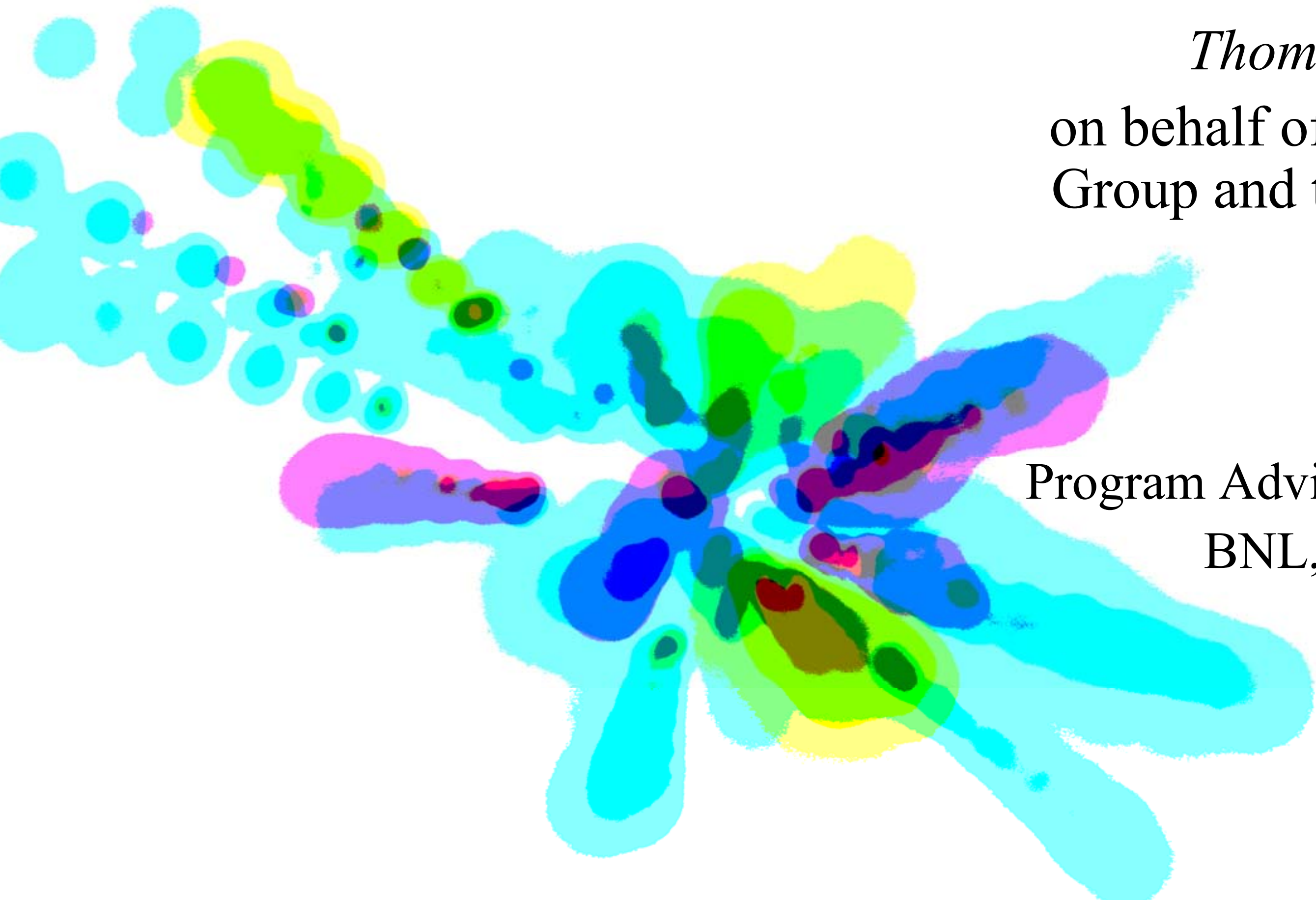
Physics Opportunities with *e*+A Collisions at an Electron Ion Collider



Thomas Ullrich, BNL

on behalf of the EIC/eA Working Group and the EIC Collaboration

Program Advisory Committee Meeting

BNL, March 29, 2007

BROOKHAVEN
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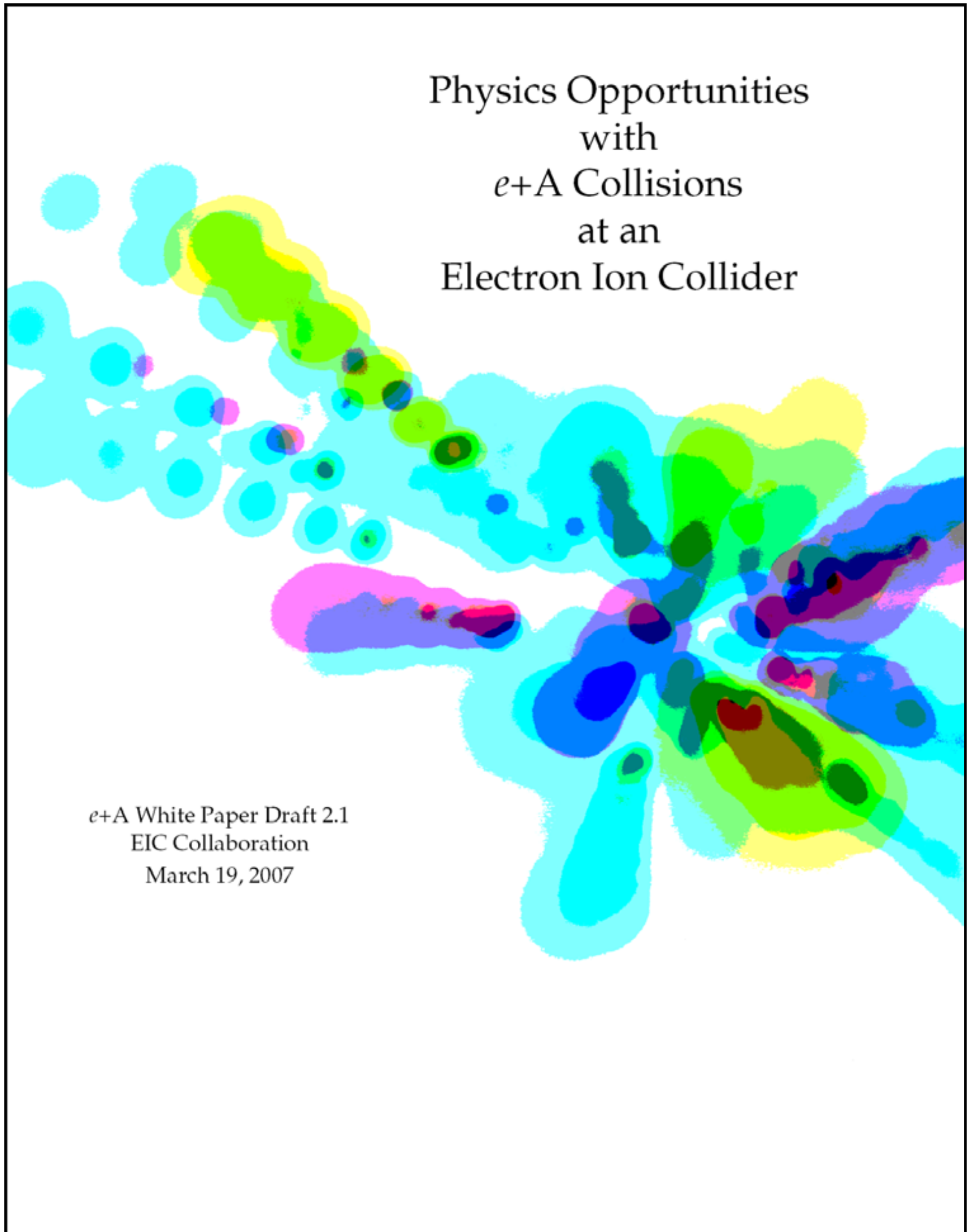
Position Paper on EIC/*e*+A Program


Physics Opportunities
with
e+A Collisions
at an
Electron Ion Collider

e+A White Paper Draft 2.1
EIC Collaboration
March 19, 2007

Abstract

We outline the compelling physics case for e+A collisions at an Electron Ion Collider (EIC). With its wide range in energy, nuclear beams, high luminosity and clean collider environment, the EIC offers an unprecedented opportunity for discovery and for the precision study of a novel universal regime of strong gluon fields in Quantum Chromodynamics (QCD). The EIC will measure, in a wide kinematic regime, the momentum and space-time distribution of gluons and sea-quarks in nuclei, the scattering of fast, compact probes in extended nuclear media and role of color neutral (Pomeron) excitations in scattering off nuclei. These measurements at the EIC will also deepen and corroborate our understanding of the formation and properties of the strongly interacting Quark Gluon Plasma (QGP) in high energy heavy ion collisions at RHIC and the LHC.

20 pages, 22 figures, 2 tables

Can be downloaded at:

http://www.phenix.bnl.gov/~dave/eic/PositionPaper_eA.pdf

What I will show here ….

in the next slides (and what is in the eA position paper) is the work of a whole group of people with a solid mix of theory and experimentalists.

