e+A measurements at a future Electron-Ion Collider

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EIC on the web: http://web.mit.edu/eicc
e+A working group: http://www.eic.bnl.gov

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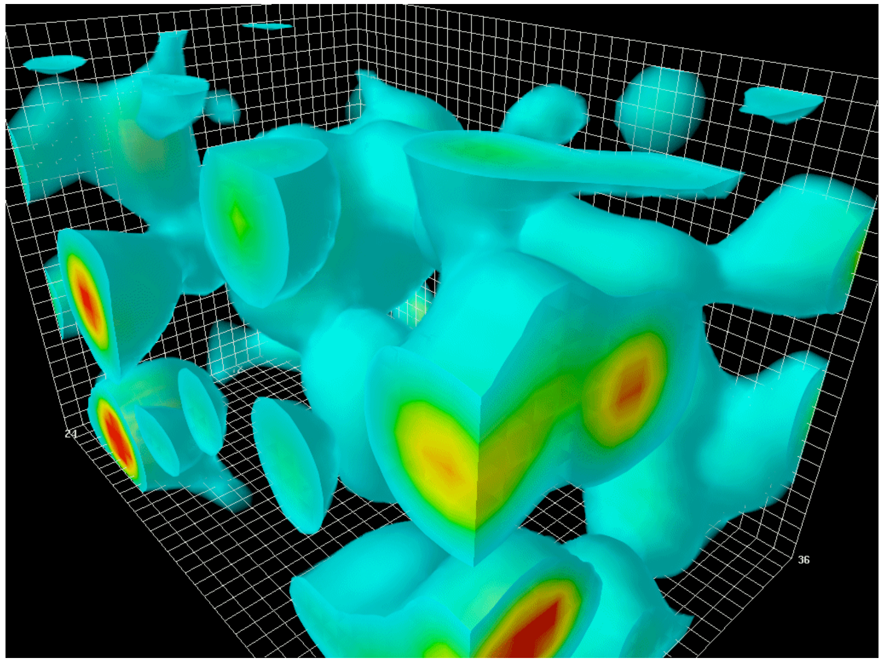
What do we know about gluons?

Glue and the QCD Lagrangian:

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- **>98% of all visible mass due to “emergent” phenomena not evident from Lagrangian**
  - χSB & Colour Confinement
- **Gluons**
  - ➡ Mediators of the strong interaction
  - ➡ Determine essential features of QCD
    - ‣ Asymptotic freedom from gluon loops
  - ➡ Dominate structure of QCD vacuum (χSB)
  - ➡ Quenched L_{QCD} gets hadron masses correct to ~ 10%



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

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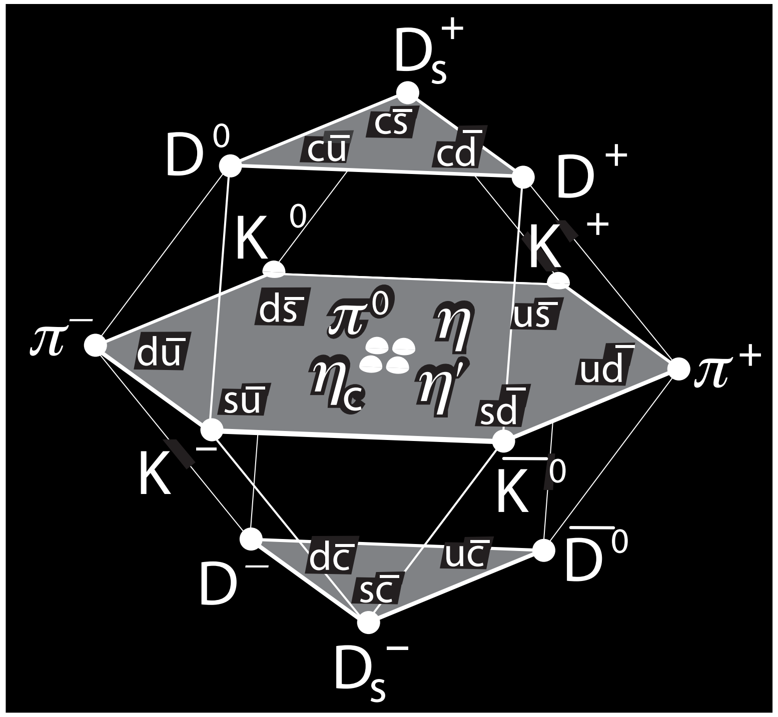
Glue and the Lagrangian

Glue and the Lagrangian

- **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 the LHC



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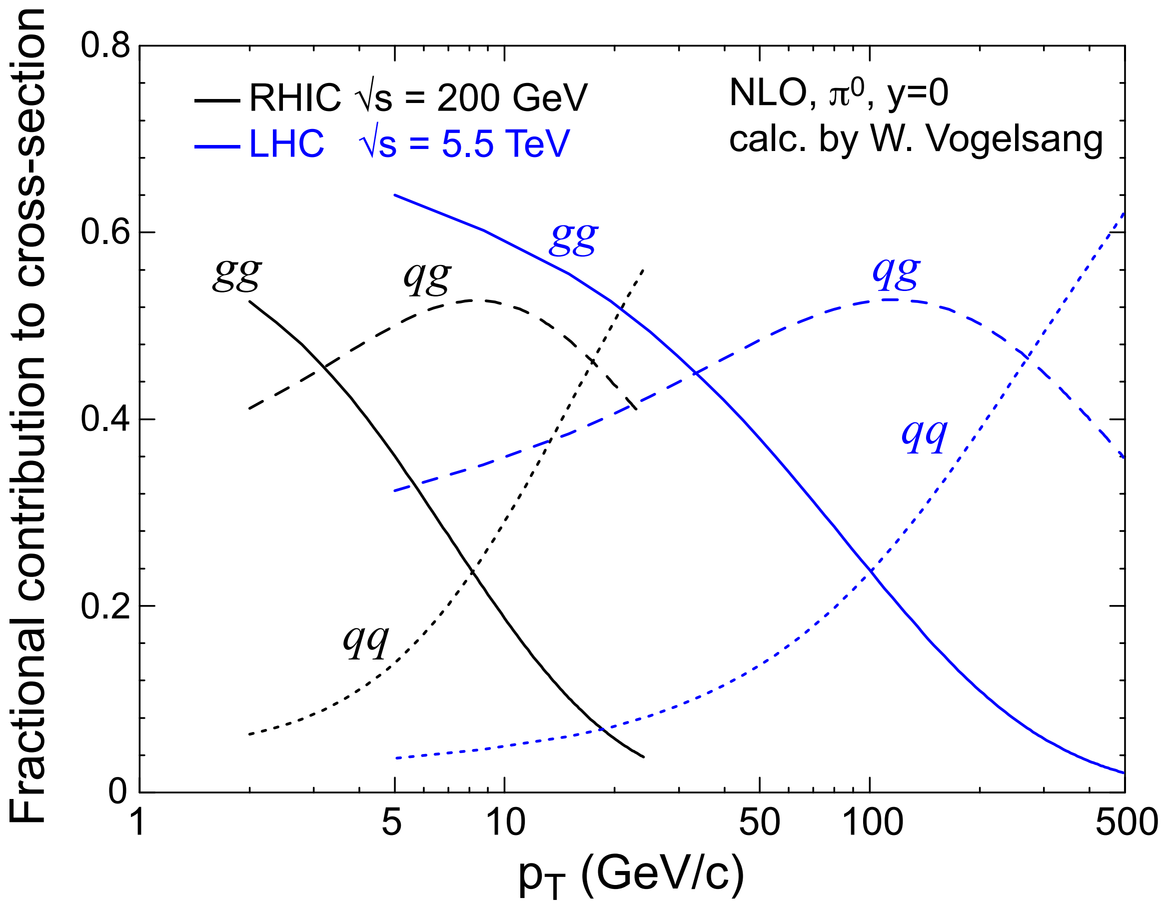
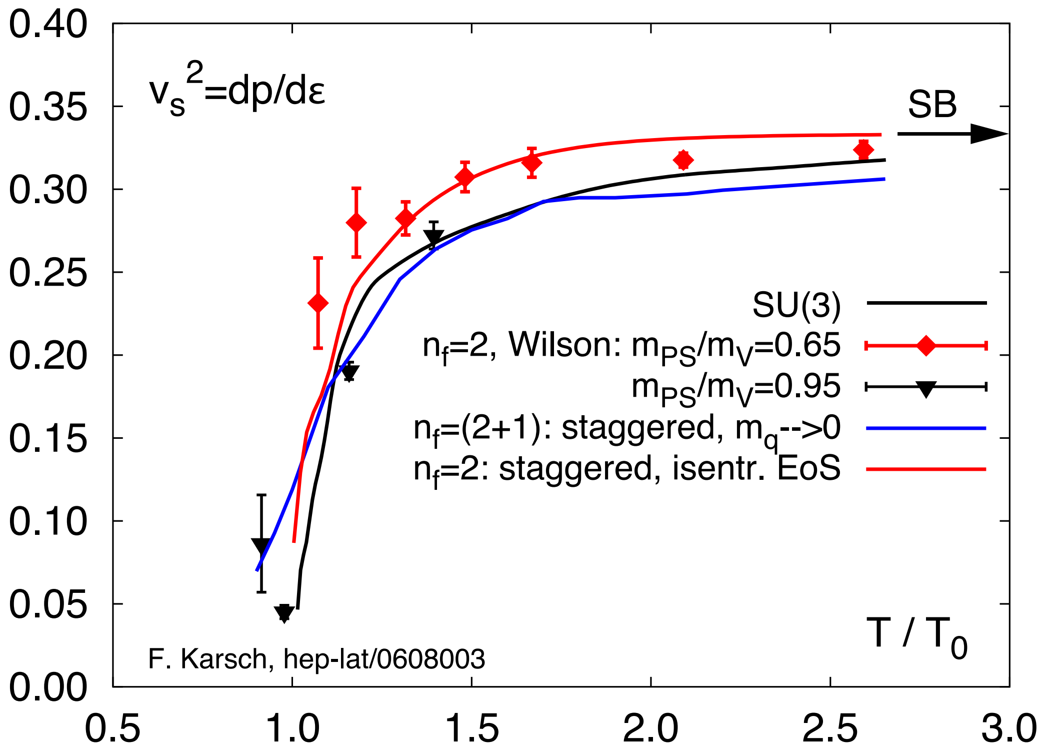
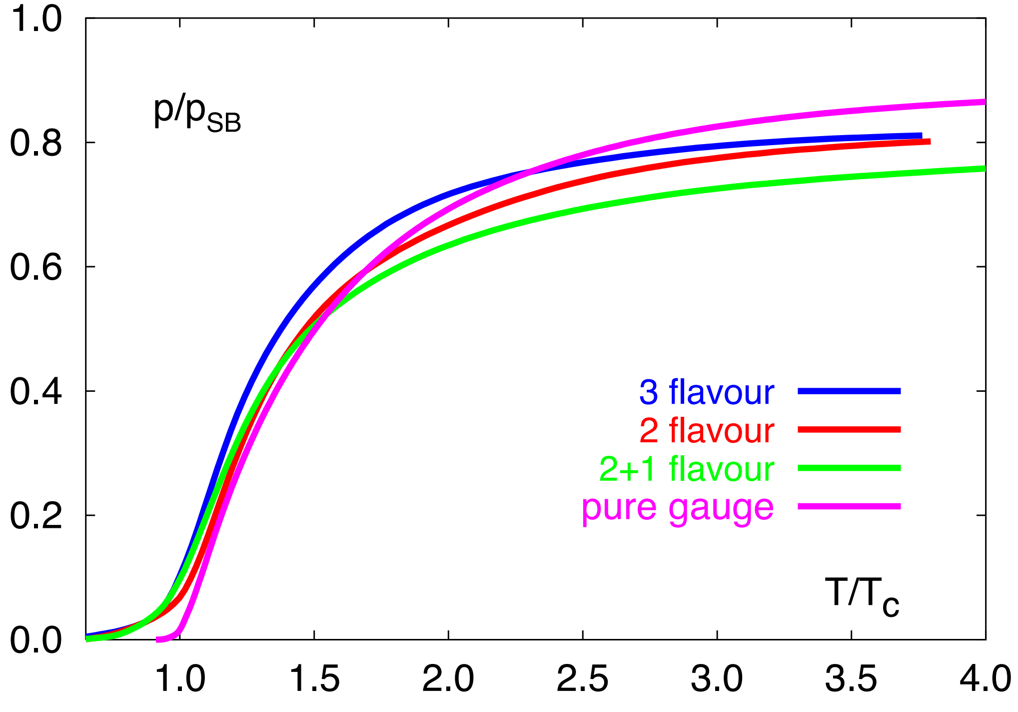
The role of Glue in Heavy-Ion collisions

Jets (π^0 production):

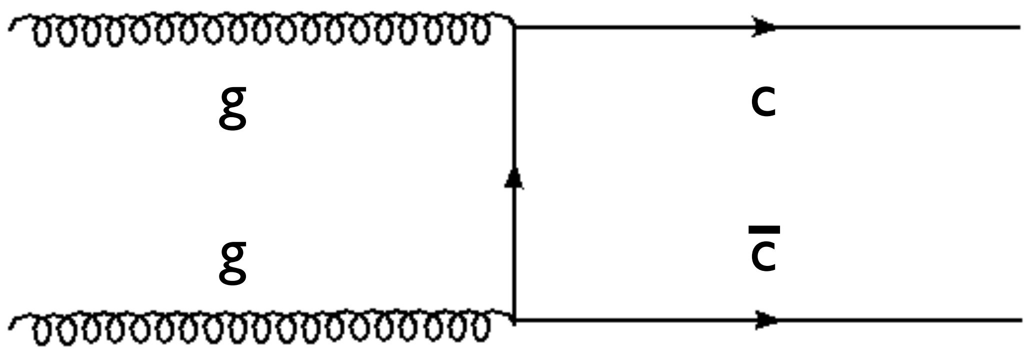


Lattice Gauge Theory:





Heavy Flavour Production:



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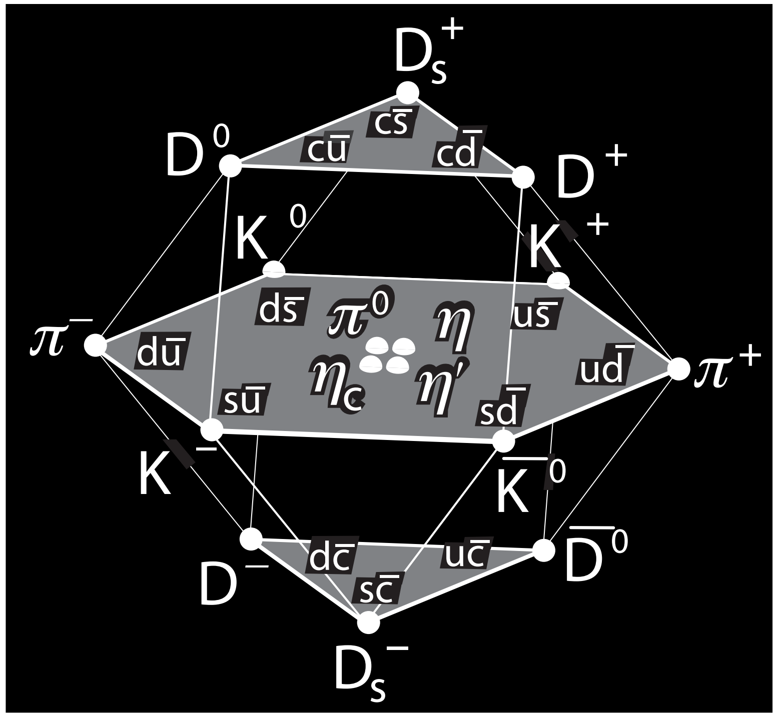
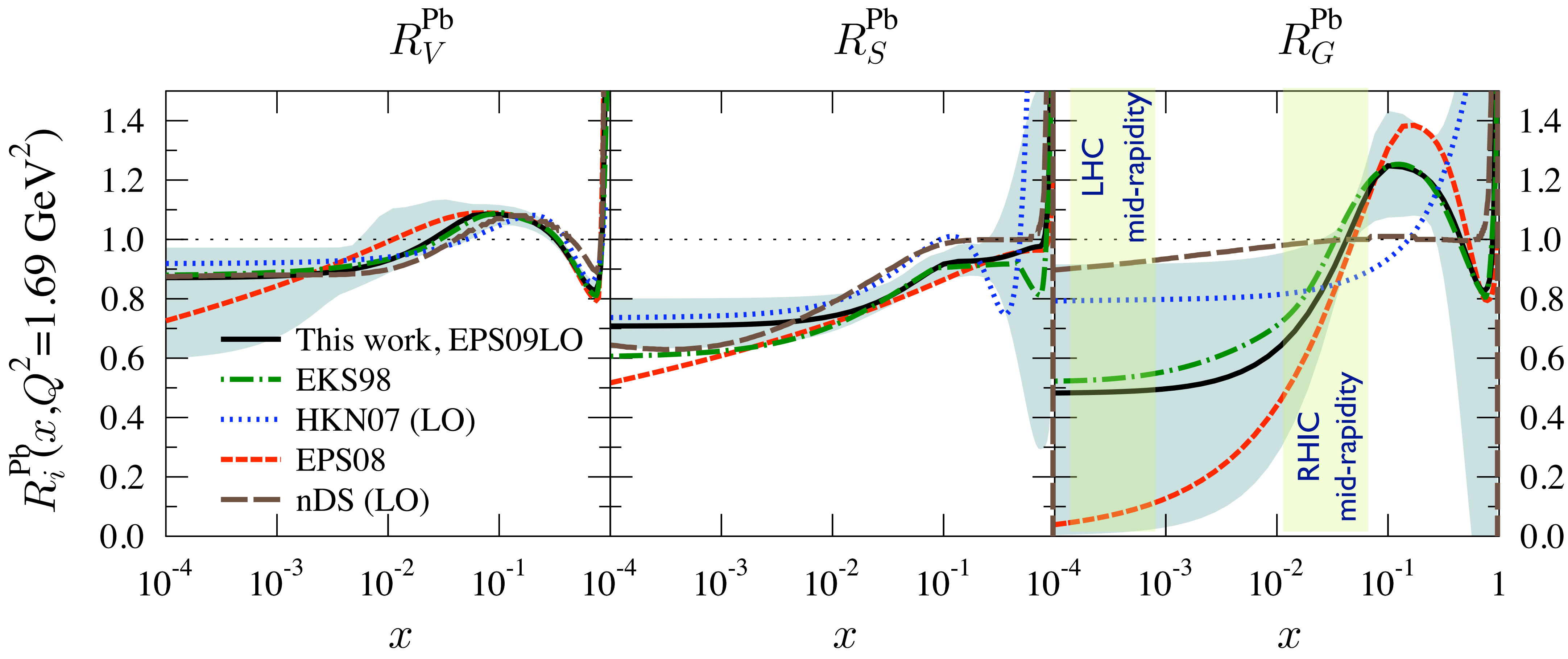


Eskola, Paukkonen, Salgado: arXiv0902.4154



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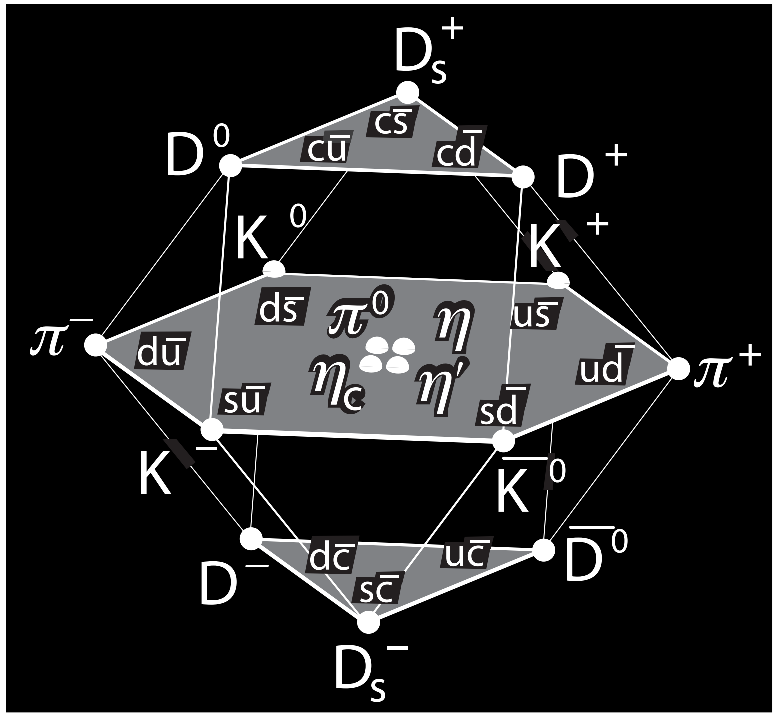

- What is the spatial and momentum distribution of gluons in nuclei/nucleons?
- What are the properties of high-density gluon matter?
- How do quarks and gluons interact as they traverse matter?
- What role do the gluons play in the spin structure of the nucleon?

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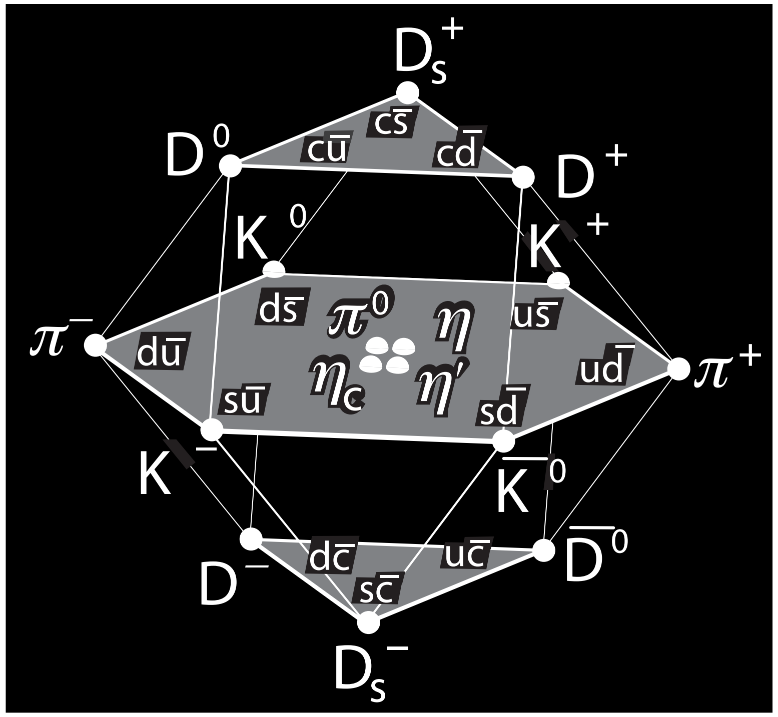

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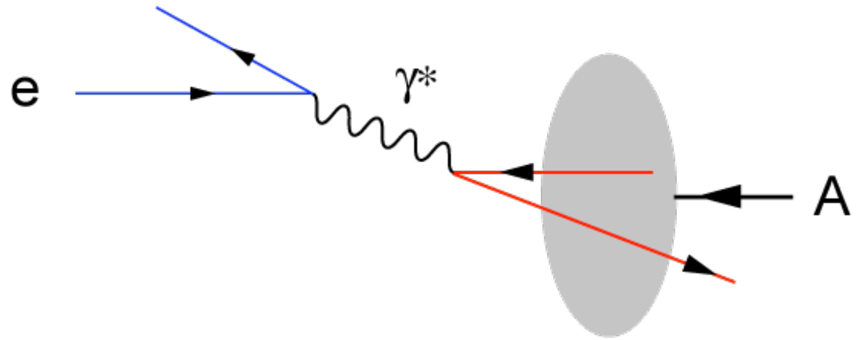
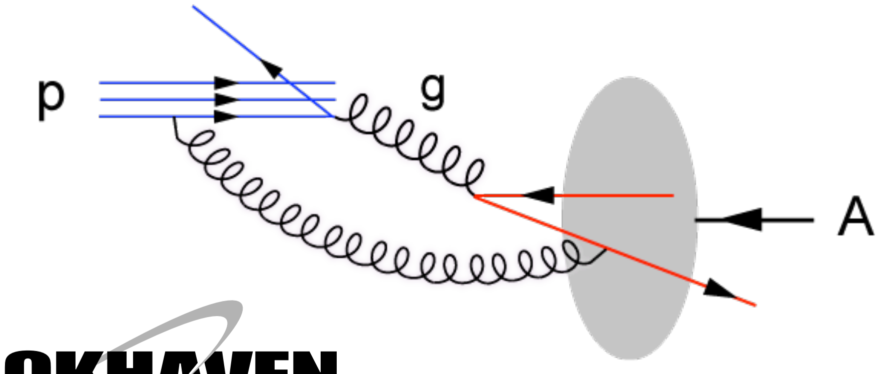
How do we get to the answers?

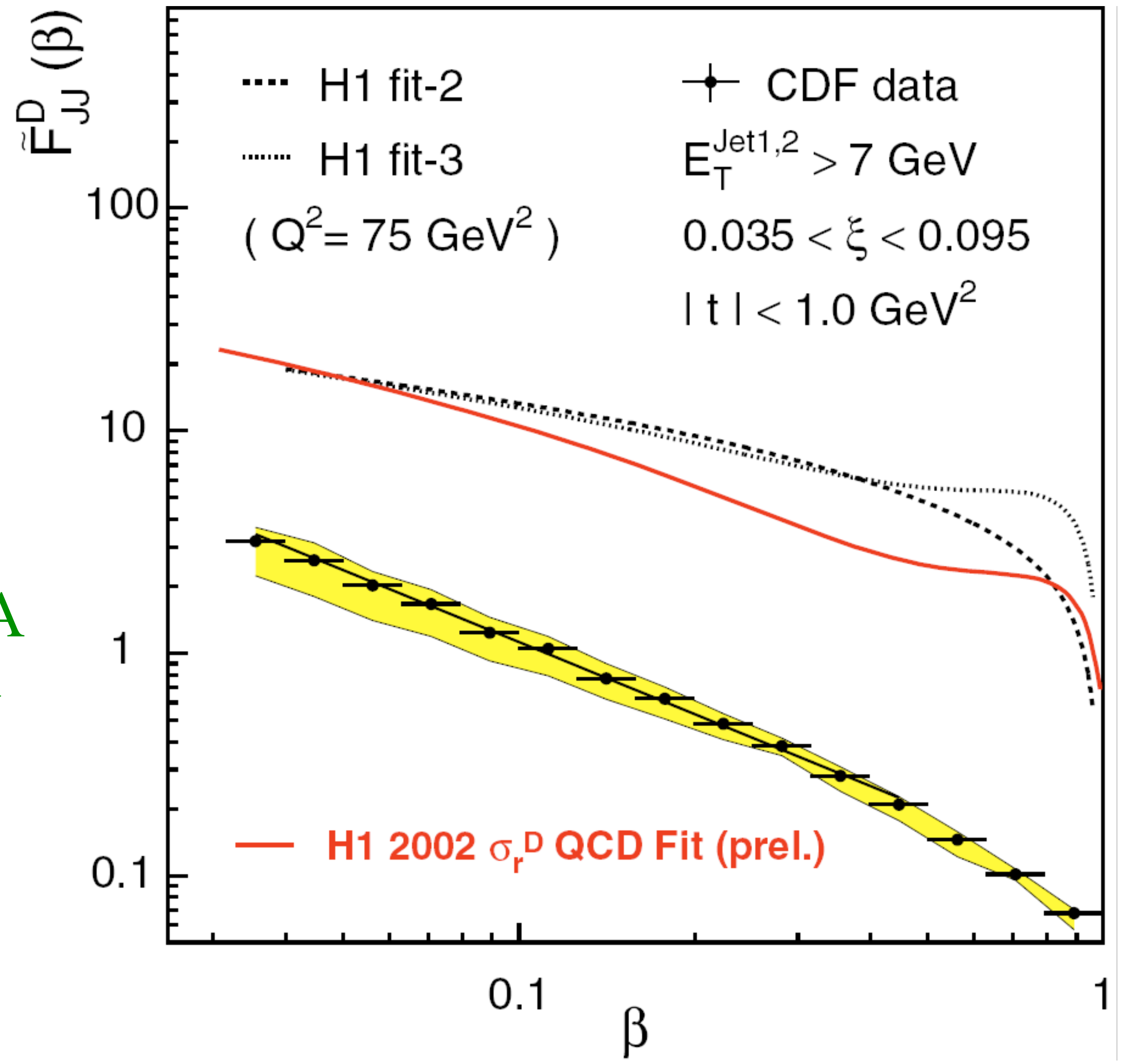
Accessing the Glue - *p*+A vs *e*+A

- Both *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 ⇒
- But:
    - ➡ soft colour interactions between p and A before and after the primary interaction





F. Schilling, hep-ex/0209001



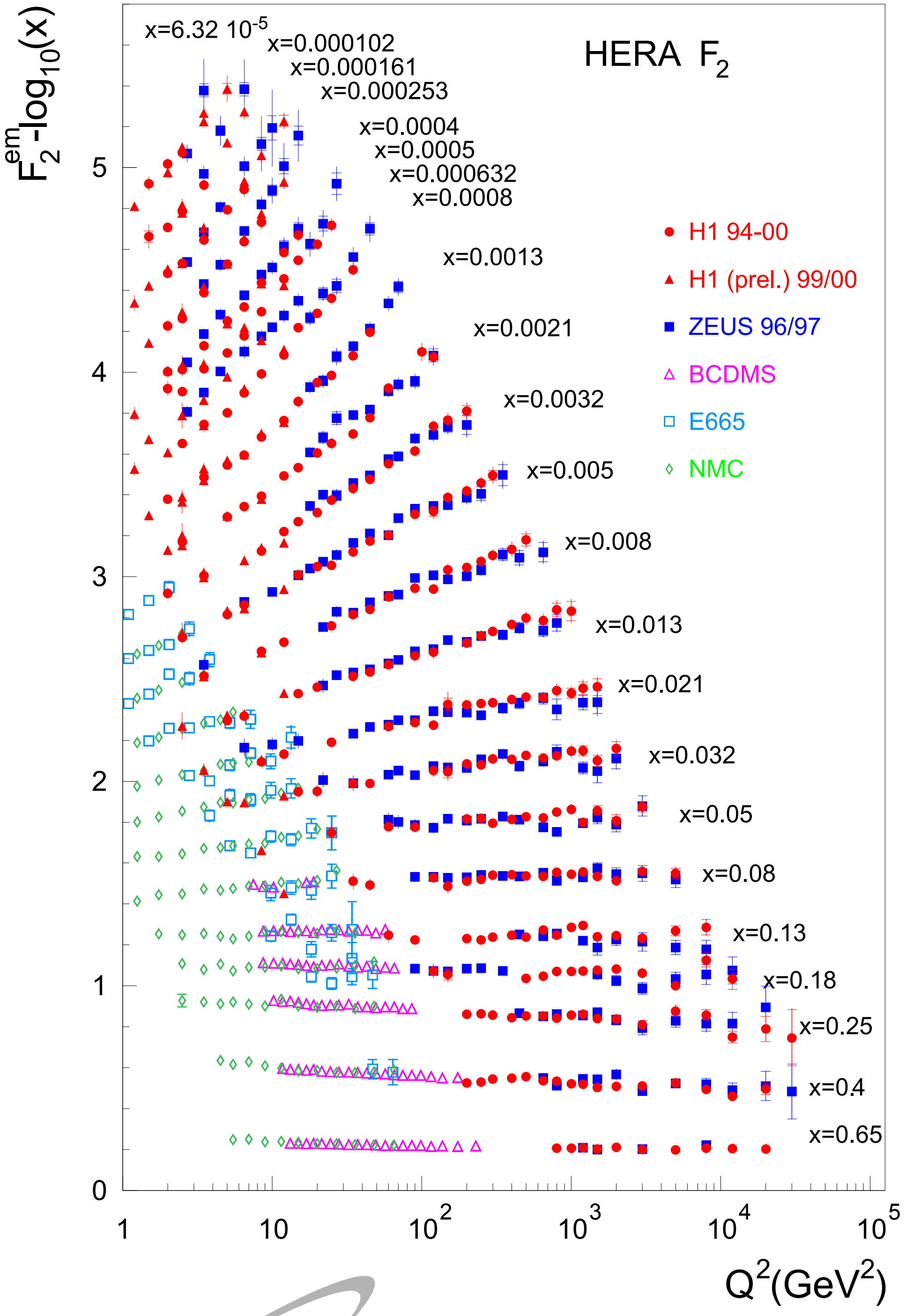
Breakdown of factorization (*e*+*p* HERA versus *p*+*p* Tevatron) seen for diffractive final states.

