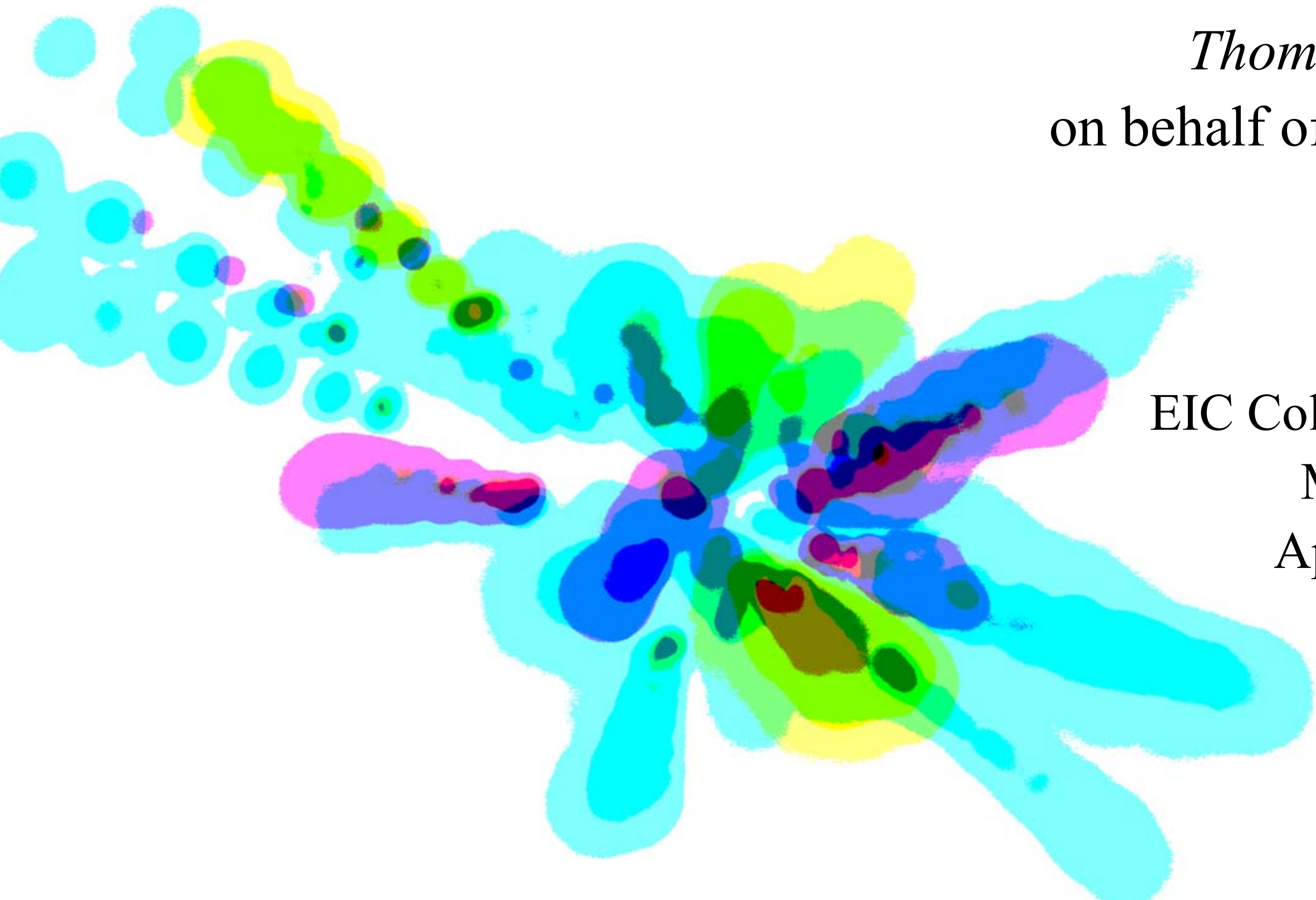
Physics Opportunities with *e*+A Collisions at an Electron Ion Collider

Thomas Ullrich, BNL
on behalf of the EIC/eA Working Group



EIC Collaboration Meeting
MIT, Boston
April 6-7, 2007

BROOKHAVEN
NATIONAL LABORATORY

EIC/eA Working Group

- Initiated by BNL – Fall ‘06
  - open to everybody in & outside of BNL
    - Heavy Ion community at universities and other labs
    - JLAB colleagues
    - and everybody else interested
  - close collaboration with ep experts
- First Steps
  - Many “intensive” of seminars and lots of discussion
    - Steep learning curve for us from heavy ions
- Near Term: Help making the case
  - NSAC Long Range Plan – Milestones:
    - Town Meeting in Rutgers, January 12-14, 2007
    - EIC/eA position paper, April 5, 2007
    - Input to Resolution Meeting (Galvestone) April 29-May 4, 2007

Logistics

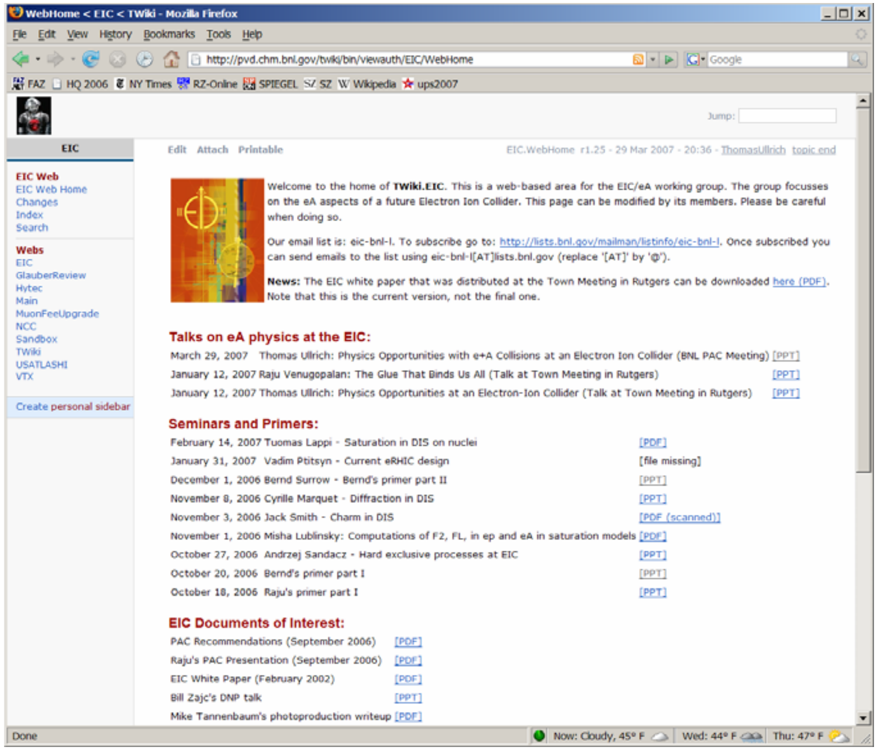
Email list for announcements & discussions:

eic-bnl-l@lists.bnl.gov

To subscribe go to:

http://lists.bnl.gov/mailman/listinfo/eic-bnl-l

(or write me tu@bnl.gov)



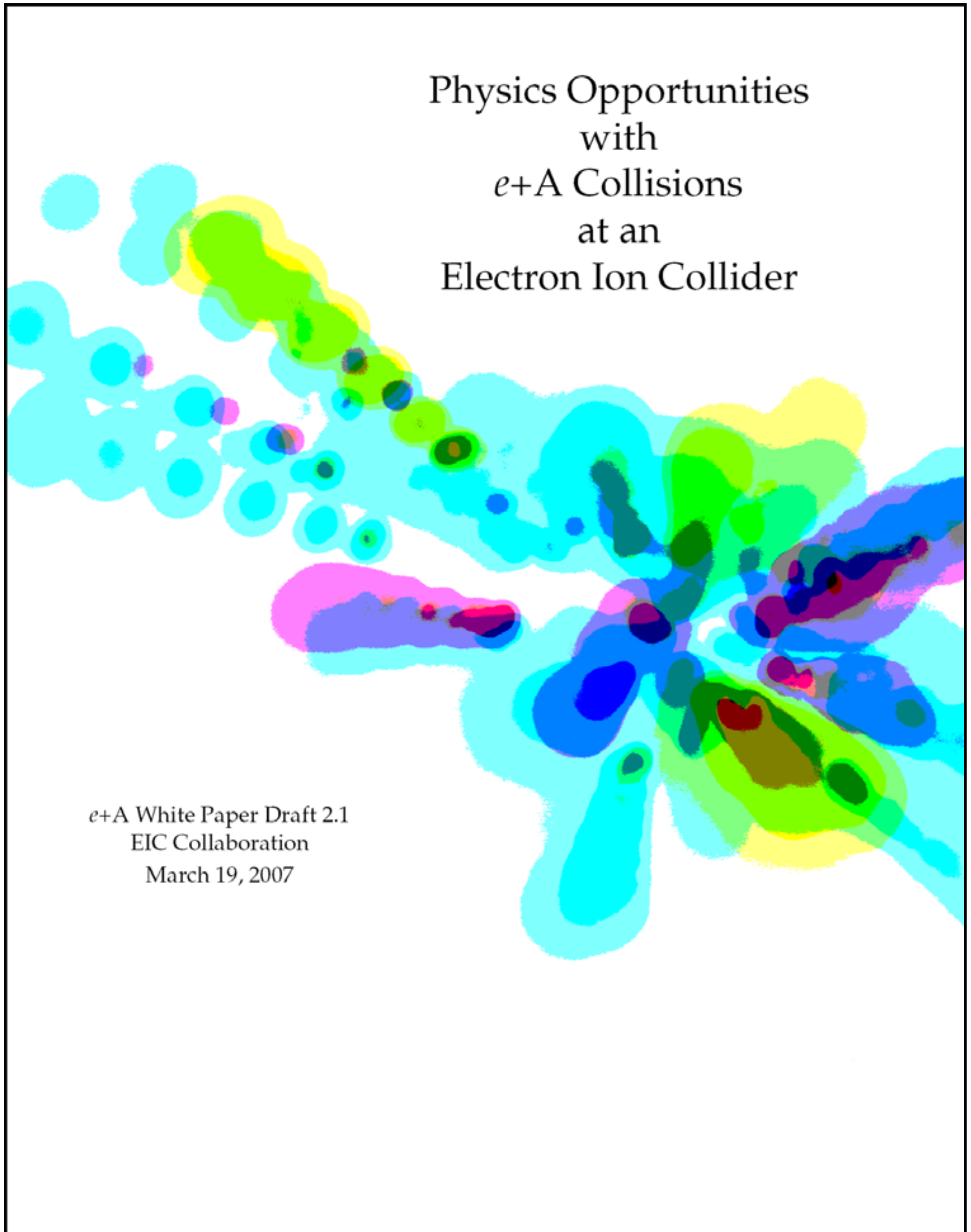
Web page holding documents, announcements, talks, and info on ongoing efforts:

http://pvd.chm.bnl.gov/twiki/bin/view/EIC/WebHome

- TWiki ⇒ editable for collaborative effort but not final solution
- Ask for password at times (ignore, press cancel, continue)

