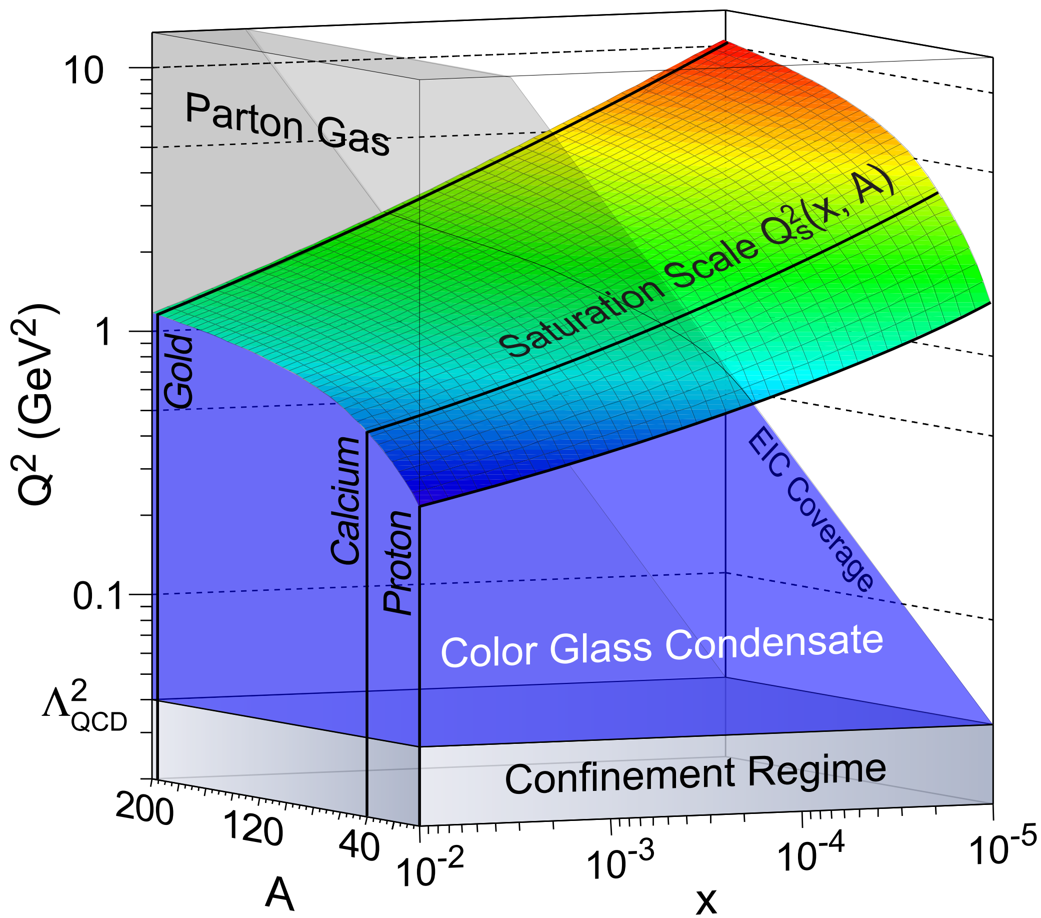
Experimental Overview of Low-x e+A Physics at an EIC



Thomas Ullrich

April 14, 2011

XIX International Workshop on Deep-Inelastic Scattering

Newport News, VA

Office of Science
U.S. Department of Energy

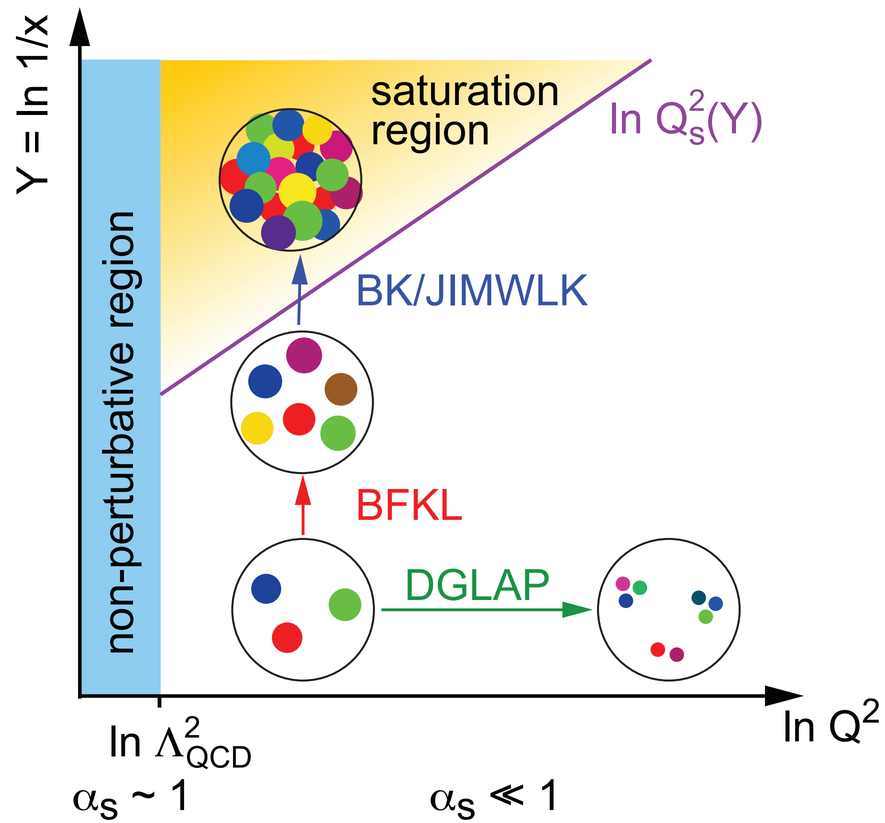
BROOKHAVEN NATIONAL LABORATORY

Science of e+A at an EIC

Investigate with precision universal dynamics of gluons and "sea" quarks that fundamentally make up nearly all the mass of the visible universe

e+A Central Topics:

- Probing the momentum-dependence of gluon densities and the onset of saturation



- Study the Physics of Strong Color Fields
  - Measure momentum distribution of glue
  - Establish the existence of the saturation regime
- How do fast probes interact with the gluonic medium?
  - Energy loss, Fragmentation processes
- Study the nature of color singlet excitations (Pomerons)

See talk by Jamal Jalilian-Marian

Raison d'être for e+A

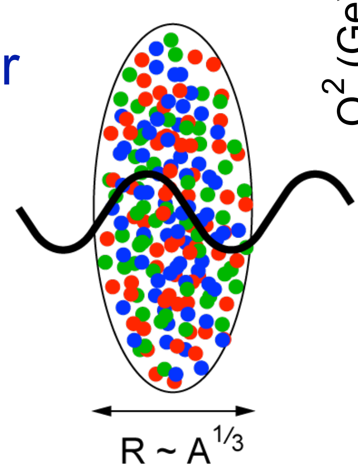
Scattering of electrons off nuclei:

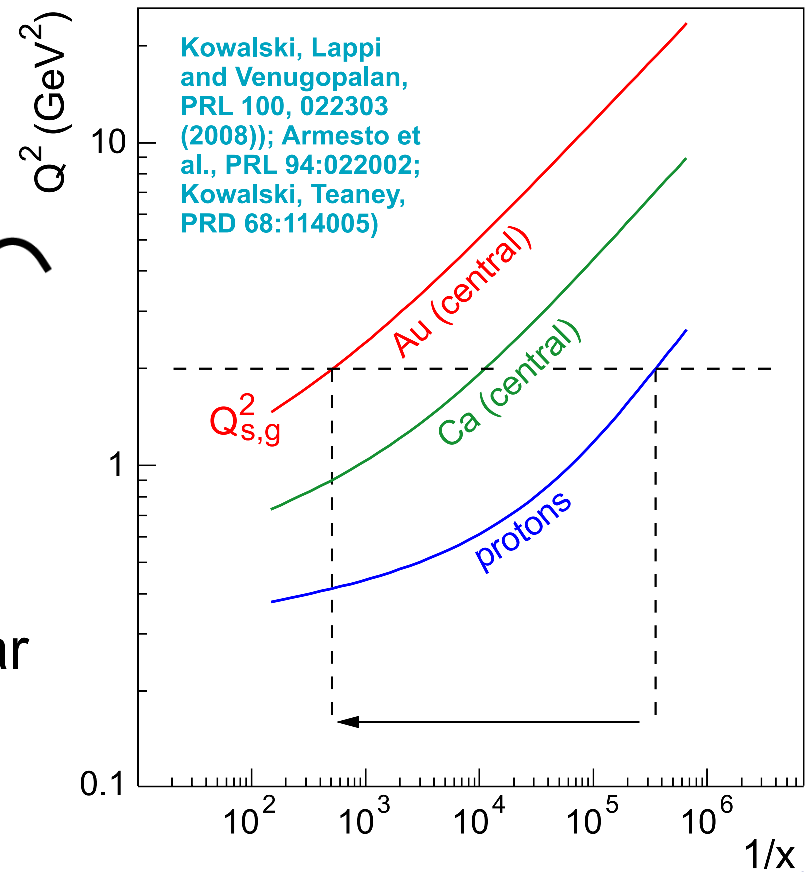
Probes interact over distances $L \sim (2m_N x)^{-1}$

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):

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





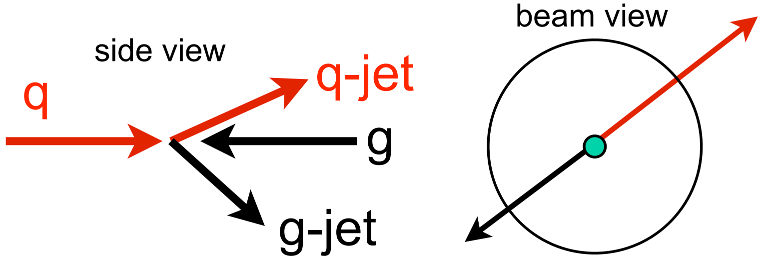
Enhancement of Q_S with A ⇒ non-linear QCD regime reached at significantly lower energy in A than in proton

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)

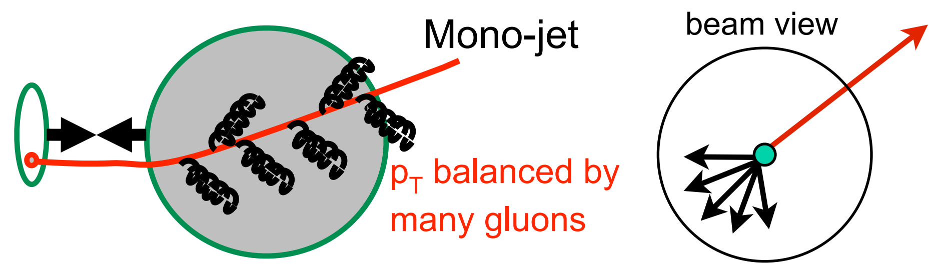
Low gluon density (pp):

