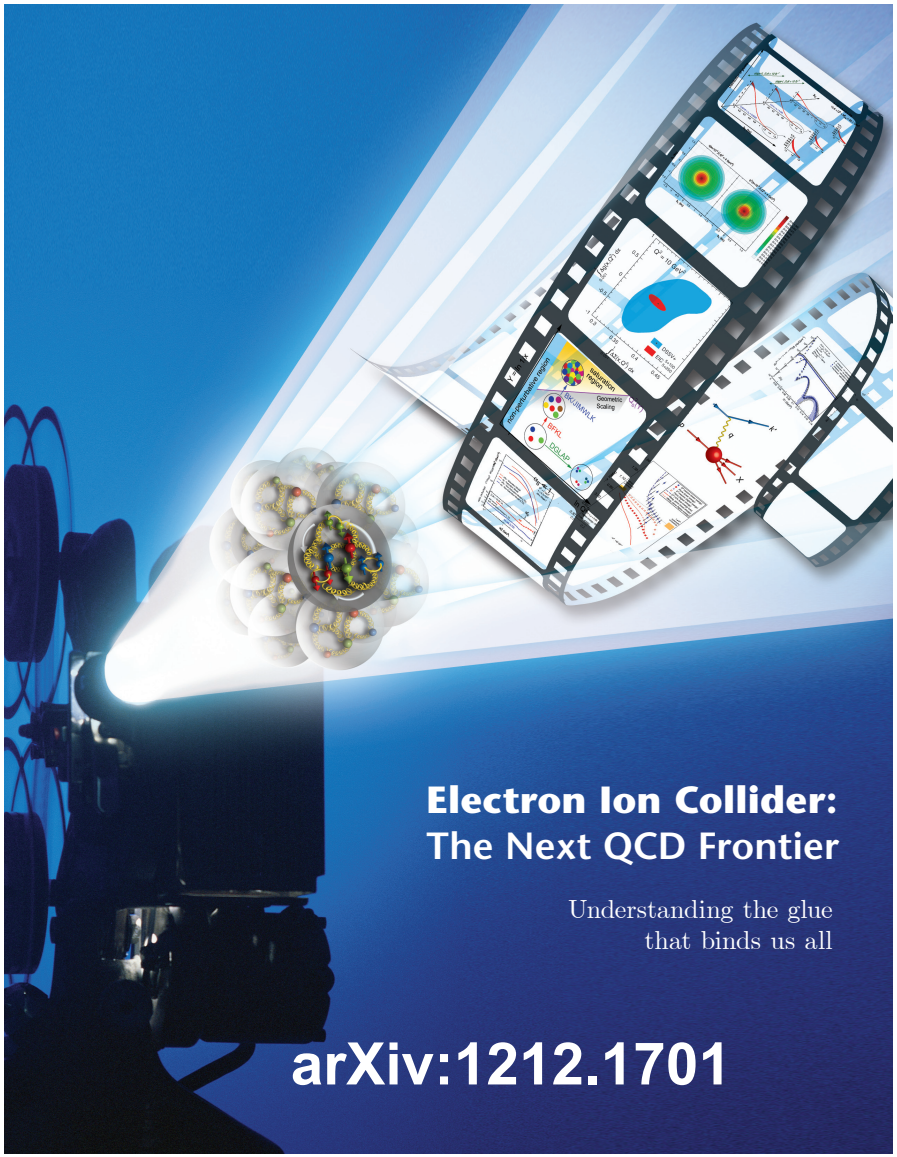
Highlights of the *e*A Program at an EIC



Thomas Ullrich

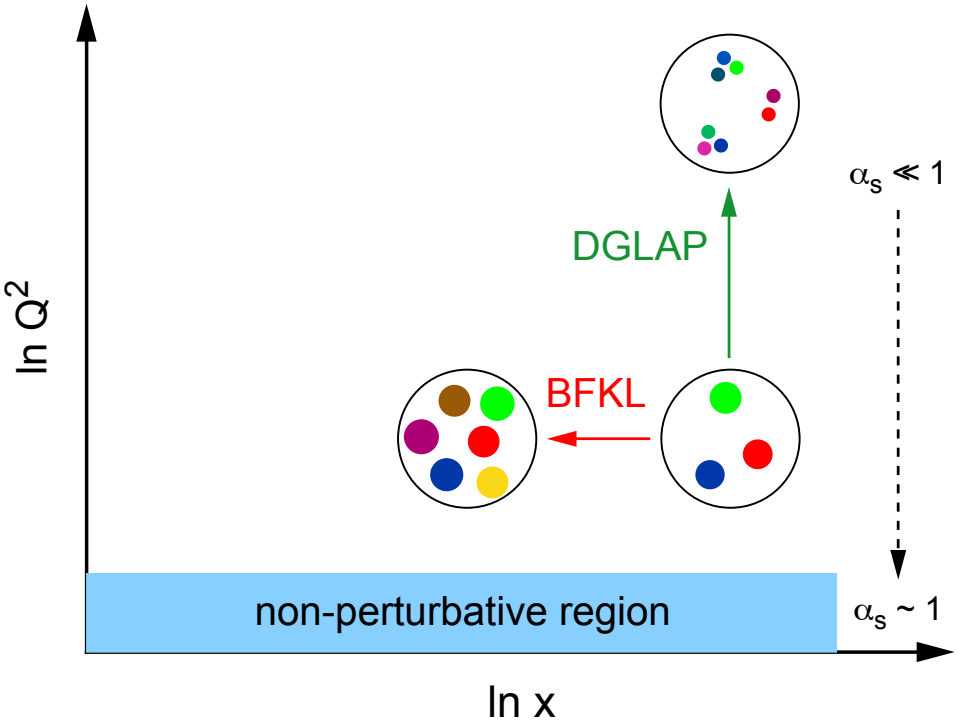
QCD Frontier ’13

Newport News

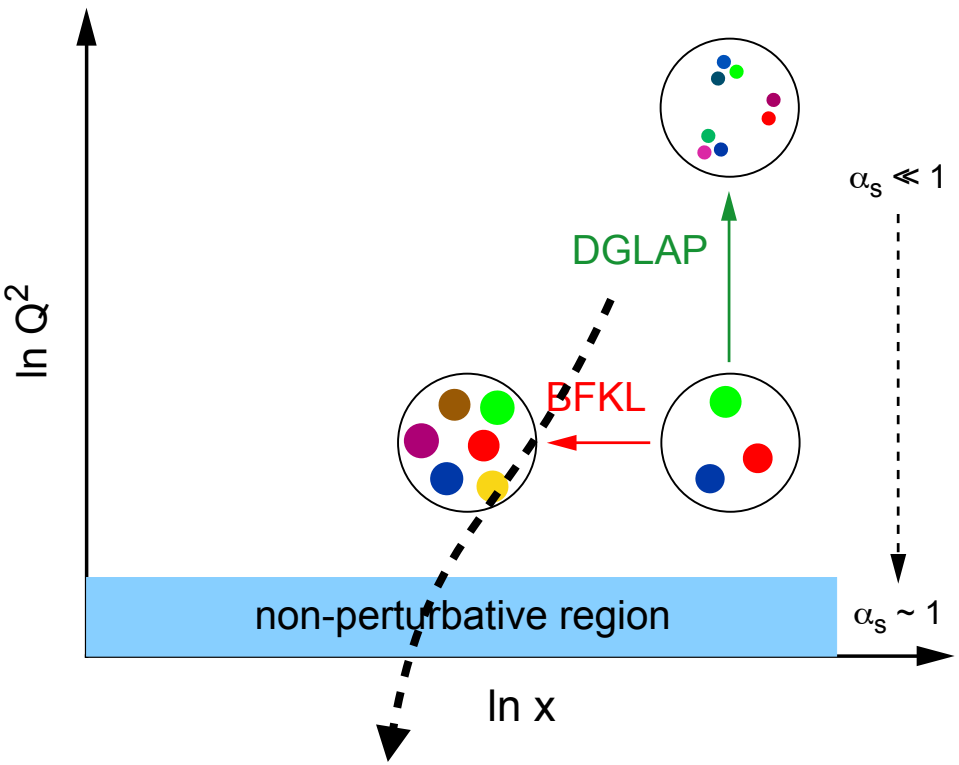
October 21-22, 2013

BROOKHAVEN
NATIONAL LABORATORY

The Low-x Puzzle

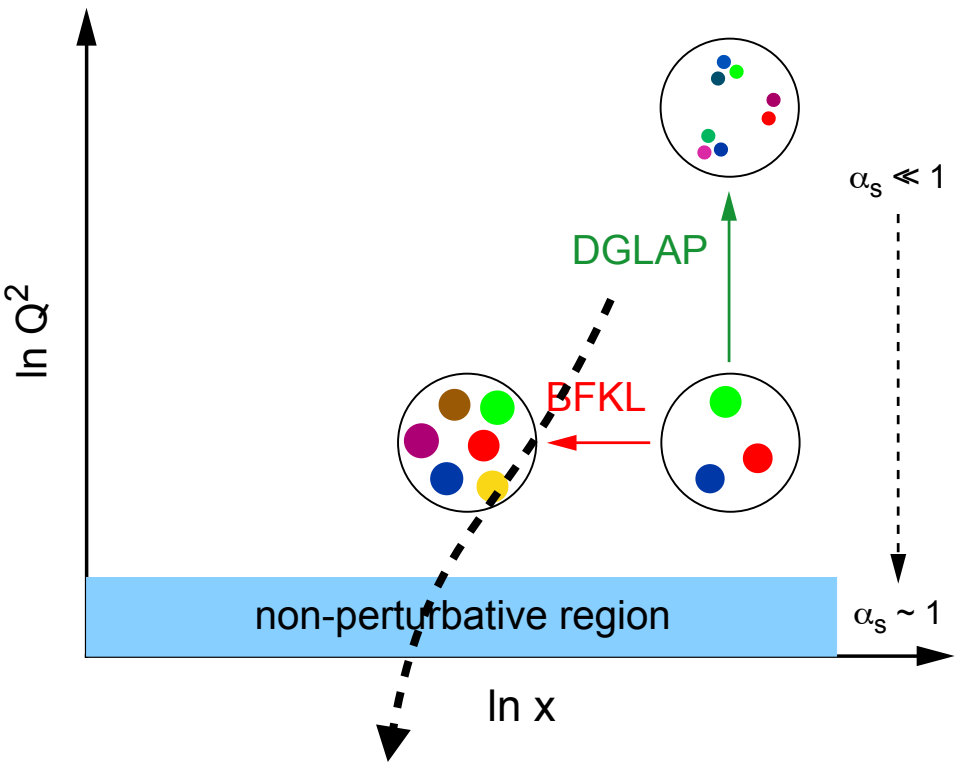


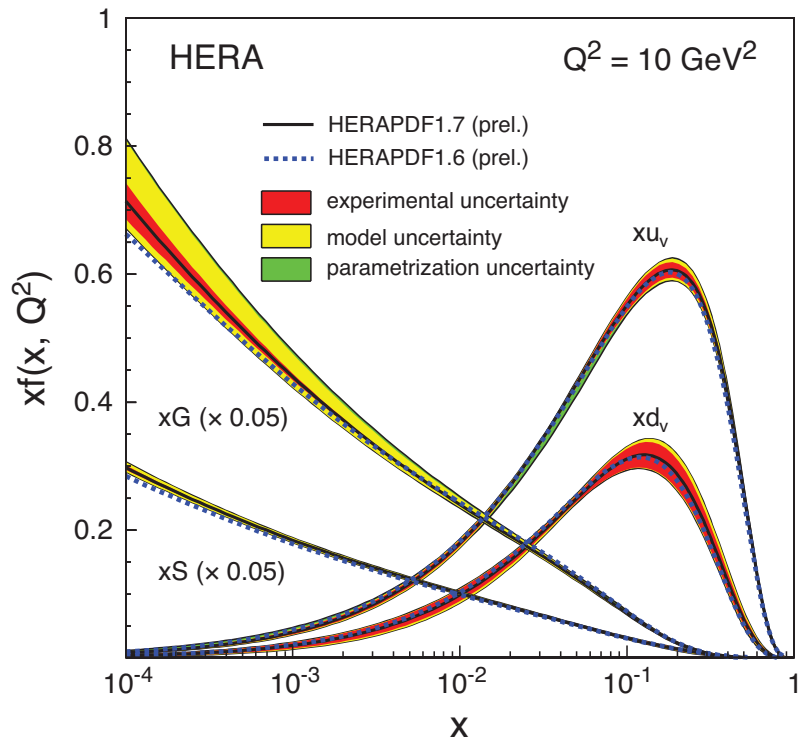
The Low-x Puzzle



pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA, RHIC, LHC, Tevatron)

The Low-x Puzzle

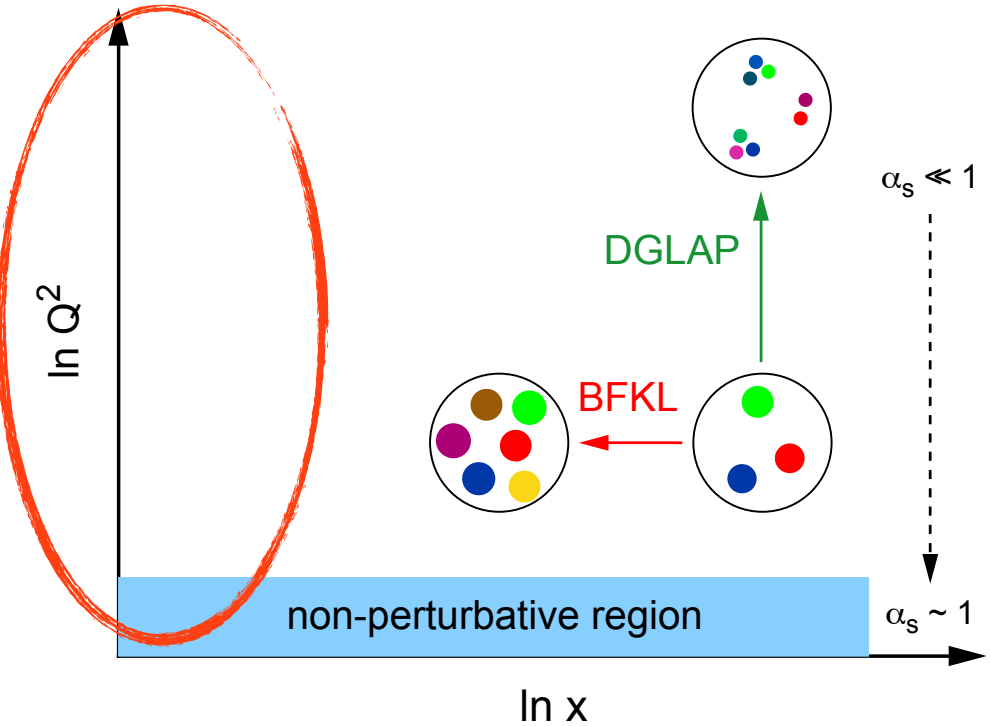


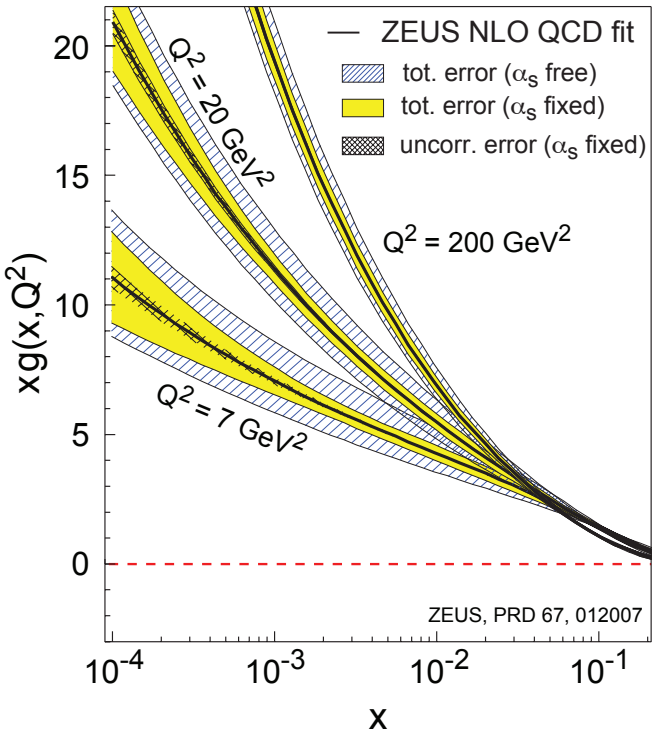


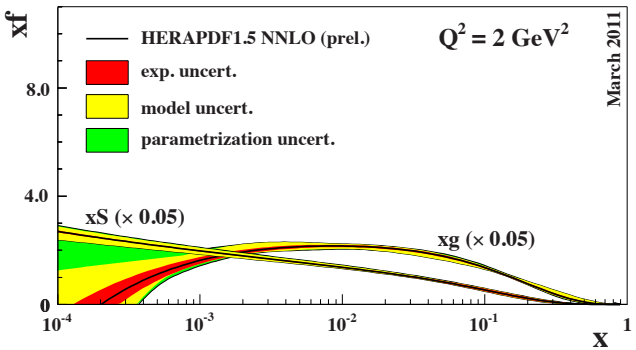
pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA, RHIC, LHC, Tevatron)

PDF: glue dominates for x < 0.1

The Low-x Puzzle





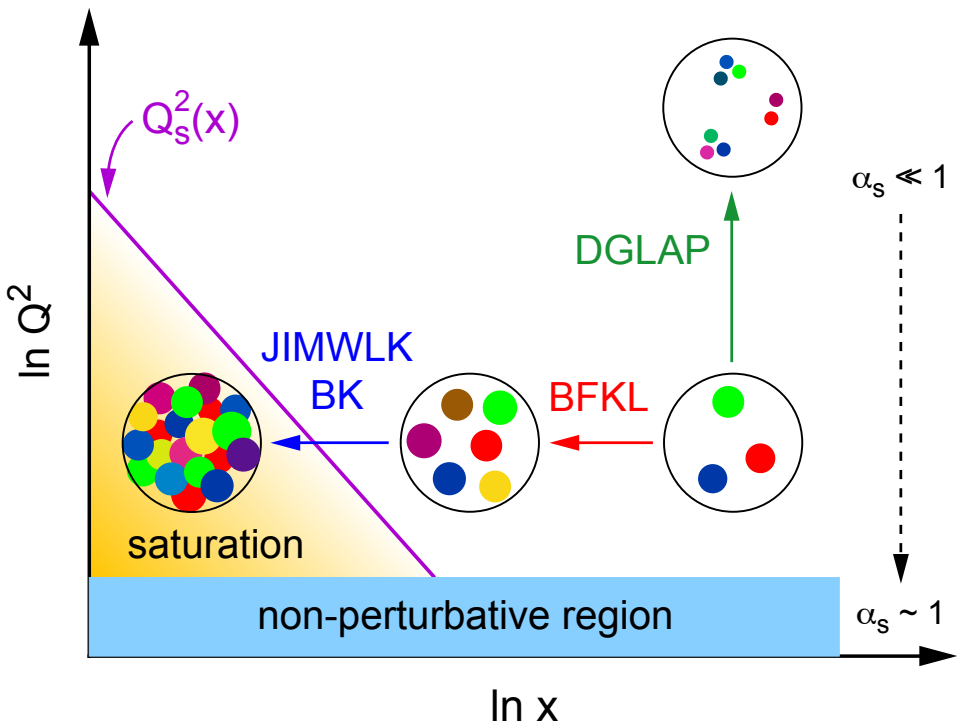


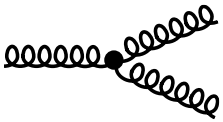
Issues with linear DGLAP/BFKL:

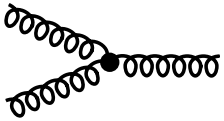
- $G_{sea}(x,Q^2) > G_{glue}(x,Q^2)$ at low Q^2 ?
- xG rapid rise violates unitary bound
- Cannot describe energy-independence of diffractive cross-section

$G(,Q^2)$ must saturate ⇒ how?

New Regime of Hadronic Wave Function?



BFKL: 

BK adds: 

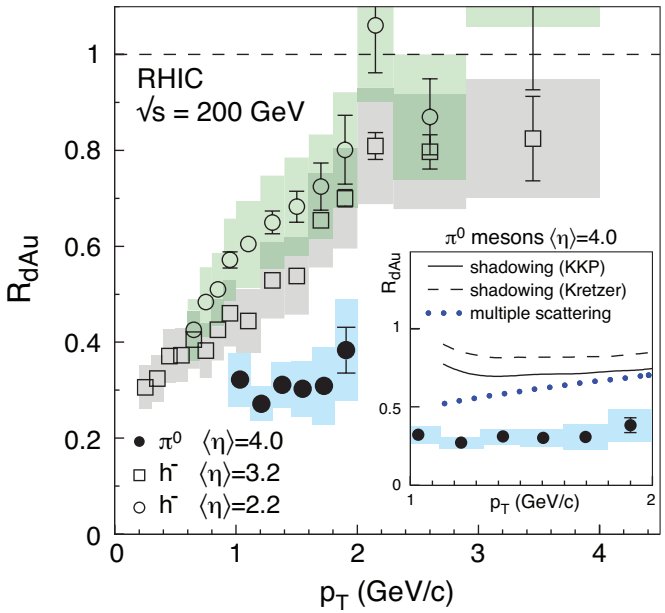
New Approach: Non-Linear Evolution

- At very high energy: recombination compensates gluon splitting
- BK/JIMWLK: non-linear effects $\Rightarrow$ saturation characterized by $Q_s(x)$
  - Describe physics at low-x & low to moderate Q^2
  - Wave function is Color Glass Condensate in IMF description

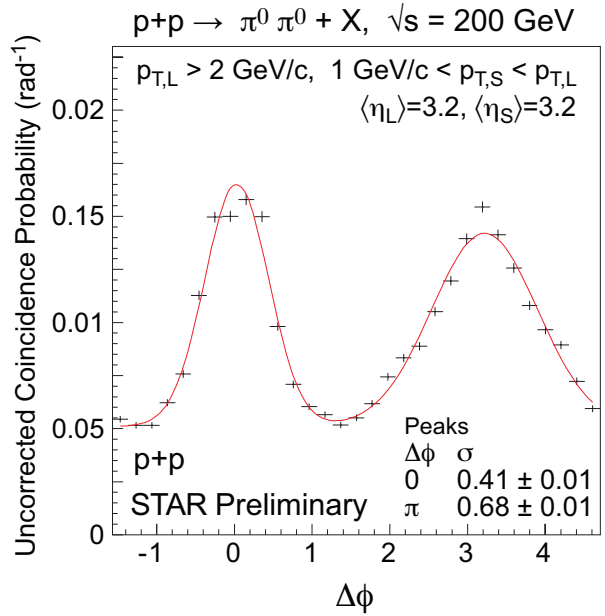
- Where does saturation of gluons sets in?
- Whats the dynamic of the saturation process?