Soon to be replaced with permanent one …

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

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

- "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

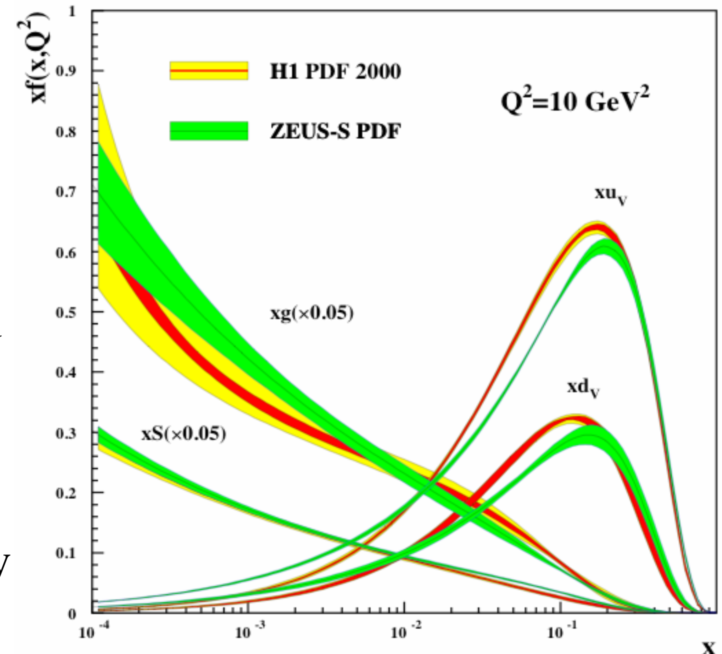
QCD requires *fundamental* investigation via *experiment*

What Do We Know About Glue in Matter?

Established Model:

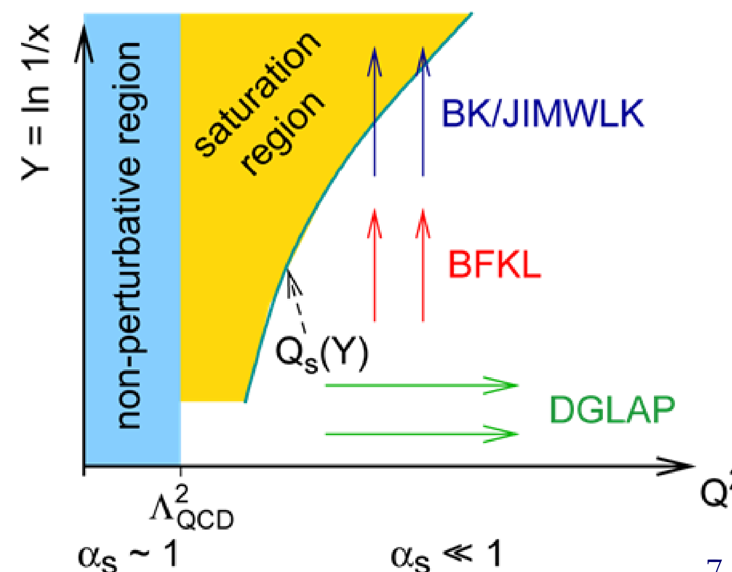
Linear DGLAP evolution scheme

- 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?
- xG rapid rise for decreasing $x \Rightarrow$ must saturate
  - What's the underlying dynamics?
  - Diffraction not explained in DGLAP $\Rightarrow$ need new approach



New picture: BK/JIMWLK based models introduce non-linear effects

- $\Rightarrow$ saturation
- characterized by a scale $Q_s(x,A)$
- grows with decreasing x and increasing A
- arises naturally in the CGC framework



$\Rightarrow$ **more in talk by Yuri Kovchegov**

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

Key Questions vs. Laundry List

Why do we emphasize only 4 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)?

There are many more … as many as there are people in this room … and Mark and Stan are not even here

However for the LRP we focused on those

- that appeared to us as the most *important* ones
- that addressing *fundamental* topics (in our view)
- those that also will catch the *interest* of the rest of the NP community (or any community) *(⇒ Krishna's talk later today)*
- we "tried" to avoid arguments (to some extent) such as:
  - wasn't measured in range X
  - can't calculate it with theory Y
  - testing QCD …

eA: Ideal to Study Non-Linear Effects

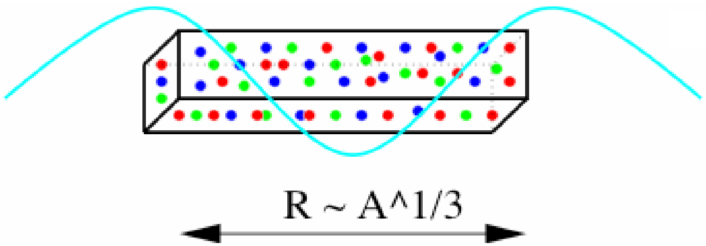
Scattering of electrons off nuclei:

- 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

⇒ **Amplification** of non-linear effects at small x.

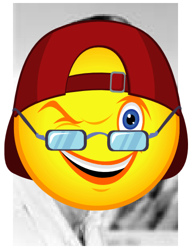
Nuclear "Oomph" Factor:

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

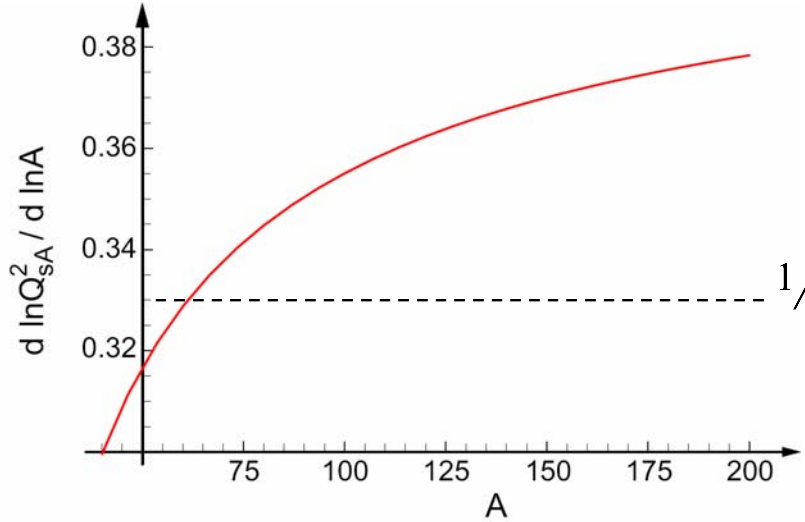


Note this is a "Pocket Formula" – there's more to it

s because of a pocket formula



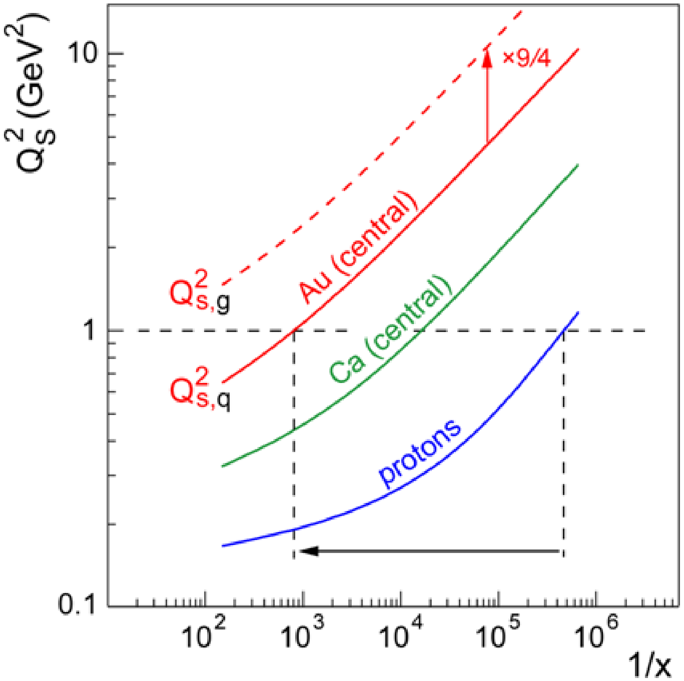
Nuclear “Oomph” Factor



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 $\delta \approx 0.3$

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



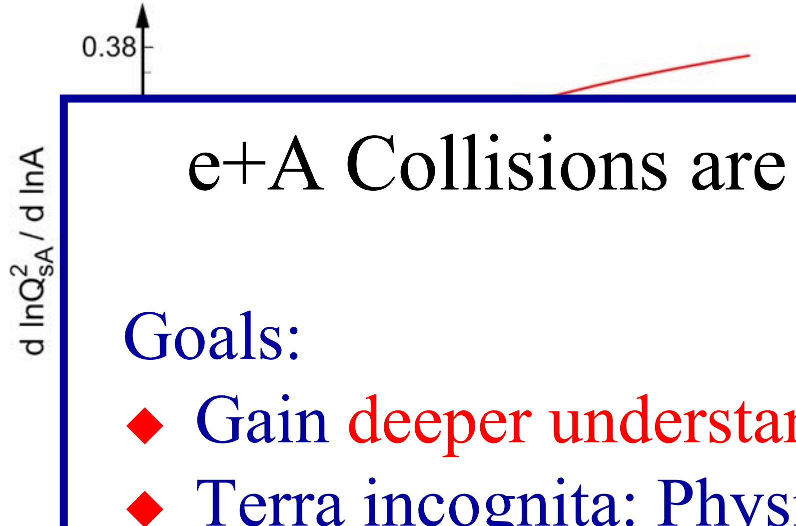
More sophisticated analyses show a more detailed picture even exceeding the *Oomph* from the pocket formula.

Armesto et al., PRL 94:022002

Kowalski, Teaney, PRD 68:114005

⇒ **see talk by Tuomas Lappi**

Nuclear “Oomph” Factor



e+A Collisions are Ideal for Studying “Glue”

Goals:

- Gain deeper understanding of QCD
- Terra incognita: Physics of Strong Color Fields
- Universality at small x?
  - Do nuclei (and all hadrons) have a component of their wave function in which they look like a dense cloud of gluons, with behavior same for nuclei as for hadrons?

