Hot Quarks and Gluons at an Electron-Ion Collider

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Brookhaven National Lab

Talk Outline

- The role of glue in HI collisions
- How to measure the gluon distributions
- eA vs *ep* and the "Nuclear Oomph" factor
- The EIC machine and detector concepts
- Where we are and where we're going

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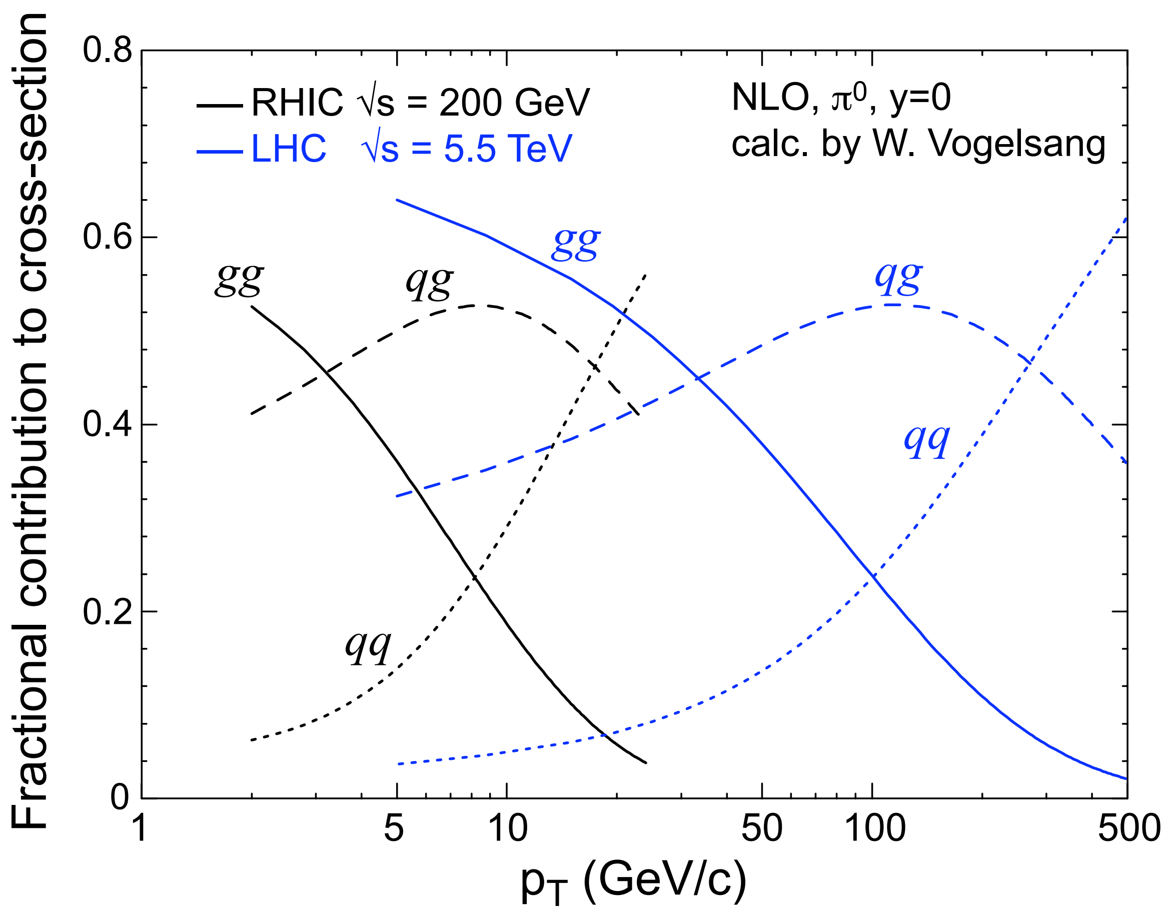
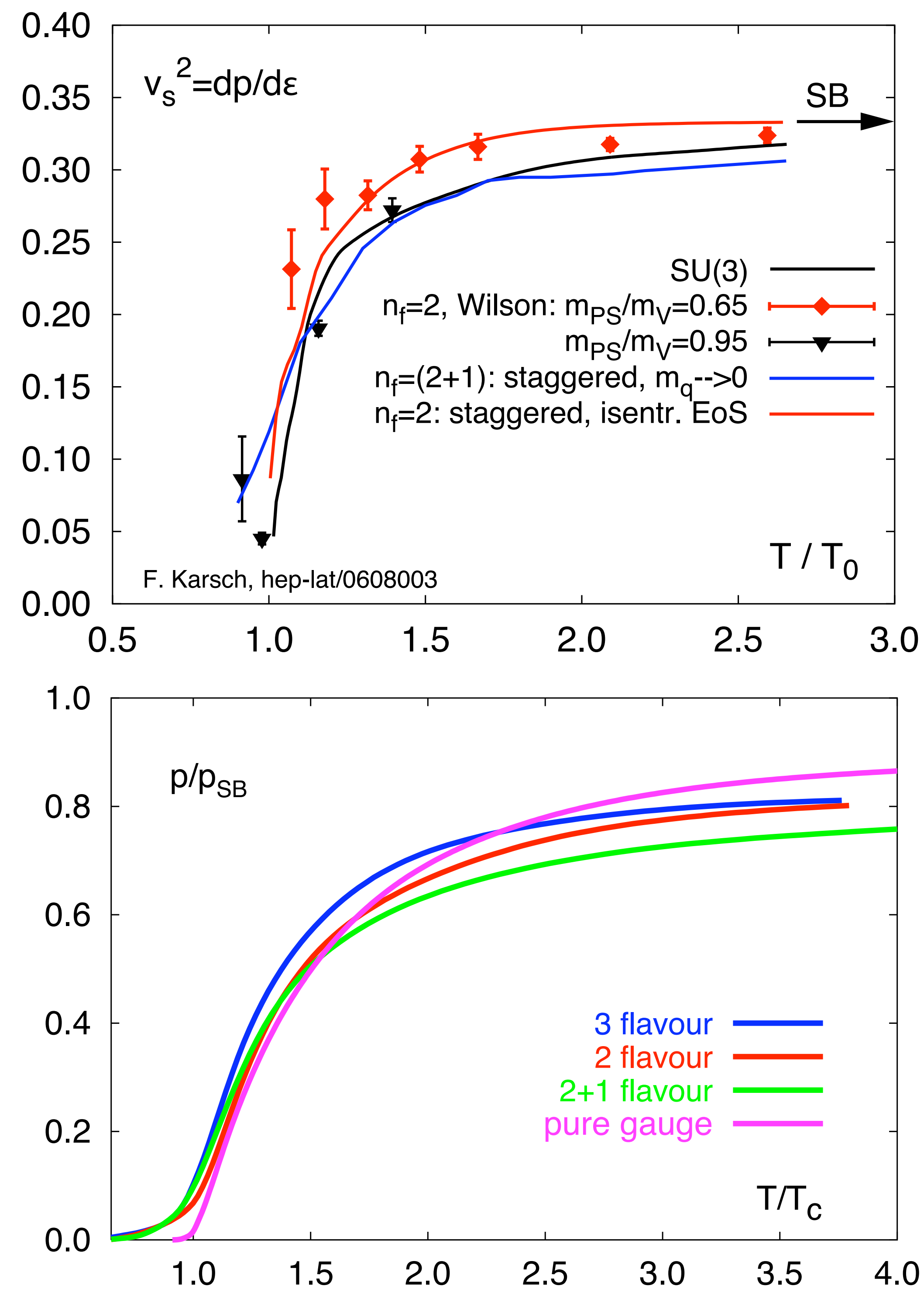
EIC on the web: http://web.mit.edu/eicc
e+A working group: http://www.eic.bnl.gov

The role of Glue in Heavy-Ion collisions

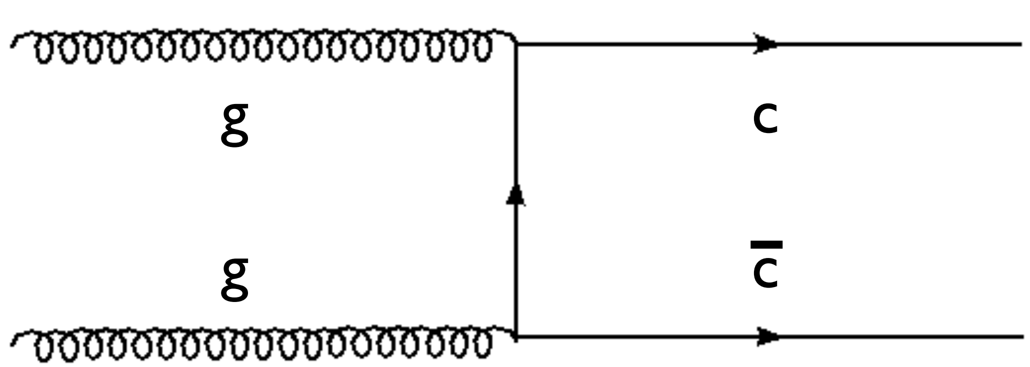
Jets (π^0 production)



Lattice Gauge Theory:



Heavy Flavour Production



The role of Glue in Heavy-Ion collisions

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Lattice Gauge Theory:

To move towards understanding HI physics quantitatively, we need to understand the role of glue in HI Collisions !!

What do we know about gluons?

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Glue and the QCD Lagrangian:

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

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  - χSB & Colour Confinement

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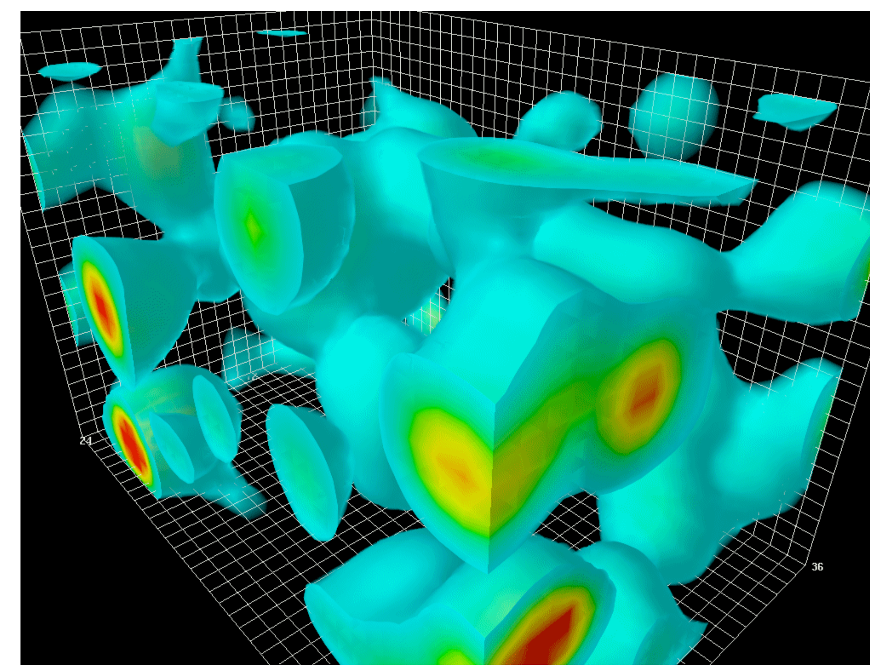

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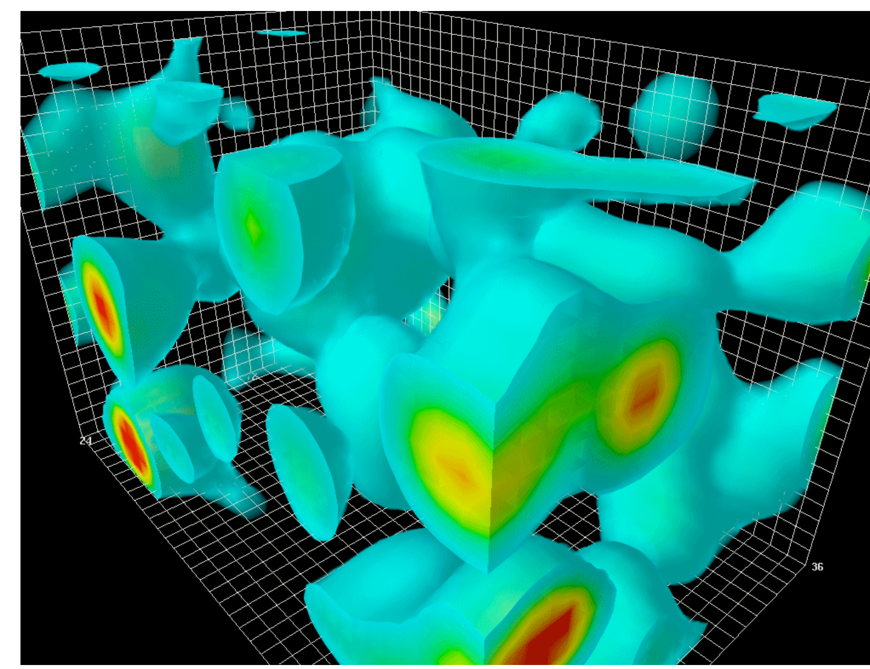
- **"Emergent" Phenomena not evident from Lagrangian**
  - χSB & Colour Confinement
- **Gluons**
  - ➡ Mediators of the strong interaction
  - ➡ Determine essential features of QCD
    - Asymptotic freedom from gluon loops
  - ➡ Dominate structure of QCD vacuum (χSB)
  - ➡ Responsible for > 98% of all visible mass



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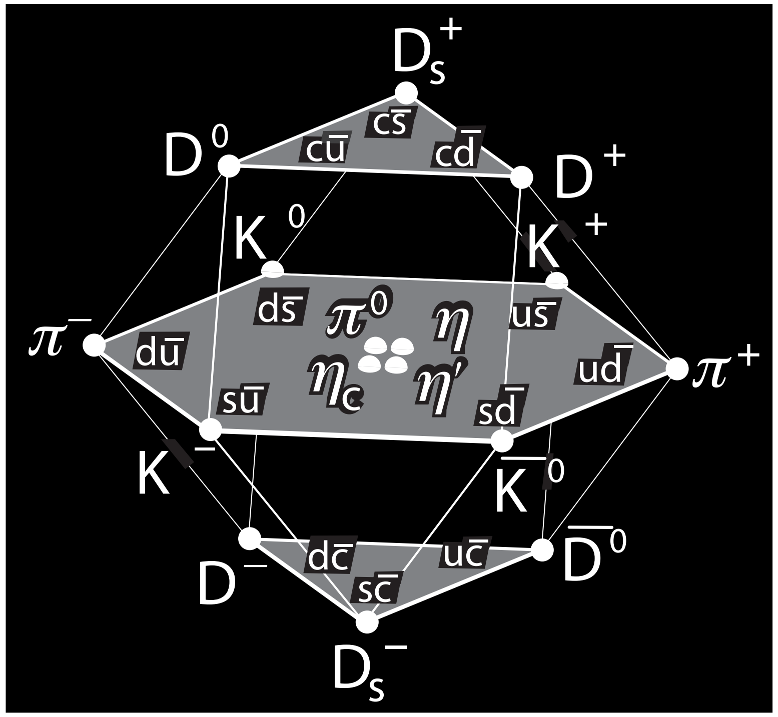
  - ➡ Gluon degrees of freedom "missing" in hadronic spectrum
    - ➡ Constituent Quark Picture?
- From DIS:
  - ➡ Drive the structure of baryonic matter already at medium-x
- Crucial players at RHIC and LHC
  - ➡ Drive the entropy
  - ➡ High energy cross-section suggest pomeron (2 gluon) exchange important



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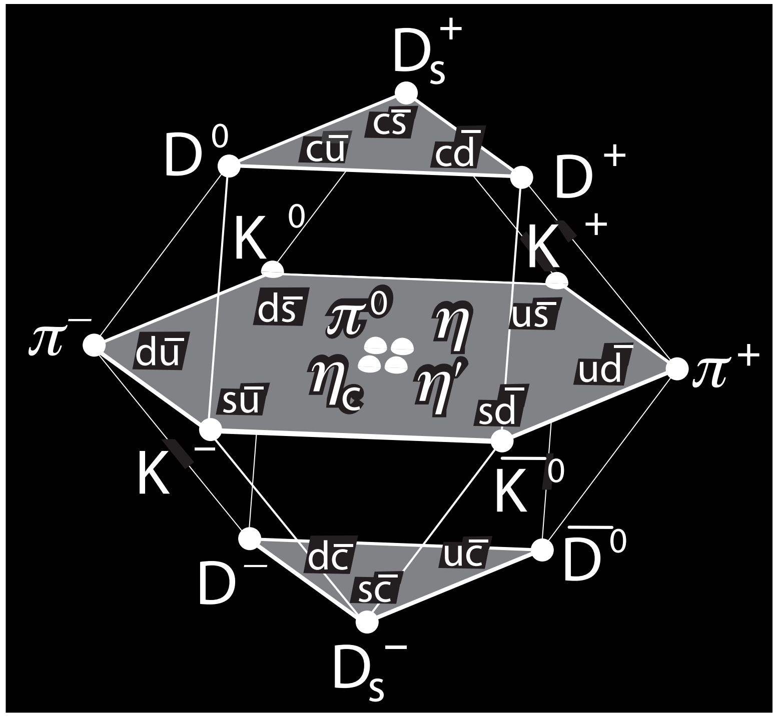

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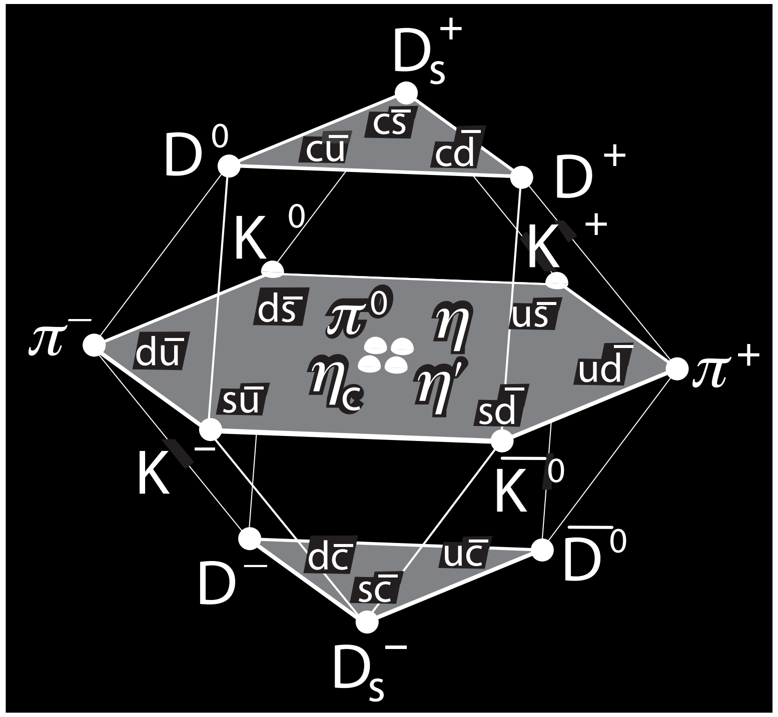

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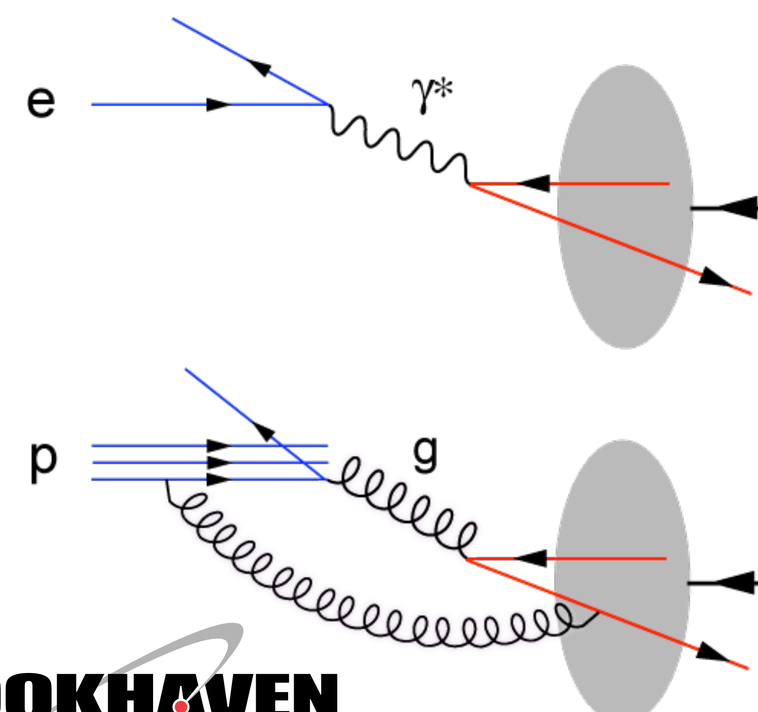
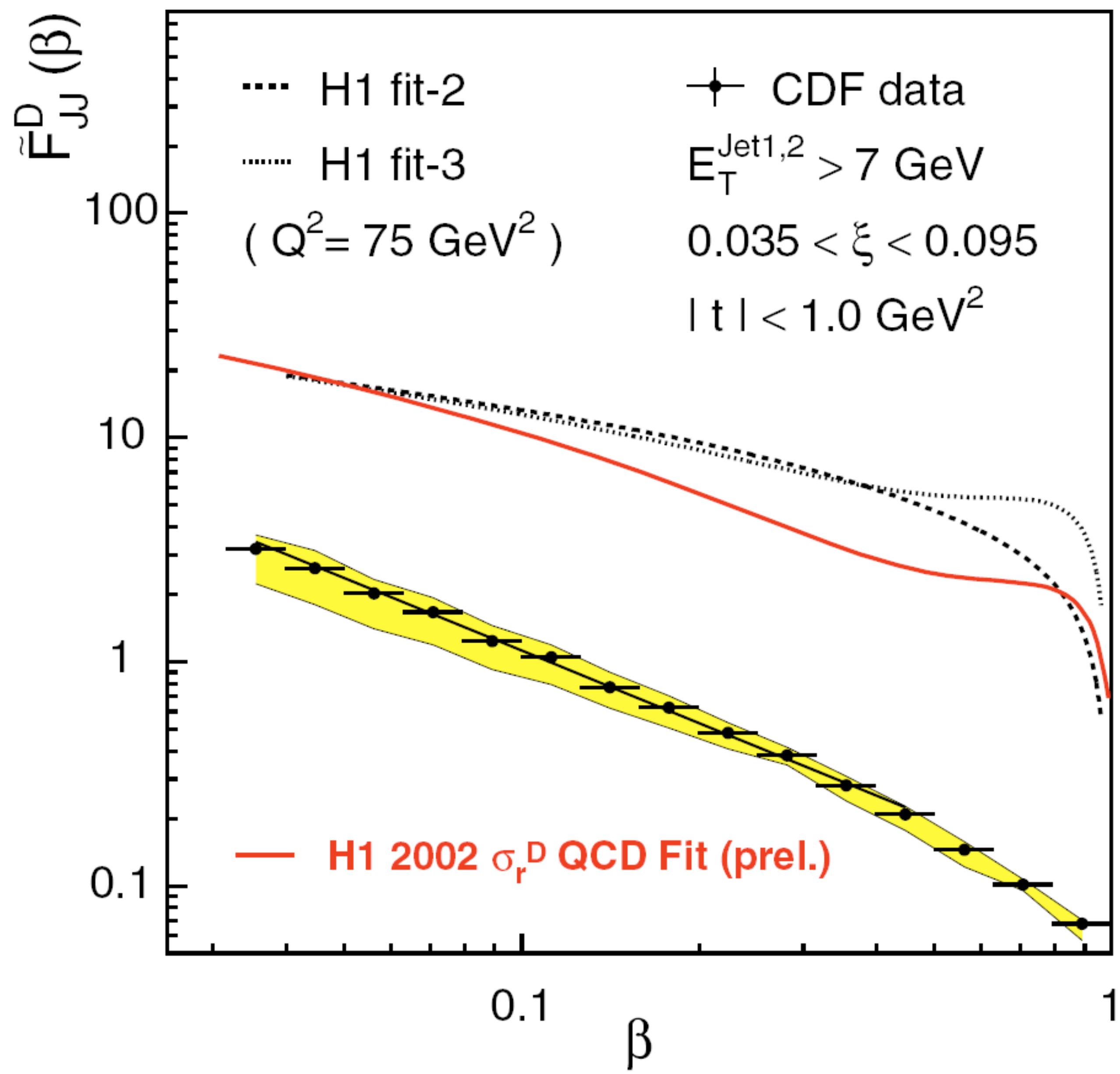
How do we get to the answers?

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

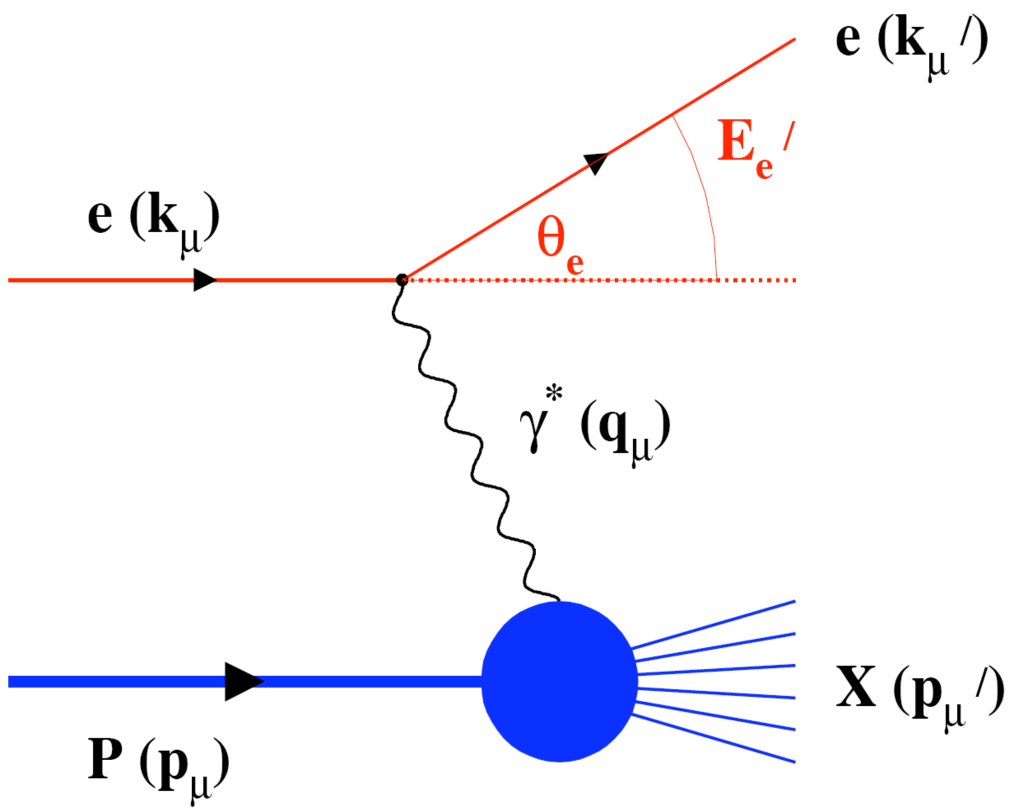


F. Schilling, hex-ex/0209001



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

DIS Kinematics



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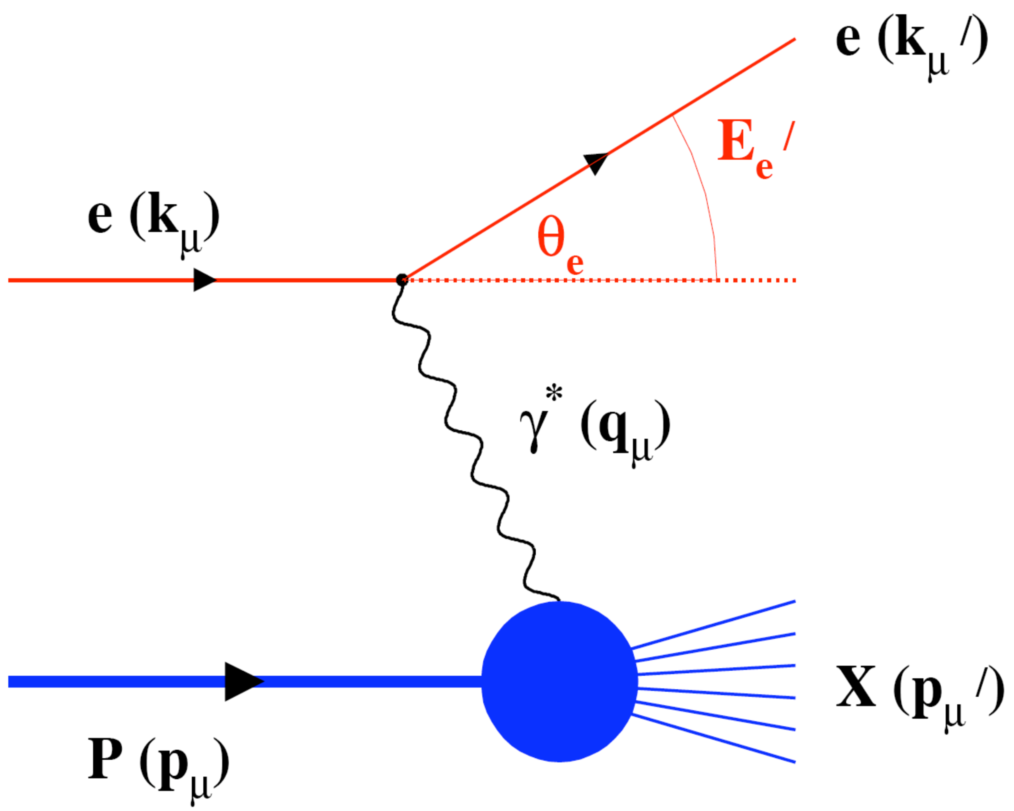

$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

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

Measure of resolution power or "Virtuality"

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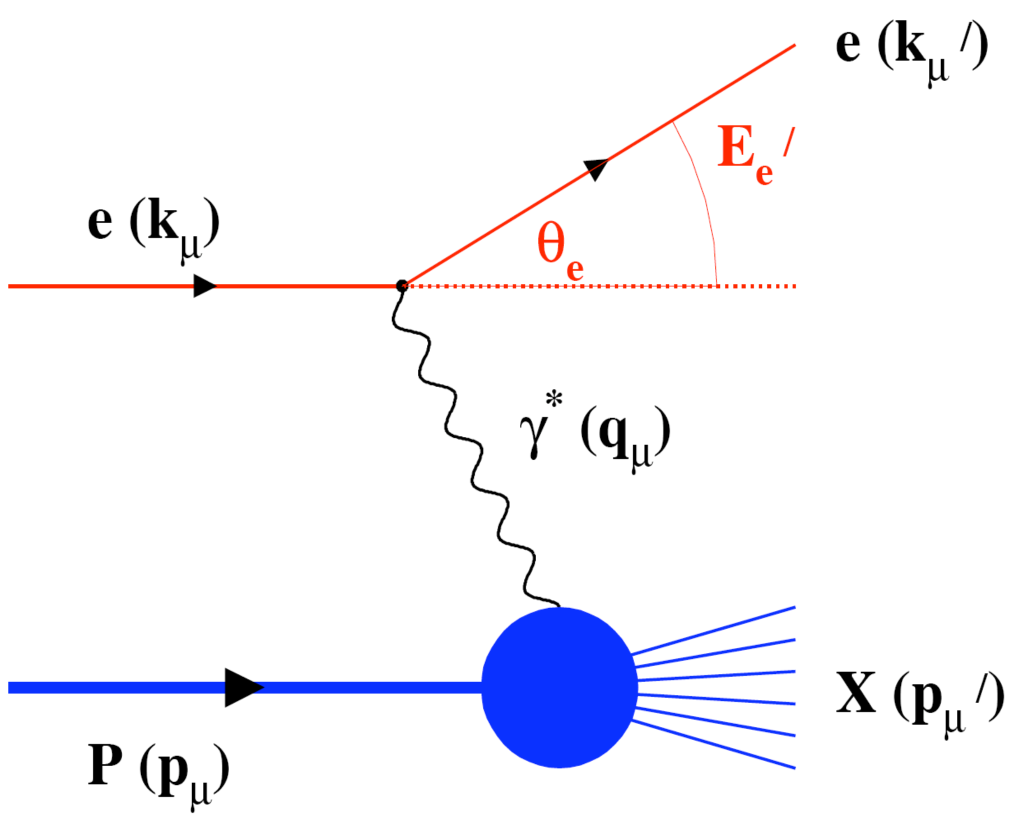

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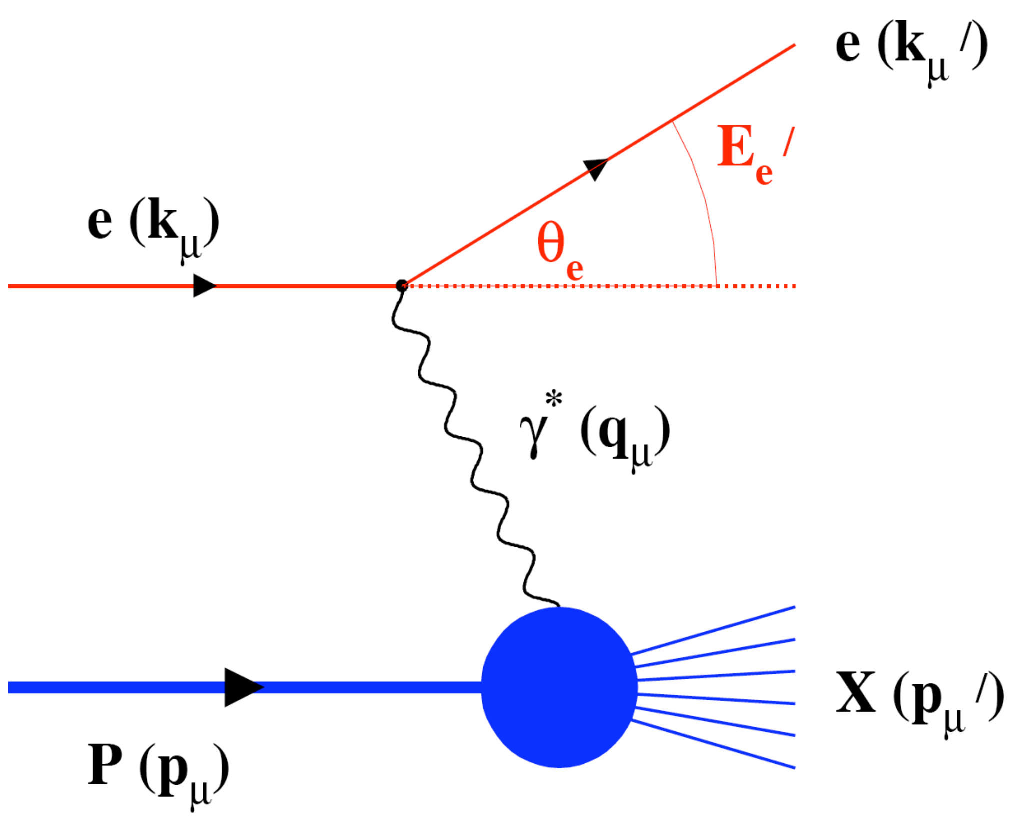

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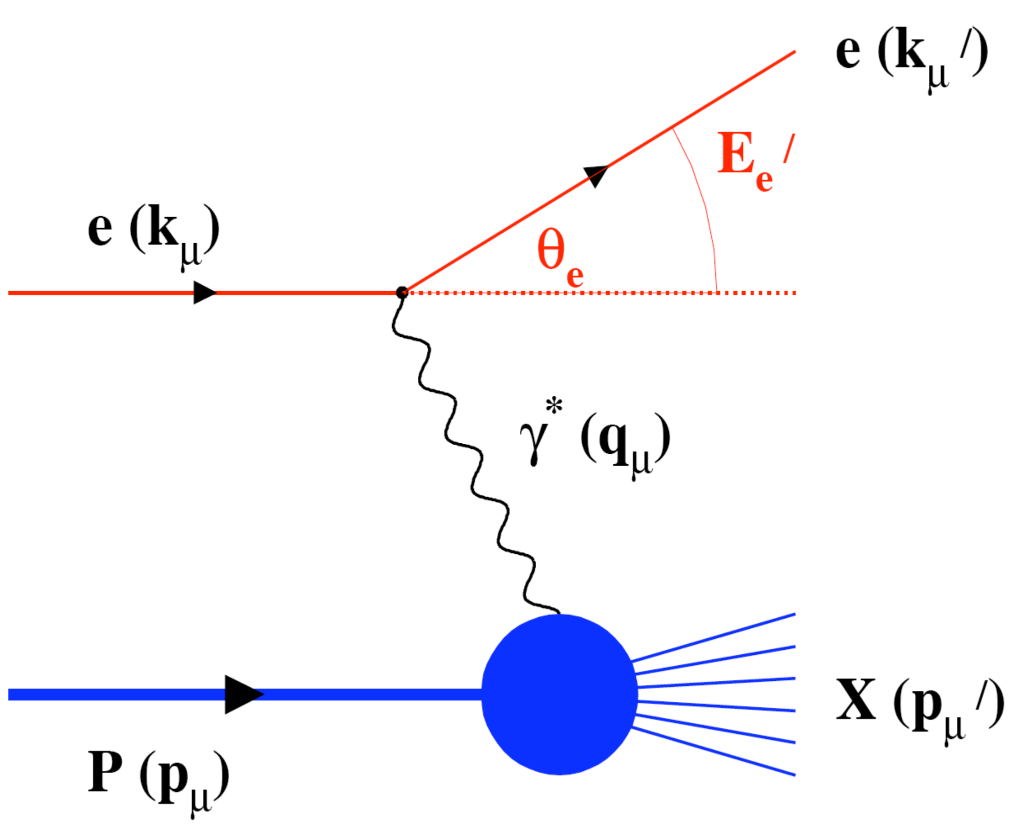

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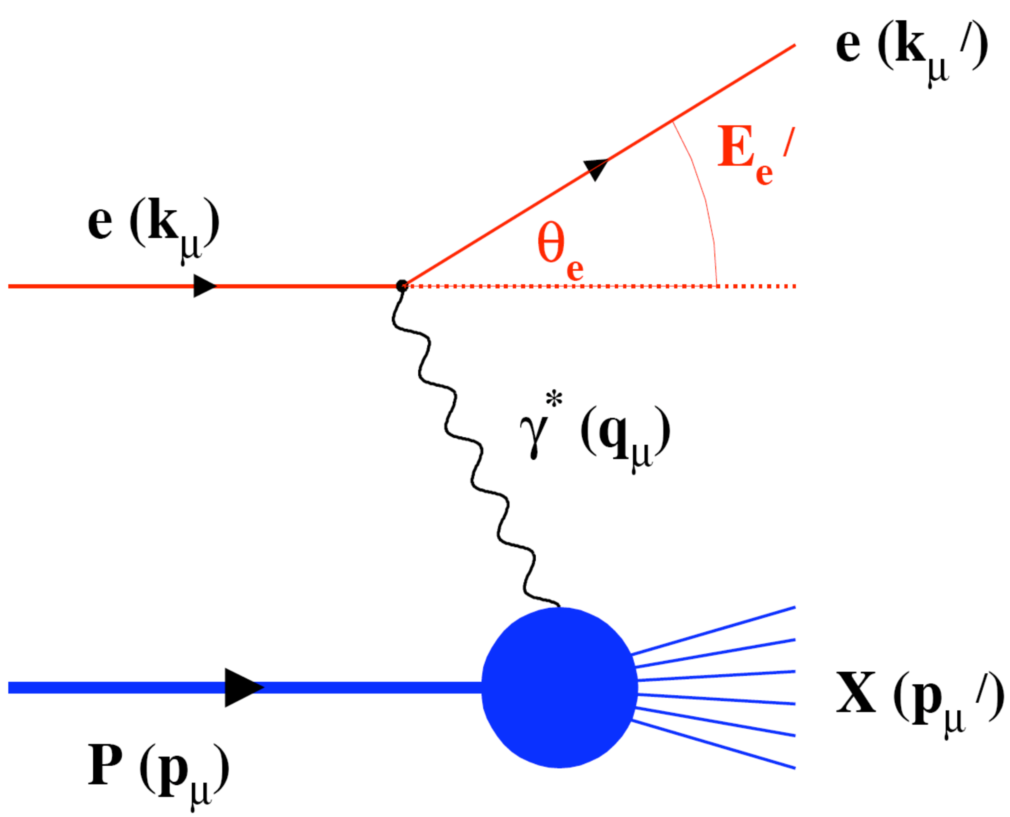

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  - $F_2(x,Q^2) \Rightarrow$ q and $\bar{q}$ momentum distributions
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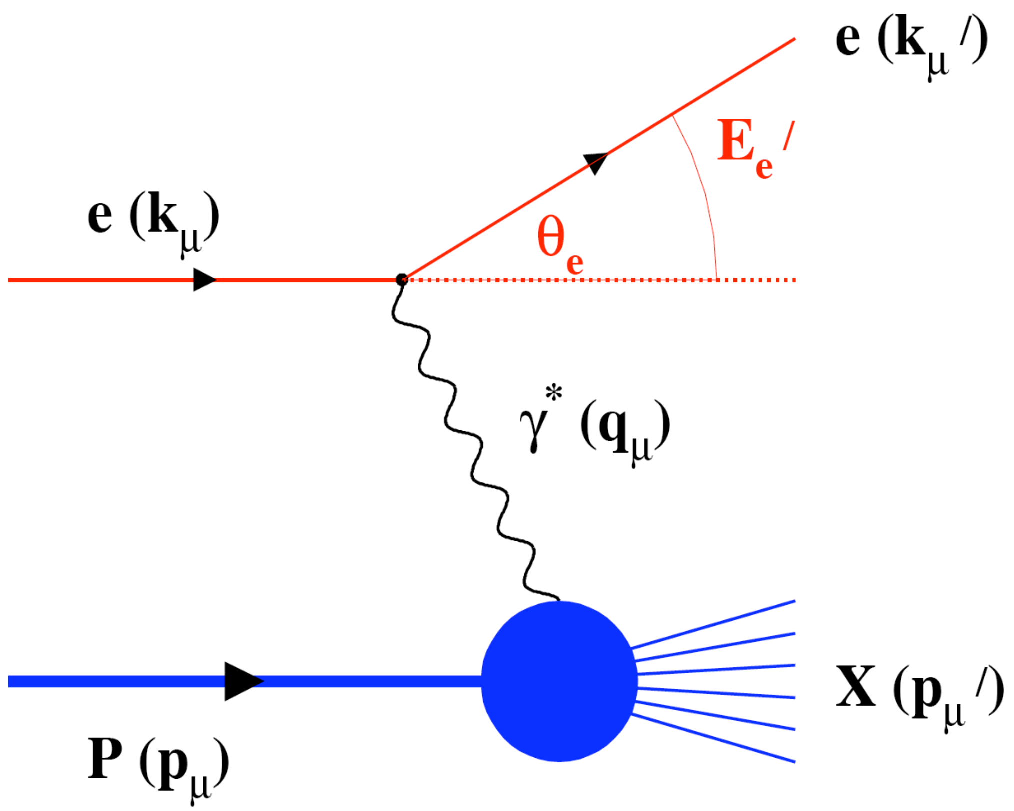

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No direct information on x, Q^2 from p+A colllisions !!

