EIC Science:
e-A Collisions

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May 9, 2011

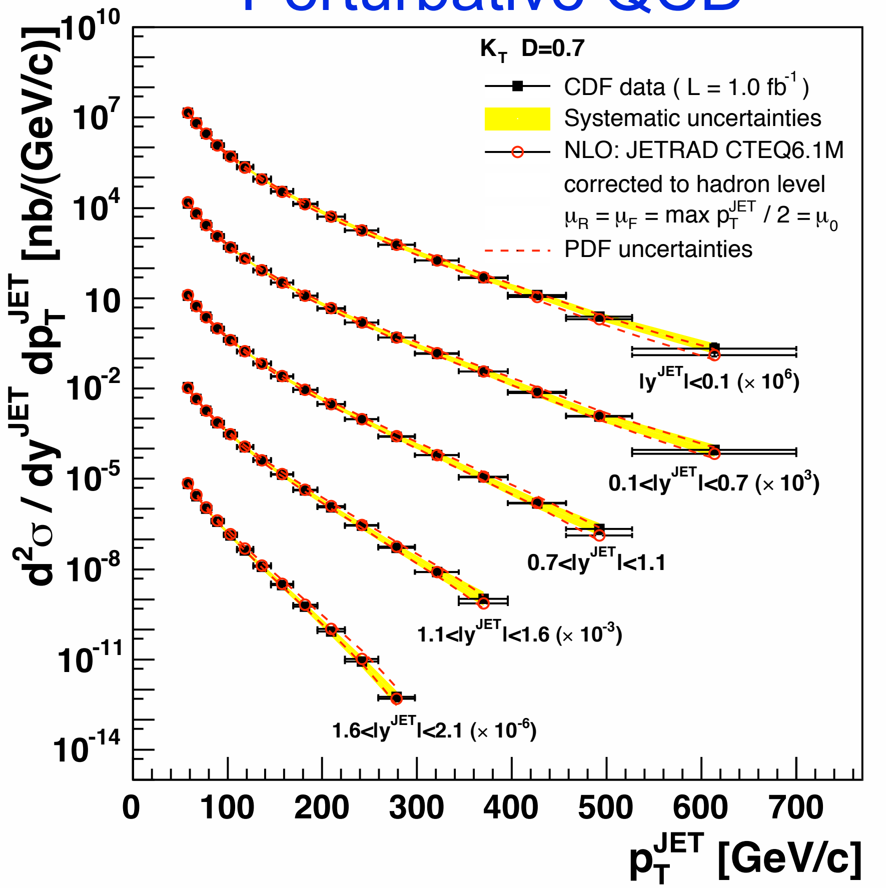
EIC Generic Detector R&D Advisory Committee Meeting

BNL

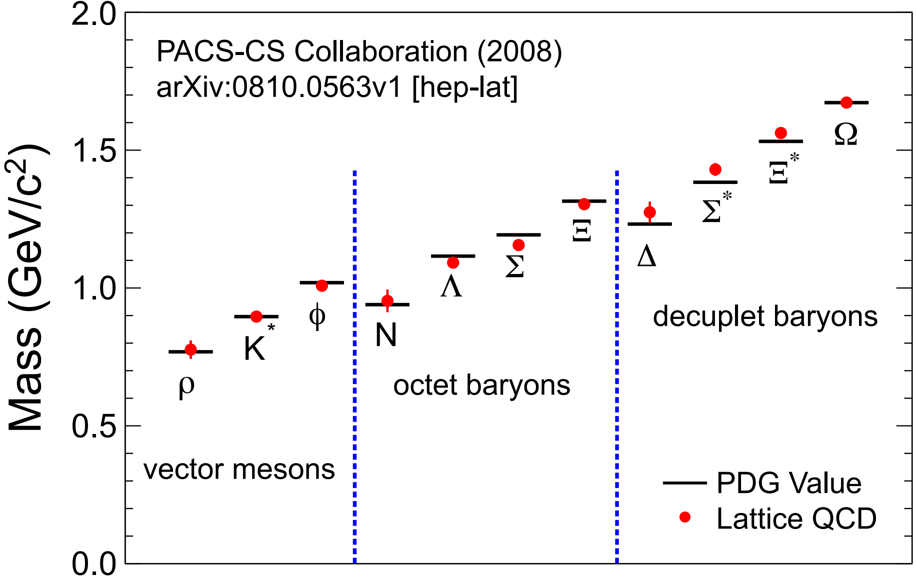
Quantum Chromodynamics QCD

- Calculations:
  - hard processes (large m, p, Q^2) ⇒ perturbative QCD
  - everything else ⇒ Lattice QCD, effective field theories, AdS/CFT?

Perturbative QCD



Lattice QCD



Impressive examples but there is much about the strongly interacting world we do not understand

New Frontier: “Gluonic” Structure of Matter

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

QCD is the “nearly perfect” fundamental theory of the strong interactions

F. Wilczek, hep-ph/9907340

- “Emergent” Phenomena not evident from Lagrangian
  - Asymptotic Freedom
  - Confinement
  - Phases of QCD ($T > 0$, $\mu_B > 0$)

New Frontier: “Gluonic” Structure of Matter

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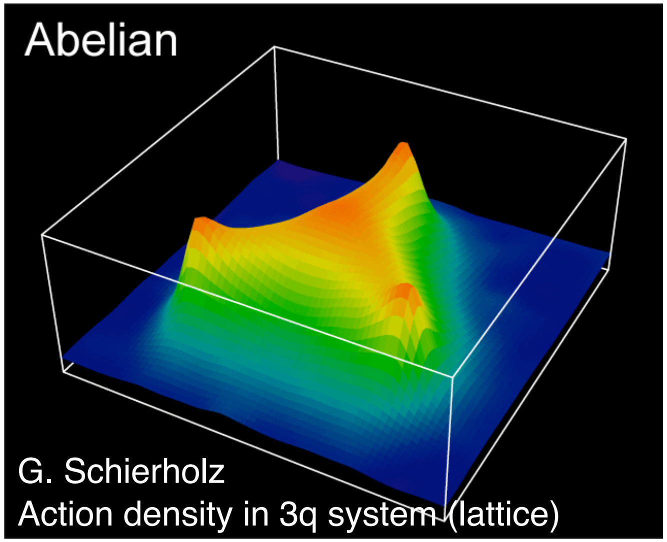
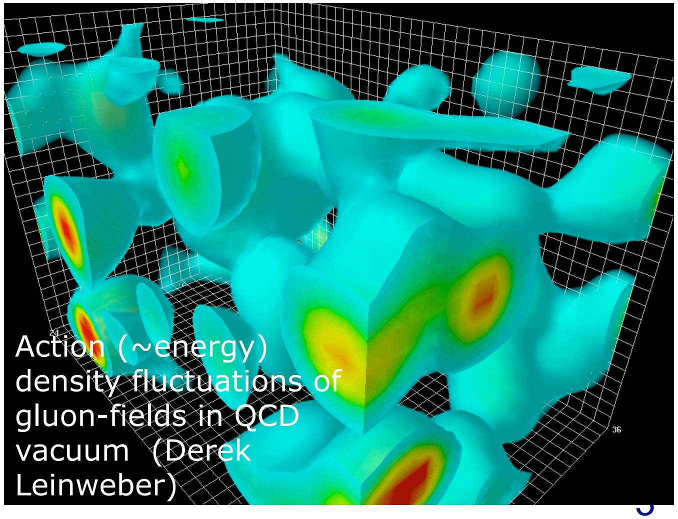
- **Gluons**
  - Self-interacting force carriers
  - Dominate structure of QCD vacuum



G. Schierholz
Action density in 3q system (lattice)



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

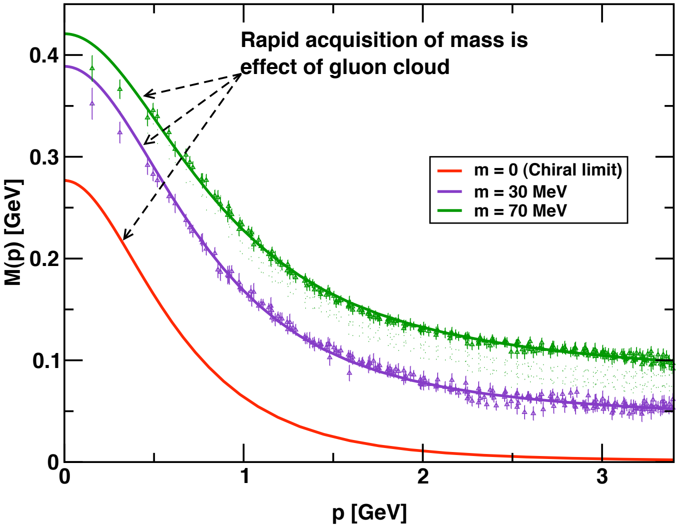
New Frontier: “Gluonic” Structure of Matter

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

- **Gluons**
  - Self-interacting force carriers
  - Dominate structure of QCD vacuum
  - Responsible for >94% if visible mass in universe
    - Quenched QCD explains mass spectrum to ± 10%
  - Determine essential features of QCD

Despite this dominance, the properties of gluons in matter remain largely unexplored

Bhagwat et al., nucl-th/0710.2059



Chiral Pertubation Theory

In chiral SU(3) limit:

M_p = 880 MeV

Meißner, hep-ph/0501009

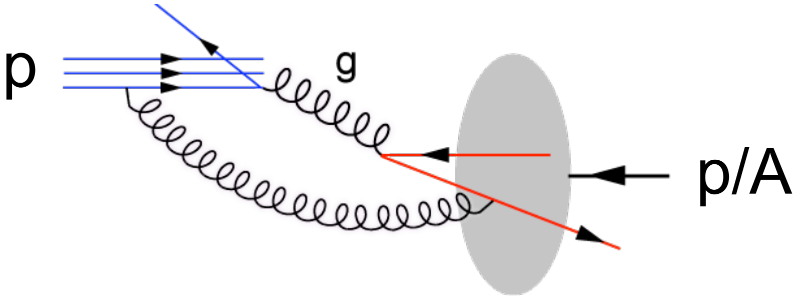
Sum Rules & Trace Anomaly

Quark kinetic + potential energy = only 1/3 of M_p

J. Ji, PRL 73, 1071

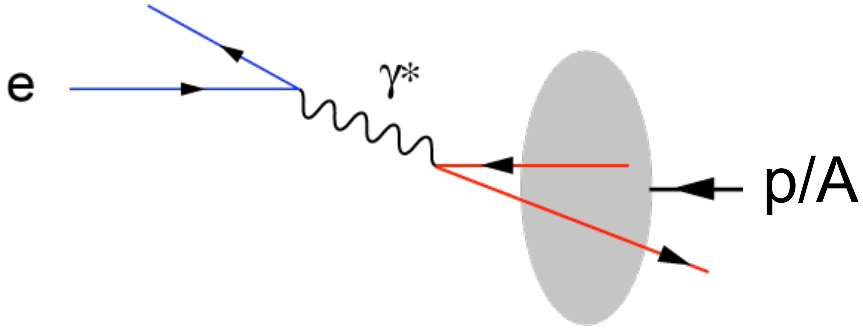
How to Study Gluons in Matter ?

Hadron-Hadron



- Test QCD
- Probe/Target interaction directly via gluons
- lacks the direct access to partons kinematics
- probe has complex structure

Electron-Hadron (DIS)

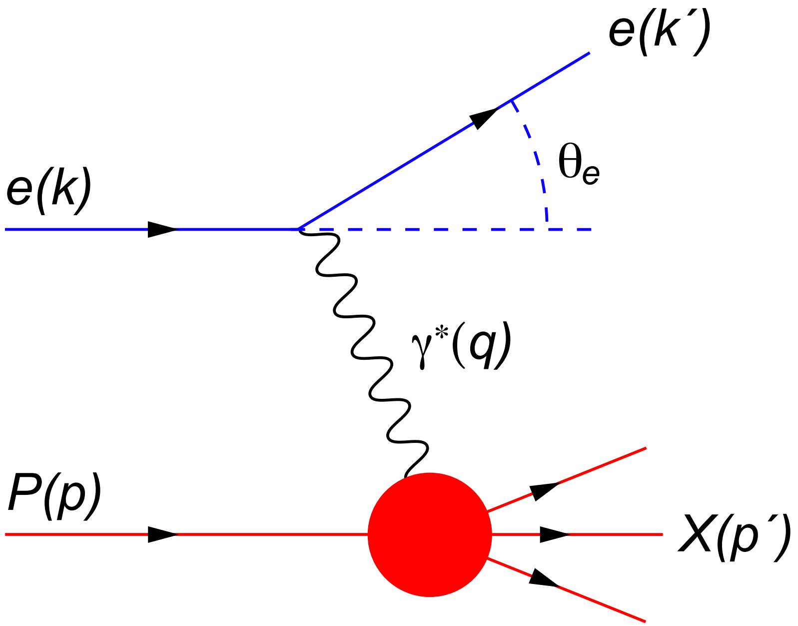


- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics
- probe point-like

Both are complementary and provide excellent information on properties of gluons in the nuclear wave functions

Precision measurements ⇒ ep, eA

Deep Inelastic Scattering (DIS)



Resolution power ("Virtuality"):

$$Q^2 = -q^2 = -(k-k')^2$$

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

Inelasticity:

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

p fraction of struck quark

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

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

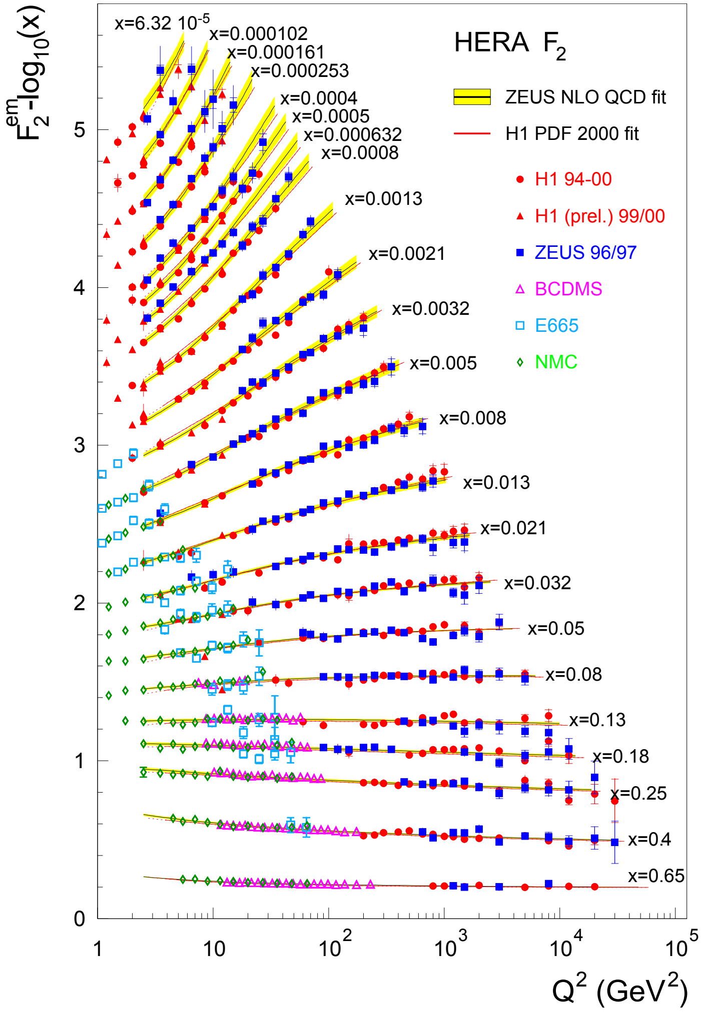
quark+anti-quark momentum distributions

gluon momentum distribution

Quark and Gluon Distributions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions.