(⇒ see Krishna’s talk)

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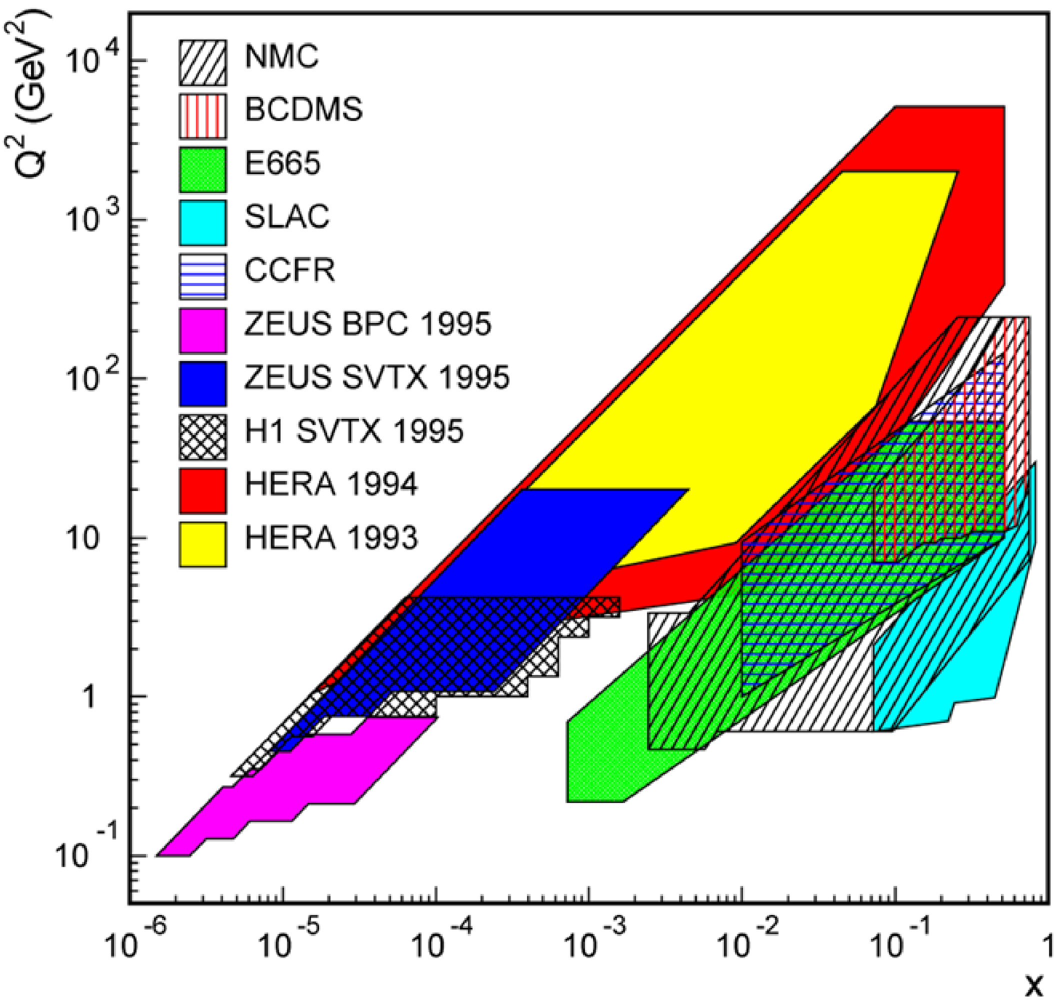
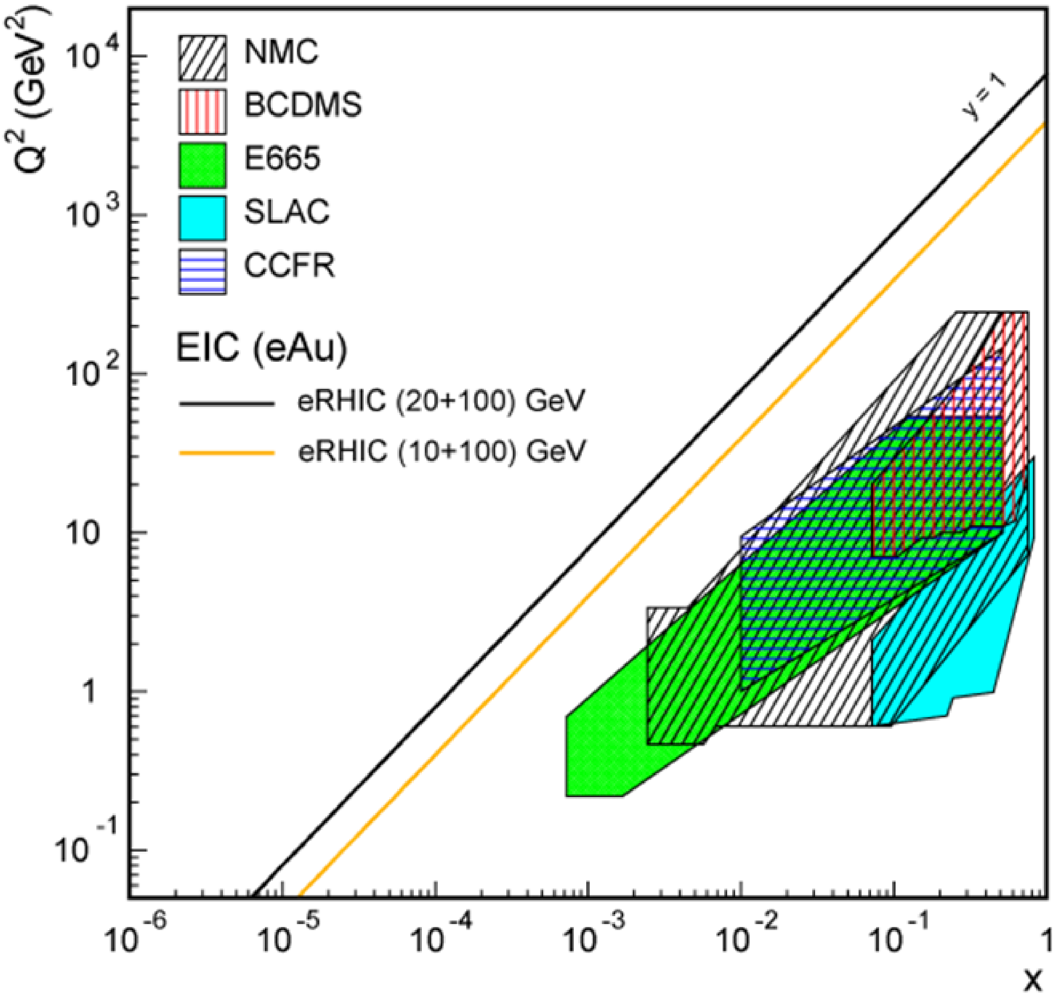
⇒ see talk by Tuomas Lappi

eA Landscape and a new Electron Ion Collider



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

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):

eRHIC (*e*+Au):

E_e = 20 GeV

E_A = 100 GeV

$\sqrt{s_{eN}}$ = 90 GeV

L_{eAu} (peak)/n ~ $2.9 \cdot 10^{33}$ cm^{-2} s^{-1}

ELIC (*e*+Ca):

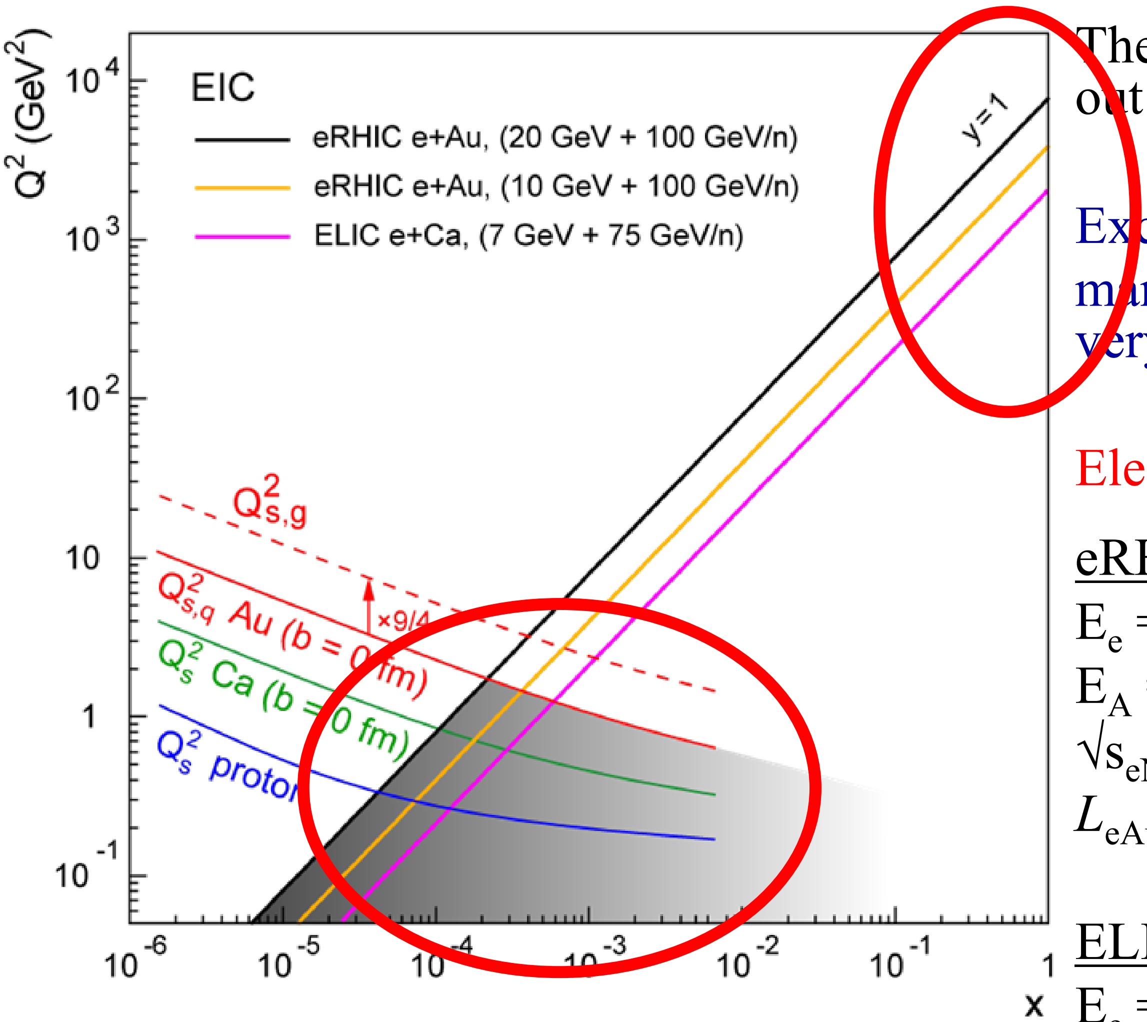
E_e = 7 GeV (9 GeV)

E_A = 75 GeV

$\sqrt{s_{eN}}$ = 46 GeV (52 GeV)

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

eA Landscape and a new Electron Ion Collider



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

What is the momentum distribution of the gluons in matter?

