

The e+A programme at a future Electron-Ion Collider facility

Matthew A. C. Lamont,
Brookhaven National Laboratory

EIC on the web: <http://web.mit.edu/eicc>

e+A working group: <http://www.eic.bnl.gov>

DIS 2008, London, England

Talk Outline

- Seminal results from RHIC Physics

- ➔ Hydrodynamics

- Initial conditions

- ➔ Jet Quenching

- Hadronization/absorption energy loss

- Understanding the Glue

- ➔ Saturation

- ➔ The Nuclear “Oomph Factor”

- EIC machines and detectors

- ➔ ELIC (Jlab) / eRHIC (BNL)

Seminal Result - Hadron flow

- Strong flow of hadrons

- ➔ Strong flow of hadrons, for the 1st time, reaches agreement with ideal hydrodynamics.

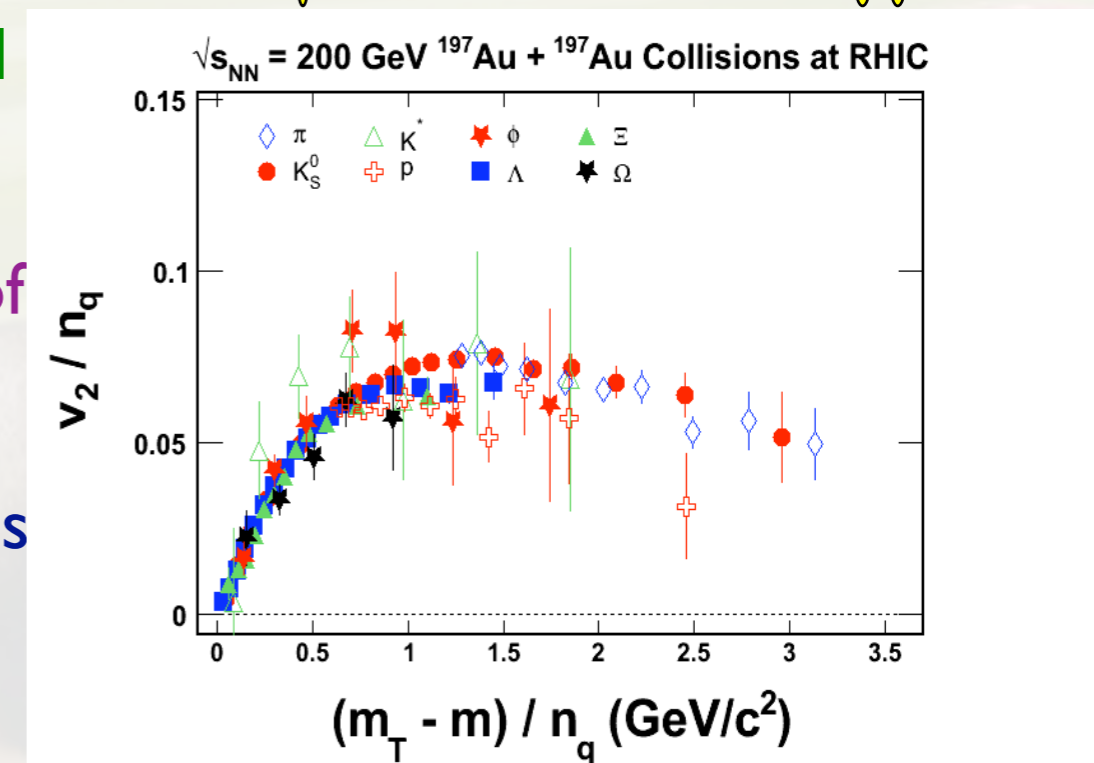
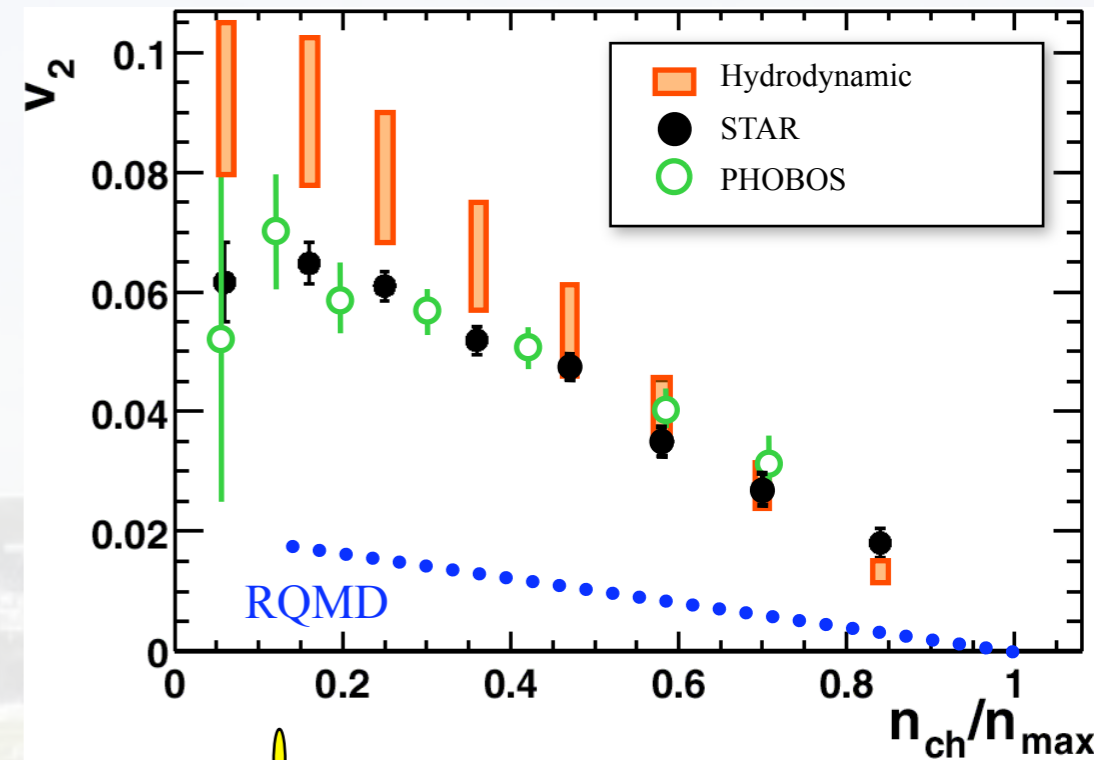
- ➔ Flow much greater than hadron-gas models can produce.

- ➔ Copious production of baryons and mesons whose flow properties are suggestive of their formation via coalescence from a hot thermal bath

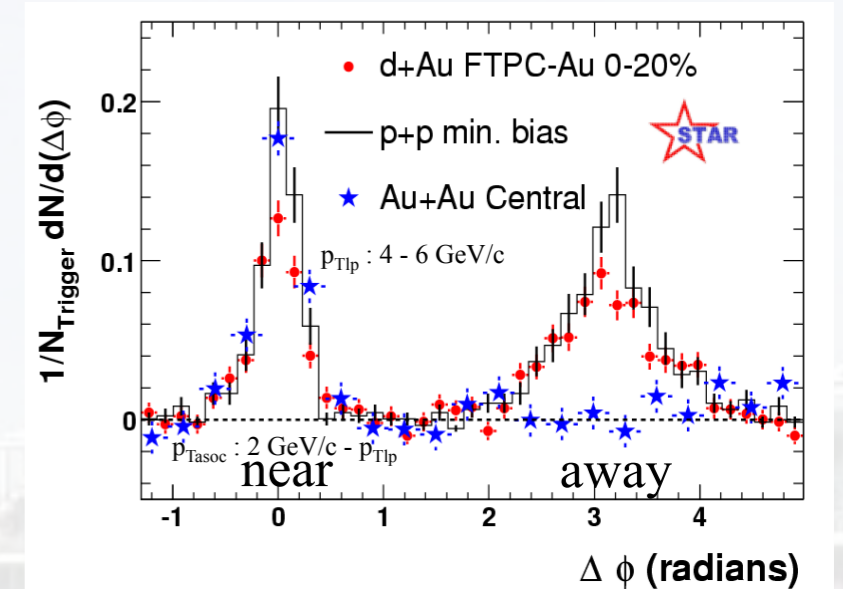
- Models suggest thermalization within 0.6 fm/c of the collision !!!!!!!

- ➔ Models sensitive to pre-equilibrium conditions

- ➔ Need to understand properties of nuclear wave function

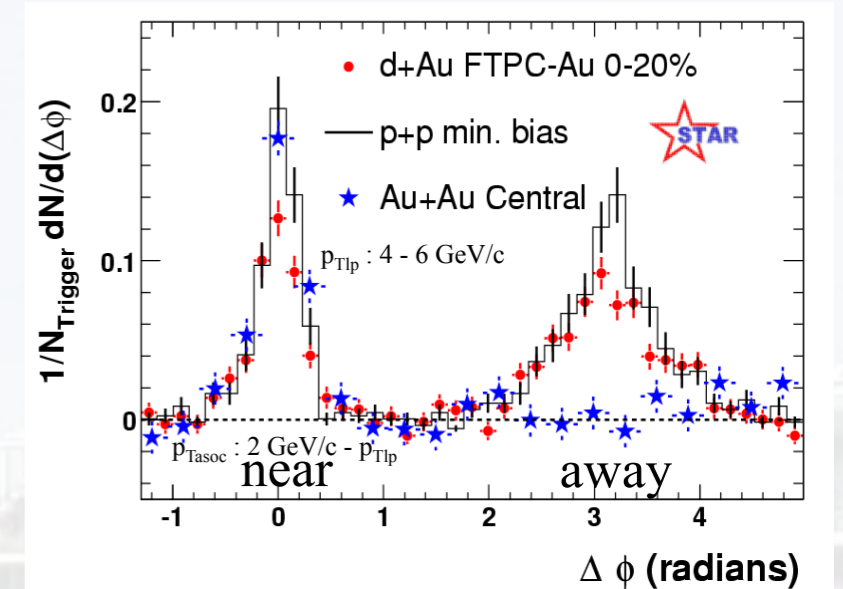


Seminal Result - Opaque Medium



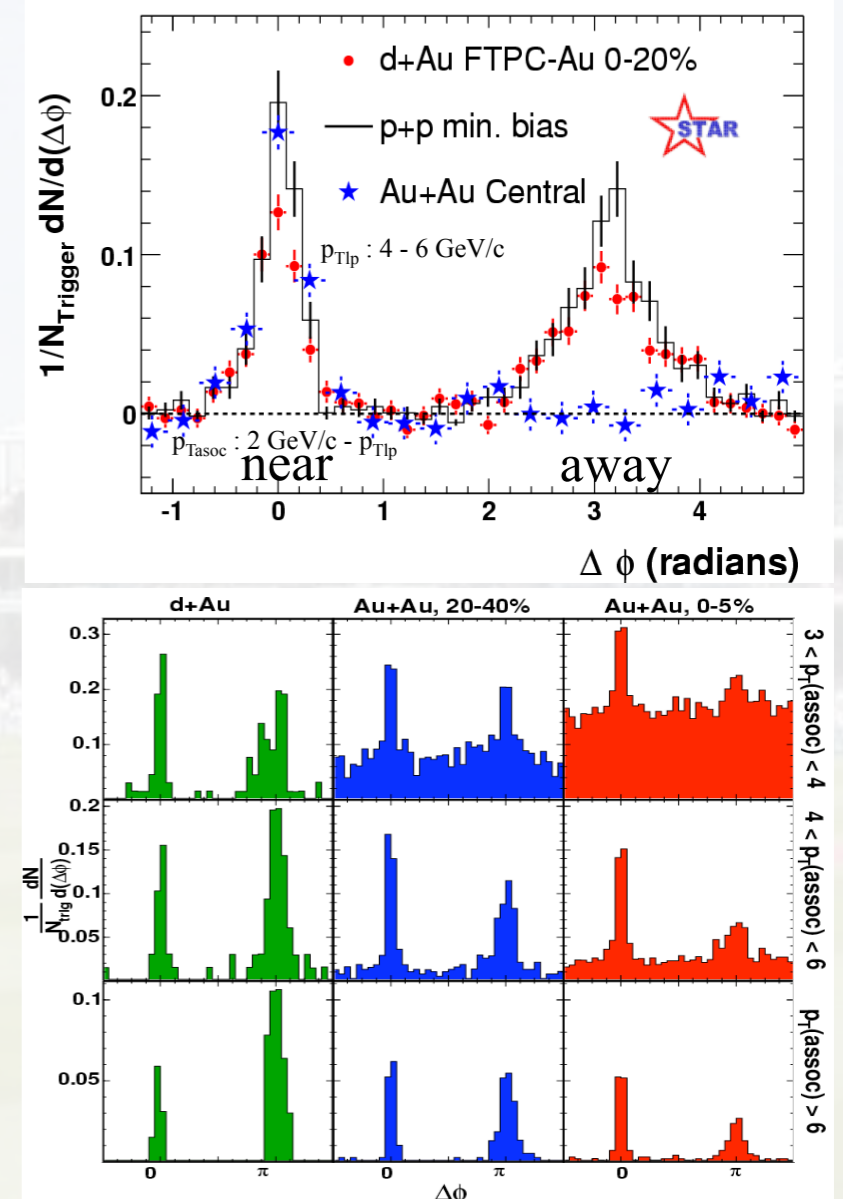
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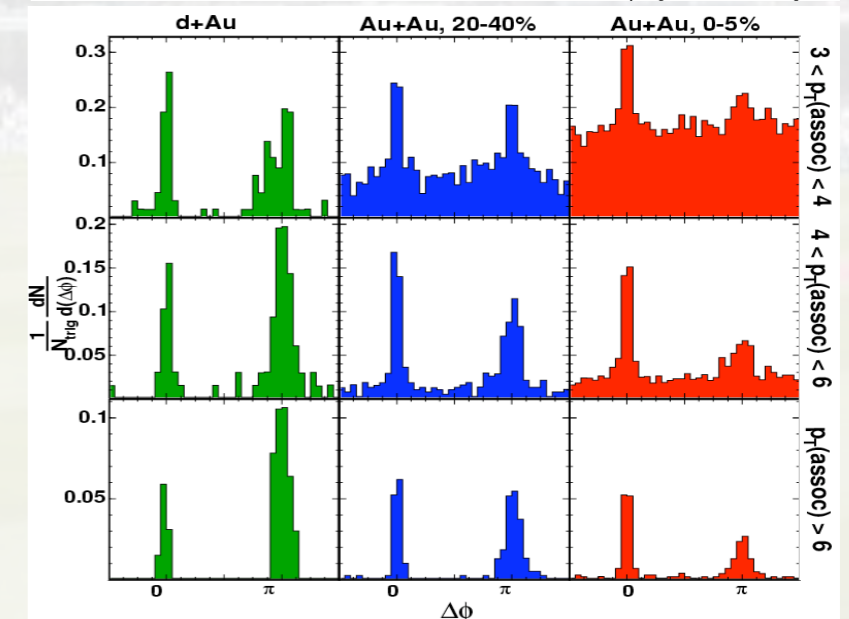
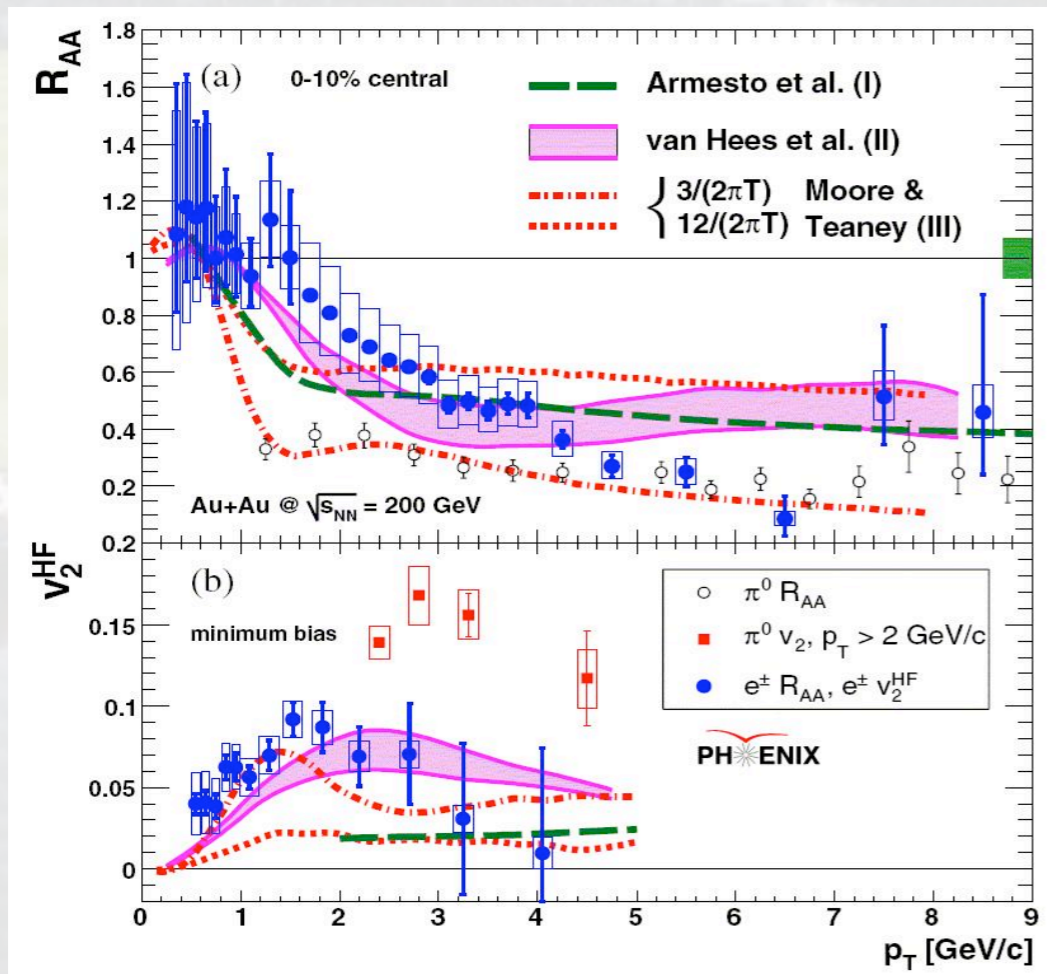
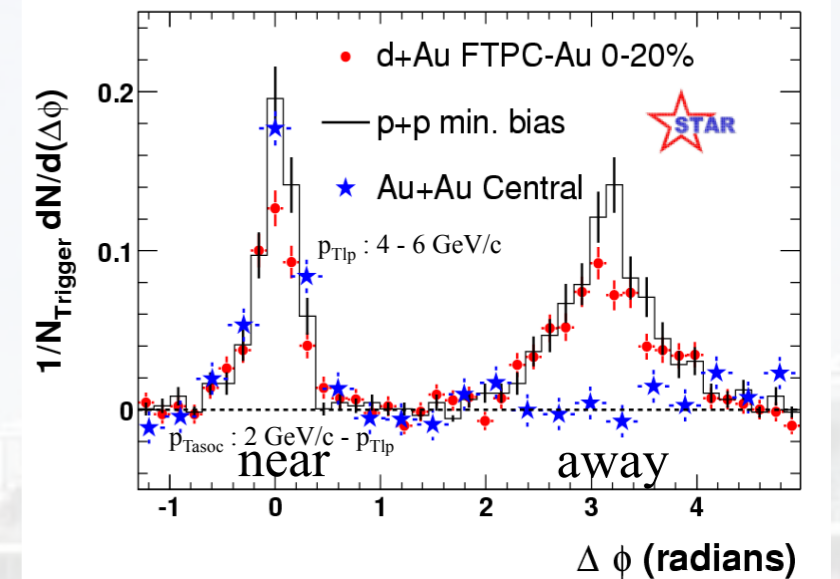
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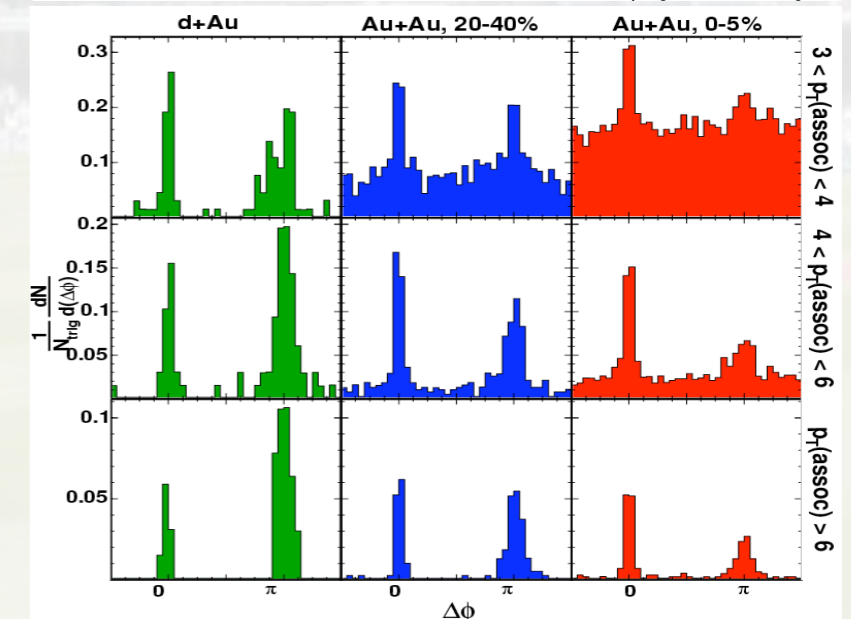
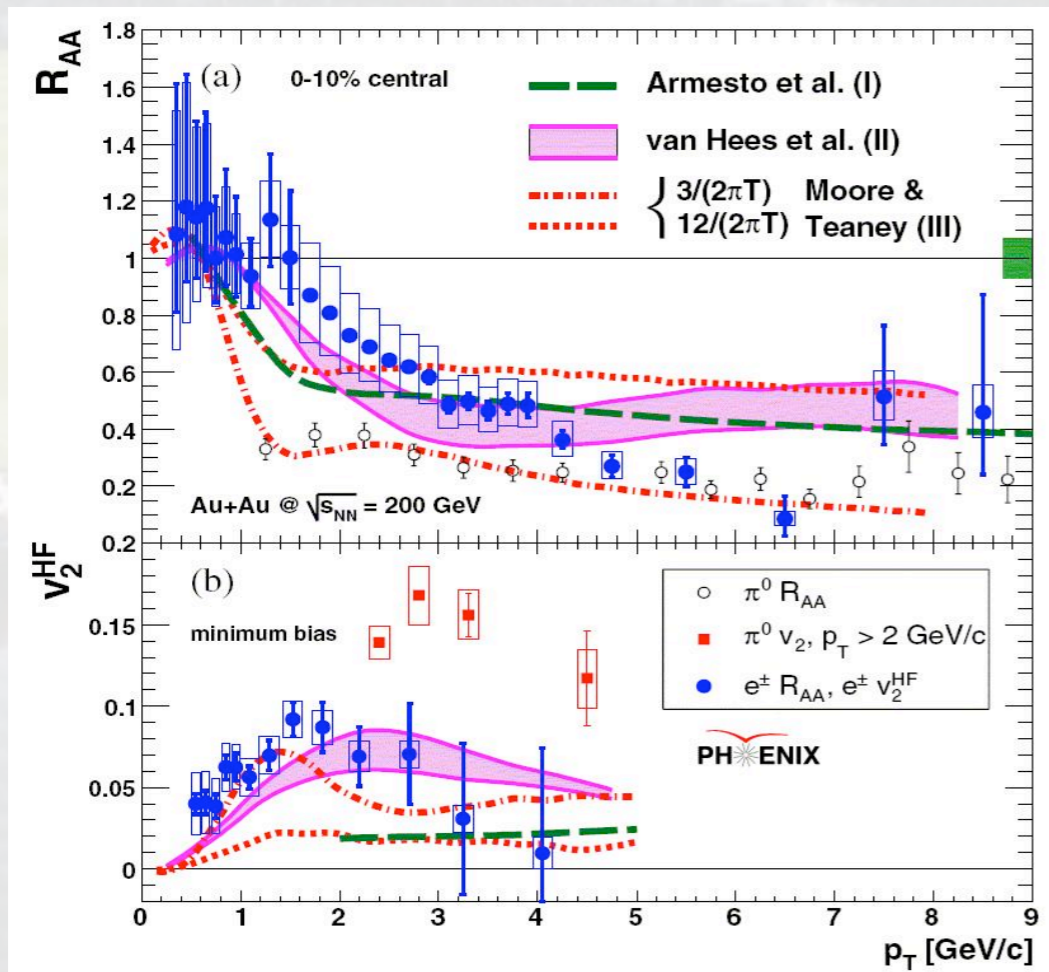
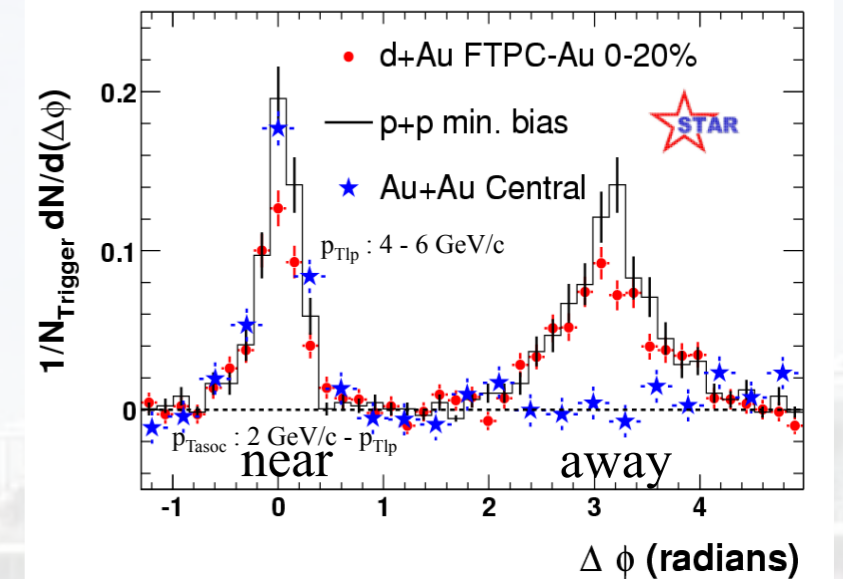
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- R_{AA} shows heavy charm quarks suppressed as much as light quarks

