The Emerging QCD Frontier: The Electron Ion Collider

Physics Opportunities with e+A Collisions at the EIC

Thomas Ullrich

MIT

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BROOKHAVEN NATIONAL LABORATORY

Theory of Strong Interactions: QCD

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

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  - Determine essential features of strong interactions
  - Dominate structure of QCD vacuum (fluctuations in gluon fields)
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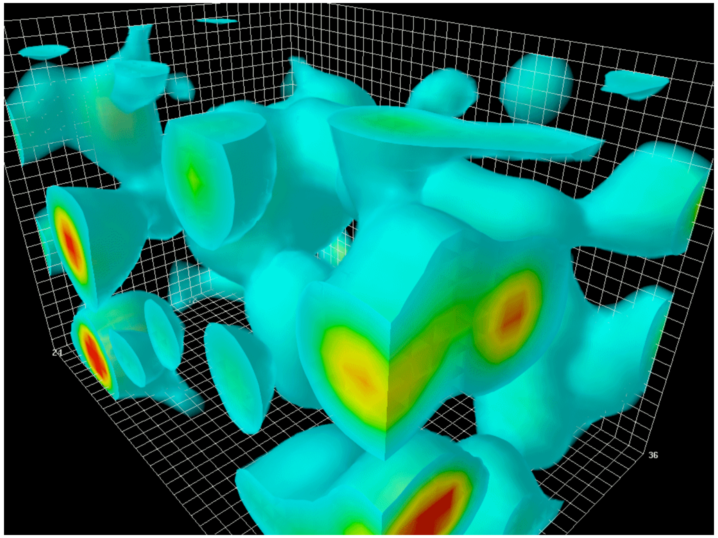

Action (~energy) density fluctuations of gluon-fields in QCD vacuum
(2.4 ×2.4× 3.6 fm)
(Derek Leinweber)

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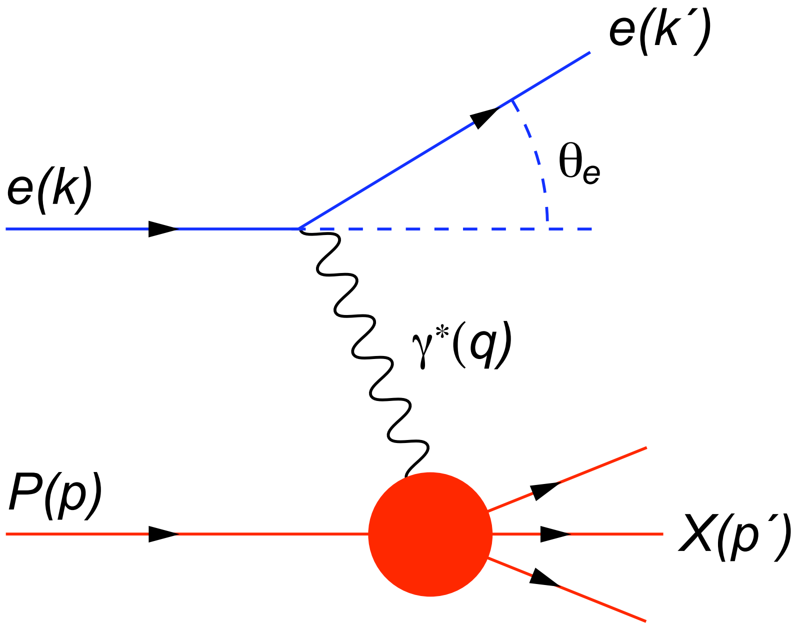
$\Rightarrow$ How to study "glue" ?

How? With Deep Inelastic Scattering Experiments!

Quantitative description of electron-proton scattering



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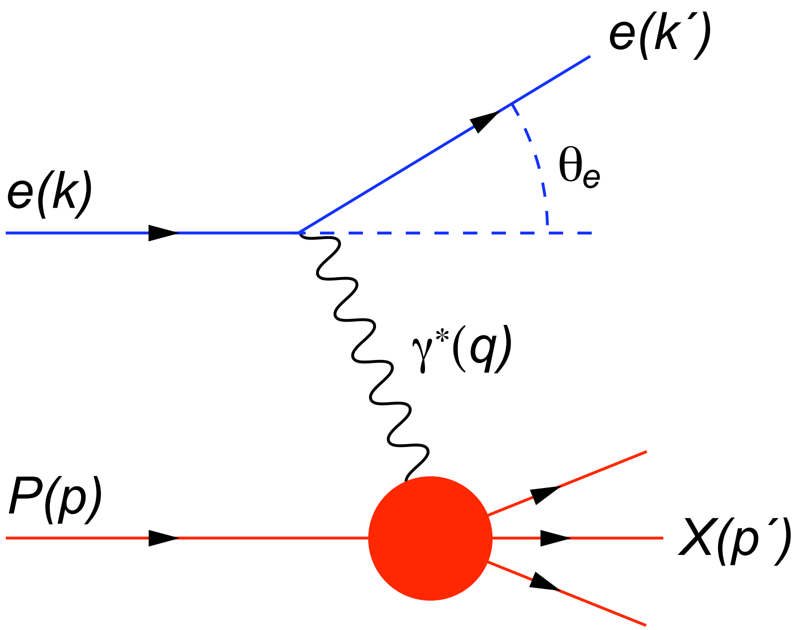

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$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power *or* "Virtuality"

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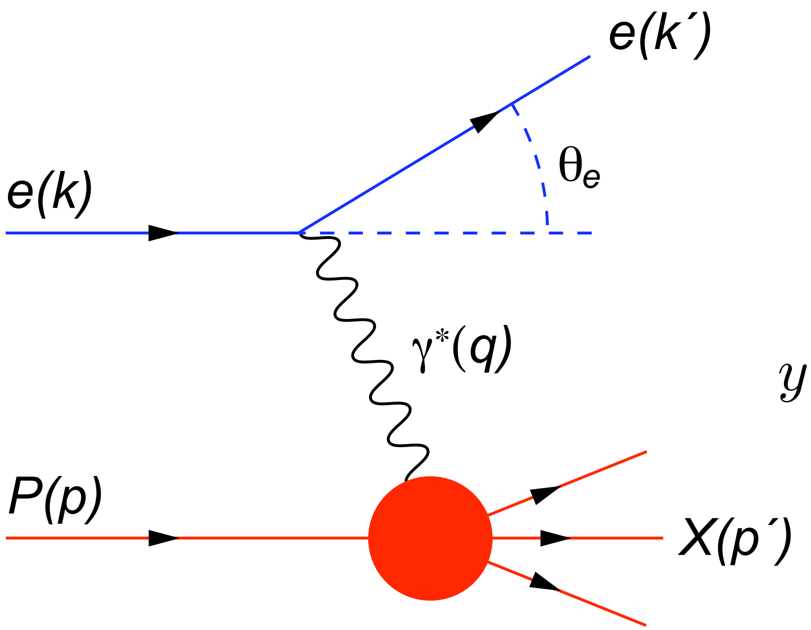

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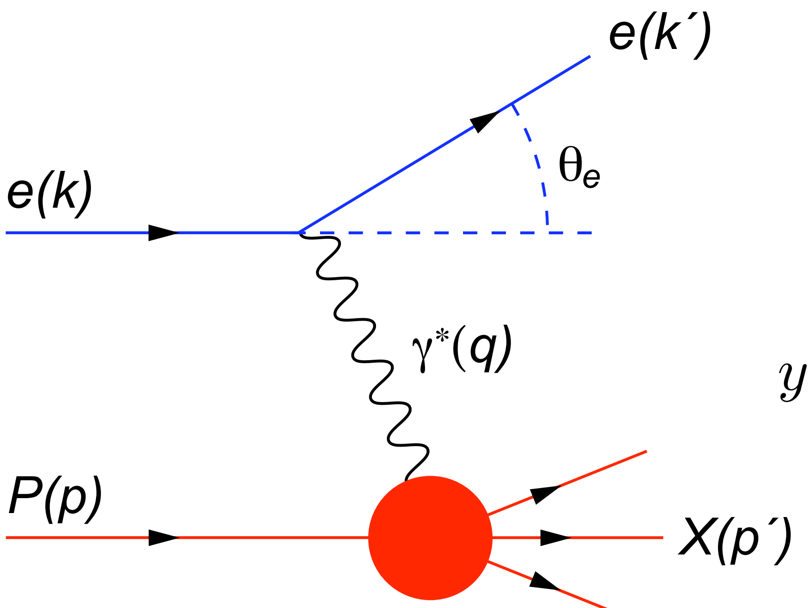

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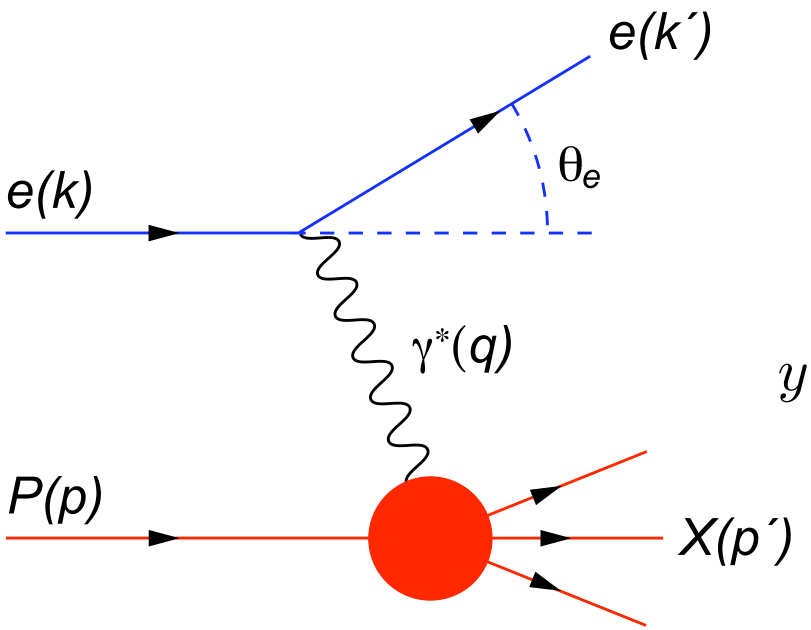

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How can we measure color charge with DIS?

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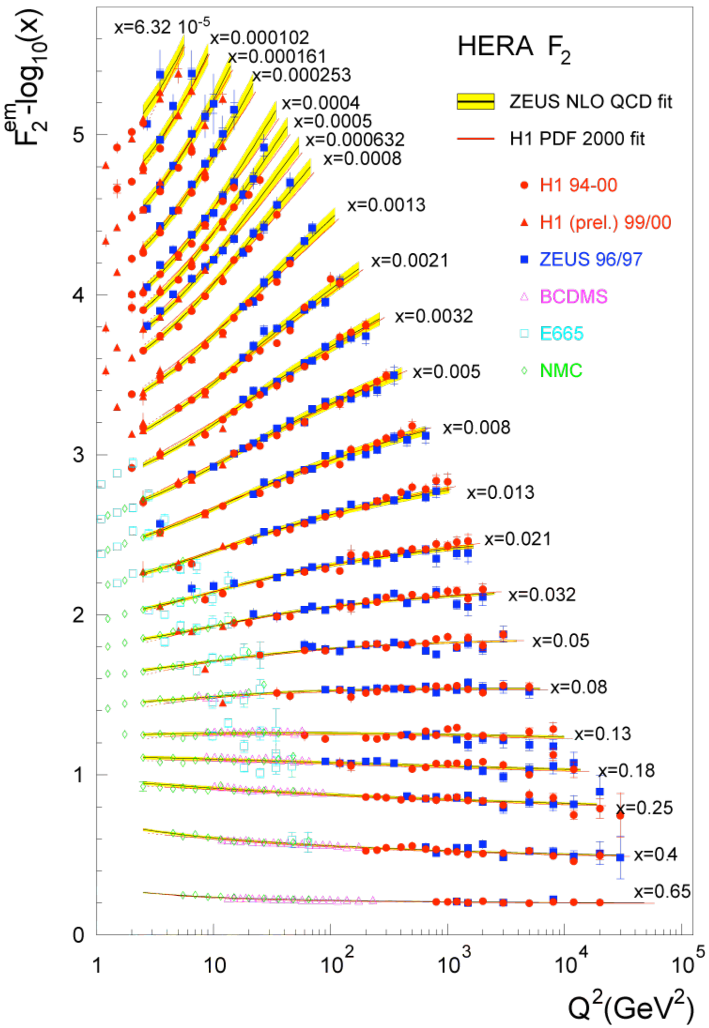

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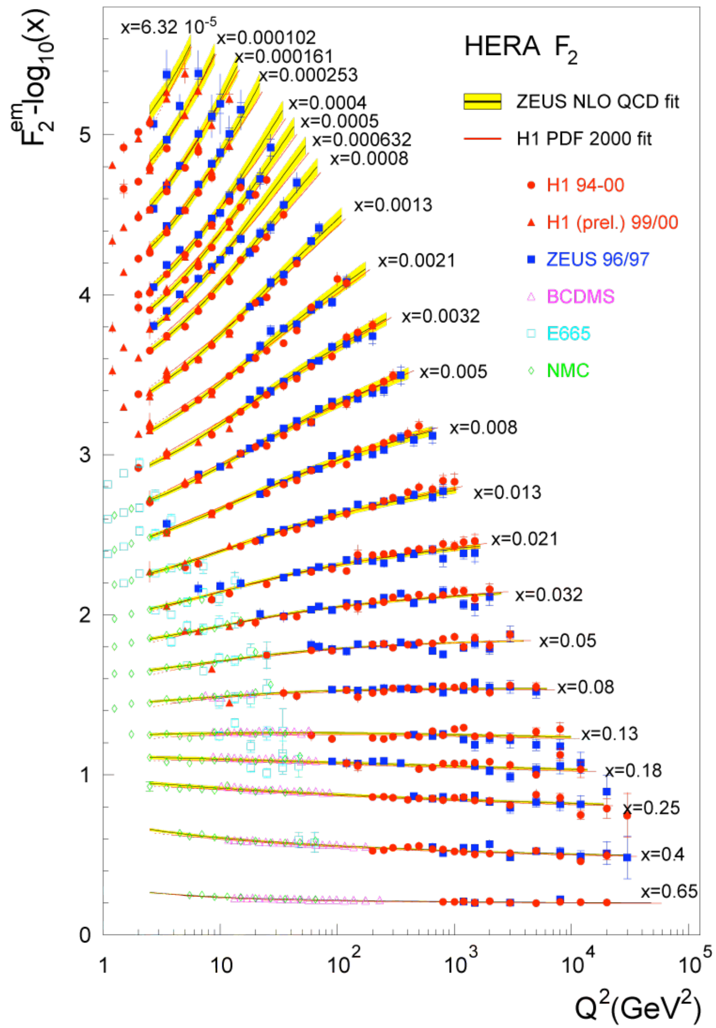
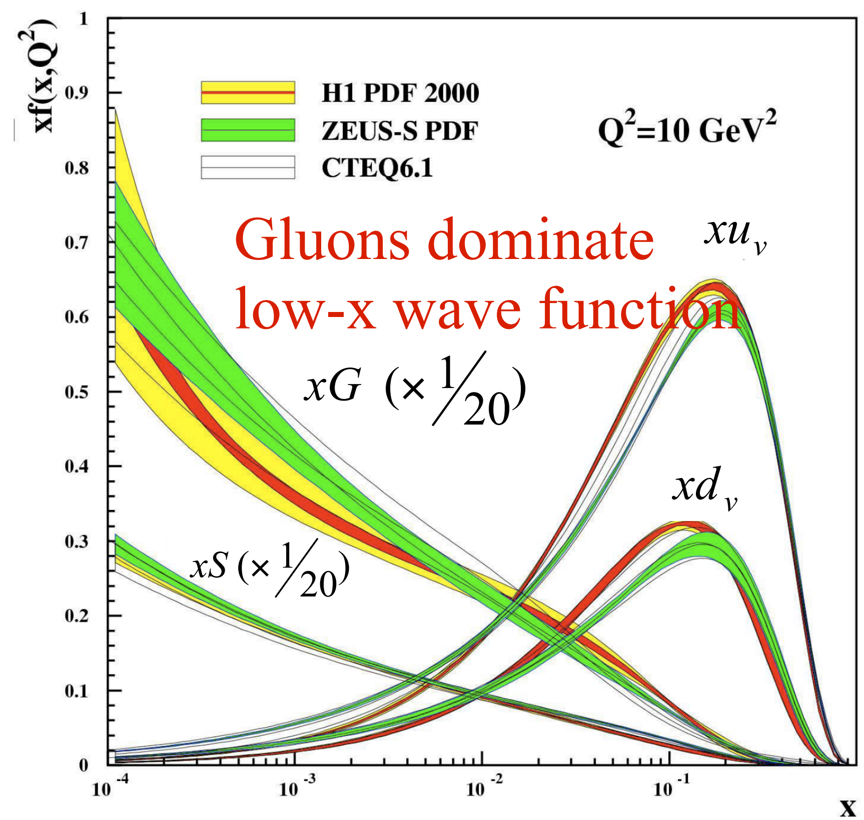


Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$



The Issue With Our Current Understanding

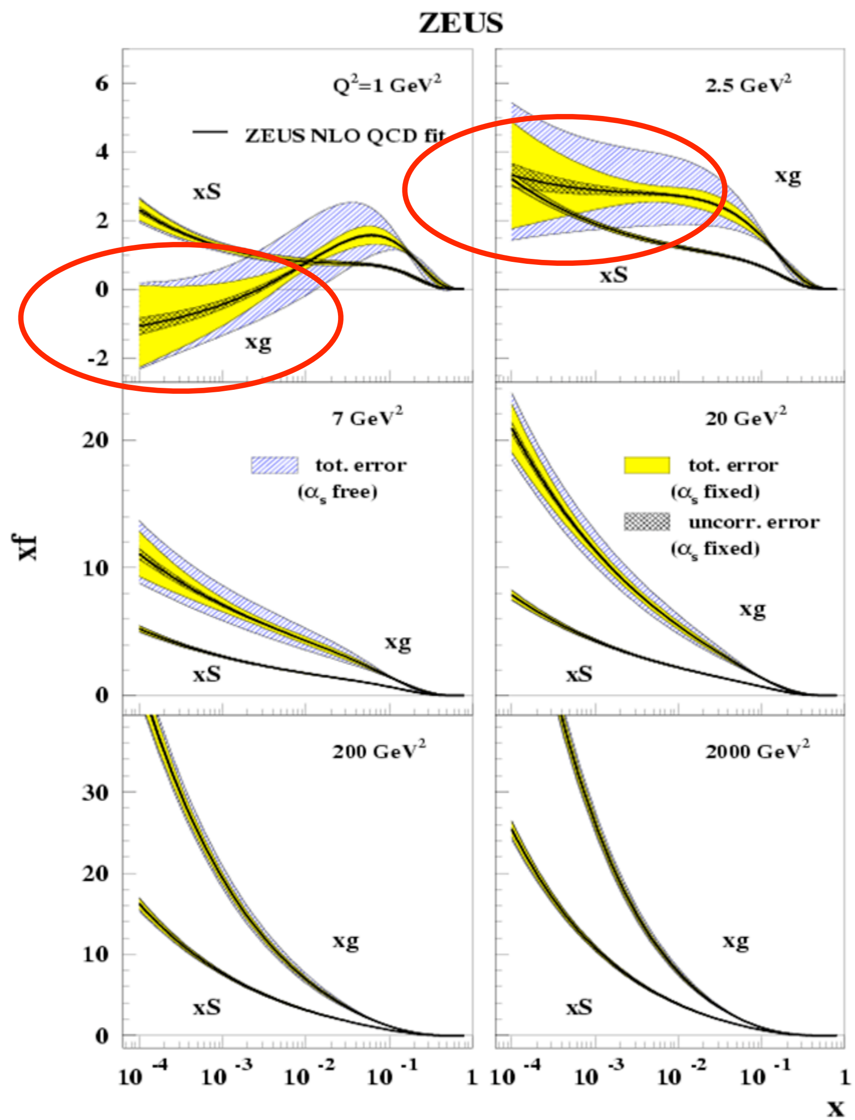
Established Model:

Linear DGLAP evolution scheme

Weird behavior of xG and F_L from HERA at small x and Q^2

- Could signal saturation, higher twist effects, need for more/better data?

