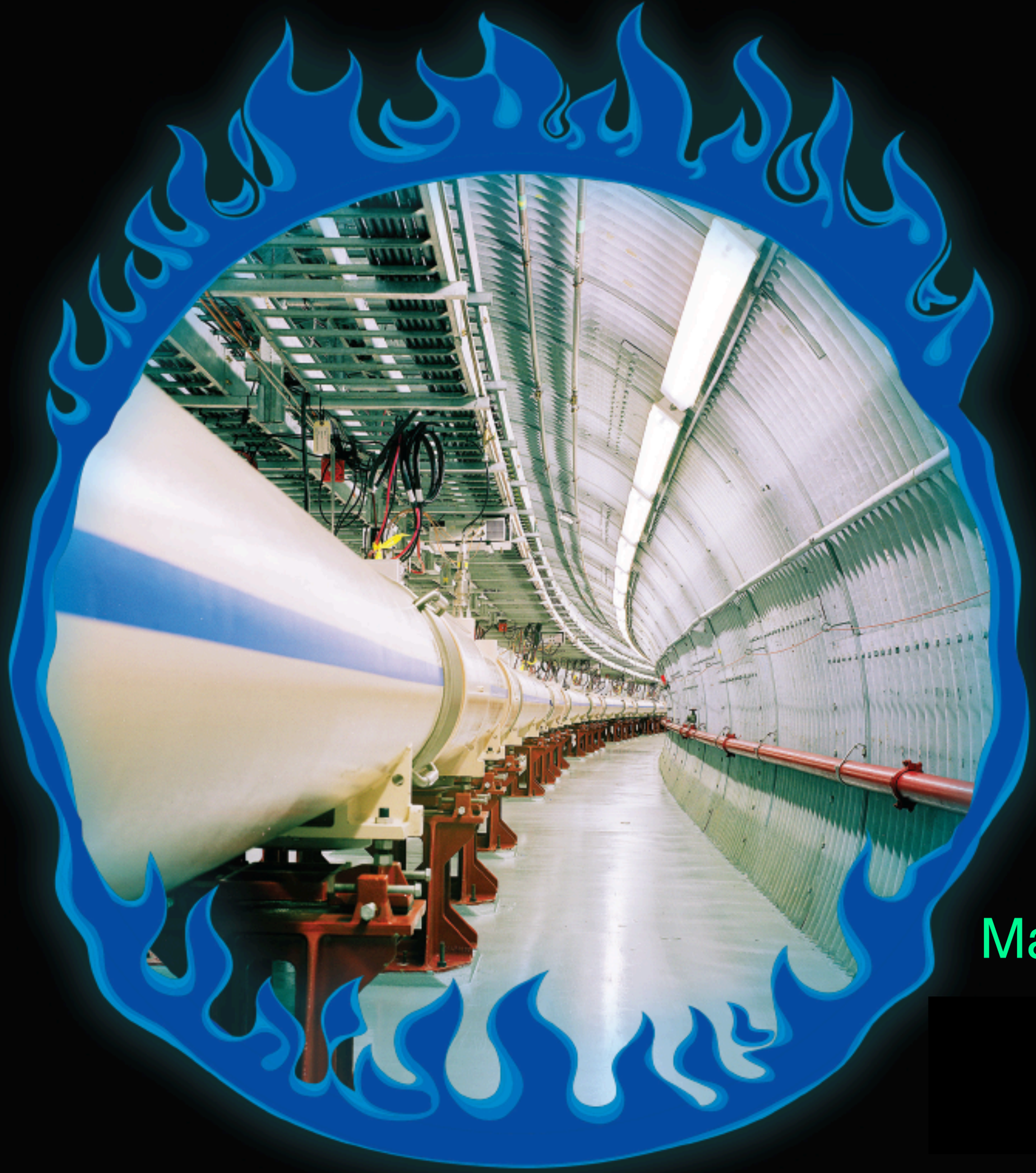

An Electron-Ion Collider at RHIC (eRHIC): A detailed study of the nucleus

Matthew A. C. Lamont
BNL

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

Editors:
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Universität Tübingen, Germany

arXiv:1108.1713

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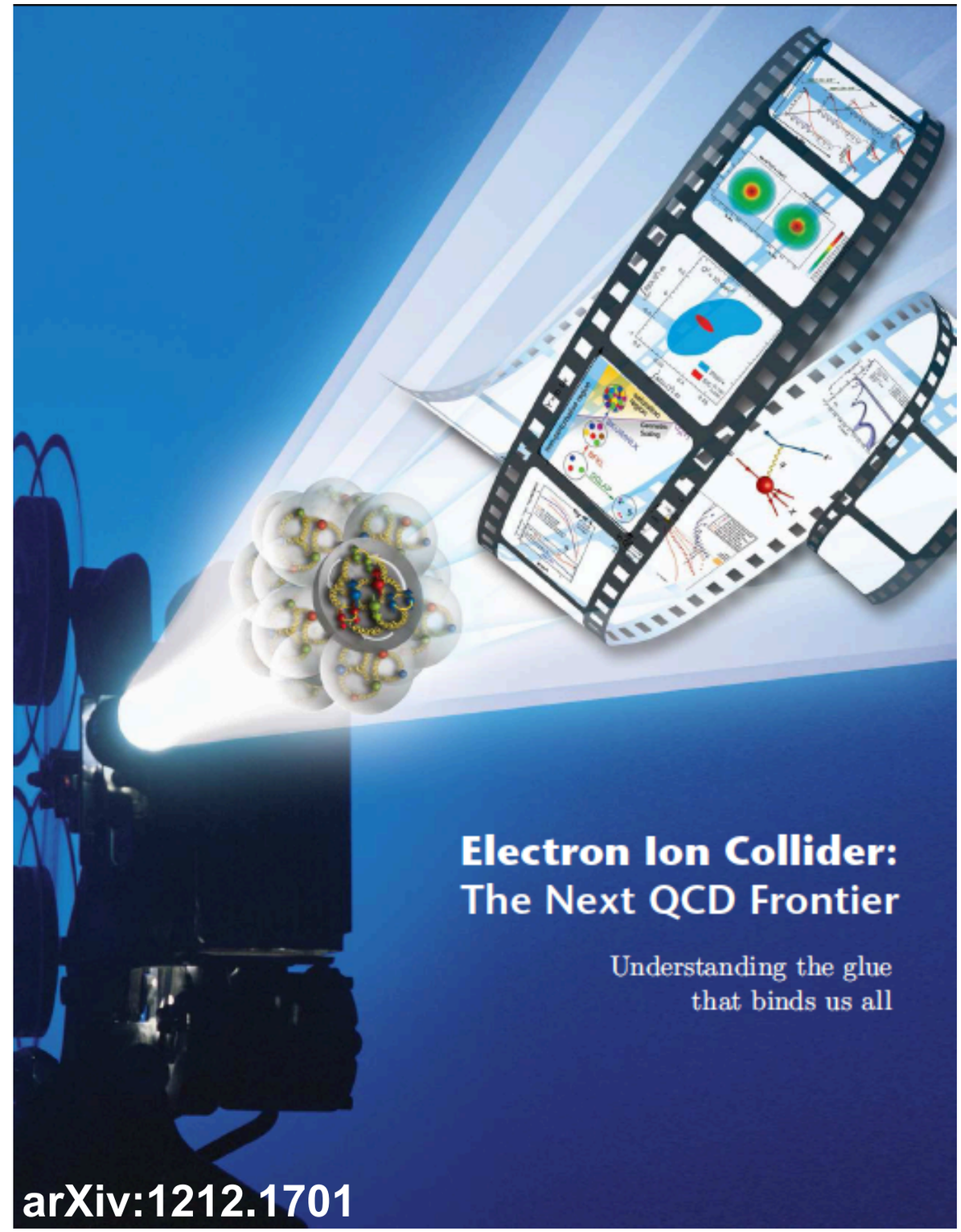
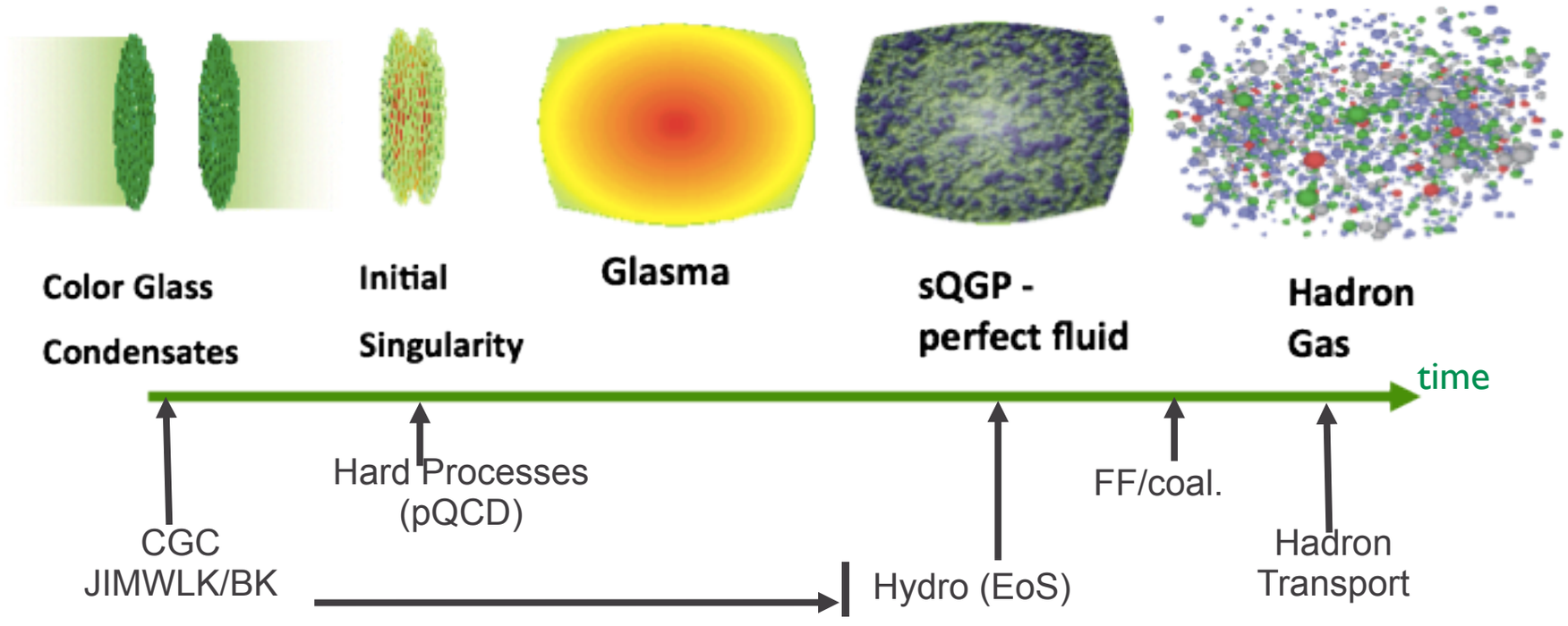
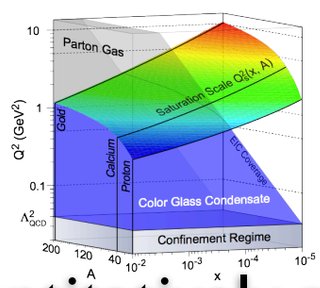


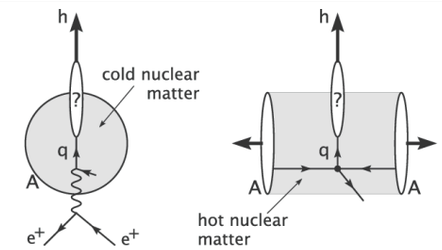
arXiv:1212.1701

Most compelling physics questions





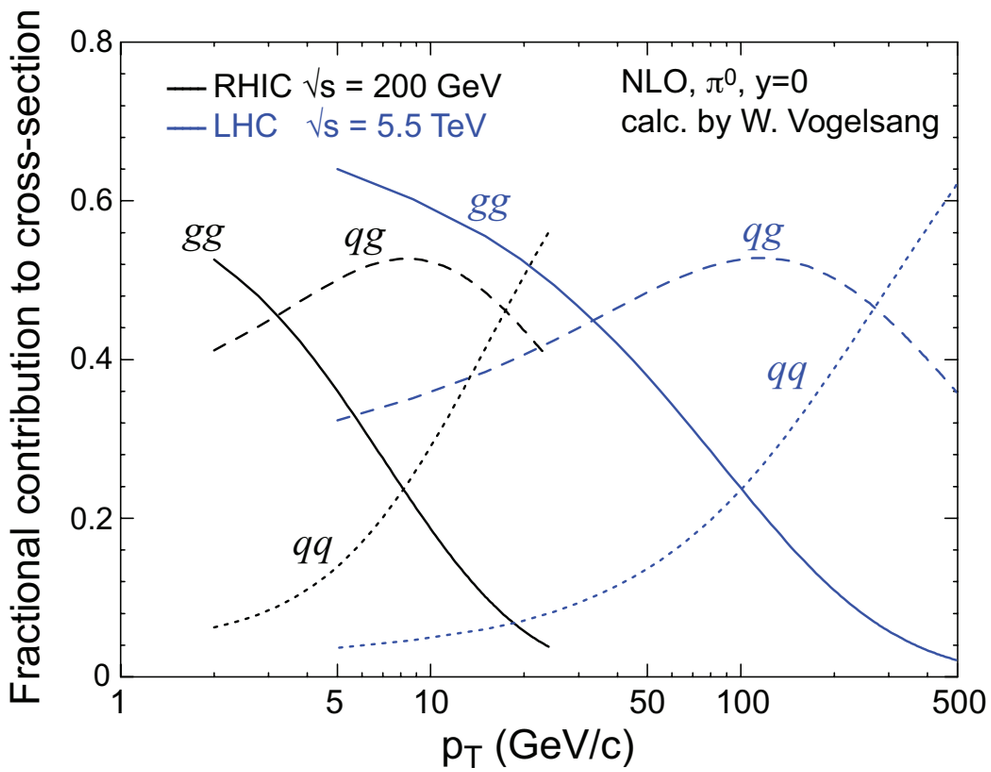
Strong Colour Fields and Hadronisation



- 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 nuclei 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 need to know the gluons - initial conditions



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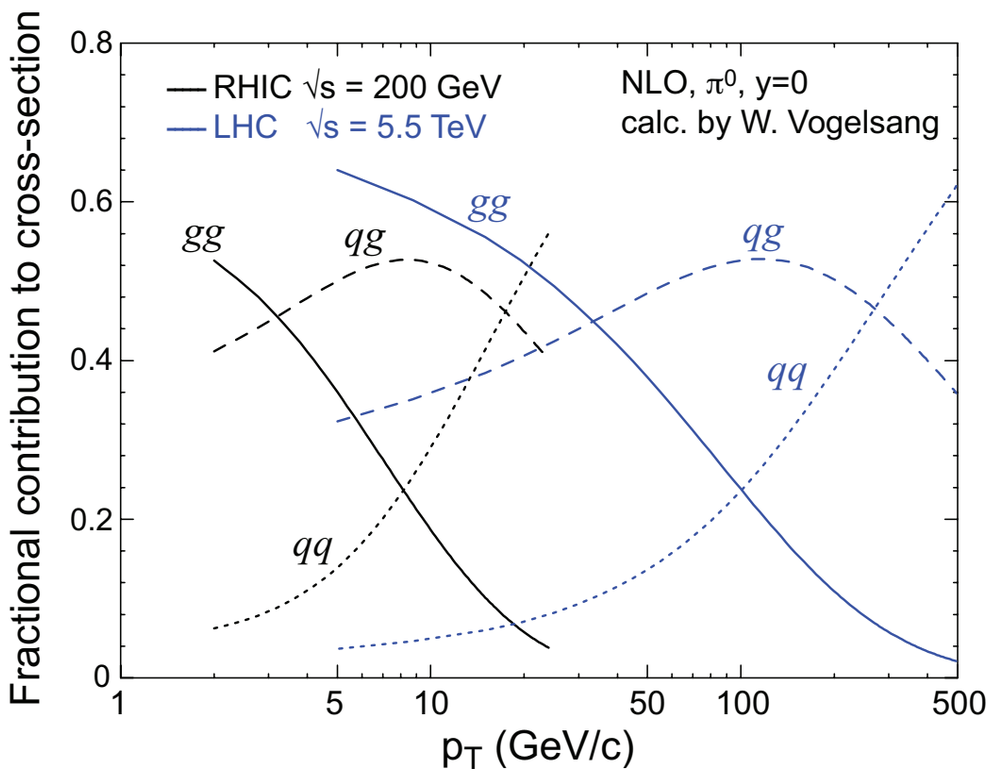

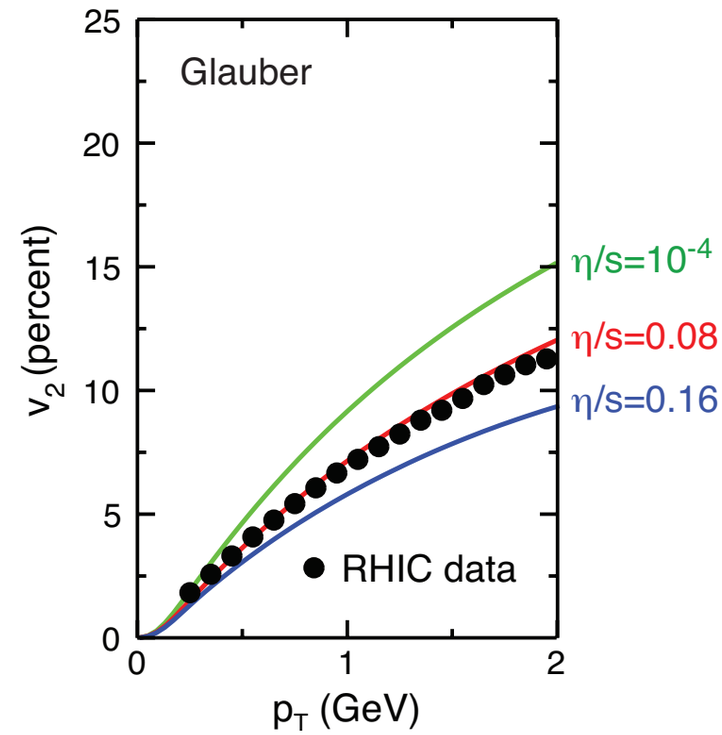

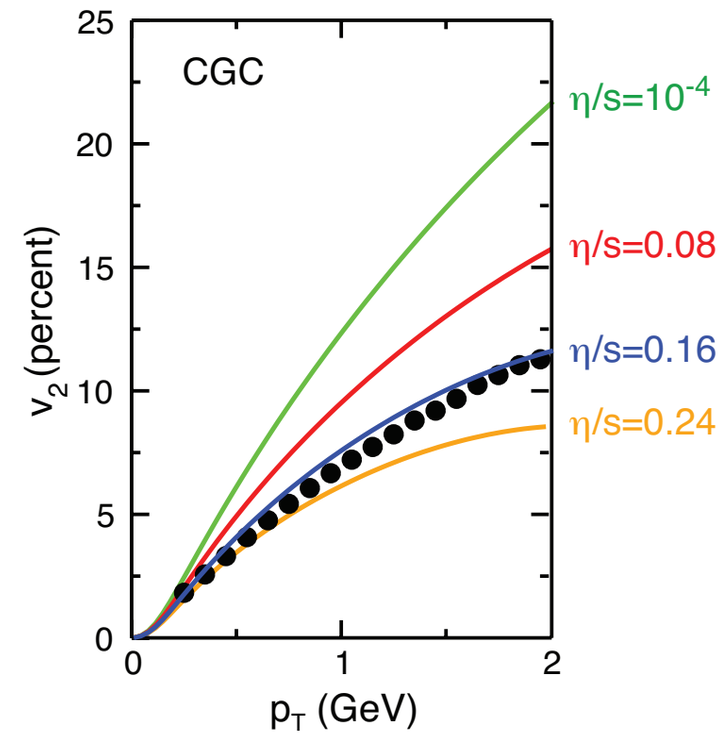

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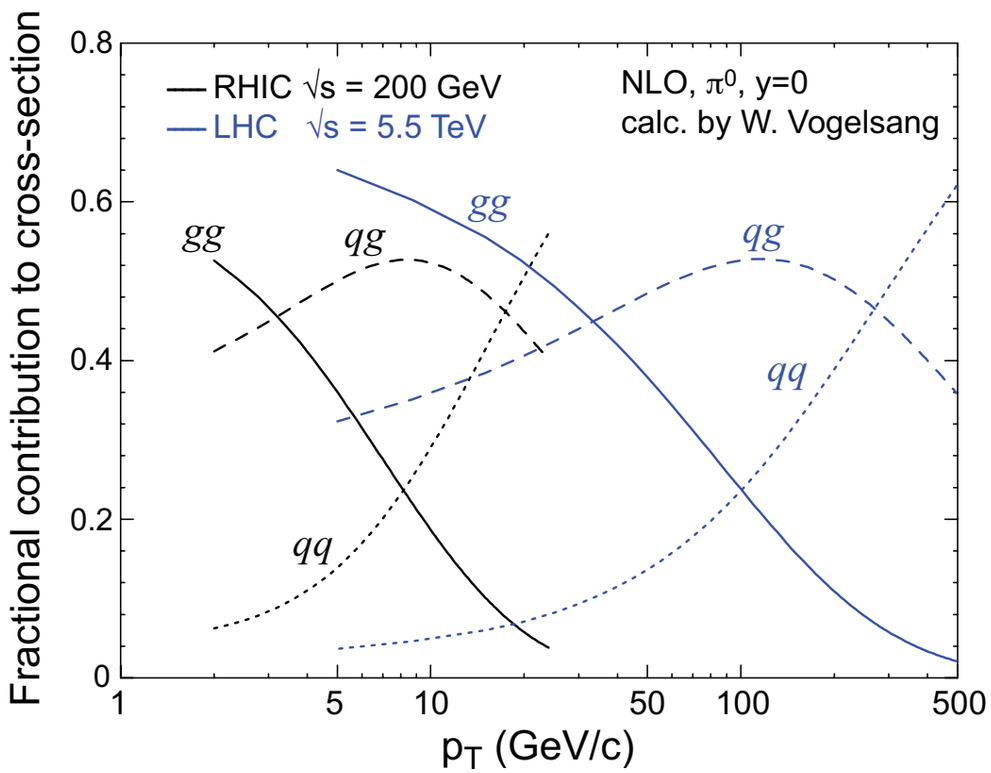

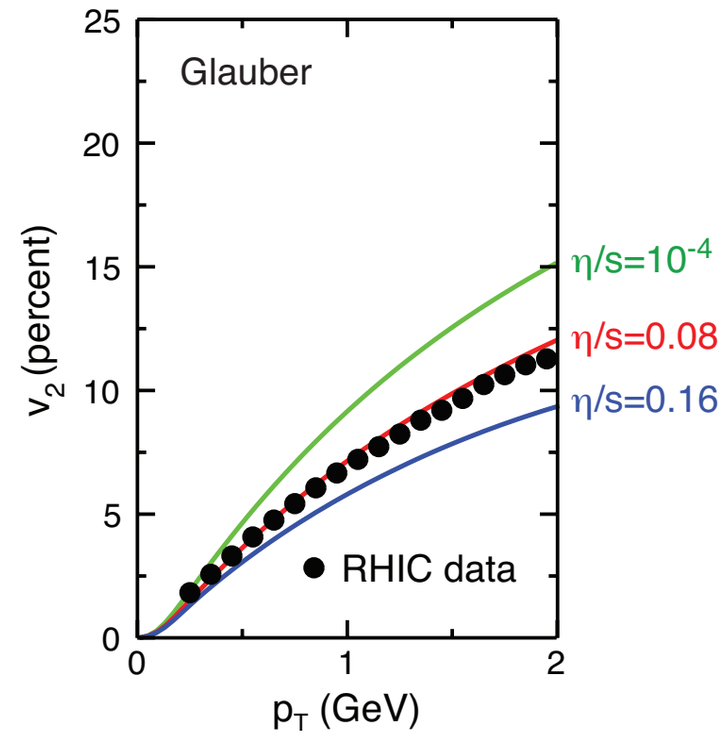

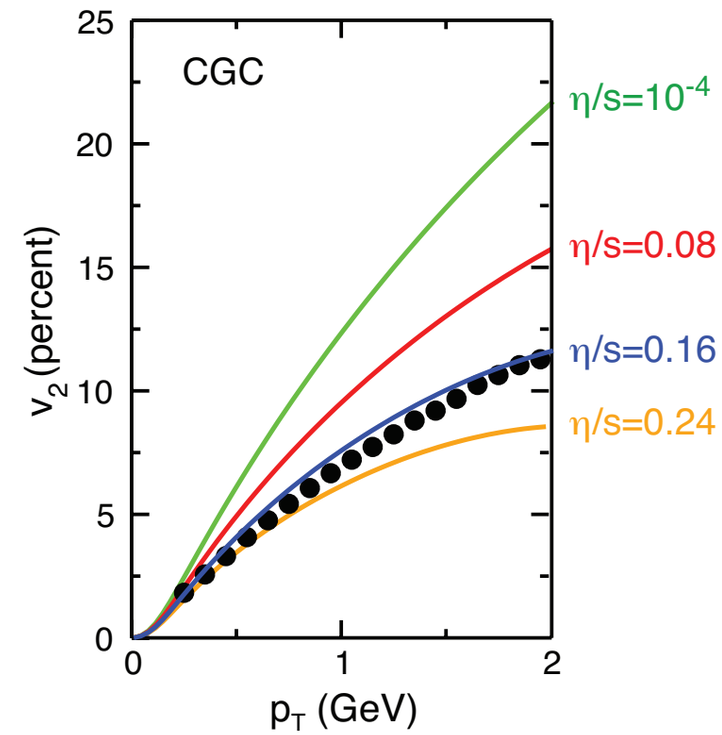

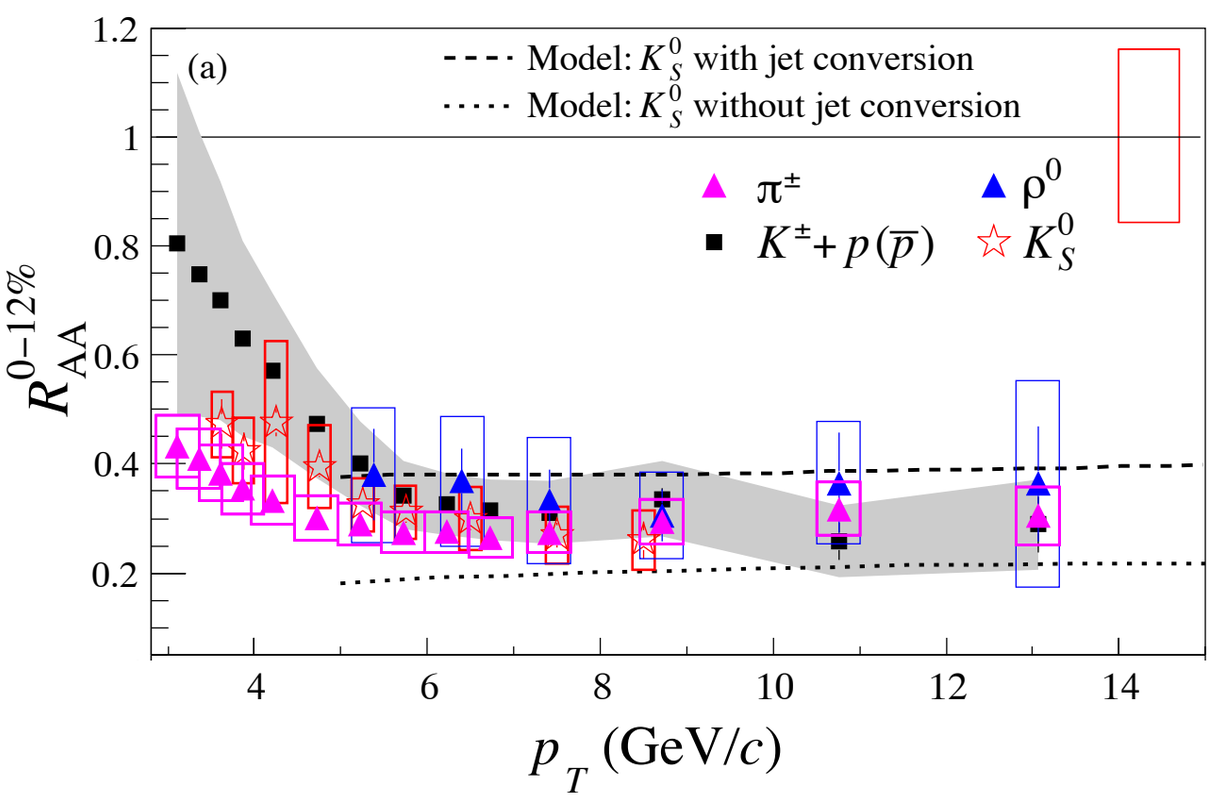

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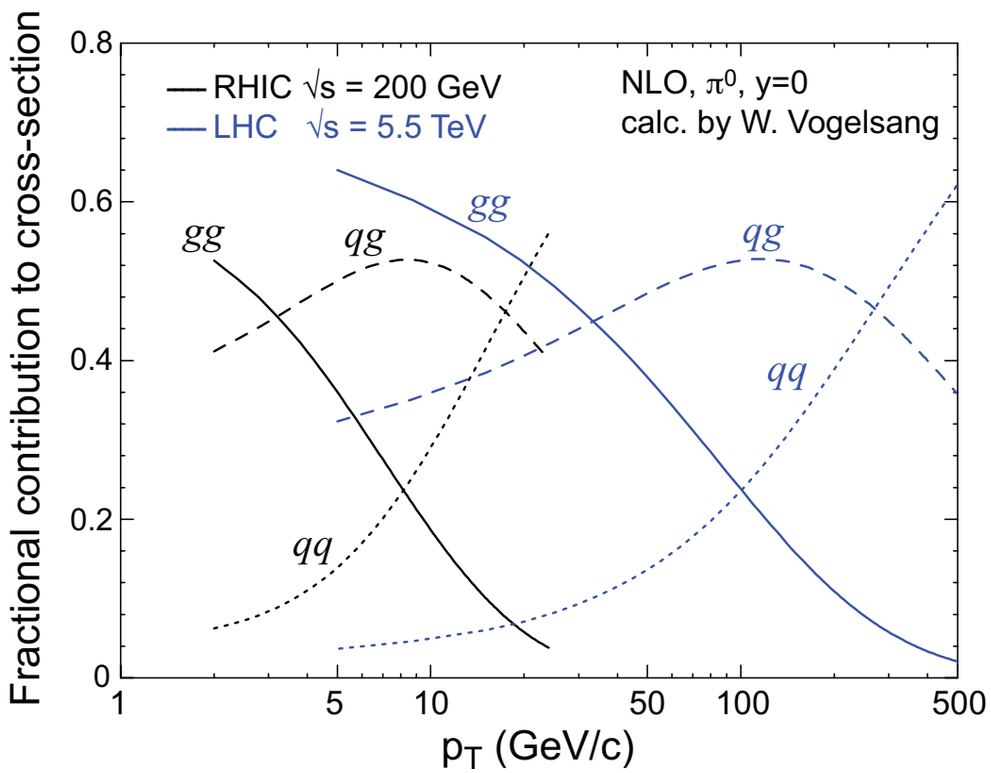
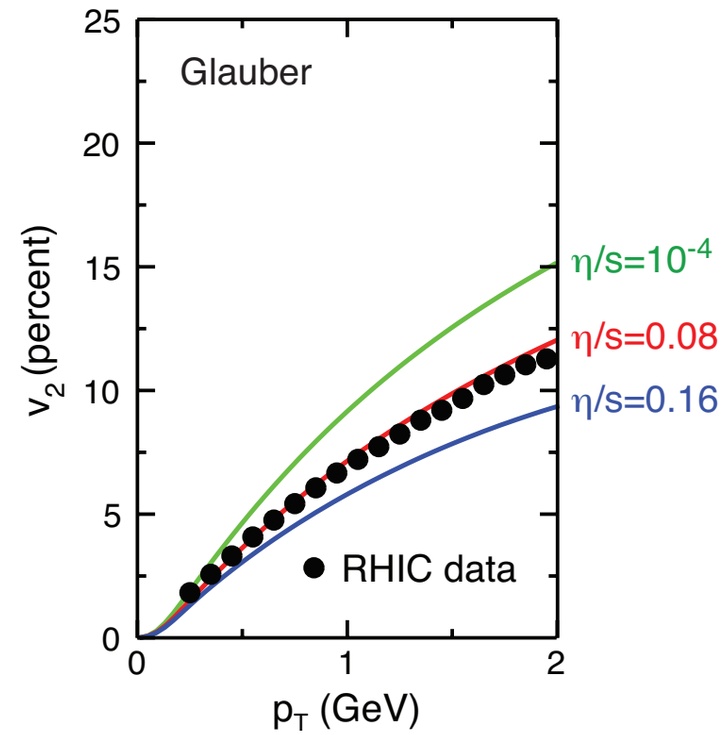
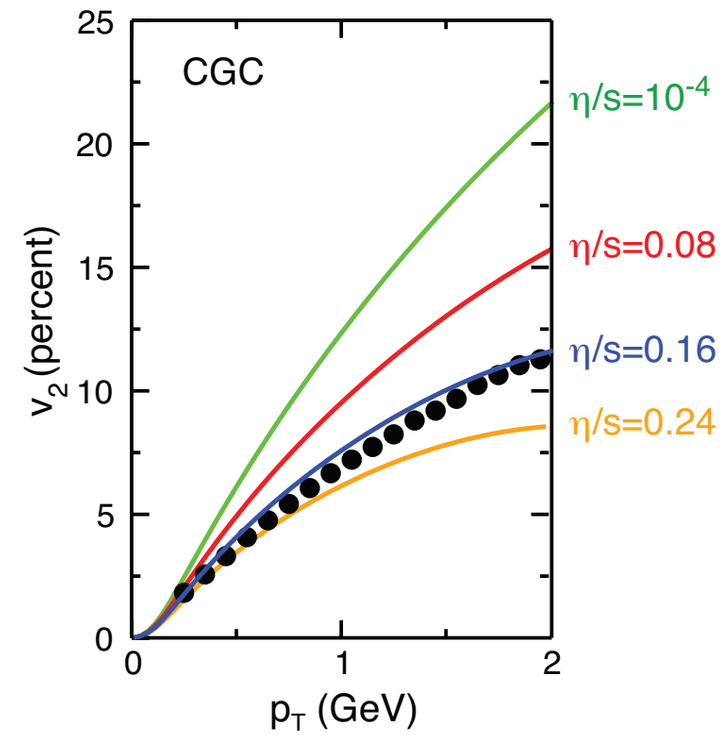
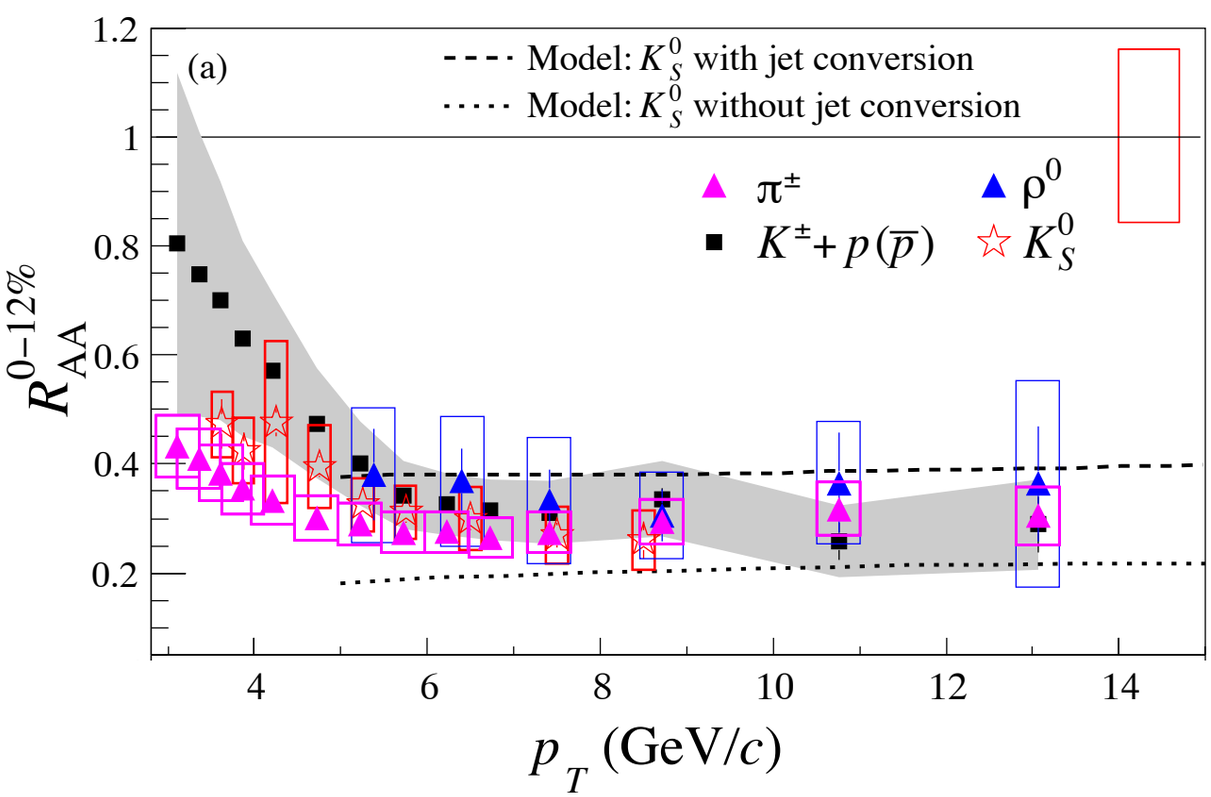
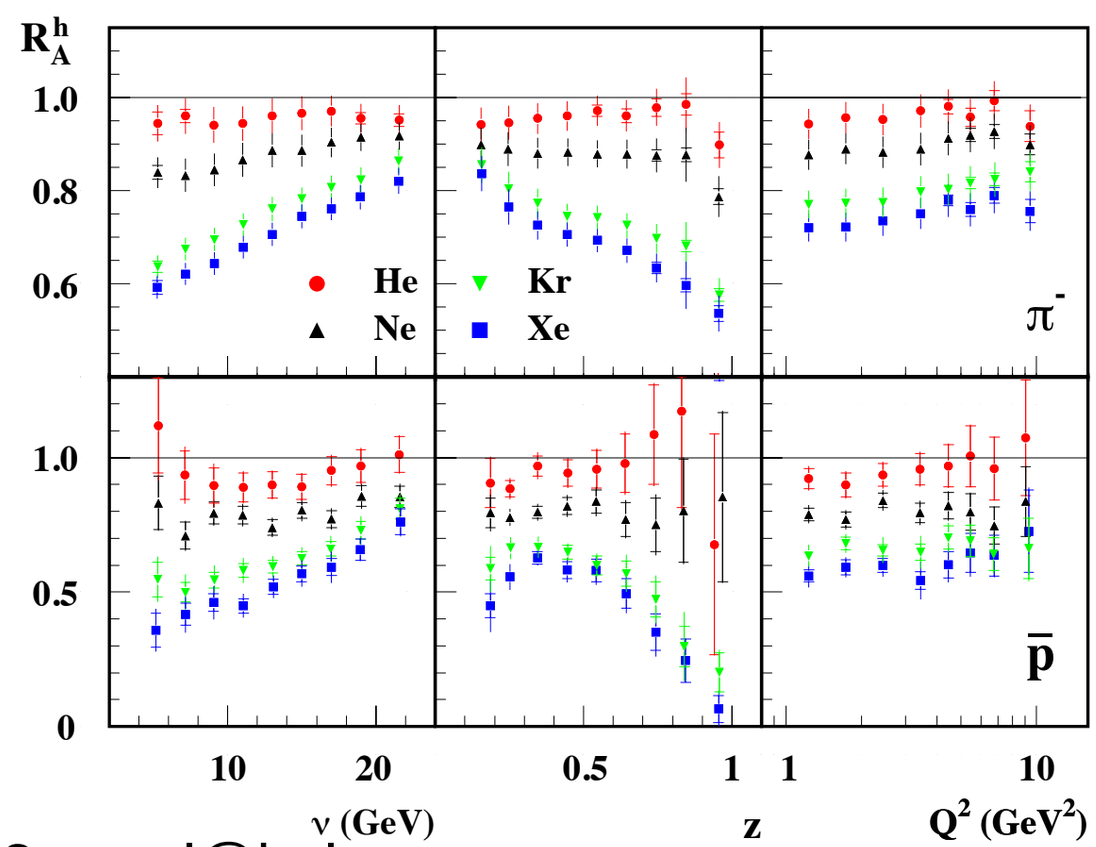




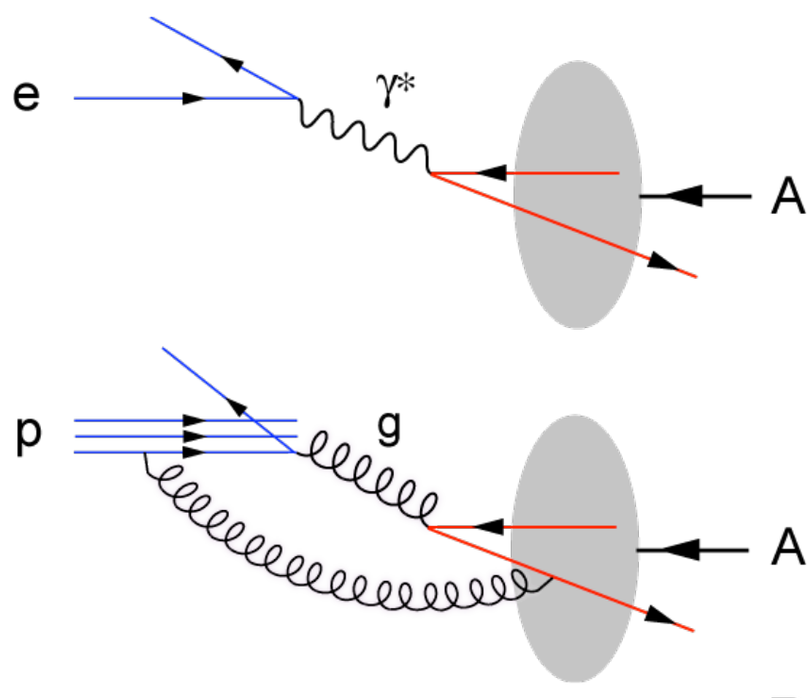






Why e+A collisions and not p+A?

- 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
- 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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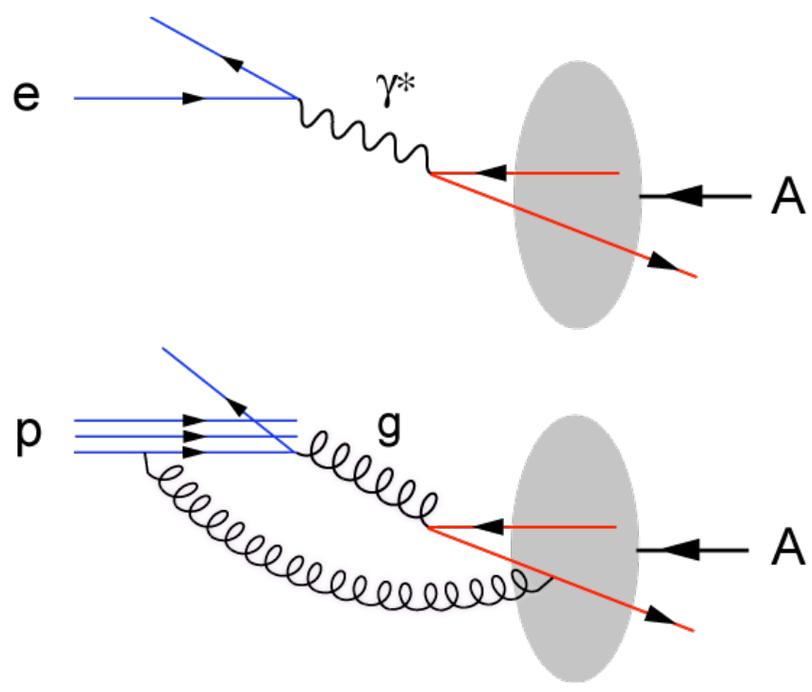

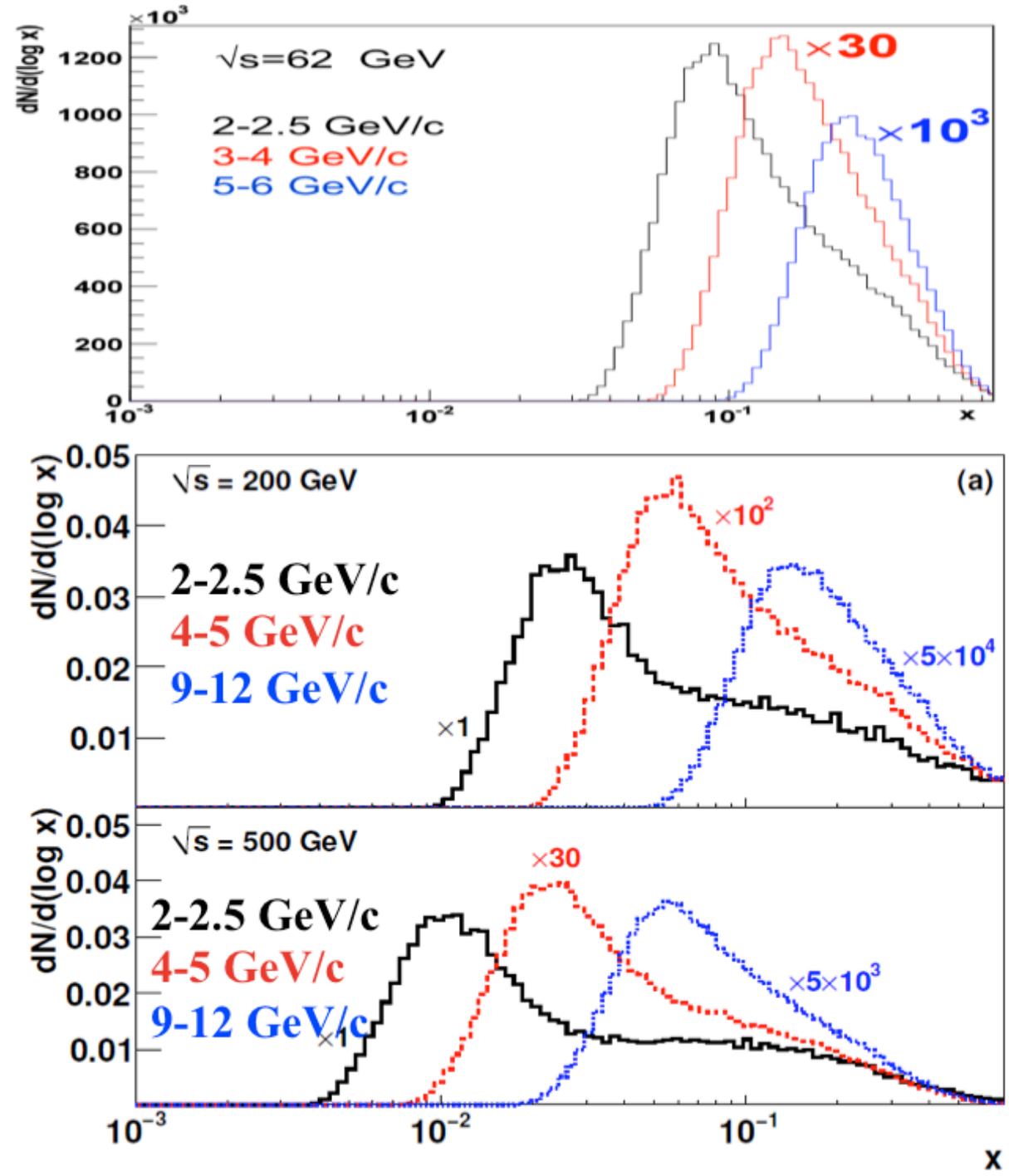

p_T - x correlation in p+p

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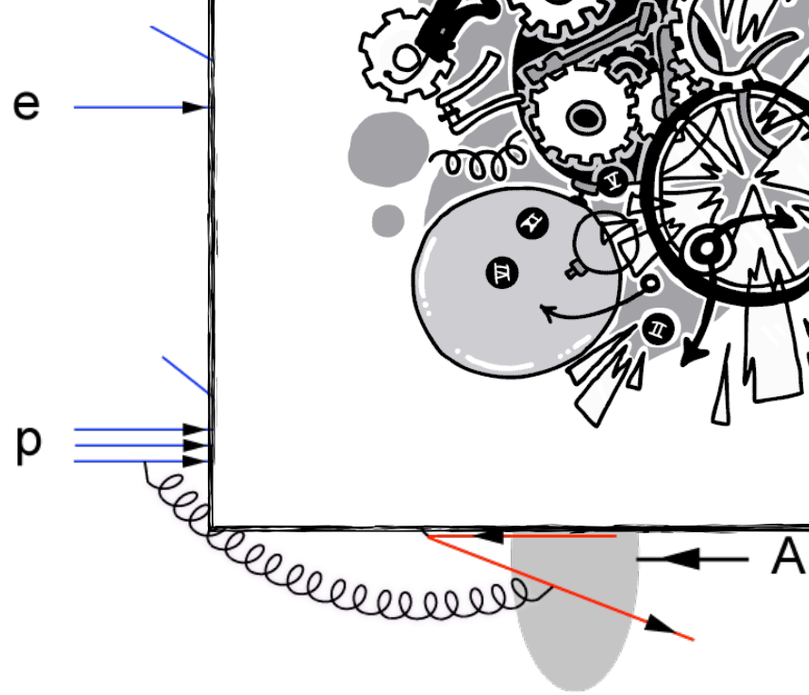
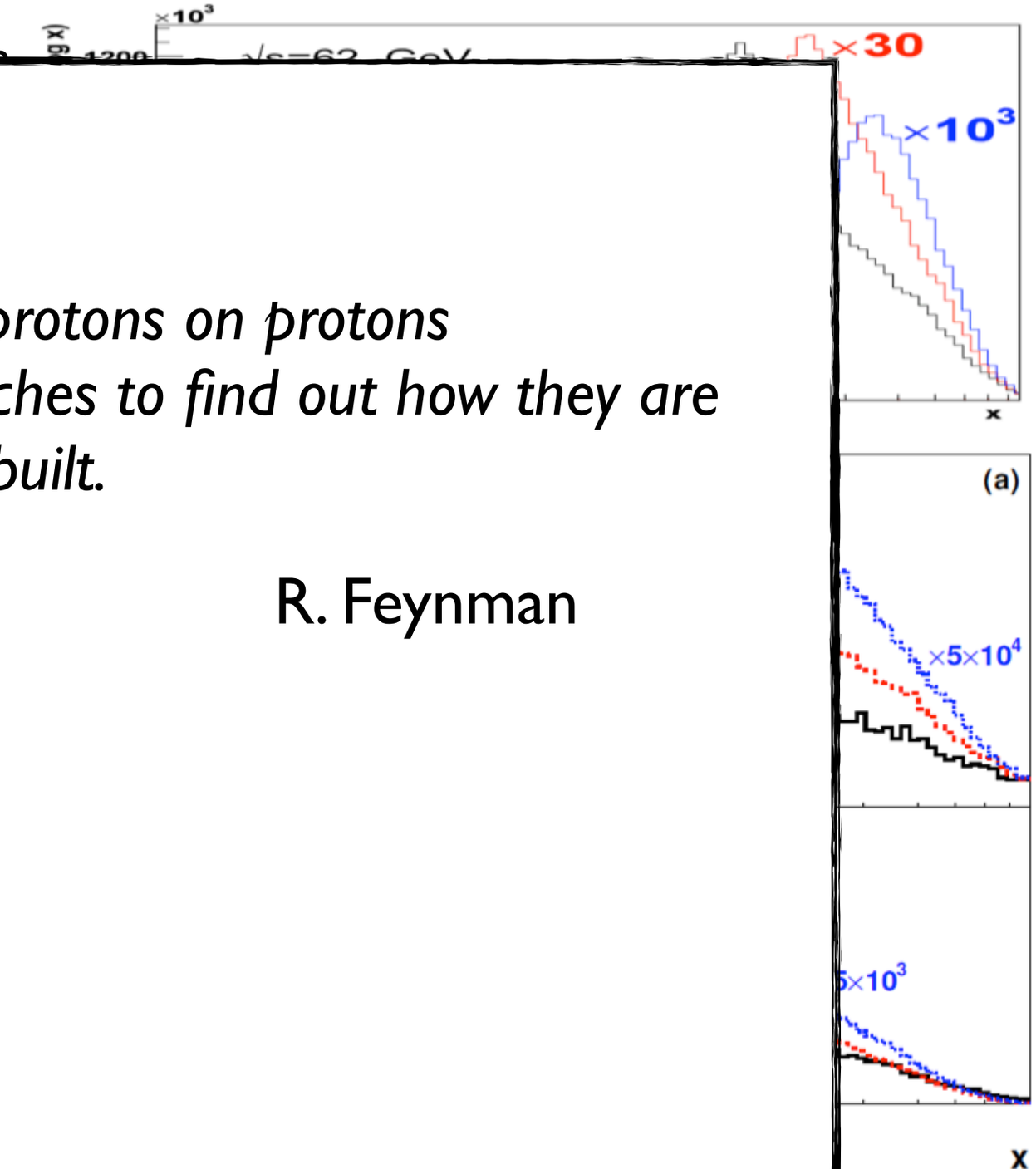


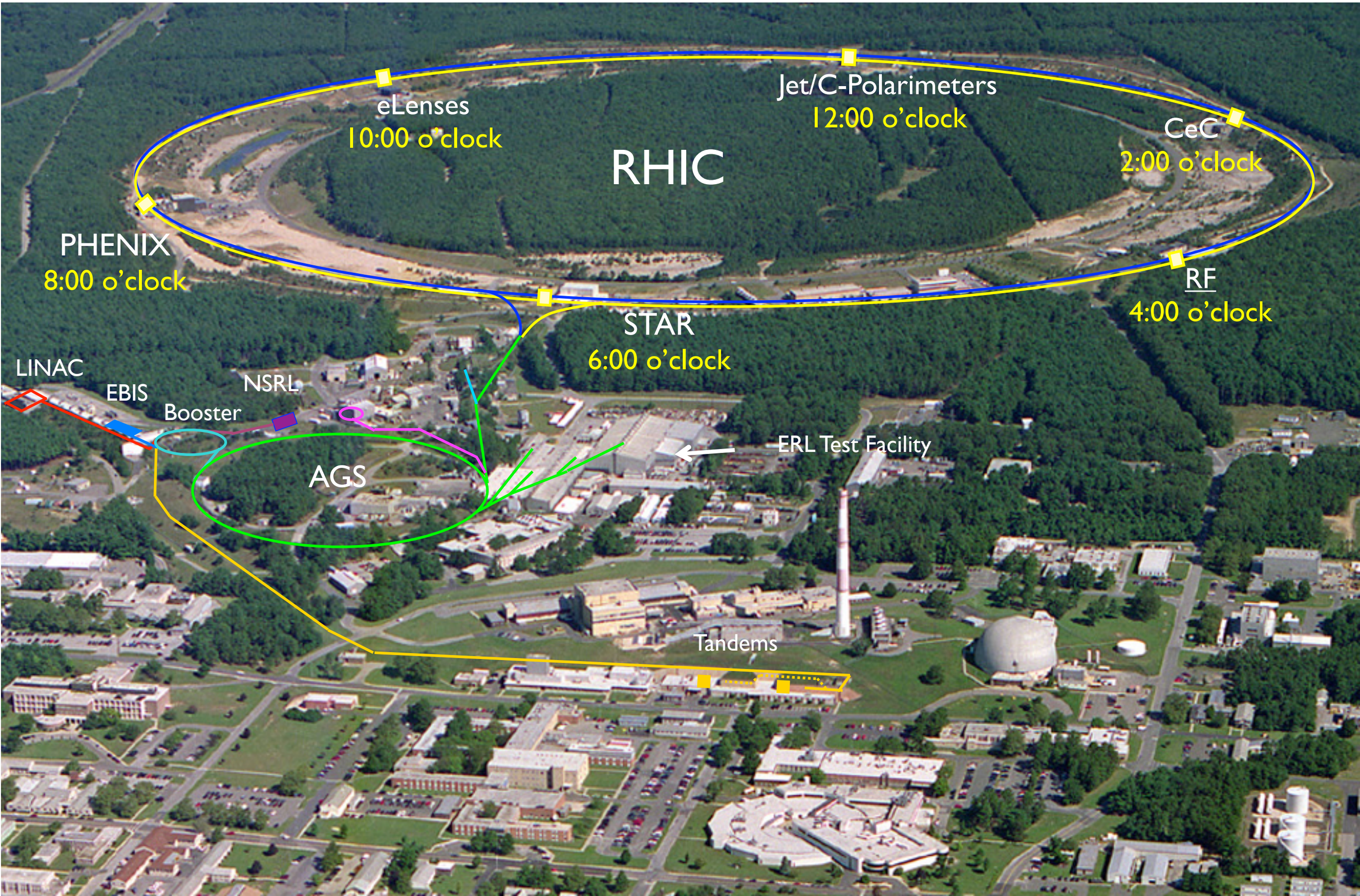


Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.