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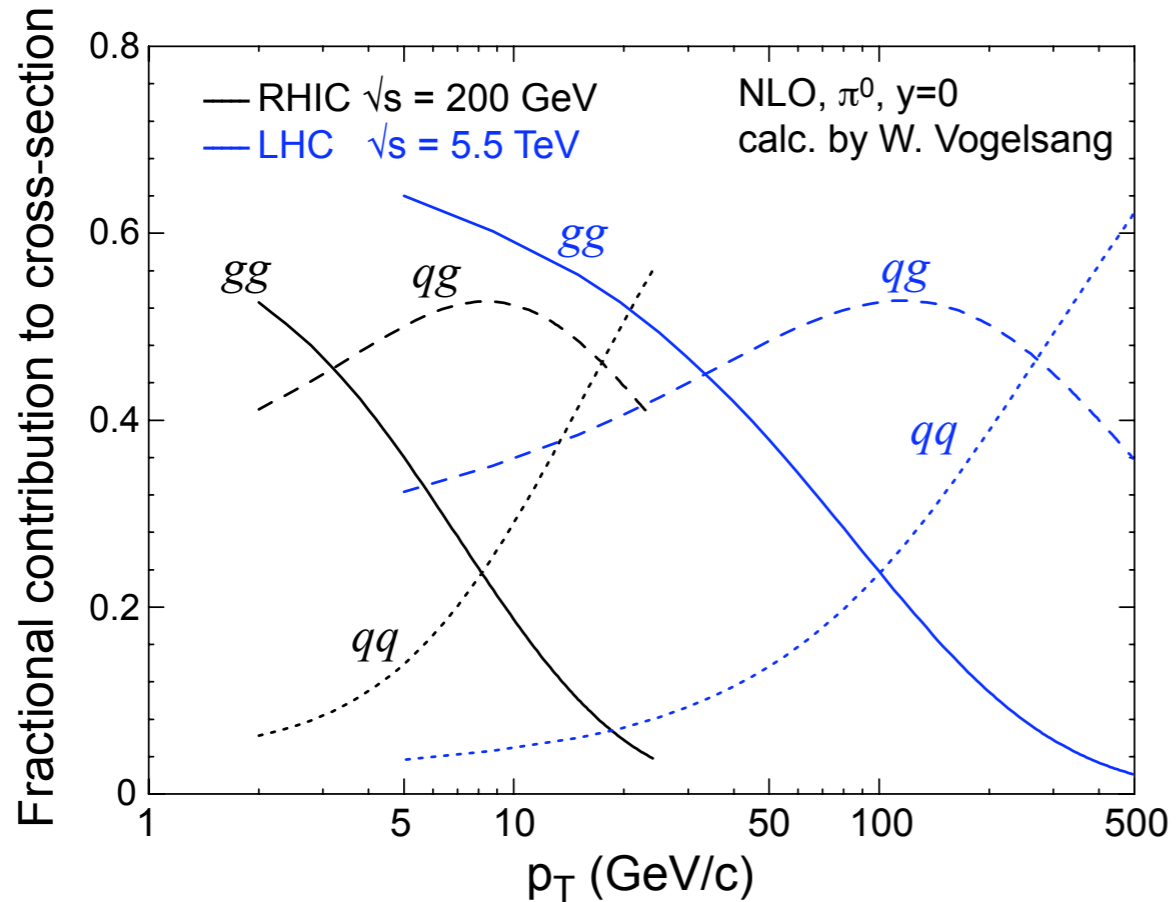
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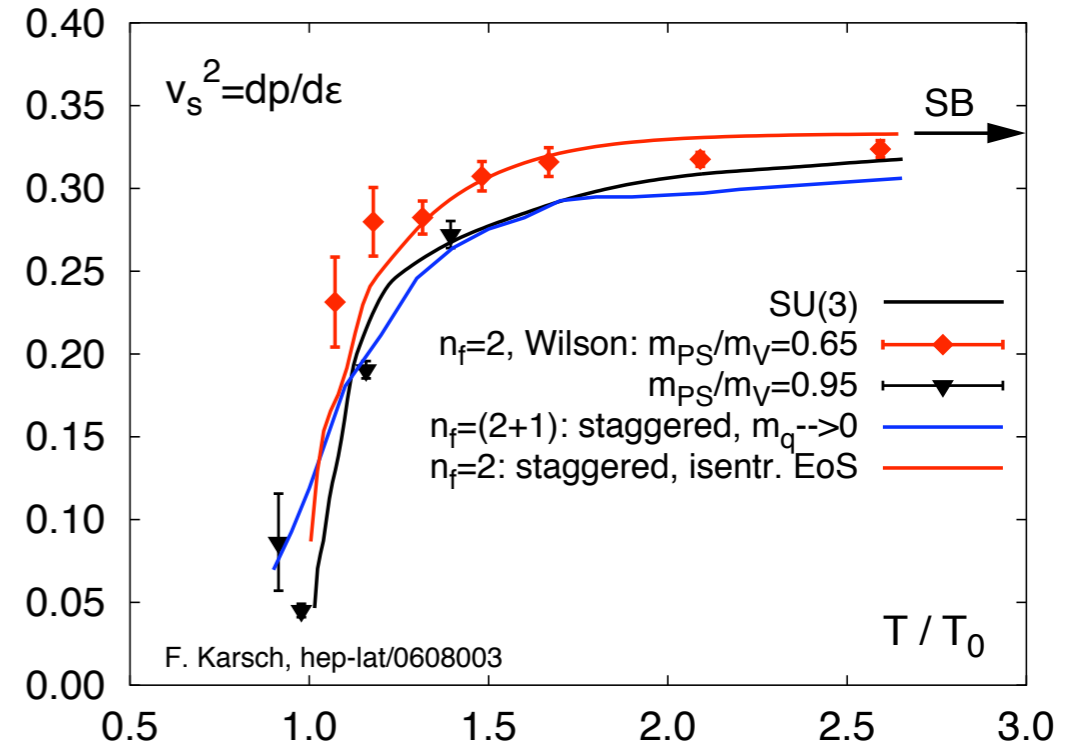
- R_{AA} shows heavy charm quarks suppressed as much as light quarks
- Need to understand hadronization and energy loss

The role of Glue in Heavy-Ion collisions

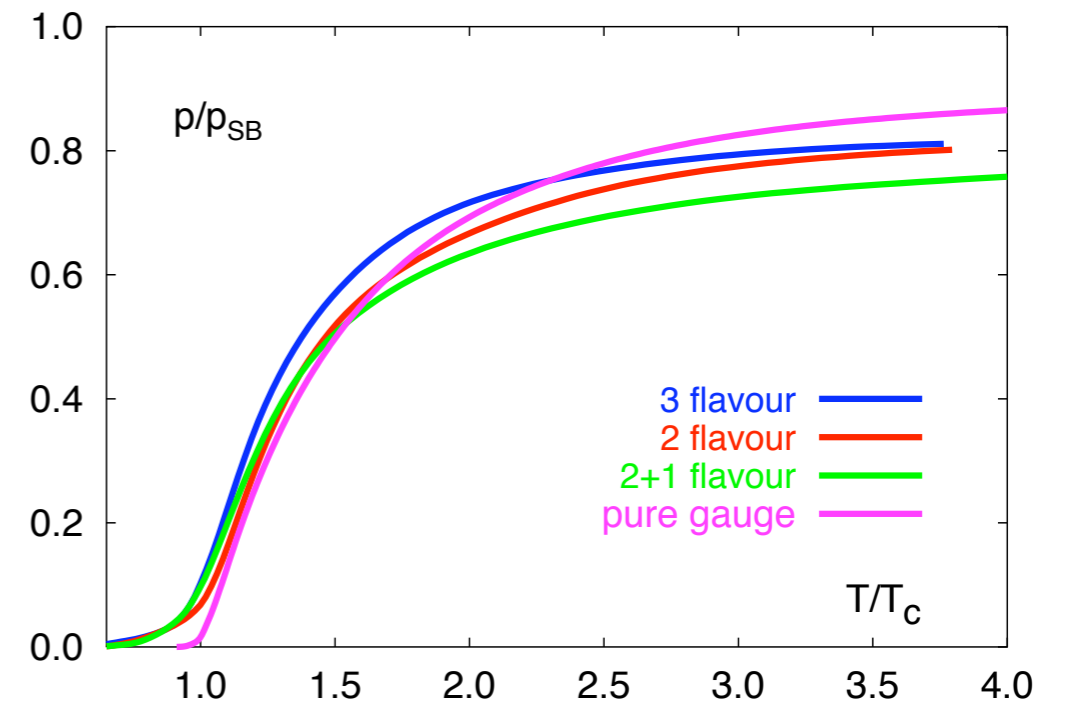
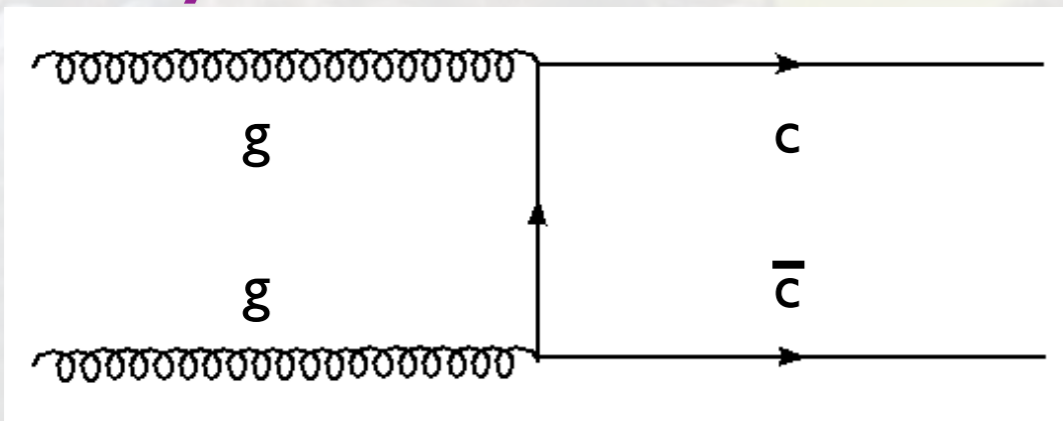
Jets (π^0 production)



Lattice Gauge Theory:



Heavy Flavour Production



Glue and the Lagrangian

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}$$

- **“Emergent” Phenomena not evident from Lagrangian**

- Asymptotic Freedom & Color Confinement

- **Gluons**

- ➔ Determine essential features of QCD

- ➔ Dominate structure of QCD vacuum

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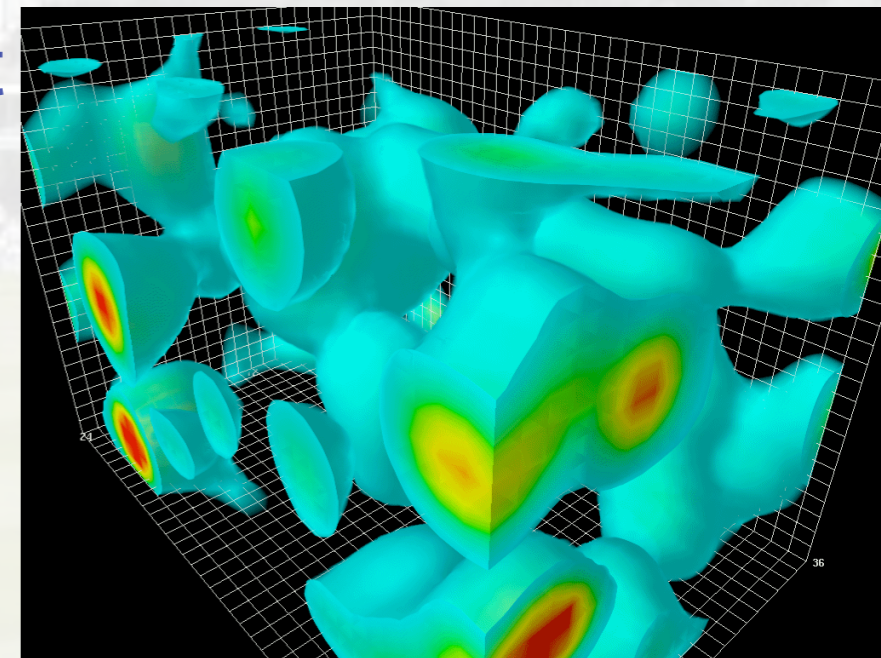
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Action (\sim energy) density fluctuations of gluon-fields in QCD vacuum ($2.4 \times 2.4 \times 3.6$ fm) (Derek Leinweber)

Glue and the Lagrangian

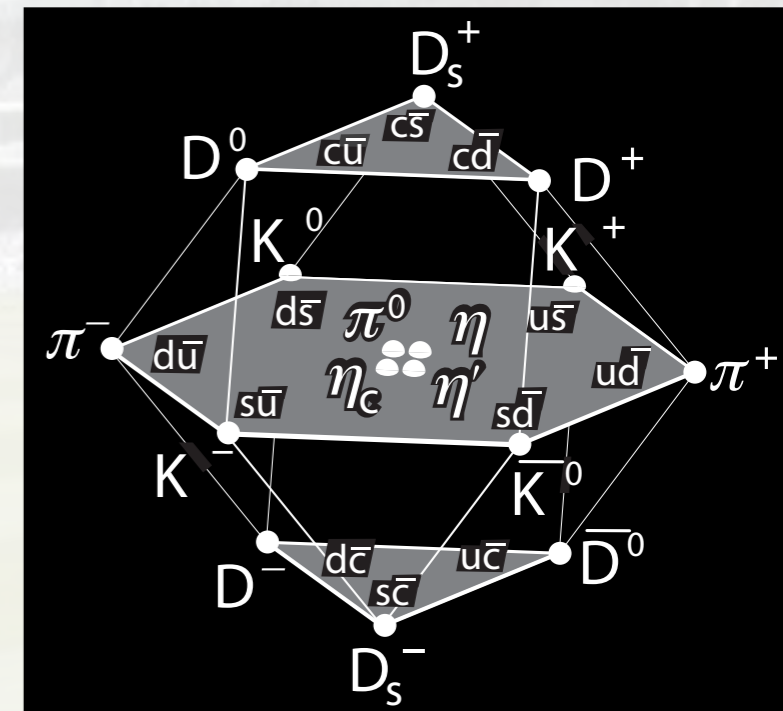
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- Hard to “see” glue in the low-energy world

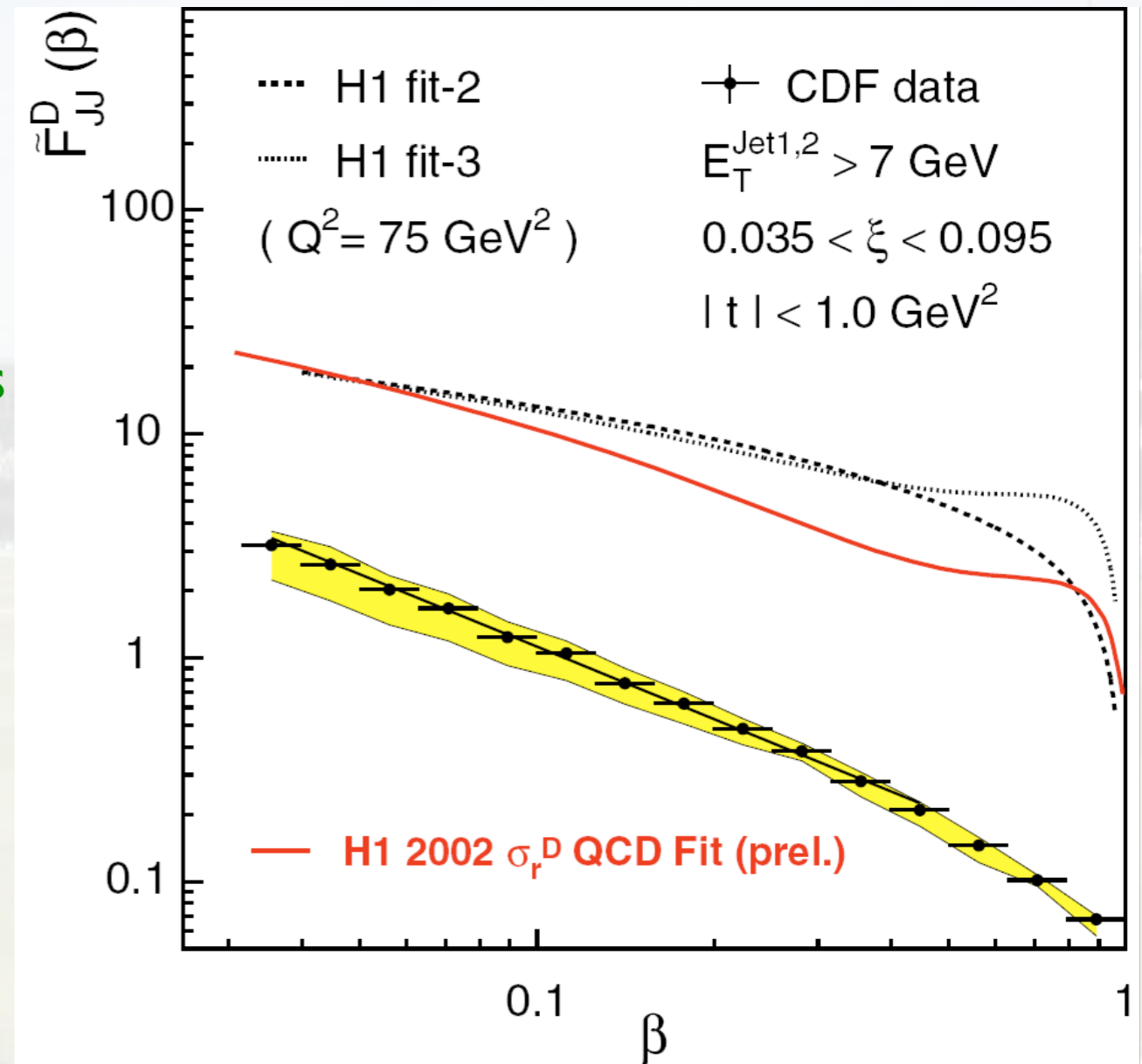
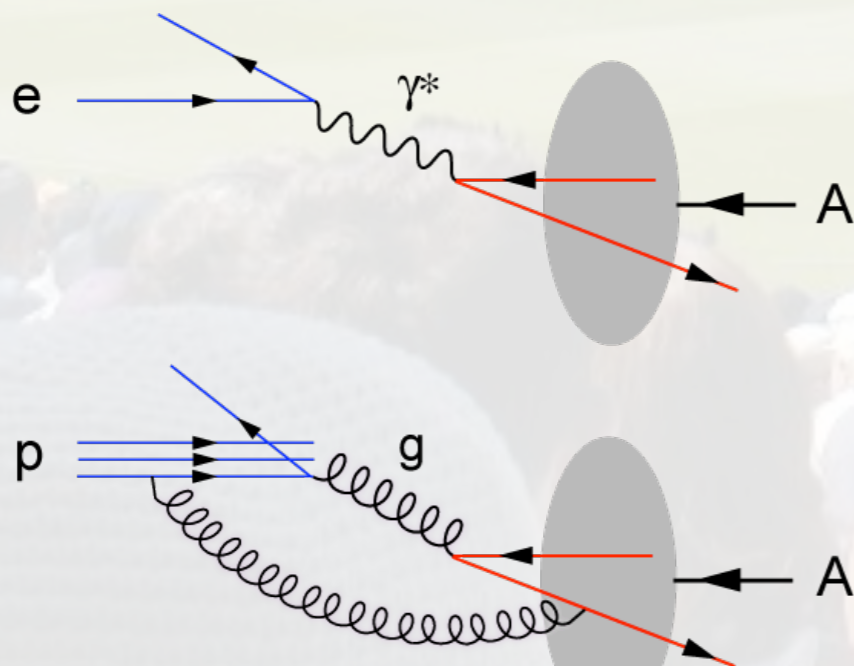
- Gluon degrees of freedom “missing” in hadronic spectrum
- Drive the structure of baryonic matter already at medium-x
- Crucial players at RHIC and LHC