Editors: Dave Morrison (BNL), Raju Venugopalan (BNL), TU (BNL)

Valuable contributions/simulations/calculations/text from:

Alberto Accardi (Iowa State), James Dunlop (BNL), Daniel de Florian (Buenos Aires), Vadim Guzey (Bochum, Germany), Tuomas Lappi (BNL), Cyrille Marquet (BNL), Jianwei Qiu (Iowa State), Peter Steinberg (BNL), Bernd Surrow (MIT), Werner Vogelsang (BNL), Zhanbu Xu (BNL)

Color code: Theory, Experiment

Theory of Strong Interactions: QCD

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

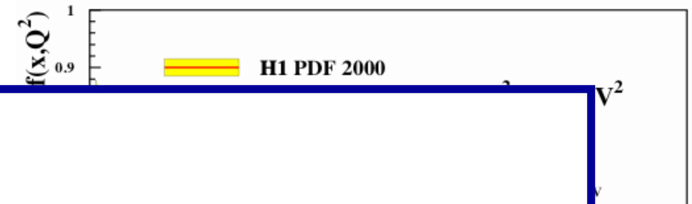
- "Emergent" Phenomena not evident from Lagrangian
  - Asymptotic Freedom
  - Color Confinement
  - In large due to non-perturbative structure of QCD vacuum
- Gluons: mediator of the strong interactions
  - Determine structure of QCD vacuum (fluctuations in gluon fields)
  - Responsible for > 98% of the visible mass in universe
  - Determine all the essential features of strong interactions
- Hard to "see" the glue in the low-energy world
  - Gluon degrees of freedom "missing" in hadronic spectrum
    - but *dominate* the structure of baryonic matter at low-x
    - are important (dominant?) player at RHIC and LHC

QCD requires *fundamental* investigation via *experiment*

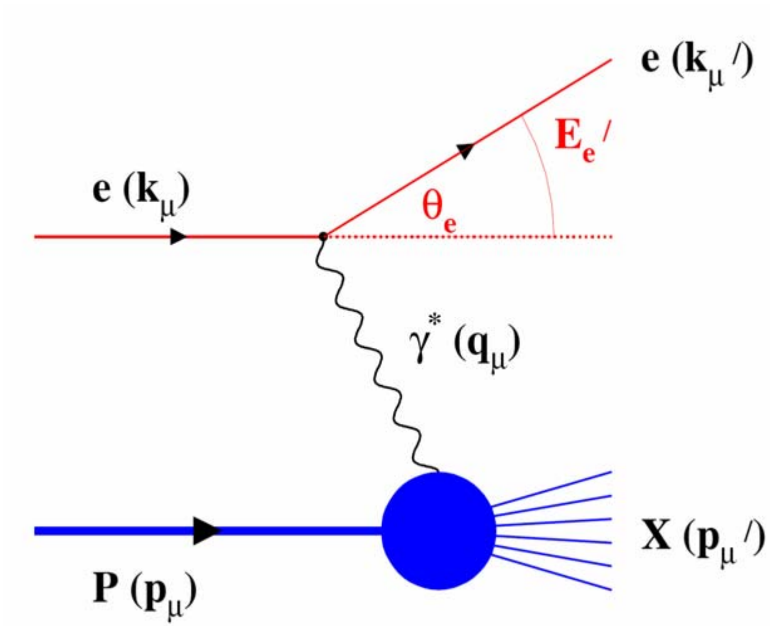
What Do We Know About Glue in Matter?

Established Model:

Lin



Deep Inelastic Scattering:



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

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

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

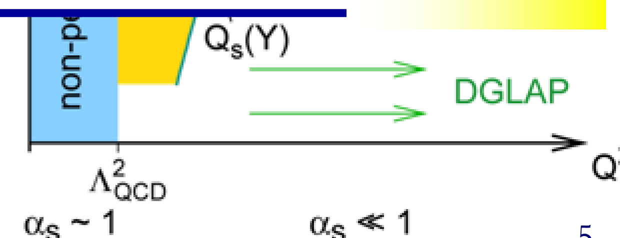
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

"Perfect" Tomography

Ne

- grows with decreasing x and increasing A
- arises naturally in the CGC framework



Understanding Glue in Matter

Understanding the role of the 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)?

What system to use?

1. e+p works, but more accessible by using e+A
2. have analogs in e+p, but have never been measured in e+A
3. have no analog in e+p

eA: Ideal to Study Non-Linear Effects

Scattering of electrons off nuclei:

- Small x partons cannot be localized longitudinally to better than size of nucleus
- Virtual photon interacts coherently with all nucleons at a given impact parameter

  $\Rightarrow$ Amplification of non-linear effects at small x.

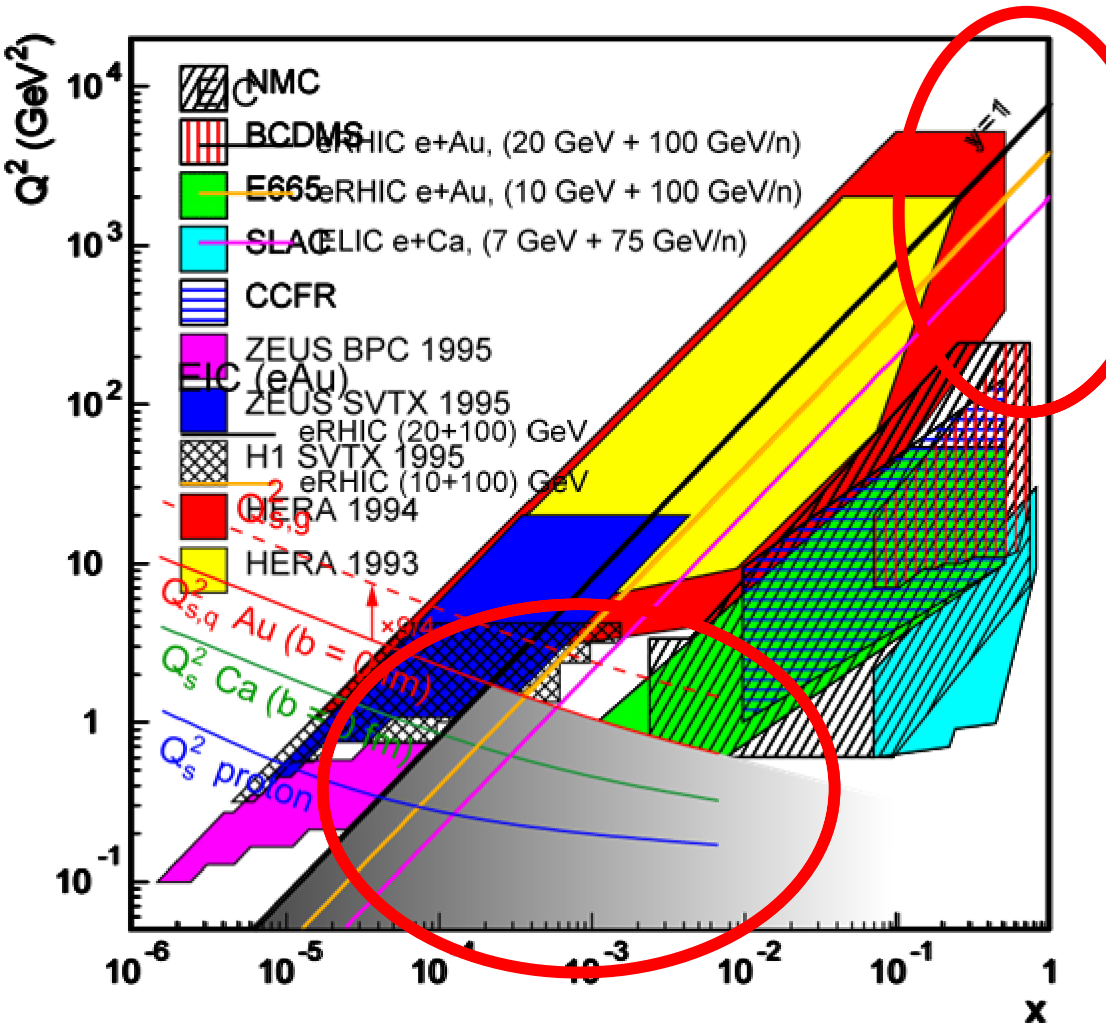
e+A Collisions are Ideal for Studying "Glue"

- Gain deeper understanding of QCD
- Terra incognita: Physics of Strong Color Fields

New MC Glauber studies: $Q_s^2(\mathrm{Au}, b_{\mathrm{median}}) = 6 \times Q_s^2(p, b_{\mathrm{median}})$

In fact, b=0 in Au would give a factor 1.5 higher (9).

eA Landscape and a new Electron Ion Collider



The x, Q^2 plane looks well mapped out – doesn't it?