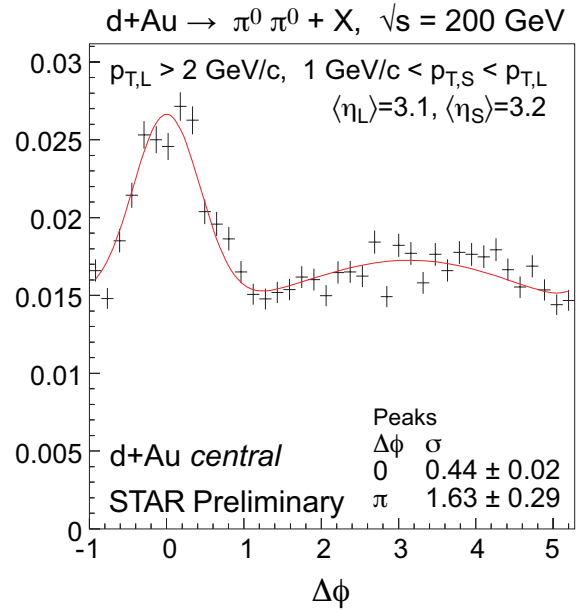
Evidence for Saturation at RHIC in dAu

Forward Hadron Spectra

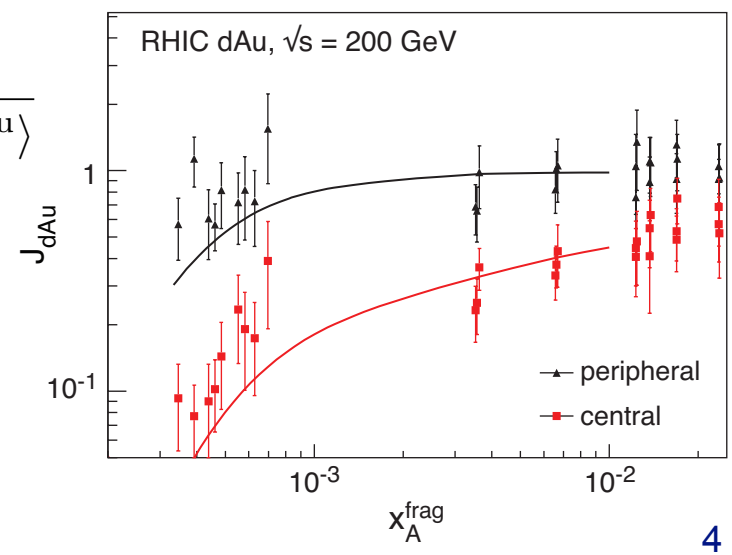


Forward Hadron Correlations



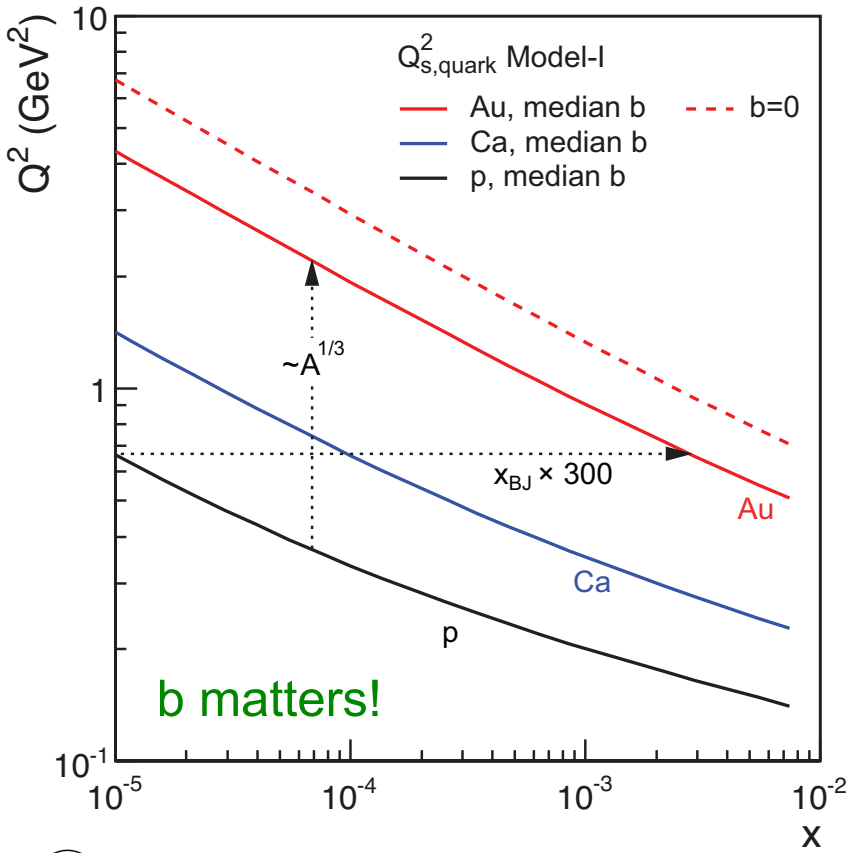


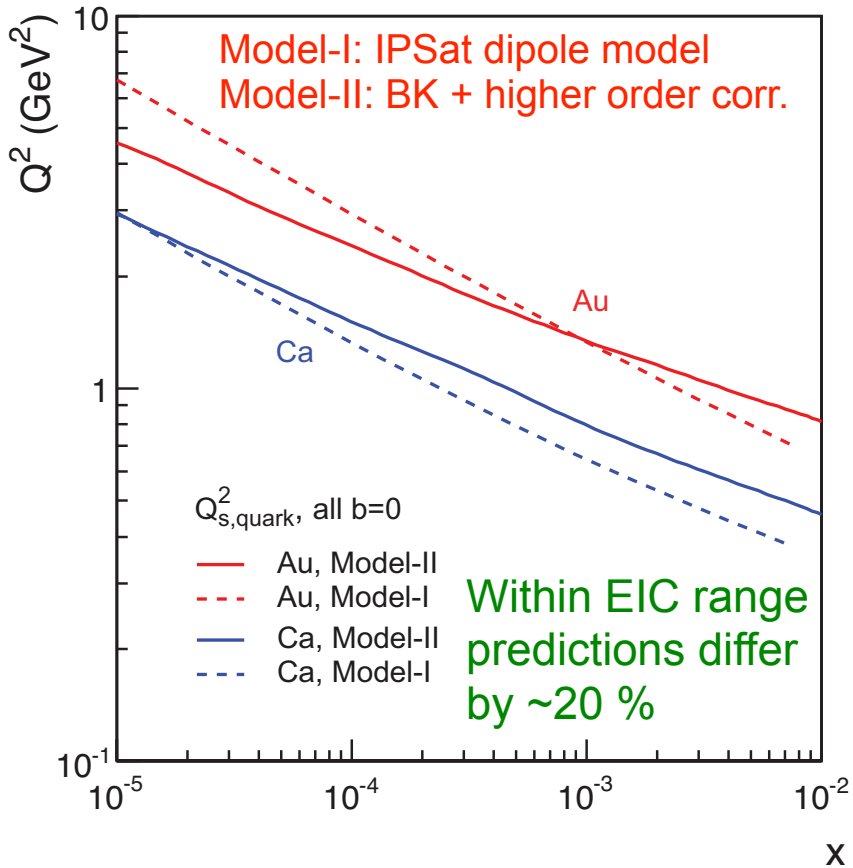
$$R_{dAu} = \frac{\text{Yield}_{dAu}}{\text{Yield}_{pp}\langle N_{bin}^{dAu}\rangle} \qquad J_{dAu} = \frac{\text{Yield}_{dAu}^{\text{Away-Side}}}{\text{Yield}_{pp}^{\text{Away-Side}}\langle N_{bin}^{dAu}\rangle}$$

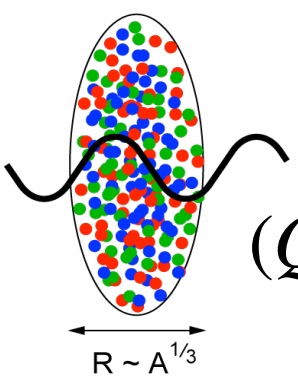


- CGC Description: T. Lappi and H. Mäntysaari, NP A908 ('13) 51-72
- LHC pAu ⇒ see Raju's talk later

Saturation Scale Q_S: What do we know?



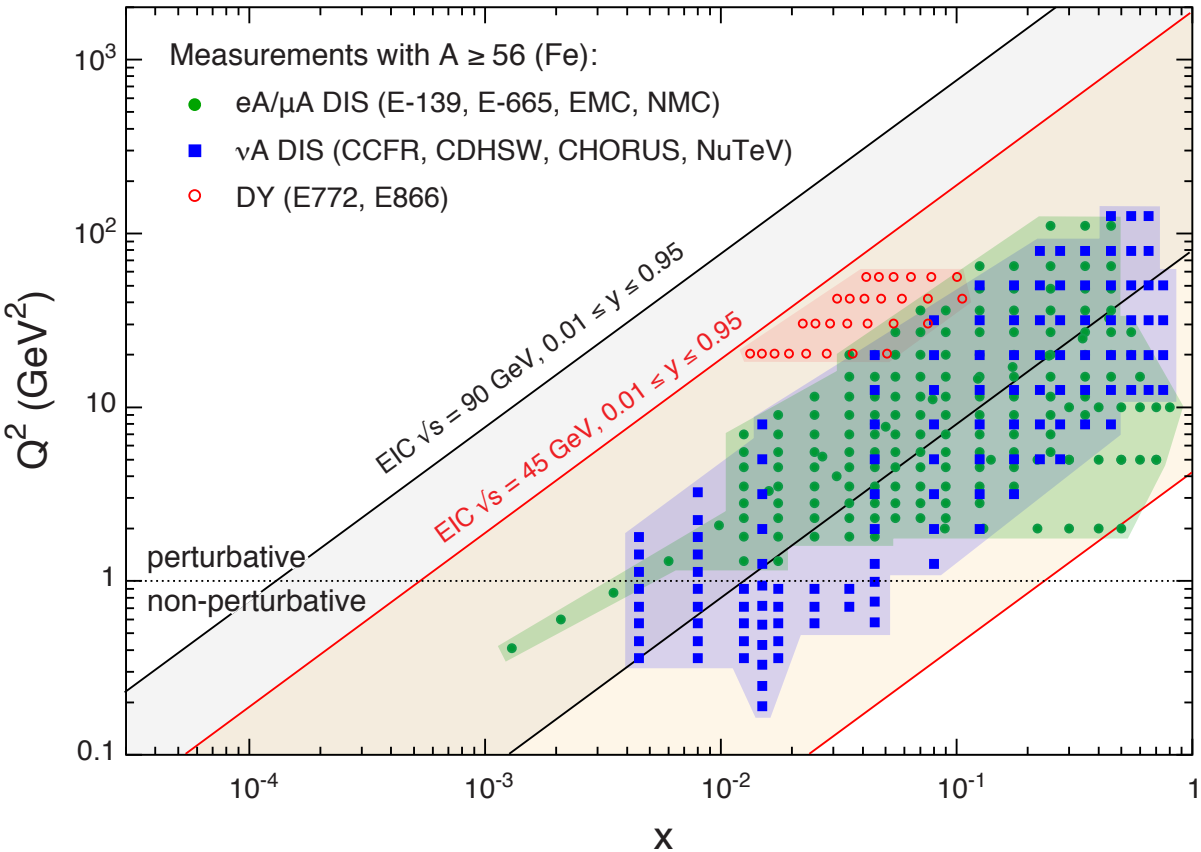




$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A $\Rightarrow$ saturation regime reached at significantly lower energy in nuclei

The Pre-EIC Era



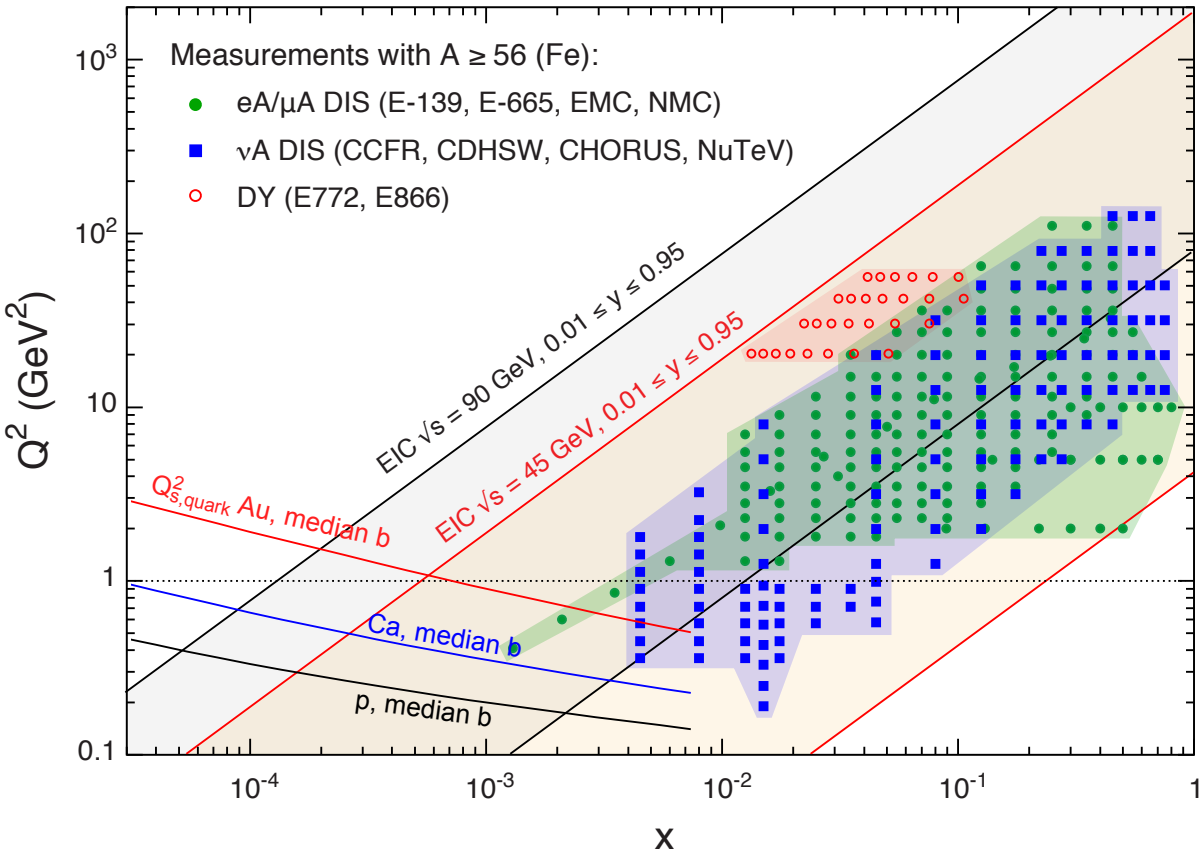
Plots has more dimensions:

- Statistics
  - typically low, large bins, no multi-differential studies
- Breadth of Measurements
  - mostly inclusive
  - often no comprehensive set of measurements (incl., SIDIS, excl., diffractive, ...)

Recall:

- 5+100 GeV $\Rightarrow \sqrt{s} \sim 45$ GeV
- 10+100 GeV $\Rightarrow \sqrt{s} \sim 63$ GeV
- 20+100 GeV $\Rightarrow \sqrt{s} \sim 90$ GeV

The Pre-EIC Era



Plots has more dimensions:

- Statistics
  - typically low, large bins, no multi-differential studies
- Breadth of Measurements
  - mostly inclusive
  - often no comprehensive set of measurements (incl., SIDIS, excl., diffractive, ...)

Recall:

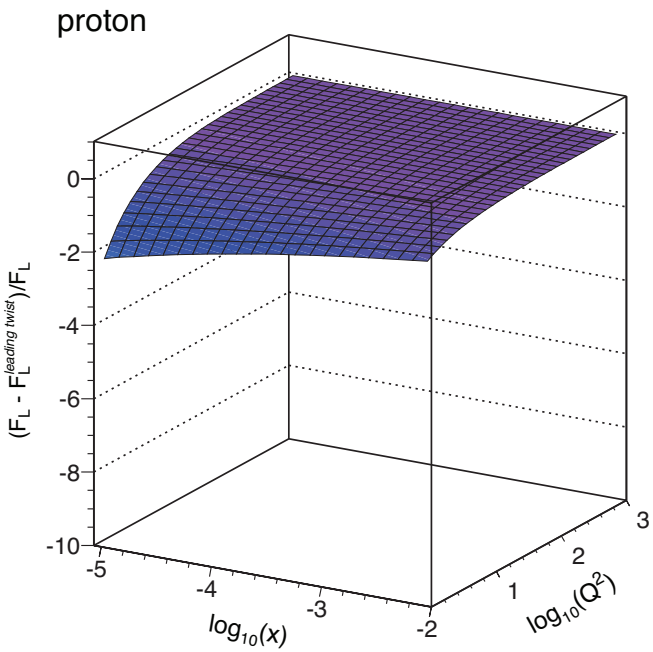
- 5+100 GeV ⇒ √s ~ 45 GeV
- 10+100 GeV ⇒ √s ~ 63 GeV
- 20+100 GeV ⇒ √s ~ 90 GeV

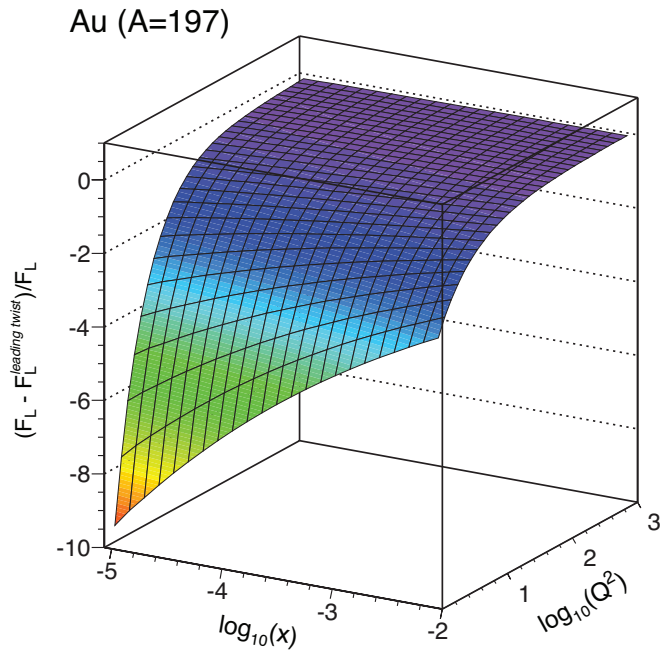
Inclusive DIS in *e*A: Bread & Butter ?

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

quark+anti-quark **gluon**

- Expect strong non-linear effects in F_L



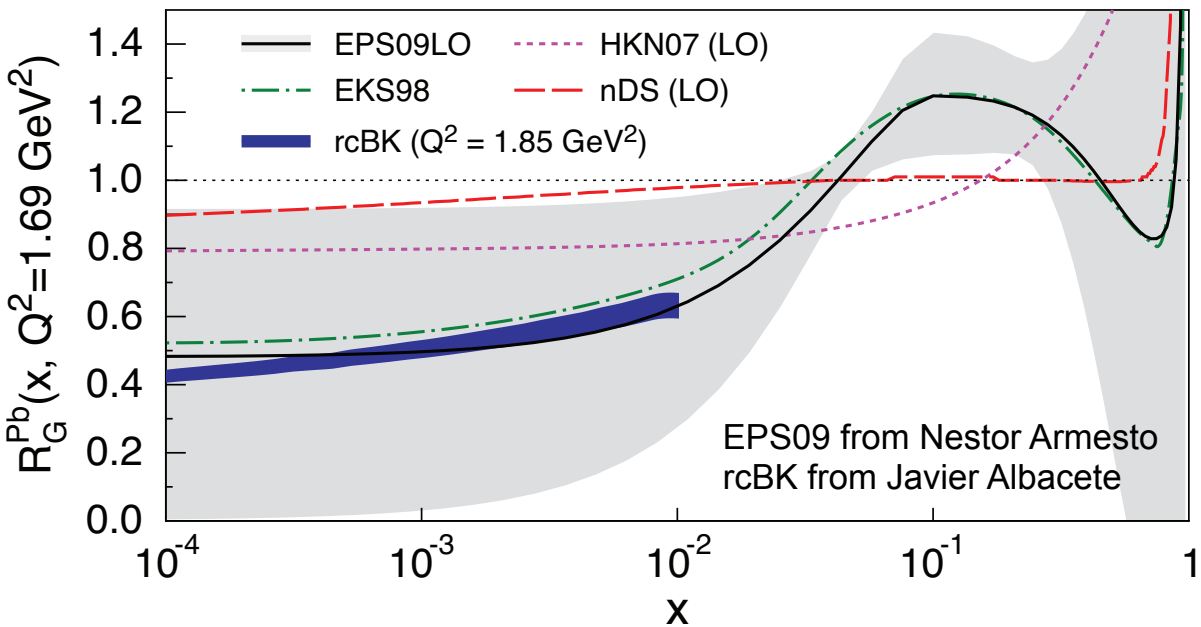


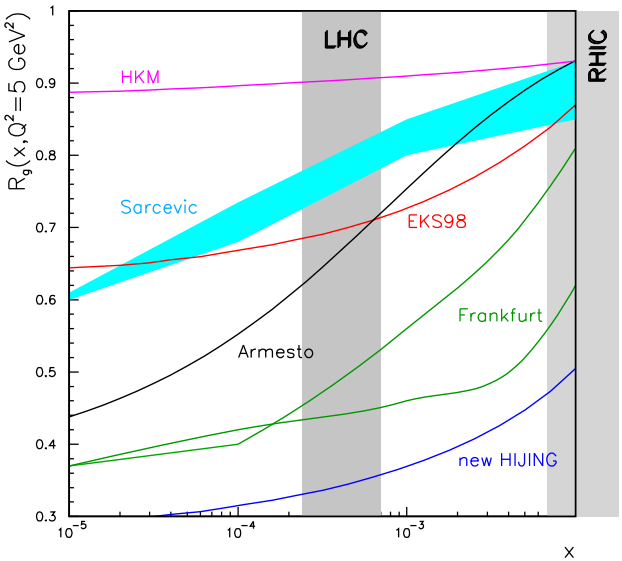
J. Bartels *et al.* Modified GBW Dipole model (*see INT proceedings*))

Relative contributions of higher twist effects to F_L amplified in *e*A

- Impressive plot but in real life F_L is hard to measure

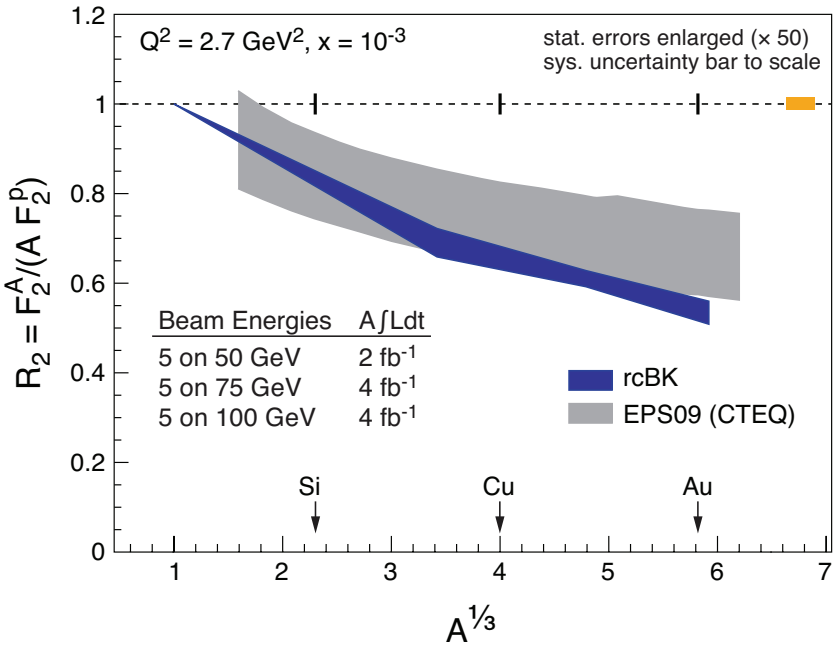
FL, F2: Usual Approach?

