Measuring the gluon distribution of nuclei: diffractive e+A collisions at eRHIC

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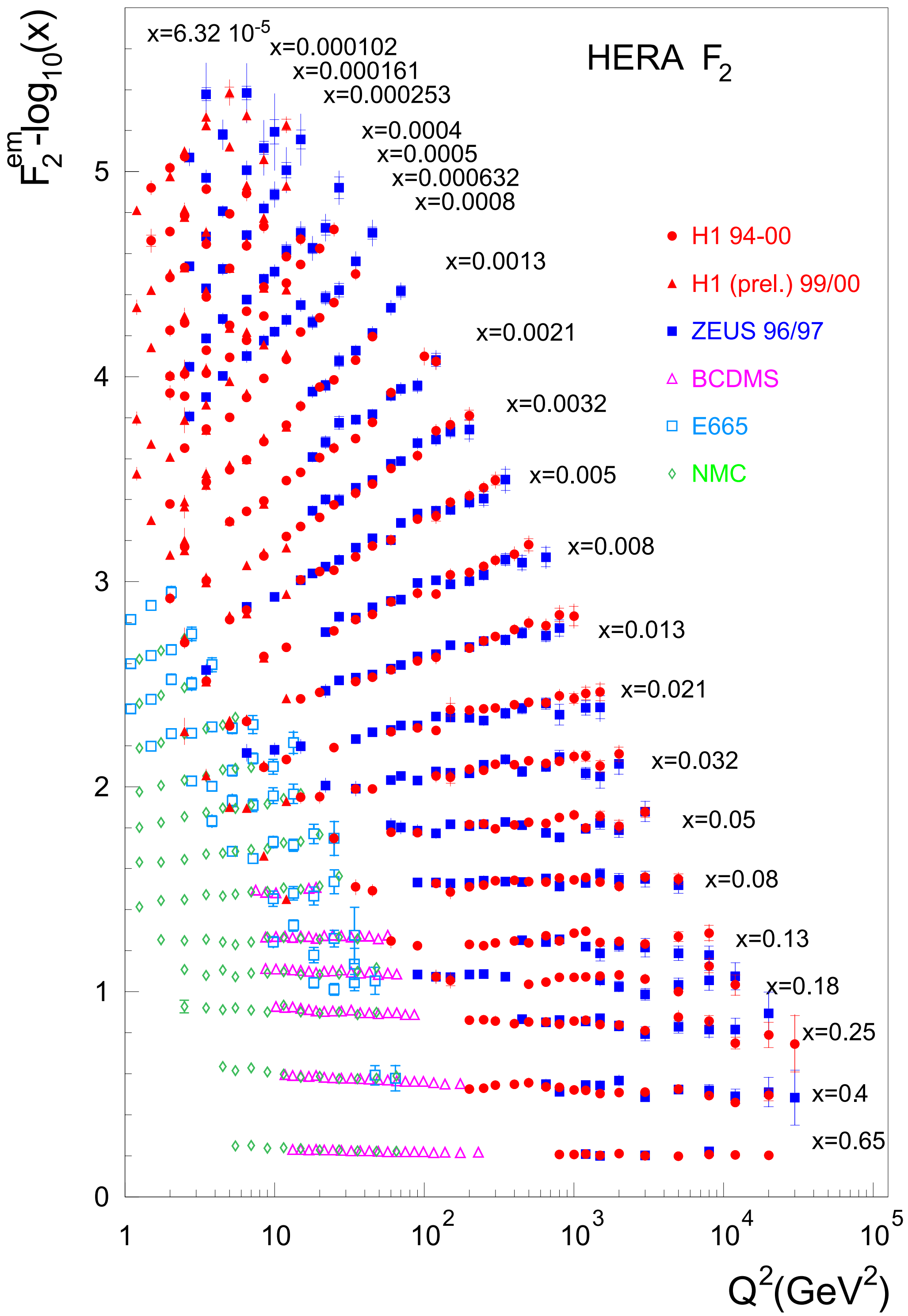
What did we learn from e+p collisions at HERA?

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

quark+anti-quark momentum distributions

gluon momentum distribution



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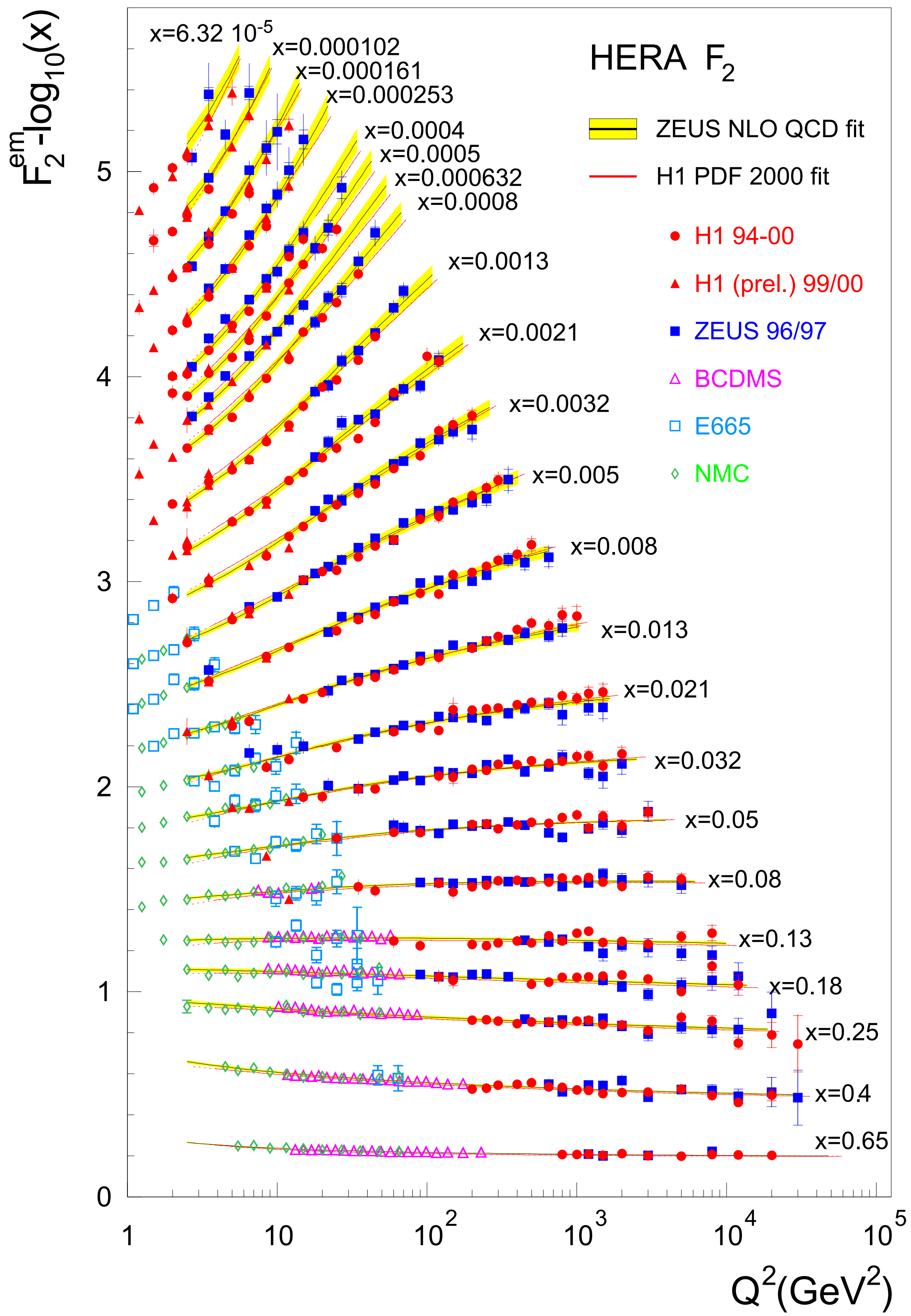

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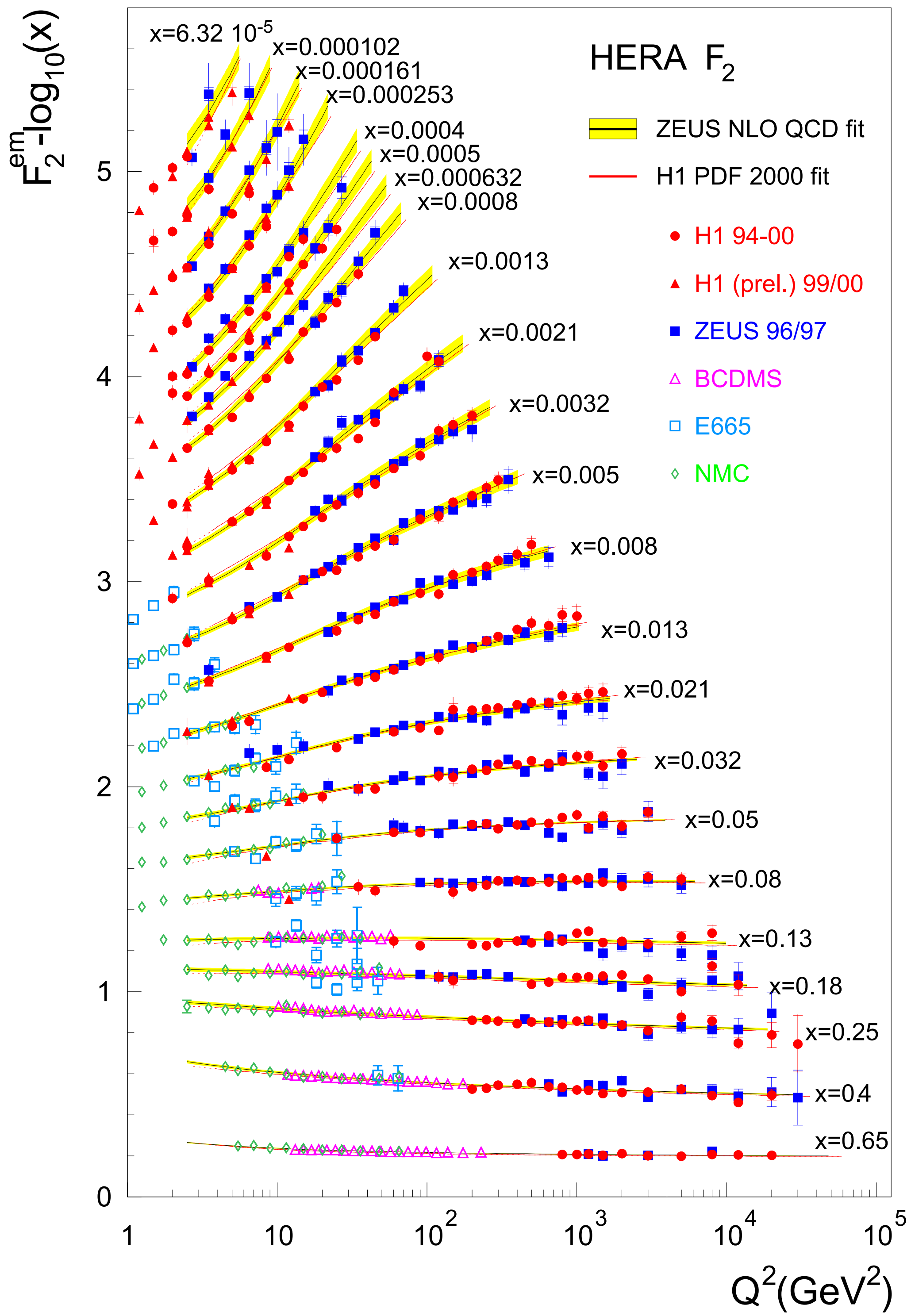

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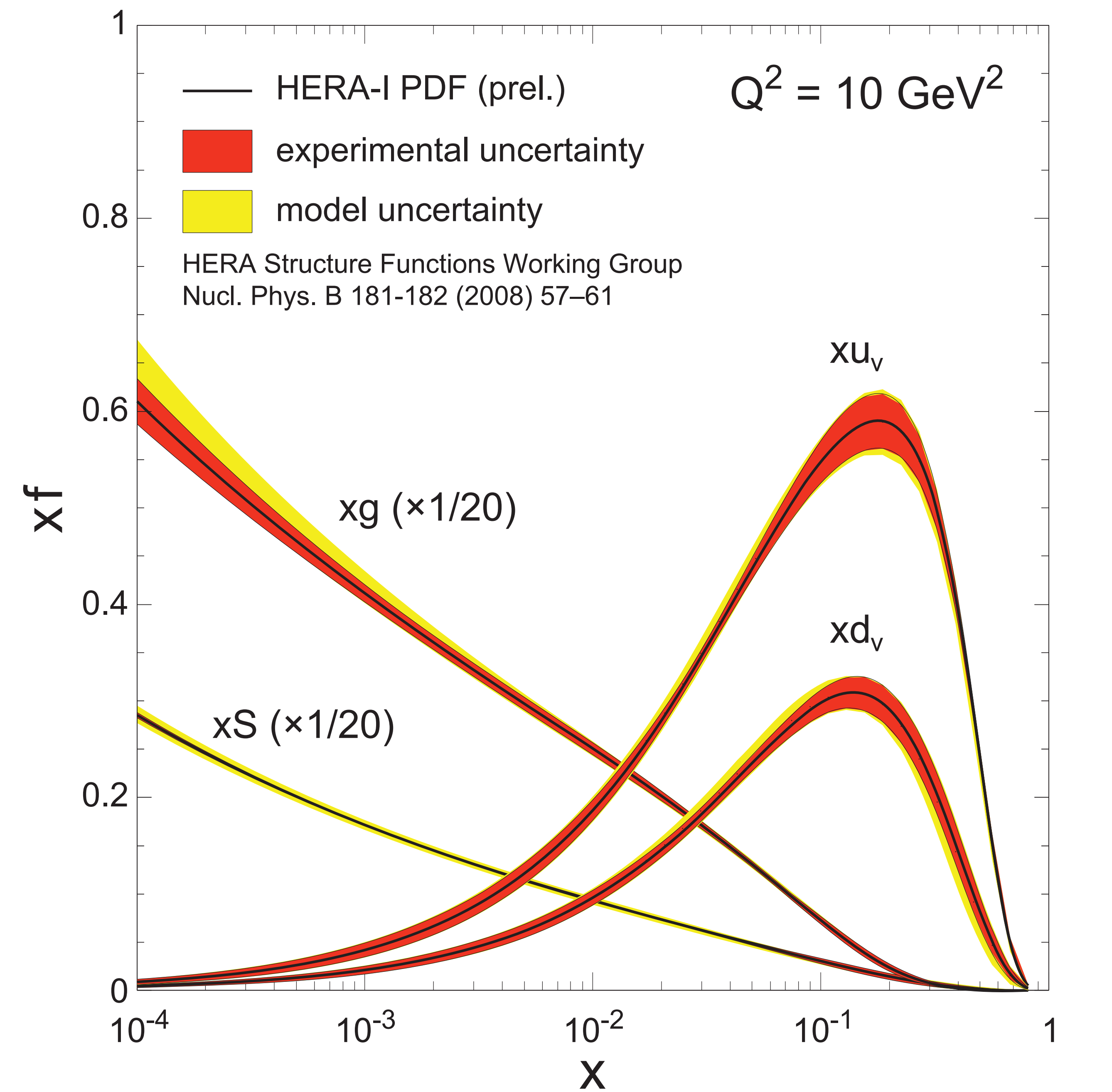

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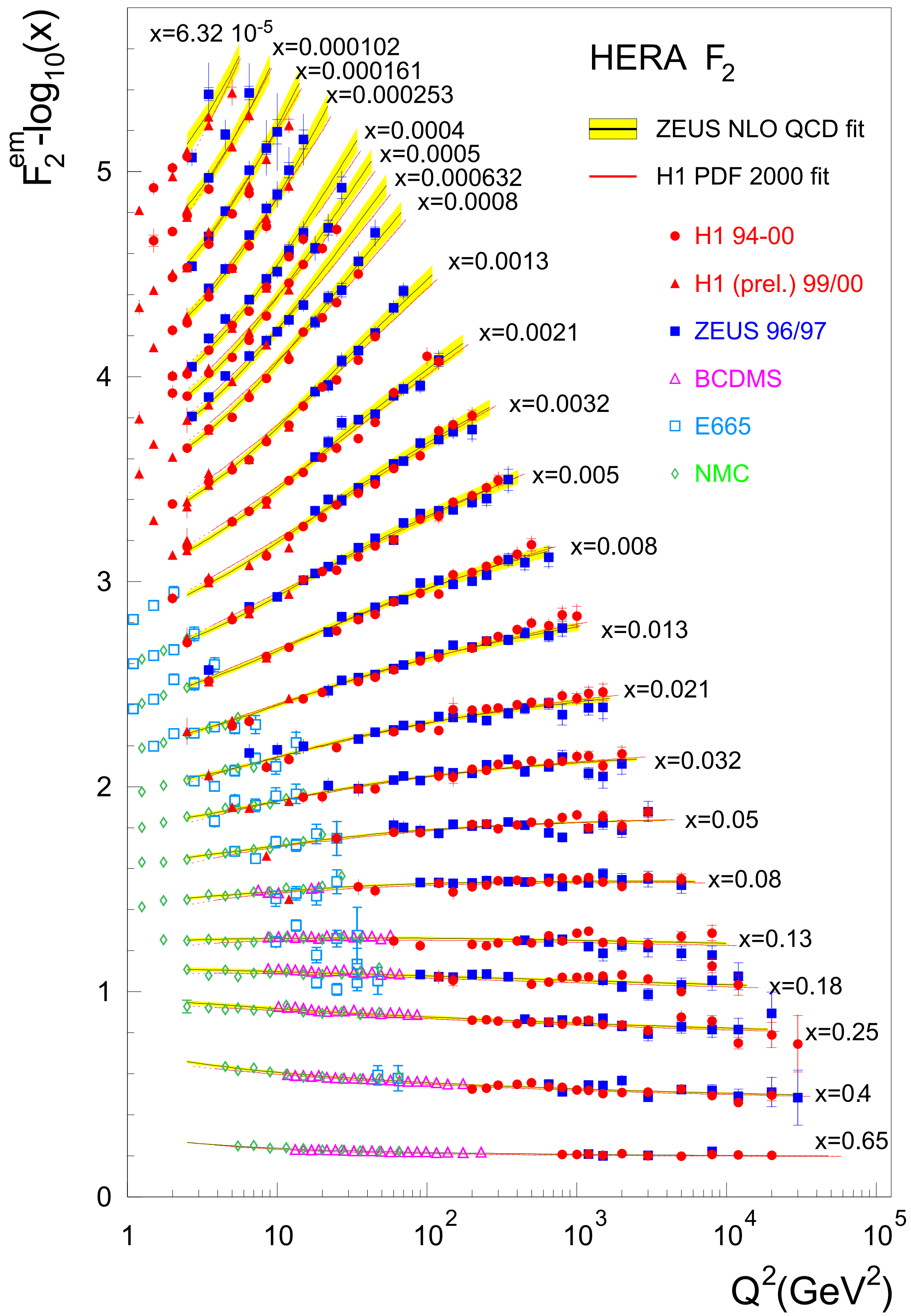

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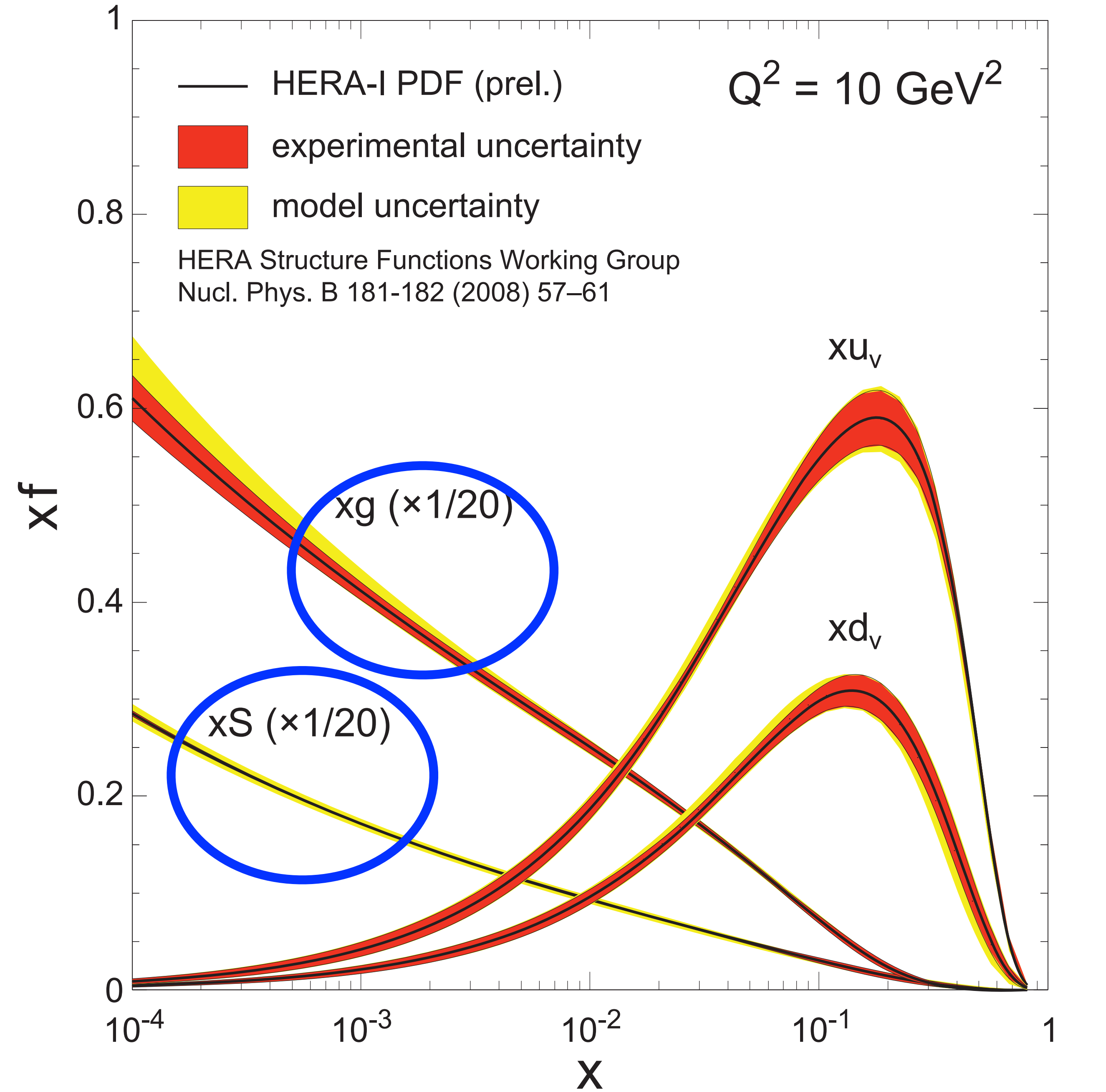

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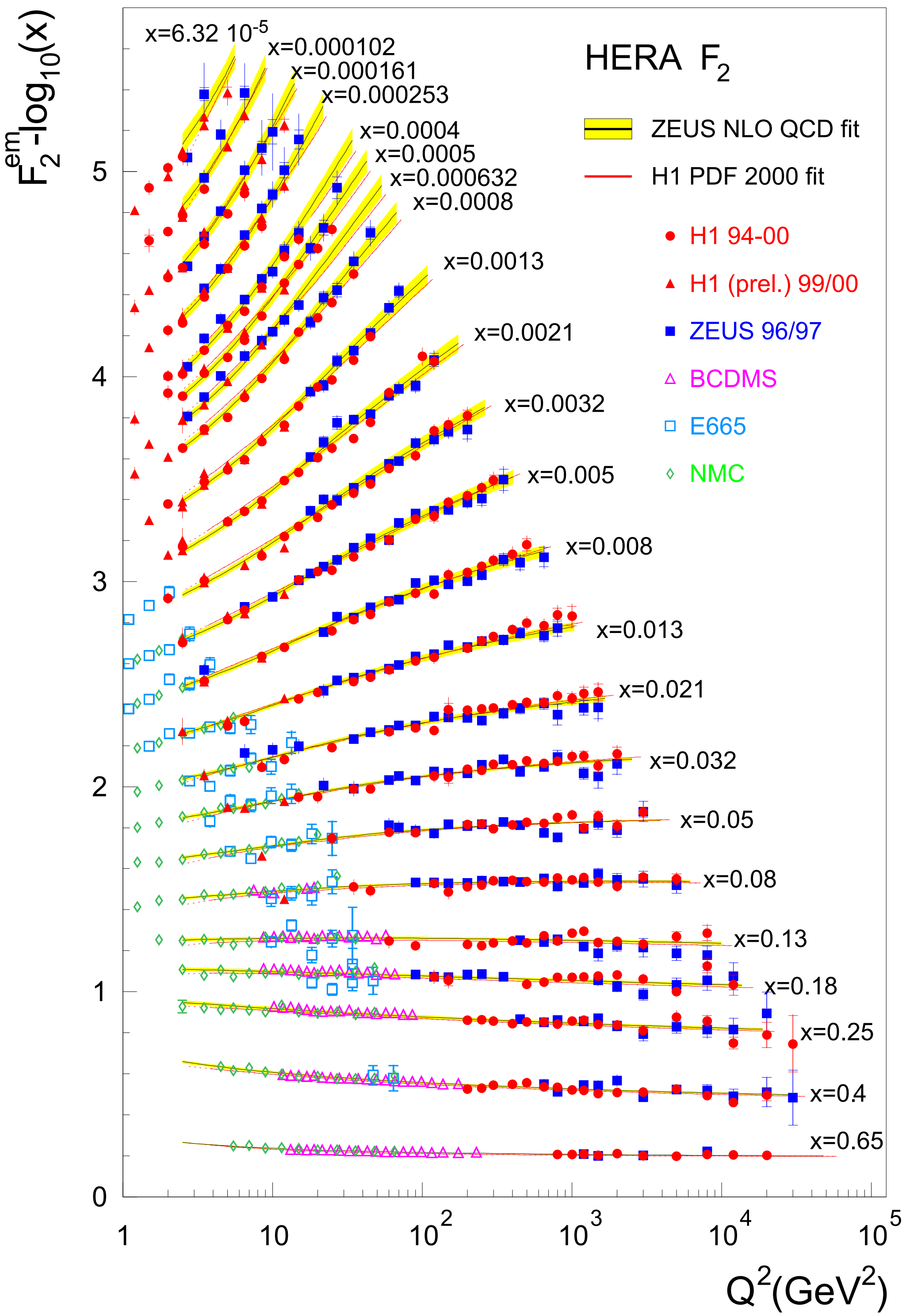

