The Emerging QCD Frontier:
The Electron Ion Collider

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Quark Matter '08
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EIC on the web: http://web.mit.edu/eicc

BROOKHAVEN NATIONAL LABORATORY

The Glue That Binds Us All

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

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  - Asymptotic Freedom & Color Confinement

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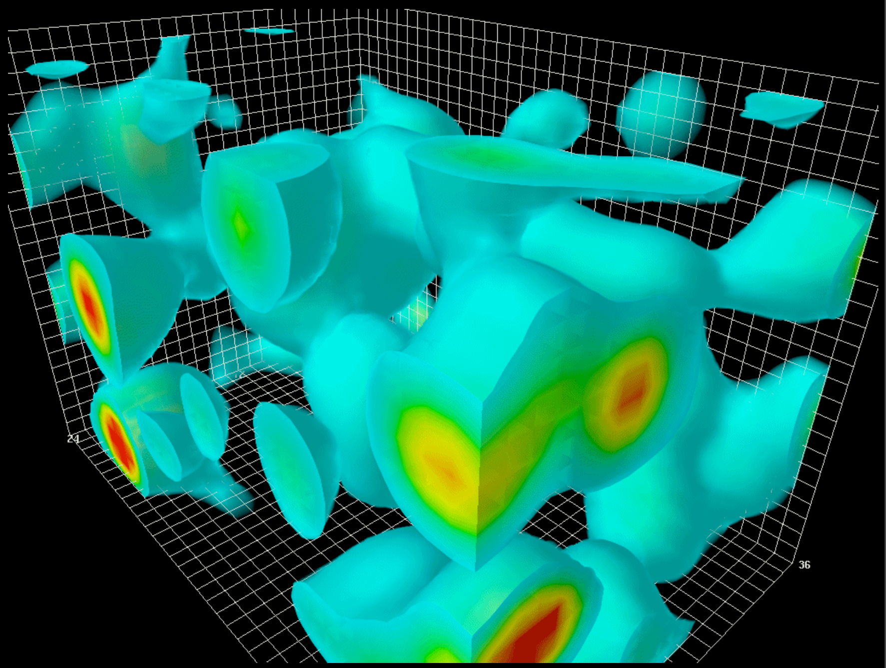

Action (~energy) density fluctuations of gluon-fields in QCD vacuum (2.4 ×2.4× 3.6 fm) (Derek Leinweber)

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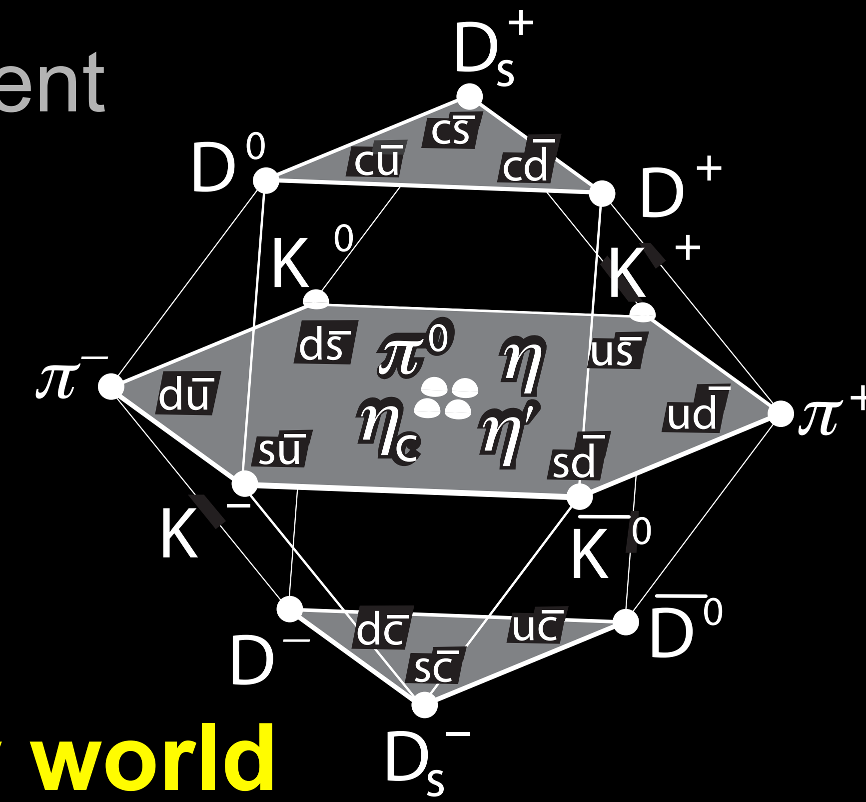
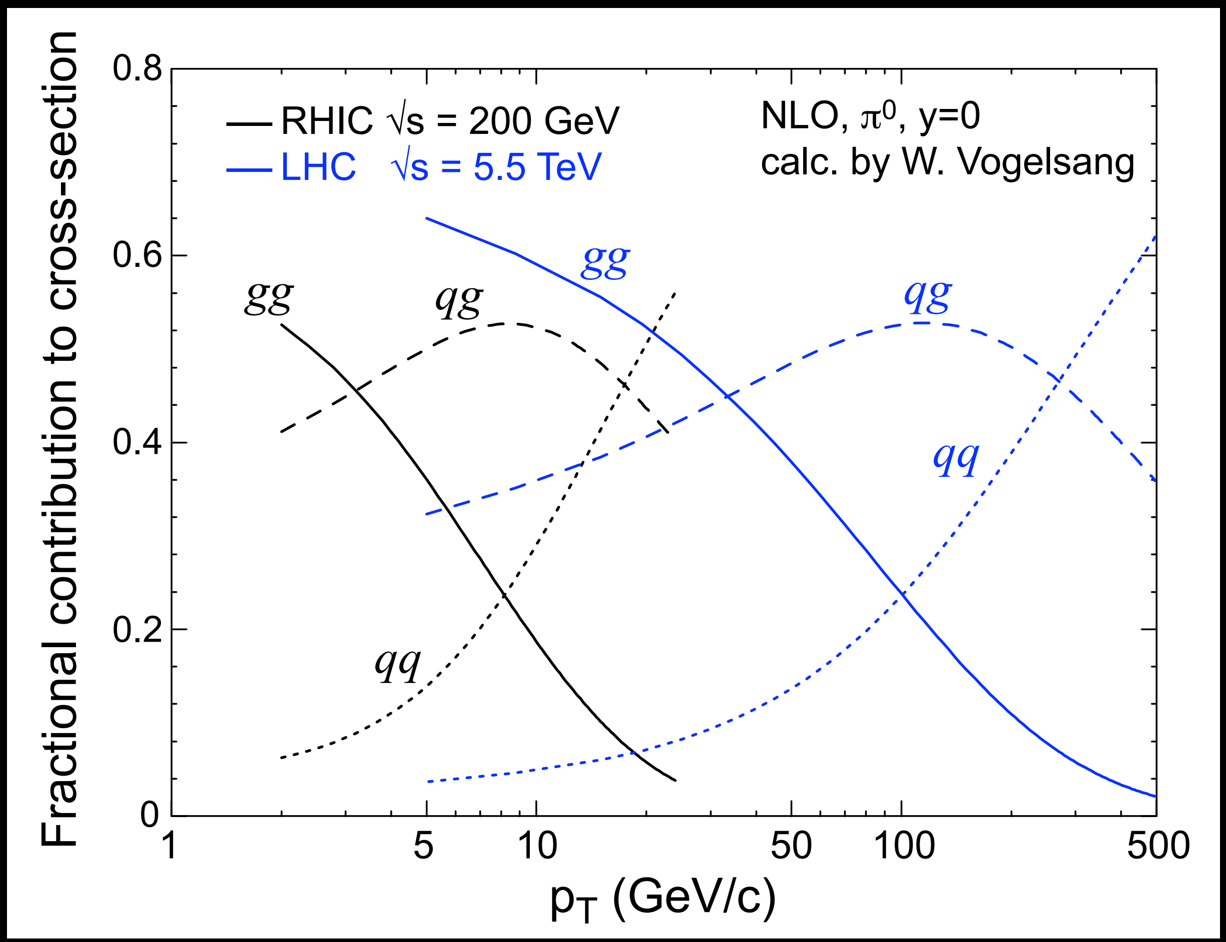


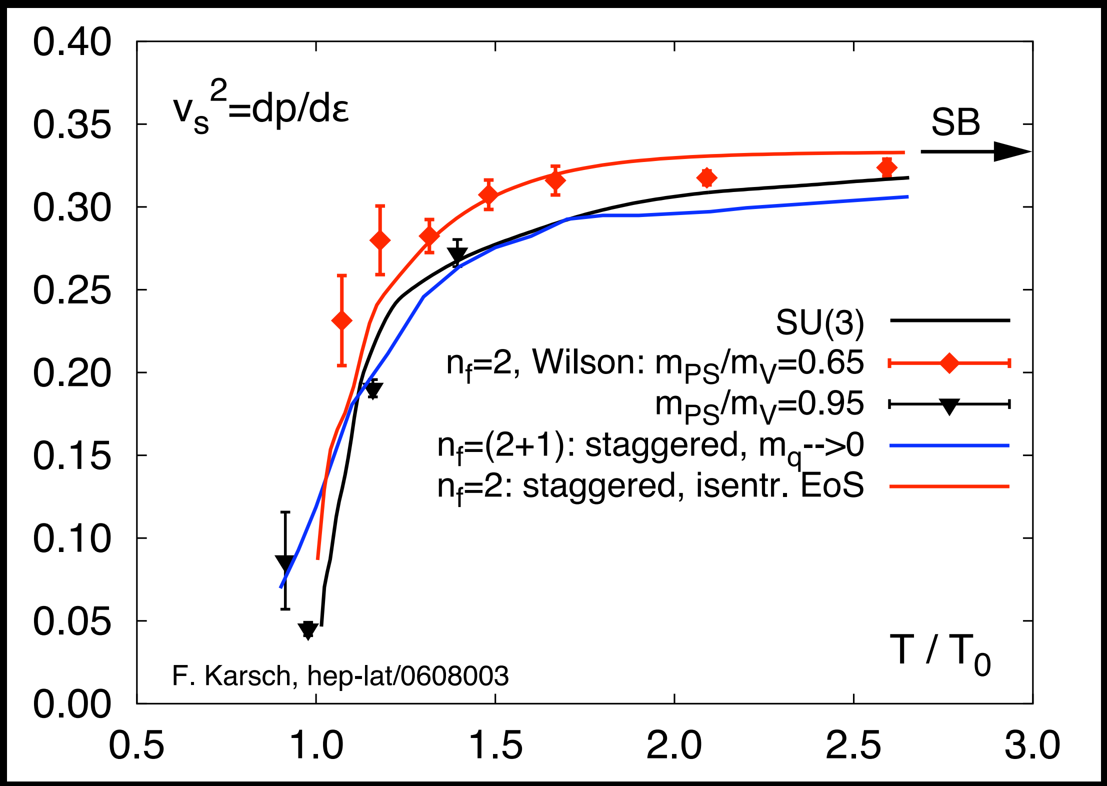
- **Hard to “see” glue in the low-energy world**
  - Gluon degrees of freedom “missing” in hadronic spectrum
  - Drive the structure of baryonic matter already at medium-x
  - Crucial players at RHIC and LHC

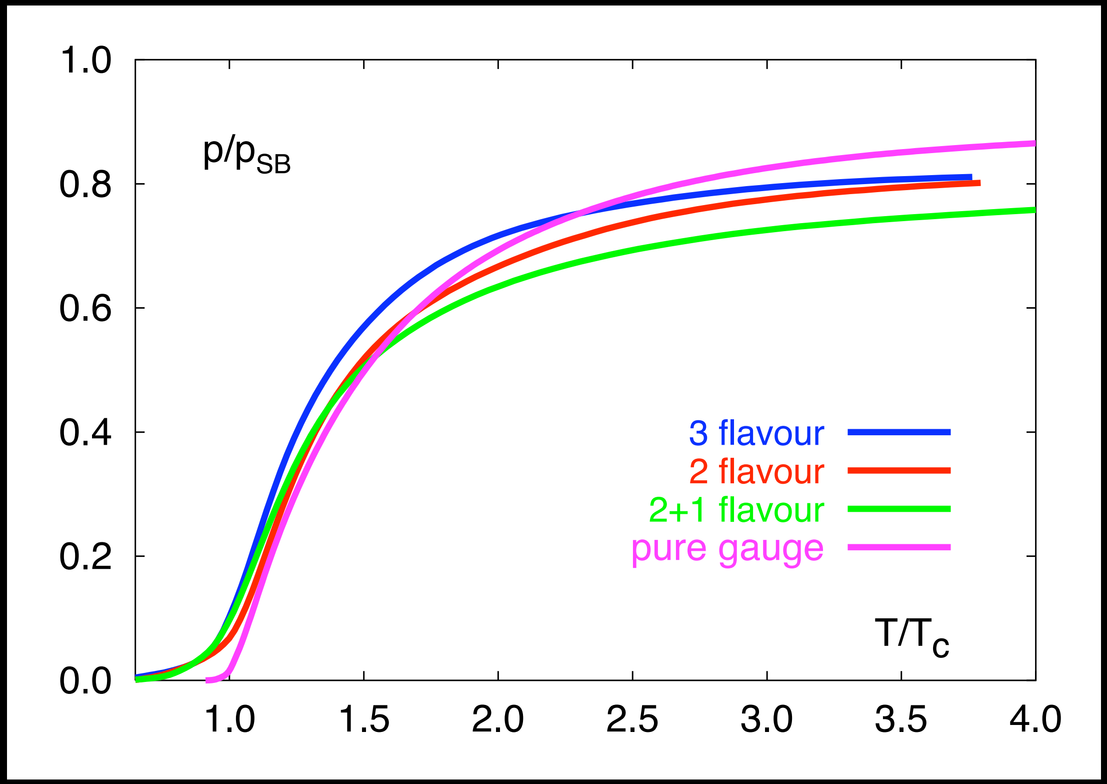
Role of Glue in Heavy-Ions

Jets (π^0) Production

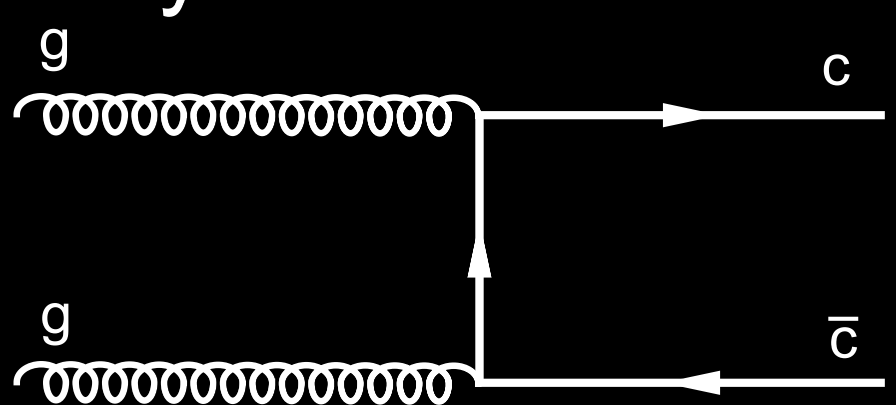


Lattice



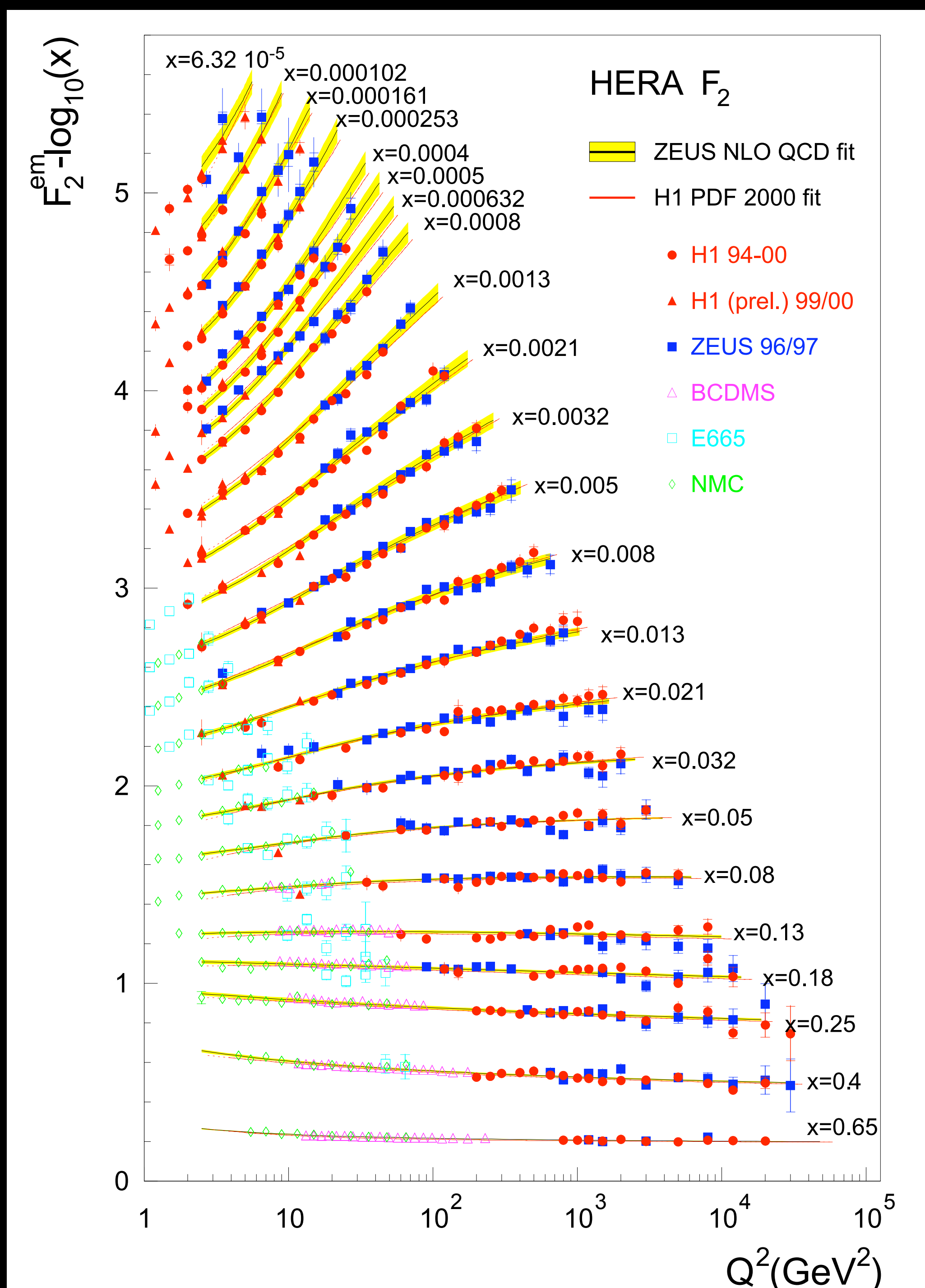


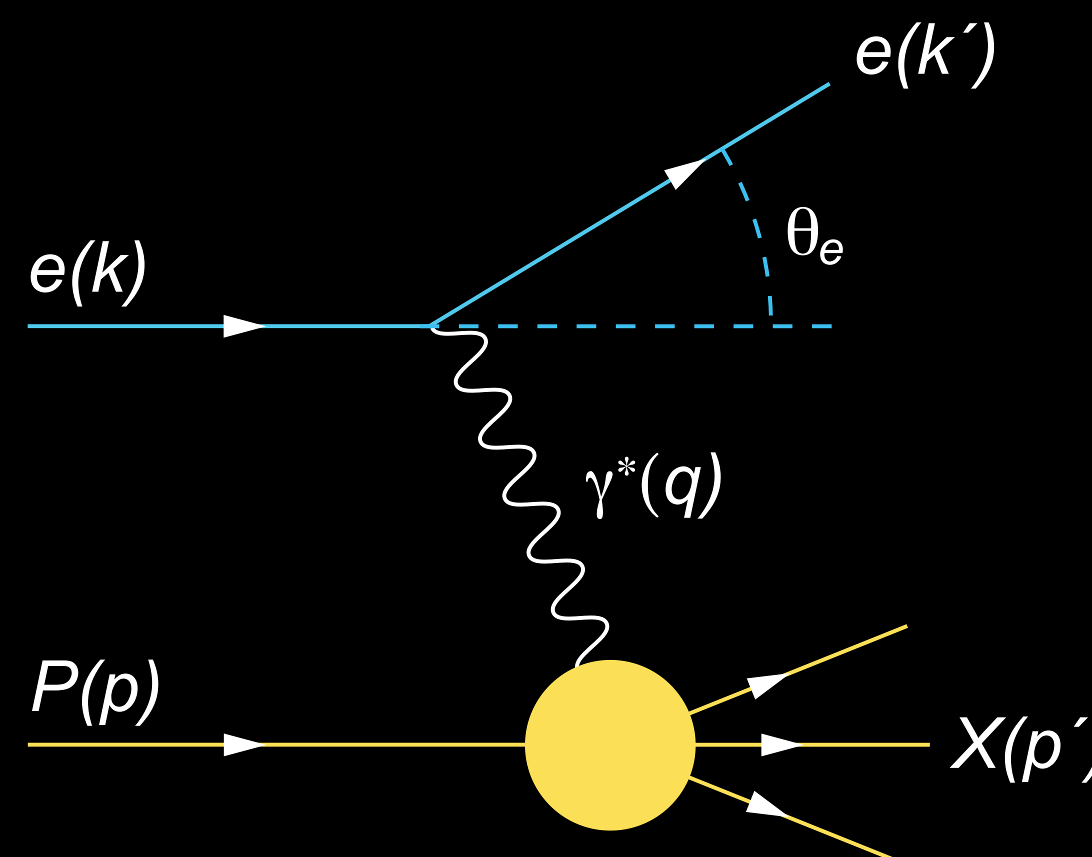
Heavy Flavor Production



How to Measure Glue ?

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





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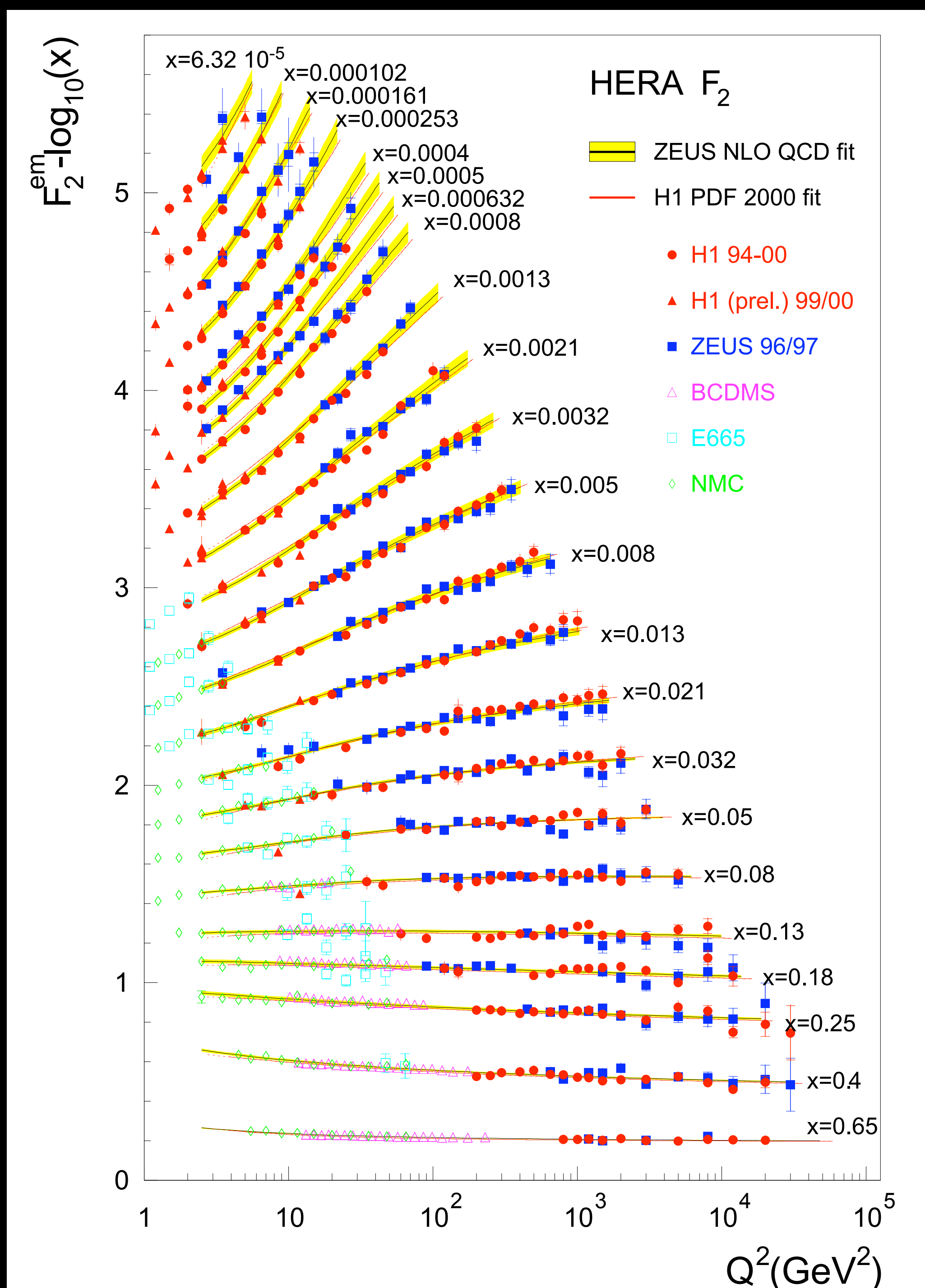
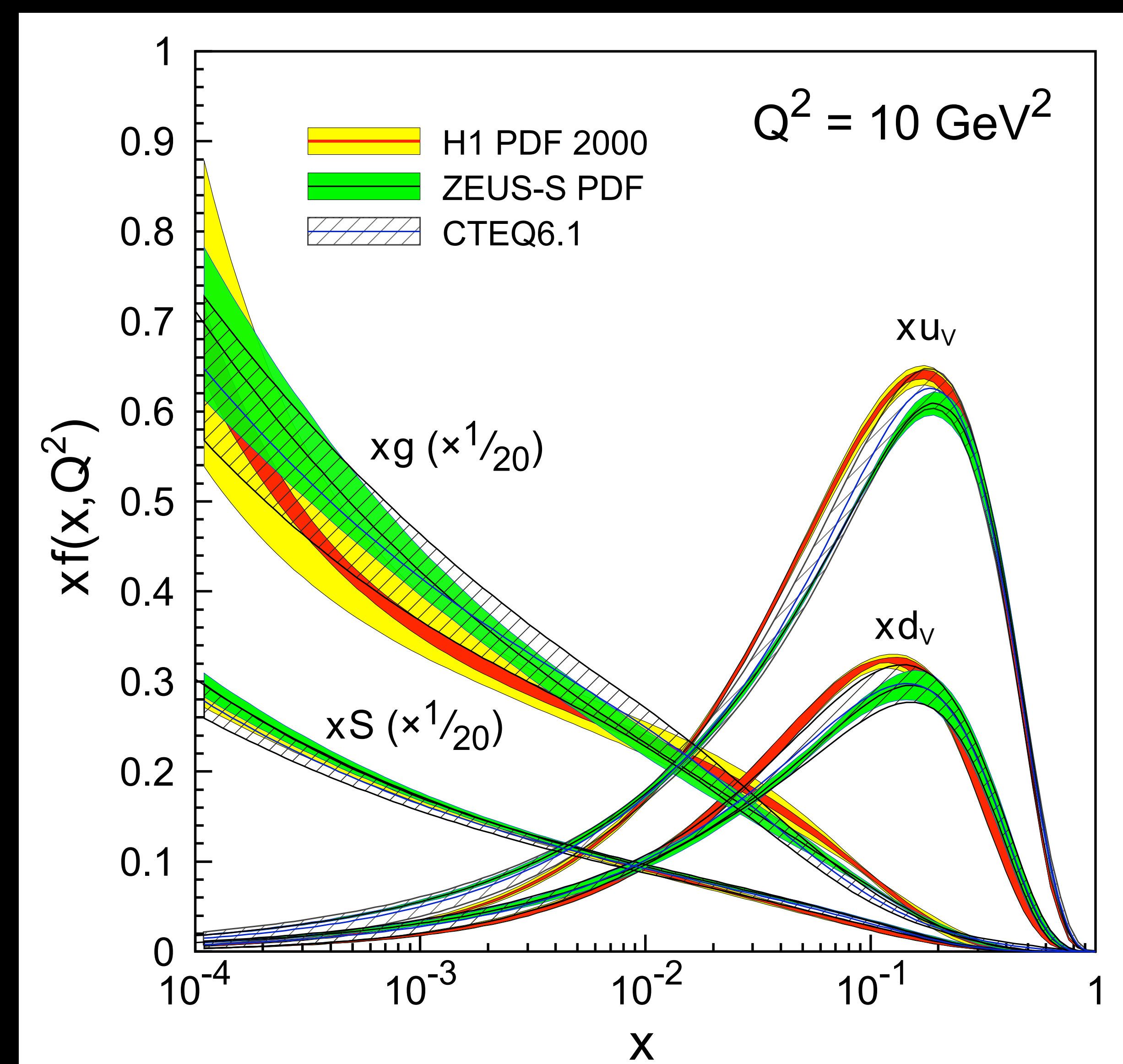


Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution $\Rightarrow$ $G(x,Q^2)$



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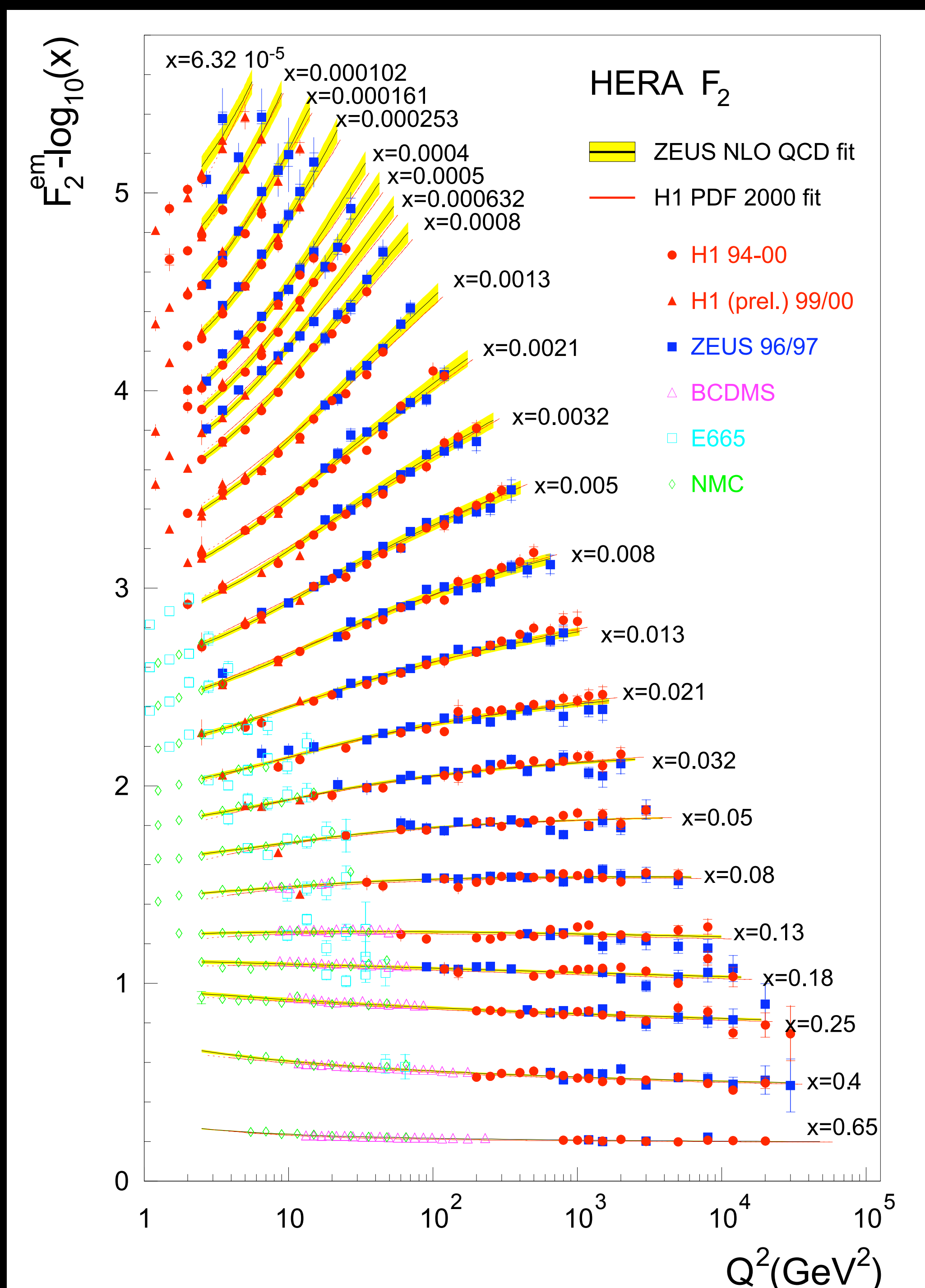

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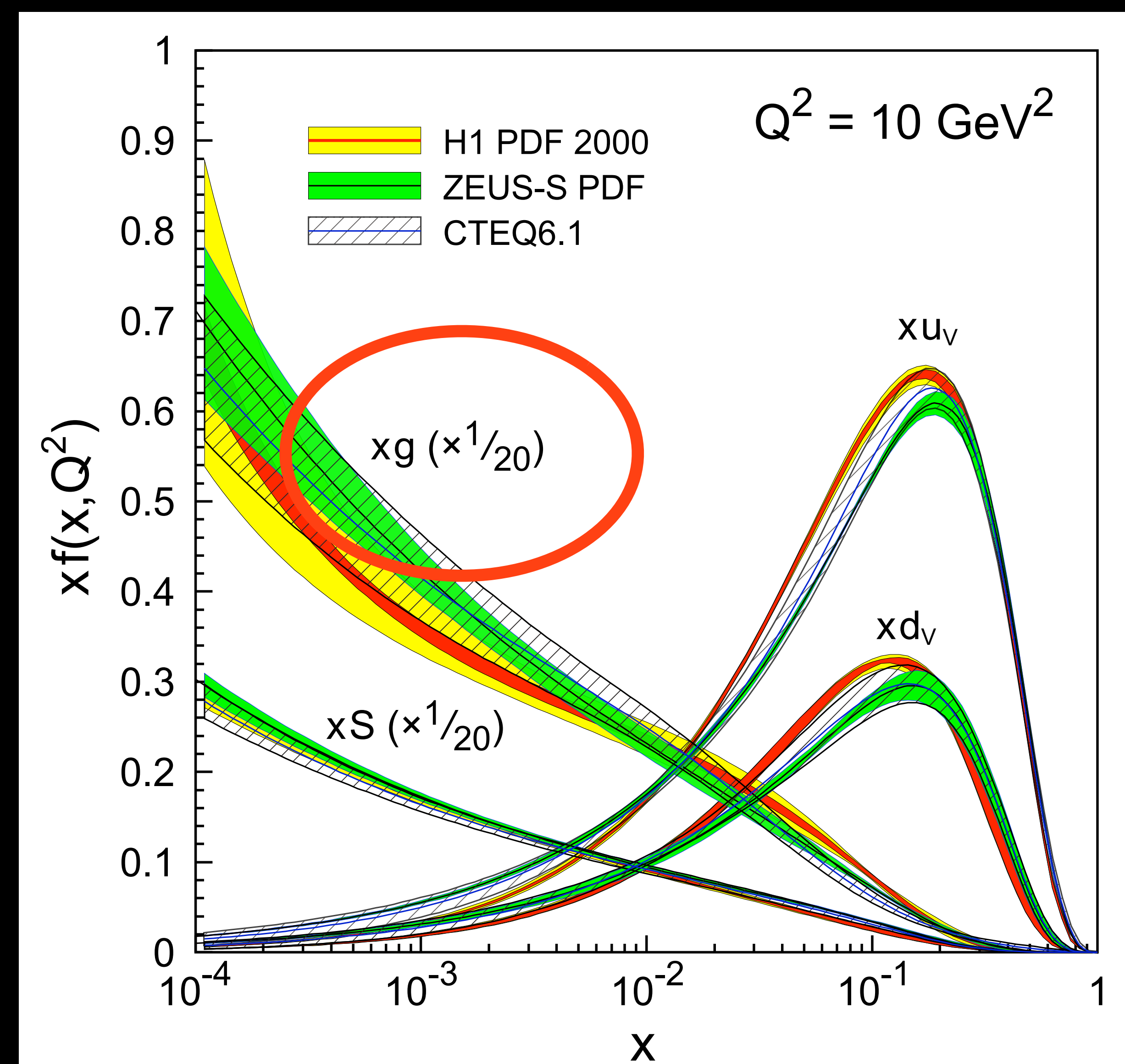
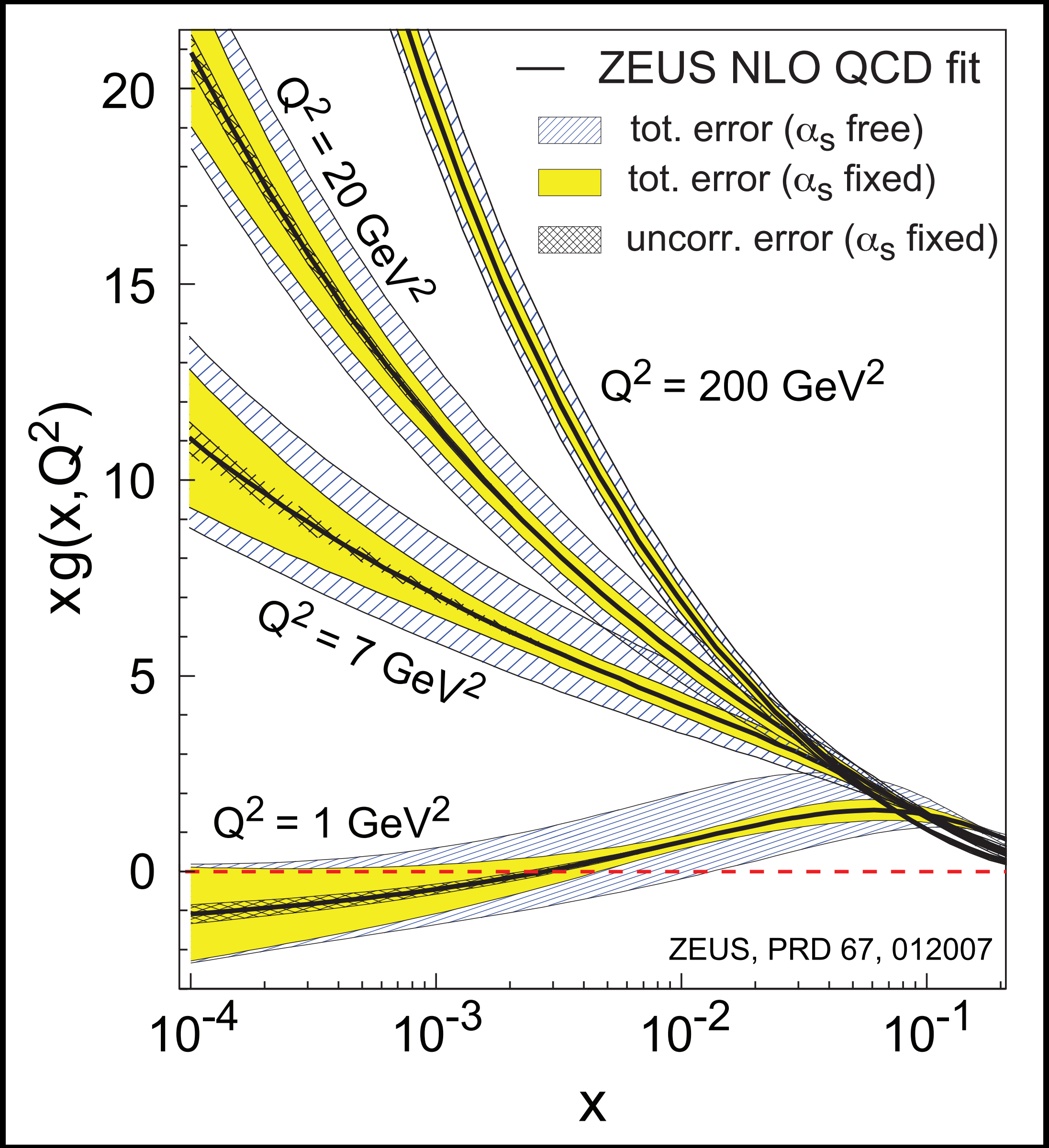


What Do We Know About Glue?



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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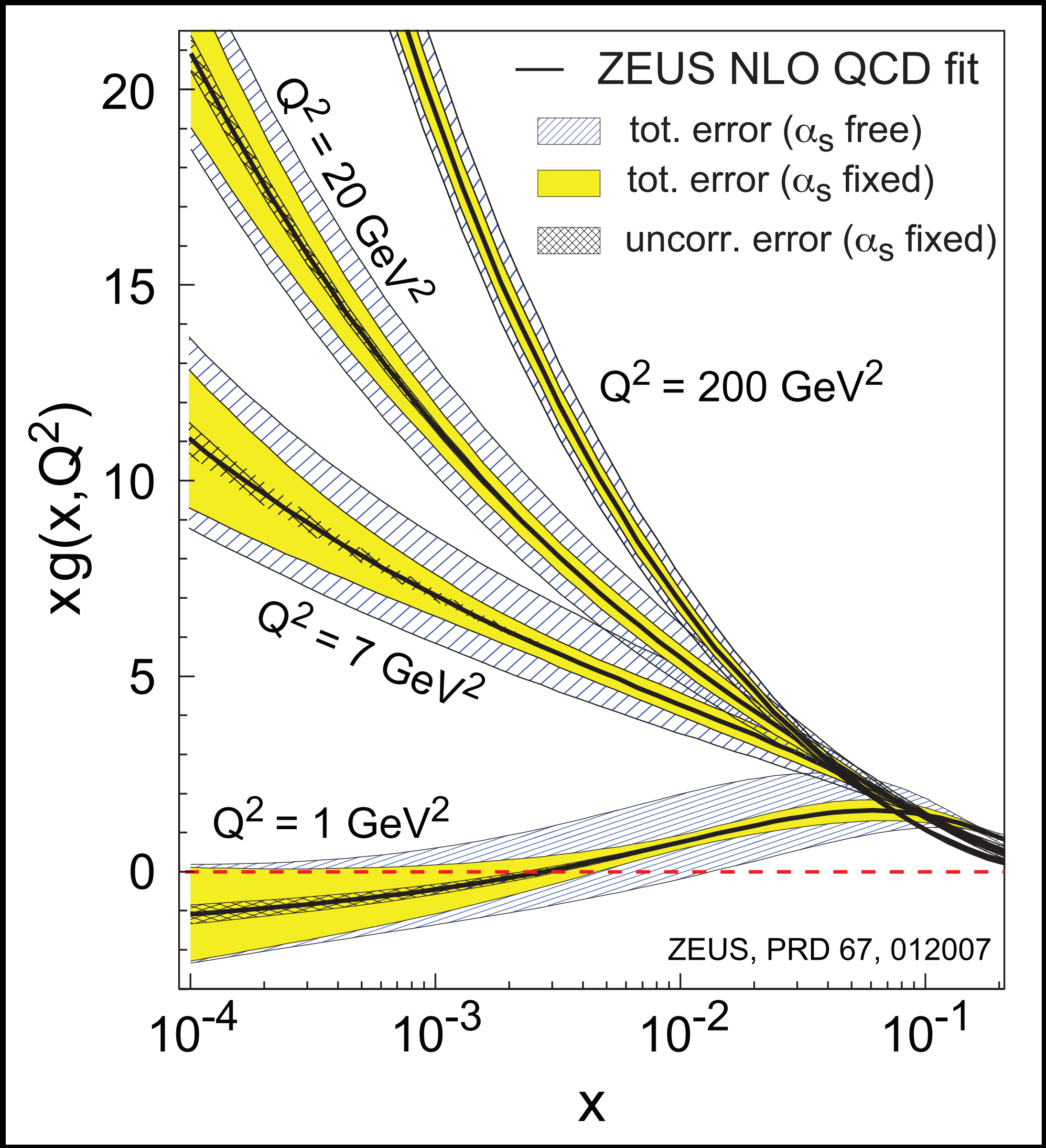

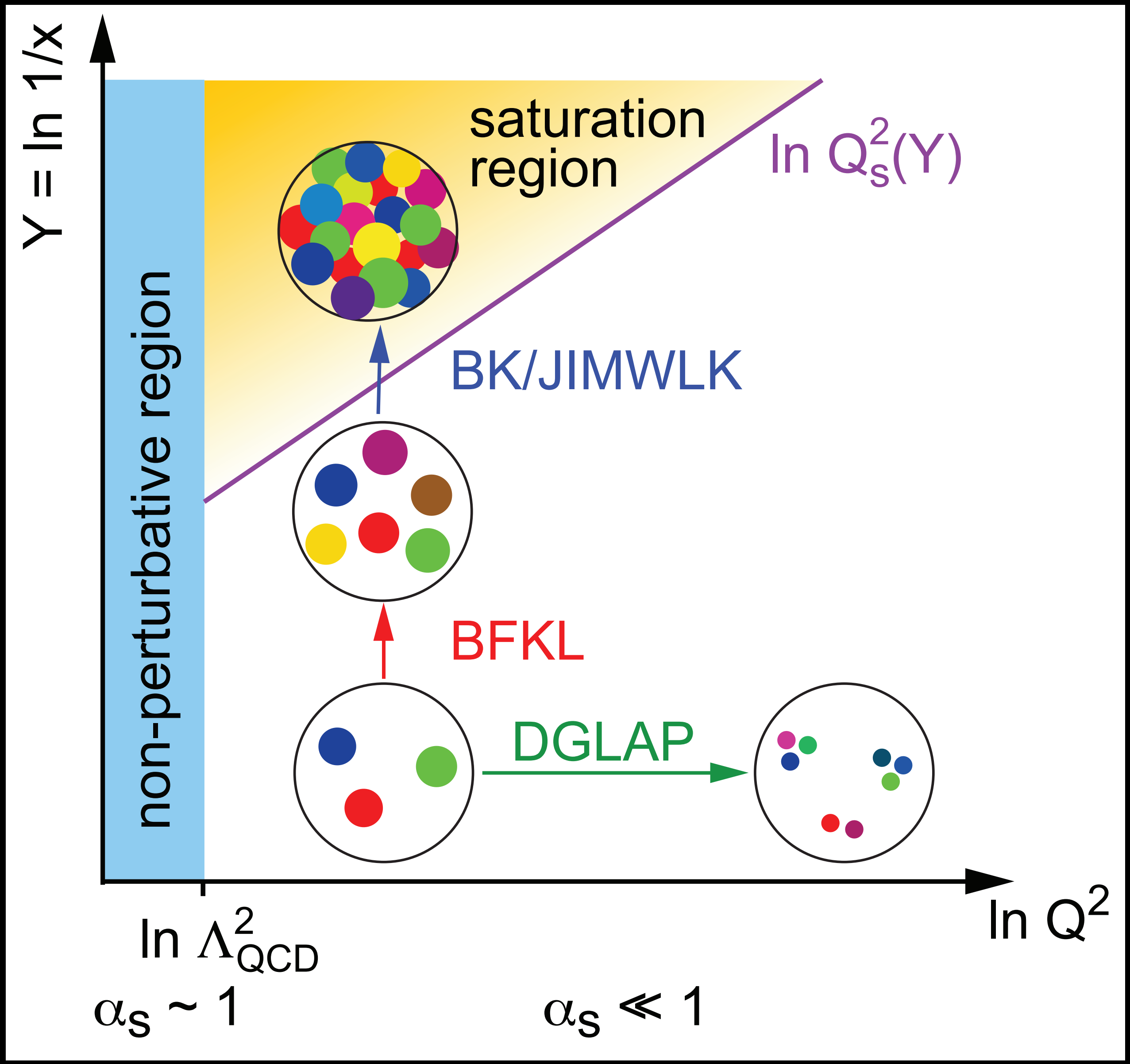

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BK/JIMWLK: *non-linear* effects ⇒ saturation

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

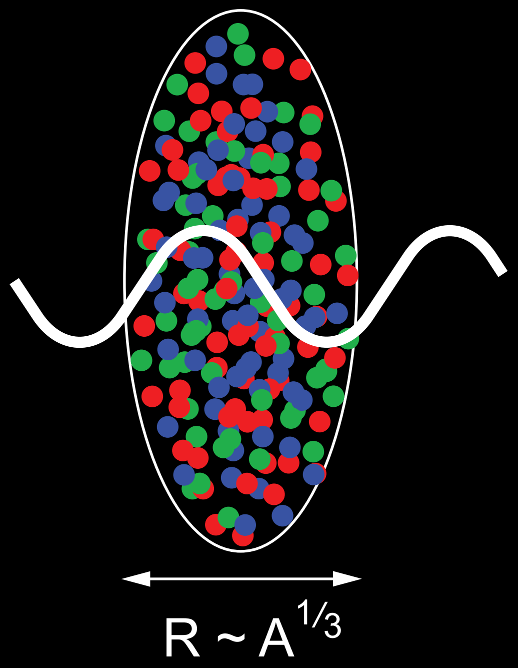
Enhancing Saturation Effects: *e*+A

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



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

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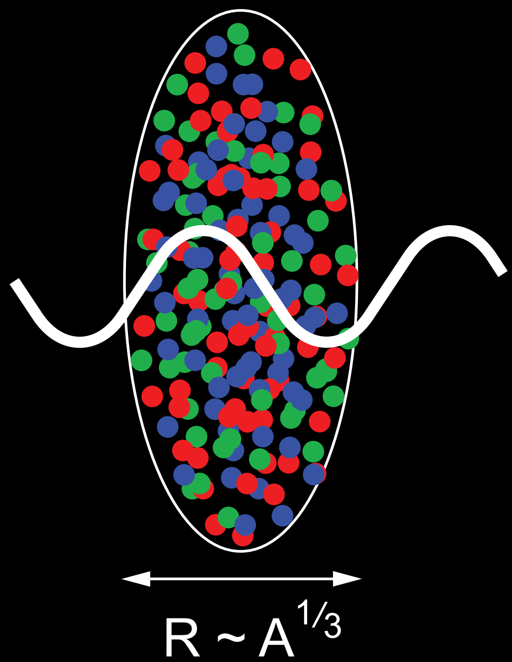

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Nuclear "Oomph" Factor: $$(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

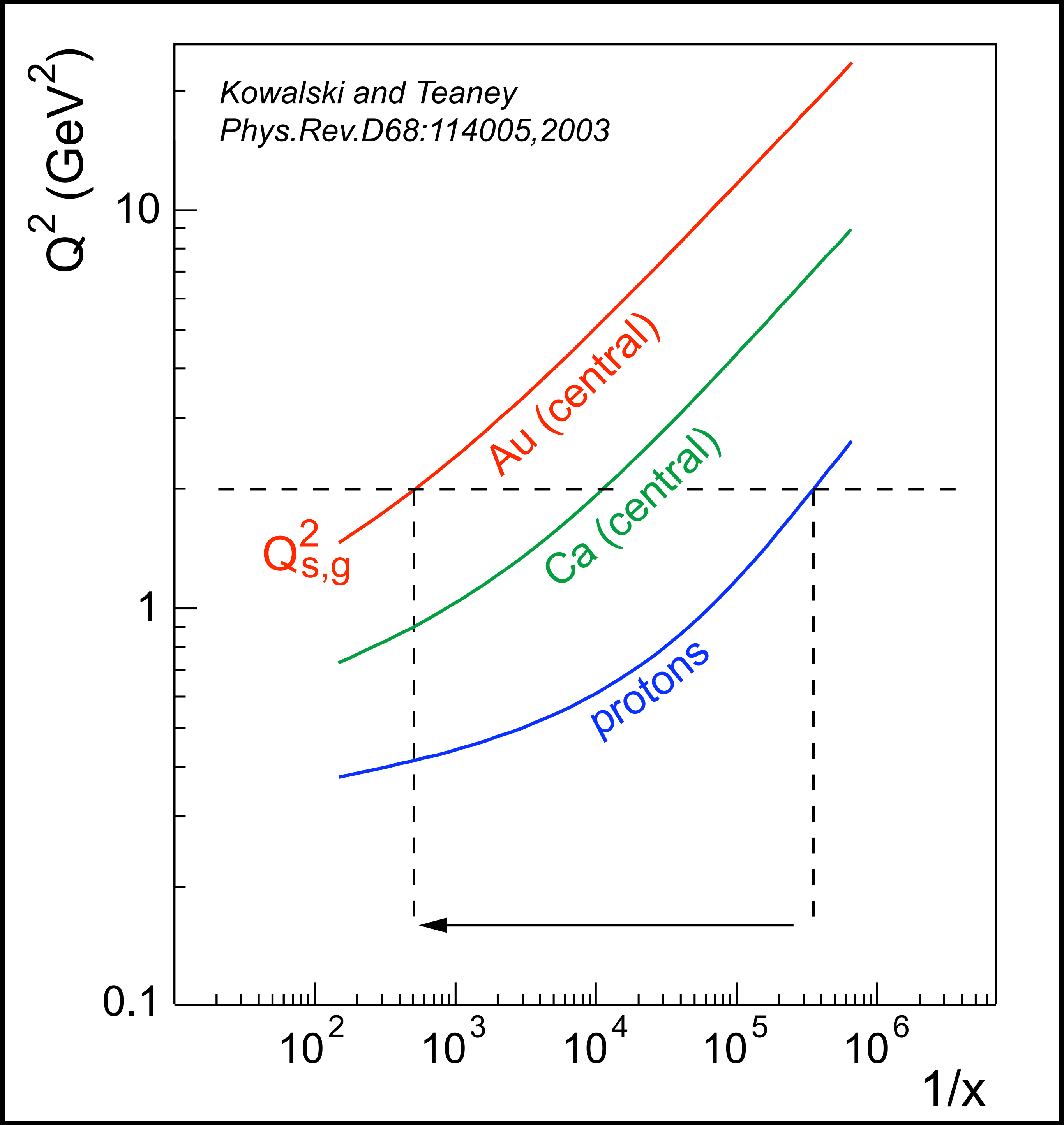
Enhancement of Q_S with A

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

The Nuclear "Oomph"