In LO: Probability to find parton with x, Q^2 in proton



$\Longrightarrow$

- F_2
- $dF_2/dlnQ^2$

+ pQCD+
DGLAP Evolution

$$f(x,Q_1^2) \rightarrow f(x,Q_2^2)$$

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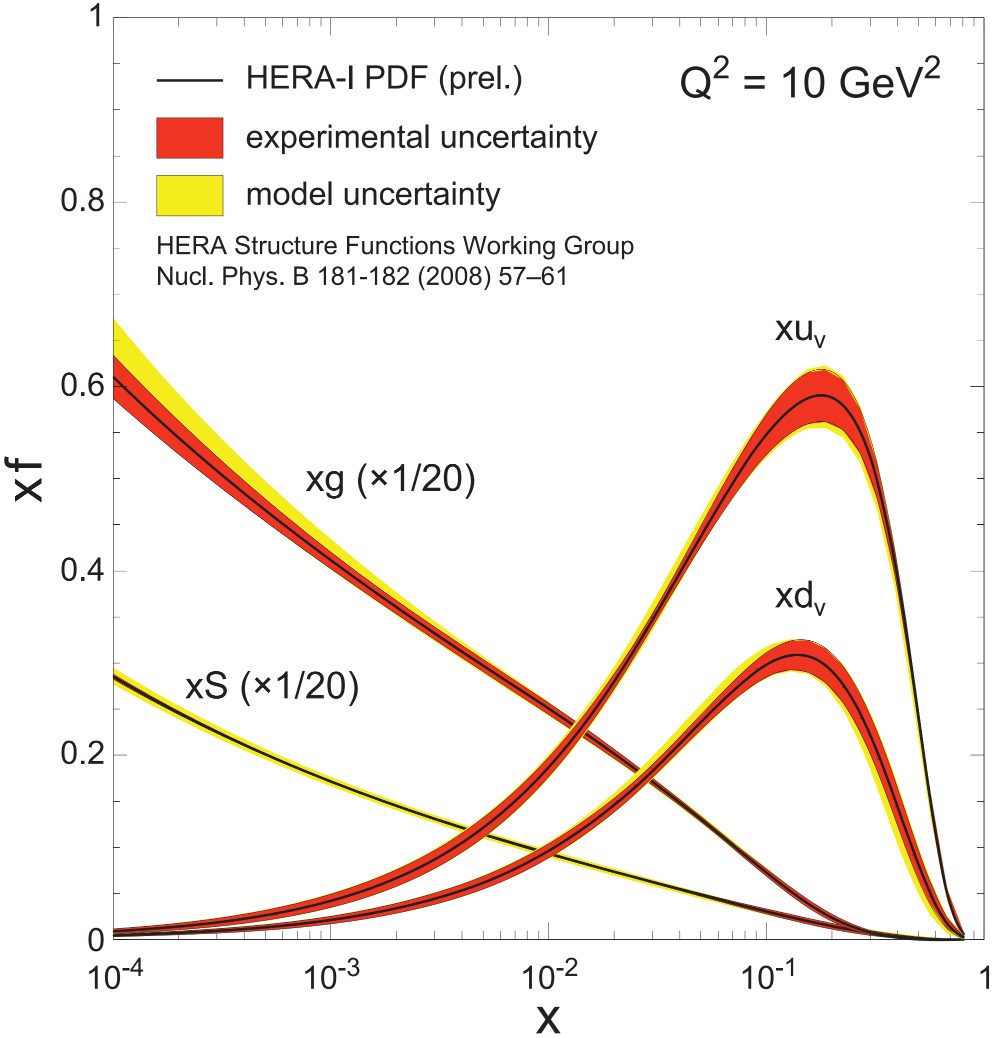

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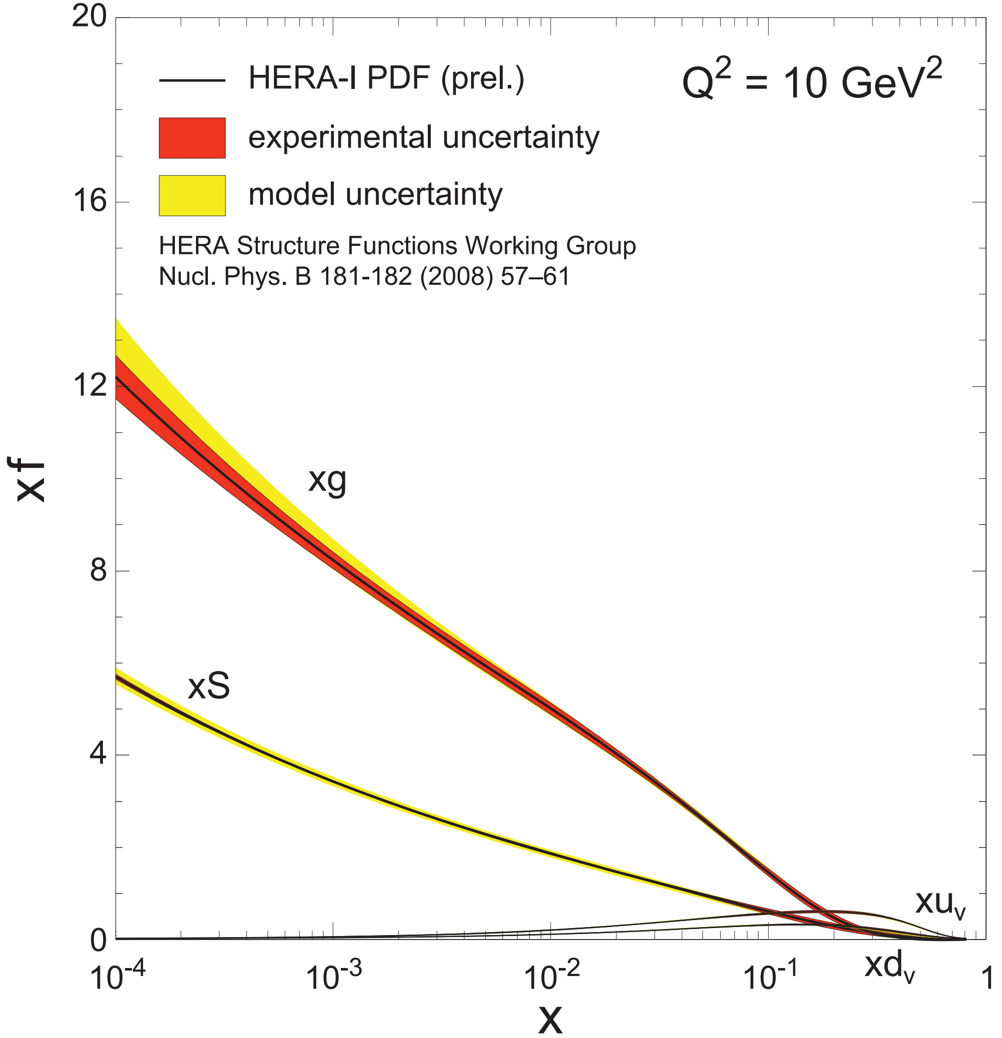


Proton is almost entirely glue by x<0.1 (for Q^2 = 10 GeV^2)

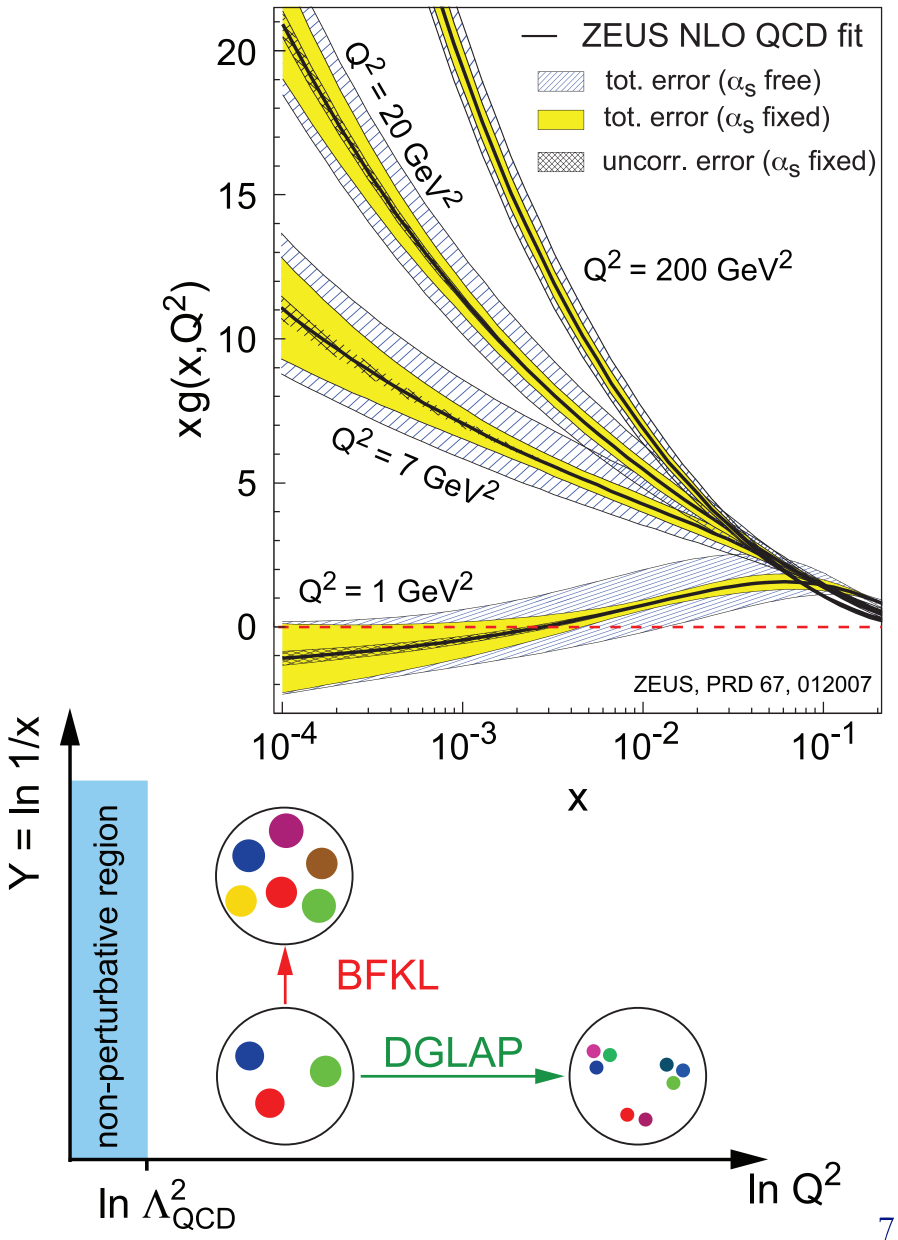
Issues with our Current Understanding

Linear DGLAP evolution scheme

- Weird behavior of xG and F_L from HERA at small x and Q^2
- $G(x,Q^2) < Q_{sea}(x,Q^2)$?
- Unexpectedly large diffractive cross-section
- built in high energy "catastrophe"
  - xG rapid rise violates unitary bound

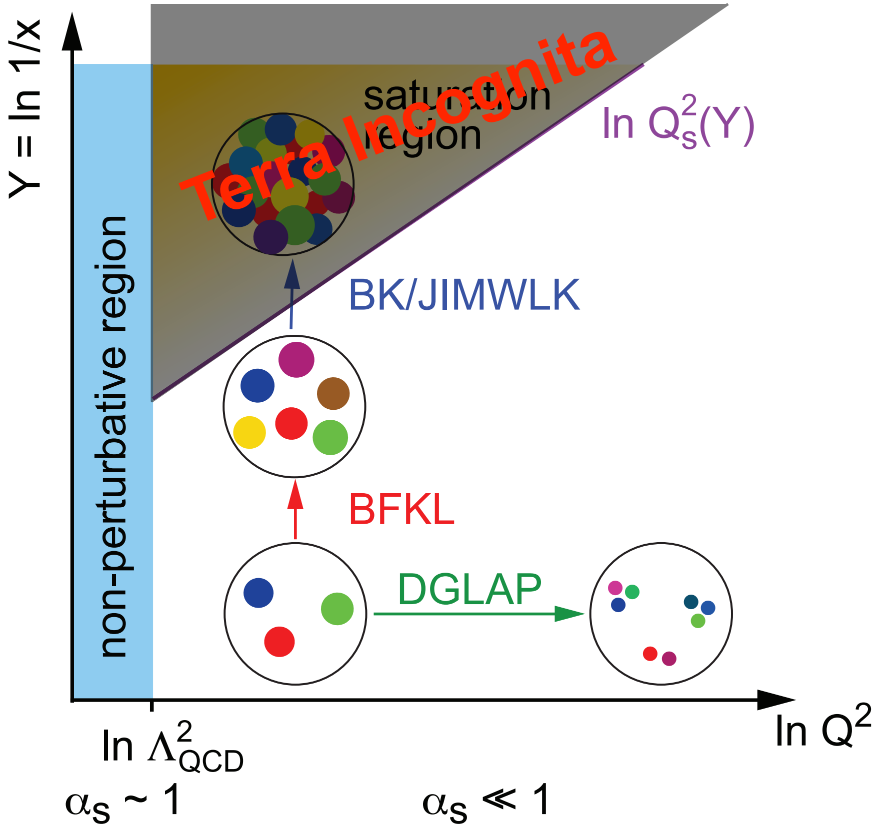
Linear BFKL Evolution

- Density along with σ grows as a power of energy: $N \sim s^\Delta$
- Can densities & cross-section rise forever?
- Black disk limit: $\sigma_{total} \leq 2 \pi R^2$



Saturation/Color Glass Condensate

In transverse plane: nucleus/ nucleon densely packed with gluons



McLerran-Venugopalan Model:

- Weak coupling description of the wave function
- Gluon field $A_\mu \sim 1/g \Rightarrow$ gluon fields are strong classical fields!
- Most gluons $k_T \sim Q_S$

Non-Linear Evolution:

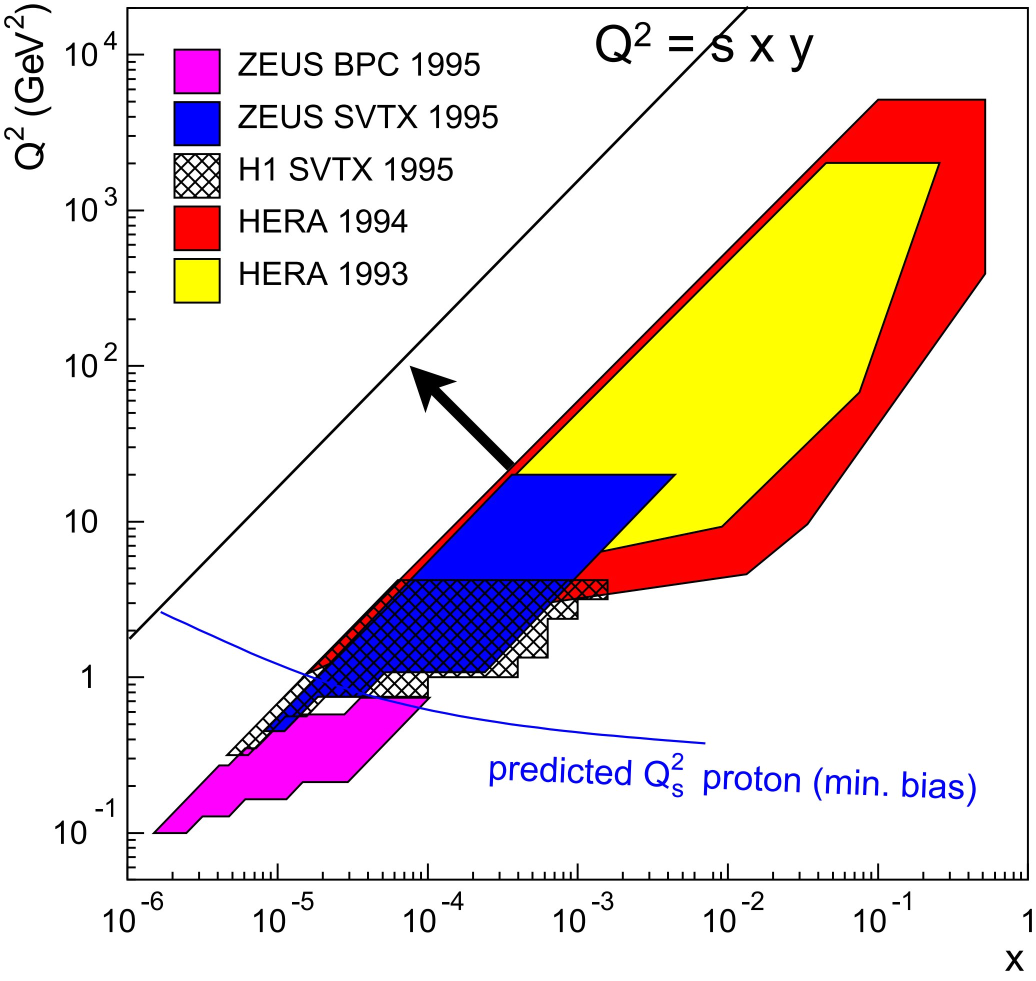
- At very high energy: recombination compensates gluon splitting
- Cross sections reach unitarity limit
- BK/JIMWLK: non-linear effects ⇒ saturation
  - characterized by $Q_s(x,A)$
  - Wave function is Color Glass Condensate in IMF description

Reaching the Saturation Region

HERA (ep):

Despite high energy range:

- F_2, $G_p(x, Q^2)$ only outside the saturation regime
- Regime where non-linear QCD matters ($Q < Q_s$) not reached (is it close?)
- Need also large Q^2 range
- Only way in ep is to increase √s



Would require a new ep collider at √s ~ 1-2 TeV (Hera ~ 0.3 TeV) ⇒ unrealistic (at least in the US)

Raison d'être for *e*+A

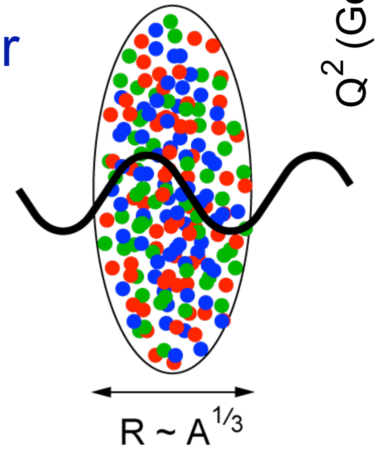
Scattering of electrons off nuclei:

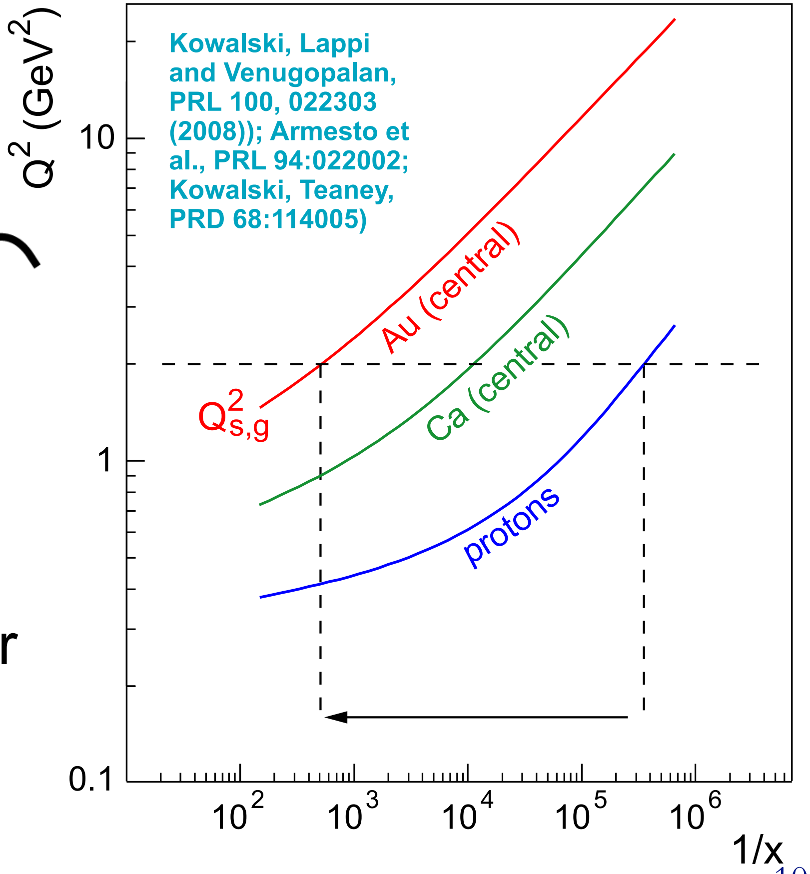
Probes interact over distances $L \sim (2m_N x)^{-1}$

For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon ⇒ probe interacts *coherently* with all nucleons

“Expected”
Nuclear Enhancement Factor
(Pocket Formula):

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




Kowalski, Lappi and Venugopalan, PRL 100, 022303 (2008)); Armesto et al., PRL 94:022002; Kowalski, Teaney, PRD 68:114005)