R. Feynman

p_T - x correlation in p+p

From RHIC to eRHIC



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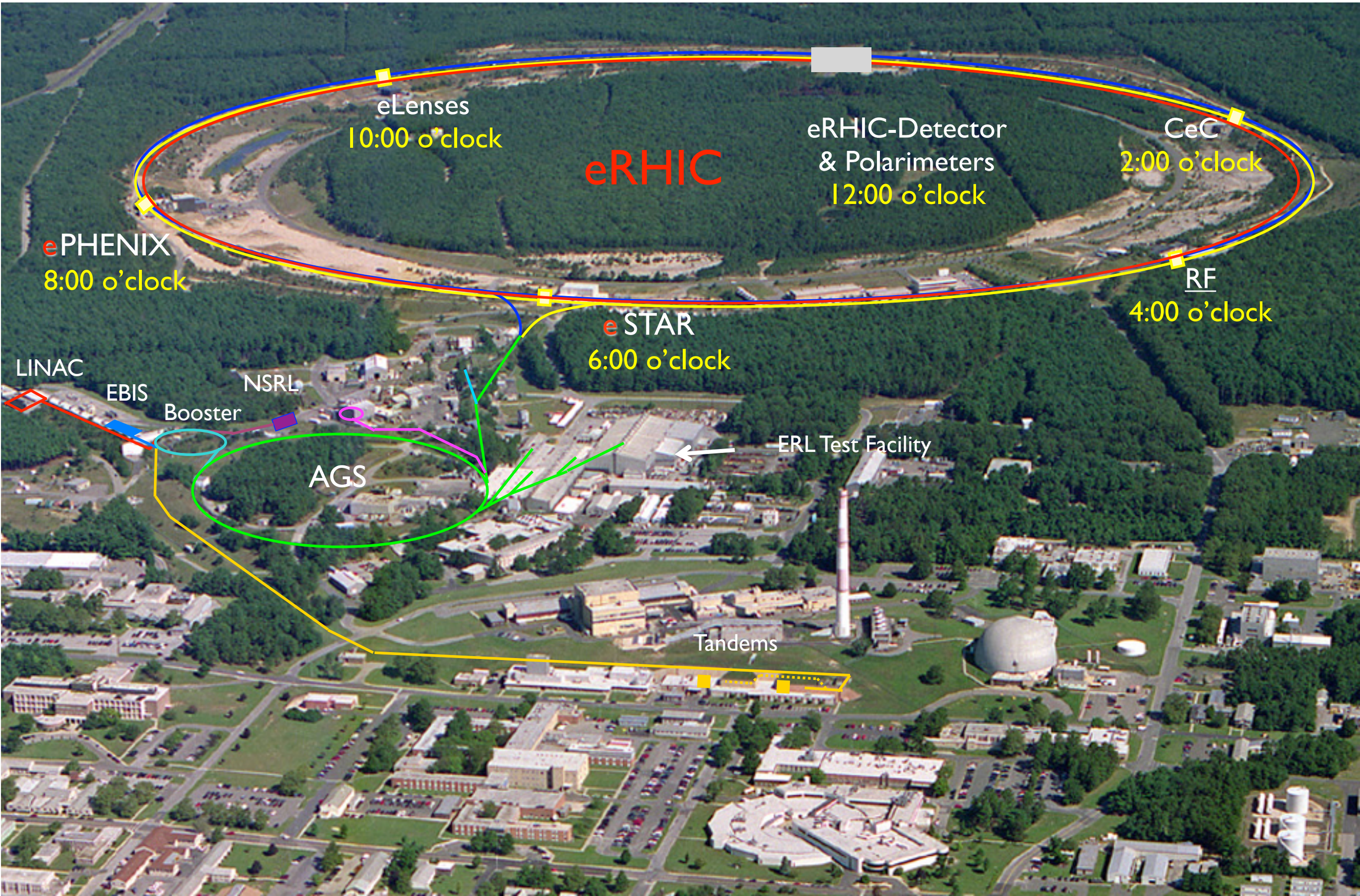
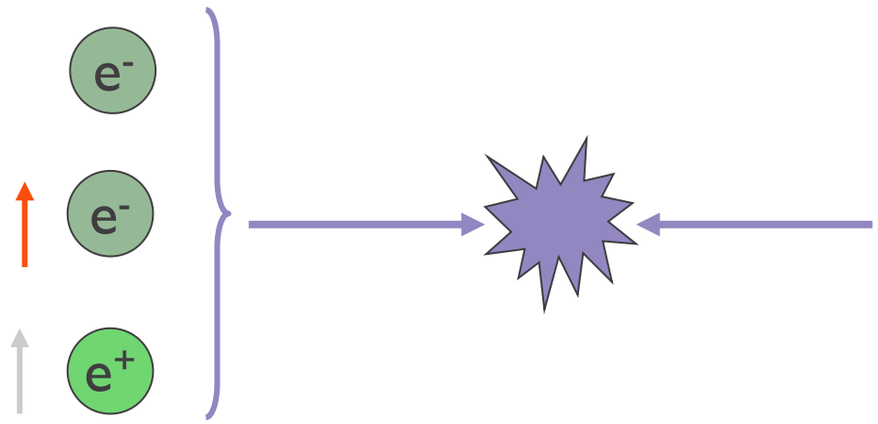


What is eRHIC?

Electron accelerator

(to be built)

Unpolarized and polarized leptons
5-20 (30) GeV

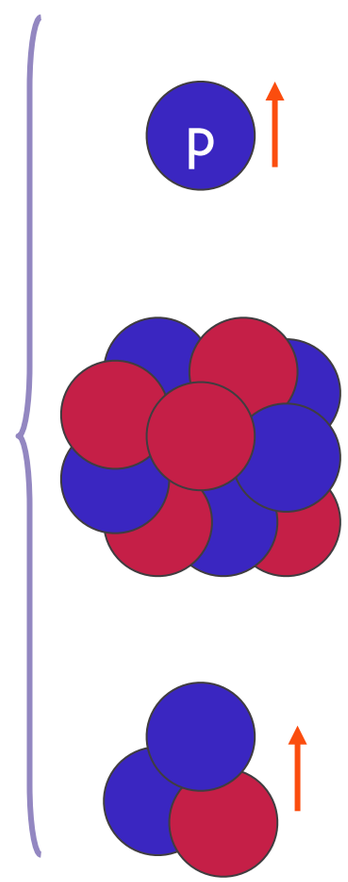


70% e^- beam polarization goal

polarized positrons?

RHIC

Existing = $2B

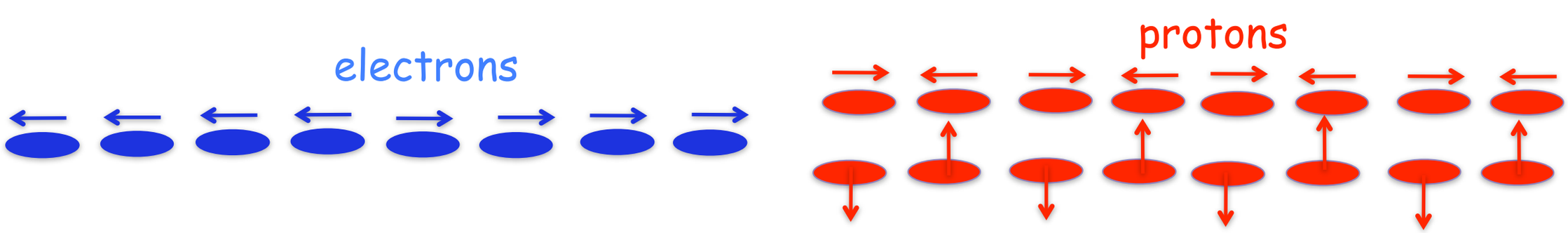


Polarized protons
50-250 GeV

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

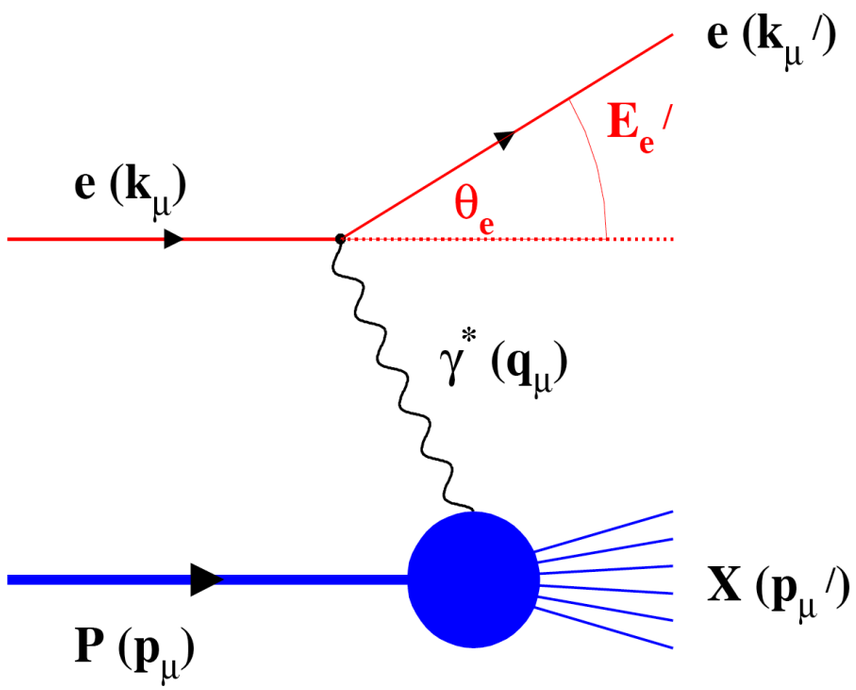
Polarized light ions He^3
166 GeV/u

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



DIS Kinematics

e(k) + p(p) → e(k') +X(px)



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

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

Measure of resolution power or "Virtuality"

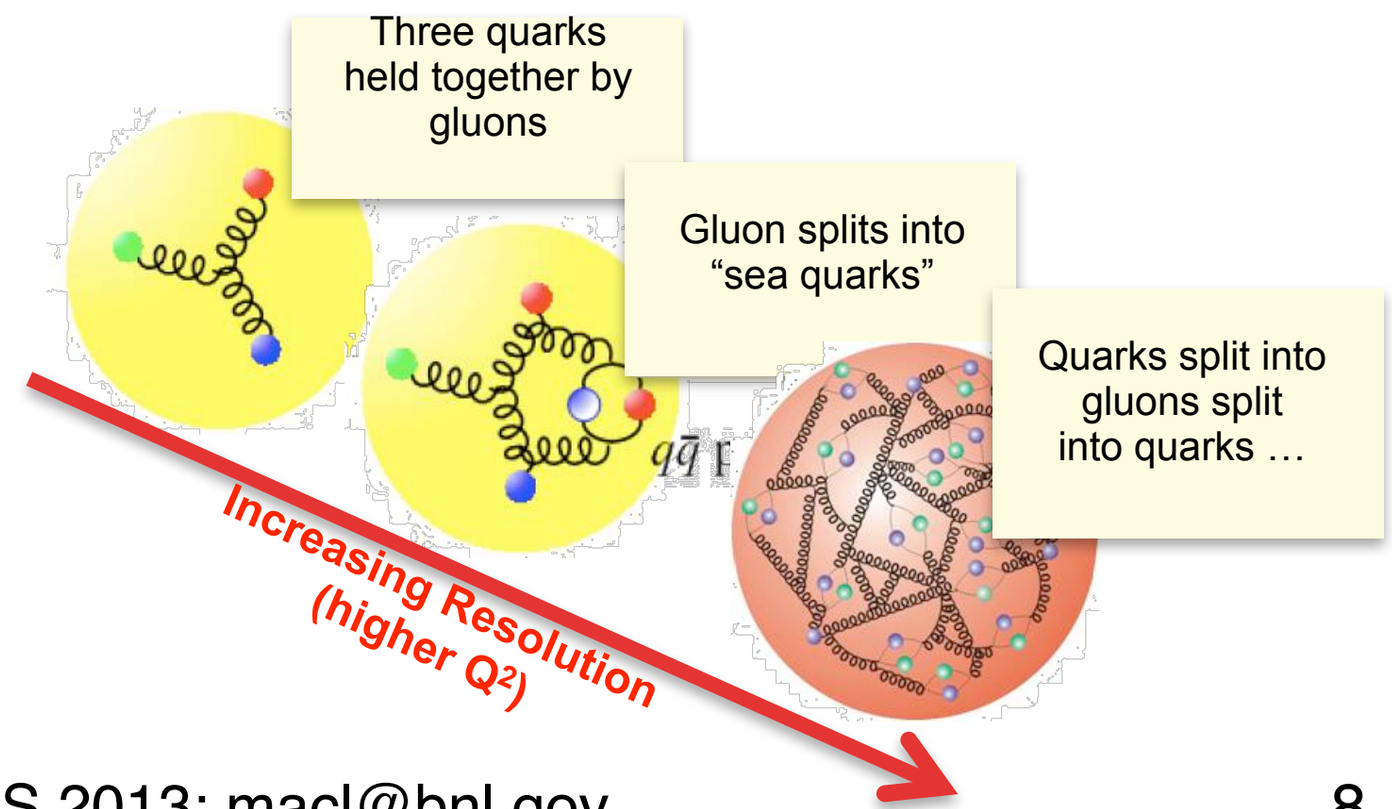
$$y = \frac{pq}{pk} = 1 - \frac{E_{e'}}{E_e} cos^2(\frac{\theta'_e}{2})$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Important to note that in order to have different y for the same x and Q^2, need to change the beam energies

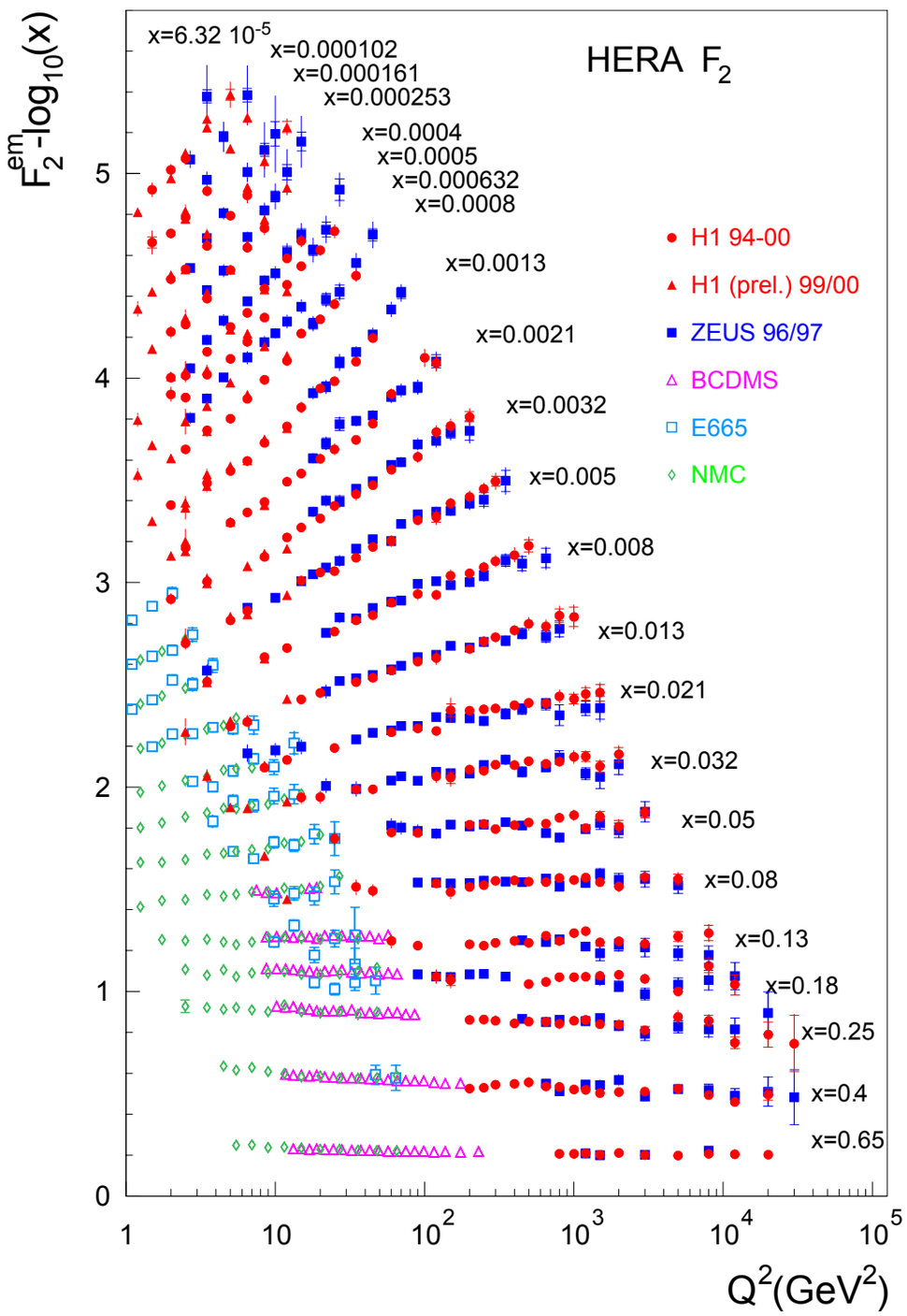


What did we learn from e+p collisions at HERA?

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

quark+anti-quark momentum distributions

gluon momentum distribution



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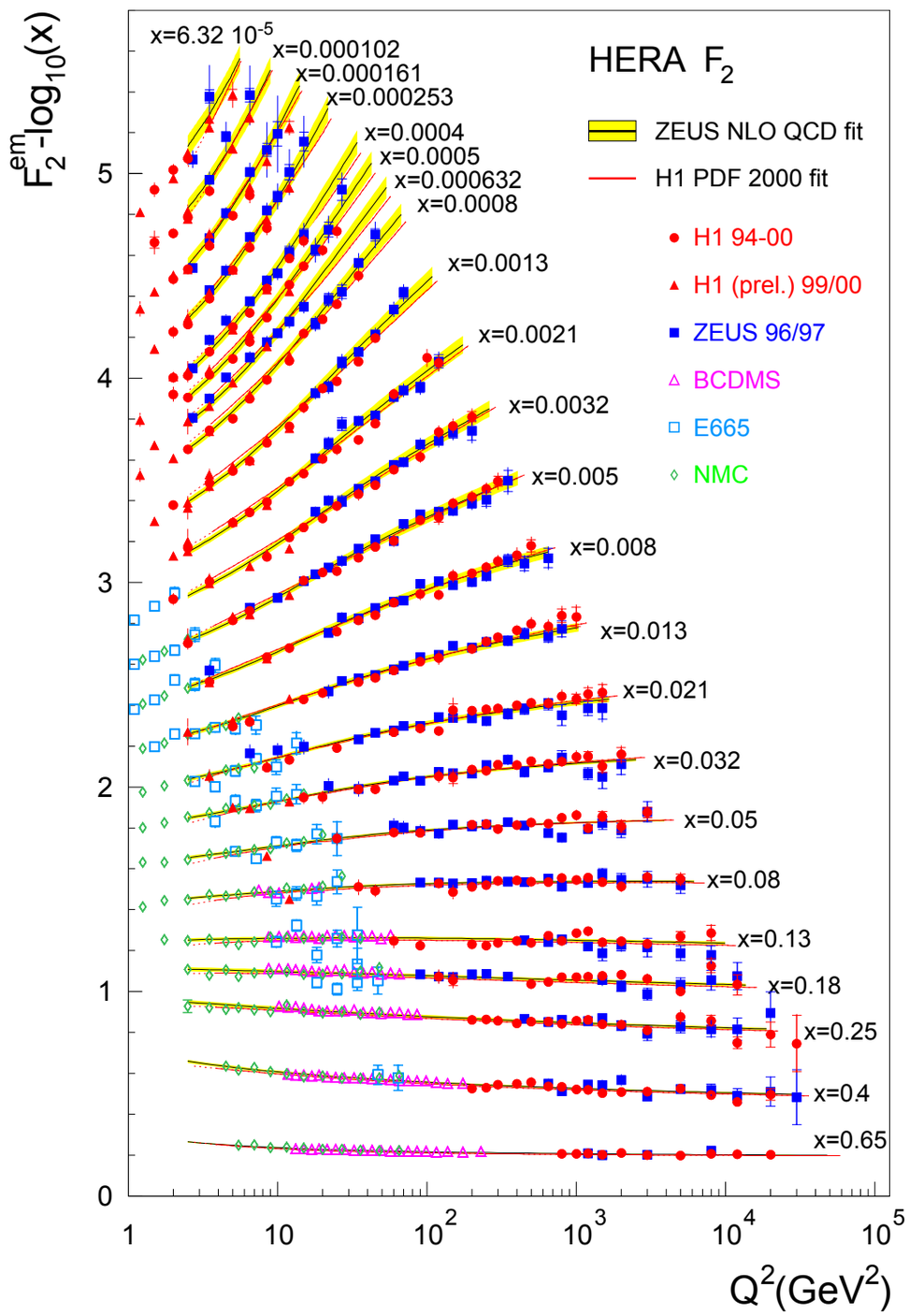

Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

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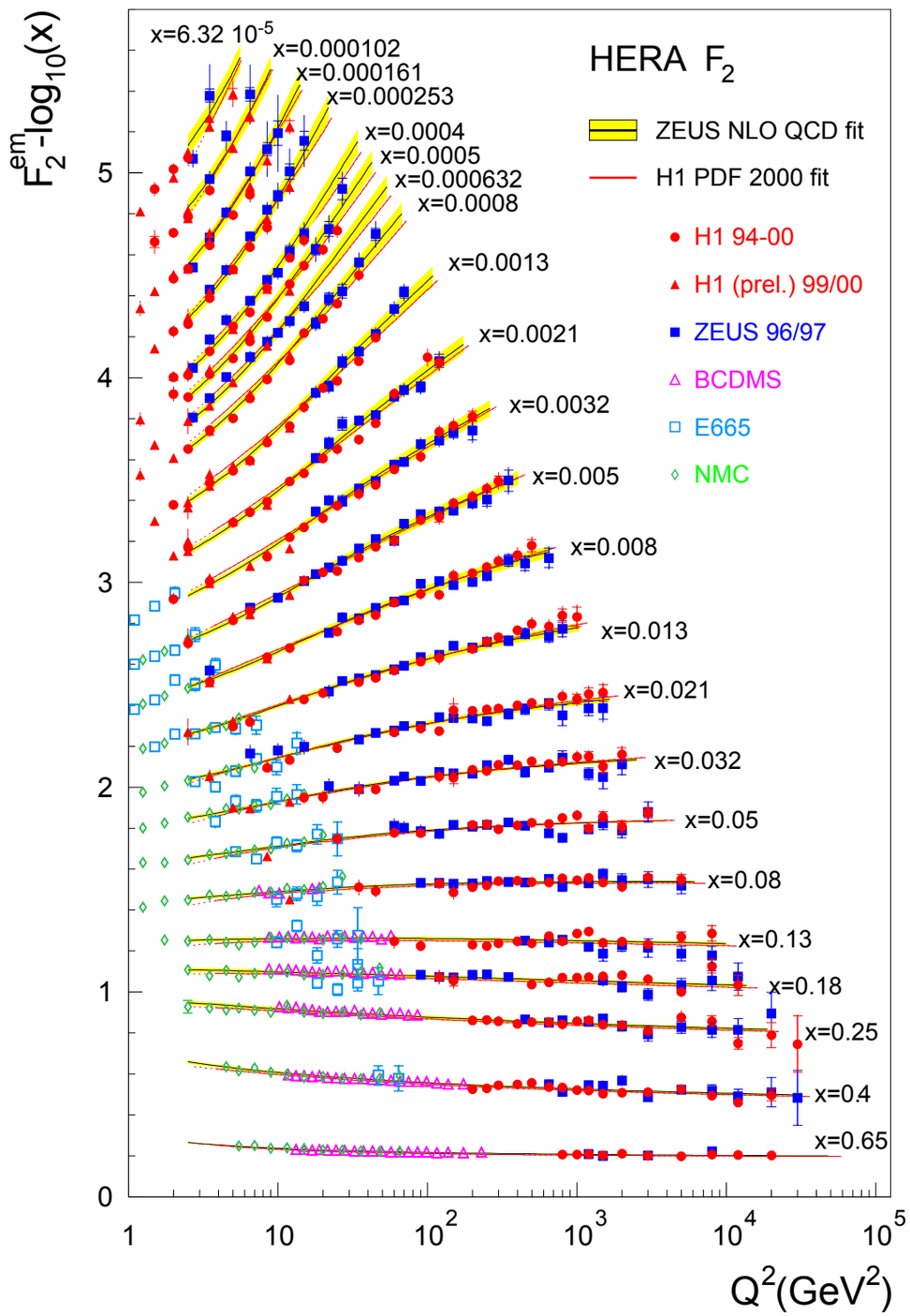

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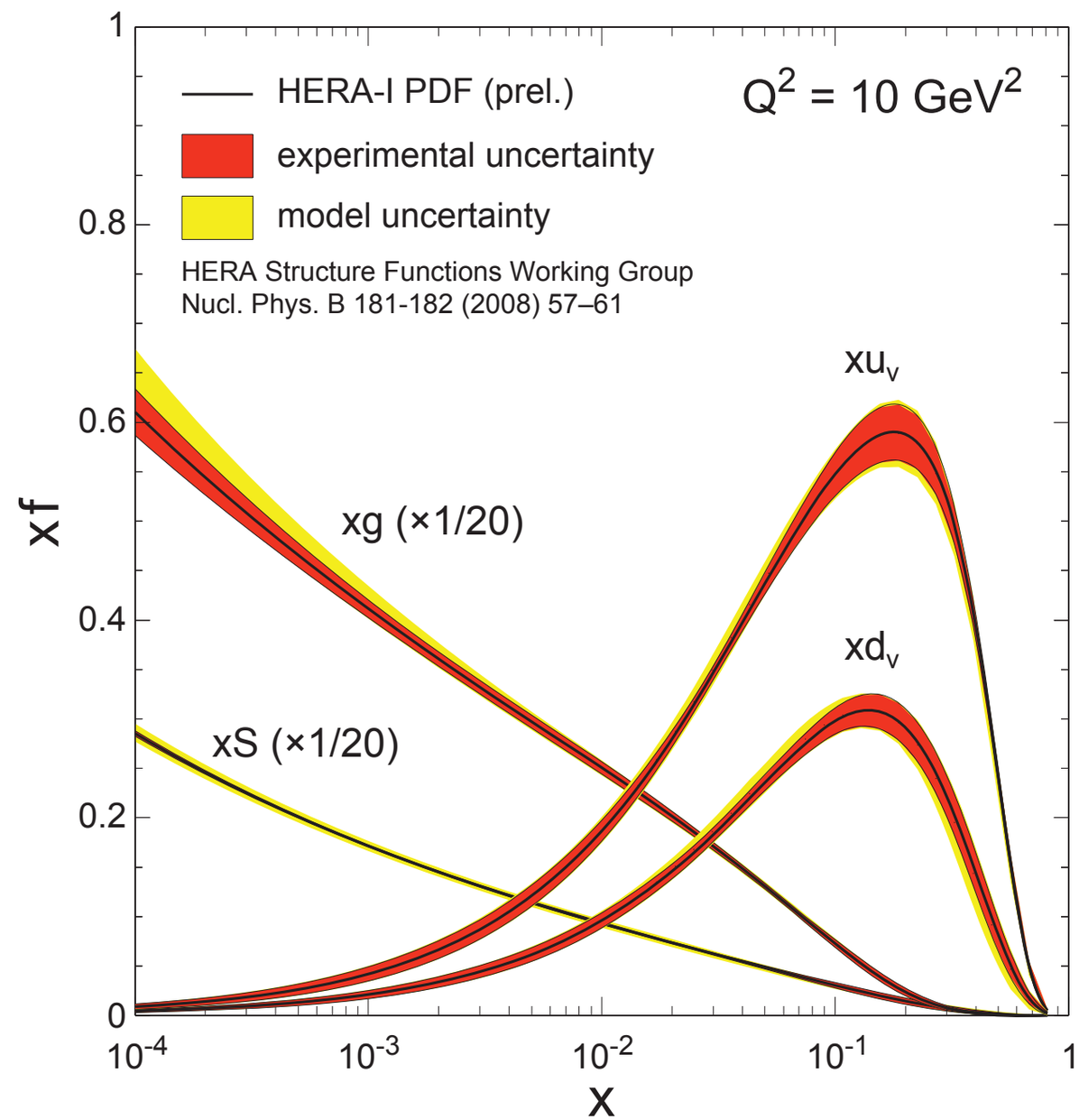

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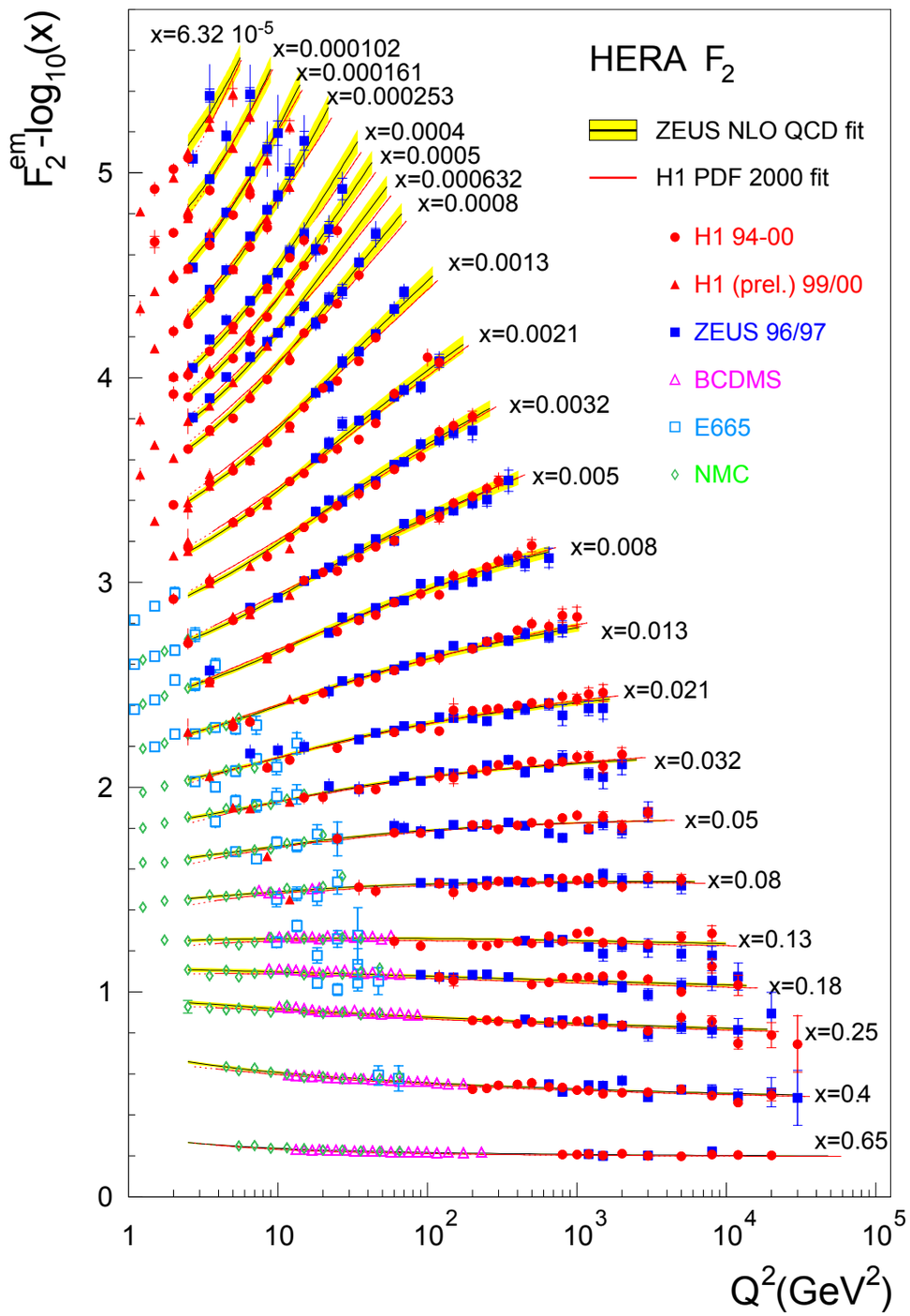

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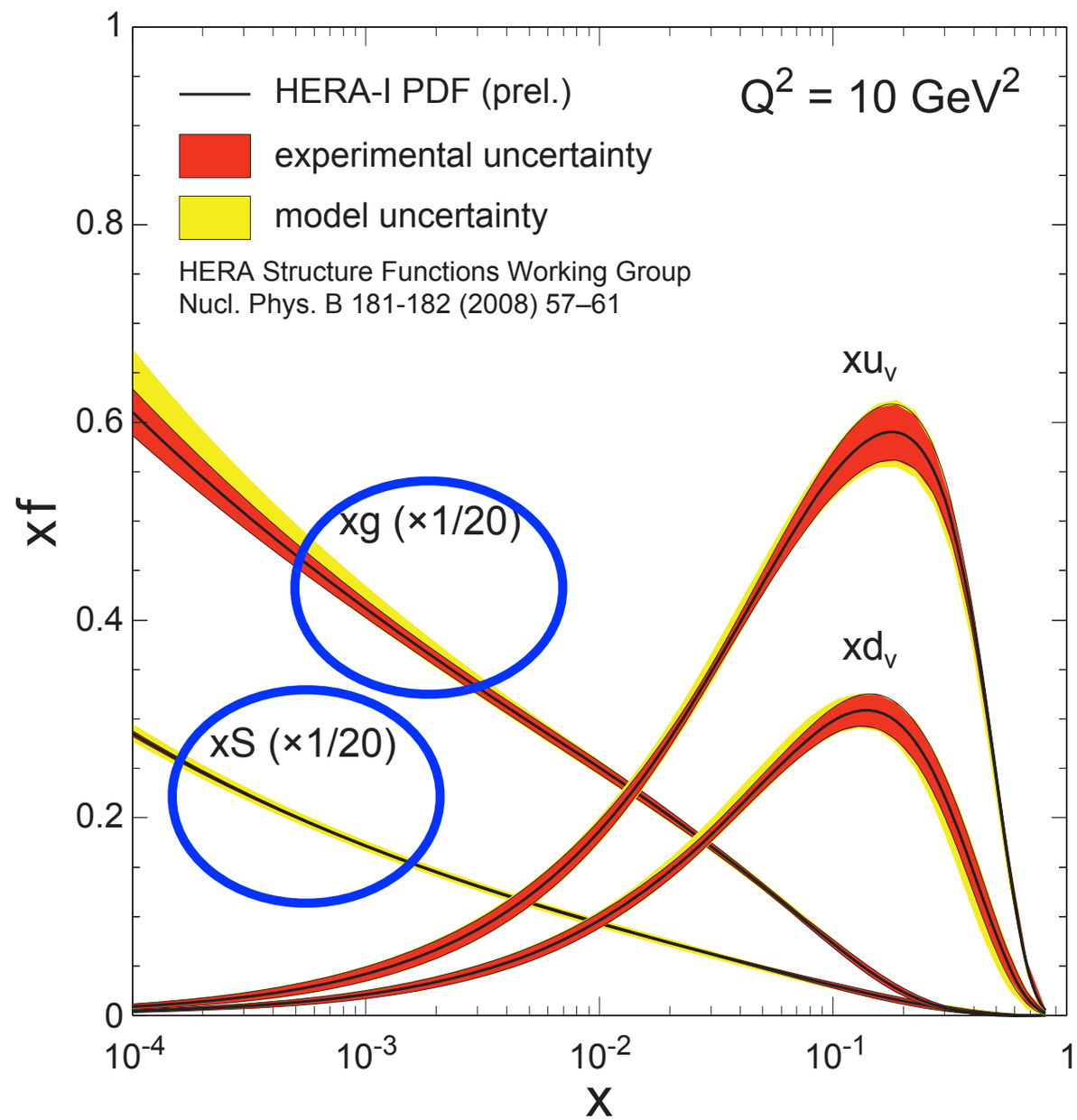

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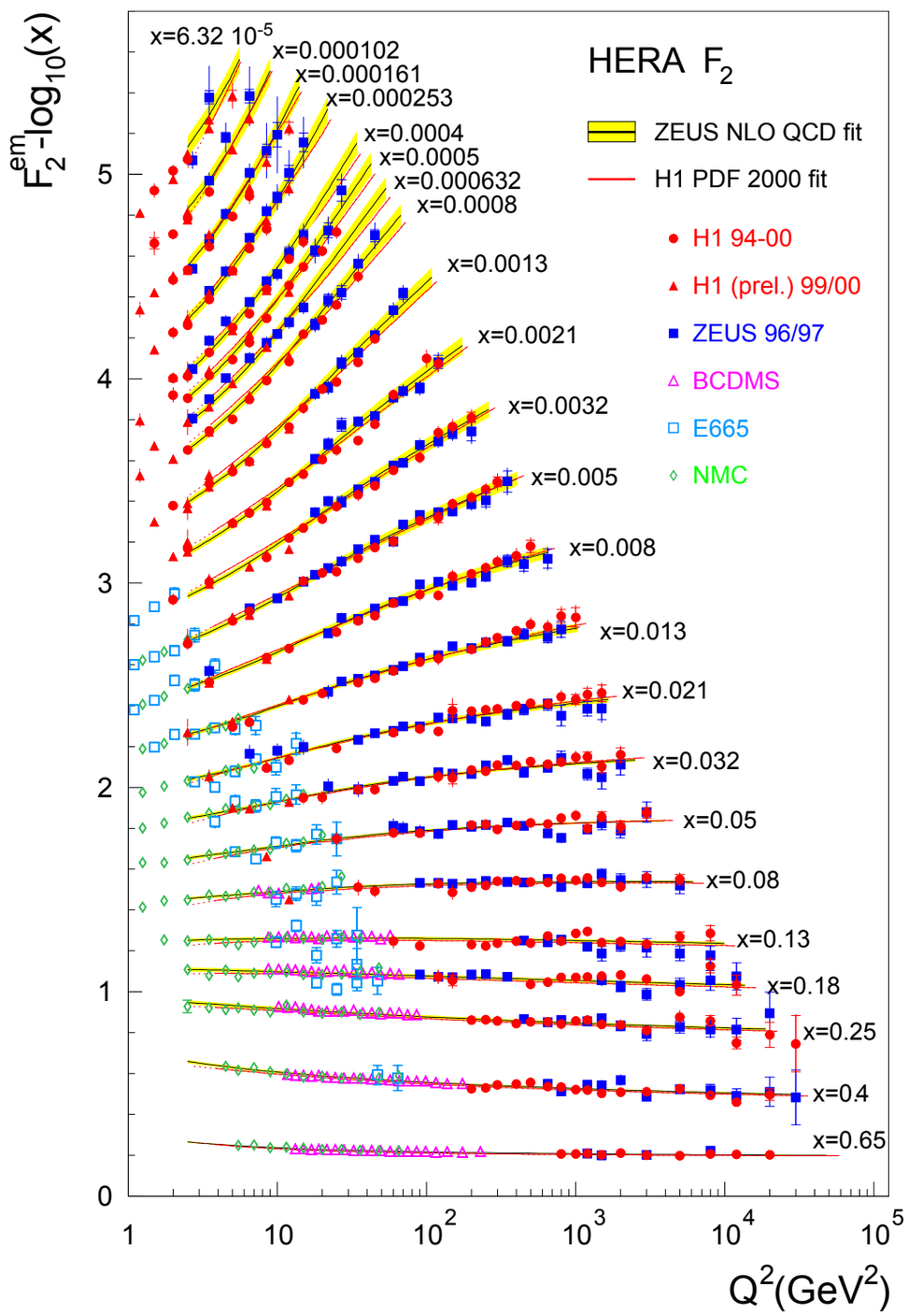

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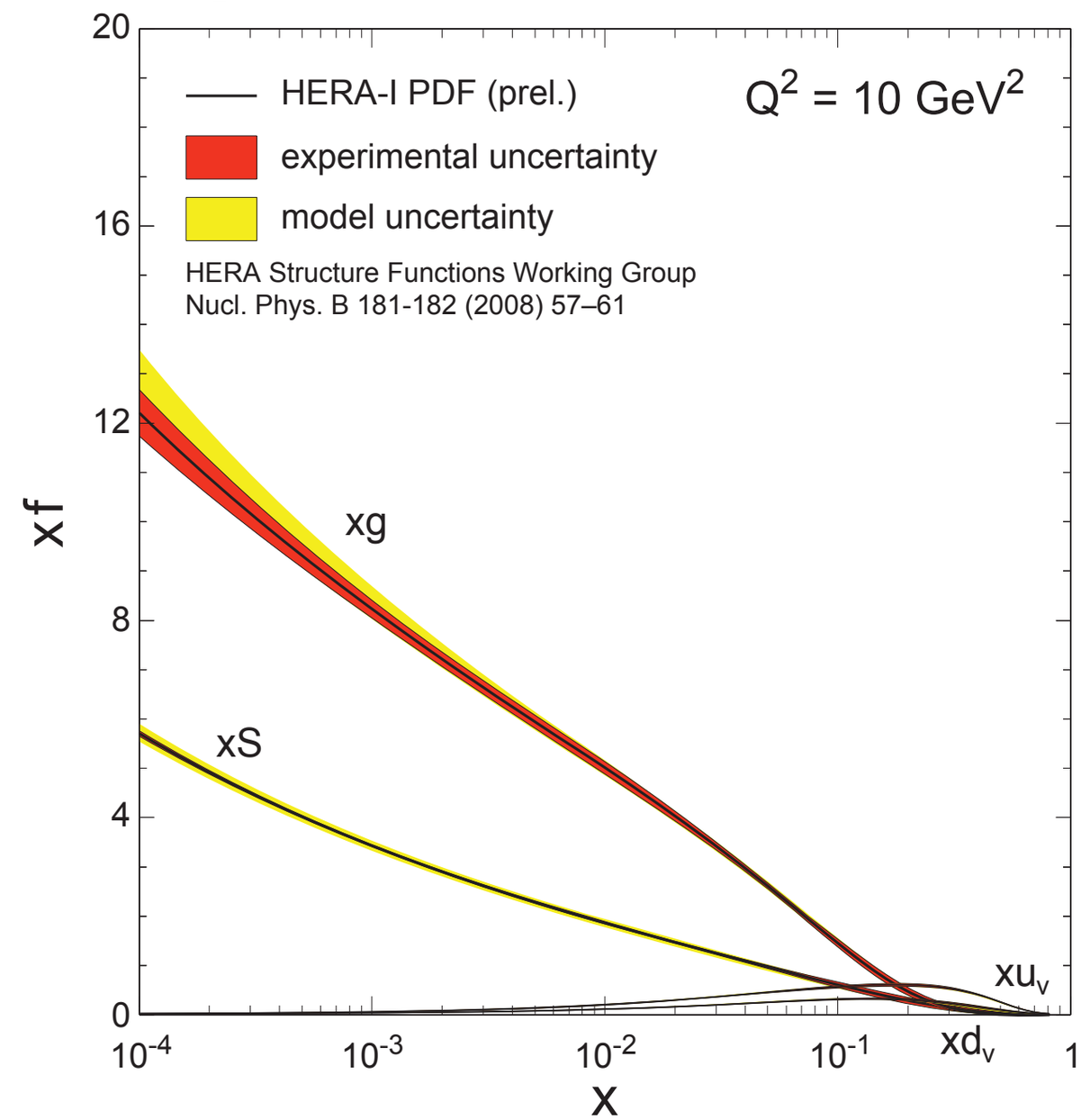
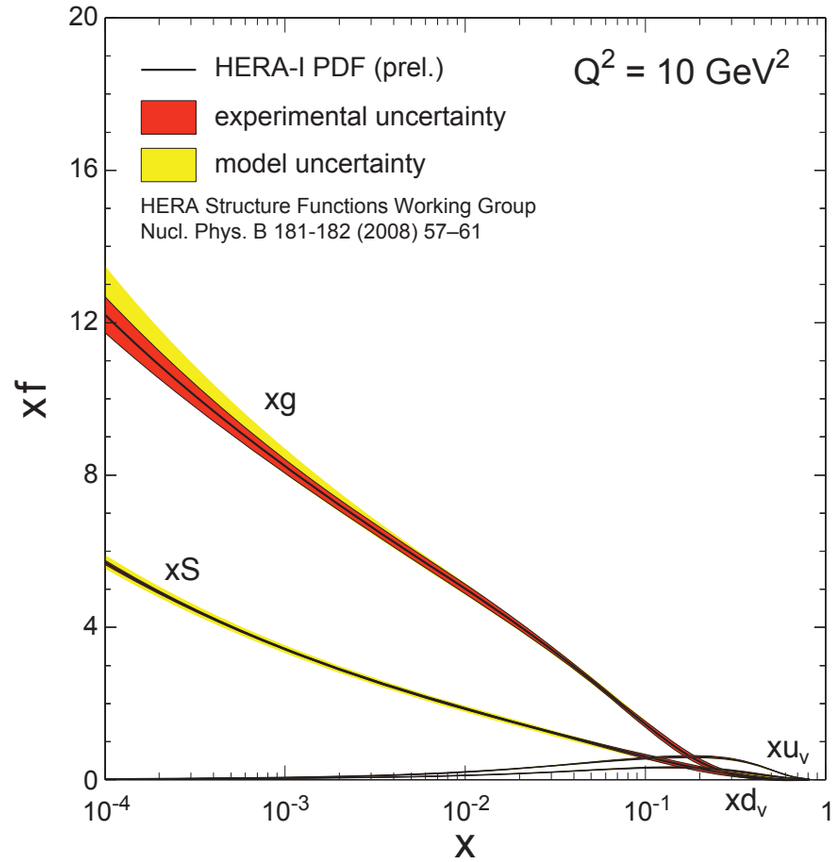
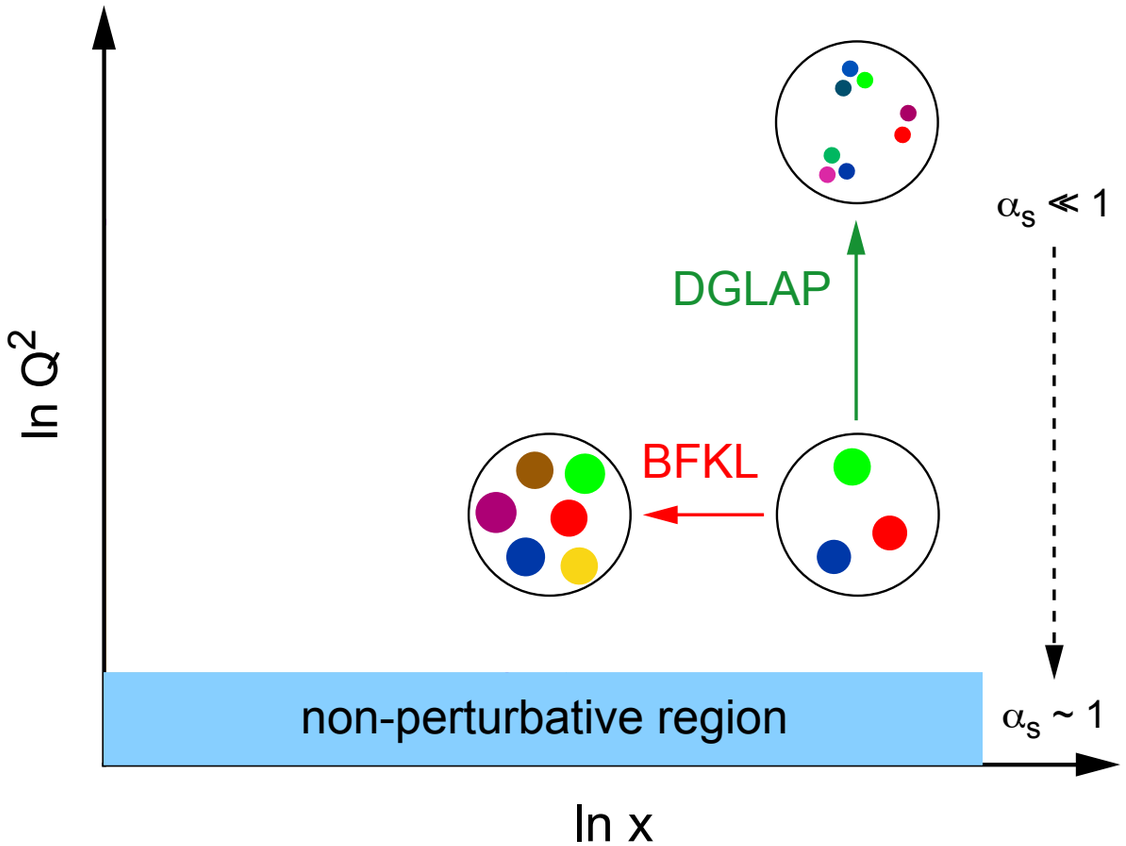
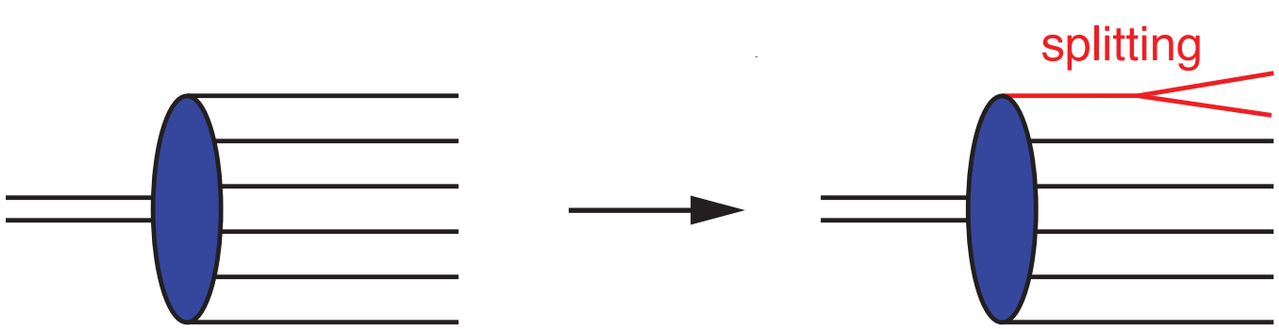


The structure of matter at small-x





- 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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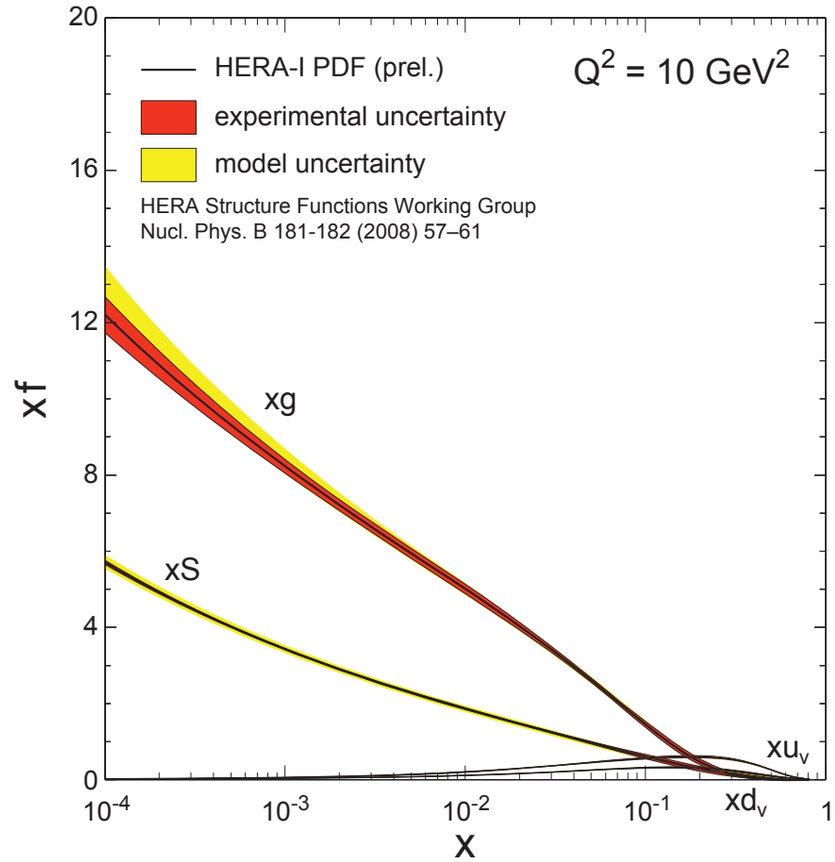
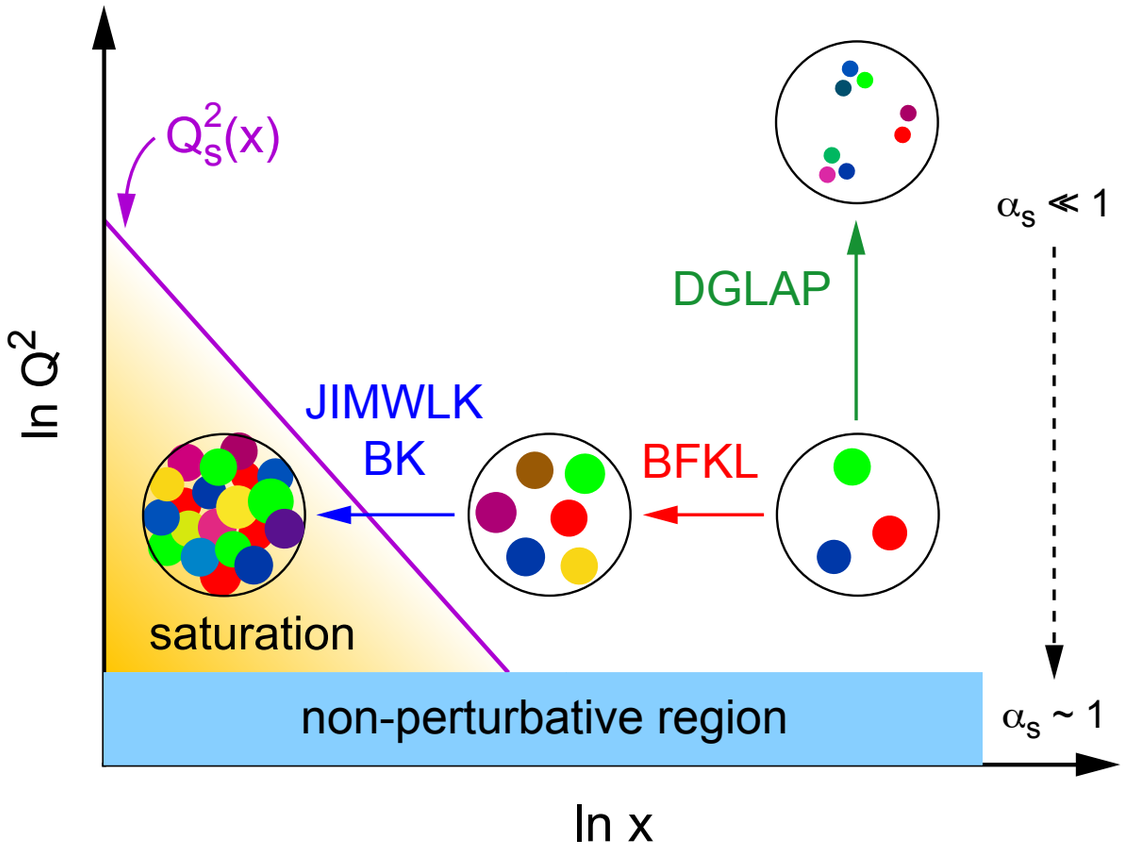
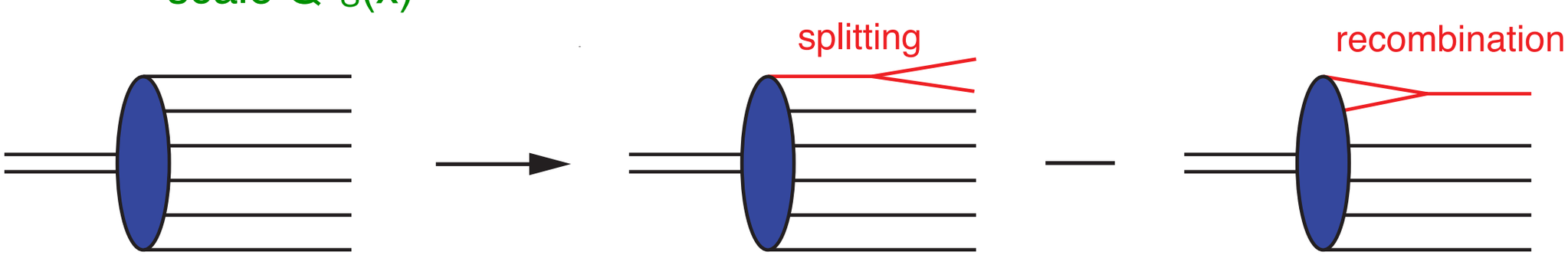




- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth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



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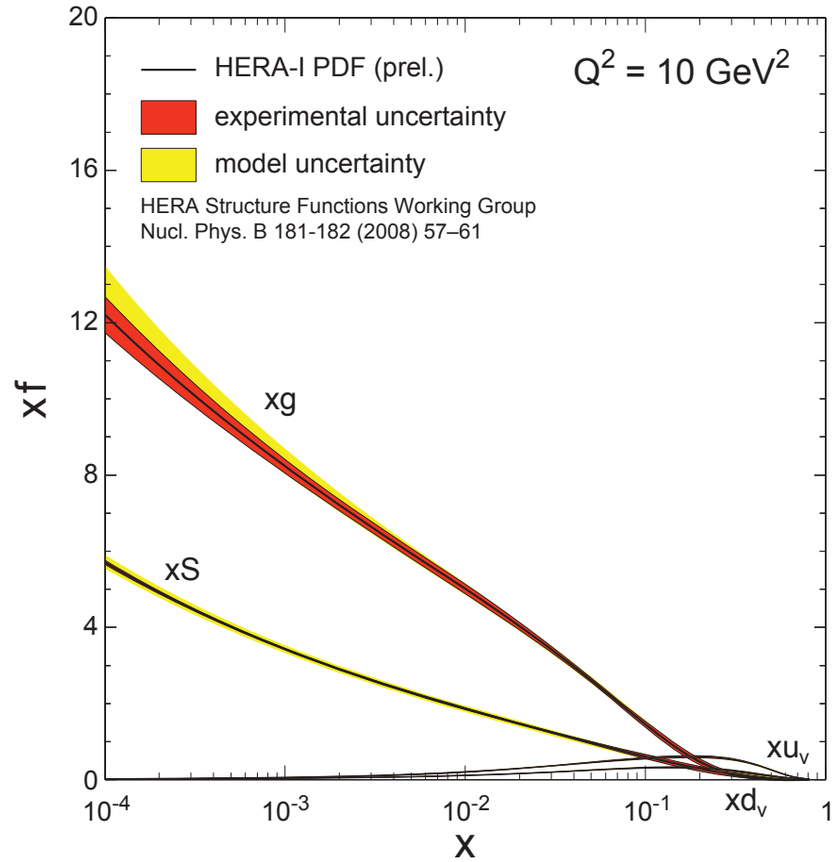

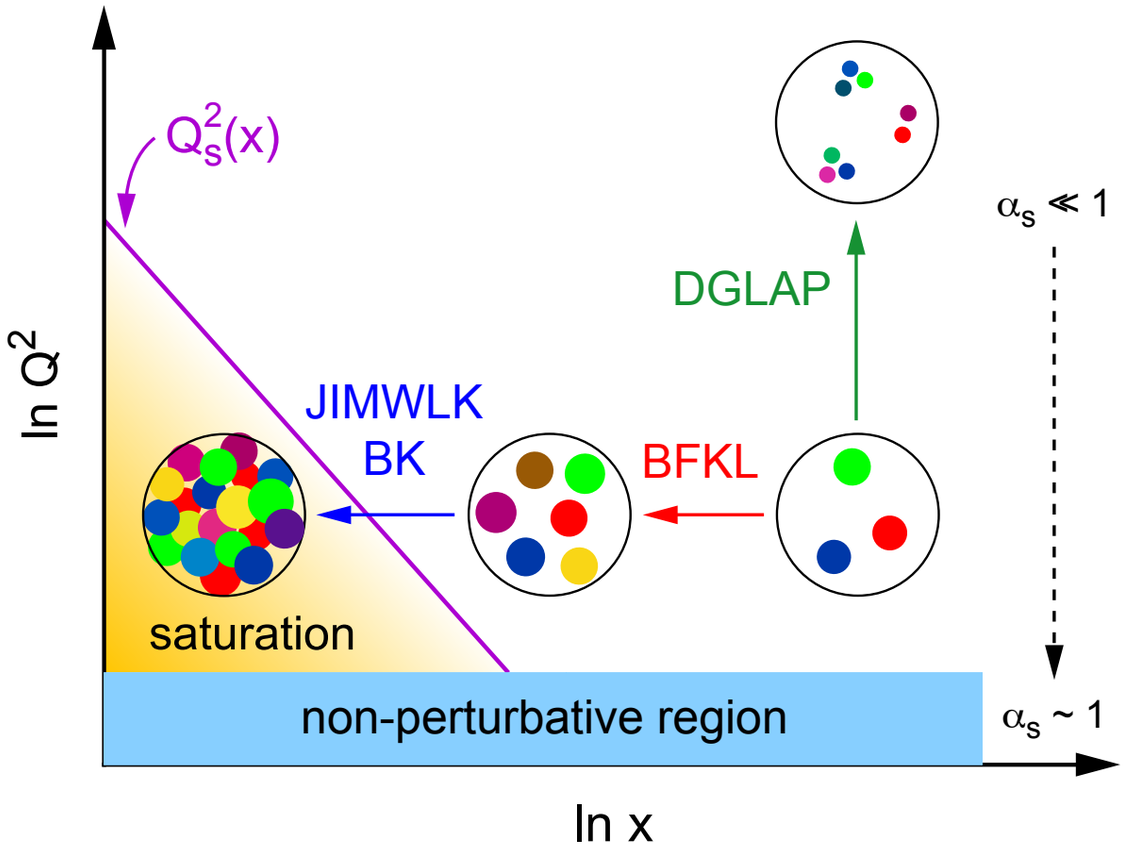

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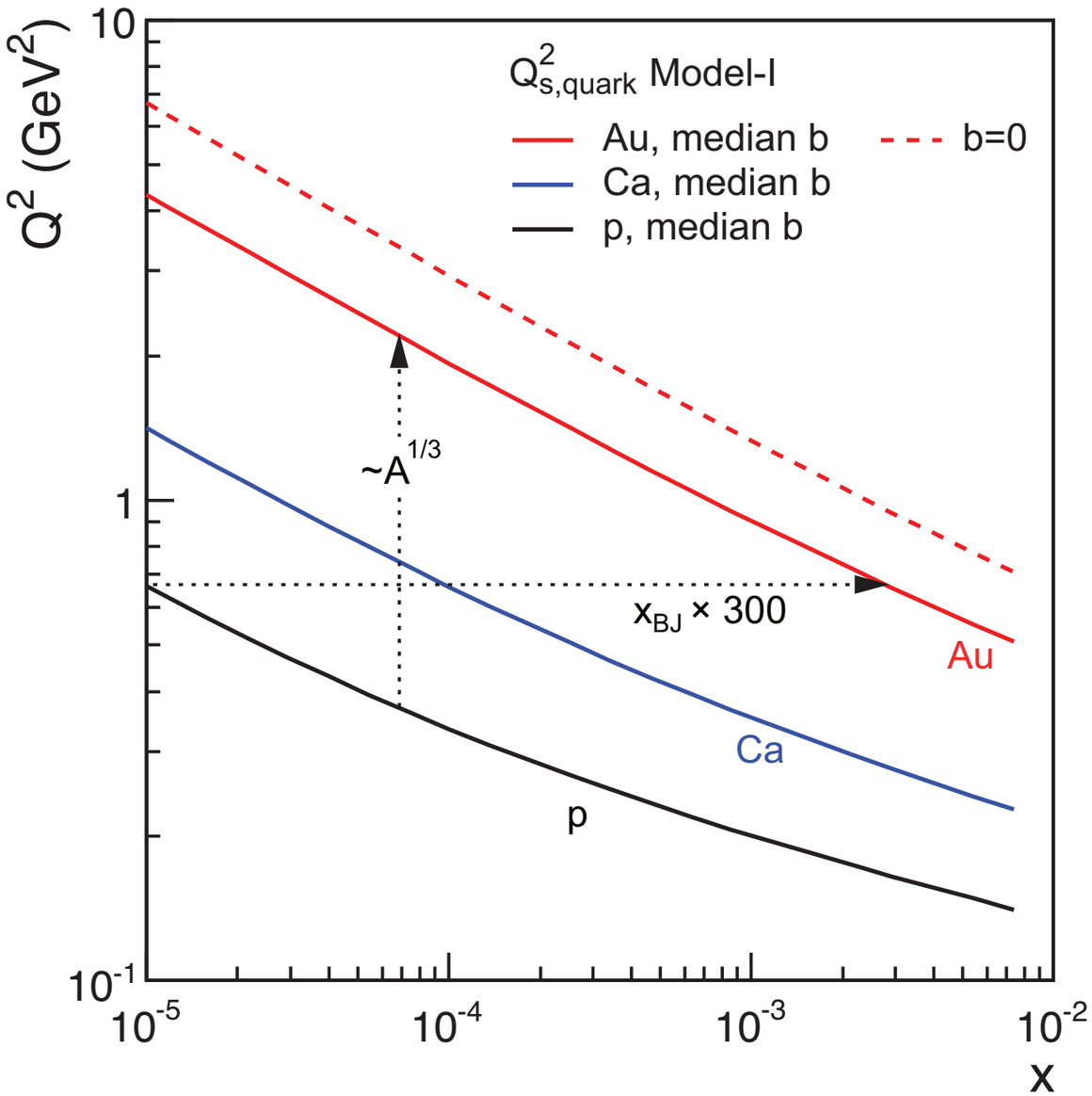
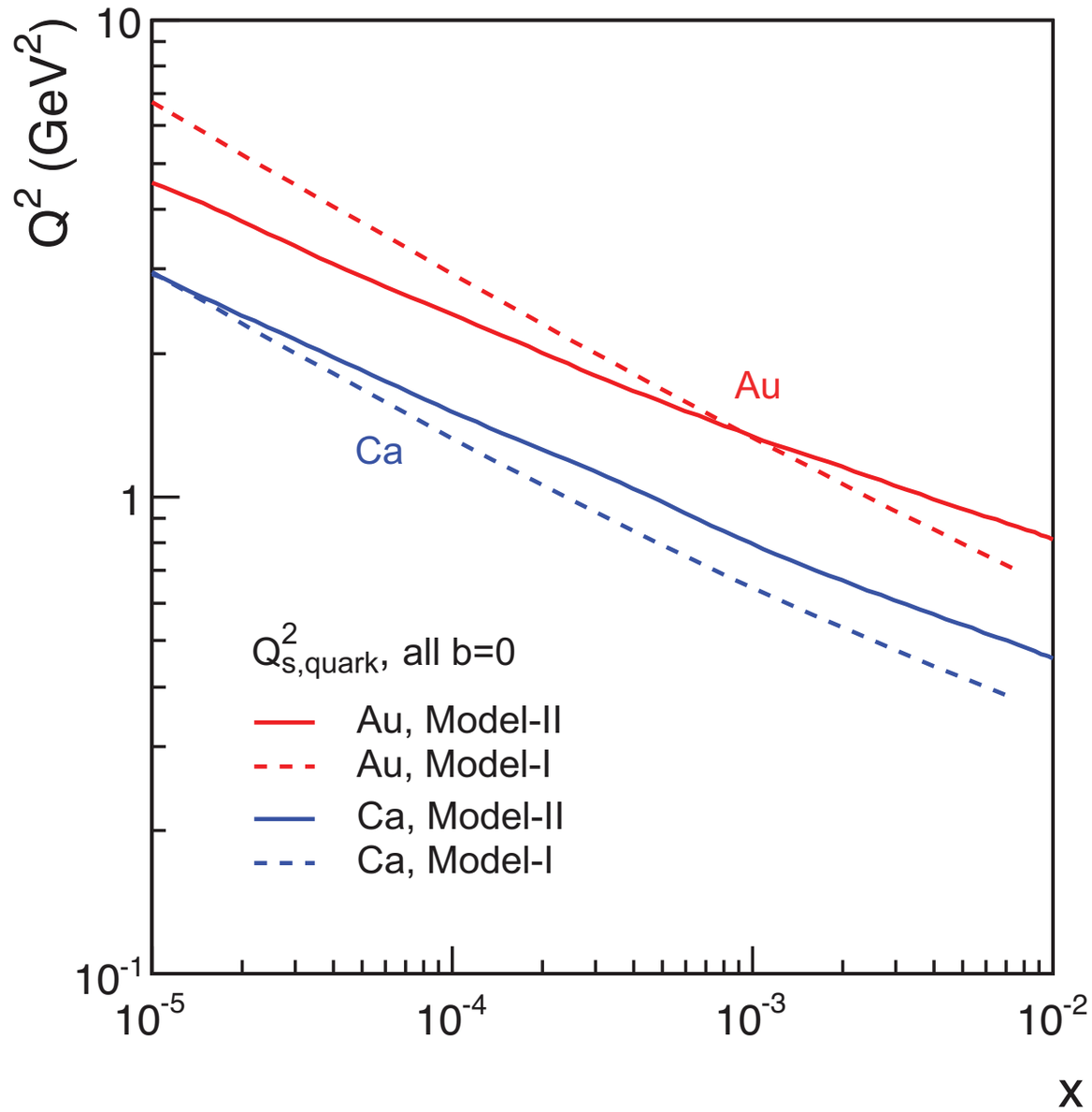
however - saturation in the gluon density is not observed in the gluon distribution at HERA -> too small an x

How can this be observed at eRHIC?

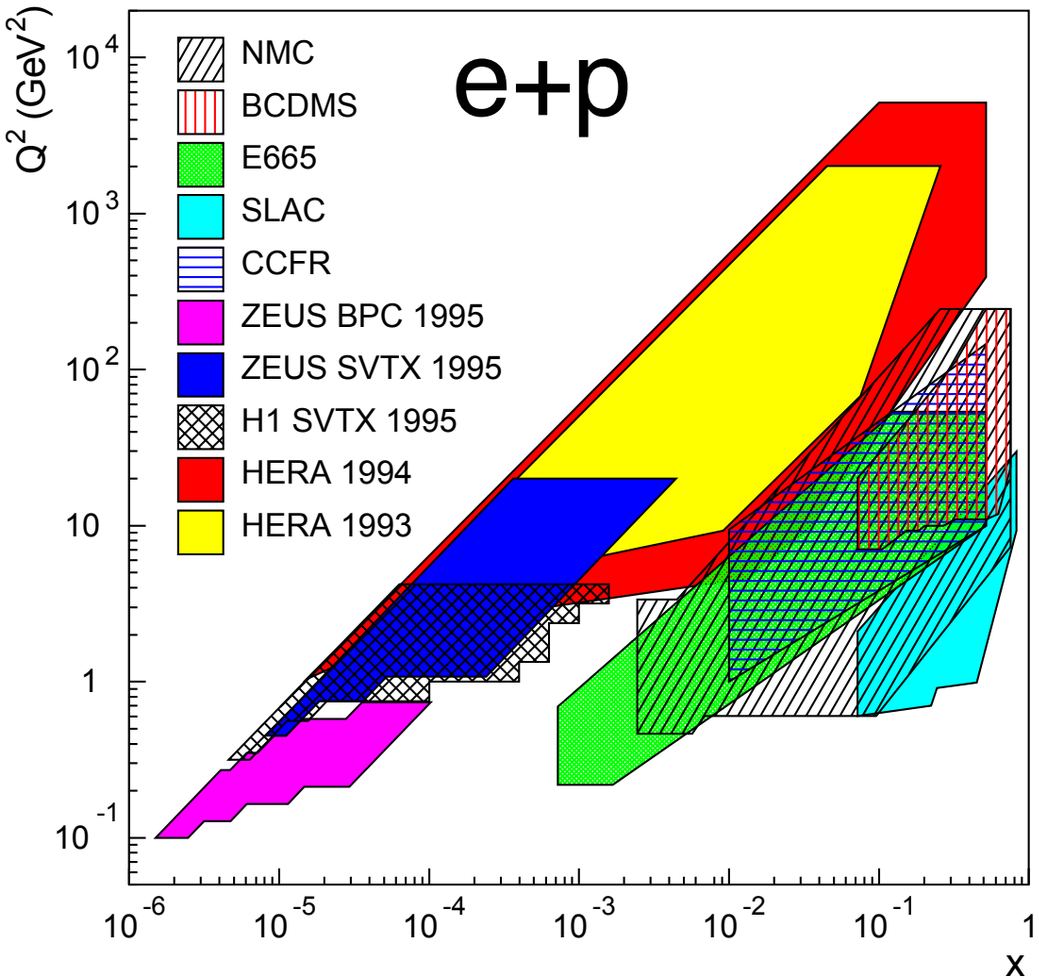
Nuclear “oomph” effect

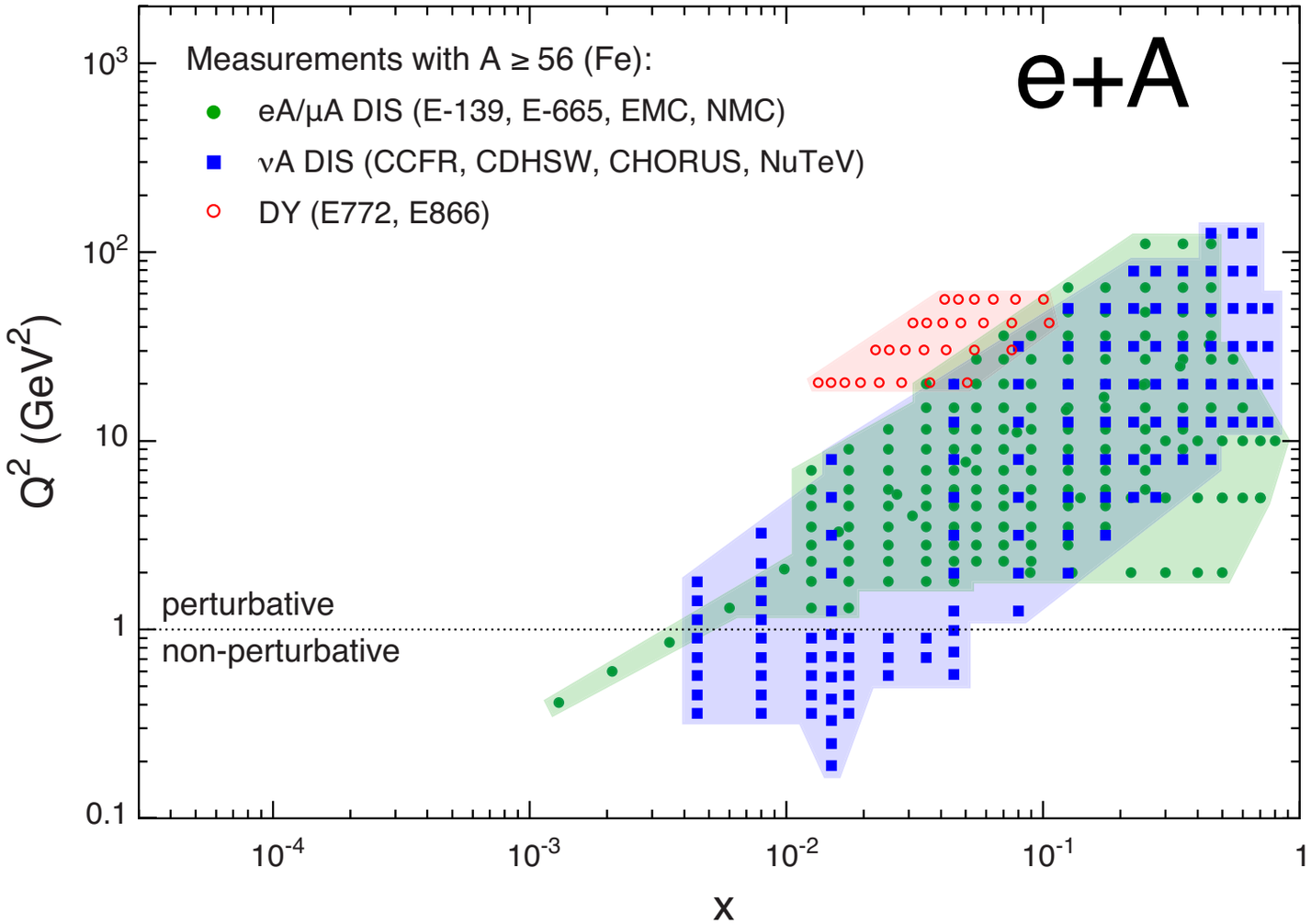
Pocket formula: $Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$





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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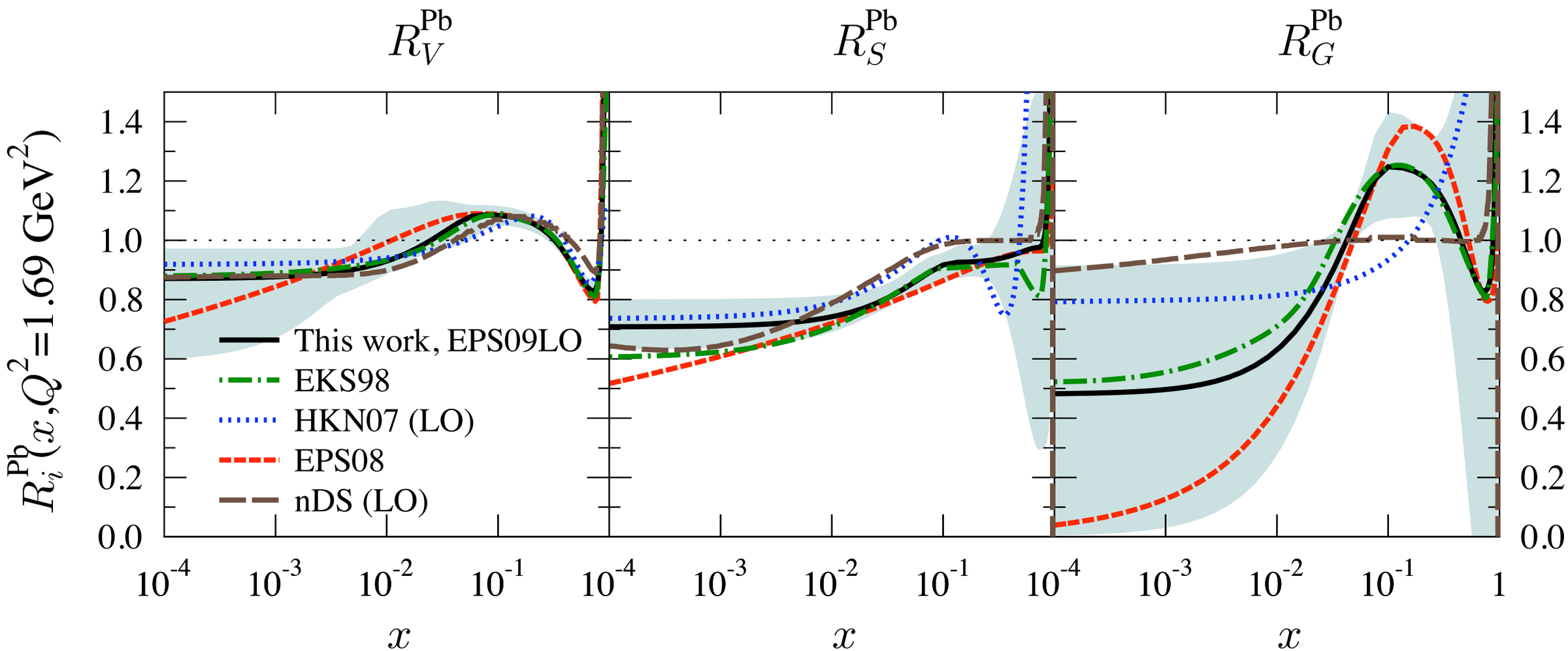

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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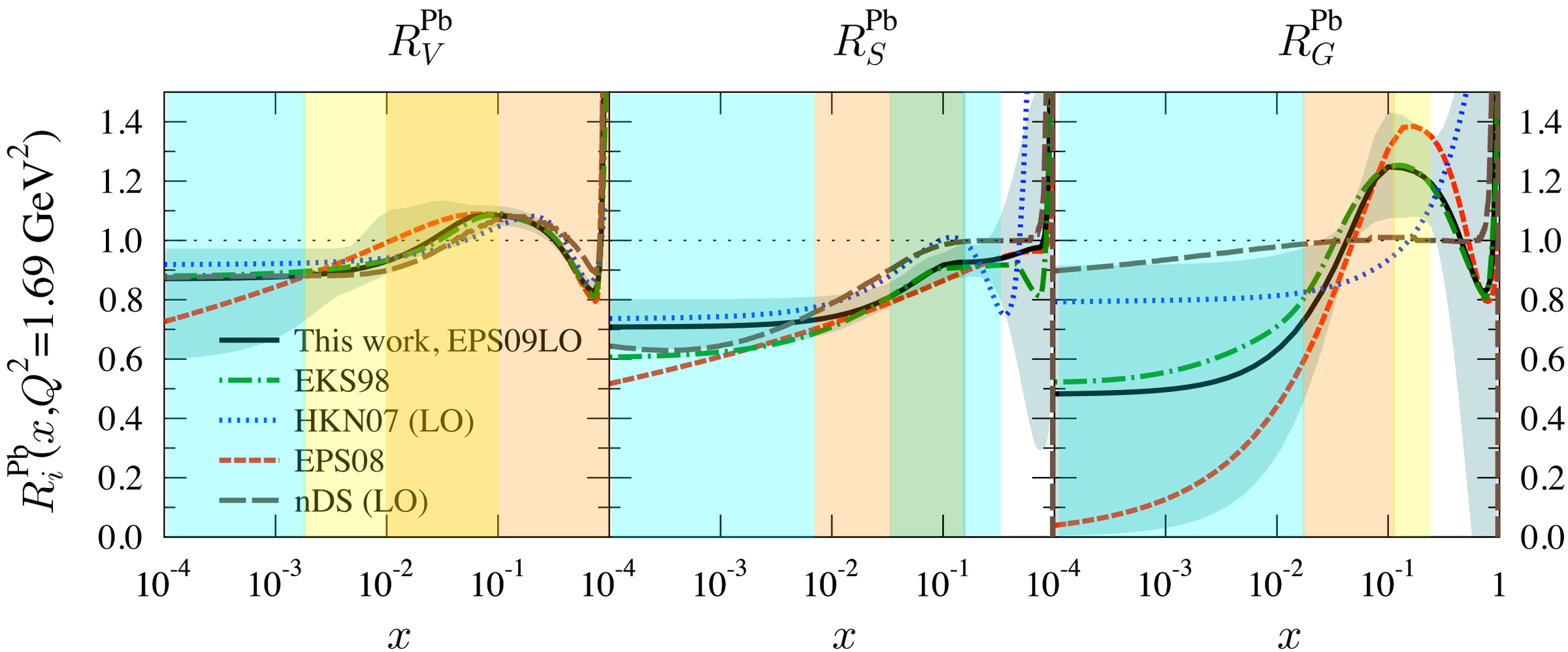

Constrained by DIS

Constrained by DY

Constrained by sum rules

Assumptions

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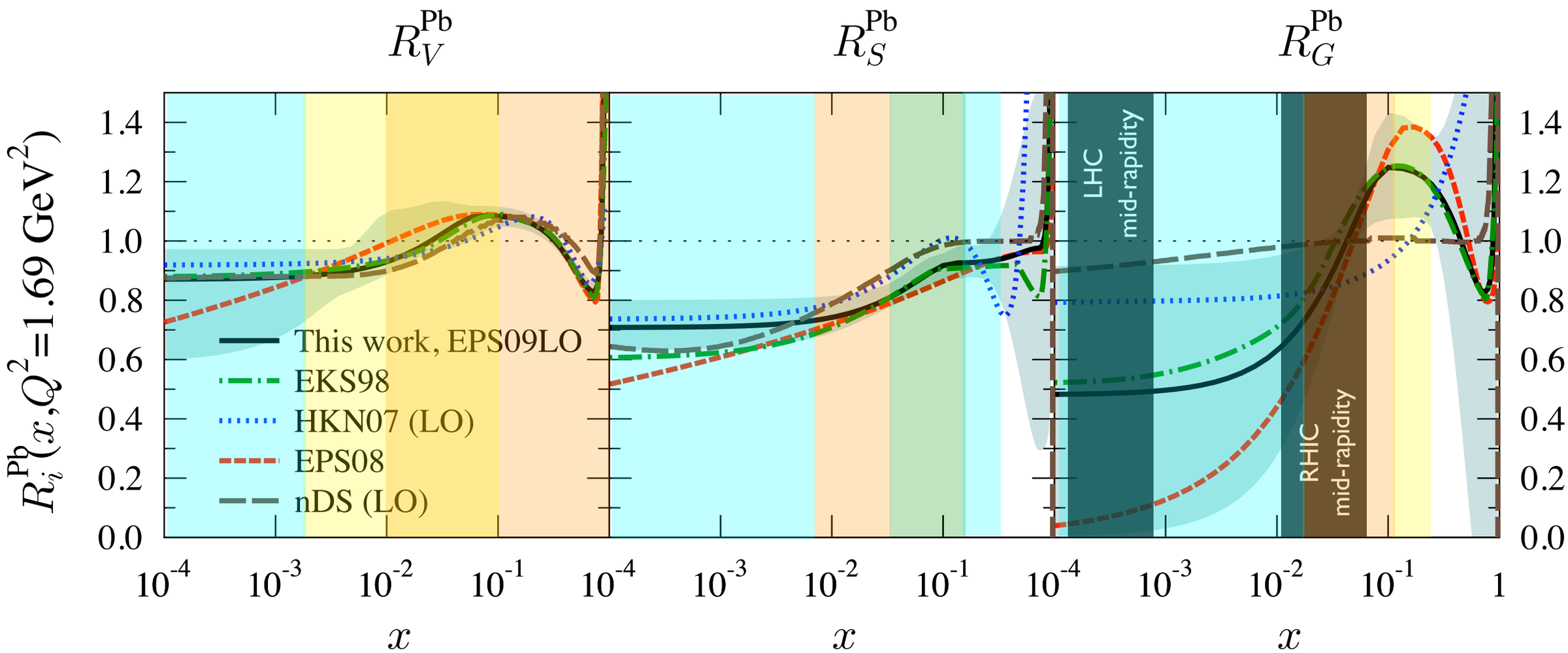

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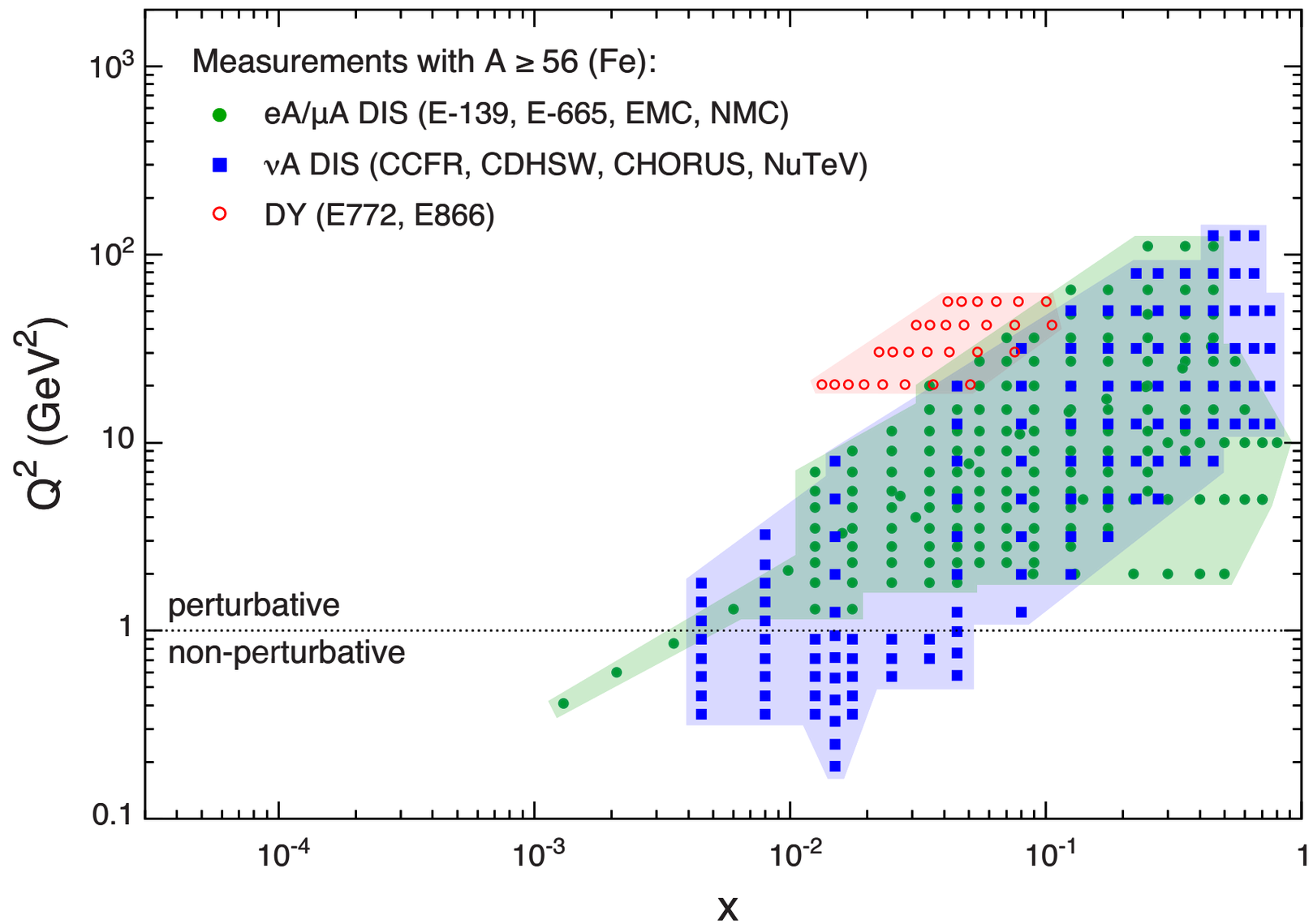
Assumptions

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 !!

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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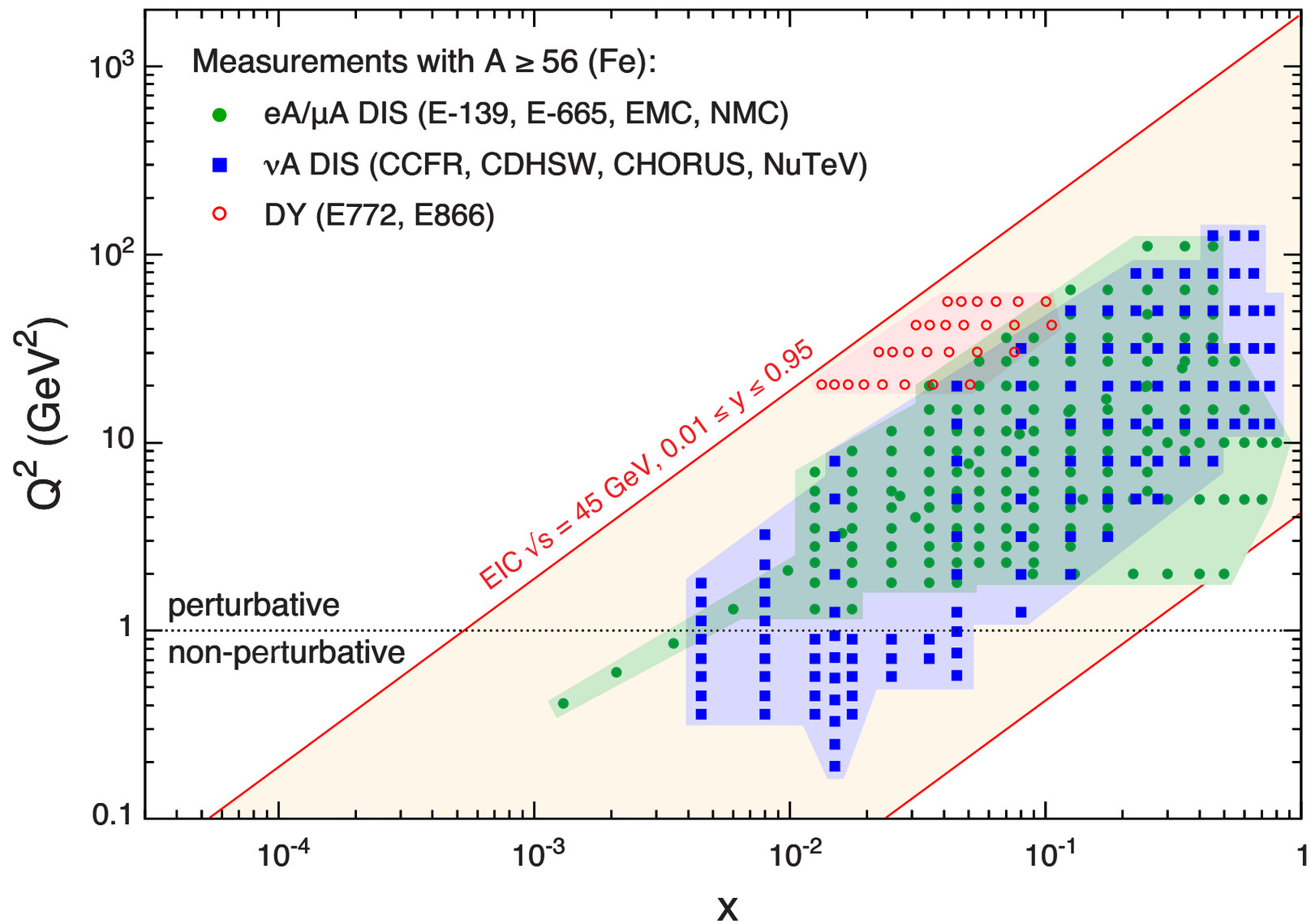

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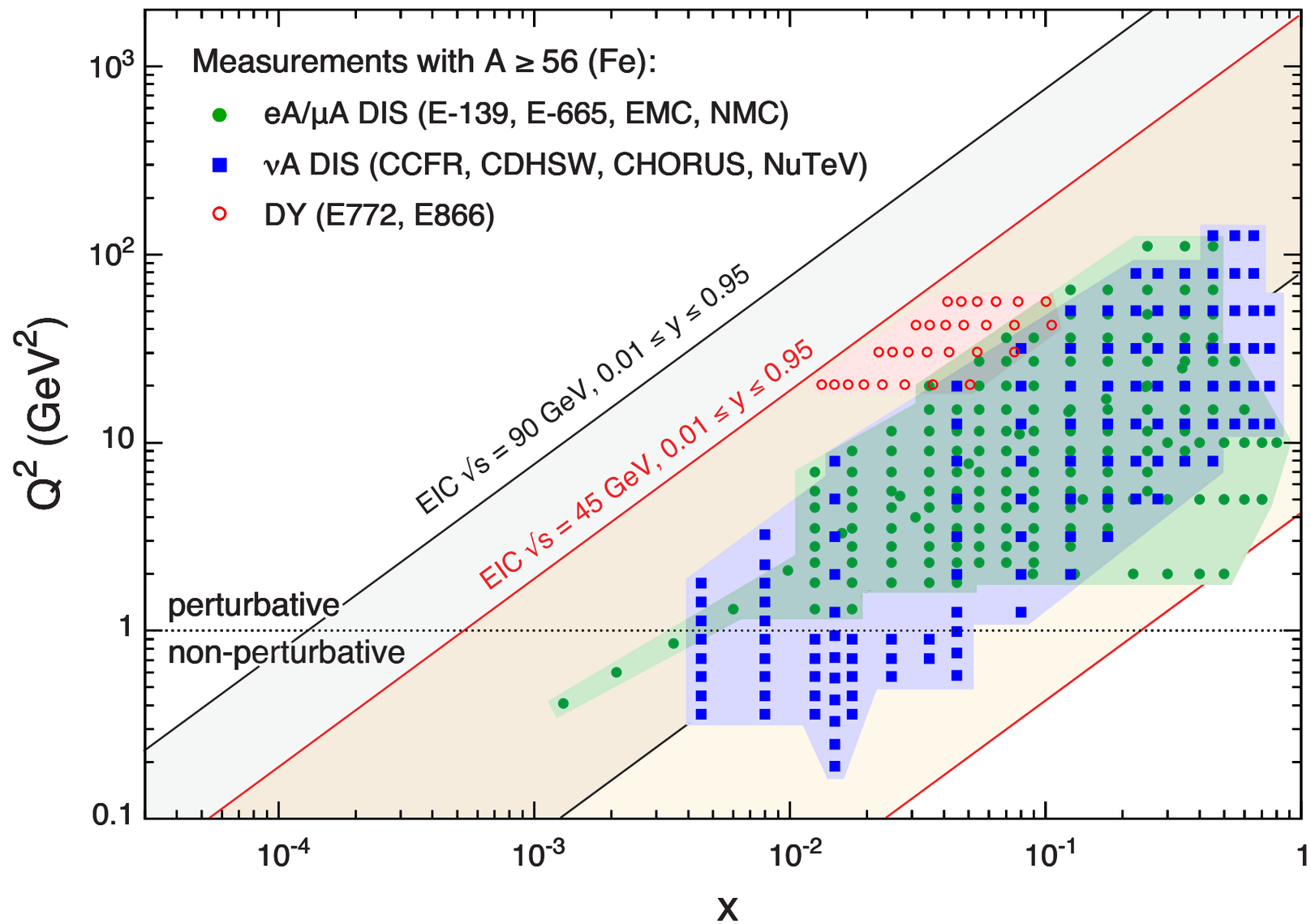

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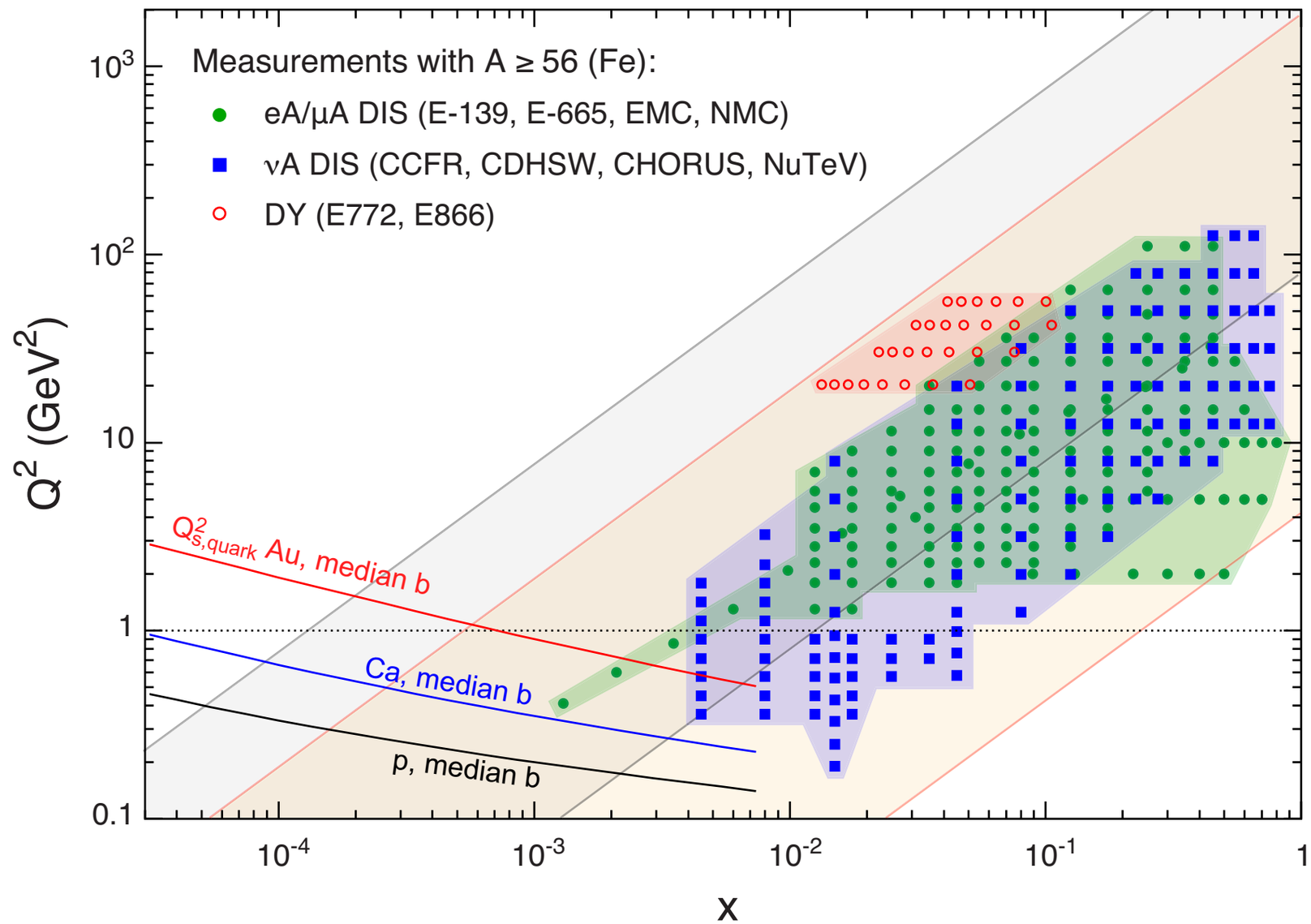


Saturation effects in the proton and nucleus

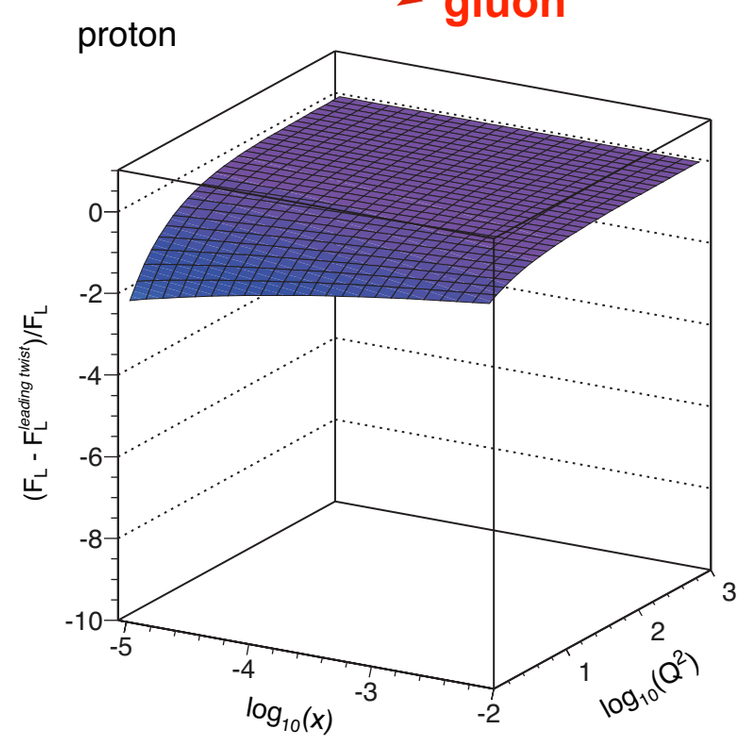
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

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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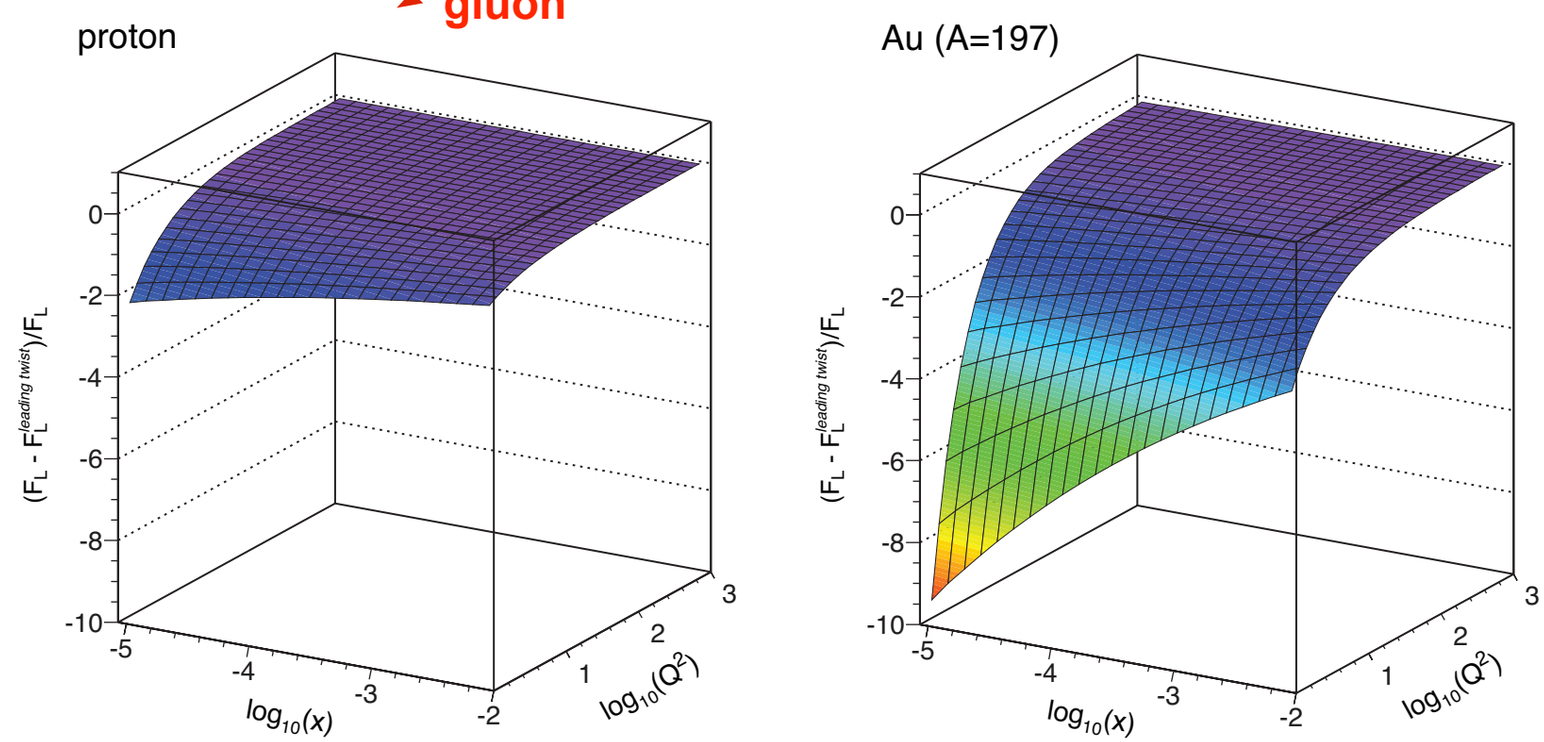

- Plotting this distribution coming out of saturation inspired GBW model
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  - ➡ Au: much larger effects are visible
    - nuclear "oomph" effects well manifested in the F_L structure function

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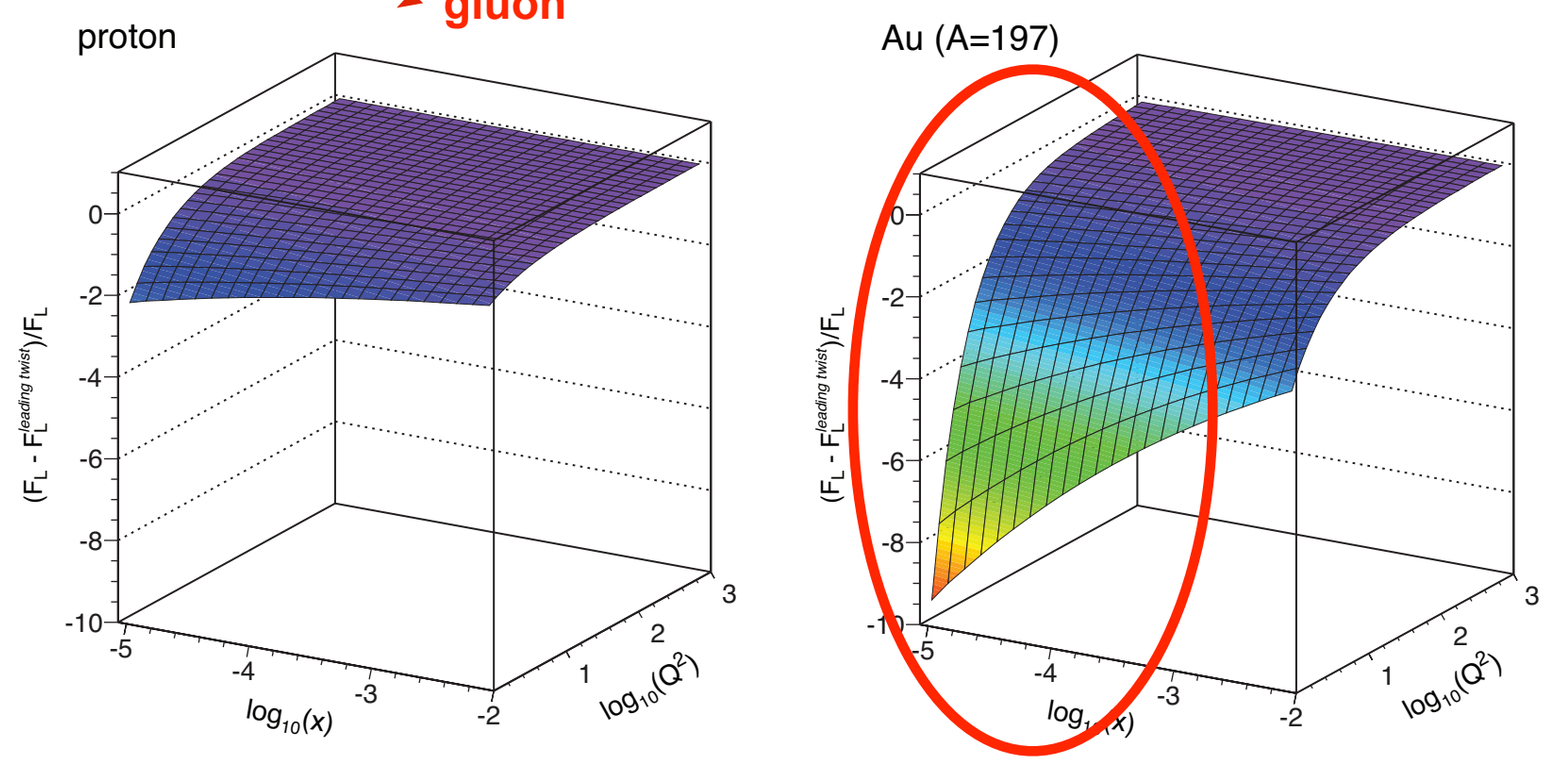

