e+A physics at an Electron-Ion Collider - understanding the glue which binds us all

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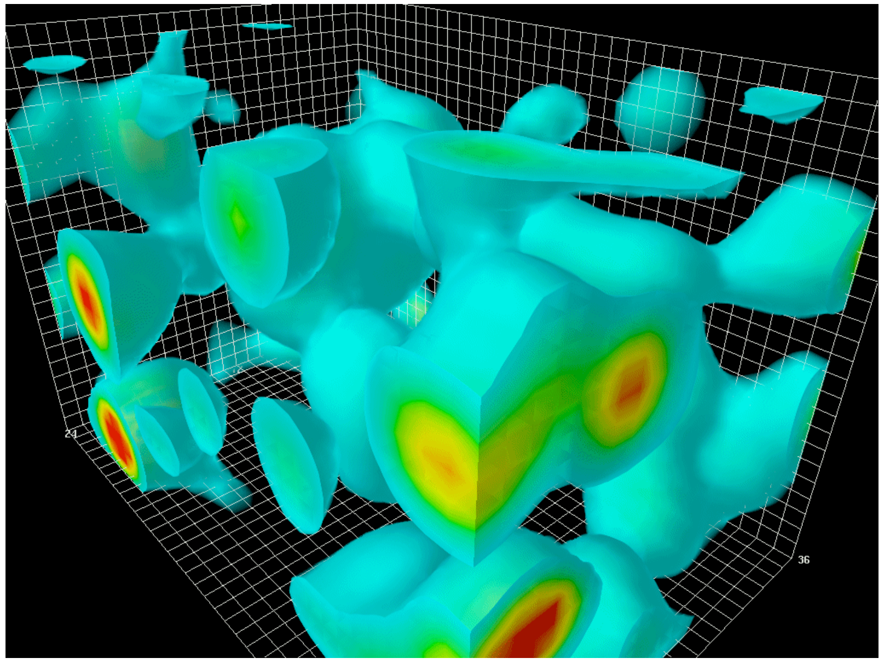
What do we know about gluons?

- **Gluons:**
  - ➡ Mediators of the strong interaction
  - ➡ Determine essential features of QCD
    - ‣ Asymptotic freedom from gluon loops
  - ➡ Dominate structure of QCD vacuum



Action (~energy) density fluctuations of gluon-fields in QCD vacuum (2.4 ×2.4× 3.6 fm) (Derek Leinweber)

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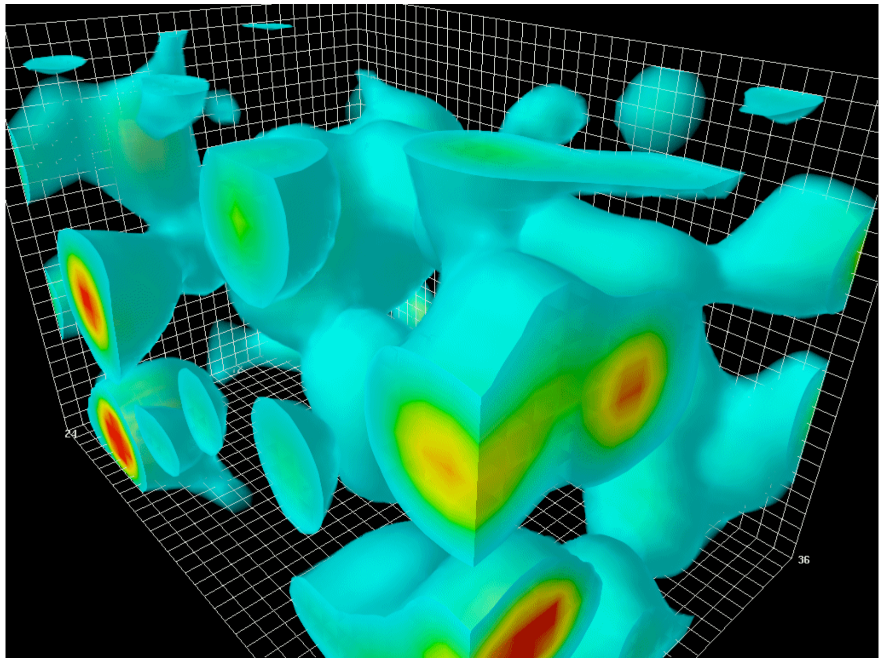

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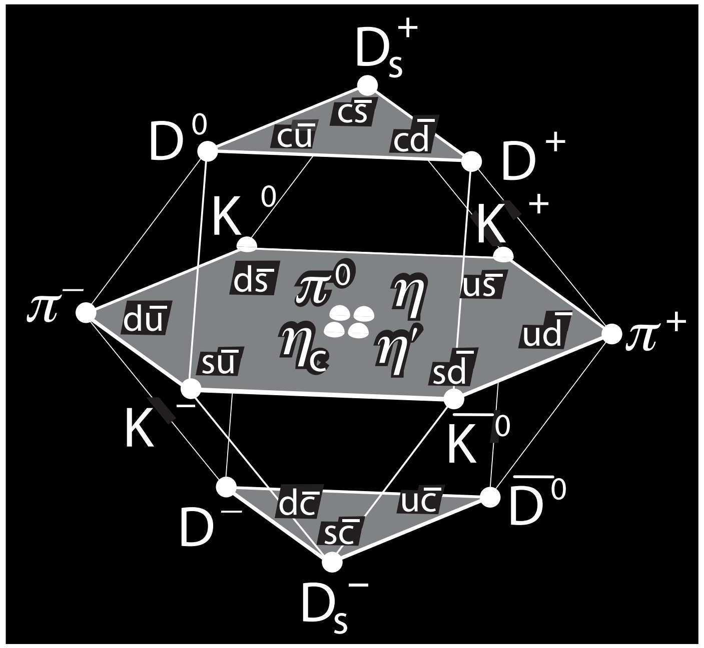
- **Hard to "see" glue in the low-energy world**
  - ➡ Gluon degrees of freedom "missing" in hadronic spectrum
    - ‣ Constituent Quark Picture?
  - ➡ From DIS:
    - \- Drive the structure of baryonic matter already at medium-x
  - ★ Crucial players at RHIC and LHC



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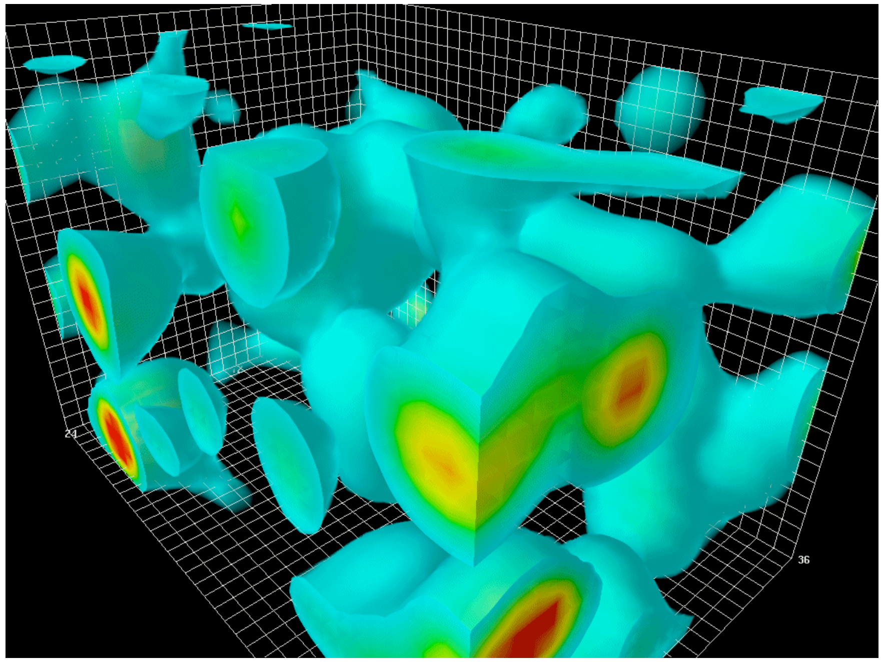

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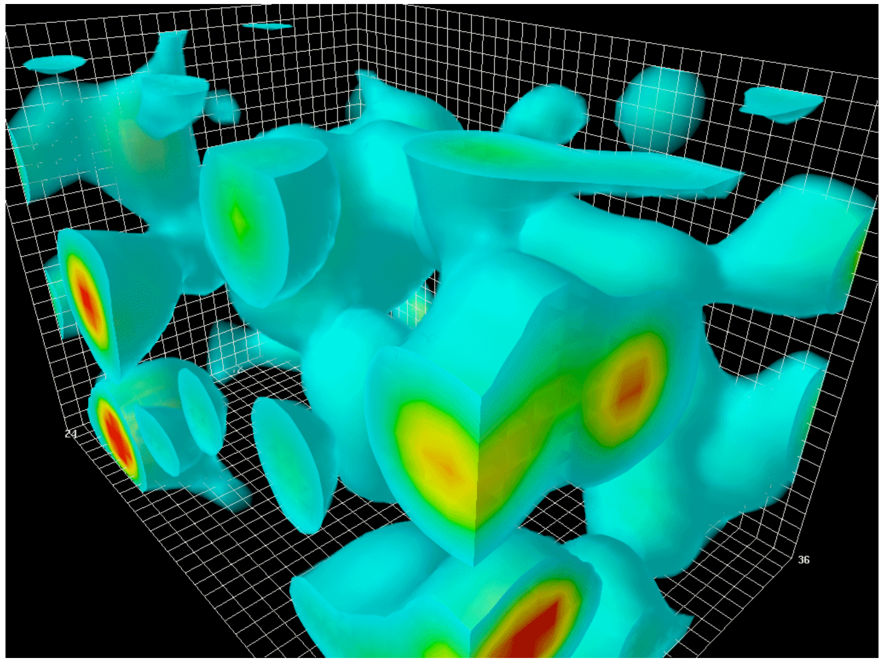

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- ➡ What are the properties of high-density gluon matter?
- ➡ How do quarks and gluons interact as they traverse matter?
- ➡ What role do the gluons play in the spin structure of the nucleon?

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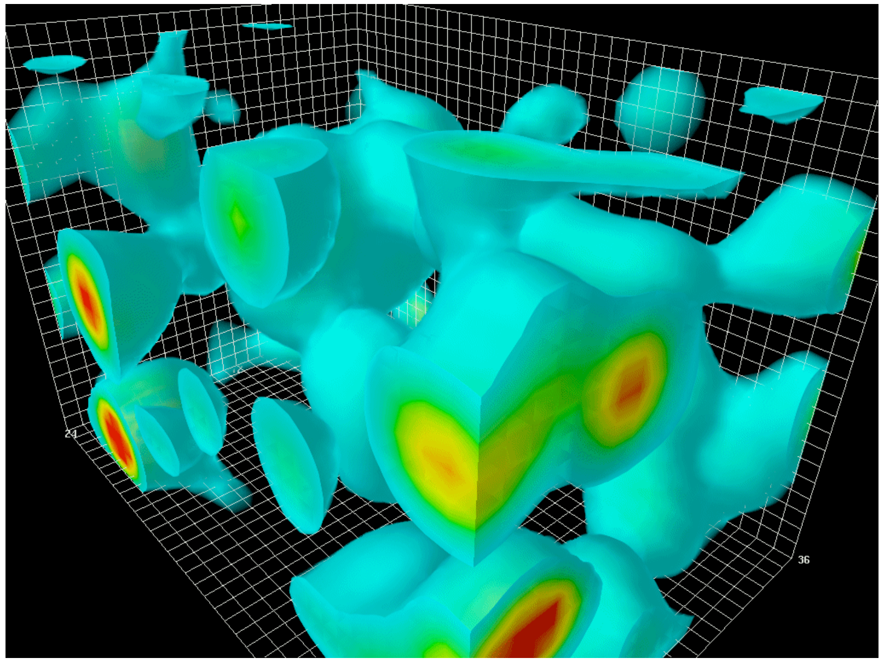

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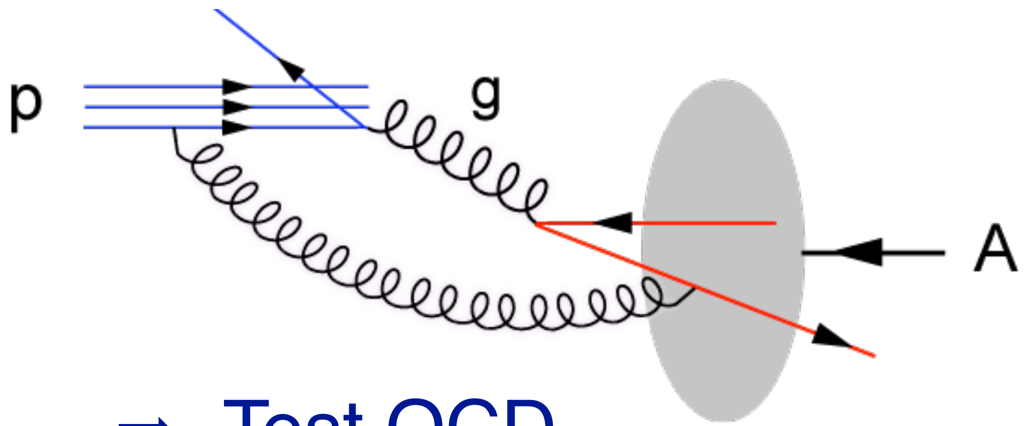
How do we get to the answers?

How do we measure Glue ?

- Hadron-Hadron



➡ Test QCD

➡ Probe/Target interaction directly via gluons

➡ Lacks the direct access to collision kinematics

➡ Interactions with other partons modifies nuclear wave function

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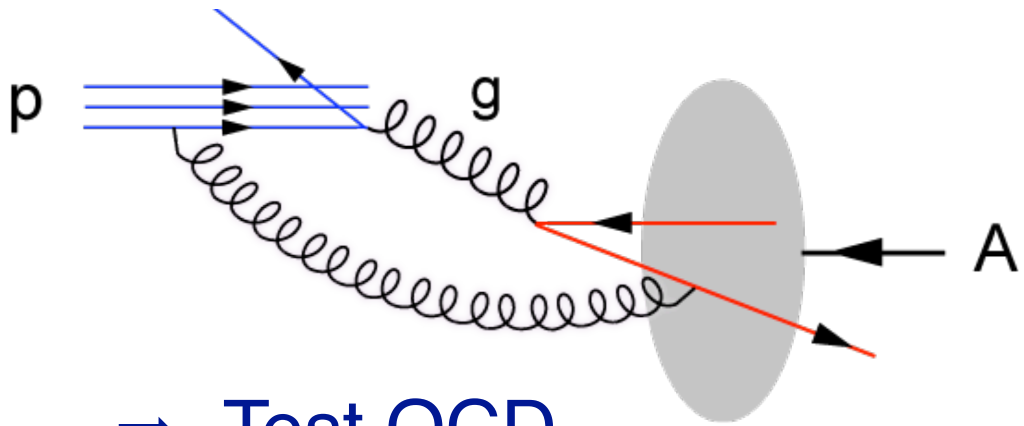

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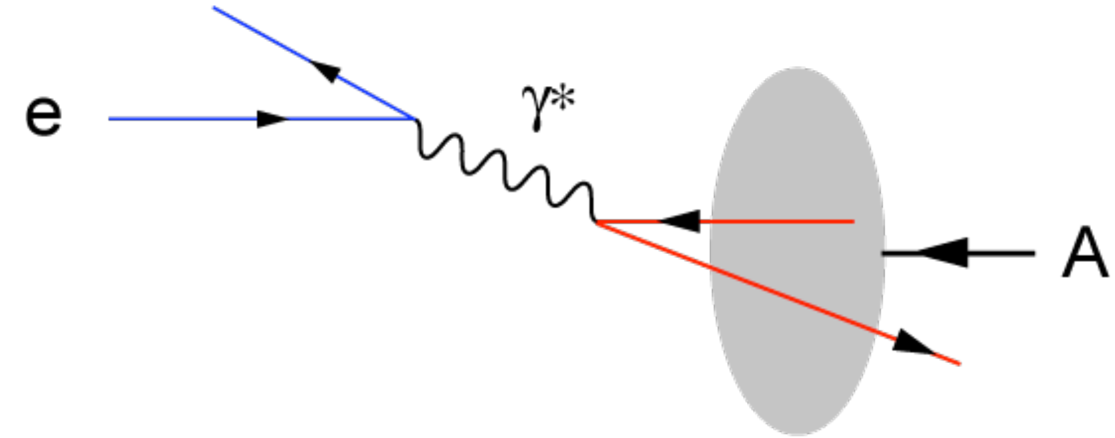
➡ Electron-Hadron (DIS)



★ Explore QCD & Hadron Structure

★ Indirect access to glue

★ High precision & access to partonic kinematics

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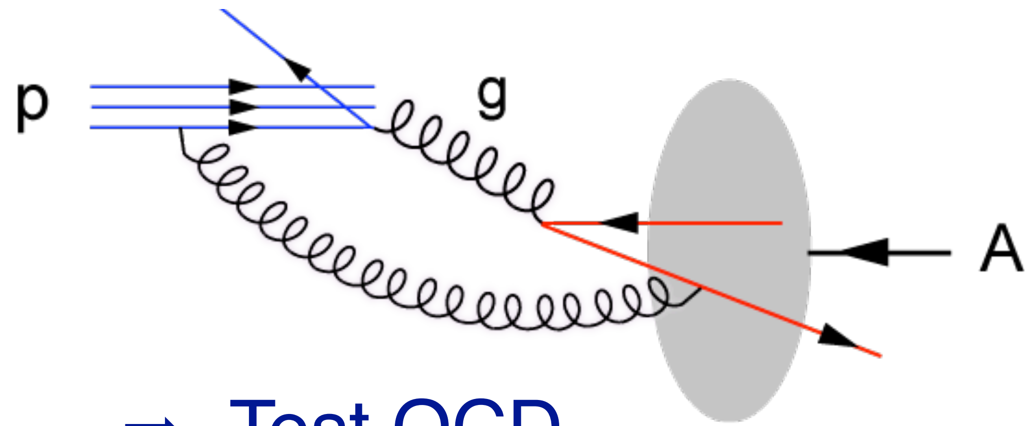

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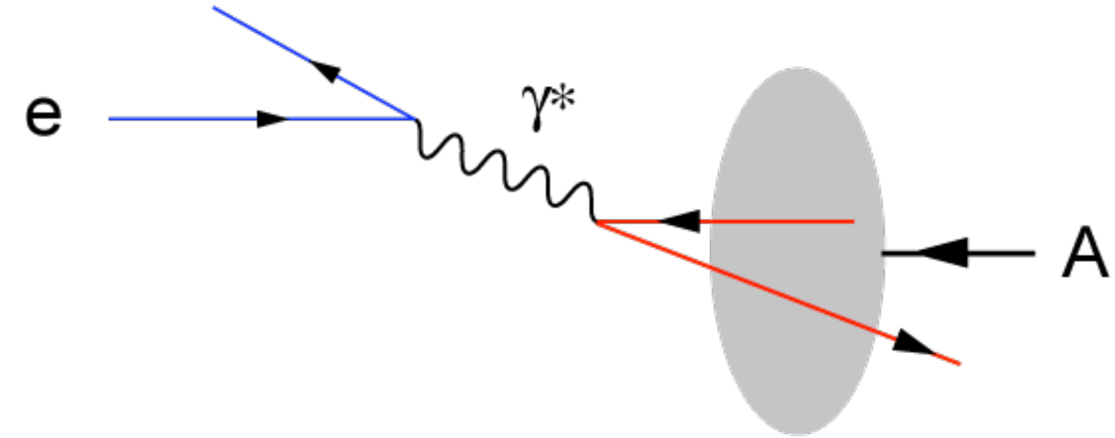


★ Explore QCD & Hadron Structure

★ Indirect access to glue

★ High precision & access to partonic kinematics

Both are complementary and provide excellent information on properties of gluons in the nuclear wave functions

Precision measurements ⇒ DIS

How do we measure Glue ?

• H

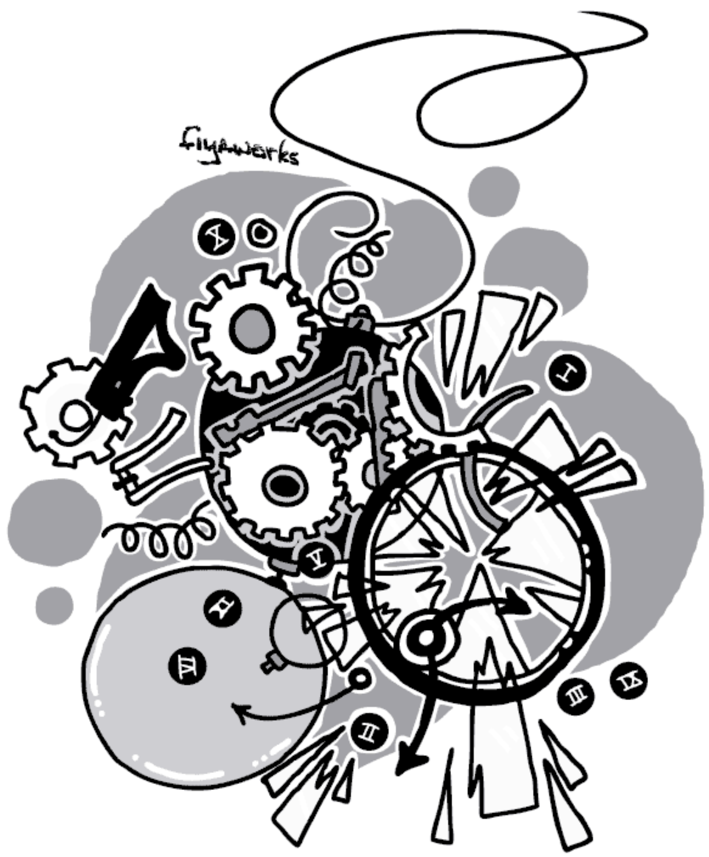
p

A

B n

Scattering of hadrons on hadrons
is like colliding Swiss watches to find out how
they are build.

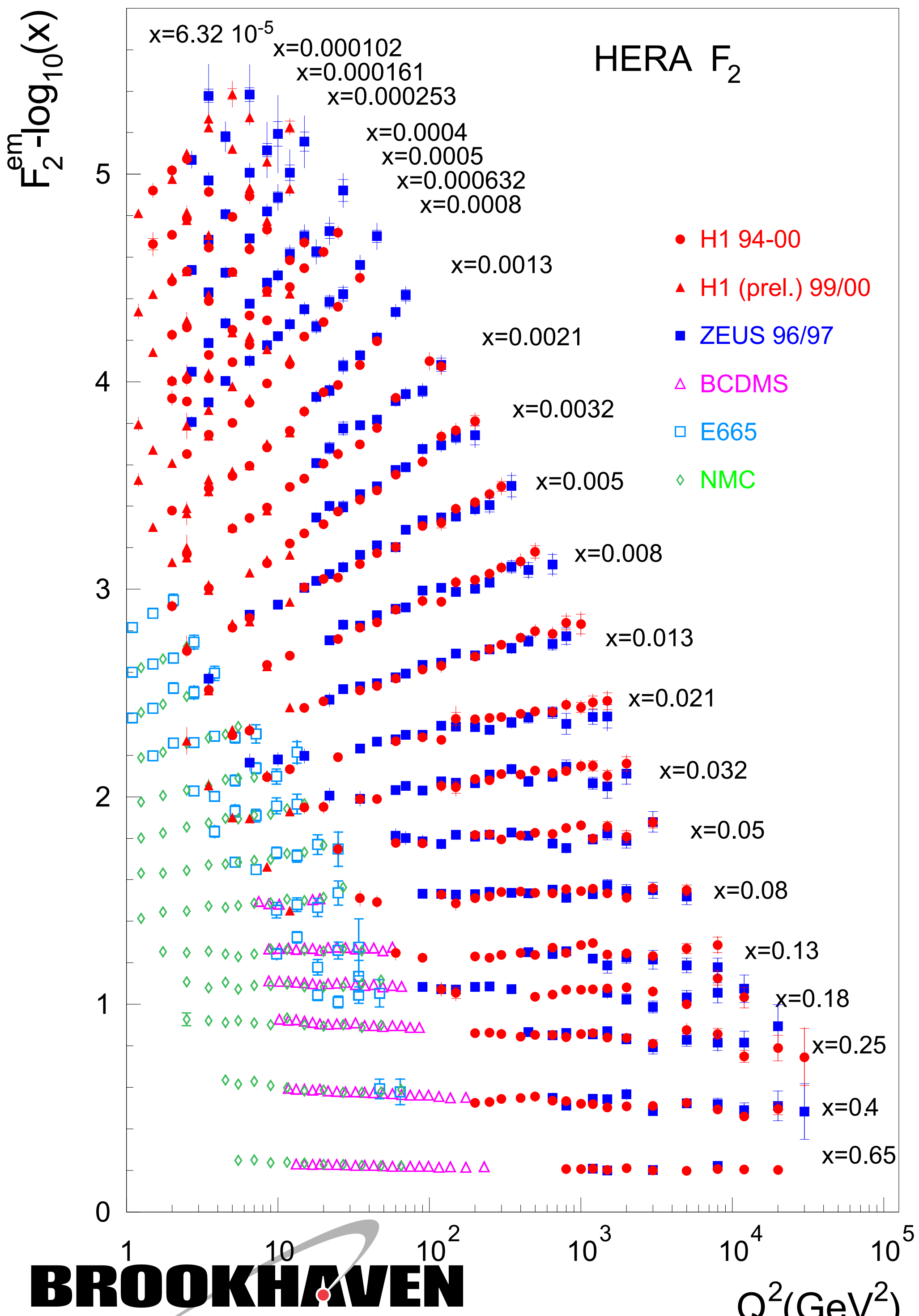
R. Feynman



Precision measurements ⇒ DIS

How to measure the glue?

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$



quark+anti-quark momentum distributions (→ F_2)

gluon momentum distribution (→ F_L)

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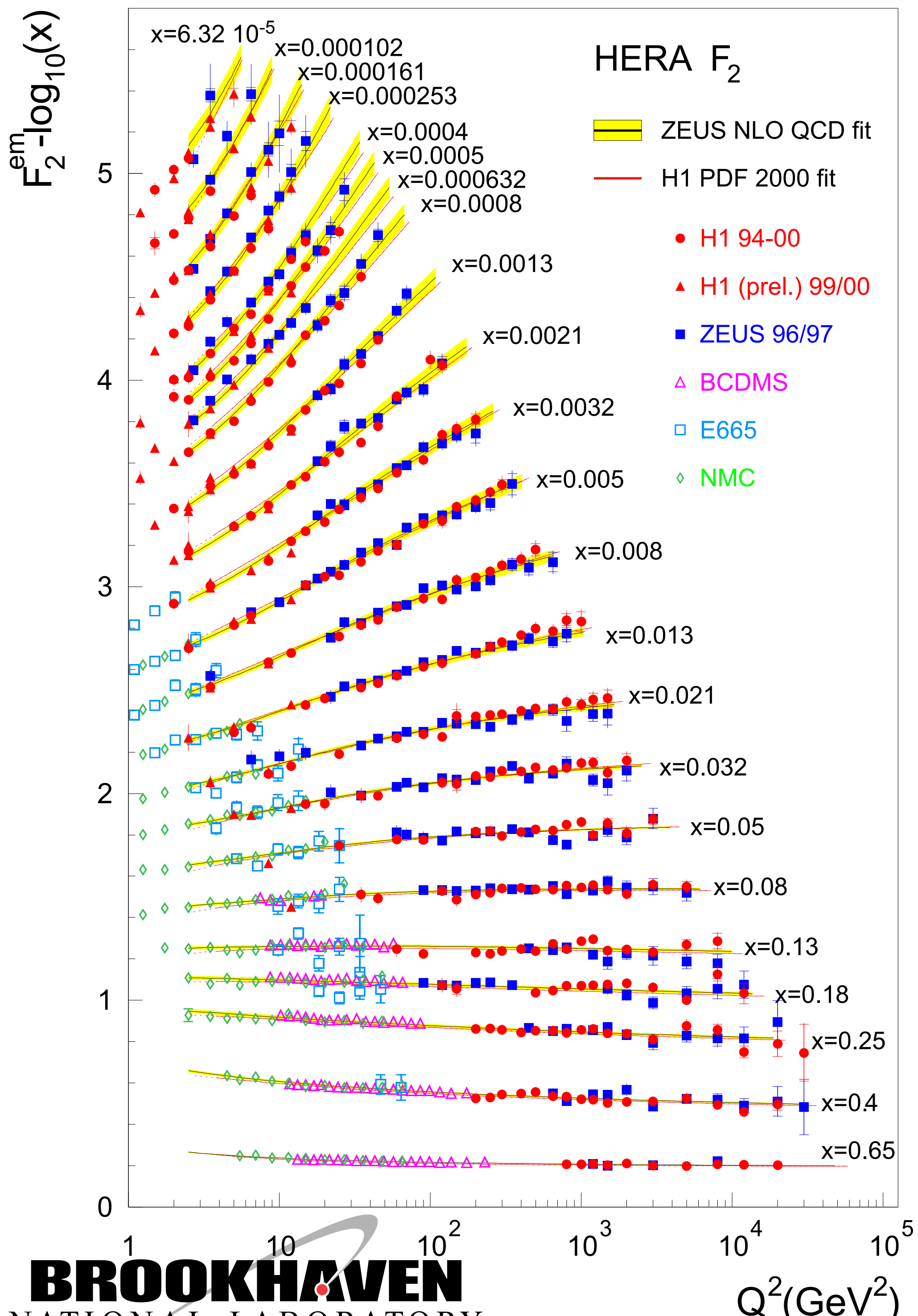

Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$

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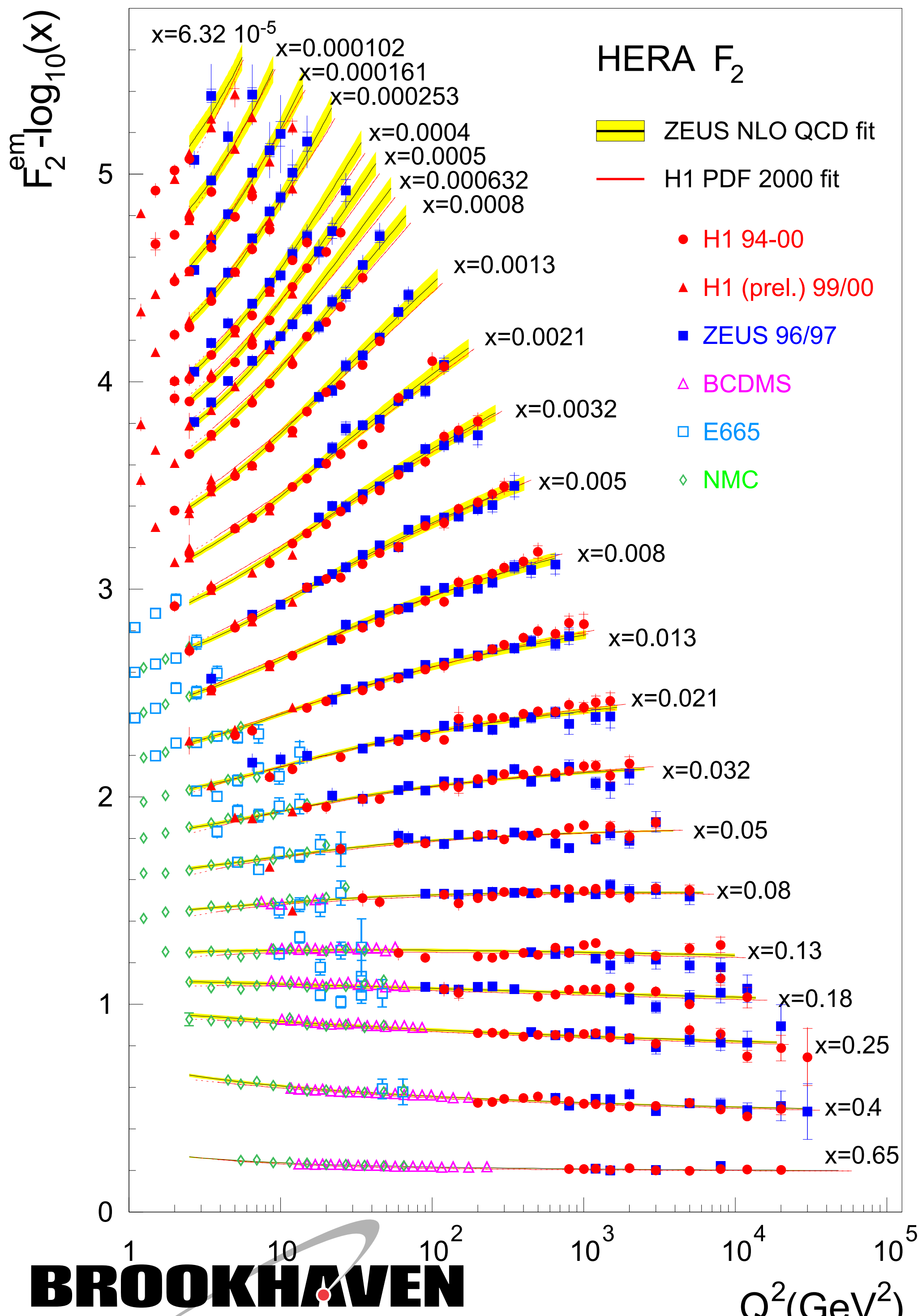
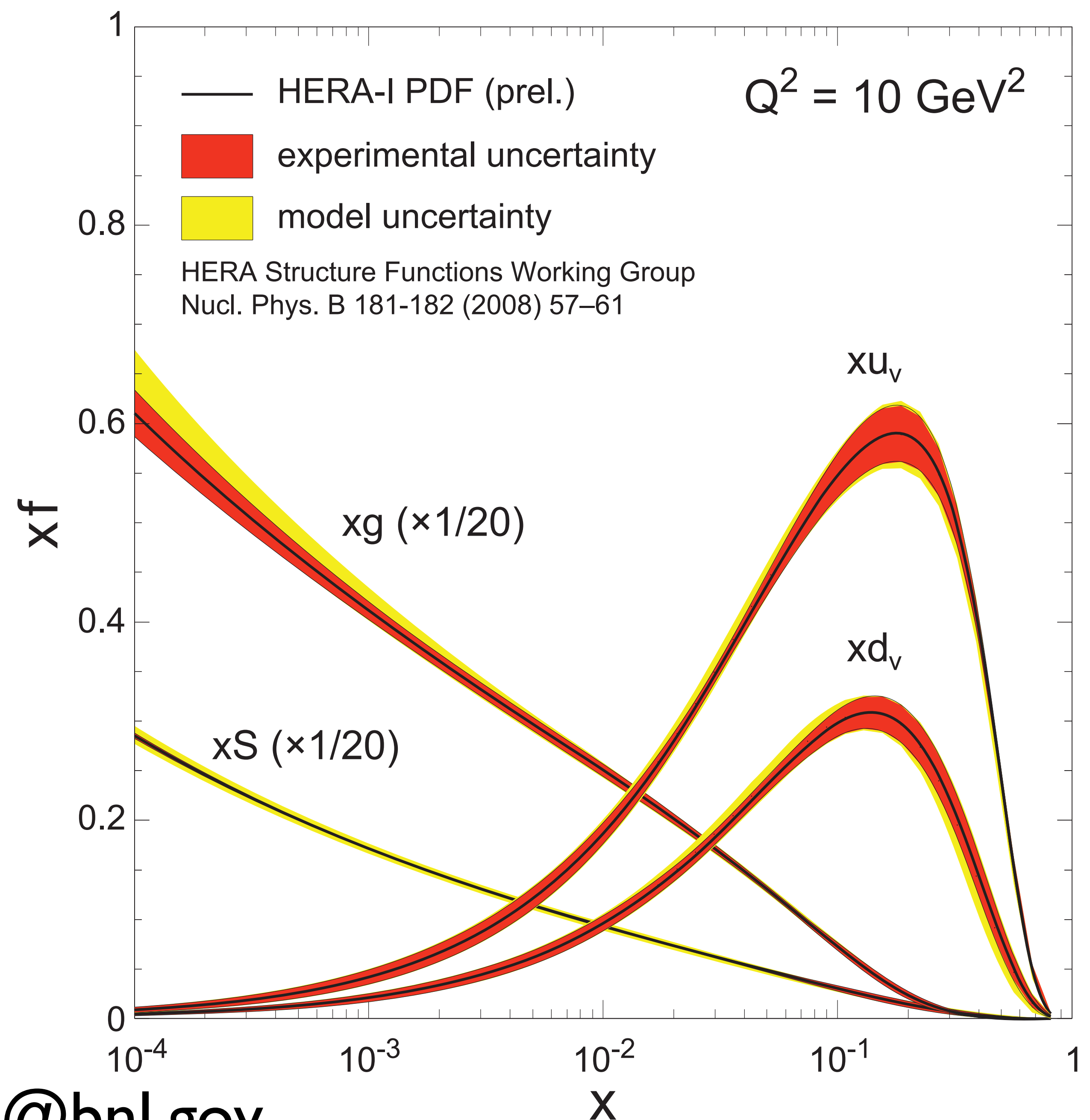


Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP

Evolution $\Rightarrow G(x,Q^2)$



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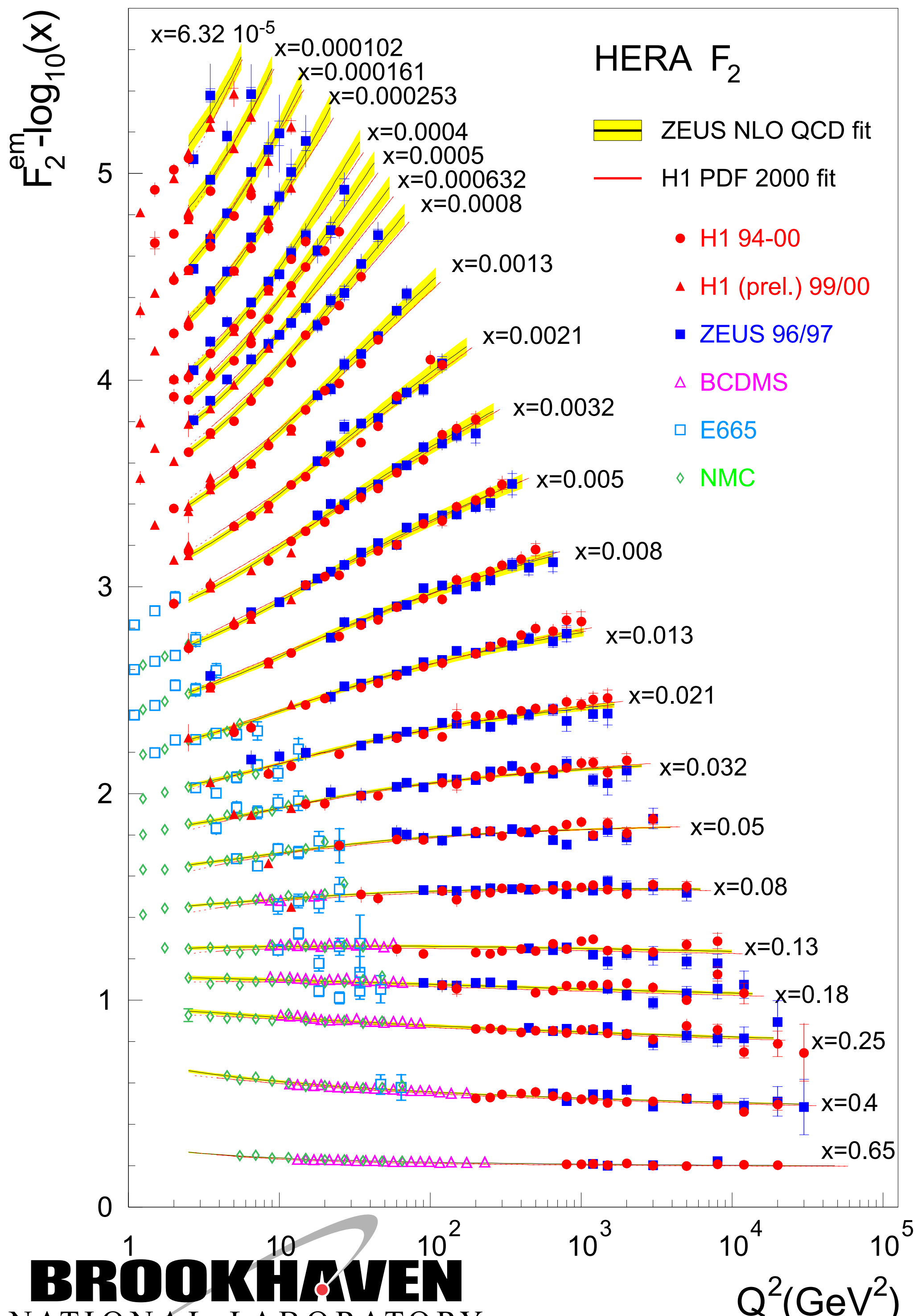

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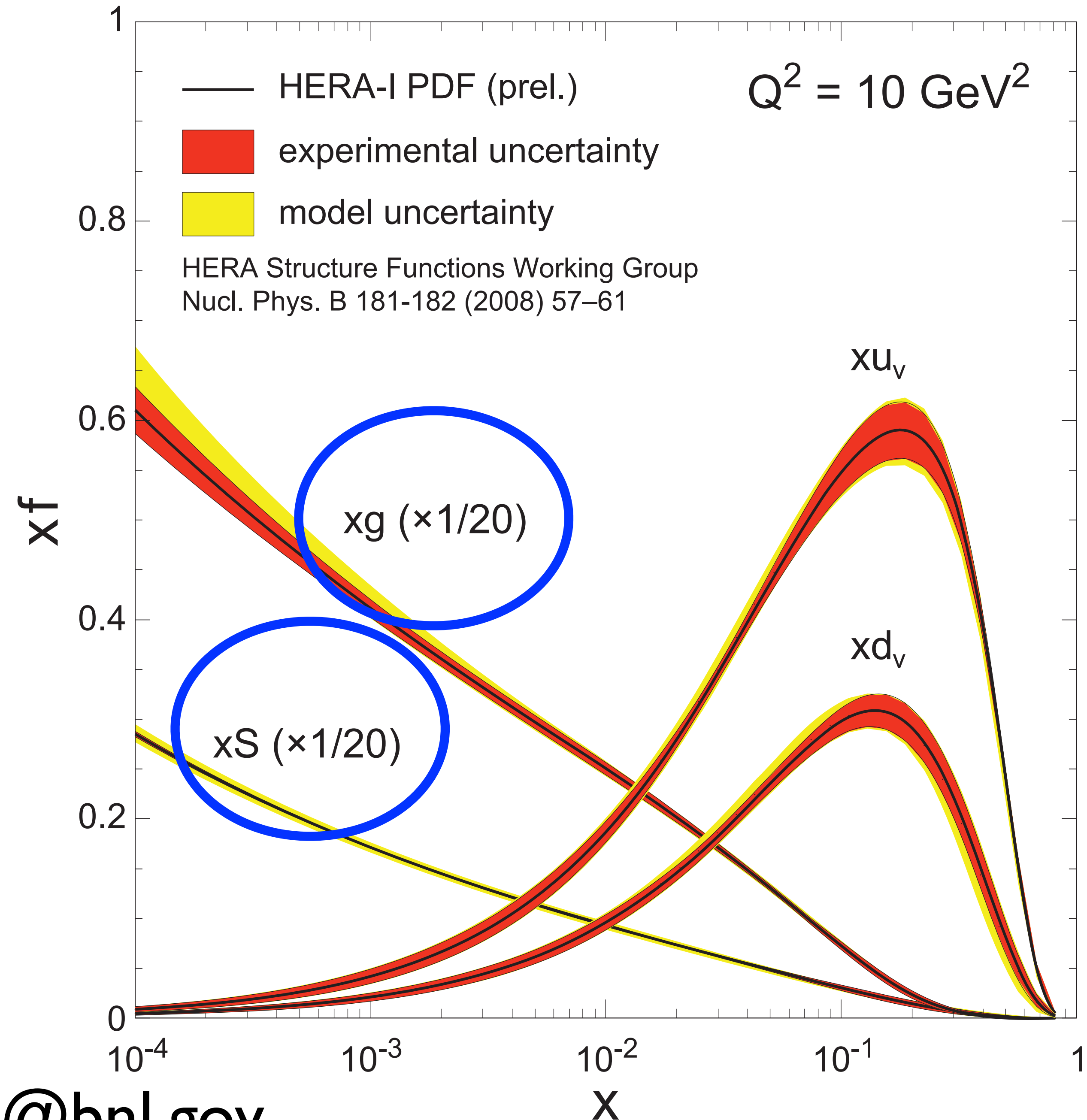

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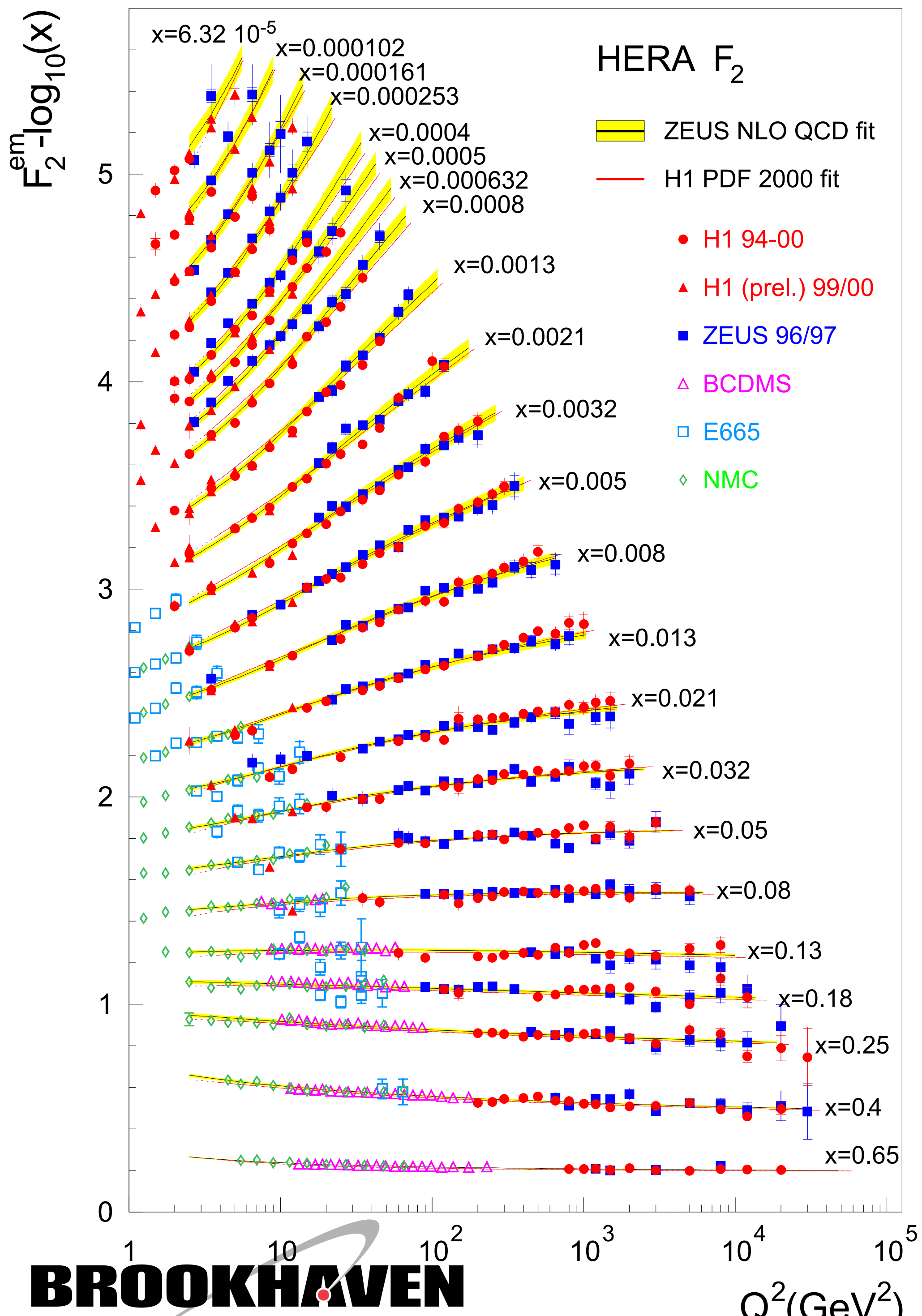

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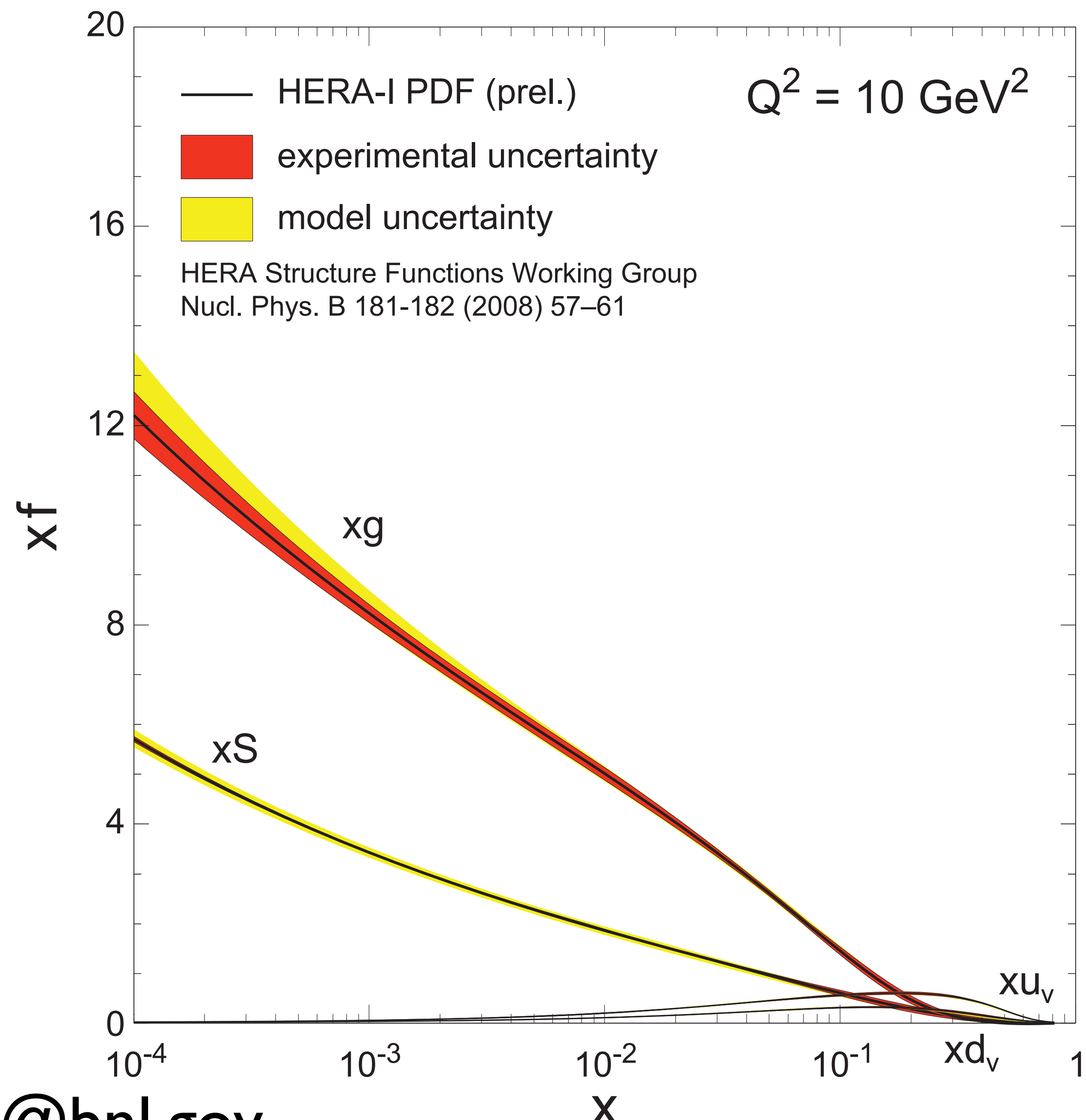

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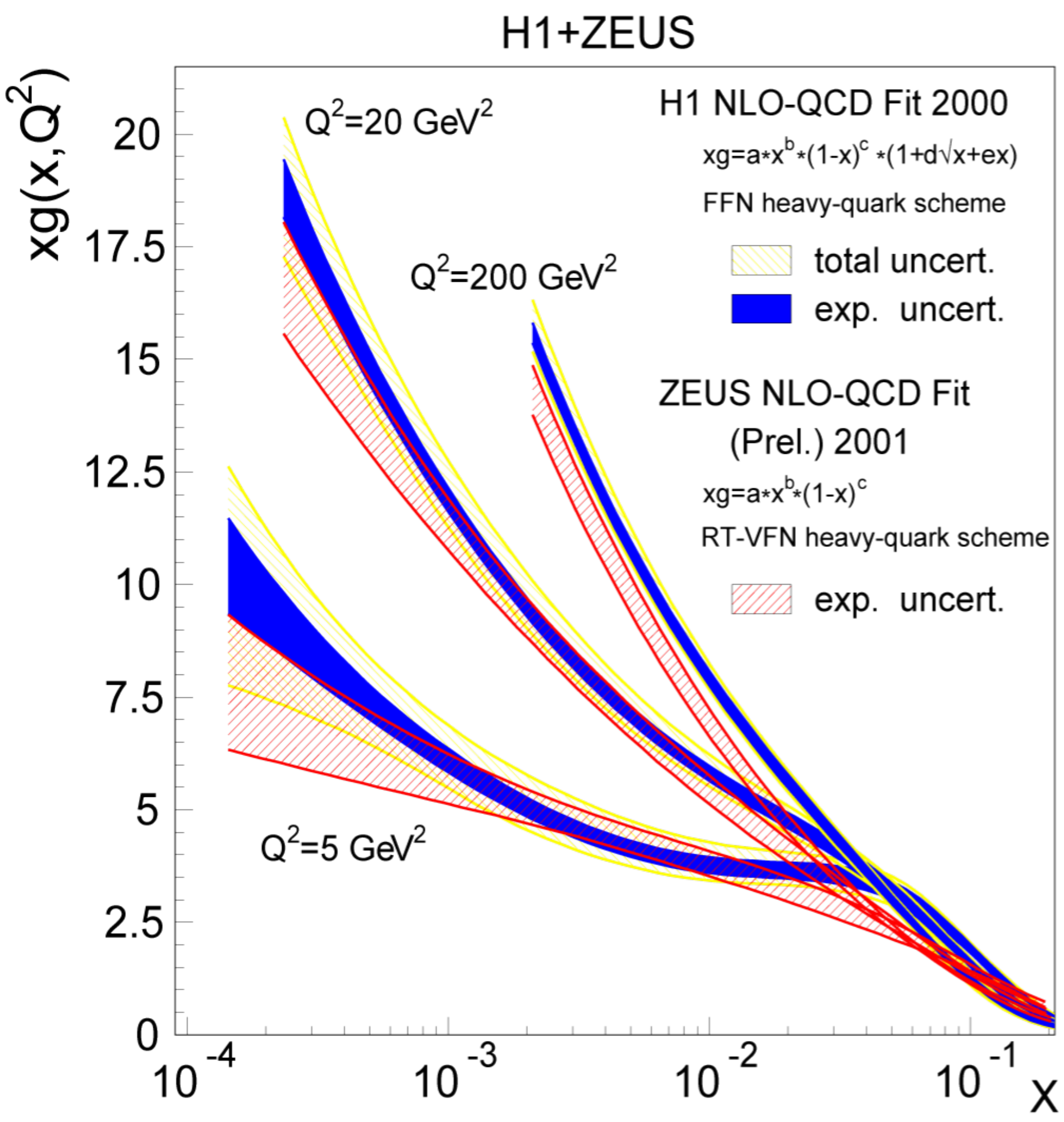
The problem with our current understanding

- Using the Linear DGLAP evolution model:
  - ➡ Linear evolution has a built-in high-energy "catastrophe"
  - ➡ *xG* has rapid rise with decreasing *x* (and increasing Q^2) ⇒ violation of Froissart unitarity bound

$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln\, s)^2$$

  - ‣ Must have saturation to tame the growth



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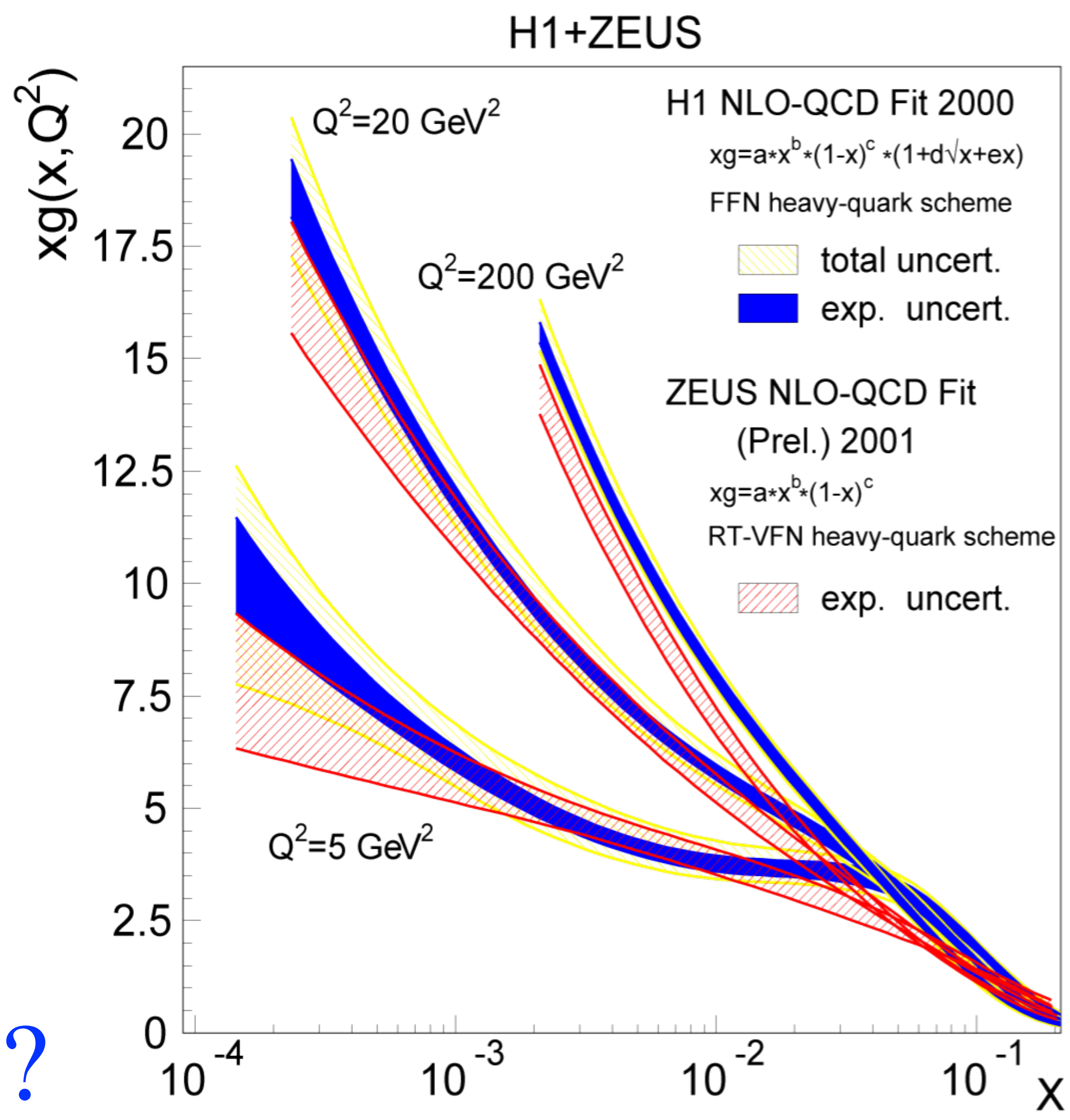
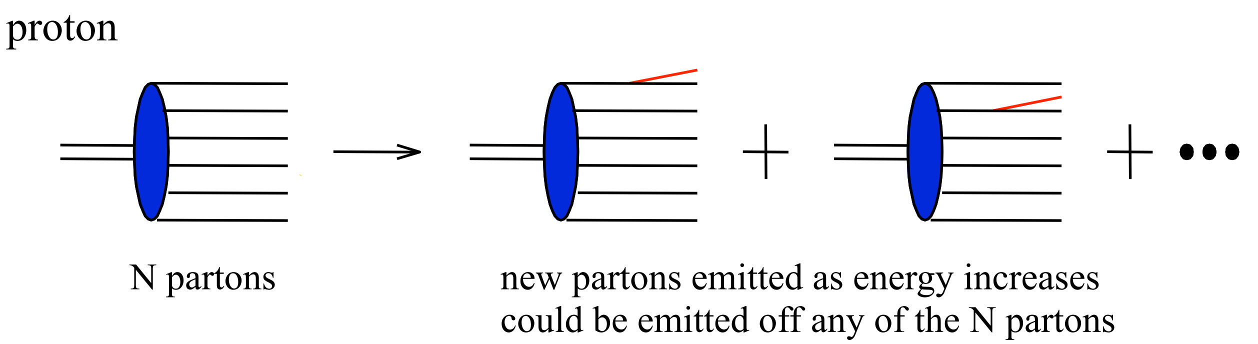


What's the underlying dynamics?