Unexpectedly large diffractive cross-section



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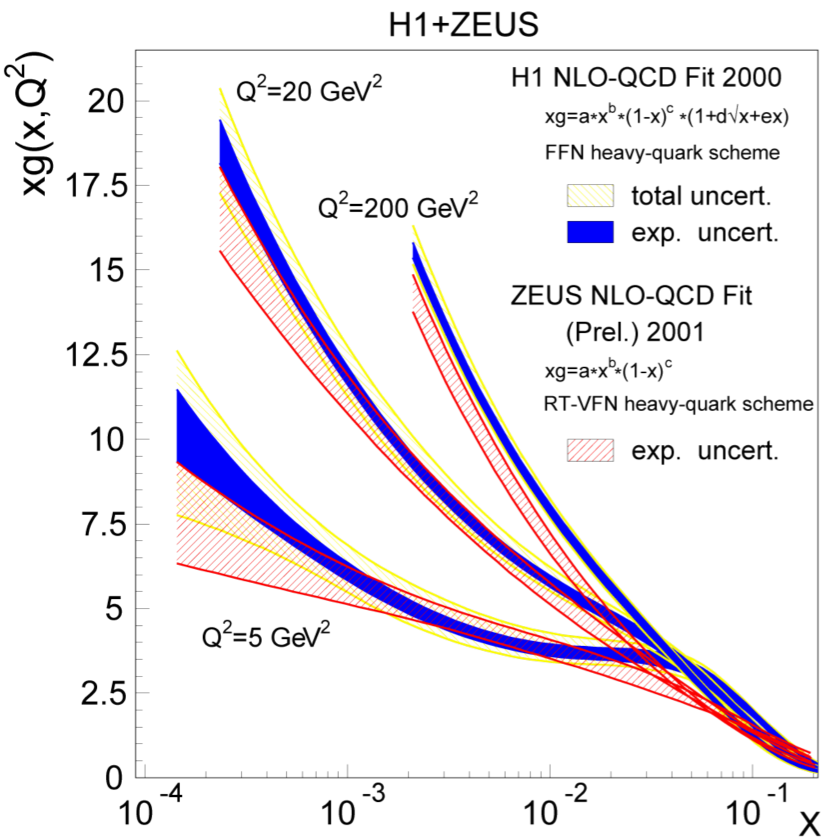
Linear Evolution has a built in high energy "catastrophe"

xG rapid rise for decreasing x and violation of (Froissart) unitary bound

⇒ **must** tame grow (saturate)

- What's the underlying dynamics?



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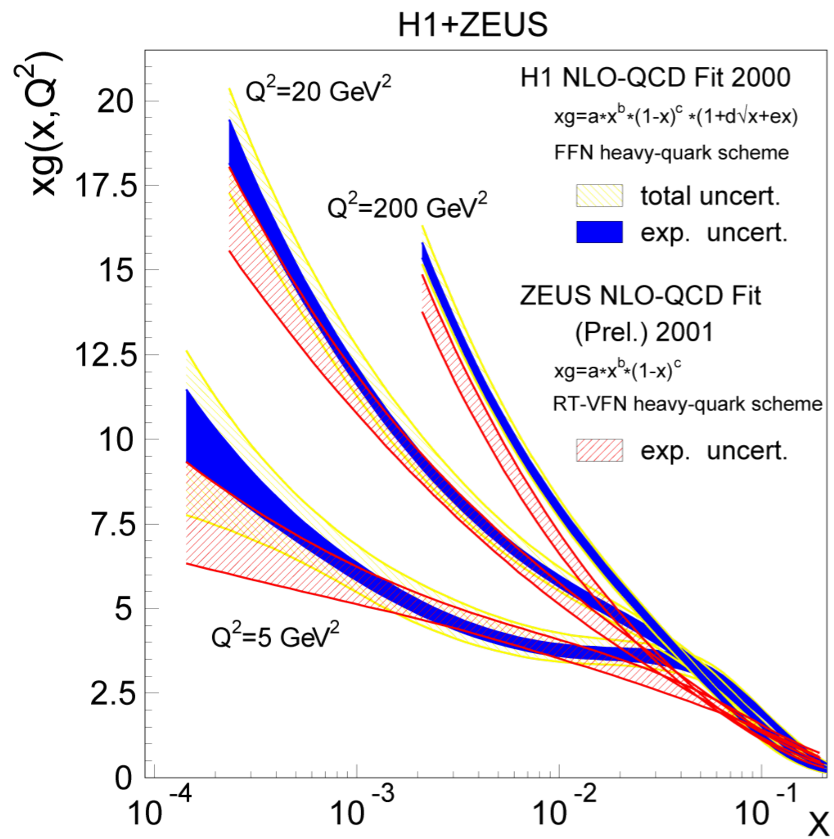
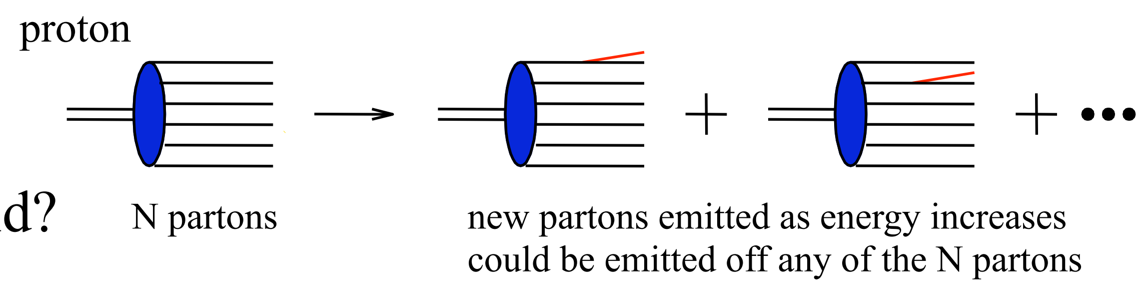


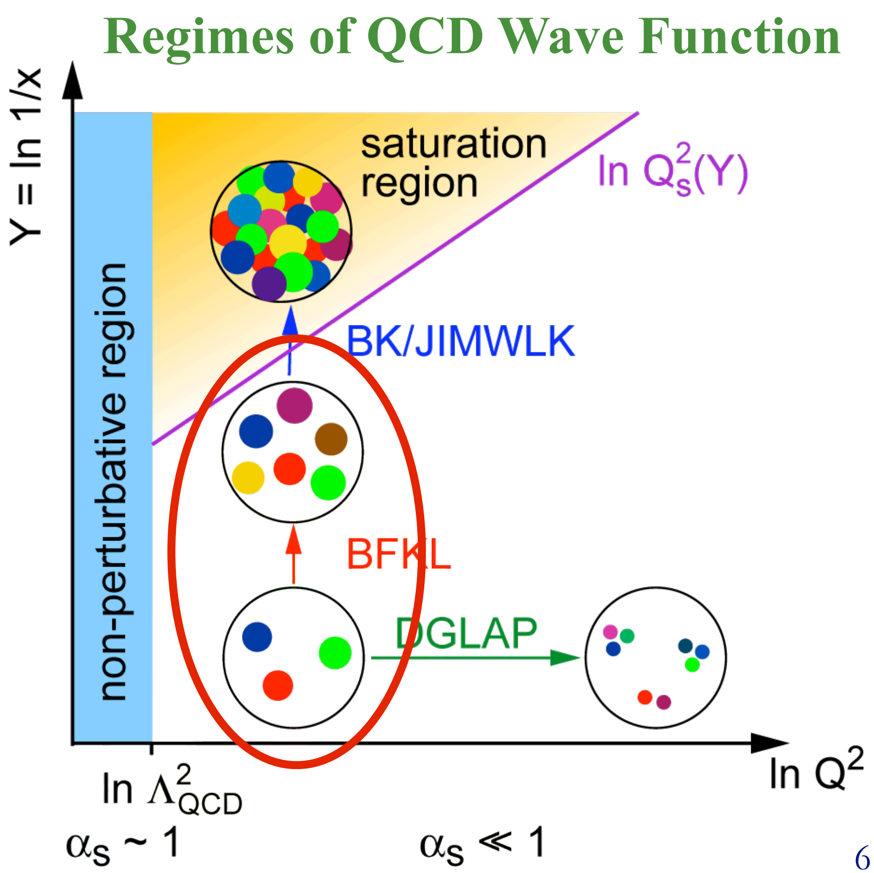
⇒ Need new approach

Non-Linear QCD - Saturation

BFKL Evolution in x

- linear
- explosion of color field?





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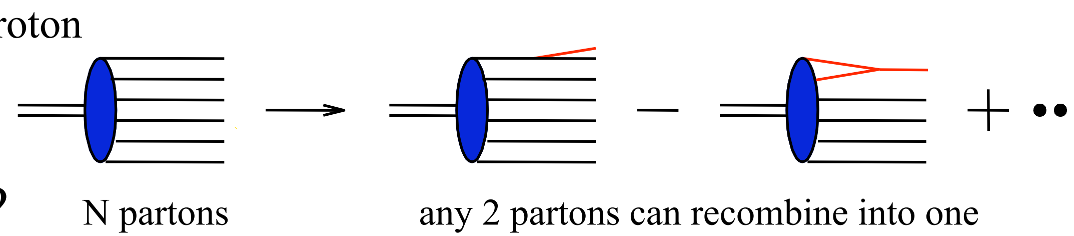
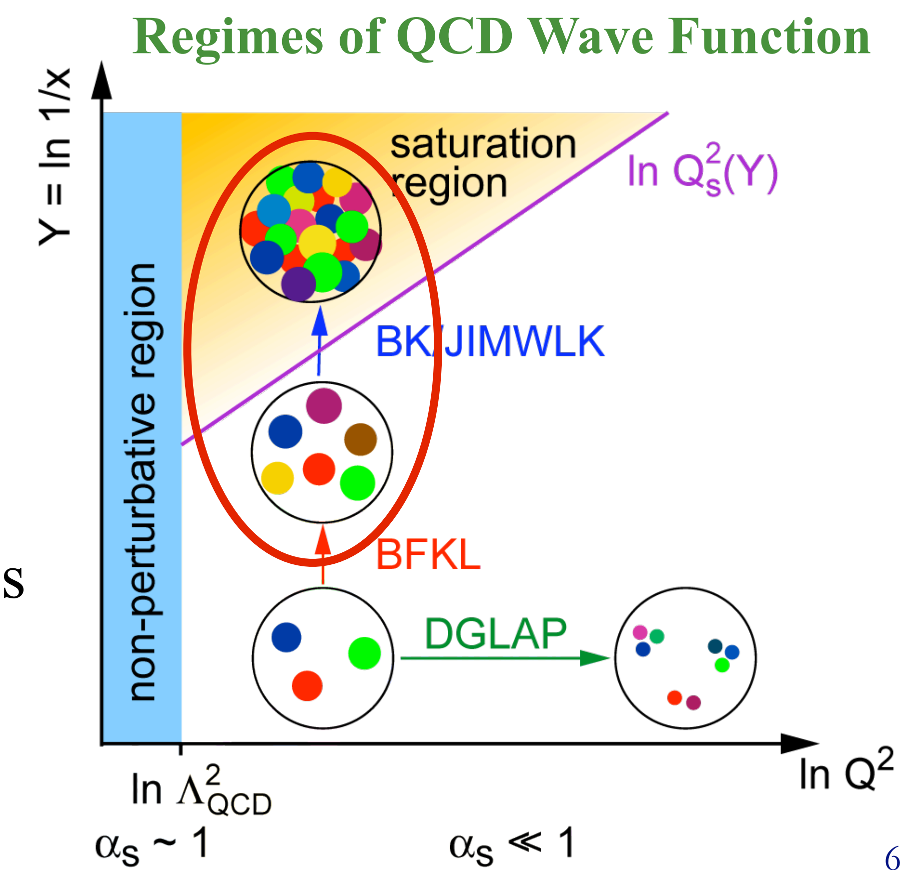




New: BK/JIMWLK based models

- introduce non-linear effects
- ⇒ saturation
- characterized by a scale $Q_s(x,A)$
- arises naturally in the Color Glass Condensate (CGC) framework

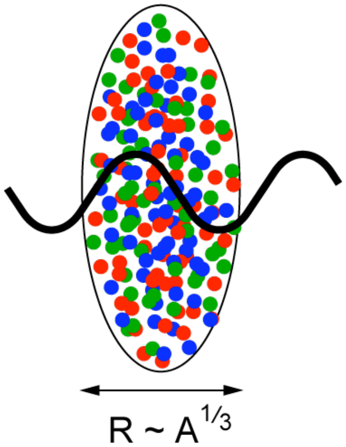
e+A: Studying Non-Linear Effects

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 nucleon

Probe interacts coherently with all nucleons



$$Q_s^2 \sim \frac{\alpha_s \, xG(x, Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: xG_A \sim A$$

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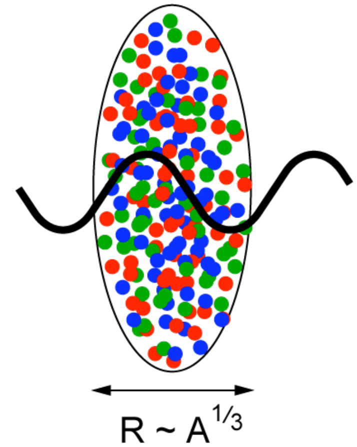

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Nuclear "Oomph" Factor

Pocket Formula:

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

Enhancement of Q_S with A ⇒ non-linear QCD regime reached at significantly lower energy in A than in proton

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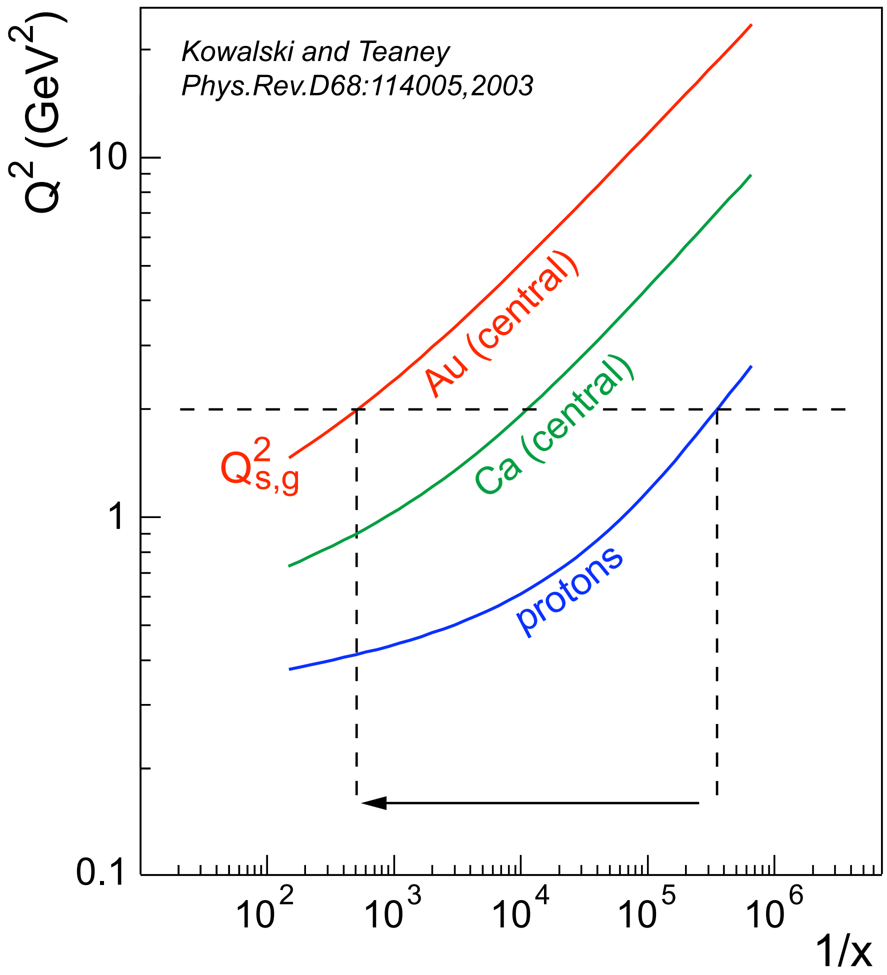

More sophisticated analyses ⇒ more detailed picture even exceeding the *Oomph* from the pocket formula

(e.g. Kowalski, Lappi and Venugopalan, arXiv:0705.3047; Armesto et al., PRL 94:022002; Kowalski, Teaney, PRD 68:114005)

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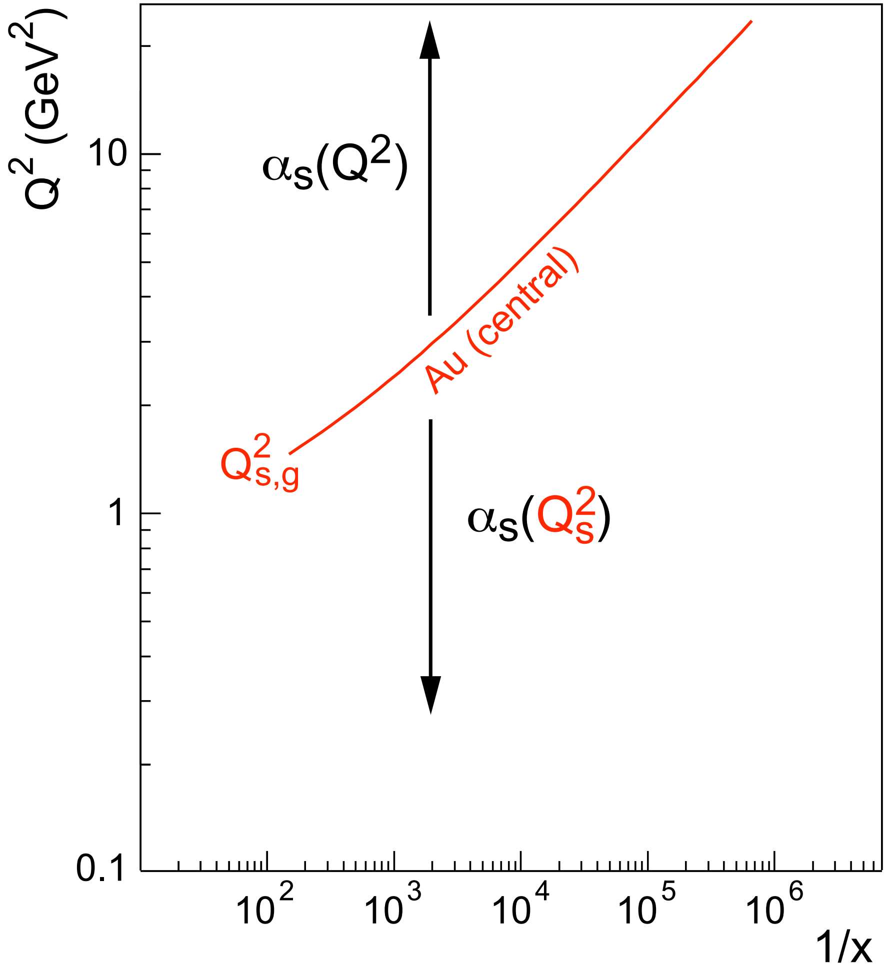
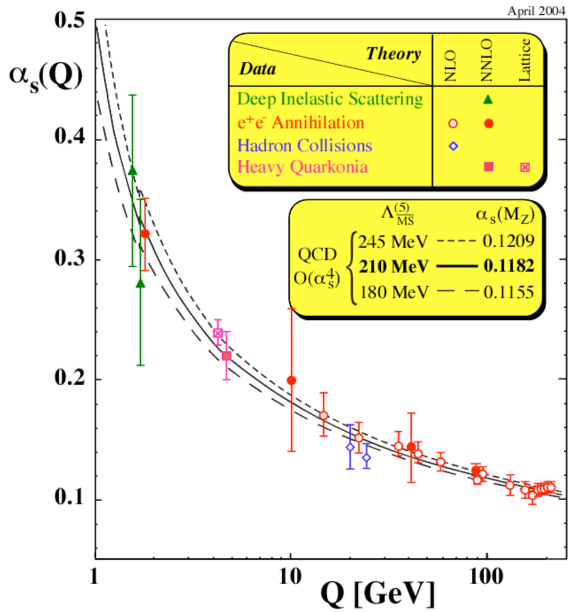