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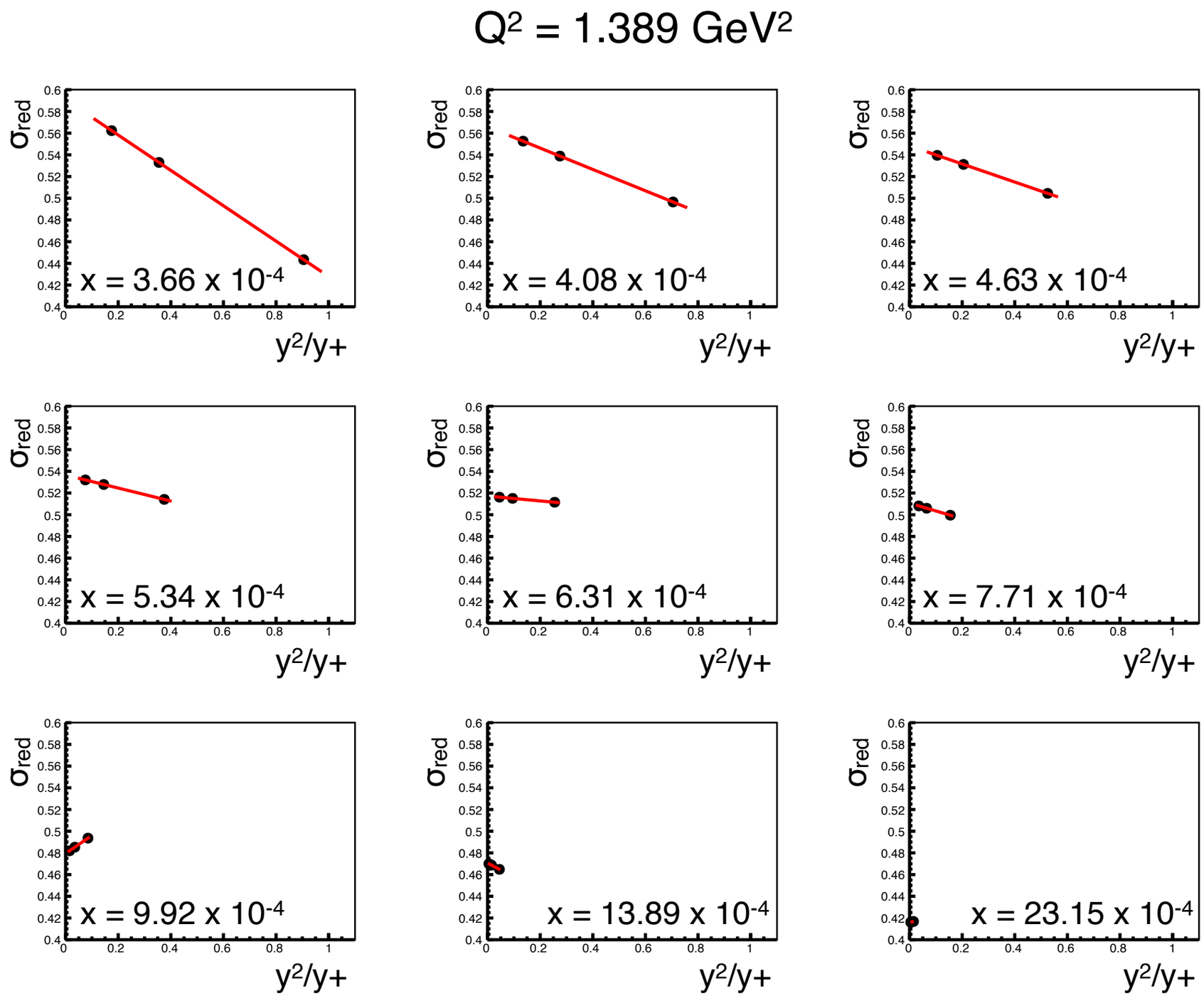
Feasibility study: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$

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

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

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



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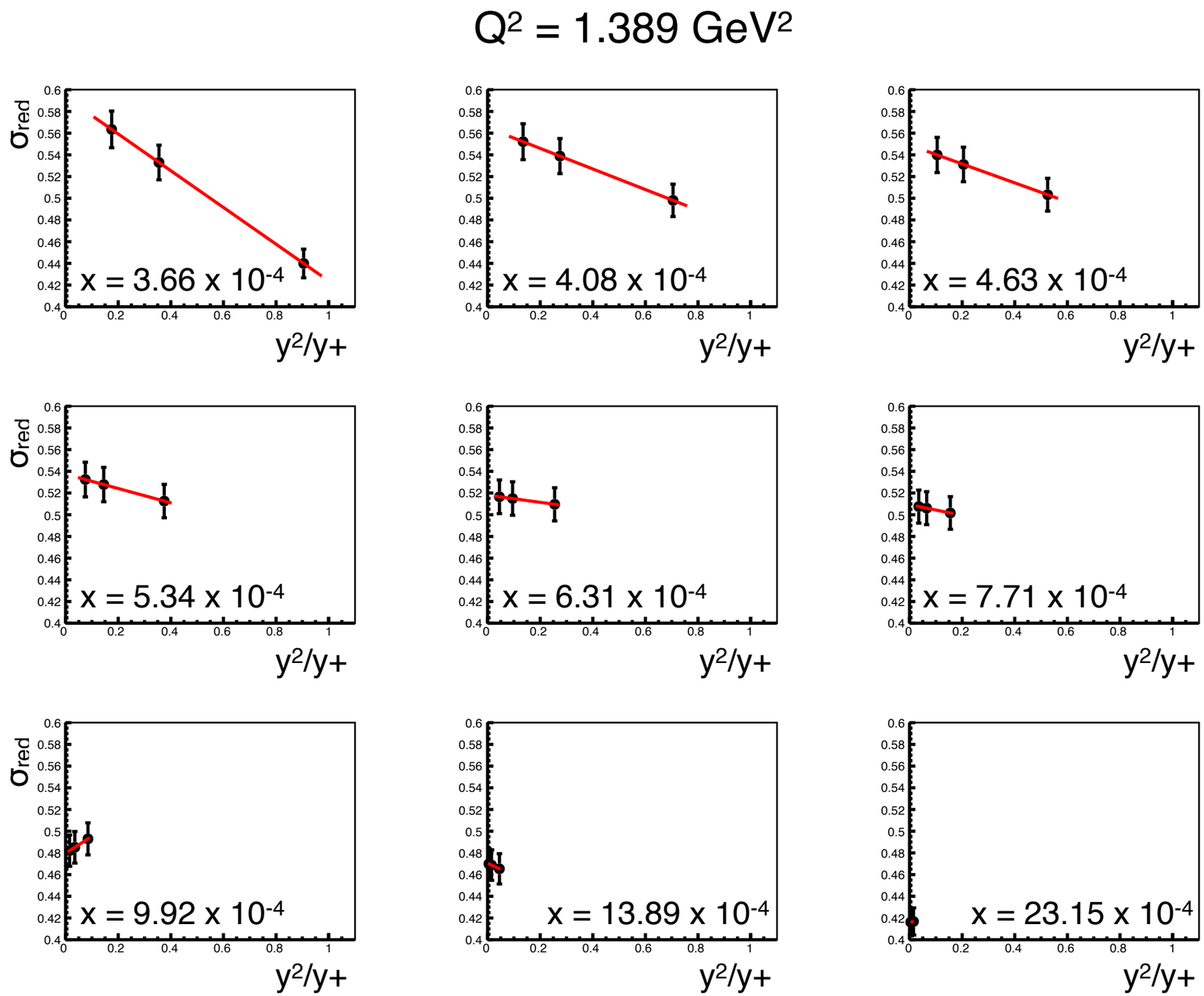

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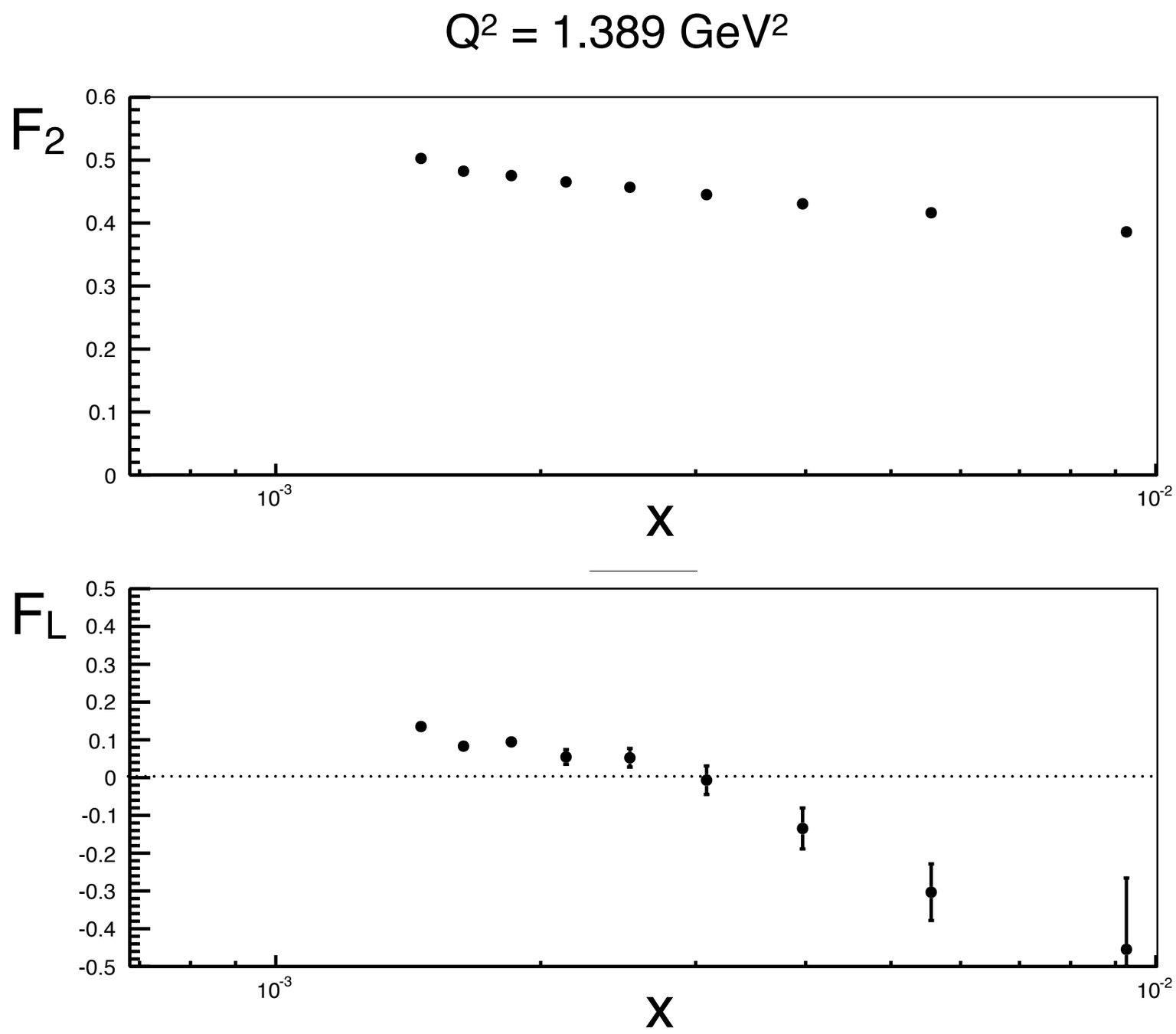

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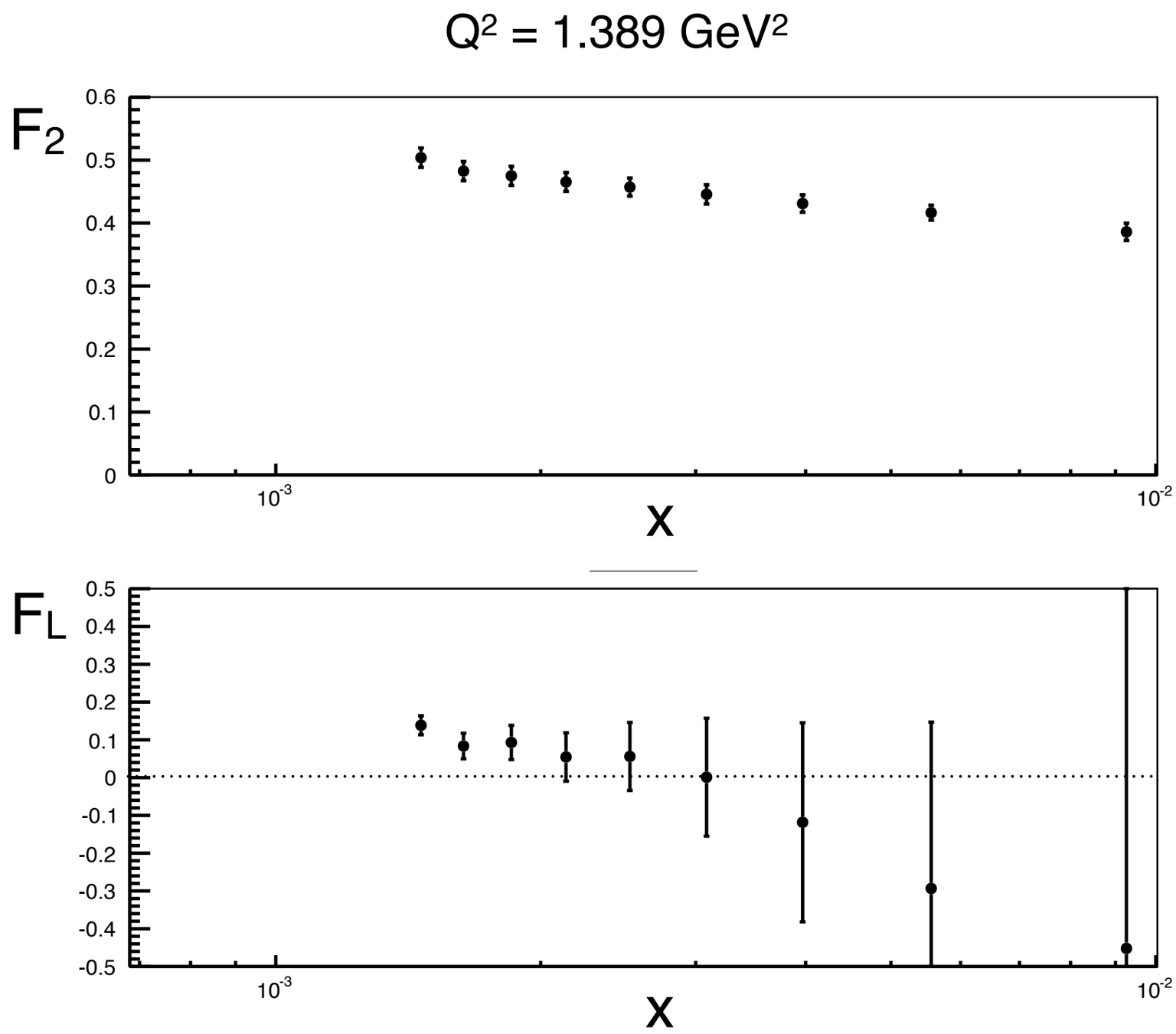

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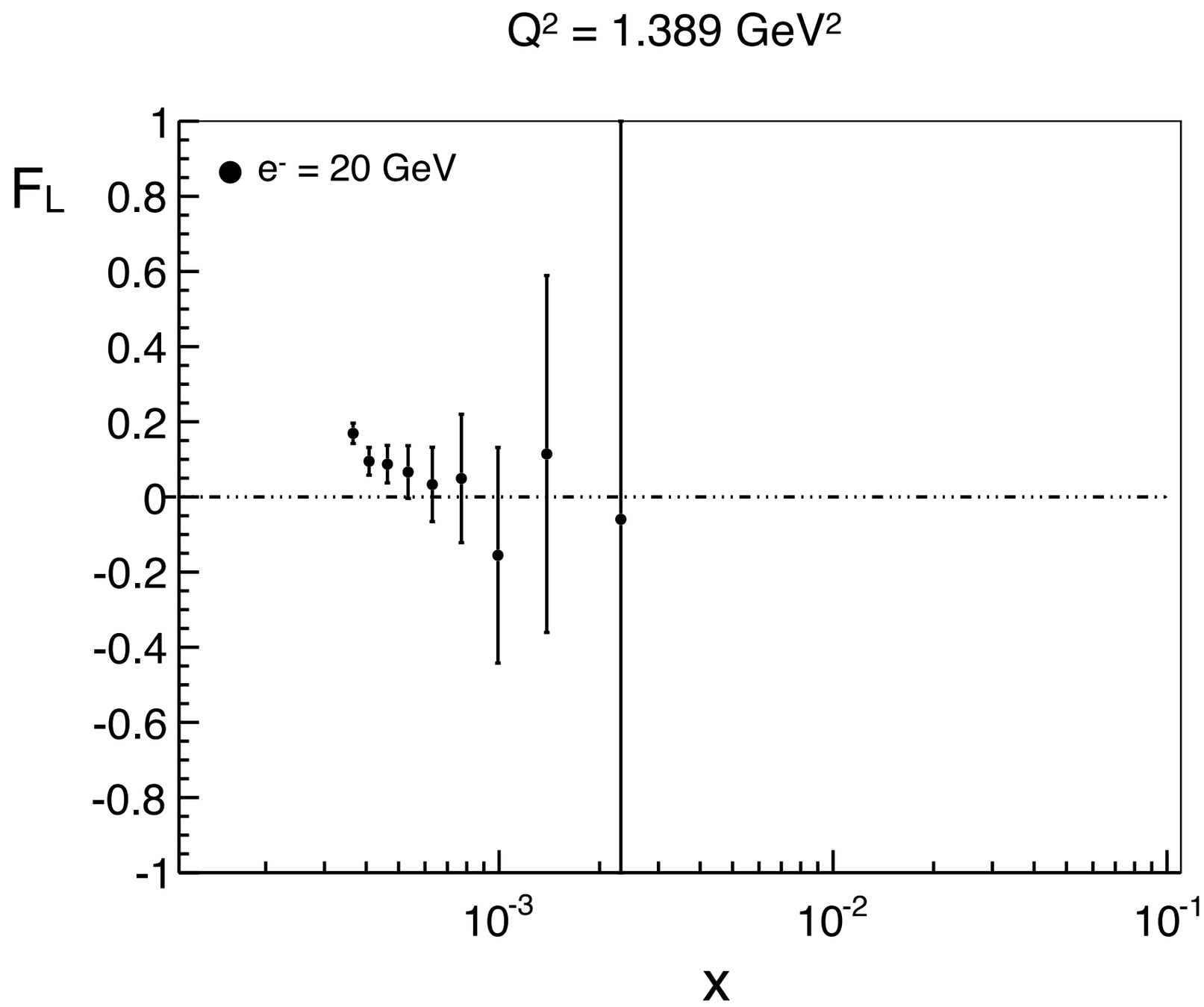

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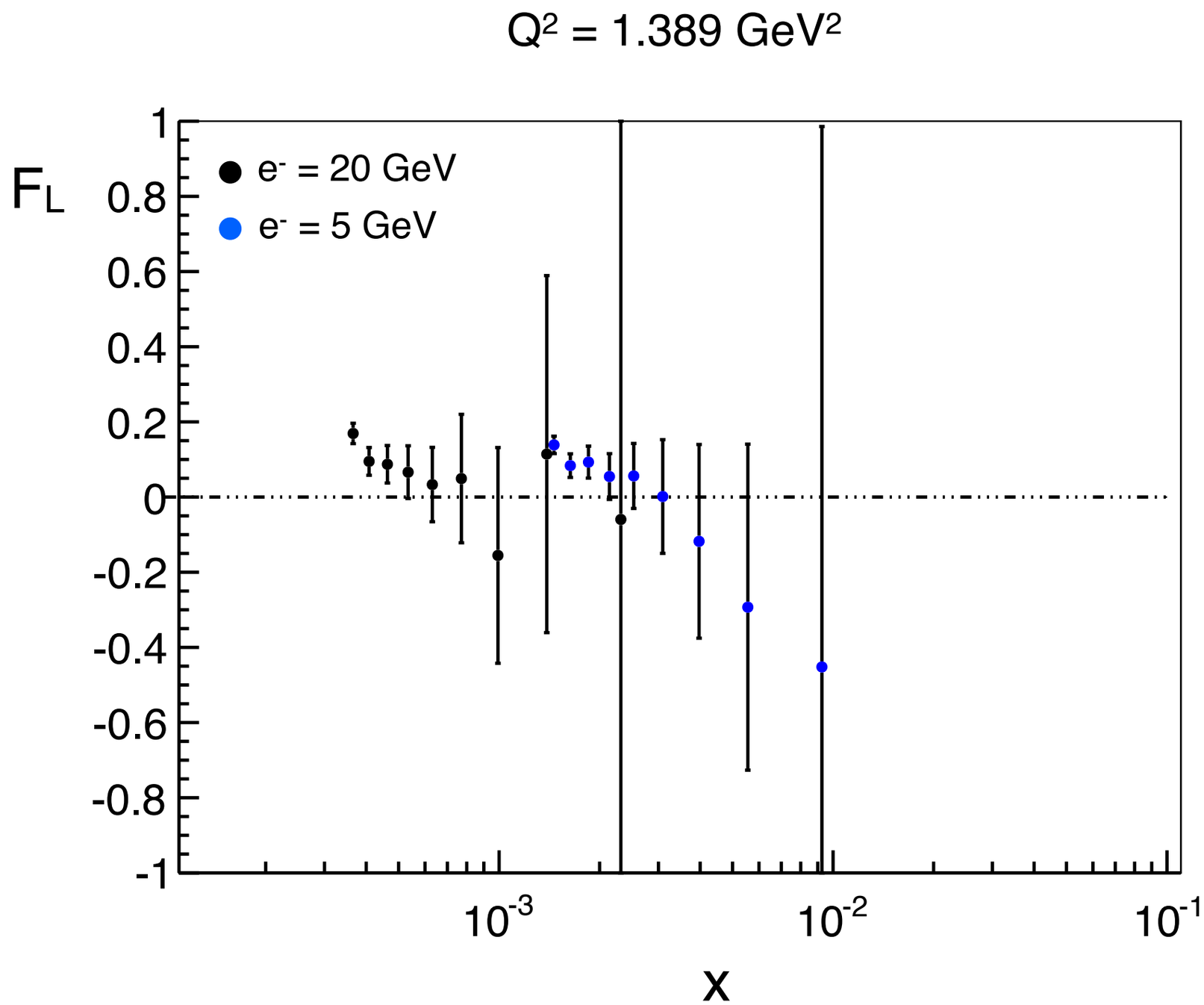

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e+Au: 1st stage
5x50 - $A\int Ldt = 2\ fb^{-1}$
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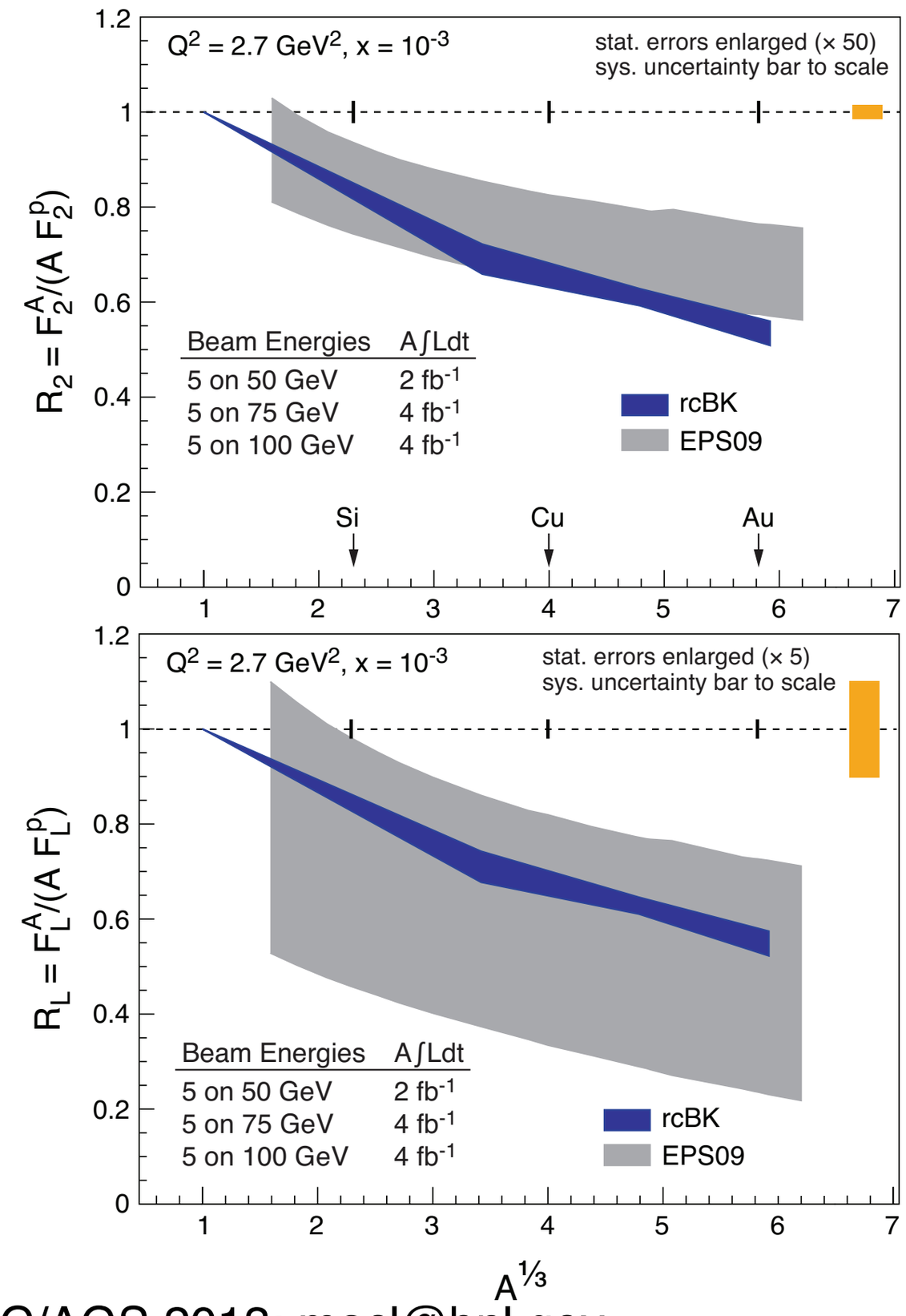
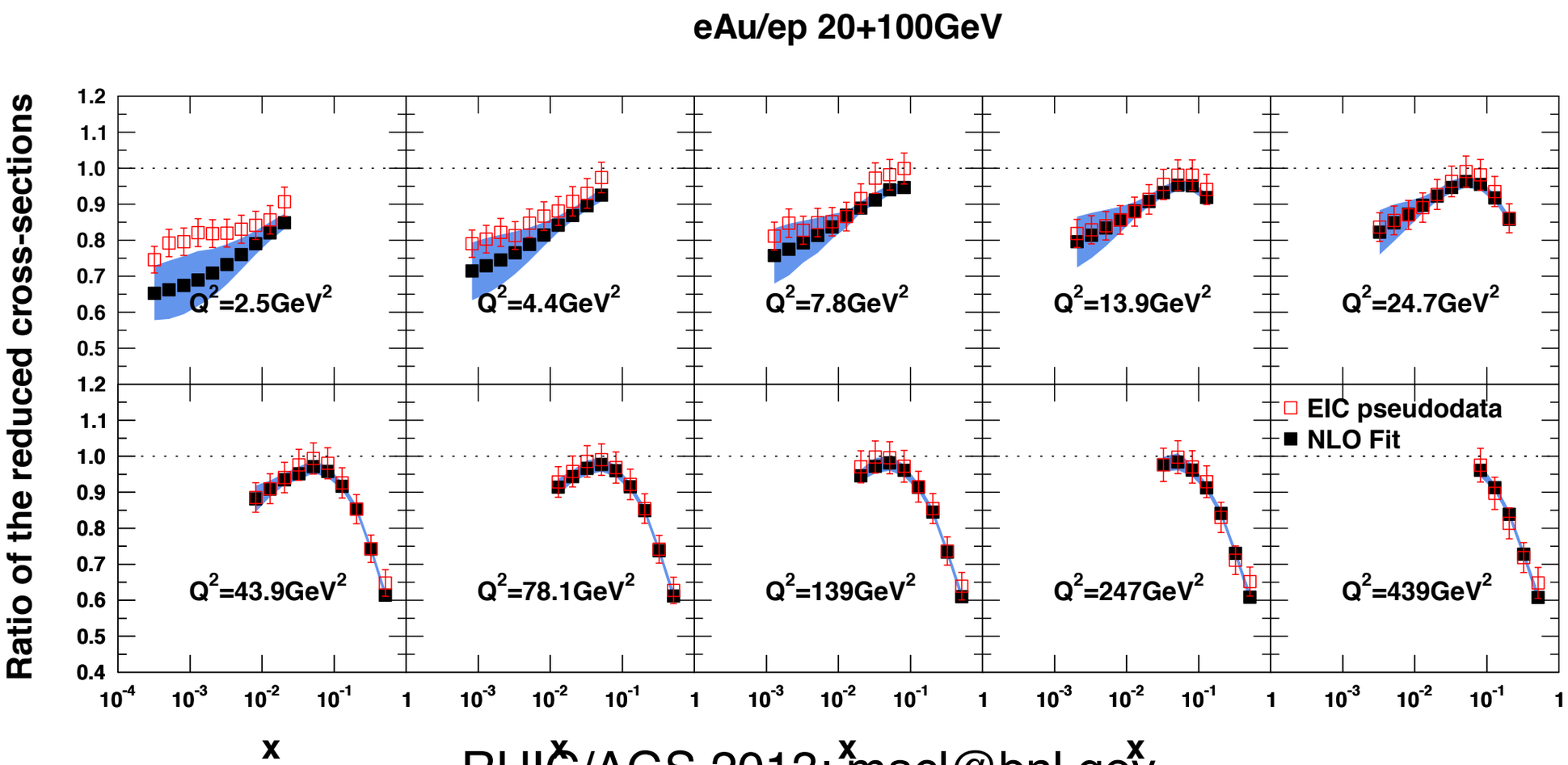


Work in progress… (H. Paukkunen)

- 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



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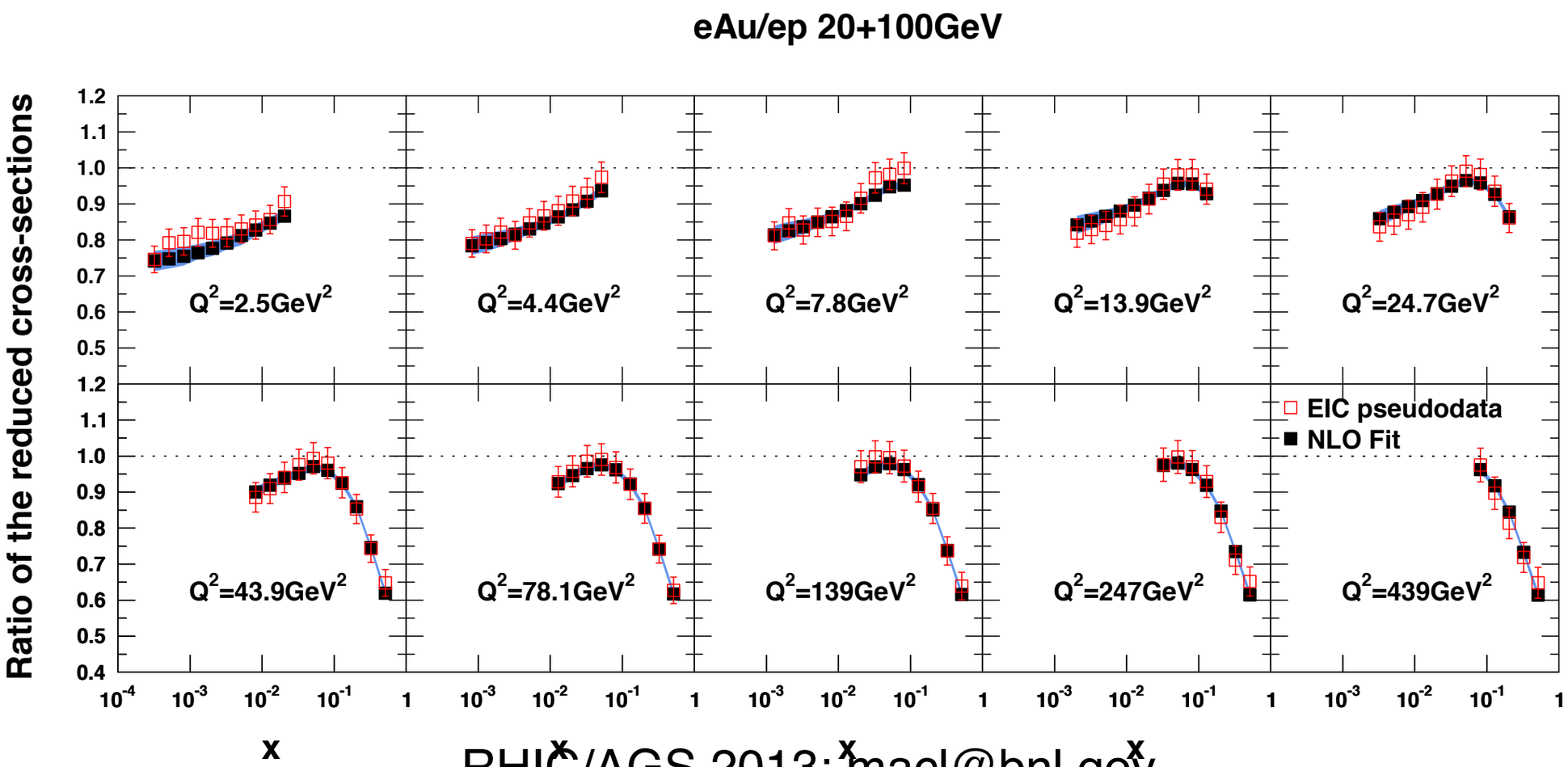

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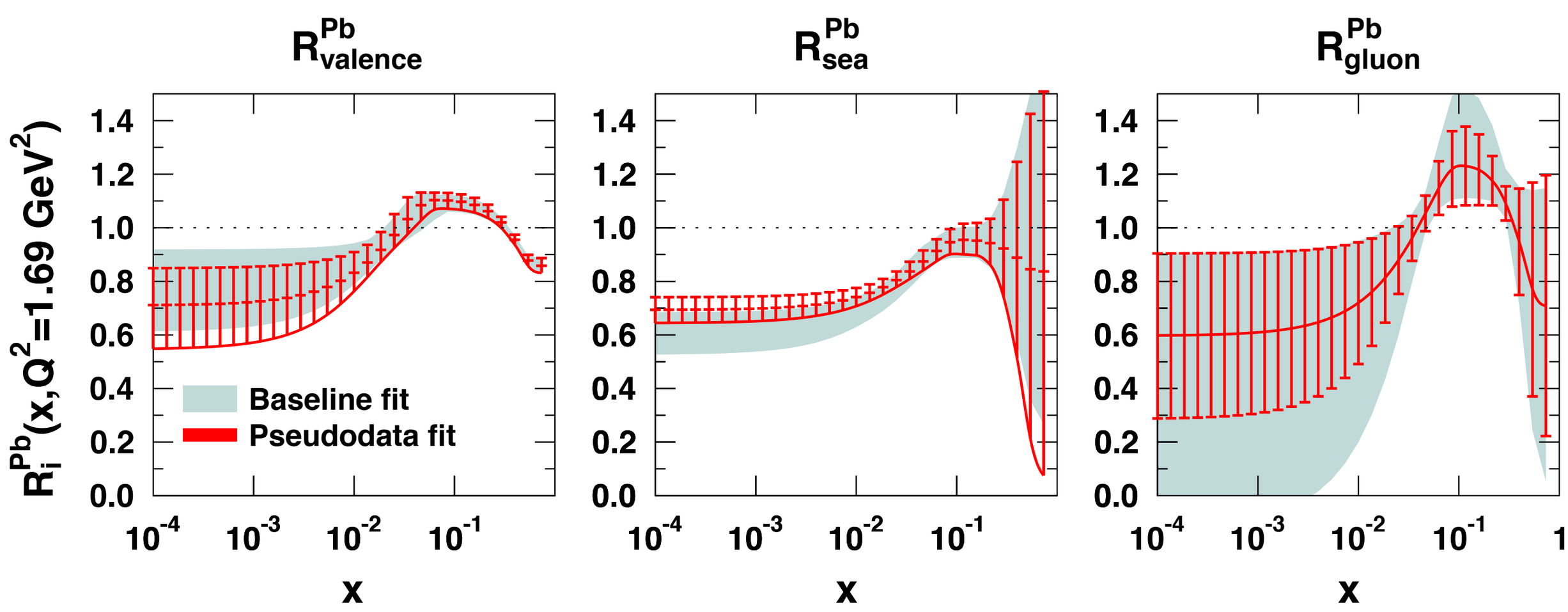

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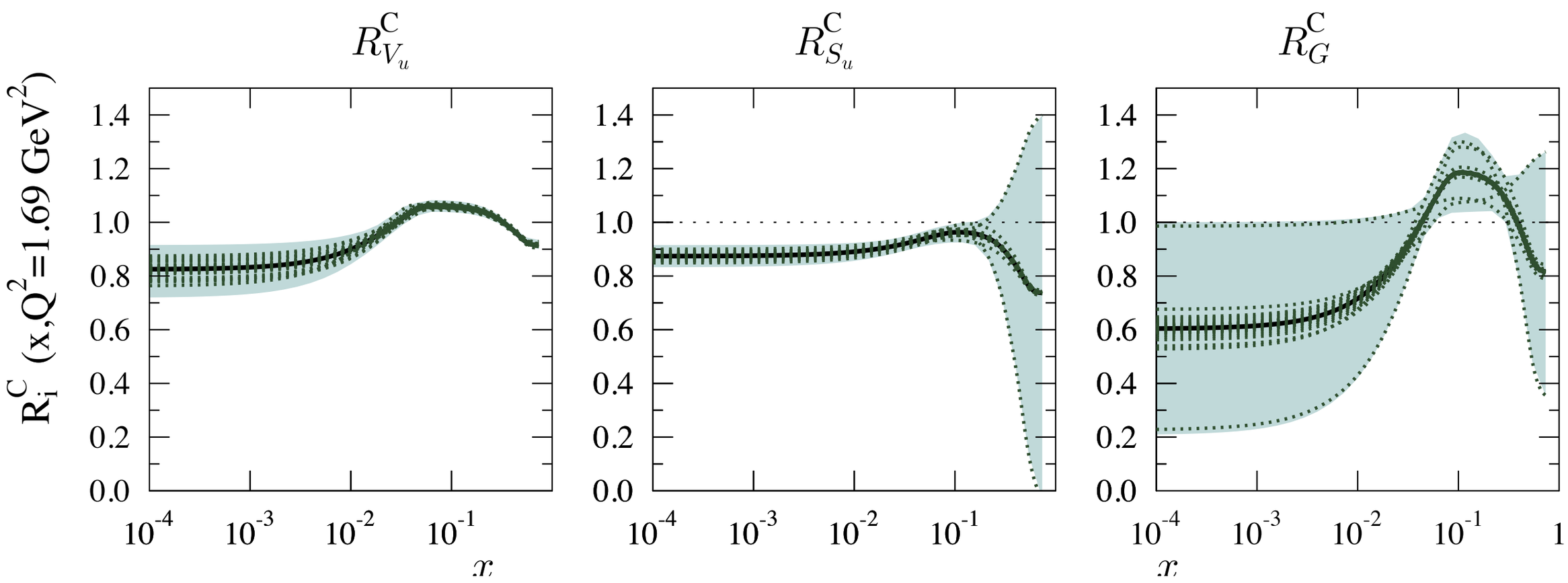
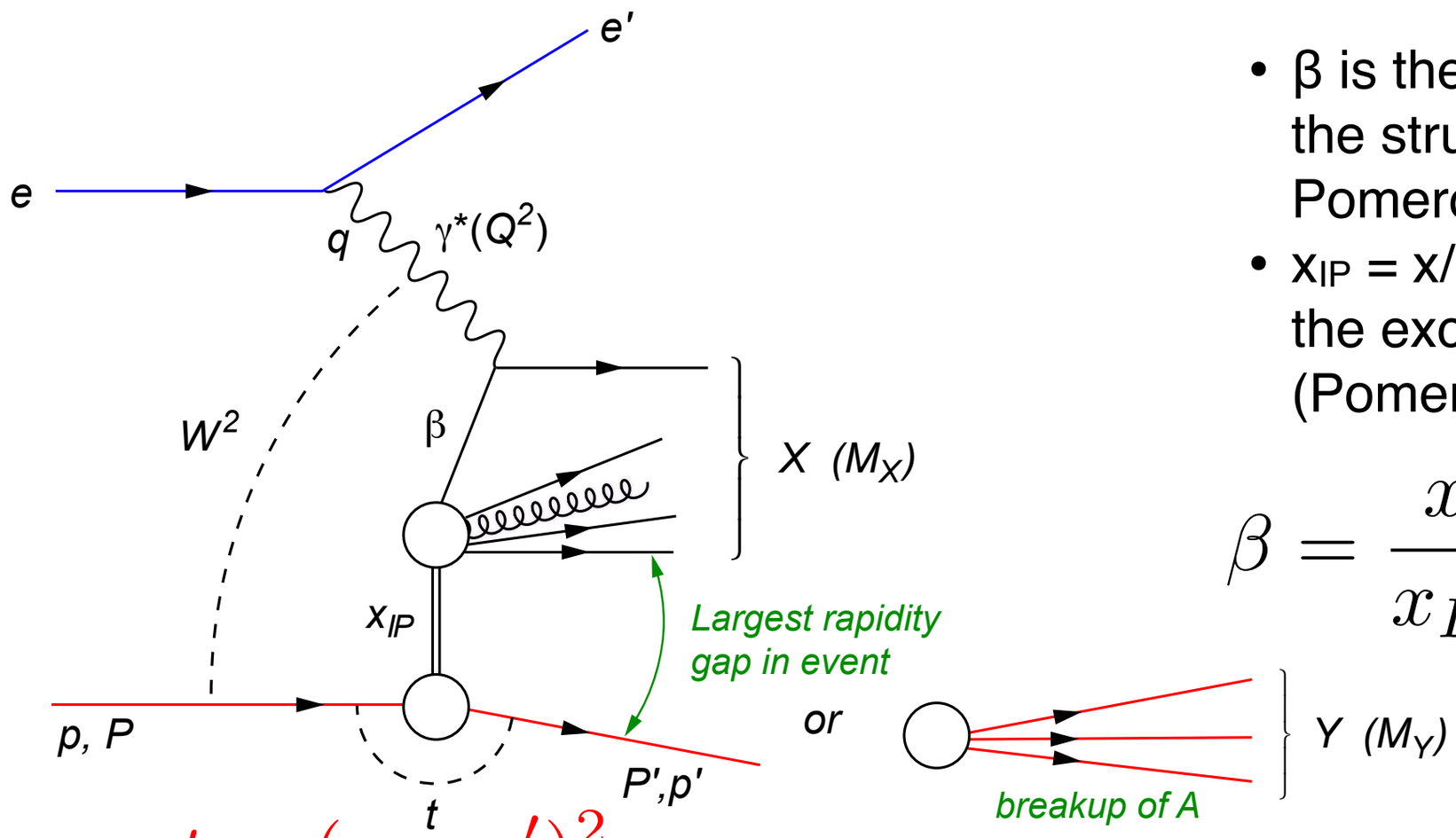


Exclusive processes in e+A - diffraction



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

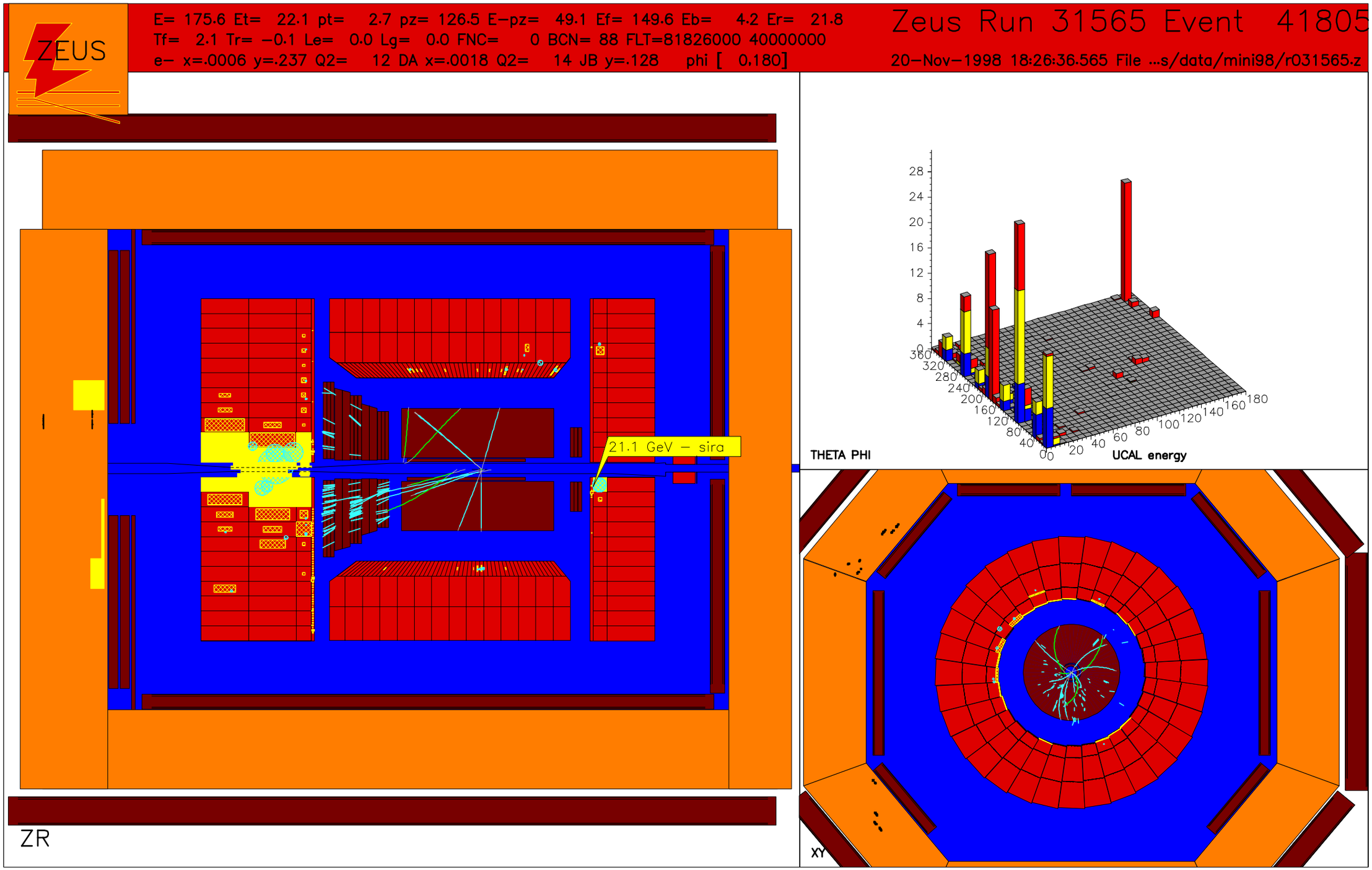
- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

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

- 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)

Visualising Diffractive events

A DIS event (experimental view)



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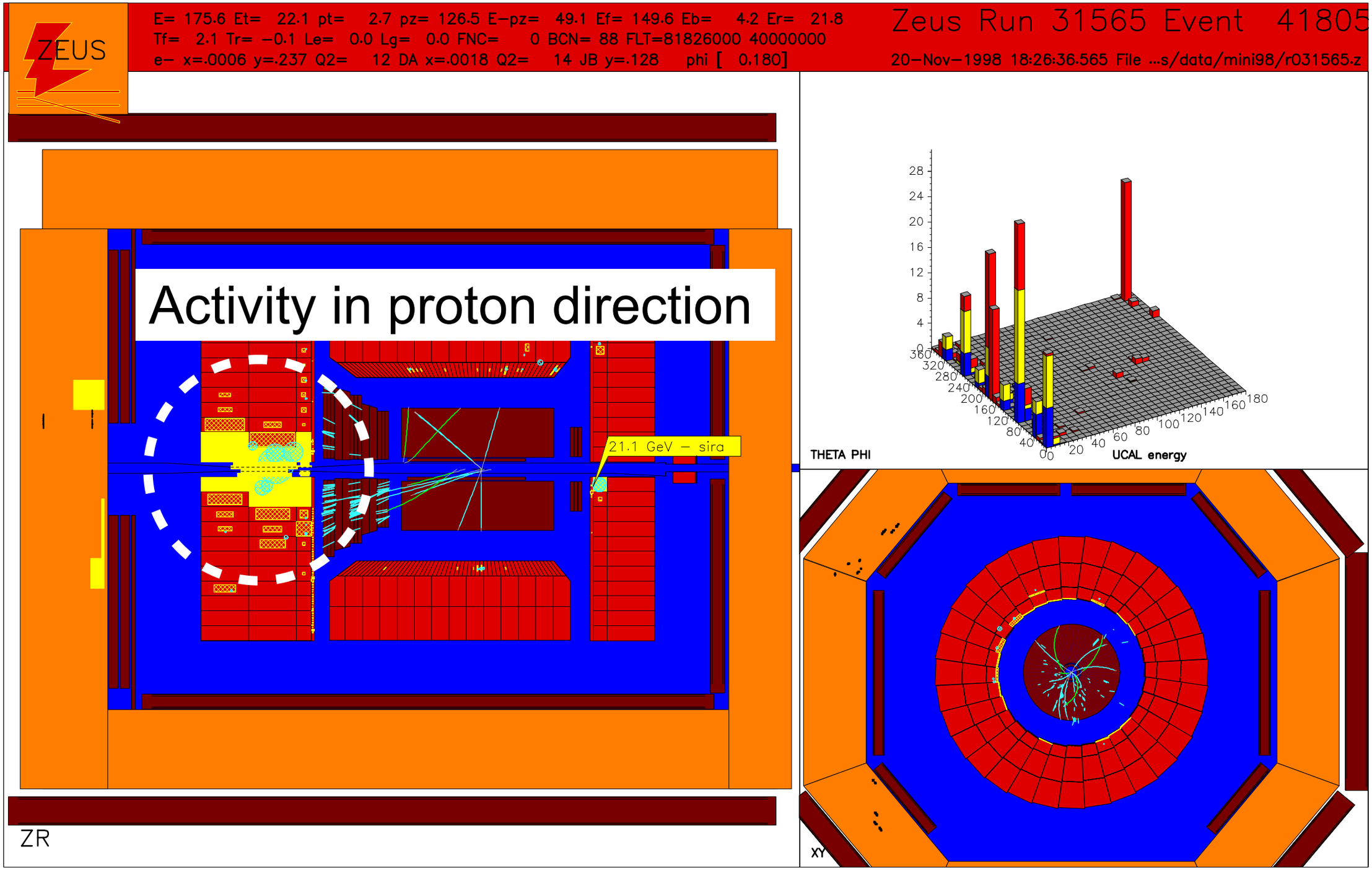

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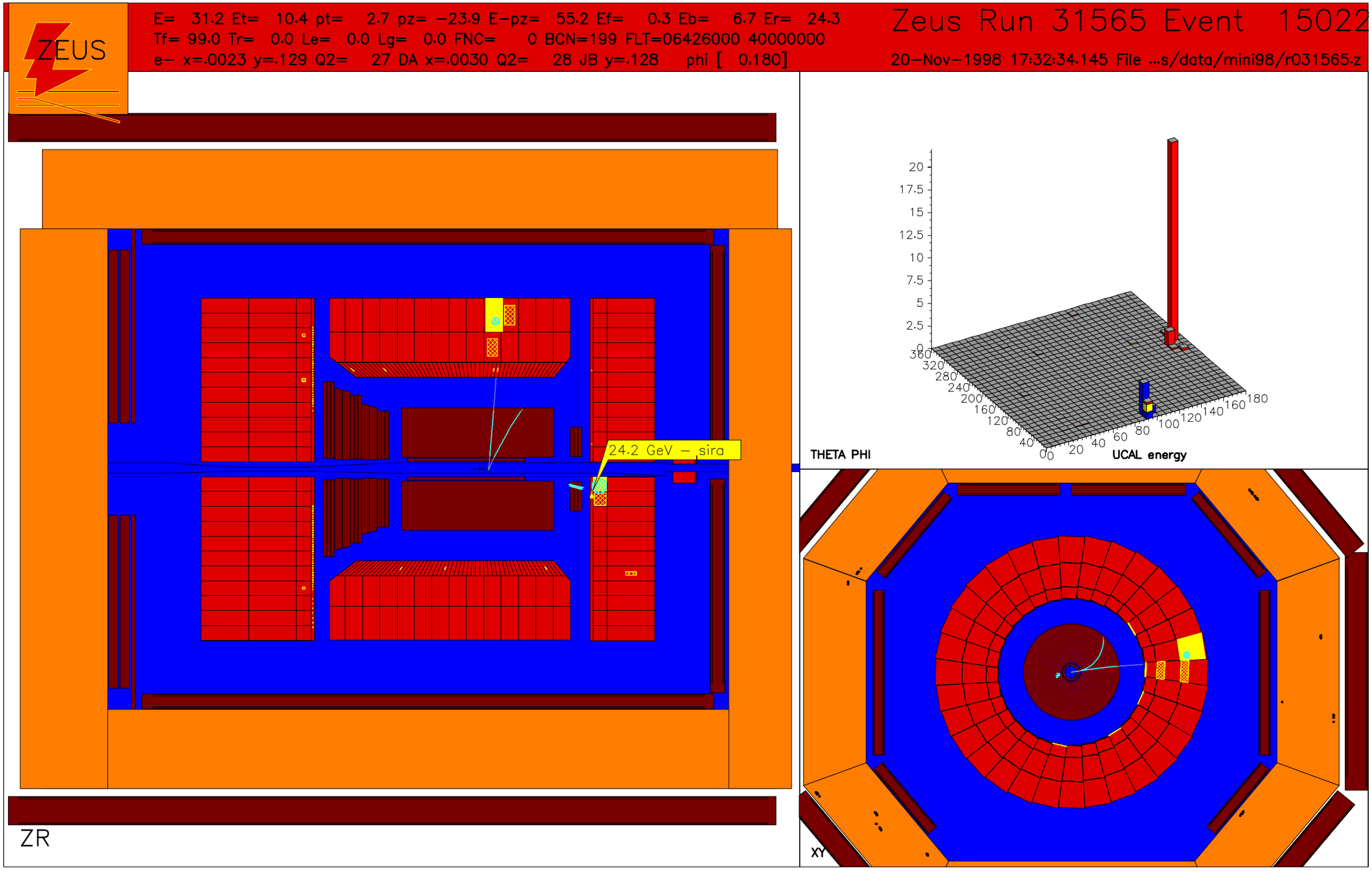