Non-linear QCD - Saturation



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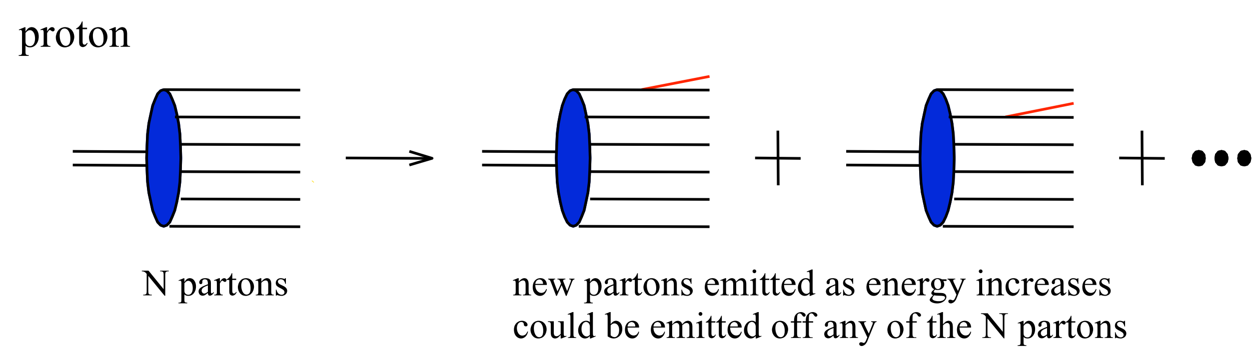

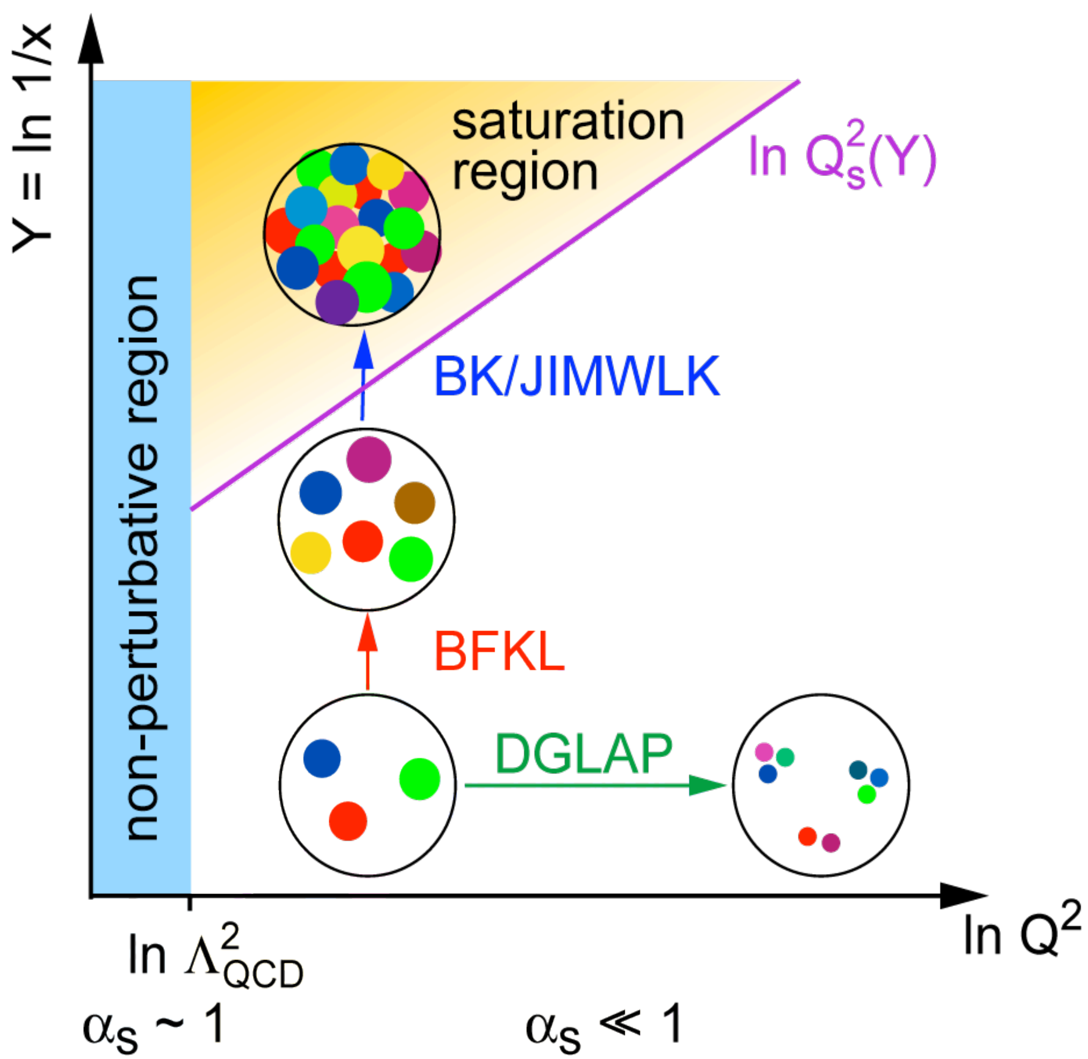

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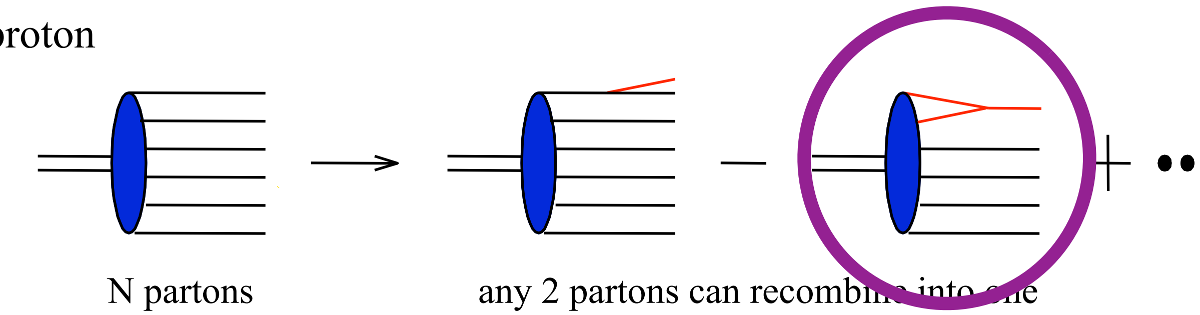
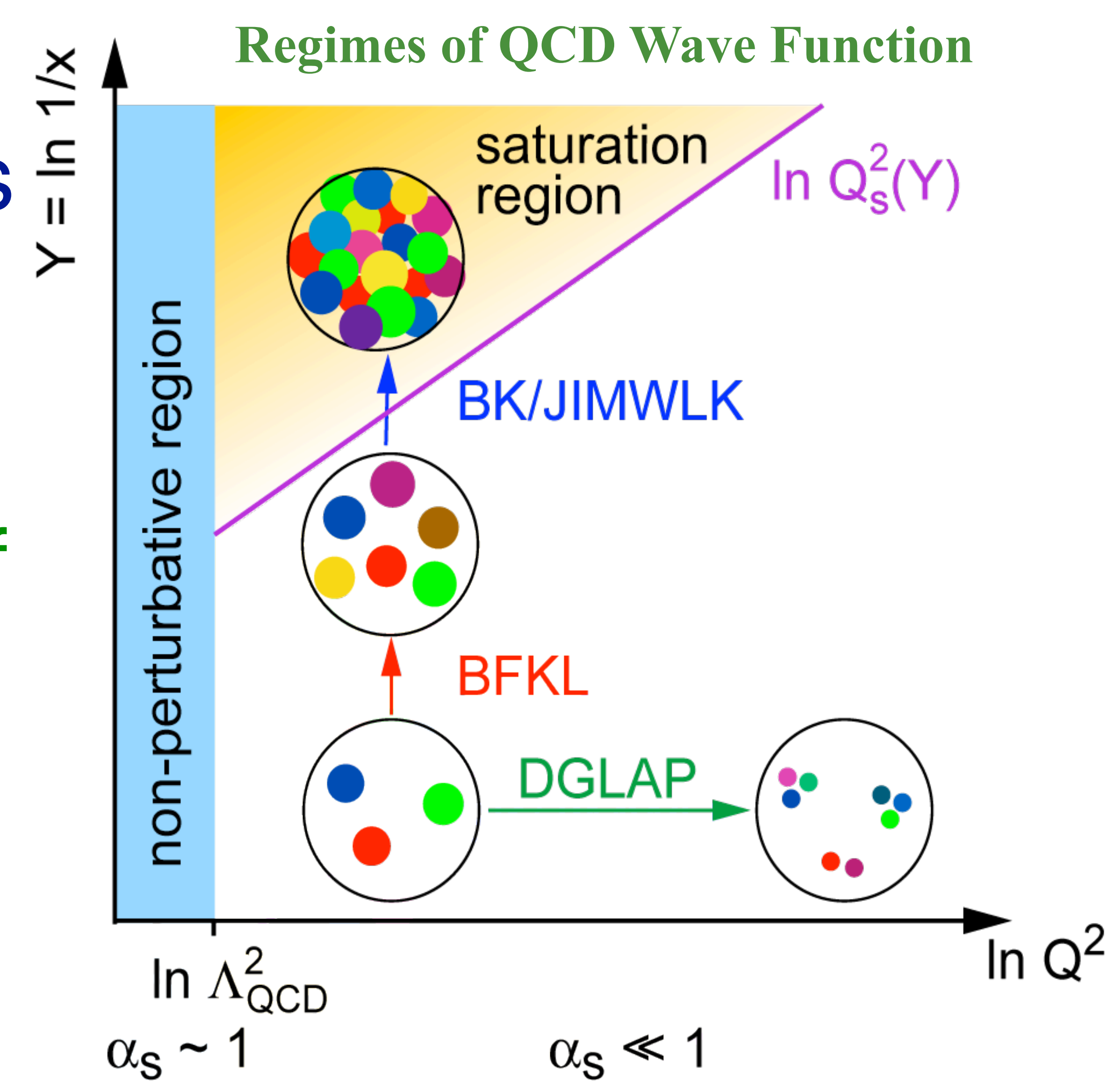


- BFKL: evolution in x
  - ➡ linear
    - explosion in colour field at low-x
- Non-linear BK/JIMWLK equations
  - ➡ non-linearity ⇒ saturation
    - Allows for the recombination of gluons in a dense gluonic medium
  - ➡ characterised by the saturation scale, $Q_S(x,A)$



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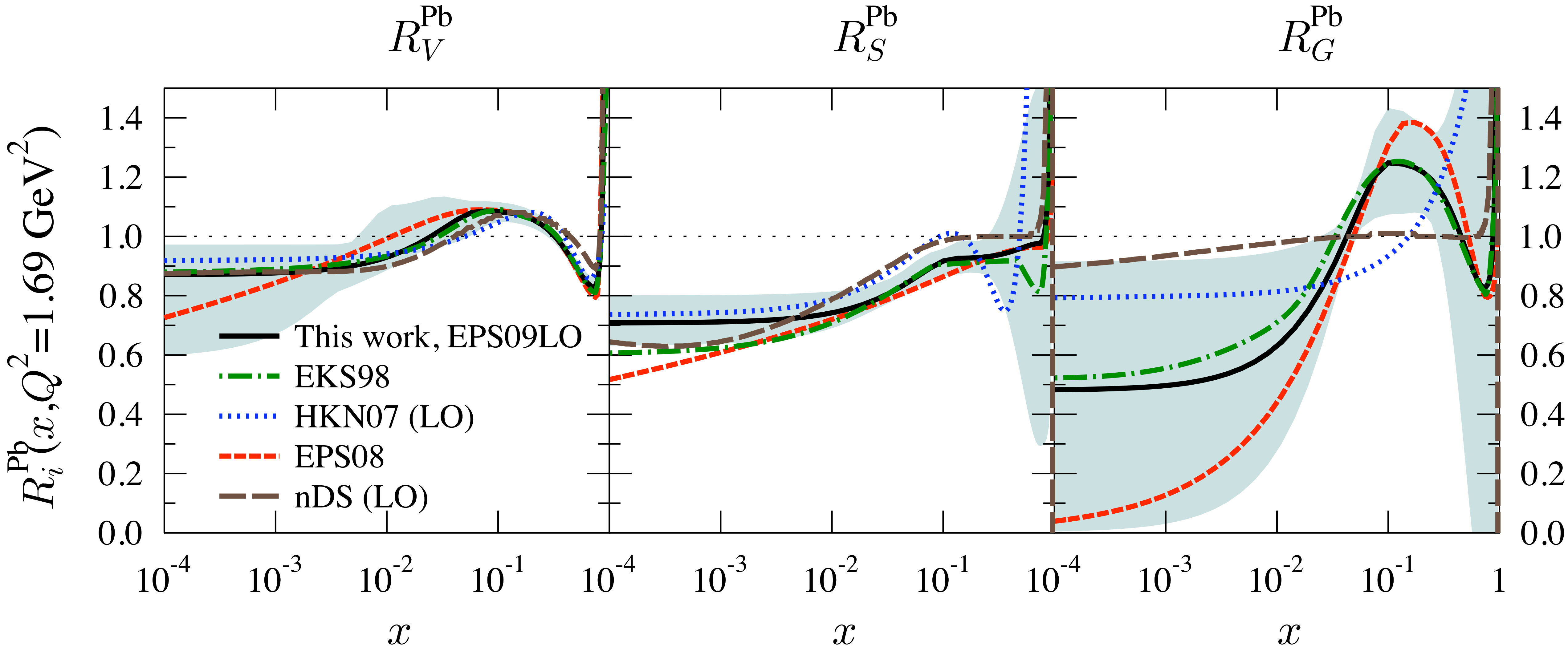

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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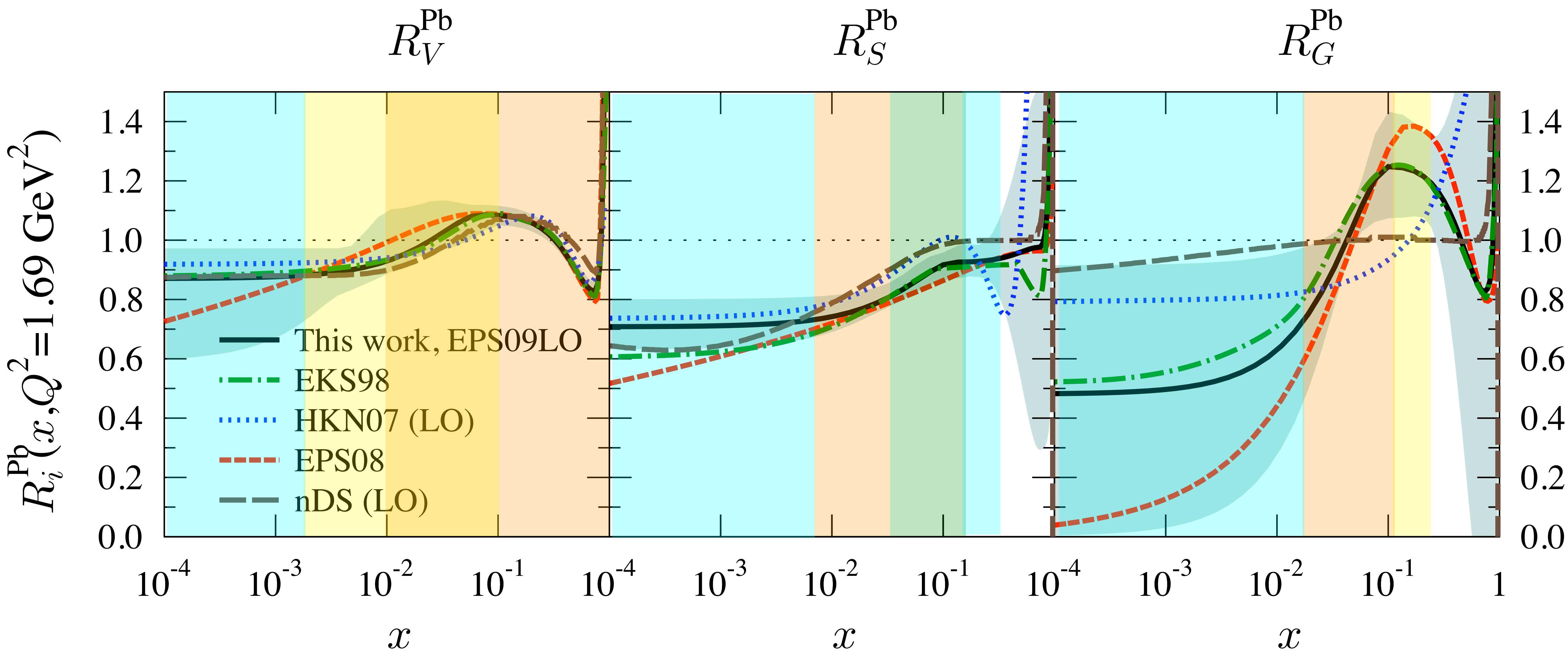

Constrained by DIS

Constrained by DY

Constrained by sum rules

Assumptions

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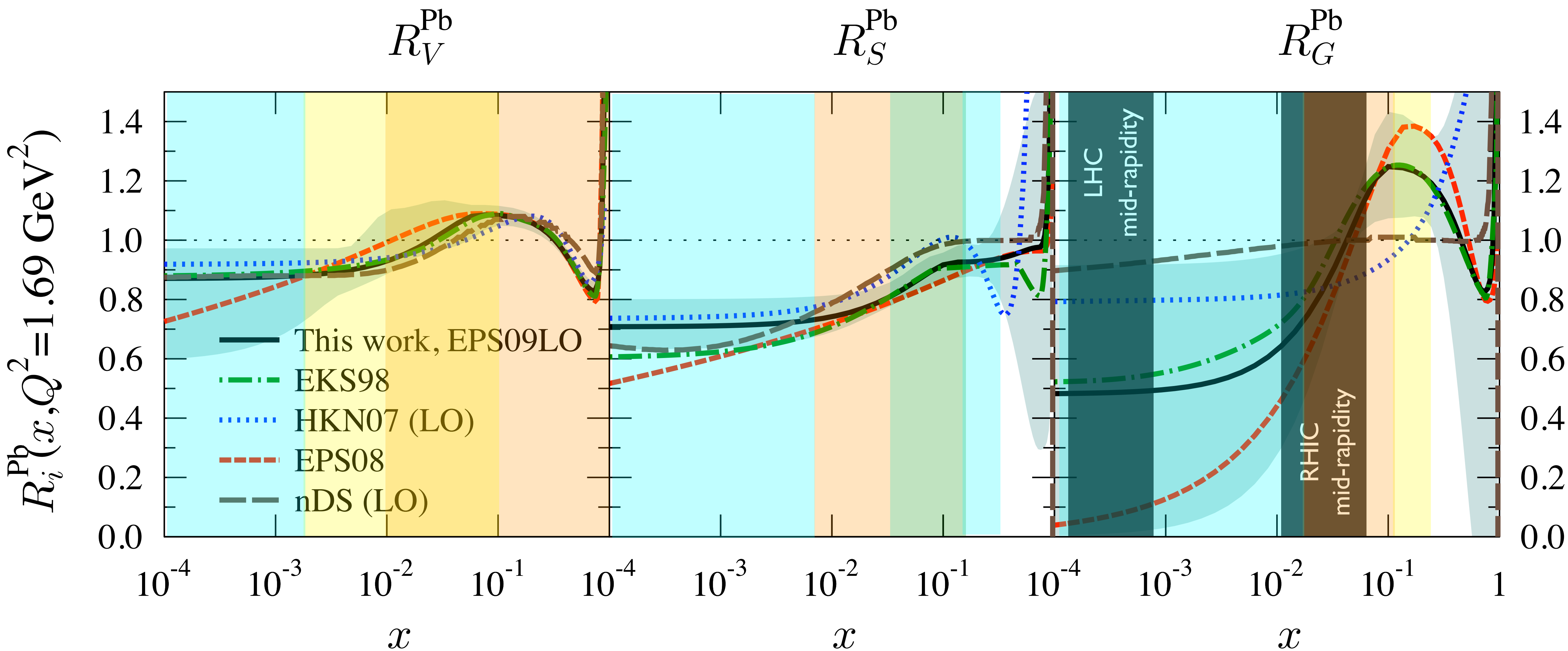

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Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

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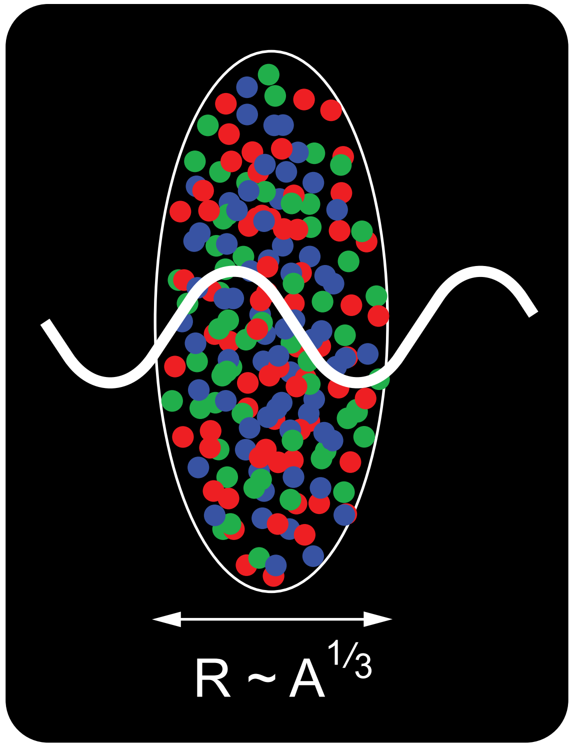
The Nuclear "Oomph Factor"

- Enhancing Saturation effects:
  - ➡ Probes interact over distances $L \sim (2m_n x)^{-1}$

    For probes where $L > 2R_A$ ($\sim A^{1/3}$) cannot distinguish between nucleons in front or back of the nucleus.

    - ‣ Probe interacts coherently with all nucleons.



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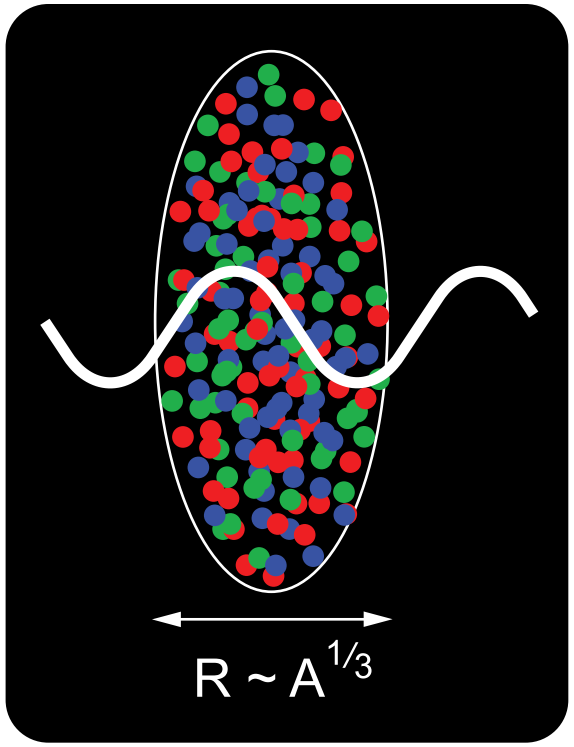


Simple geometric considerations lead to:

$$Q_s^2 \propto \frac{\alpha_s xG(x, Q_s^2)}{\pi R_A^2}$$ HERA: $$xG \propto \frac{1}{x^{1/3}}$$ A dependence: $$xG_A \propto A$$

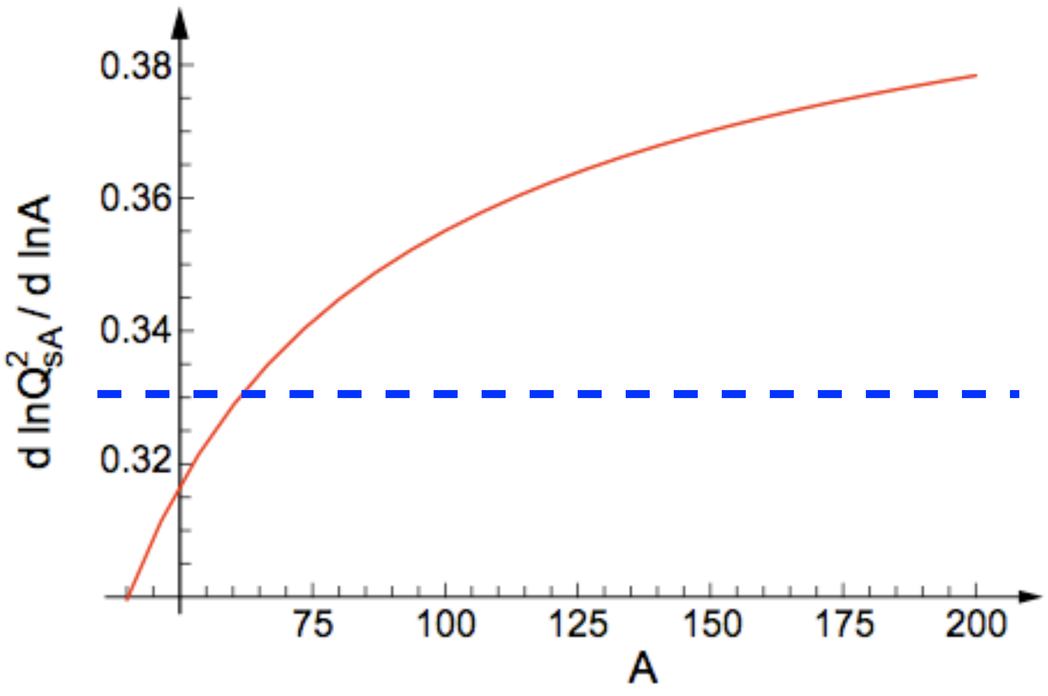
Nuclear "Oomph" Factor: $$(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Qs with A: ⇒ non-linear QCD regime reached at significantly lower energy in e+*A* than in *e*+*p*

The Nuclear "Oomph Factor"

More sophisticated analyses ⇒ confirm (exceed) pocket formula for high A

e.g. Kowalski, Lappi and Venugopalan, PRL 100, 022303 (2008); Armesto et al., PRL 94:022002; Kowalski, Teaney, PRD 68:114005



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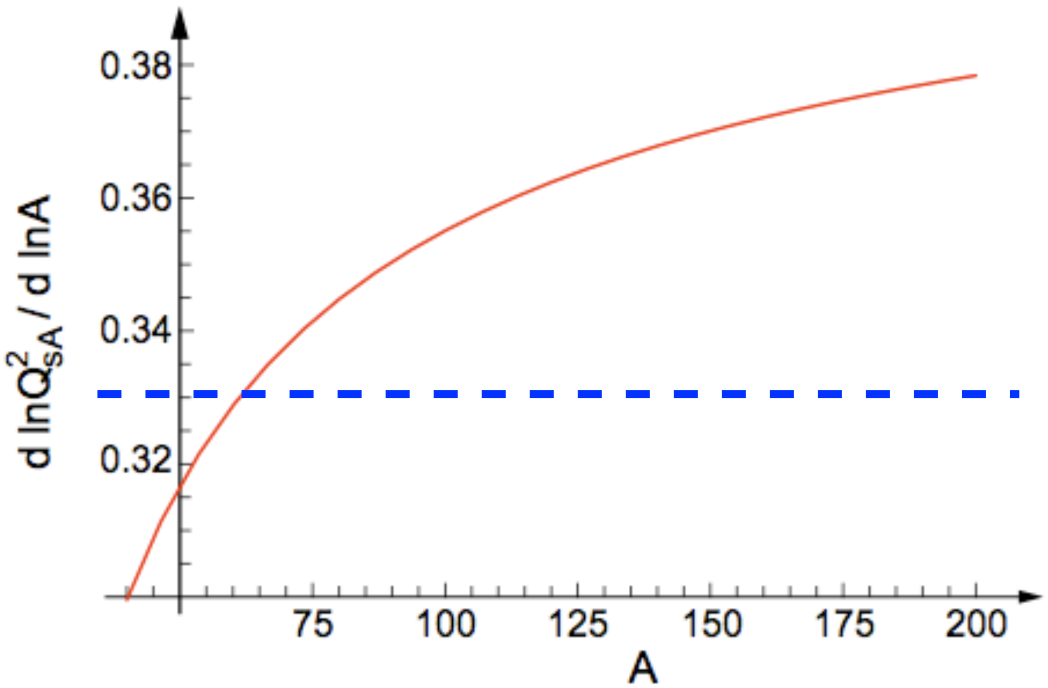
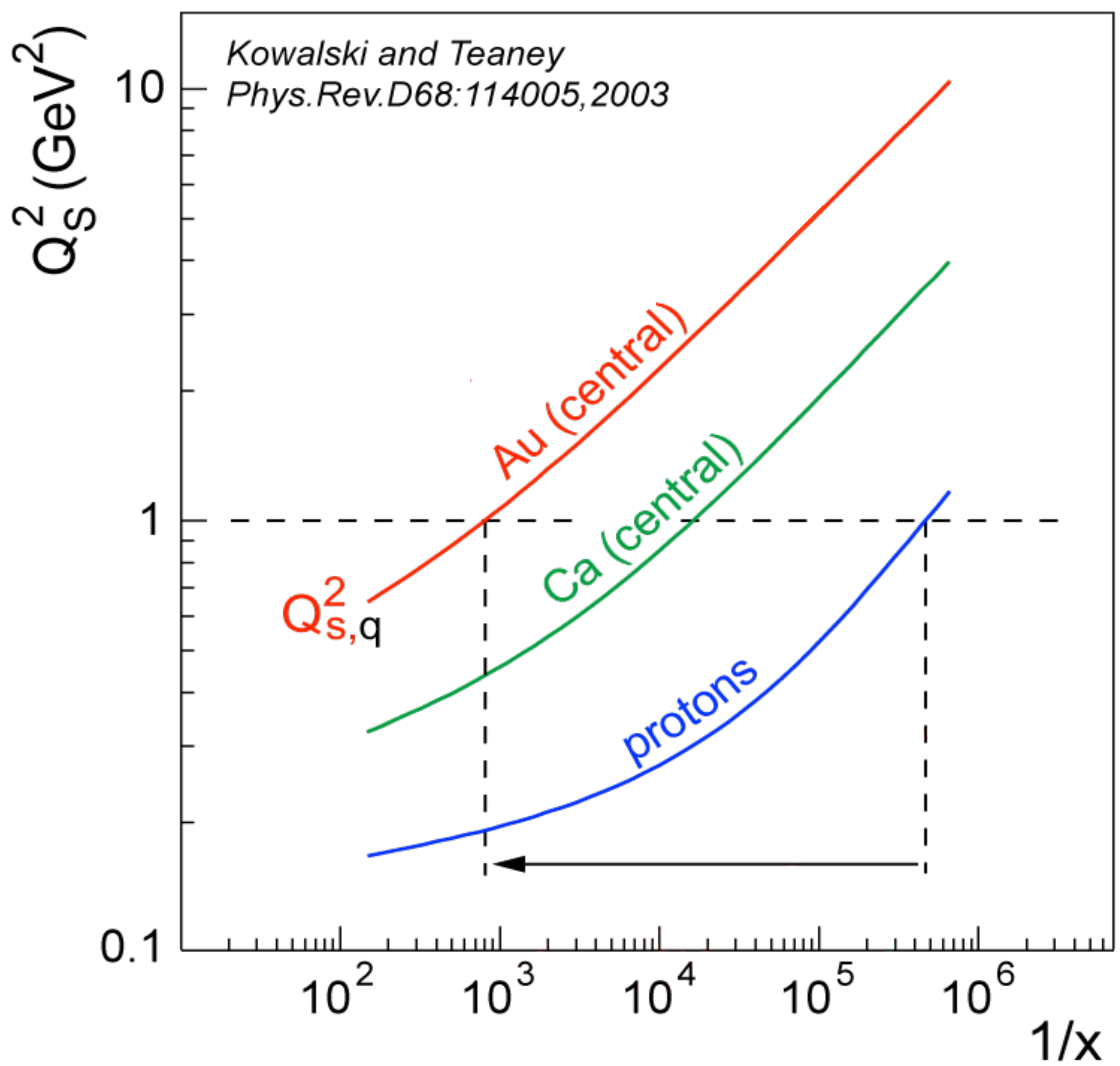
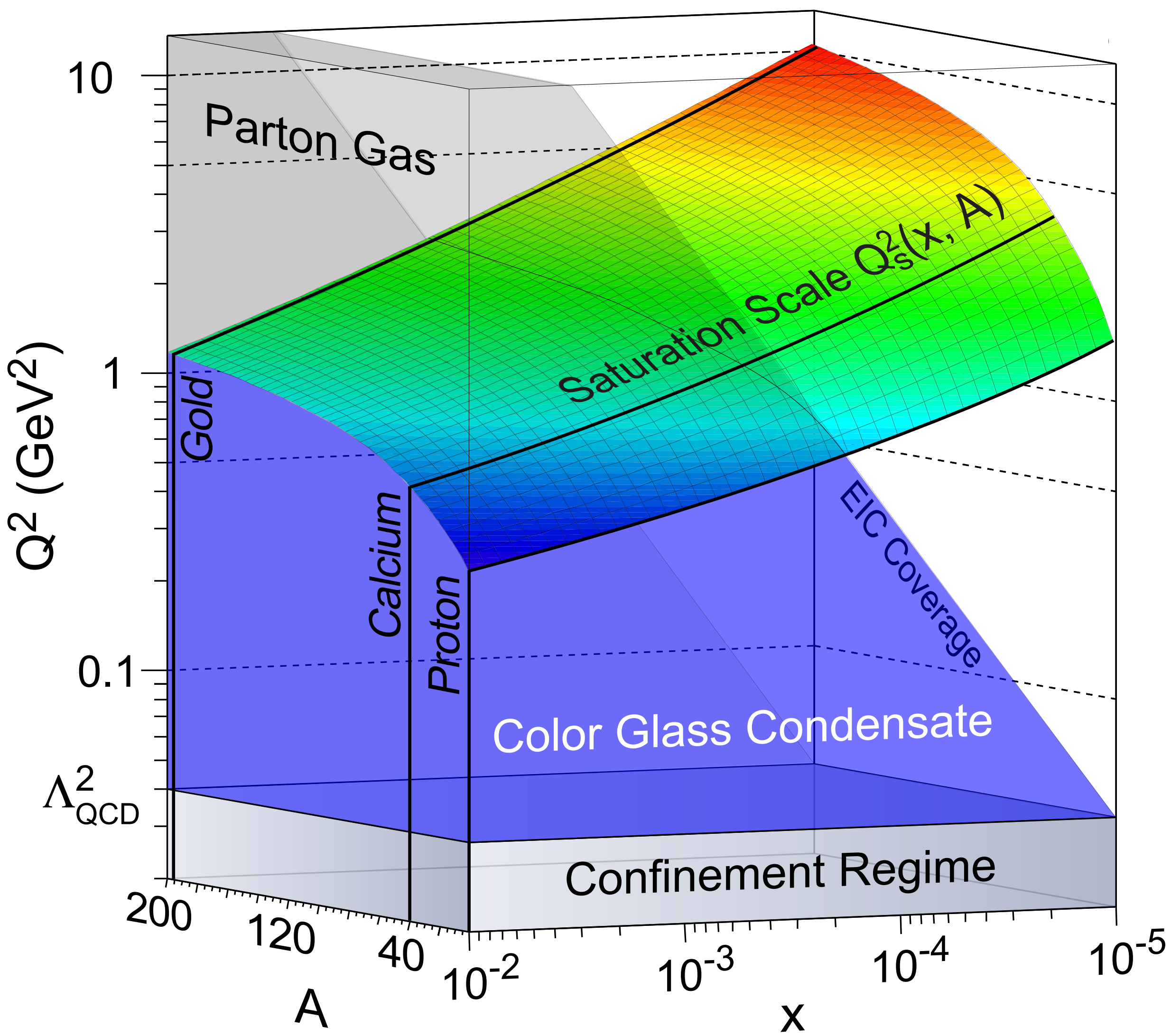


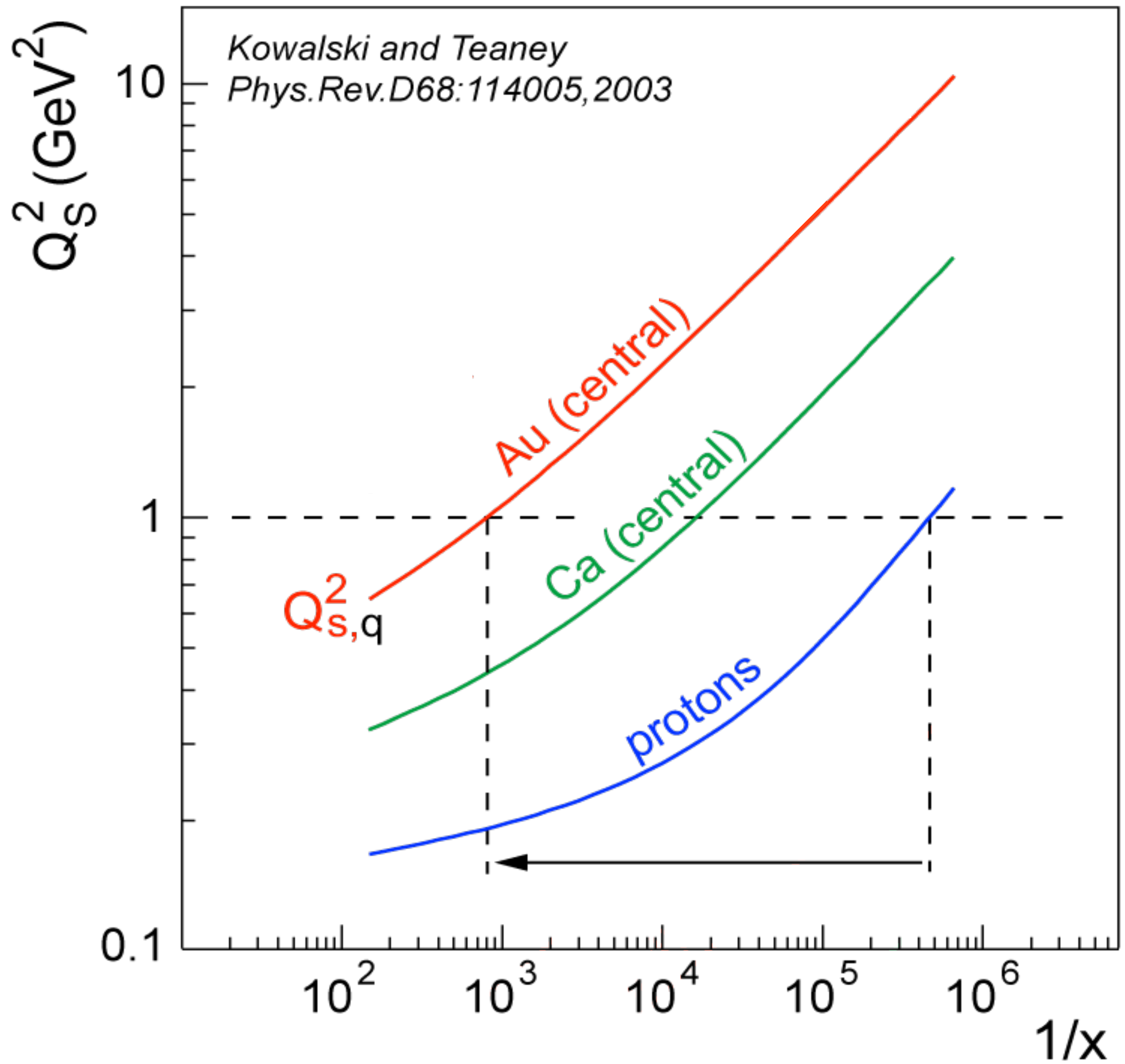


One would require an energy in e+p ~ 10-100 x e+A to get to same Q^2_s

The Nuclear "Oomph Factor"



Plot by T. Ullrich



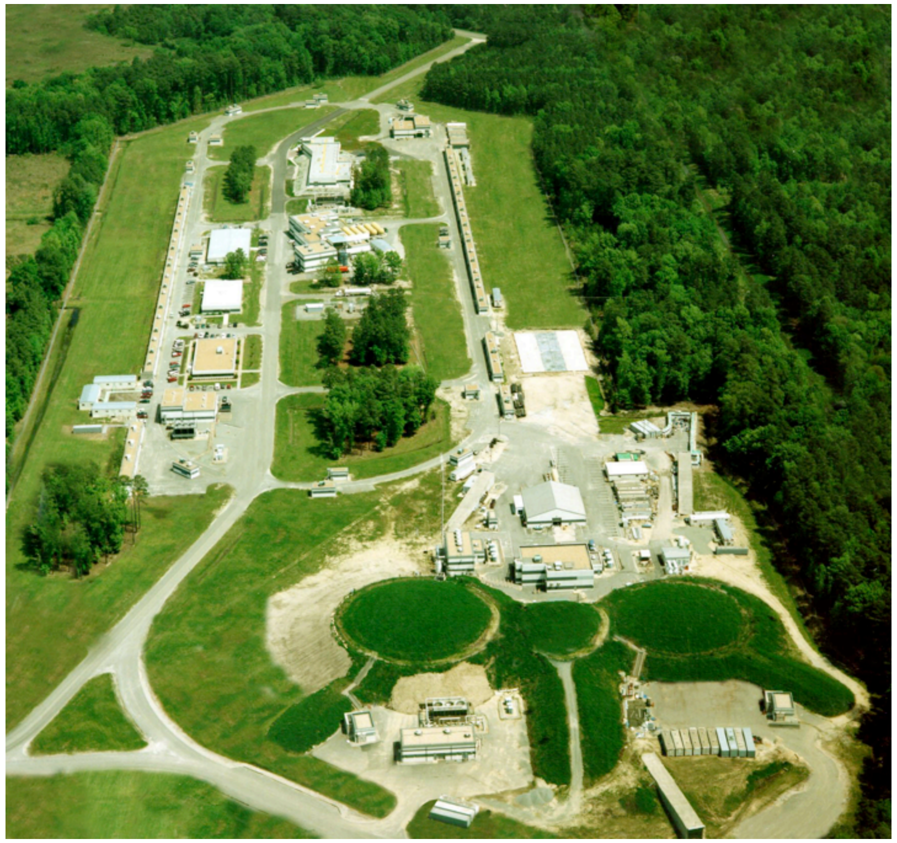
One would require an energy in e+p ~ 10-100 x e+A to get to same Q^2_S

Do EIC energies match the requirements?

eRHIC = RHIC + Energy-Recovery Linac

Both designs in 2 stages

ELIC = CEBAF + Hadron Ring



eRHIC:

1. stage: 5+100 GeV/n e+Au ($\sqrt{s}$=45 GeV/n)
2. stage: 30+130 GeV/n e+Au ($\sqrt{s}$=125 GeV/n)

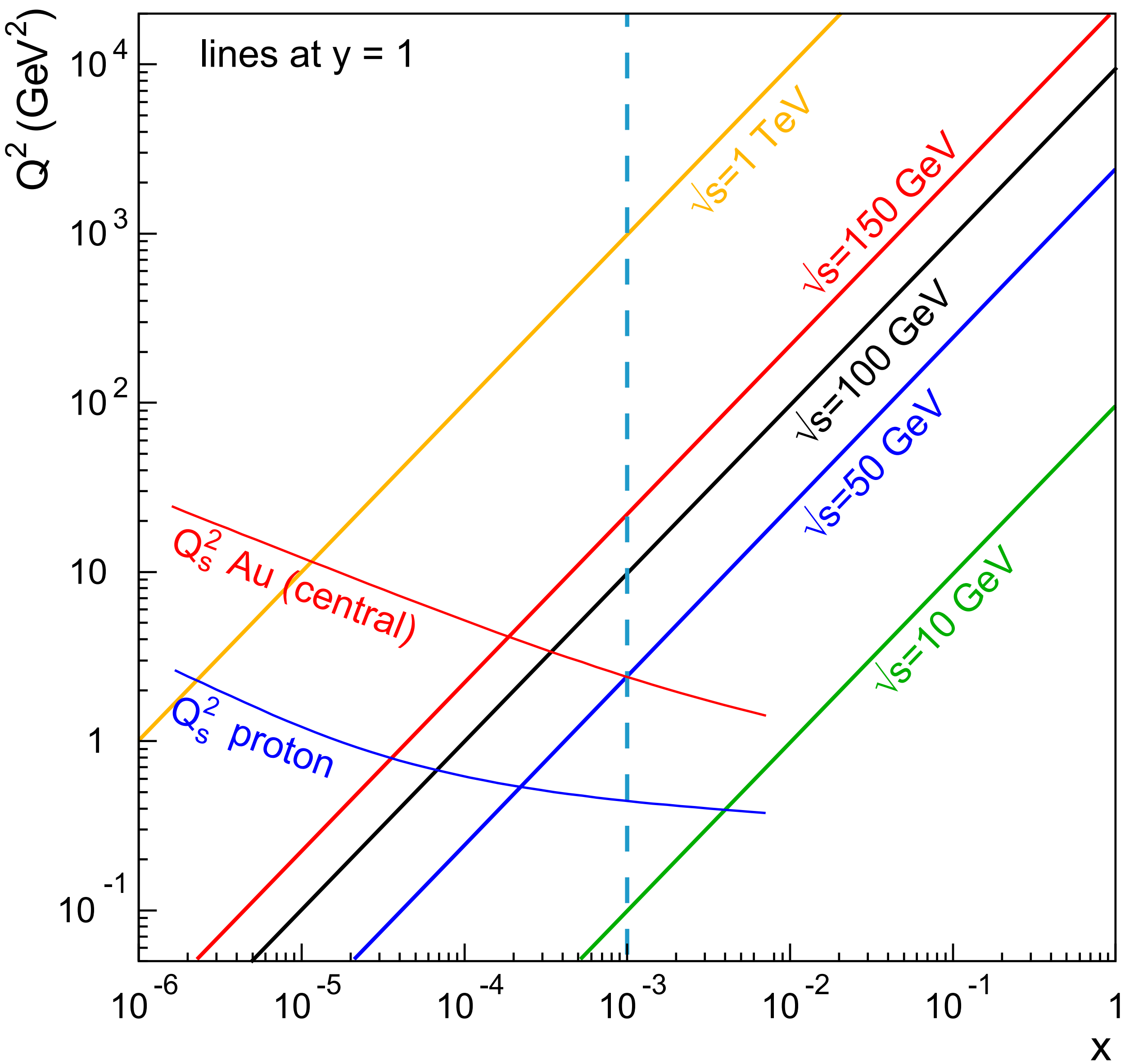
ELIC:

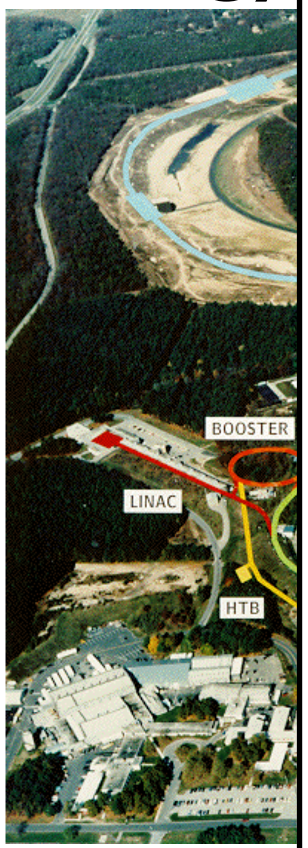
1. stage: 11+40 GeV/n e+Au ($\sqrt{s}$=42 GeV/n)
2. stage: 20+100 GeV/n e+Au ($\sqrt{s}$=89 GeV/n)

Do EIC energies match the requirements?

eRH ... F +

Energy ... g





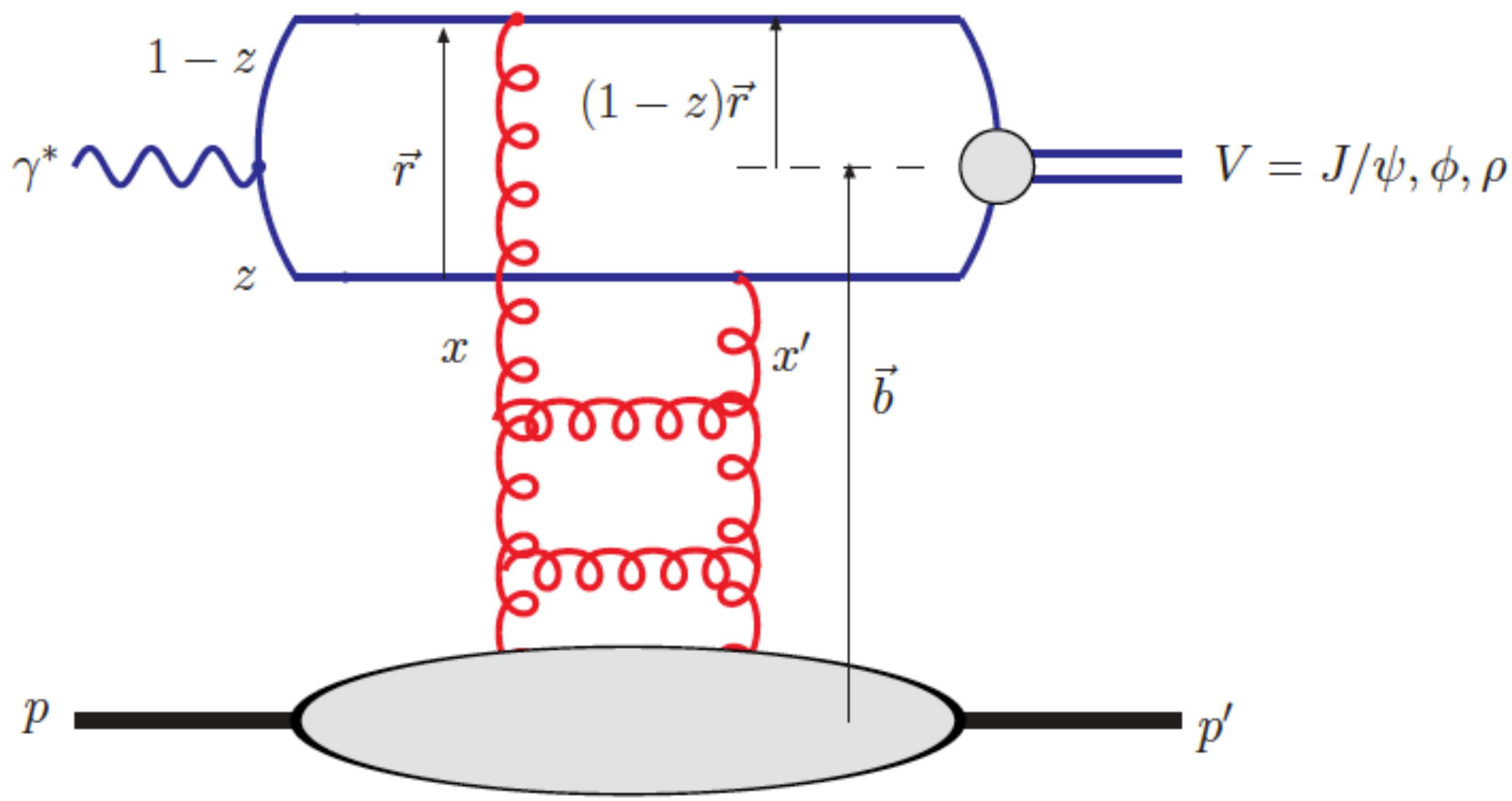
1. stage: ... /n e+Au ... /n)

2. sta ... /n e+Au ... /n)

- In both cases 1st stage is ~OK but offers little Q^2 lever arm
- 2nd stage will match requirements fully

