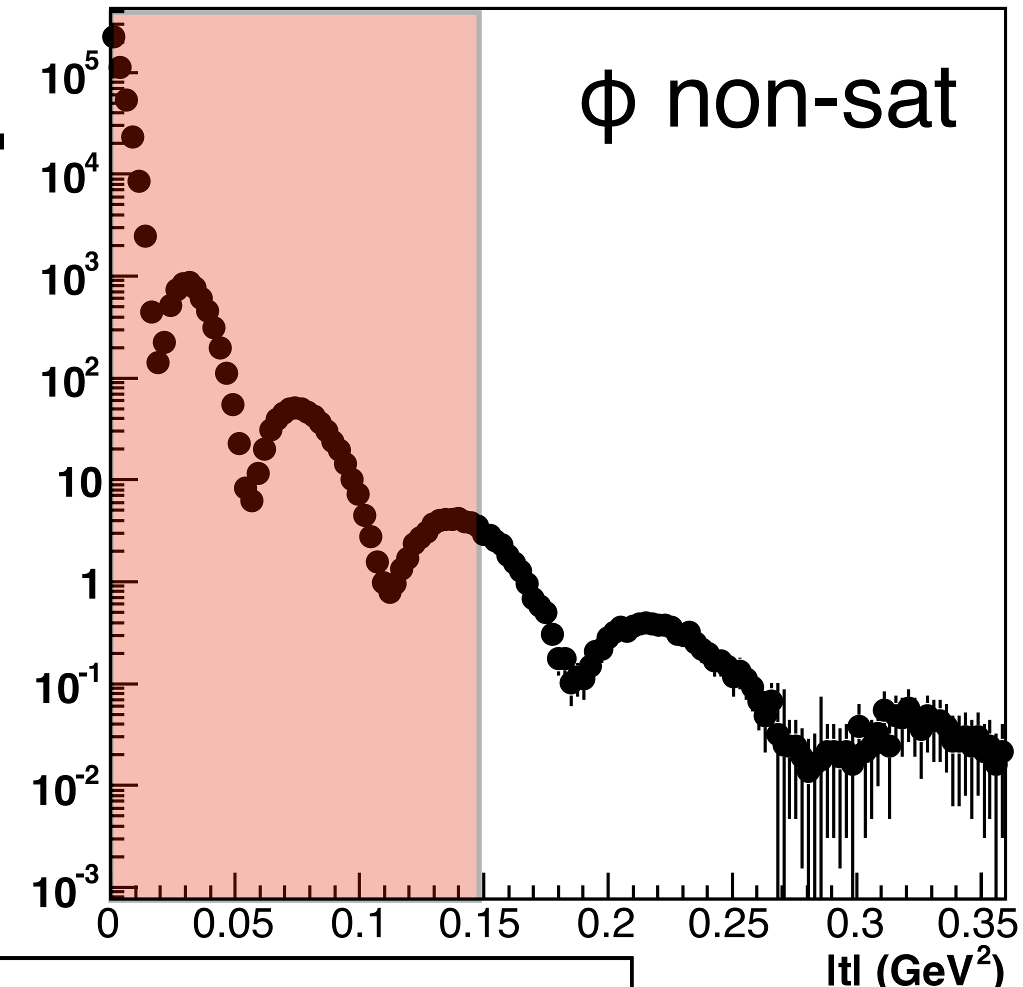

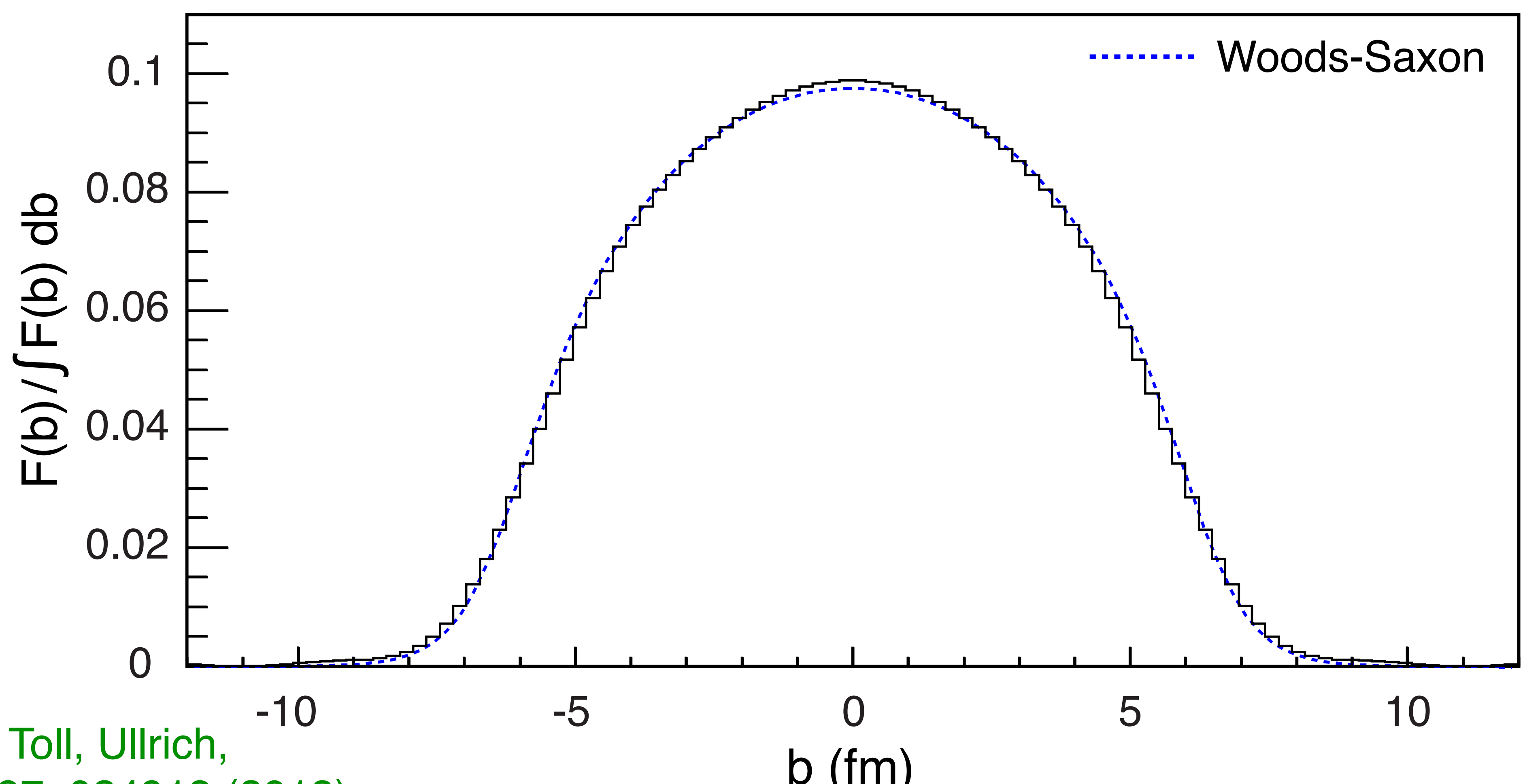

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