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

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

DIS 2008, London, England

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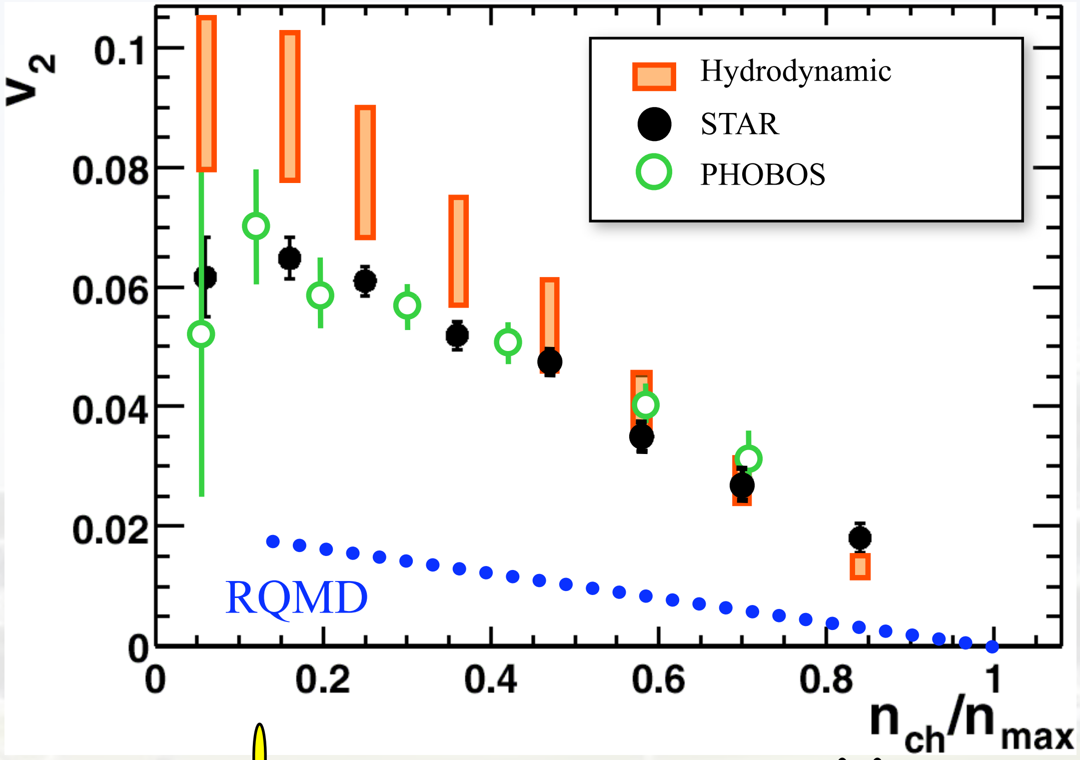
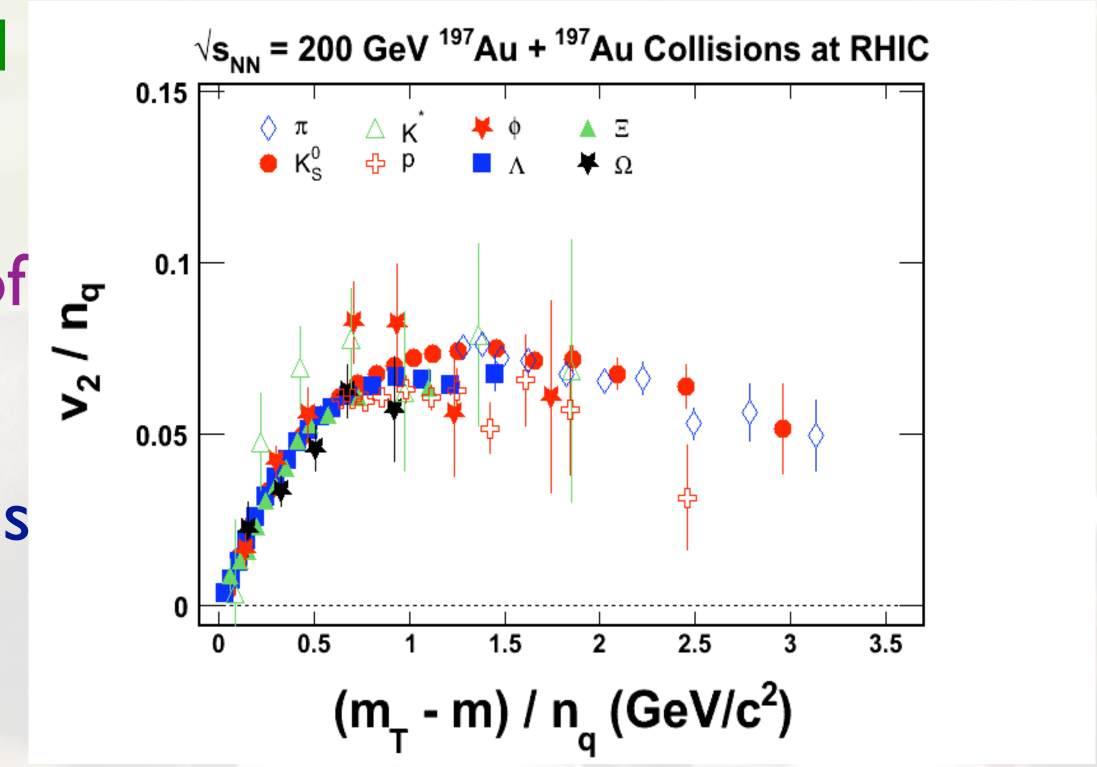
Talk Outline

- 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)

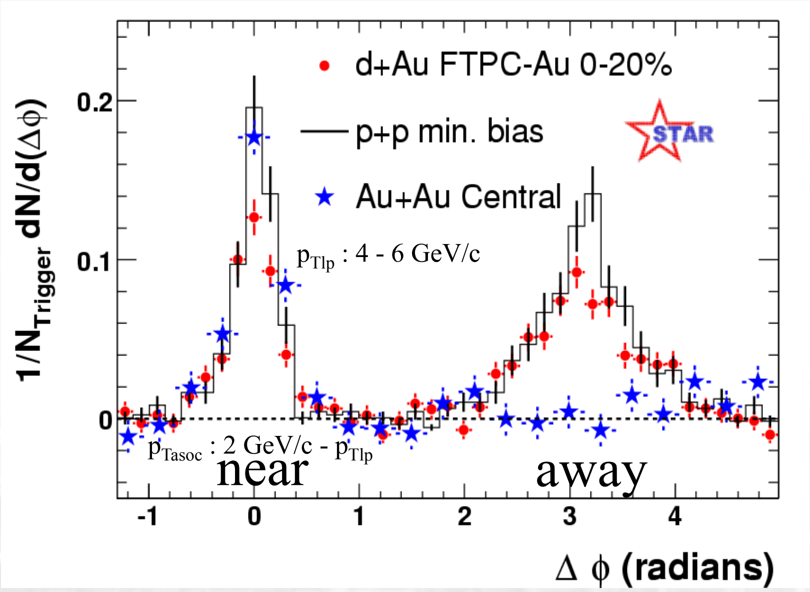
Seminal Result - Hadron flow

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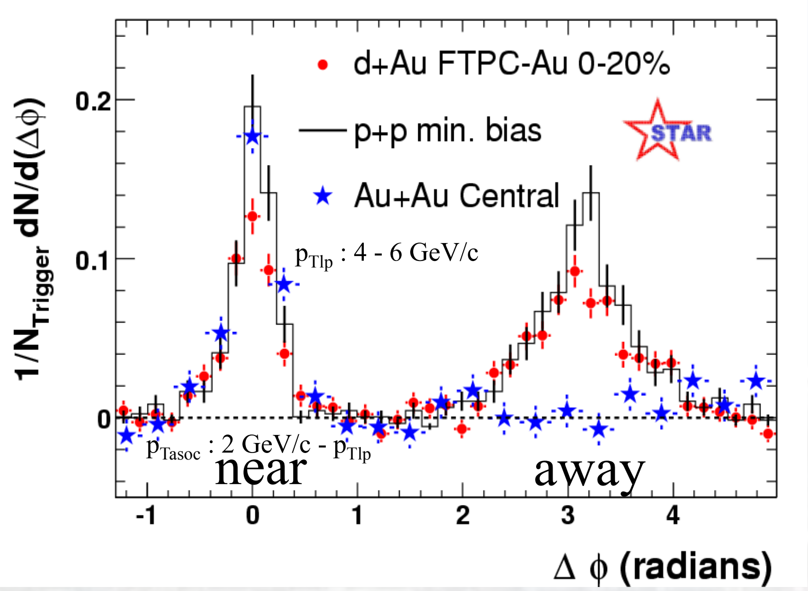
- Triggering on di-hadron correlations reveals an absence of back-to-back jets in Au+Au collisions



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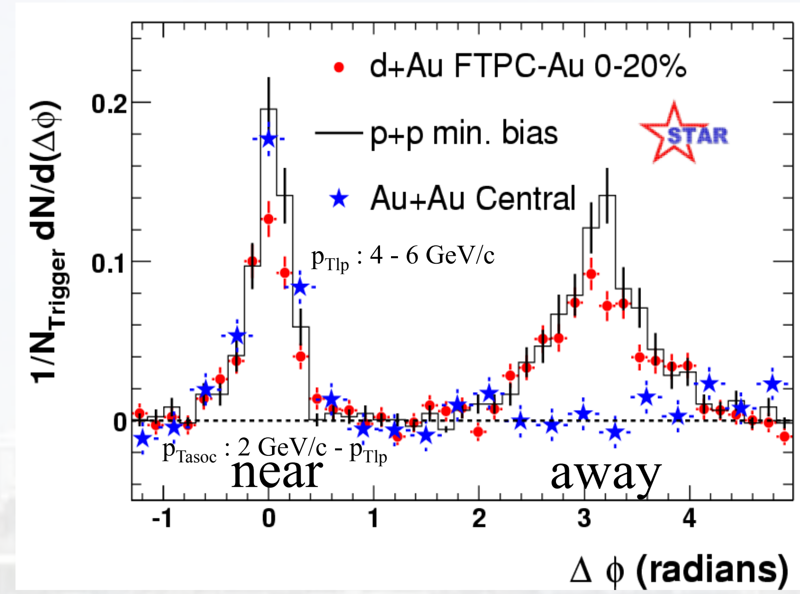
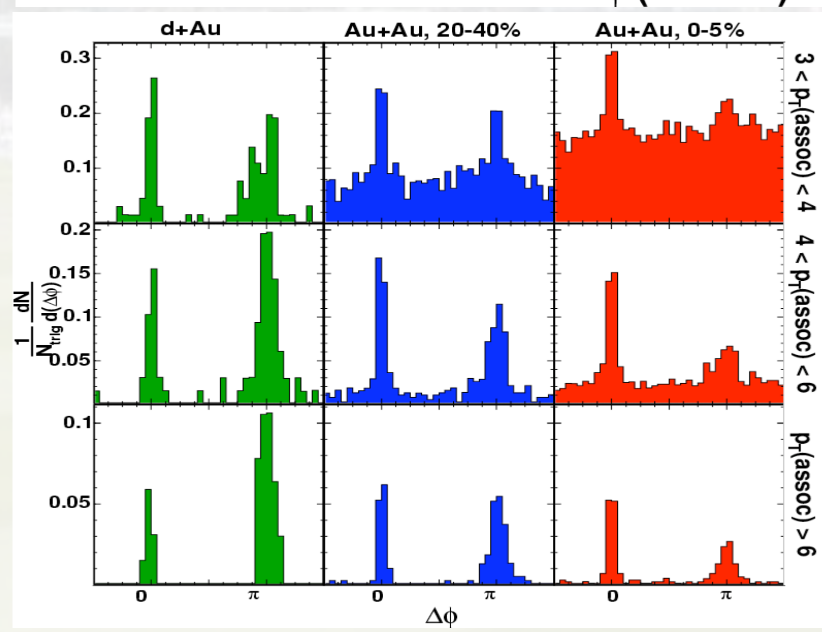
- At high-enough p_T, "away-side" jets re-appear in central Au+Au collisions





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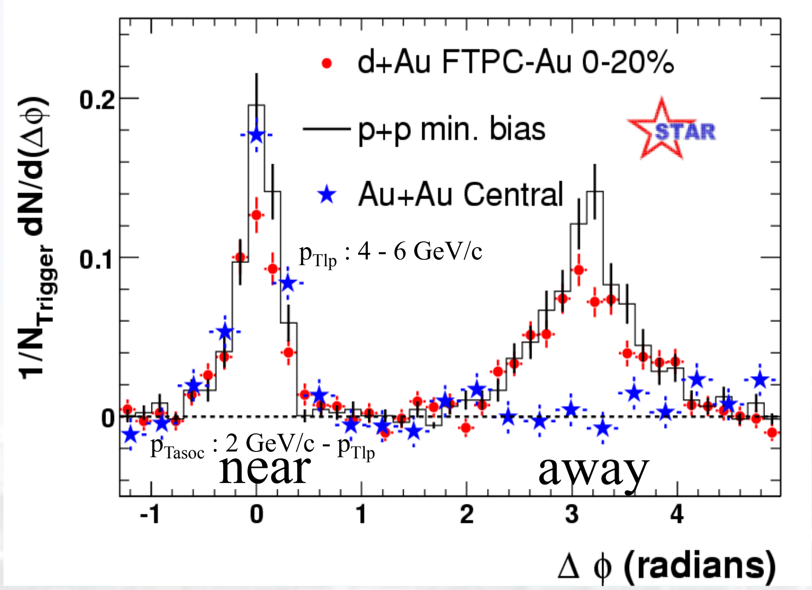

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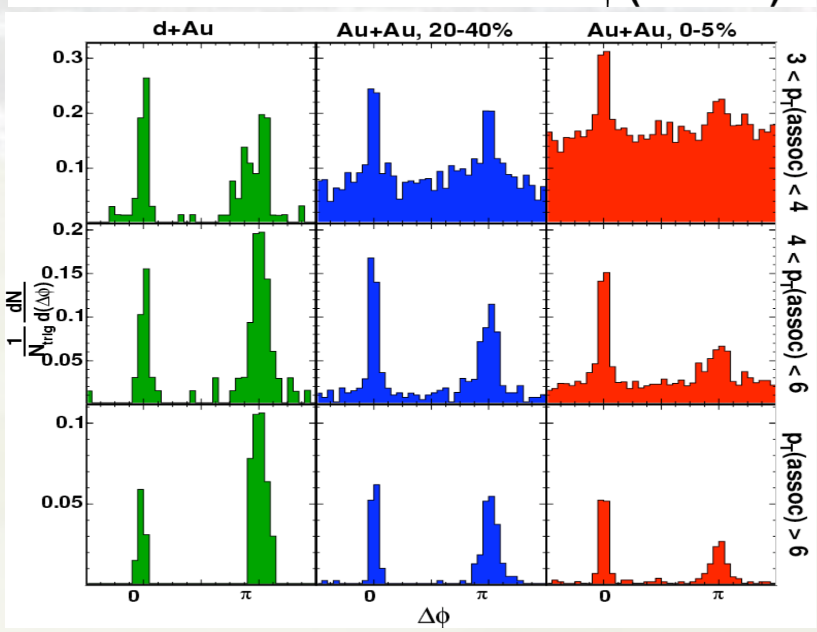

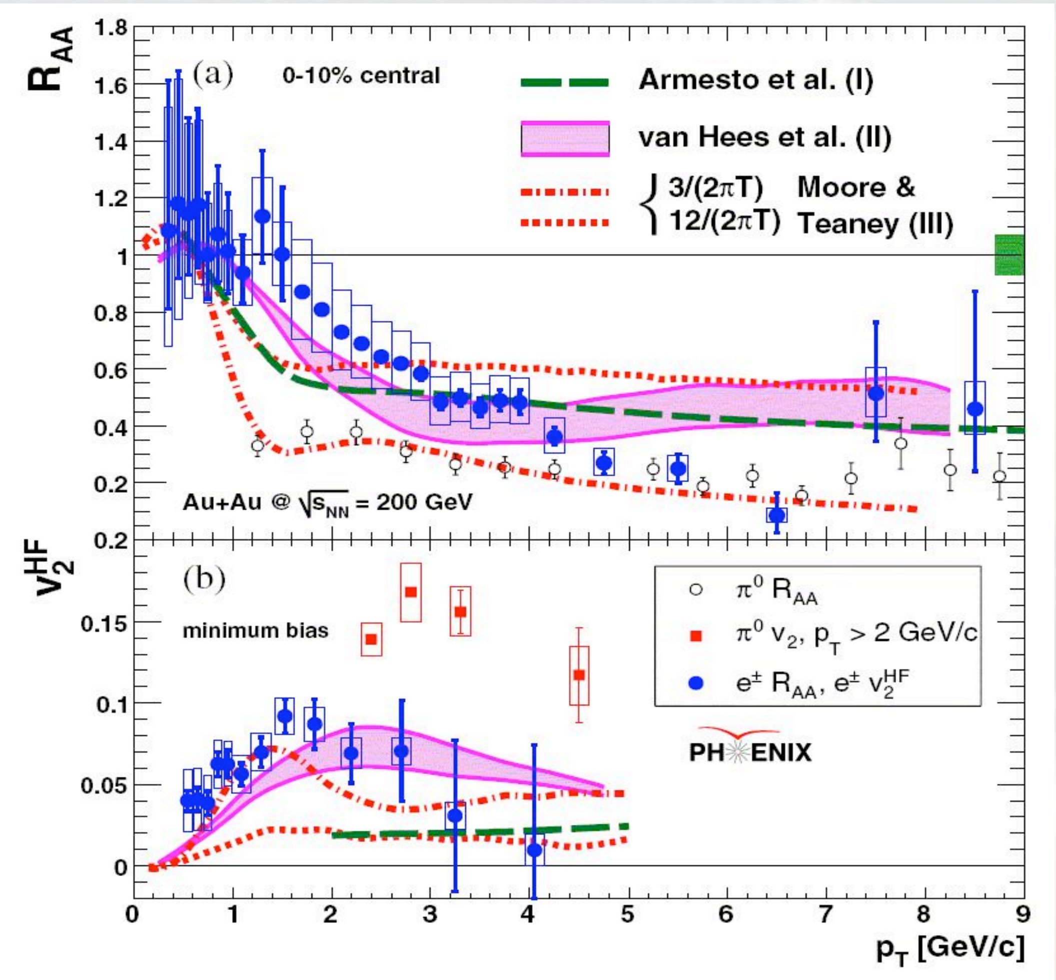

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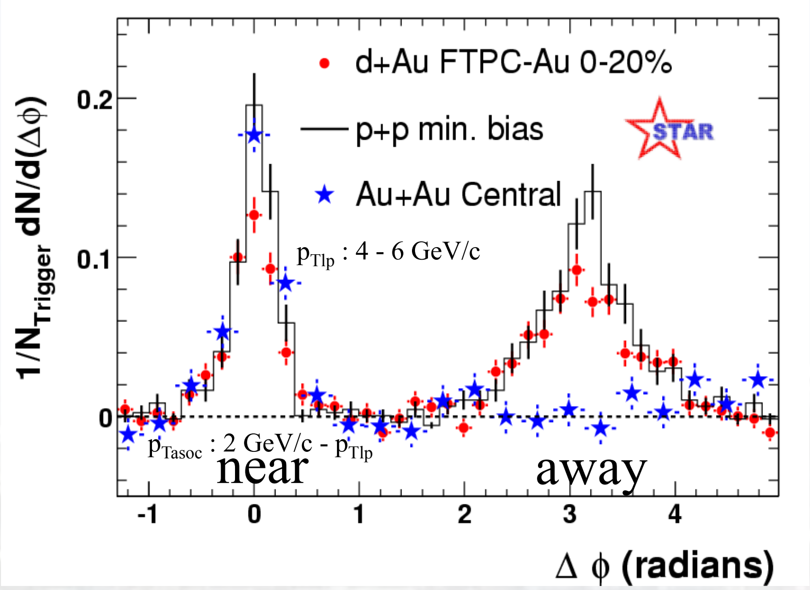
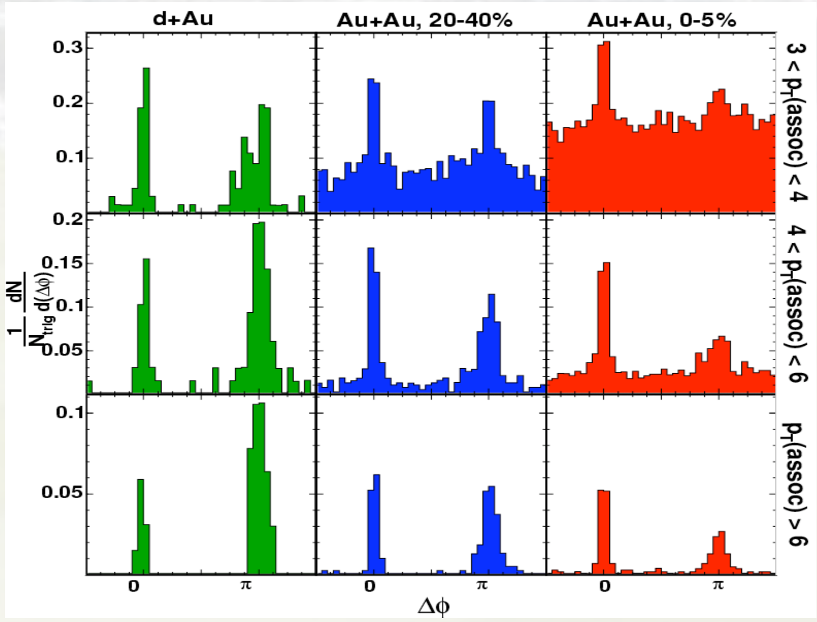
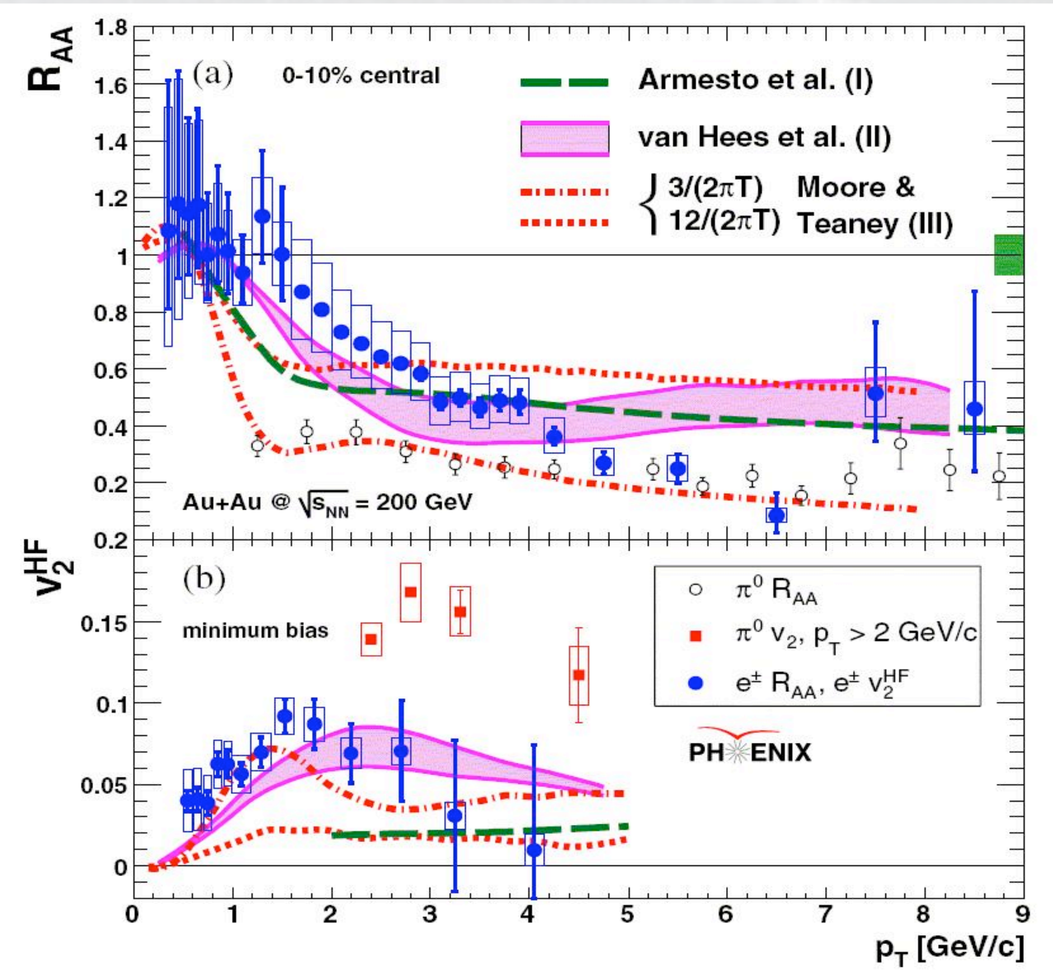