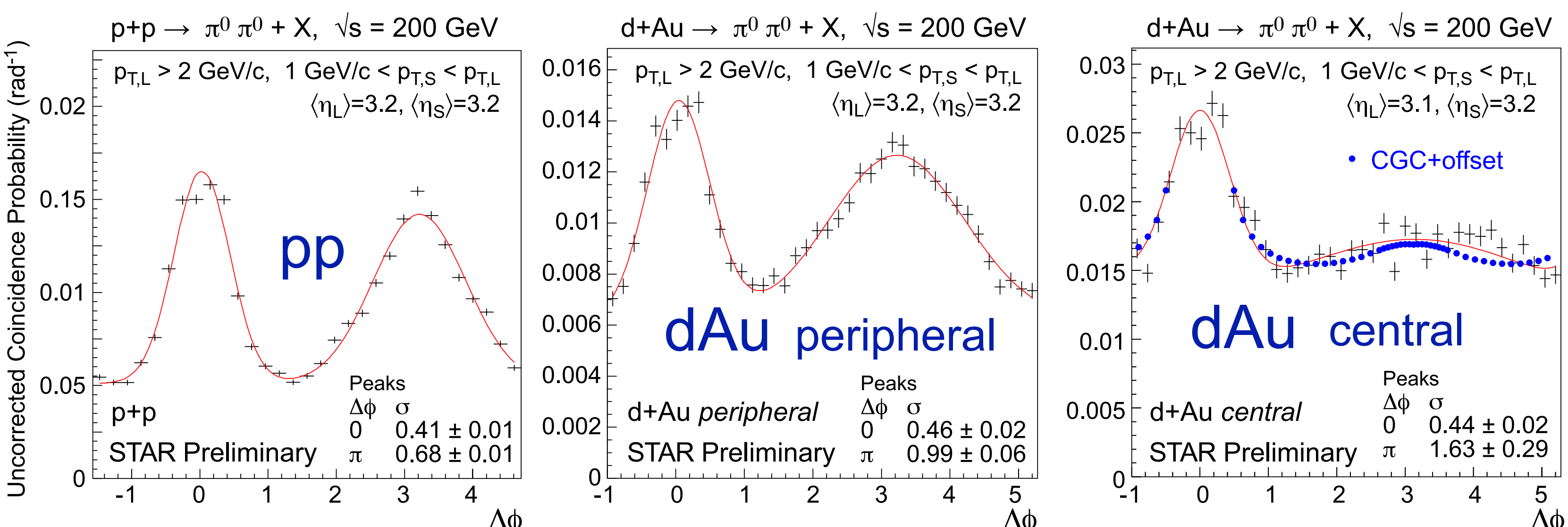
pQCD predicts 2→2 process
⇒ back-to-back di-jet



High gluon density (pA):

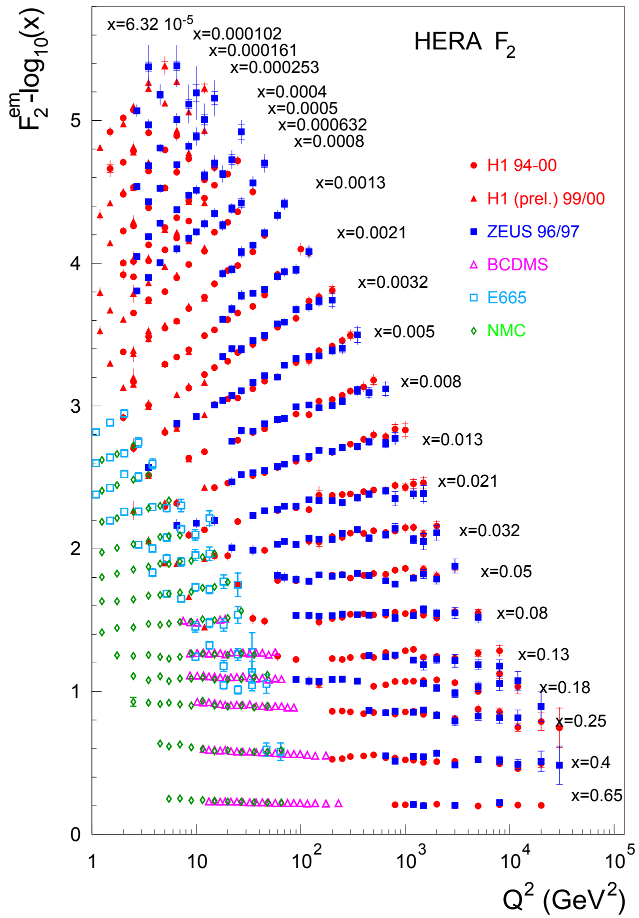
2→1 (2→many) process ⇒ mono-jet

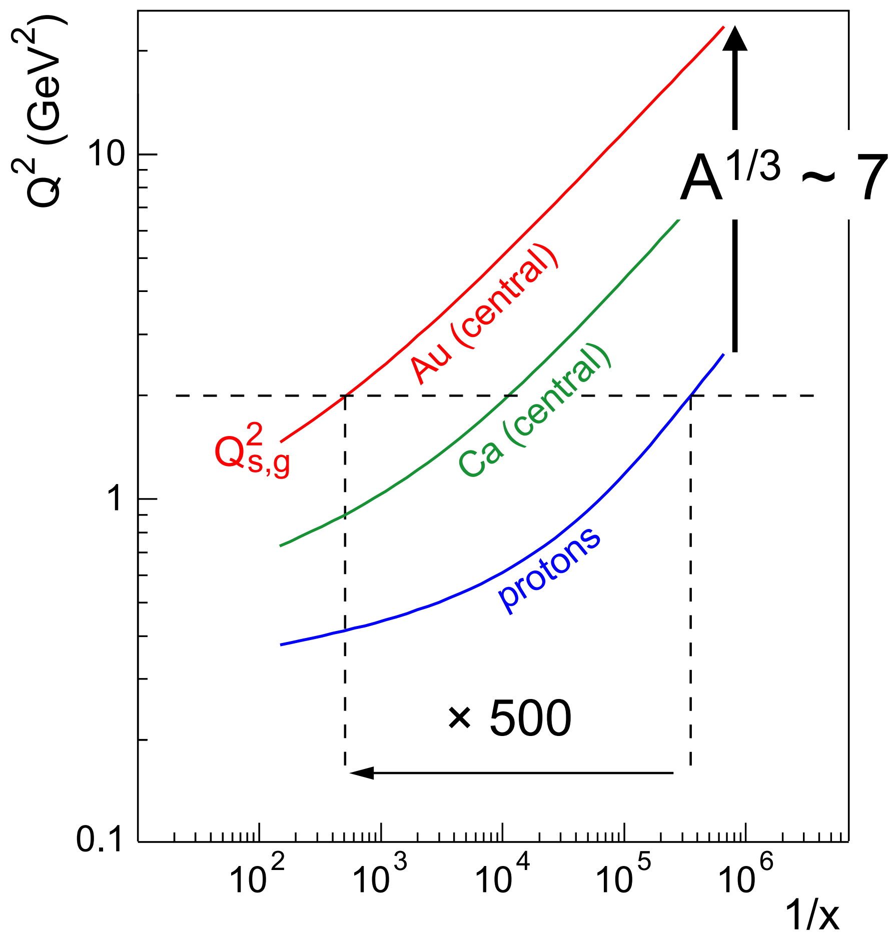




arXiv:1008.3989v1, see talk by C. Perkins & J. Albacete

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=1-5 GeV^2

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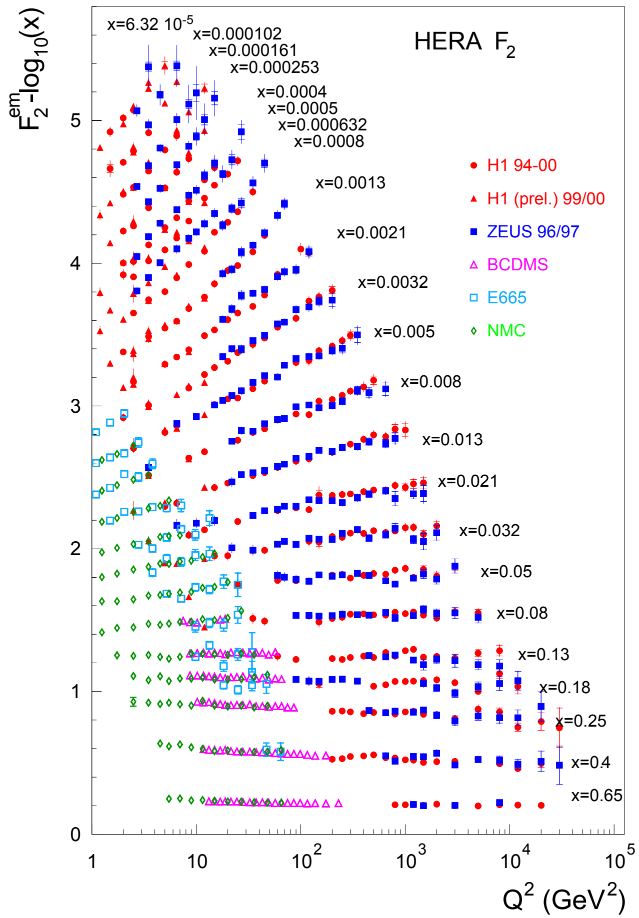