Except for ℓ+A (νA) many of those with small A and very low statistics

Electron Ion Collider (EIC):

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}

Terra incognita: small-x, $Q \approx Q_s$

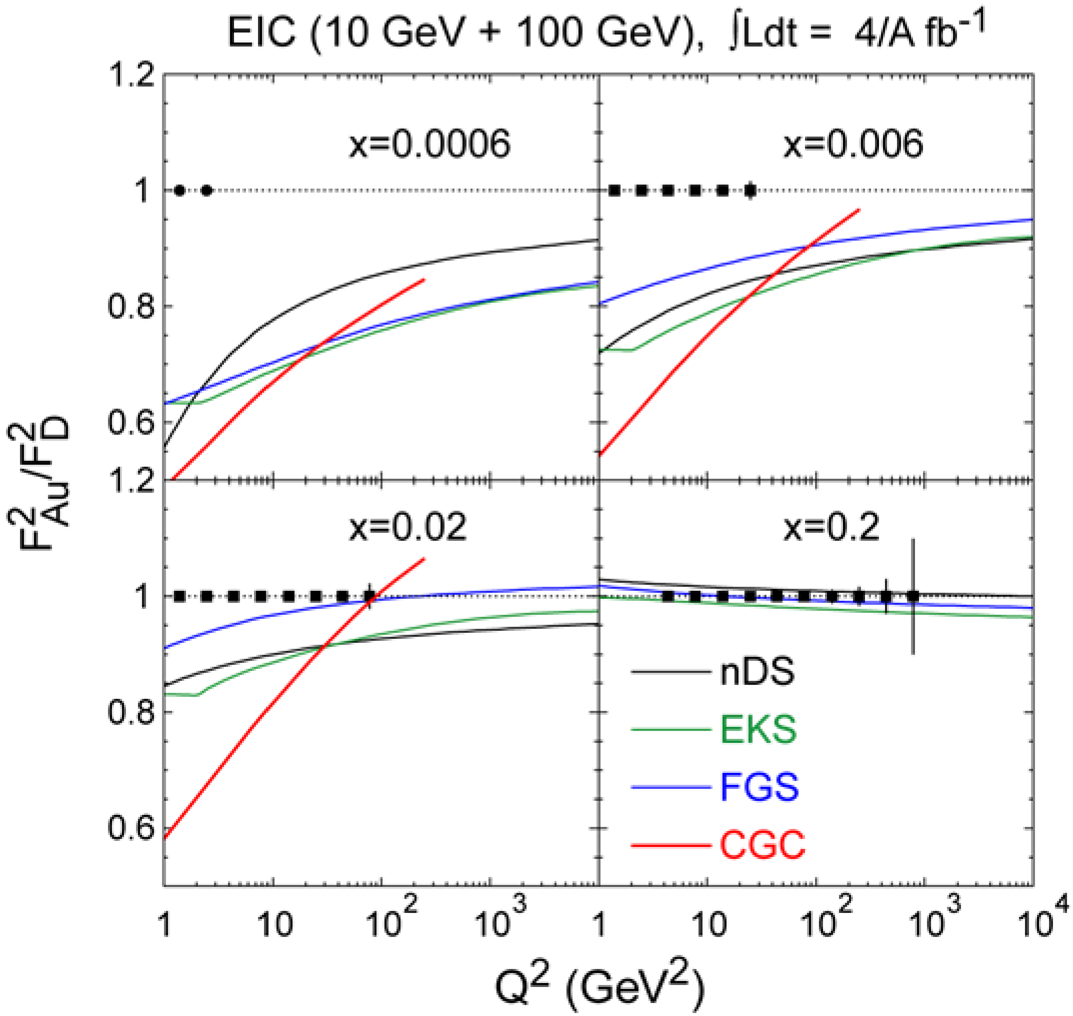
high-x, large Q^2

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)?

- Gluon distribution $G(x,Q^2)$
  - $F_L \sim \alpha_s\, G(x,Q^2)$ (BTW: requires $\sqrt{s}$ scan)
  - Extract from scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - 2+1 jet rates (needs jet algorithm and modeling of hadronization for inelastic hadron final states)
  - inelastic vector meson production (e.g. J/ψ)

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



F_2 will be one of the first measurements at EIC

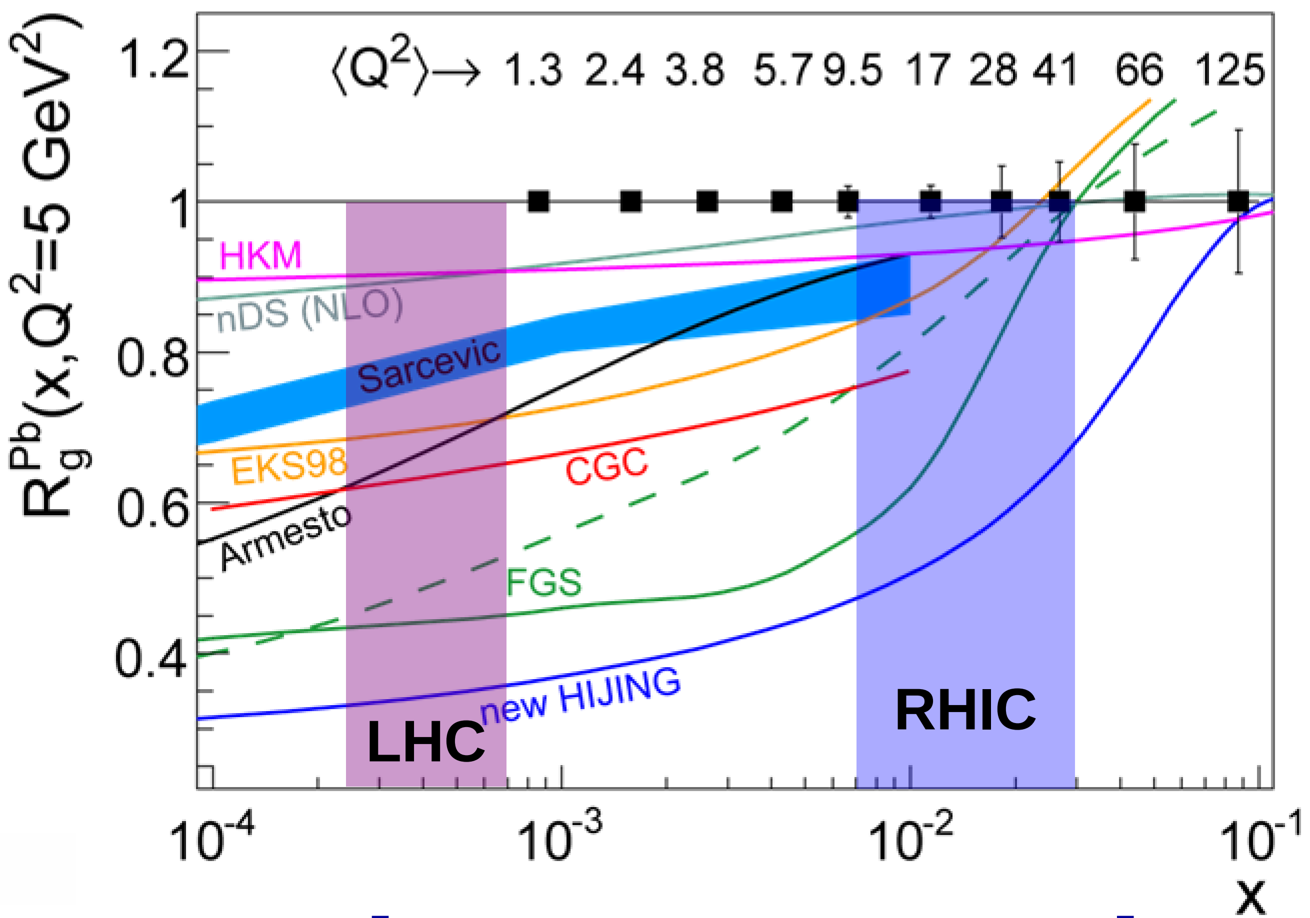
nDS, EKS, FGS:

pQCD models with different amounts of shadowing

EIC will allow to distinguish between pQCD and saturation models predictions

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

F_L at EIC: Measuring the Glue Directly



EIC: (10+100) GeV
$\int L dt = 2/A\ fb^{-1}$

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

$Q^2/xs = y$

Needs √s scan

EIC will allow to measure $G(x,Q^2)$ with great precision

How EIC will Address the Important Questions

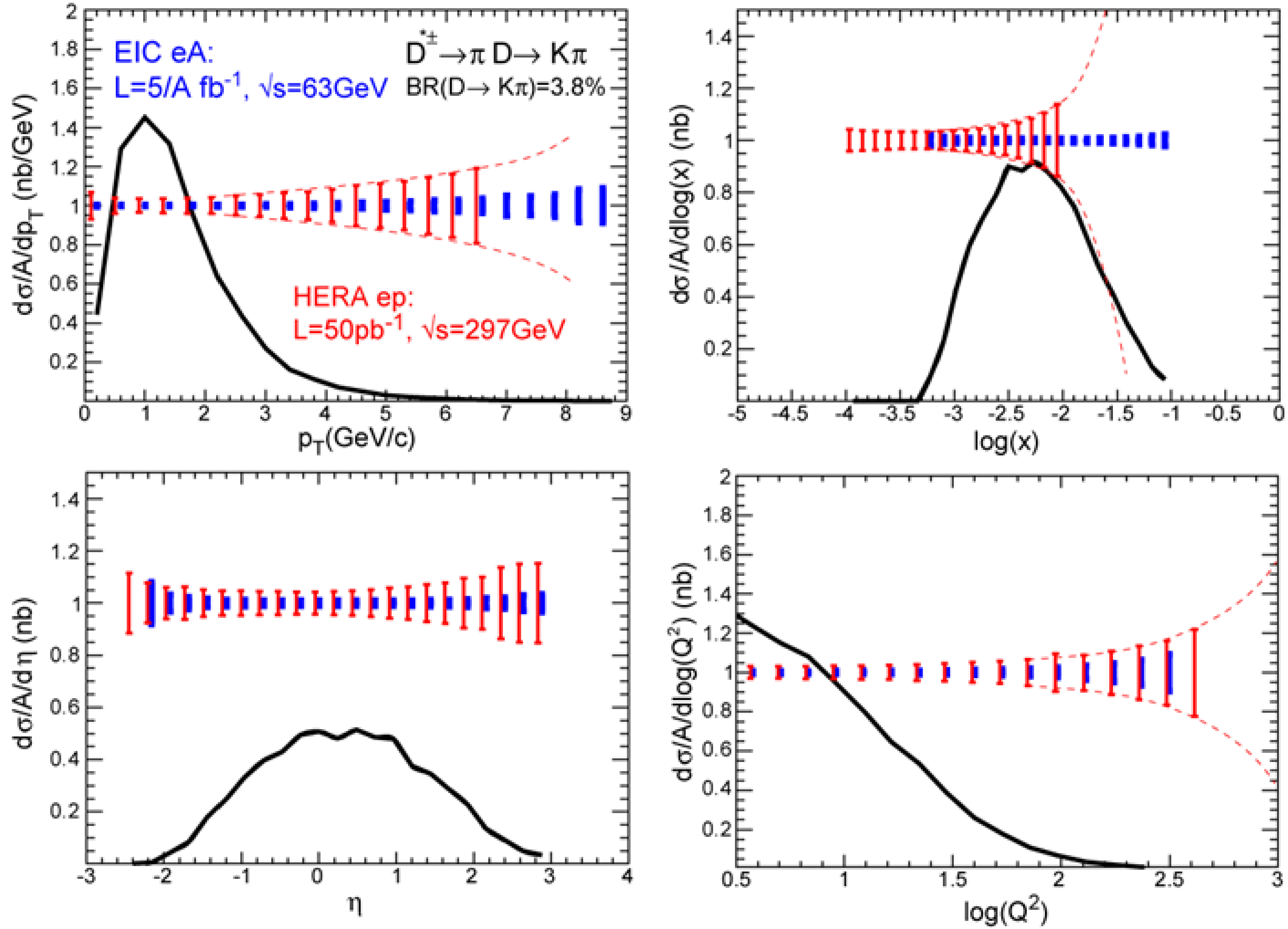
- What is the momentum distribution of the gluons in matter?
- What is the space-time distributions of gluons in matter?
- How do fast probes interact with the gluonic medium?
- Do strong gluon fields effect the role of color neutral excitations (Pomerons)?