Gluon distribution $G(x,Q^2)$

- Studied/looked at so far:
  - $F_L \sim \alpha_s G(x,Q^2)$ (BTW: requires $\sqrt{s}$ scan)
  - Extract from scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
- Not done so far, needs work (simulations)
  - 2+1 jet rates (needs jet algorithm and modeling of hadronization for inelastic hadron final states)
  - inelastic vector meson production (e.g. J/ψ)
  - diffractive vector meson production - very sensitive to $G(x,Q^2)$

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

Luminosity measures for e+A

In good approximation:

$$L \sim \mathrm{A}^{-1} \quad \text{(at RHIC)}$$

or

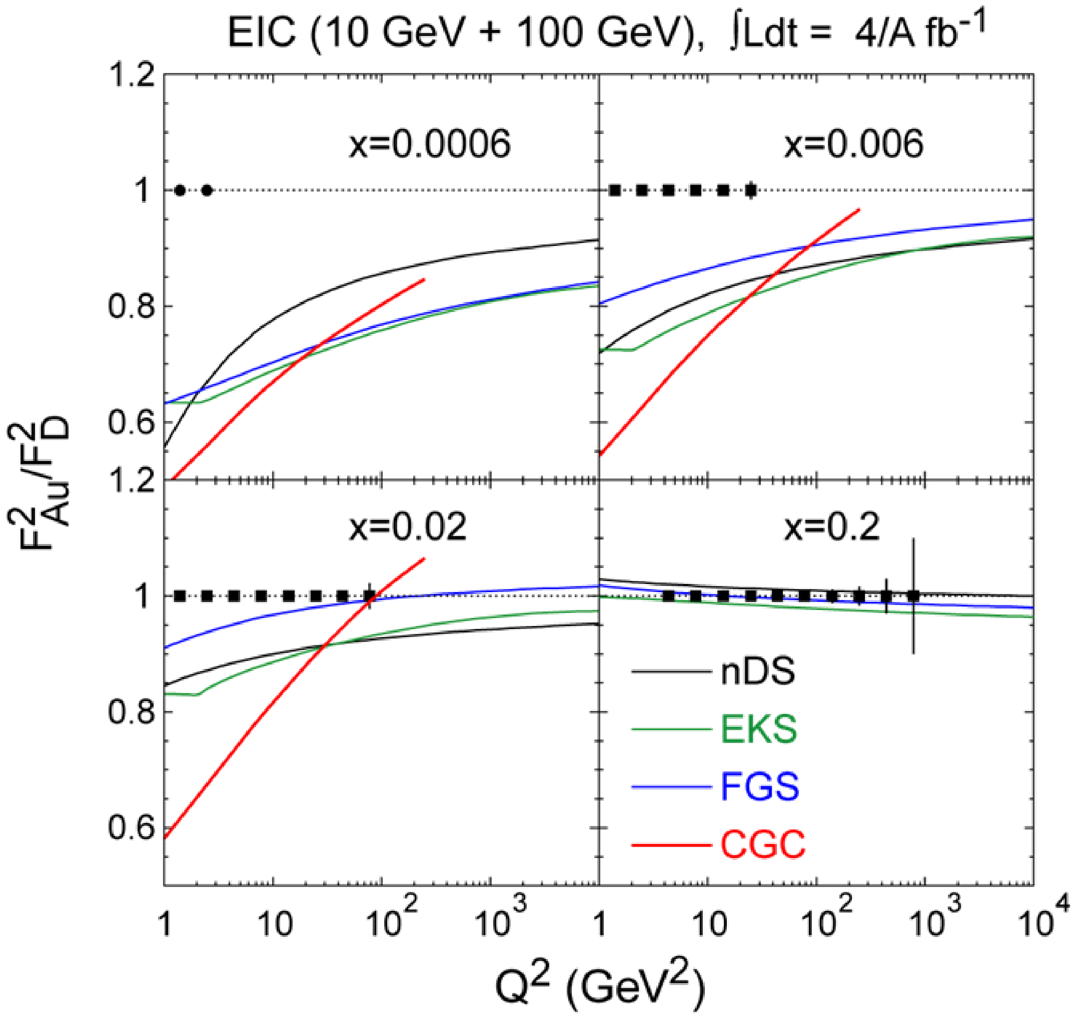
$$L(\text{ions}) = L(\text{nucleons})/\mathrm{A}$$

So, 10^{33} for nucleons converts to $\sim 5 \cdot 10^{30}$ for Au ions

We quote integrated luminosity in units of A:

Example: $\int L\, dt = 4/\mathrm{A}\ \mathrm{fb}^{-1}$ (nominal L and 10 weeks running)

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



F_2 will be one of the first measurements at EIC

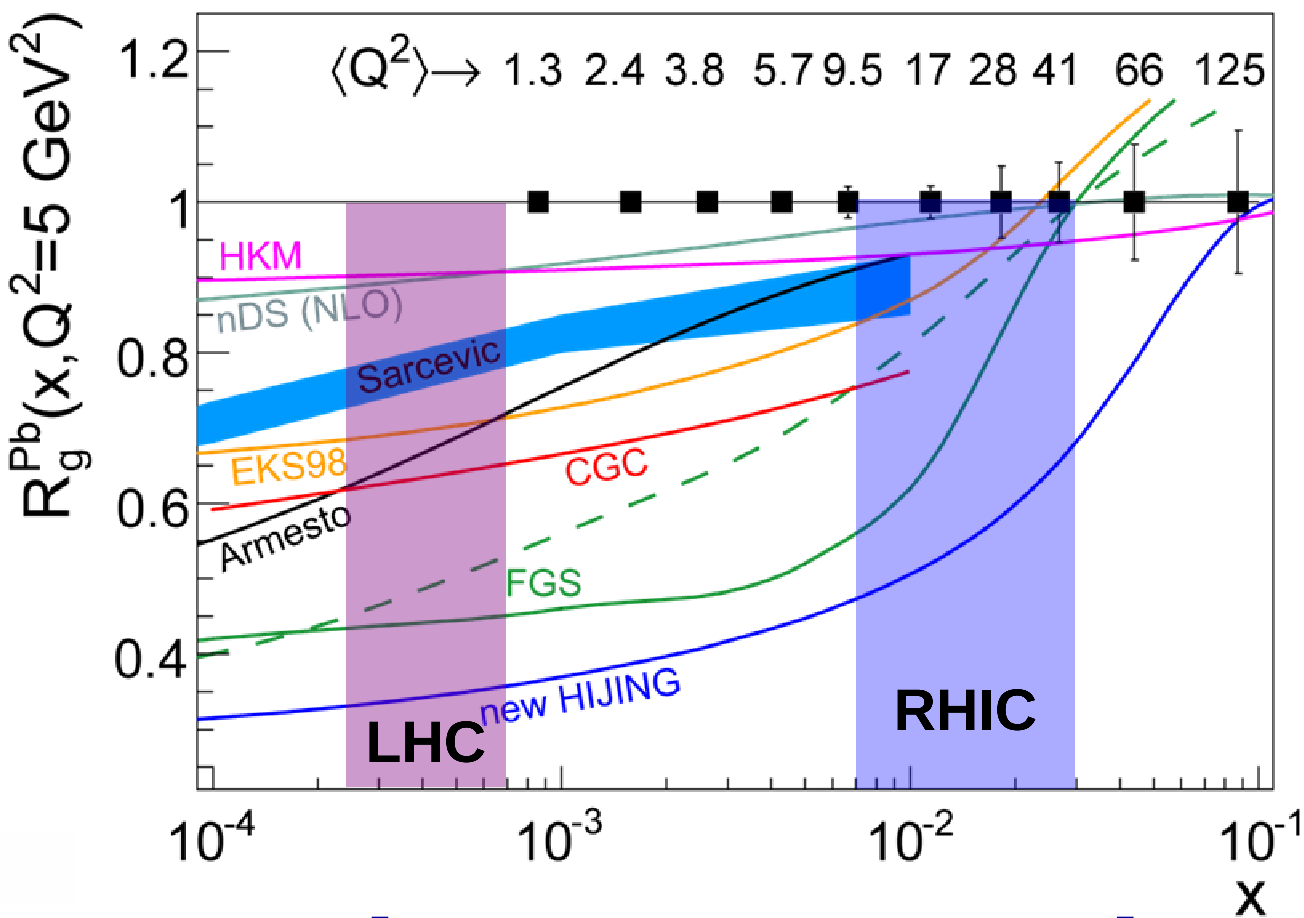
nDS, EKS, FGS:

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



Ratio of $G(x,Q^2)$ in Pb over those in *d* extracted from respective F_L

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

statistical error only

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

$Q^2/xs = y$
Needs √s scan

⇒ **see talk by Jamie Dunlop**

The Gluon Space-Time Distribution

What we know is mostly the momentum distribution of glue.

How is the glue distributed spatially in nuclei?

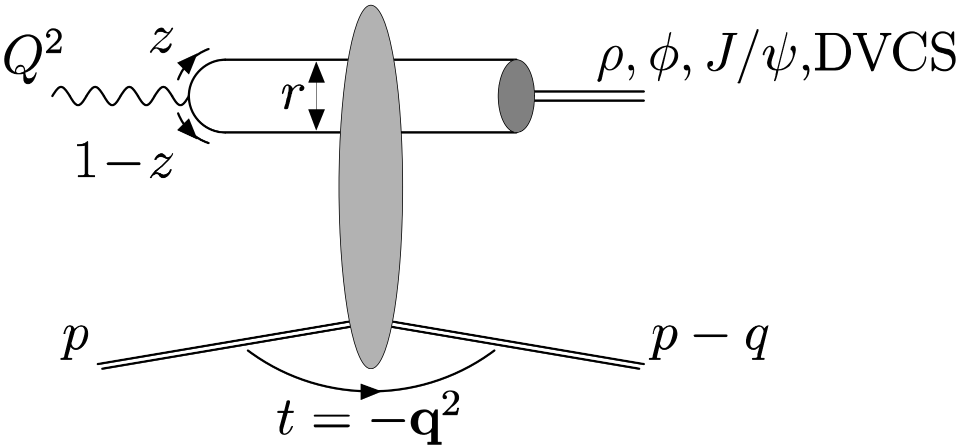
Gluon density profile: small clumps or uniform ?