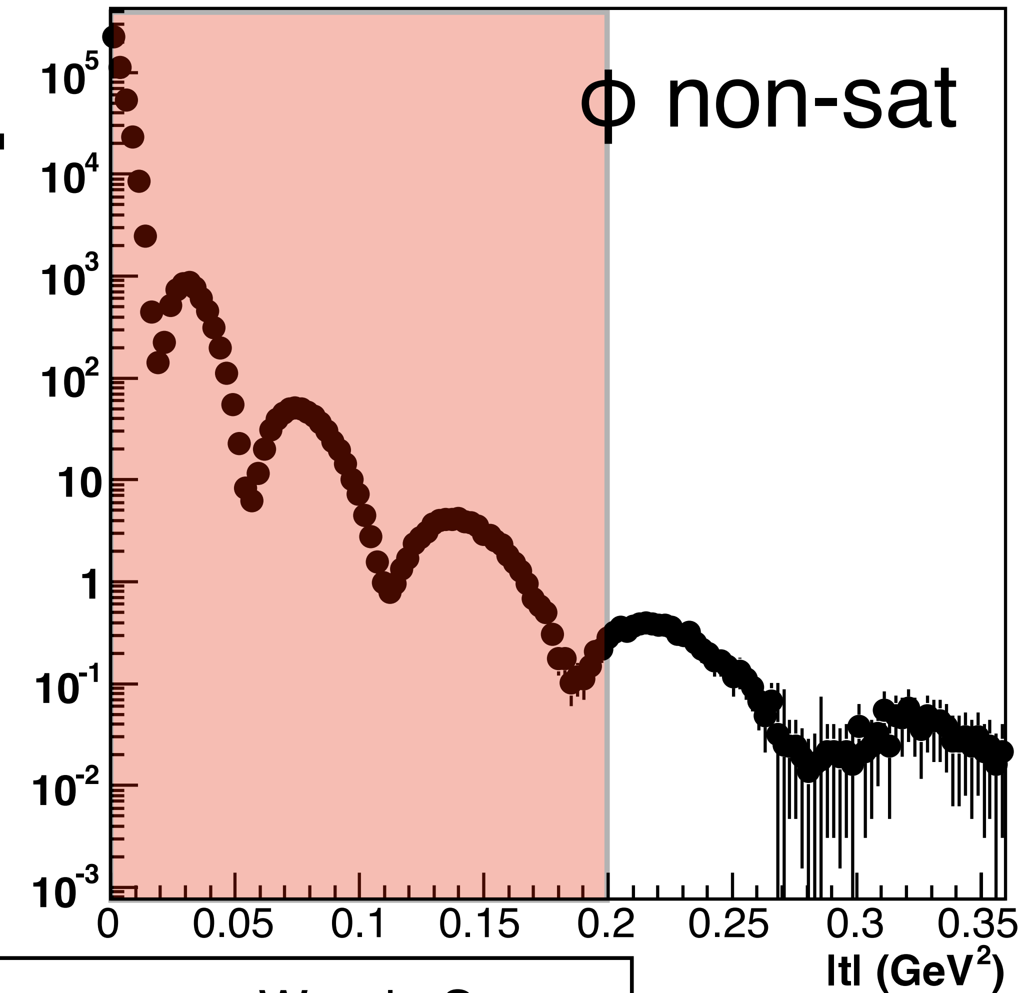

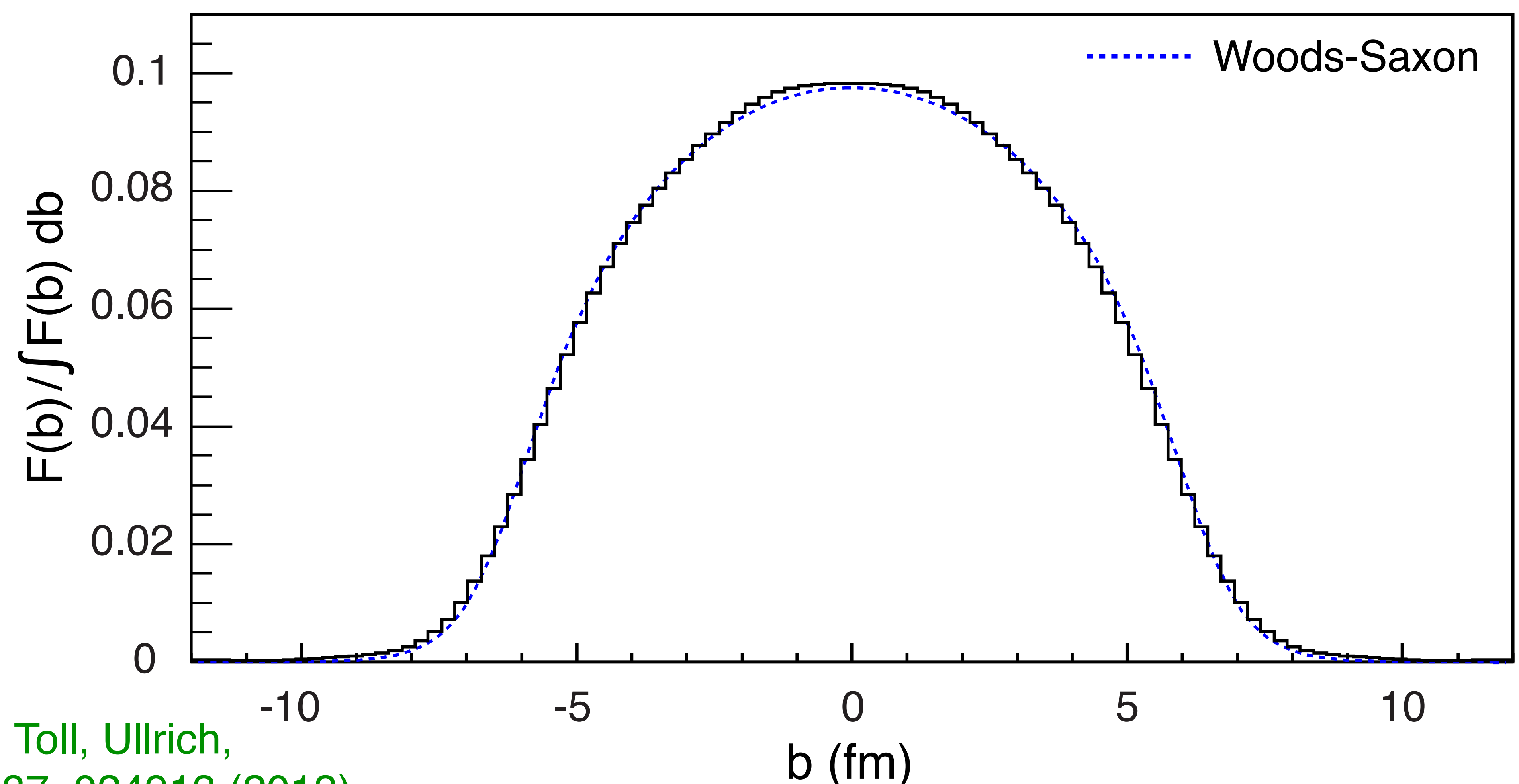