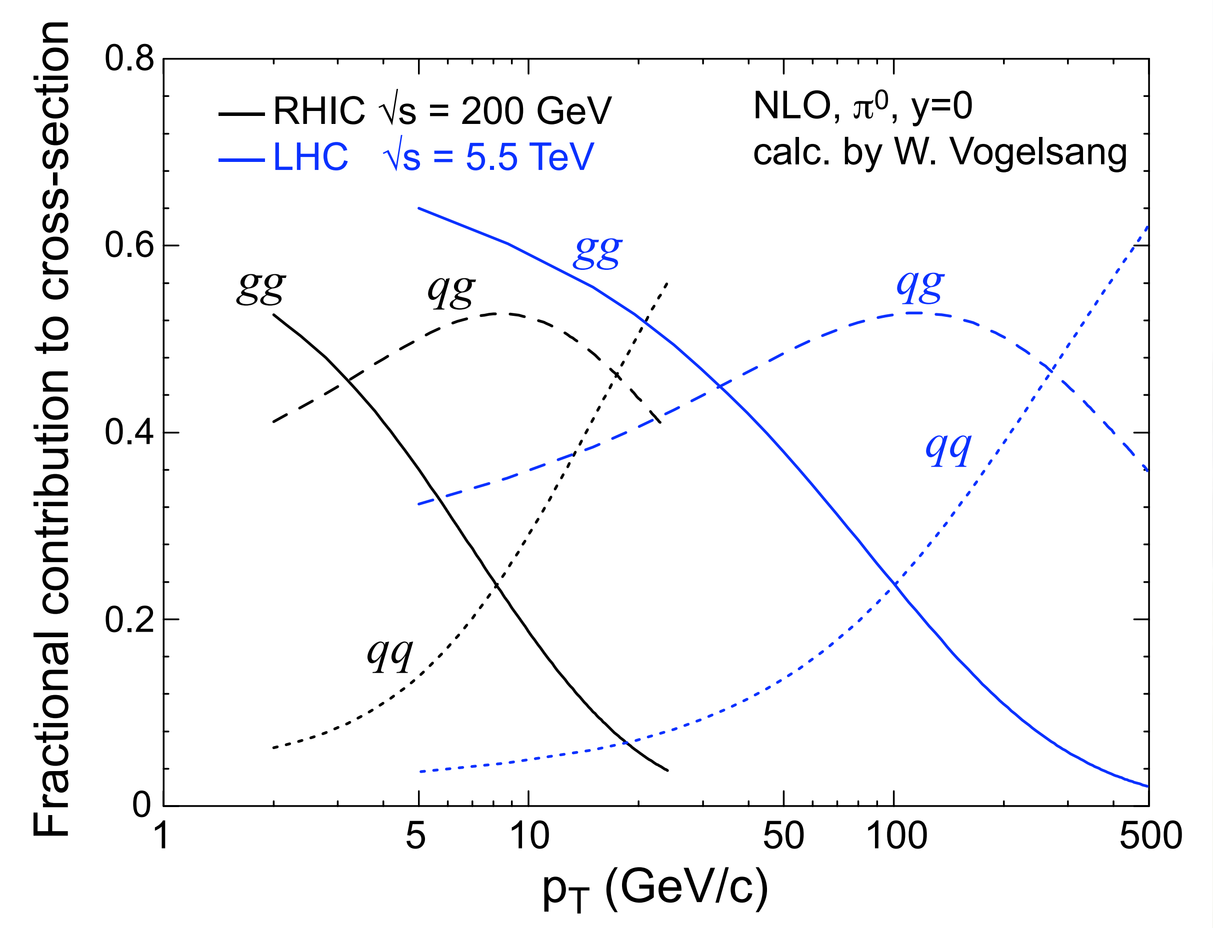


- R_{AA} shows heavy charm quarks suppressed as much as light quarks

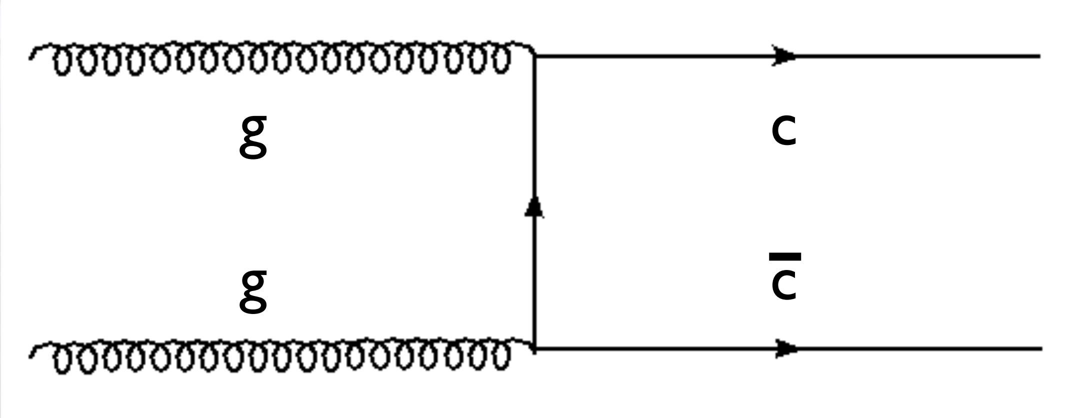
- Need to understand hadronization and energy loss

The role of Glue in Heavy-Ion collisions

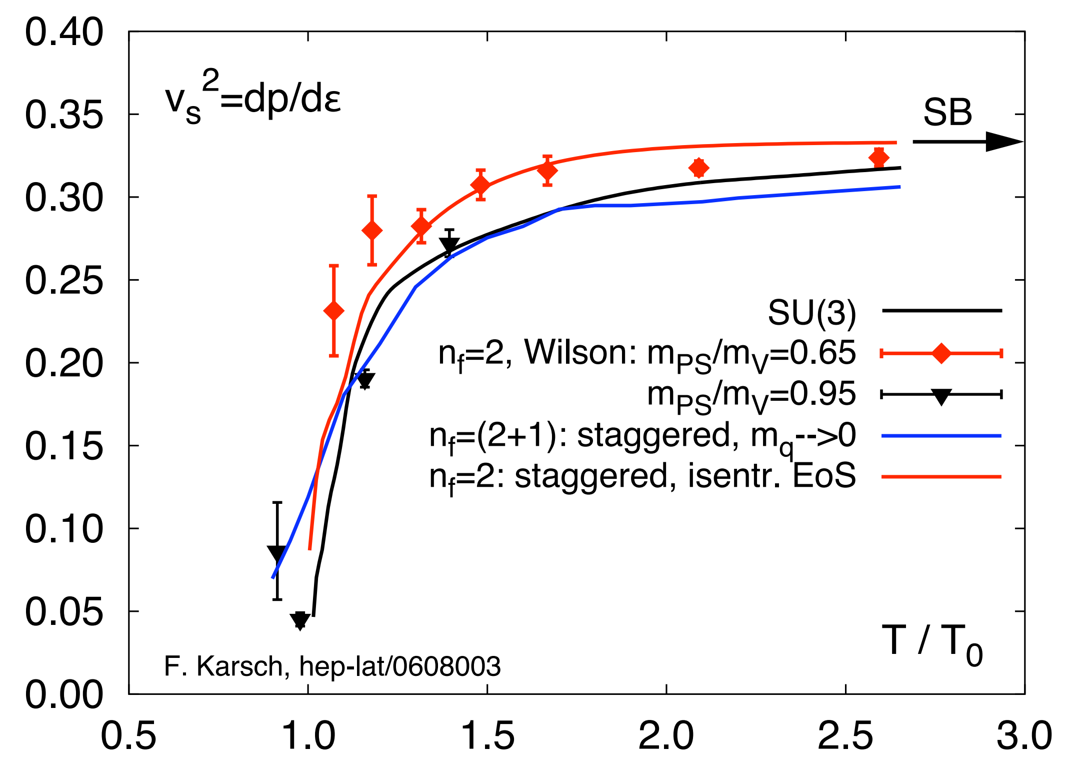
Jets (π^0 production)

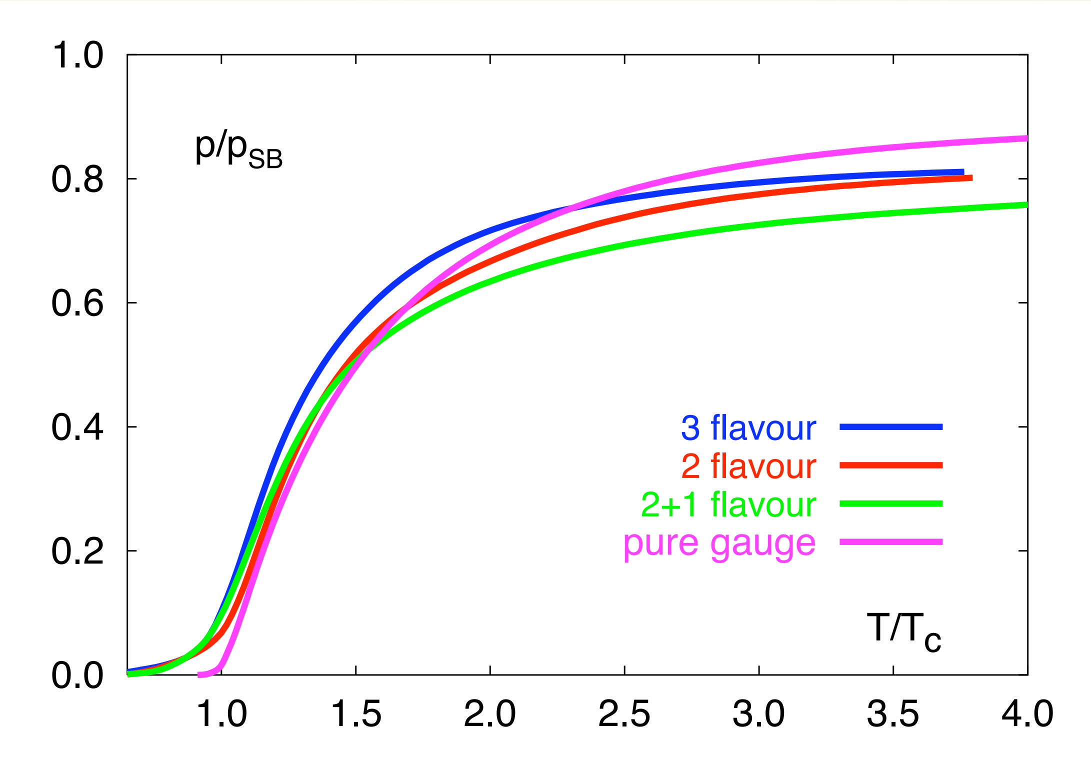


Heavy Flavour Production



Lattice Gauge Theory:





Glue and the Lagrangian

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

- **“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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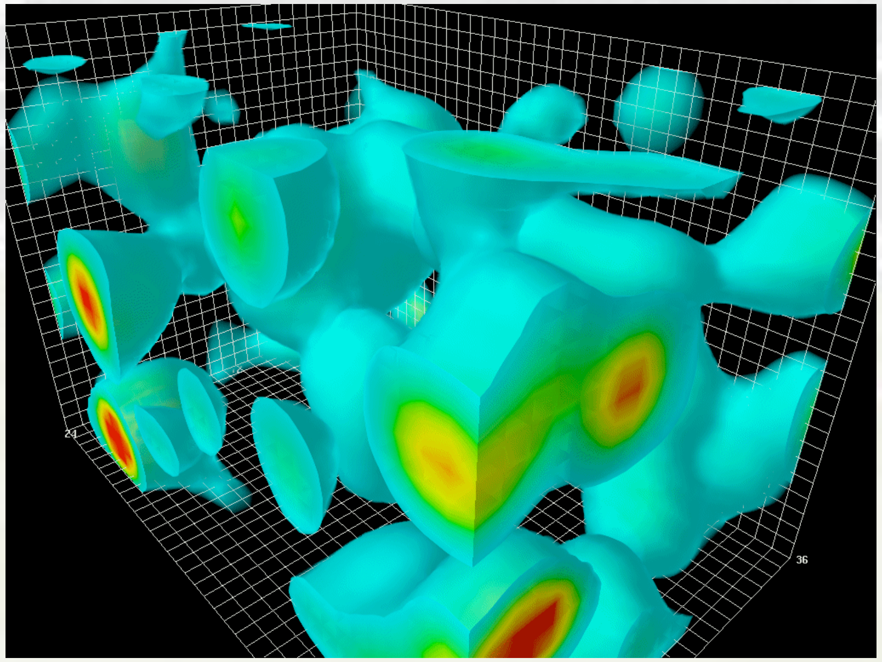

Action (~energy) density fluctuations of gluon-fields in QCD vacuum (2.4 ×2.4× 3.6 fm) (Derek Leinweber)

Glue and the Lagrangian

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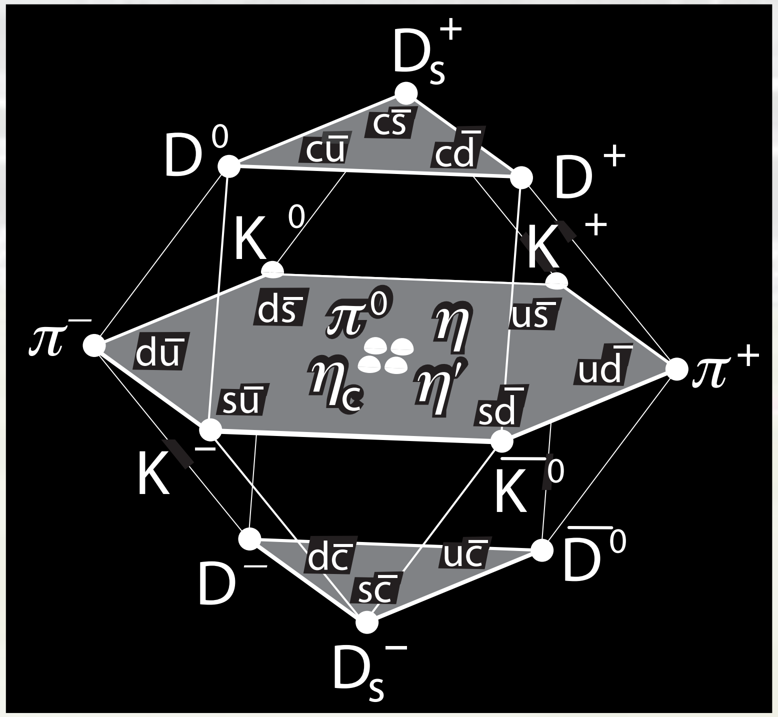

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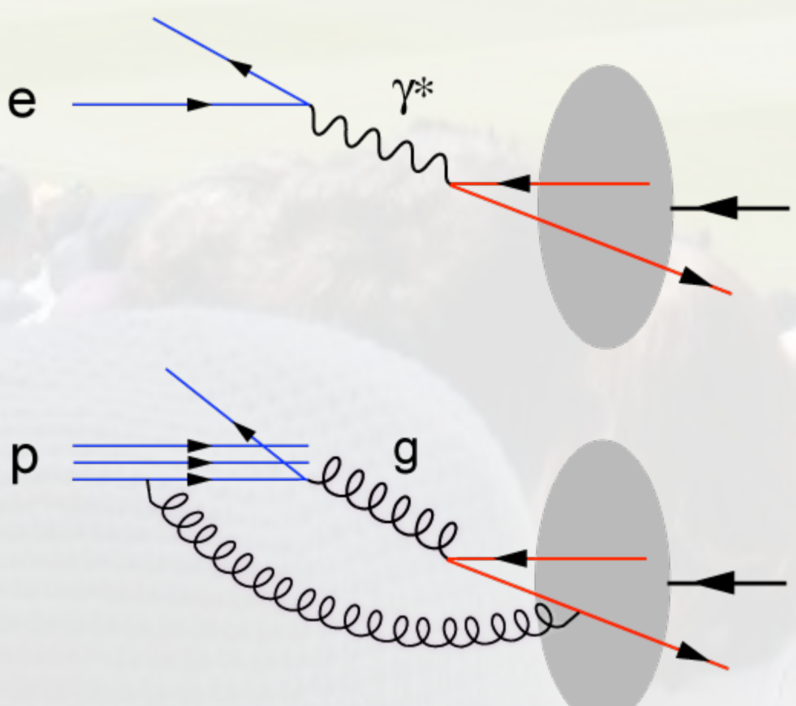
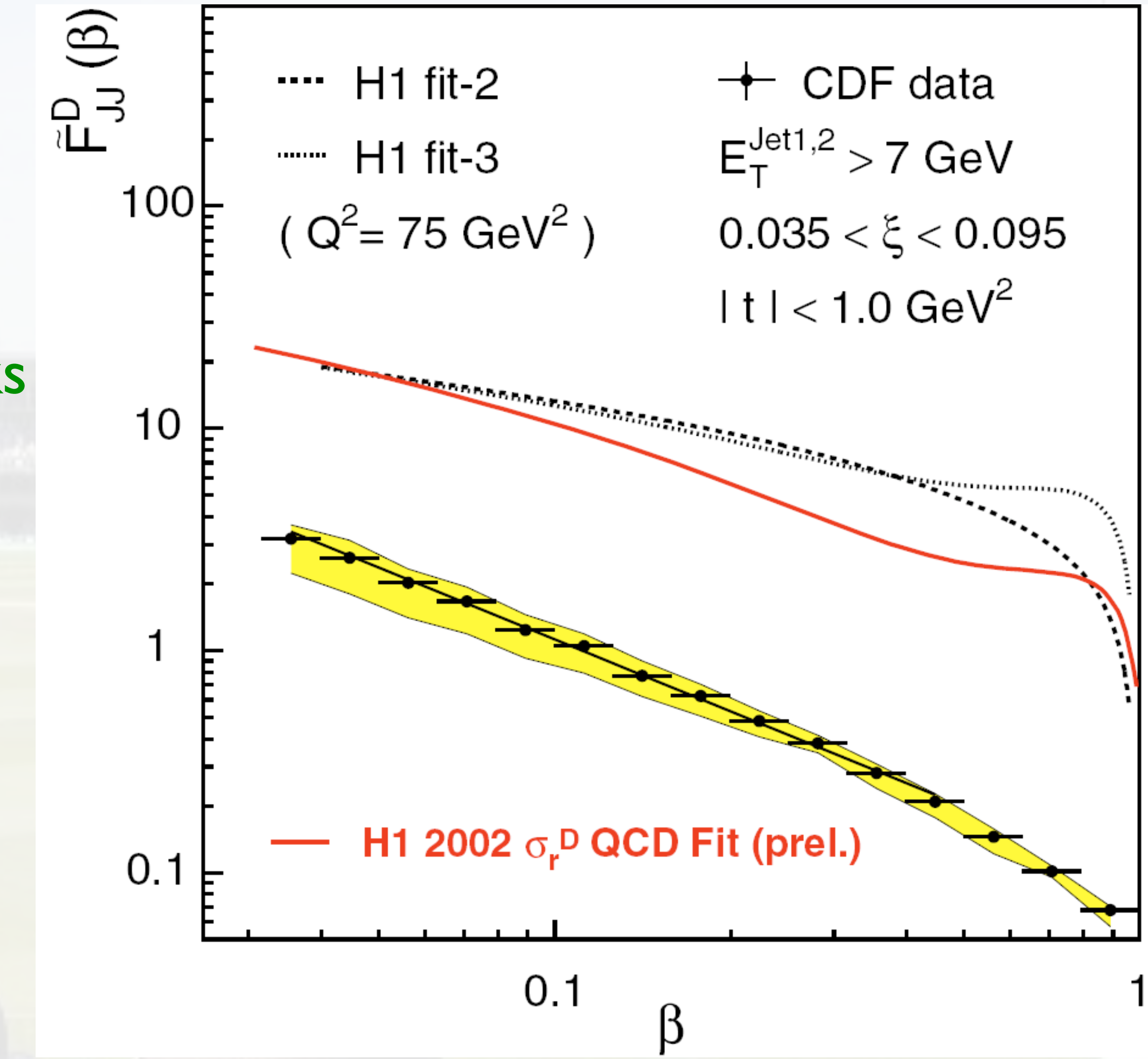
- **Hard to "see" glue in the low-energy world**
  - Gluon degrees of freedom "missing" in hadronic spectrum
  - Drive the structure of baryonic matter already at medium-x
  - Crucial players at RHIC and LHC

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 ⇒
- Issues:
  - ➡ p+A lacks the direct access to x, Q^2

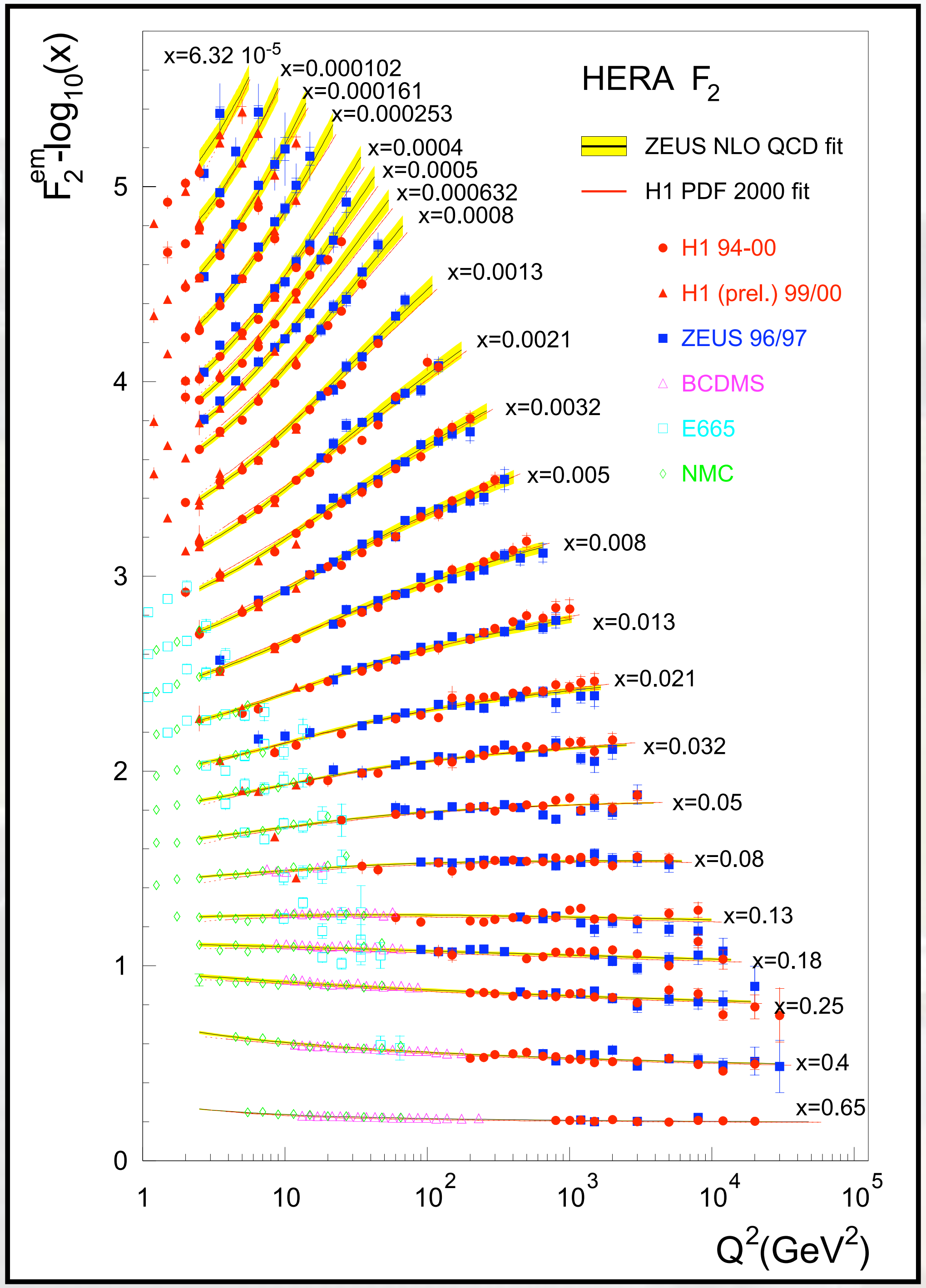




Breakdown of factorization (*e*+*p* HERA versus *p*+*p* Tevatron) seen for diffractive final states.