How to Measure the Glue ?

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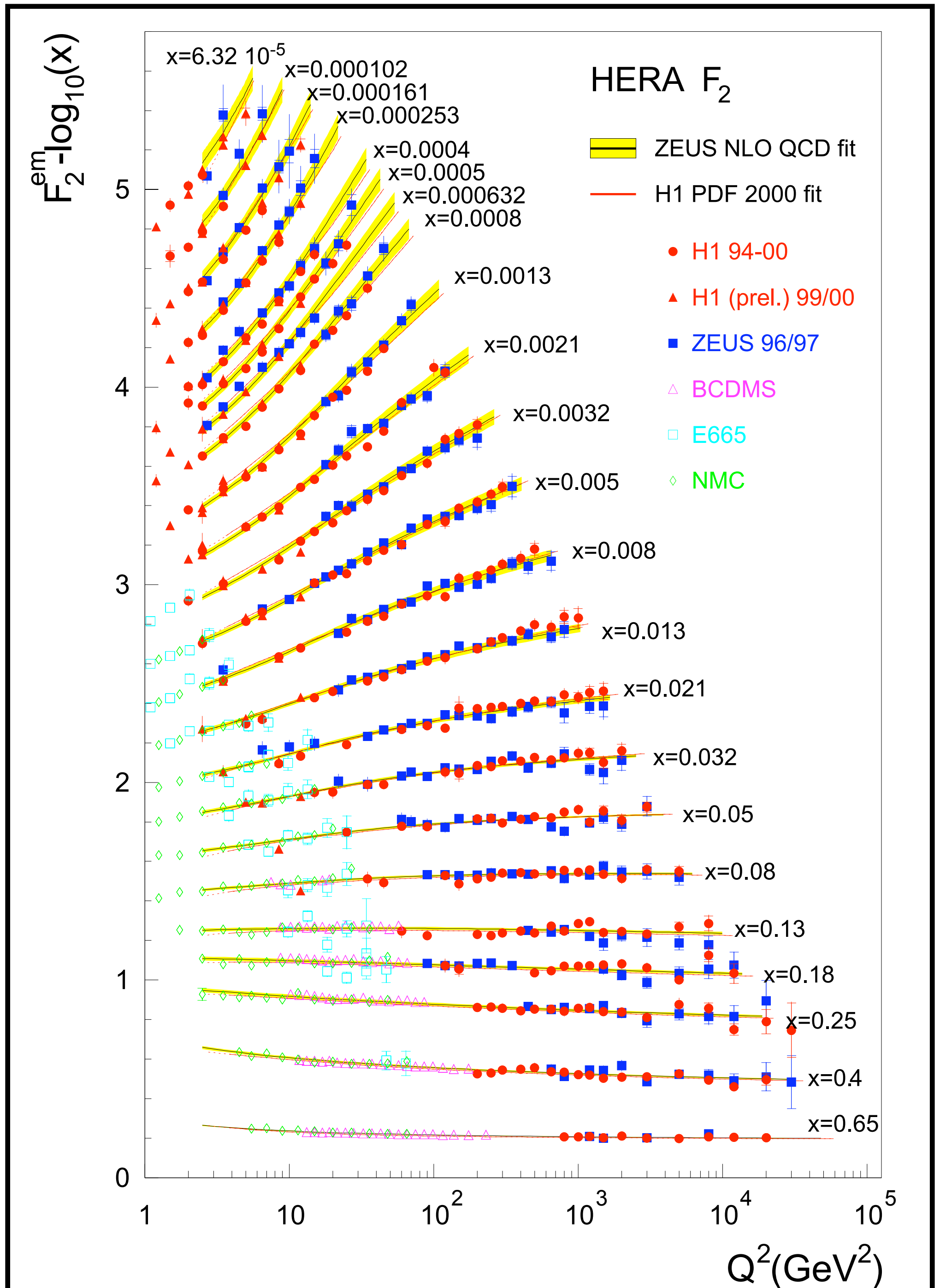

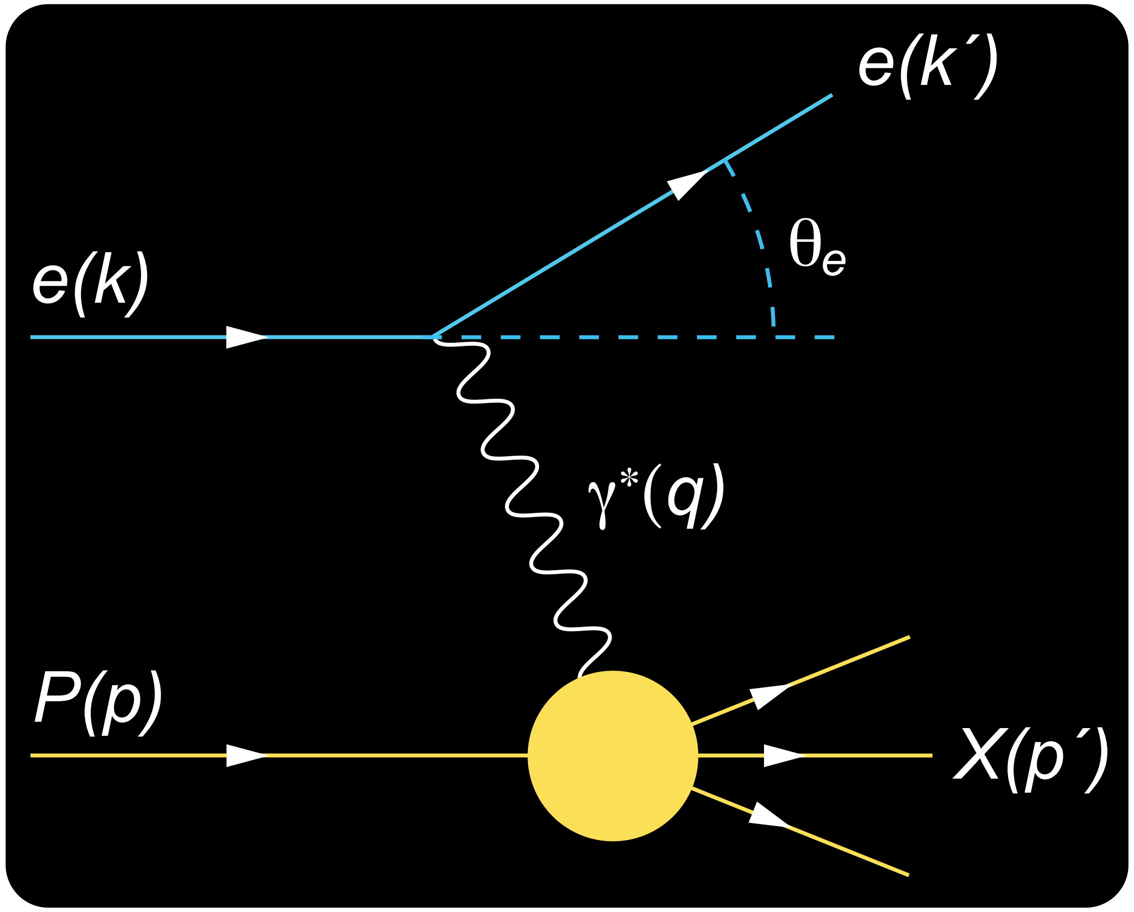

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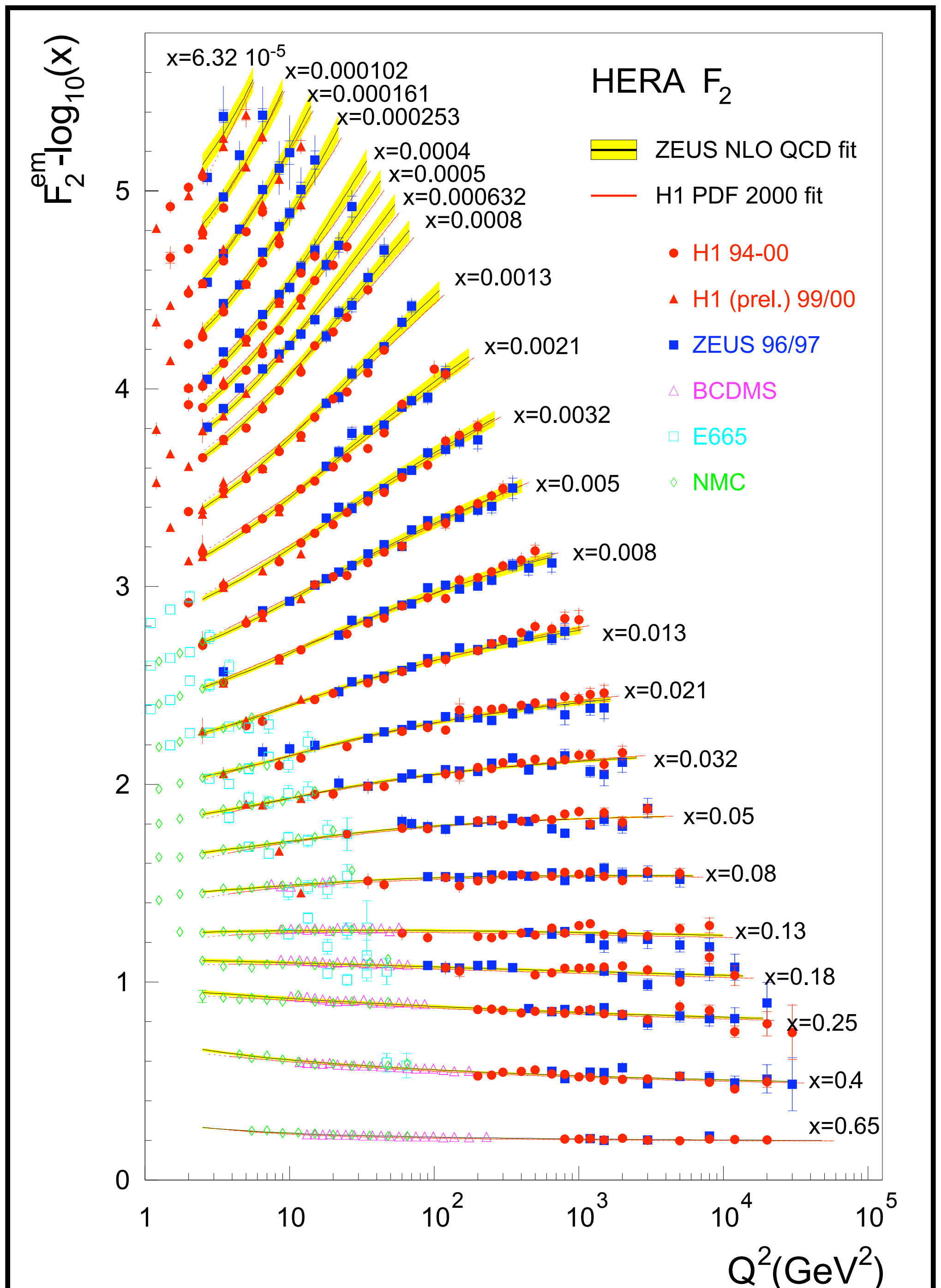

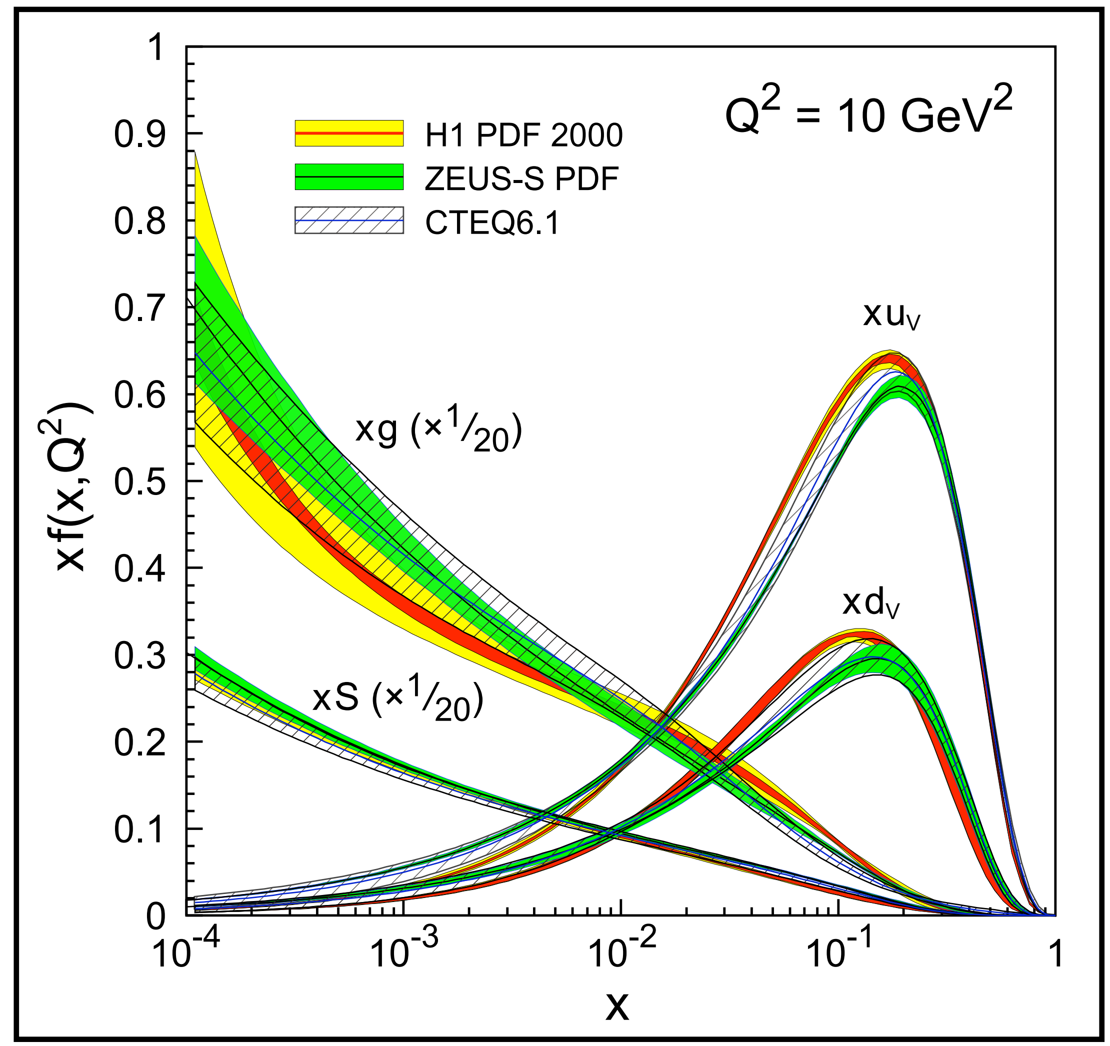

Scaling violation of $dF_2/d\ln Q^2$ and linear DGLAP evolution $\Rightarrow xG(x,Q^2)$

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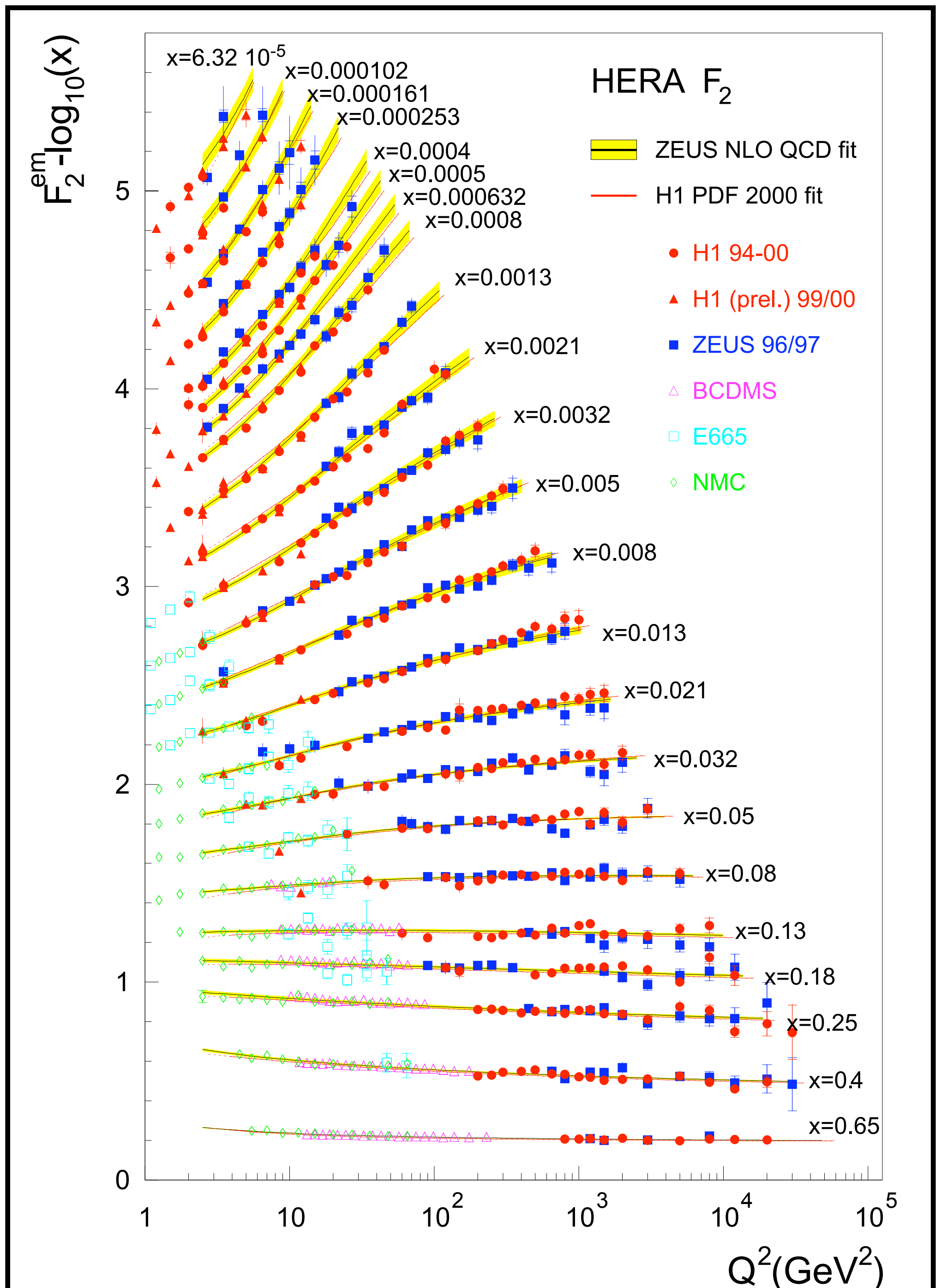

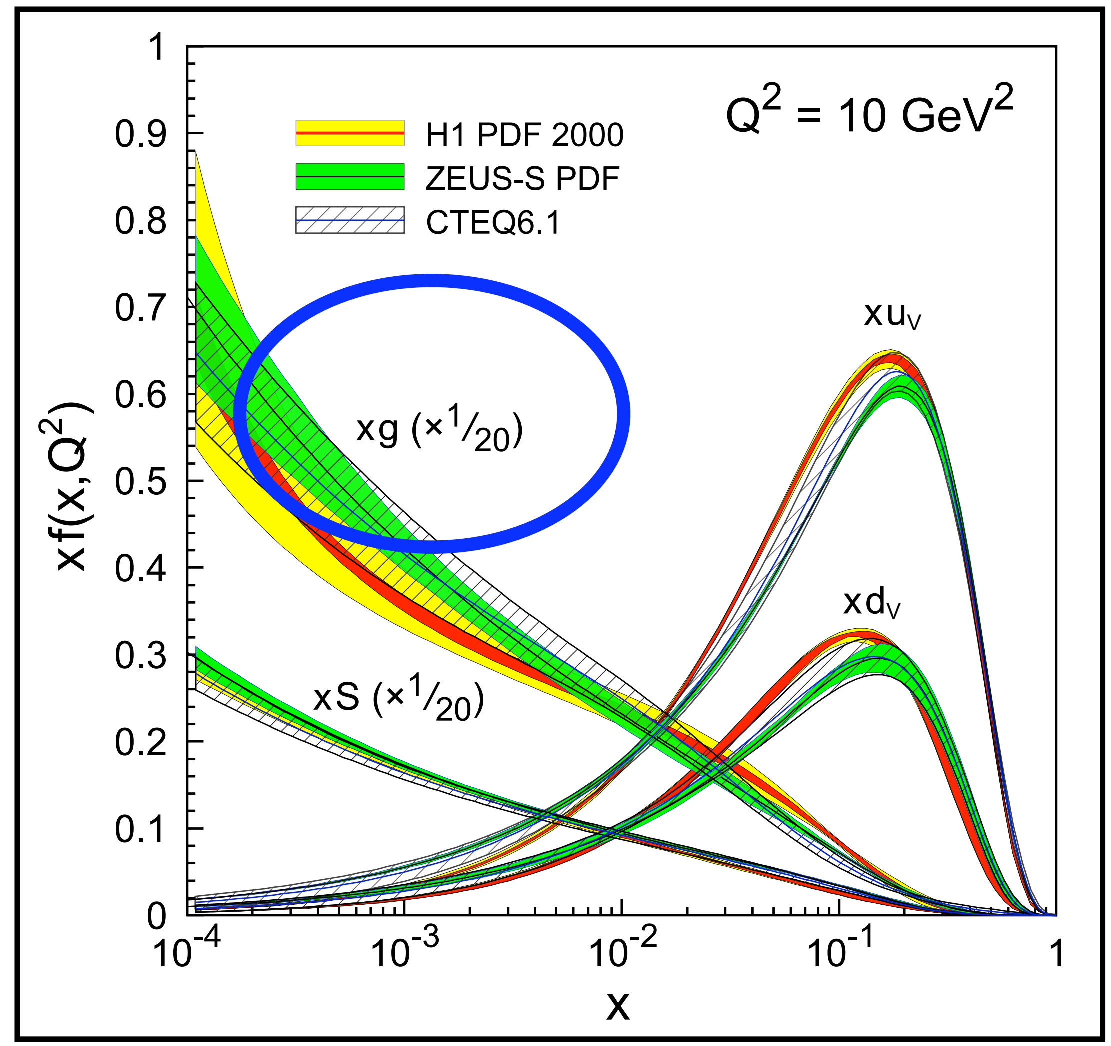

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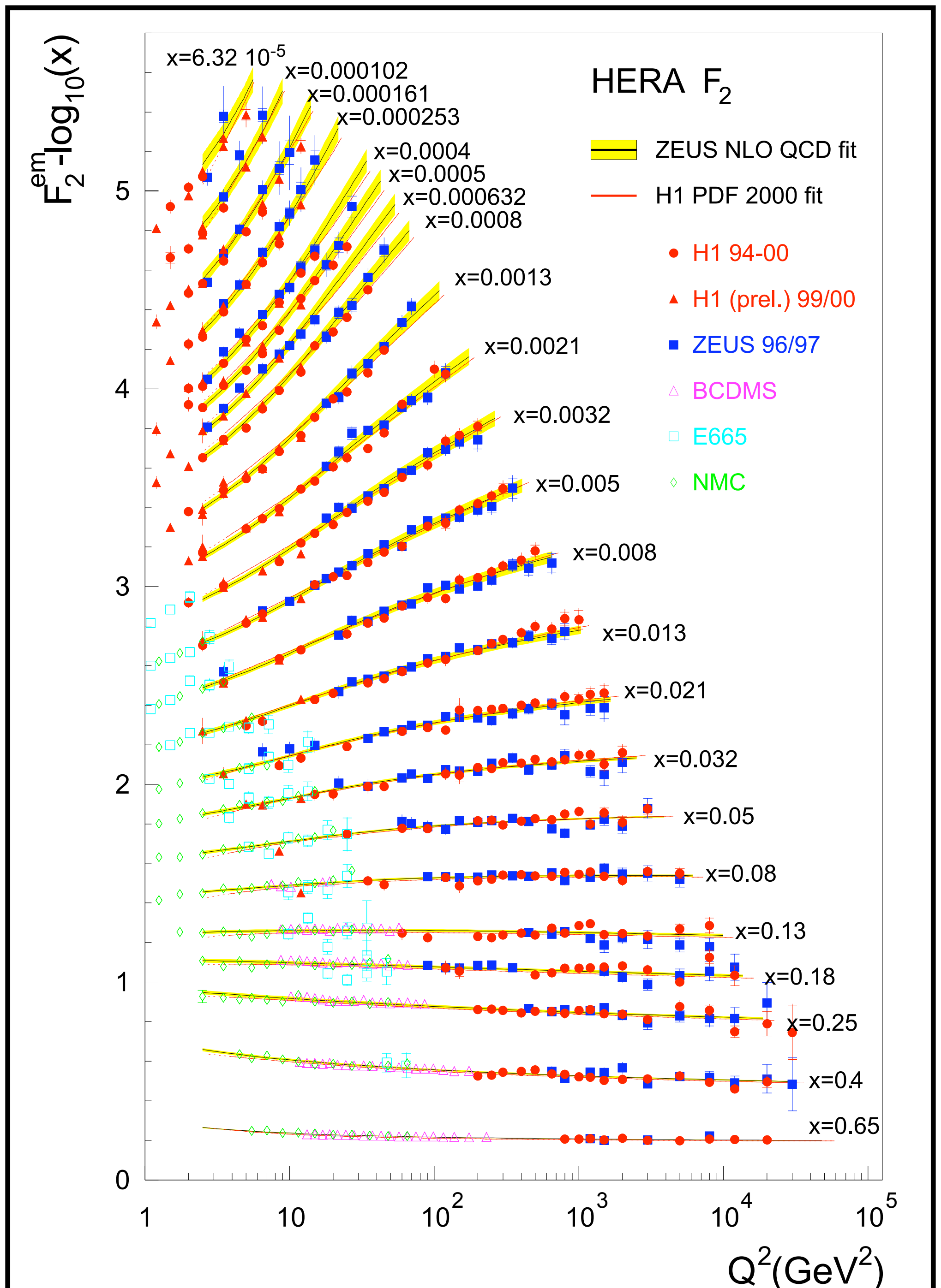

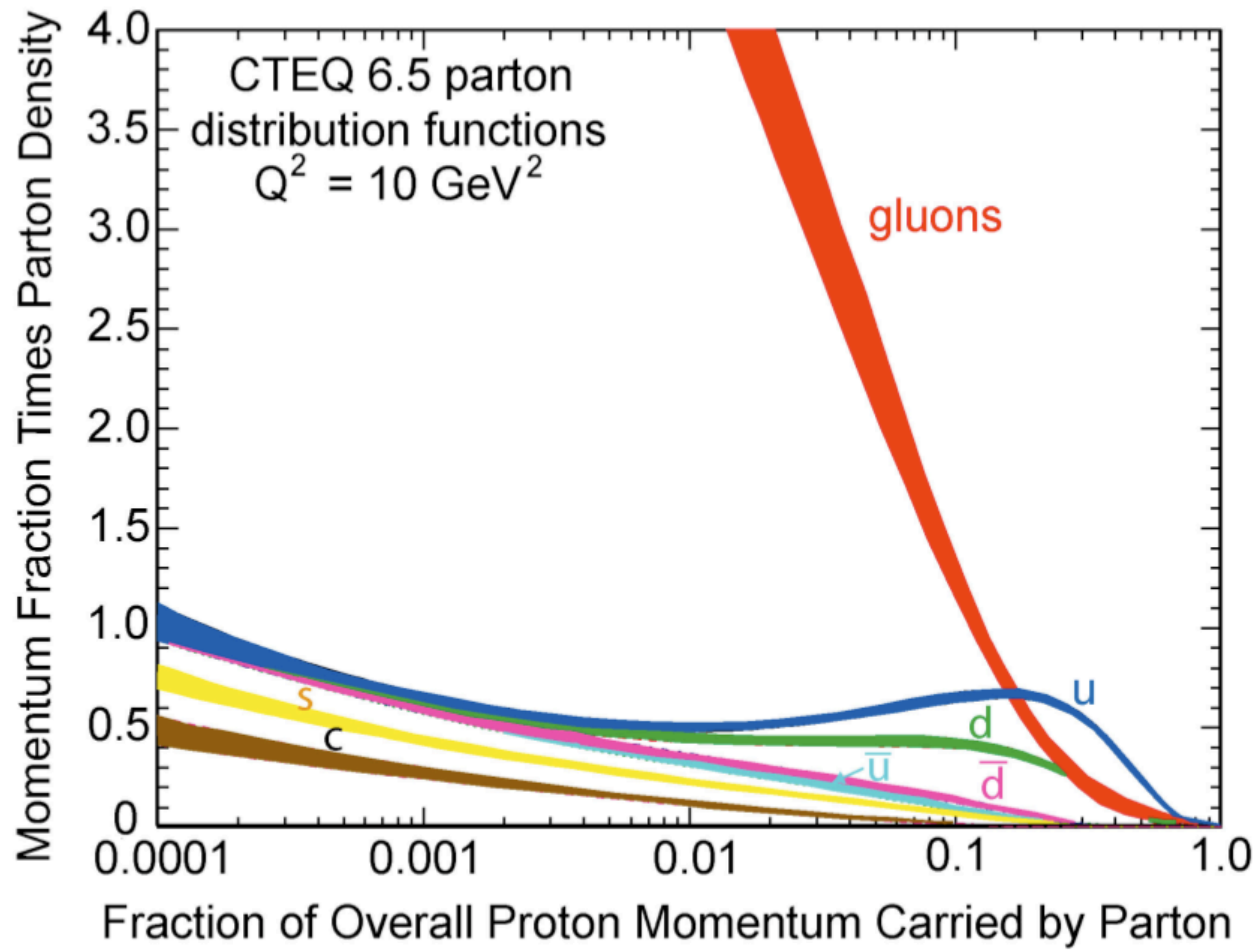

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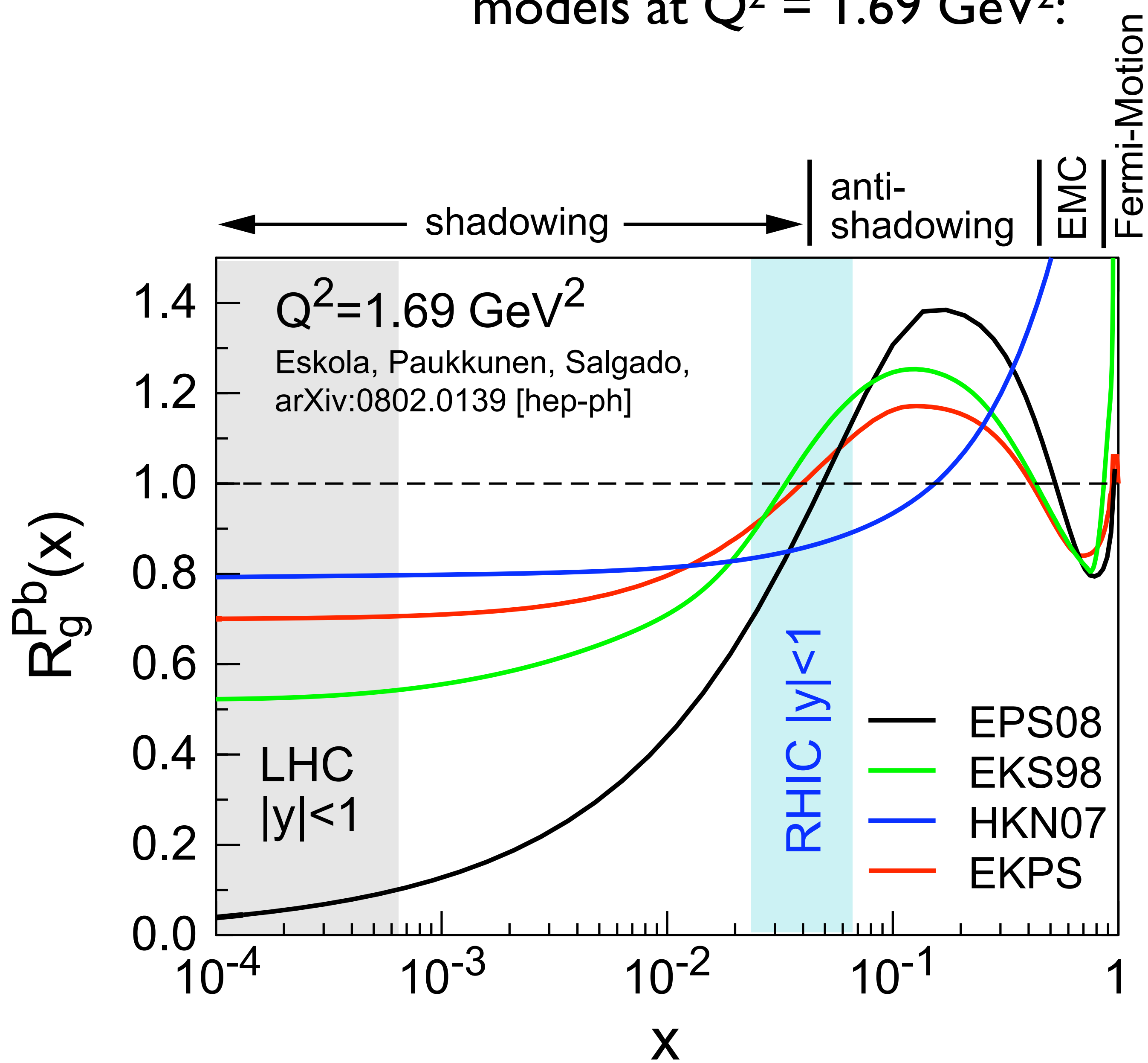
How to Measure the Glue ?