Getting a "Feel" for Non-Linear QCD

Dipole Model:



$$\frac{d\sigma_{q\bar{q}}}{d^2b} = 2\mathcal{N}(x,r,b)$$

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

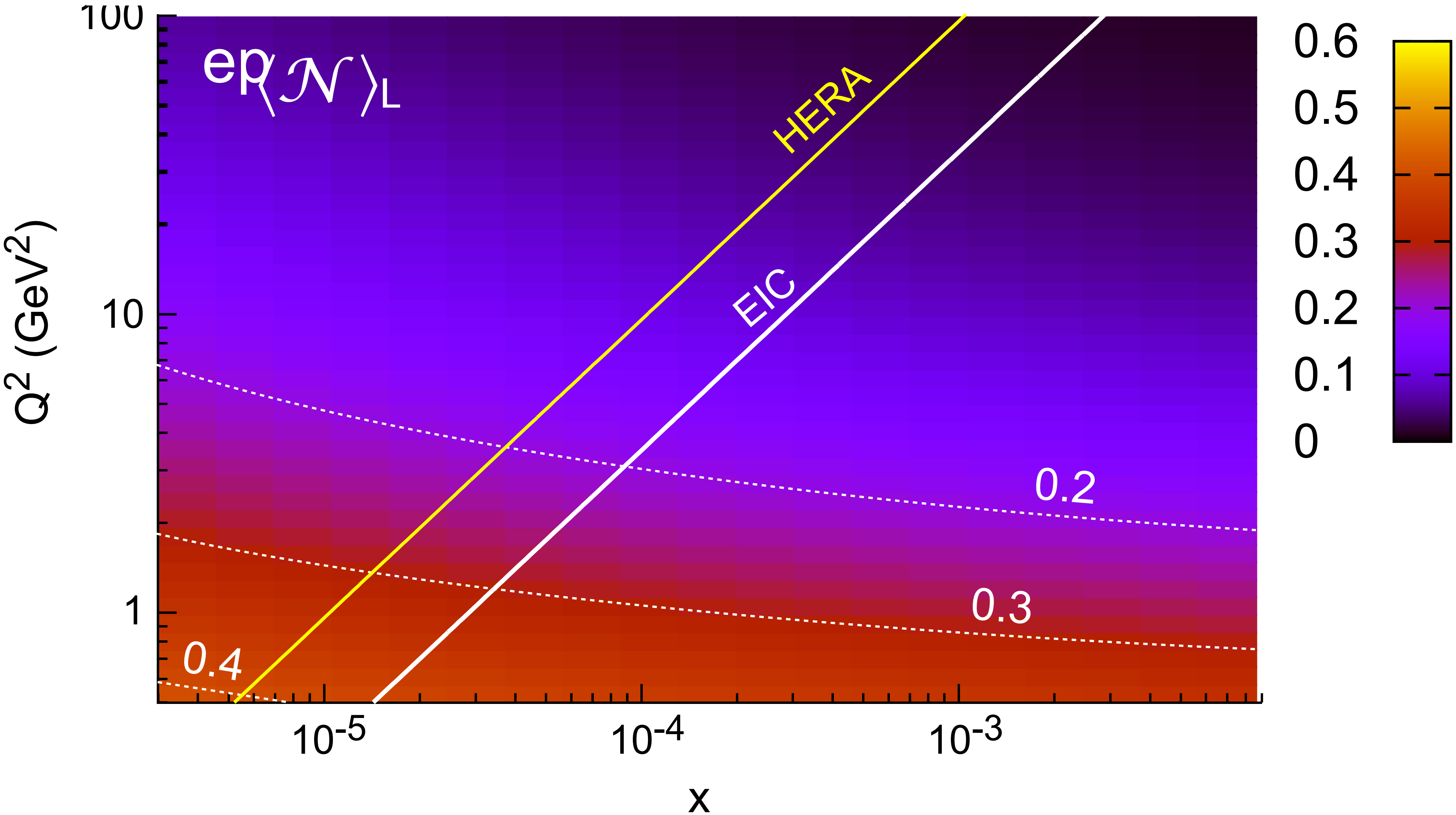
$\mathcal{N} =$ Dipole Scattering Amplitude

- 0 dilute system, linear QCD
- 1 saturated, non-linear regime

Getting a "Feel" for Non-Linear QCD

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

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

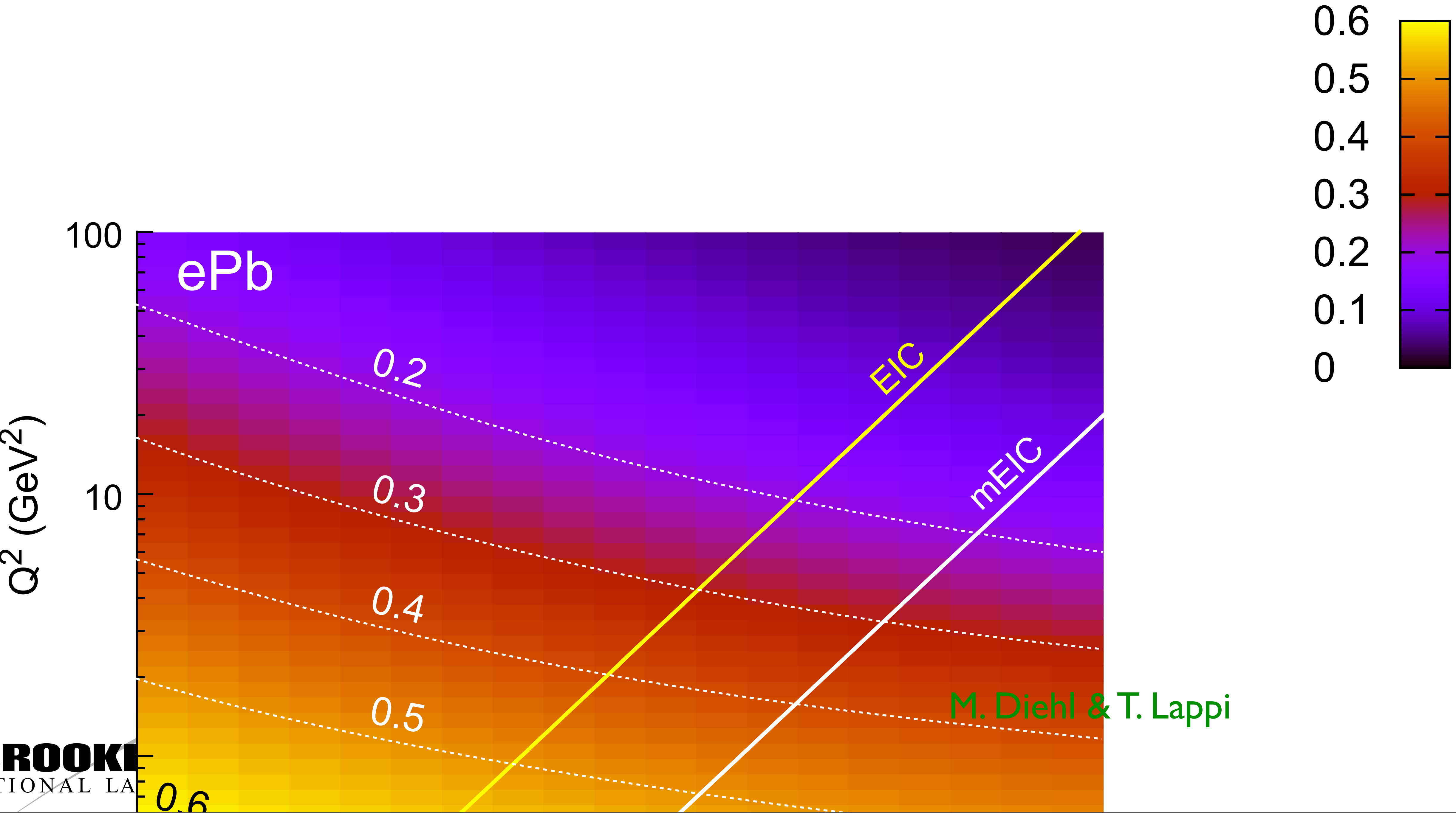


M. Diehl & T. Lappi

Getting a "Feel" for Non-Linear QCD

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

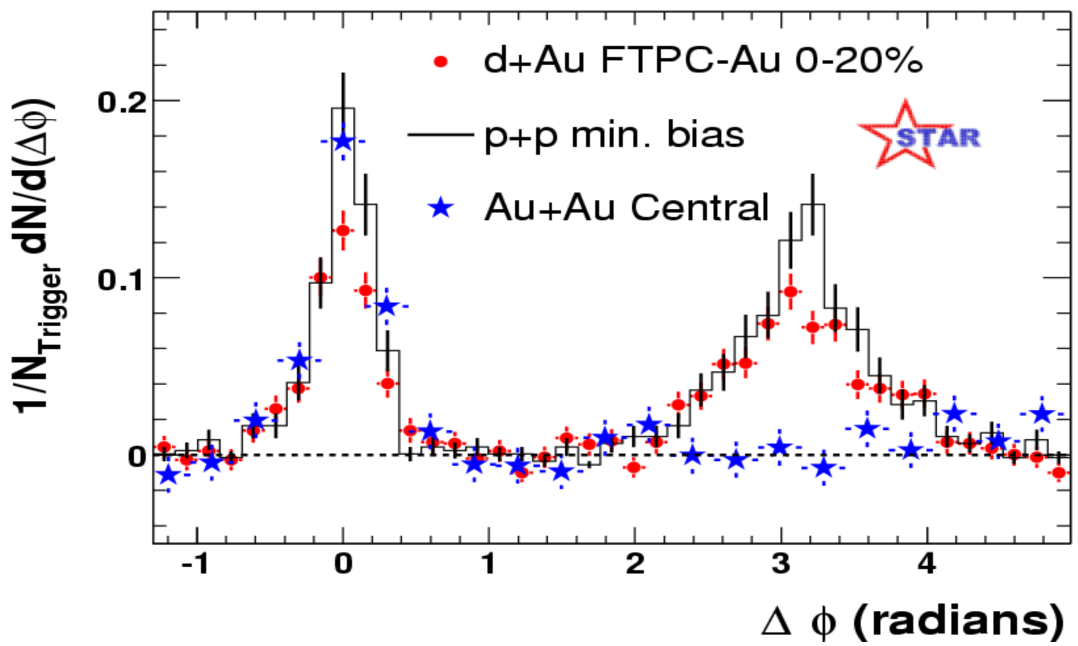
$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}^2}{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}}$$

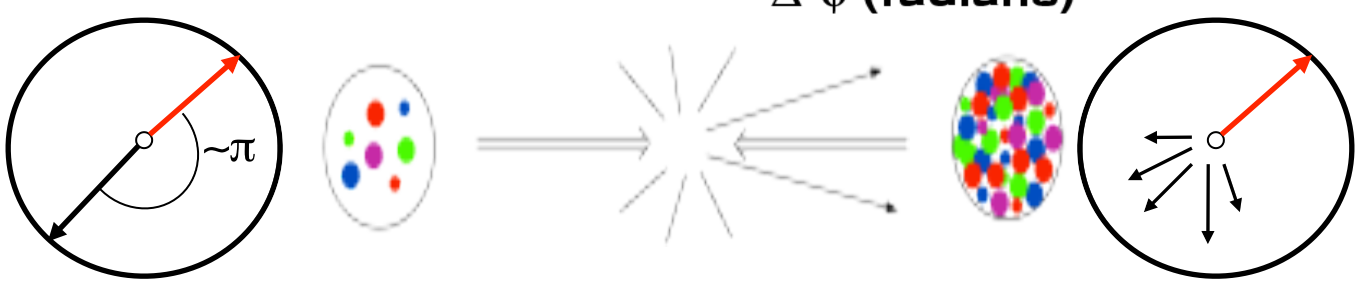


M. Diehl & T. Lappi

di-hadron angular 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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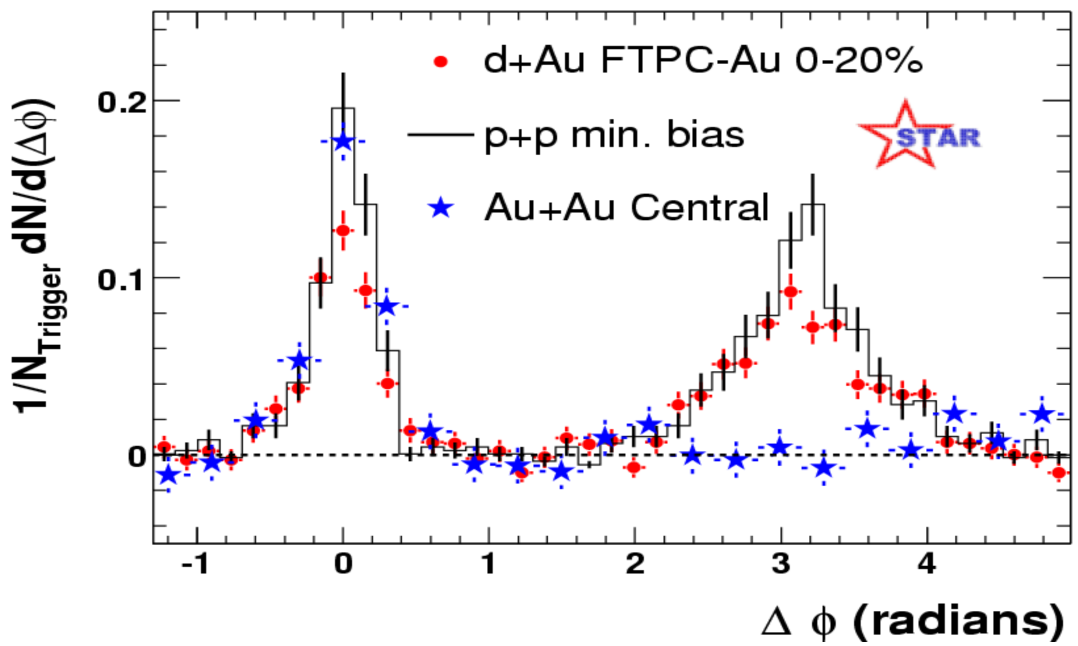

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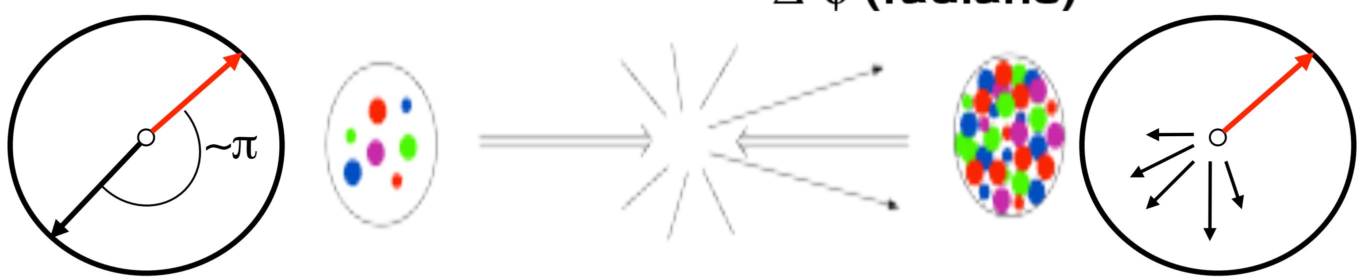
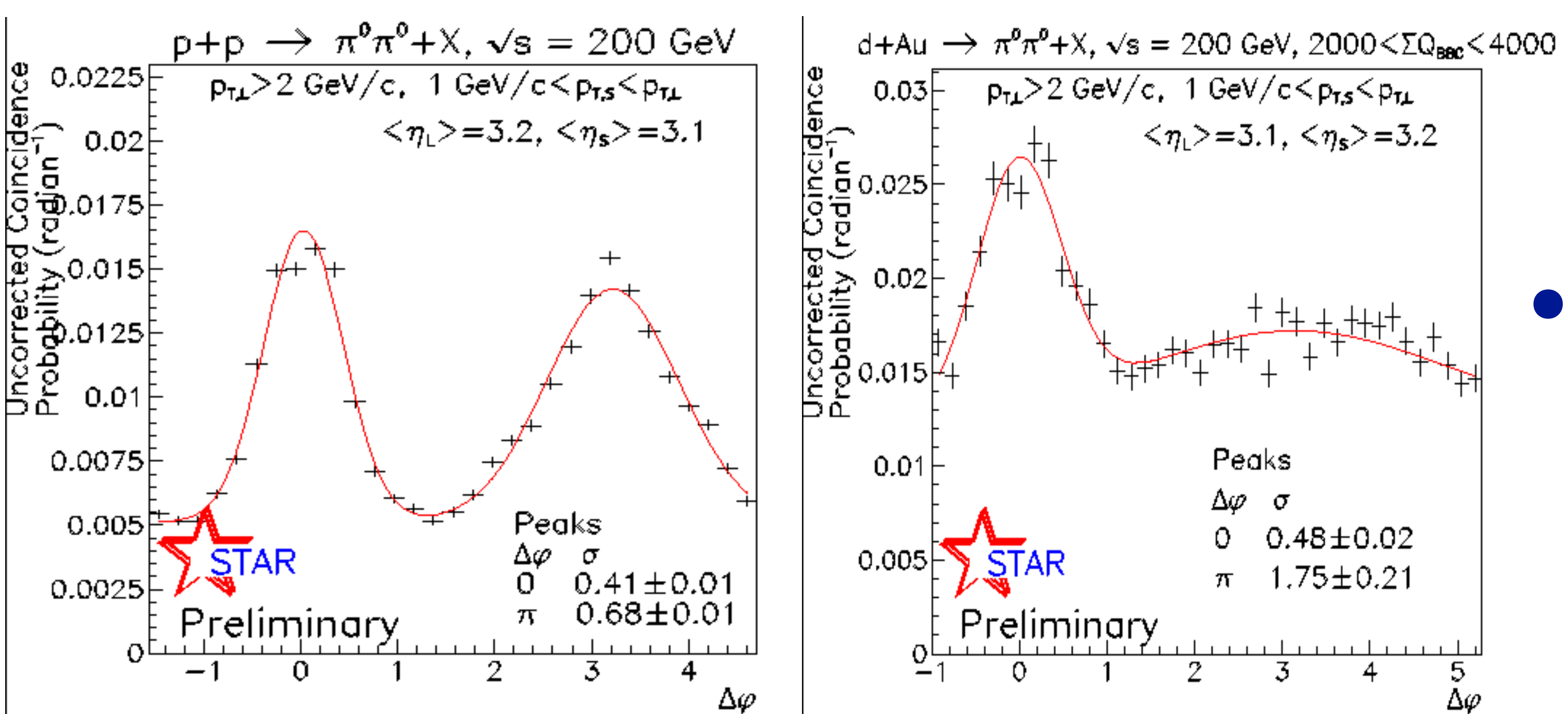




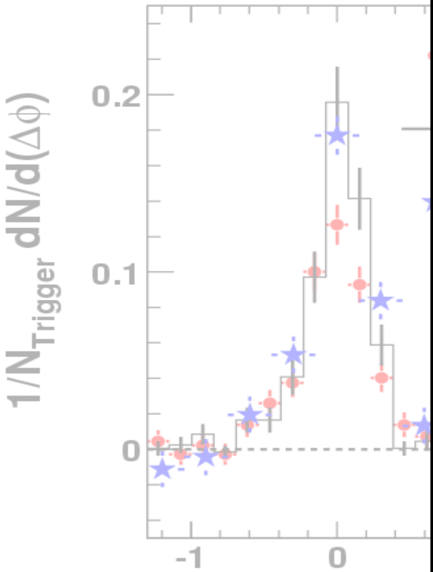
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

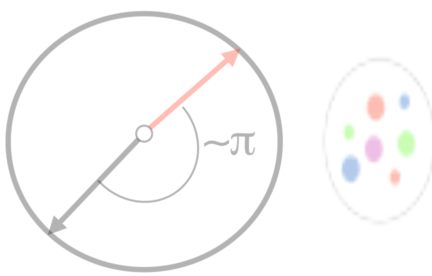
➡ x ~ 10^{-3}

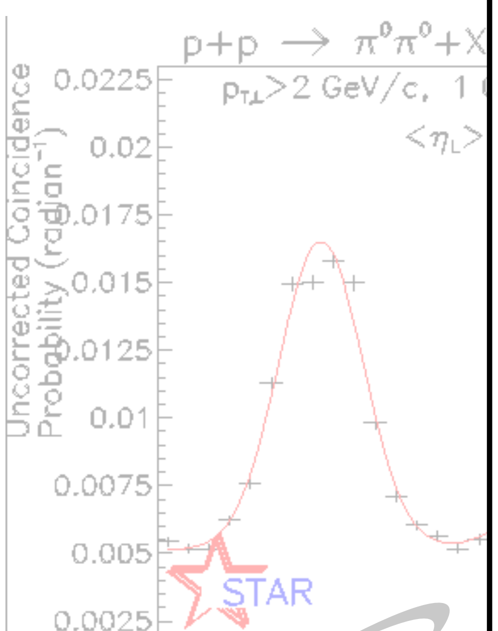
di-hadron angular correlations in d+A

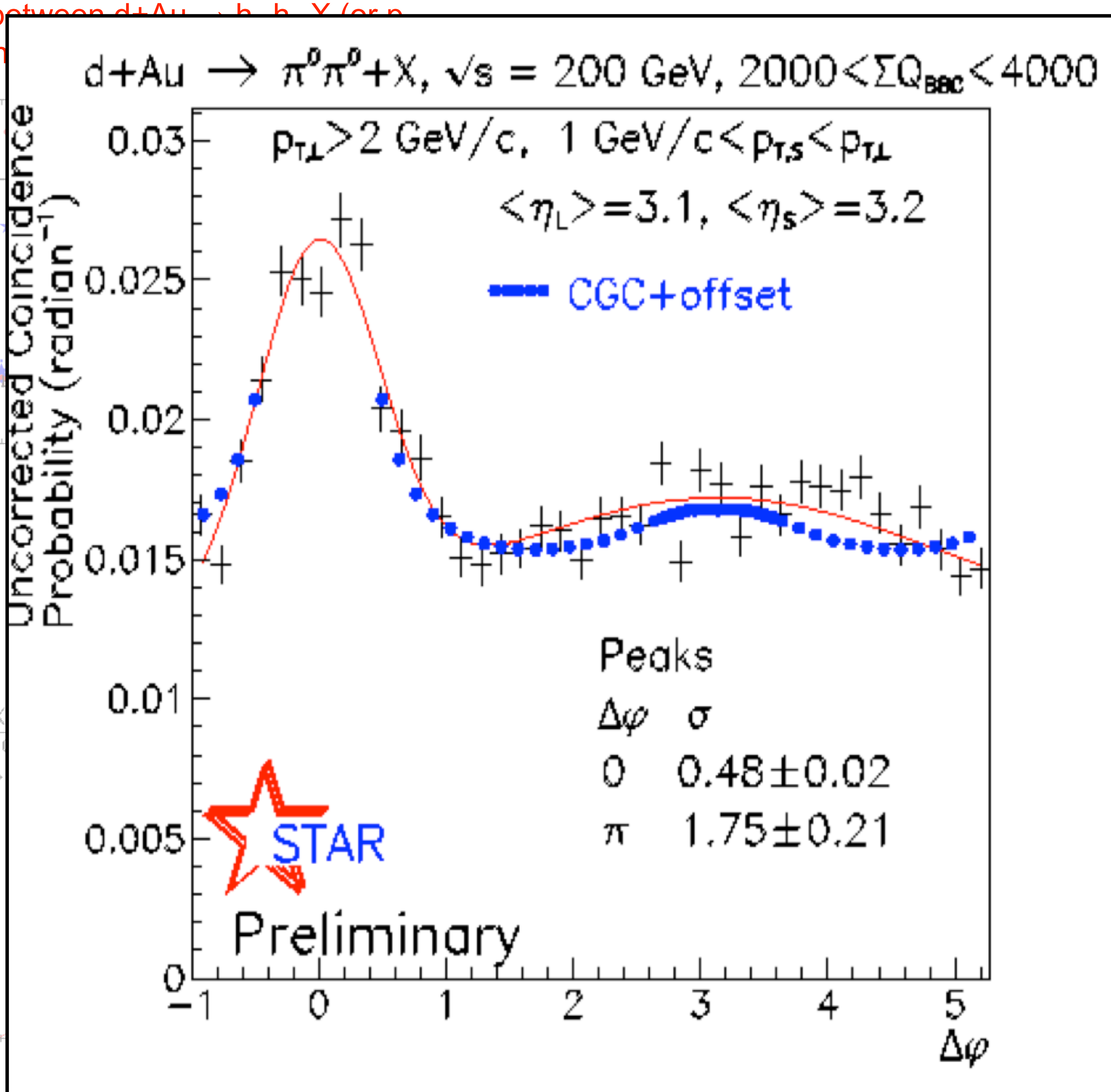
comparisons b

+Au → h_1 h









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$+ k_2 e^{-y_2}$

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orward

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+Au

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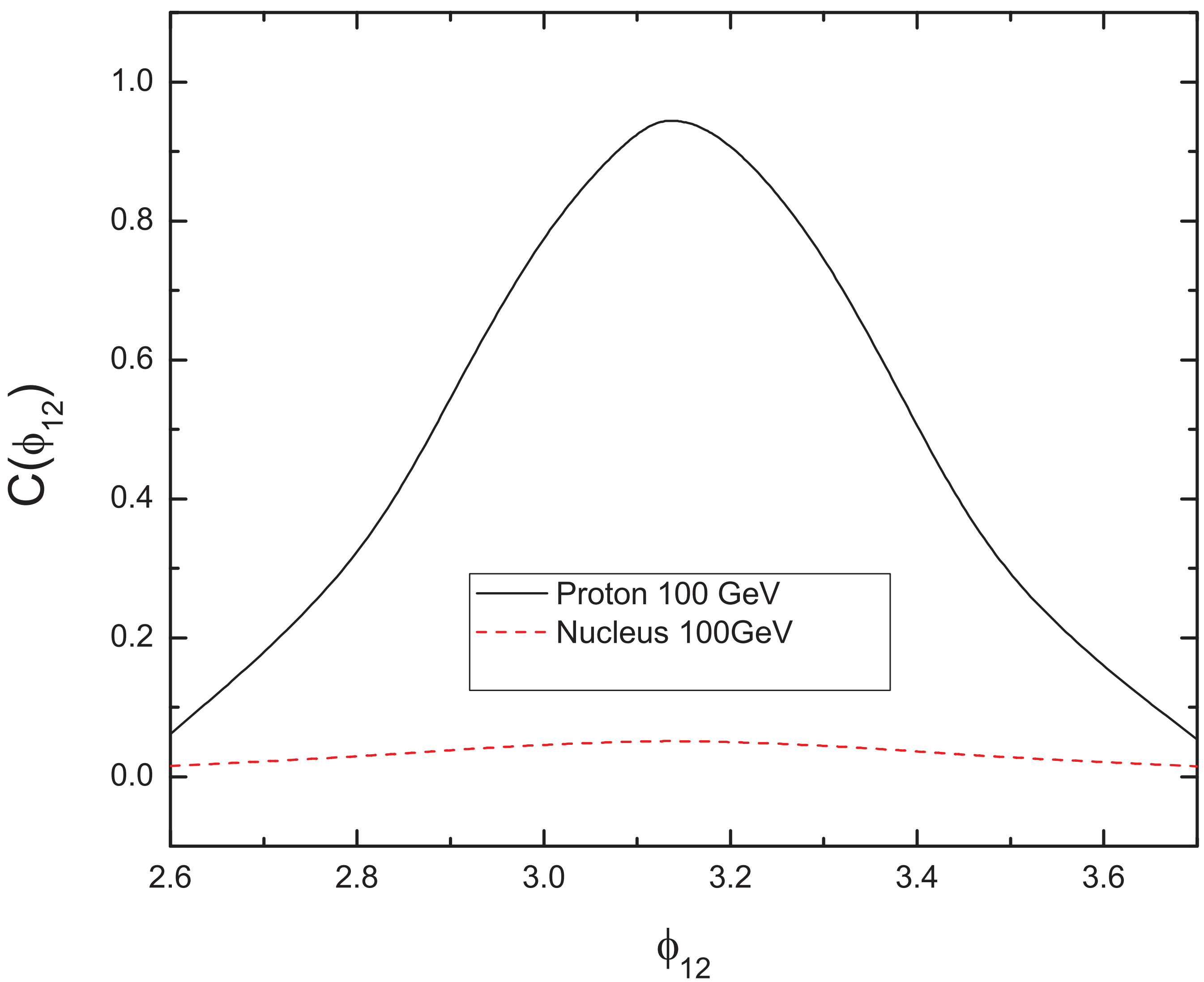
di-hadron correlations in e+A

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



Dominguez, Xiao and Yuan (2010)

- At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations
  - ➡ The non-linear evolution of multi-gluon distributions is different from that of single-gluon distributions and it is equally important that we understand it
- The d+Au RHIC data is therefore subject to many uncertainties
  - ➡ these correlations in e+A can help to constrain them better

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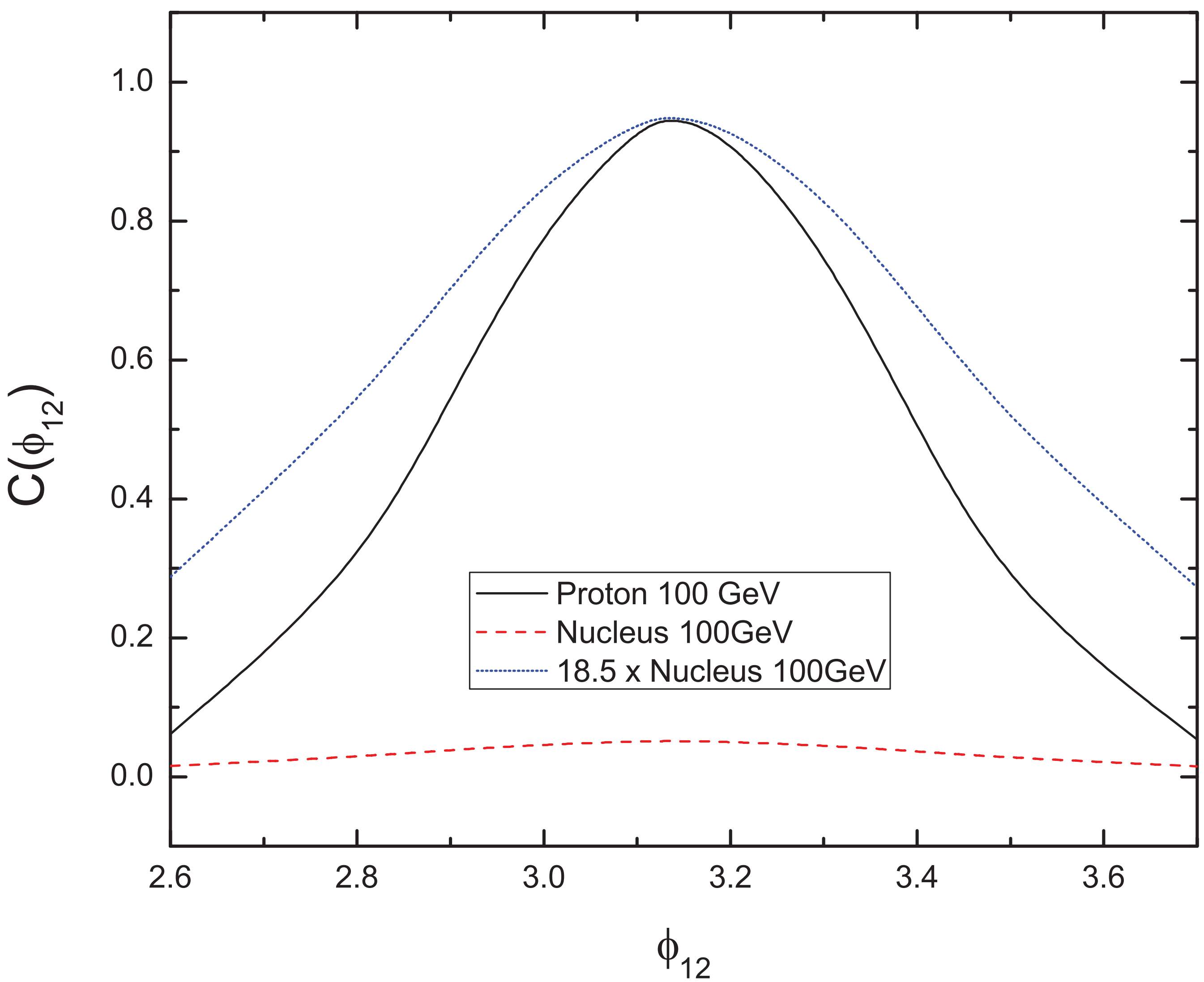

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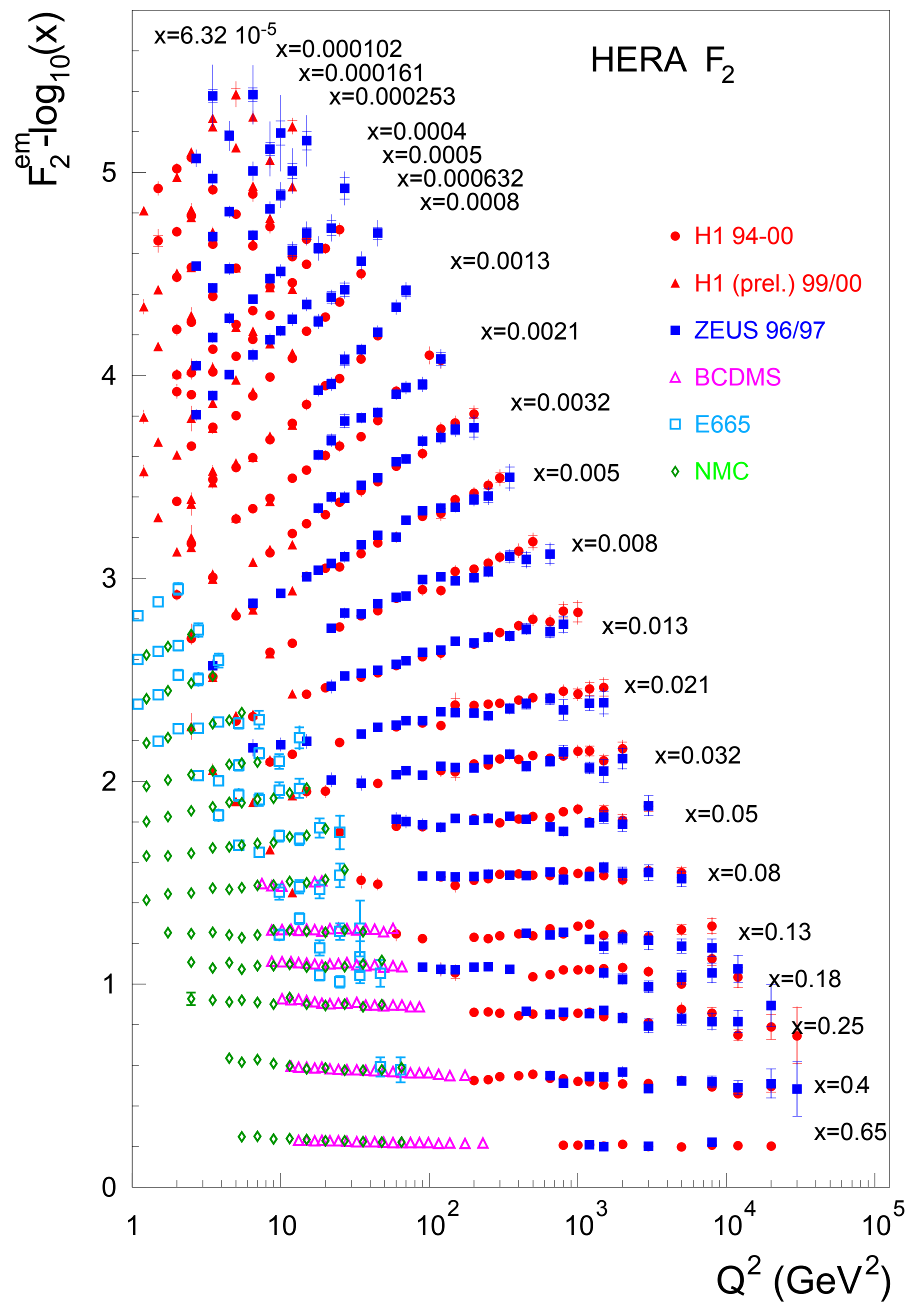
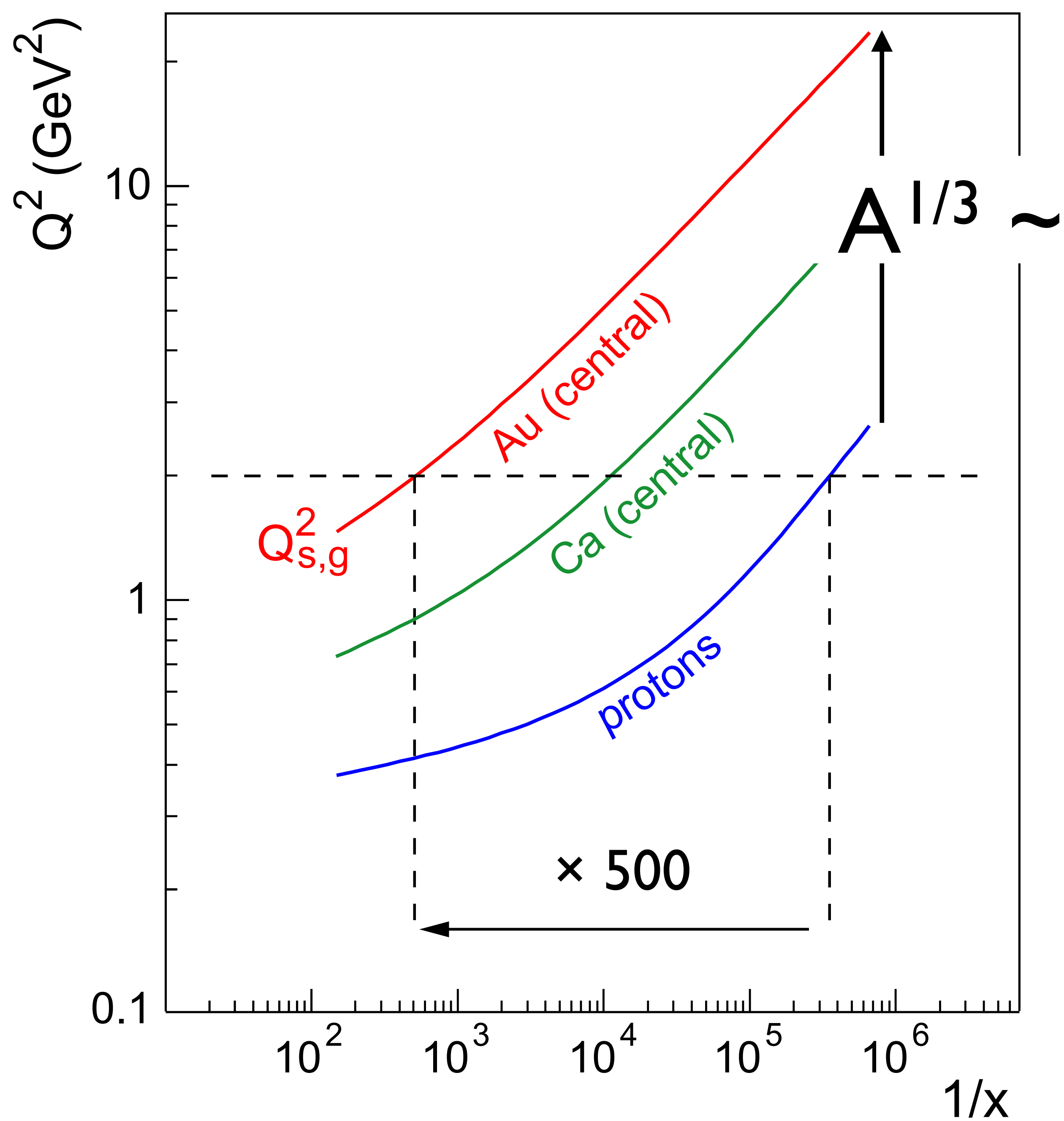
Are RHIC & HERA Results consistent?





- **Strong hints** of saturation from RHIC: x ~ 10^{-3} in Au
- ep: **No/weak hints** in DIS at HERA up to x=$6.32 \cdot 10^{-5}$, Q^2=1-5 GeV^2

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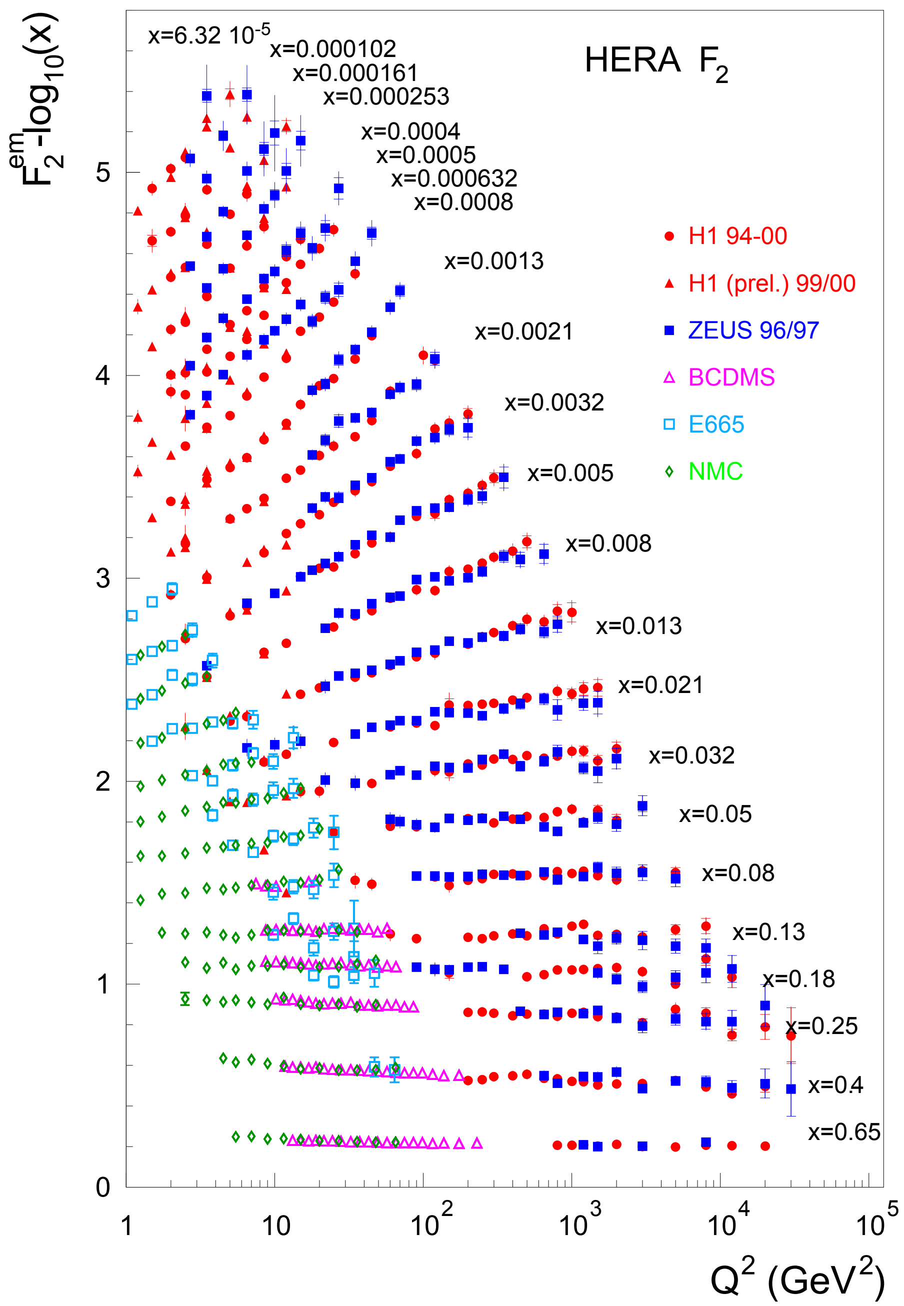

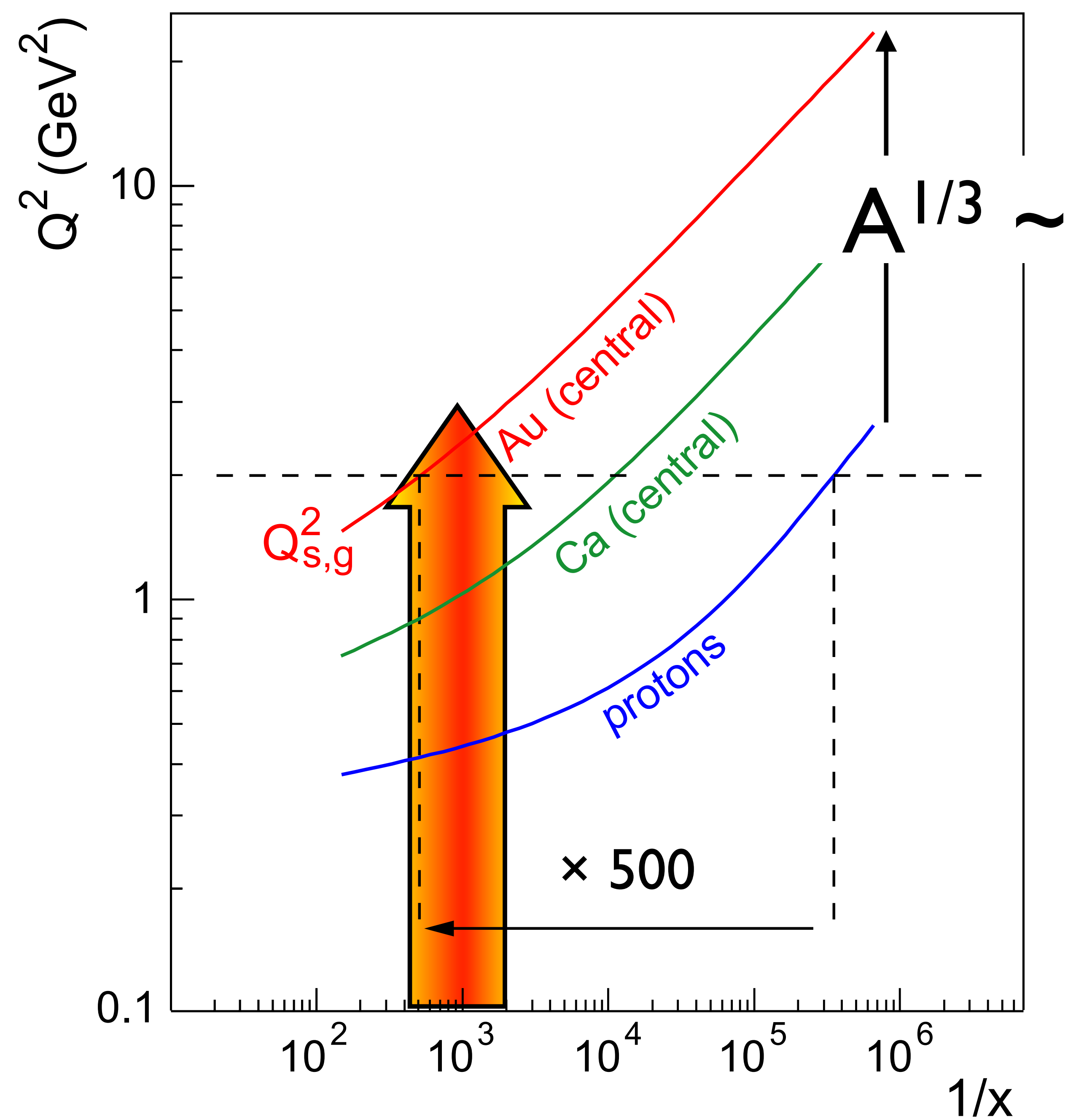

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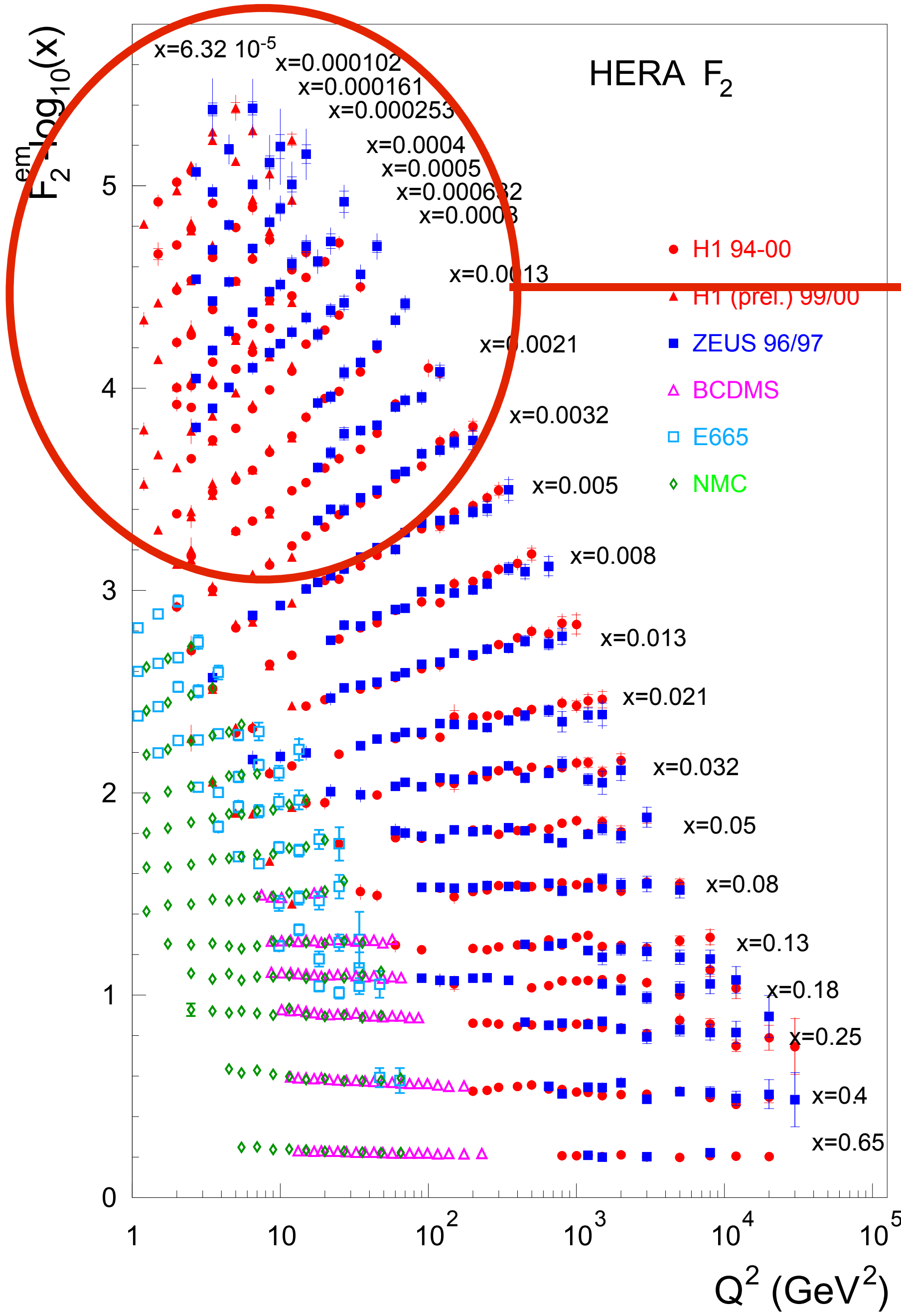

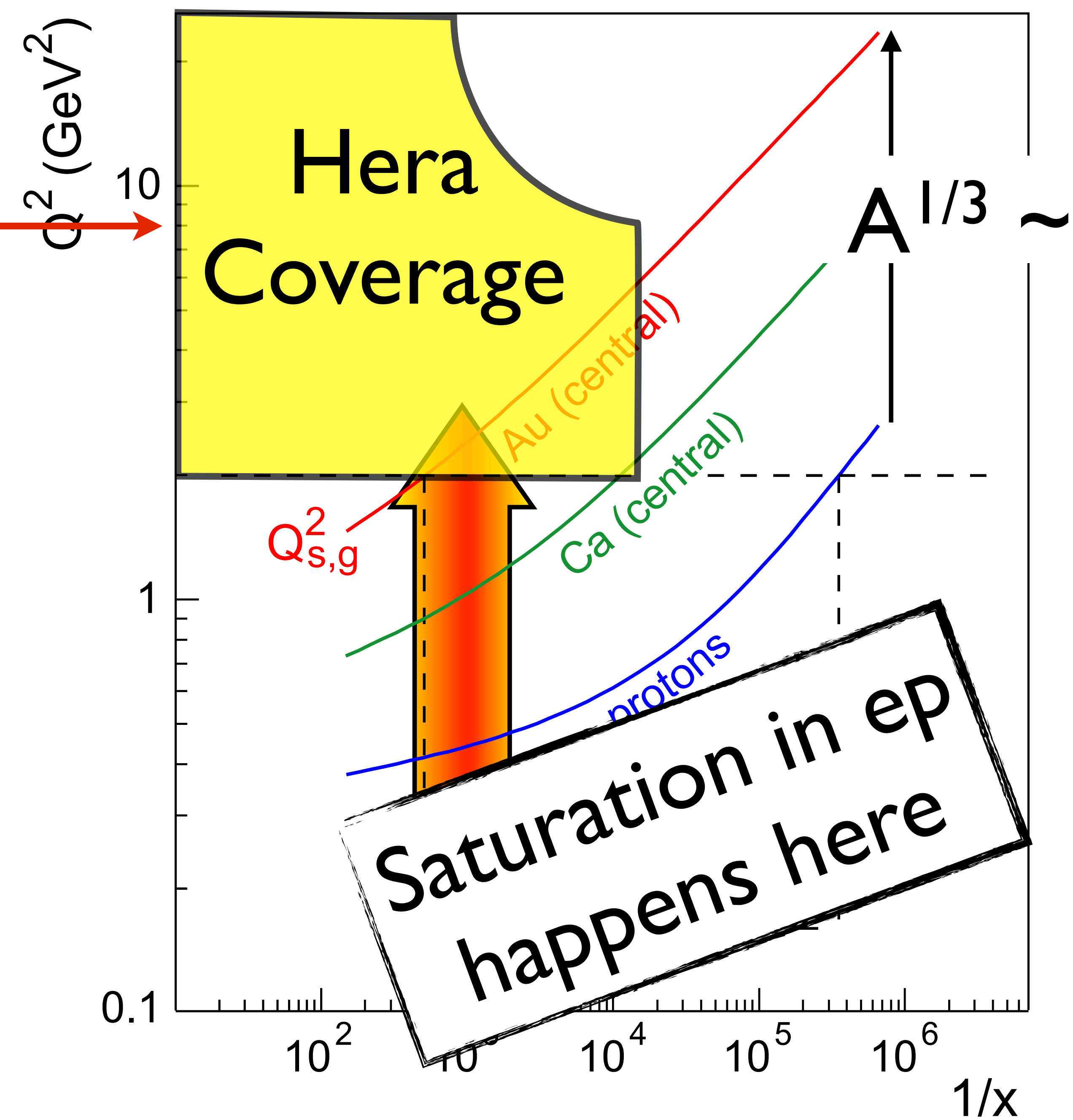

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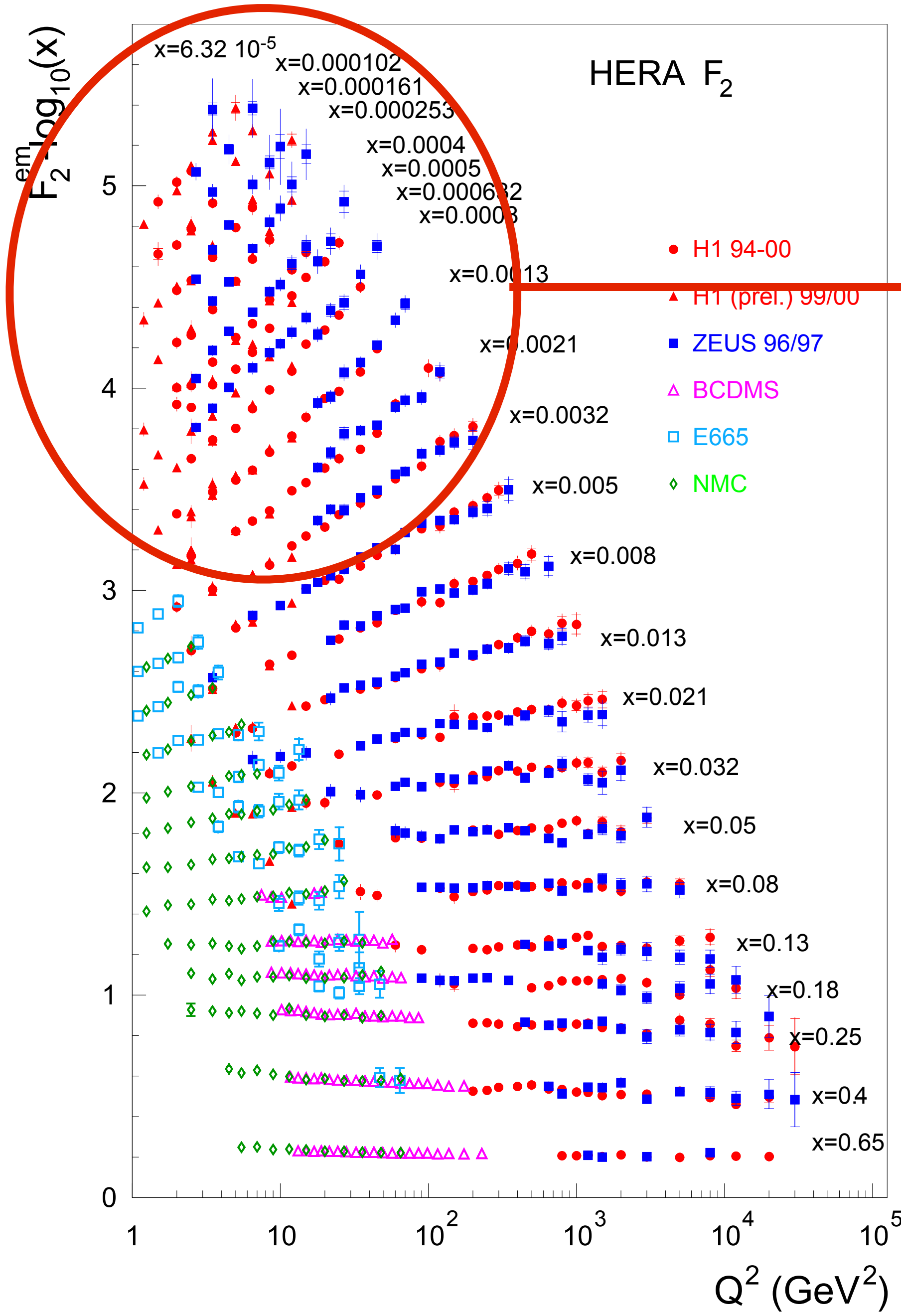

