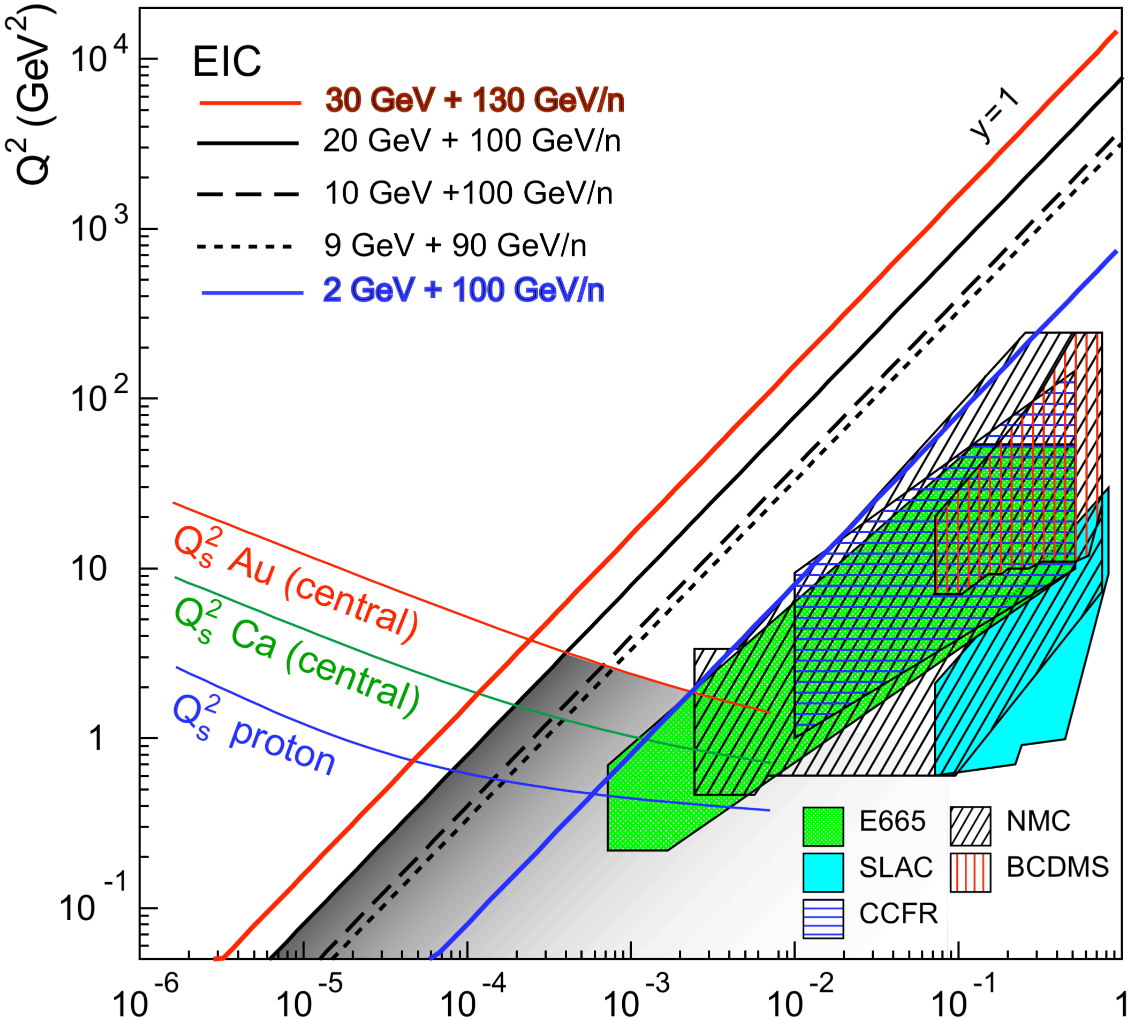
e-A and the Low-x Structure of Matter



James Dunlop

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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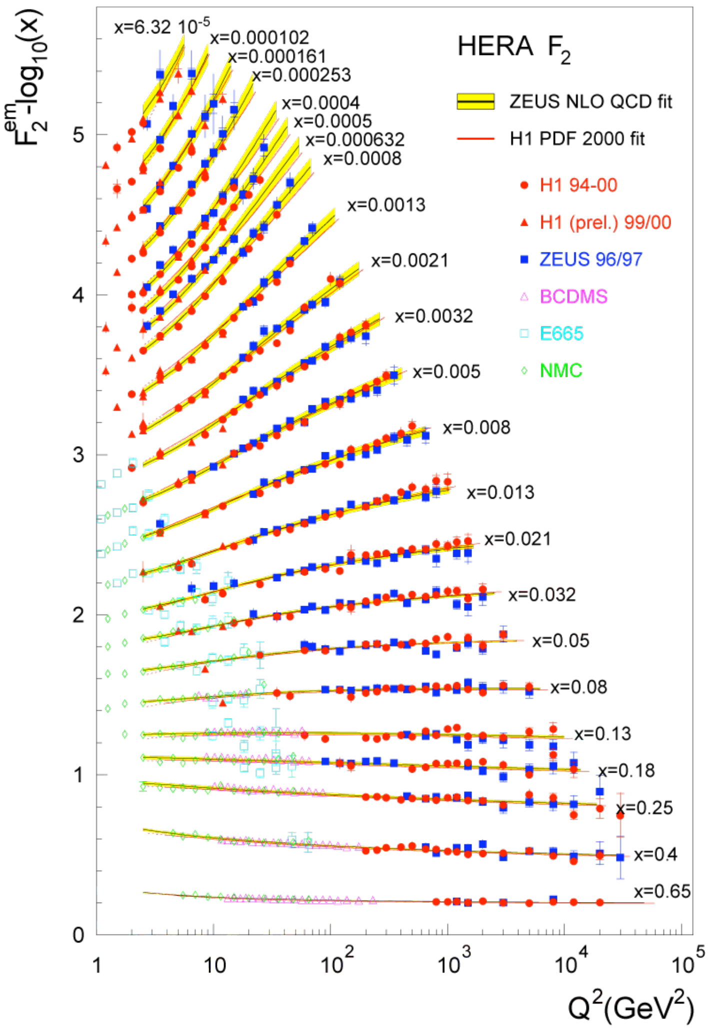
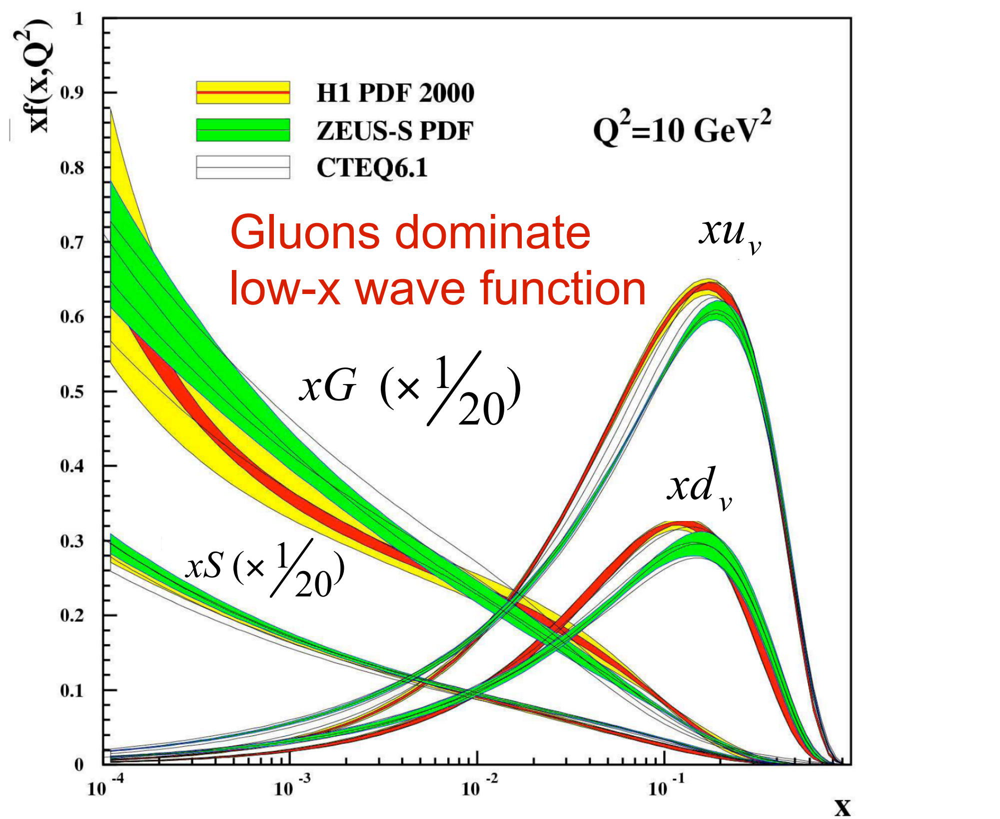
$\Rightarrow$ QCD requires *fundamental* investigation via *experiment*

What Do We Know About Glue in Matter?

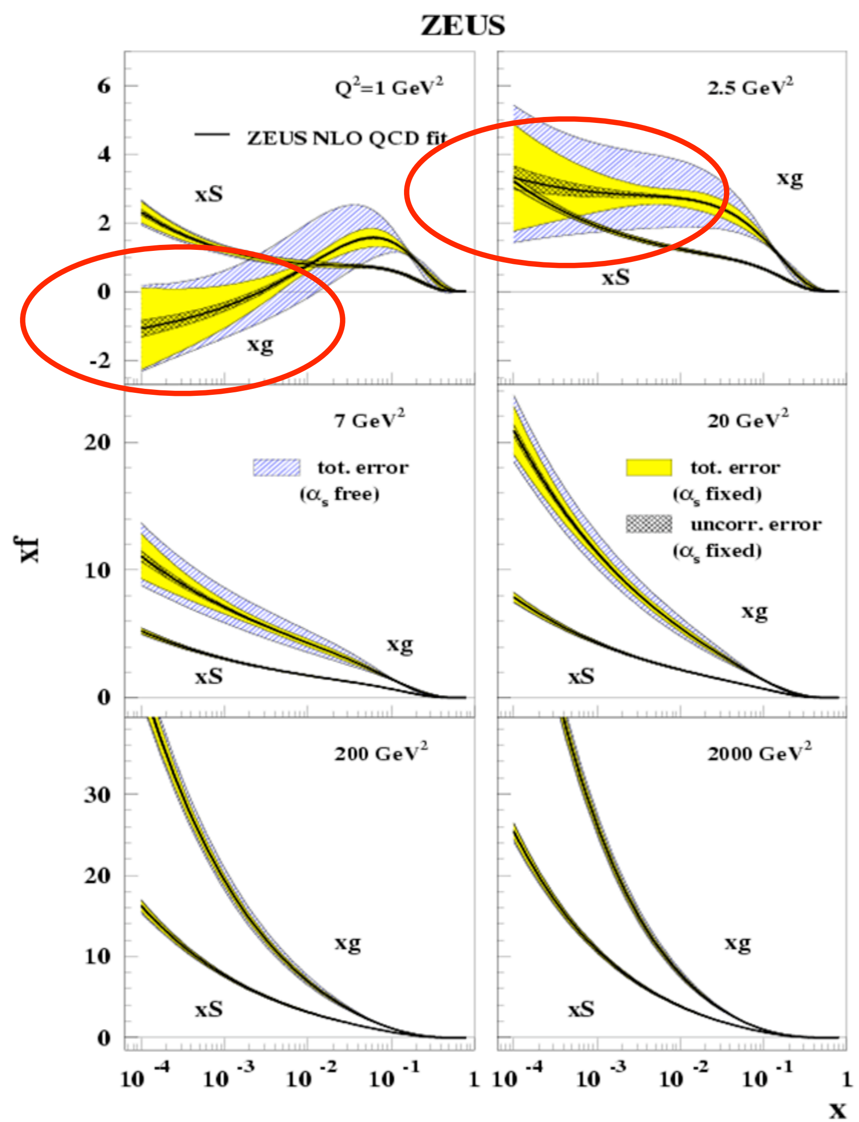
Deep Inelastic Scattering : $$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$