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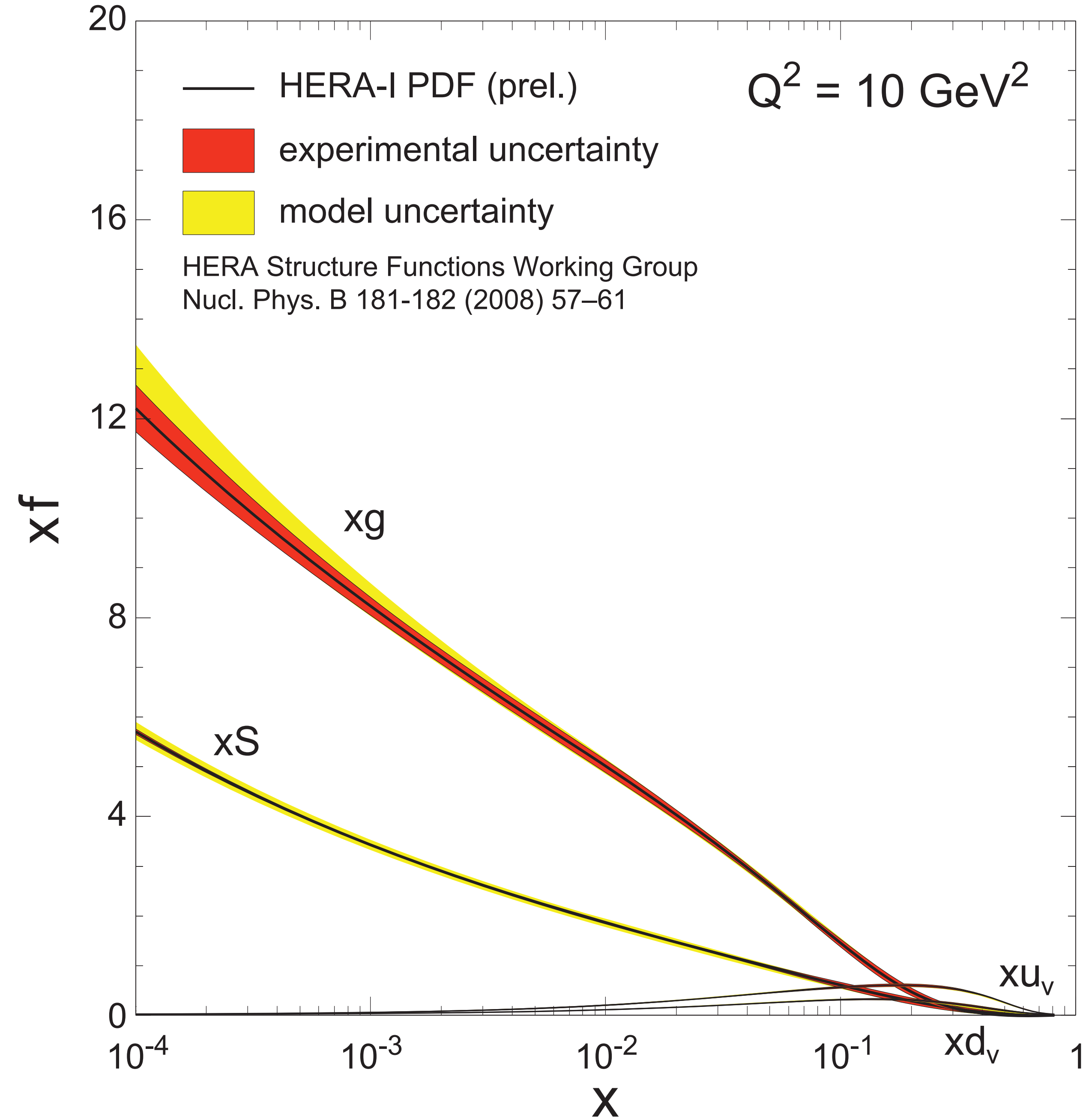
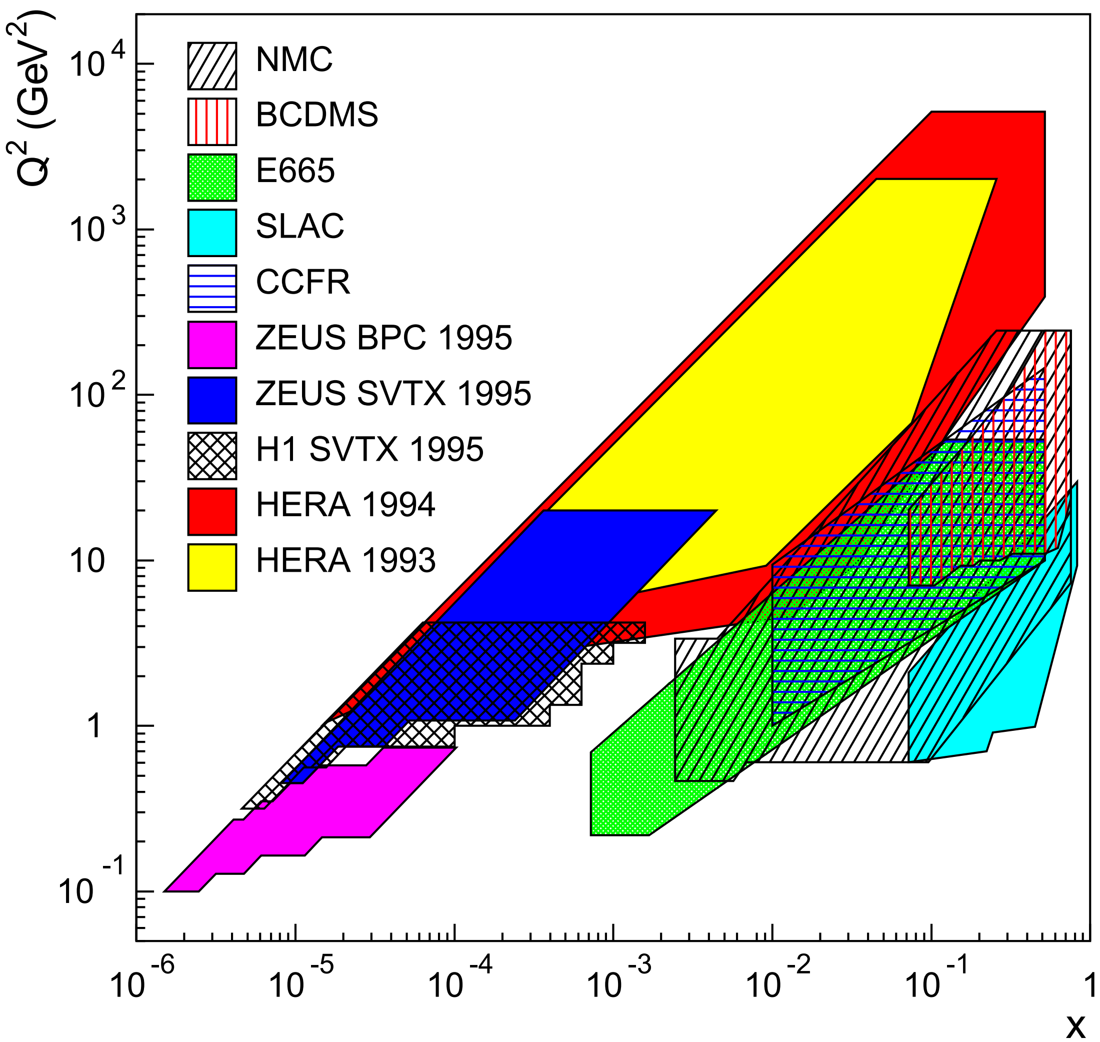
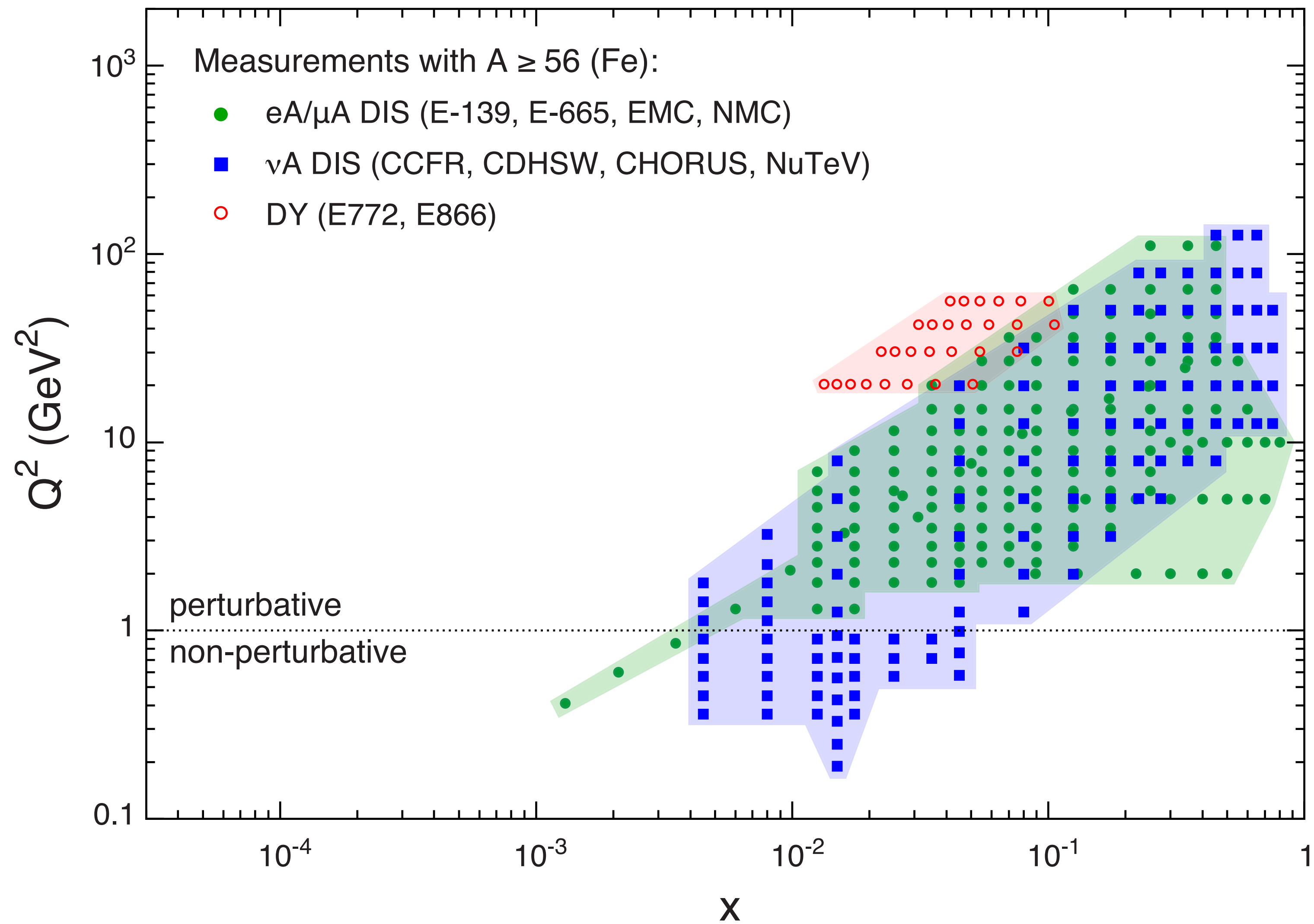


What do we know about the structure of nuclei?

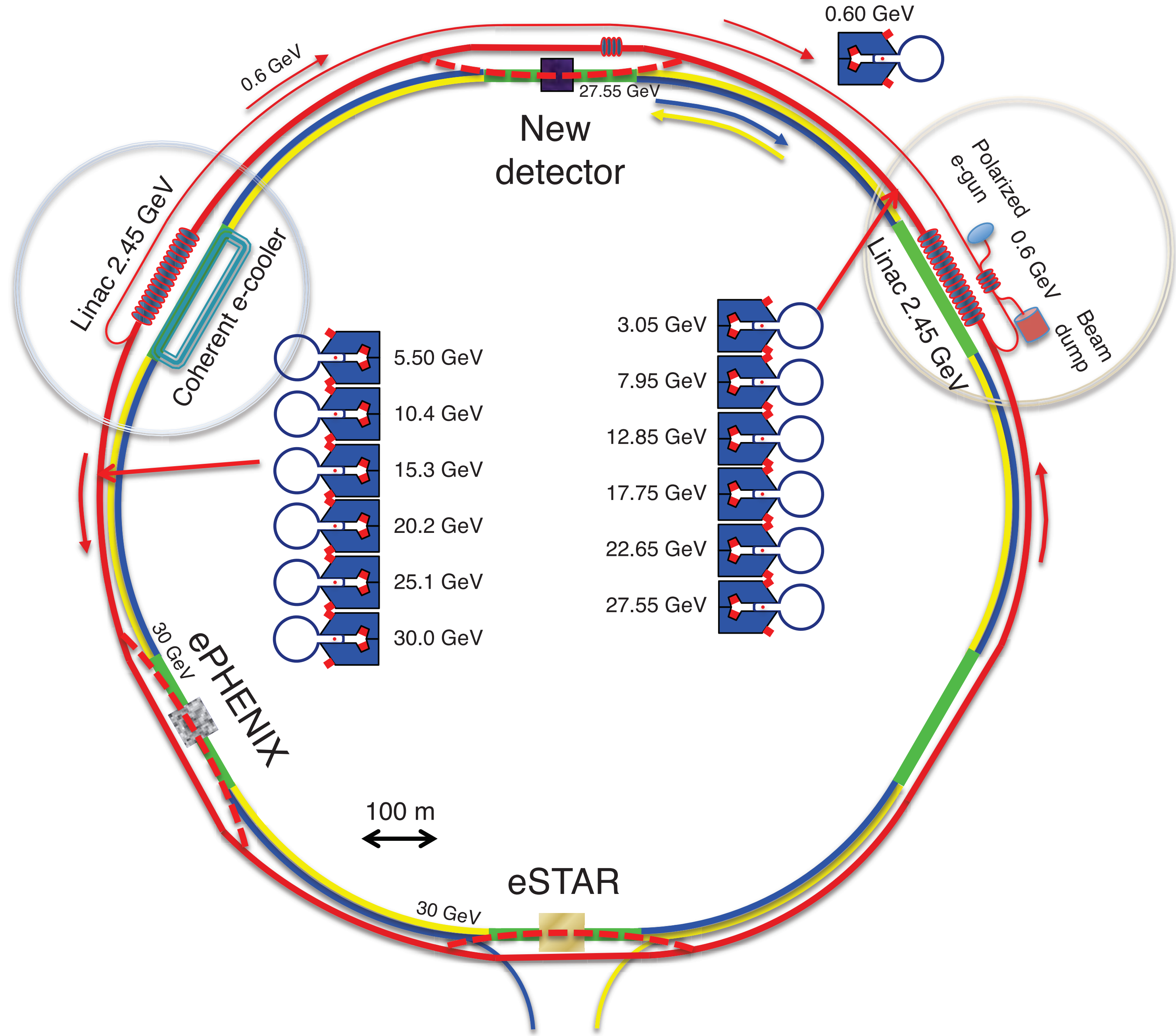




- e+p data covers large part of phase space
  - ➡ low x and large Q^2
- e+A data only a small fraction of this (e+A was a fixed target programme at HERA)
  - ➡ high-medium x and low Q^2

The eRHIC project

- eRHIC:
  - ➡ Utilises the RHIC ion beams
  - ➡ Two 2.45 GeV Energy Recovery Linacs (ERLs) accelerate the e⁻ beam
    - 6 separate rings accelerate the e⁻ up to a maximum energy of 30 GeV
  - ➡ 2-stage approach
    - Stage 1: e⁻ 5-10 GeV
    - Stage 2: e⁻ 20-30 GeV
  - ➡ Space for new detector at IP12
    - Possibilities for collisions in current STAR and PHENIX IPs



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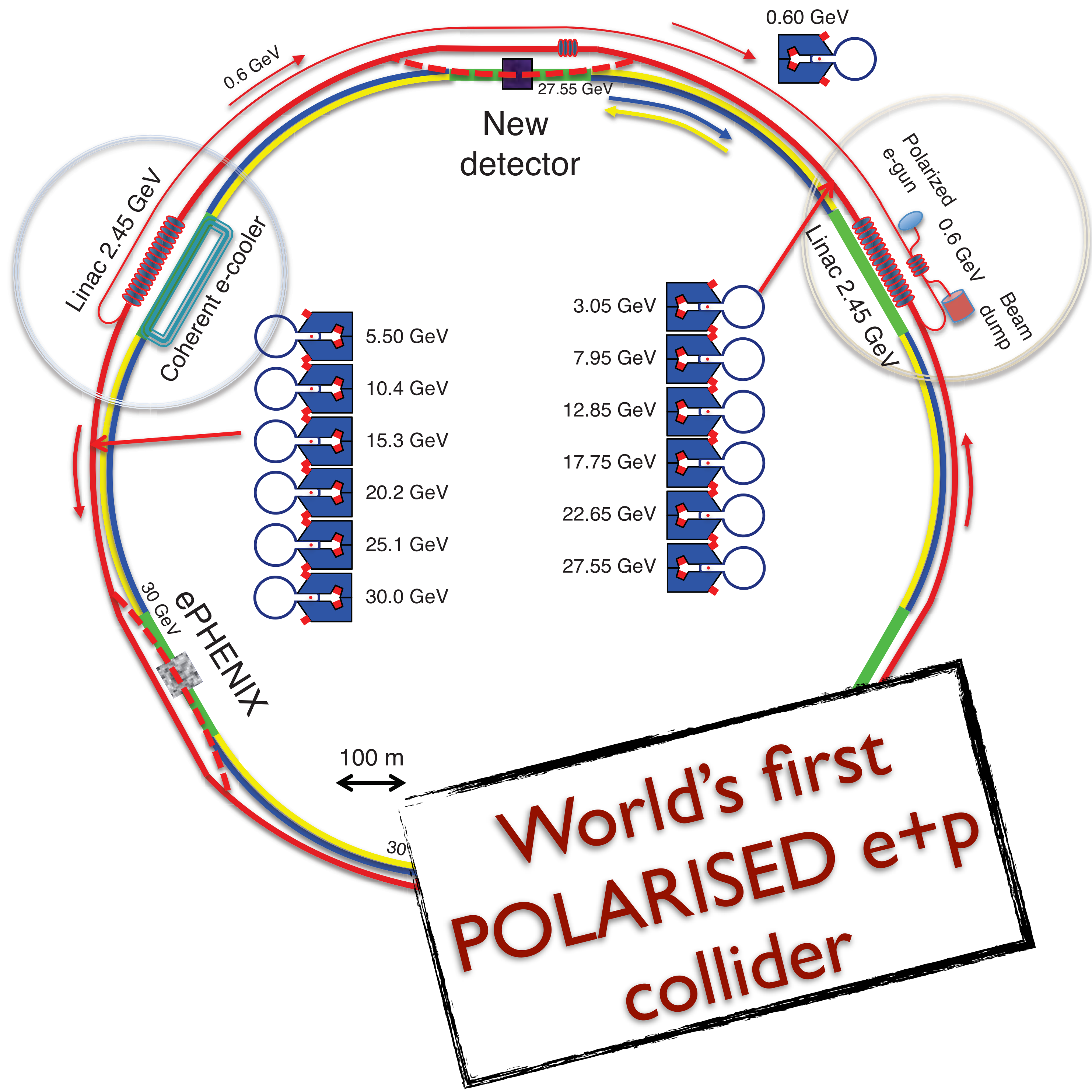

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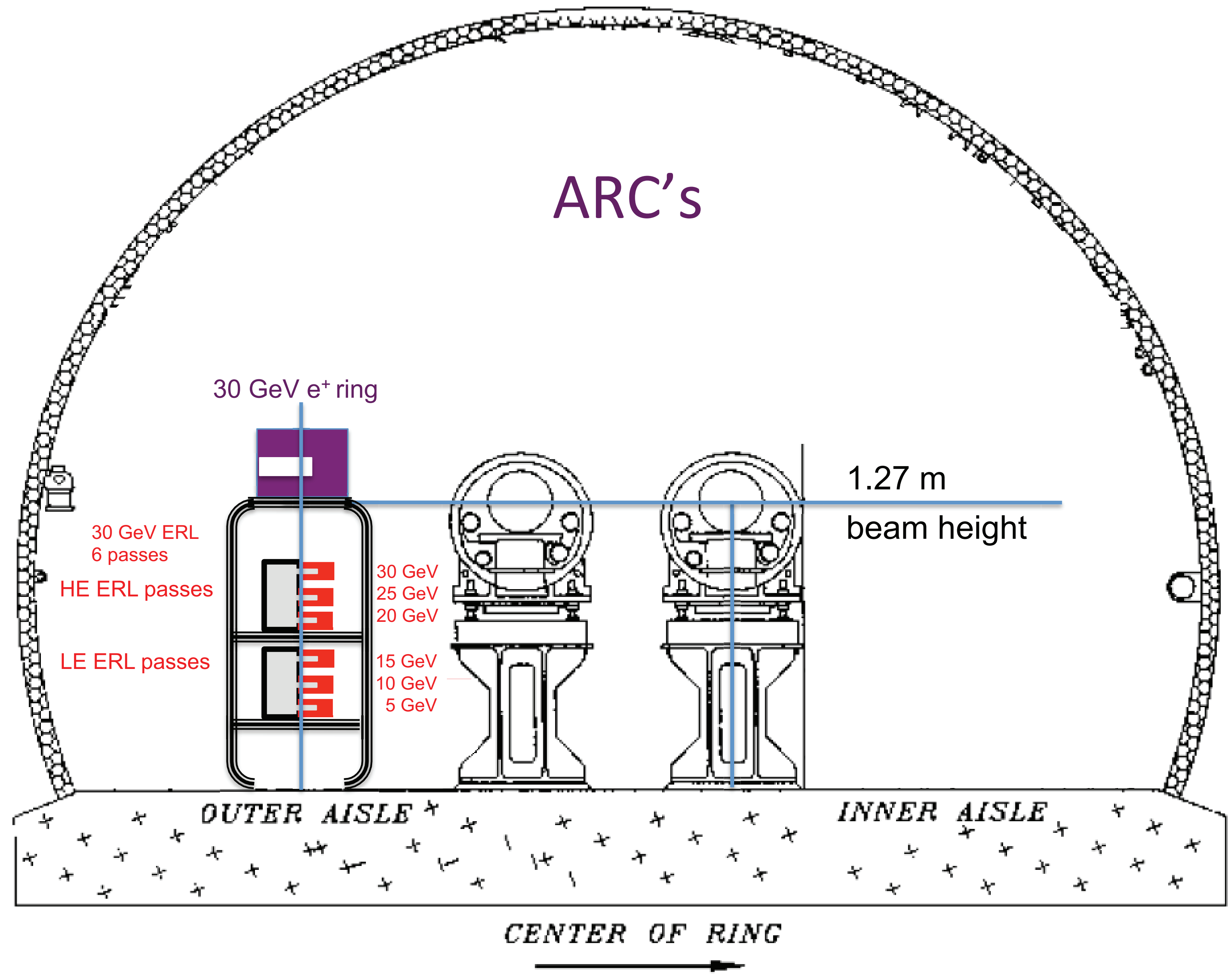

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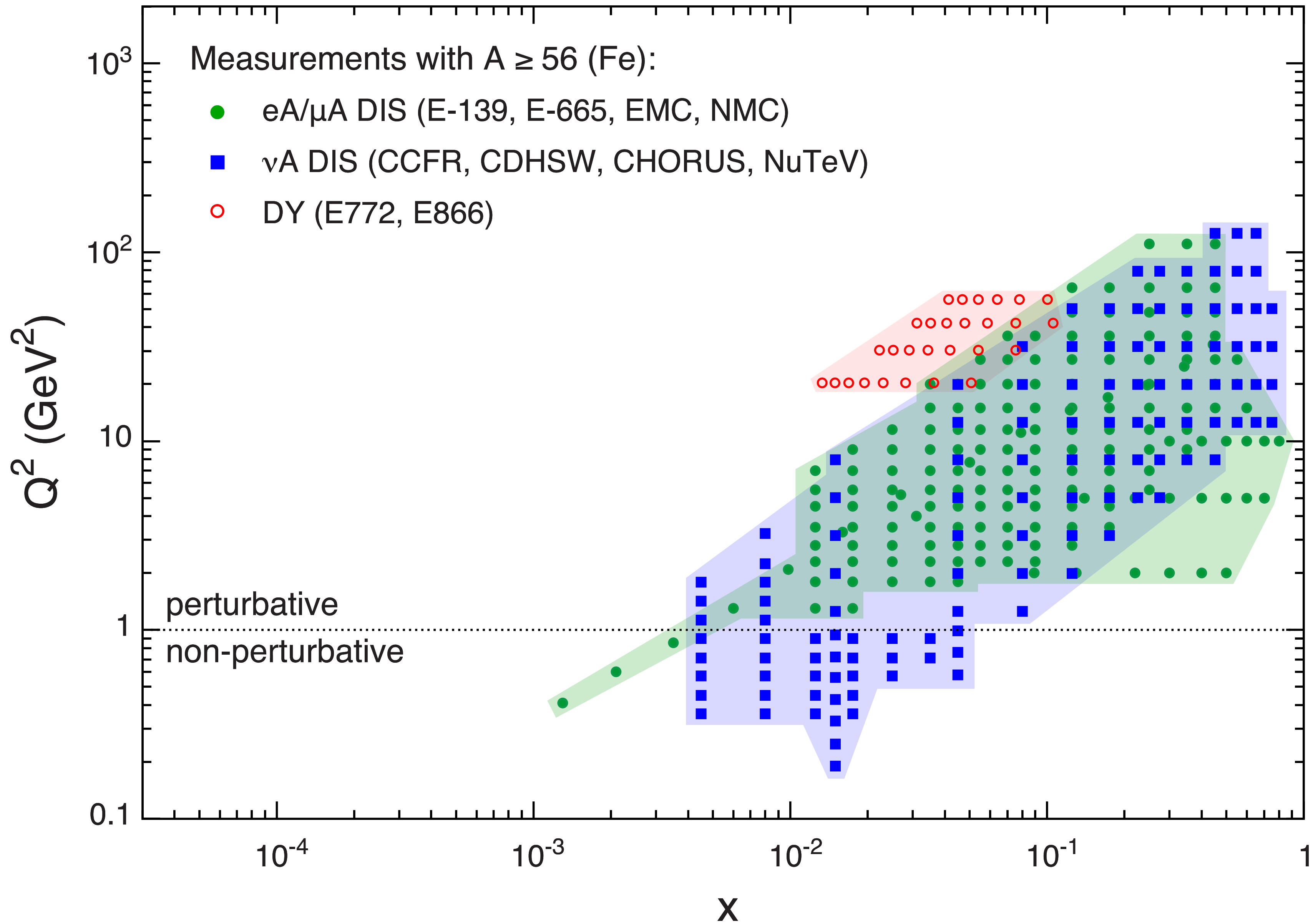

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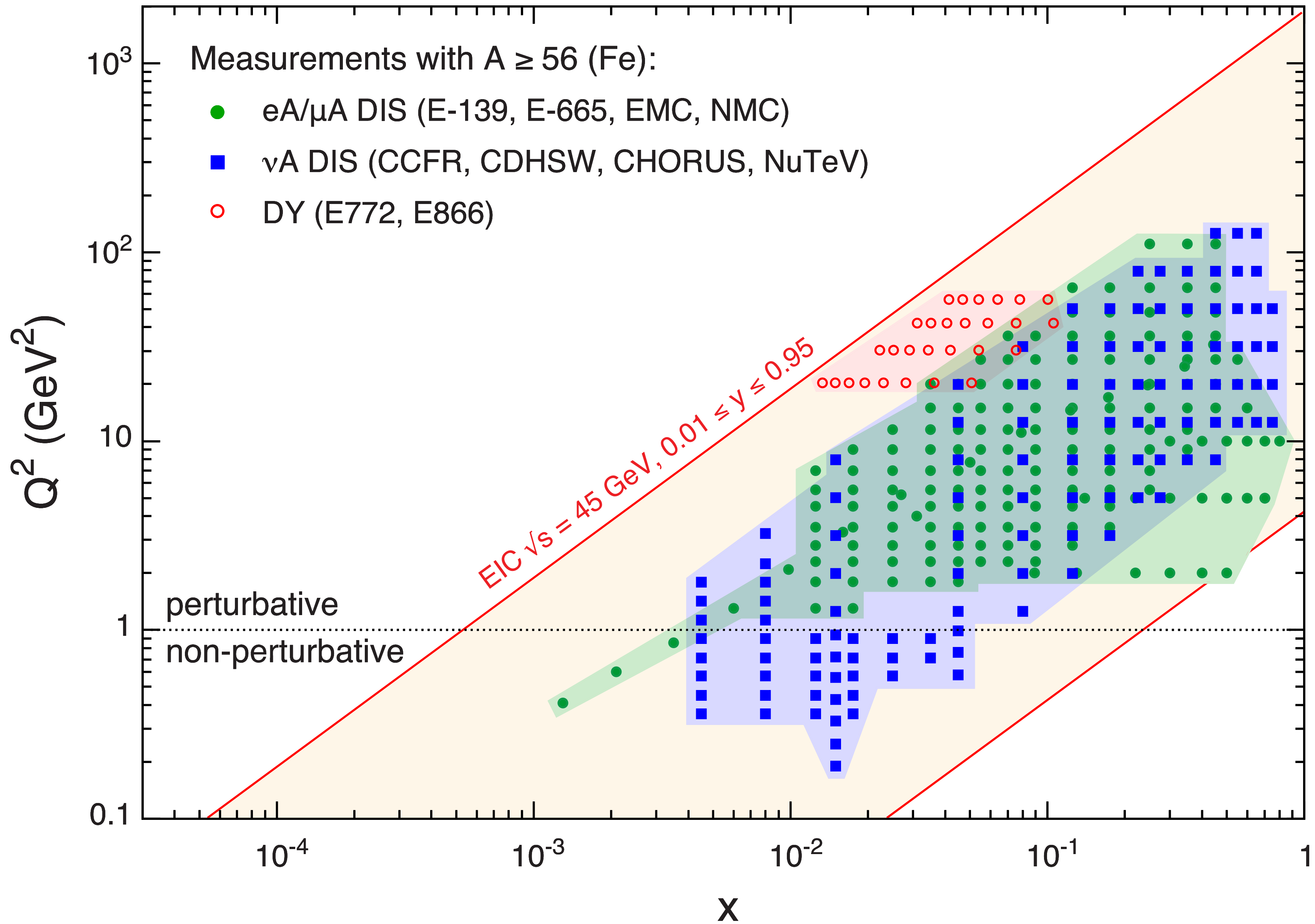

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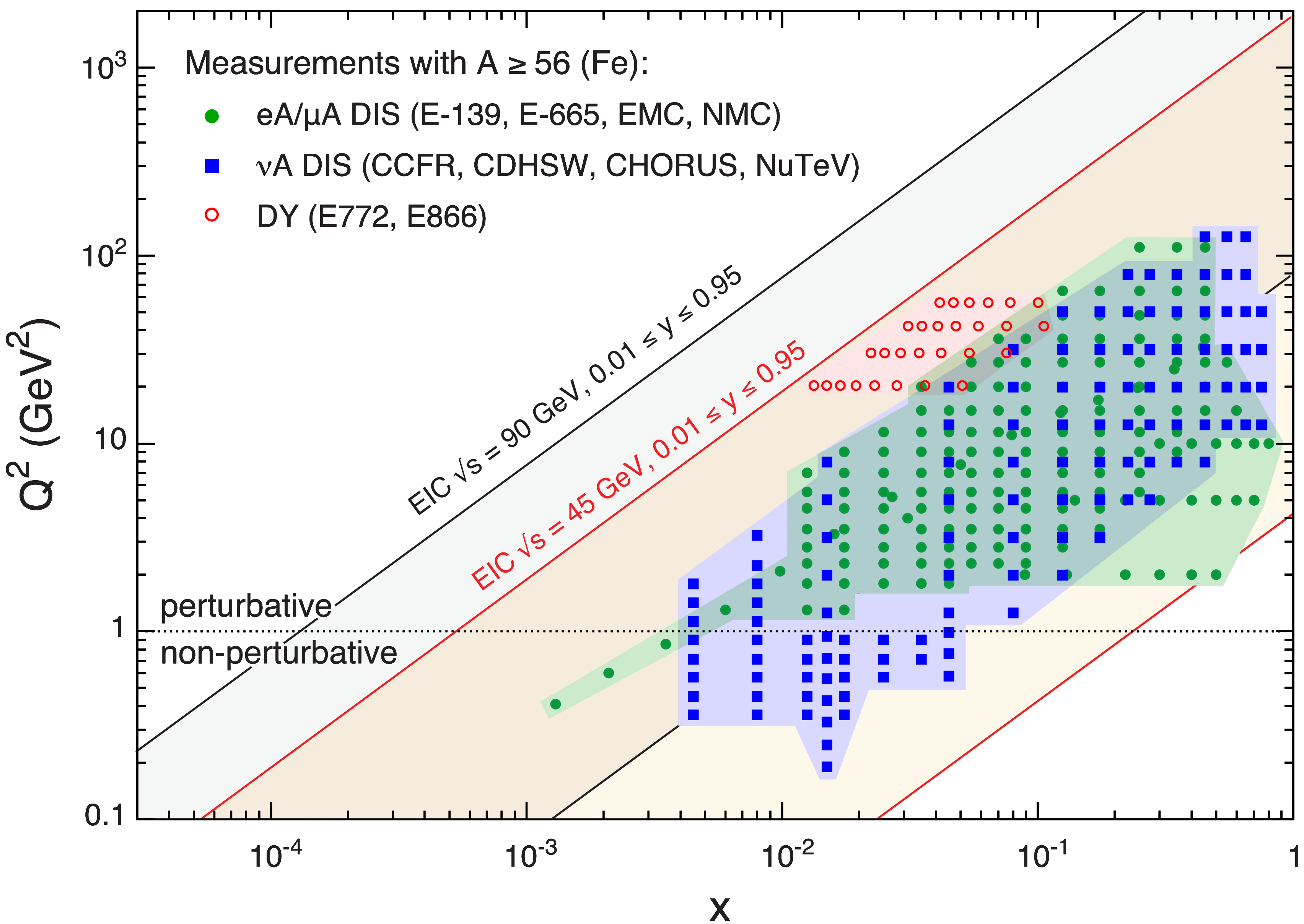

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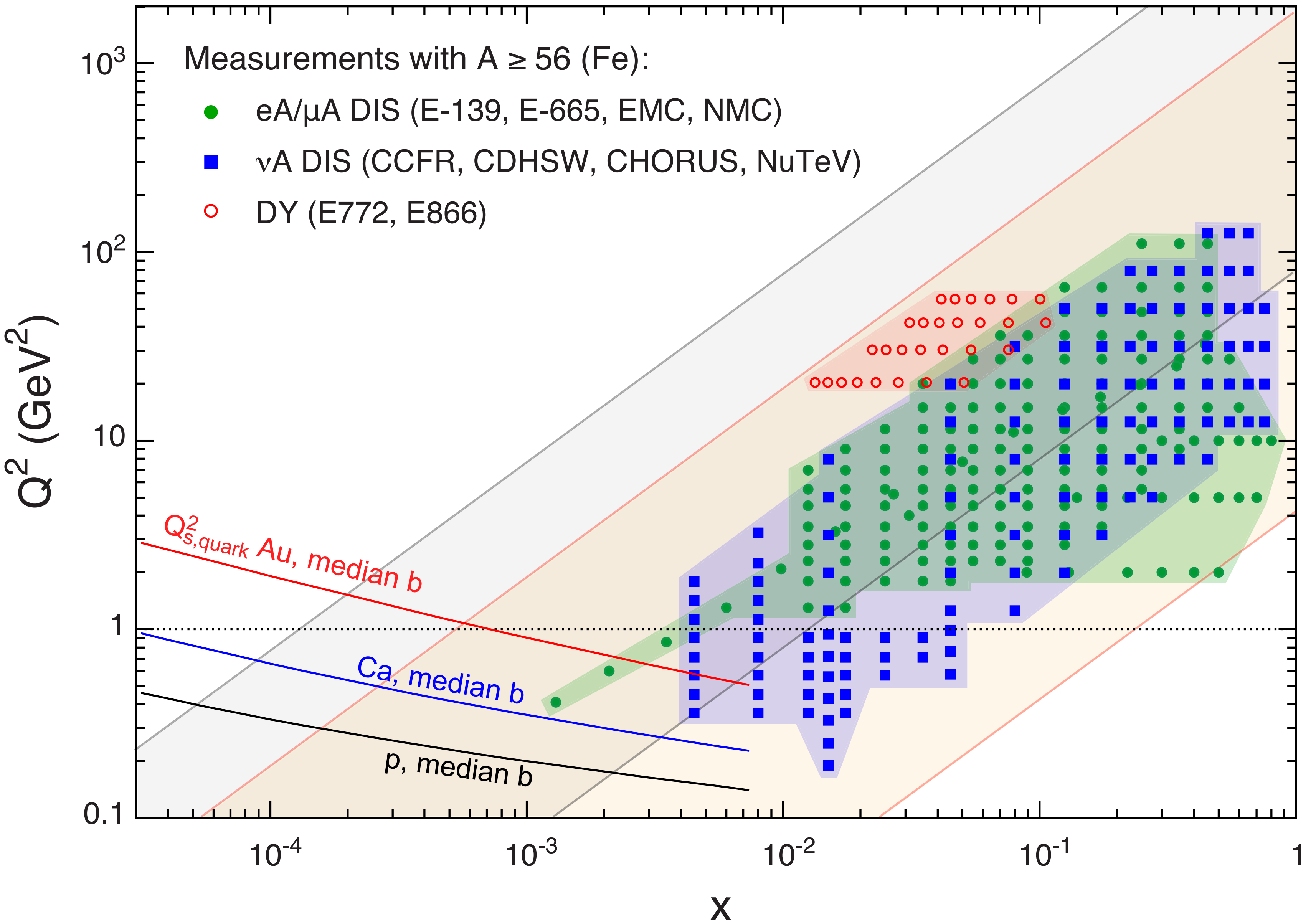

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- Can we experimentally find the evidence of non-linear QCD evolution in high-energy scattering off nuclei?
- What is the momentum and spatial distribution of gluons and sea quarks in nuclei?
- Are there strong colour (quark and gluon density) fluctuations inside of a large nucleus? How does the nucleus respond to the propagation of a colour charge through it?