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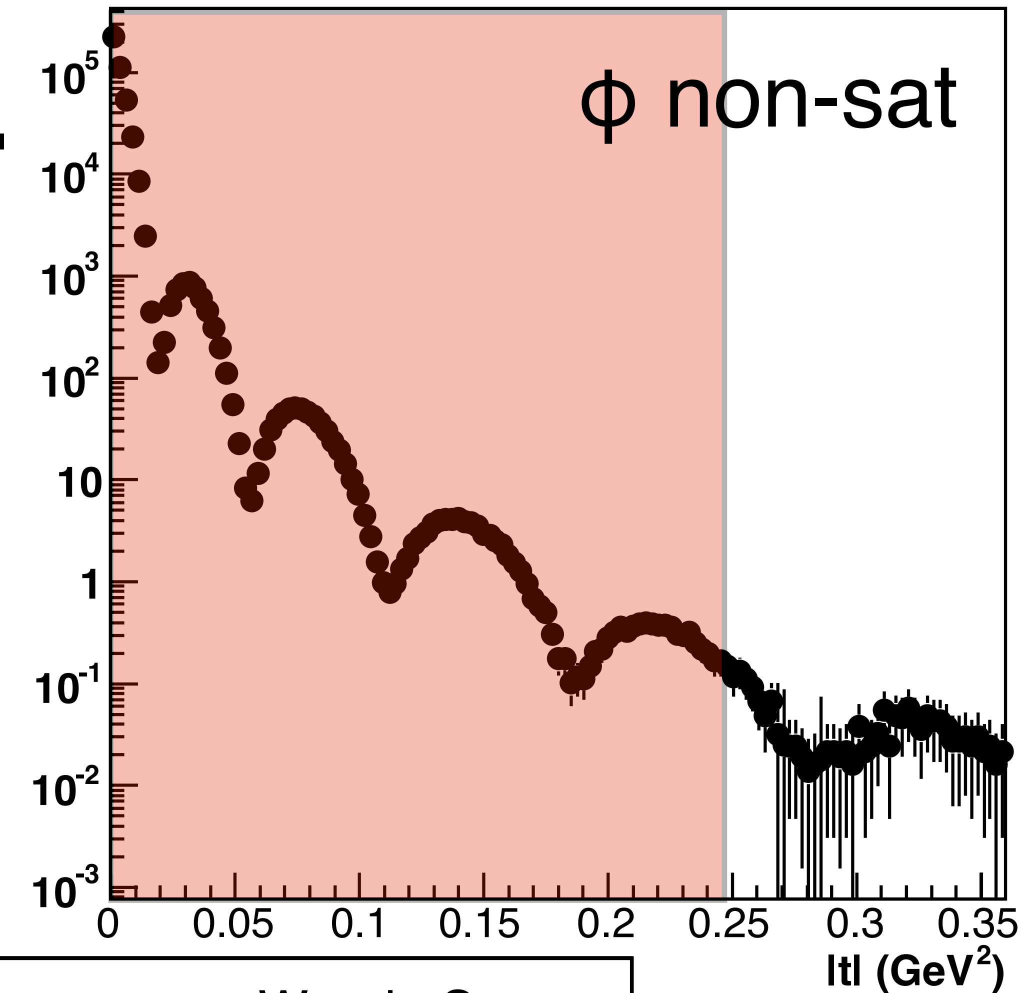

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