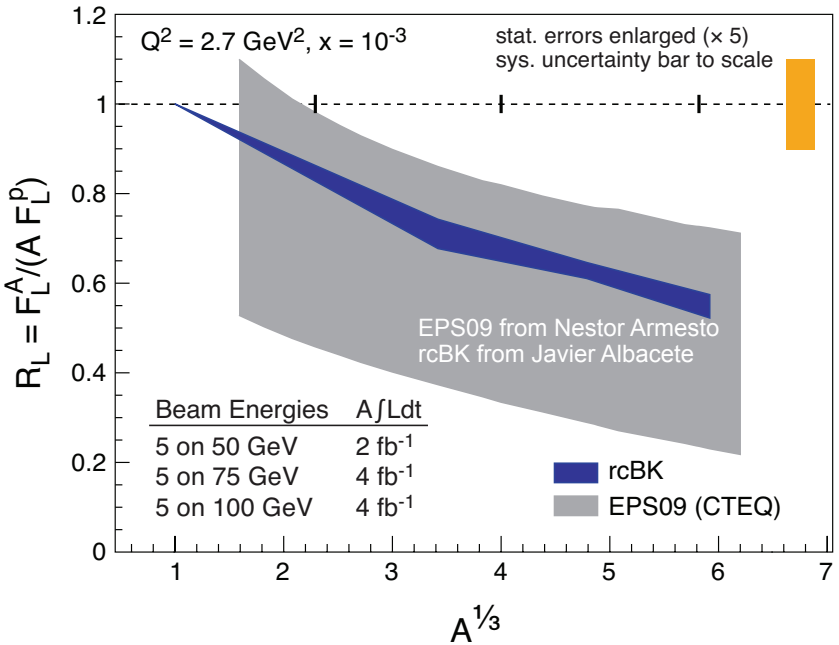




- Many plots of this type on the market
  - Zoo of curves often with outdated nPDFs
  - No single clear prediction, one curve will fit at the end!?
  - Most solid approach: repeat constraint fit with EIC pseudo-data
    - see Hannu's talk
- WP: Use different approach to distinguish saturation versus standard DGLAP picture: **A** dependence
  - CGC $A^{1/3}$ dependence, pQCD not so clear

Inclusive DIS in eA





- Measurement of F_L requires running at different $\sqrt{s}$
- Rosenbluth separation: slope of $y^2/Y+$ for different s at fixed x & Q^2

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$$

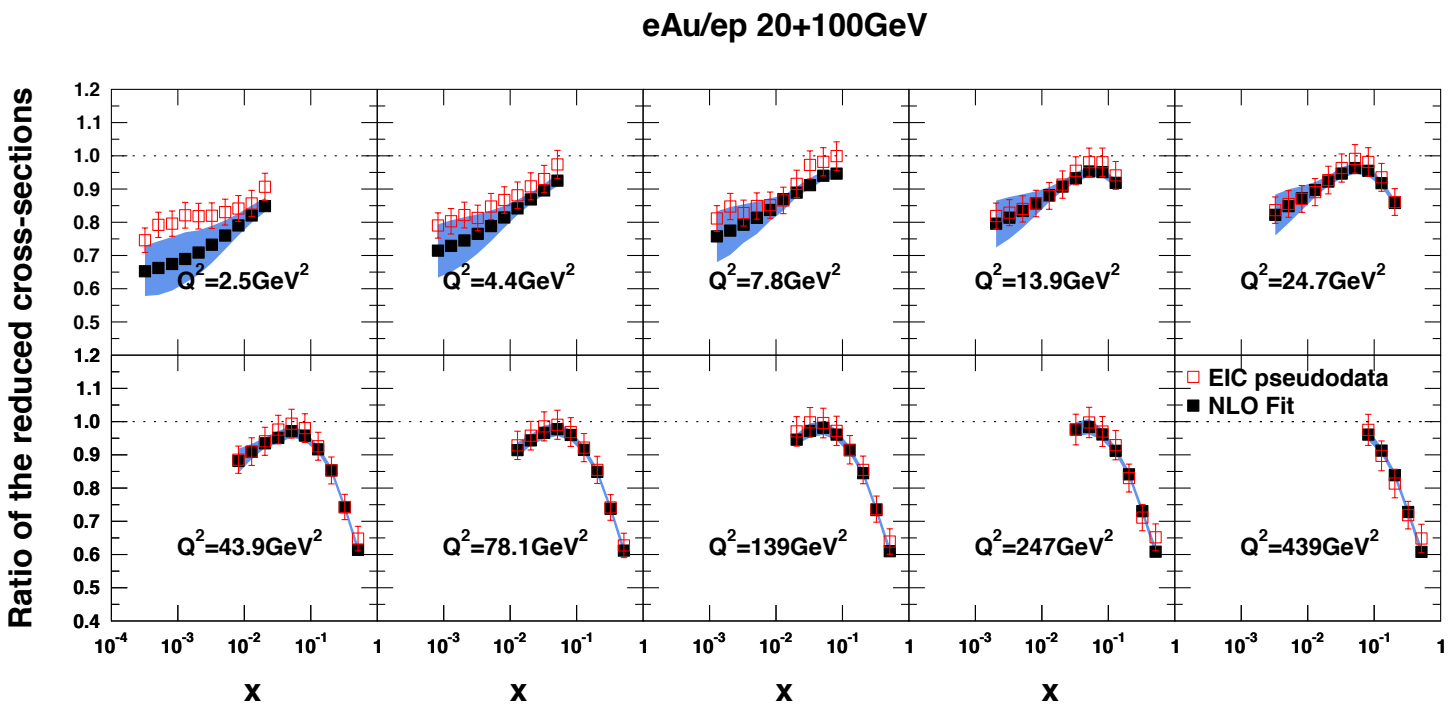
- F_2, F_L: negligible stat. error, systematics dominated
  - absolute normalization uncertainty 1% assumed (HERA ~2%)
- Precision nPDF: Huge impact on pA, AA programs
- Issue: Need overlap between sat. models and DGLAP where both applicable: $Q^2 \gtrsim$ 1-2 GeV^2 and x~1-5×10^{-4} ⇒ $\sqrt{s} \gtrsim$ 80 GeV

New: Constraints from EIC Pseudo Data

⇒ see next talk by Hannu

Work in progress… (*H. Paukkunen*)

- EIC pseudo-data included in global EPS09 fit
- Only 20+100 GeV and 5+100 GeV included so far
- more coming ... (also charm)

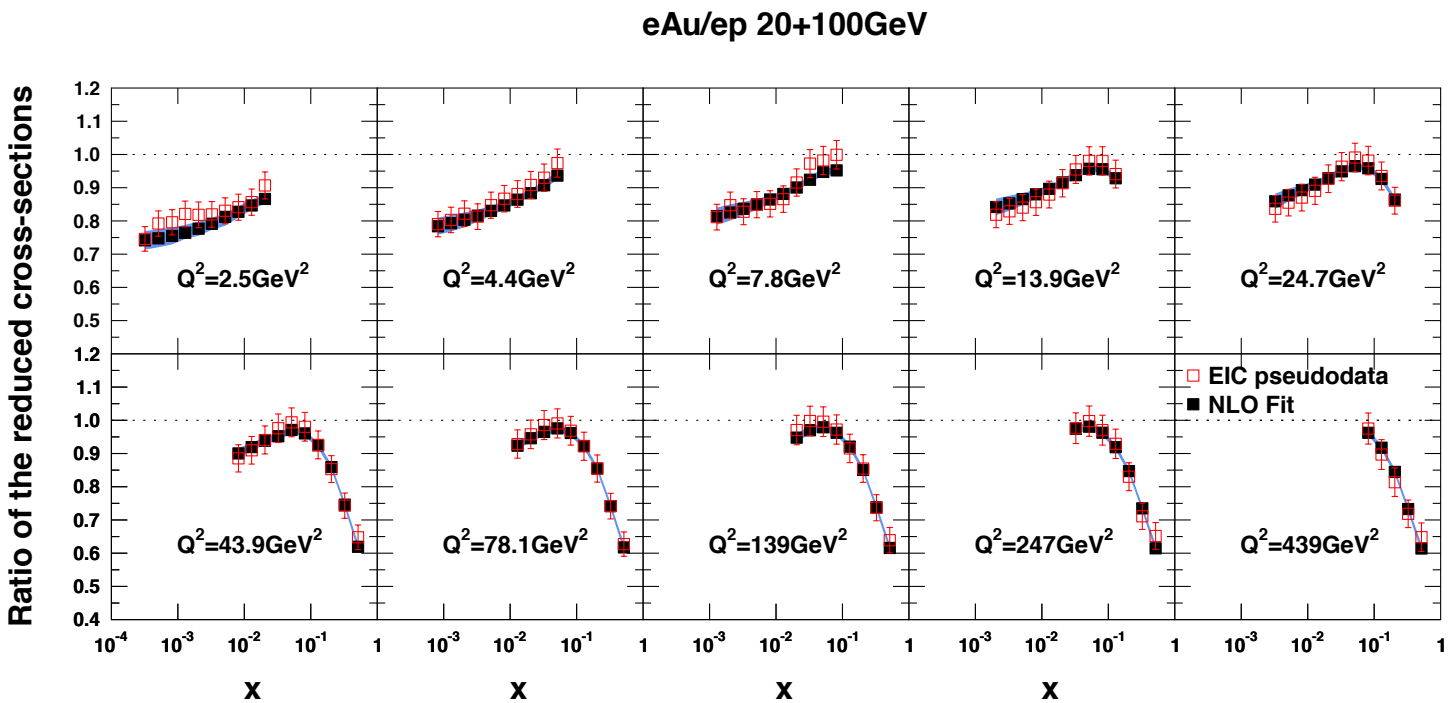


New: Constraints from EIC Pseudo Data

⇒ see next talk by Hannu

Work in progress… (*H. Paukkunen*)

- EIC pseudo-data included in global EPS09 fit
- Only 20+100 GeV and 5+100 GeV included so far
- more coming ... (also charm)

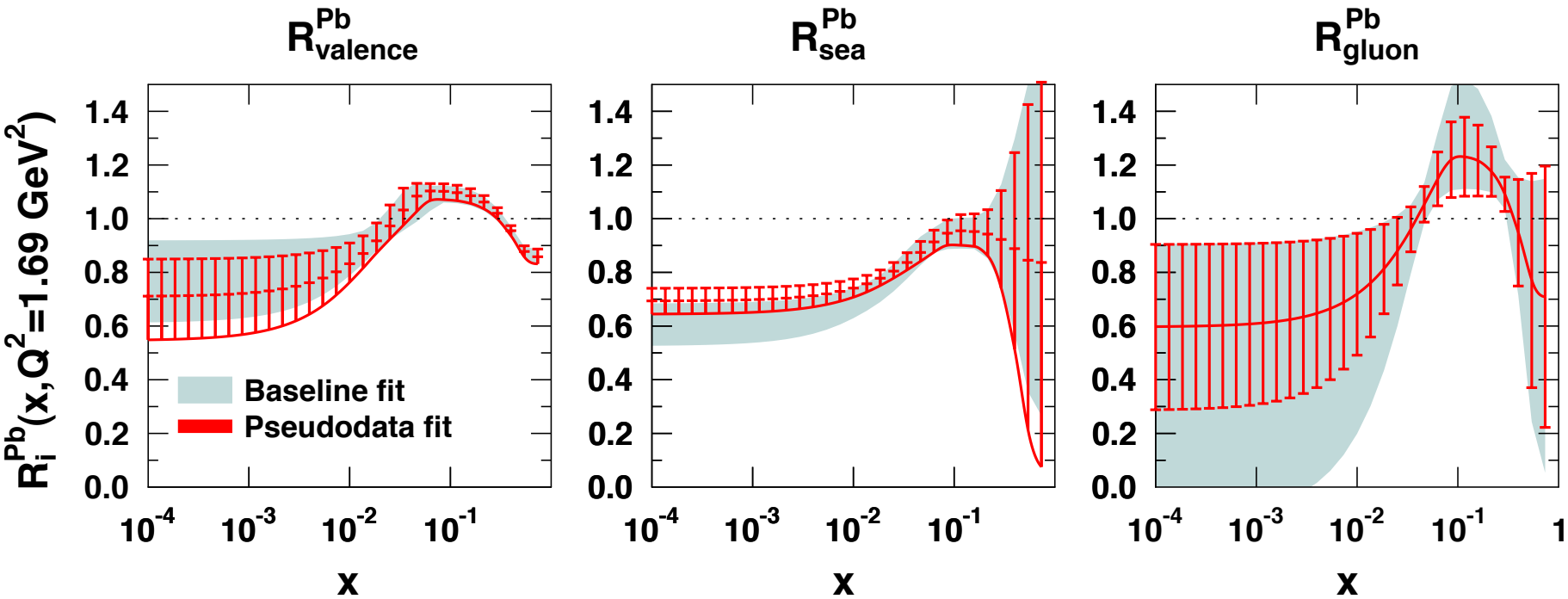


New: Constraints from EIC Pseudo Data

⇒ see next talk by Hannu

Work in progress… (*H. Paukkunen*)

- EIC pseudo-data included in global EPS09 fit
- Only 20+100 GeV and 5+100 GeV included so far
- more coming ... (also charm)



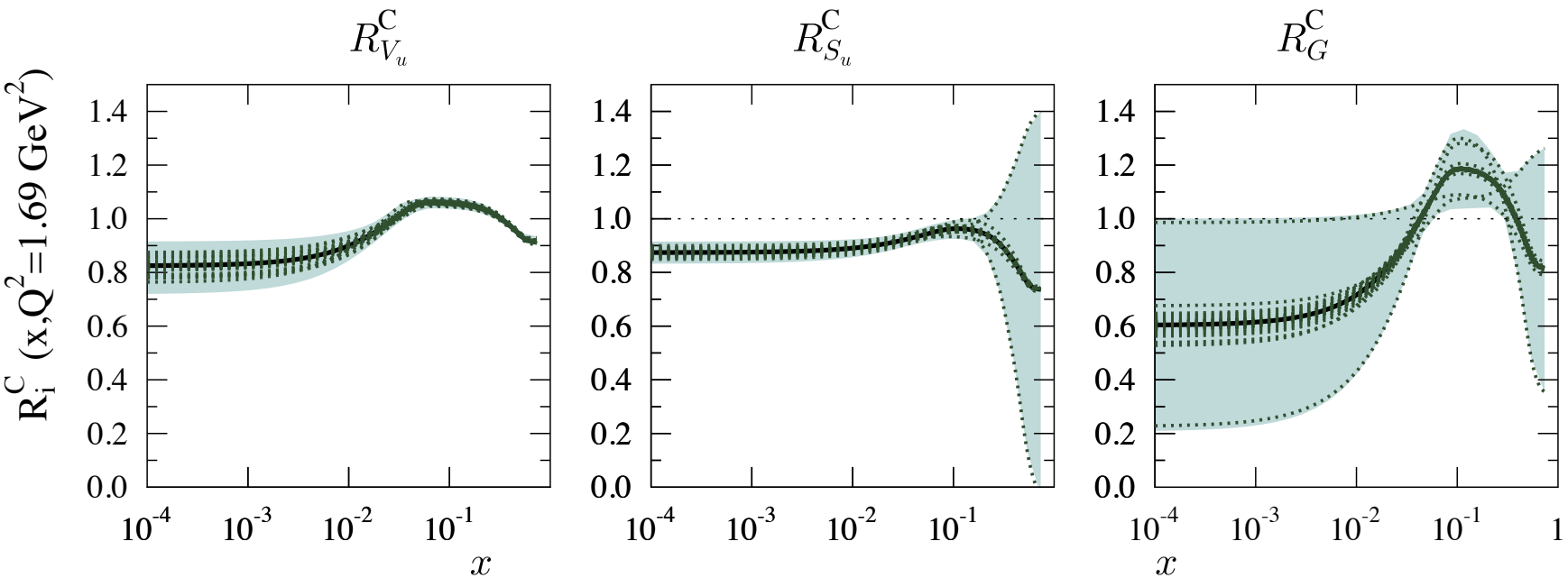
New: Constraints from EIC Pseudo Data

⇒ see next talk by Hannu

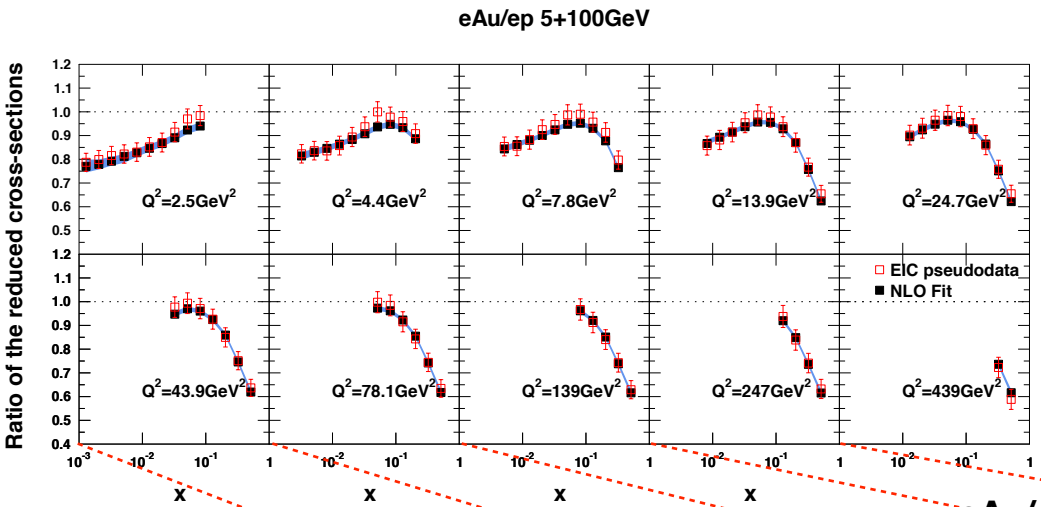
Work in progress… (*H. Paukkunen*)

- EIC pseudo-data included in global EPS09 fit
- Only 20+100 GeV and 5+100 GeV included so far
- more coming ... (also charm)

