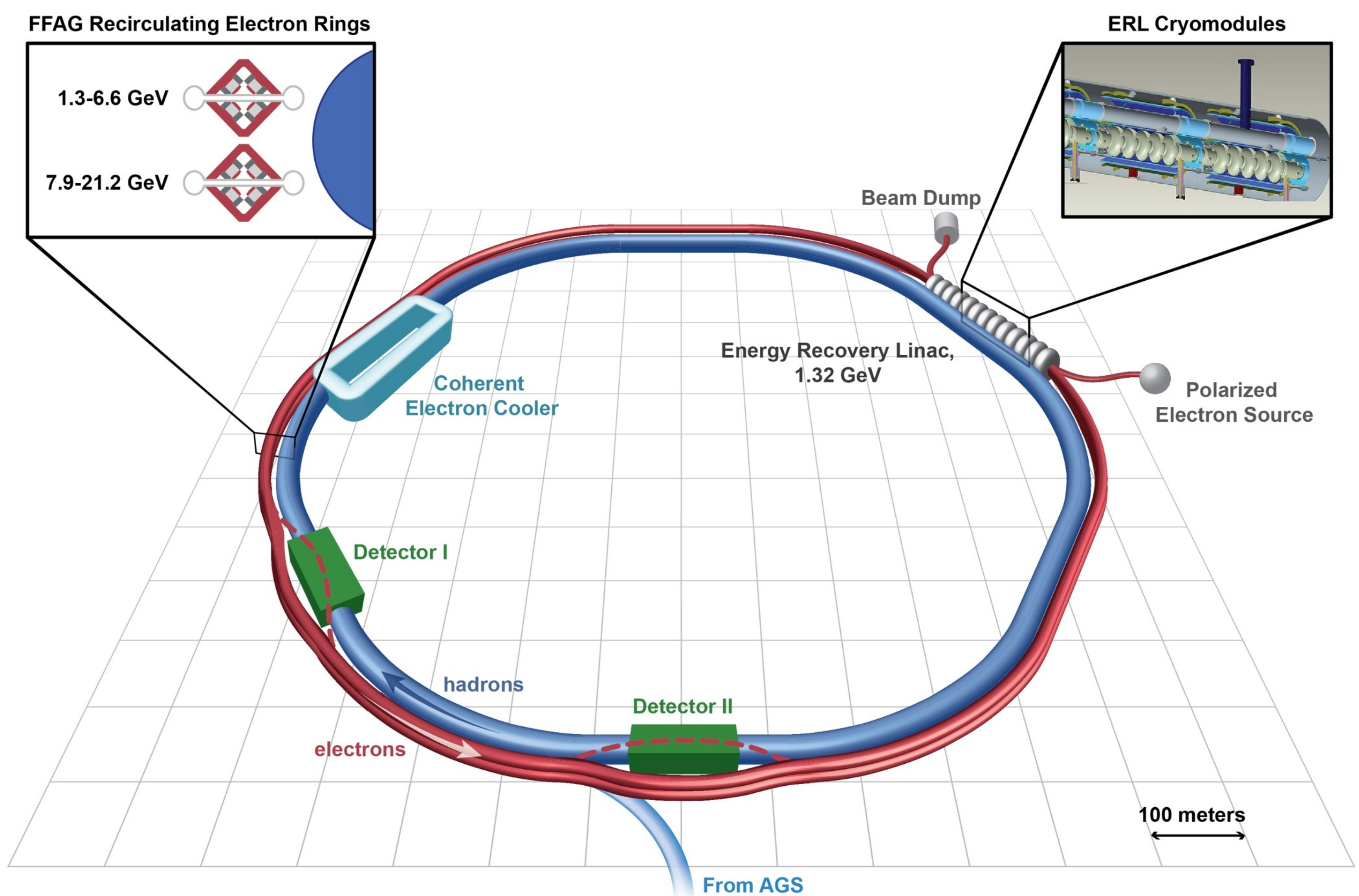
The experimental future of e+A physics at an EIC



Matthew A. C. Lamont
BNL

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Fundamental questions of QCD

- Confinement, chiral symmetry breaking, quantitative understanding of hadron masses, structure of the nucleon and the nucleus

- QCD under extreme conditions:
  - ➡ finite T (heavy ions, early Universe)
  - ➡ finite μB (neutron stars)
  - ➡ high energy QCD asymptotics

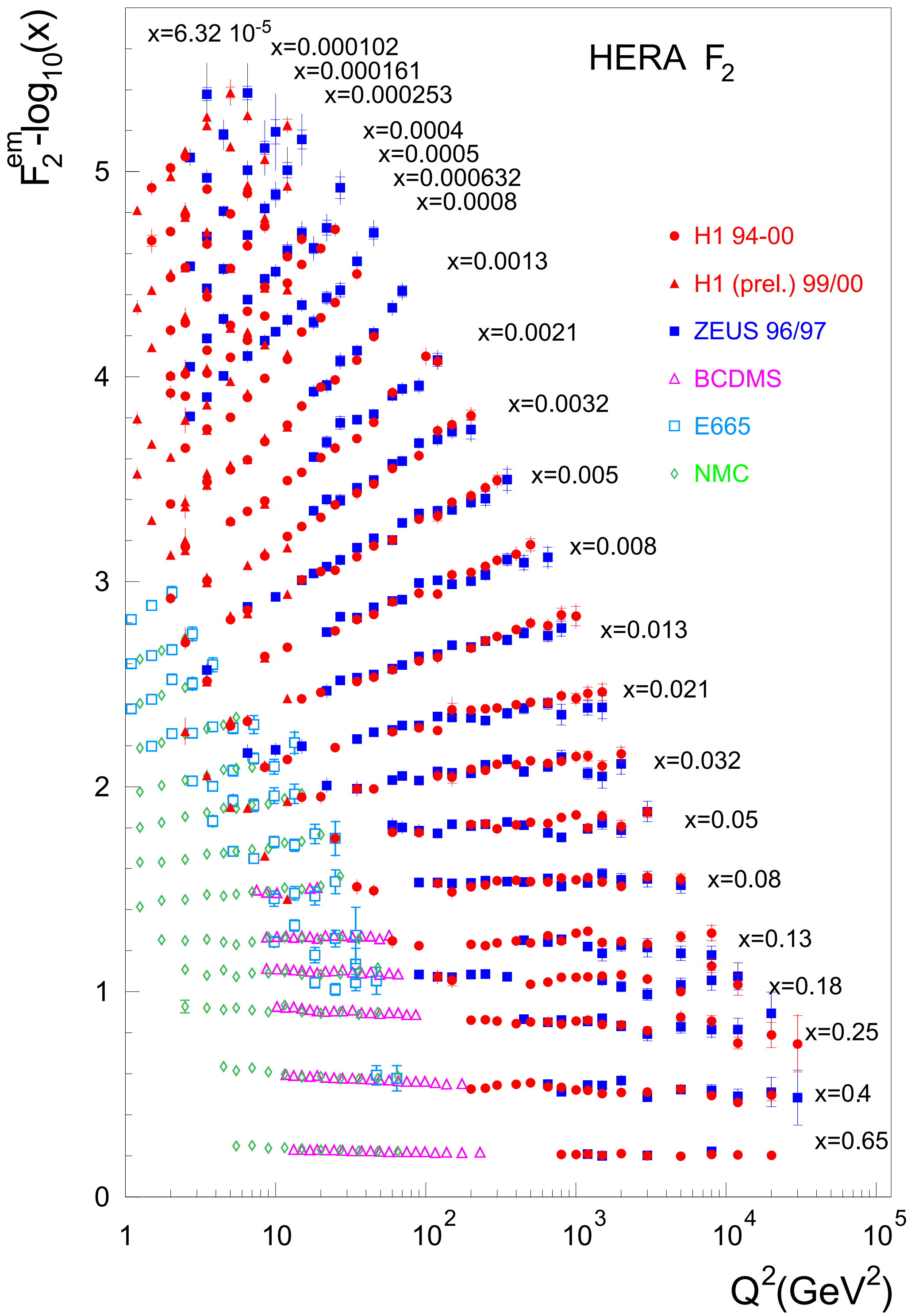
Fundamental questions of QCD at an EIC

- Confinement, chiral symmetry breaking, quantitative understanding of hadron masses, structure of the nucleon and the nucleus

- QCD under extreme conditions:
  - ➡ finite T (heavy ions, early Universe)
  - ➡ finite µB (neutron stars)
  - ➡ high energy QCD asymptotics

What did we learn from e+p collisions at HERA?

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

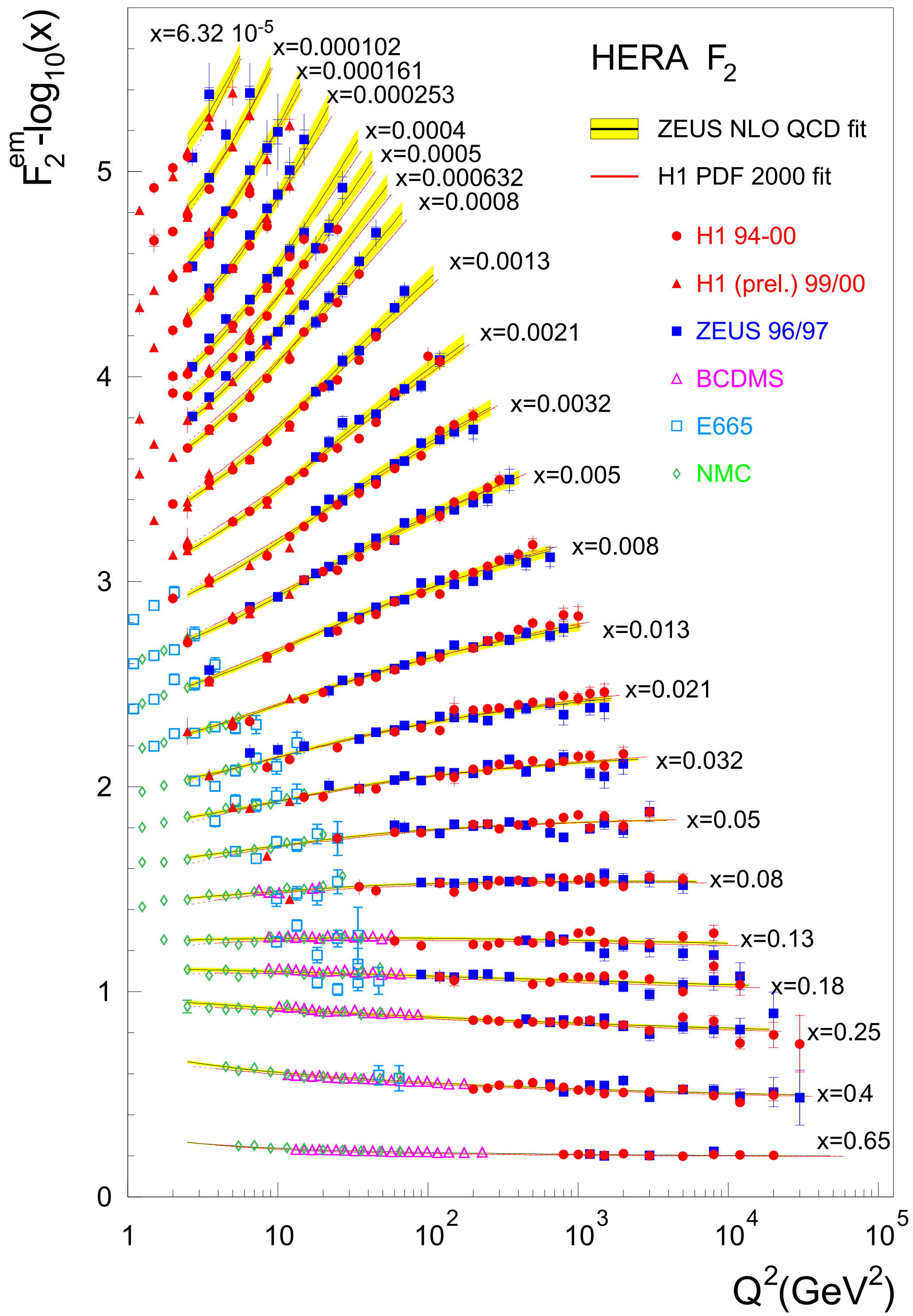


quark+anti-quark momentum distributions

gluon momentum distribution

What did we learn from e+p collisions at HERA?

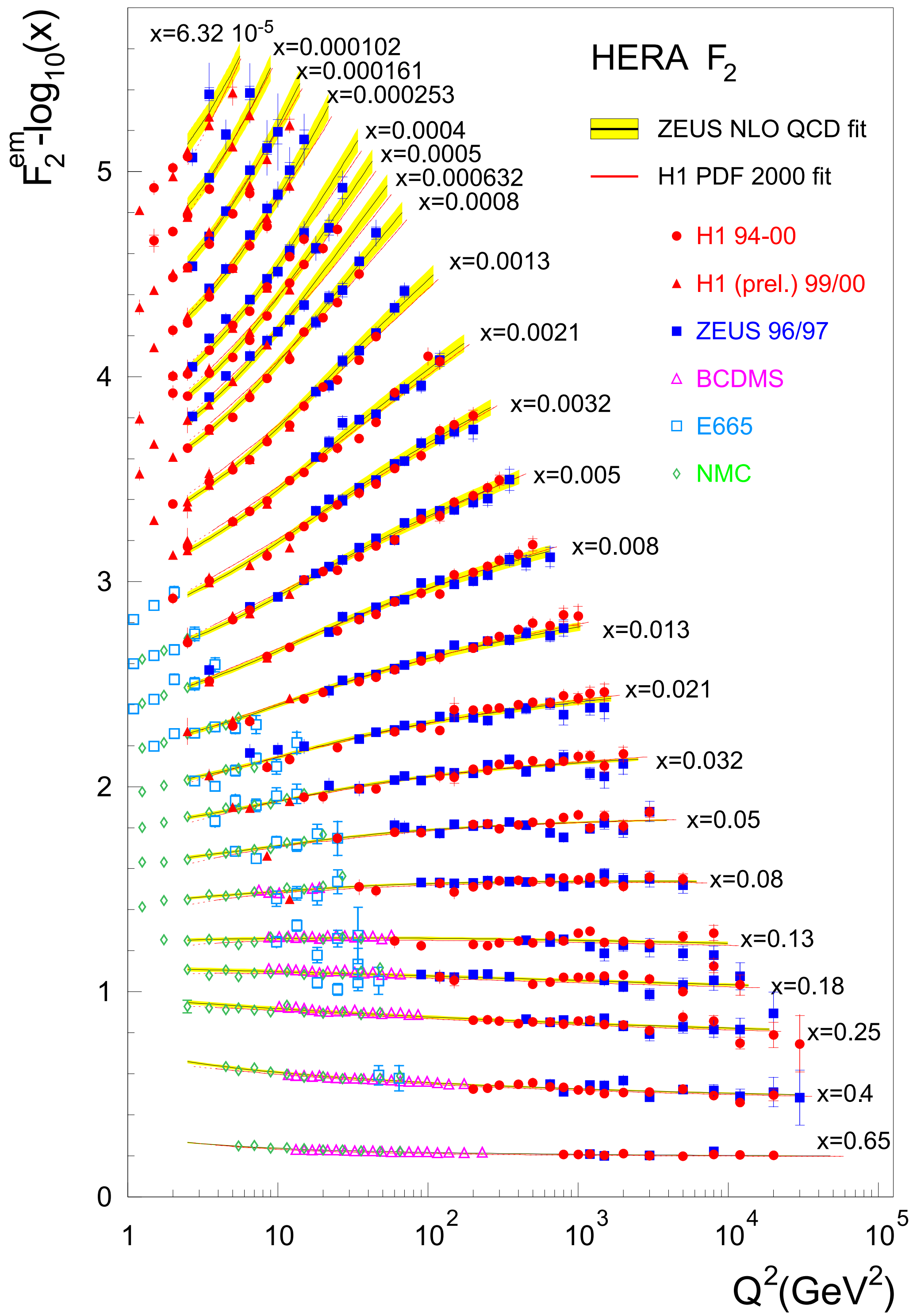
$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$



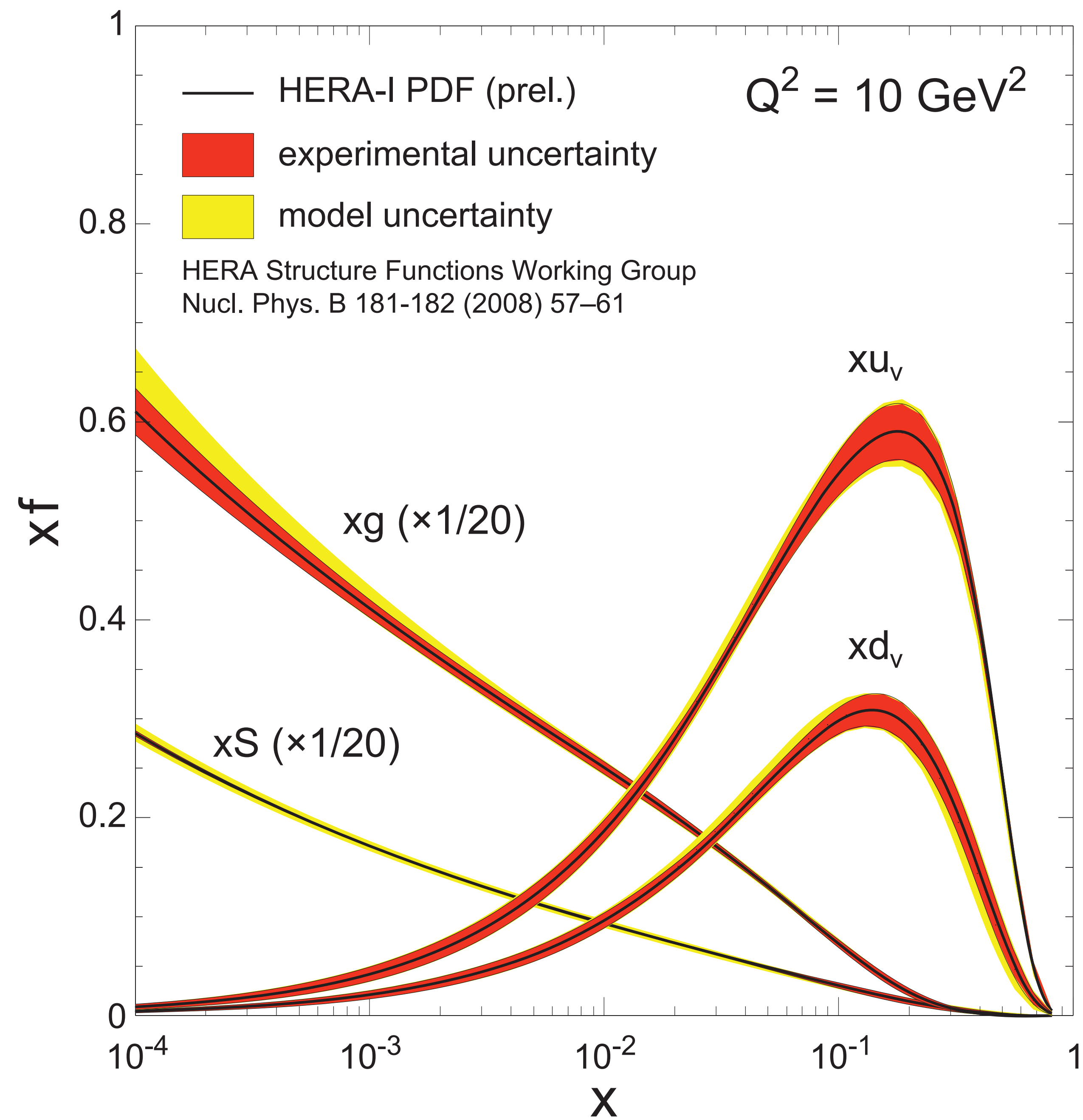
Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

What did we learn from e+p collisions at HERA?

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

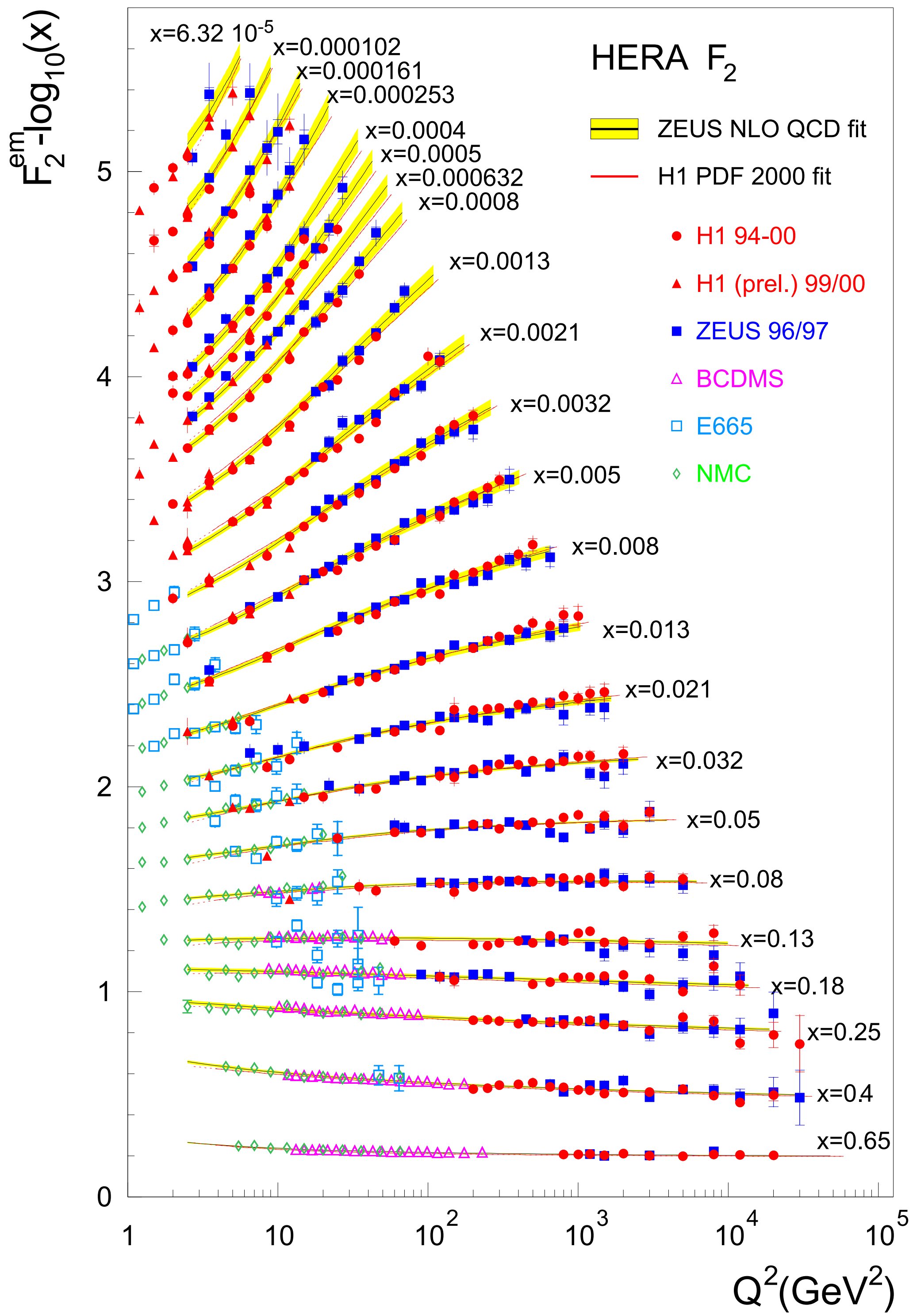


Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$

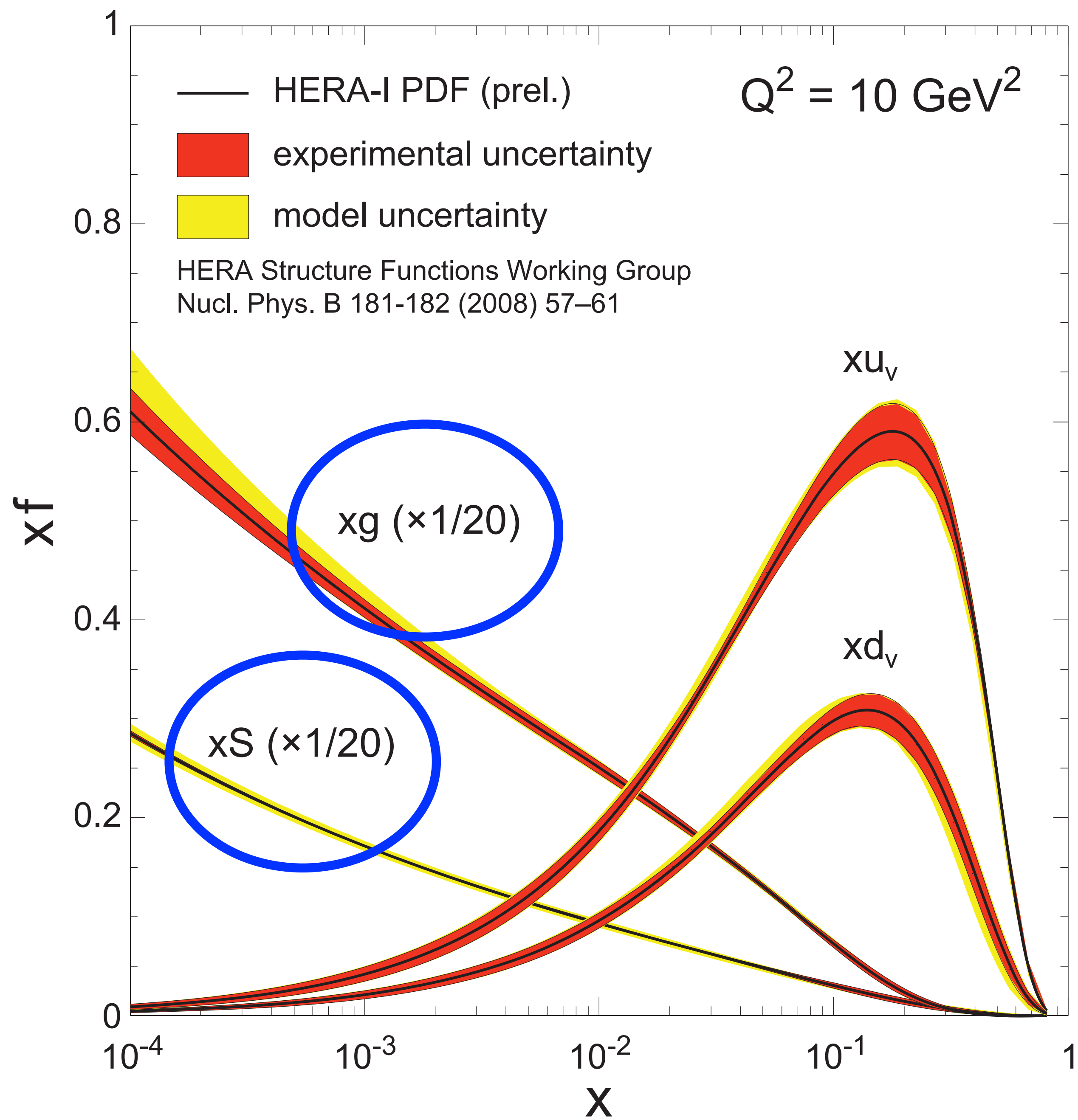


What did we learn from e+p collisions at HERA?

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

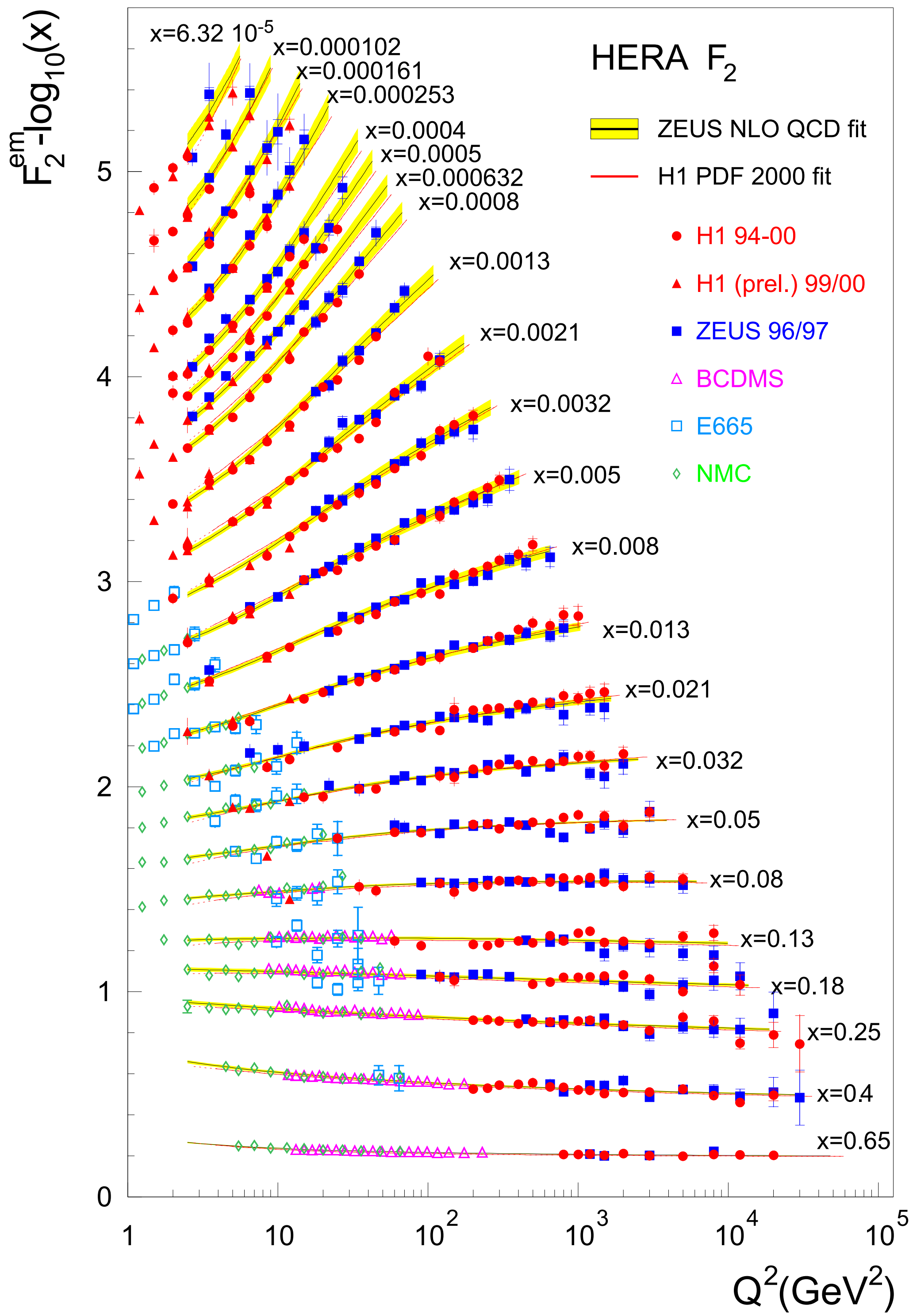


Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$

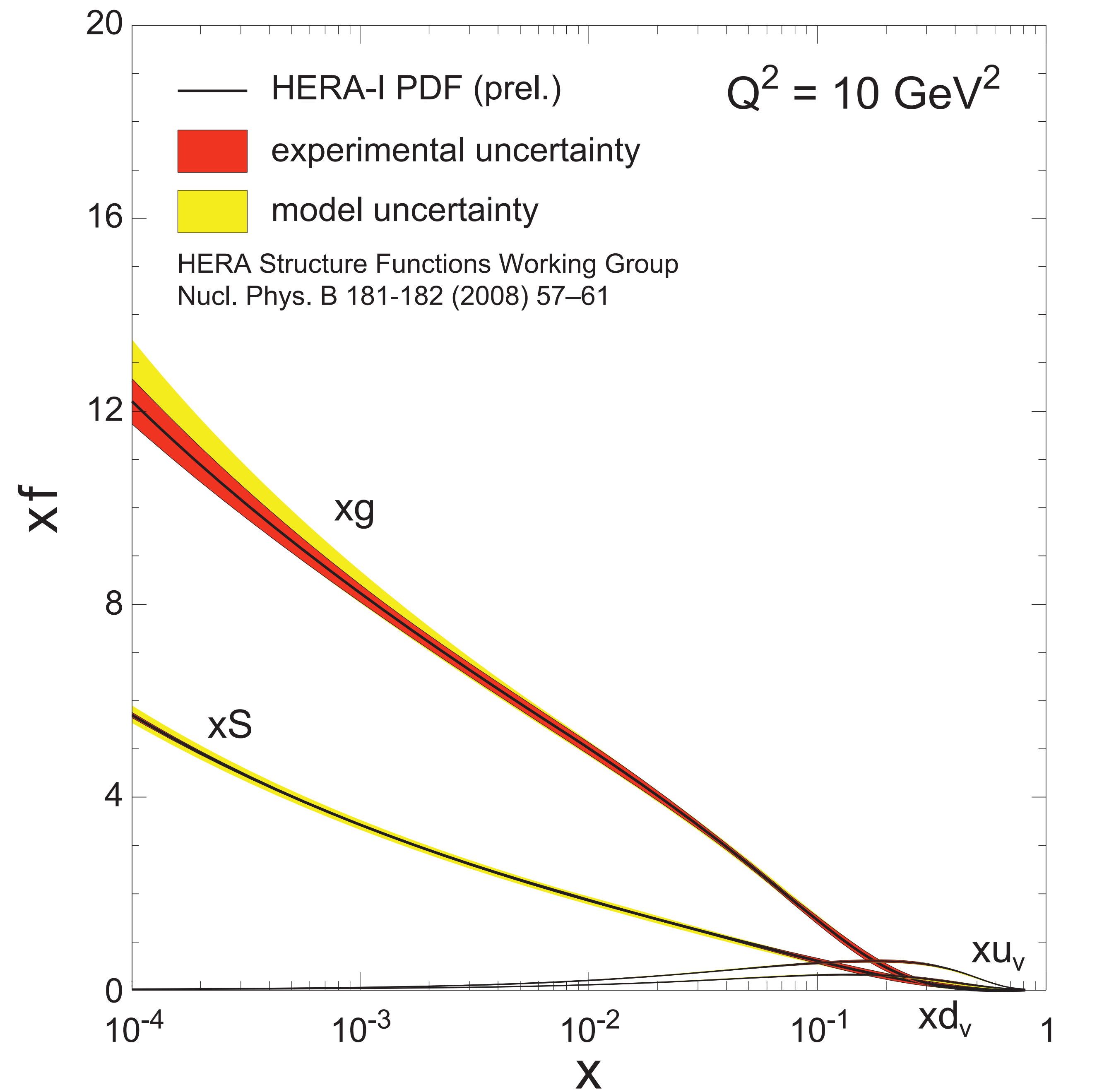


What did we learn from e+p collisions at HERA?

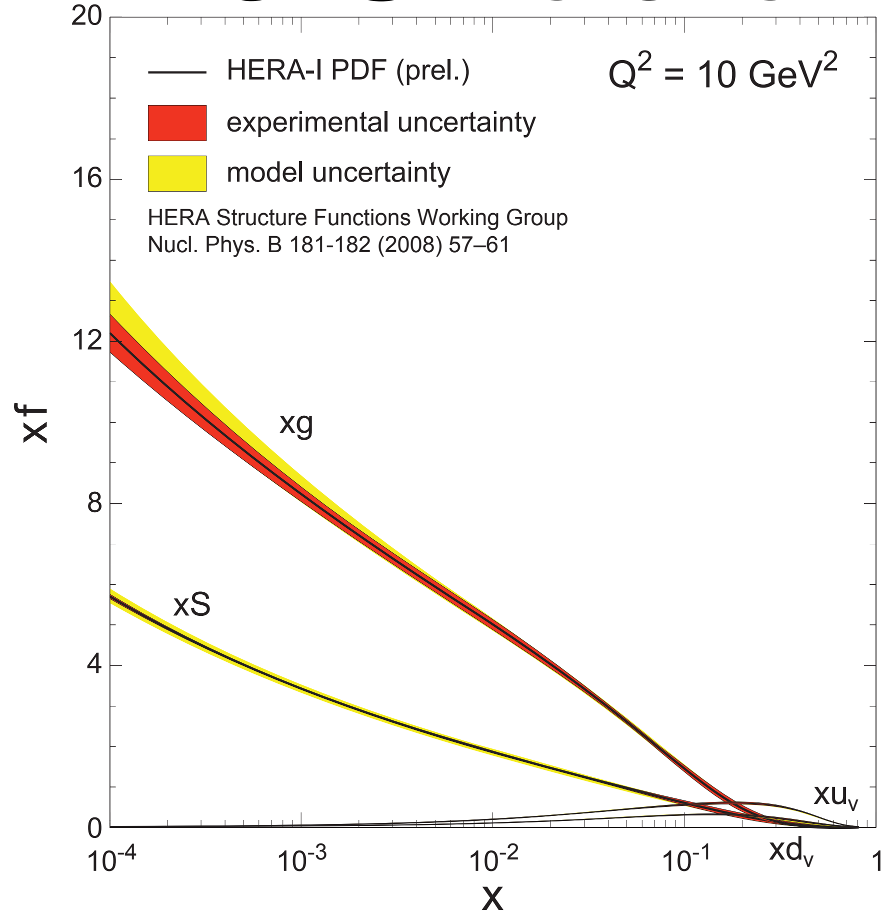
$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$