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

F. Schilling, hex-ex/0209001

- $e+A$ 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 \Rightarrow
- Issues:

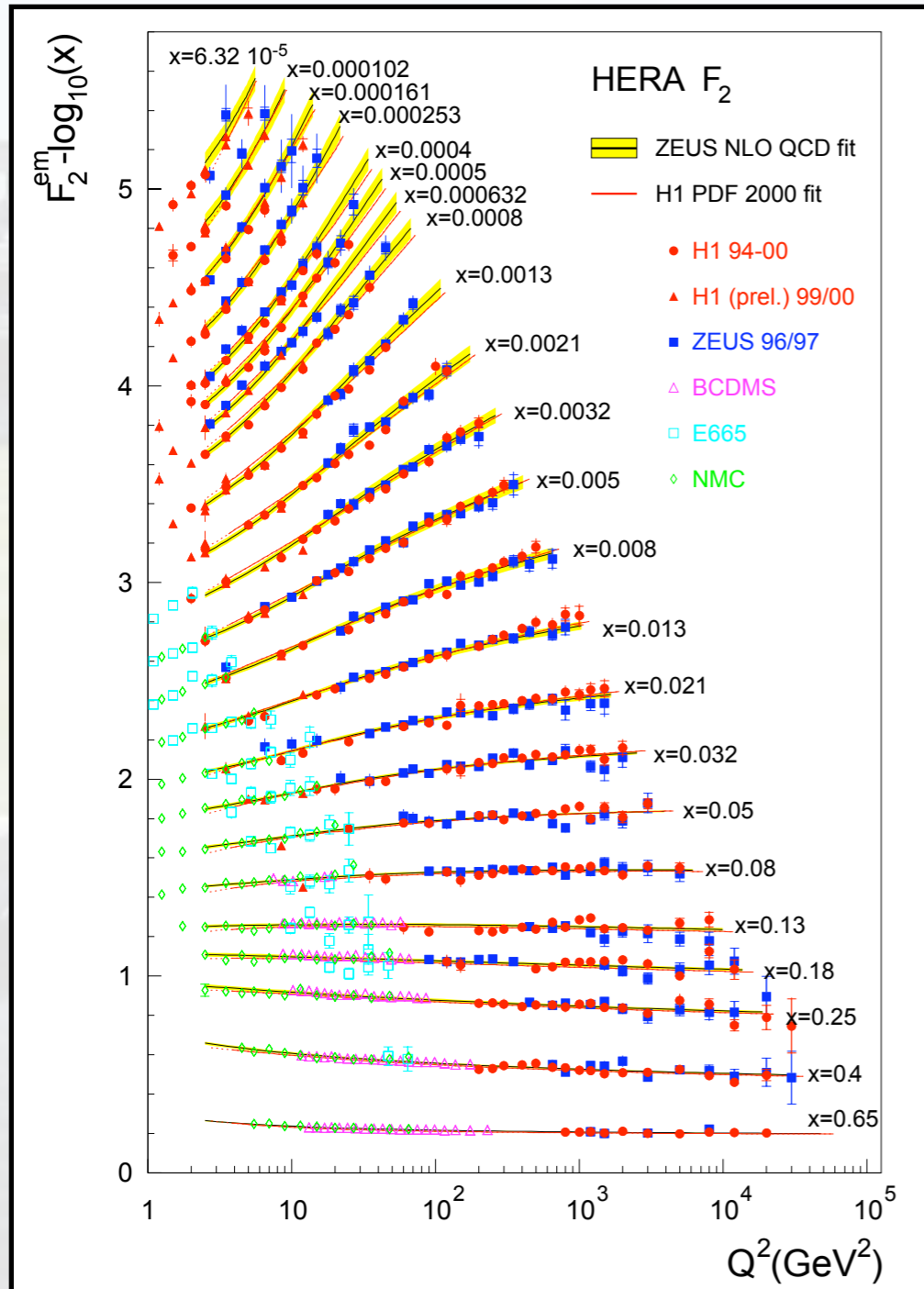
\rightarrow $p+A$ lacks the direct access to x, Q^2



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

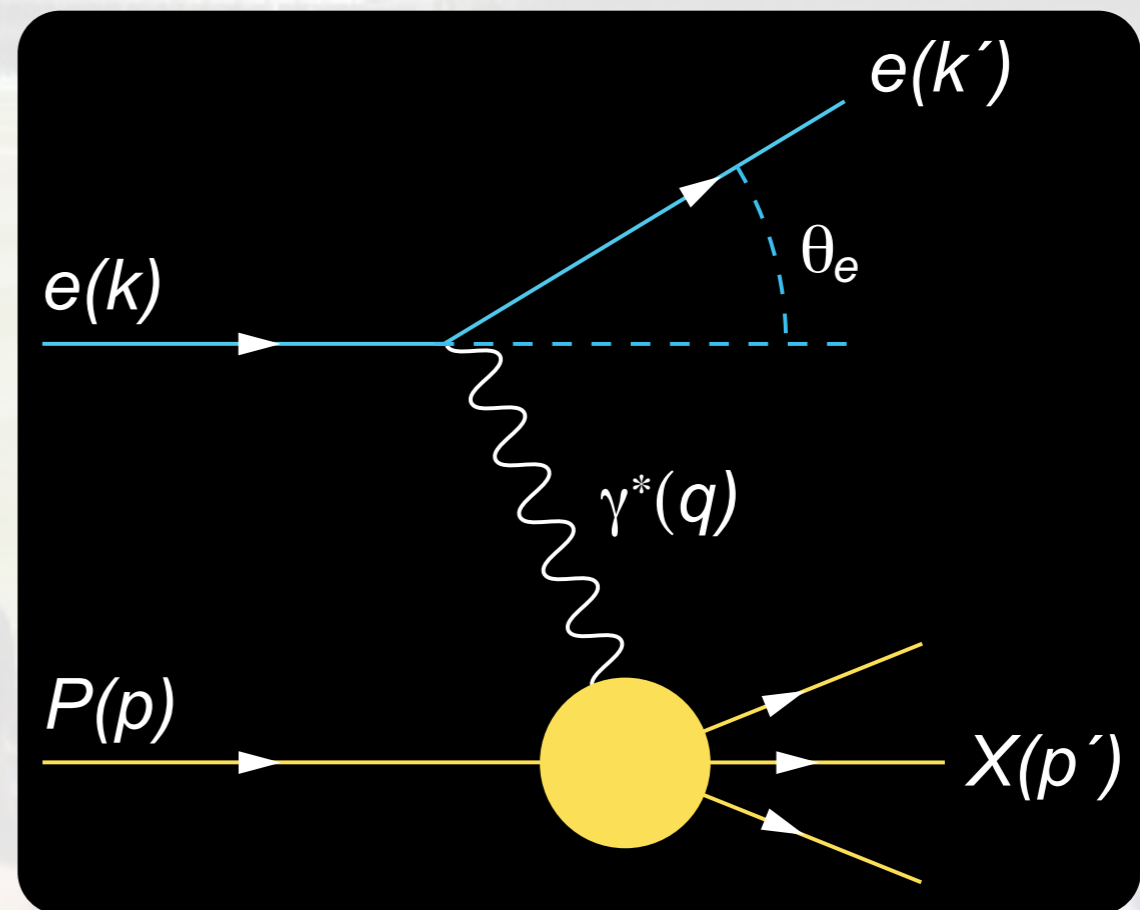
How to Measure the Glue ?

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



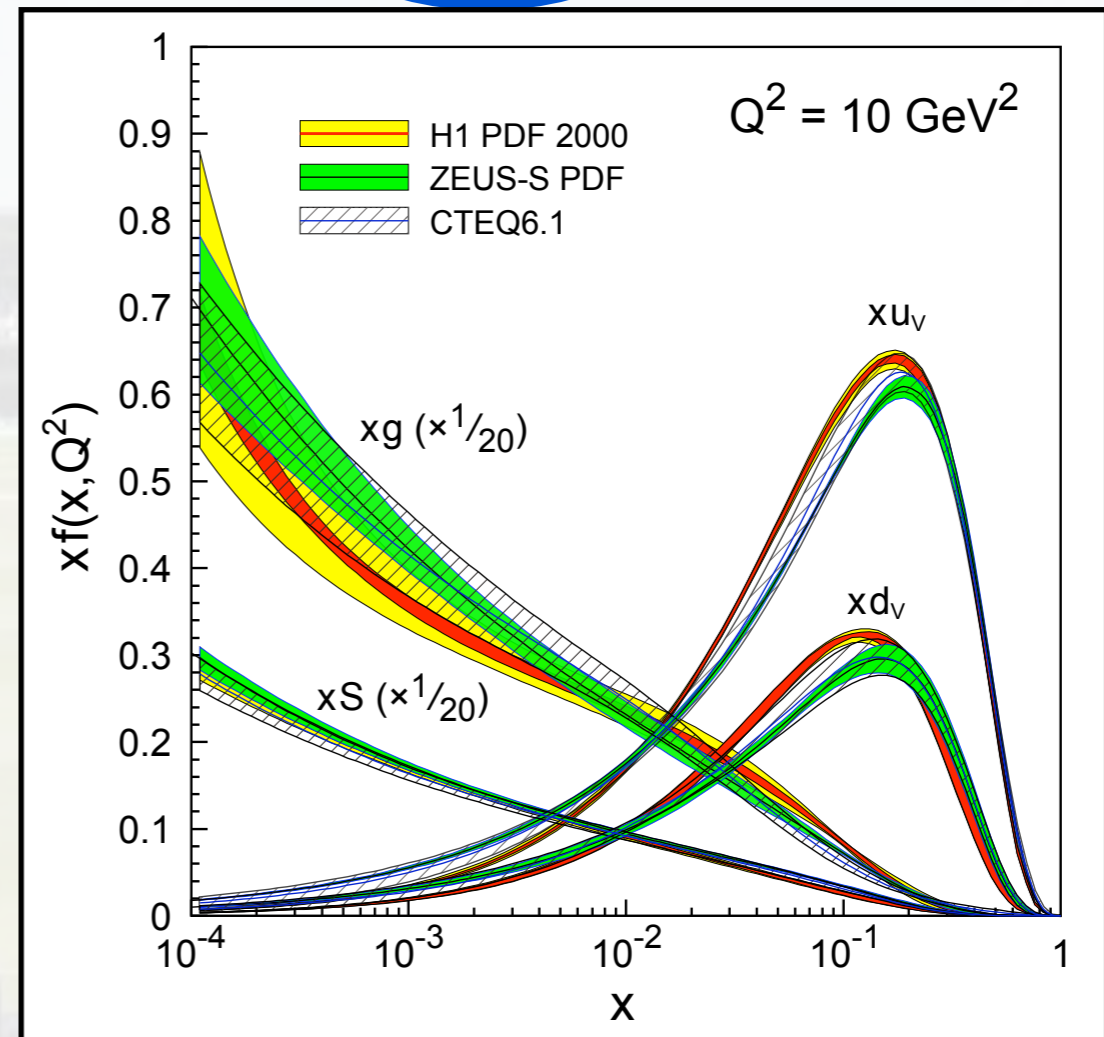
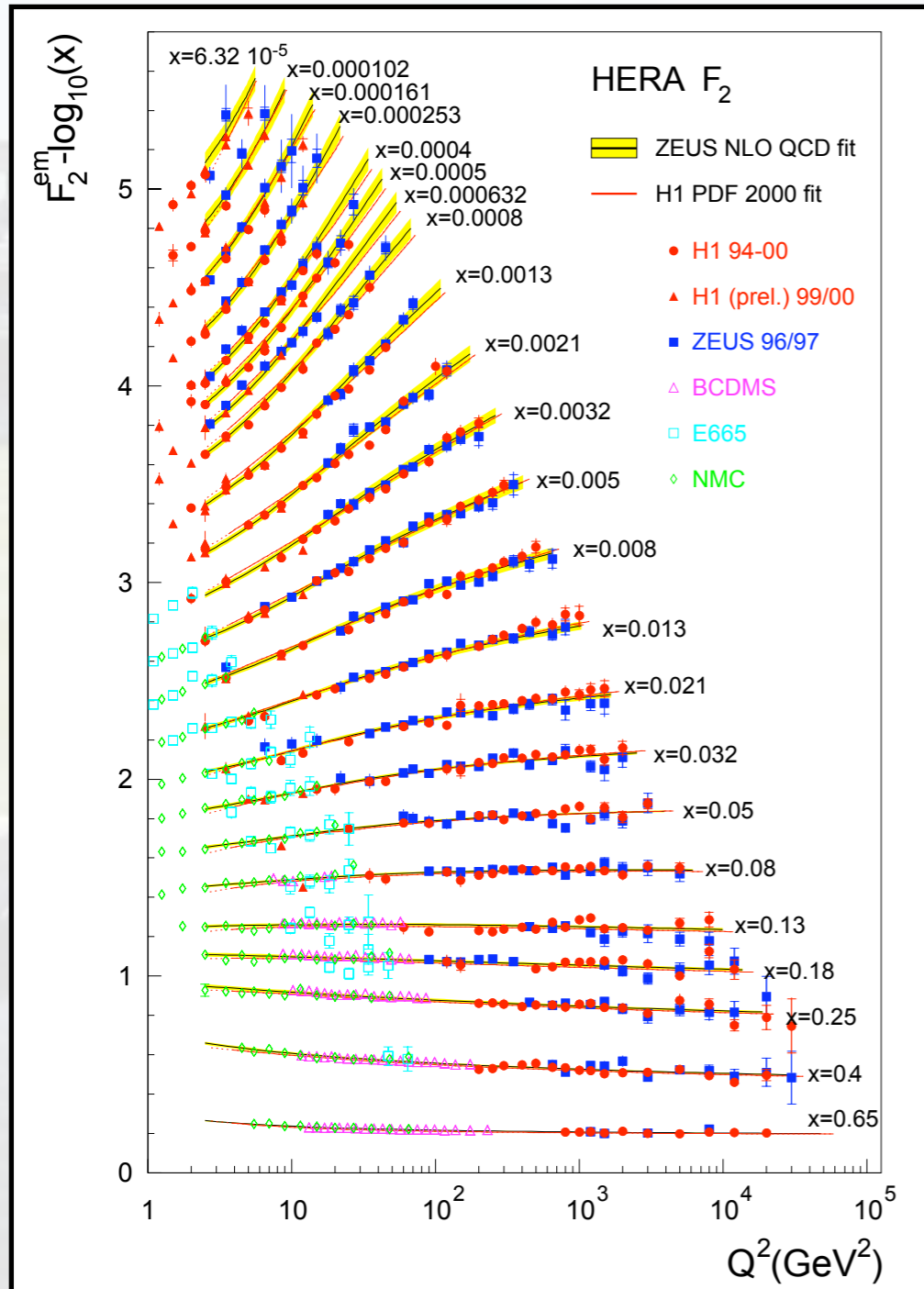
$F_2(x, Q^2) \Rightarrow$ q and \bar{q} mom distributions

$F_L(x, Q^2) \Rightarrow$ g mom distribution



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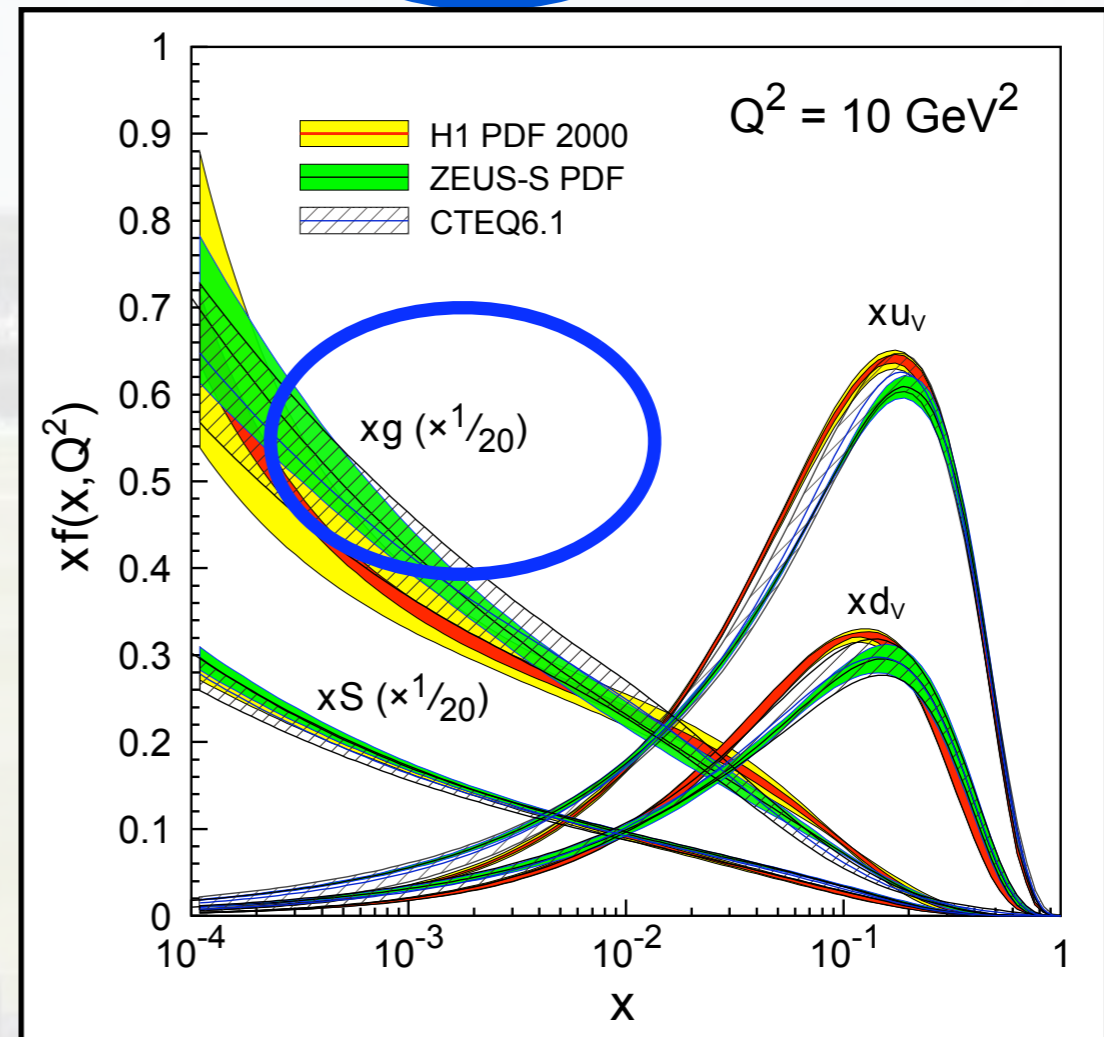
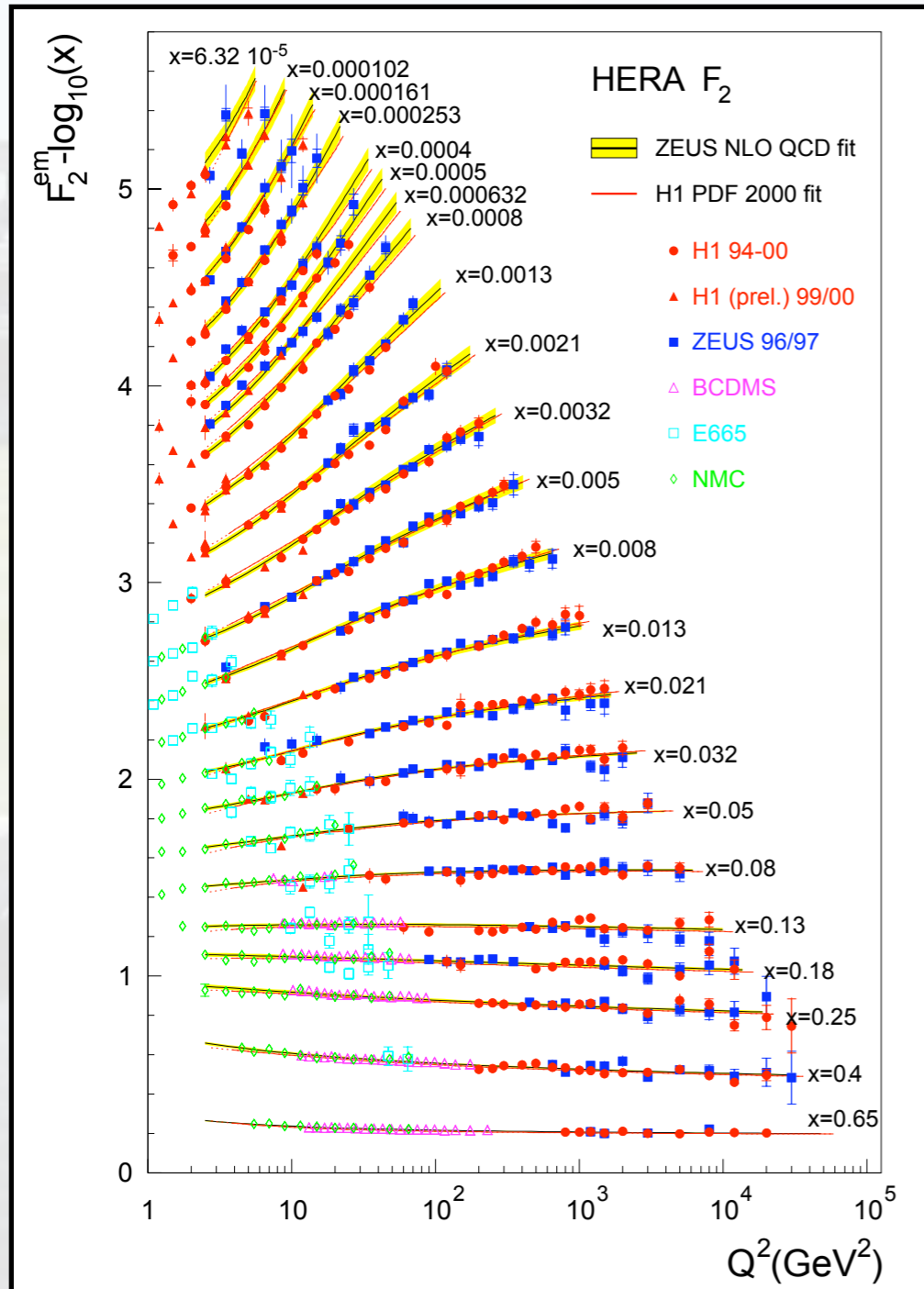
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Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x, Q^2)$