Important 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
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
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

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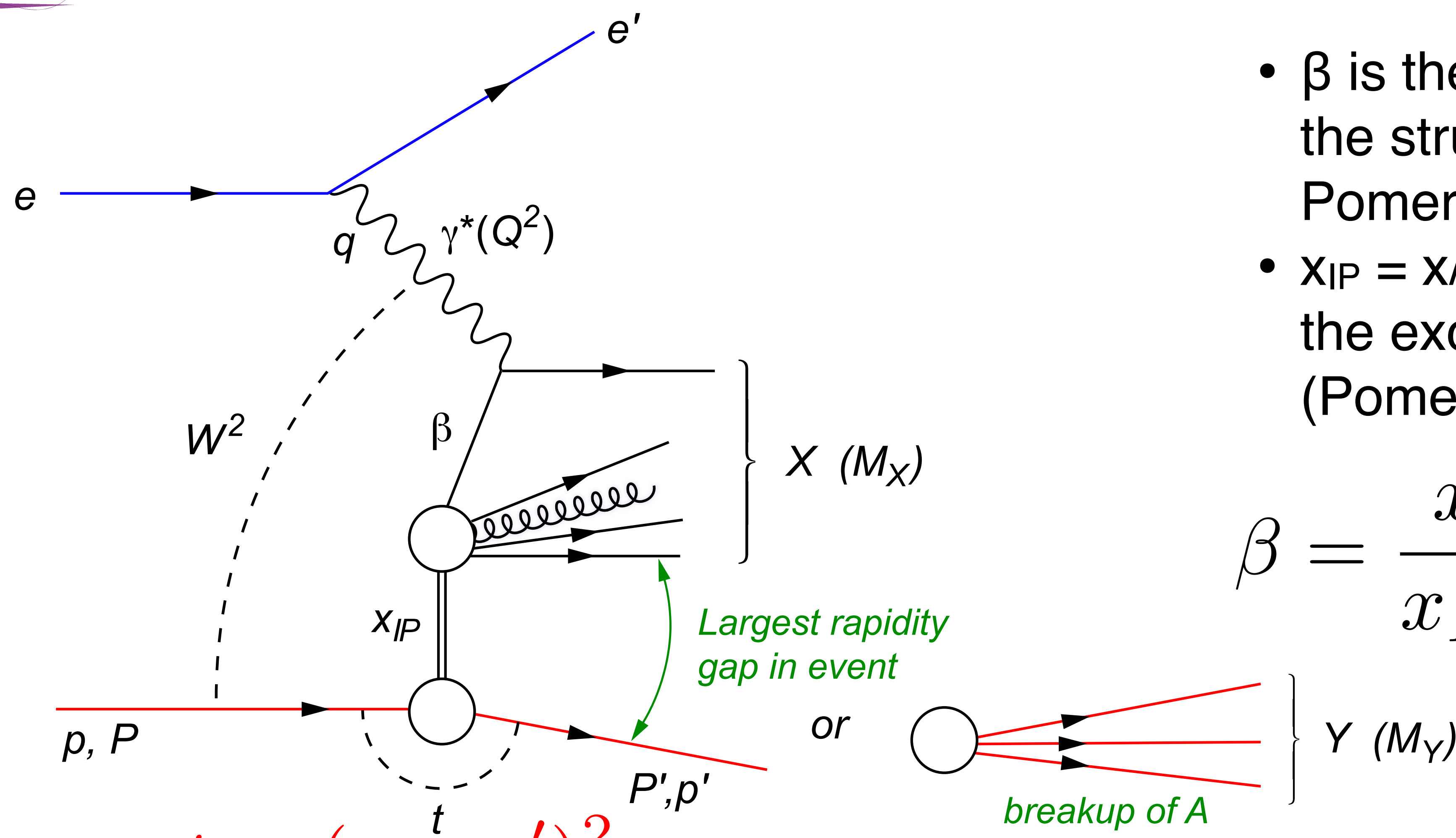
Hard Diffraction



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

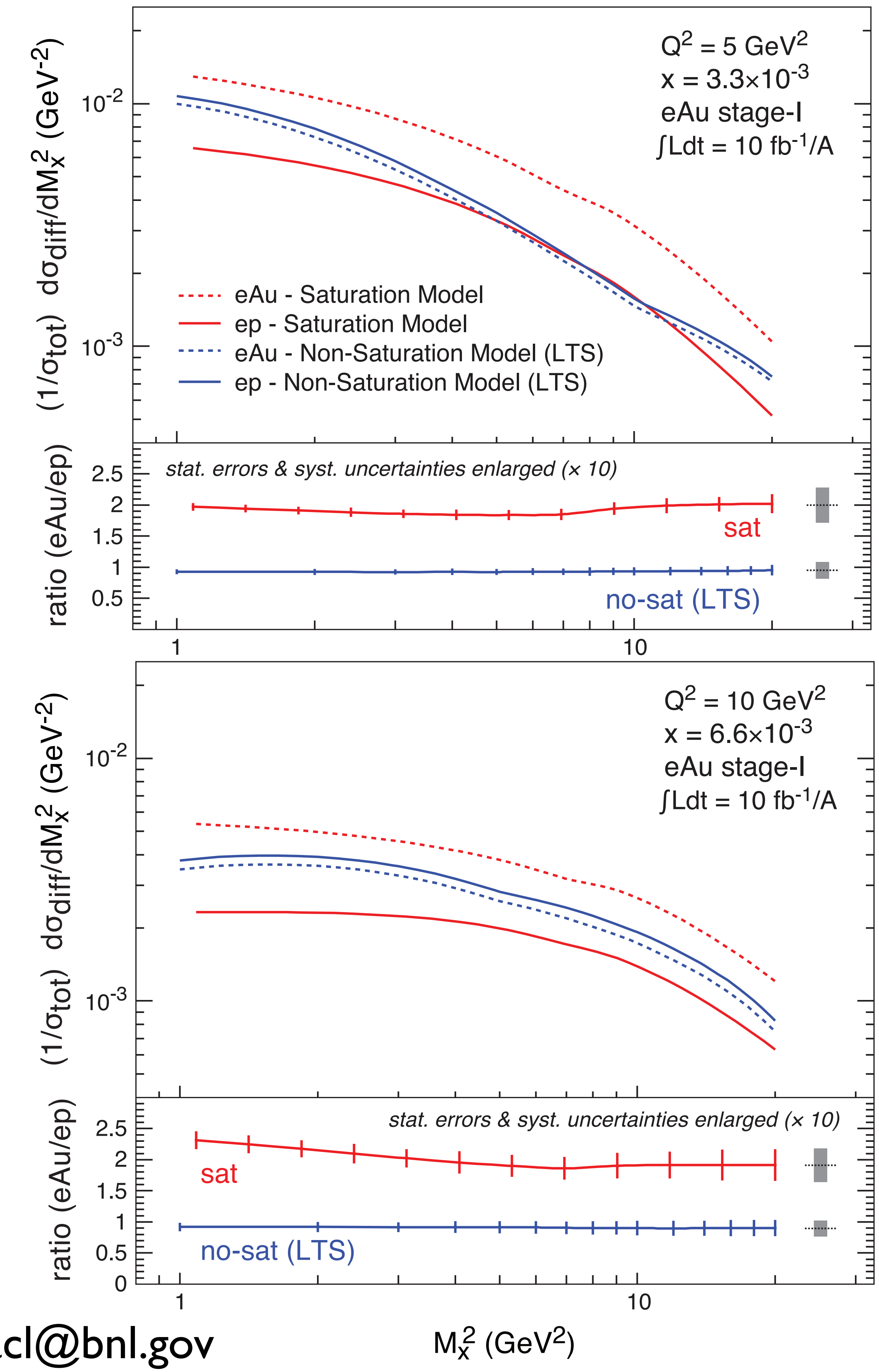
- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

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

- 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)

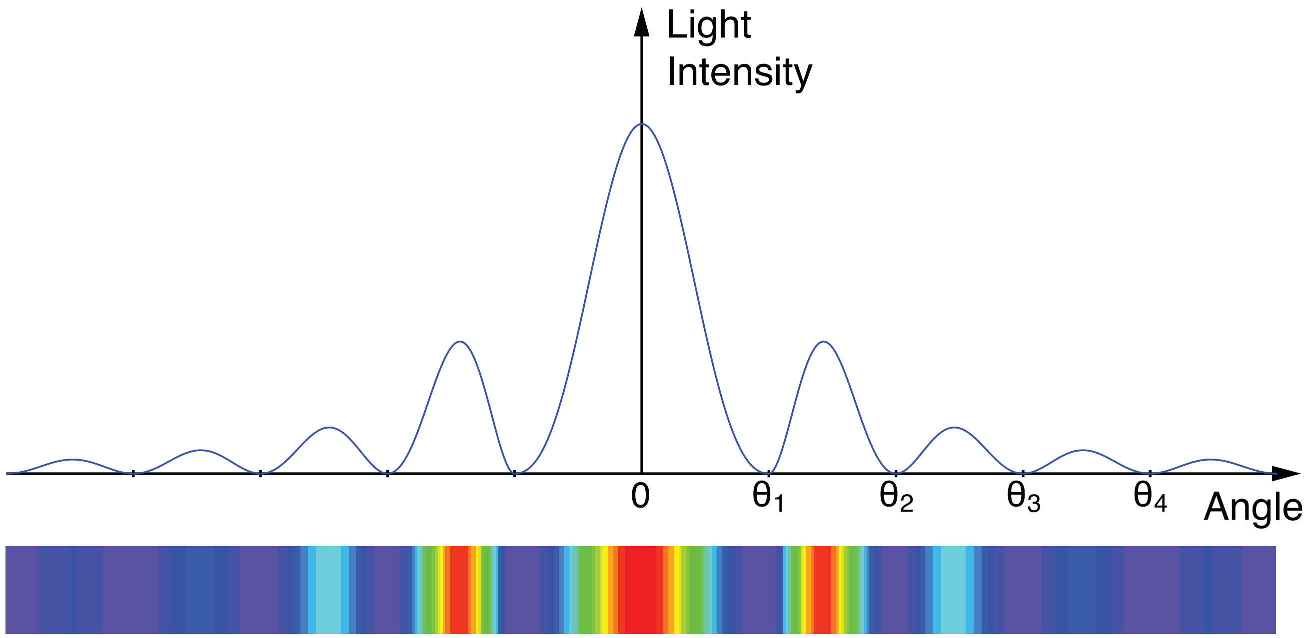
Diffractive cross-sections: Saturation vs Non-Sat

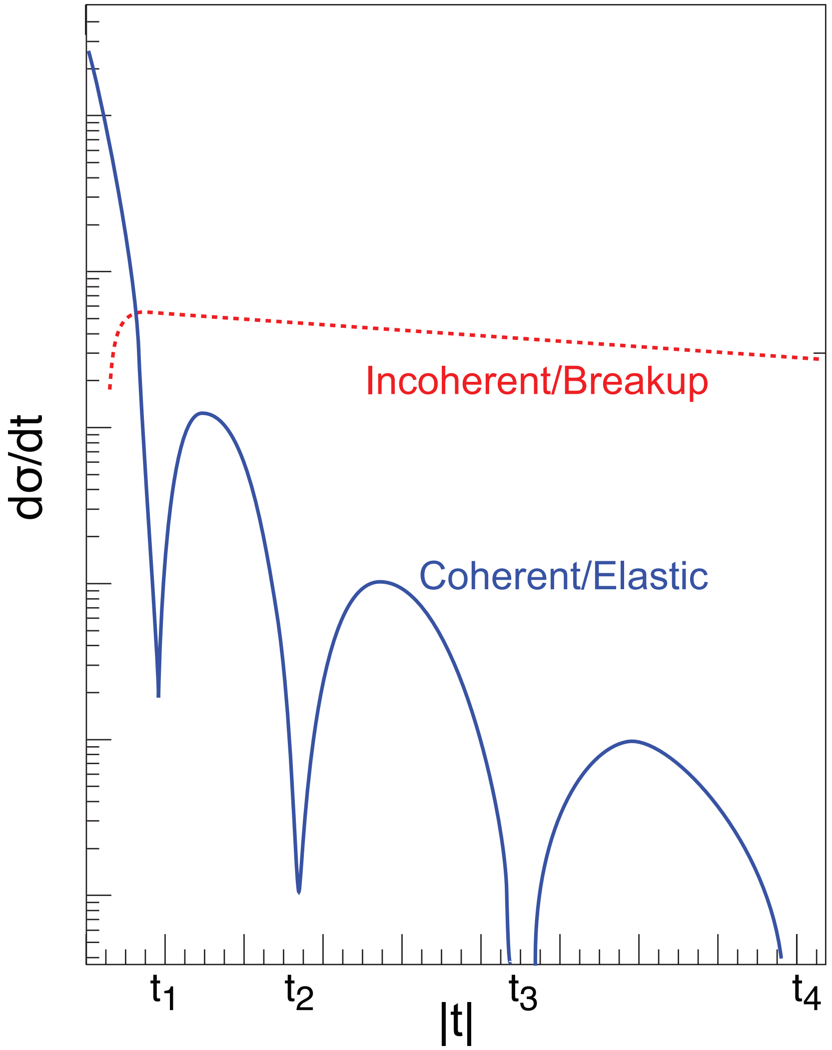
- Ratio of diffractive to total cross-sections between saturation model (Marquet) and Leading-Twist Shadowing (Guzey, Strickman).
  - ➡ Very little difference for LTS between e+p and e+Au, independent of Q^2
  - ➡ For saturation model, e+Au ~ 2*e+p, again independent of Q^2
  - ➡ Simulated error bars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



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

➡ $\theta_i \sim 1/(kR)$

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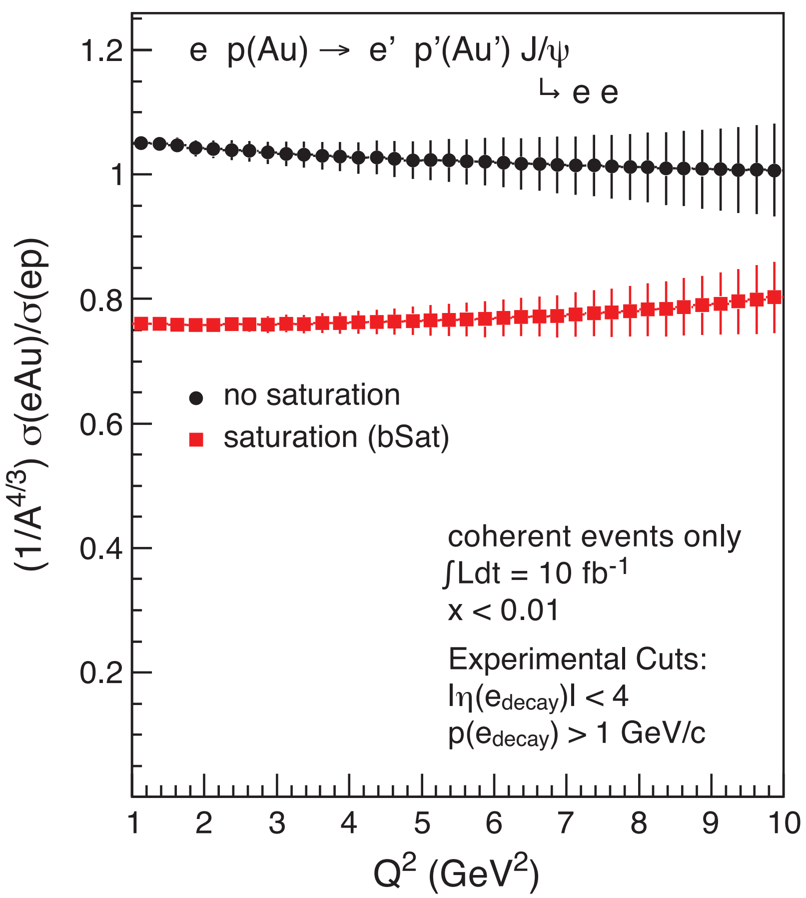
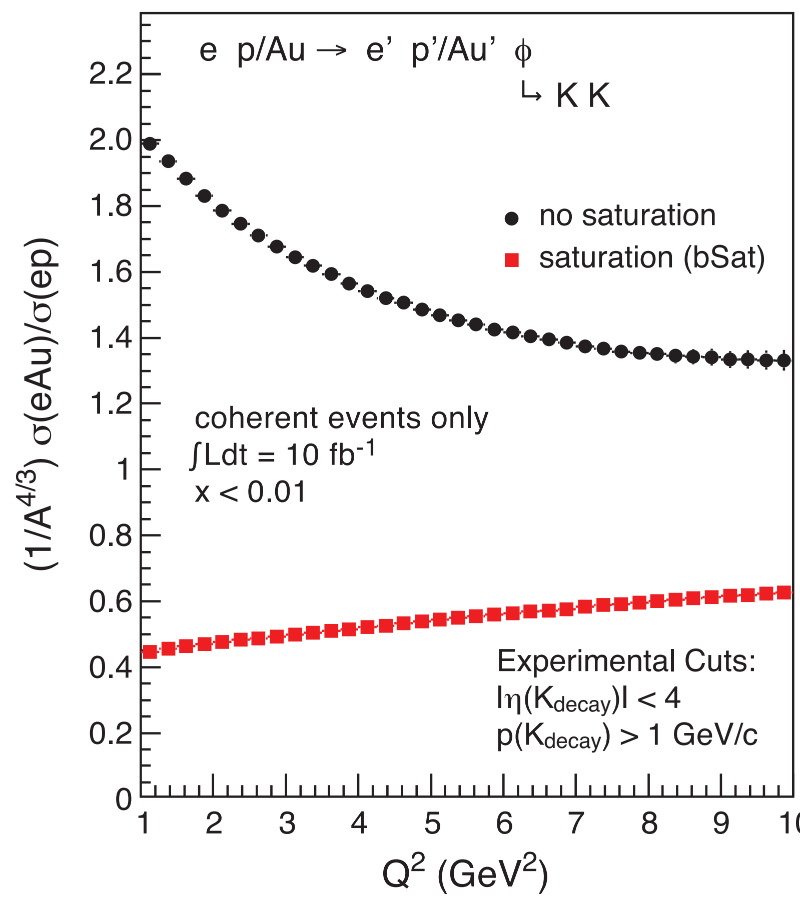
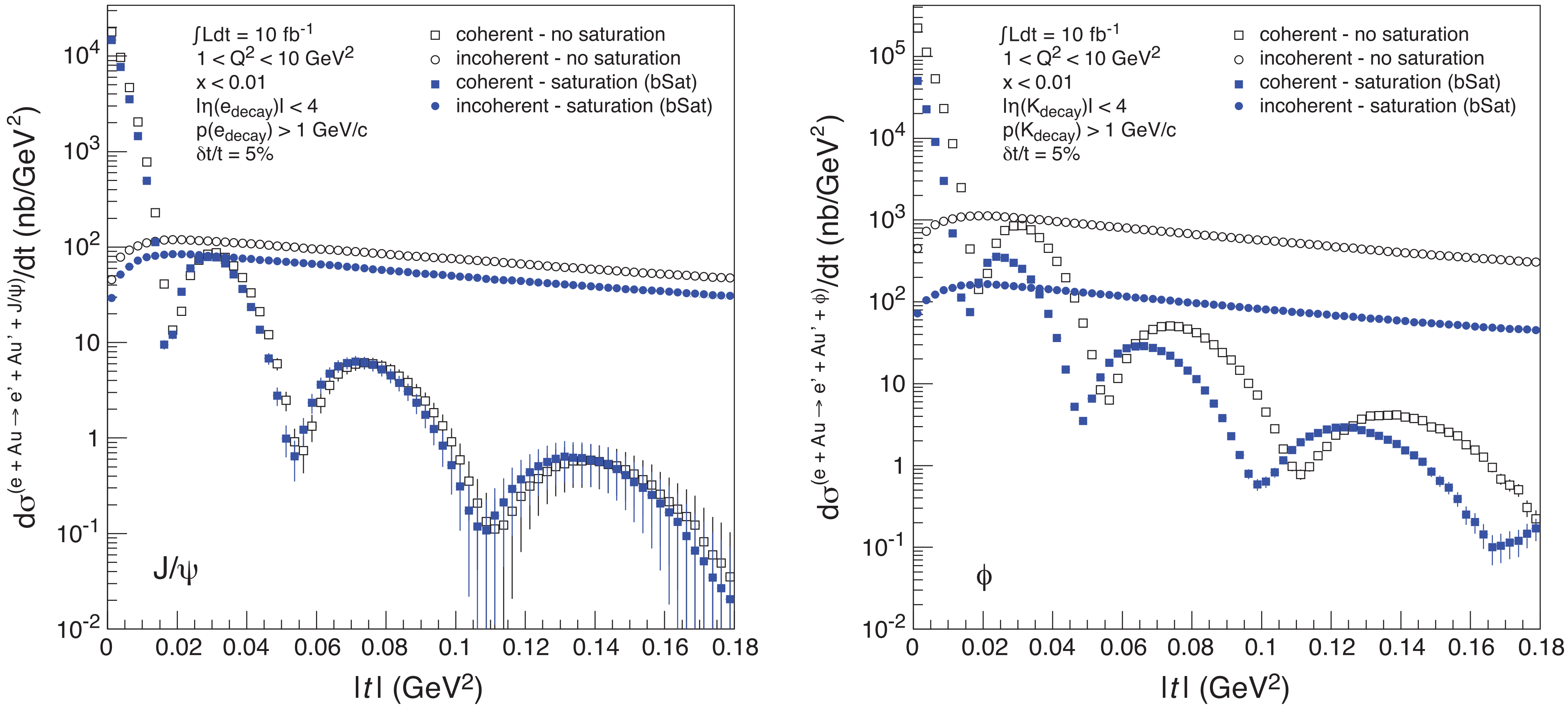




- Diffraction with final state VM - plots from Sartre event generator
  - ➡ Clean - only one new final state particle generated
  - ➡ Unambiguously identified via the presence of a rapidity gap
  - ➡ J/ψ less sensitive to saturation effects that phi
    - expected as ϕ has larger wave function

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

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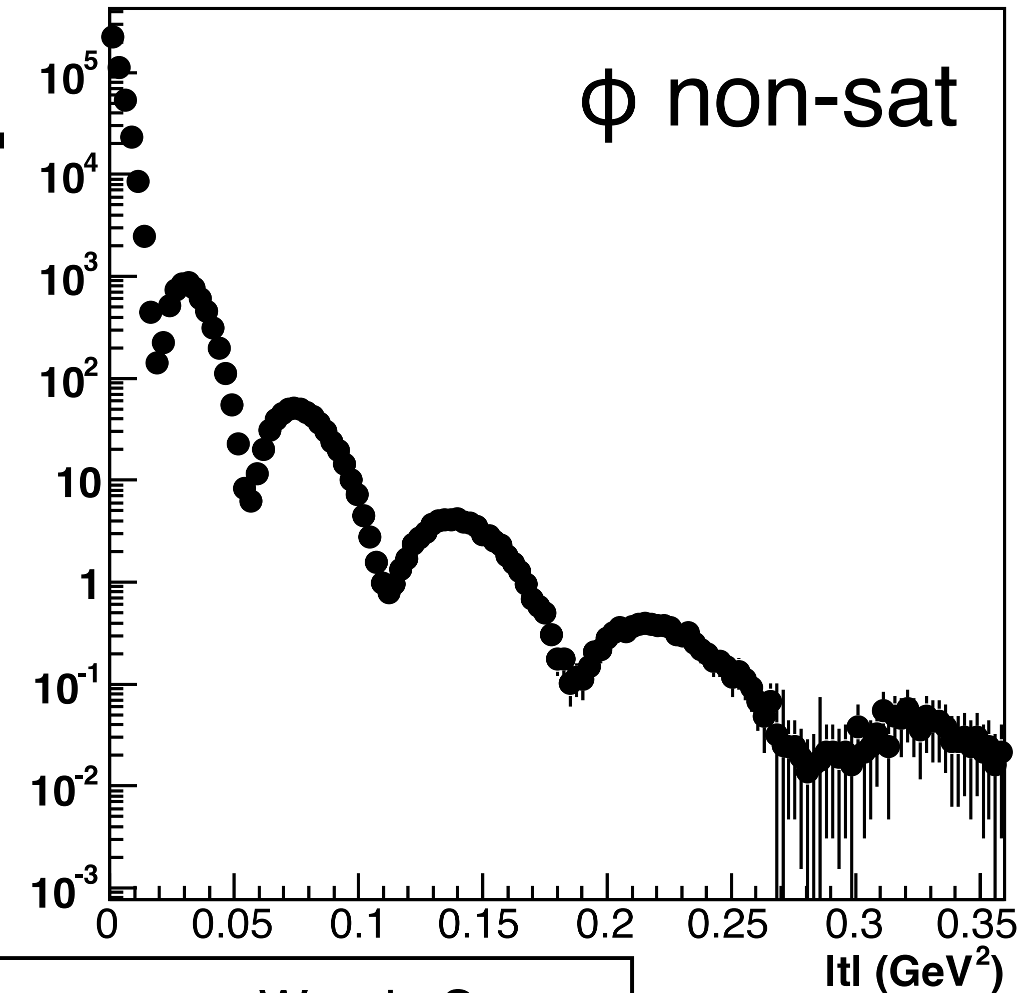
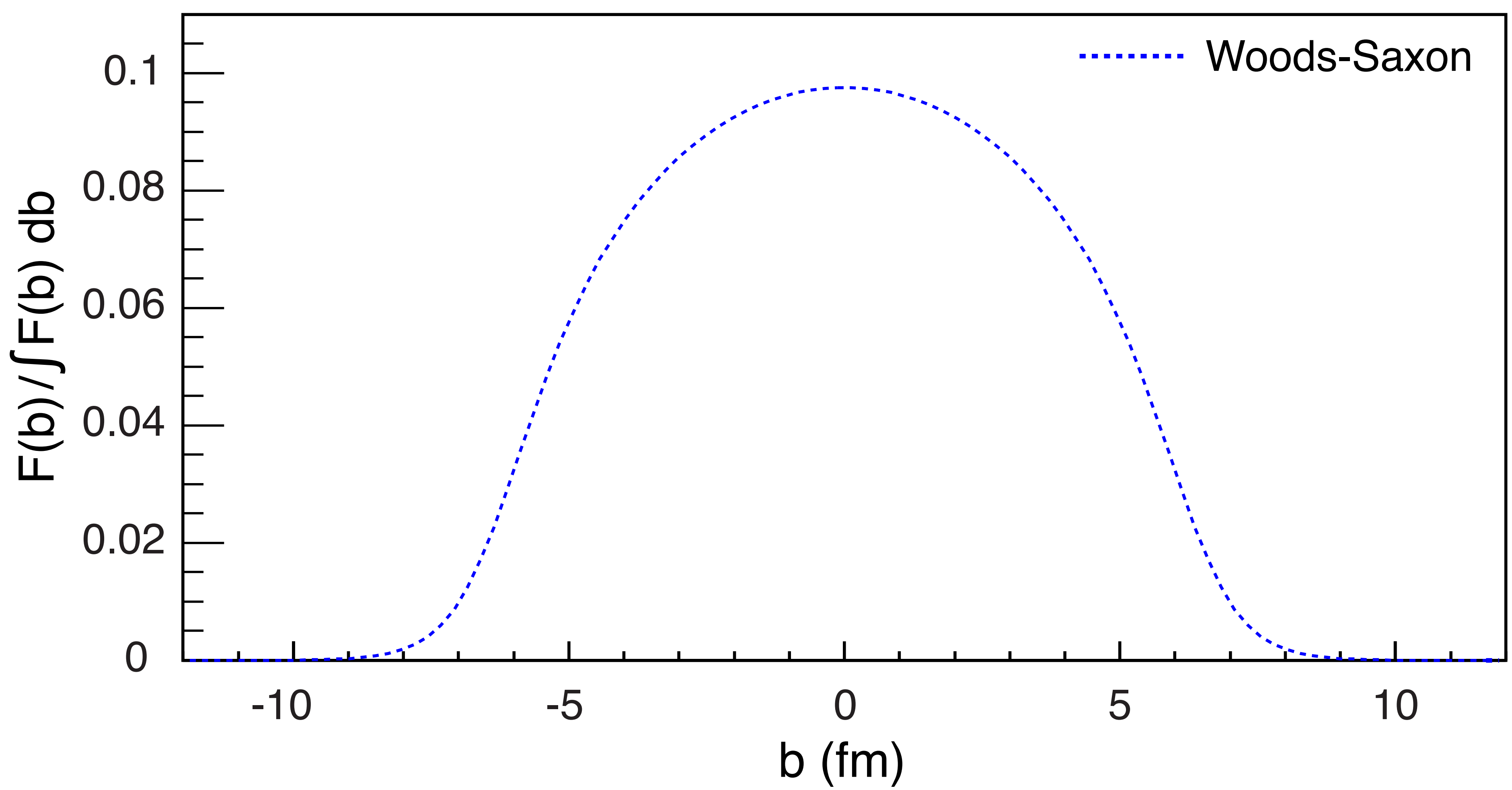


- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

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

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



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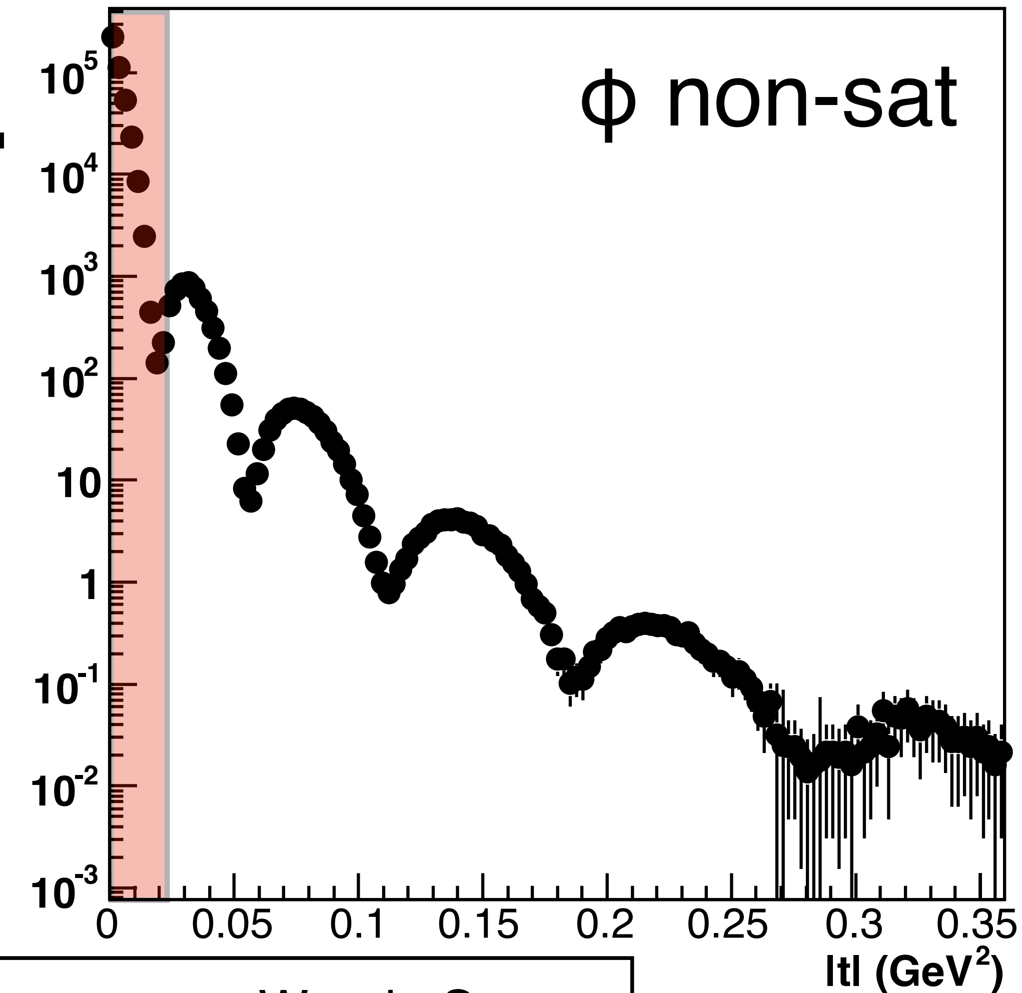

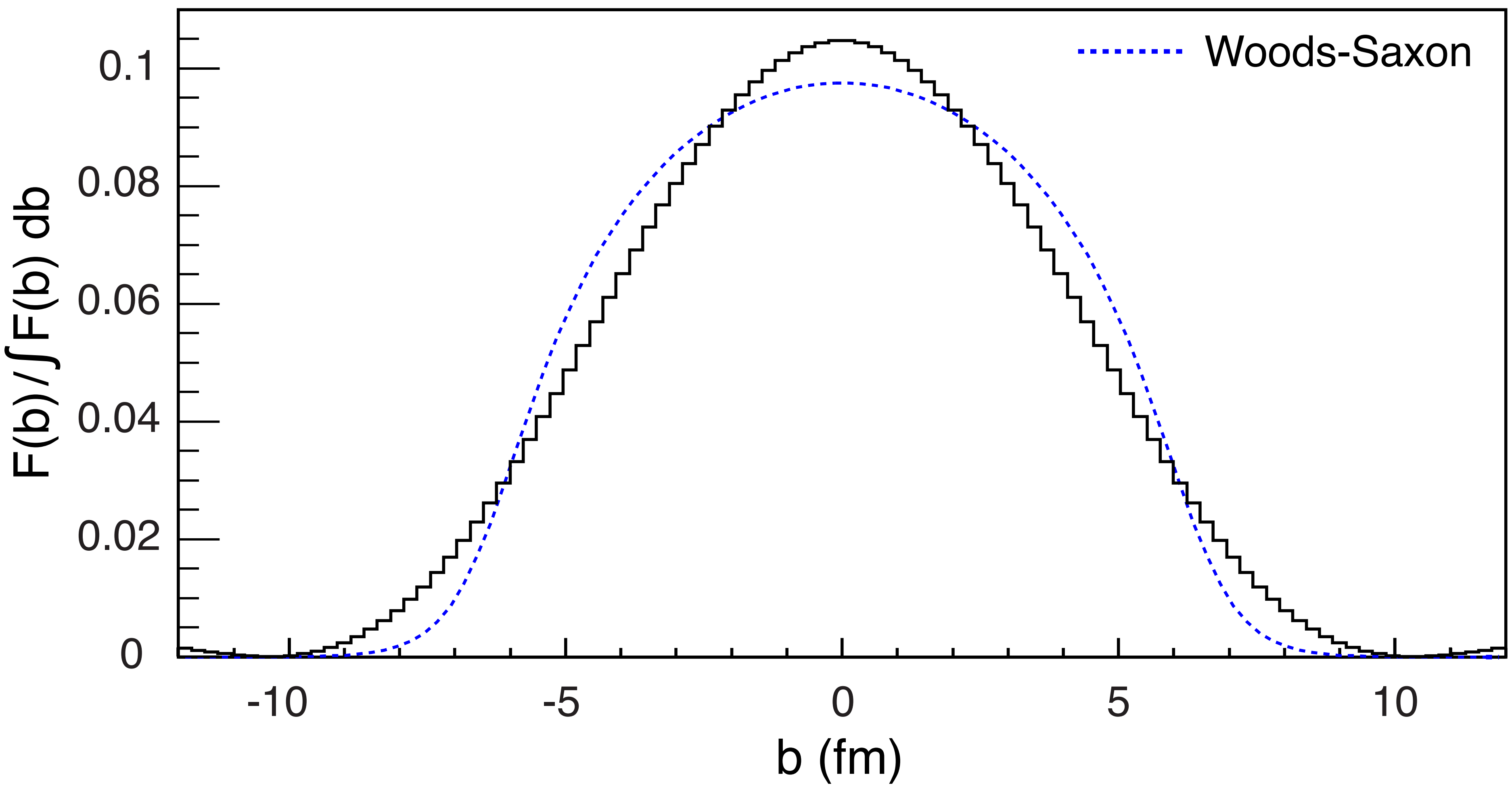

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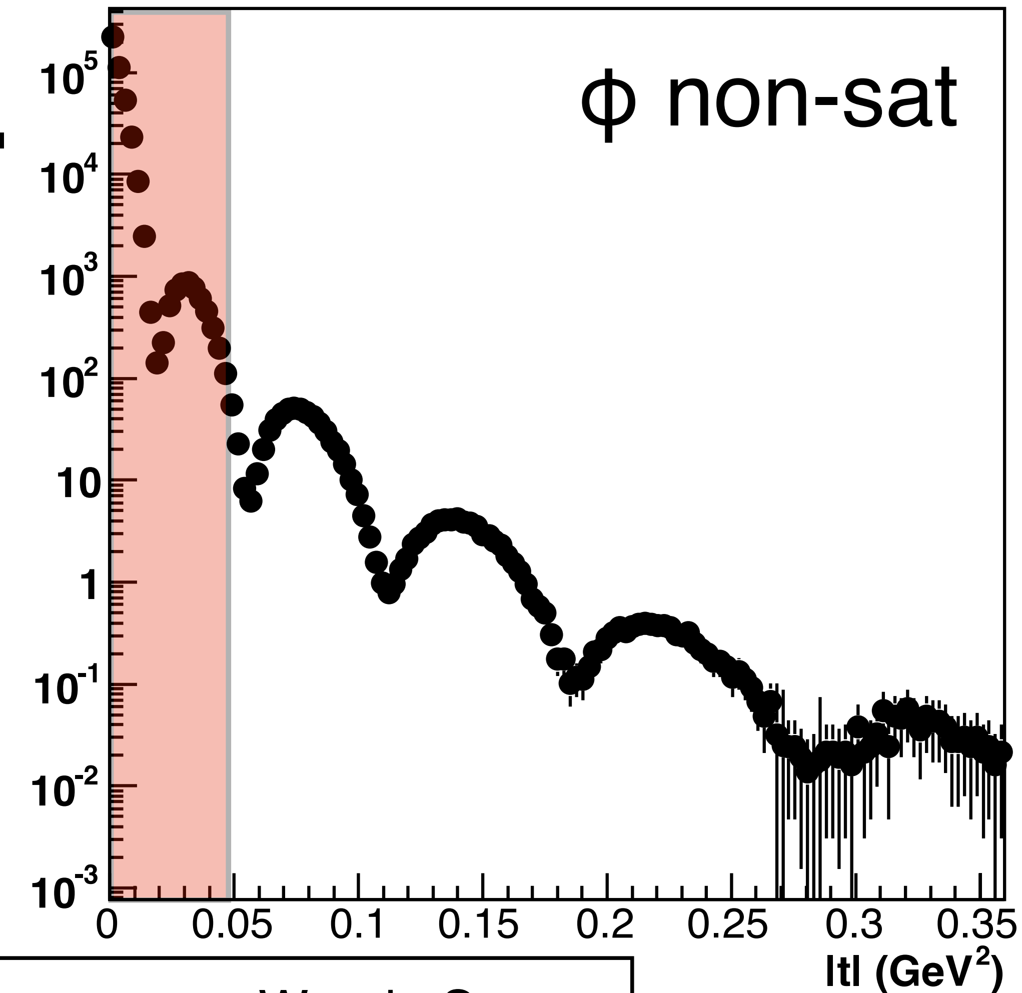

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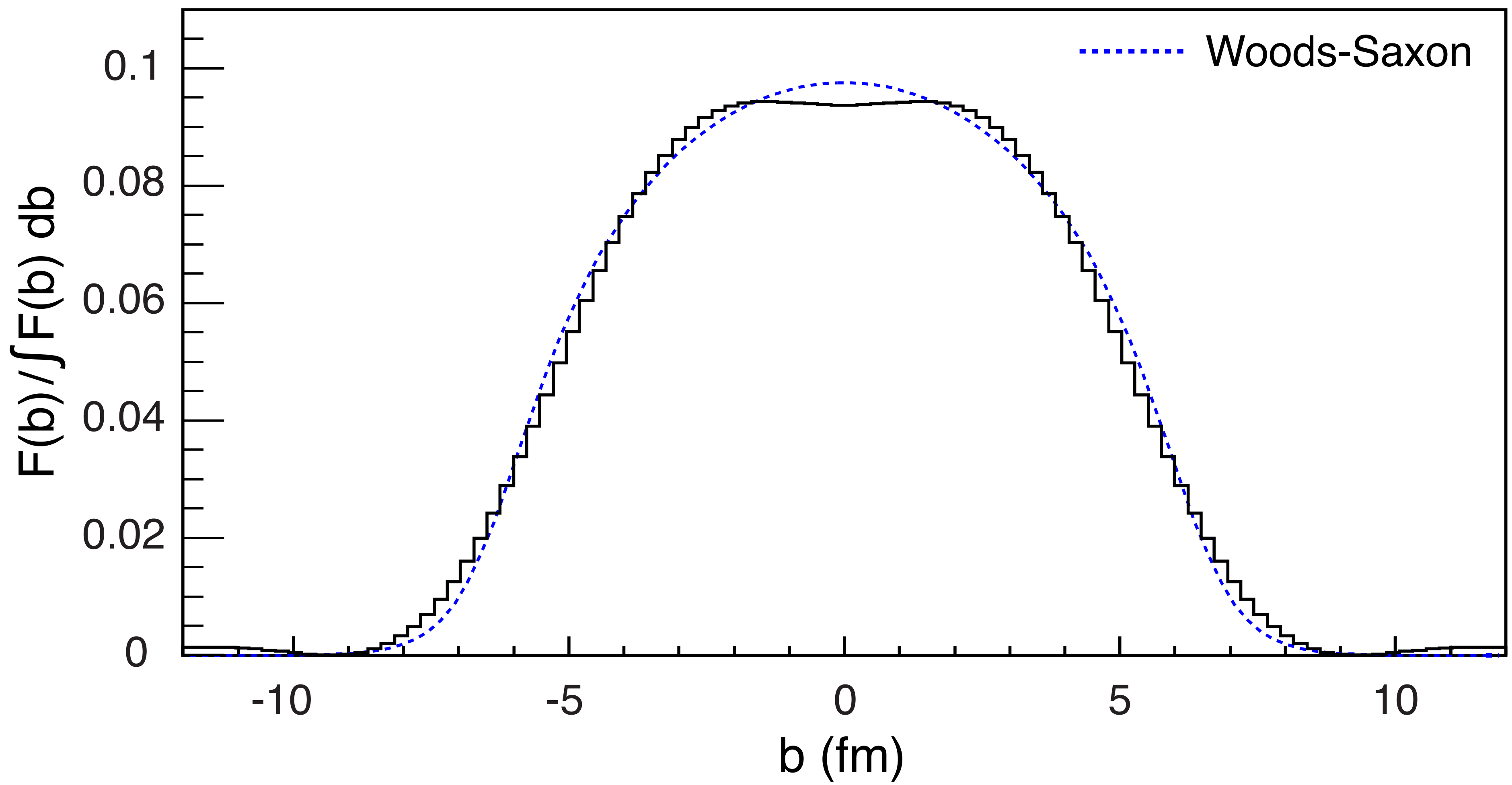

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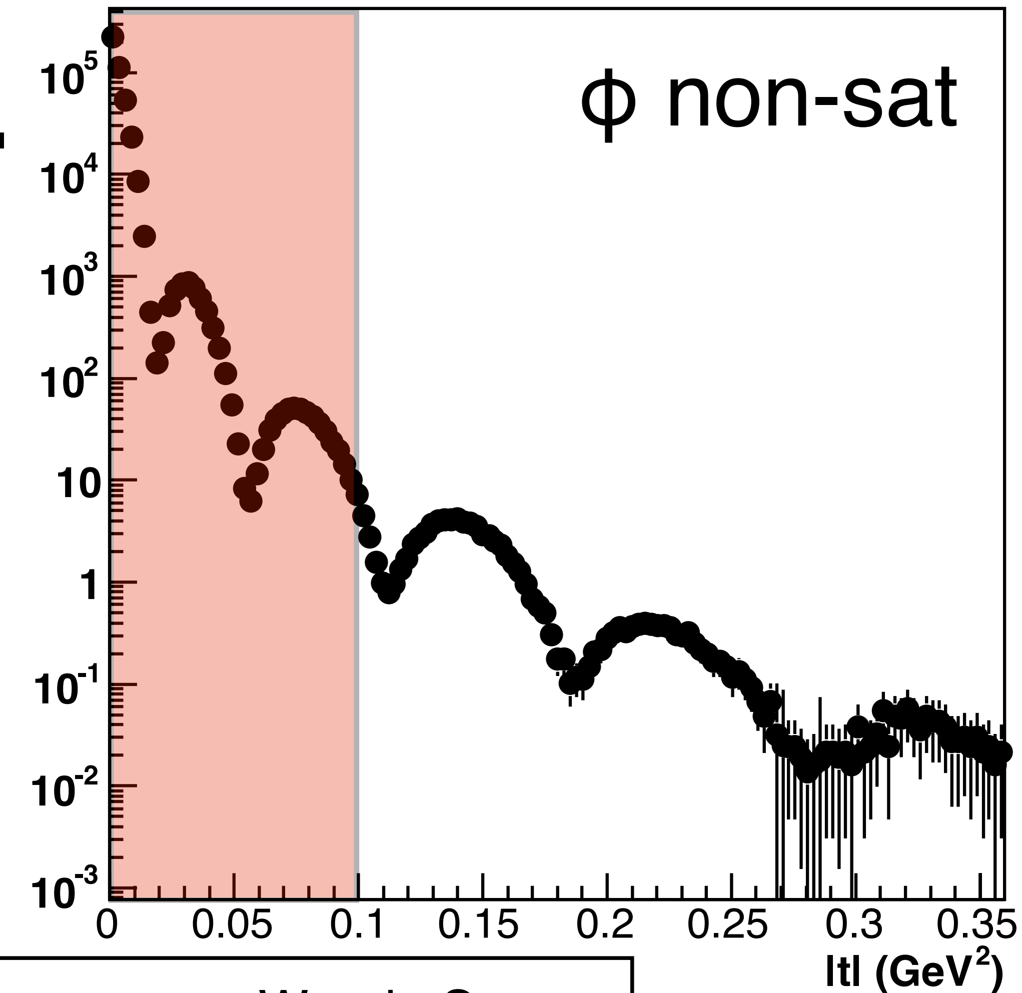

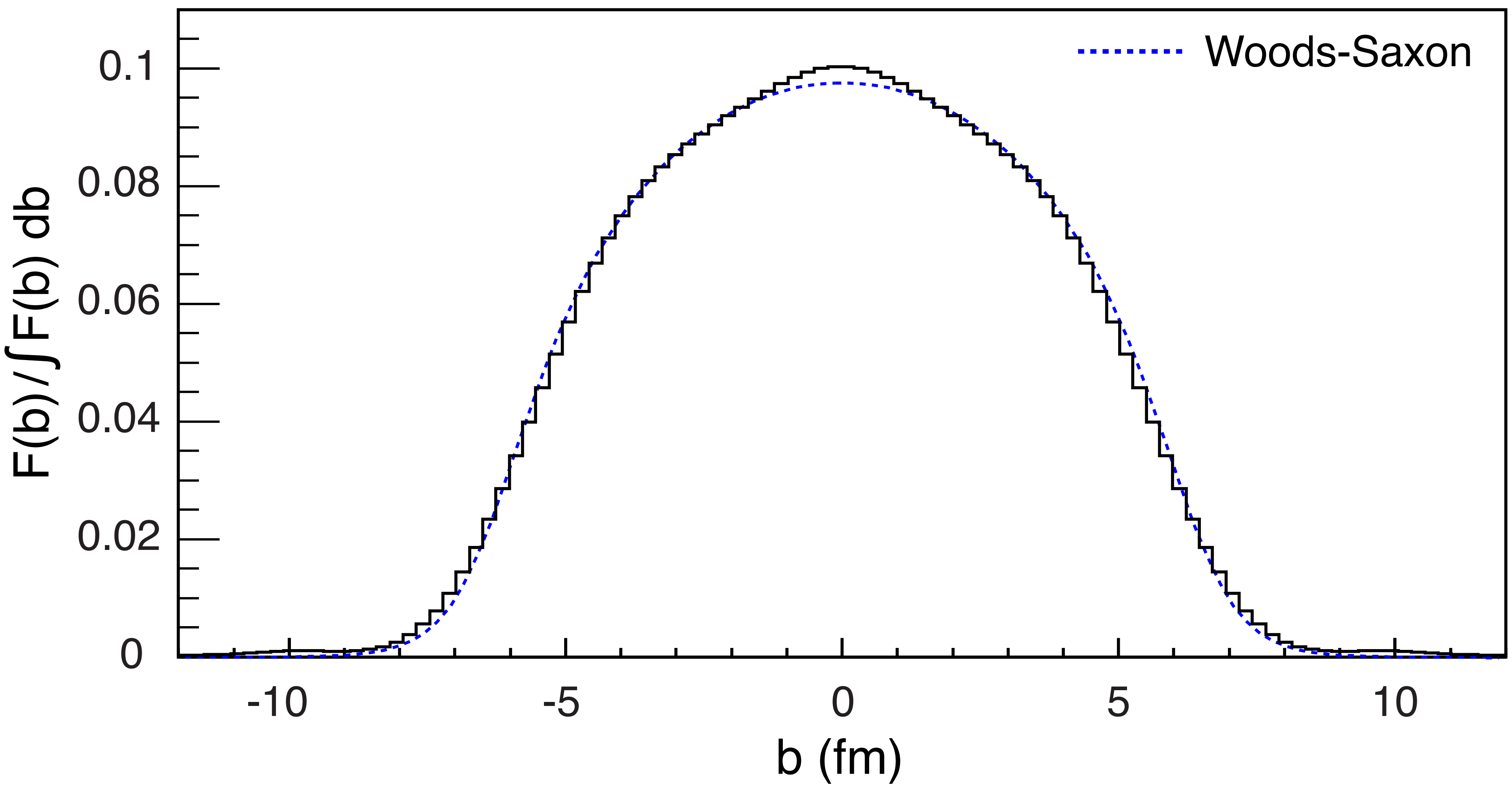

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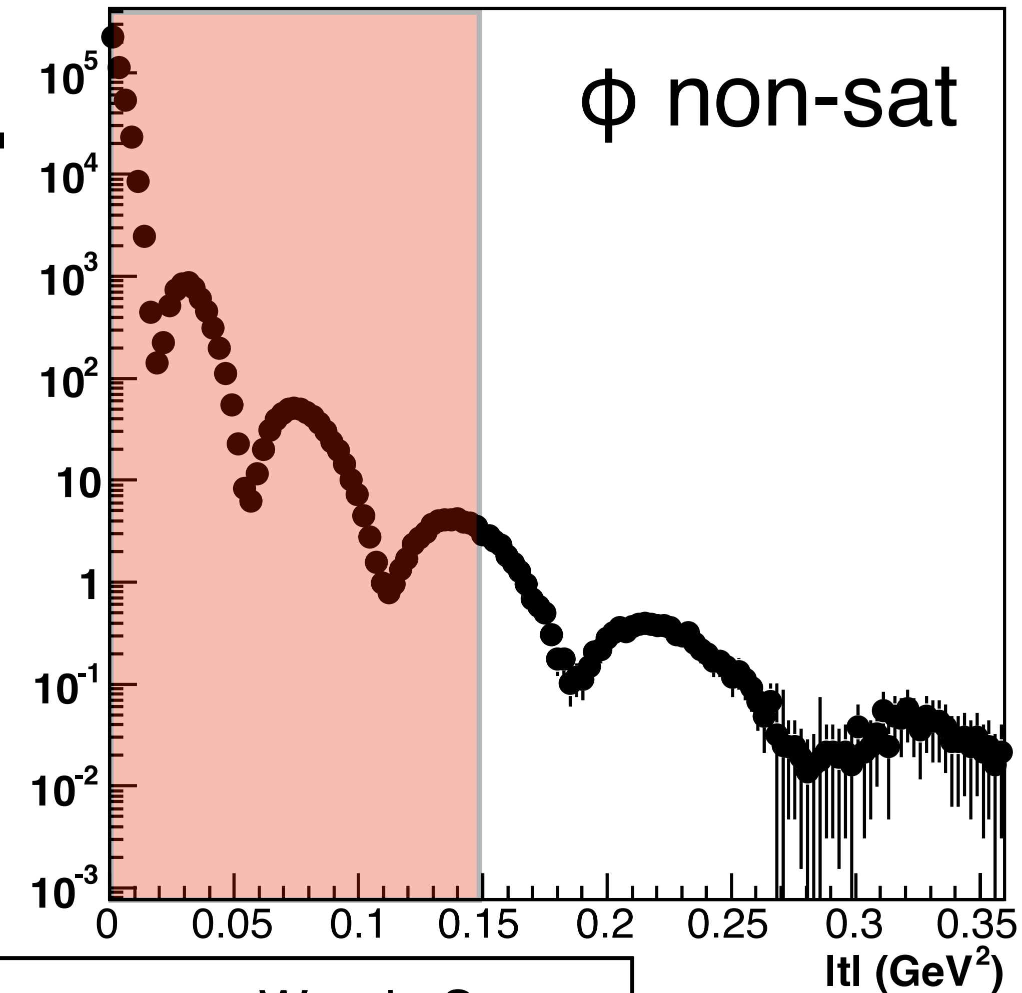

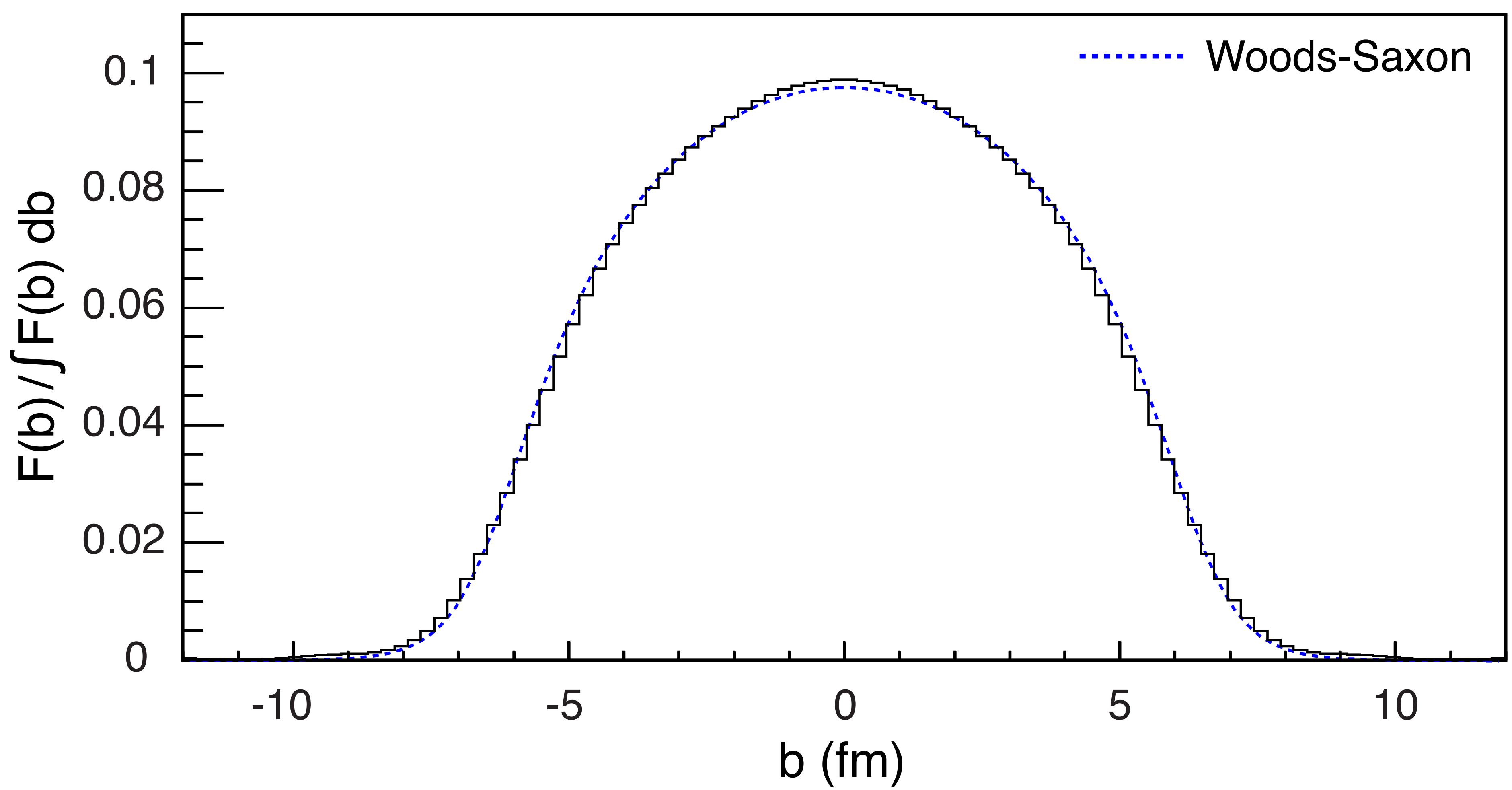

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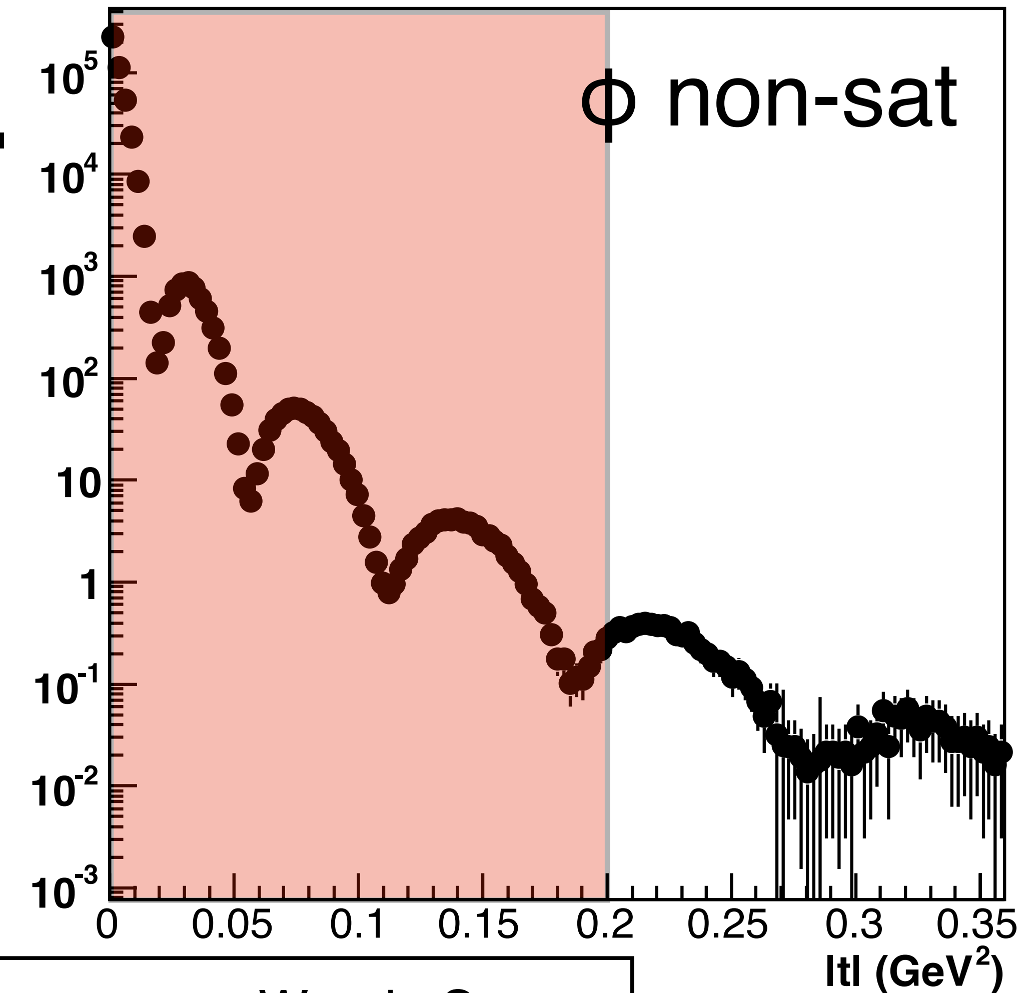