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

Raison d'être for e+A

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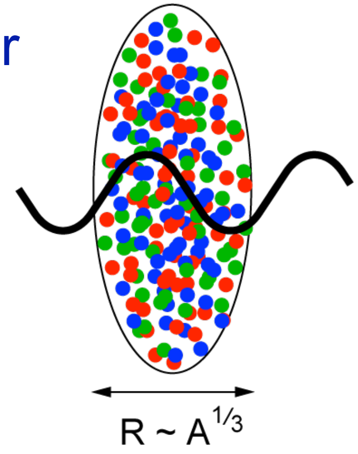
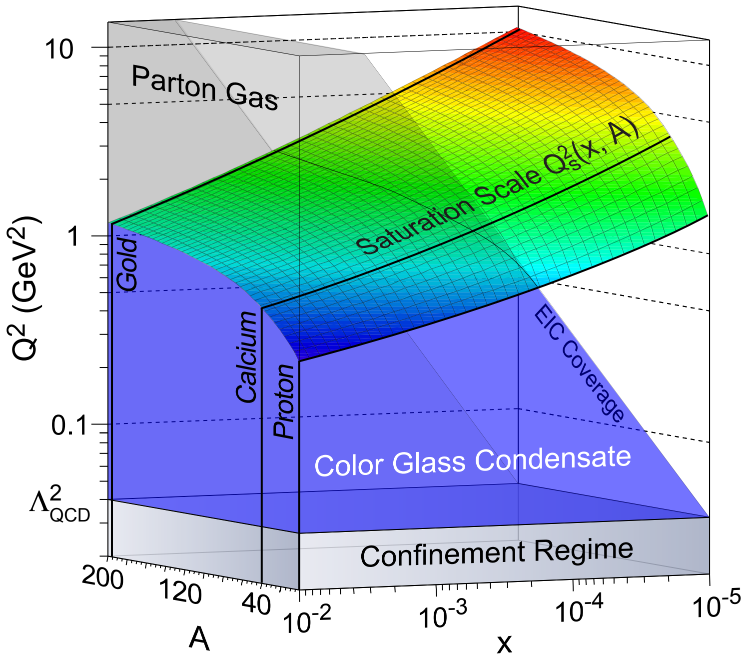




- EIC Strong hints of saturation from RHIC: $x \sim 10^{-3}$ in Au
  - $\sqrt{s} \sim 100$ GeV: $E_e = 5\text{-}30$ GeV, $E_A = 50\text{-}130$ GeV
  - L(EIC) > 100 × L(HERA)

e+A Science Matrix & Golden Measurements

Primary new science deliverables	What we hope to fundamentally learn	Basic measurements	Typical required precision	Special requirements on accelerator/ detector	What can be done in phase I	Alternatives in absence of an EIC	Gain/Loss compared with other relevant facilities	Comments
integrated nuclear gluon distribution	The nuclear wave function throughout x-Q^2 plane	F_L, F_2, F_L^c, F_2^c	What HERA reached for F2 with combined data	displaced vertex detector for charm	stage I: large-x & large-Q^2 need full EIC, for F_L and F_2^c	p+A at LHC (not as precise though) & LHeC	First experiment with good x, Q^2 & A range	This is fundamental input for A+A collisions
k_T dependence of gluon distribution and correlations	The non-linear QCD evolution - Qs	SIDIS & di-hadron correlations with light and heavy flavors		Need low-pt particle ID	SIDIS for sure TBD: saturation signal in di-hadron p_T imbalance	1) p+A at RHIC/LHC, although e+A needed to check univerality 2) LheC	Cleaner than p+A: reduced background	
b dependence of gluon distribution and correlations	Interplay between small-x evolution and confinement	Diffractive VM production and DVCS, coherent and incoherent parts	50 MeV resolution on momentum transfer	hermetic detector with 4pi coverage low-t: need to detect nuclear break-up	Moderate x with light and heavy nuclei	LHeC	Never been measured before	Initial conditions for HI collisions – eccentricity fluctuations

e+A Science Matrix & Golden Measurements

- Nuclear gluons at small-x
  - Inclusive structure functions (F_2, F_L, F_2^c, F_L^c)
  - Di-hadrons (and di-jet) imbalance
  - Exclusive diffractive production (J/ψ, ϕ, ρ and DVCS)
    - coherent & incoherent
- Nuclear gluons at larger-x
  - Gluon anti-shadowing / EMC effect
- Jets and hadronization
  - Use nuclei to test in-medium fragmentation, pQCD energy loss and parton showers

All Measurements need to be conducted in e+p for reference as well as with varying A

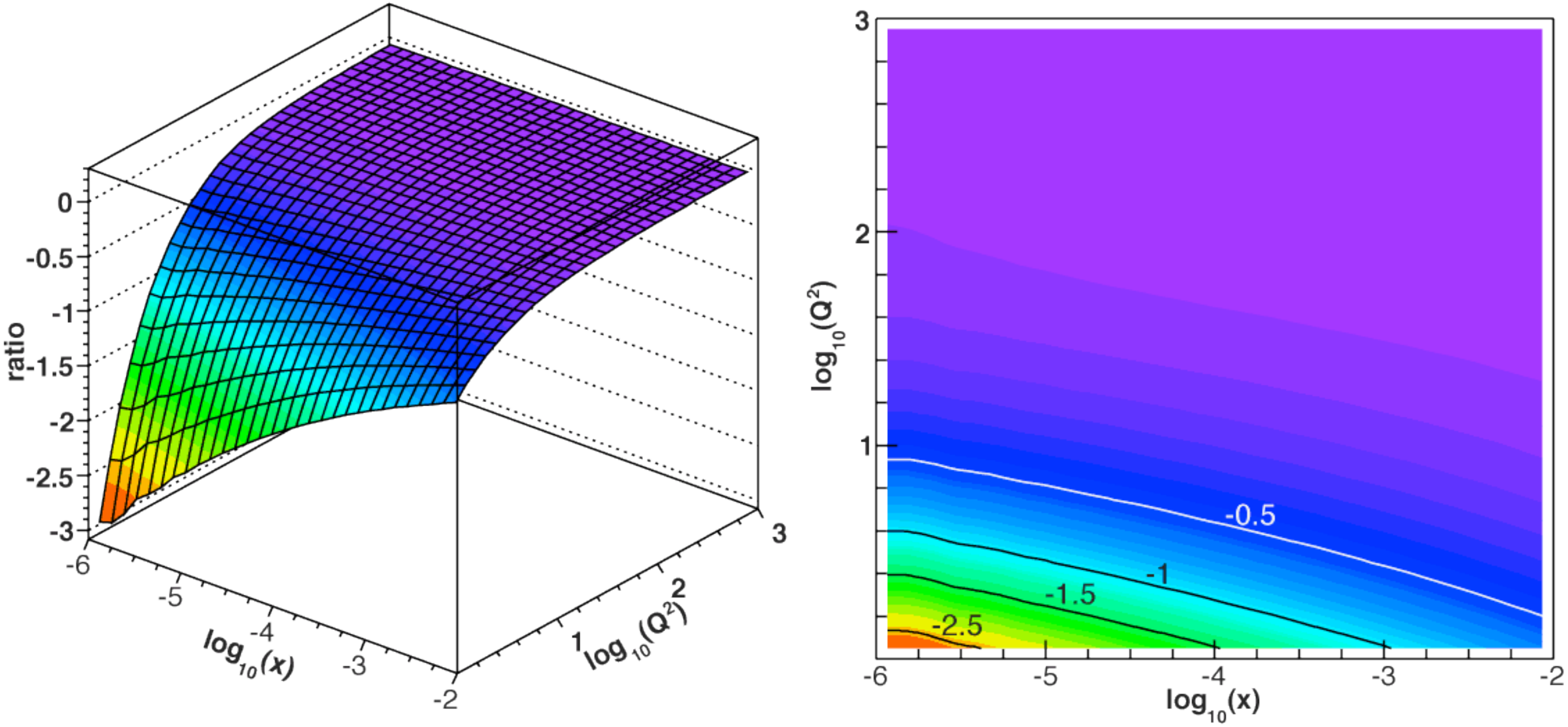
Example 1: F_L Structure Function

$$F_L\,(x,Q^2) \sim xG(x,Q^2)$$

Momentum distribution of glue

$$\text{ratio} = \frac{F_L^{\text{total}} - F_L^{\text{leading twist}}}{F_L^{\text{total}}}$$

e+p



J. Bartels, K. Golec-Biernat and L. Motyka, 2011

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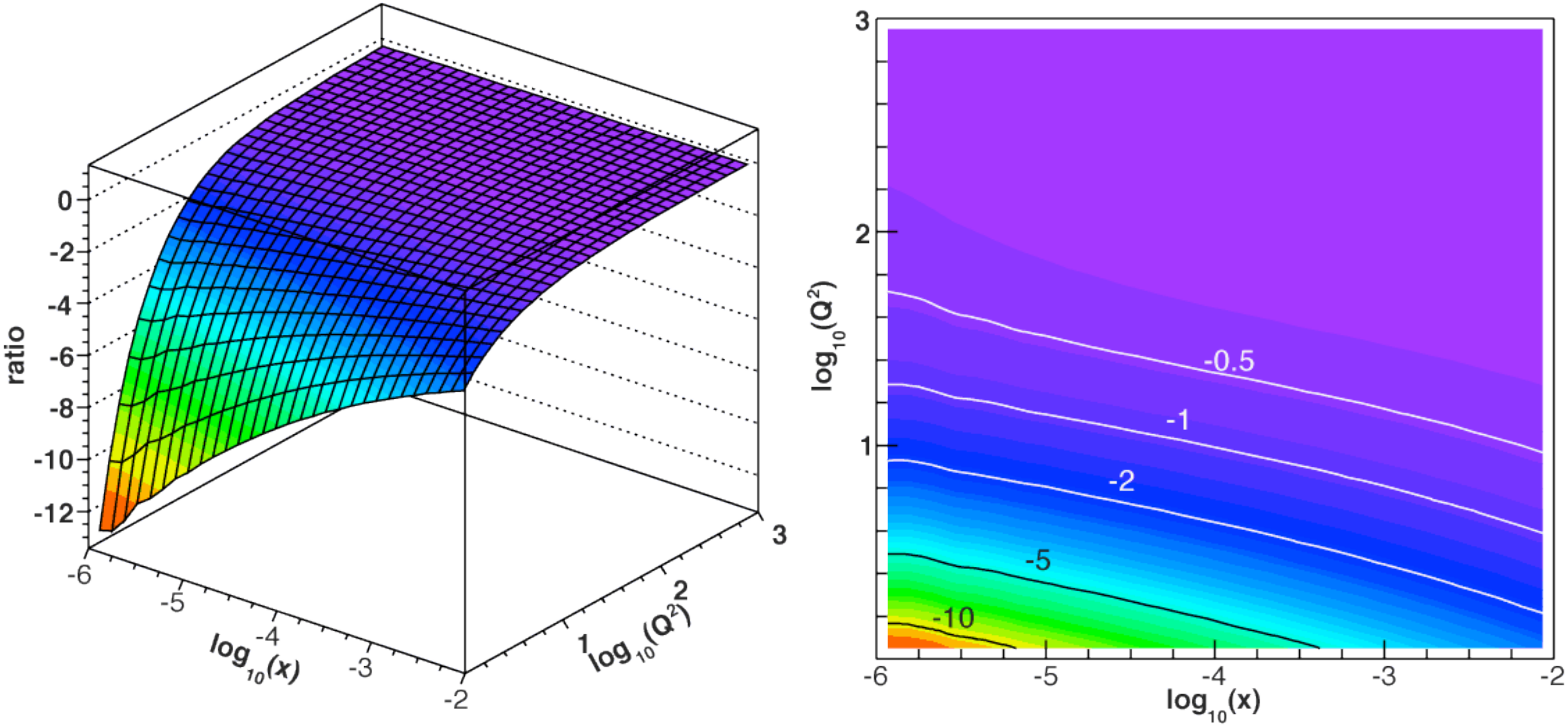
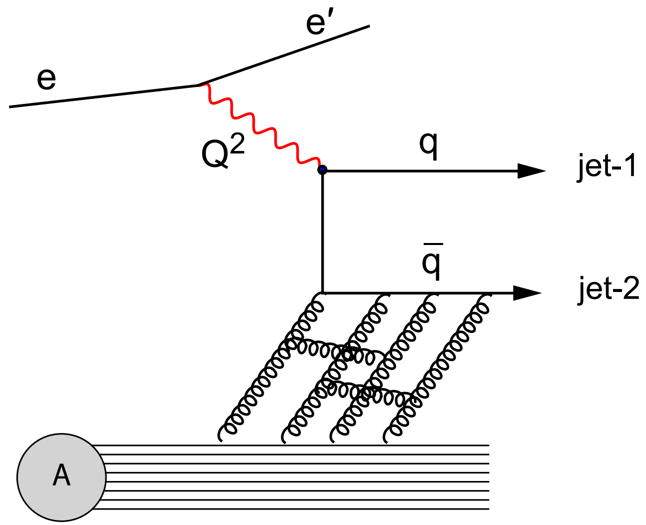
e+Au



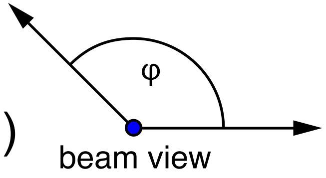
J. Bartels, K. Golec-Biernat and L. Motyka, 2011

Example 2: Dihadron Correlations

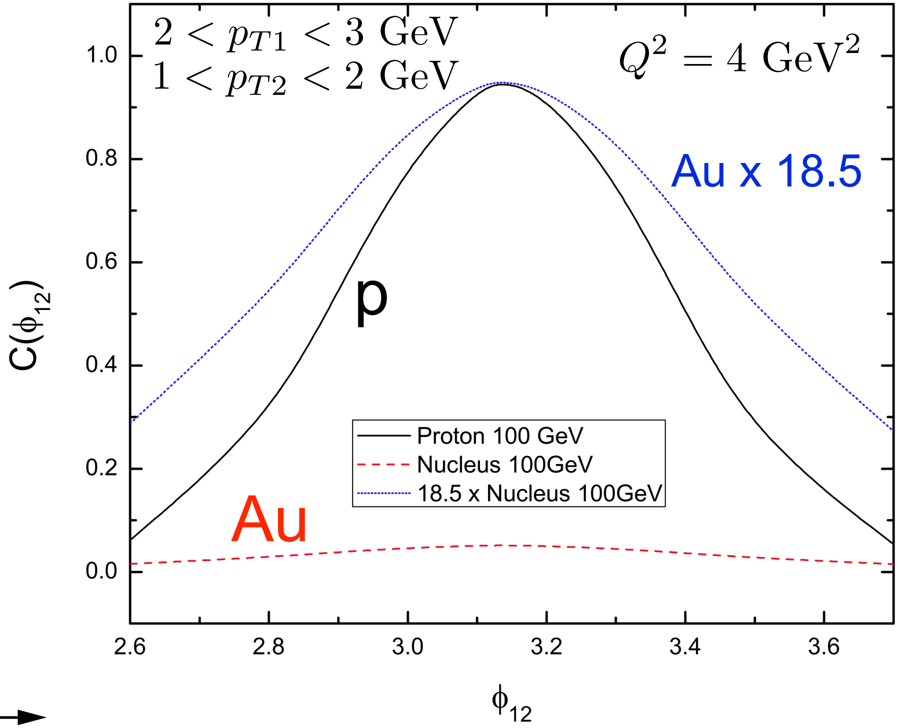
Excellent saturation signature:



Either Jets or use leading hadrons from jets (dihadrons)



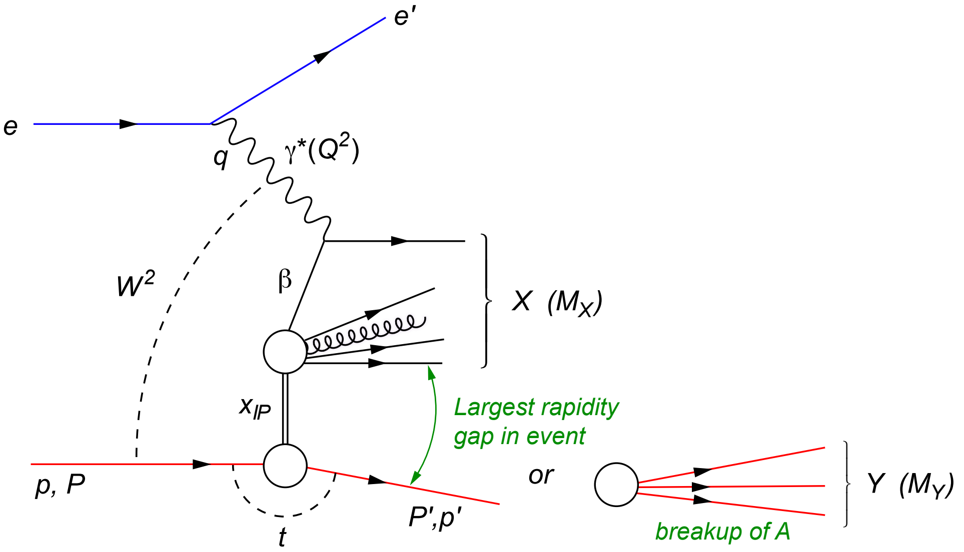
Dominguez, Xiao and Yuan (2010)