Note:

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

$$Q^2 < Q_s^2 \quad \Rightarrow \alpha_s = \alpha_s(Q_s^2)$$



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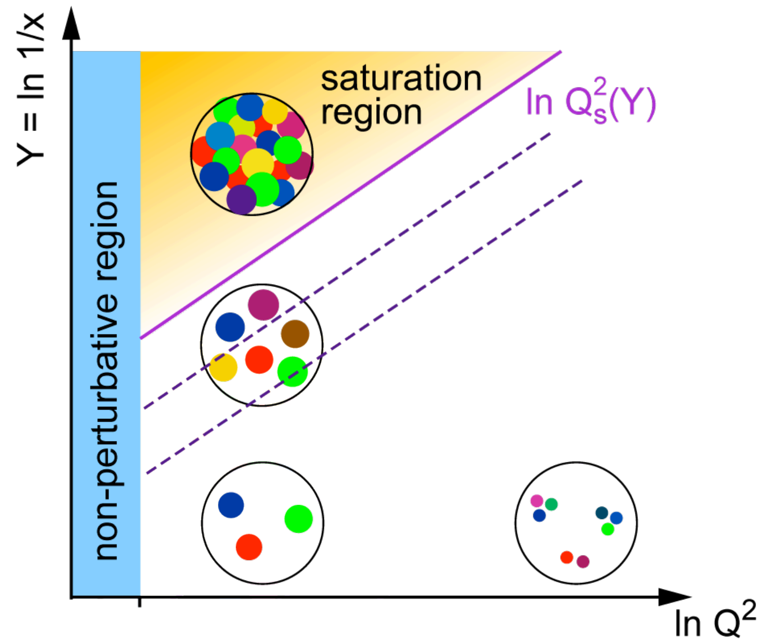
Universality & Geometric Scaling

Crucial *consequence* of non-linear evolution towards saturation:

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



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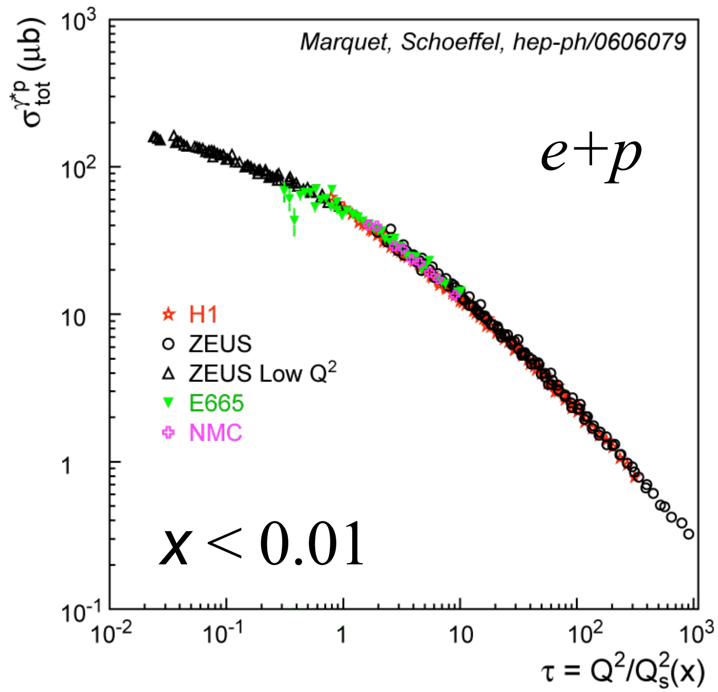
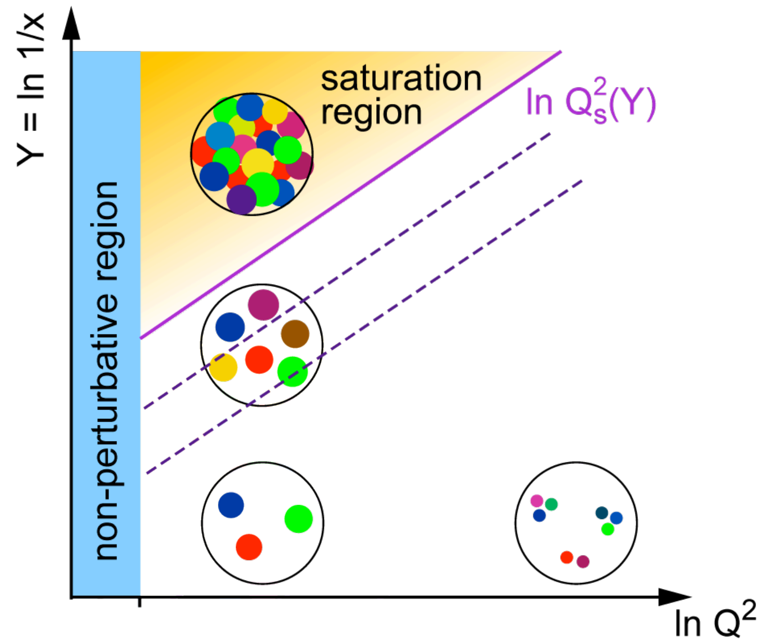


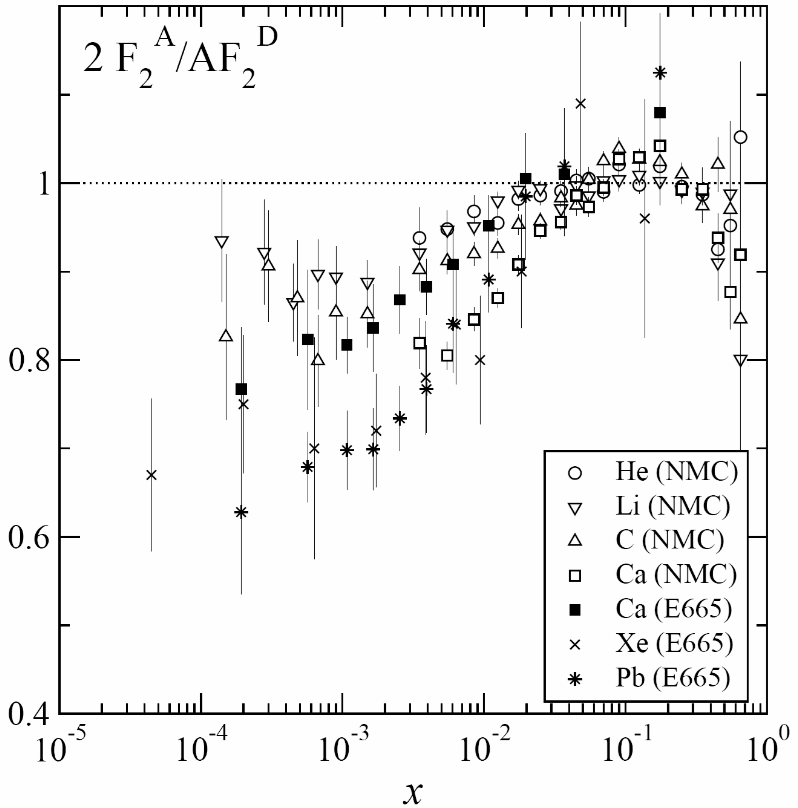


⇐ Geometric Scaling

- Consequence of saturation which manifests itself up to $k_T > Q_s$

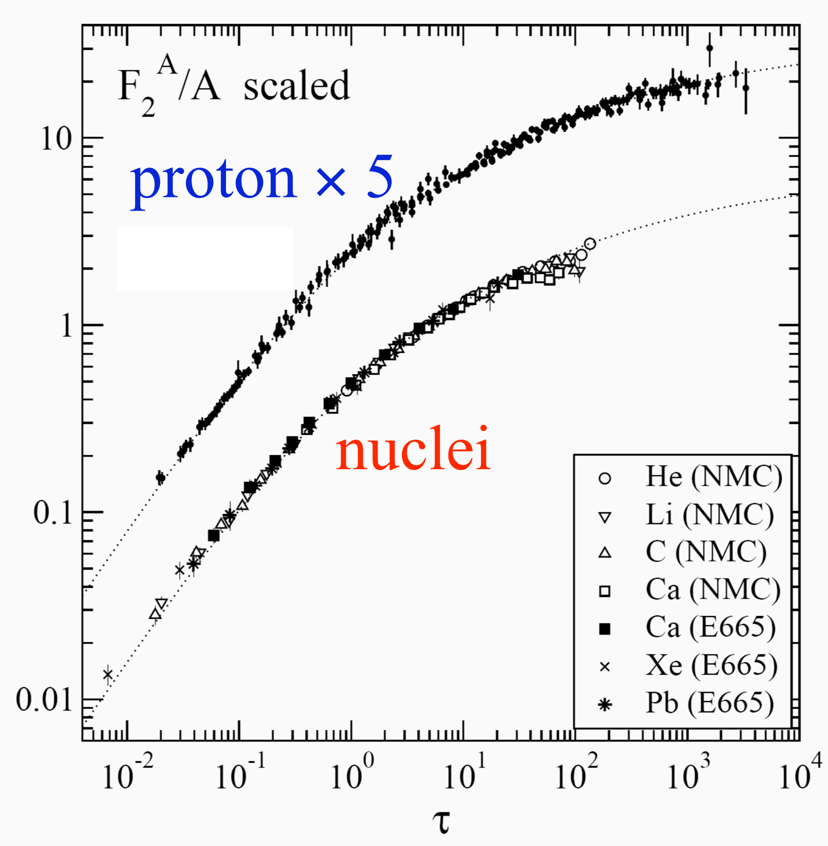
Q_s - A Scale that Binds them All ?

Nuclear shadowing:



Freund et al., hep-ph/0210139

Geometrical scaling



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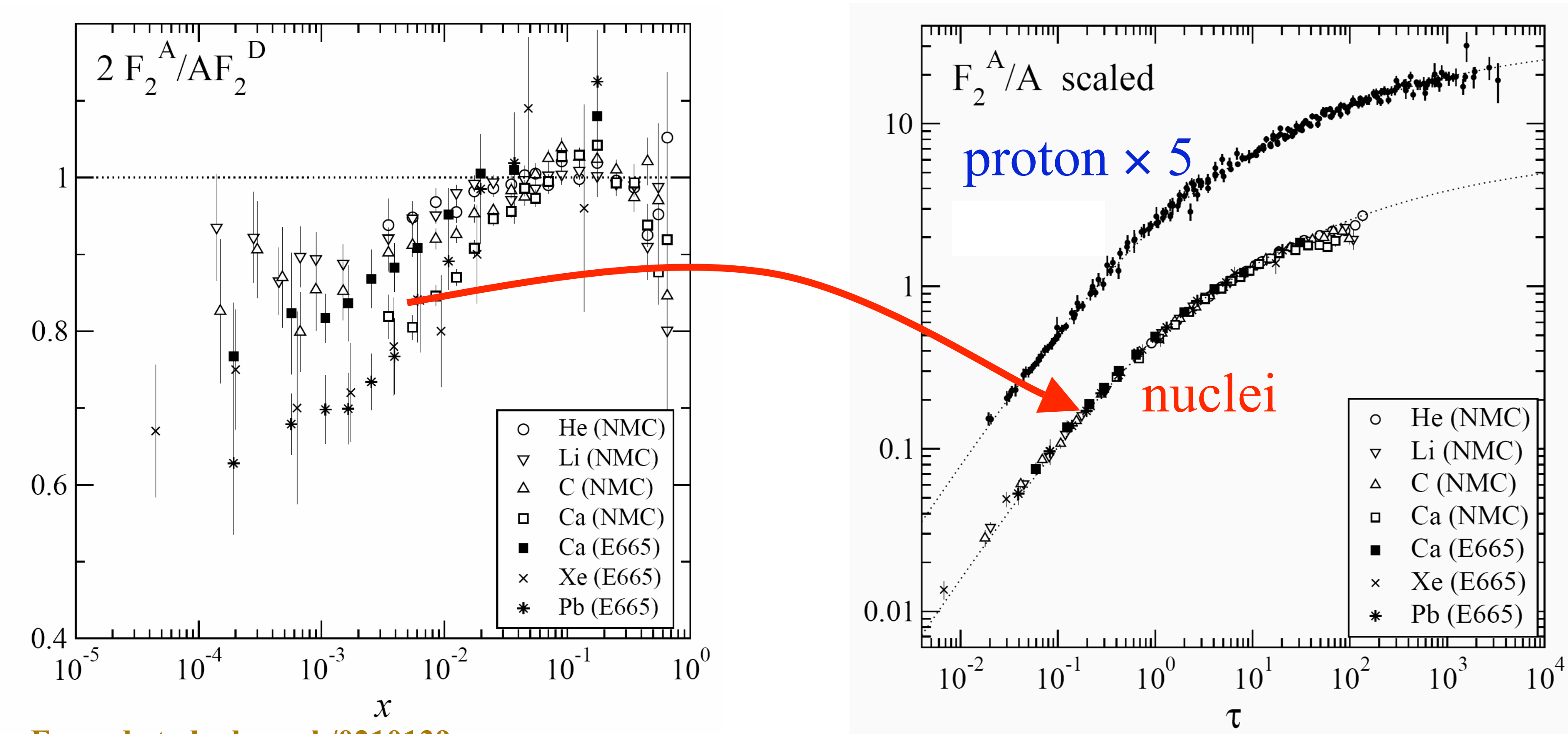
Nuclear shadowing: Geometrical scaling



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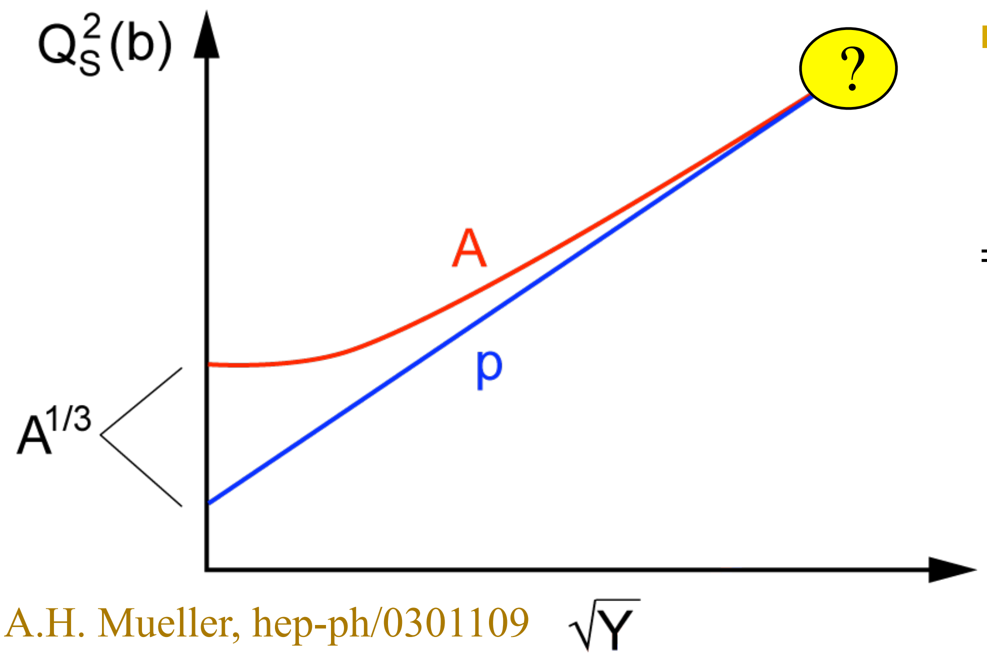
Are hadrons **and** nuclei wave function universal at low-*x* ?

A Truly Universal Regime ?



A.H. Mueller, hep-ph/0301109

Small x QCD evolution predicts:

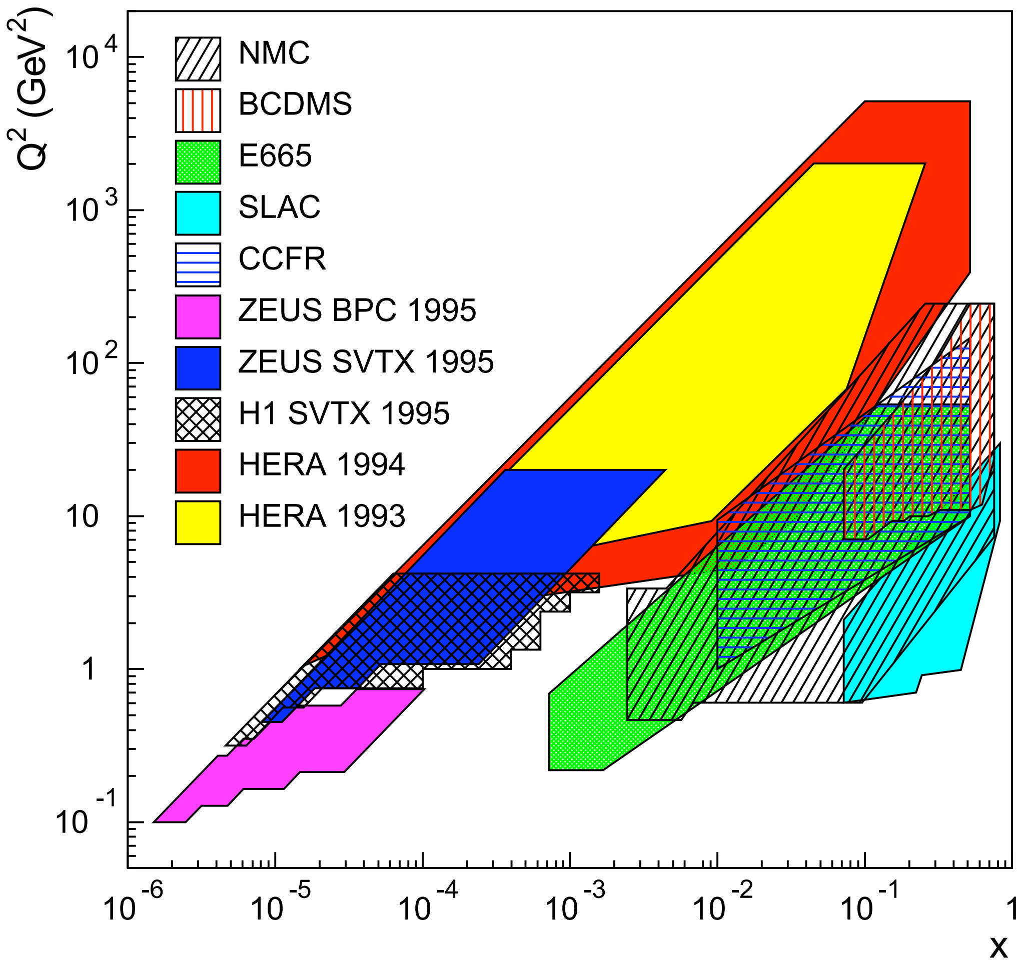
- Q_S approaches universal behavior for *all* hadrons and nuclei