  - Measurement of structure functions for various mass numbers A (shadowing, EMC effect) and its impact parameter dependence
  - Deep virtual compton scattering (DVCS) – $\sigma_{DVCS} \sim A^{4/3}$
  - color transparency ⟺ color opacity
  - exclusive final states (e.g. vector meson production ρ, J/ψ, …)

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)?

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

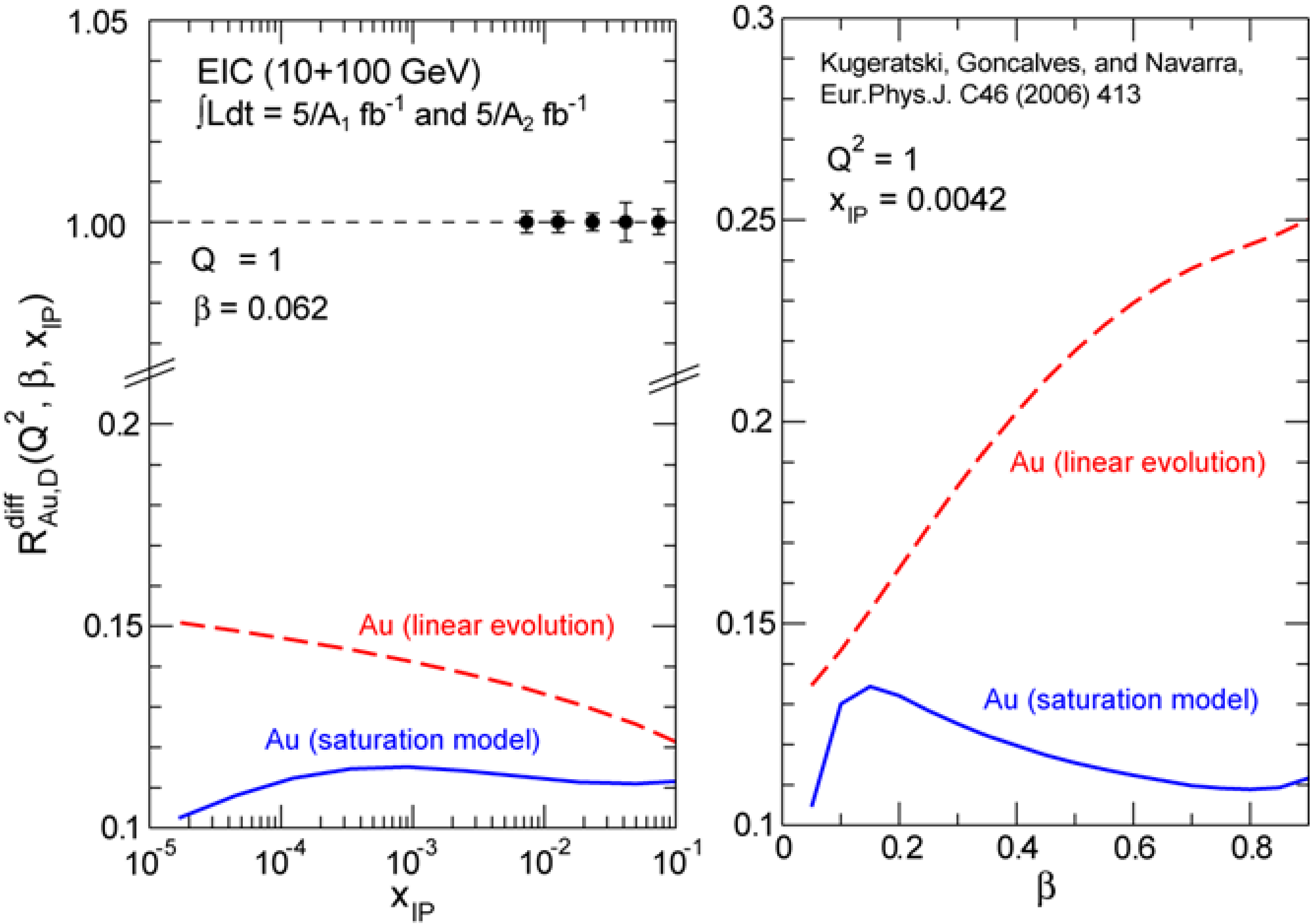
How EIC will Address the Important Questions

- 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)?
  - diffractive cross-section $\sigma_{diff}/\sigma_{tot}$
    - HERA/ep: 10% of all events are hard diffractive EIC/eA: 30%?
  - 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 Structure Function F_2^D at EIC

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



x_{IP} = momentum fraction of the Pomeron with respect to the hadron

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

$x_{IP} = x/\beta$

EIC allows to distinguish between linear evolution and saturation models

Connection to RHIC & LHC Physics

The

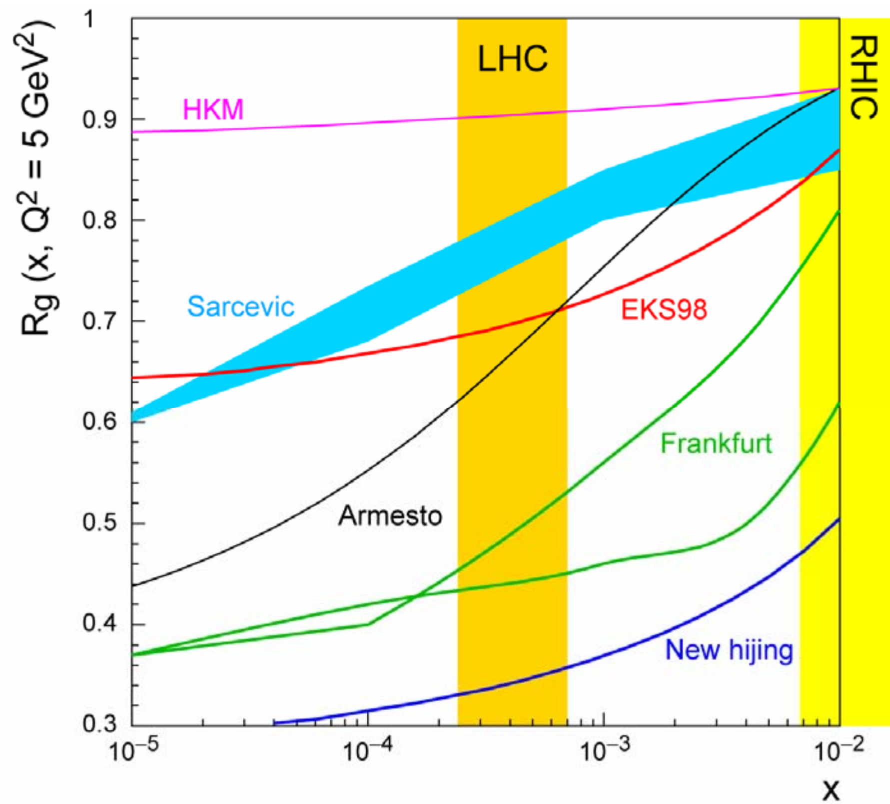
n
loss)

Jet

For

Even more crucial at LHC:

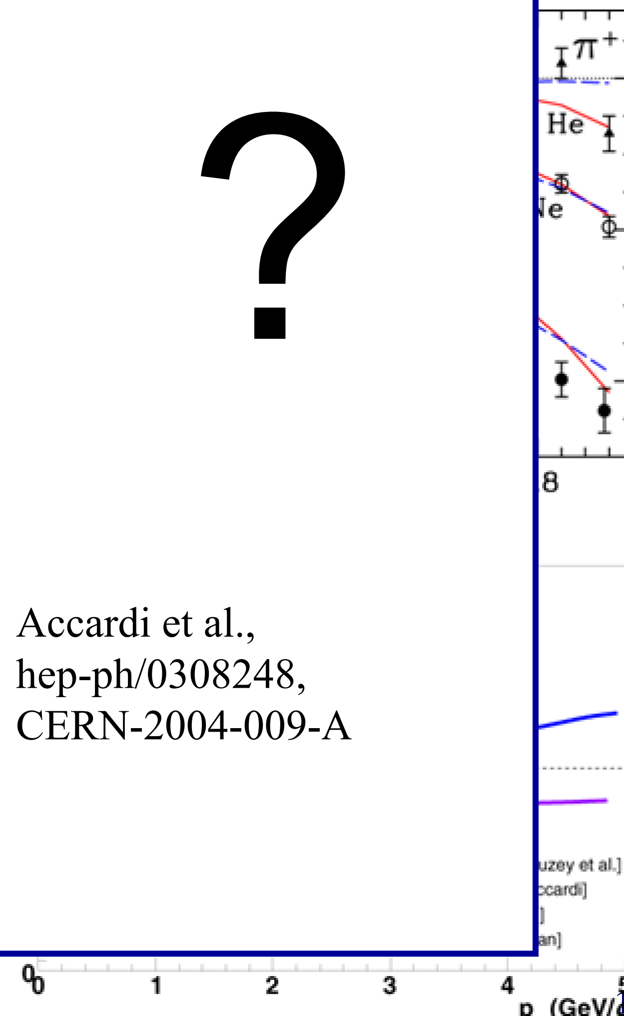
Ratios of gluon distribution functions for Pb versus x from different models at $Q^2 = 5$ GeV^2:



?