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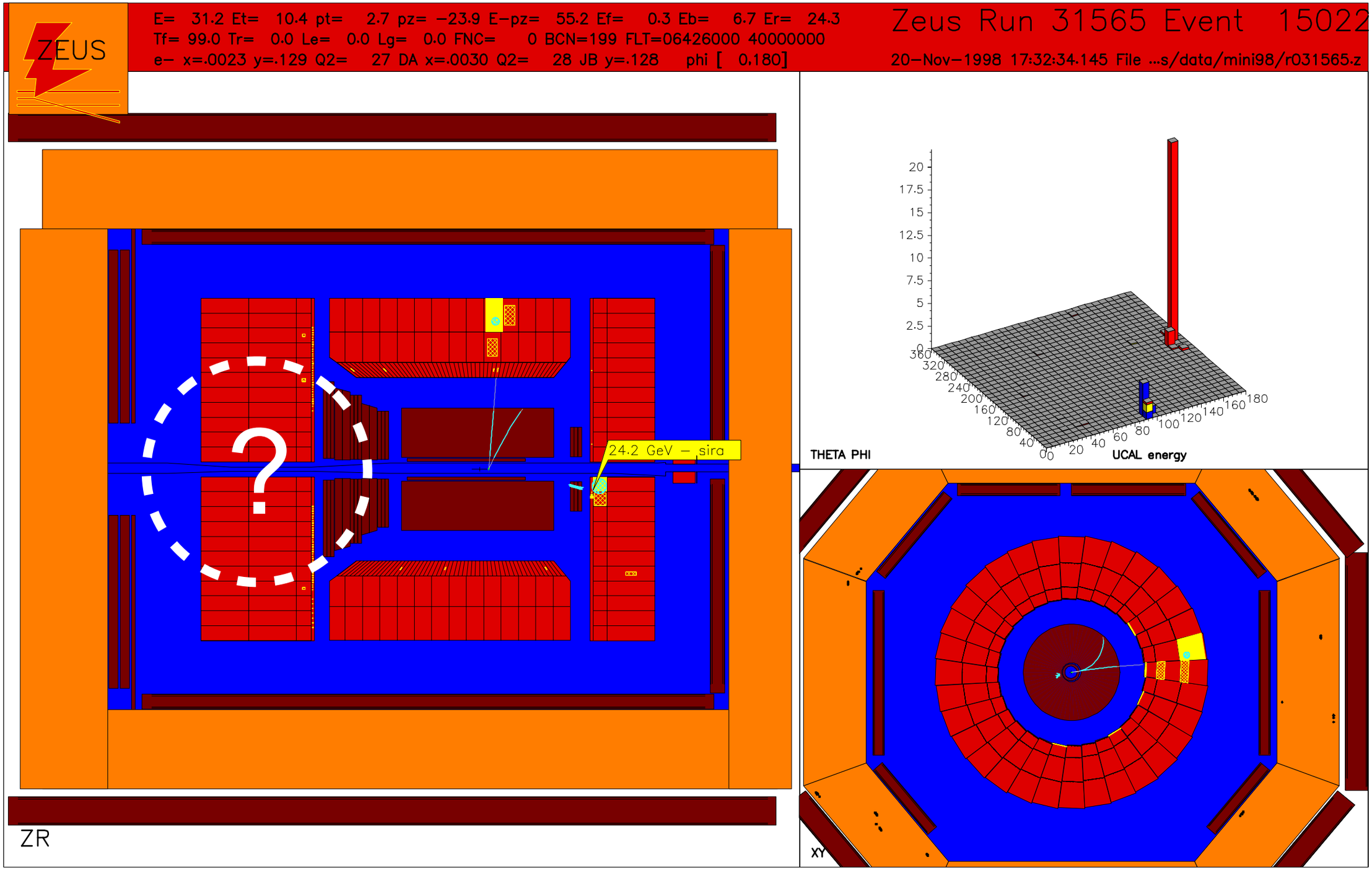
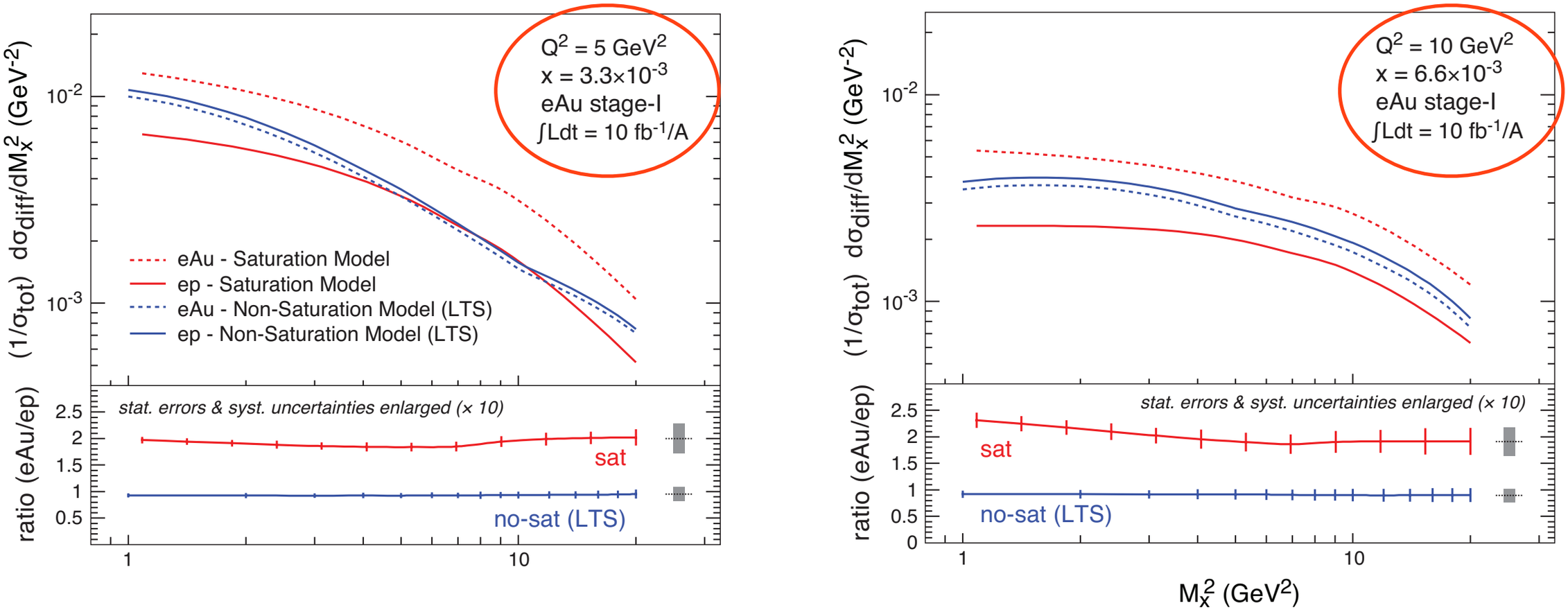
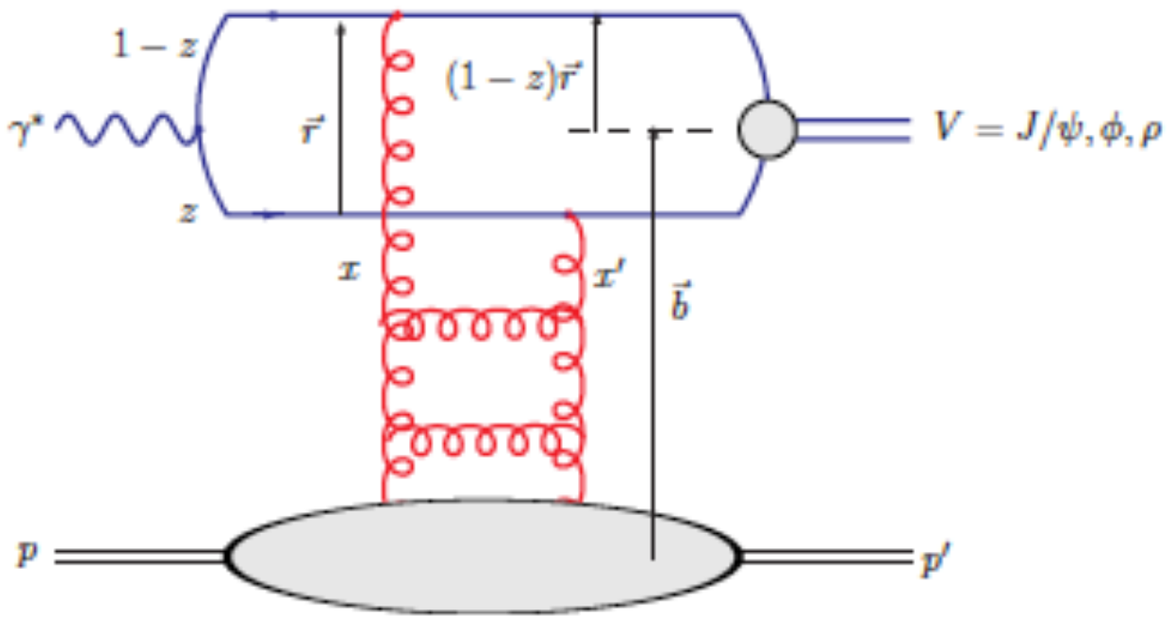


Day 1: Diffractive Cross-sections

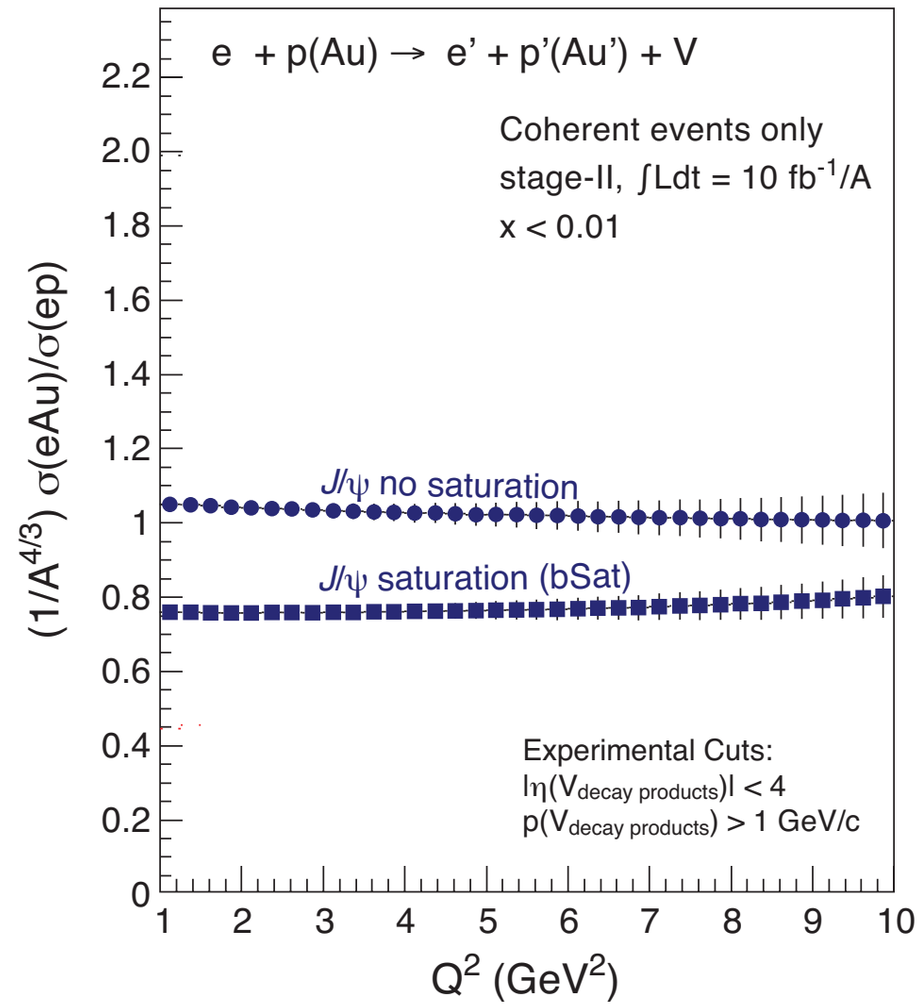


- Ratio of diffractive-to-total cross-section drastically different between saturation (Marquet) and non-saturation (Frankfurt, Guzey, Strikman) models
- Expected experimental error bars (simulated for 10 fb^{-1} of data for a low-energy eRHIC) can distinguish between the two scenarios

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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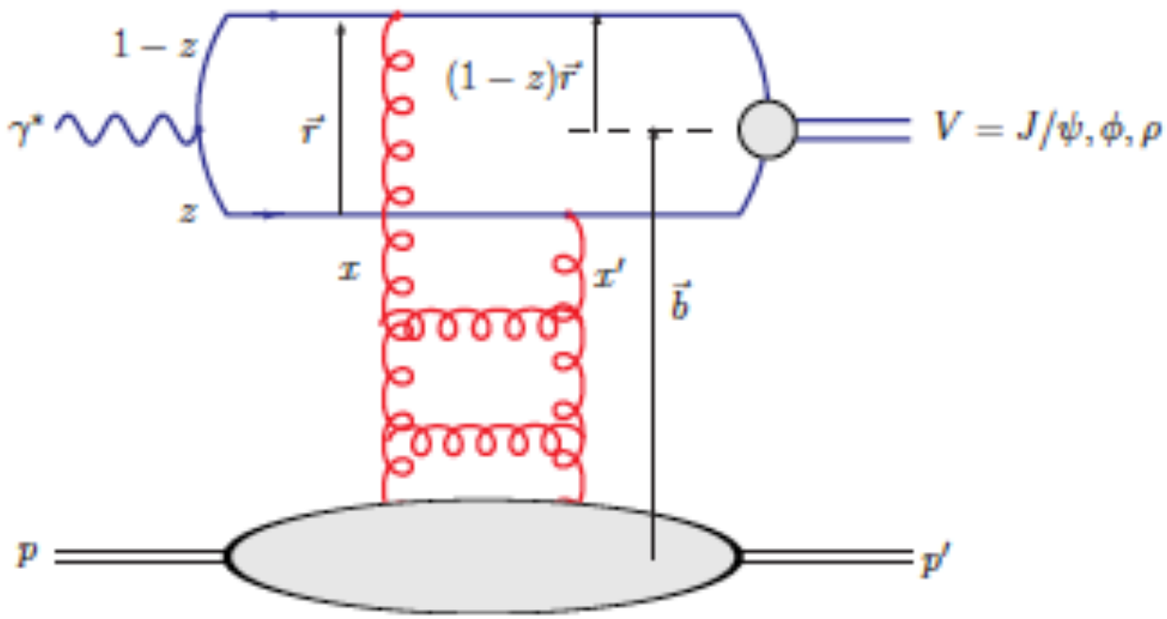

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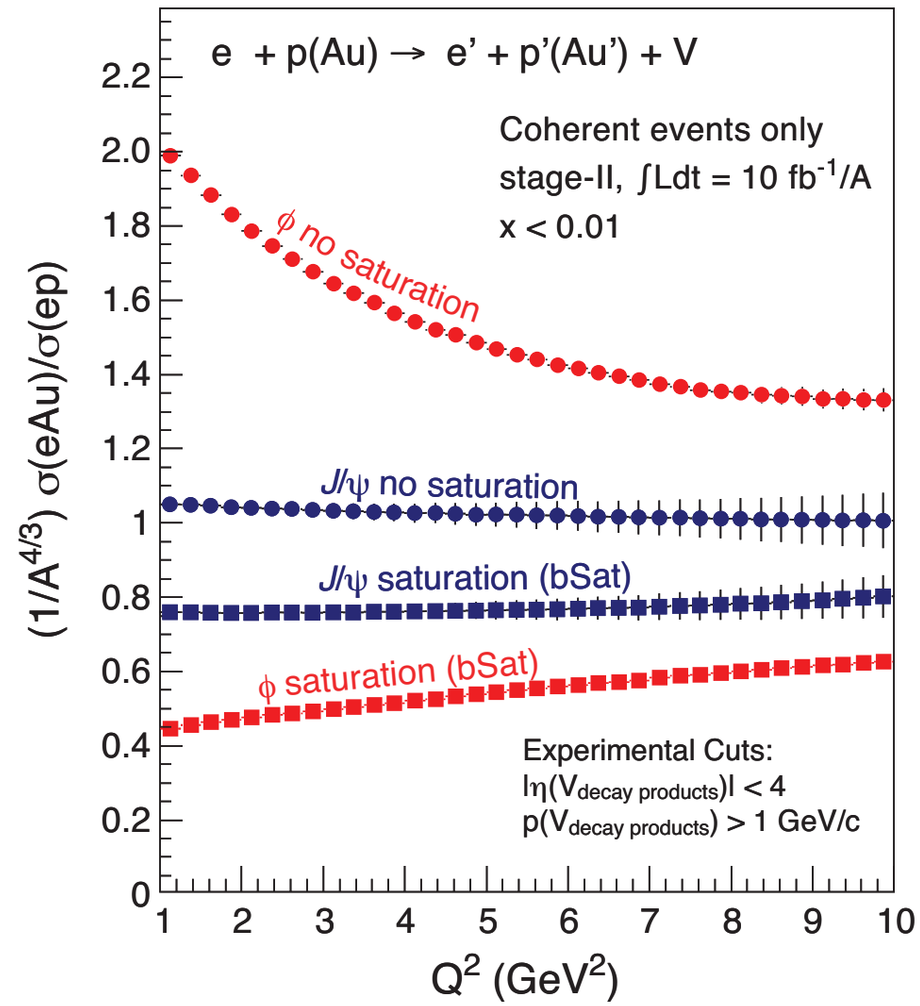
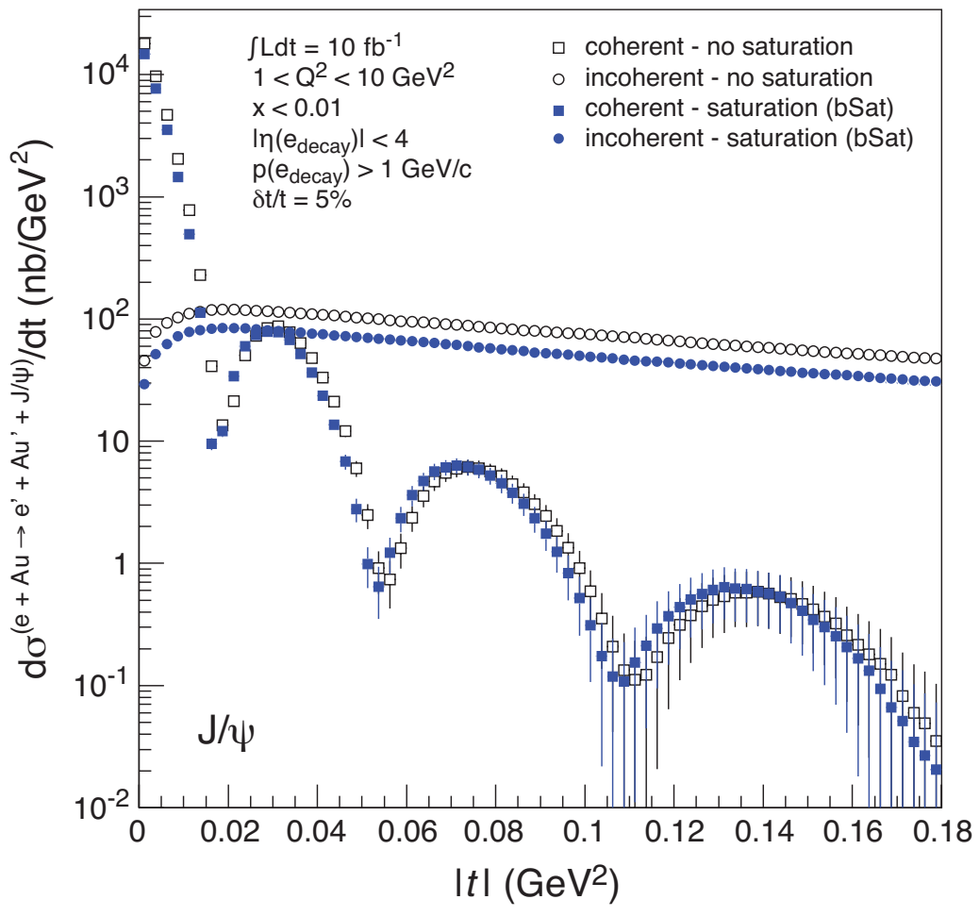
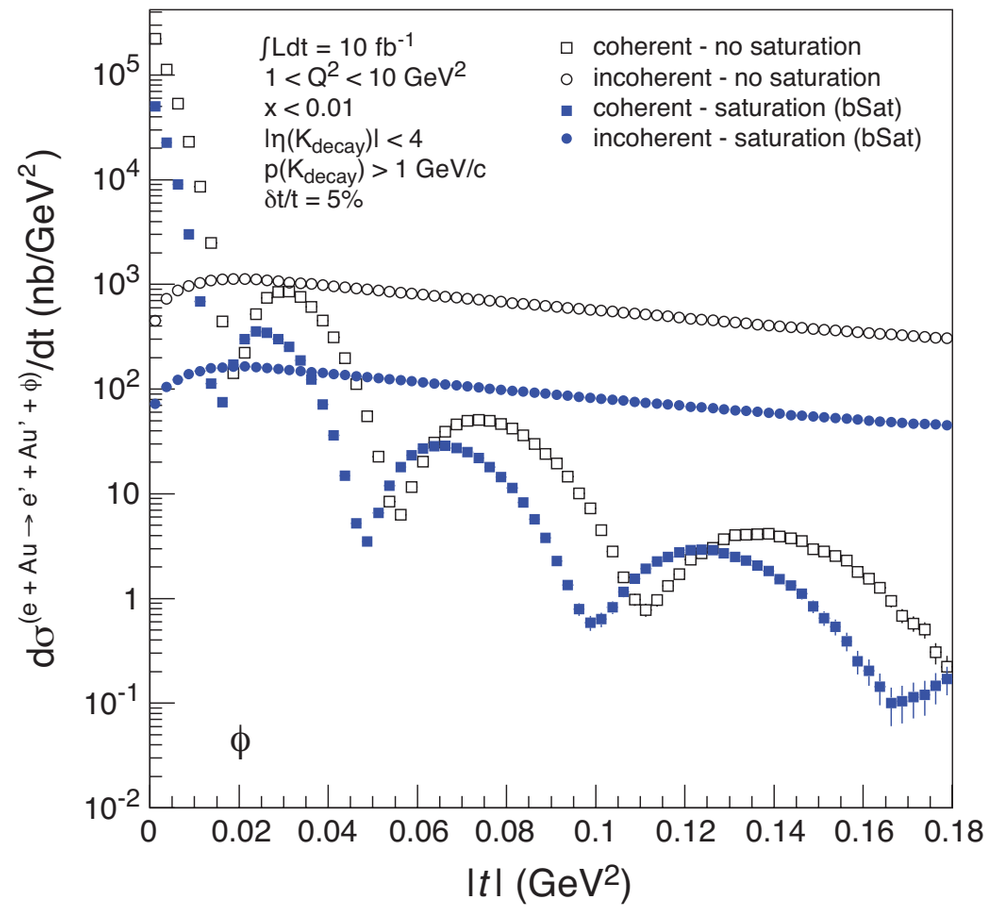


- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference
  - ➡ wave function for ϕ is larger and hence more sensitive to saturation effects

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

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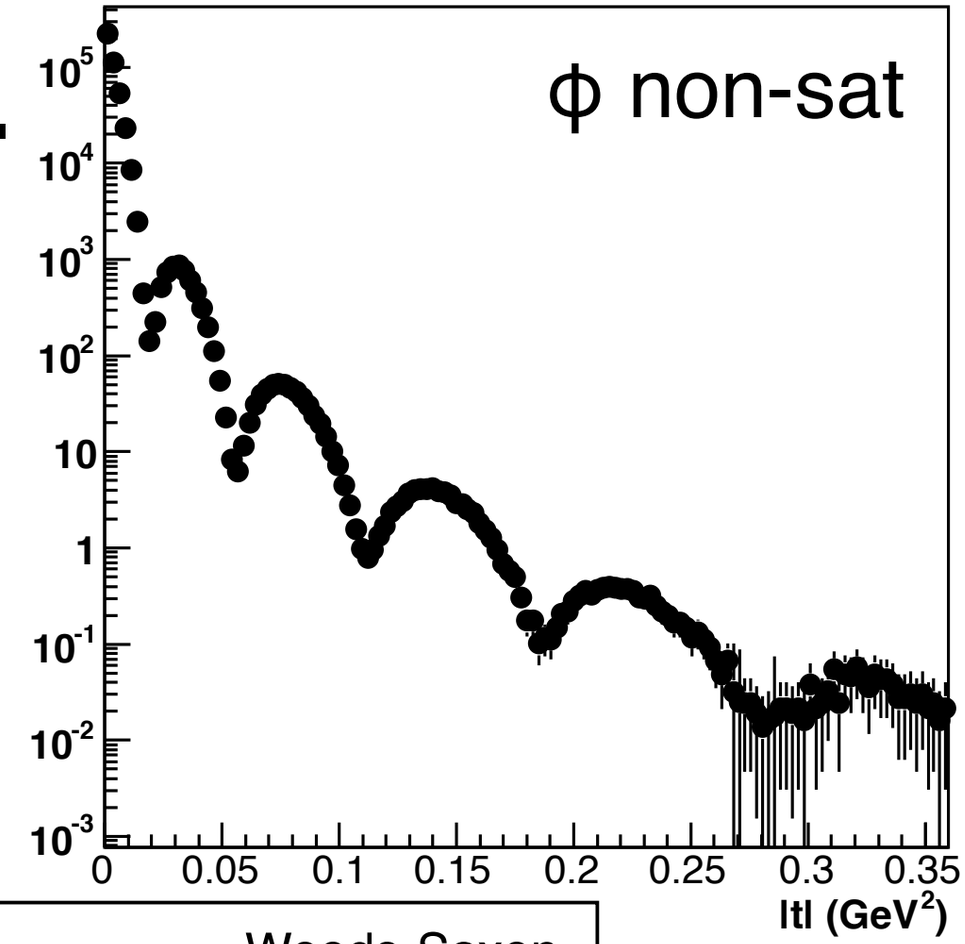

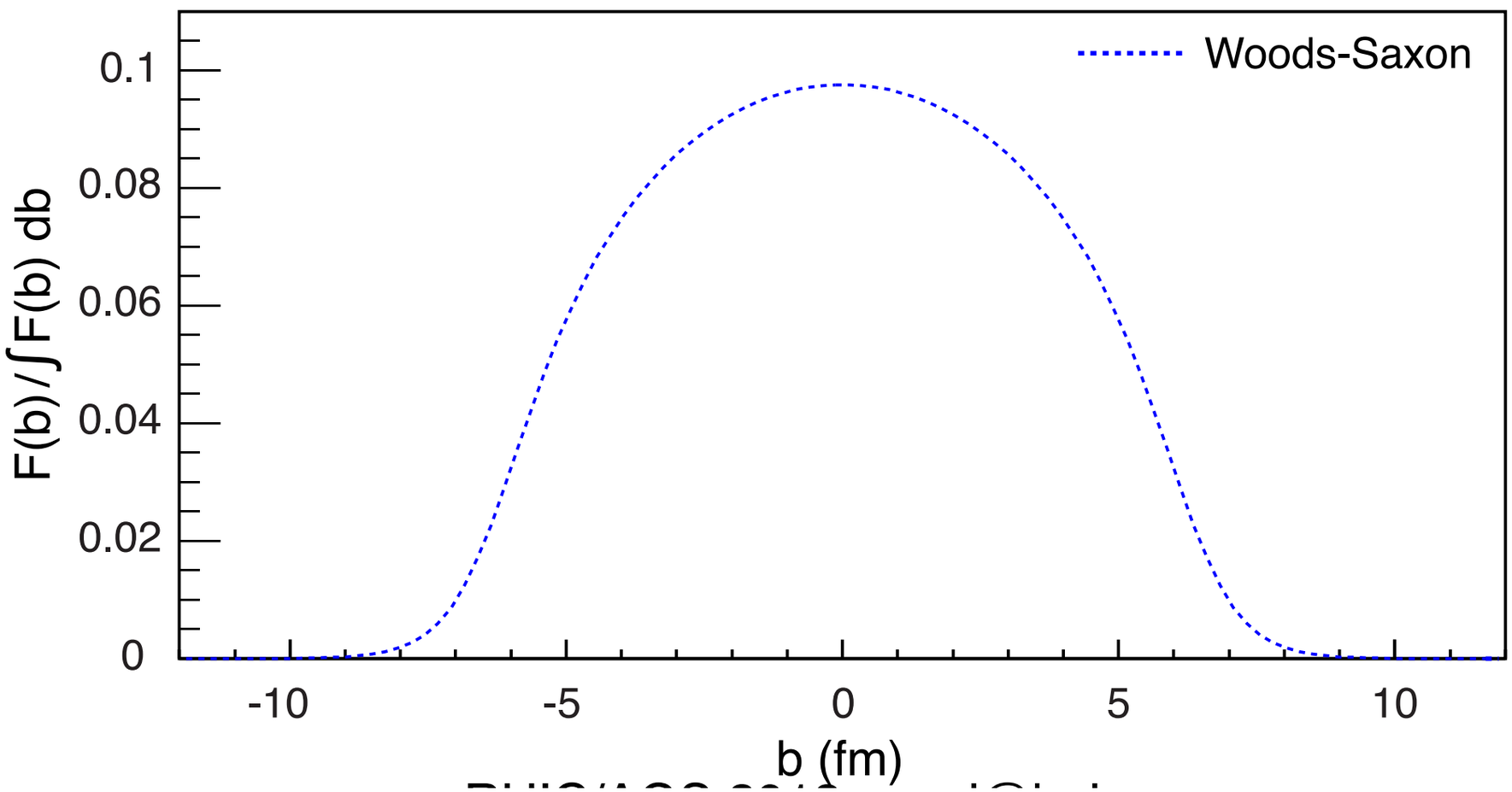

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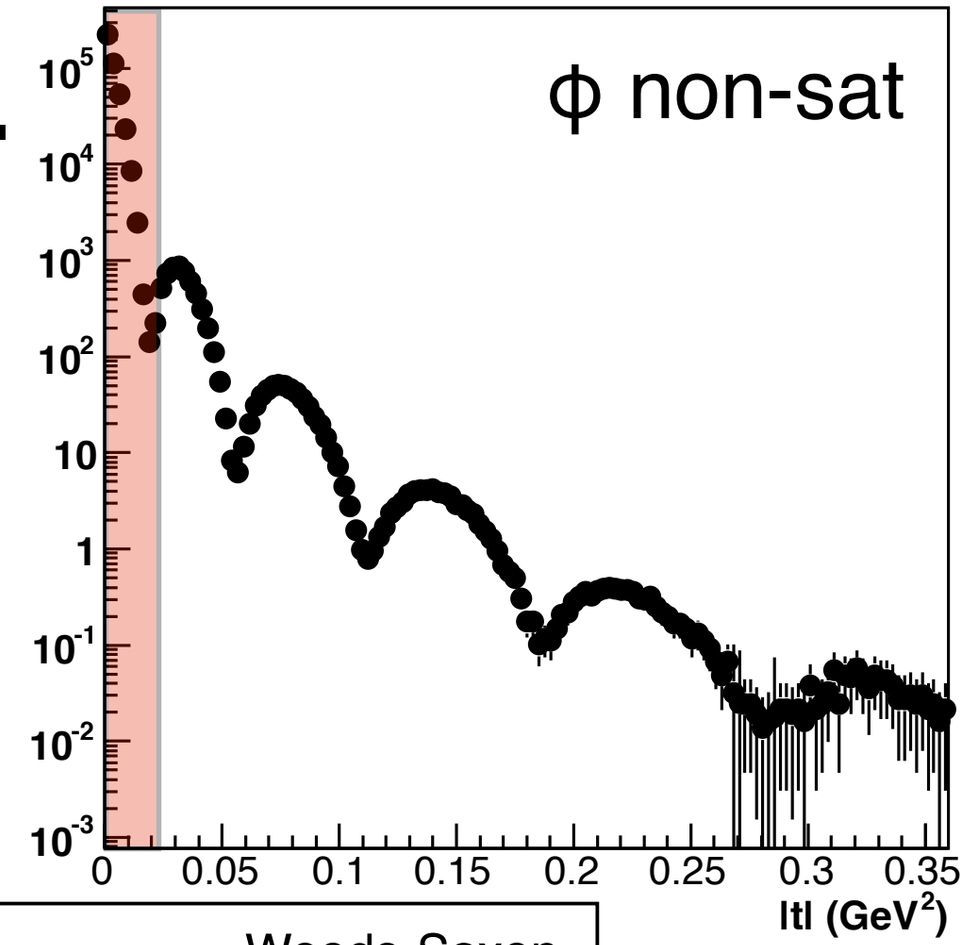

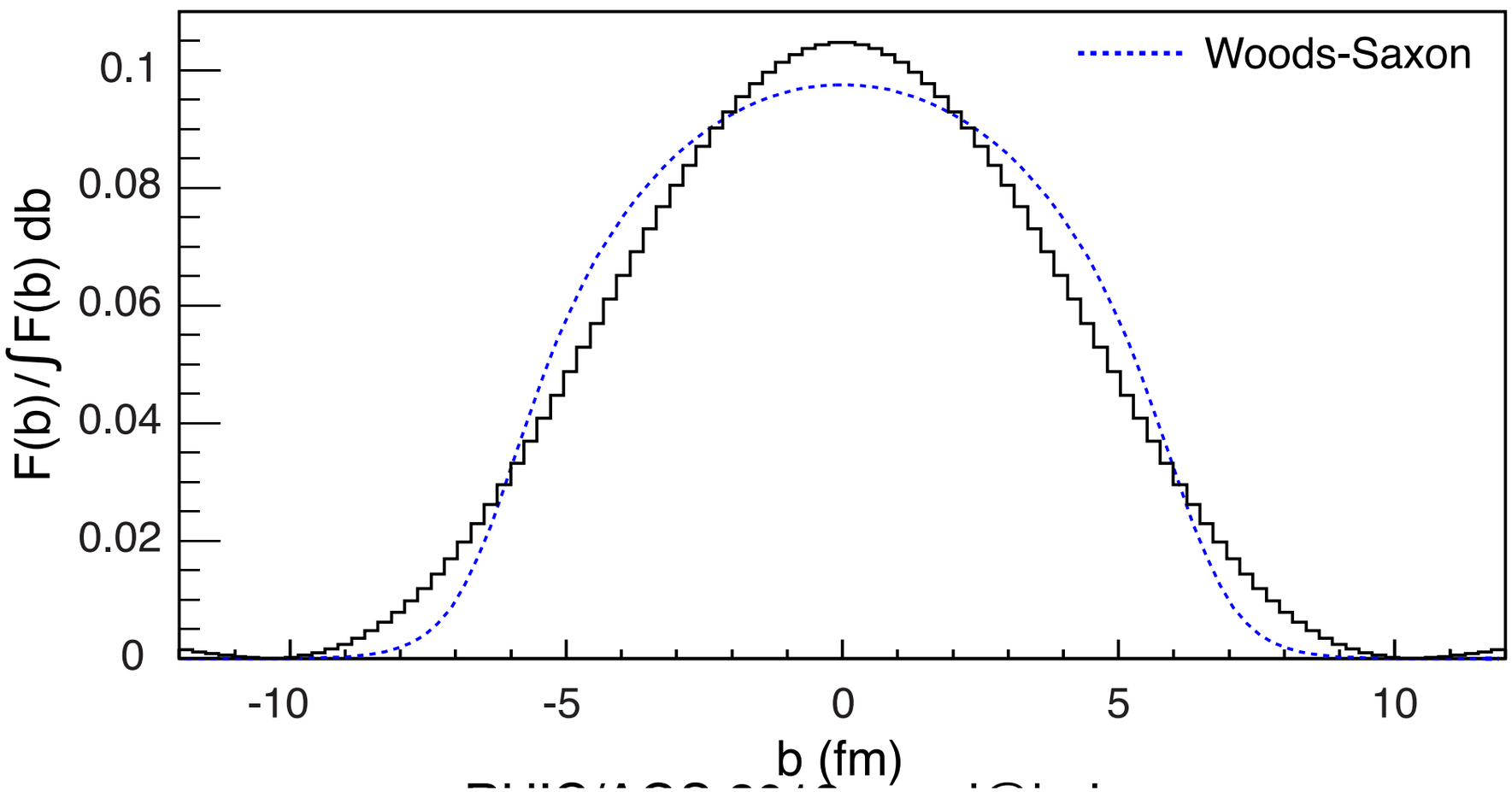

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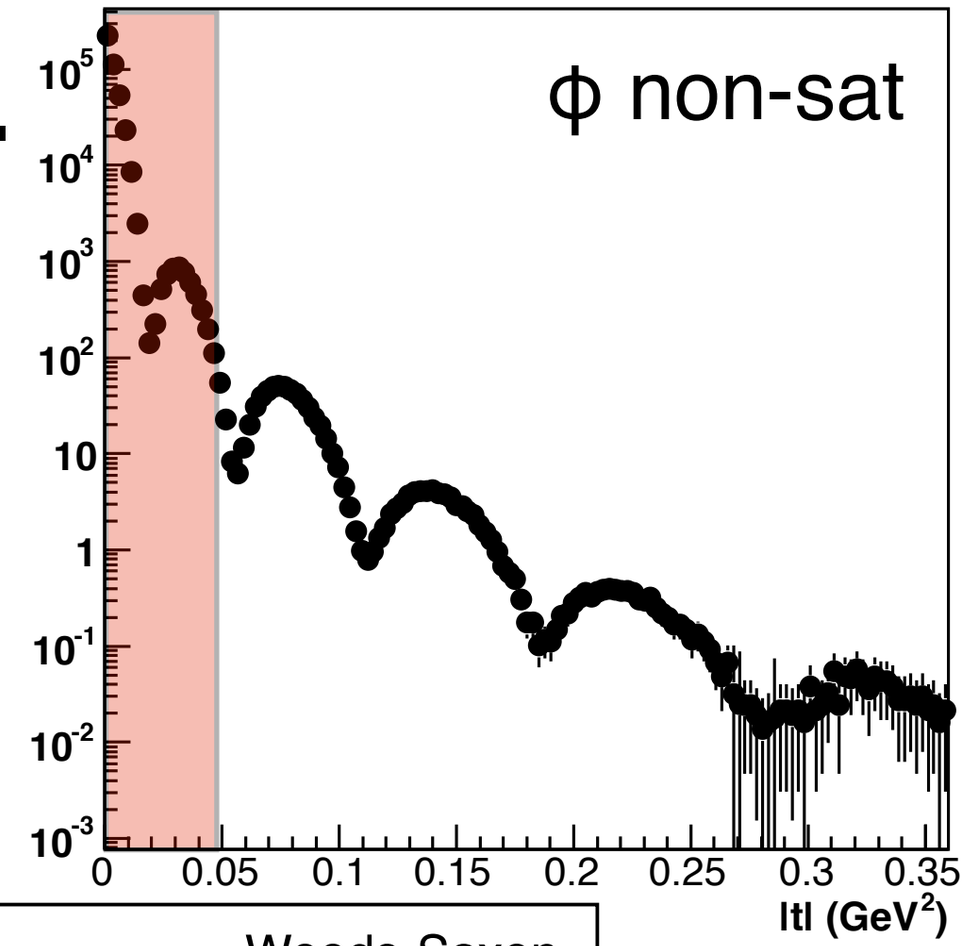

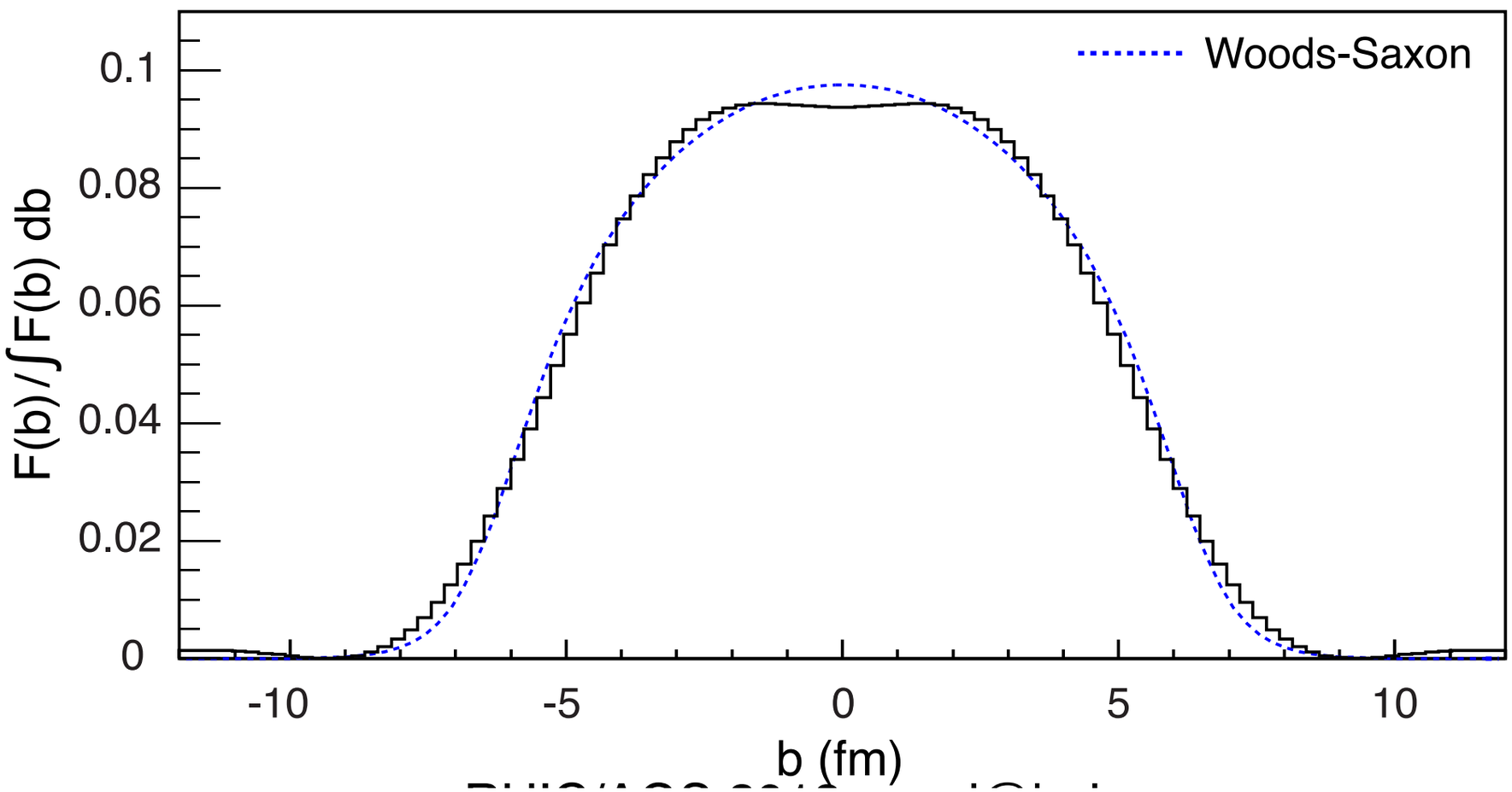

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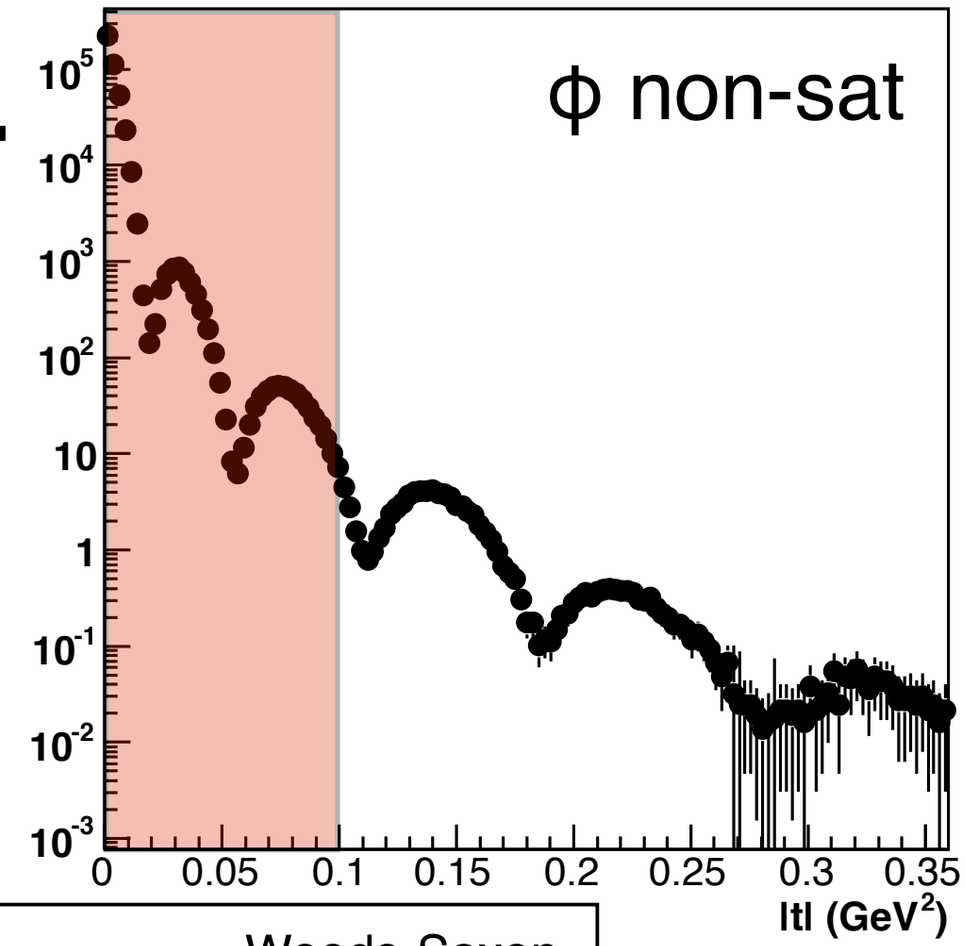

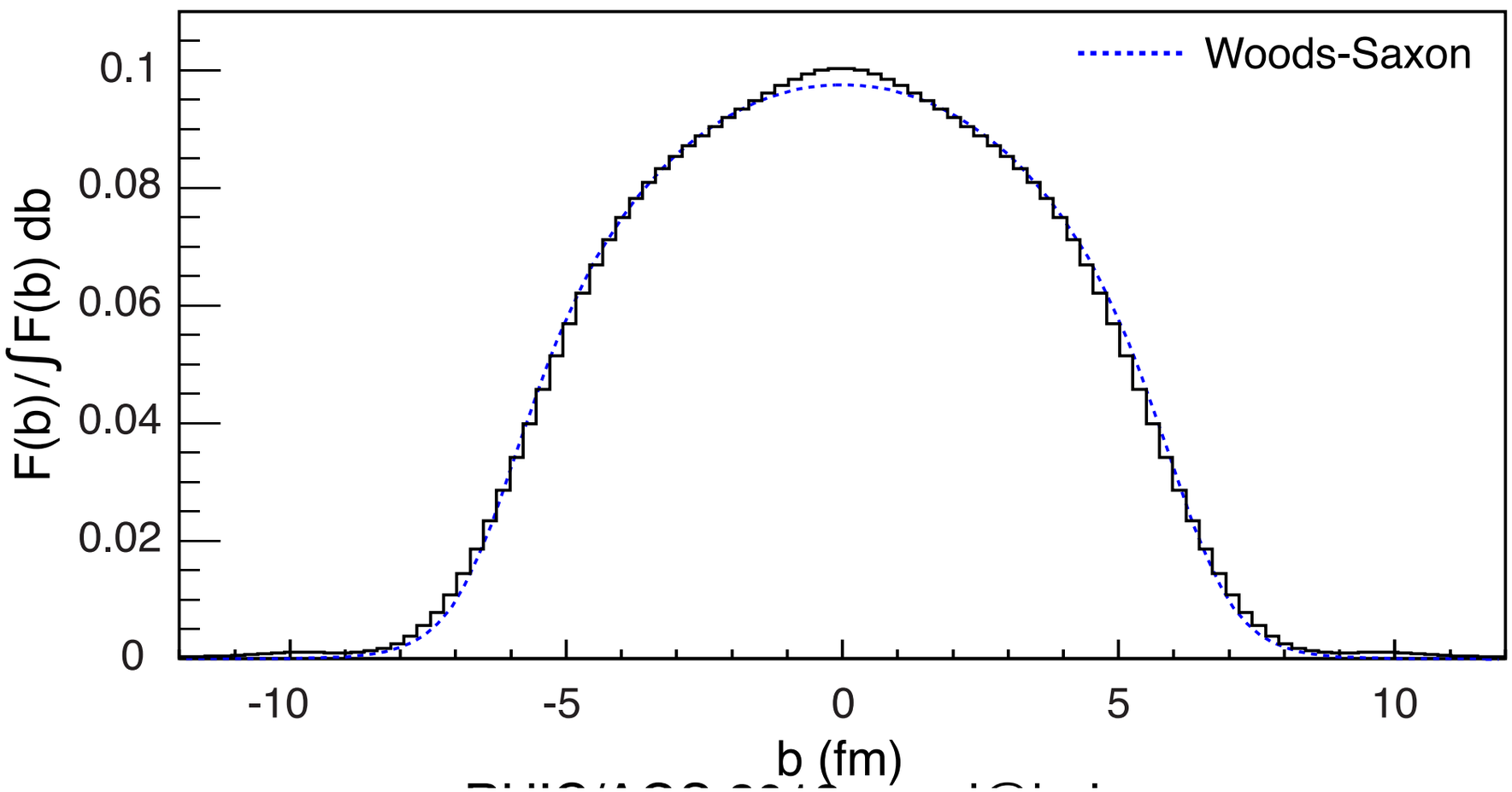

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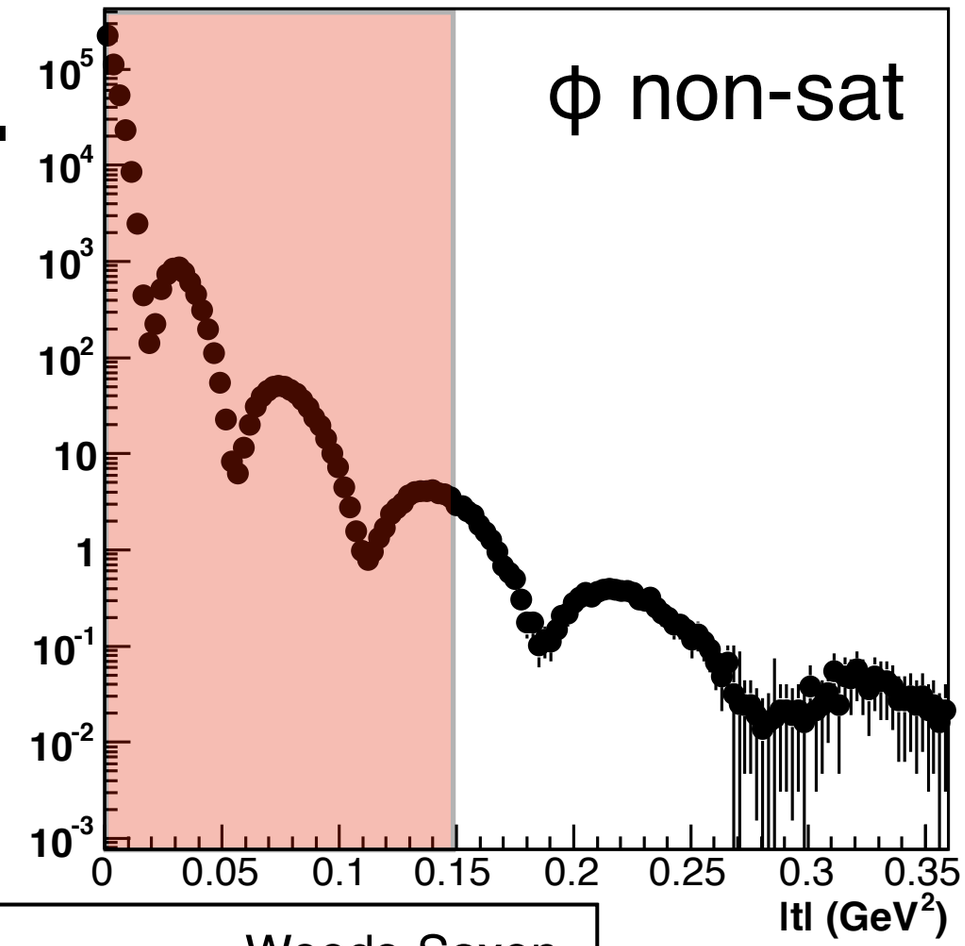

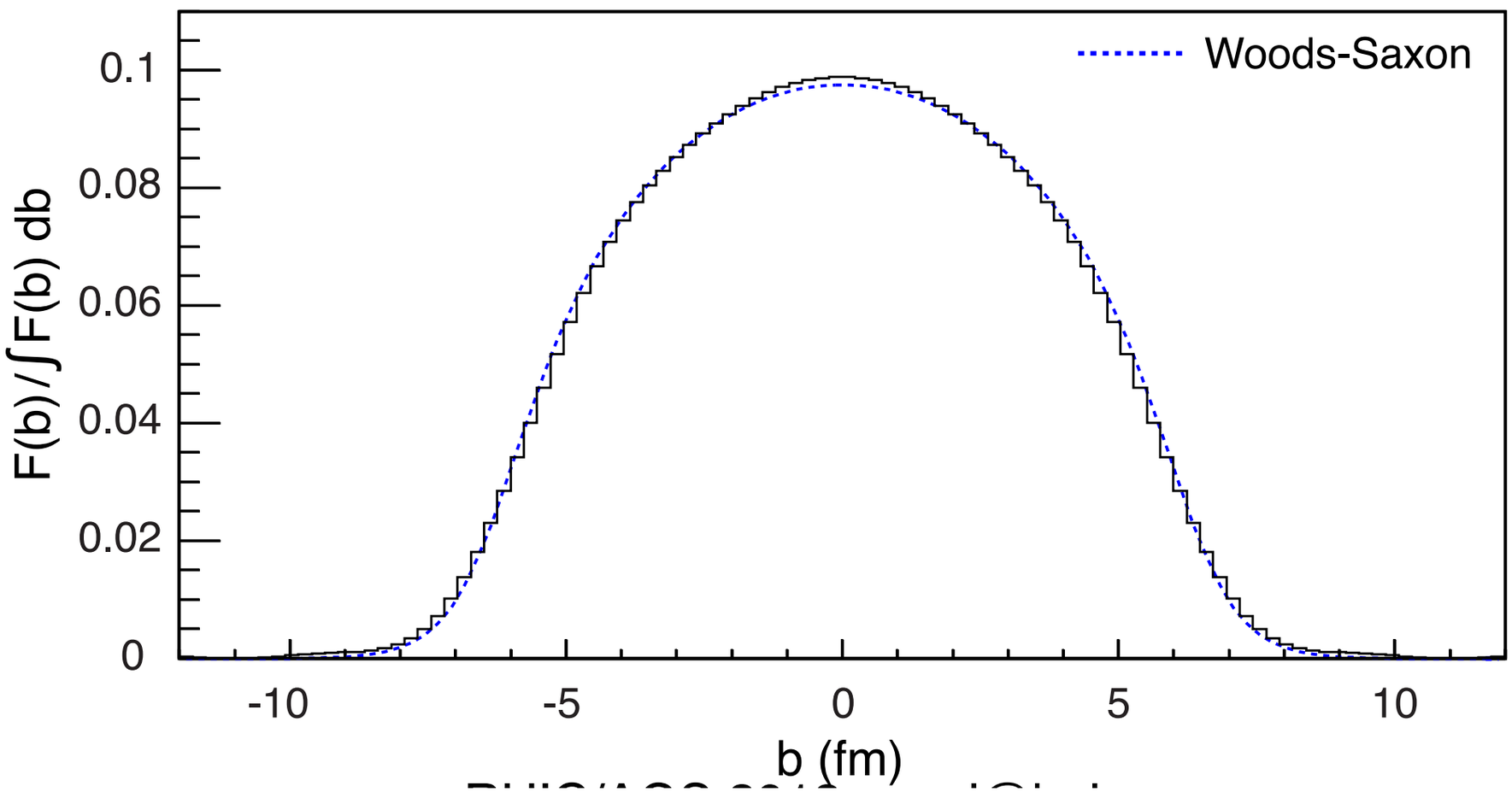

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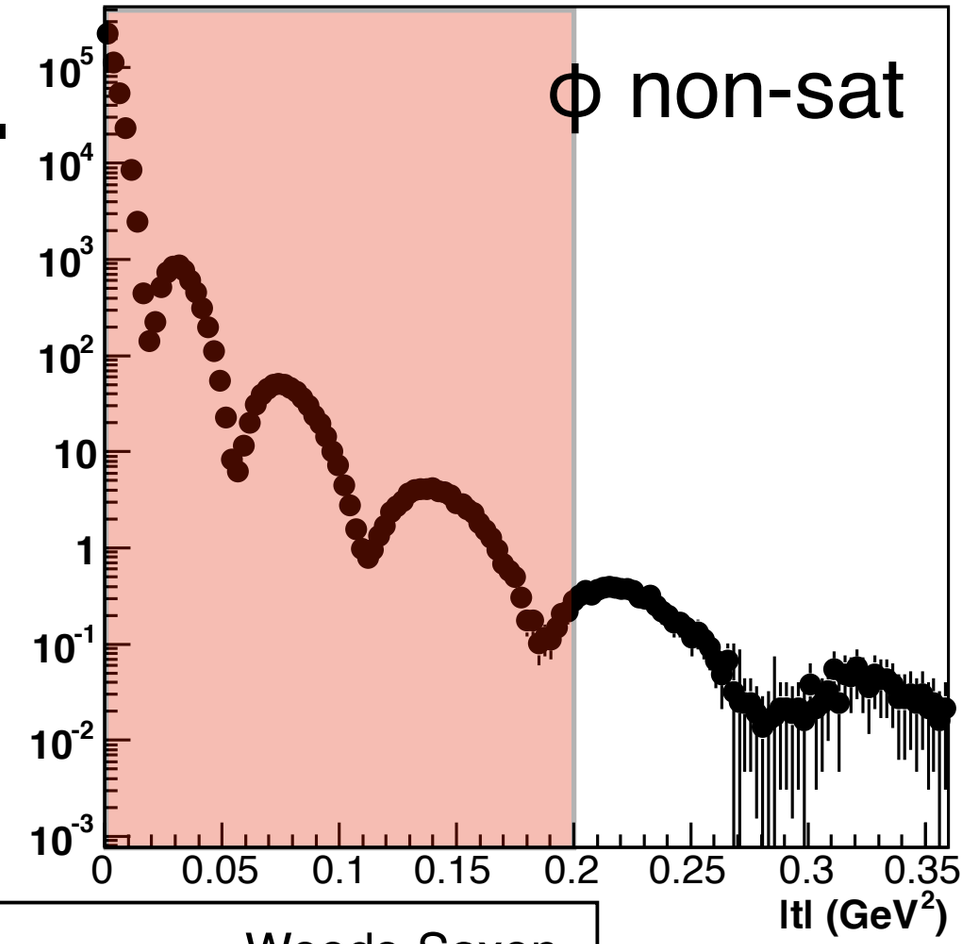