$\Rightarrow$ Not only functional form f(Q_s) universal but even Q_s 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

eA Landscape and A New Electron Ion Collider



Well mapped in e+p

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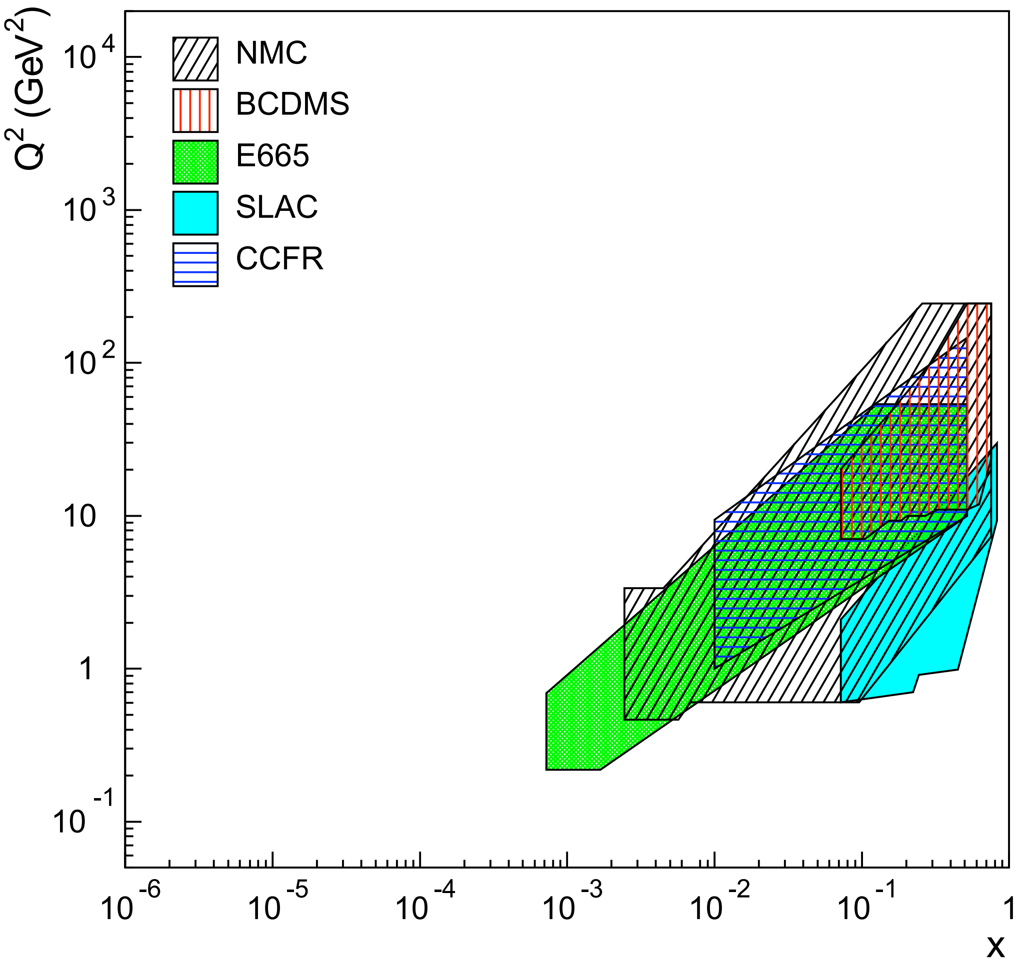

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many of those with small A and very low statistics

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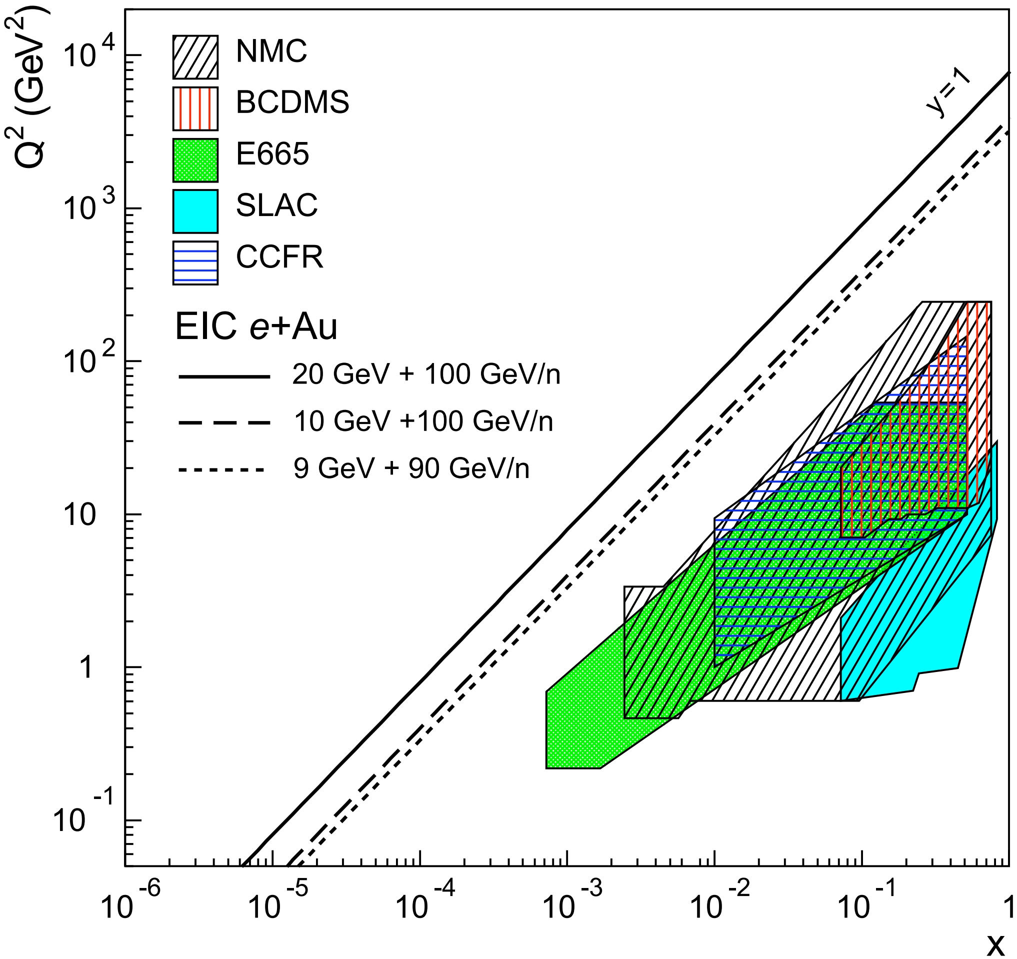

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Electron Ion Collider (EIC):
L(EIC) > 100 × L(HERA)

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E_e = 10 GeV (20 GeV)

E_A = 100 GeV

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

High $L_{eAu} \sim 6\cdot10^{30}$ cm^{-2} s^{-1}

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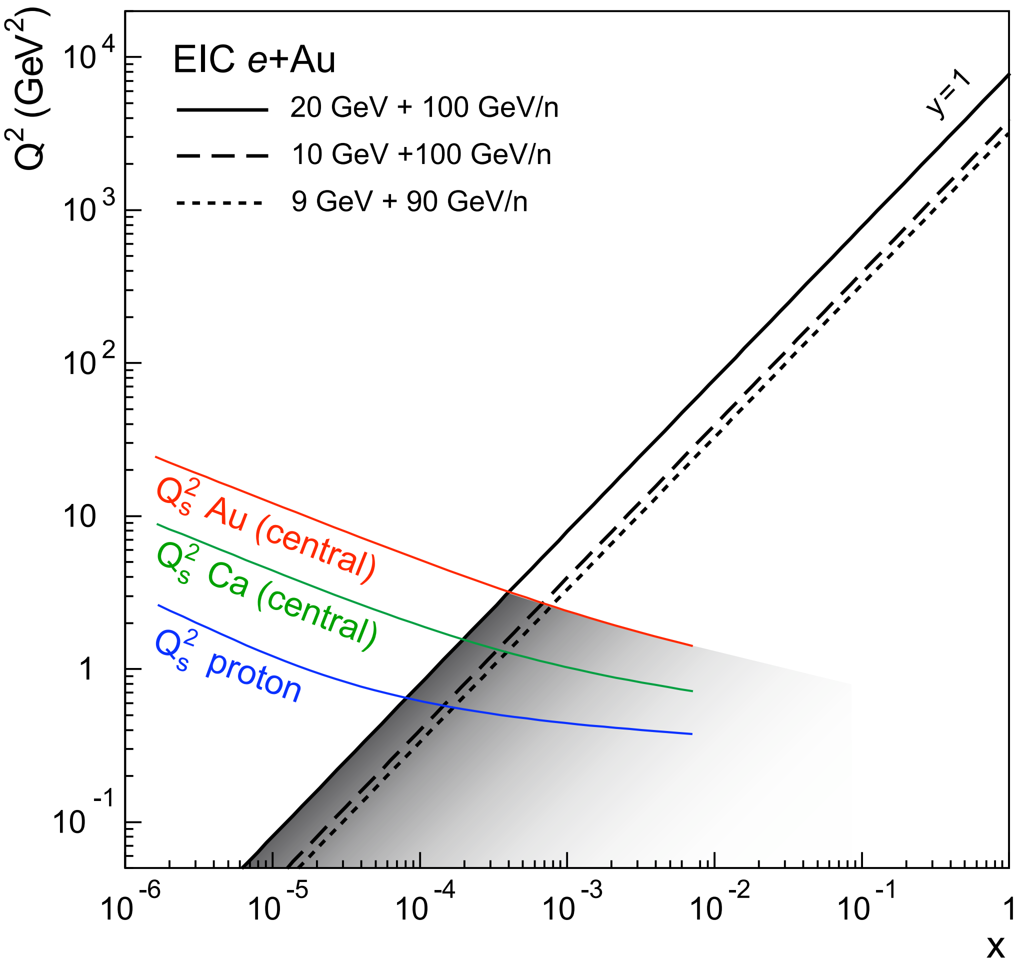

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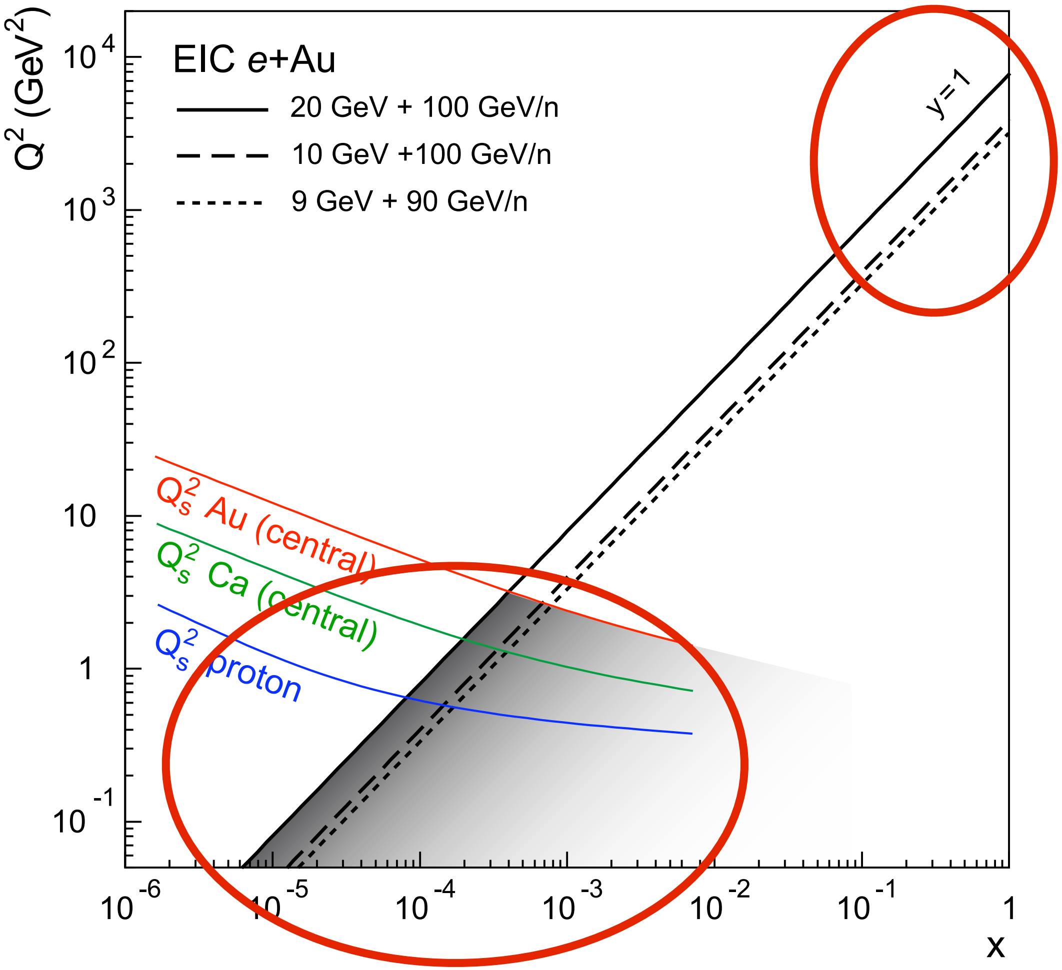

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Terra incognita: small-*x*, $Q \approx Q_s$
high-*x*, large Q^2

Electron Ion Collider Concepts

*e*RHIC (BNL): Add Energy Recovery Linac to RHIC

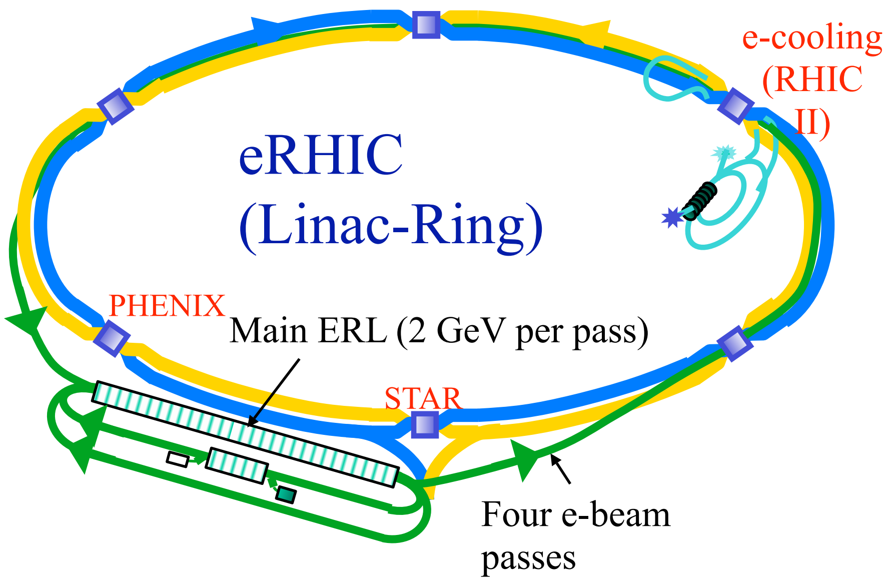
E_e = 10 (20) GeV

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}

TPC(2007$) ≈ $700 M



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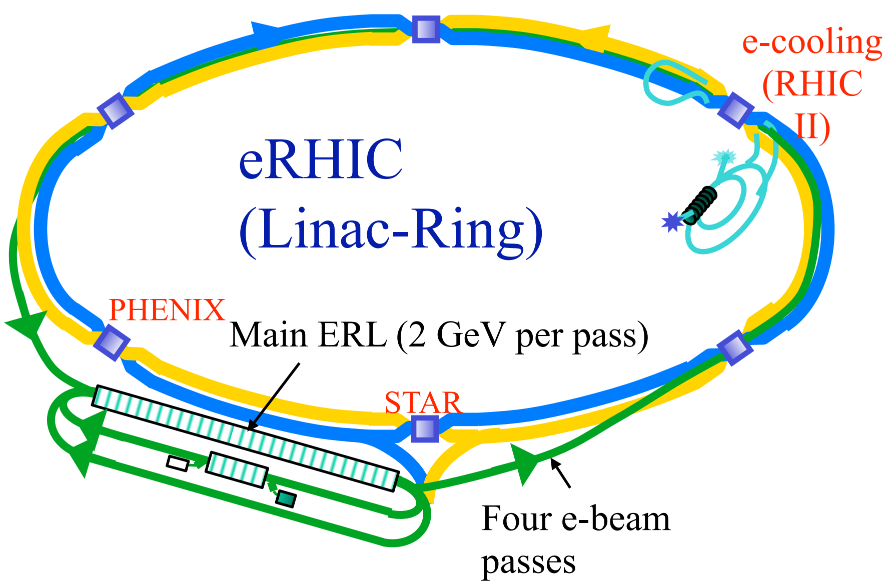


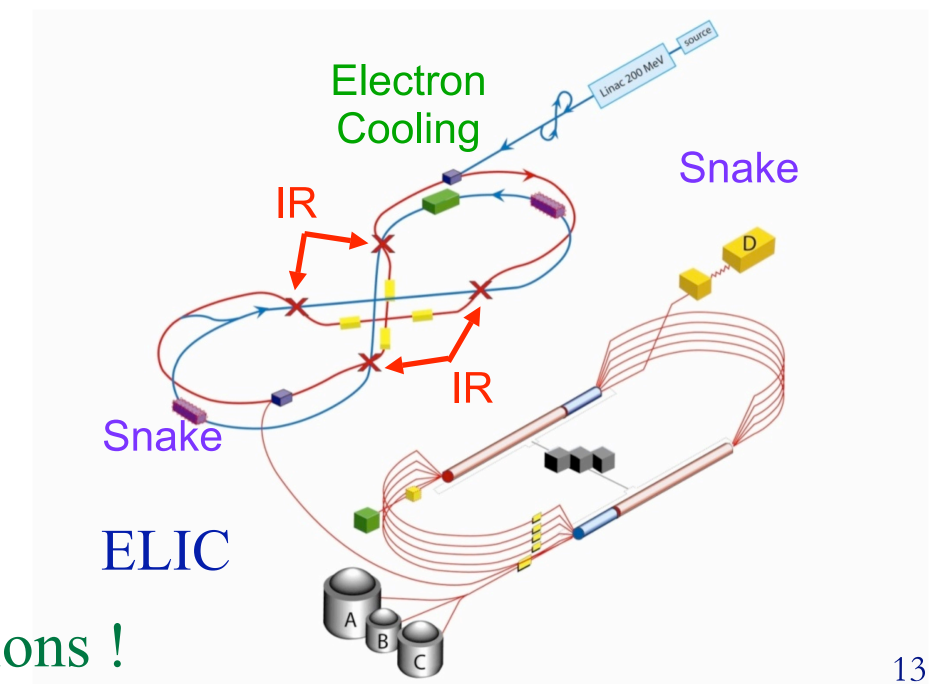
ELIC (JLAB): Add hadron beam facility to existing electron facility CEBAF

E_e = 9 GeV

E_A = 90 GeV (up to Au)

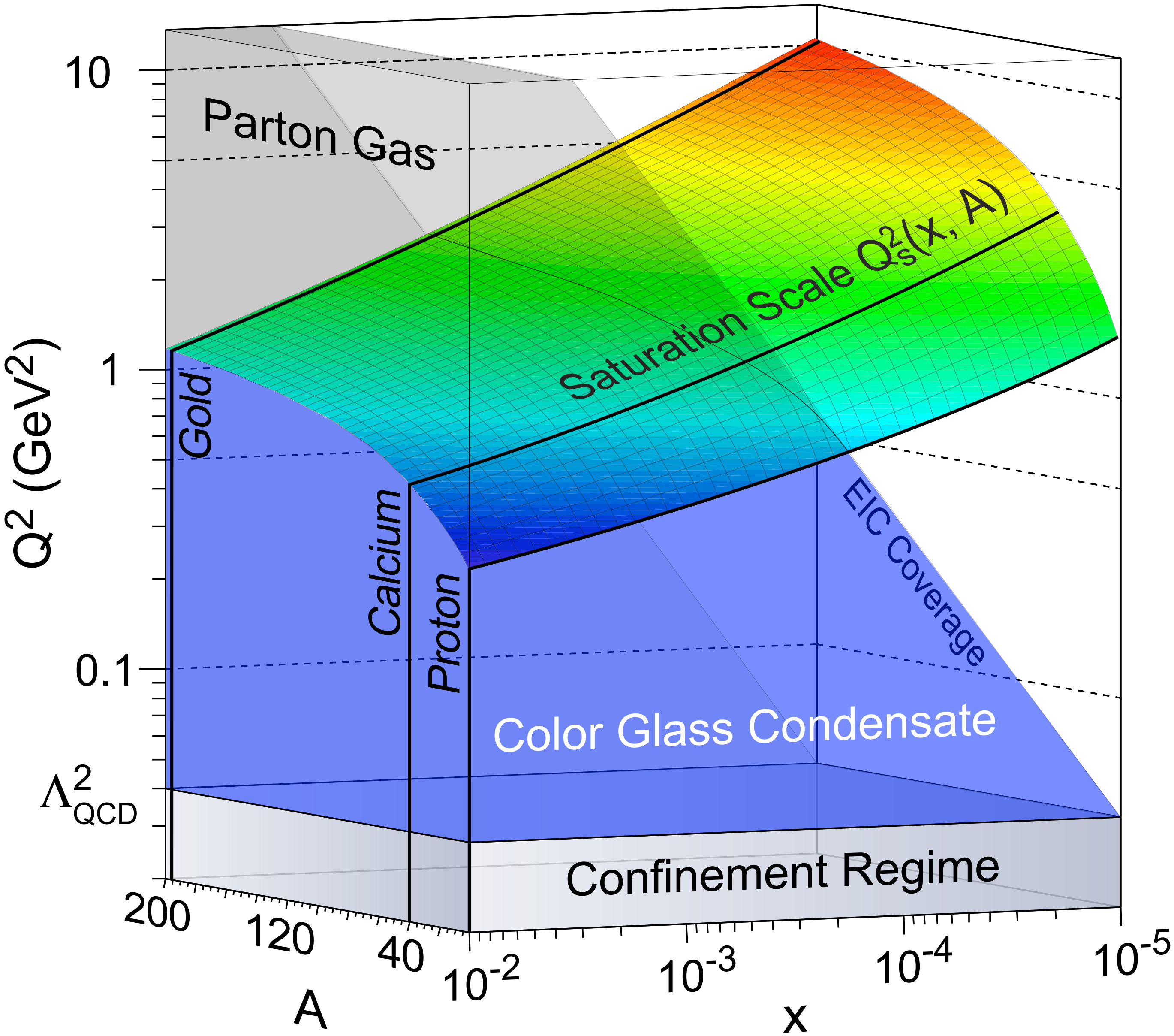
$\sqrt{s_{eN}}$ = 57 GeV

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



Both allow for polarized e+p collisions !