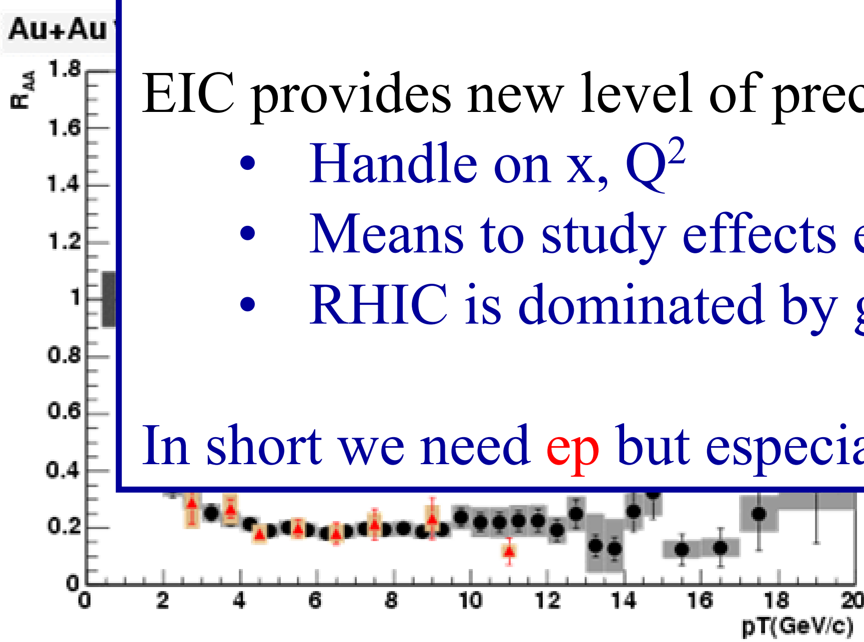
$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{A\, f_i^{\text{nucleon}}(x,Q^2)}, \quad f_i = q, \bar{q}, g$$

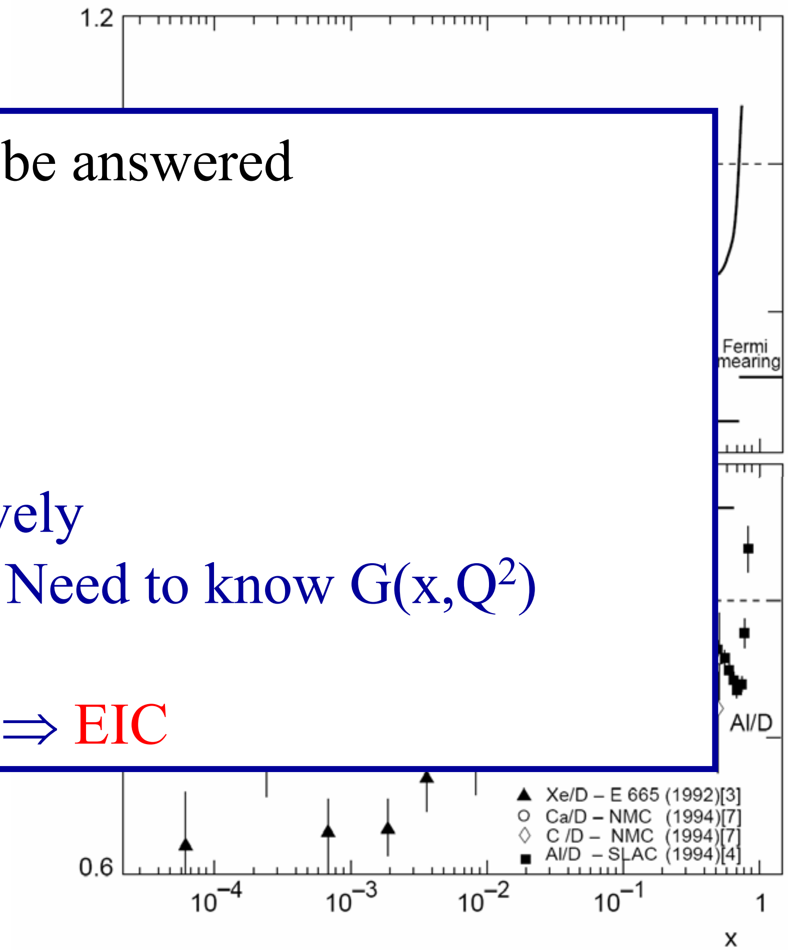
Accardi et al.,
hep-ph/0308248,
CERN-2004-009-A



Many New Questions w/o Answers …

Latest News:





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 ⇒ Need to know $G(x,Q^2)$

In short we need ep but especially **eA** ⇒ EIC

EIC Collider Aspects

Requirements for EIC/eA Program:

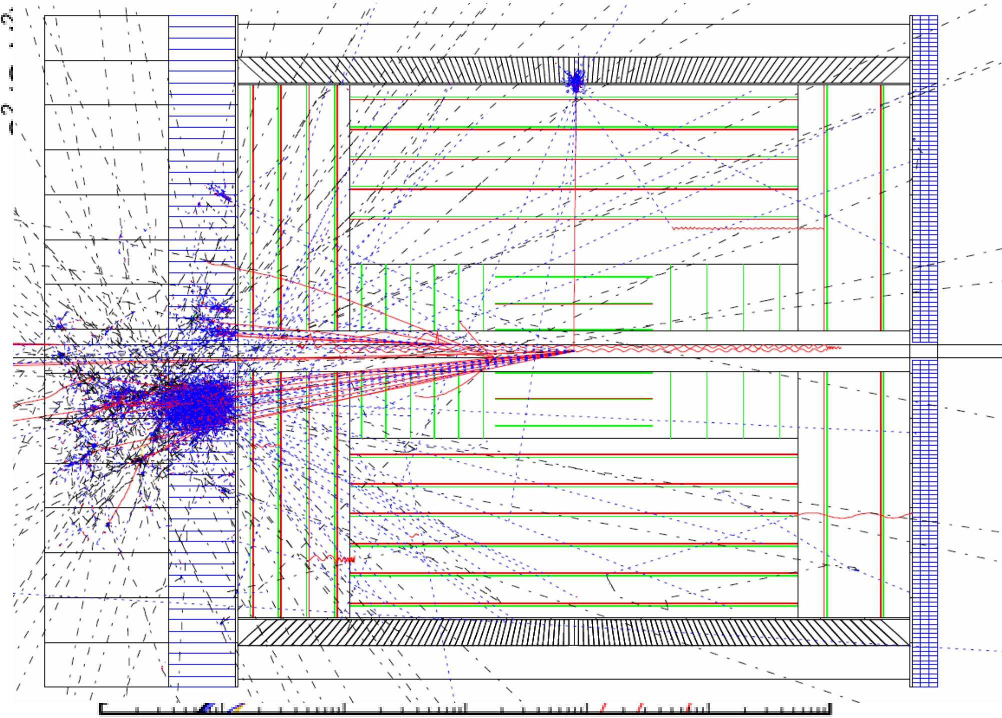
- maximal ion mass A
- √s ~ 100 GeV
- moderate to high luminosity ($L > L_{Hera}$)

There are two complementary concepts to realize EIC:

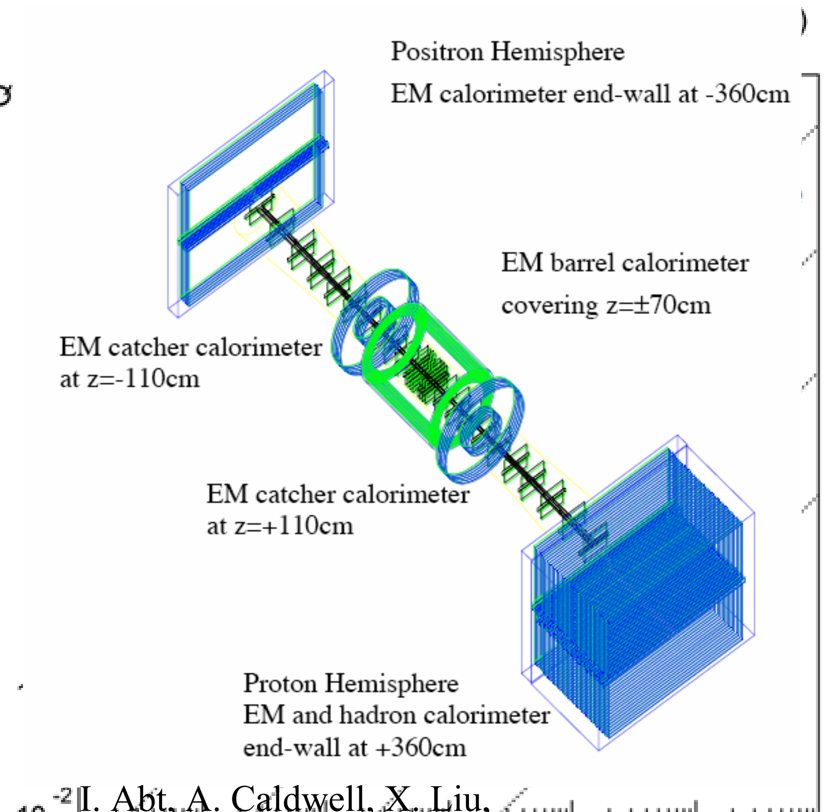
- eRHIC
  - construct electron beam to collide with the existing RHIC ion complex
  - high luminosity ($6 \cdot 10^{30}$ $cm^{-2}s^{-1}$), ions up to U, √s ~ 100 GeV
- ELIC
  - construct ion complex to collide with the upgraded CEBAF accelerator
  - very high luminosity ($4 \cdot 10^{34}$ $cm^{-2}s^{-1}$/A), only light ions*, √s ~ 50 GeV

*Very recent: revised ELIC design now up to A=200 and higher E

Experimental Aspects



J. Pasukonis, B.Surrow, physics/0608290



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

Concepts:

1. 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
2. Focus on a wide acceptance detector system similar to HERA experiments

Questions and Answers (I)

Q: What would be a “baseline machine”

A:

- From RHIC experience: unpolarized collisions are less complex
  - RHIC: 48 PRL from unpolarized AA/*d*A/*pp* before first ‘spin’ PRL (April ’04)
- much can be achieved in *e*+A already with moderate luminosity say $\int L dt = 1/\mathrm{A}\ \mathrm{fb}^{-1}$ (see error bars on plots shown)
- some things will need time: F_L needs runs at various $\sqrt{s}$
- In short: eA can deliver early
  - the RHIC community has demonstrated it

Questions and Answers (II)

Q: What might be the "highlight" PRLs from the first 5 years of operation of EIC?

A: eA is terra incognita –all base line measurements mentioned earlier are PRLs

but since we were asked:

1. First measurement from scaling violations of nuclear gluon distributions (for $Q^2 > 2$ GeV^2 and $x < 10^{-2}$ down to $5 \cdot 10^{-4}$ in 20+100 configuration). Comparison to (i) DGLAP based shadowing and (ii) saturation models. (20 weeks-year 1 measurement)
2. Study of centrality/A dependence of nuclear quark and gluon distributions. Comparison to model predictions. Extract A dependence of Q_s in saturation framework (would require more than 1 species in year 1)
3. First measurement of charm distributions in cold nuclear matter- energy loss (from Au over proton, or better deuteron). Consistency check of extracted gluon distributions to that from scaling violations.
4. First measurement of F_L in nuclei at small x (will complement $e+p$ PRL on wide extension of measured range). Extraction of gluon distribution, test of higher twist effects, saturation,... (will require energy scan)
5. First measurement of diffractive structure function in nuclei F_2^D - study of scaling violations of F_2^D with Q^2. (year 1-low luminosity measurement)
6. Precision measurements of elastic J/ψ production - detailed tests of color transparency/opacity

Questions and Answers (III)

Q: What are the three or four most important R&D activities for the next 5 years?

A:

- Calorimetry: Compact, high resolution, e/h separation, extreme forward rapidities
- Tracking: High-rate, low dead material, high occupancy (forward direction!)
- Particle ID: needed for heavy flavor (charm), vector meson production, energy loss, fragmentation studies
- Measurement of nuclear fragments/spectators for centrality (eA!) and diffractive physics: Roman pot technology … (needs brain storming)
- One or two detectors? If only one possible – integration of both concepts into one (magnetic field configuration)

Summary

eA collisions at an EIC allow us to:

- 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)
- Study and understand nuclear effects
  - shadowing, EMC effect, Energy Loss in cold matter
- Test and study the limits of universality (eA vs. pA)
- Cross-fertilization: DIS (Hera), RHIC/LHC, JLAB
- EIC/eA: Unique opportunity to maintain US and BNL leadership in high energy nuclear physics and precision QCD physics

Additional Material

Future Plans

LDRD Grant (TU):

in process of hiring postdoc to work on EIC/eA physics and detector simulation (join current efforts by A. Caldwell and B. Surrow on detector simulation with focus on eA)

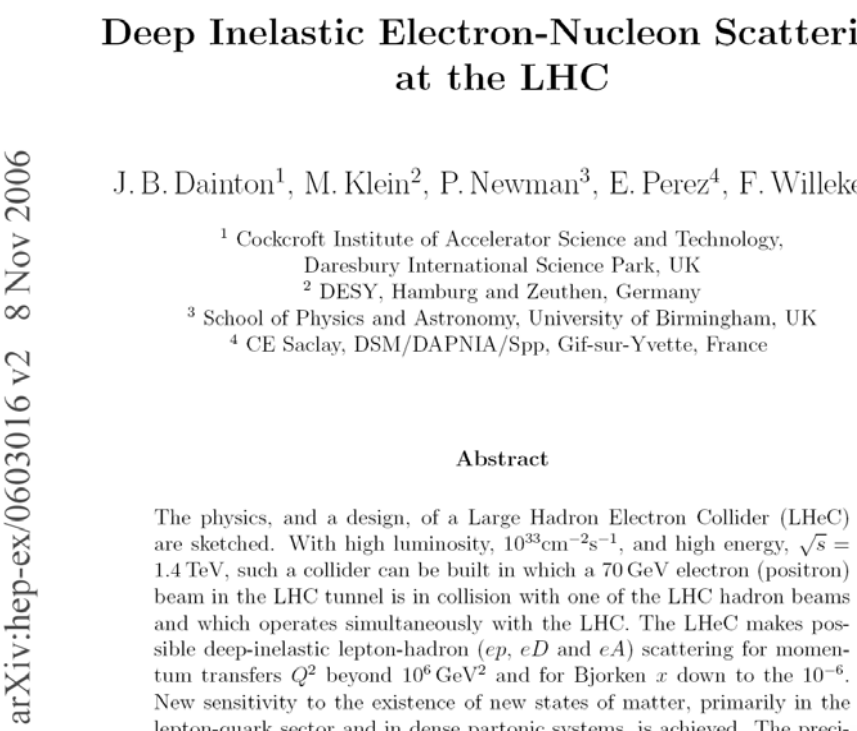
Strengthen eA WG at BNL:

Had 1-2 seminars/discussion sessions weekly from November until RHIC start, need to continue

Near future:

possibly add 2 postdocs to work on EIC/eA

LHeC



arXiv:hep-ex/0603016 v2 8 Nov 2006

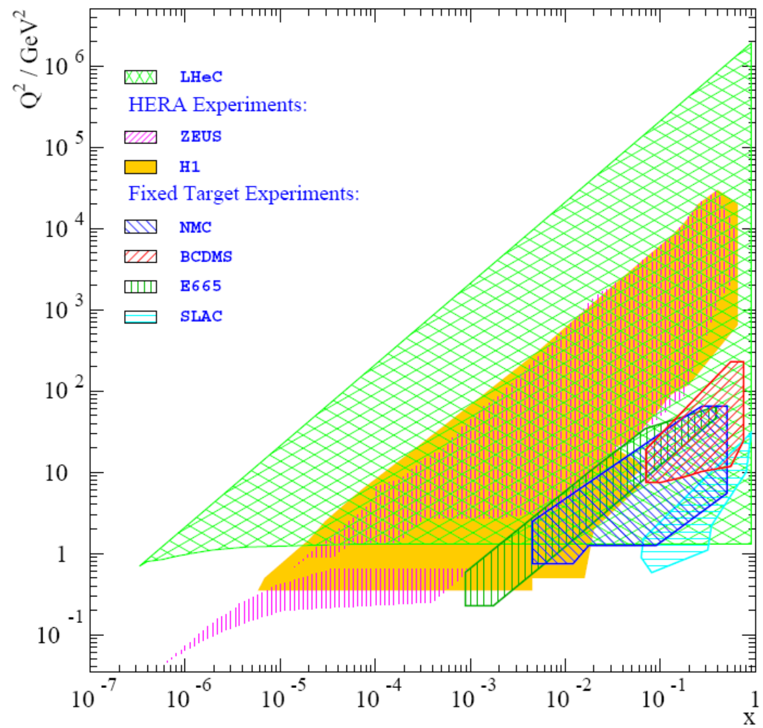
Deep Inelastic Electron-Nucleon Scattering at the LHC

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and high energy, $\sqrt{s} =$ 1.4 TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,\mathrm{GeV}^2$ and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The preci-