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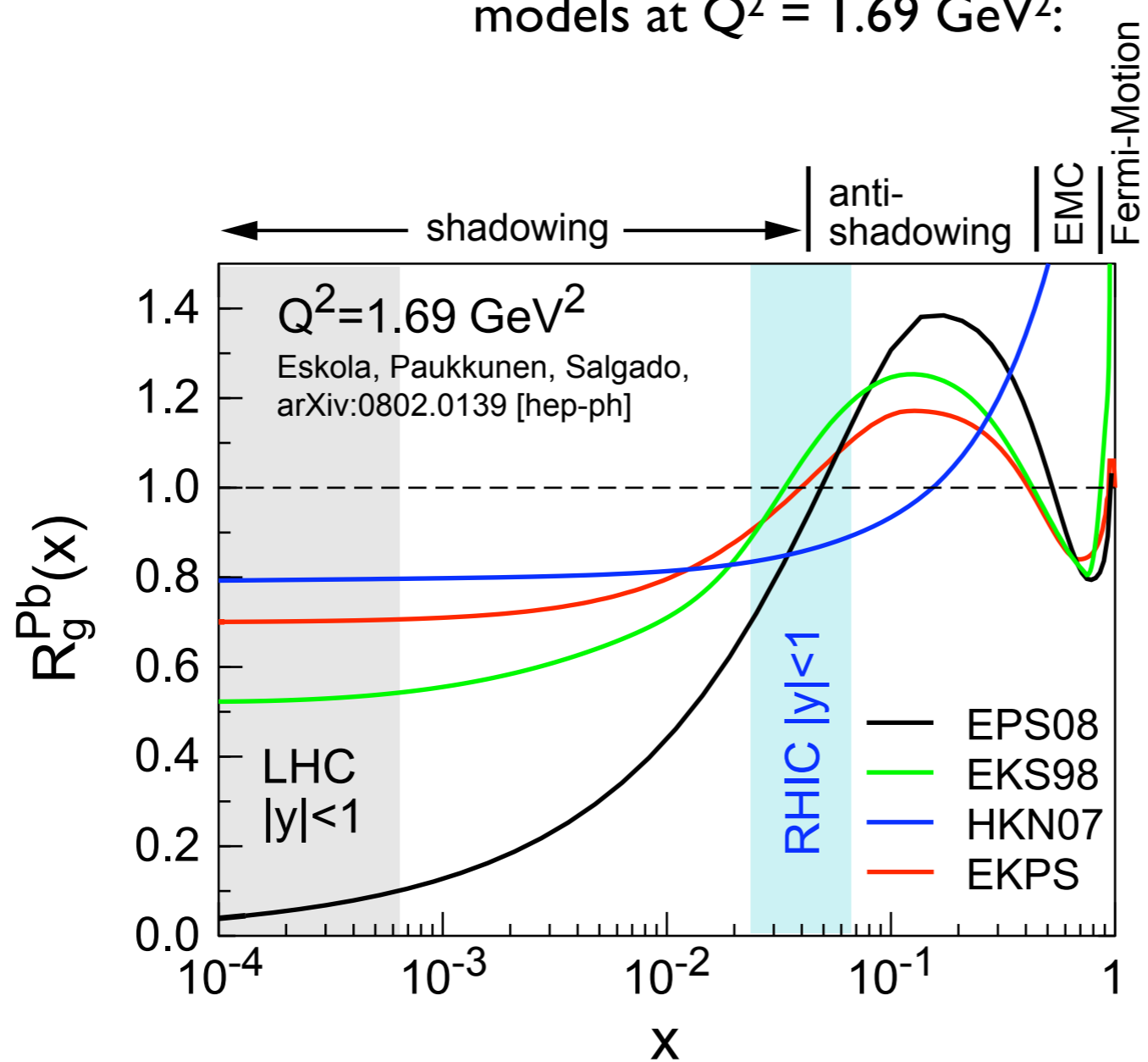
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$\frac{d^2 \sigma^{ep}}{dx dQ^2}$

x^2

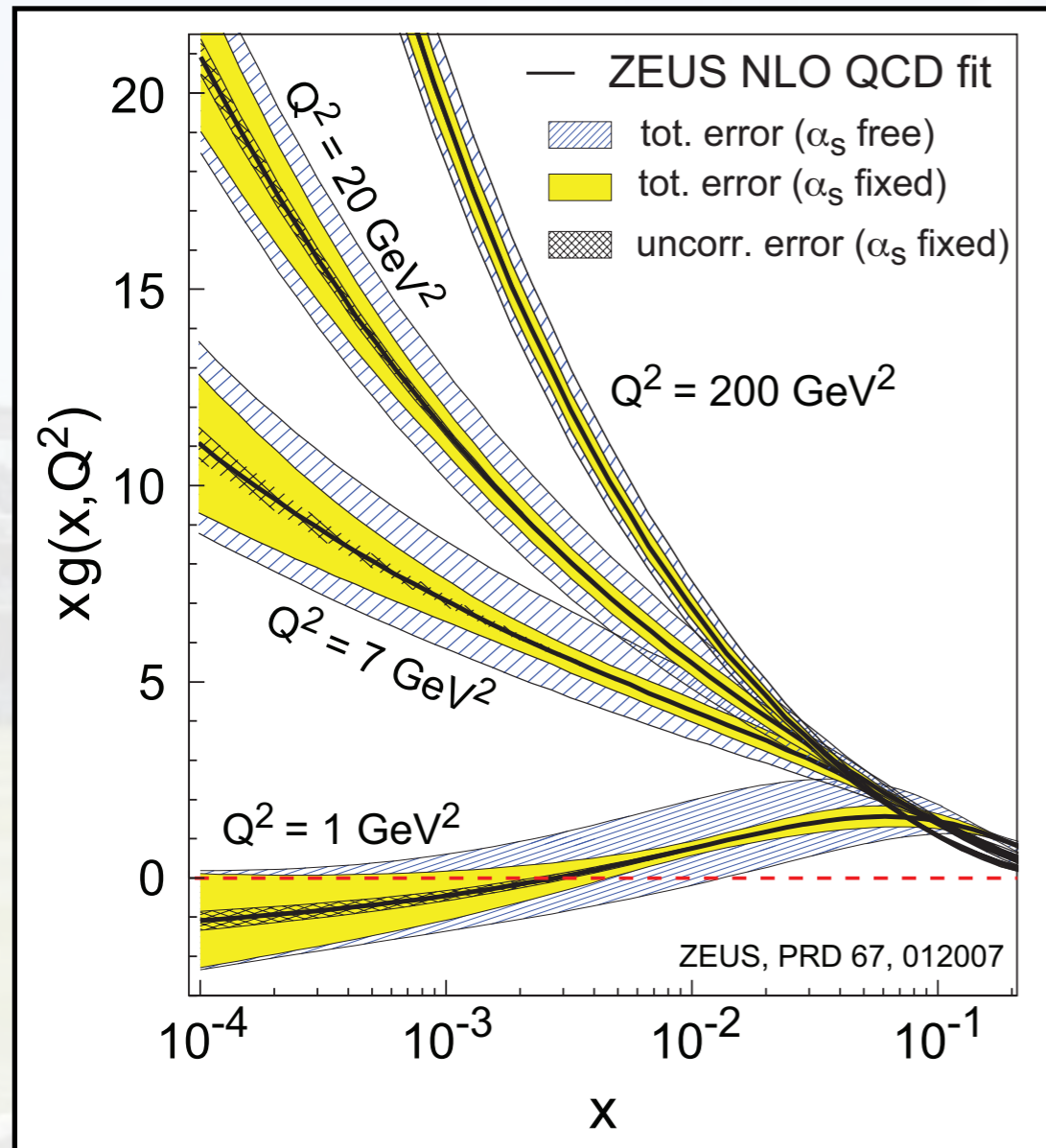
Important for RHIC and LHC:

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



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

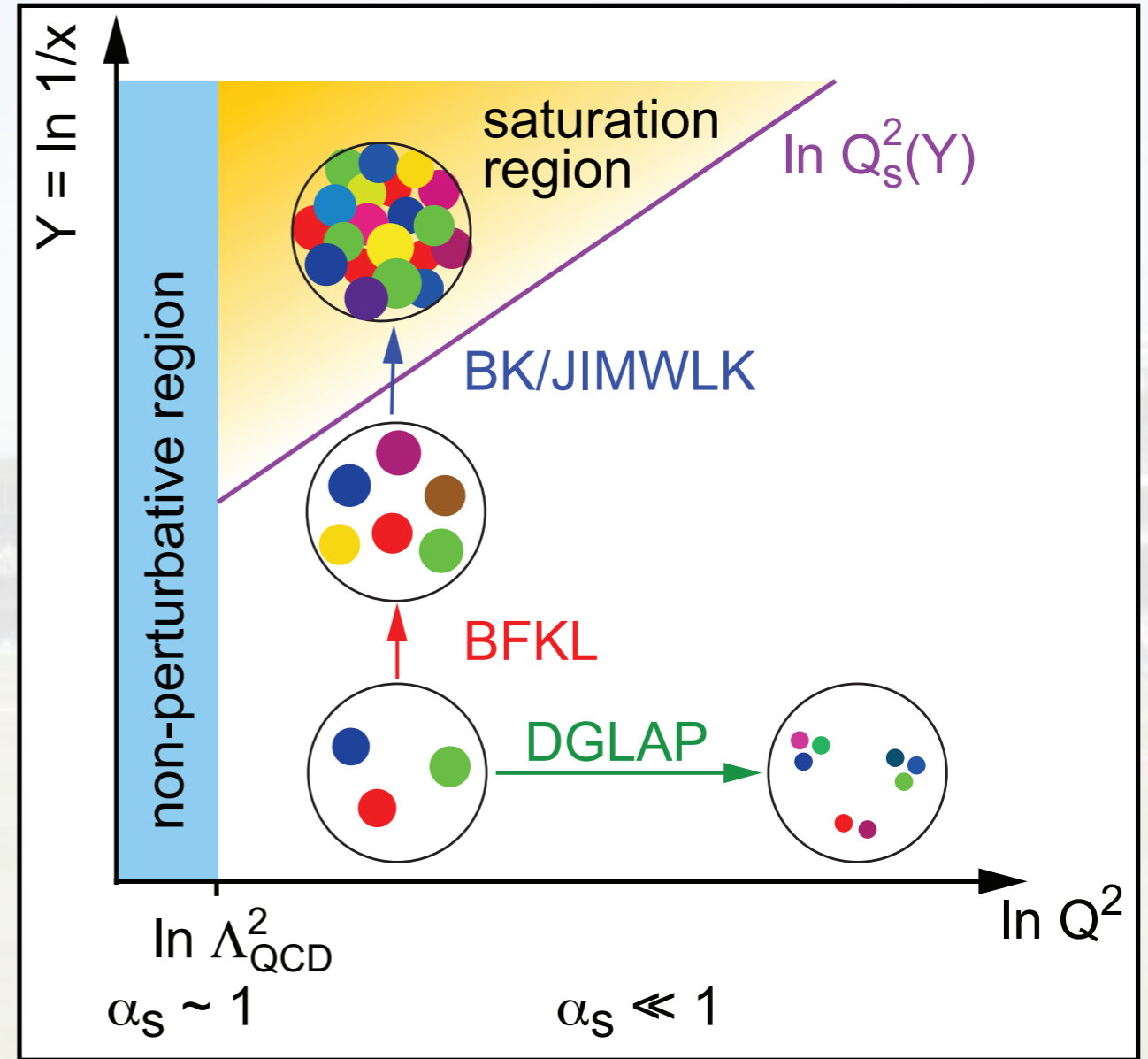
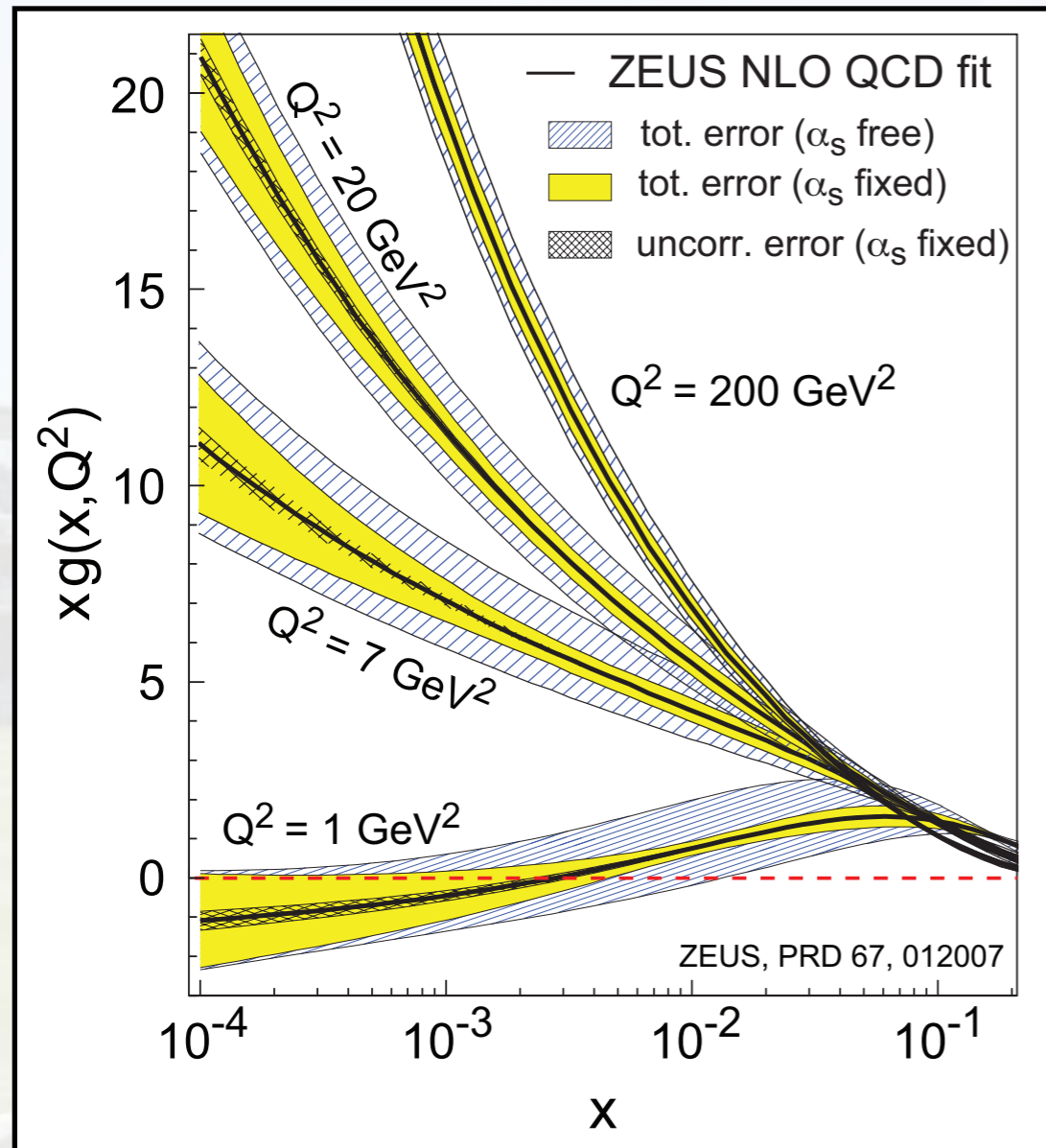
What Do We Know About Glue?



Linear DGLAP evolution

- negative $G(x, Q^2)$ at low Q^2 ?
 - built in high energy “catastrophe”
 - xG rapid rise violates unitary bound
- xG must saturate** \Rightarrow new approach

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BK/JIMWLK: non-linear effects \Rightarrow saturation

- characterized by $Q_s(x, A)$
- believed to have properties of a *Colour Glass Condensate*

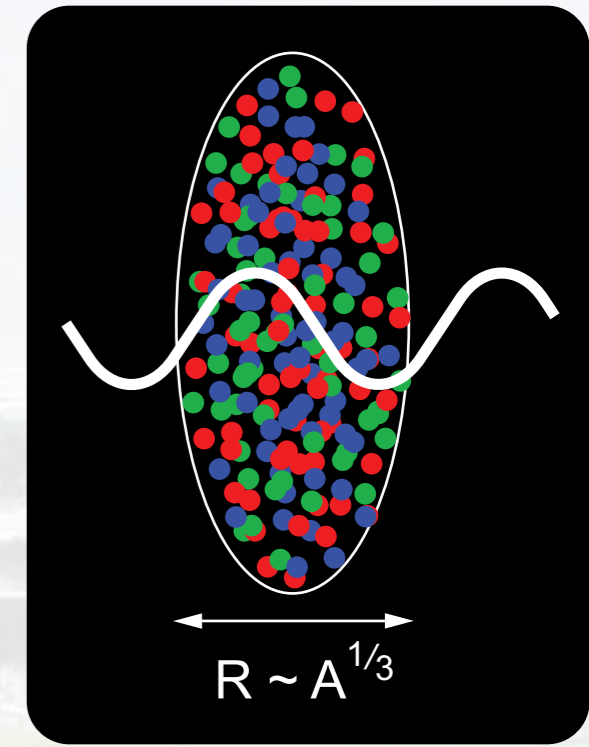
Enhancing Saturation Effects: e+A

Scattering of electrons off nuclei:

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

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



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

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

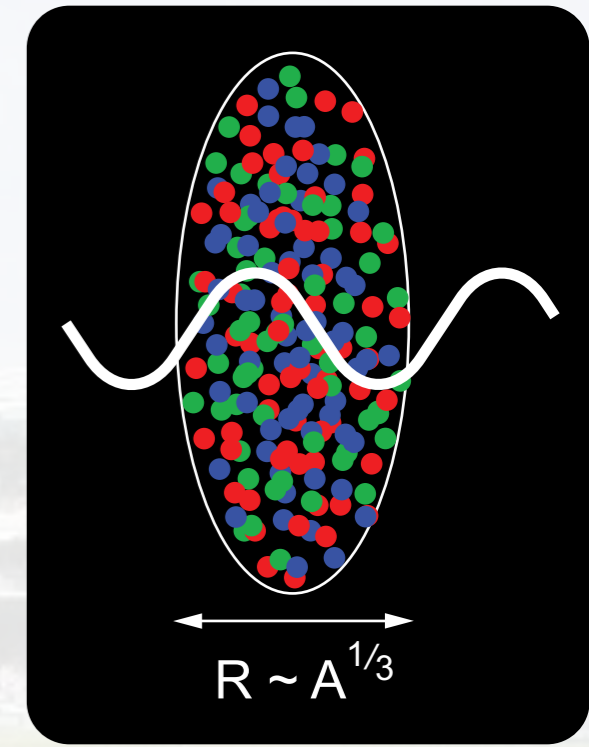
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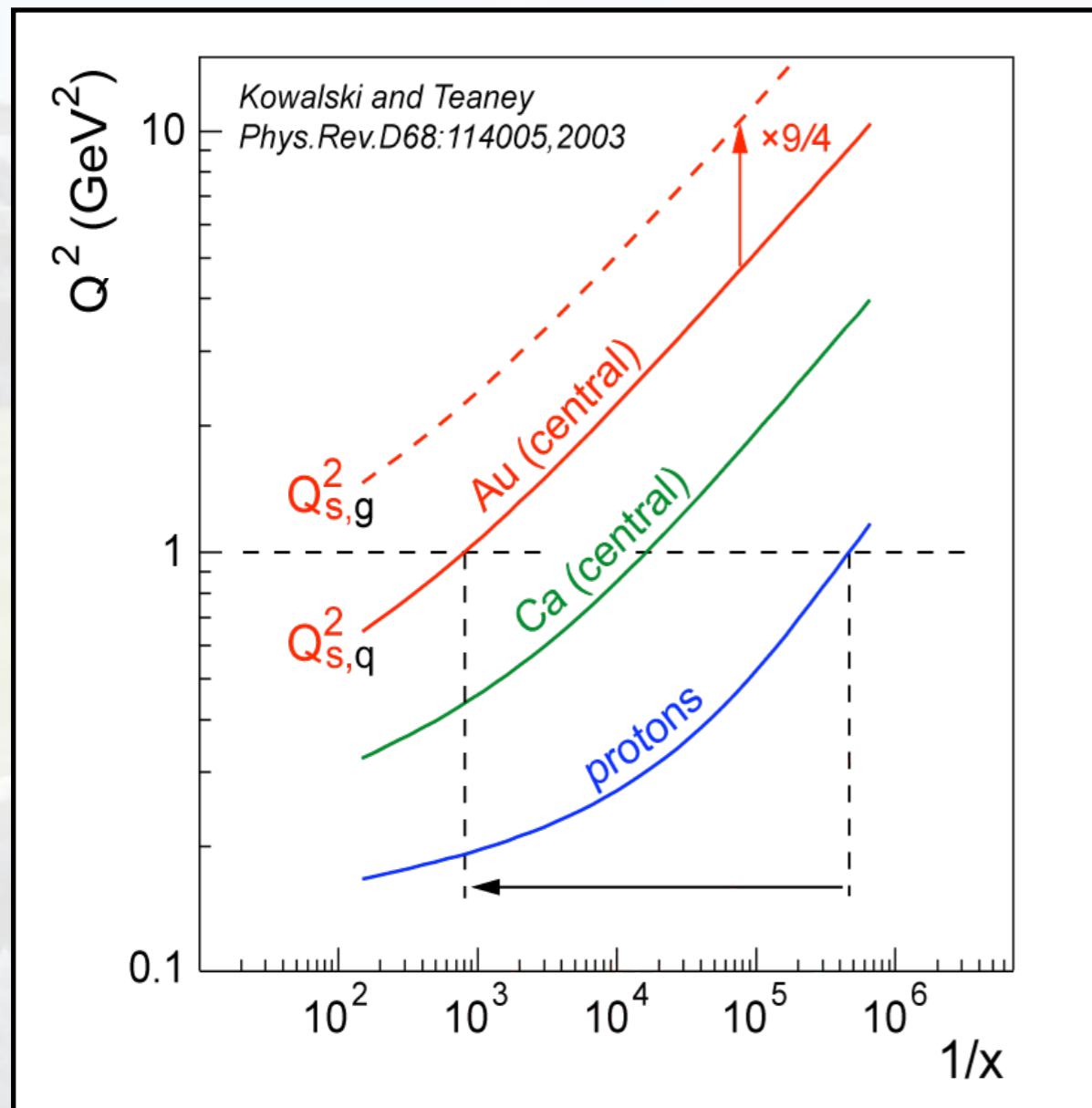
Enhancement of Q_s with A :