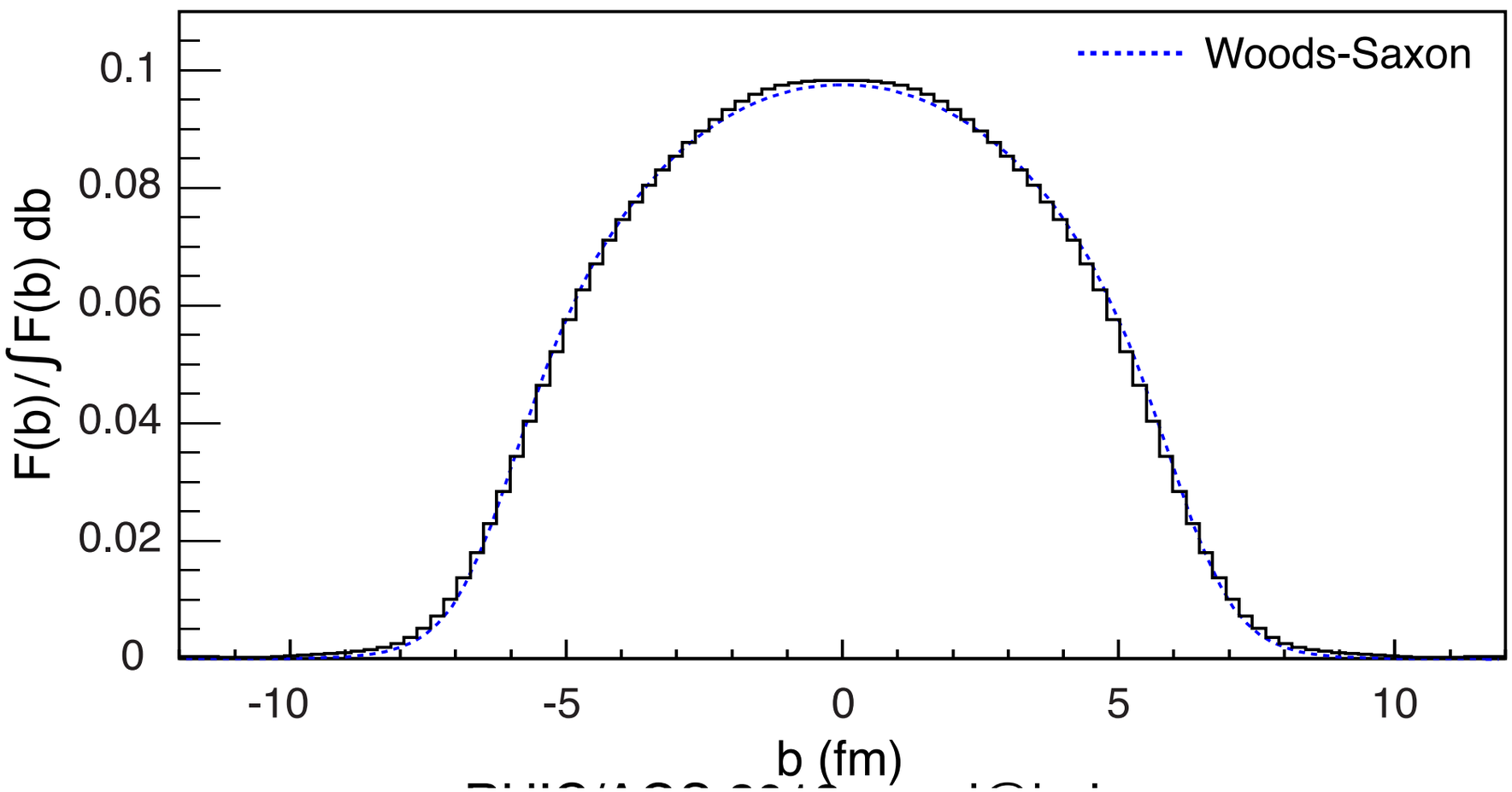

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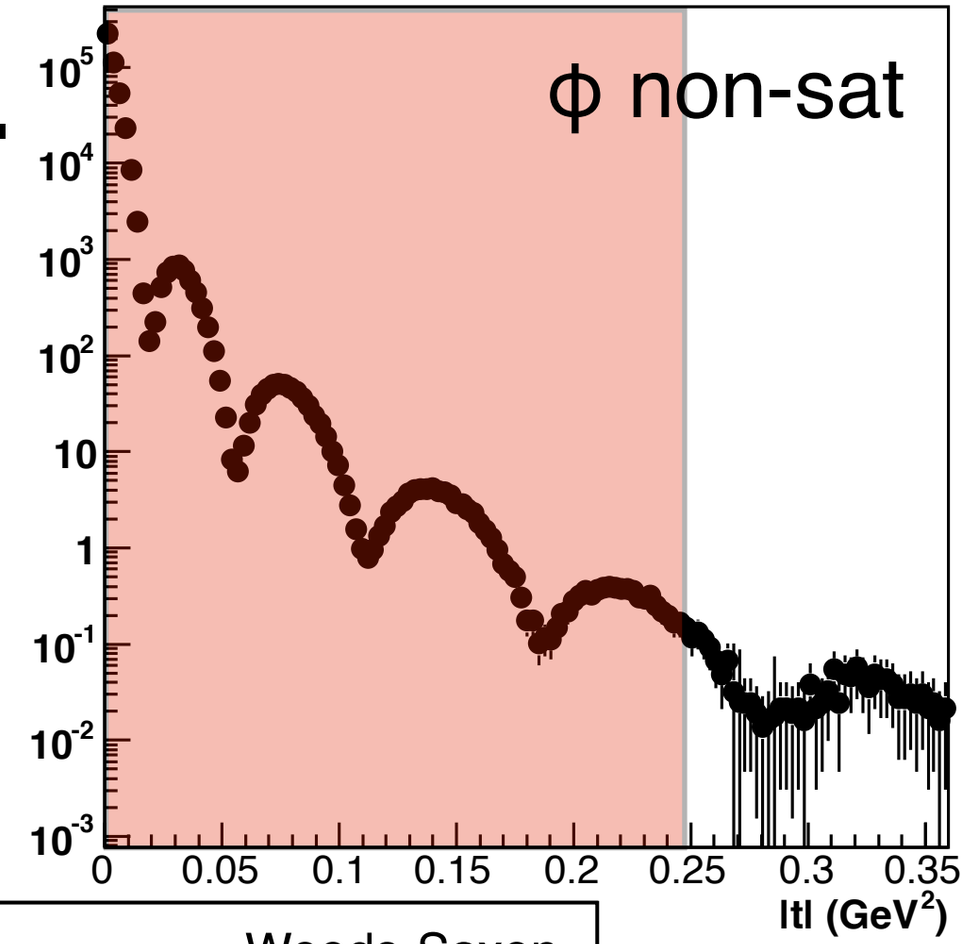

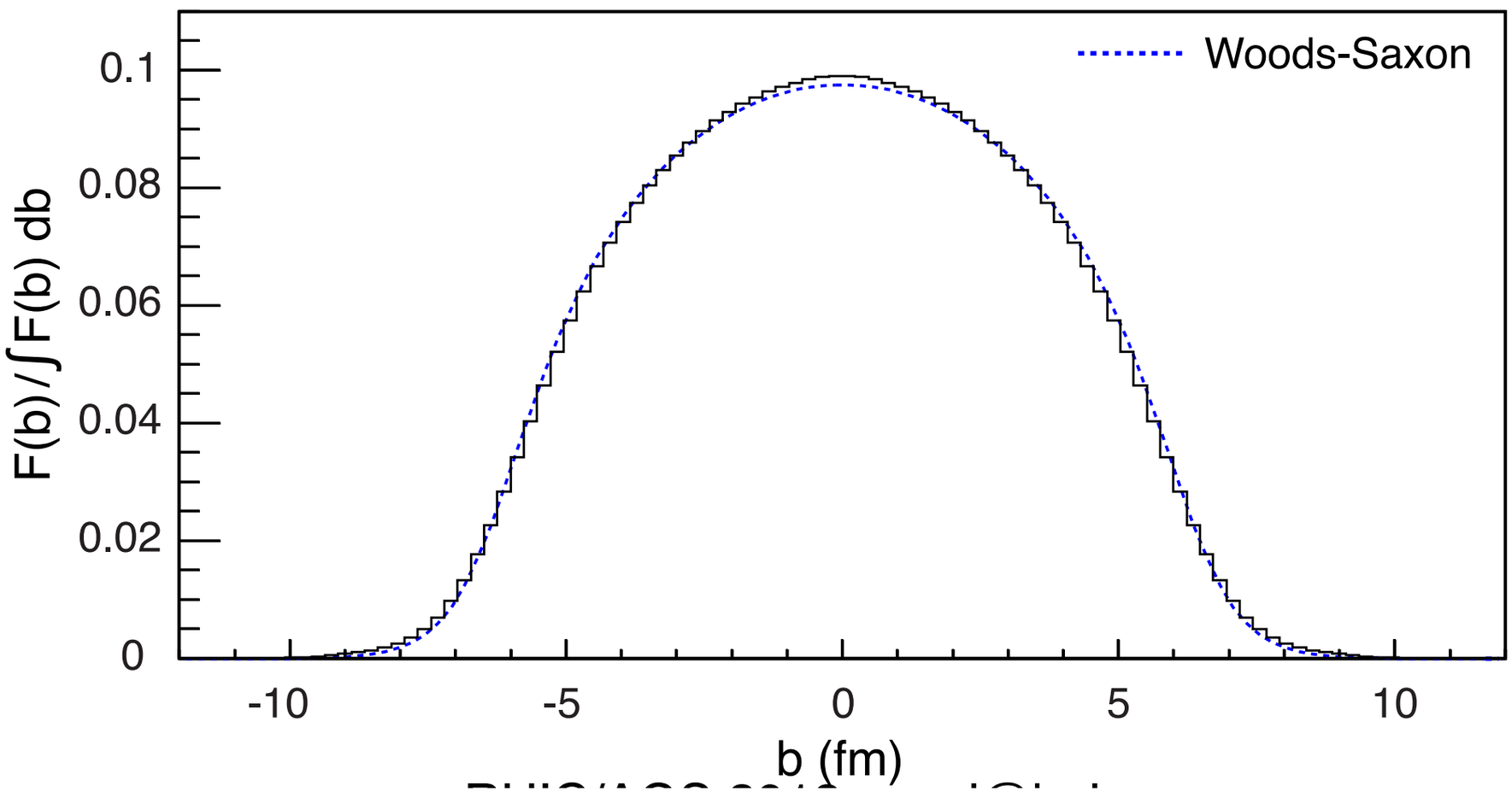

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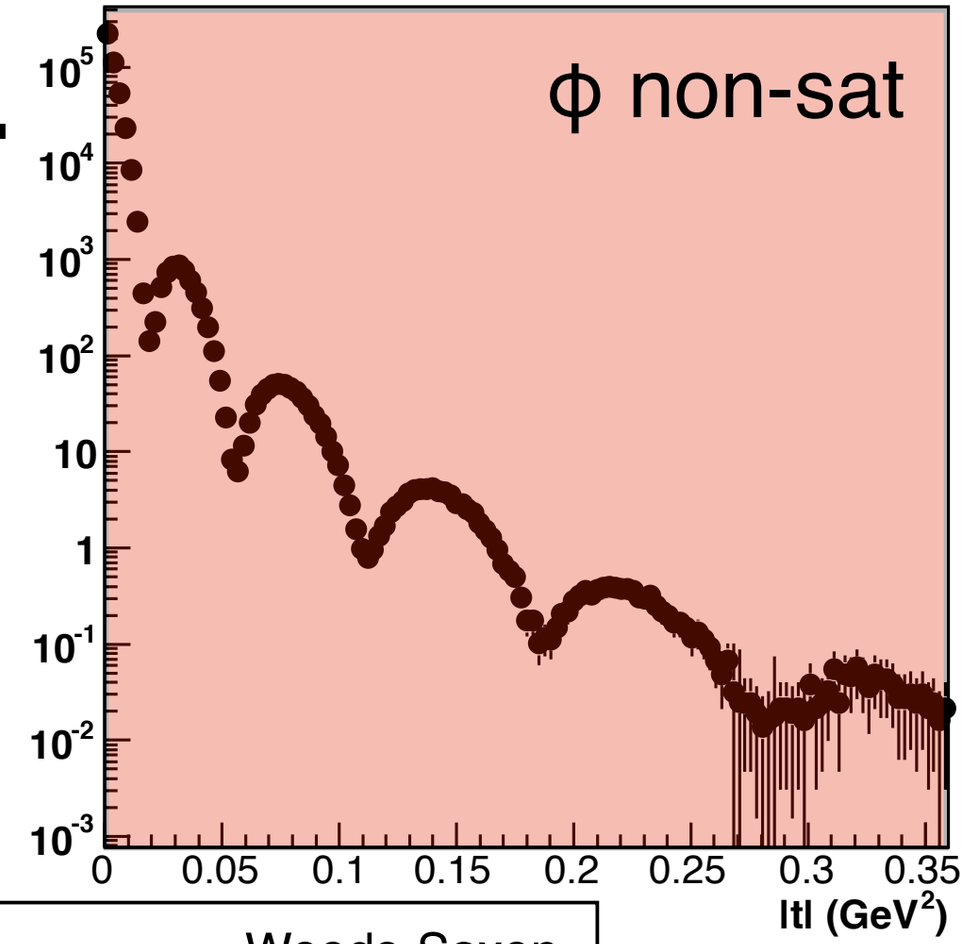
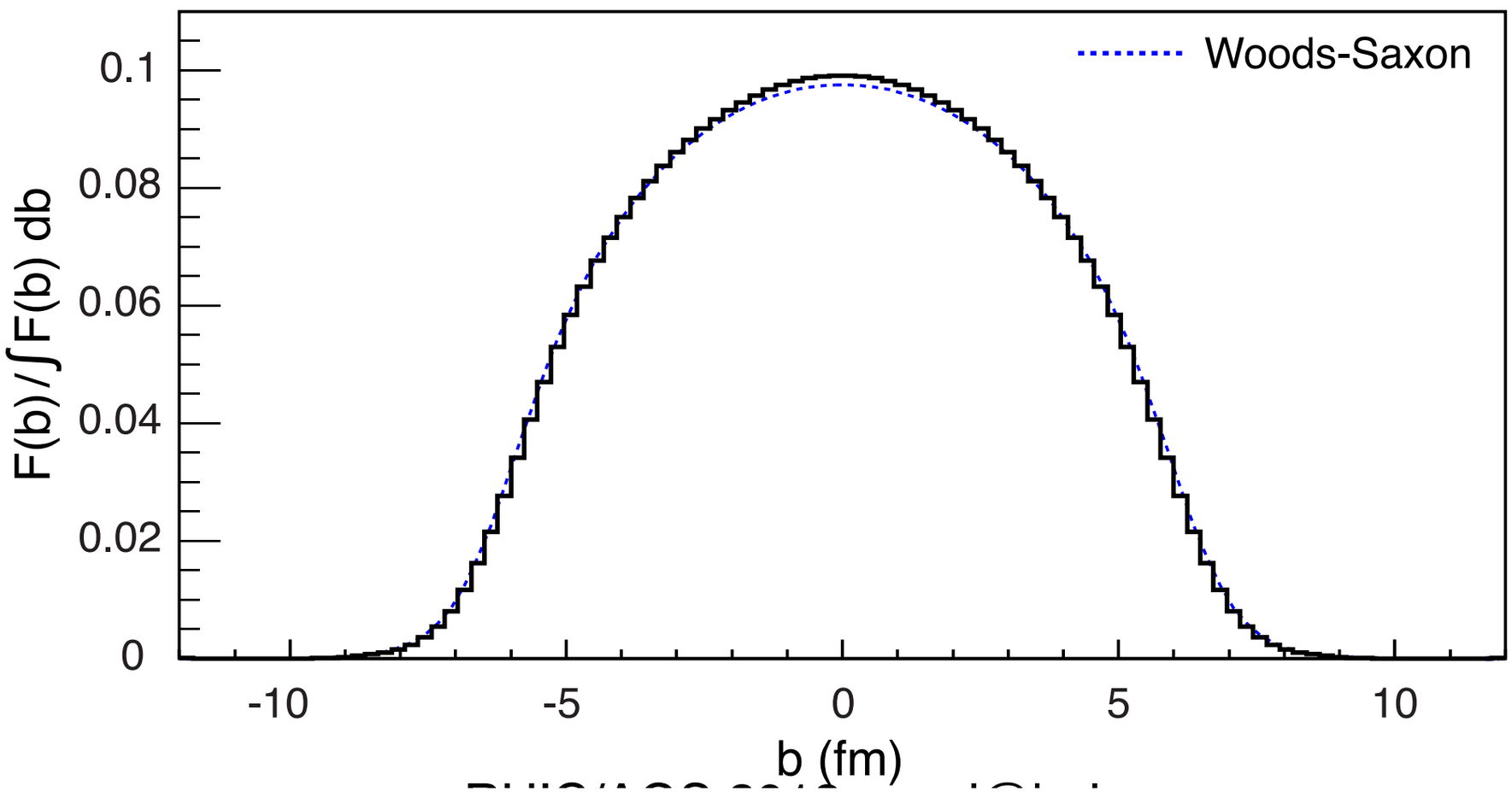
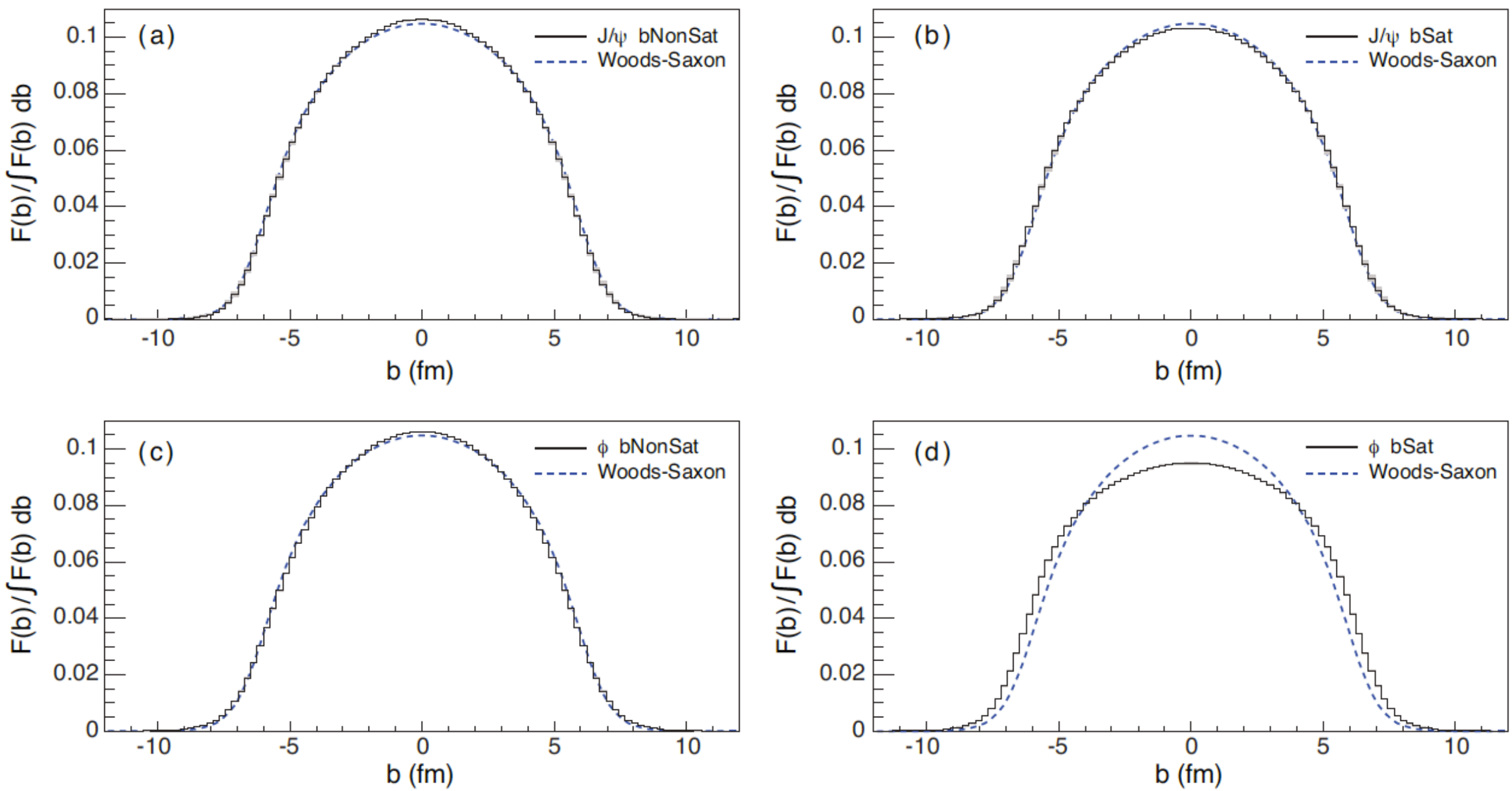




Finding the source...

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



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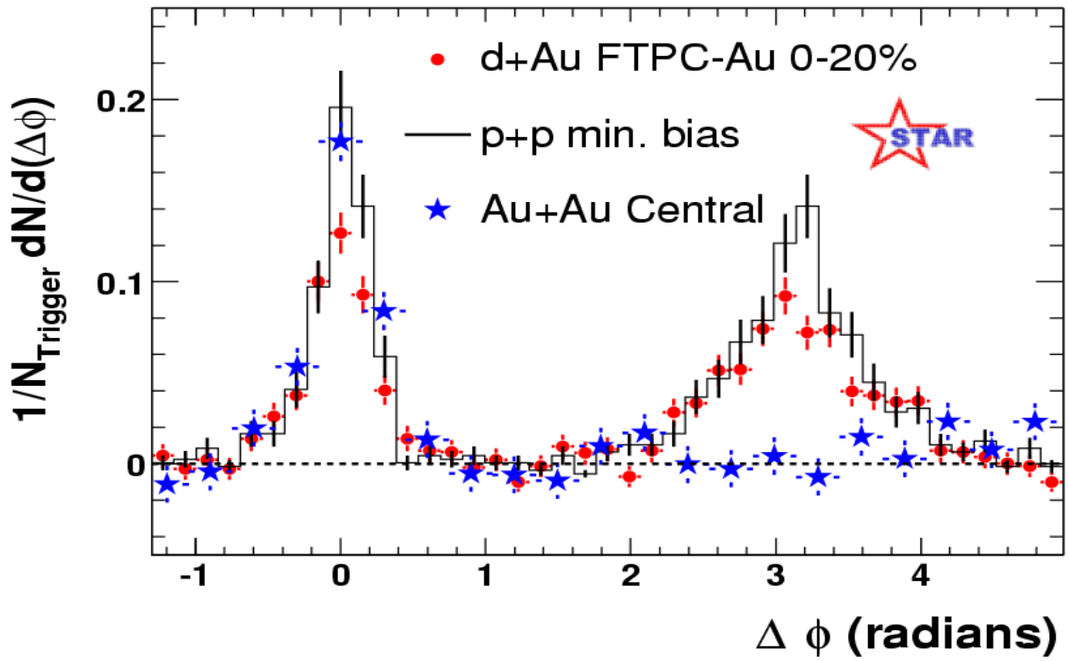

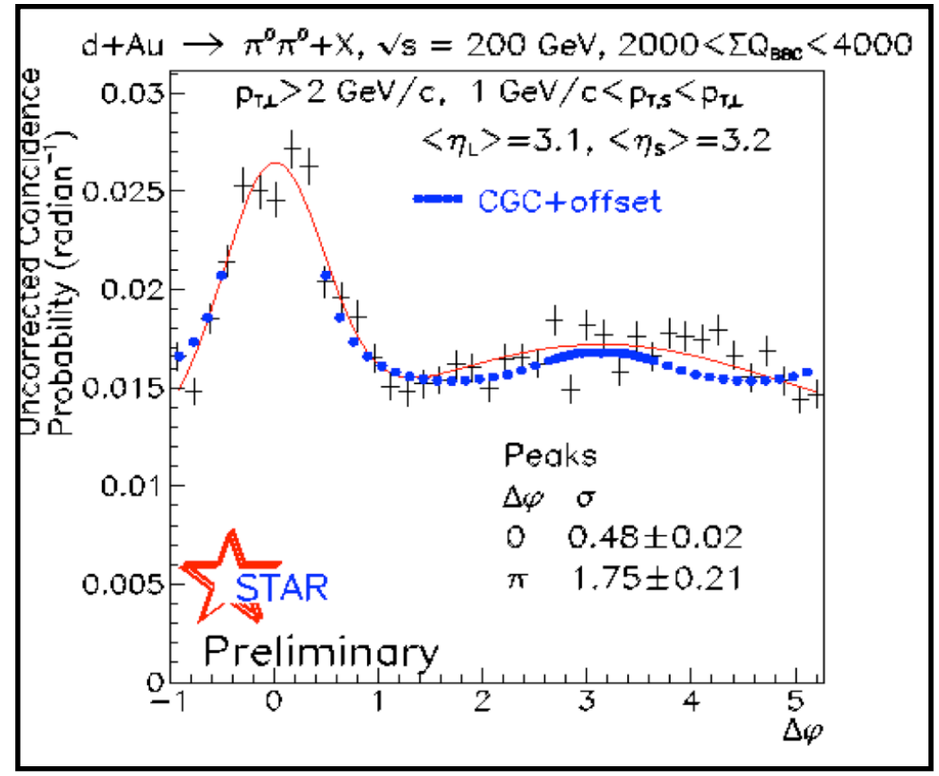

- y=0 (x ~ 10^{-2}): suppression of away-side jet is observed in Au+Au collisions
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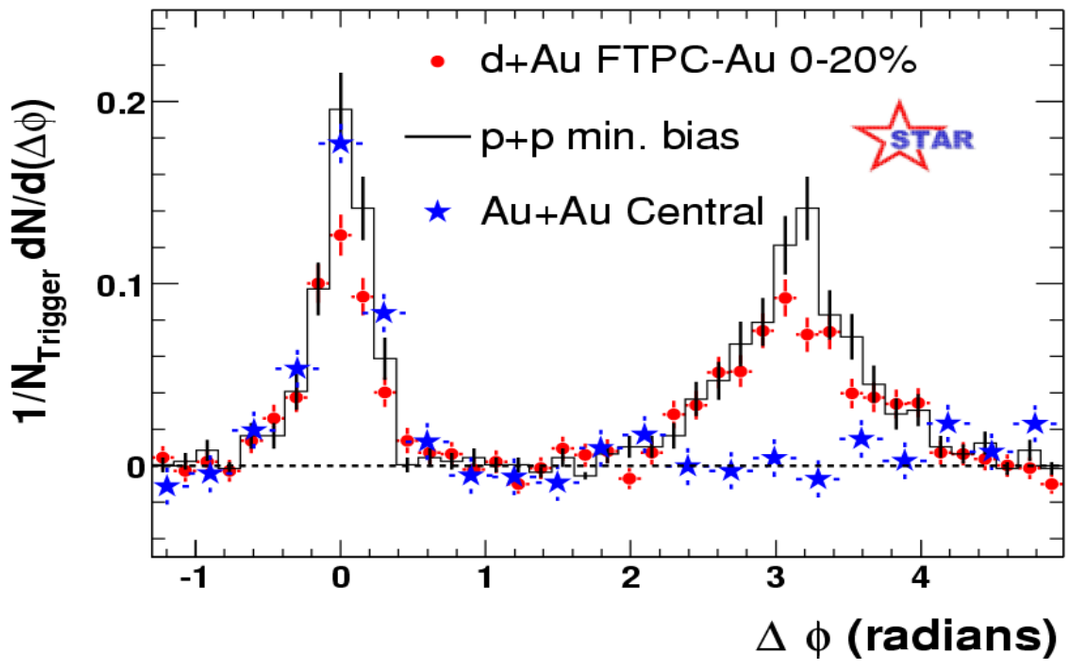

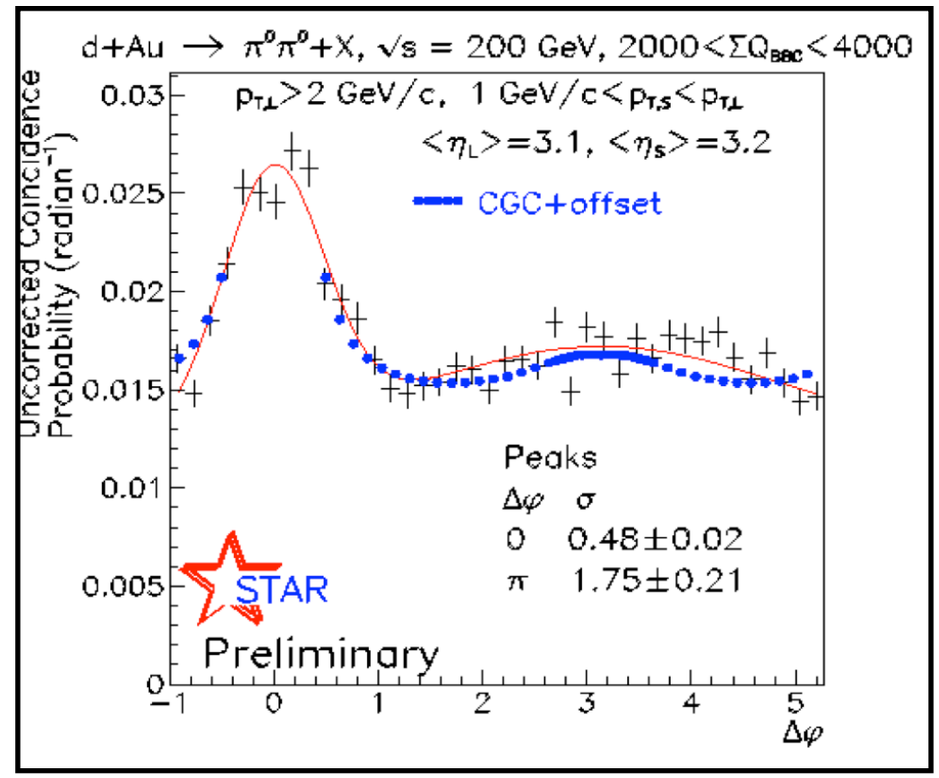

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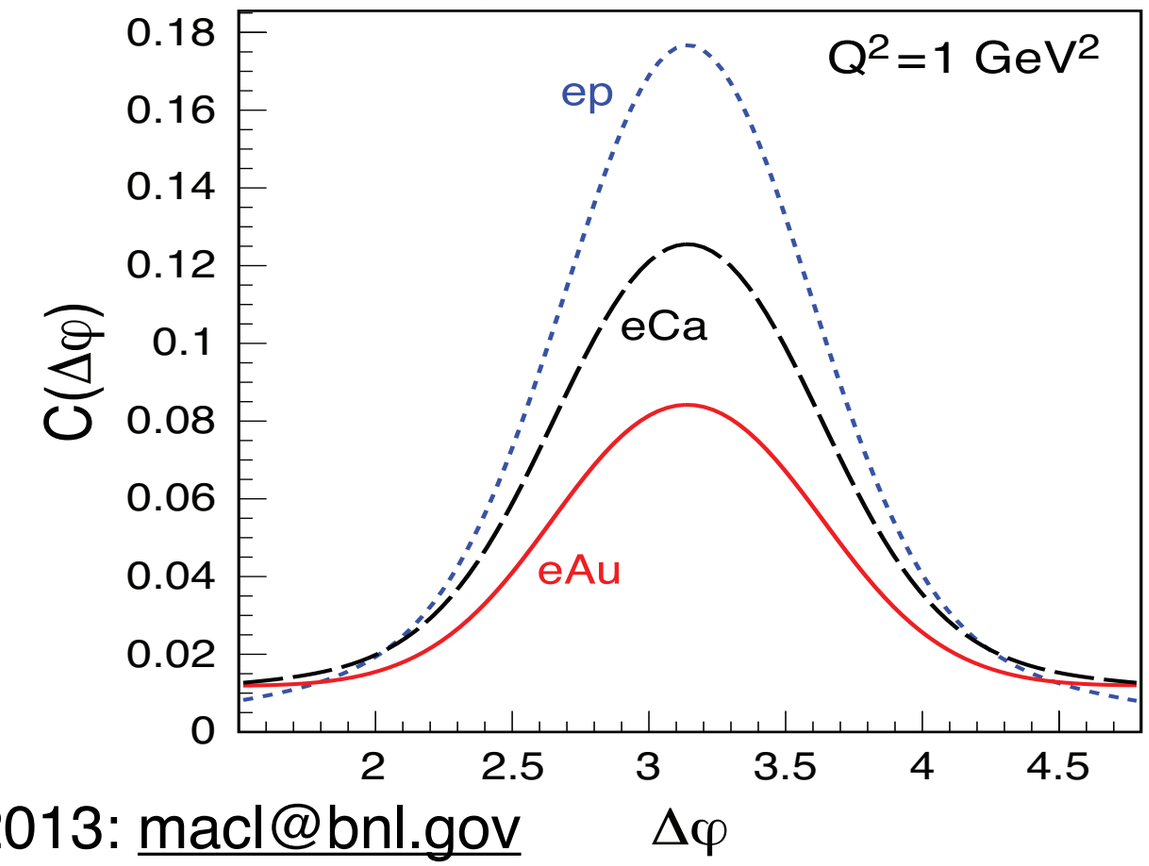

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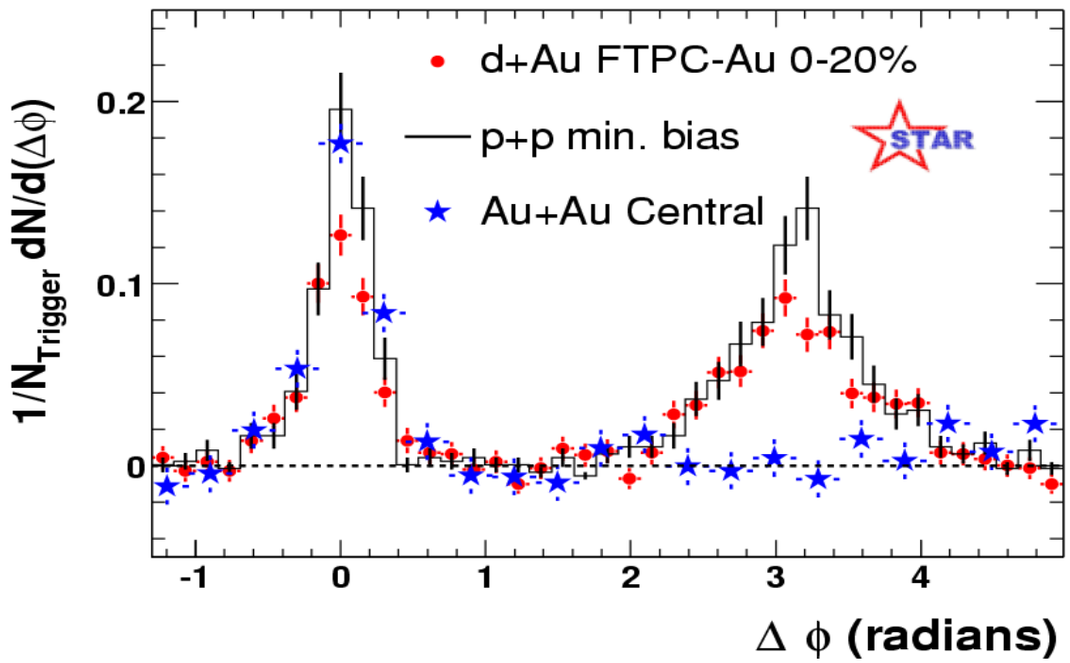

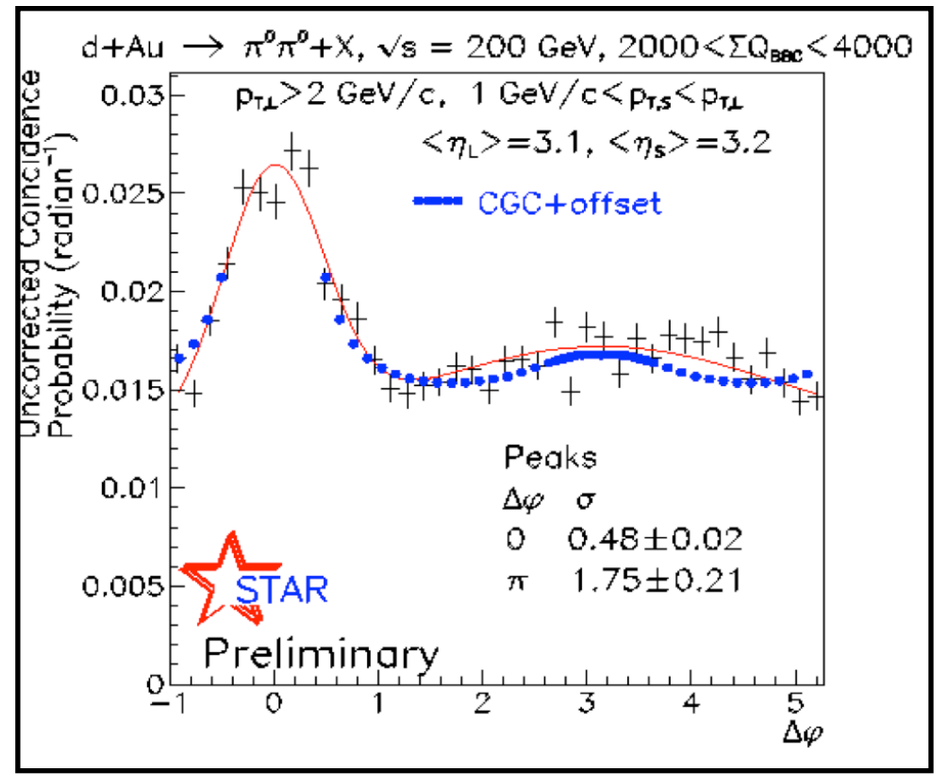

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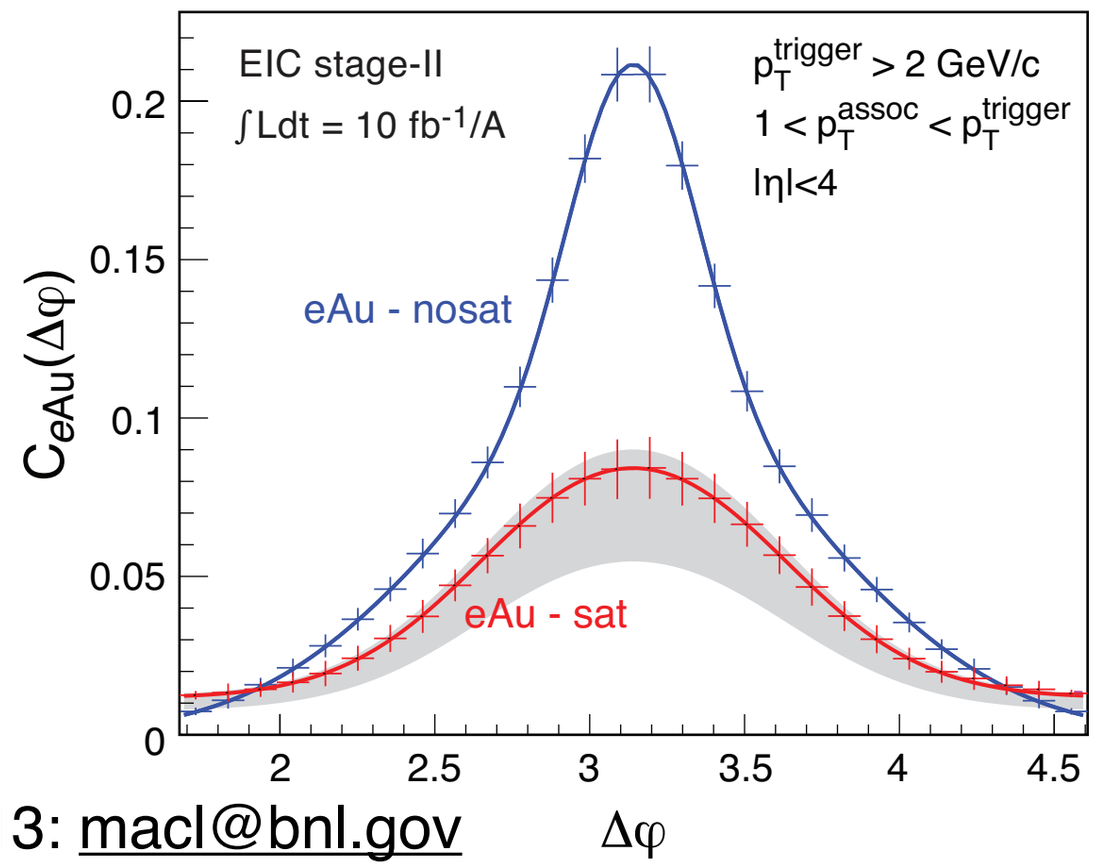

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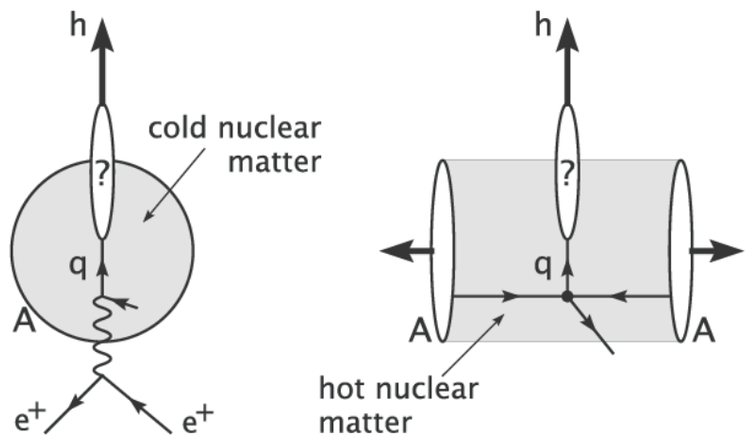

- Observables
  - ➡ Broadening:

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_p$$

    - direct link to saturation scale
  - ➡ Attenuation:

$$R_A^h(Q^2, \nu, z_h, p_T^2)$$

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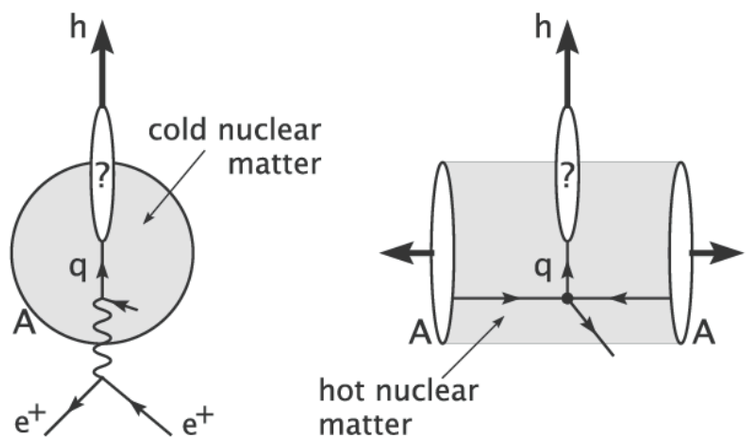

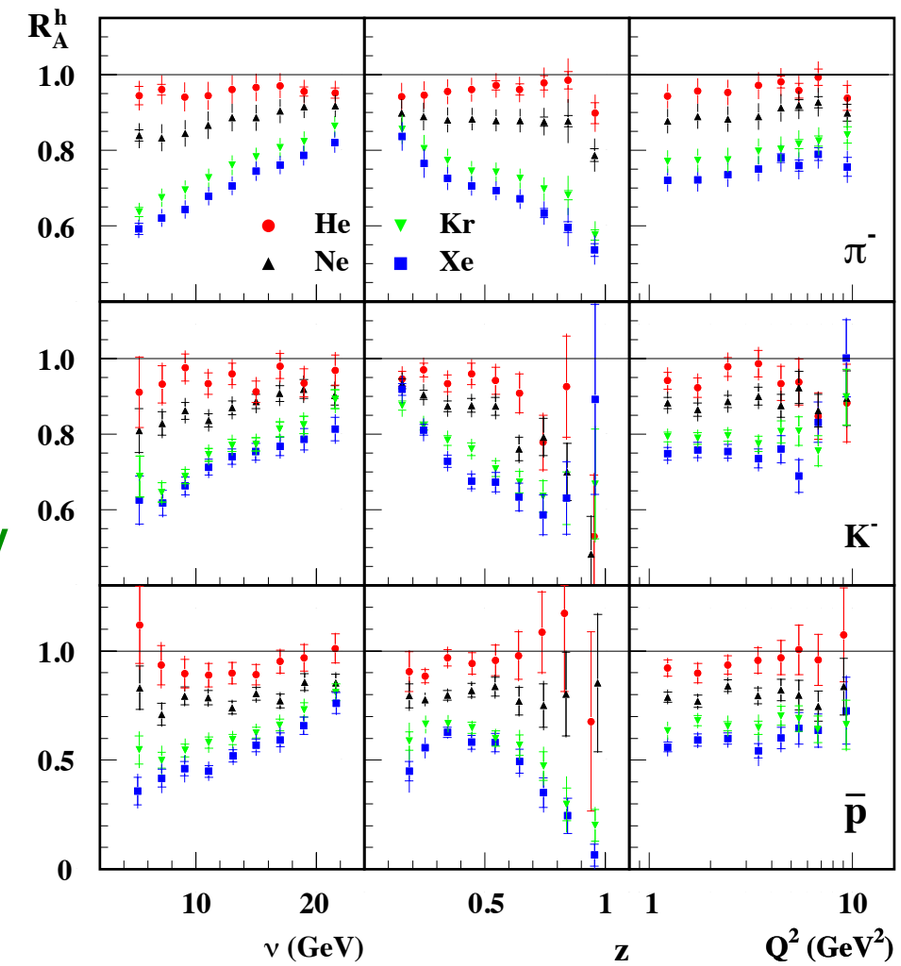

ν = virtual photon energy

$Z_h = E_h/\nu$

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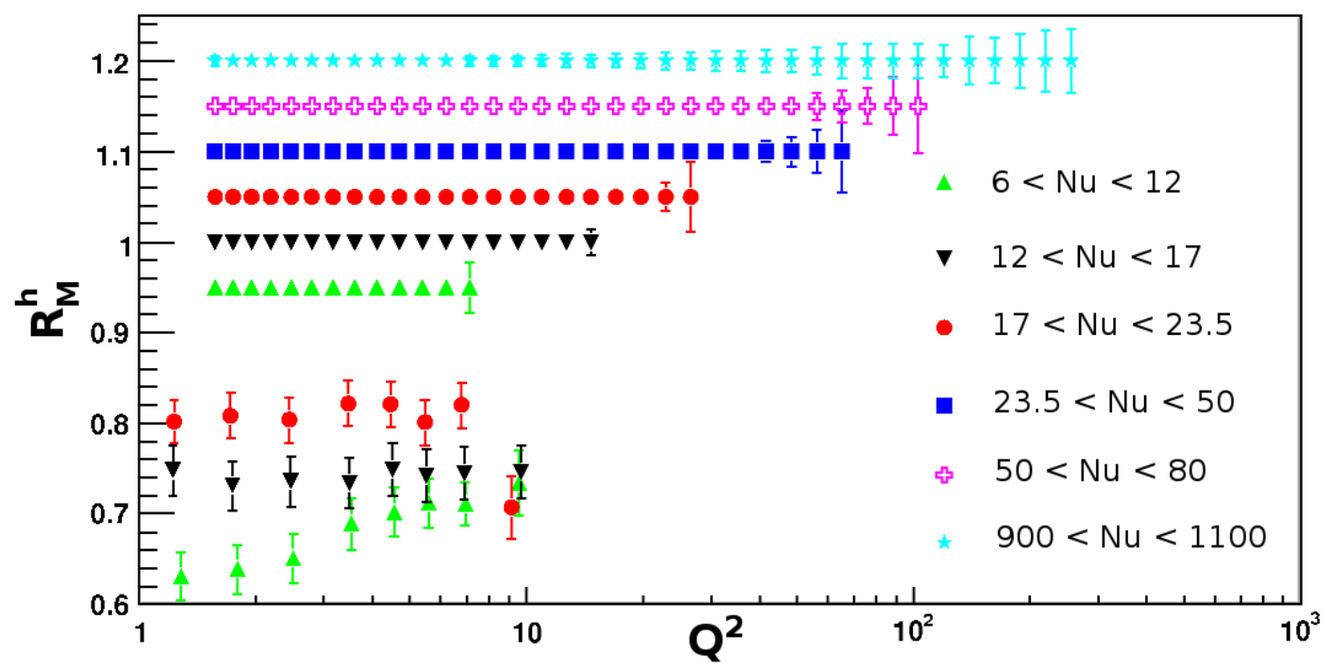

Summary and Conclusions

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  - ➡ Low-x: Measure the properties of gluons where saturation is the dominant governing phenomena
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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

Measuring the gluons: extracting F_L

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- $F_L \sim \alpha_s \, xG(x,Q^2)$
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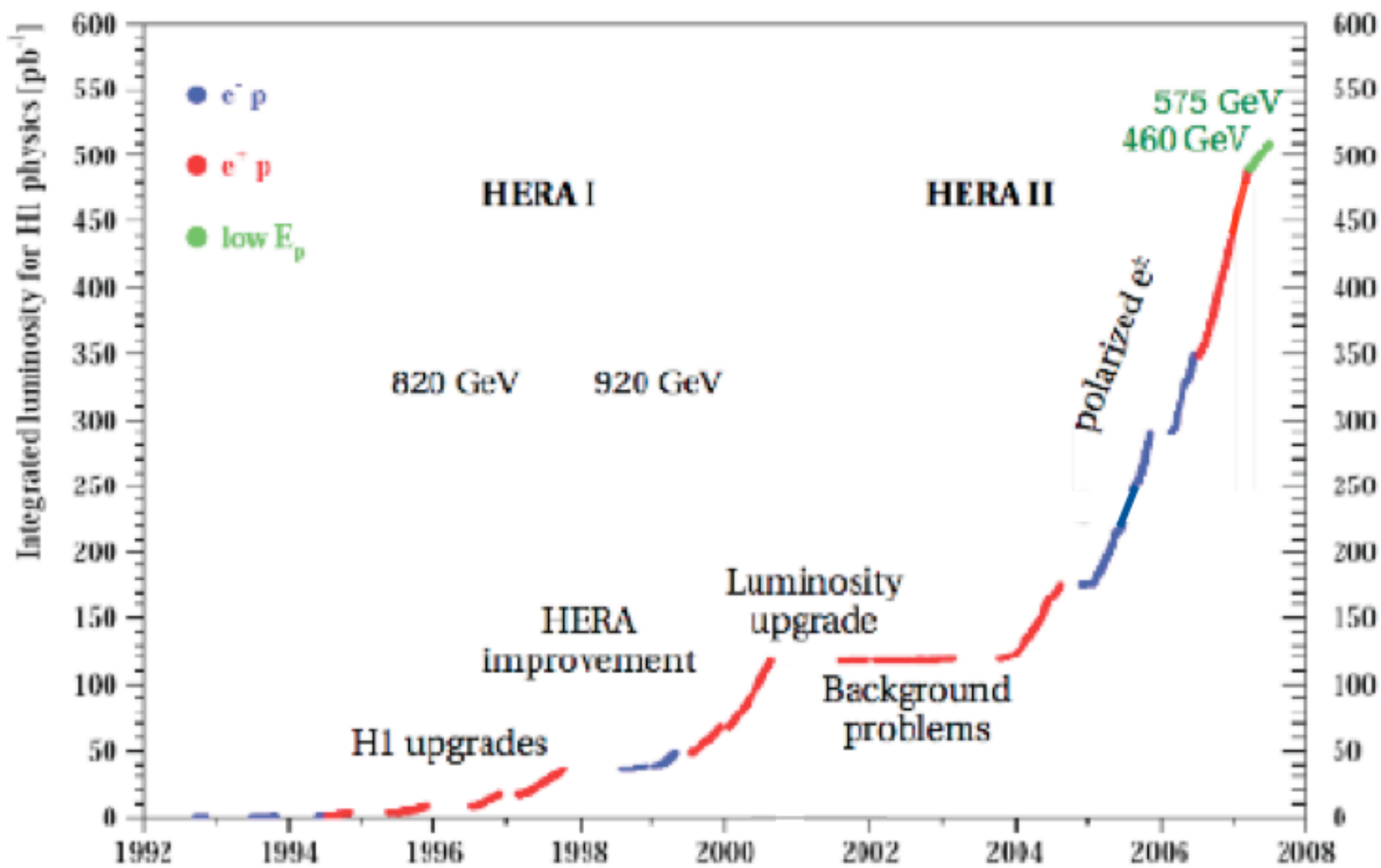

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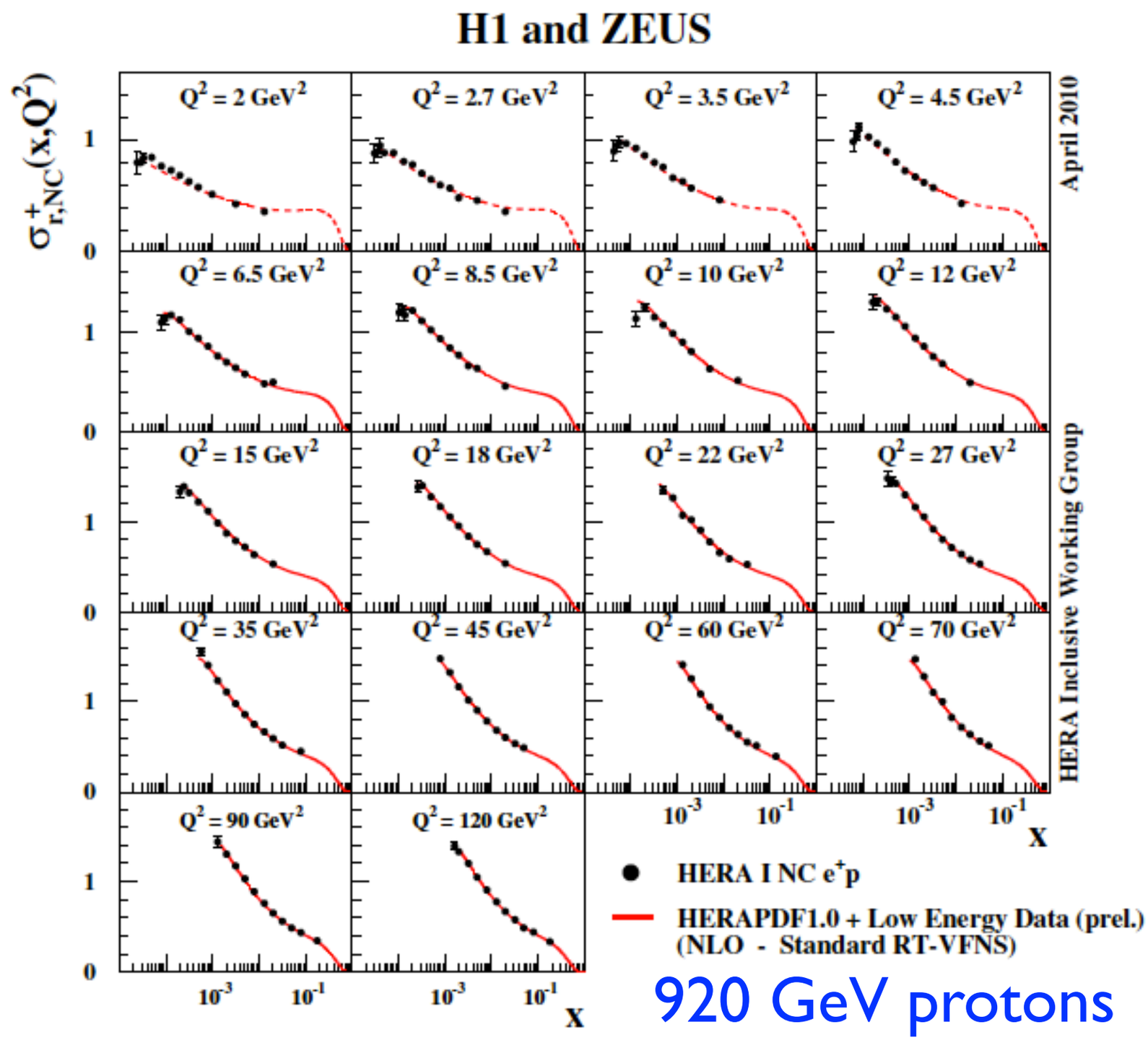