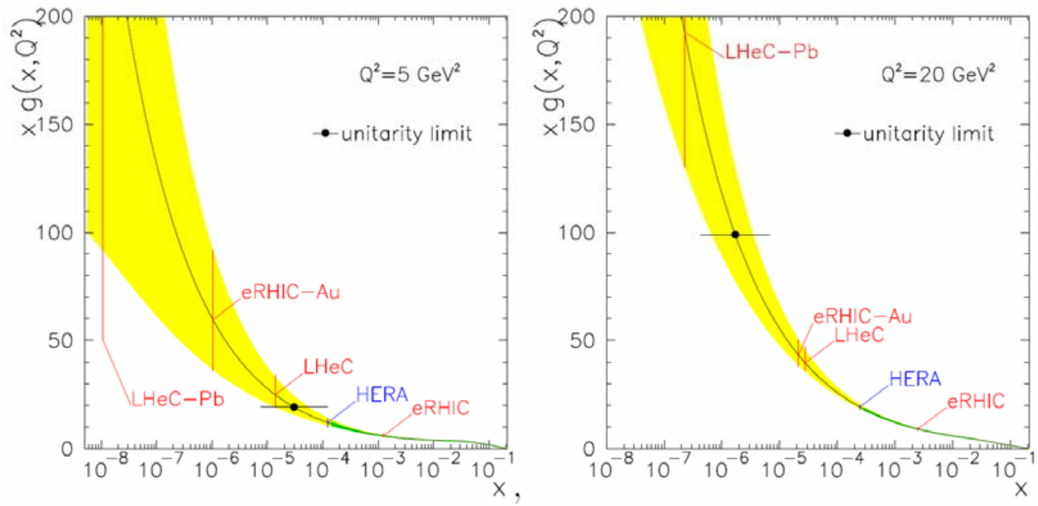


70 GeV e beam in LHC tunnel

Take place of LHCb eA

⇒ New physics beyond the standard model

Operation at EIC allows to reach very low-x region competitive with LHeC (ep)

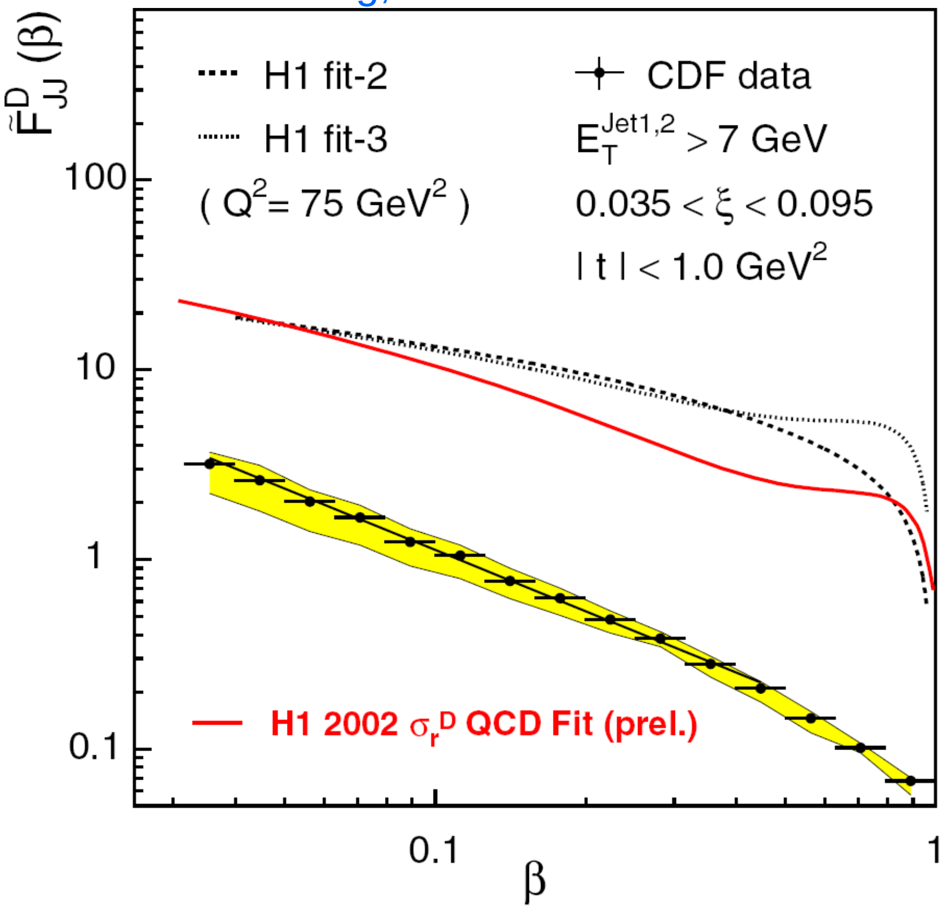


Connection to *p*+A Physics

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportinity to perform stringent checks of factorization/universality
- Issues:
  - e+A: dominated by one photon exchange ⇒ preserve properties of partons in nuclear wave function
  - p+A: contribution of color exchange of probe and target ⇒ correction of order $1/Q^4$ (or higher)

N.B: p+A lacks the direct access to x, Q2 ⇒ needs modeling

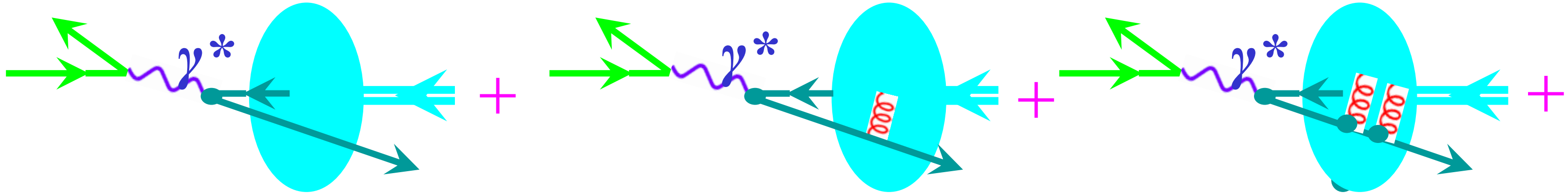
F. Schilling, hex-ex/0209001



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

eA vs pA: similarities and differences

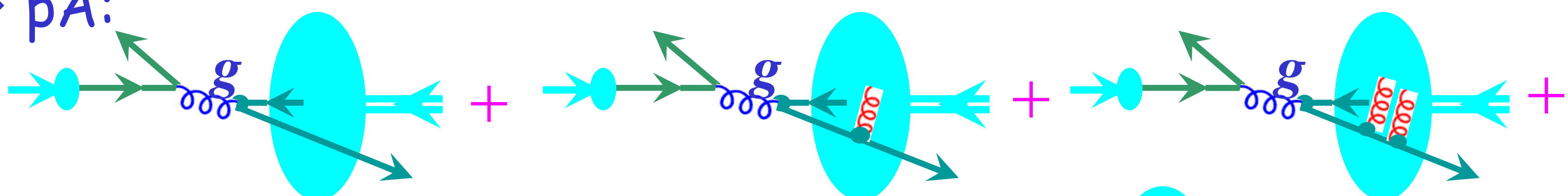
❖ DIS:



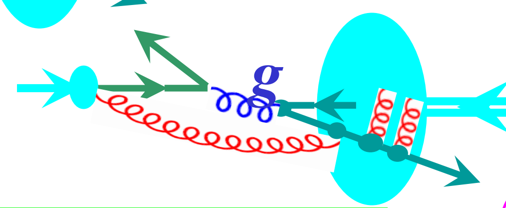
$$\sigma_{\ell A} \approx \hat{\sigma}^{(S)}_{\ell f} \otimes \varphi_{f/A} + \hat{\sigma}^{(D)}_{\ell f} \otimes T^{(D)}_{f/A} + \hat{\sigma}^{(T)}_{\ell f} \otimes T^{(T)}_{f/A} + \ldots$$

✓ Factorized expansion in all powers of Q_s/Q

❖ pA:



$$\sigma_{pA} \approx \varphi_{f/p} \otimes \hat{\sigma}^{(S)}_{ff'} \otimes \varphi_{f'/A}$$

+ 

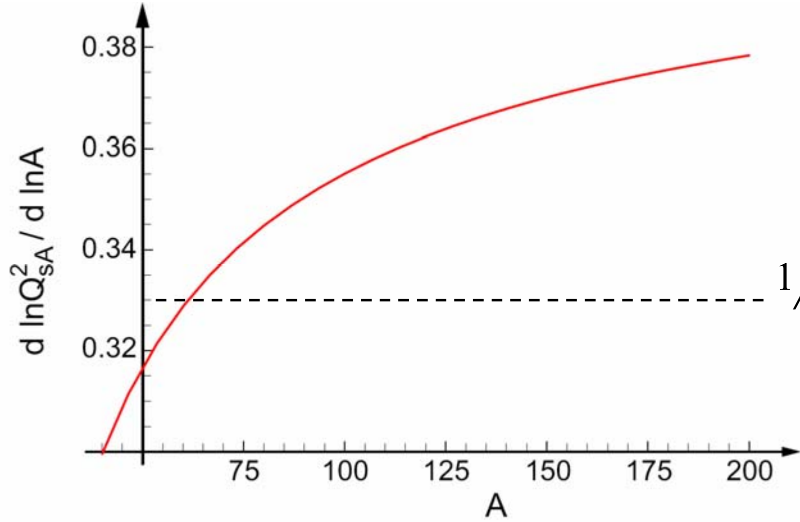
+ ...

$$+ \varphi_{f/p} \otimes \hat{\sigma}^{(D)}_{ff_i} \otimes T^{(D)}_{f_i/A} + T^{(D)}_{f_i/A} \otimes \hat{\sigma}^{(D)}_{f_i f'} \otimes \varphi_{f/A} + O\left(\frac{Q_s^2}{Q^2}\right)^2$$