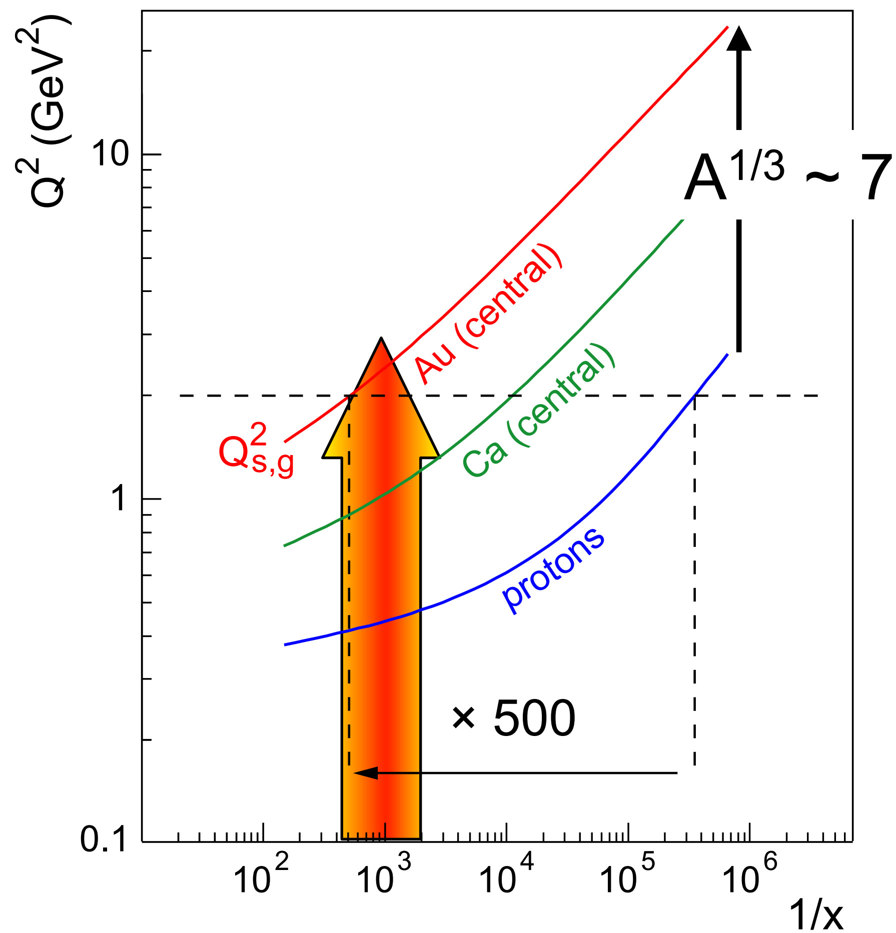

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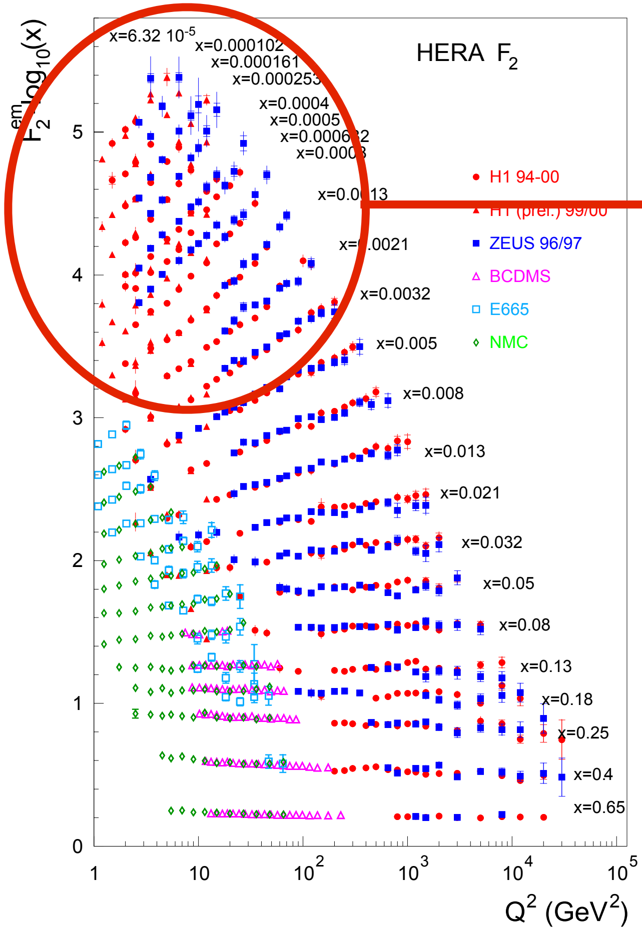

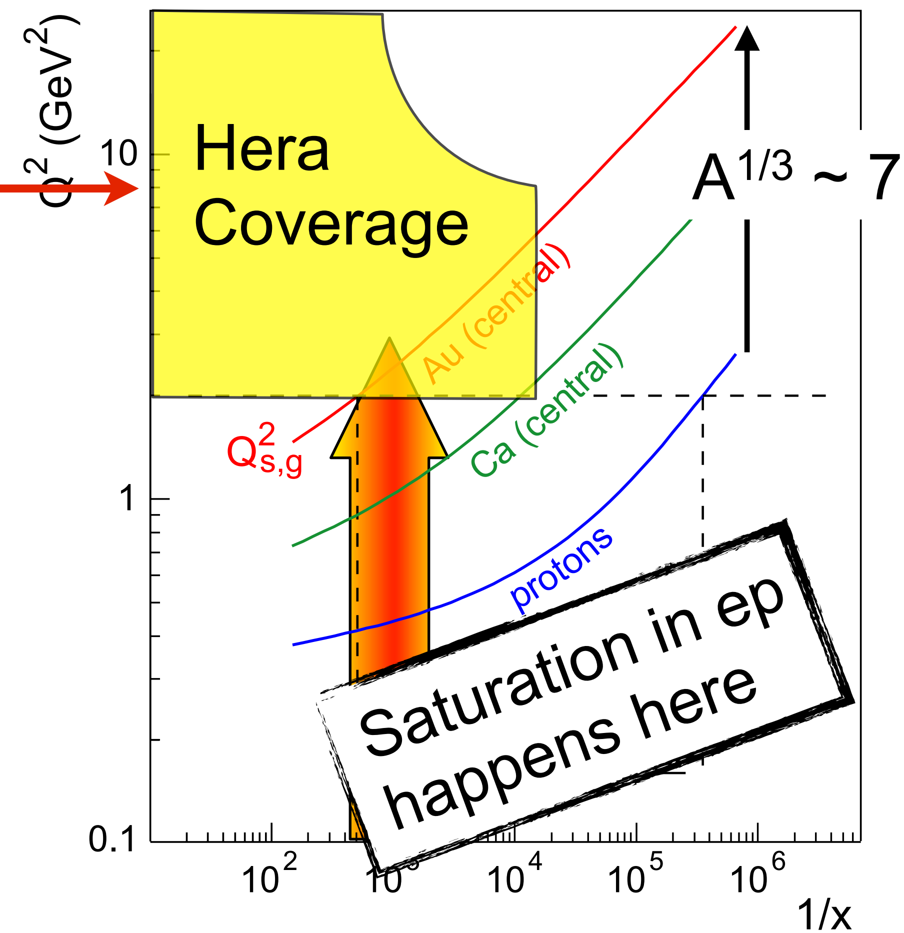

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- Finding RHIC and Hera & Q_s scalings consistent
- At pA in RHIC we see the Nuclear "Oomph" $Q_s^2 \sim Q_0^2 (A/x)^{1/3}$

Do EIC energies match the requirements?

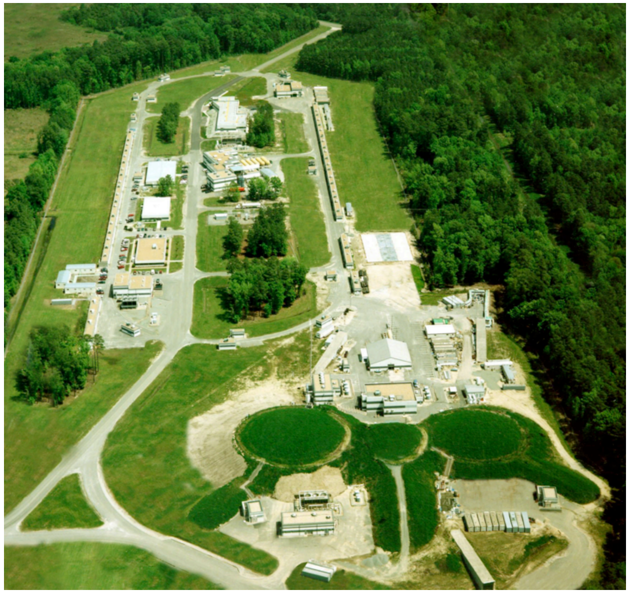
eRHIC = RHIC +
Energy-Recovery Linac

see talk by Vladimir Litvinenko

1. stage: 5+100 GeV/n e+Au
   ($\sqrt{s}$=45 GeV/n)
2. stage: 30+130 GeV/n e+Au
   ($\sqrt{s}$=125 GeV/n)

Both designs in 2 stages

ELIC = CEBAF +
Hadron Ring



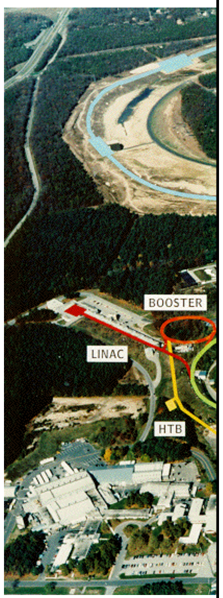
see talk by Vasiliy Morozov

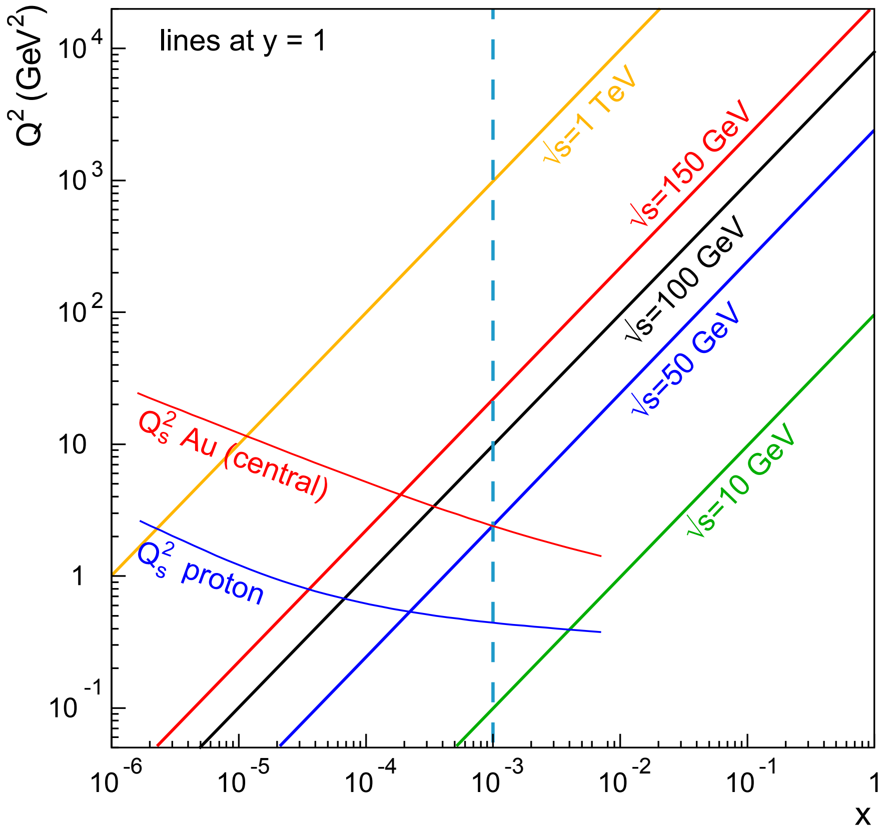
1. stage: 11+40 GeV/n e+Au
   ($\sqrt{s}$=42 GeV/n)
2. stage: 20+100 GeV/n e+Au
   ($\sqrt{s}$=89 GeV/n)