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

gluon momentum distribution



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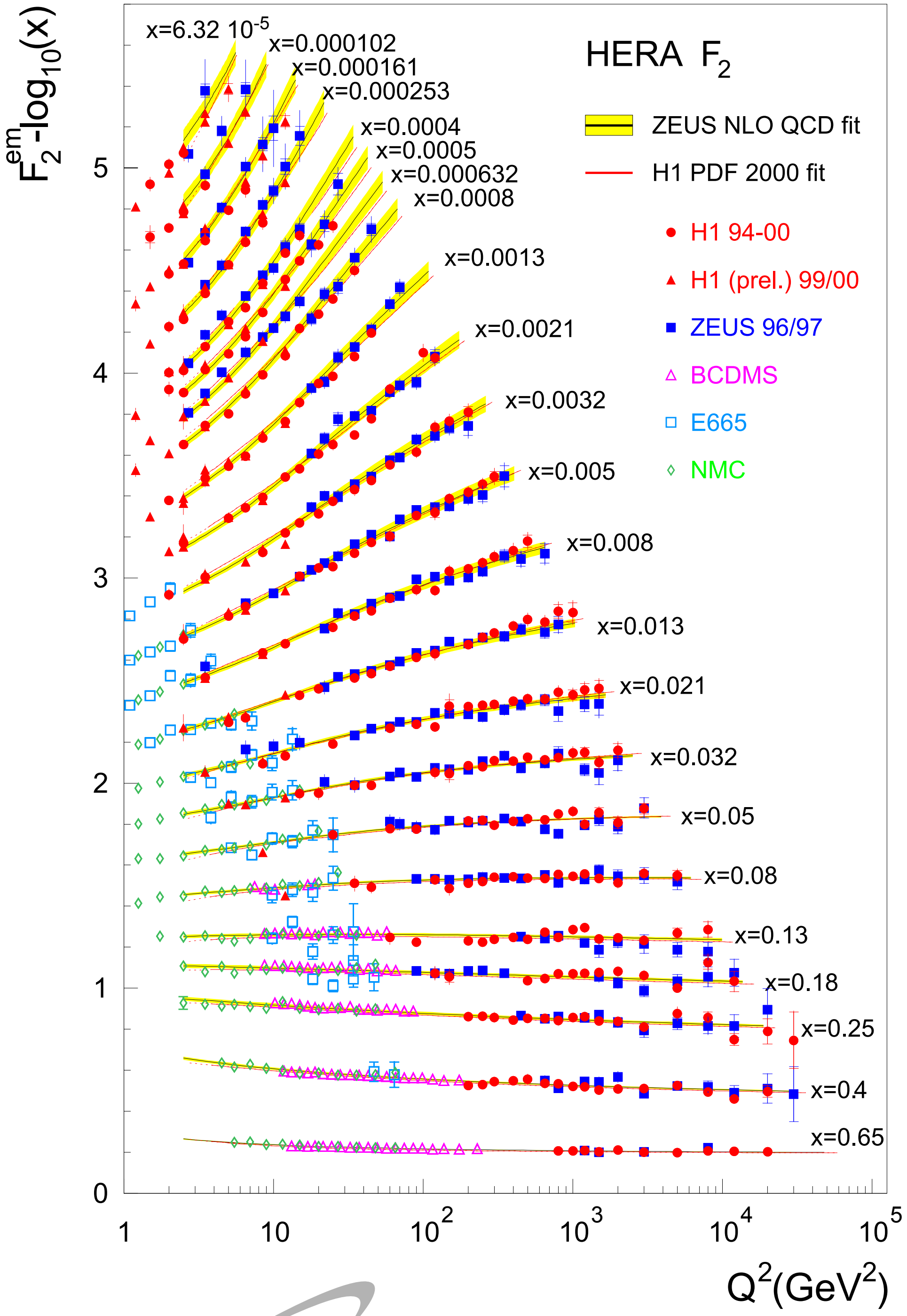

Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP

Evolution ⇒ $G(x,Q^2)$

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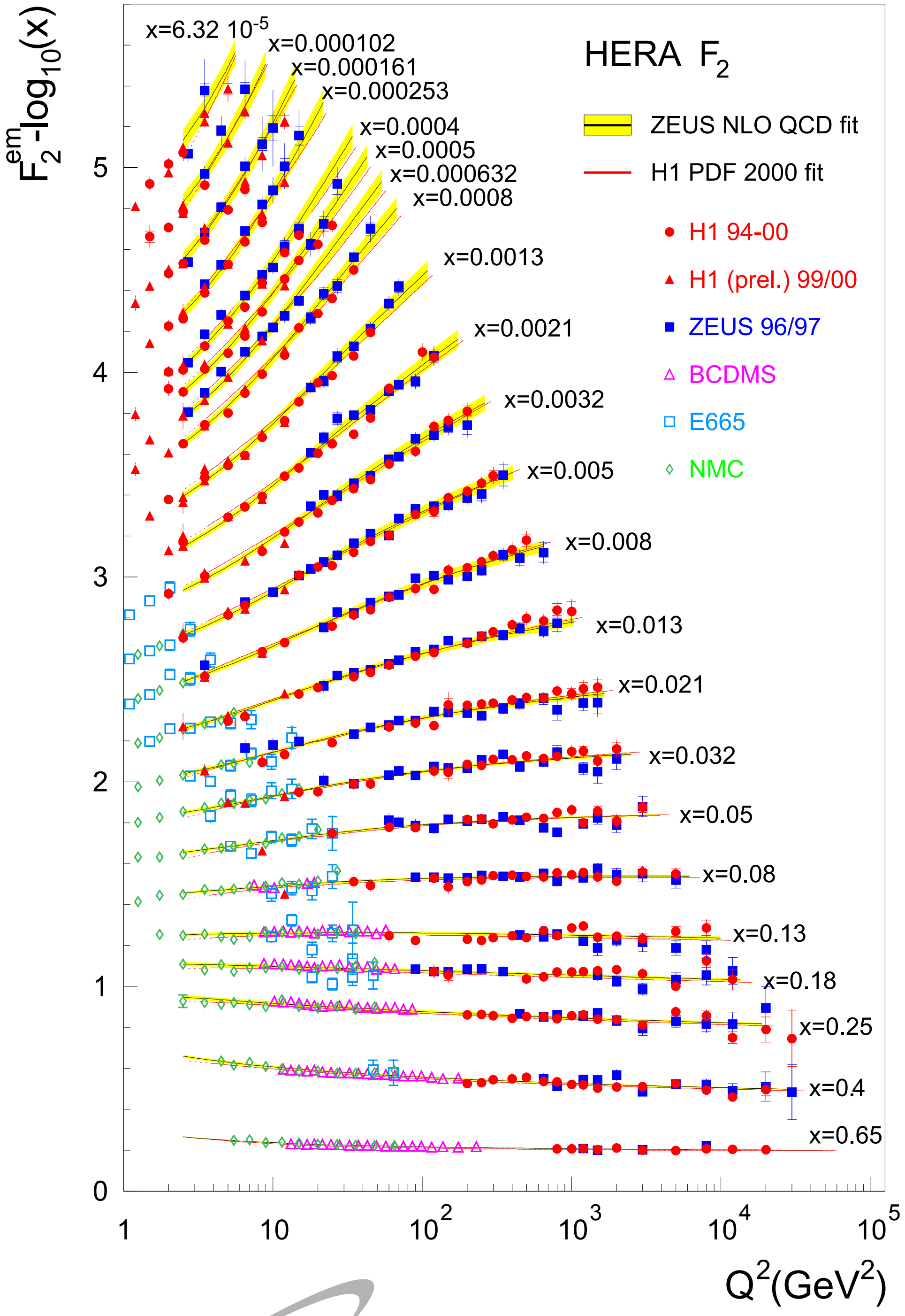

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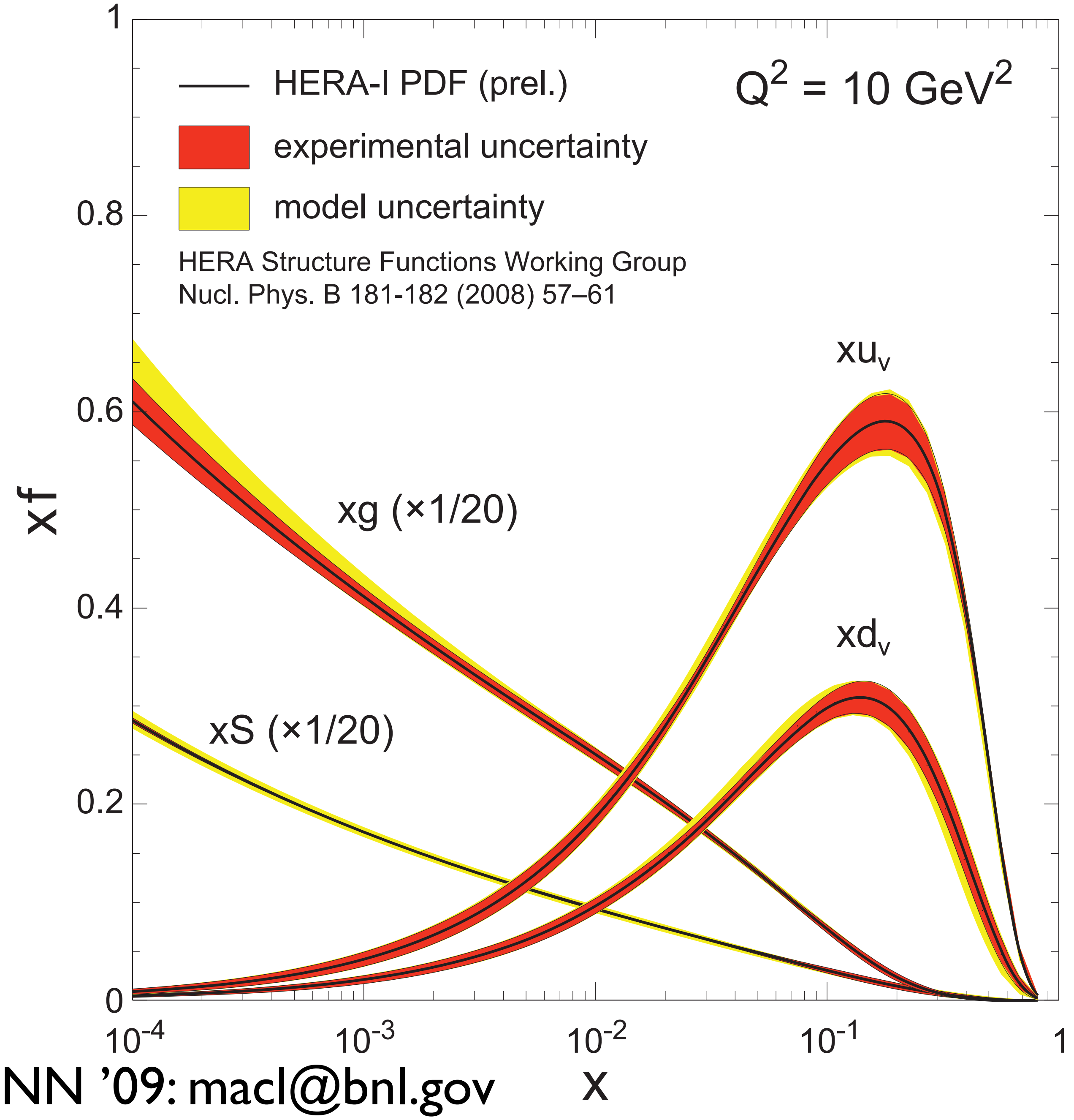

HERA Structure Functions Working Group
Nucl. Phys. B 181-182 (2008) 57–61

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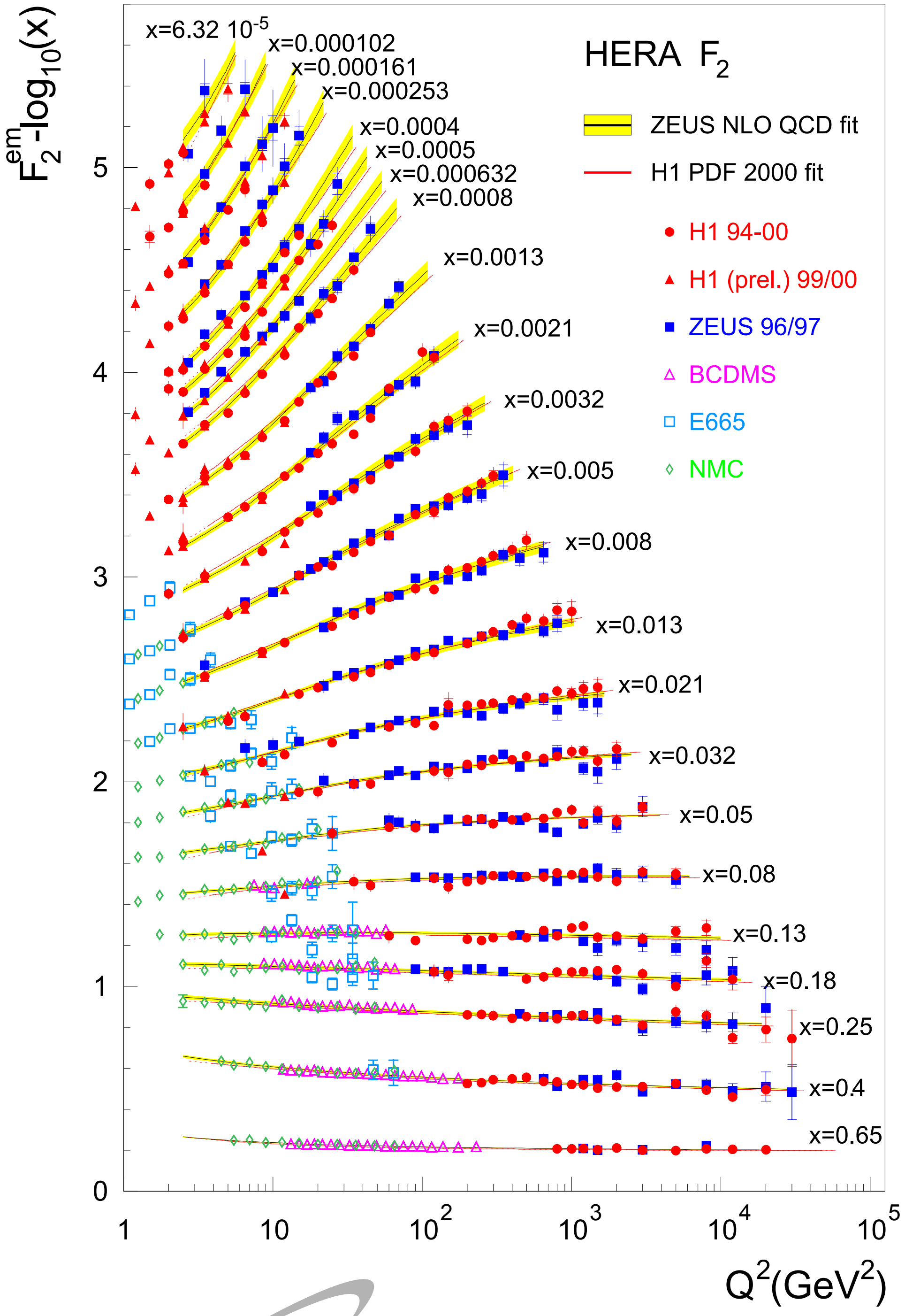

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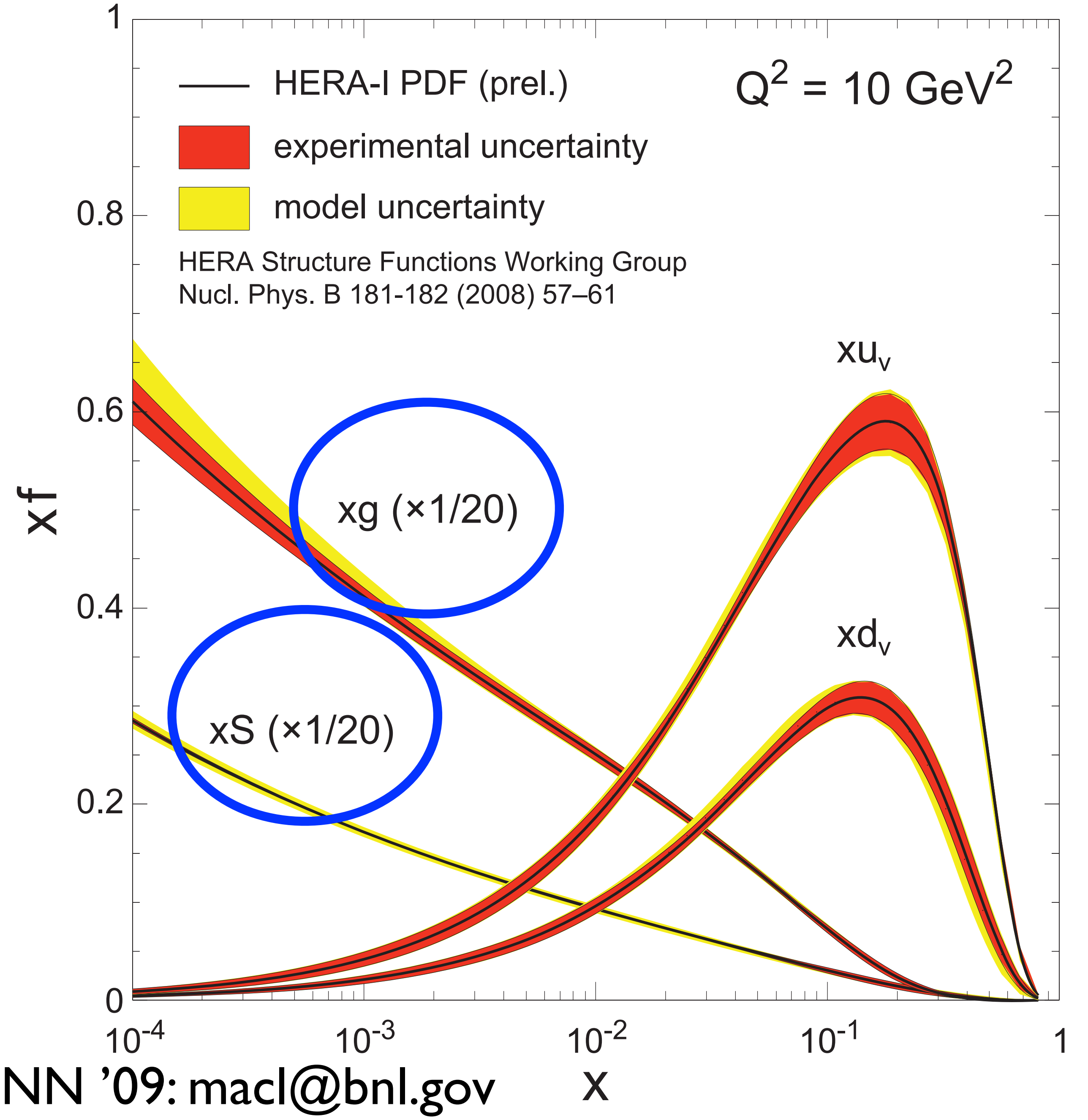

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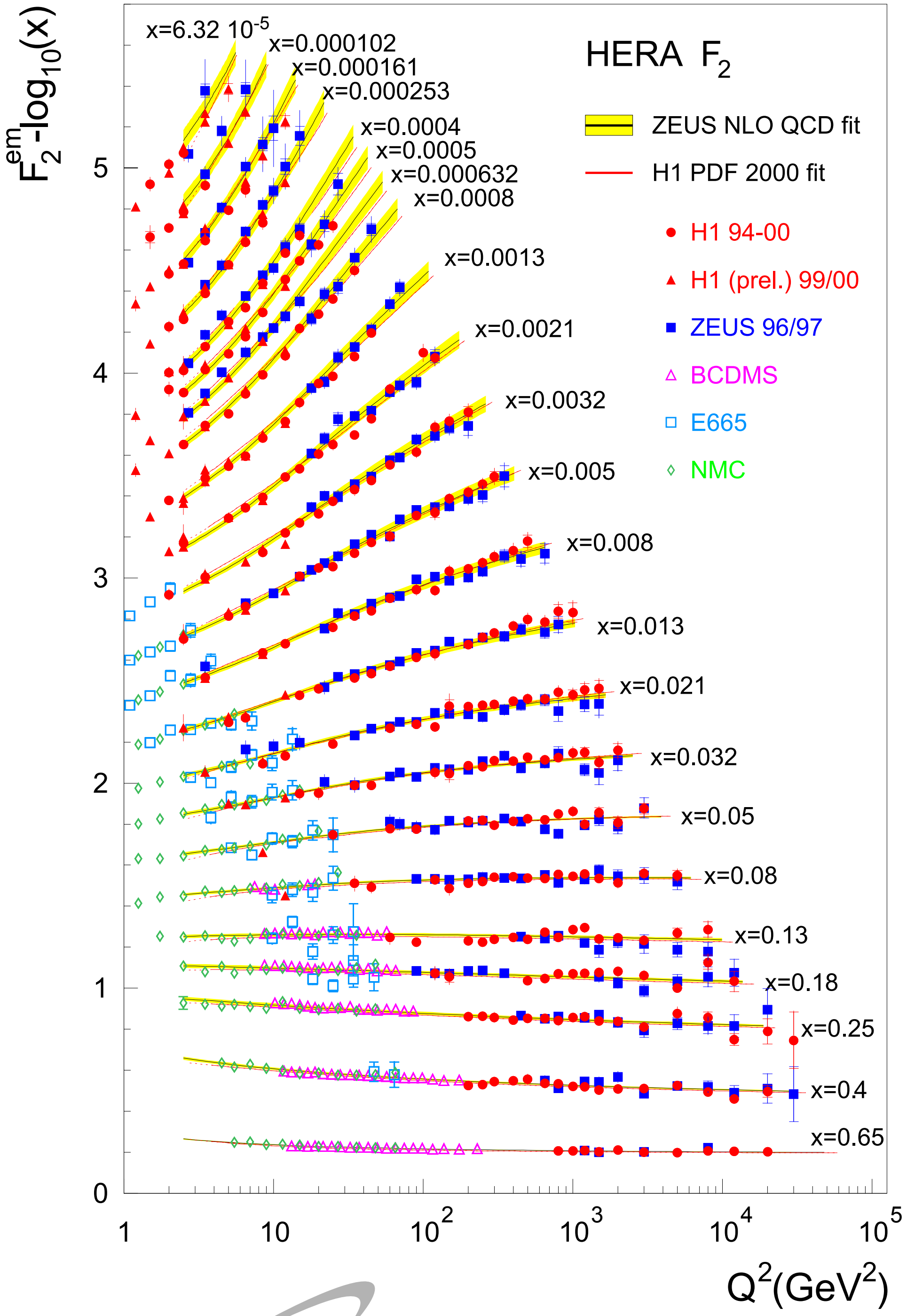

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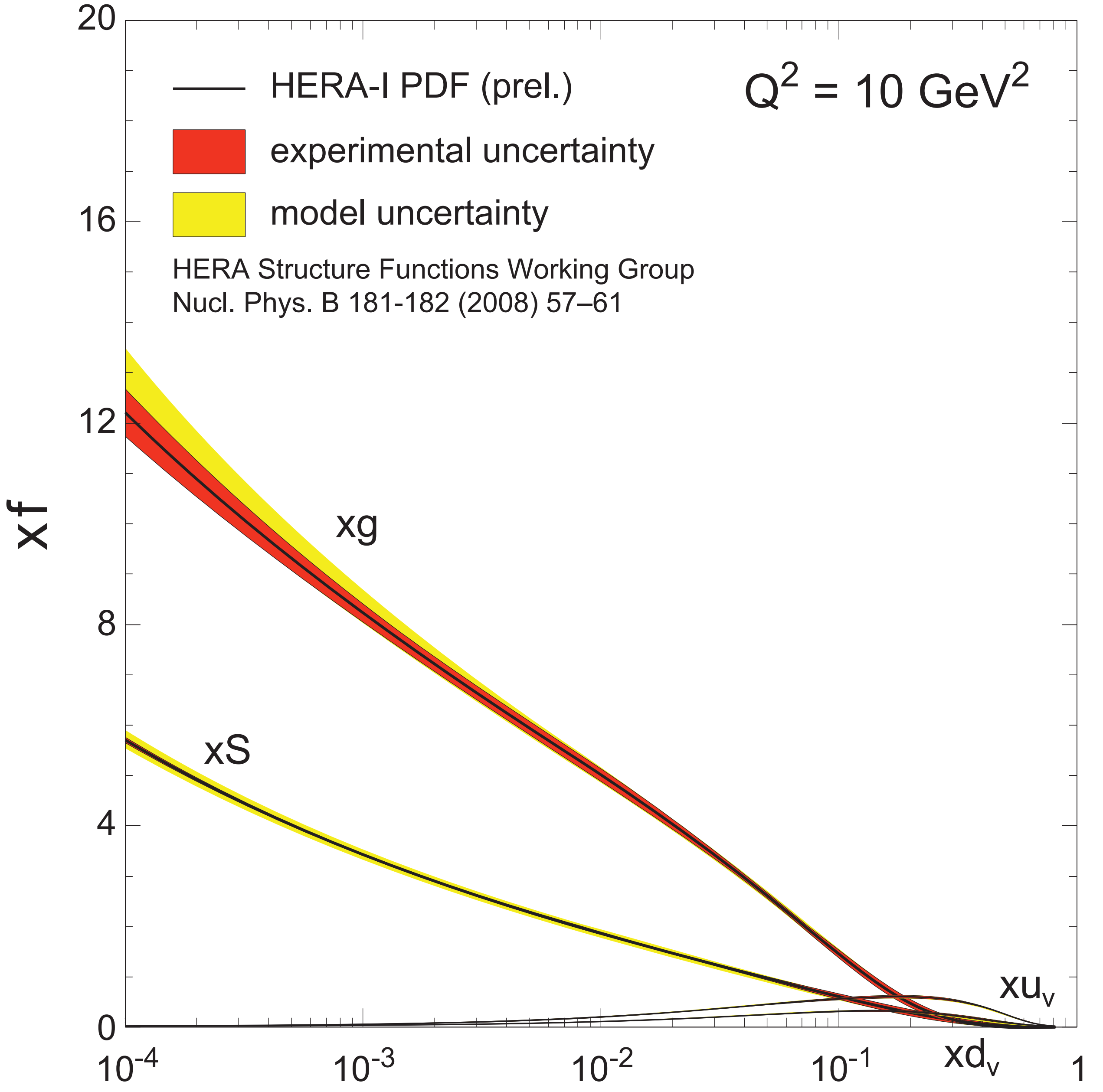

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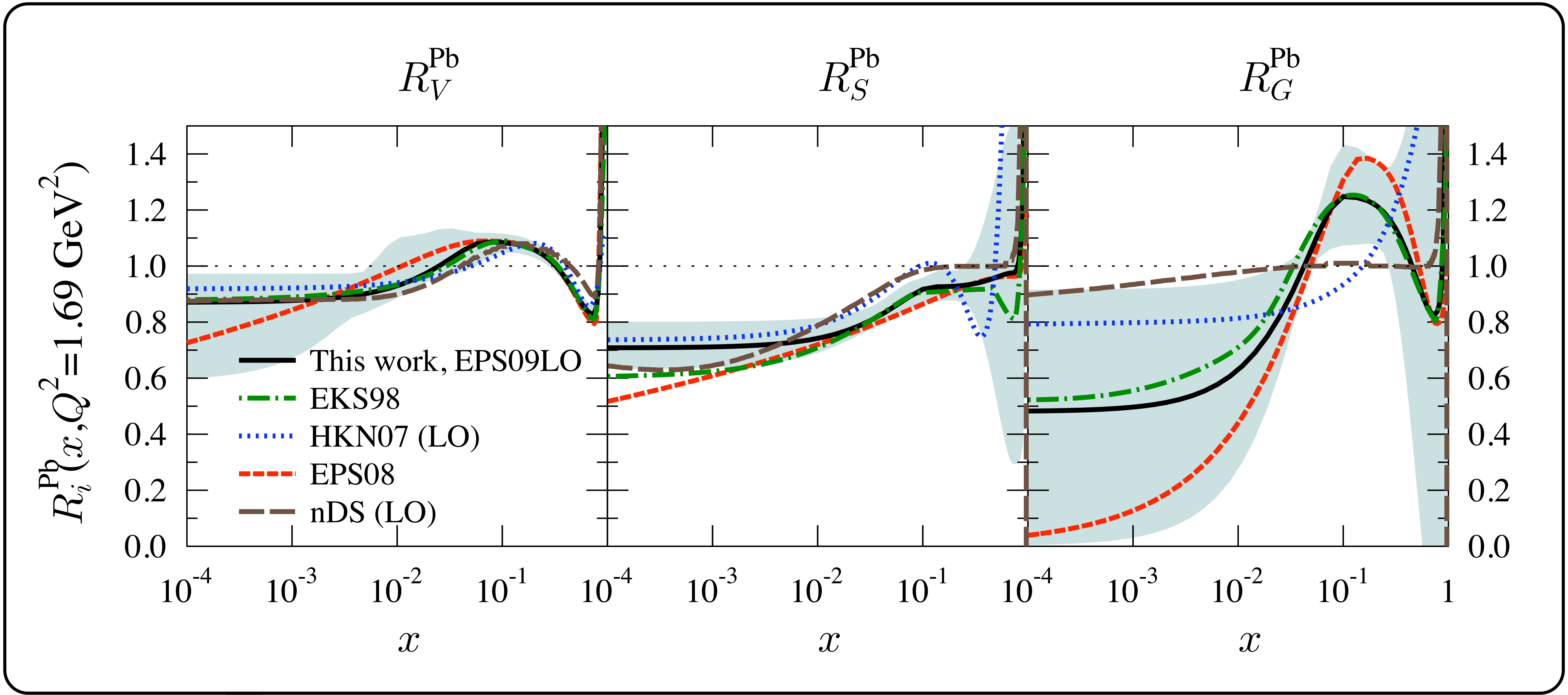
Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$



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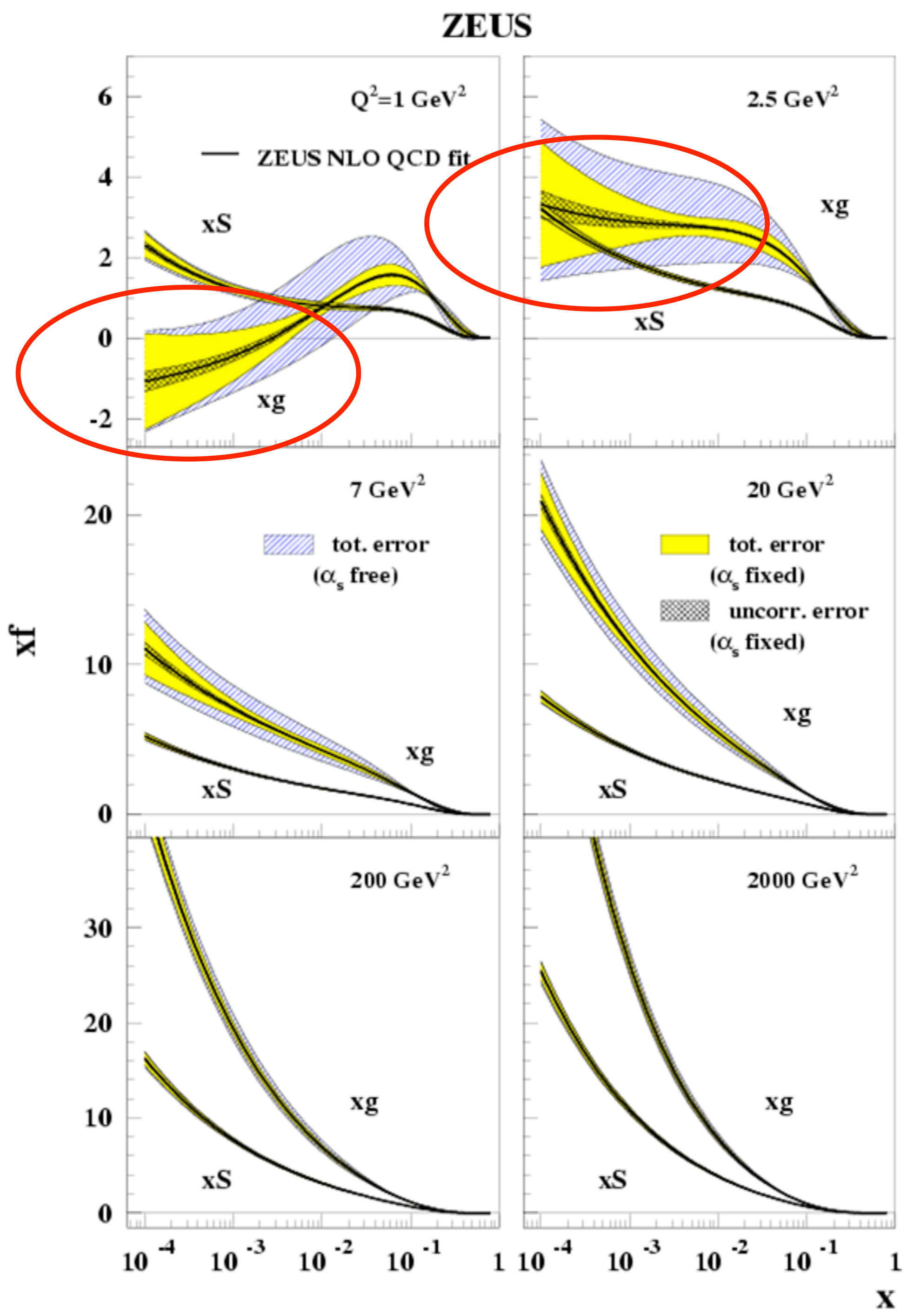
The problem with our current understanding



The problem with our current understanding

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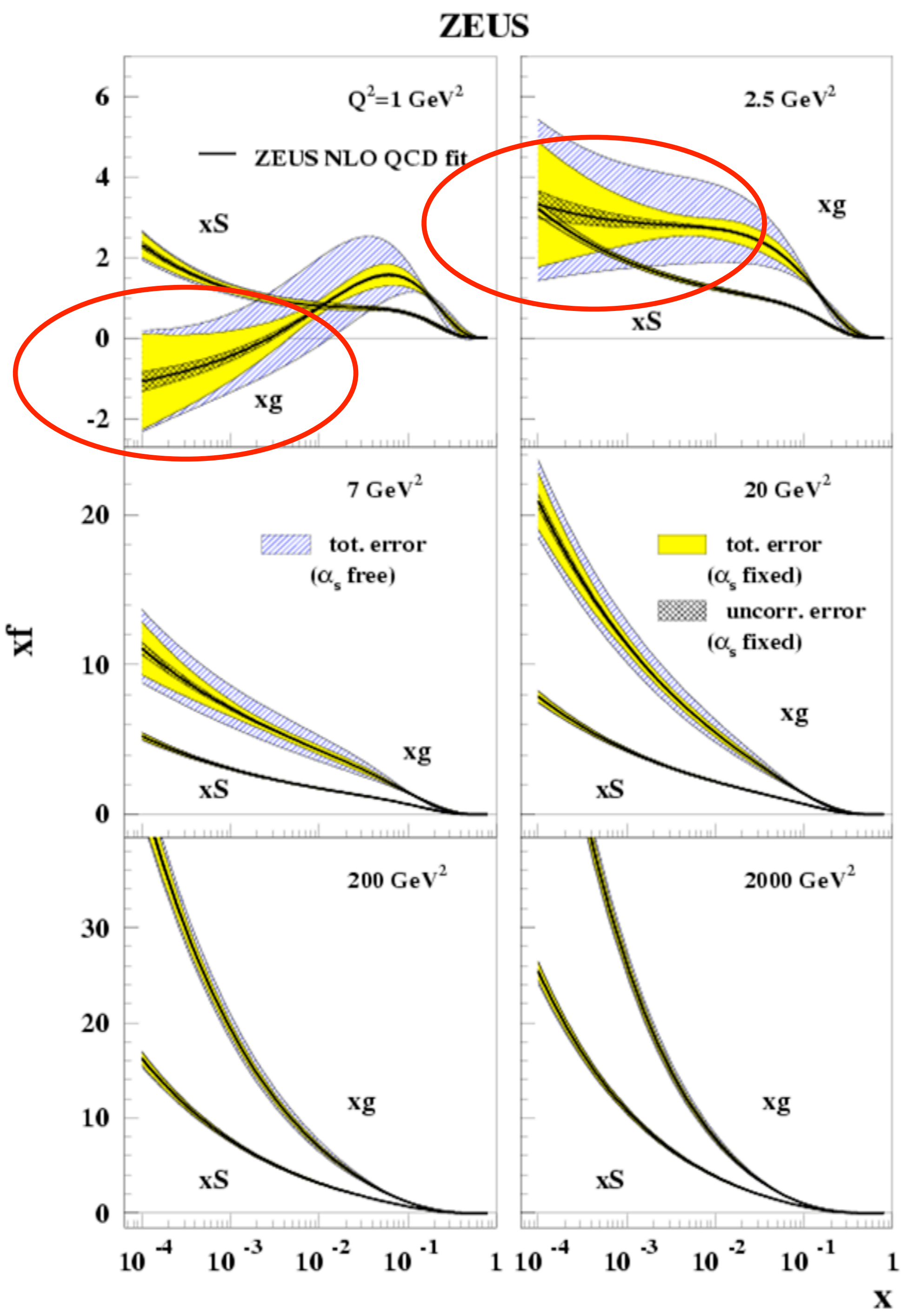
  - ➡ Weird behaviour of xG at low-x and low Q^2 in HERA data
    - xS > xG, though sea quarks come from gluon splitting ...