Many methods:

- Exclusive final states (e.g. vector meson production ρ, J/ψ, …)
  - color transparency ⇔ color opacity
- Deep virtual compton scattering (DVCS)
- Measurement of structure functions for various mass numbers A (shadowing, EMC effect) and its impact parameter dependence

Vector Meson Production

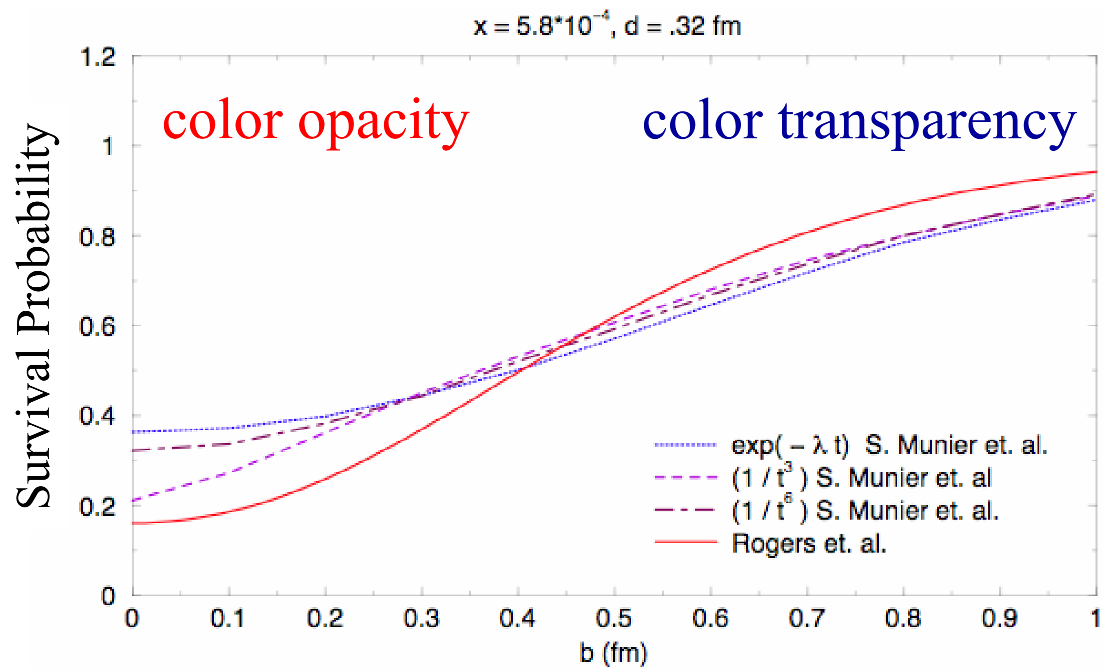
"color dipole" picture



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

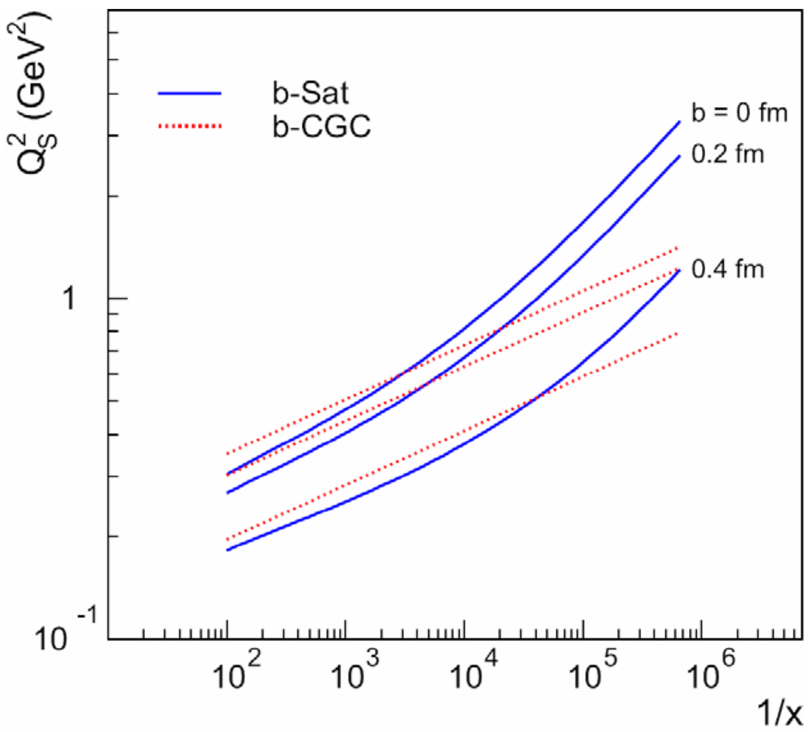
HERA: Survival prob. of $\bar{q}q$ pair of d=0.32 fm scattering off a proton from elastic vector meson production (here ρ). Strong gluon fields in center of p at HERA ($Q_s \sim 0.5$ GeV^2)?

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

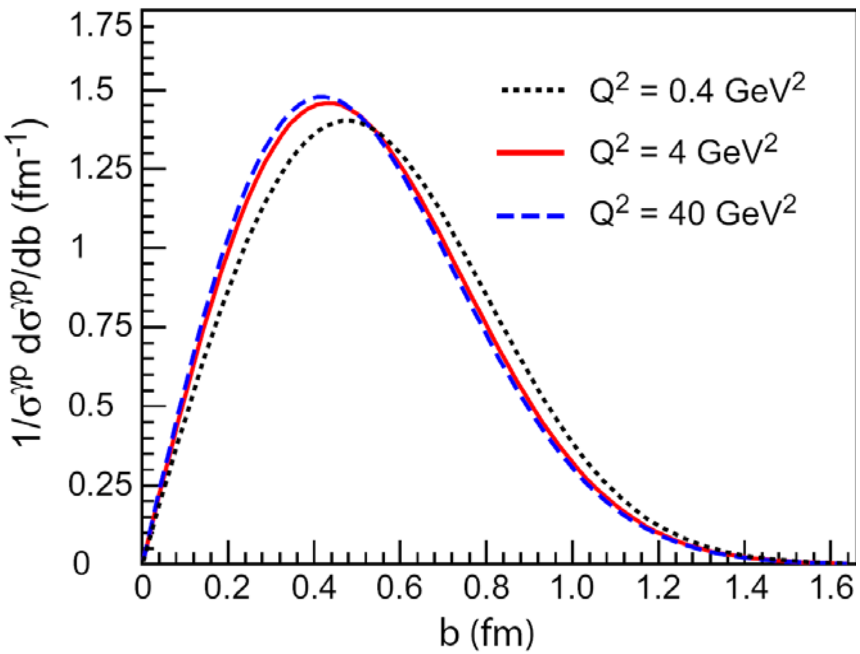


In the Nucleon …

Estimates of quark saturation scale from P(survival)



Dipole cross-section (b)



Kowalski, Motyka, Watt, PRD 74:074016

Kowalski and Teaney, PRD 68:114005

Cross-section is dominated by b ~ 0.4 fm and hence small values of the saturation scale

- Saturation effects difficult to isolate in DIS off protons
- Things are "easier" in nuclei (more uniform b-profile)

Deep Virtual Compton Scattering

DVCS: $\gamma^* + A \rightarrow \gamma + A$ can provide detailed info on distribution and correlation of partons in nuclei (3D picture)

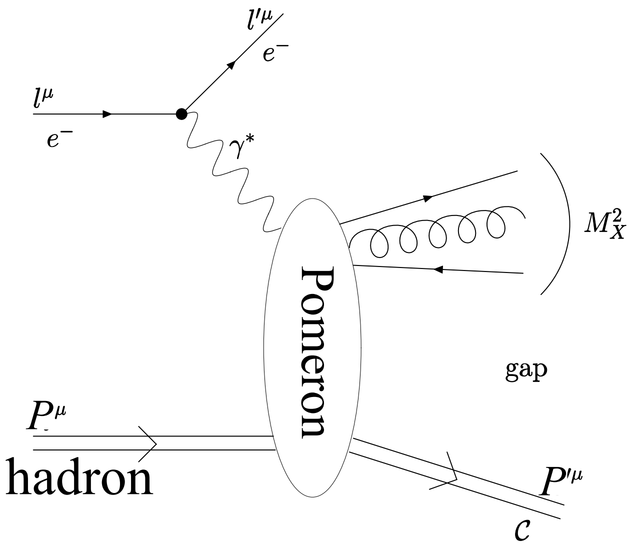
Issue: interferes with Bethe-Heitler process

but in 10 GeV + 100 GeV/n DVCS dominates!