Do EIC energies match the requirements?

eRHIC = RHIC + | ELIC = CEBAF +

Energy





see talk by Vla

1. stage | /n e+Au

(√s=4

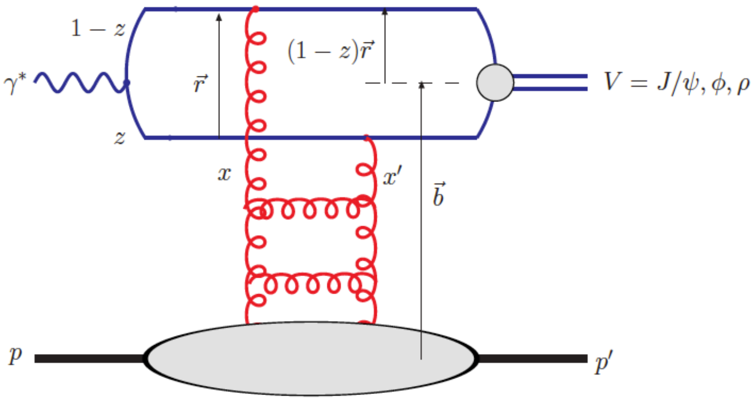
2. stage | V/n e+Au

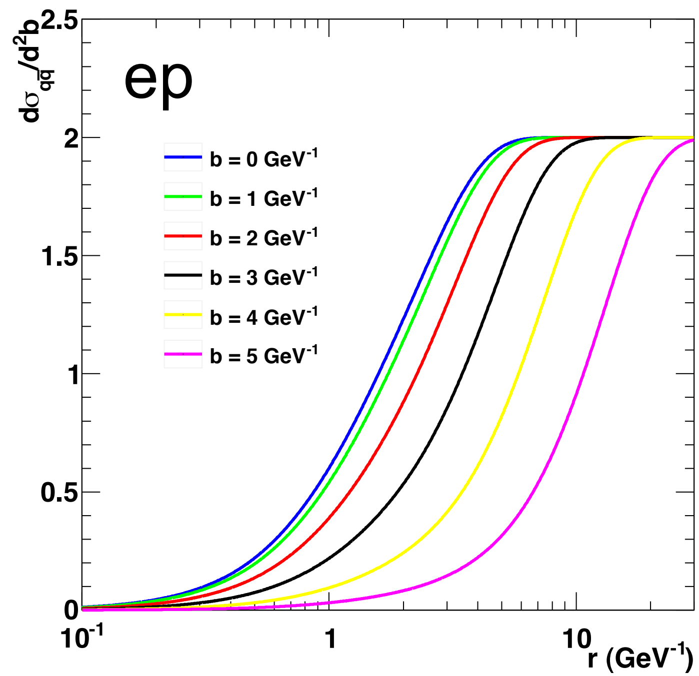
(√s=1

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

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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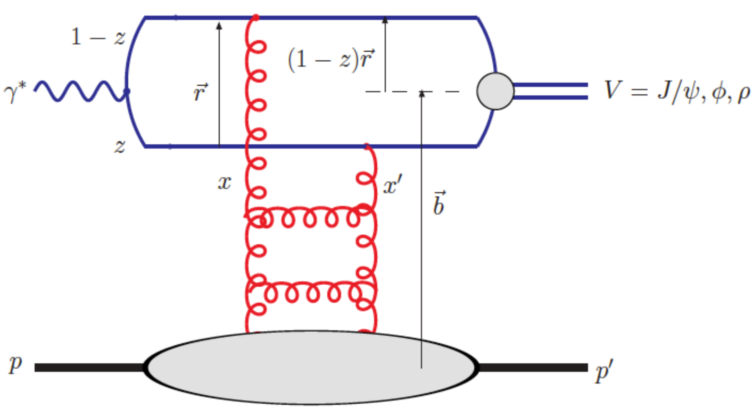

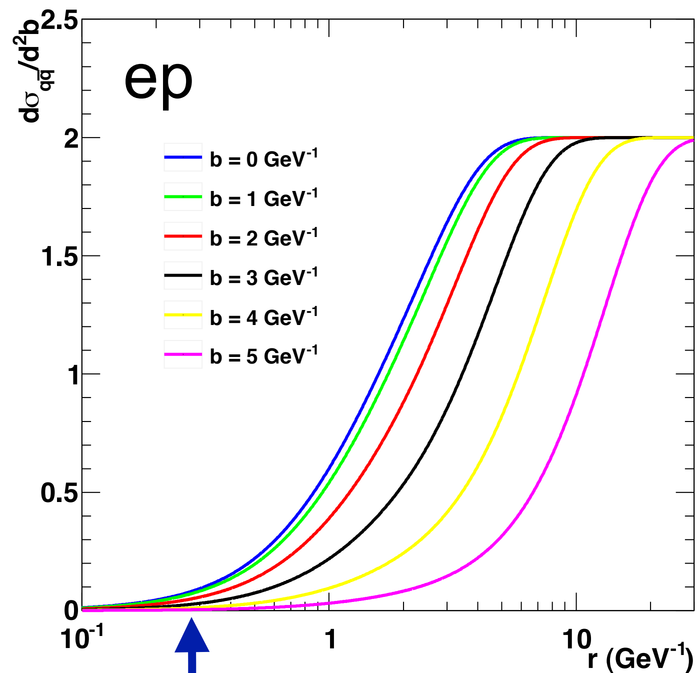

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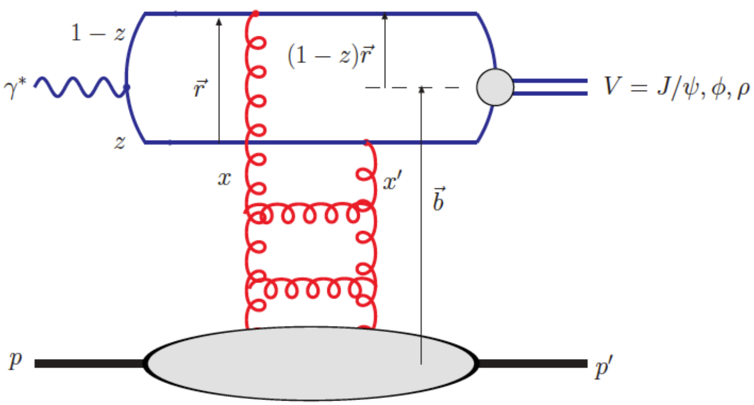

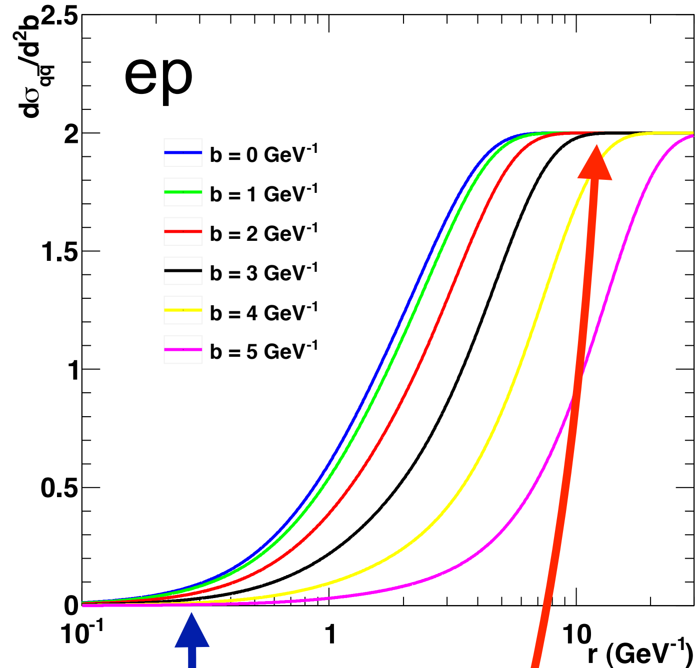

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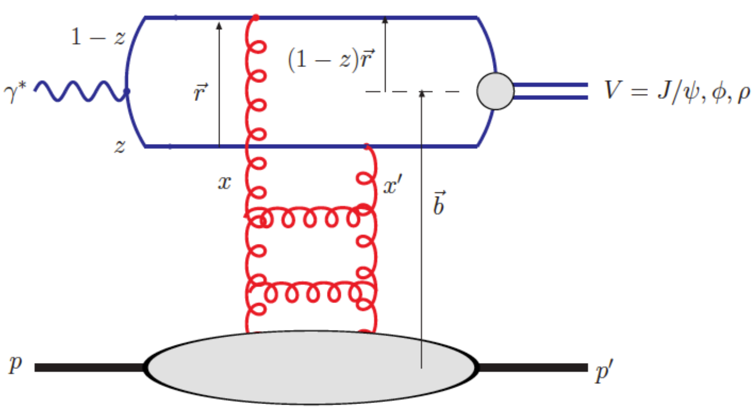