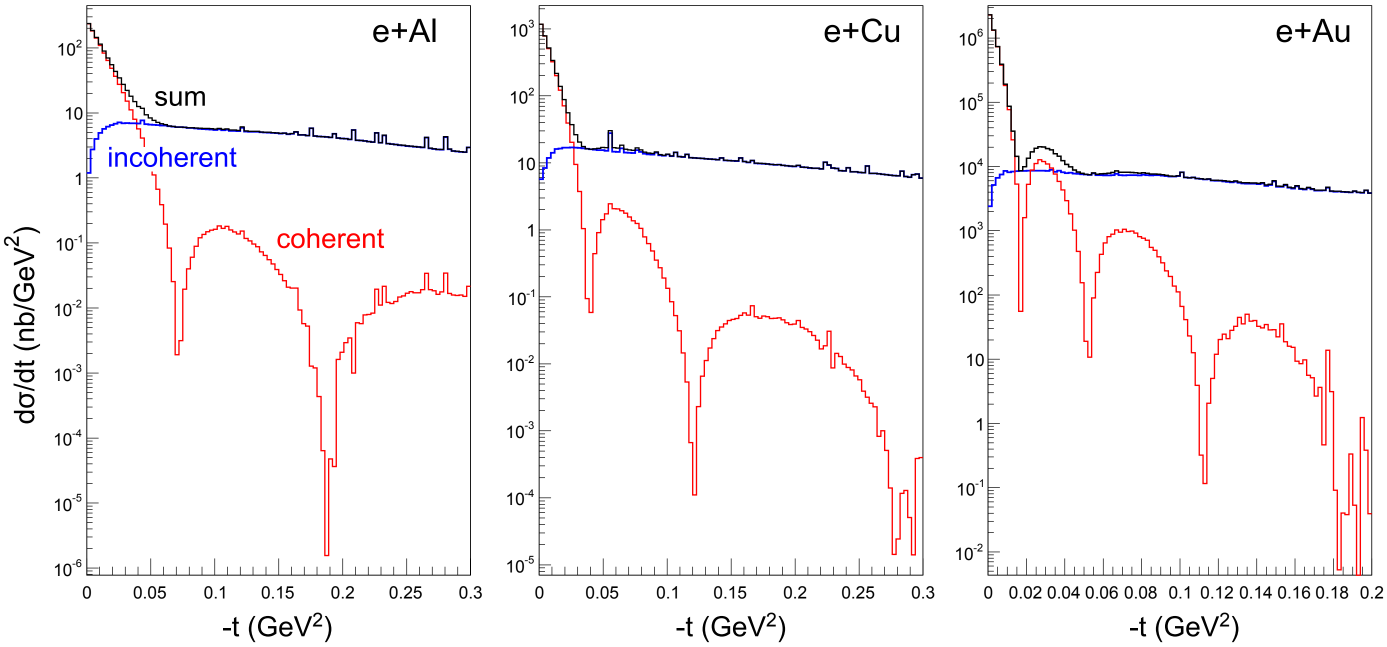


At small x, multi-gluon distributions are as important as single-gluon distributions, they contribute to such di-hadron correlations

Example 3: Diffractive Events

- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A predicted to be ~25-40%
- Process most sensitive to $xG(x,Q^2)$
- Rich physics program on momentum & spatial gluon distribution





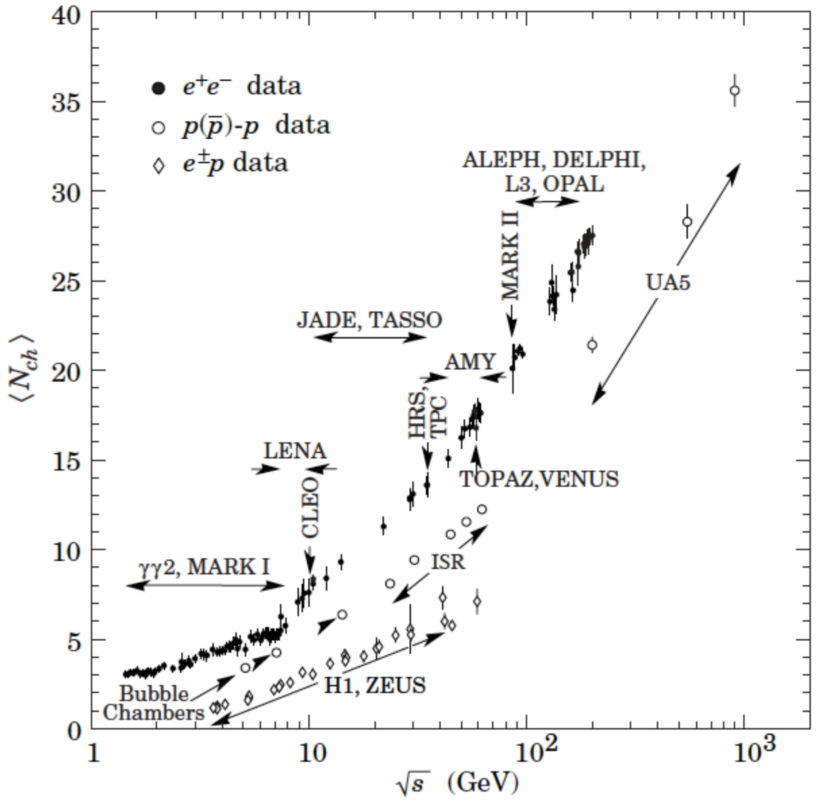
$e + A \rightarrow e' + J/\psi + A'$

dσ/dt is Fourier Transform of $\rho_{glue}(b)$

"Gluonic Form Factor"

Experimental Aspects of e+A

- Multiplicity is low
  - $N_{ch}(ep) \sim N_{ch}(eA) < N_{ch}(pp)$
- Cross-section is small
  - σ(ep): 0.030 – 0.060 mb
  - σ(pp) ~ 1000 x σ(ep):
- Moderate interaction rate
  - 300-600 kHz for 10^{34} $cm^{-2}\ s^{-1} = 10^{7}\ mb^{-1}\ s^{-1}$



Experimental requirements (acceptance, resolution, granularity) are identical to those in e+p with 2 exceptions due to:

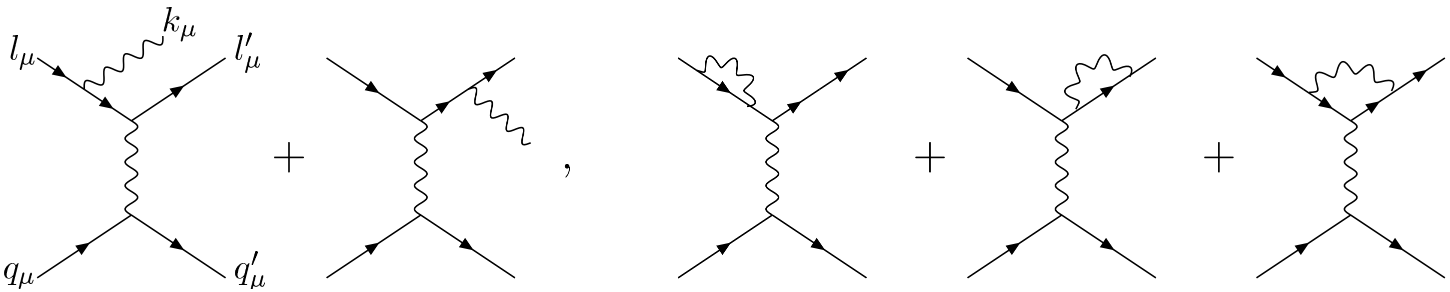
1. Radiative corrections
2. Detecting nuclear breakup (incoherent vs. coherent diffraction)

Issue for e+A: Radiative corrections

Emission of real photons

- experimentally often not distinguished from non-radiative processes: soft photons, collinear photons

⇒ ”radiative corrections”



“Ideal” case: $Q^2 = -(l - l')^2, \quad x_B = \dfrac{Q^2}{2P \cdot (l - l')}$

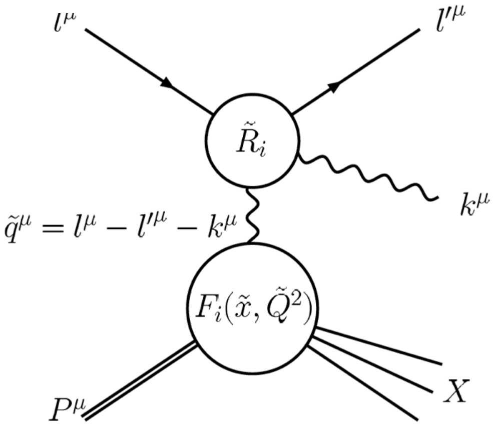
True case: $\tilde{Q}^2 = -(l - l' - k)^2, \quad \tilde{x}_B = \dfrac{\tilde{Q}^2}{2P \cdot (l - l' - k)}$

Effect of radiative corrections

Distortion of observed structure function:

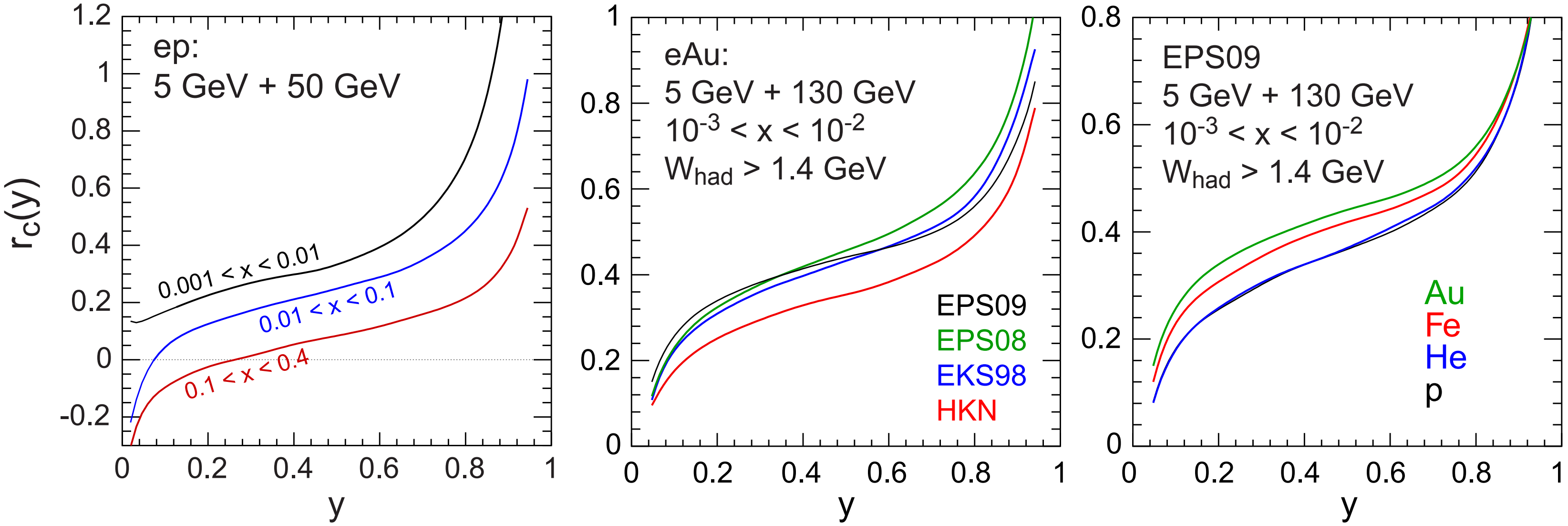
$$F_i^{\text{obs}}(x_B, Q^2) = \int \mathrm{d}\tilde{x}_B \mathrm{d}\tilde{Q}^2 \, R_i(x_B, Q^2, \tilde{x}_B, \tilde{Q}^2) F_i^{\text{true}}(\tilde{x}_B, \tilde{Q}^2)$$

Radiator functions $R_i(l, l', k)$



Correction function is fct. of y:

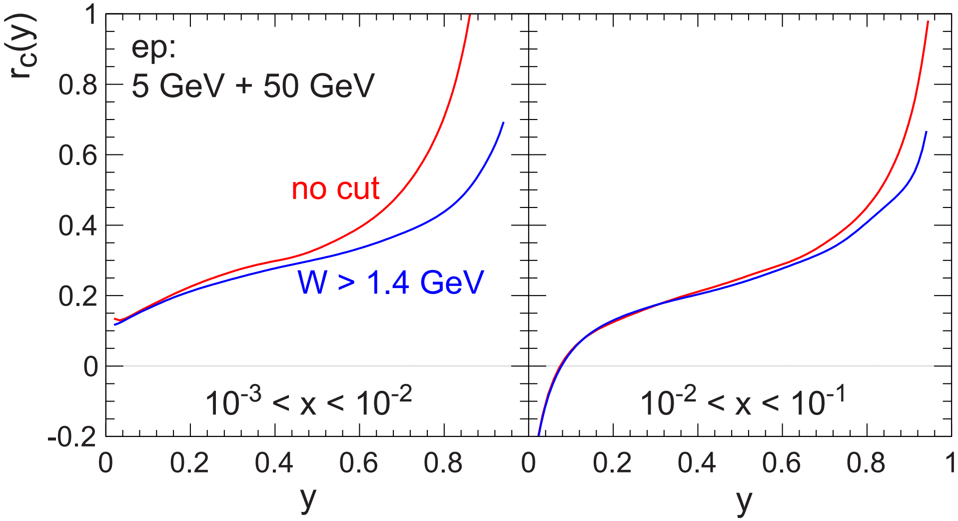
$$r_c(y) = \frac{\mathrm{d}\sigma/\mathrm{d}y|_{O(\alpha)}}{\mathrm{d}\sigma/\mathrm{d}y|_{Born}} - 1$$



Dealing with radiative corrections

Method 1

- simple kinematic cuts in W reduce corrections slightly
- not very effective



Method 2

- reconstruct x, Q^2 via hadronic final state

$$\delta_{had} = \sum_{i}^{\#hadrons} E_i(1-\cos\theta_i) = E_{had} - p_{z\,had}$$

$$p_{t\,had}^2 = \left(\sum_{i}^{\#hadrons} p_{x\,i}\right)^2 + \left(\sum_{i}^{\#hadrons} p_{y\,i}\right)^2$$

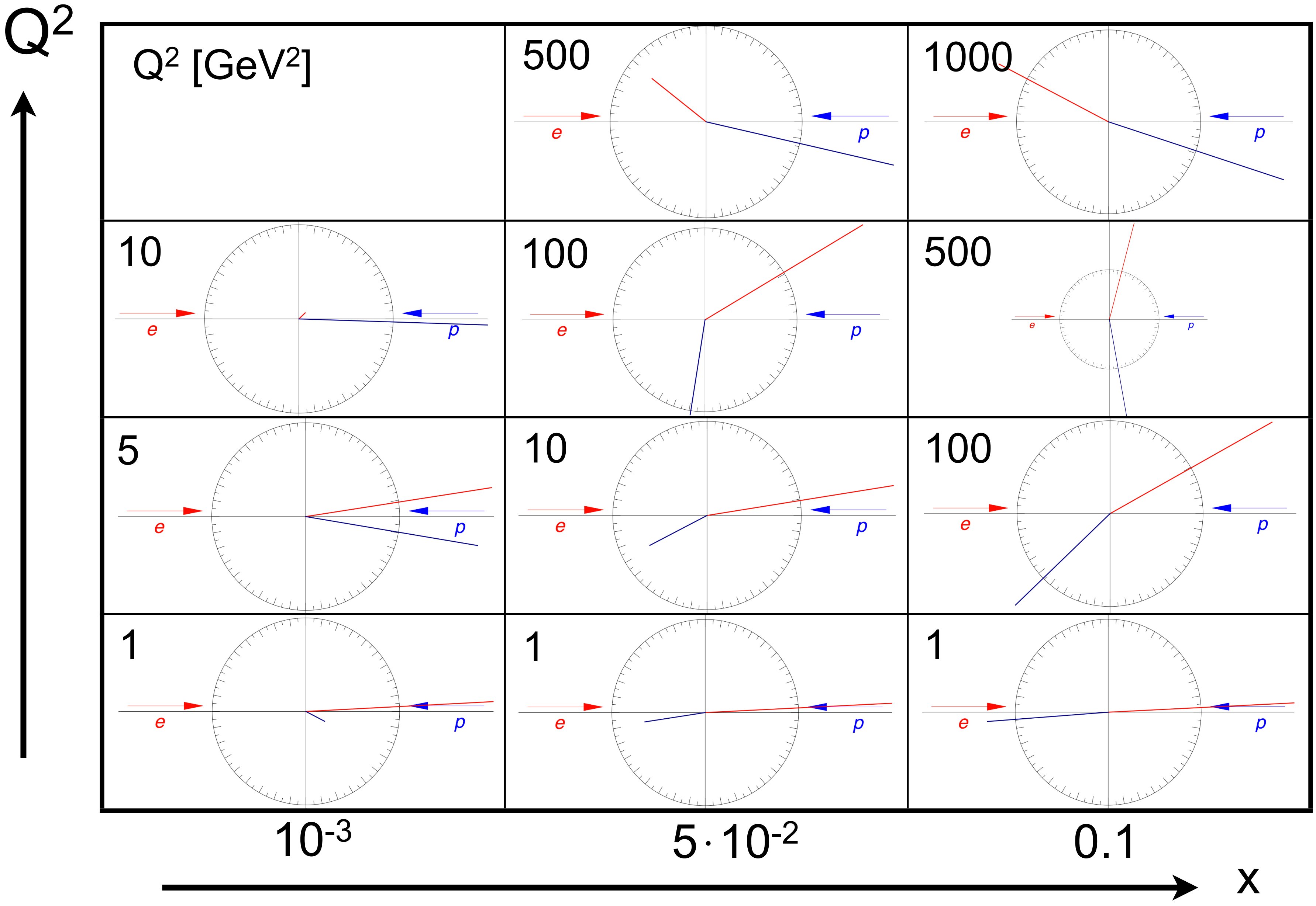
$$y = \frac{\delta_{had}}{2E_e},$$

$$Q^2 = \frac{p_{t\,had}^2}{1-y},$$

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

Problem in e+A: parton/hadron energy-loss, secondary particle production (typical at low-p_T)

DIS: Where Goes What at Which x, Q^2



Summary (e+A)

The e+A program at an EIC is unprecedented, allowing the study of matter in a new regime where physics is not described by “ordinary” QCD

- Explore the Physics of Strong Color Fields
  - Measure properties (momentum & space-time) of glue
  - Explore non-linear QCD
  - Existence of universal saturation regime ?
- Understand how fast partons interact as they traverse nuclear matter & new insight into fragmentation processes
- Clarify the nature of Pomerons

Machine requirements: low-x reach with enough Q^2 lever arm
$\Rightarrow$ large $\sqrt{s}$ (needs stage 2 energies)