Important for RHIC and LHC:

Ratios of gluon distribution functions for Pb/p versus x from different models at Q^2 = 1.69 GeV^2:

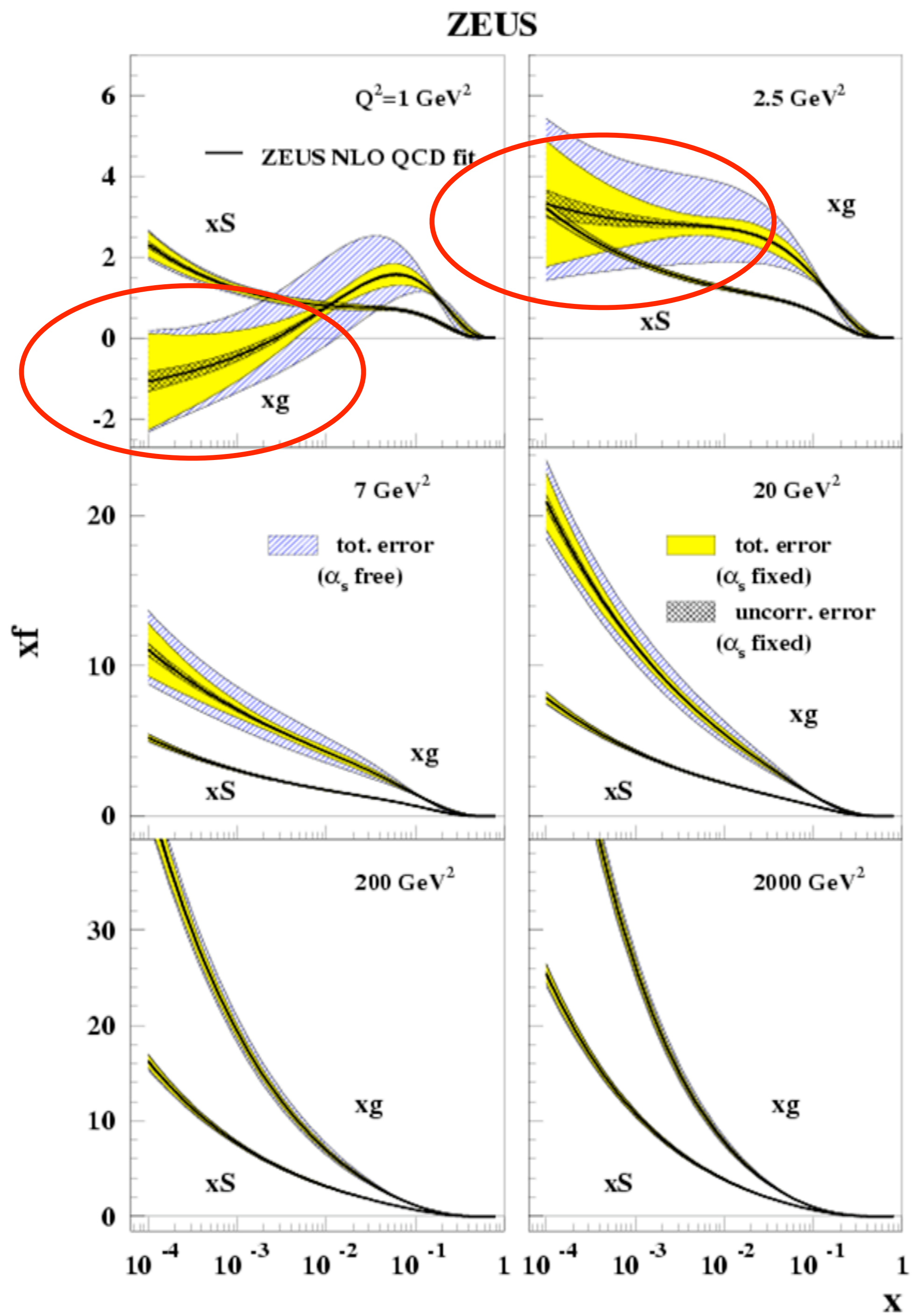


$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{A\, f_i^{\text{nucleon}}(x,Q^2)}, \quad f_i = q, \bar{q}, g$$

?

Models agree well for mid-rapidity RHIC, but discrepancies are there for forward RHIC rapidities as well as mid-rapidity at the LHC

The problem with our current understanding



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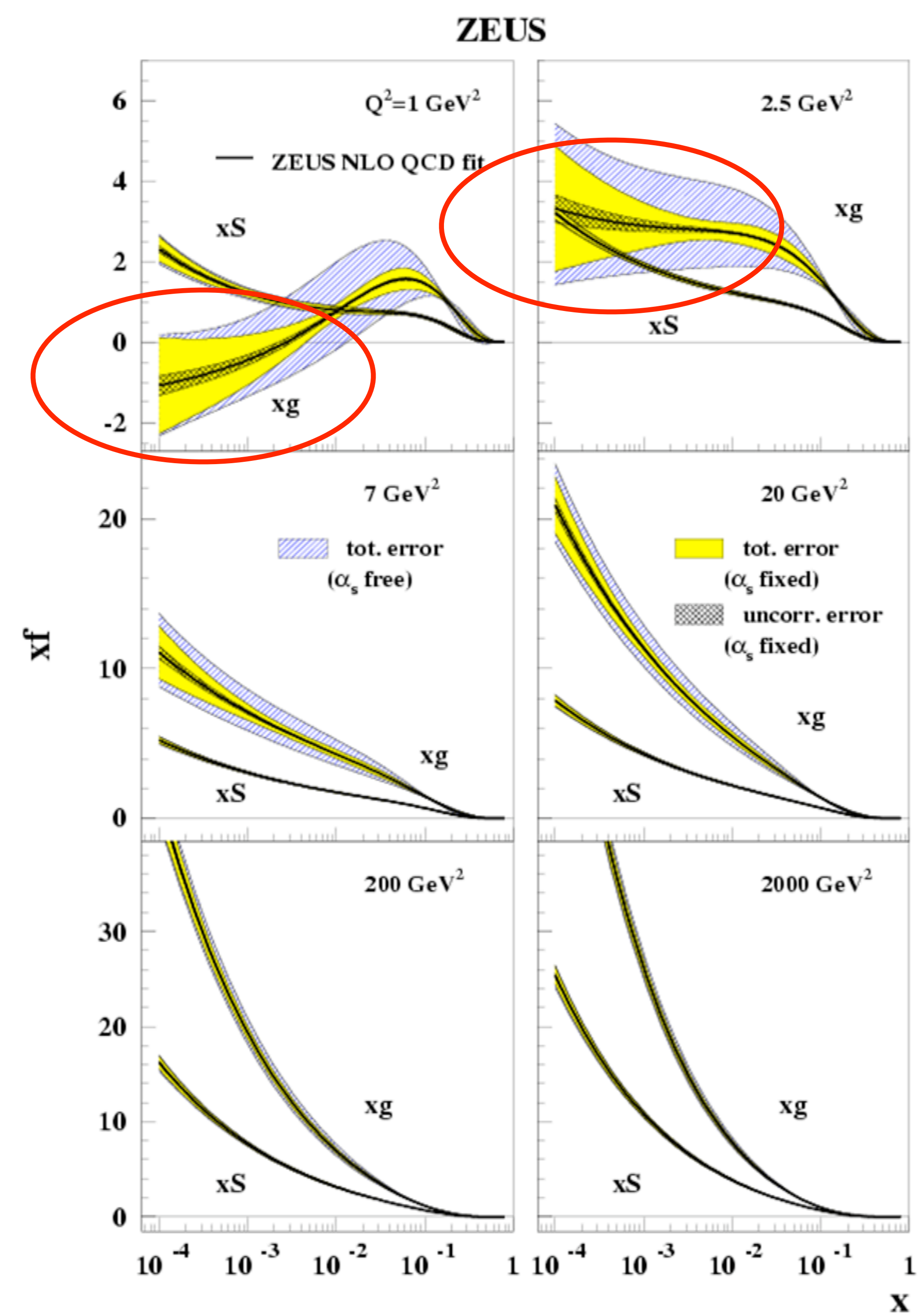

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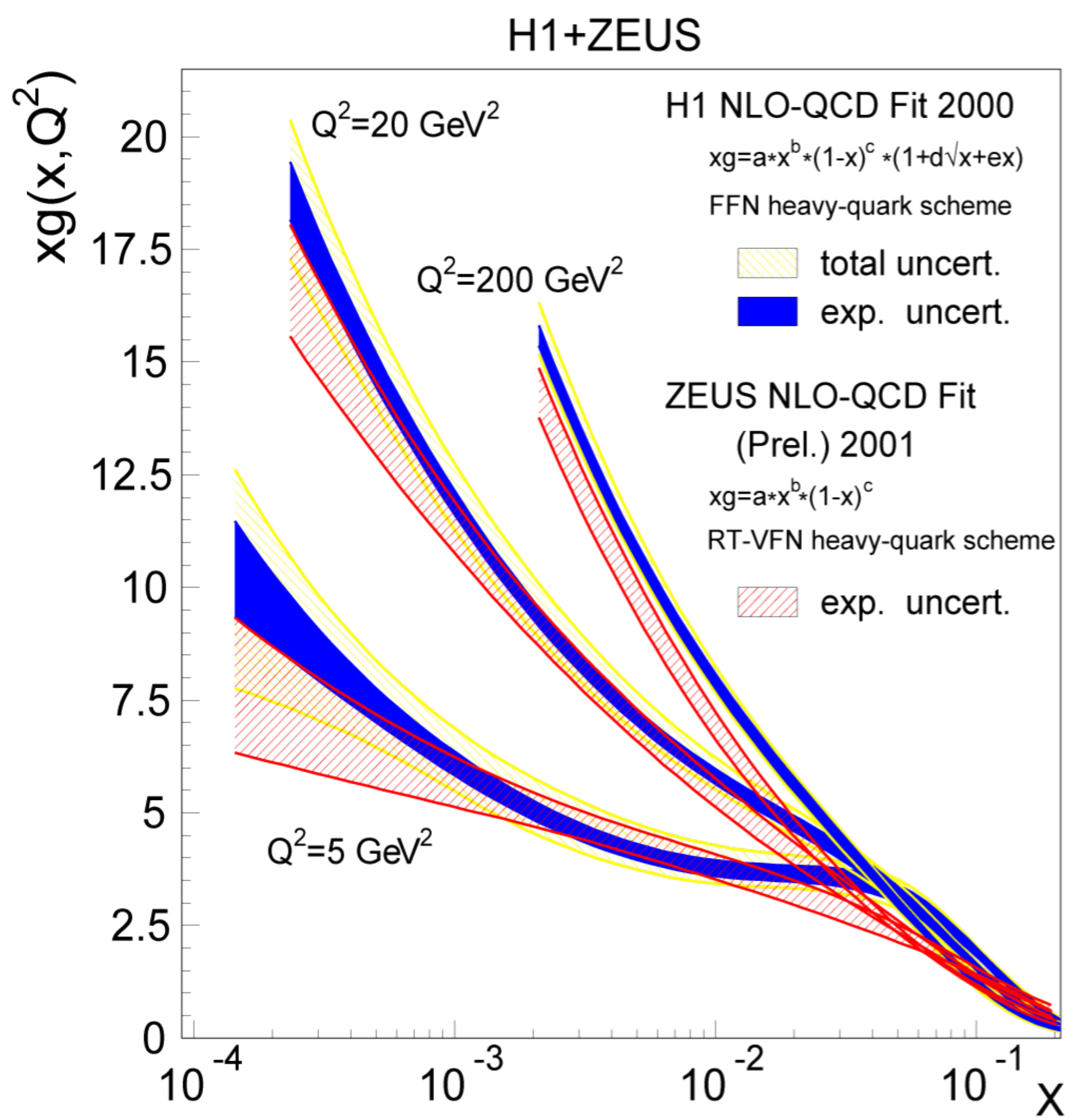
  - ➡ Linear evolution has a built-in high-energy “catastrophe”
  - ➡ *xG* has rapid rise with decreasing *x* (and increasing Q^2) ⇒ violation of Froissart unitarity bound
    - Must have saturation



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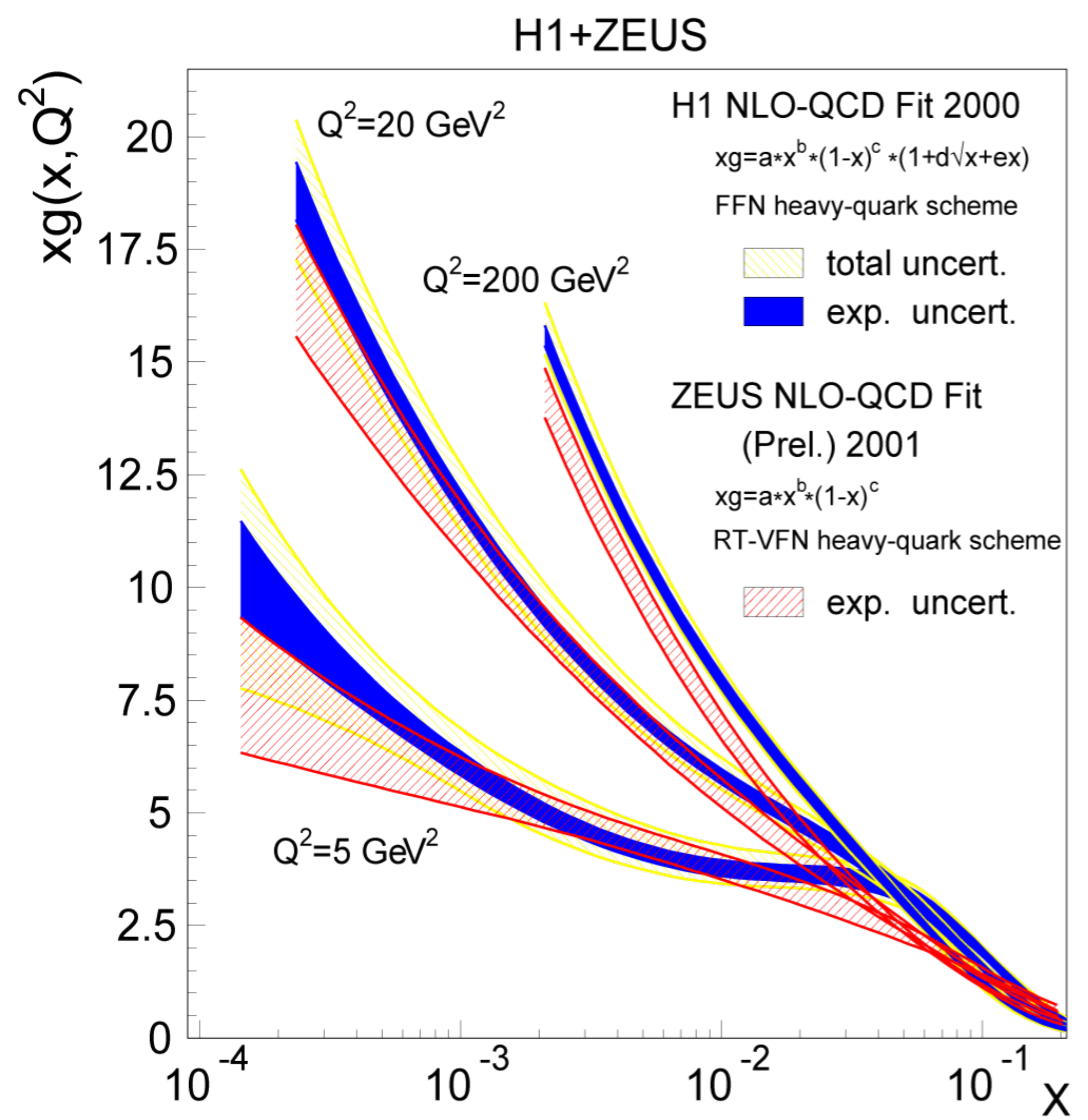
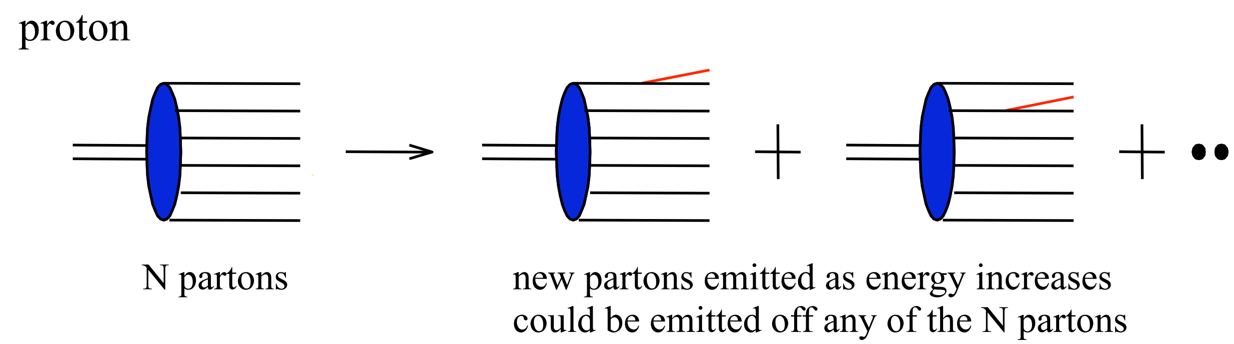


What’s the underlying dynamics?

Non-linear QCD - Saturation



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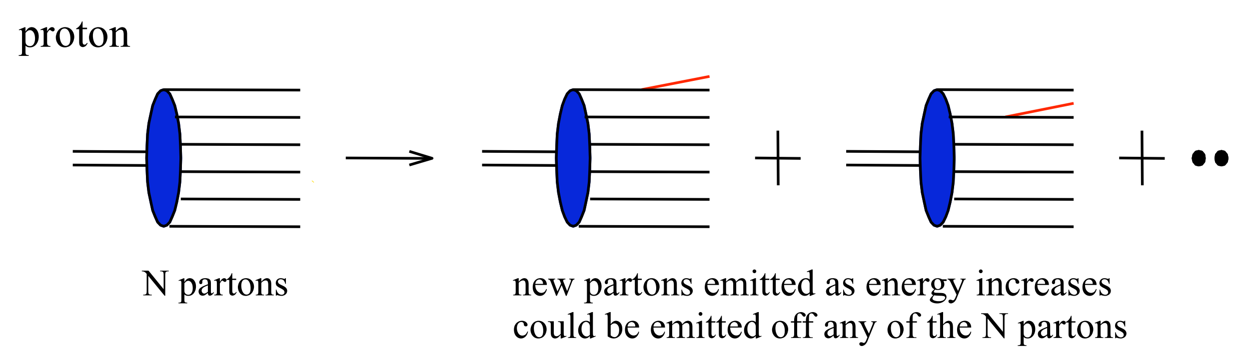

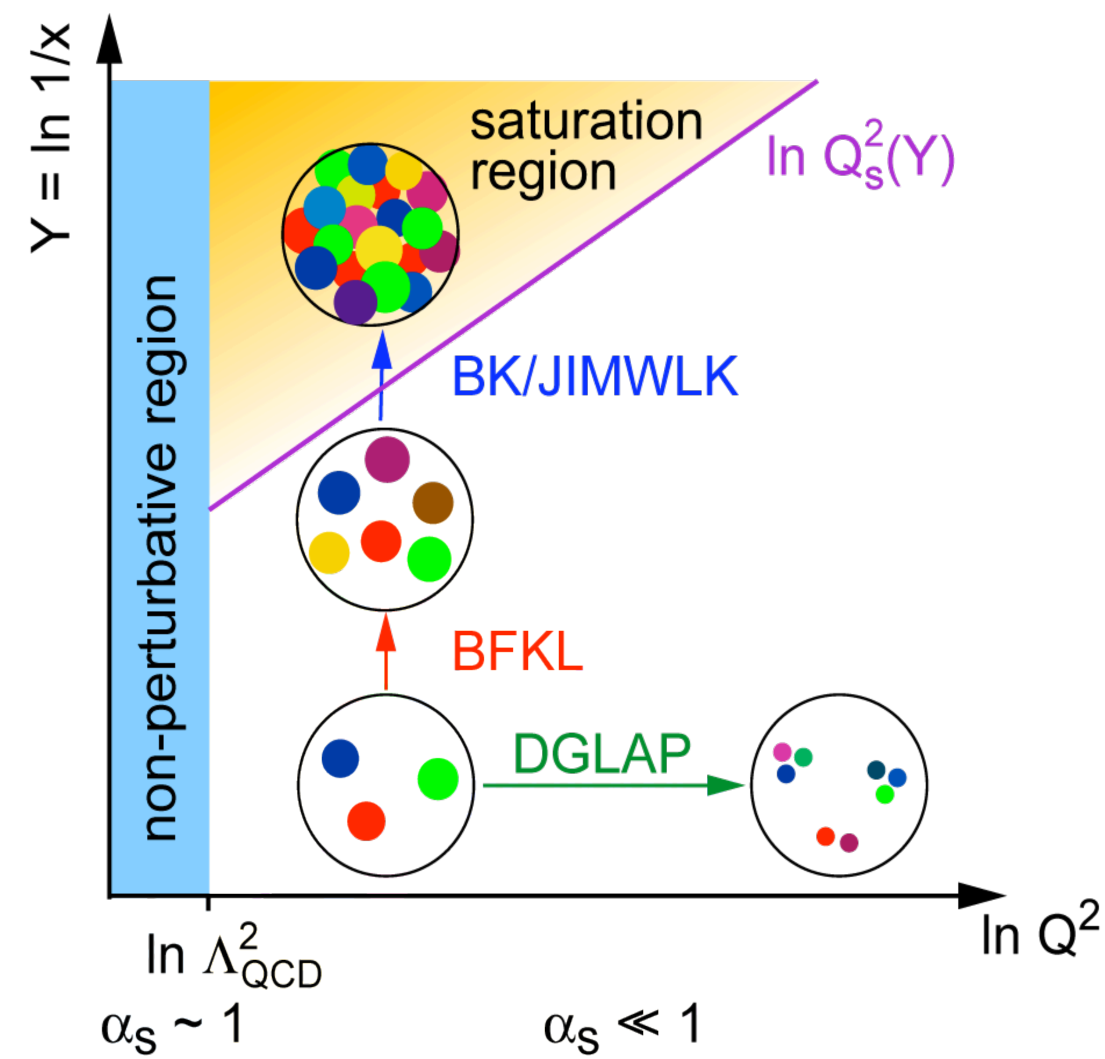

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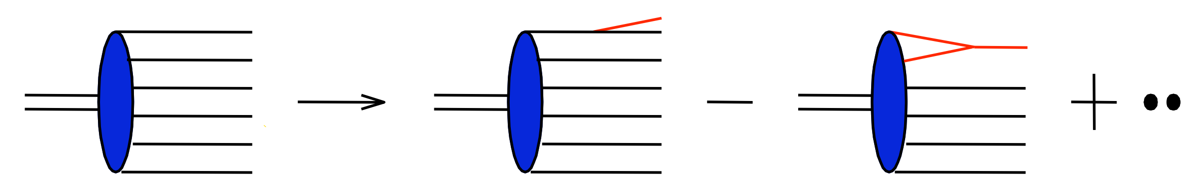

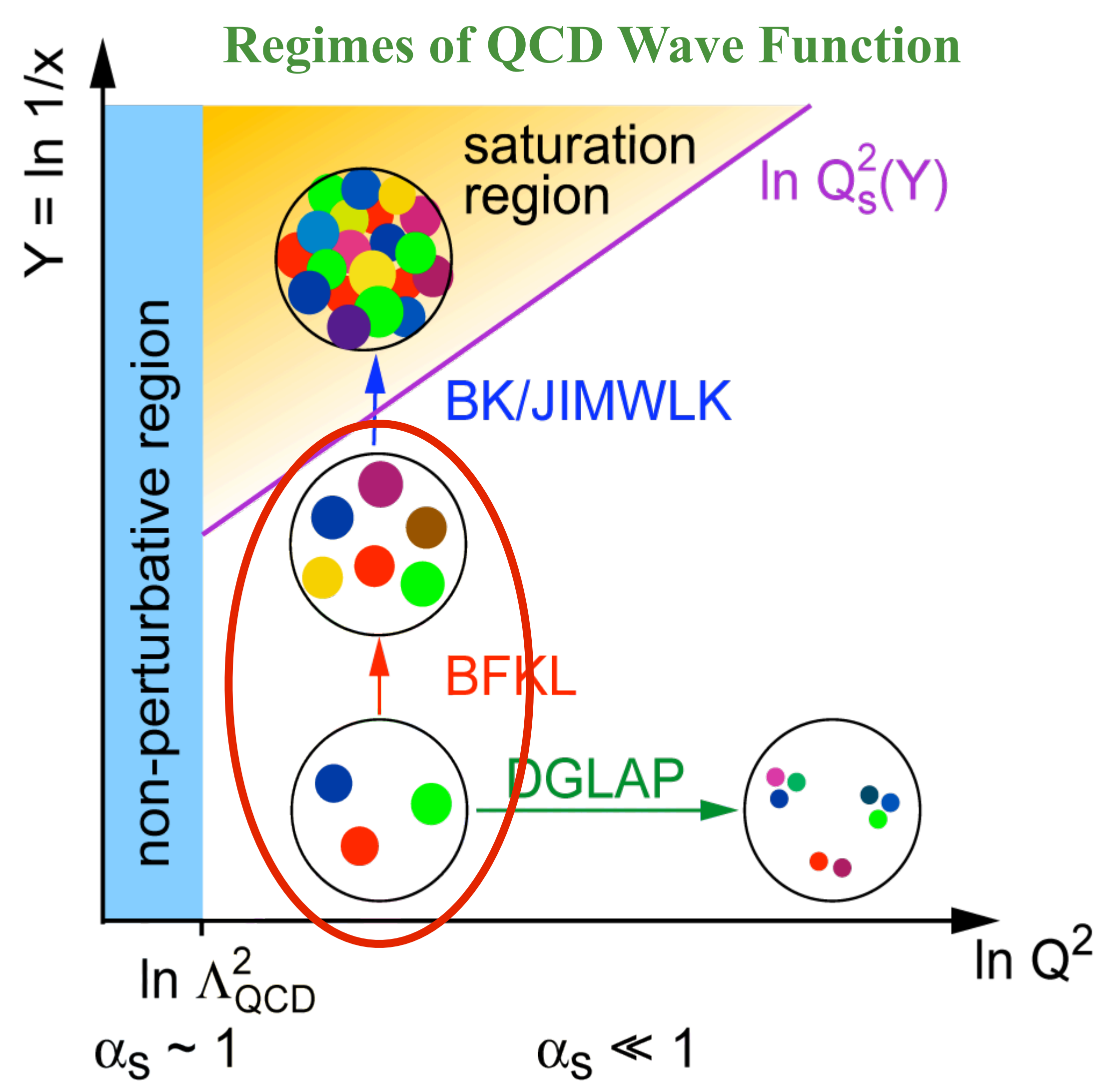

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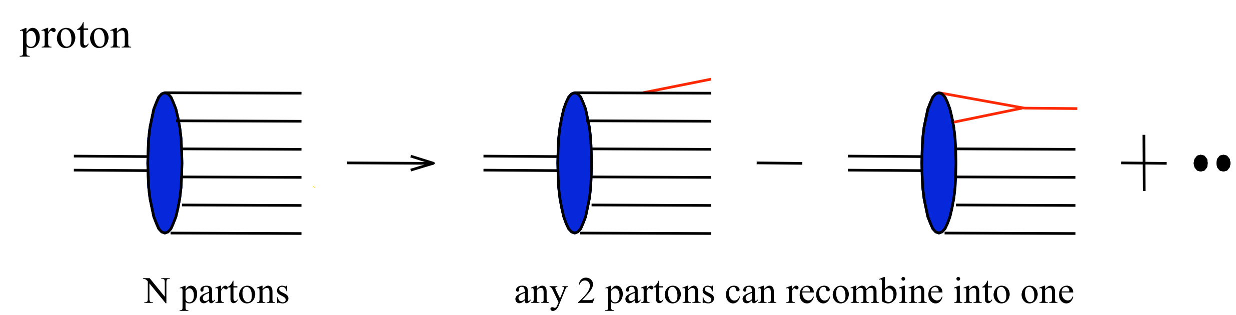
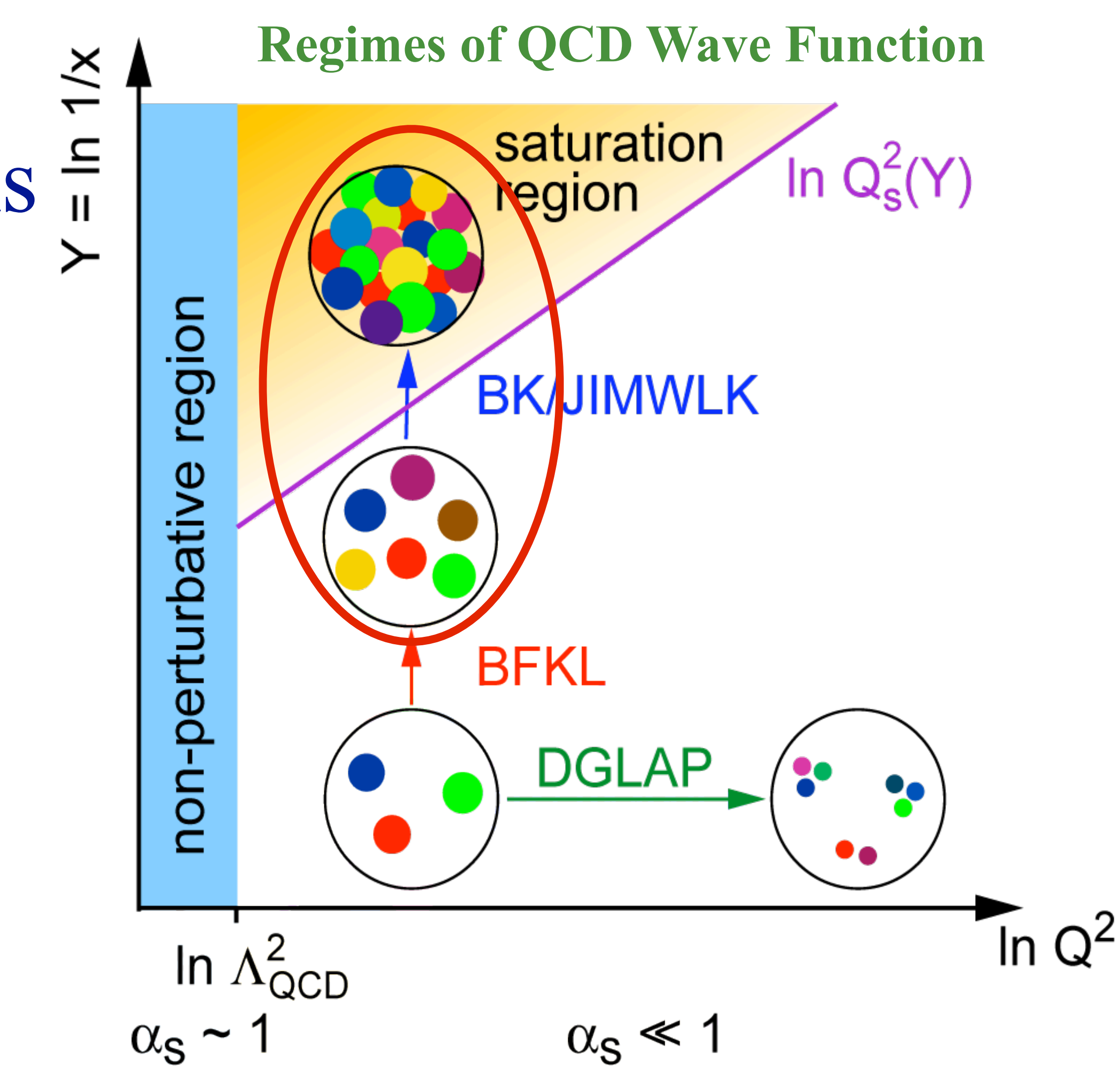
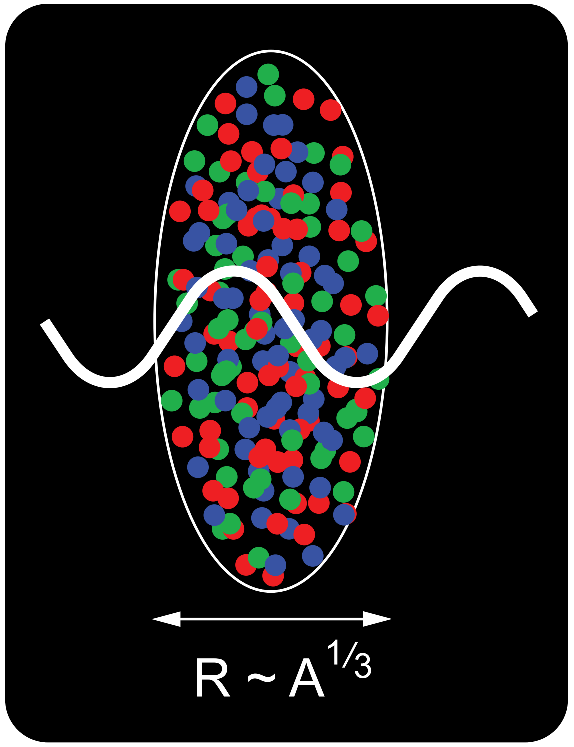




Why study e+A instead of e+p?

Enhancing Saturation Effects:



Scattering of electrons off nuclei:

Probes interact over distances $L \sim (2 m_N x)^{-1}$

For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nuclei

⇒ Probe interacts *coherently* with all nucleons

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

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

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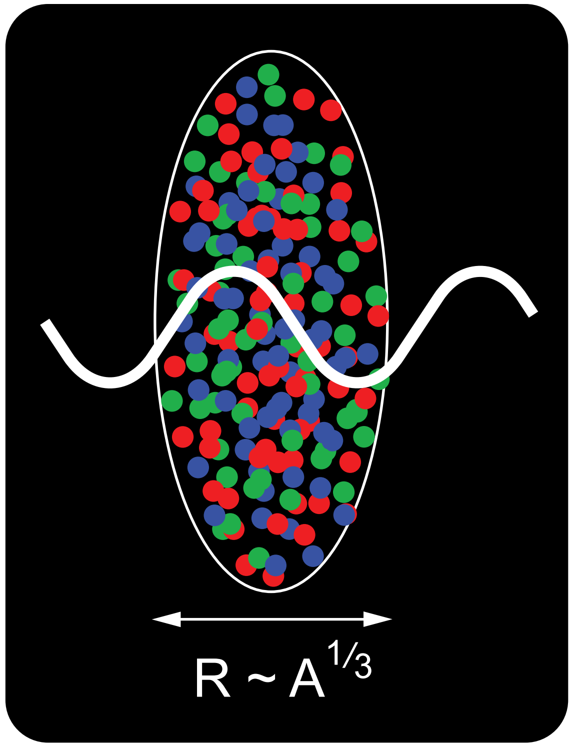


$$Q_s^2 \propto \frac{\alpha_s x G(x, Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \ xG \propto \frac{1}{x^{1/3}} \qquad \text{A dependence}: \ xG_A \propto A$$

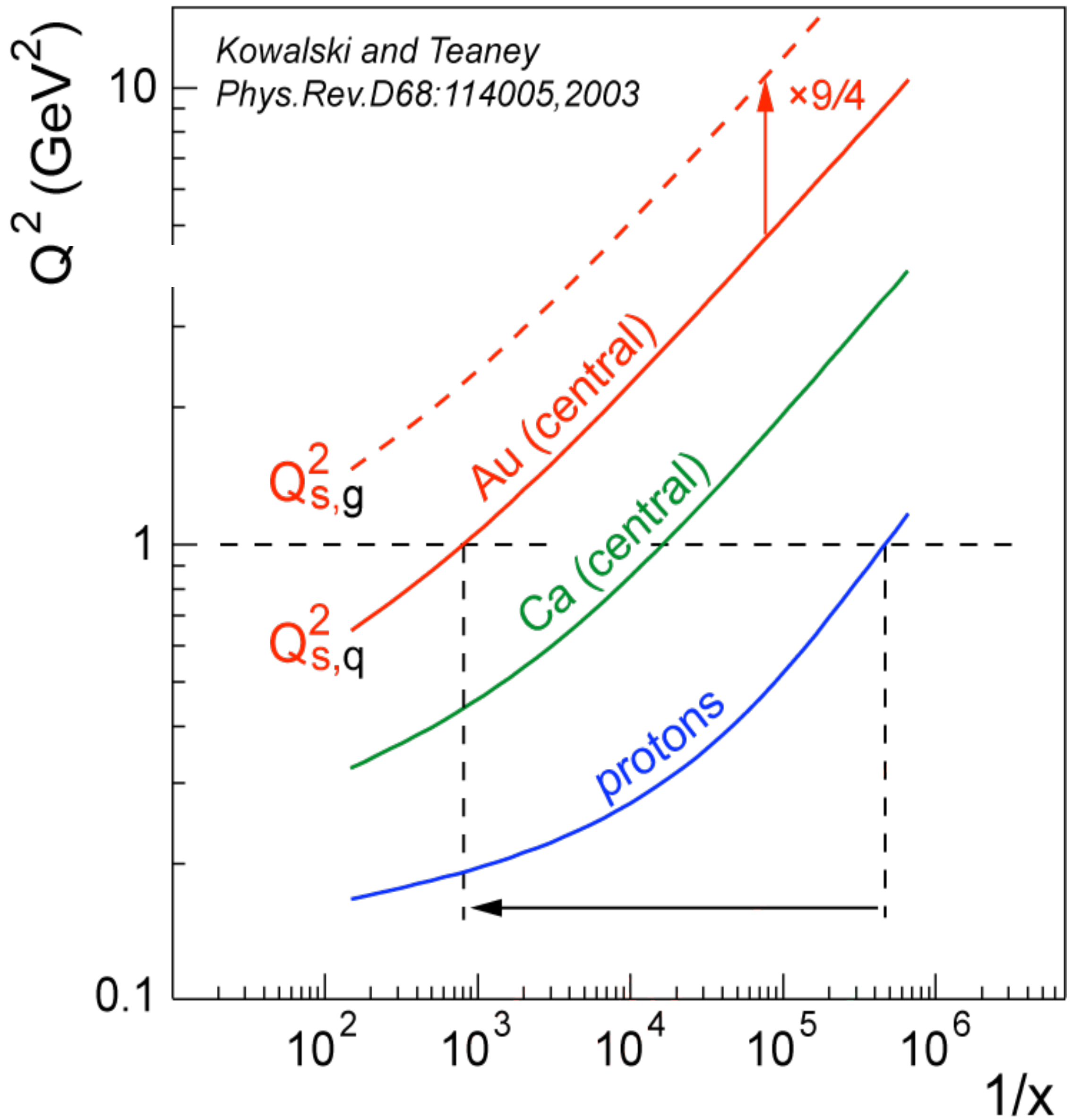
Nuclear "Oomph" Factor: $$(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

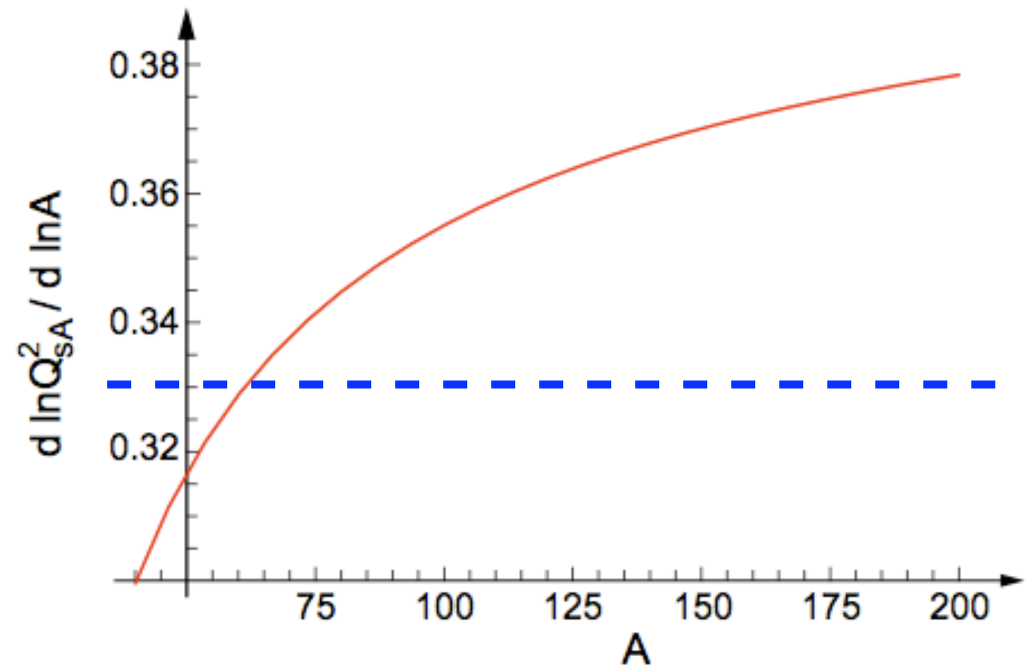
Enhancement of Q_S with A: ⇒ non-linear QCD regime reached at significantly lower energy in e+*A* than in *e*+*p*