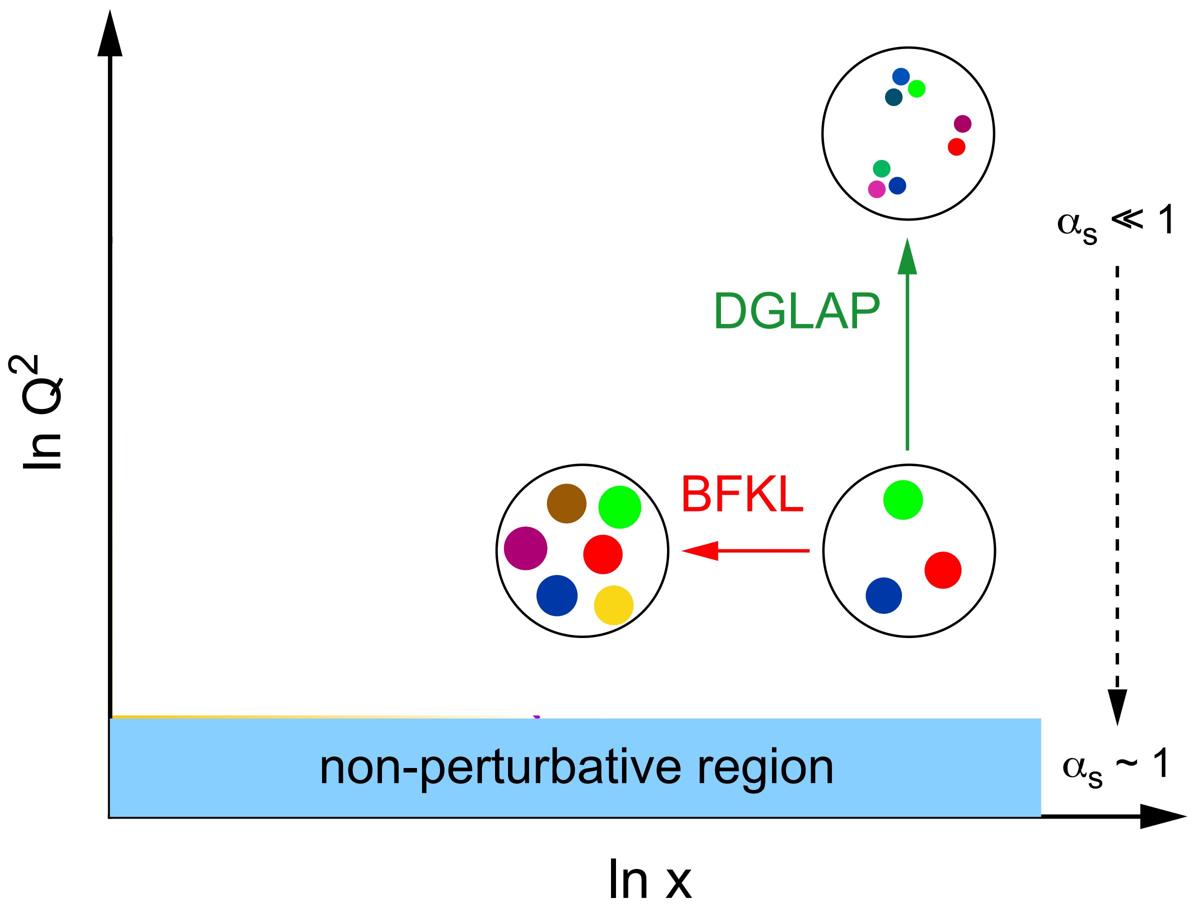


Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$

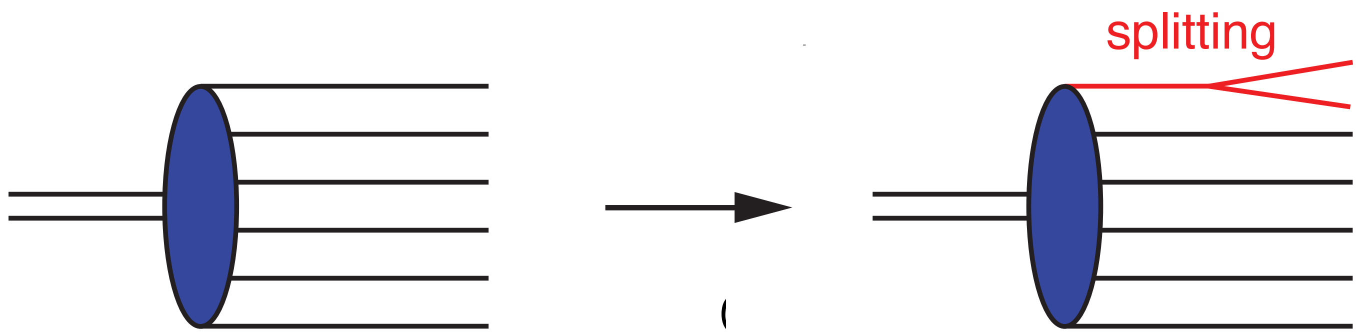


The structure of matter at small-x

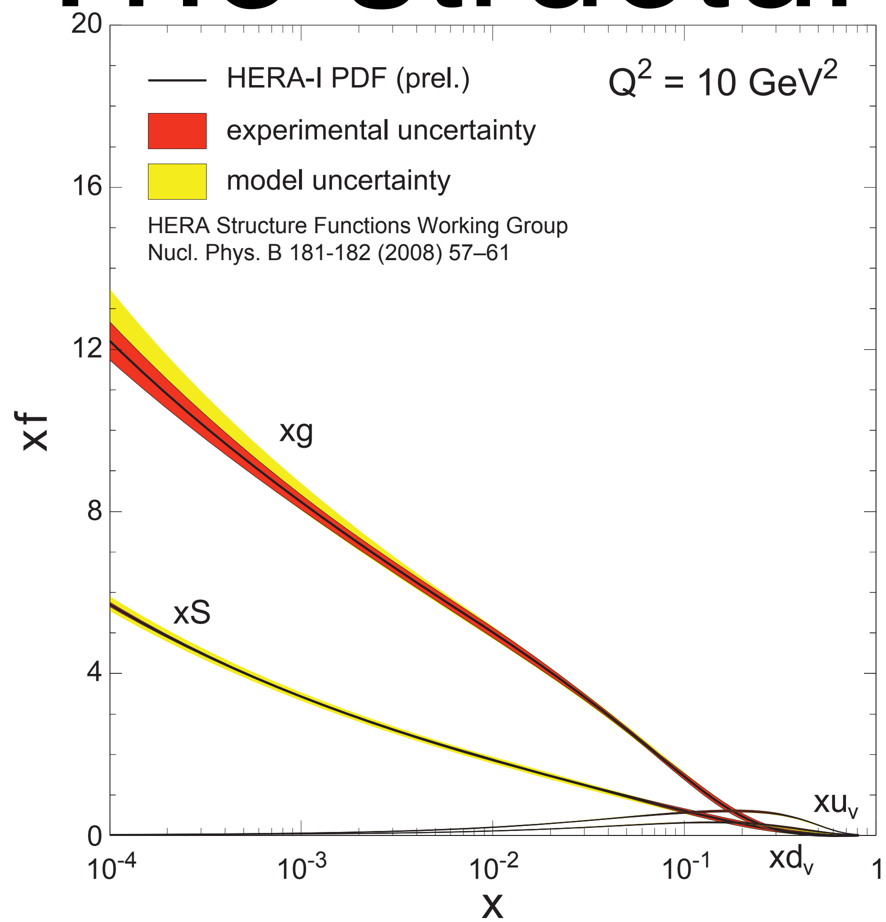


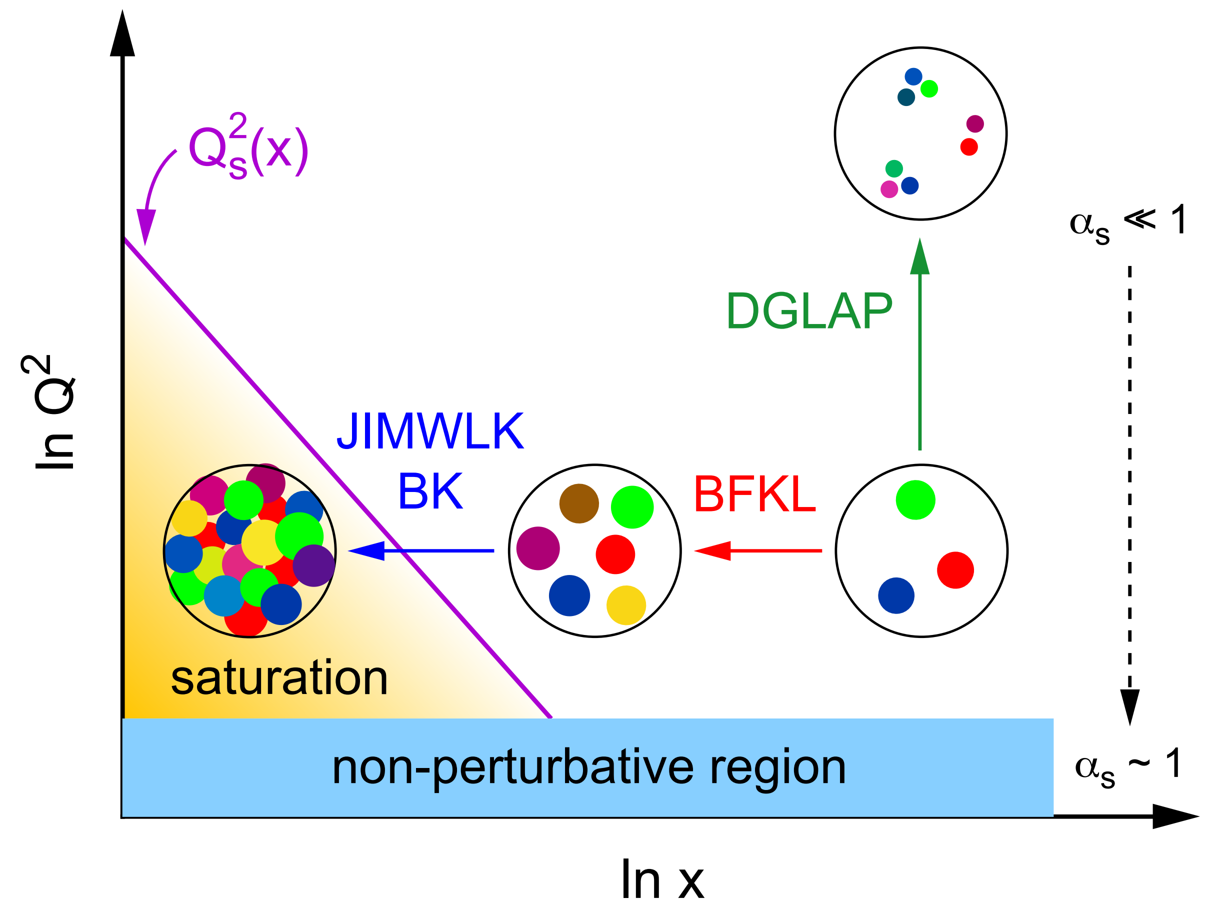


- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations

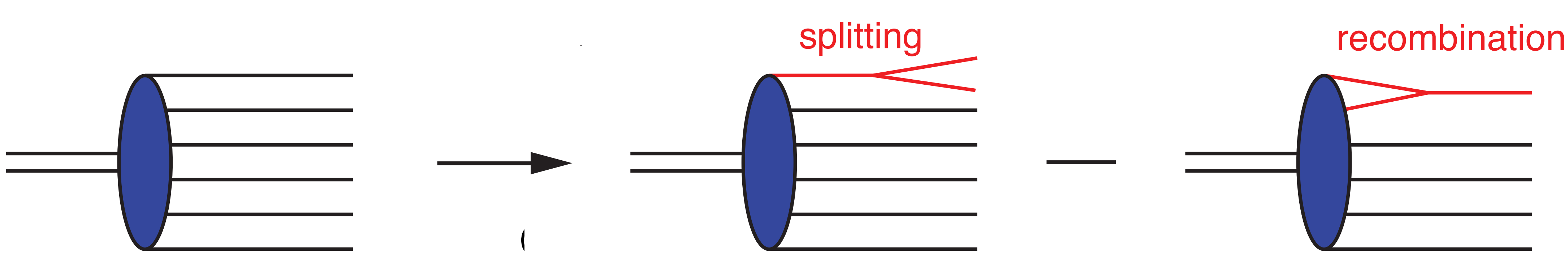


The structure of matter at small-x

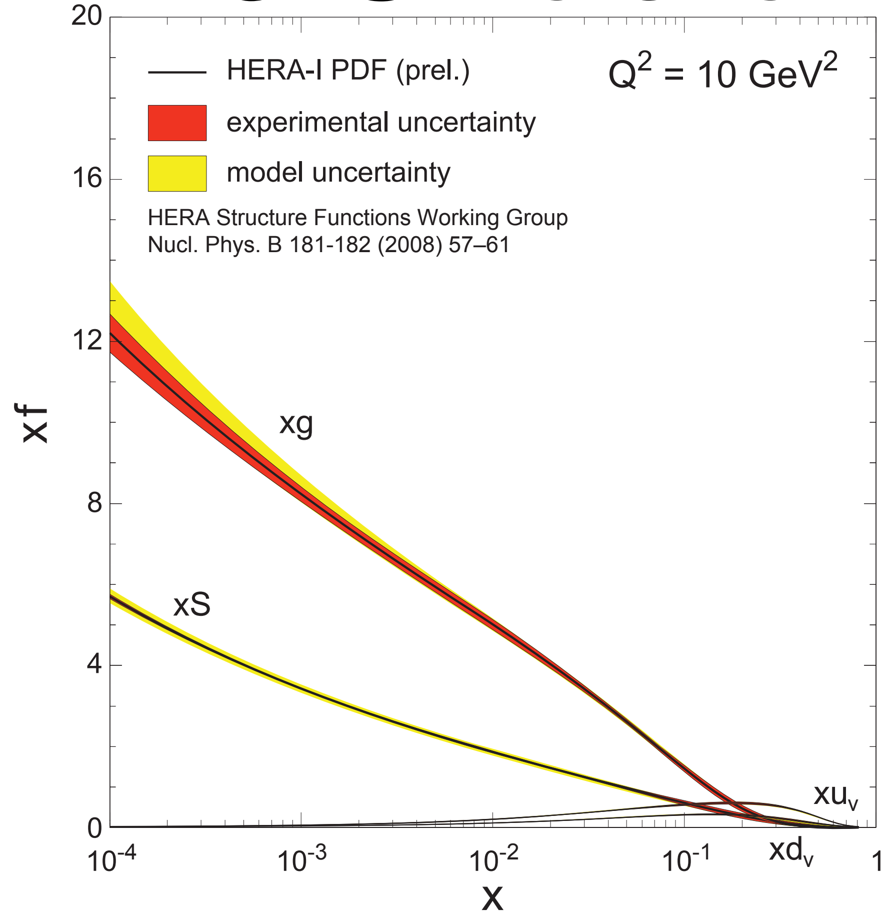


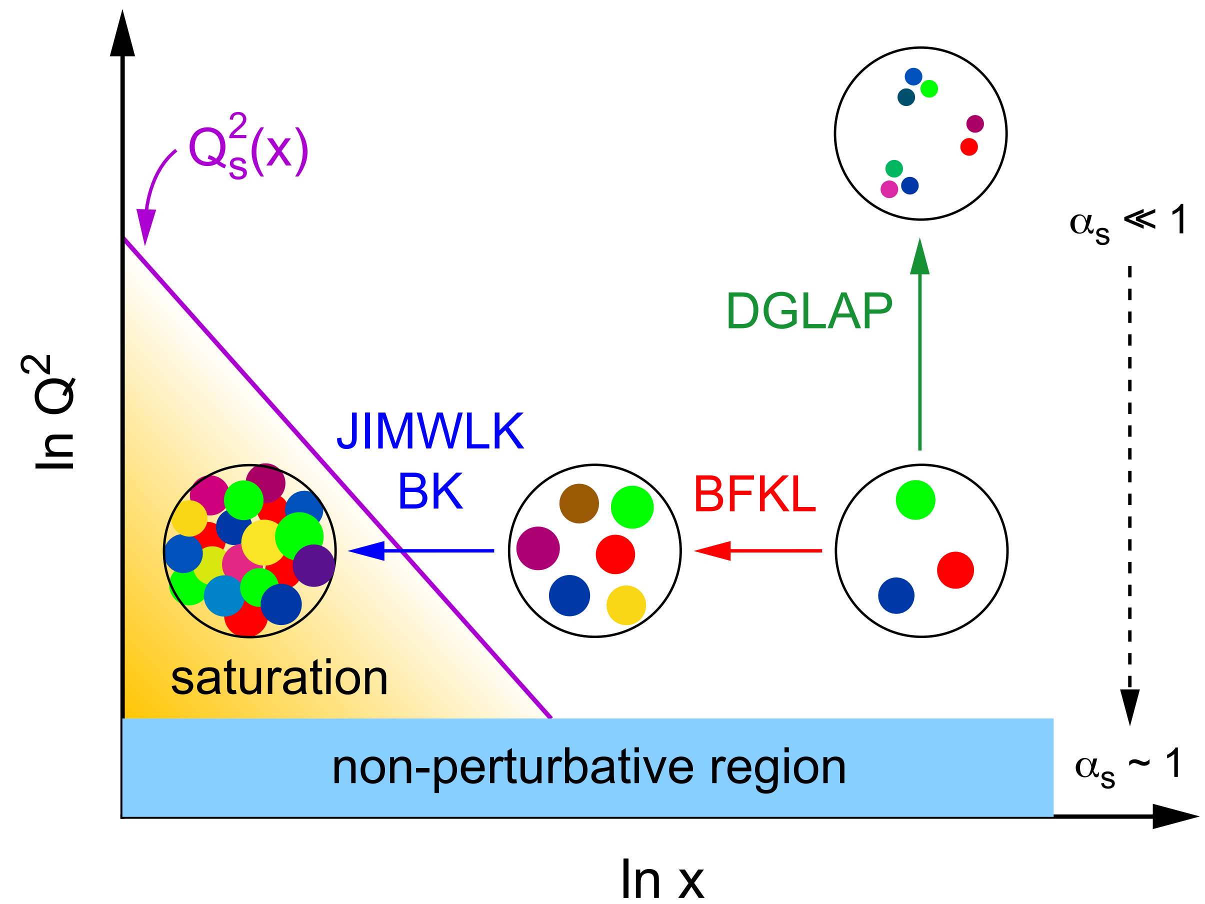


- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)
  - Rapid rise in gluons described naturally by linear pQCD evolution equations
  - This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2{}_S(x)$



The structure of matter at small-x

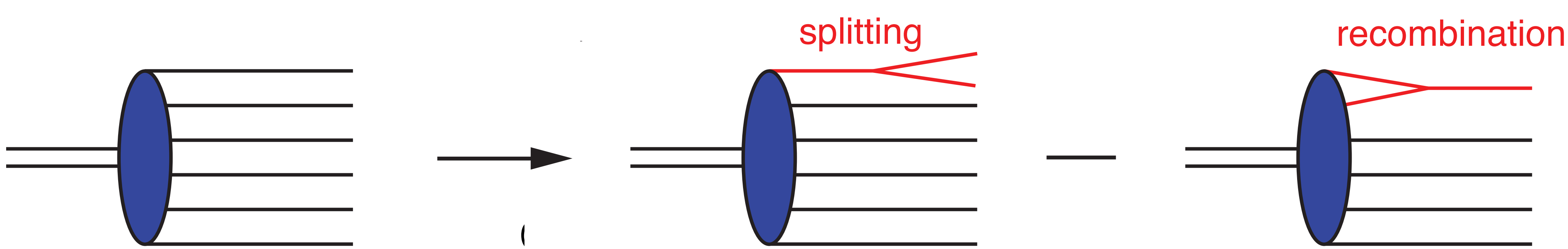




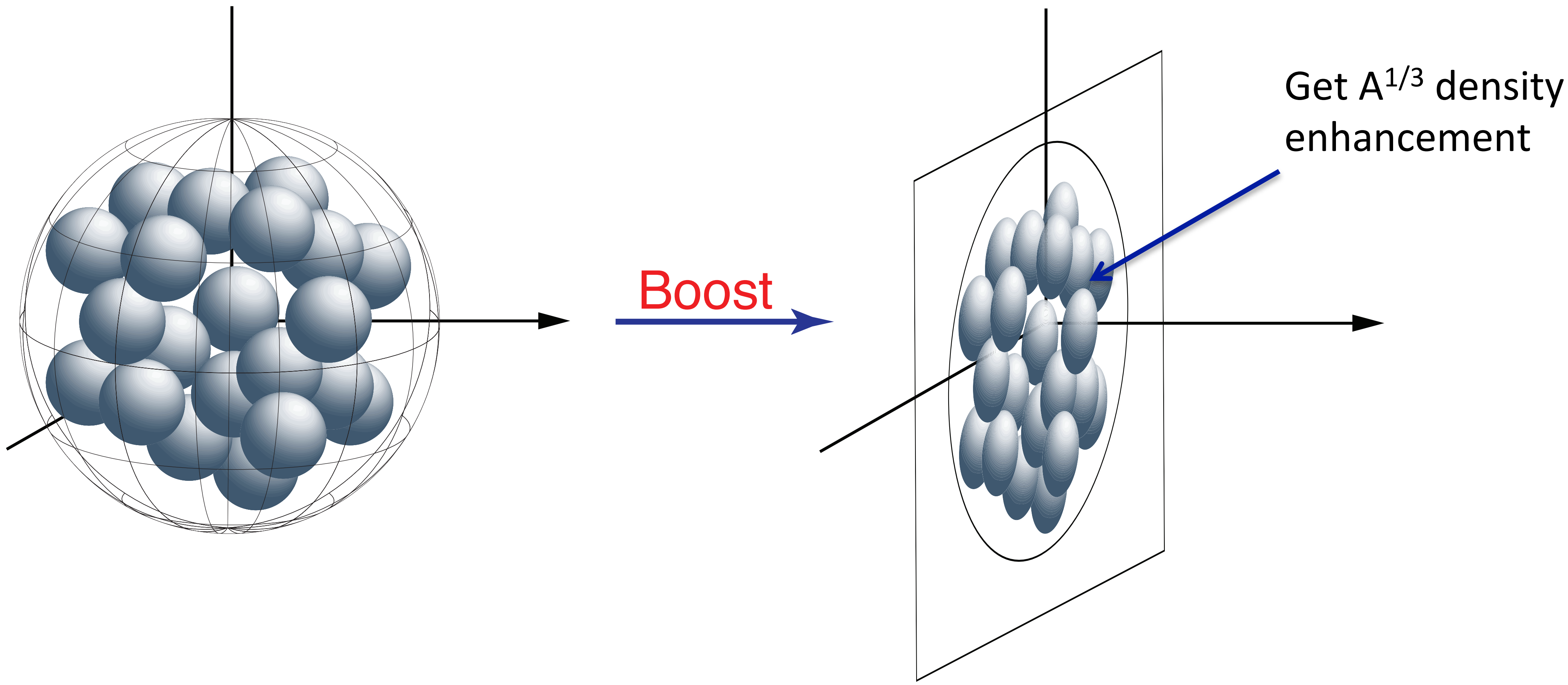
- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)

however - only tantalising hints of saturation in the gluon density from measurements at HERA -> too small an x

How can this be observed at eRHIC?



McLerran-Venugopalan Model



- Large gluon density gives a large momentum (saturation) scale, Q_s^2. Q_s^2 ~ #gluons per unit density ~$A^{1/3}$
- For $Q_s >> \Lambda_{QCD}$, theory is weak coupling ($\alpha_s (Q_s^2) << 1$) and the leading gluon field is classical

High energy QCD: saturation physics

- The non-linear BK/JIMWLK equations and the MV model lead to a large internal momentum scale Q_s which grows with both decreasing x, increasing energy s (λ~0.3) and increasing atomic number A

$$Q_S^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

- such that:

$$\alpha_S = \alpha_S(Q_S) << 1$$

- We can calculate total cross-sections, parton multiplicities, correlations… from first principles

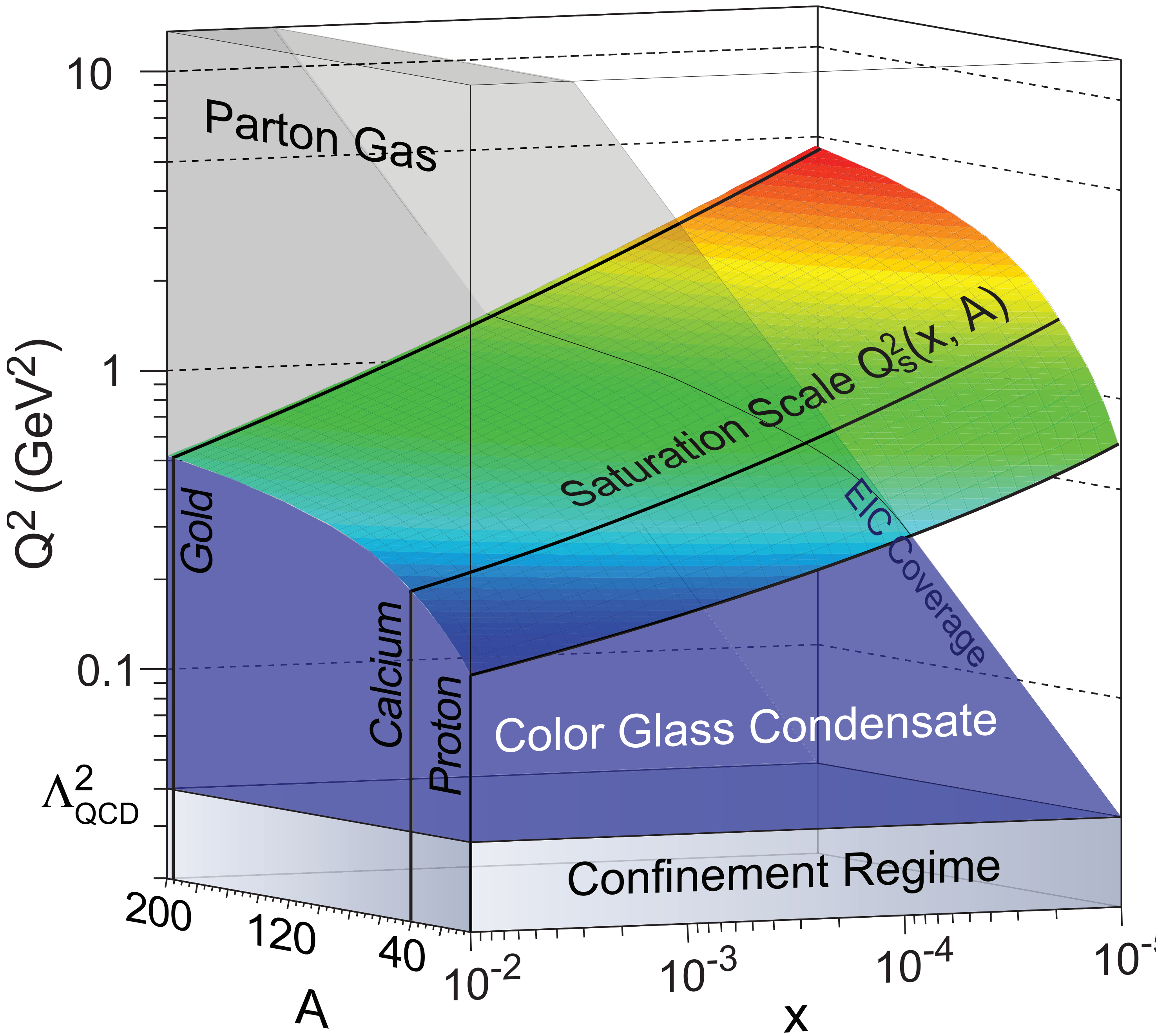
- Bottom line:

  ➡ Coupling is weak, Feynman diagrams work

  ➡ But: the system is dense and physics is nonlinear!

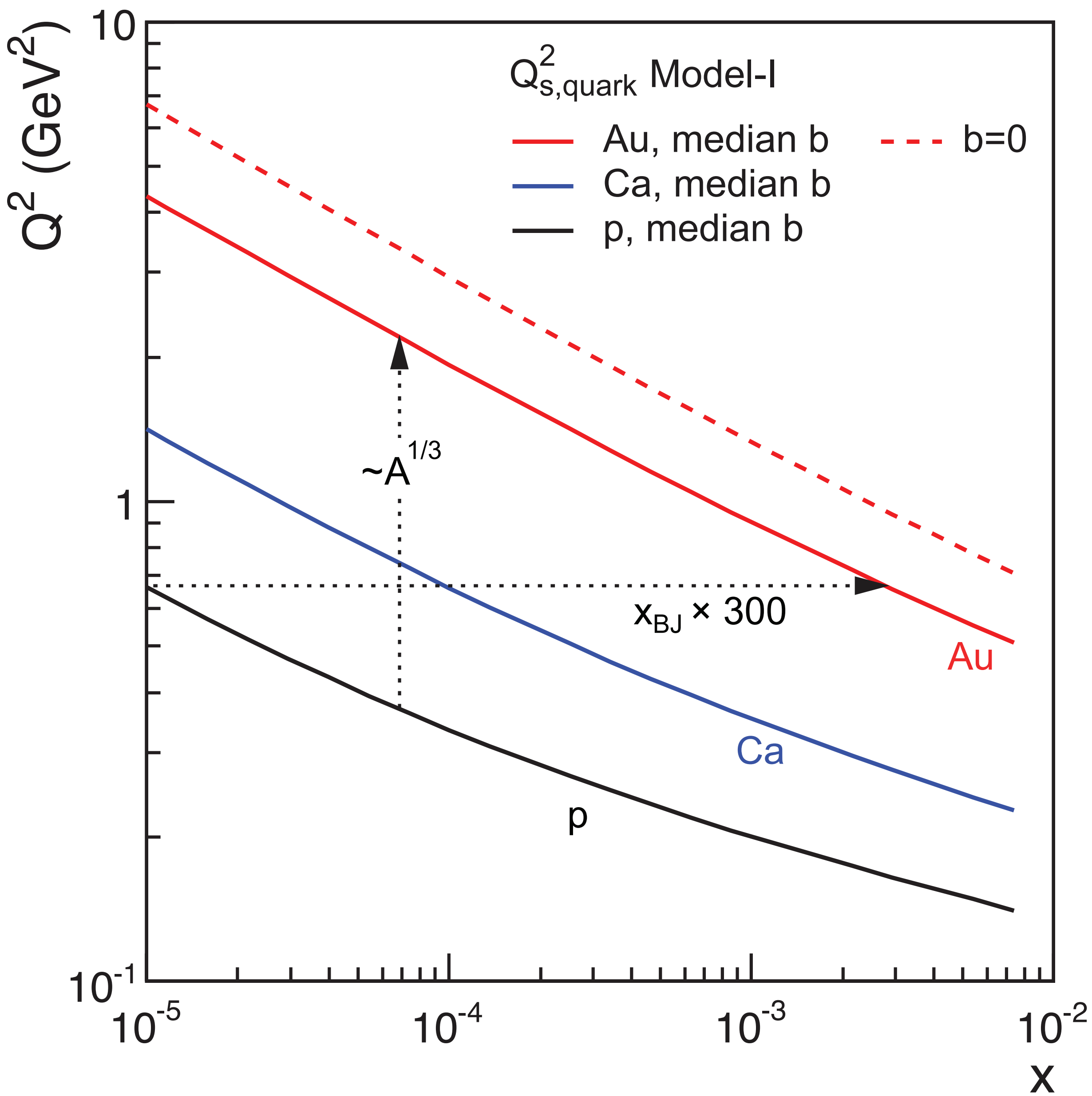
High energy QCD: saturation physics

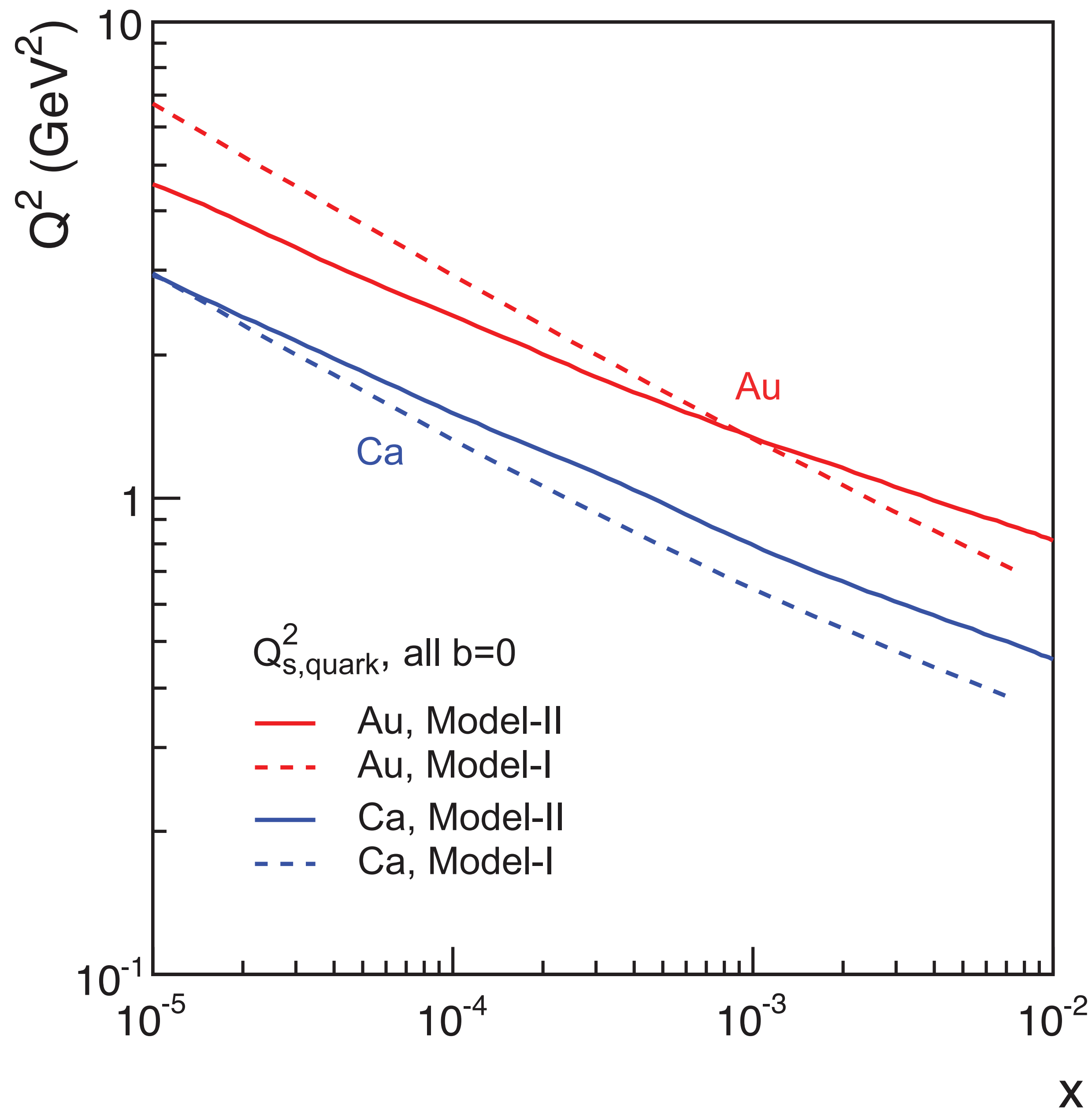
$$Q_s^2 \sim \left(\frac{A}{x}\right)^{1/3}$$



Nuclear “oomph” effect

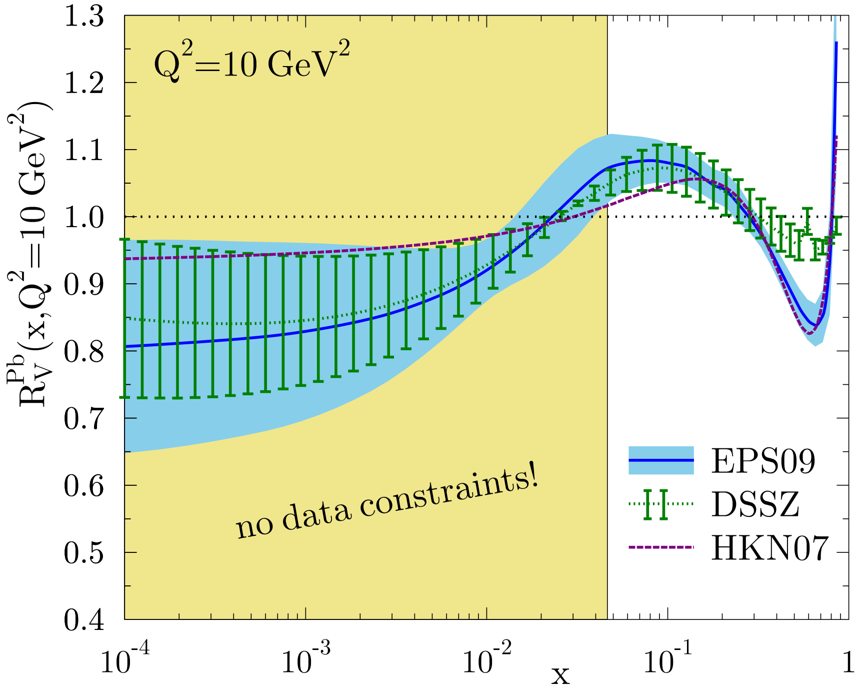
Pocket formula: $Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$



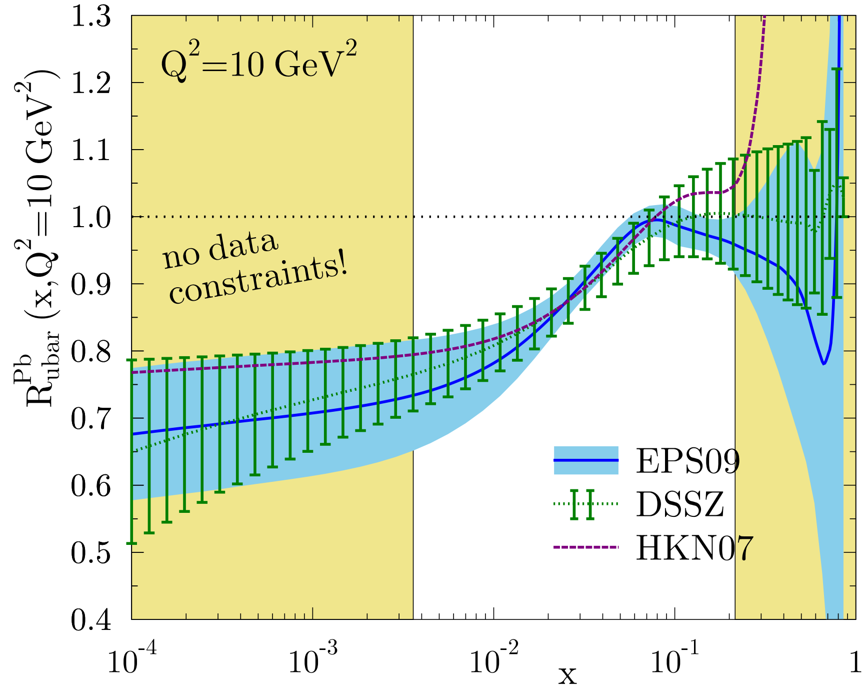


What do we know about the structure of nuclei?

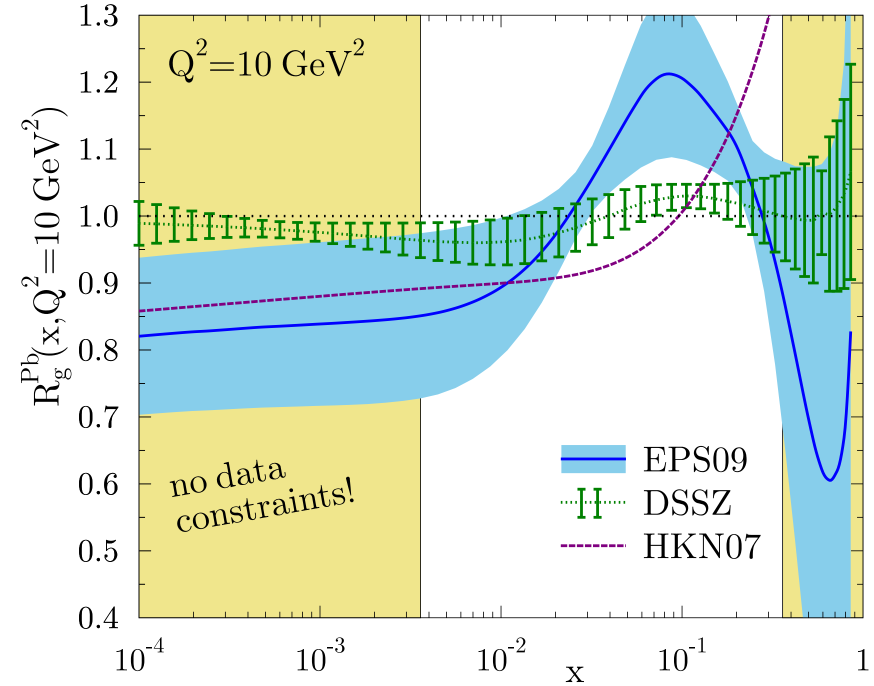
R_V^{Pb}



R_S^{Pb}



R_g^{Pb}

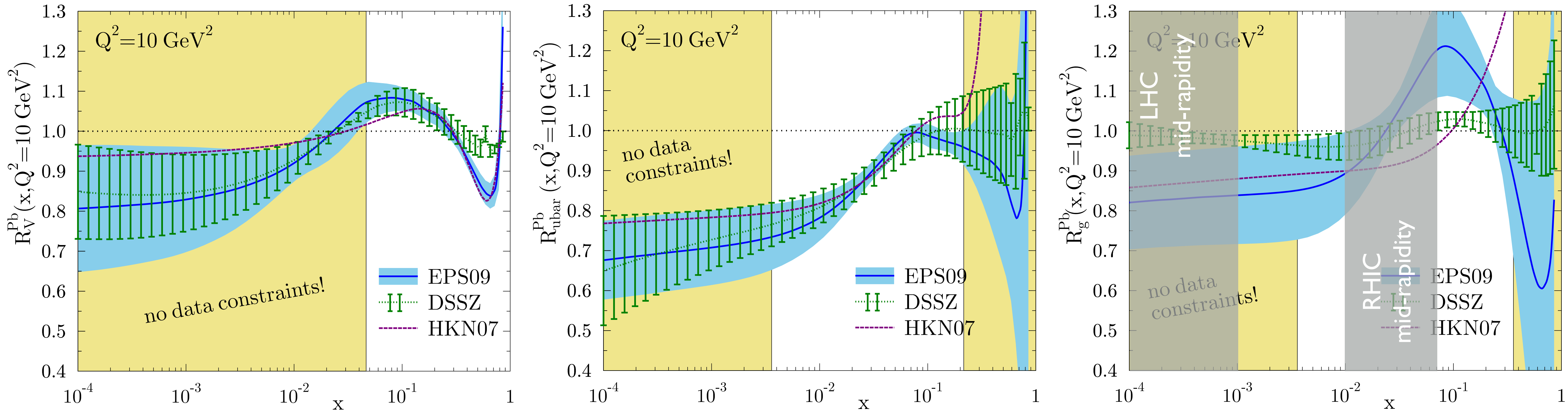


H. Paukkunen

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

What do we know about the structure of nuclei?

R_V^{Pb} R_S^{Pb} R_g^{Pb}



H. Paukkunen

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities, even for $Q^2 = 10$ GeV^2

Fundamental questions to be answered in e+A

Nucleus serves as:

- What is the fundamental quark-gluon structure of light and heavy nuclei? } Object of interest

- Can we experimentally find and explore a novel universal regime of strongly correlated QCD dynamics?

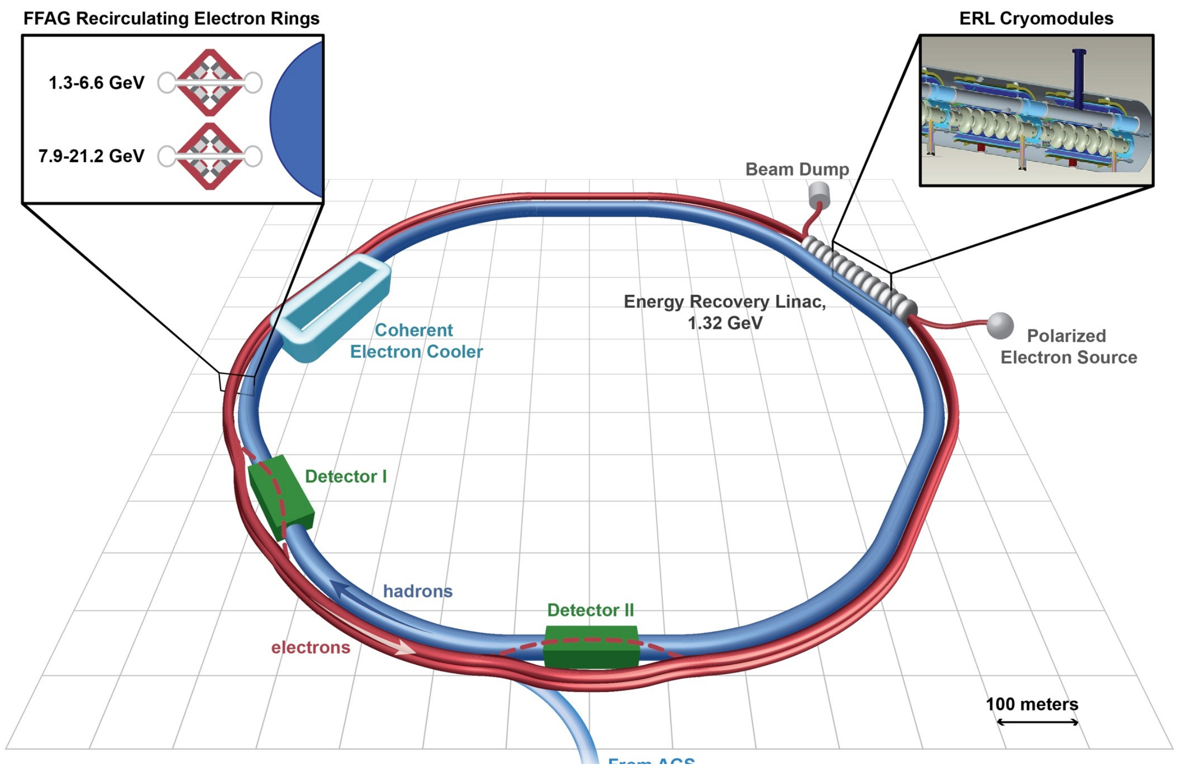
- What is the role of saturated strong gluon fields? What are the degrees of freedom in this strongly interacting regime?