920 GeV protons

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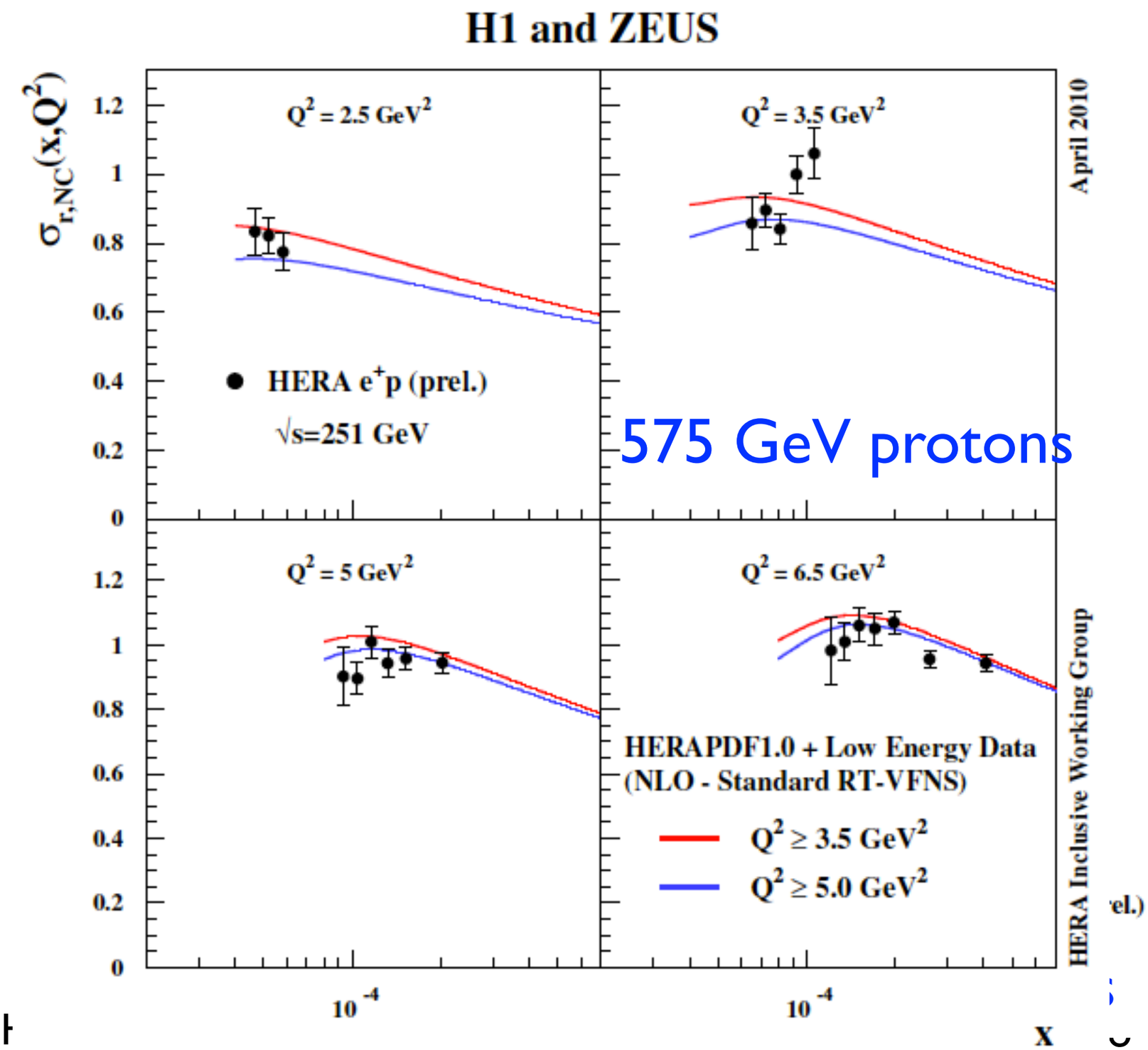

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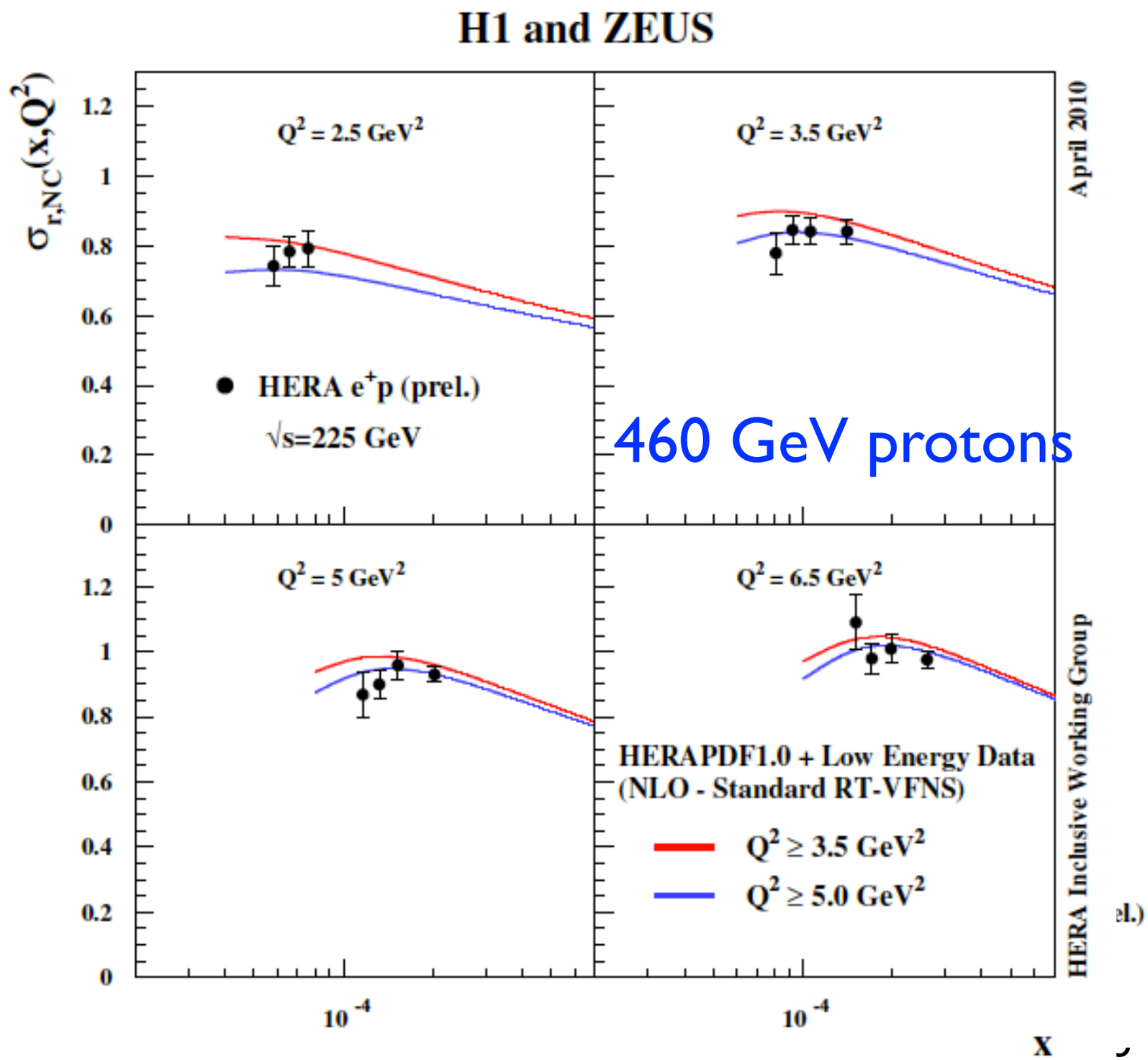

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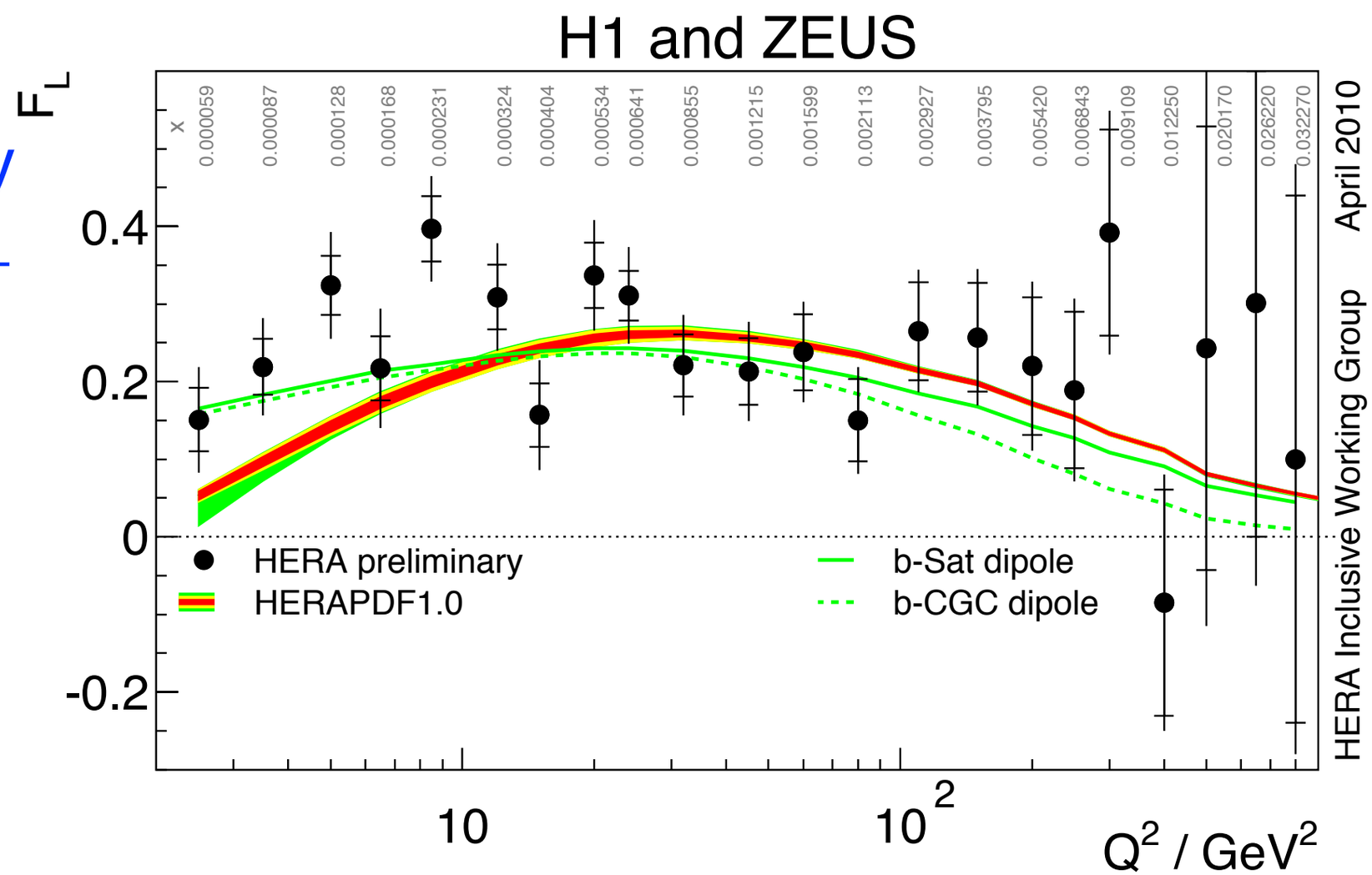
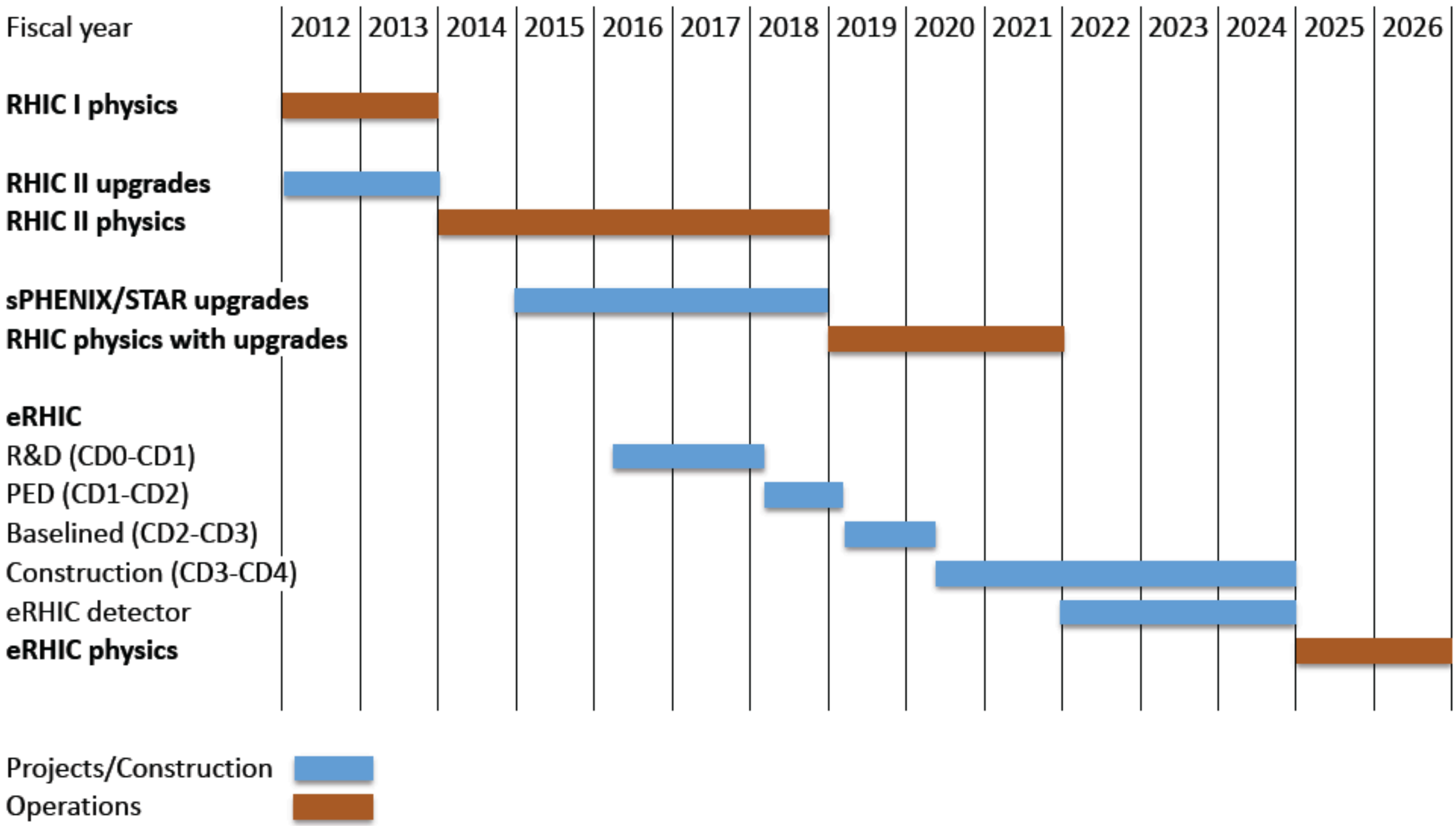
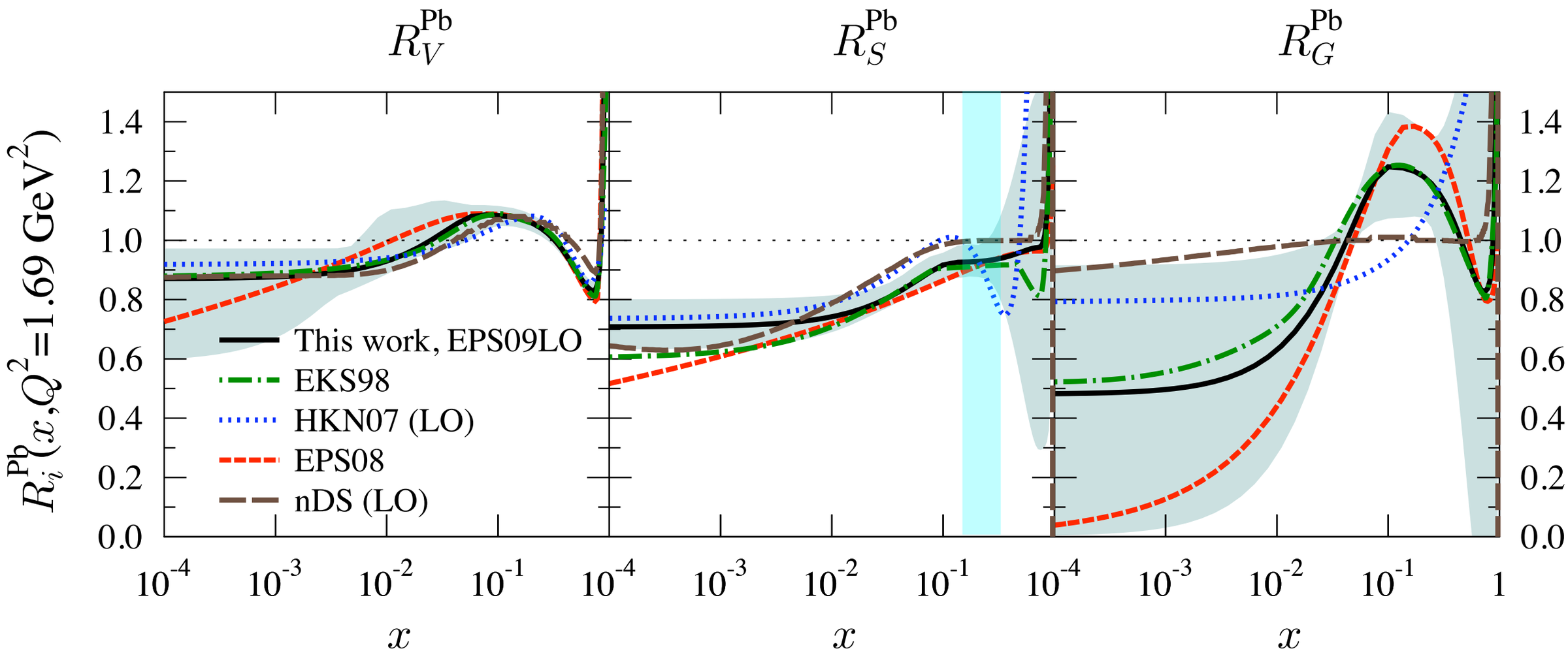


Possible Schedule To Realise eRHIC



What do we know about the structure of nuclei?



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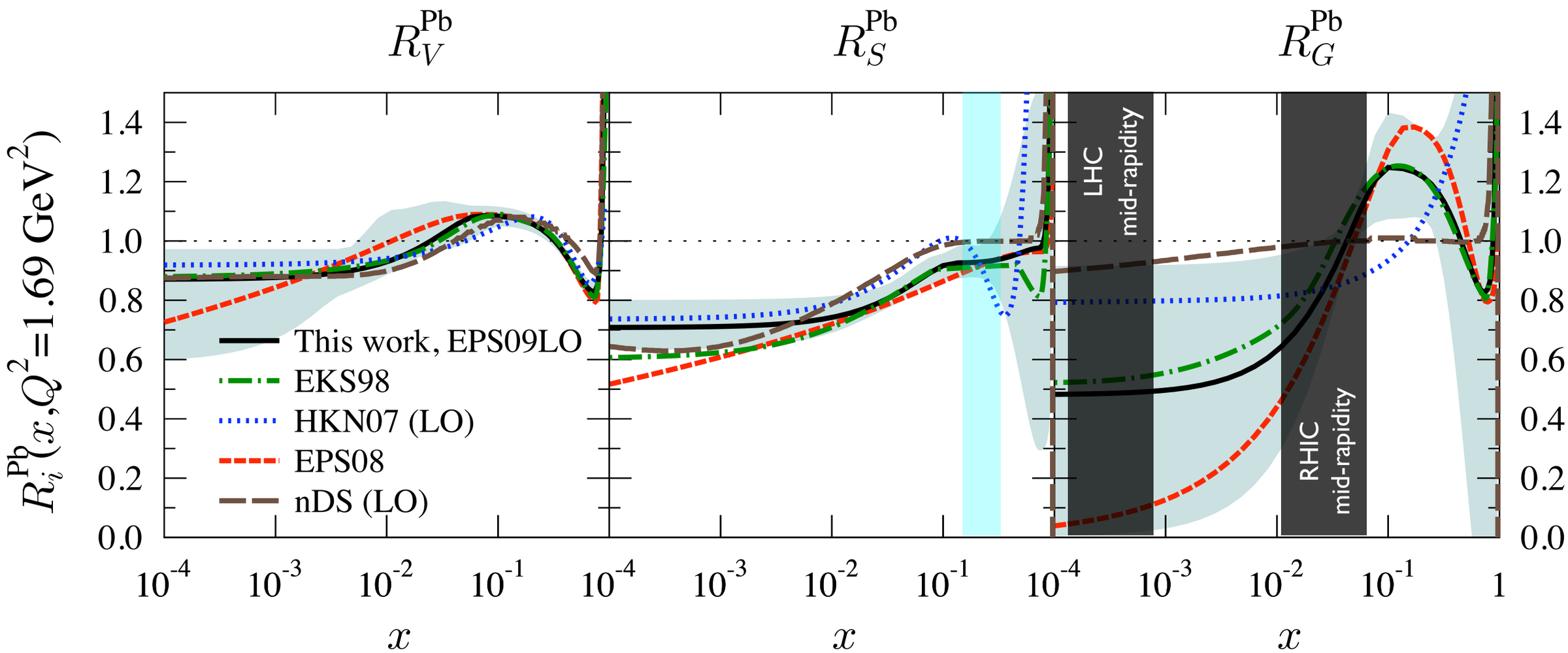

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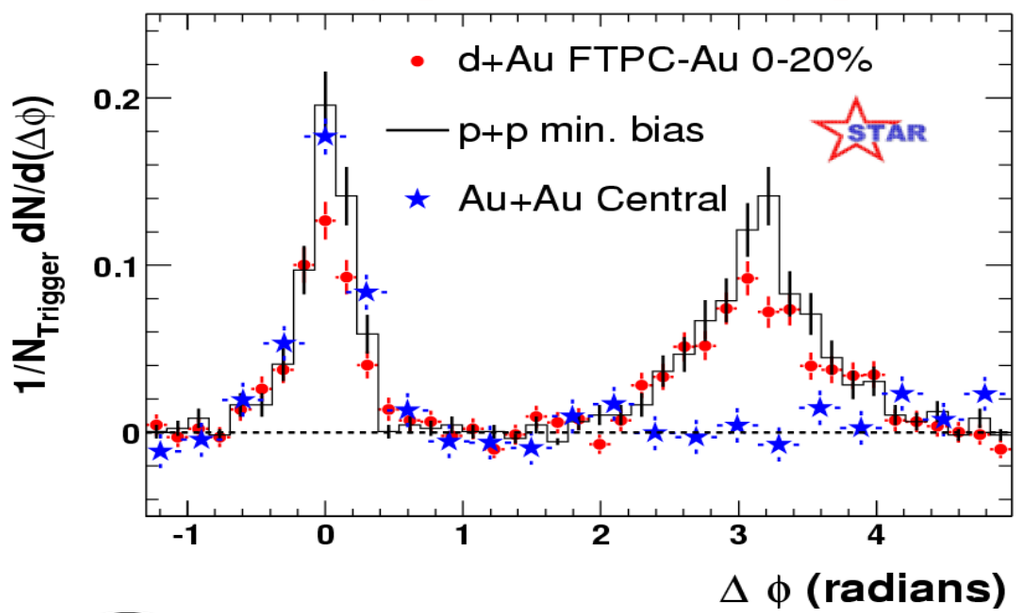
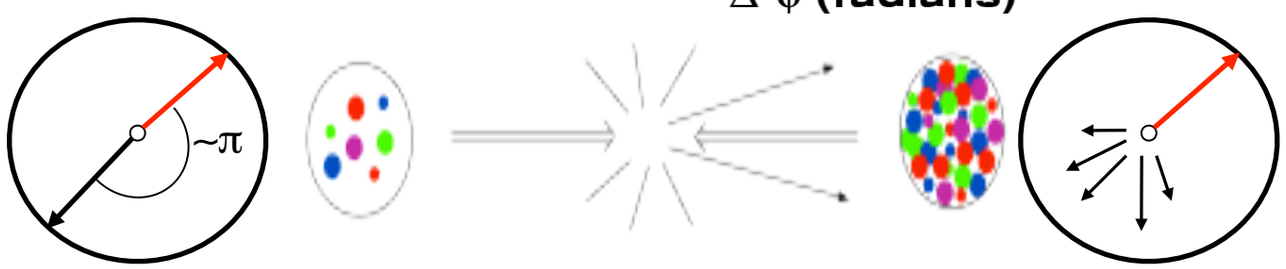
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

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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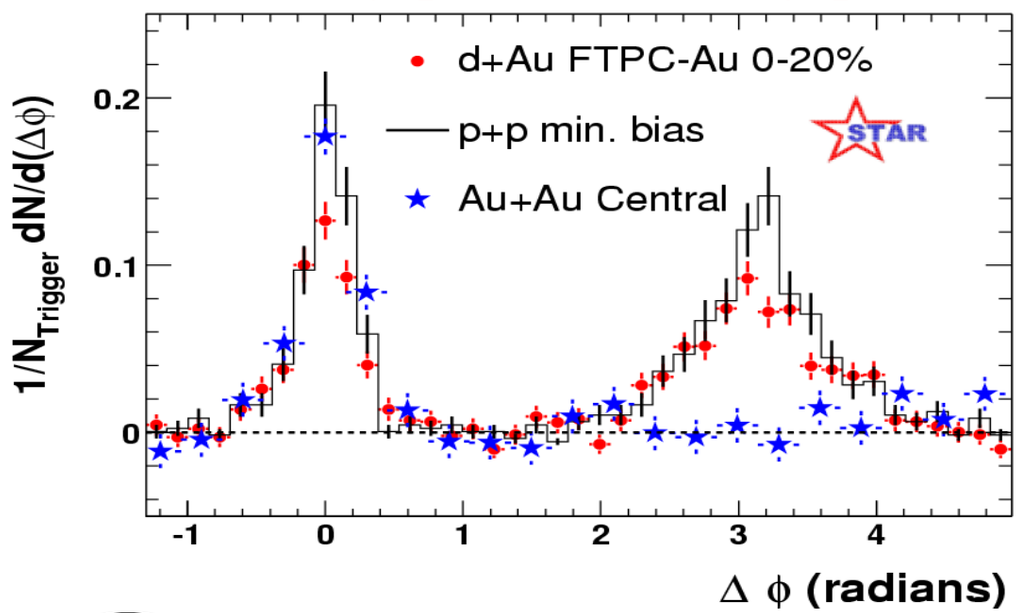

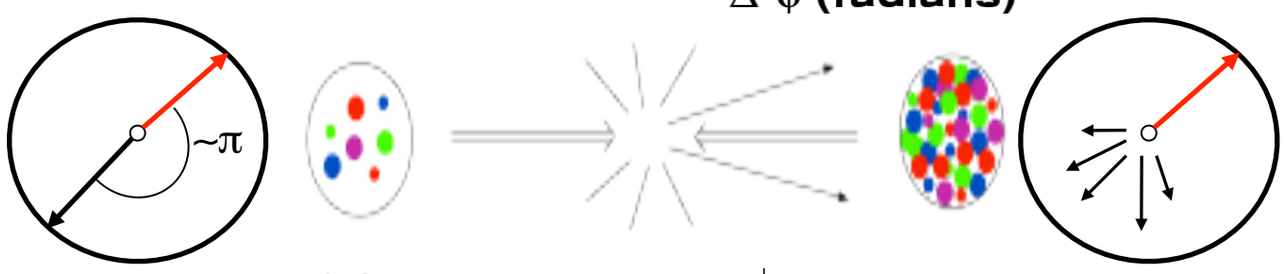

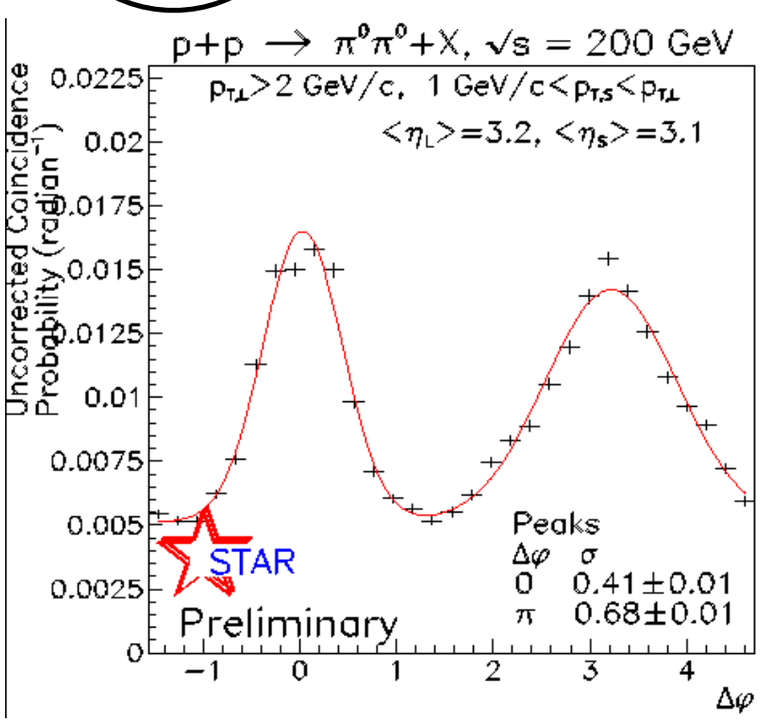

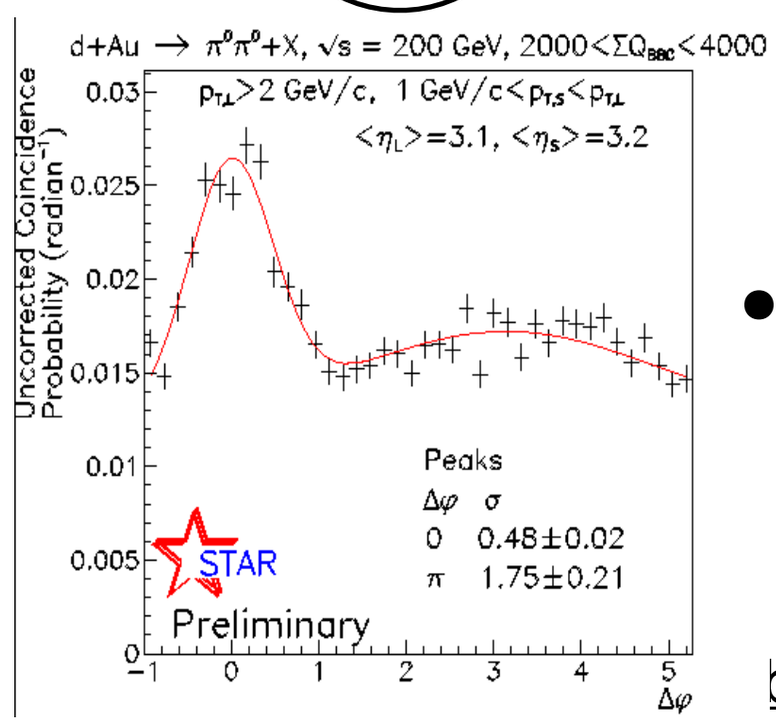

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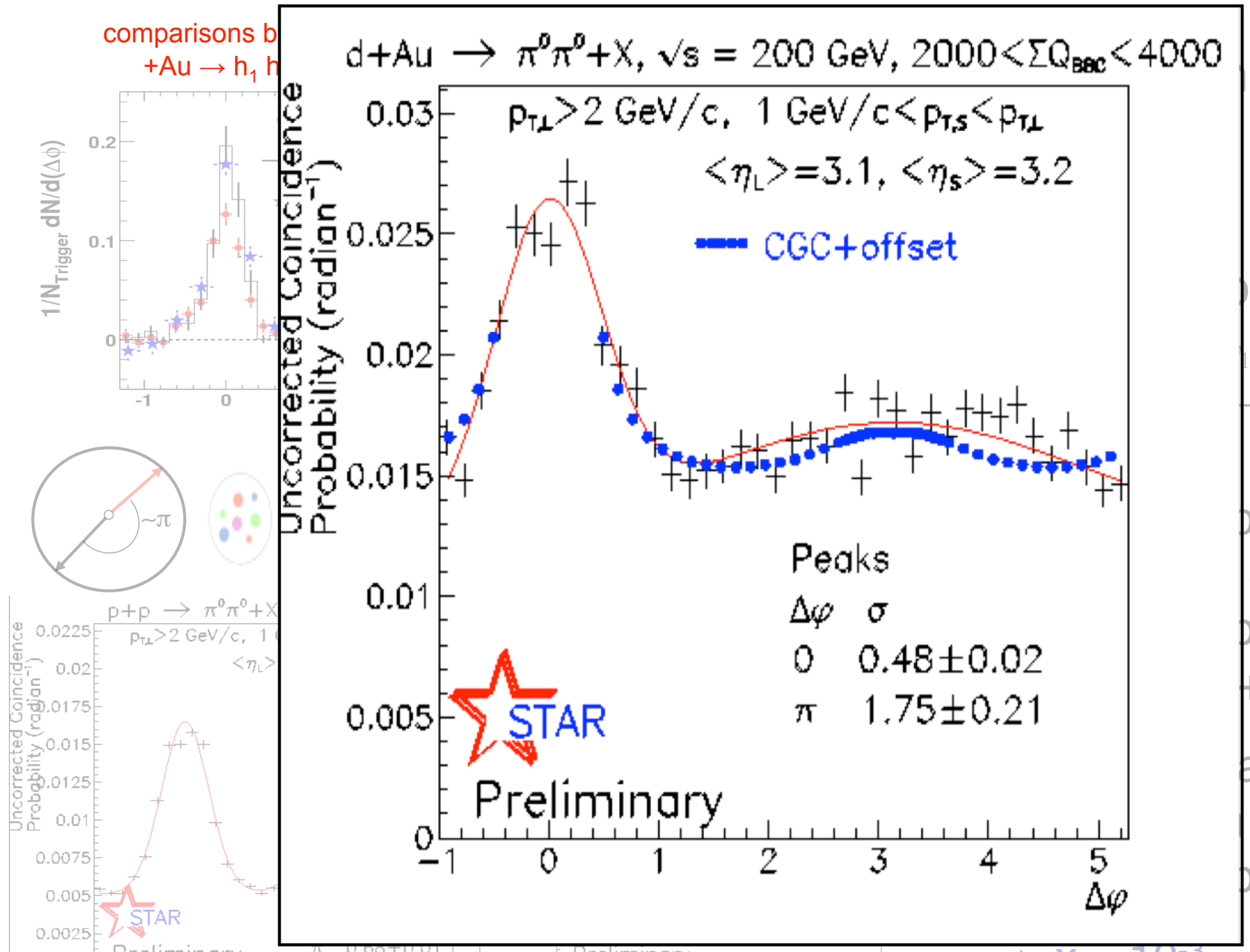
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

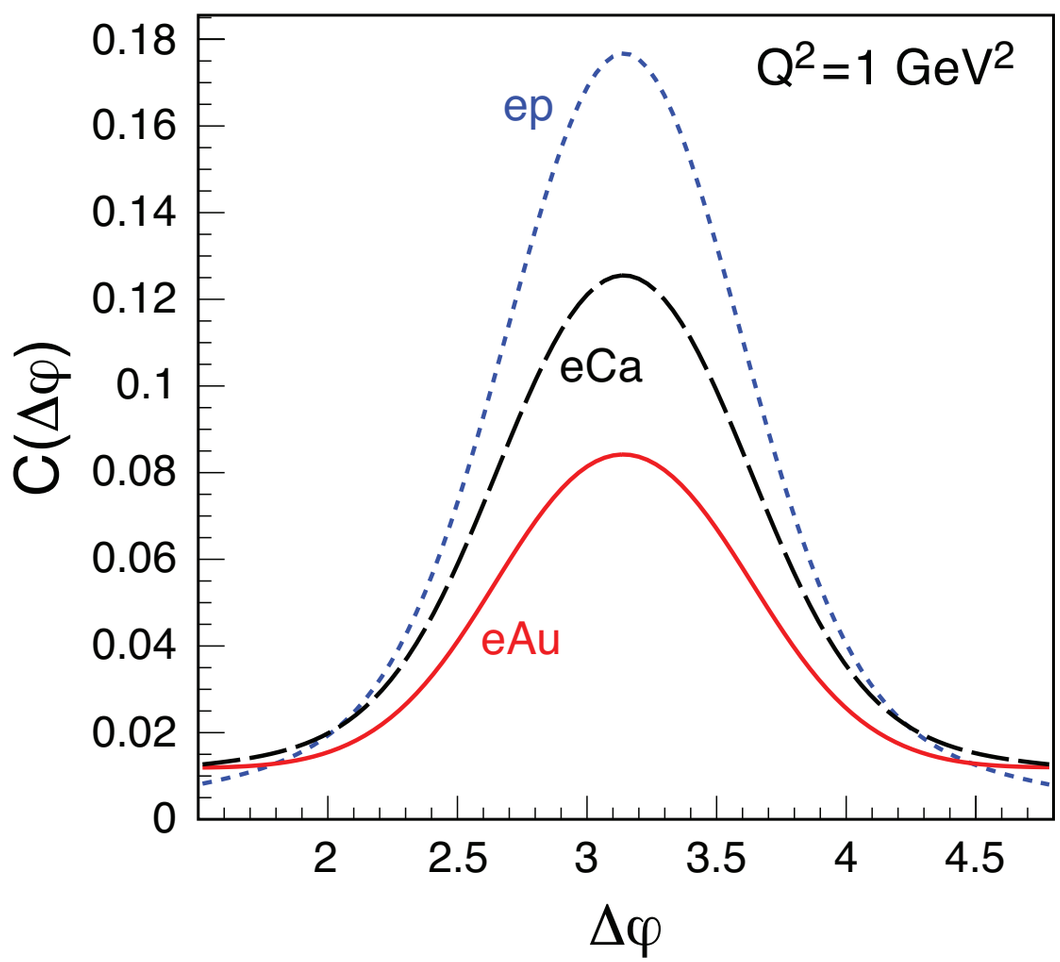
➡ x ~ 10^{-3}

di-hadron correlations in d+A



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
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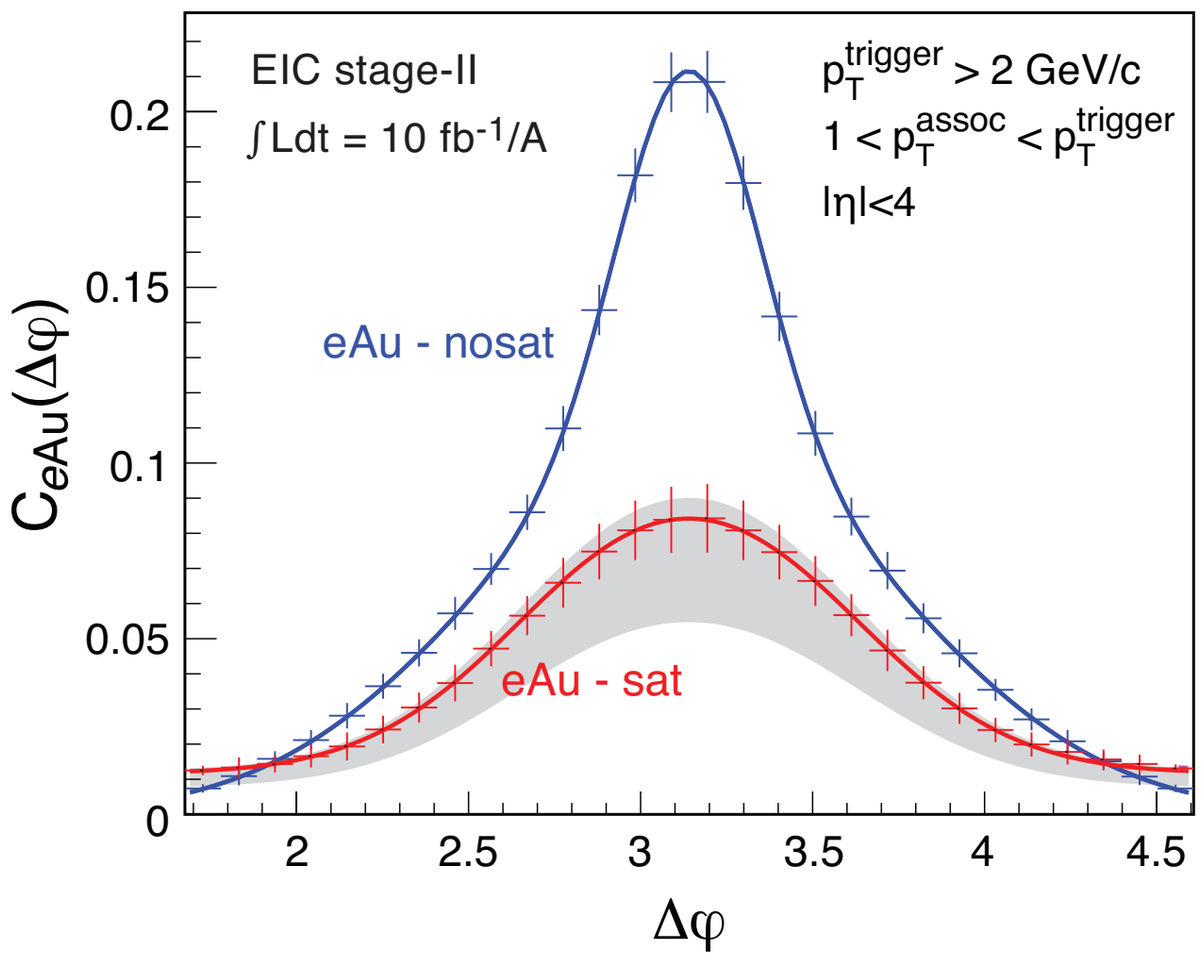

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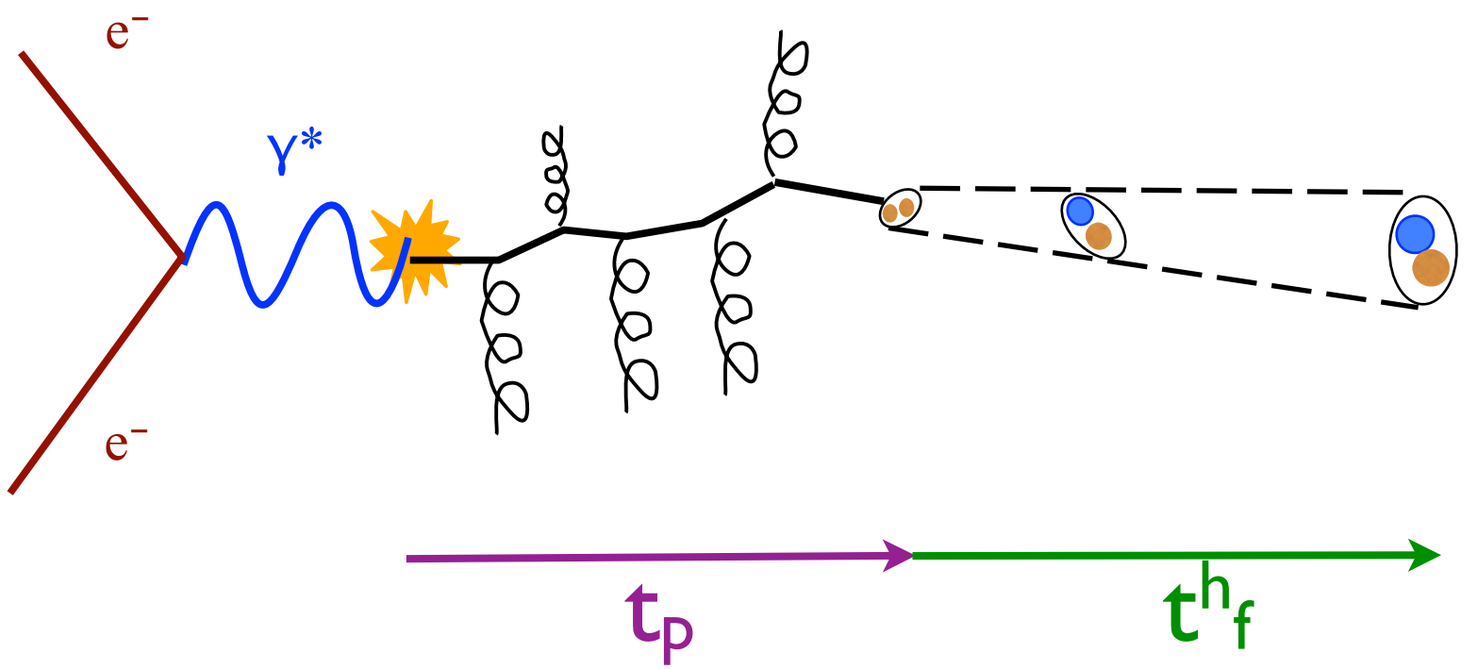

- t_p - production time of propagating quark
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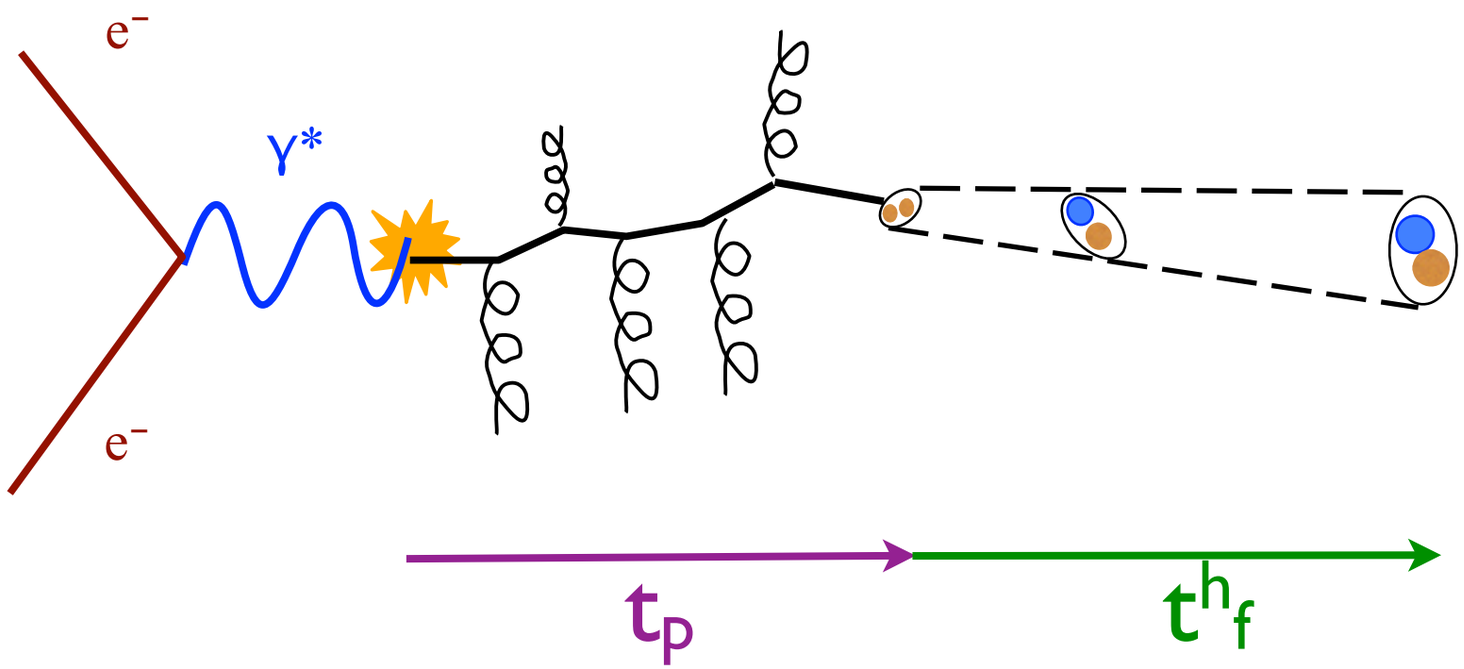

What happens if we add a nuclear medium?