The Nuclear "Oomph" factor

More sophisticated analyses ⇒ confirm (exceed) pocket formula

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





Models need to use realistic b-dependence for nuclei and nucleons

⇒ b = 0 for proton ≠ b_{med}

The Nuclear “Oomph” factor

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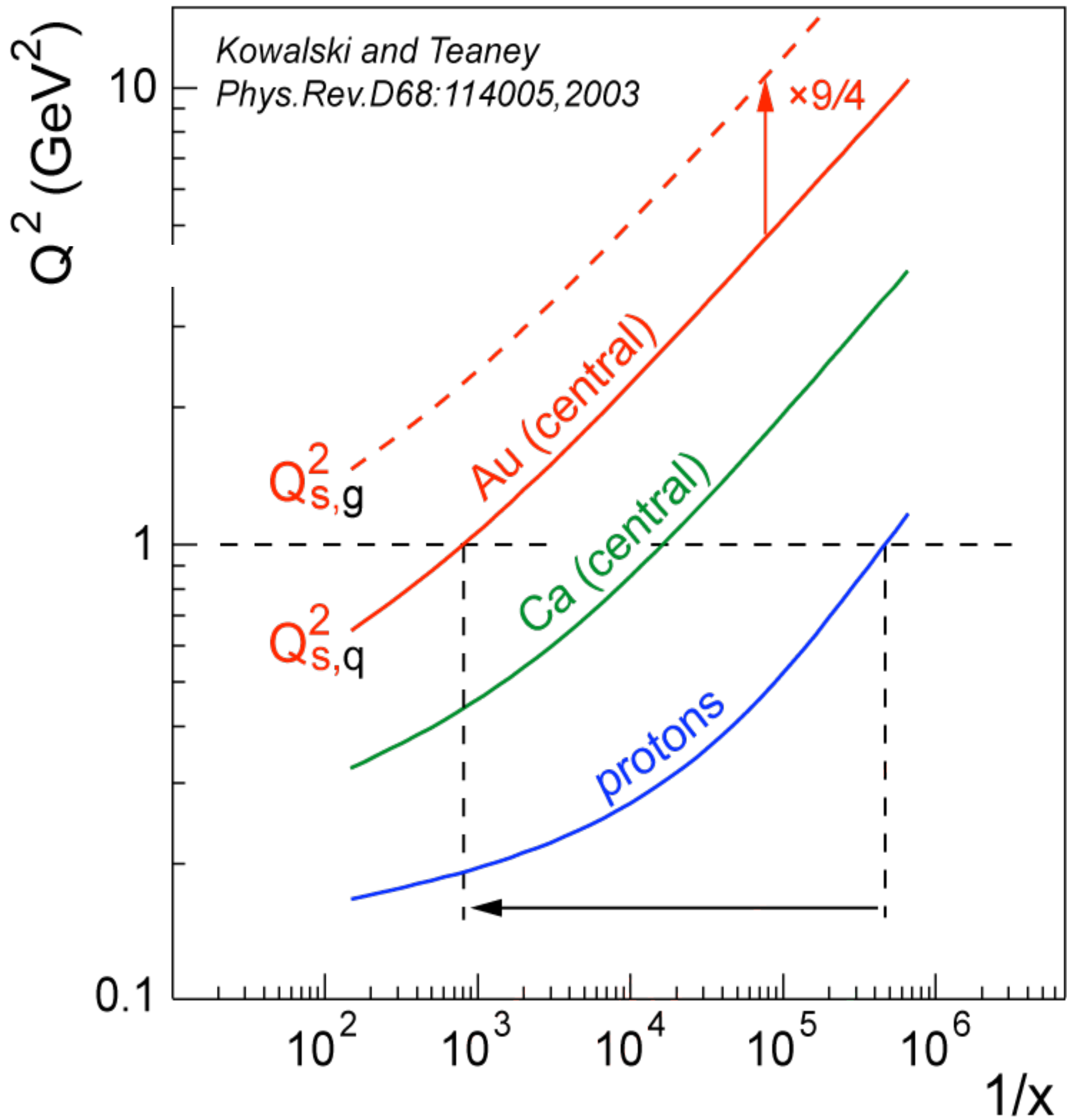

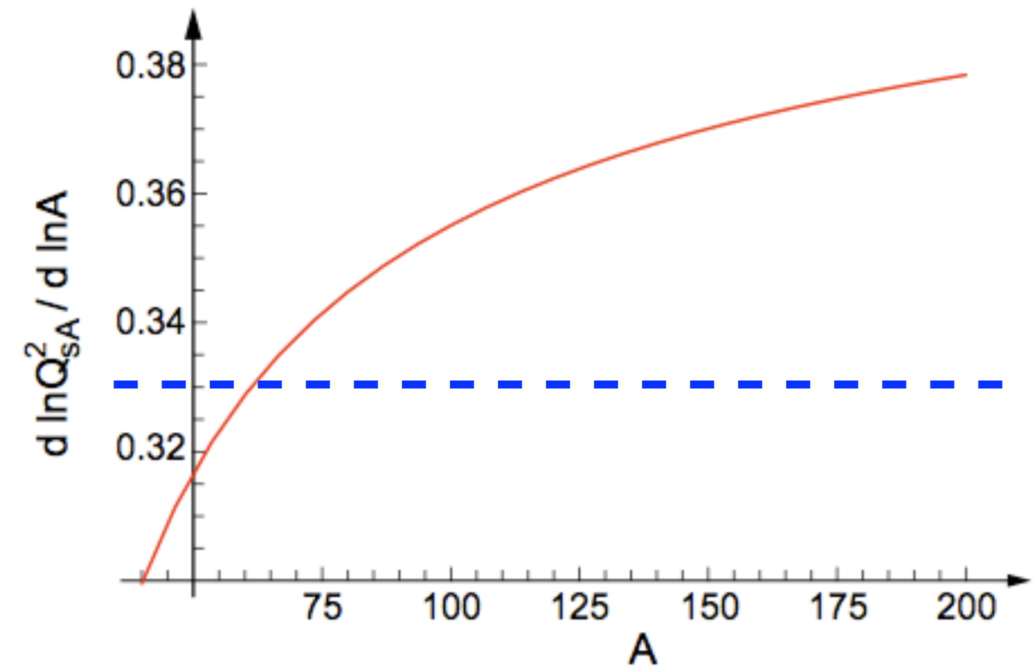

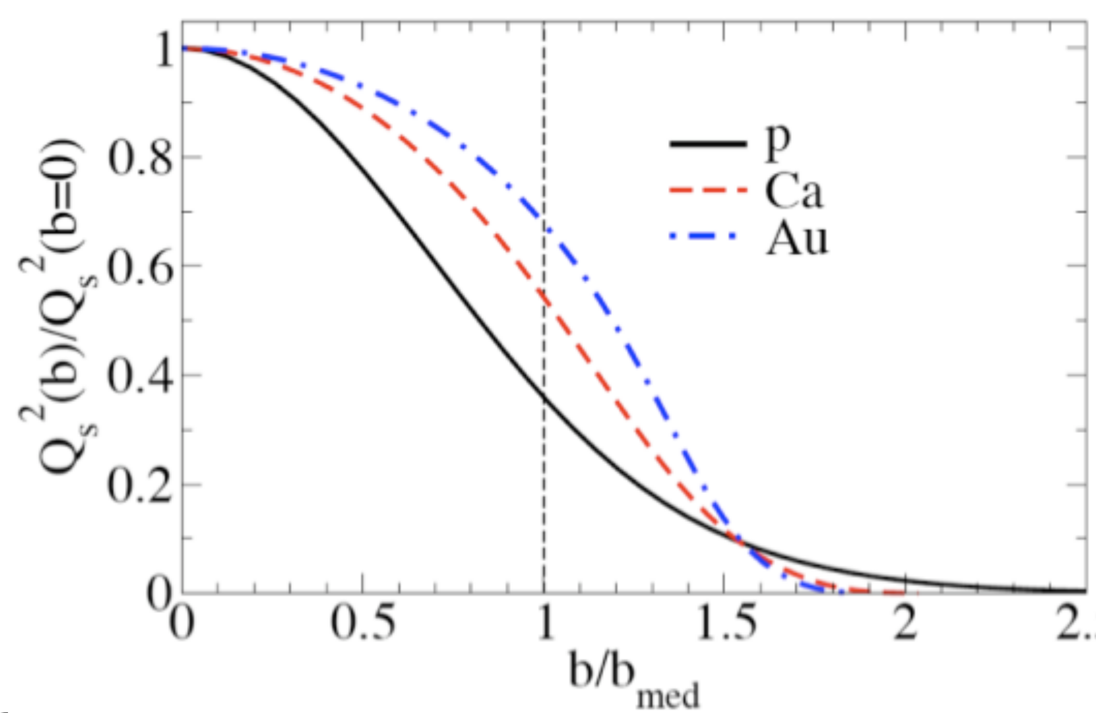

Key Measurements in e+A

- ***Momentum* distribution of gluons *G(x,Q²)***
  - ➡ Extract via scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
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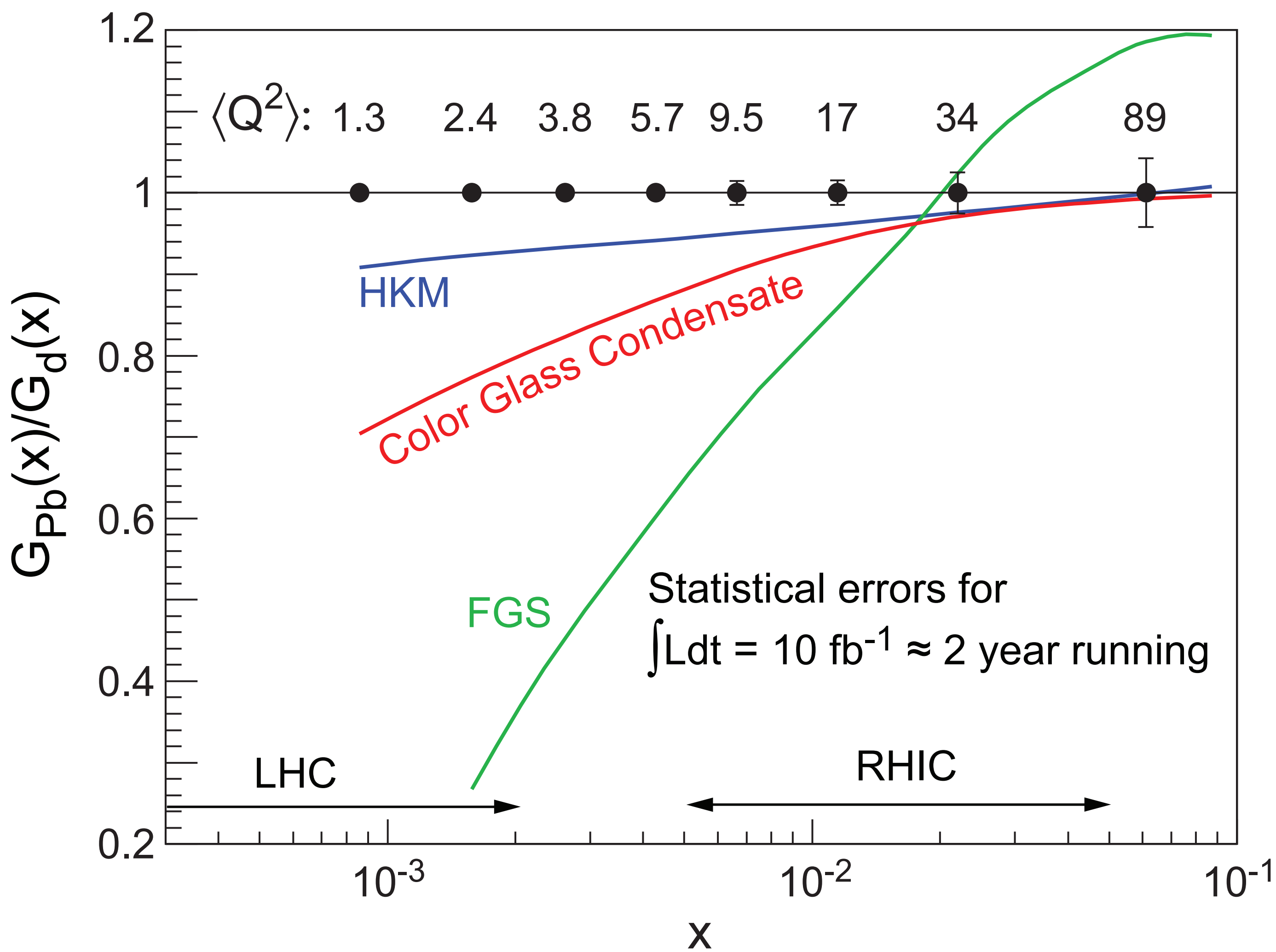
Example of Key Measurements:

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



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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

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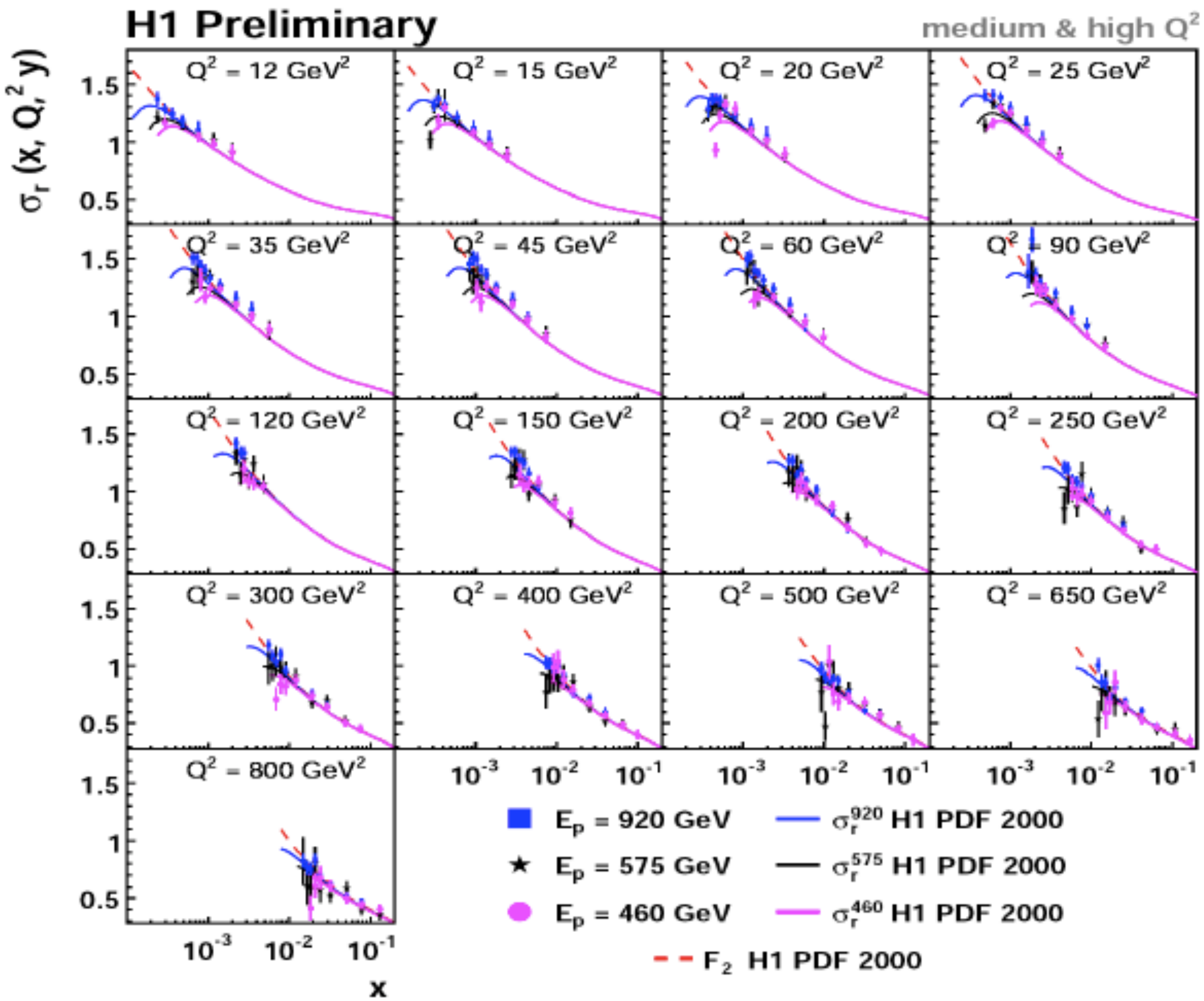

Preliminary F_L measurements

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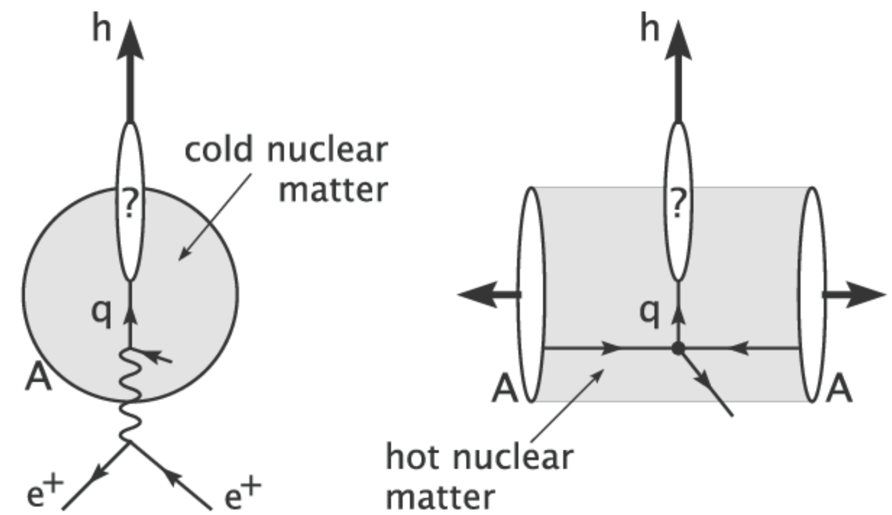
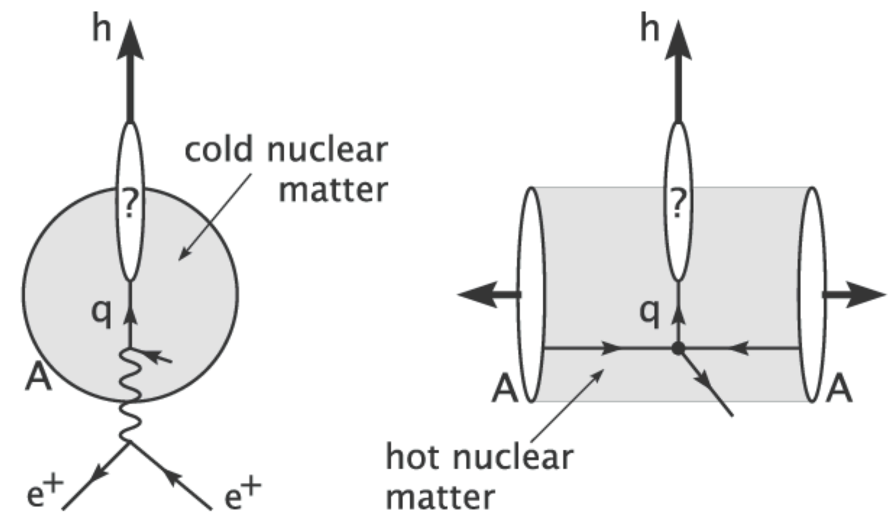
Hadronization and Energy Loss



Hadronization and Energy Loss

nDIS:

- Clean measurement in 'cold' nuclear matter



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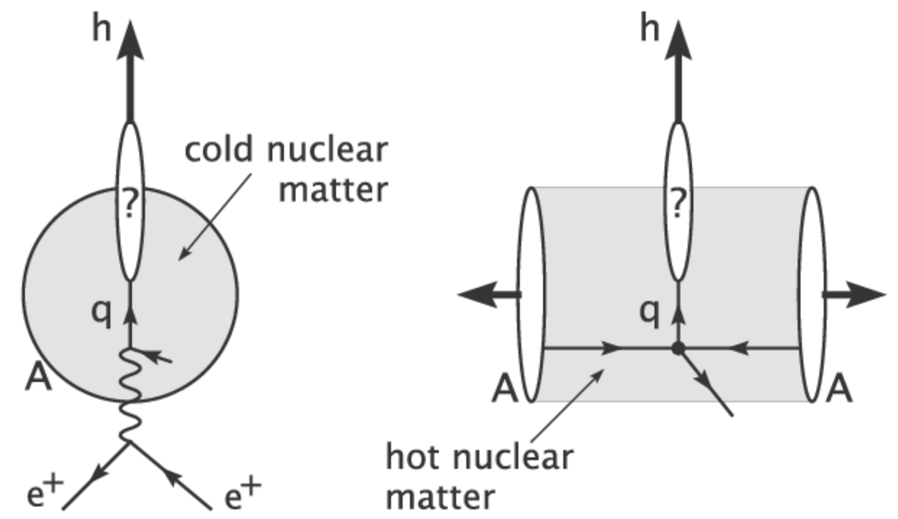

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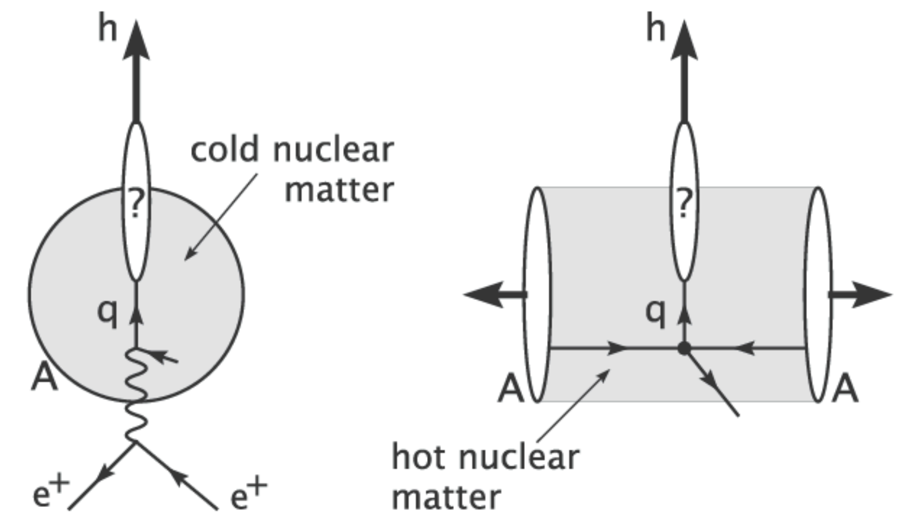

Fundamental question:
When do coloured partons get neutralized?

Parton energy loss vs.
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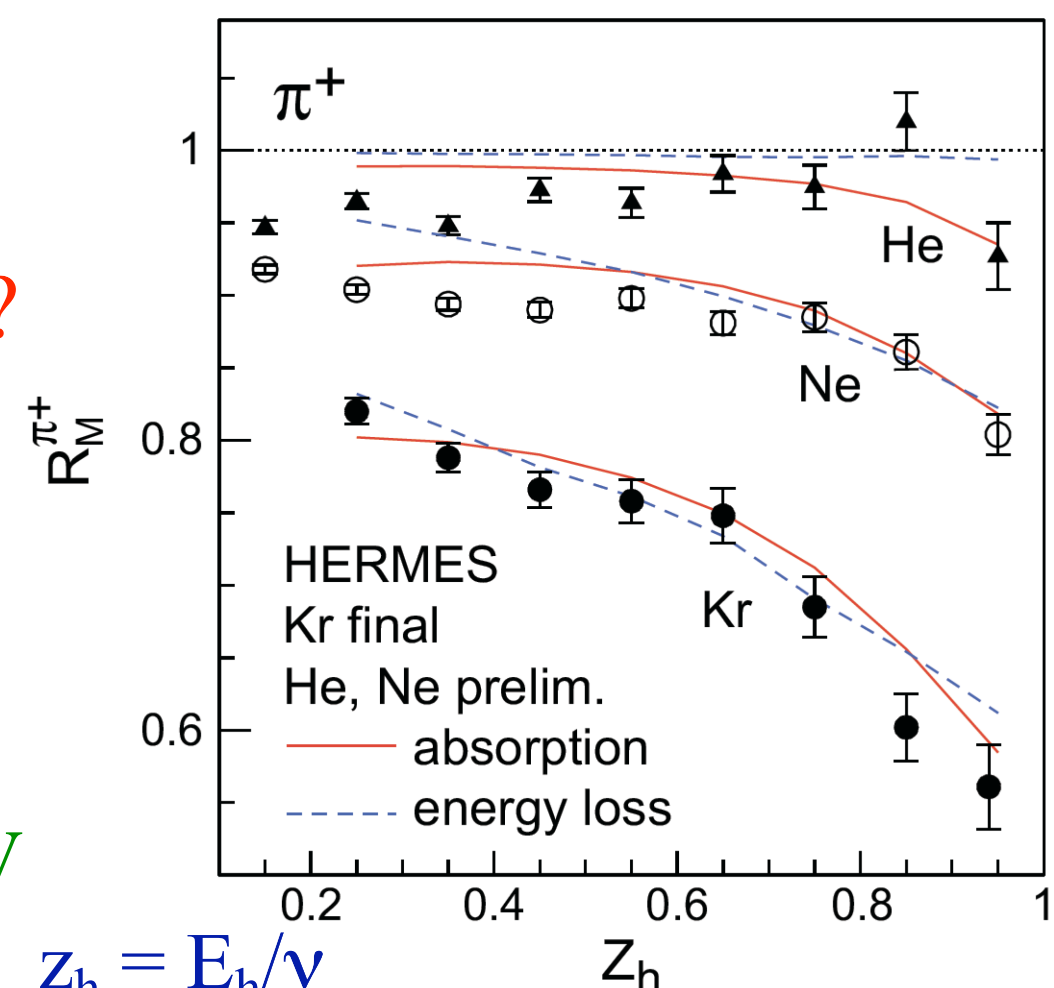

Energy transfer in lab rest frame
EIC: $10 < \nu < 1600$ GeV   HERMES: 2-25 GeV
EIC: can measure *heavy flavour* energy loss $z_h = E_h/\nu$

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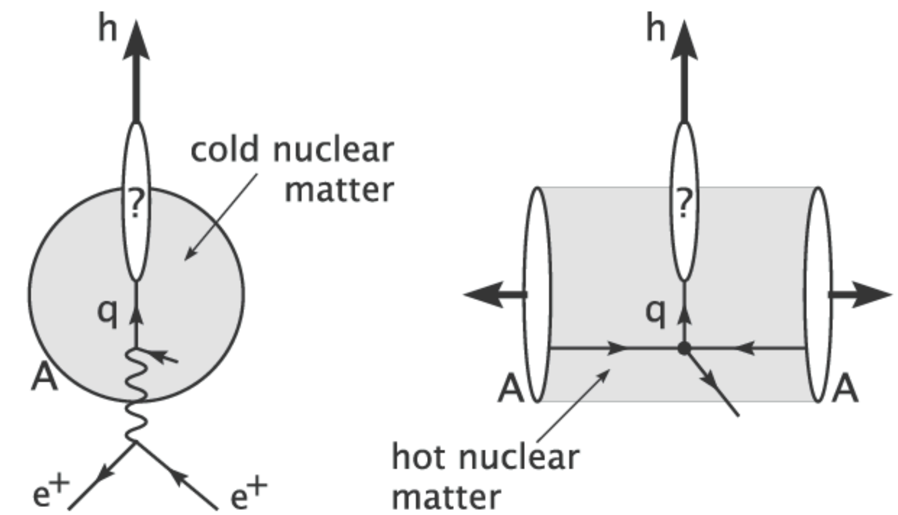

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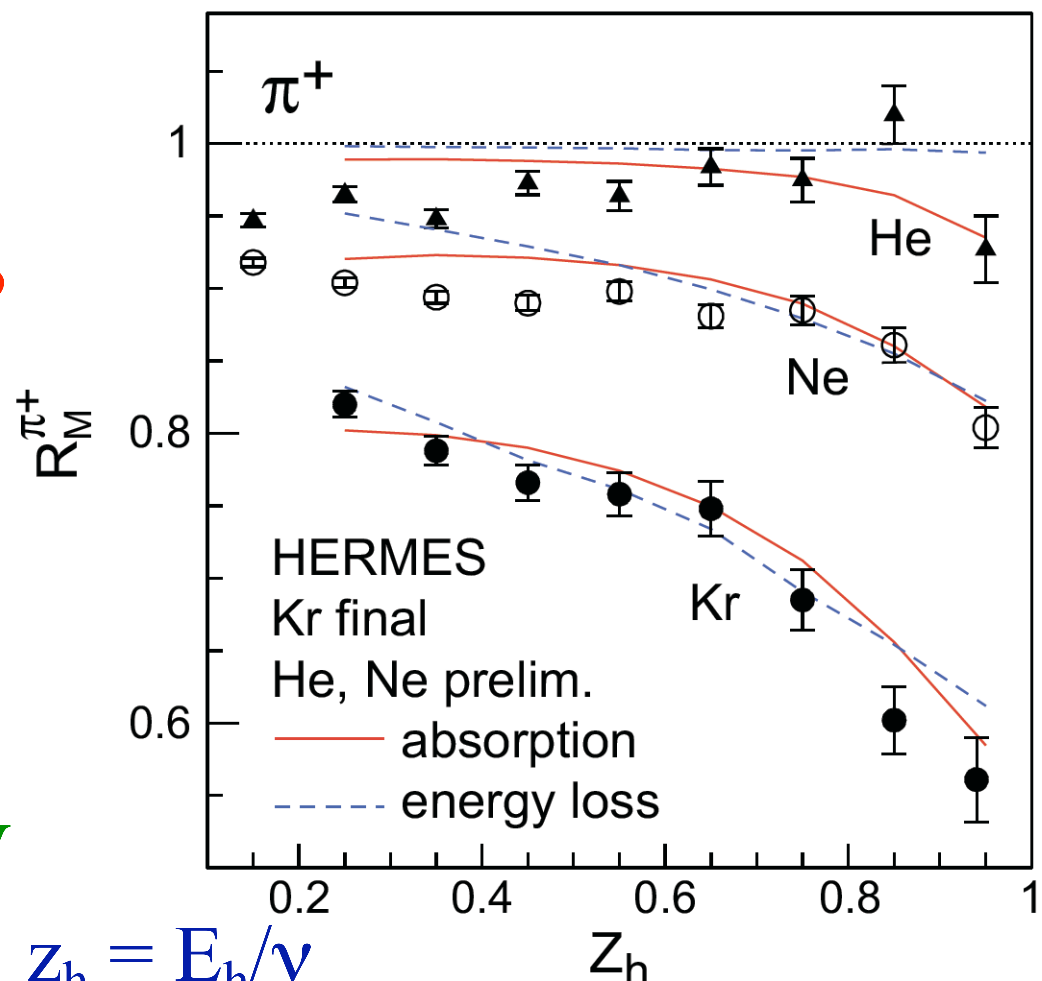

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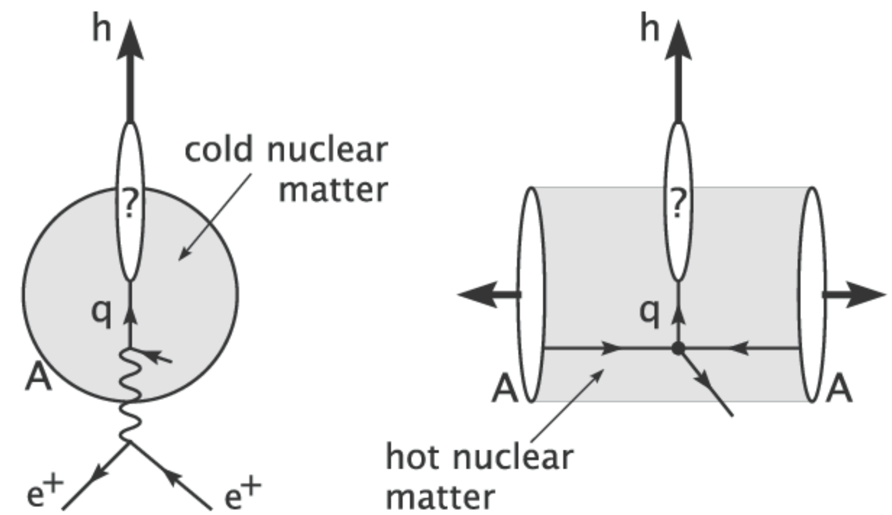

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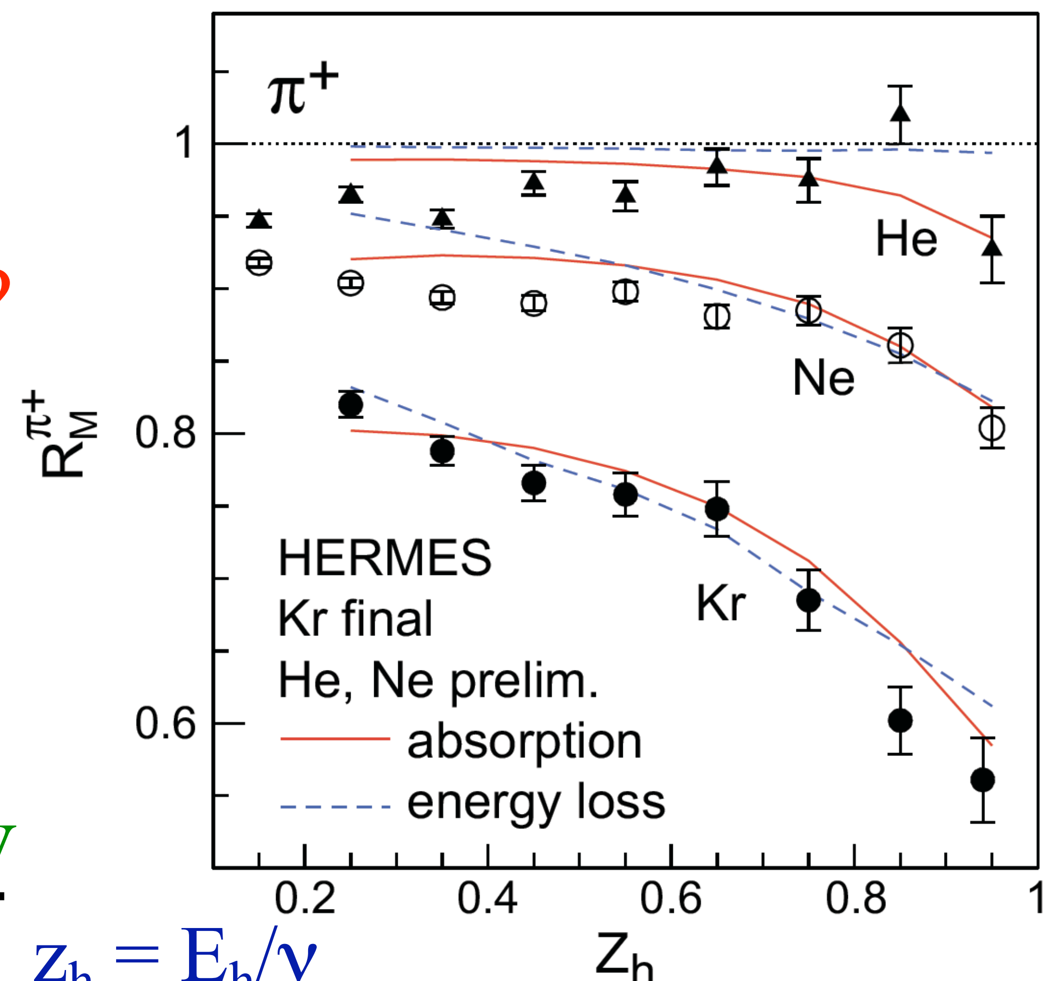

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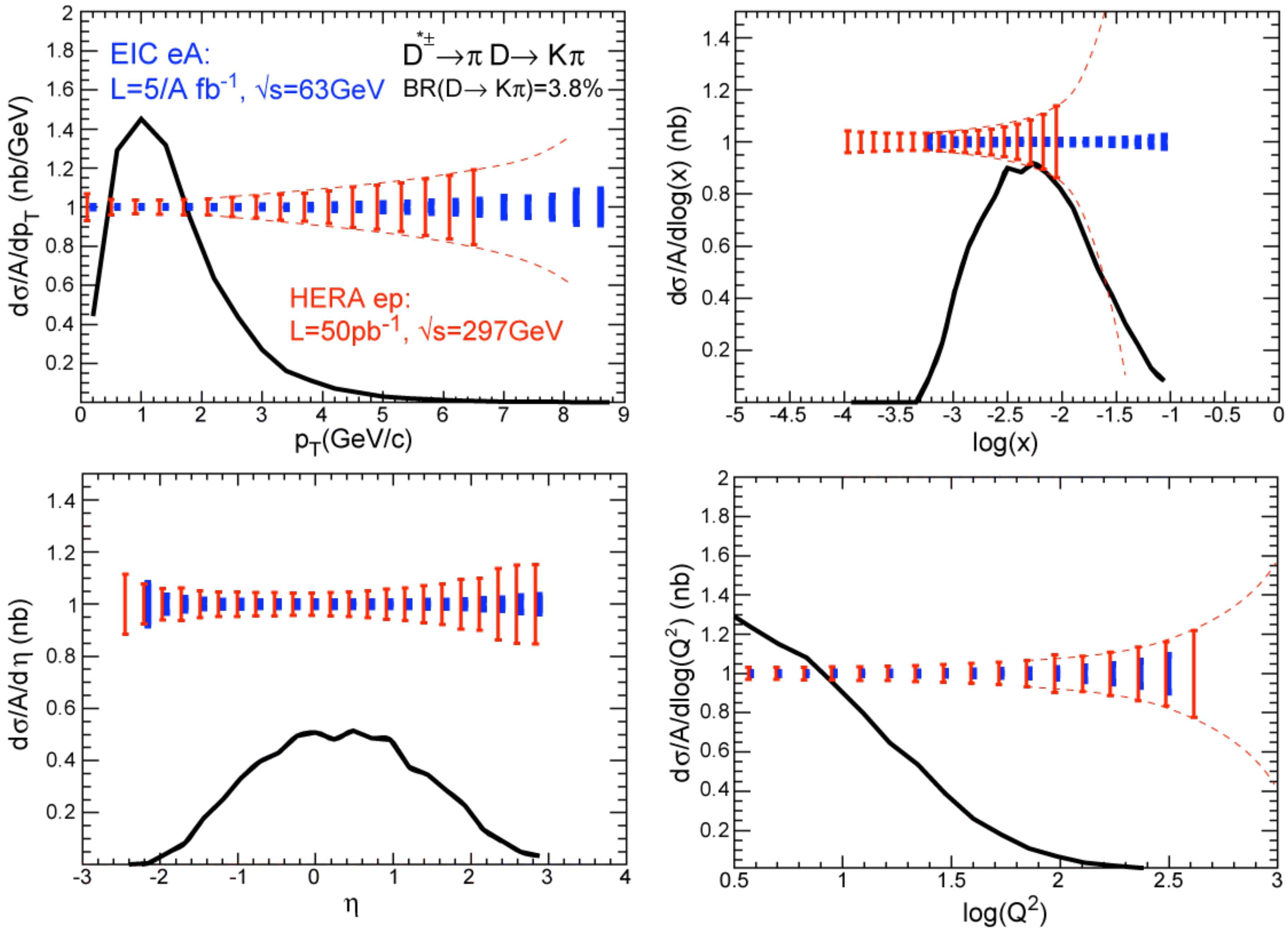
Charm at an EIC