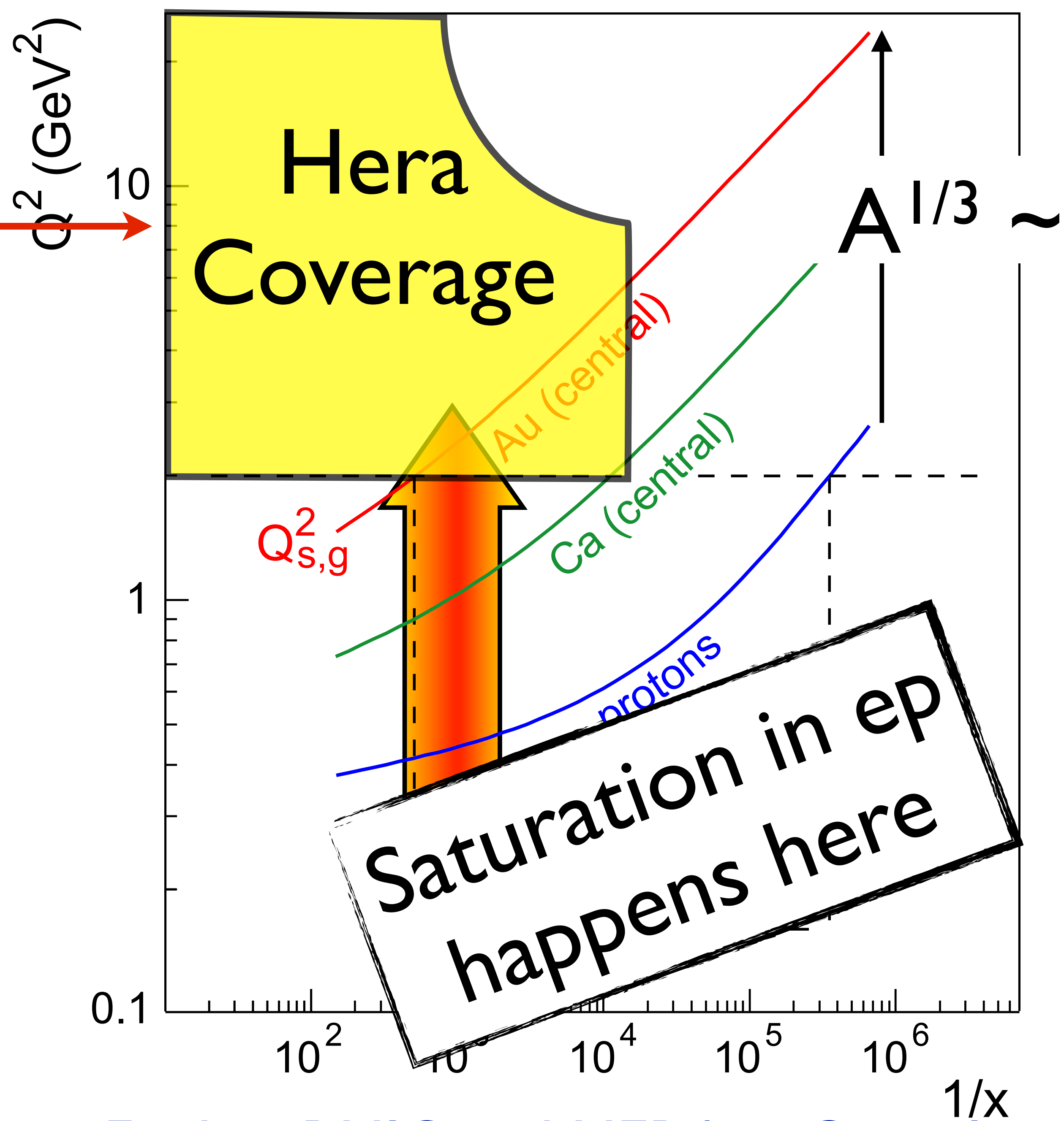

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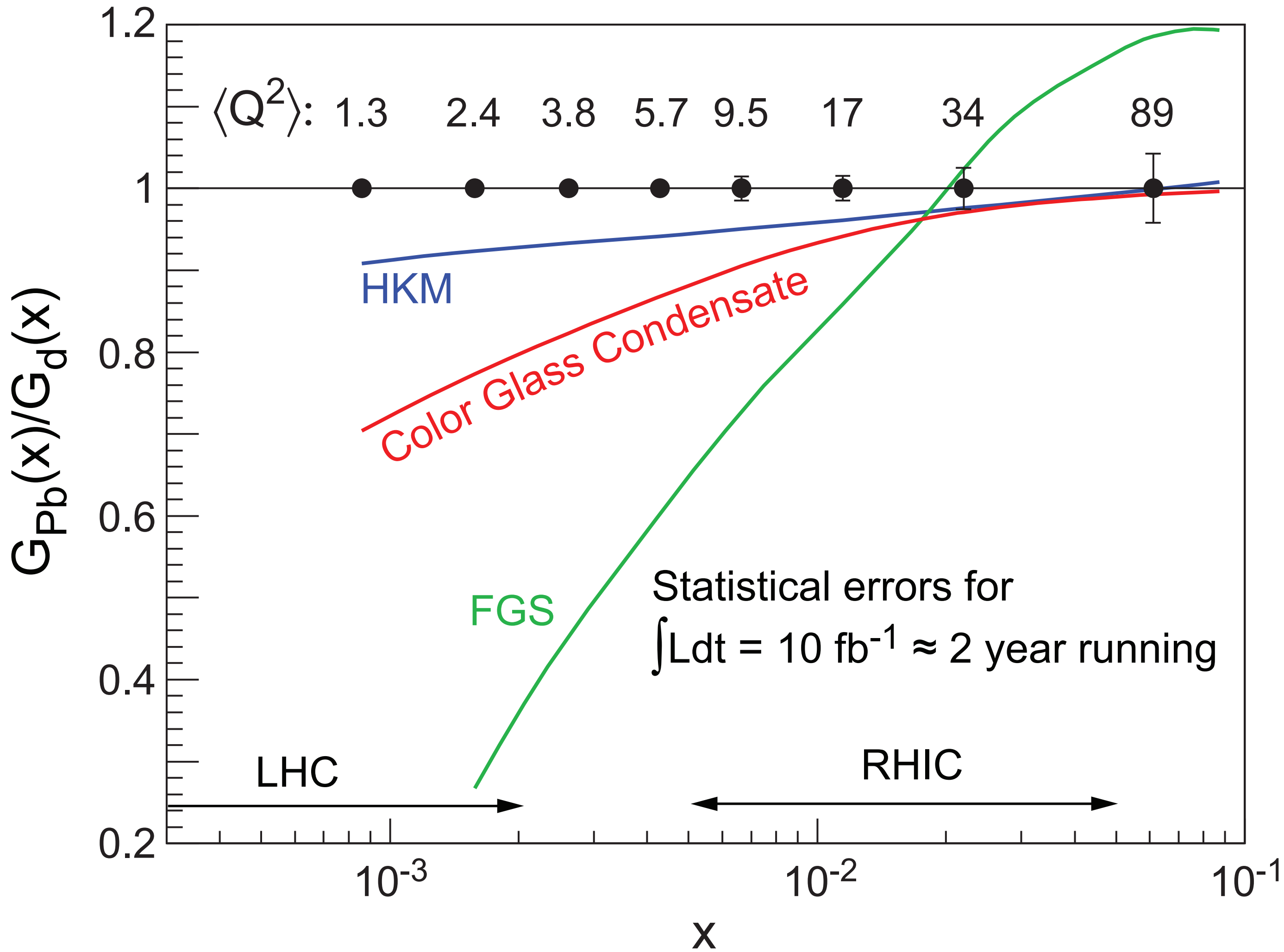
- ep: **No/weak hints** in DIS at HERA up to $x=6.32\cdot10^{-5}$, $Q^2=1\text{-}5\ GeV^2$
- Finding RHIC and HERA & Q_s scalings consistent
- At d+A in RHIC we see the Nuclear "Oomph" $Q_s^2 \sim Q_0^2\ (A/x)^{1/3}$

Key Measurements in e+A

- ***Momentum*** **distribution of gluons** ***$xG(x,Q^2)$***
  - ➡ Extract via scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - ➡ Direct measurement: $F_L \sim xG(x,Q^2)$ (requires √s scan)
  - ➡ 2+1 jet rates
  - ➡ Inelastic vector meson production (*e.g.* J/ψ)
  - ➡ Diffractive vector meson production ~ $[xG(x,Q^2)]^2$

Example of Key Measurements: F_L

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



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

requires $\sqrt{s}$ scan, $Q^2/xs = y$

Here:

$\int Ldt$ = 4/A fb^{-1} (10+100) GeV
= 4/A fb^{-1} (10+50) GeV
= 2/A fb^{-1} (5+50) GeV

statistical error only

HKM and FGS are "standard" shadowing parameterizations that are evolved with DGLAP

Syst. studies of $F_L(A,x,Q^2)$:

- $xG(x,Q^2)$ with great precision
- Distinguish between models

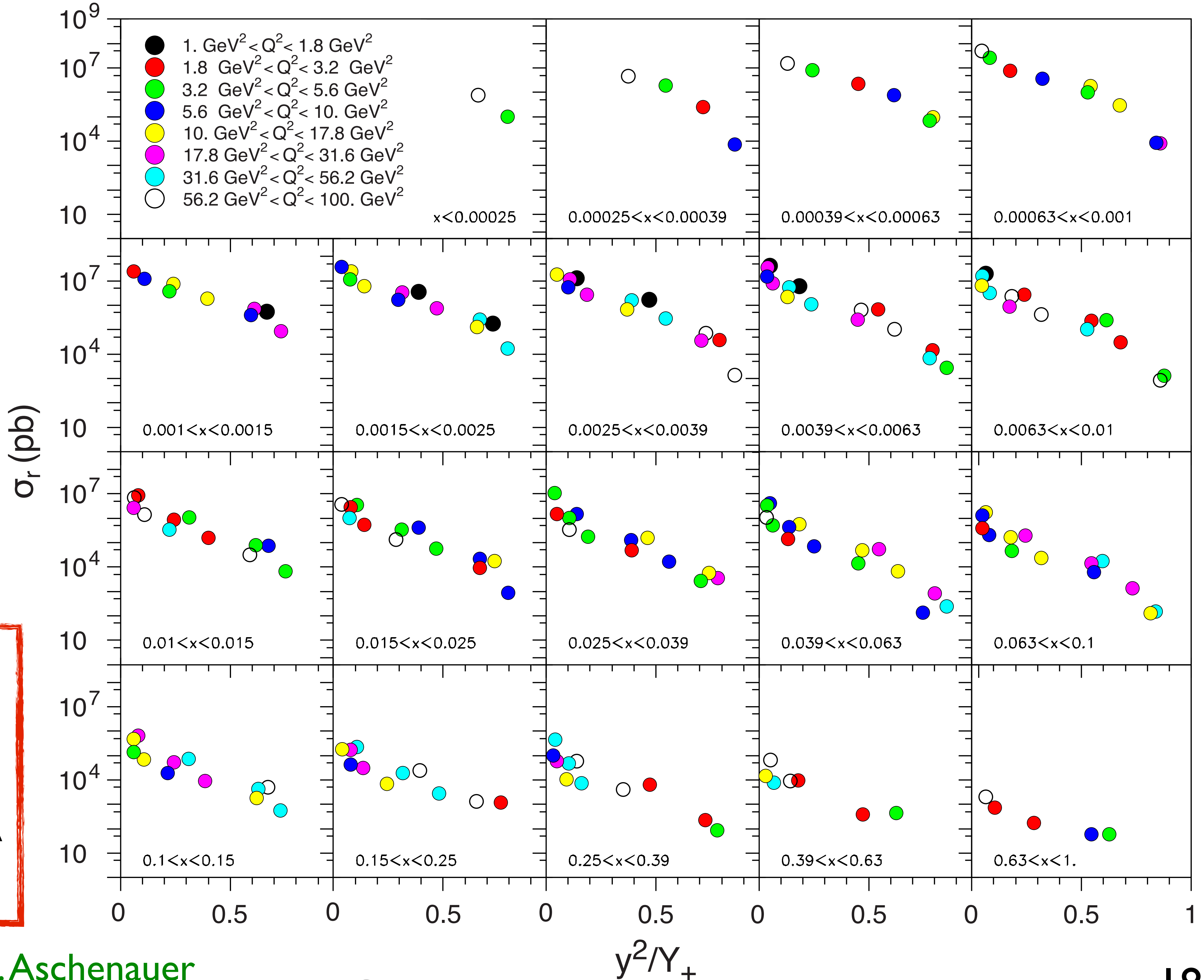
Feasibility study: $\sigma_r = F_2(x,Q^2) - y^2/Y_+ \cdot F_L(x,Q^2)$

$Y_+ = 1 + (1-y)^2$

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

e+p: 1st stage
5x50 - 5x325
running combined
4 weeks/each
(50% eff)

stat. error shown and negligible

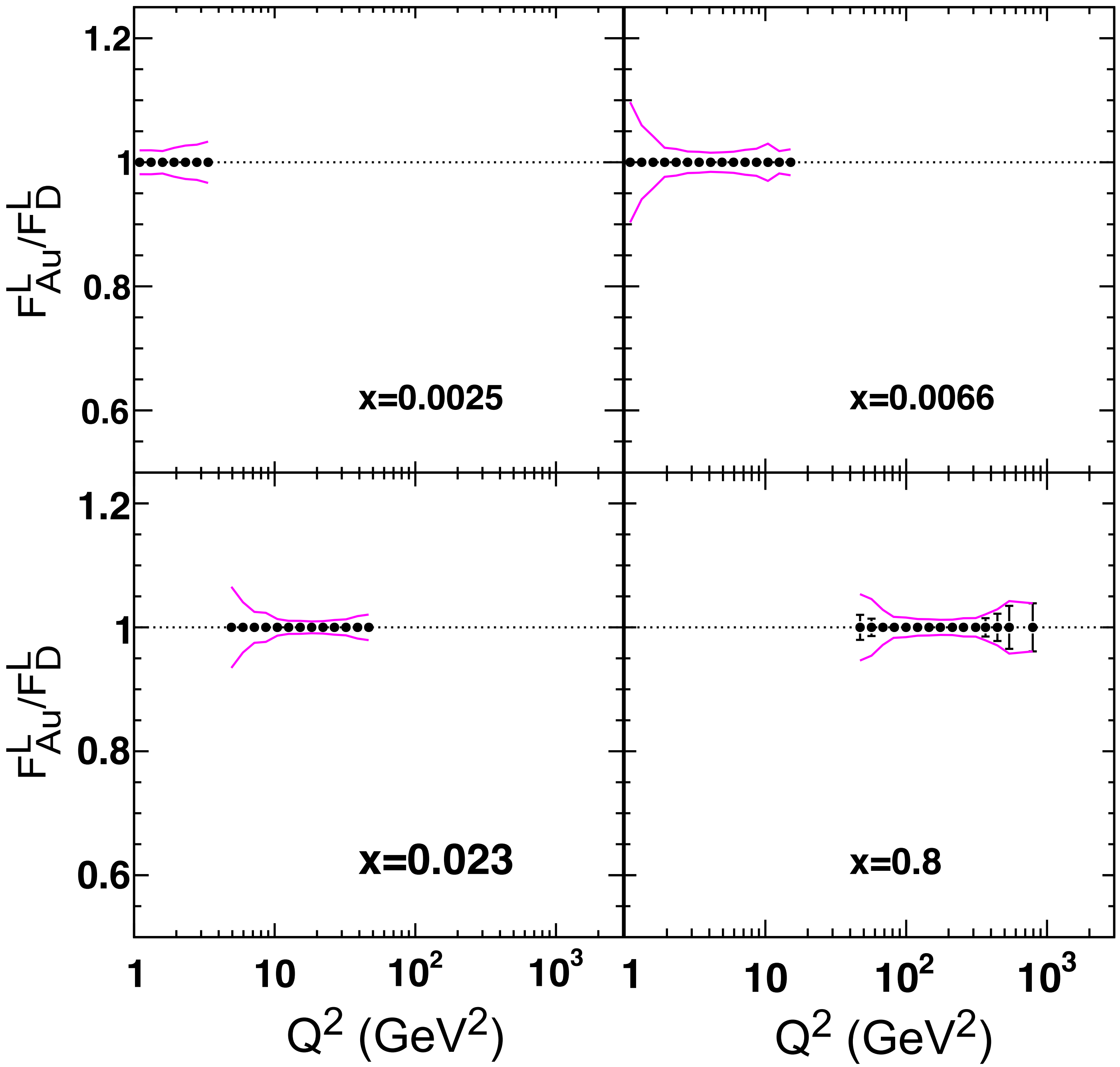


To Do:
refine method & test how well we can extract F_L in e+A collisions

Syst. Uncertainties in F_L for staged EIC

- F_L for electron energy fixed at 4 GeV and proton energies: 50, 70, 100, 250 GeV ($4fb^{-1}$ each)

Plot from J. Dunlop



The magenta curves show the statistical and systematic errors (1% uncertainty in normalization) added in quadrature.

Again, the extraction of F_L is dominated by systematic uncertainties

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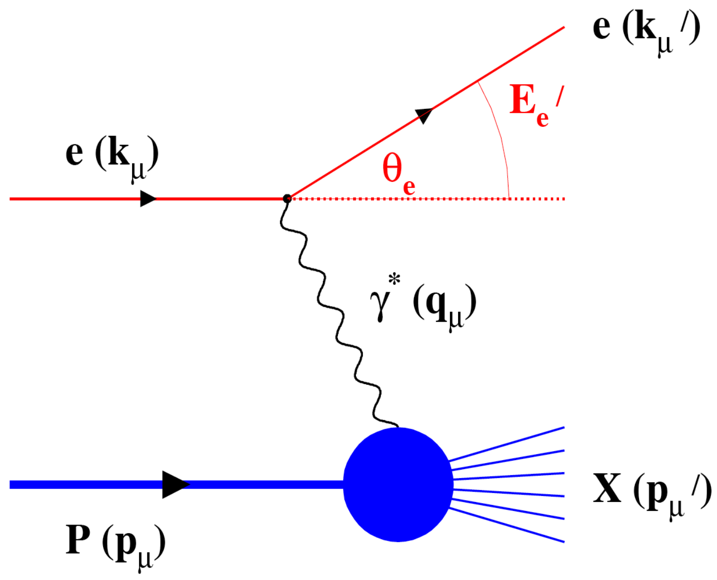
  - ➡ 2+1 jet rates
  - ➡ Inelastic vector meson production (*e.g.* J/ψ)
  - ➡ Diffractive vector meson production $\sim [xG(x,Q^2)]^2$
- ***Space-time*** **distributions of gluons in matter**
  - ➡ Exclusive final states (*e.g.* vector meson production ρ, J/ψ)
  - ➡ Deep Virtual Compton Scattering (DVCS) - $\sigma \sim A^{4/3}$
  - ➡ F_2, F_L for various A and impact parameter dependence
- **Interaction of fast probes with *gluonic* medium?**
  - ➡ Hadronization, Fragmentation
  - ➡ Energy loss (charm!)

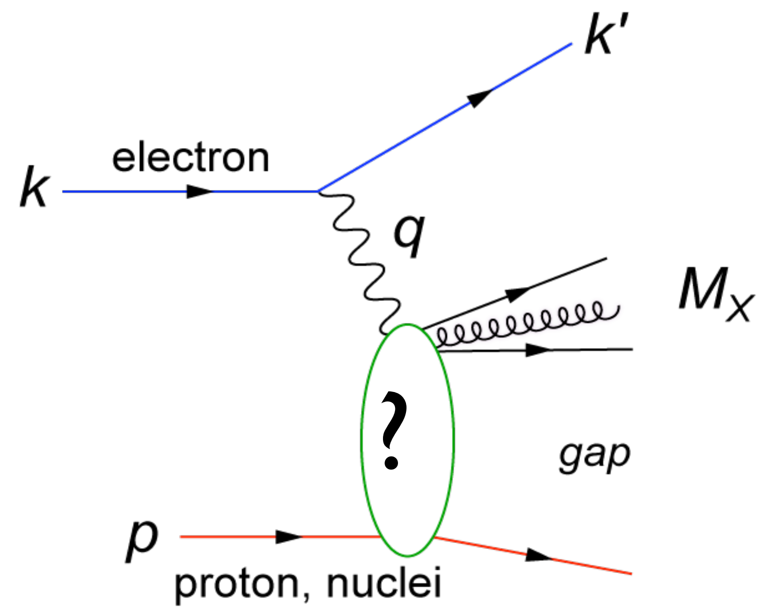
See next talk by A. Accardi

- **Role of colour neutral excitations (Pomerons)**
  - ➡ Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ (HERA/*ep*: 10% , EIC/eA: 30%?)
  - ➡ Diffractive structure functions and vector meson production
  - ➡ Abundance and distribution of rapidity gaps

Role of colour-neutral (Pomeron) excitations

$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* \to M_X A) \propto \alpha^2[G_A(x,Q^2)]^2$$





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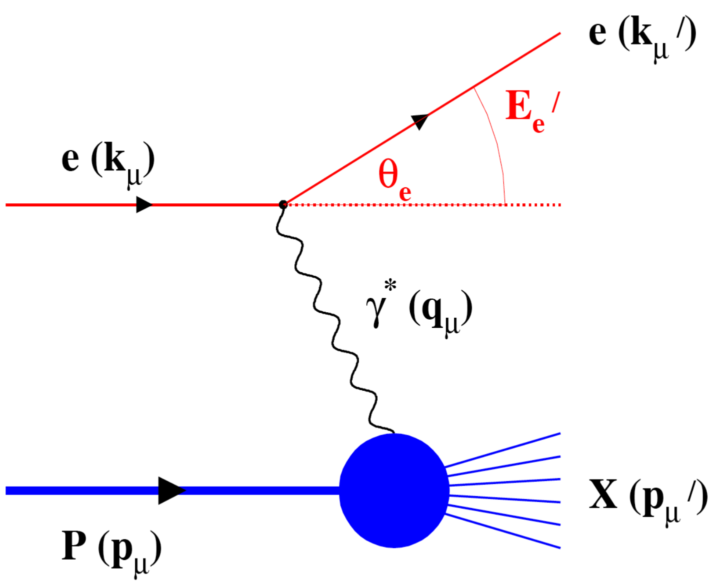
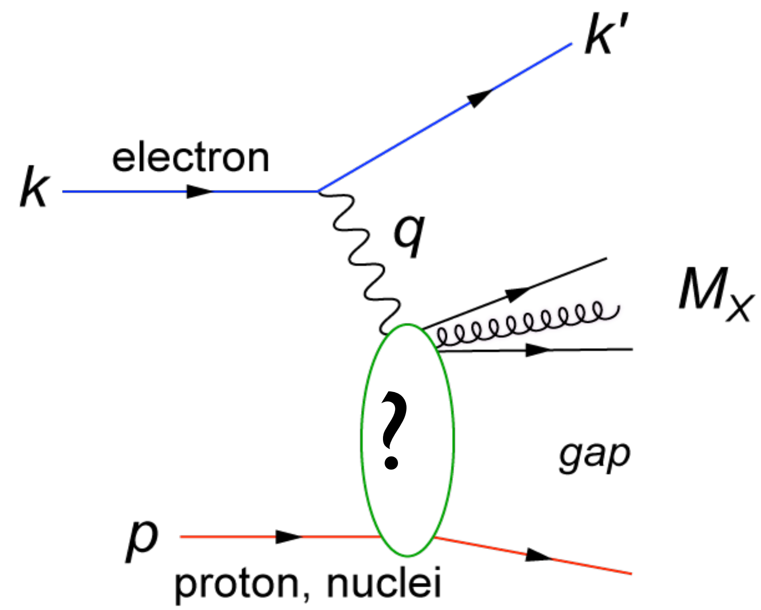
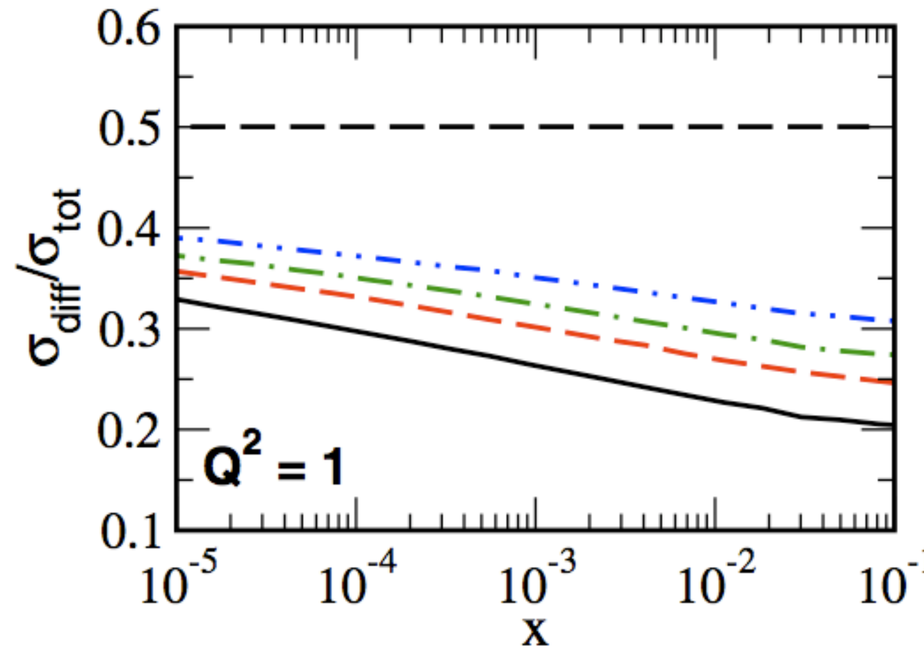
Curves: Kugeratski, Goncalves, Navarra, EPJ C46, 413







HERA/ep: 15% of all events are hard diffractive

Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A ?

- Predictions: ~25-40%?

Look inside the "Pomeron"

- Diffractive structure functions

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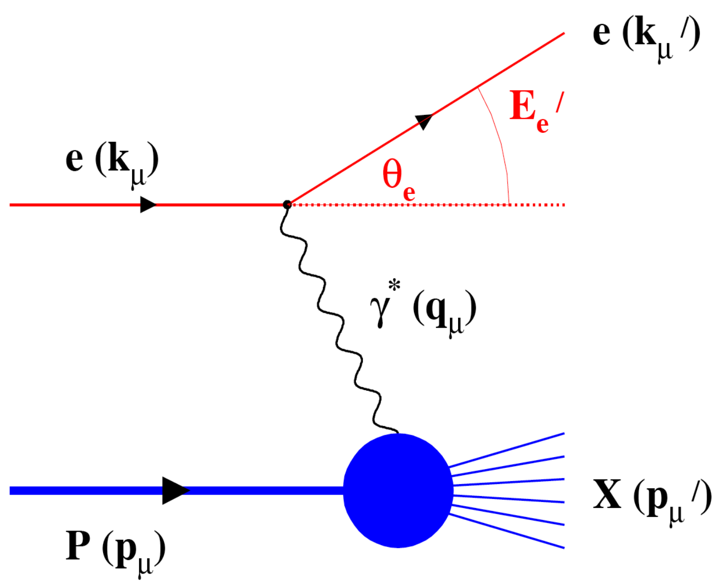

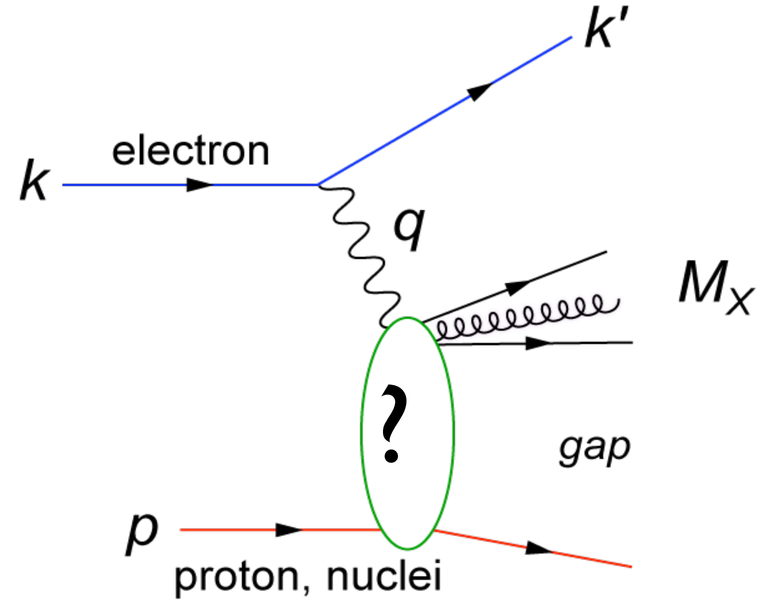

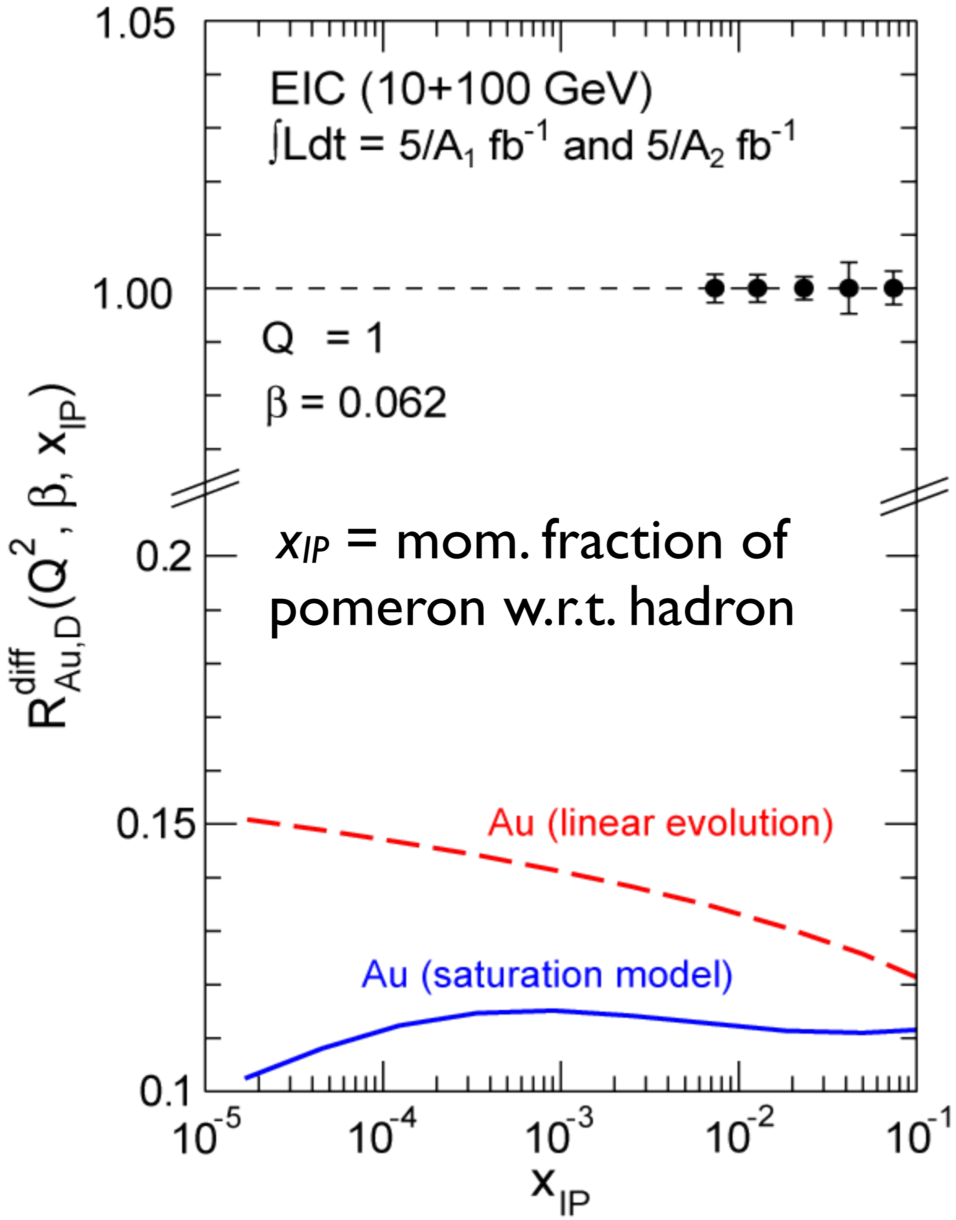

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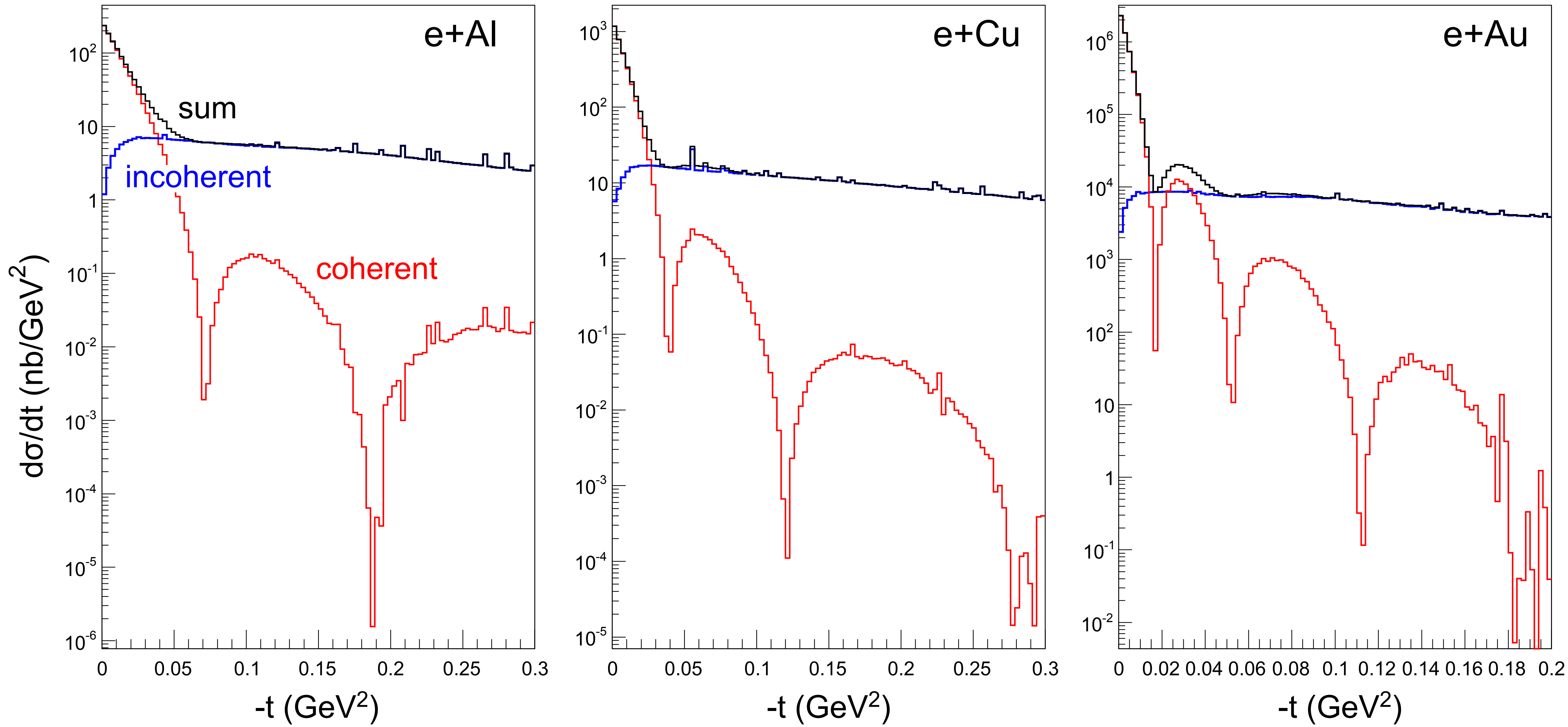
Distinguish between linear evolution and saturation models

Diffraction in e+A

$e + A \rightarrow e' + J/\psi + A'$



- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A predicted to be ~25-40%
- Process most sensitive to $xG(x,Q^2)$
- Rich physics program on momentum & spatial gluon distribution
- Coherent vs Incoherent: requires detection of breakup with ~ $1\text{-}10^{-4}$ efficiency

Never done at a collider!

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Detecting Nuclear Breakup

- Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- Focus on n emission
  - ➡ Zero-Degree Calorimeter
  - ➡ Requires careful design of IR

- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

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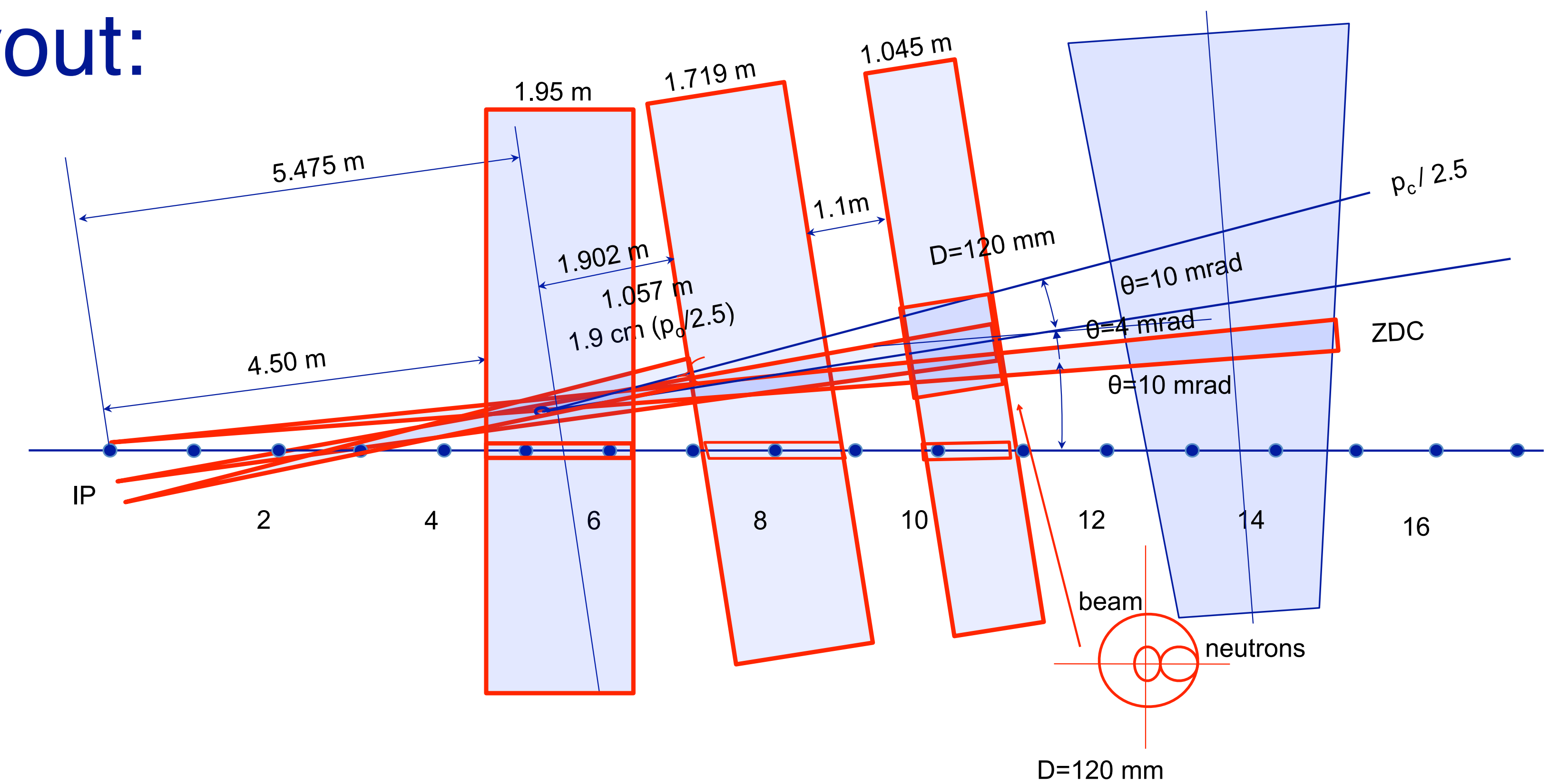
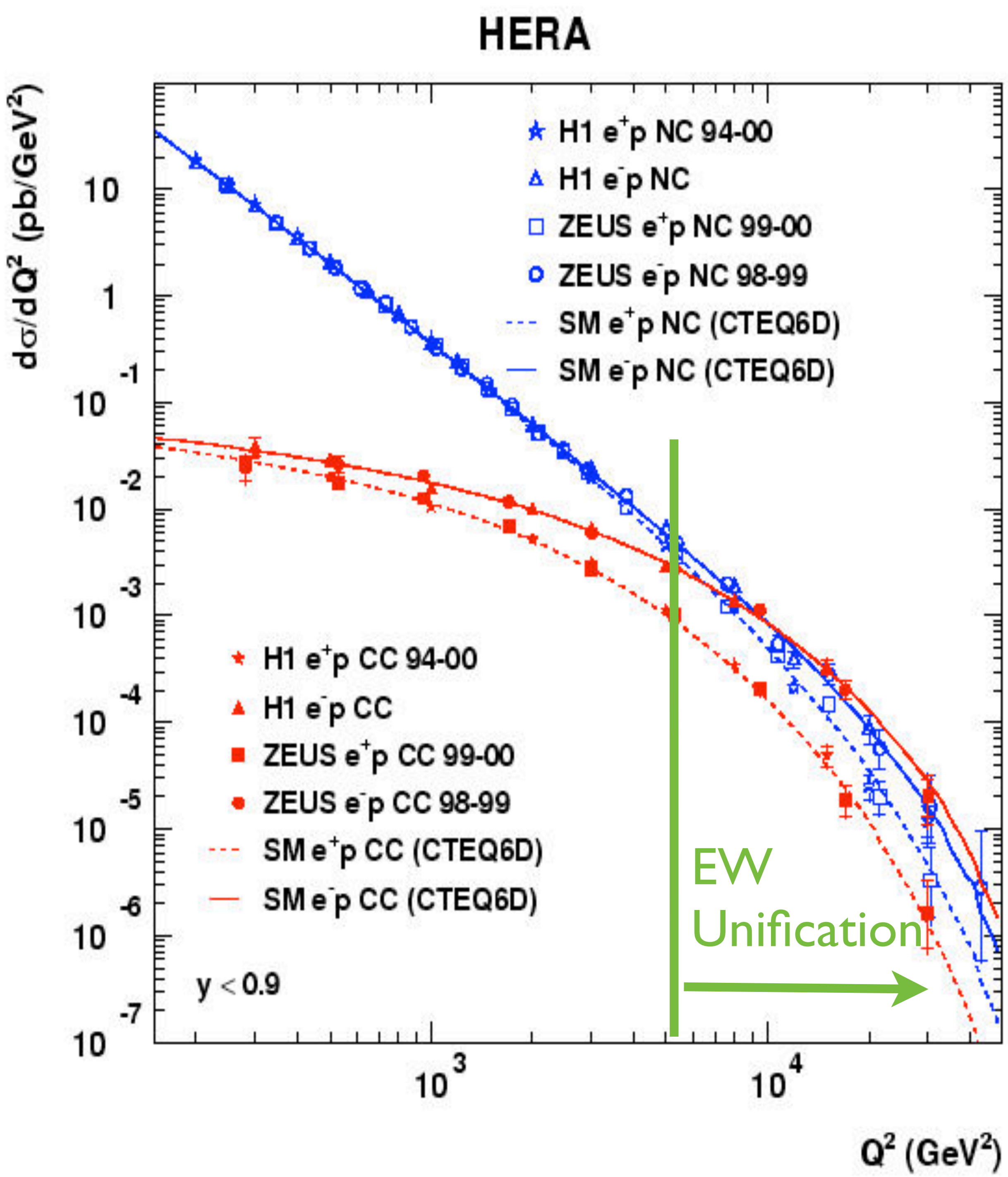
- Proposed eRHIC IR layout:
  - ➡ Need ±X mrad opening
  - ➡ through triplet for *n* and
  - ➡ room for ZDC



EW unification at HERA



- From DIS at HERA:
  - ➡ At small-medium Q^2, σ(NC) >> σ(CC)
  - ➡ For $Q^2 > M_Z^2$ and M_W^2, σ(NC) ~ σ(CC)
    - EW Unification
- Already a textbook figure ...

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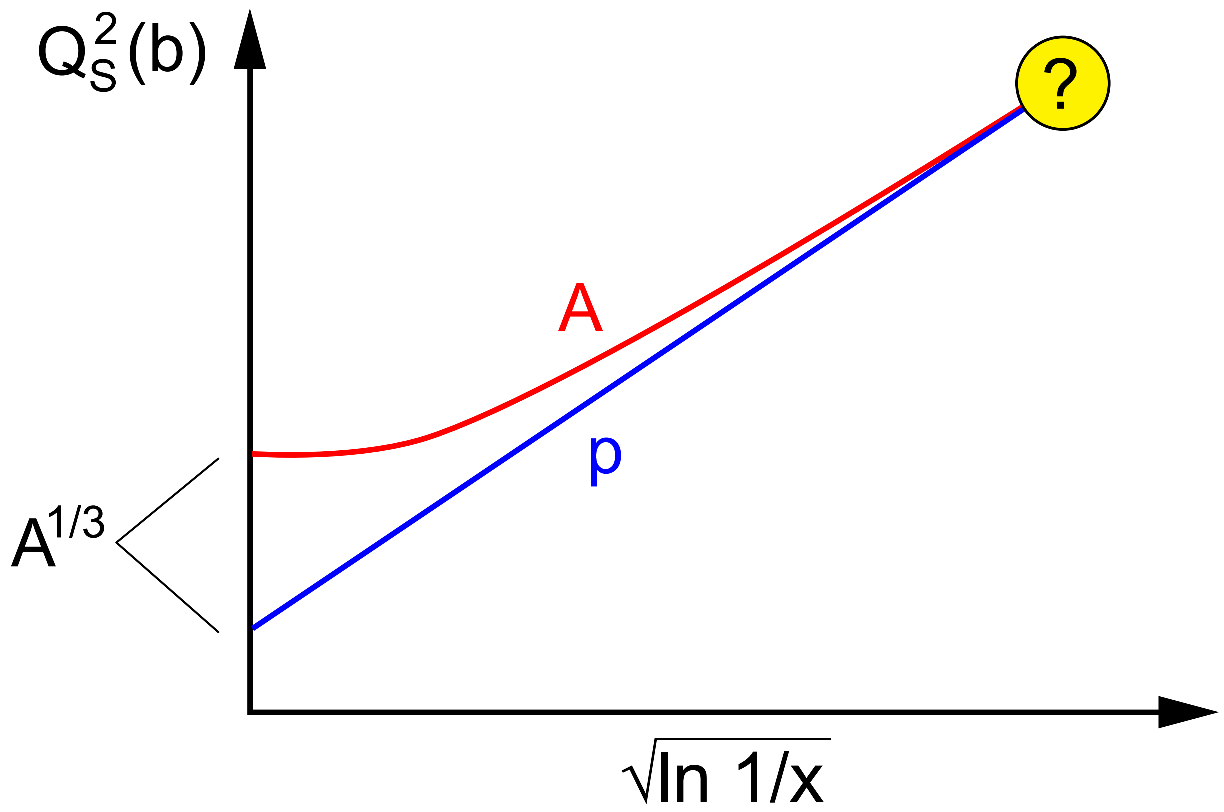
Matter at low-x: A truly universal regime?

What about on the parton scale?