\Rightarrow non-linear QCD regime reached at significantly lower energy in eA than in ep

The Nuclear “Oomph” factor

More sophisticated analyses \Rightarrow confirm (exceed) pocket formula

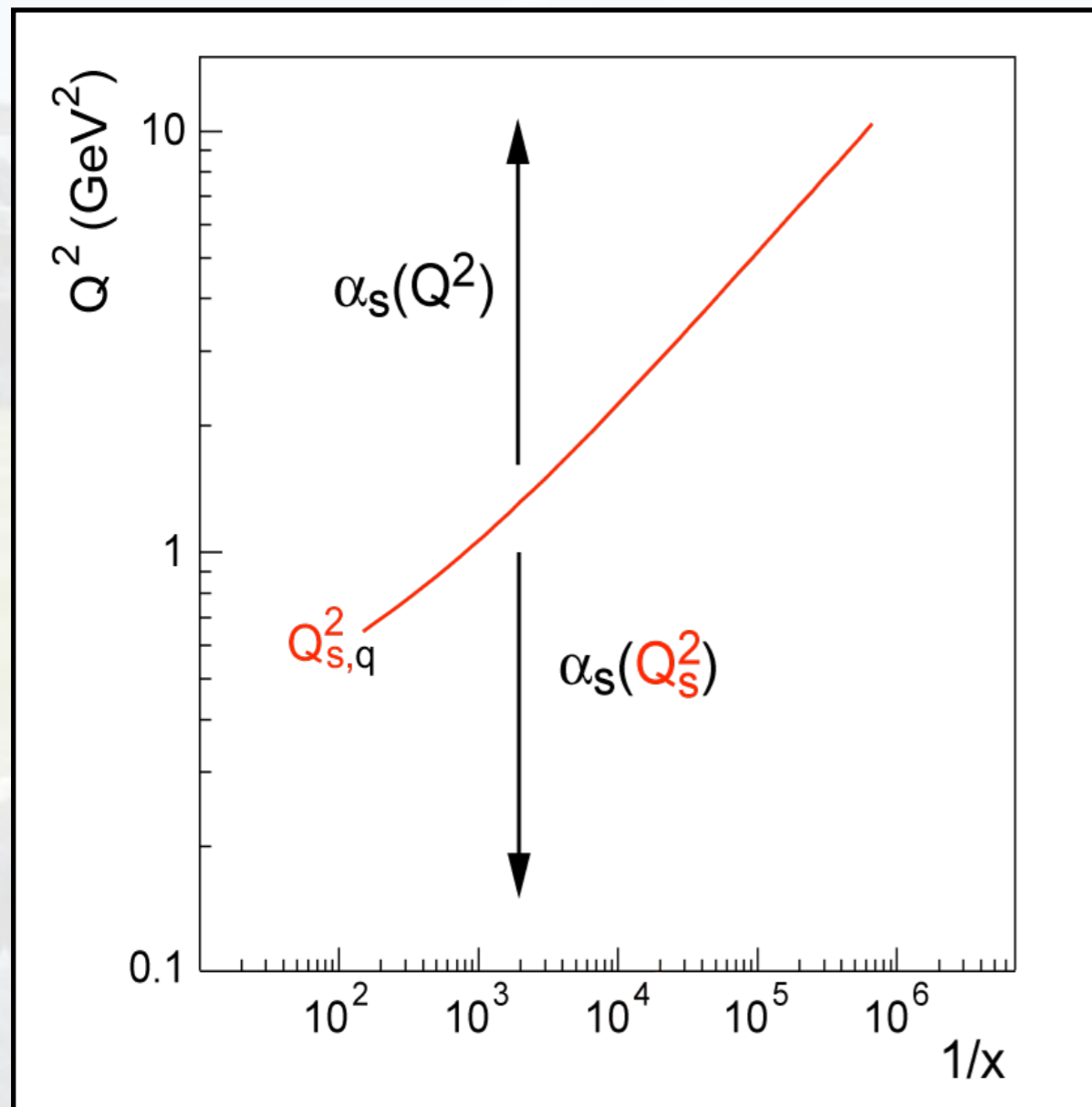
(e.g. Kowalski, Lappi and Venugopalan, PRL 100, 022303 (2008); Armesto et al., PRL 94:022002; Kowalski, Teaney, PRD 68:114005)



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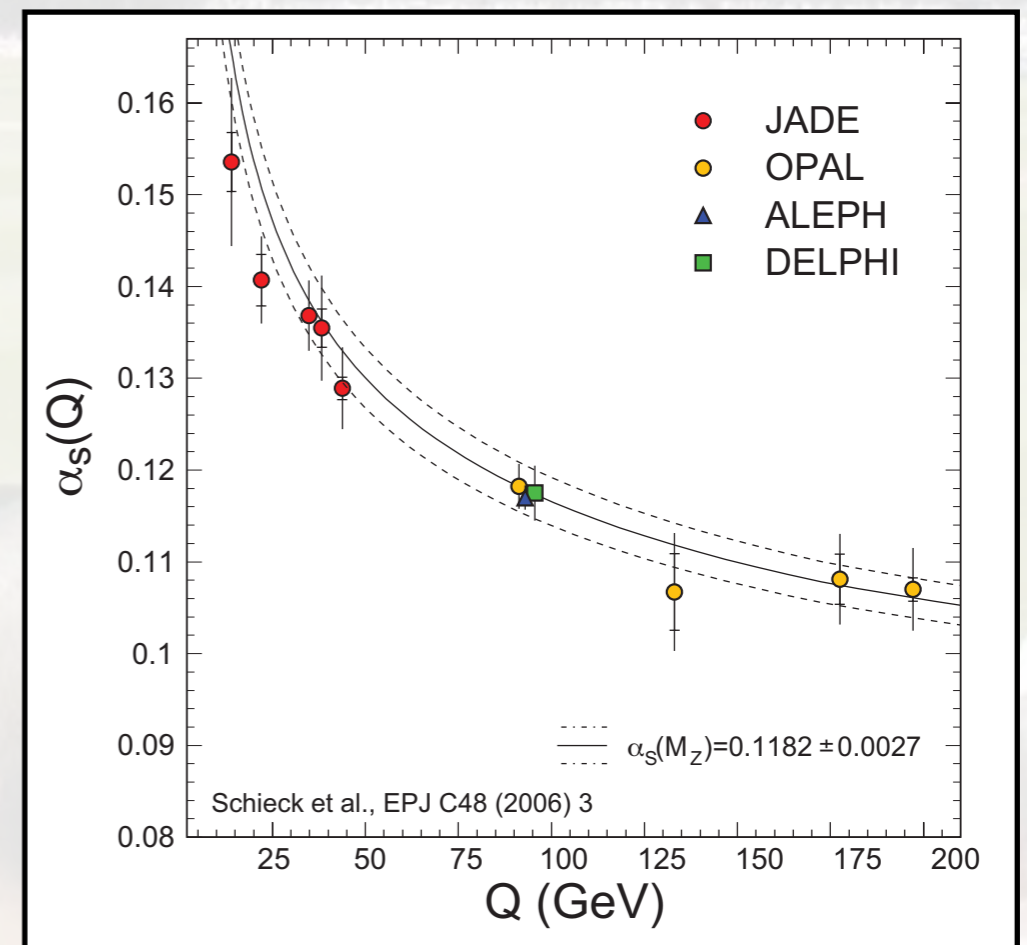
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Note:

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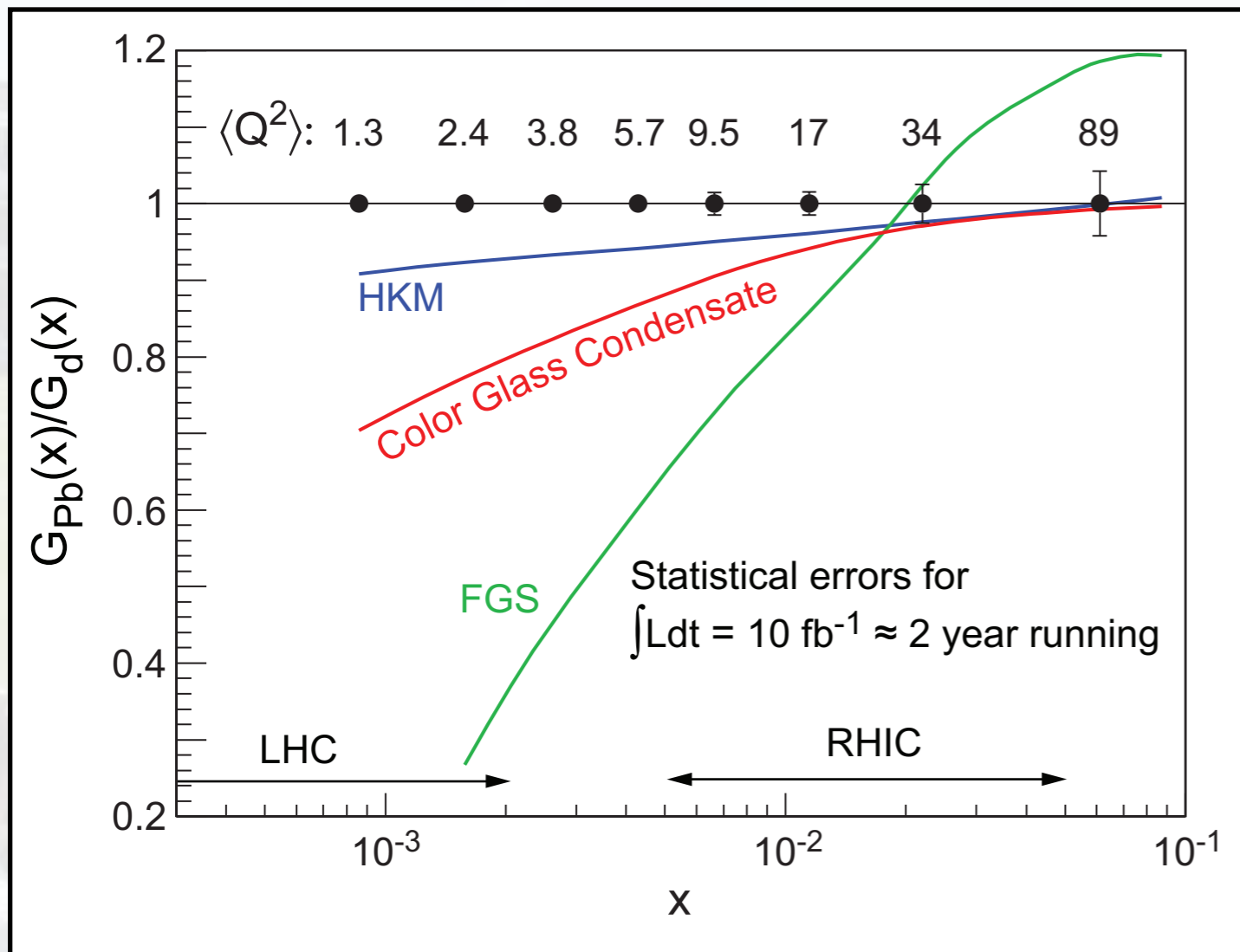


Key Measurements in $e+A$

- **Momentum distribution of gluons $G(x, Q^2)$**
 - ➔ Extract via scaling violation in F_2 : $\delta F_2 / \delta \ln Q^2$
 - ➔ Direct measurement: $F_L \sim G(x, Q^2)$ (requires \sqrt{s} scan)
 - ➔ 2+1 jet rates
 - ➔ Inelastic vector meson production (e.g. J/ψ)
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Example of Key Measurements: F_L

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

Here:

$$\begin{aligned} \int \mathcal{L} dt &= 4/A \text{ fb}^{-1} (10+100) \text{ GeV} \\ &= 4/A \text{ fb}^{-1} (10+50) \text{ GeV} \\ &= 2/A \text{ fb}^{-1} (5+50) \text{ GeV} \end{aligned}$$

statistical error only

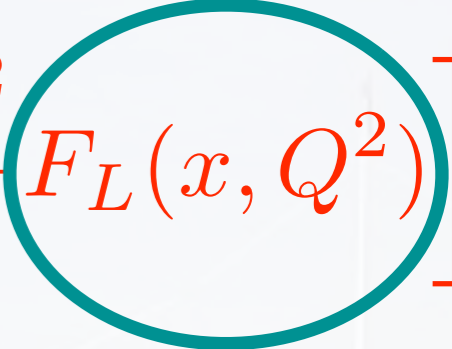
Syst. studies of $F_L(A, x, Q^2)$:

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

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

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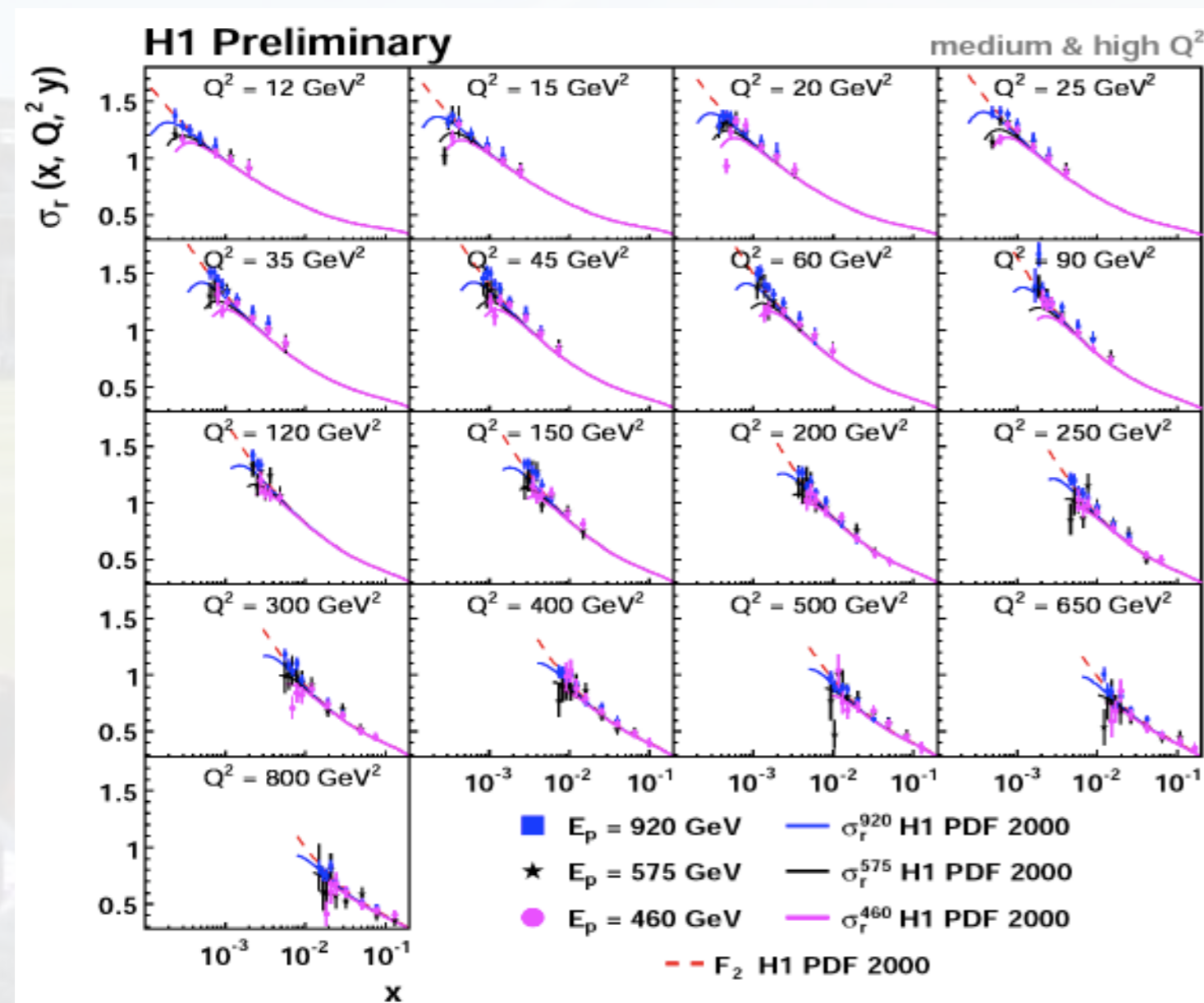
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Preliminary F_L measurements

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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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 - ➔ Hadronization, Fragmentation
 - ➔ Energy loss (charm!)

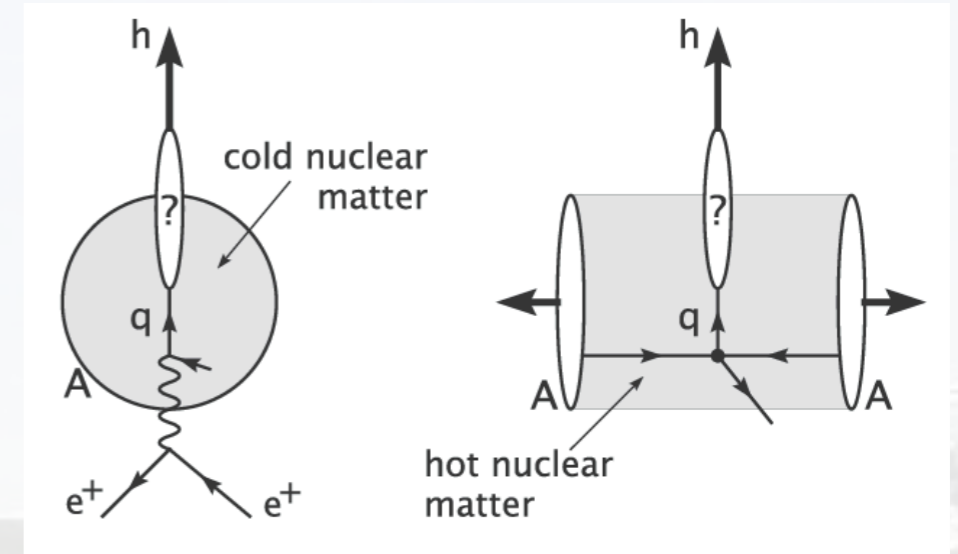
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- **Role of colour neutral excitations (Pomerons)**
 - ➔ Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ (HERA/ ep : 10% , EIC/ eA : 30%?)
 - ➔ Diffractive structure functions and vector meson production
 - ➔ Abundance and distribution of rapidity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

Hadronization and Energy Loss

nDIS:

- Suppression of high- p_T hadrons analogous but *weaker* than at RHIC
- Clean measurement in 'cold' nuclear matter



Fundamental question:

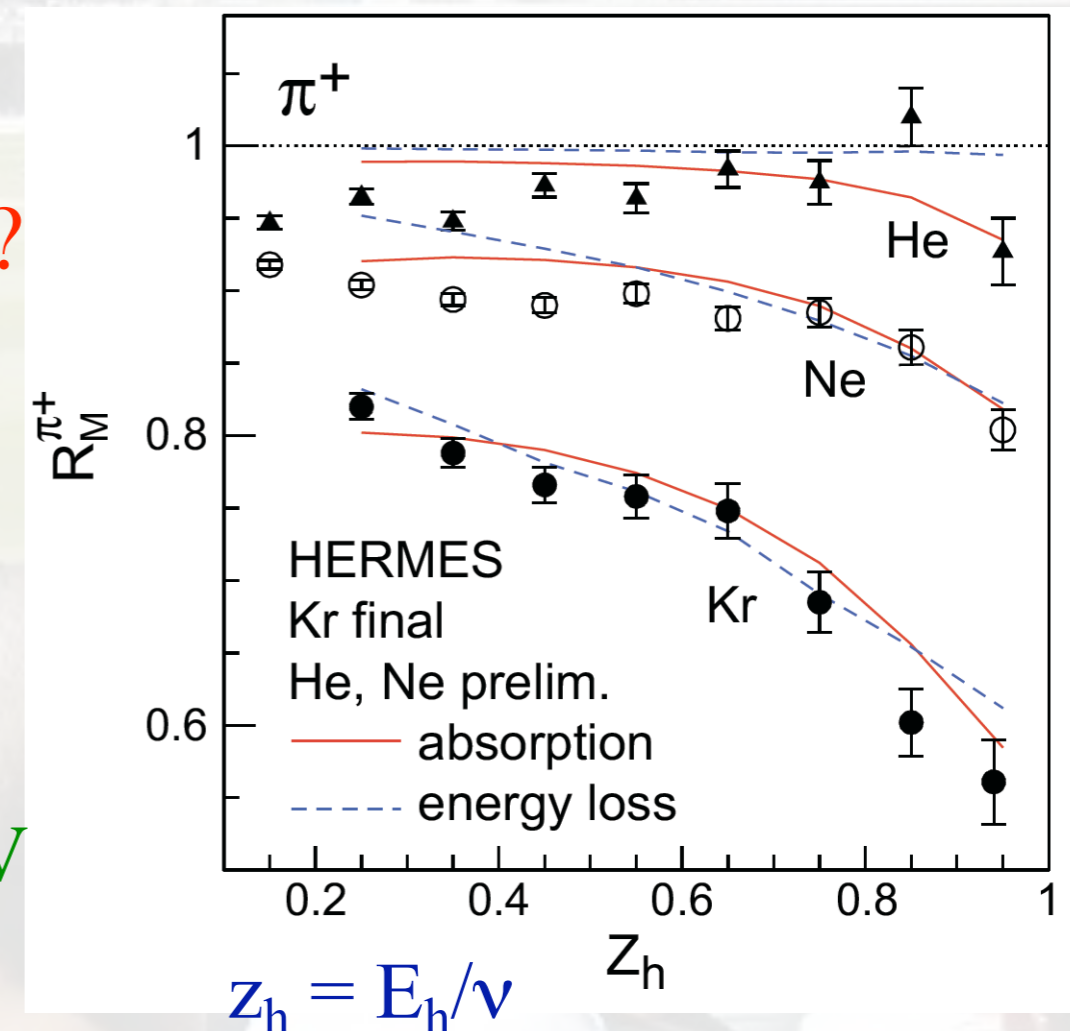
When do coloured partons get neutralized?