Based on HVQDIS model, J. Smith

- 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

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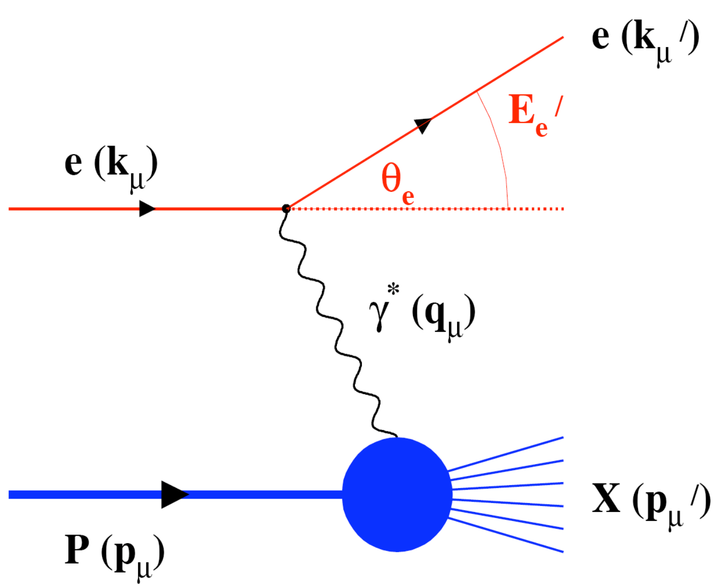
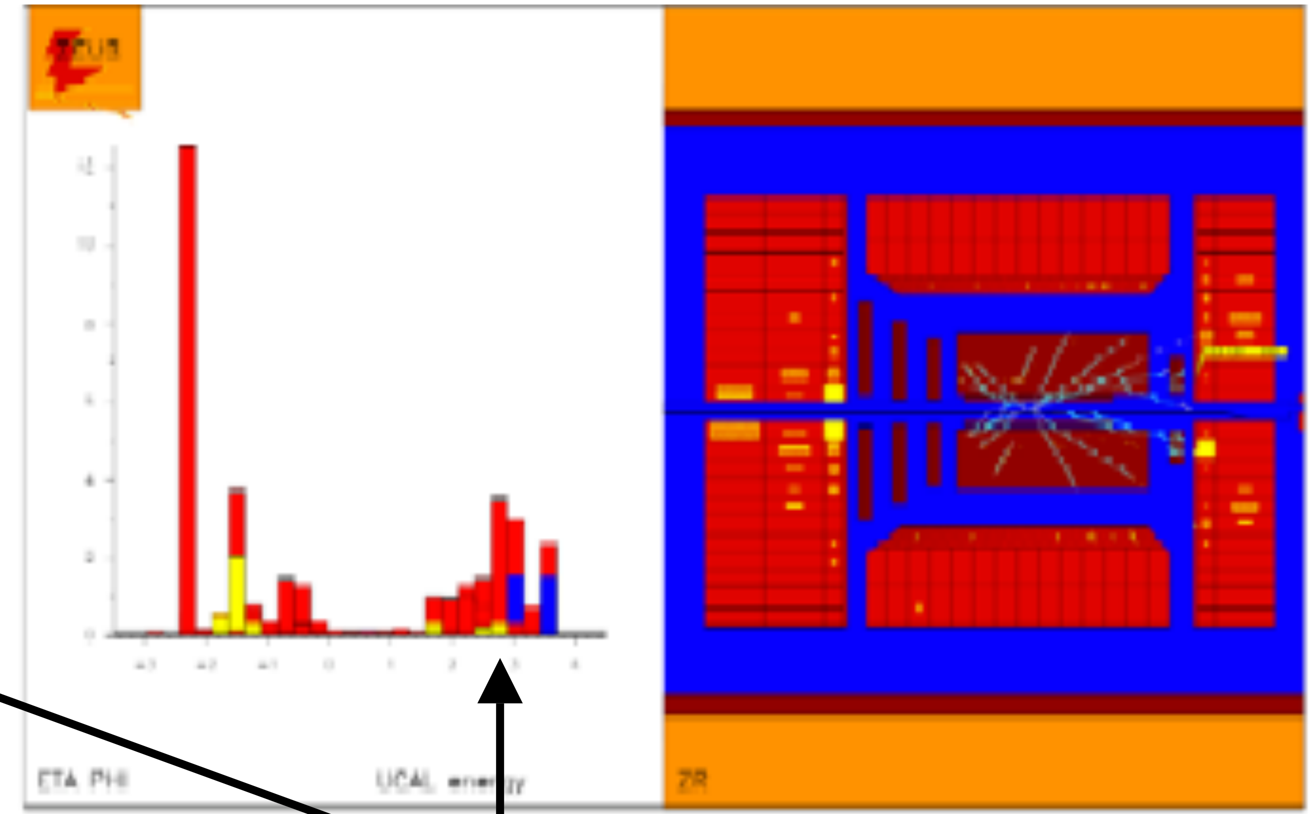
Diffractive Physics in e+A

'Standard DIS event'

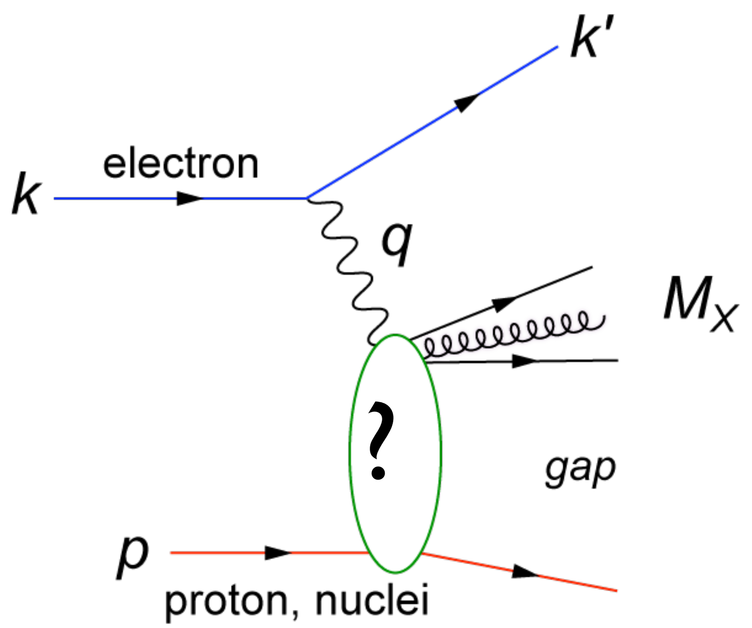


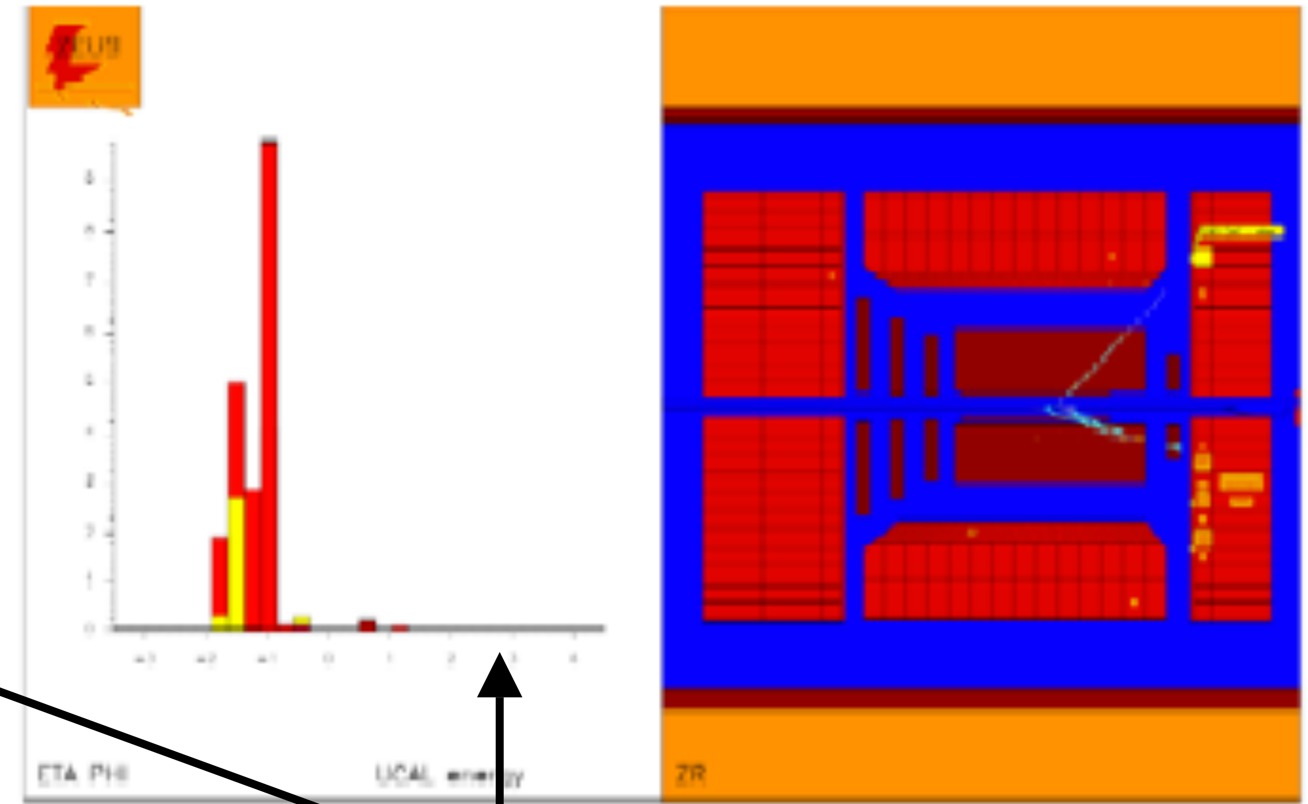


Activity in proton direction

Diffractive Physics in e+A

Diffractive event





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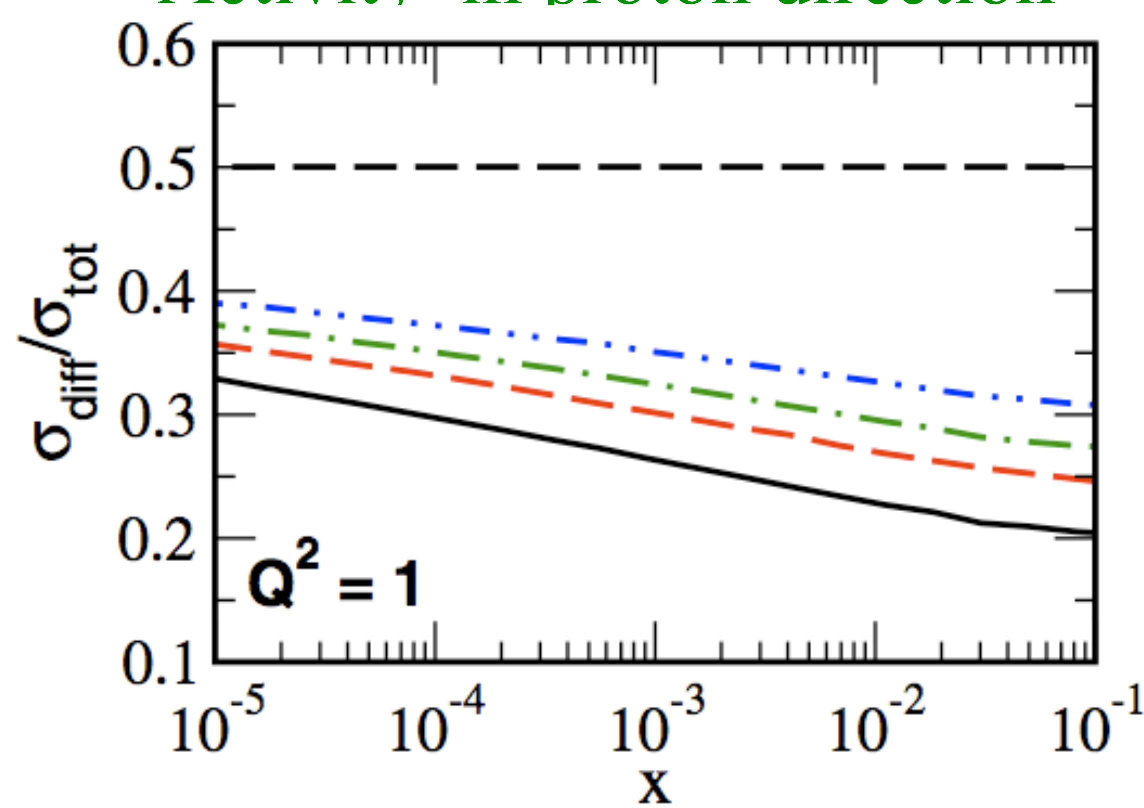

Curves: Kugeratski, Goncalves, Navarra, EPJ C46, 413

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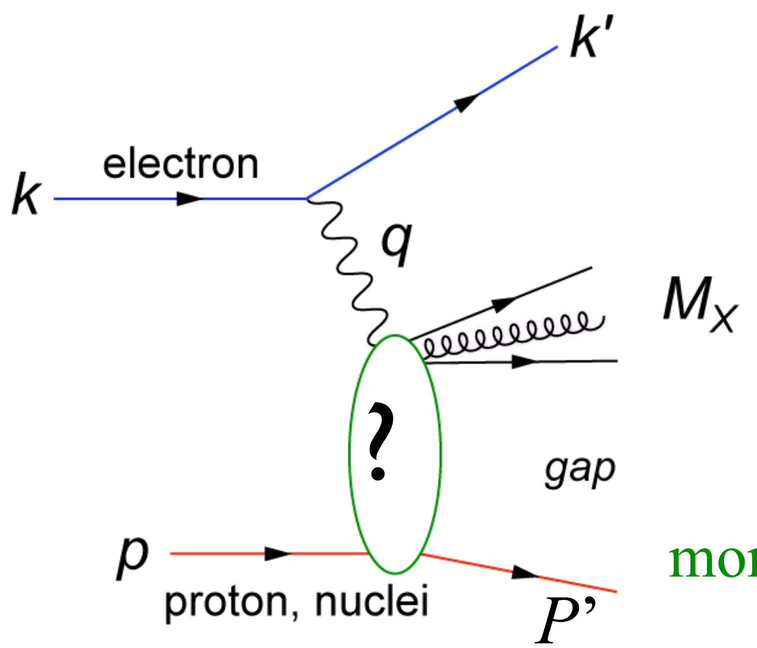
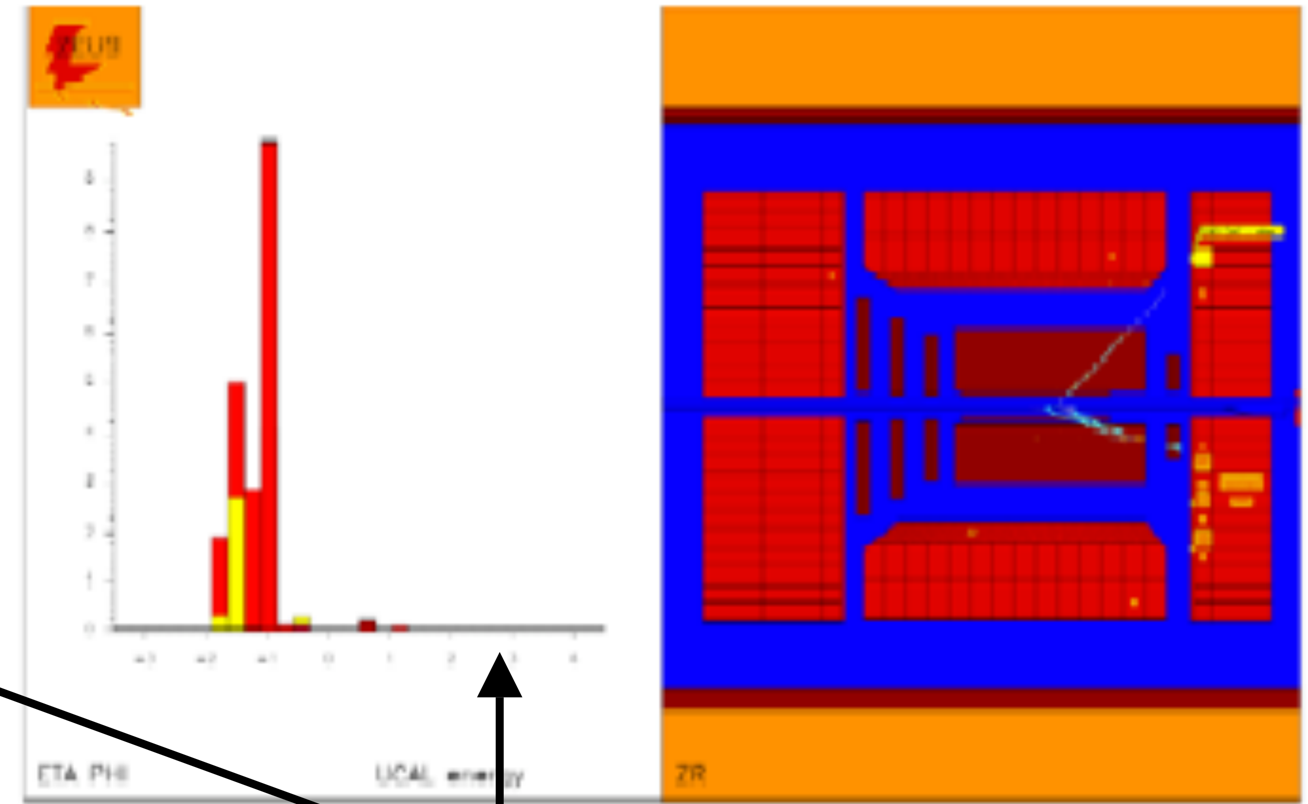


momentum transfer:
$t = (P\text{-}P')^2$



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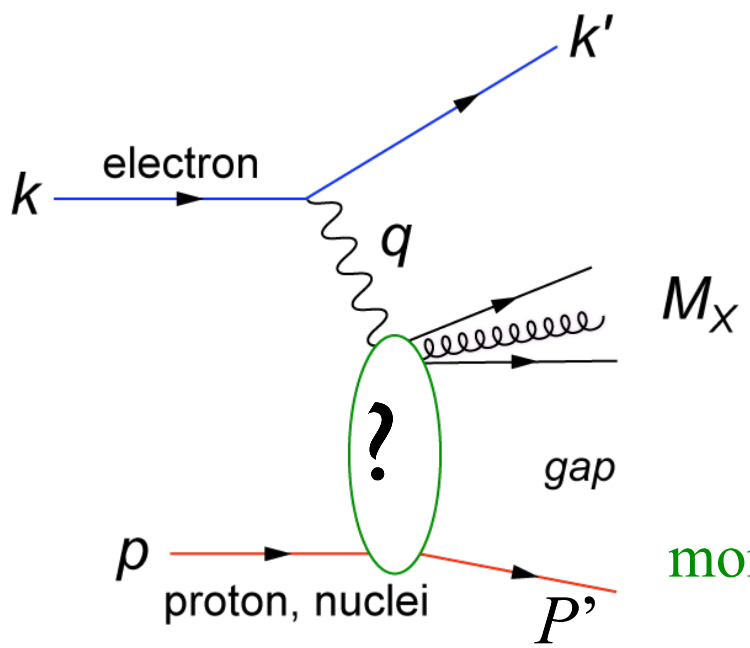

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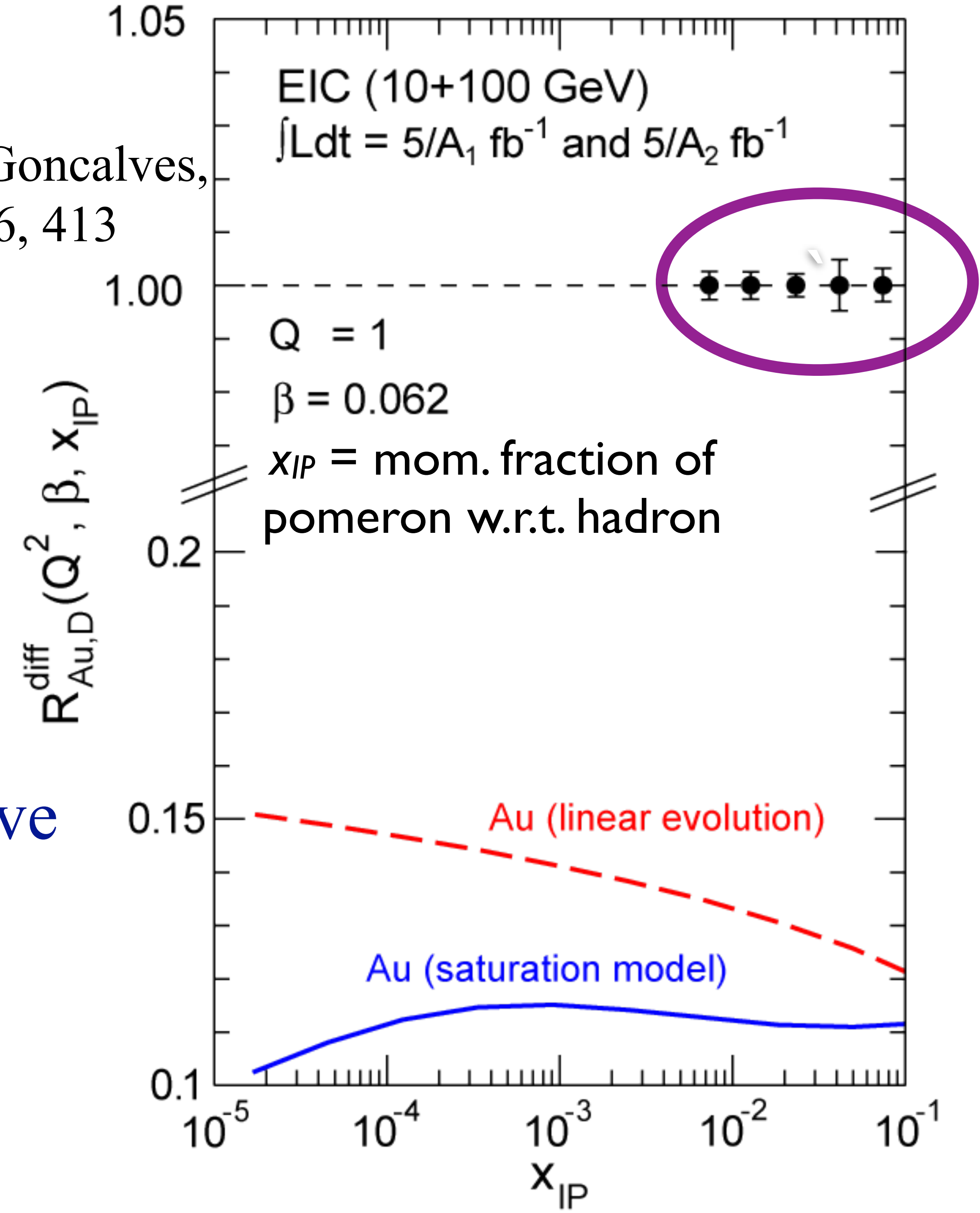

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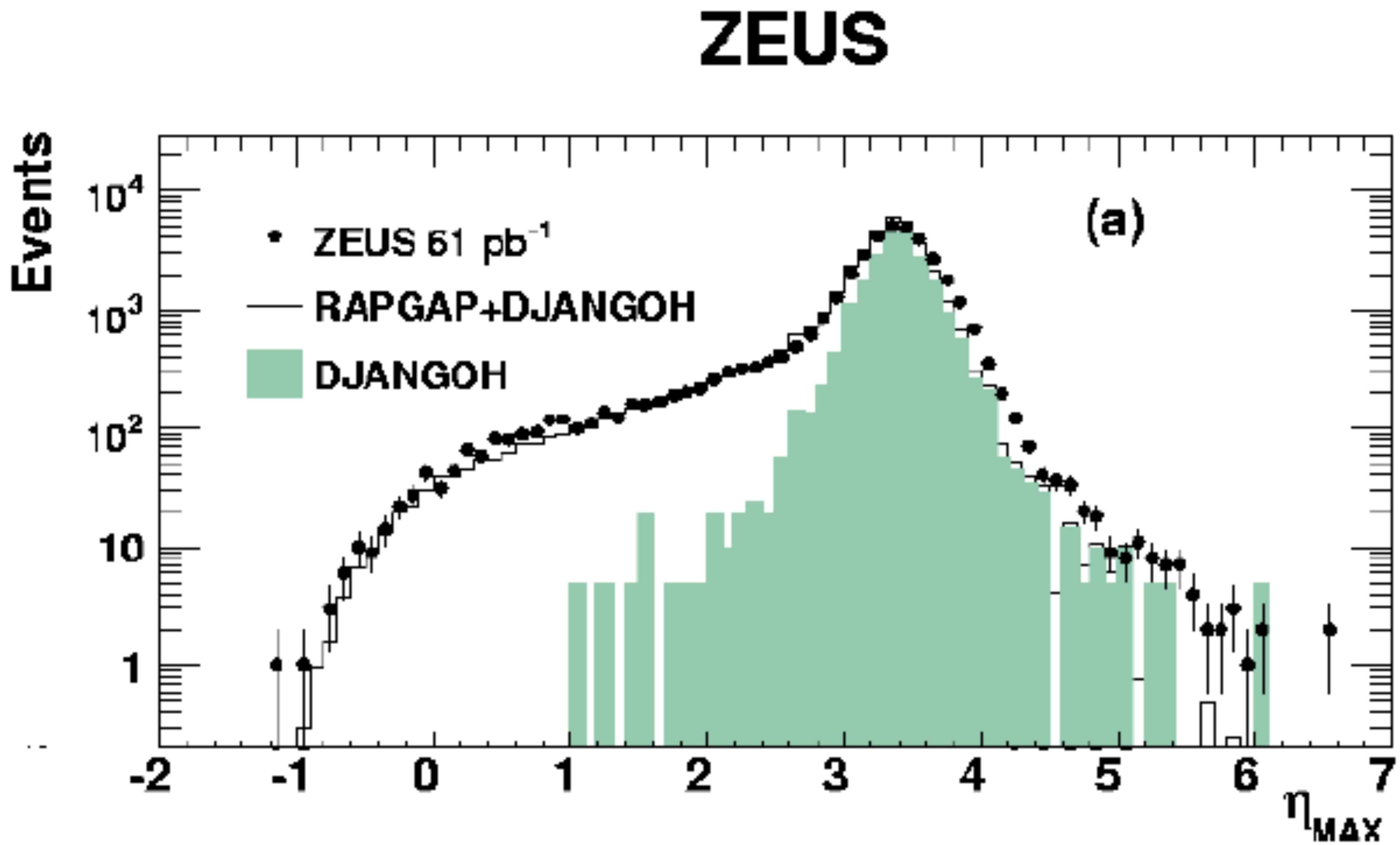
Diffractive Physics in e+A

- 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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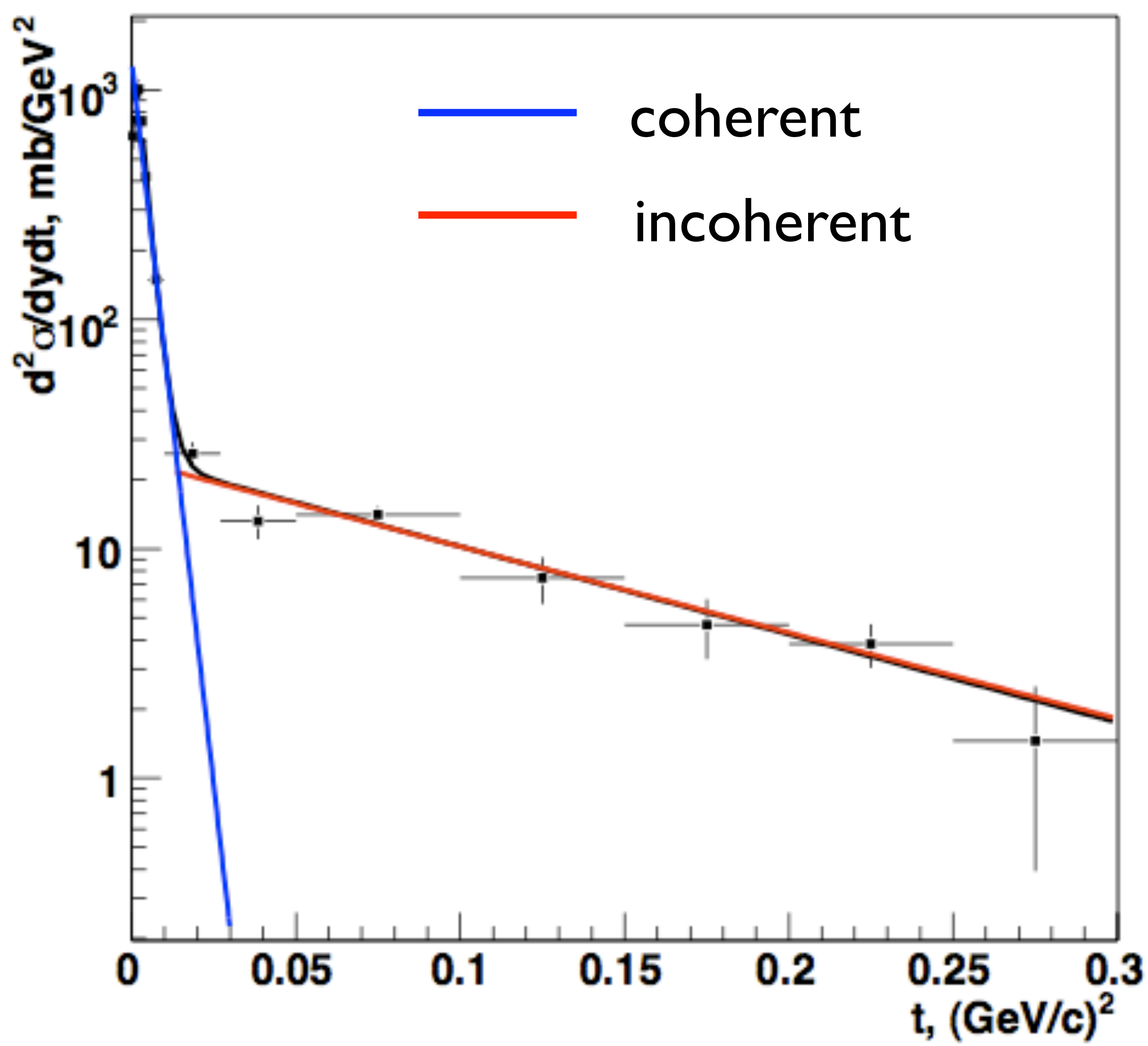
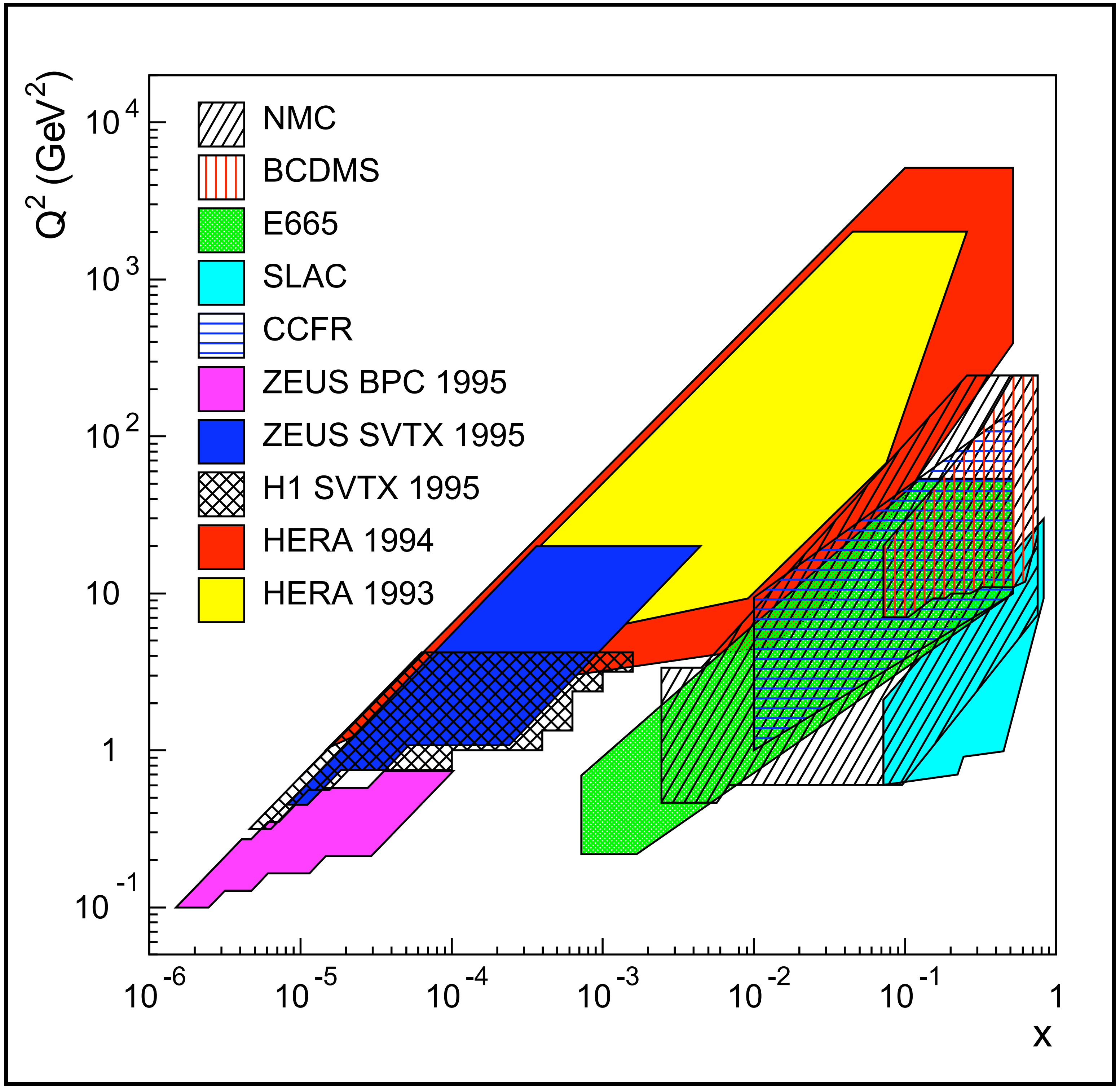
STAR - UPC Collisions



- 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 - $t \sim p_T^2$)

Requirements for an Electron Ion Collider



Well mapped in *e+p*

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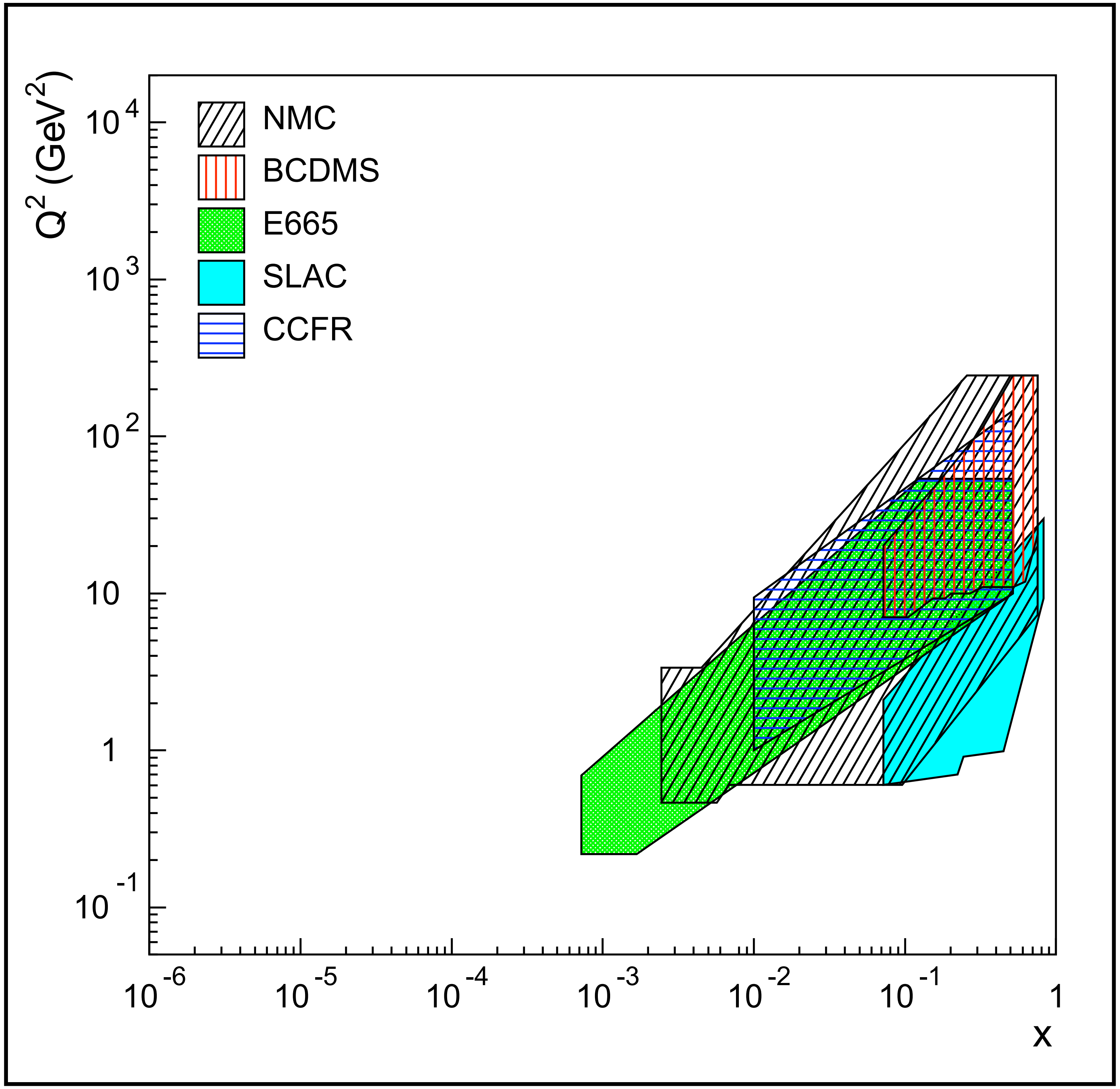