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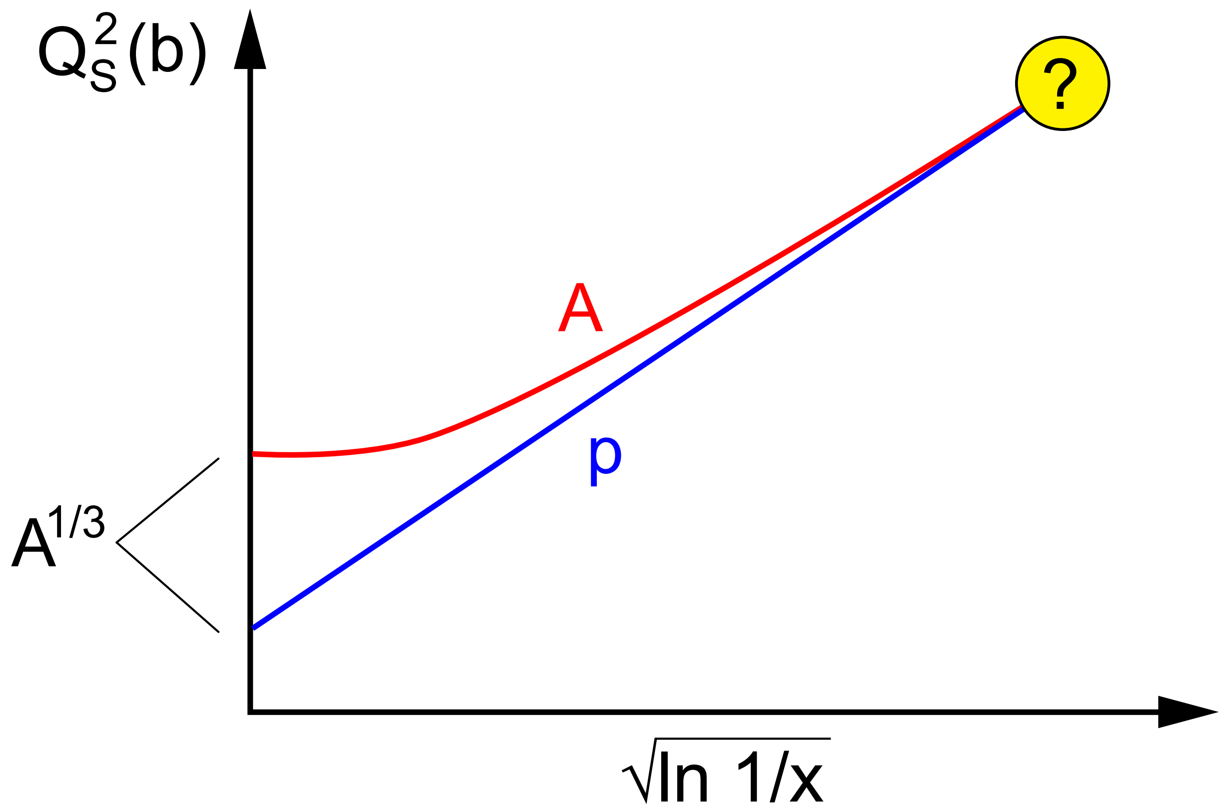

A.H. Mueller, hep-ph/0301109

- Small-x running-coupling BFKL QCD evolution predicts:
  - Q_S approaches universal behaviour for all hadrons and nuclei
  - No dependence on A!!
  - Not only functional form $f(Q_S)$ universal, but even Q_S itself becomes universal

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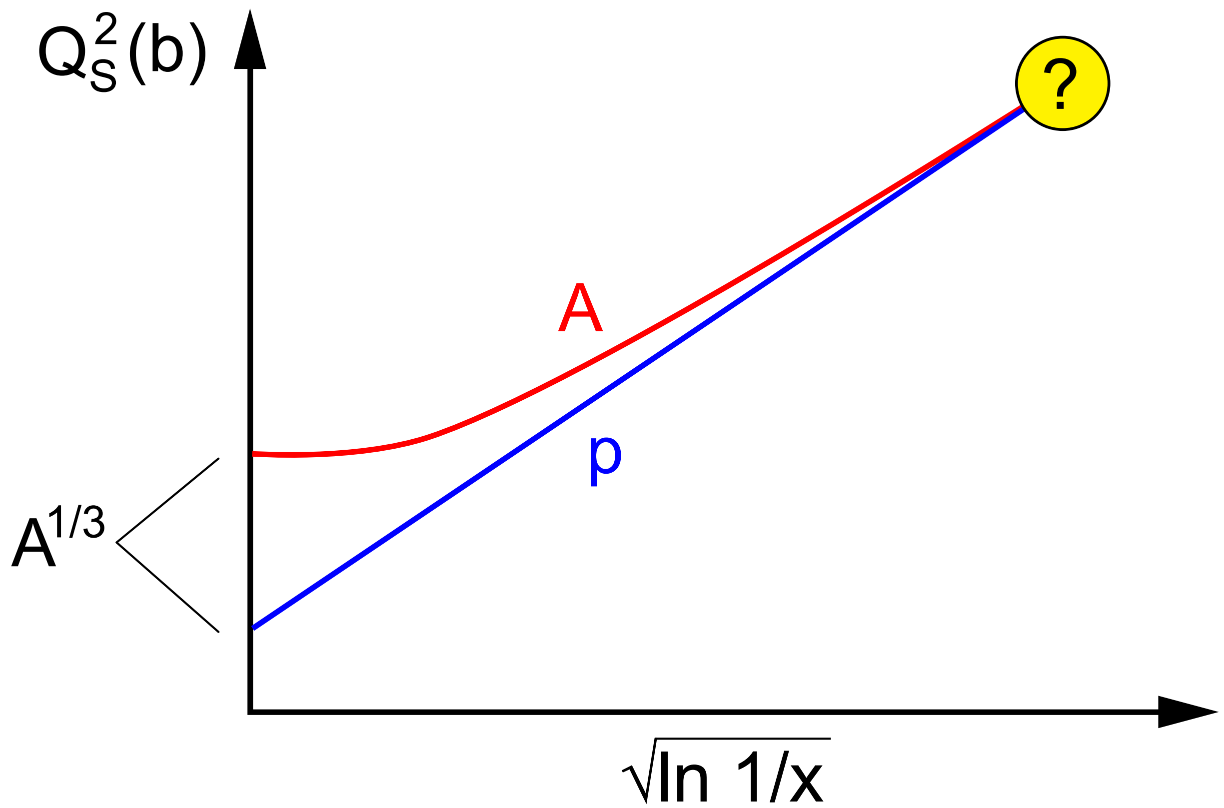

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Radical View:

➡ Nuclei and all hadrons have a component of their wave function with the *same* behaviour

➡ This is a conjecture! Needs to be tested

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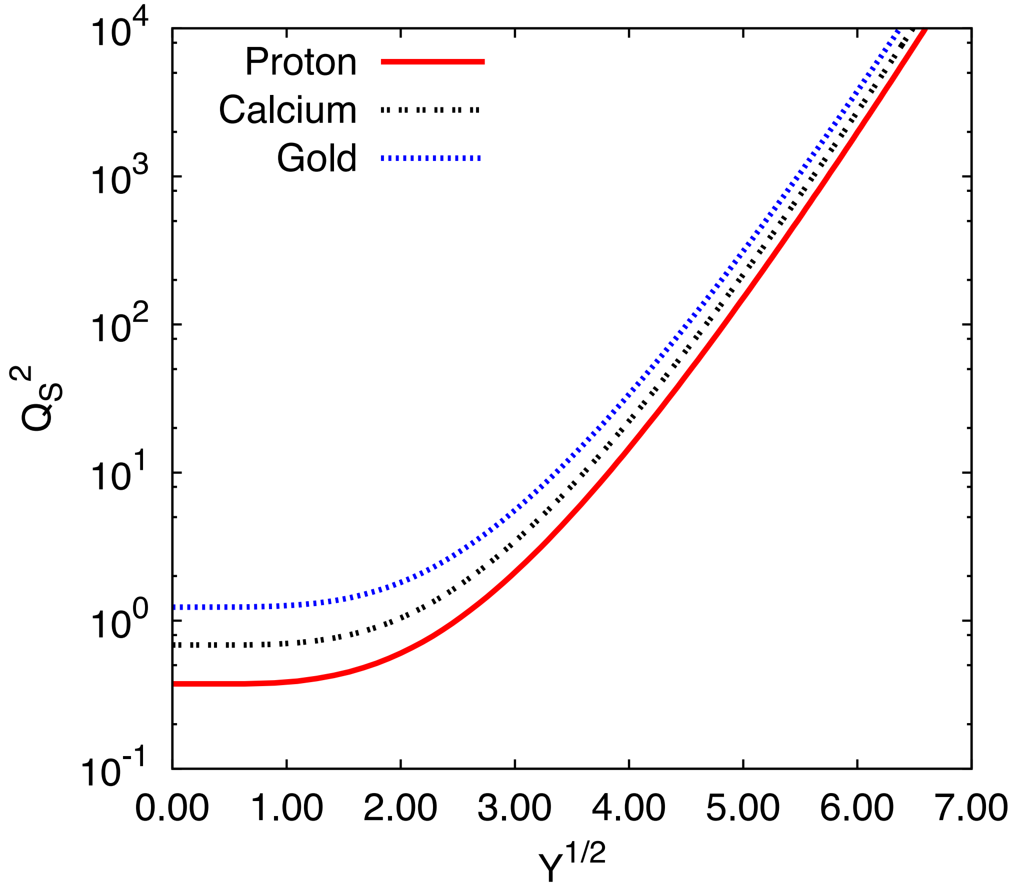

Dusling, Gelis, Lappi and Venugopalan arXiV:0911.2720

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Summary

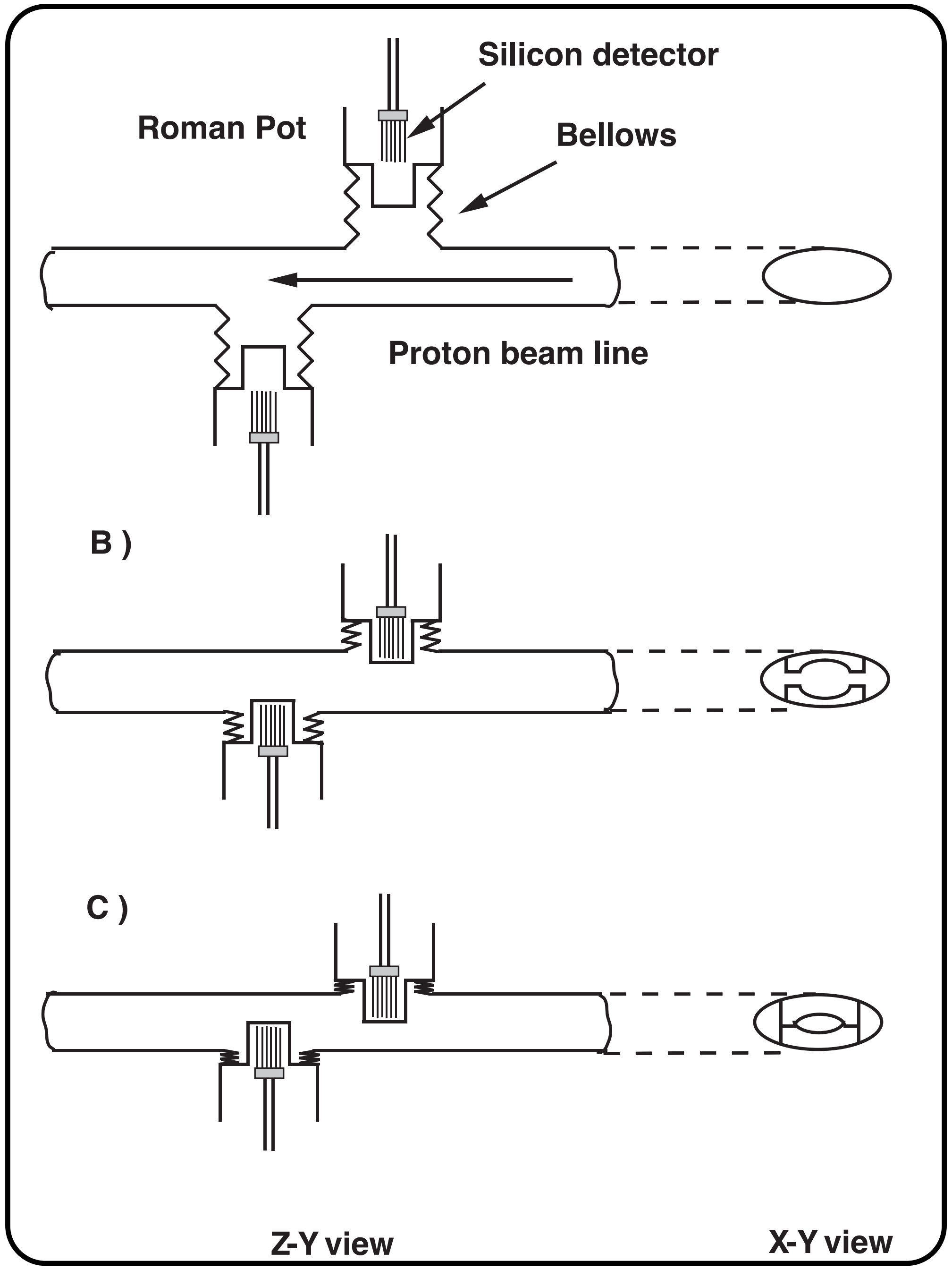
- The e+A programme at an EIC will allow for the unprecedented study on nuclear matter, not well described by linear QCD
- Very little is known about the nuclear structure at low-x
  - ➡ inclusive structure functions and exclusive vector meson production data only available at high-x/light nuclei
  - ➡ diffractive structure functions have never been measured
- Crucial measurements at an EIC:
  - ➡ inclusive and diffractive structure functions
  - ➡ di-hadron correlations: the kT dependence of gluon correlations
  - ➡ coherent diffraction: spatial distribution of gluons
  - ➡ incoherent diffraction: spatial correlations between low-x gluons
- However, many experimental challenges need to be resolved
  - ➡ Differentiating coherent and incoherent diffractive events
  - ➡ Radiative corrections for e+A collisions

BACKUP

How to measure coherent diffraction in e+A ?

$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* \to M_X A) \propto \alpha^2 [G_A(x, Q^2)]^2$$

A)



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- Coherent diffraction == low t

How to measure coherent diffraction in e+A ?

$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* \rightarrow M_X A) \propto \alpha^2 [G_A(x,Q^2)]^2$$

- Coherent diffraction == low t
- Can measure the nucleus if it is separated from the beam in Si (Roman Pot) “beamline” detectors

macl@bnl.gov

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For large A, nucleus cannot be separated from beam without breaking up

How else to measure diffraction in e+A?

Large Rapidity Gap Method:

In diffractive events, a large gap in rapidity occurs between outgoing p and final state particles

activity in the proton direction

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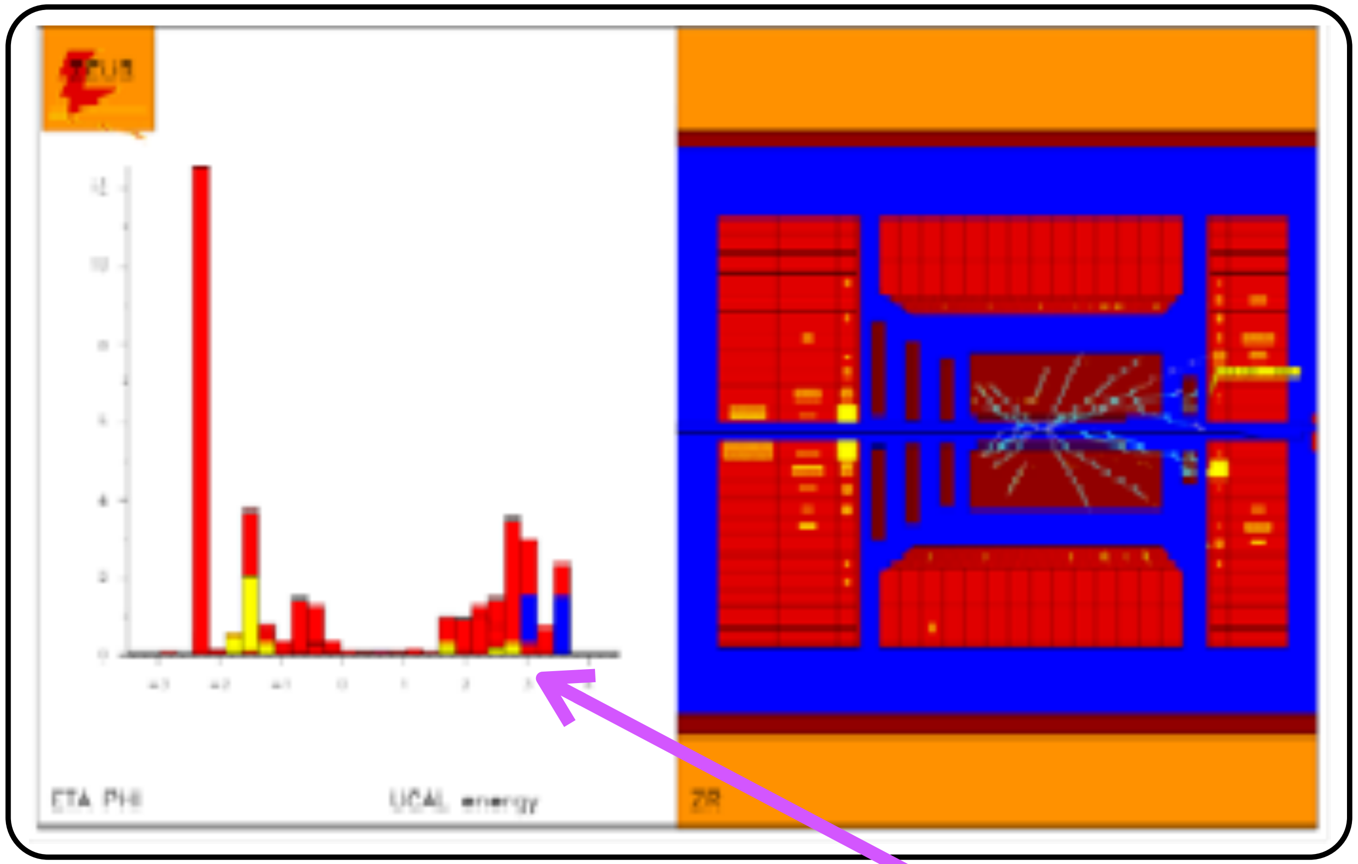

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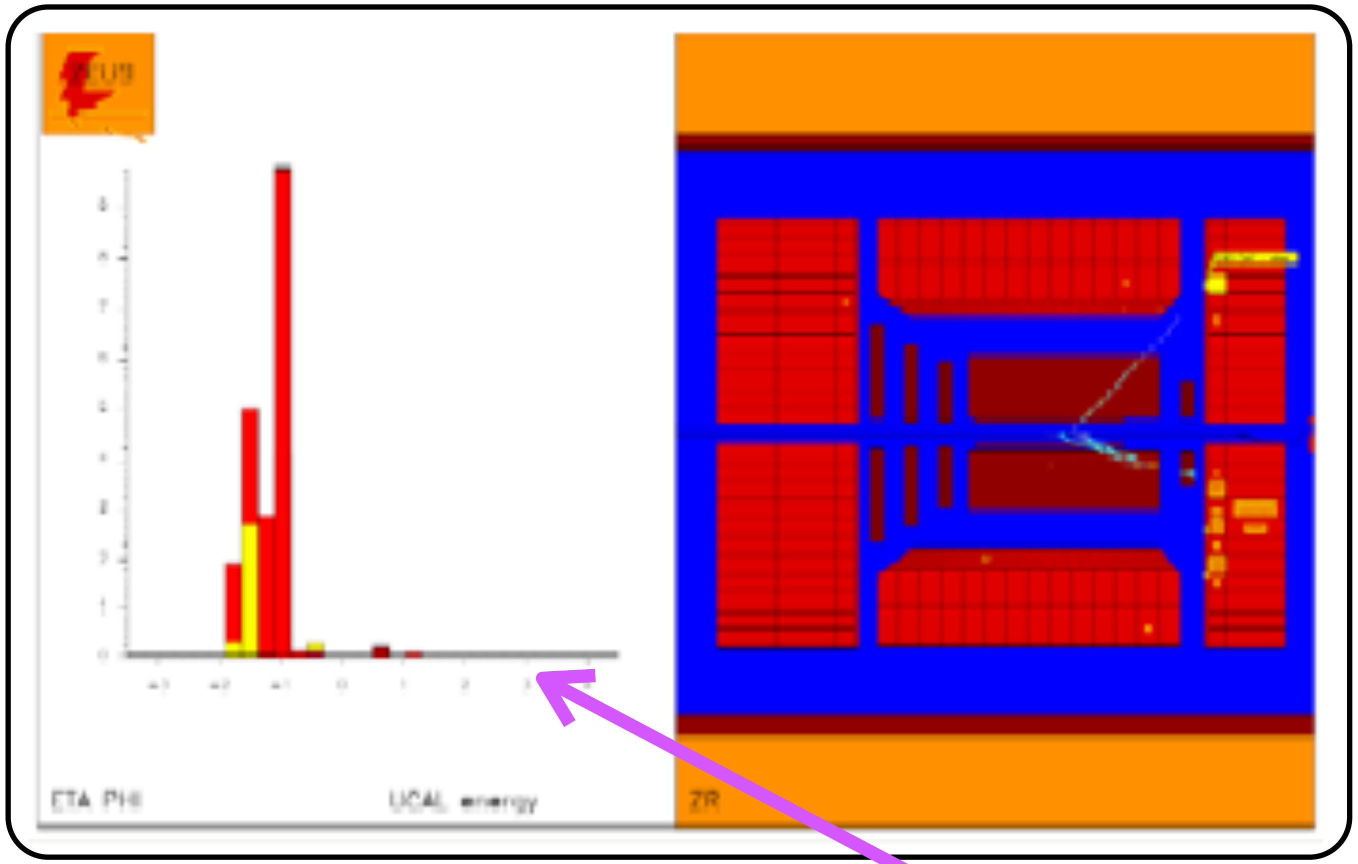

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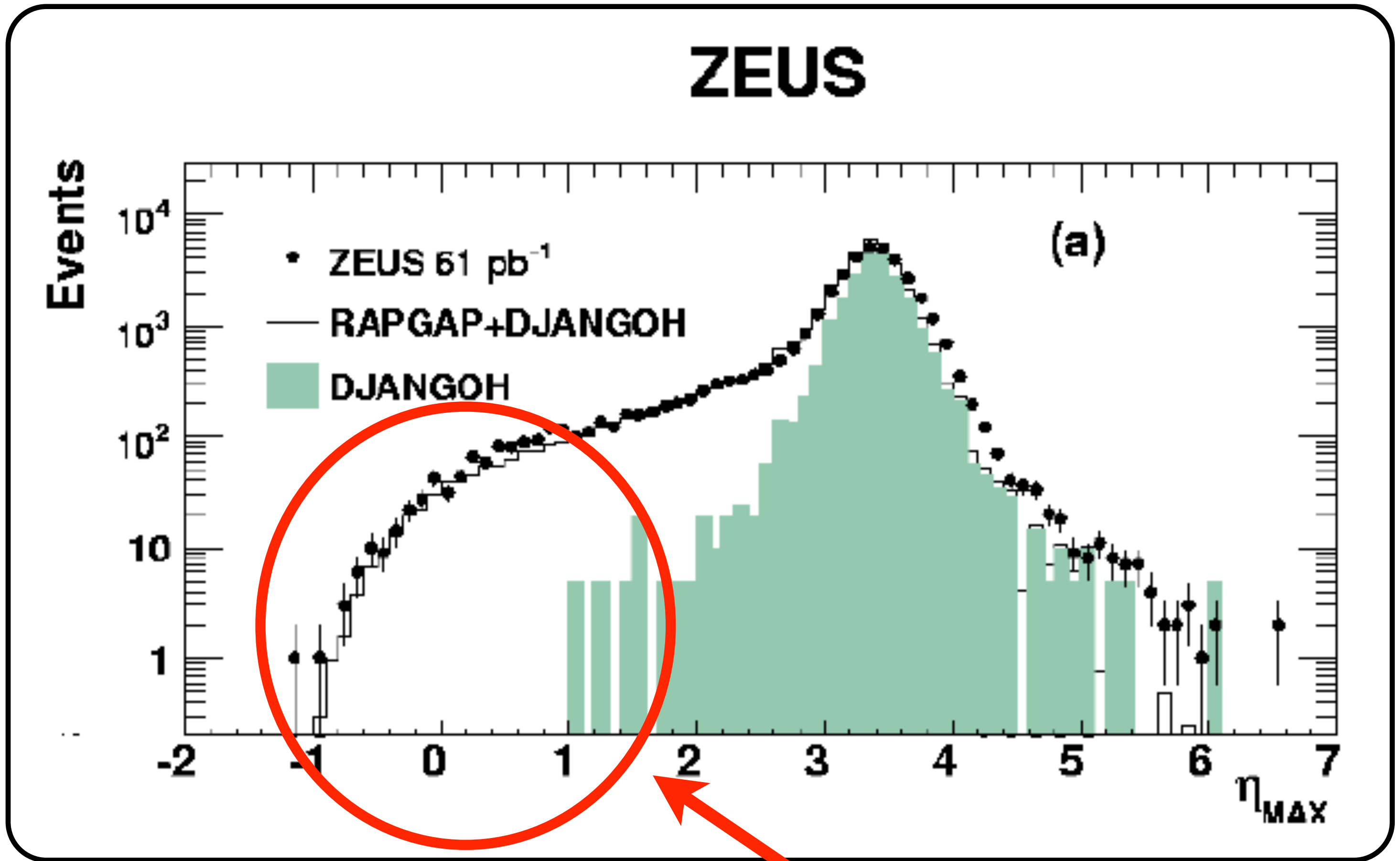

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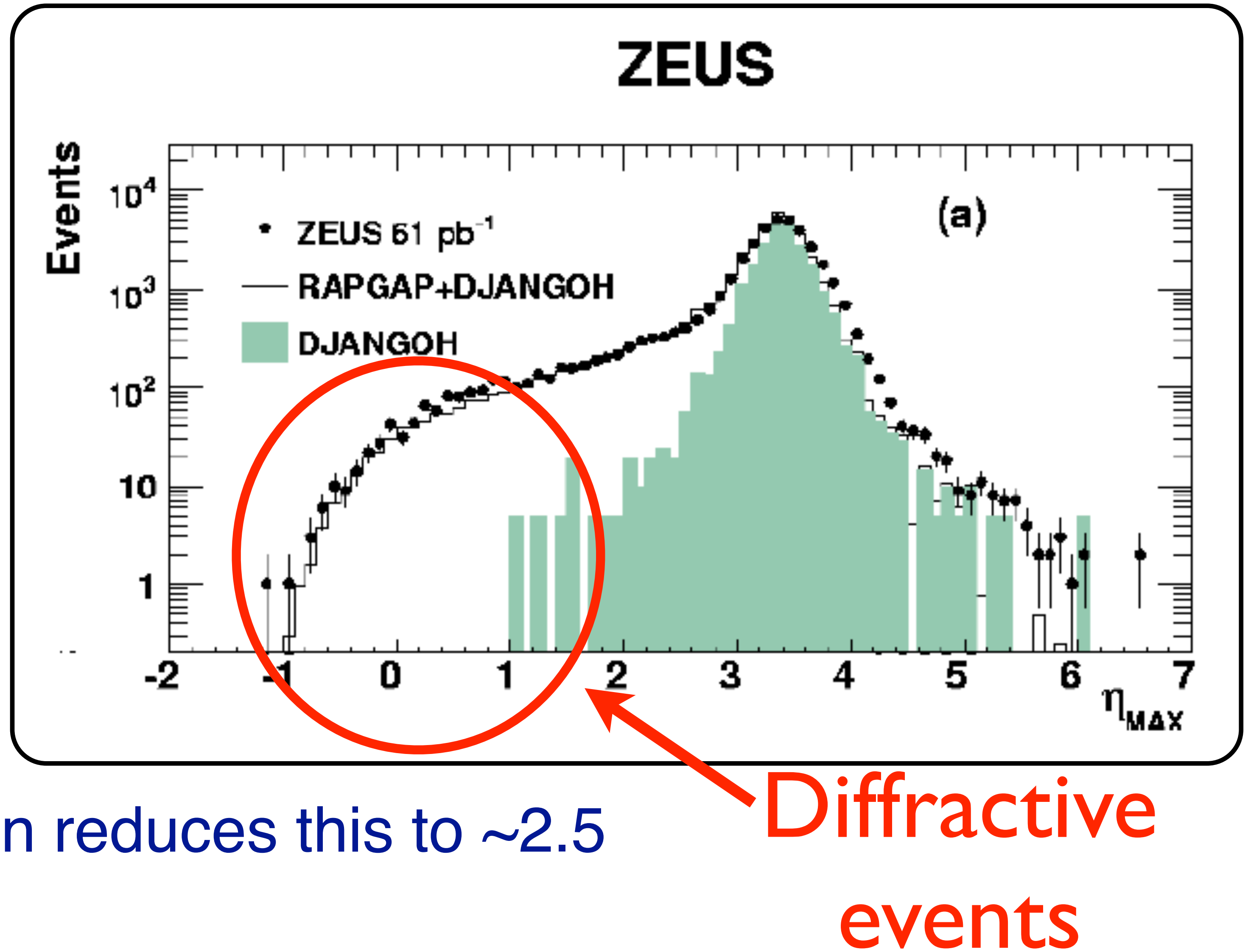

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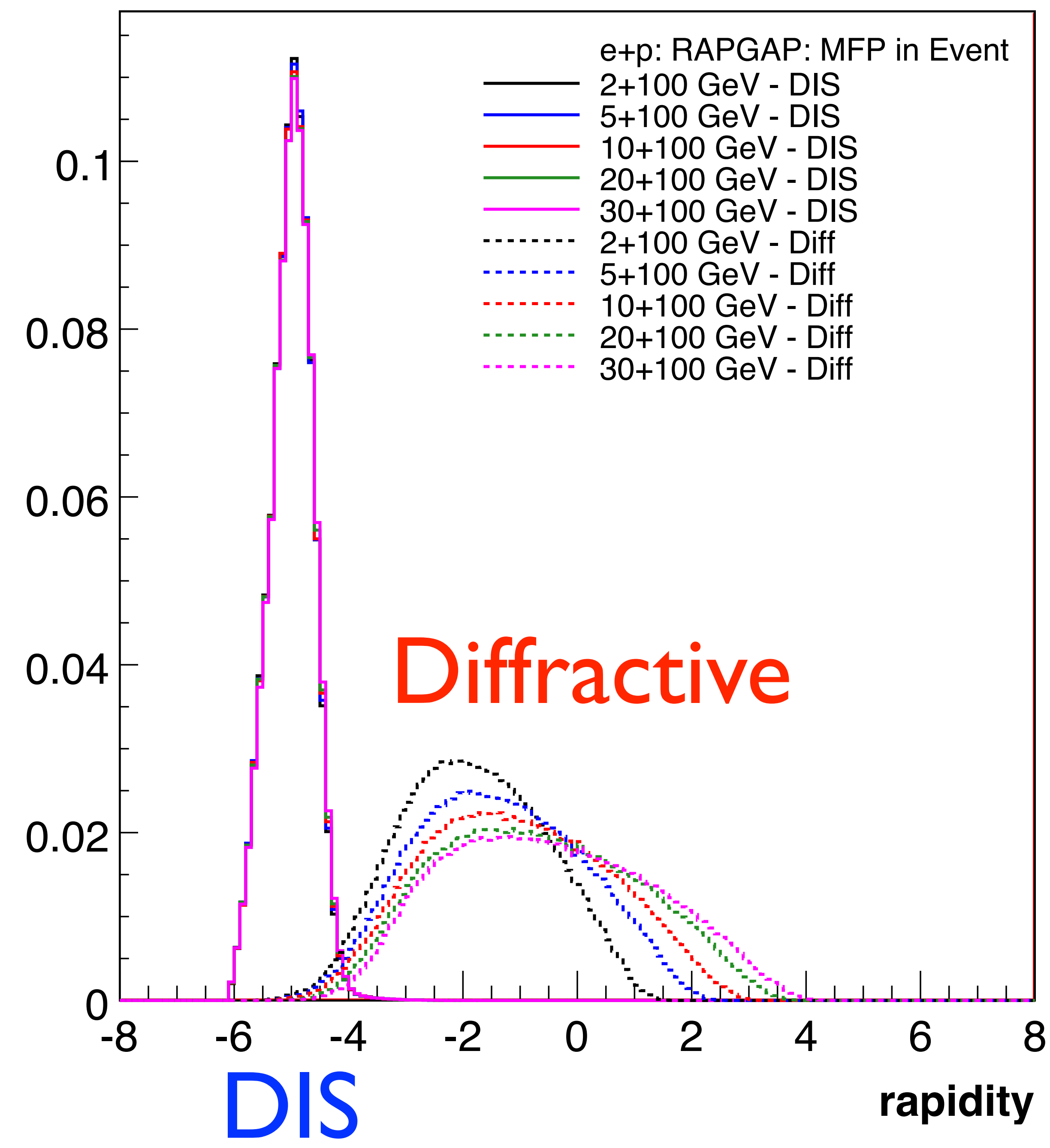
Can this method be used at an EIC?

Large rapidity gaps at eRHIC



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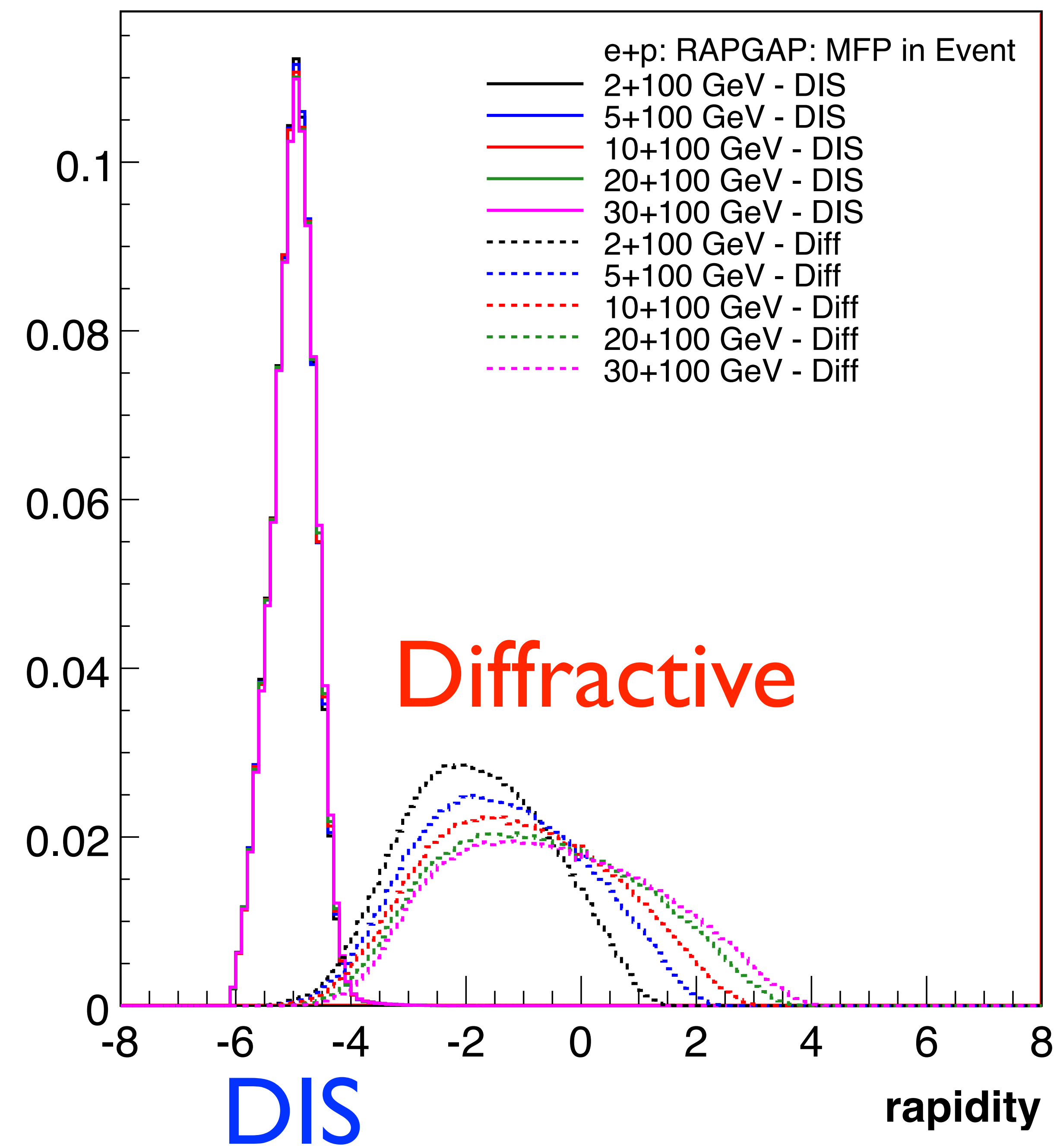

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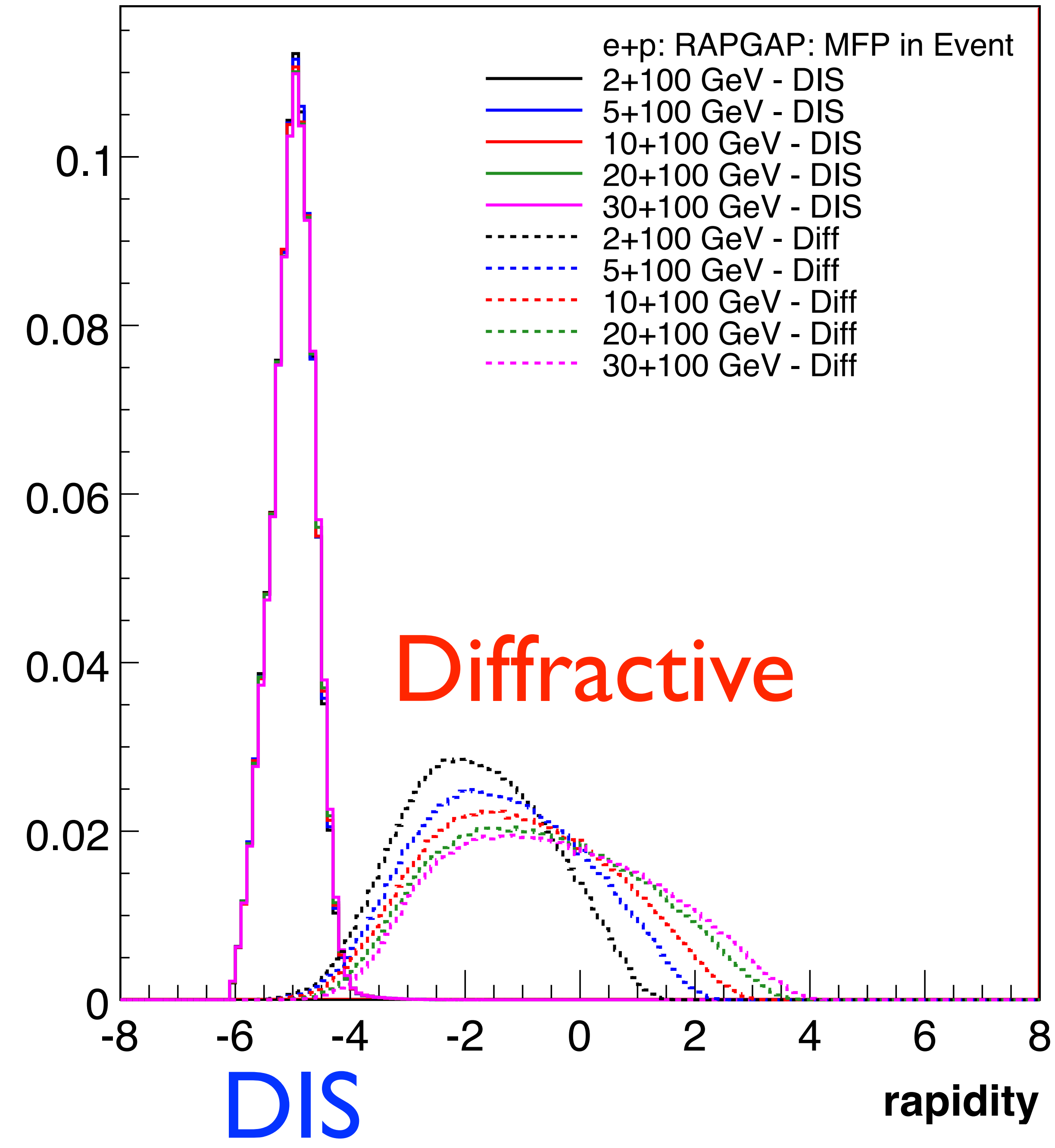

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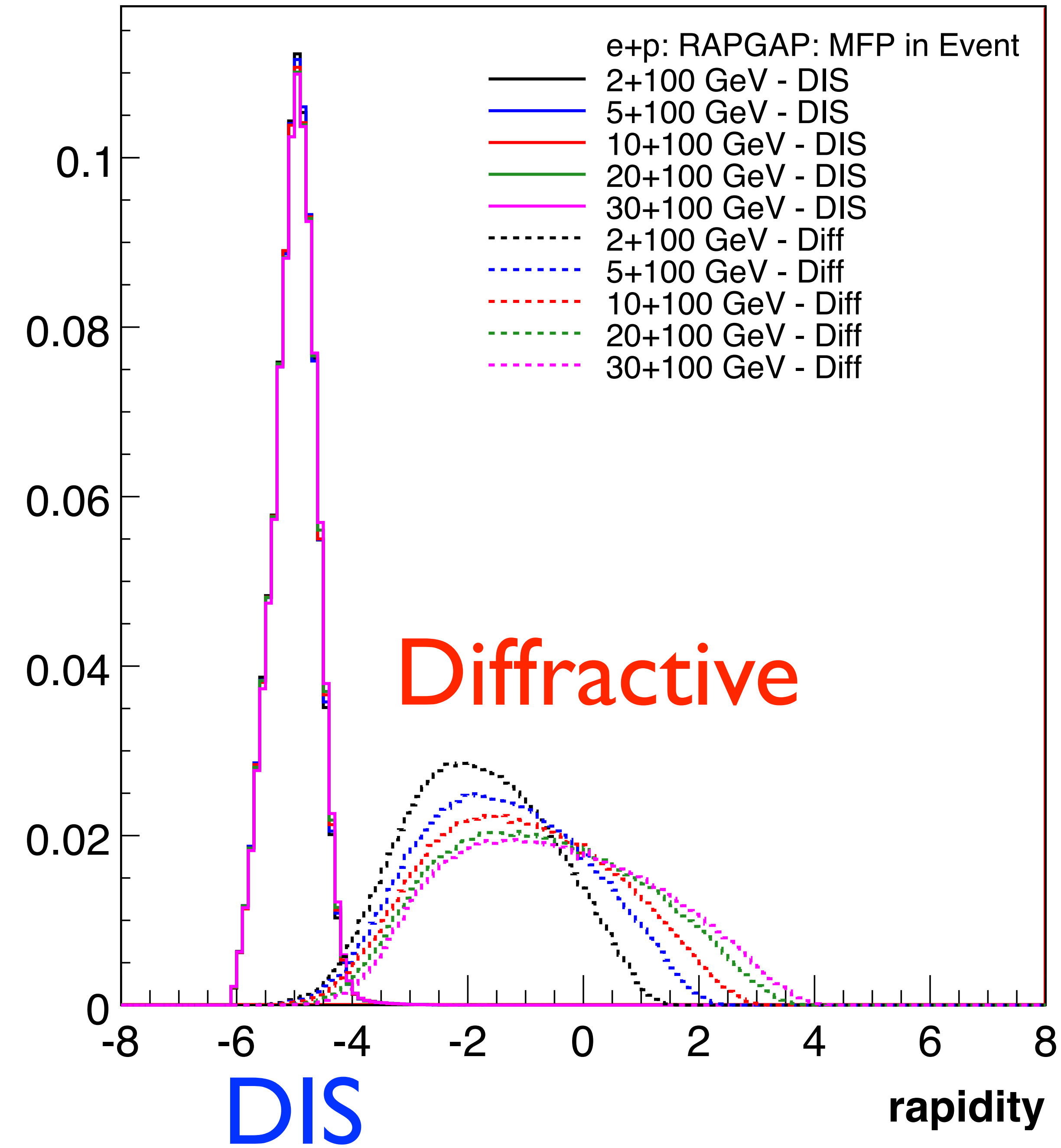

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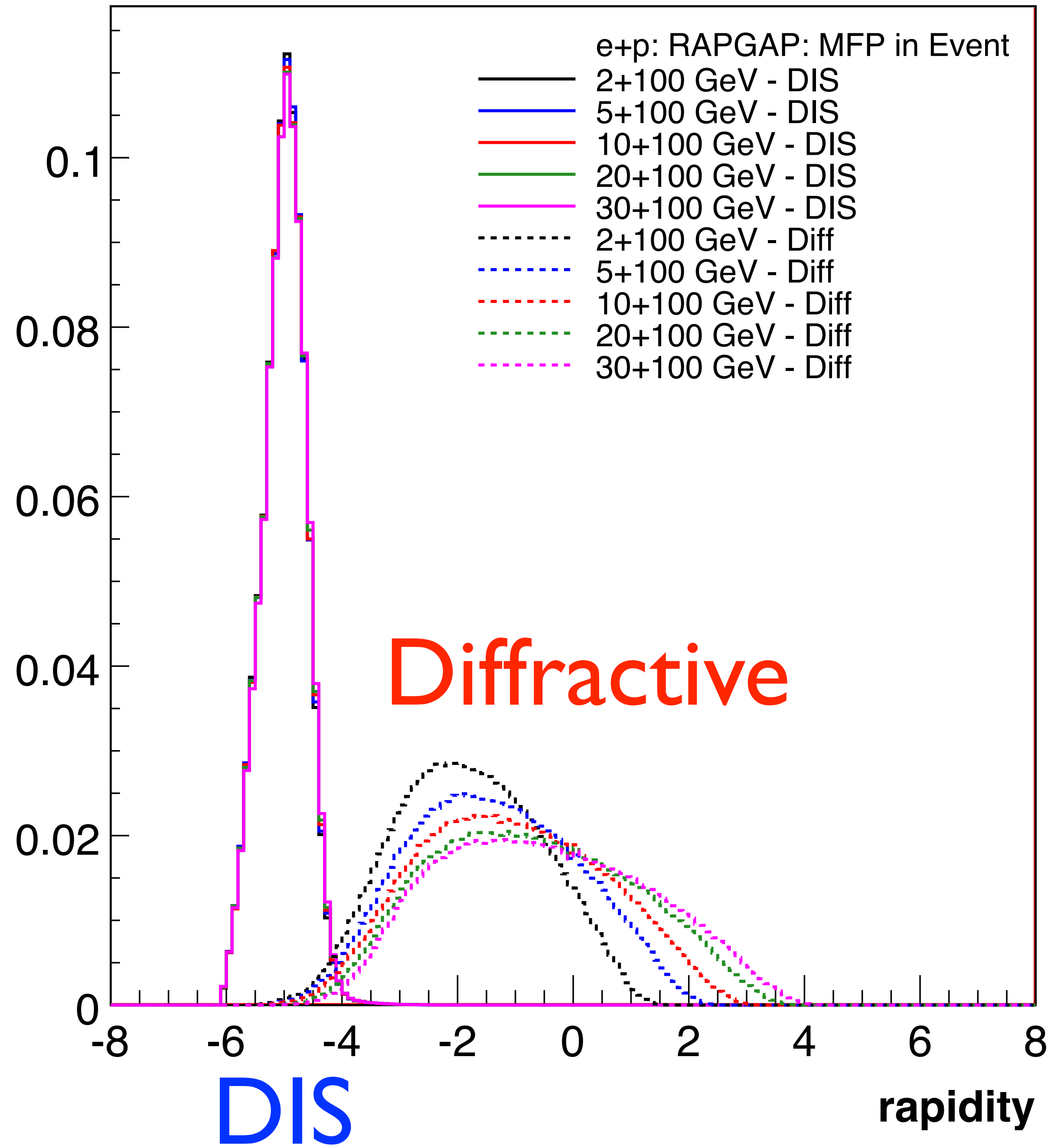

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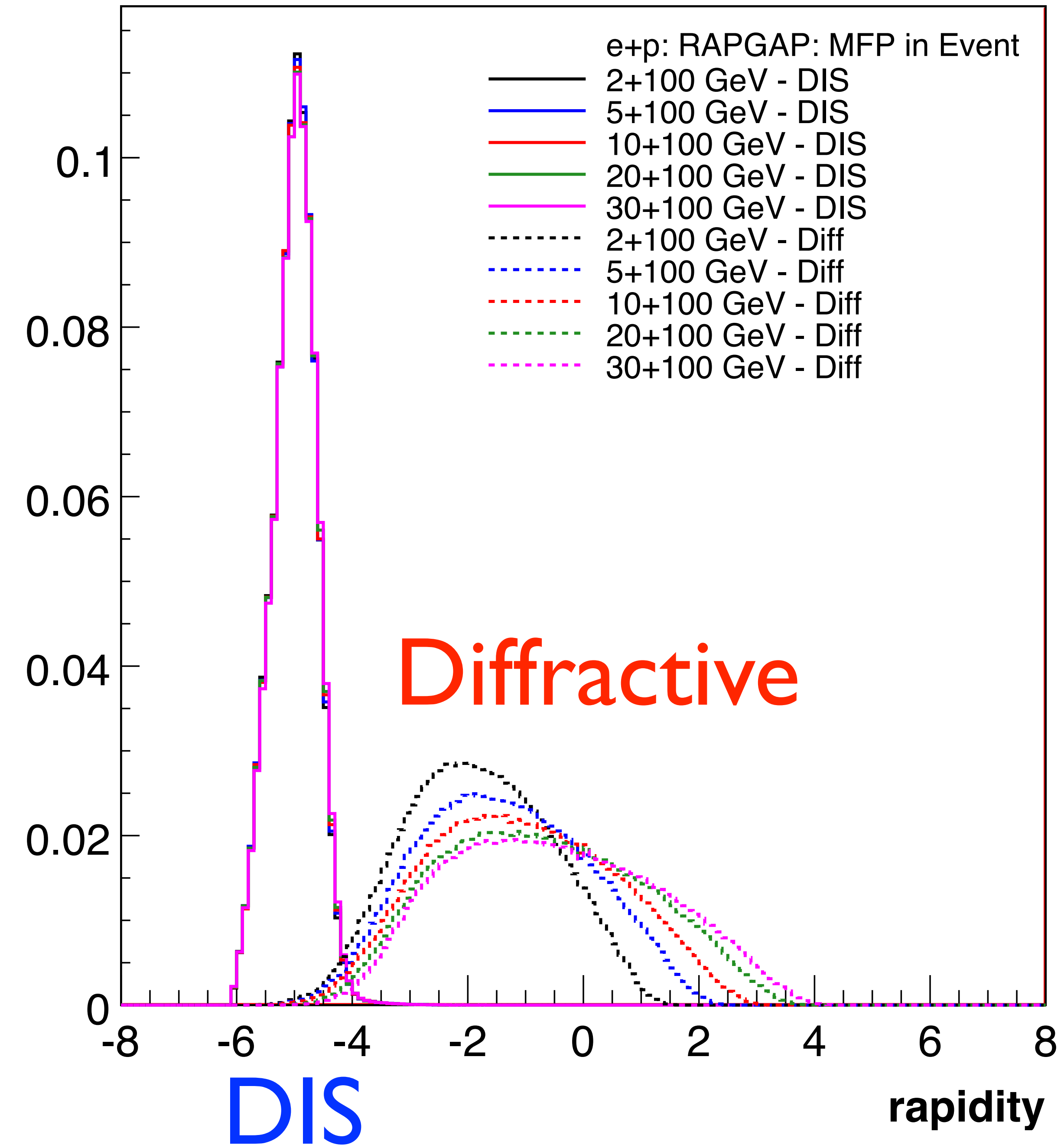

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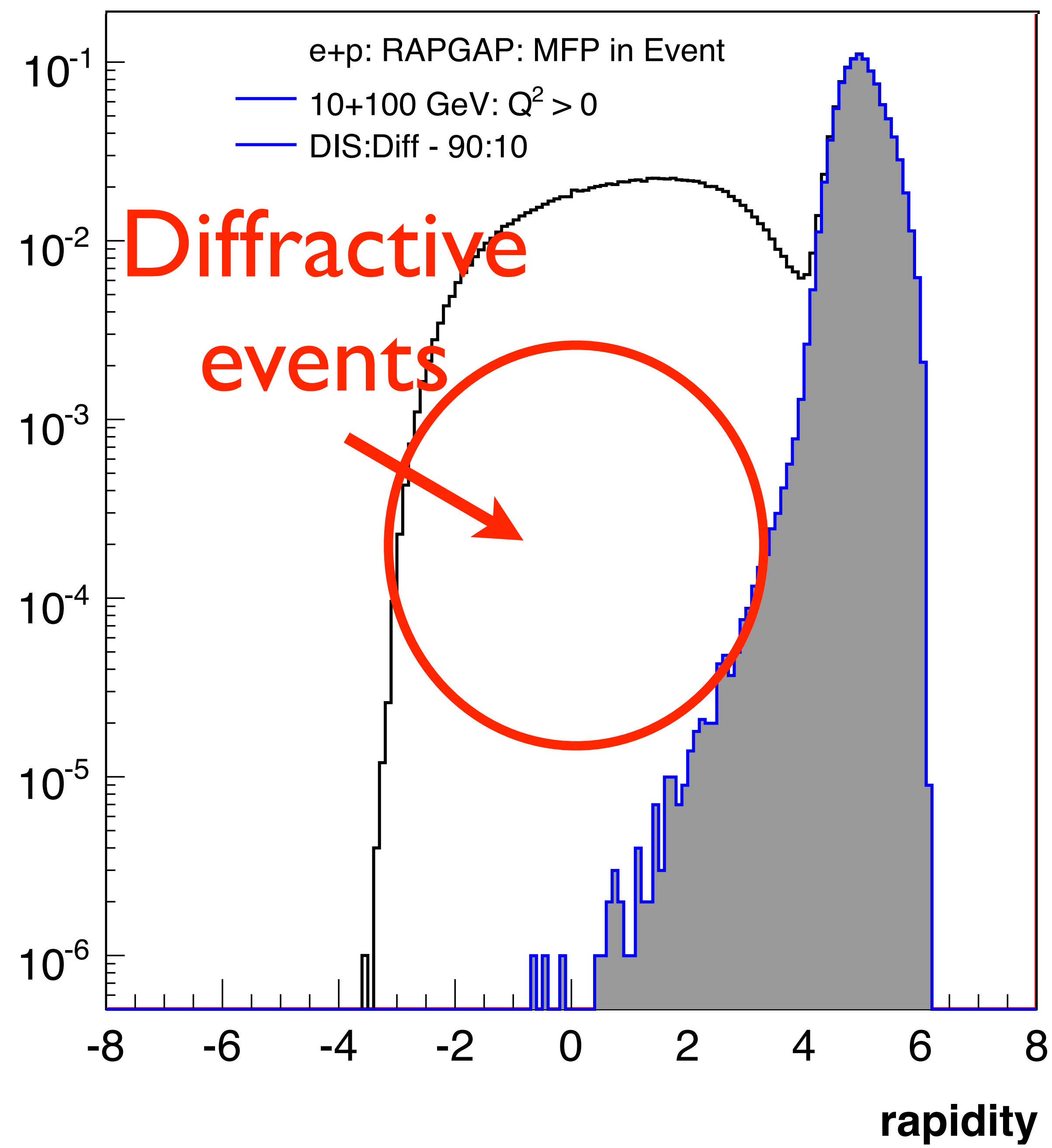
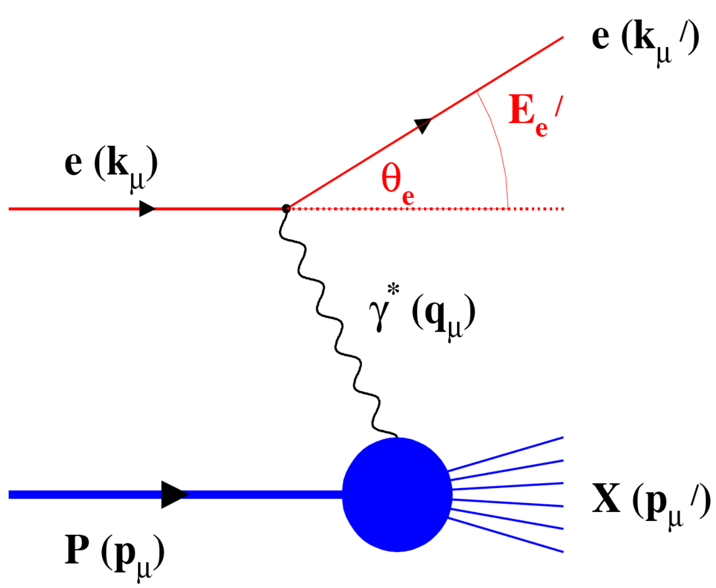
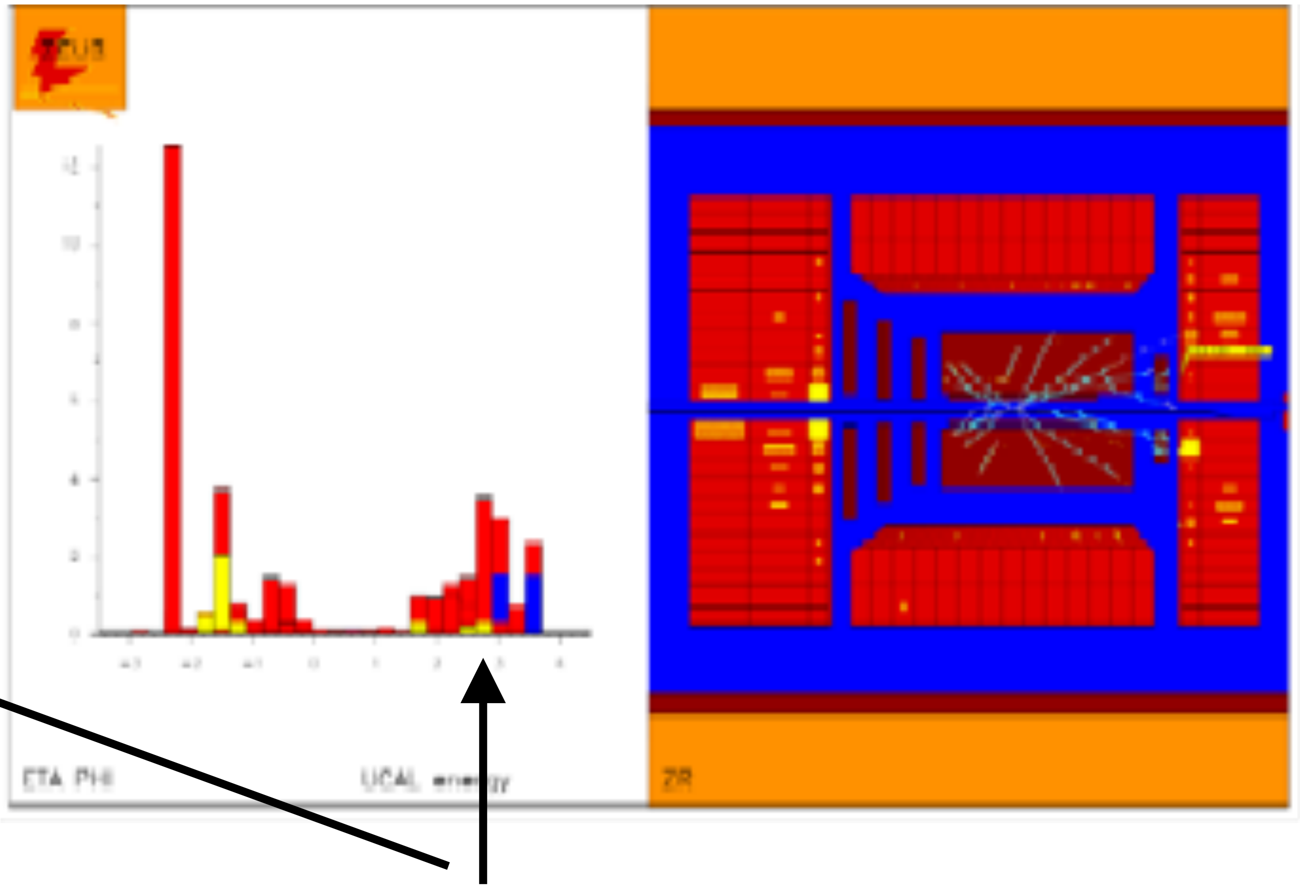


Diffractive Physics in e+A

'Standard DIS event'