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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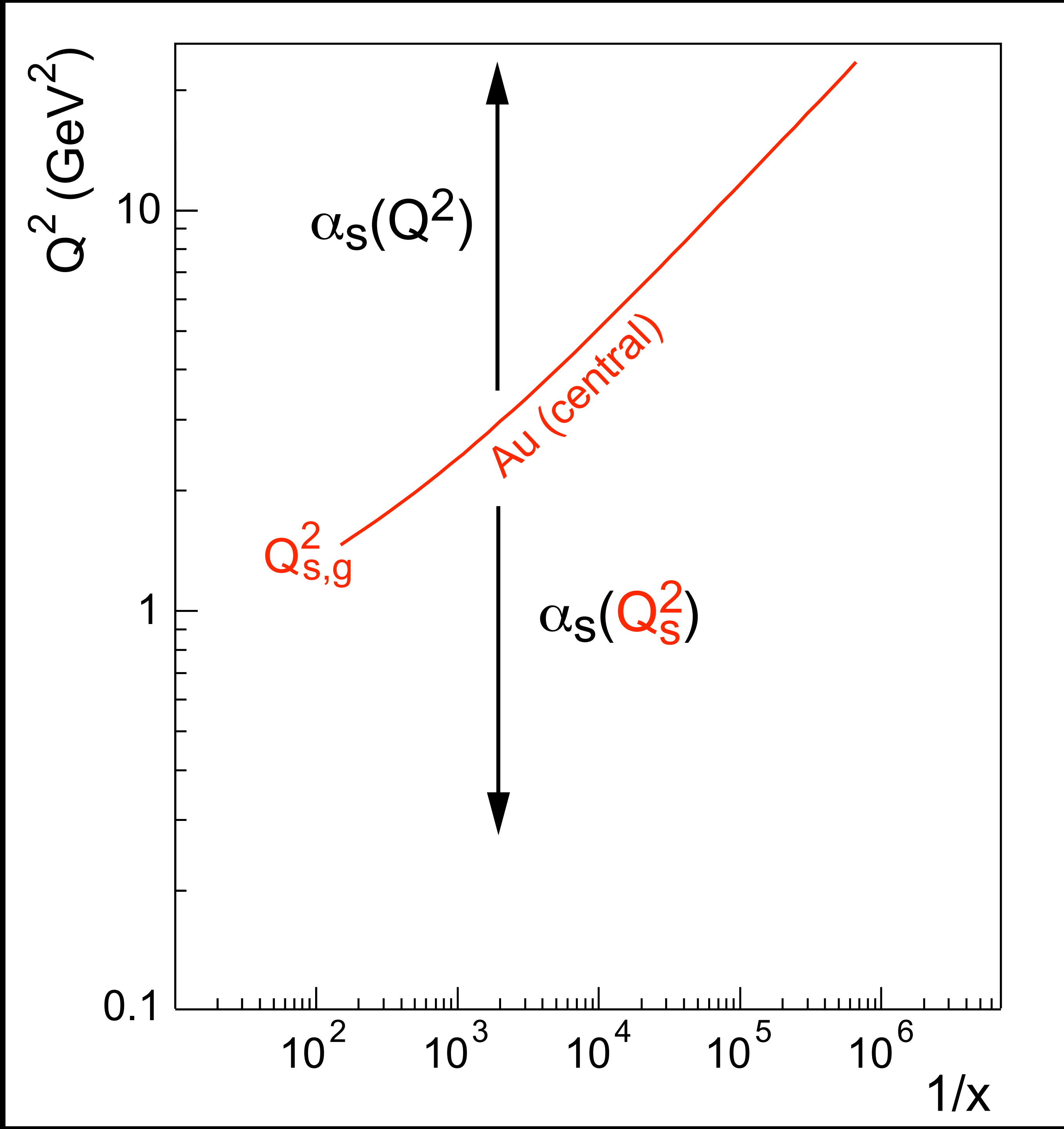

Note:

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

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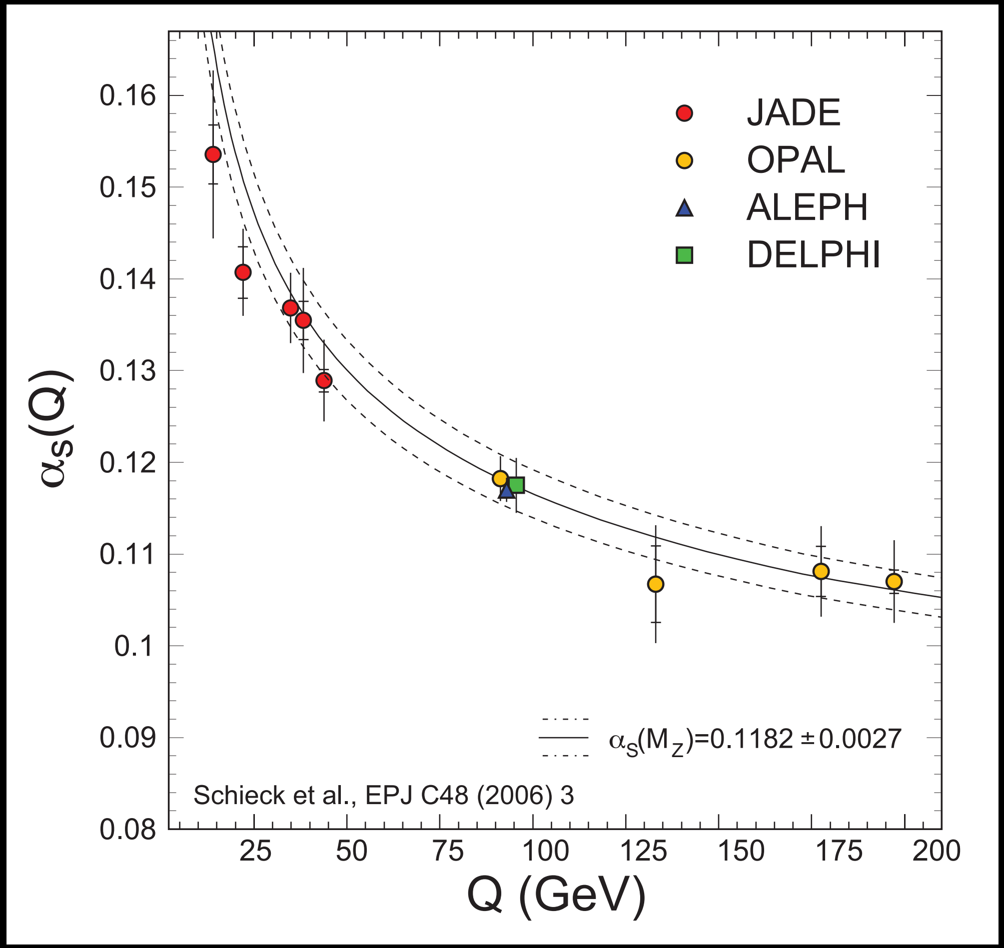
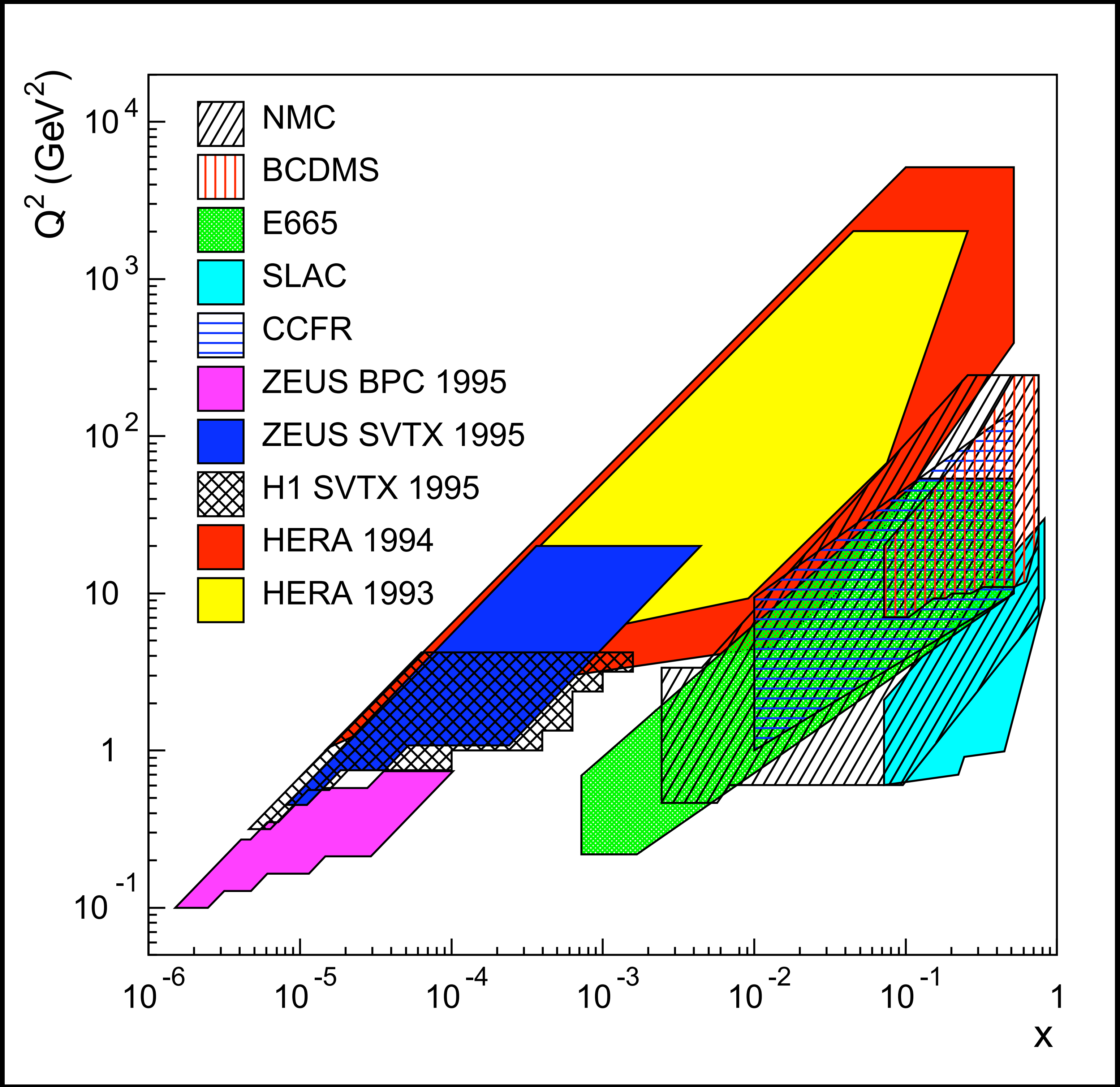


Requirements for an Electron Ion Collider



Well mapped in e+p

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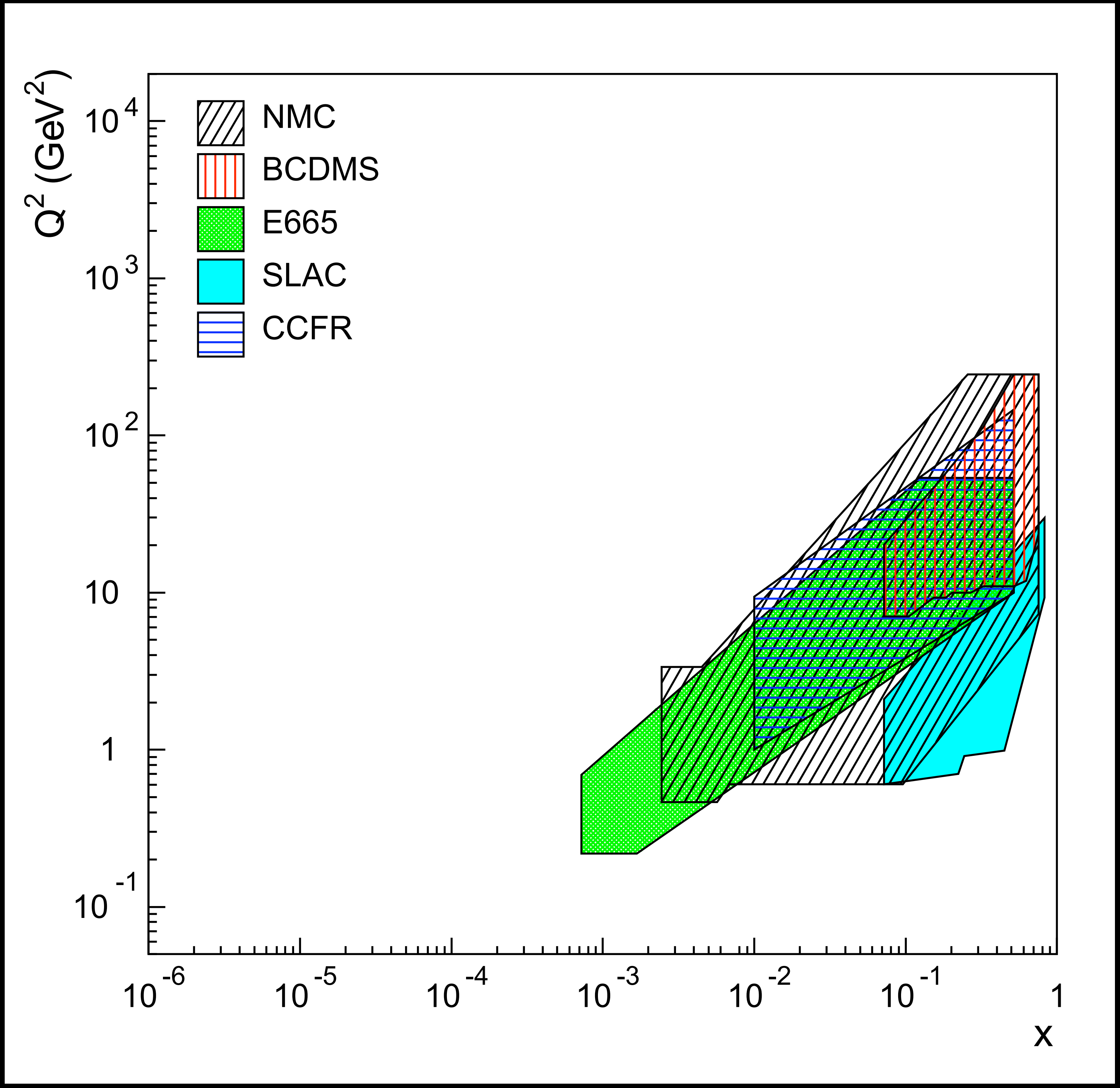

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- many with small A
- low statistics

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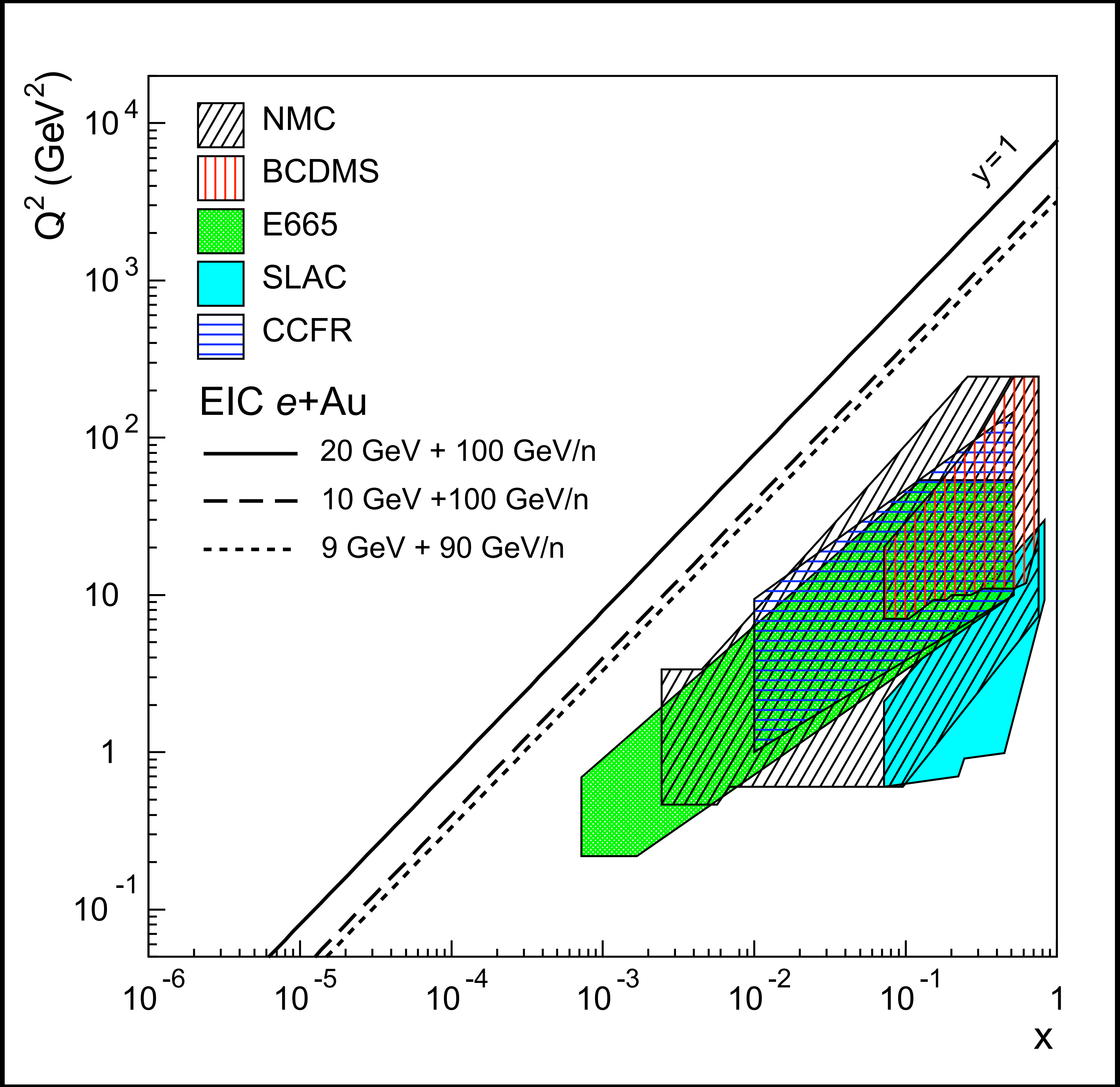

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Electron Ion Collider:

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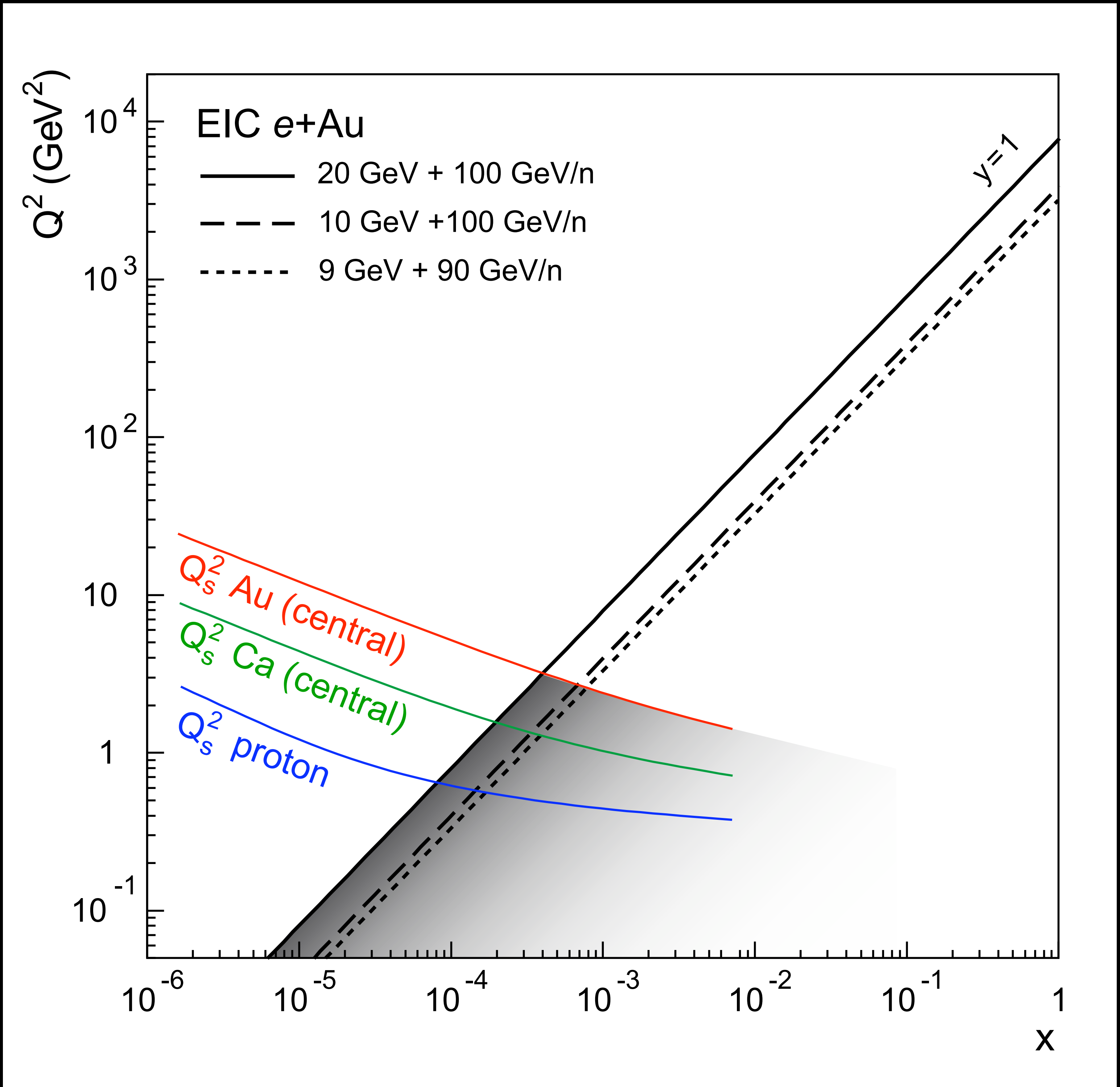

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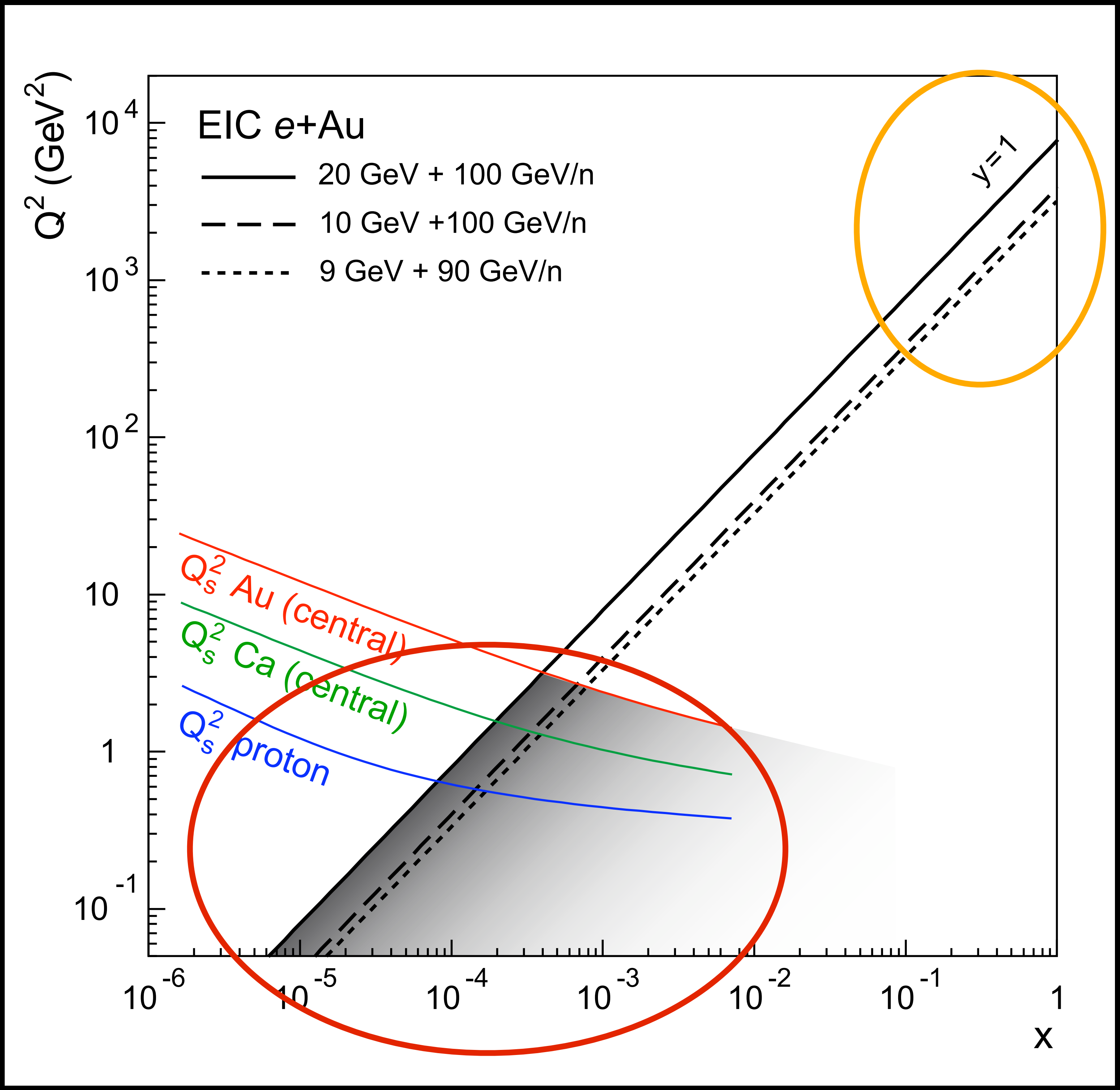