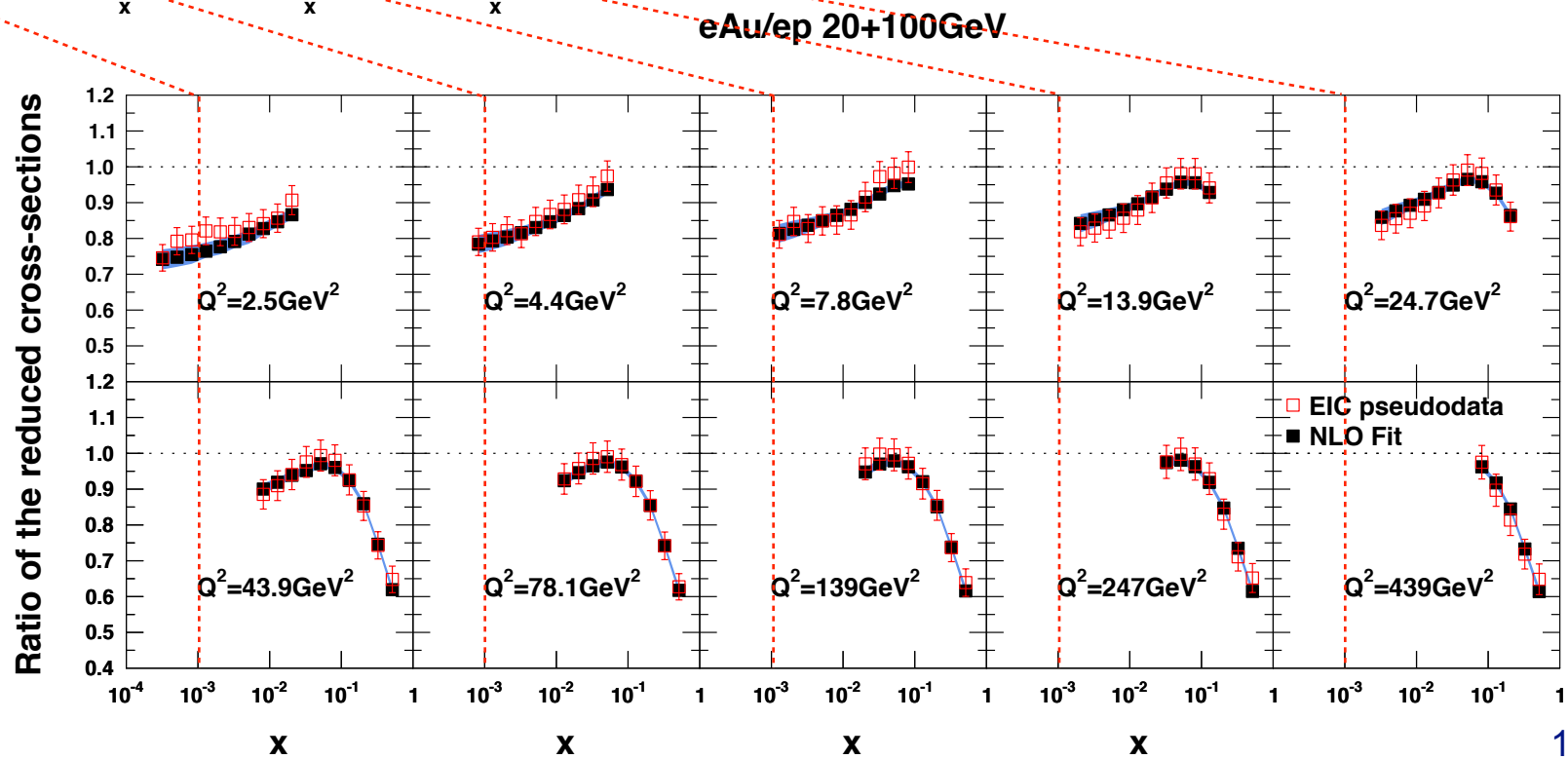
Carbon (scaled from Pb)



New: Constraints from EIC Pseudo Data

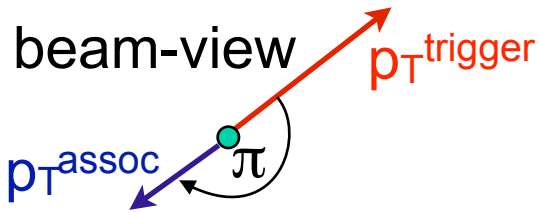


Compare 5+100 with 20+100 GeV: Noticeable loss at low-x increasing and larger Q^2



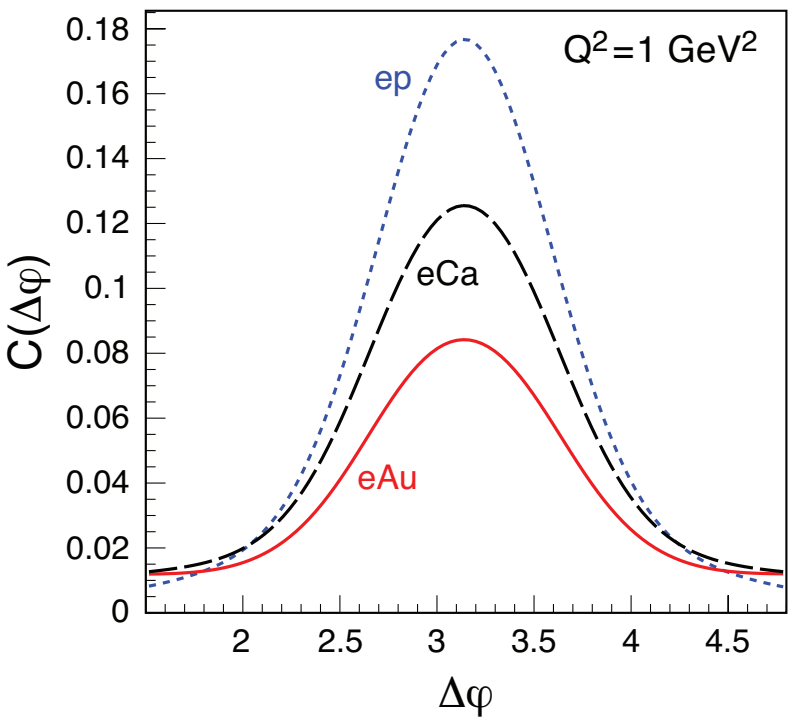
Semi-inclusive DIS: eA Dihadron Correlations

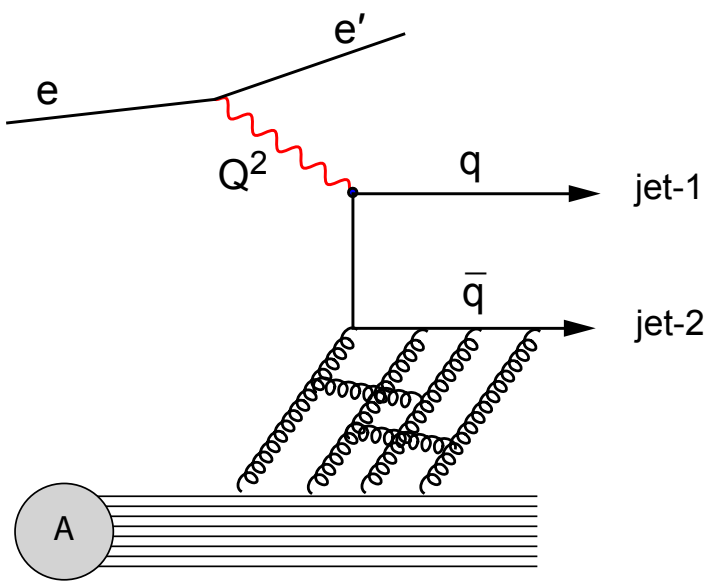
Simple Measurement



Theory (Bo-Wen, Feng, et al.)

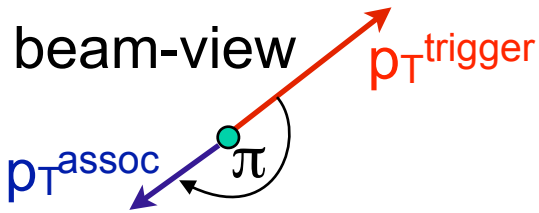
Pronounced saturation effect





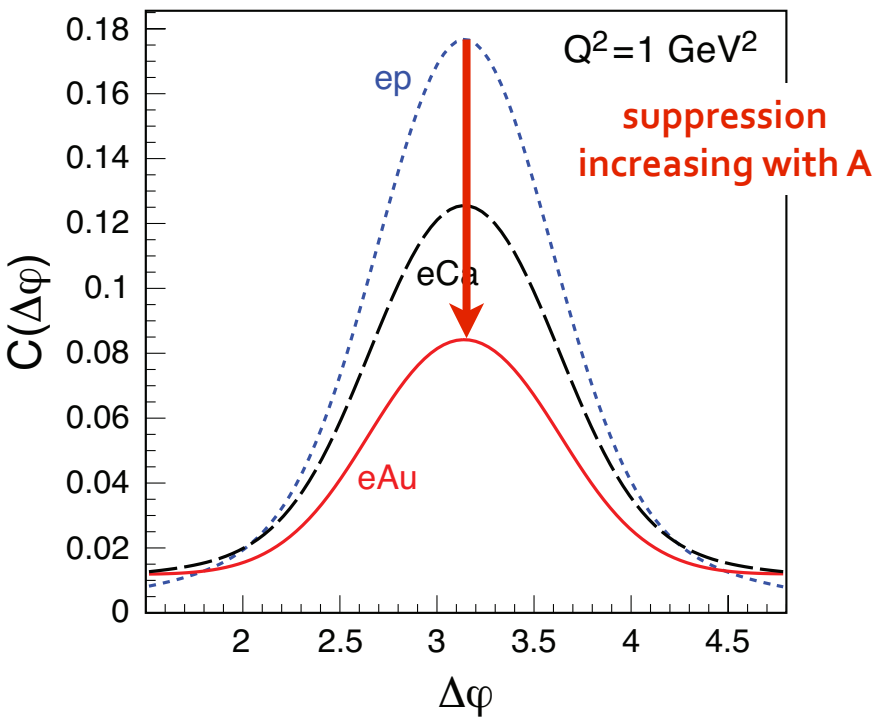
Semi-inclusive DIS: eA Dihadron Correlations

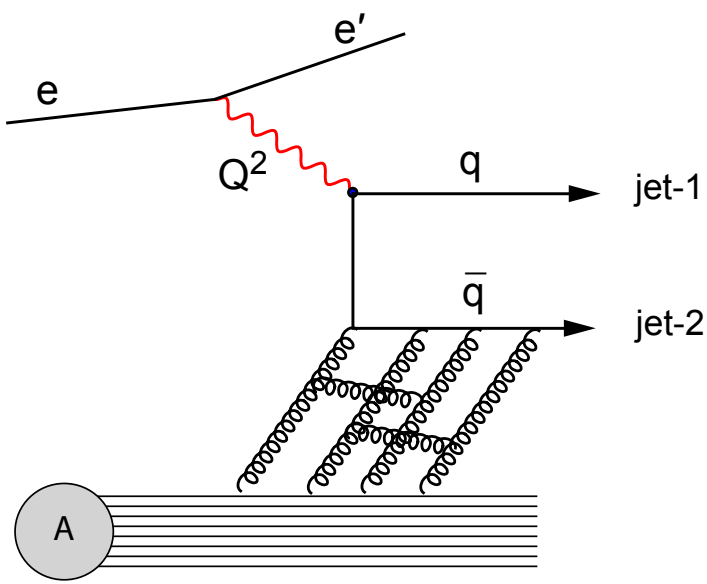
Simple Measurement



Theory (Bo-Wen, Feng, et al.)

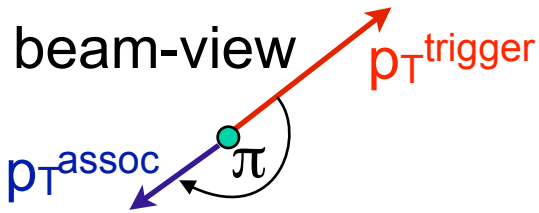
Pronounced saturation effect





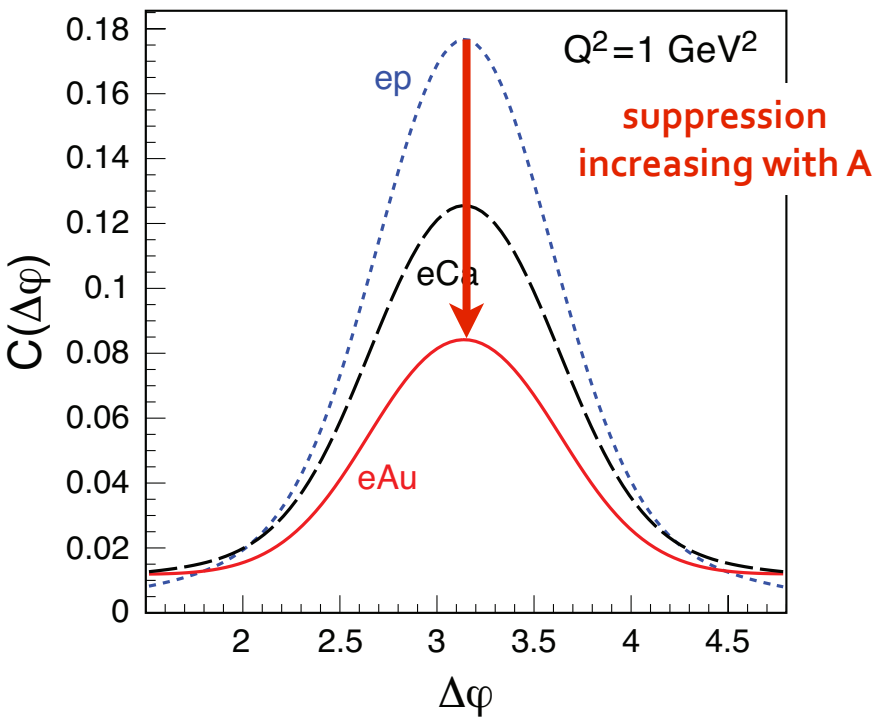
Semi-inclusive DIS: eA Dihadron Correlations

Simple Measurement



Theory (Bo-Wen, Feng, et al.)

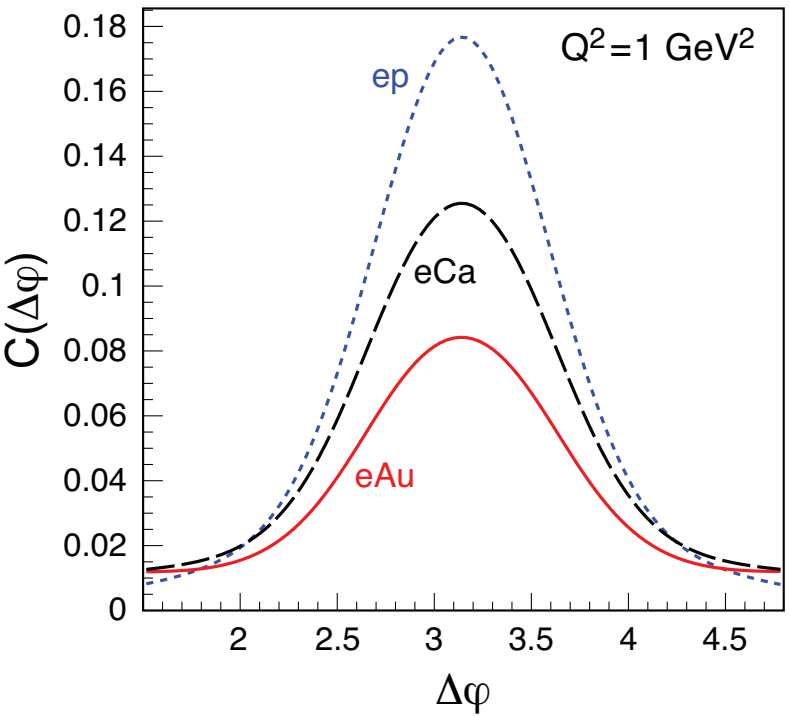
Pronounced saturation effect

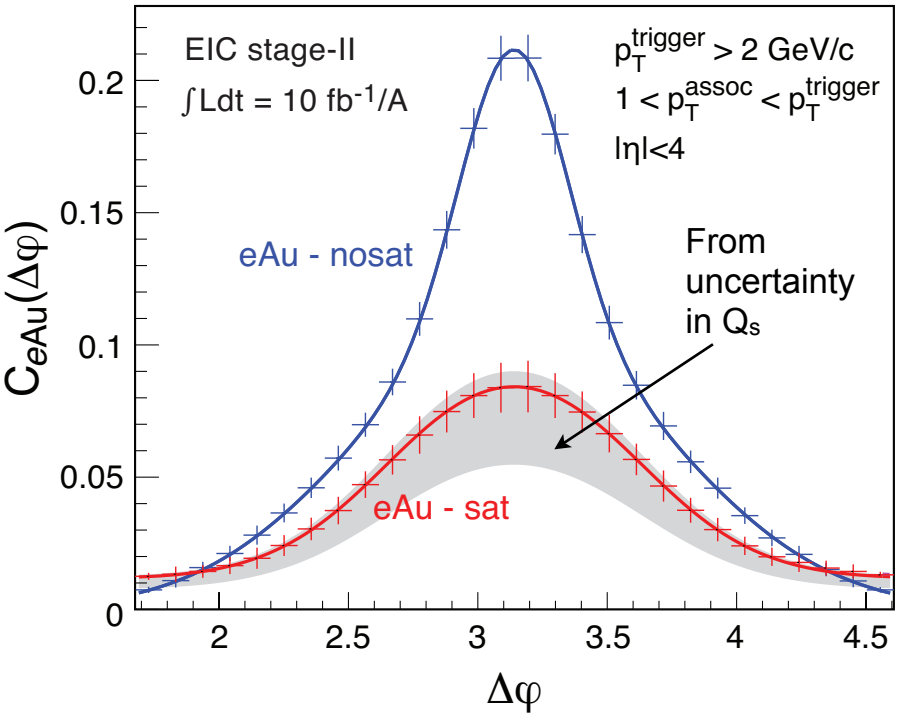


Compare with what?

- LTS model/MC
- Use PYTHIA (ep) with nPDF (EPS09) + nuclear effects from DPMJet-III
  - Caution: DPMJet has issues in other parts

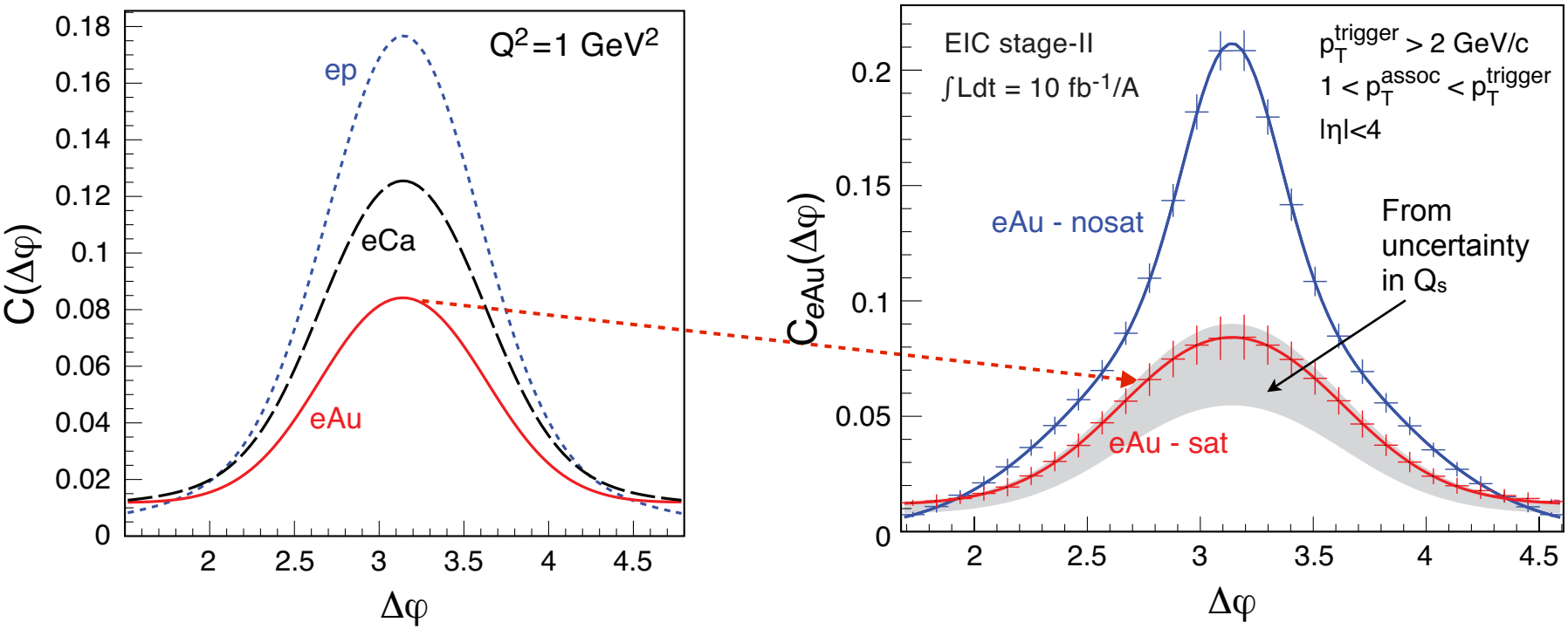
Semi-inclusive DIS: eA Dihadron Correlations





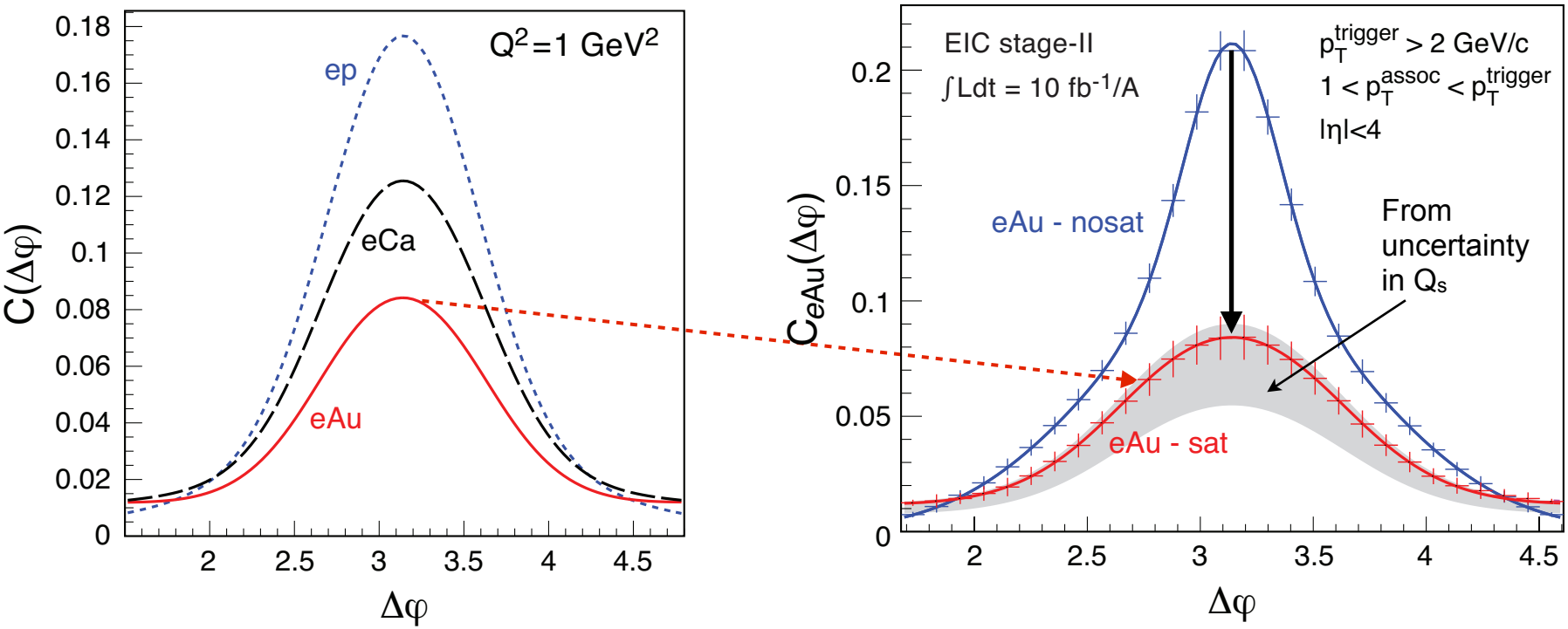
- Clear key measurement
- Significant difference between sat and non-sat case
- Need to adjust theory predictions due to lack of parton showers (see next slide how to avoid)
- Has equivalent to pA (e.g. RHIC forward measurements)