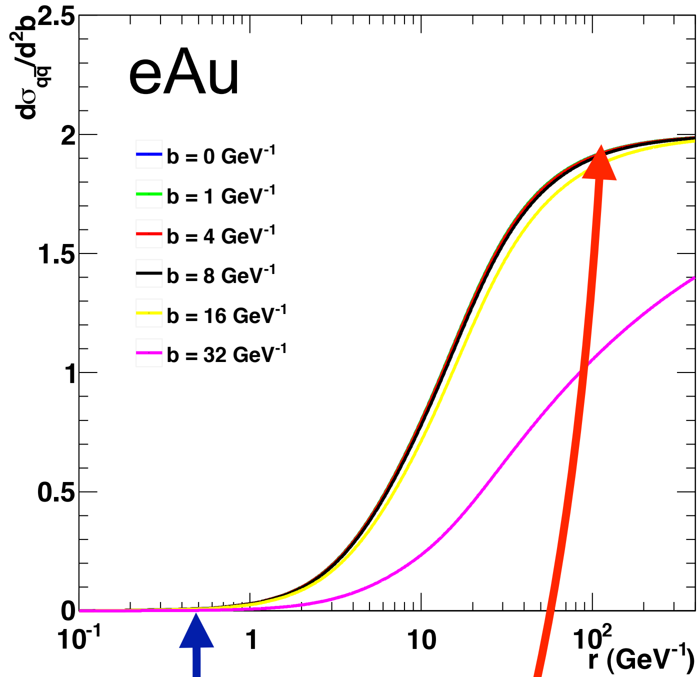

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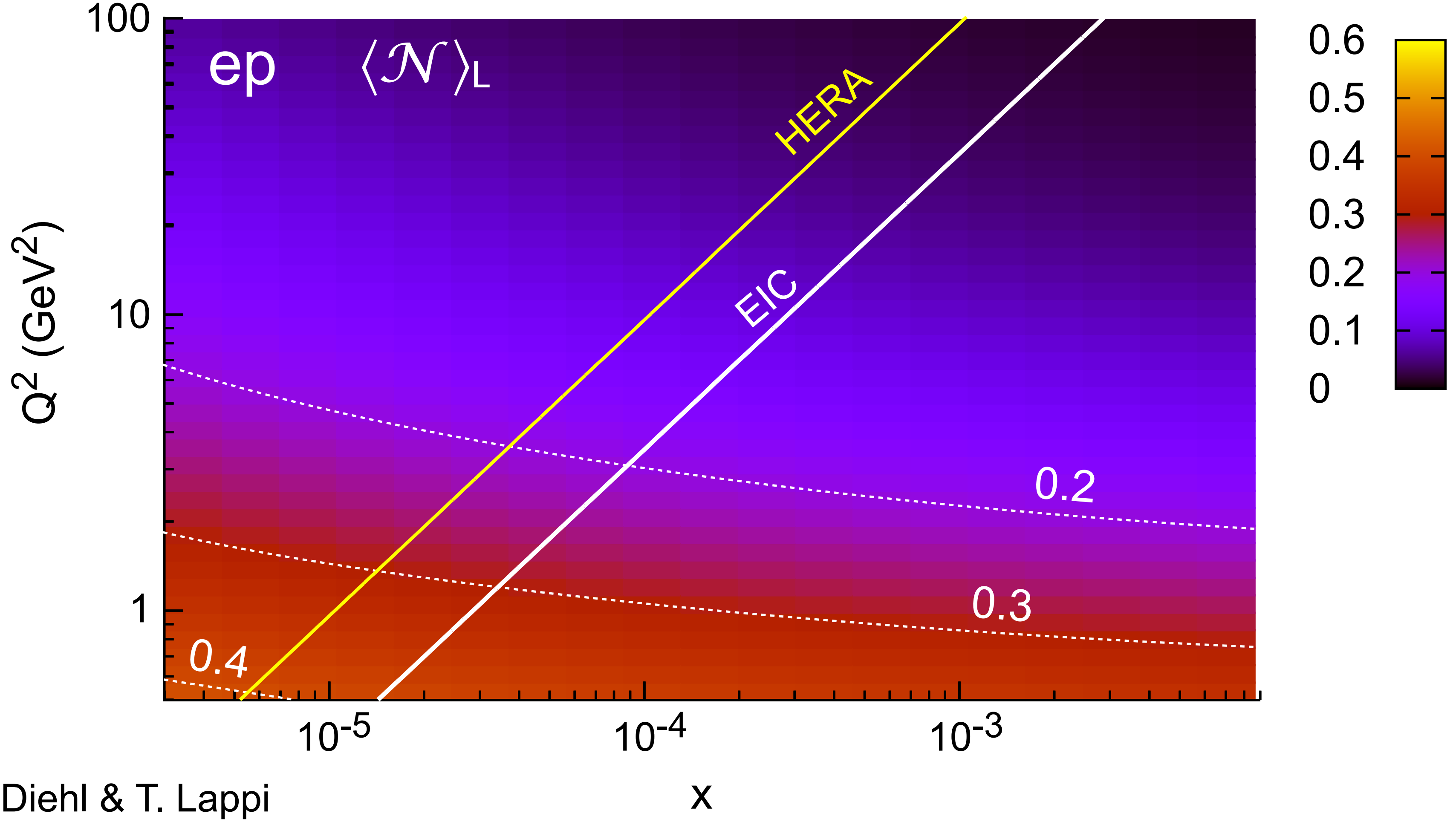
Getting a Feel for Non-Linear QCD

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

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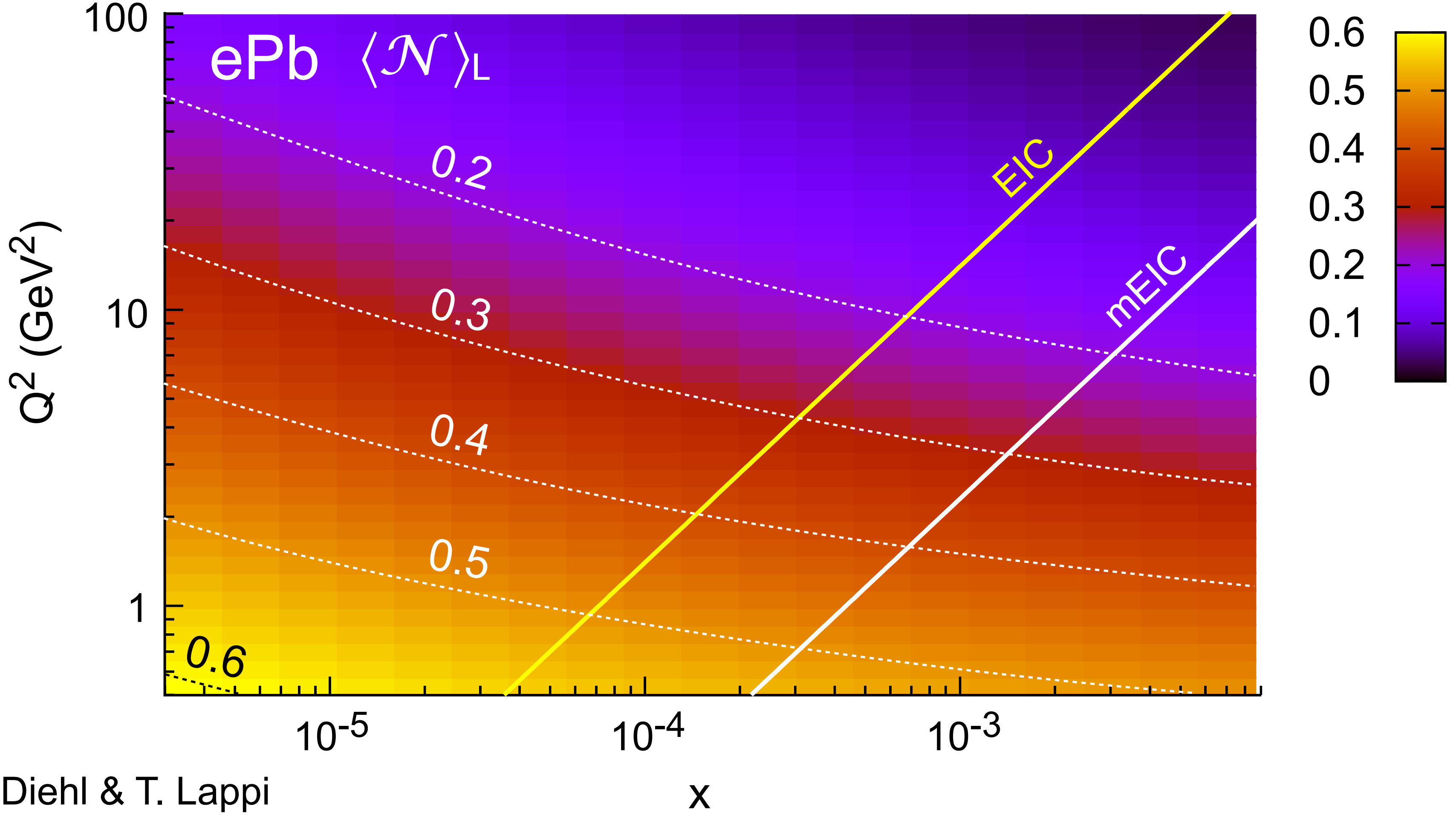


M. Diehl & T. Lappi

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 1: 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

Feasibility Studies for e+A

- Many (most) studies can be conducted using e+p
  - DIS kinematic in e+A identical to e+p when assuming $M_A/A = m_p$
  - Rich set of generators available for e+p
    - PYTHIA6, LEPTO, Milou, PEPSI, gmc_trans, RAPGAP3, CASCADE, ...
  - Few for e+A
    - DMPJet-III, DJANGO, Sartre (see talk by Tobias Toll)
- Important: compare saturation vs. non-saturation scenarios (BK/JIMWLK vs. DGLAP, BFKL)
- However, there are a few critical things in e+A that are
  - unique to e+A (e.g. incoherent diffraction)
  - more critical than in e+p (e.g. radiative corrections)