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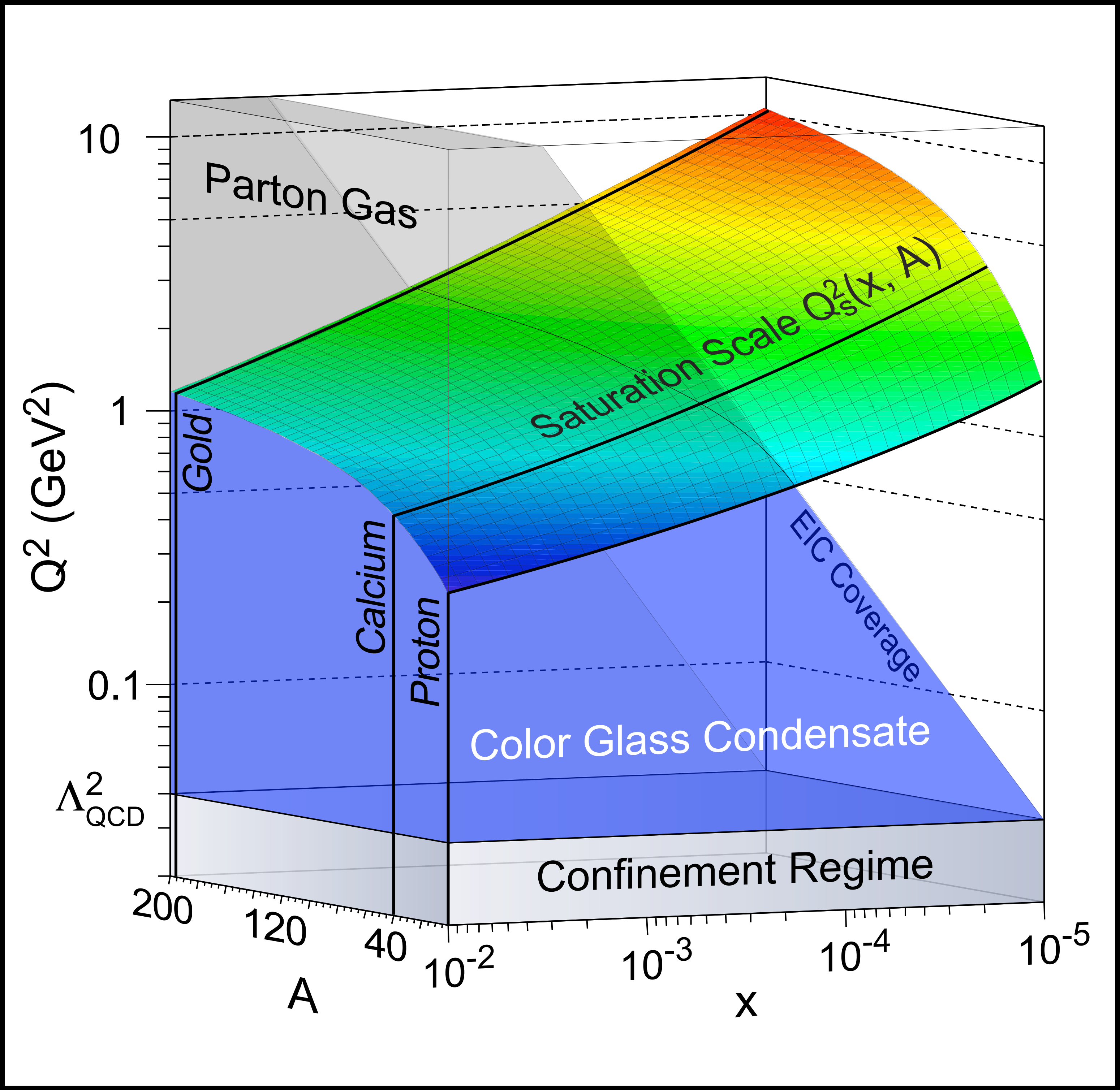

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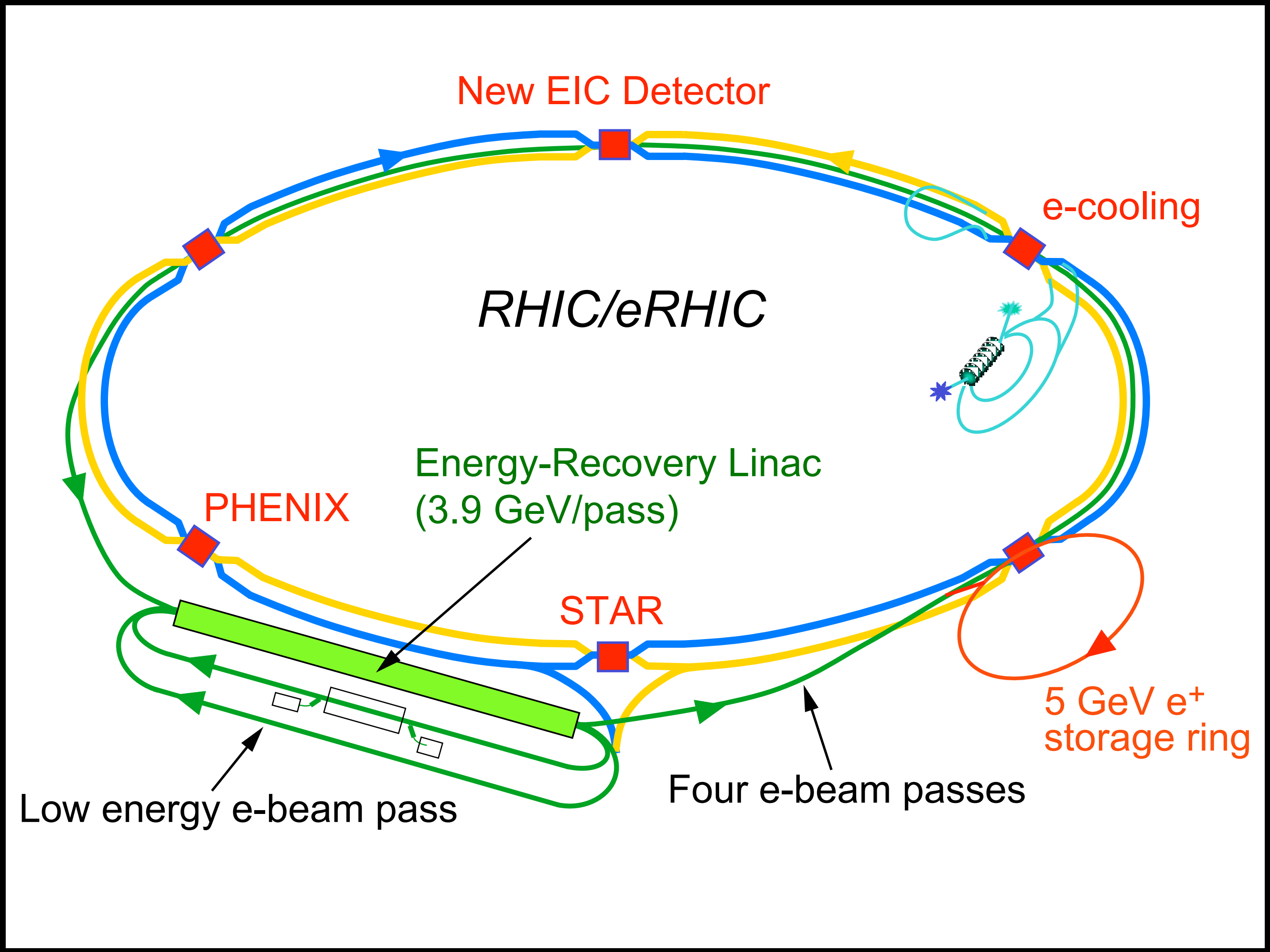
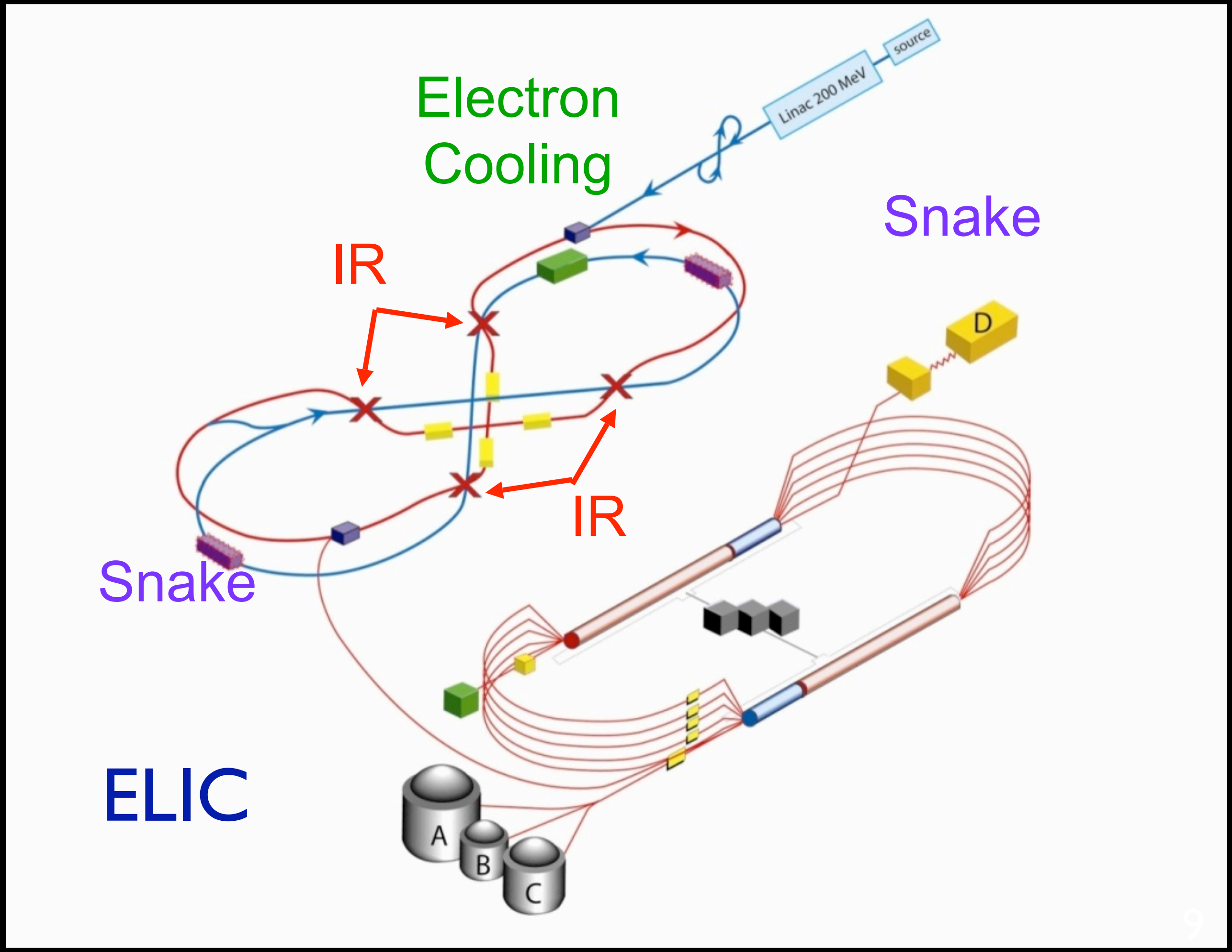
Electron Ion Collider Concepts

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}





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 √s scan)
  - 2+1 jet rates
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- **Role of color 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

Example of Key Measurement: F_L

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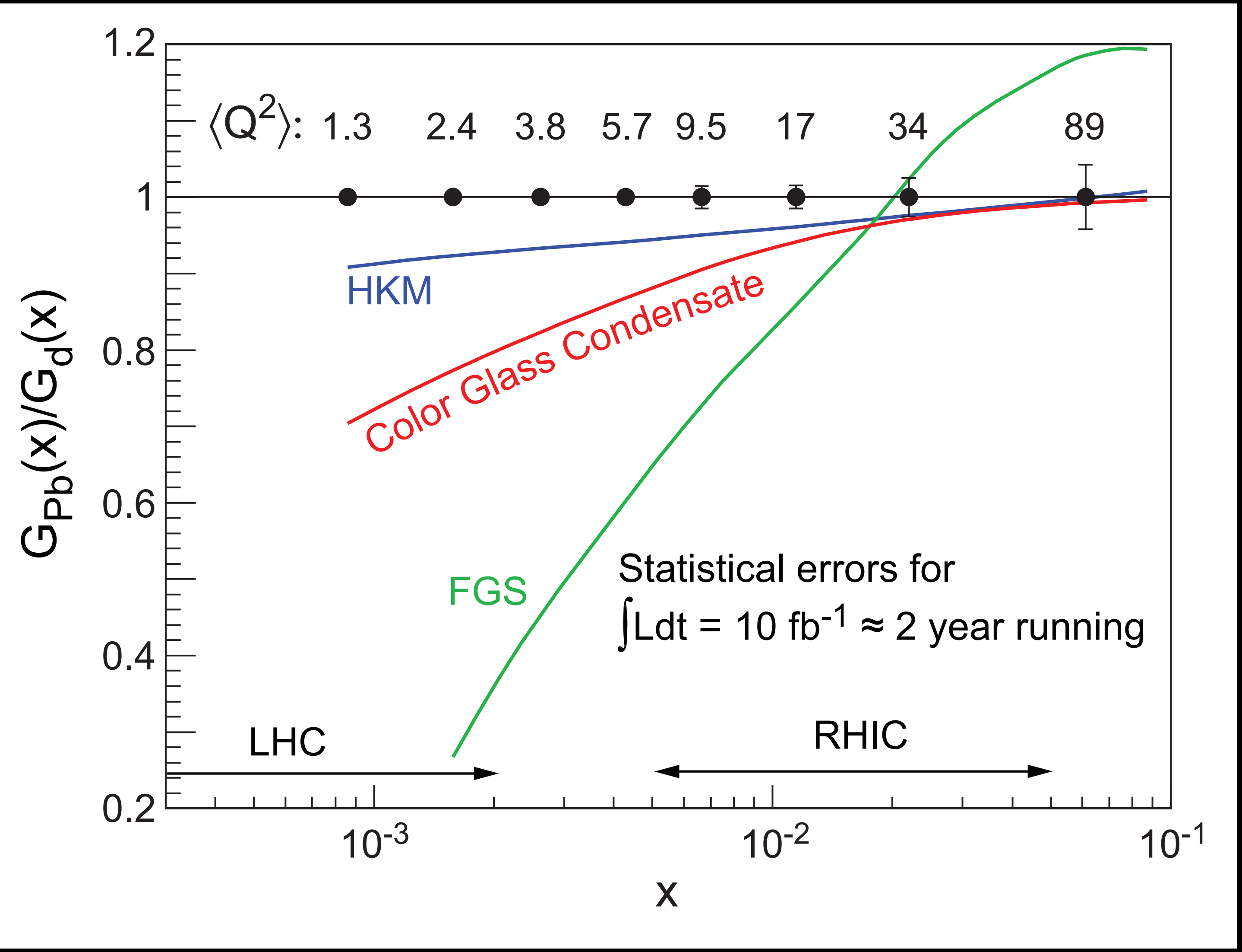


$F_L \sim \alpha_s\, G(x,Q^2)$
requires $\sqrt{s}$ scan, $Q^2/xs = y$

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

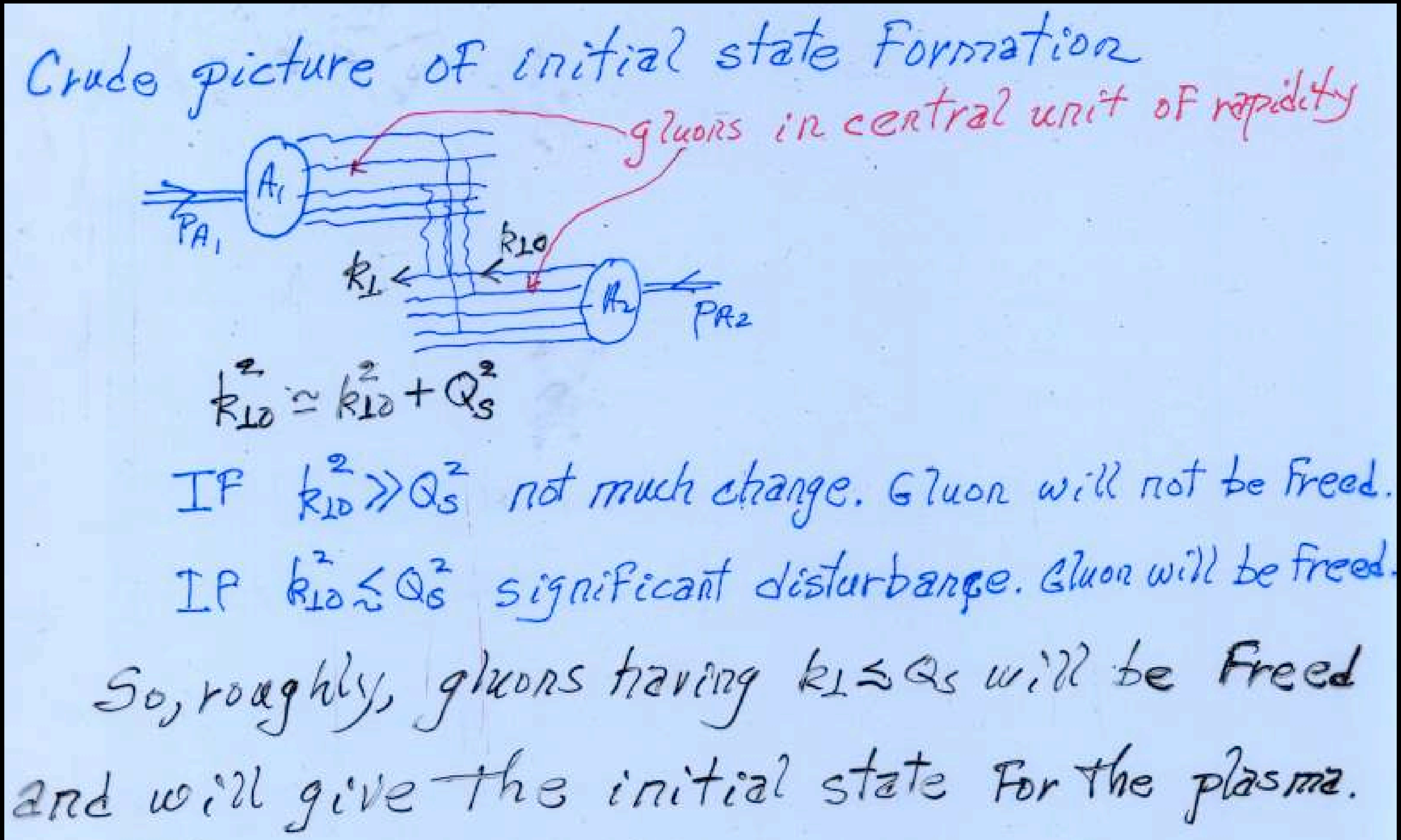
statistical error only

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

Symbiosis between EIC and HI

- Thermalization:
  - At RHIC system thermalizes (locally) fast ($\tau_0 < 1$ fm/c)
  - We don't know why and how? Initial conditions?



At present no first principle understanding of thermalization in QCD

Need: $G(x,Q^2)$

Al Mueller (2007)

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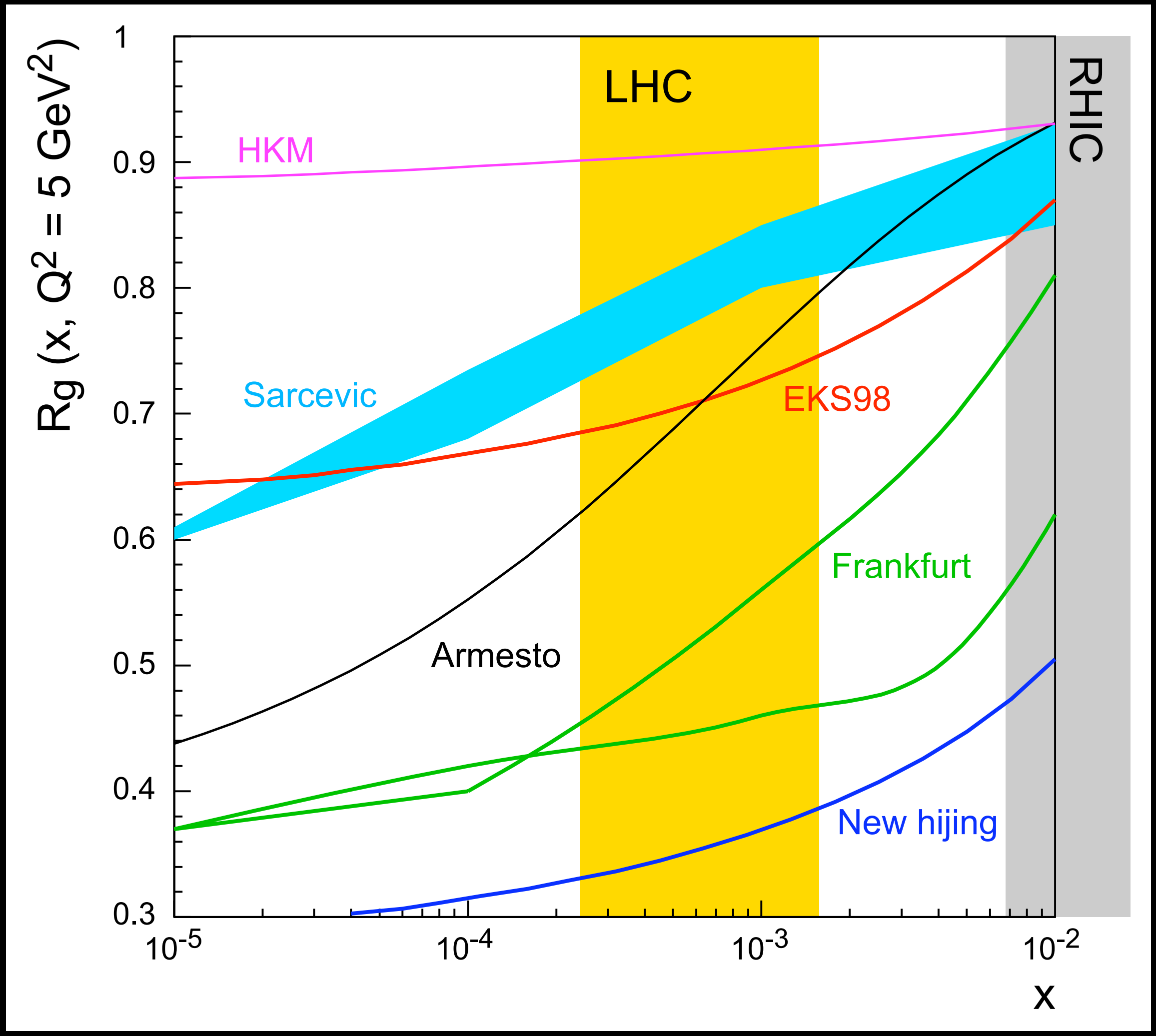
  - RHIC → suppression in forward region
  - LHC → midrapidity ?
    - bulk (< 2-3 GeV/c)



Accardi et al., hep-ph/0308248, CERN-2004-009-A

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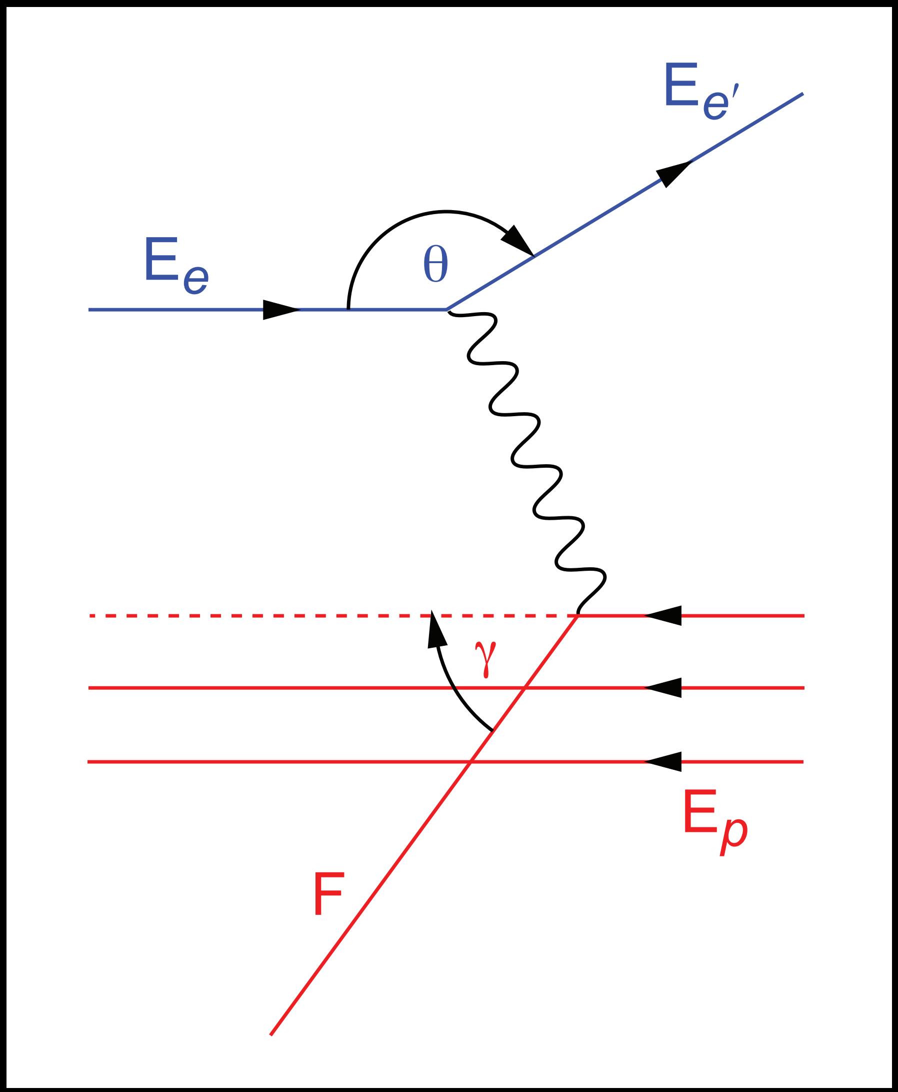
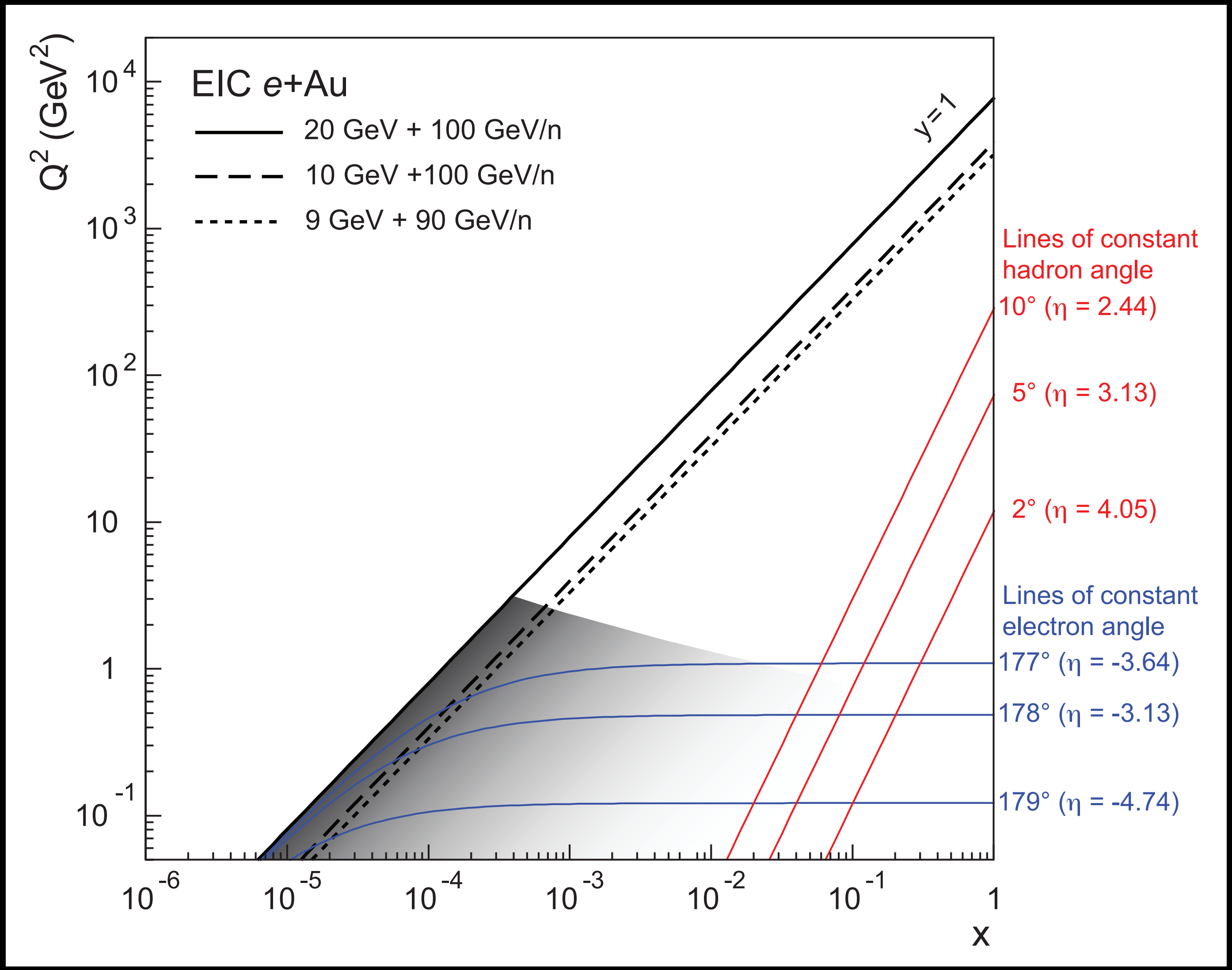
- Jet Quenching:
  - Need Refererence: E-loss in cold matter
  - No HERMES data for:
    - charm energy loss
    - in LHC energy range