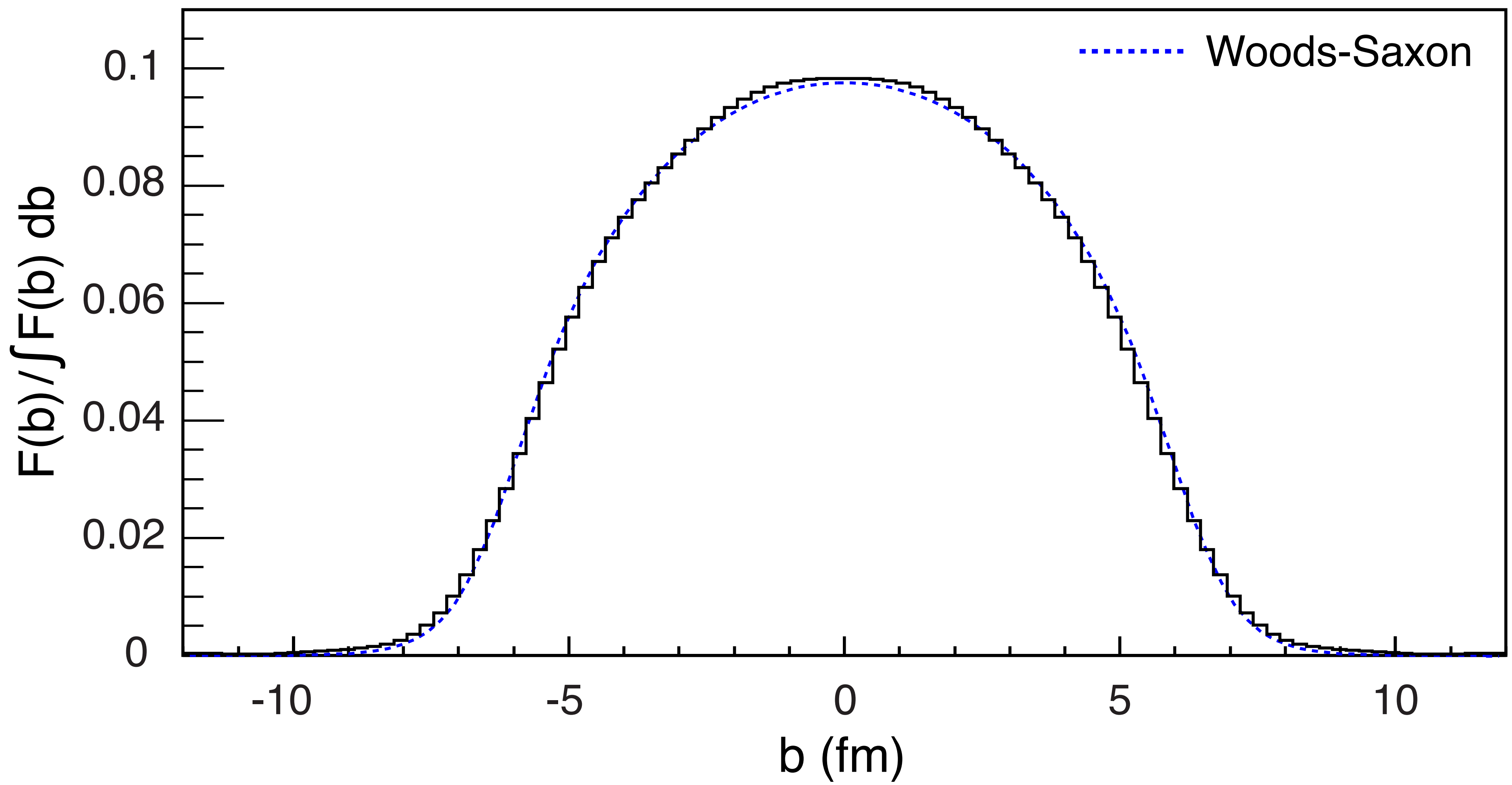

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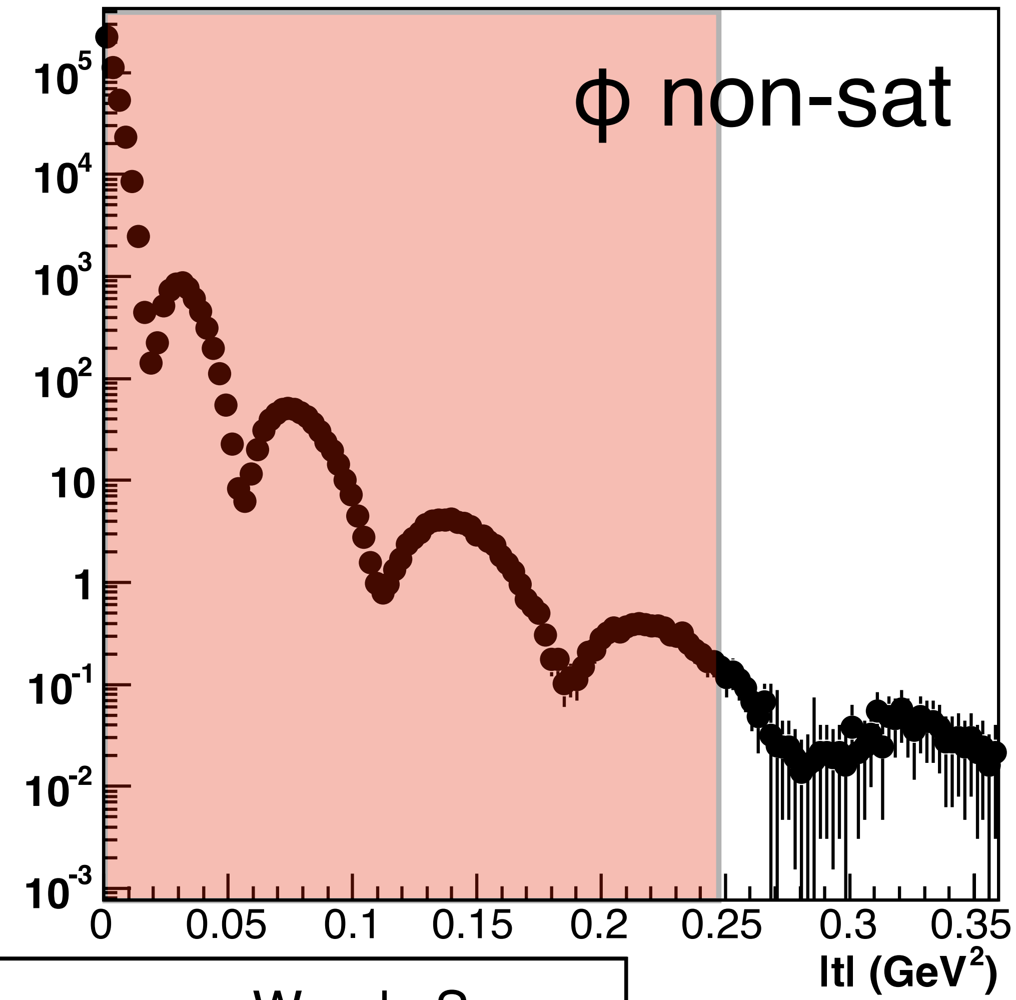

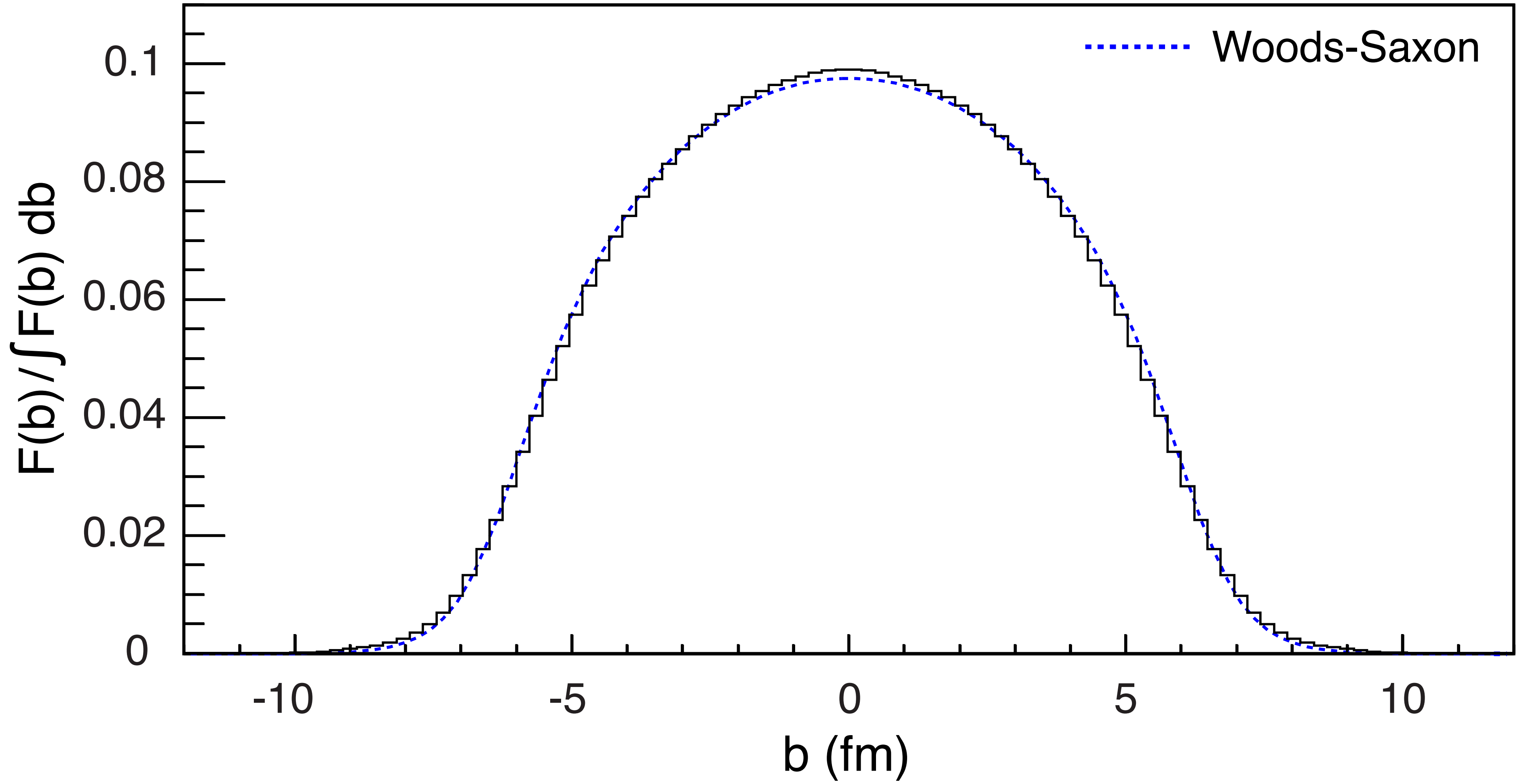

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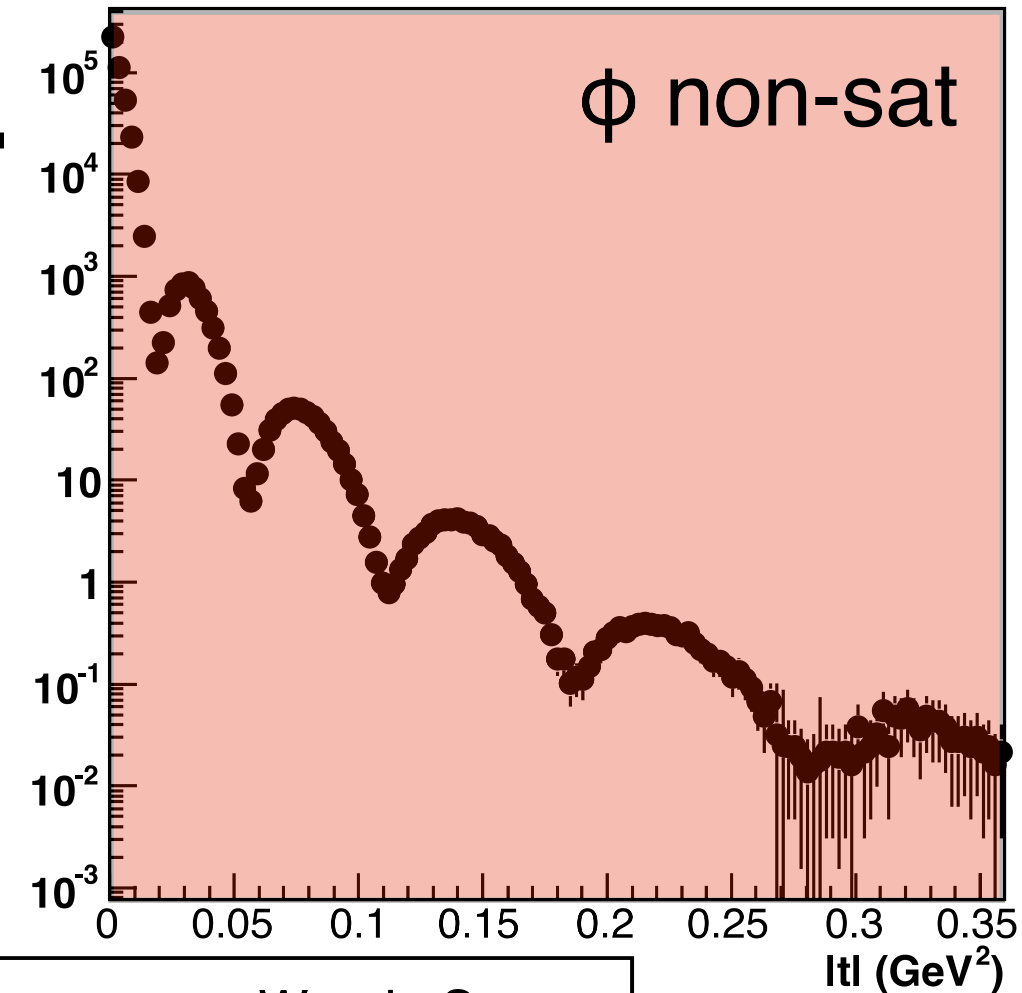
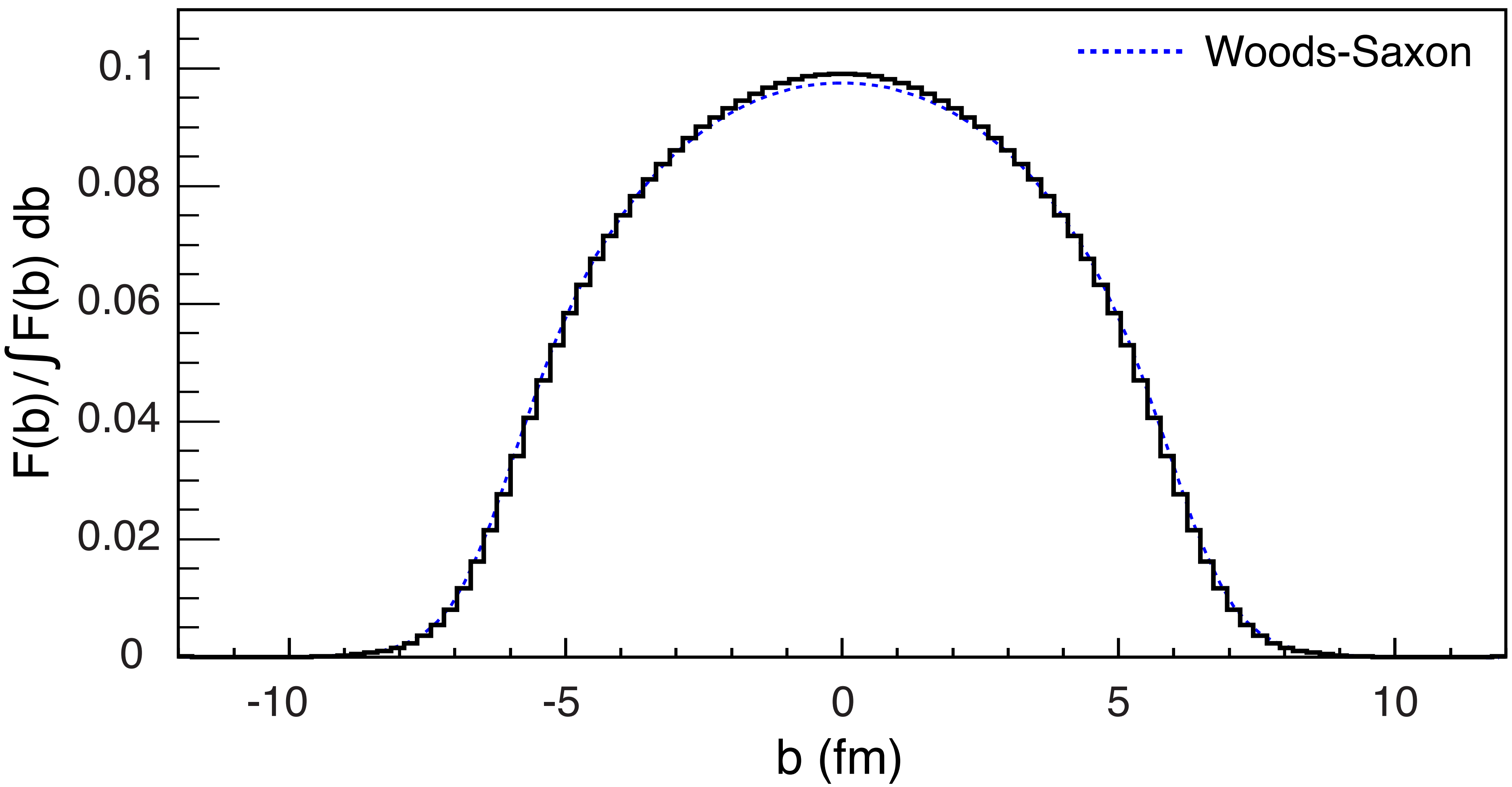


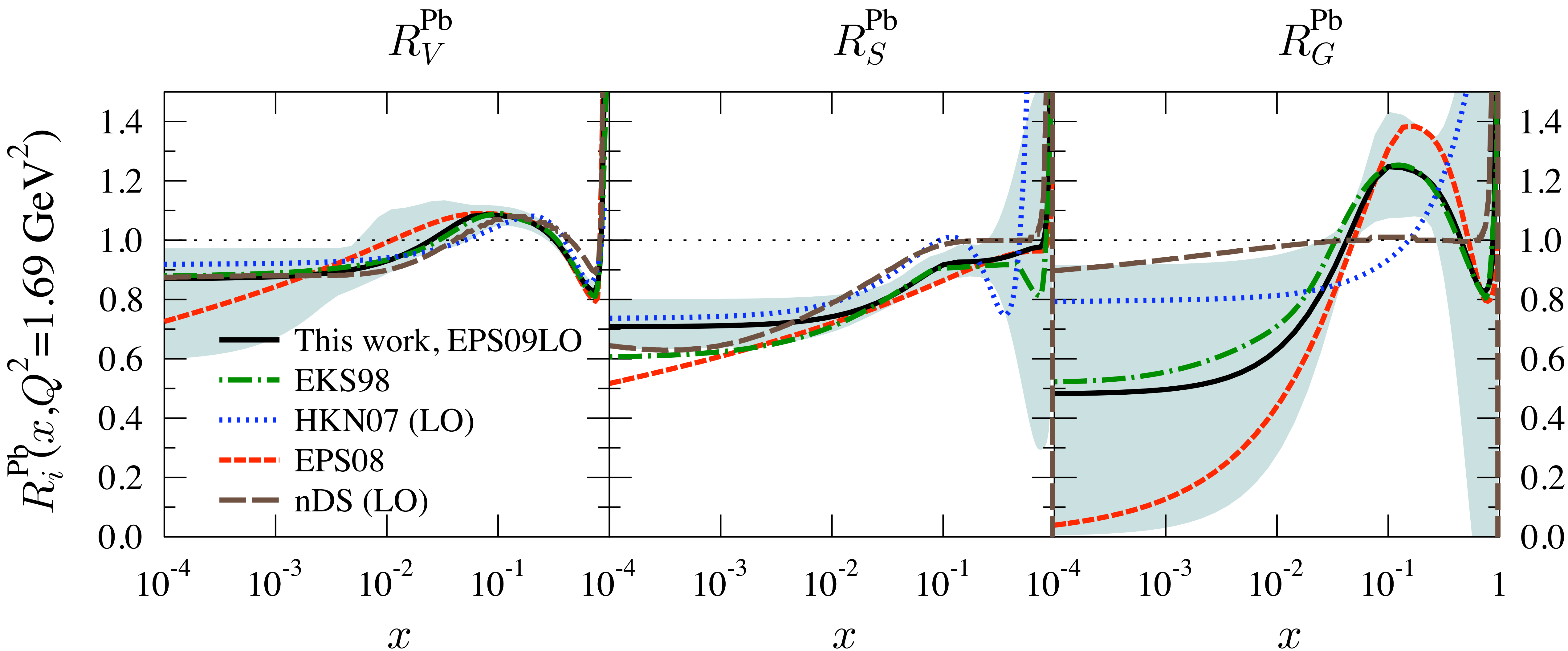


Summary/Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei at small-x
  - ➡ We can measure the properties of gluons where saturation is the dominant governing phenomena
  - ➡ Understanding the role of gluons in nuclei is also crucial to a quantitative understanding of RHIC (and LHC) heavy-ion results
- Diffractive collisions will give us a good handle on the gluon distribution
  - ➡ The ratio of the cross-sections of diffractive collisions in e+A/e+p itself will help differentiate between linear and non-linear effects
  - ➡ A Fourier Transform of the coherent dσ/dt distribution of diffractive vector mesons can allow us to extract the b-dependent initial gluon distribution

BACKUP

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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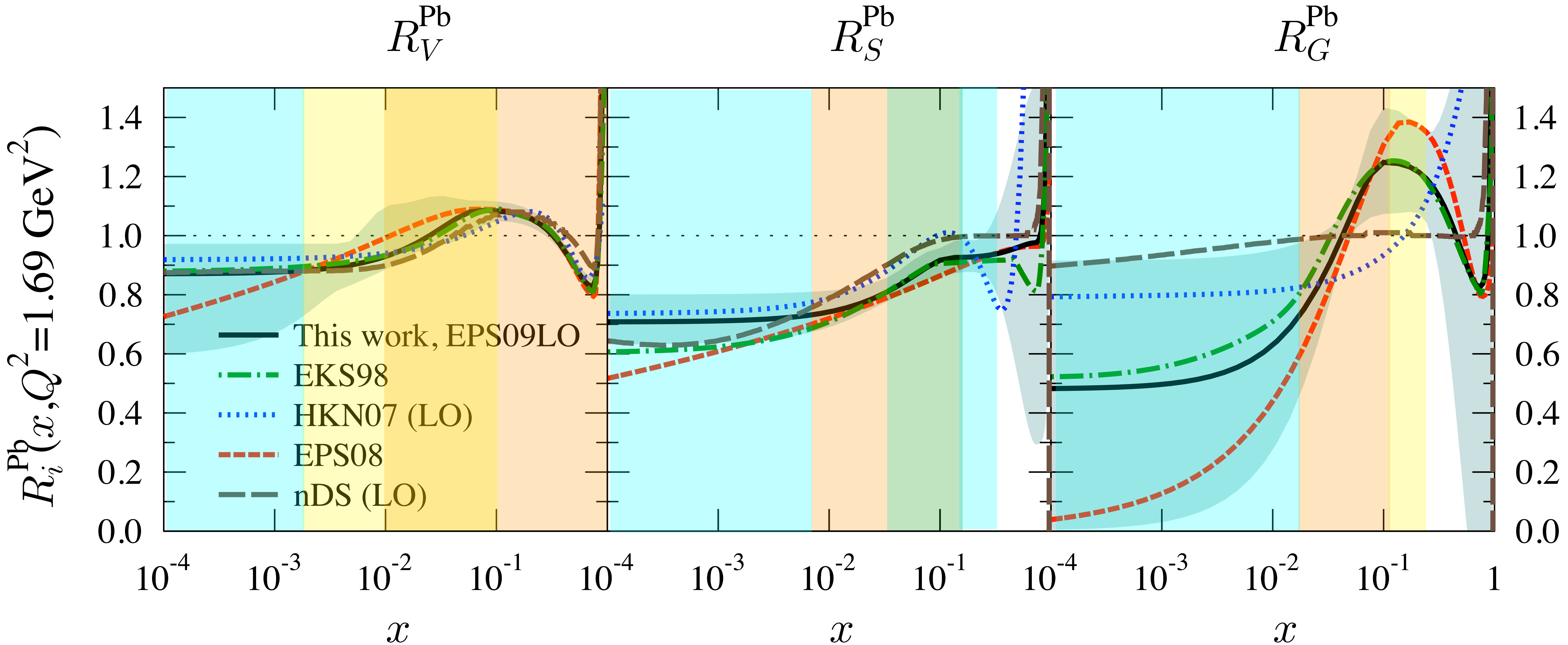

Constrained by DIS

Constrained by DY

Constrained by sum rules

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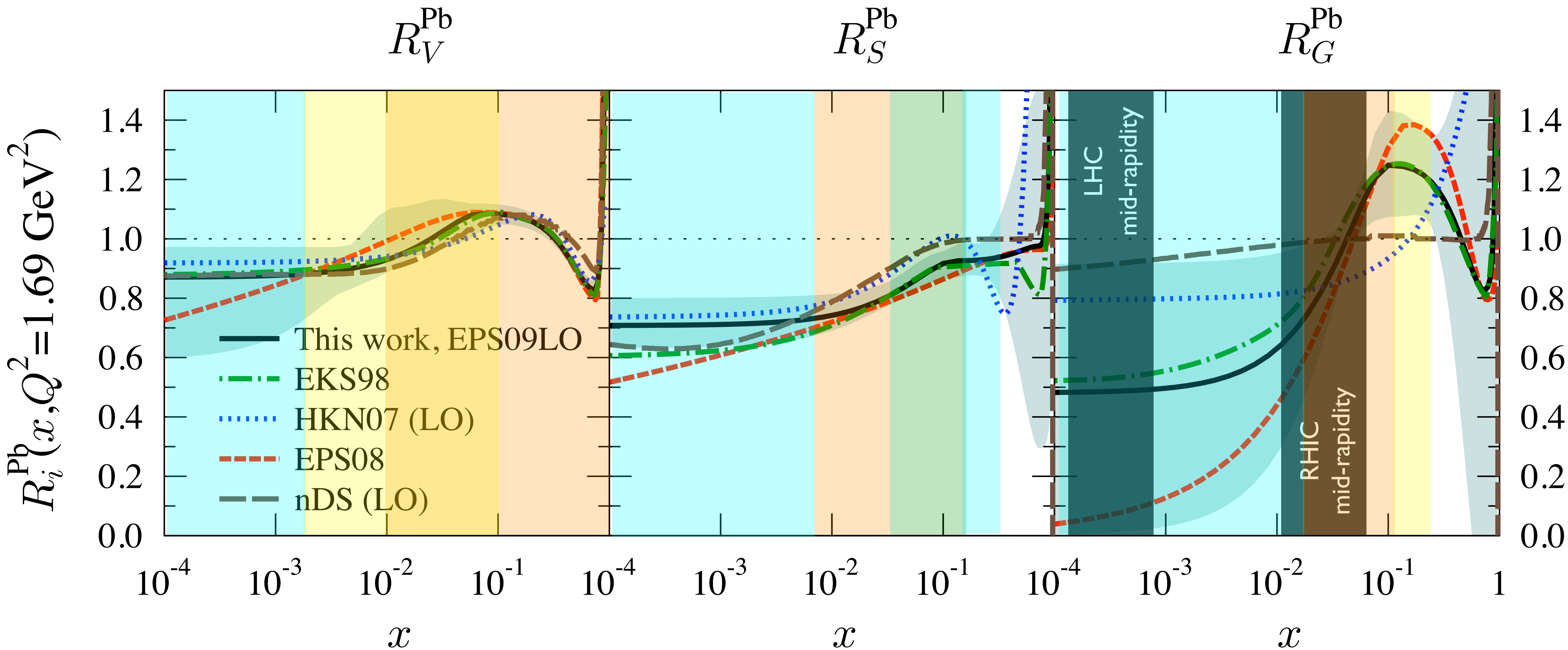

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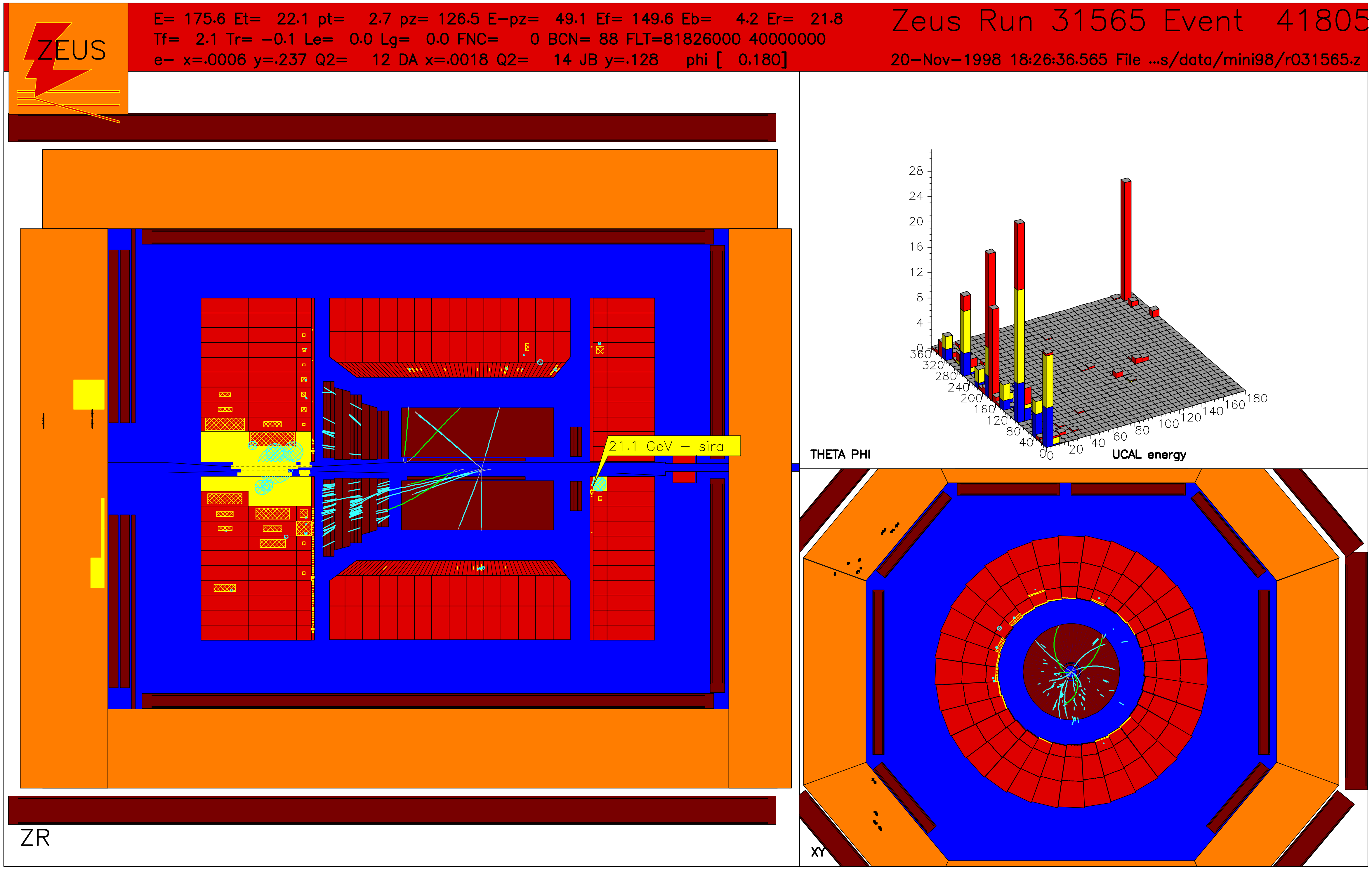
Assumptions