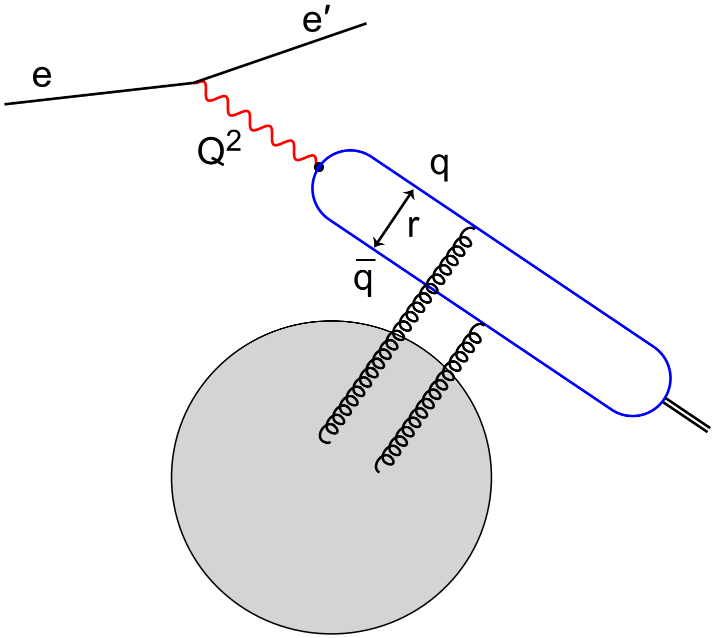
Detector requirements: as in e+p with exception of forward region
for detection of break-up of nuclei

Additional Slides

Saturation Seen from Different Frames

Rest frame of nucleon/nucleus:

- $\bar{q}q$ dipole (Muller dipole)
- DGLAP: $\sigma_{qq} \propto r^2 \alpha_s(\mu^2)\, xG(x,\mu^2)$
    - explodes with r^2
    - violates unitarity



Saturation Seen from Different Frames

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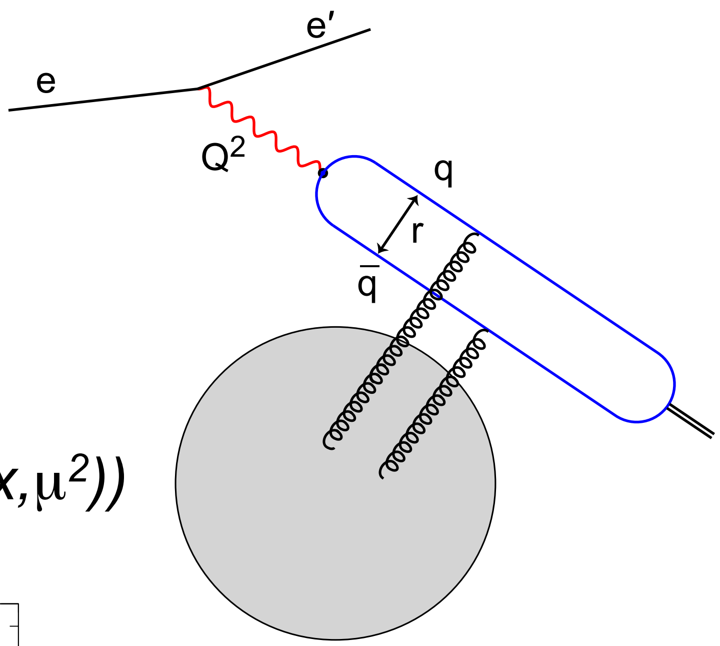

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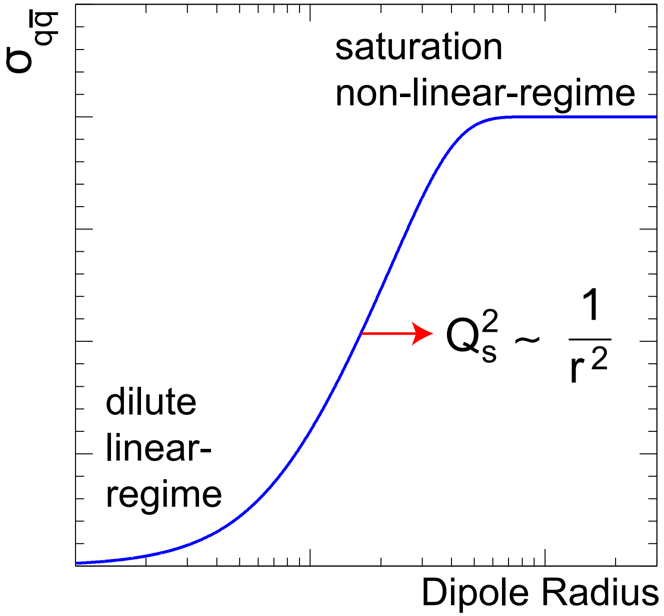
- DGLAP: $\sigma_{qq} \propto r^2\, \alpha_s(\mu^2)\, xG(x,\mu^2)$
  - explodes with r^2
  - violates unitarity
- Saturation: $\sigma_{qq} \propto 1-\exp(-r^2\, \alpha_s(\mu^2)\, xG(x,\mu^2))$

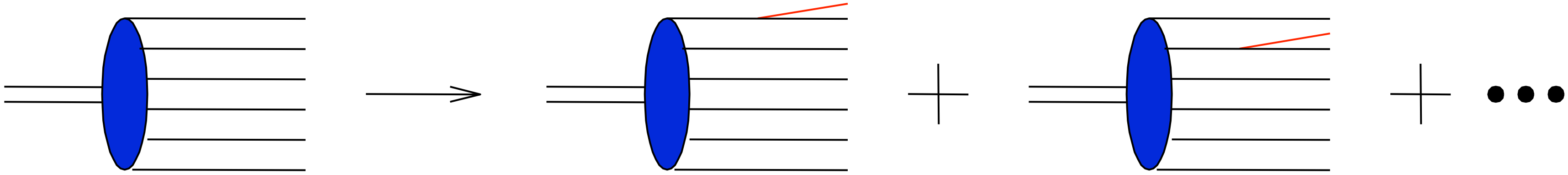


Saturation Seen from Different Frames

Infinite Momentum Frame:

- BFKL (linear QCD): splitting functions ⇒ gluon density grows

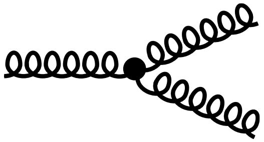
proton



N partons

new partons emitted as energy increases
could be emitted off any of the N partons

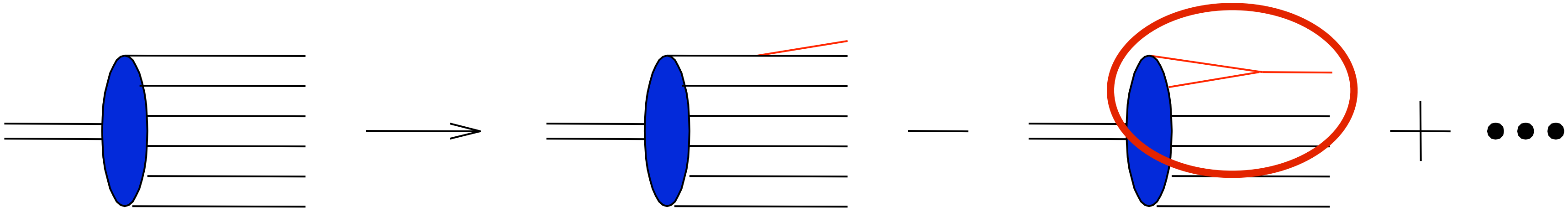
BFKL:

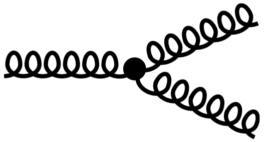


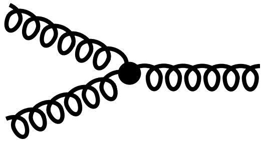
Saturation Seen from Different Frames

Infinite Momentum Frame:

- BFKL (linear QCD): splitting functions ⇒ gluon density grows
- BK (non-linear): recombination of gluons ⇒ gluon density tamed



BFKL: 

BK adds: 

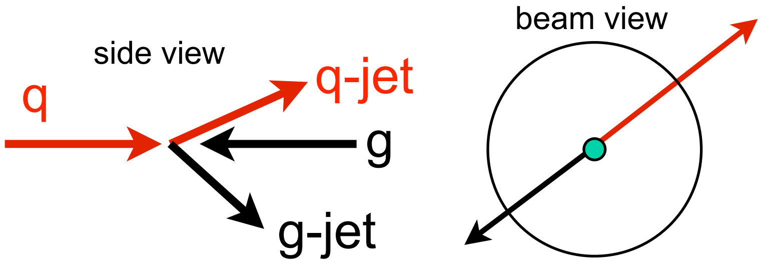
- At Q_s: gluon emission balanced by recombination

Strong Hints from RHIC: Saturation at $x=10^{-3}$?

Disappearance of angular correlations in Run 8 dAu data at forward rapidities (log x ~ 2.5 - 3)

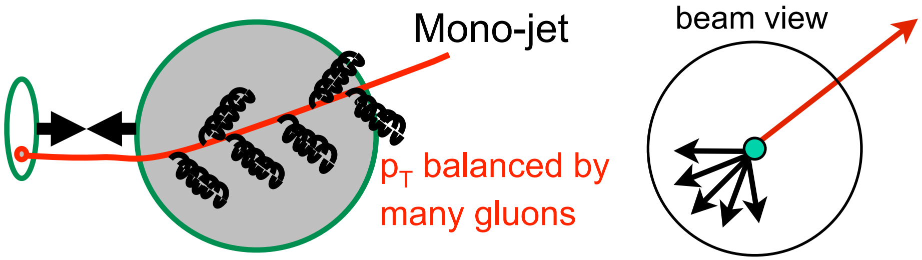
Low gluon density (pp):

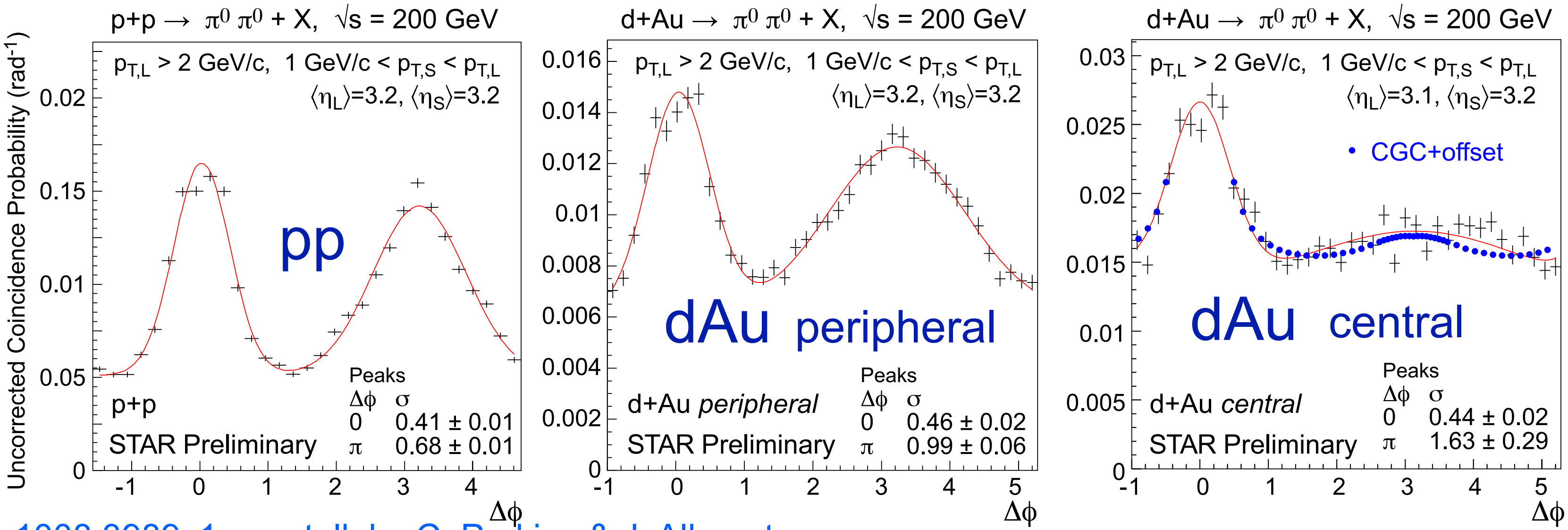
pQCD predicts 2→2 process
⇒ back-to-back di-jet



High gluon density (pA):

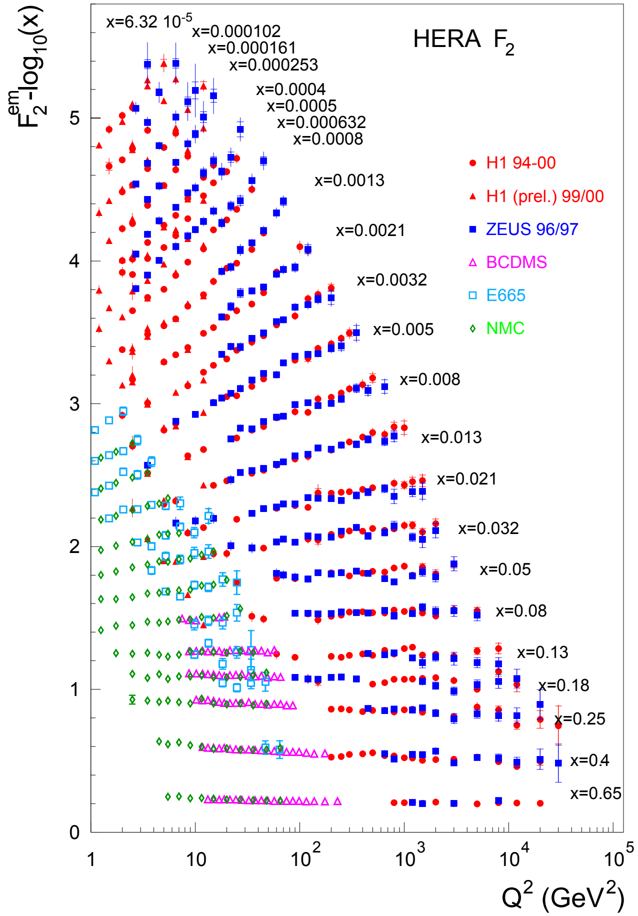
2→1 (2→many) process ⇒ mono-jet

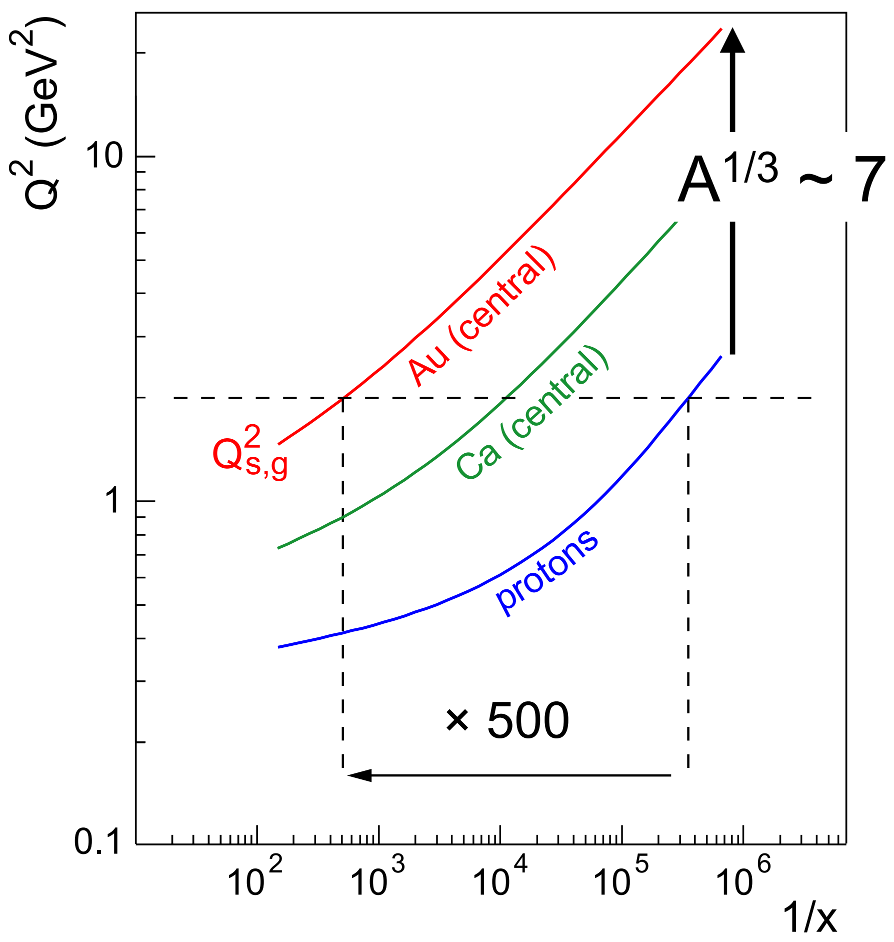




arXiv:1008.3989v1, see talk by C. Perkins & J. Albacete

Are RHIC & HERA Results consistent?