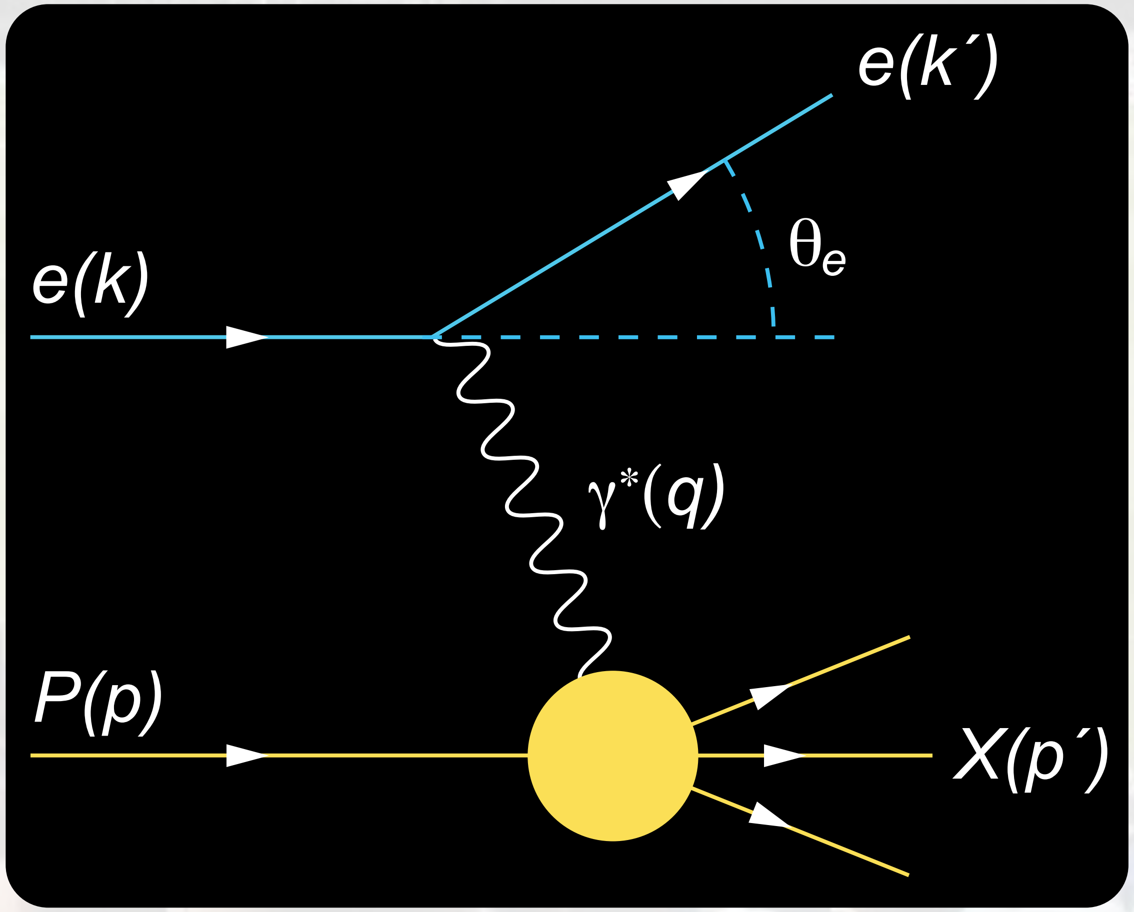
How to Measure the Glue ?

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



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

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



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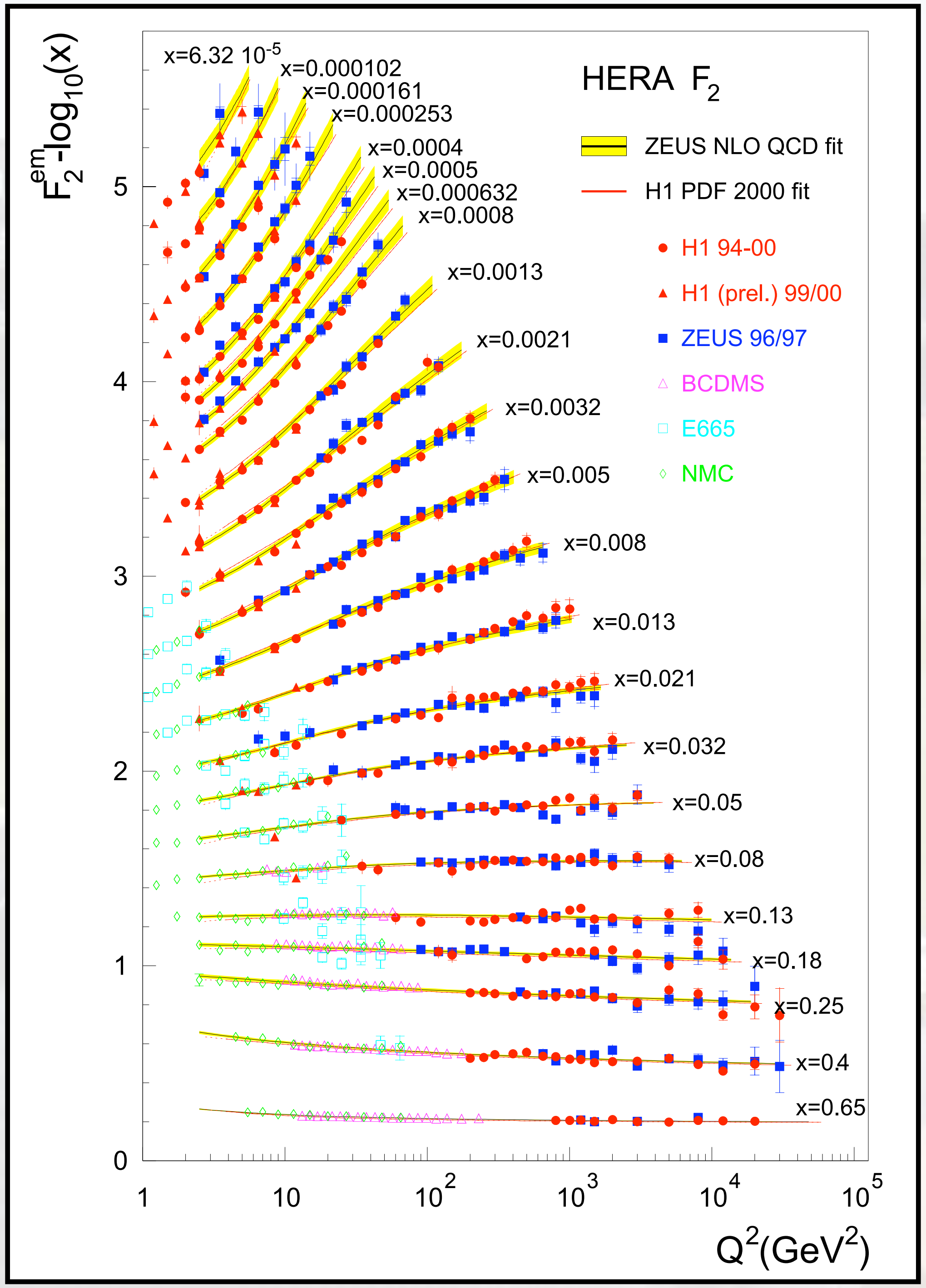

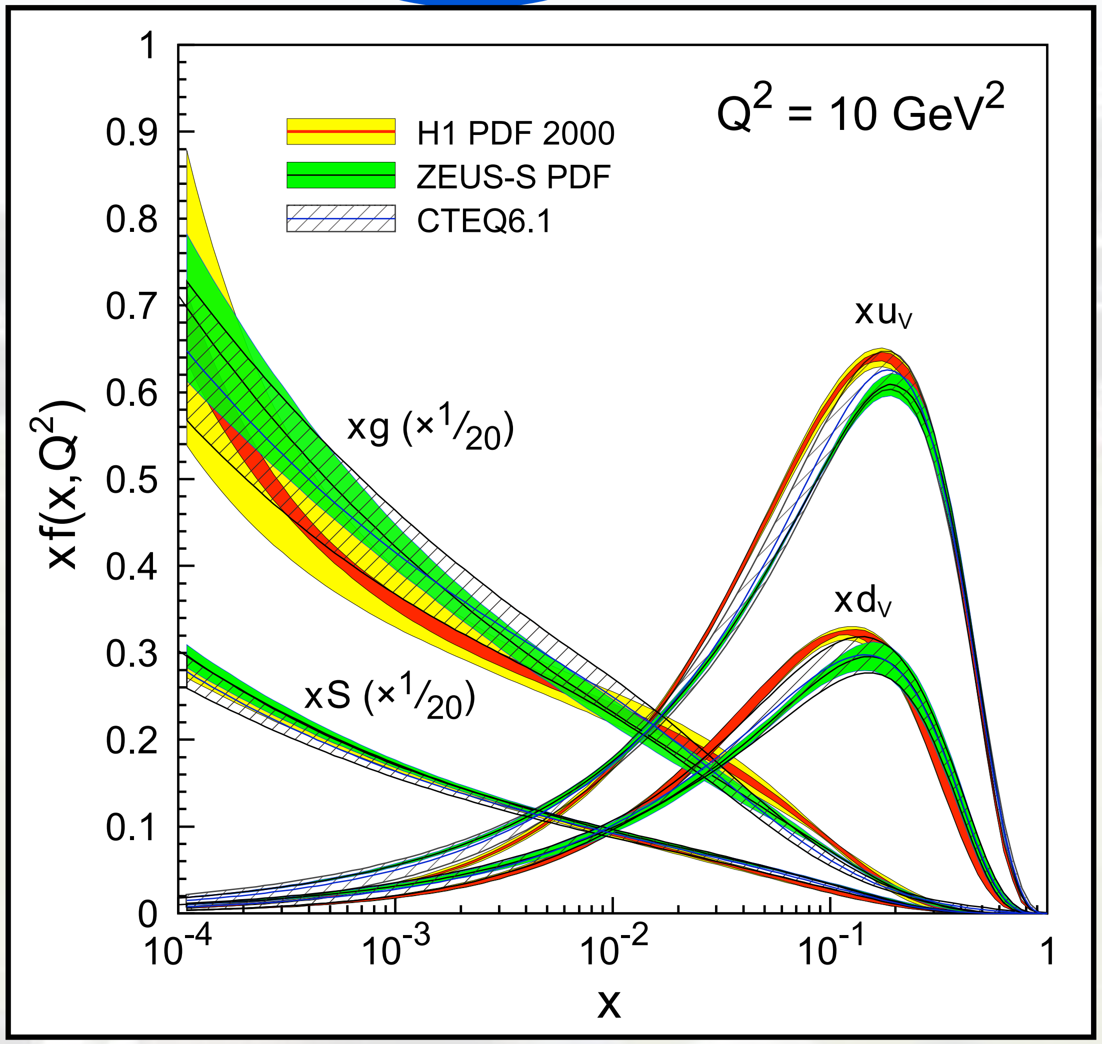

Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$

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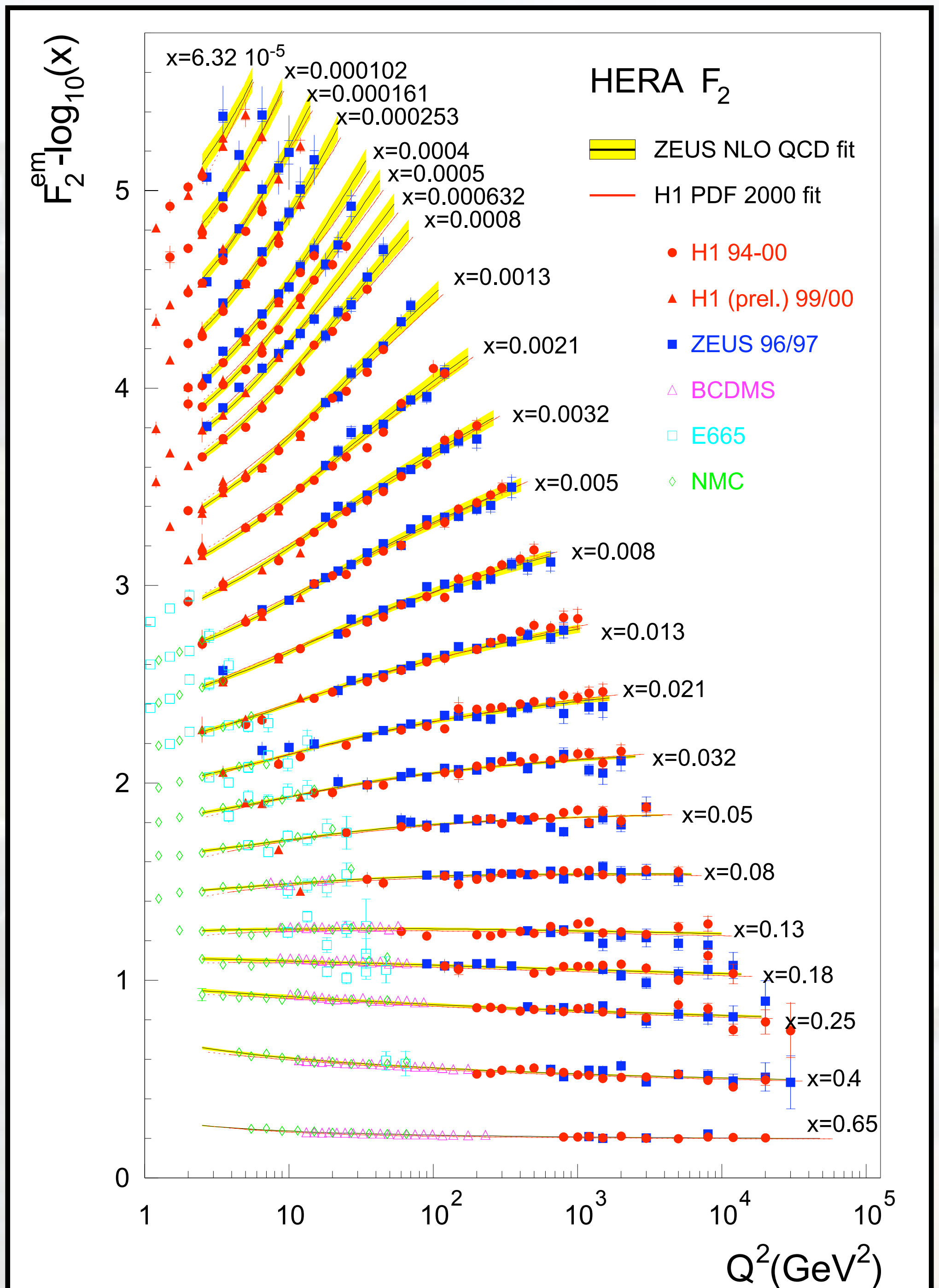

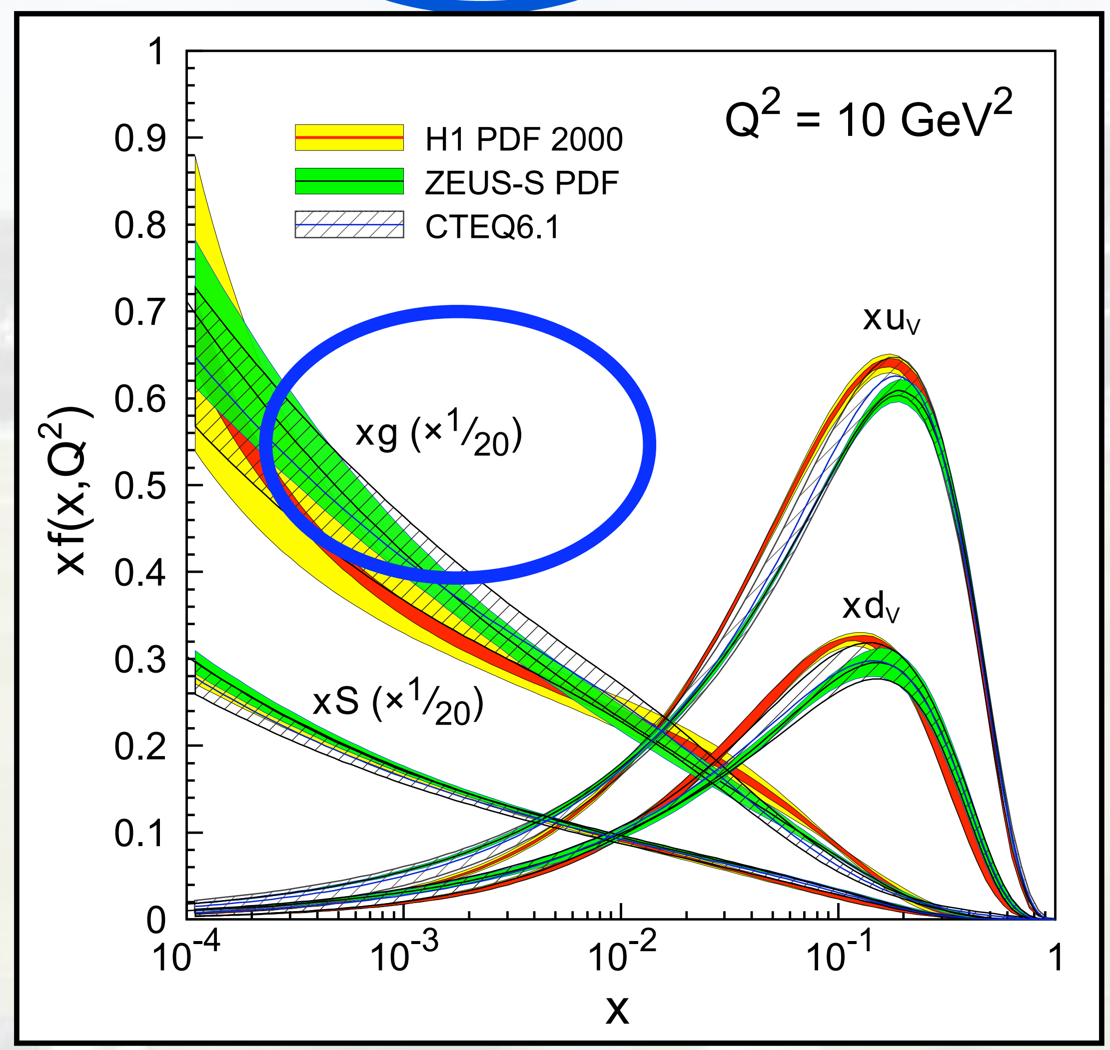

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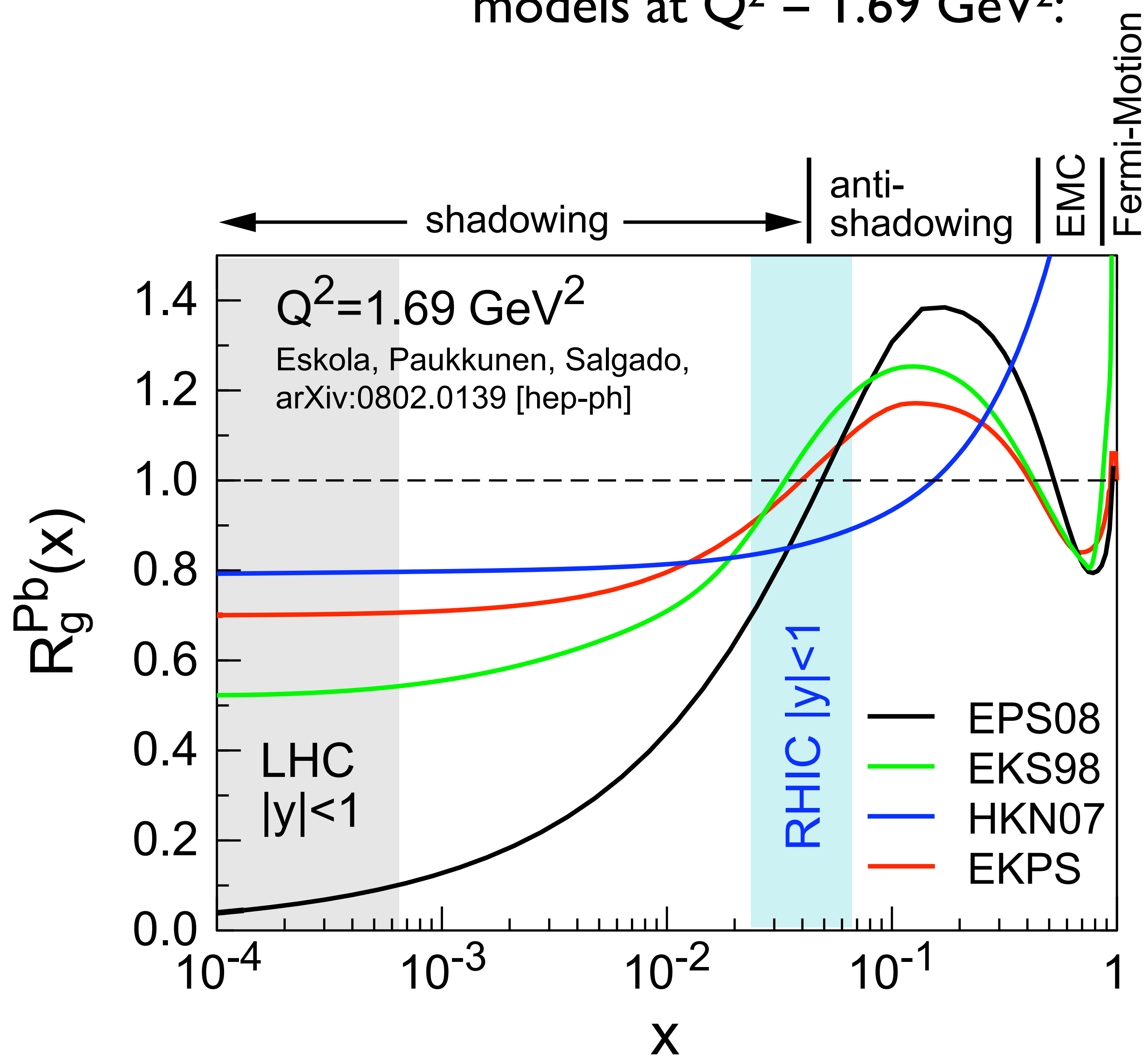
How to Measure the Glue ?