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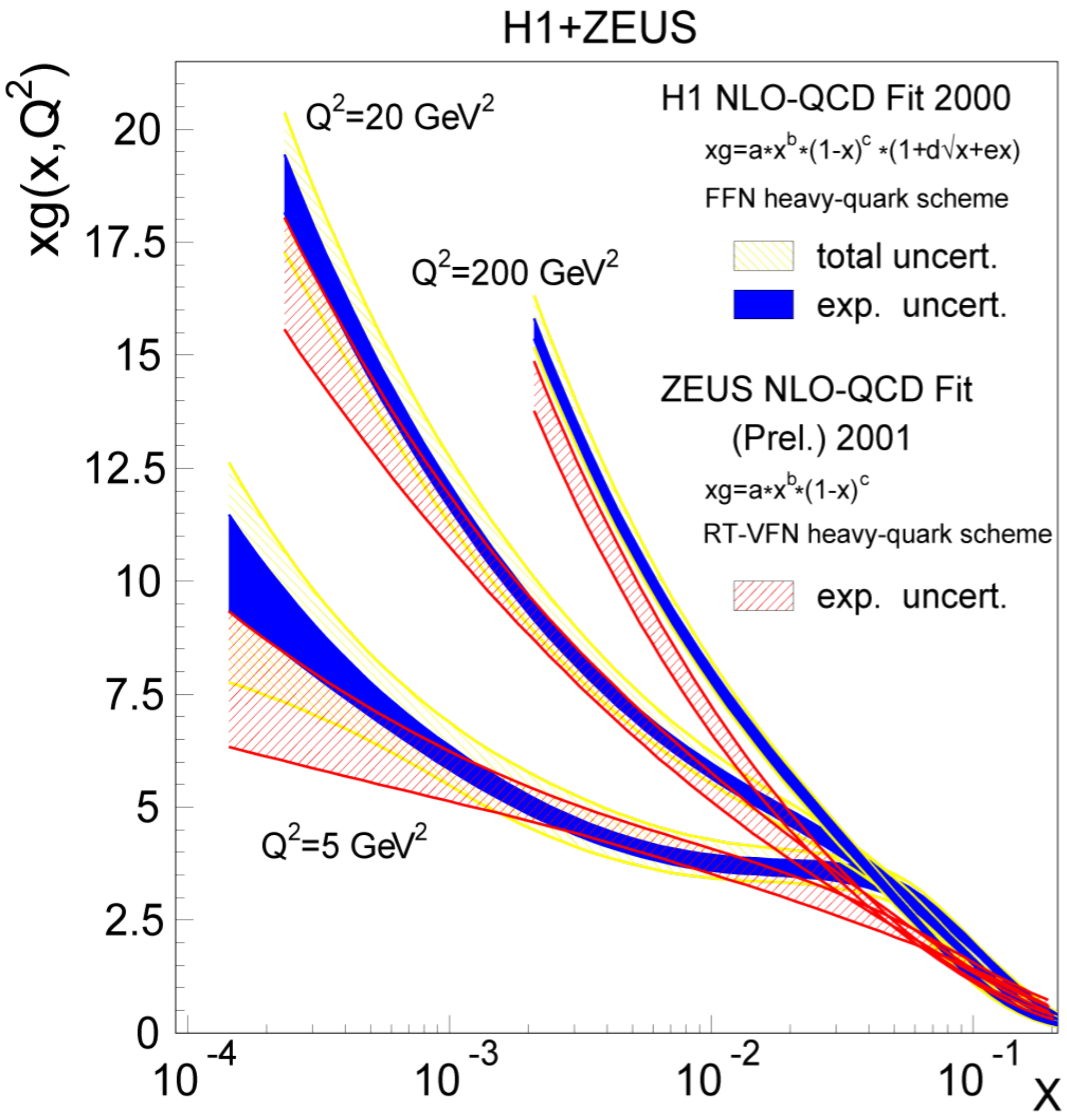
- More severe
  - ➡ Linear evolution has a built-in high-energy “catastrophe”
  - ➡ *xG* has rapid rise with decreasing *x* (and increasing Q^2) ⇒ violation of Froissart unitarity bound
    - ▶ Must have saturation



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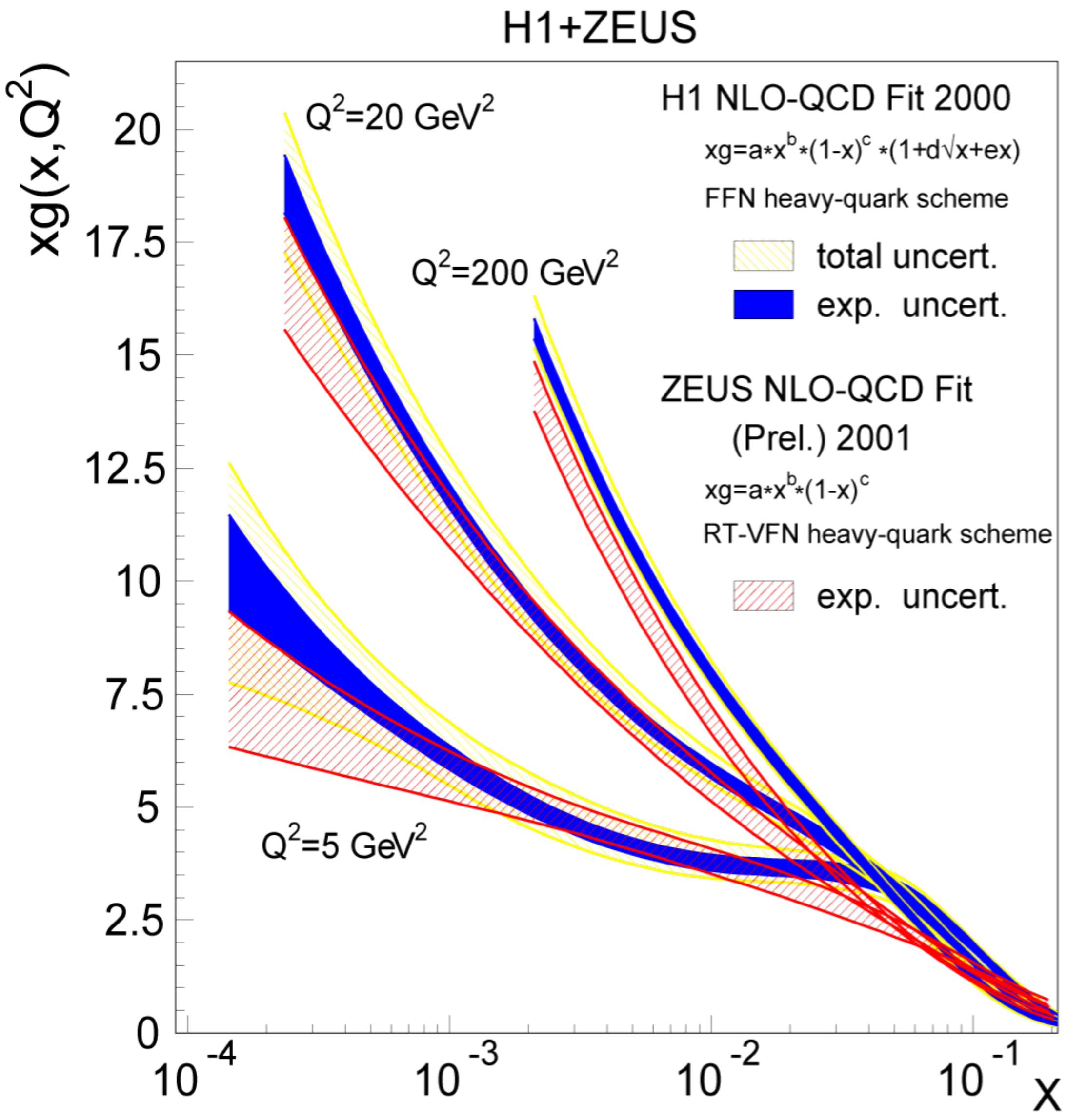
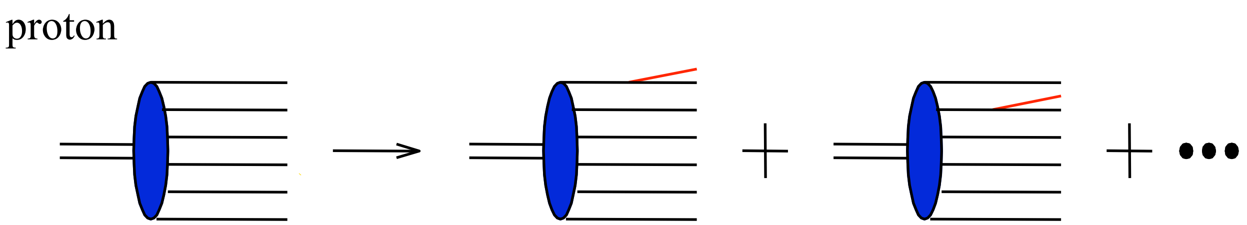


What’s the underlying dynamics?

Non-linear QCD - Saturation

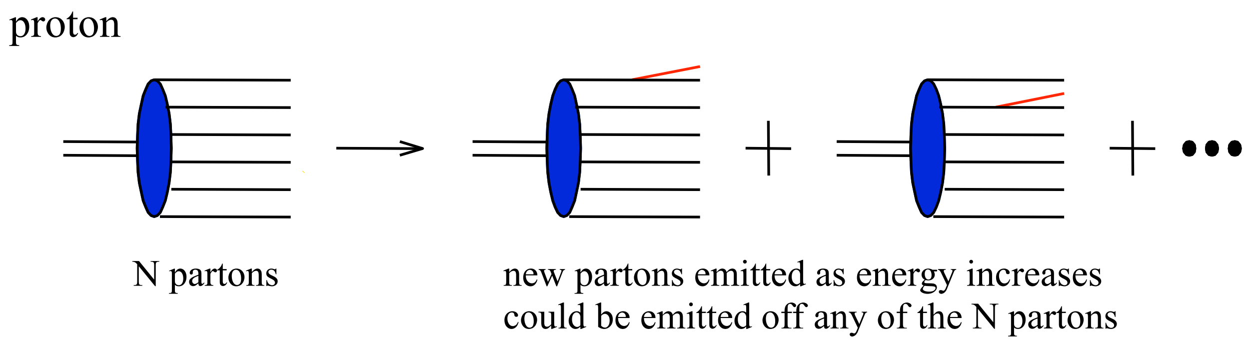


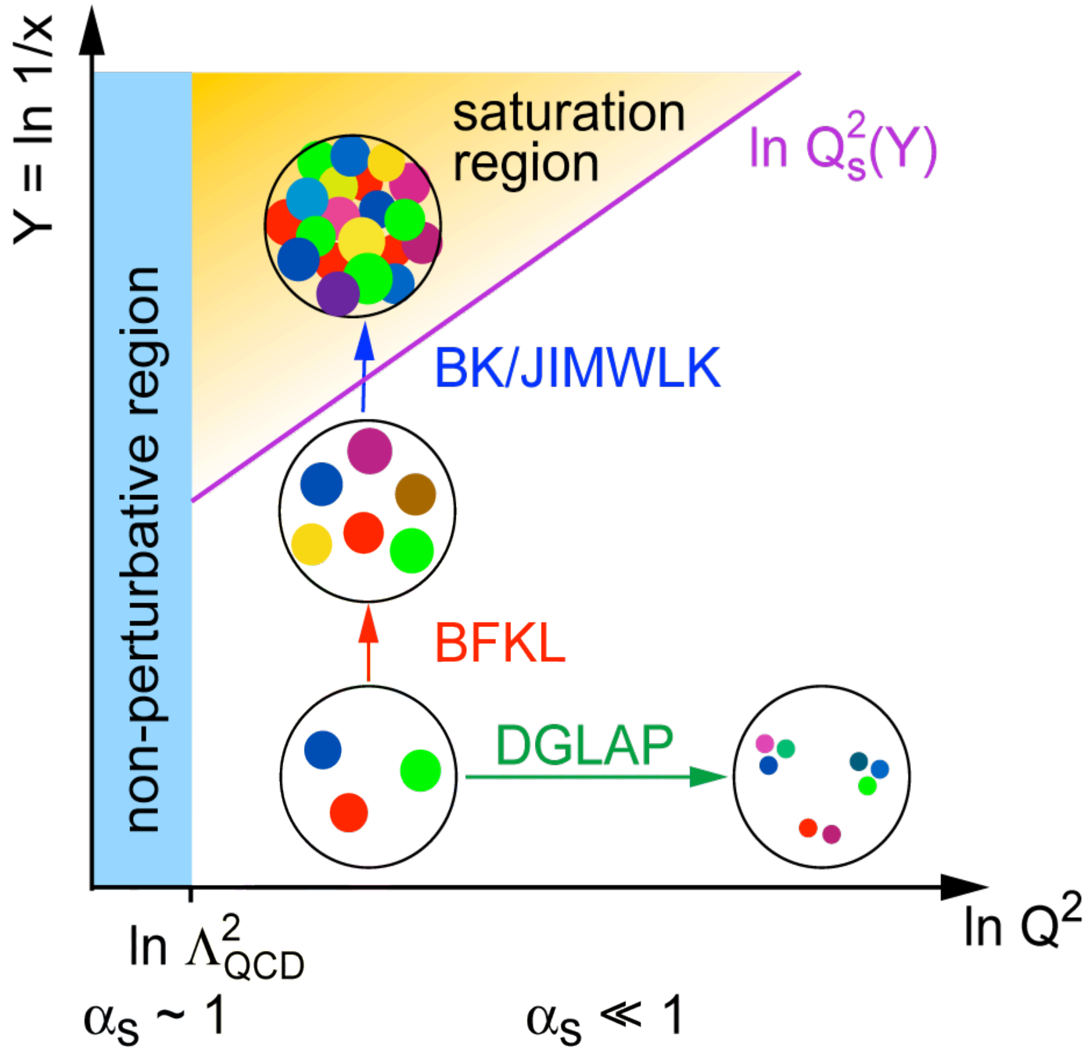
N partons

new partons emitted as energy increases
could be emitted off any of the N partons

Non-linear QCD - Saturation

- BFKL: evolution in x
  - ➡ linear
    - ‣ explosion in colour field at low-x





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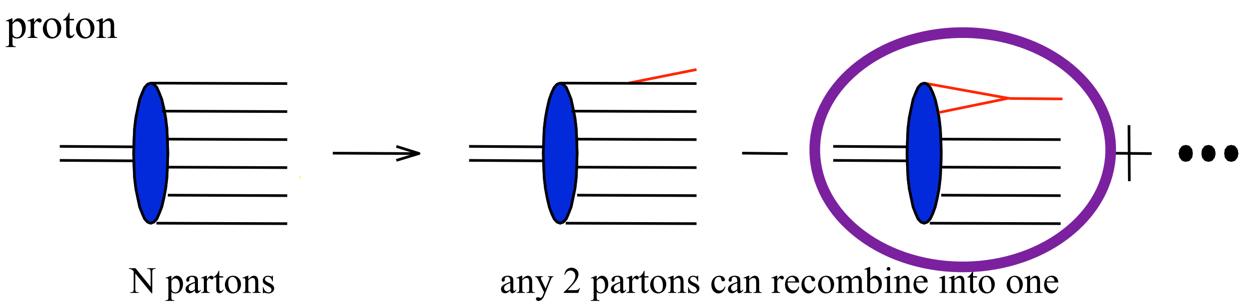
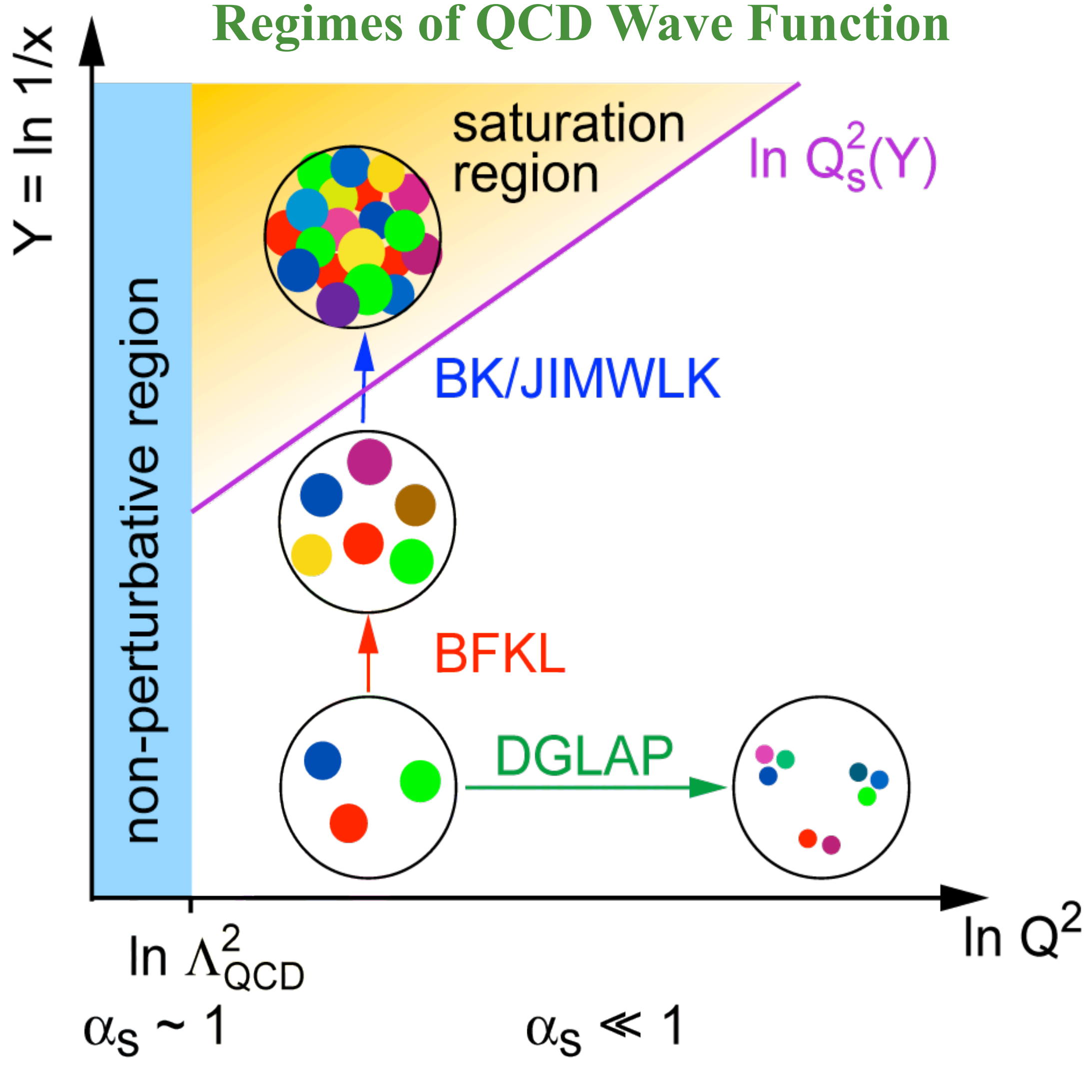


- BFKL: evolution in x
  - ➡ linear
    - ▸ explosion in colour field at low-x
- Non-linear BK/JIMWLK equations
  - ➡ non-linearity ⇒ saturation
  - ➡ characterised by the saturation scale, $Q_S(x,A)$
  - ➡ arises naturally in the Colour Glass Condensate (CGC) EFT

Regimes of QCD Wave Function



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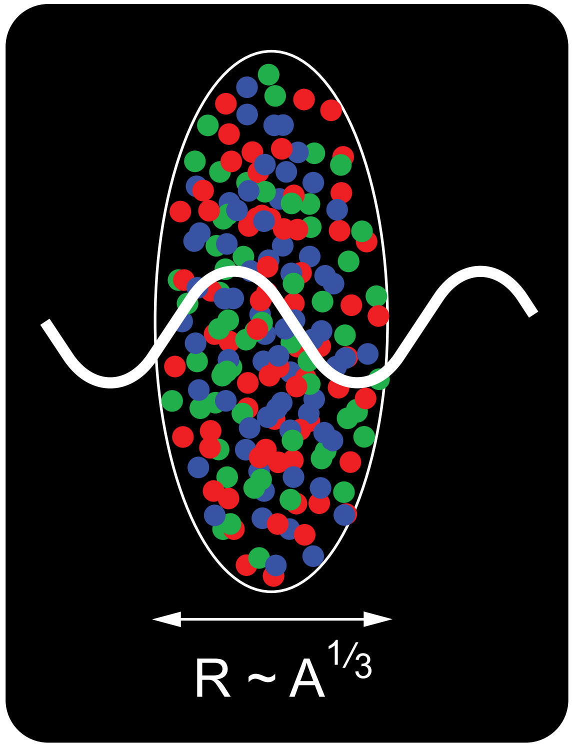
The Nuclear Enhancement Factor

- 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 the front or back of of of the nucleus.
    - ▶ Probe interacts coherently with all nucleons.
  - ➡ Probes with transverse resolution $1/Q^2$ ($\ll \Lambda^2_{QCD}$) ~ 1 fm^2 will see large colour charge fluctuations.
    - ▶ This kick experienced in a random walk is the resolution scale.



The Nuclear Enhancement Factor

Simple geometric considerations lead to:

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

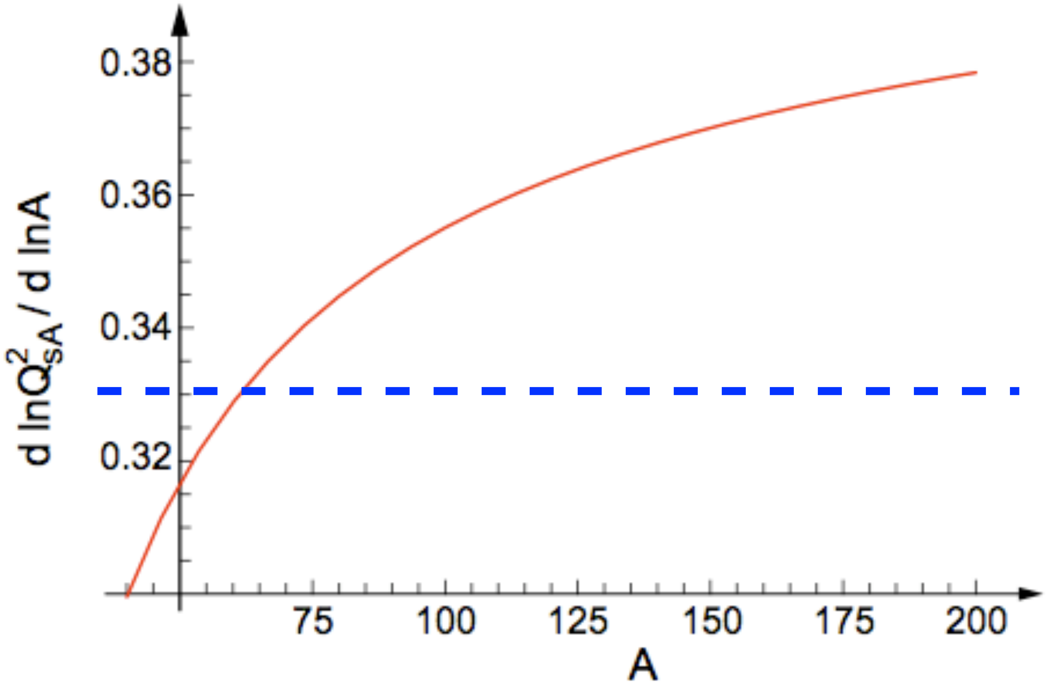
Nuclear Enhancement Factor: $$(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

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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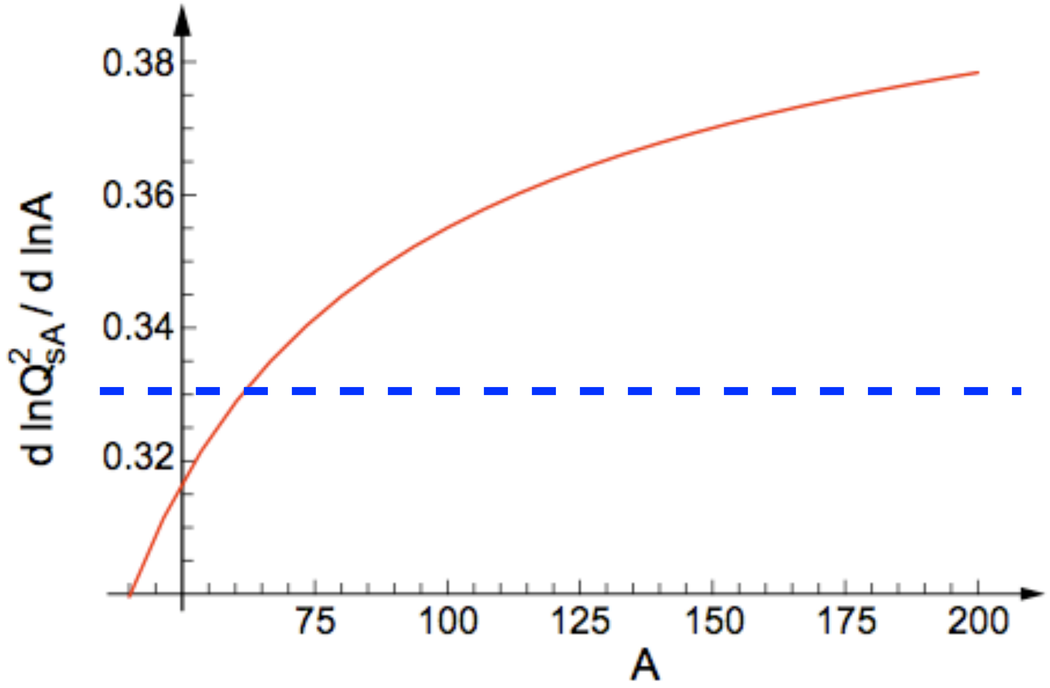

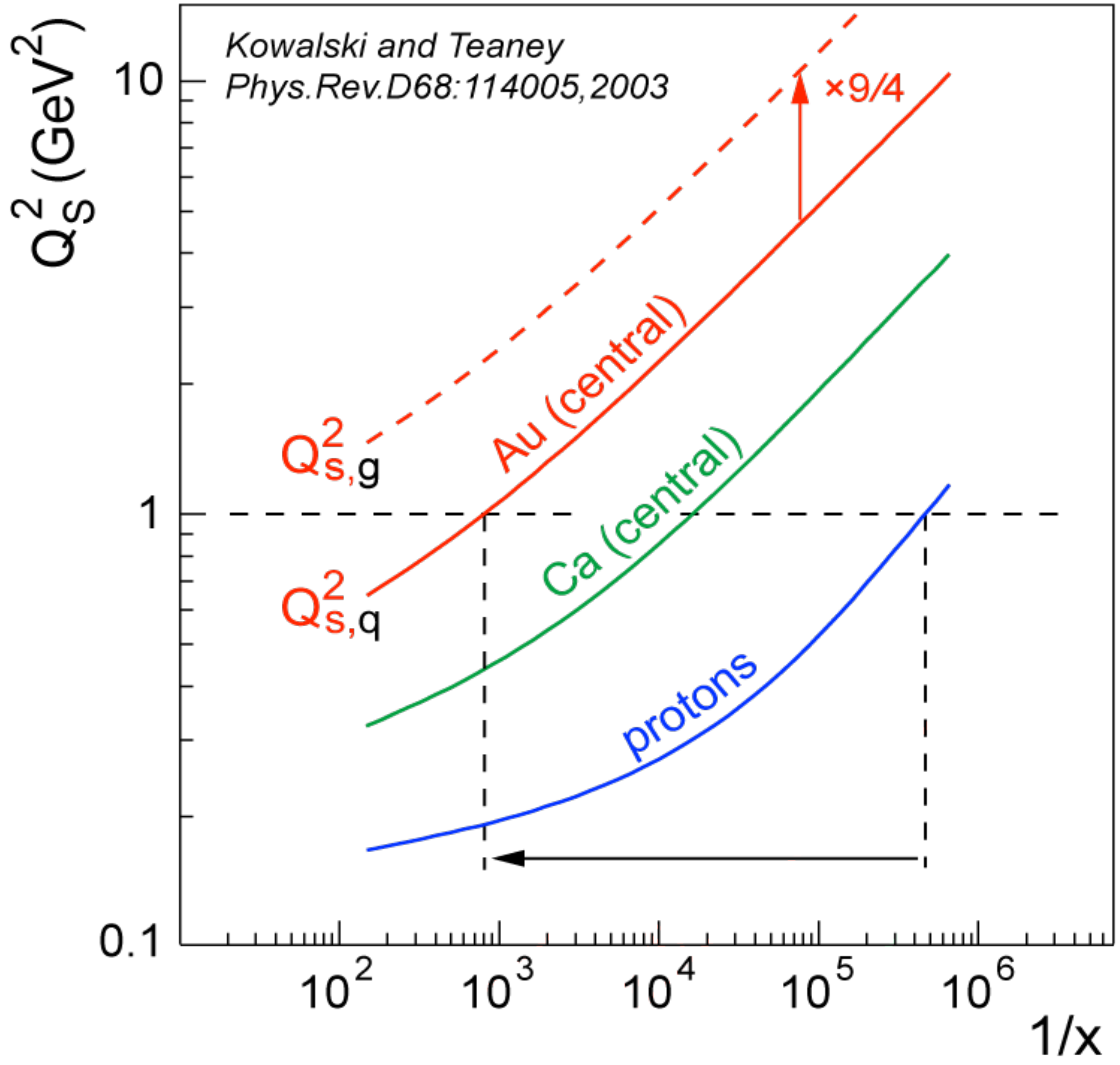

One would require an energy in e+p ~ 10-100 x e+A to get to same Q^2_S

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Key Measurements in e+A

- **Momentum distribution of gluons $G(x,Q^2)$**
  - ➡ 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 $\sim [xG(x,Q^2)]^2$

Example of Key Measurements: F_L

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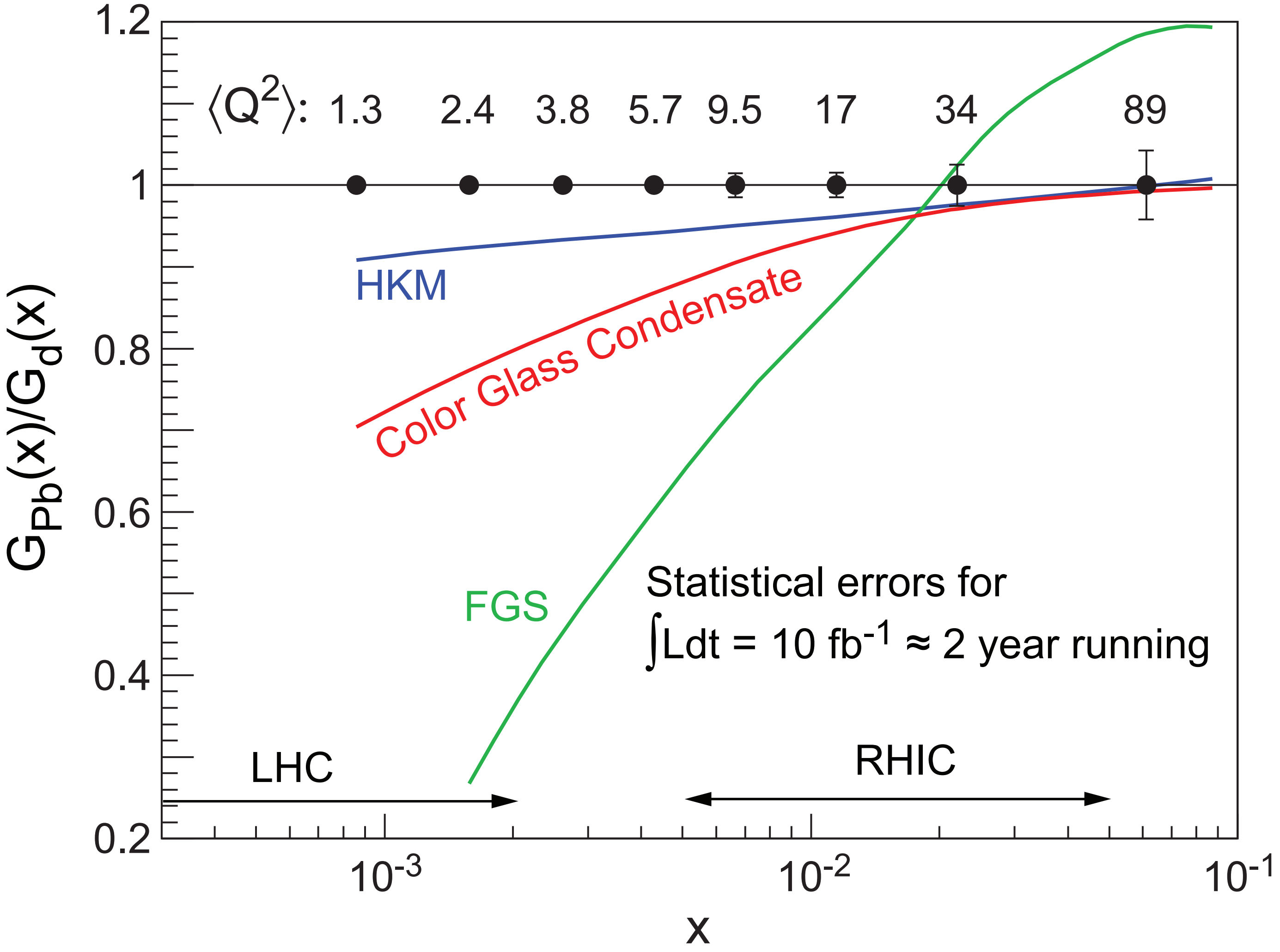

Statistical errors for $\int Ldt = 10\ \mathrm{fb}^{-1} \approx 2$ year running

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

requires √s scan, $Q^2/xs = y$

Here:

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

$= 4/A\ \mathrm{fb}^{-1}$ (10+50) GeV

$= 2/A\ \mathrm{fb}^{-1}$ (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

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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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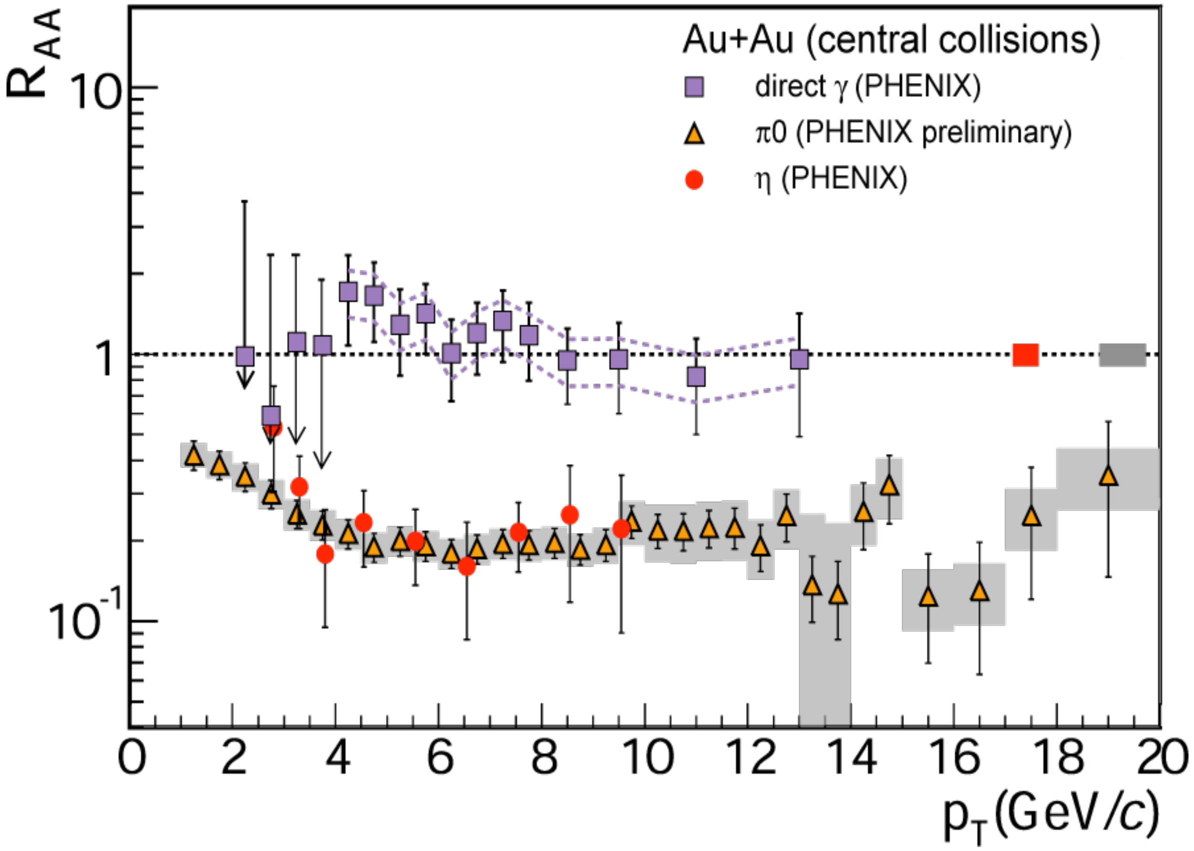
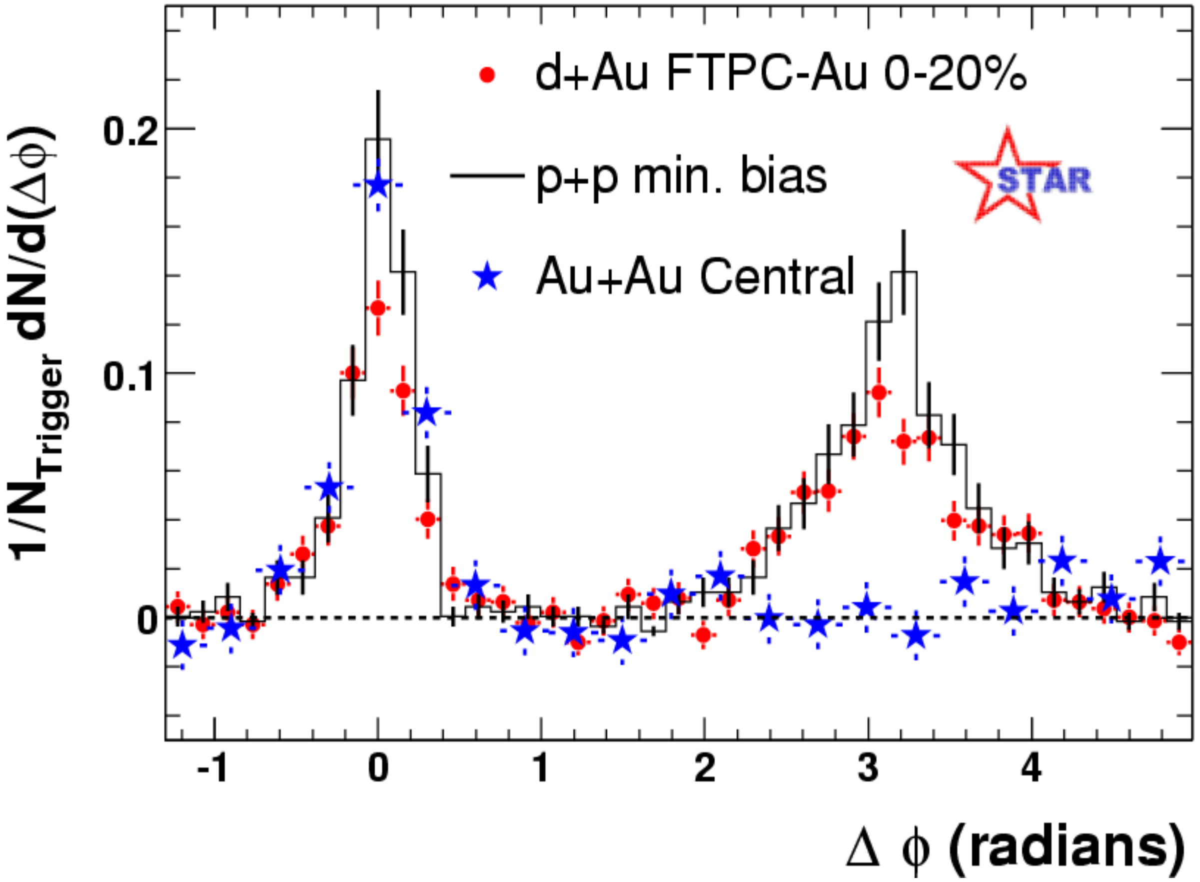
    - F_2, F_L for various A and impact parameter dependence
- **Interaction of fast probes with *gluonic* medium?**
    - Hadronization, Fragmentation
    - Energy loss (charm, bottom!)