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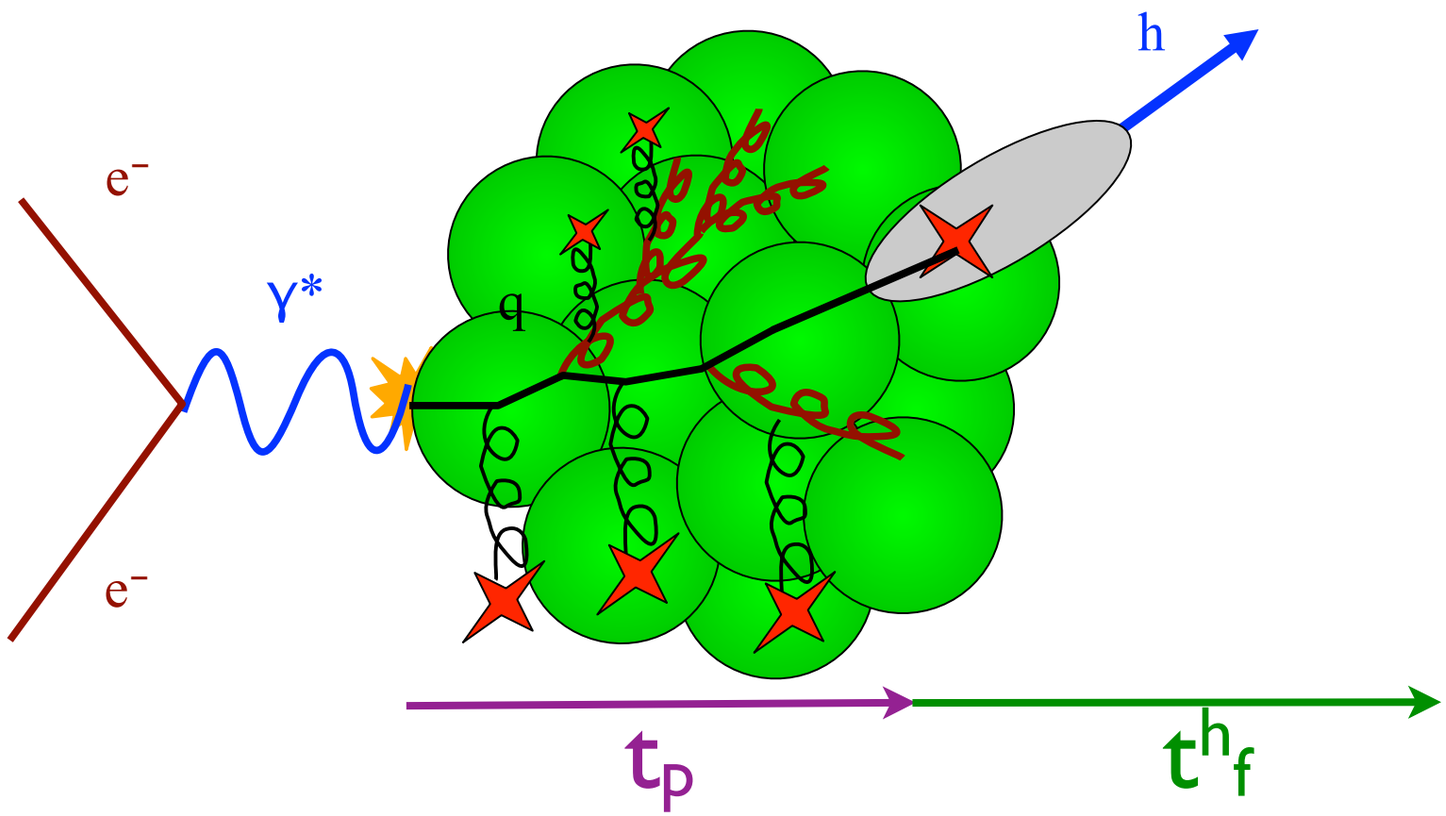

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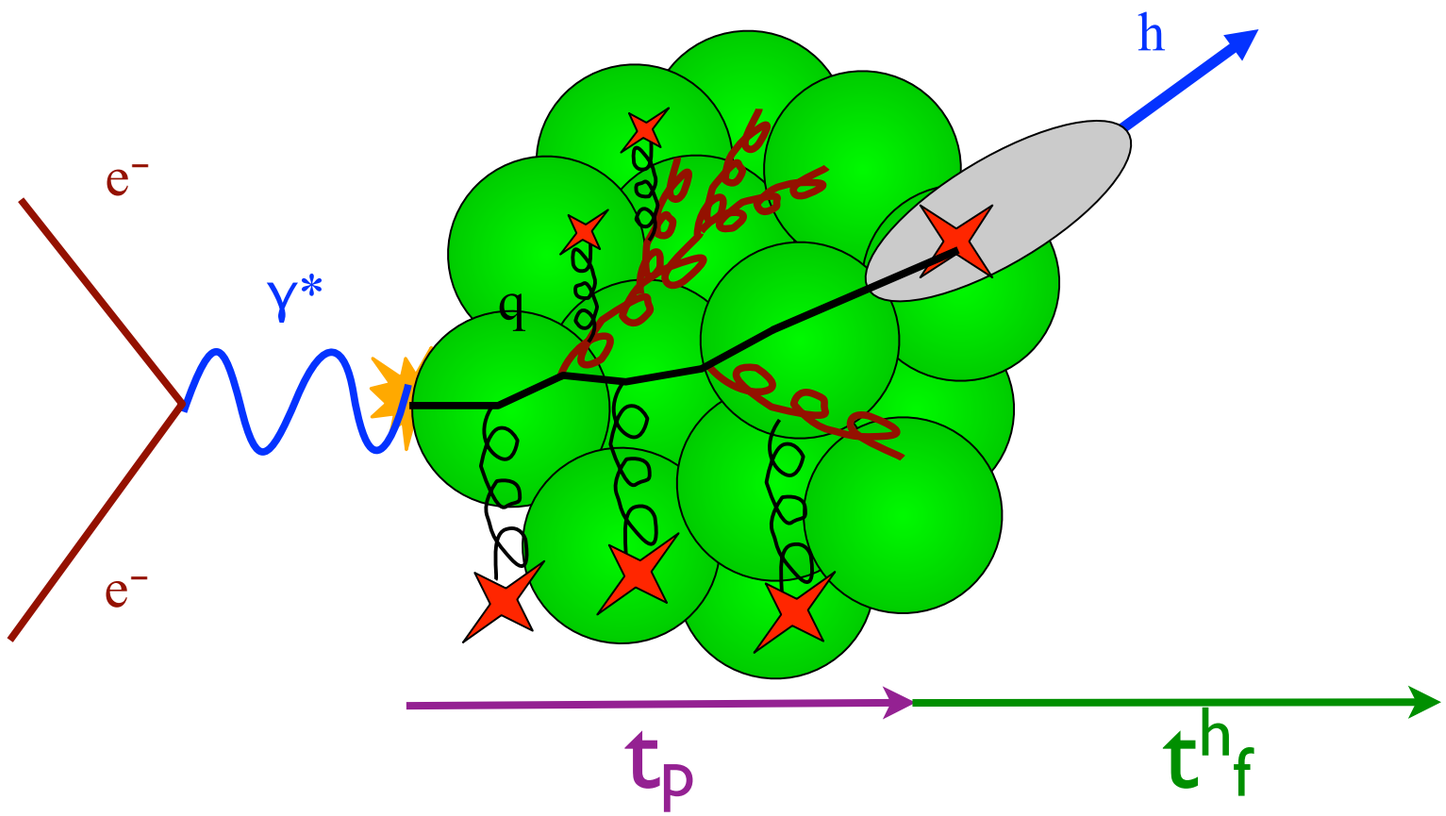

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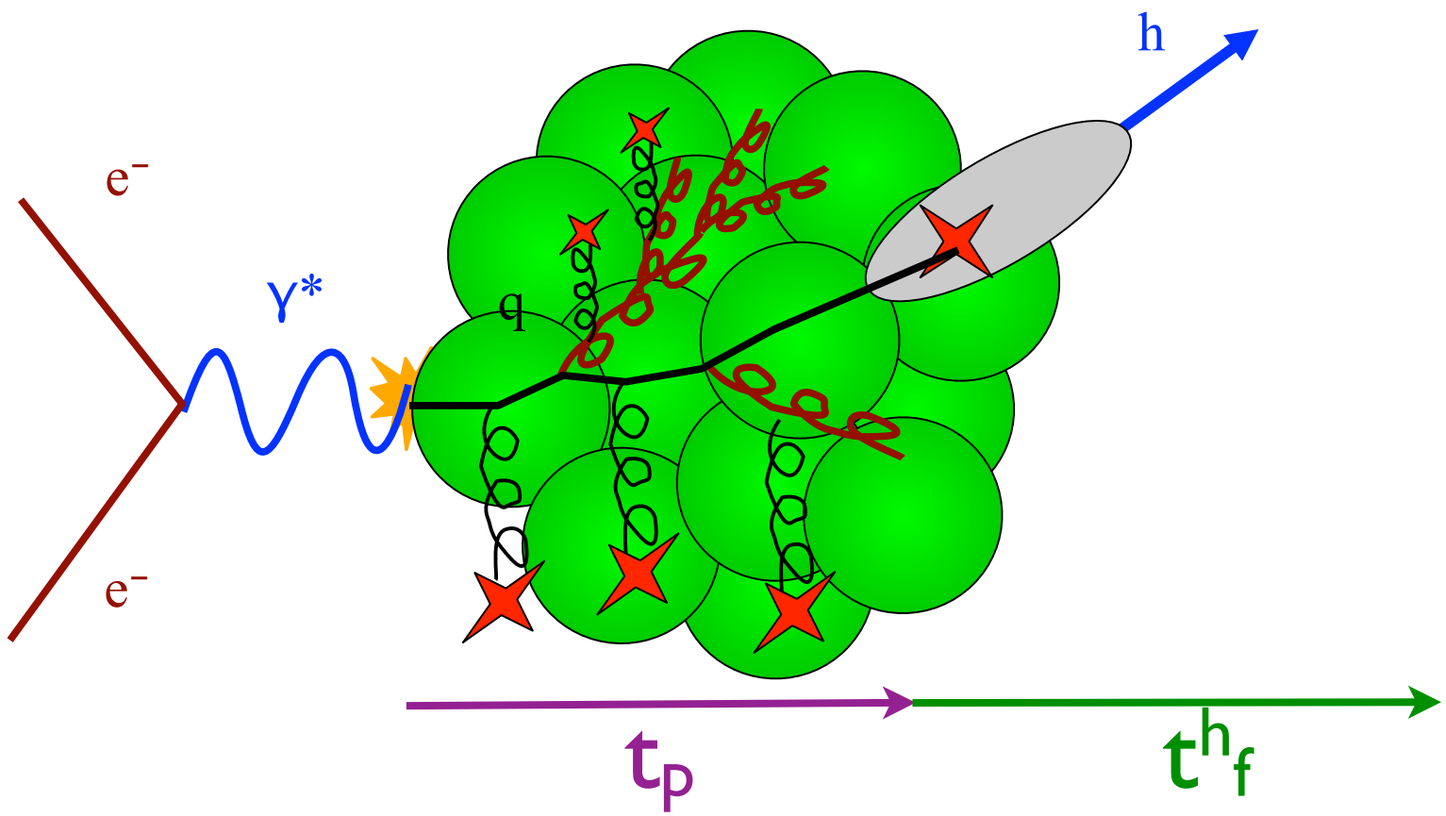

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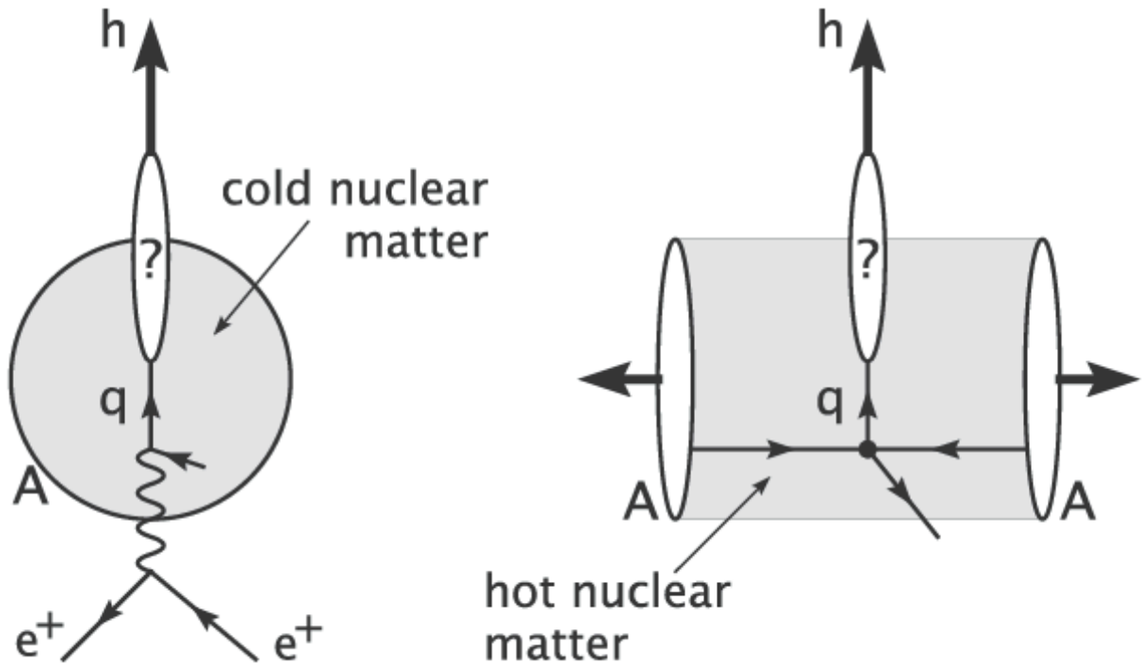

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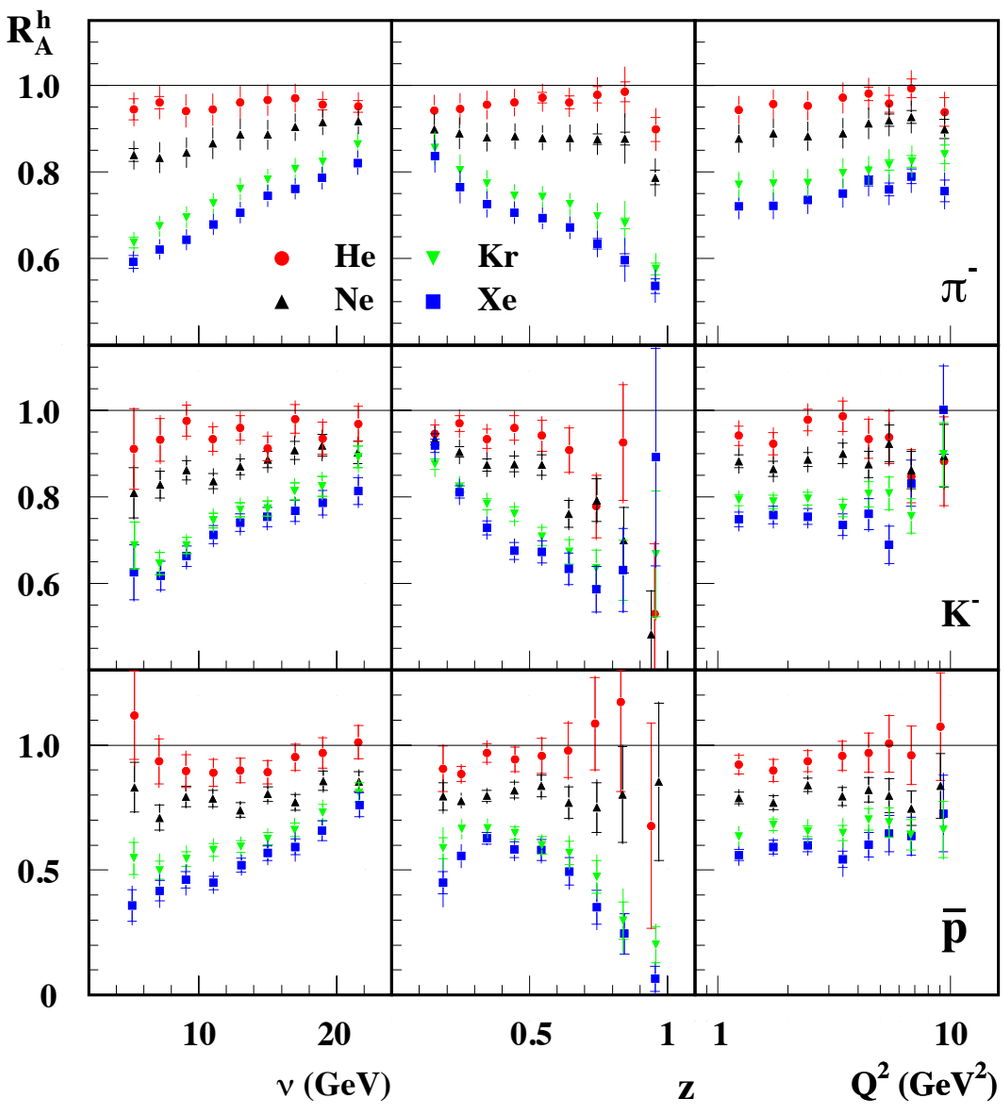
HERMES:

E_e = 27 GeV → $\sqrt{s}$ = 7.2 GeV

E_h = 2-15 GeV



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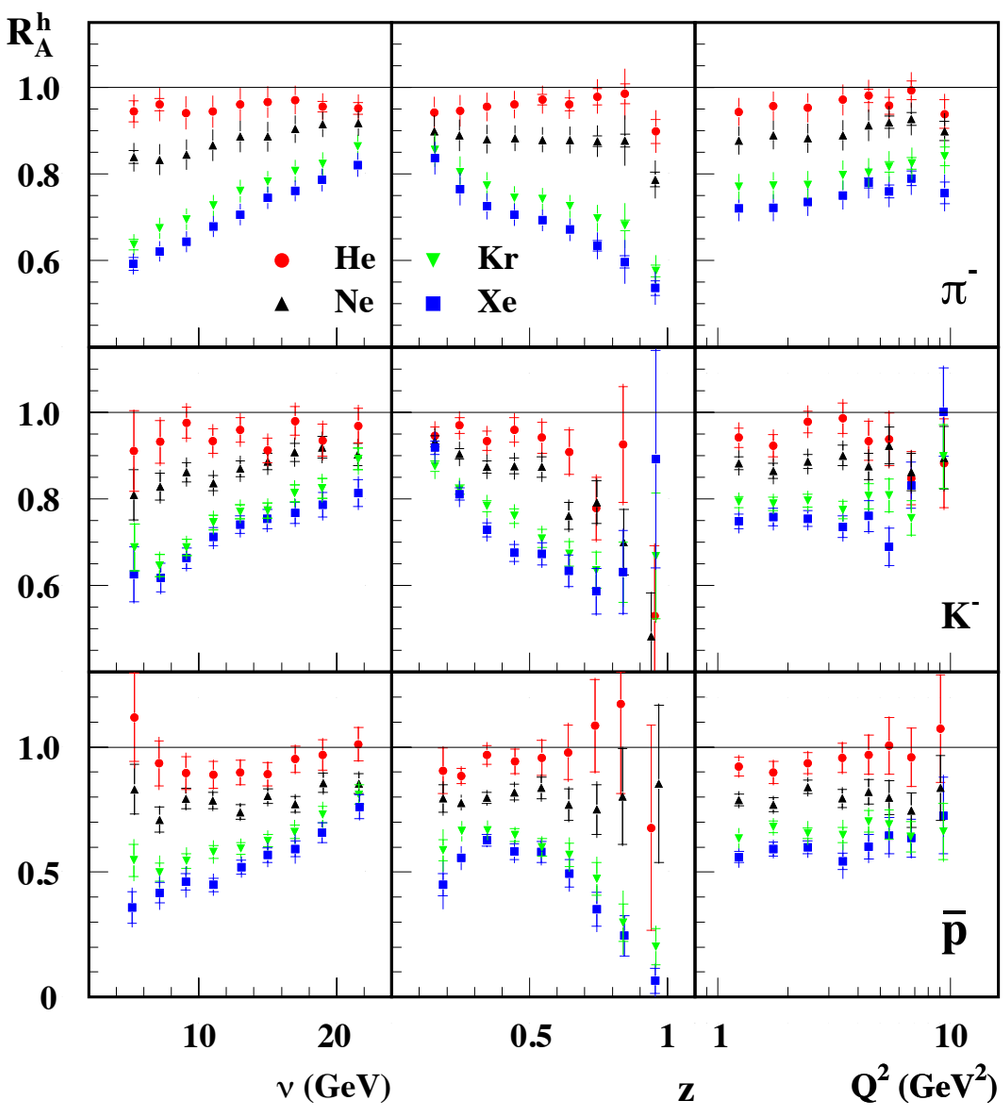

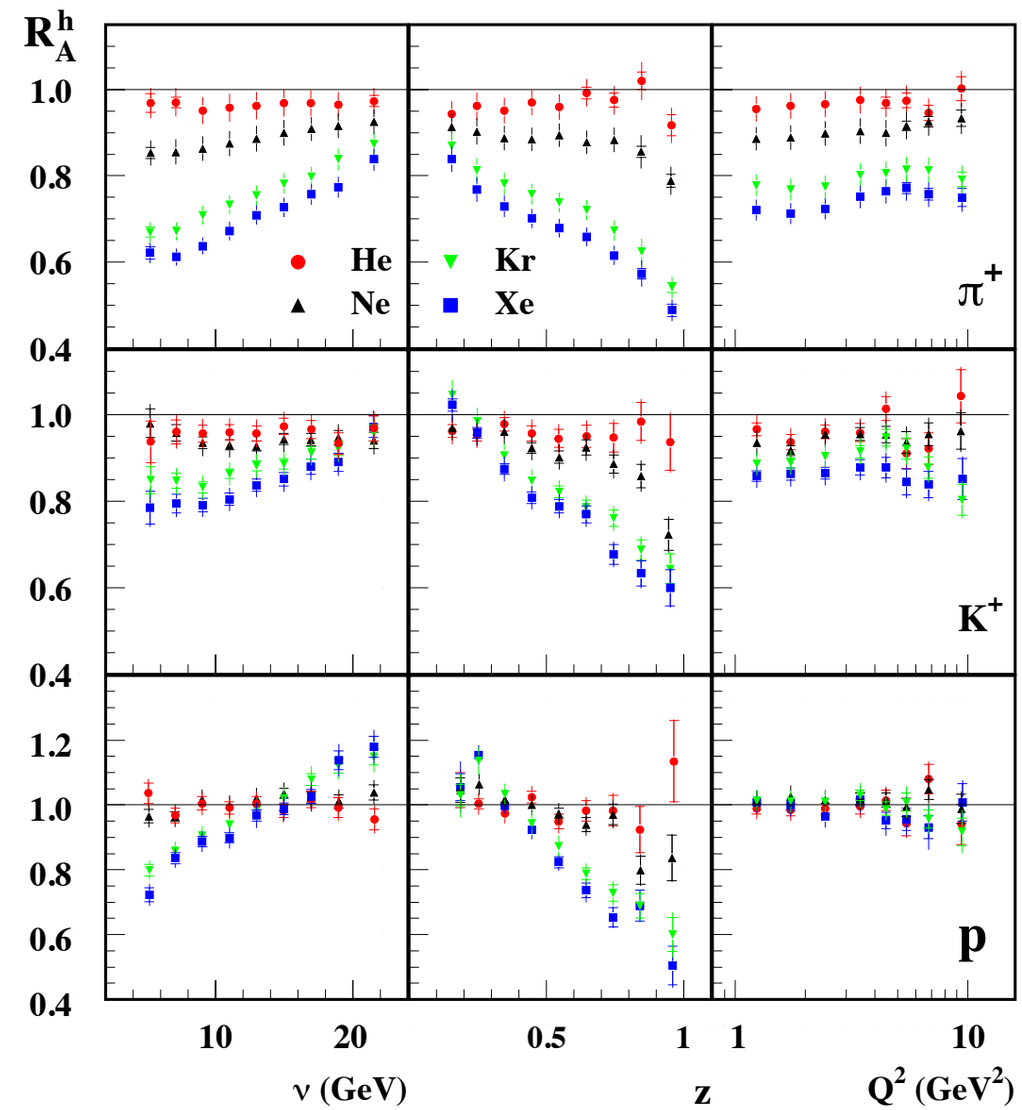

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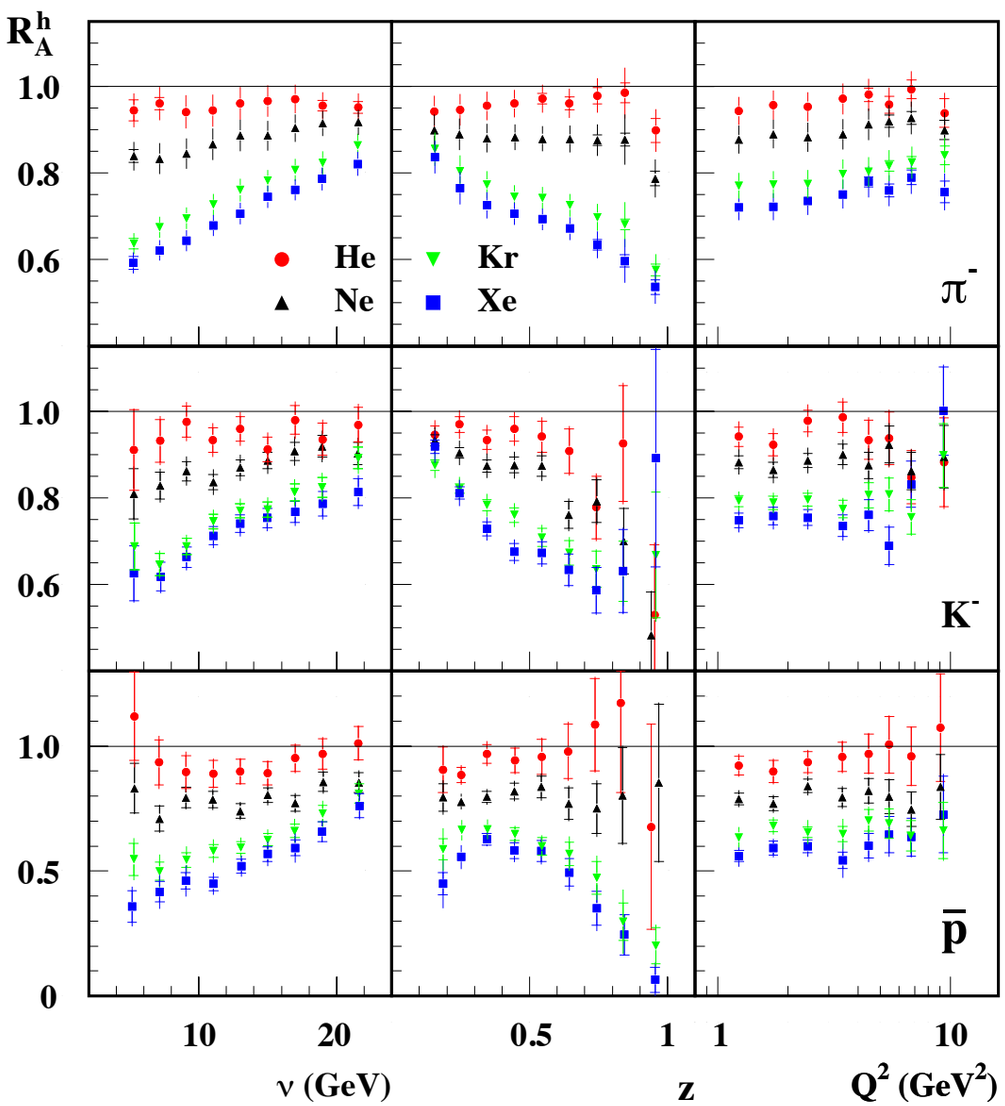

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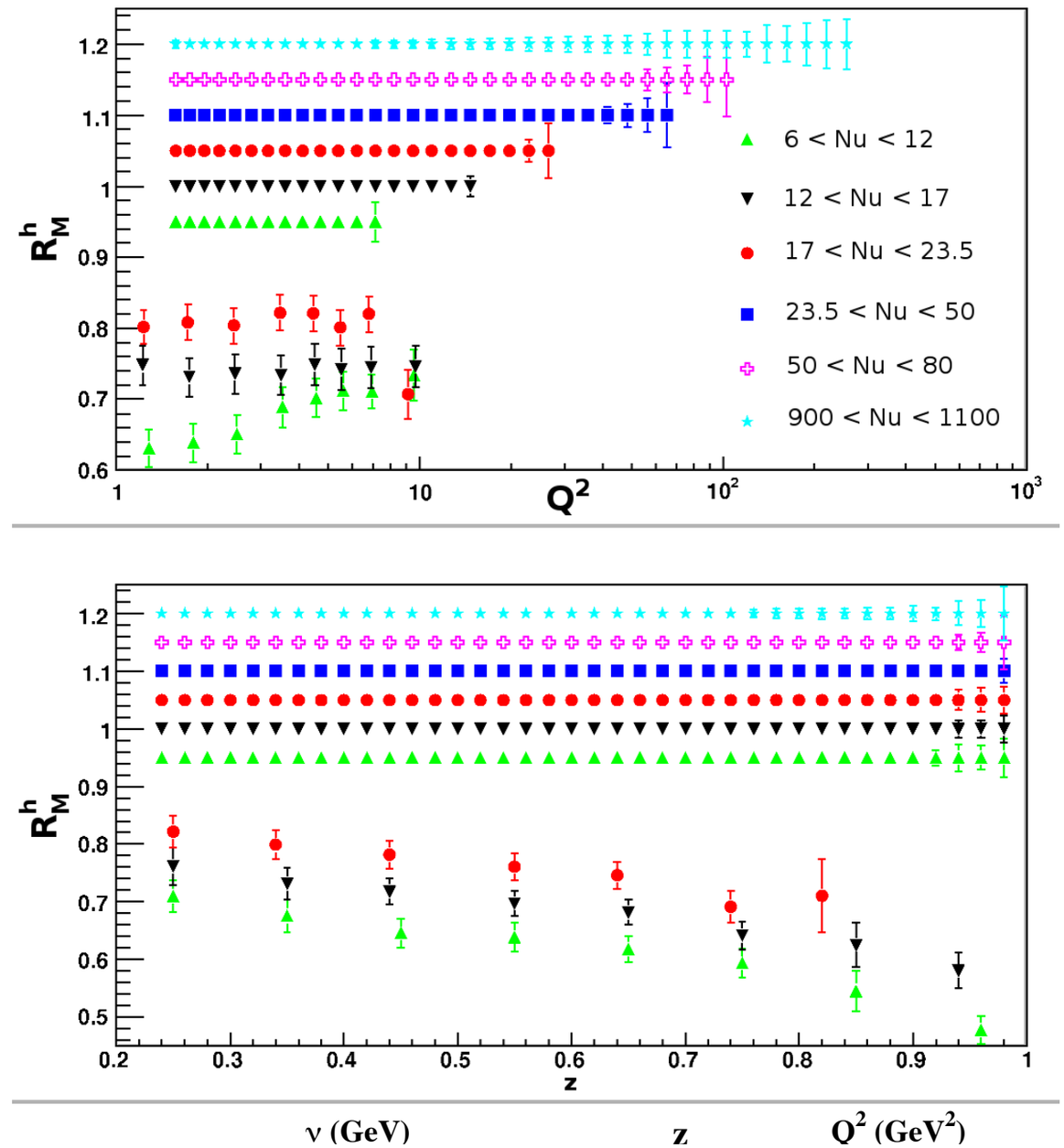
light hadrons:



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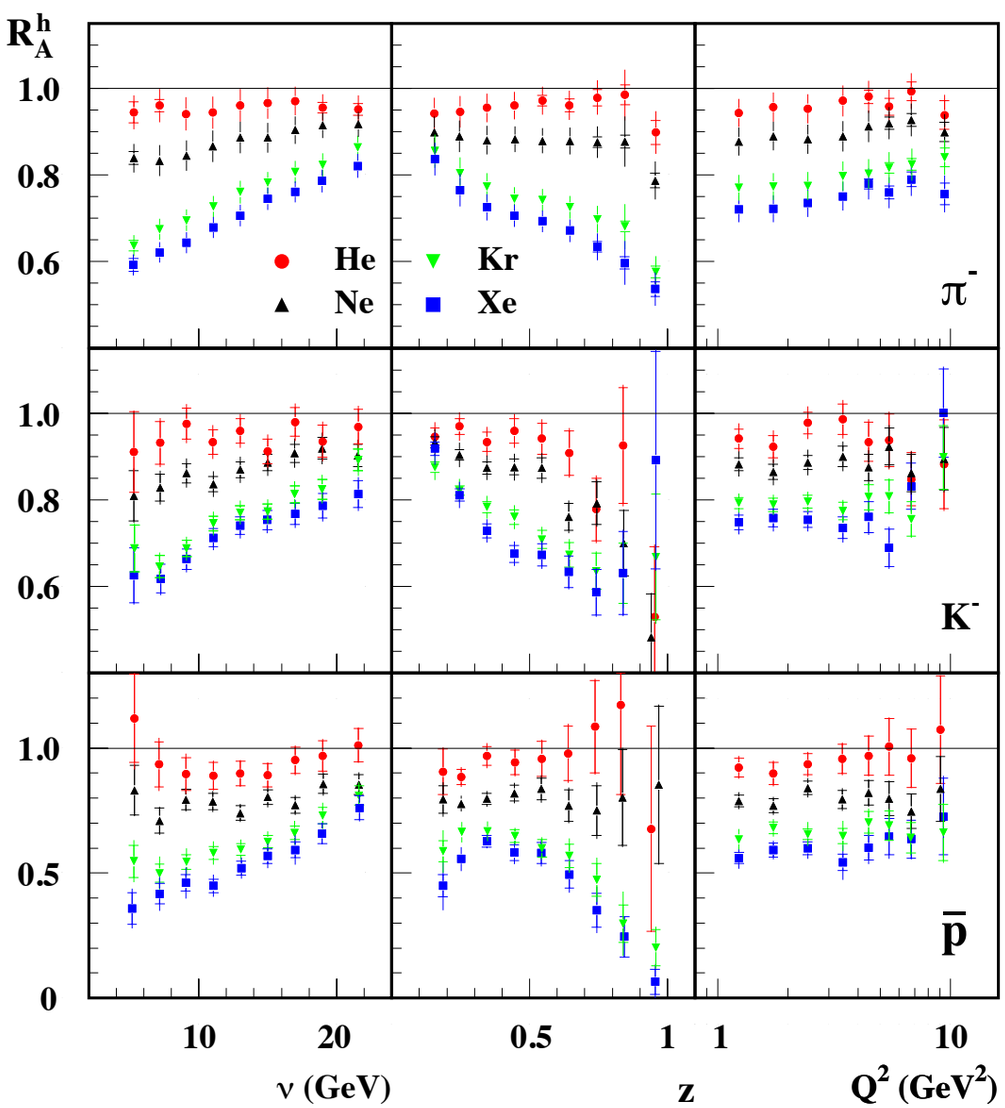
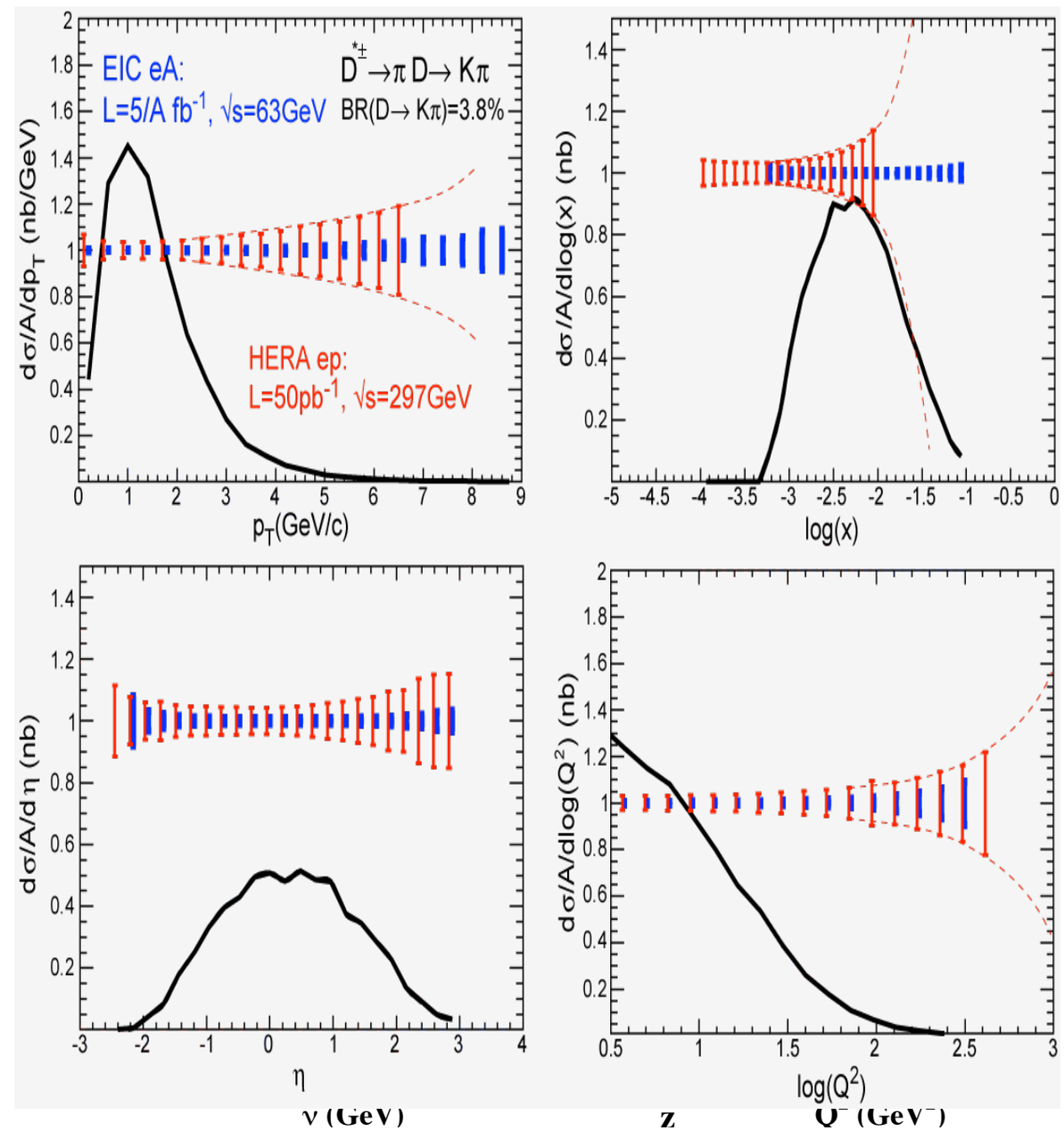


EIC:

charm hadrons:



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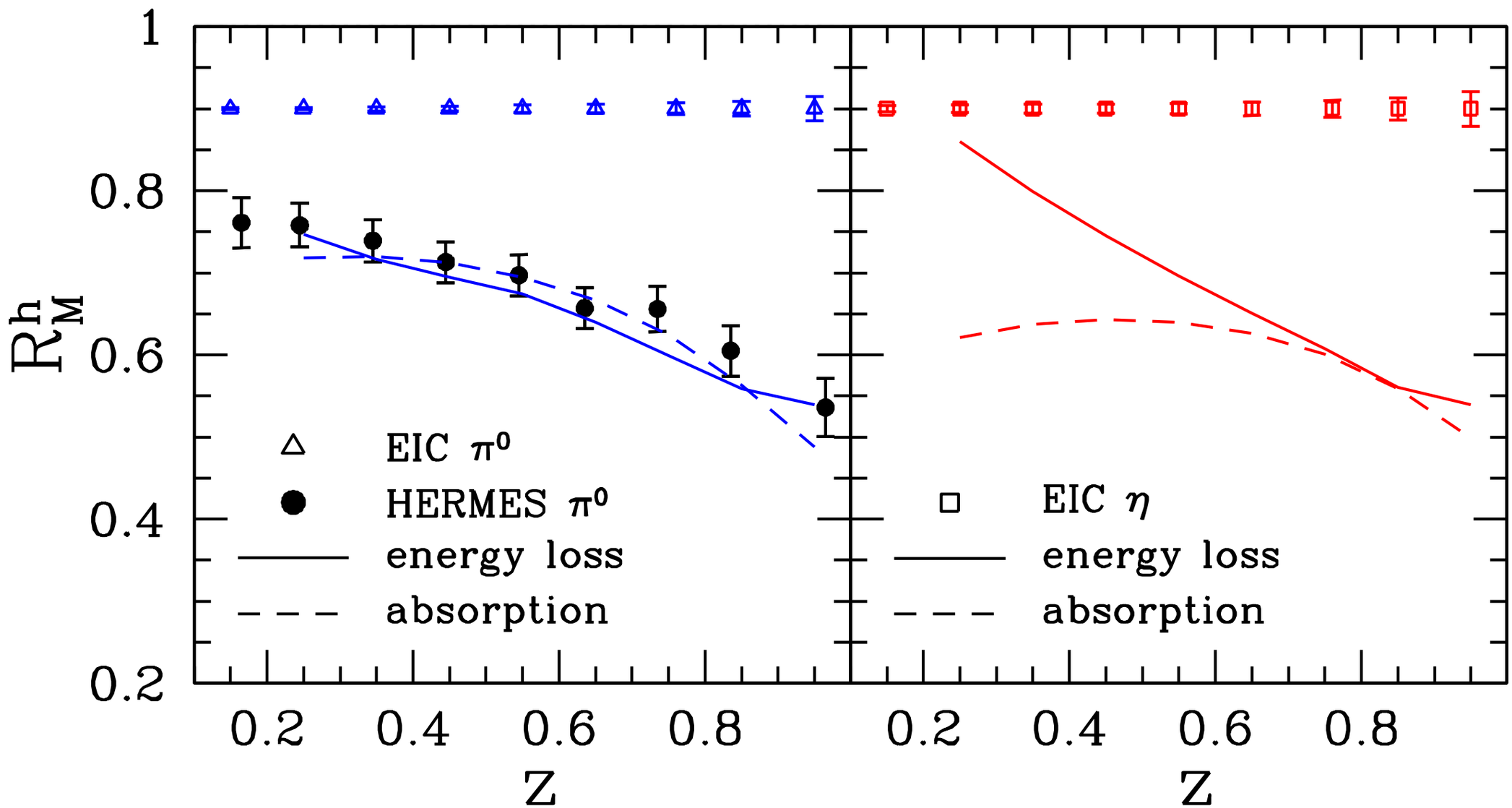

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Jets at an EIC

- E665 at FNAL have measured jets in μ+A at $\sqrt{s} \sim 30$ GeV
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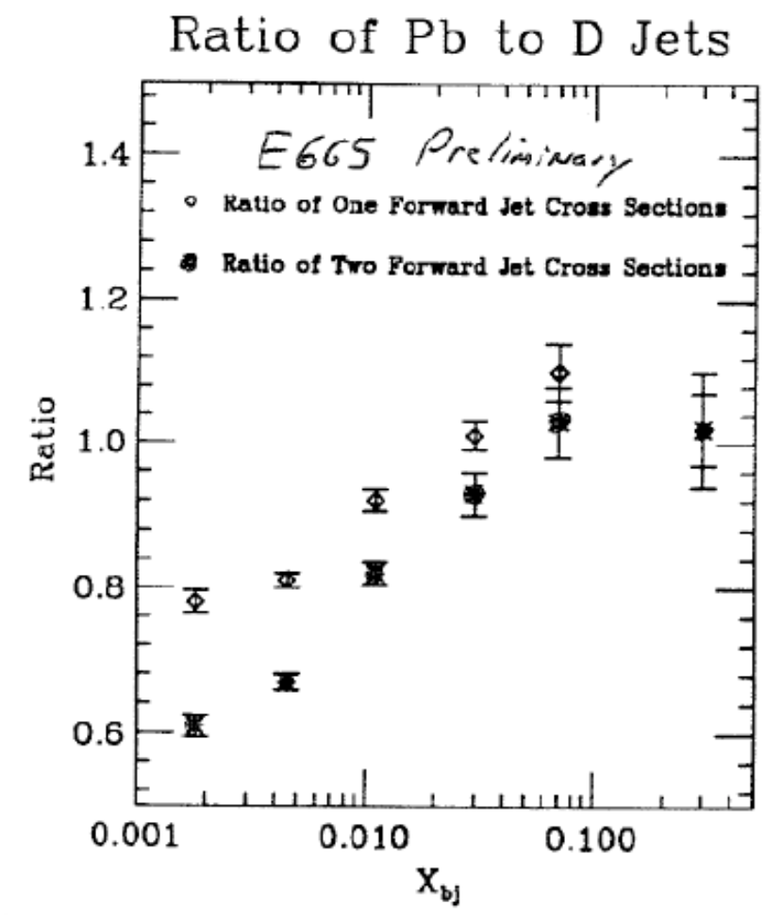

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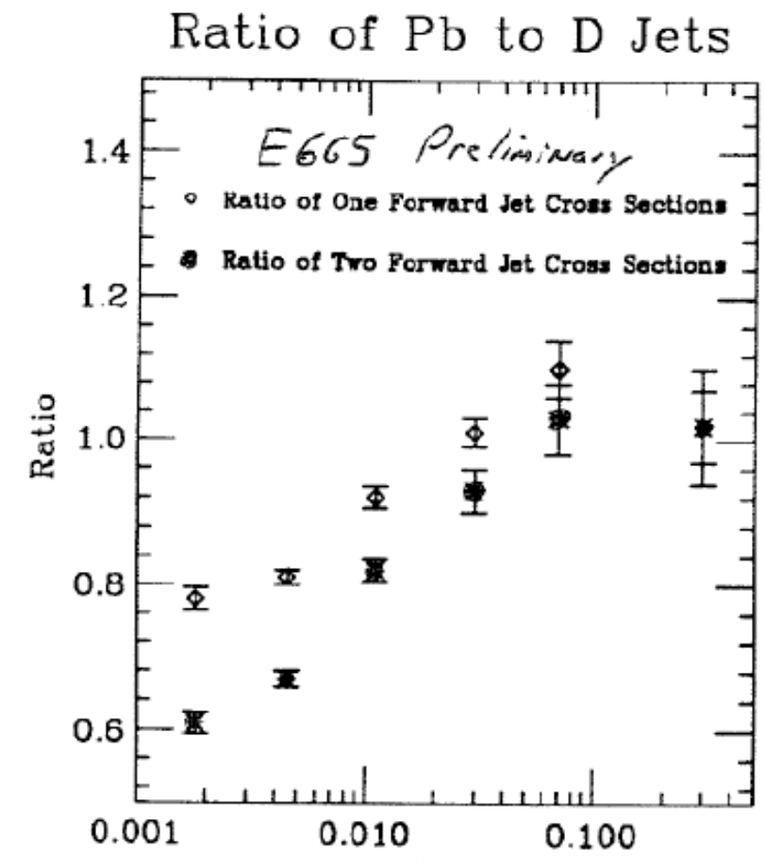
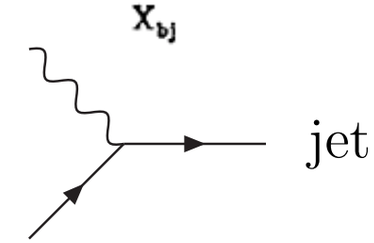


1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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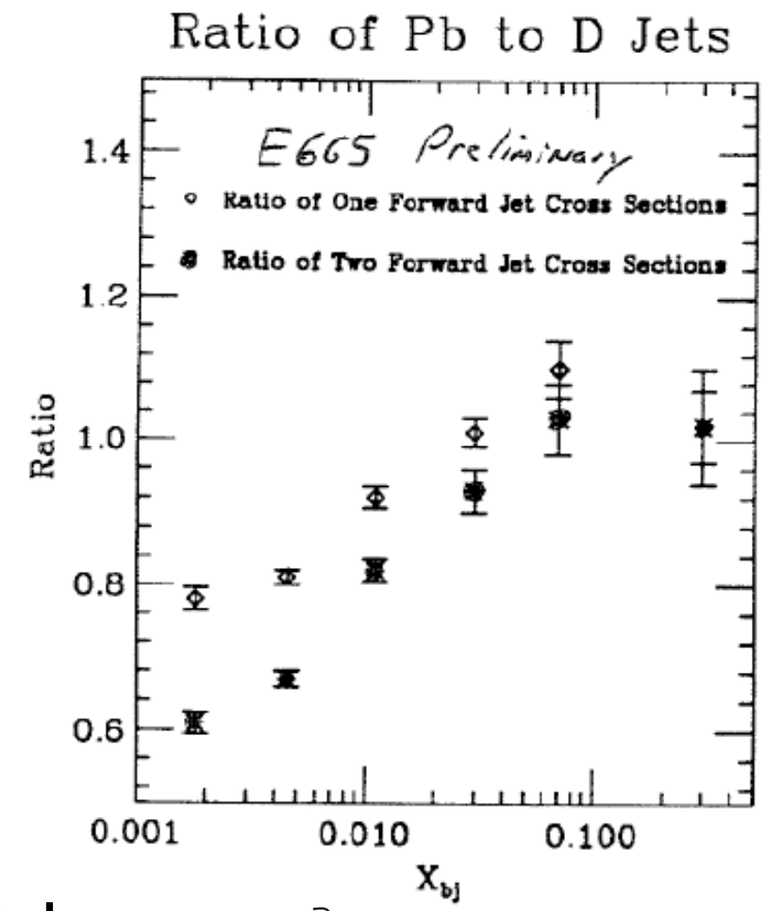

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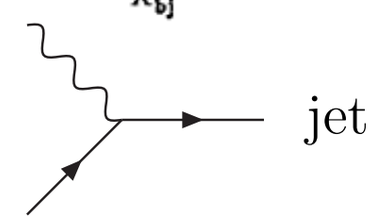

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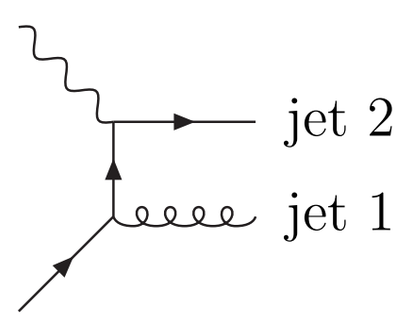

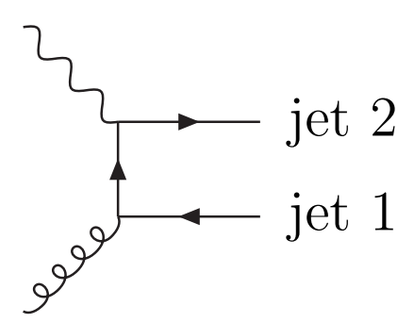

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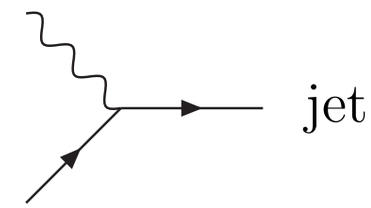

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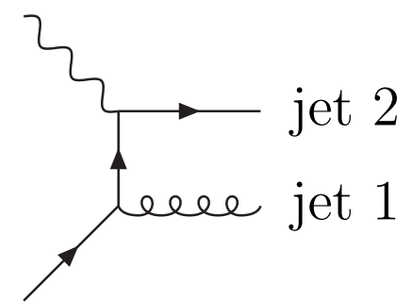

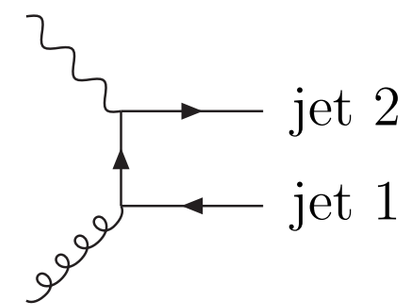

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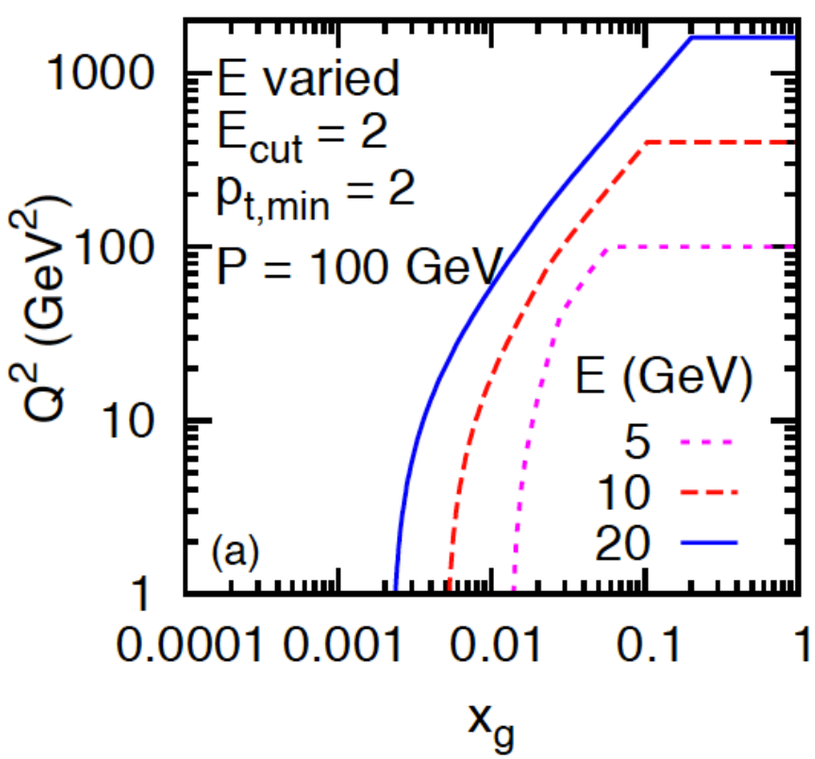
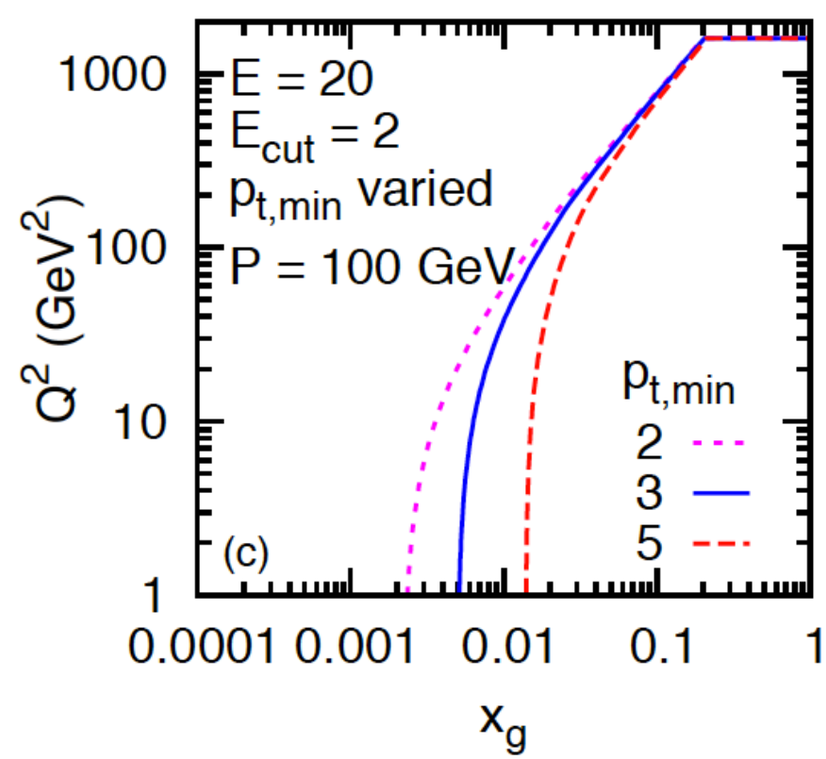




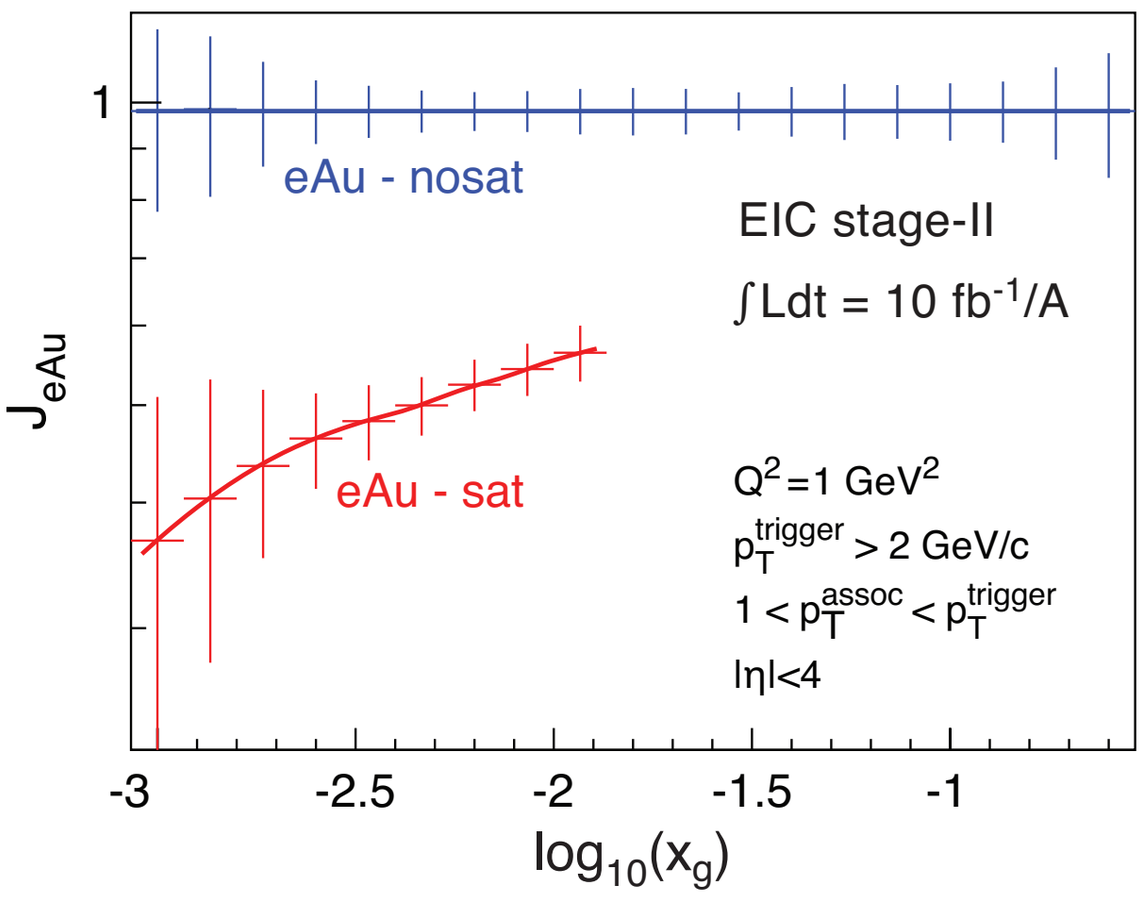
di-hadron Correlations - relative yields

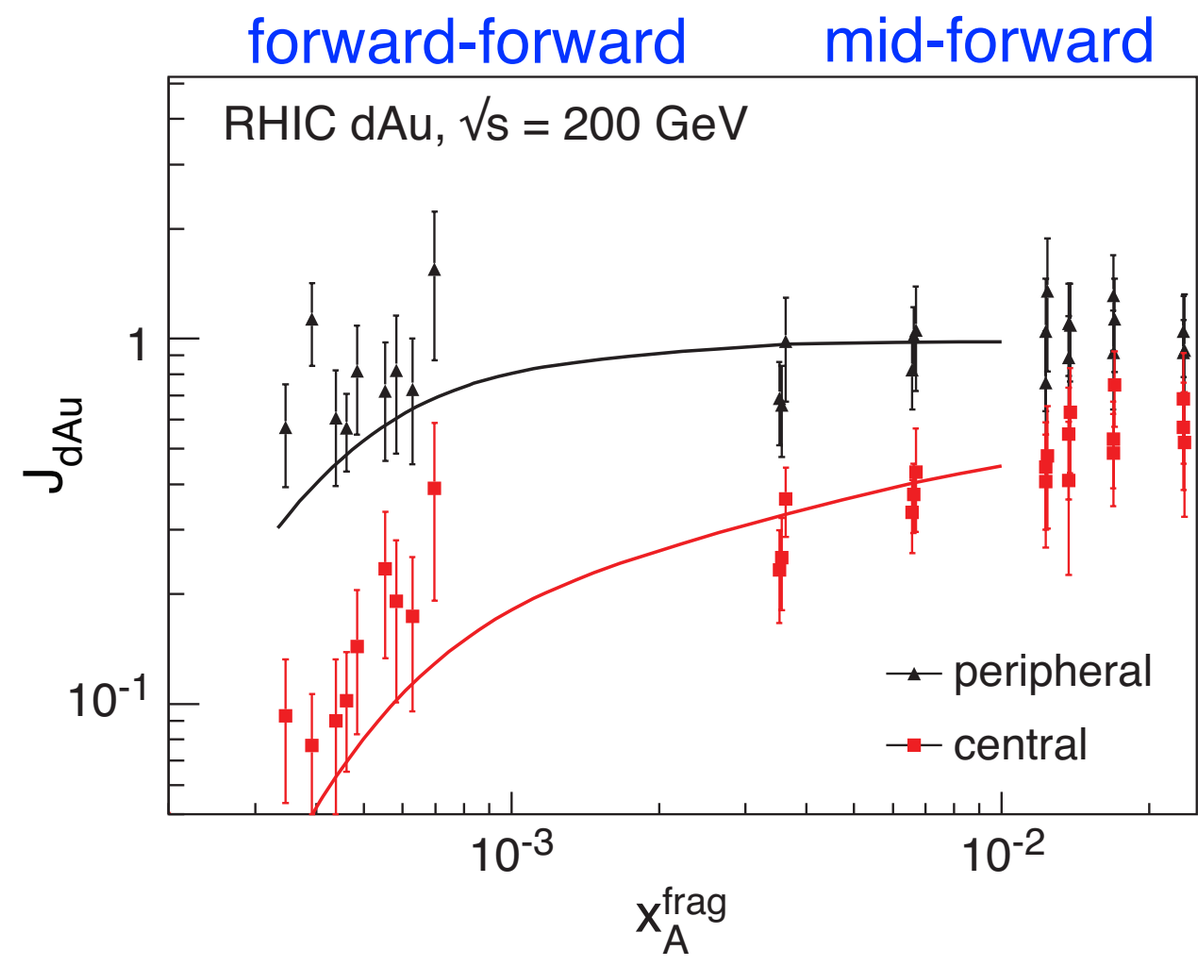
- PHENIX measured J_{dAu} - relative yield of di-hadrons produced in d+Au compared to p+p collisions

➡ 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)