Important for RHIC and LHC:

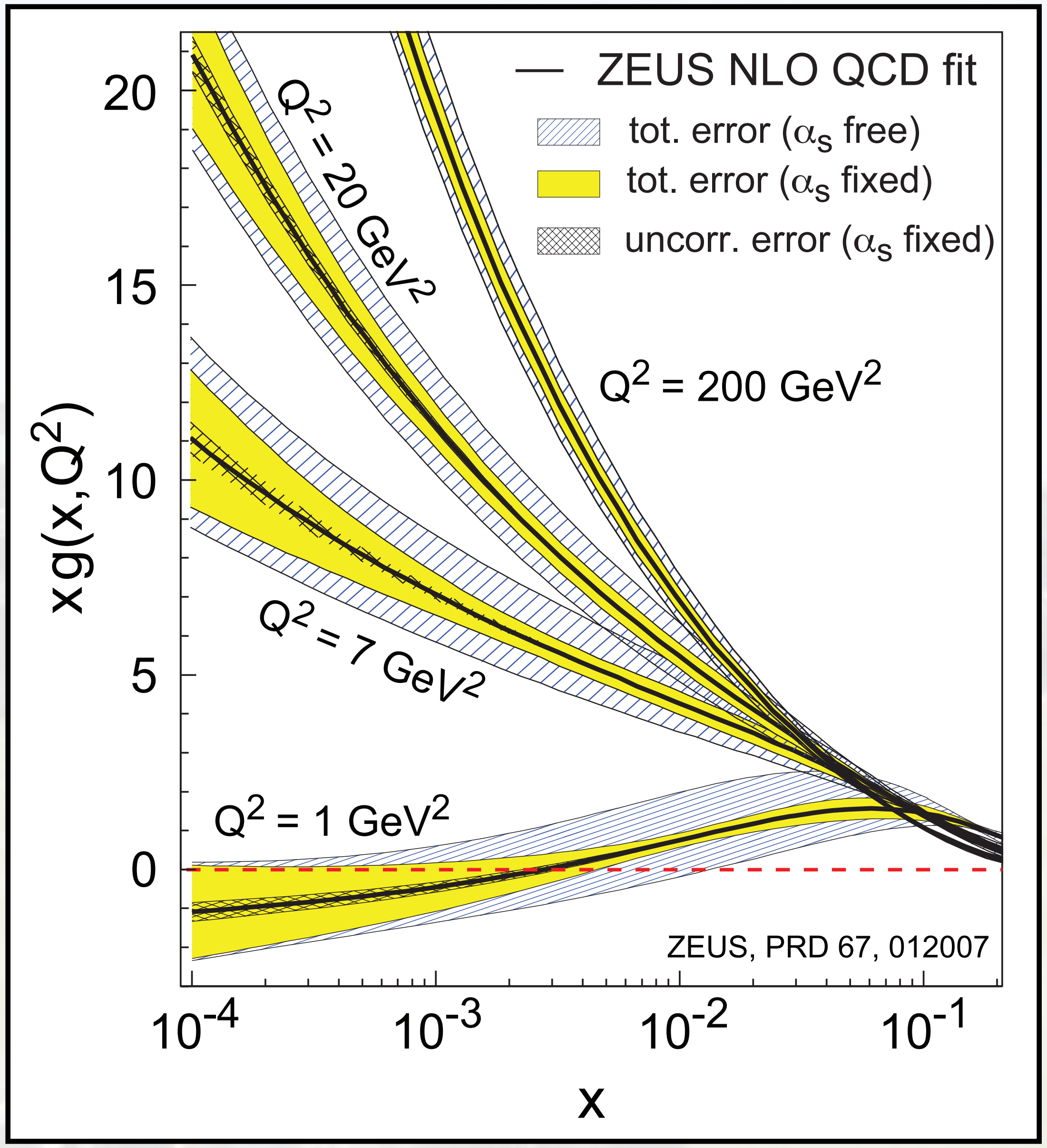
Ratios of gluon distribution functions for Pb/*p* versus x from different models at Q^2 = 1.69 GeV^2:



?

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

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 ⇒ new approach

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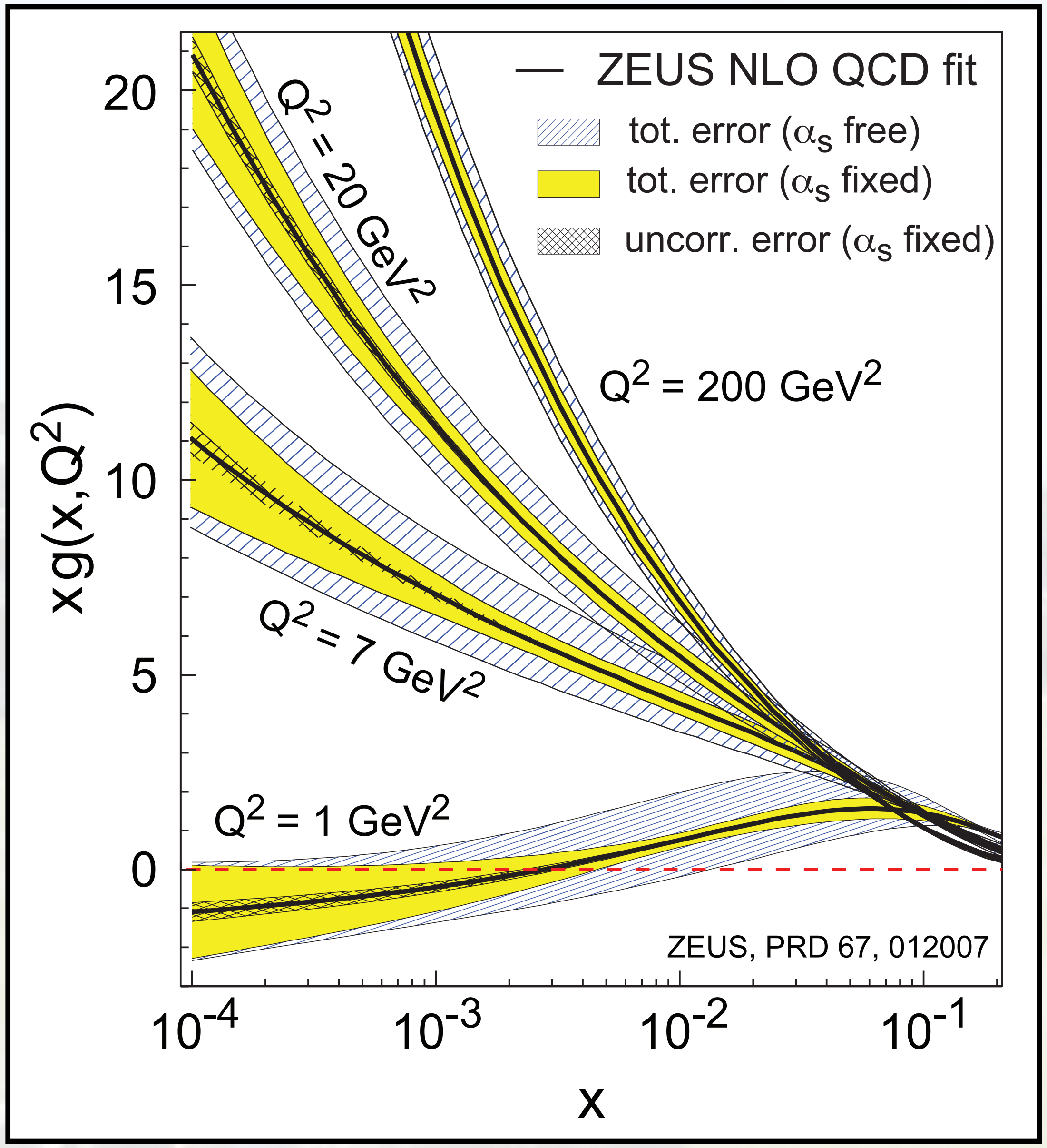

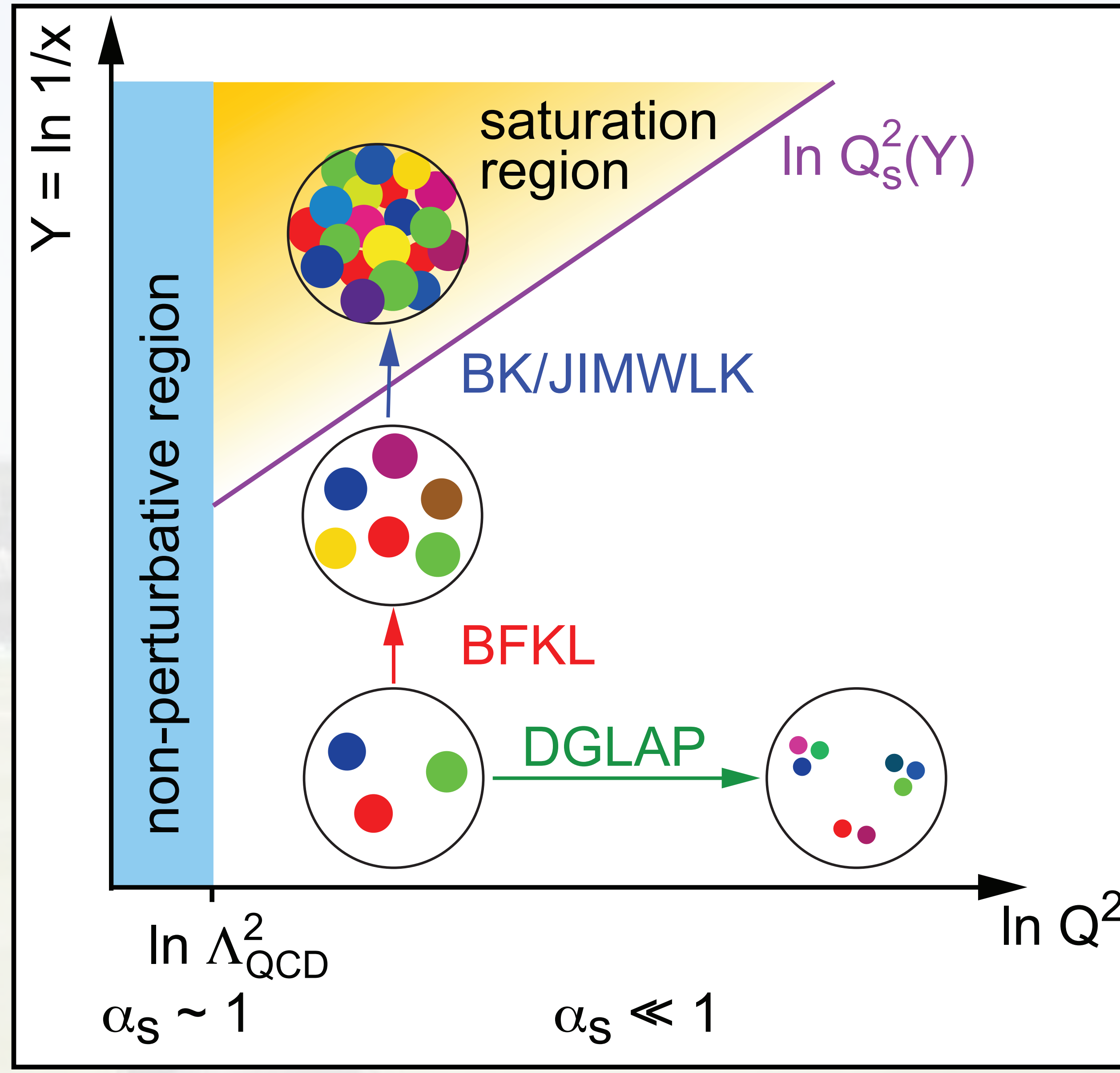

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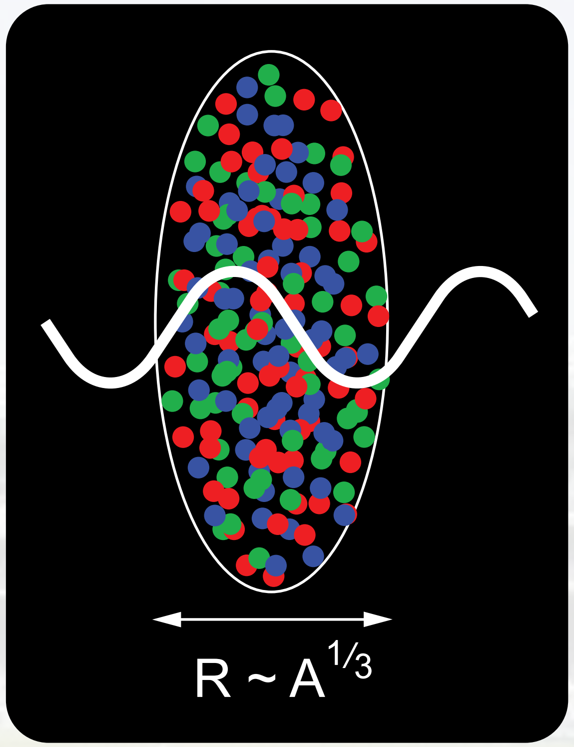
BK/JIMWLK: *non-linear* effects ⇒ saturation

- 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

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

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

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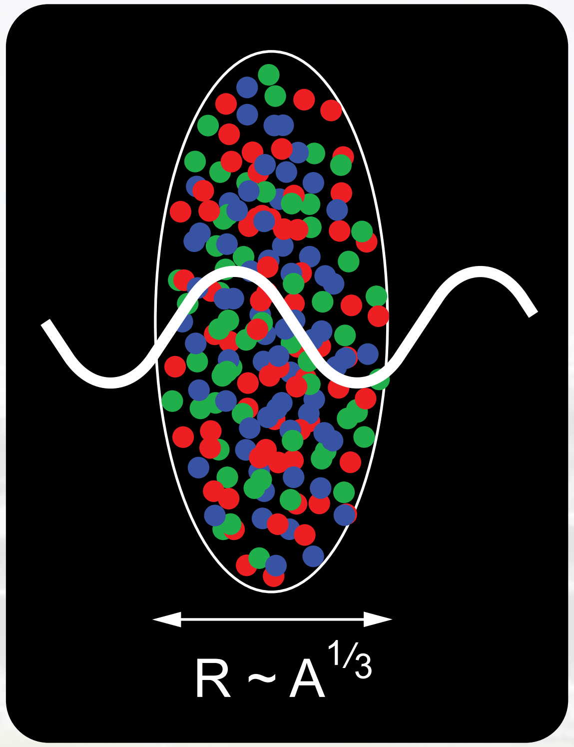

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Enhancement of Q_S with A:

⇒ non-linear QCD regime reached at significantly lower energy in e*A* than in *ep*

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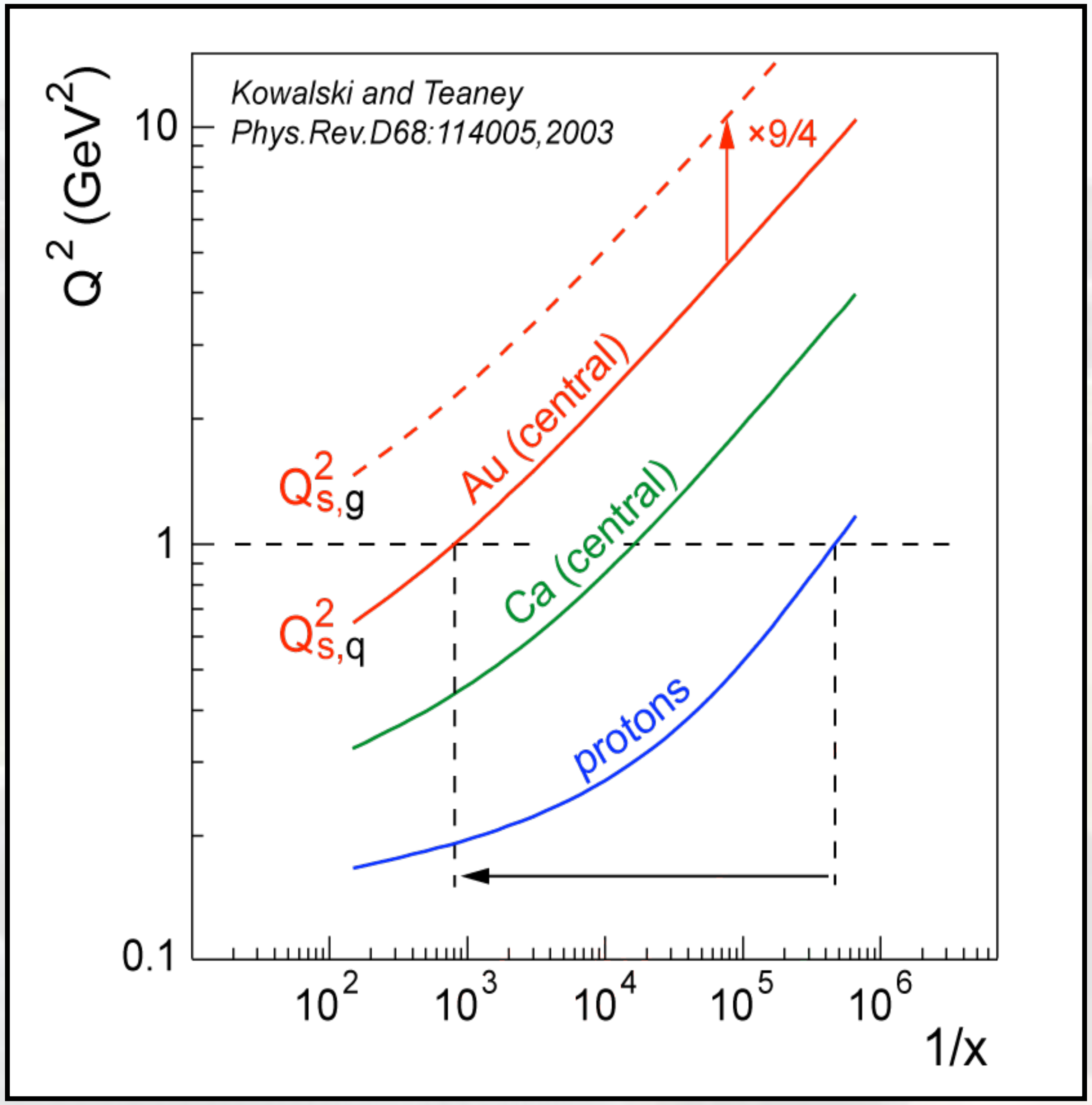
The Nuclear "Oomph" factor

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)



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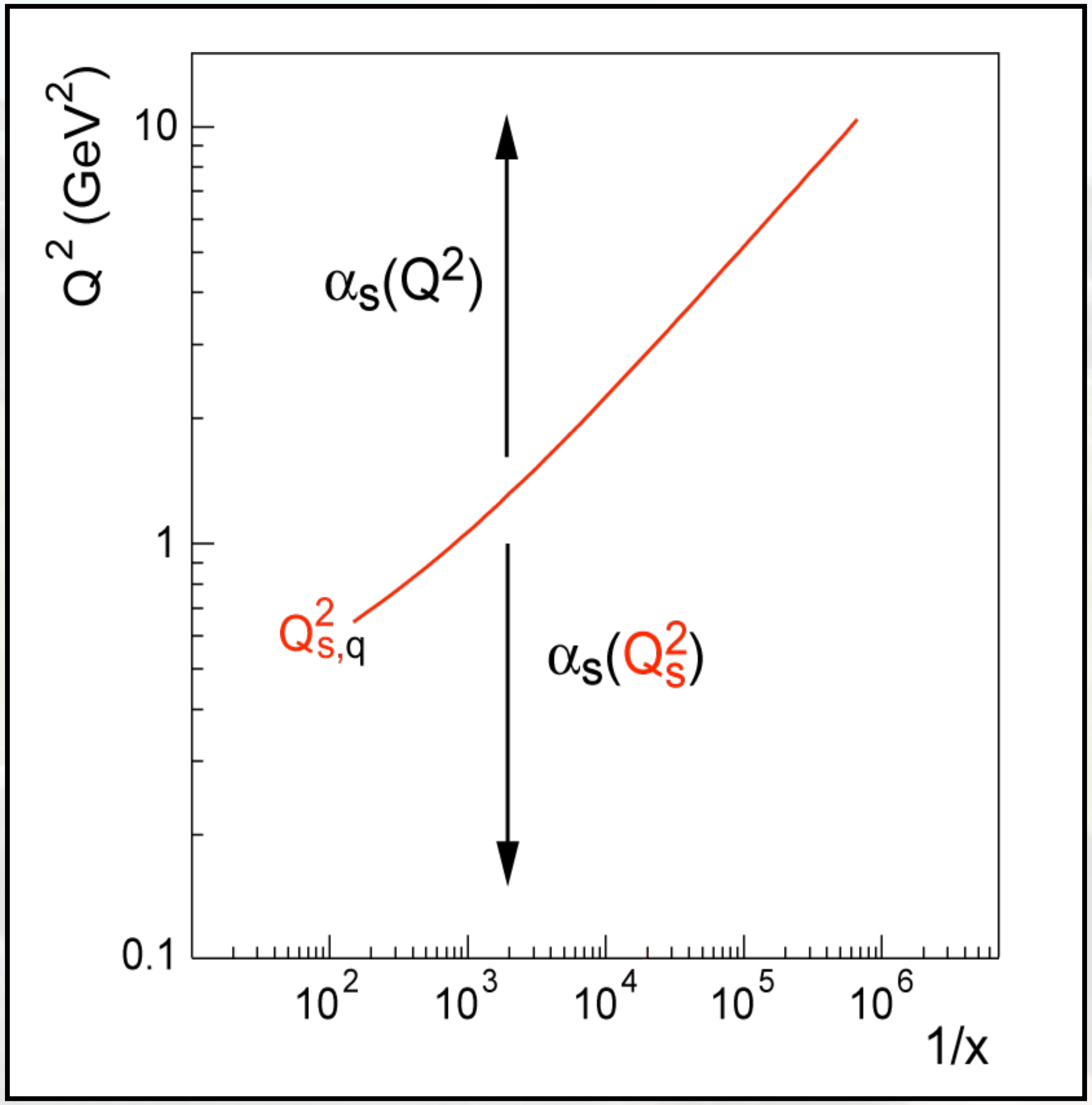