Parton energy loss vs. (pre)hadron absorption

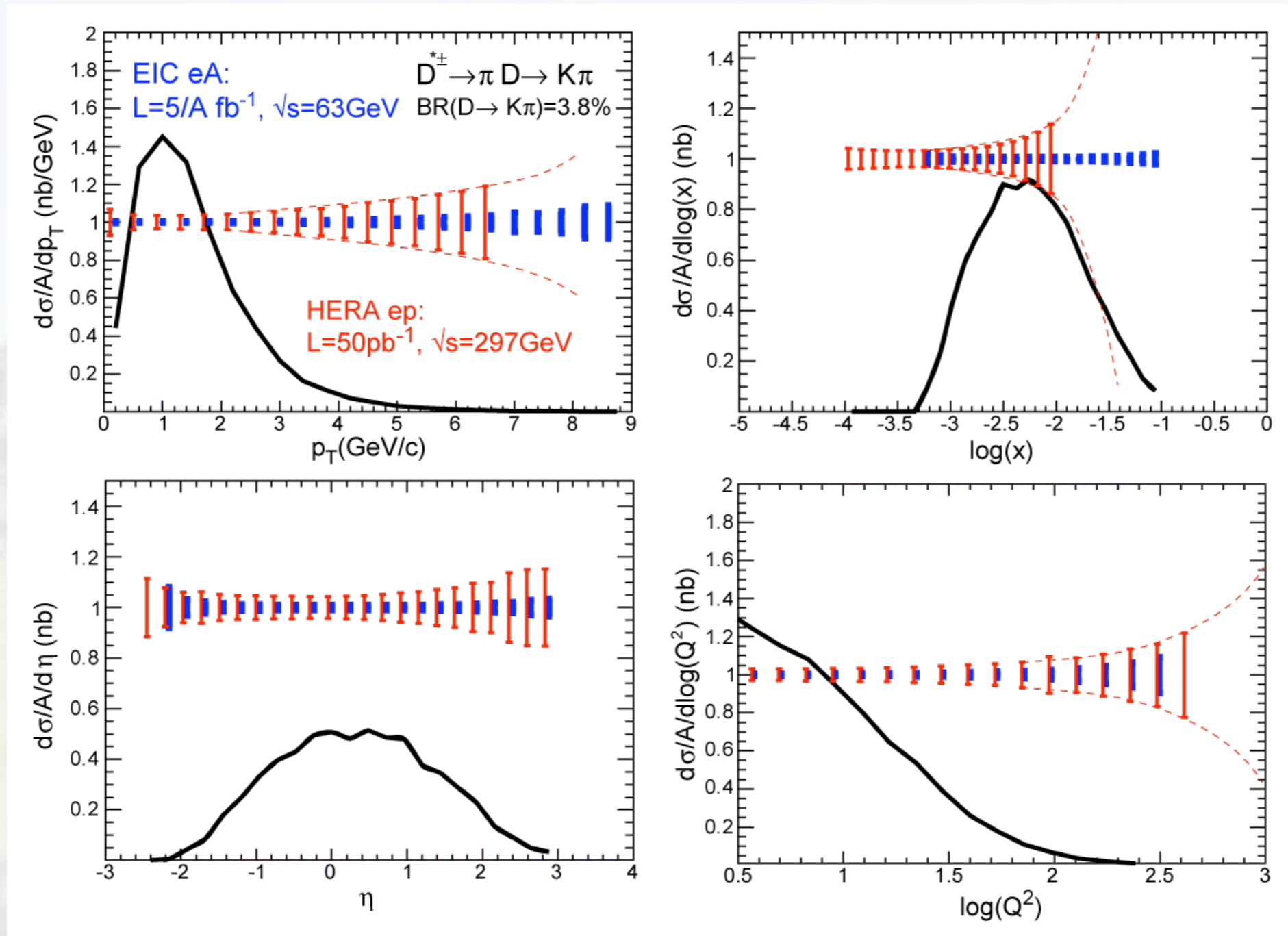
Energy transfer in lab rest frame

EIC: $10 < \nu < 1600$ GeV HERMES: 2-25 GeV

EIC: can measure *heavy flavour* energy loss



Charm at an EIC

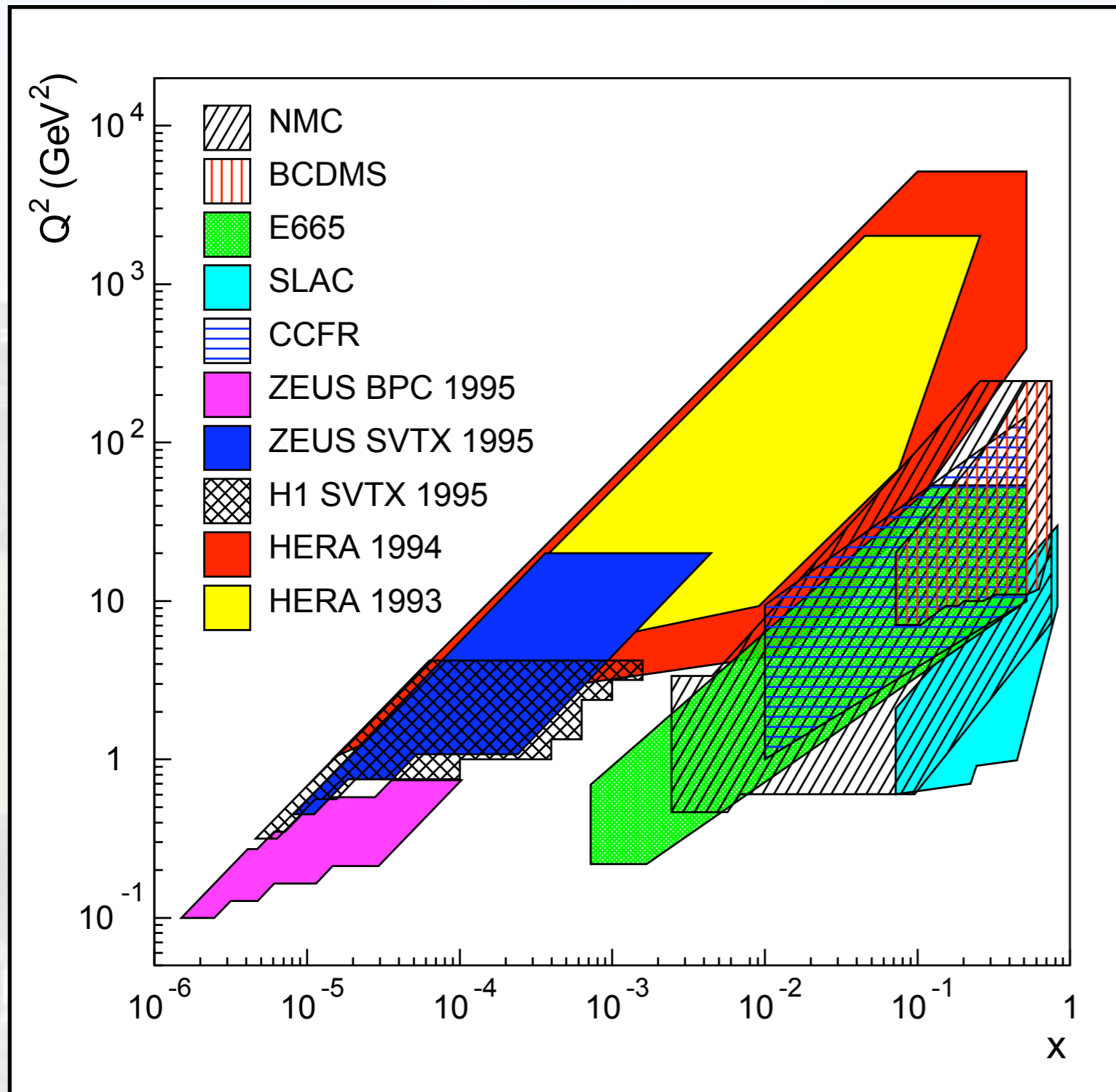


Based on HVQDIS model, J. Smith

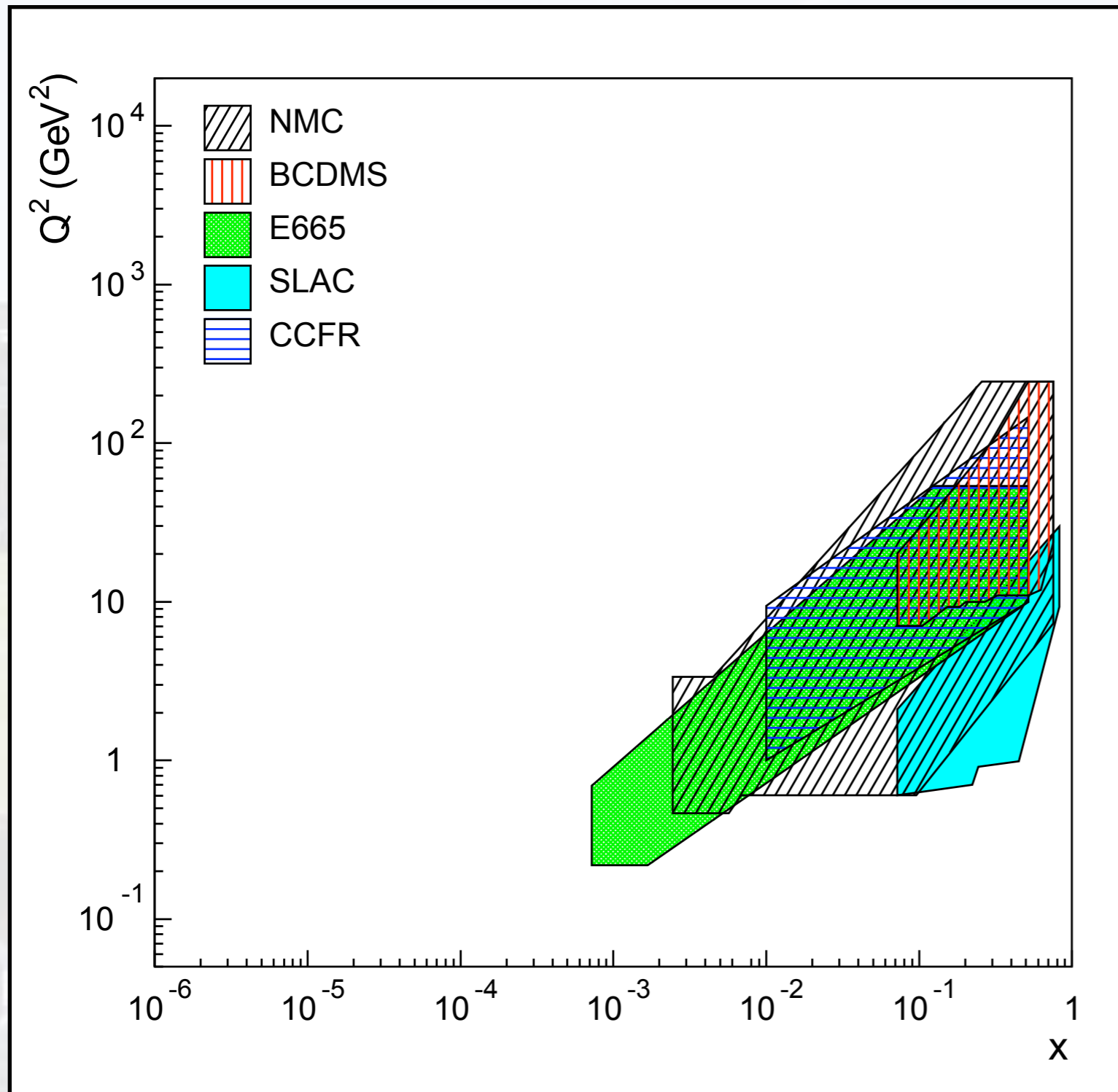
- EIC: allows multi-differential measurements of heavy flavour
- covers and extend energy range of SLAC, EMC, HERA, and JLAB allowing study of wide range of formation lengths

Requirements for an Electron Ion Collider

Well mapped in $e+p$



Requirements for an Electron Ion Collider

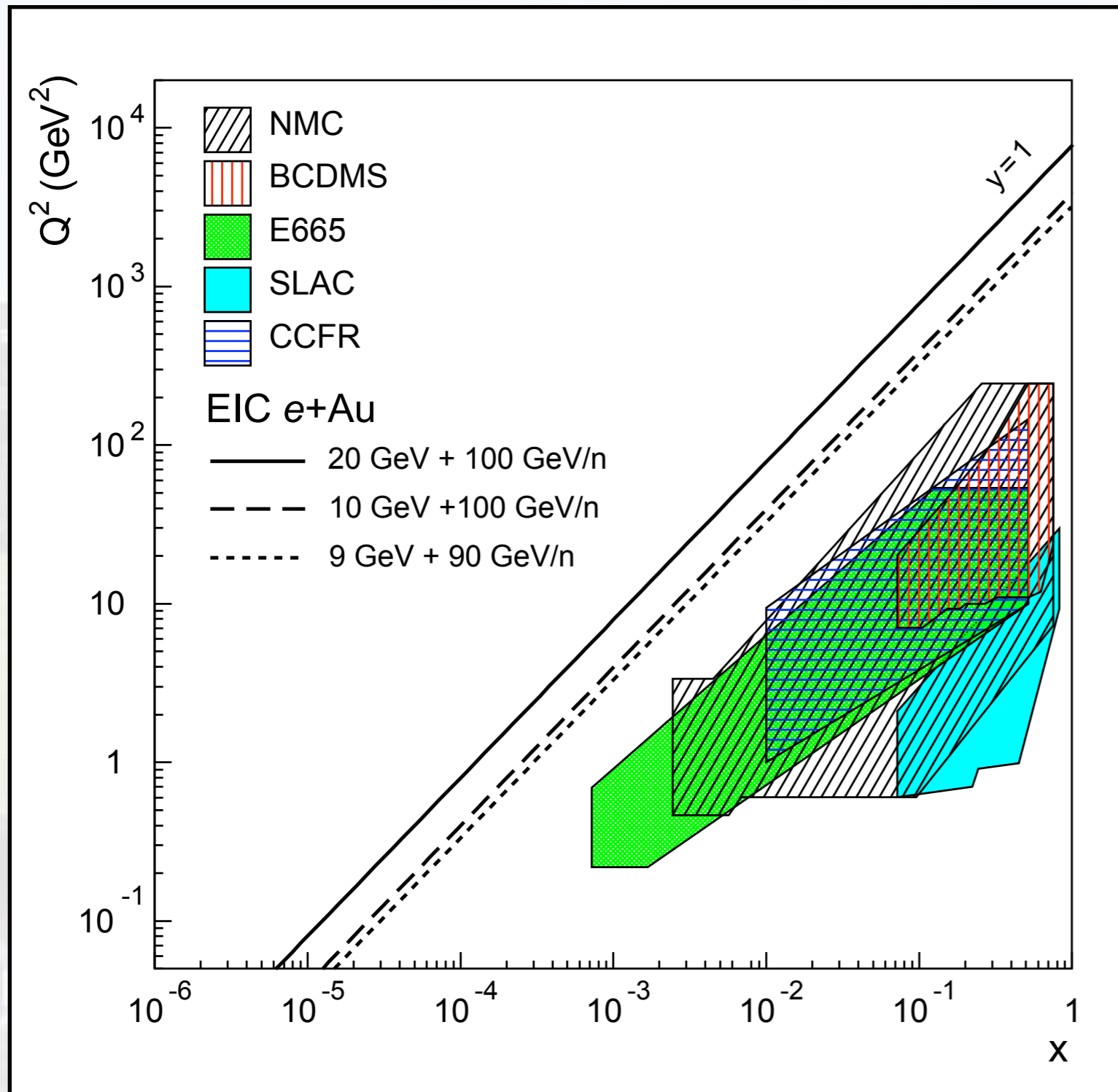


Well mapped in $e+p$

Not so for $\ell+A$ ($\nu+A$)

- many with small A
- low statistics

Requirements for an Electron Ion Collider



Well mapped in $e+p$

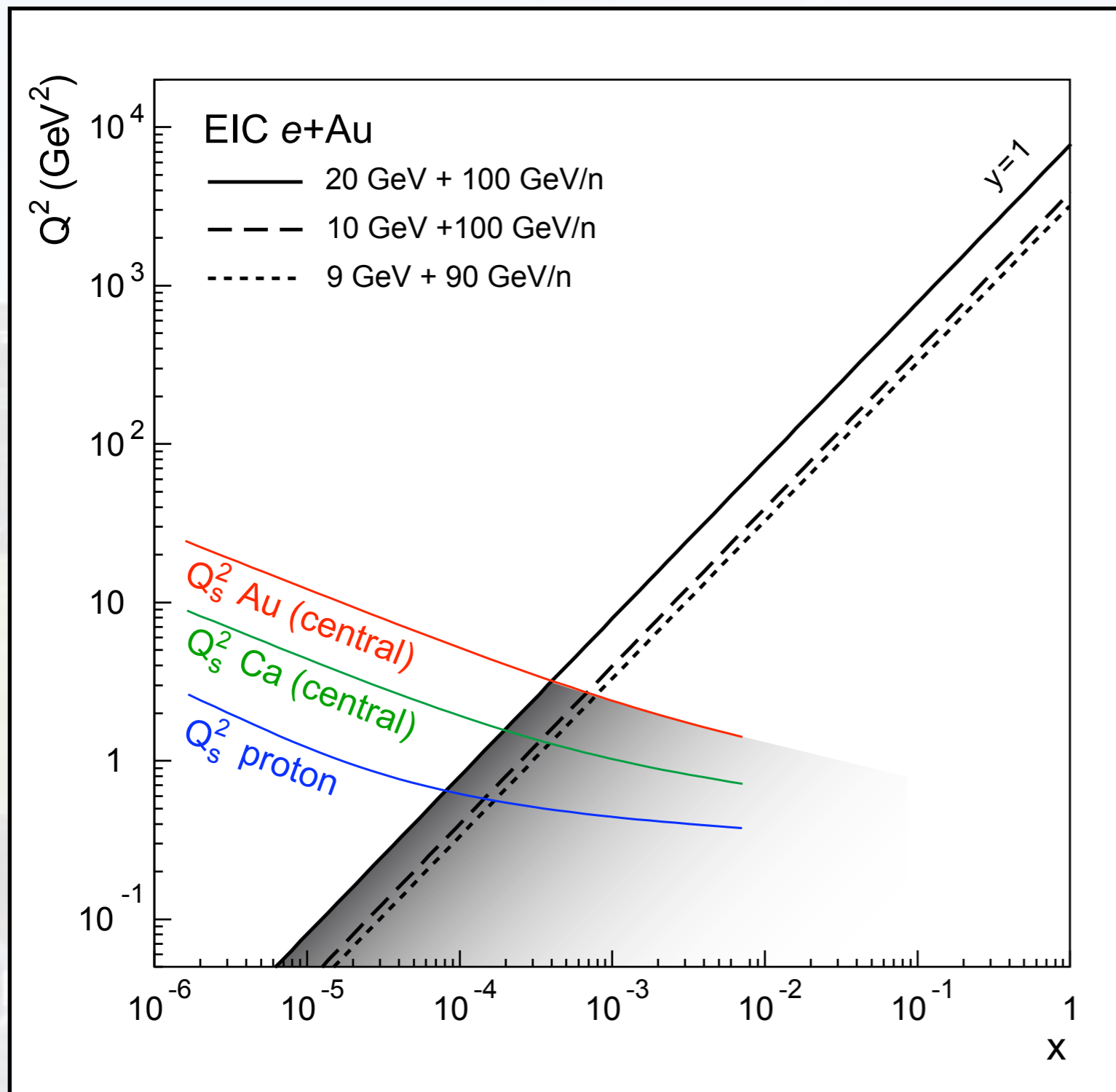
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Electron Ion Collider:

- $\mathcal{L}(\text{EIC}) > 100 \times \mathcal{L}(\text{HERA})$
- Electrons
 - $E_e = 3 - 20$ GeV
 - polarized
- Hadron Beams
 - $E_A = 100$ GeV
 - $A = p \rightarrow U$
 - polarized p & light ions