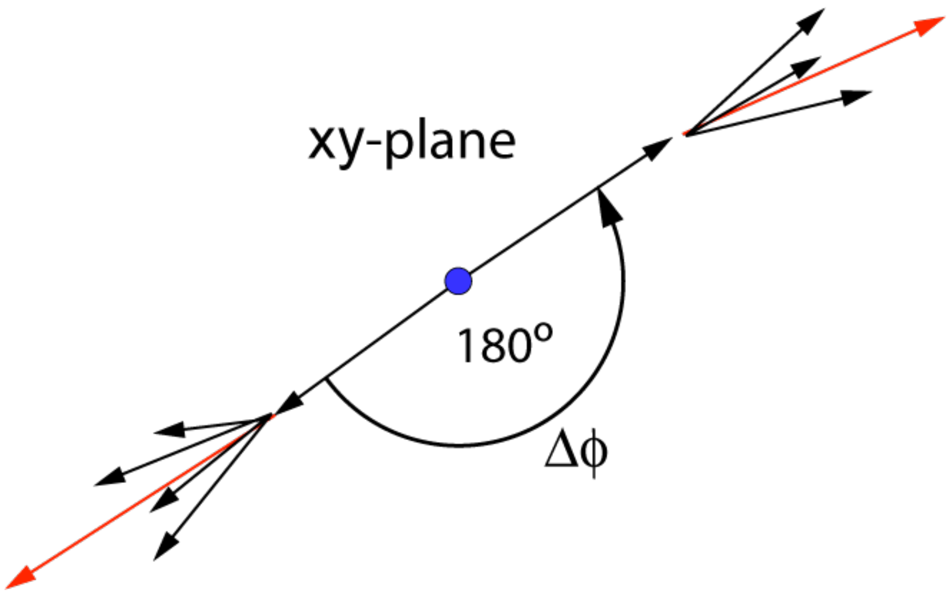
Interaction of fast probes with gluonic medium

RHIC Au+Au @ 200 GeV/n





Interaction of fast probes with gluonic medium



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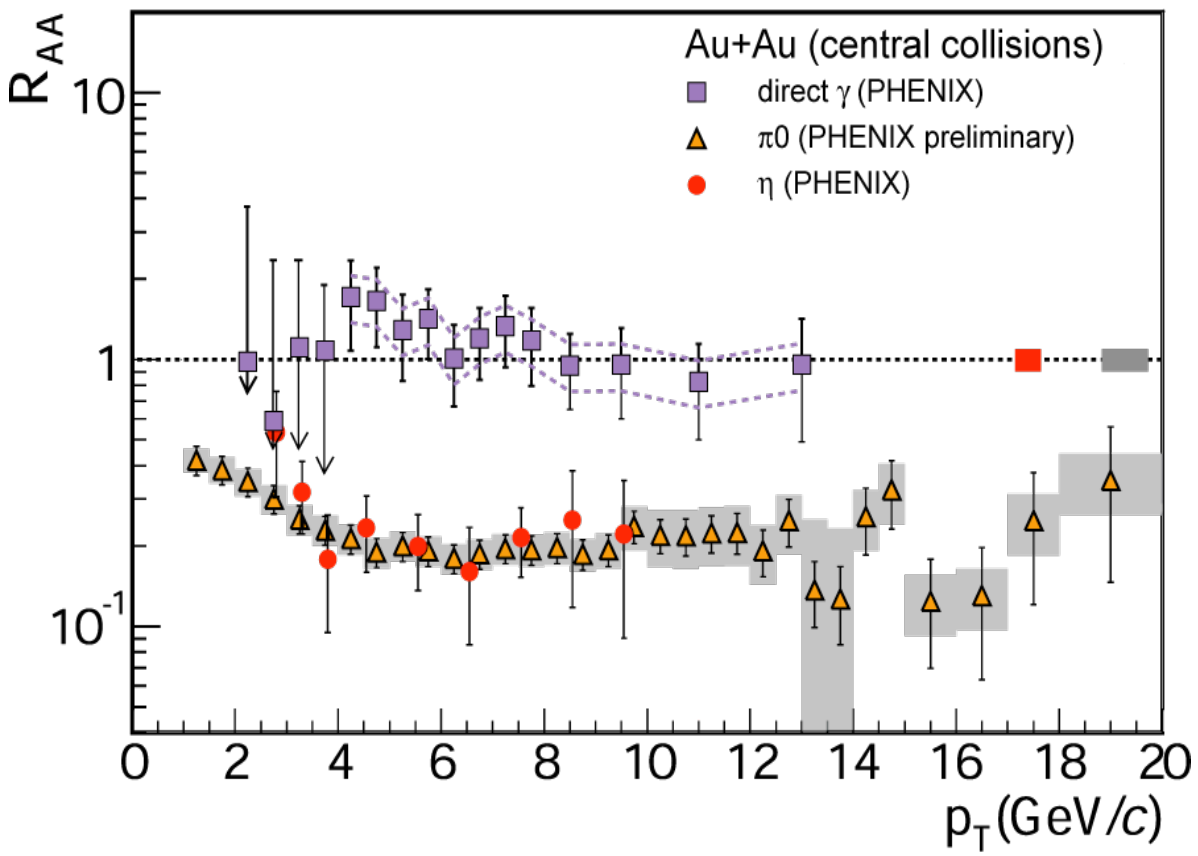

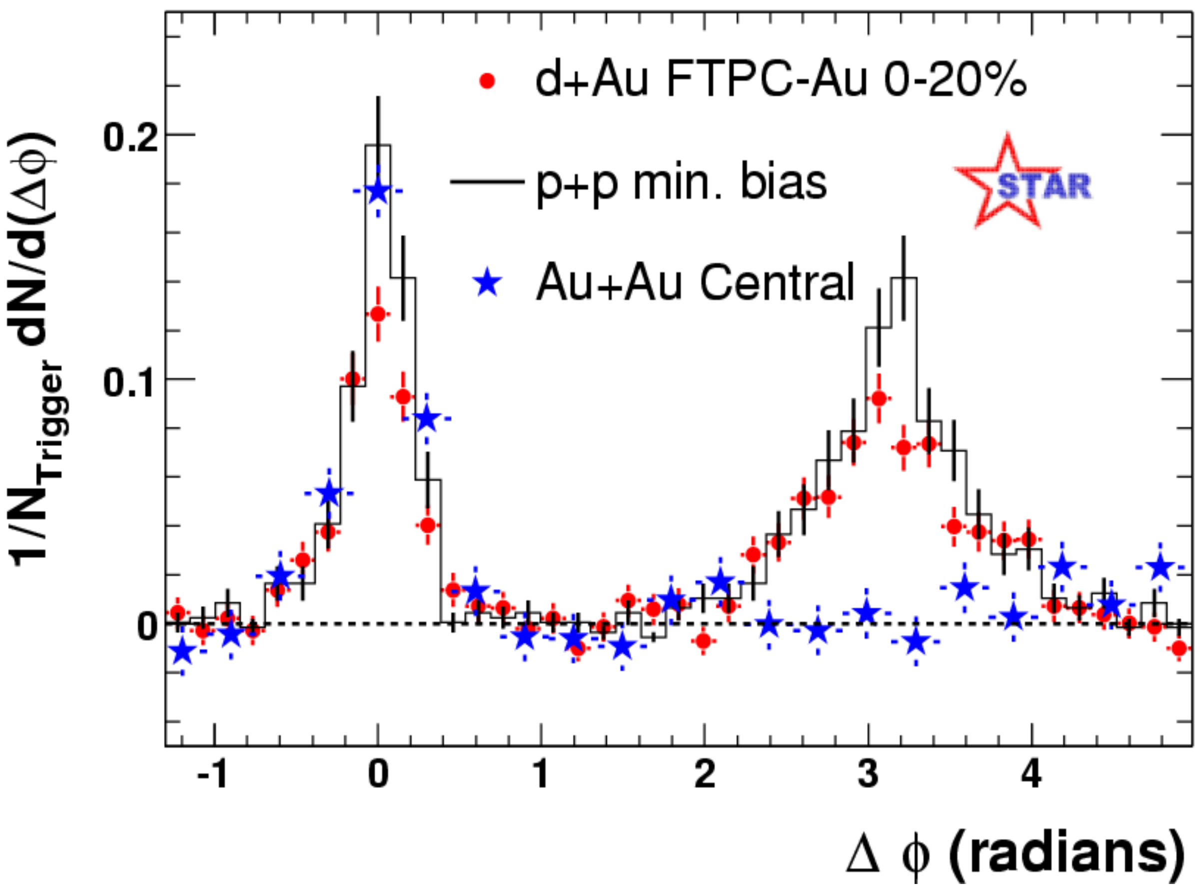

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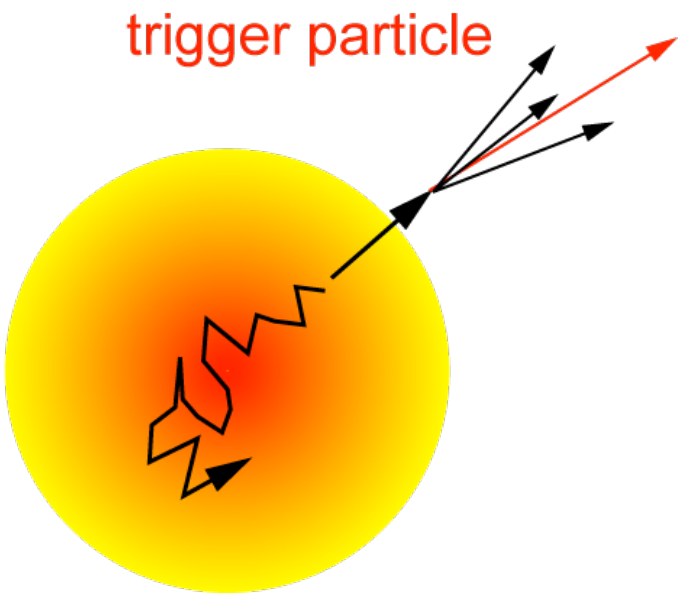

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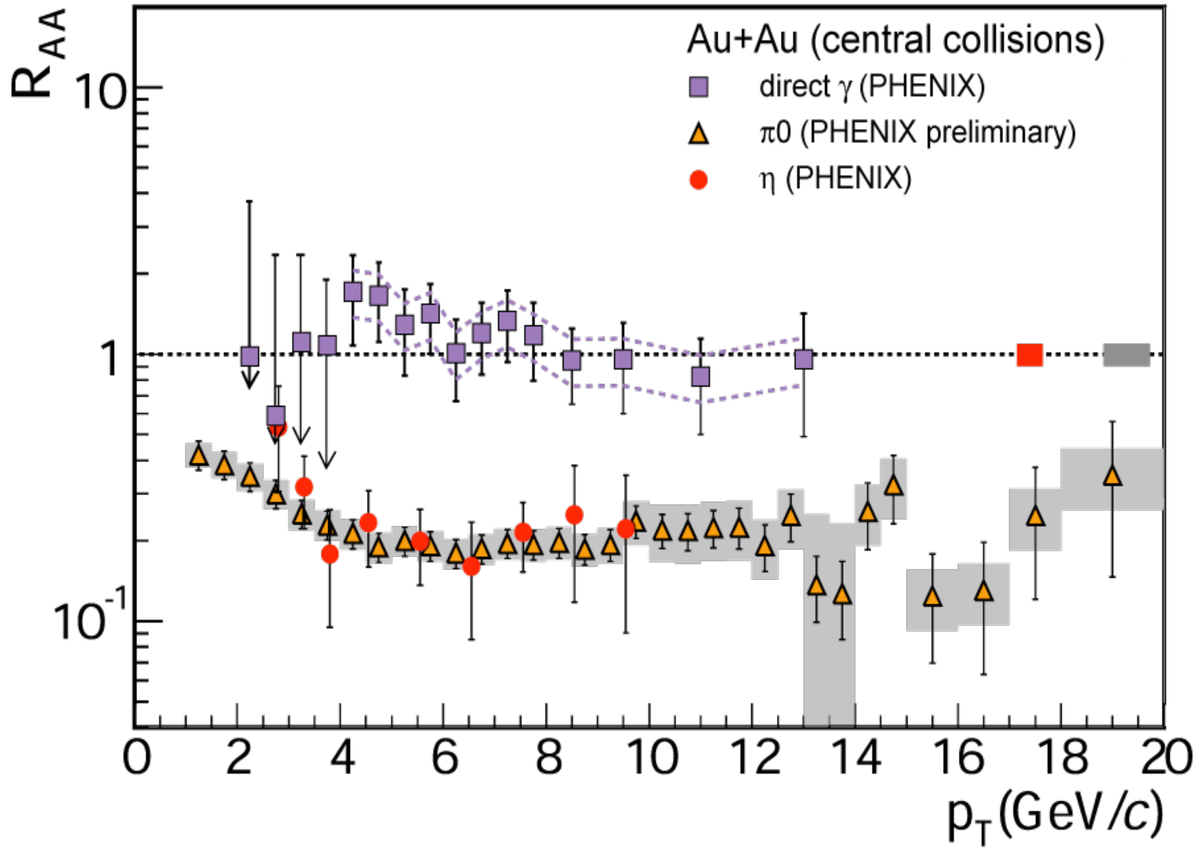
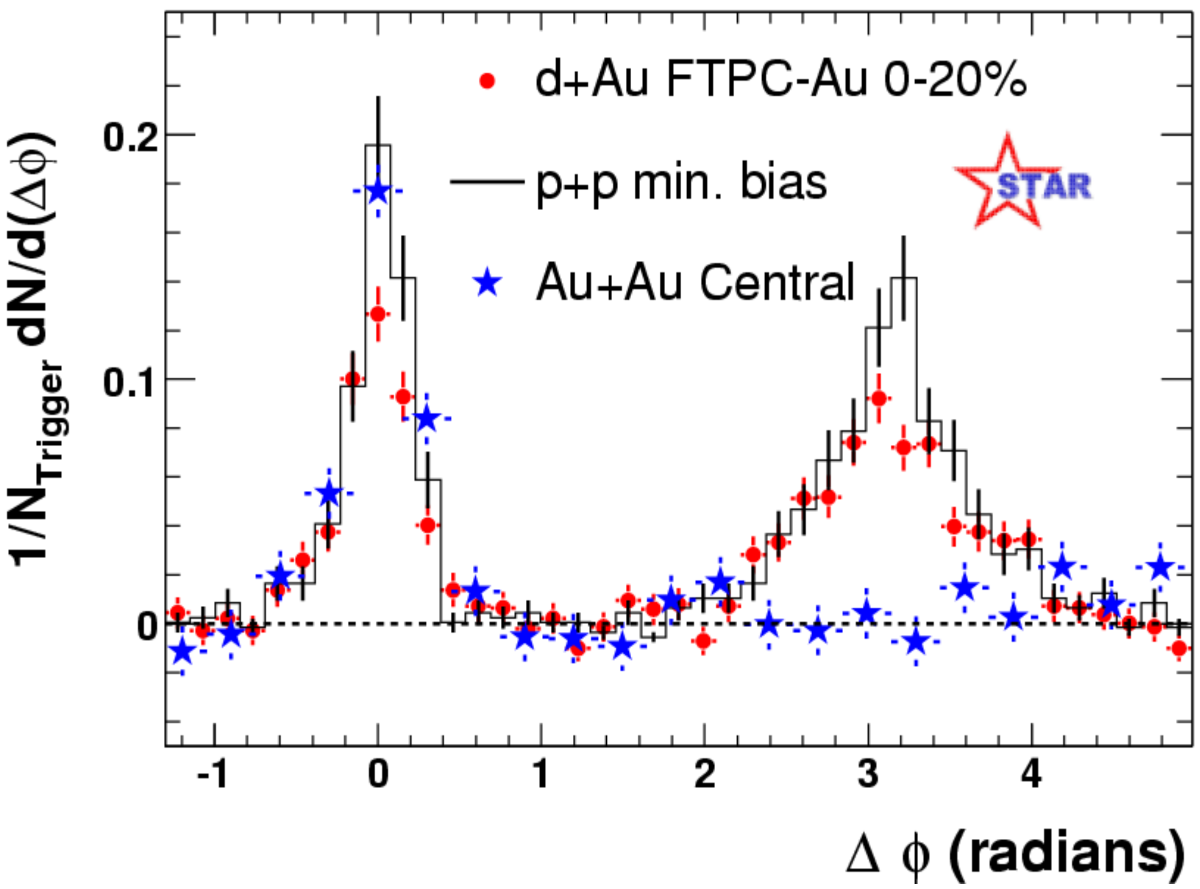
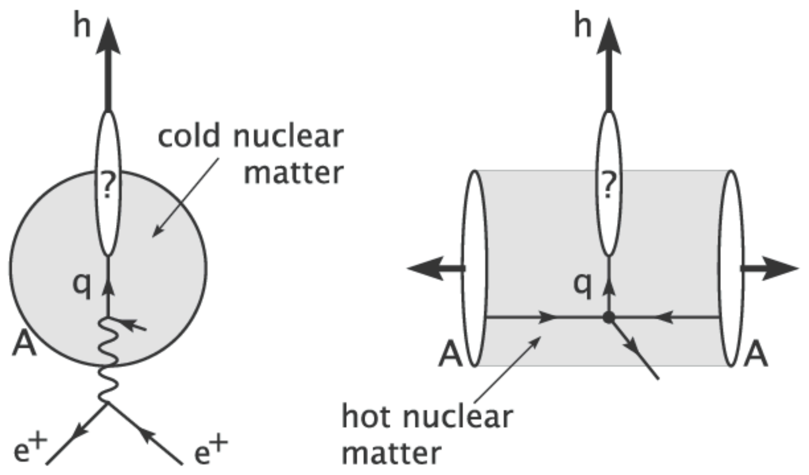




Interaction of fast probes with gluonic medium

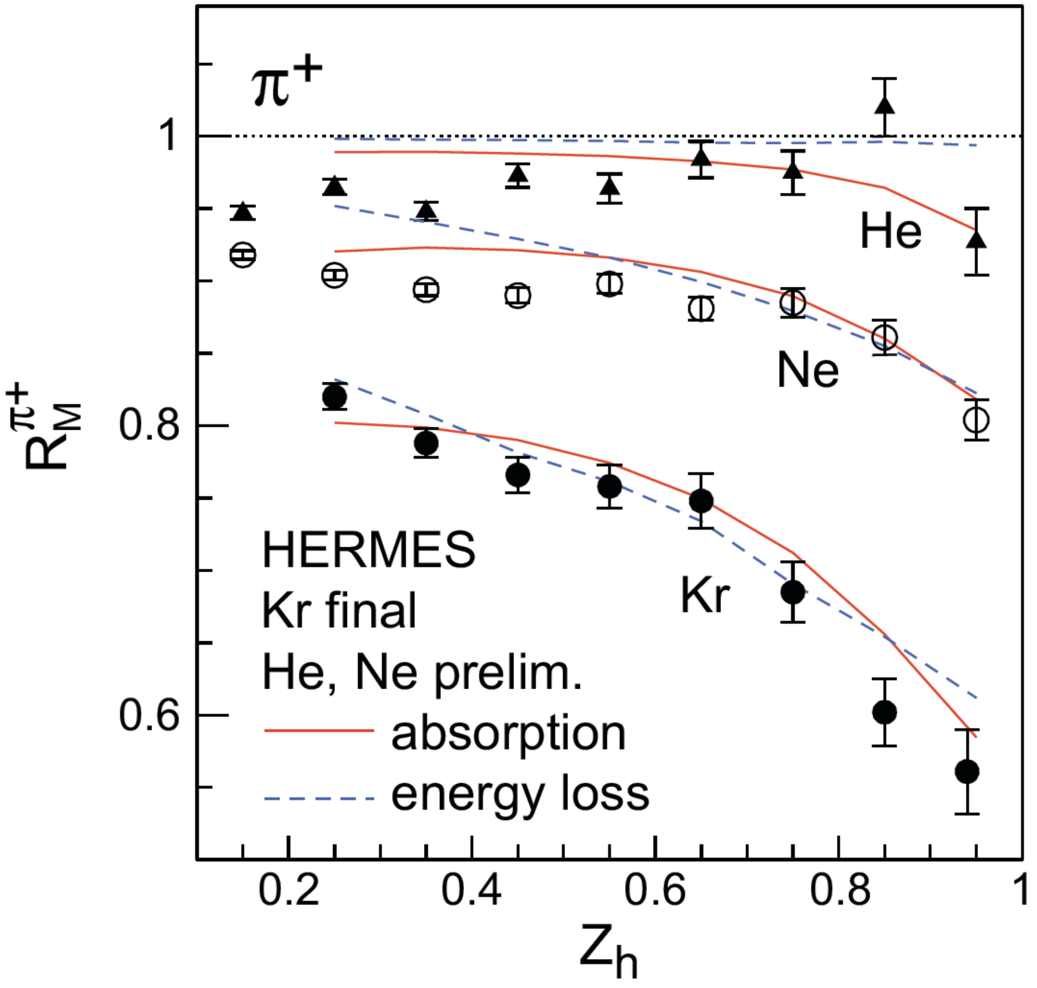
- nDIS:
  - ➡ Clean measurement in ‘cold’ nuclear matter
  - ➡ Suppression of high-p_T hadrons analogous to, but weaker than at RHIC



- 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



$z_h = E_h/\nu$

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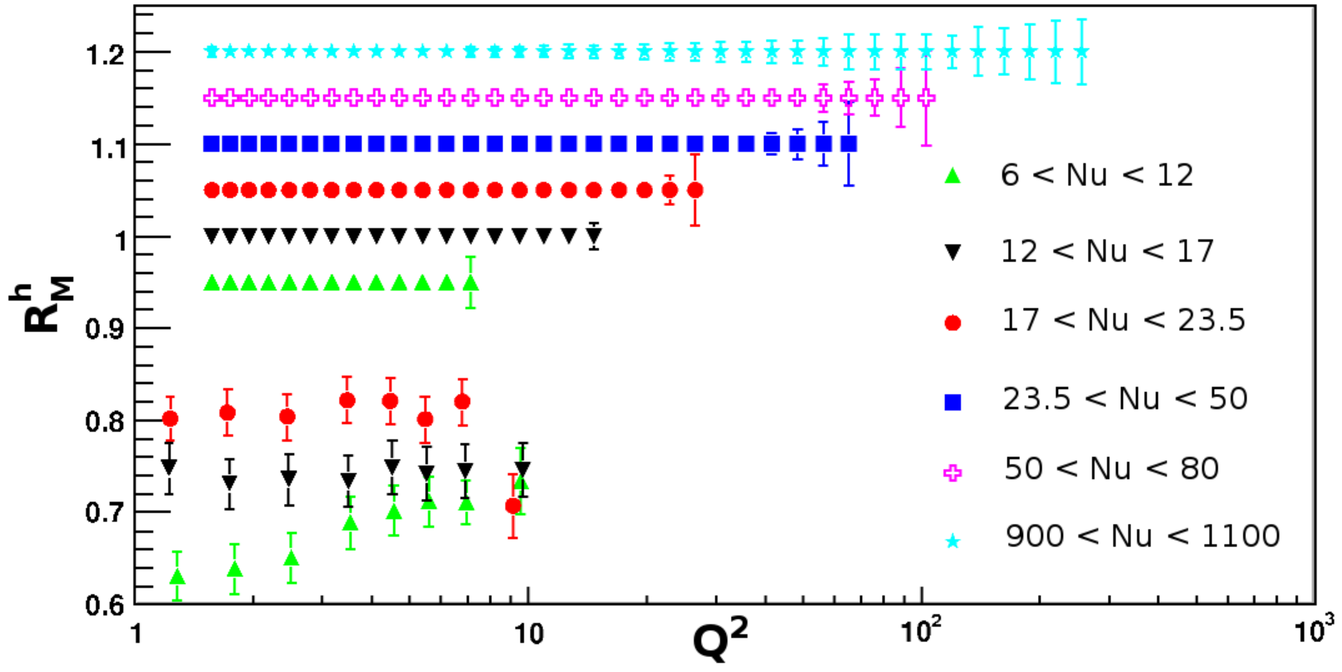