Semi-inclusive DIS: eA Dihadron Correlations



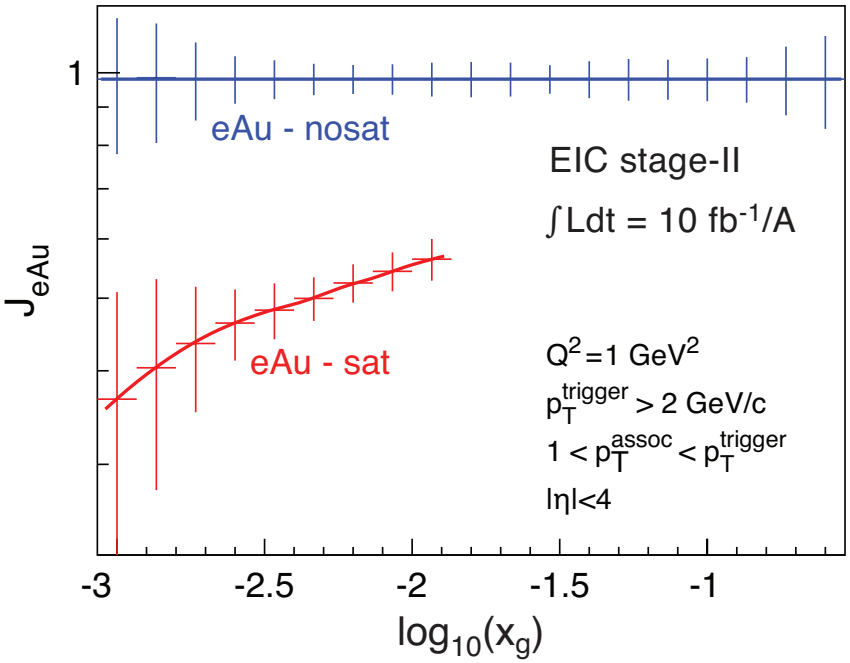
- Clear key measurement
- Significant difference between sat and non-sat case
- Need to adjust theory predictions due to lack of parton showers (see next slide how to avoid)
- Has equivalent to pA (e.g. RHIC forward measurements)

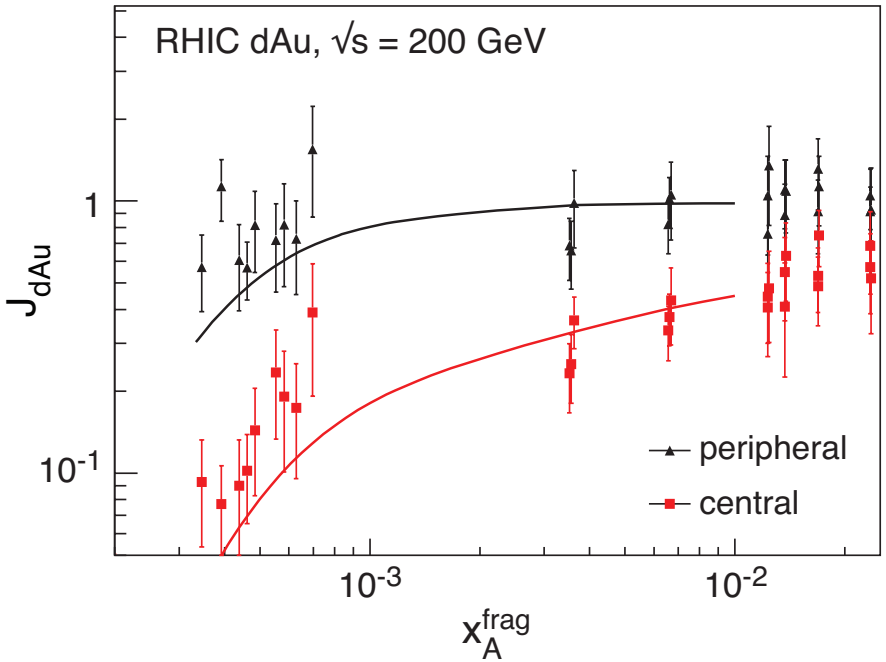
Semi-inclusive DIS: eA Dihadron Correlations



- Clear key measurement
- Significant difference between sat and non-sat case
- Need to adjust theory predictions due to lack of parton showers (see next slide how to avoid)
- Has equivalent to pA (e.g. RHIC forward measurements)

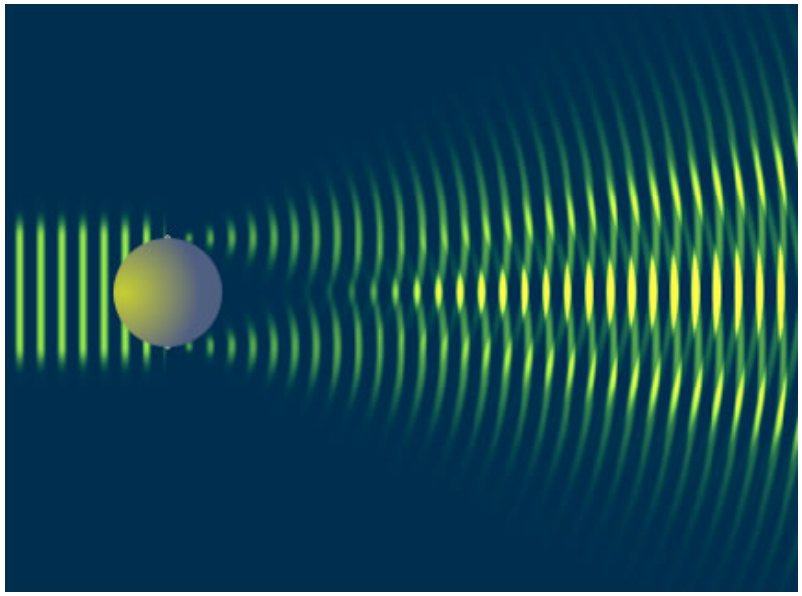
Semi-inclusive DIS: eA Dihadron Correlations

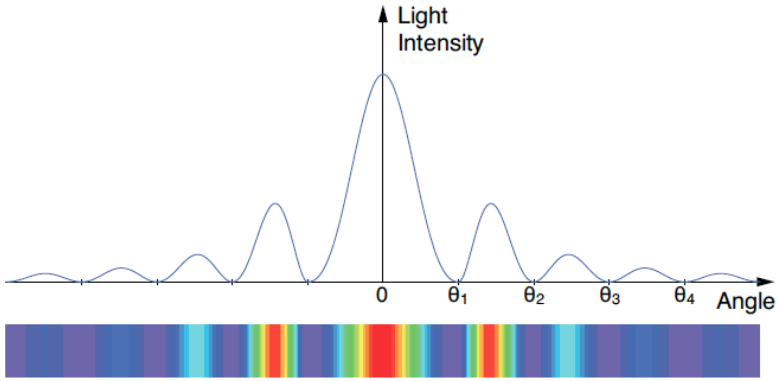




- $J_{eAu} = Yield_{eAu}/Yield_{ep}$ avoids peak/shape issues (almost)
- **Issues**
  - x_A^{frag} in pA is a very rough estimate of x_g
  - in eA situation is better but will require also some modeling
- Differential studies (Q^2, x (or W), $p_T^{trigger}$, p_T^{assoc} bins) will require considerable luminosity (above 10 fb^{-1})

Diffractive Processes in eA



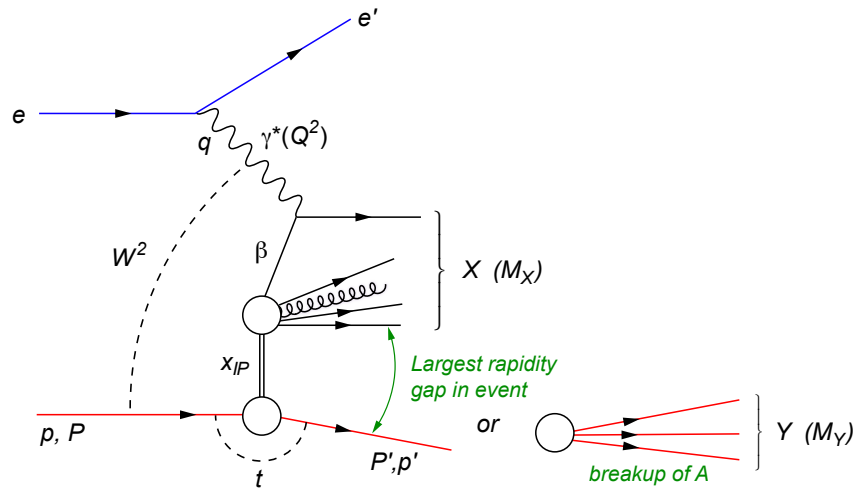


Diffractive physics will be ***the*** major component of the eA program at an EIC

- High sensitivity: $\sigma \sim [g(x,Q^2)]^2$
- Only known process where spatial gluon distributions can be extracted

Diffractive Events: Experimental Side

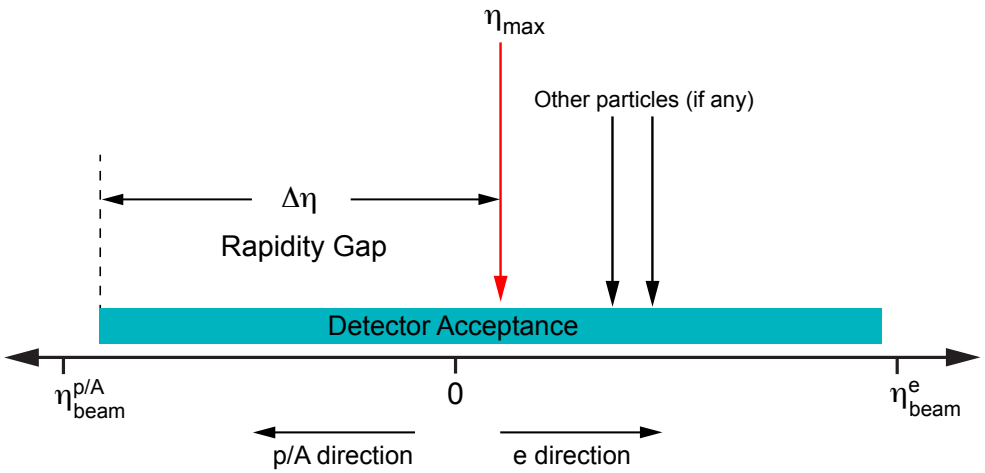
How to identify diffractive events?



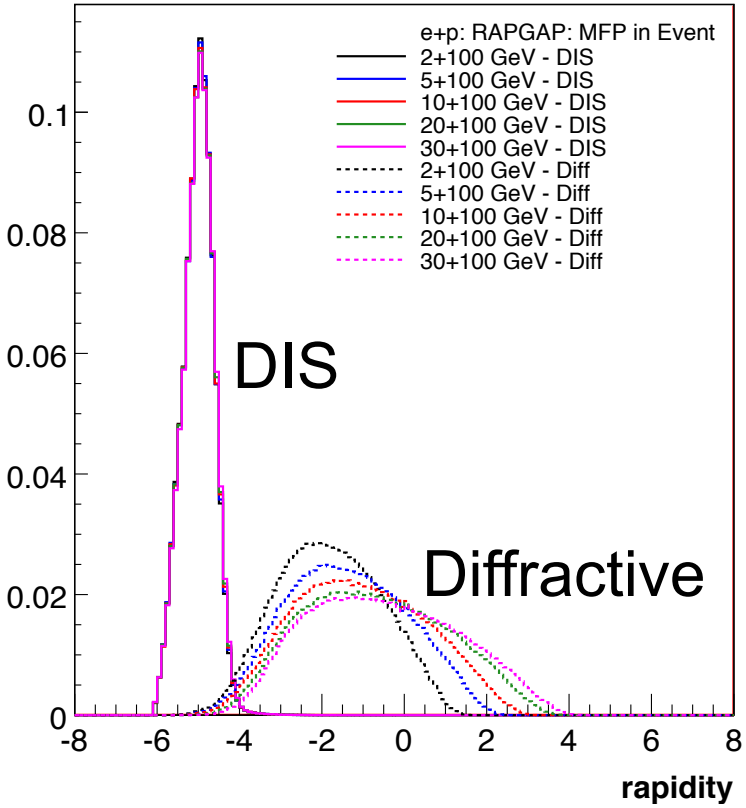
- Rapidity Gap
  - requires hermetic (large acceptance) detector
- Separating coherent from incoherent diffraction
  - detector and IR needs to be carefully designed to detect nuclear breakup
- Limitation at a collider
  - Coherent: scattered ion cannot be measured, *t* not directly measurable (may be in very light ions)
  - Breakup can be detected using emitted *n* and γ, some charged fragments can be measured in Roman Pots

Large Rapidity Gap Method (LRG)

- Identify Most Forward Going Particle (MFP)
  - Works at HERA but higher √s
  - EIC smaller beam rapidities



Diffractive ρ^0 production at EIC: η of MFP



Hermeticity requirement:

- needs just to detector presence
- does not need momentum or PID
- simulations: √s not a show stopper for EIC (can achieve 1% contamination, 80% efficiency)

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

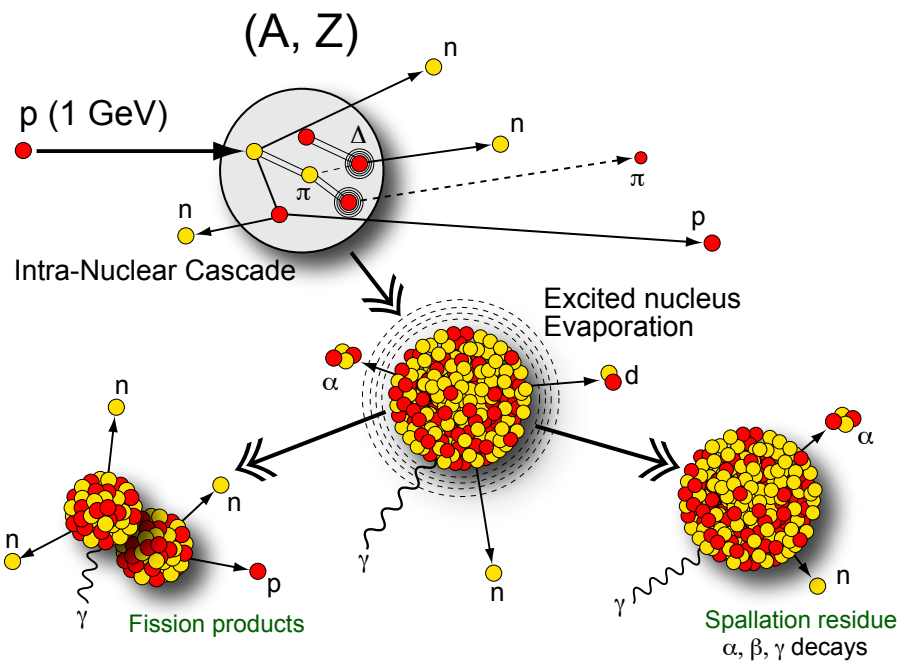
Traditional modeling done in pA:

Intra-Nuclear Cascade

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

De-Excitation

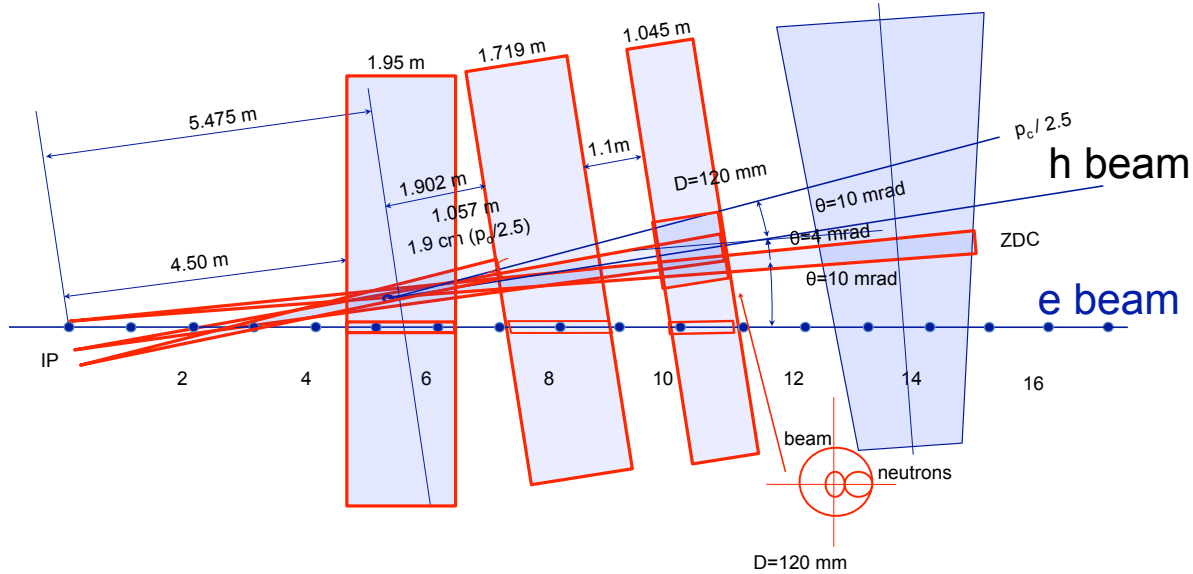
- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)



Experimental Reality

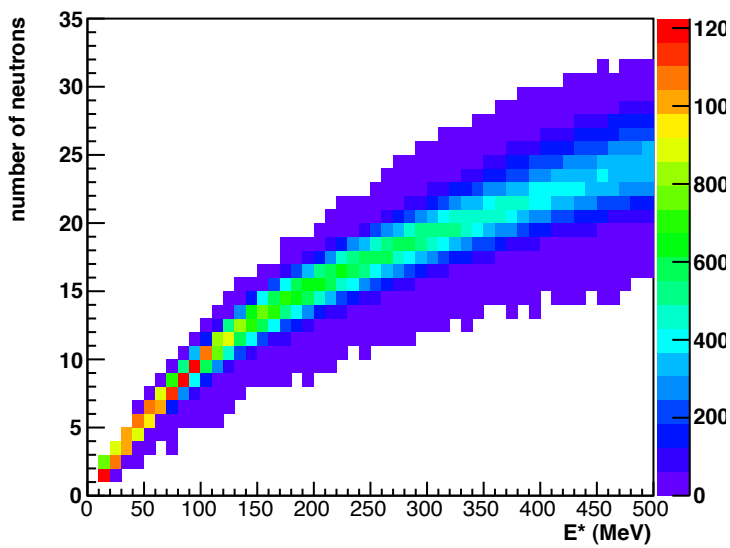
Here eRHIC IR layout:

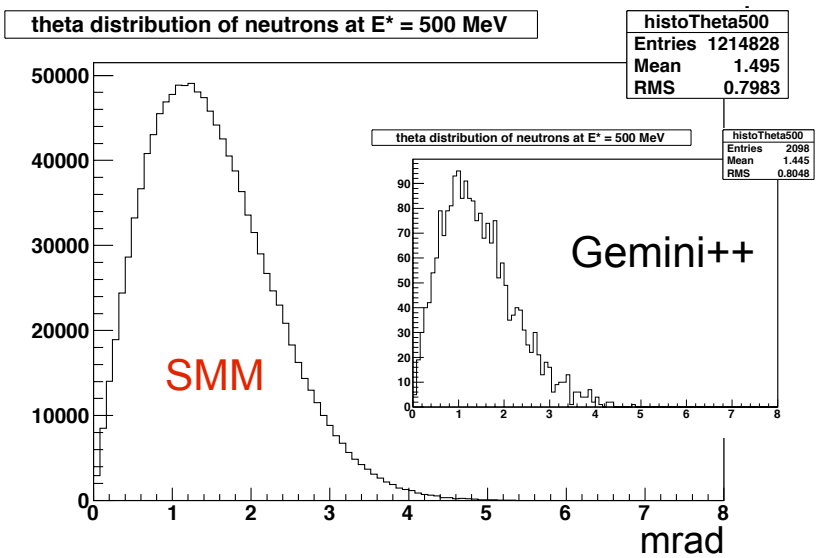
Need ±X mrad opening through triplet for *n* and room for ZDC



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

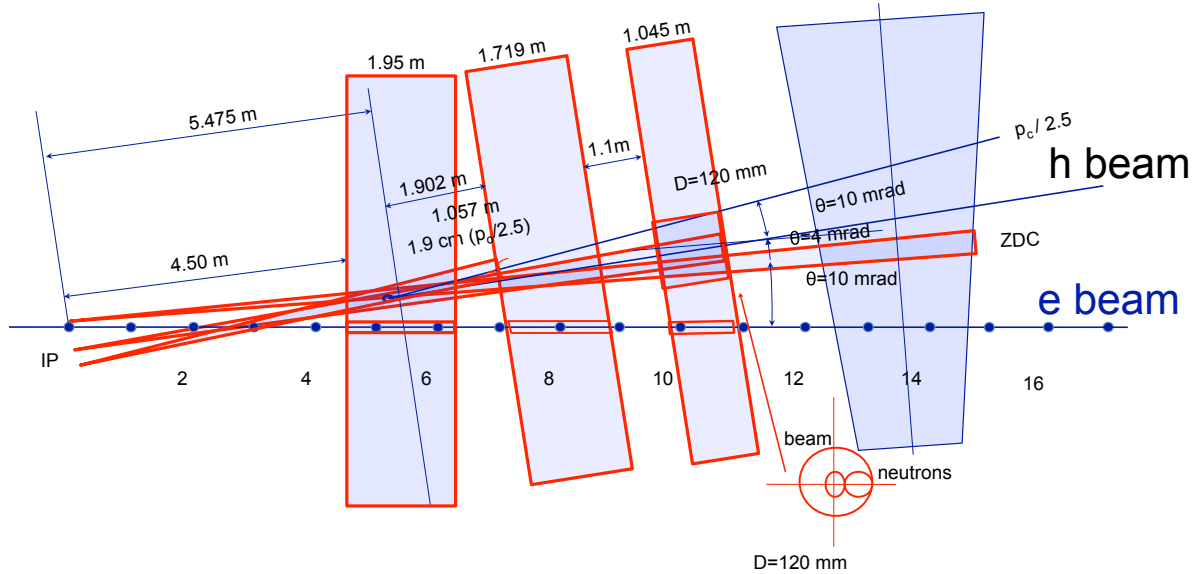




Experimental Reality

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

Simulations using Gemini++ & SMM show it works:

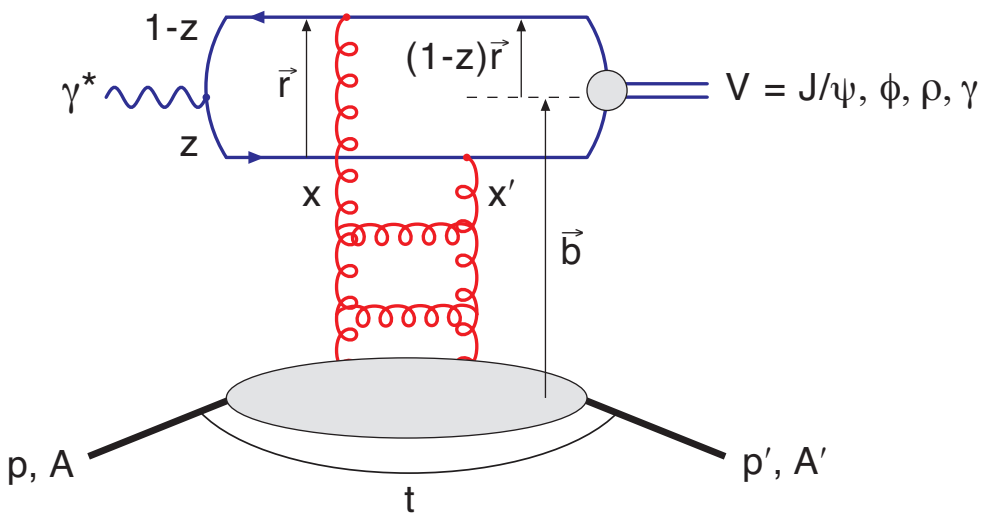
- For $E^*_{tot} \geq 10$ MeV and 2.5 mrad *n* acceptance we have rejection power of at least 10^5.
- Separating incoherent from coherent diffractive events is possible at a collider with *n*-detection via ZDCs alone

Exclusive Vector Meson Production

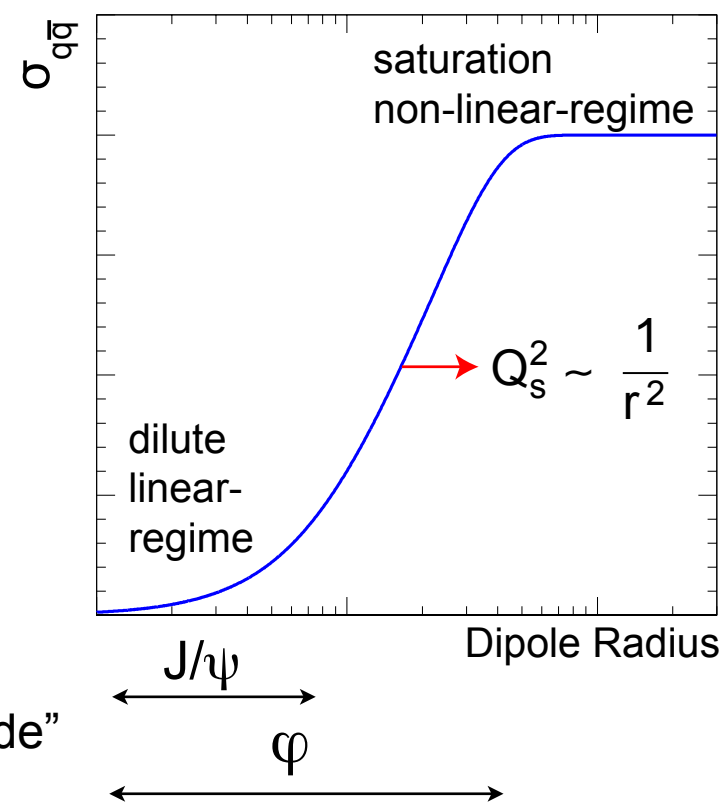
- Unique probe - allows to measure momentum transfer *t* in eA diffraction
  - in general, one cannot detect the outgoing nucleus and its momentum
  - here:

$$\mathbf{t} = (\mathbf{p_A} - \mathbf{p_{A'}})^2 = (\mathbf{p_{VM}} + \mathbf{p_{e'}} - \mathbf{p_e})^2$$

$$\approx (p_T(e') + p_T(VM))^2$$



Dipole Cross-Section:



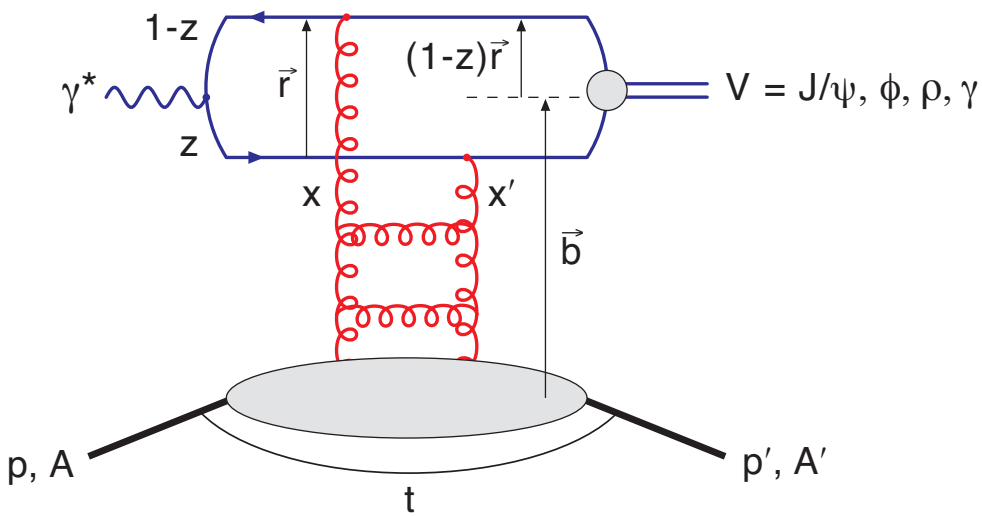
- **small size (J/Ψ)**: cuts off saturation region
- **large size (φ,ρ, ...)**: "sees more of dipole amplitude" → more sensitive to saturation

Exclusive Vector Meson Production

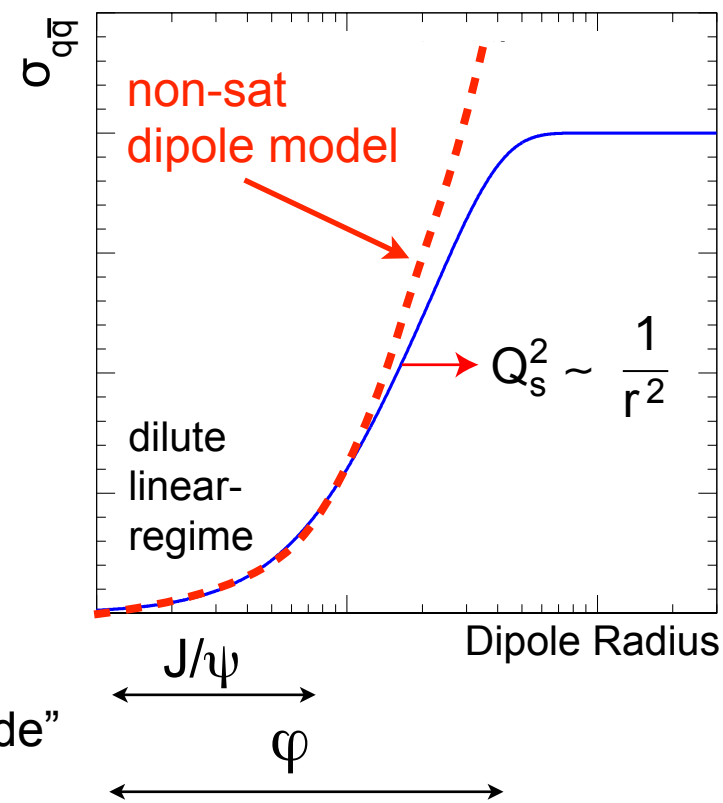
- Unique probe - allows to measure momentum transfer *t* in eA diffraction
  - in general, one cannot detect the outgoing nucleus and its momentum
  - here:

$$\mathbf{t} = (\mathbf{p_A} - \mathbf{p_{A'}})^2 = (\mathbf{p_{VM}} + \mathbf{p_{e'}} - \mathbf{p_e})^2$$

$$\approx (p_T(e') + p_T(VM))^2$$

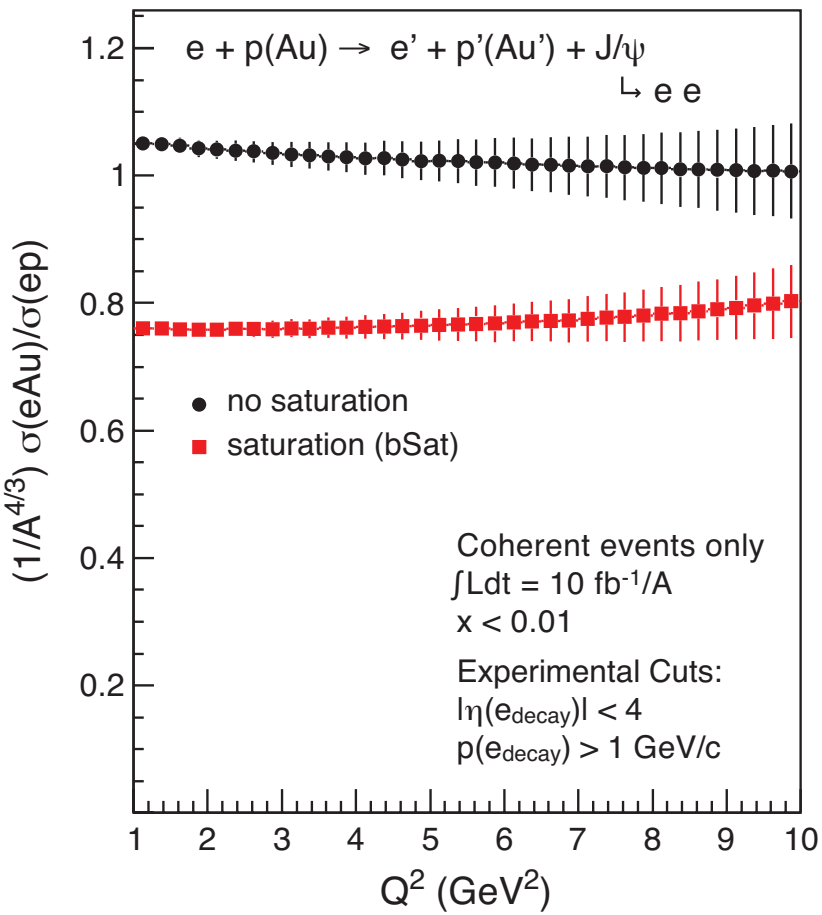


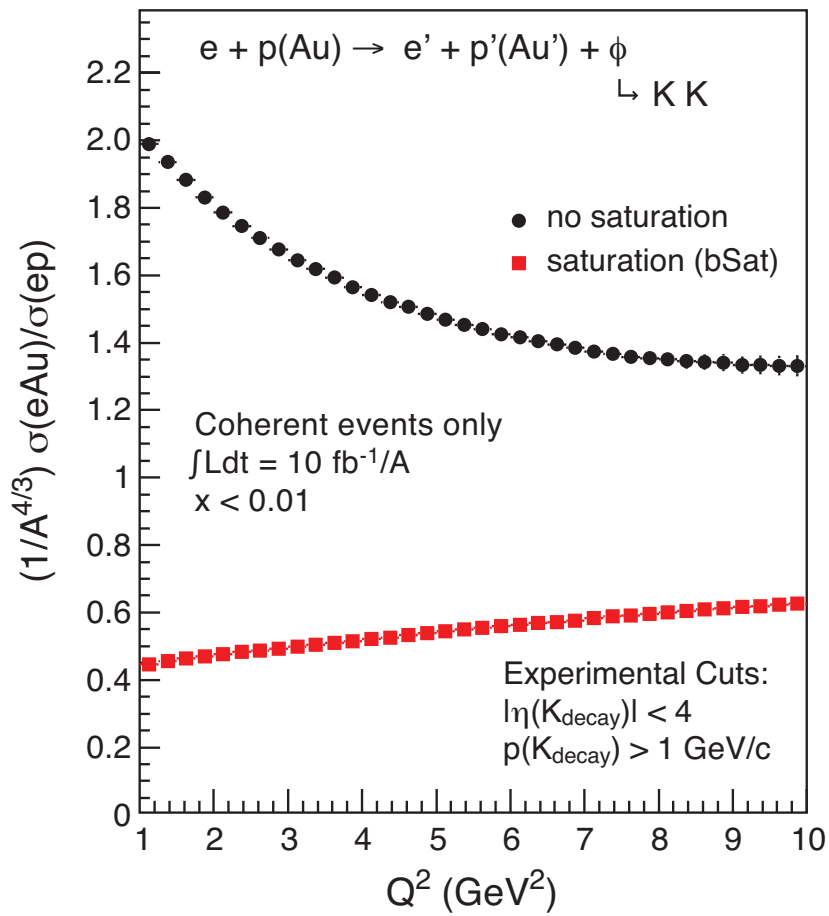
Dipole Cross-Section:



- **small size (J/Ψ)**: cuts off saturation region
- **large size (φ,ρ, ...)**: "sees more of dipole amplitude" → more sensitive to saturation

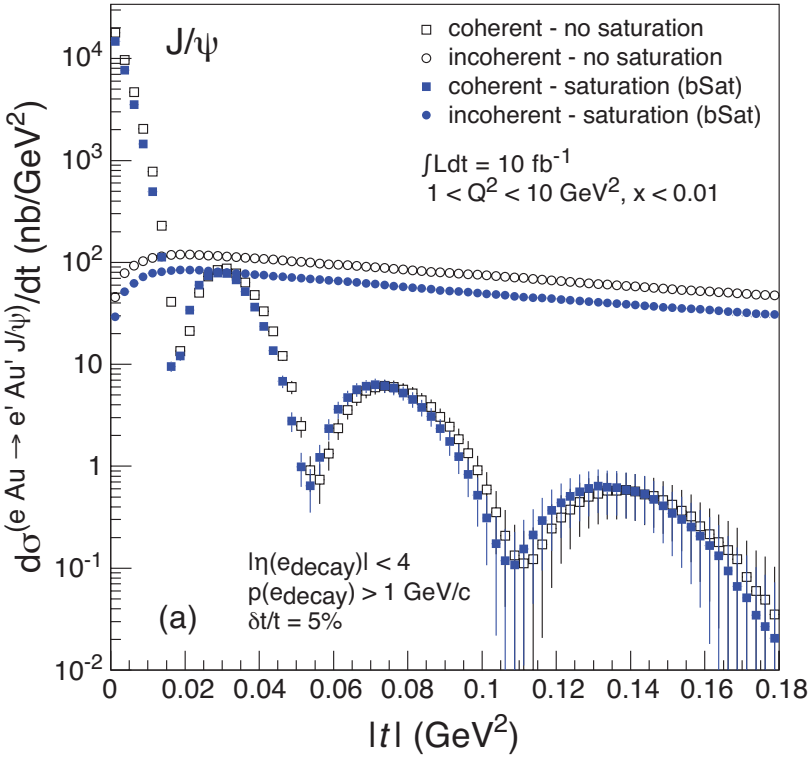
Exclusive Vector Meson Production

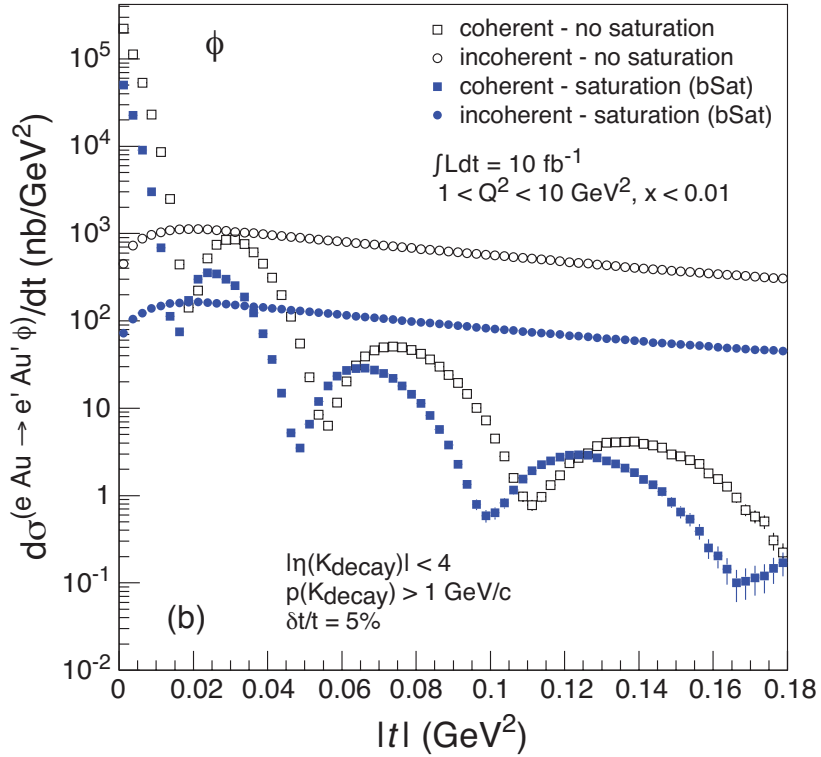




- Sartre event generator (bSat & bNonSat = linearized bSat)
- As expected: big difference for ϕ less so for J/ψ
- Note: $A^{4/3}$ scaling strictly only valid at large Q^2

The Holy Grail dσ/d*t*





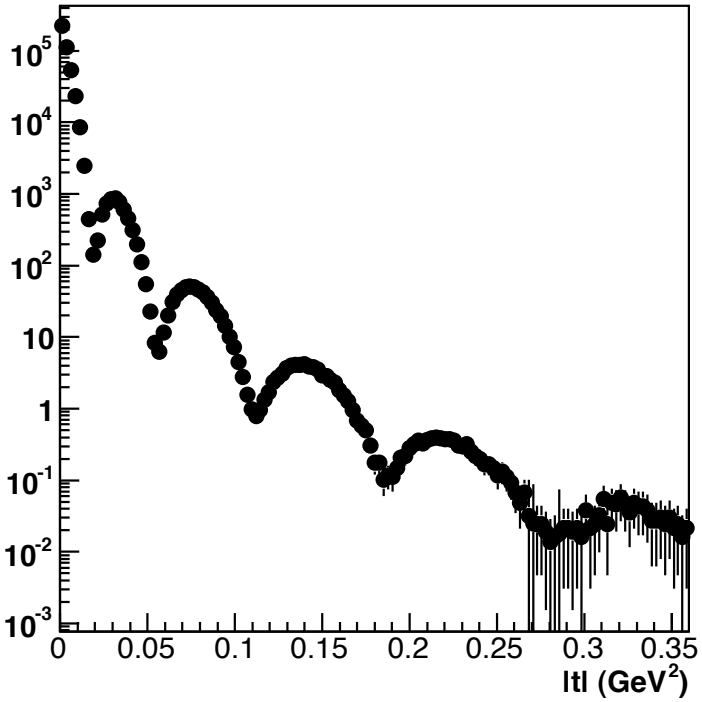
- Goal: going after the source distribution of gluons through Fourier transform of dσ/dt
- Find: Typical diffractive pattern for coherent (non-breakup) part
- As expected: J/Ψ less sensitive to saturation than ϕ
- Need this sliced in x bins ⇒ luminosity hungry
- Crucial: *t* resolution and reach

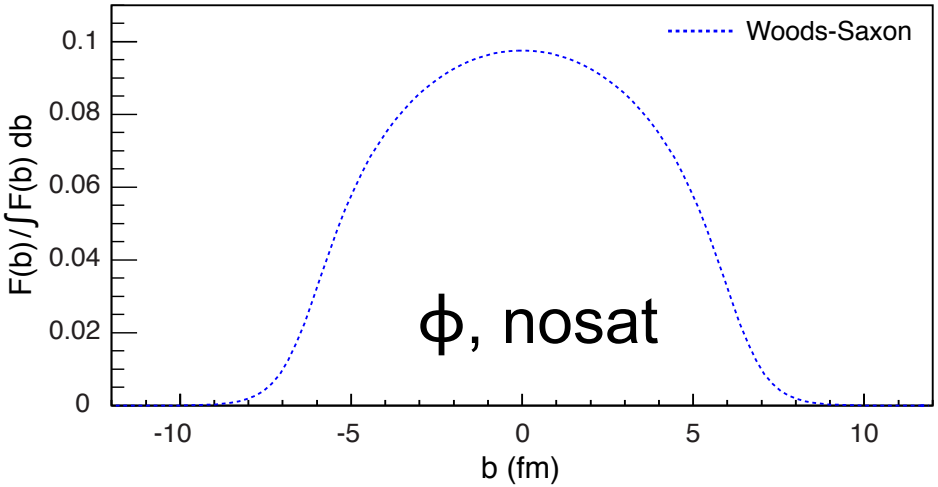
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