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



The Issue With Our Current Understanding



The Issue With Our Current Understanding

Established Model:

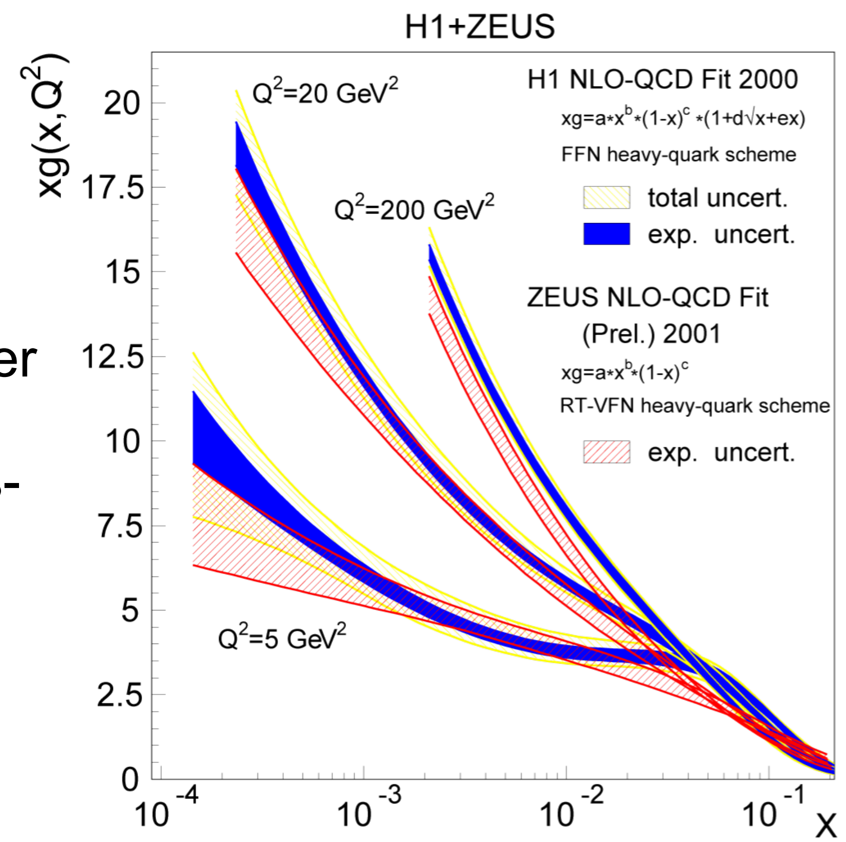
Linear DGLAP evolution scheme

- 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

more severe:

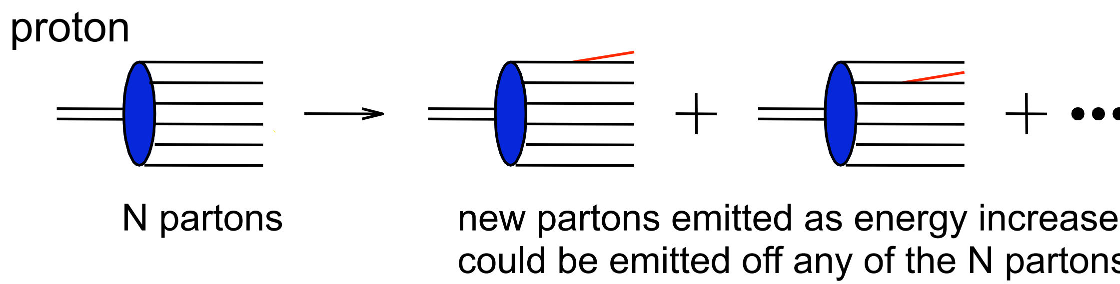
Linear Evolution has a built in high energy "catastrophe"

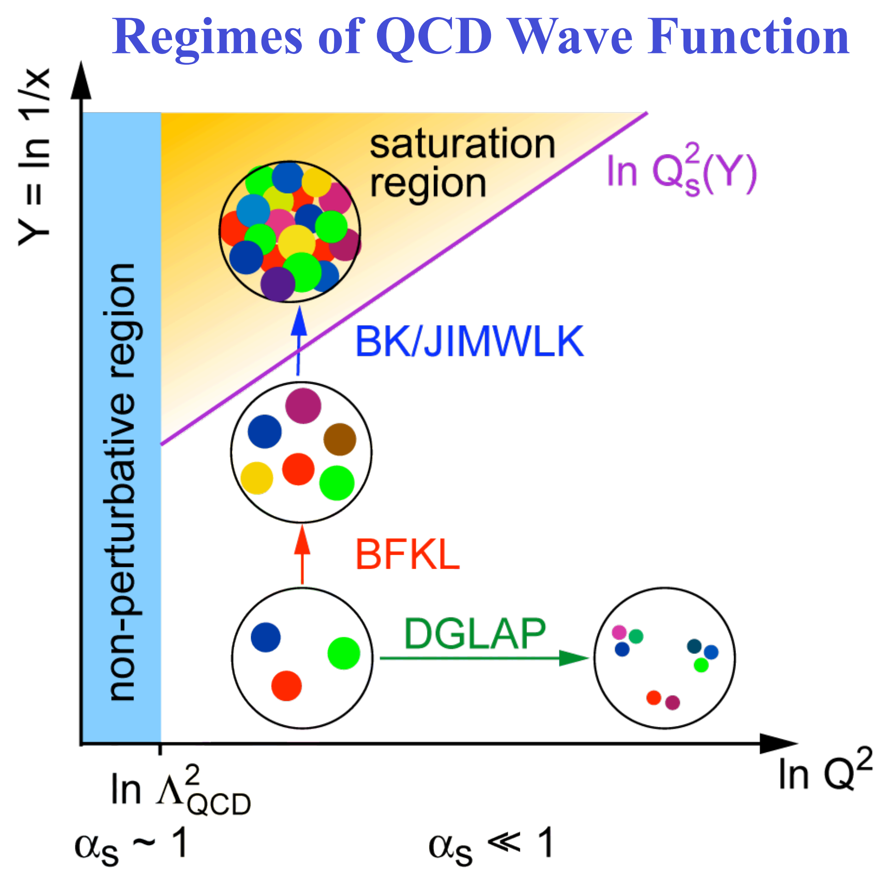
- xG rapid rise for decreasing x and violation of (Froissart) unitary bound
- ⇒ **must** saturate
  - What's the underlying dynamics?



⇒ Need new approach

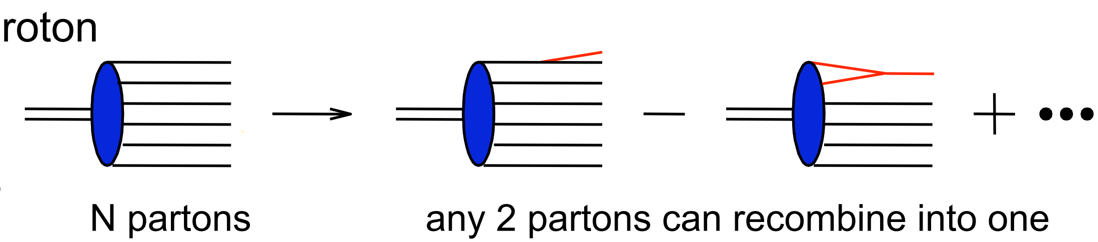
Non-Linear QCD - Saturation

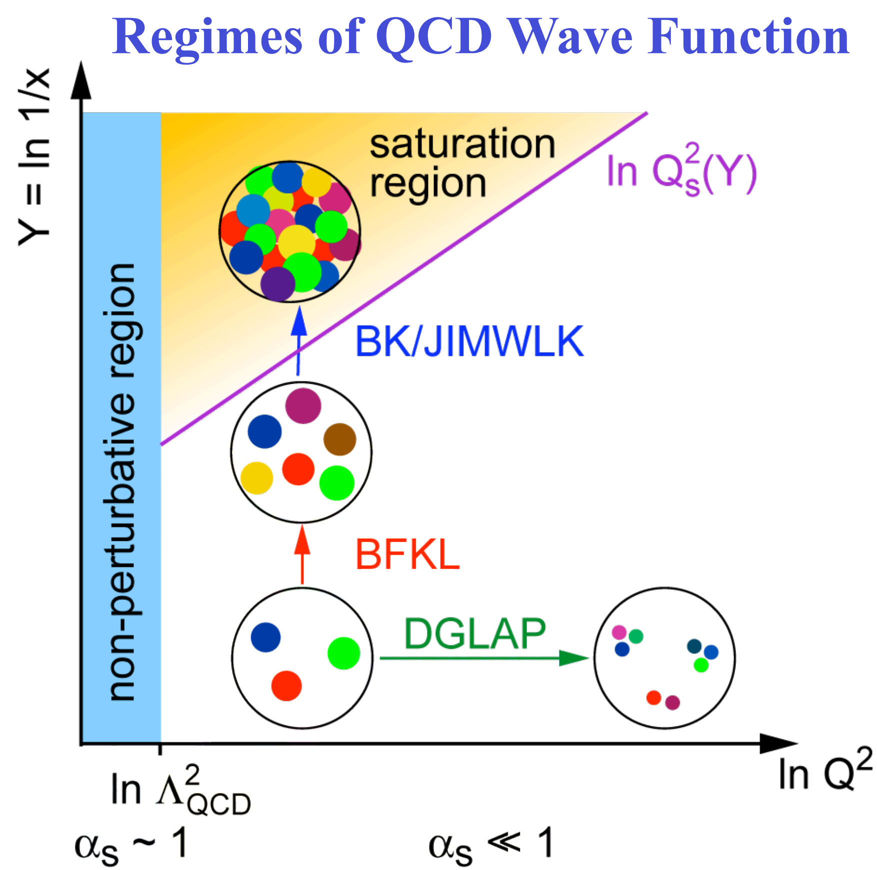




Non-Linear QCD - Saturation

- BFKL Evolution in x
  - linear
  - explosion of color field?