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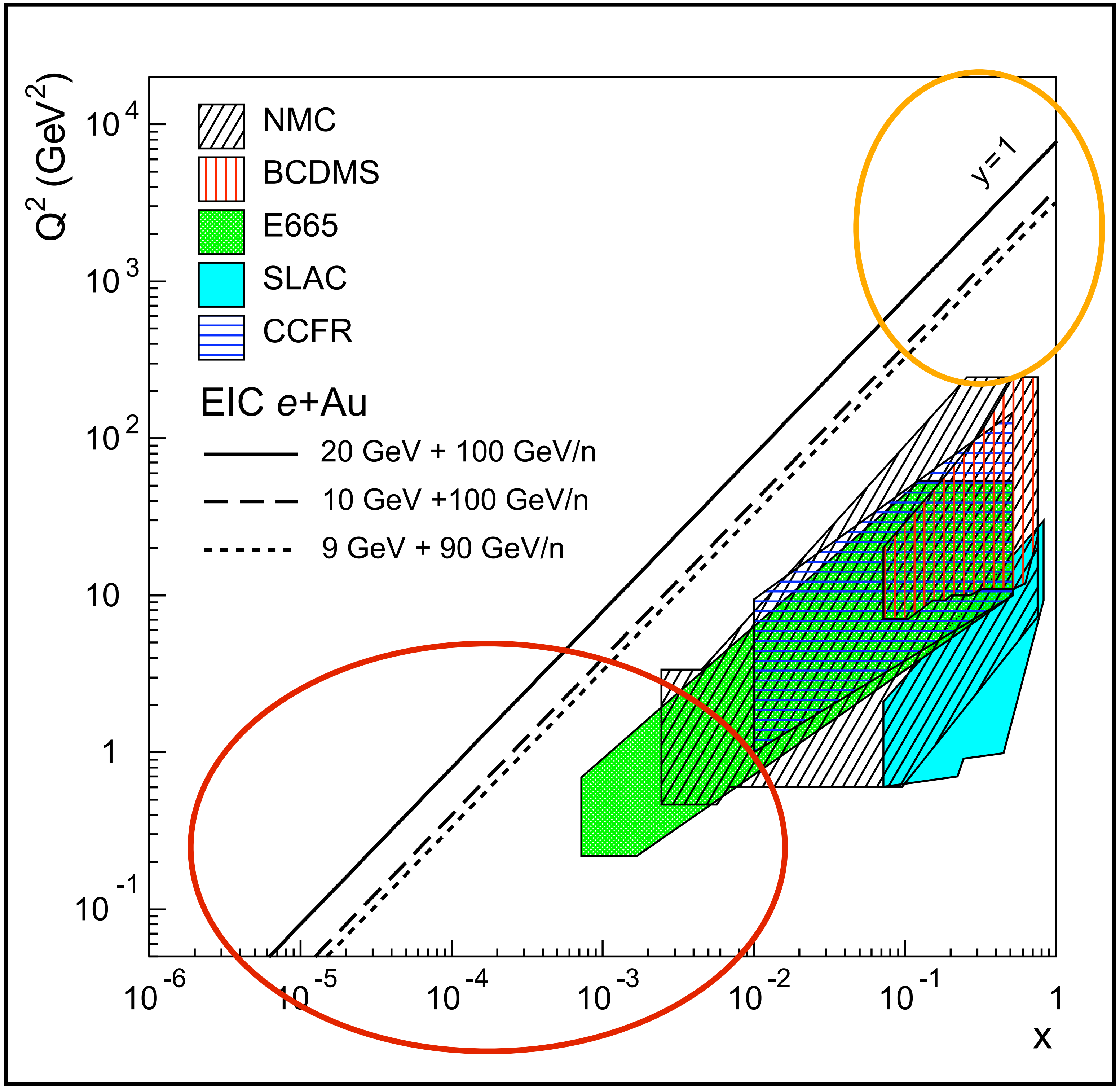

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  - E_e = 3 - 20 GeV
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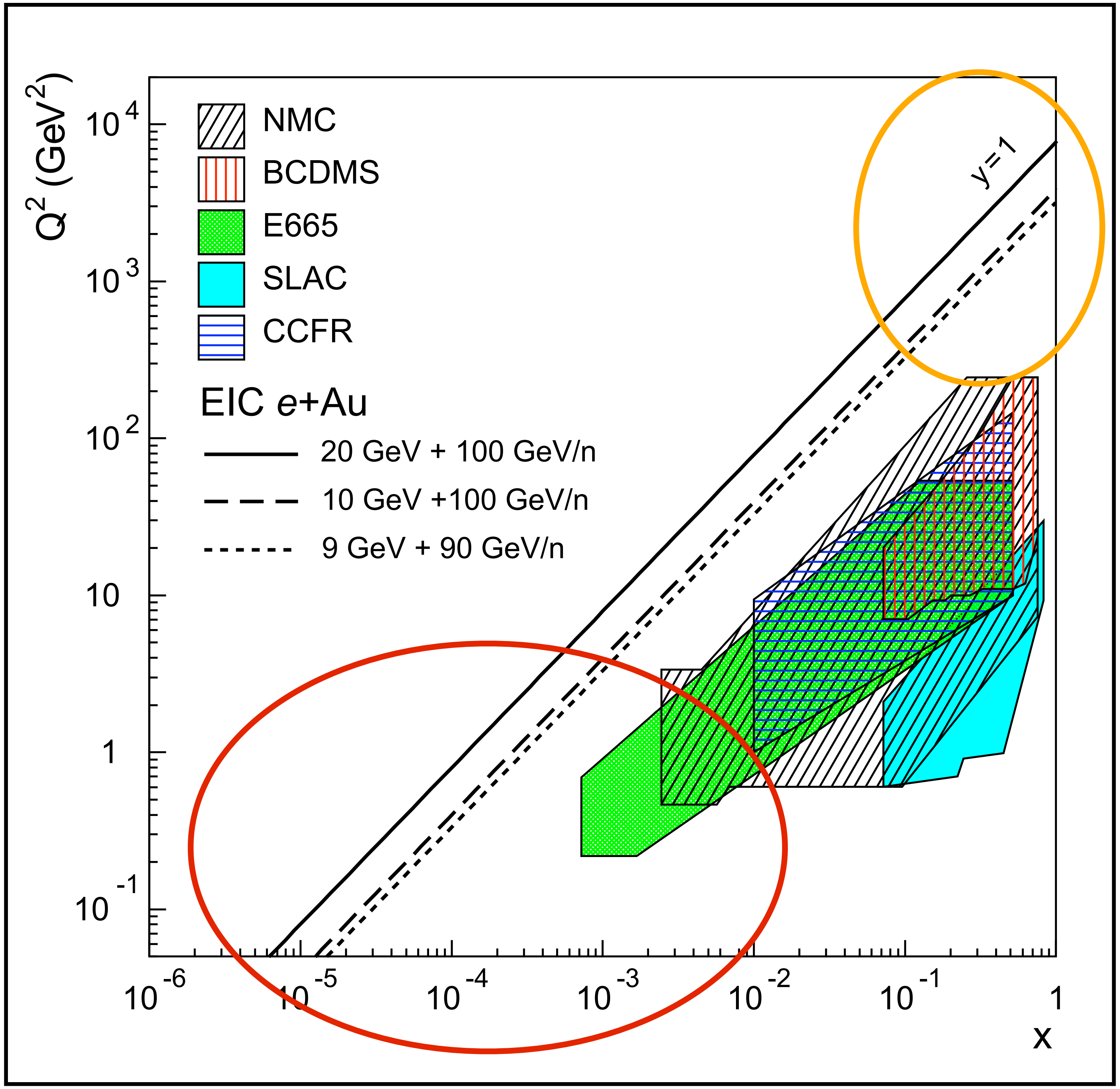

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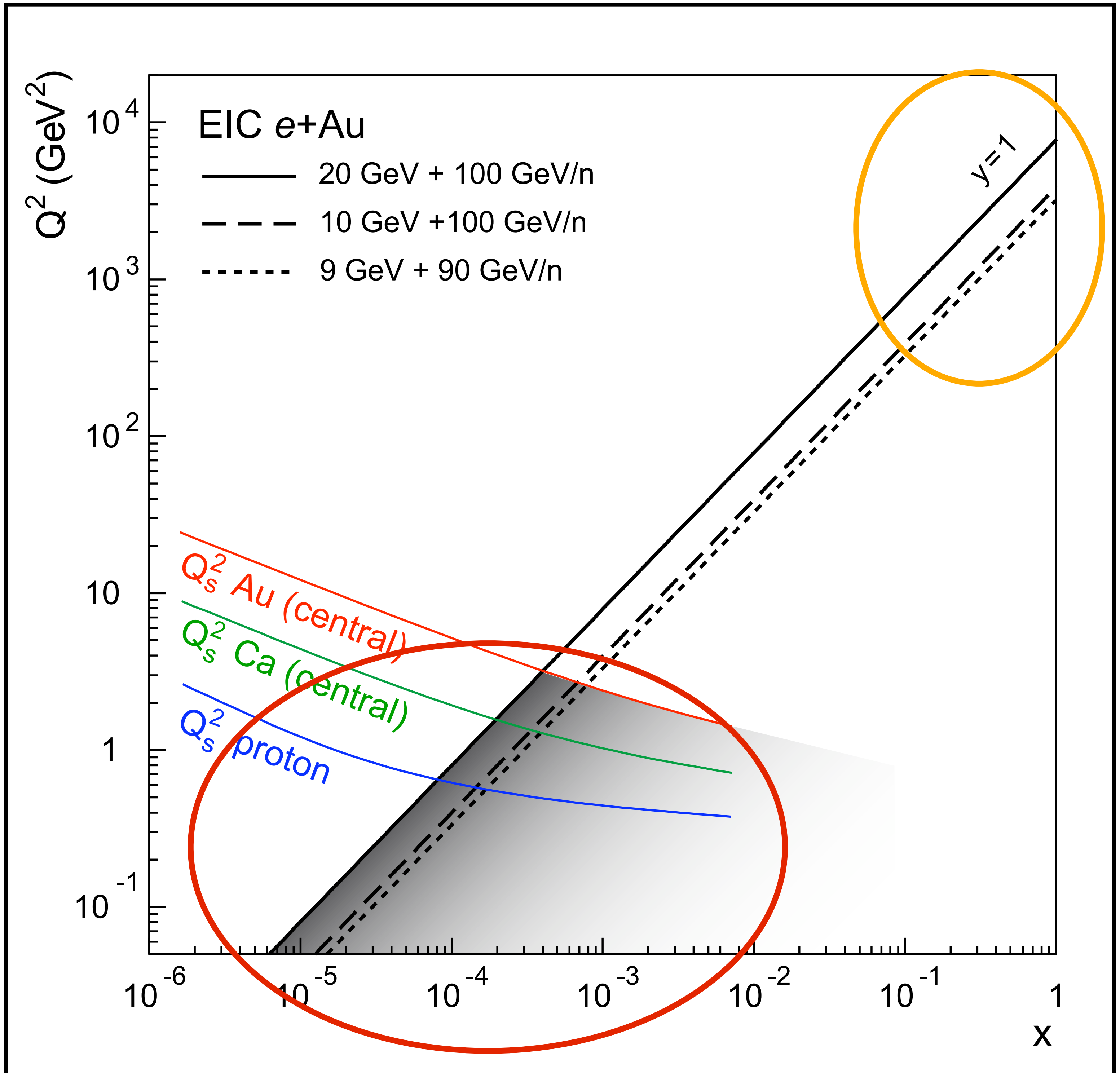

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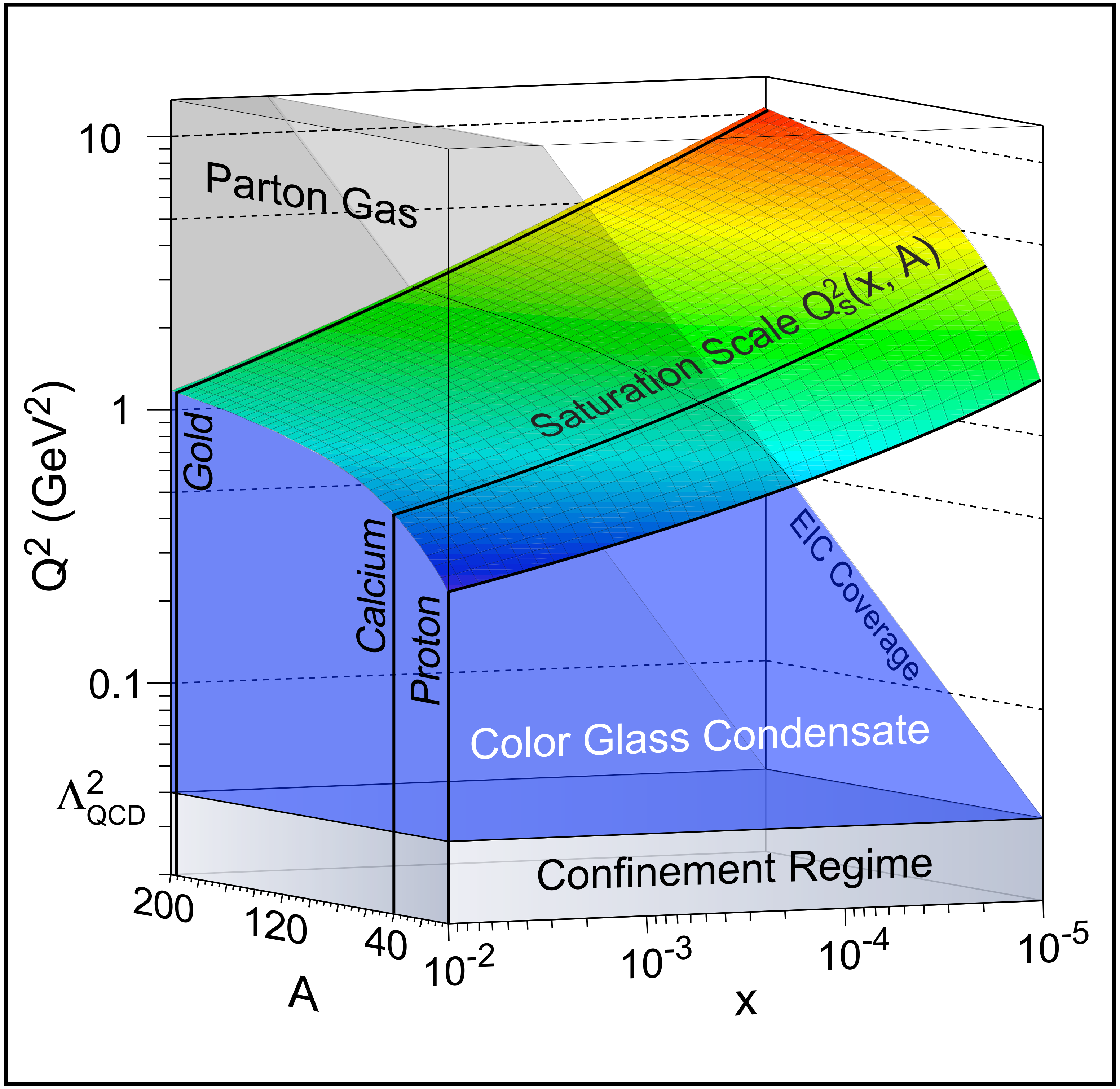

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EIC Collider concepts

***e*RHIC** (RHIC/BNL):

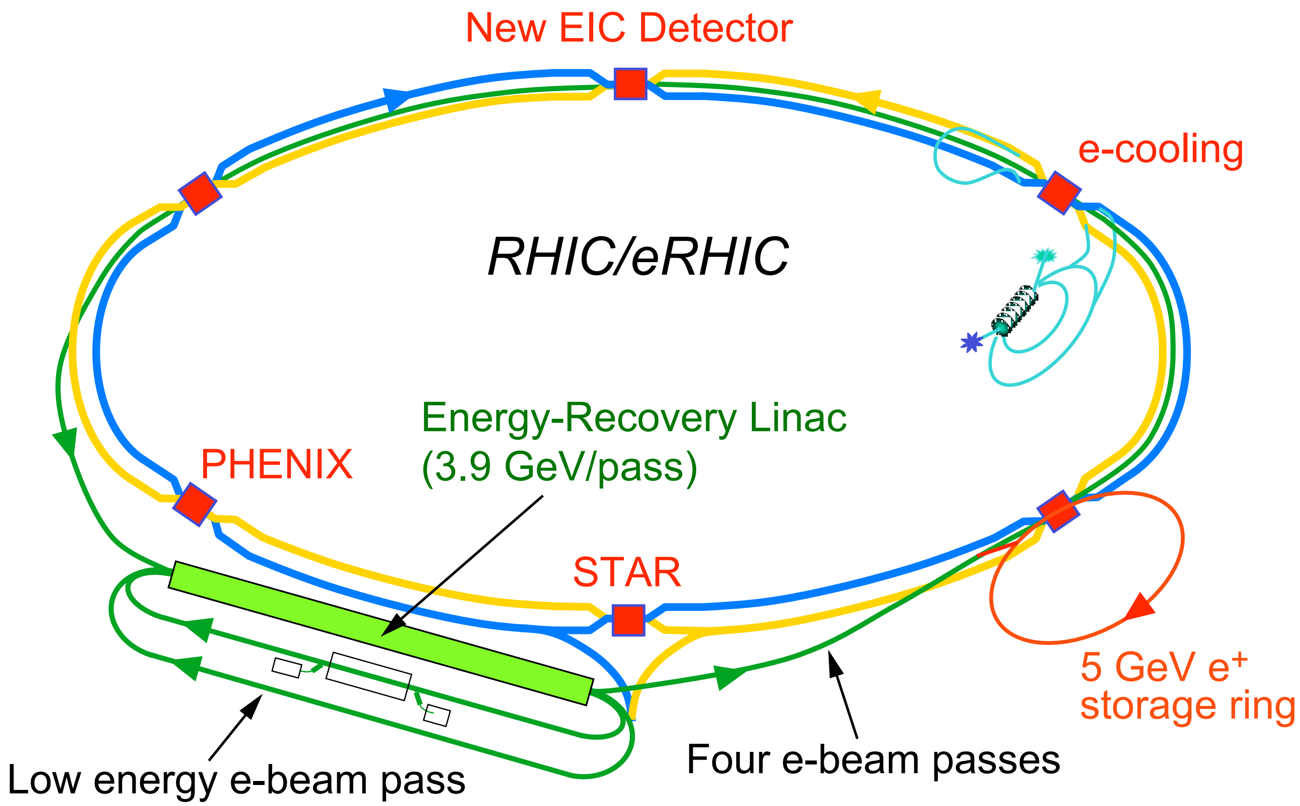
Add Energy Recovery Linac

$E_e = 10\ (20)$ GeV

$E_A = 100$ GeV (up to U)

$\sqrt{s_{eN}} = 63\ (90)$ GeV

L_{eAu} (peak)/n ~ $2.9 \cdot 10^{33}$ cm^{-2} s^{-1}



EIC Collider concepts

*e*RHIC (RHIC/BNL):

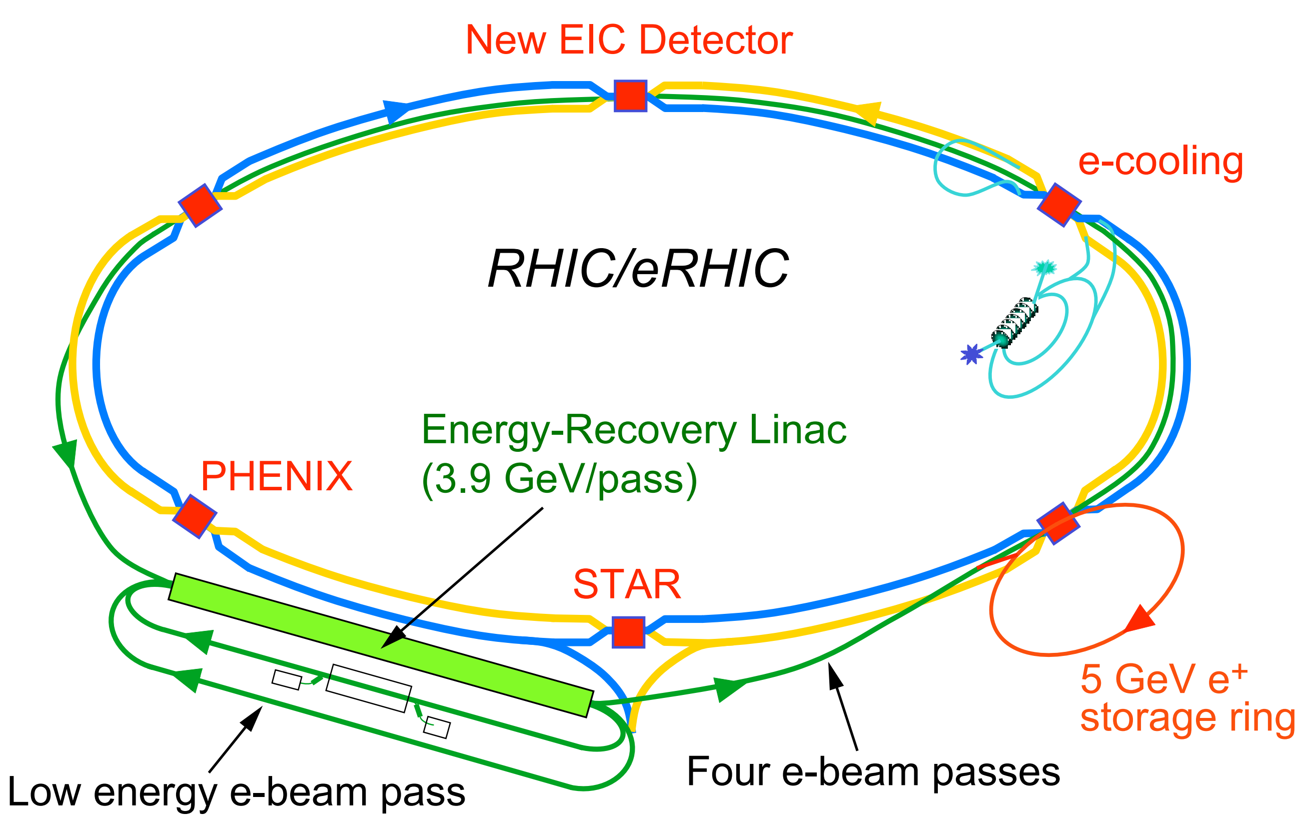
Add Energy Recovery Linac

$E_e = 10\ (20)$ GeV

$E_A = 100$ GeV (up to U)

$\sqrt{s_{eN}} = 63\ (90)$ GeV

L_{eAu} (peak)/n ~ $2.9 \cdot 10^{33}$ cm^{-2} s^{-1}



ELIC (CEBAF/JLAB):

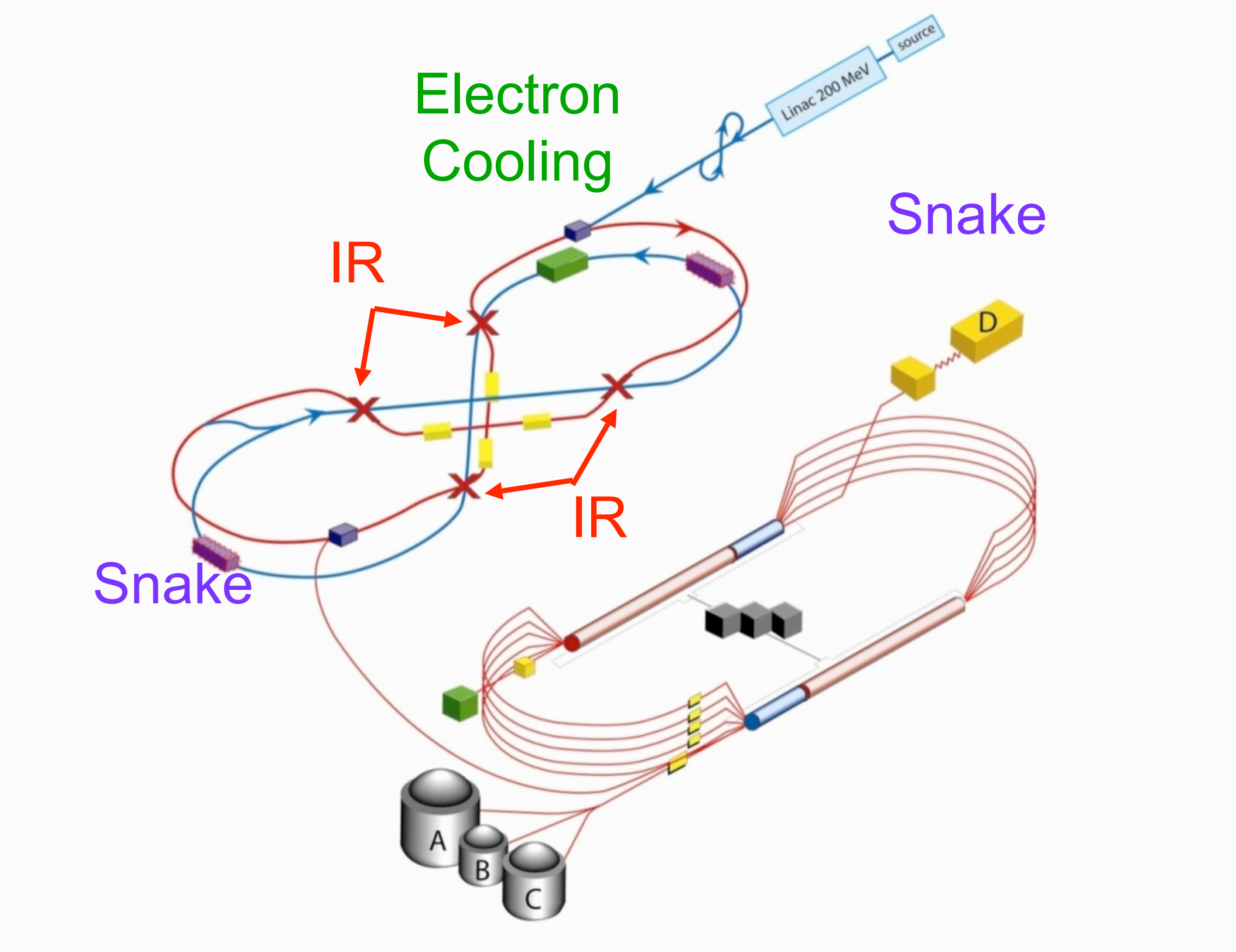
Add hadron machine

$E_e = 9$ GeV

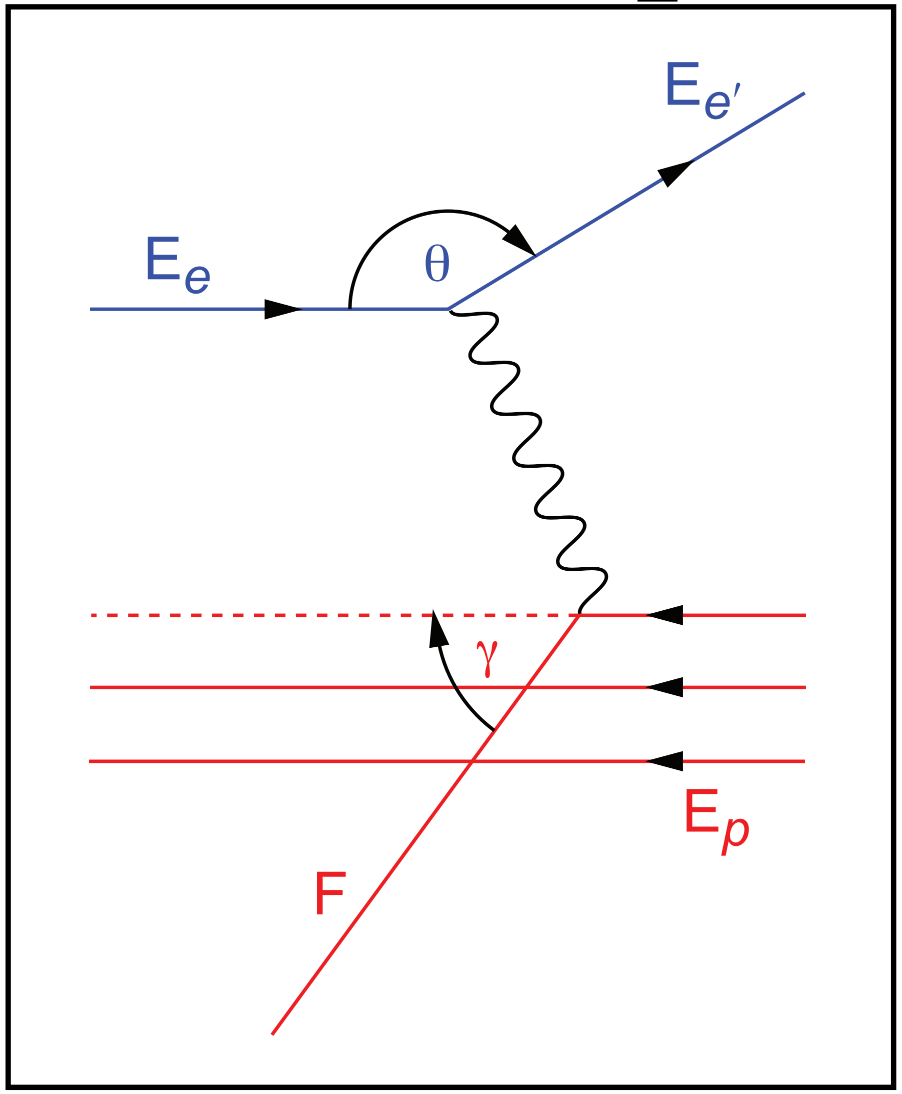
$E_A = 90$ GeV (up to Au)

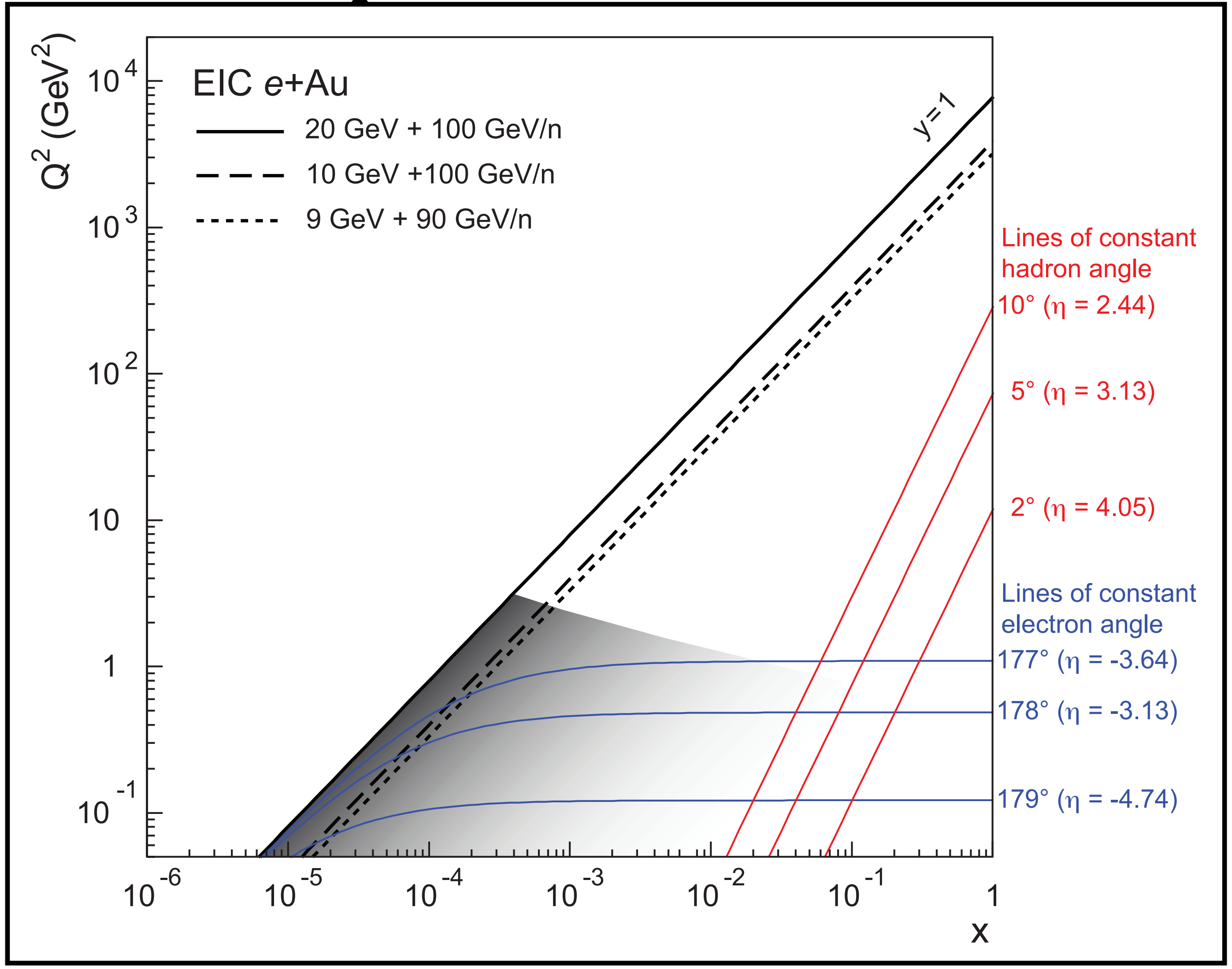
$\sqrt{s_{eN}} = 57$ GeV

L_{eAu} (peak)/n ~ $1.6 \cdot 10^{35}$ cm^{-2} s^{-1}



Experimental Aspects





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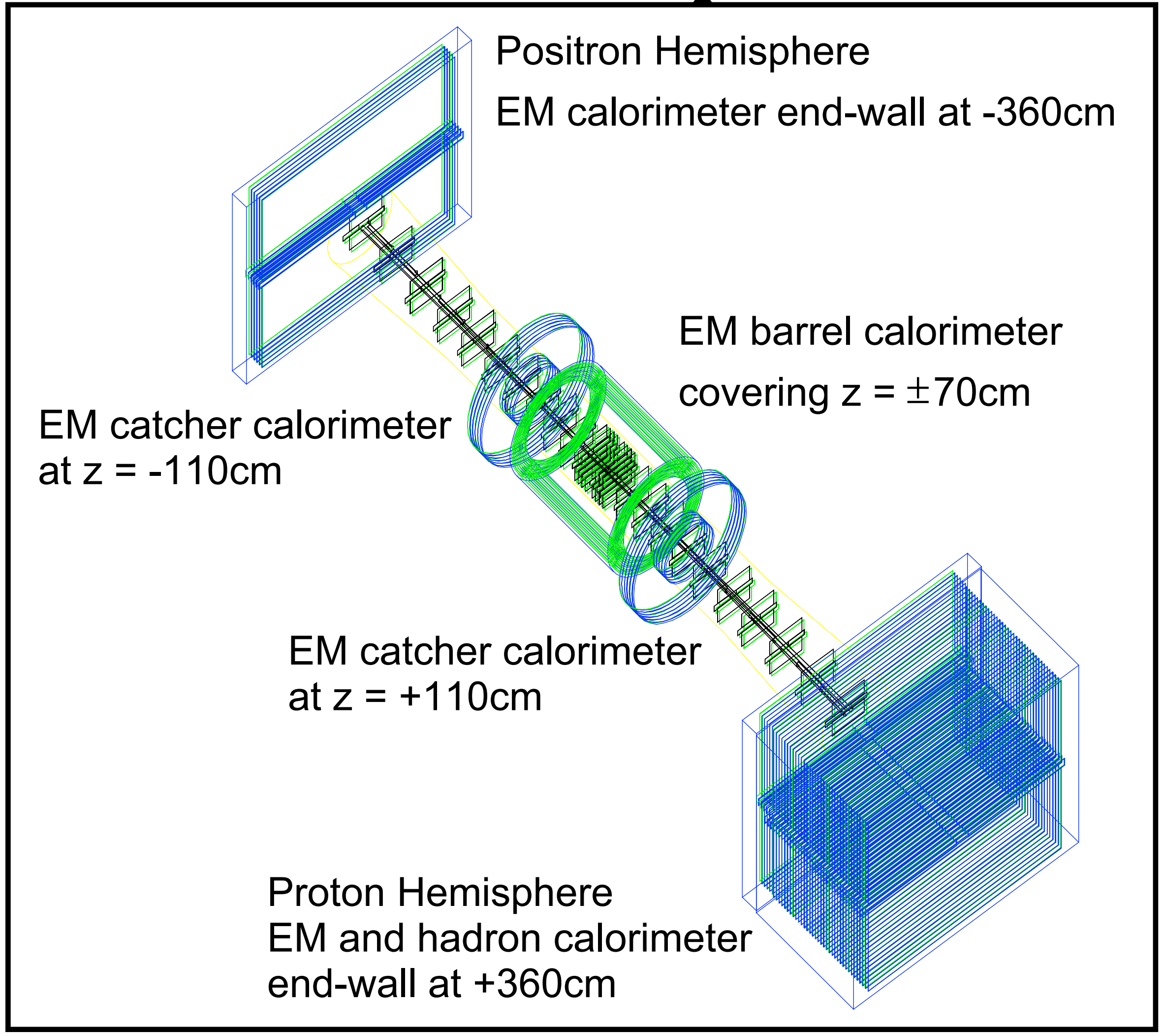
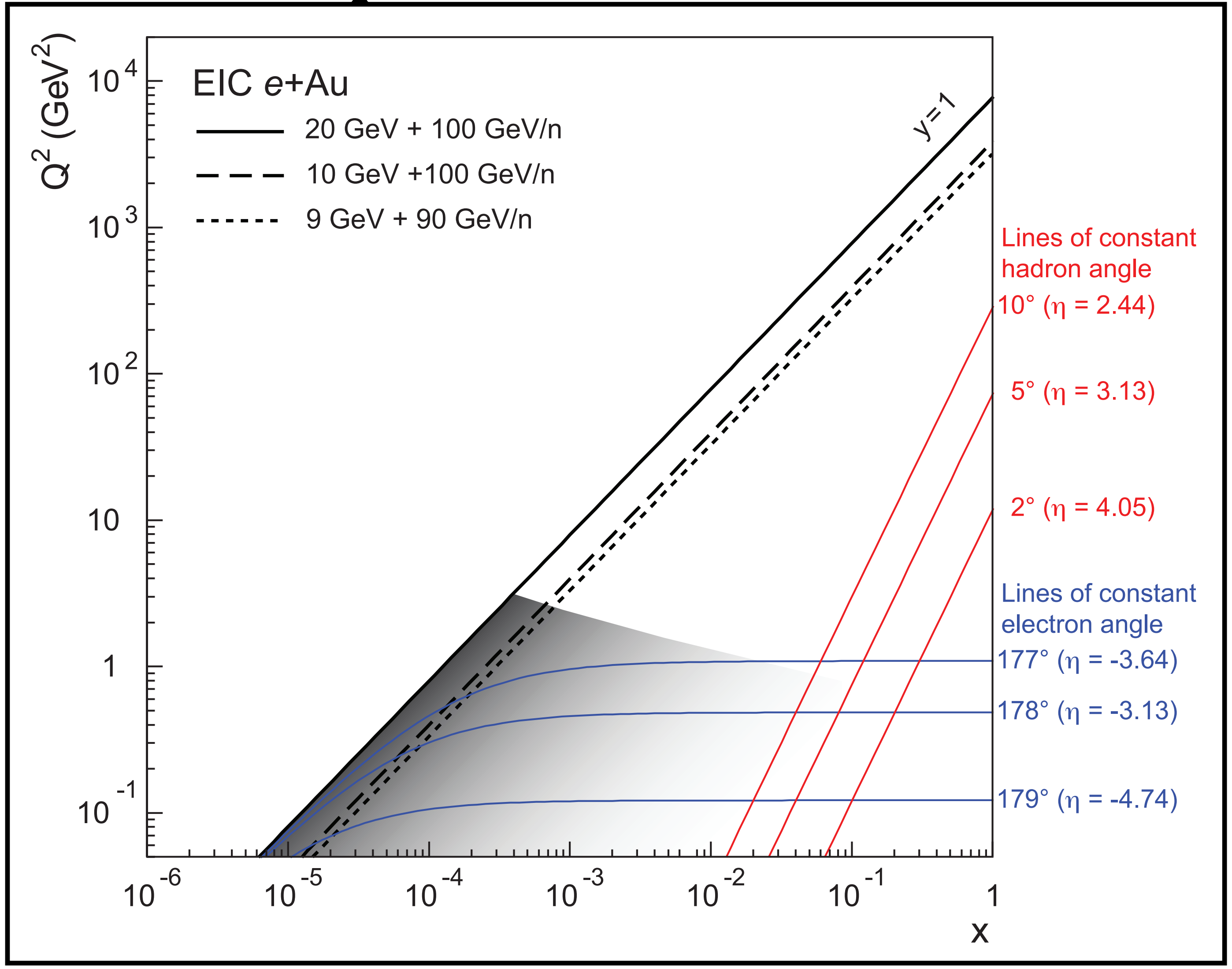