Experimental Aspects





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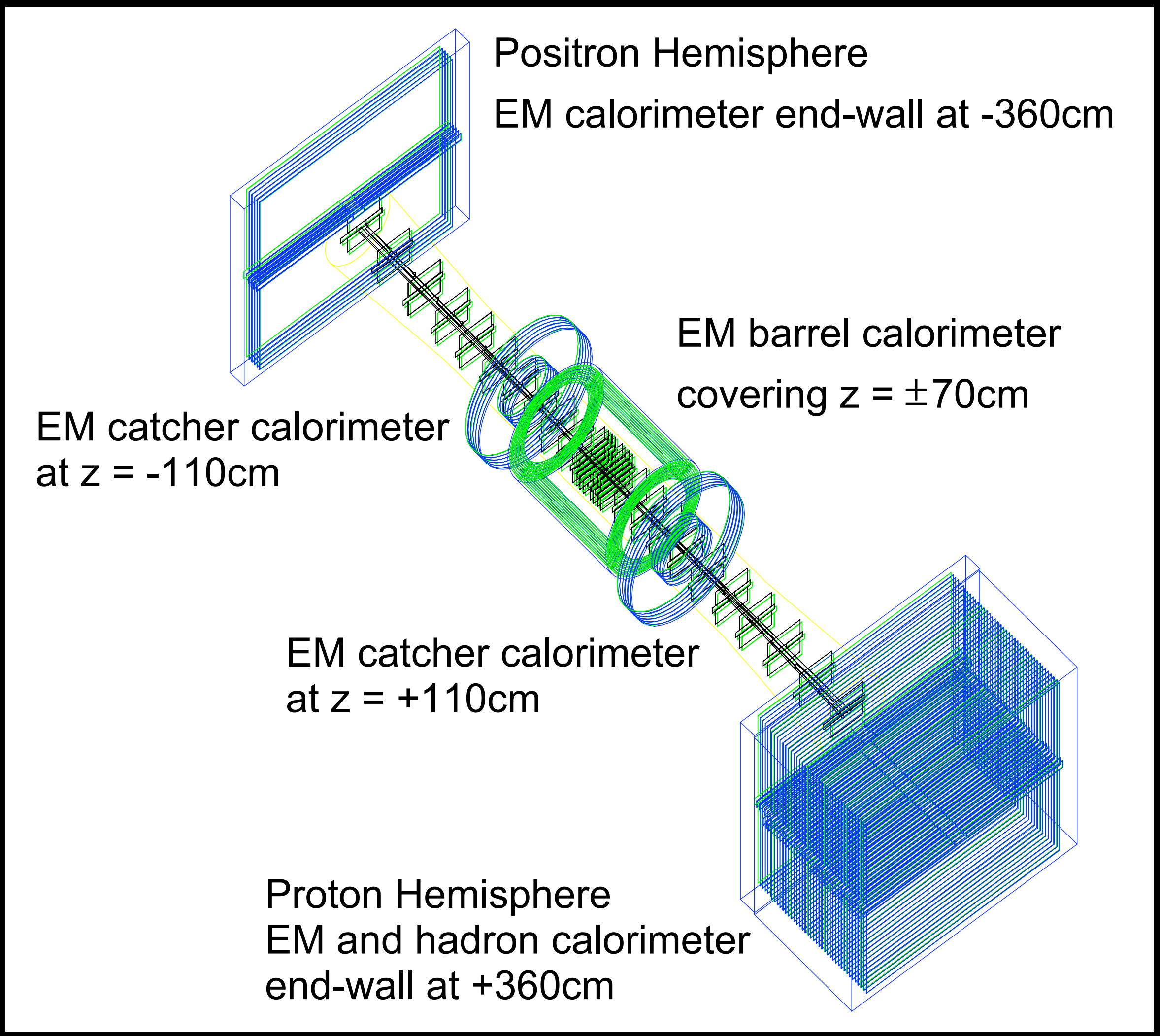
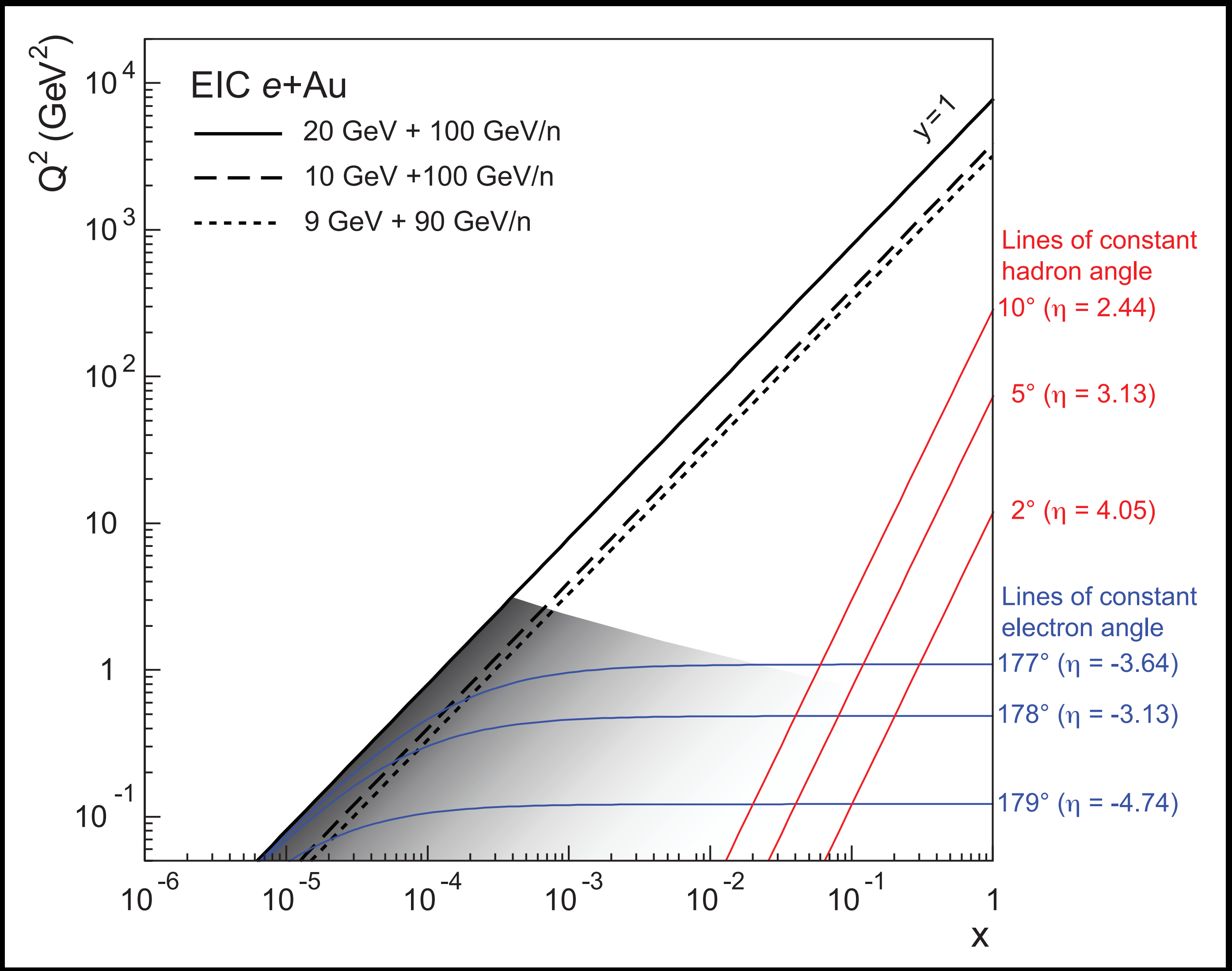


I. Abt, A. Caldwell, X. Liu, J. Sutiak, hep-ex 0407053



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

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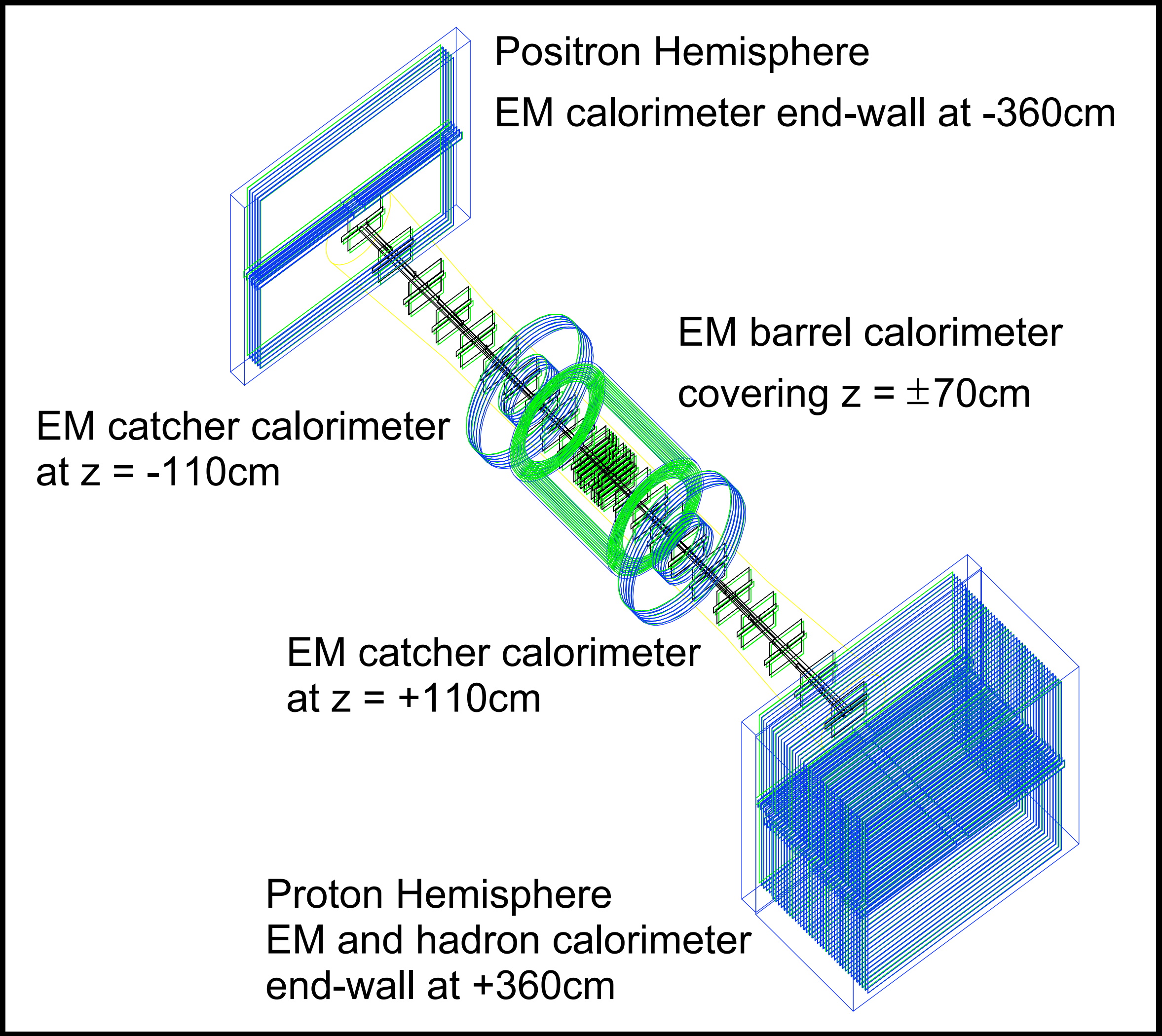
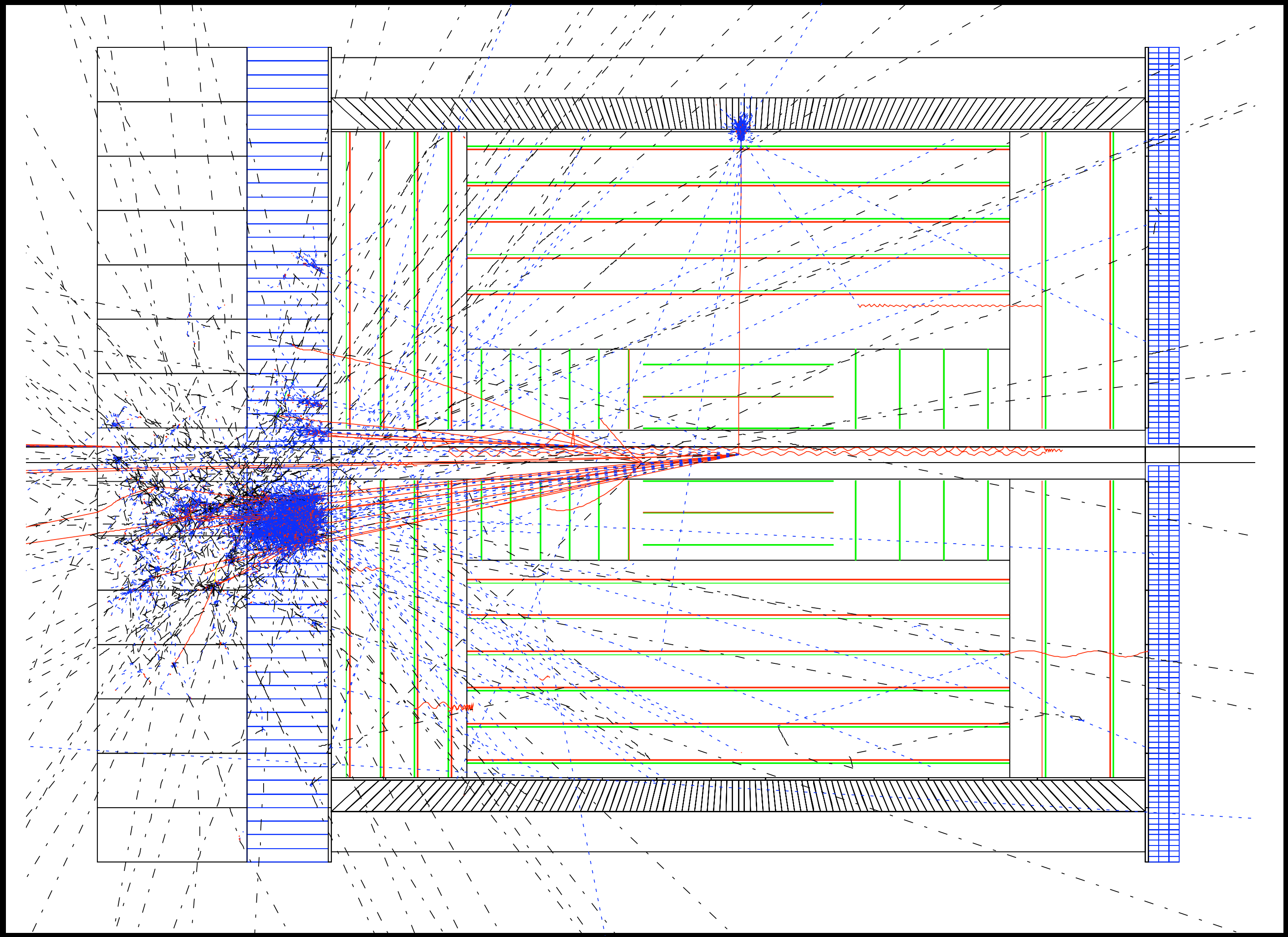


I. Abt, A. Caldwell, X. Liu, J. Sutiak, hep-ex 0407053



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.

Summary

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

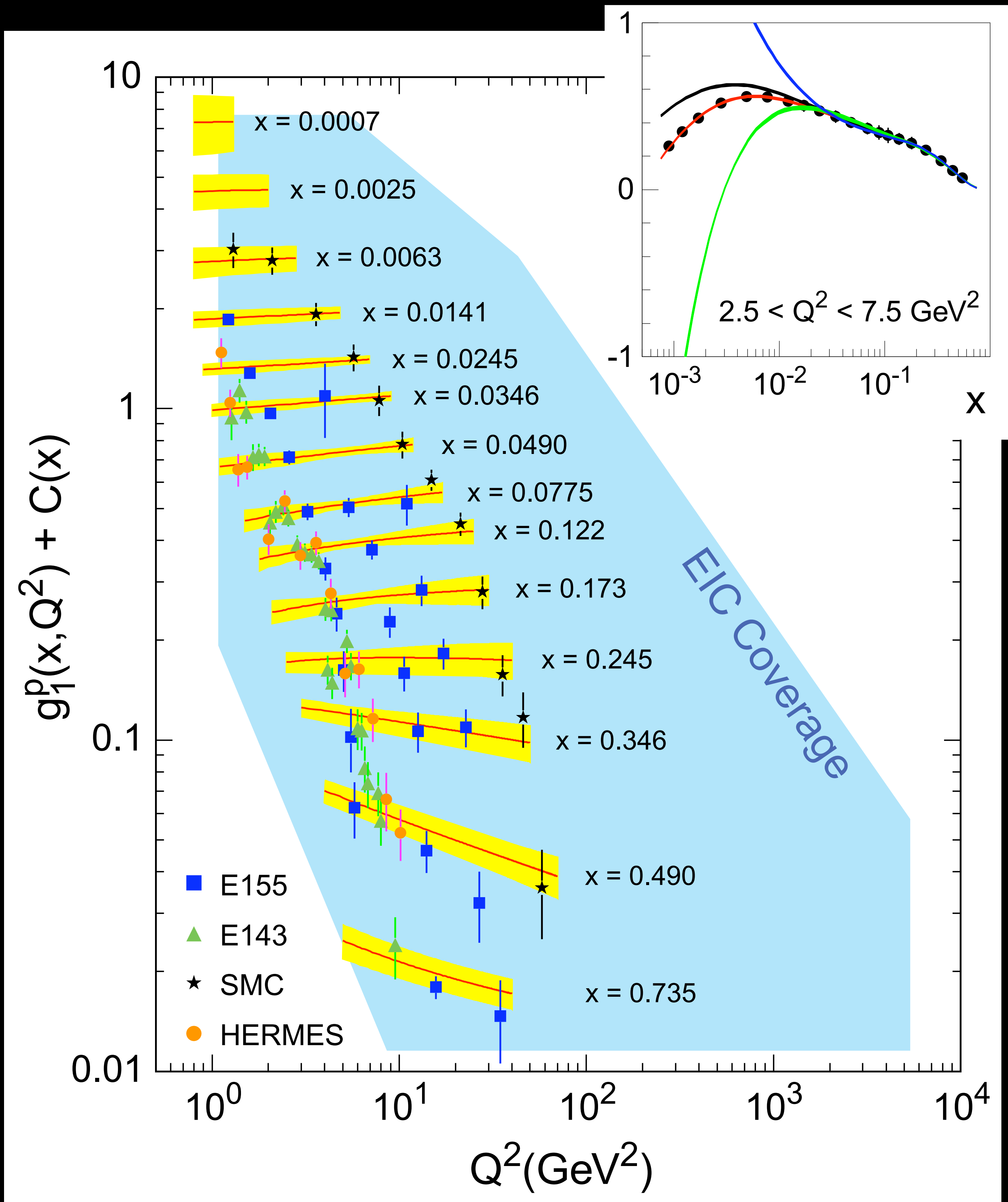
e+A	Polarized e+p
• Study the Physics of Strong Color Fields – Establish (or not) the existence of the saturation regime and its properties – Explore non-linear QCD – Measure momentum & space-time of glue • Study the nature Pomerons • Test and study the limits of universality	• Precisely image the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon

- 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)

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

Additional Slides

Spin Physics at the EIC



Spin Structure of the Proton

½ = ½ ΔΣ + ΔG + L_q + L_g

quark contribution ΔΣ ≈ 0.3

gluon contribution ΔG ≈ -0.2 ± 0.7

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

Measure through scaling violation:

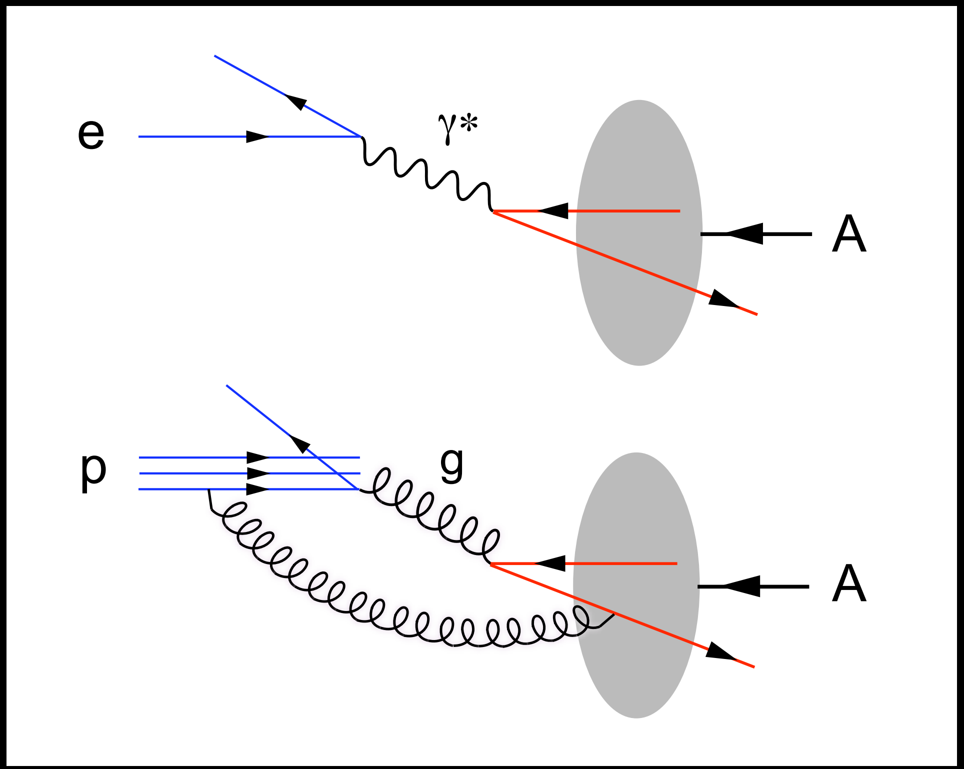
$$\frac{dg_1}{dlogQ^2} \propto -\Delta g(x, Q^2)$$

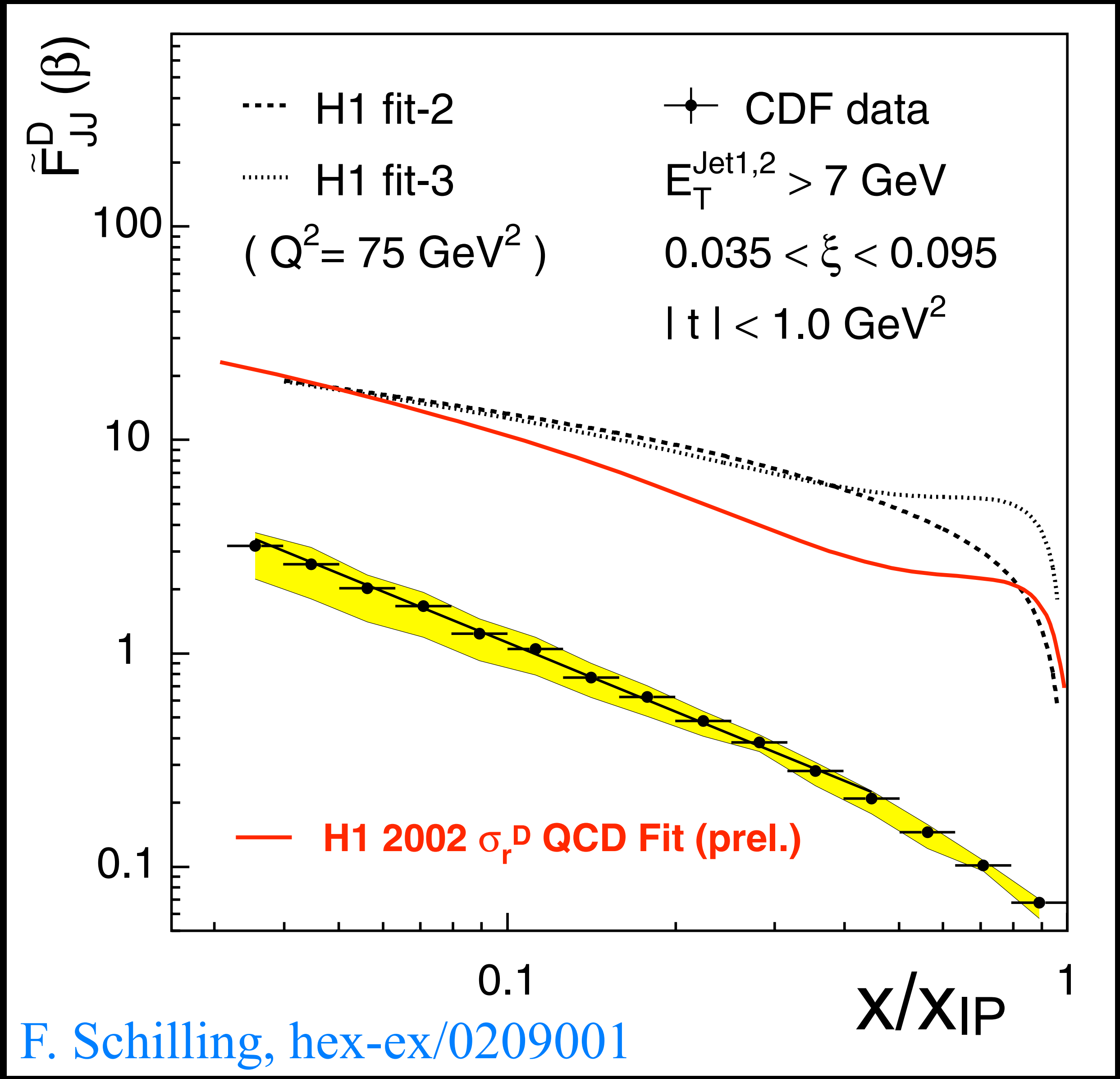
$$\Delta G = \int_{x=0}^{x=1} \Delta g(x, Q^2) dx$$

Superb sensitivity to Δg at small x!