Allows clean study of DVCS amplitude (imaginary part)

Integrated DVCS cross-section: $\sigma_{DVCS} \sim A^{4/3}$

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

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

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

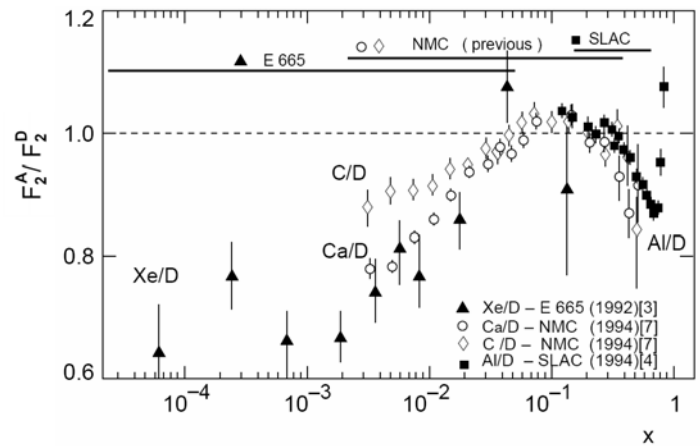
$$\frac{d^4\sigma^{eh\to eXh}}{dx dQ^2 d\beta dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2^{D,4}(x,Q^2,\beta,t) - \frac{y^2}{2} F_L^{D,4}(x,Q^2,\beta,t)\right]$$

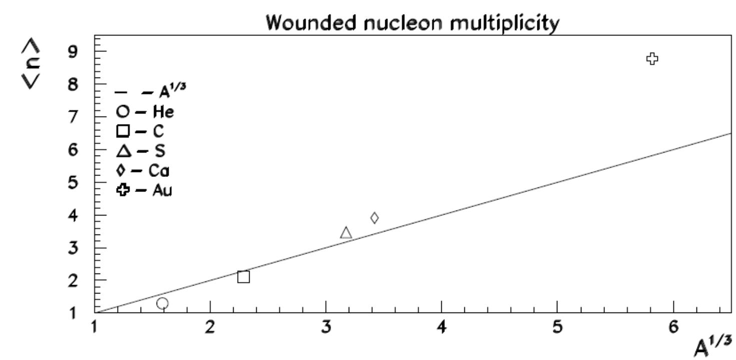
HERA/ep: 10% of all events are hard diffractive

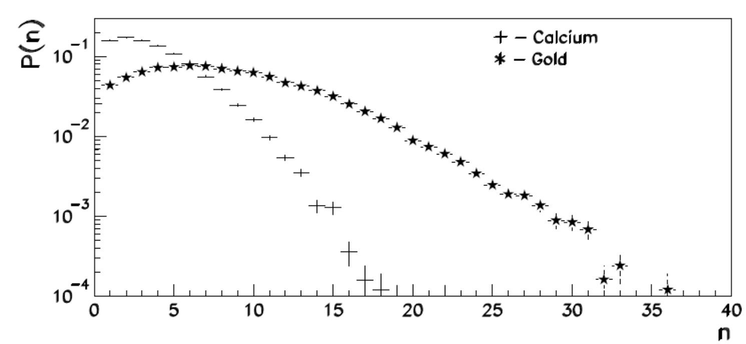
⇒ see talk by Cyrille Marquet

Centrality & Nuclear Fragments – How ?

- Many reason to study nuclear effects such as shadowing as a function of centrality.
- In *e*+A this was never attempted
- Studying diffractive events also implies measuring the nuclear fragments (or better their absence)
- Both require the measurement of "wounded" nucleons and fragments
  - $\Rightarrow$ studies and R&D
  - Need reliable generators that include good descripton of nuclear breakup dynamics





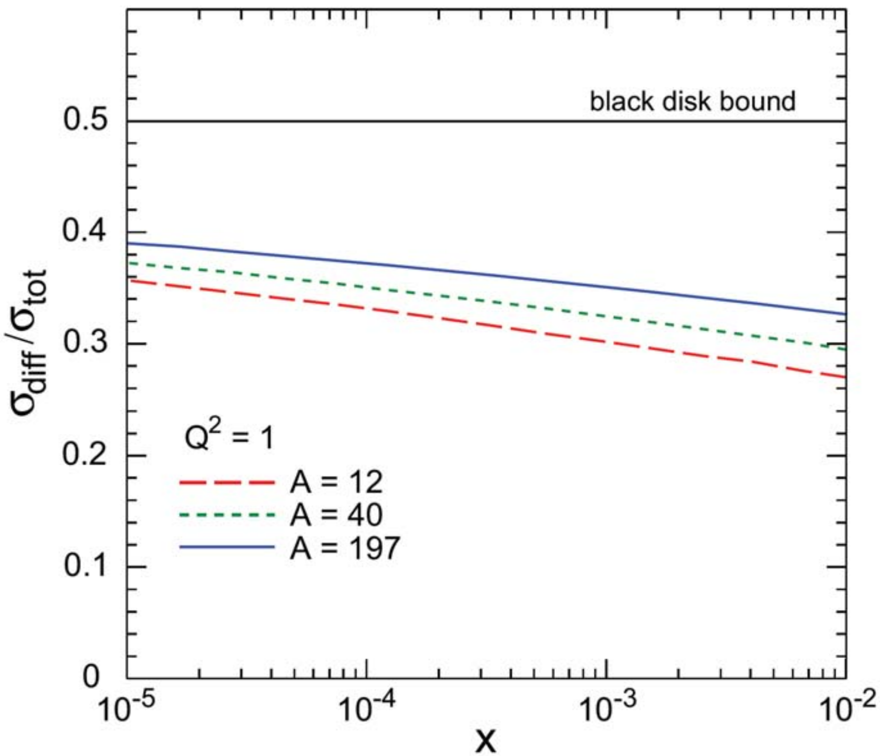


(see talk by Brian Cole)

Only known study so far (using VENUS): Chwastowski,hep-ex/0206043

$\sigma_{diff}/\sigma_{tot}$

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



Note that calculations and figures in the paper appear to be not in sync [curves OK – Raju]
b dependence not taken into account

Dipole model prediction by Kugeratski, Goncalves, Navarra EPJ C46:413

Small sized dipole ($d < 1/Q_s$):

- linear small x evolution

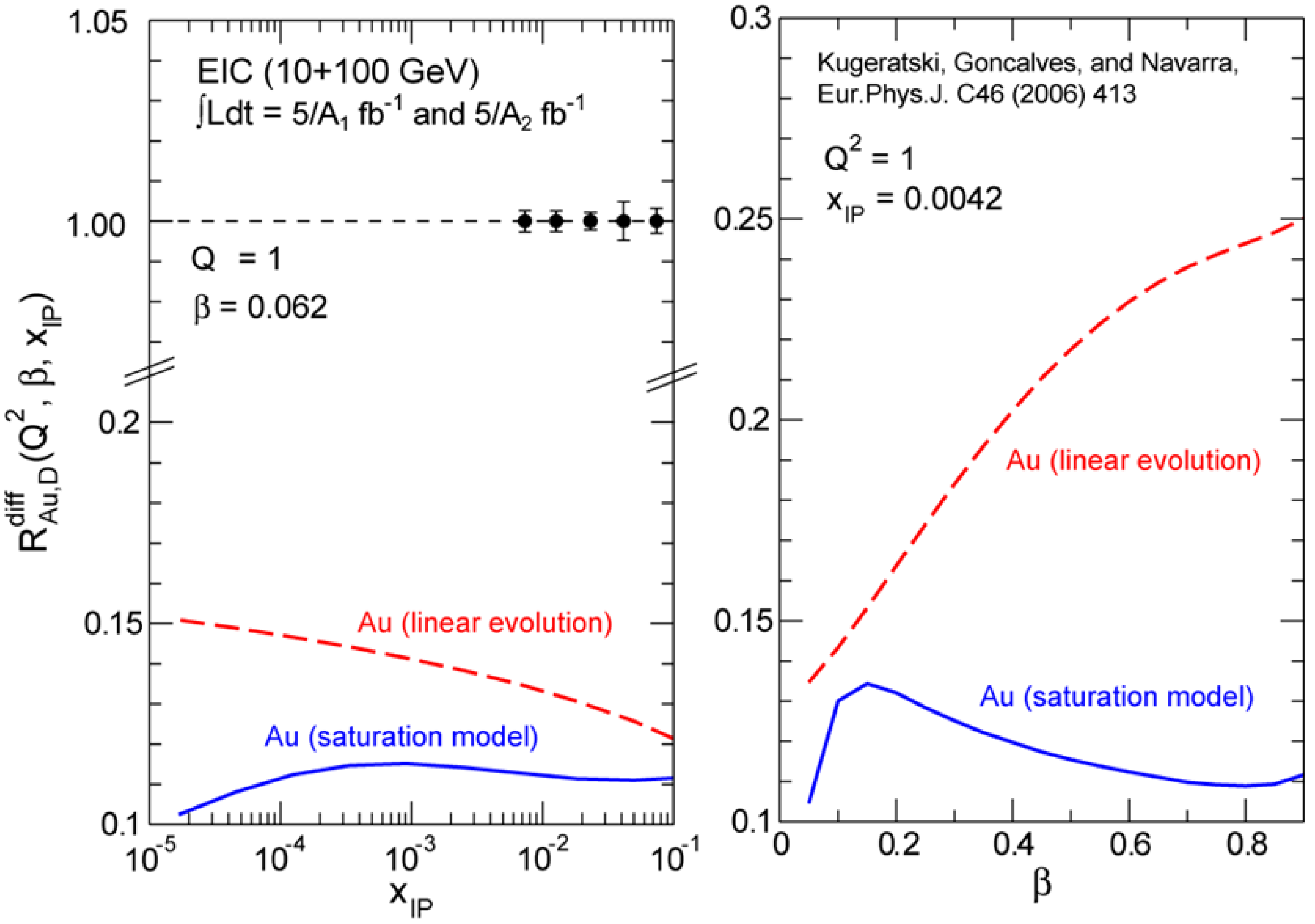
Large sized dipole ($d > 1/Q_s$):

- include saturation effects

Although nuclei intact the diffractively produced final states are semi-hard with momenta ~ (QsA)2.
Harder with increasing A !

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

Hadronization and Energy Loss

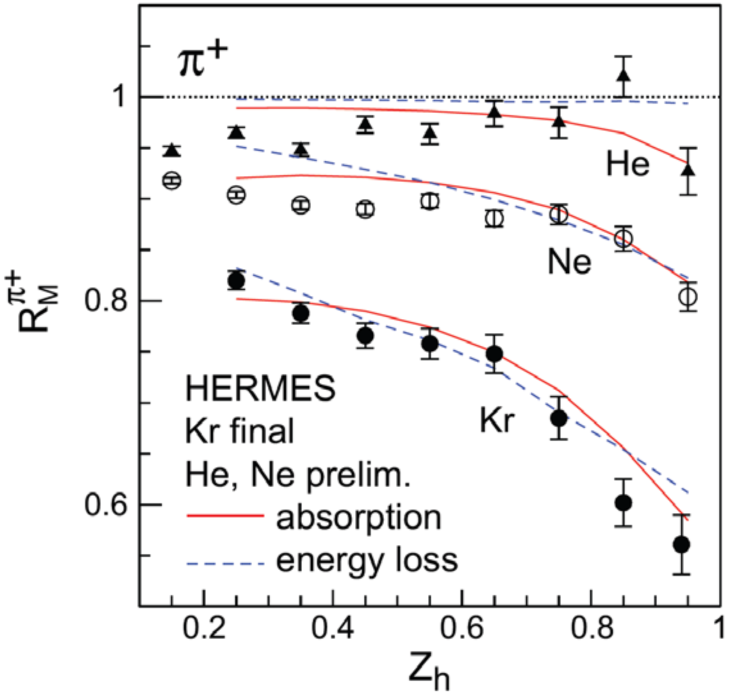
nDIS:

- Suppression of high-p_T hadrons analogous but weaker to RHIC
- DIS is clean environment to study nuclear modifications of hadron production in "cold' nuclear matter (~ d+Au in RHIC)

Fundamental questions:

When do colored partons get neutralized

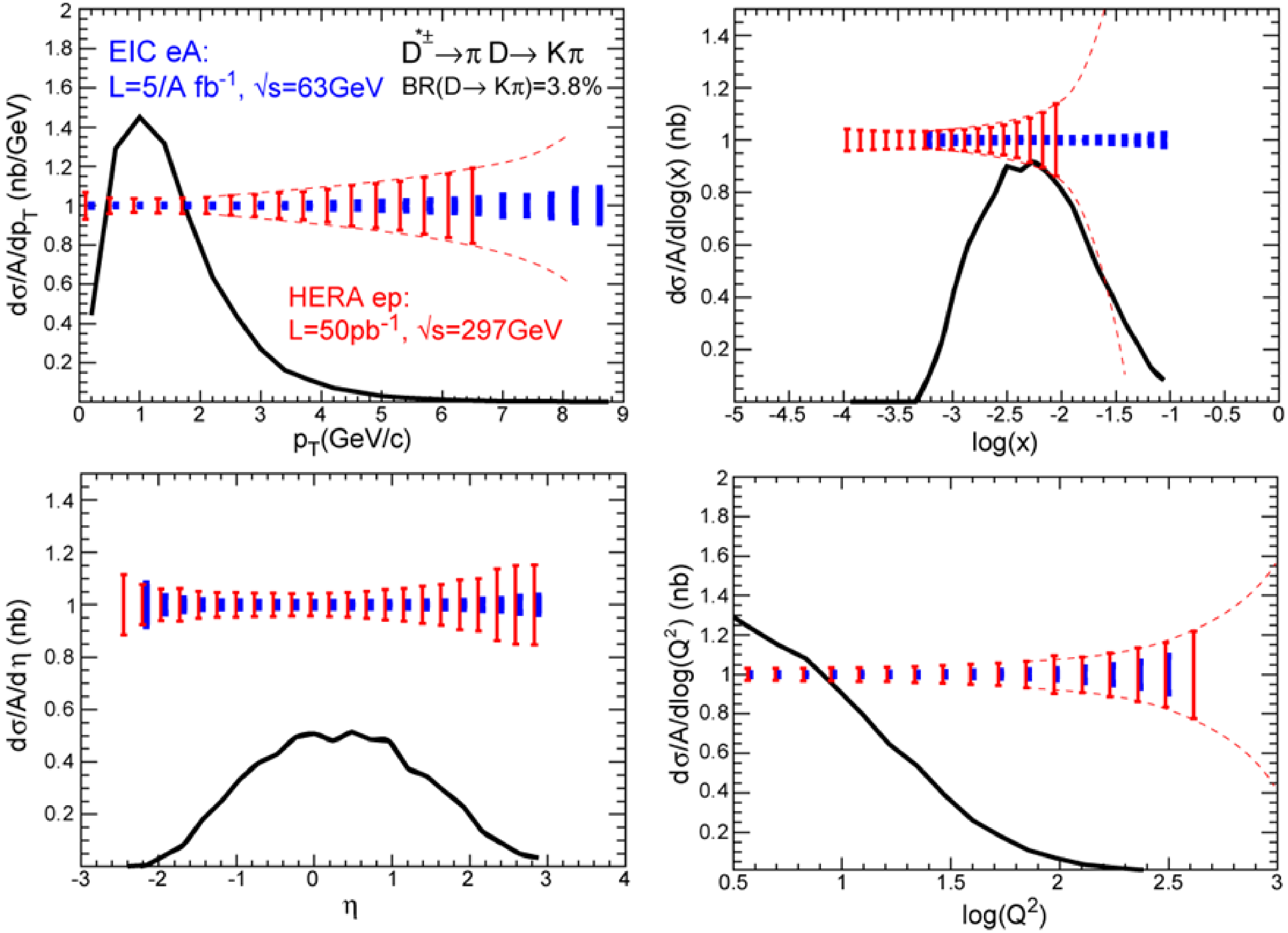
- Energy loss models
  - long color neutralization times with pre-hadron formation outside the medium
  - parton energy loss is premium mechanism for energy loss
- Absorption models
  - short color neutralization times
  - absorption as primary mechansim for energy loss
  - support from HERMES and JLAB data?



$z_h = E_h/\nu$

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

Charm at EIC



Based on HVQDIS model, J. Smith

⇒ **see talk by Zhangbu Xu**

EIC: allows multi-differential measurements of heavy flavor

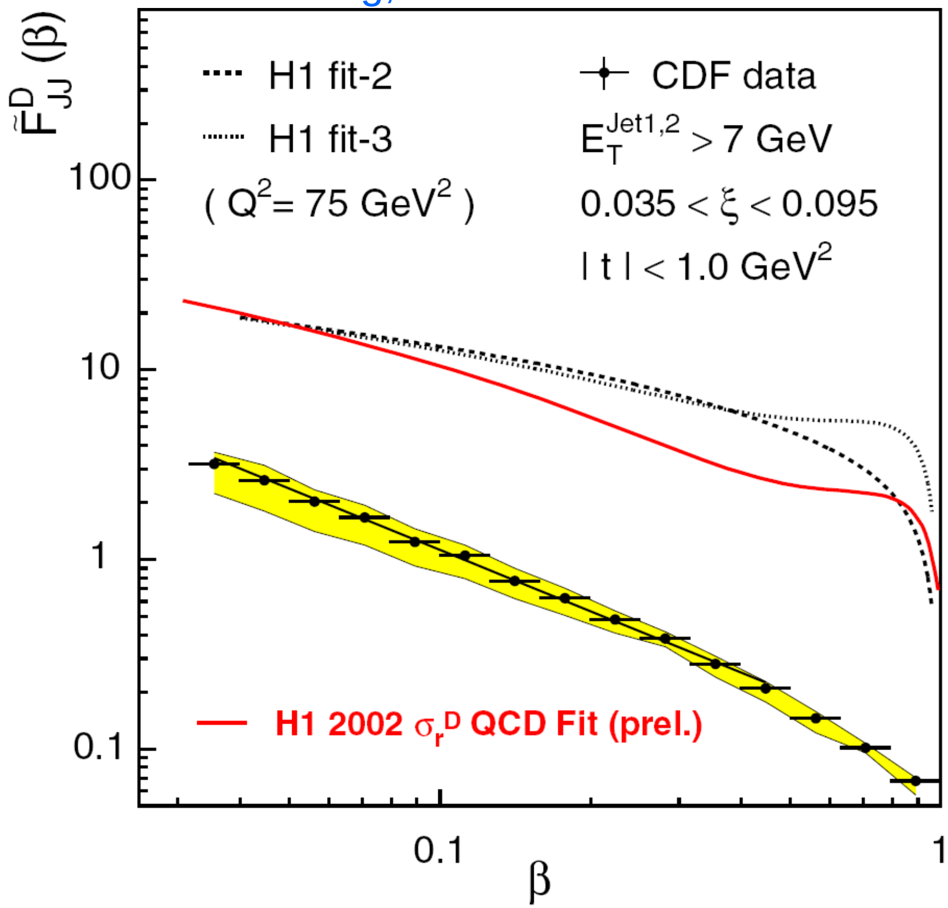
covers and extend energy range of SLAC, EMC, HERA, and JLAB allowing study of wide range of formation lengths

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:
  - 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, Q^2 ⇒ needs modeling

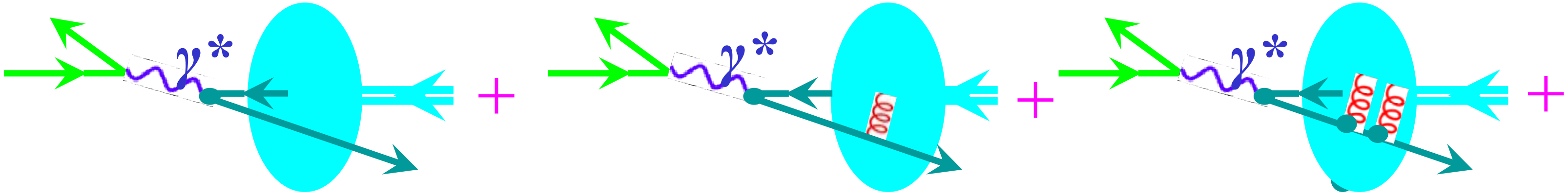
F. Schilling, hex-ex/0209001



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

eA vs pA: similarities and differences

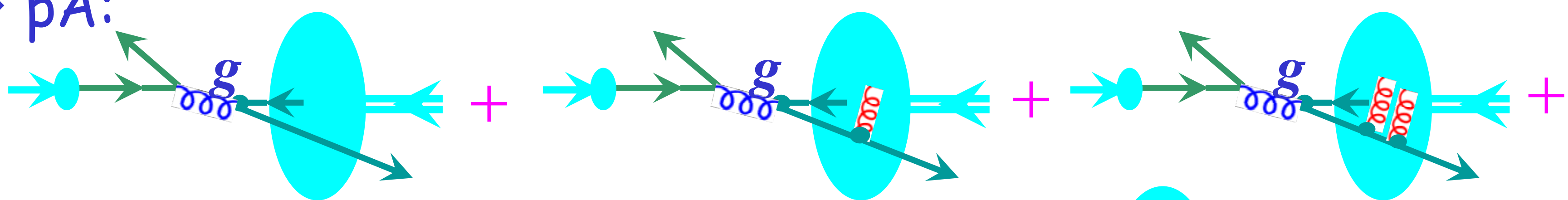
- DIS:



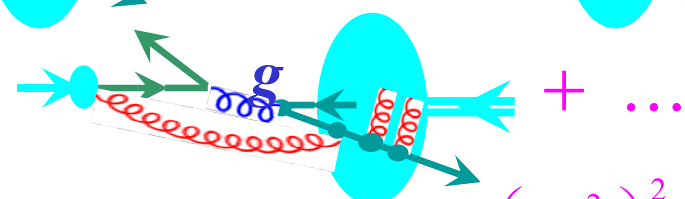
$$\sigma_{\ell A} \approx \hat{\sigma}^{(S)}_{\ell f} \otimes \varphi_{f/A} + \hat{\sigma}^{(D)}_{\ell f} \otimes T^{(D)}_{f/A} + \hat{\sigma}^{(T)}_{\ell f} \otimes T^{(T)}_{f/A} + \ldots$$

✓ 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 $1/Q^2$

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?