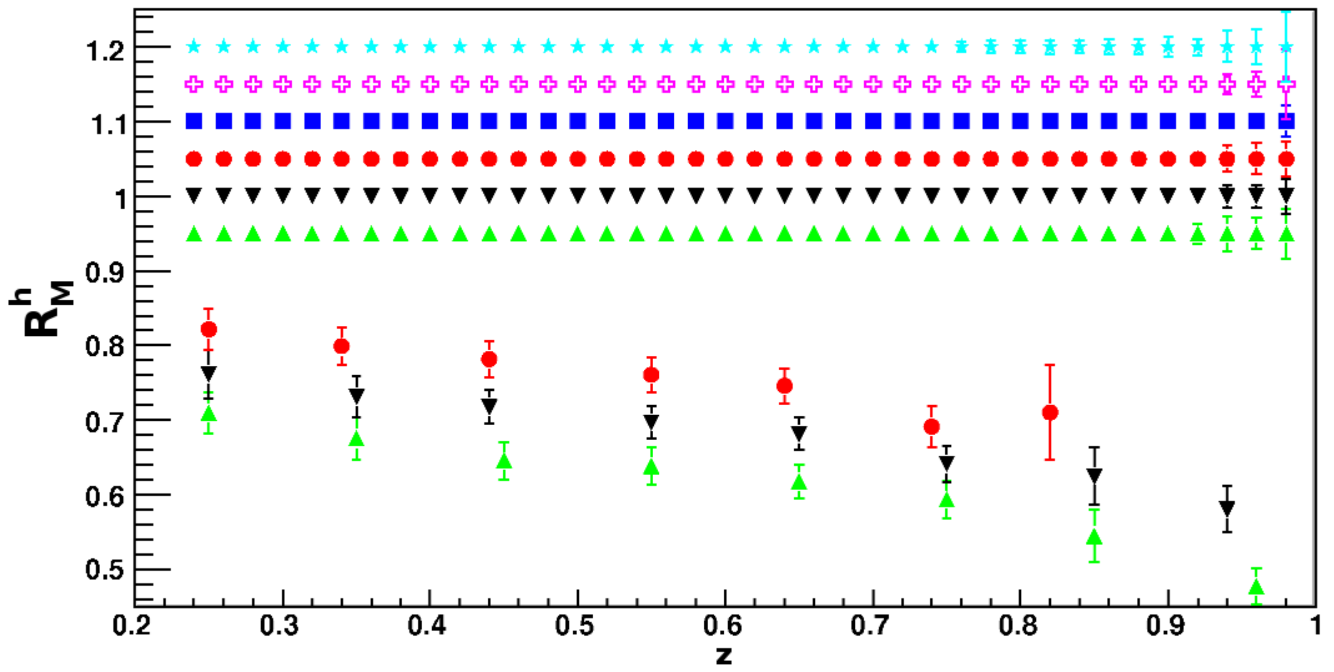

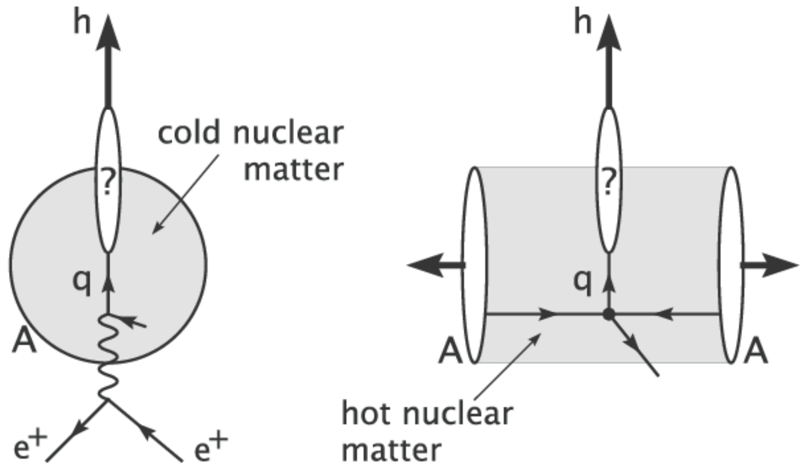

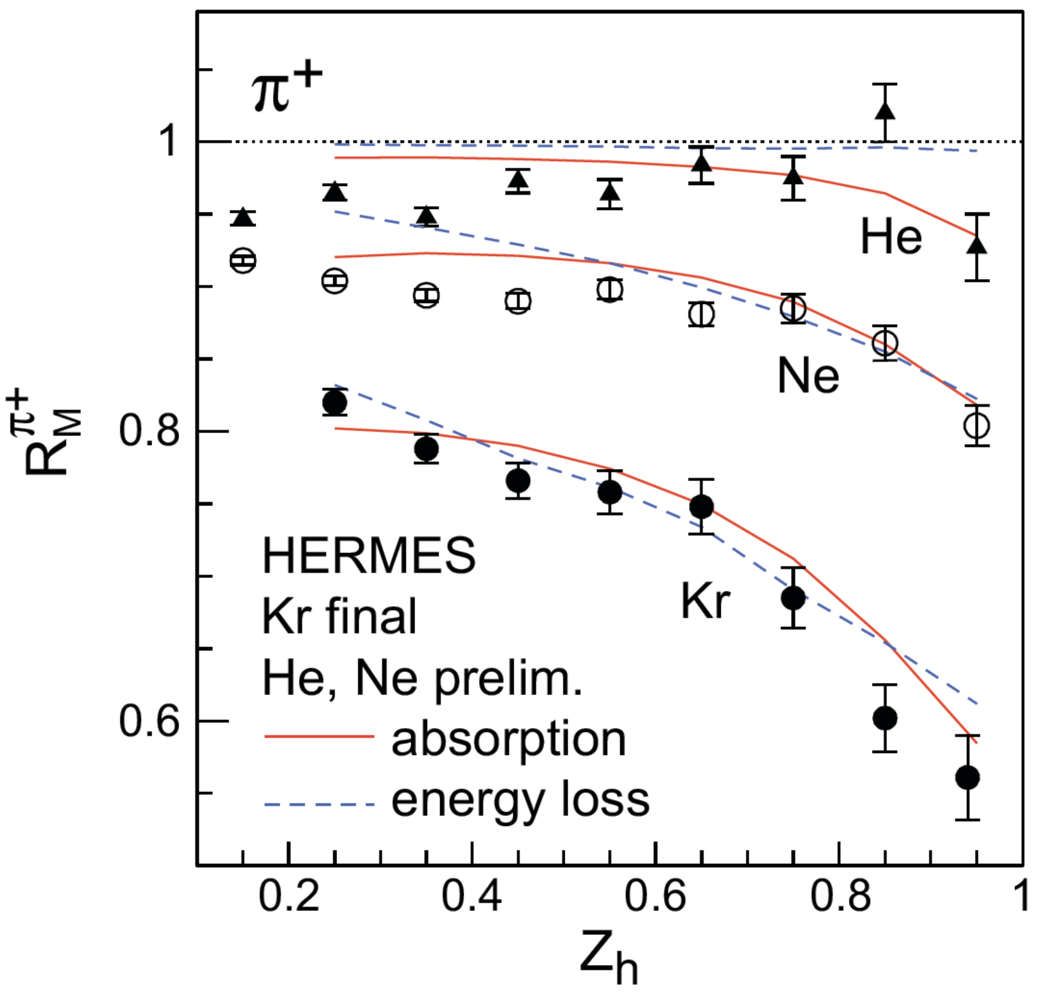

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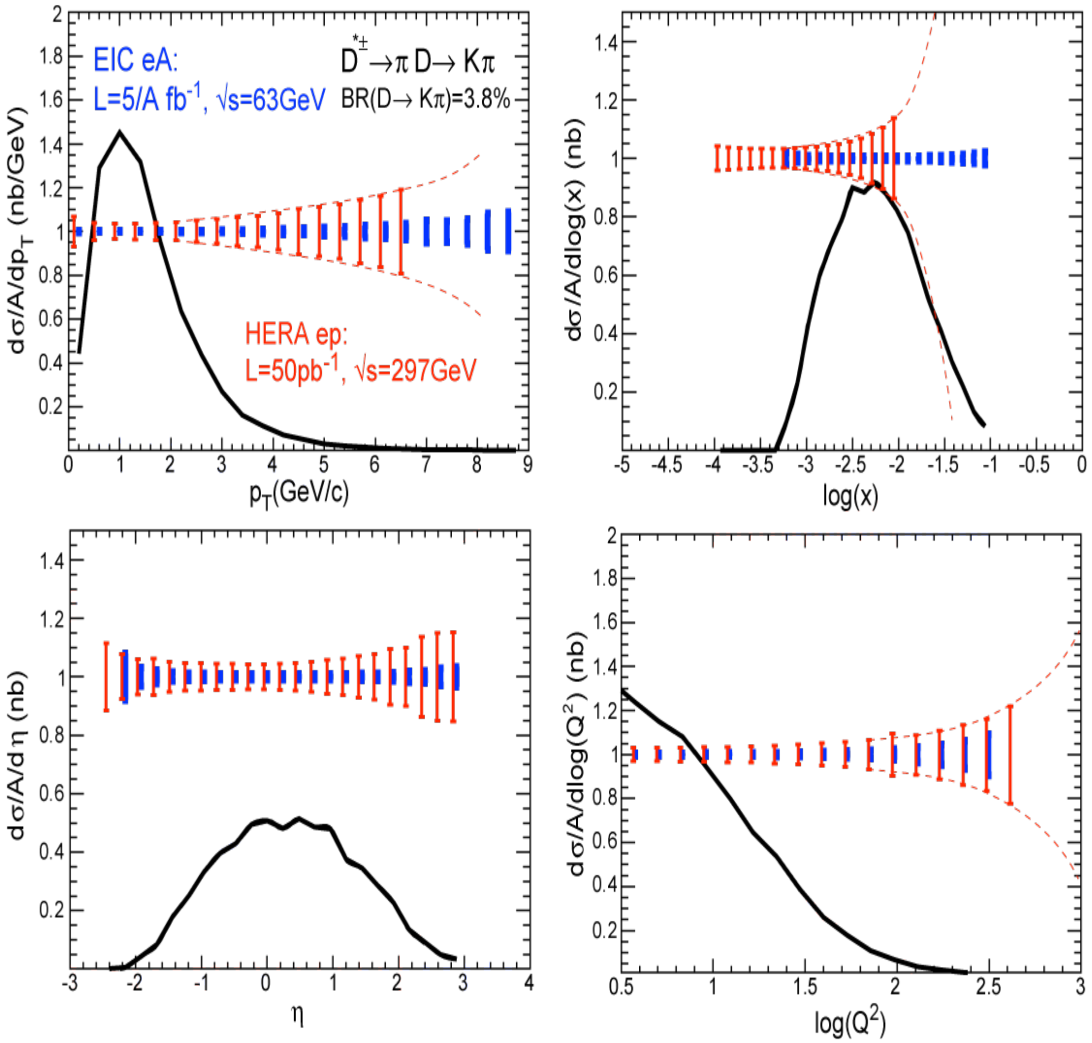
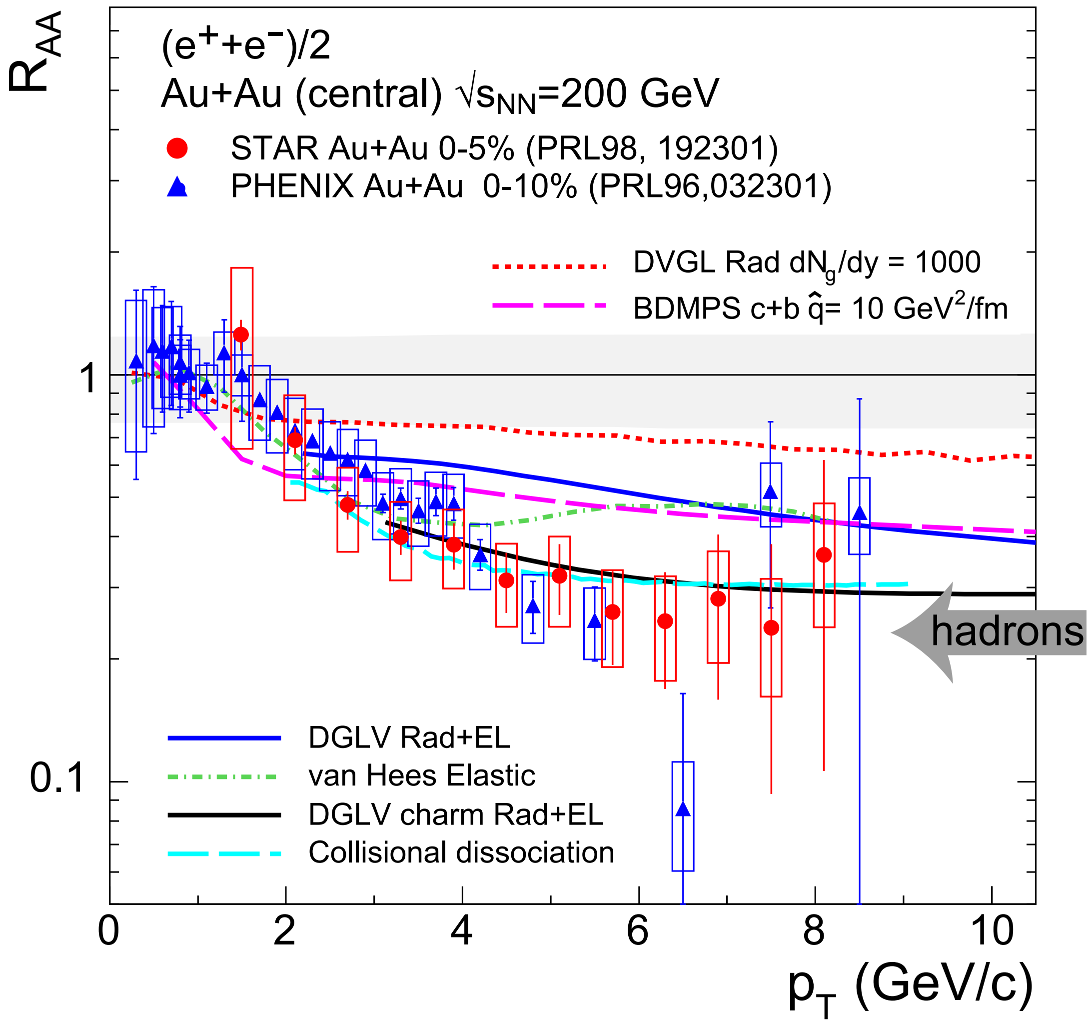
Charm measurements at an EIC

Charm also suppressed at RHIC - above and beyond model predictions





- EIC: allows multi-differential measurements of heavy flavour
- Covers and extends energy range of SLAC, EMC, HERA, and JLAB allowing for the study of wide range of formation lengths

Key Measurements in e+A

- ***Momentum* distribution of gluons $G(x,Q^2)$**
  - ➡ 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 ~ $[xG(x,Q^2)]^2$
- ***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!)
- **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

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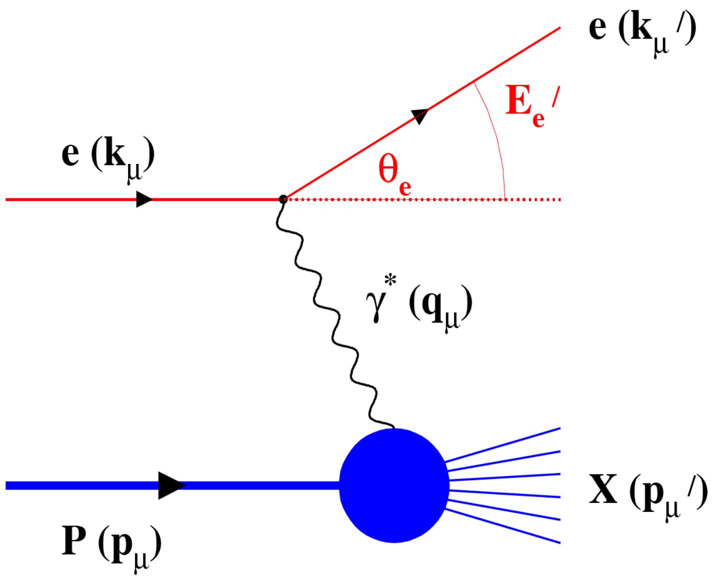
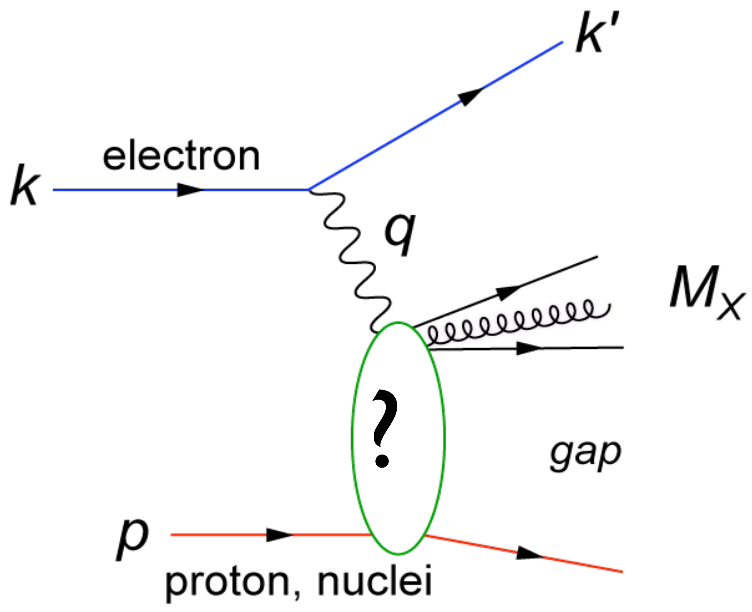
$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* A \rightarrow M_X A) \propto \alpha^2 [G_A(x,Q^2)]^2$$





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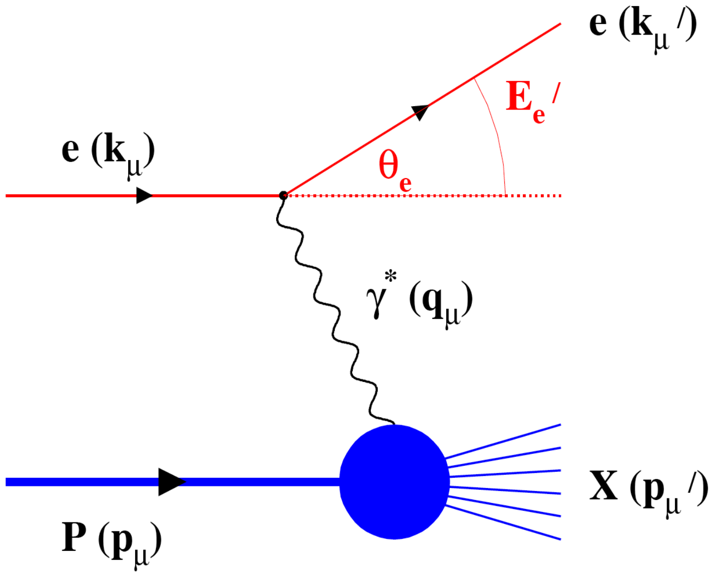

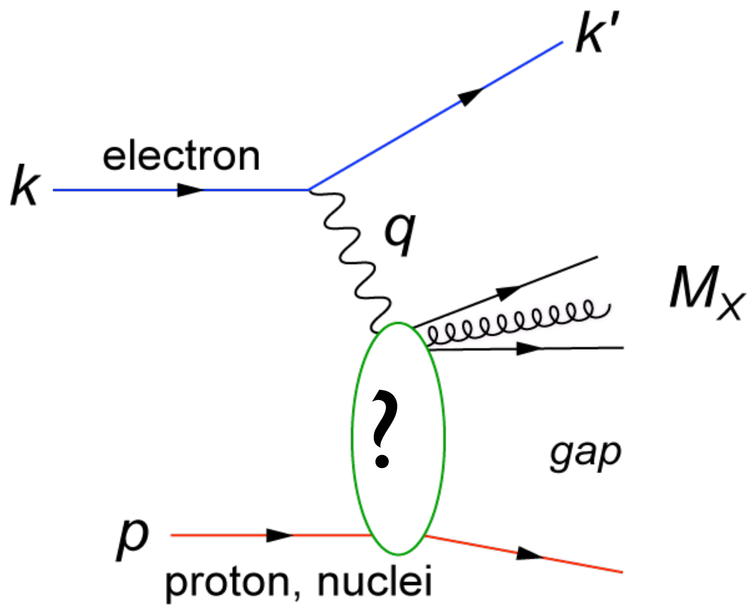

HERA/ep: 15% of all events are hard diffractive

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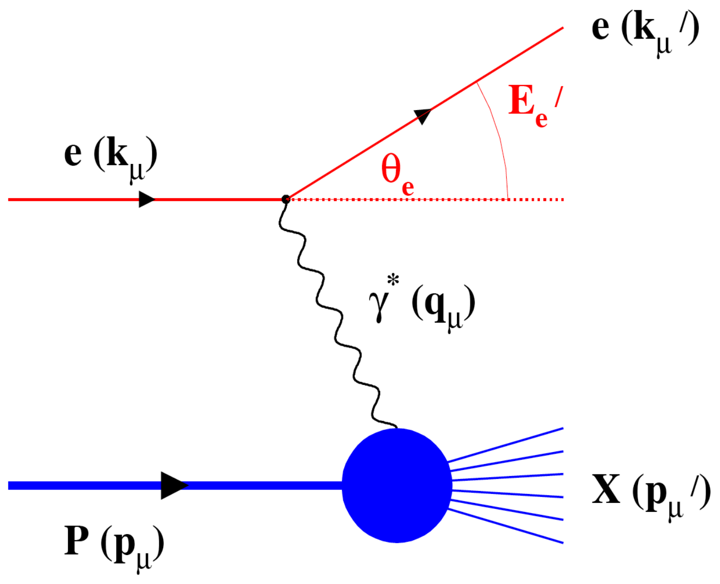

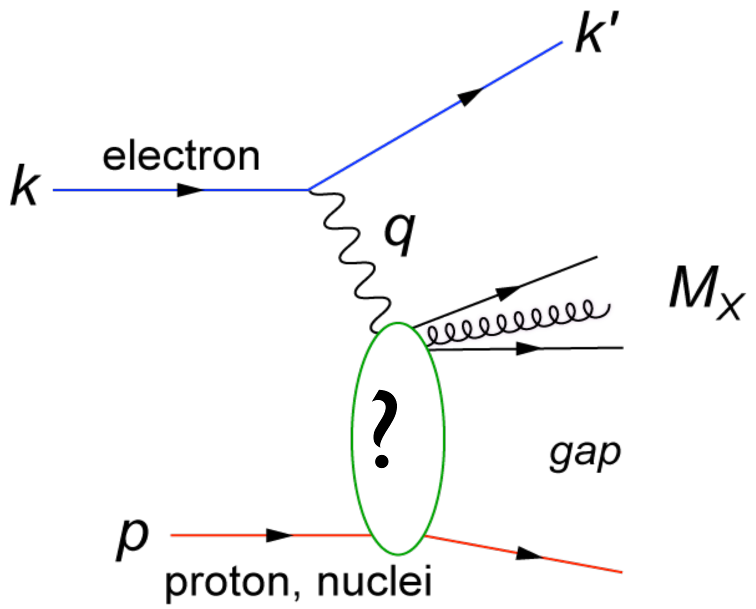

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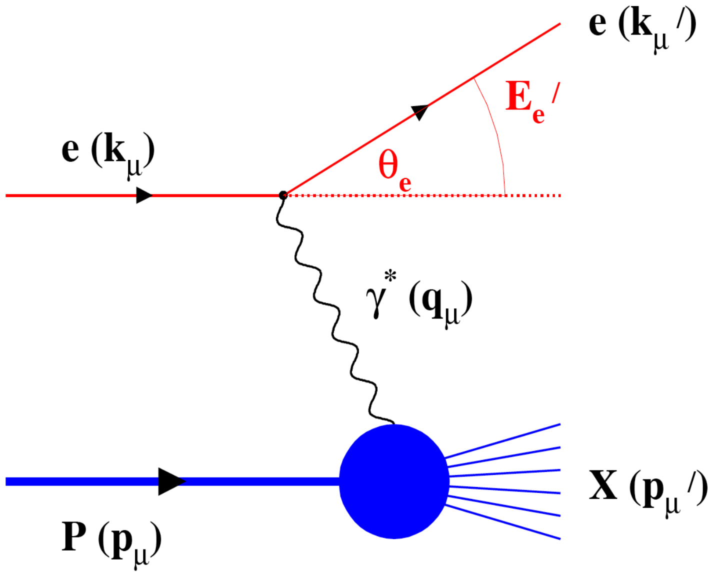
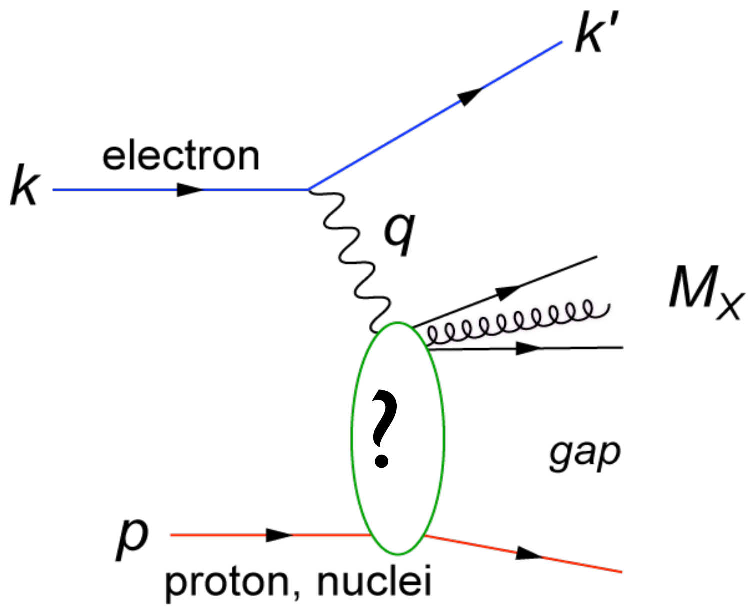
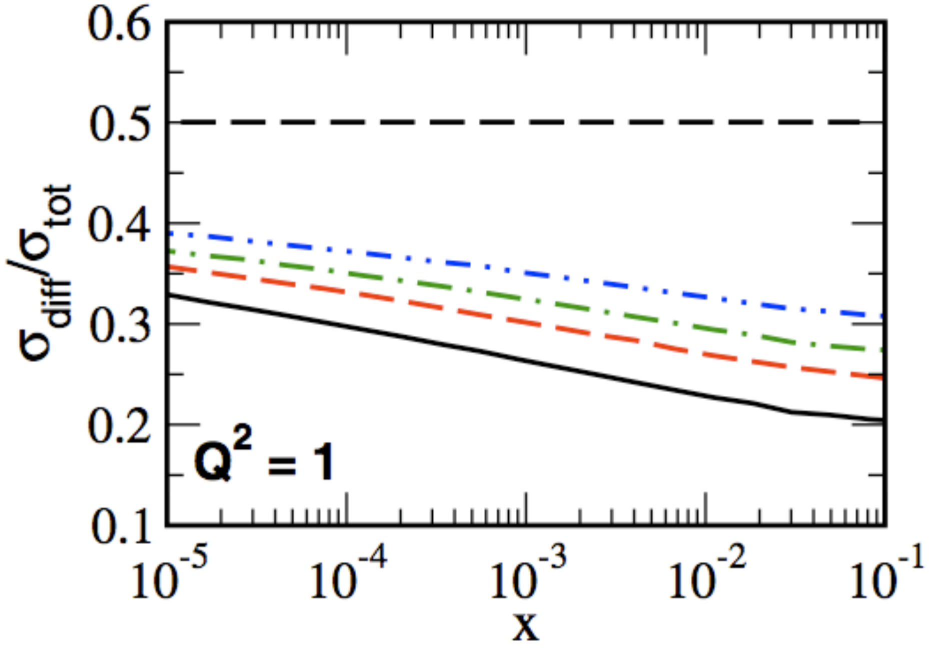




Curves: Kugeratski, Goncalves,
Navarra, EPJ C46, 413



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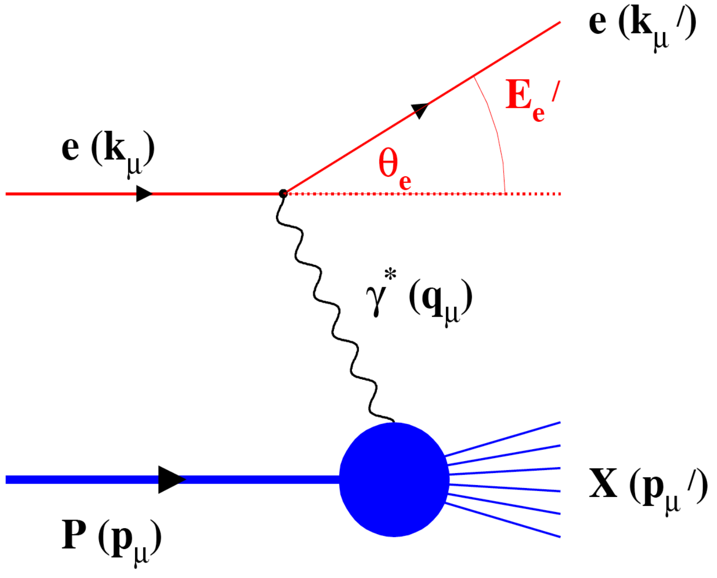

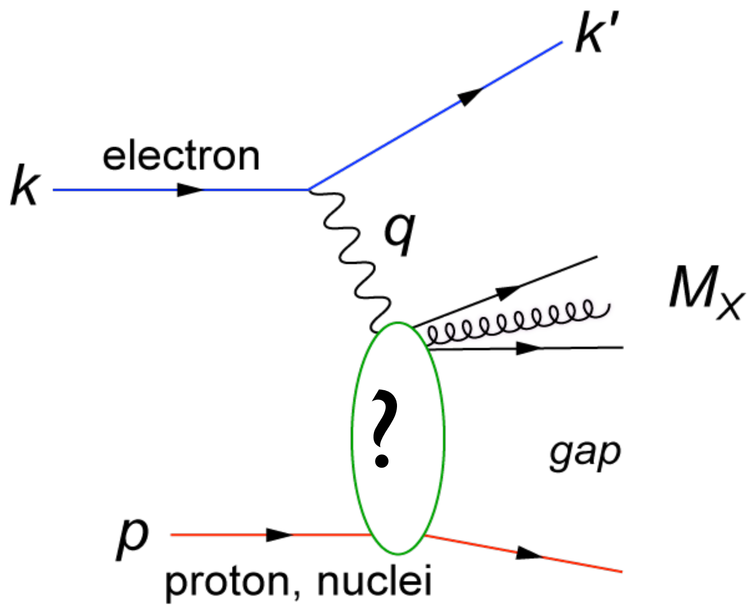

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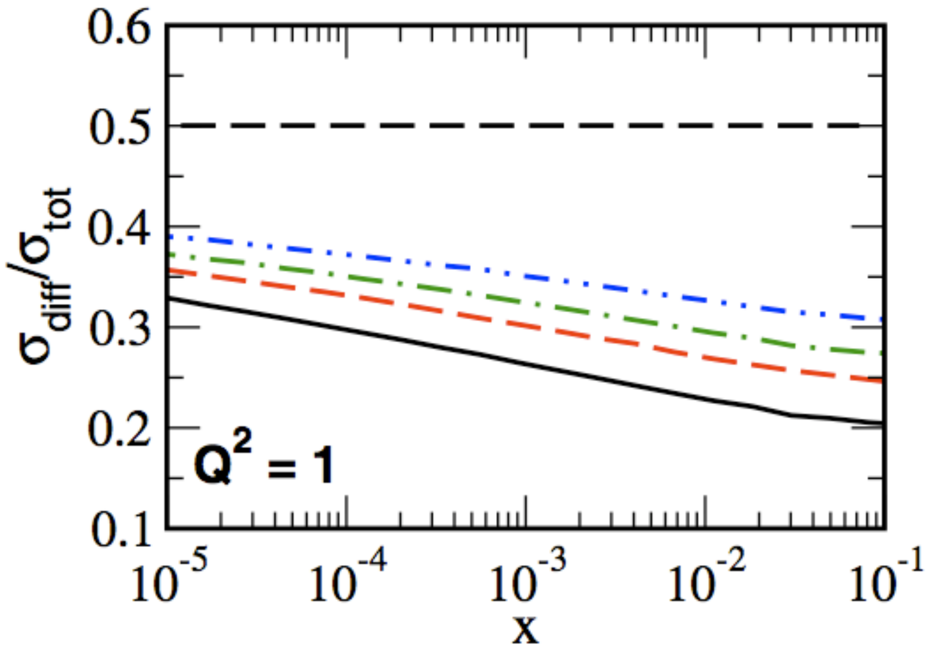

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- Diffractive structure functions

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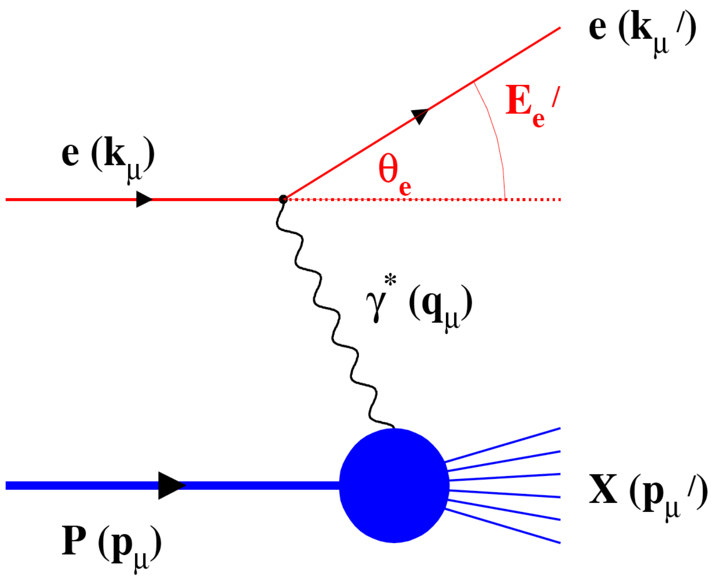

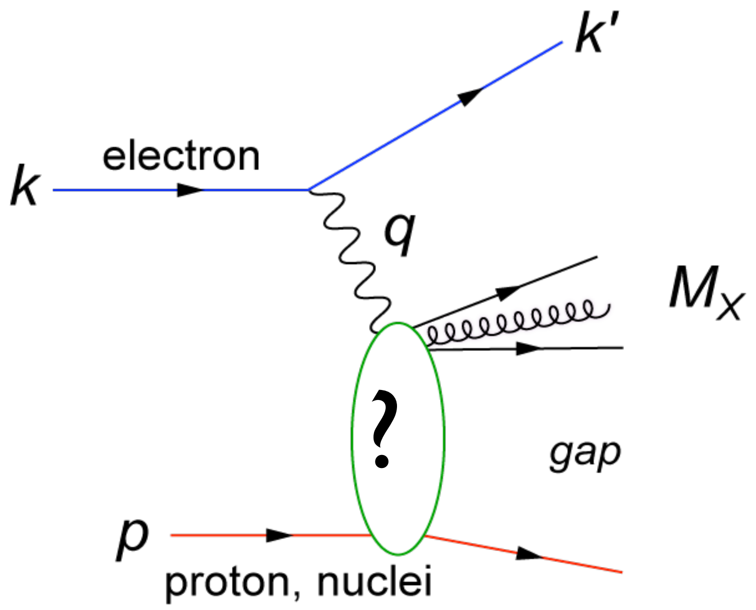

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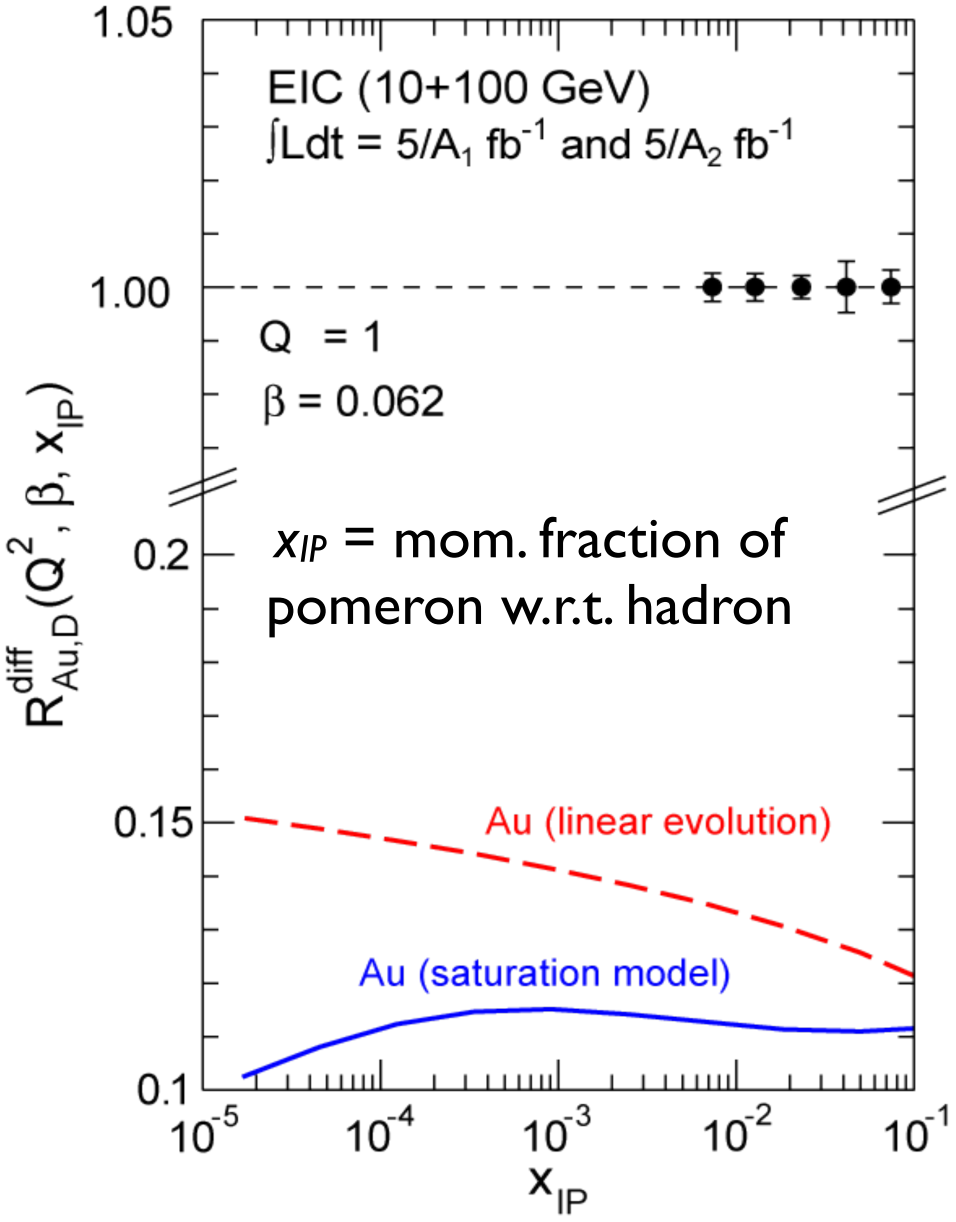

x_{IP} = mom. fraction of pomeron w.r.t. hadron

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Distinguish between linear evolution and saturation models

How to measure coherent diffraction in e+A ?