Connection to *p*+A

- *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 access to x, Q^2
  - *G* from *p*+A ? (model dependent)





e+*p* HERA versus *p*+*p* Tevatron
⇒ Breakdown of *factorization* seen for diffractive final states

The EIC and the LHeC

EIC: $L > 1x10^{33}$ $cm^{-2}s^{-1}$
E_{cm} = 20 - 100 GeV

- Variable energy range
- Polarized and heavy ion beams
- High luminosity in energy region of interest for nuclear science

Nuclear science goals:

- Explore the new QCD frontier: strong color fields in nuclei
- Precisely image the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon.

LHeC: $L = 1.1x10^{33}$ $cm^{-2}s^{-1}$
E_{cm} = 1.4 TeV

- Add 70-100 GeV electron ring or Linac to interact with LHC ion beam
- Use LHC-B or ALICE IR
- High luminosity mainly due to large γ's (= E/m) of beams

High-Energy physics goals:

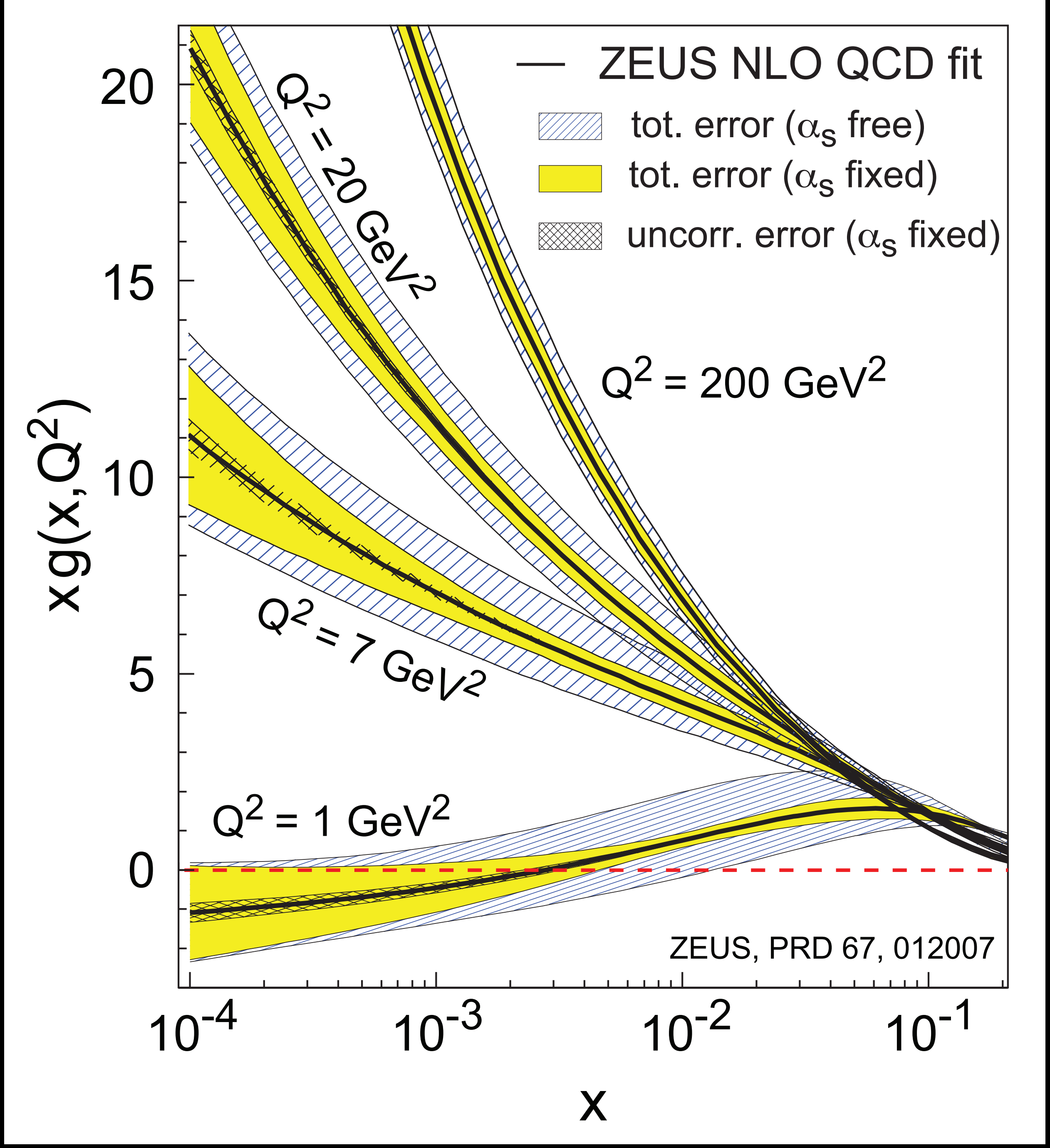
- Parton dynamics at the TeV scale
  - physics beyond the Standard Model
  - physics of high parton densities (low x)

Important cross fertilization of ideas:
Significant European interest in an EIC
EIC collaborators on LHeC Science Advisory Committee
(with Research Directors of CERN, FNAL, DESY)

Why Hera did not do EIC Physics

- eA physics:
  - Up to Ca beams considered (Hera III)
  - Low luminosity (1000 compared to EIC)
  - Would have needed ~$100M to upgrade the source to have more ions, but still the low luminosity
- Polarized e-p physics
  - HERA-p ring is not planar
  - No. of Siberian snake magnets required to polarize beam estimated to be 6-8: Not enough straight sections for Siberian snakes and not enough space in the tunnel for their cryogenics
  - Technically difficult
- DESY was a HEP laboratory focused on the high energy frontier (Tesla).

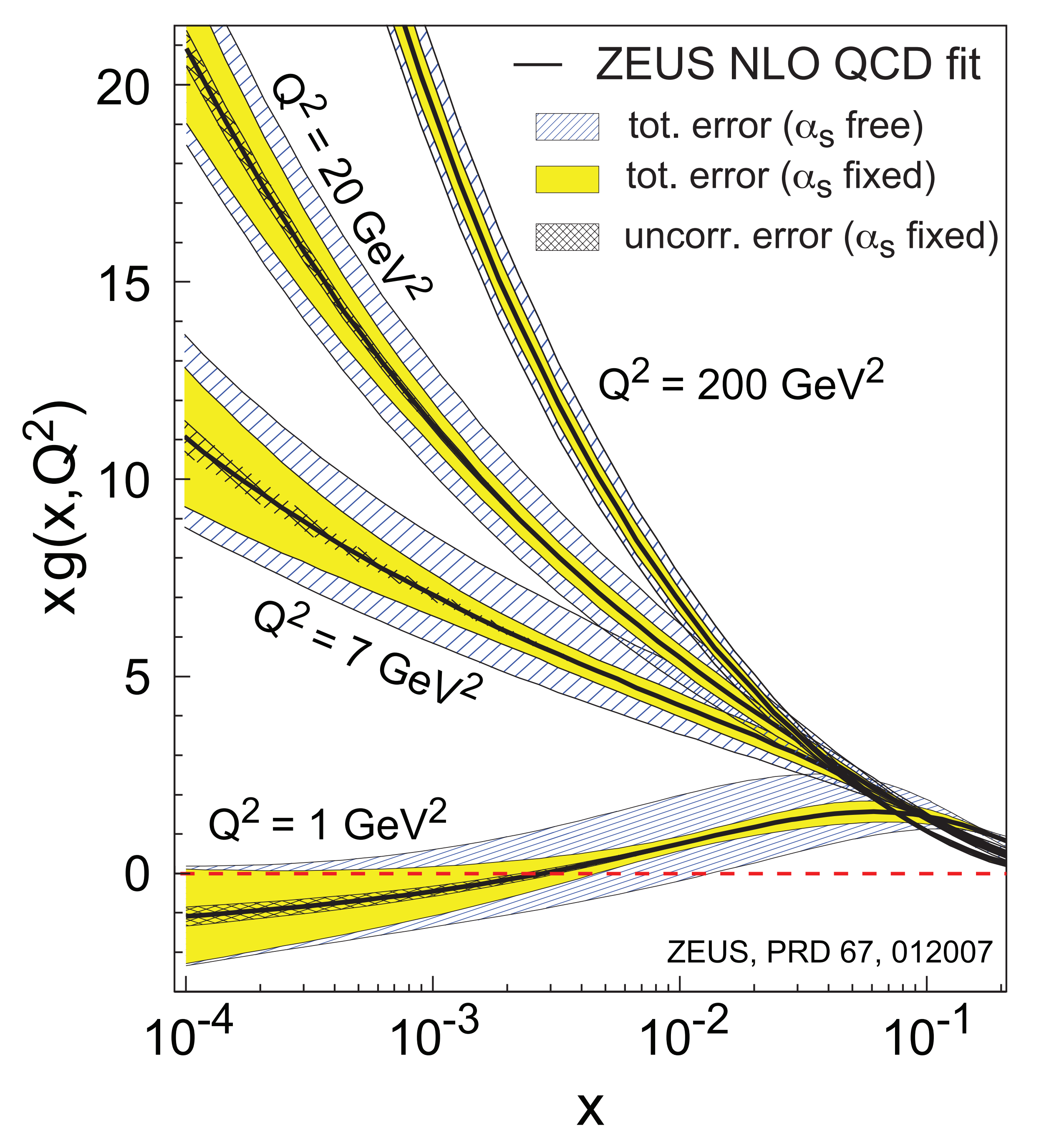
Issues With Our Understanding



Established Model:

- Linear **DGLAP** evolution scheme
  - Weird behavior of xG at small x, Q^2
  - Could signal saturation, higher twist effects, need for more/better data?
  - Unexpectedly large diffractive cross-section

Issues With Our Understanding



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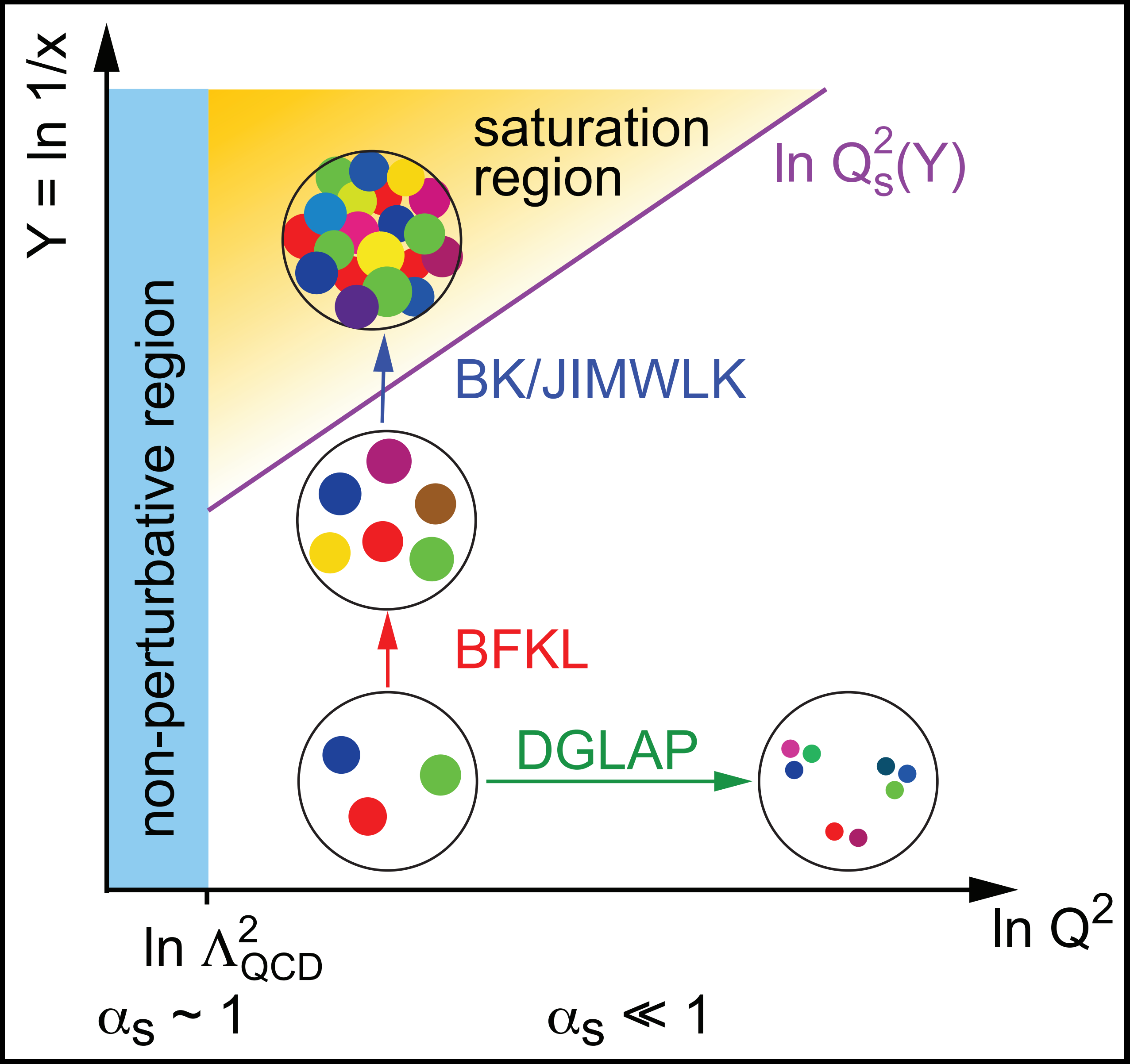
more severe:

- Linear Evolution has a built in high energy "catastrophe"
  - xG rapid rise for decreasing x and violation of (Froissart) unitary bound

$\Rightarrow$ *must tame growth* (**saturate**)

- Underlying dynamics?

New Approach: Non-Linear QCD

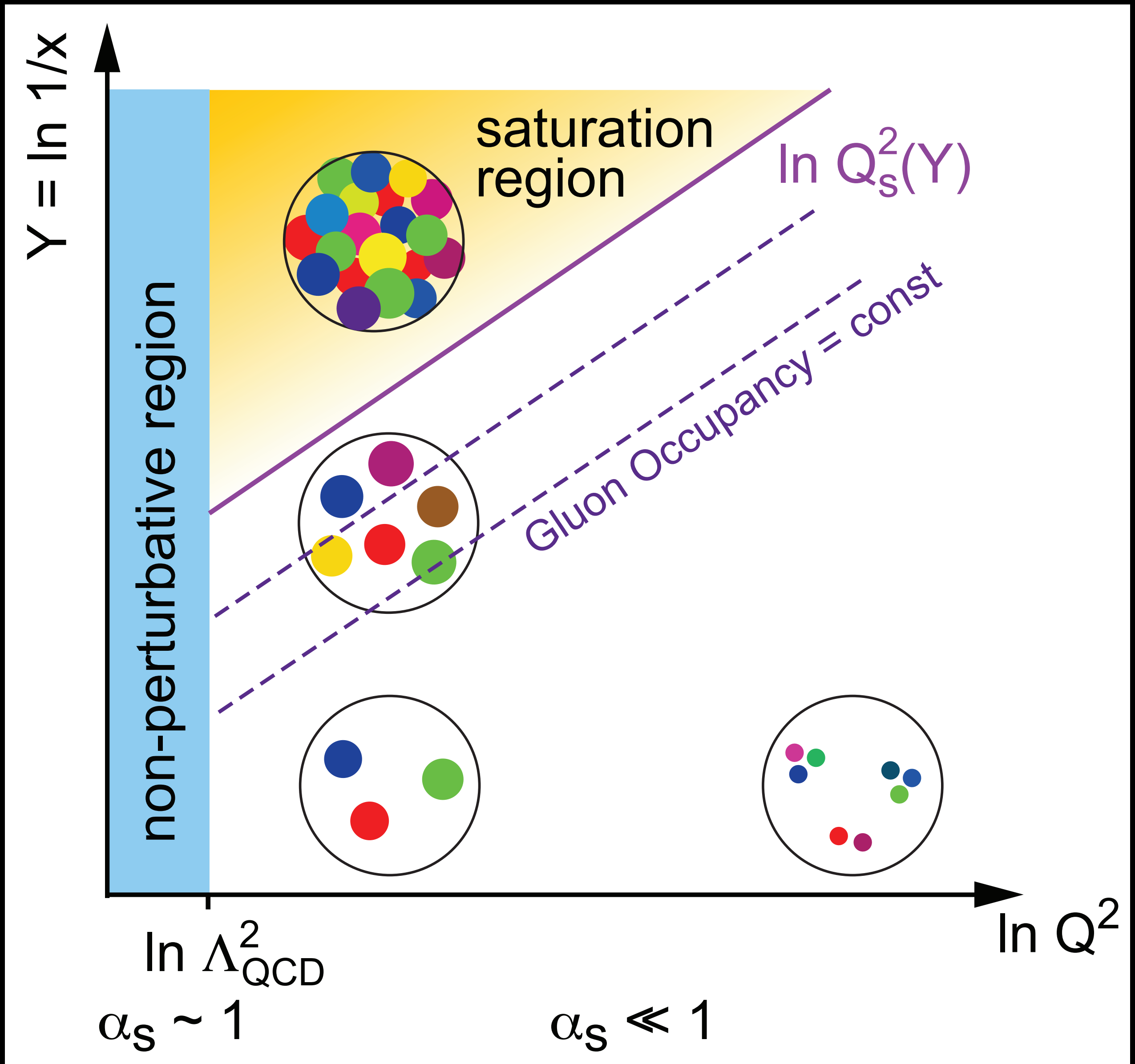


BK/JIMWLK: *non-linear* effects

$\Rightarrow$ **saturation**

- characterized by $\boldsymbol{Q_s(x,A)}$
- believed to have properties of a *Color Glass Condensate*

New Approach: Non-Linear QCD



Consequence of non-linear evolution:

- Physics invariant along trajectories parallel to saturation regime
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately

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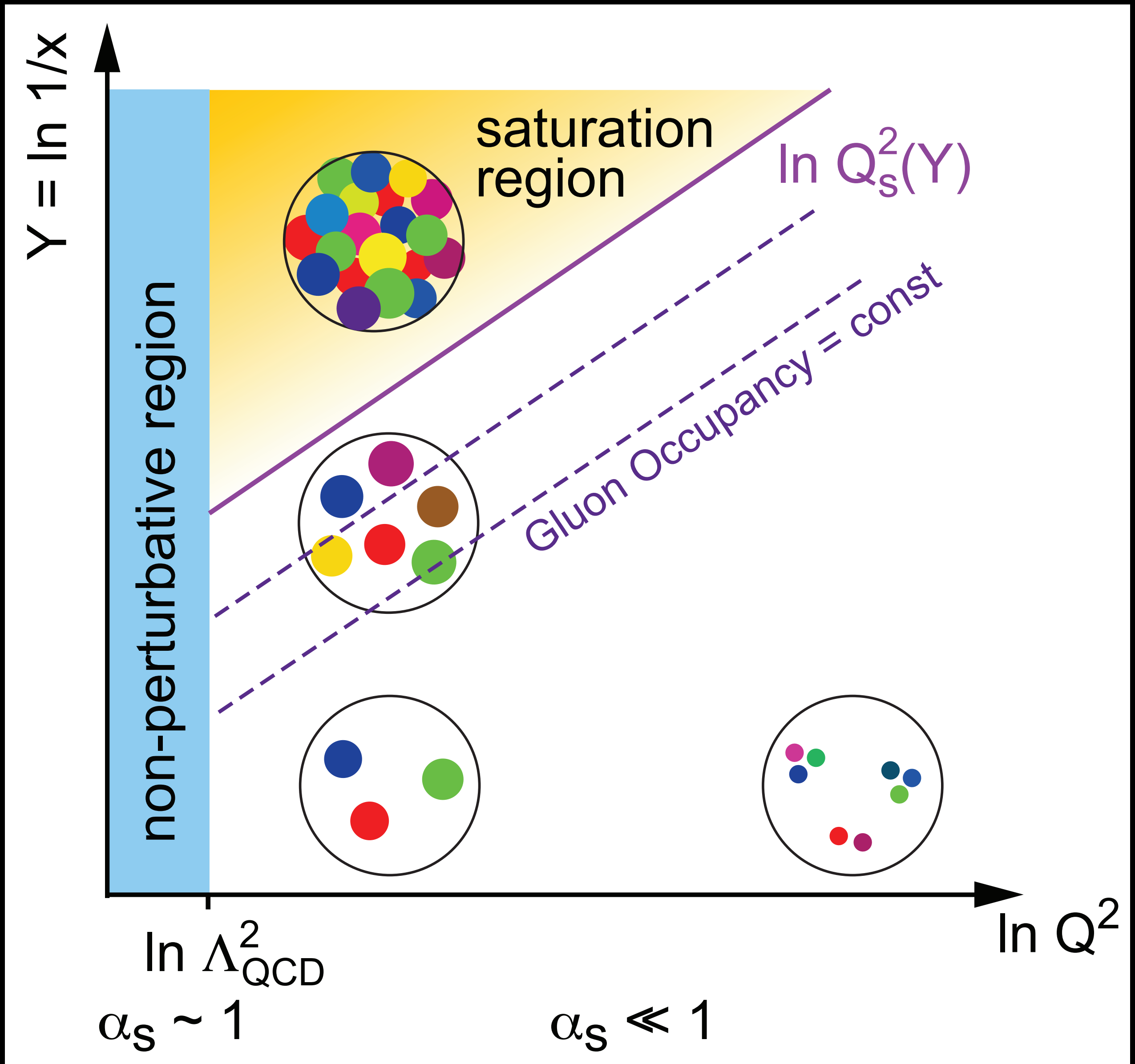

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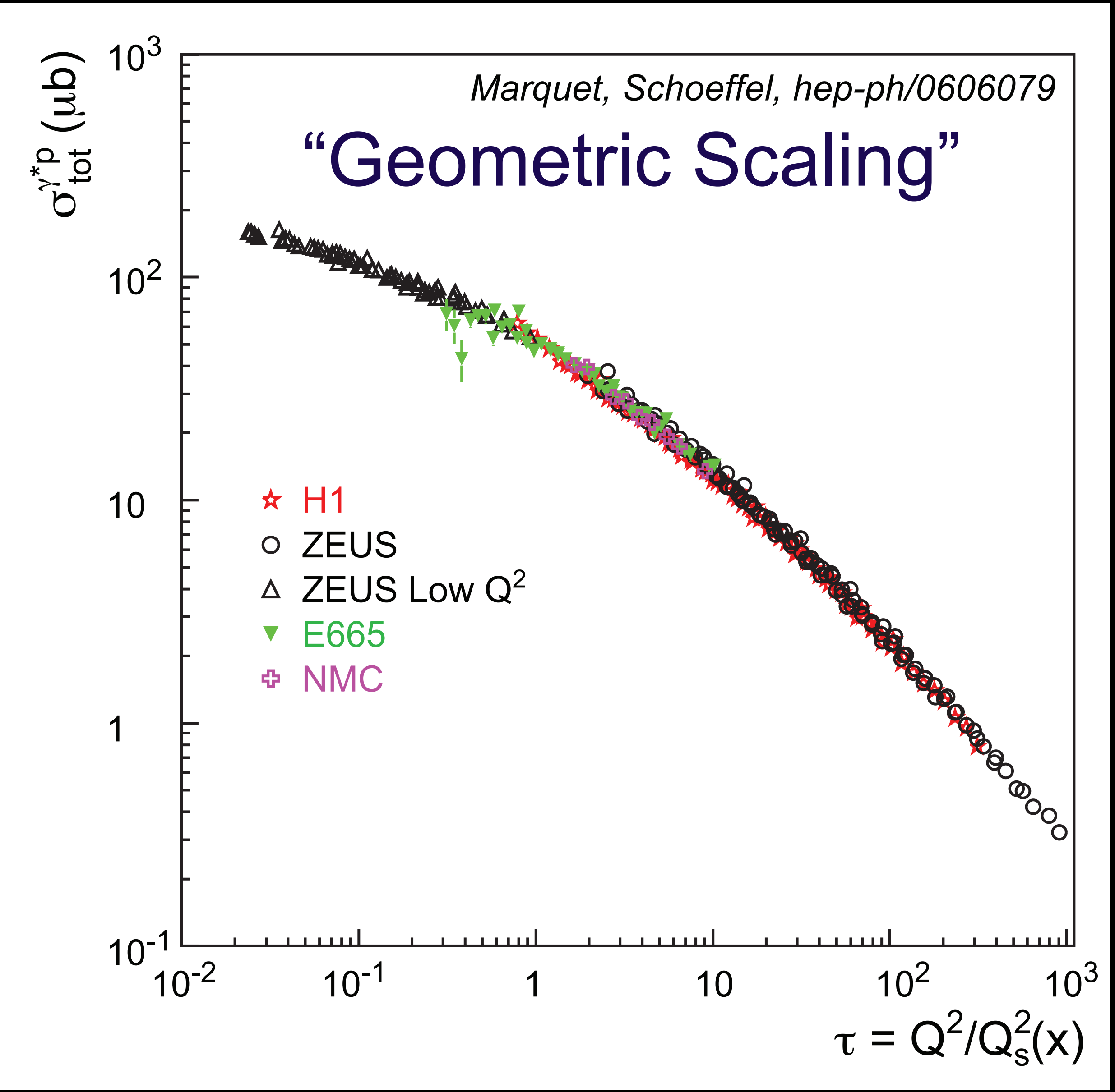