} Amplifier of physical phenomena

- Can the nuclear colour filter provide novel insight into propagation, attenuation and hadronization of coloured probes? } Analyzer of physical phenomena

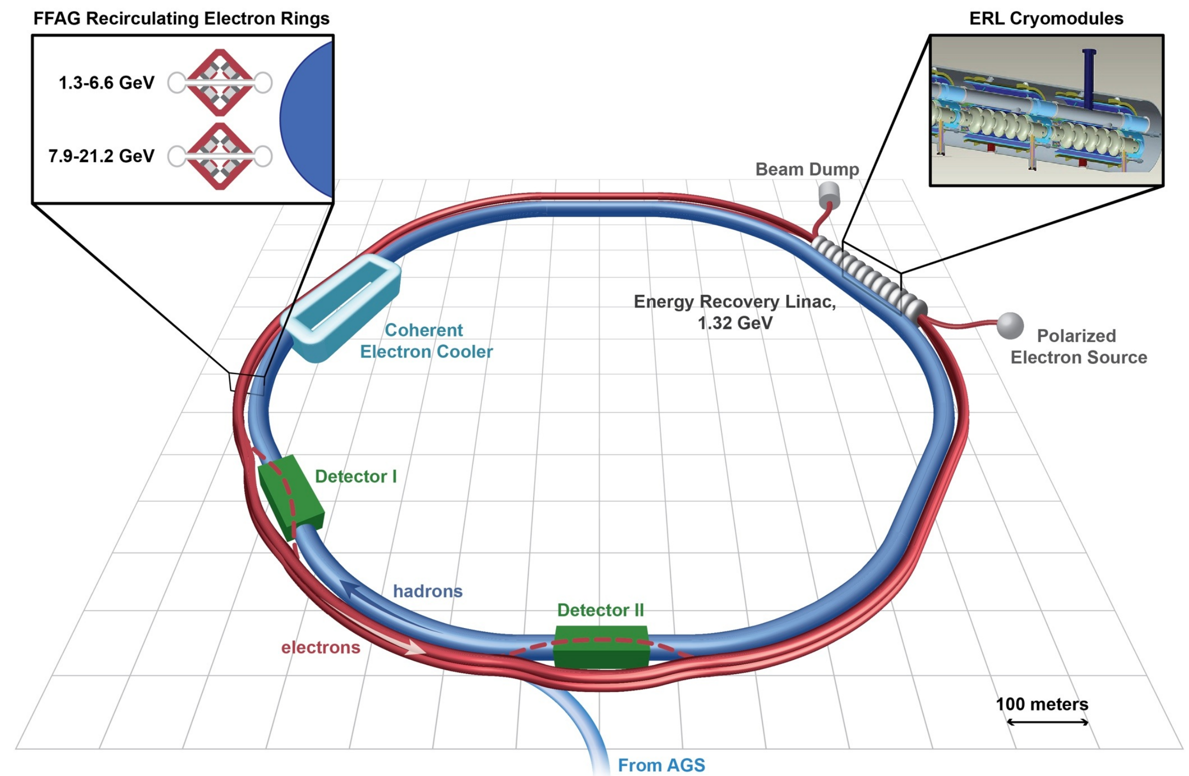
The realization of an Electron-Ion Collider

- eRHIC (BNL) arXiv:1409.1633
  - Add ERL+FFAG recirculating e rings to RHIC facility
  - Electrons: 6.3→15.9 & 21.2 GeV
  - Ions: up to 100 GeV/A
  - $\sqrt{s} \simeq 20 \rightarrow 93$ GeV
  - $L \simeq 1.7 \times 10^{33}\ cm^{-2} s^{-1}$/A at $\sqrt{s} = 80$ GeV

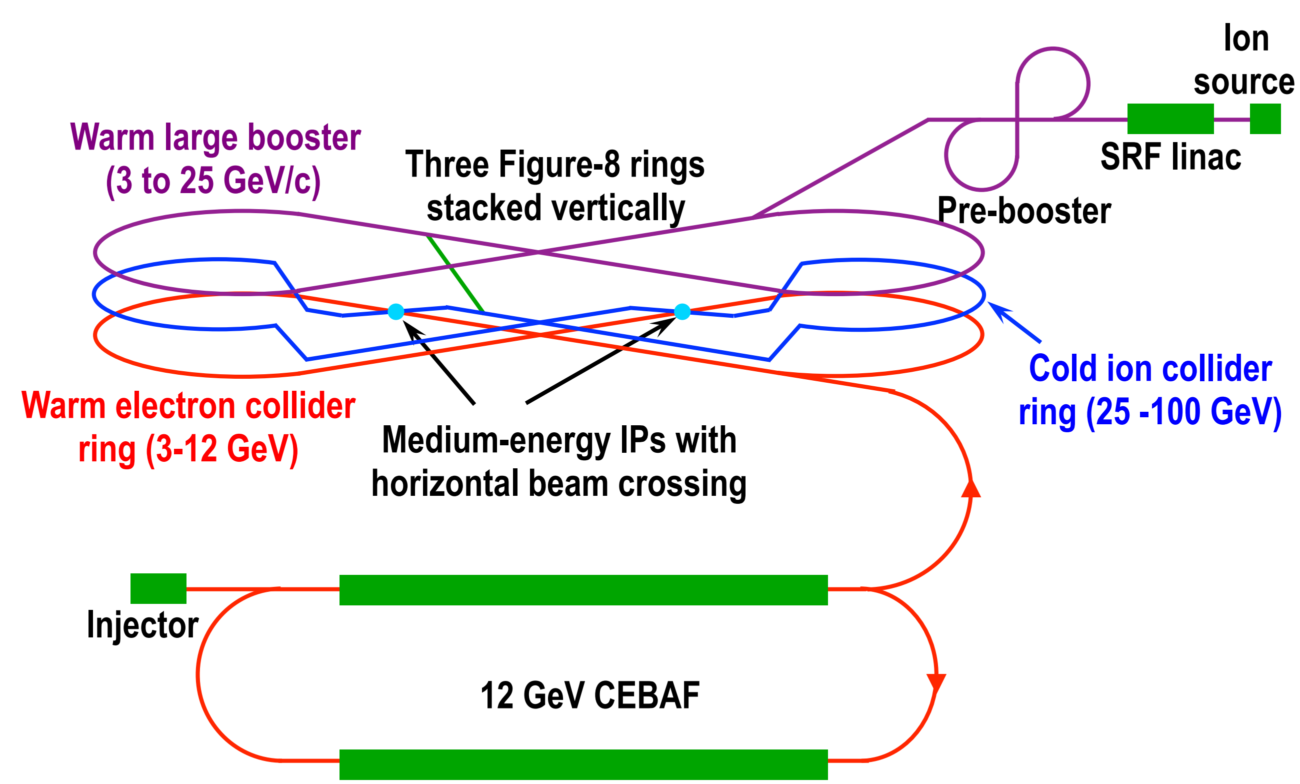


The realization of an Electron-Ion Collider

- eRHIC (BNL) arXiv:1409.1633
  - Add ERL+FFAG recirculating e rings to RHIC facility
  - Electrons: 6.3→15.9 & 21.2 GeV
  - Ions: up to 100 GeV/A
  - $\sqrt{s} \simeq 20 \rightarrow 93$ GeV
  - $L \simeq 1.7 \times 10^{33}$ cm^{-2} s^{-1}/A at $\sqrt{s} = 80$ GeV

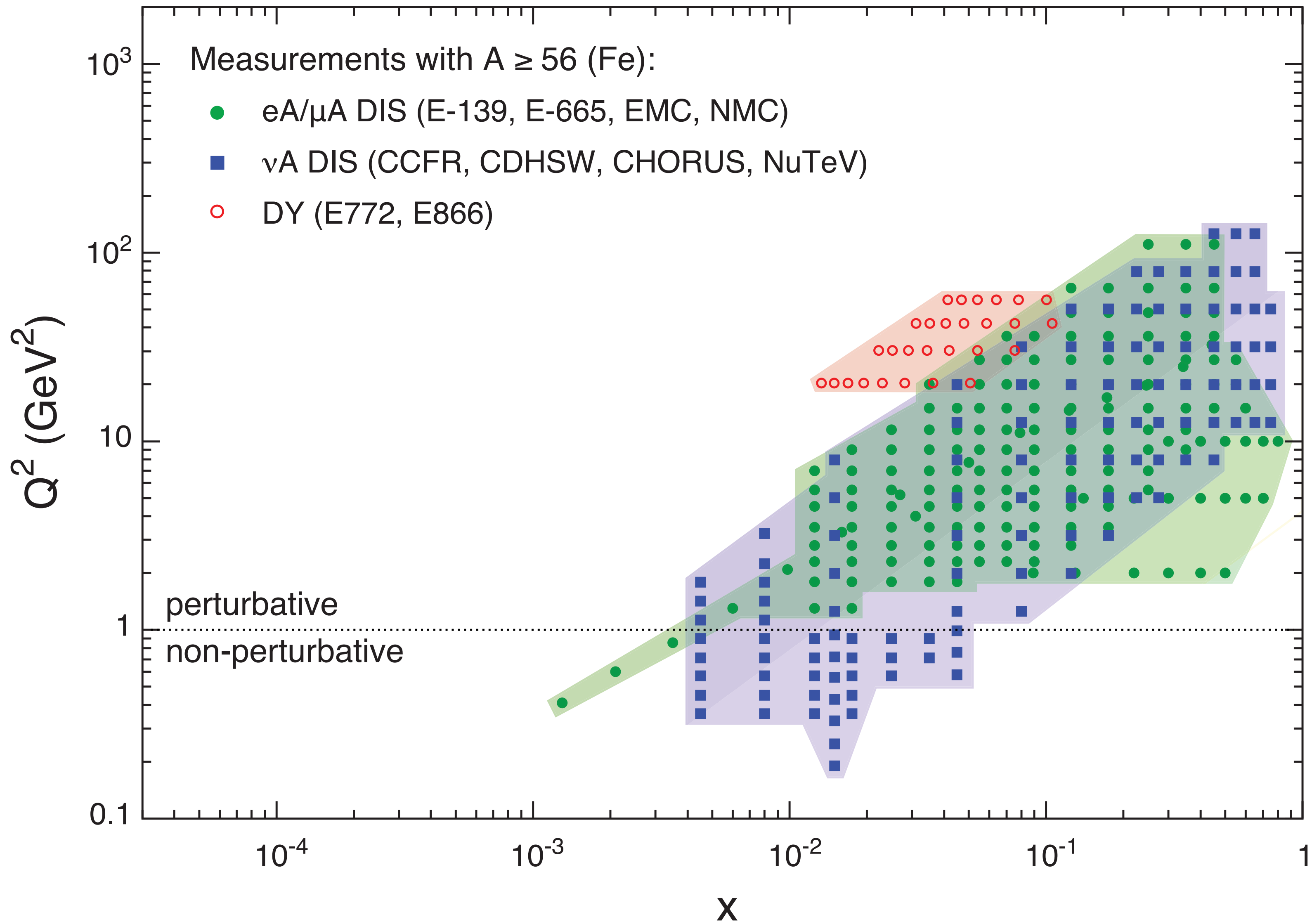


- MEIC (JLAB) arXiv:1209.0757
  - Add a Figure-of-8 ring-ring collider to CEBAF
  - Electrons: 3 → 12 GeV
  - Ions: 12 → 40 GeV/A
  - $\sqrt{s} \simeq 11 \rightarrow 45$ GeV
  - $L \simeq 2.4 \times 10^{34}$ cm^{-2} s^{-1}/A at $\sqrt{s} = 22$ GeV



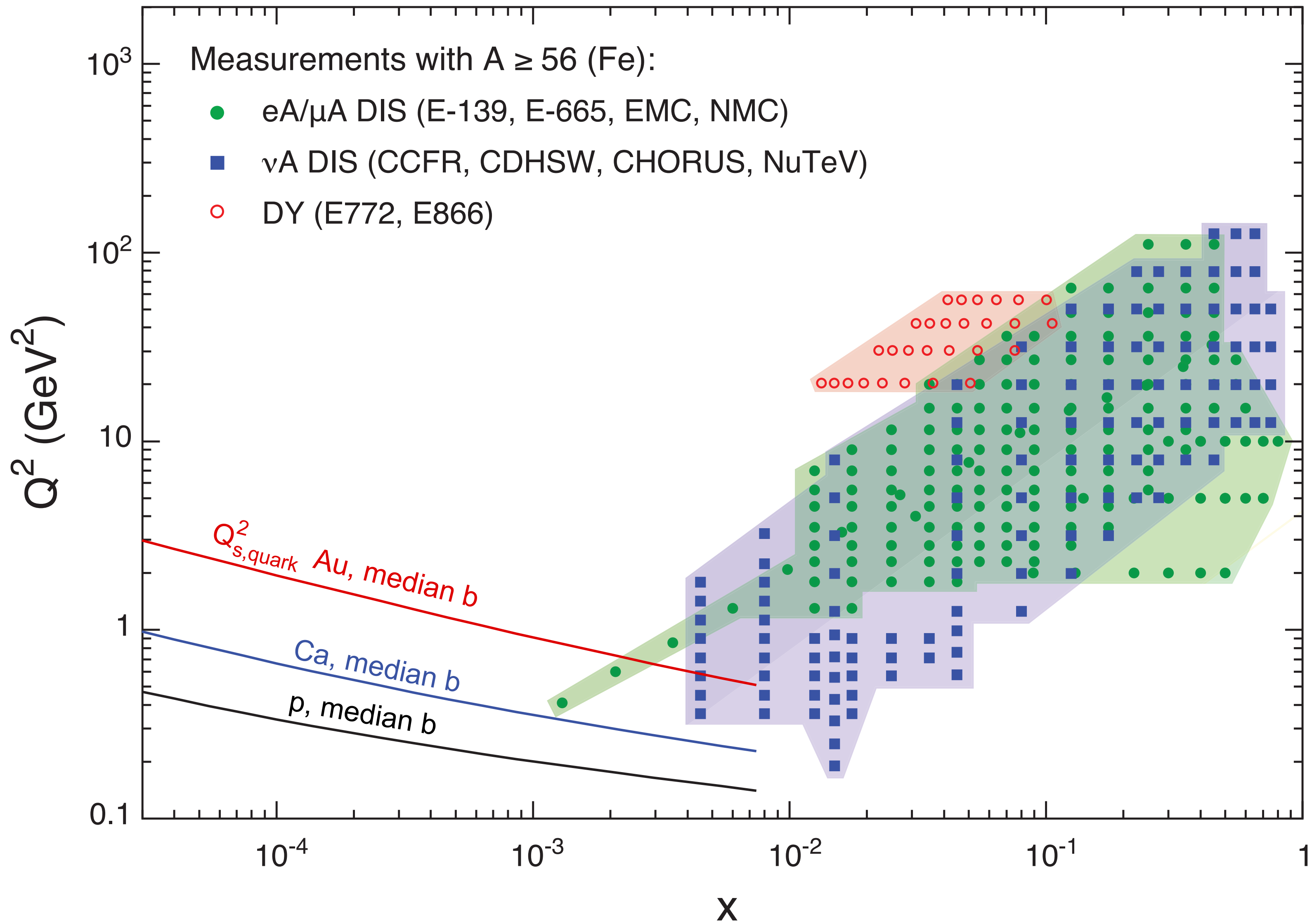
The landscape of e+A collisions

- Existing data is sparse - typically low energy and low A
- Not a large coverage in (x,Q^2) phase-space (unlike e+p)



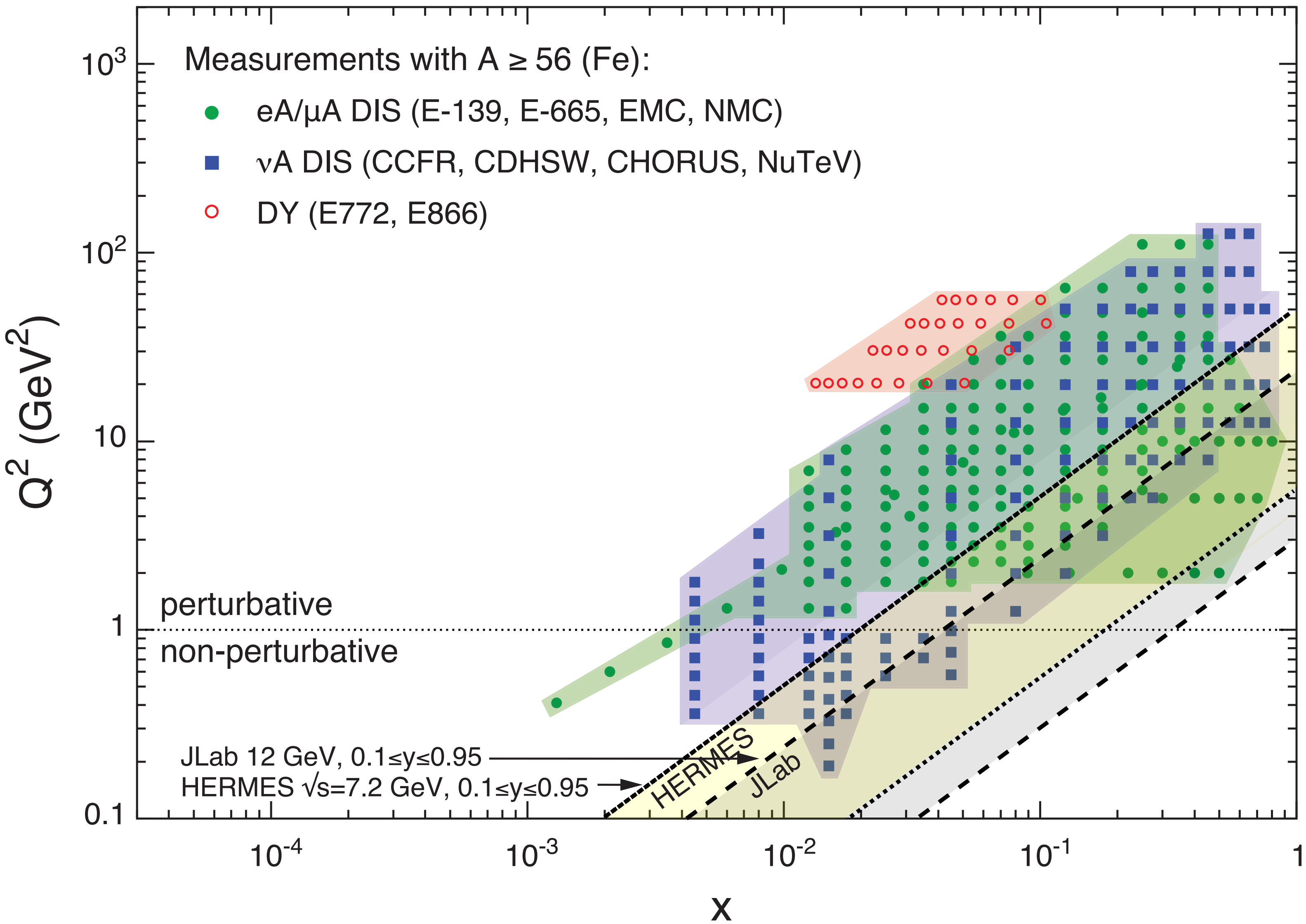
The landscape of e+A collisions

- Existing data is sparse - typically low energy and low A
- Not a large coverage in (x,Q^2) phase-space (unlike e+p)
    - ➡ Existing data is well away from the saturation regime



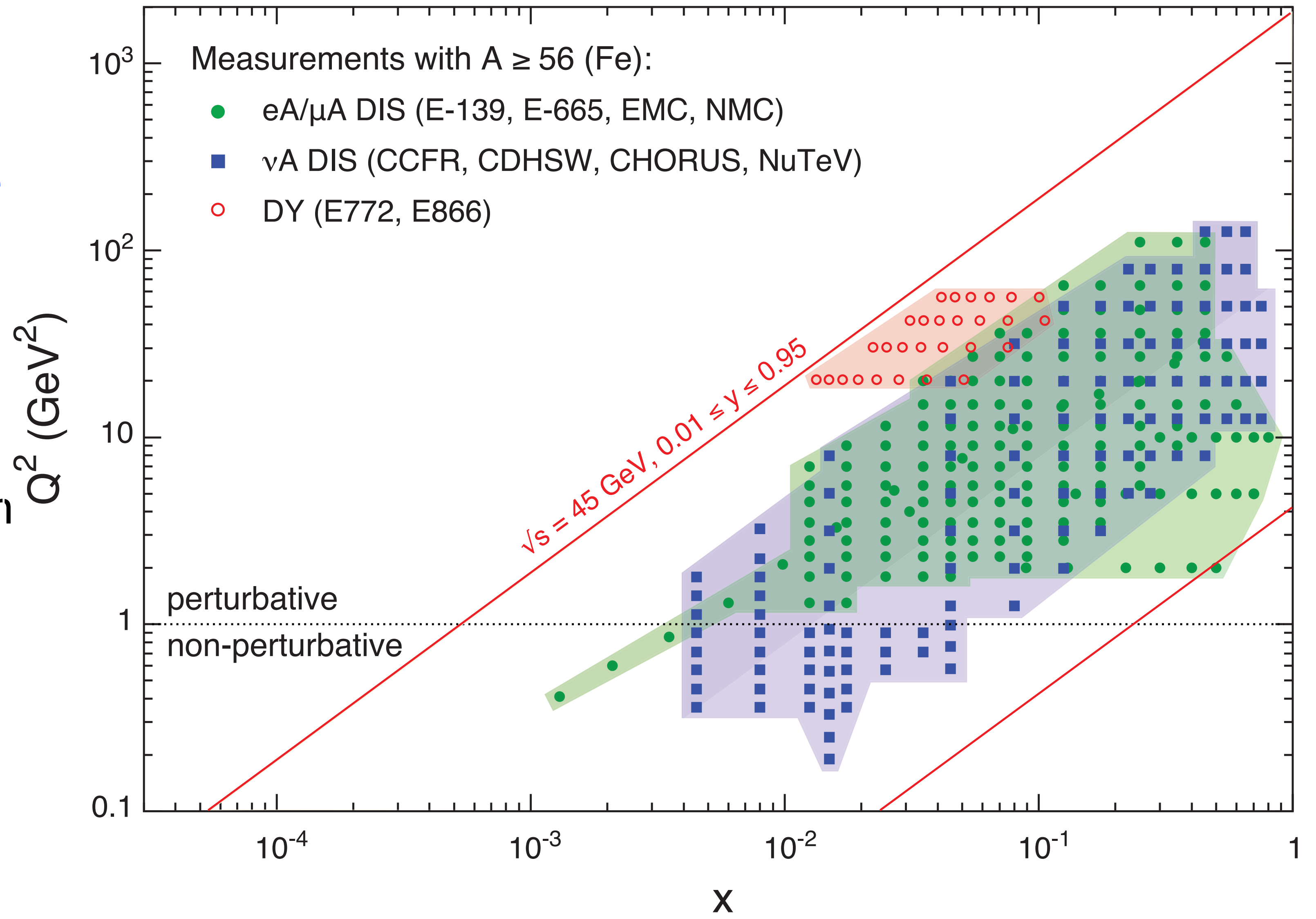
The landscape of e+A collisions

- Existing data is sparse - typically low energy and low A
- Not a large coverage in (x,Q^2) phase-space (unlike e+p)
  - ➡ Existing data is well away from the saturation regime
- JLab 12 GeV upgrade will explore the landscape at high x



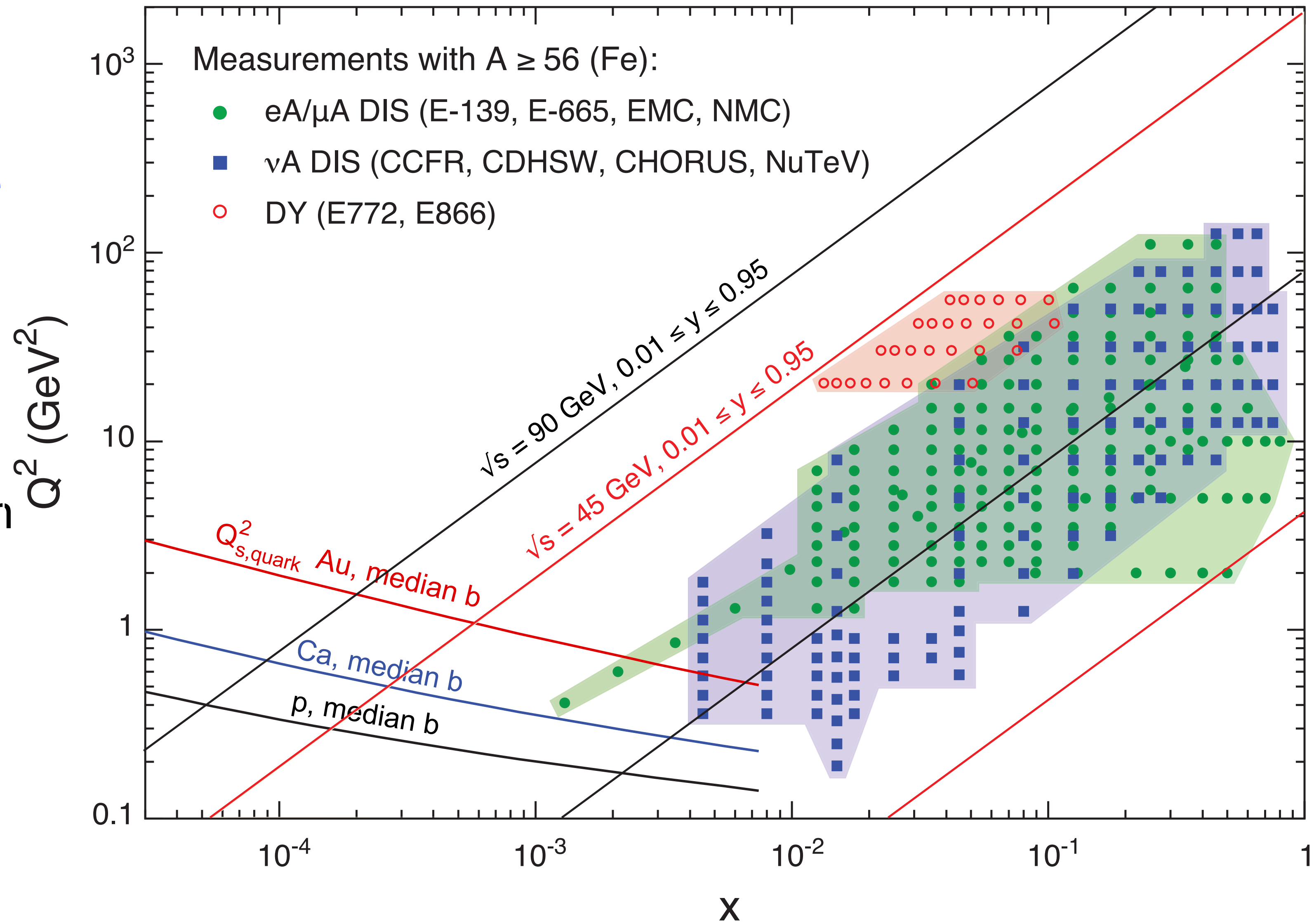
The landscape of e+A collisions

- Existing data is sparse - typically low energy and low A
- Not a large coverage in (x,Q^2) phase-space (unlike e+p)
  - ➡ Existing data is well away from the saturation regime
- JLab 12 GeV upgrade will explore the landscape at high x
- To go to lower x and explore saturation physics, need higher energies
  - ➡ A low-energy EIC, with $\sqrt{s}$=45 GeV/A (e.g. 5x100 GeV) goes some way to this whilst also maintaining the ability to study high-x phenomena



The landscape of e+A collisions

- Existing data is sparse - typically low energy and low A
- Not a large coverage in (x,Q^2) phase-space (unlike e+p)
  - ➡ Existing data is well away from the saturation regime
- JLab 12 GeV upgrade will explore the landscape at high x
- To go to lower x and explore saturation physics, need higher energies
  - ➡ A low-energy EIC, with √s=45 GeV/A (e.g. 5x100 GeV) goes some way to this whilst also maintaining the ability to study high-x phenomena
  - ➡ However, we really need higher energies to explore low-x in detail e.g. 20x100 GeV -> √s = 90 GeV/A



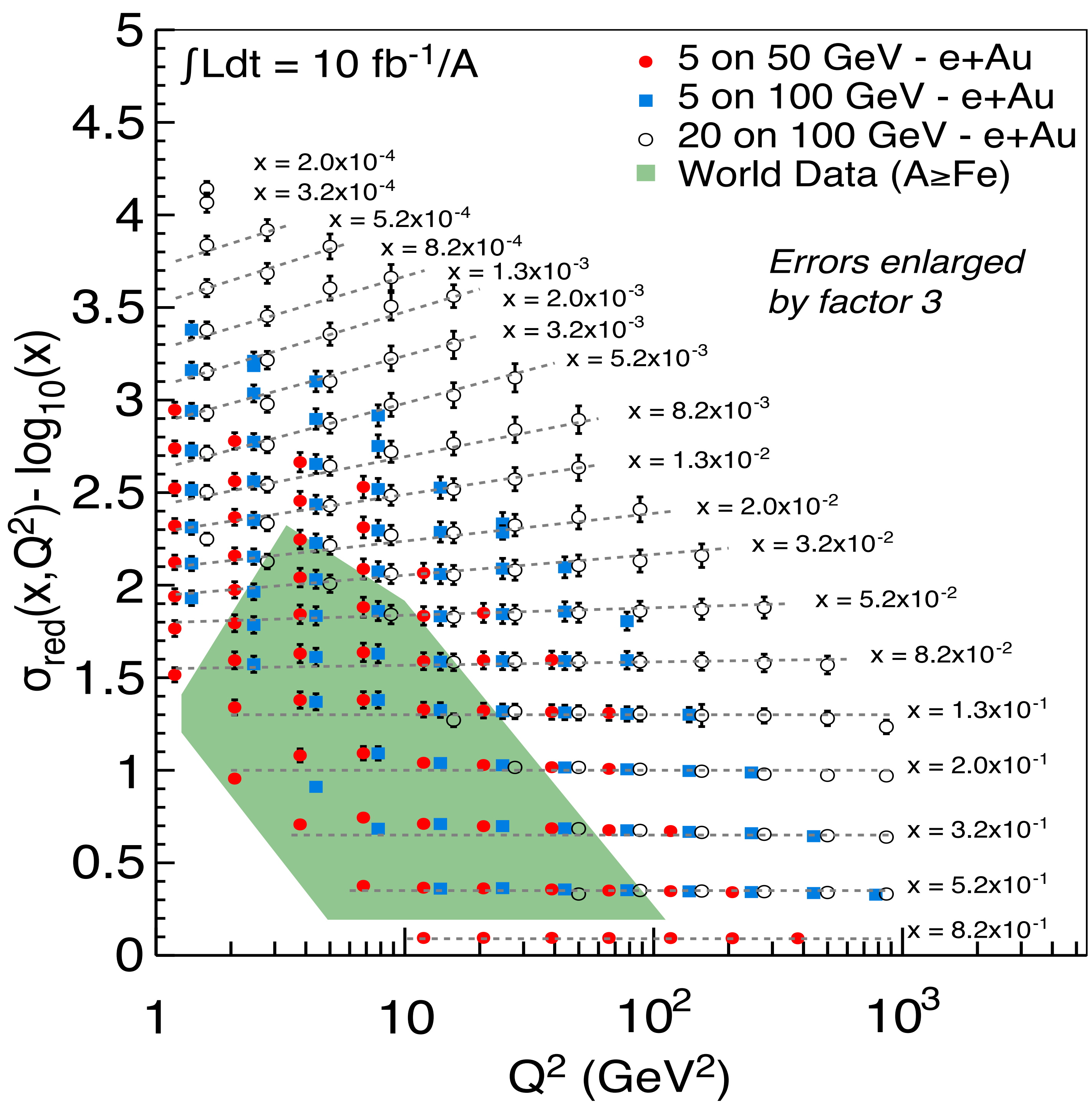
Inclusive nDIS - Structure functions F_2^A and F_L^A

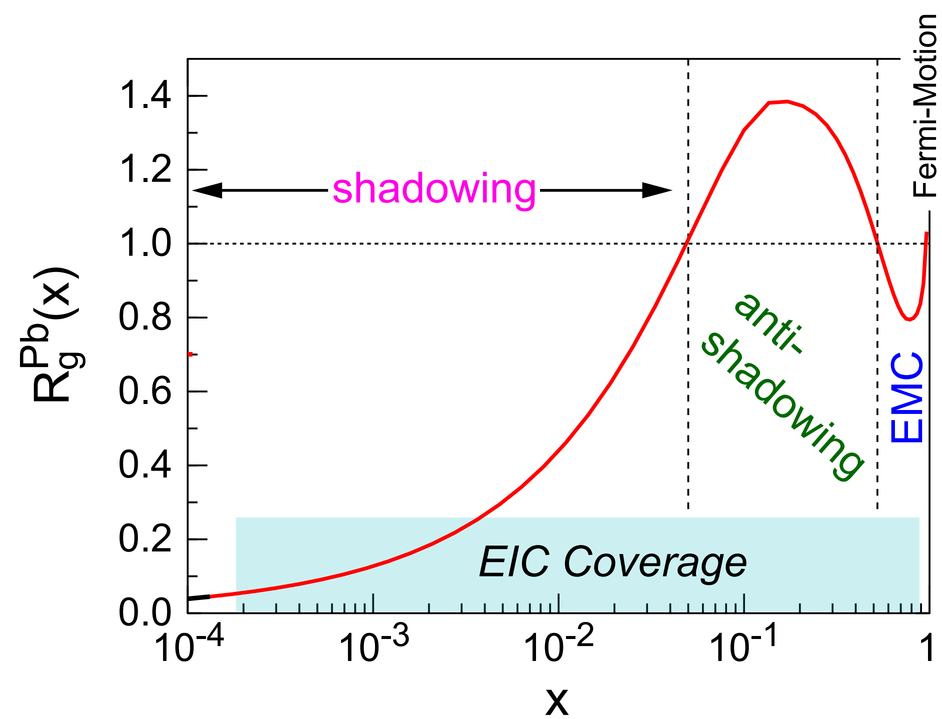
$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

- The reduced cross-section can be written in terms of structure functions:
- $F_2(x,Q^2)$: A measure of the momentum distribution of quarks and anti-quarks
- $F_L(x,Q^2)$: A measure of the momentum distribution of gluons
- $F_2(x,Q^2)$ and $F_L(x,Q^2)$ are benchmark measurements - theory/models have to be able to describe the structure functions and their evolution

Inclusive nDIS - Structure functions F_2^A and F_L^A

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

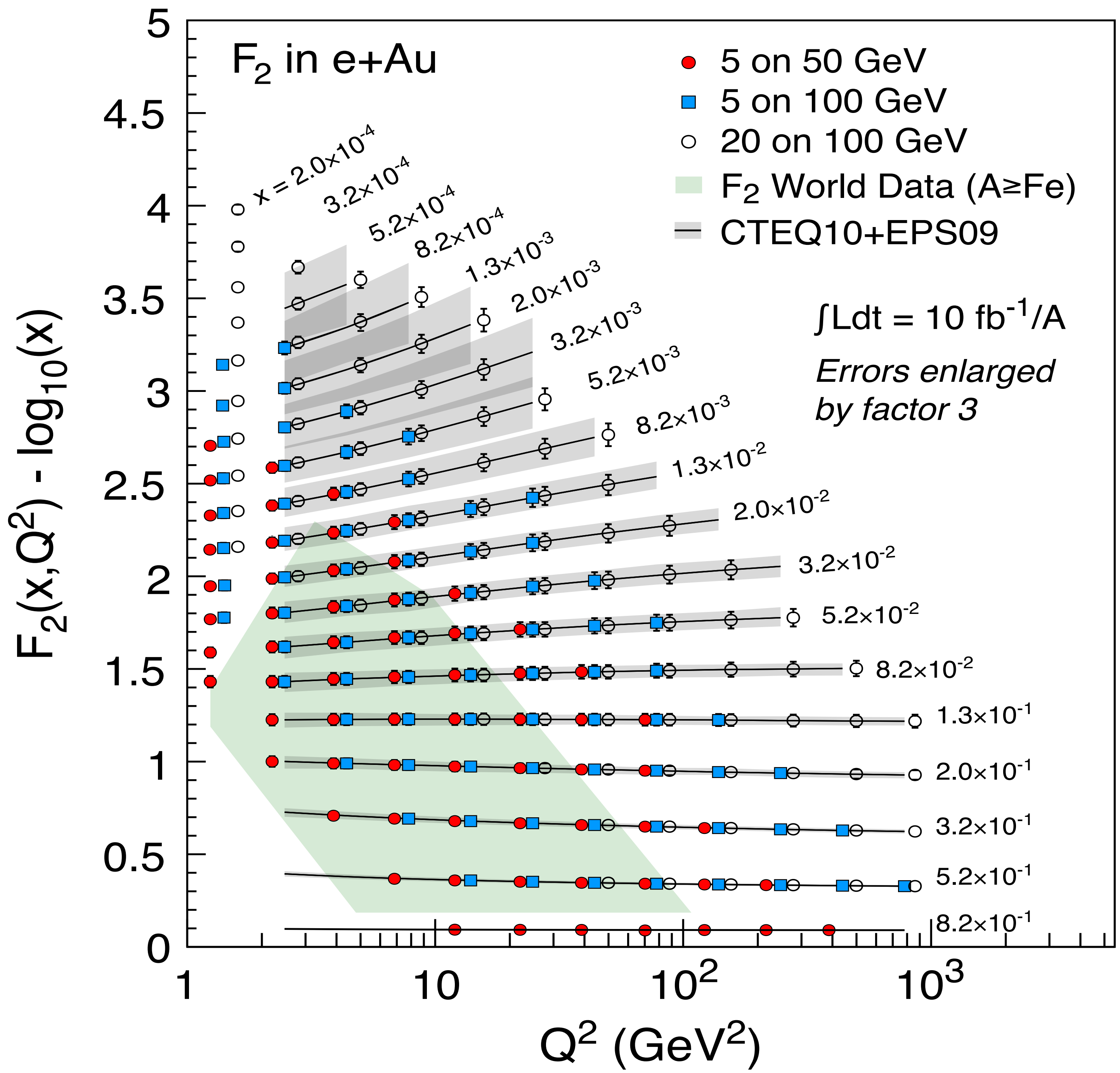




- Use Pythia + EPS09 to generate data
- Generate 10^7 events, then scale to 10 fb^{-1}
  - ➡ Statistical uncertainty is negligible
- Assume a realistic 3% systematic uncertainty
- Points offset in Q^2 for different energies for visibility

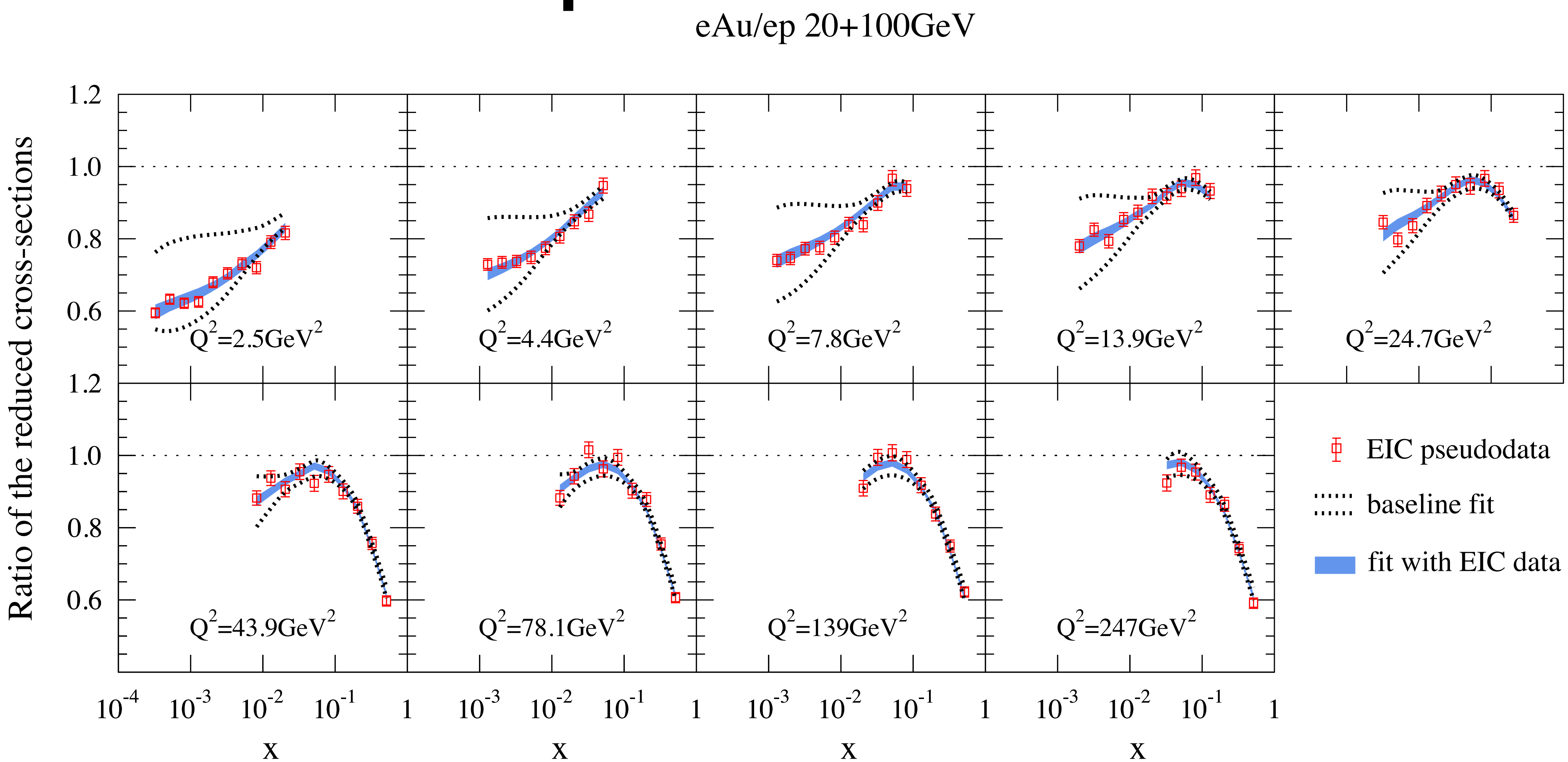
Inclusive nDIS - F_2^A Structure Function