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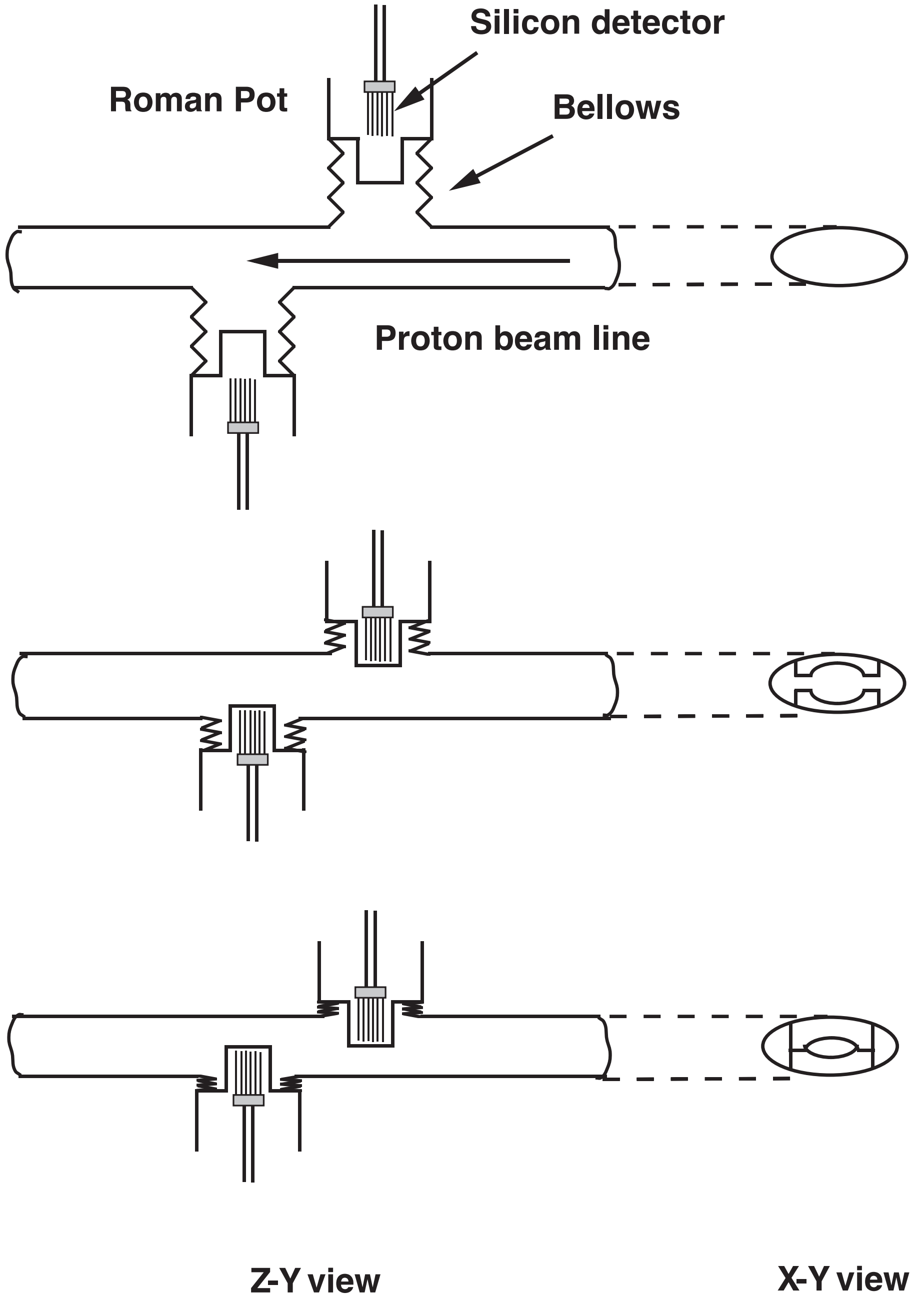

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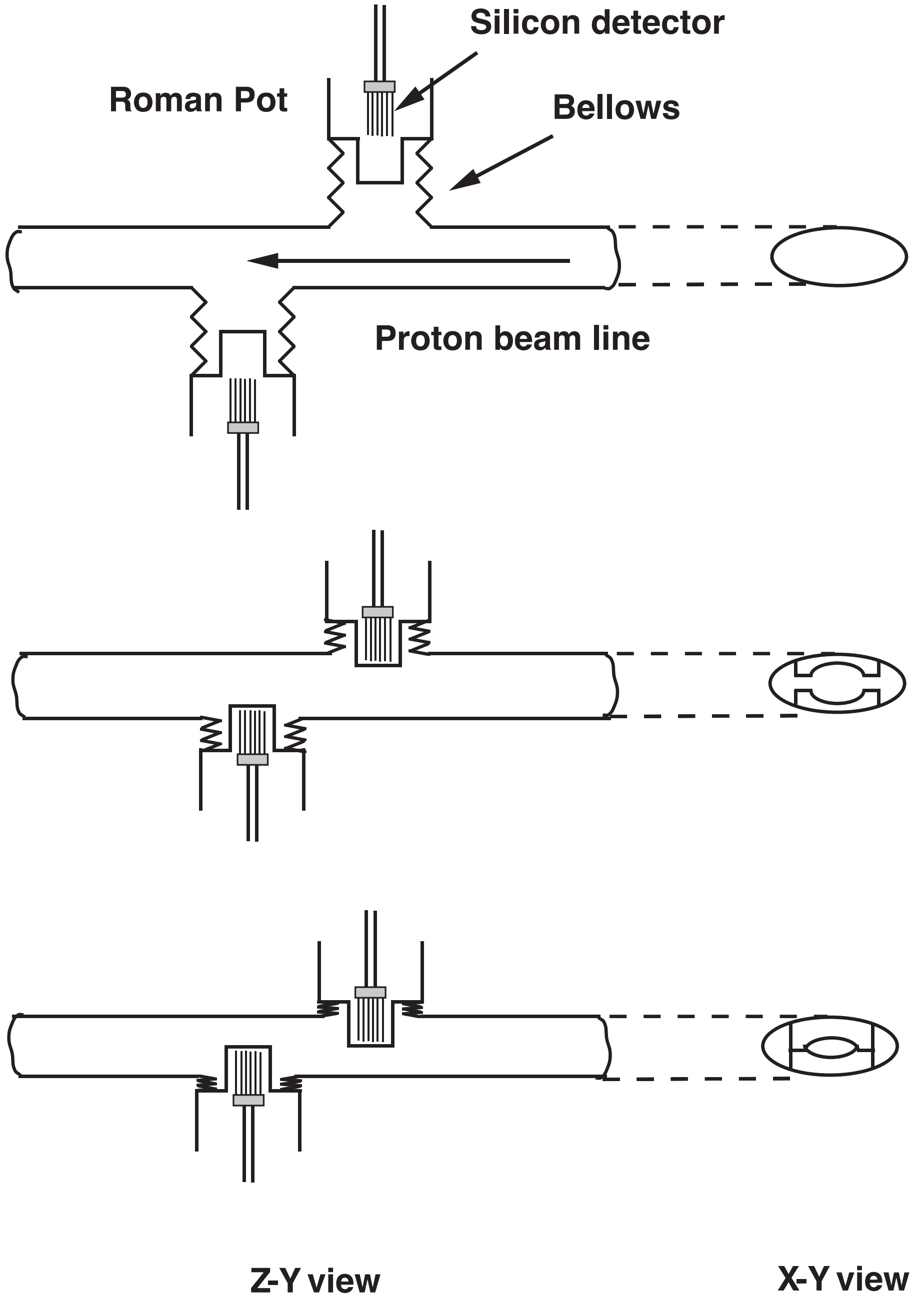
- Can measure the nucleus if it is separated from the beam in Si (Roman Pot) “beamline” detectors
  - ➡ $p_T^{min} \sim pA\theta_{min}$
    - For beam energies = 100 GeV/n and $\theta_{min} = 0.08$ mrad:



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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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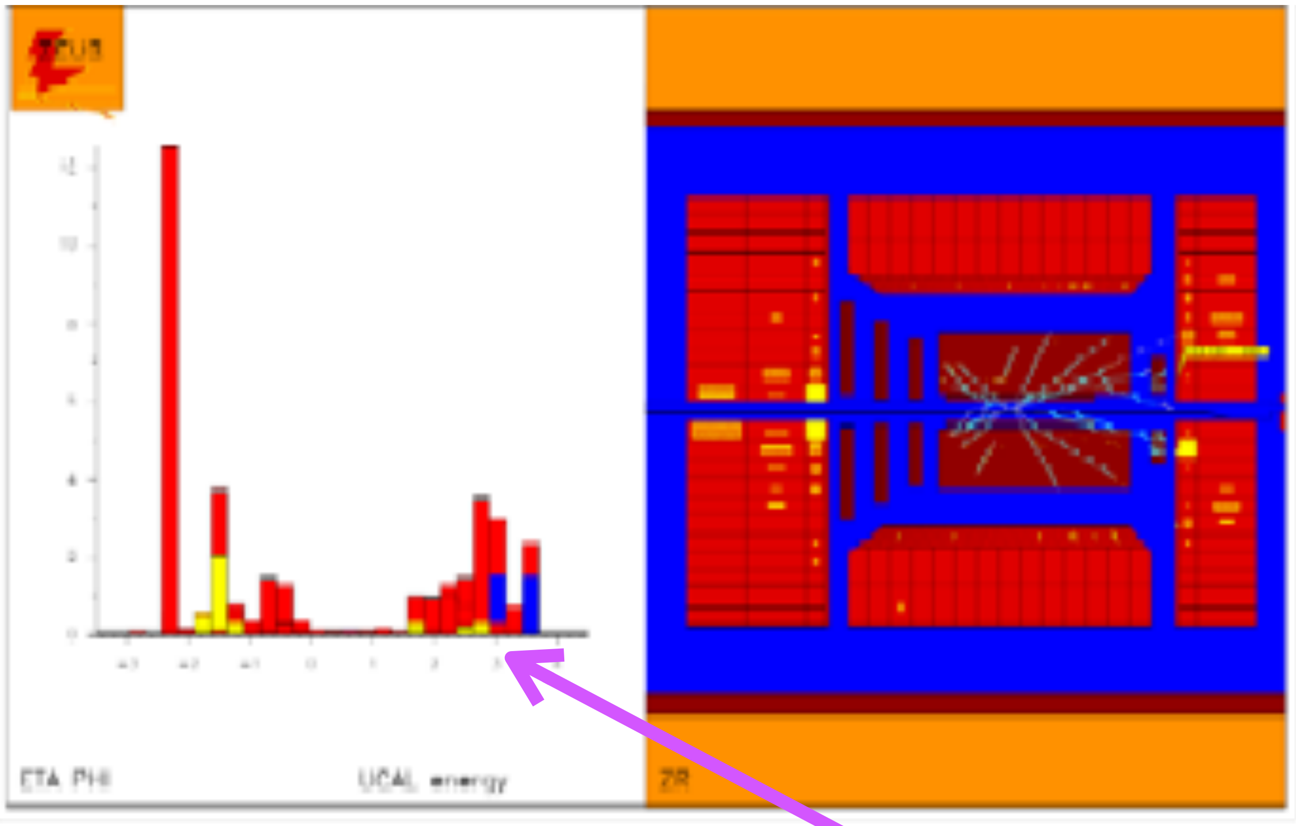

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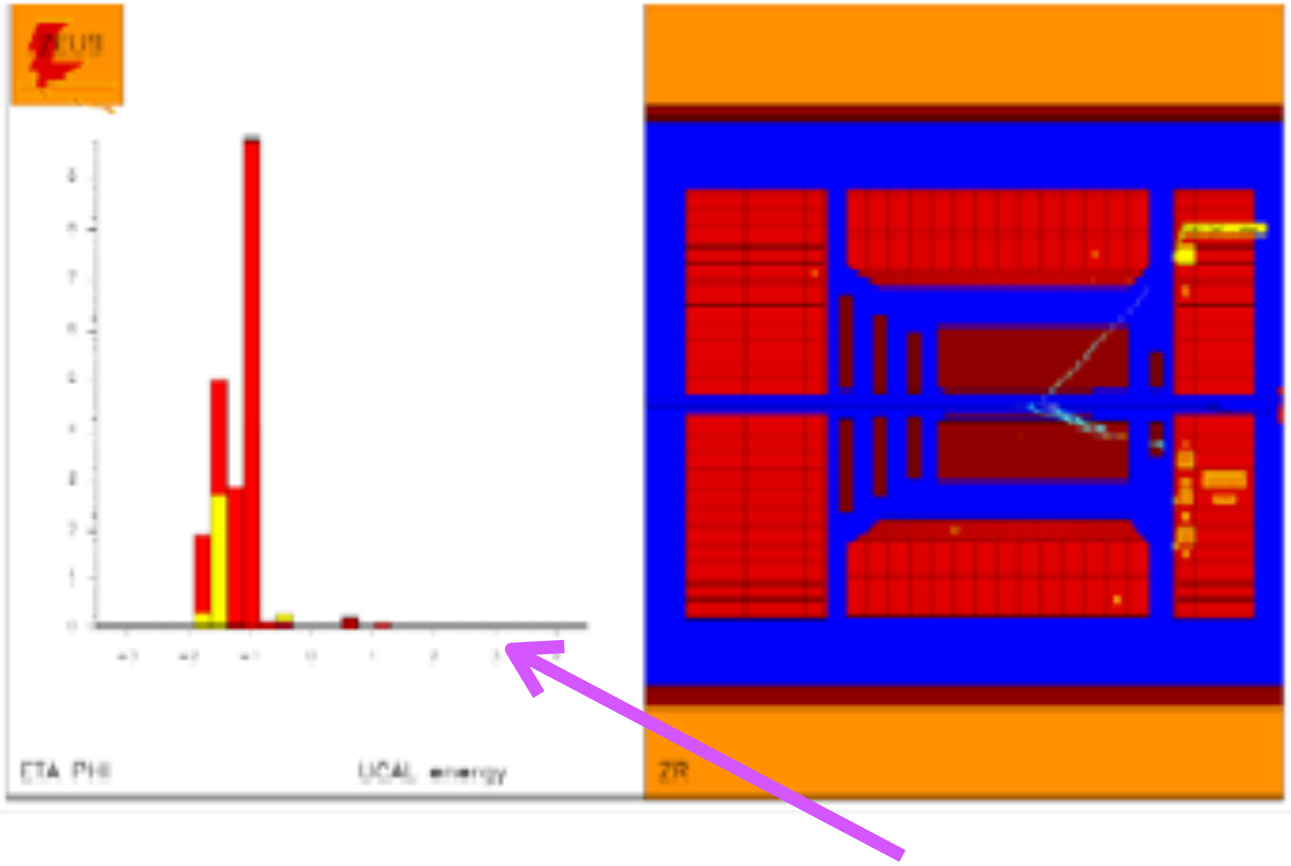

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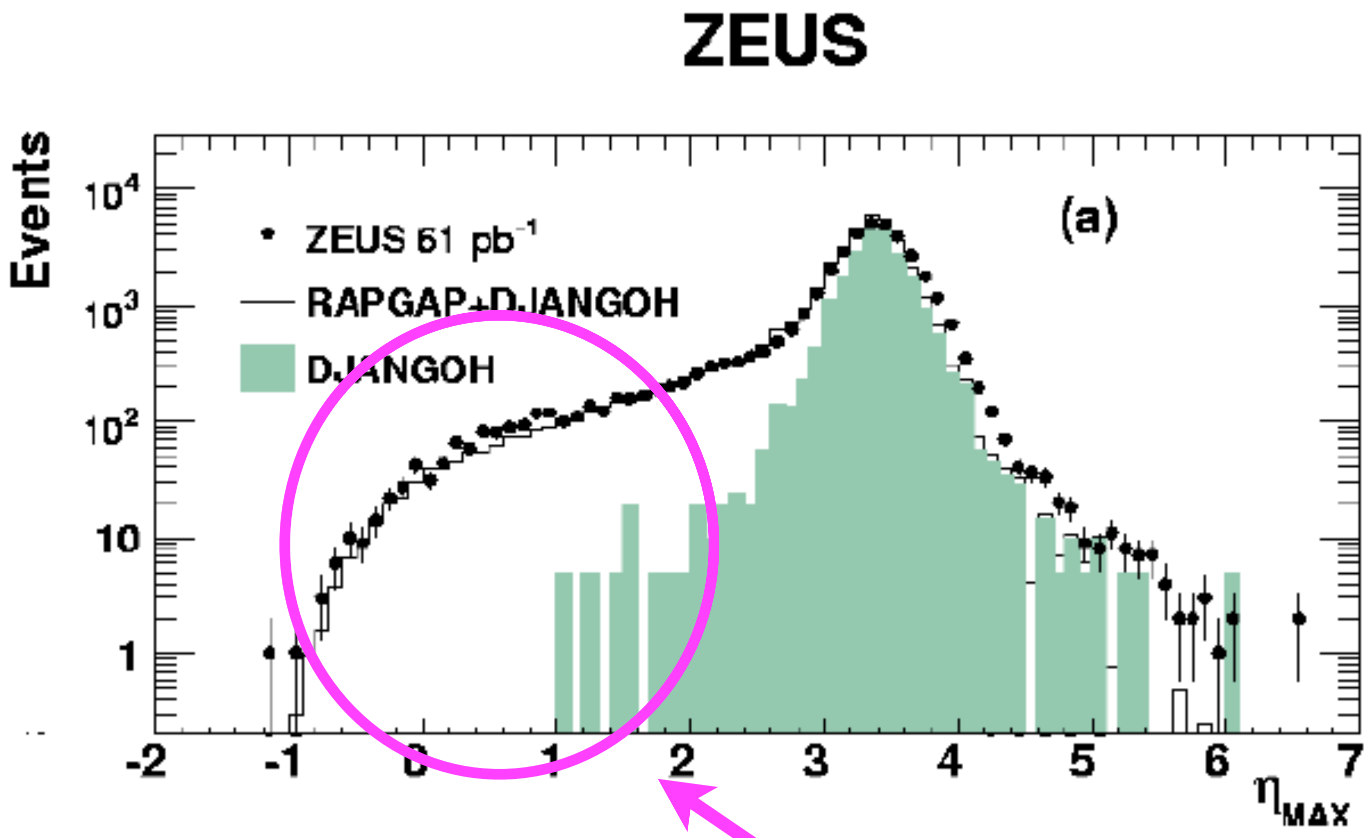

Diffractive events

- At HERA: Δη ~7 ⇒ hadronization reduces this to ~2.5
- Pros
  - ➡ Lots of statistics
- Cons
  - ➡ Sensitive to detector acceptance
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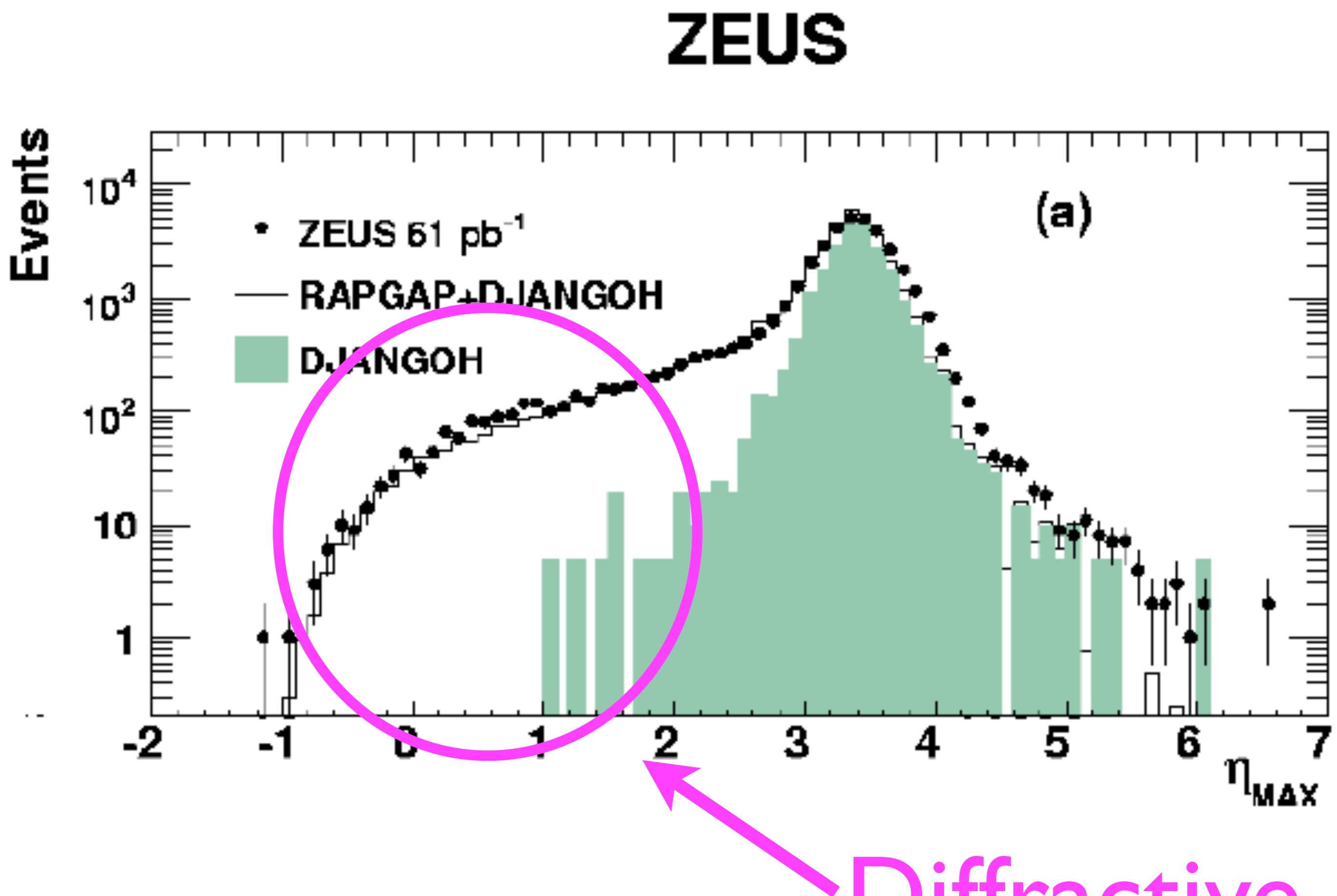

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Can this method be used at an EIC?

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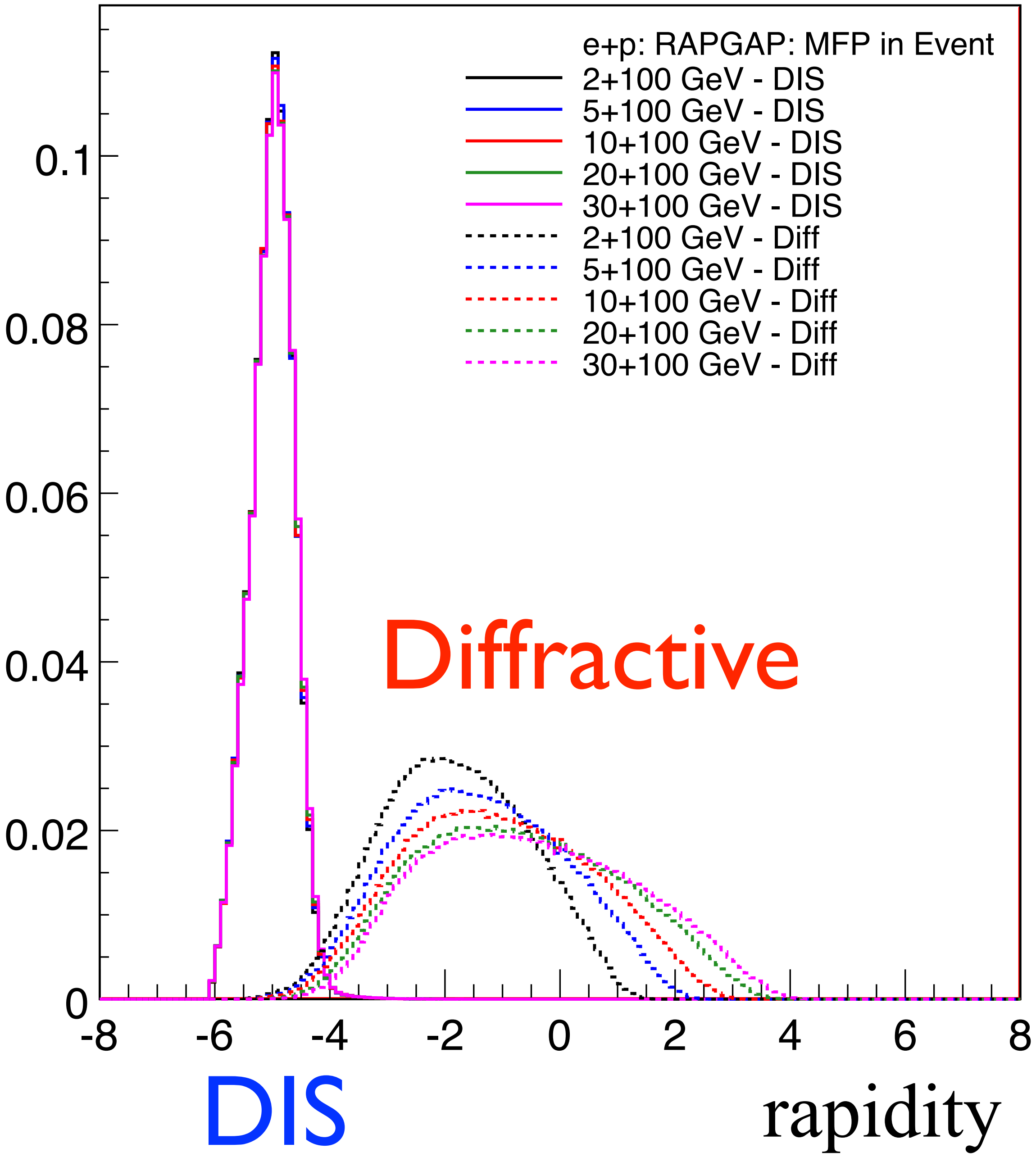
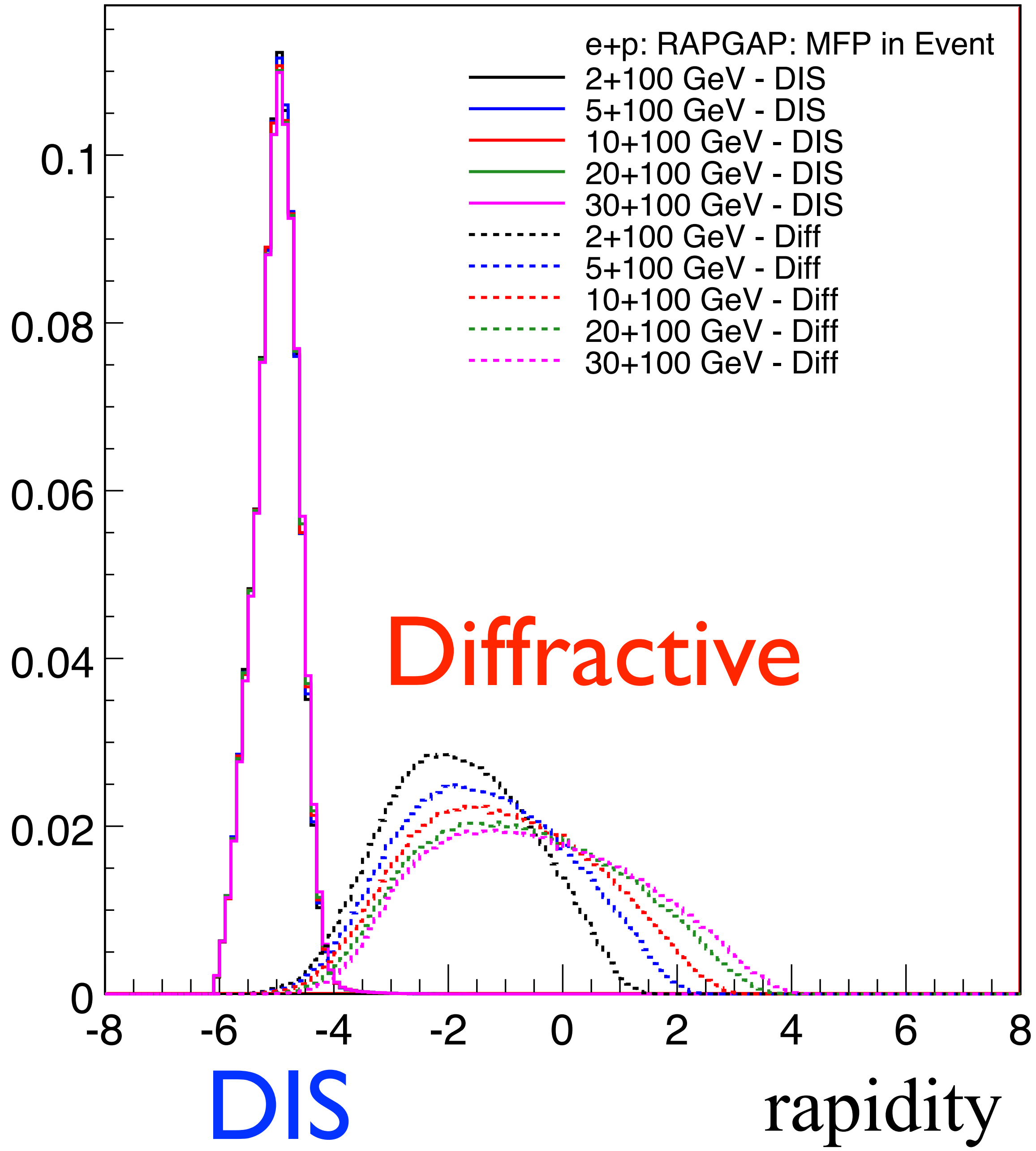
Large rapidity gaps at an EIC



Large rapidity gaps at an EIC

- Method:
  - ➡ Use RAPGAP in diffractive and DIS modes to simulate e+p collisions at EIC energies
  - ➡ Clear difference between DIS and Diffractive modes in "most forward particle in event" distributions
    - ▶ Little change in distributions with increasing energy



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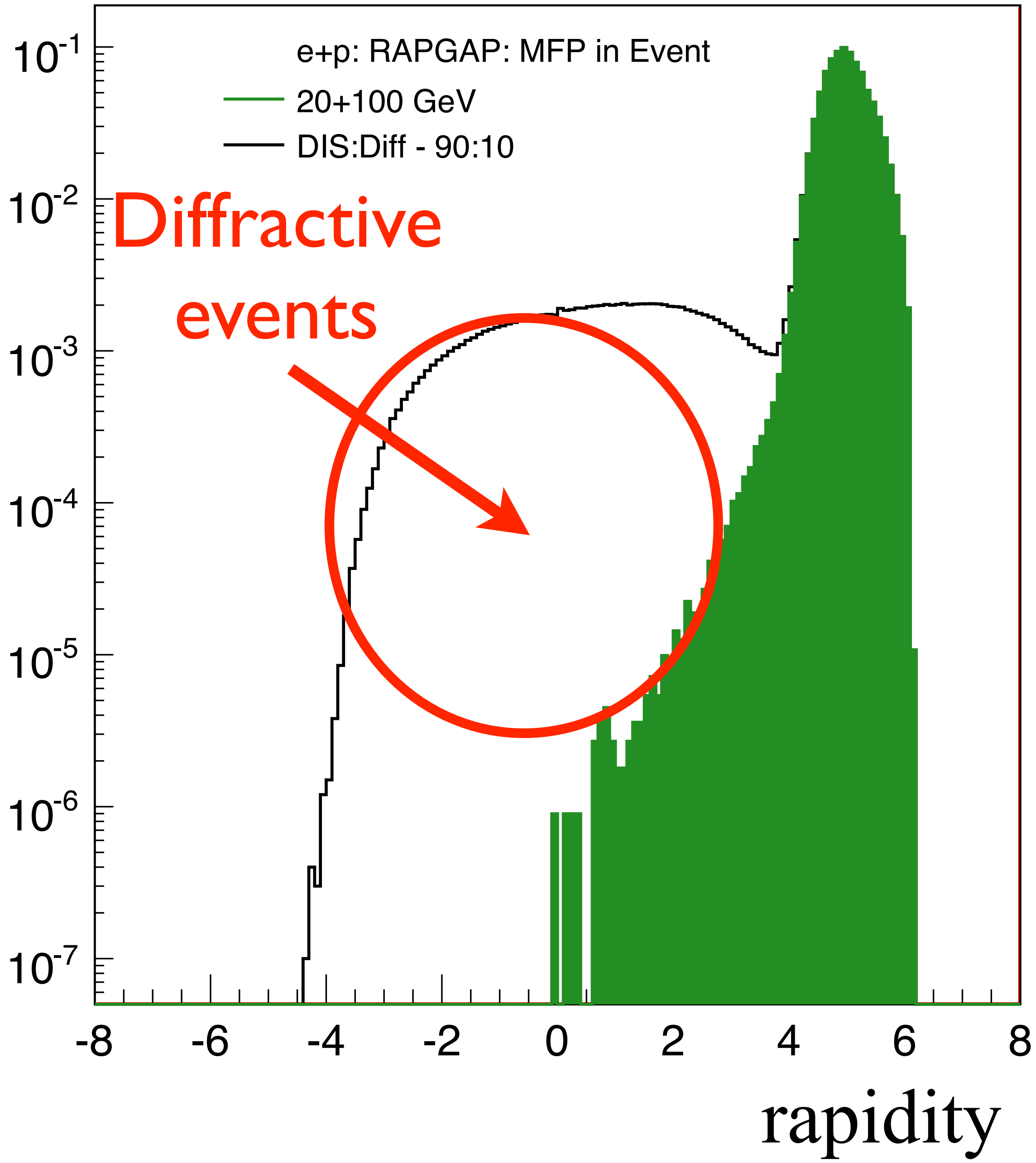
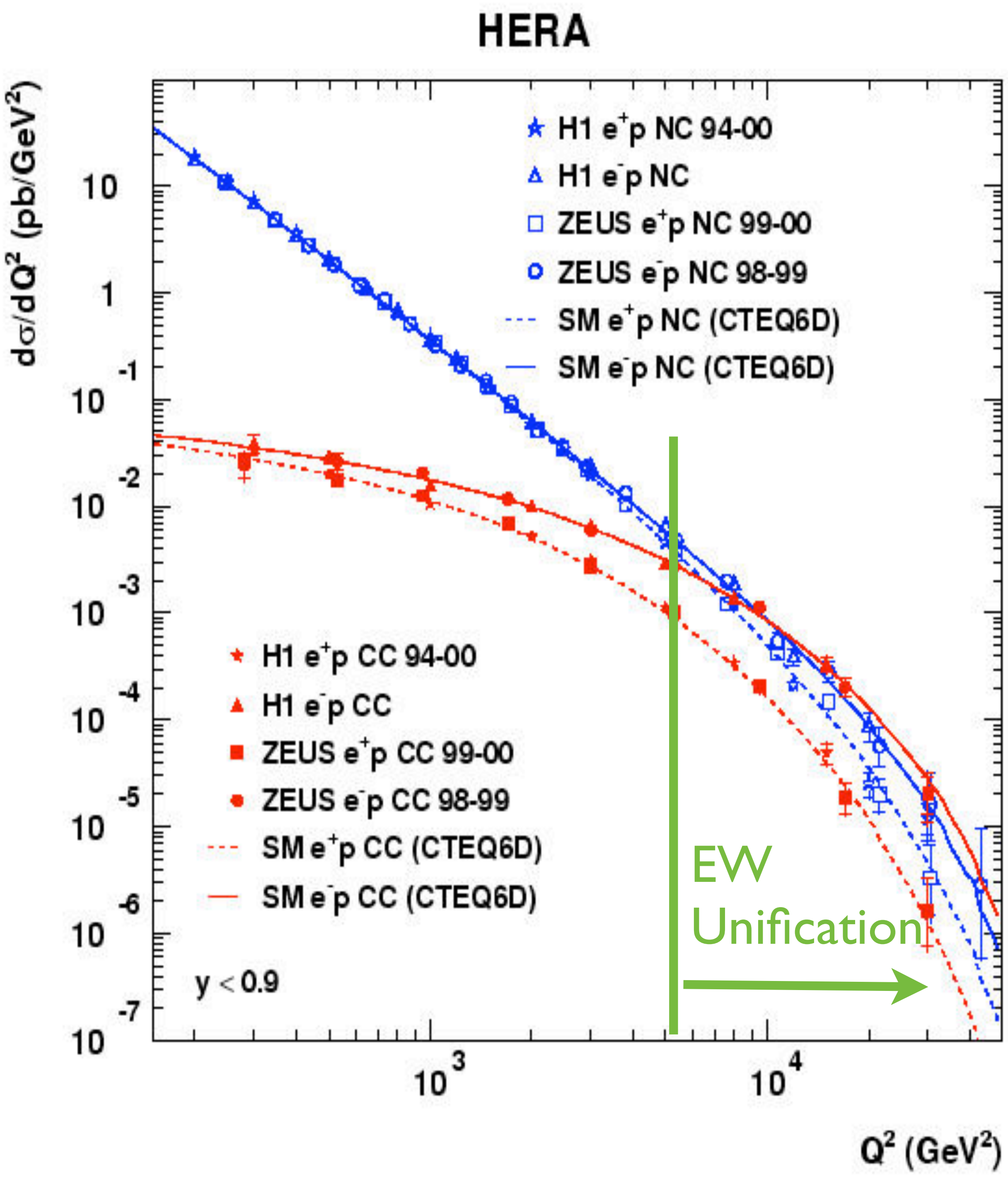
  - ➡ Can reproduce "ZEUS-like" plots



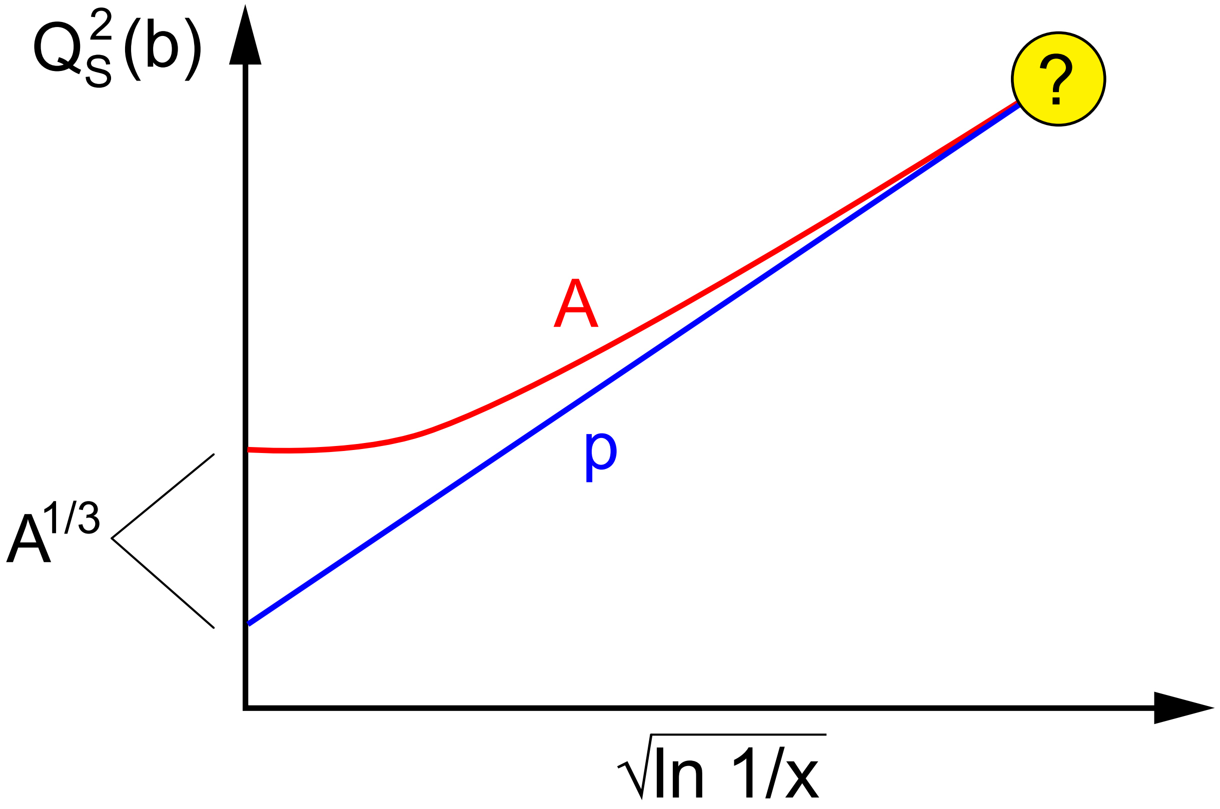
EW Unification at HERA



- 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 ...