- **Strong hints** of saturation from RHIC: x ~ 10^{-3} in Au
- ep: **No/weak hints** in DIS at Hera up to $x=6.32\cdot10^{-5}$, $Q^2=1\text{-}5$ GeV^2

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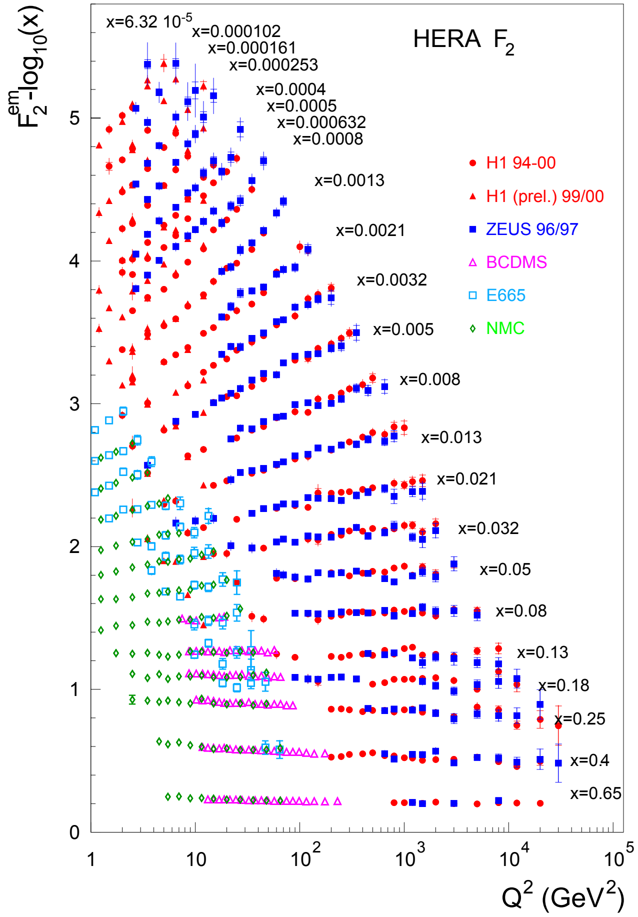

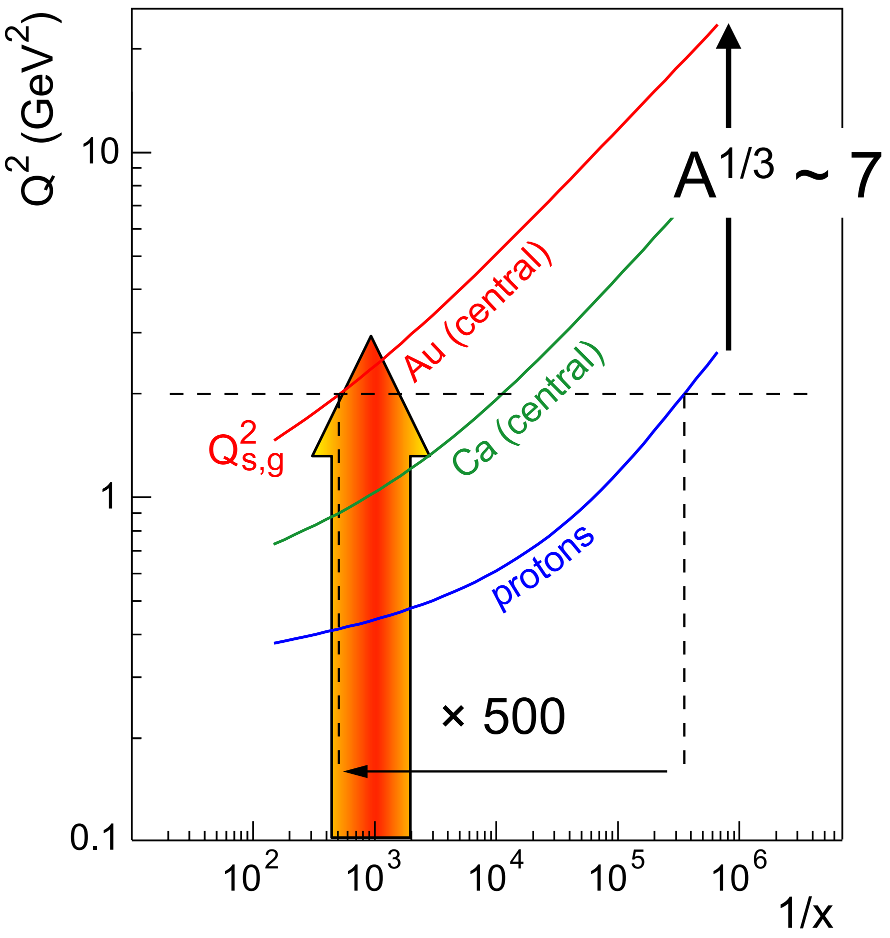

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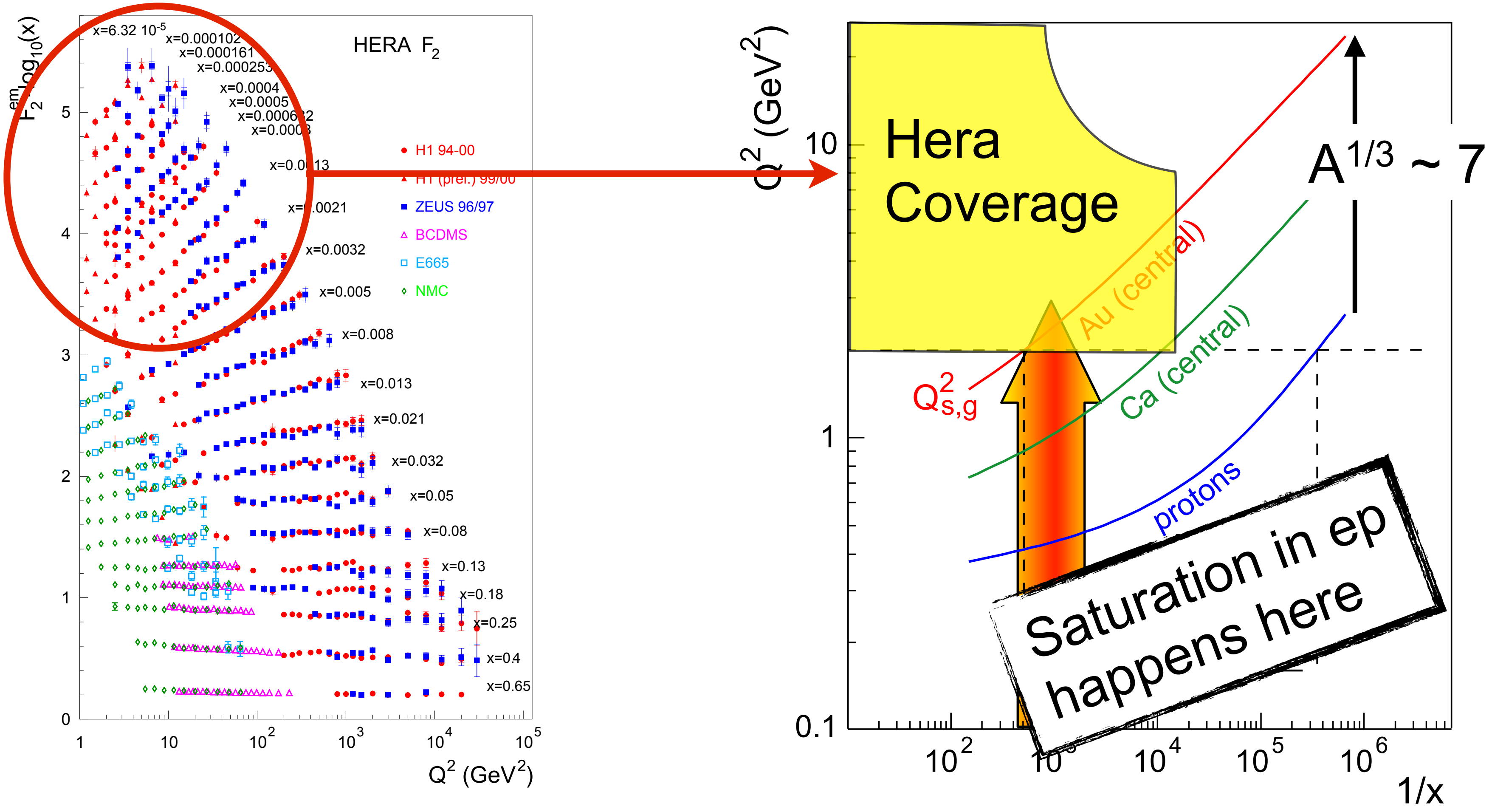


- **Strong hints** of saturation from RHIC: x ~ 10^{-3} in Au
- ep: **No/weak hints** in DIS at Hera up to x=6.32·10^{-5}, Q^2=1-5 GeV^2

- Finding RHIC and Hera & Q_s scalings consistent
- At pA in RHIC we see the Nuclear "Oomph" $Q_s^2 \sim Q_0^2 (A/x)^{1/3}$

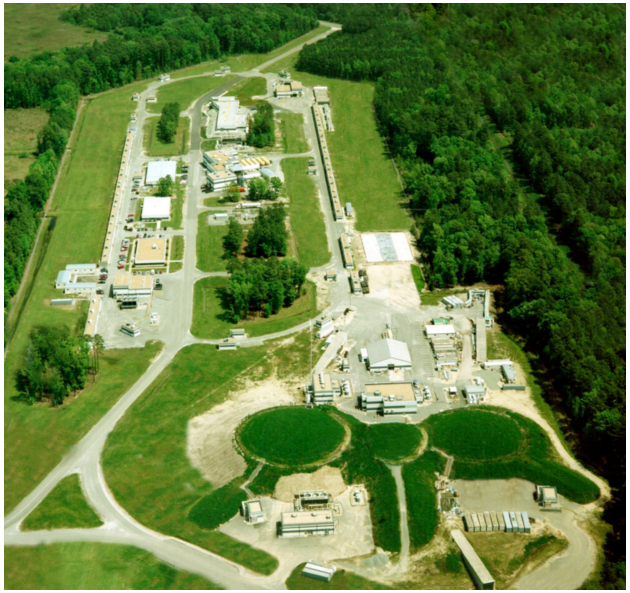
Do EIC energies match the requirements?

eRHIC = RHIC +
Energy-Recovery Linac

see talk by Vladimir Litvinenko

Both designs in 2 stages

ELIC = CEBAF +
Hadron Ring



see talk by Vasiliy Morozov

1. stage: 5+100 GeV/n e+Au
   (√s=45 GeV/n)
2. stage: 30+130 GeV/n e+Au
   (√s=125 GeV/n)

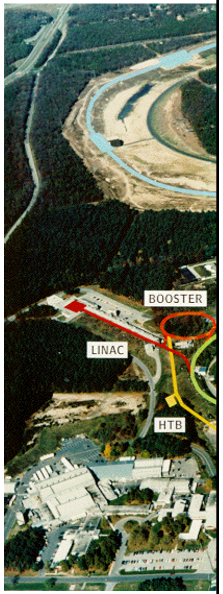
1. stage: 11+40 GeV/n e+Au
   (√s=42 GeV/n)
2. stage: 20+100 GeV/n e+Au
   (√s=89 GeV/n)

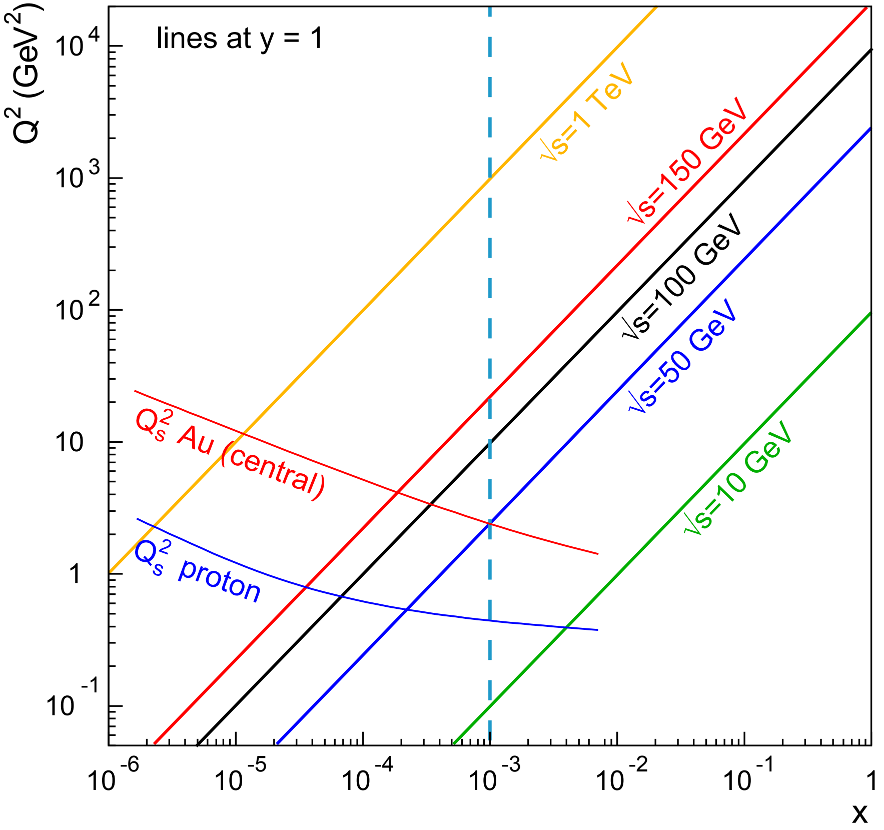
Do EIC energies match the requirements?

eRHIC = RHIC +

ELIC = CEBAF +

Energy





- In both cases 1st stage is ~OK but offers little Q^2 lever arm
- 2nd stage will match requirements fully

see talk by Vla

1. stage
   (√s=4

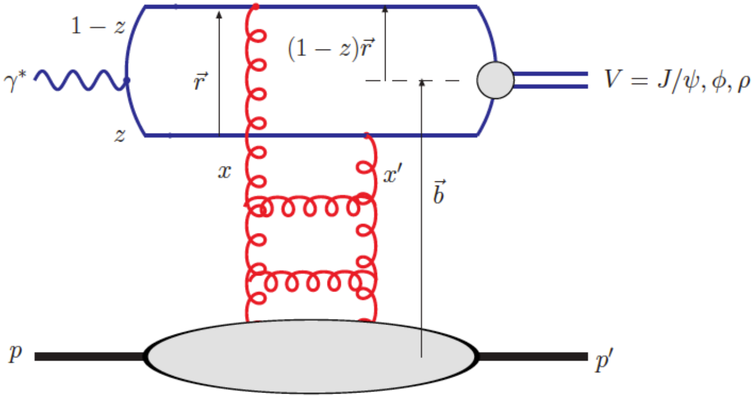
2. stage
   (√s=1

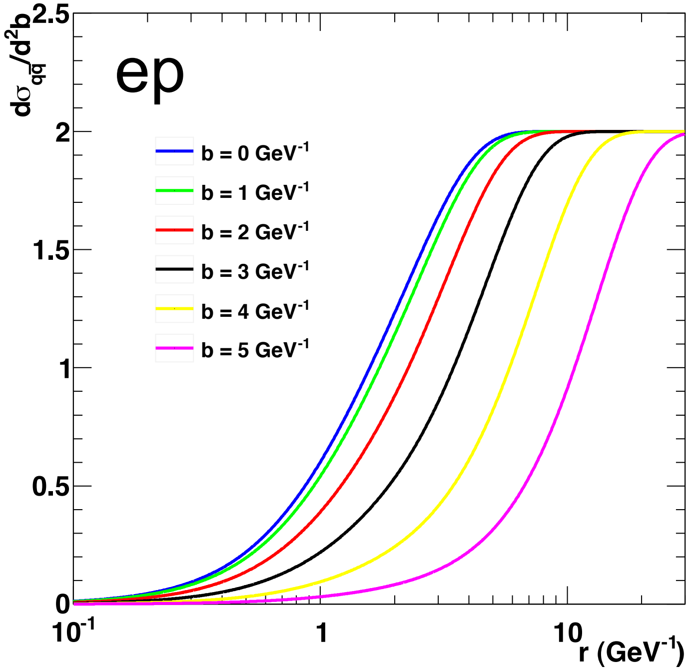
/n e+Au

V/n e+Au

Getting a “Feel” for Non-Linear QCD

Dipole Model:





$$\frac{d\sigma_{q\bar{q}}}{d^2b} = 2\mathcal{N}(x, r, b)$$

$$\mathcal{N}(x, r, b) = 2\left[1 - \exp\left(-r^2\frac{\pi^2}{2N_c}\alpha_s(\mu^2)xG(x, \mu^2)T(b)\right)\right]$$

$\mathcal{N} =$ Dipole Scattering Amplitude

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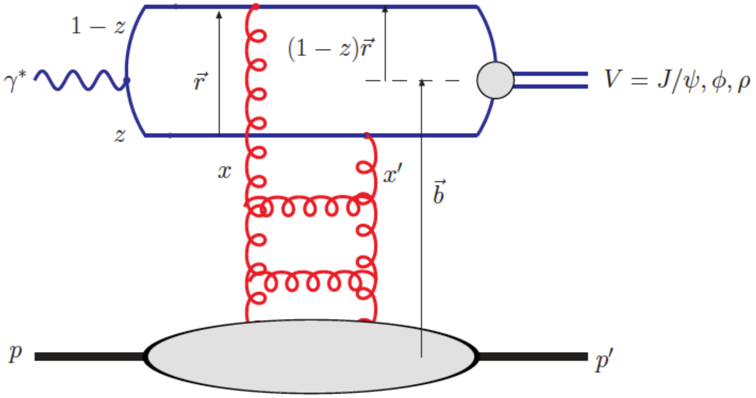

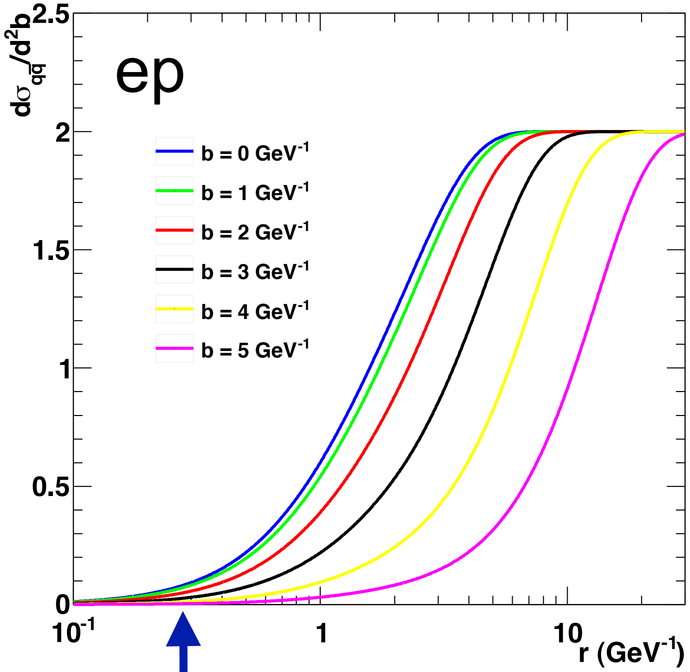

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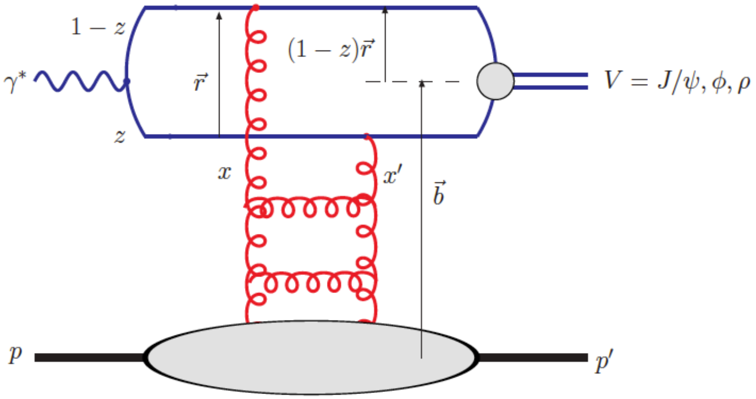