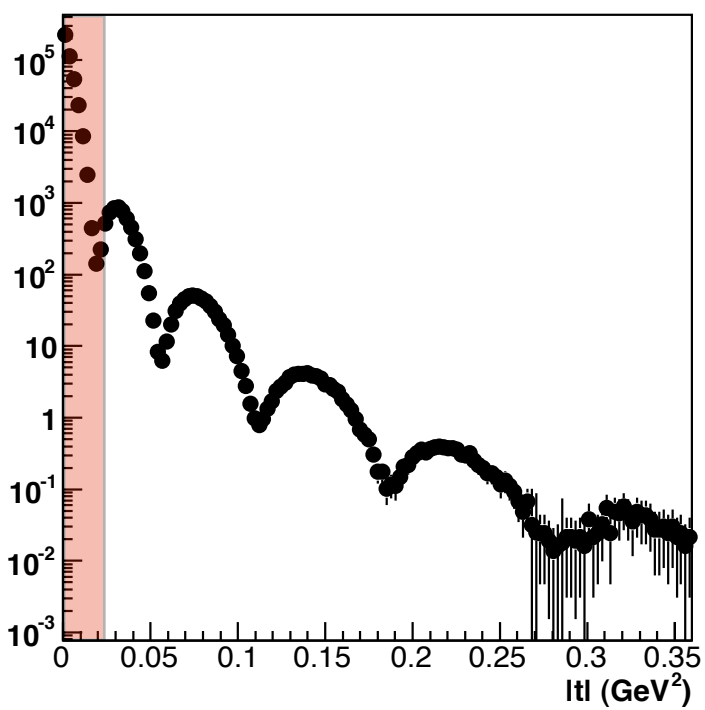
Golden eA measurement for EIC

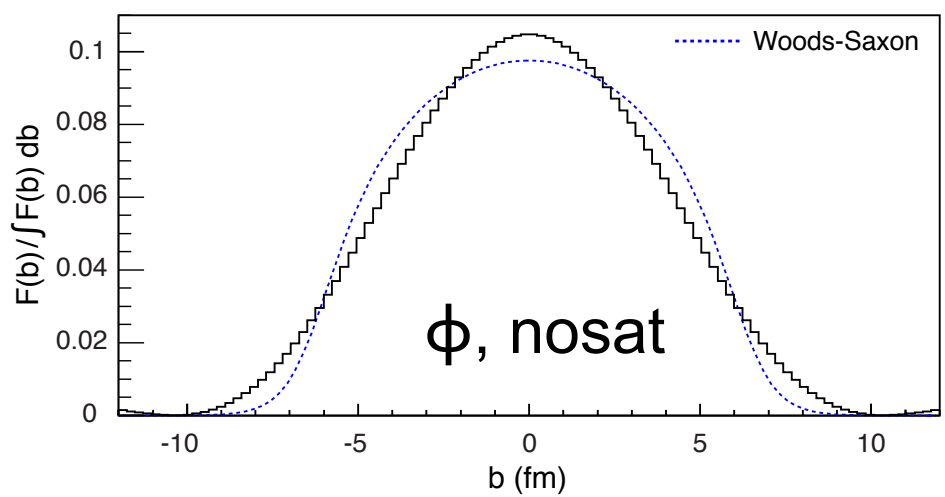
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





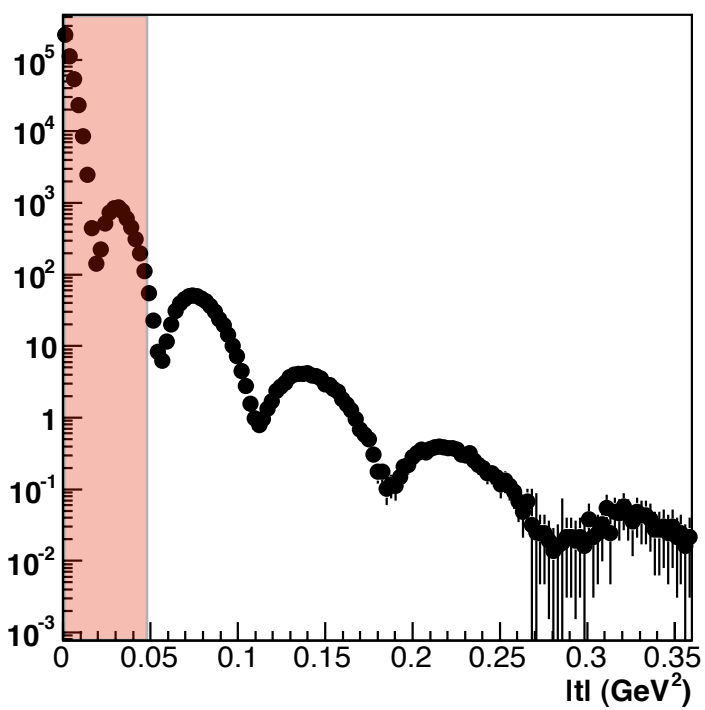
Golden eA measurement for EIC

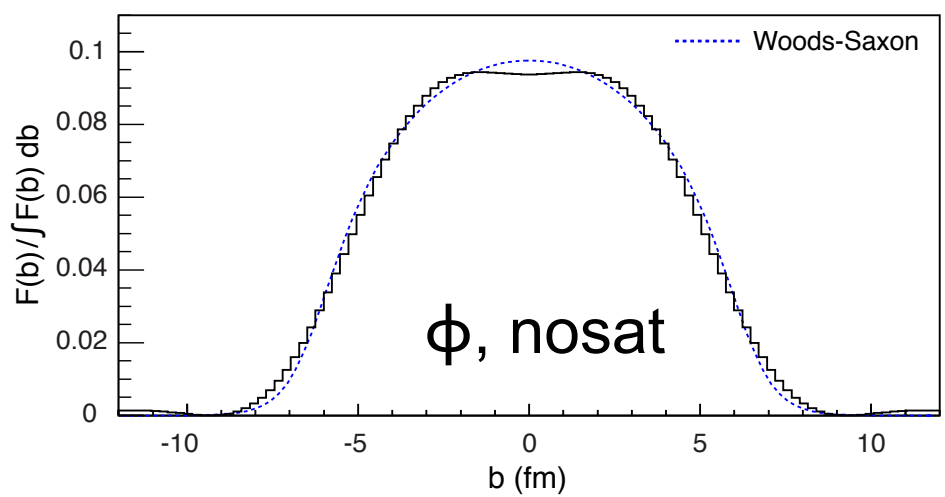
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





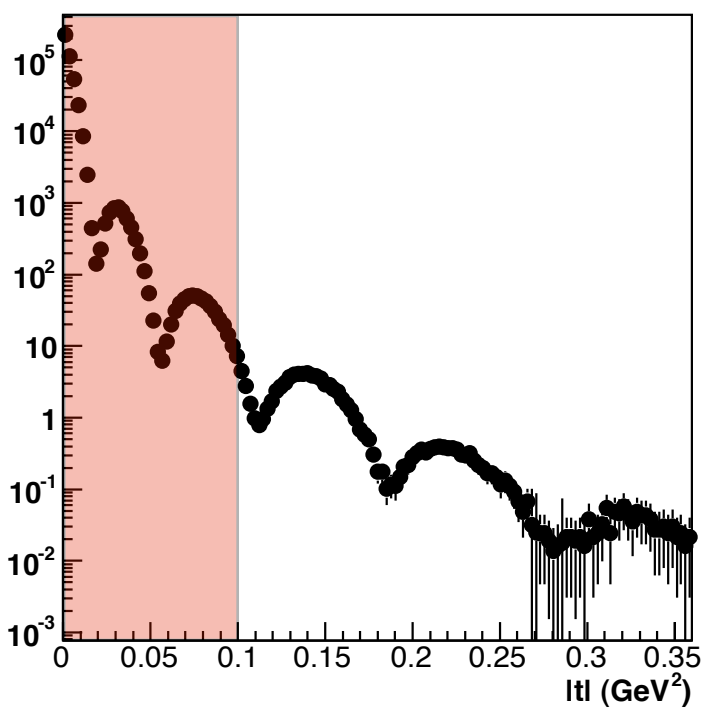
Golden eA measurement for EIC

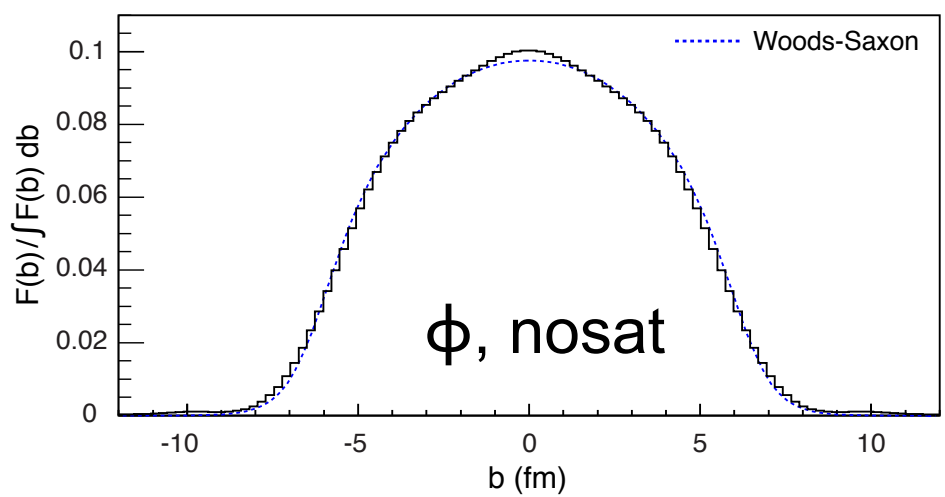
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





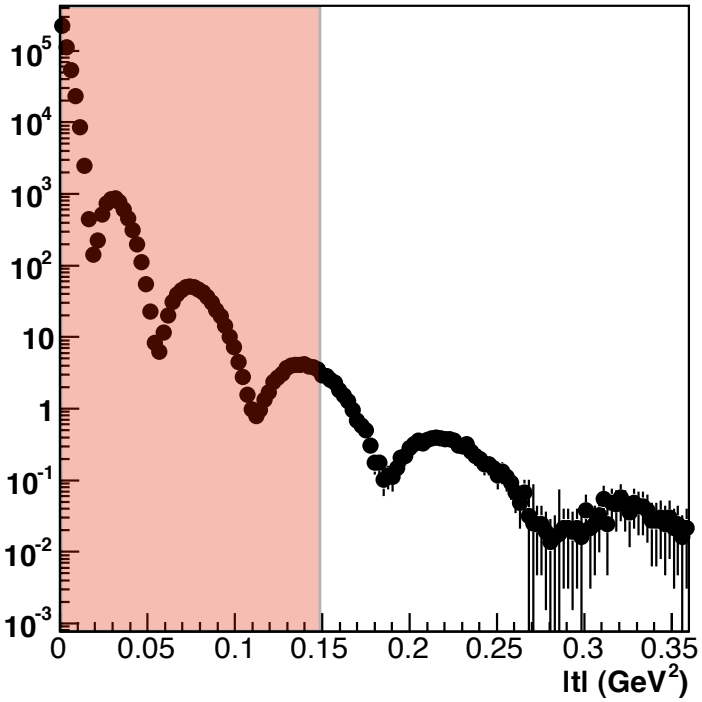
Golden eA measurement for EIC

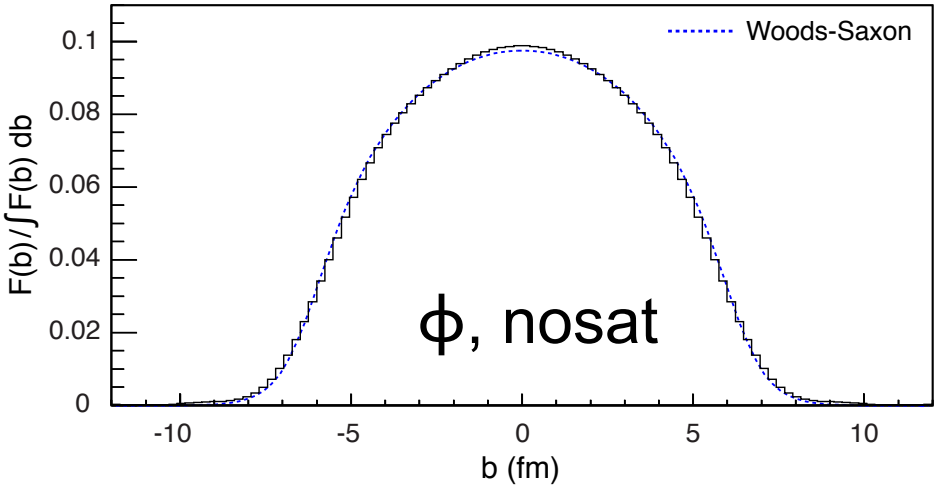
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





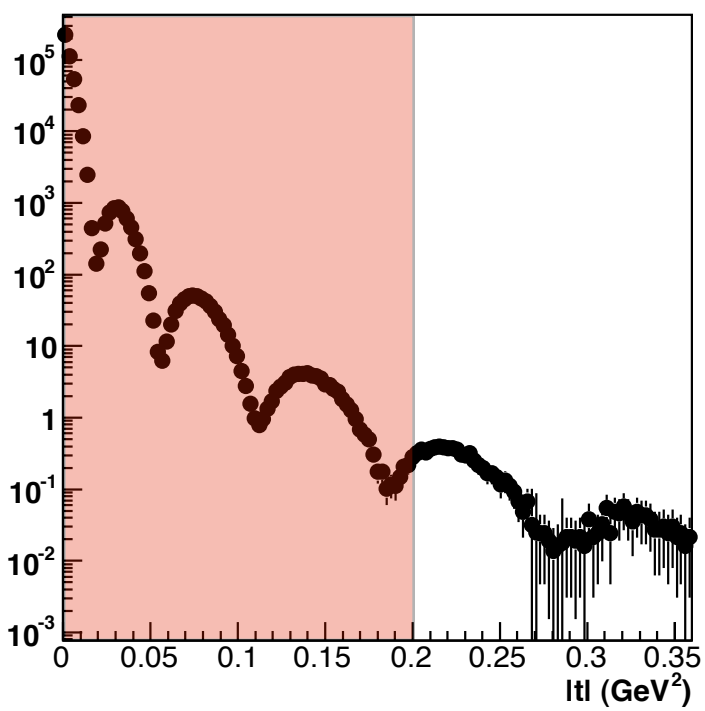
Golden eA measurement for EIC

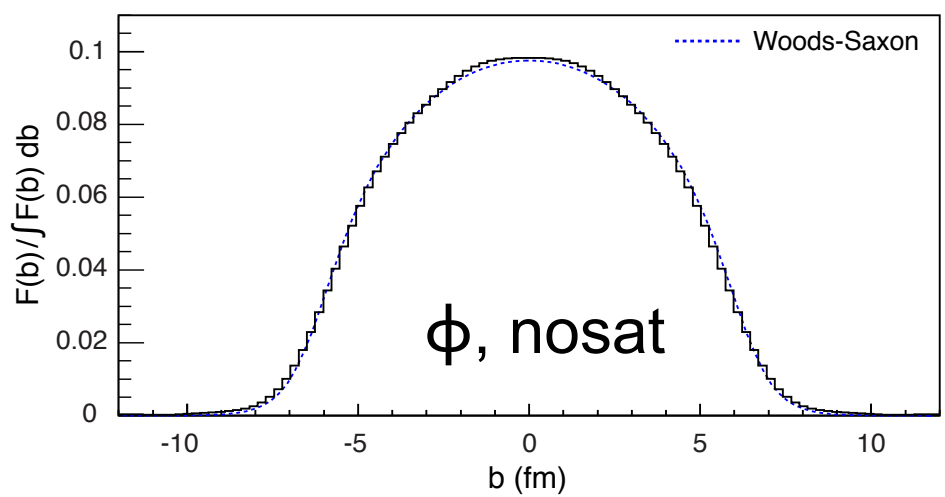
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





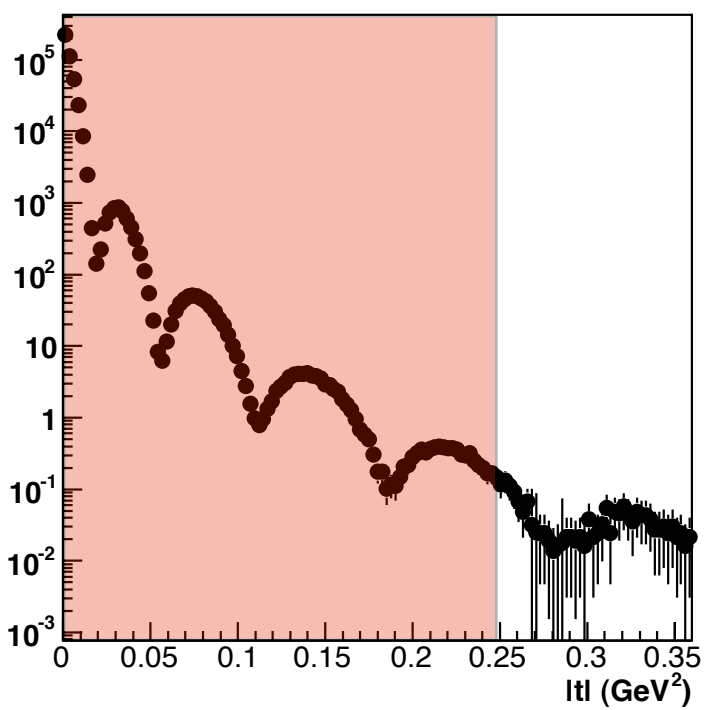
Golden eA measurement for EIC

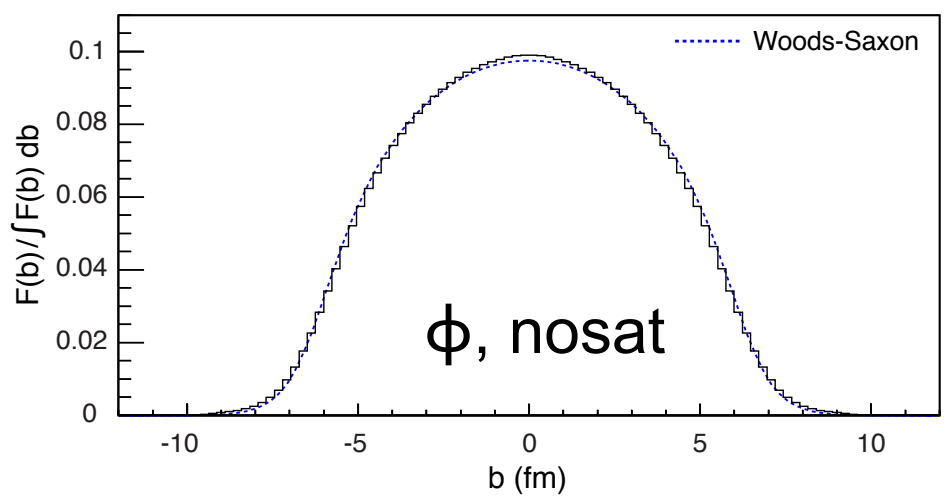
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





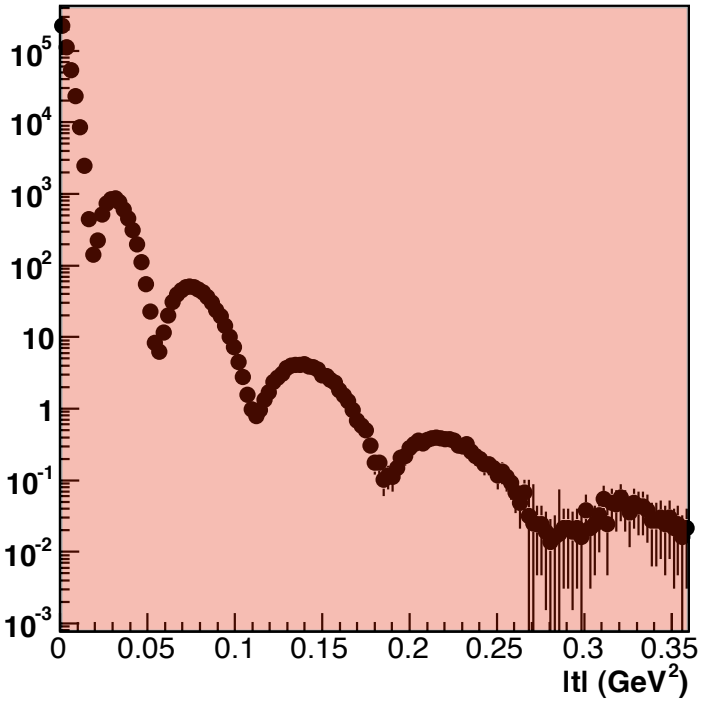
Golden eA measurement for EIC

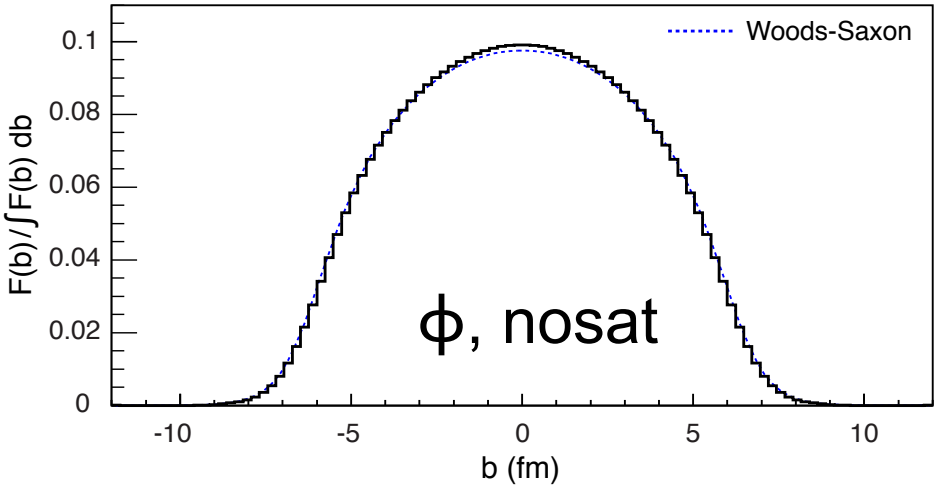
New: Spatial Gluon Distribution

- **Idea**: momentum transfer *t* conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large *t*) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$