Note:

$$Q^2 > Q_s^2 \Rightarrow \alpha_s = \alpha_s(Q^2)$$

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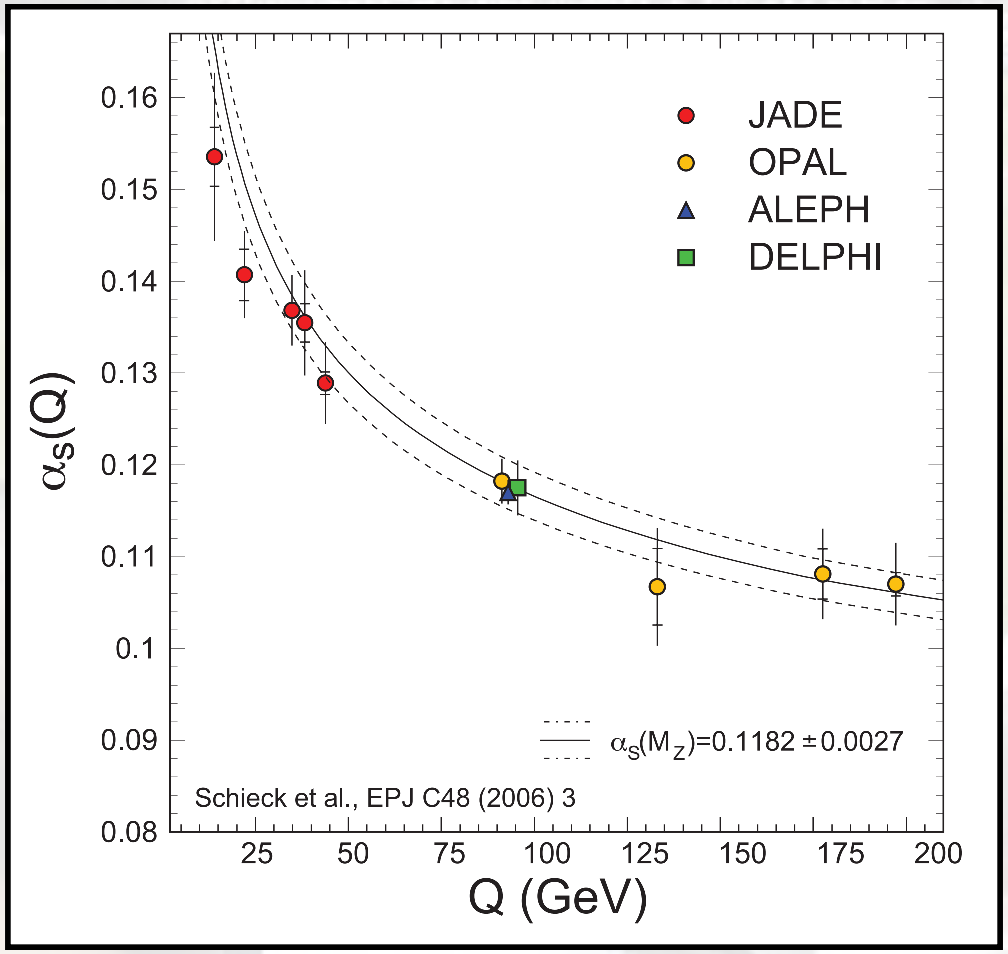

Key Measurements in e+A

- ***Momentum* distribution of gluons $G(x,Q^2)$**
  - ➡ Extract via scaling violation in F_2: $\delta F_2/\delta lnQ^2$
  - ➡ Direct measurement: $F_L \sim G(x,Q^2)$ (requires √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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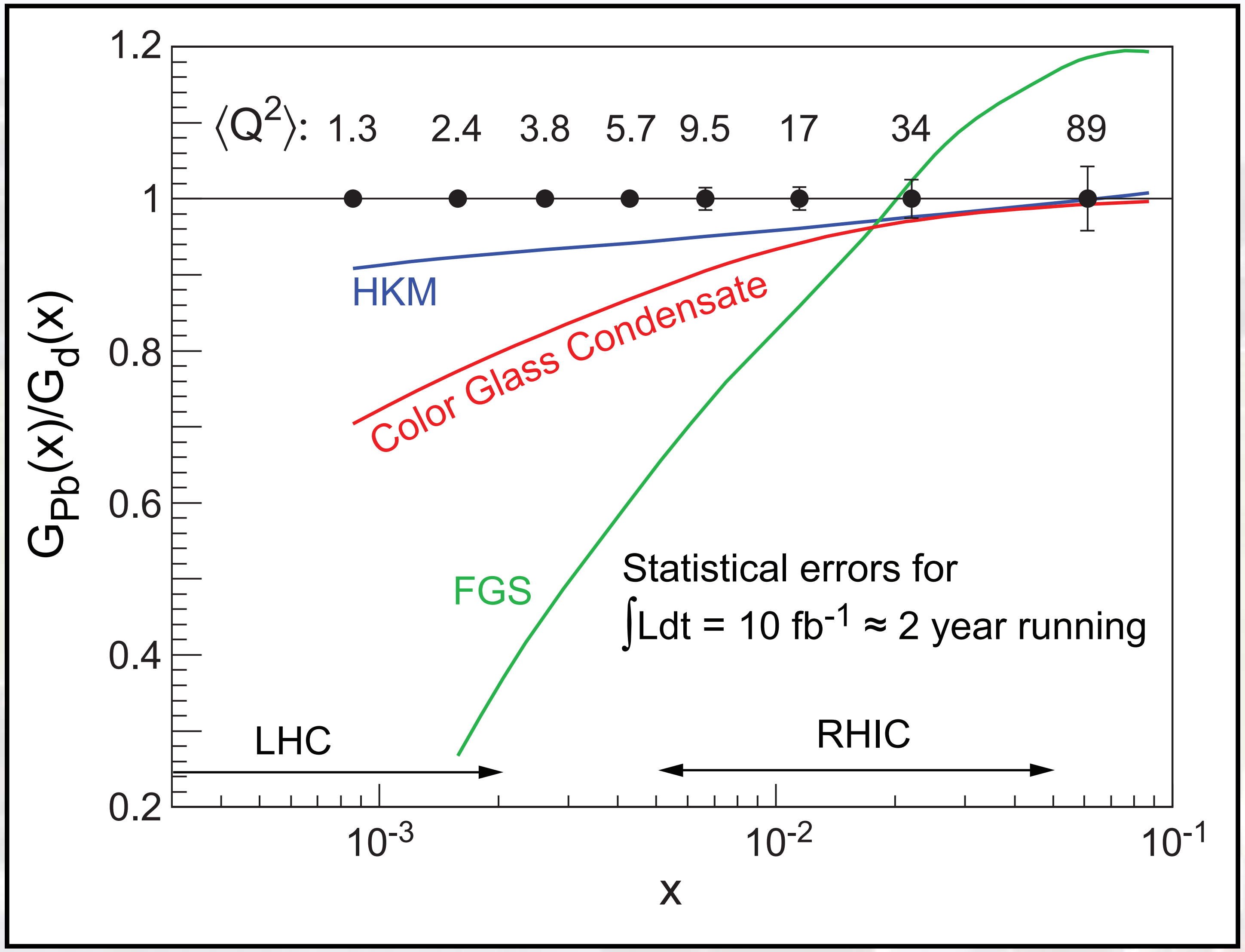

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requires $\sqrt{s}$ scan, $Q^2/xs = y$

Here:

$\int \mathcal{L}dt$ = 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 $F_L(A,x,Q^2)$:

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

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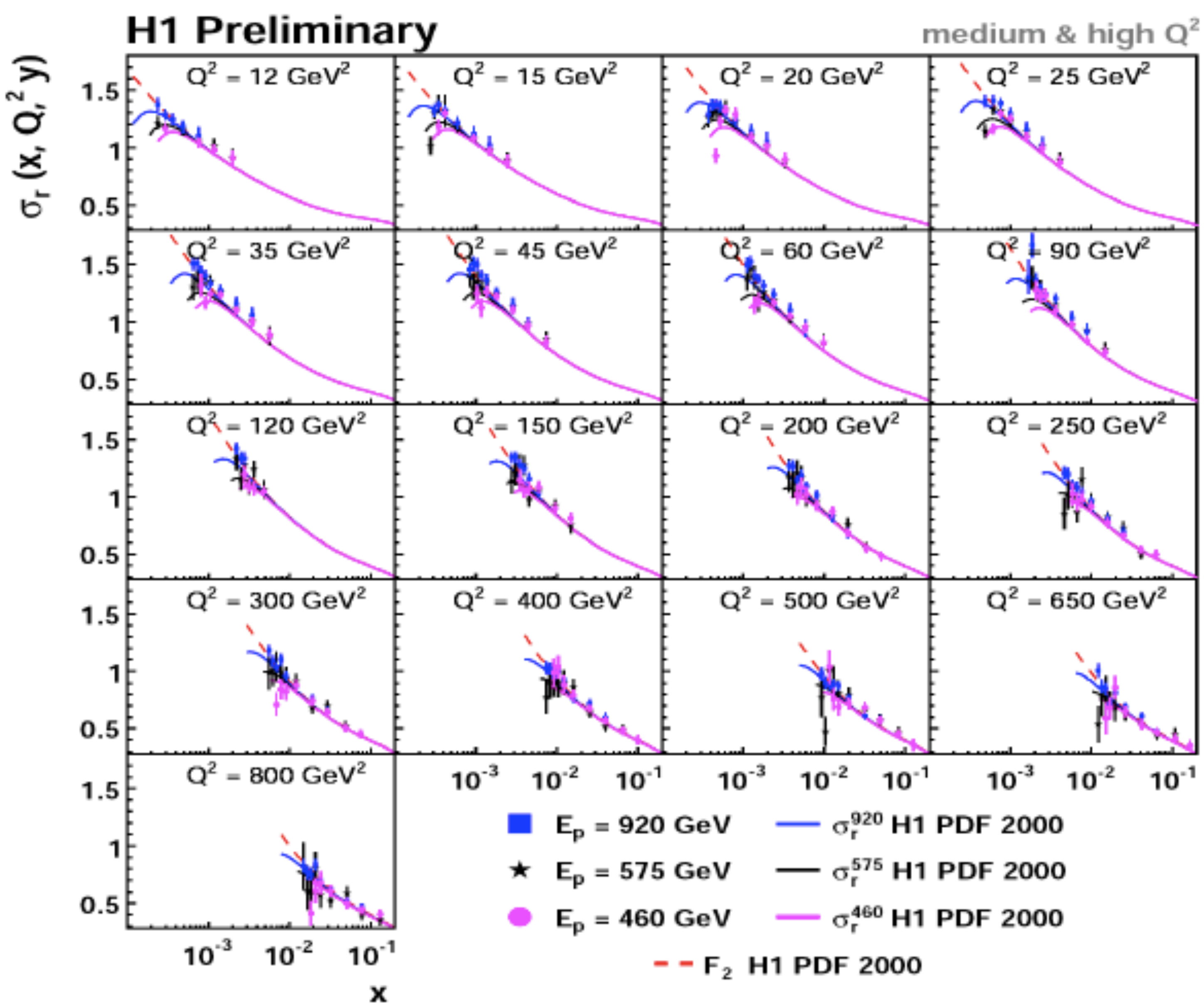

Preliminary F_L measurements

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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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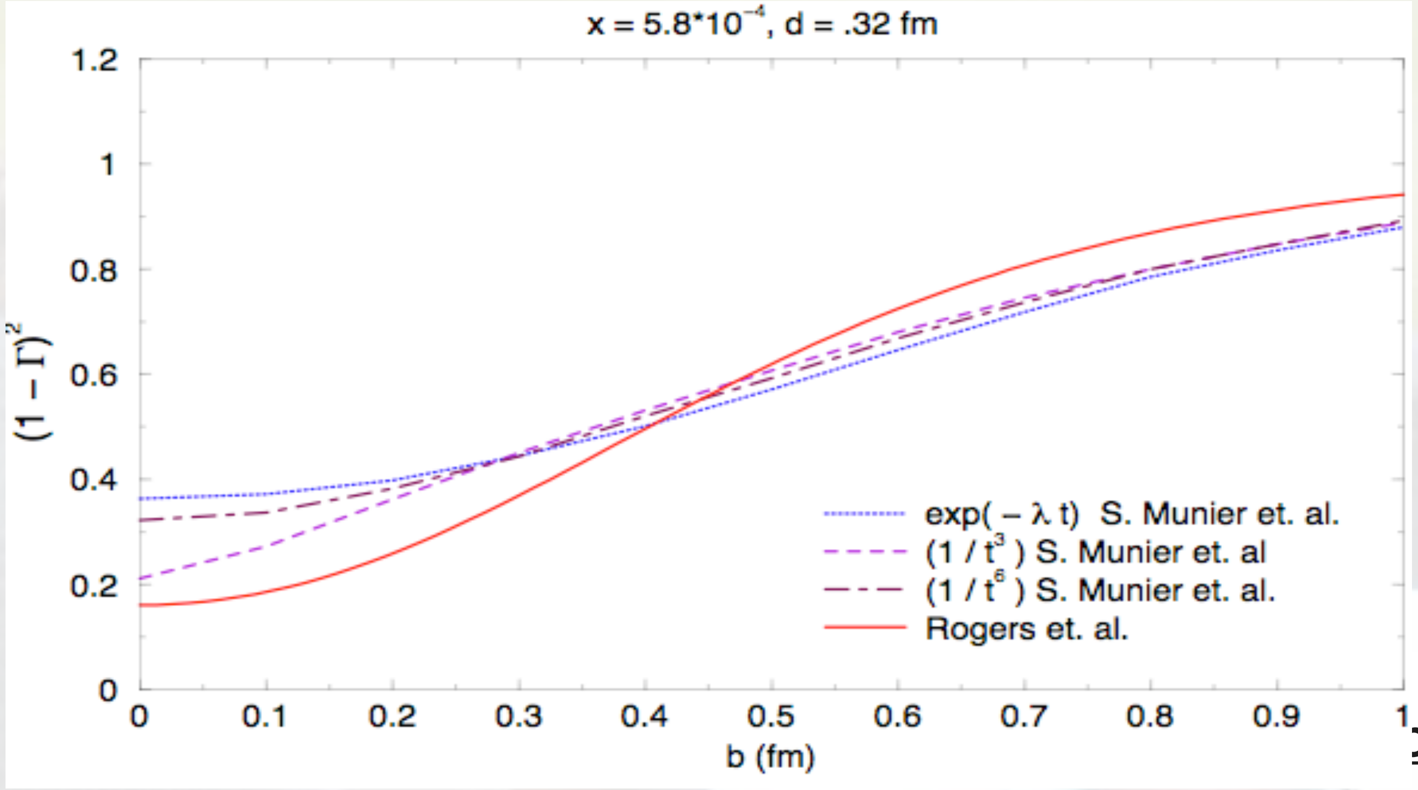

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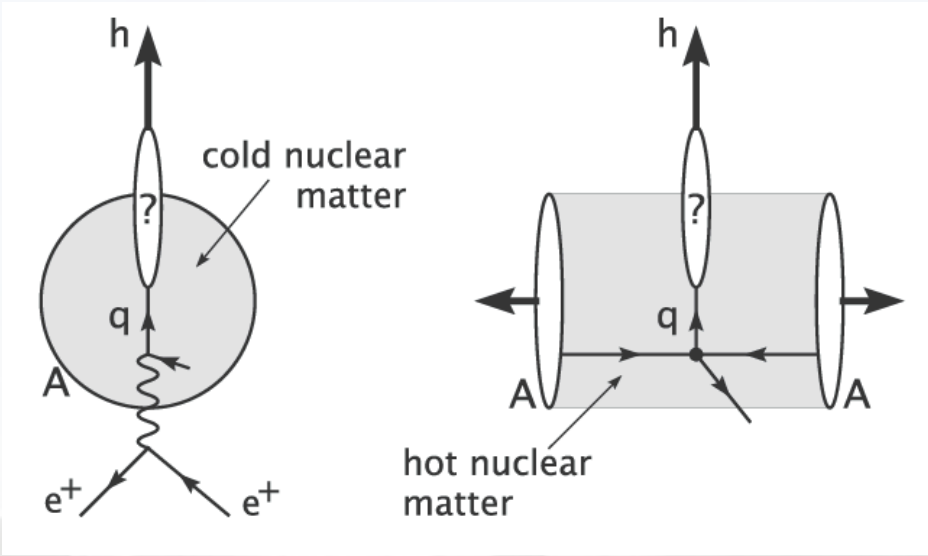
  - ➡ F_2, F_L for various A and impact parameter dependence
- **Interaction of fast probes with *gluonic* medium?**
  - ➡ Hadronization, Fragmentation
  - ➡ Energy loss (charm!)

Key Measurements in e+A

- ***Momentum* distribution of gluons *G(x,Q²)***
  - ➡ Extract via scaling violation in F_2: $\delta F_2/\delta lnQ^2$
  - ➡ 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)
  - ➡ Diffractive vector meson production ~ $[G(x,Q^2)]^2$
- ***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

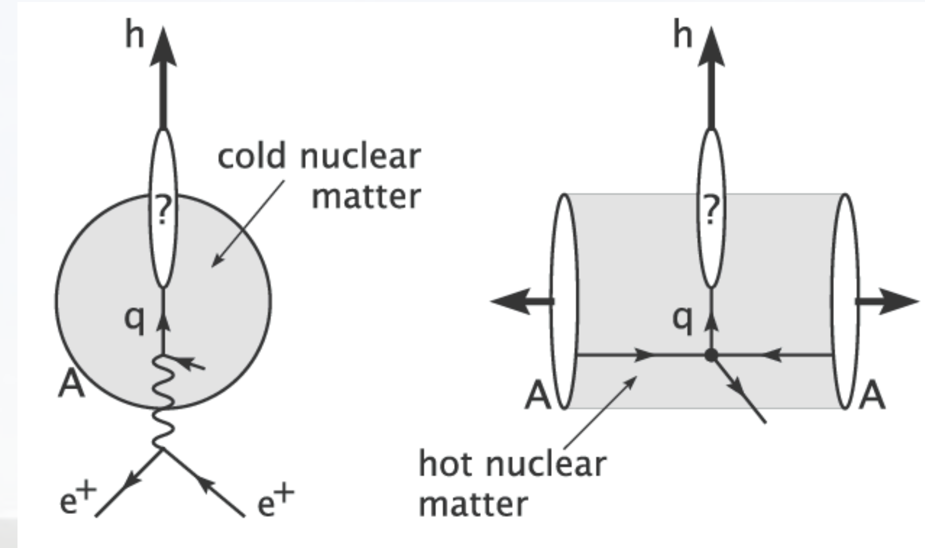
Hadronization and Energy Loss



Hadronization and Energy Loss

nDIS:

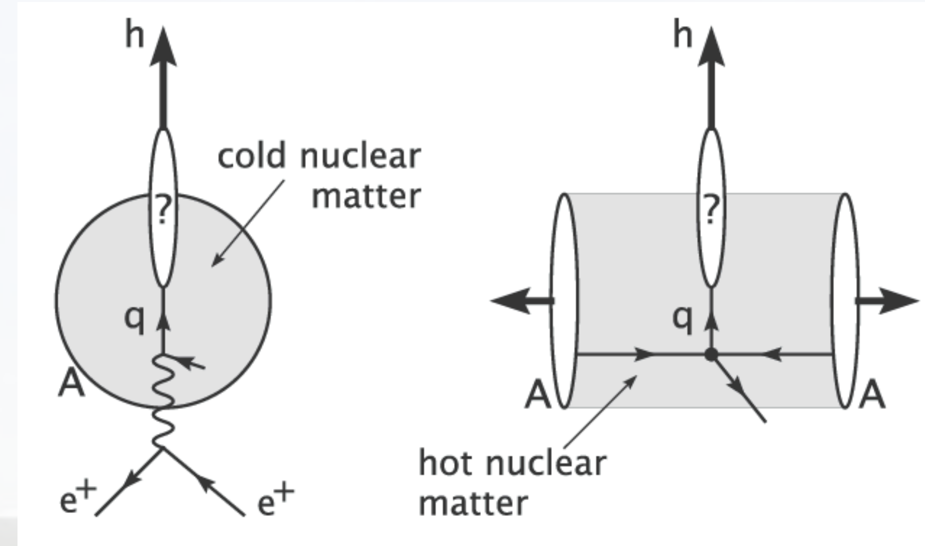
- Clean measurement in 'cold' nuclear matter



Hadronization and Energy Loss

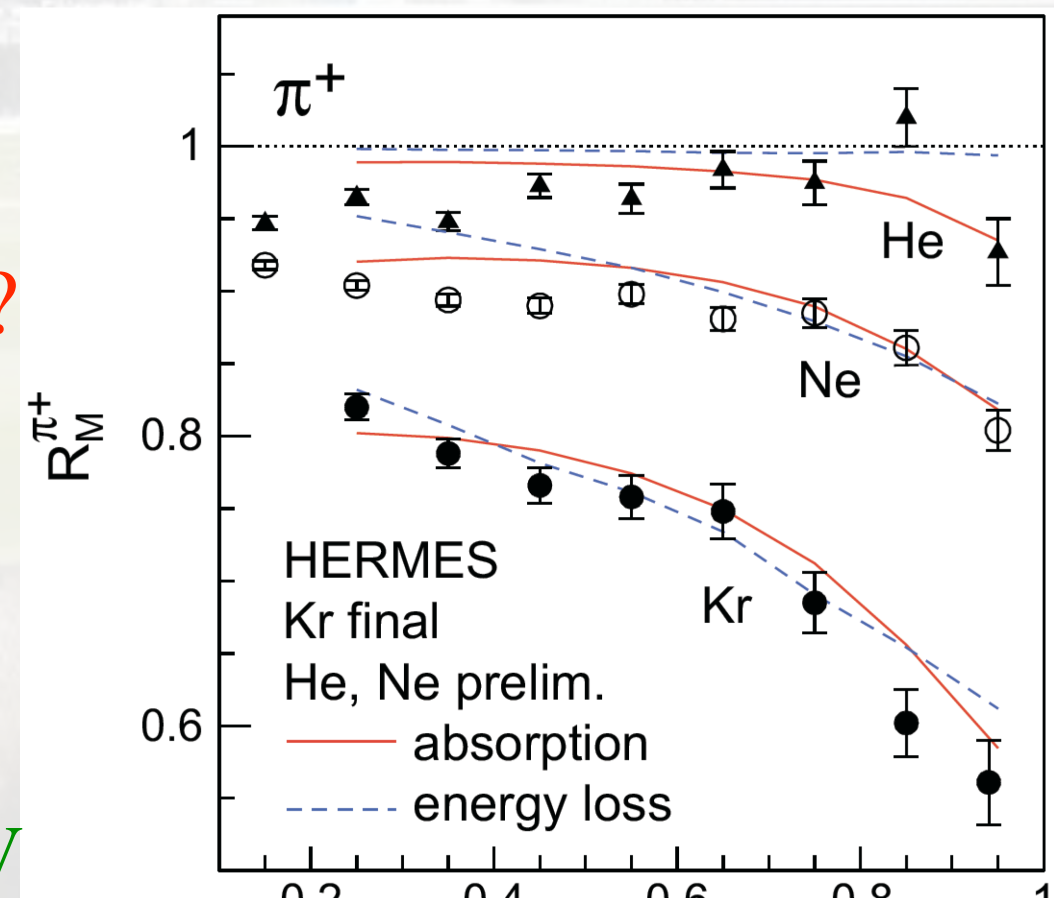
nDIS:

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



Fundamental question:
When do coloured partons get neutralized?