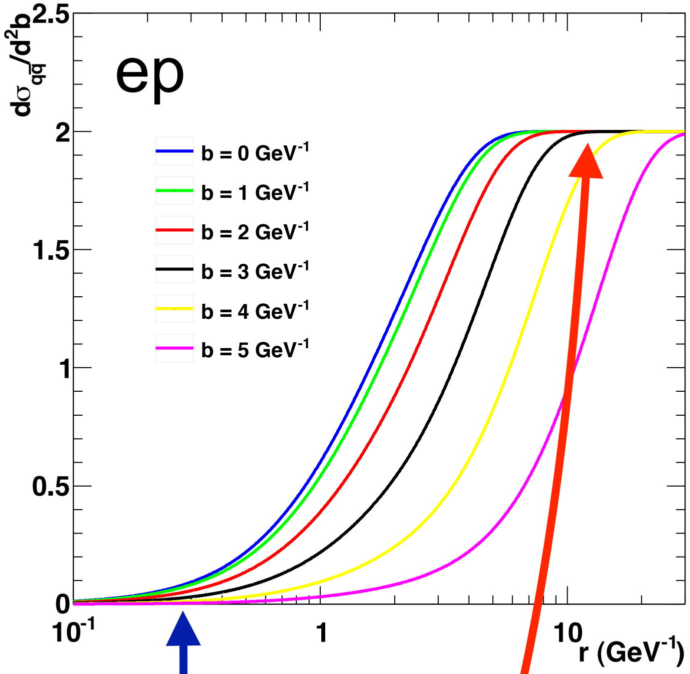

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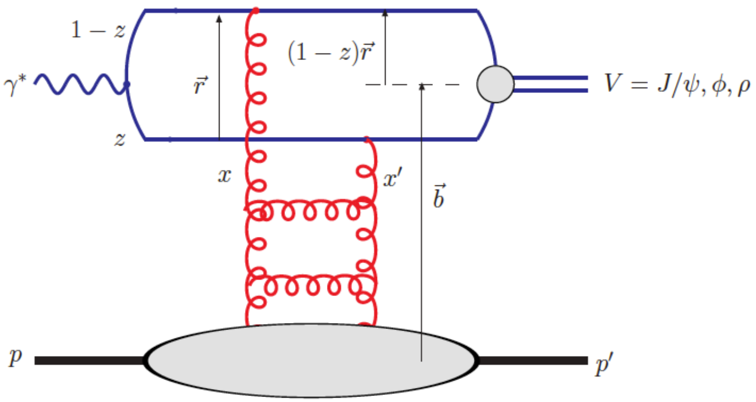

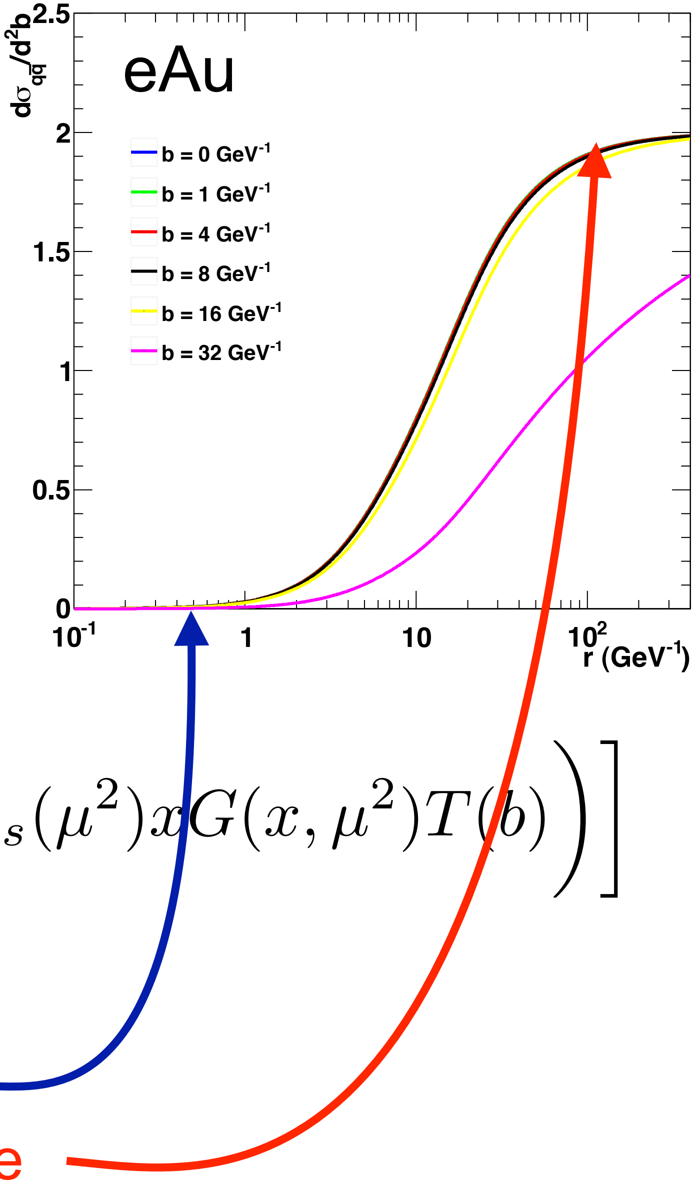

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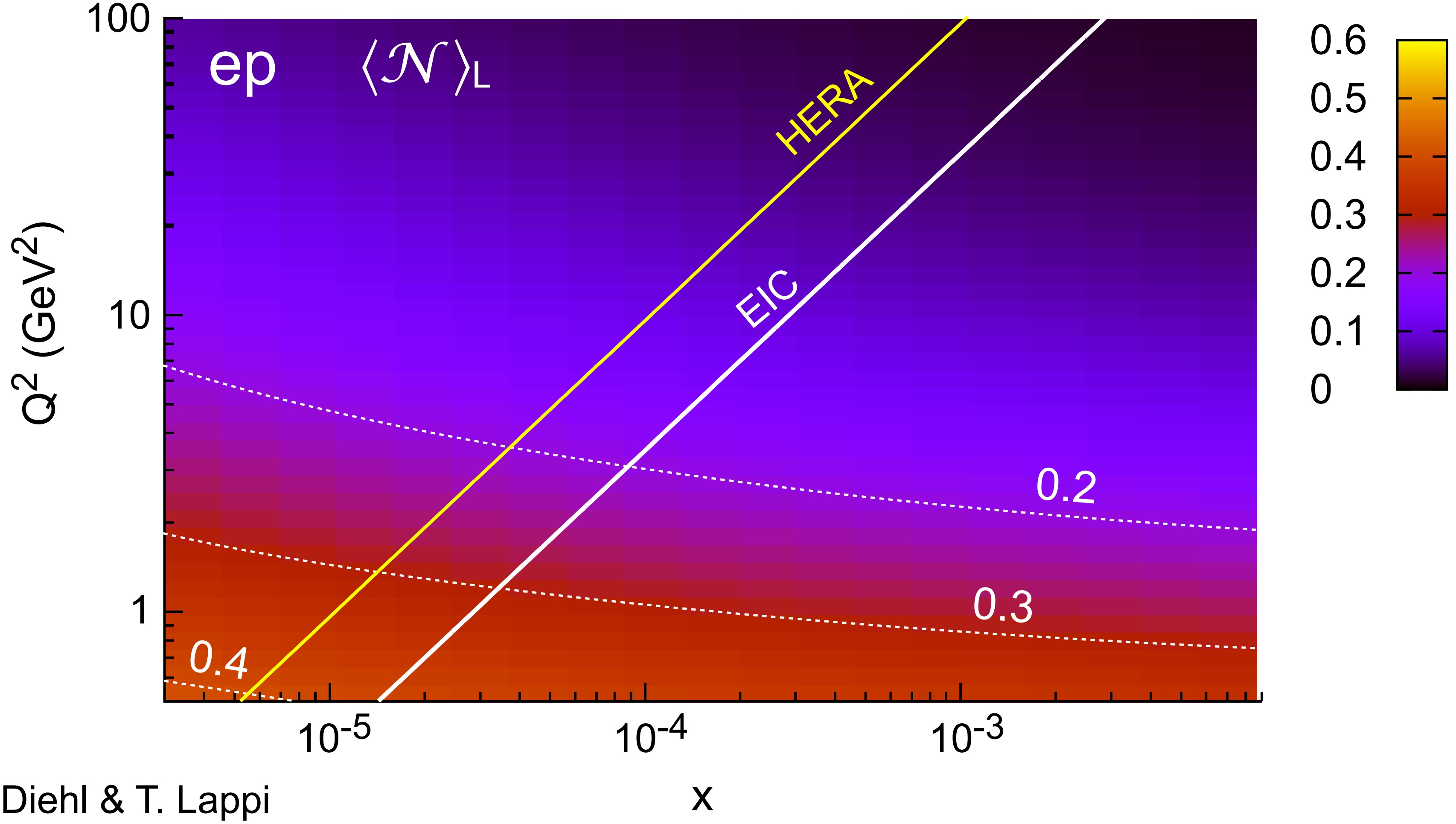
Getting a Feel for Non-Linear QCD

To assess typical values of $\mathcal{N}$ calculate average:

$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}^2}{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}}$$



M. Diehl & T. Lappi

Getting a Feel for Non-Linear QCD

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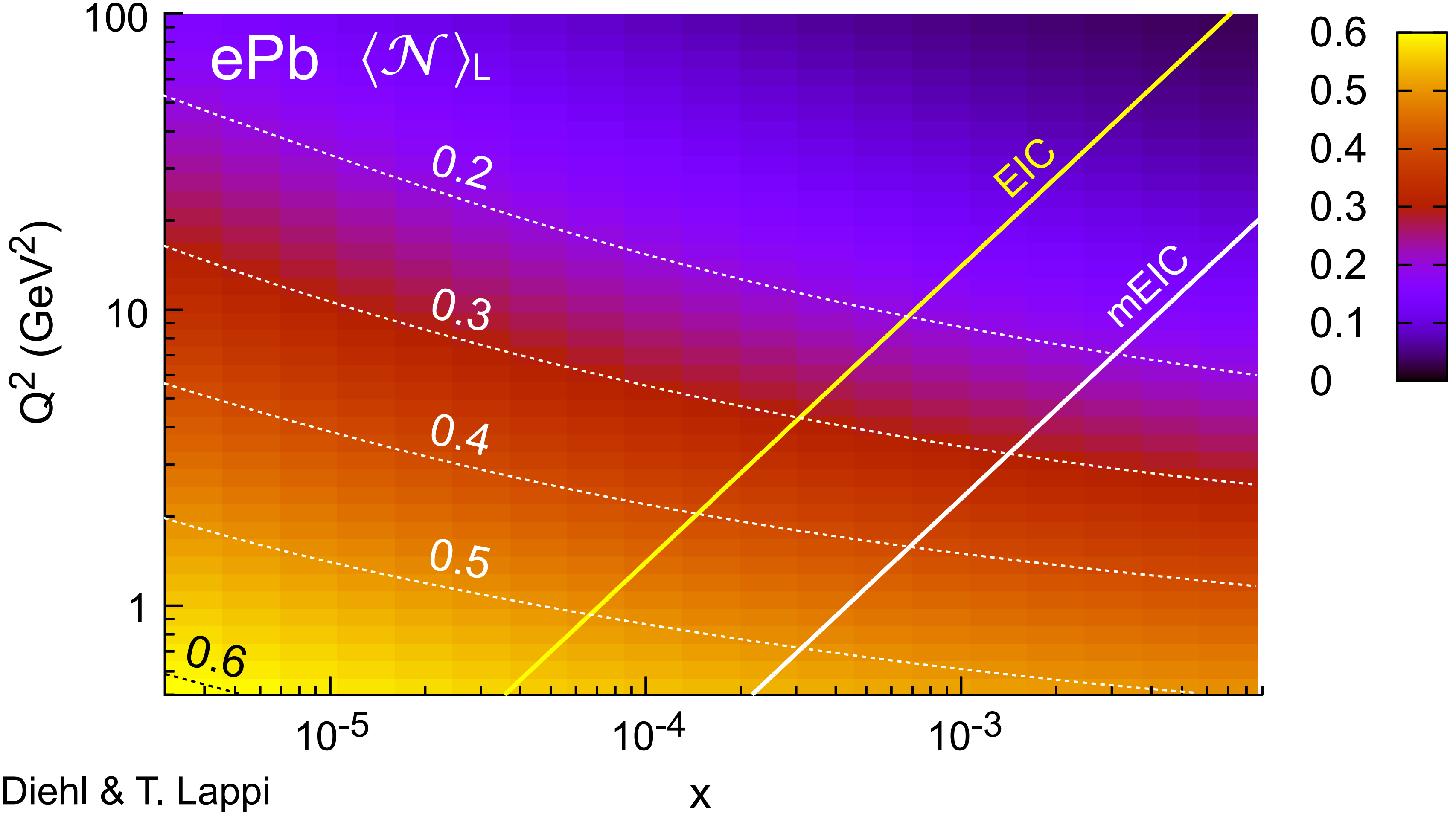


M. Diehl & T. Lappi

Measuring F_L with the EIC

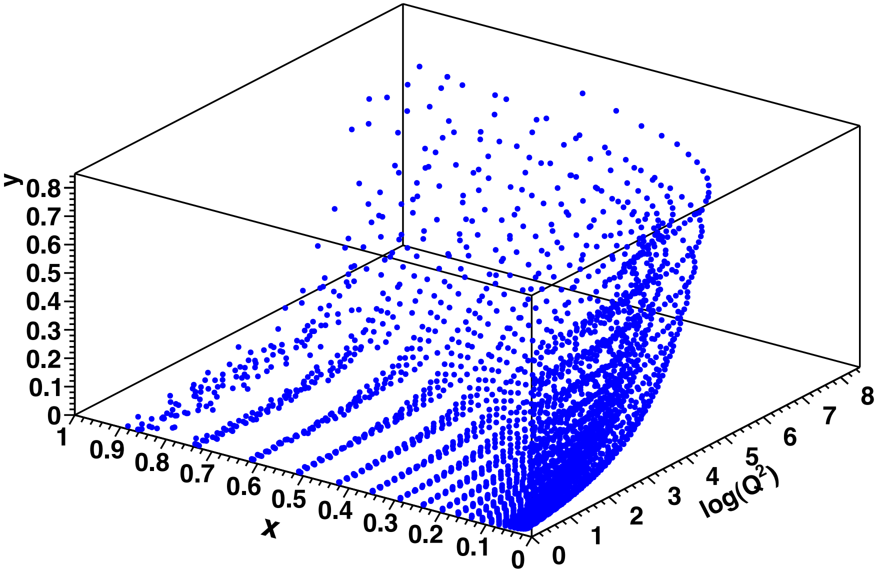
$F_L \sim \alpha_s\, G(x,Q^2)$: the most "direct" way to $G(x,Q^2)$

F_L runs at various √s

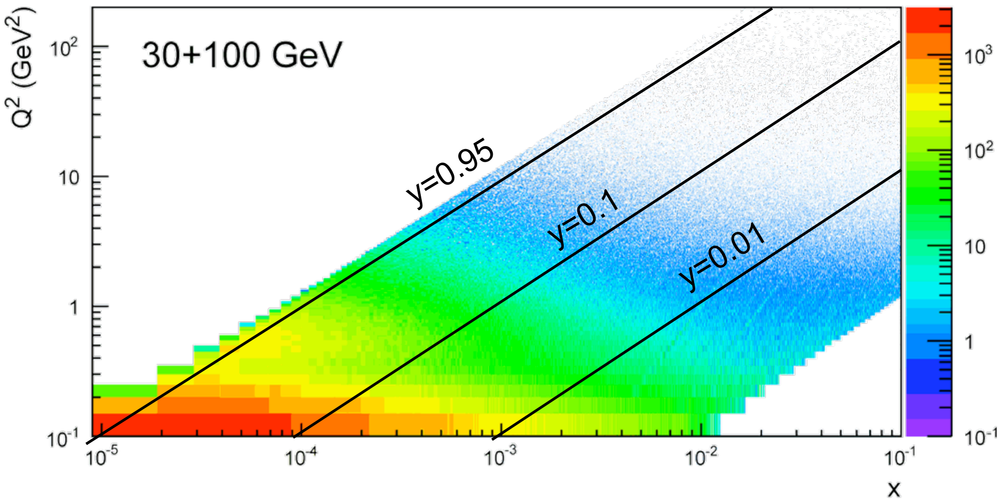
⇒ longer program

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

In order to extract F_L one needs at least two measurements of the inclusive cross section with "wide" span in inelasticity parameter **y** ($Q^2 = sxy$)



Coverage in x and Q^2 for inclusive cross section measurements



What y range can be achieved?