BK/JIMWLK: *non-linear* effects

⇒ **saturation**

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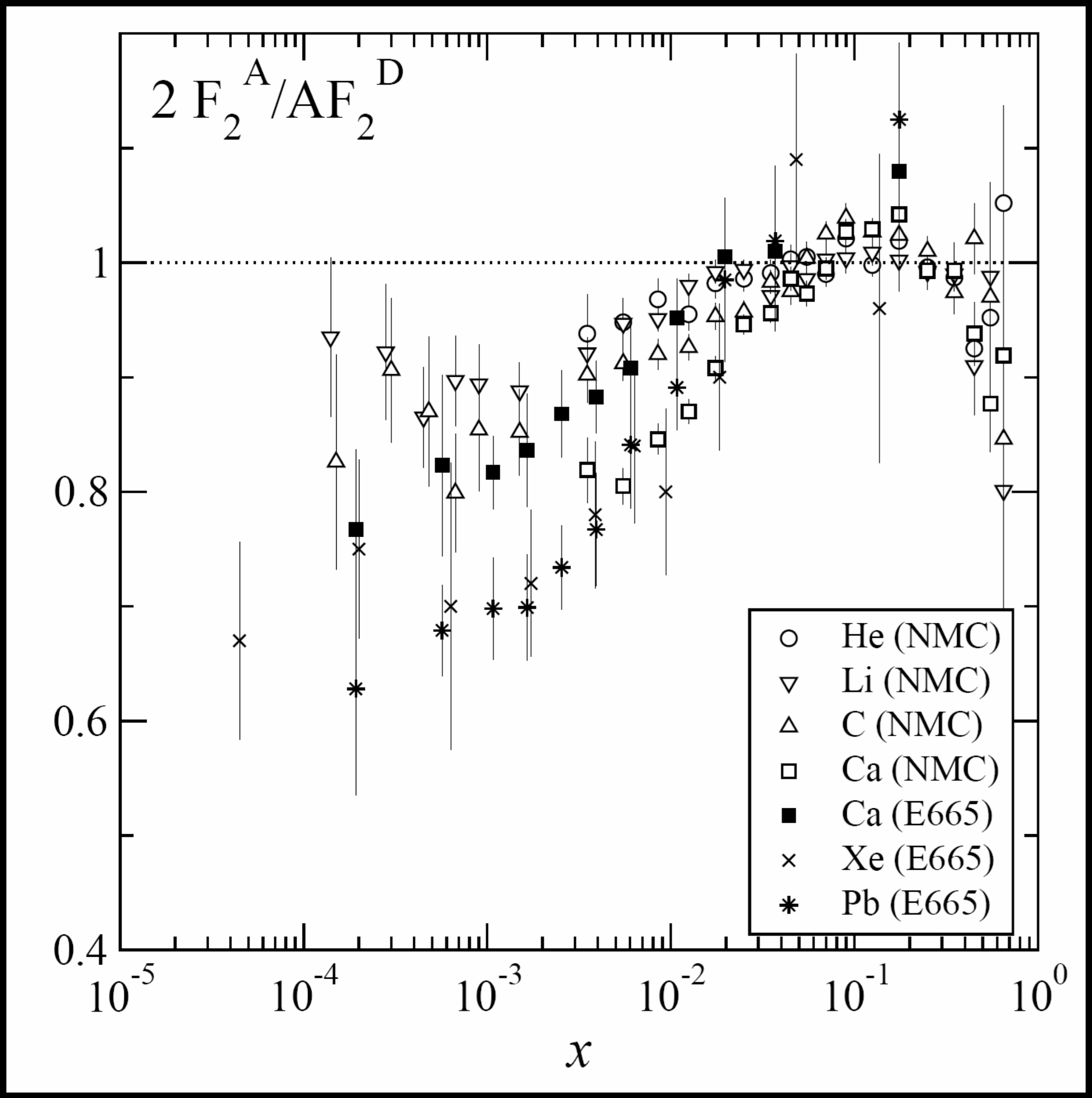
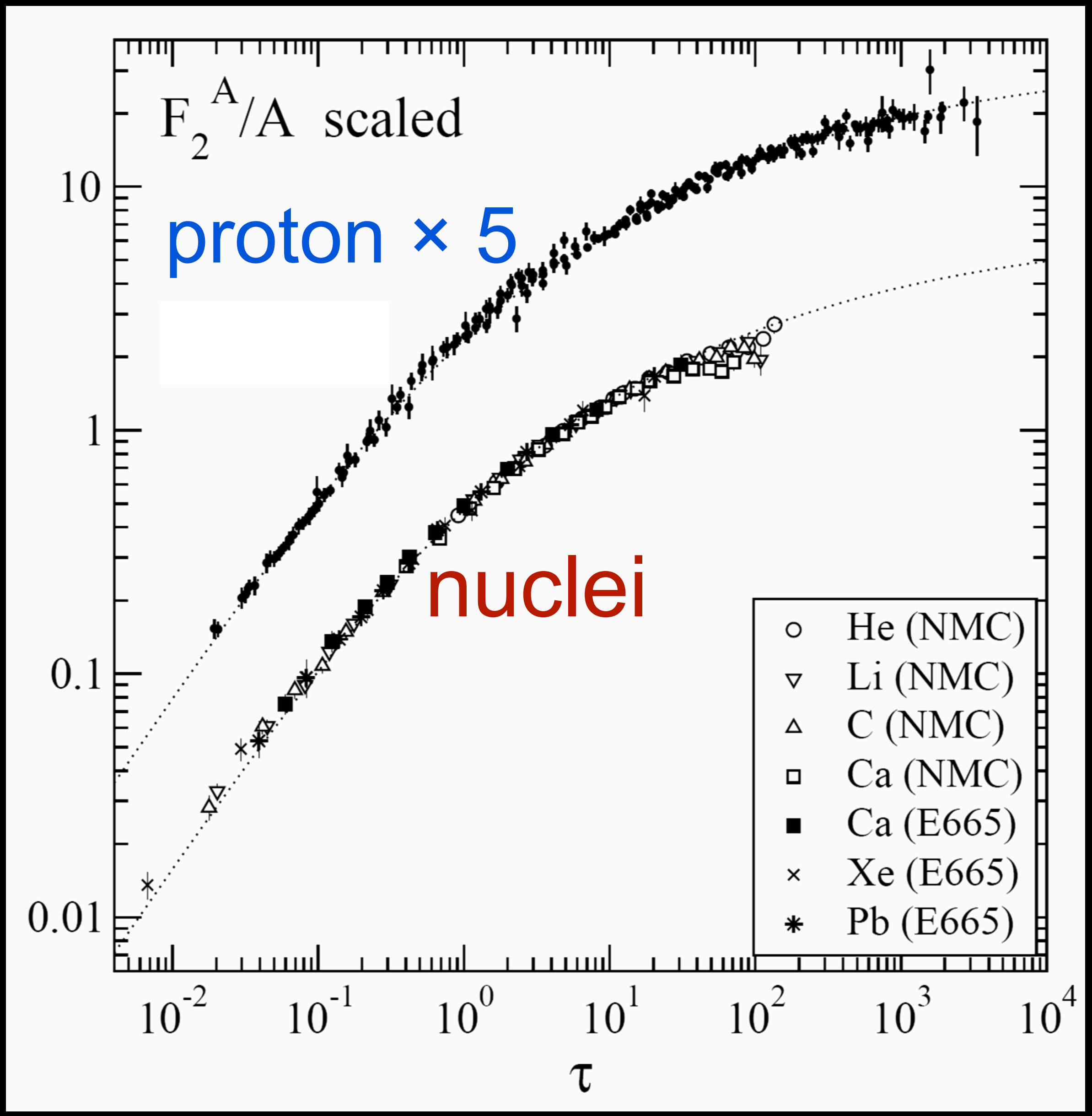
Q_s - A Scale that Binds them All ?

Nuclear shadowing:



Freund et al., hep-ph/0210139

Geometrical scaling



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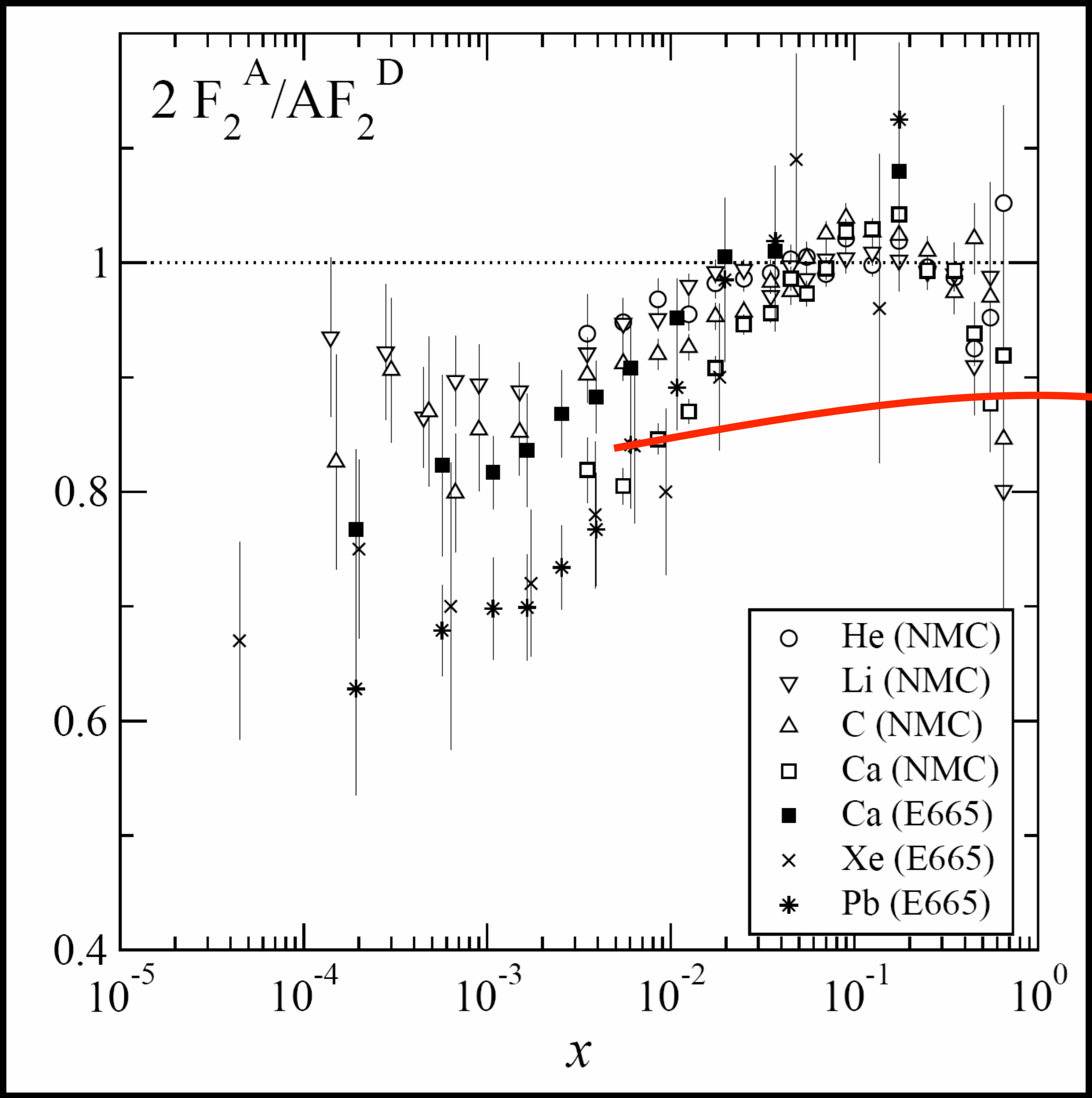

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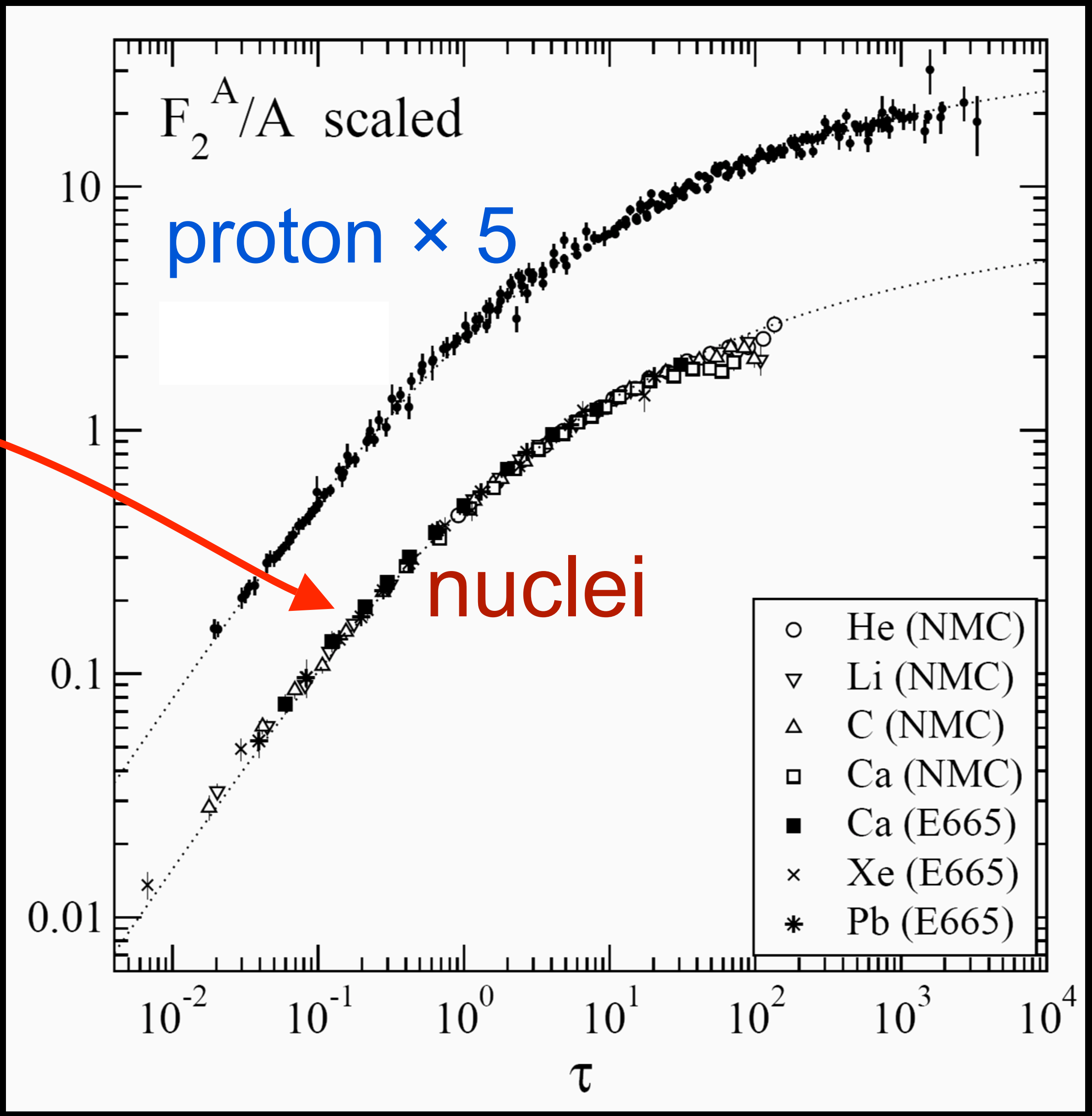
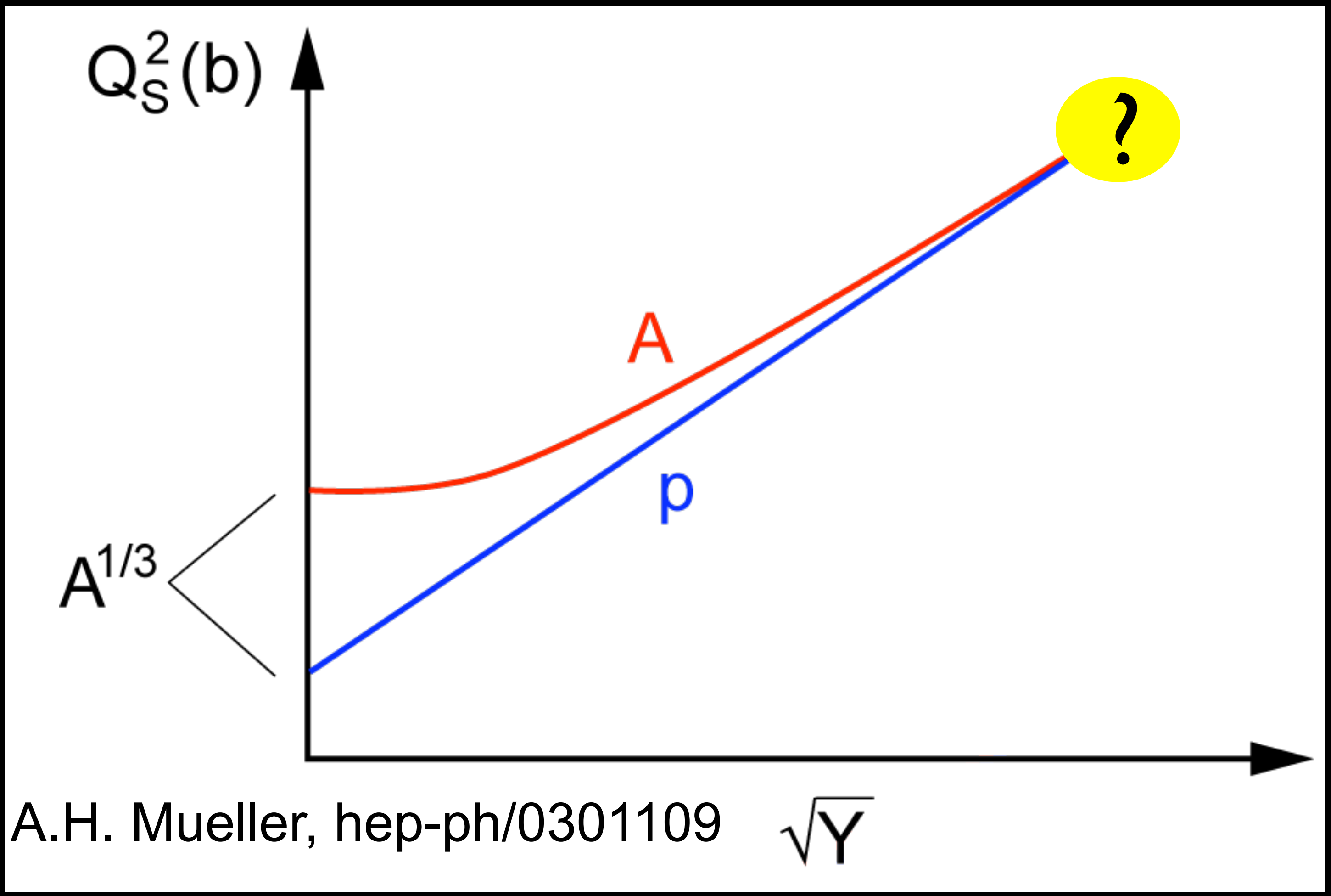


Are hadrons **and** nuclei wave function universal at low-*x* ?

A Truly Universal Regime ?



Small *x* QCD evolution predicts:

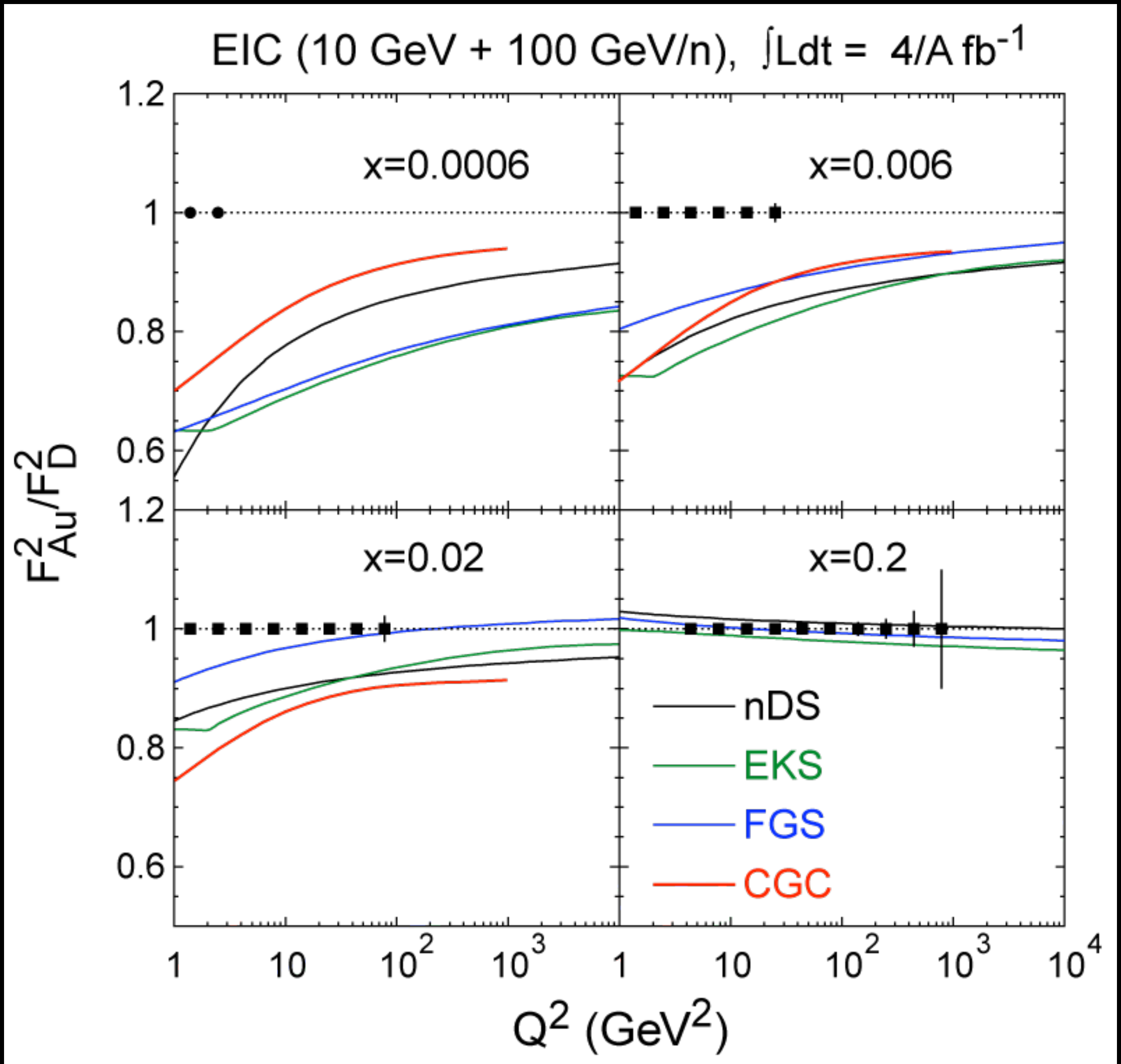
Q_S approaches *universal* behavior for *all* hadrons and nuclei

⇒ Not only functional form f(Qs) universal but even Qs becomes the same

Radical View:

Nuclei and all hadrons have a component of their wave function with the *same* behavior.
This is a conjecture! Needs to be tested.