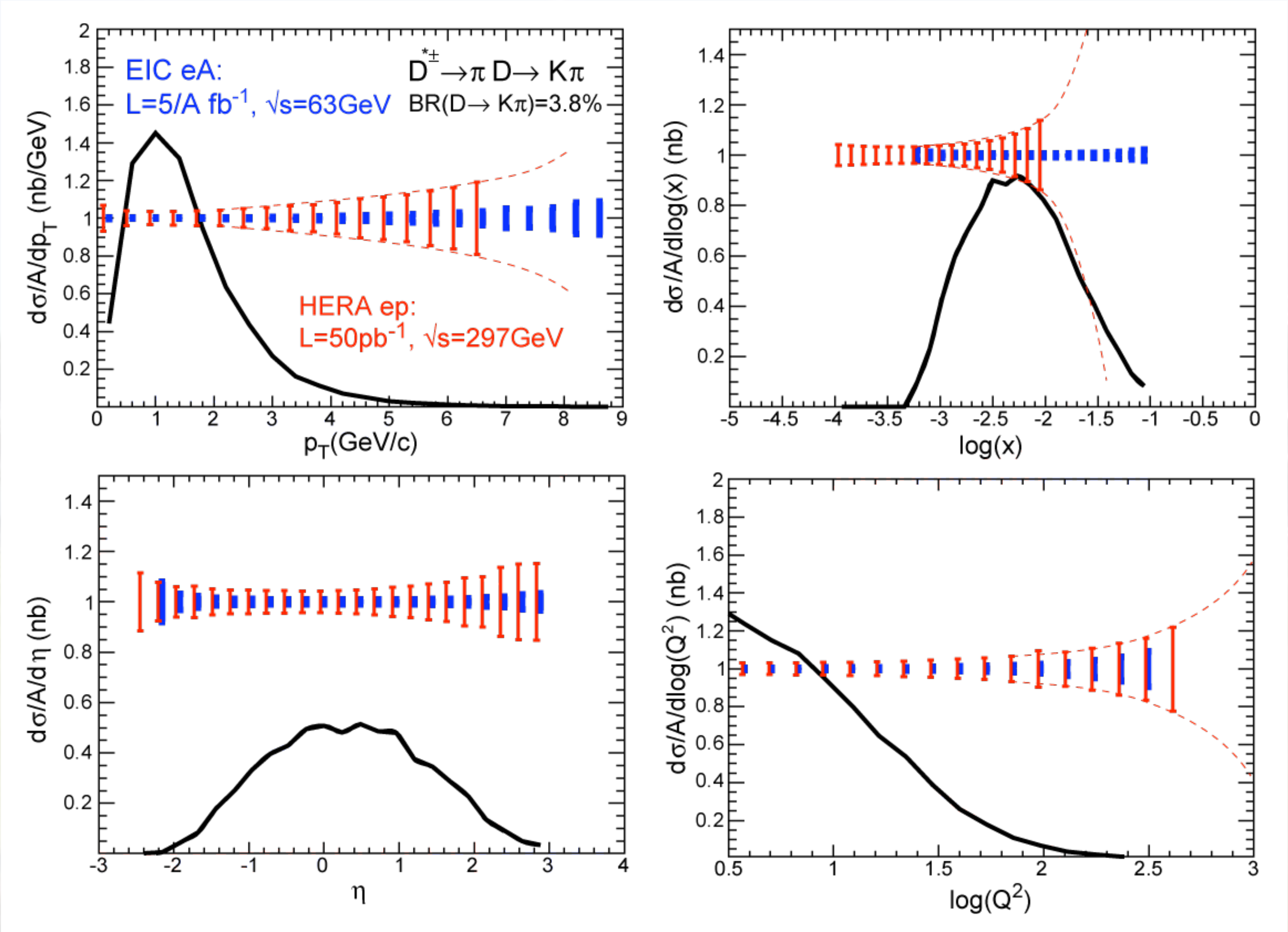
Parton energy loss vs.
(pre)hadron absorption



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

$z_h = E_h/\nu$

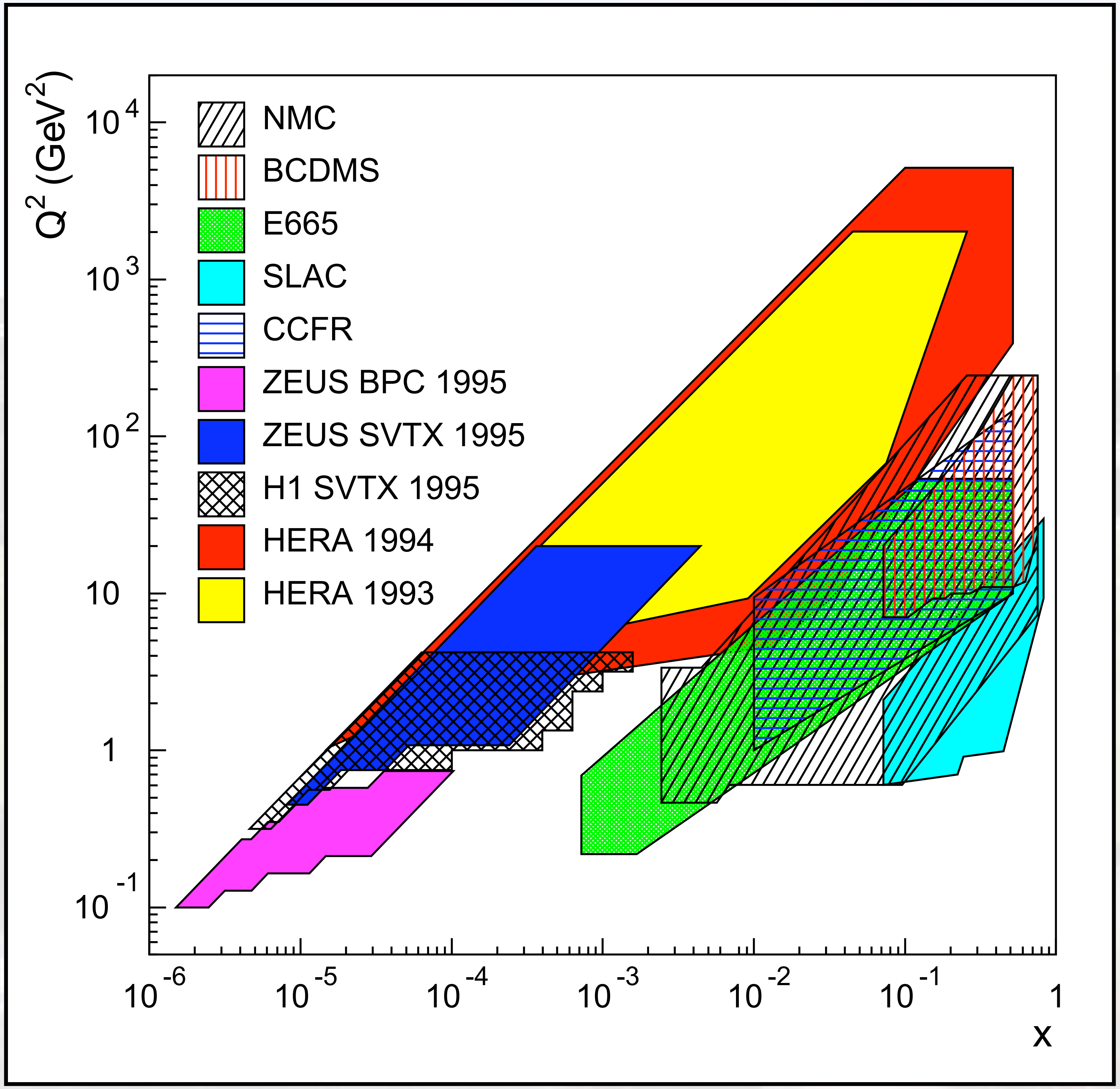
Charm at an EIC



Based on HVQDIS model, J. Smith

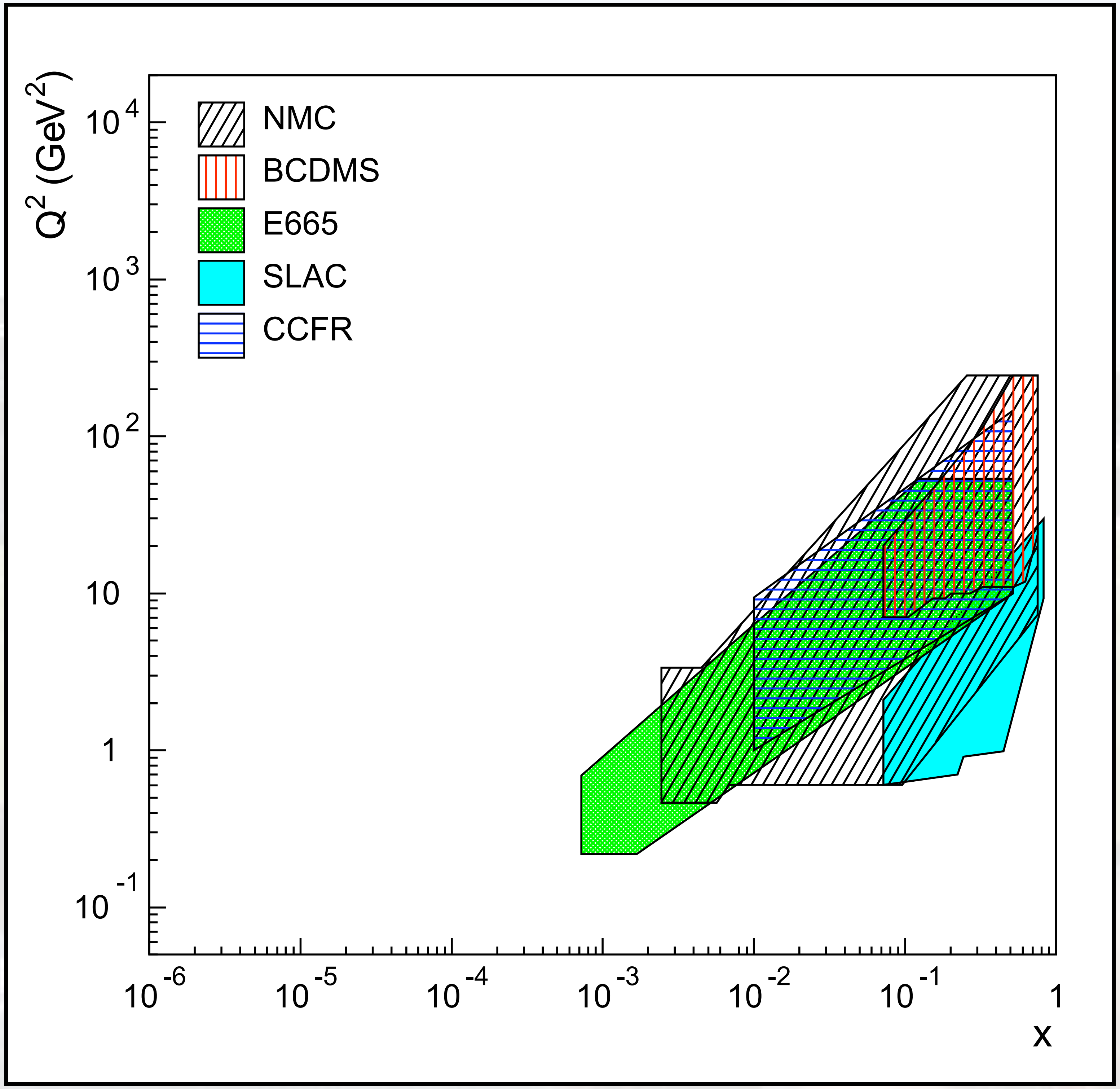
- EIC: allows multi-differential measurements of heavy flavour
- covers and extend energy range of SLAC, EMC, HERA, and JLAB allowing study of wide range of formation lengths

Requirements for an Electron Ion Collider



Well mapped in $e+p$

Requirements for an Electron Ion Collider



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Not so for ℓ+A (ν+A)

- many with small A
- low statistics

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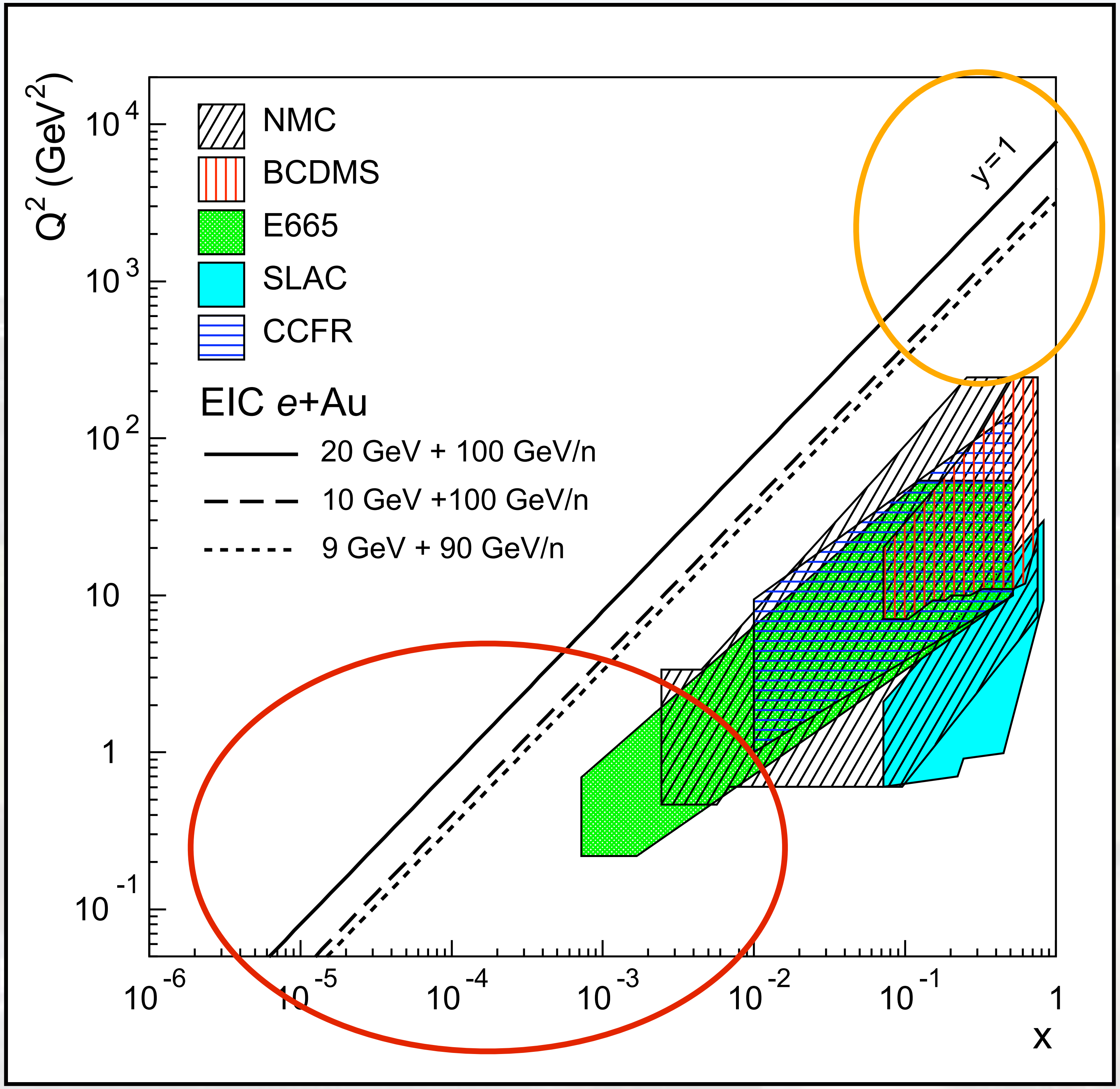

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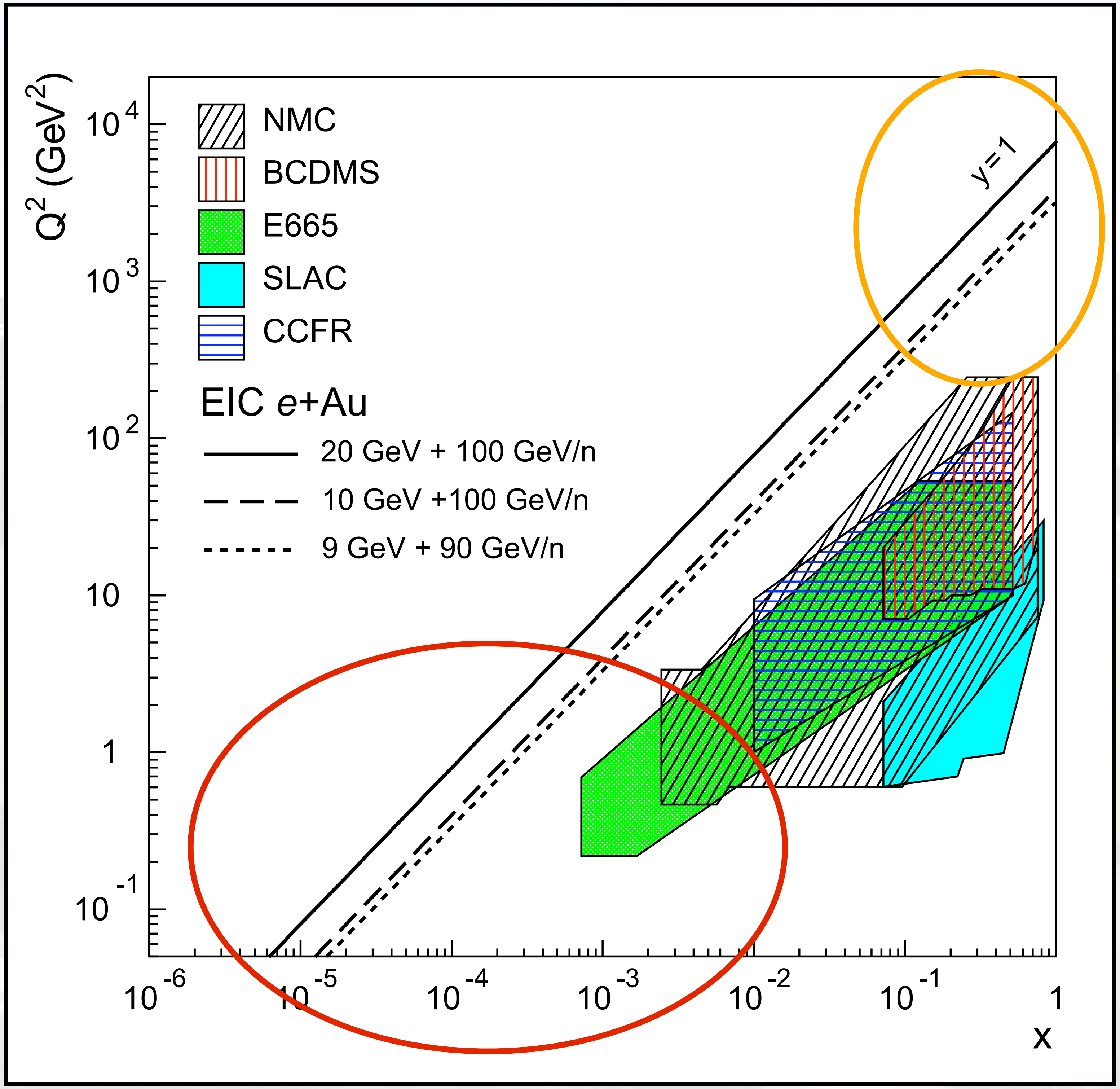
Electron Ion Collider:

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

Requirements for an Electron Ion Collider



Terra incognita: small-x, $Q \leq Q_s$
high-x, large Q^2

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macl@bnl.gov: DIS 2008, London - http://www.eic.bnl.gov

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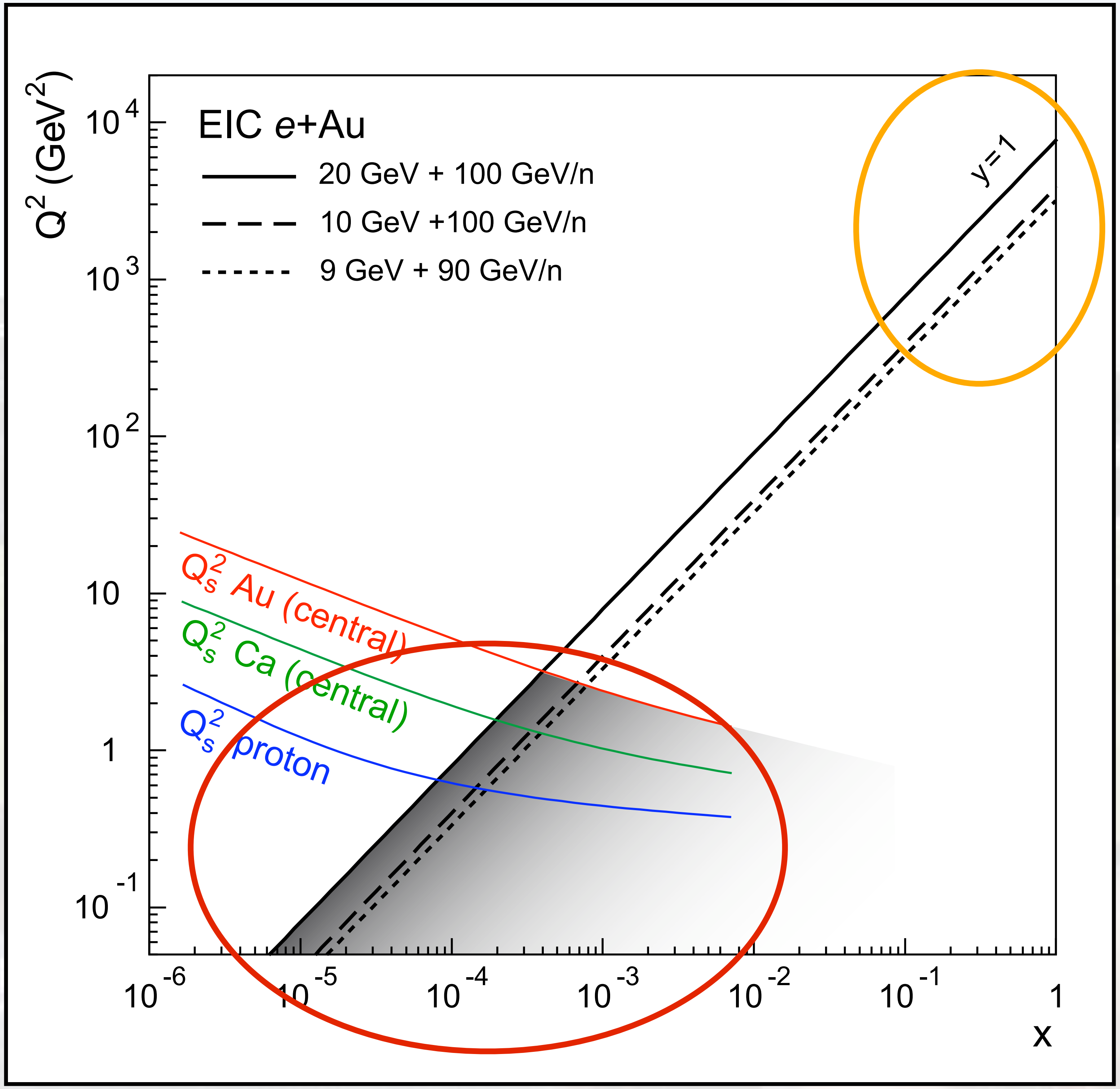