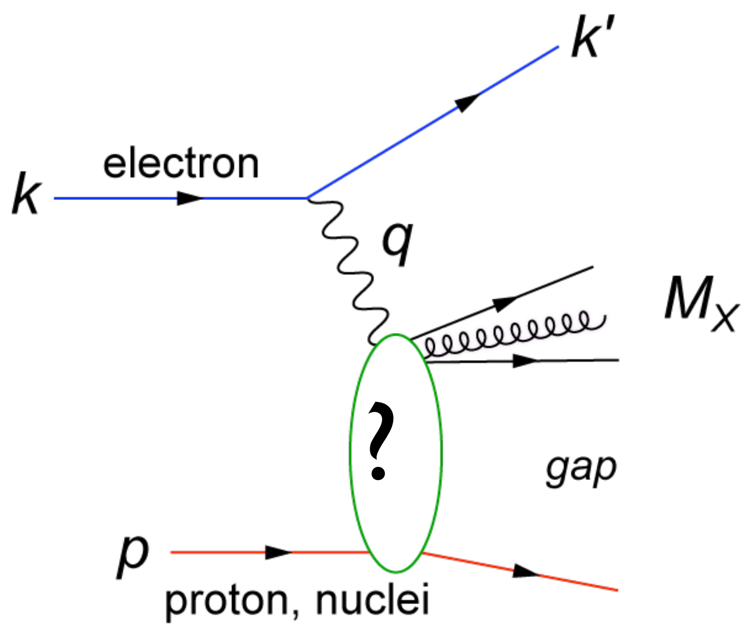


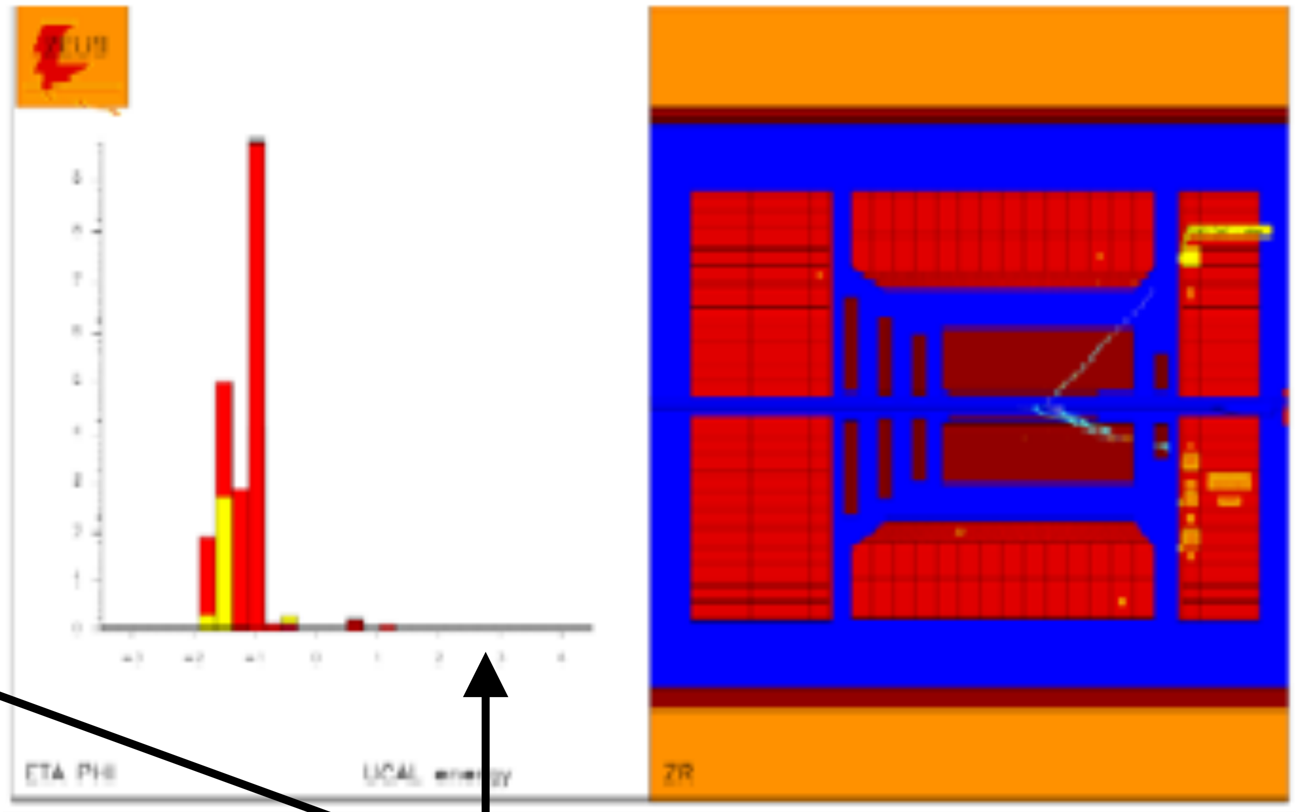


Activity in proton direction

Diffractive Physics in e+A

Diffractive event





- HERA/ep: 15% of all events are hard diffractive

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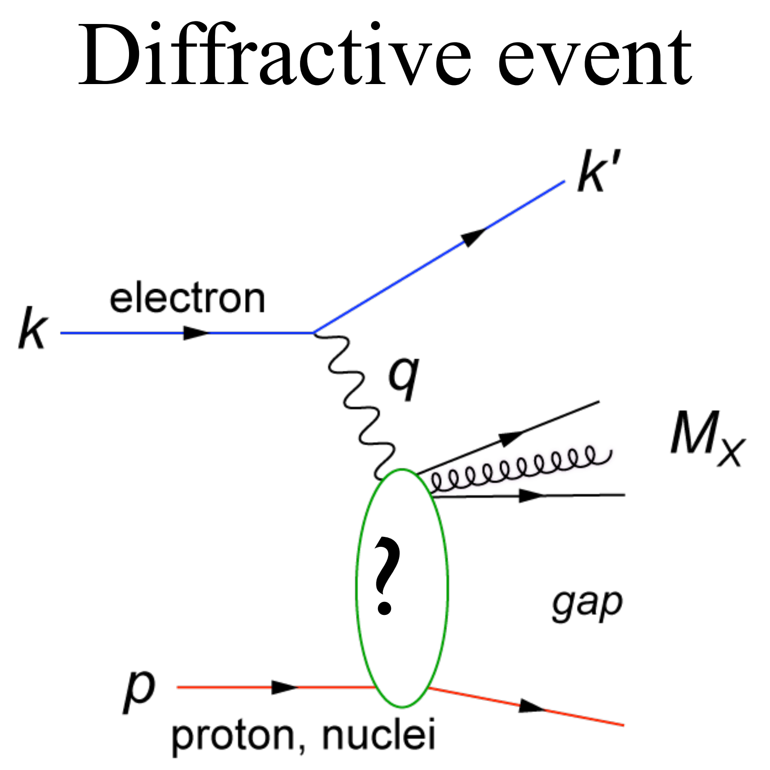

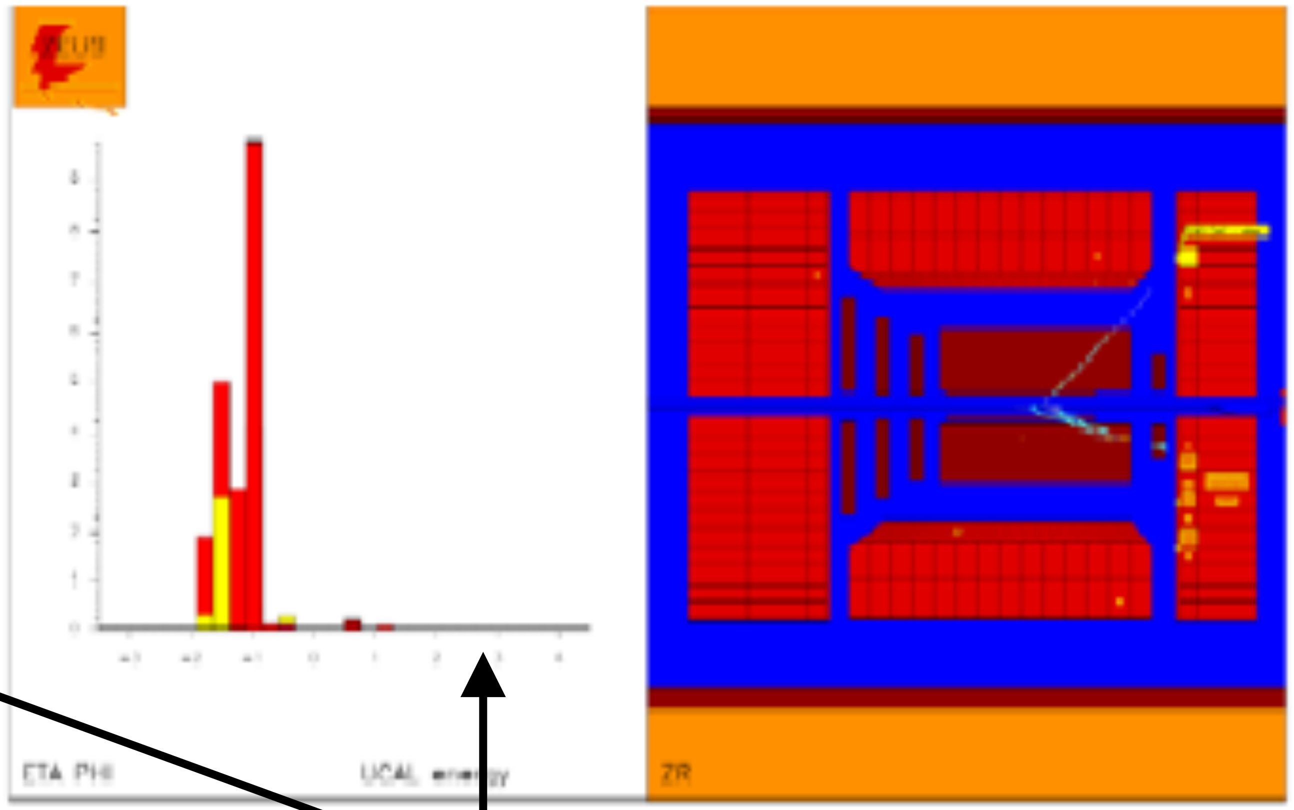

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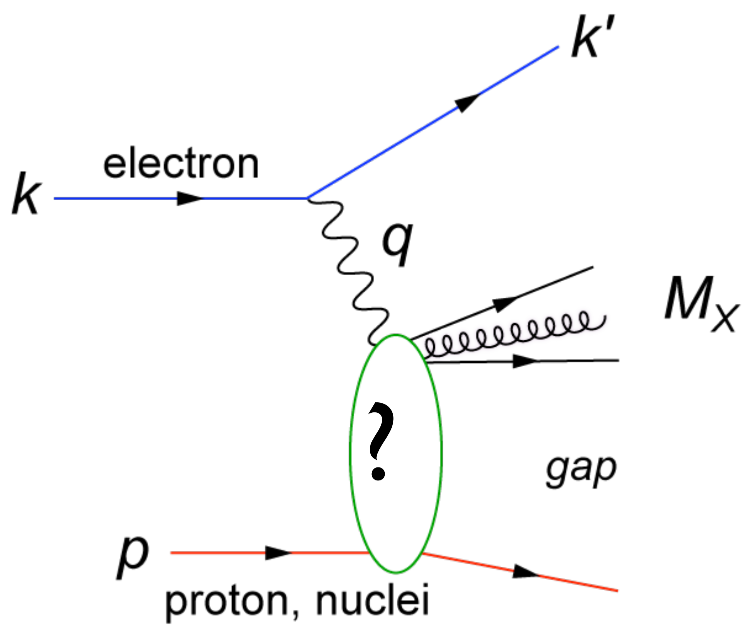

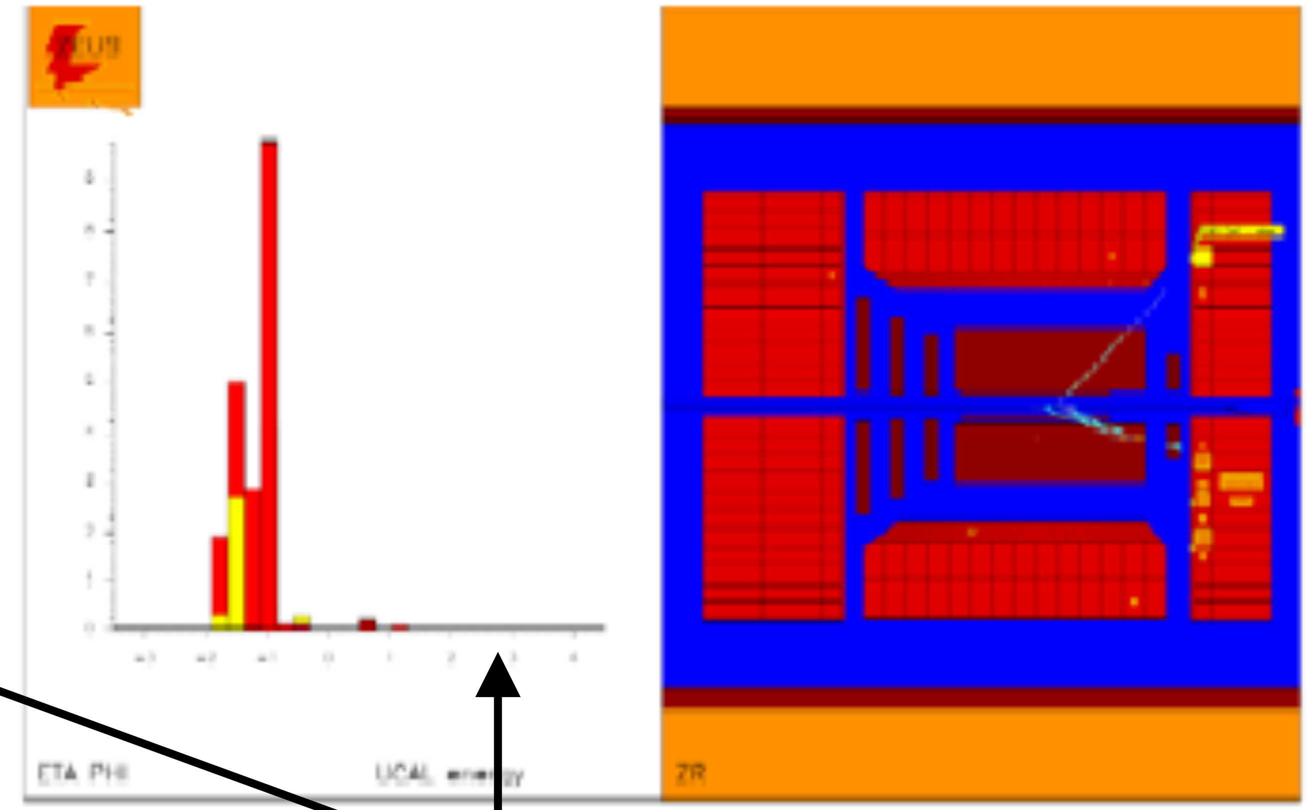

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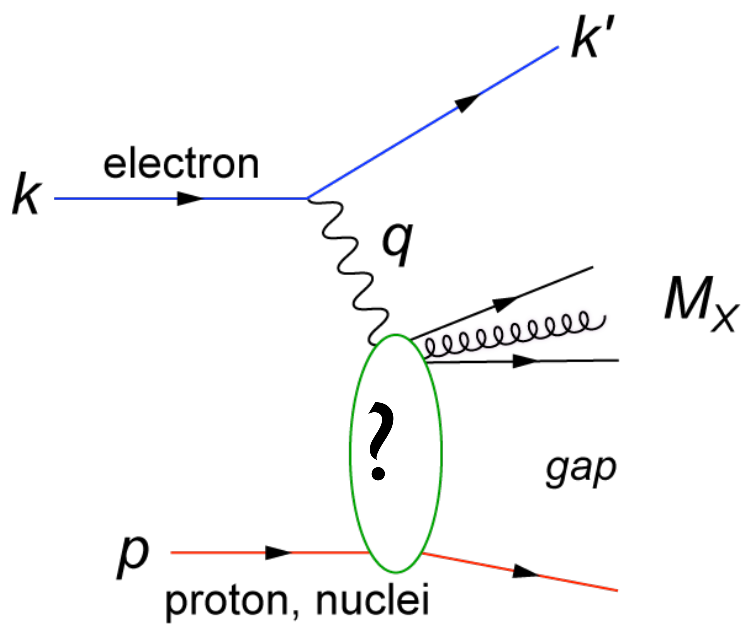

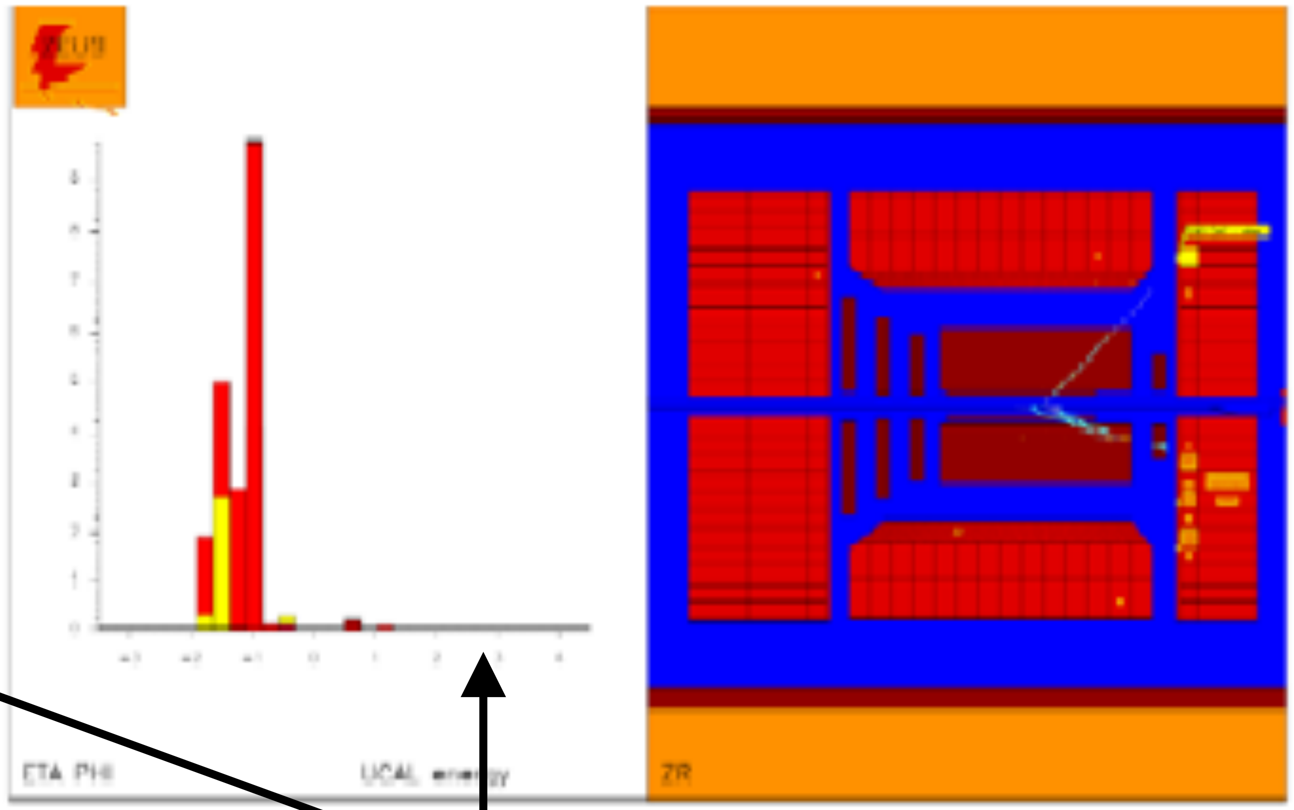

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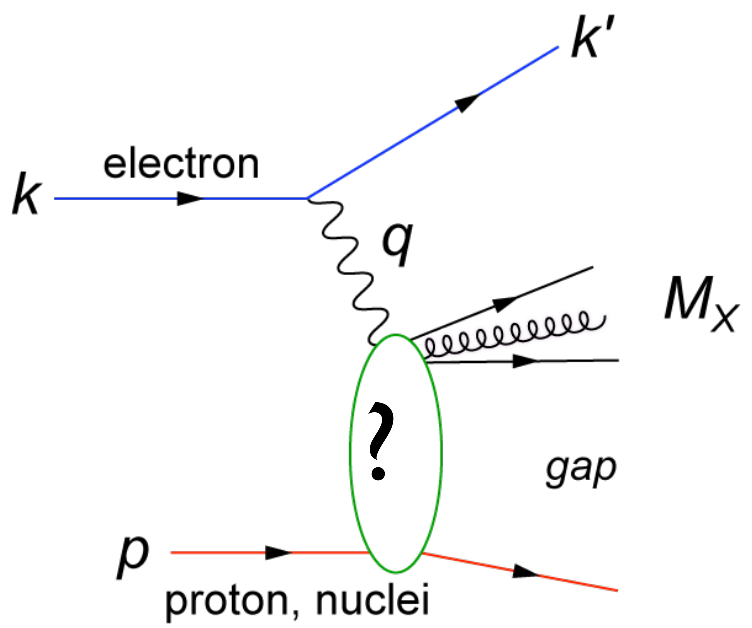

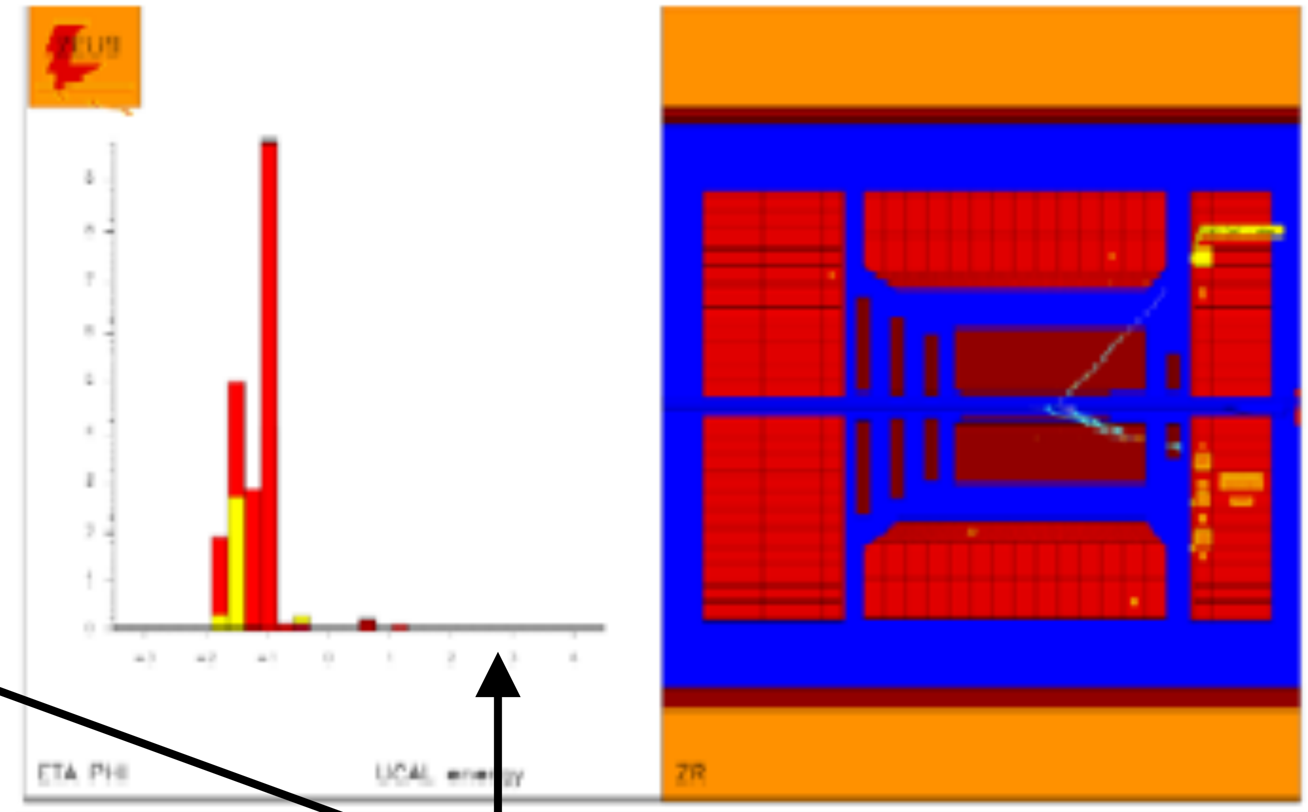

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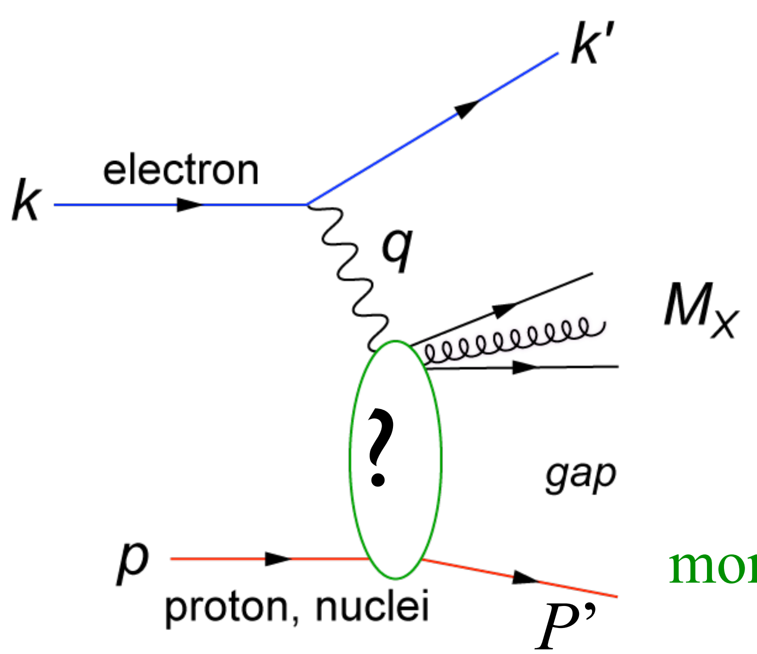
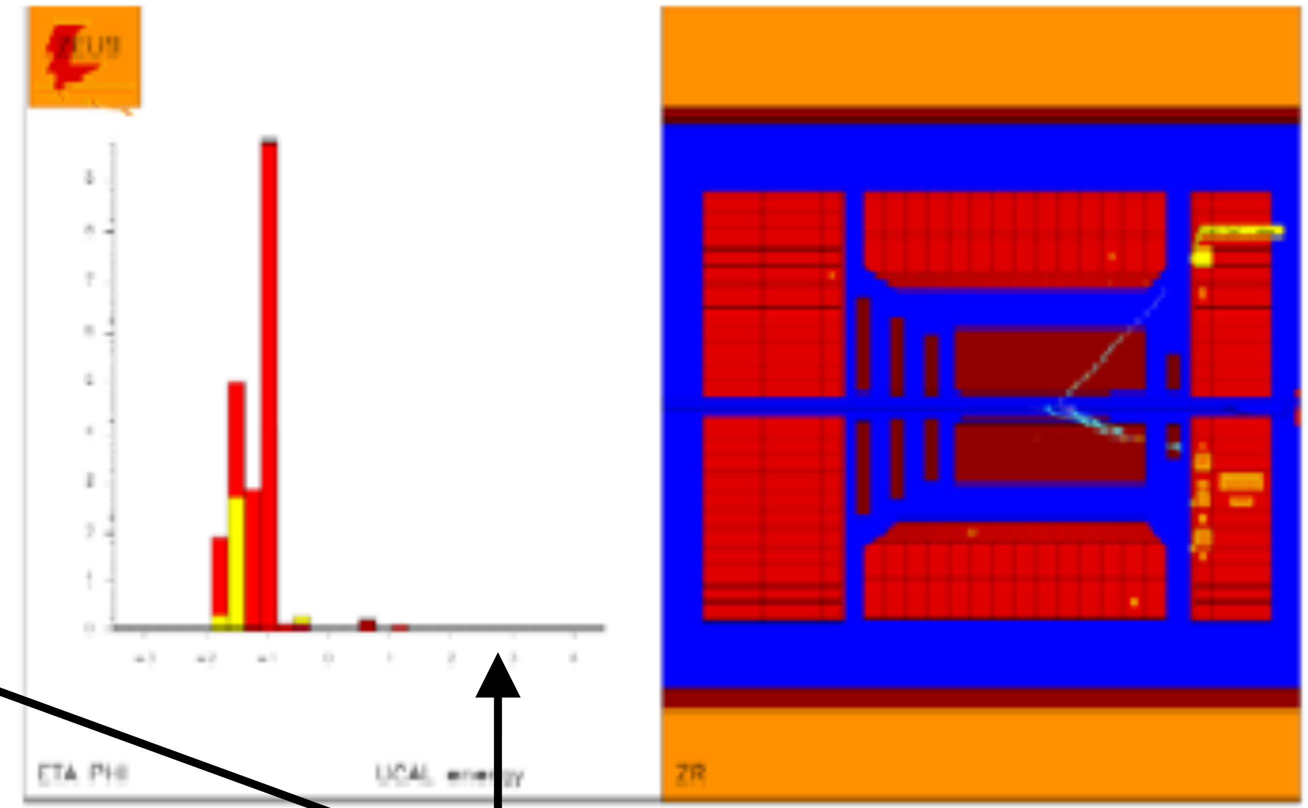


momentum transfer:
$t = (P-P')^2$



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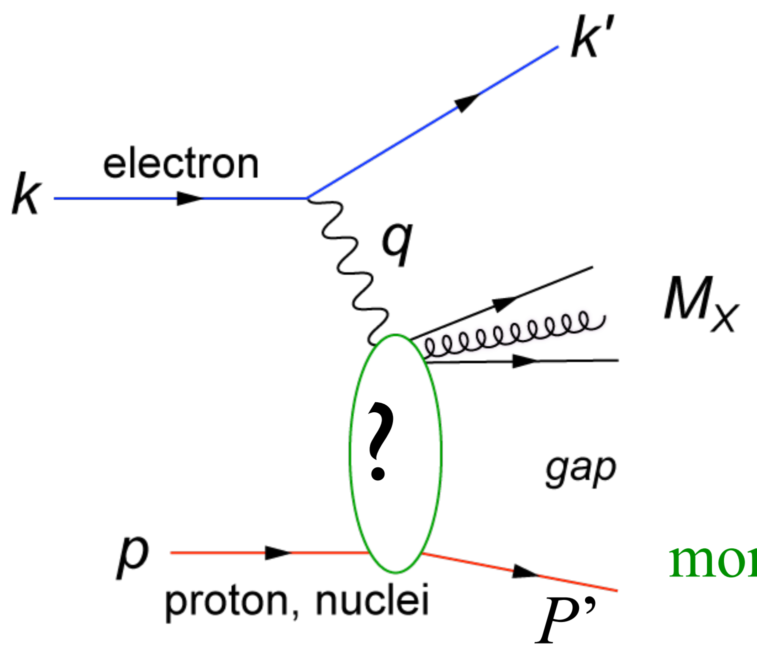

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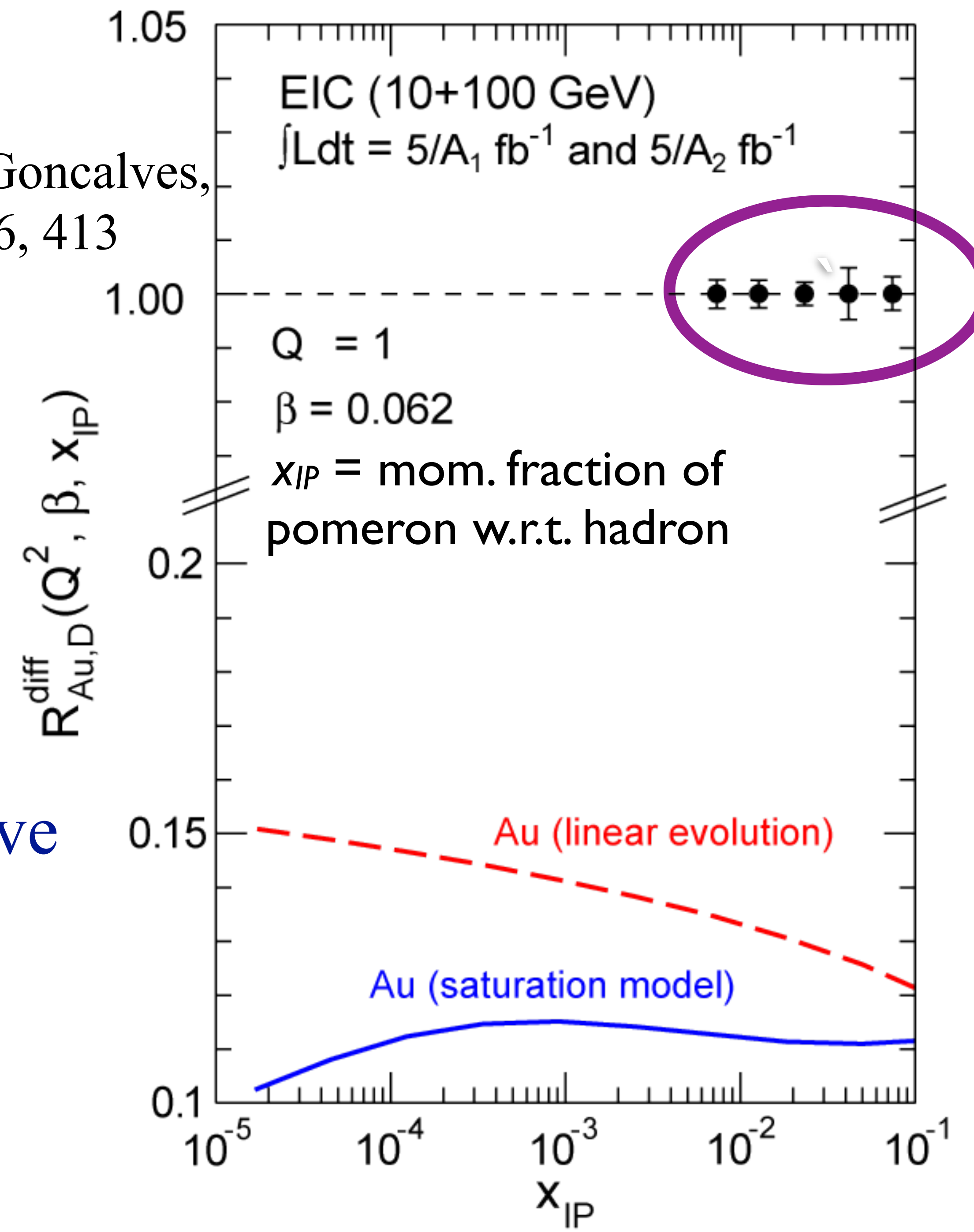
Curves: Kugeratski, Goncalves, Navarra, EPJ C46, 413



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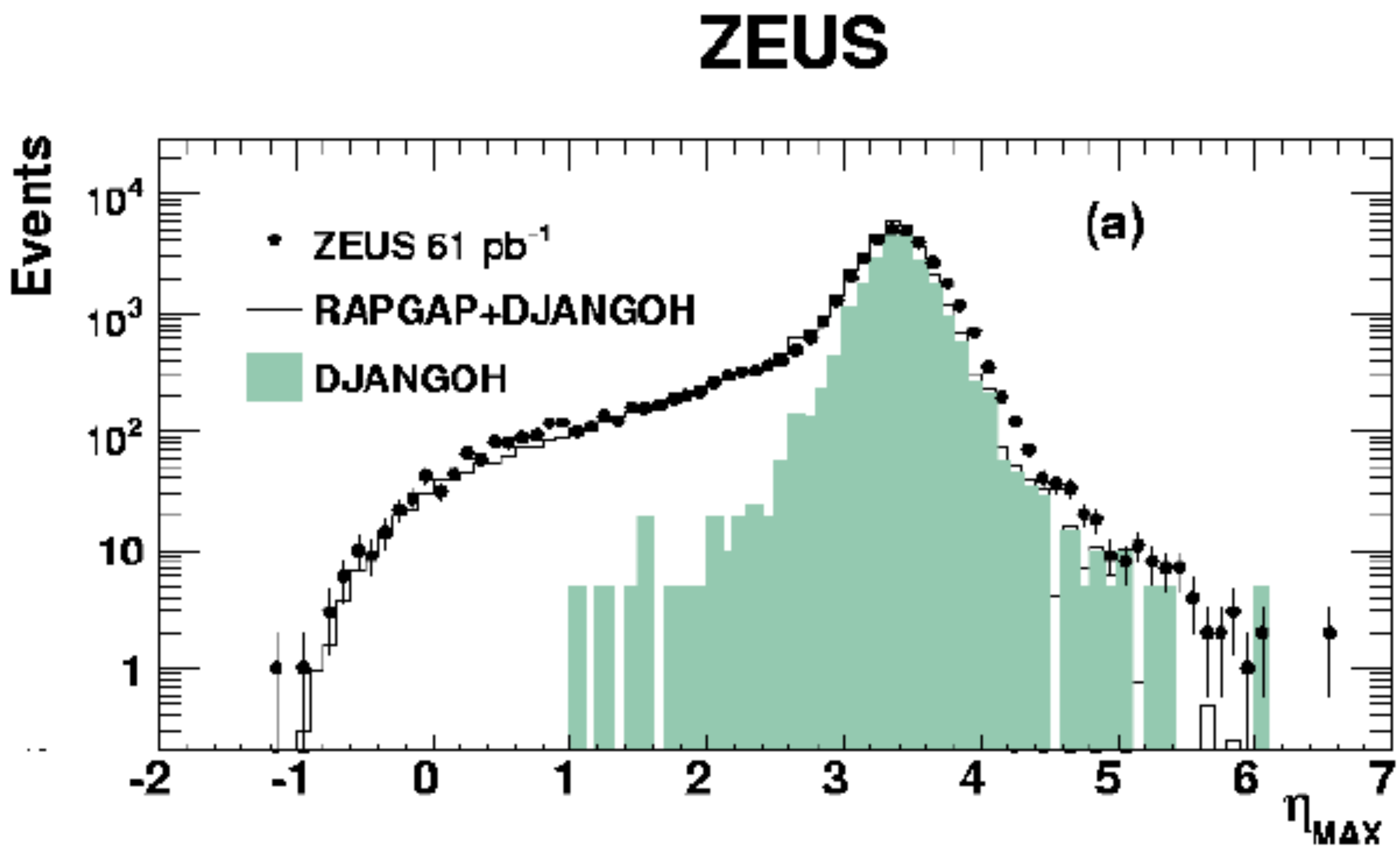
- Distinguish between linear evolutions and saturation models

Diffractive Physics in e+A

- How to measure diffraction in e+A?
  - ➡ Use HERA method of Large Rapidity Gaps
  - ➡ Ideal gap of ~7.7 at HERA units reduced to 3-4 due to spread from hadronisation



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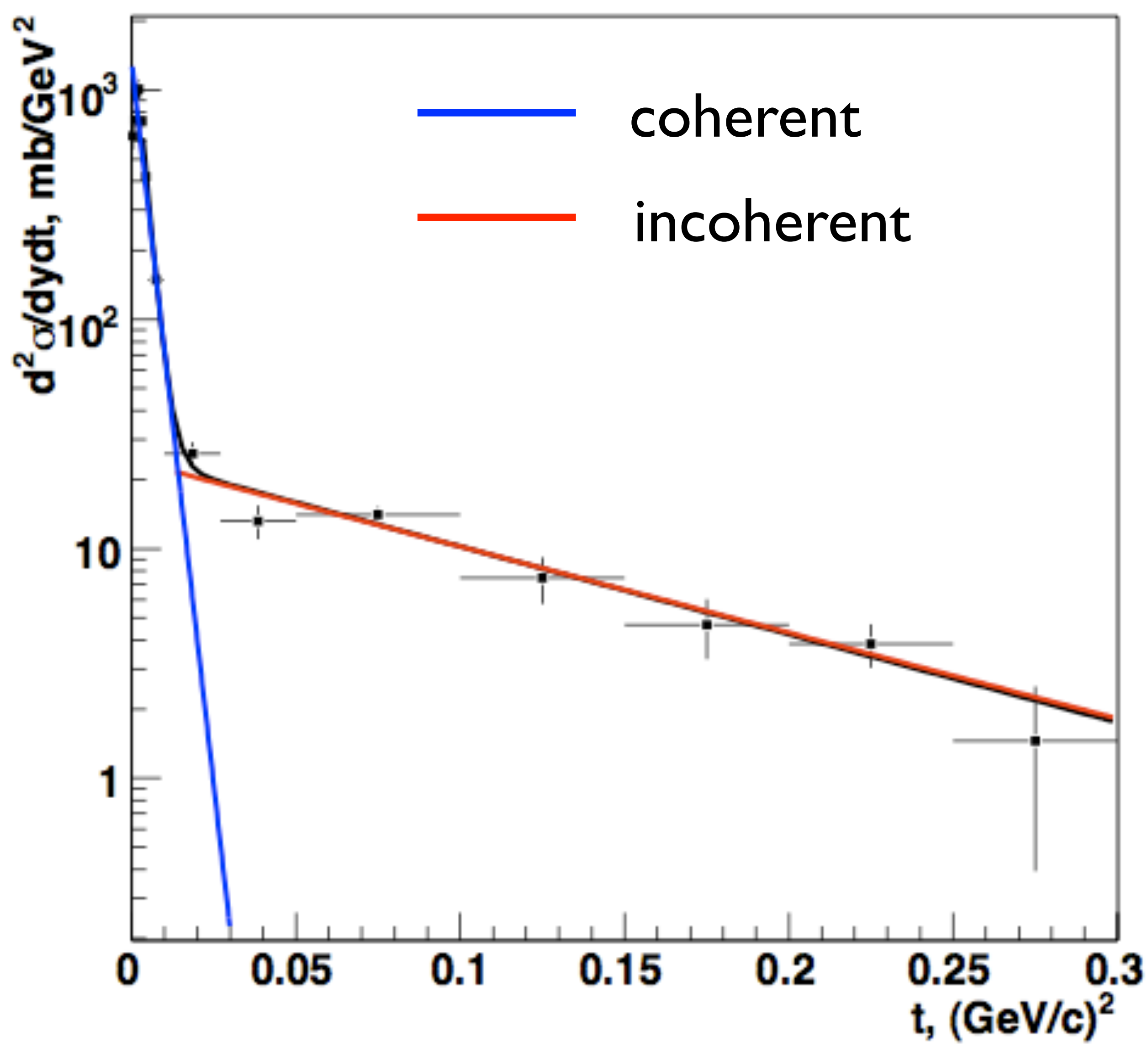
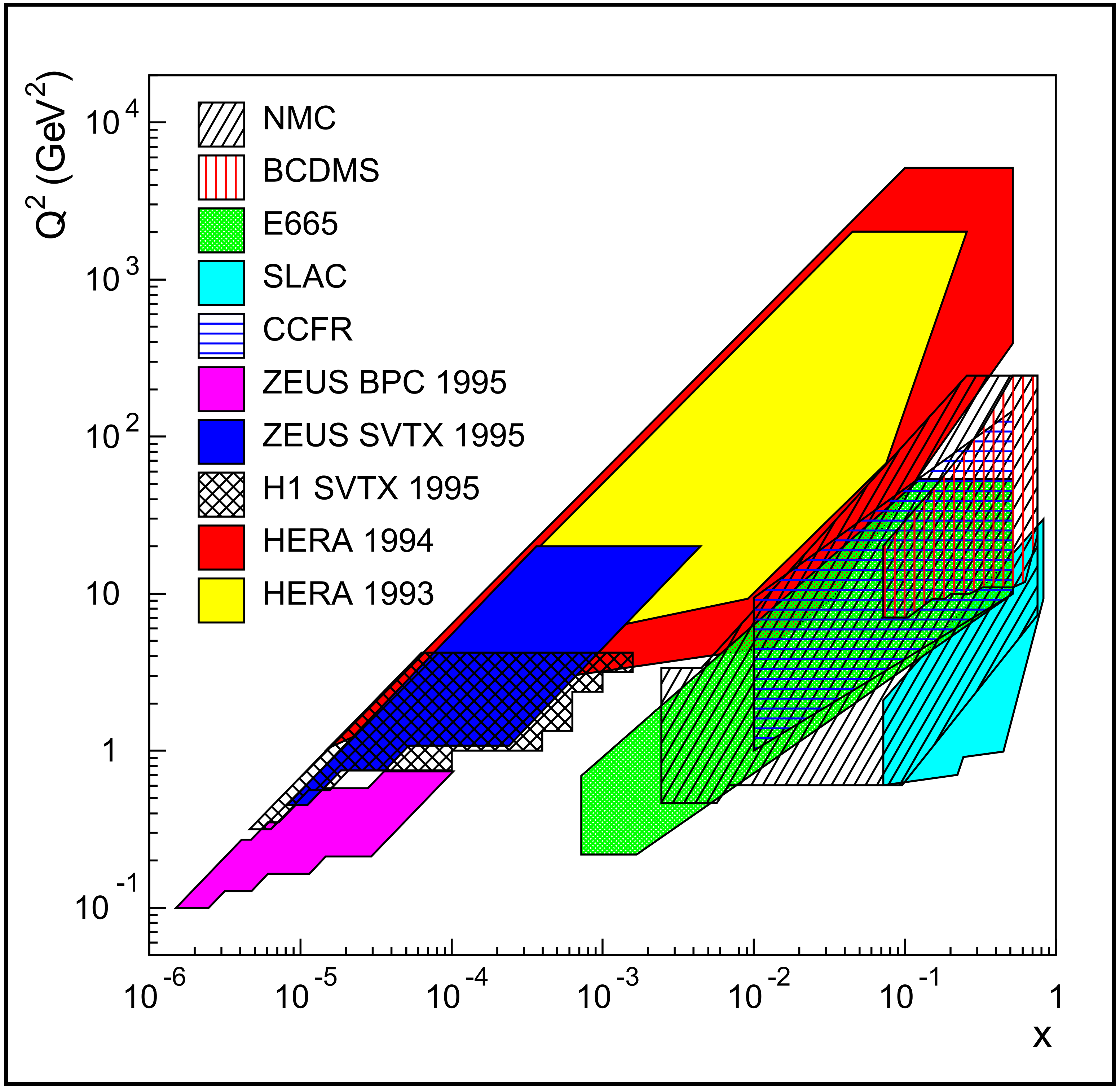
- Issues with measuring diffractive physics in e+A:
  - ➡ t required for nucleus to break-up is small (~ 30 MeV/c^2)
  - ➡ t required for nucleus to be measured in detector >> 30 MeV/c^2
  - ➡ To measure t dependence, must measure exclusive diffraction (e.g. vector mesons - $t \sim p_T^2$)

STAR - UPC Collisions



Requirements for an Electron Ion Collider



Well mapped in *e+p*

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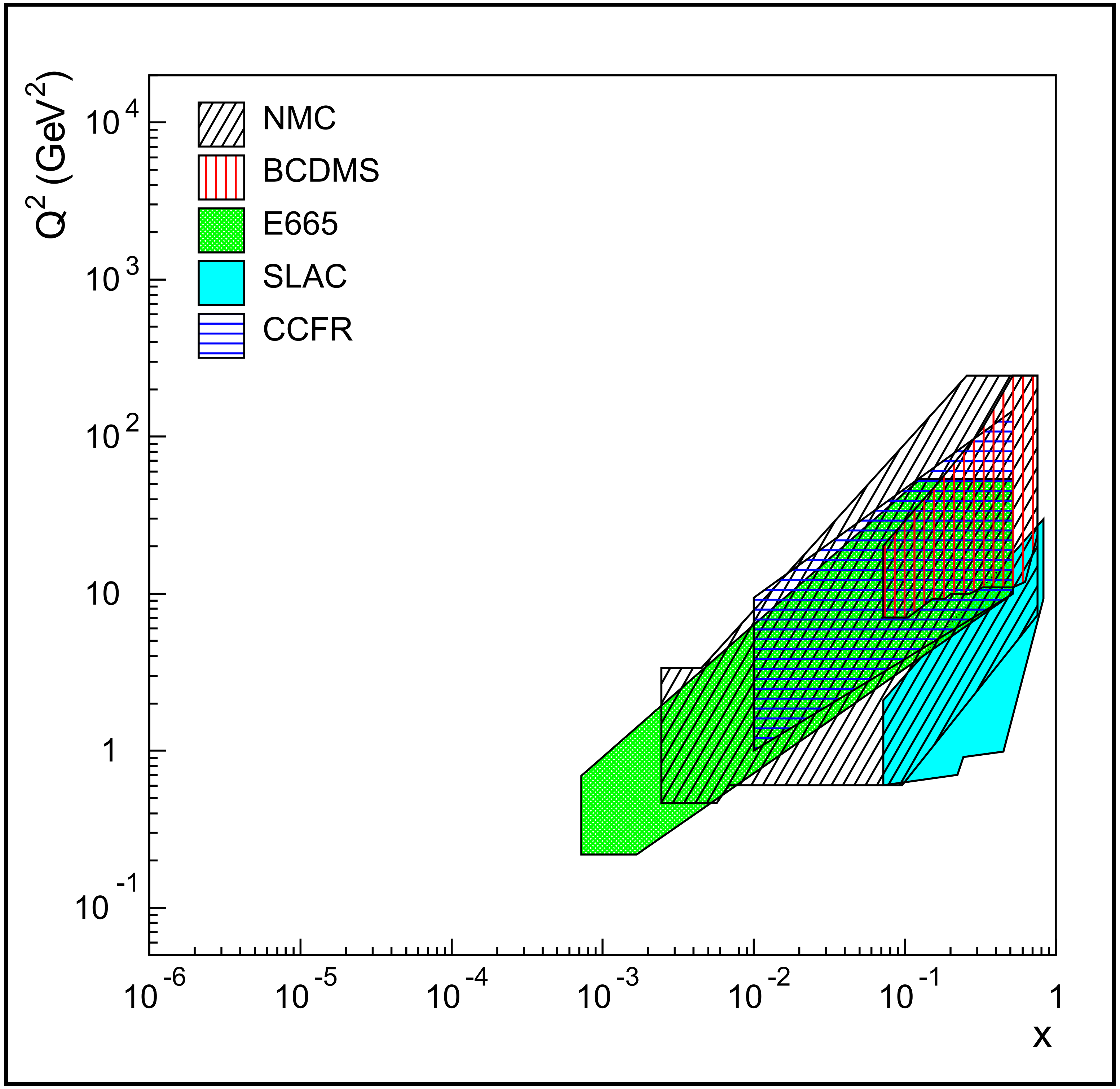

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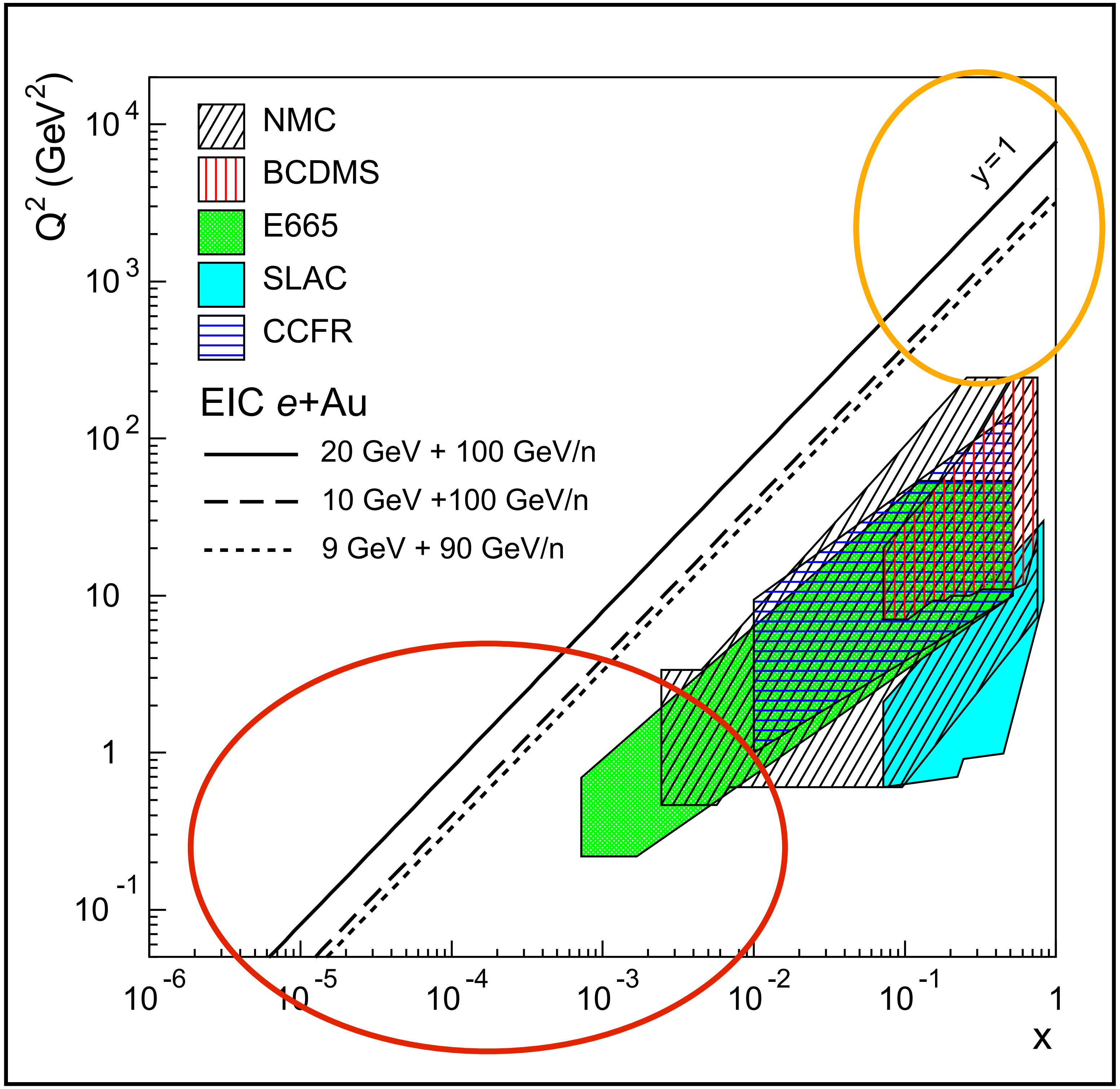

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Electron Ion Collider:

- $\mathcal{L}$(EIC) > 100 × $\mathcal{L}$(HERA)
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  - E_e = 3 - 20 GeV
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- Hadron Beams
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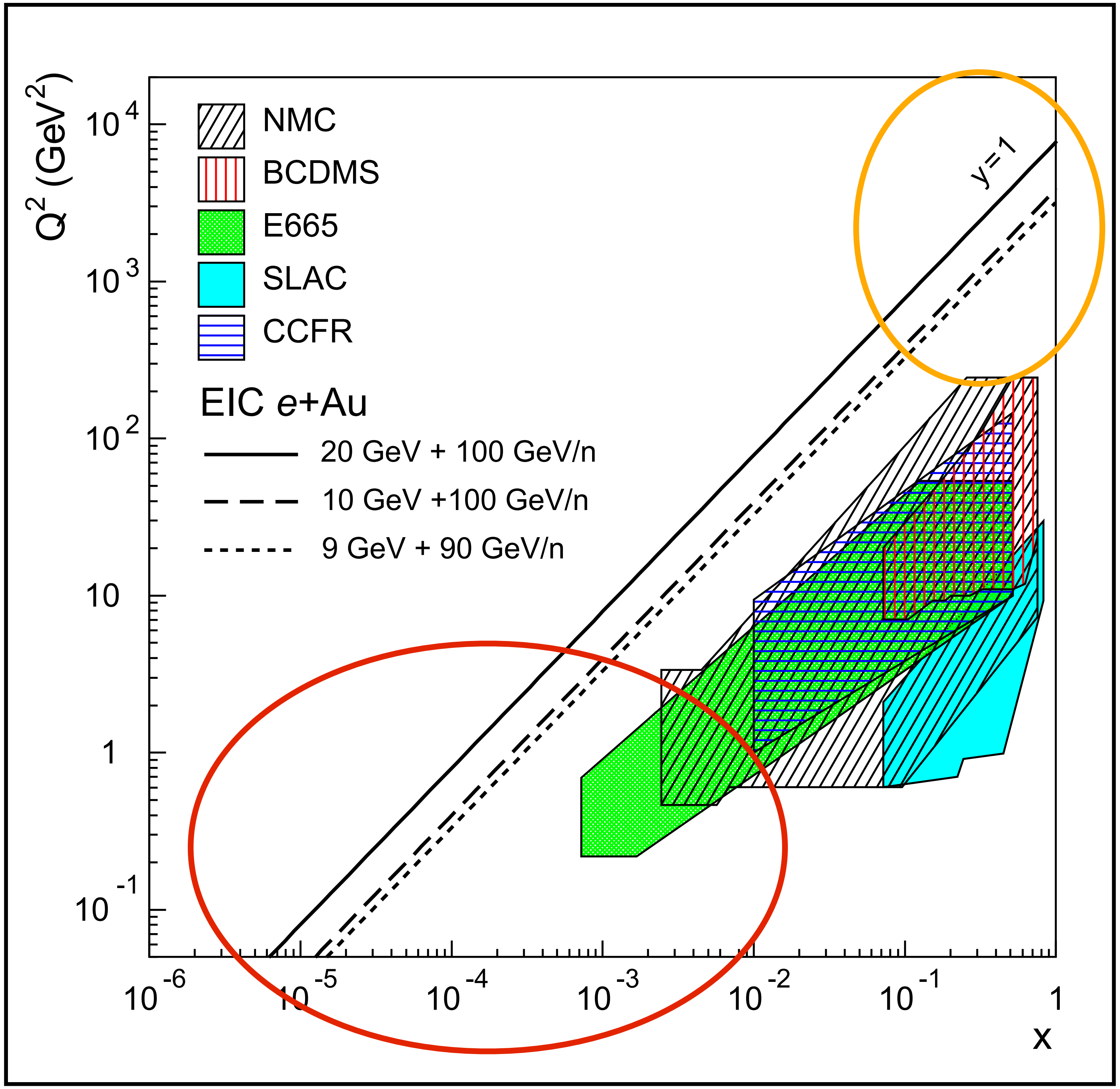