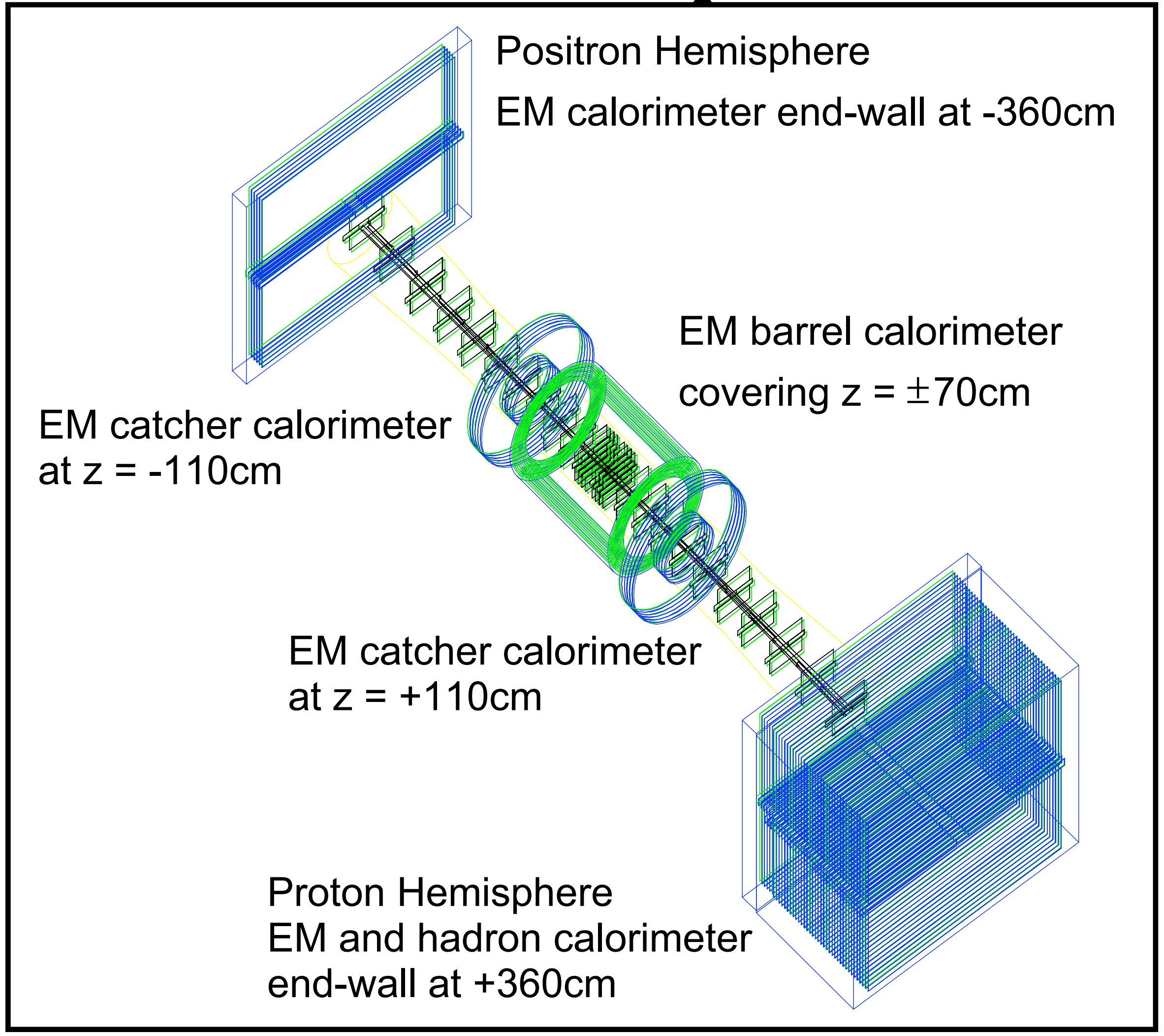
I. Abt, A. Caldwell, X. Liu, J. Sutiak, hep-ex 0407053

Concepts:

(a) Focus on the rear/forward acceptance and thus on low-*x* / high-*x* physics

- compact system of tracking and central electromagnetic calorimetry inside a magnetic dipole field and calorimetric end-walls outside

Experimental Aspects



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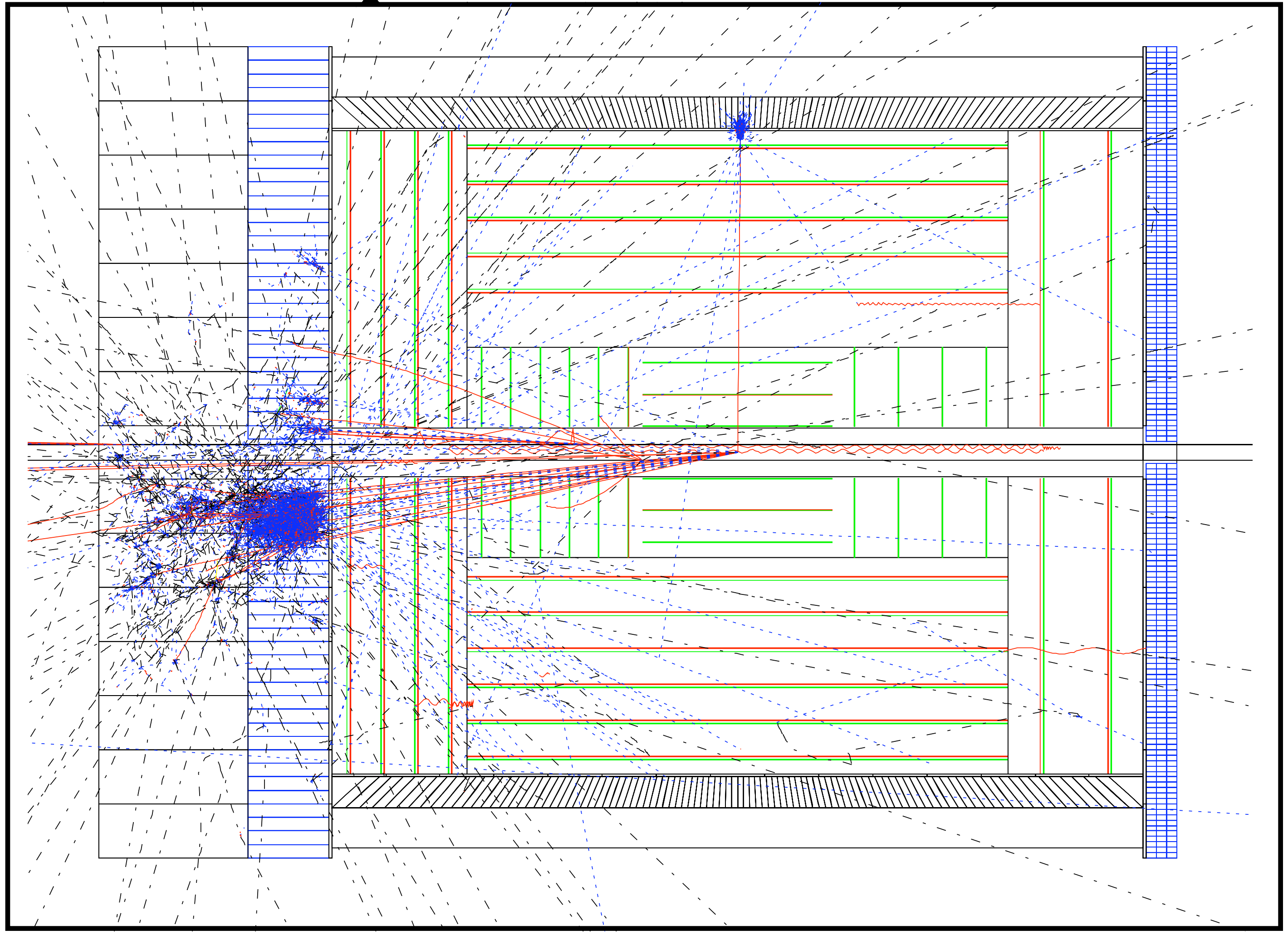


J. Pasukonis, B.Surrow, physics/0608290

Concepts:

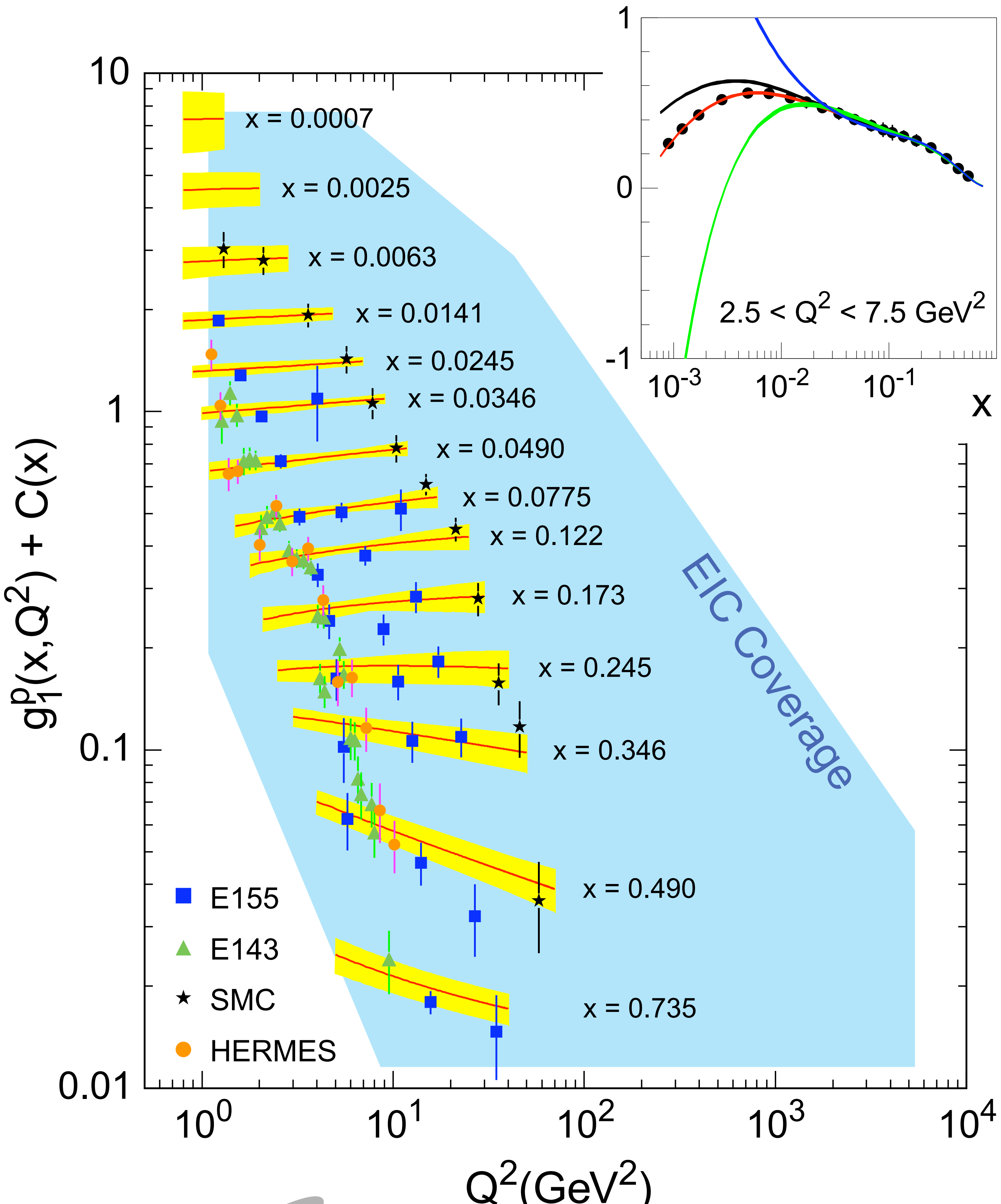
(a) Focus on the rear/forward acceptance and thus on low-x / high-x physics

- compact system of tracking and central electromagnetic calorimetry inside a magnetic dipole field and calorimetric end-walls outside

(b) Focus on a wide acceptance detector system similar to HERA experiments

- allow for the maximum possible Q^2 range.

EIC as an $e+\vec{p}$ machine - The Quest for ΔG



Spin Structure of the Proton

$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$

quark contribution $\Delta\Sigma \approx 0.3$

gluon contribution $\Delta G \approx 1 \pm 1$?

ΔG: a "quotable" property of the proton (like mass, charge)

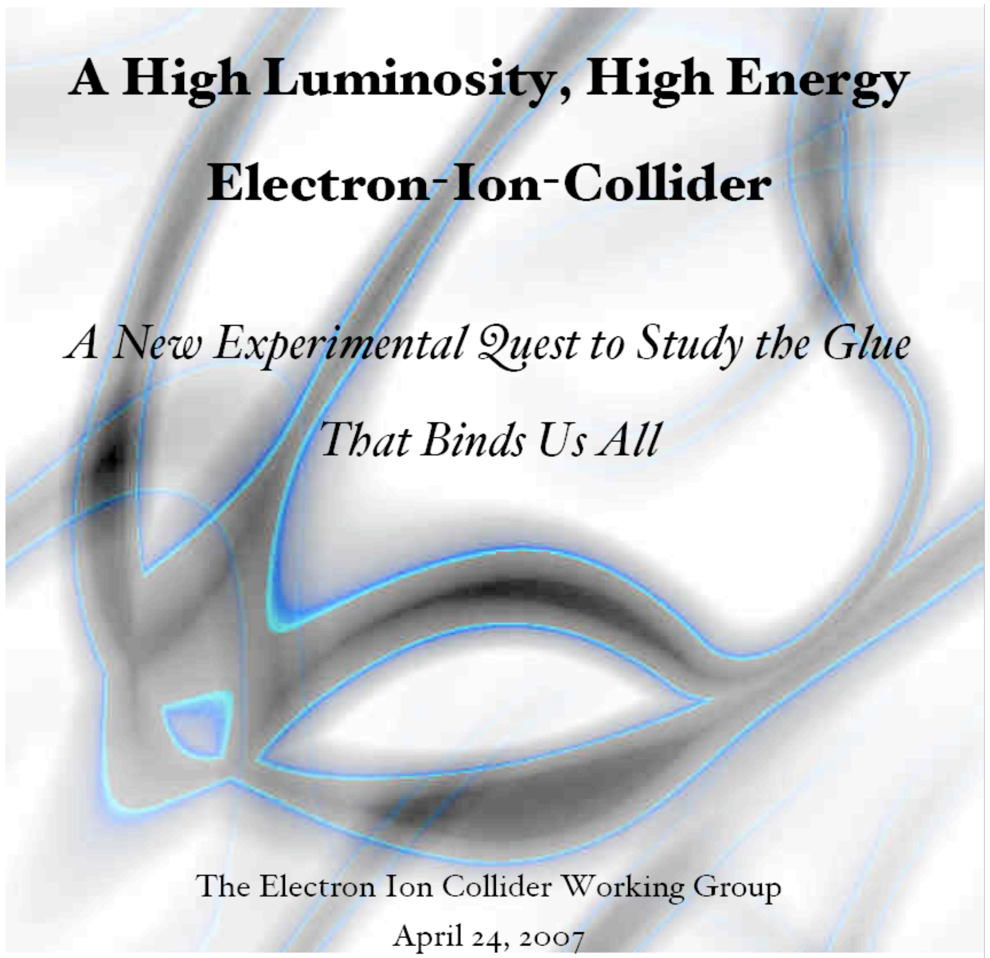
Measure through scaling violation:

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$

$$\Delta G = \int_{x=0}^{x=1} \Delta g(x,Q^2)\,dx$$

Superb sensitivity to ΔG at small x!

Status of the EIC Project: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A New Experimental Quest to Study the Glue That Binds Us All

The Electron Ion Collider Working Group
April 24, 2007

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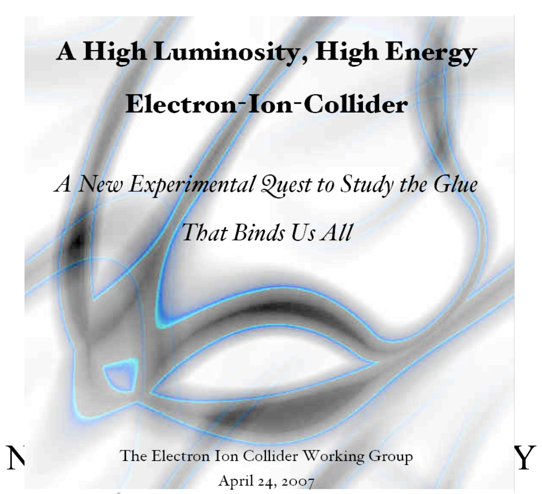

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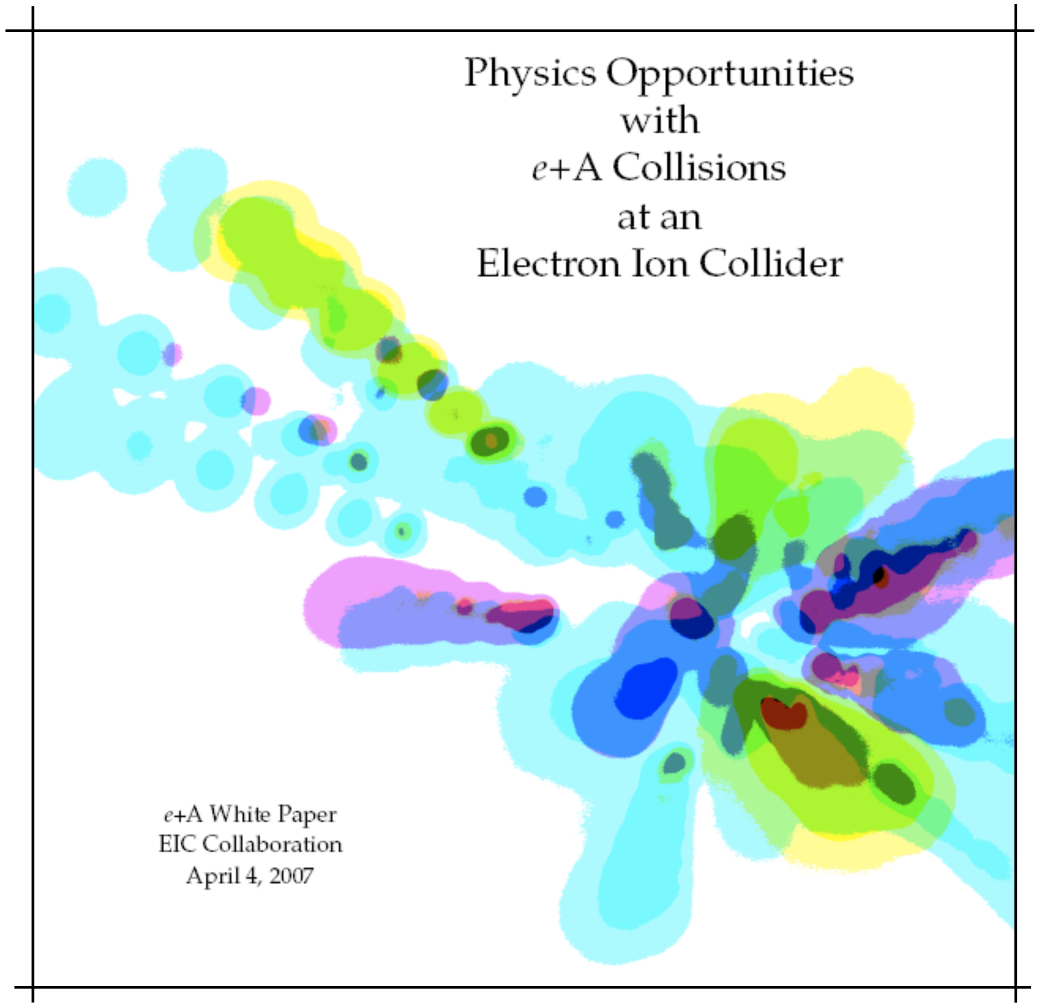

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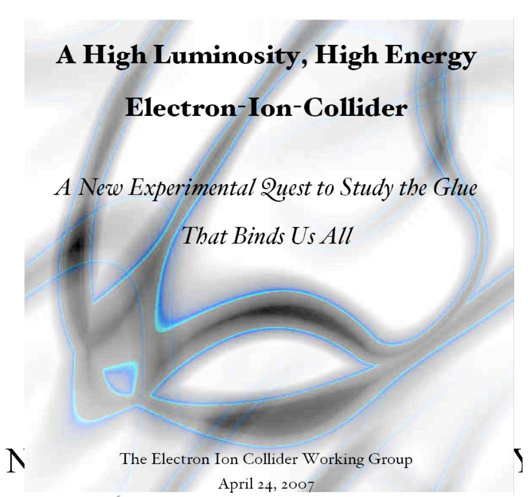

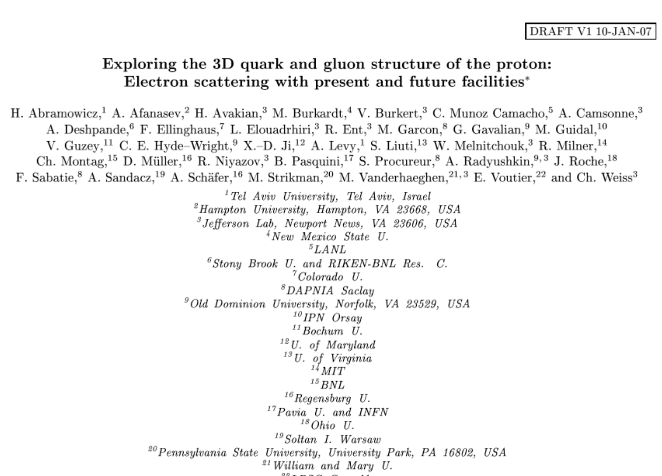

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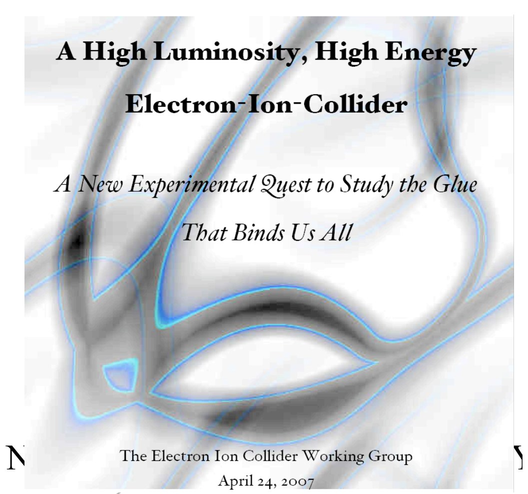

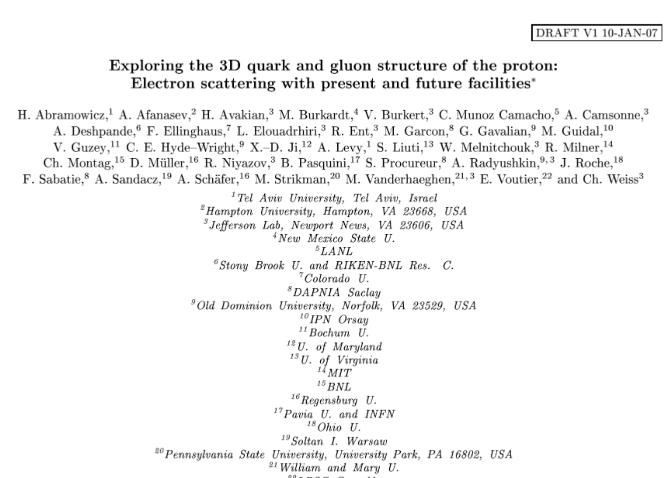

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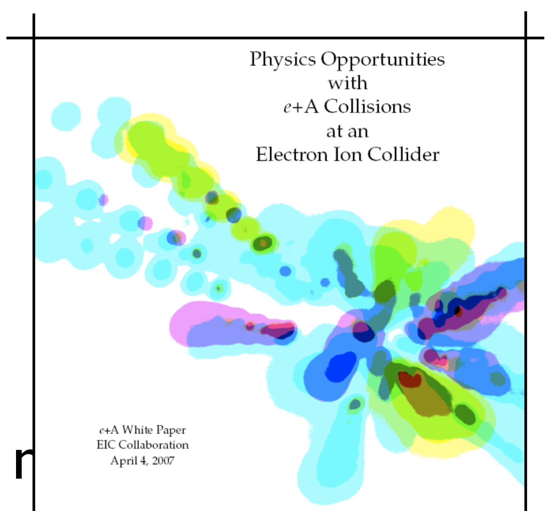

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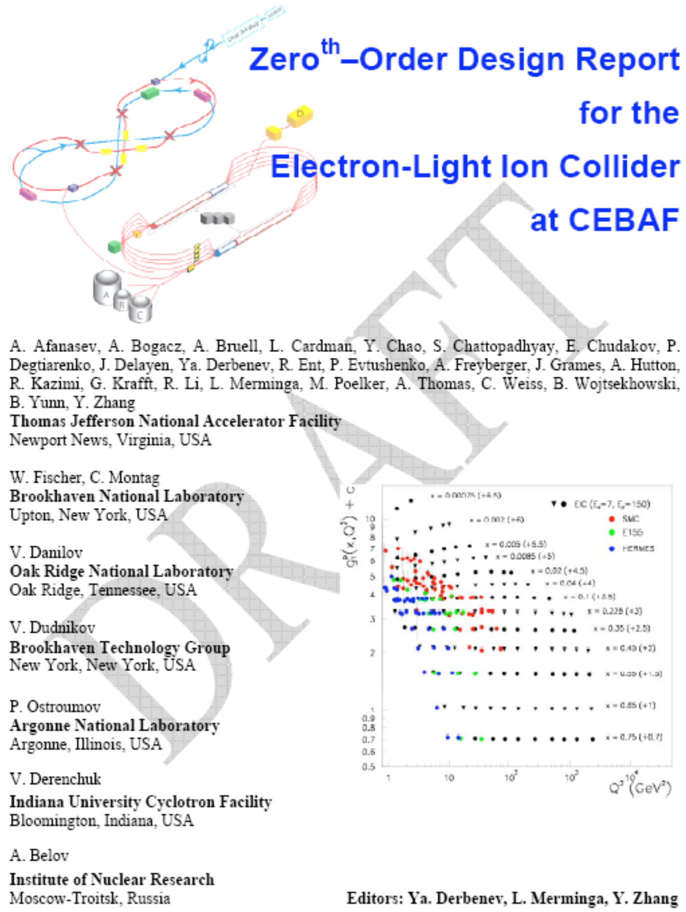
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Editors: Ya. Derbenev, L. Merminga, Y. Zhang

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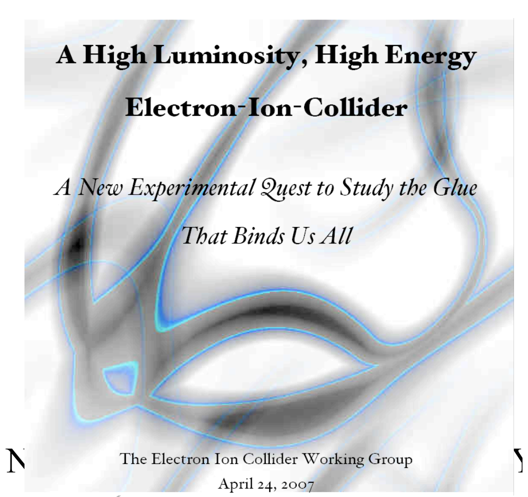
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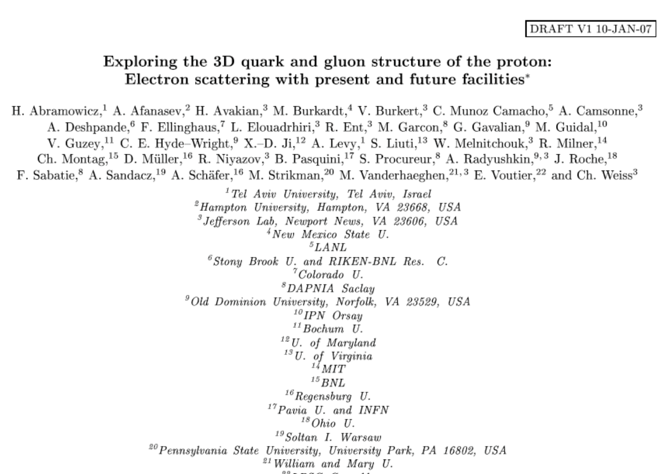
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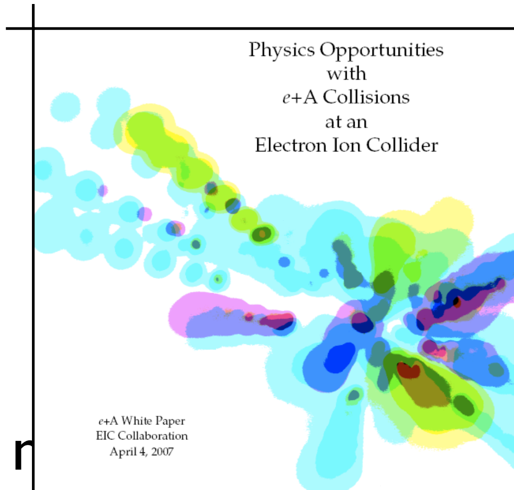
Physics Opportunities
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e+A White Paper
EIC Collaboration
April 4, 2007


eRHIC Accelerator Position Paper

For NSAC Long Range Plan 2007

January 2007

Status of the EIC Project:

[Available at:](#)

- NSAC LRP2007 home page
- Rutgers Town Meeting page
- **http://web.mit.edu/eicc**

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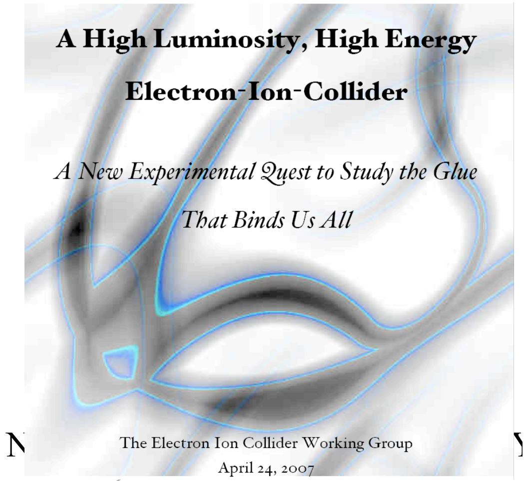

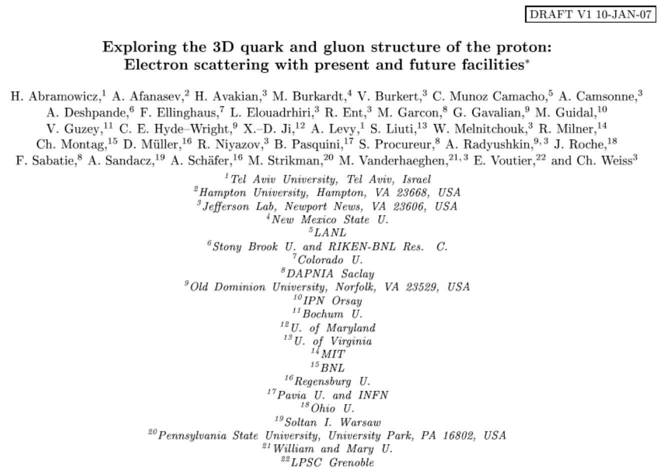
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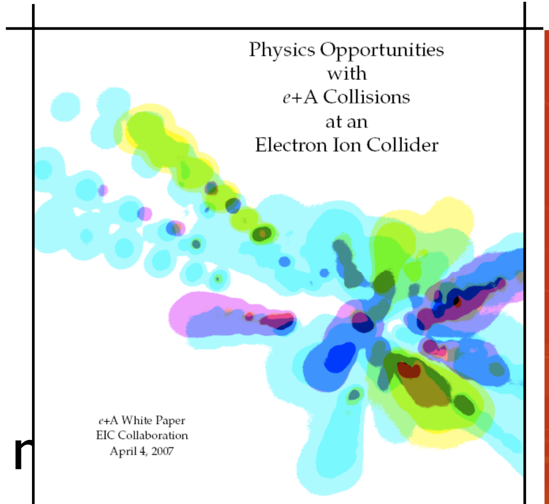

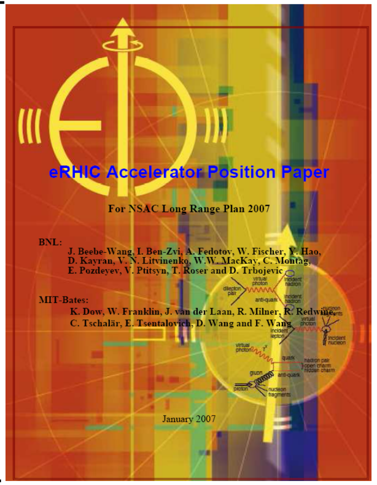

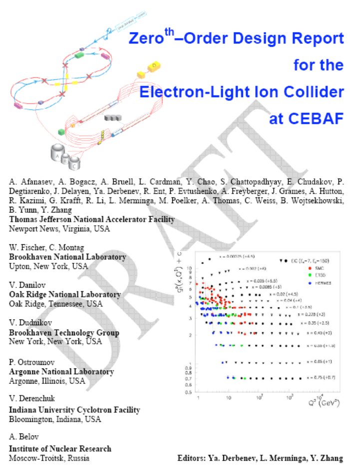
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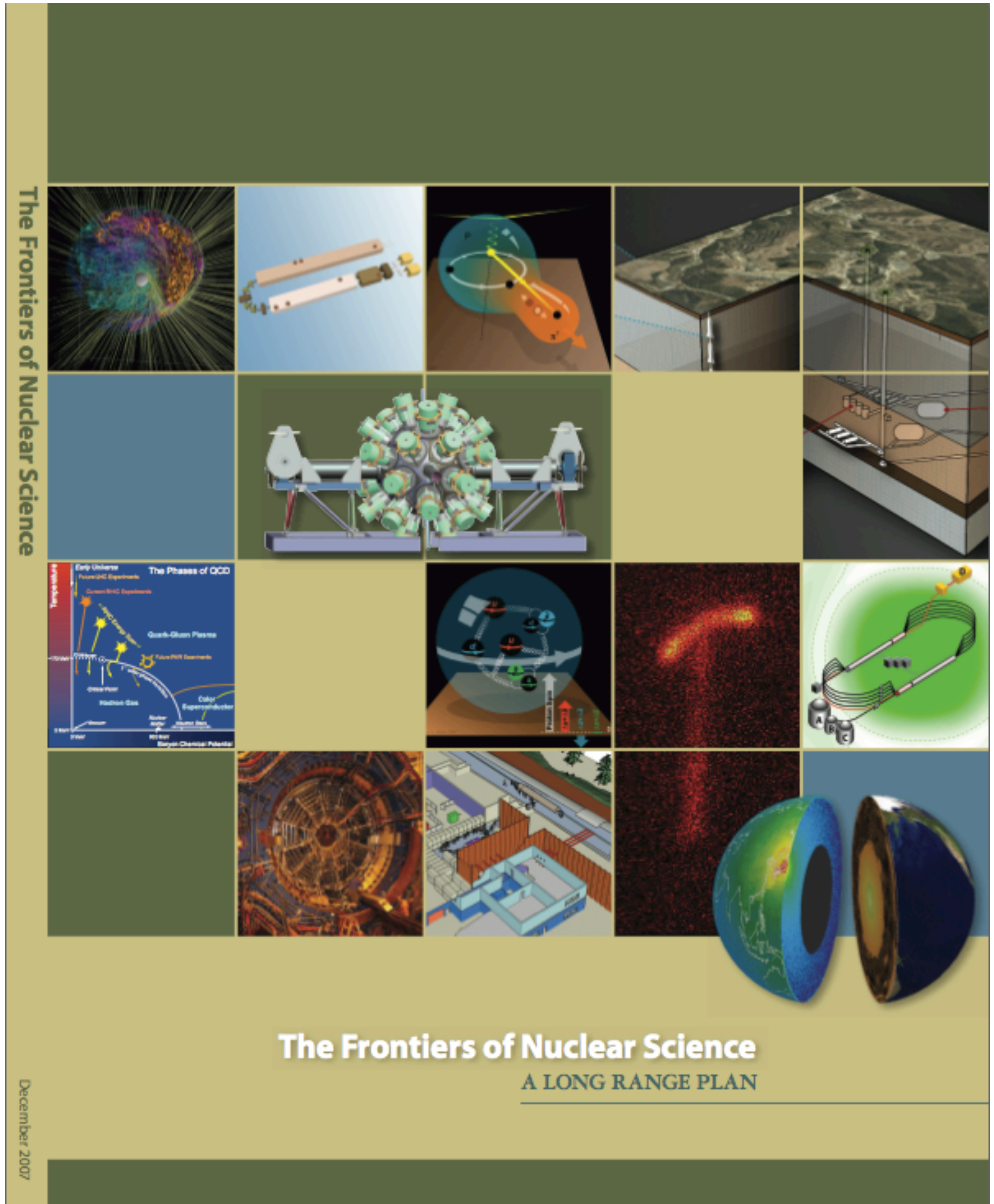
2007 NSAC Long Range Plan



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FURTHER INTO THE FUTURE

Gluons and their interactions are critical to QCD. But their properties and dynamics in matter remain largely unexplored. Recent theoretical breakthroughs and experimental results suggest that both nucleons and nuclei, when viewed at high energies, appear as dense systems of gluons, creating fields whose intensity may be the strongest allowed in nature. The emerging science of this universal gluonic matter drives the development of a next-generation facility, the high-luminosity Electron-Ion Collider (EIC). The EIC's ability to collide high-energy electron beams with high-energy ion beams will provide access to those regions in the nucleon and nuclei where their structure is dominated by gluons. Moreover, polarized beams in the EIC will give unprecedented access to the spatial and spin structure of gluons in the proton.