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

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

Visualising Diffractive events

A DIS event (experimental view)



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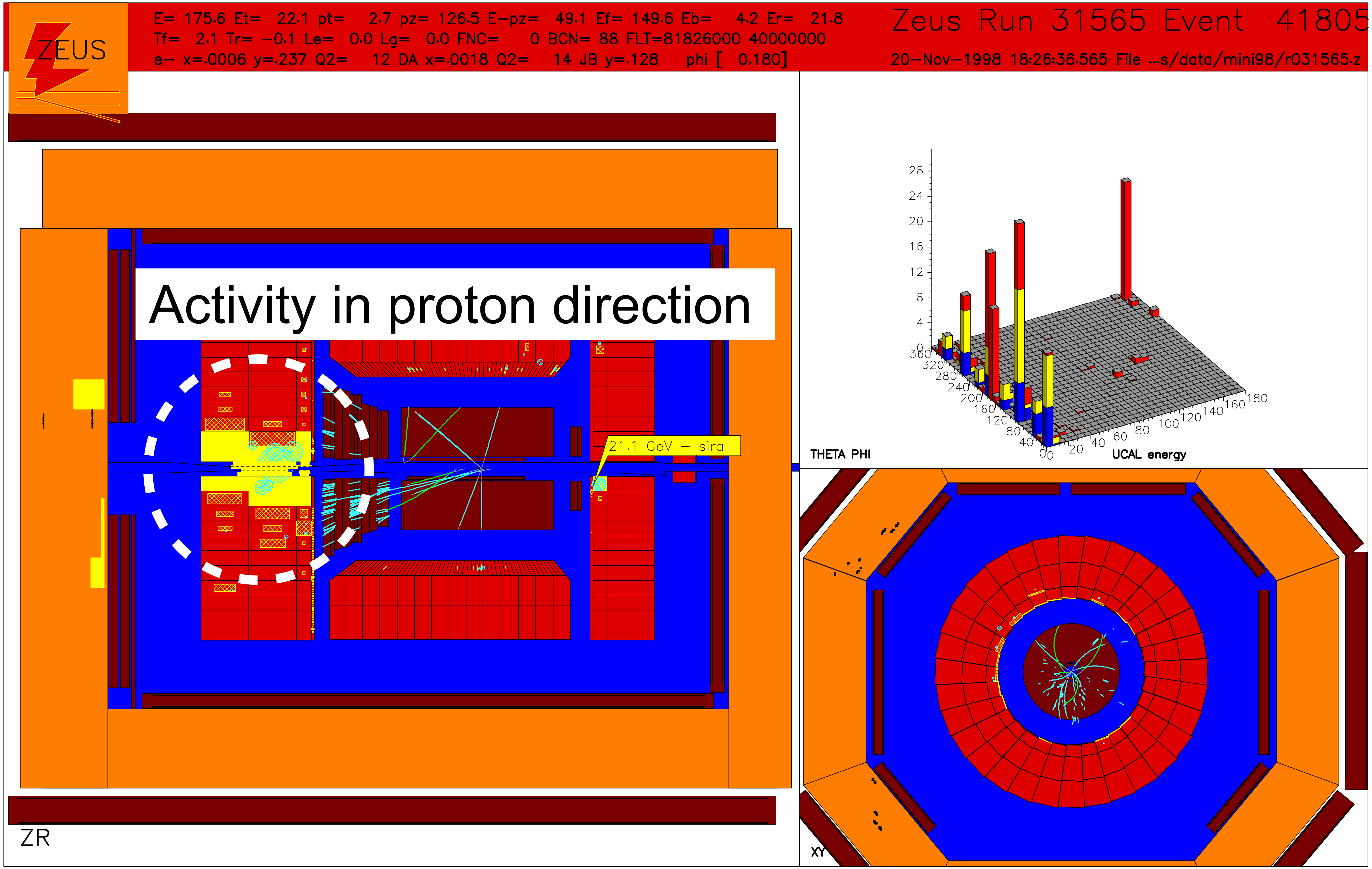

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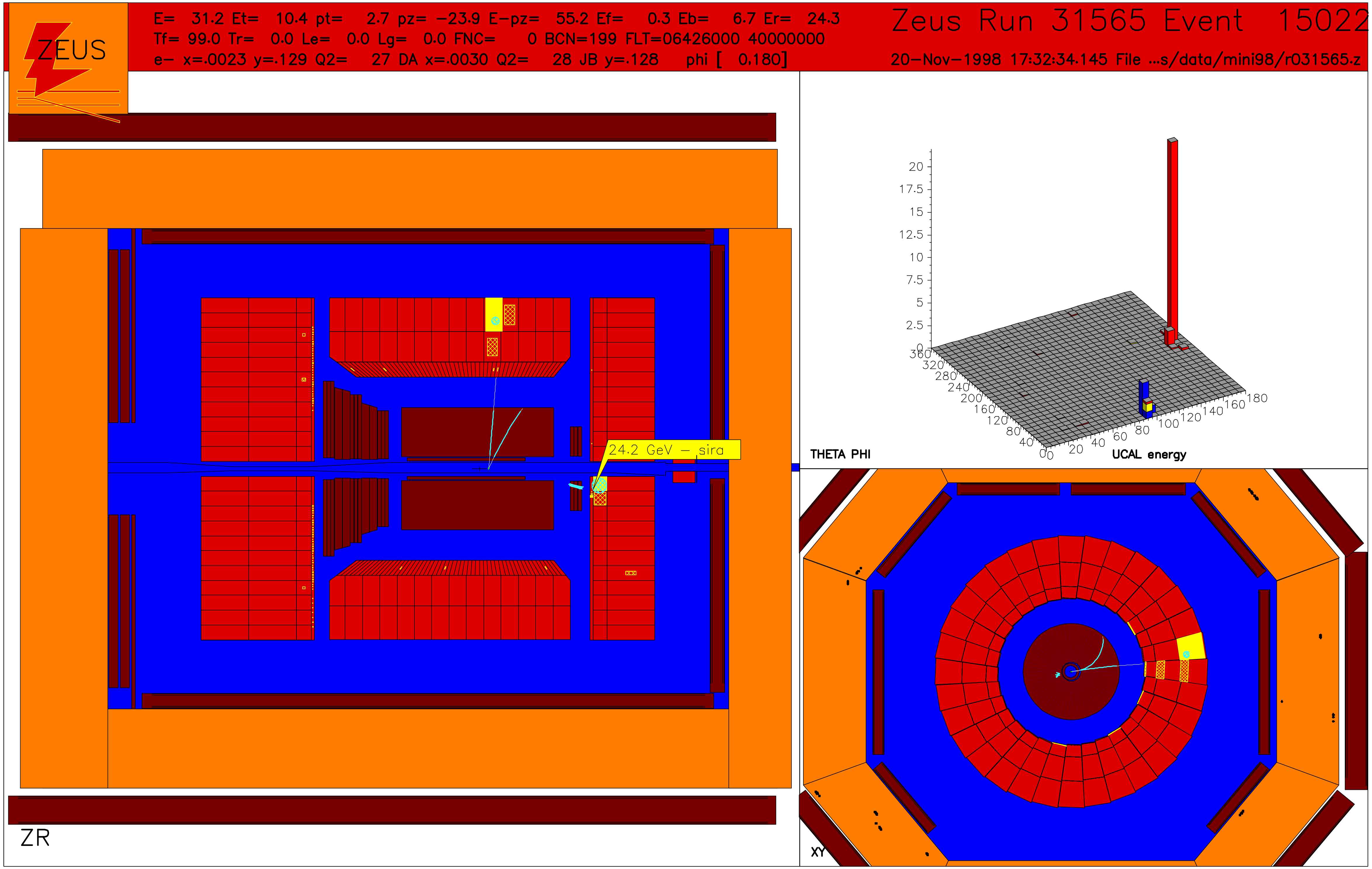

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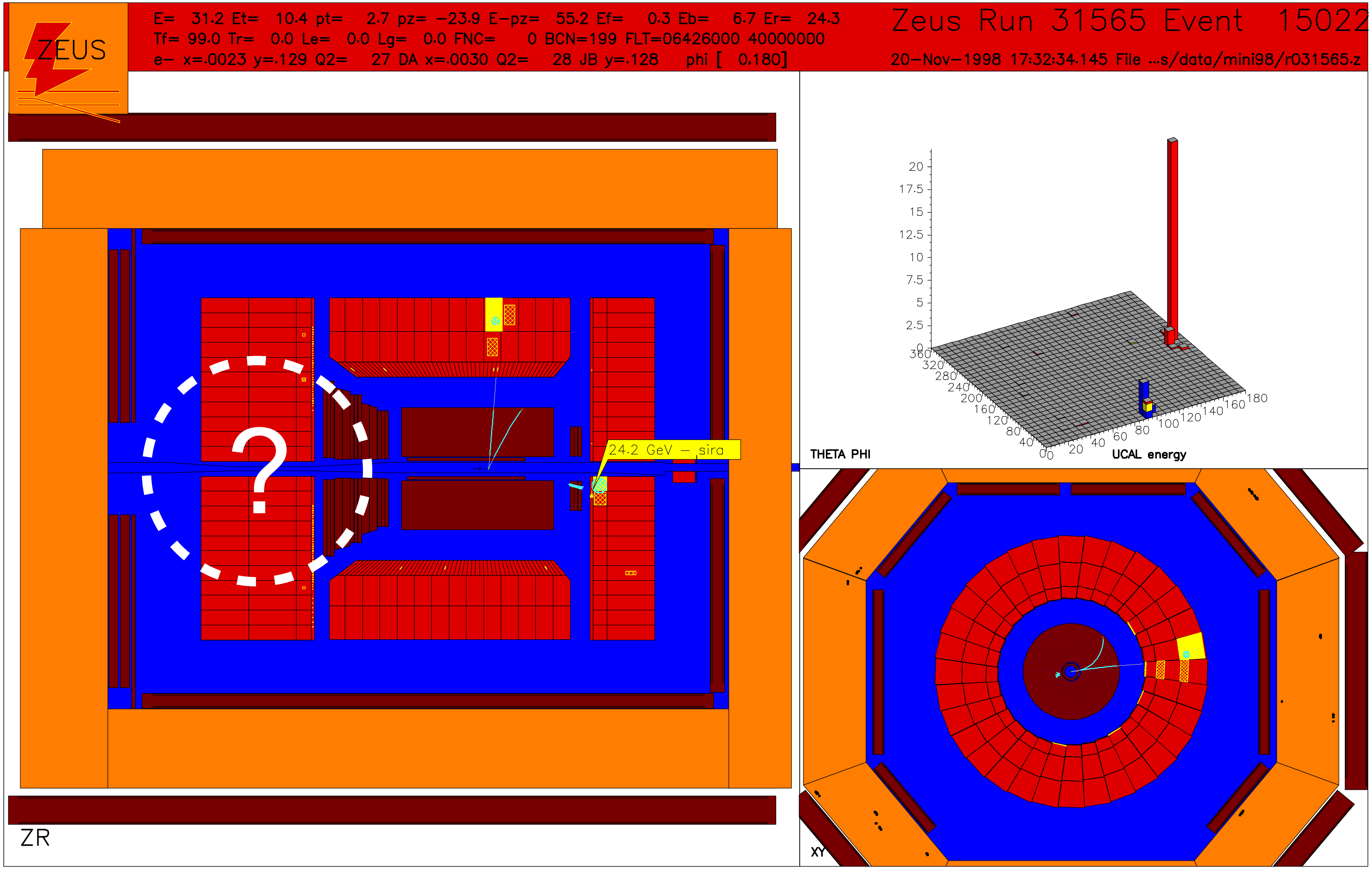

Exclusive Vector Meson Production in e+A

- 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

b-dependent gluons from DVCS and DVMP

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

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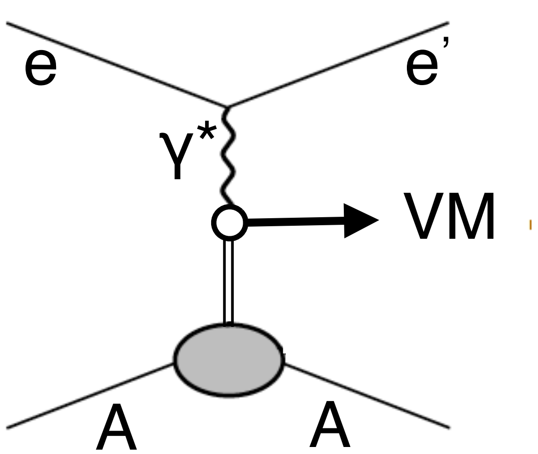
DVMP



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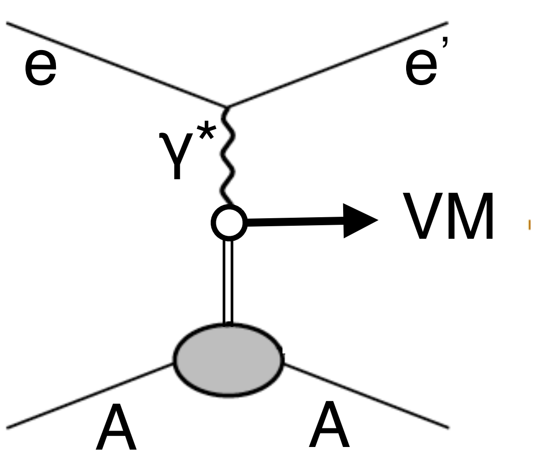
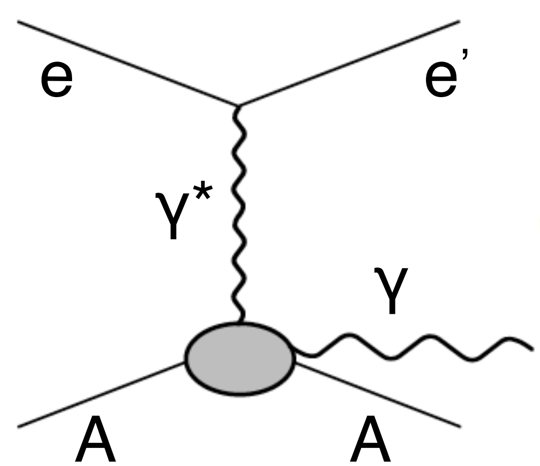


DVCS



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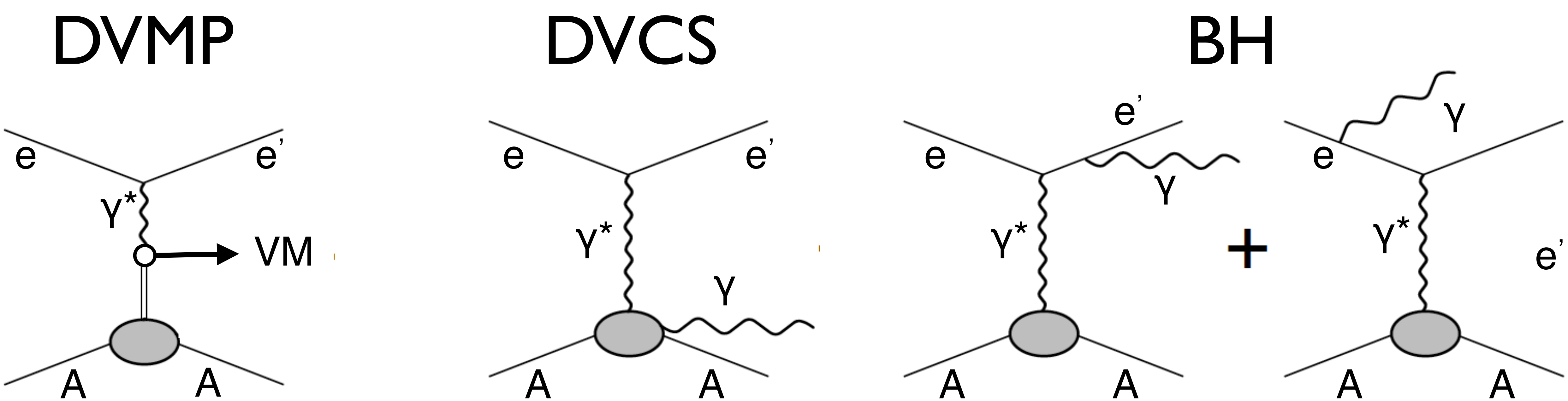
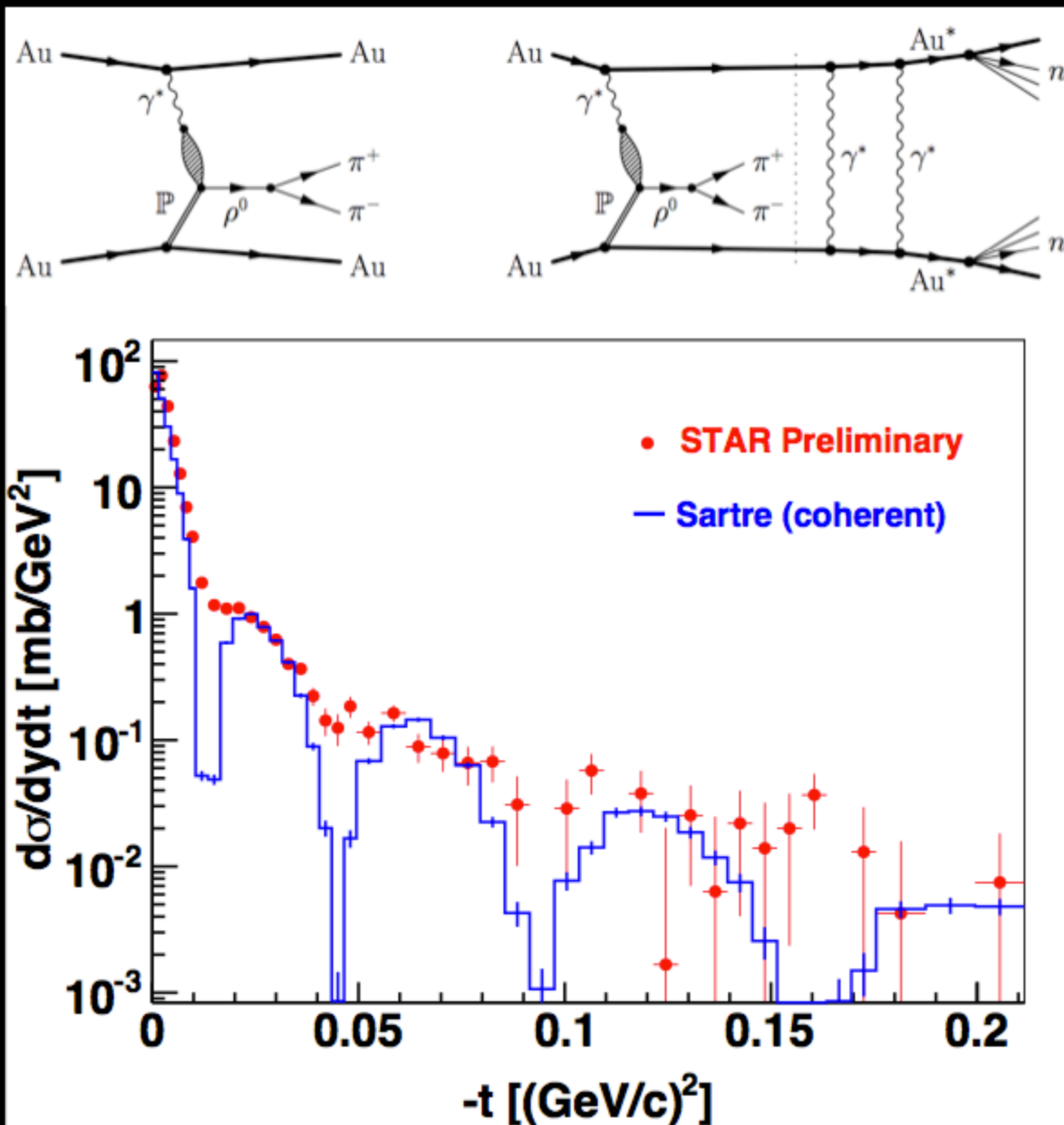


DVCS and Bethe-Heitler interference terms become difficult to distinguish experimentally

Comparison of Sartre to preliminary STAR UPC data

Coherent Diffraction (γ^*+IP)
in UPC at RHIC



- Coherent diffractive ρ production in Au +Au at $\sqrt{s_{NN}}$=200 GeV
- Data: STAR/RHIC Ultra-peripheral AuAu Collision
- Simulation: Sartre

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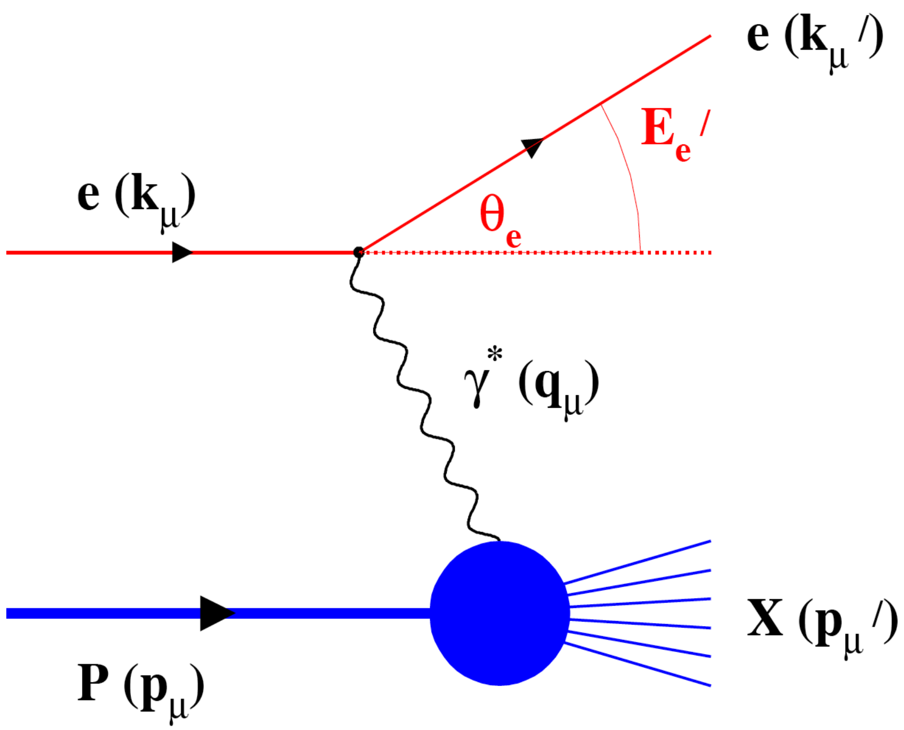
DIS Kinematics

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



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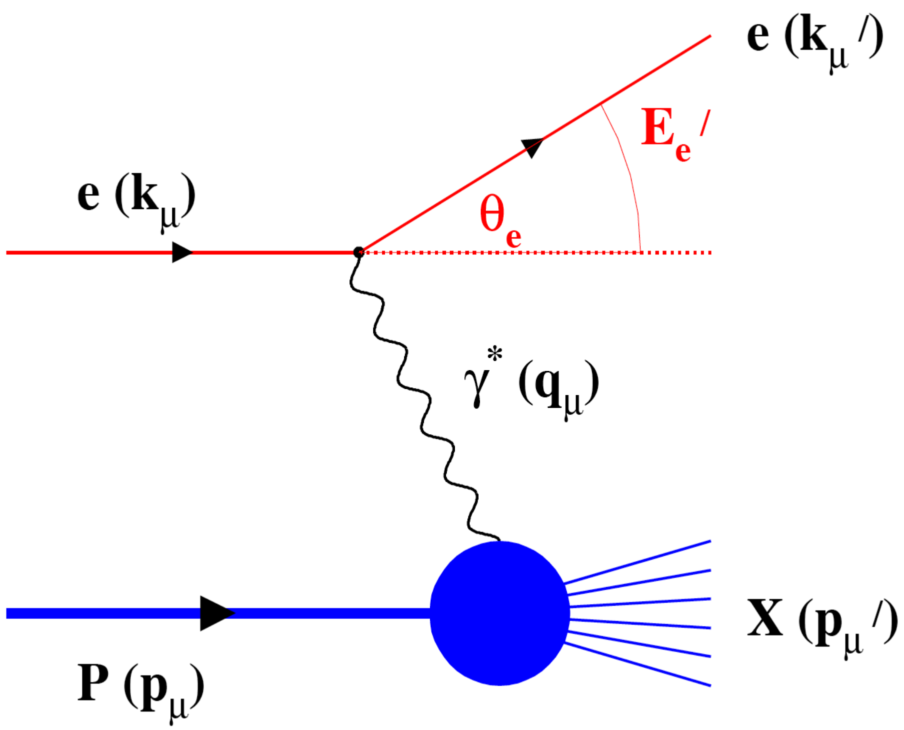

$$Q^2 = -q^2 = -(k_\mu - k_\mu^{'})^2$$

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

Measure of resolution power or "Virtuality"

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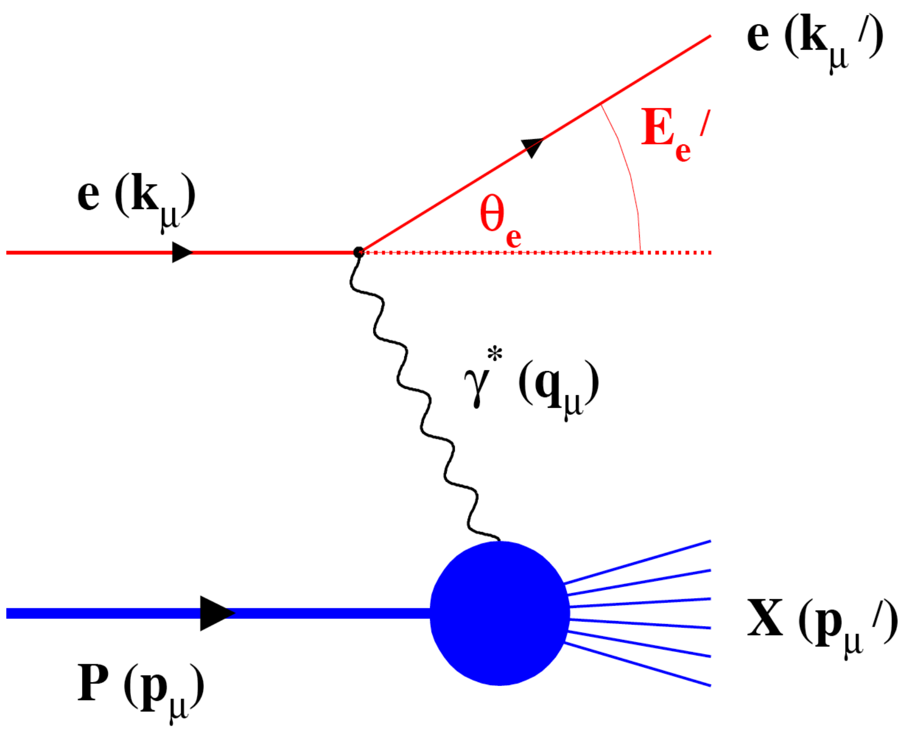

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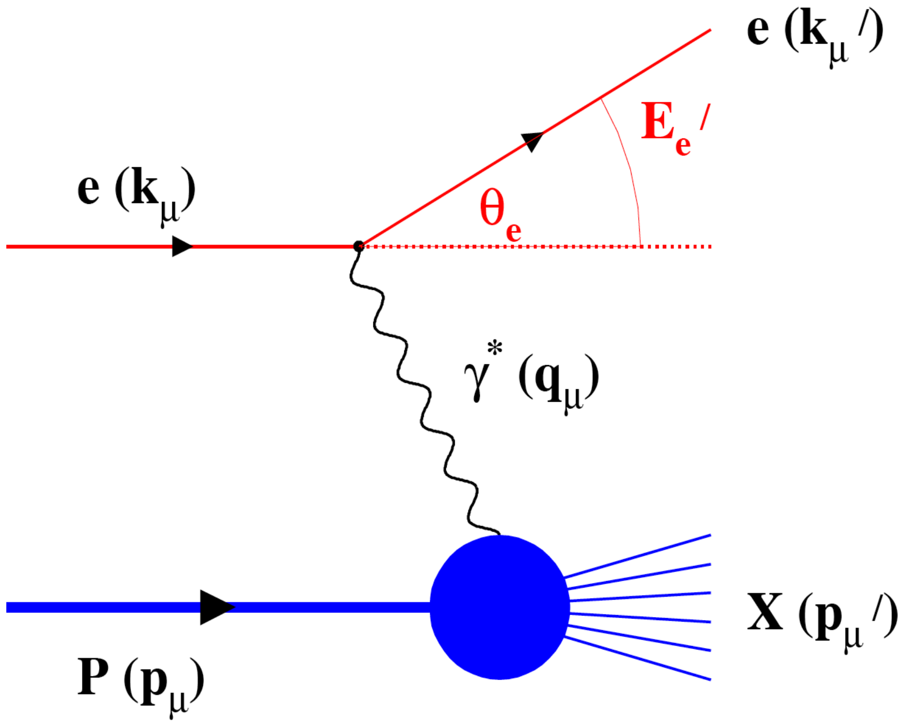

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Measure of momentum fraction of struck quark