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



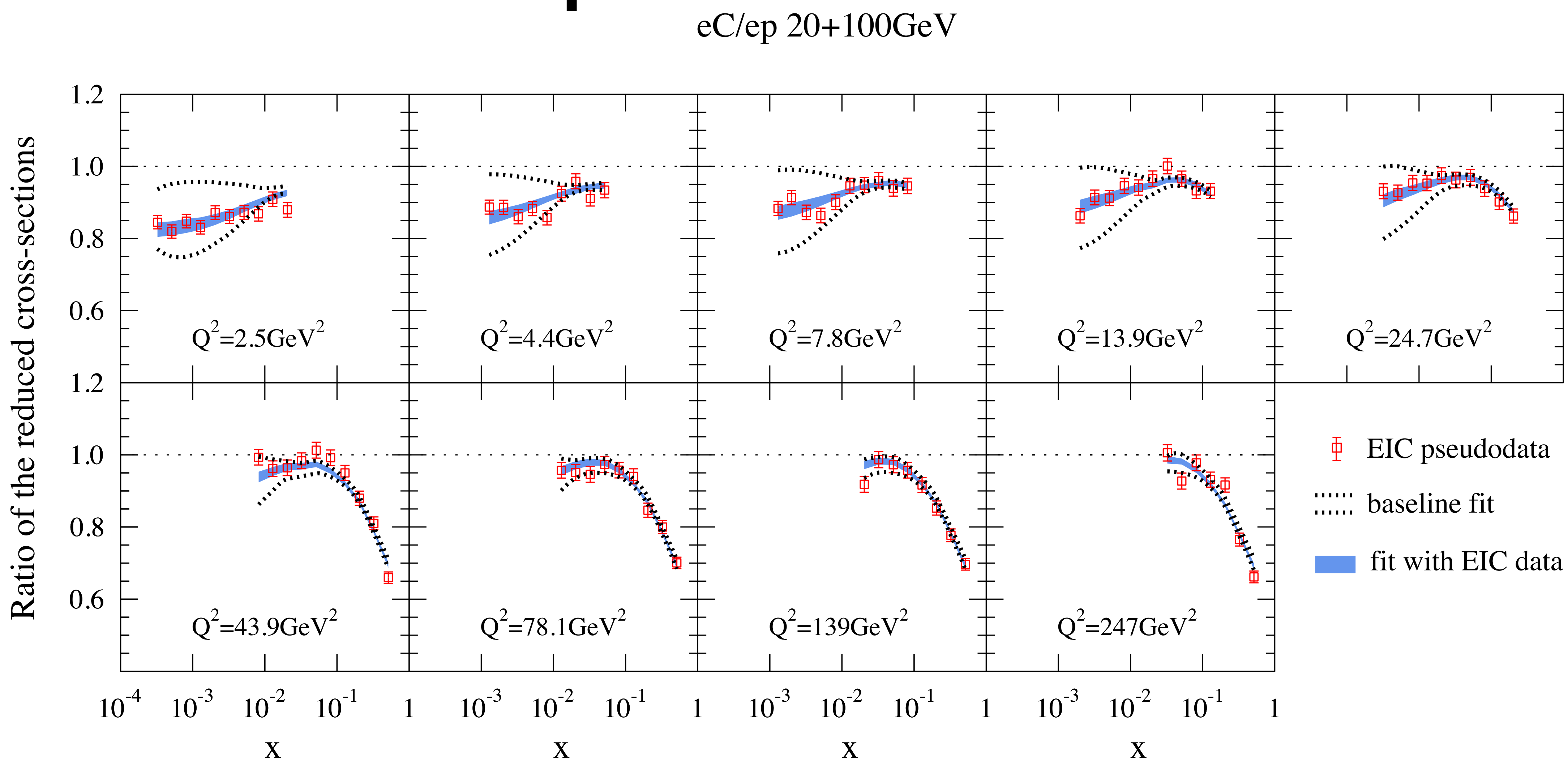
- Use HERMES method to calculate F_2 from σ_r
- The pseudo-data is scaled to the EPS09 calculation
  - ➡ Errors on pseudo-data and EPS09 are scaled for visibility
- At higher x, uncertainties on EPS09 and pseudo-data are negligible
- At smaller x, pseudo-data uncertainties are much smaller than EPS09

Effect of EIC psuedo-data on EPS09



- Ratio of reduced cross-sections, e+Au/e+p
- Large reduction in the cross-sections at low-Q^2
    - ➡ low-x and low-Q^2 is dominated by gluons and sea-quarks
- High-Q^2 is well constrained with existing data

Effect of EIC psuedo-data on EPS09



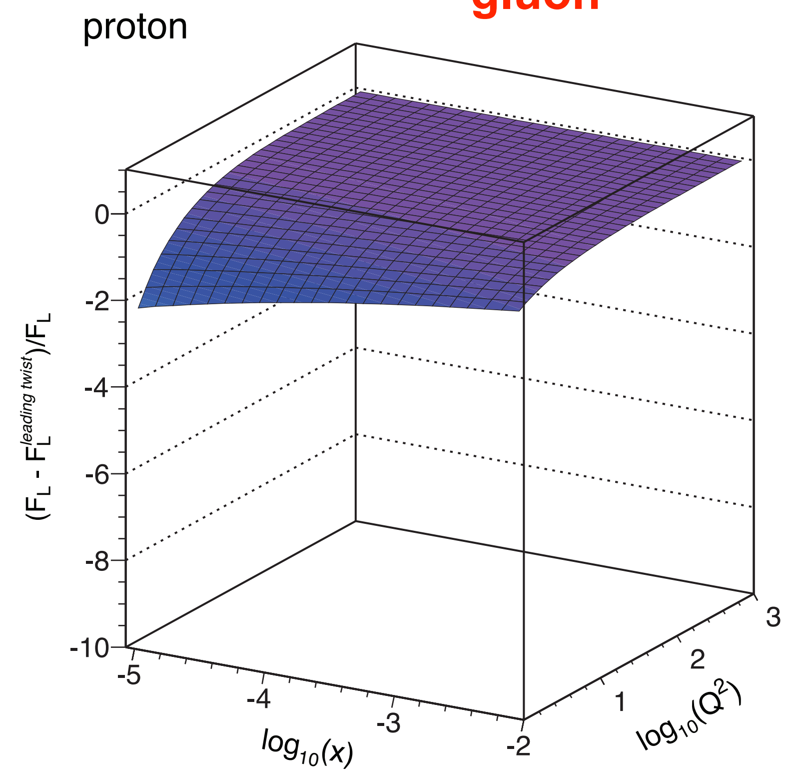
- Ratio of reduced cross-sections, e+C/e+p
- Large reduction in the cross-sections at low-Q^2
  - ➡ low-x and low-Q^2 is dominated by gluons and sea-quarks
- High-Q^2 is well constrained with existing data
- The A-dependence of eRHIC allows us to constrain smaller nuclei such as Carbon, which has uncertainties almost as large as Au!

Saturation effects in the proton and nucleus

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

quark+anti-quark (F_2) — **gluon** (F_L)

Measure of non-linear effects in the F_L structure function



Dipole model (J. Bartels *et al.*)

- Plotting this distribution coming out of saturation inspired GBW model
  - ➡ p: small effect only starting to come in at small-x and small Q^2

Saturation effects in the proton and nucleus

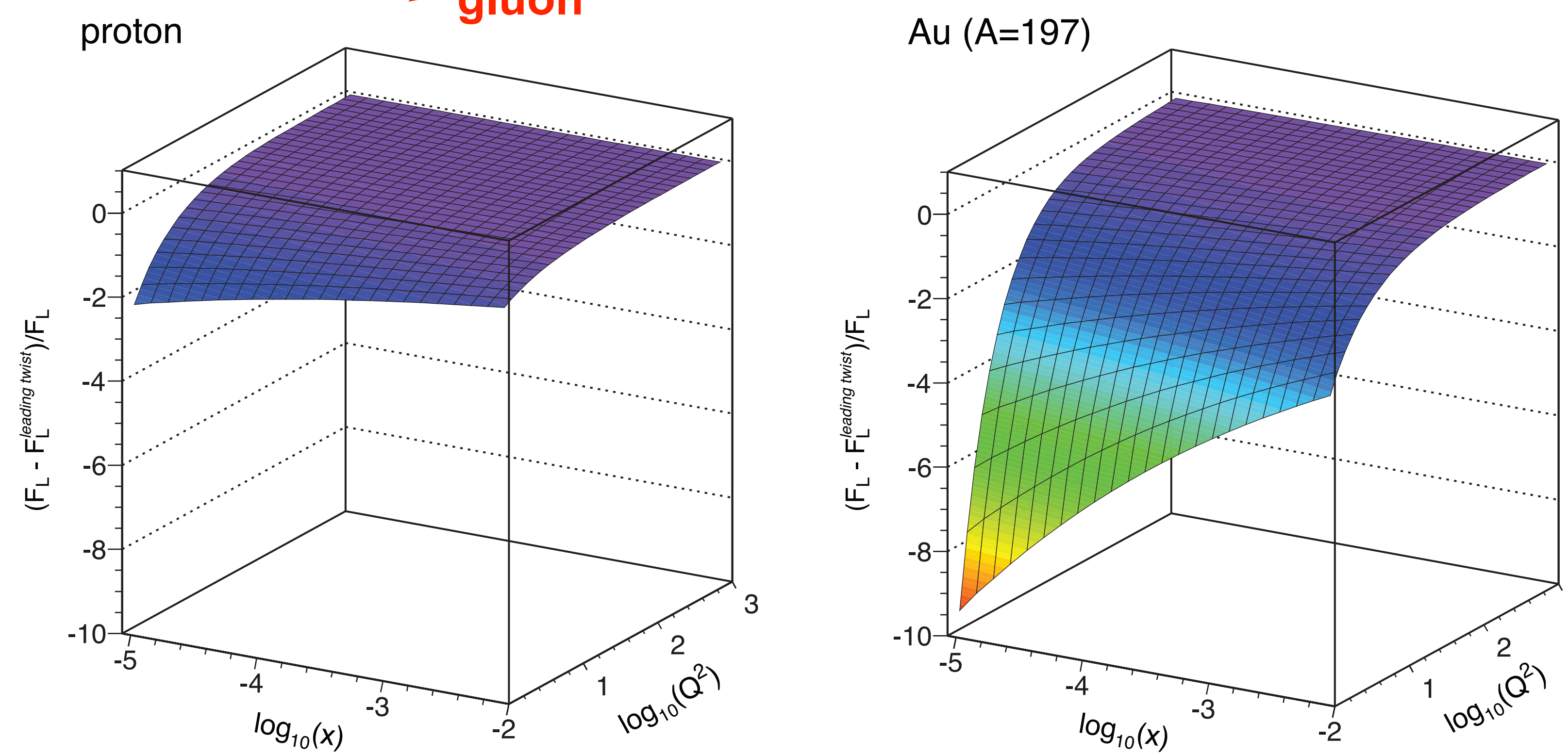
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

gluon

Measure of non-linear effects in the F_L structure function

Dipole model (J. Bartels *et al.*)



- Plotting this distribution coming out of saturation inspired GBW model
  - ➡ p: small effect only starting to come in at small-x and small Q^2
  - ➡ Au: much larger effects are visible
    - nuclear “oomph” effects well manifested in the F_L structure function

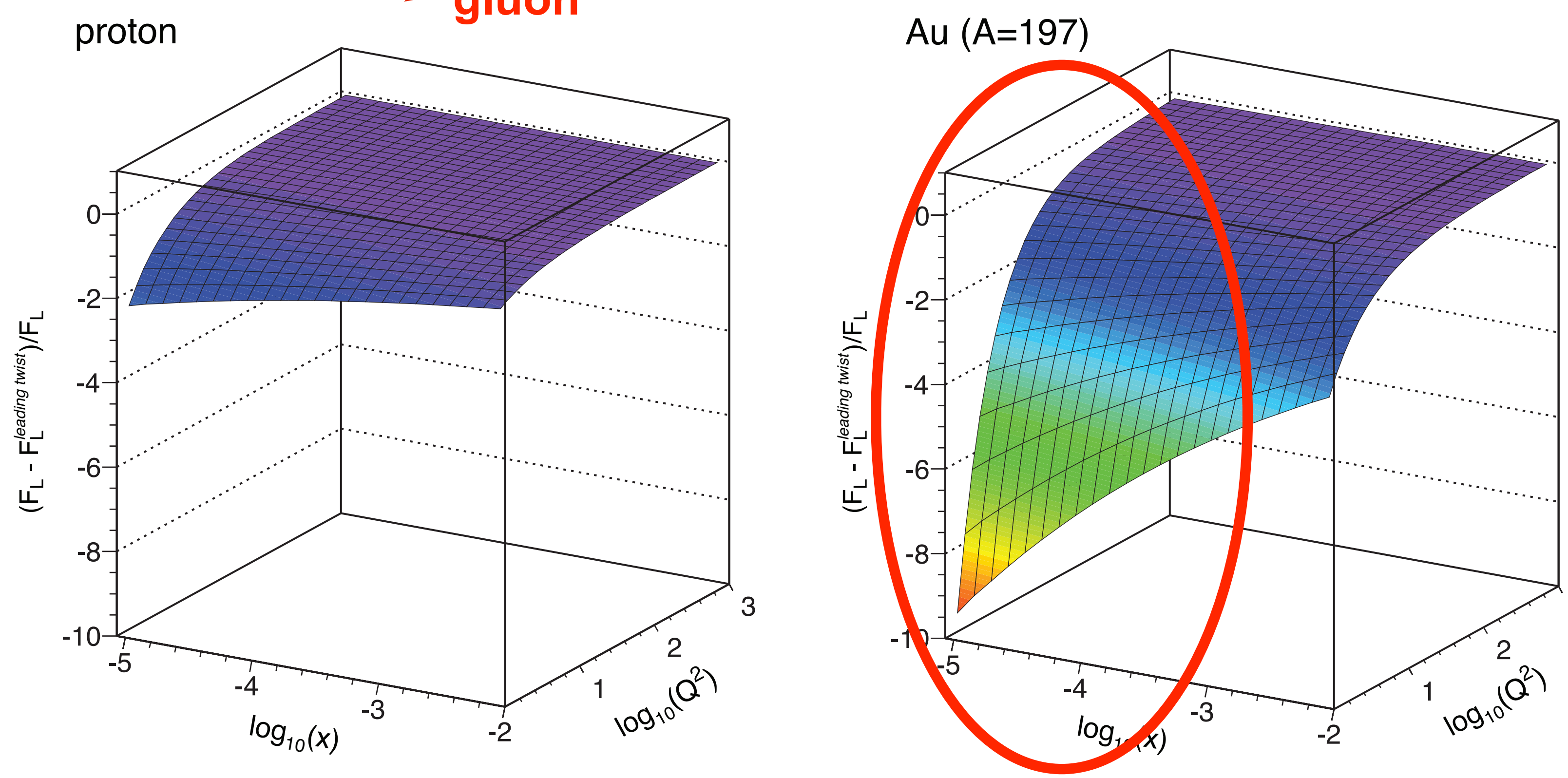
Saturation effects in the proton and nucleus

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

quark+anti-quark (F_2) **gluon** (F_L)

Measure of non-linear effects in the F_L structure function

Dipole model (J. Bartels *et al.*)



- Plotting this distribution coming out of saturation inspired GBW model
  - ➡ p: small effect only starting to come in at small-x and small Q^2
  - ➡ Au: much larger effects are visible
    - nuclear “oomph” effects well manifested in the F_L structure function

Feasibility study:

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

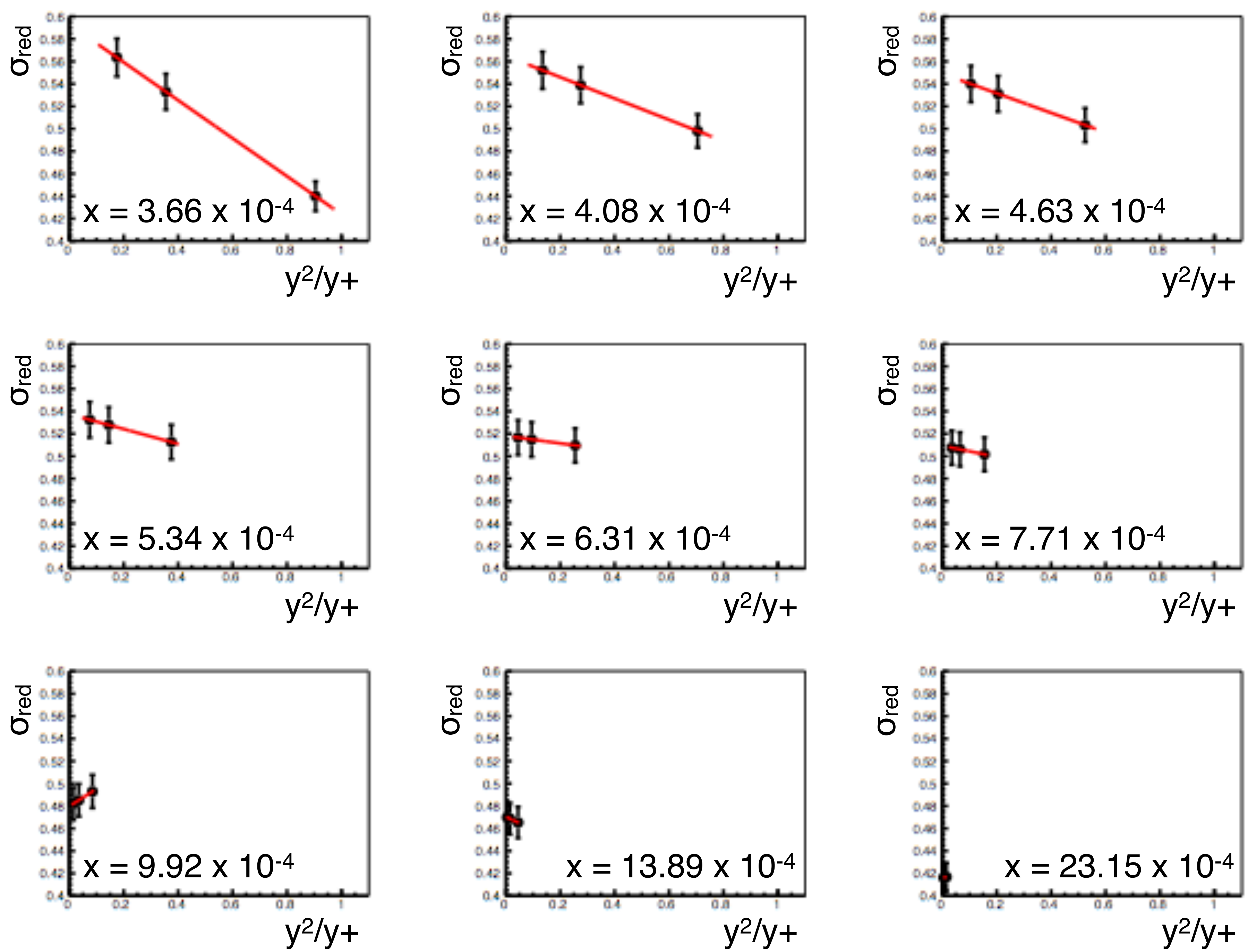
Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+Au:
20x50 - A∫Ldt = 2 fb^{-1}
20x75 - A∫Ldt = 4 fb^{-1}
20x100 - A∫Ldt = 4 fb^{-1}
running combined
~6 months total running (50% eff)

statistical errors are swamped by the 3% systematic errors

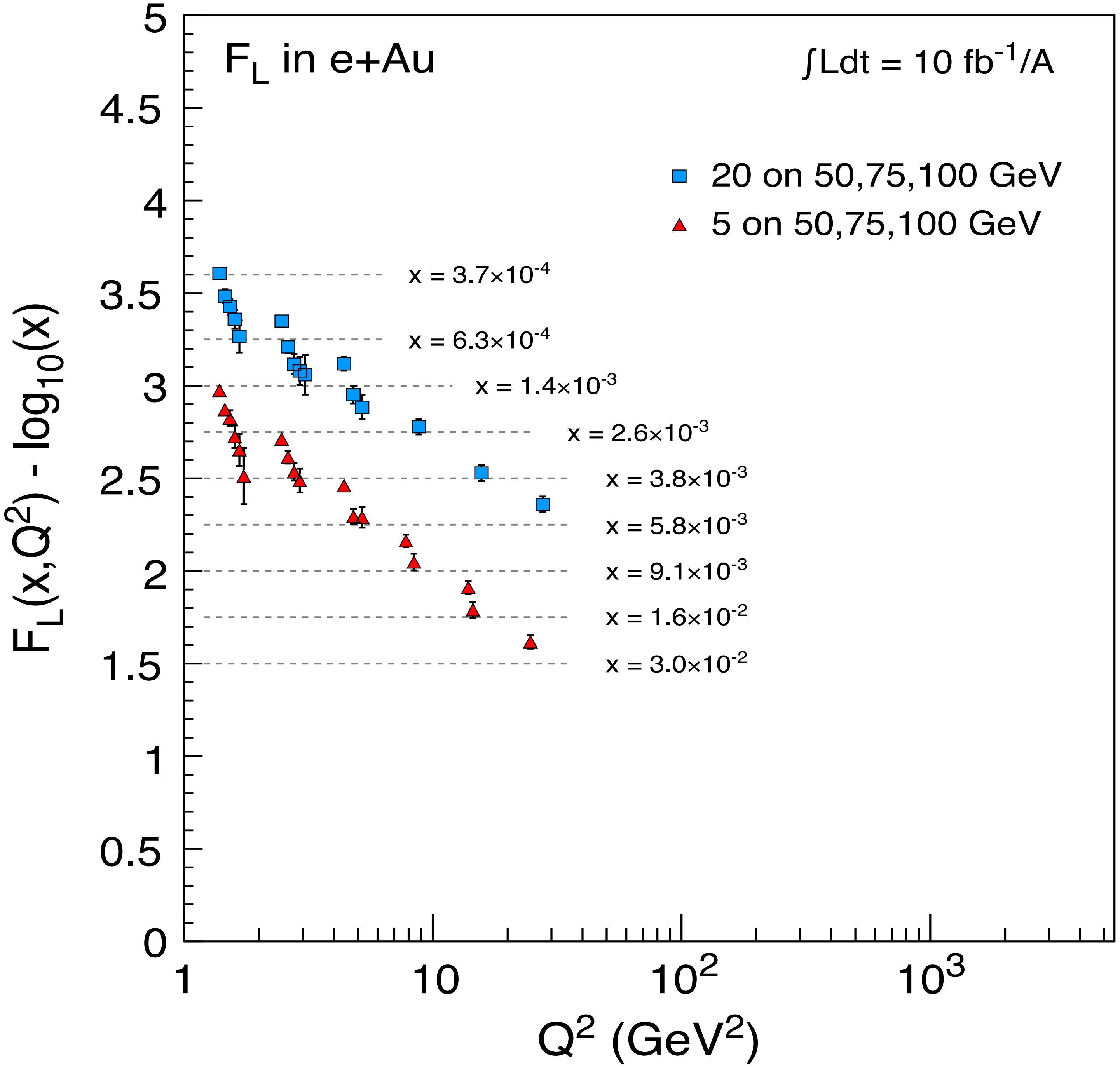
Will be dominated by systematics, but would need a full detector simulation in order to estimate them

Q^2 = 1.389 GeV^2



Inclusive nDIS - F_L^A Structure Function

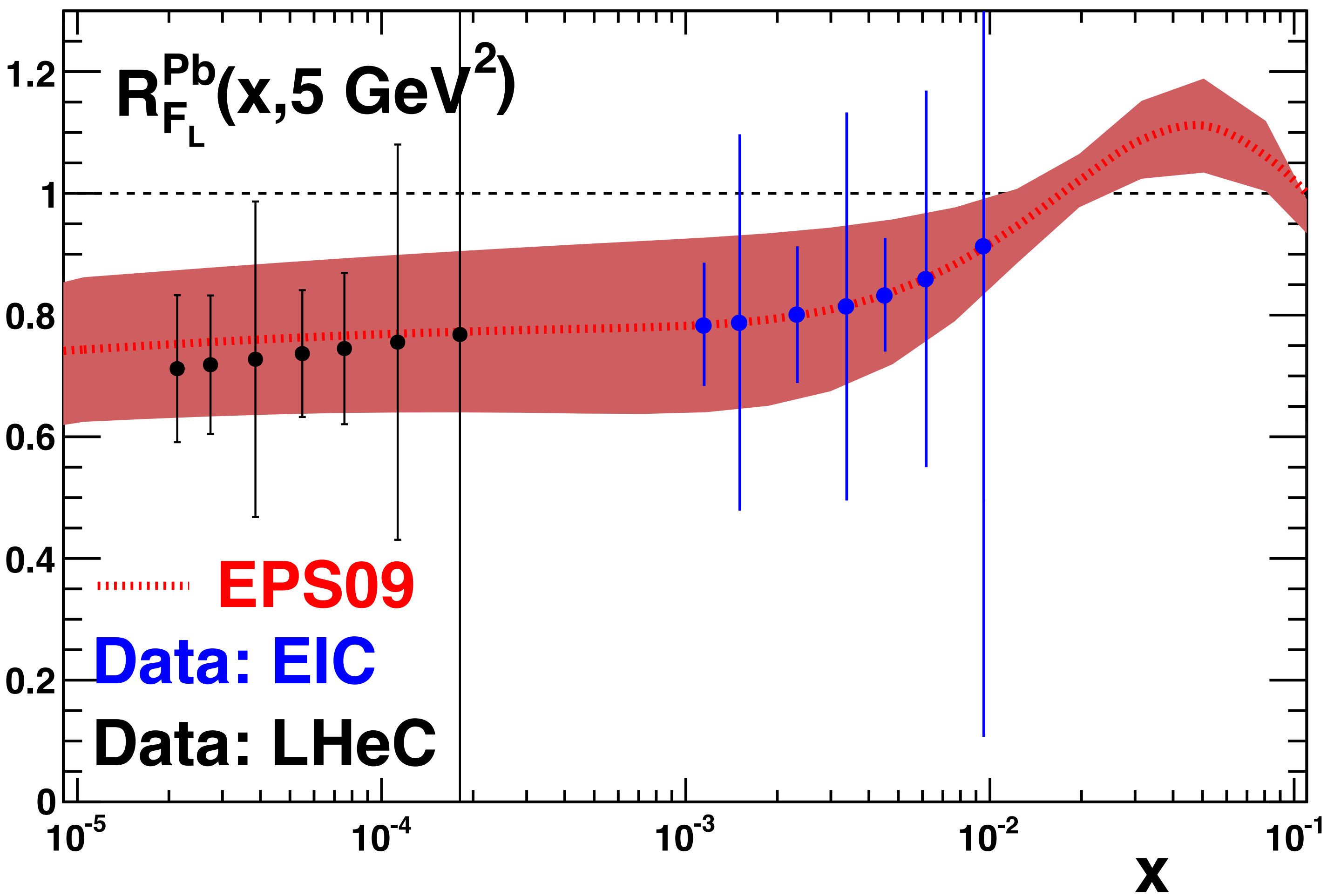
$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$



- The measurement of F_L however is a different beast
- Require data from 3 different energies in each x,Q^2 bin
  - ➡ Use Rosenbluth Separation technique to extract F_L
- Much larger uncertainties and much smaller acceptance than the F_2 measurement

Inclusive nDIS - F_L^A Structure Function

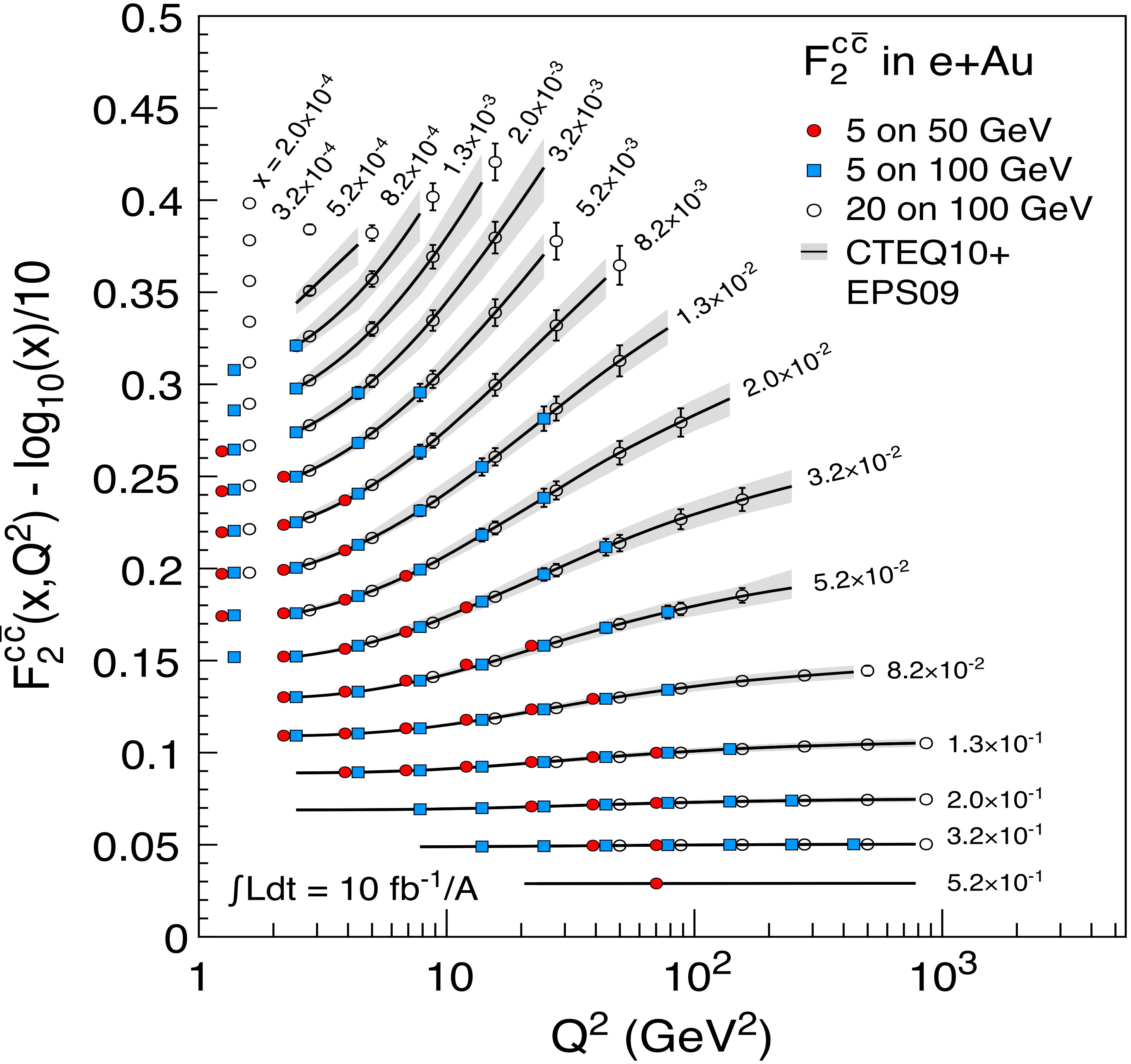
$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

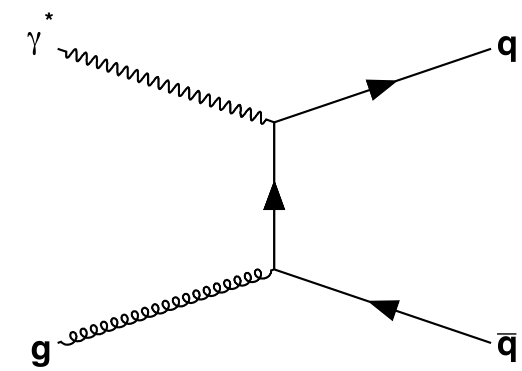


Plot taken from LHeC CDR, courtesy of N. Armesto

- The measurement of F_L however is a different beast
- Require data from 3 different energies in each x,Q^2 bin
  - ➡ Use Rosenbluth Separation technique to extract F_L
- Much larger uncertainties and much smaller acceptance than the F_2 measurement
- Good complementarity with F_L measurement at LHeC
  - ➡ Both measurements are limited by their uncertainties and σ_r is the best way to constrain the nuclear PDFs

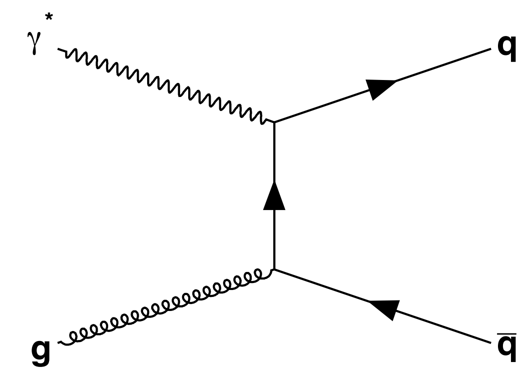
Inclusive nDIS - $F_2^{c,A}$ Structure Function

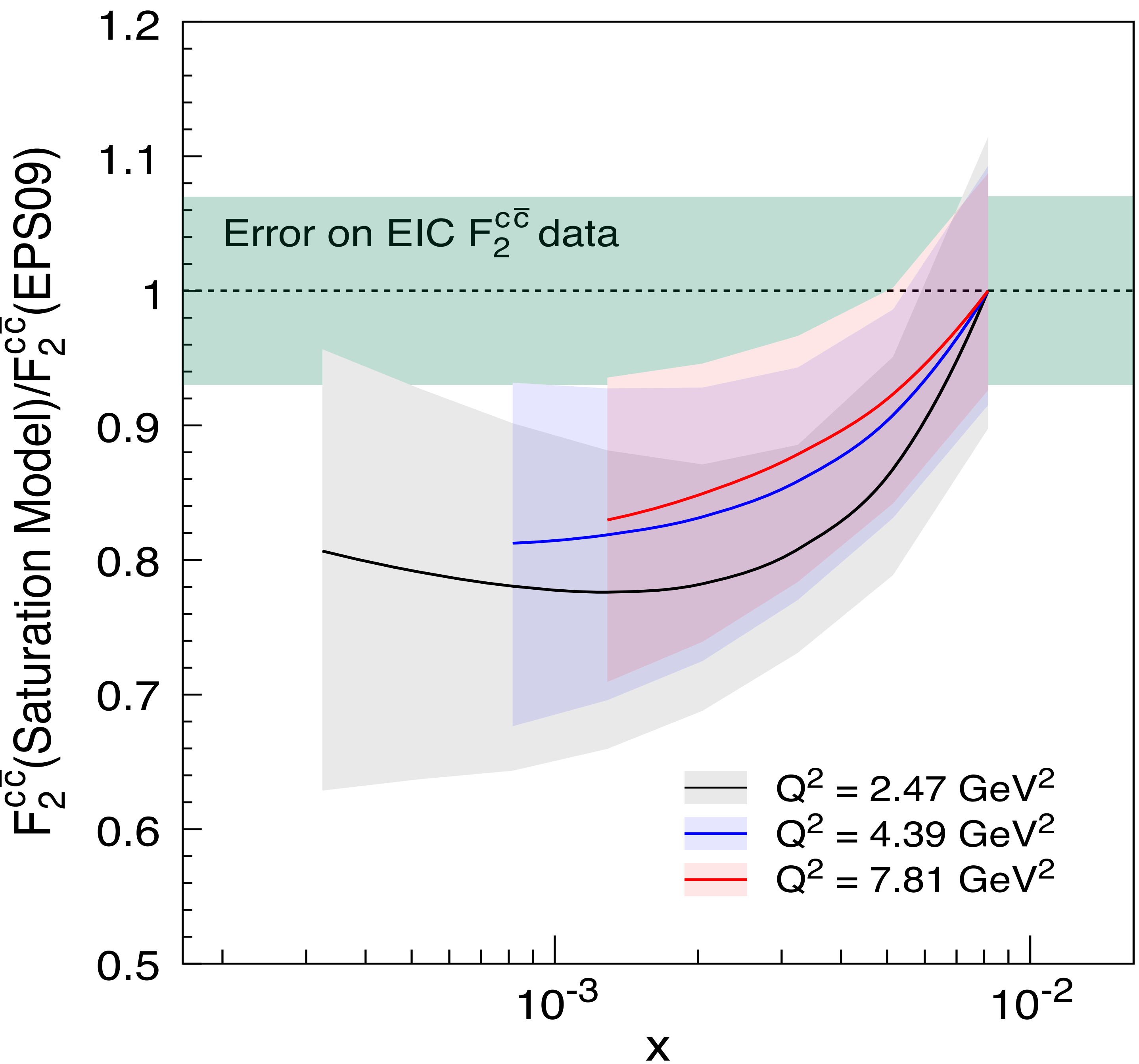




- F_2^c only driven by photon-gluon fusion (PGF)
- As F_L is a difficult measurement, F_2^c may be the way forward
  - ➡ Larger uncertainties than F_2 but smaller than F_L
  - ➡ Statistics are not an issue
- At low x, uncertainties are smaller than EPS09
  - ➡ Will provide some constraints. How much needs to be evaluated

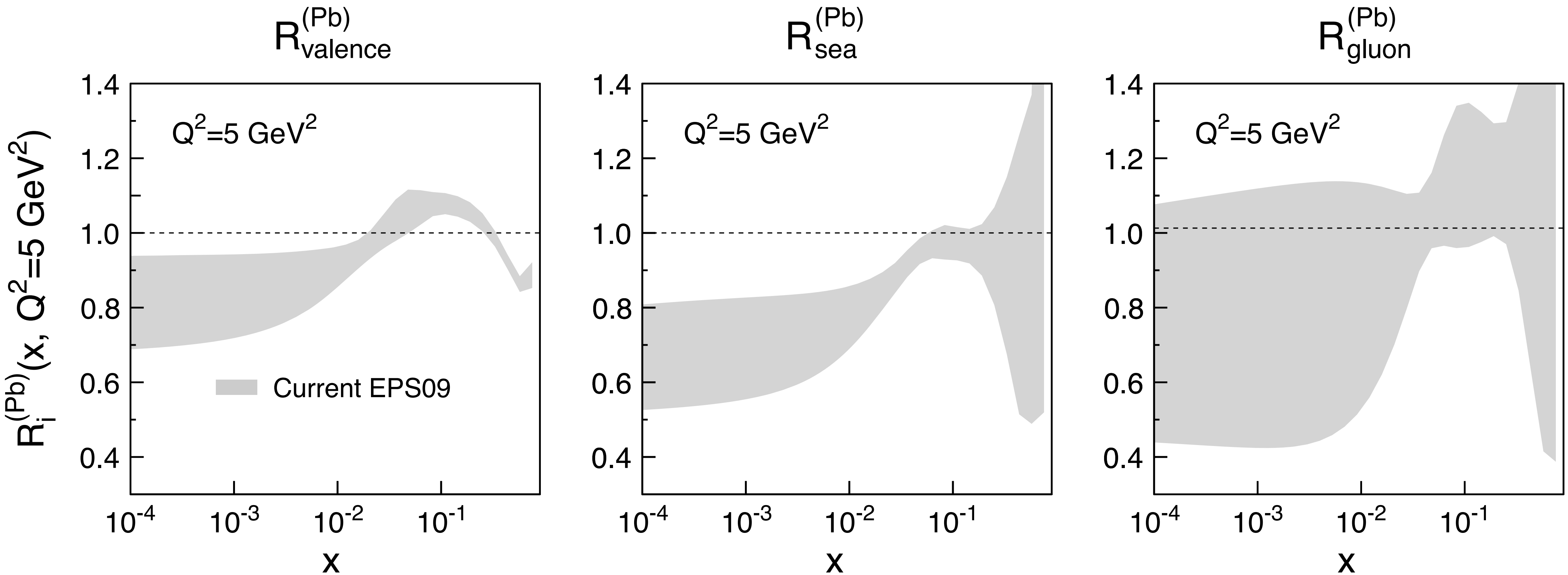
Inclusive nDIS - $F_2^{c,A}$ Structure Function