Requirements for an Electron Ion Collider



Well mapped in $e+p$

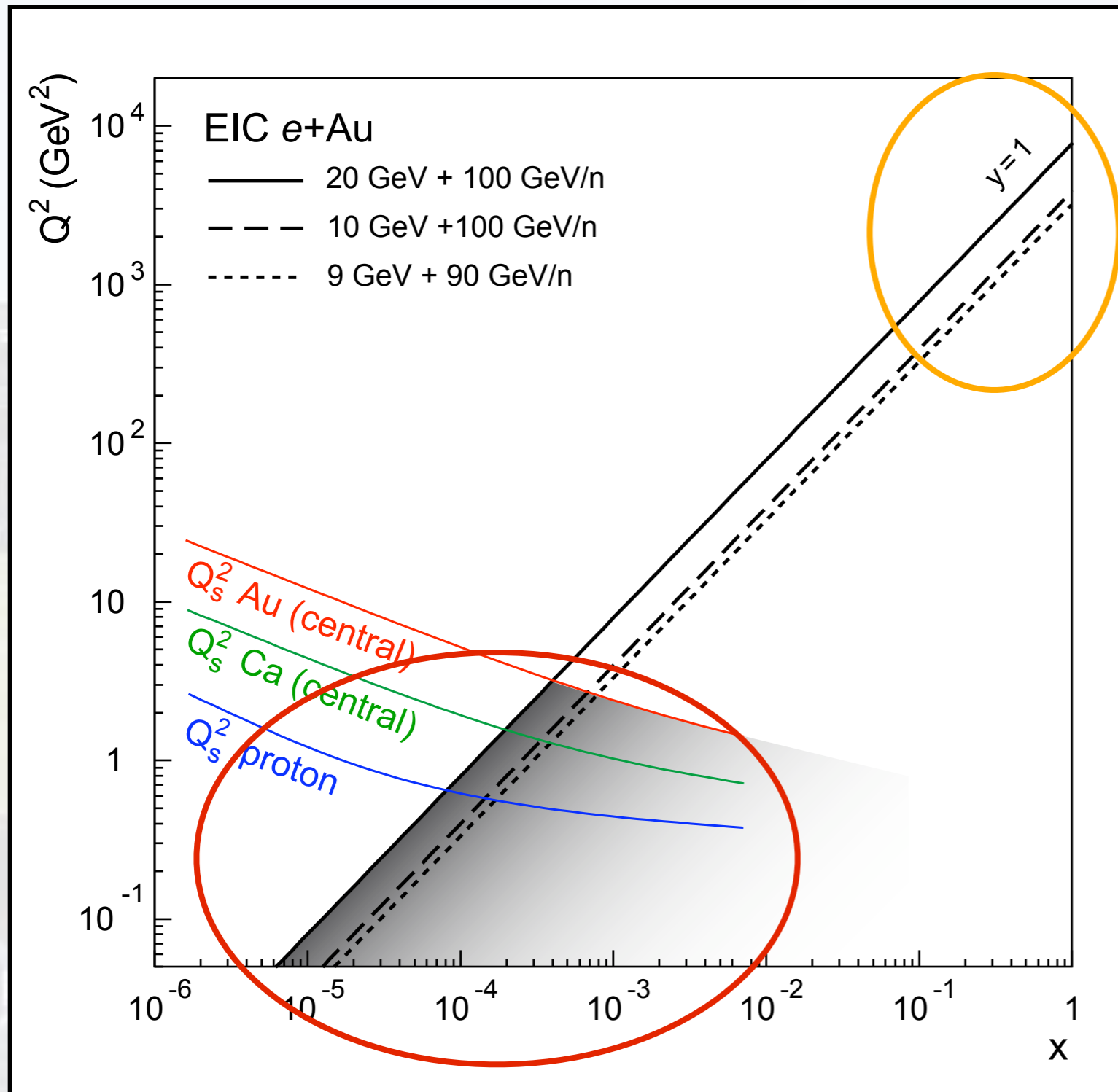
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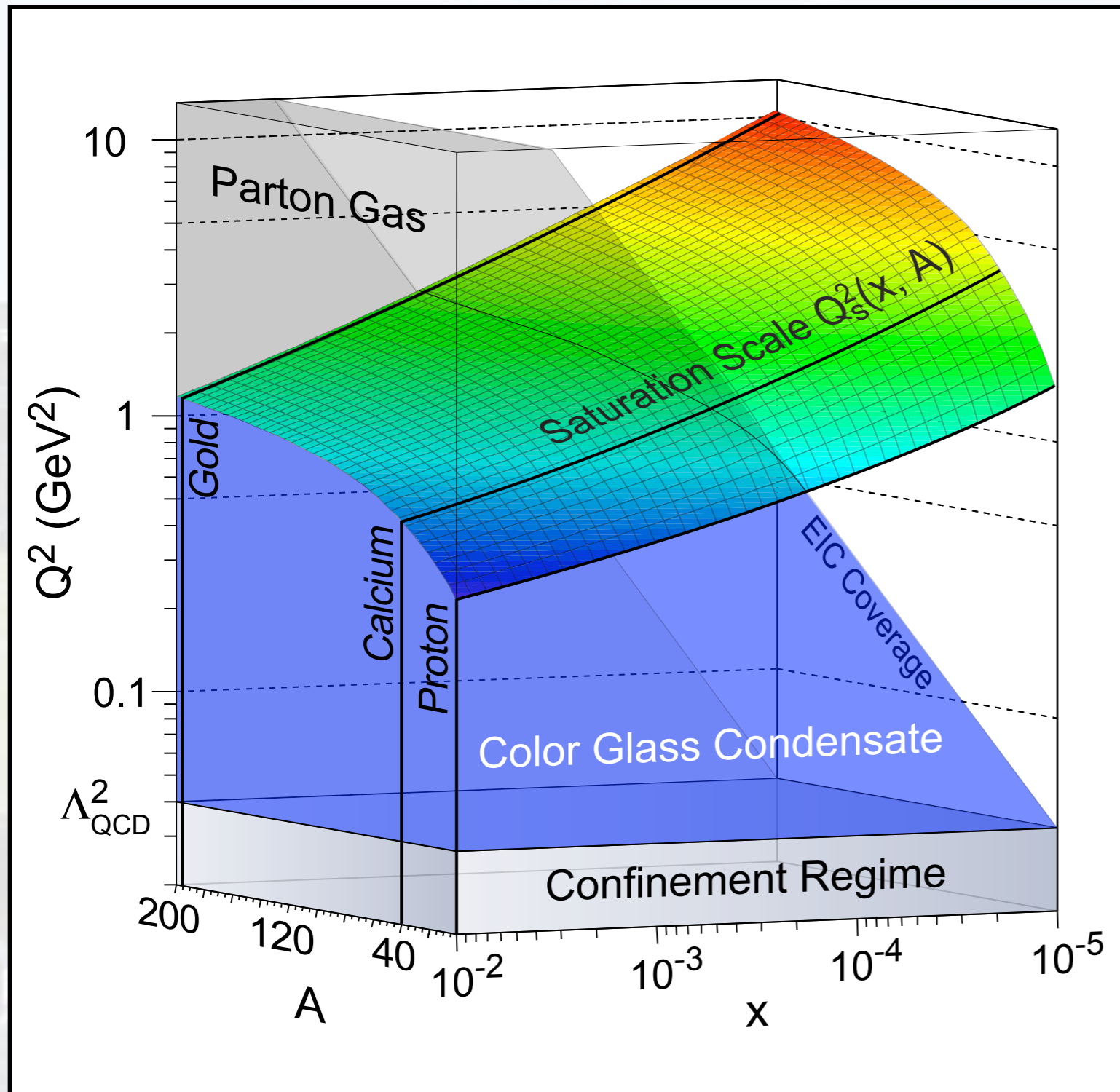
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high- x , large Q^2

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EIC Collider concepts

eRHIC (RHIC/BNL):

Add Energy Recovery Linac

$$E_e = 10 \text{ (20) GeV}$$

$$E_A = 100 \text{ GeV (up to U)}$$

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

$$\mathcal{L}_{eAu} \text{ (peak)/n} \sim 2.9 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

ELIC (CEBAF/JLAB):

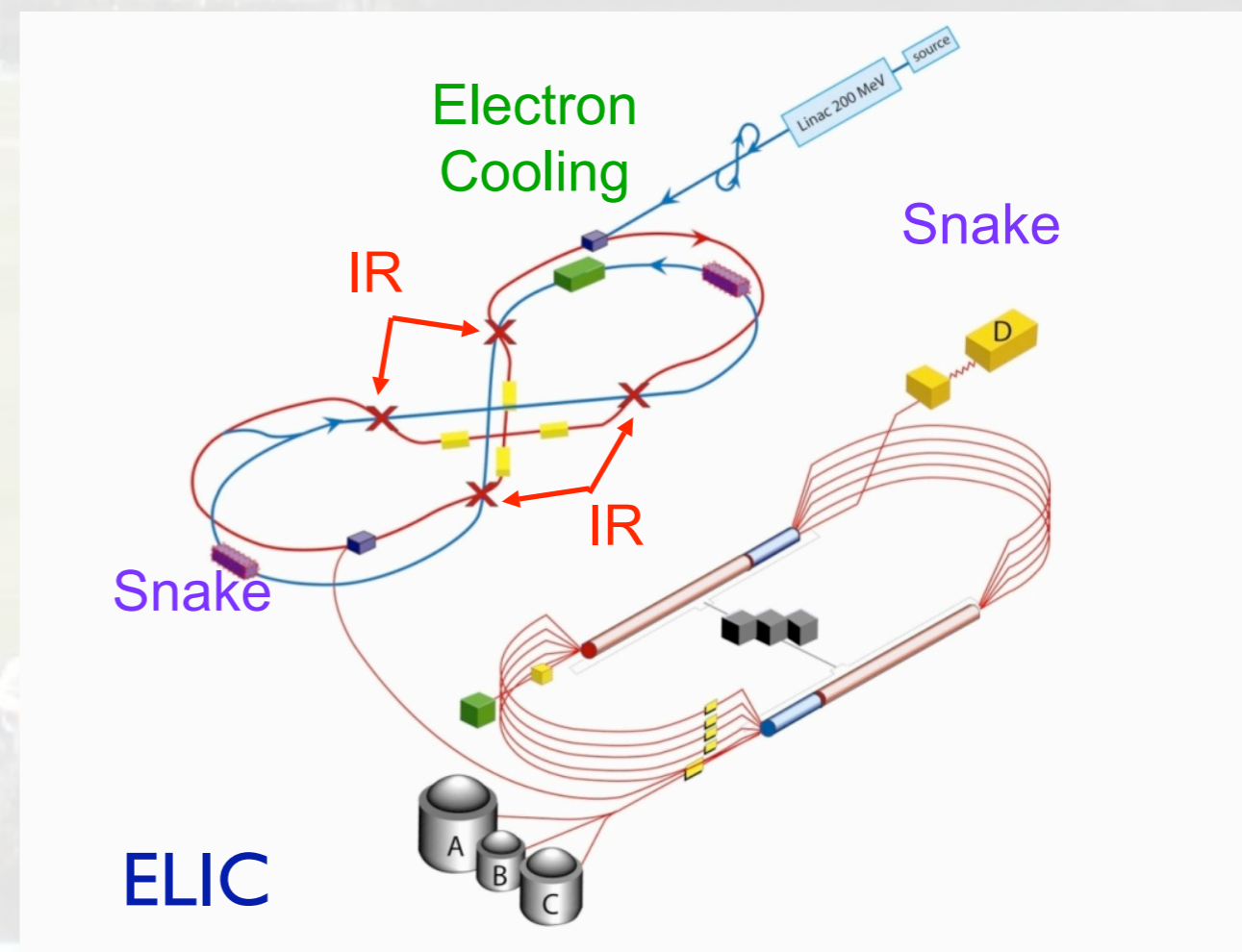
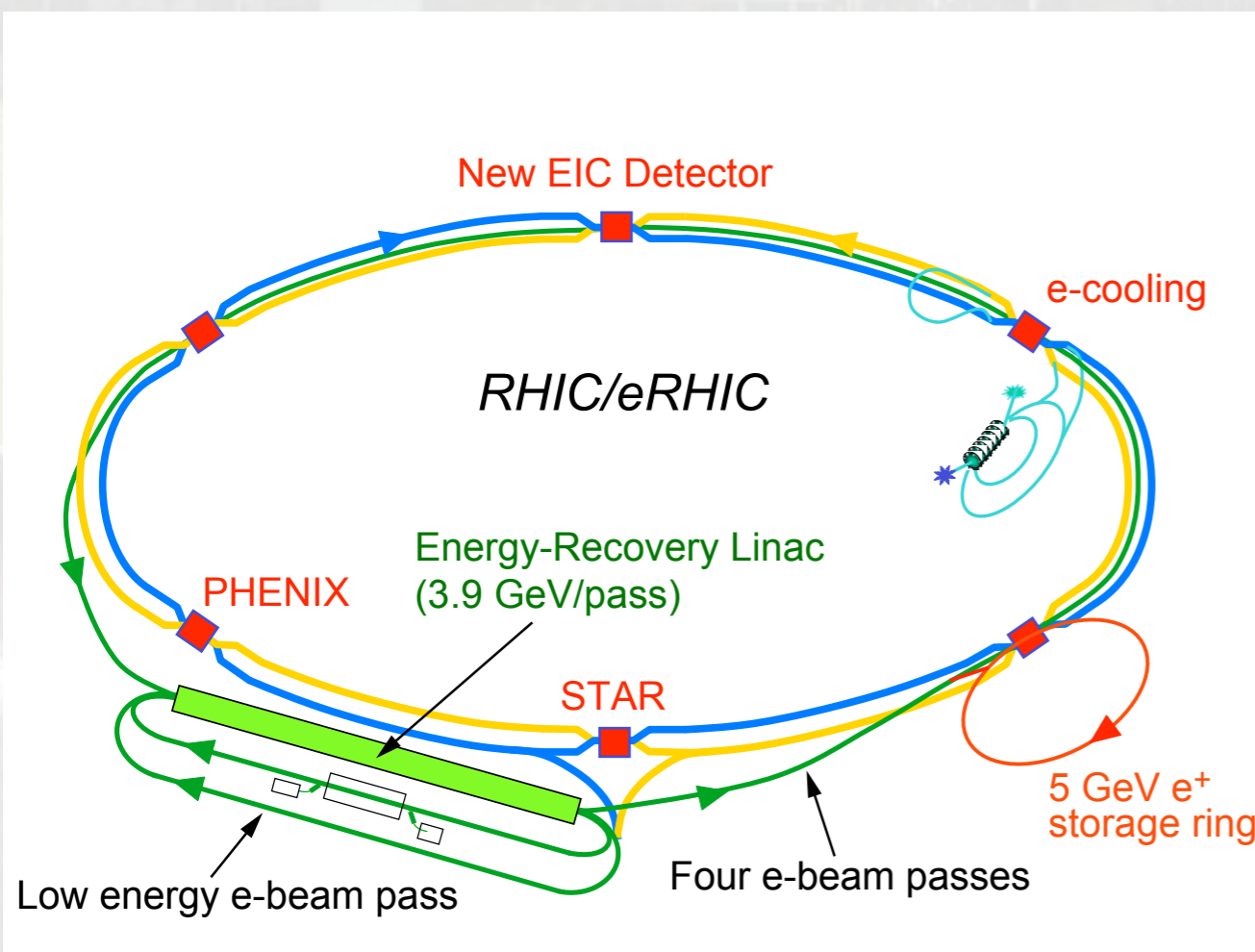
Add hadron machine

$$E_e = 9 \text{ GeV}$$

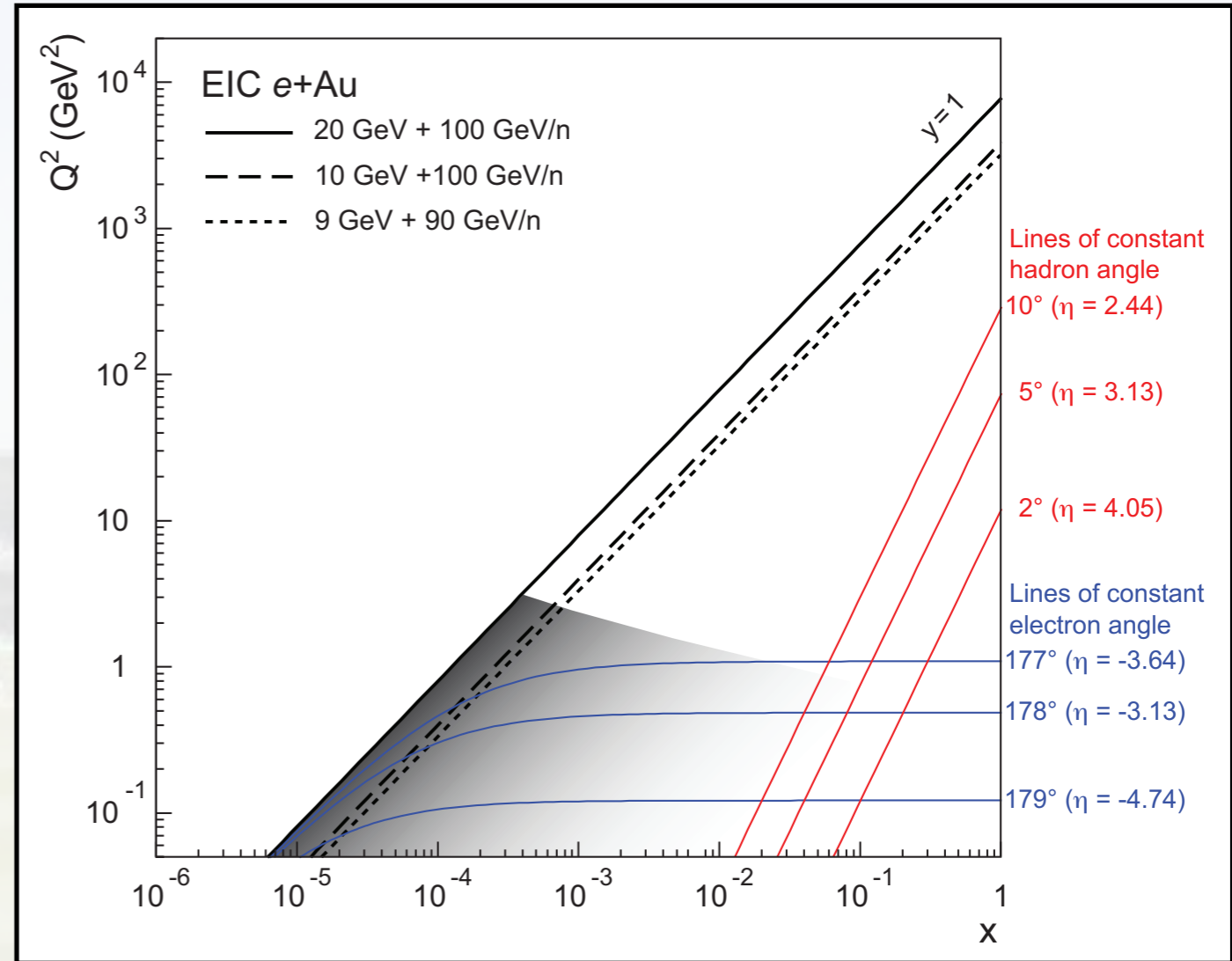
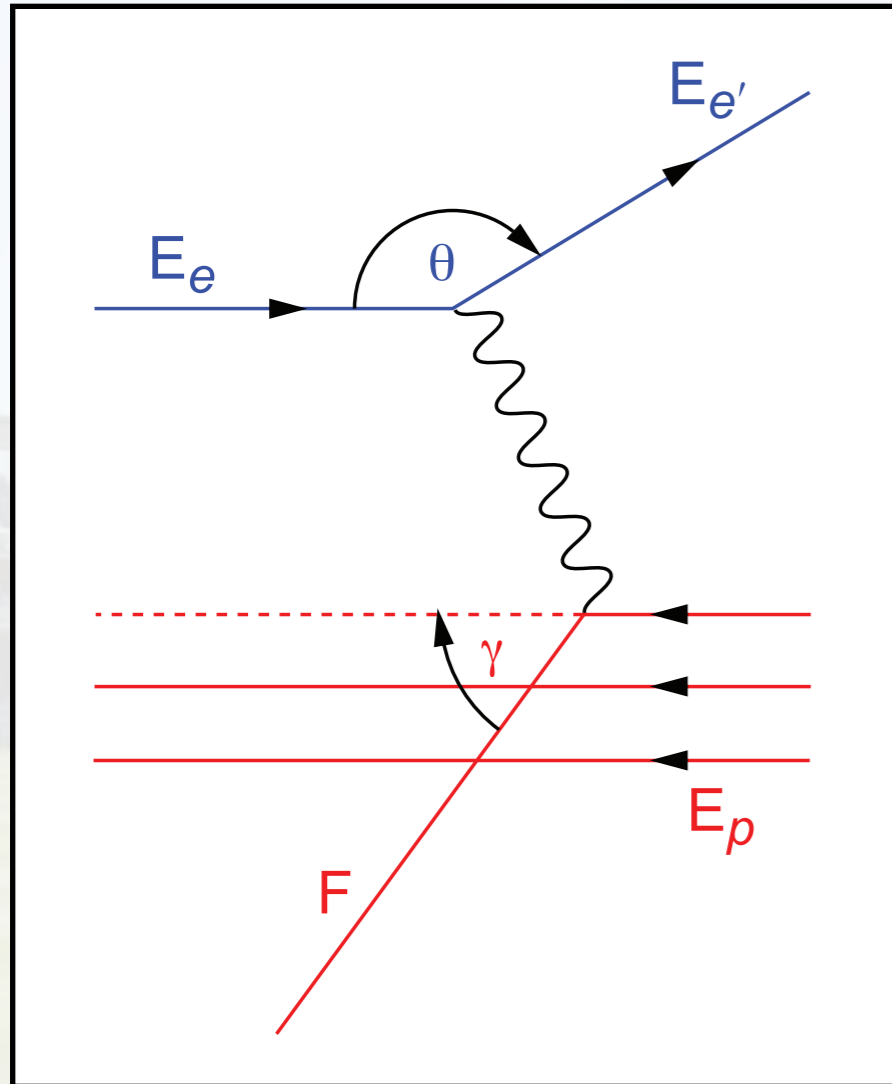
$$E_A = 90 \text{ GeV (up to Au)}$$