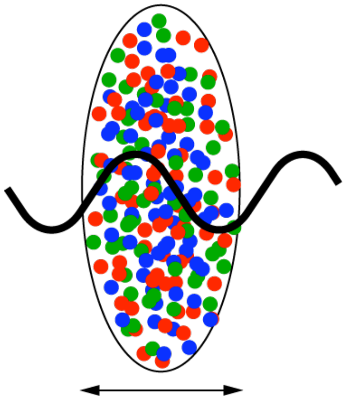
- New: BK/JIMWLK based models
  - introduce *non-linear* effects

  ⇒ 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



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

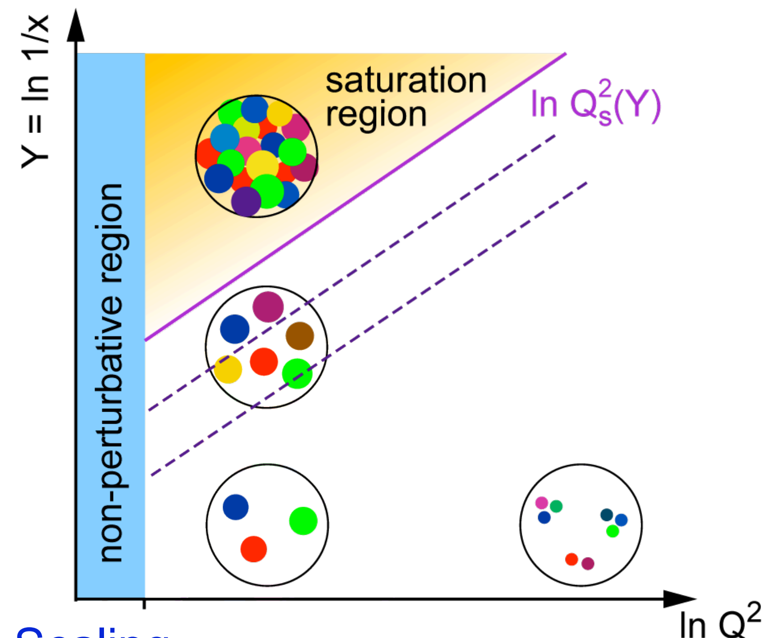
Nuclear "Oomph" Factor
Pocket Formula:

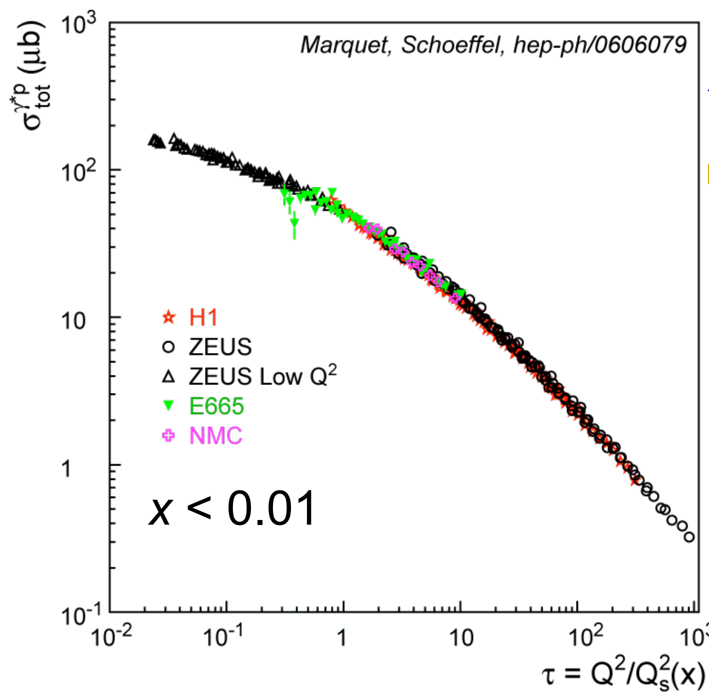
$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

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

Hints for Saturation at HERA & 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





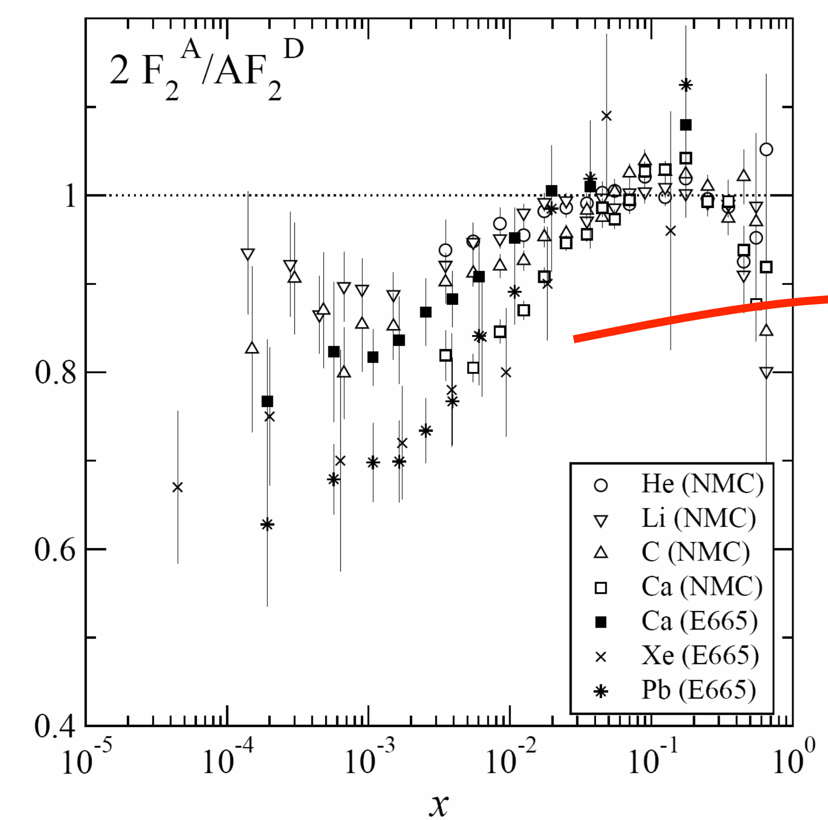
⇐ Geometric Scaling

- Consequence of saturation which manifests itself up to $k_T > Q_s$
- Also seen in other final states (diffraction & VM production)

Scaling not proof but allows to set upper limit for saturation effects $x < 10^{-2}$

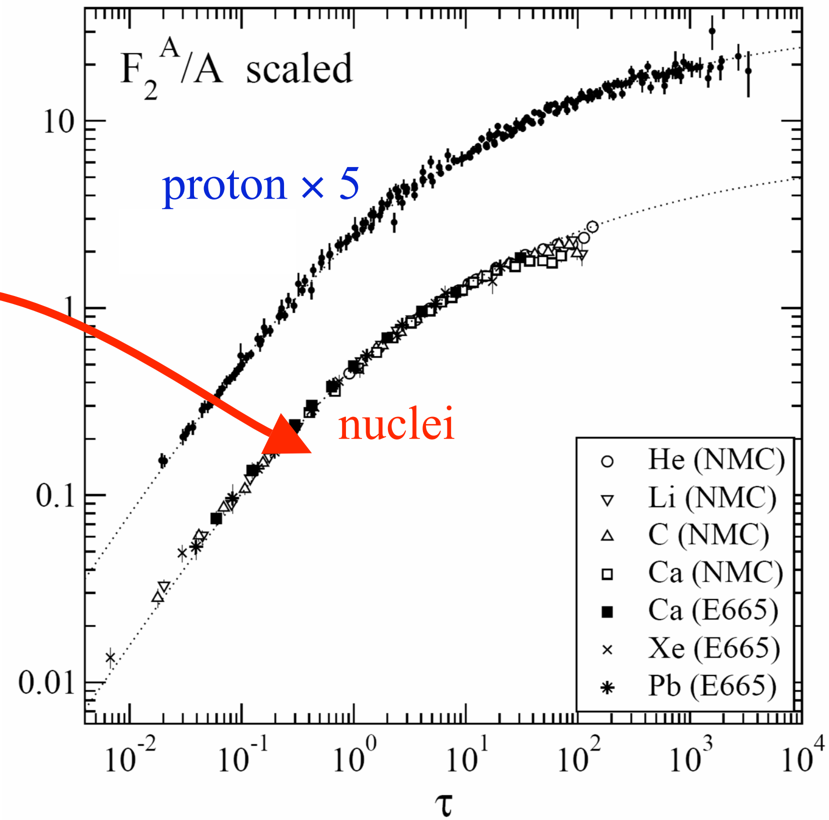
Earlier Nuclear Experiments and Saturation

Nuclear shadowing:



Freund et al., hep-ph/0210139

Geometrical scaling



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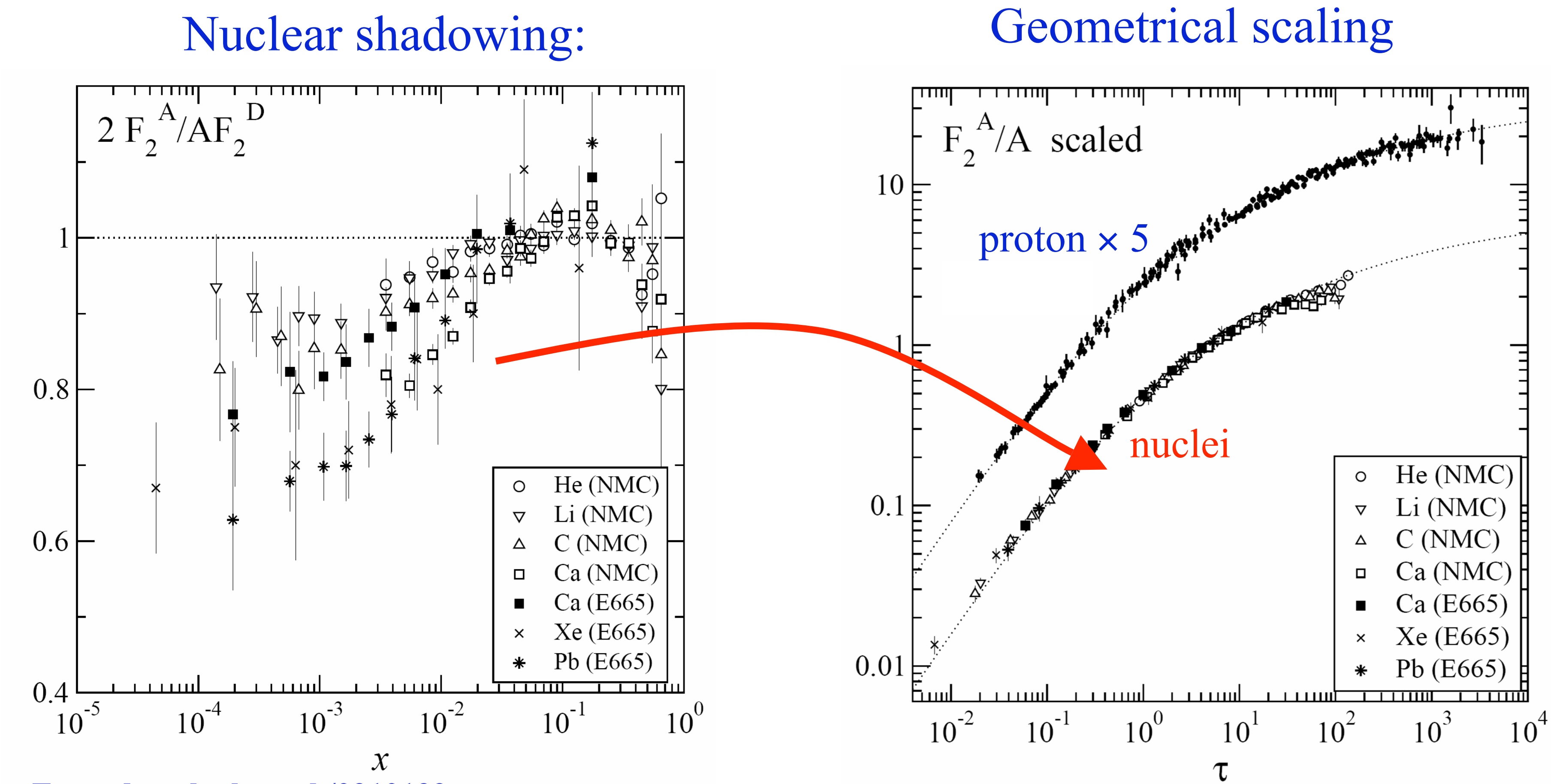


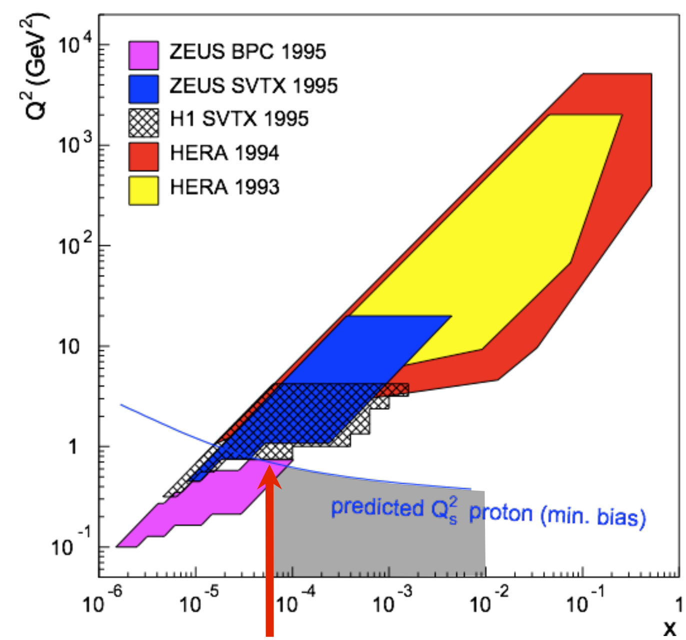
Freund et al., hep-ph/0210139

Geometrical scaling also found in nuclear experiments

HERA & Saturation

- HERA (ep):
- Despite energy range far higher than EIC:
- $G_p(x, Q^2)$ through scaling violation known only outside (or in a very small region of) the saturation regime
- Same for $G_p(x, Q^2)$ through F_L

- HERA will provide a first direct measurement of $G(x, Q^2)$ in the proton BUT
- Regime where non-linear QCD (saturation phenomena) matter ($Q < Q_s$) out of reach!



- EIC: all relies on the Nuclear OOMPH (i.e. increasing Q_s)

The Oomph Factor

- 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 *e*+*p*

$$\begin{aligned} s_{Hera} &\approx (330 \text{ GeV})^2 \\ s_{EIC} &\approx (63 \text{ GeV})^2 \\ \frac{s_{EIC}}{s_{Hera}} &\approx \frac{1}{27} \end{aligned}$$

Instead of extending *x*, *Q* reach we increase Q_s

$Q^2 \sim sx$: EIC factor 27 behind (10+100 GeV)

$$\begin{aligned} Q_s^2(Hera) &= Q_s^2(EIC) \rightarrow Q_0^2\, x_{Hera}^{-1/3} = c\, Q_0^2\, A^{1/3}\, x_{EIC}^{-1/3} \\ x_{EIC} &= x_{Hera} \cdot c^3 A \\ c^3 A &= 0.5^3 \cdot 197 \approx 25 \end{aligned}$$

State-of-the-Art Oomph

- The e+A program lives and dies with the enhancement of Q_s^A over Q_s^p

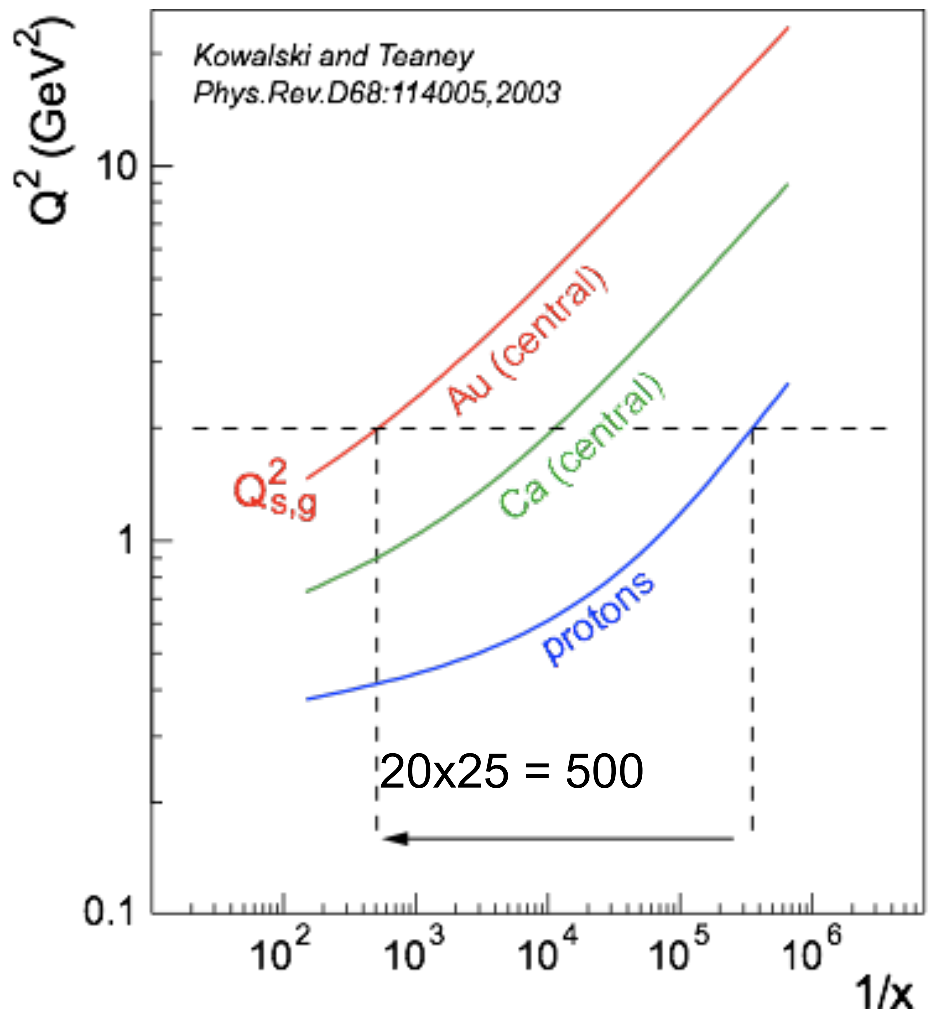
  This factor is huge (500)

  but

  it's a model calculation!

- Assuming it's correct we "reach" further compared to HERA by 500/27 = 18
- (where we see no striking saturation effects)