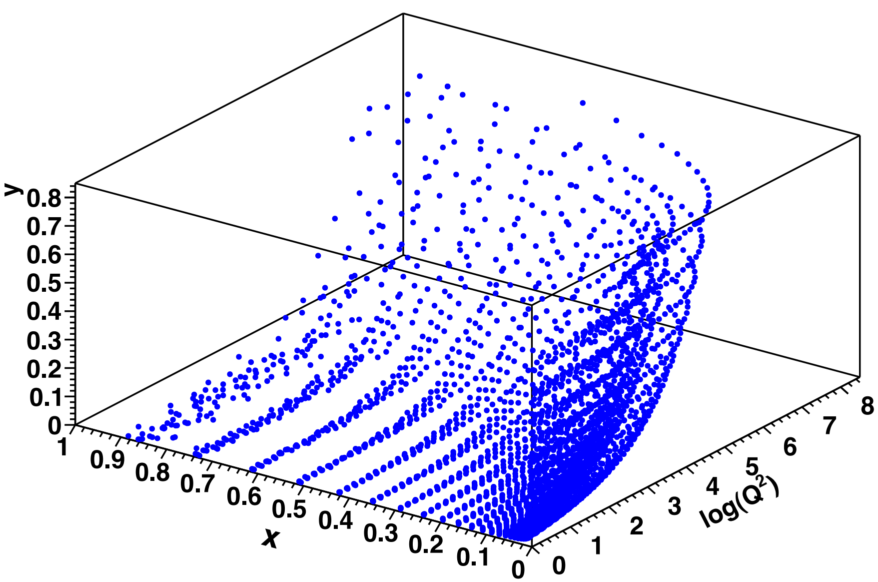
Measuring F_L with the EIC

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

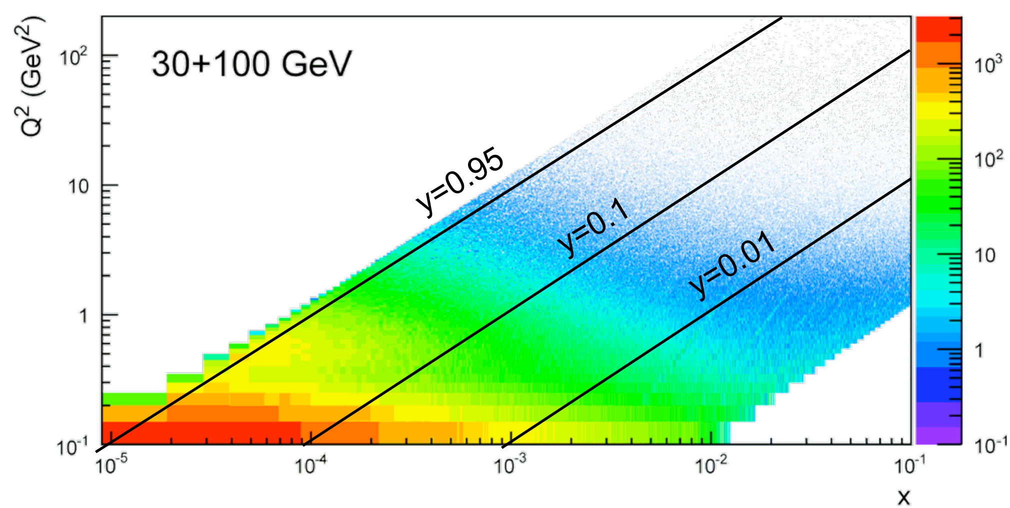
F_L runs at various $\sqrt{s}$
$\Rightarrow$ longer program

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

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

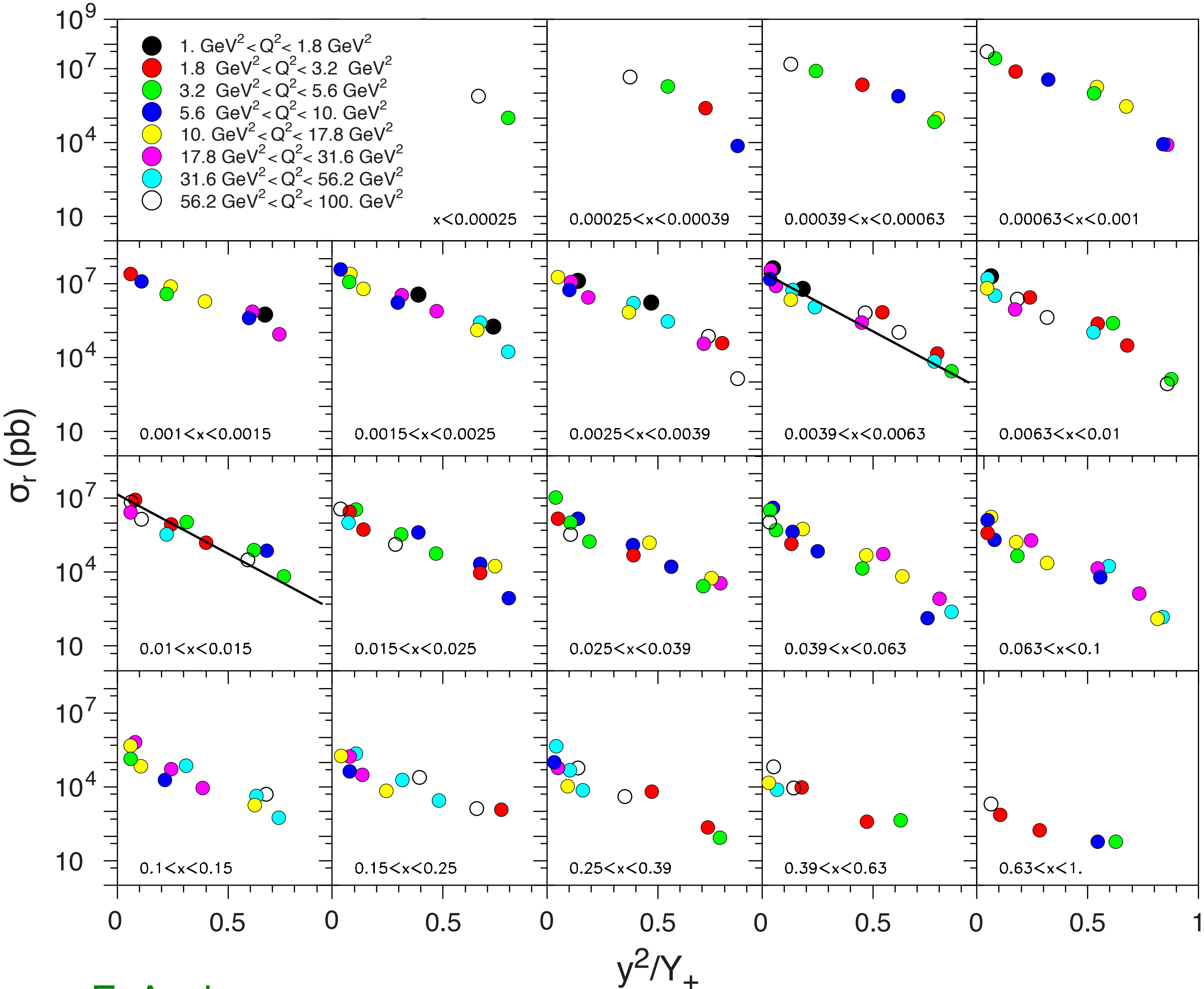
e+p: 1st stage

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

stat. error shown and negligible

To Do:

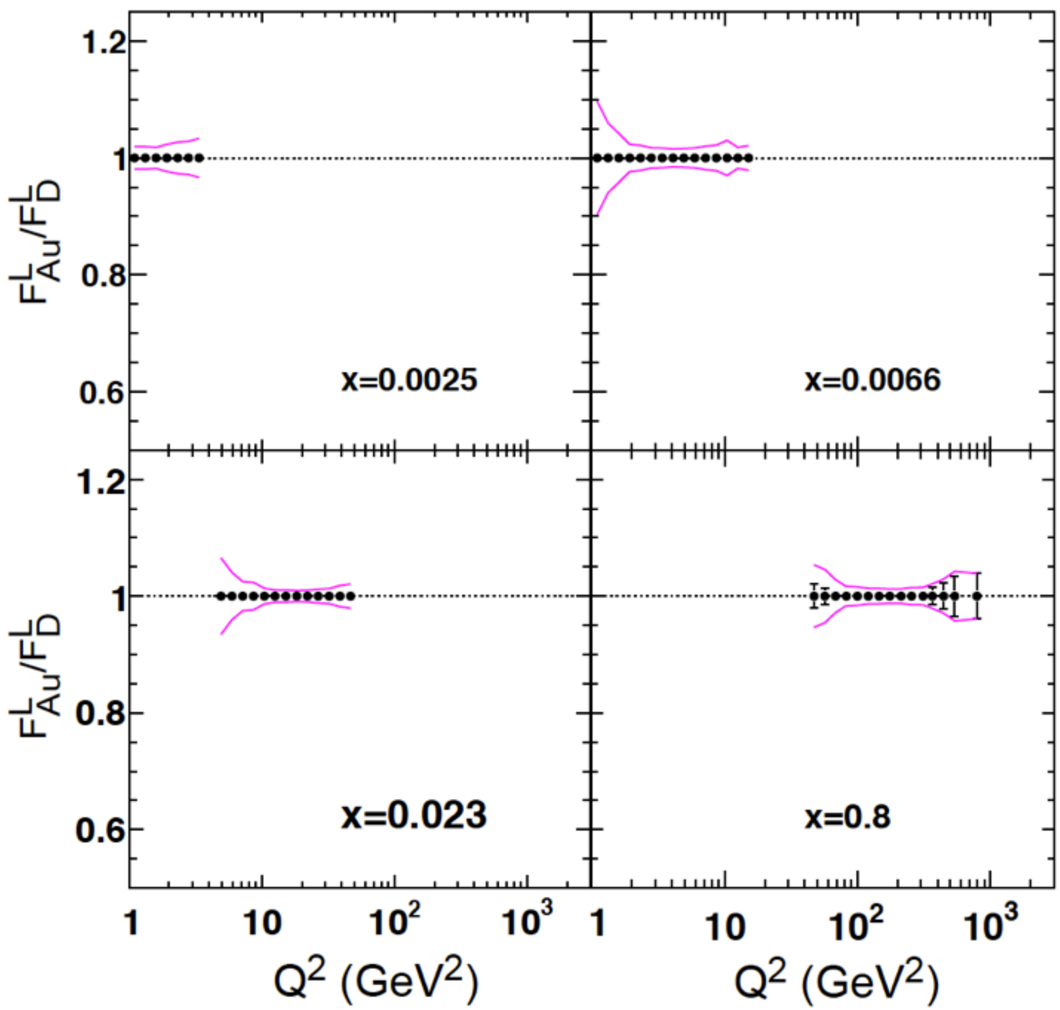
Rosenbluth extraction & Detector effects



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

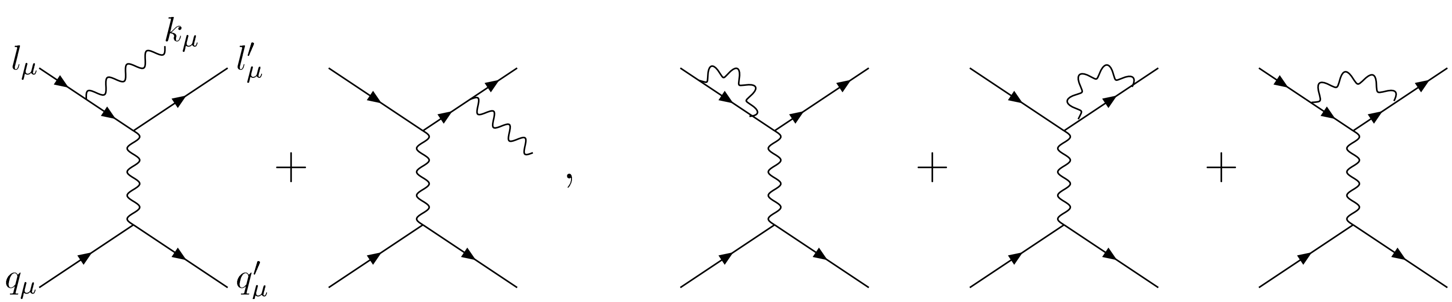
High precision requires knowledge of higher-order corrections