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

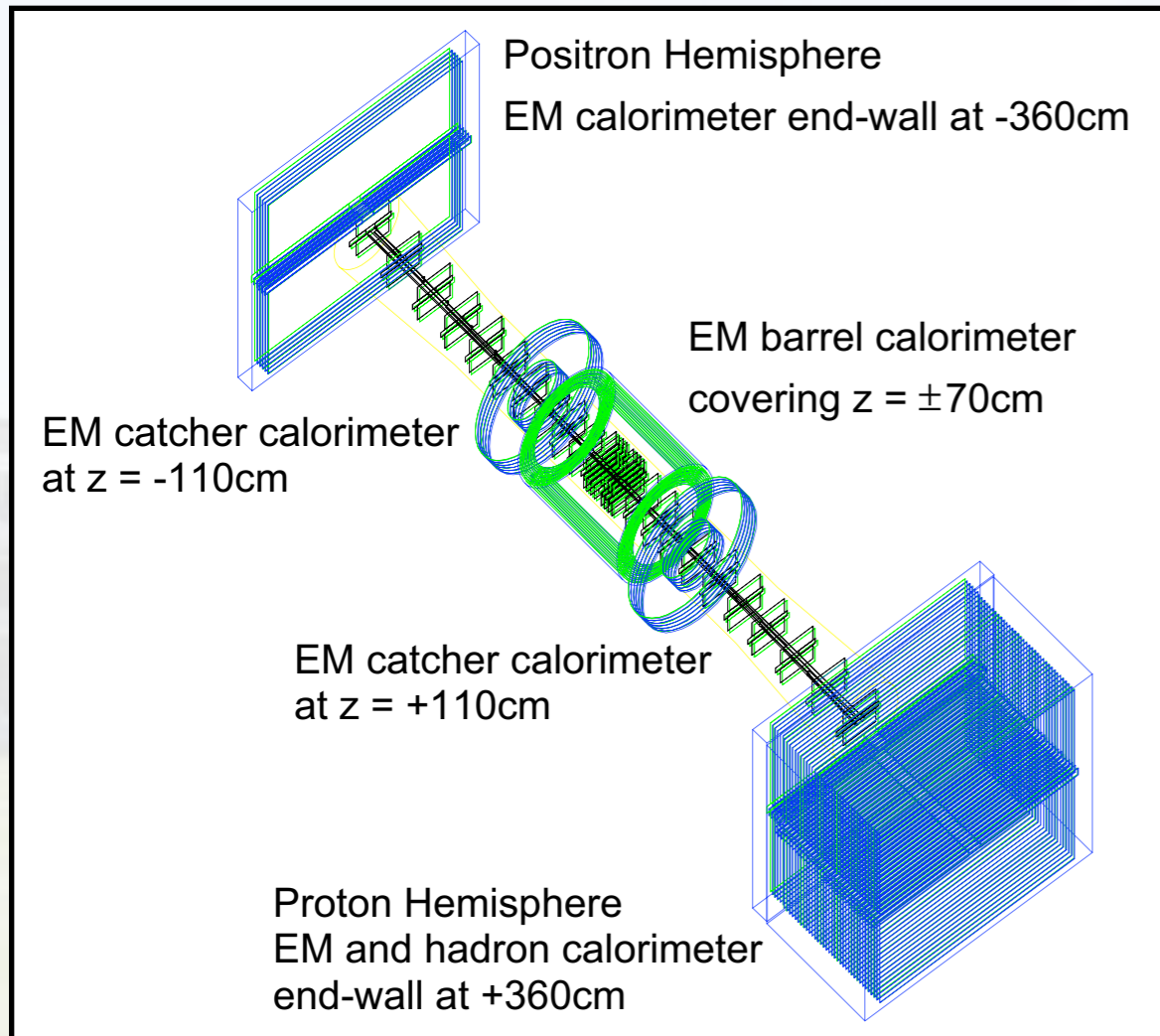
$$\mathcal{L}_{eAu} \text{ (peak)/n} \sim 1.6 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$$



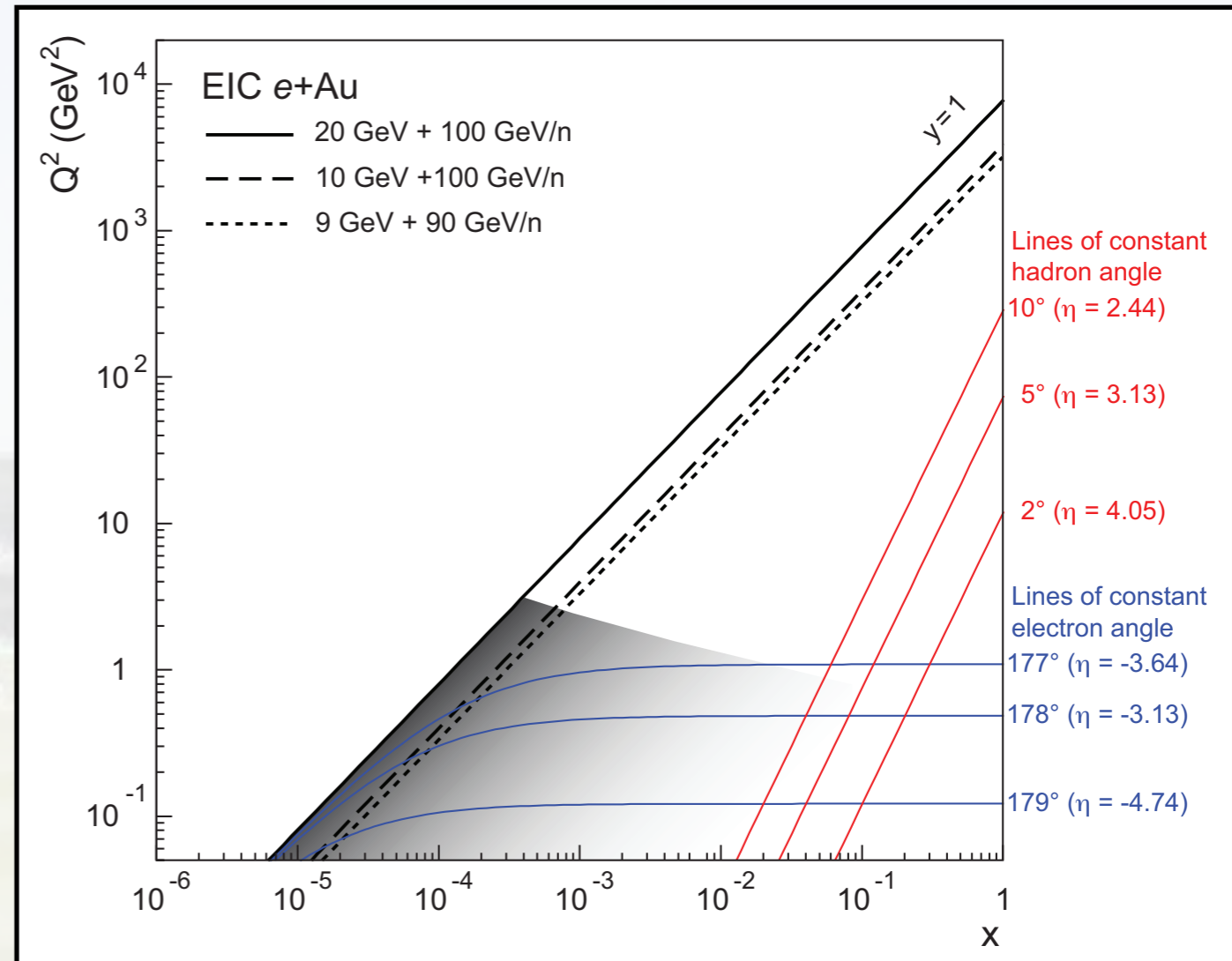
Experimental Aspects



Experimental Aspects



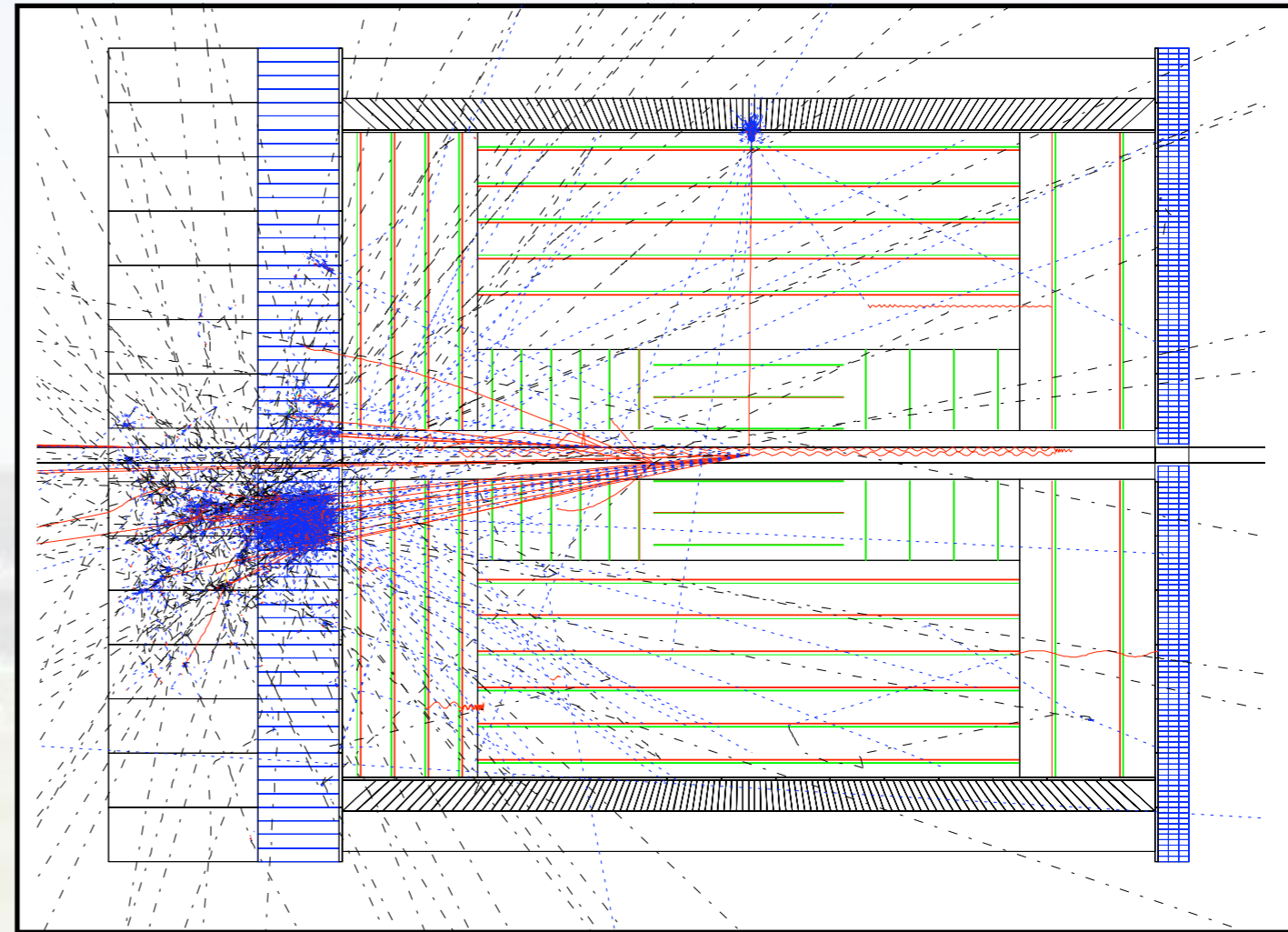
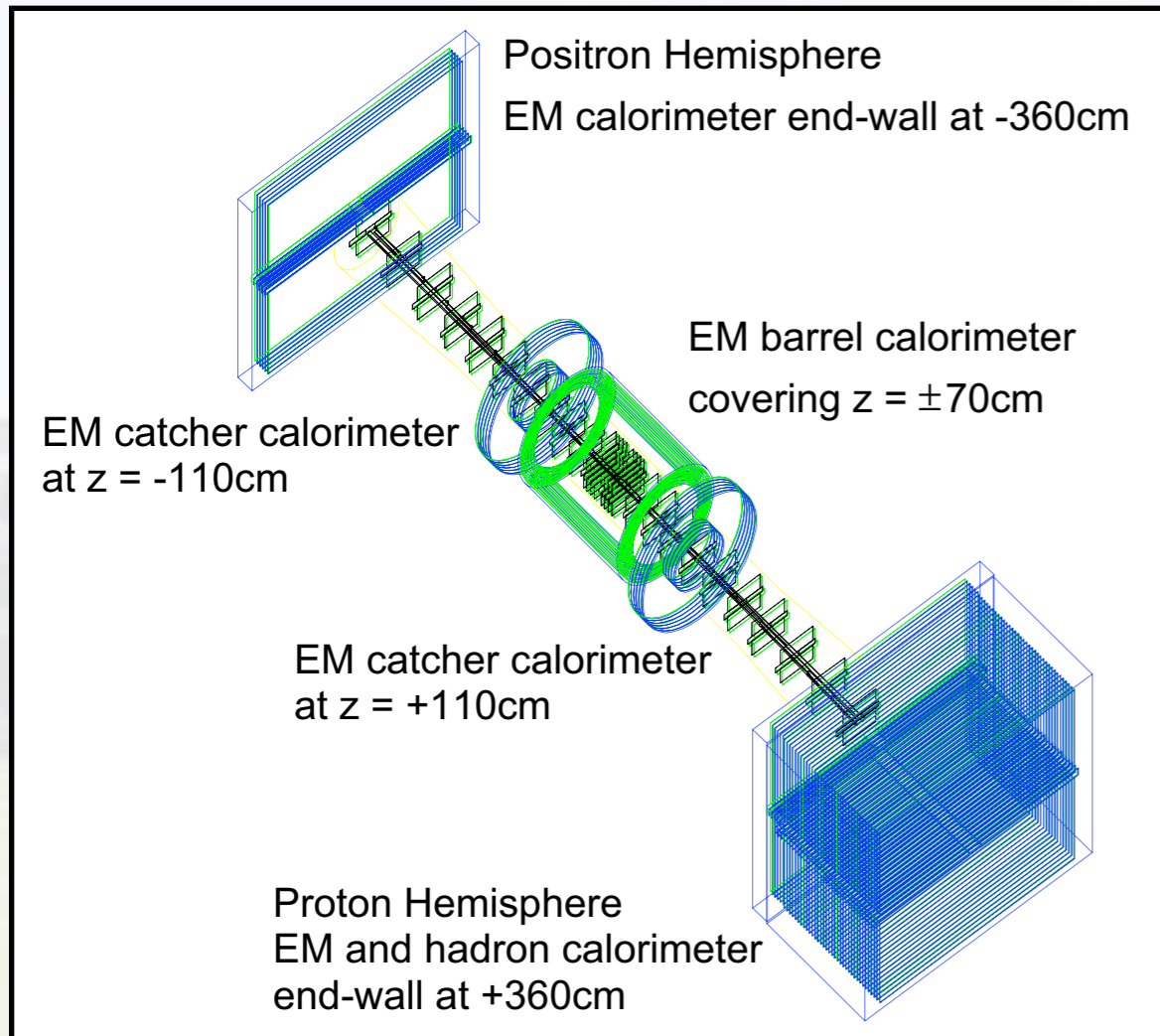
I. Abt, A. Caldwell, X. Liu, J. Sutiak, hep-ex 0407053



Concepts:

- 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



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

J. Pasukonis, B.Surrow, physics/0608290

Concepts:

- 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.

e+A Summary: Connection to RHIC & LHC Physics

● Thermalization:

- ➔ At RHIC system thermalizes (locally) fast ($\tau_0 \sim 0.6 \text{ fm}/c$)
- ➔ We don't know why and how? Initial conditions?

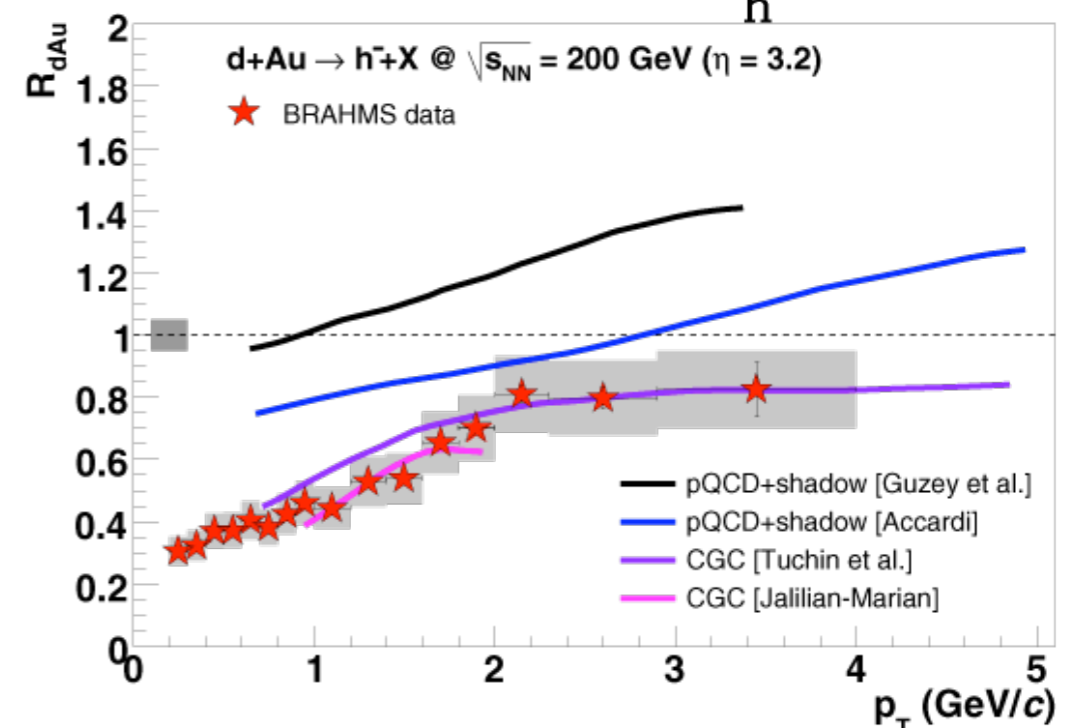
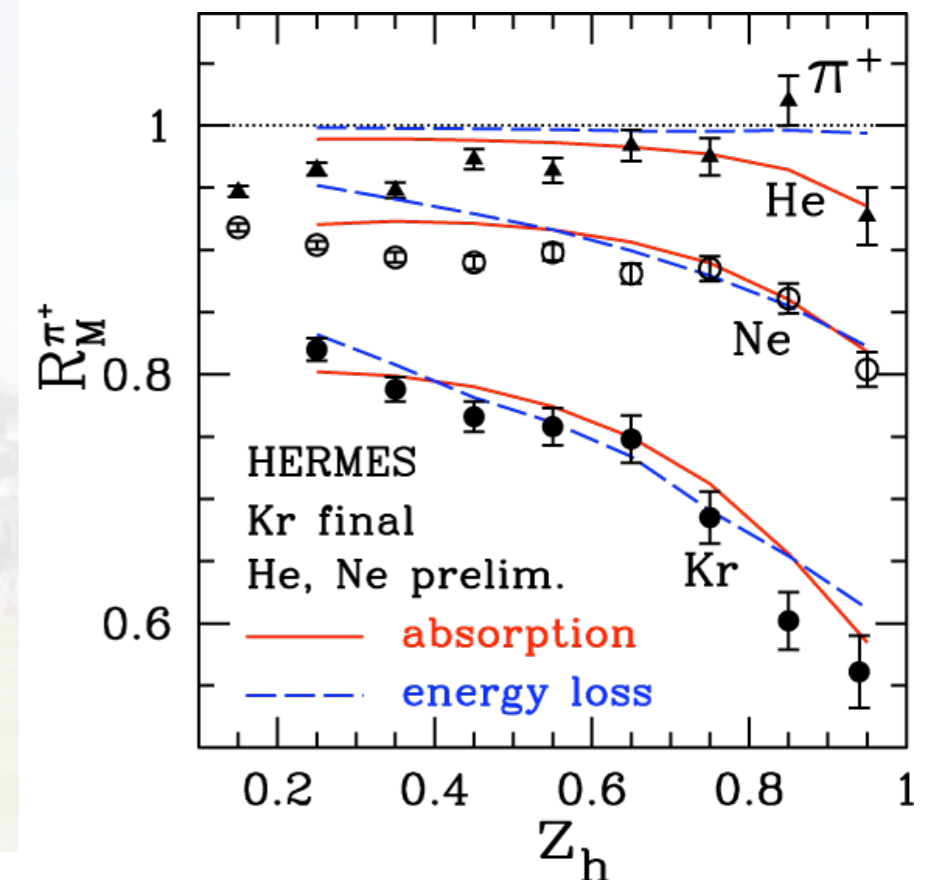
● Jet Quenching:

- ➔ Reference: E-loss in cold matter
- ➔ $p/d+A$ alone won't do, need more precision
- ➔ no data on charm from HERMES

● Forward Region:

- ➔ Suppression at forward rapidities
 - Color Glass Condensate ?
 - Gluon Distributions ?

FF modification
(parton energy loss)



Symbiosis between EIC and HI

- Thermalization:

- ➔ At RHIC system thermalizes (locally) fast ($\tau_0 < 0.6$ fm/c)

- ➔ We don't know why and how? Initial conditions?

Crude picture of initial state formation

$k_{T0}^2 \simeq k_{T0}^2 + Q_s^2$

IF $k_{T0}^2 \gg Q_s^2$ not much change. Gluon will not be freed.

IF $k_{T0}^2 \lesssim Q_s^2$ significant disturbance. Gluon will be freed.

So, roughly, gluons having $k_{T0} \lesssim Q_s$ will be freed and will give the initial state for the plasma.

At present
no first principle
understanding of
thermalization in
QCD

Al Mueller (2007)

Summary

- EIC presents a unique opportunity in high energy nuclear physics and precision QCD physics
- Embraced by NSAC in NP Long Range Plan
 - Recommendation: R&D on the level of \$6M/year over next 5 years
- Plan: EIC Proposal ready for Next Long Range Plan (2012)

Electron Ion Collider
Welcome to the e+A Working Group

e+A working group: <http://www.eic.bnl.gov>

Home Intro Documents Talks Meetings Computing Contacts

Welcome

This is the home page of the EIC e+A Working Group. The group focusses on the e+A aspects of a future Electron Ion Collider (EIC). If you are curious about the EIC and its physics please visit our [Introduction](#) page. There you can learn about the physics opportunities in e+A collisions with an Electron Ion Collider and much more. More information can be found on the [official EIC Collaboration web site](#). If you are looking for more details on current machine concepts, good places to start are the [eRHIC](#) pages at BNL and the ELIC material available on the [JLAB](#) web site. If you are interested in the project please join our mailing list. Our [Contact](#) page explains how. The [Documents](#) site contains all a lot of material related to e+A physics but also provides more general information about the EIC. Our [Talks](#) page lists all talks given at our EIC seminars and presentation given by members of the group. The [Computing](#) page provide information on computing resources available to us, our software and information on how to get started. This page is for collaborators only. See our [Contact](#) page if you want to get in touch with one of the e+A working group conveners. This page is hosted by [Brookhaven National Laboratory](#).

News

EIC Seminars at BNL
Our EIC seminars are currently taking a Spring Break. Look under the Talks link for previous seminars. When resumed, they will take place on Thursdays at 10:30am usually in the Orange Room. Speakers and/or meeting topics will be announced on the mailing list and here. (3/25/2008, macl)

Last updated: Wed, Mar 25, 2008 by macl

EIC on the web: <http://web.mit.edu/eicc>