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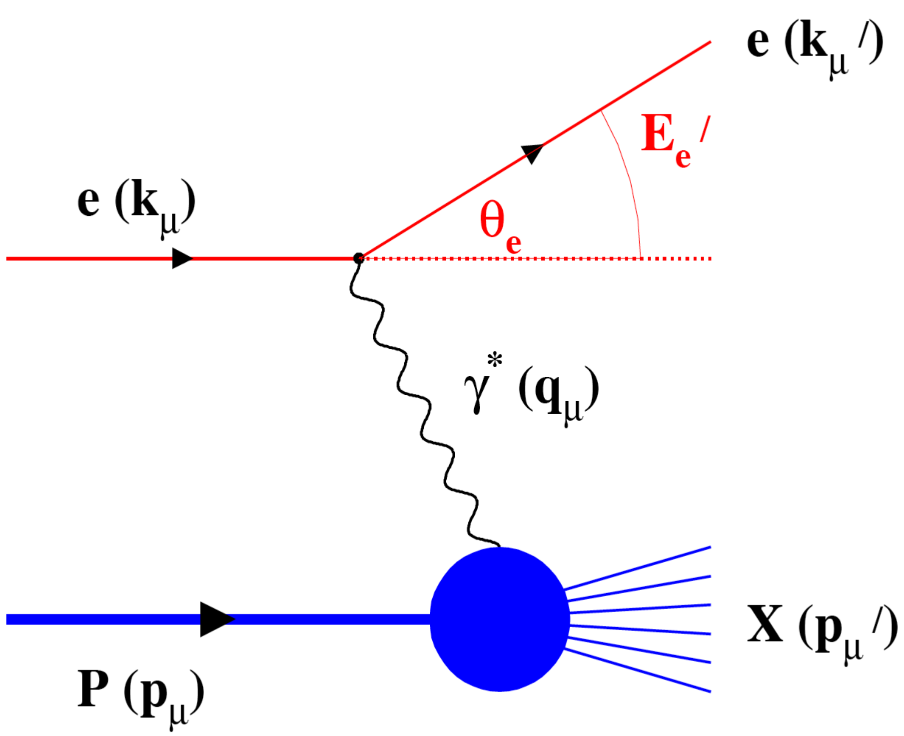

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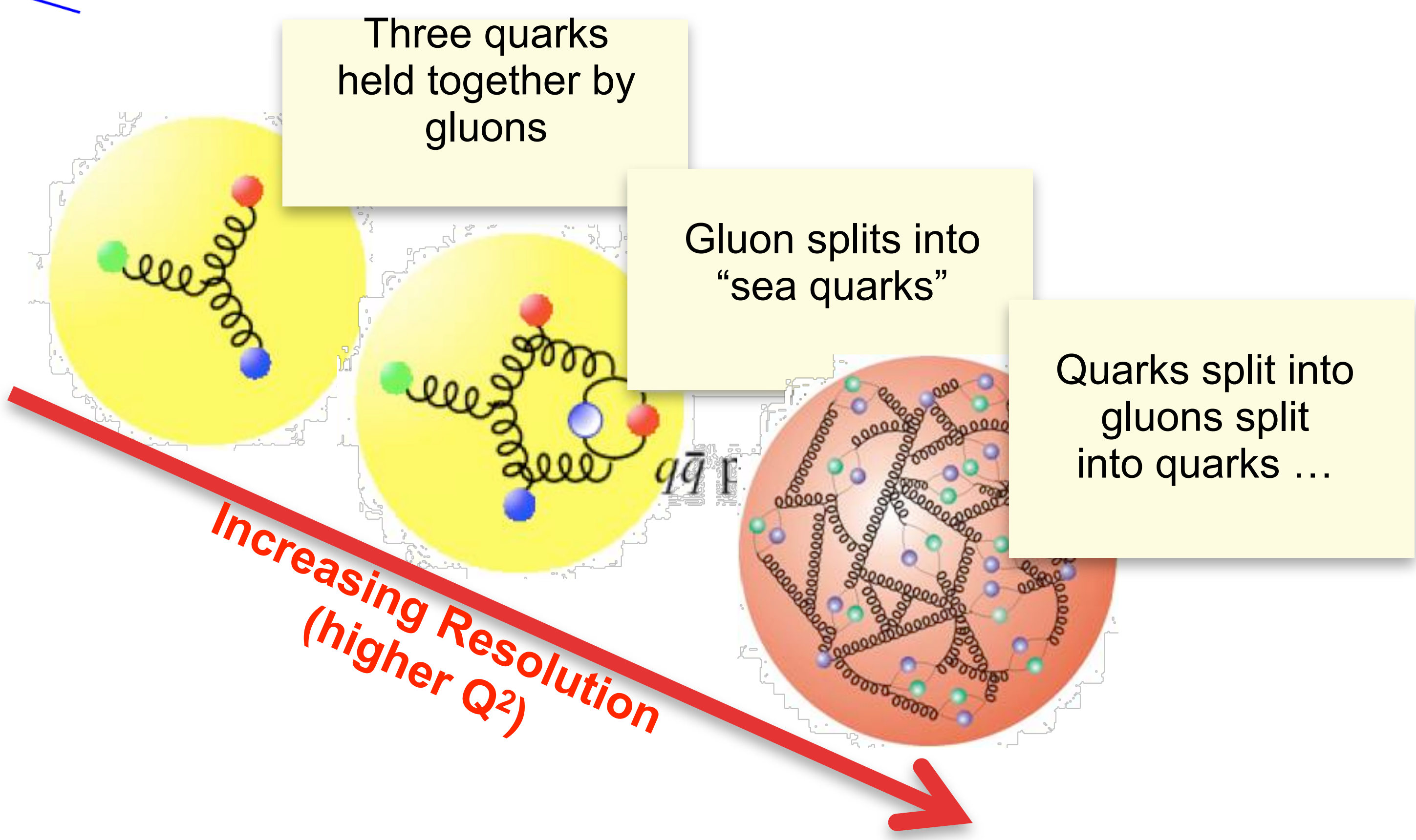
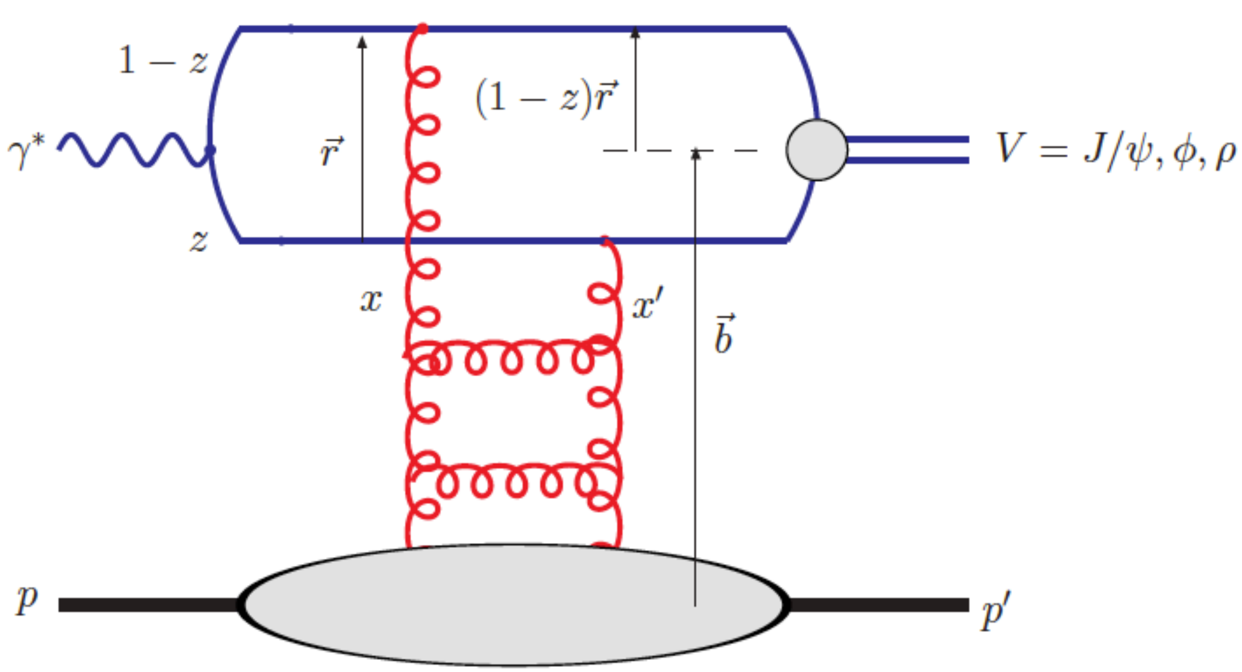
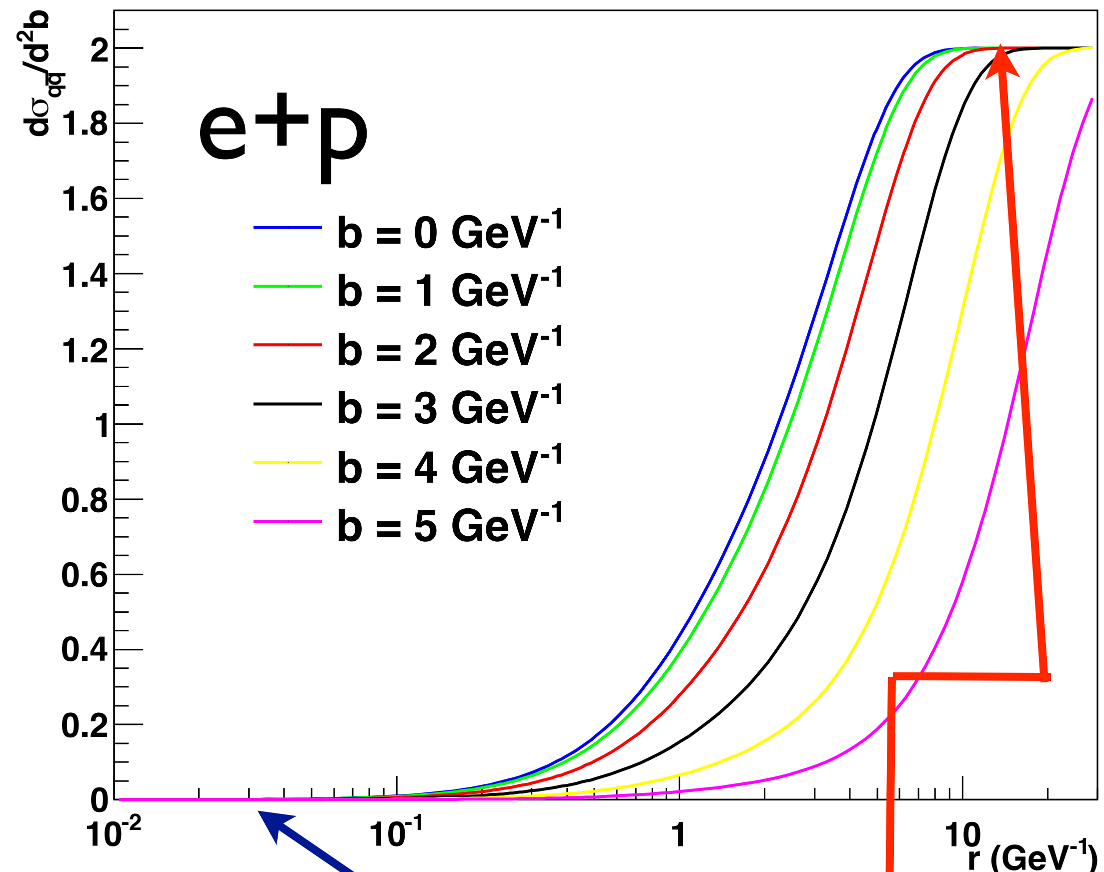


Getting a “Feel” for Non-Linear QCD

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





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

$\mathcal{N} =$ Dipole Scattering Amplitude

0 dilute system, linear QCD

1 saturated, non-linear regime

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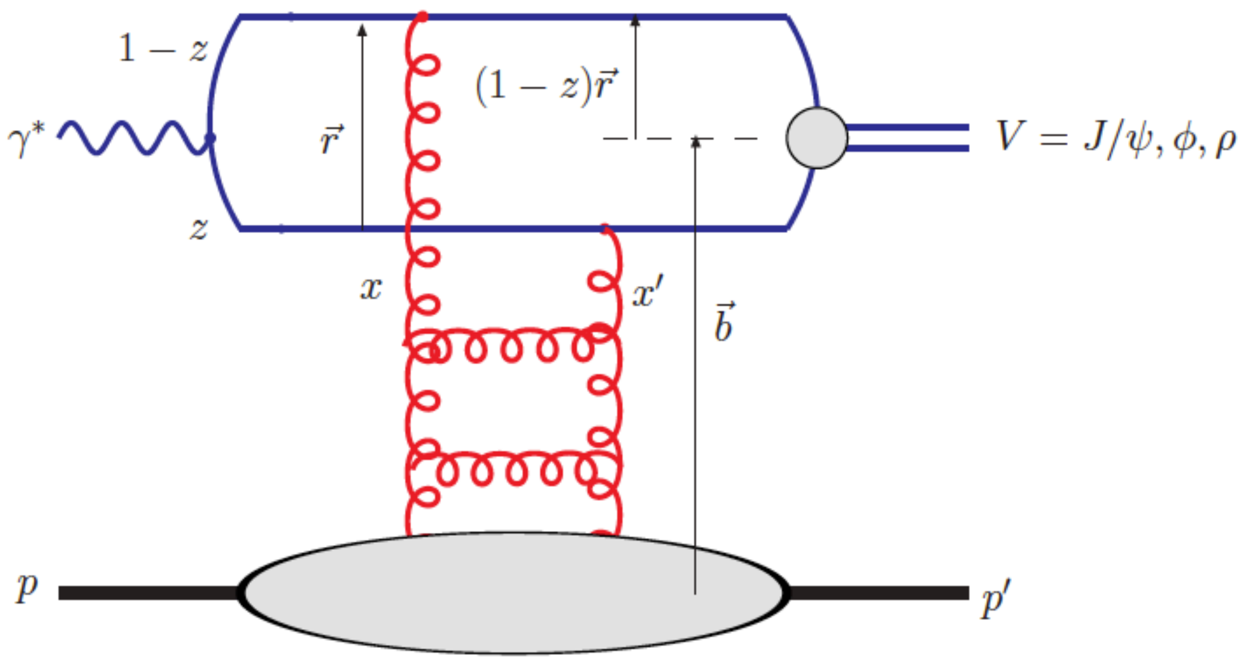

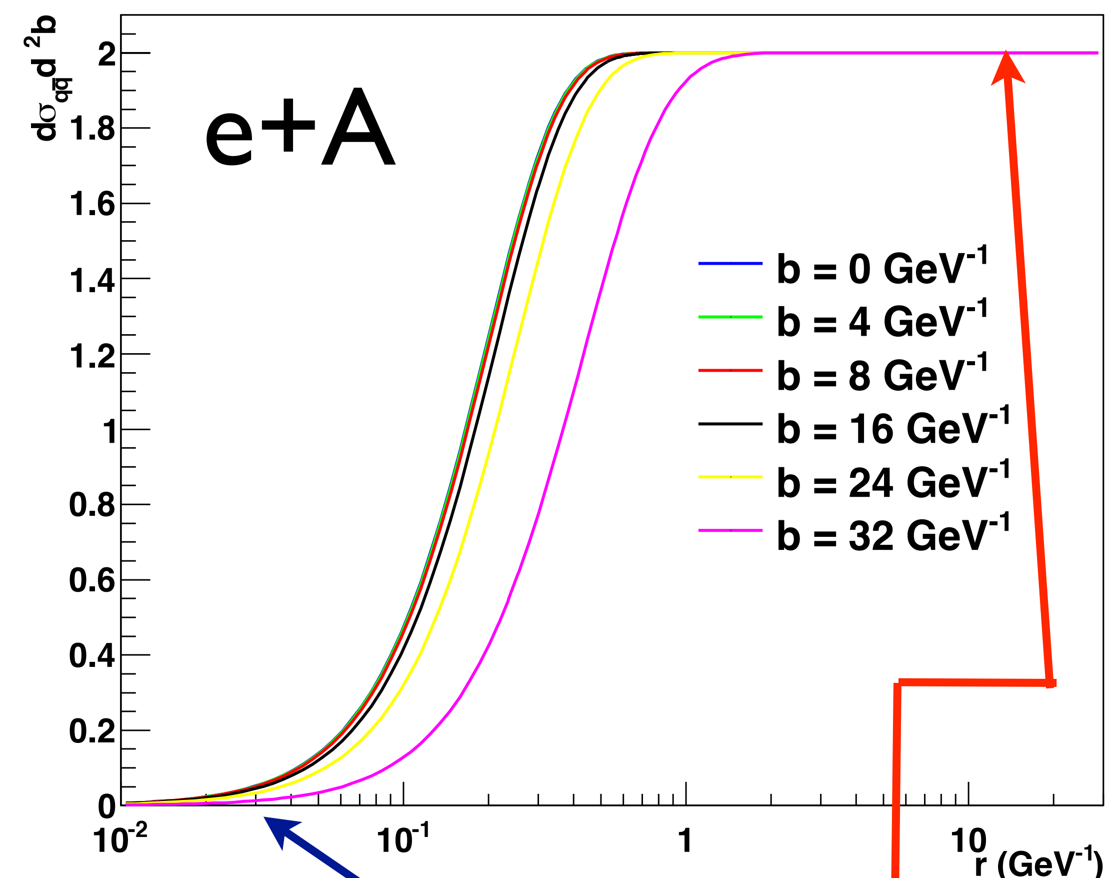

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To assess typical values of $\mathcal{N}$ calculate average:

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

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

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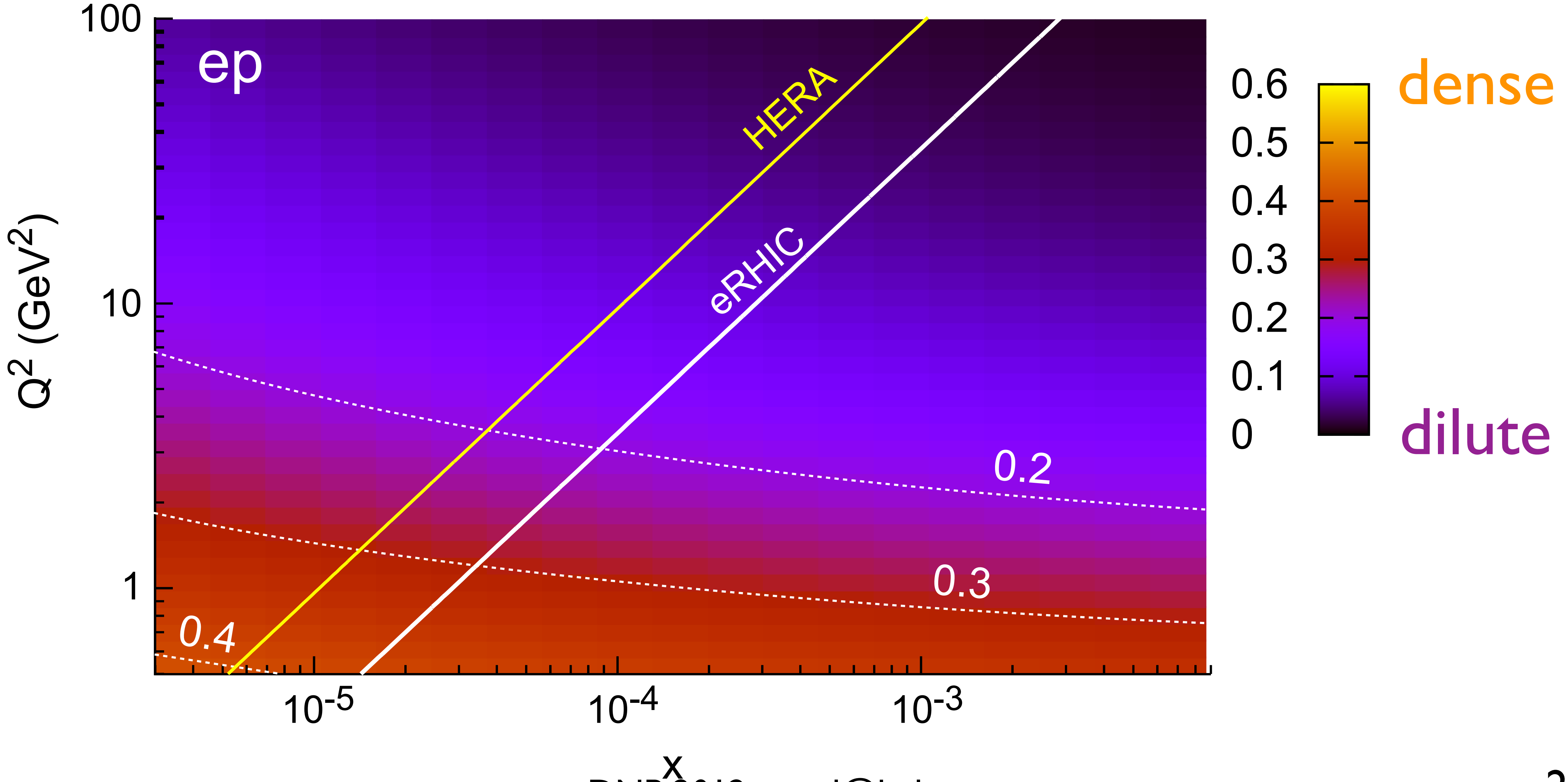

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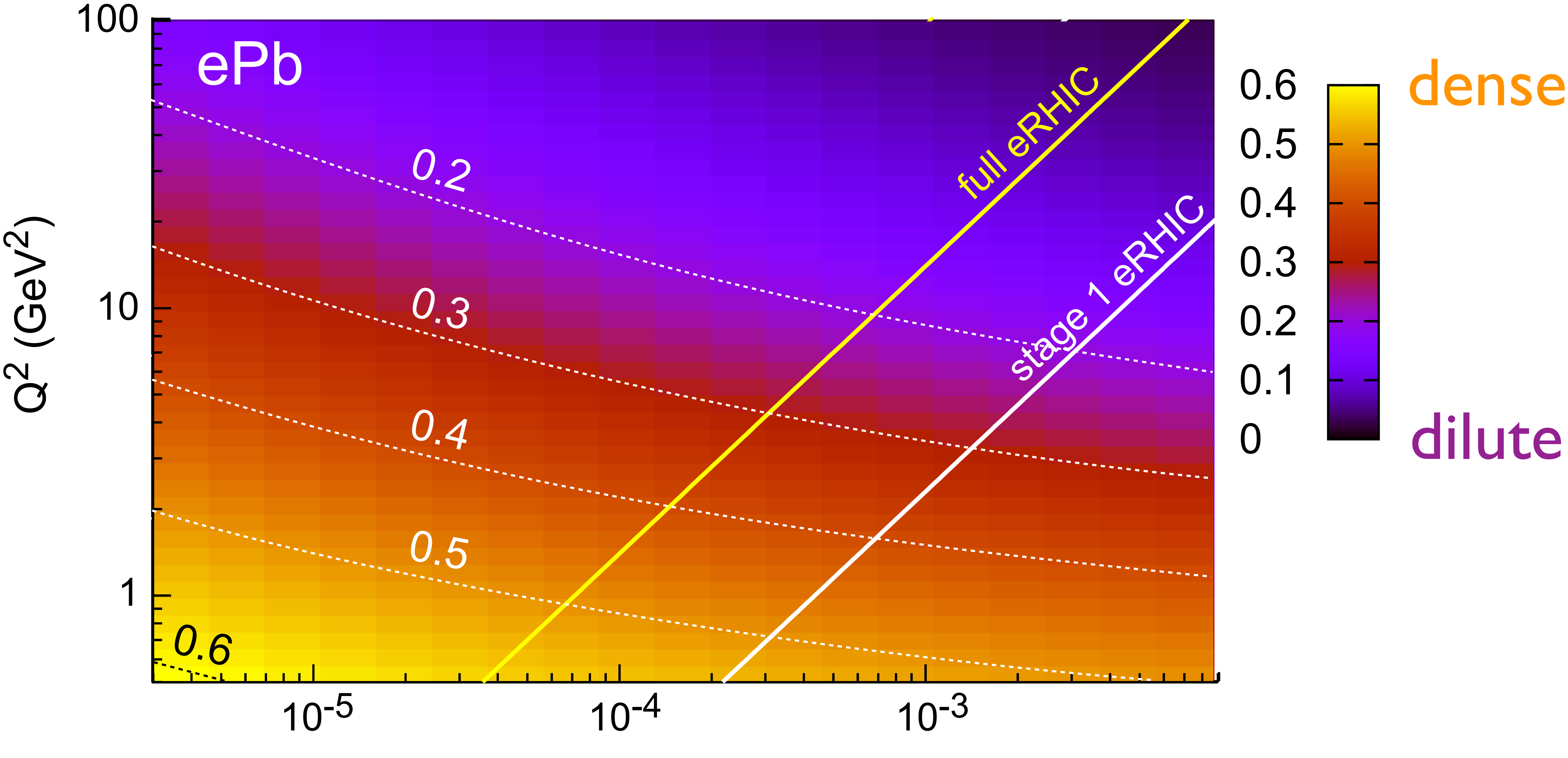
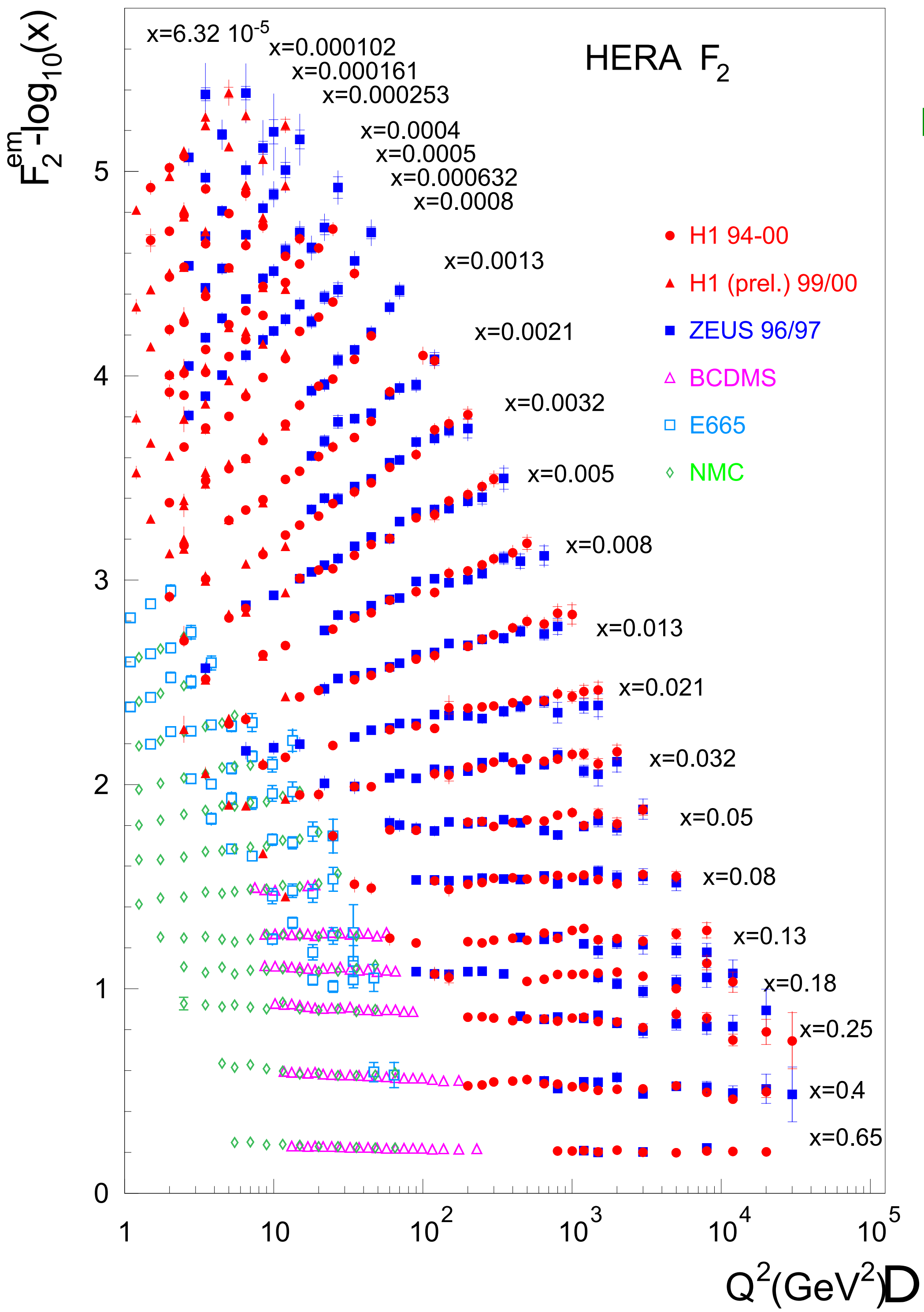


Measuring the glue via Structure Functions

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

quark+anti-quark momentum distributions

gluon momentum distribution



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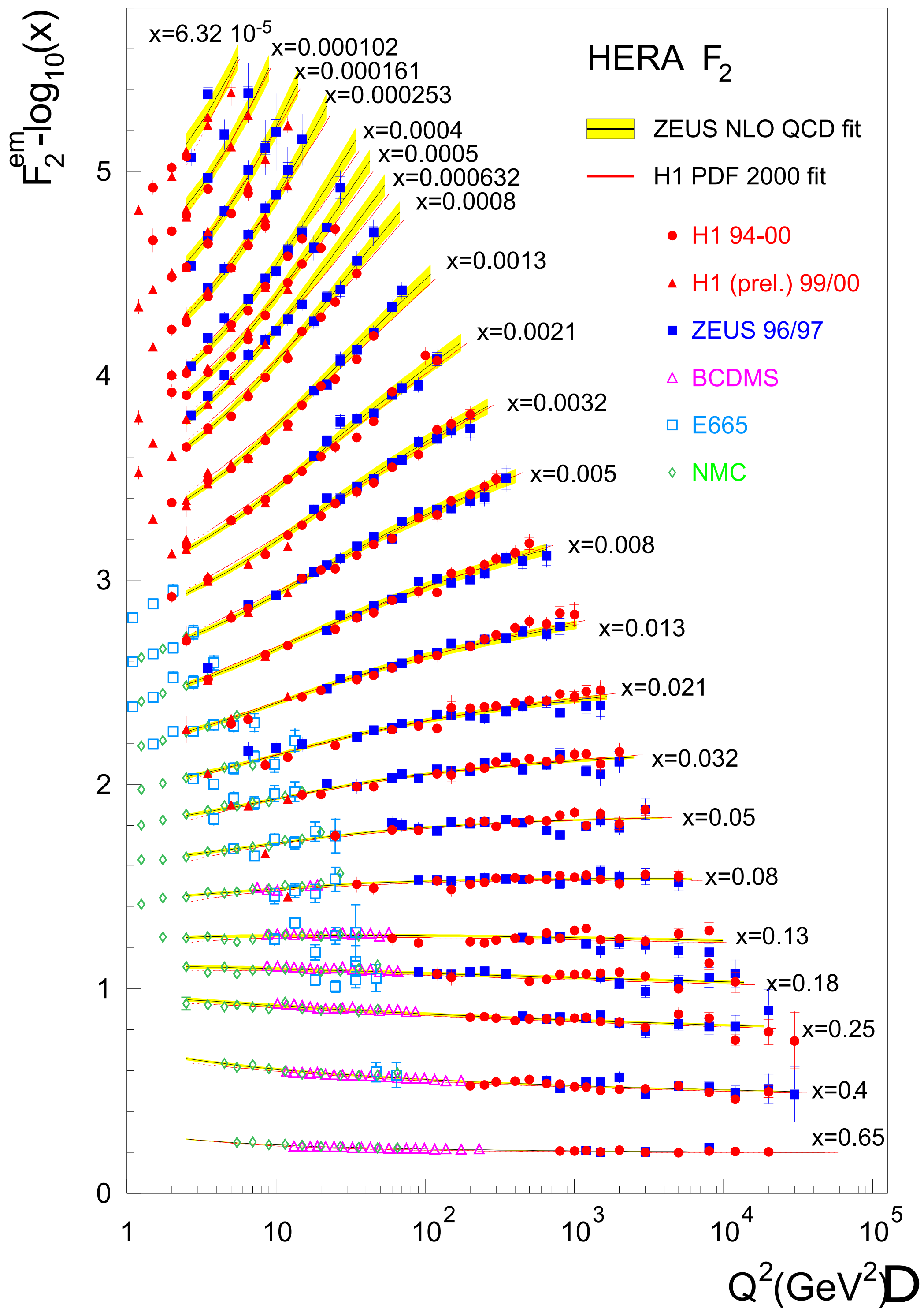