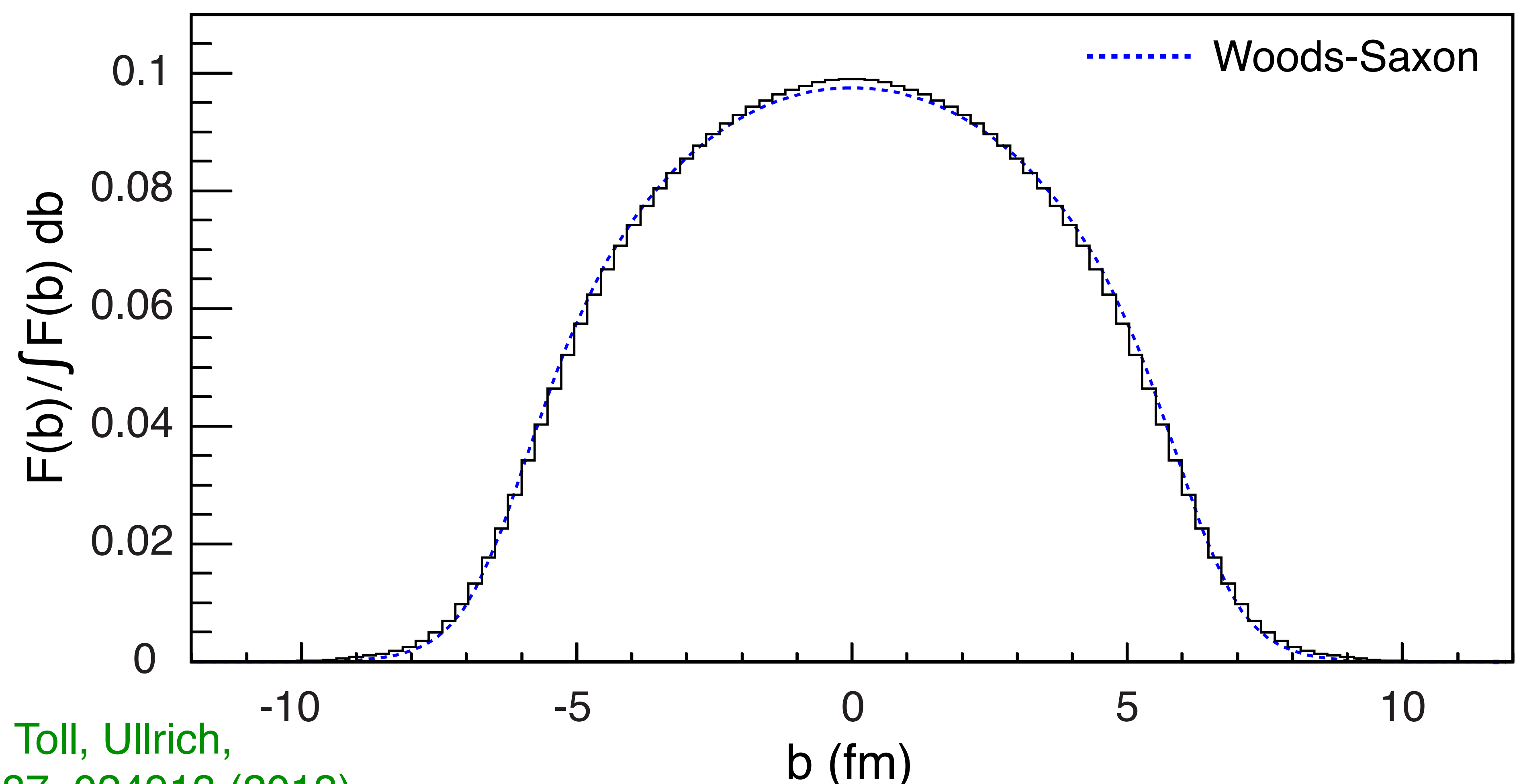

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