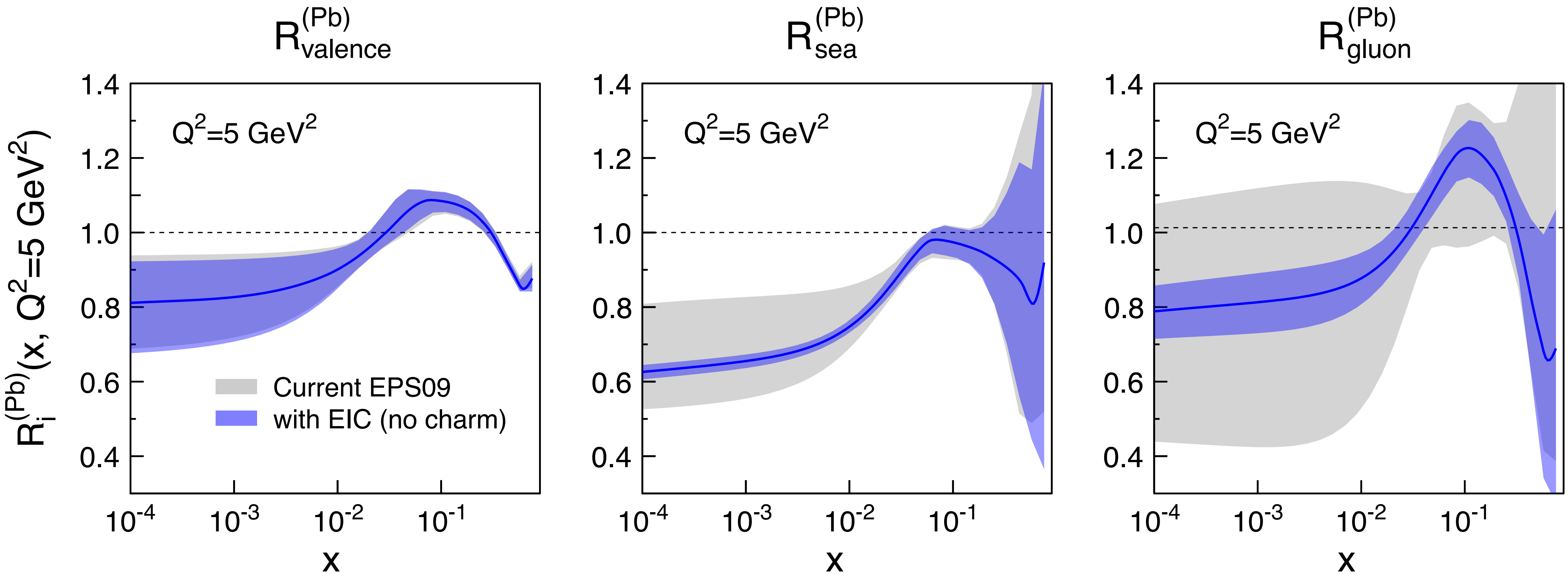
- F_2^c only driven by photon-gluon fusion (PGF)
- As F_L is a difficult measurement, F_2^c may be the way forward
  - ➡ Larger uncertainties than F_2 but smaller than F_L
  - ➡ Statistics are not an issue
- At low x, uncertainties are smaller than EPS09
  - ➡ Will provide some constraints. How much needs to be evaluated
- Can provide access to differences between models
  - ➡ Ratio of rcBK to EPS09 shows the possible discriminatory power of this measurement

Effect of EIC psuedo-data on EPS09 fits



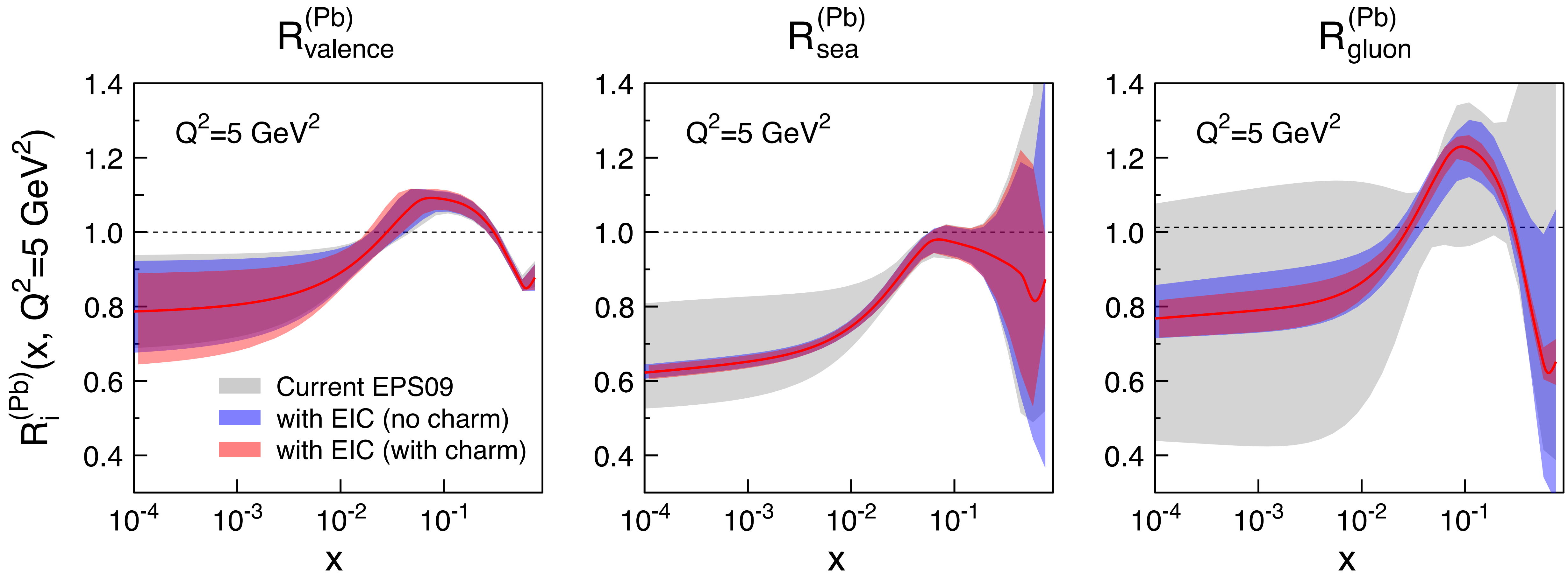
- Ratio of reduced cross-sections, e+Au/e+p
- Without EIC pseudo-data, large uncertainties, especially for sea quarks and gluons

Effect of EIC psuedo-data on EPS09 fits



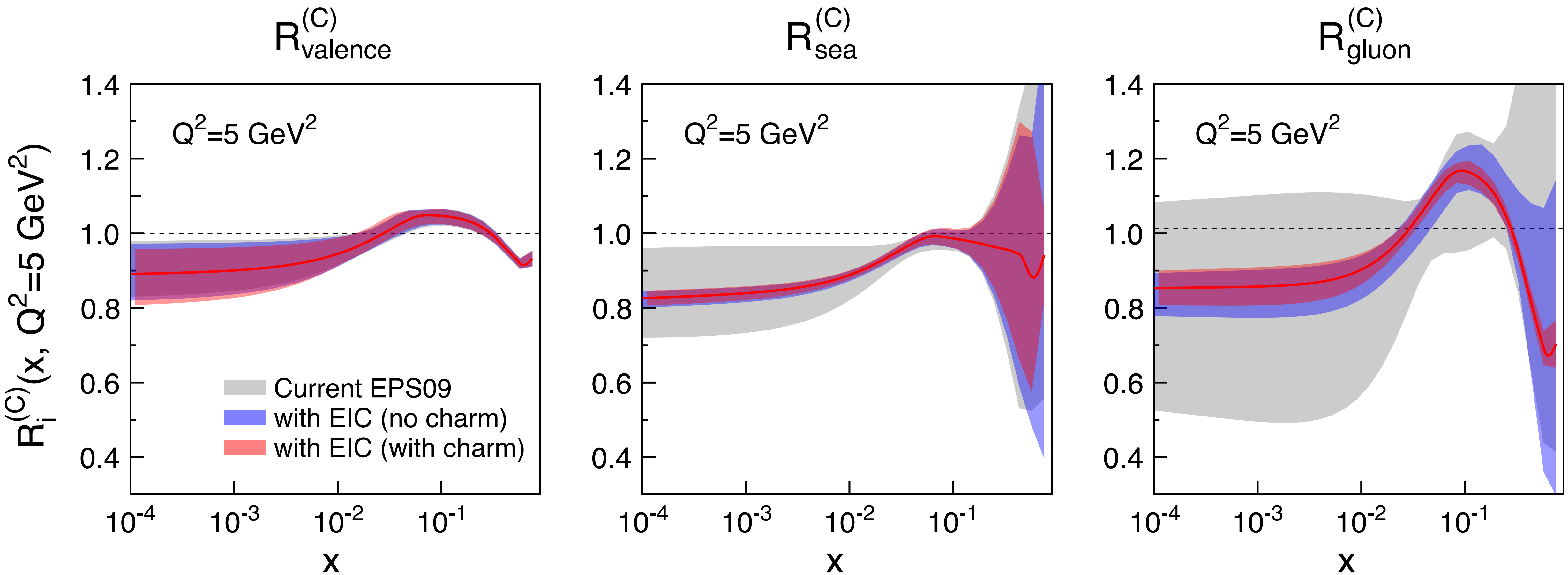
- Ratio of reduced cross-sections, e+Au/e+p
- Without EIC pseudo-data, large uncertainties, especially for sea quarks and gluons
- Adding in EIC pseudo-data significantly reduces the uncertainties for sea quarks and gluons, particularly at small-x

Effect of EIC psuedo-data on EPS09 fits



- Ratio of reduced cross-sections, e+Au/e+p
- Without EIC pseudo-data, large uncertainties, especially for sea quarks and gluons
- Adding in EIC pseudo-data significantly reduces the uncertainties for sea quarks and gluons, particularly at small-x
- Fitting the charm pseudo-data has a dramatic effect at high-x
  - ➡ Something the LHC, for example, will not be able to address

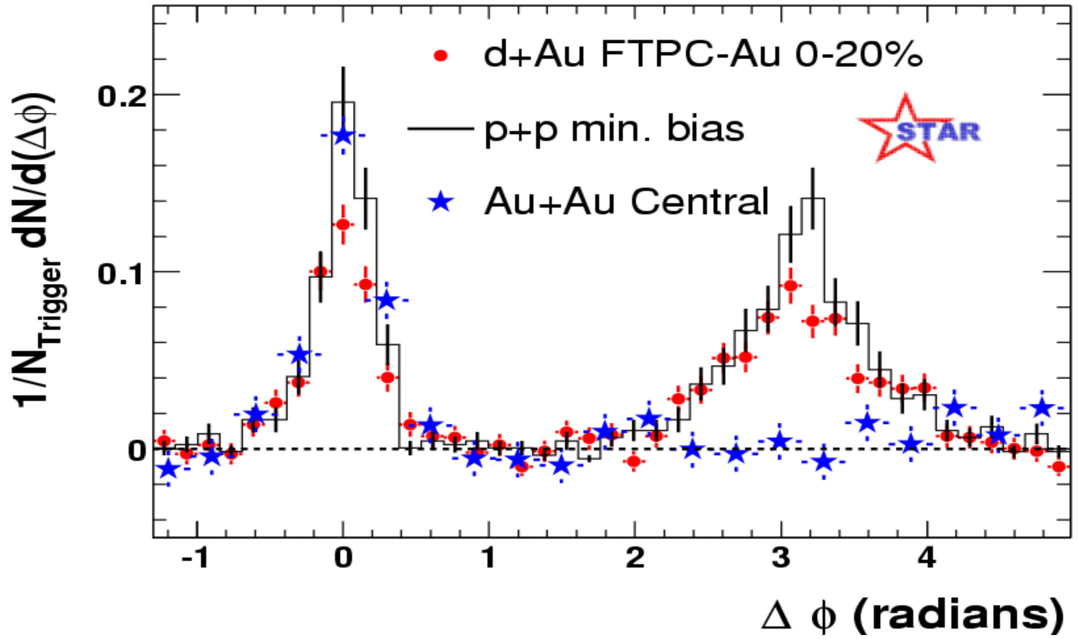
Effect of EIC psuedo-data on EPS09 fits

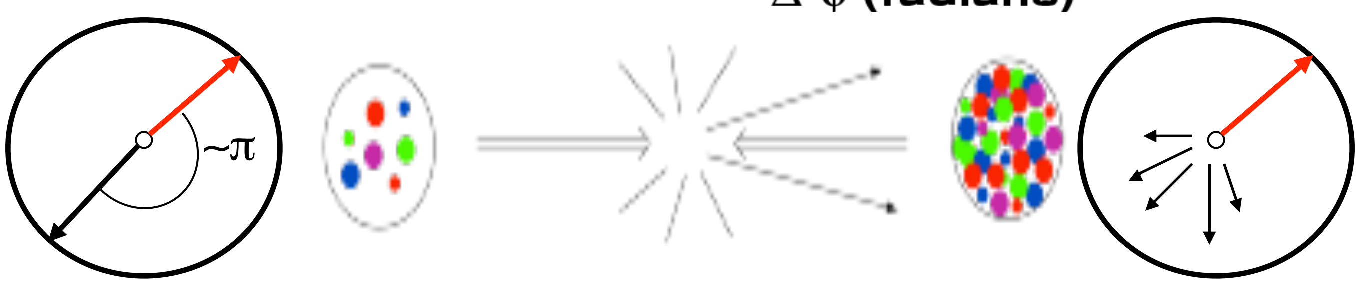


- Ratio of reduced cross-sections, e+C/e+p
- Without EIC pseudo-data, large uncertainties, especially for sea quarks and gluons
- Adding in EIC pseudo-data significantly reduces the uncertainties for sea quarks and gluons, particularly at small-x
- Fitting the charm pseudo-data has a dramatic effect at high-x
    - ➡ Something the LHC, for example, will not be able to address

di-hadron angular correlations in d+A

comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → h_1 h_2 X





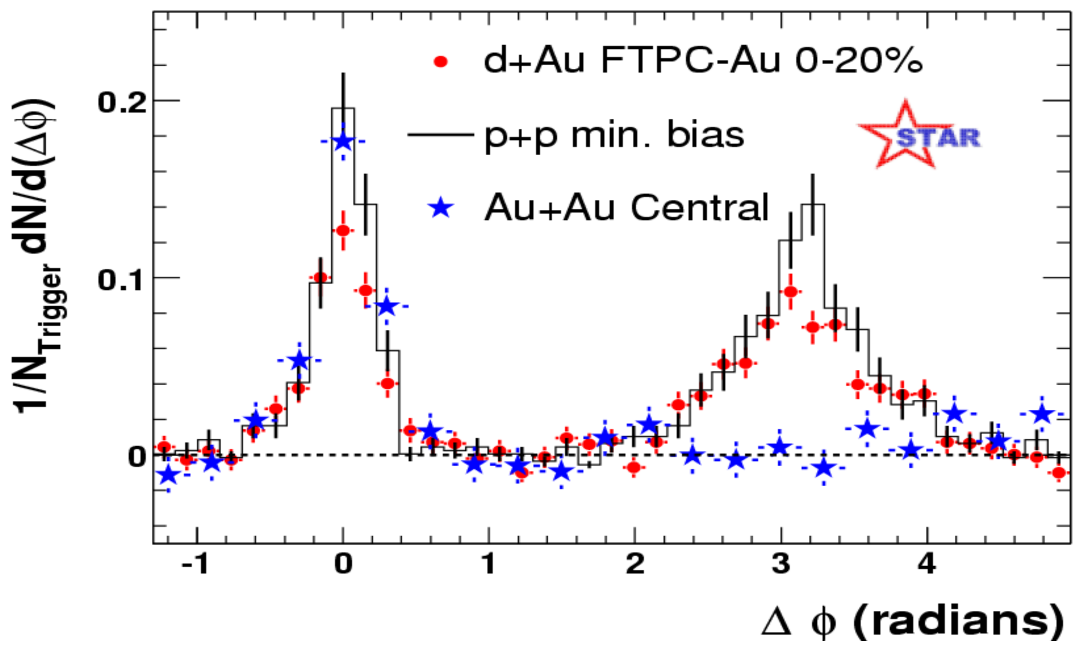
- At y=0, suppression of away-side jet is observed in A+A collisions
- No suppression in p+p or d+A

➡ x ~ 10^{-2}

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$$

di-hadron angular correlations in d+A

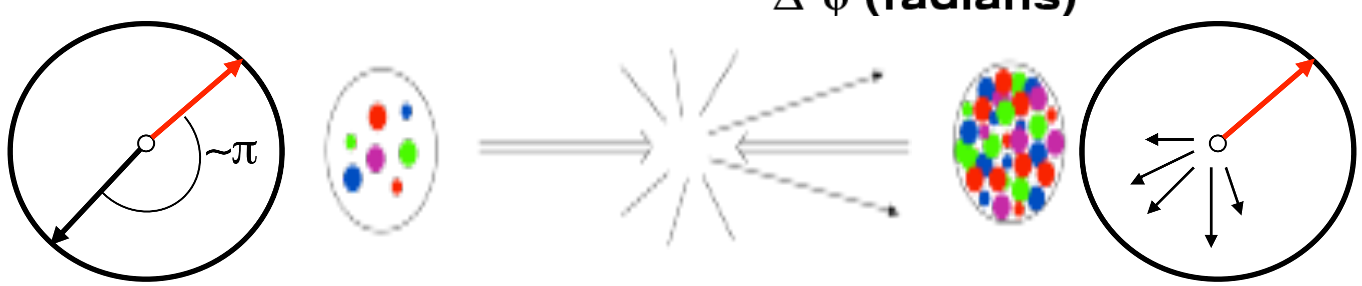
comparisons between d+Au → h_1 h_2 X (or p +Au → h_1 h_2 X) and p+p → h_1 h_2 X

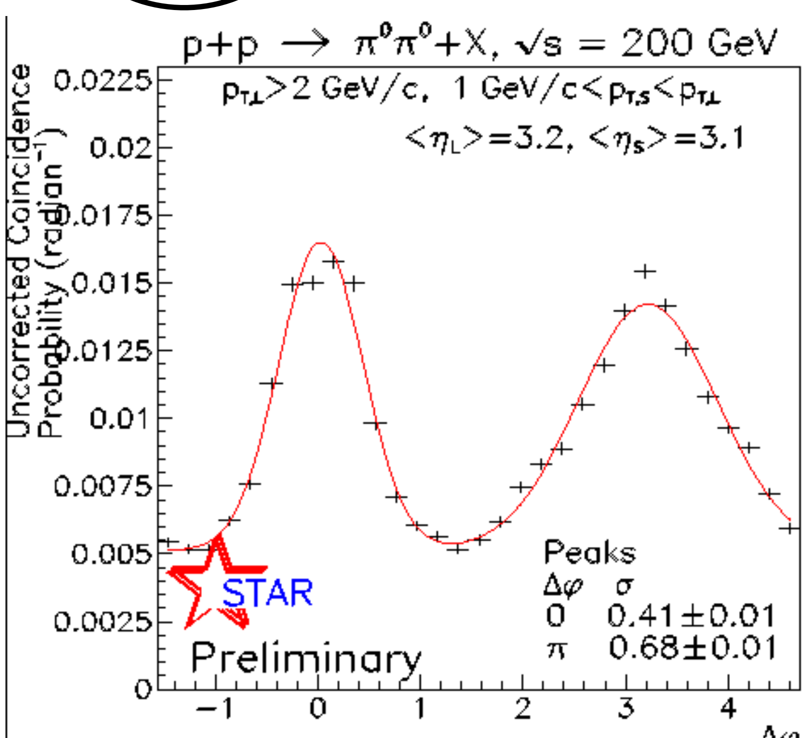


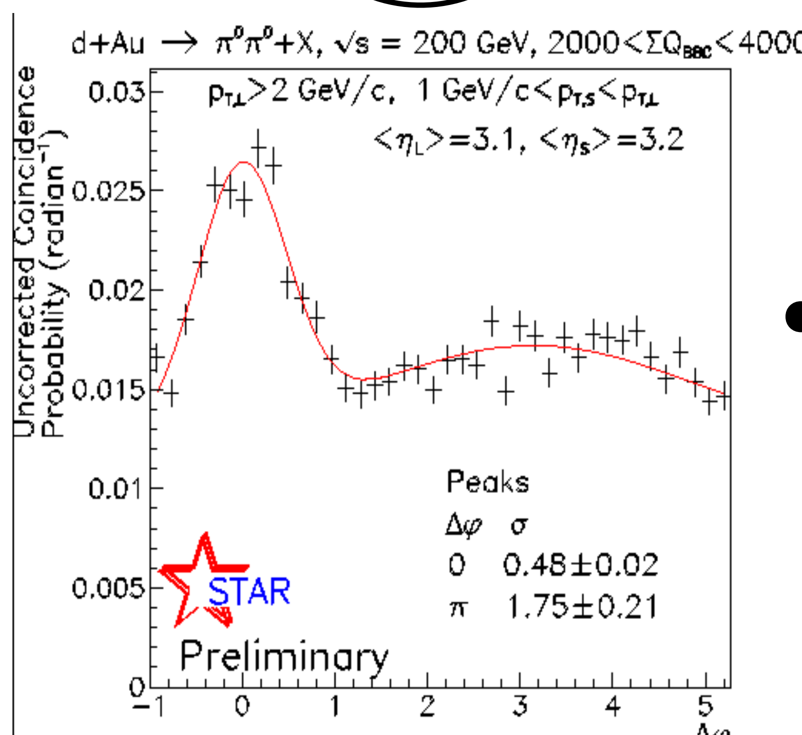
- At y=0, suppression of away-side jet is observed in A+A collisions
- No suppression in p+p or d+A

➡ x ~ 10^{-2}

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$$







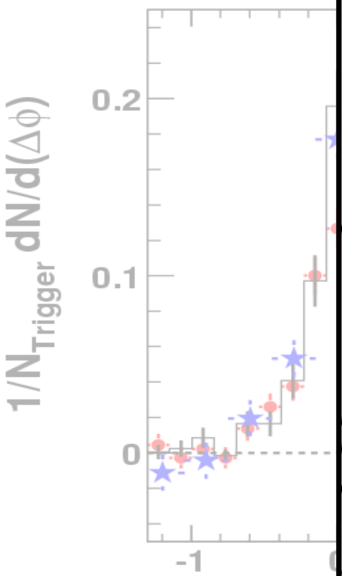
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

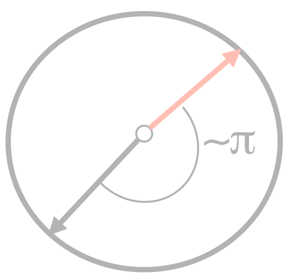
➡ x ~ 10^{-3}

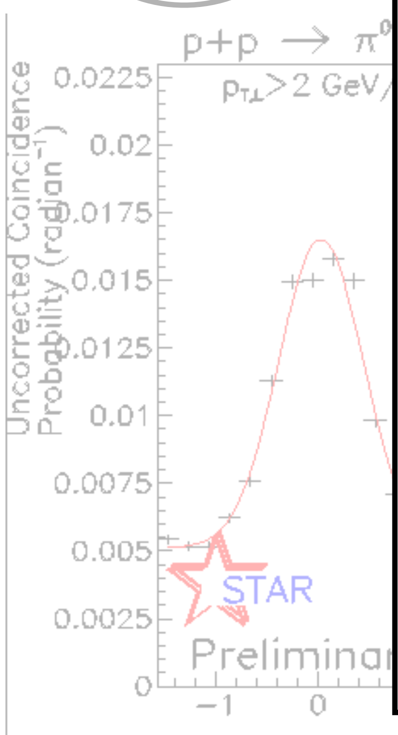
nl.gov

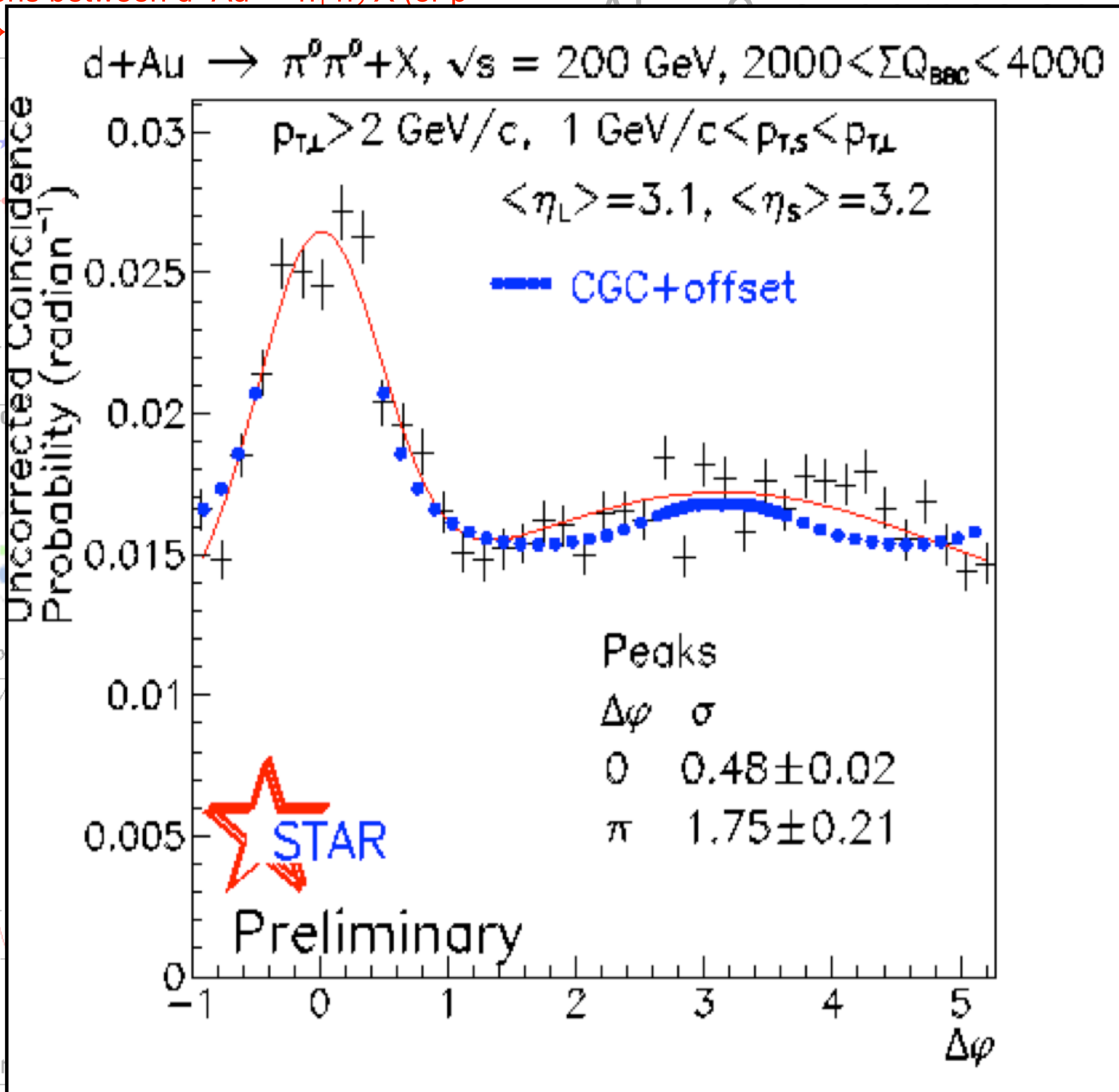
di-hadron angular correlations in d+A

comparisons between d+Au → h_1 h_2 X (or p +Au →









of away-side
A collisions

p or d+A

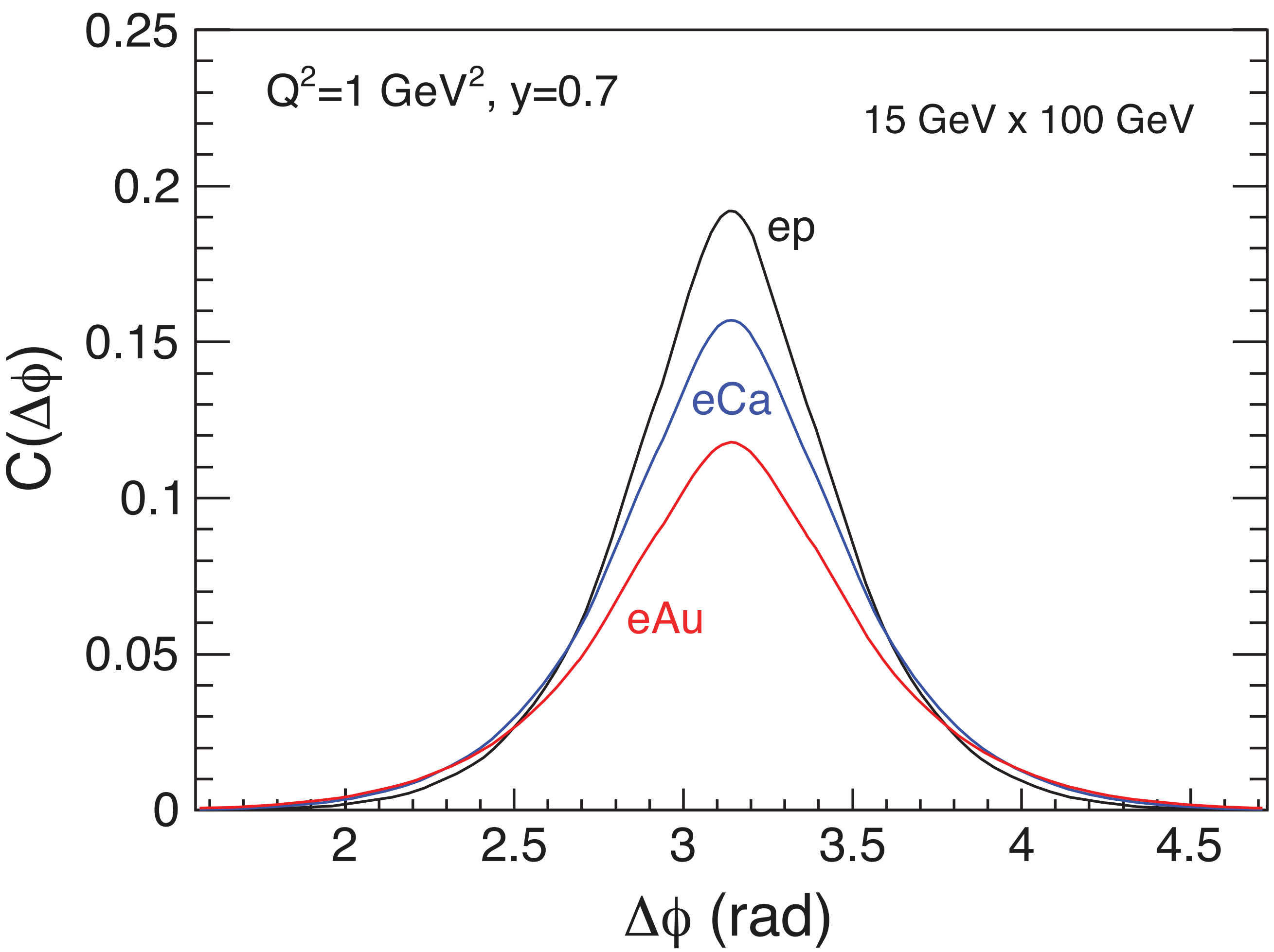
$e^{-y_1} + k_2 e^{-y_2}$ / $\sqrt{s}$ << 1

forward
~ 3.1), an
uppression is
d+Au

peak also much
Au compared to

di-hadron correlations in e+A

Never been measured - we expect to see the same effect in e+A as in d+A



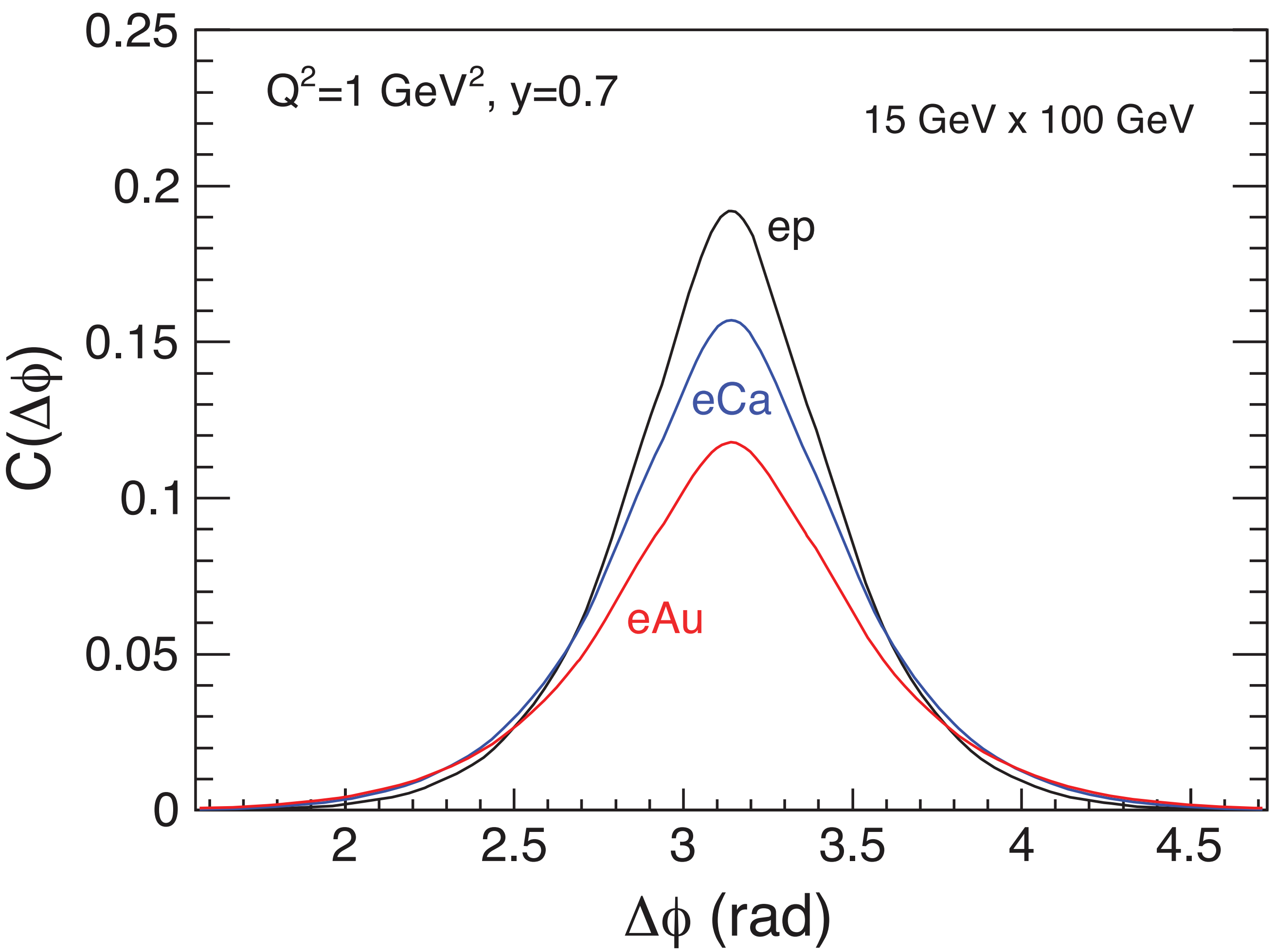
Dominguez et al. PRD83, 105005 (2011), PRL 106, 022301 (2011)

- At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations
  - ➡ The non-linear evolution of multi-gluon distributions is different from that of single-gluon distributions and it is equally important that we understand it
- The d+Au RHIC data is therefore subject to many uncertainties
  - ➡ these correlations in e+A can help to constrain them better

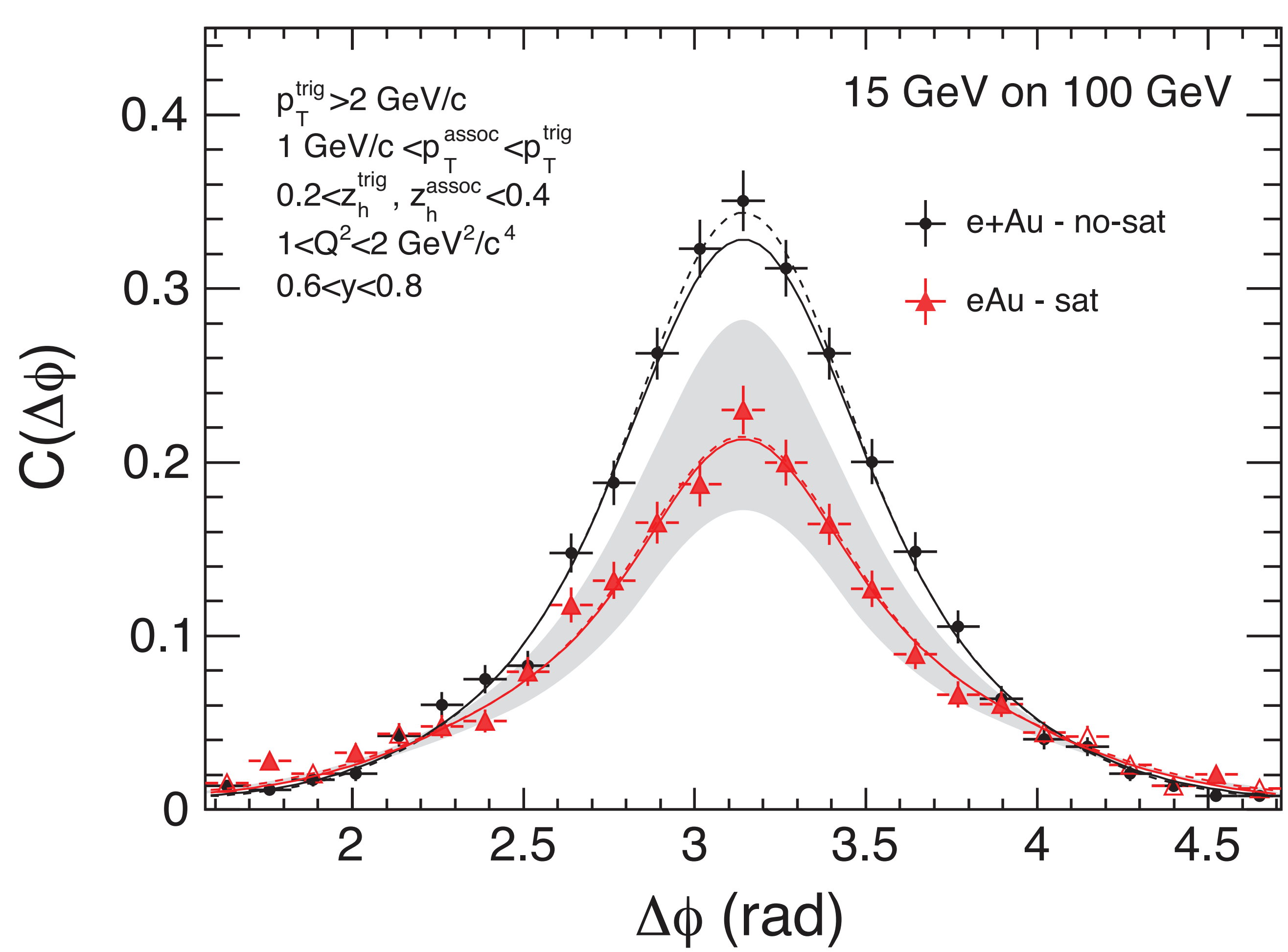
di-hadron correlations in e+A

Never been measured - we expect to see the same effect in e+A as in d+A

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



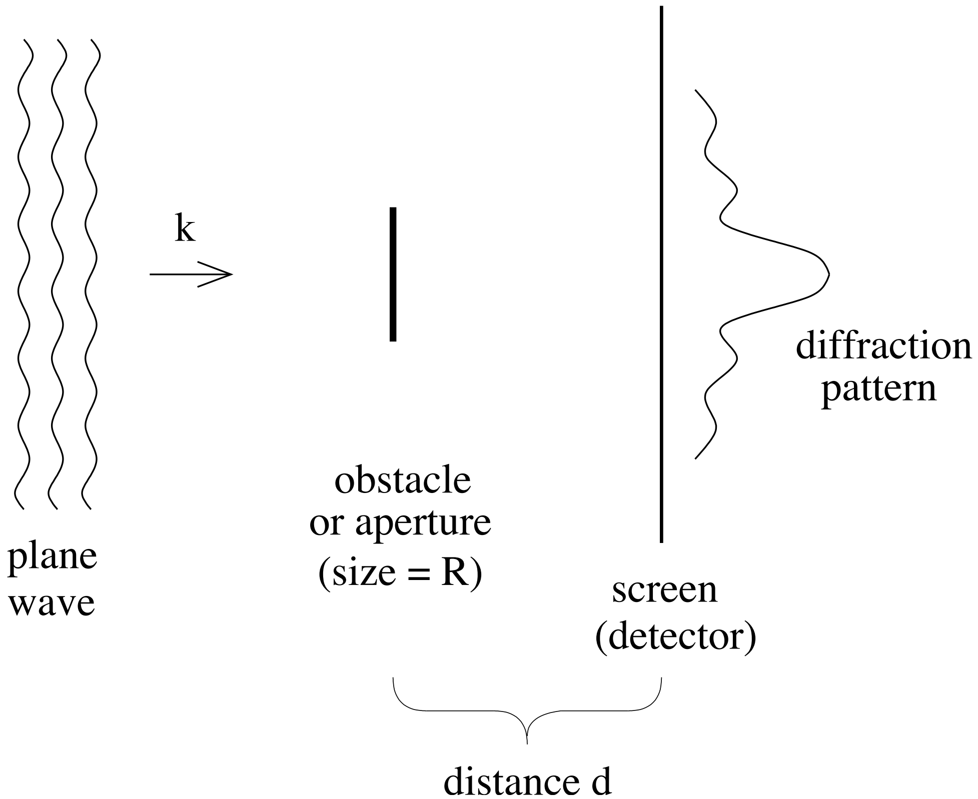
Dominguez et al. PRD83, 105005 (2011), PRL 106, 022301 (2011)