Feasibility study: $\sigma_r = F_2(x,Q^2) - y^2/Y_+ \cdot F_L(x,Q^2)$

$$Y_+ = 1 + (1-y)^2$$

Strategies:

slope of y^2/Y_+ for different s at fixed x & Q^2

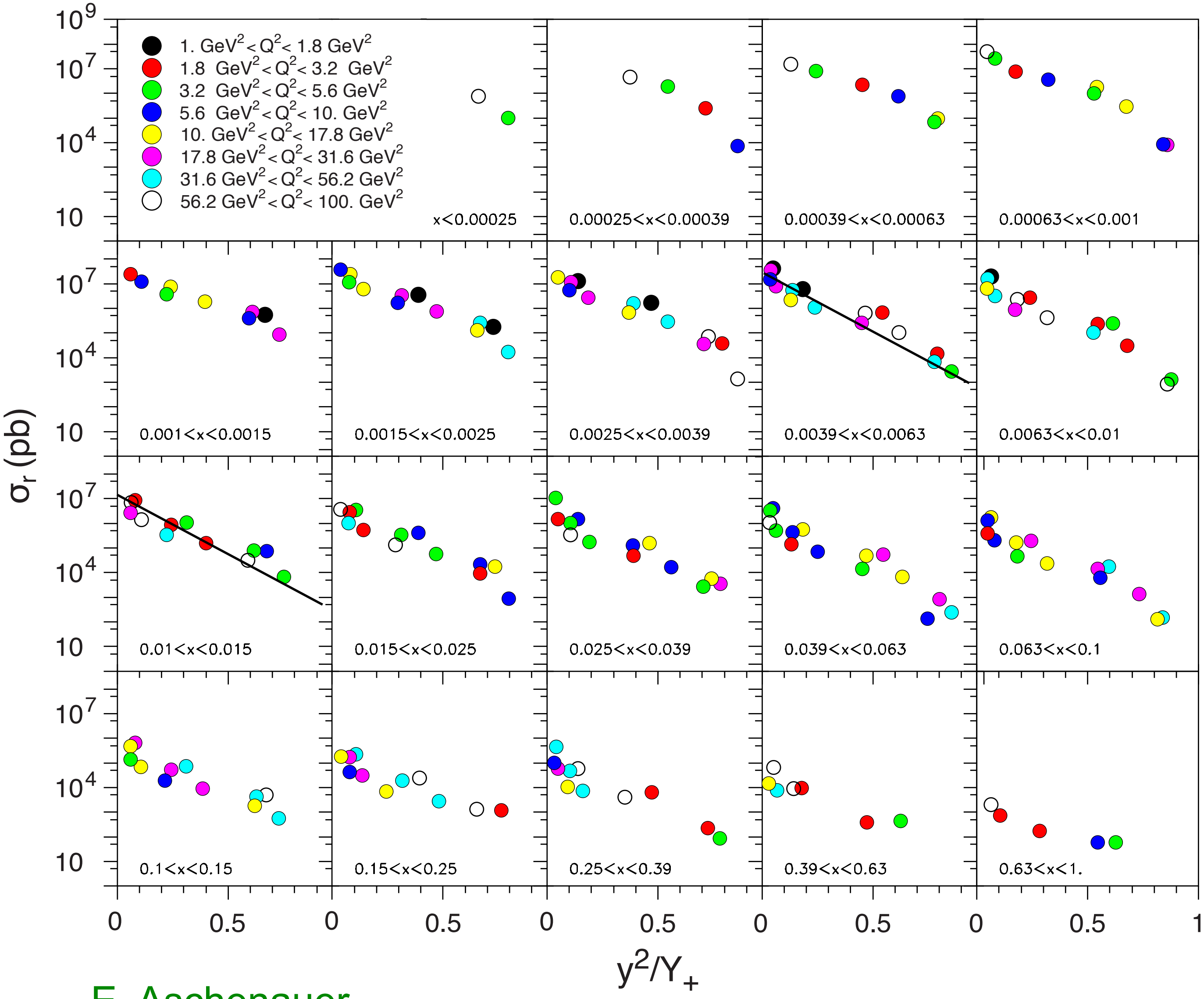
e+p: 1st stage

5x50 - 5x325 running combined 4 weeks/each (50% eff)

stat. error shown and neglible

To Do:

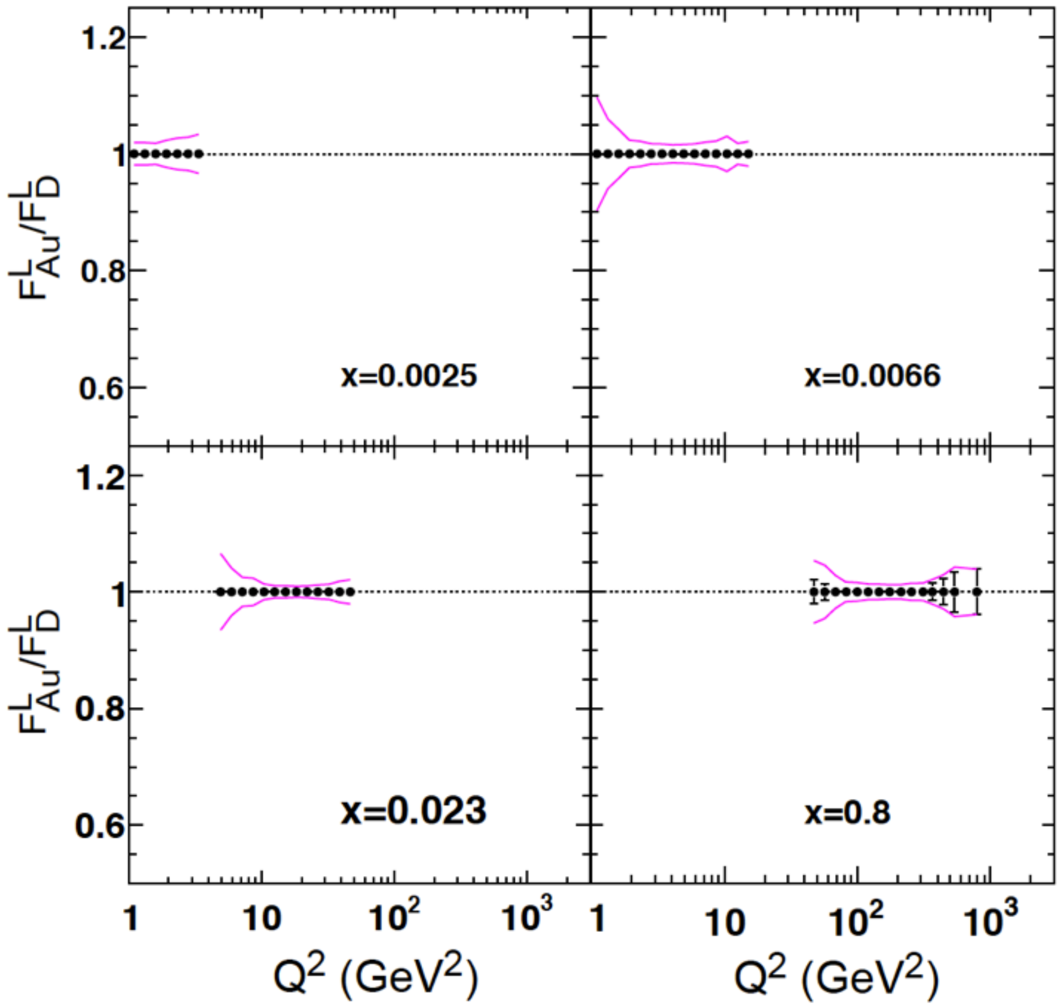
Rosenbluth extraction & Detector effects



E. Aschenauer

Syst. Uncertainties in F_L for staged EIC

F_L for electron energy fixed at 4 GeV and proton energies: 50, 70, 100, 250 GeV (4 fb^{-1} each)



The magenta curves show the statistical and systematic errors (1% uncertainty in normalization) added in quadrature.

Again, the extraction of F_L is dominated by systematic uncertainties

Big issue for e+A: Radiative corrections

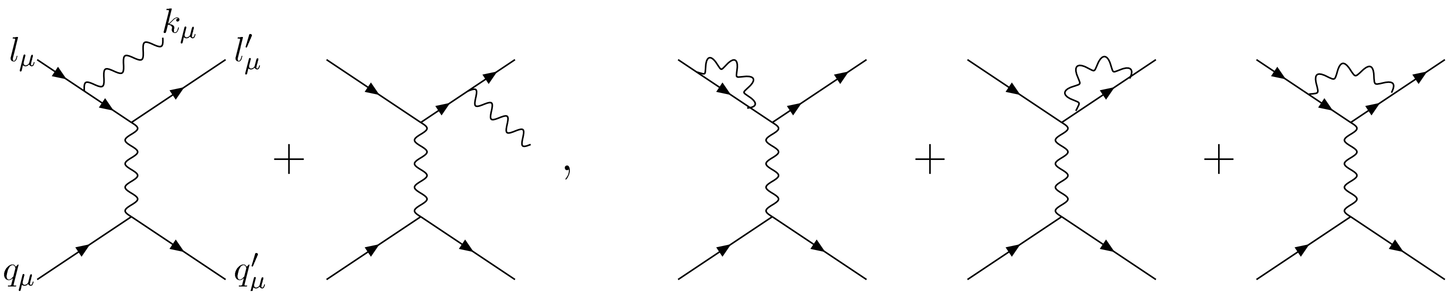
High precision requires knowledge of higher-order corrections

$$\sigma_{\text{experiment}} \Leftrightarrow \sigma_{\text{theory}}[Fn(x,Q^2)] = \sigma^{(0)} + \alpha_{em}\sigma^{(1)} + \ldots$$

Emission of real photons

- experimentally often not distinguished from non-radiative processes: soft photons, collinear photons

⇒ ”radiative corrections”



“Ideal” case: $Q^2 = -(l-l')^2, \quad x_B = \dfrac{Q^2}{2P\cdot(l-l')}$

True case: $\tilde{Q}^2 = -(l-l'-k)^2, \quad \tilde{x}_B = \dfrac{\tilde{Q}^2}{2P\cdot(l-l'-k)}$

Detecting Nuclear Breakup

- Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- Focus on n emission
  - Zero-Degree Calorimeter
  - Requires careful design of IR
- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

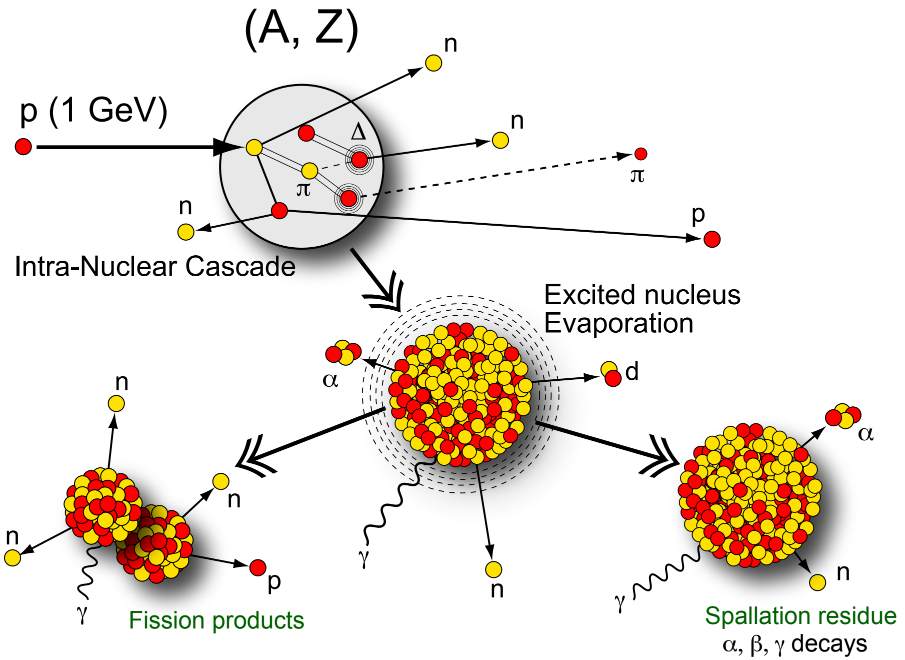
Traditional modeling done in pA:

Intra-Nuclear Cascade

- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

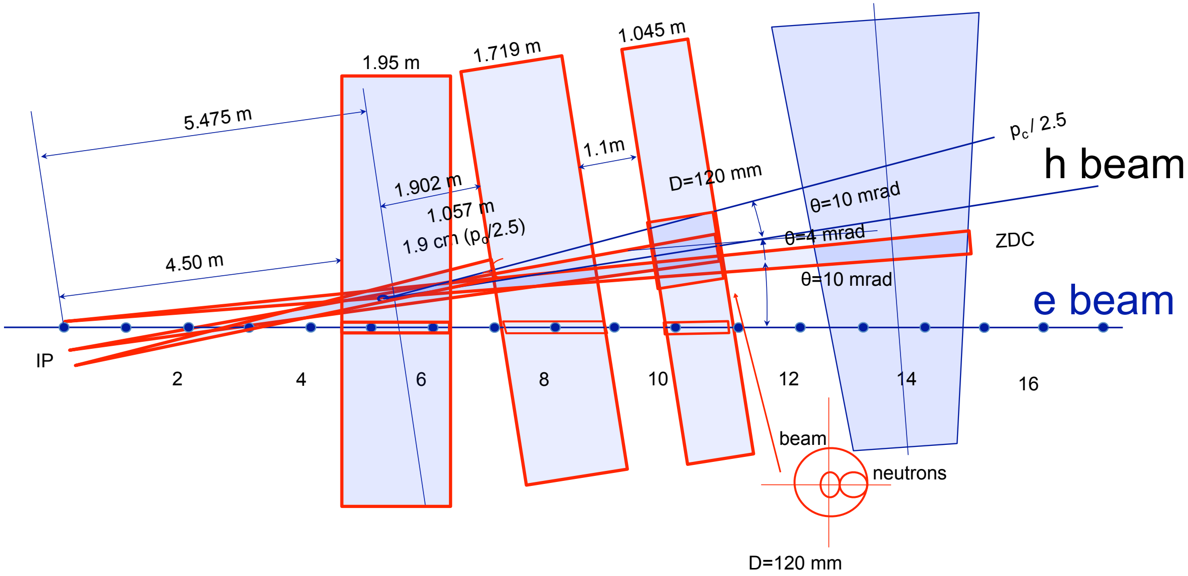
De-Excitation

- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)



Experimental Reality

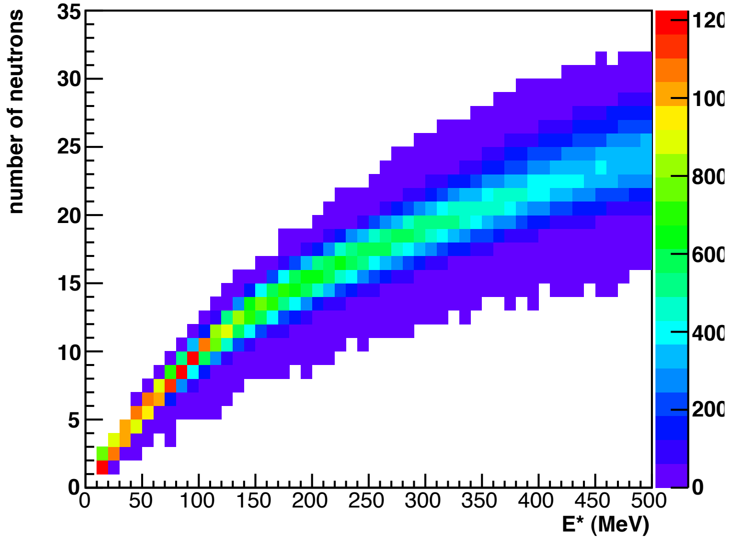
Here eRHIC IR layout:

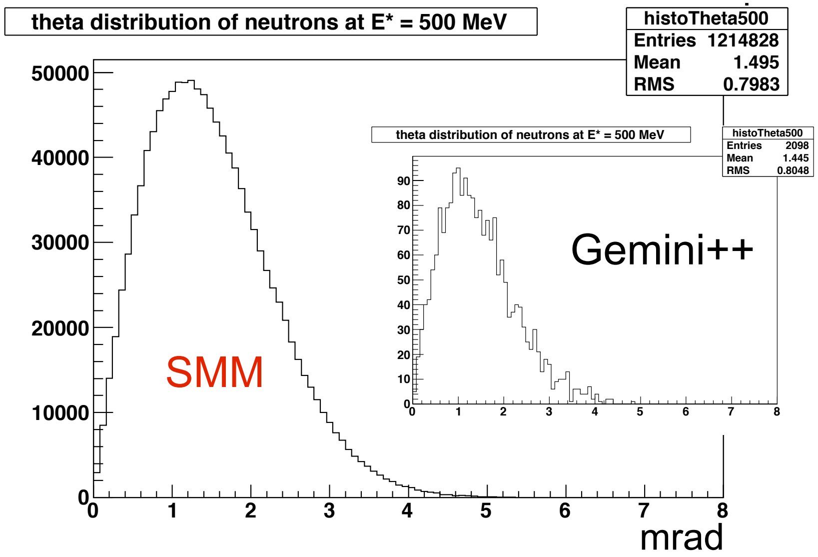


Need ±X mrad opening through triplet for *n* and room for ZDC

Big questions:

- Excitation energy E*?
- ep: $d\sigma/M_Y \sim 1/M_Y^2$
- eA? Assume ep and use $E^* = M_Y - m_p$ as lower limit





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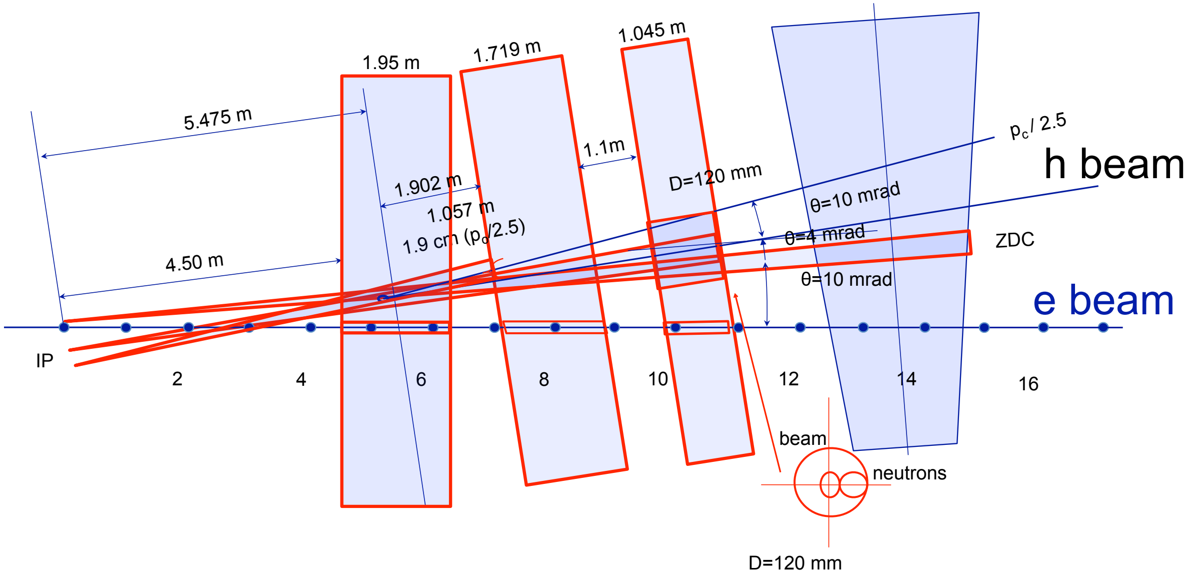

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Breakup simulators SMM & Gemini++ show it works:

- For $E^*_{tot} \geq 10$ MeV and 2.5 mrad *n* acceptance we have rejection power of at least 10^5.
- Separating incoherent from coherent diffractive events is possible at a collider with *n*-detection via ZDCs alone