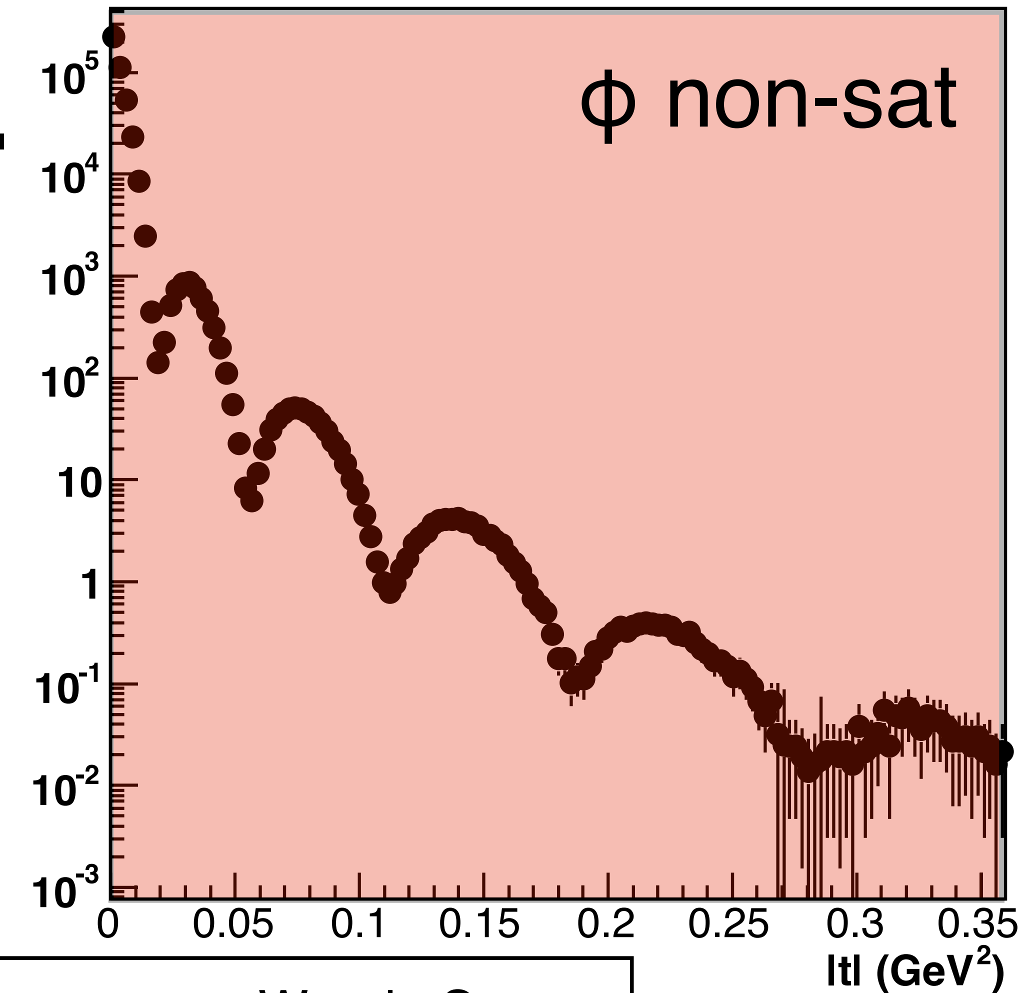

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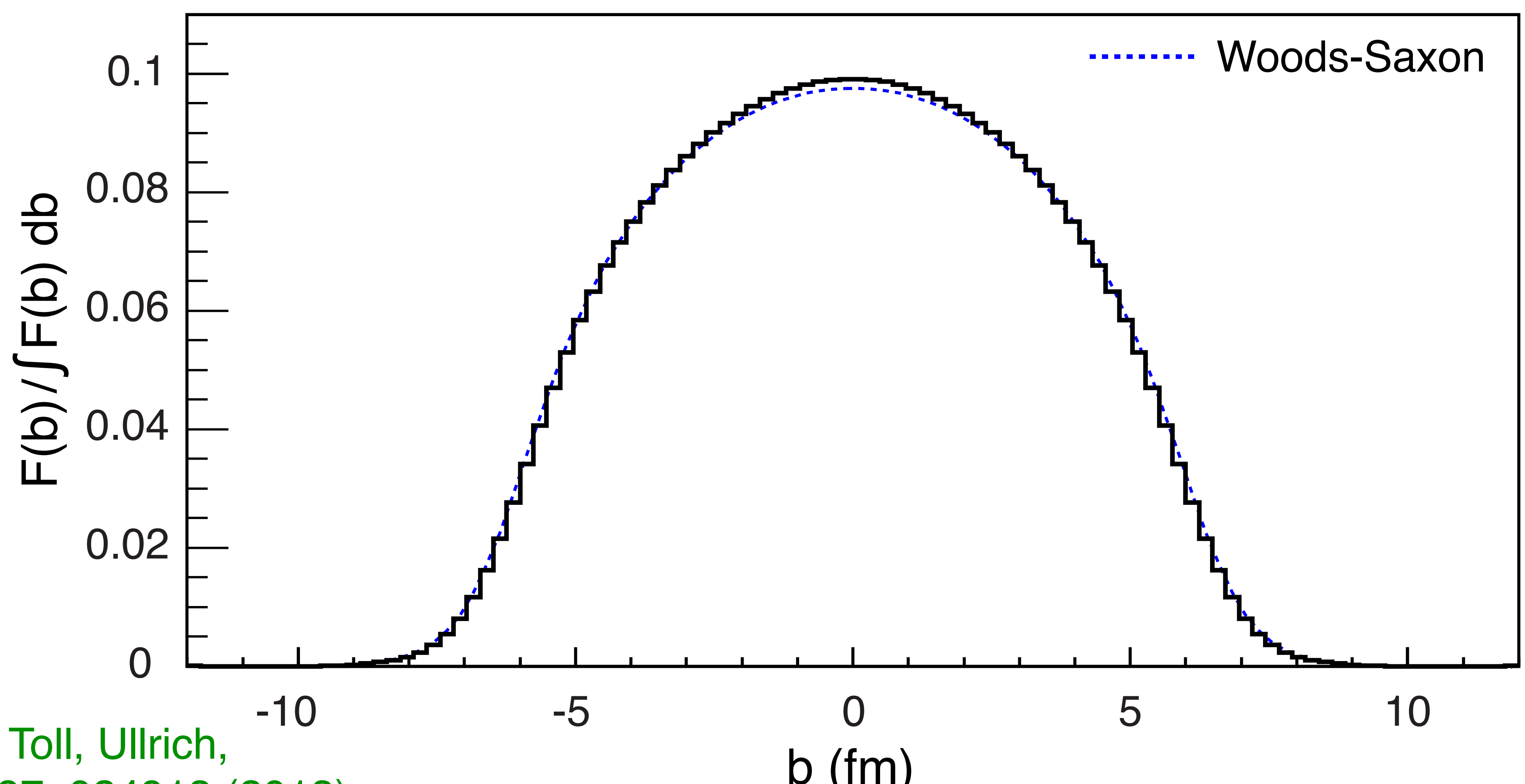