F_2: Sea (Anti)Quarks Generated by Glue



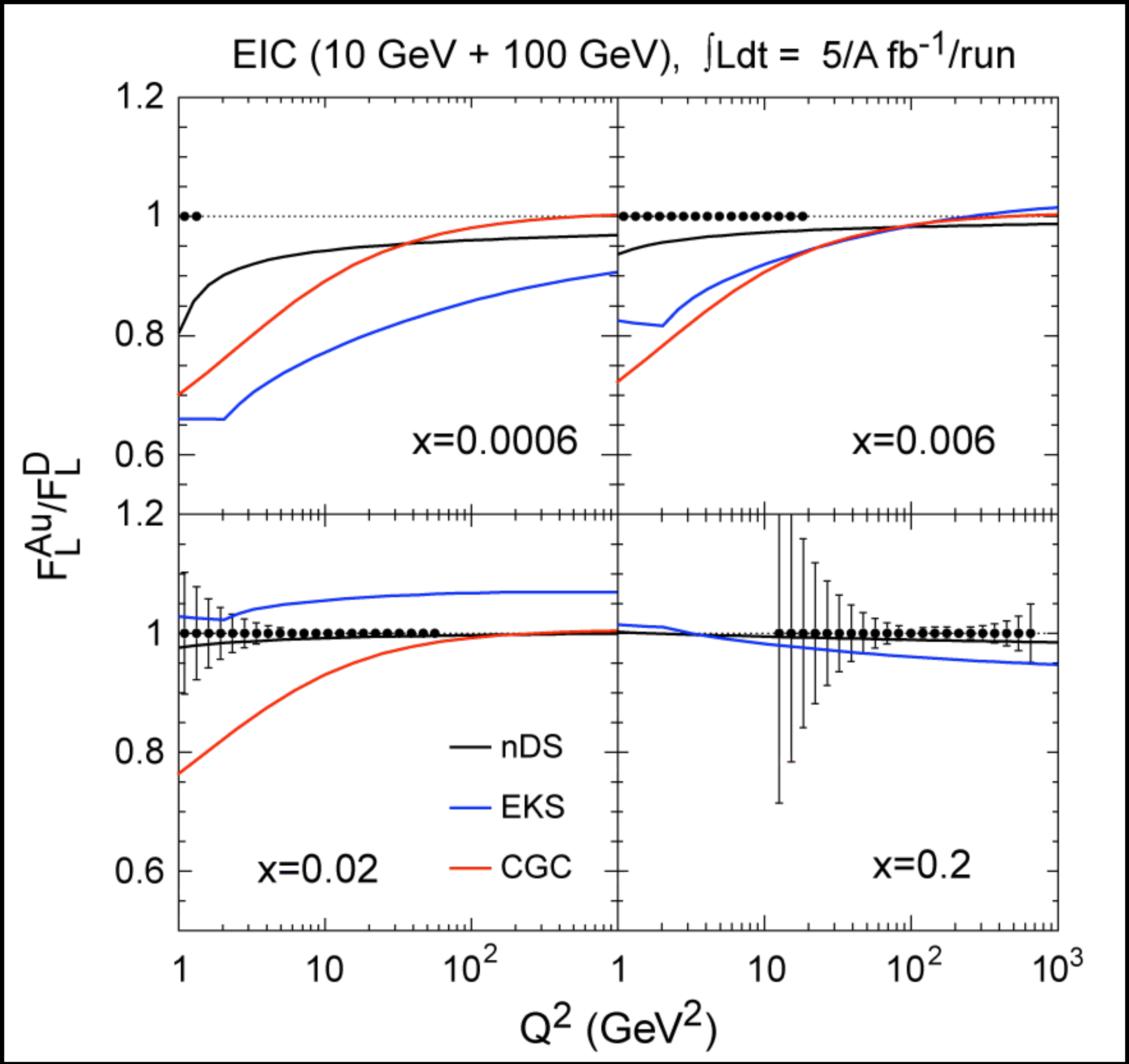
F_2 will be one of the first measurements at EIC

nDS, EKS, FGS:
pQCD based models with different amounts of shadowing

Syst. studies of $F_2(A, x, Q^2)$:
⇒ $G(x,Q^2)$ with precision
⇒ distinguish between models

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

F_L at EIC: Measuring the Glue



F_L requires $\sqrt{s}$ scan

$Q^2/xs = y$

Here:

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

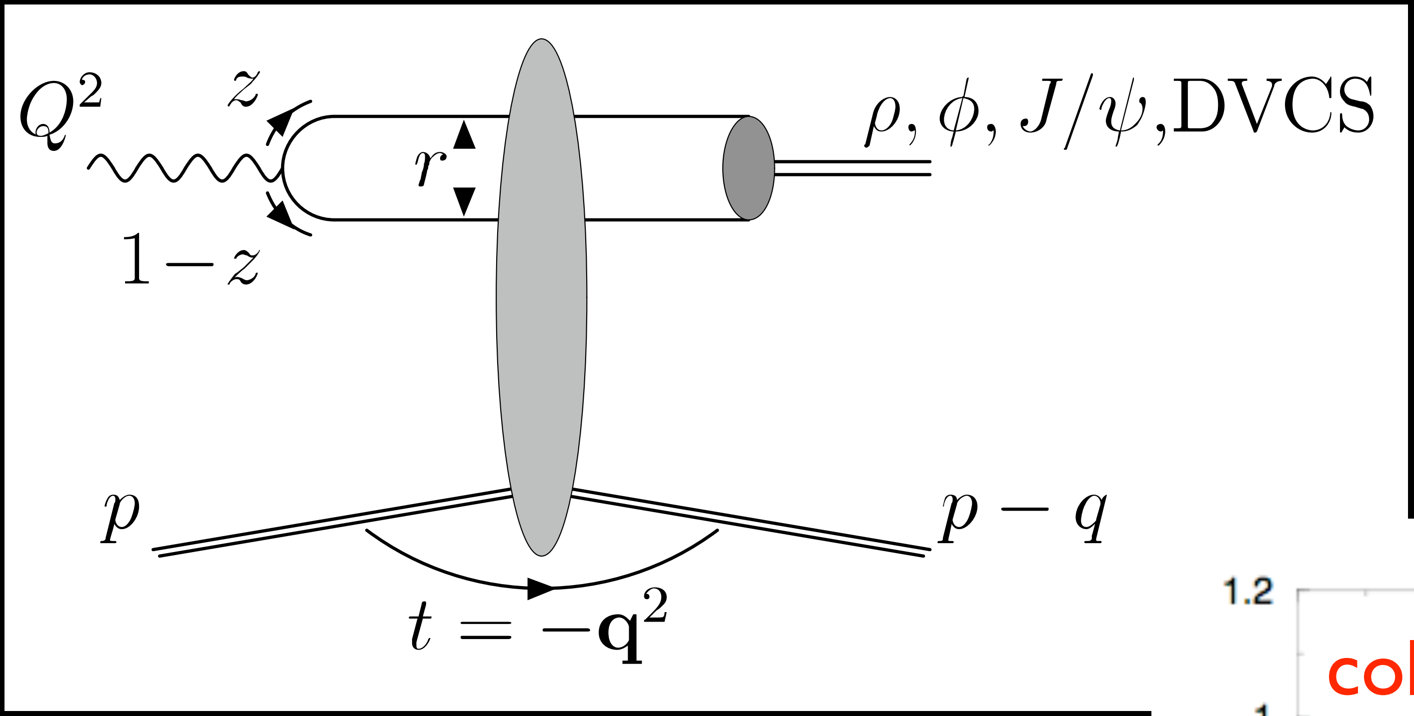
statistical error only

nDS and EKS are "standard" shadowing parameterizations that are evolved with DGLAP

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

Vector Meson Production

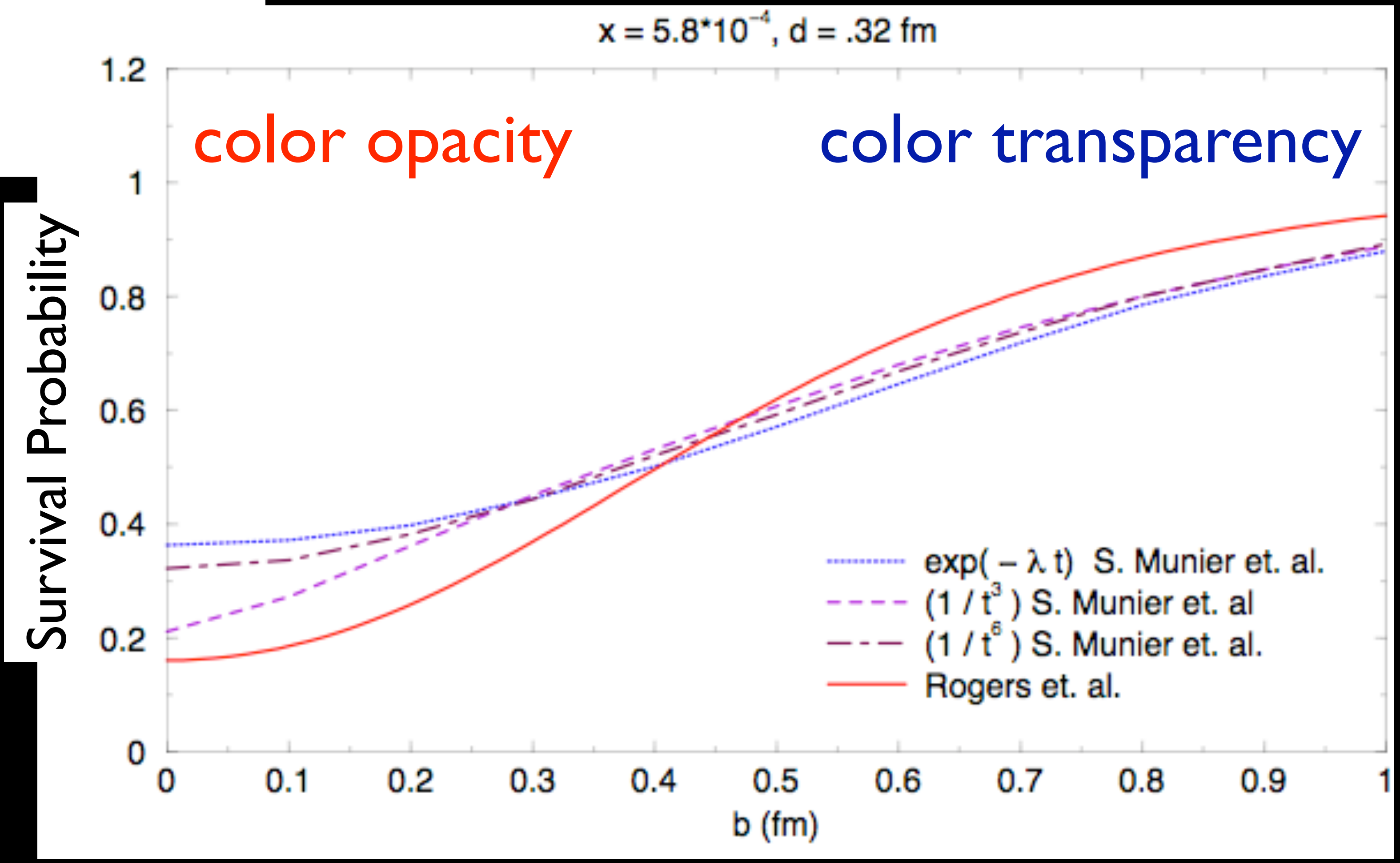
"color dipole" picture



$$\sigma_{q\bar{q},N}(E_{inc}) = \frac{\pi^2}{3} r_t^2 \alpha_s(Q^2) x g_N(x, Q^2)$$

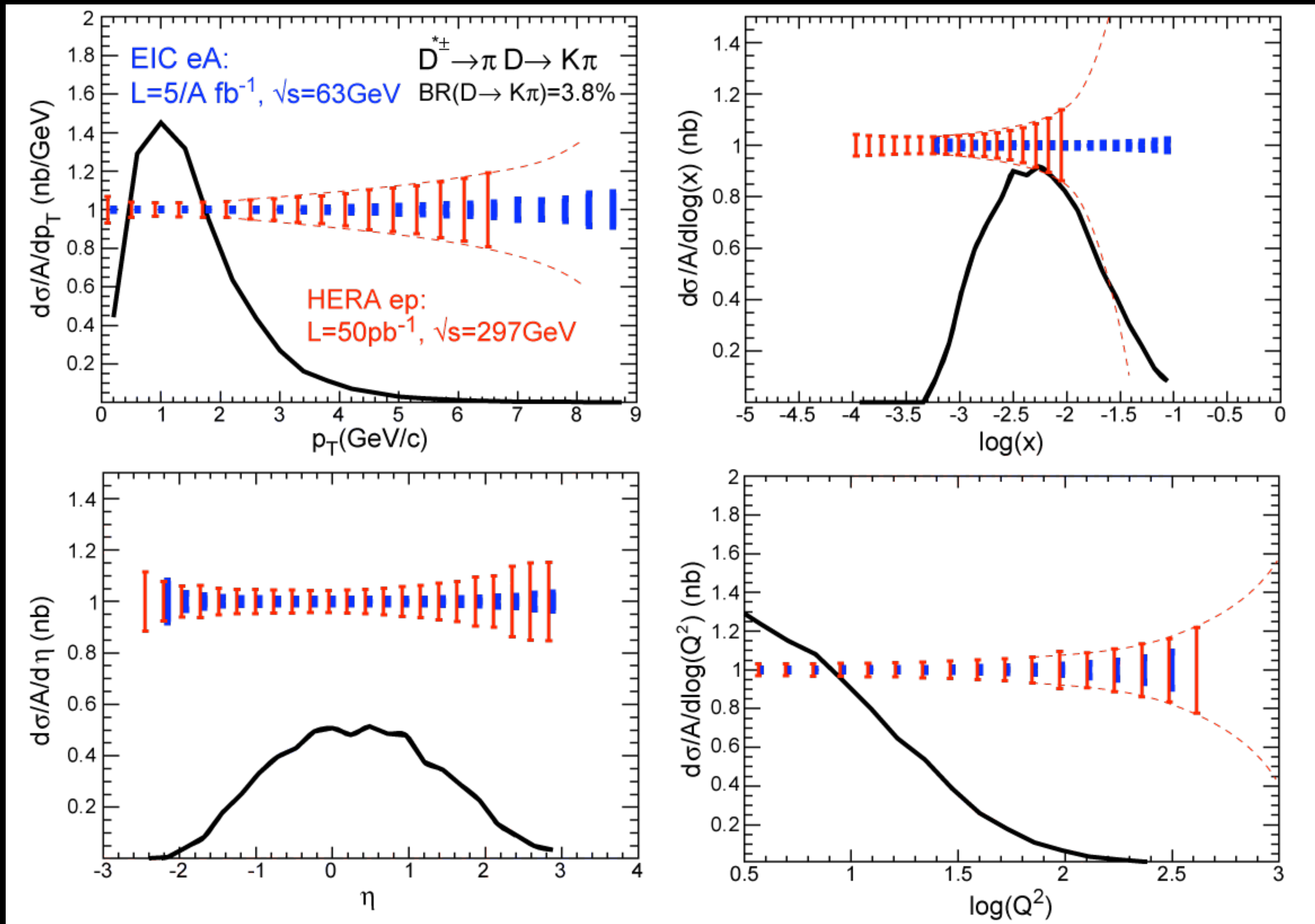
HERA: Survival prob. of vector mesons ($q\bar{q}$ pair) as fct. of b extracted from elastic vector meson production (Munier curve: ρ0, Rogers: J/ψ)

Strong gluon fields in center of p at HERA ($Q_s \sim 0.5$ GeV^2)?



Note: b profile of nuclei more uniform and $Q_s \sim 2$ GeV^2

Charm at EIC

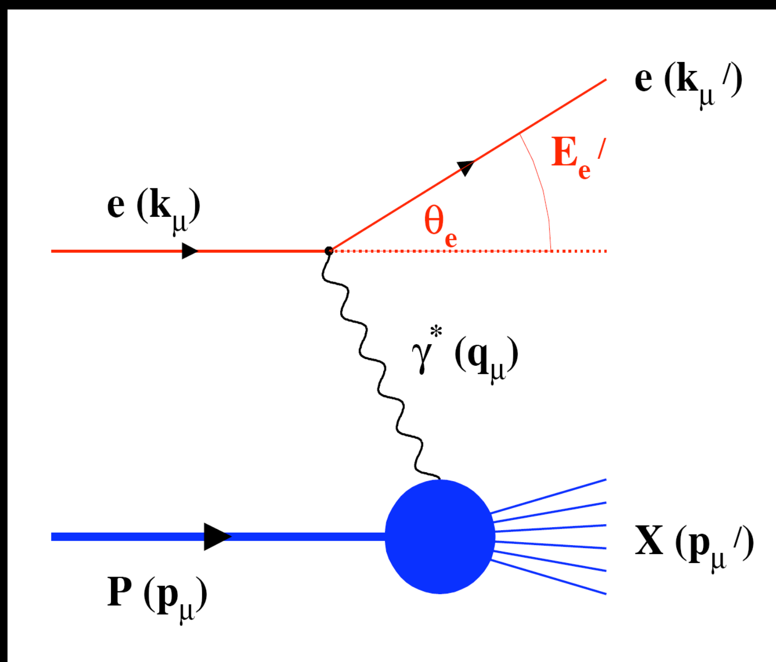


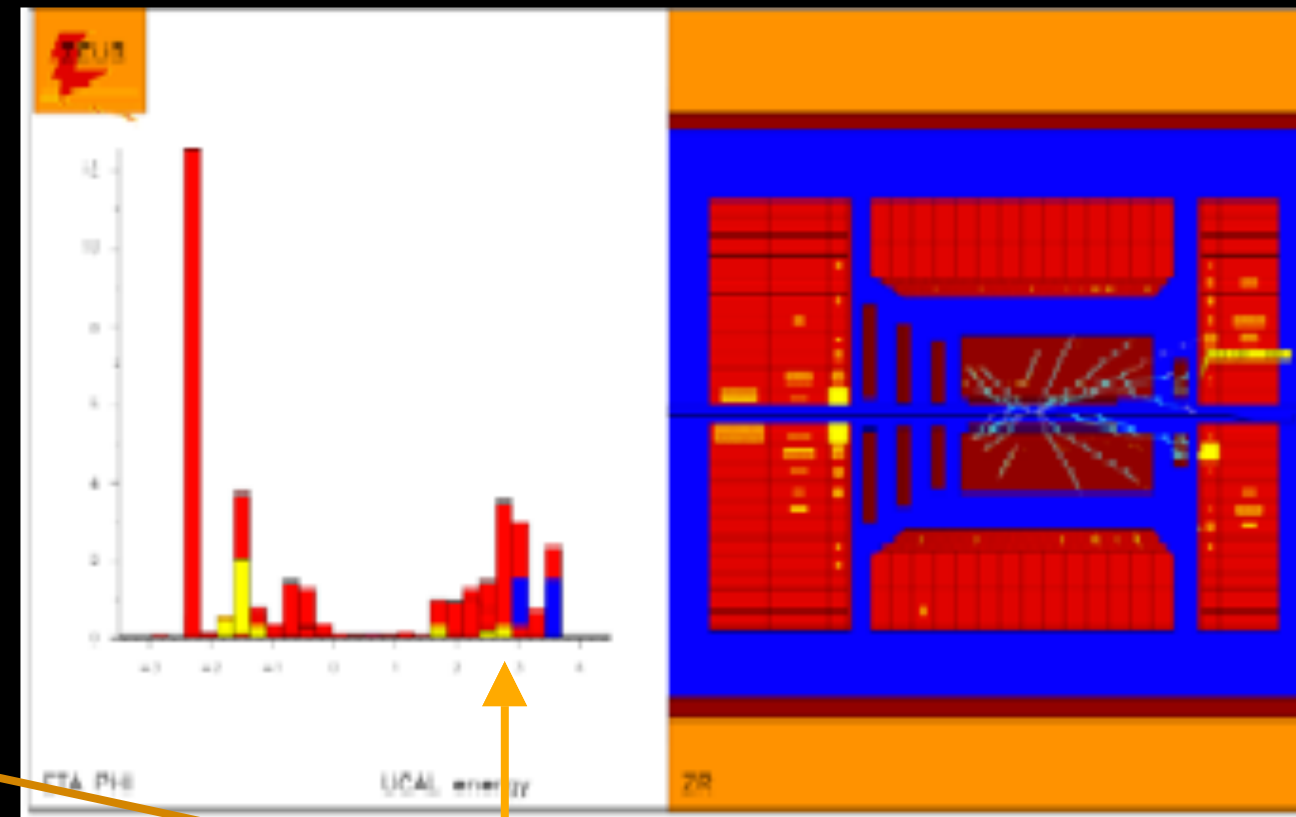
Based on HVQDIS model, J. Smith

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

Diffractive Physics in *e*+A

‘Standard DIS event’

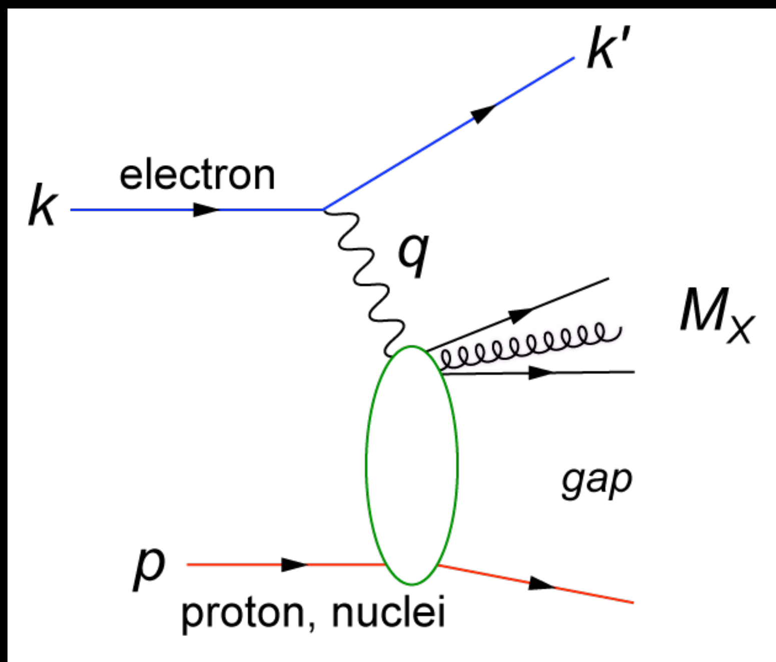


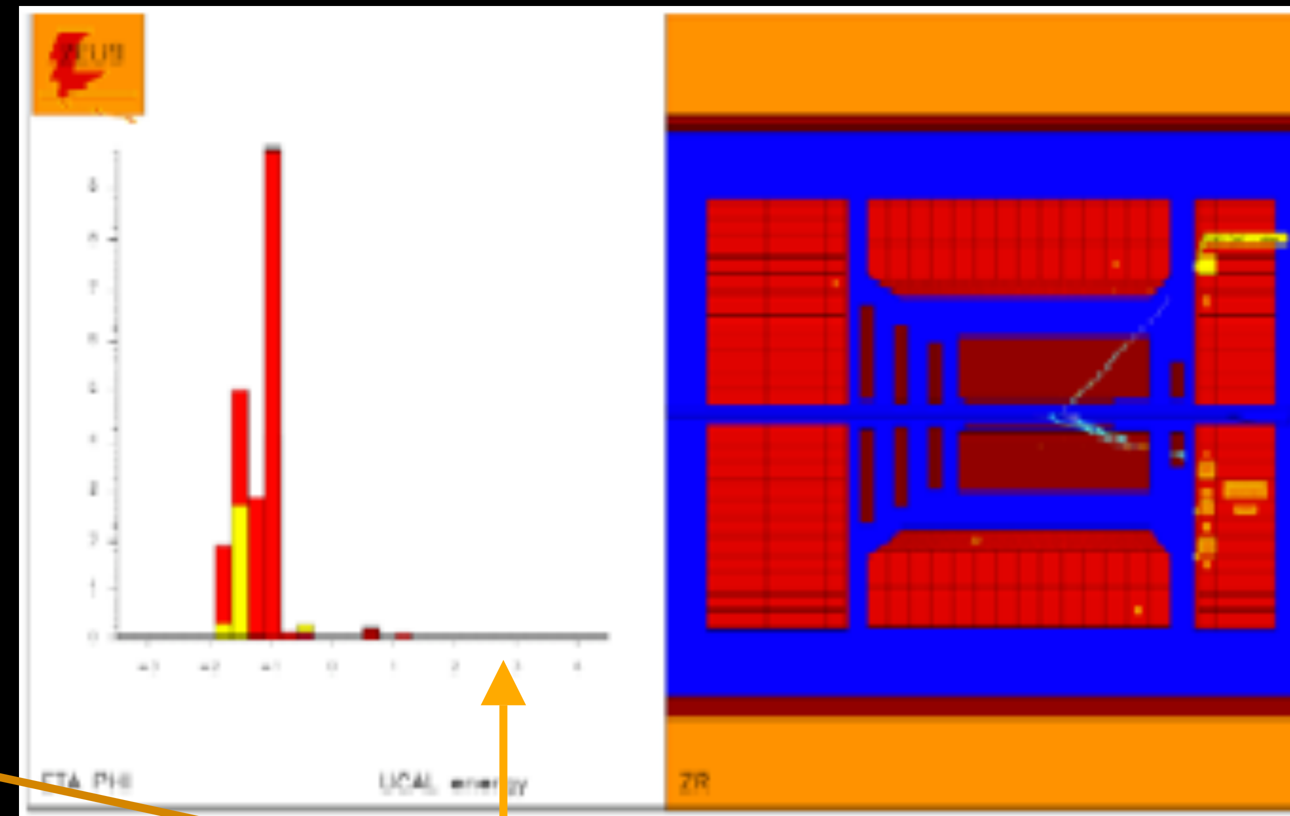


Activity in proton direction

Diffractive Physics in *e*+A

Diffractive event

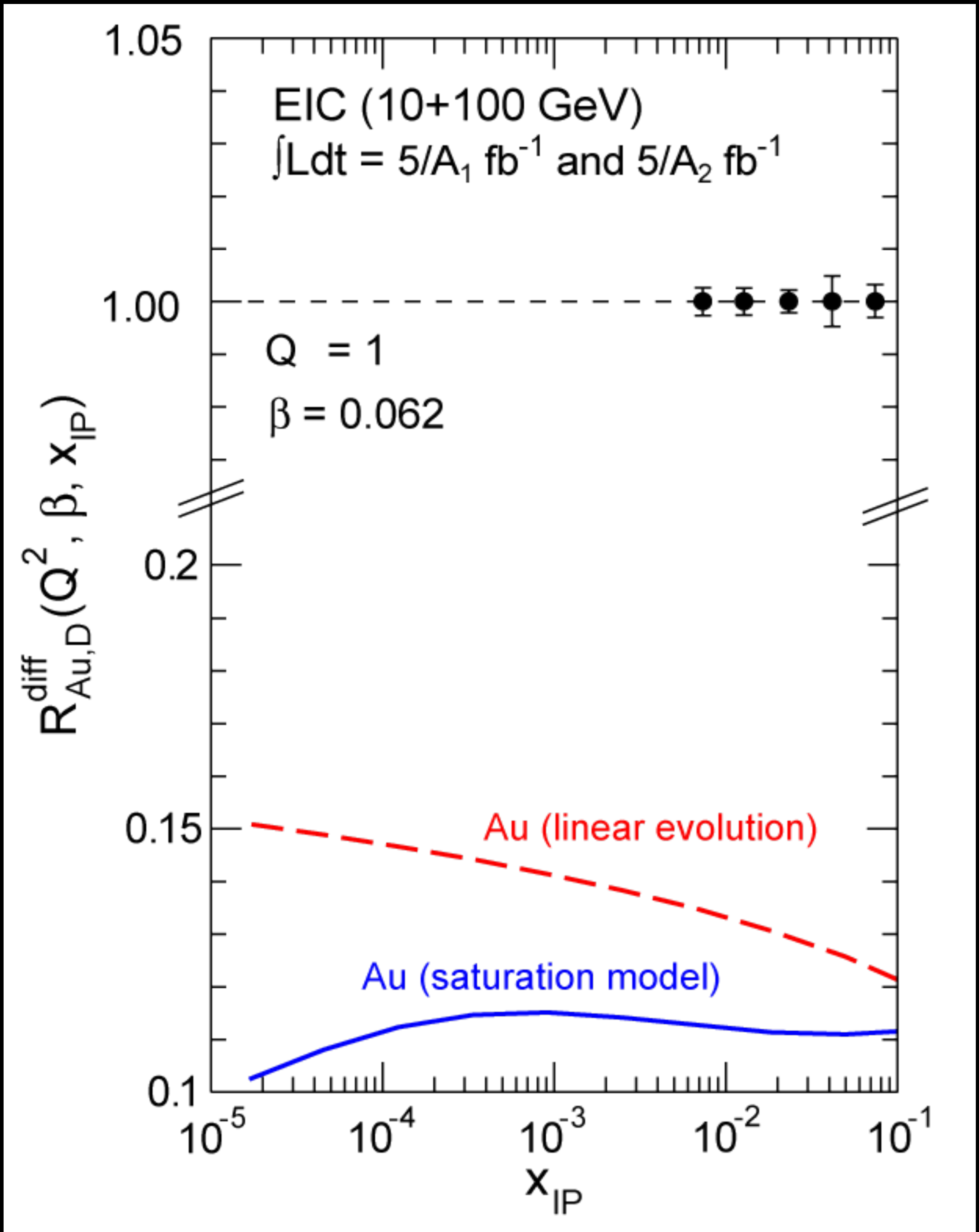




Activity in proton direction

- HERA/ep: 15% of all events are hard diffractive
- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in *e*+A ?
  - Predictions: ~25-40%?
- Look inside the "Pomeron"
  - Diffractive structure functions
  - Diffractive vector meson production ~ $[G(x,Q^2)]^2$

Diffractive Structure Function F_2^D



$$\frac{d^4\sigma^{eA\rightarrow eAX}}{dx\,dQ^2\,d\beta\,dt} = \frac{4\pi\alpha_{e.m}^2}{\beta^2 Q^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2^D - \frac{y^2}{2}F_L^D\right]$$

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

⇒ Distinguish between linear evolution and saturation models
⇒ Insight into the nature of pomeron
⇒ Search for exotic objects (Odderon)

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

Connection to Other Fields