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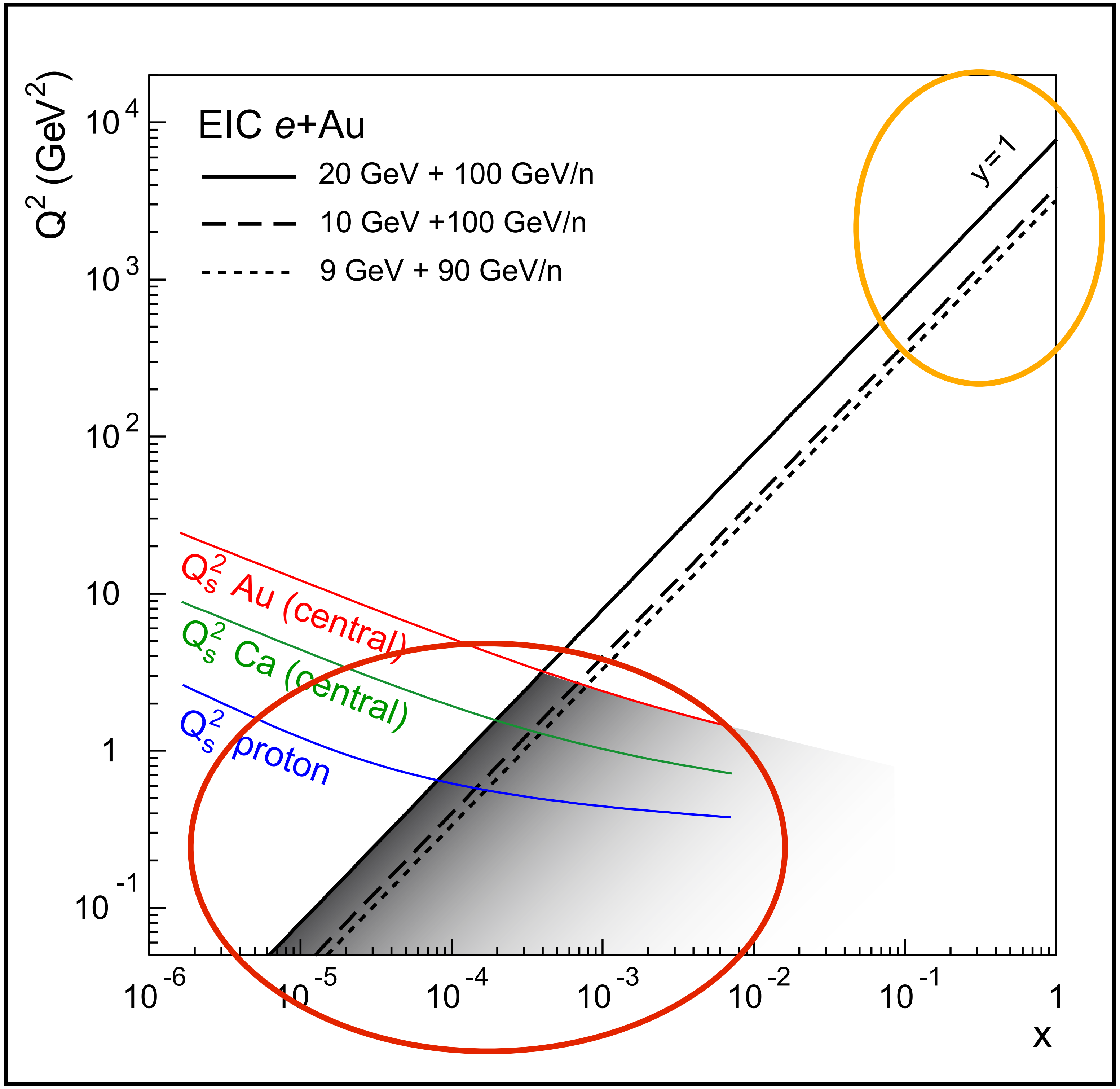

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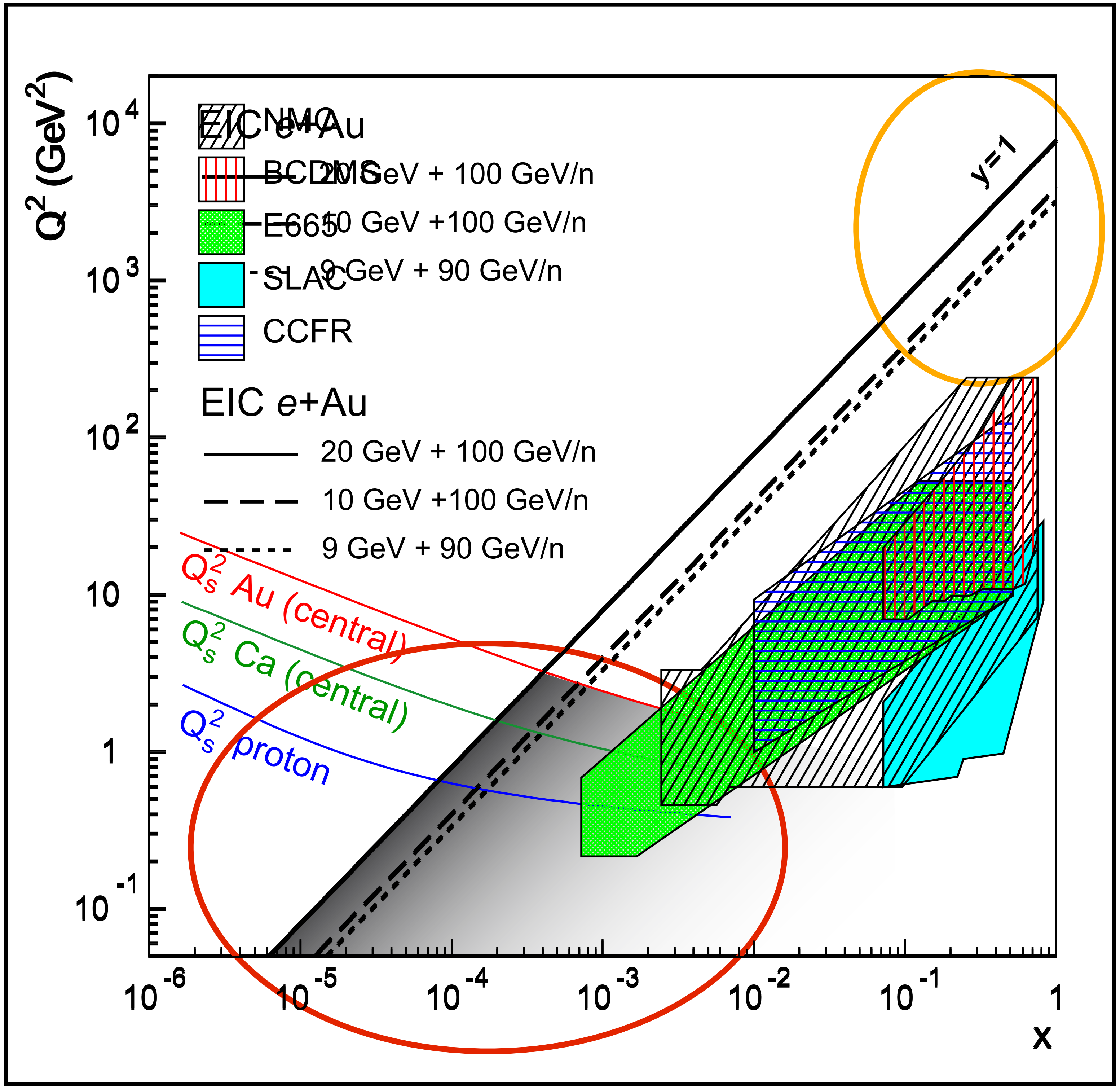

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Experimental Reality

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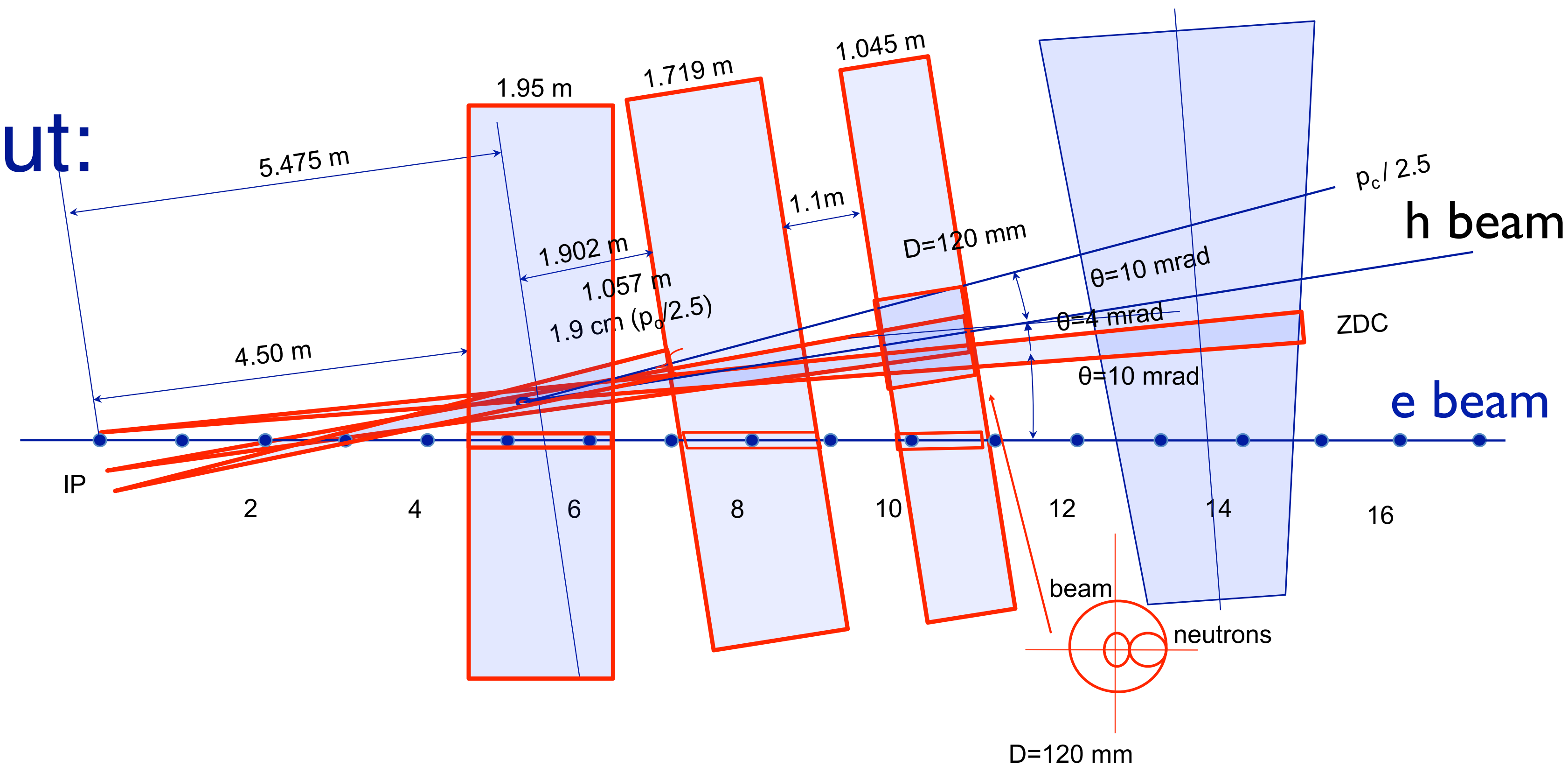

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- through triplet for *n* and
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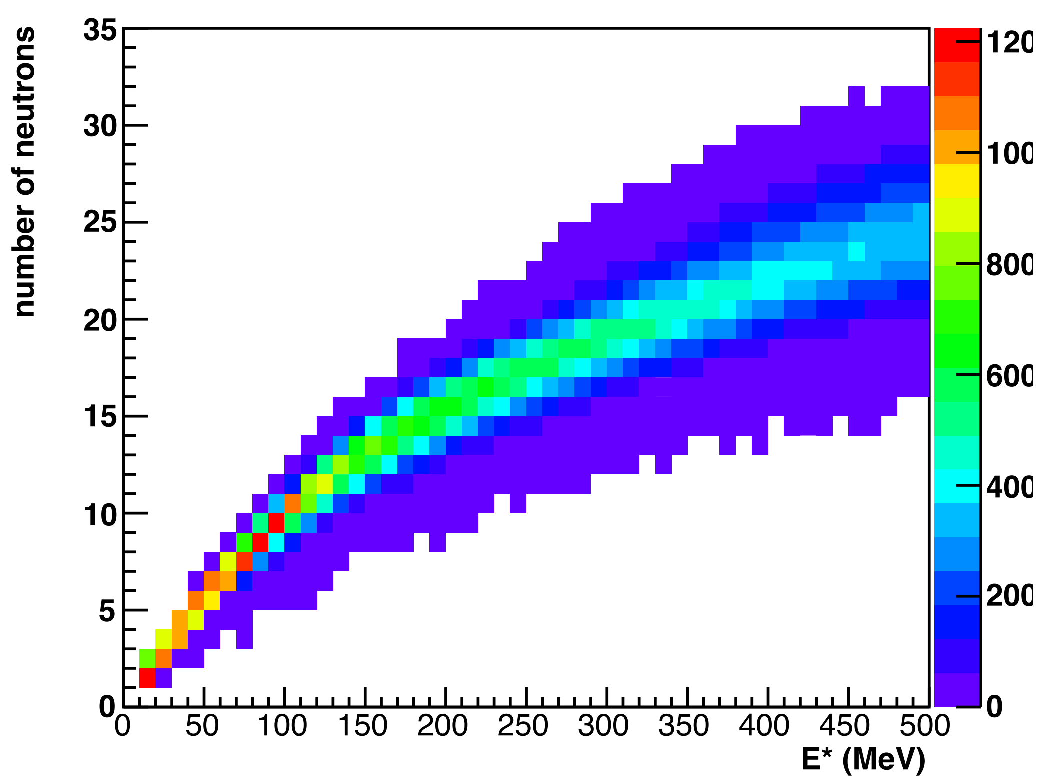

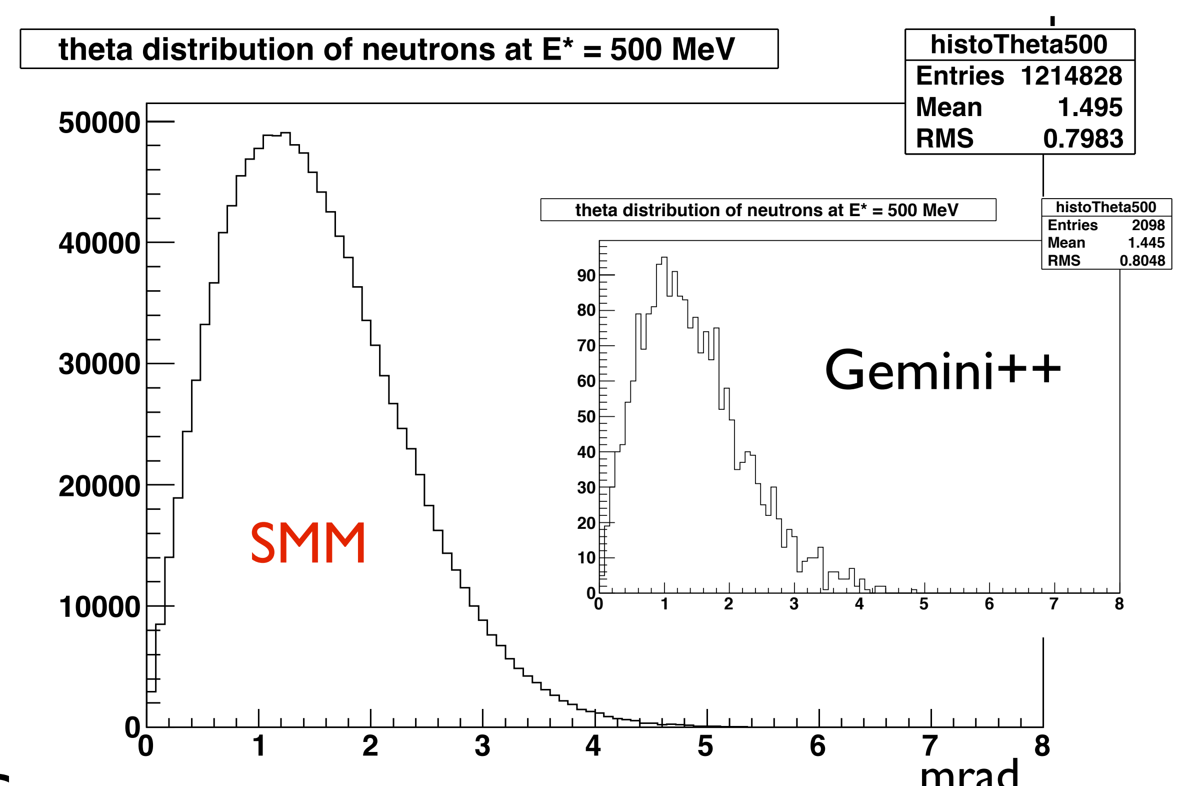

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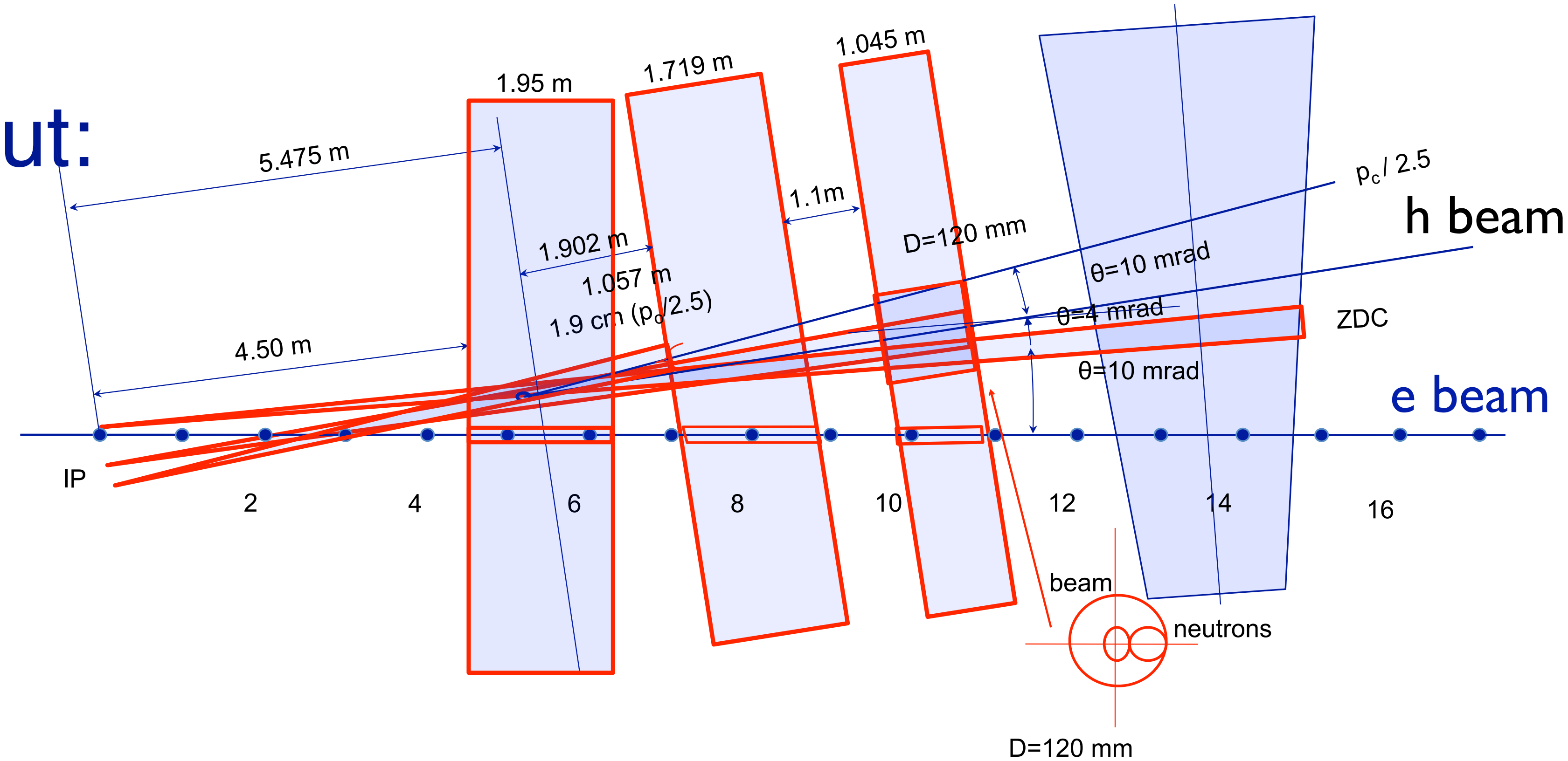

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All breakup simulators show it works:

- For $E^*_{tot} \geq$ 10 MeV and 2.5 mrad *n* acceptance we have rejection power of at least 10^5.
- Separating incoherent from coherent diffractive events is possible at a collider with *n*-detection via ZDCs alone

Detecting Nuclear Breakup

- ➡ Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- ➡ Focus on n emission
  - Zero-Degree Calorimeter
  - Requires careful design of IR

- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

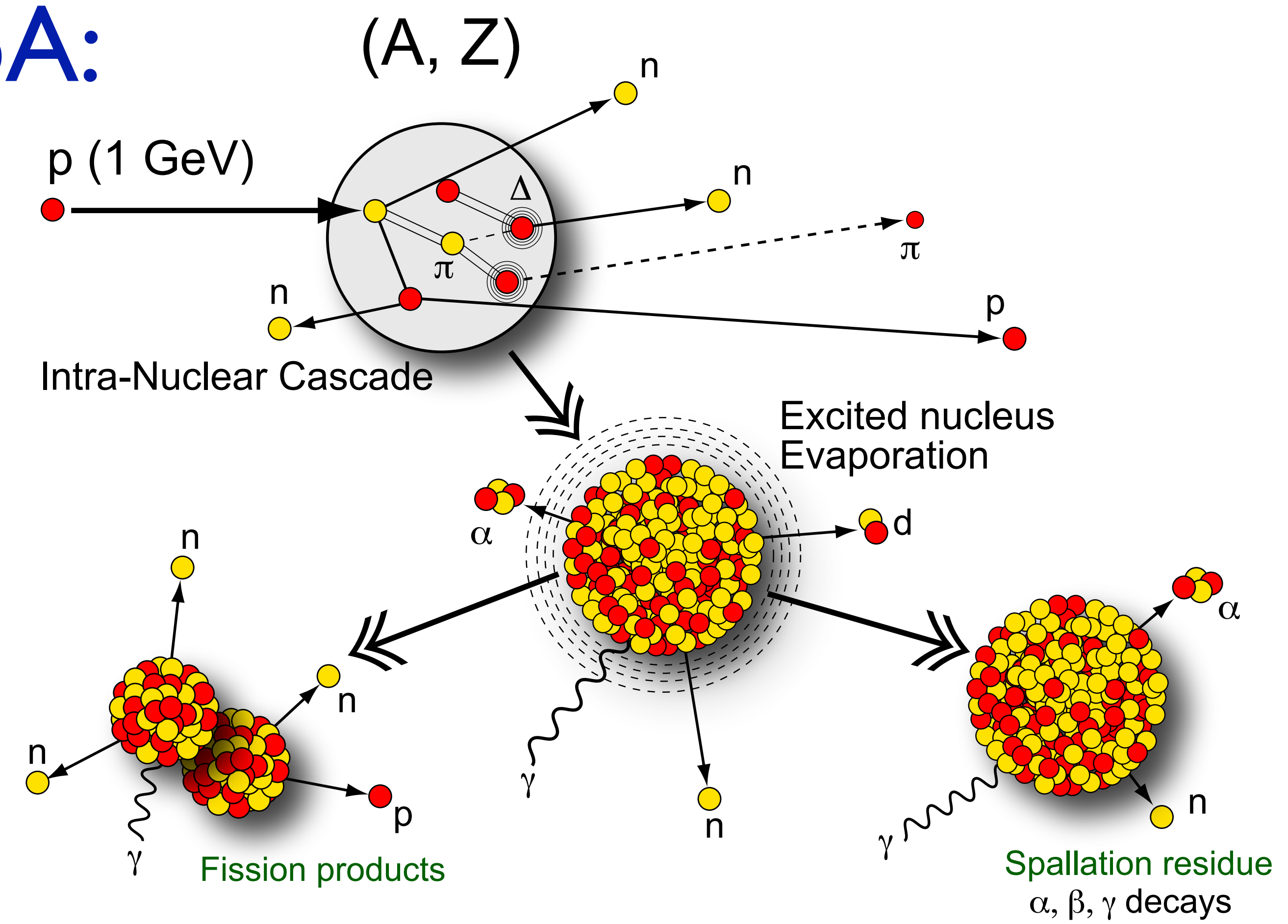
Traditional modeling done in pA:

Intra-Nuclear Cascade

- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

De-Excitation

- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)



Key Measurements in e+A

- ***Momentum*** **distribution of gluons** ***$xG(x,Q^2)$***
  - ➡ Extract via scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - ➡ Direct measurement: $F_L \sim xG(x,Q^2)$ (requires √s scan)
  - ➡ 2+1 jet rates
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- ***Space-time*** **distributions of gluons in matter**
  - ➡ Exclusive final states (*e.g.* vector meson production ρ, J/ψ)
  - ➡ Deep Virtual Compton Scattering (DVCS) - $\sigma \sim A^{4/3}$
  - ➡ F_2, F_L for various A and impact parameter dependence

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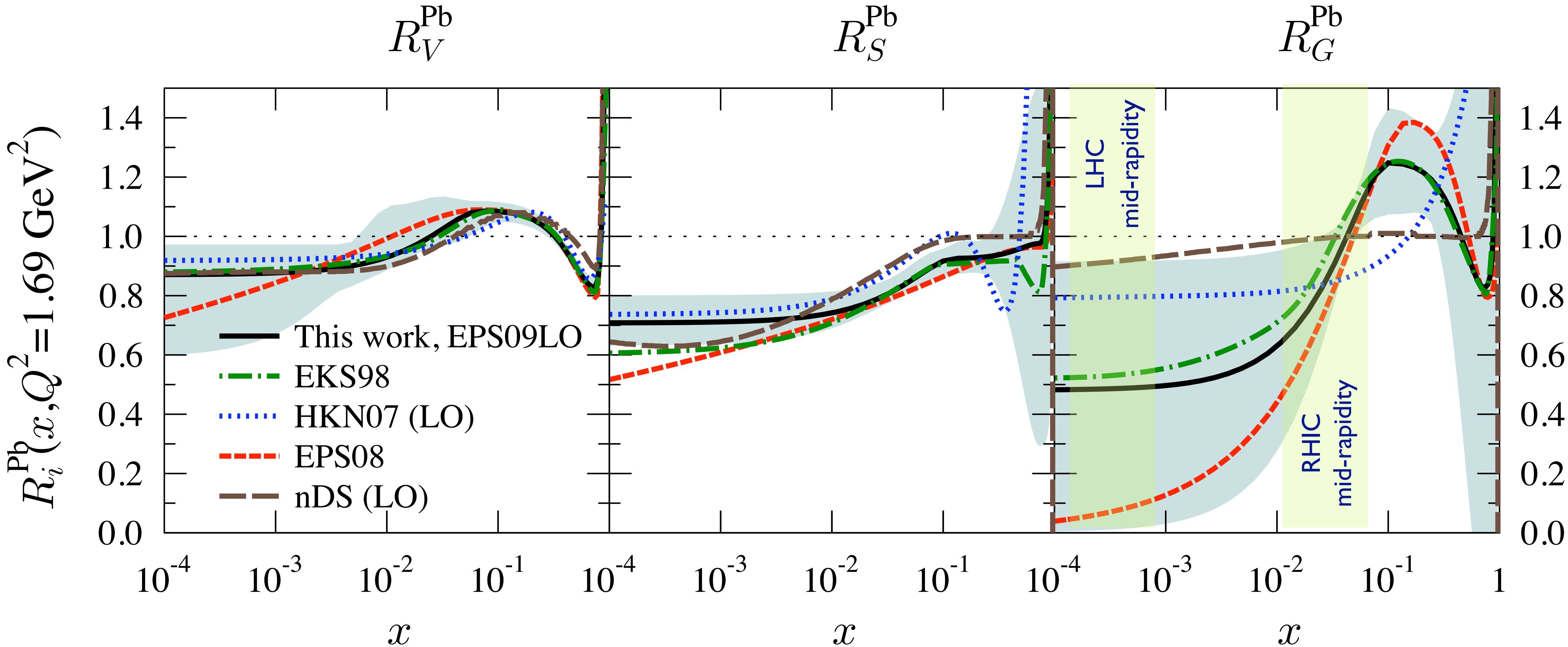
- ***Momentum*** **distribution of gluons** $xG(x,Q^2)$
  - ➡ Extract via scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - ➡ Direct measurement: $F_L \sim xG(x,Q^2)$ (requires $\sqrt{s}$ scan)
  - ➡ 2+1 jet rates
  - ➡ Inelastic vector meson production (*e.g.* J/ψ)
  - ➡ Diffractive vector meson production $\sim [xG(x,Q^2)]^2$
- ***Space-time*** **distributions of gluons in matter**
  - ➡ Exclusive final states (*e.g.* vector meson production ρ, J/ψ)
  - ➡ Deep Virtual Compton Scattering (DVCS) - $\sigma \sim A^{4/3}$
  - ➡ F_2, F_L for various A and impact parameter dependence
- **Interaction of fast probes with *gluonic* medium?**
  - ➡ Hadronization, Fragmentation
  - ➡ Energy loss (charm, bottom!)

See next talk by A. Accardi

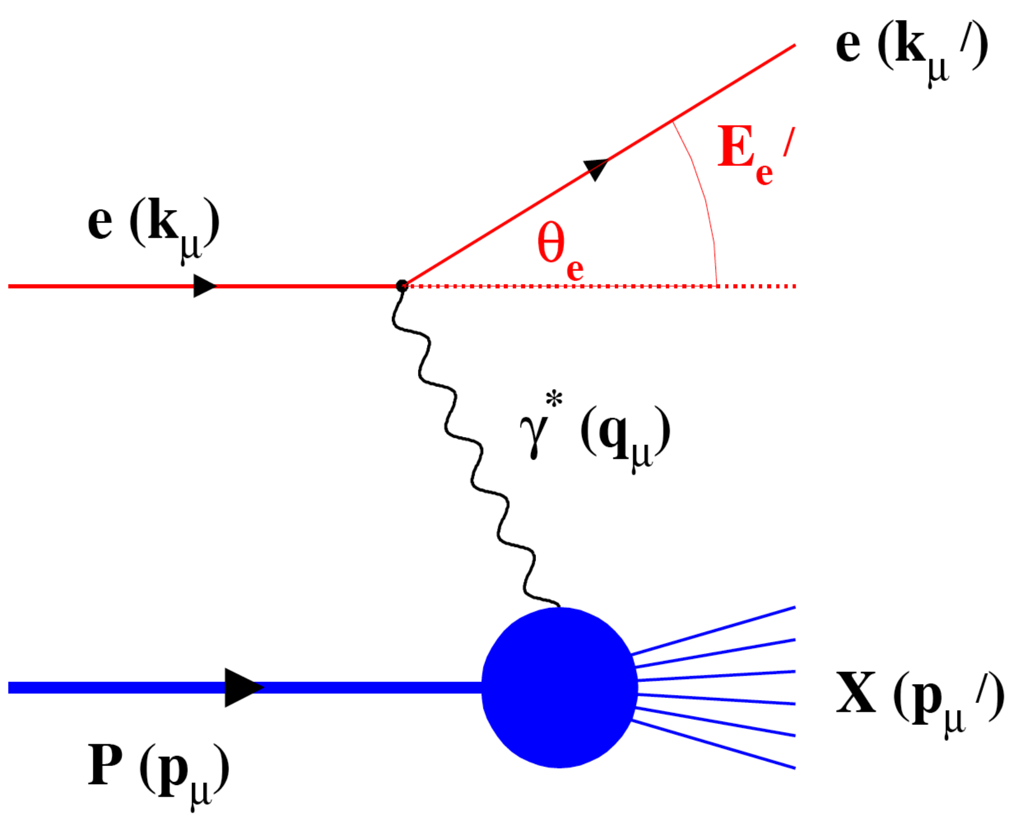
What about gluons in nuclei?



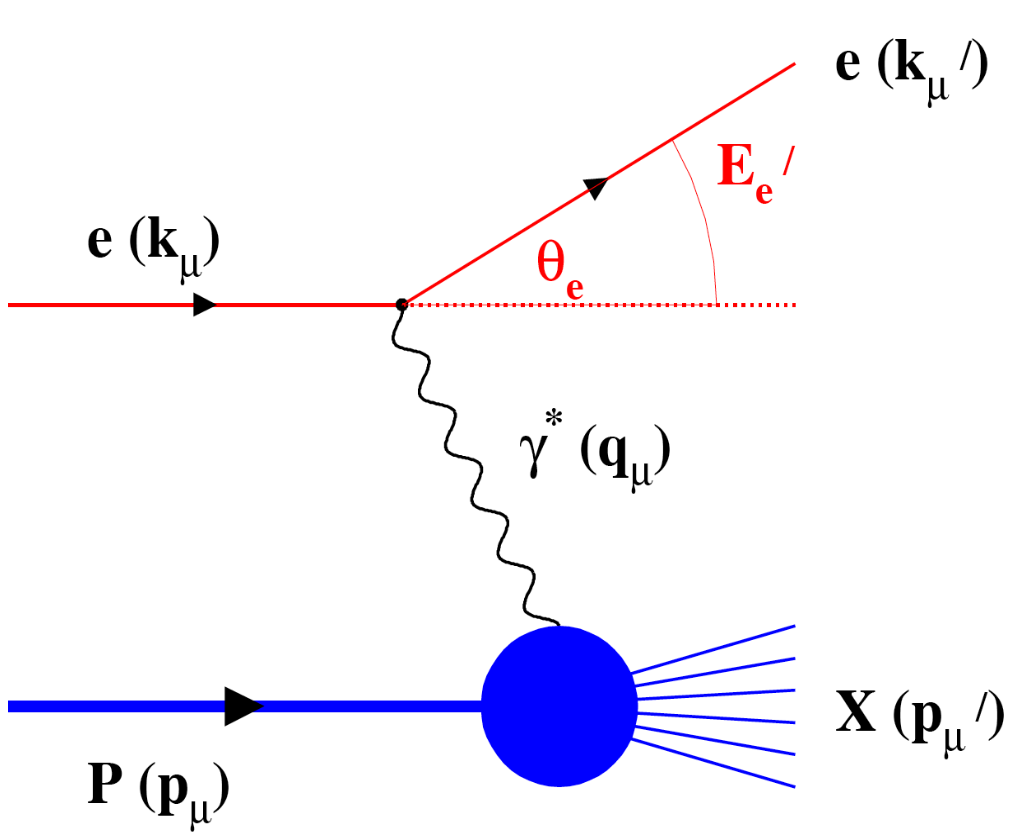
The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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

DIS Kinematics



DIS Kinematics

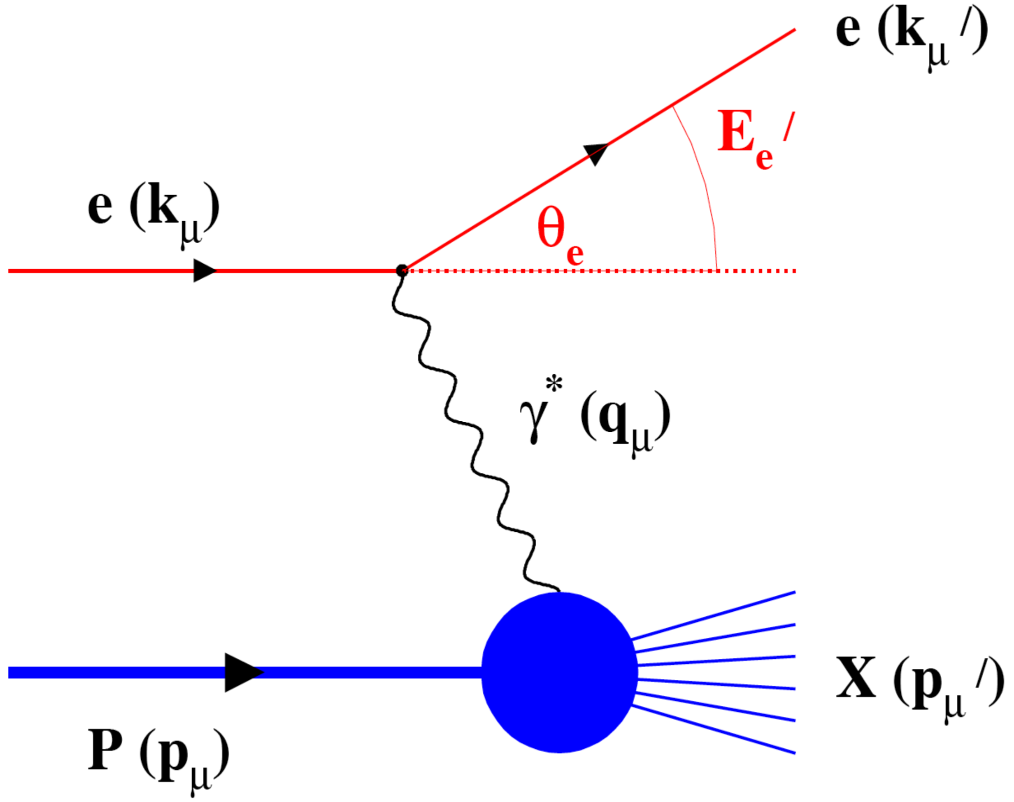


$$Q^2 = -q^2 = -(k_\mu - k_\mu^{'})^2$$

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

Measure of resolution power or "Virtuality"

DIS Kinematics



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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

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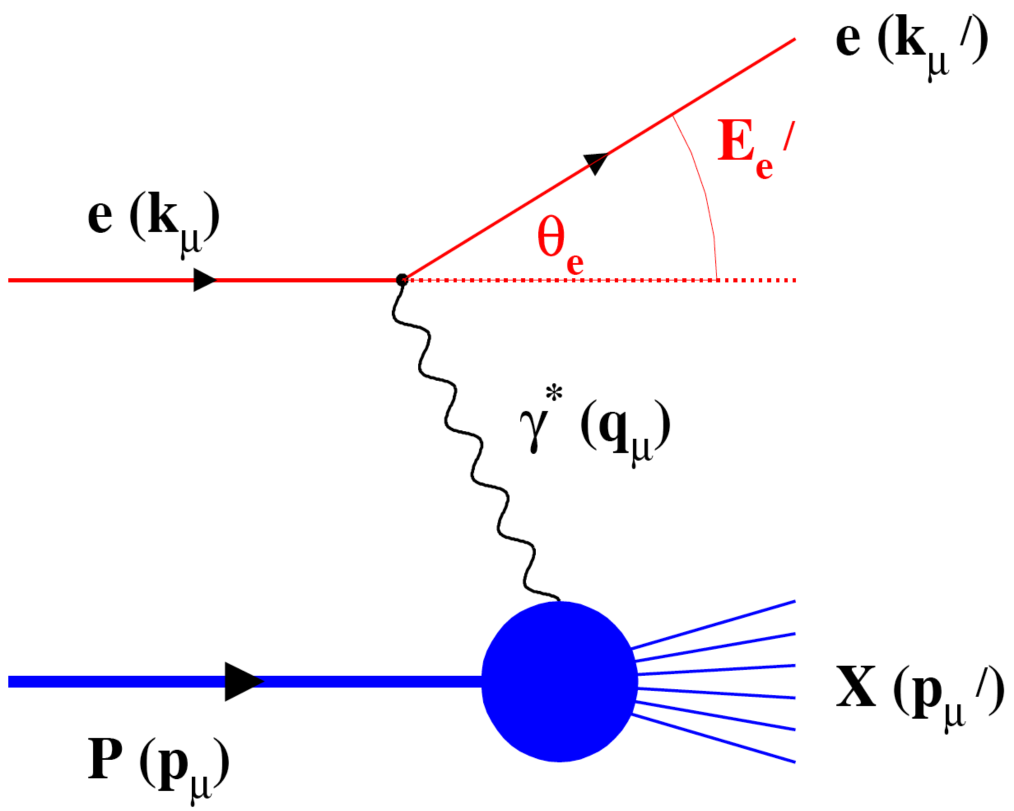

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Measure of inelasticity

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

Measure of momentum fraction of struck quark

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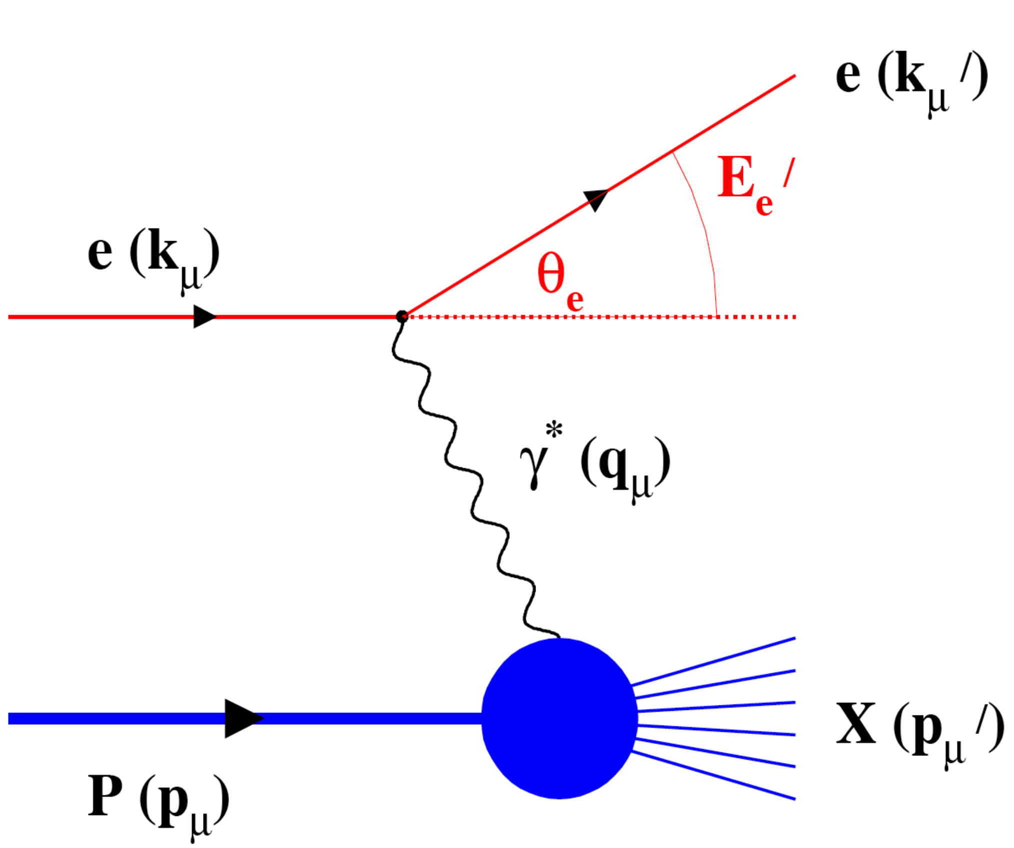
macl@bnl.gov

DIS Kinematics



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

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

Measure of resolution power or "Virtuality"

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

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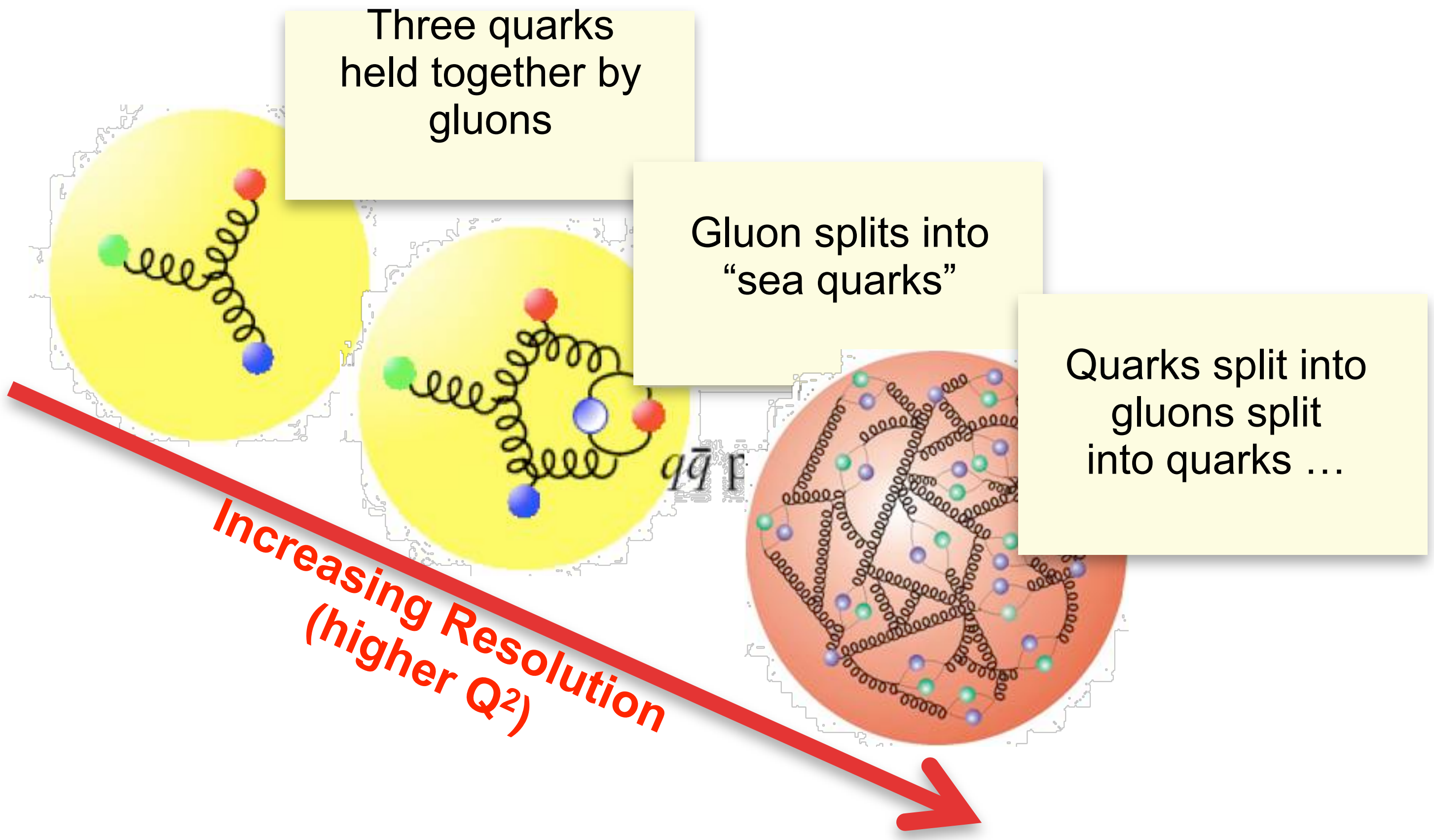
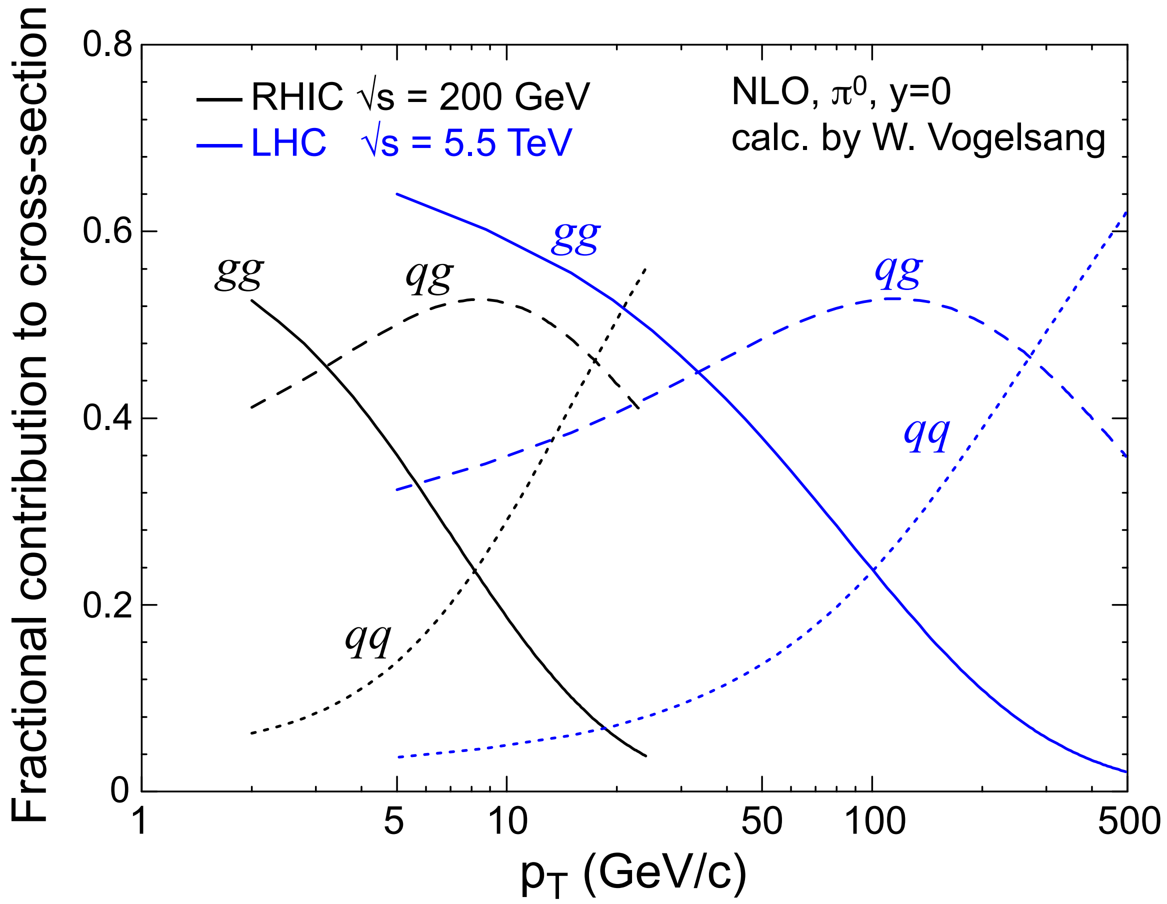


The role of Glue in Heavy-Ion collisions

Jets (π^0 production)



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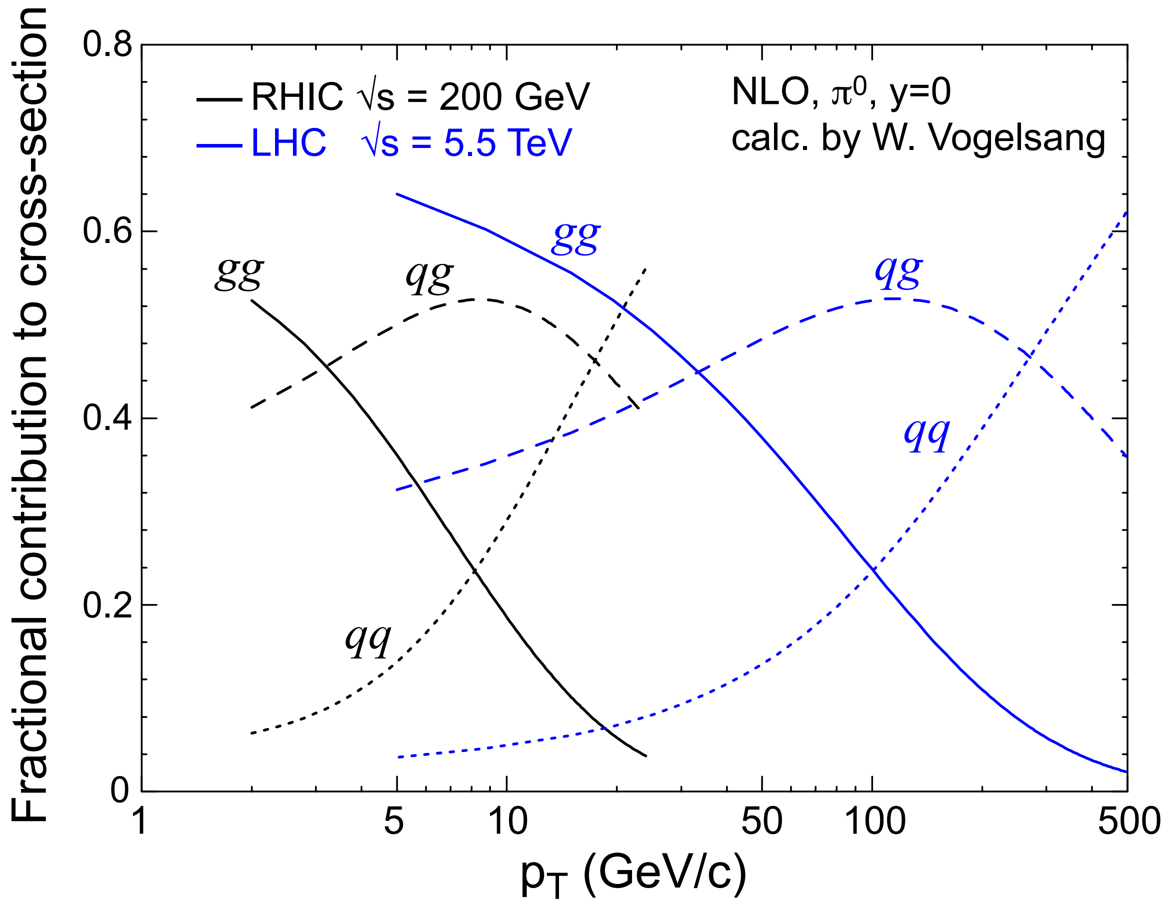
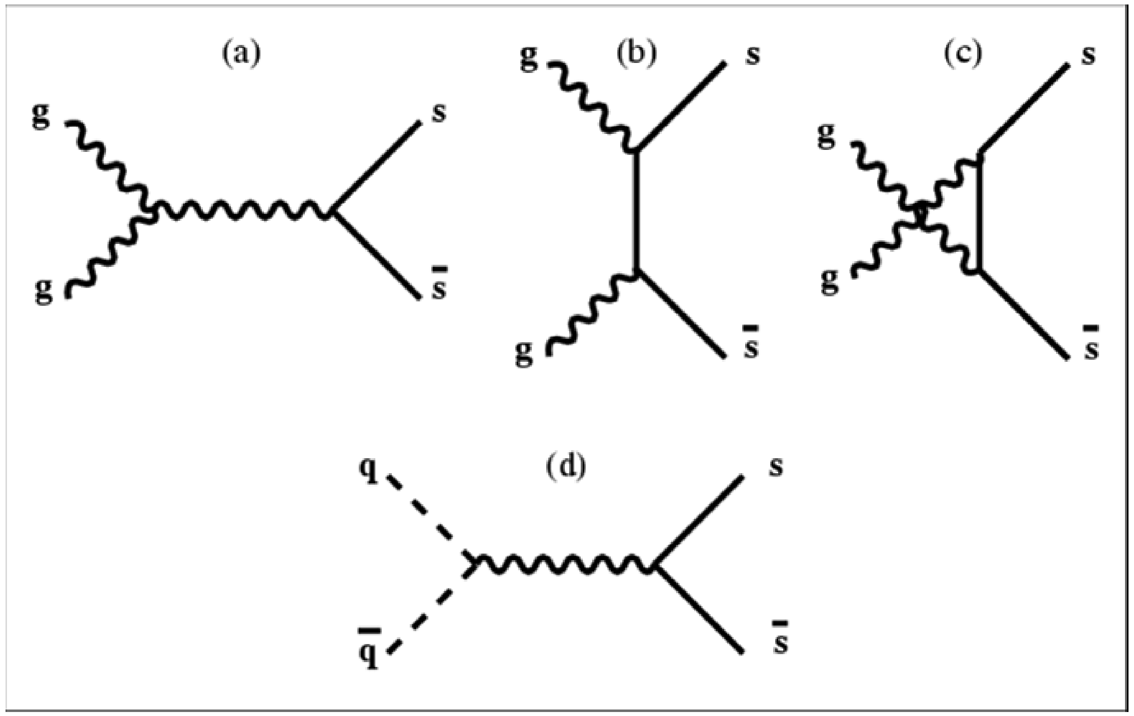