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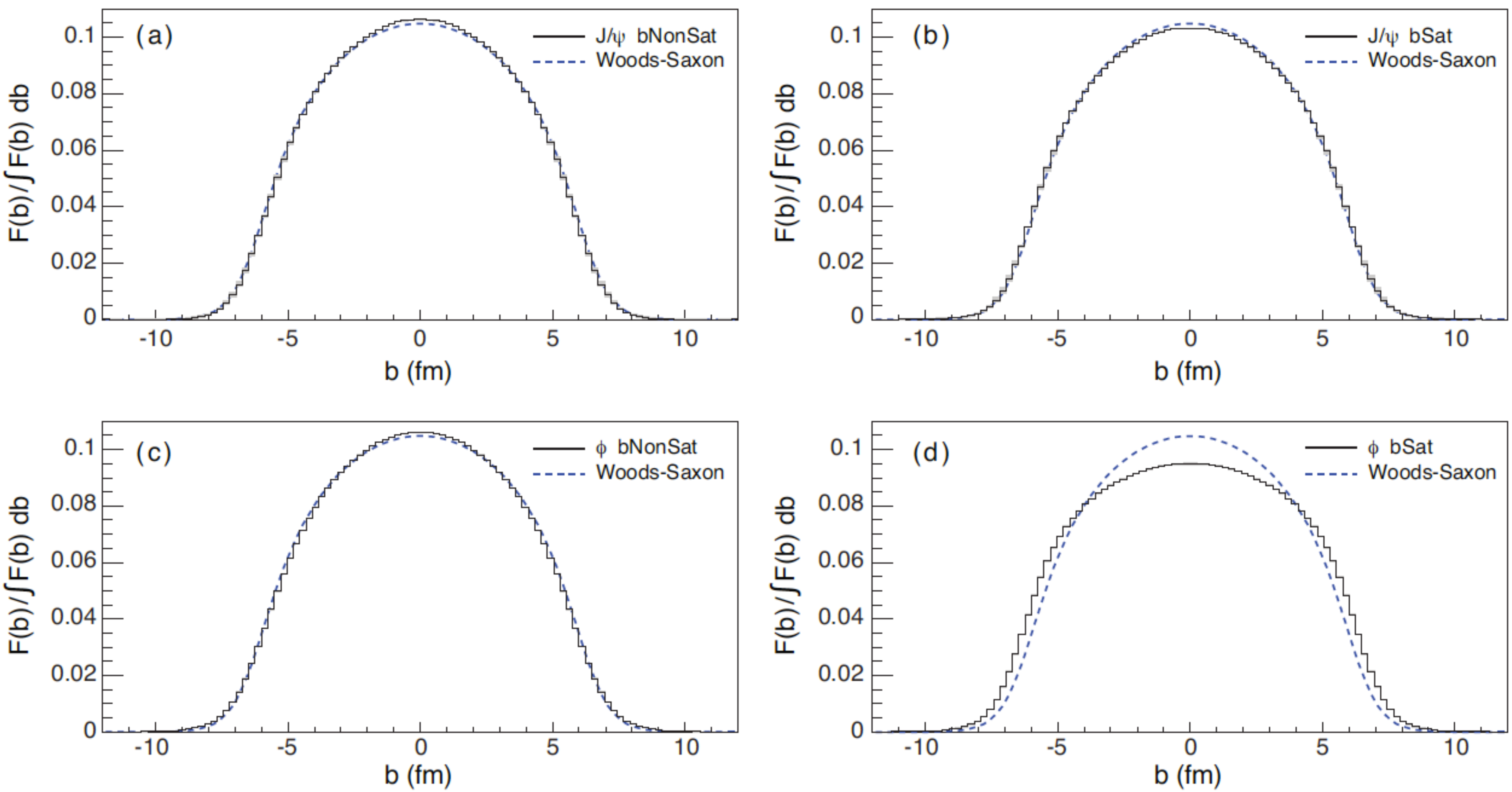
Finding the source...

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



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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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