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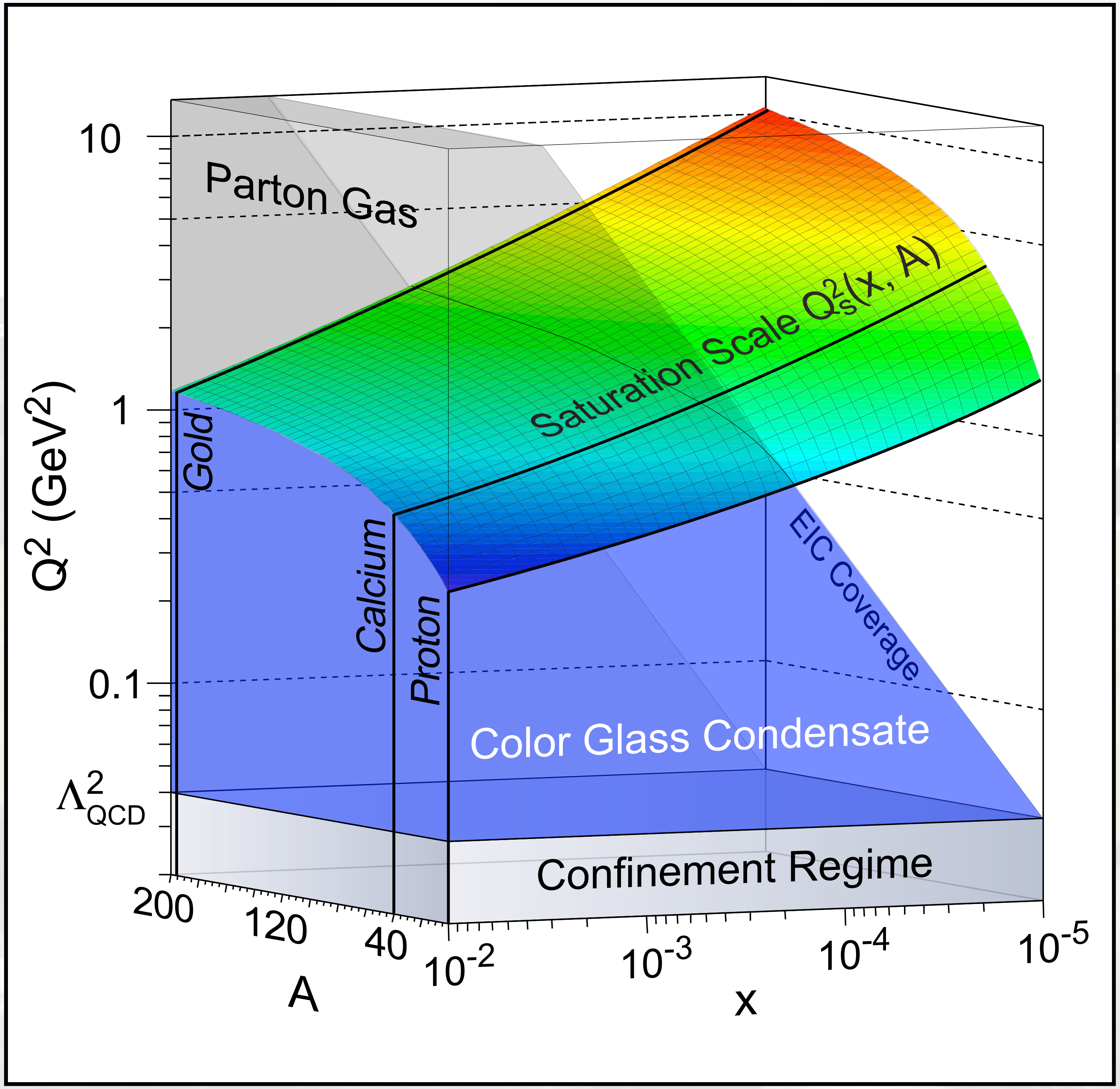

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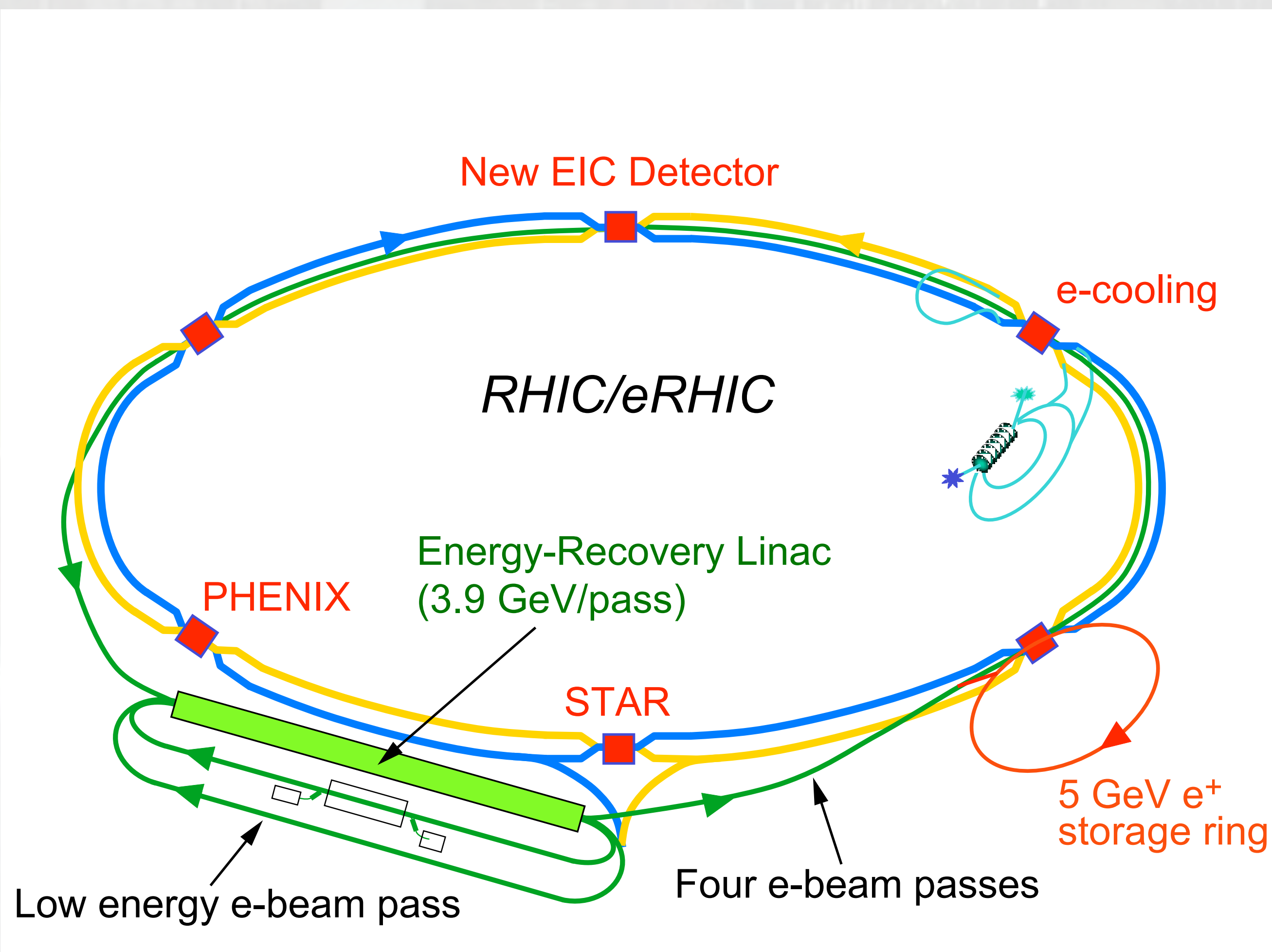
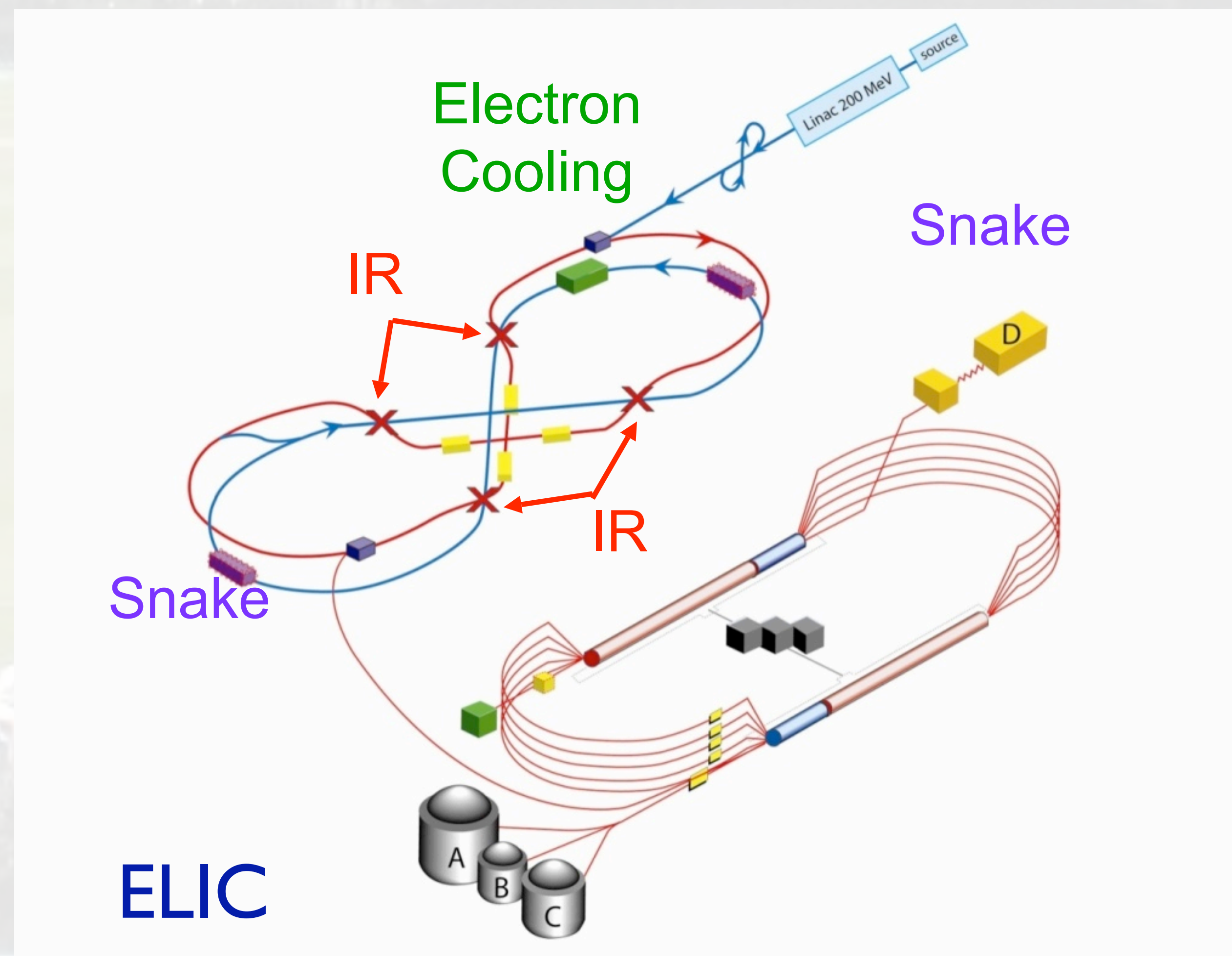
- Hadron Beams
  - E_A = 100 GeV
  - A = p → U
  - polarized *p* & light ions

EIC Collider concepts

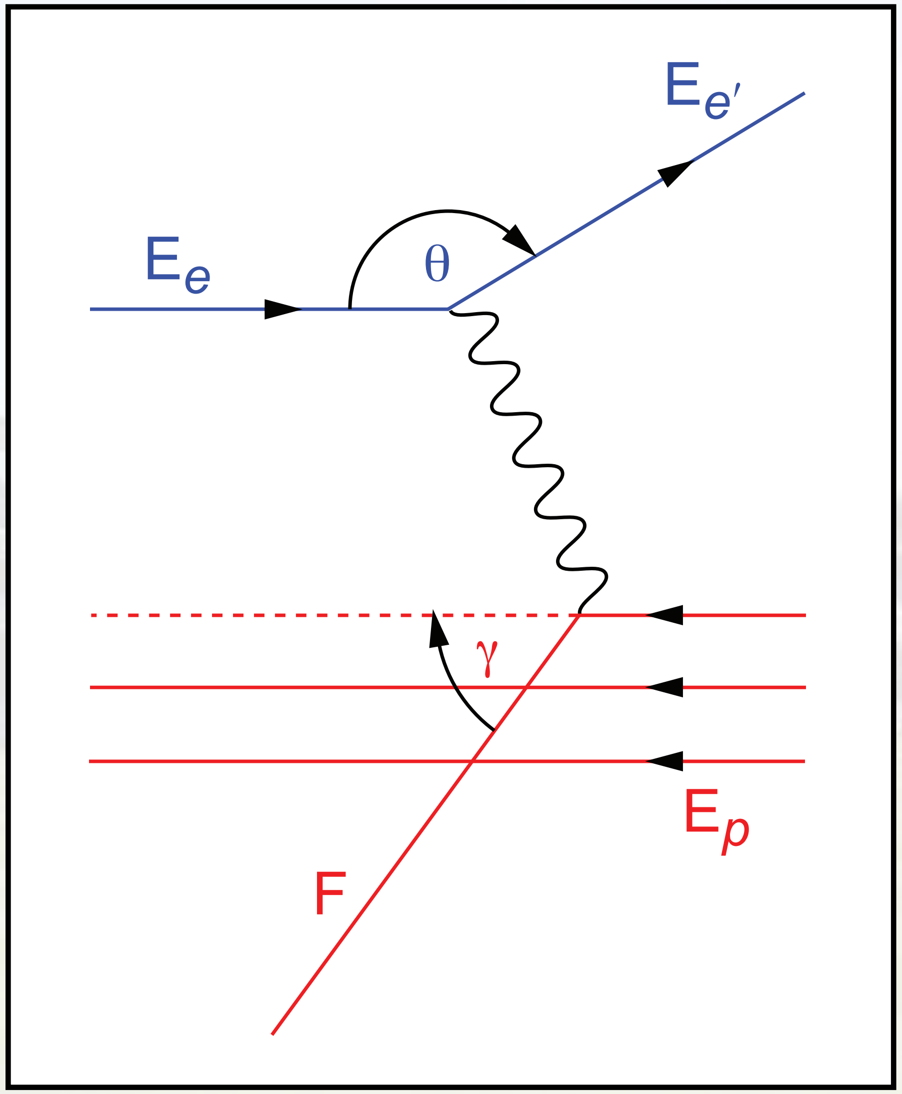
eRHIC (RHIC/BNL):
Add Energy Recovery Linac
E_e = 10 (20) GeV
E_A = 100 GeV (up to U)
$\sqrt{s_{eN}}$ = 63 (90) GeV
$\mathcal{L}_{eAu}$ (peak)/n ~ $2.9 \cdot 10^{33}$ cm^{-2} s^{-1}

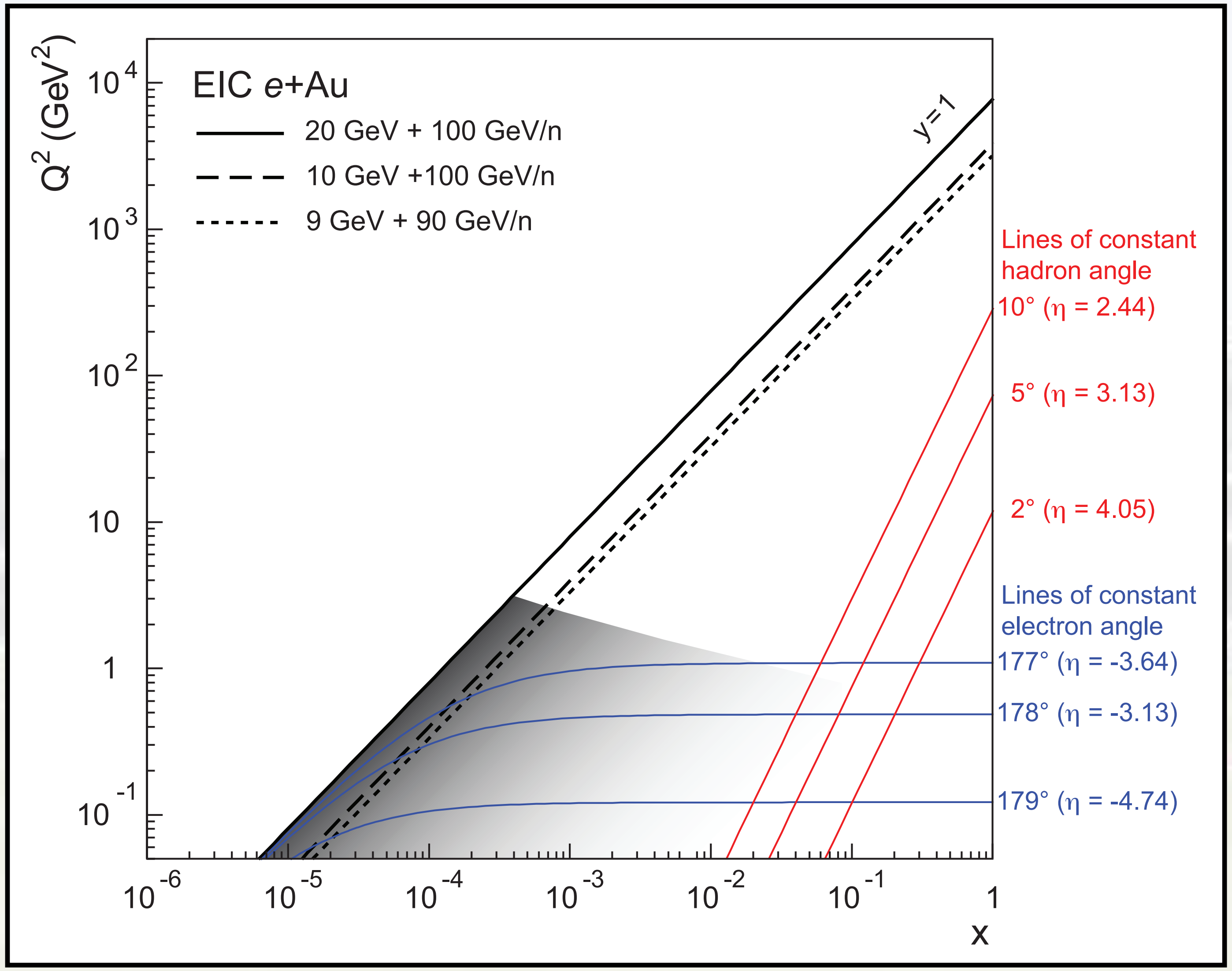
ELIC (CEBAF/JLAB):
Add hadron machine
E_e = 9 GeV
E_A = 90 GeV (up to Au)
$\sqrt{s_{eN}}$ = 57 GeV
$\mathcal{L}_{eAu}$ (peak)/n ~ $1.6 \cdot 10^{35}$ cm^{-2} s^{-1}





Experimental Aspects





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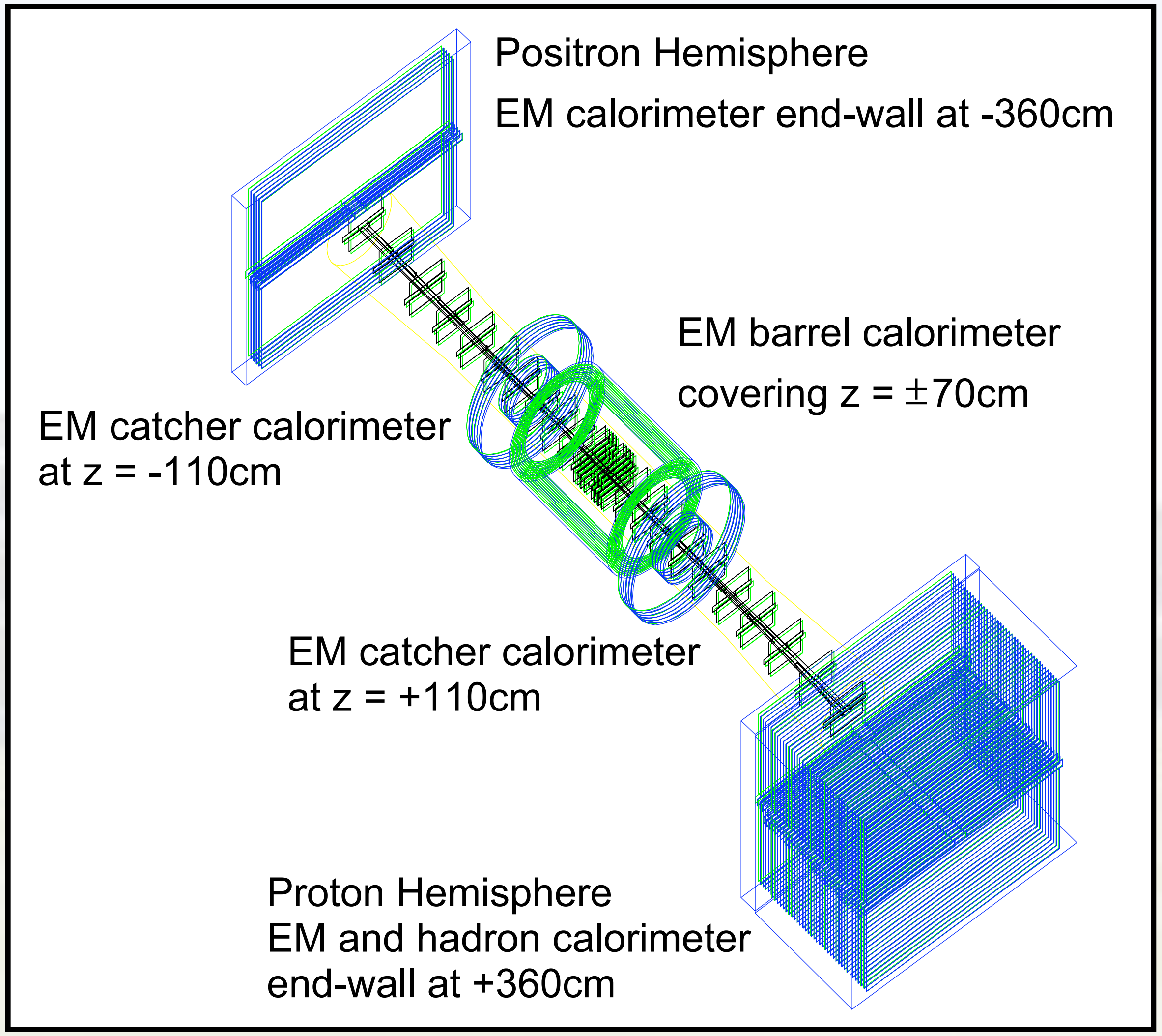
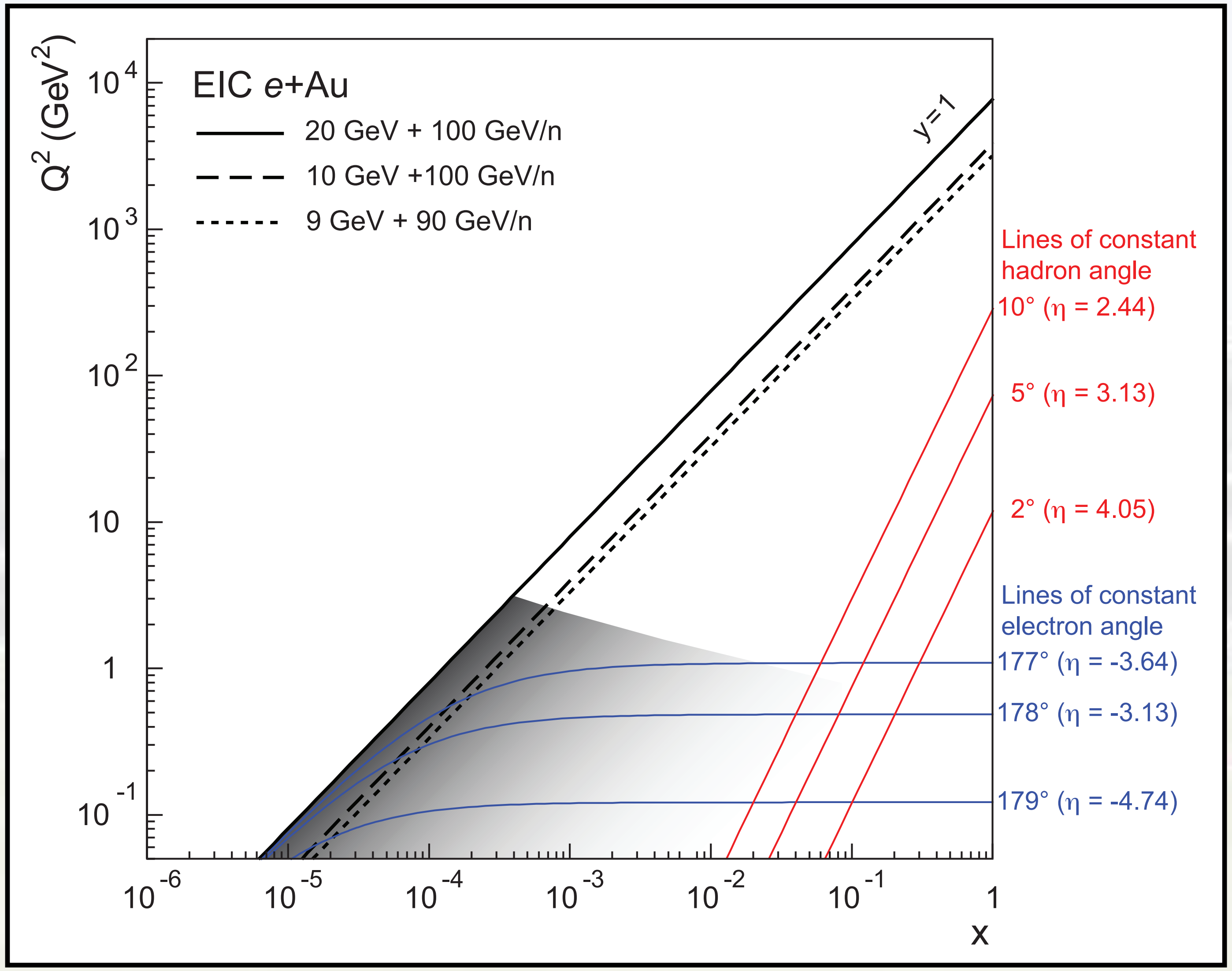