Zheng et al., PRD89 (2014) 074037

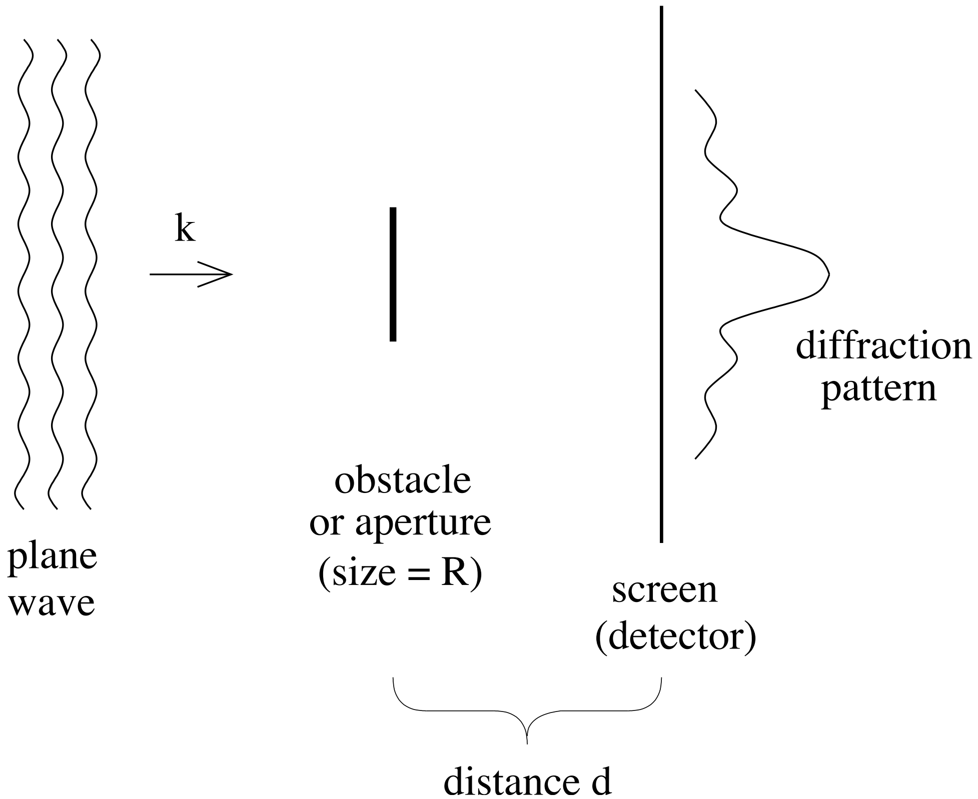
Pythia+DPMJet+Fluka+EPS09+E-loss

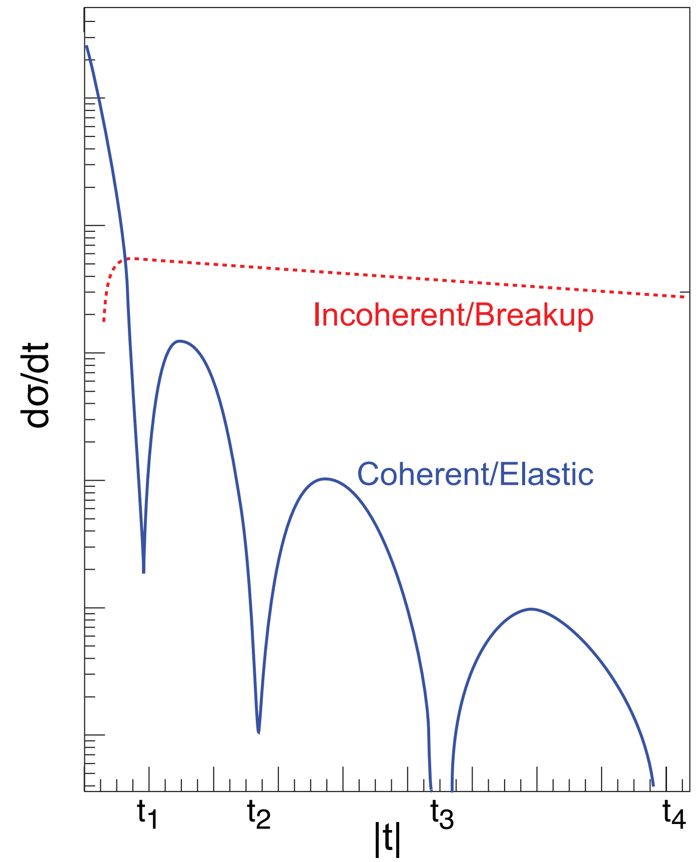
Diffraction in nuclei



- The diffraction pattern contains information about the size (R) of the obstacle and about the optical “blackness”
- In optics, diffraction is studied as a function of θ

Diffraction in nuclei





Coherent diffraction: nuclei stays intact

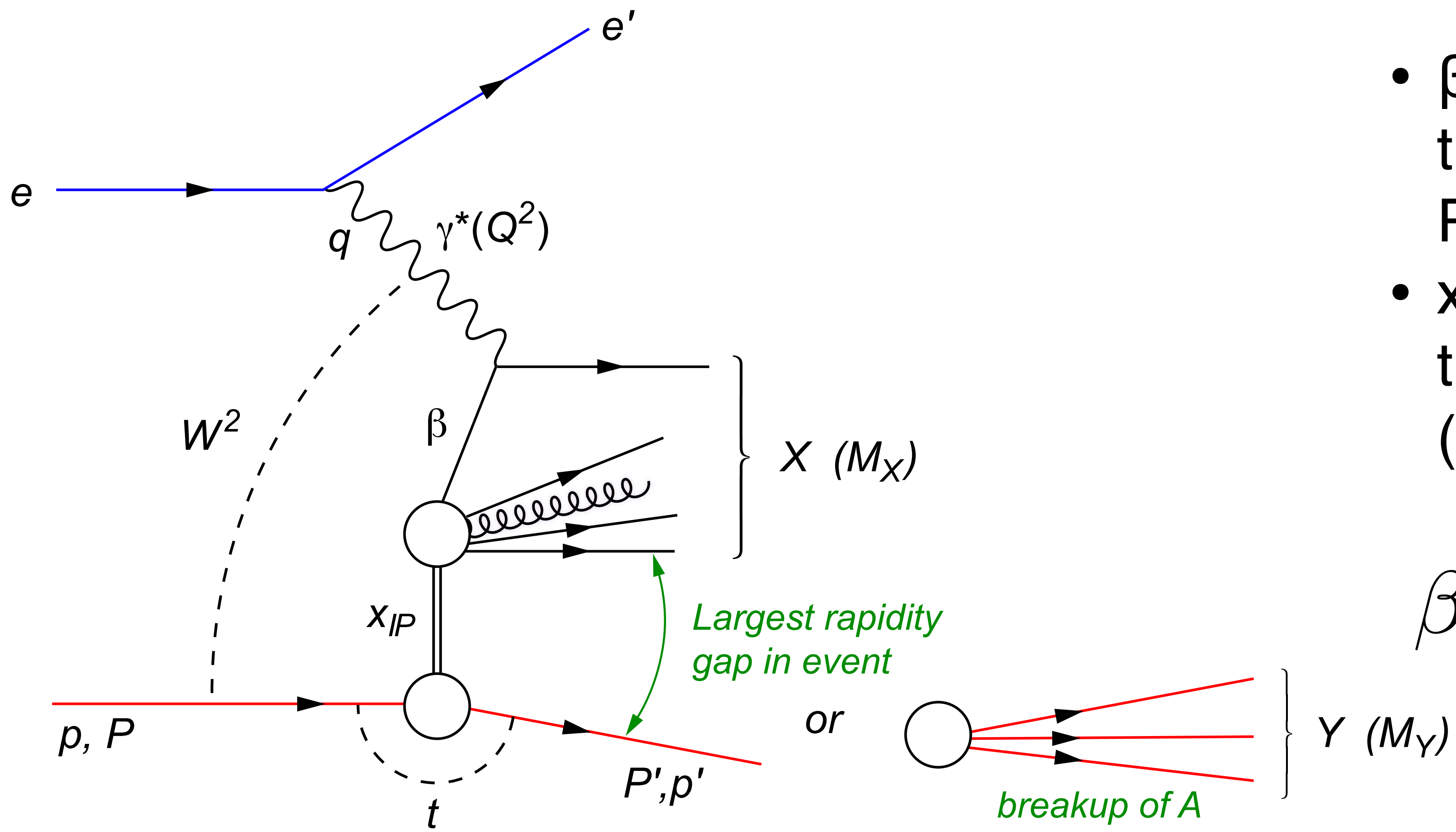
Incoherent diffraction: nuclei breaks up, nucleons stays intact

- The diffraction pattern contains information about the size (R) of the obstacle and about the optical "blackness"

- In optics, diffraction is studied as a function of θ

- In high energy scattering, an analogous measurement can be made in terms of the Mandelstam variable t ($t = k\sin\theta$)

Exclusive processes in e+A - diffraction



$$t = (p - p')^2$$

- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\beta = \frac{x}{x_{\mathbb{P}}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- Detecting diffractive events:
  - ➡ Rapidity gap
    - – Required a hermetic detector
  - ➡ Discriminating between coherent and incoherent
    - – Roman Pots (e+p)
    - – detect neutrons in the ZDC (eAu)

Diffractive cross-section

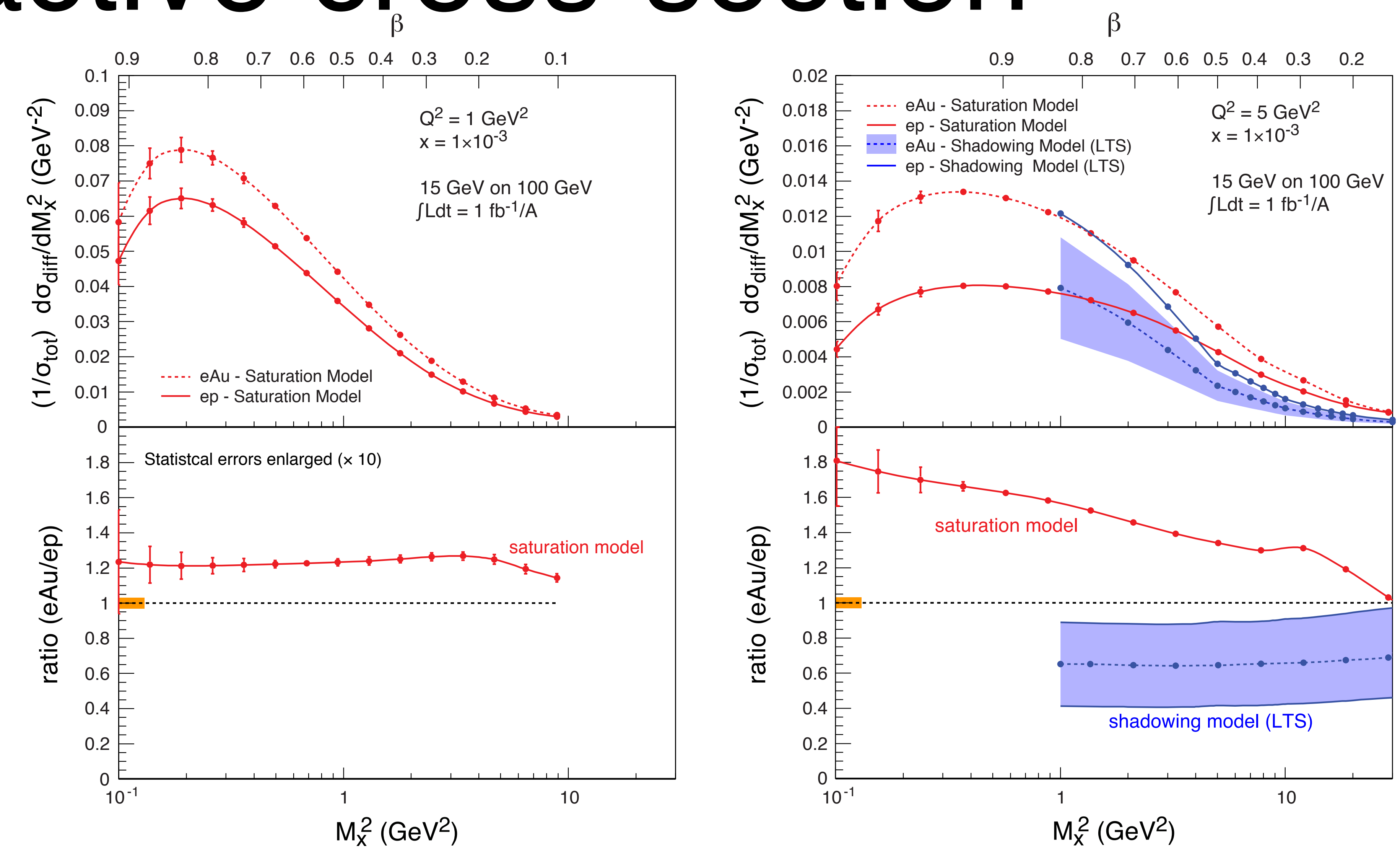
At HERA, in e+p, the diffractive cross-section was ~15% of the total cross-section

Predictions for e+A collisions at an EIC have this even higher

Diffractive cross-section

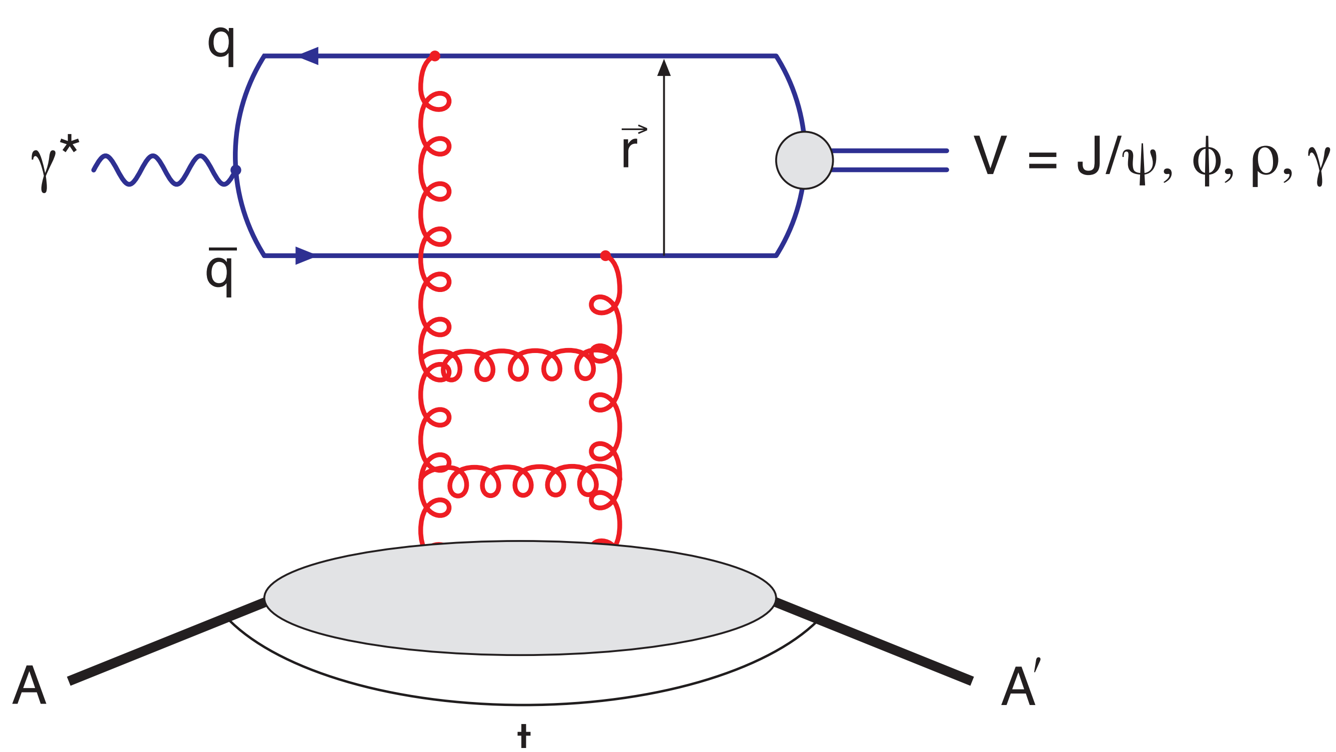
At HERA, in e+p, the diffractive cross-section was ~15% of the total cross-section

Predictions for e+A collisions at an EIC have this even higher



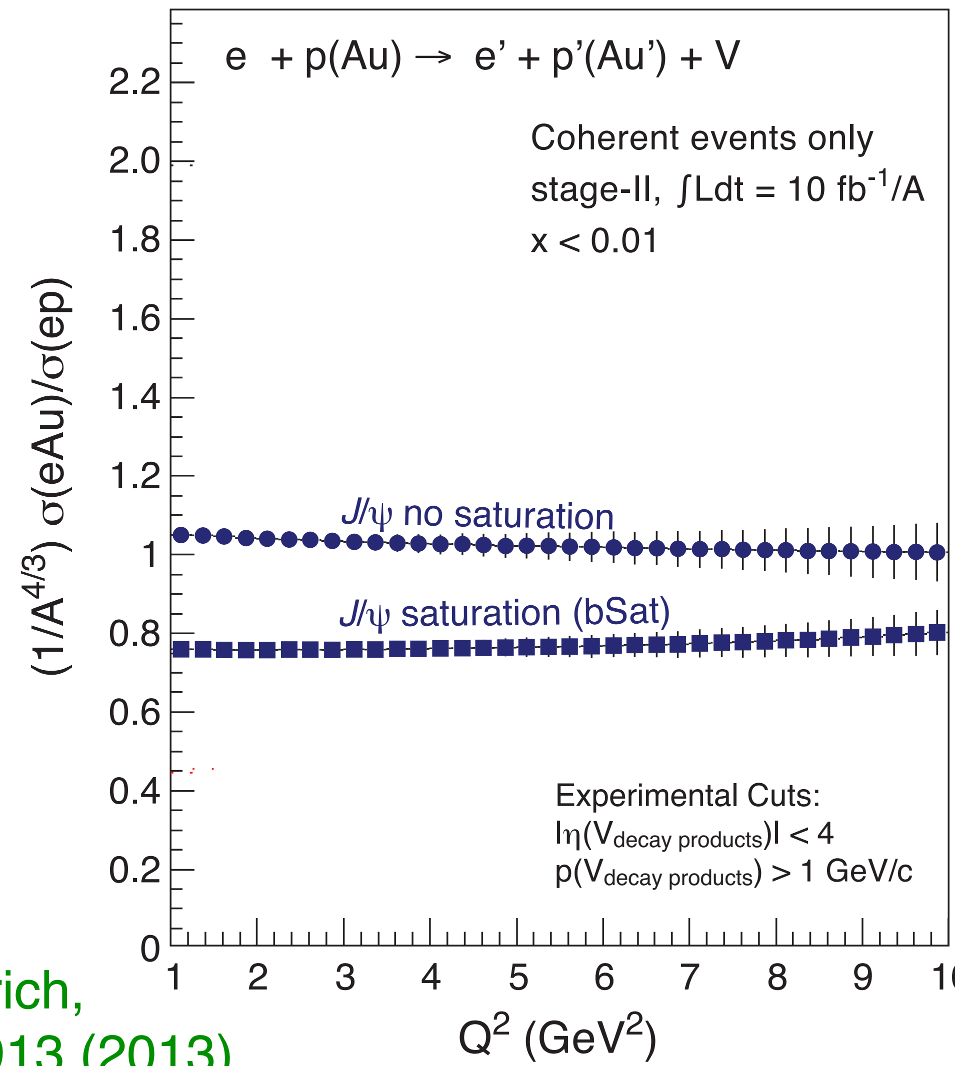
- For $Q^2 = 1$ GeV^2 and $x = 1\text{x}10^{-3}$, saturation models predict this to be about 25%
- This increases at higher Q^2 (and the same x), but non-saturation models have a smaller ratio than in e+p
- This is easy to check → a "day 1" measurement

Exclusive vector meson production



$$d\sigma \propto g(x)^2$$

Sartre: Toll, Ullrich,
Phys.Rev. C87, 024913 (2013)

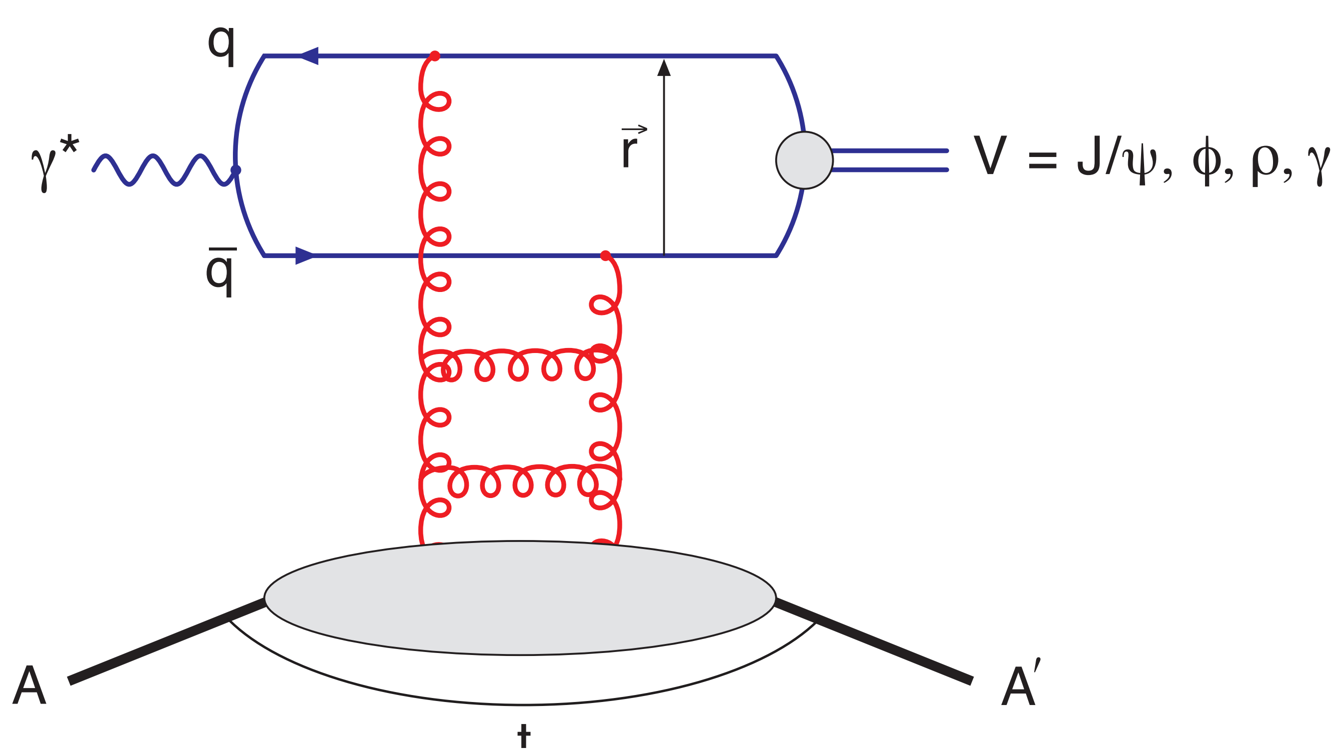


- Exclusive vector meson production is most sensitive to the gluon distribution

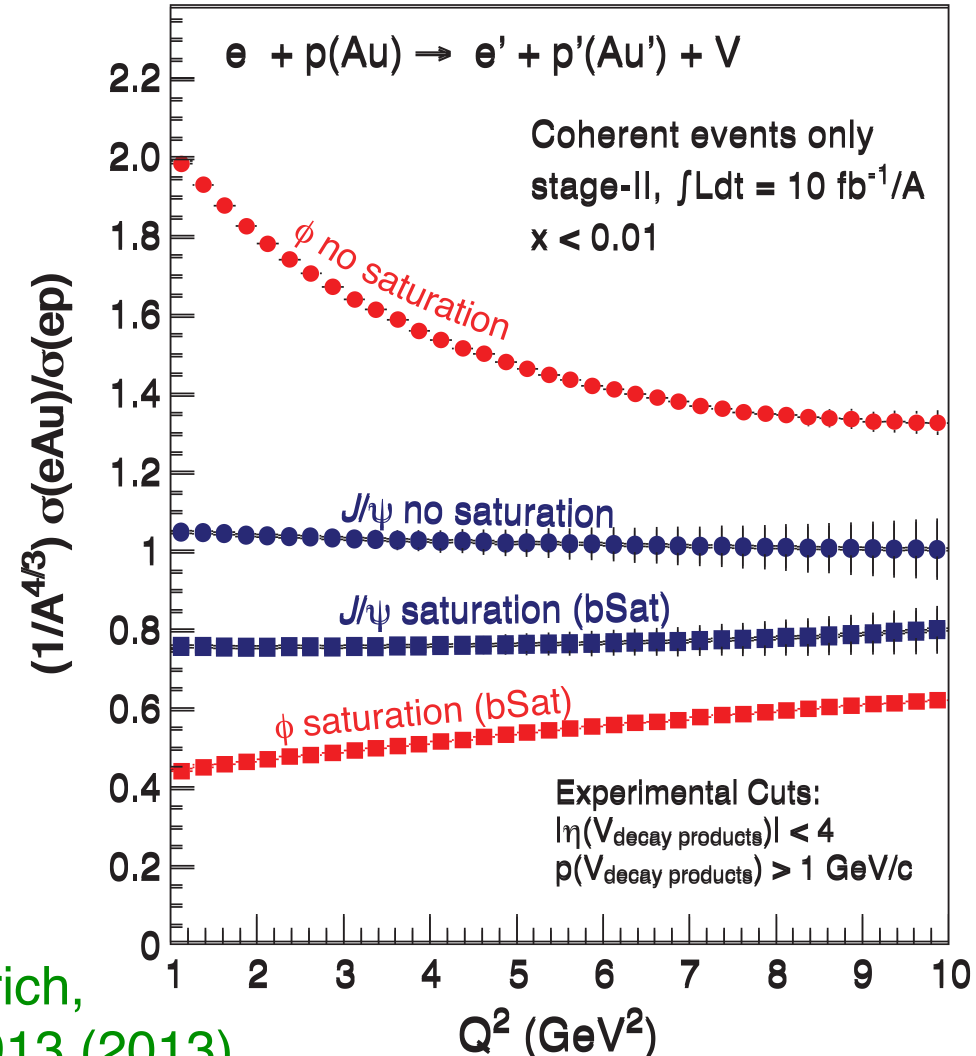
  ➡ colour-neutral exchange of gluons

- J/ψ shows some difference between saturation and no-saturation

Exclusive vector meson production



$$d\sigma \propto g(x)^2$$



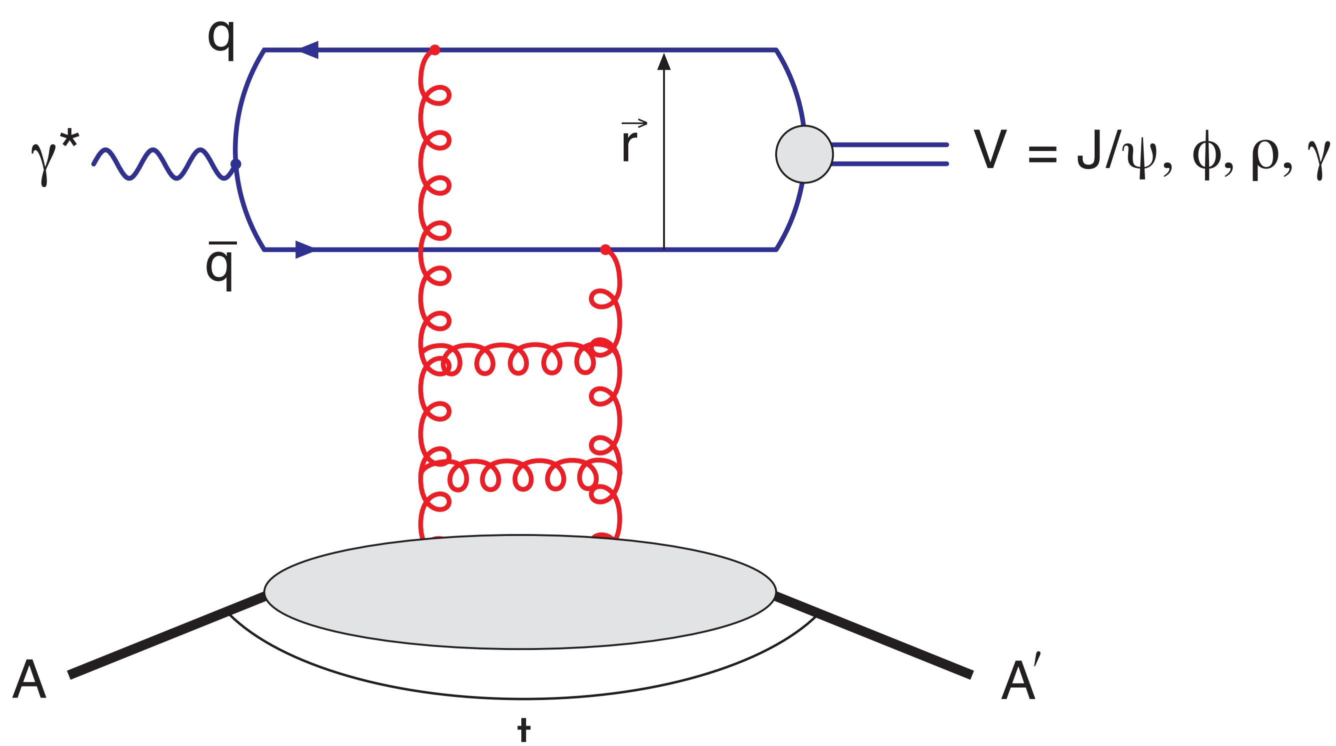
Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

- Exclusive vector meson production is most sensitive to the gluon distribution

  ➡colour-neutral exchange of gluons

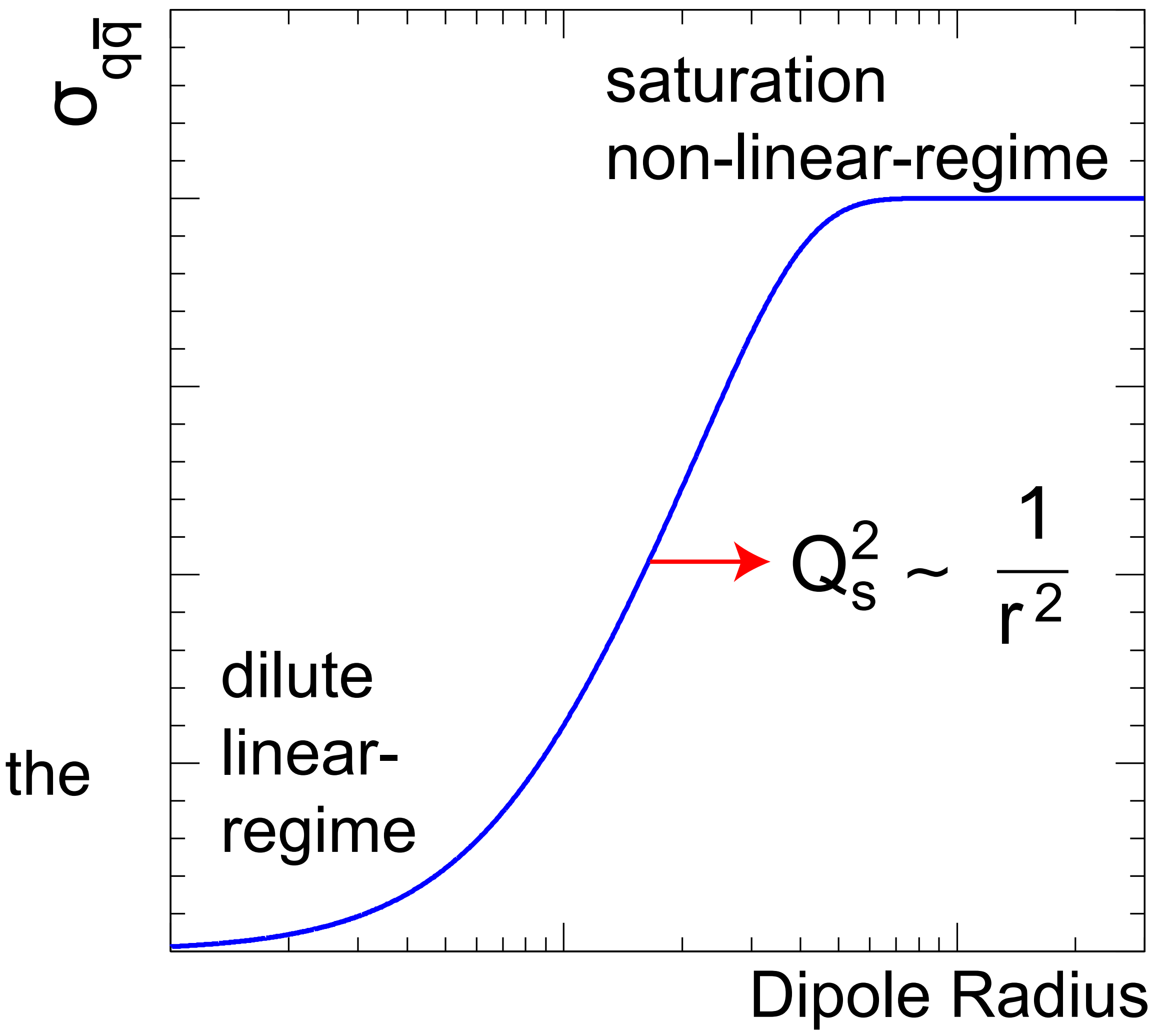
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference

J/ψ vs ϕ - Saturation effects

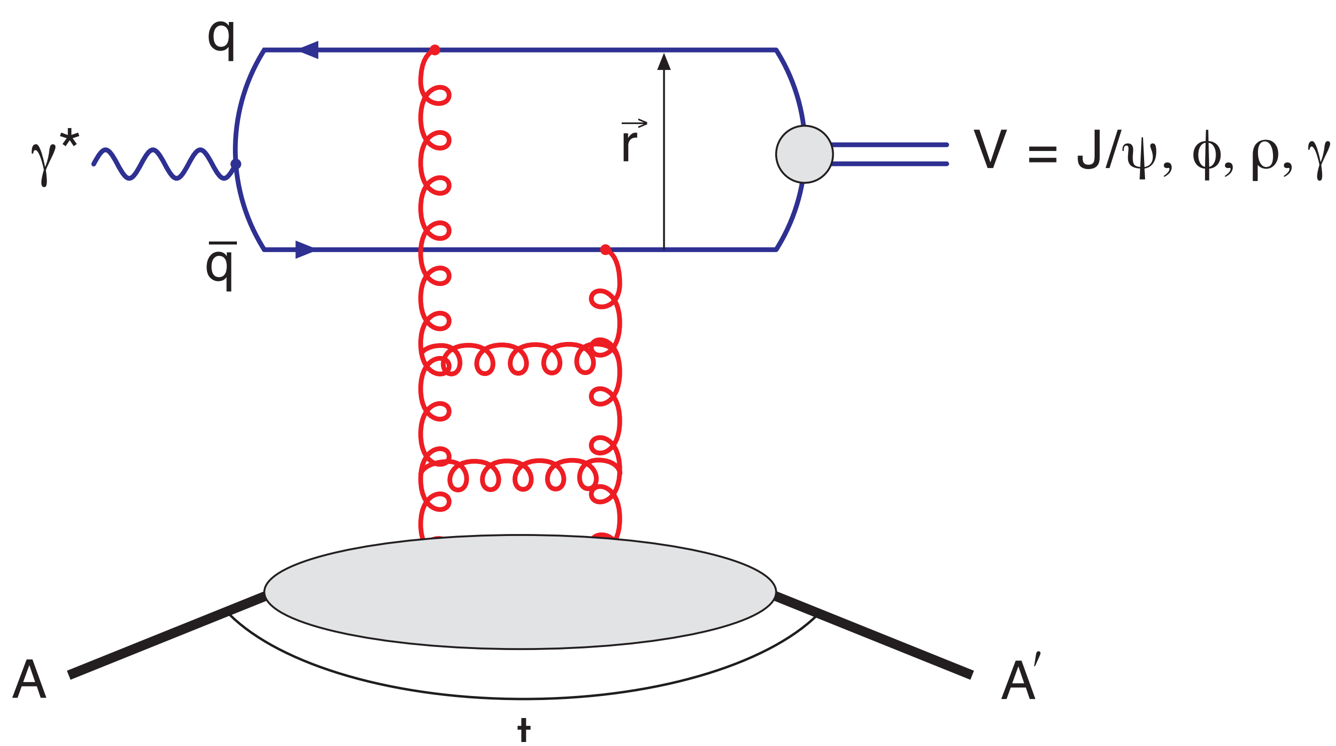


$$d\sigma \propto g(x)^2$$

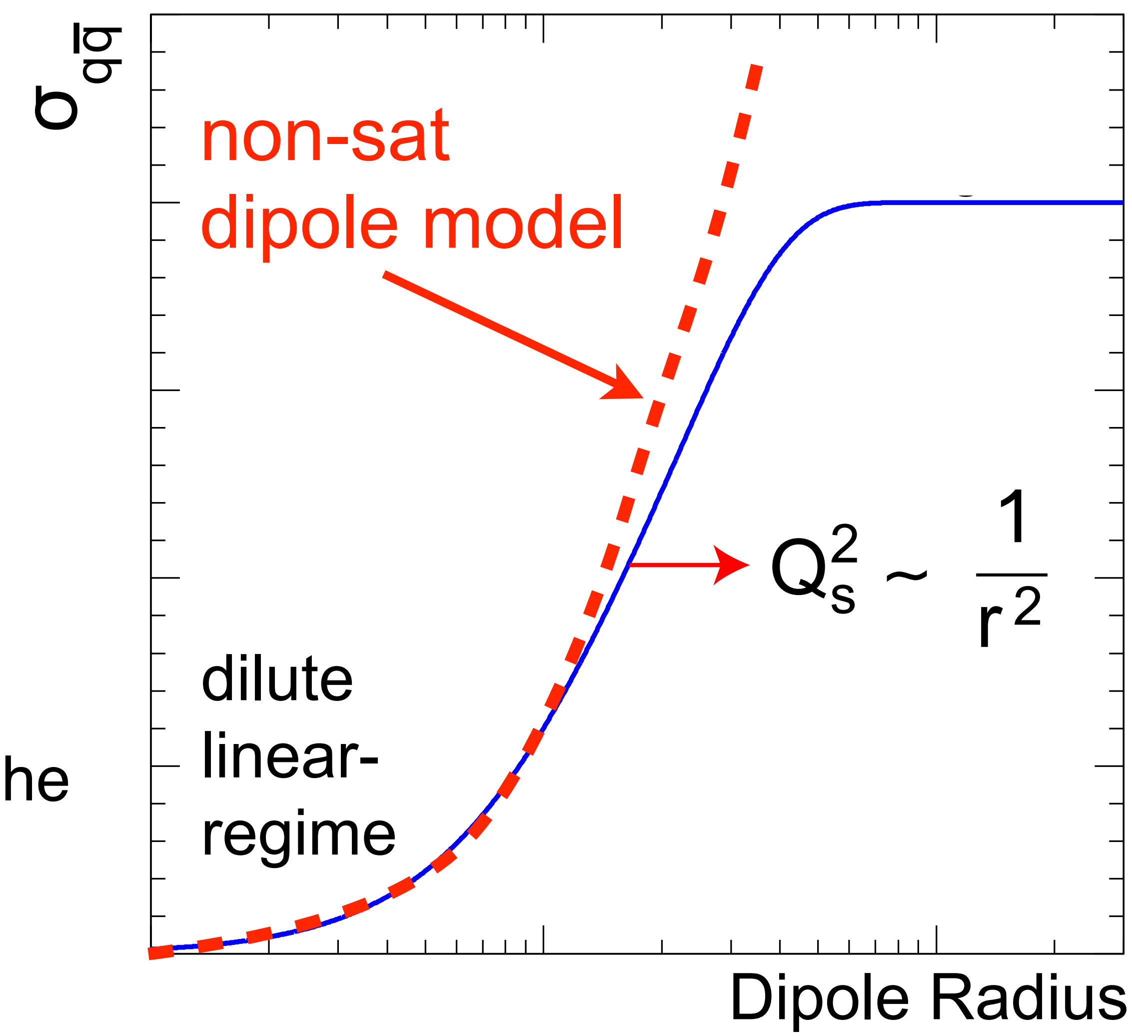
- Dipole cross-section is saturated as it approaches the black-disk limit