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

Emission of real photons

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

⇒ ”radiative corrections”



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

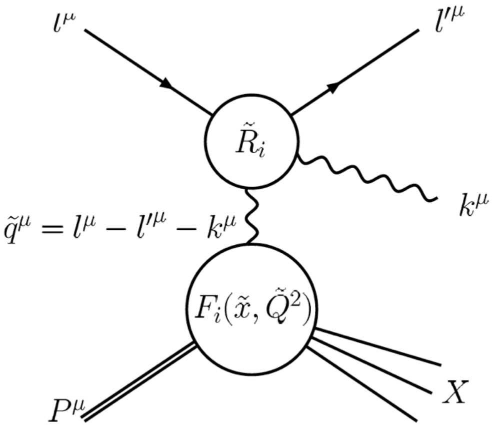
True case: $\tilde{Q}^2 = -(l-l'-k)^2, \quad \tilde{x}_B = \dfrac{\tilde{Q}^2}{2P\cdot(l-l'-k)}$

Effect of radiative corrections

Distortion of observed structure function:

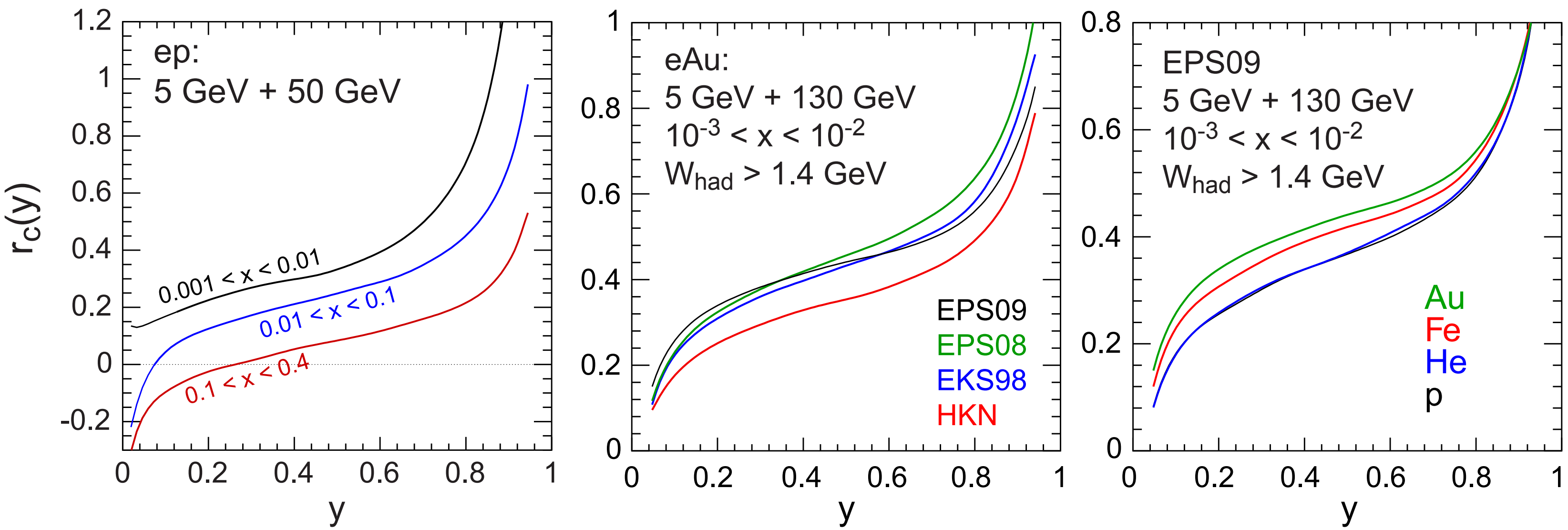
$$F_i^{\mathrm{obs}}(x_B, Q^2) = \int \mathrm{d}\tilde{x}_B \mathrm{d}\tilde{Q}^2\, R_i(x_B, Q^2, \tilde{x}_B, \tilde{Q}^2) F_i^{\mathrm{true}}(\tilde{x}_B, \tilde{Q}^2)$$

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



Correction function is fct. of y:

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



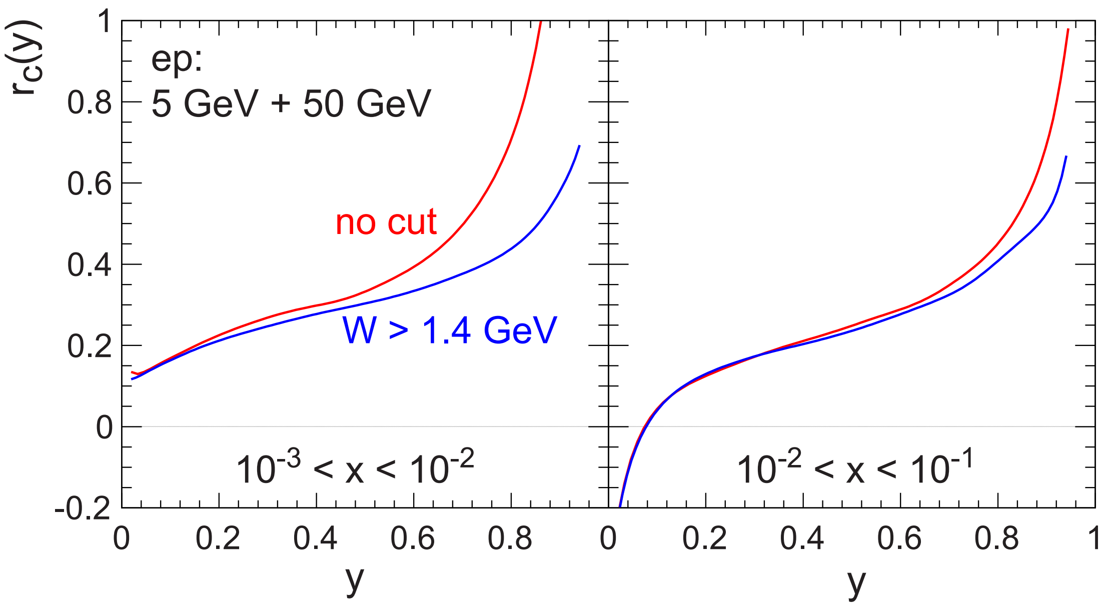
Dealing with radiative corrections

Method 1

- reconstruct x, Q^2 via hadronic final state
  - Jacquet-Blondel, or mixed e-h approaches
  - increases y_{max}/y_{min} reach
- works for e+p, tricky in e+A
  - parton/hadron energy-loss, secondary particle production
  - still possible since sum matters & particle at small θ carry little p_T
  - Needs further studies

Method 2

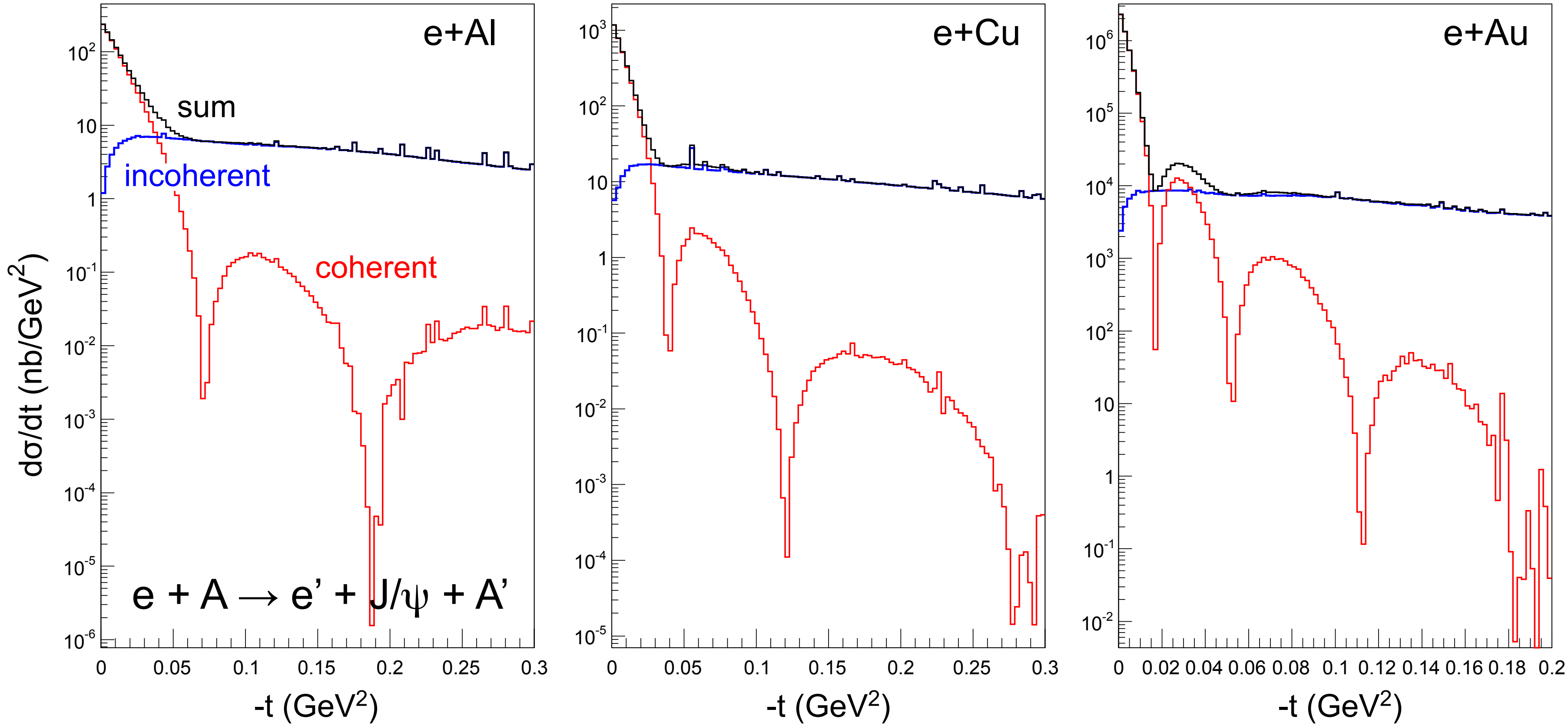
- simple kinematic cuts in W reduce corrections slightly



Method 3

- Unfolding and data corrections
  - requires profound understanding of corrections in e+A

Diffraction in e+A



- 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
- Coherent vs Incoherent: requires detection of breakup with ~ $1\text{-}10^{-4}$ efficiency

Never done at a collider!