An EIC with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. While significant progress has been made in developing concepts for an EIC, many open questions remain. Realization of an EIC will require advancements in accelerator science and technology, and detector research and development. The nuclear science community has recognized the importance of this future facility and makes the following recommendation.

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An EIC with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. While significant progress has been made in developing concepts for an EIC, many open questions remain. Realization of an EIC will require advancements in accelerator science and technology, and detector research and development. The nuclear science community has recognized the importance of this future facility and makes the following recommendation.

2007 NSAC Long Range Plan

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We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.

What is happening now

- EIC "Collaboration" formed in 2007
  - ➡ Bi-Annual collaboration meetings
    - Next meeting, 11th - 13th December, 2008, LBNL
- INT
  - ➡ Week long workshop - Autumn 2009
  - ➡ 3-month programme just approved - Autumn 2010
- e+A working group
  - ➡ Convenors: T. Ullrich, D. Morrison, R. Venugopalan, V. Guzey
  - ➡ weekly(ish) meetings at BNL + phone bridge
    - http://www.eic.bnl.gov/ for details (and previous seminars)
  - ➡ Current focus of work - understanding diffraction in e+A physics
    - How do we measure diffractive events? ⇒ detector design
  - ➡ Last week of September, mini-workshop at BNL to start work on putting together an *e*+A MC code for both DIS and diffractive events

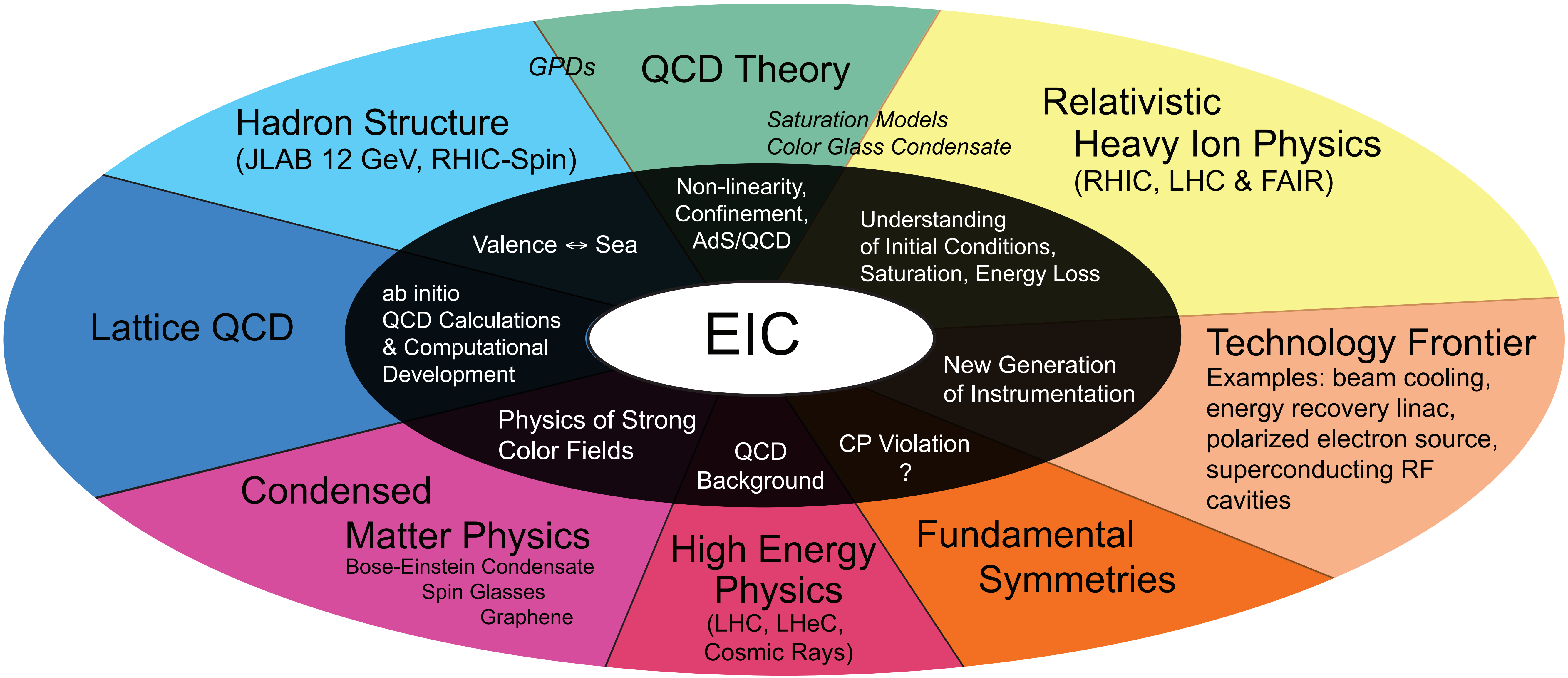
Summary

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

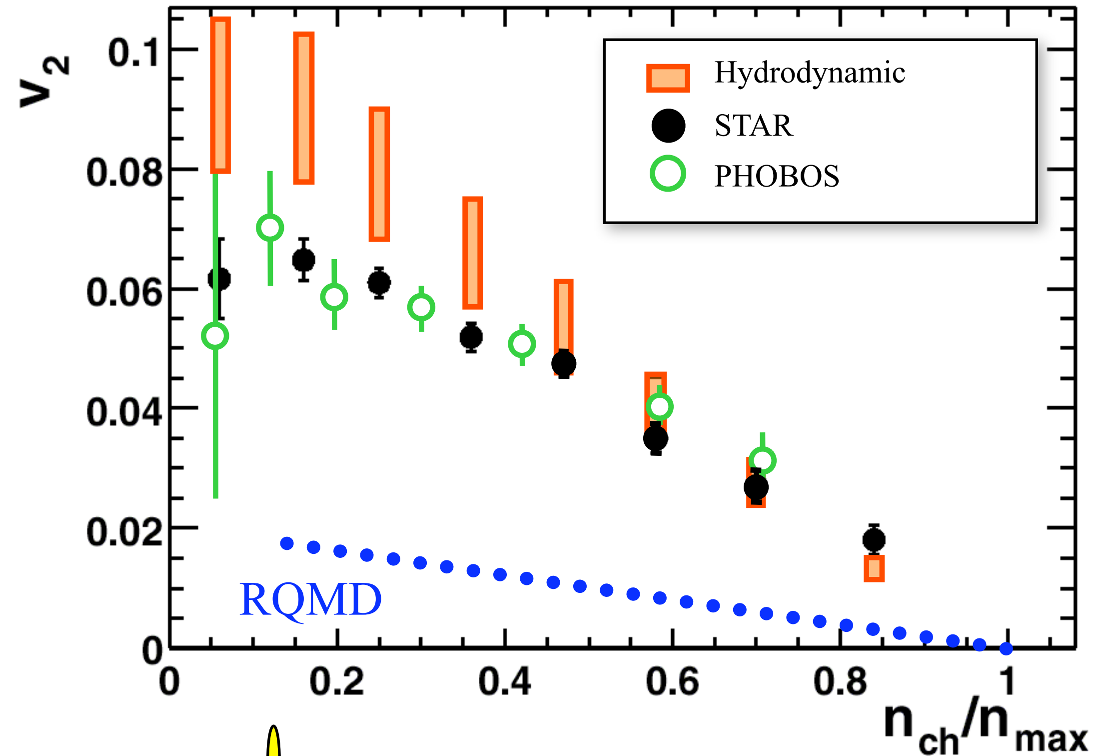
- Embraced by NSAC in Long Range PLan
  - Recommendation of $30M for R&D over next 5 years
- EIC Long Term Goal - start construction in next decade
- Possibility of Staged Approach
  - Cheap (no civil construction costs)
  - Early timescale (operation by ~2016)
  - Cons - lower energy and luminosity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

Connection to other fields

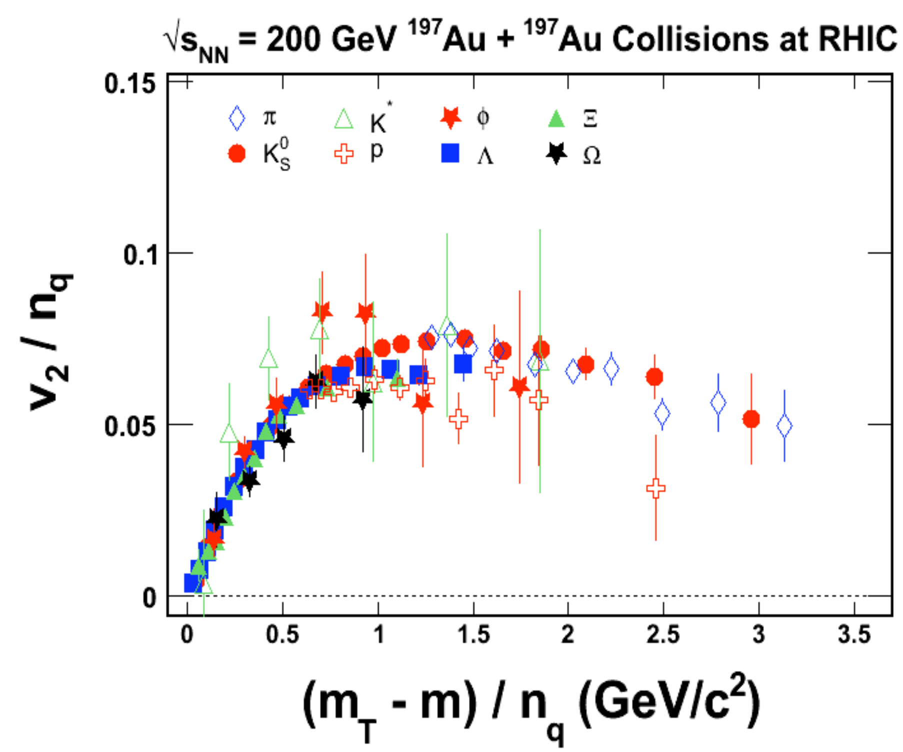


Seminal Result - Hadron flow

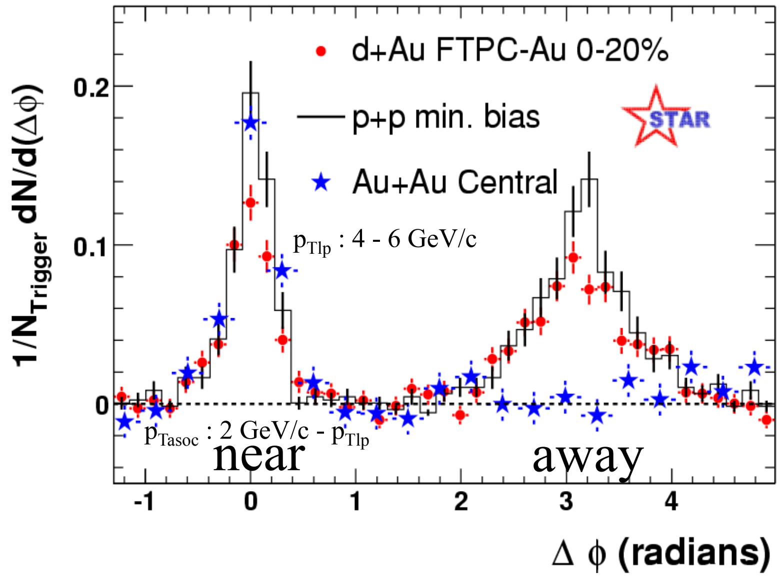
- Strong flow of hadrons
  - ➡ Strong flow of hadrons, for the 1st time, reaches agreement with ideal hydrodynamics.
  - ➡ Flow much greater than hadron-gas models can produce.
  - ➡ Copious production of baryons and mesons whose flow properties are suggestive of their formation via coalescence from a hot thermal bath



- Models suggest thermalization within 0.6 fm/c of the collision !!!!!!!
  - ➡ Models sensitive to pre-equilibrium conditions
  - ➡ Need to understand properties of nuclear wave function



Seminal Result - Opaque Medium



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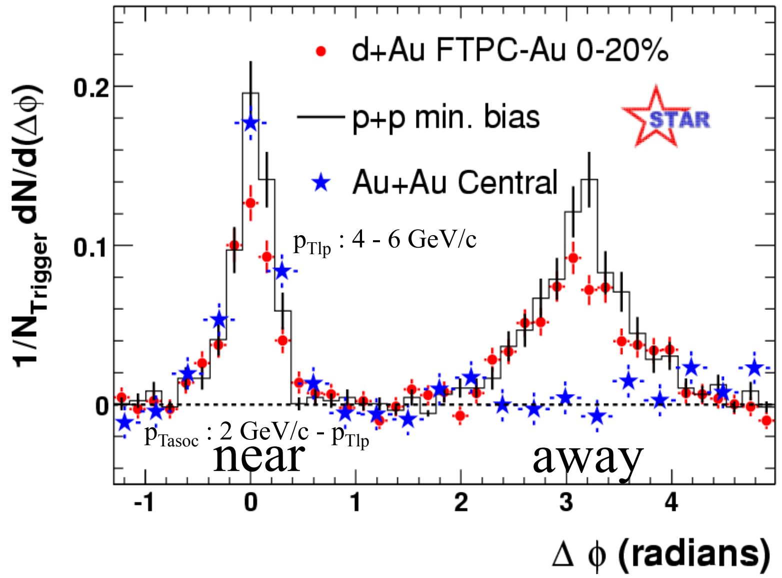
- Triggering on di-hadron correlations reveals an absence of back-to-back jets in Au+Au collisions



Seminal Result - Opaque Medium

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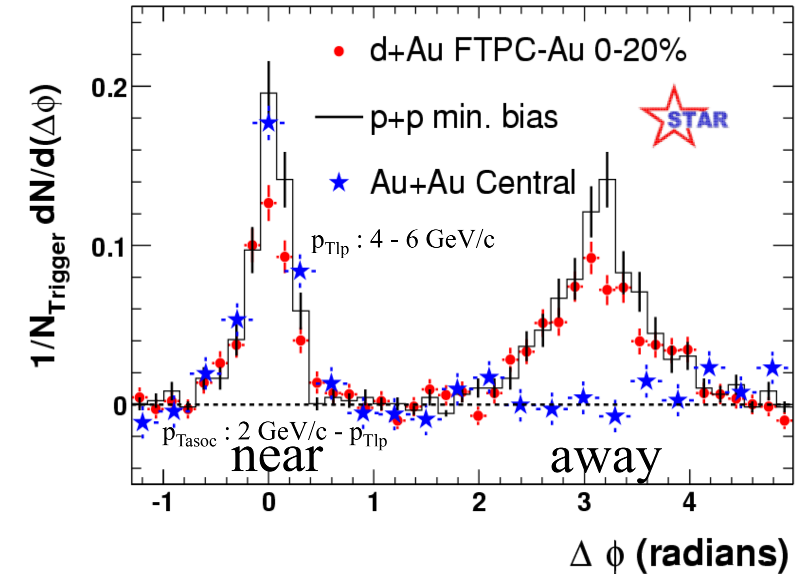
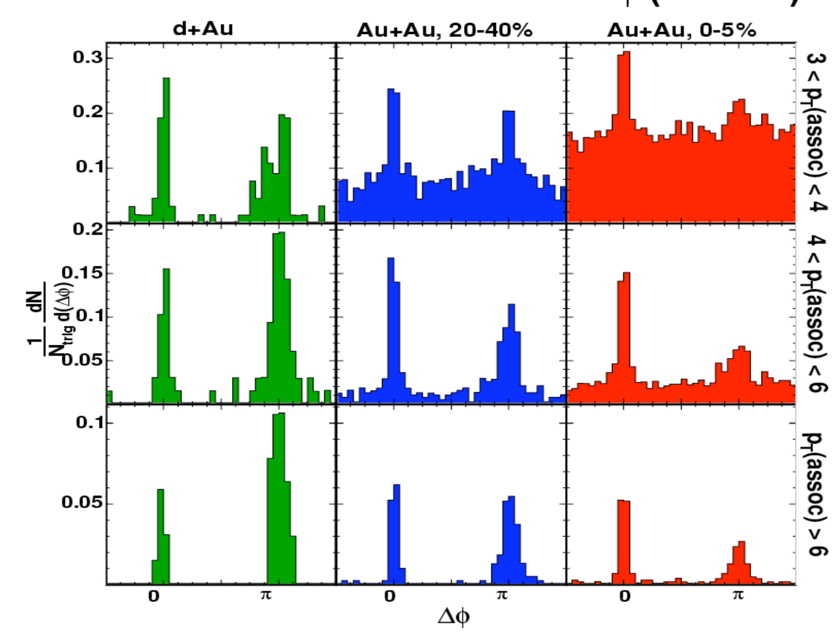
- At high-enough p_T, "away-side" jets re-appear in central Au+Au collisions





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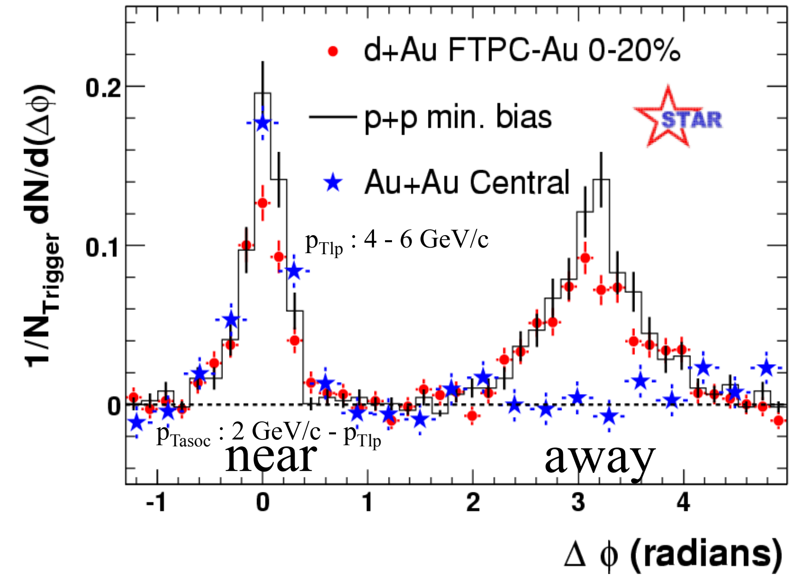

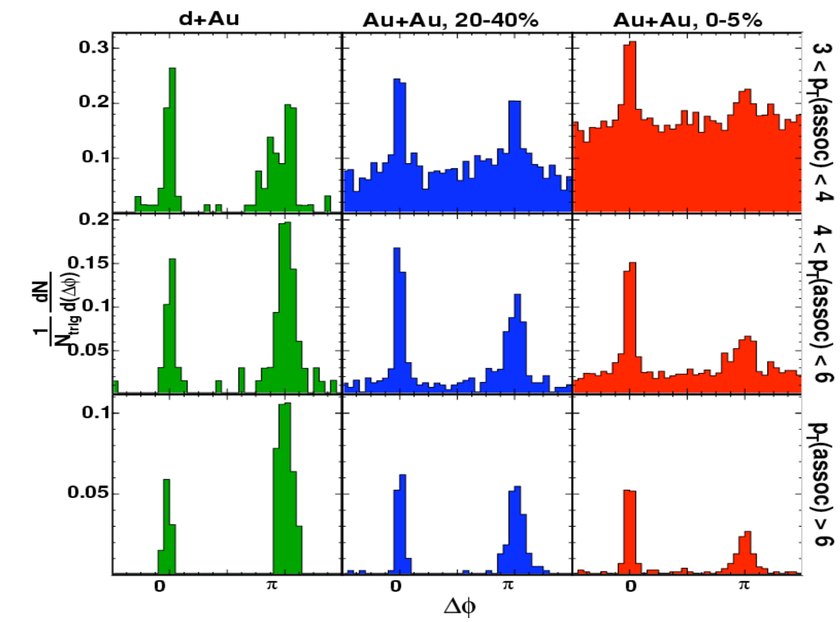

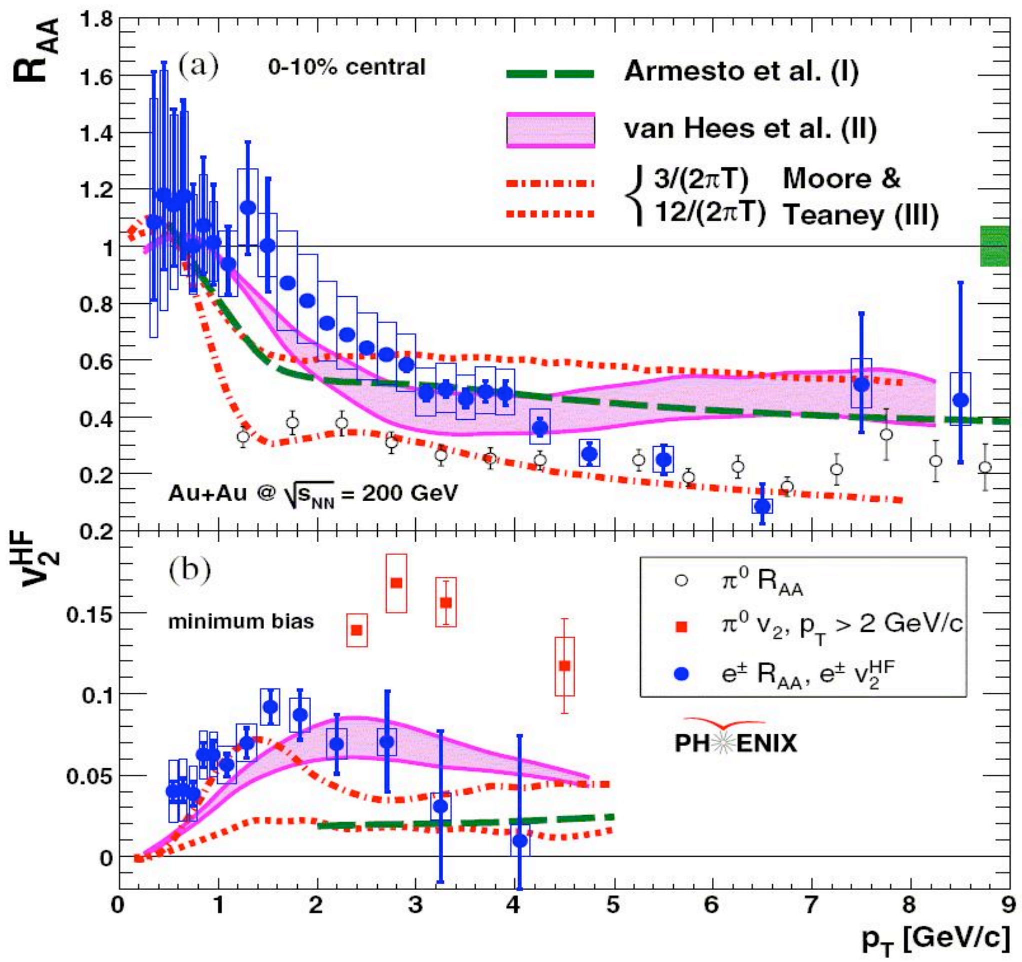

- R_{AA} shows heavy charm quarks suppressed as much as light quarks

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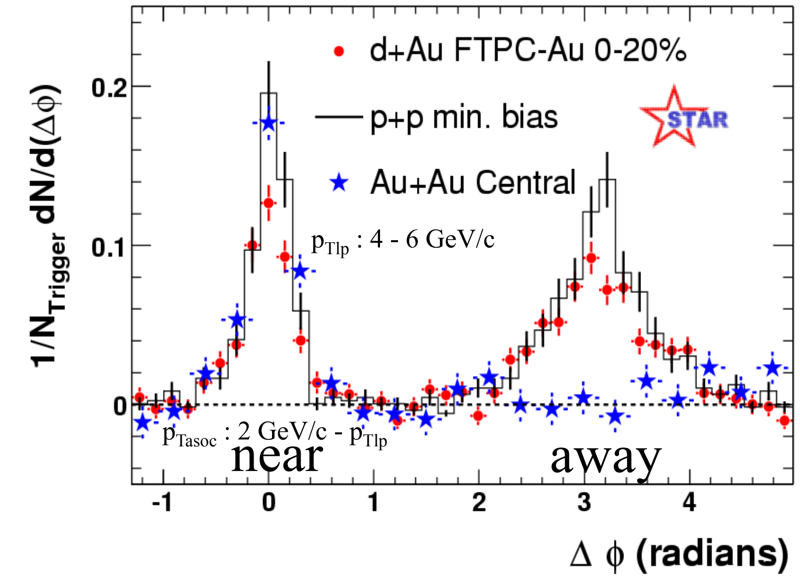

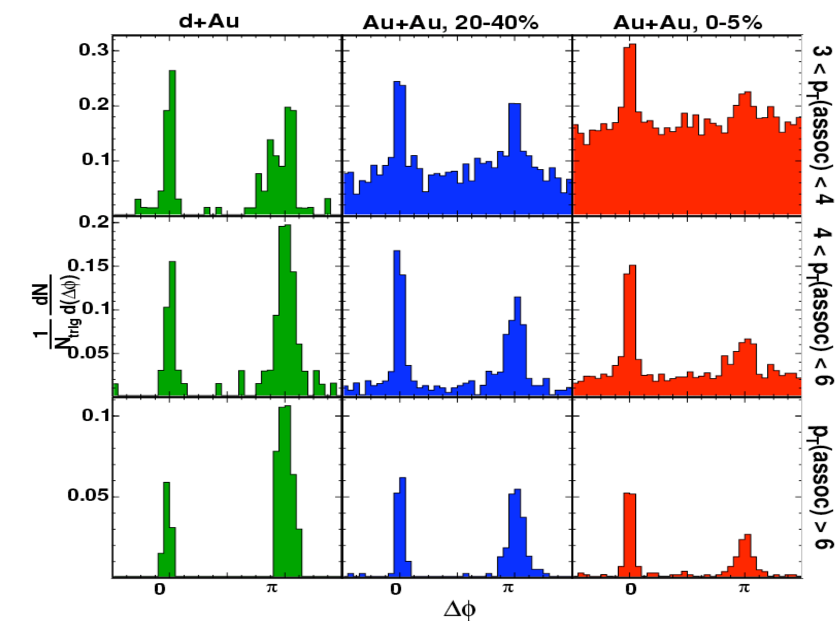

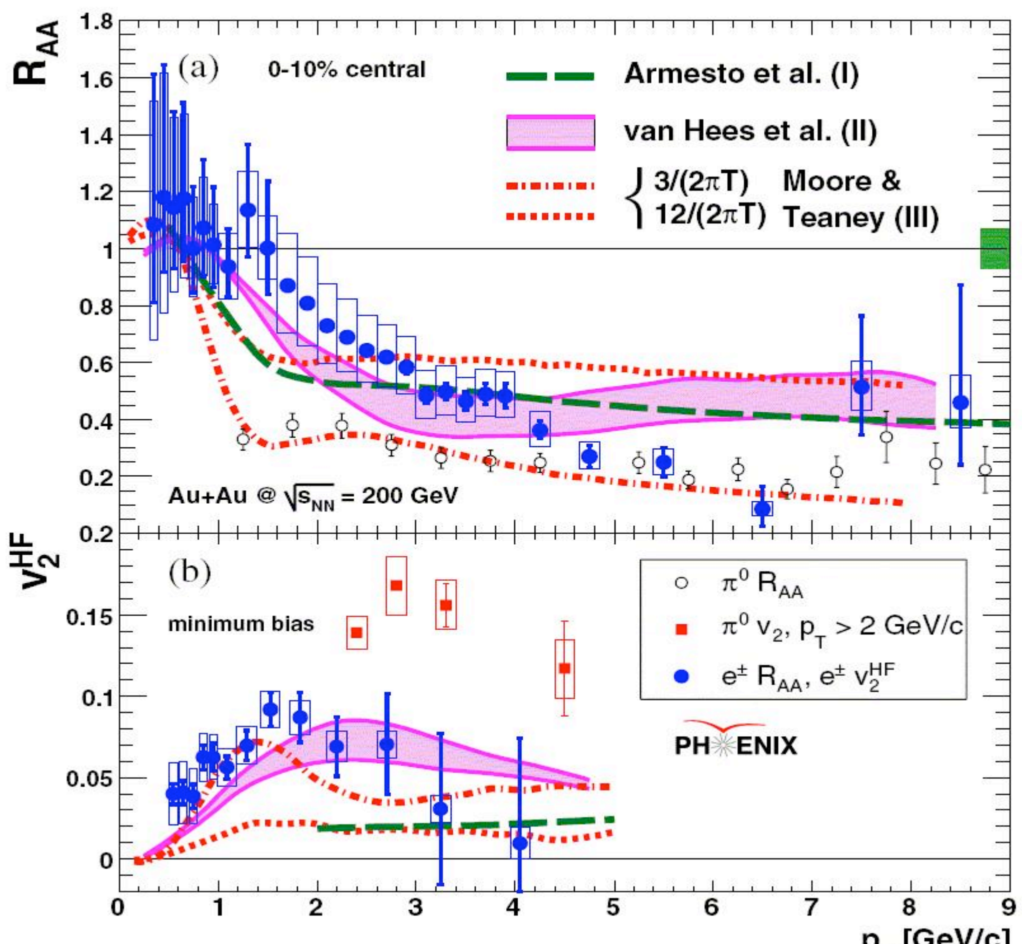

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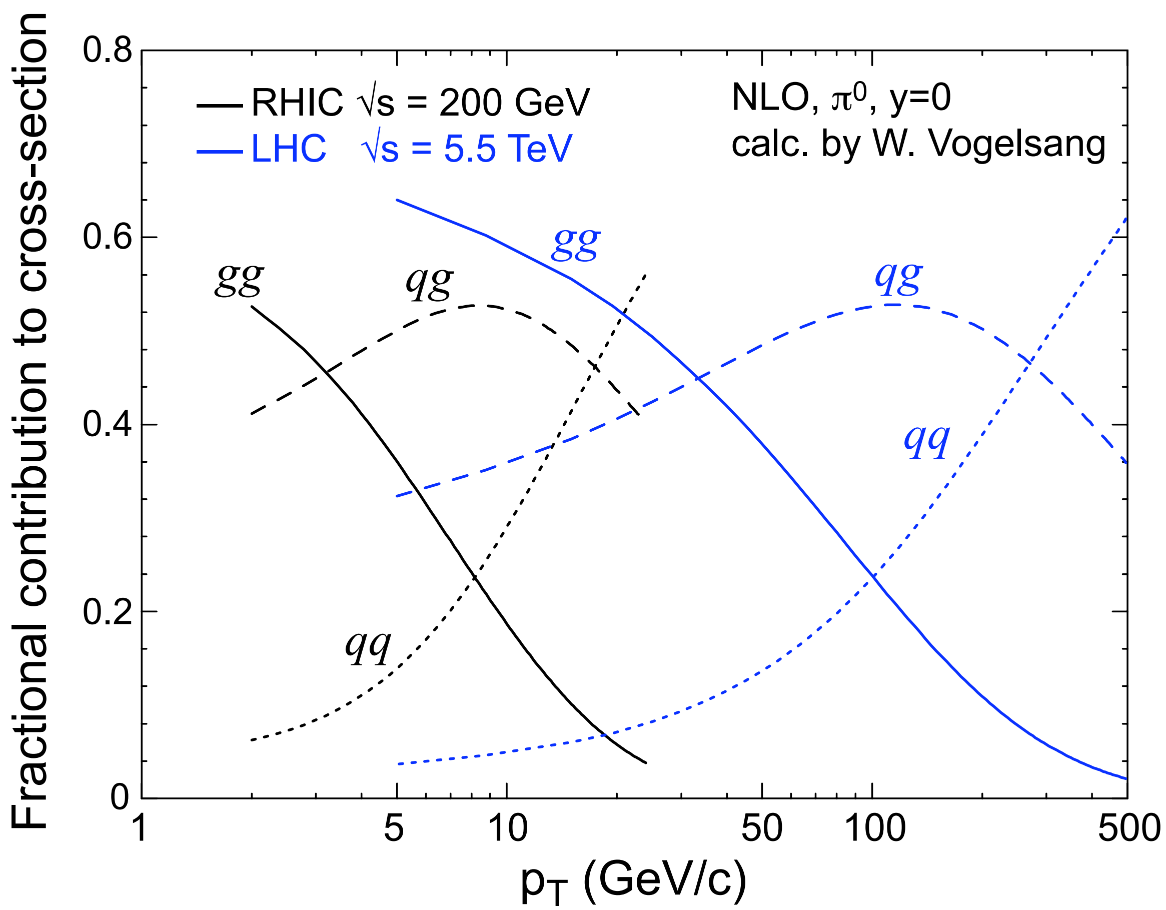
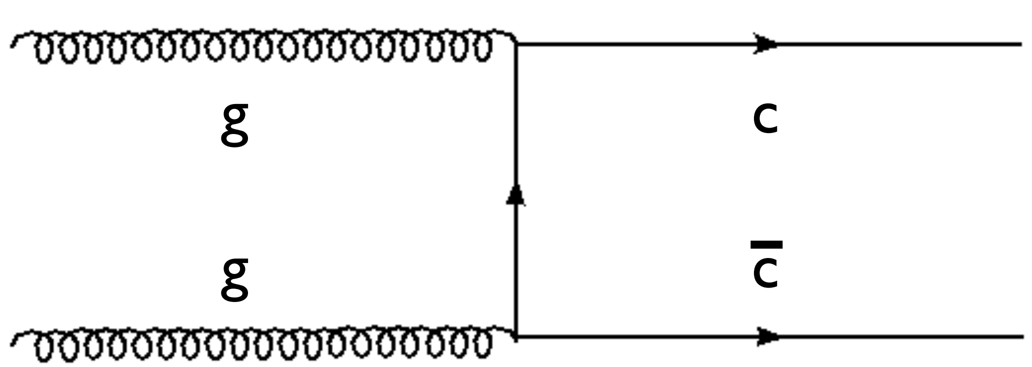
- Need to understand hadronization and energy loss

The role of Glue in Heavy-Ion collisions

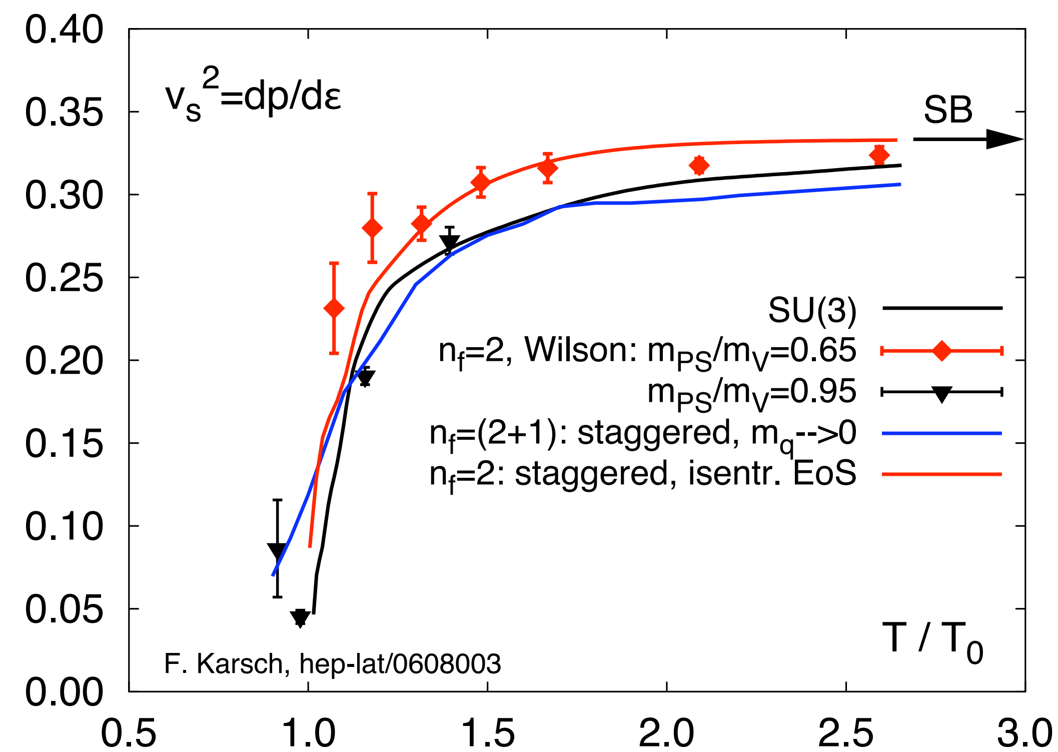
Jets (π^0 production)

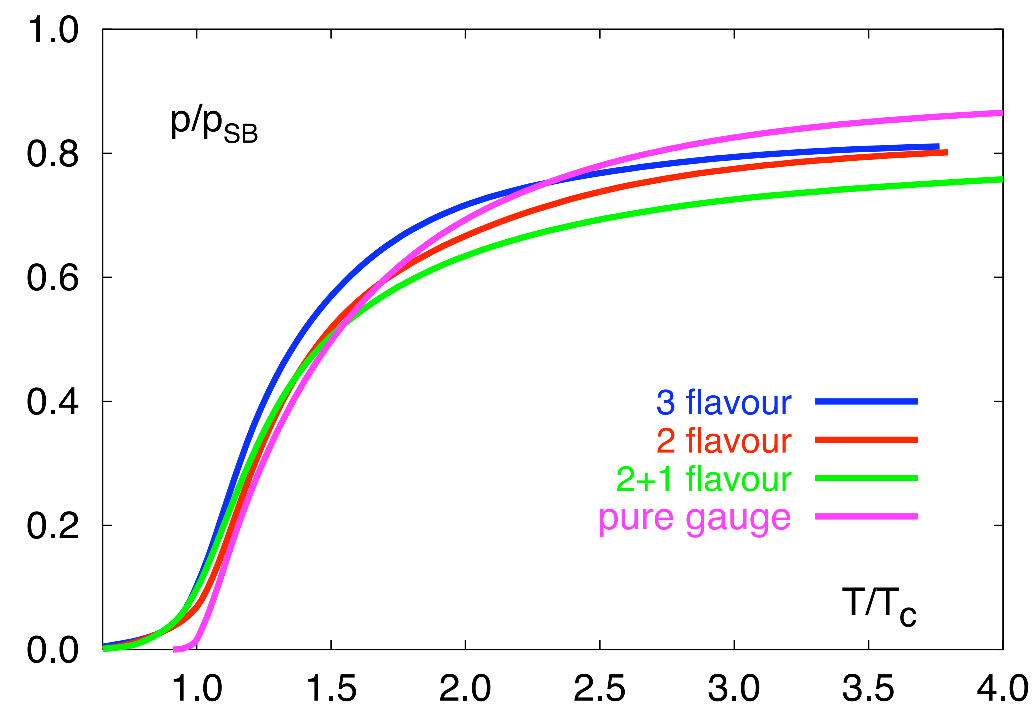


Heavy Flavour Production



Lattice Gauge Theory:





The role of Glue in Heavy-Ion collisions

Jets (π^0 production)

Lattice Gauge Theory:

To move towards understanding HI physics quantitatively, we need to understand the role of glue in HI Collisions !!