EIC Covers Relevant Kinematic Region



Understanding Glue in Matter ...

... involves understanding its key properties which in turn define the required measurements:

- What is the momentum distribution of the gluons in matter?
- What is the space-time distributions of gluons in matter?
- How do fast probes interact with the gluonic medium?
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?

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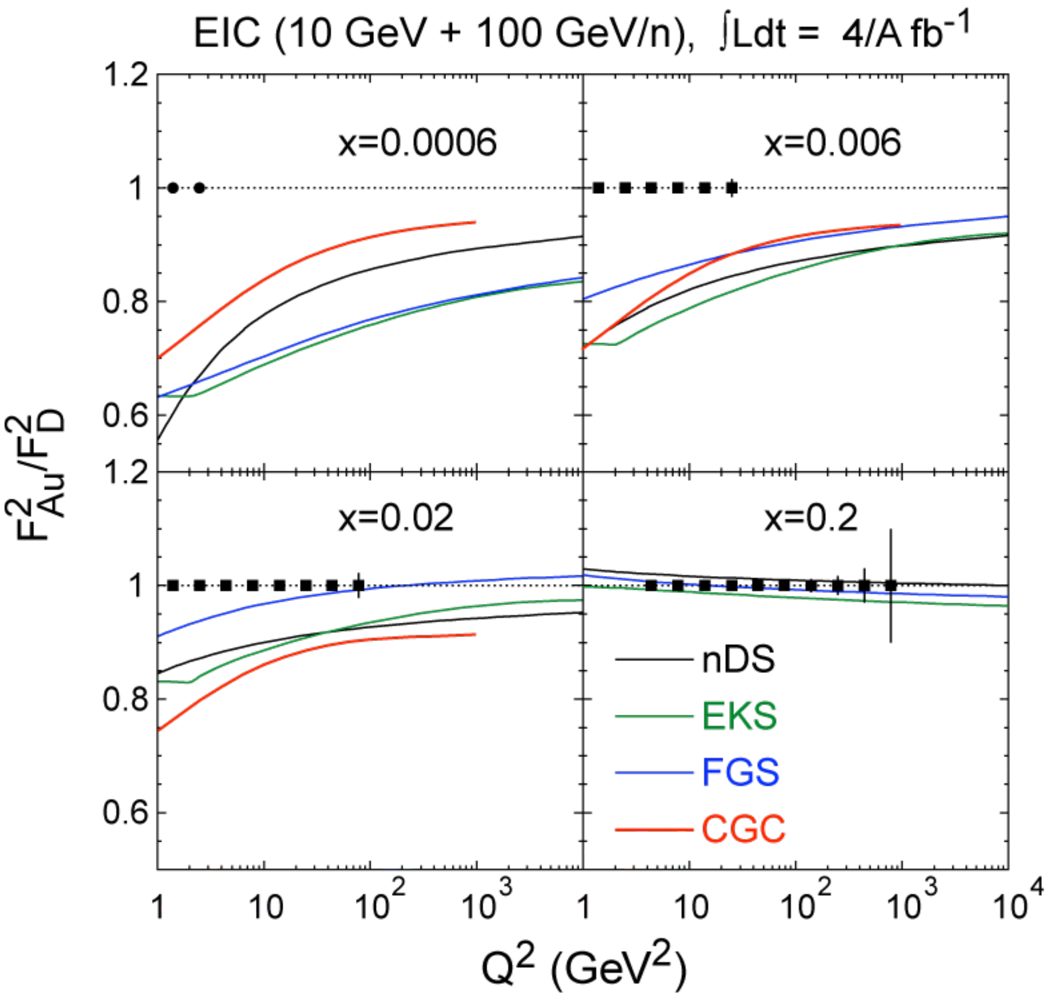
3. have no analog in e+p

Understanding Glue in Matter ...

... involves understanding its key properties which in turn define the required measurements:

- What is the momentum distribution of the gluons in matter?
  - Extract from scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - $F_L \sim \alpha_s G(x,Q^2)$ (BTW: requires $\sqrt{s}$ scan)
  - 2+1 jet rates (needs modeling of hadronization)
  - inelastic vector meson production (e.g. J/ψ)
  - diffractive vector meson production ~ $[G(x,Q^2)]^2$
- What is the space-time distributions of gluons in matter?
- How do fast probes interact with the gluonic medium?
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?

F_2 : Sea (Anti)Quarks Generated by Glue at Low x



F_2 will be one of the first measurements at EIC

nDS, EKS, FGS:

pQCD based models with different amounts of shadowing

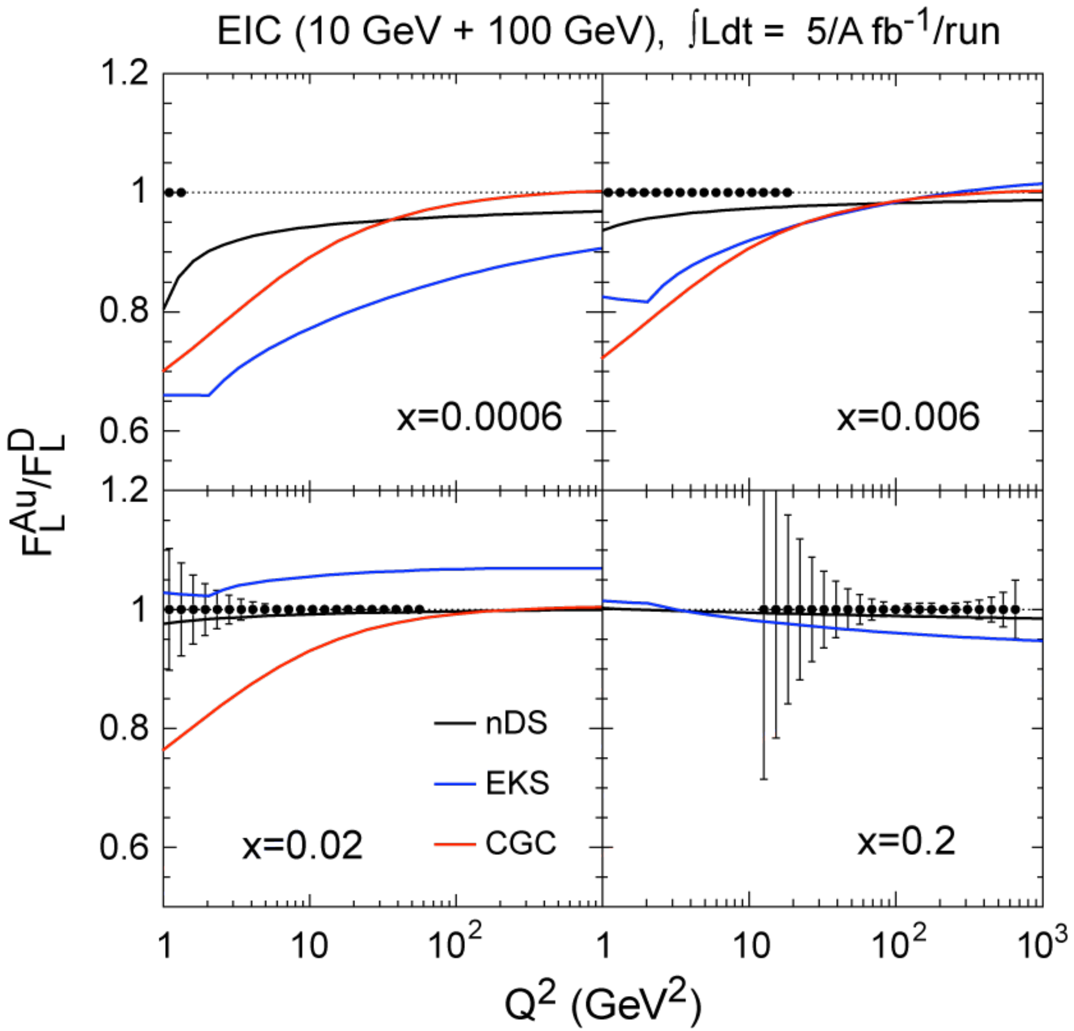
Syst. studies of $F_2(A, x, Q^2)$:

⇒ $G(x,Q^2)$ with precision

⇒ distinguish between models

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

F_L at EIC: Measuring the Glue Directly



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

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

F_L at EIC: Integrated over Q^2

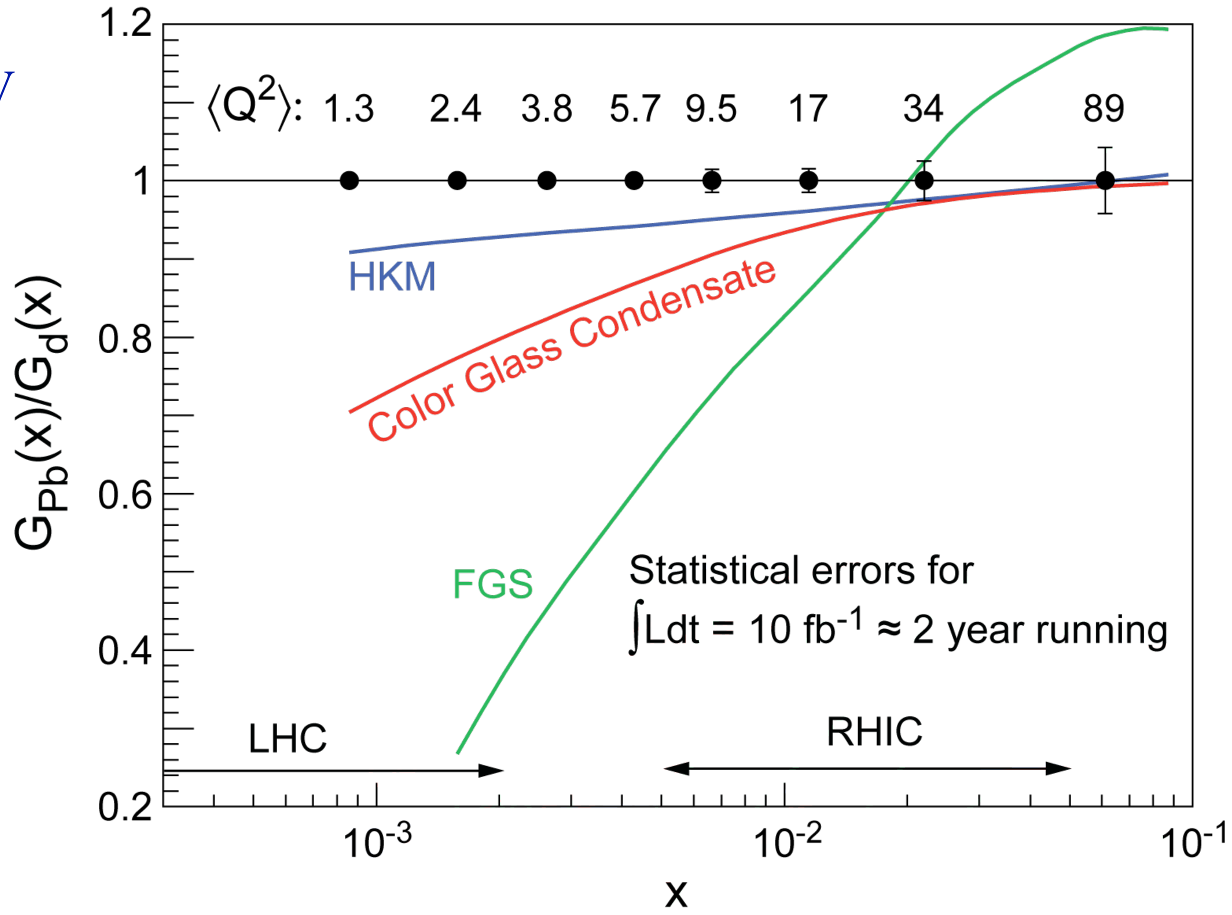
Here:

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

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

= 2/A fb^{-1} (5+50) GeV

statistical error only



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

How EIC will Address the Important Questions

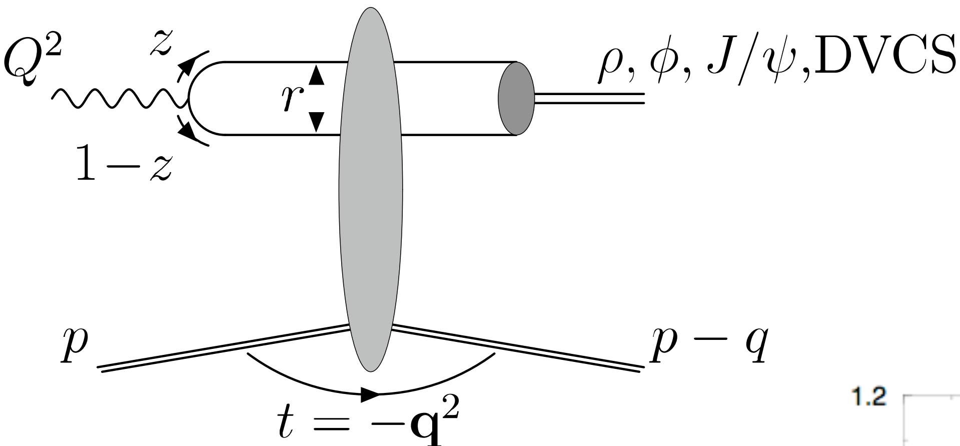
- What is the momentum distribution of the gluons in matter?
- What is the space-time distributions of gluons in matter?
- How do fast probes interact with the gluonic medium?
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?

How EIC will Address the Important Questions

- What is the momentum distribution of the gluons in matter?
- What is the space-time distributions of gluons in matter?
  - Various techniques & methods:
    - Exclusive final states (e.g. vector meson production ρ, J/ψ)
      - color transparency $\Leftrightarrow$ color opacity
    - Deep Virtual Compton Scattering (DVCS) $\gamma^* A \rightarrow \gamma A$
    - Integrated DVCS cross-section: $\sigma_{DVCS} \sim A^{4/3}$
    - Measurement of structure functions for various mass numbers A (shadowing, EMC effect) and its impact parameter dependence
- How do fast probes interact with the gluonic medium?
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?

Vector Meson Production

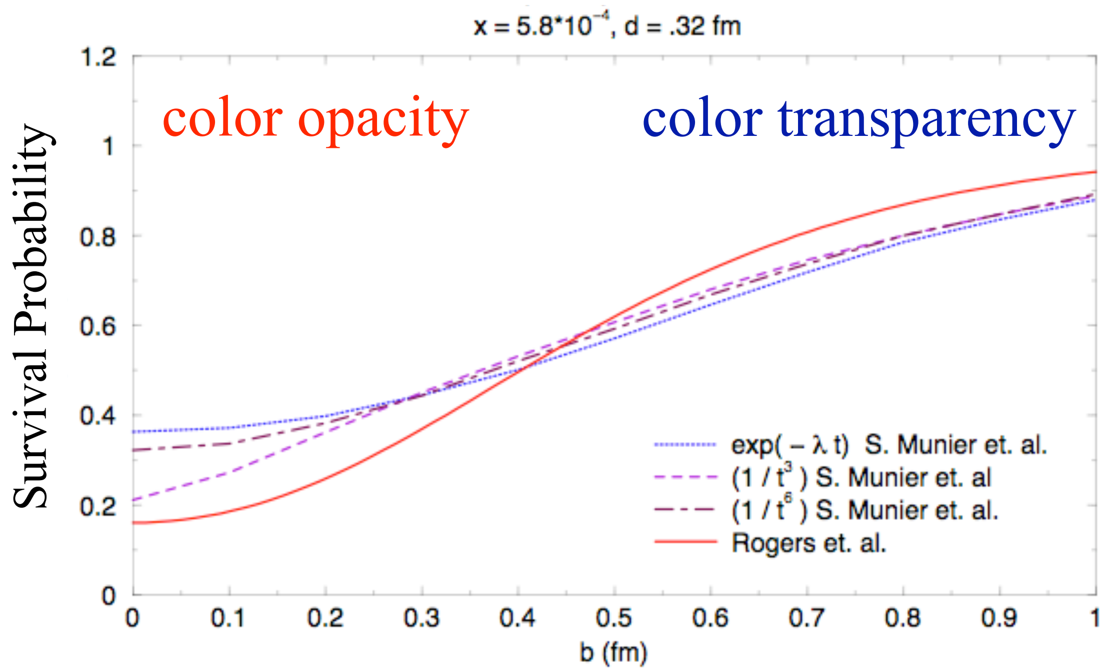
"color dipole" picture



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

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

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How EIC will Address the Important Questions

- What is the momentum distribution of the gluons in matter?
- What is the space-time distributions of gluons in matter?
- How do fast probes interact with the gluonic medium?
  - Hadronization, Fragmentation
  - Energy loss (charm!)
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?

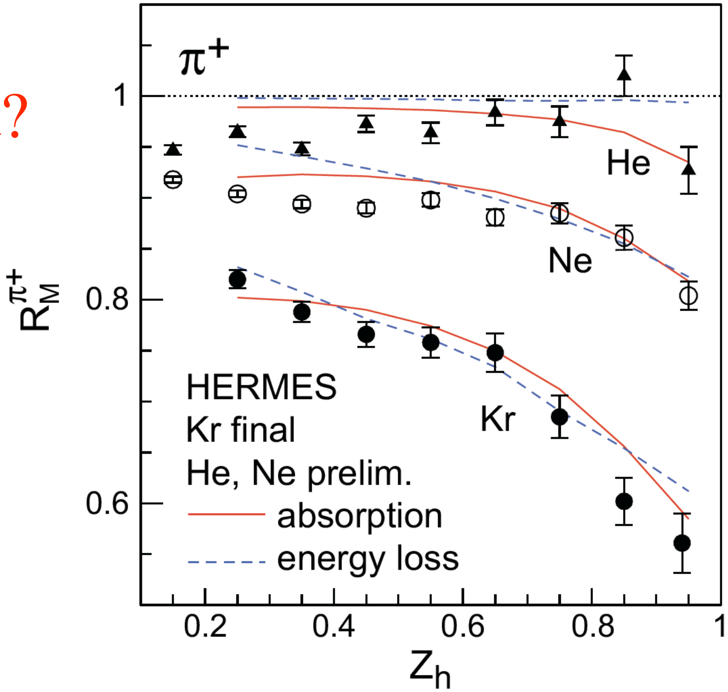
Hadronization and Energy Loss

nDIS:

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

Fundamental question:
When do colored partons get neutralized?