Matter at low-x: A truly universal regime?

What about on the parton scale?



- 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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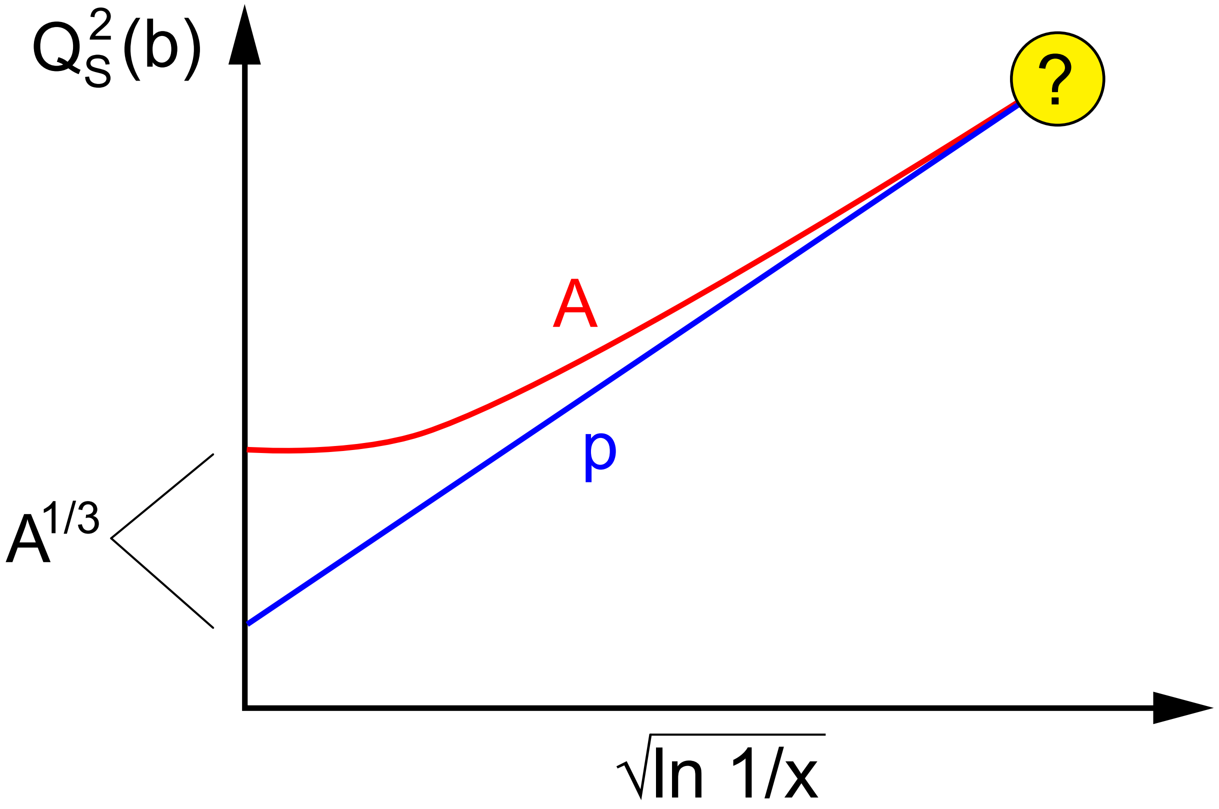

A.H. Mueller, hep-ph/0301109

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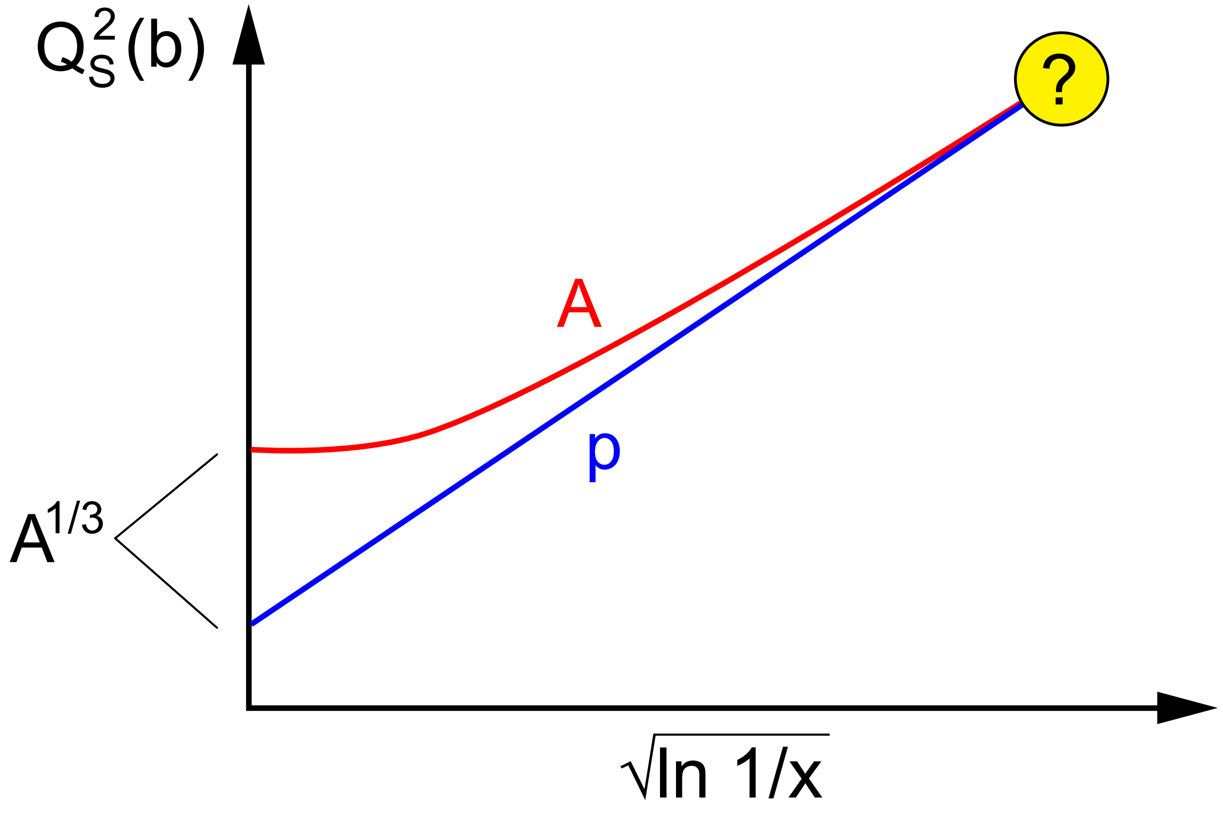

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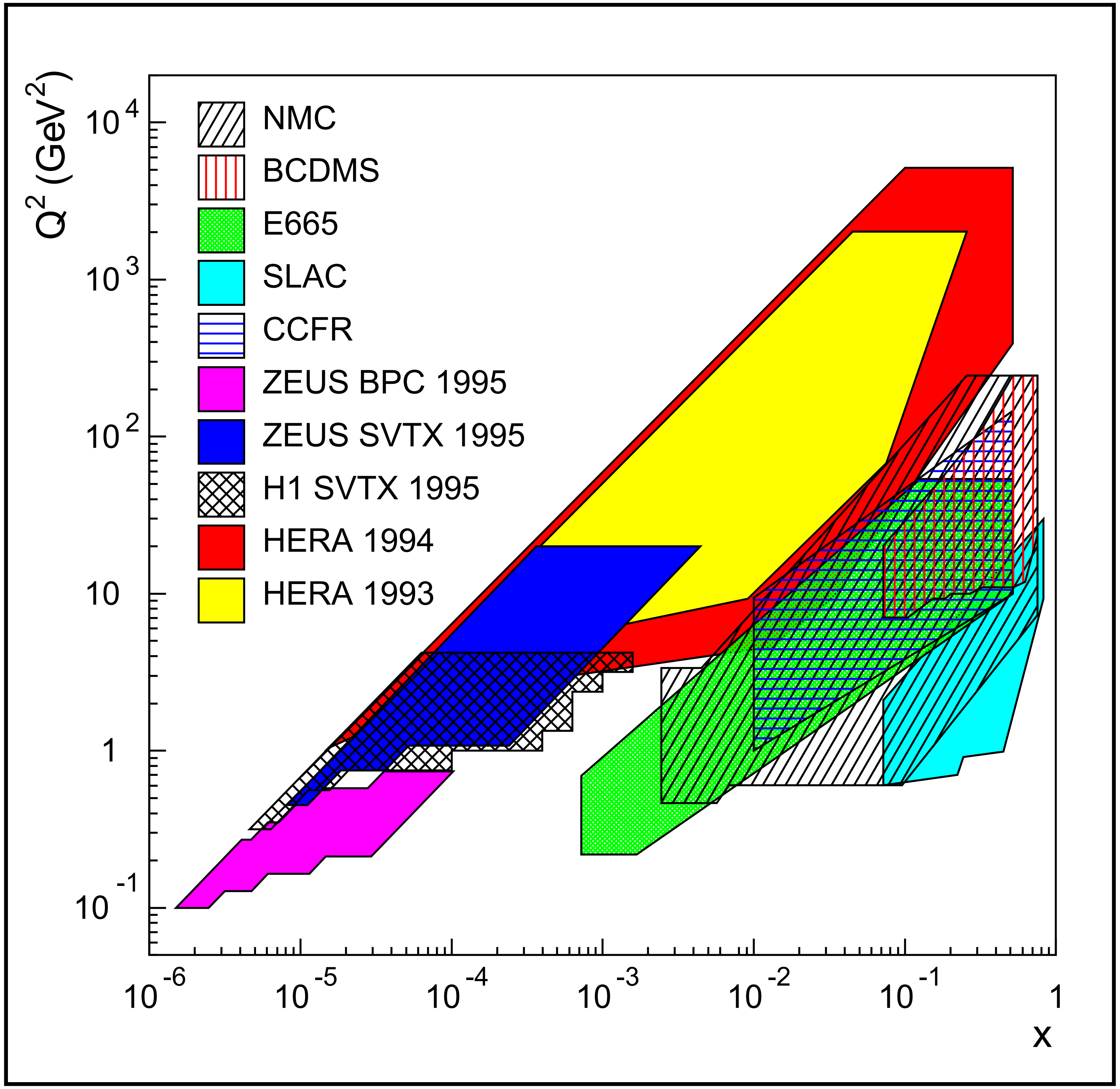
Radical View:

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

➡ This is a conjecture! Needs to be tested

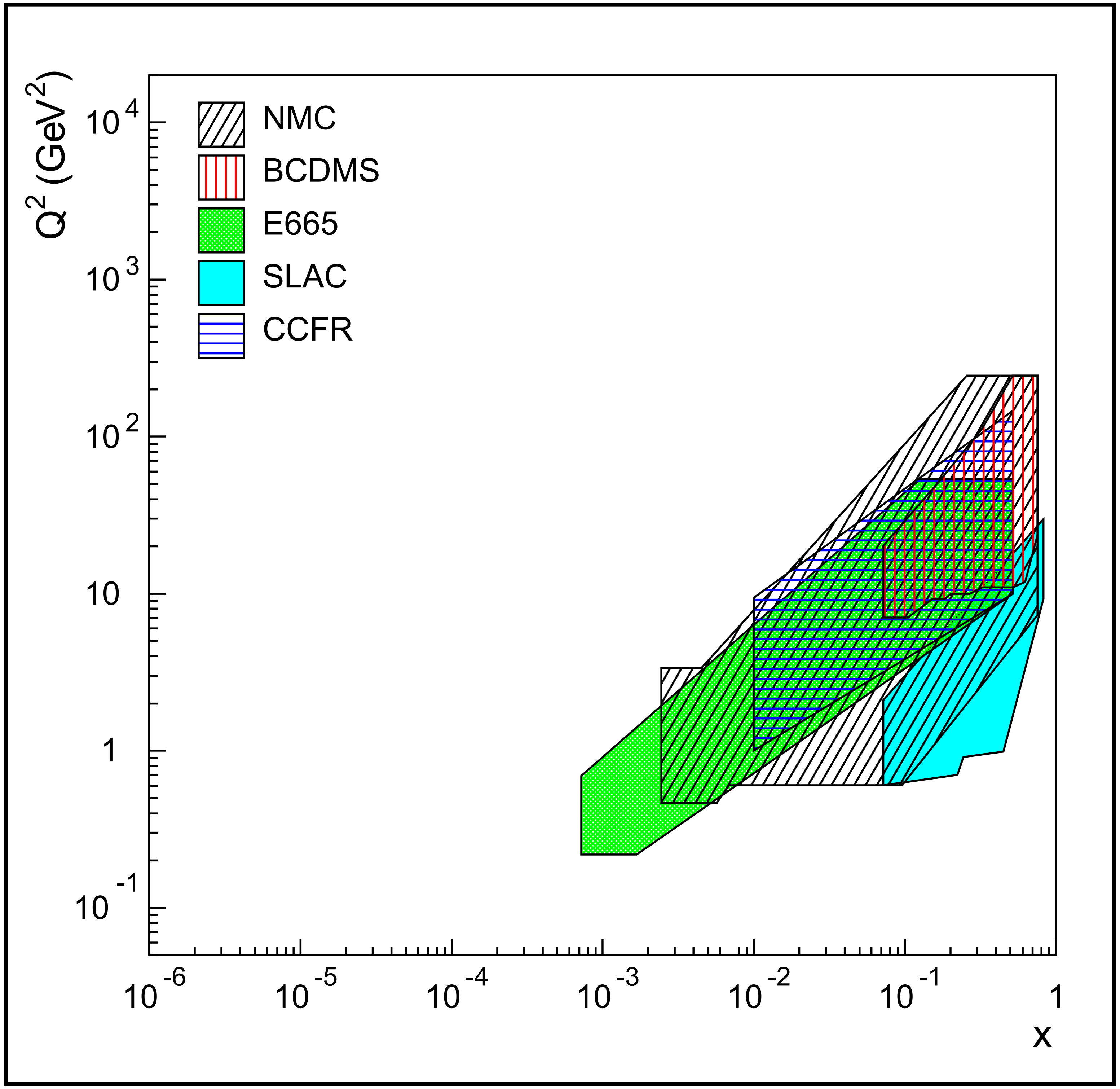
Requirements for an Electron Ion Collider



Well mapped in *e+p*

Matt Lamont - EINN ’09: macl@bnl.gov

Requirements for an Electron Ion Collider



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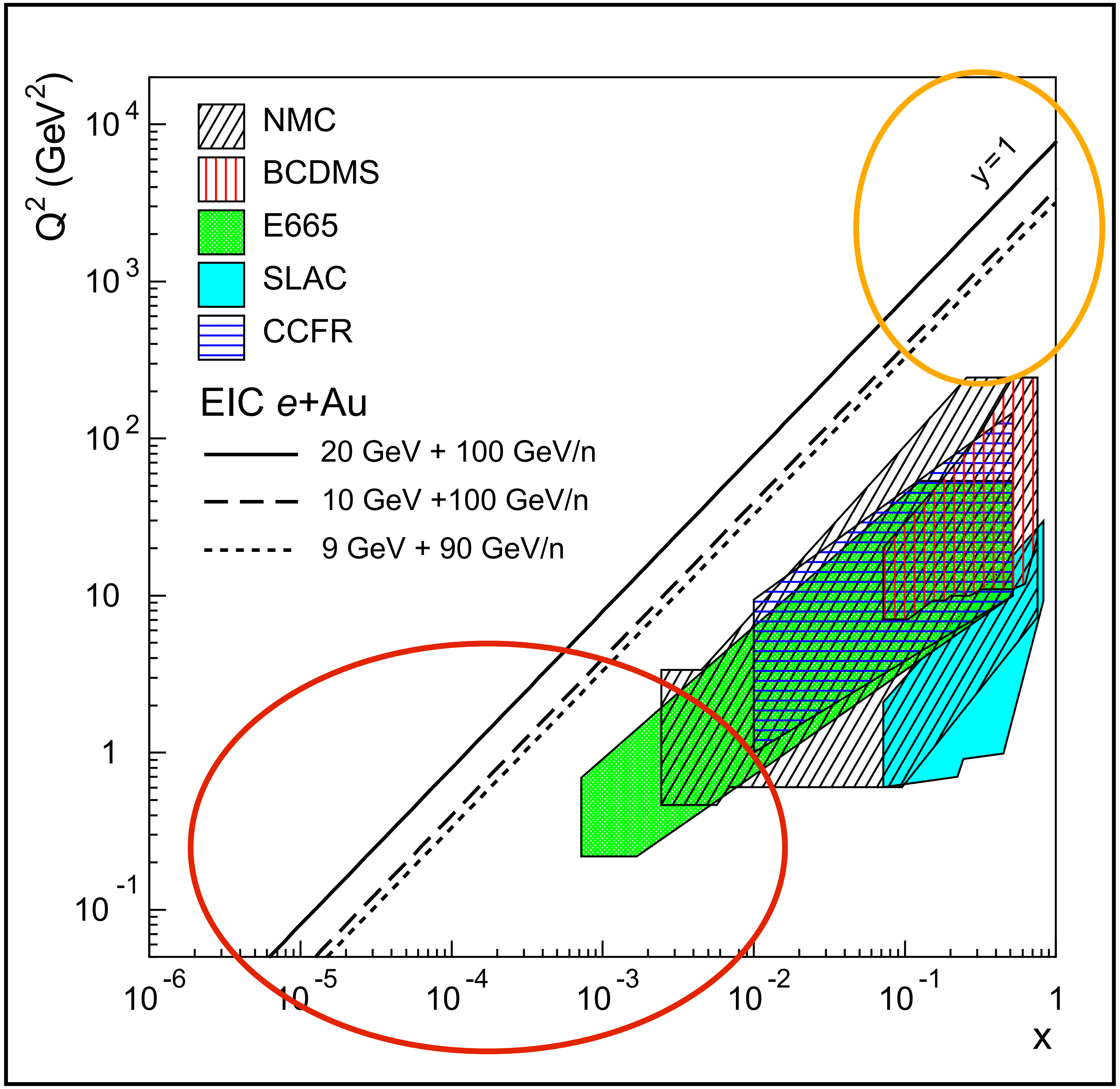

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Electron Ion Collider:

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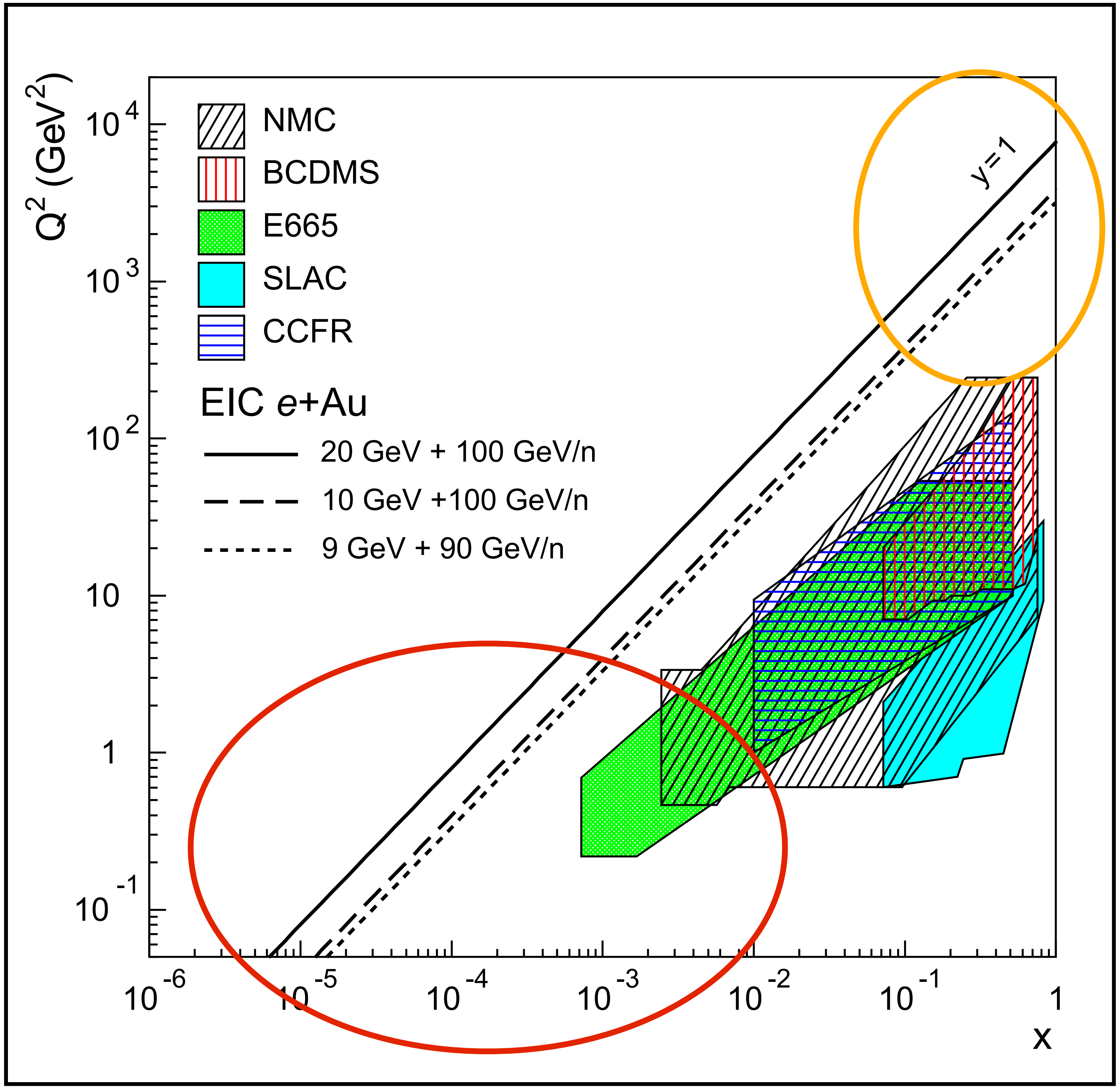

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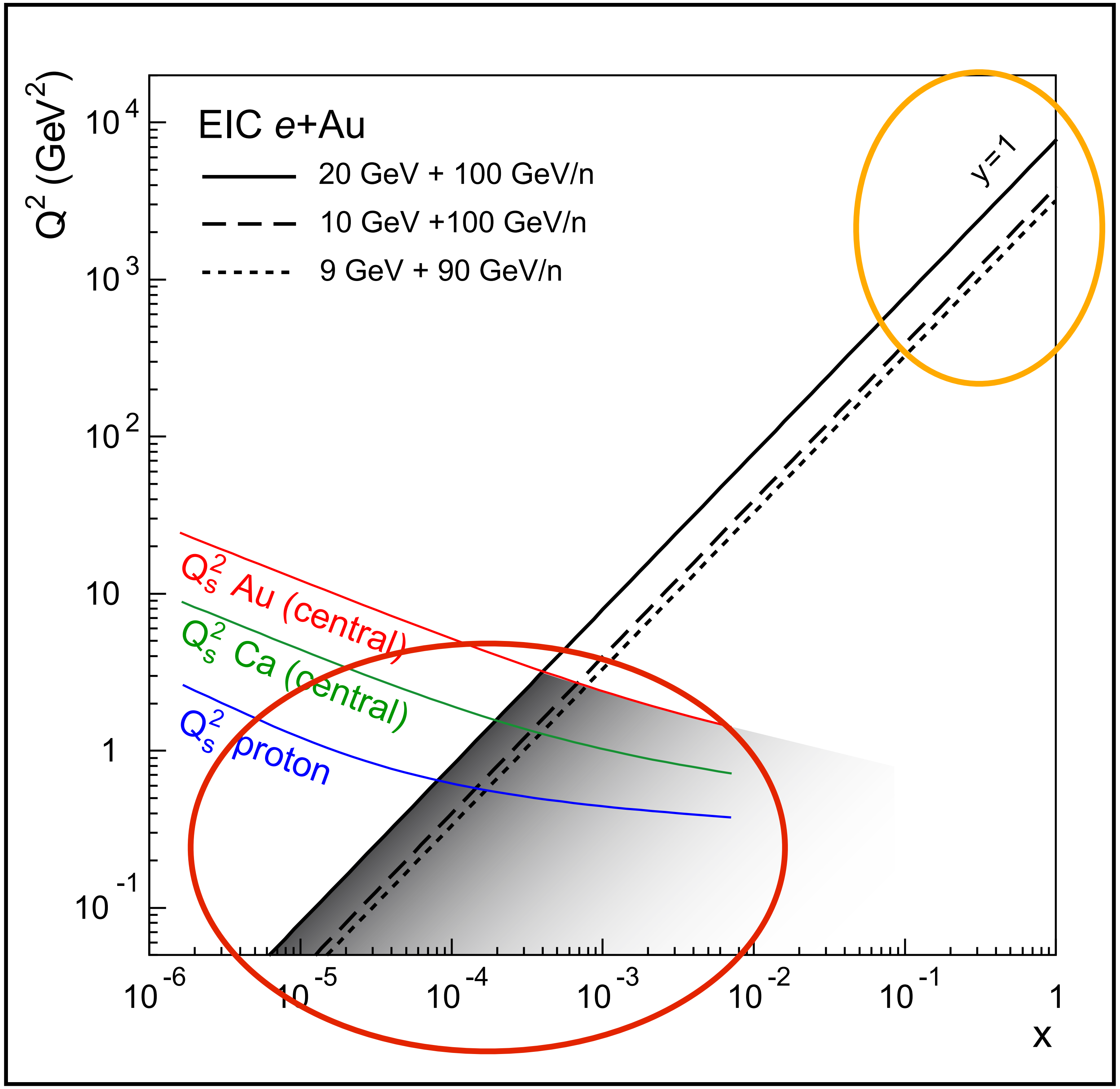

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BROOKHAVEN NATIONAL LABORATORY

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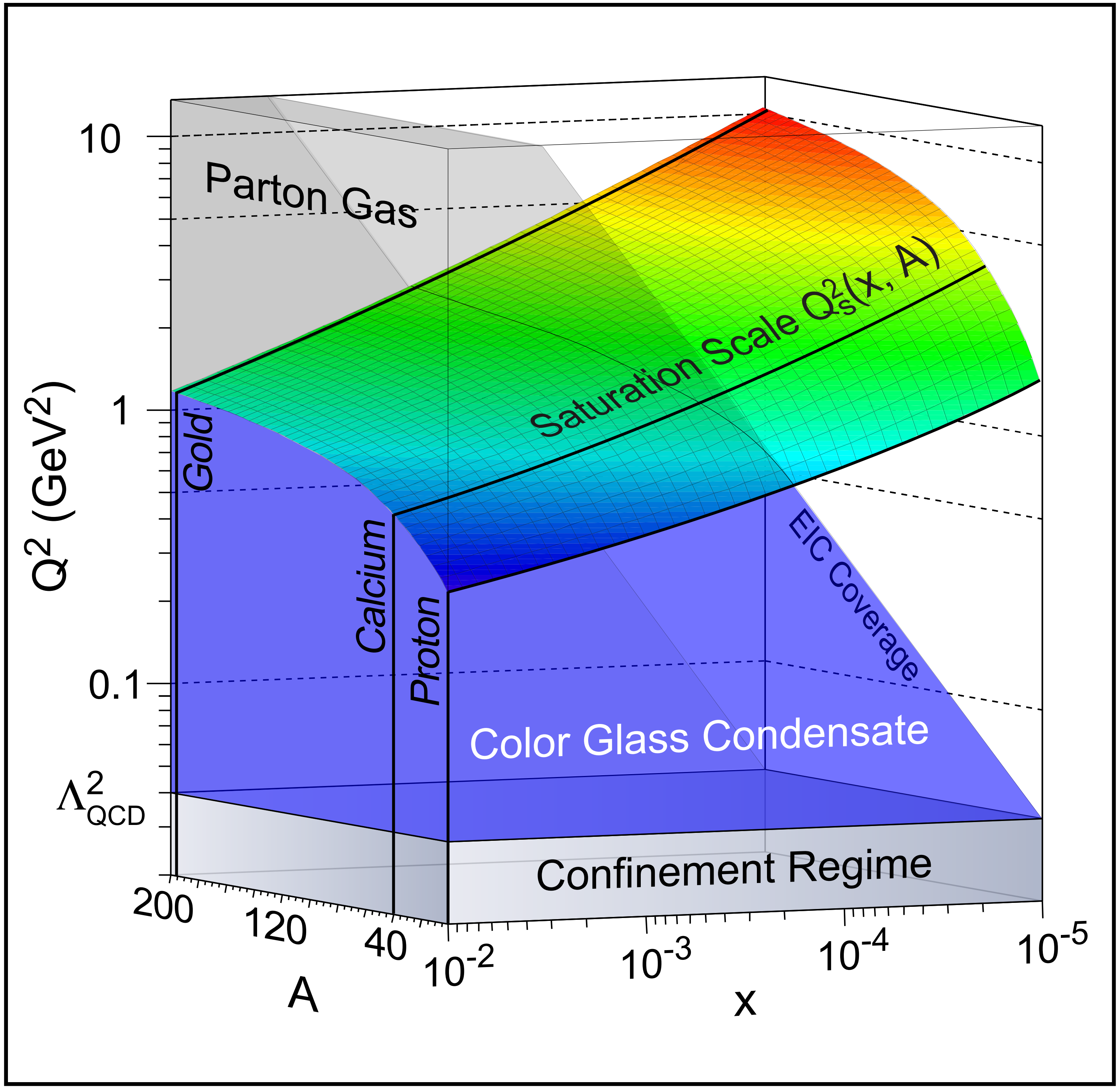

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What is happening now - e+A notes

In the process of composing eA “EIC notes” linking theory, experiment and simulations on distinct topics

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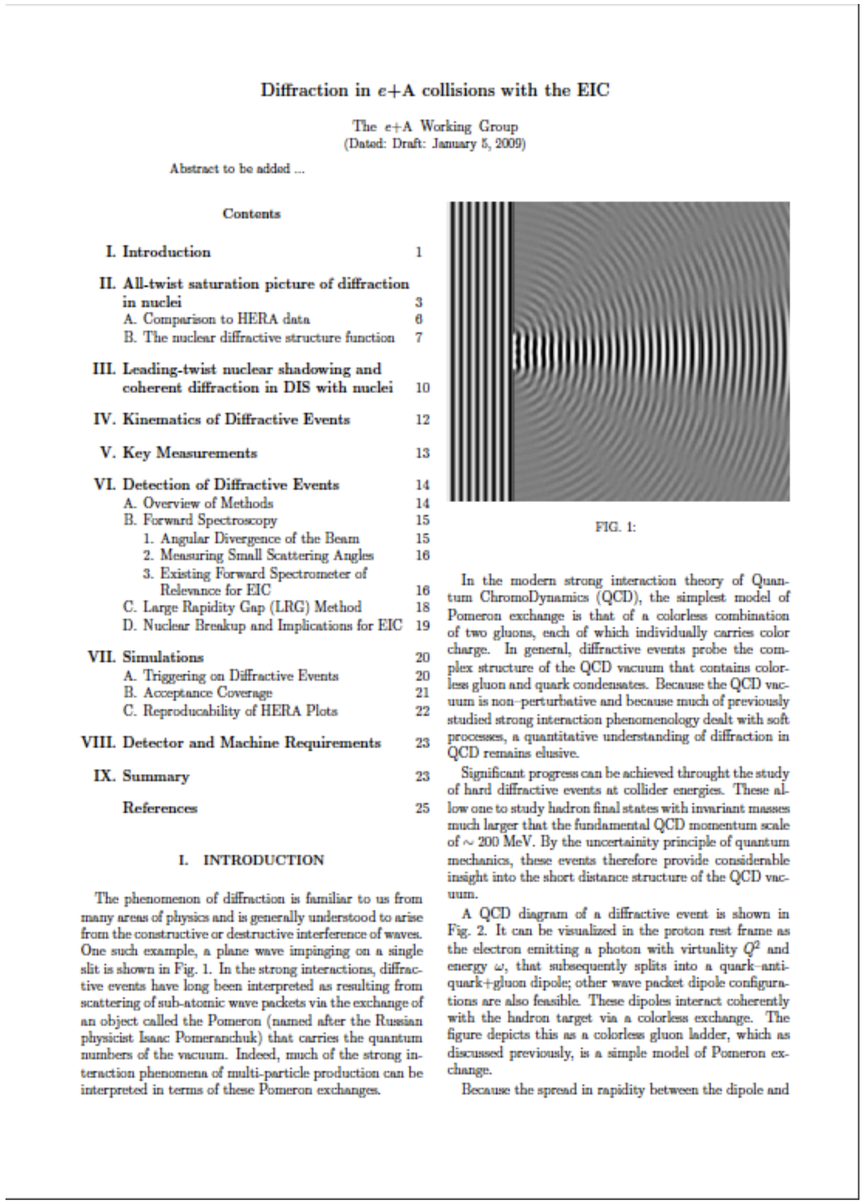
Diffraction



Diffraction in e+A collisions with the EIC

The e+A Working Group
(Dated: Draft: January 5, 2009)

Abstract to be added ...