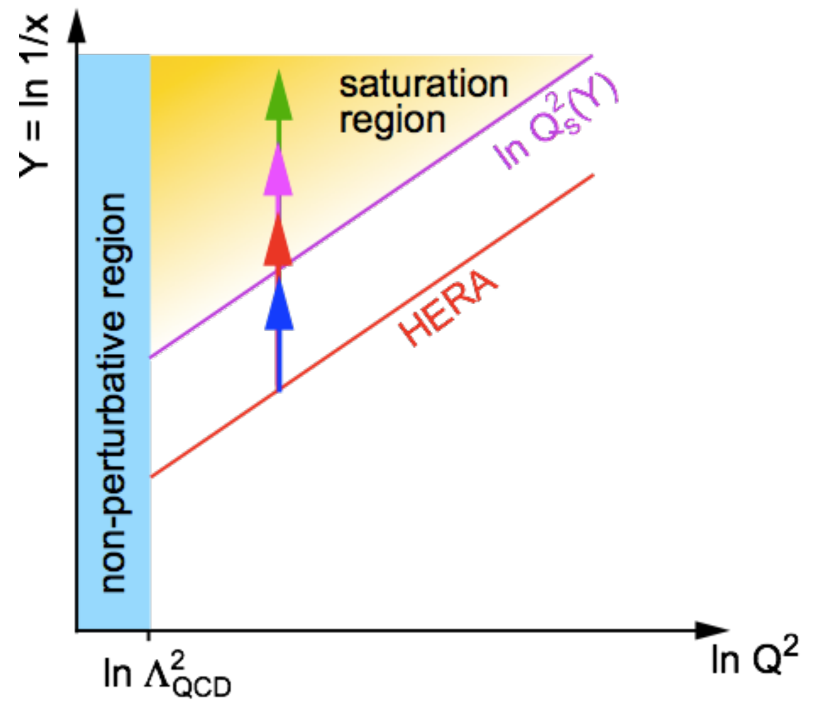
Here: protons for $b=b_{med}$



Reaching Saturation: Oomph versus HERA

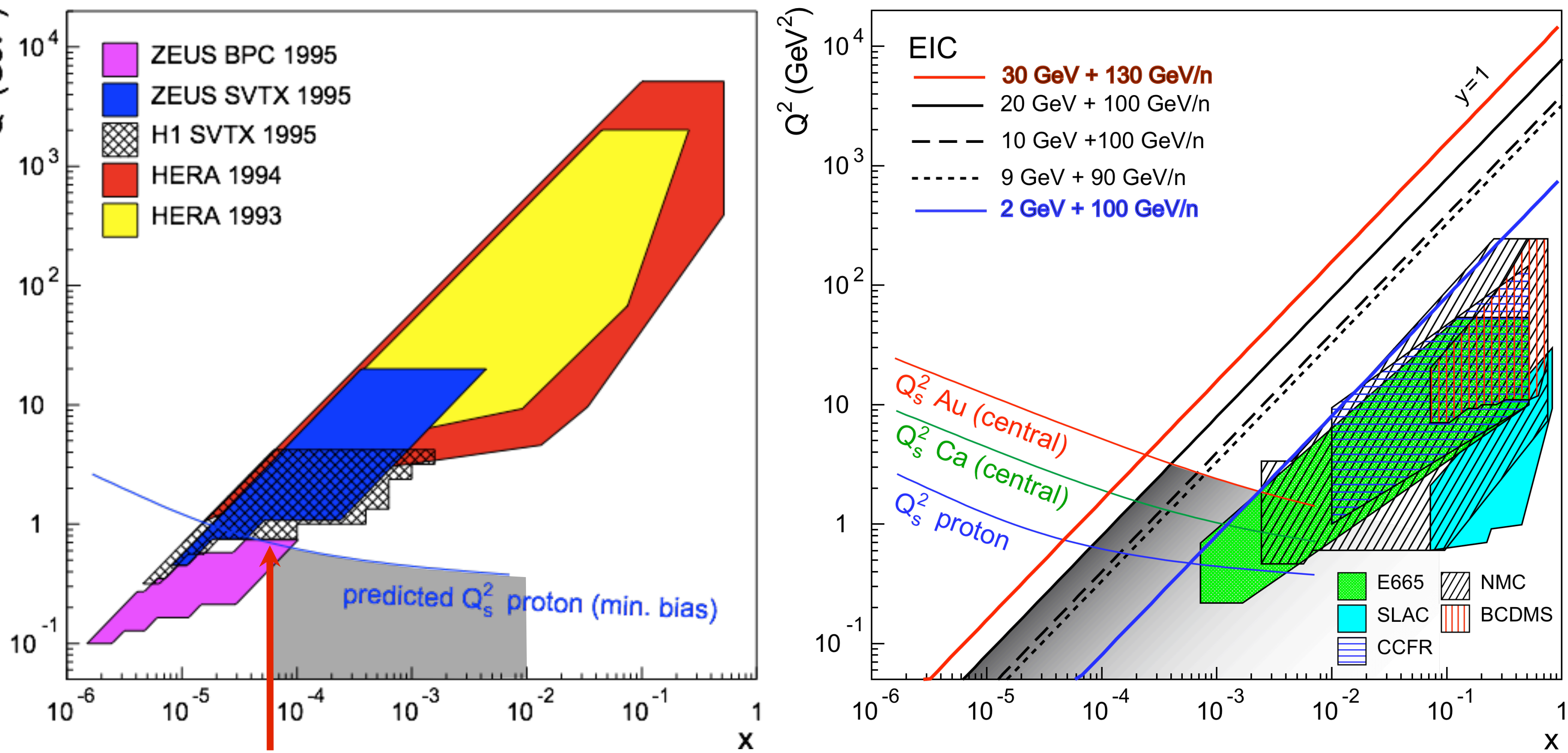
Beam Energy (GeV)	√s (GeV)	s_{EIC}/ s_{HERA}	"virtual" x reach boost over HERA at Q^2=const
2+100	28	1/140	4
10+100	63	1/27	18
20+100	89	1/14	36
20+130	102	1/10	50
30+130	125	1/7	71

Numbers are rounded and approx. only



Note: We do not know (until we measured it) how far HERA was away from the saturation physics regime

Reach compared with previous facilities



Staged option: begins to reach into the saturation regime for heavy nuclei

Experience with nuclei have shown that we need to reach deeply into a new regime for assurance that the new regime has been reached

And, we need a safety margin (models can and have been wrong before)

Measurements: Understanding Glue in Matter

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  - Strength of *e*+A
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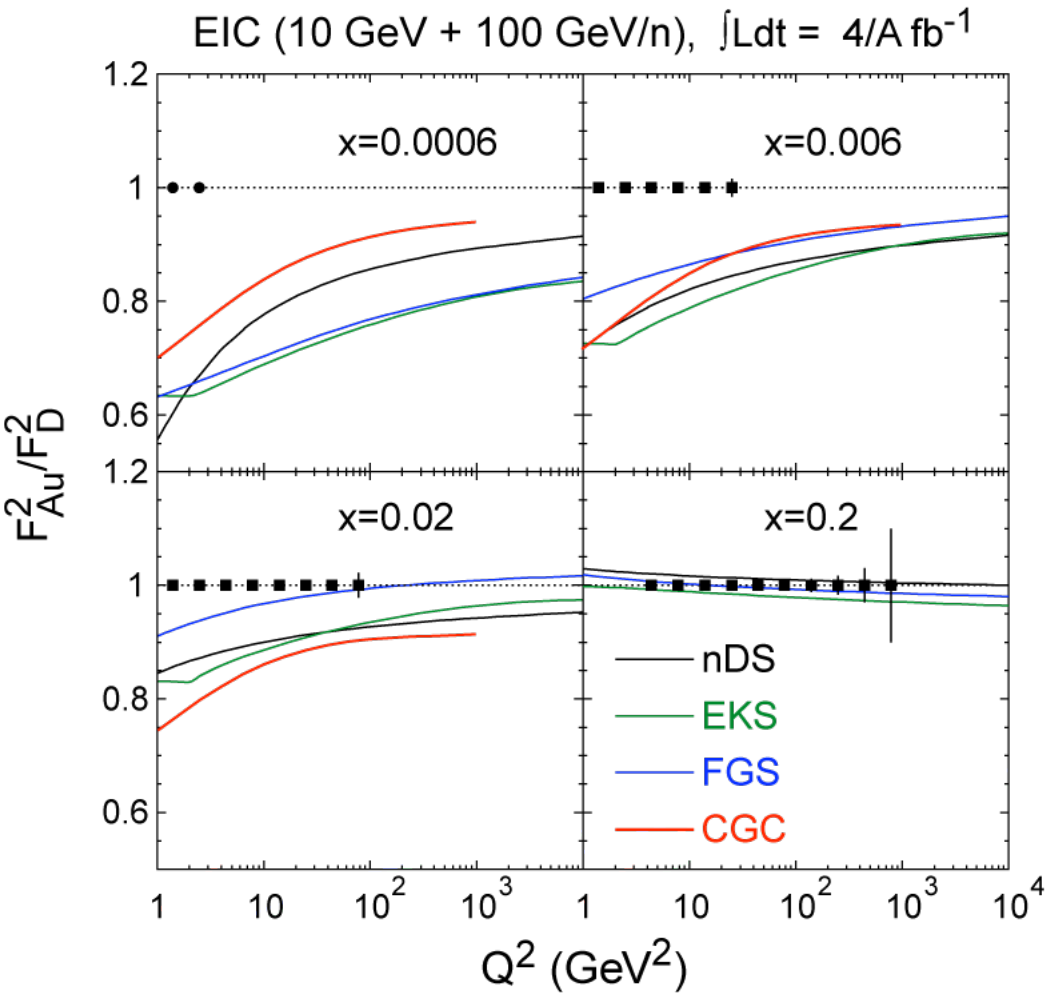
What is the Momentum Distribution of Gluons?

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

- Shown here:
  - Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - $F_L \sim \alpha_s G(x,Q^2)$
- Other Methods:
  - 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 ~ $[G(x,Q^2)]^2$
    - Active area of investigation
    - See M. Lamont's talk later today

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

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

F_L: measure glue directly

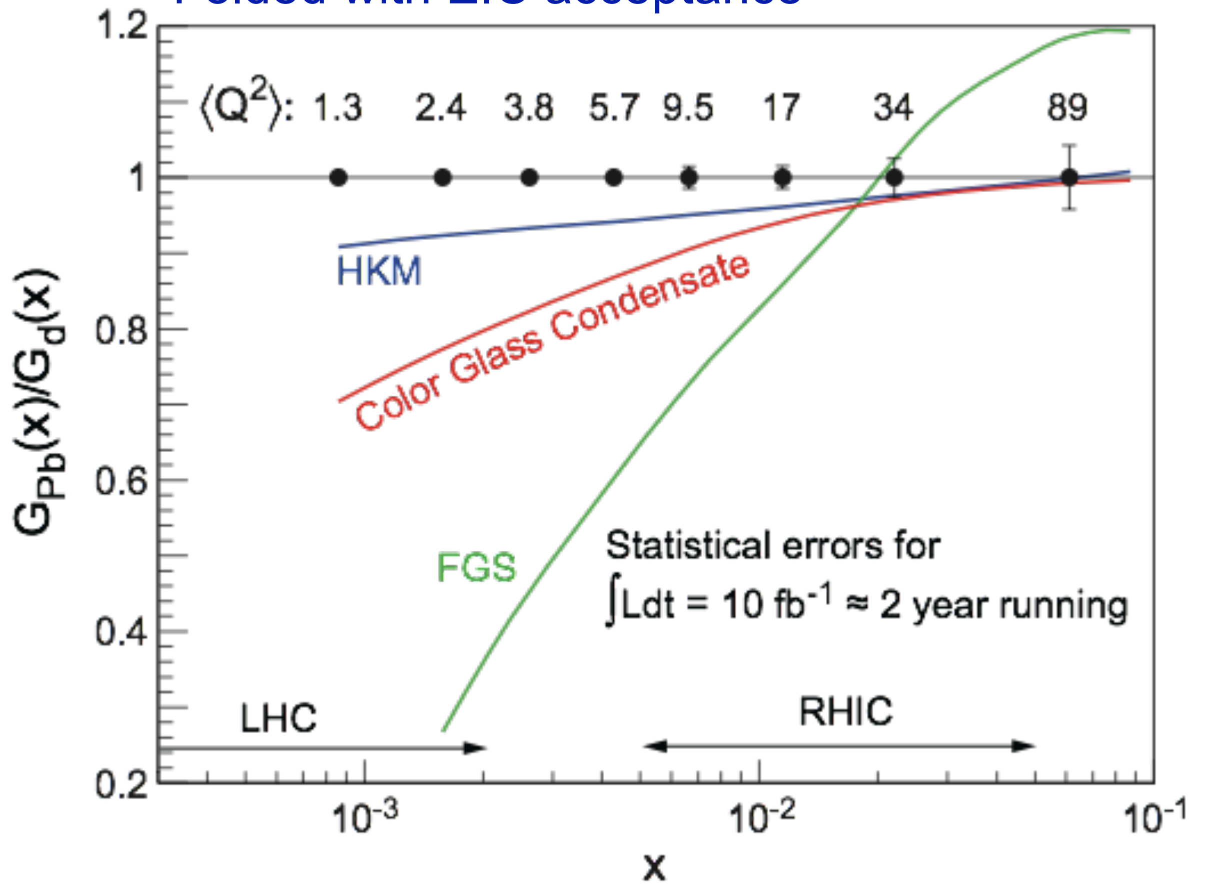
$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