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

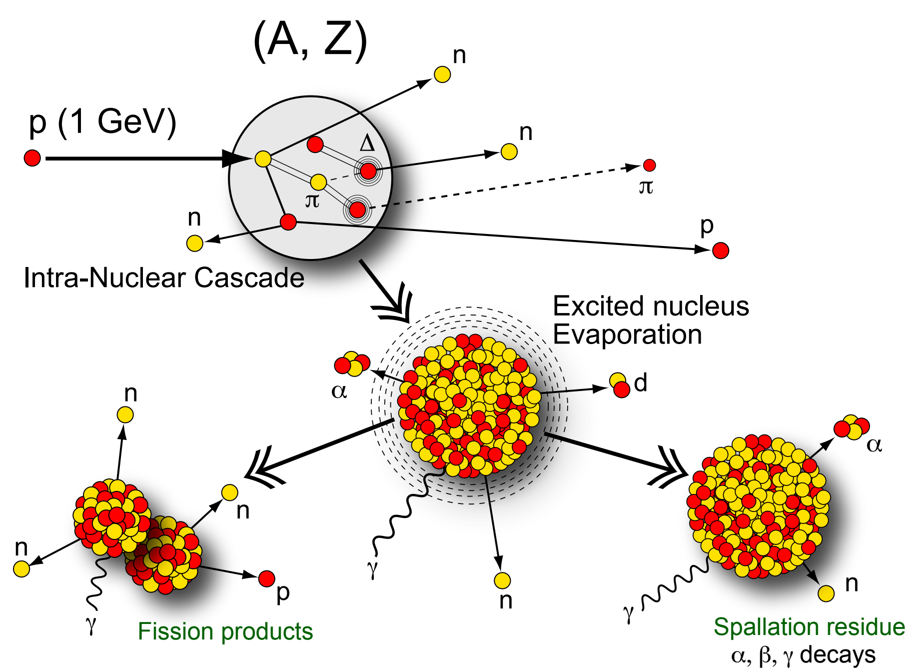
Traditional modeling done in pA:

Intra-Nuclear Cascade

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

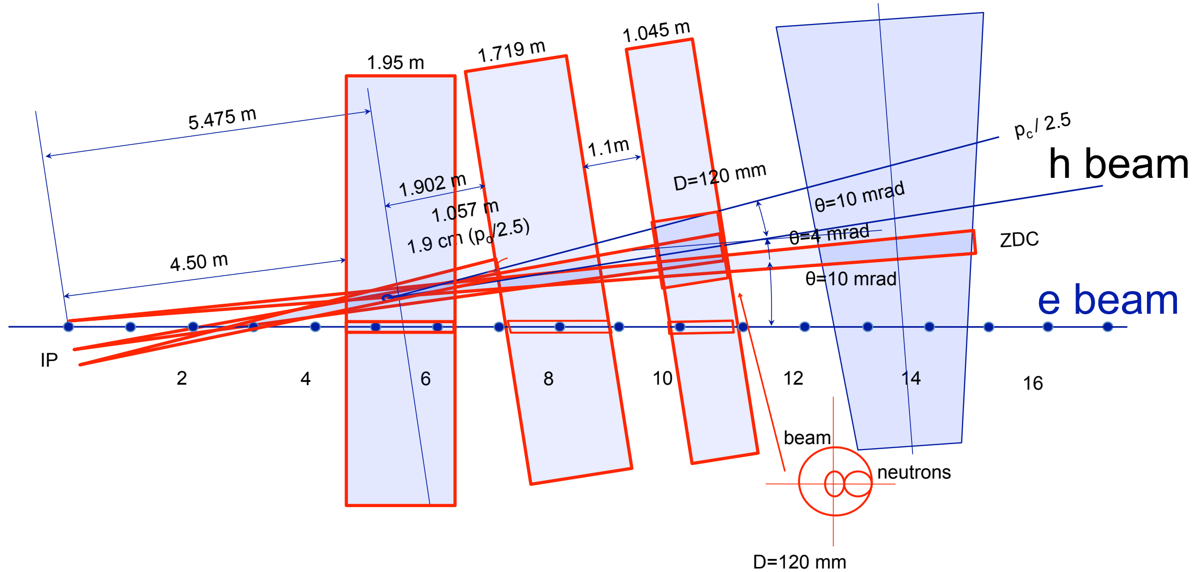
De-Excitation

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



Experimental Reality

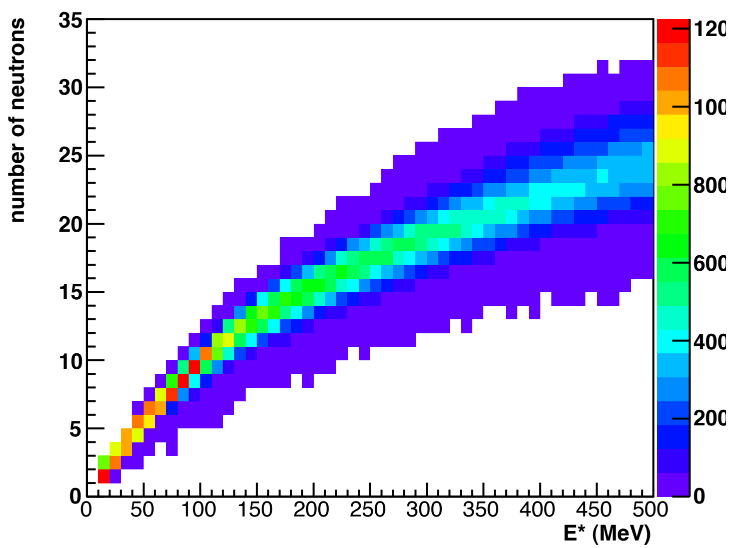
Here eRHIC IR layout:

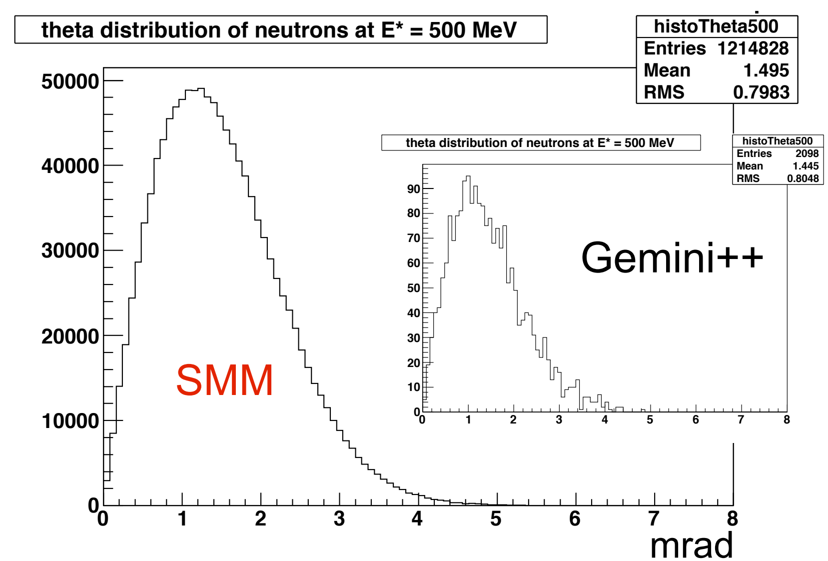


Need ±X mrad opening through triplet for *n* and room for ZDC

Big questions:

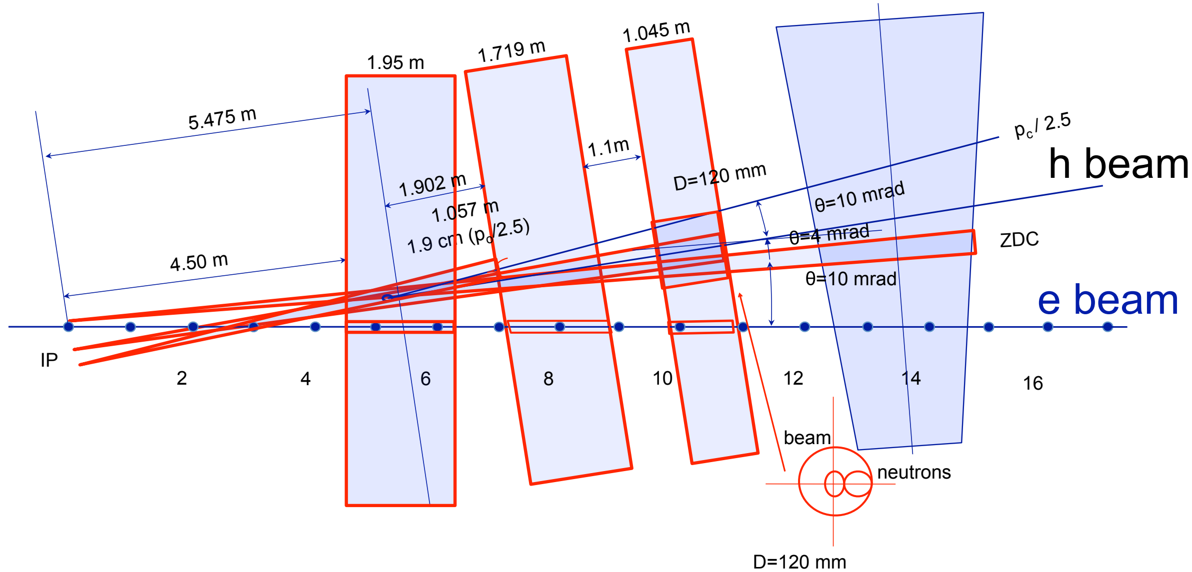
- Excitation energy E*?
- ep: $d\sigma/M_Y \sim 1/M_Y^2$
- eA? Assume ep and use $E^* = M_Y - m_p$ as lower limit





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

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

Summary

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

Studies on feasibility of measurements (detector requirements, acceptance, ...) are hindered by lack of generator "suite" as available for e+p.

Many initial studies can conducted in e+p ...

but e+A also brings new experimental challenges, e.g:

- Radiative corrections (x, Q^2 from hadronic final states)
  - work in progress
- Diffractive physics (nuclear breakup)
  - solvable (n-emission) with careful IR design