Parton energy loss vs.
(pre)hadron absorption

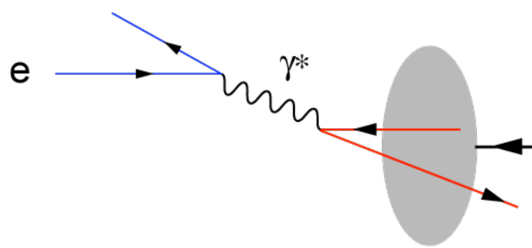


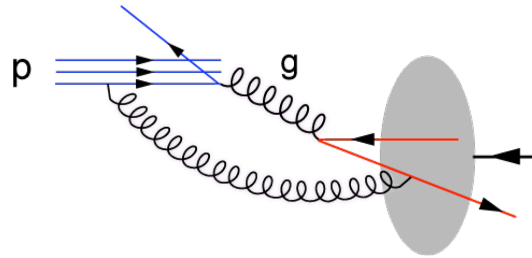
Energy transfer in lab rest frame
EIC: $10 < \nu < 1600$ GeV   HERMES: 2-25 GeV
EIC: can measure *heavy flavor* energy loss

$z_h = E_h/\nu$

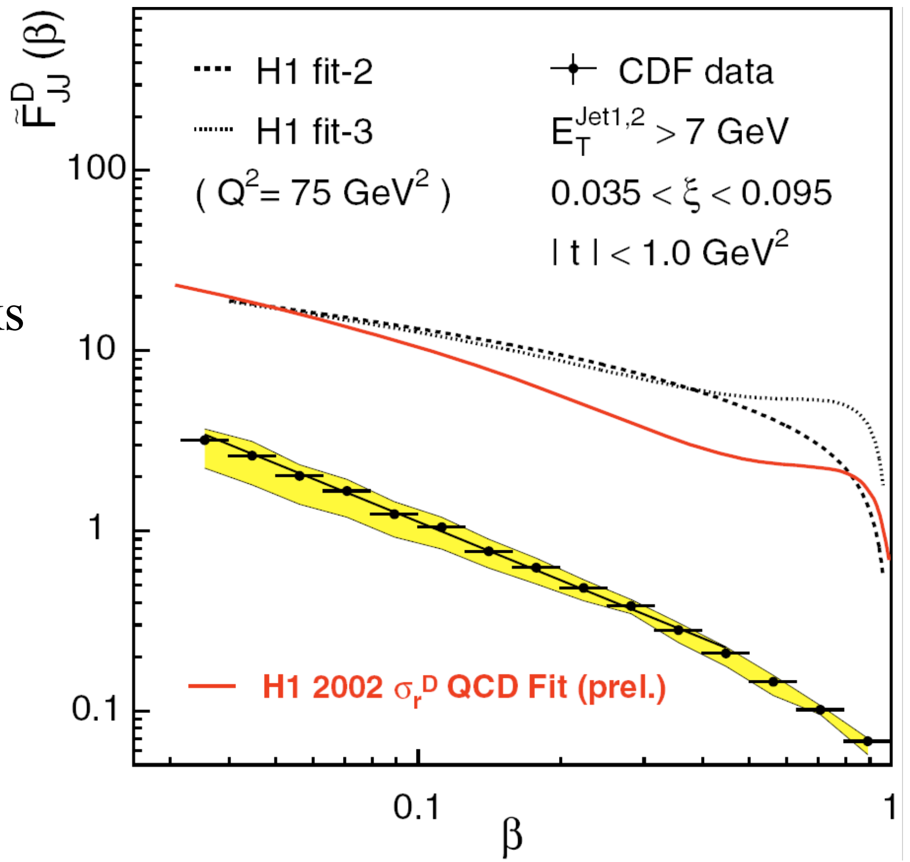
Connection to *p*+A Physics

- *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



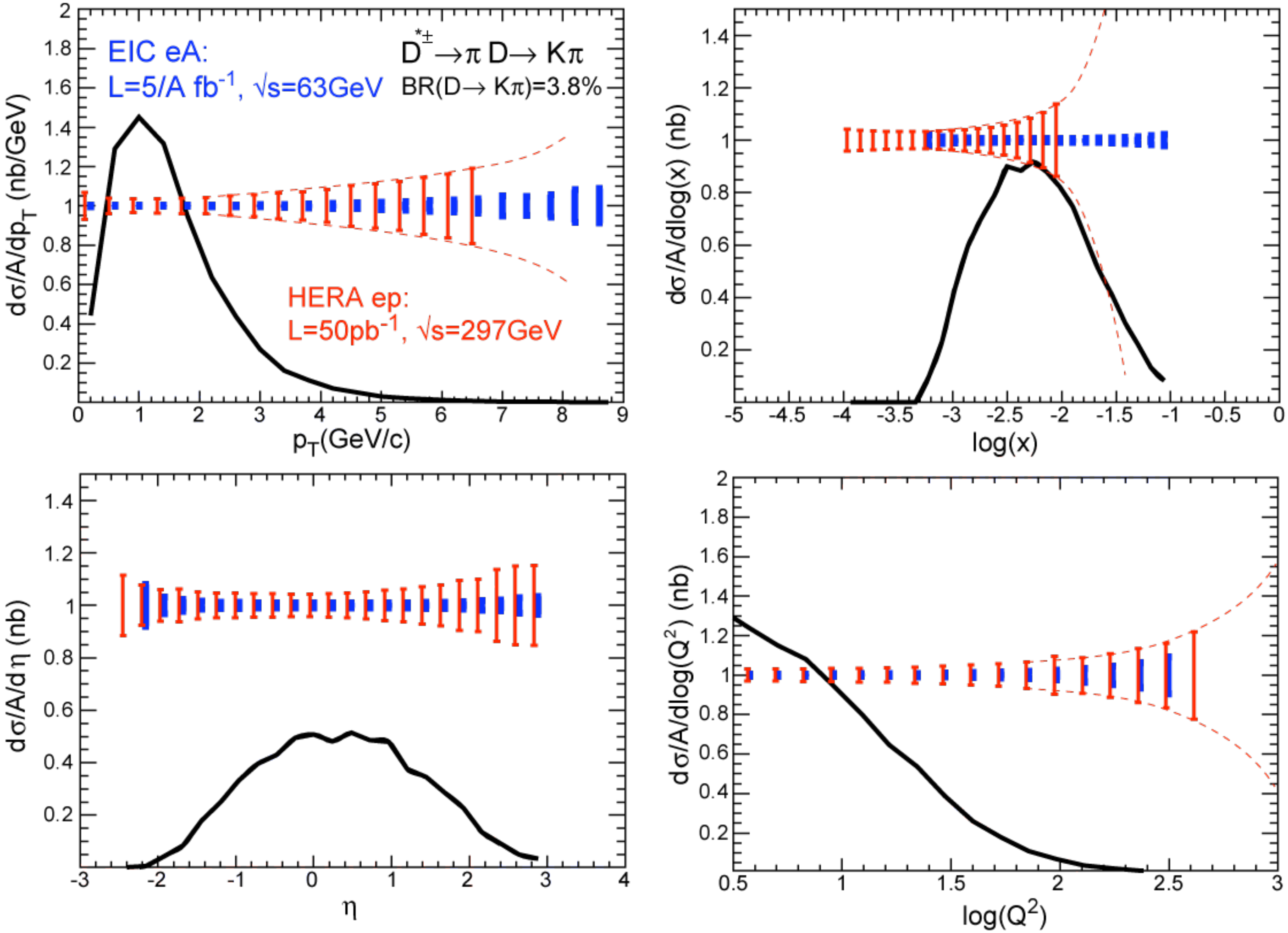


F. Schilling, hex-ex/0209001



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

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

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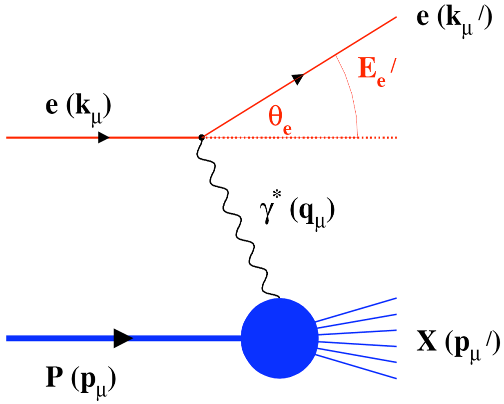
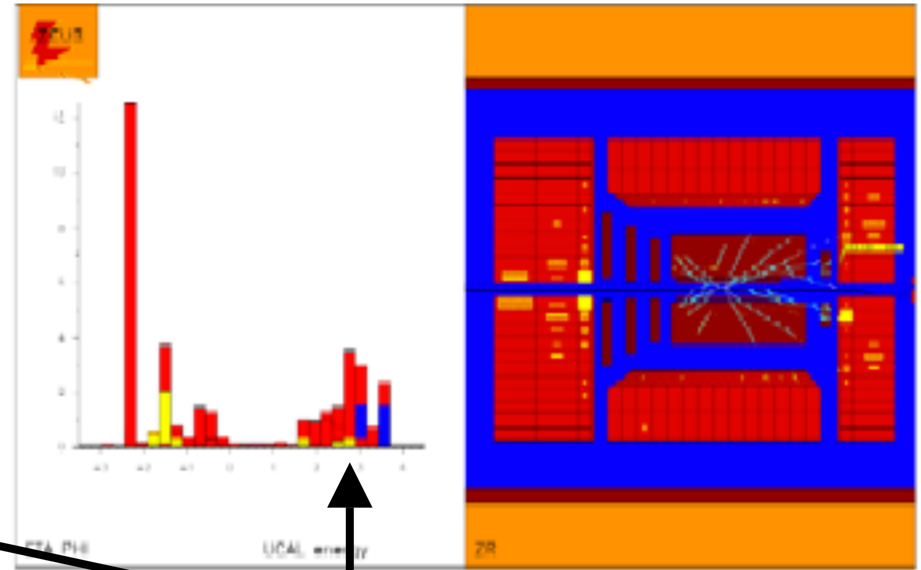
- How do fast probes interact with the gluonic medium?
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?
  - diffractive cross-section $\sigma_{diff}/\sigma_{tot}$
  - diffractive structure functions
  - shadowing == multiple diffractive scattering ?
  - diffractive vector meson production - very sensitive to $G(x,Q^2)$

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

Diffractive Physics in e+A

'Standard DIS event'

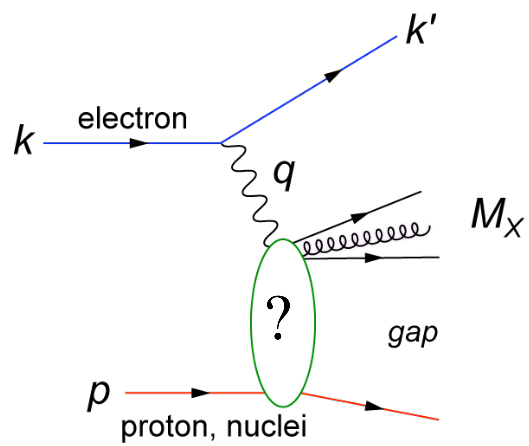


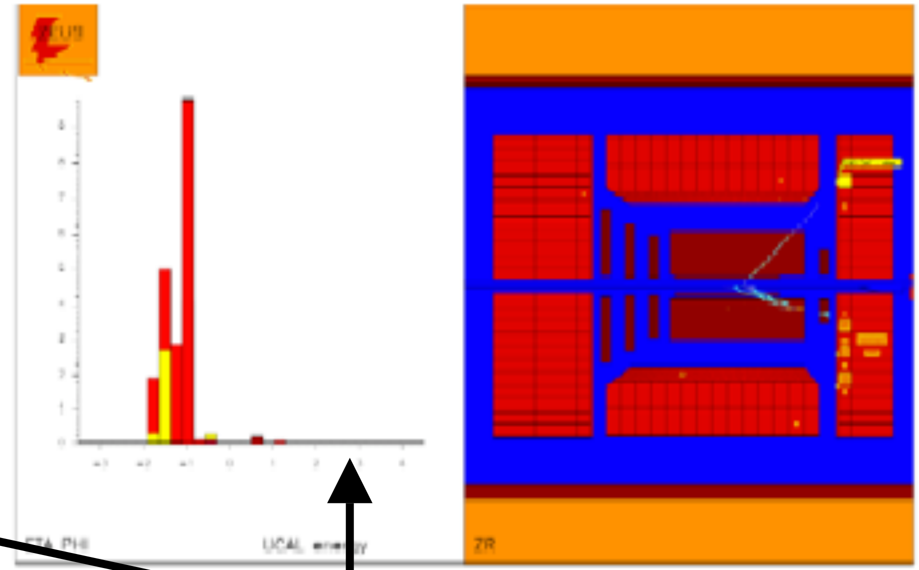


Activity in proton direction

Diffractive Physics in *e*+A

Diffractive event



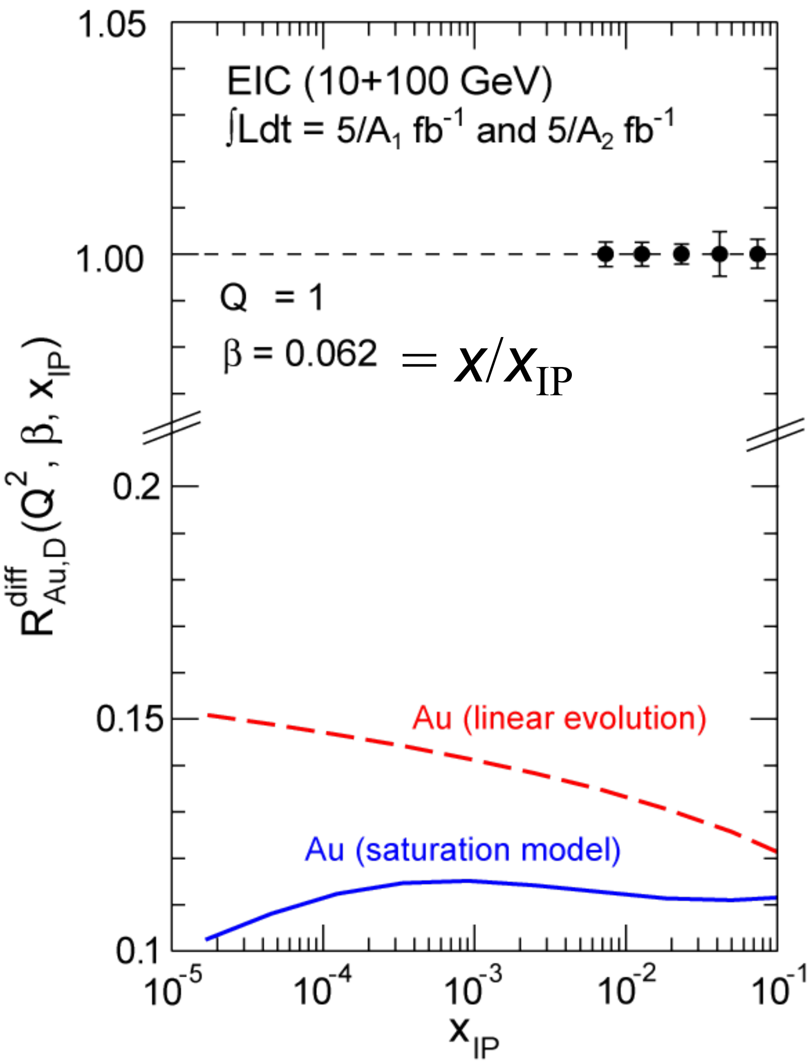


Activity in proton direction

- 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 at EIC

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



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 RHIC & LHC Physics

Thermalization:

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

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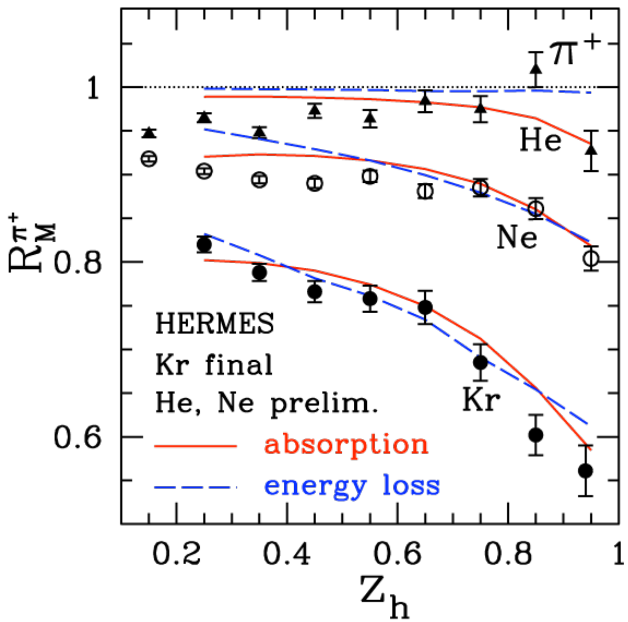
    - ⇒ need more precise handles
- no data on charm from HERMES

FF modification
(parton energy loss)



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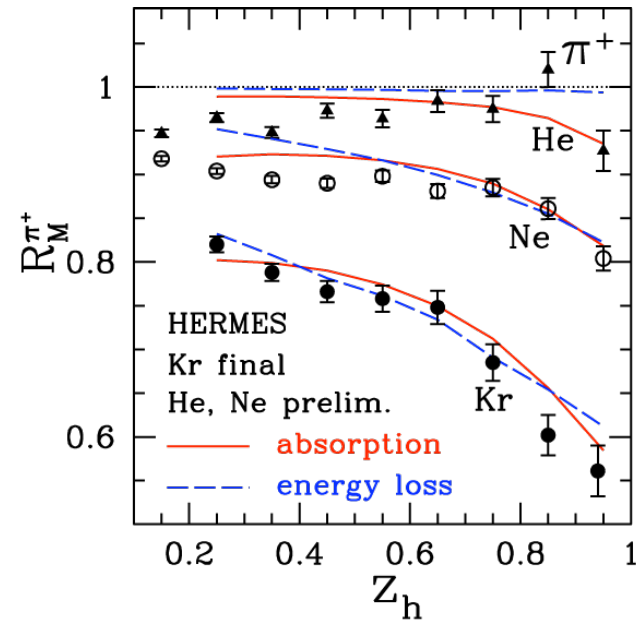
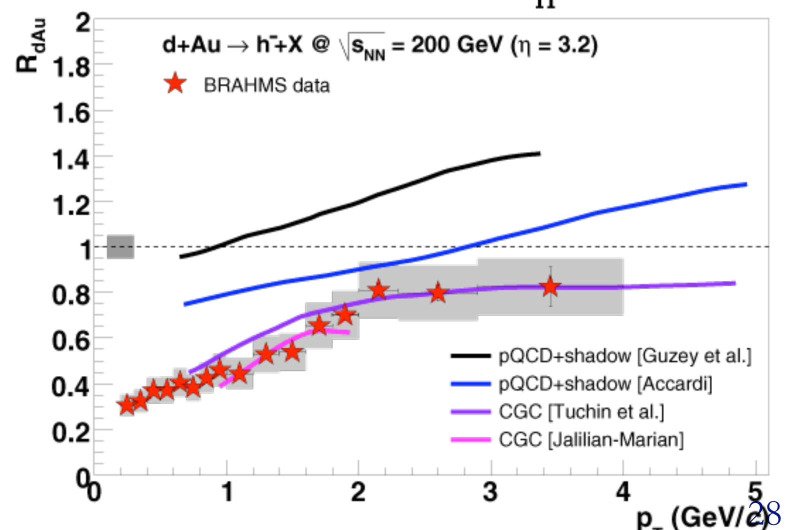
Forward Region:

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

FF modification
(parton energy loss)



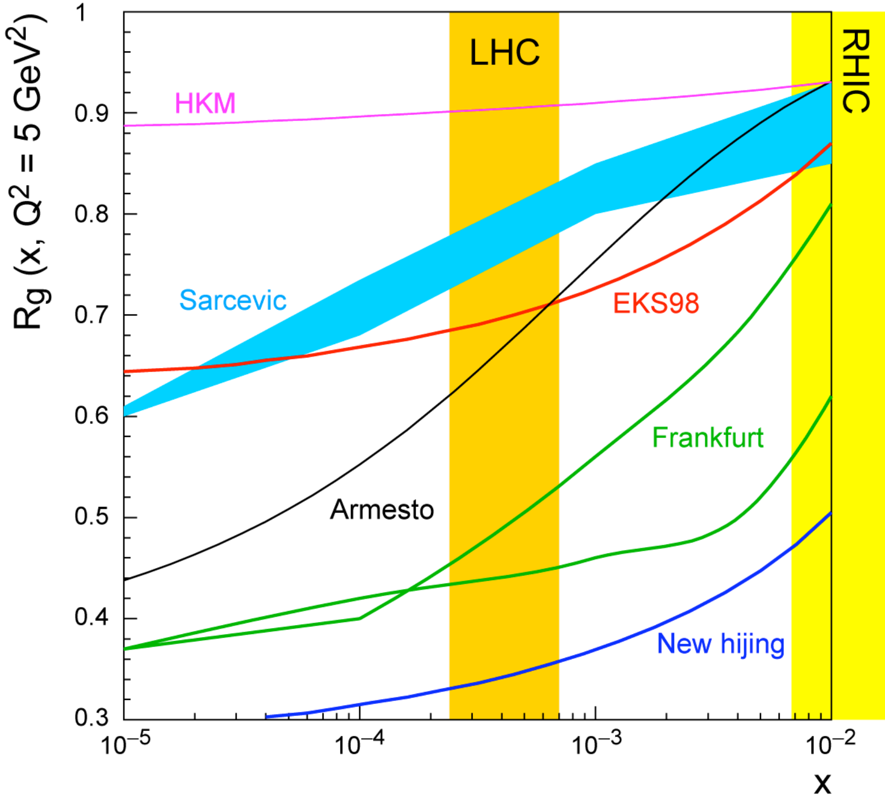


Connection to RHIC & LHC Physics

Ther

Even more crucial at LHC:

Ratios of gluon distribution functions for Pb versus x from different models at $Q^2 = 5$ GeV^2:



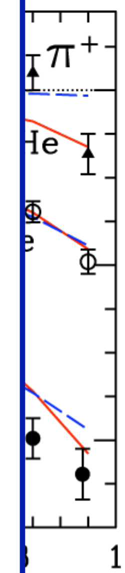
?