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I. INTRODUCTION

The phenomenon of diffraction is familiar to us from many areas of physics and is generally understood to arise from the constructive or destructive interference of waves. One such example, a plane wave impinging on a single slit is shown in Fig. 1. In the strong interactions, diffractive events have long been interpreted as resulting from scattering of sub-atomic wave packets via the exchange of an object called the Pomeron (named after the Russian physicist Isaac Pomeranchuk) that carries the quantum numbers of the vacuum. Indeed, much of the strong interaction phenomena of multi-particle production can be interpreted in terms of these Pomeron exchanges.

FIG. 1:

In the modern strong interaction theory of Quantum ChromoDynamics (QCD), the simplest model of Pomeron exchange is that of a colorless combination of two gluons, each of which individually carries color charge. In general, diffractive events probe the complex structure of the QCD vacuum that contains colorless gluon and quark condensates. Because the QCD vacuum is non–perturbative and because much of previously studied strong interaction phenomenology dealt with soft processes, a quantitative understanding of diffraction in QCD remains elusive.

Significant progress can be achieved throught the study of hard diffractive events at collider energies. These allow one to study hadron final states with invariant masses much larger that the fundamental QCD momentum scale of ~ 200 MeV. By the uncertainity principle of quantum mechanics, these events therefore provide considerable insight into the short distance structure of the QCD vacuum.

A QCD diagram of a diffractive event is shown in Fig. 2. It can be visualized in the proton rest frame as the electron emitting a photon with virtuality Q^2 and energy ω, that subsequently splits into a quark–anti-quark+gluon dipole; other wave packet dipole configurations are also feasible. These dipoles interact coherently with the hadron target via a colorless exchange. The figure depicts this as a colorless gluon ladder, which as discussed previously, is a simple model of Pomeron exchange.

Because the spread in rapidity between the dipole and

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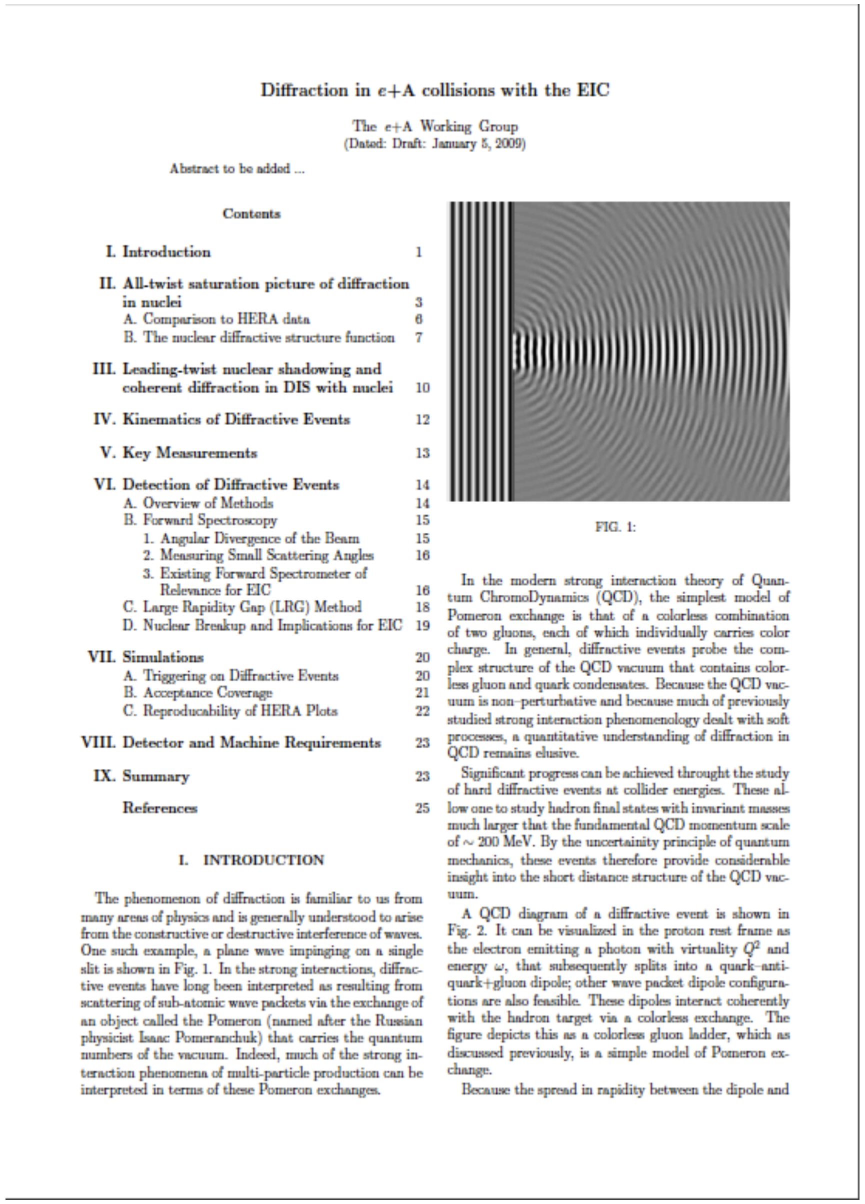

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Hadronization

Draft, 10 December 2008

Parton propagation and fragmentation at the EIC

Alberto Accardi[1,2], Raphaël Dupré[3,4] and Kawtar Hafidi[3,2]

[1] Hampton University, Hampton, VA, 23668, USA
[2] Jefferson Lab, Newport News, VA 23606, USA
[3] Physics Division, Argonne National Laboratory, Argonne, IL, USA
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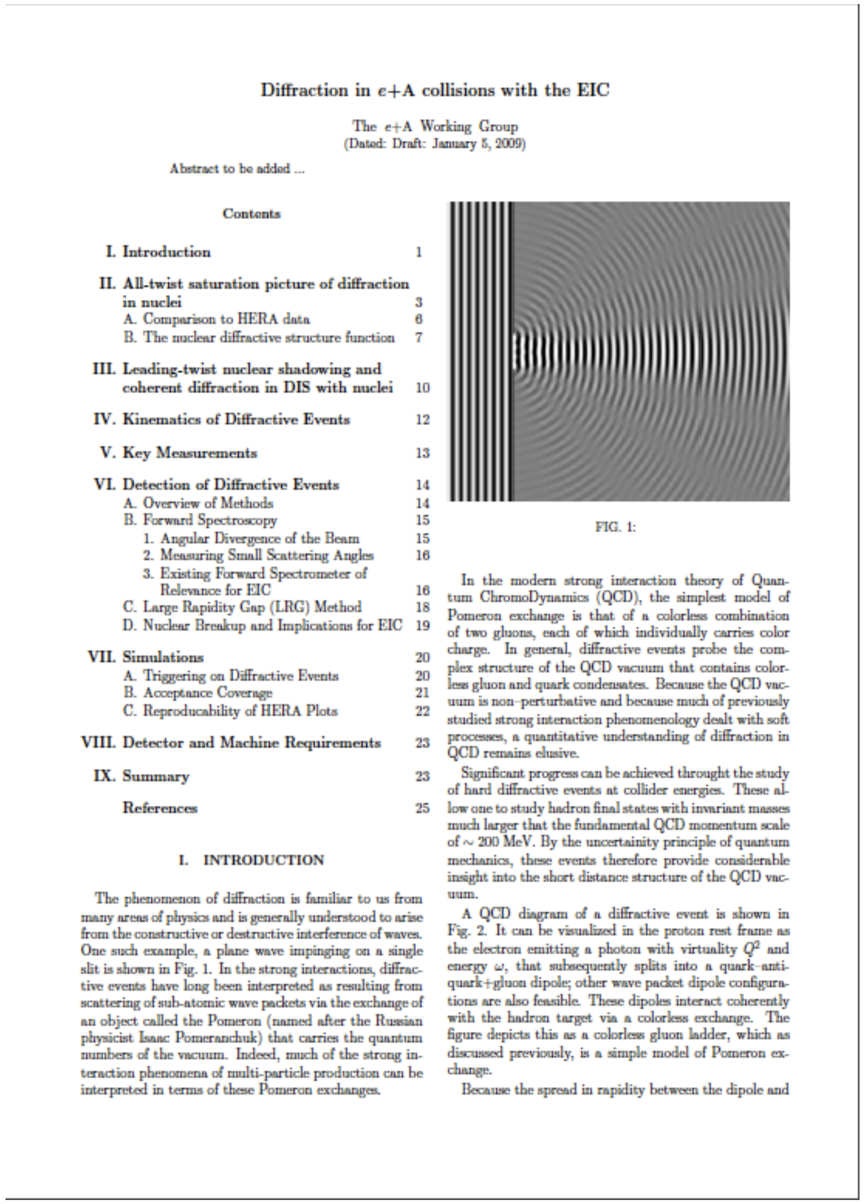

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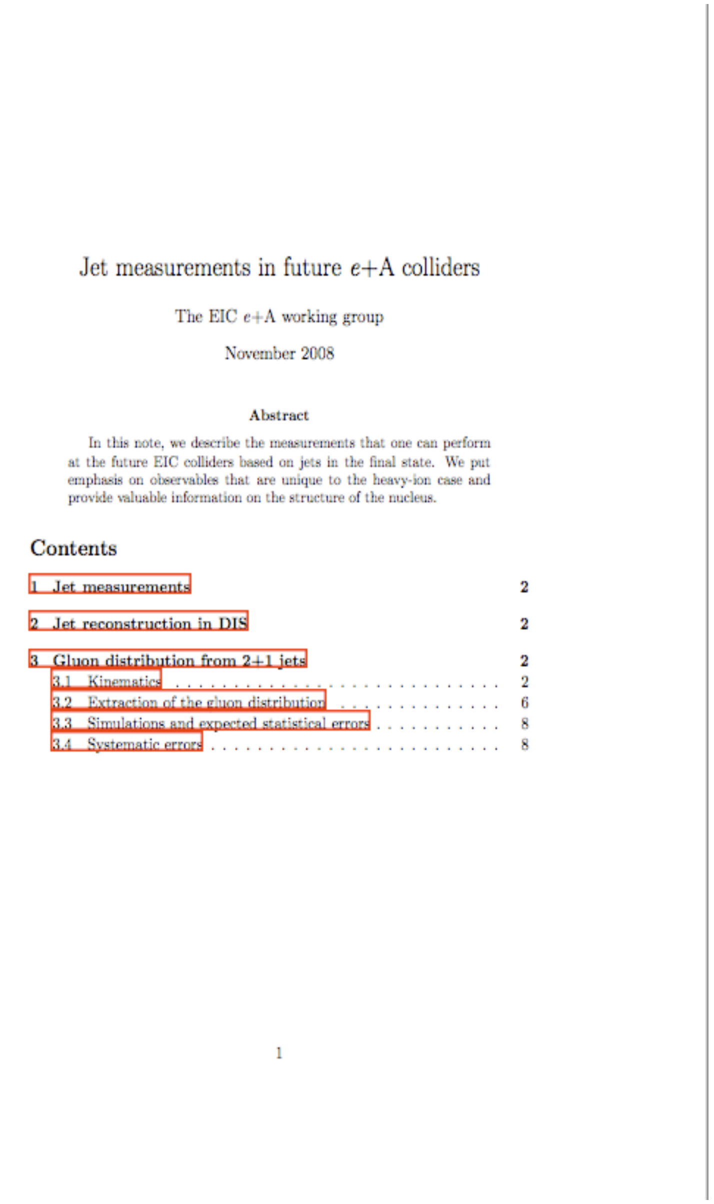
Jets



Jet measurements in future e+A colliders

The EIC e+A working group

November 2008

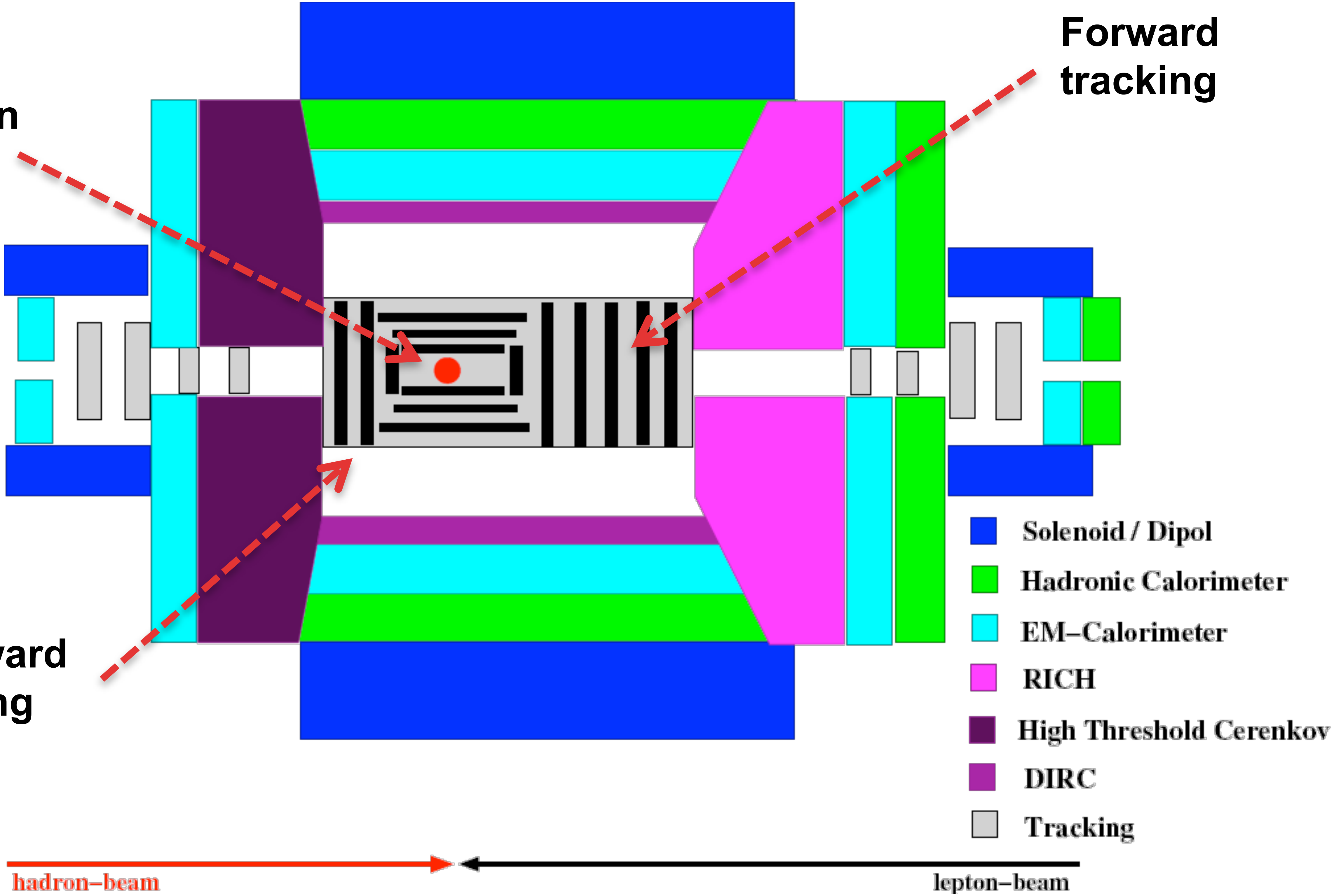
Abstract

In this note, we describe the measurements that one can perform at the future EIC colliders based on jets in the final state. We put emphasis on observables that are unique to the heavy-ion case and provide valuable information on the structure of the nucleus.

Contents

1

Detector design



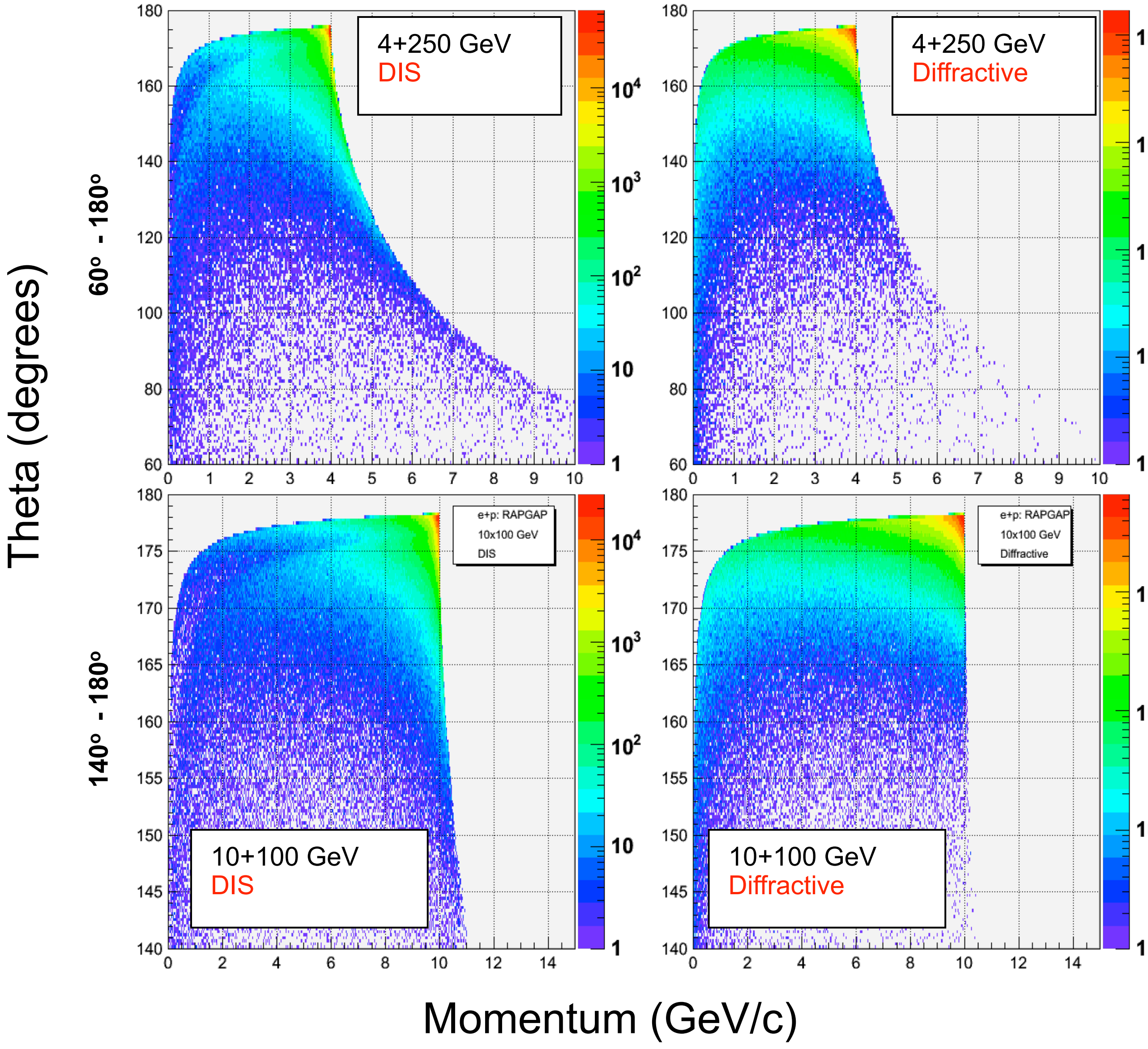
Collision point

Forward tracking

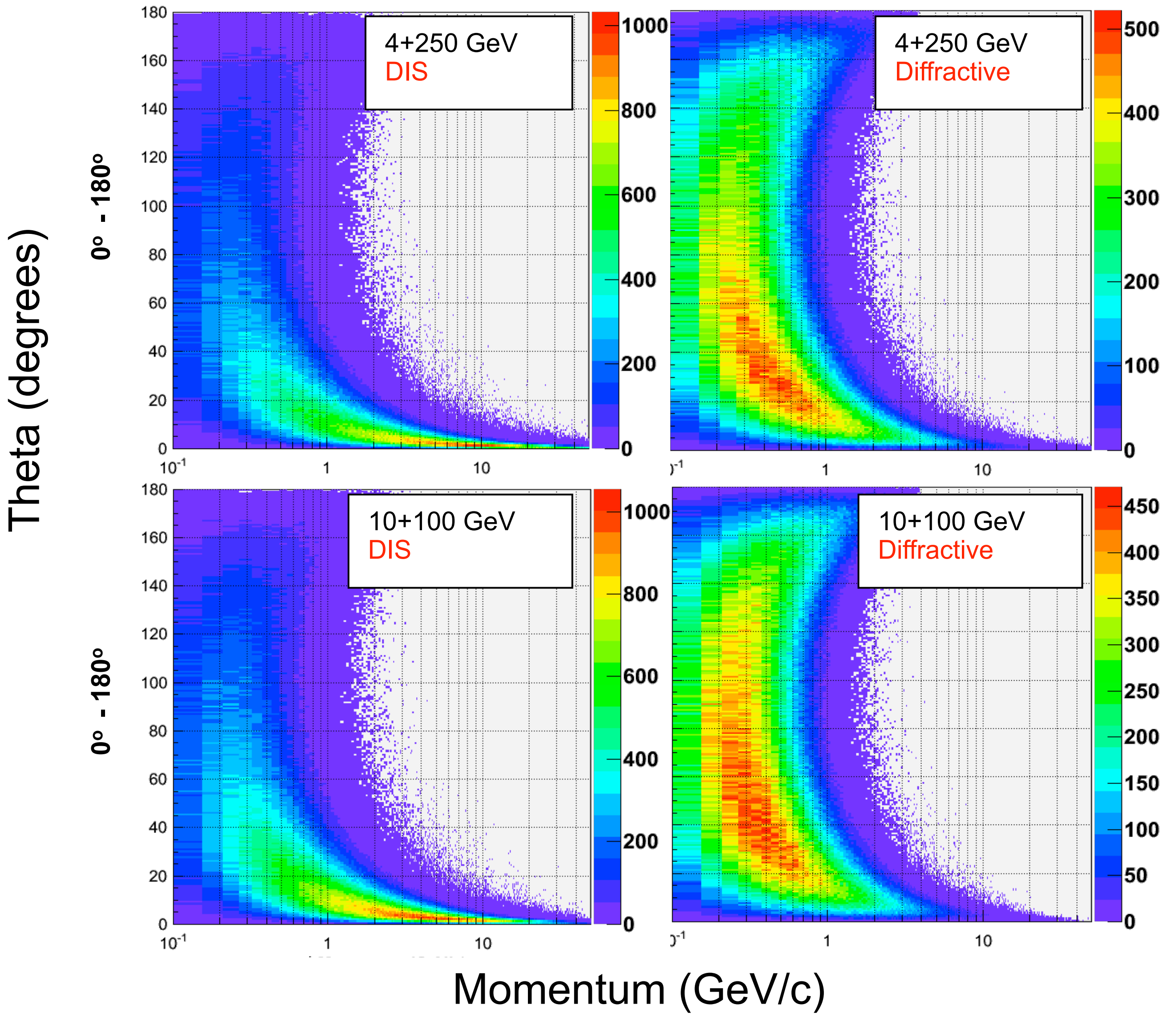
Backward tracking

Detector design

Scattered e^-



Scattered π^-



Plots courtesy of Will Foreman and Anders Kirleis, freshmen at SUNY-SB

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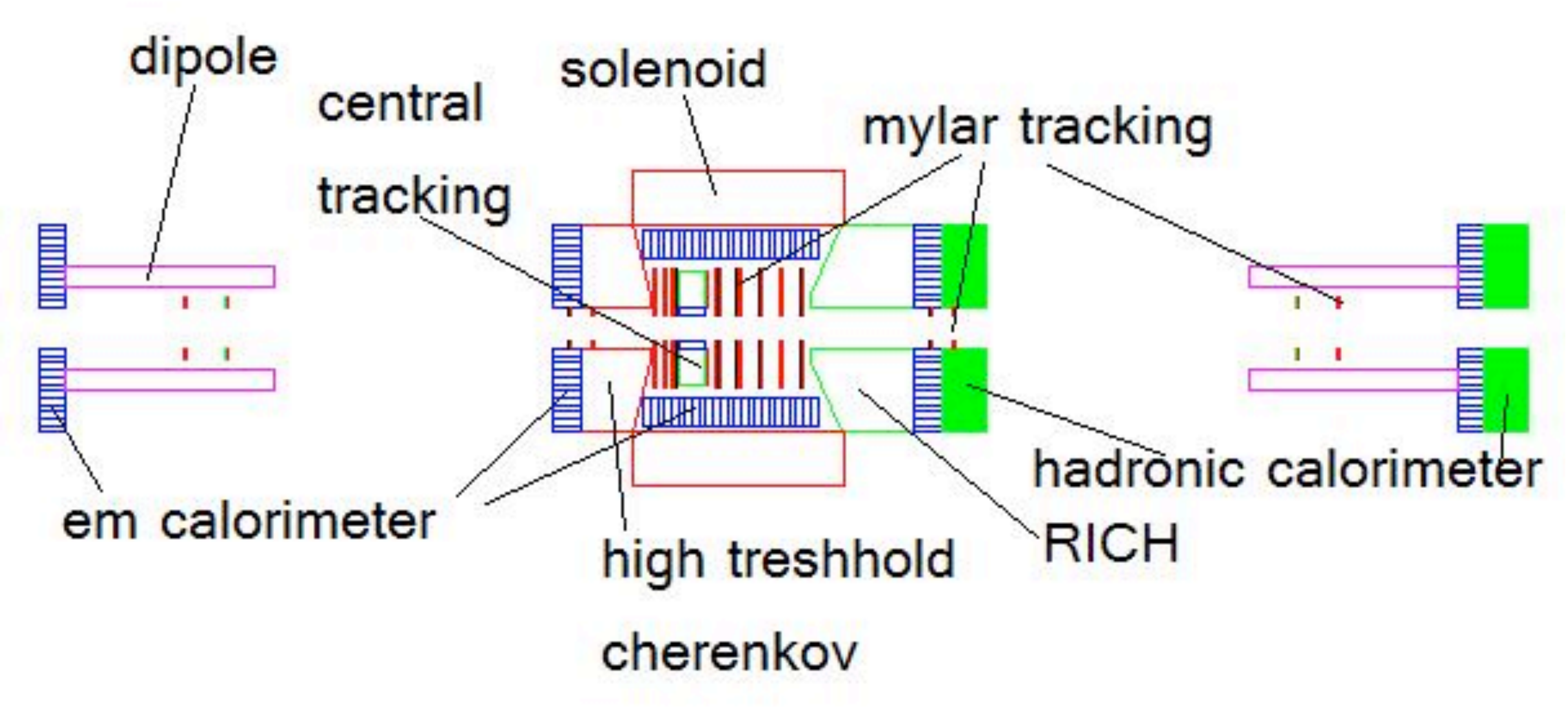

DIRC is present but not seen due to position of cut

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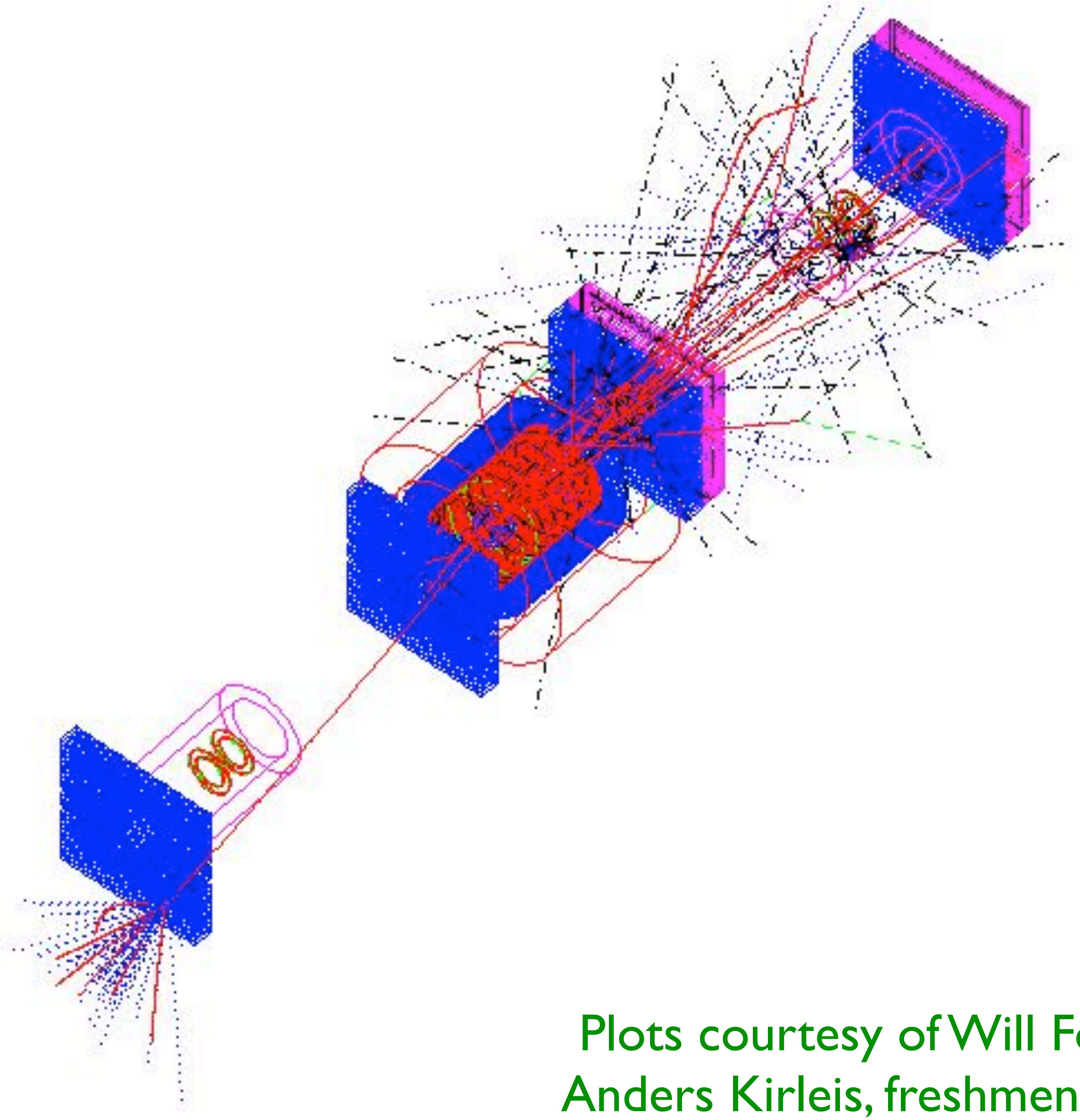

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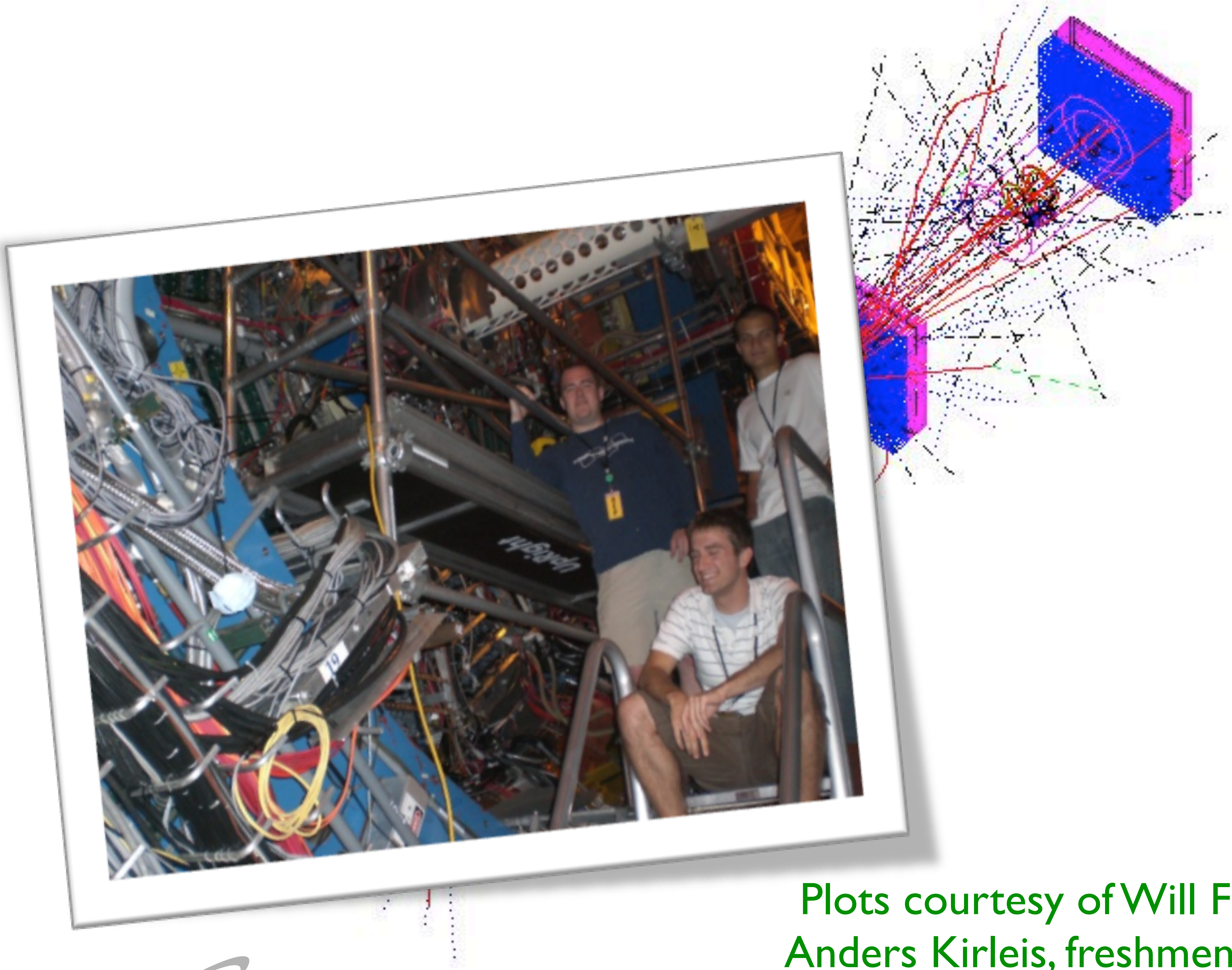

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Summary

An EIC presents a unique opportunity in high energy nuclear physics and precision QCD physics

e+A	Polarized e+p
◆ Study the Physics of Strong Colour Fields • Establish (or not) the existence of the saturation regime • Explore non-linear QCD • Measure momentum & space-time of glue ◆ Study the nature of colour singlet excitations (Pomerons) ◆ Test and study the limits of universality (eA vs. pA)	◆ Precisely image the sea-quarks and gluons to determine the spin, flavour and spatial structure of the nucleon

- Embraced by NSAC in Long Range Plan
  - Recommendation of $30M for R&D over next 5 years
- EIC Long Term Goal - start construction in next decade
- Possibility of Staged Approach
  - Cheap (no civil construction costs)
  - Early time-scale for realisation (operation by ~2016)
  - Cons - lower energy and luminosity than full design

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