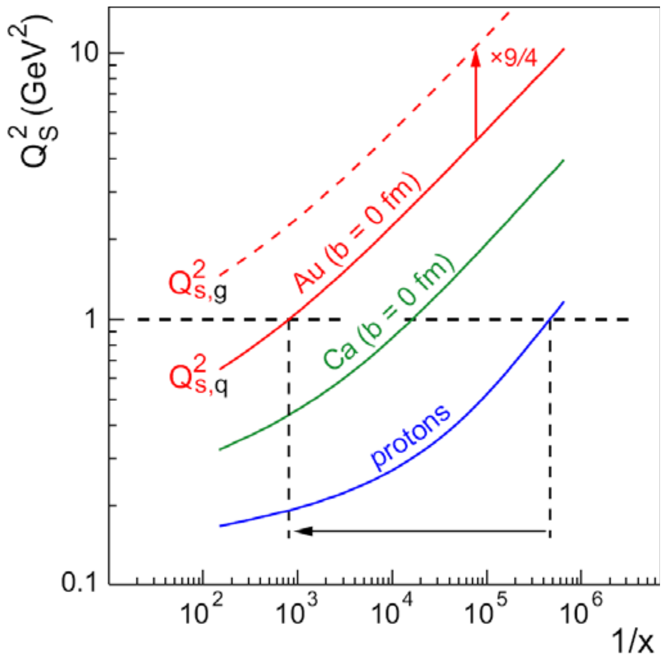
☒ General hadronic factorization fails at the power of $1/Q^4$

☑ $A^{1/3}$ enhanced terms should be factorized to all powers of $1/Q^2$

Nuclear "Oomph" Factor



Armesto, Salgado, Wiedemann, PRL 94:022002



Fit to HERA data based on Golec-Biernat-Wusthoff (GBW) saturation model gives:
$(Q_s^p)^2 \approx Q_0^2 x^{-\delta}$ where $\delta \approx 0.3$

The simple pocket formula is useful:

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

More sophisticated analyses show a more detailed picture even exceeding the *Oomph* from the pocket formula.

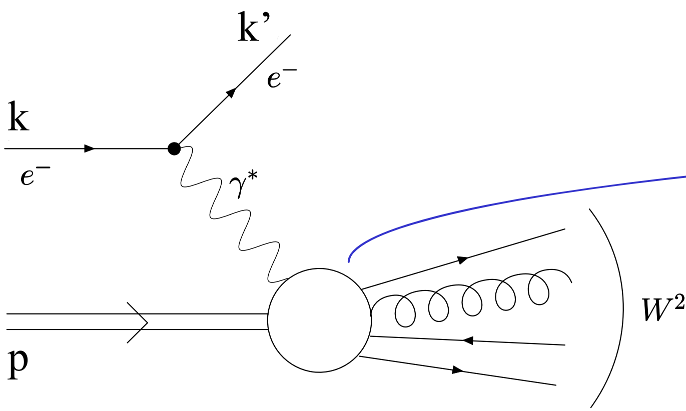
Armesto et al., PRL 94:022002
Kowalsi, Teaney, PRD 68:114005

N.B.: The nuclear profile seen by the e is not comparable to what one is used to in AA where two nuclei profiles are involved

eA From a “Dipole” Point of View

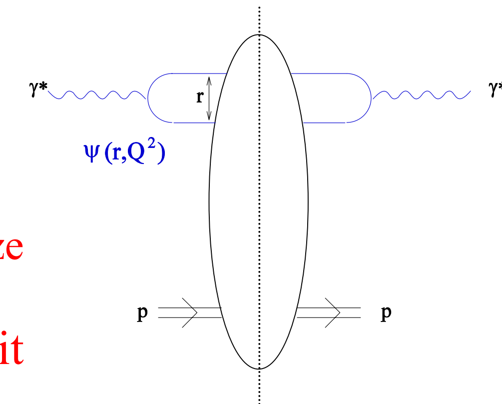
In the rest frame of the nucleus:

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 $\bar{q}q$: $L \sim 1/2m_N x$

L >> 2R

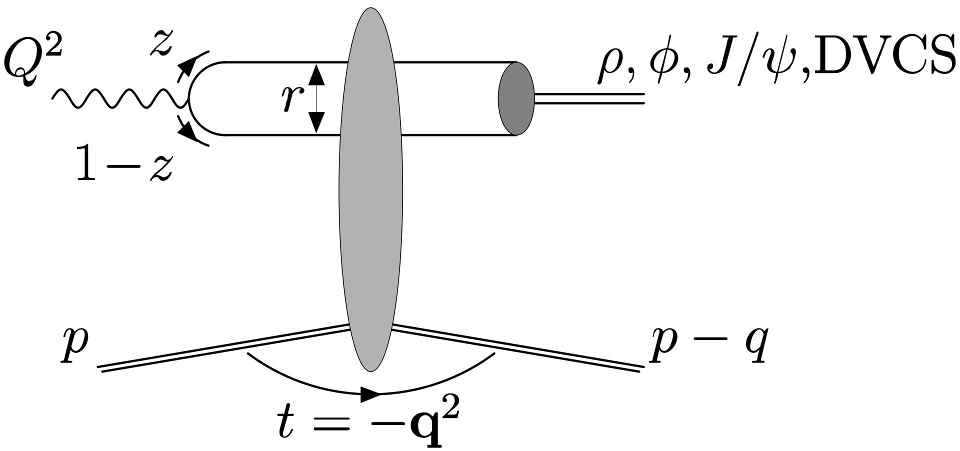
- Physics of strong color fields
- Shadowing
- Diffraction

L << 2R

- Energy Loss
- color transparency
- EMC effect

Vector Meson Production

"color dipole" picture

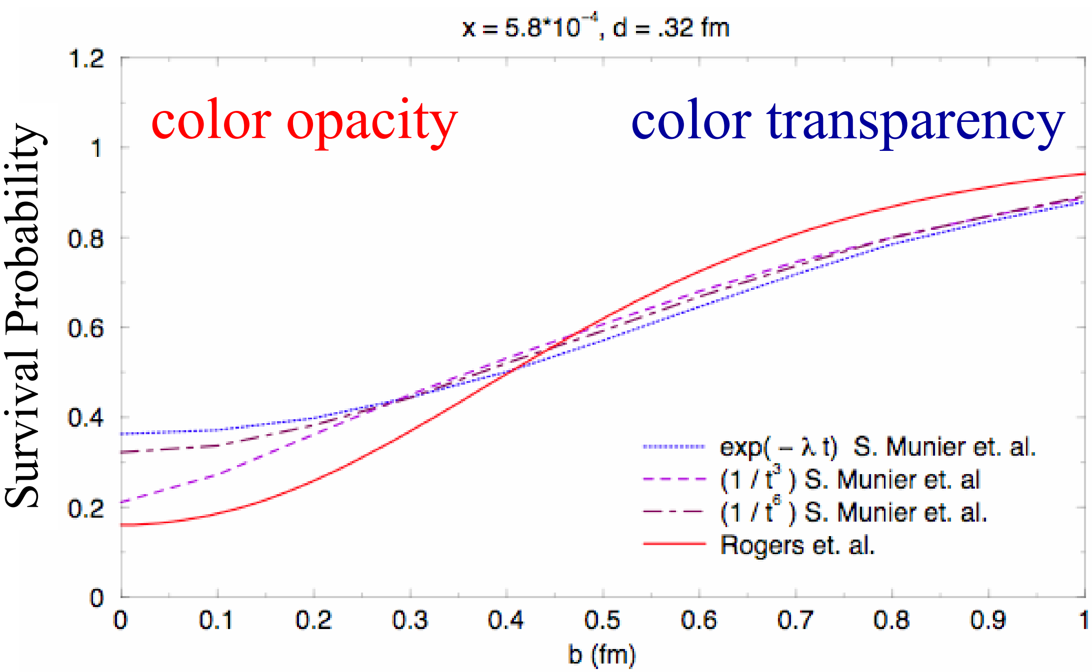


$$\sigma_{q\bar{q},N}(E_{inc}) = \frac{\pi^2}{3} r_t^2 \alpha_s(Q^2) x g_N(x, Q^2),$$

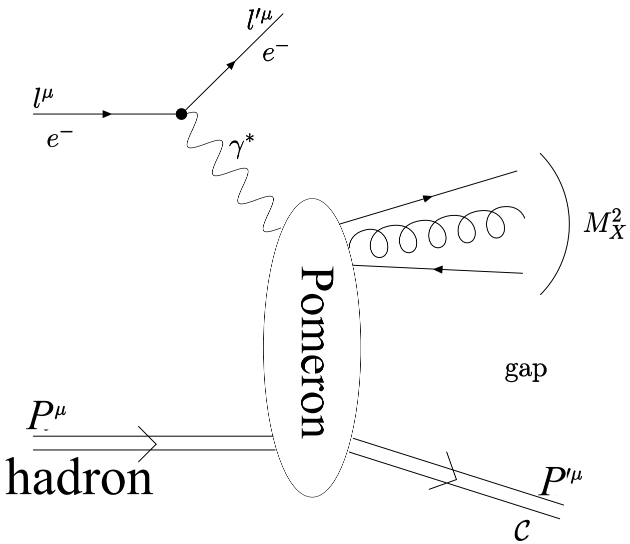
HERA: Survival prob. of $\bar{q}q$ pair of d=0.32 fm scattering off a proton from elastic vector meson production.

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

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



Diffractive DIS is …



when the hadron/nuclei remains intact

momentum transfer
$t = (P\text{-}P')^2 < 0$

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

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

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

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

HERA/ep: 10% of all events are hard diffractive EIC/eA: 30%?
Black Disk Limit: 50%