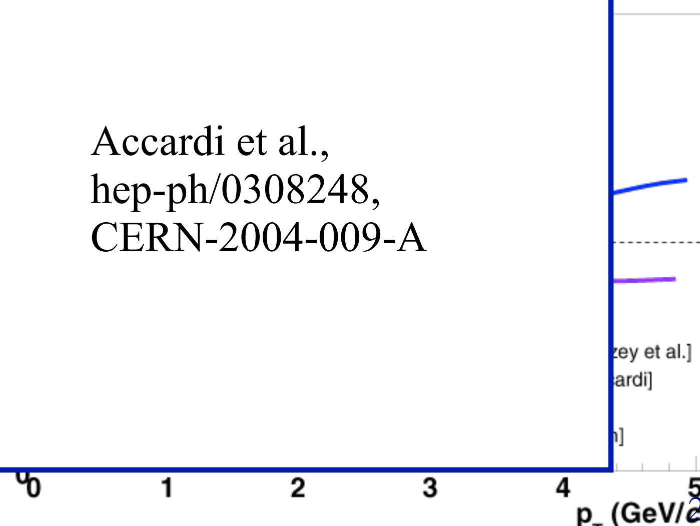
Accardi et al., hep-ph/0308248, CERN-2004-009-A

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

Jet C

Forw

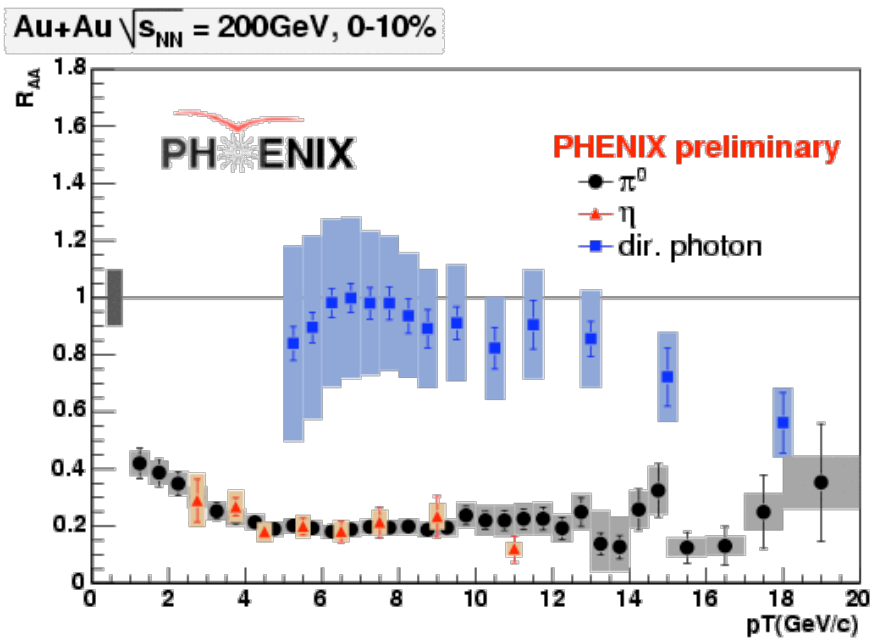


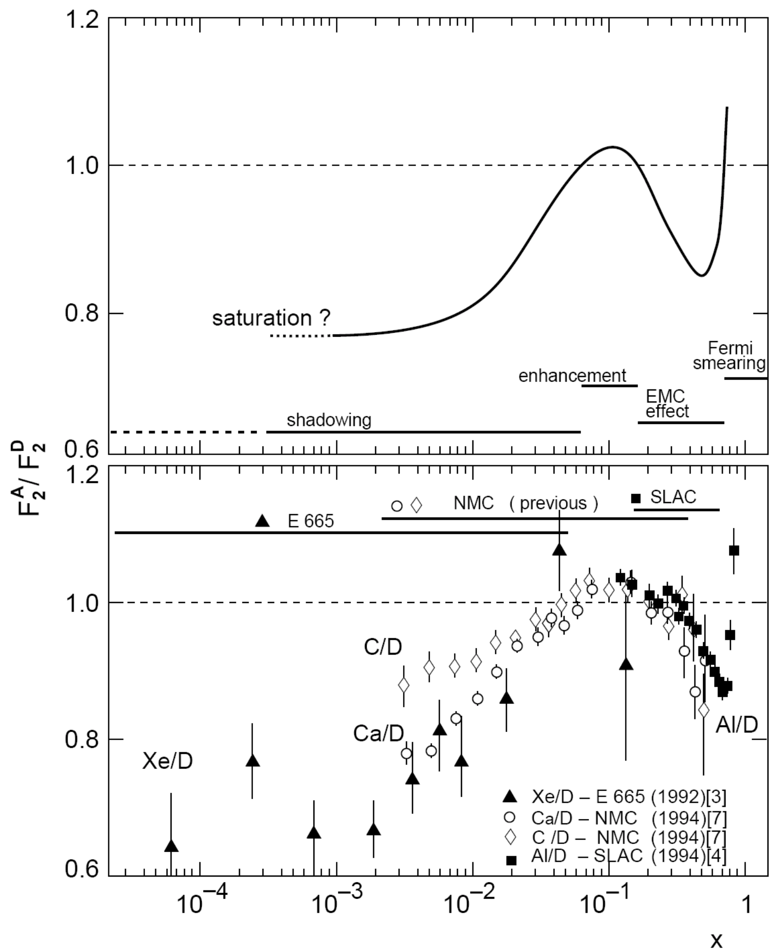


Many New Questions w/o Answers …

From RHIC:

- Observe "E-loss" of direct photons
  - Are we seeing the EMC effect?





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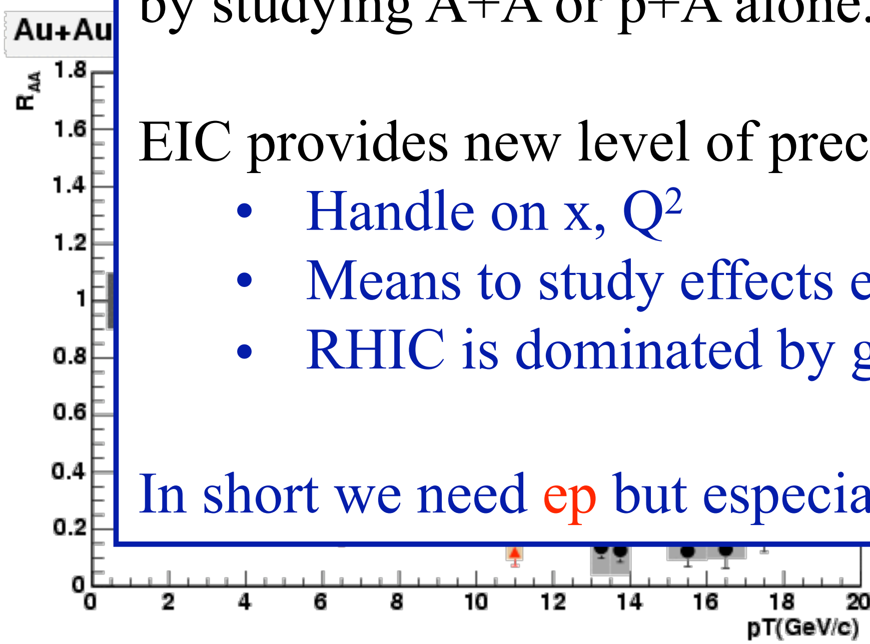
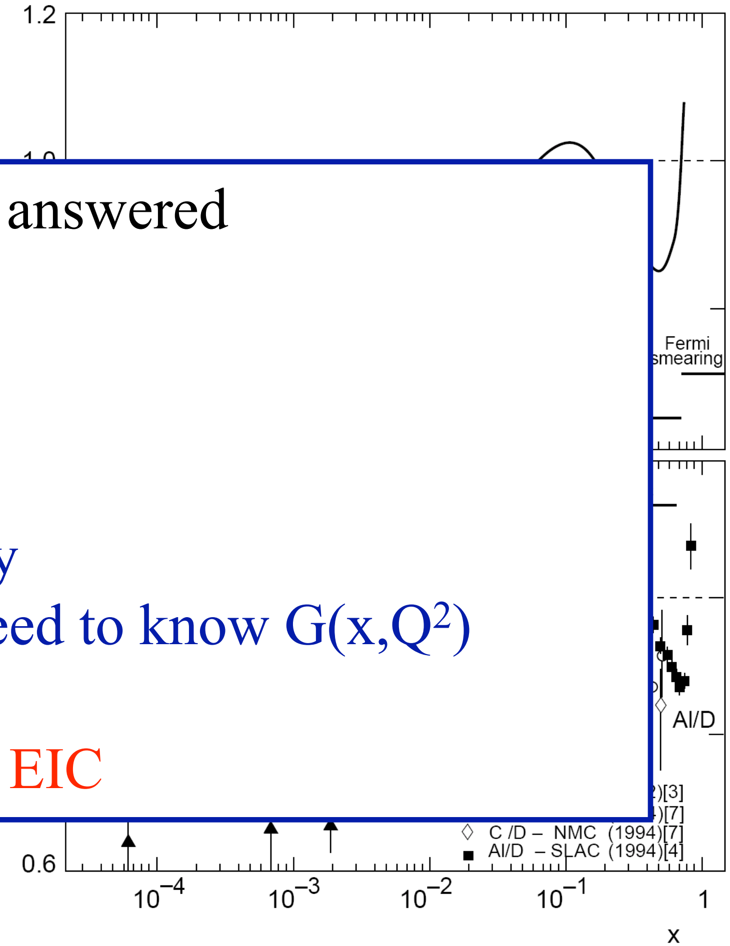




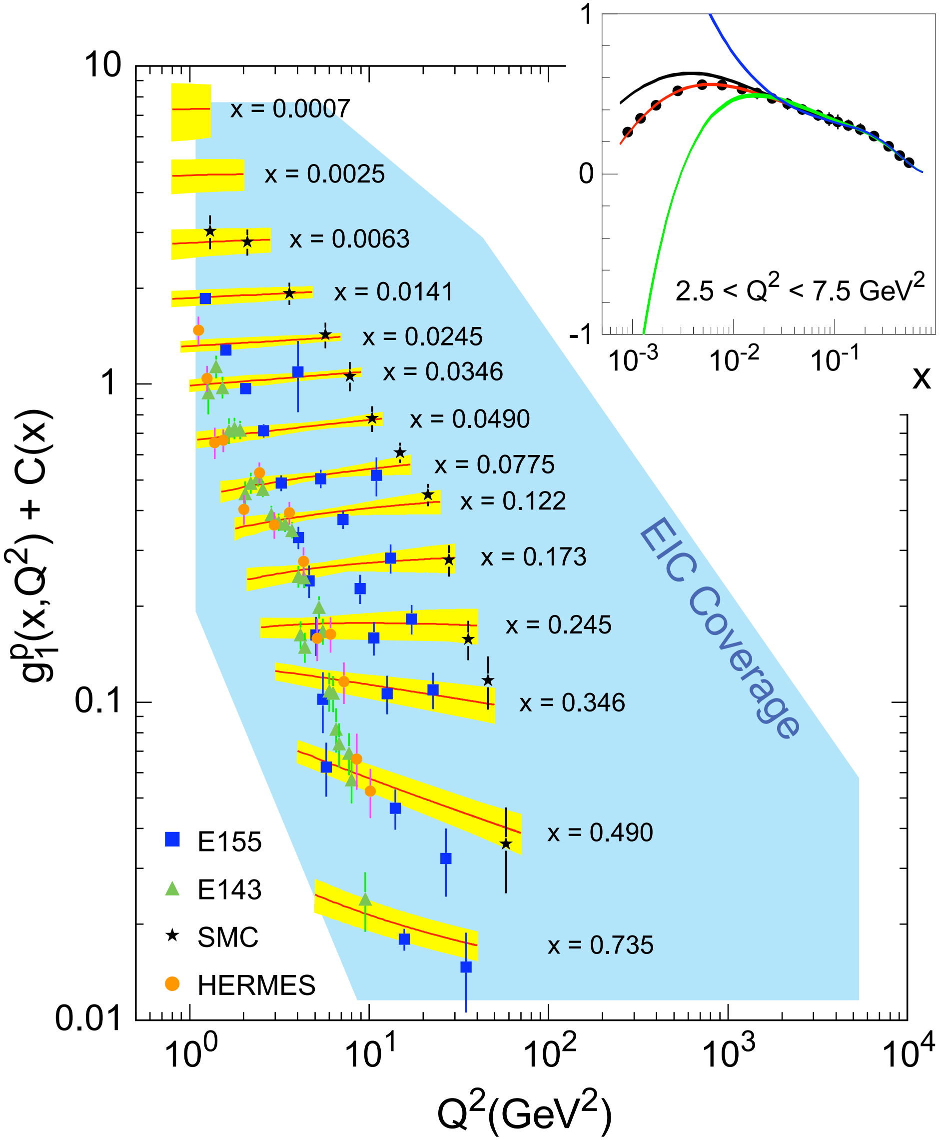
Many (all?) of these questions cannot be answered by studying A+A or p+A alone.

EIC provides new level of precision:

- Handle on x, Q^2
- Means to study effects exclusively
- RHIC is dominated by glue $\Rightarrow$ Need to know $G(x,Q^2)$

In short we need ep but especially eA $\Rightarrow$ EIC

Spin Physics at the EIC - 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)

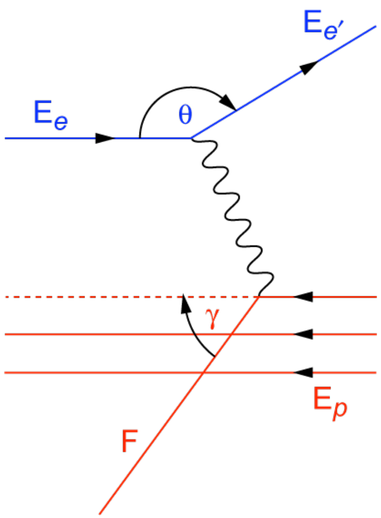
Measure through scaling violation:

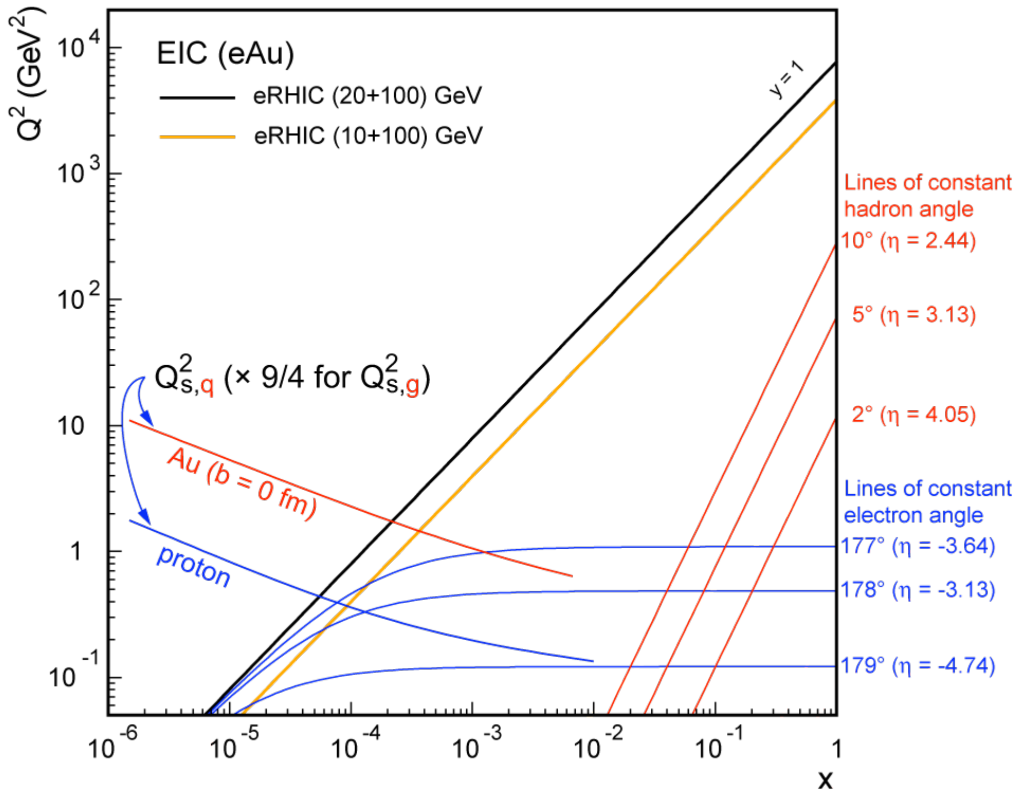
$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$

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

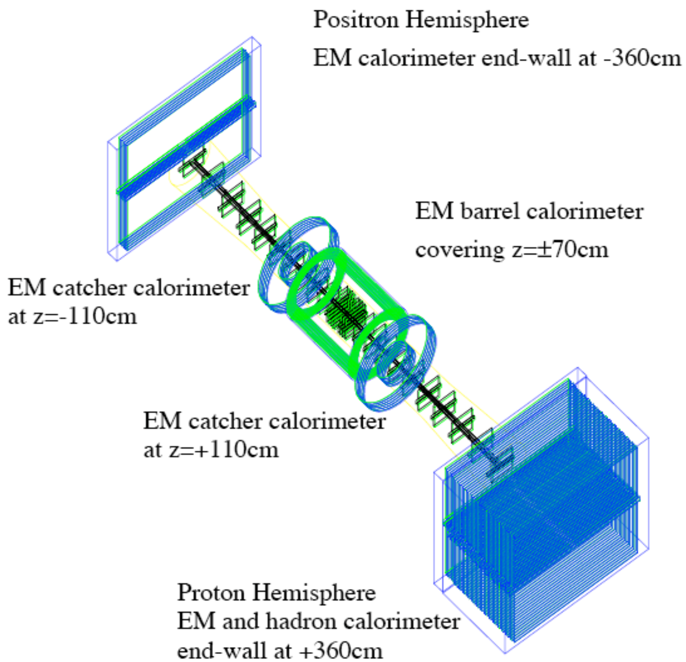
Superb sensitivity to Δg at small x!