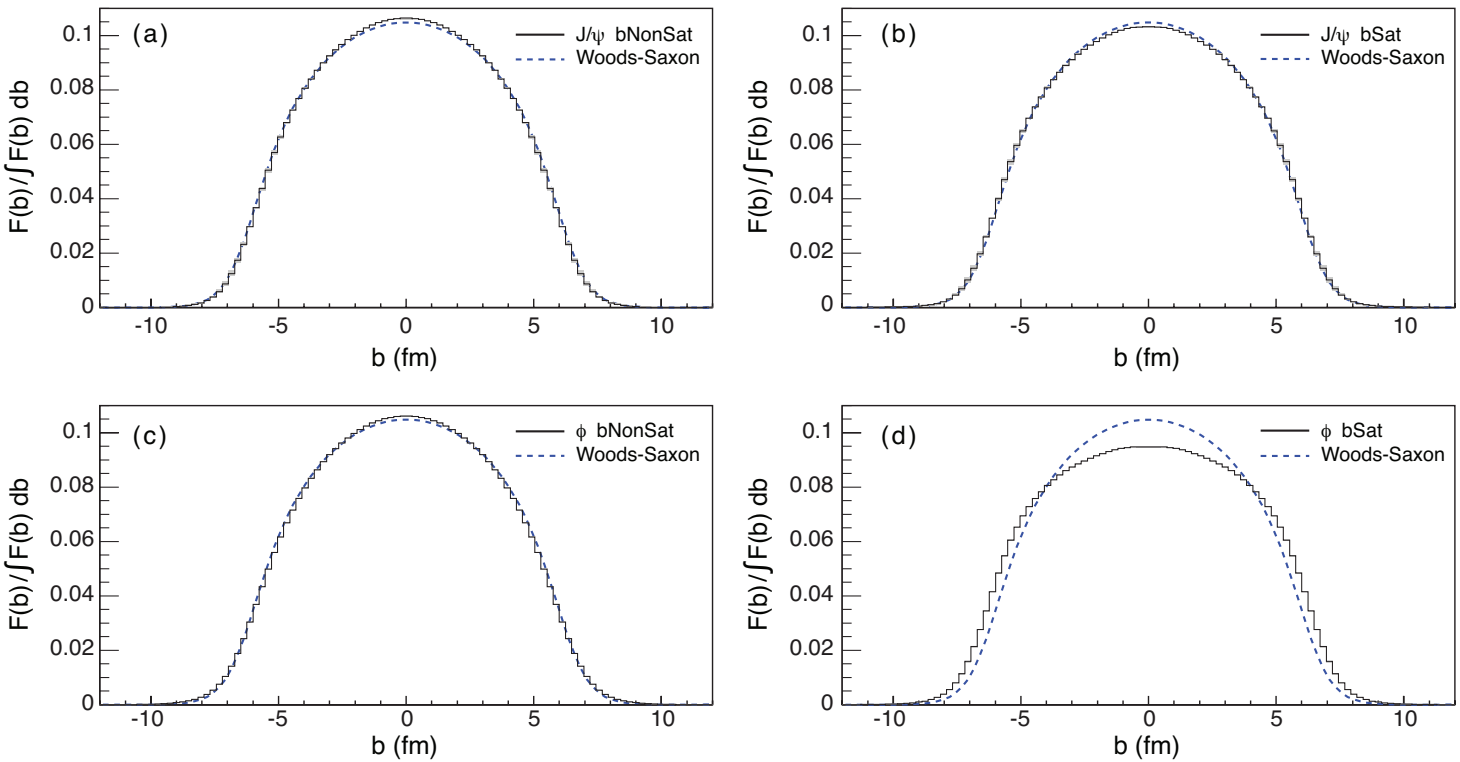
$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





Golden eA measurement for EIC

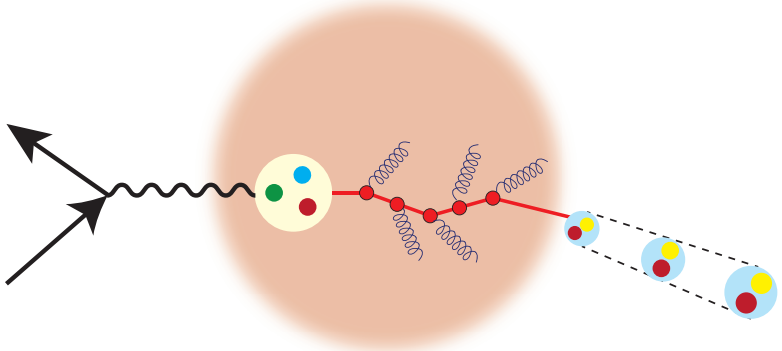
New: Spatial Gluon Distribution



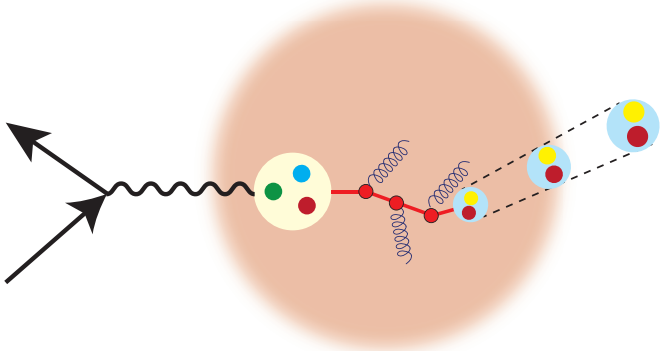
- J/ψ perfect for obtaining $F(b)$ in both cases sat and non-sat
- ϕ less so since coherence distorts $F(b)$
- but also: difference in $F(b)$ of ϕ and J/ψ reveals saturation
- Note: Error calculation is tricky here (btw: plots have errors). Recent studies: Fourier transformation runs into trouble at 1 fb^{-1}

Parton Propagation and Fragmentation

Hadronization not well understood non-perturbative process



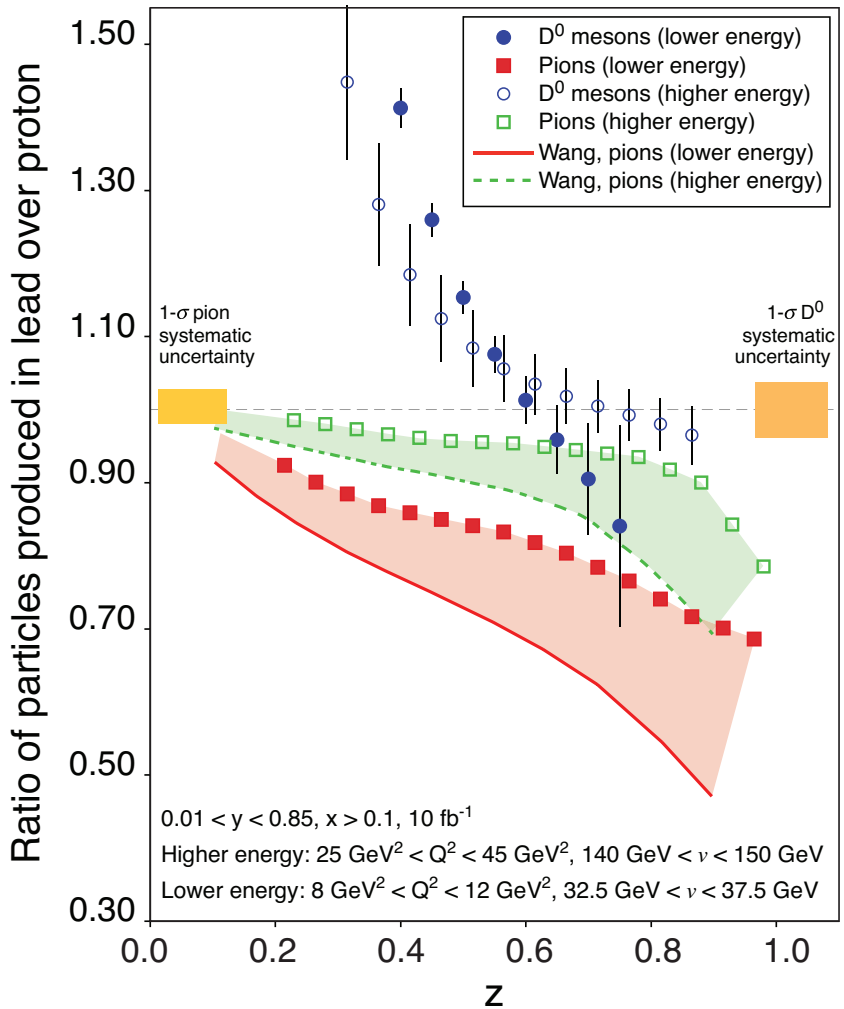
- Nuclei as space-time analyzer
- EIC can measure:
  - fragmentation time scales to understand dynamic
  - in medium energy loss to characterize medium



- Observables
  - p_T distribution broadening: $\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$
  - attenuation of hadrons:

$$R_A^h(Q^2, x_{Bj}, z, P_T) = \frac{N_A^h(Q^2, x_{Bj}, z, P_T) / N_A^e(Q^2, x_{Bj})}{N_D^h(Q^2, x_{Bj}, z, P_T) / N_D^e(Q^2, x_{Bj})}$$

Semi-Inclusive Studies



HERMES: ν = 2-25 GeV

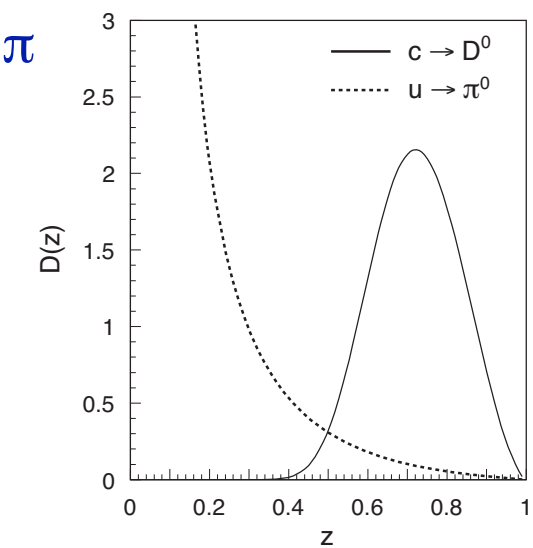
EIC: 10 < ν < 1600 GeV

EIC: *heavy flavor*!

Points: energy loss models with attenuation of pre-hadrons + medium induced energy loss.

Lines: pure energy loss calculations

Difference D, π from D(z)

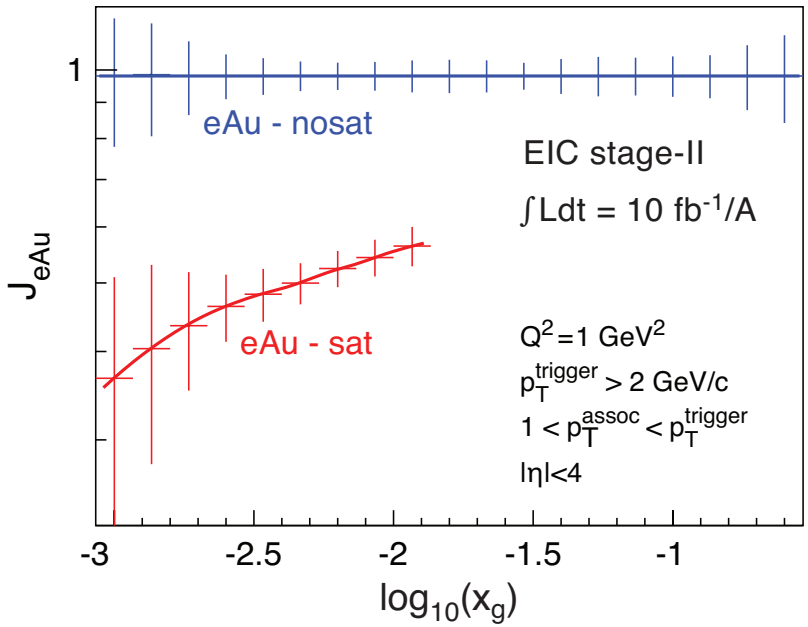


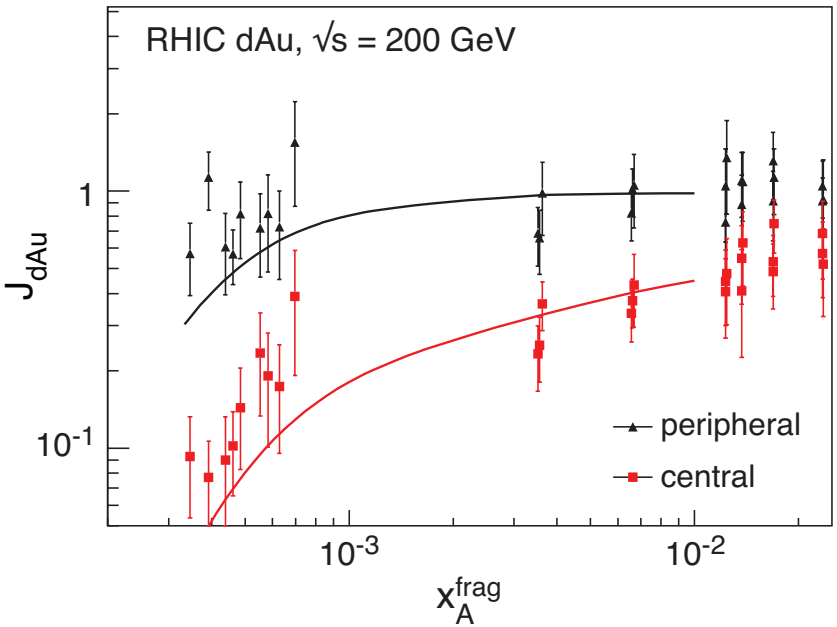
- Slope of D's sensitive to $\hat{q}$ and FF
- Strong Sensitivity of Shape on ν is powerful tool

eA at EIC: Connections

pA:

- Saturation effects at forward rapidities (di-hadrons, ridge)





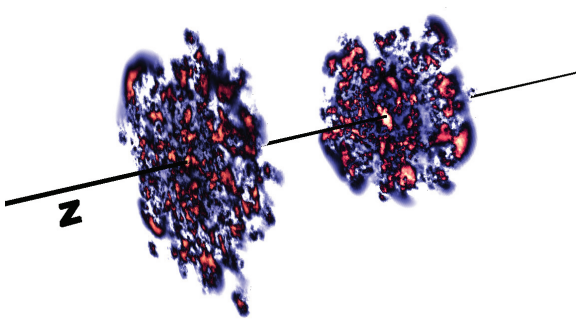
eA at EIC: Connections

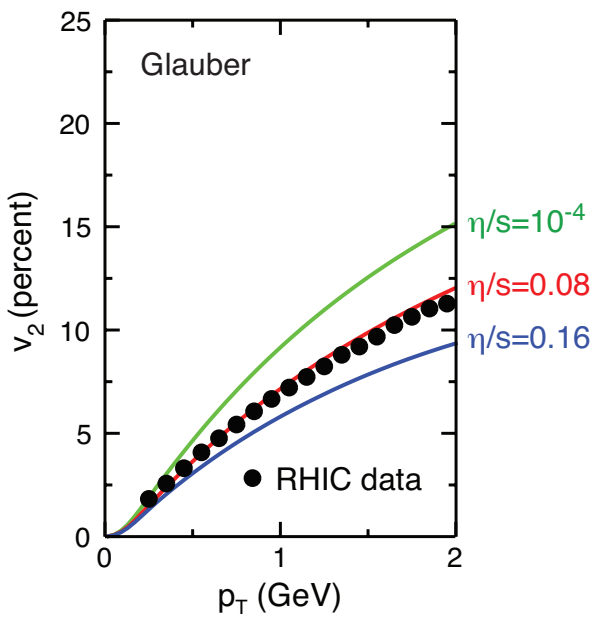
pA:

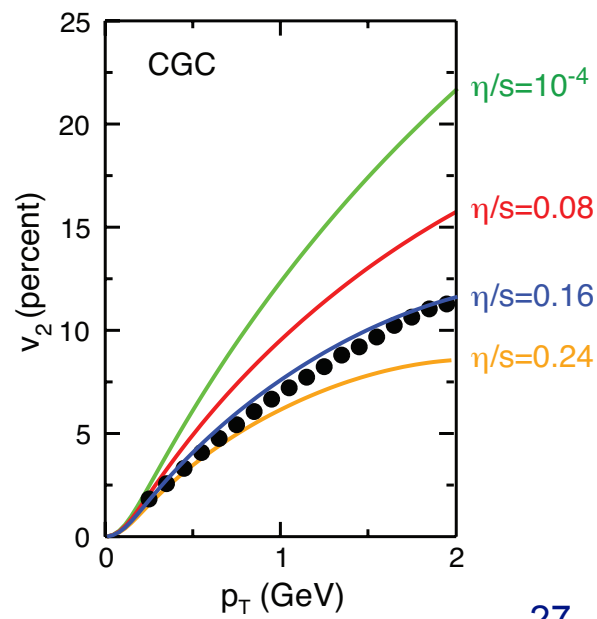
- Saturation effects at forward rapidities (di-hadrons, ridge)

AA:

- Initial conditions, $G(x, Q^2, b_T, k_T)$
  - understanding of v_n, ultimately η/s,







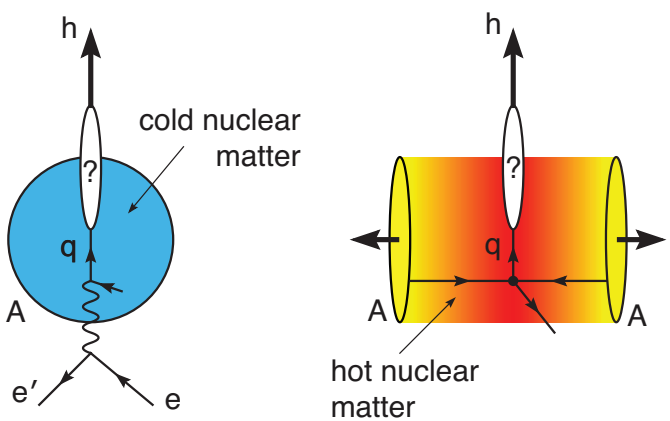
eA at EIC: Connections

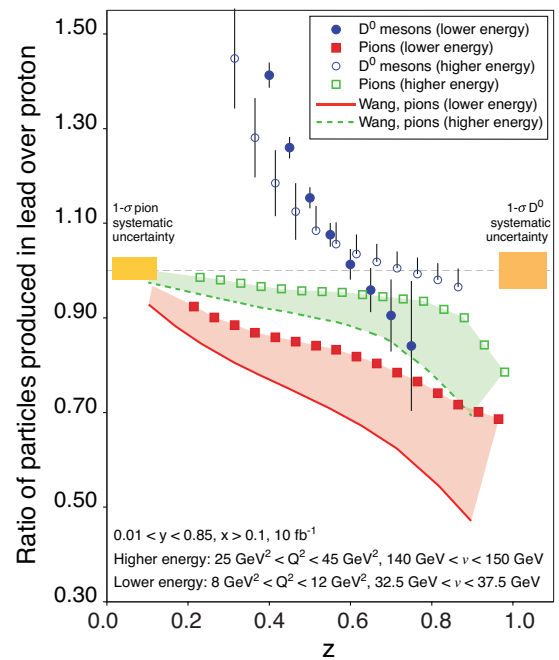
pA:

- Saturation effects at forward rapidities (di-hadrons, ridge)

AA:

- Initial conditions, $G(x, Q^2, b_T, k_T)$
  - understanding of v_n, ultimately η/s,
- Energy loss & hadronization
  - cold matter energy loss, hadron formation





eA at EIC: Connections

pA:

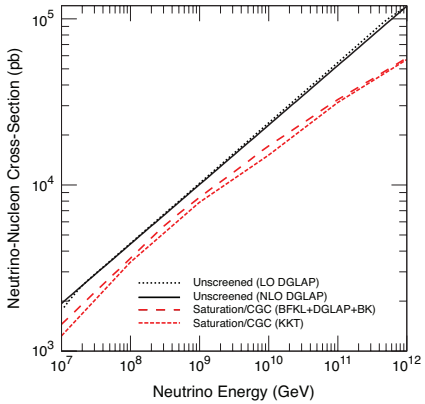
- Saturation effects at forward rapidities (di-hadrons, ridge)

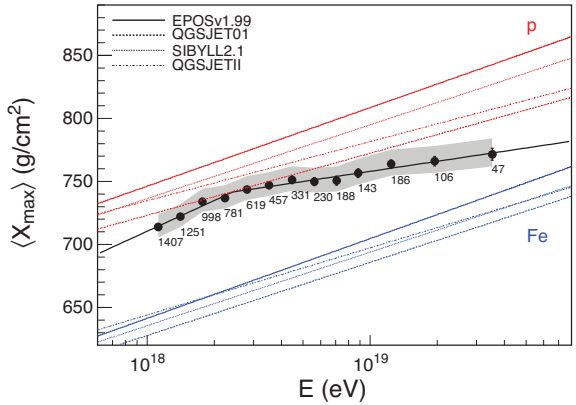
AA:

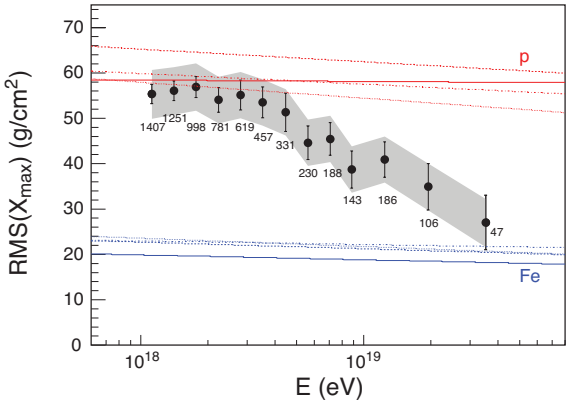
- Initial conditions, $G(x, Q^2, b_T, k_T)$
  - understanding of v_n, ultimately η/s,
- Energy loss & hadronization
  - cold matter energy loss, hadron formation

Cosmic Ray Physics:

- Cross-section ν+A (ultra-high cosmic ray showers)
- Depth of shower maxima in air shower (onset of saturation)







Take Away Message

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

- non-linear QCD/saturation/higher twist effects,
- properties of glue (momentum & space-time)
- cold matter energy loss
- new insight into fragmentation processes

Take Away Message

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

- non-linear QCD/saturation/higher twist effects,
- properties of glue (momentum & space-time)
- cold matter energy loss
- new insight into fragmentation processes

The e+A program is also a challenge experimentally

- new difficulties compared to e+p
- measurements never conducted in a collider
- no show stoppers found so far