Strangeness Production



The role of Glue in Heavy-Ion collisions

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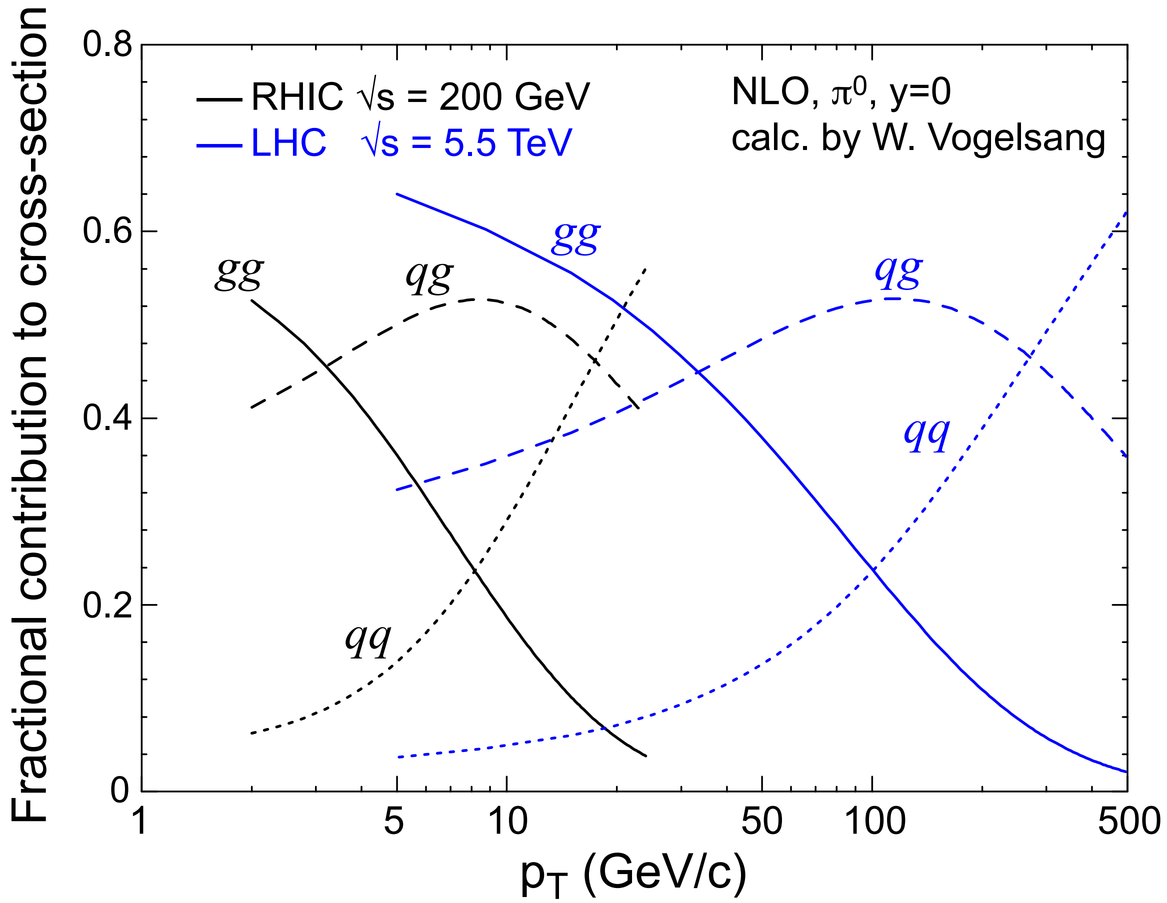
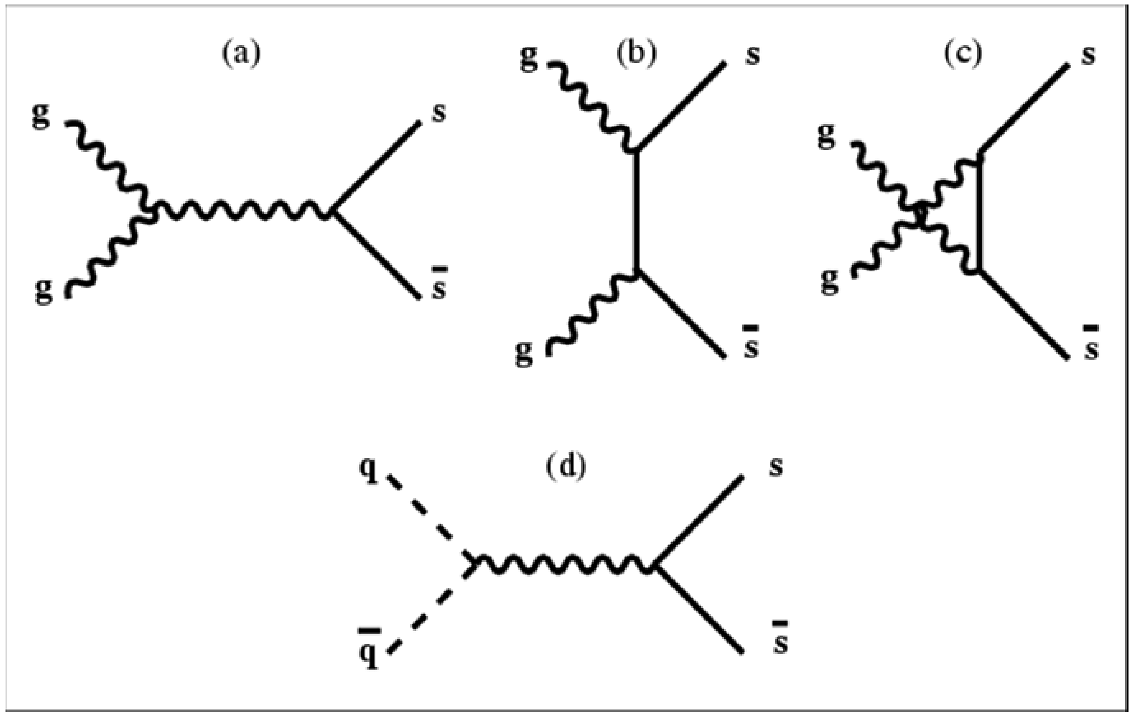
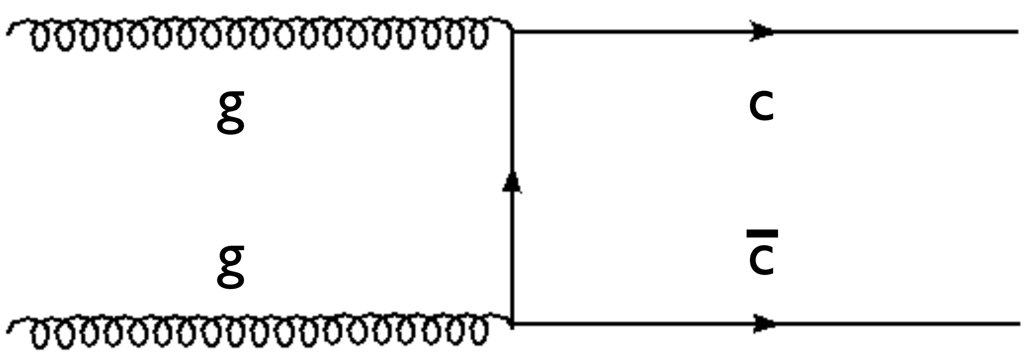


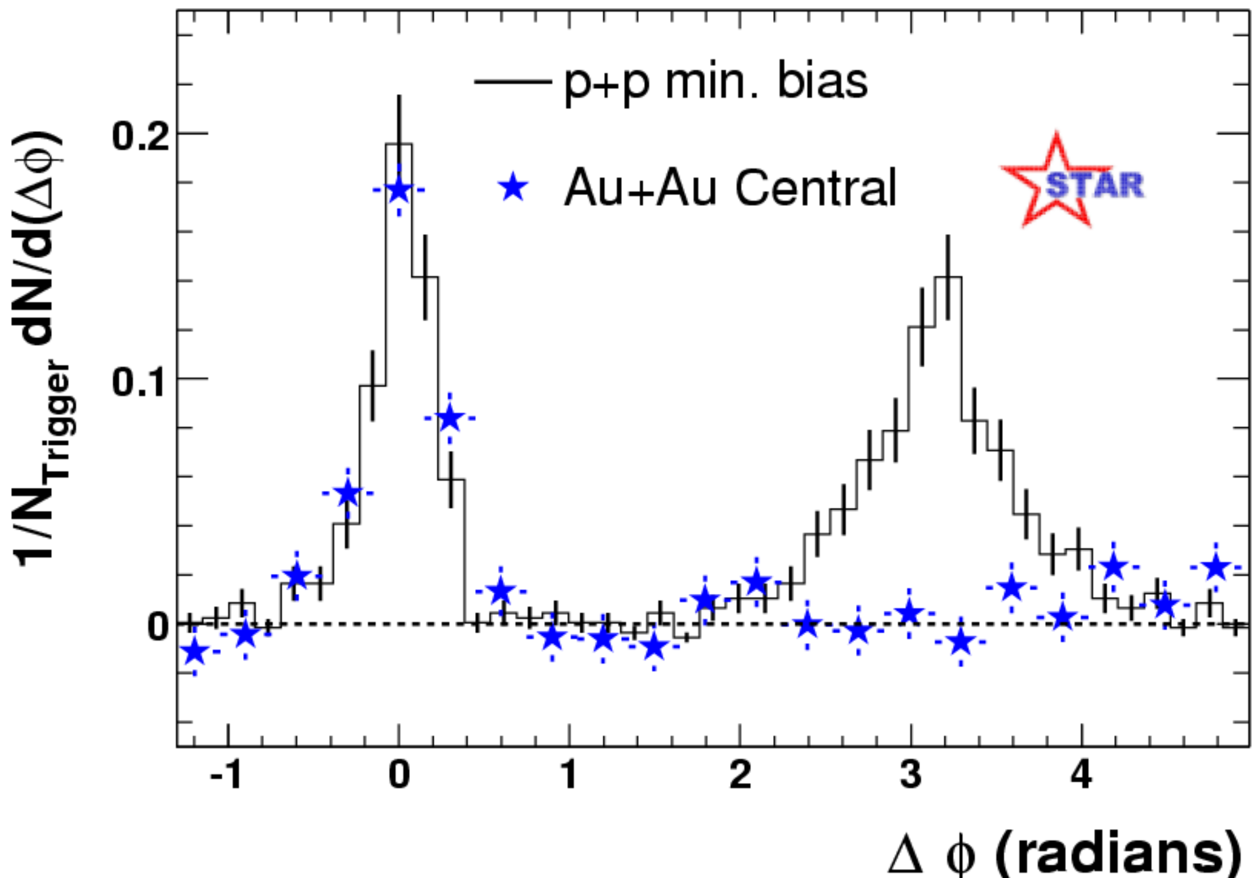
Strangeness Production



Heavy Flavour Production

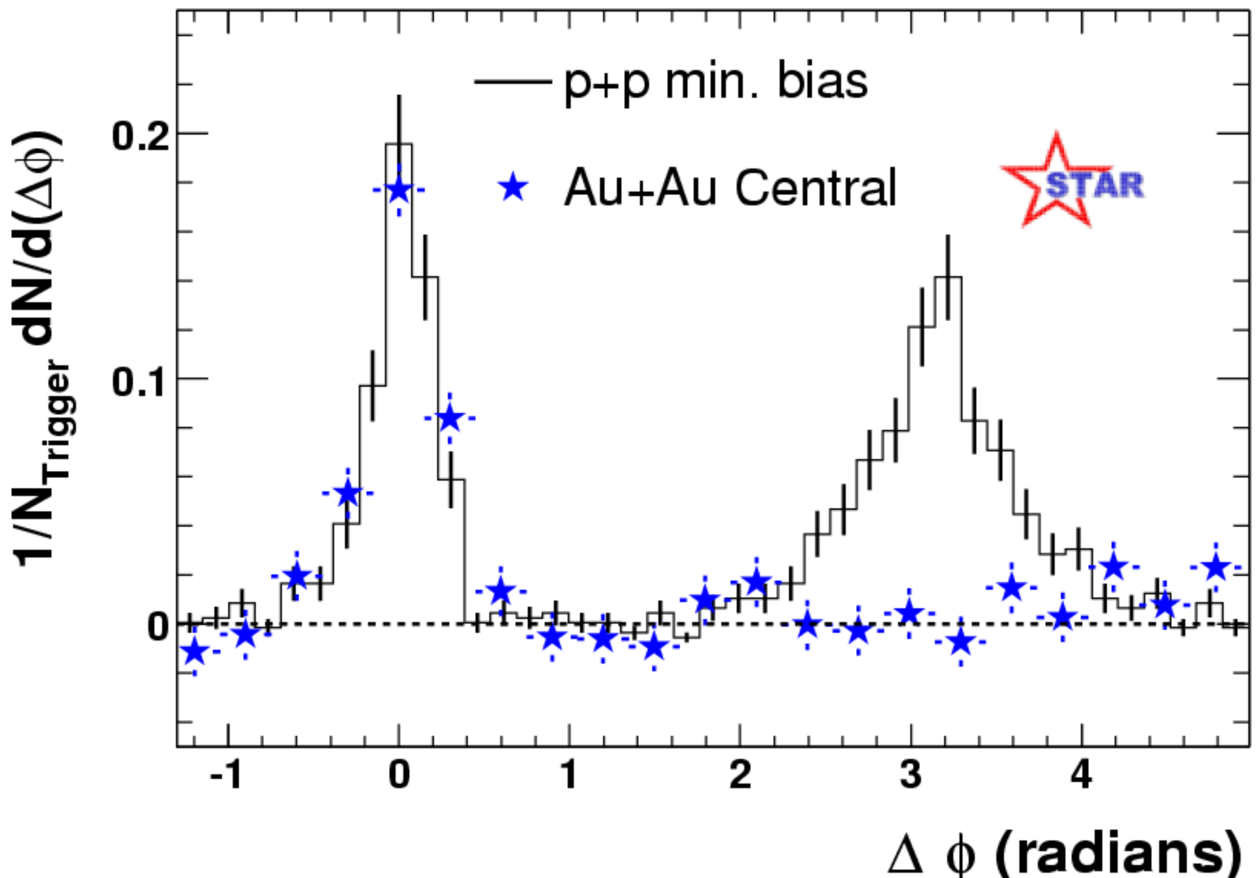


Jet suppression: final or initial state effect?



Jet suppression: final or initial state effect?

- In d+Au collisions, deconfinement is not expected
  - Measure correlations in d+Au collisions to determine if this is an initial or a final state effect



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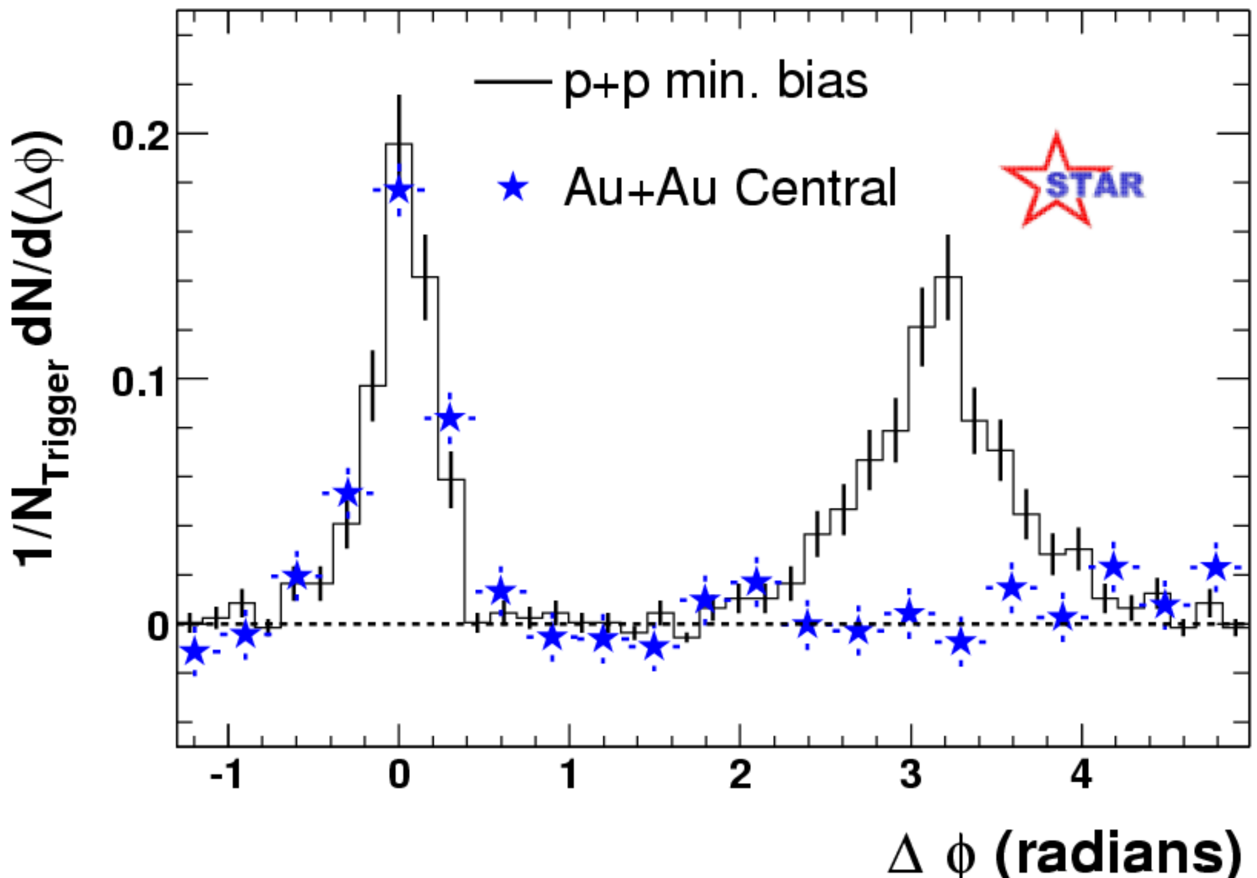
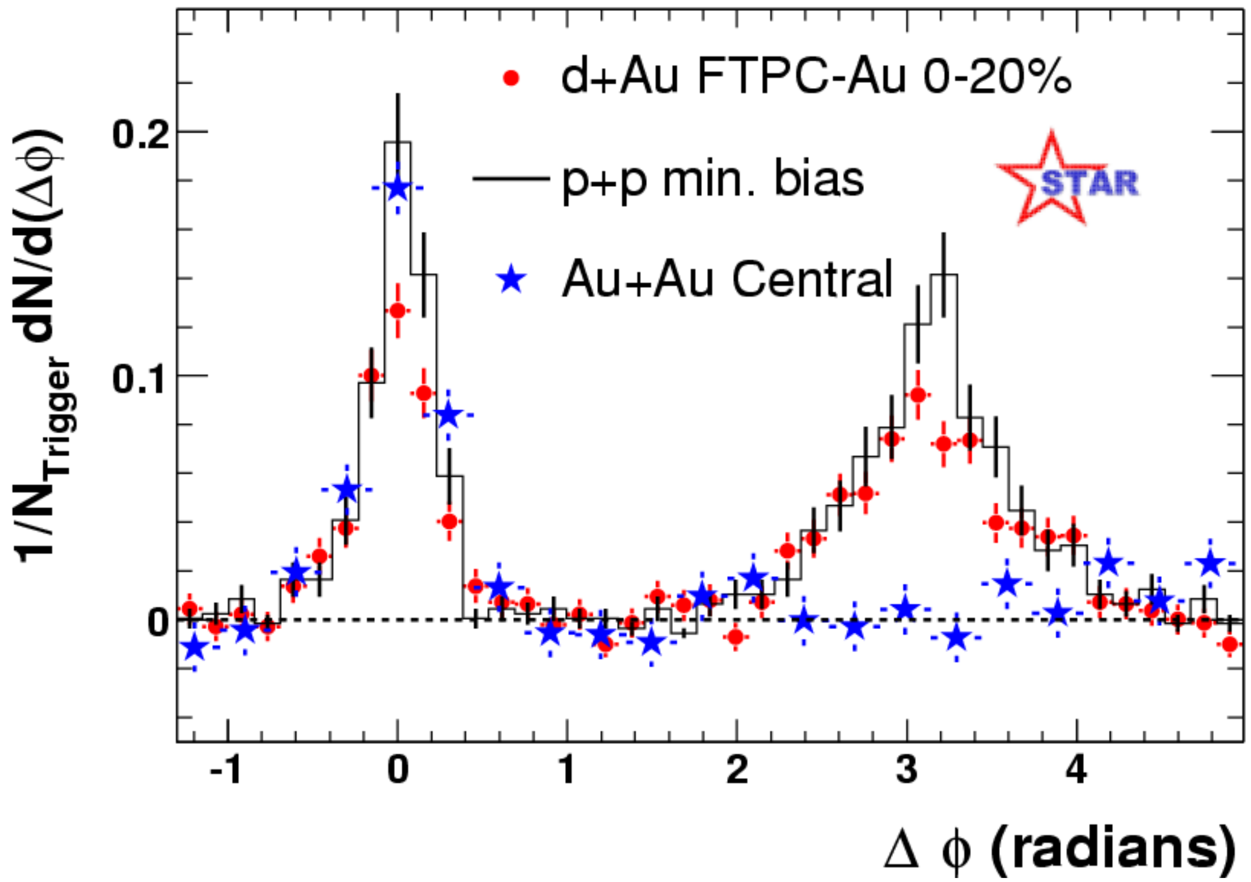
Jet suppression: final or initial state effect?

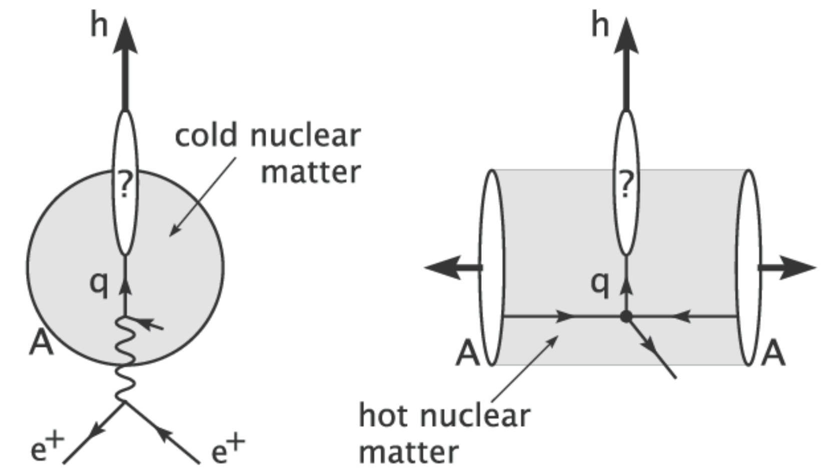
- In d+Au collisions, deconfinement is not expected
  - Measure correlations in d+Au collisions to determine if this is an initial or a final state effect
- No suppression is observed in d+Au collisions at **mid-rapidity** at RHIC
  - Jet suppression a final state effect?



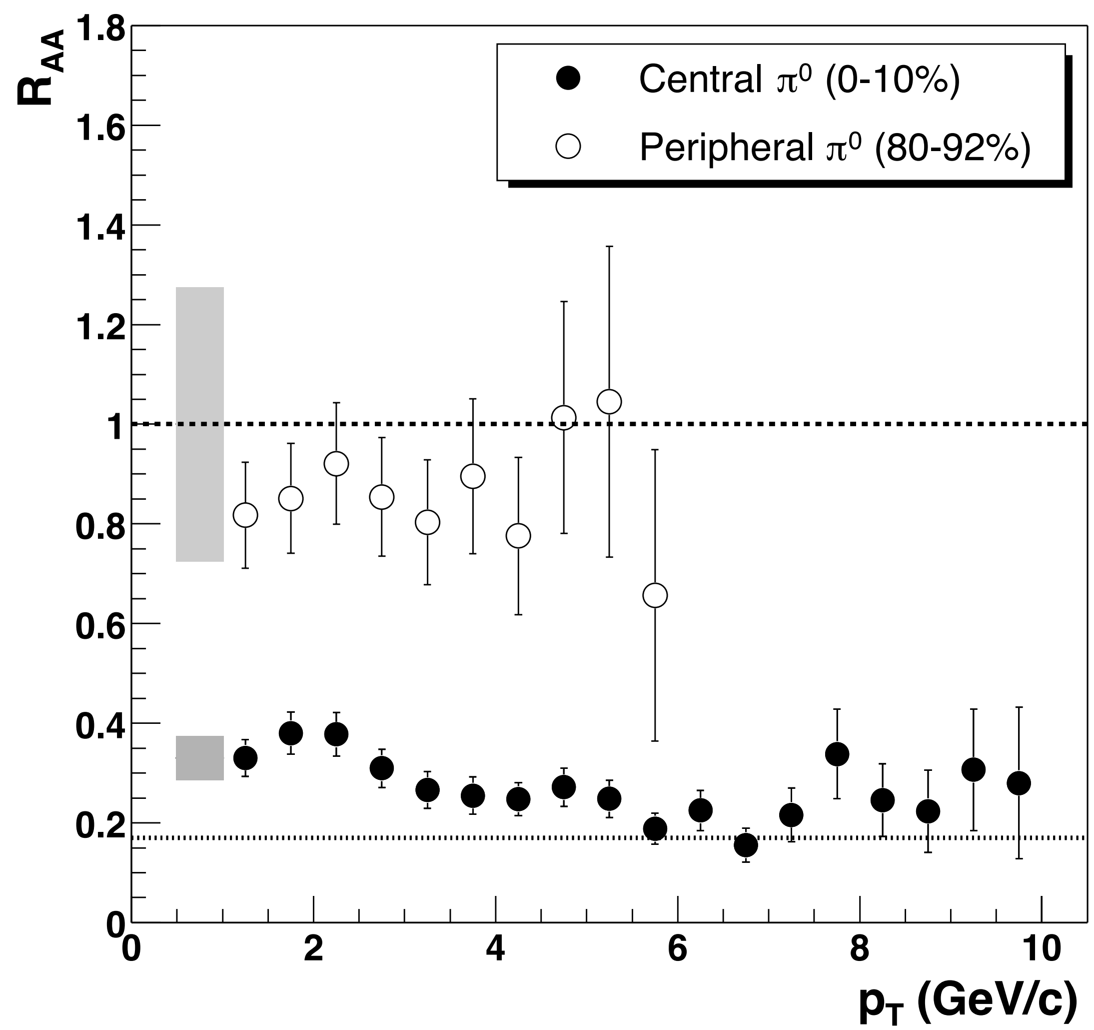


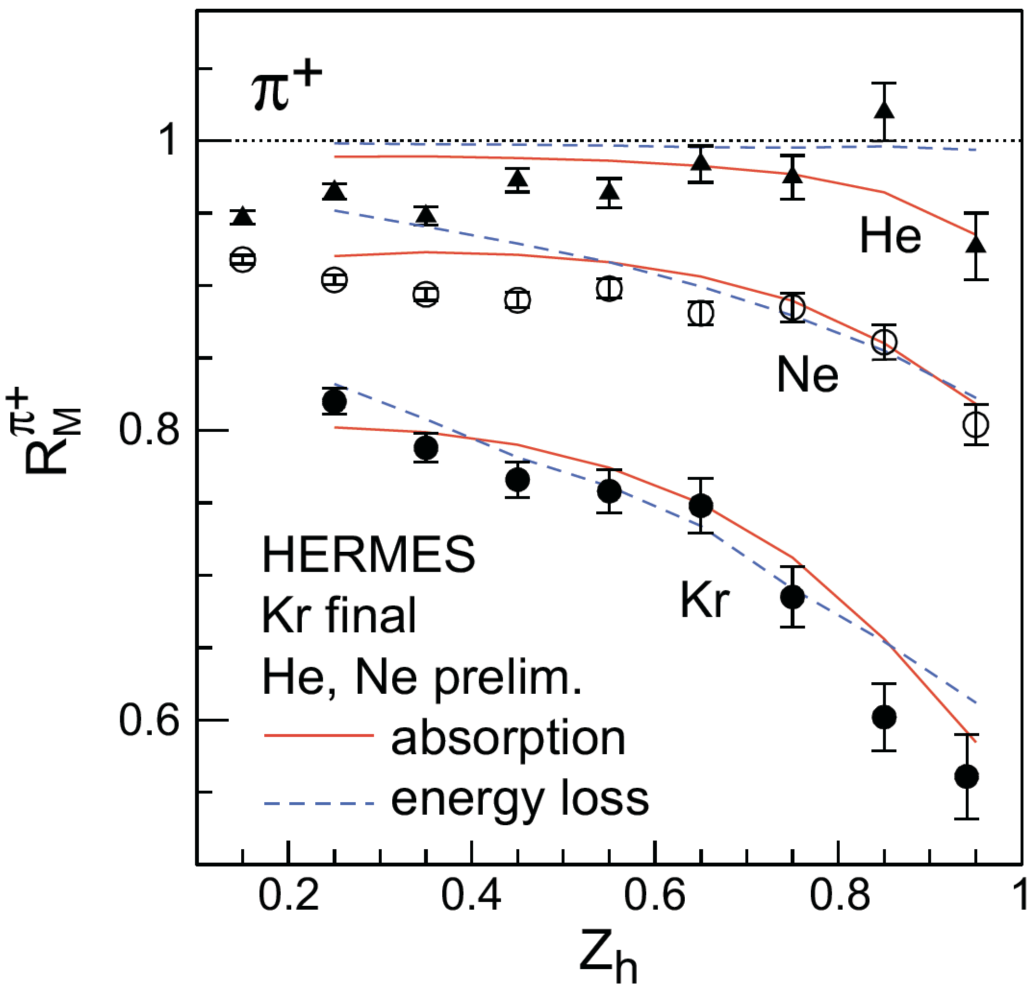
Interaction of fast probes with gluonic medium

- nDIS:
  - ➡ Clean measurement in 'cold' nuclear matter
  - ➡ Suppression of high-p_T hadrons analogous to, but weaker than at RHIC



PHENIX expt: Phys.Rev.Lett.91:072301 (2003)





ν = virtual photon energy

$Z_h = E_h/\nu$

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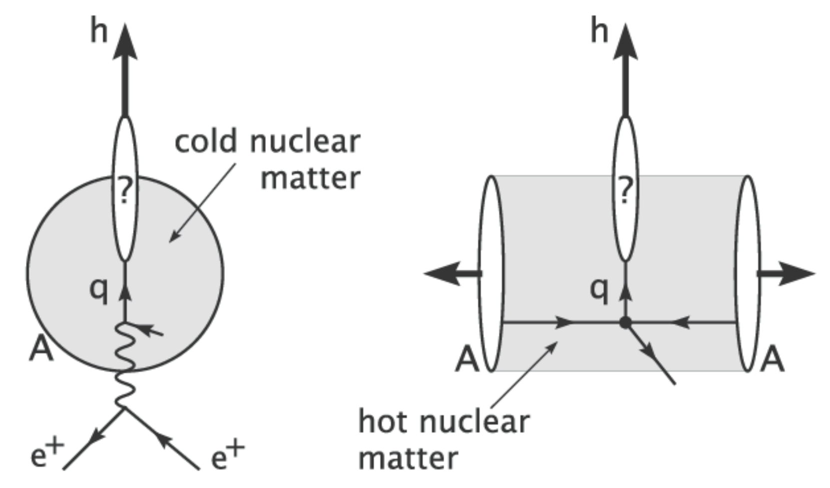
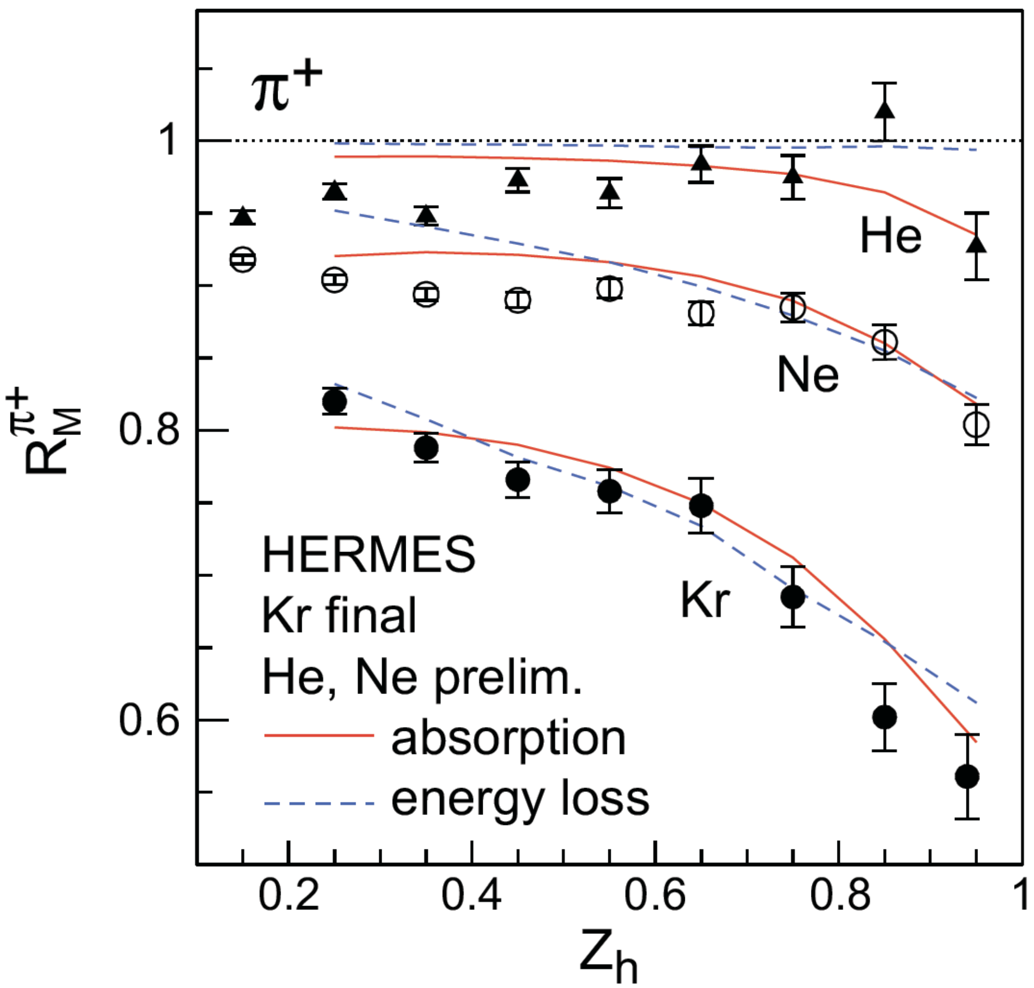


- Fundamental question:
  - When do partons get colour neutralized?

Parton energy loss vs. (pre)hadron absorption



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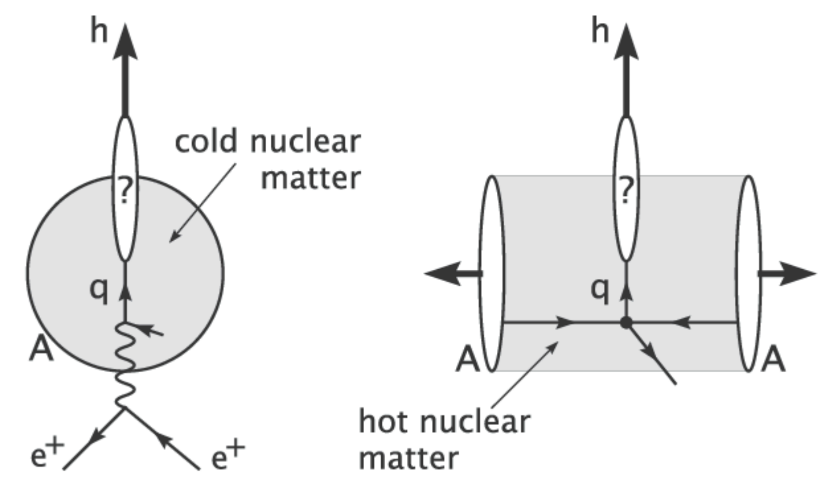
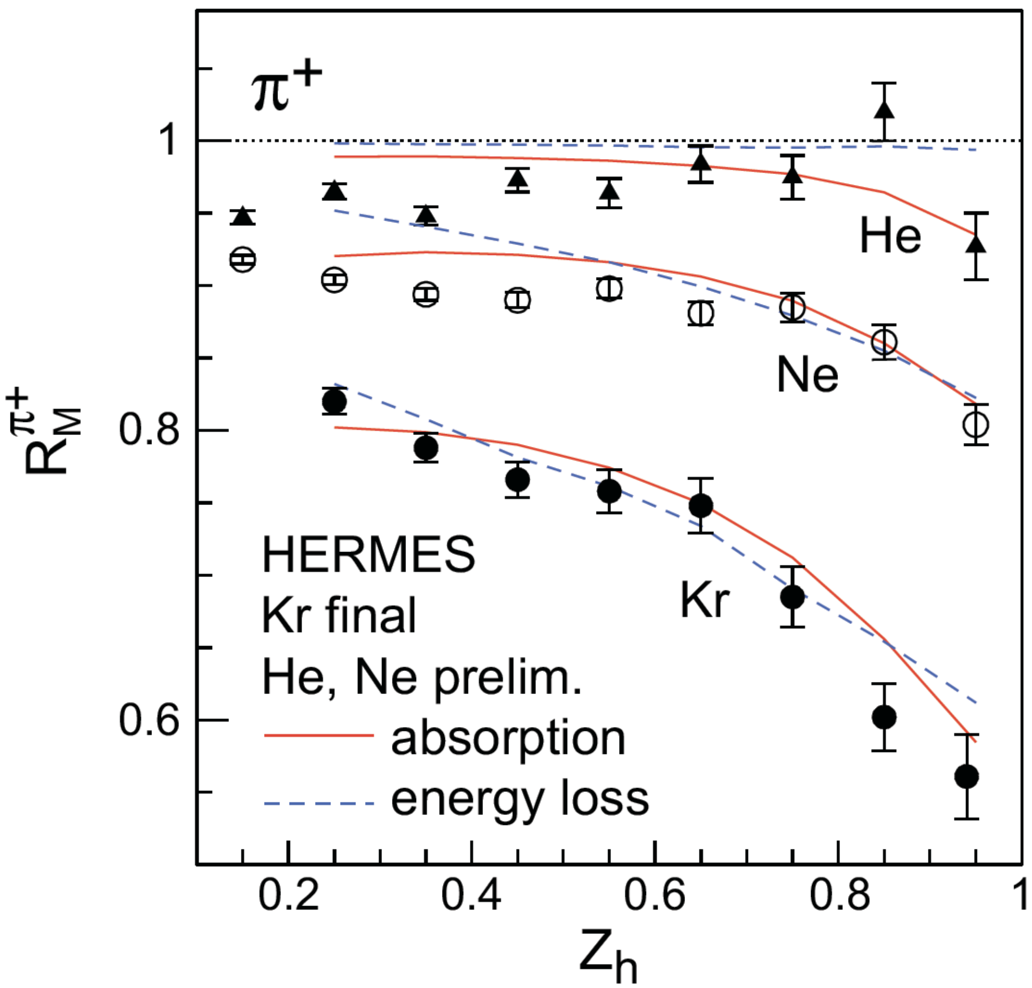


- Fundamental question:
  - When do partons get colour neutralized?

Parton energy loss vs. (pre)hadron absorption

Energy transfer in lab rest frame:
EIC: $10 < \nu < 1600$ GeV
HERMES: 2-25 GeV



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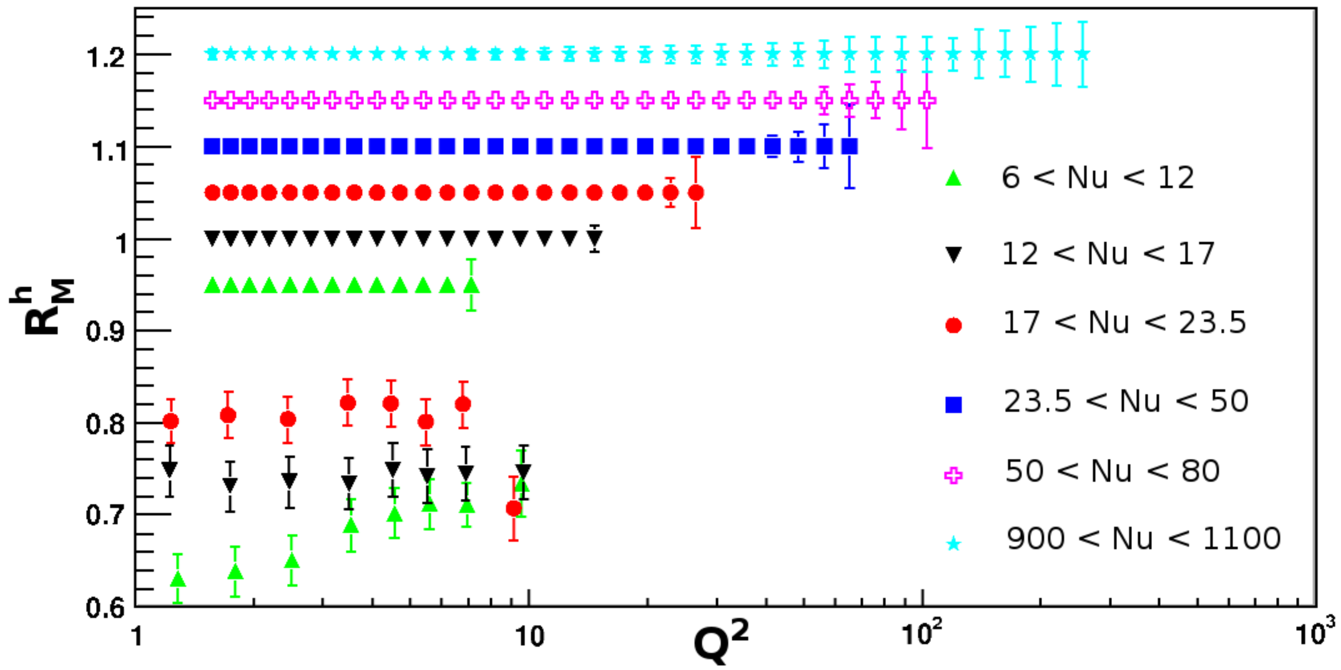

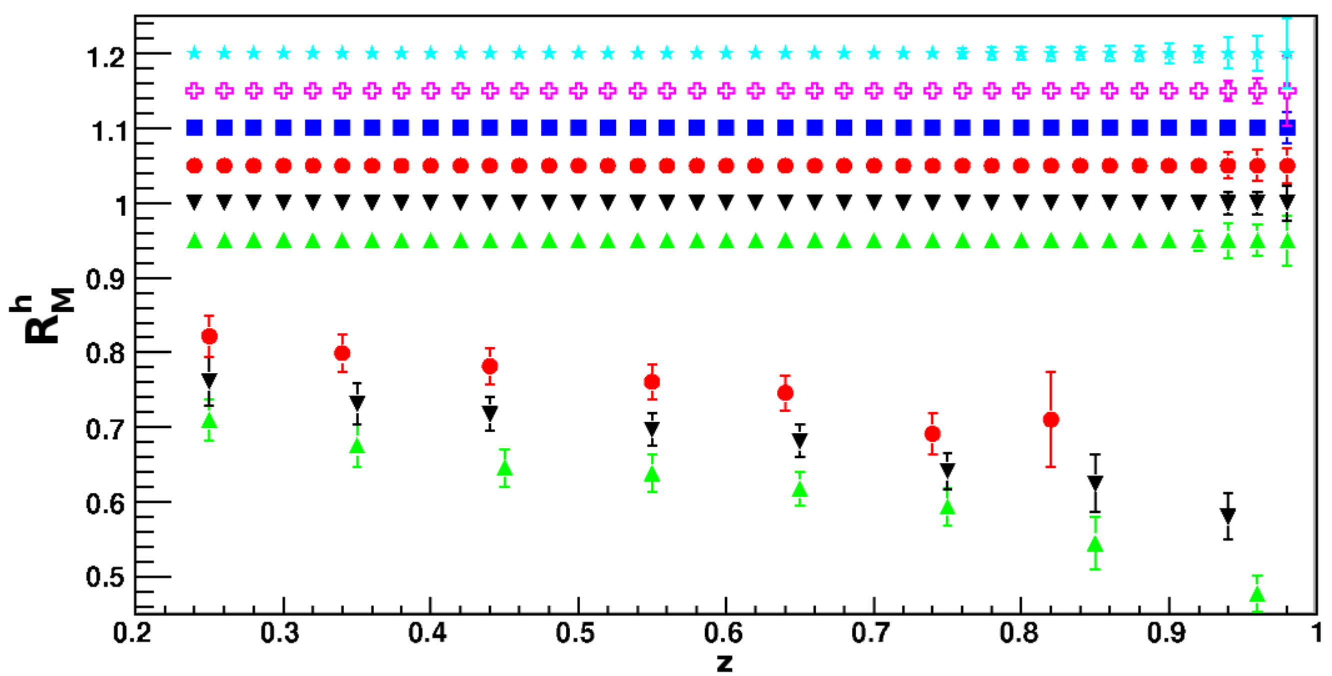

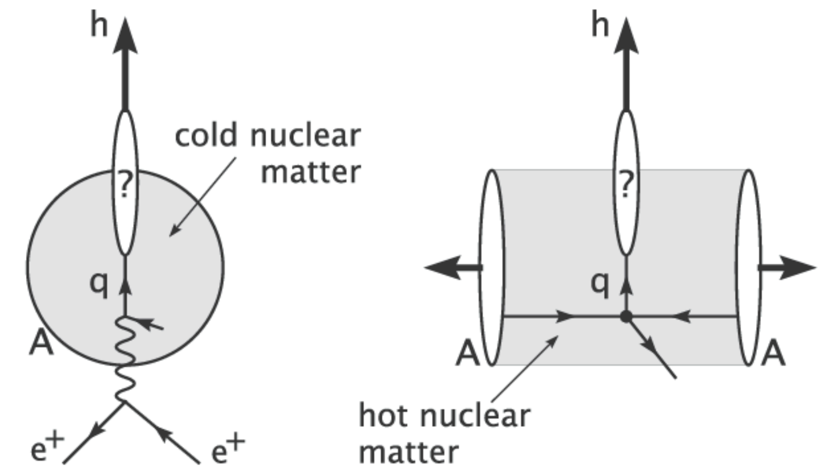

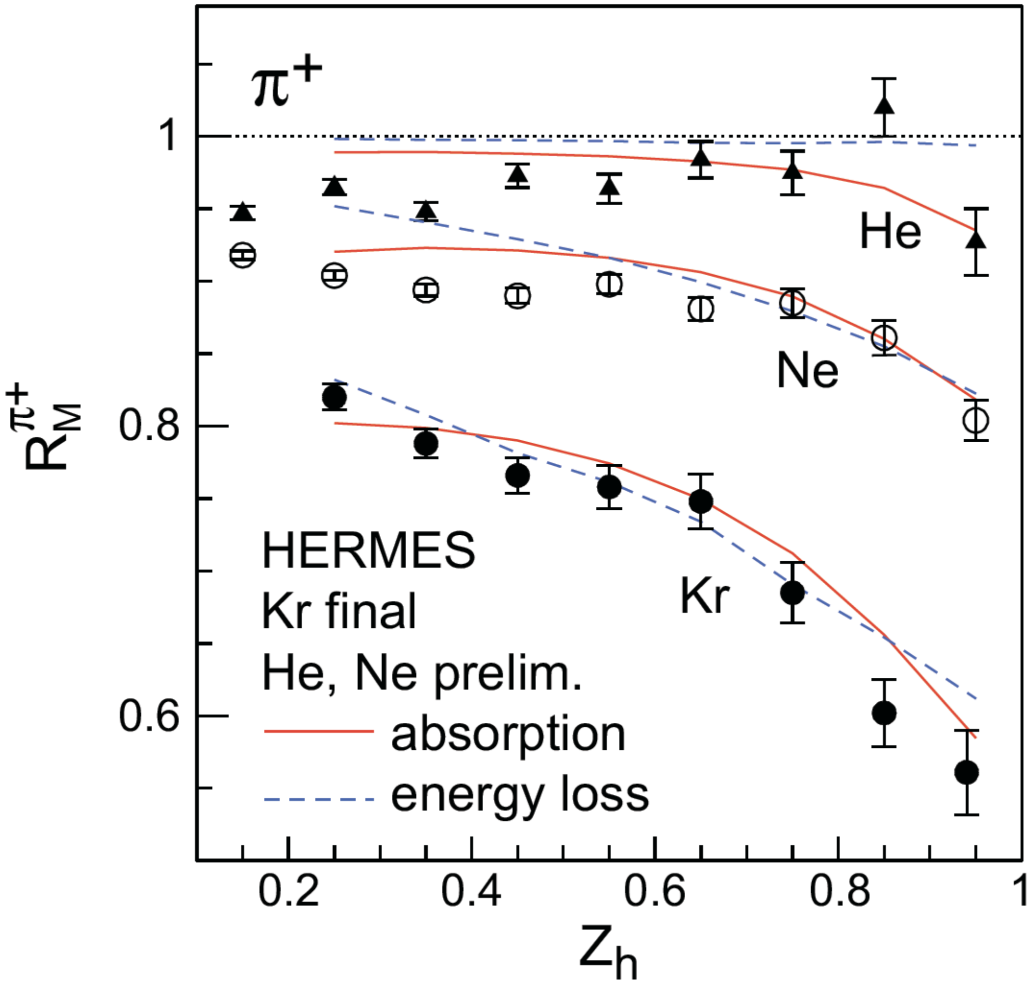

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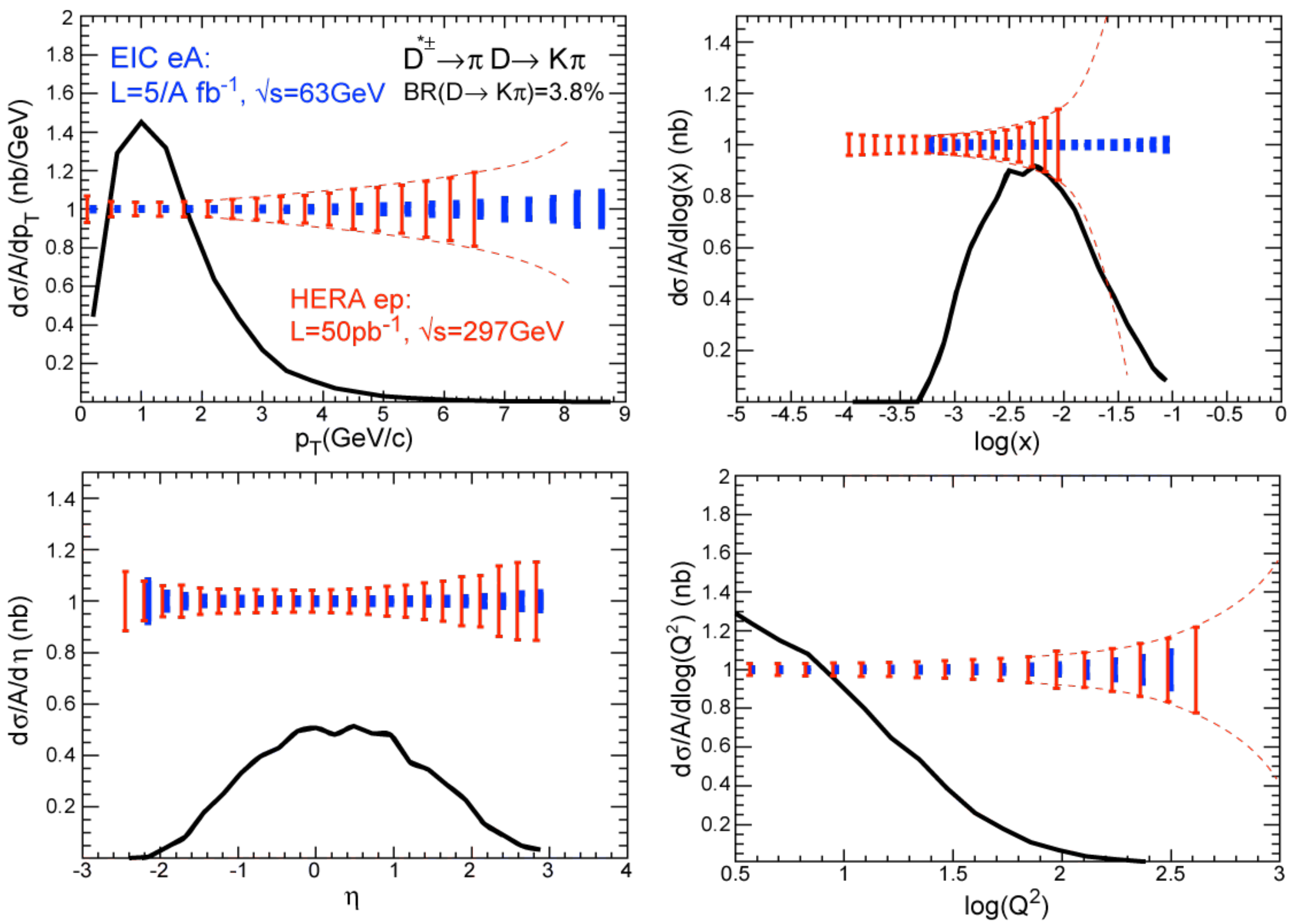
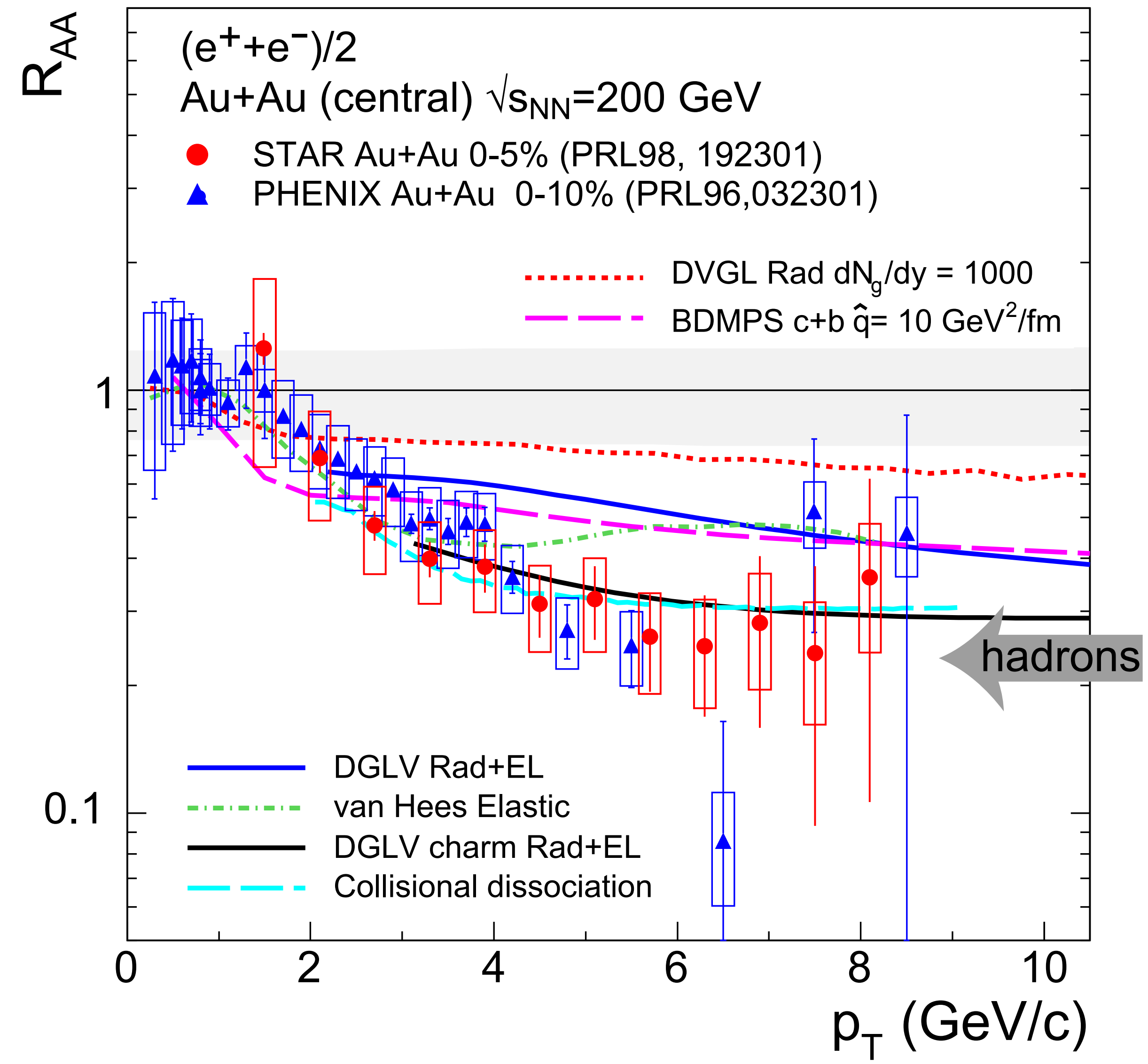
Charm at an EIC





- ➡ EIC allows multi-differential measurements of heavy flavour
- ➡ covers and extends energy range of previous experiments, allowing for the study of a wide range of formation lengths