Experimental Aspects at the EIC

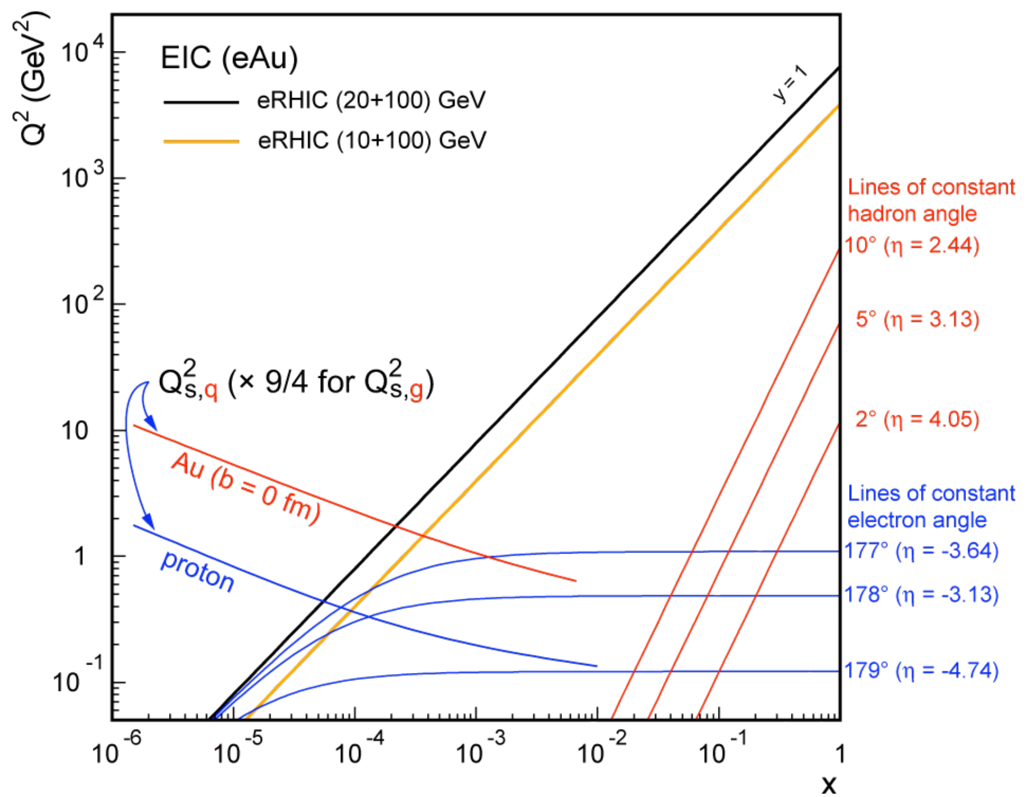




Experimental Aspects at the EIC



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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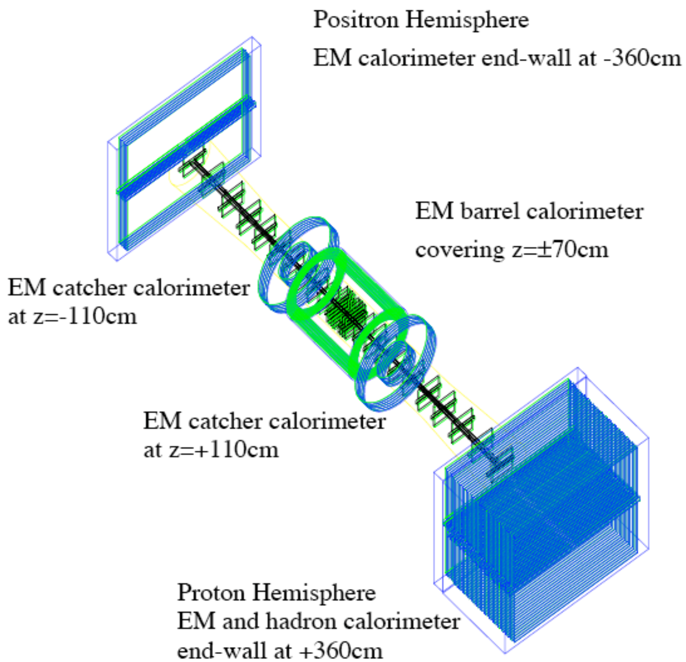

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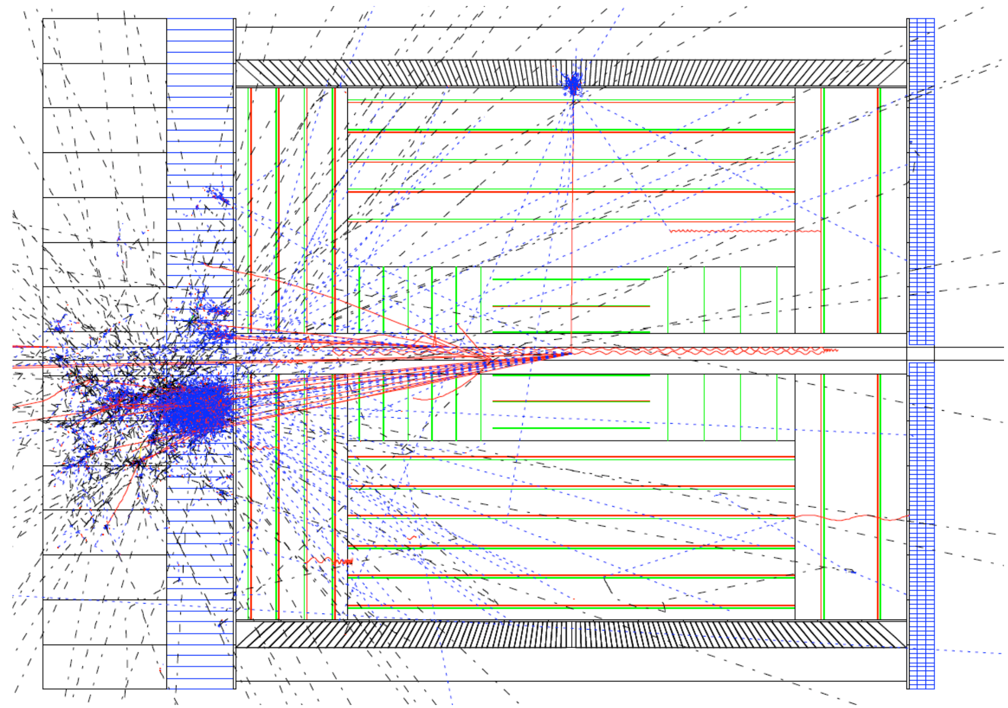


J. Pasukonis, B.Surrow, physics/0608290

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
- Focus on a wide acceptance detector system similar to HERA experiments
  - allow for the maximum possible Q2 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 • Explore non-linear QCD • Measure momentum & space-time of glue ◆ Study the nature of color singlet excitations (Pomerons) ◆ Test and study the limits of universality (eA vs. pA)	◆ 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 $30M for R&D over next 5 years
- EIC Long Term Goal: Start construction in next decade

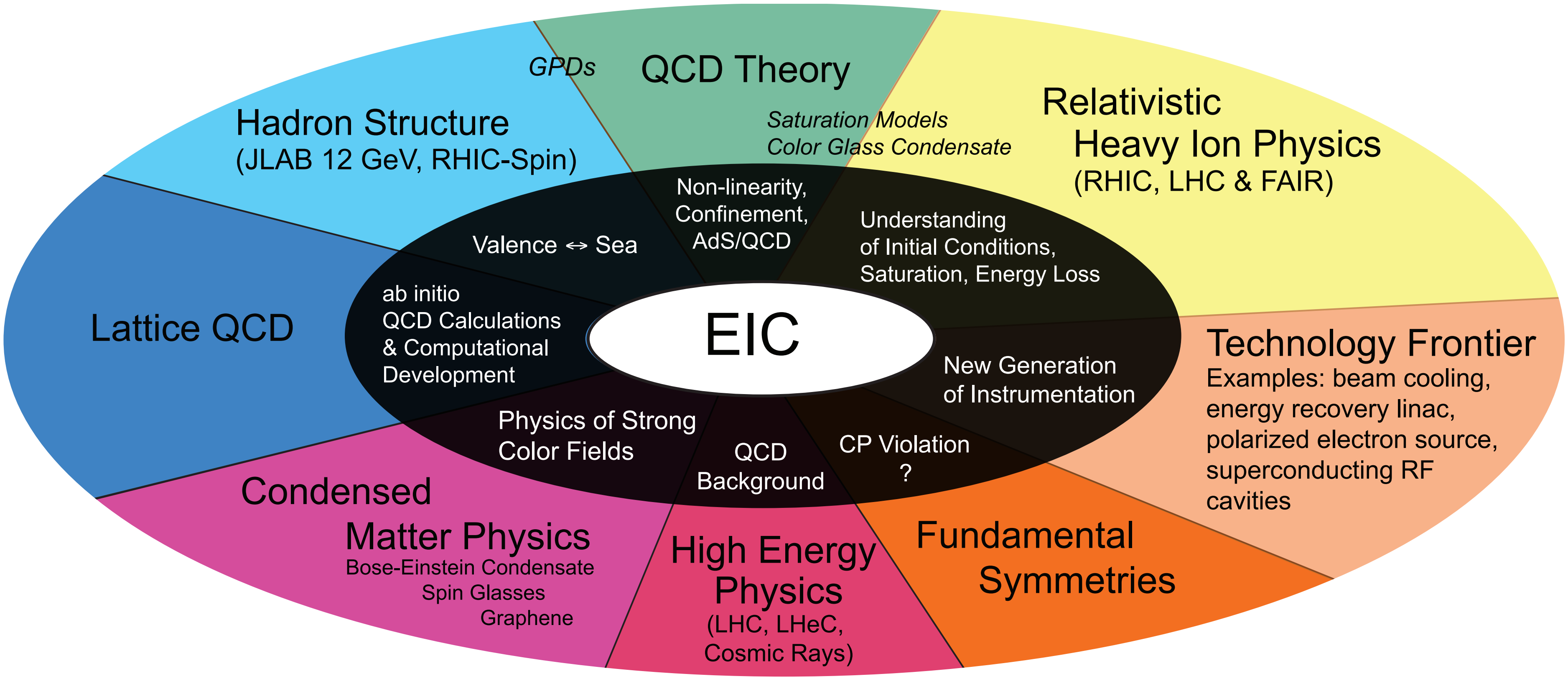
EIC Open Collaboration Meeting

Stony Brook University
7-8 December, 2007

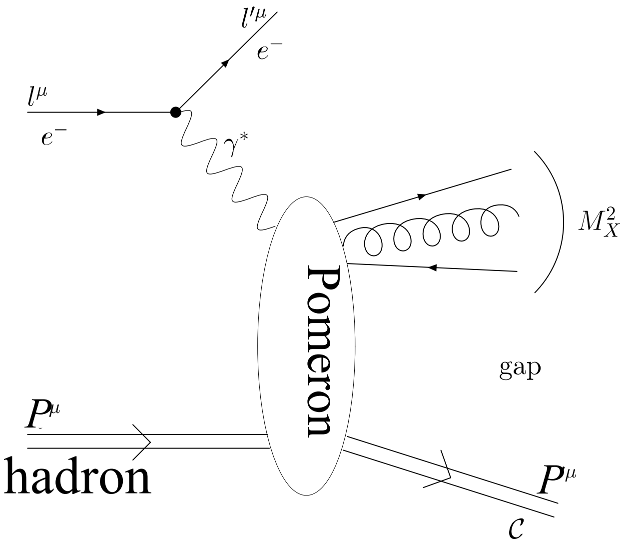
`http://web.mit.edu/eicc/SBU07/index.html`

Additional Slides

Connection to Other Fields



Diffractive DIS is …



when the hadron/nuclei remains intact

momentum transfer
$t = (P-P')^2 < 0$

diffractive mass of the final state
$M_X^2 = (P-P'+l-l')^2$

$$\beta = \frac{Q^2}{2\,(P-P').(l-l')} = \frac{Q^2}{M_X^2 - t + Q^2}$$

β ~ momentum fraction of the struck parton with respect to the Pomeron

$x_{pom} = x/\beta$ rapidity gap : $\Delta\eta = \ln(1/x_{pom})$

x_{pom} ~ momentum fraction of the Pomeron with respect to the hadron

$$\frac{d^4\sigma^{eh\to eXh}}{dx\,dQ^2\,d\beta\,dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2^{D,4}(x, Q^2, \beta, t) - \frac{y^2}{2} F_L^{D,4}(x, Q^2, \beta, t)\right]$$

EIC Timeline & Status

- NSAC Long Range Plan 2007
  - Recommendation: $6M/year for 5 years for machine and detector R&D
- Goal for Next Long Range Plan 2012
  - High-level (top) recommendation for construction
- EIC Roadmap (Technology Driven)

Finalize Detector Requirements from Physics	2008
Revised/Initial Cost Estimates for eRHIC/ELIC	2008
Investigate Potential Cost Reductions	2009
Establish process for EIC design decision	2010
Conceptual detector designs	2010
R&D to guide EIC design decision	2011
EIC design decision	2011
"MOU's" with foreign countries?	2012

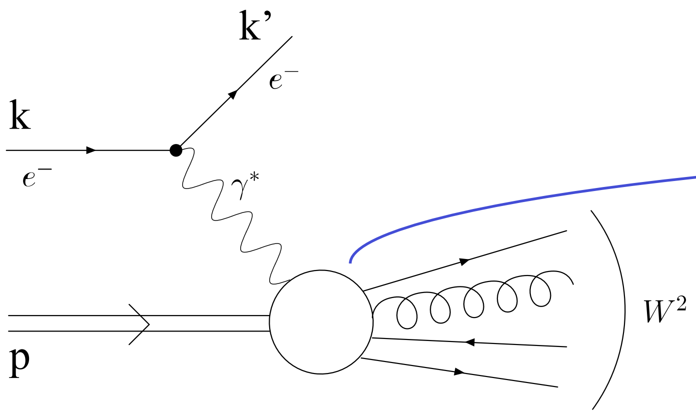
Why HERA did not do EIC physics?

- eA physics:
  - Up to Ca beams considered
  - 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.

eA From a "Dipole" Point of View

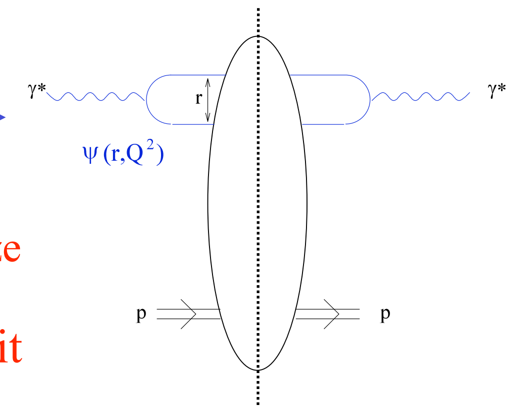
In the rest frame of the nucleus:

Propagation of a small pair, or "color dipole"



r : dipole size

valid in the small-x limit



Coherence length of virtual photon's fluctuation into $q\bar{q}$: $L \sim 1/2m_N x$

L >> 2R

- Physics of strong color fields
- Shadowing
- Diffraction

L << 2R

- Energy Loss
- color transparency
- EMC effect

The EIC Collaboration

[17]C. Aidala, [28]E. Aschenauer, [10]J. Annand, [1]J. Arrington, [26]R. Averbeck, [3]M. Baker, [26]K. Boyle, [28]W. Brooks, [28]A. Bruell, [19]A. Caldwell, [28]J.P. Chen, [2]R. Choudhury, [10]E. Christy, [8]B. Cole, [4]D. De Florian, [3]R. Debbe, [26,24-1]A. Deshpande, [18]K. Dow, [26]A. Drees, [3]J. Dunlop, [2]D. Dutta, [7]F. Ellinghaus, [28]R. Ent, [18]R. Fatemi, [18]W. Franklin, [28]D. Gaskell, [16]G. Garvey, [12,24-1]M. Grosse-Perdekamp, [1]K. Hafidi, [18]D. Hasell, [26]T. Hemmick, [1]R. Holt, [8]E. Hughes, [22]C. Hyde-Wright, [5]G. Igo, [14]K. Imai, [10]D. Ireland, [26]B. Jacak, [15]P. Jacobs, [28]M. Jones, [10]R. Kaiser, [17]D. Kawall, [11]C. Keppel, [7]E. Kinney, [18]M. Kohl, [9]H. Kowalski, [17]K. Kumar, [2]V. Kumar, [21]G. Kyle, [13]J. Lajoie, [3]M. Lamont, [16]M. Leitch, [27]A. Levy, [27]J. Lichtenstadt, [10]K. Livingstone, [20]W. Lorenzon, [14]S. Matis, [12]N. Makins, [6]G. Mallot, [18]M. Miller, [18]R. Milner, [2]A. Mohanty, [3]D. Morrison, [26]Y. Ning, [15]G. Odyniec, [13]C. Ogilvie, [2]L. Pant, [26]V. Pantuyev, [21]S. Pate, [26]P. Paul, [12]J.-C. Peng, [18]R. Redwine, [1]P. Reimer, [15]H.-G. Ritter, [10]G. Rosner, [25]A. Sandacz, [7]J. Seele, [12]R. Seidl, [10]B. Seitz, [2]P. Shukla, [15]E. Sichtermann, [18]F. Simon, [3]P. Sorensen, [3]P. Steinberg, [24]M. Stratmann, [22]M. Strikman, [18]B. Surrow, [18]E. Tsentalovich, [11]V. Tvaskis, [3]T. Ullrich, [3]R. Venugopalan, [3]W. Vogelsang, [28]C. Weiss, [15]H. Wieman,[15]N. Xu,[3]Z. Xu, [8]W. Zajc.

[1]Argonne National Laboratory, Argonne, IL; [2]Bhabha Atomic Research Centre, Mumbai, India; [3]Brookhaven National Laboratory, Upton, NY; [4]University of Buenos Aires, Argentina; [5]University of California, Los Angeles, CA; [6]CERN, Geneva, Switzerland; [7]University of Colorado, Boulder,CO; [8]Columbia University, New York, NY; [9]DESY, Hamburg, Germany; [10]University of Glasgow, Scotland, United Kingdom; [11]Hampton University, Hampton, VA; [12]University of Illinois, Urbana-Champaign, IL; [13]Iowa State University, Ames, IA; [14]University of Kyoto, Japan; [15]Lawrence Berkeley National Laboratory, Berkeley, CA; [16]Los Alamos National Laboratory, Los Alamos, NM; [17]University of Massachusetts, Amherst, MA; [18]MIT, Cambridge, MA; [19]Max Planck Institüt für Physik, Munich, Germany; [20]University of Michigan Ann Arbor, MI; [21]New Mexico State University, Las Cruces, NM; [22]Old Dominion University, Norfolk, VA; [23]Penn State University, PA; [24]RIKEN, Wako, Japan; [24-1]RIKEN-BNL Research Center, BNL, Upton, NY; [25]Soltan Institute for Nuclear Studies, Warsaw, Poland; [26]SUNY, Stony Brook, NY; [27]Tel Aviv University, Israel; [28]Thomas Jefferson National Accelerator Facility, Newport News, VA

96 Scientists, 28 Institutions, 9 countries