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

- <u>Assume:</u>
- L = 3.8 10^{33} cm^{-2} s^{-1}
- T = 10 weeks
- duty cycle: 50%
- L ~ 1/A (approx)
- ∫Ldt = 11 fb^{-1}

Plot contains:
∫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

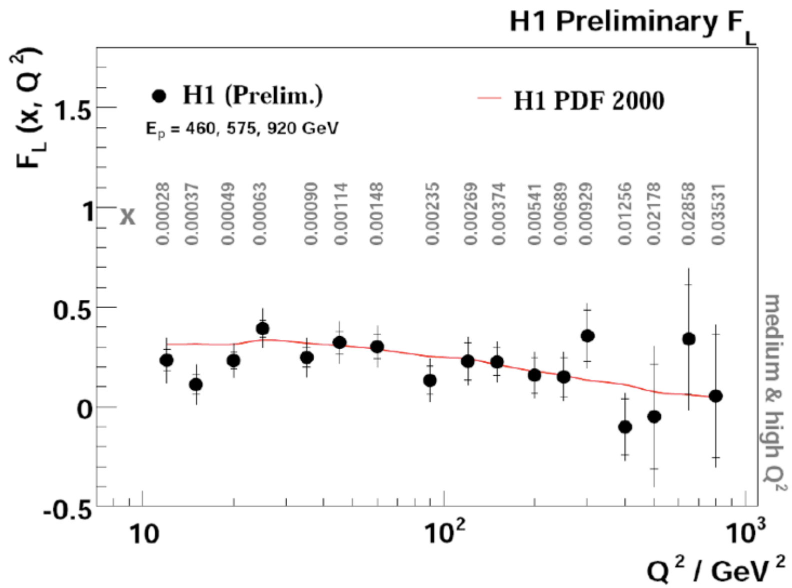
Folded with EIC acceptance

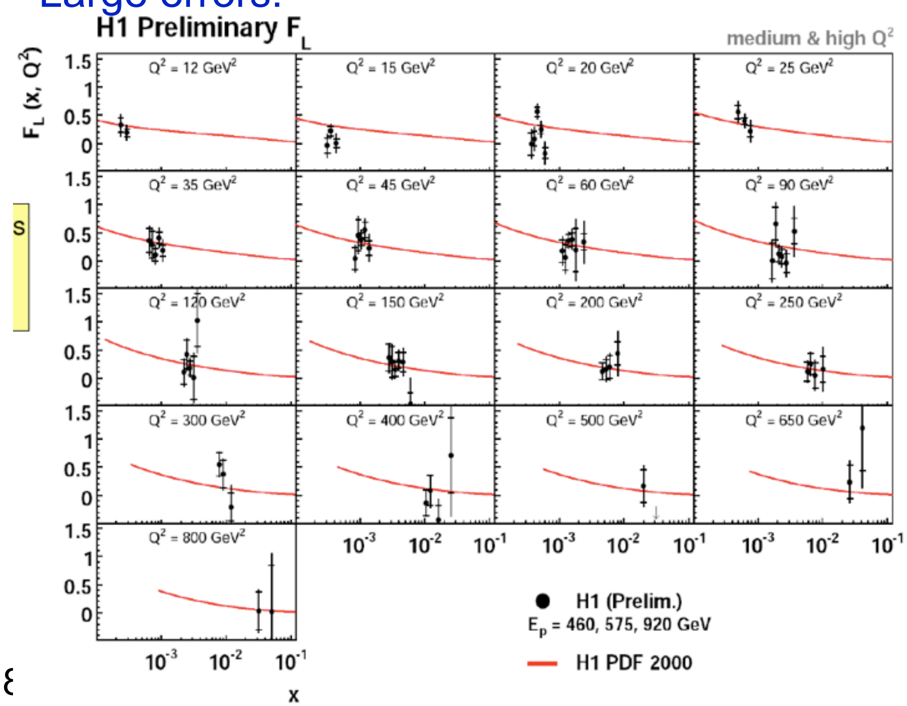


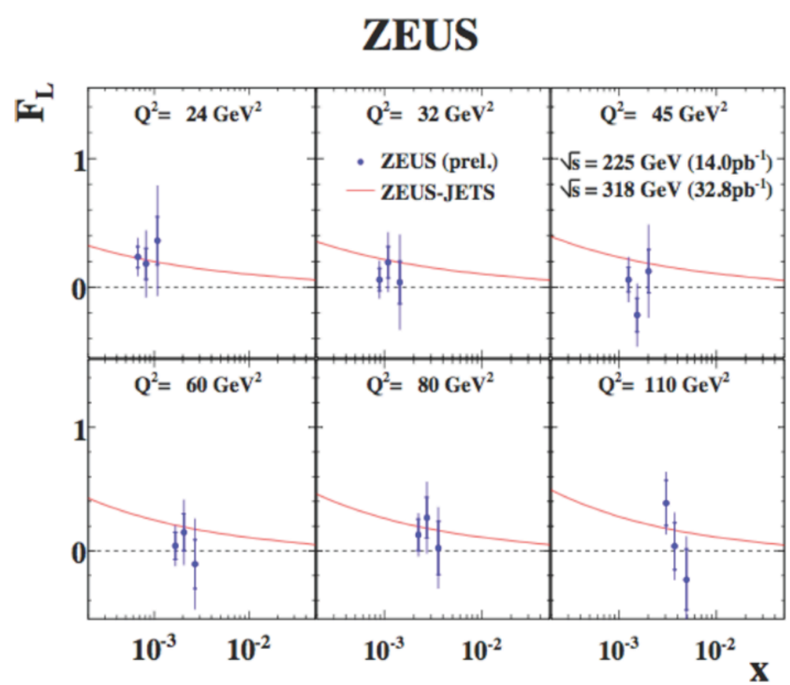
Existing F_L measurements: Hera

- Runs in 2007:
  - High s - E_p=920 GeV (H1 = 21.9 pb^{-1})
  - Low s - E_p=460 GeV (H1 = 12.4 pb^{-1})
  - Medium s - E_p=575 GeV (H1 = 6.2 pb^{-1})
- Sensitivity to F_L requires high y
- Challenge - high y means low electron energy
- HERA: F_L(H1) > F_L(Zeus) ?

  limited to large Q ($Q>Q_s$) $x = 10^{-4} \dots 10^{-1}$
- Large errors!





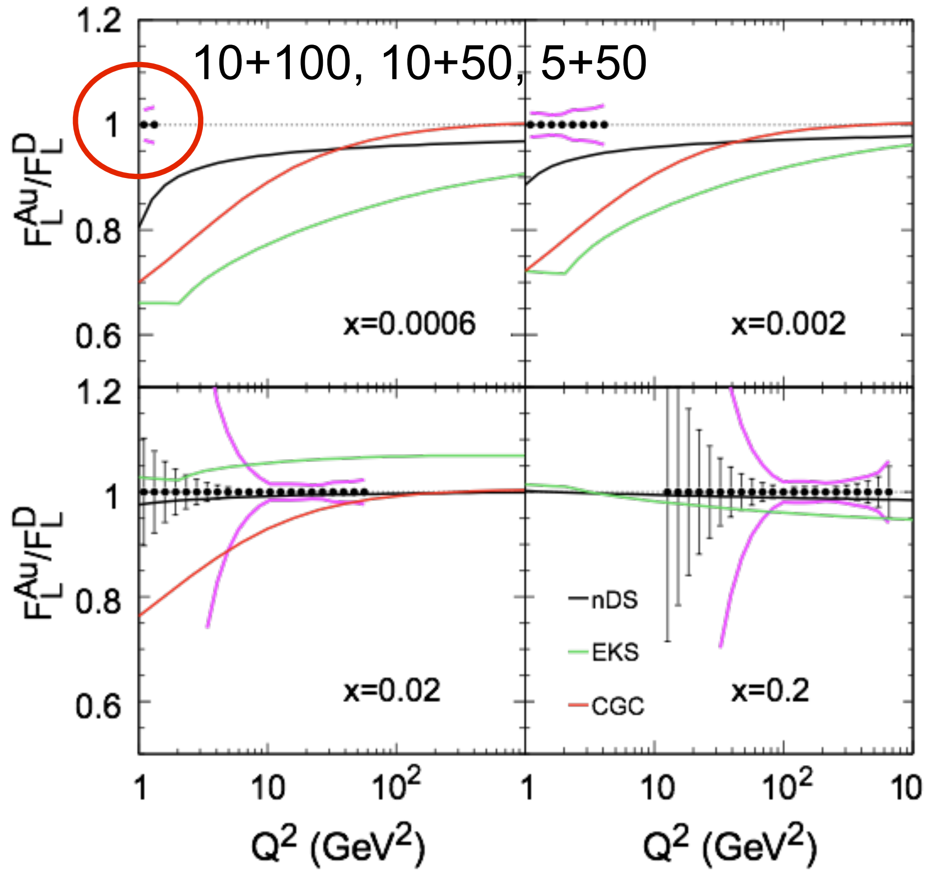


F_L and Syst. Errors

- W/o at least a rough detector design and lots of simulations it is hard to estimate sys. uncertainties

Simple estimate J. Dunlop/A. Bruell:
1% energy-to-energy normalization (only)
following discussions at MIT EIC Mtg.

•How realistic are the assumptions?
•Compare to current HERA studies ?



Conclusion from this study:
Dominated by sys. Uncertainties
Luminosity not the limit, but need more detailed studies (w detector)

Need to maximize y range, maximize range of s scanned

e.g. x=0.005, Q^2 = 2 GeV^2: y from 0.5 (2+100) to 0.03 (30+130)

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 ?