Jet Quenching:

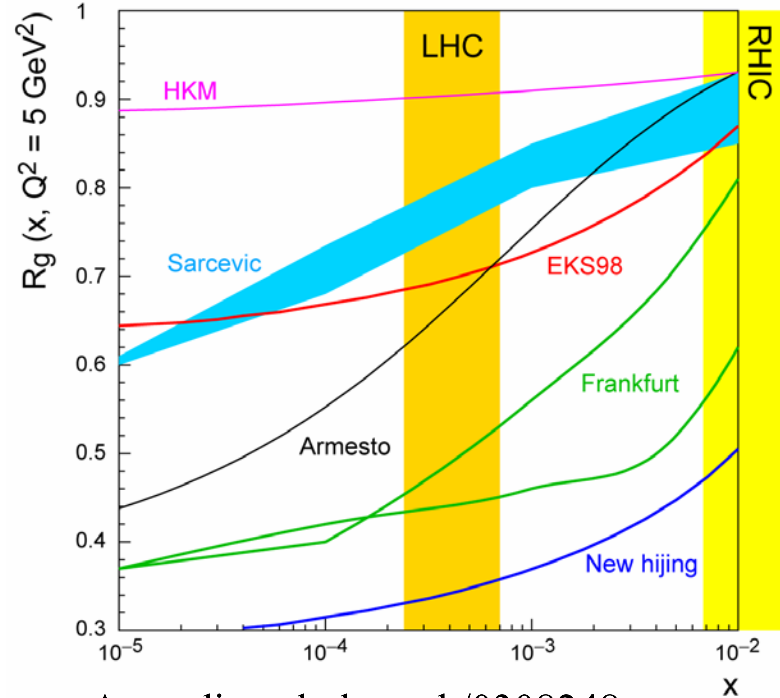
- Refererence: E-loss in cold matter
- d+A alone won't do
  - $\Rightarrow$ need more precise handles
- HERMES: charm?, $\nu < \nu$(LHC)

Forward Region:

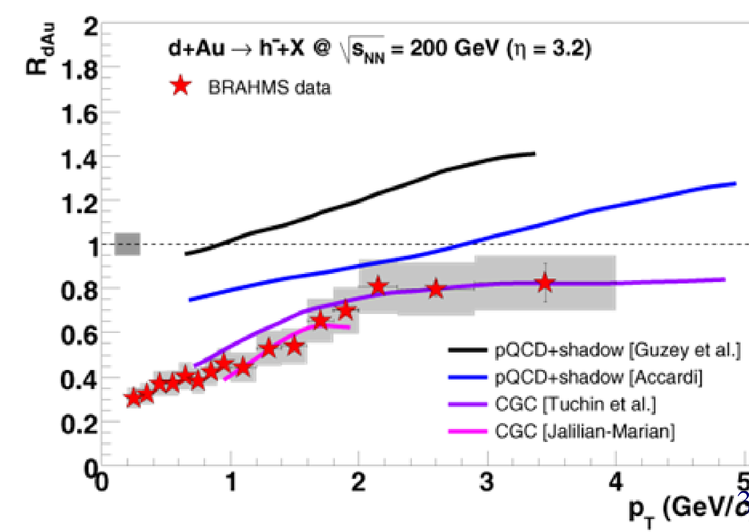
- Suppression at forward rapidities
  - Color Glass Condensate ?

Prticle Production at LHC:

- Mini-jet production depends strongly on $G(x,Q^2)$ – (Note: jets are off and away in high Q^2 land >> Q_s^2)
- Saturation effects vs. in-medium effects ?



Accardi et al., hep-ph/0308248



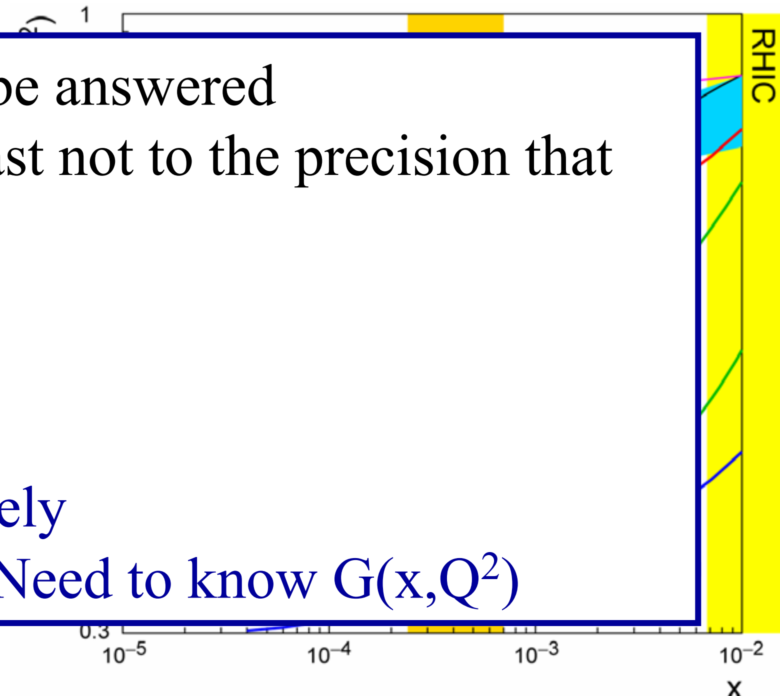
Connection to RHIC & LHC Physics

Ther...

Jet Q...

> Many (all?) of these questions cannot be answered by studying A+A or p+A alone – at least not to the precision that might be required (?)
>
> EIC provides new level of precision:
>
> - Handle on x, Q^2
> - Means to study effects exclusively
> - RHIC is dominated by glue ⇒ Need to know $G(x,Q^2)$

- HERMES: charm?, $\nu < \nu$(LHC)



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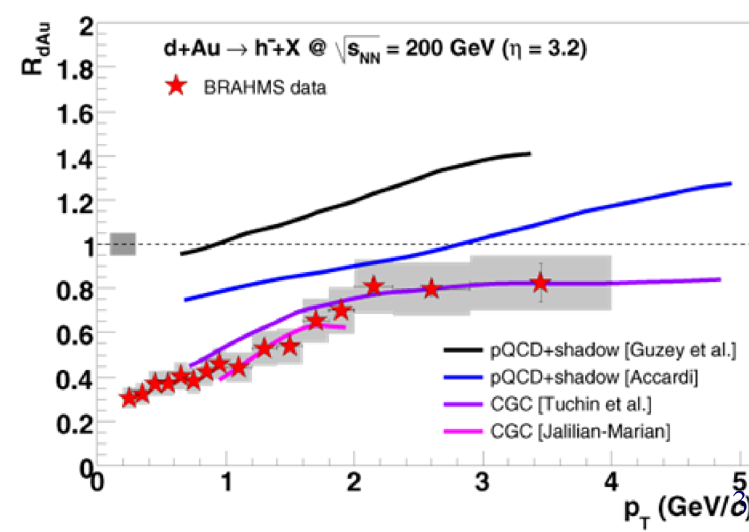


Connection to RHIC & LHC Physics

Ther

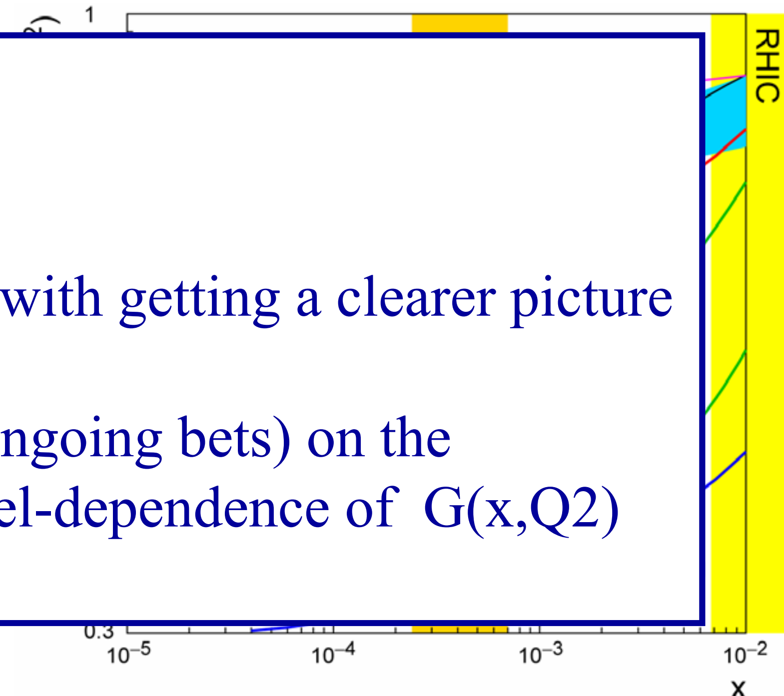
- A
  (
- V
  c

Jet Q

- F
- c

But: EIC will come very late …

- certainly for RHIC
- probably even for LHC
- but then there's nothing wrong with getting a clearer picture a few years late
- There's some discussion (and ongoing bets) on the feasibility/validity/quality/model-dependence of G(x,Q2) from pp, pA, AA



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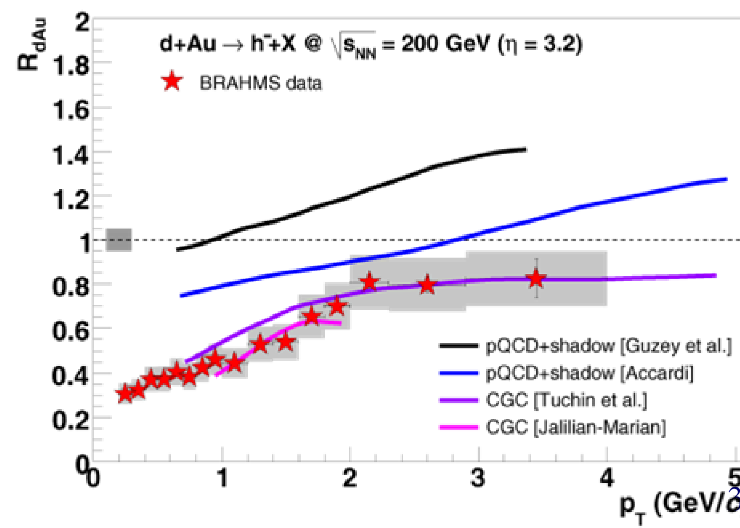

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Summary

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)

My Personal Take: We have good case for eA @ EIC

But there's a loooong way to go:
need brainstorming, simulations, and conduct detailed studies
in other words manpower