I. Abt, A. Caldwell, X. Liu, J. Sutiak, hep-ex 0407053



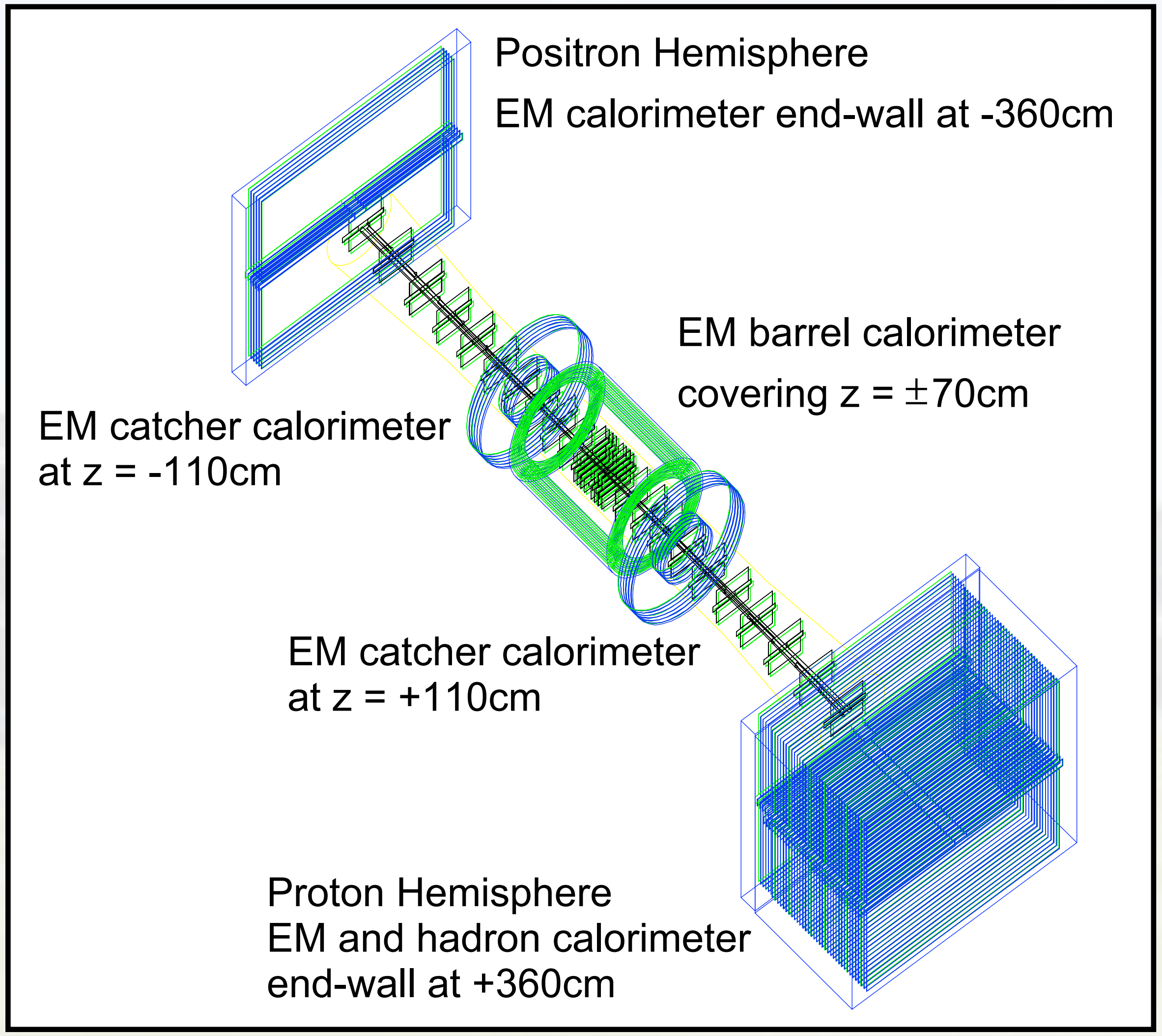
Concepts:

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

BROOKHAVEN NATIONAL LABORATORY

Experimental Aspects



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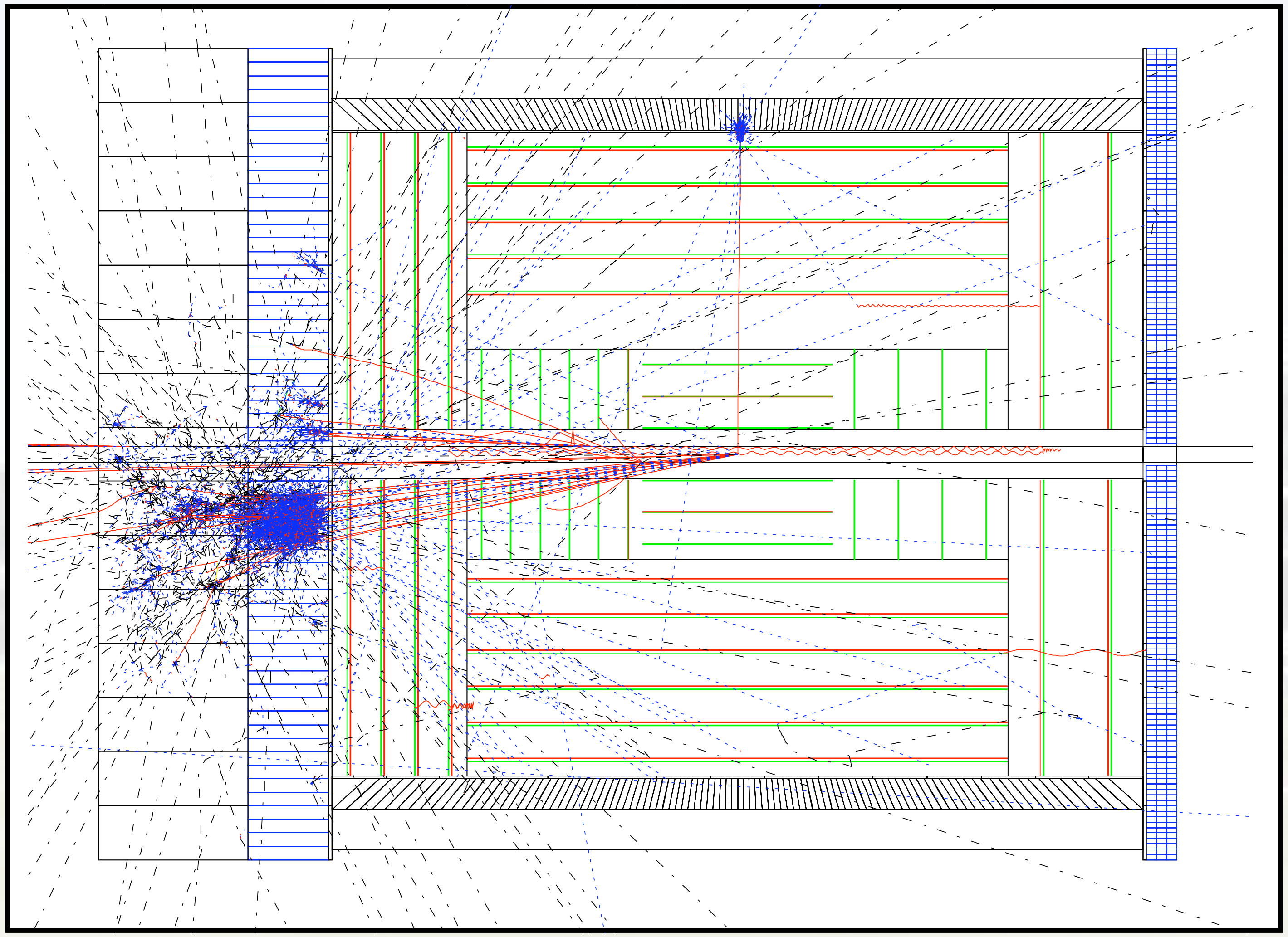


J. Pasukonis, B.Surrow, physics/0608290

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

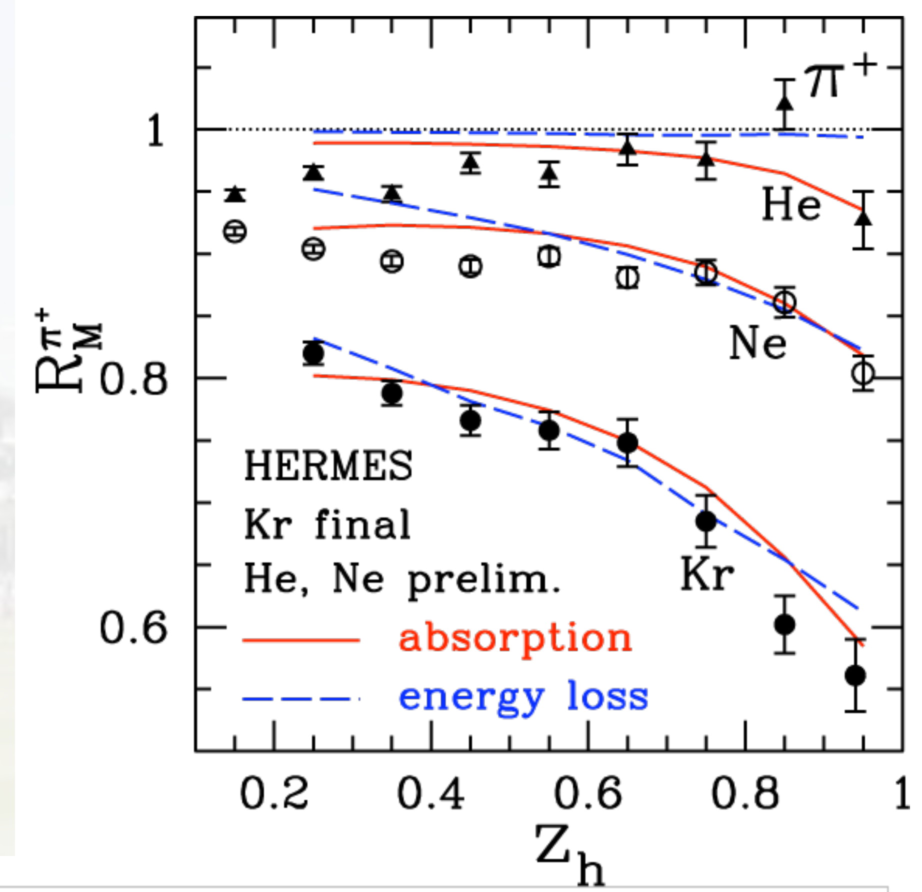
(b) Focus on a wide acceptance detector system similar to HERA experiments

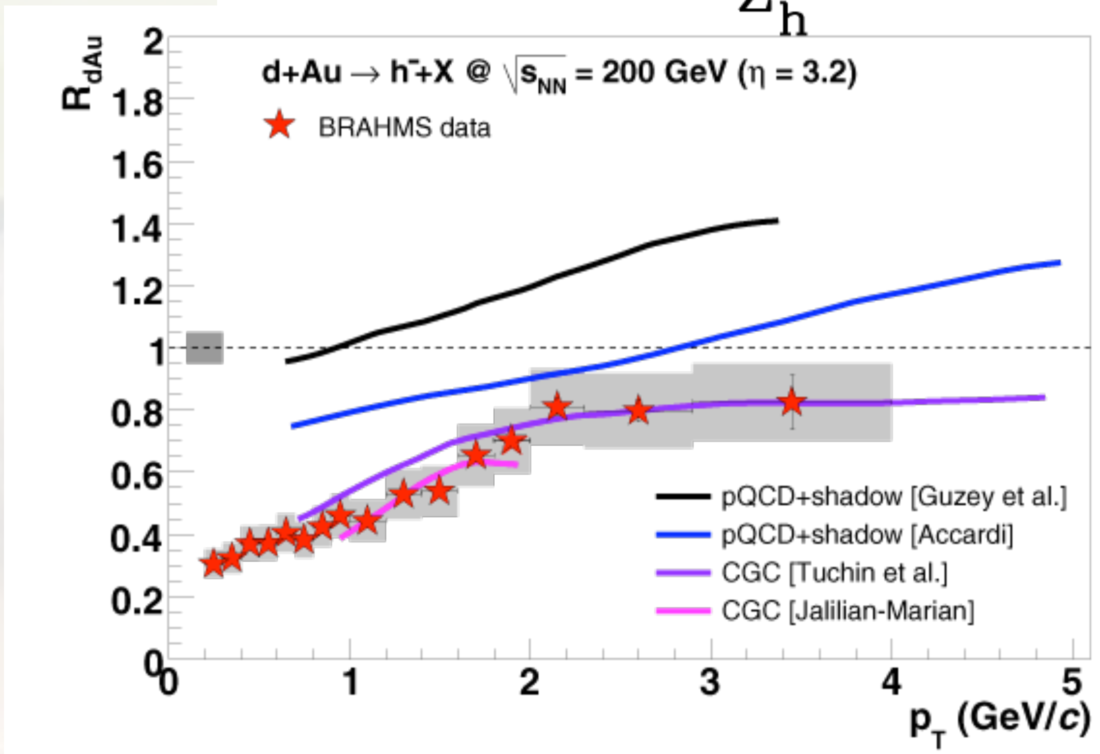
- allow for the maximum possible Q^2 range.

e+A Summary: Connection to RHIC & LHC Physics

- **Thermalization:**
  - ➡ At RHIC system thermalizes (locally) fast (τ_0 ~ 0.6 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 ?

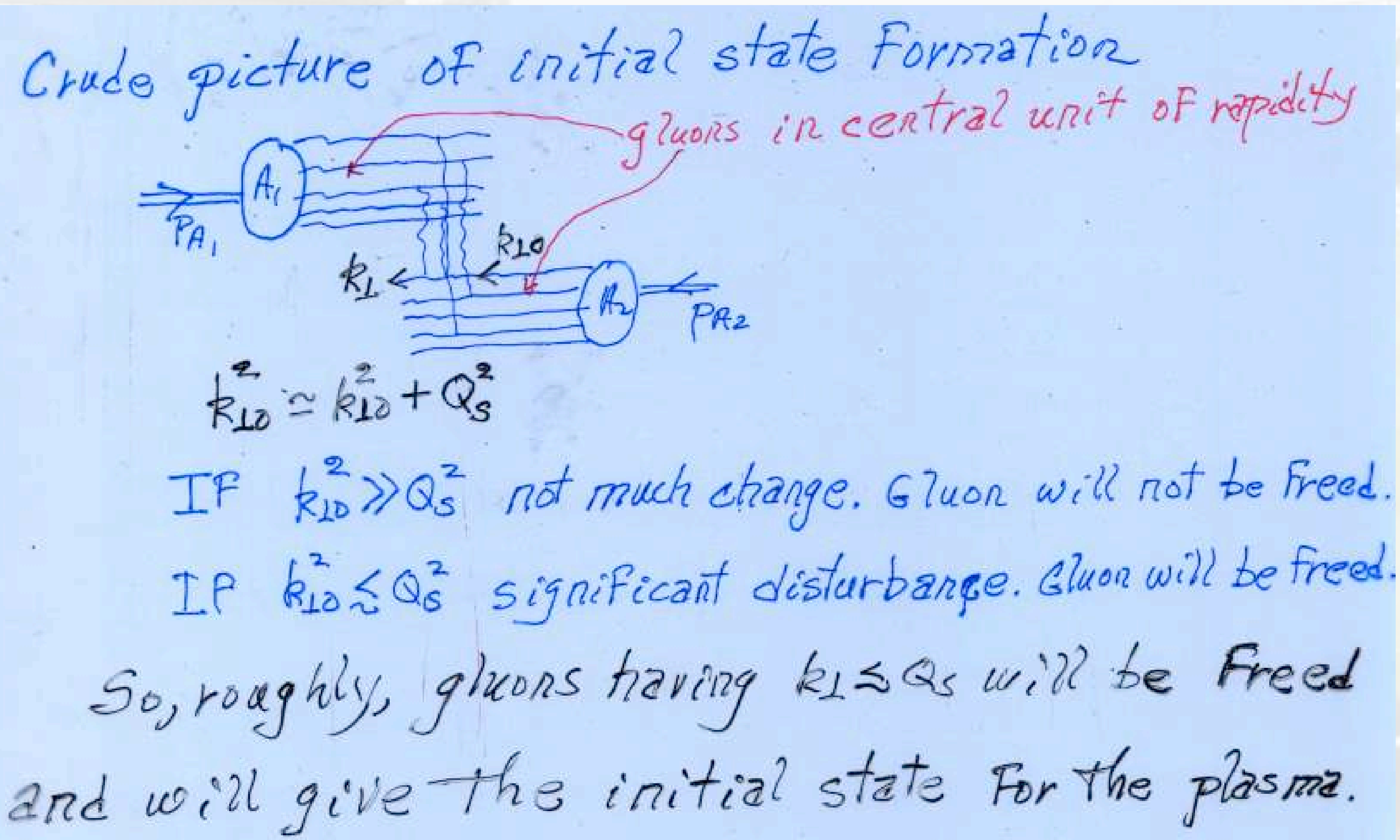
FF modification
(parton energy loss)





Symbiosis between EIC and HI

- Thermalization:
  - ➡ At RHIC system thermalizes (locally) fast (τ_0 < 0.6 fm/c)
  - ➡ We don't know why and how? Initial conditions?

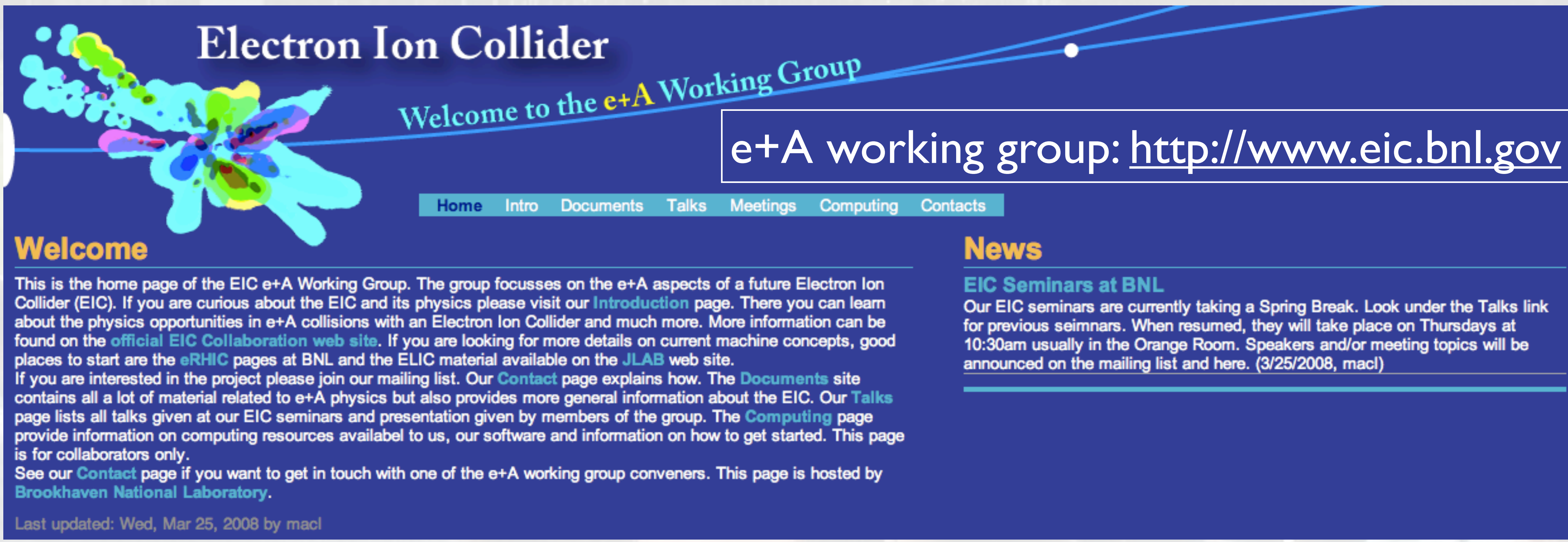


At present no first principle understanding of thermalization in QCD

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)



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

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