- Various techniques & methods:
  - Exclusive final states (e.g. vector meson production ρ, J/ψ, DVCS)
    - color transparency ⇔ color opacity
  - Deep Virtual Compton Scattering (DVCS)
    - 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

- Promising direction: fundamentally new approach in nuclei from which much can be learned even at the lower energies

Hadronization and Energy Loss

nDIS:

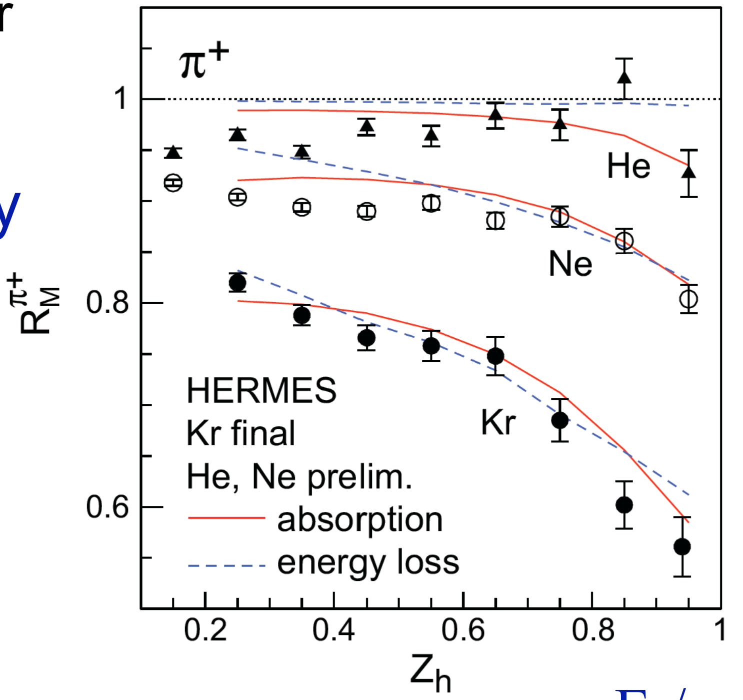
- Suppression of high-p_T hadrons analogous but *weaker* than at RHIC
- Clean measurement in 'cold' nuclear matter

Fundamental question:

What is the mechanism for QCD energy loss in matter?

When do colored partons get neutralized?

Parton energy loss vs. (pre)hadron absorption



$z_h = E_h/\nu$

Energy transfer in lab rest frame

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

EIC: can measure *heavy flavor* energy loss

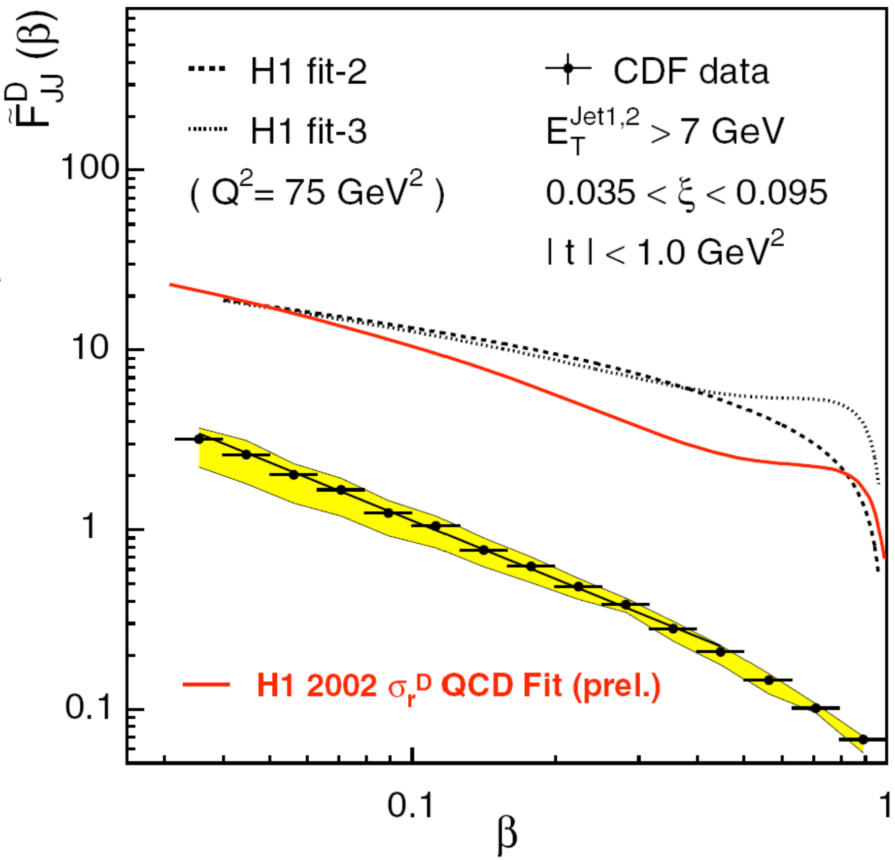
Mass effects not understood at RHIC, control time scales

x range not required to be small, can start at 2+100

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

F. Schilling, hex-ex/0209001



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

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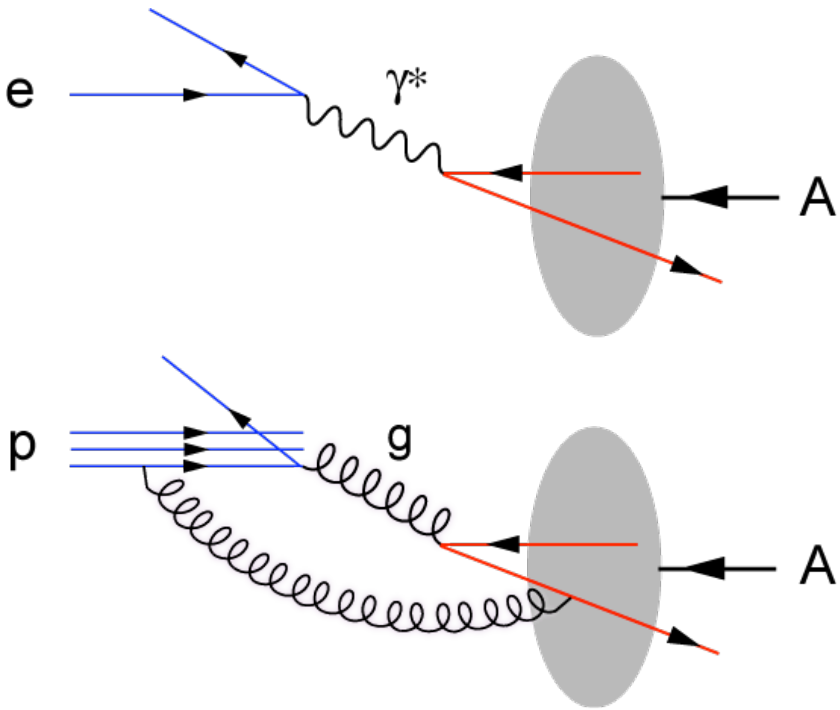
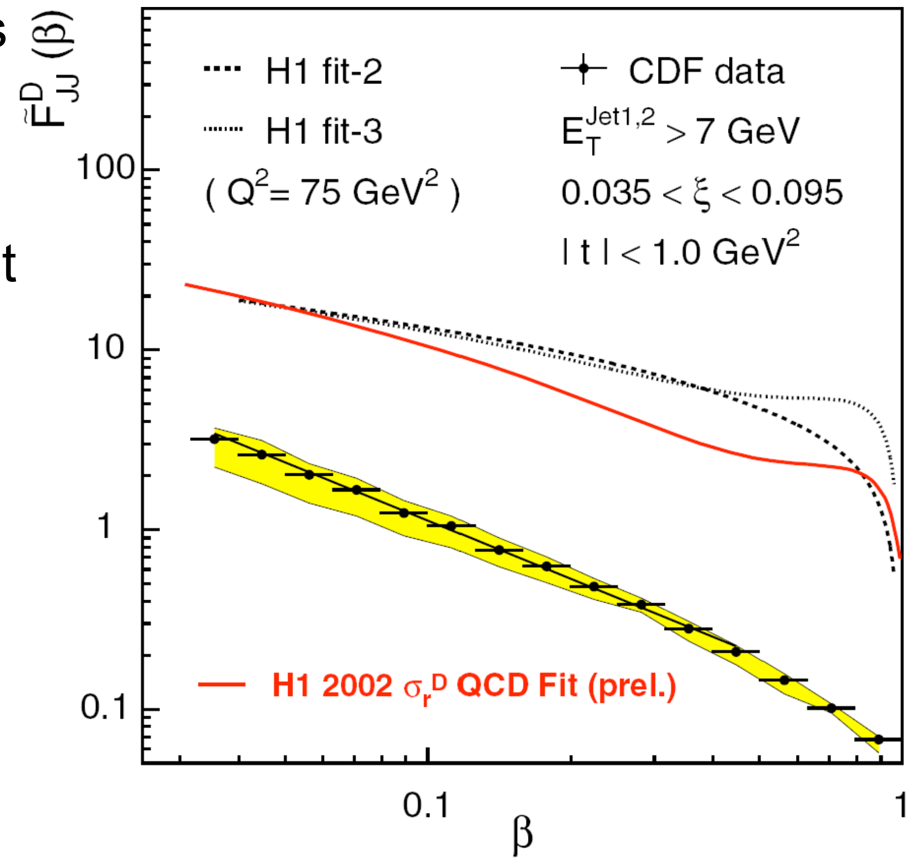
– Both are complementary and offer the opportunity to perform stringent checks of factorization/universality



F. Schilling, hex-ex/0209001



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

Connection to RHIC & LHC Physics

Matter at RHIC:

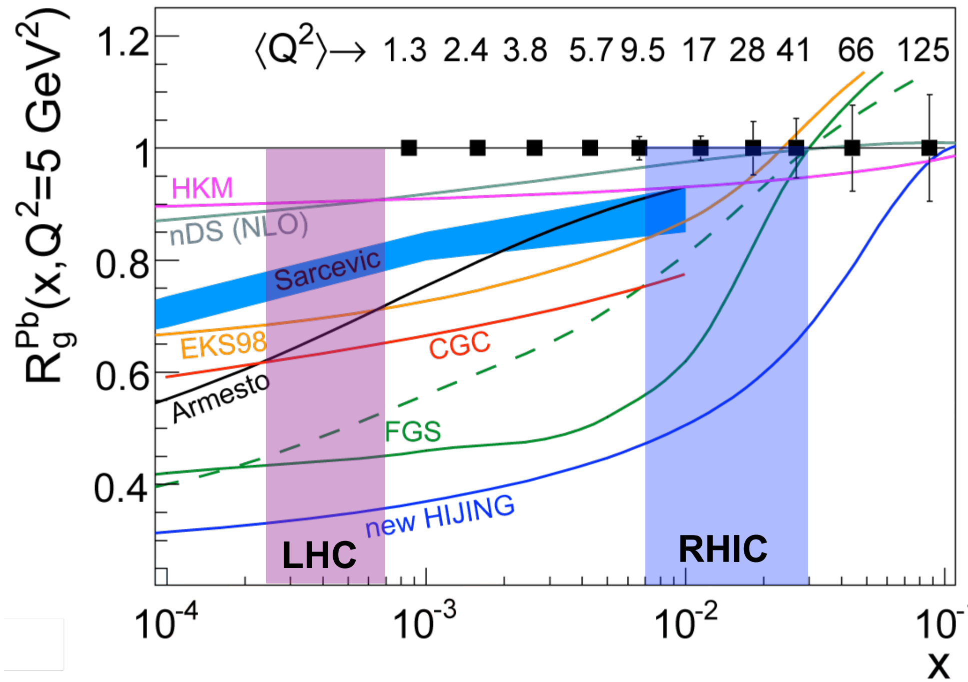
- thermalizes fast (τ_0 ~ 0.6 fm/c)
- We don't know why and how?
- Initial conditions? ⇒ $G(x, Q^2)$

Role of saturation ?