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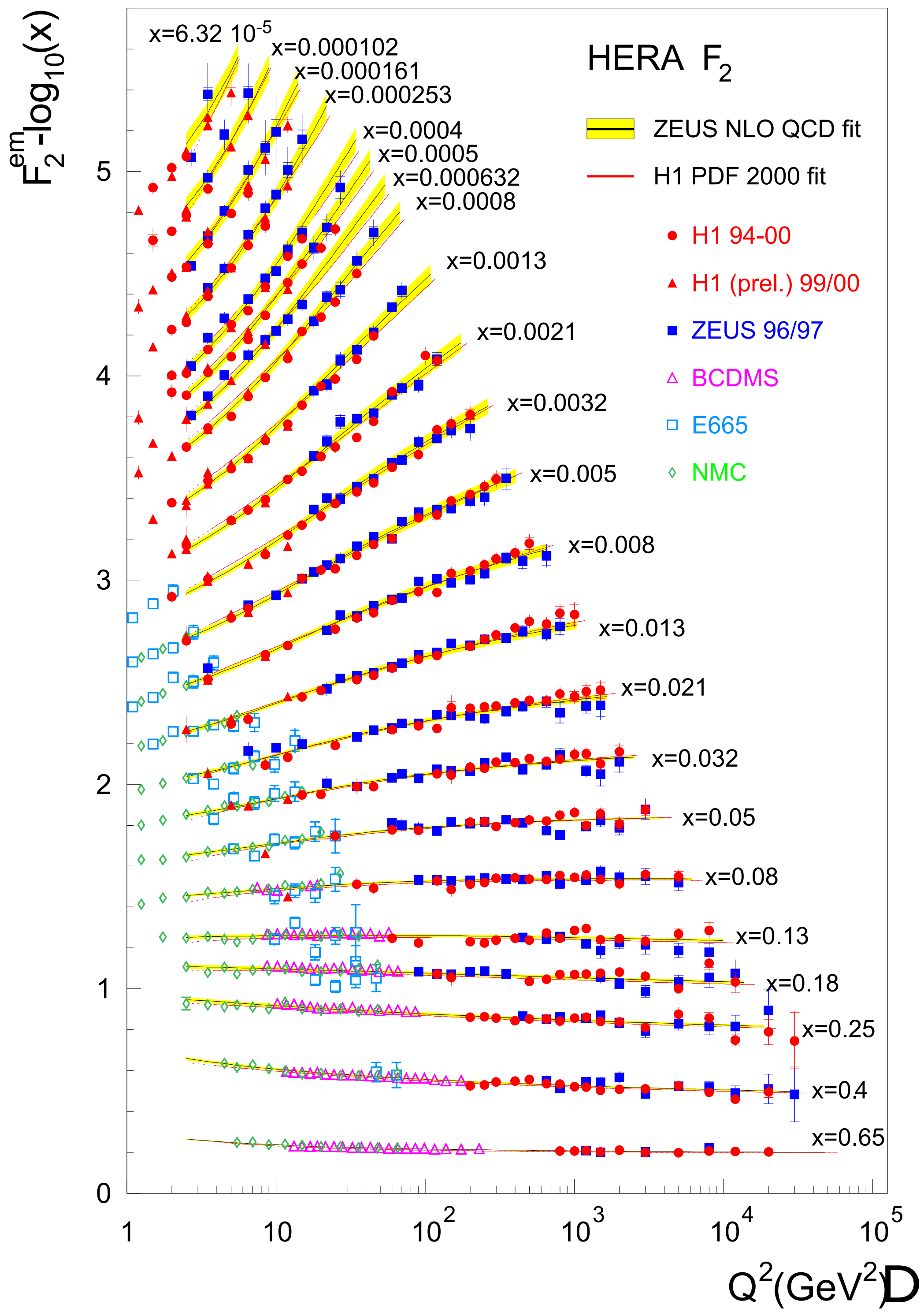
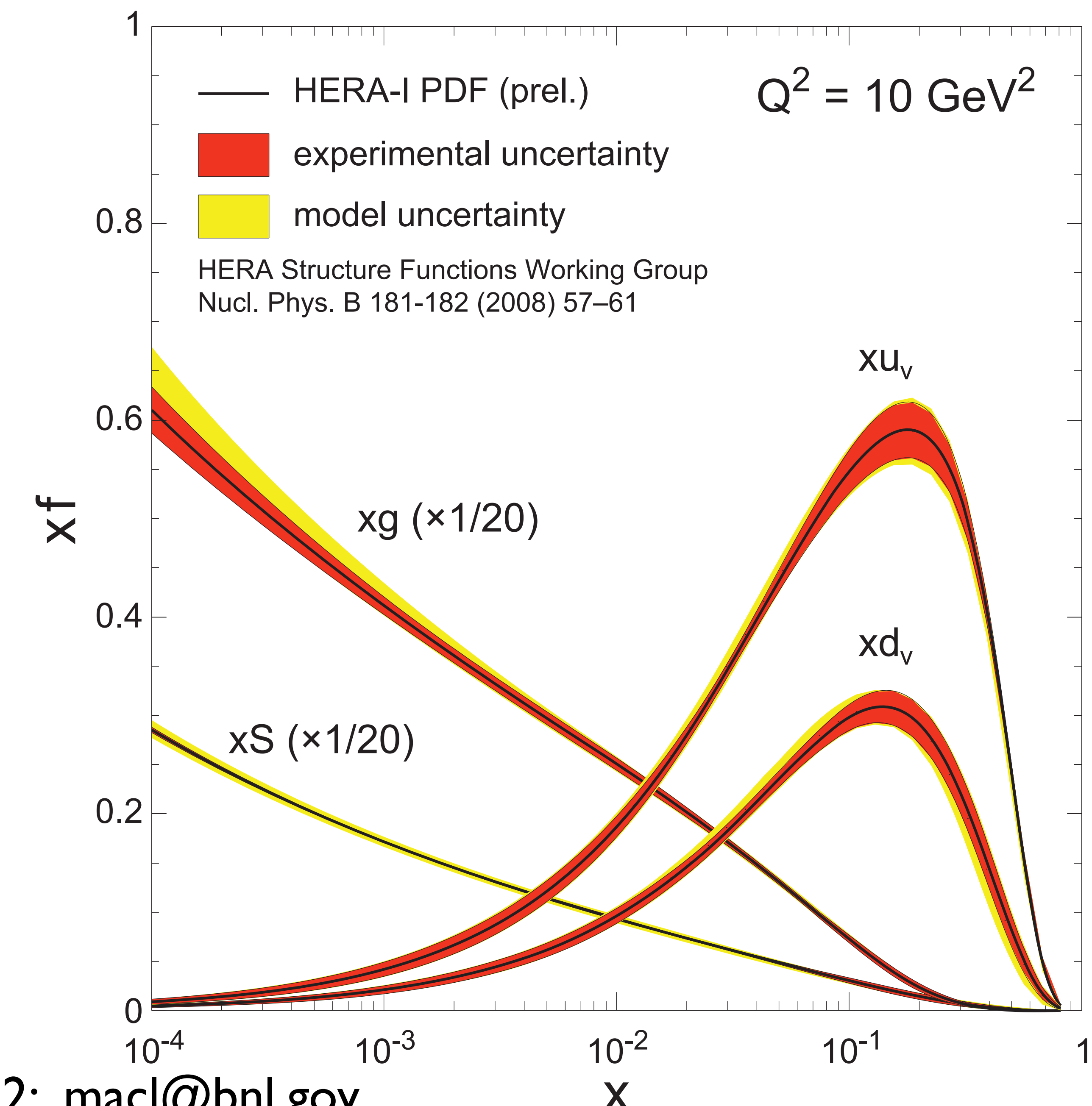


Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$



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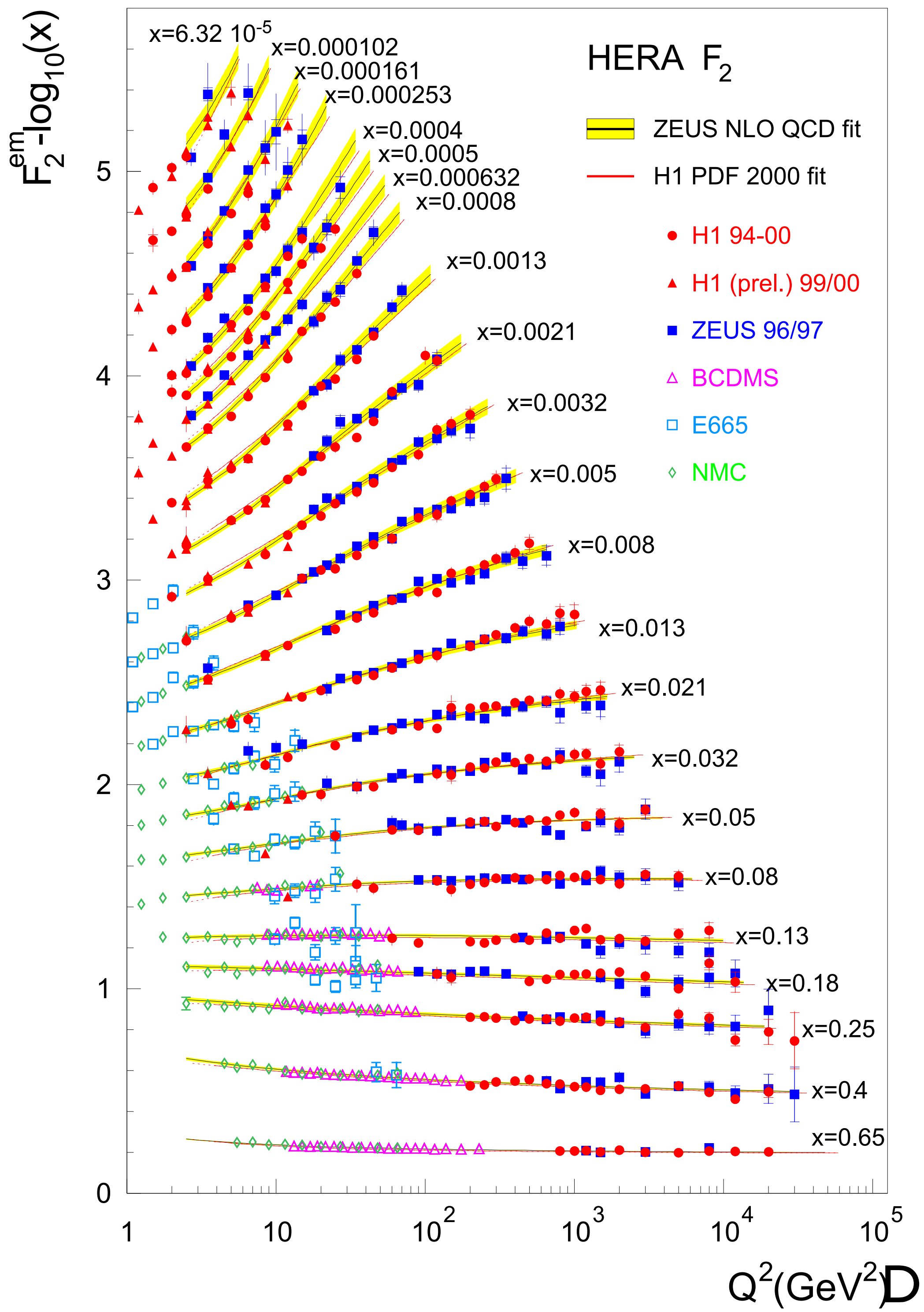

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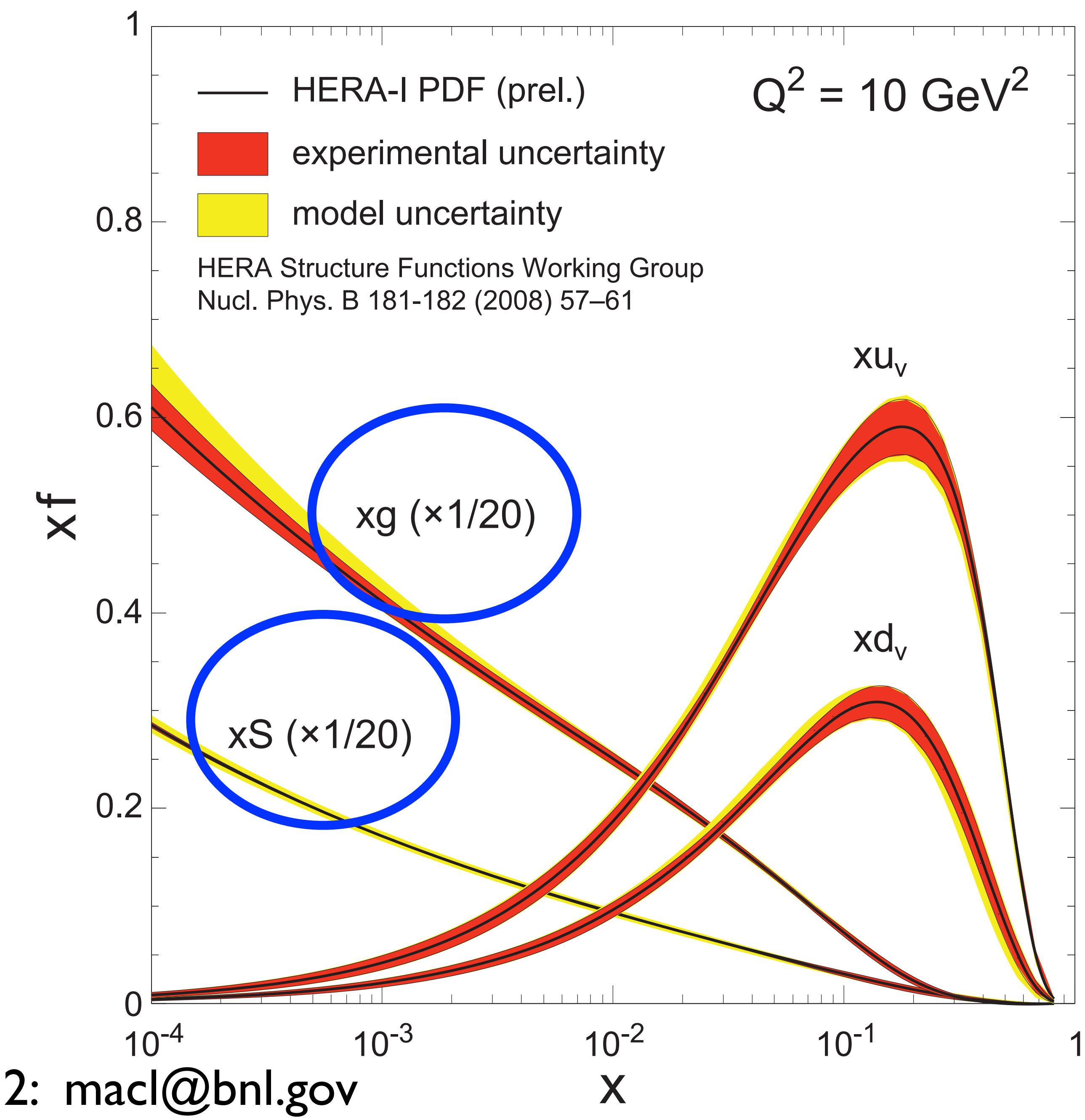

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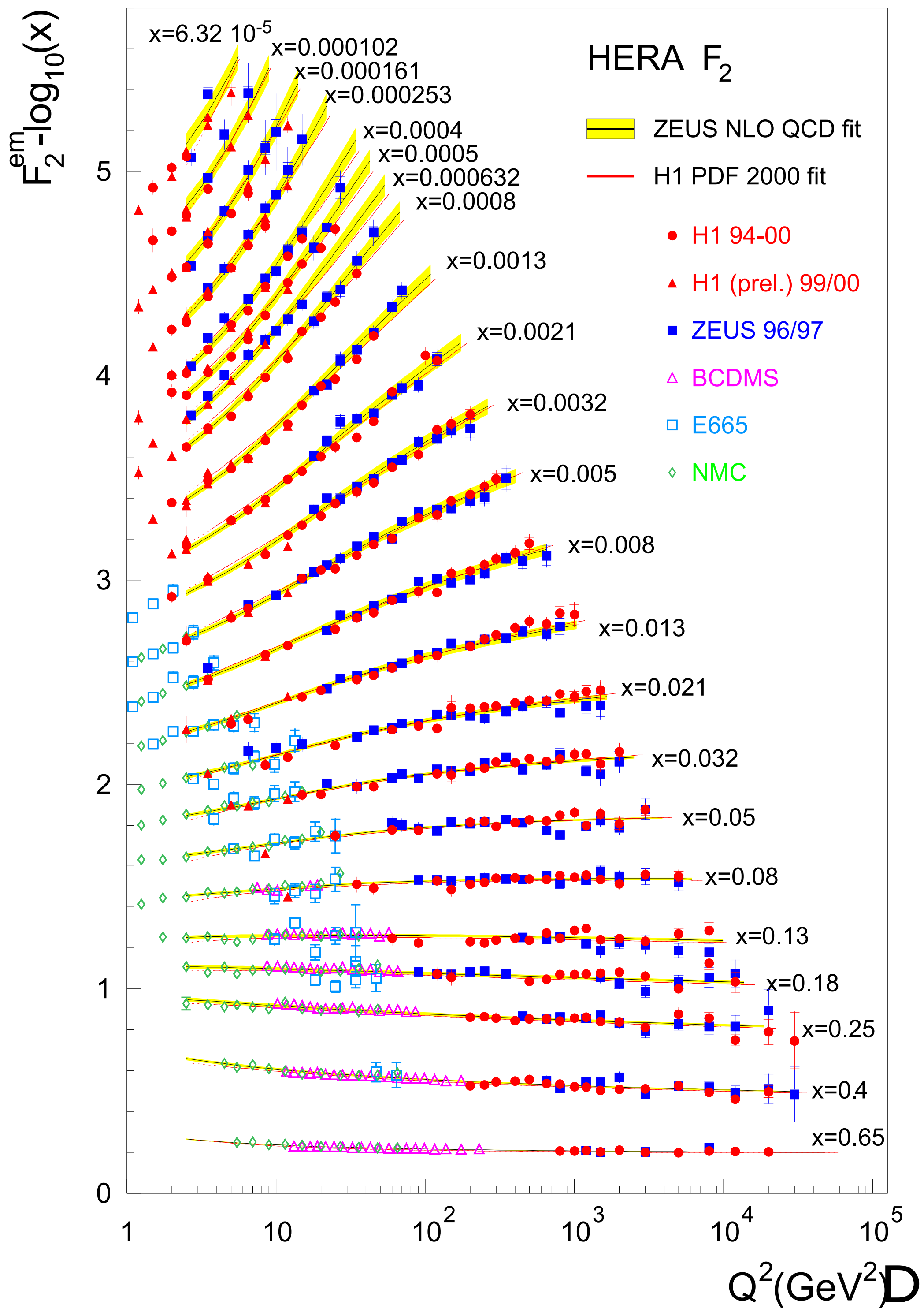

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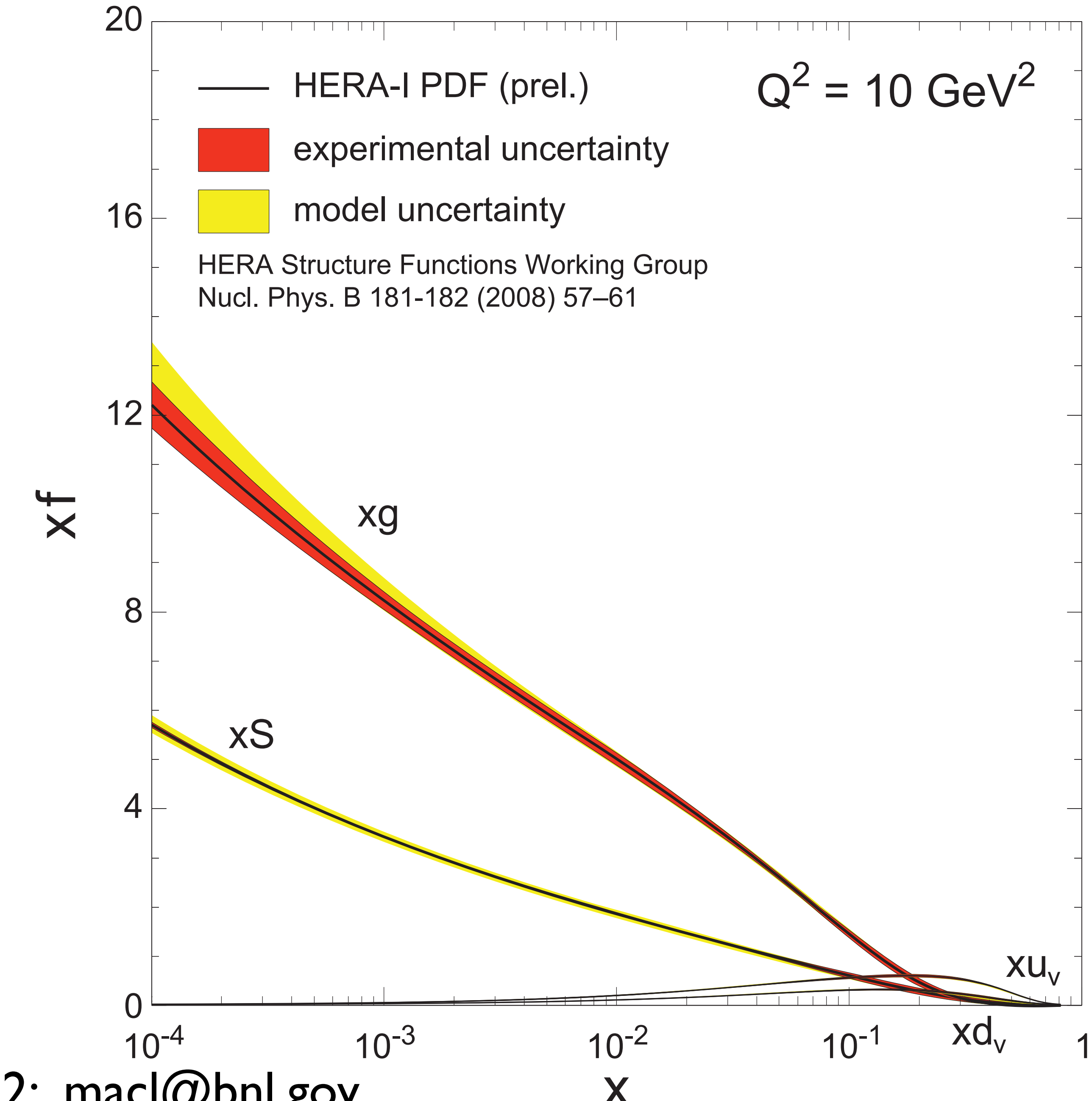
Evolution ⇒ $G(x,Q^2)$



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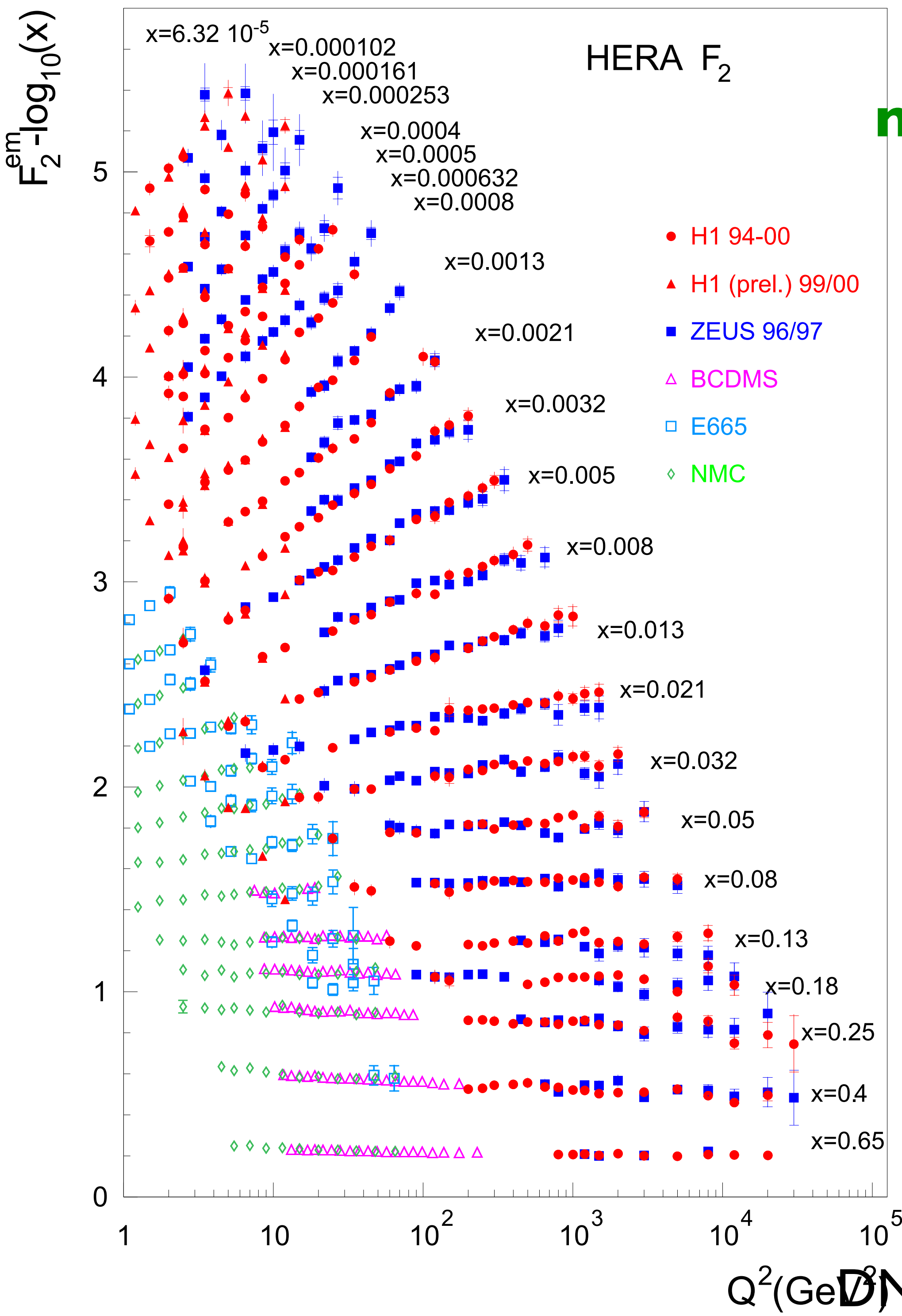

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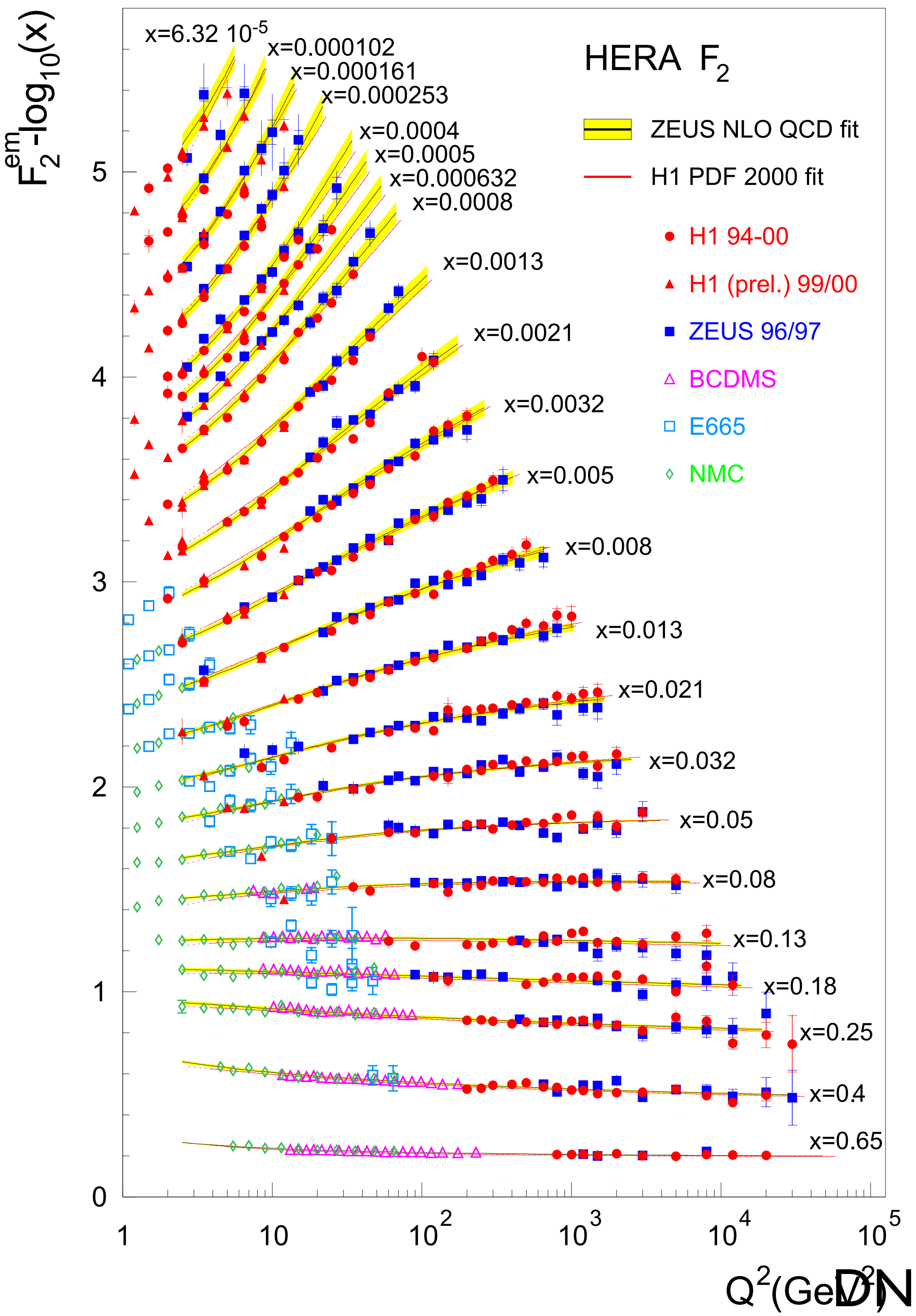

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