- RHIC → forward region
- LHC → midrapidity
  - bulk (low-p_T matter) & semi-hard jets

Jet Quenching:

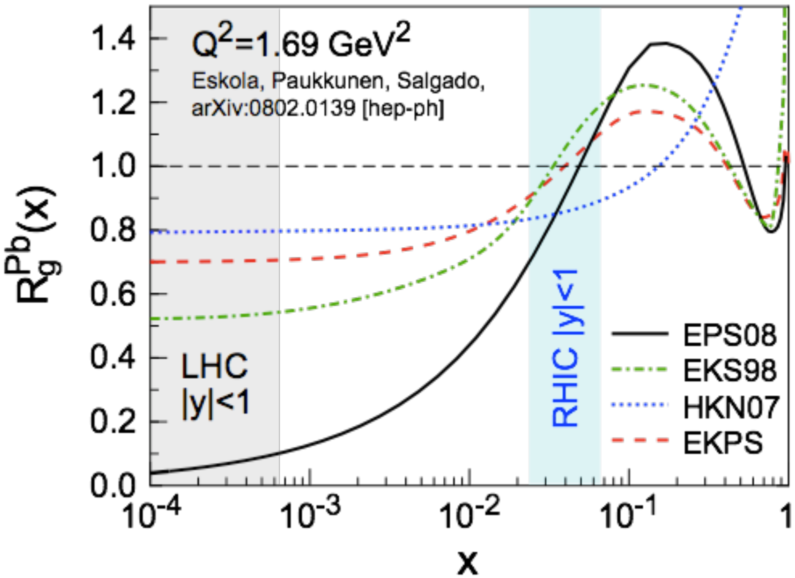
- Need Refererence: E-loss in cold matter
- No HERMES data for
  - charm energy loss
  - in LHC energy range



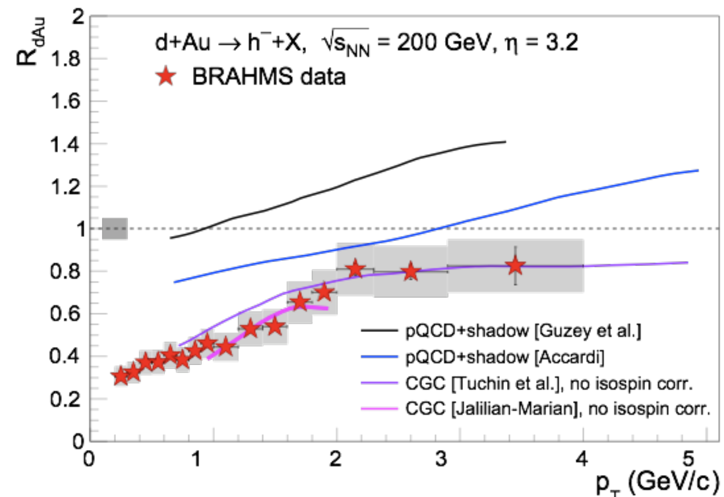
EIC provides new essential input:
- Precise handle on x, Q^2
- Means to study exclusive effects

Connections with RHIC and LHC

Shadowing|Antishadowing|EMC

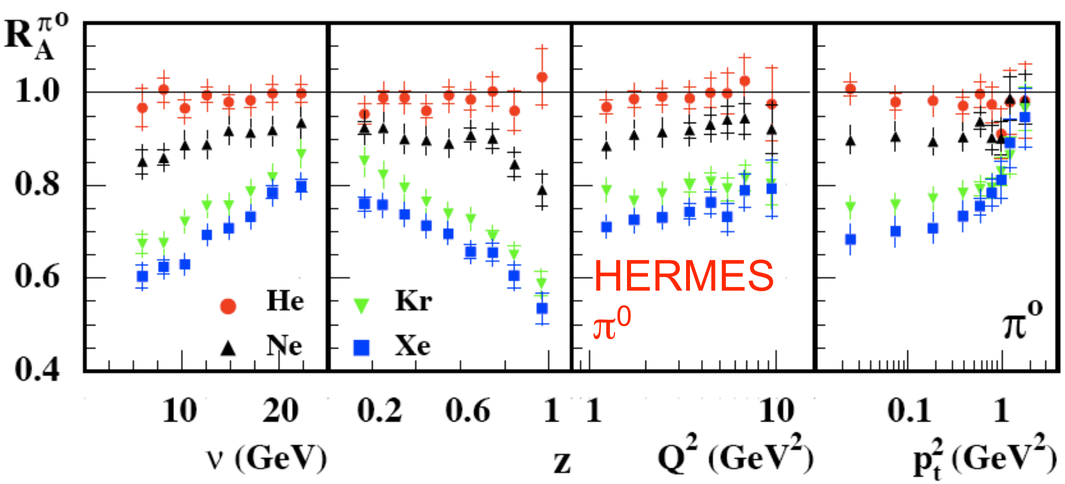


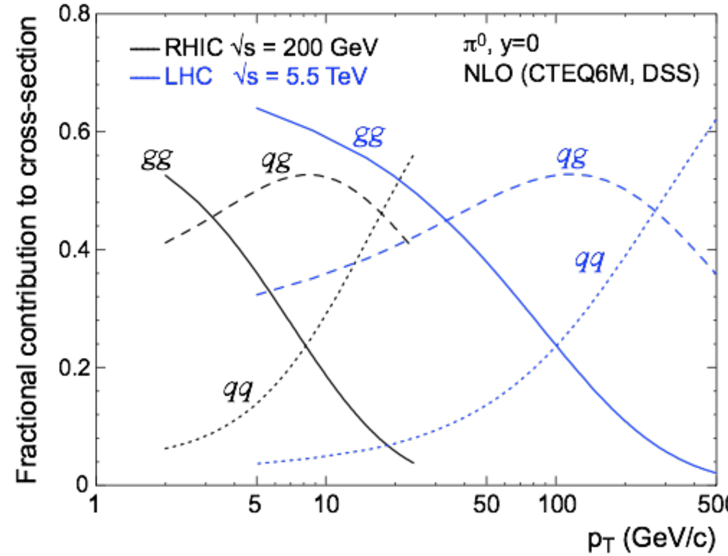
Saturation (initial state) effects (RHIC fwrd, LHC mid-rapidity)



Particle Production

Hadron attenuation|Eloss in cold matter



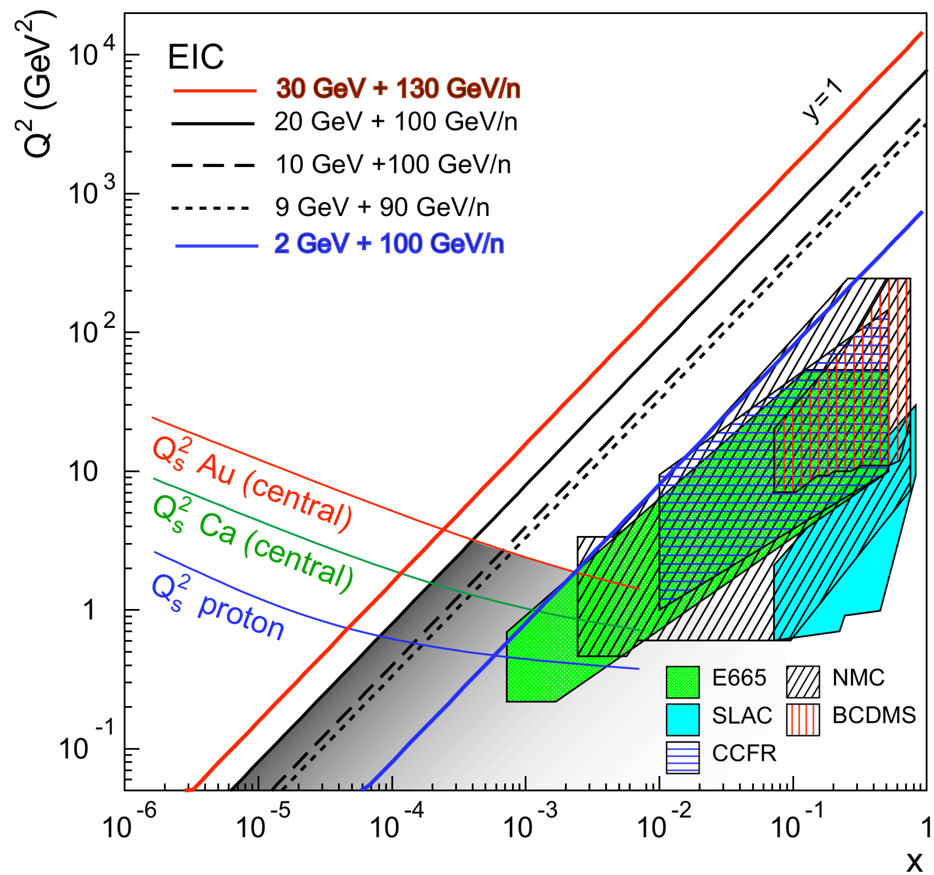


Summary

EIC provides a chance to dive deeply into a fundamentally new regime of one of the four basic forces, QCD

Issues:

- Need to broaden and deepen measurements
  - Diffraction
  - Jet-medium interactions
  - ...
- Need to develop connections
  - To RHIC/LHC
  - To larger scientific community



What is the smoking gun for crossing the saturation scale?