J/ψ vs ϕ - Saturation effects

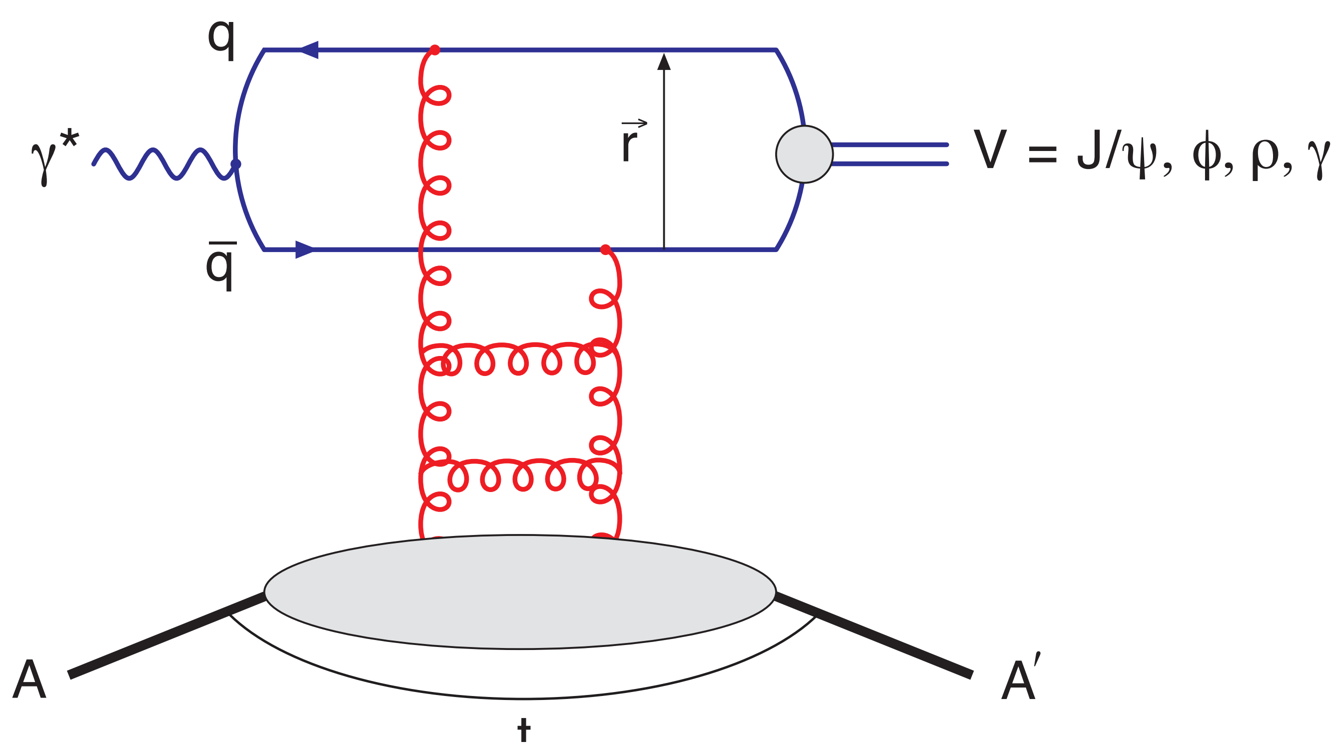


$$d\sigma \propto g(x)^2$$



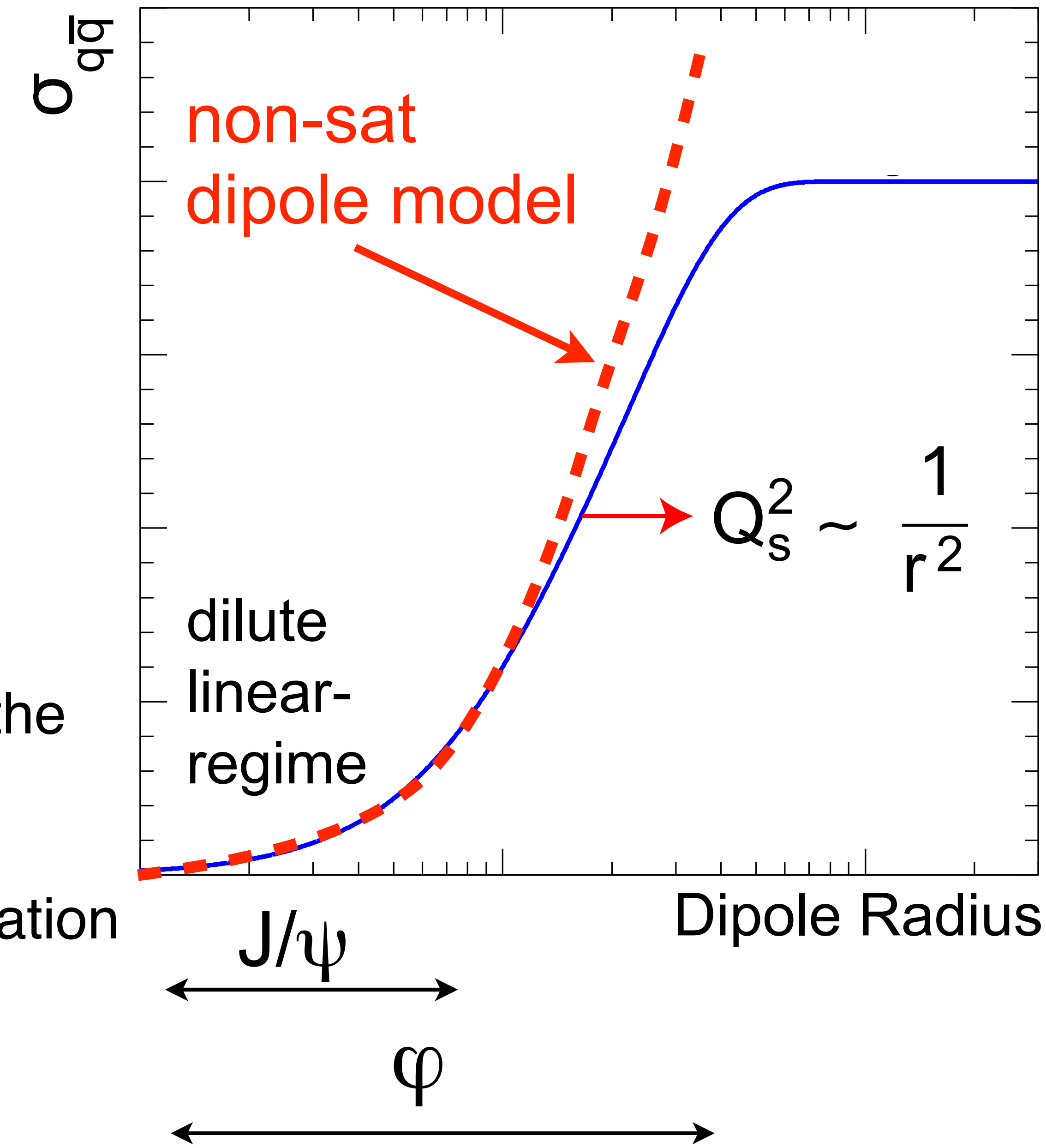
- Dipole cross-section is saturated as it approaches the black-disk limit

J/ψ vs ϕ - Saturation effects

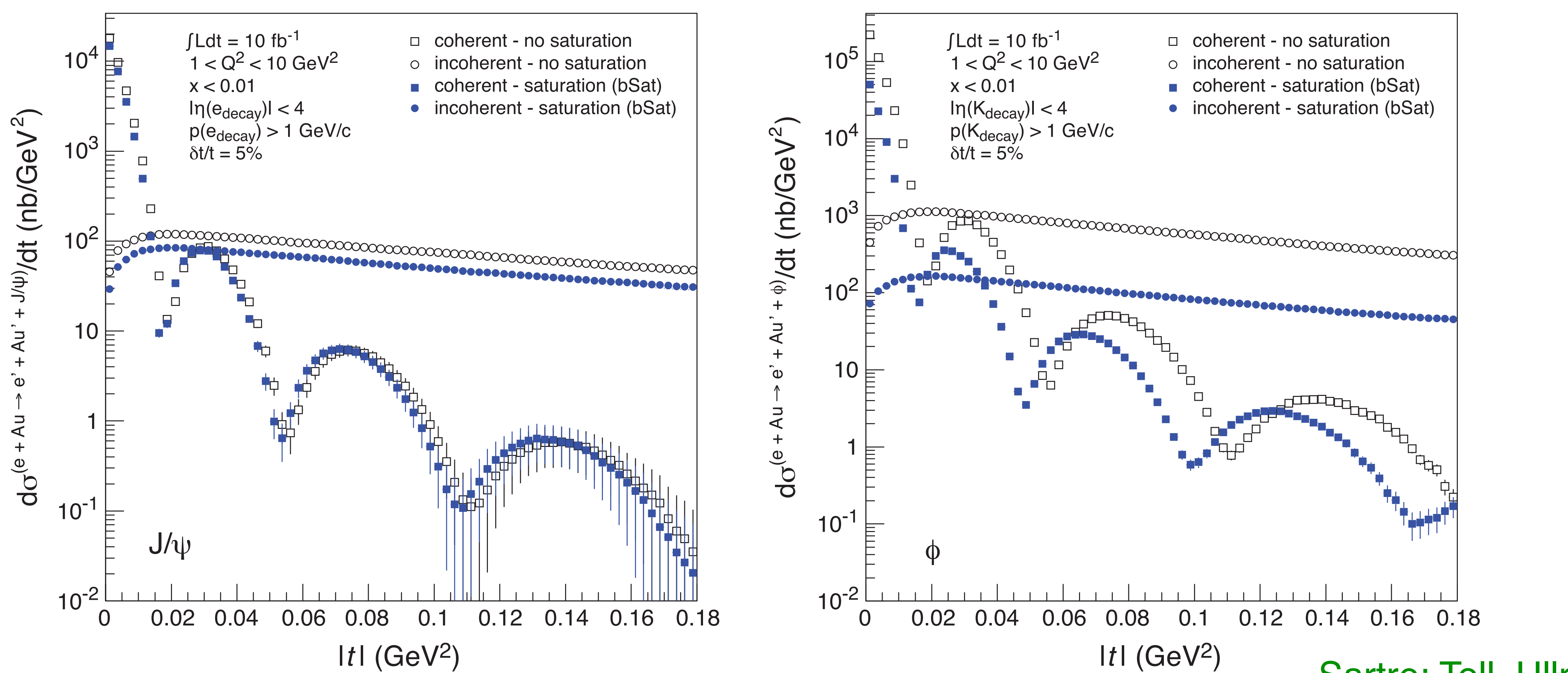


$$d\sigma \propto g(x)^2$$

- Dipole cross-section is saturated as it approaches the black-disk limit
- J/ψ has a small radius - not much affected by saturation
- ϕ shows a much larger difference
  - ➡wave function for ϕ is larger and hence more sensitive to saturation effects



Exclusive Vector Meson Production in e+A



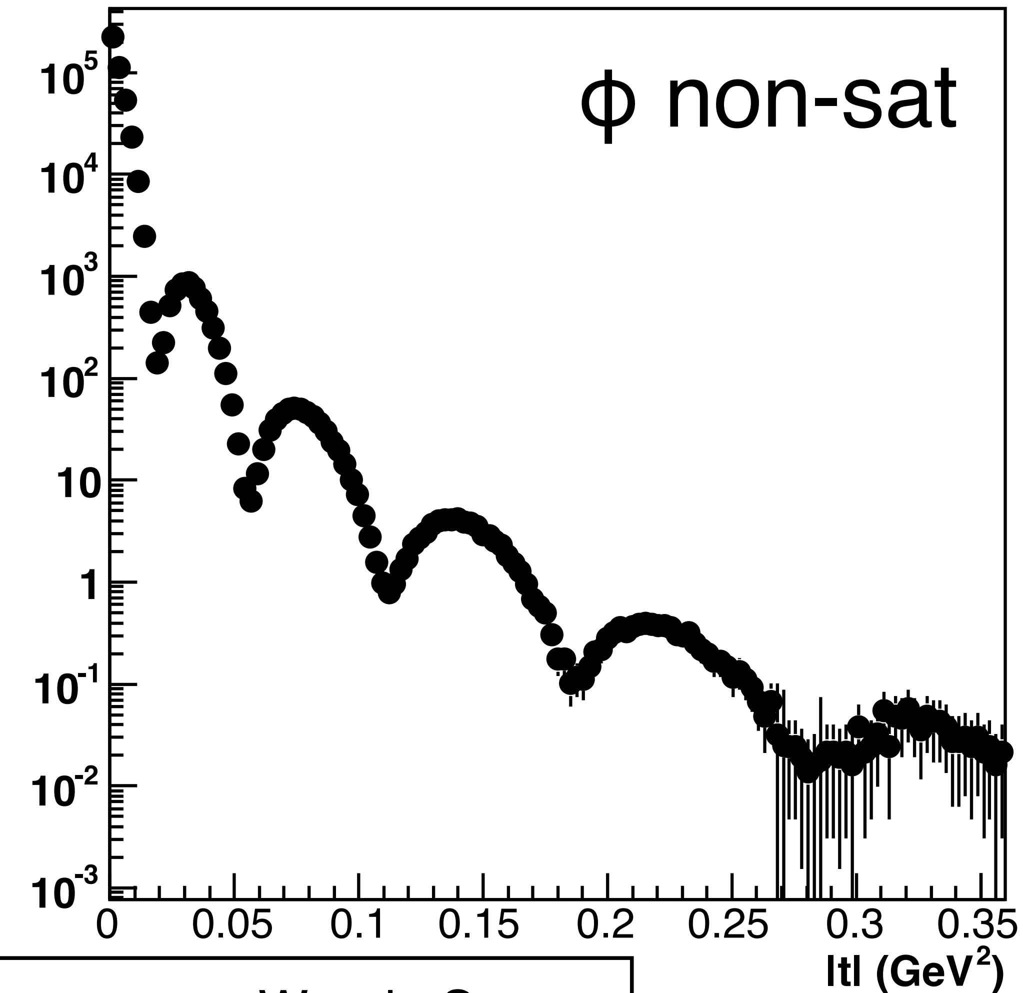
Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations

➡Need good breakup detection efficiency to discriminate between the two scenarios

- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

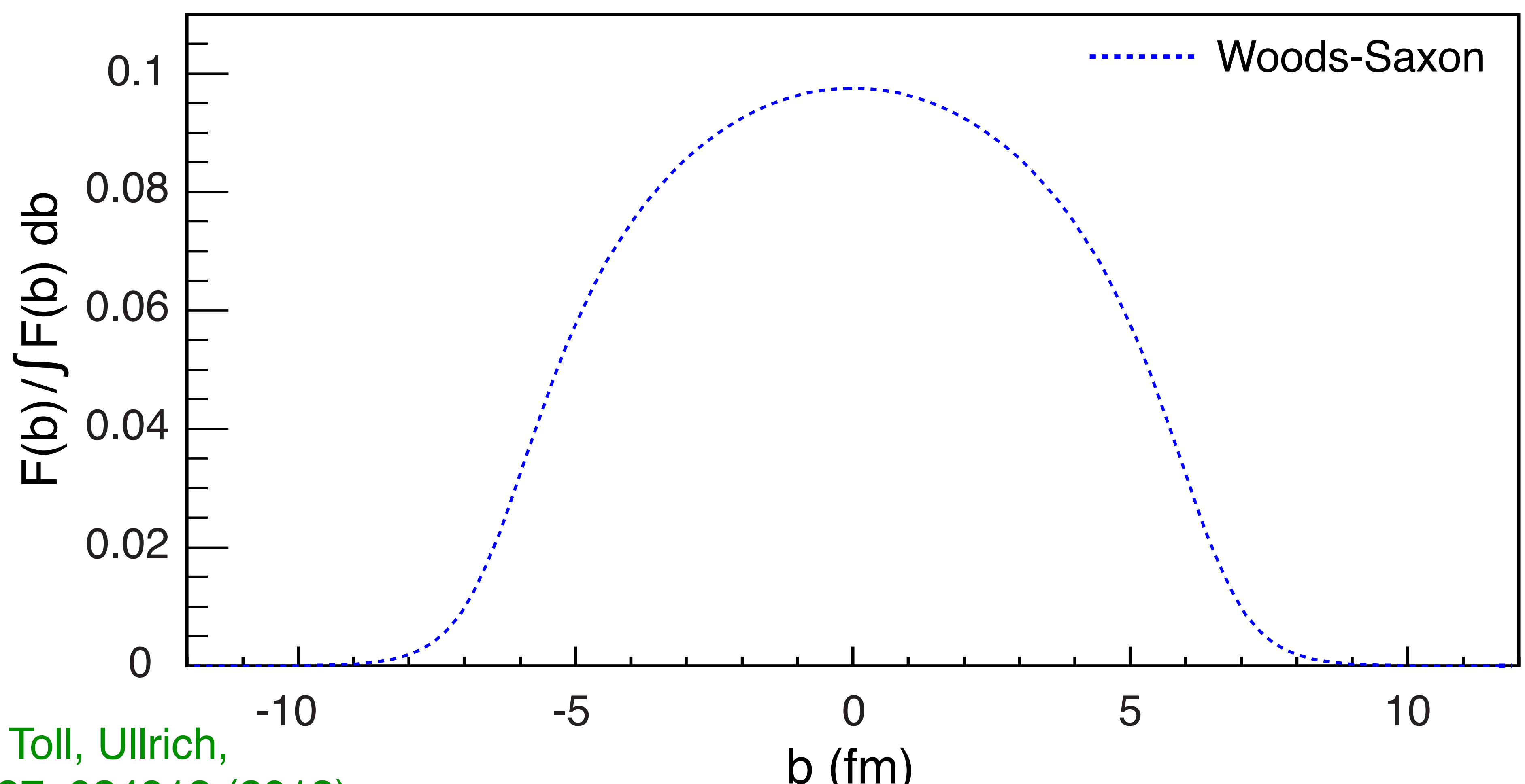
Finding the source...



- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

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

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



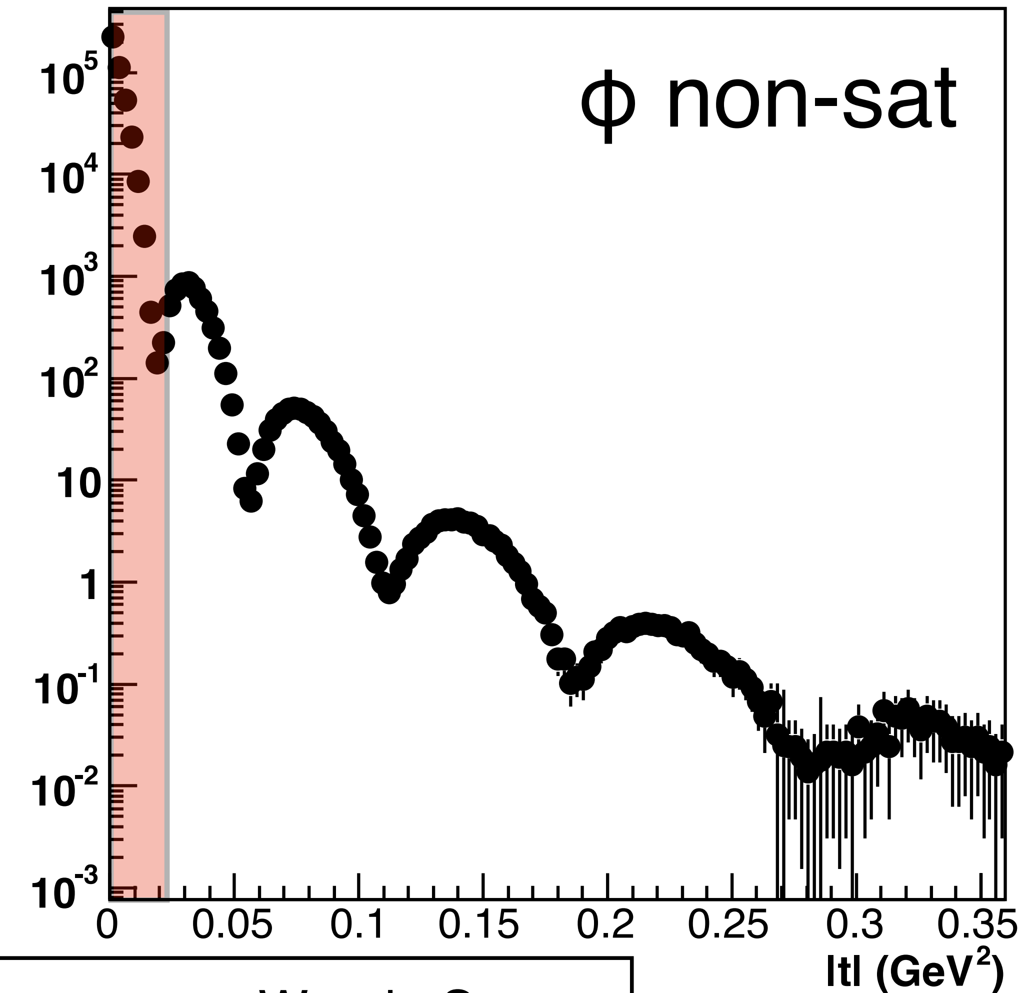
Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

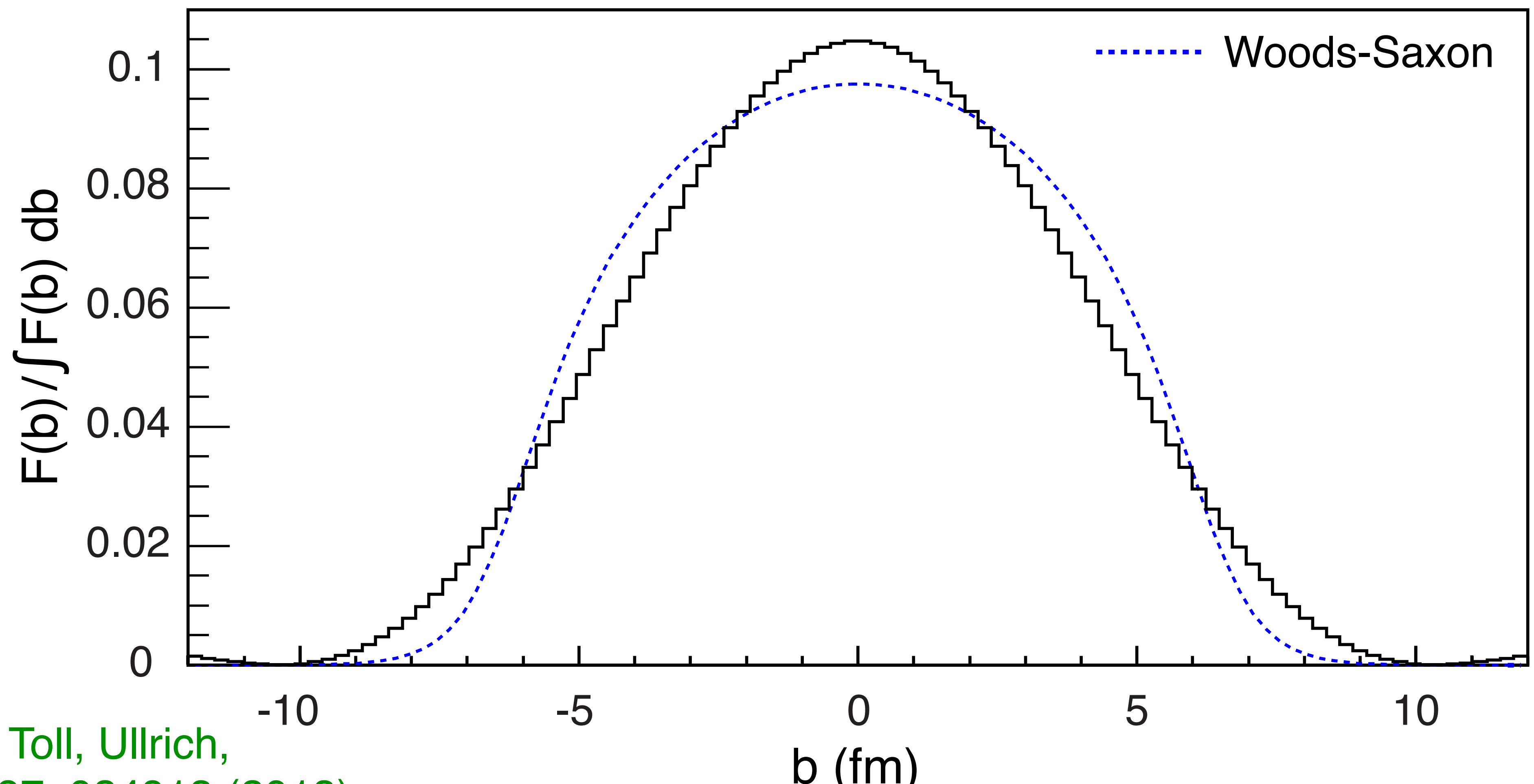
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

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

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

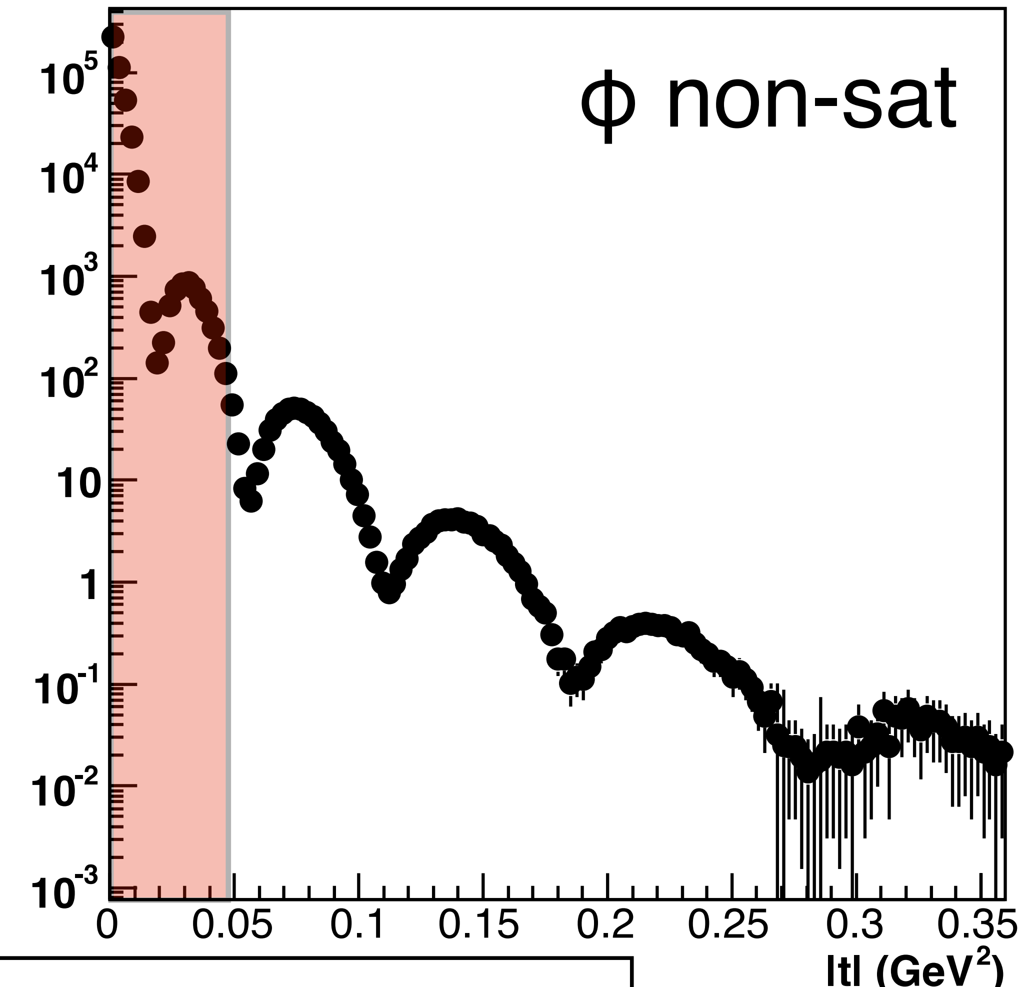




Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

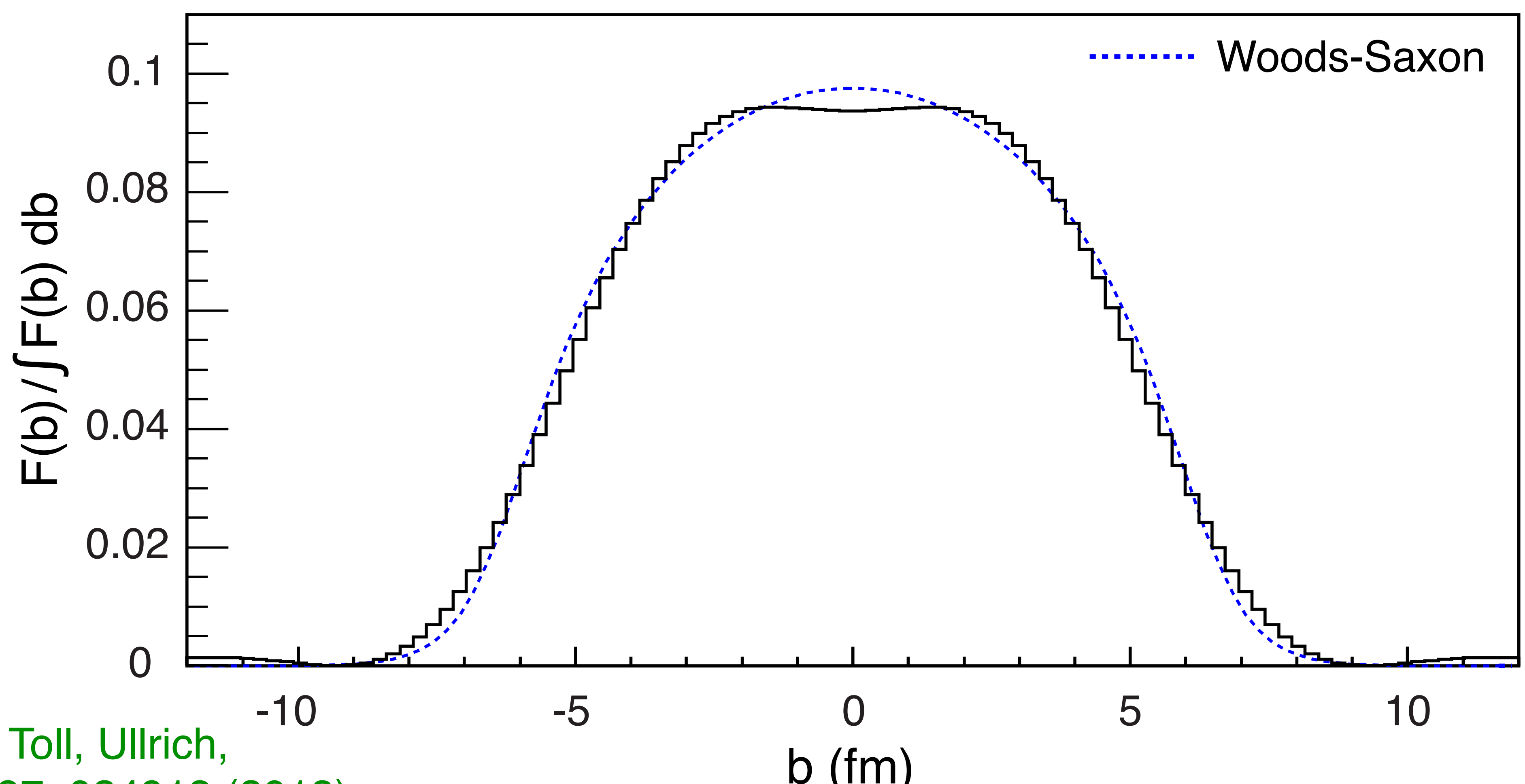
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons



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

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



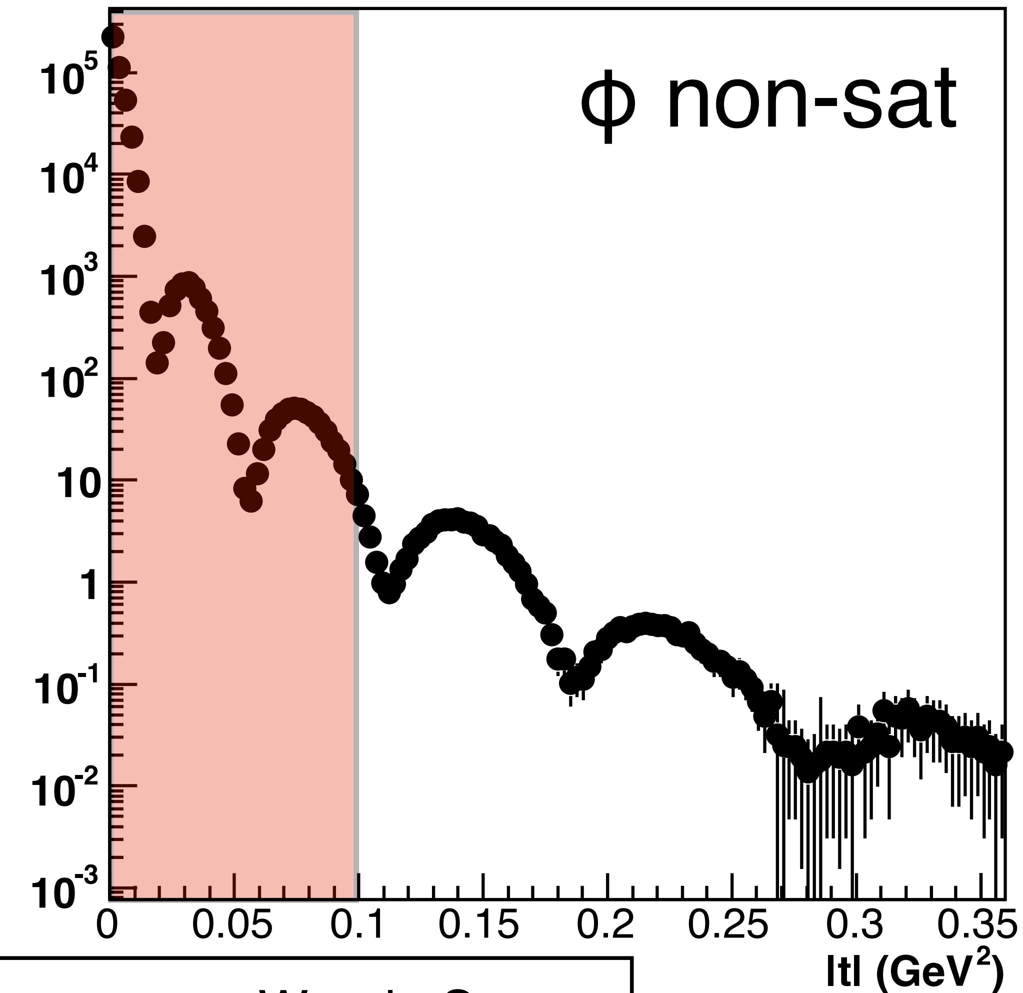
Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

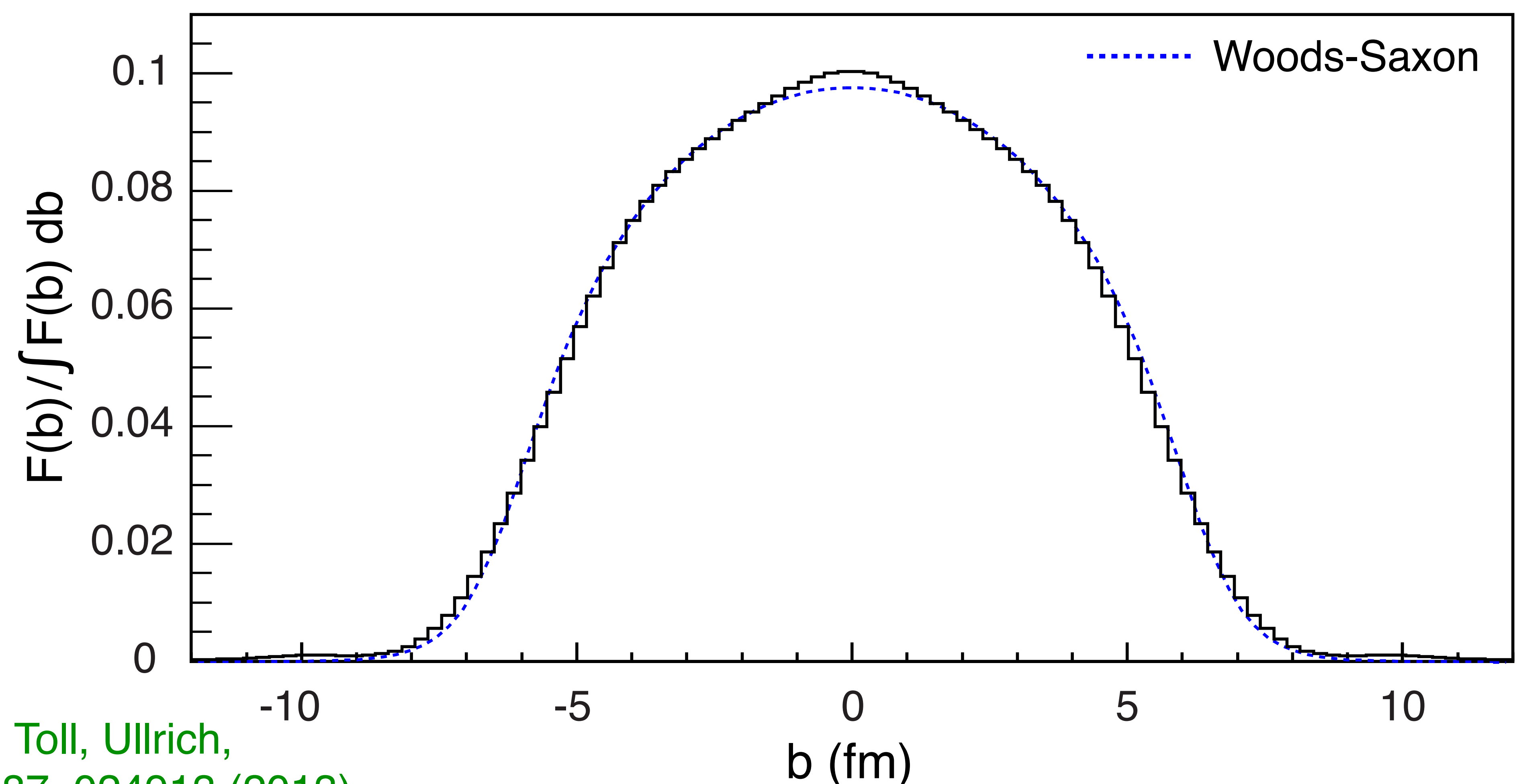
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

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

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

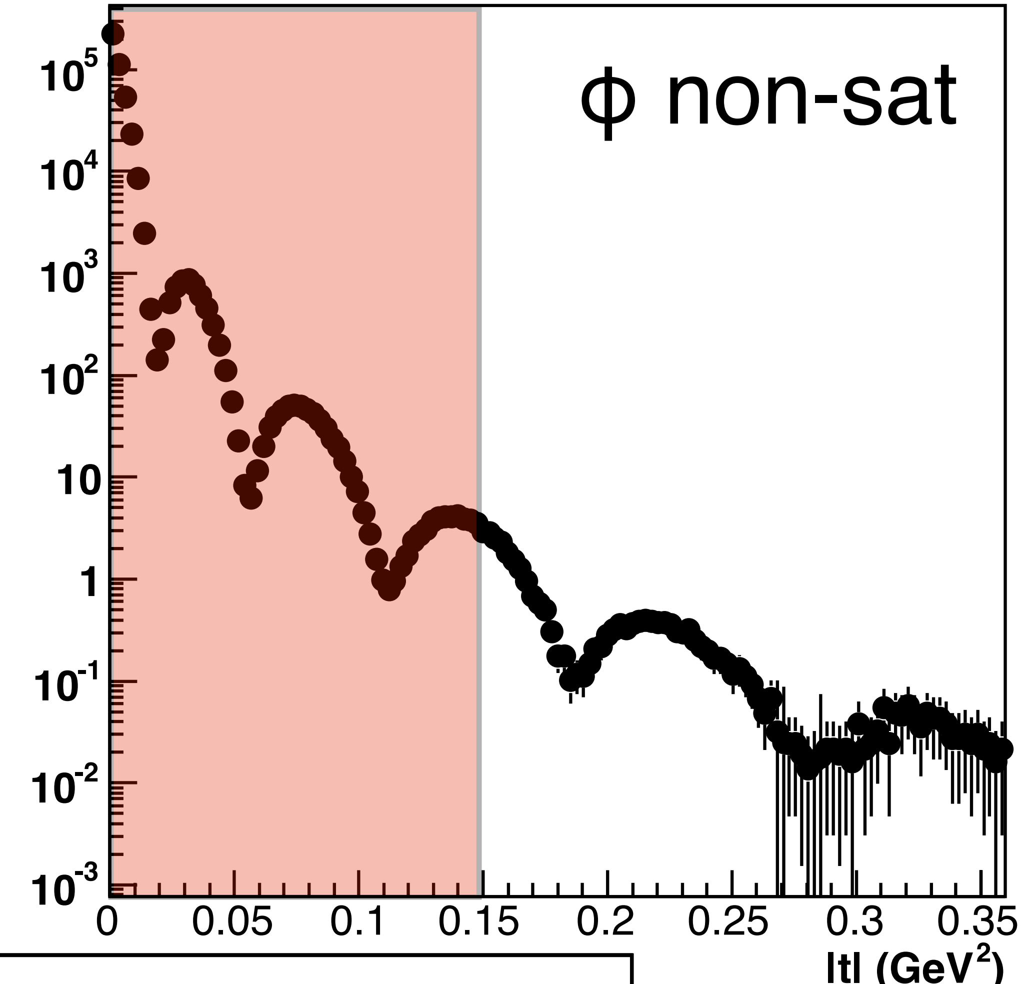




Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

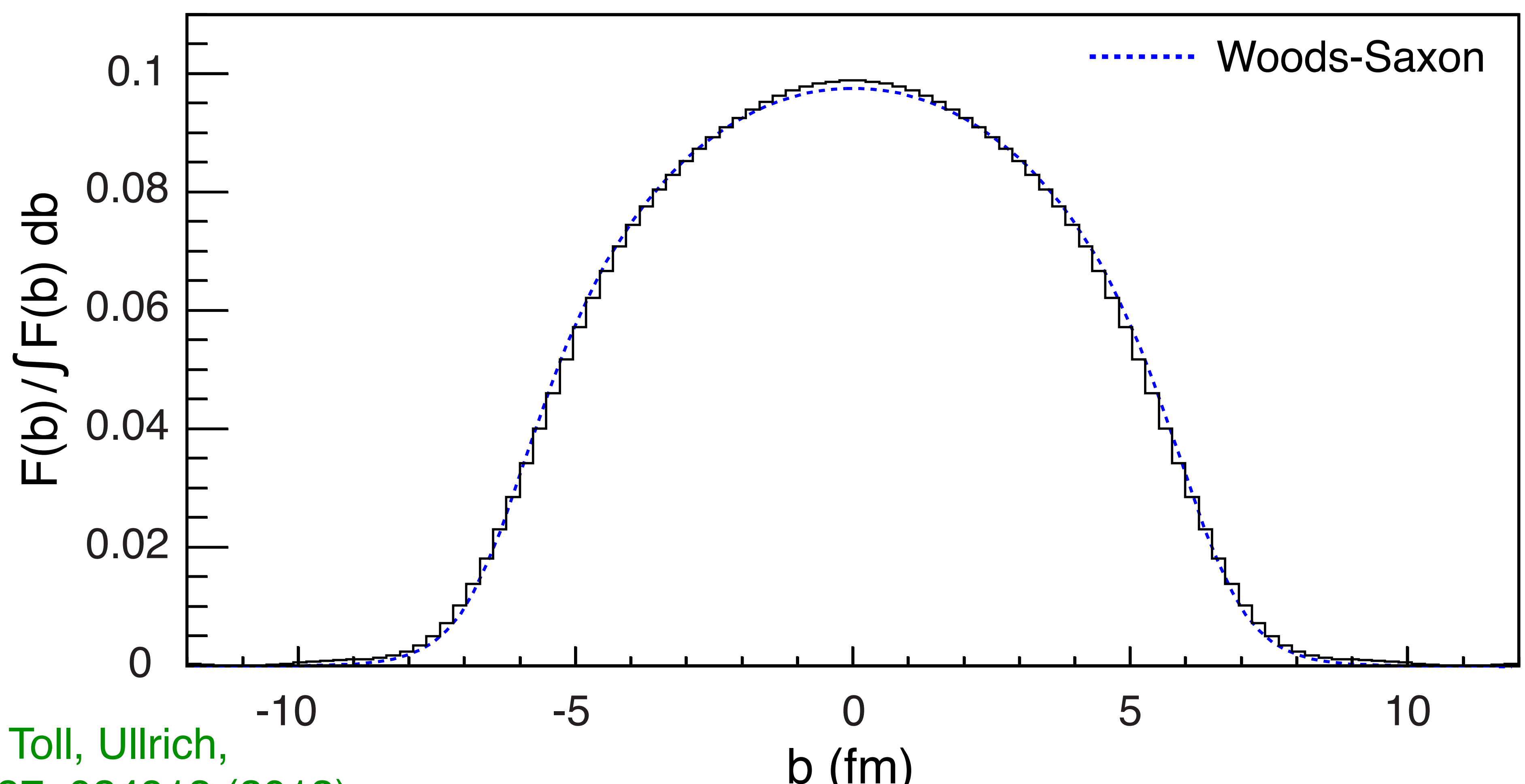
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons



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

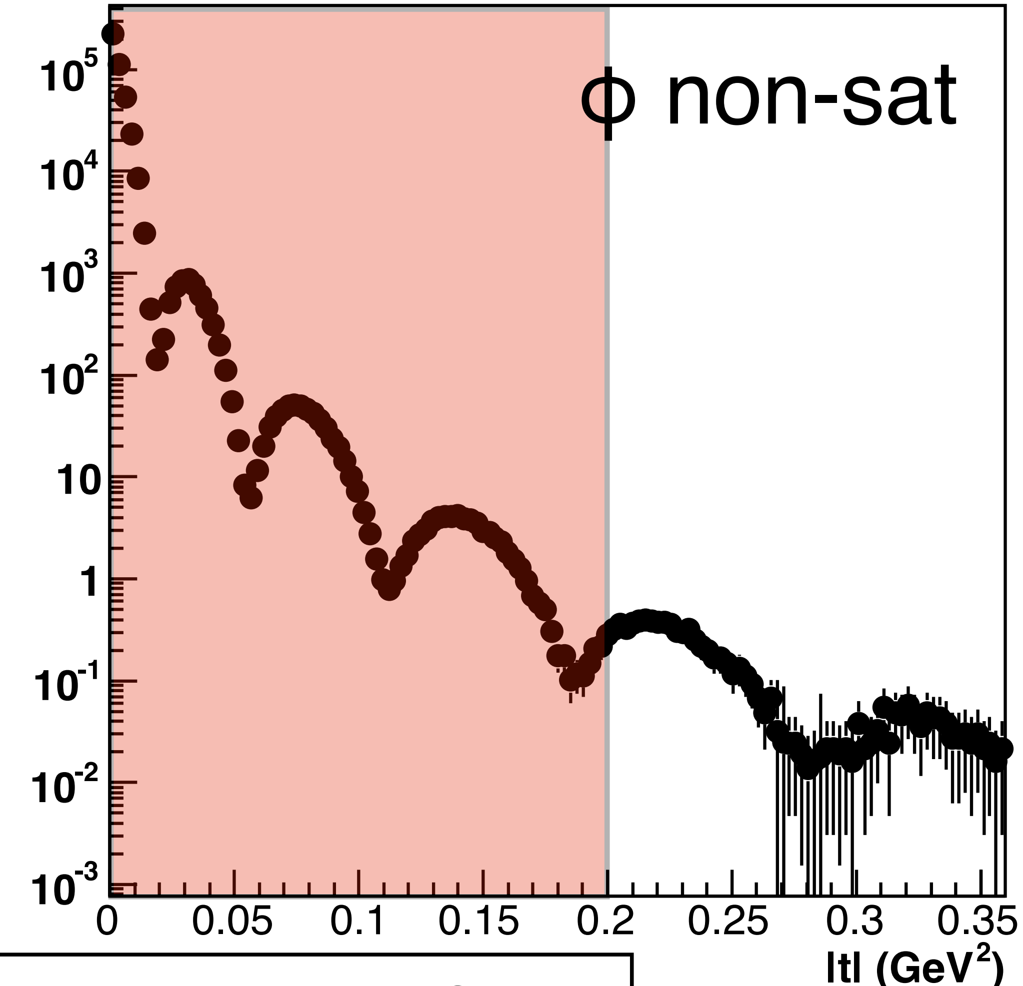
$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)



Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

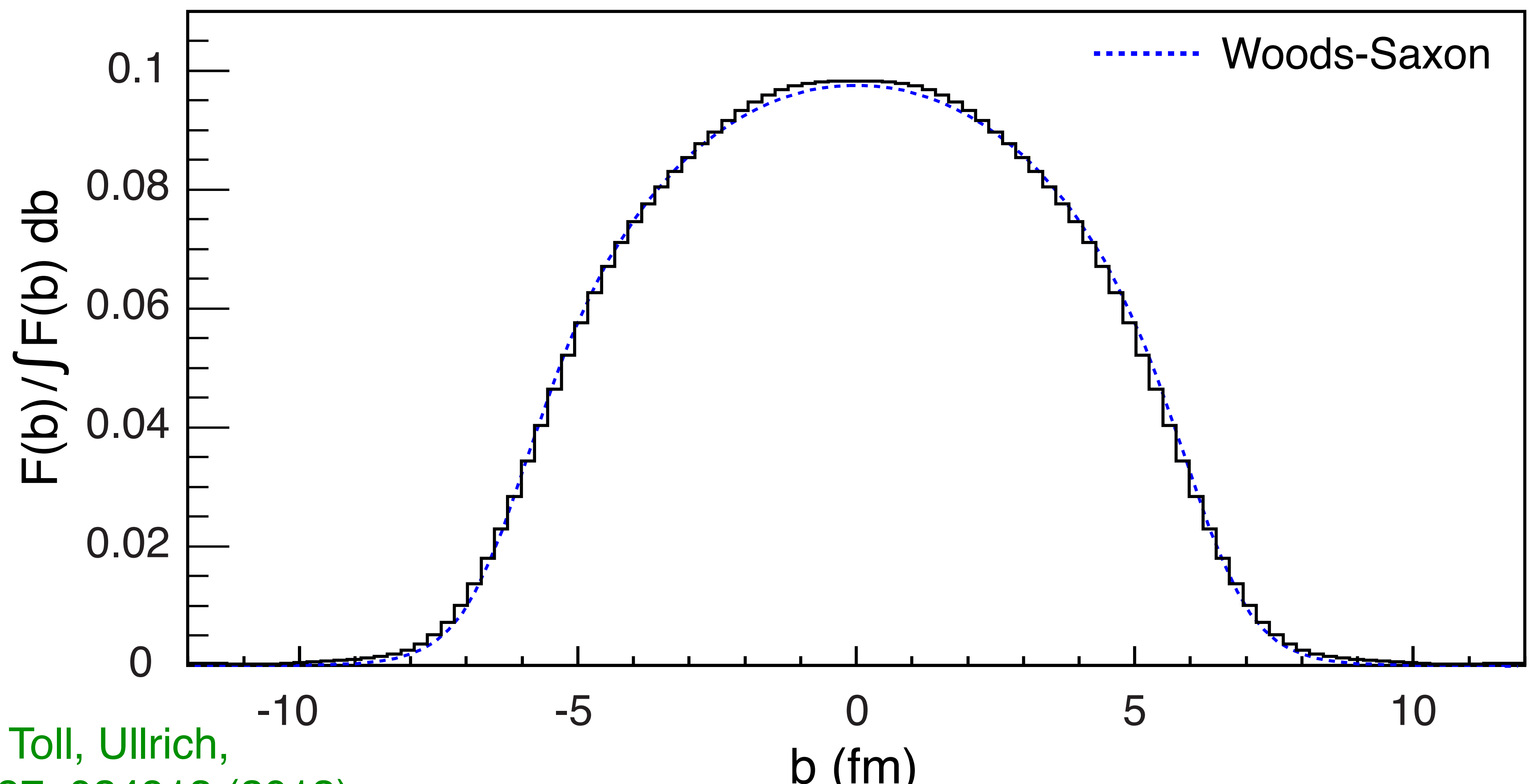
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons



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

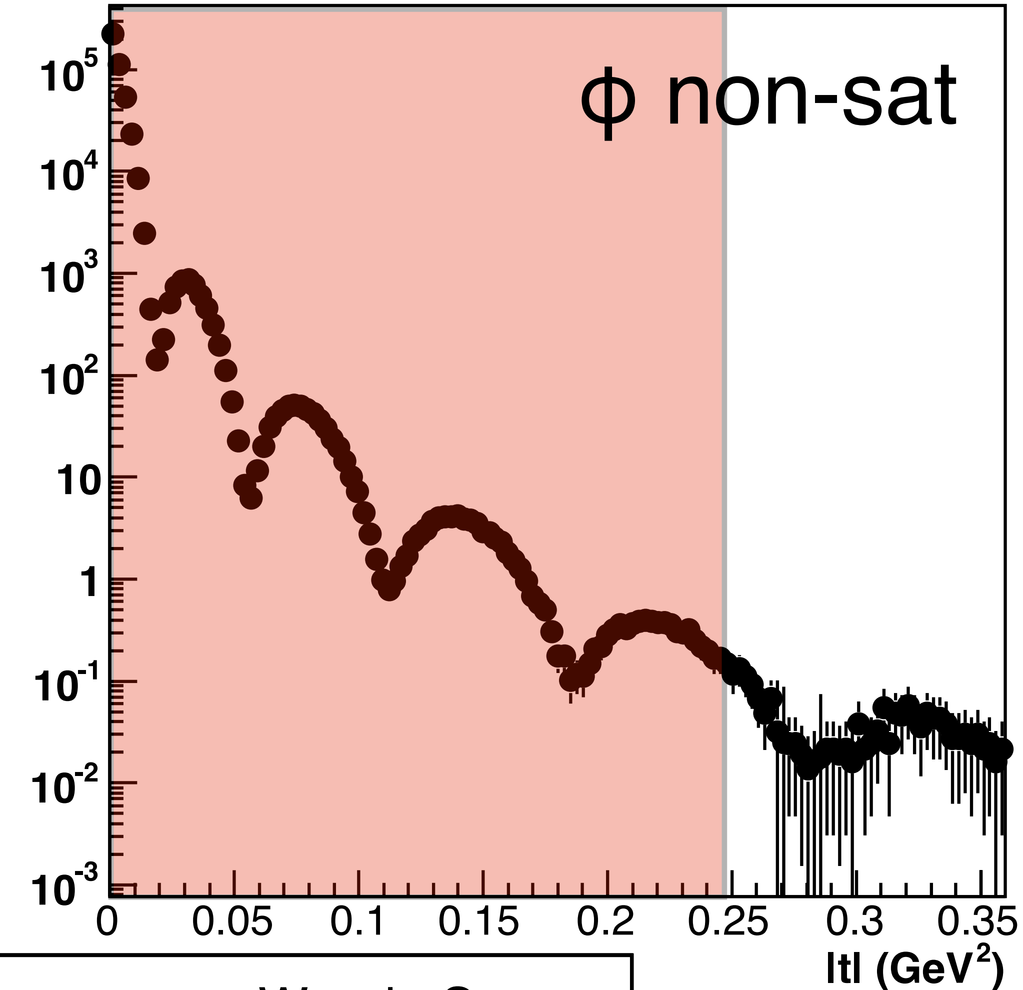
$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)



Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

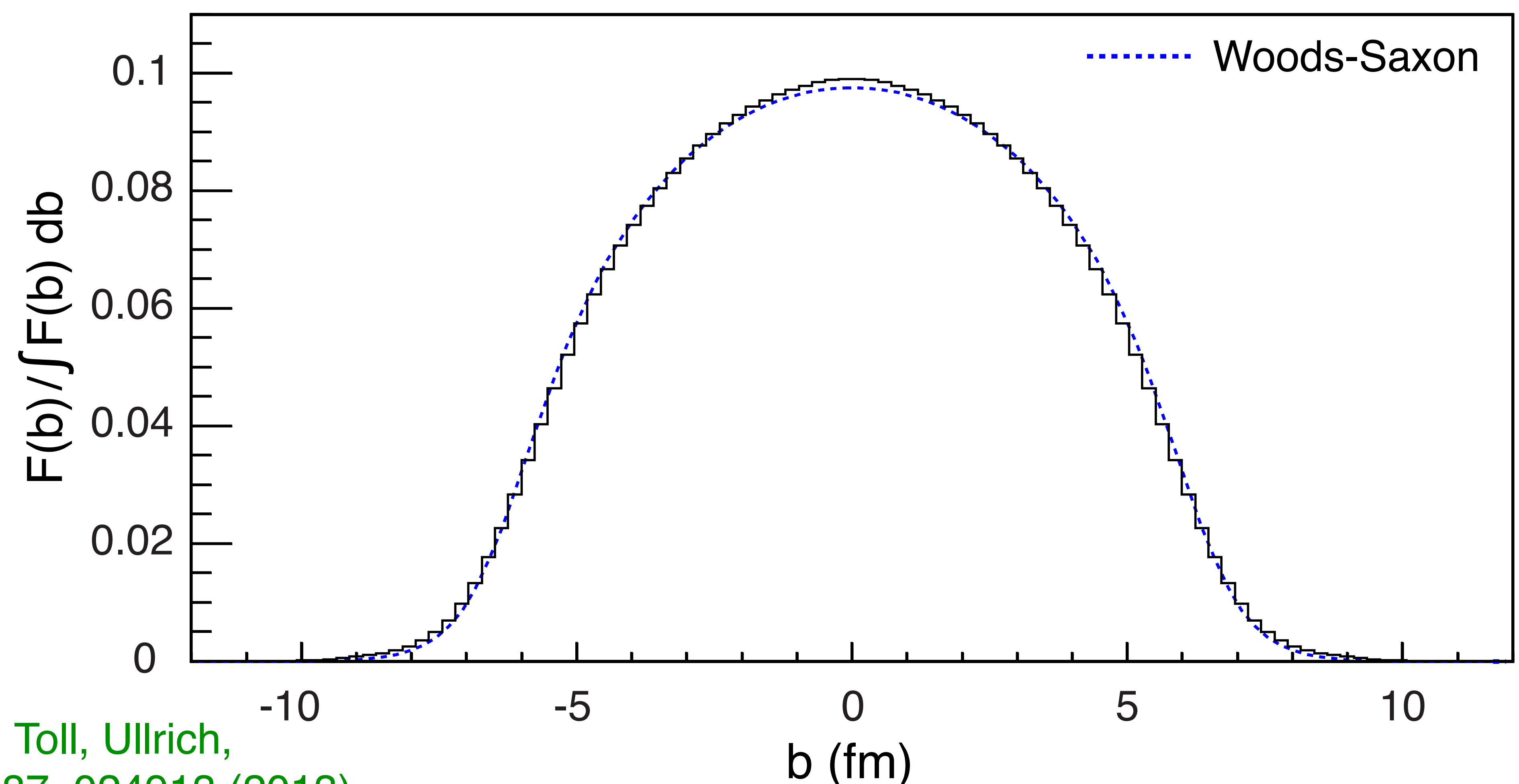
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons



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

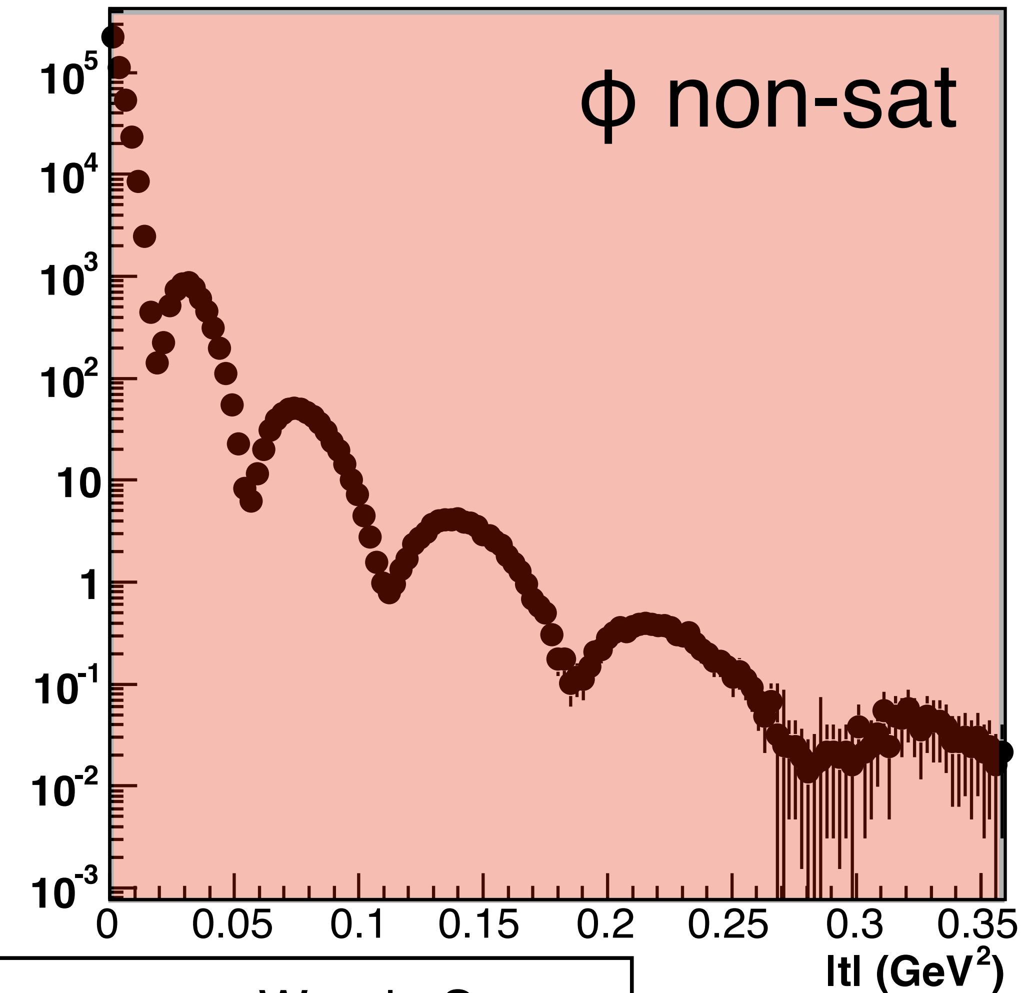
$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)



Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

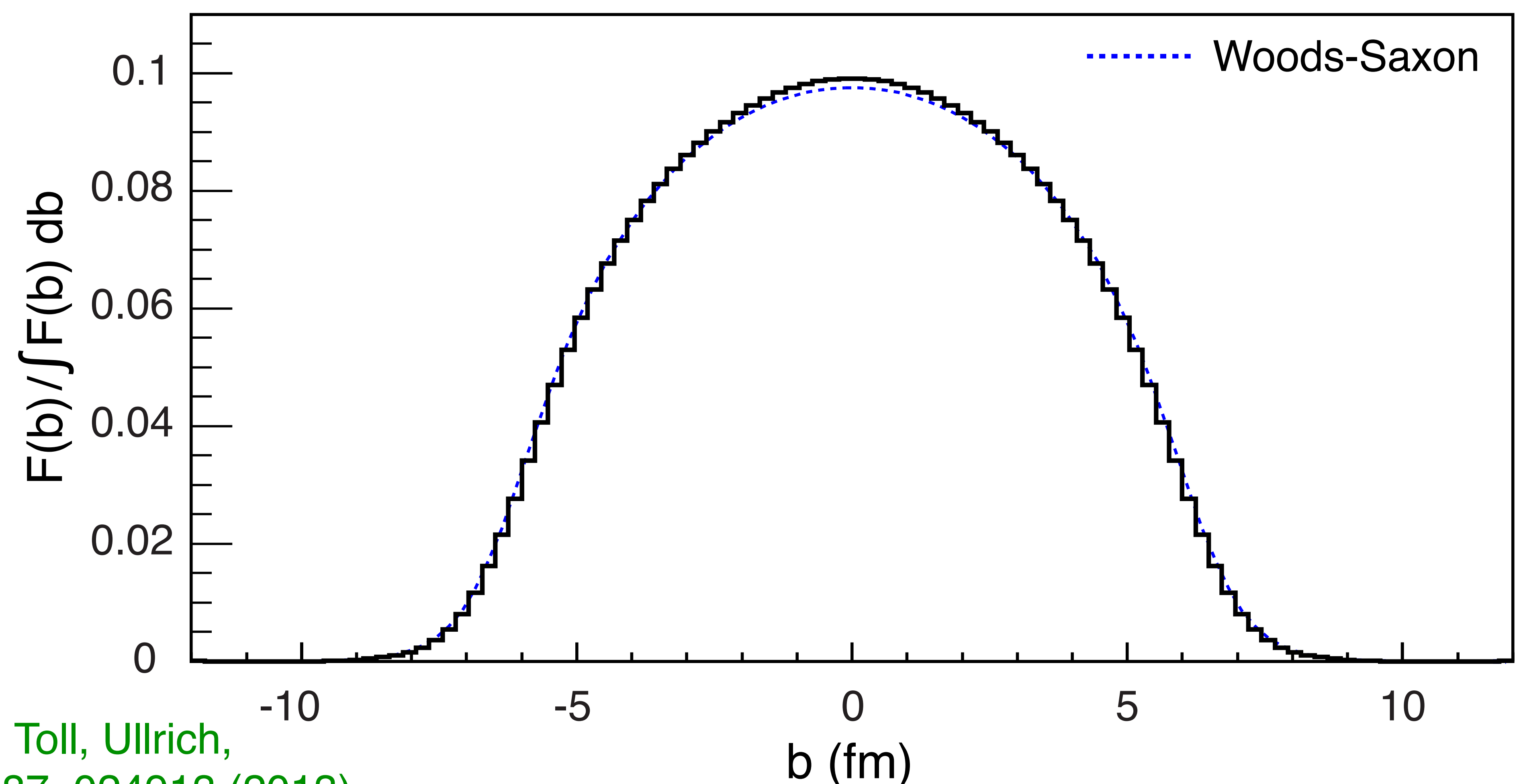
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons



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

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



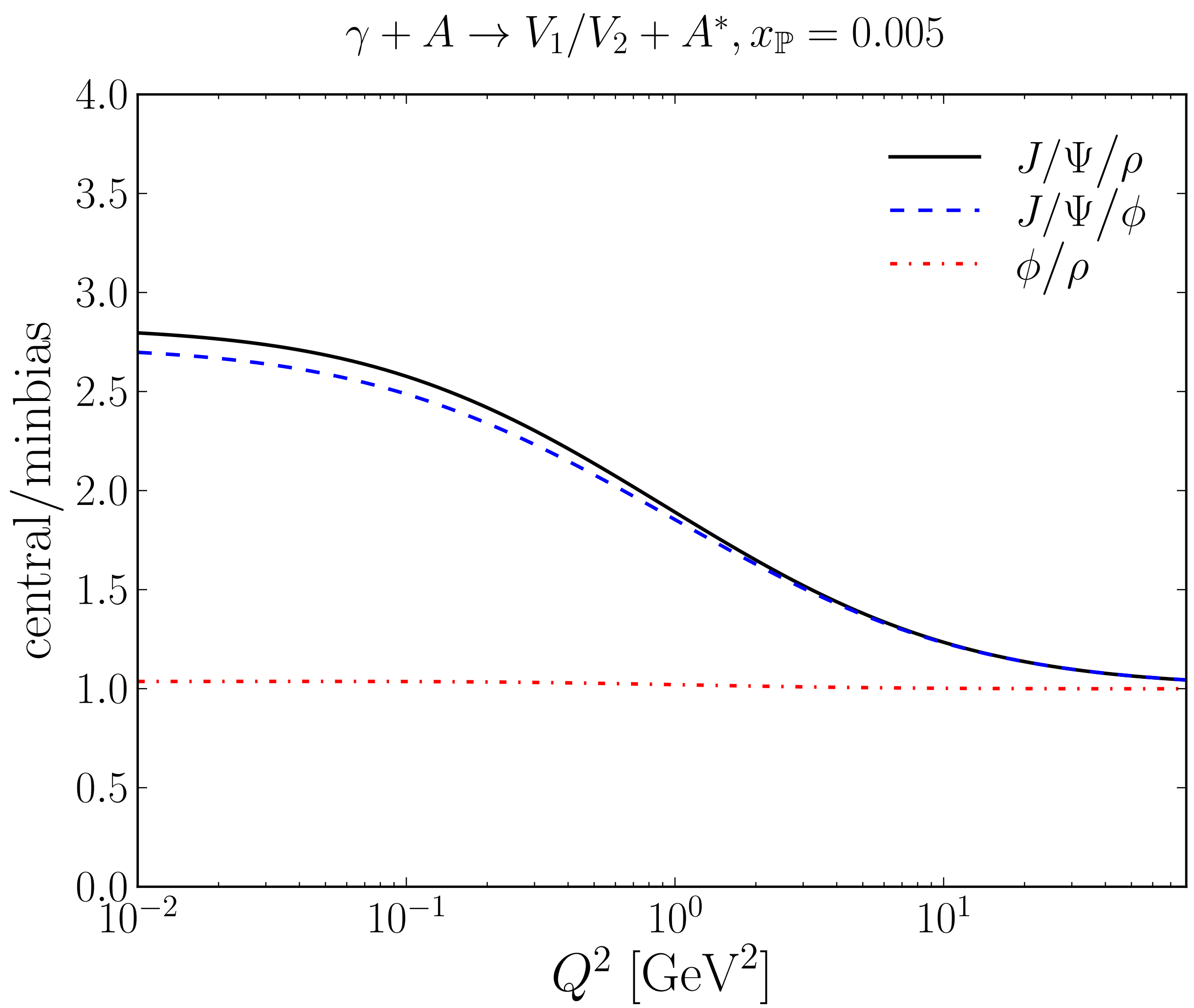
Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

Centrality Determination in e+A collisions

- A recent paper by Lappi, Mäntysaari and Venugopalan shows that the centrality of an e+A collisions can be calculated by measuring the "ballistic" protons knocked out of the nucleus
  - ➡ Measured in Roman Pot detectors downstream of the interaction
  - ➡ Multiplicity of ballistic protons is a measure of collision centrality

Centrality Determination in e+A collisions

- A recent paper by Lappi, Mäntysaari and Venugopalan shows that the centrality of an e+A collisions can be calculated by measuring the "ballistic" protons knocked out of the nucleus
  - Measured in Roman Pot detectors downstream of the interaction
  - Multiplicity of ballistic protons is a measure of collision centrality
- Although the ρ and ϕ wave-functions are large and hence insensitive to collision centrality, the small wave-function of the J/ψ is sensitive to this
  - The ratio of the J/ψ cross-sections in central/minbias collisions is proportional to the ratio of the saturation scale, Q_S, in central to minbias collisions..
  - The ratio of J/ψ to ρ or ϕ shows a strong enhancement at low Q^2



Lappi, Mäntysaari and Venugopalan - ArXiv:1411.0887

Why e+A collisions and not p+A?

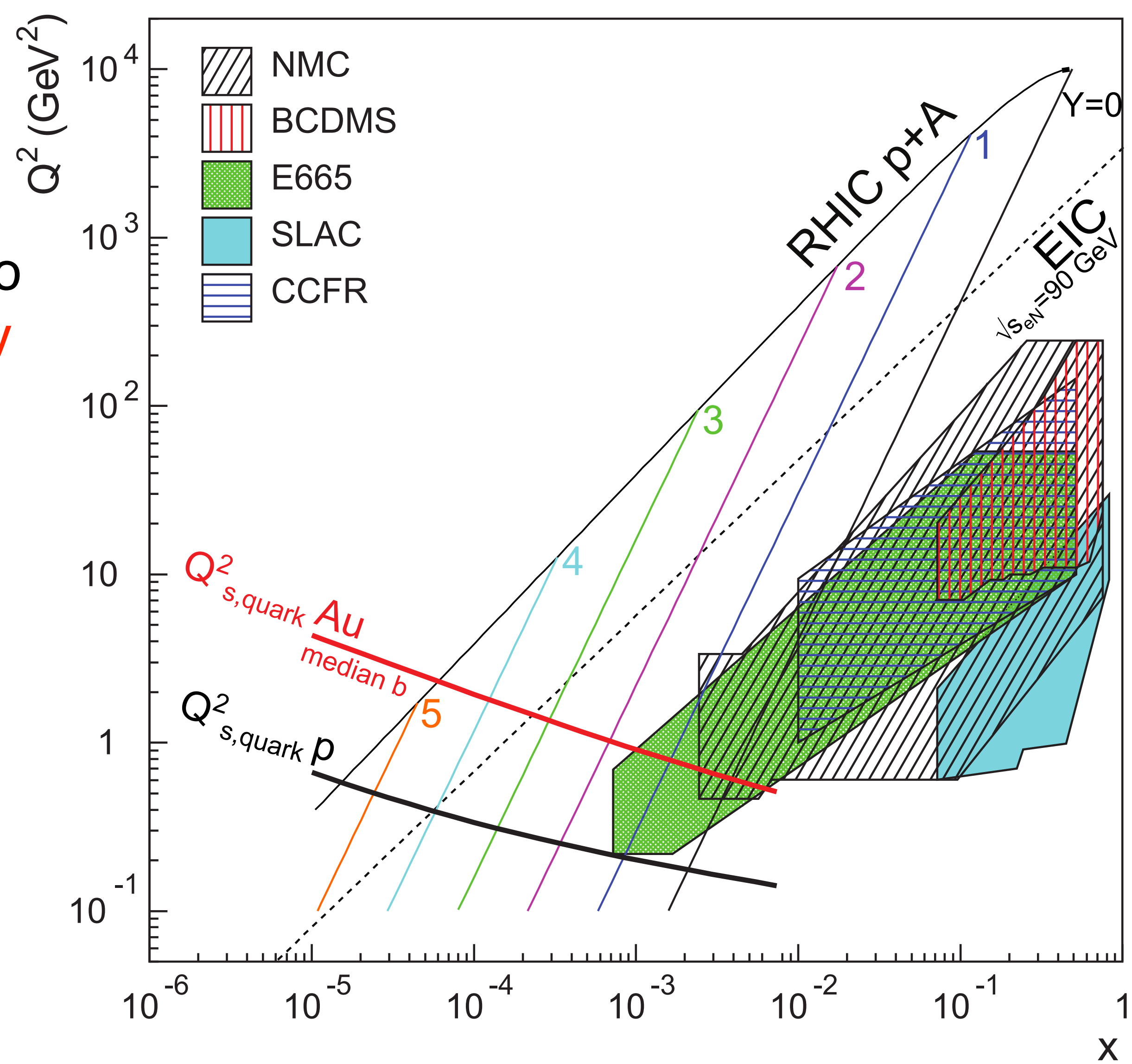
- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions

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

Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions

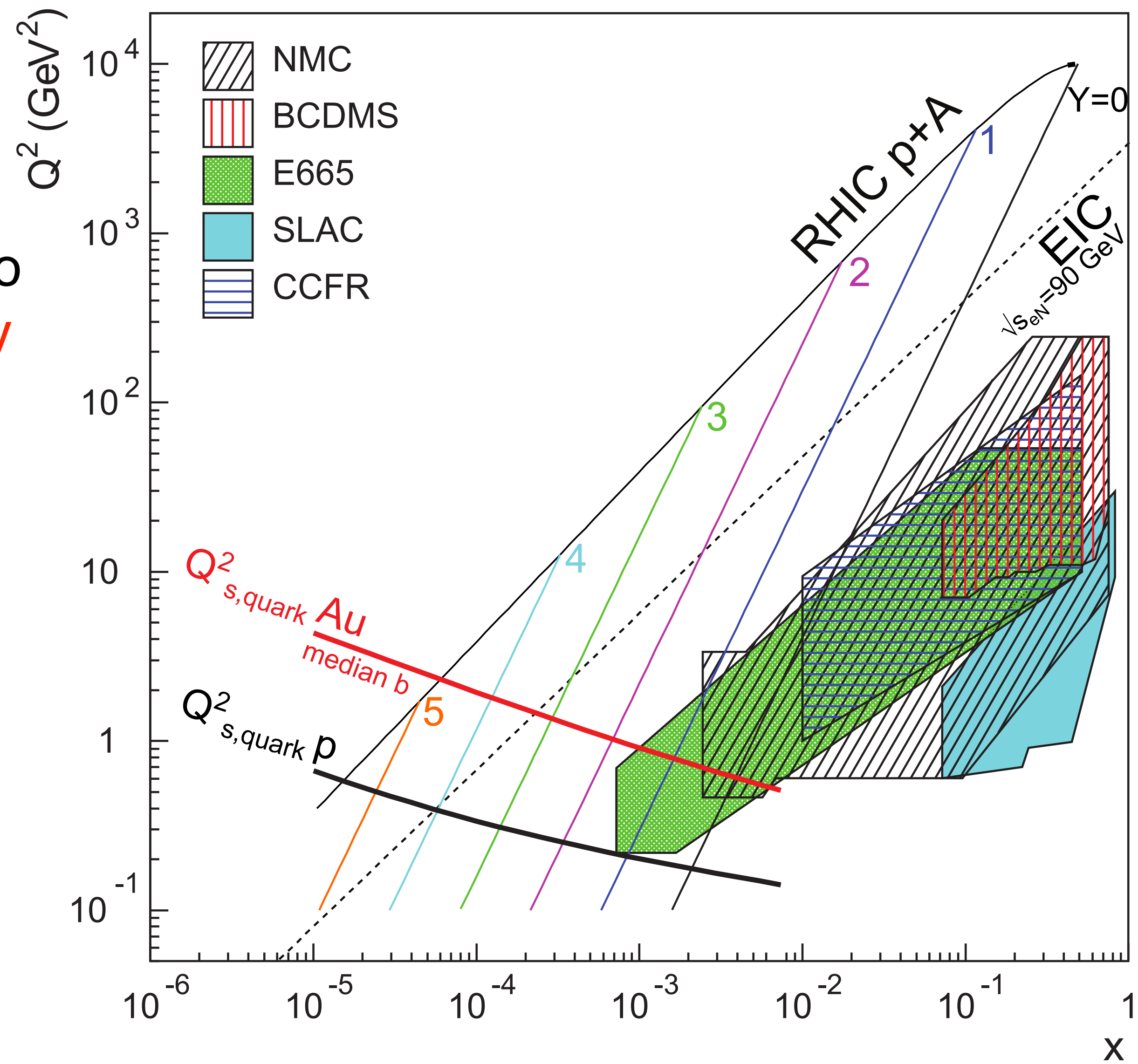
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality

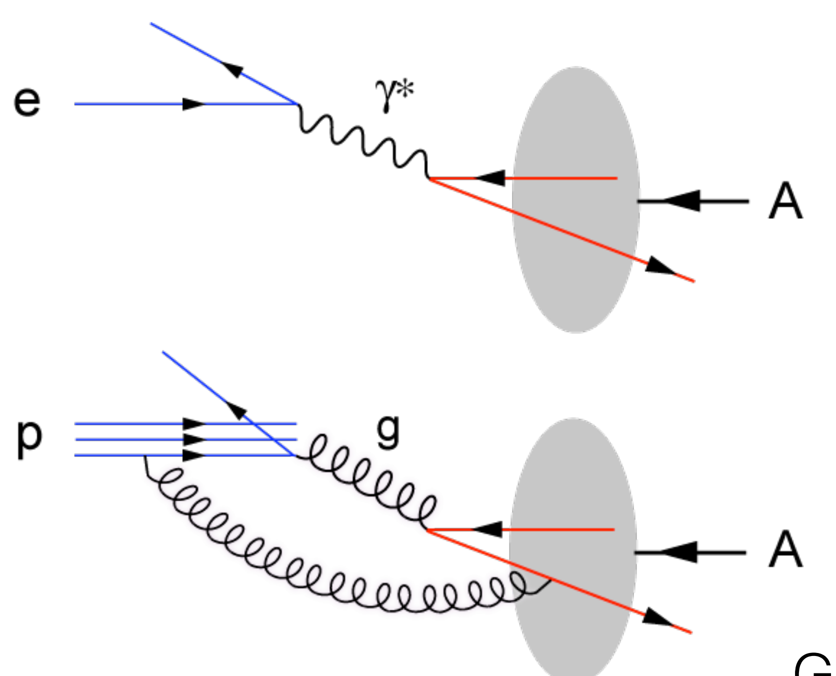


- Collisions of p+A at RHIC will allow us to go to lower-x than eRHIC at the most forward energies
- This would allow us greater access to a saturation regime

Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality
- Issues:
  - ➡ p+A combines initial and final state effects
  - ➡ multiple colour interactions in p+A
  - ➡ p+A lacks the direct access to (x, Q^2)





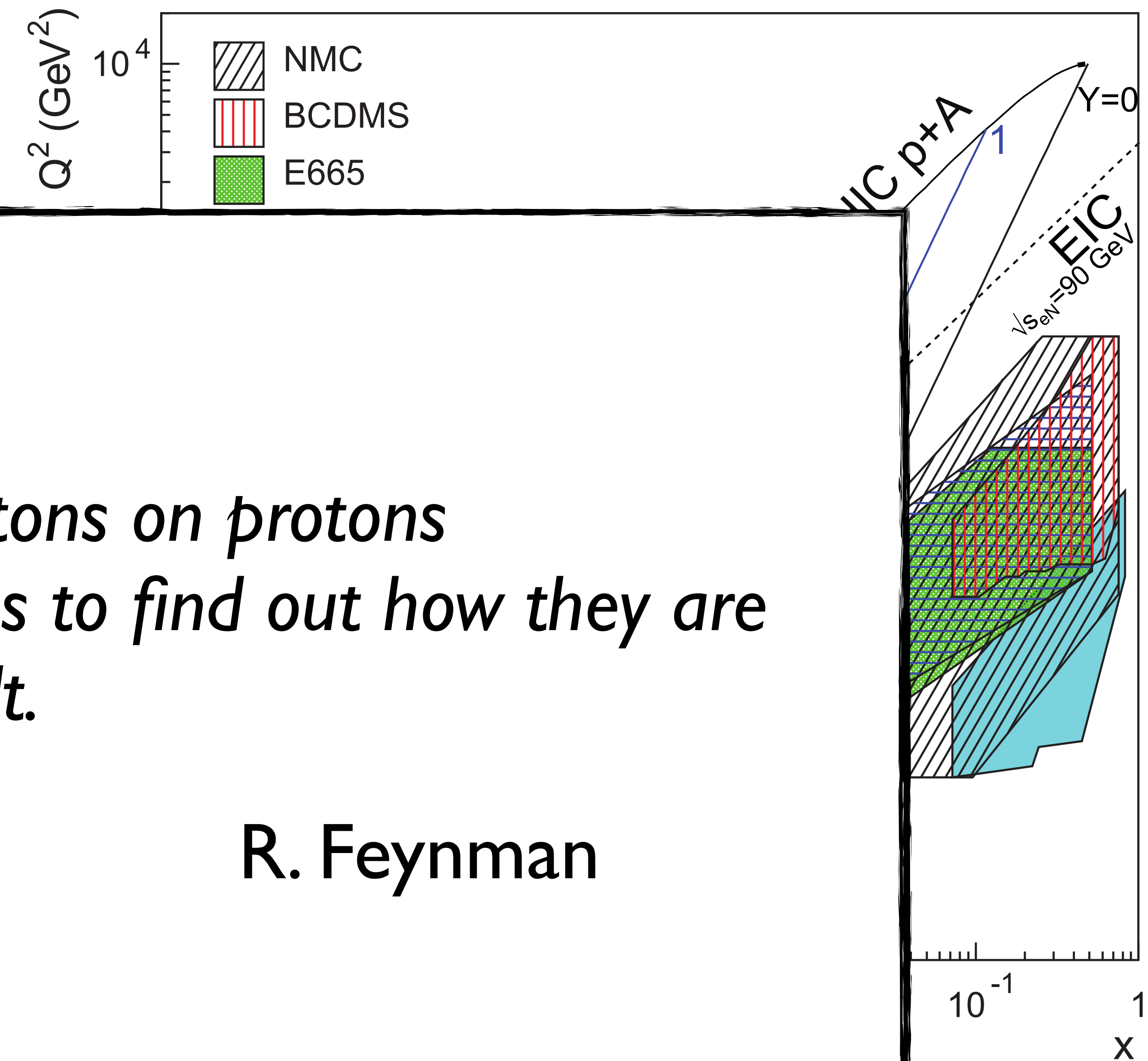
- Collisions of p+A at RHIC will allow us to go to lower-x than eRHIC at the most forward energies
- This would allow us greater access to a saturation regime

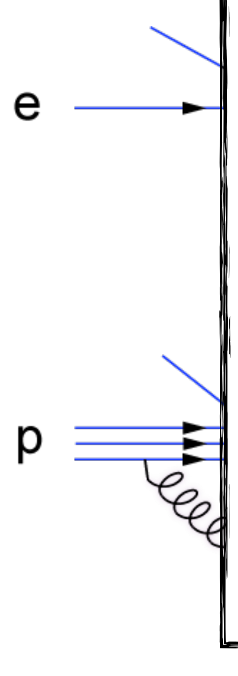
Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions

- Both are c… perform st…

- Issues:
  - ➡ p+A cor…
  - ➡ multiple…
  - ➡ p+A lac…



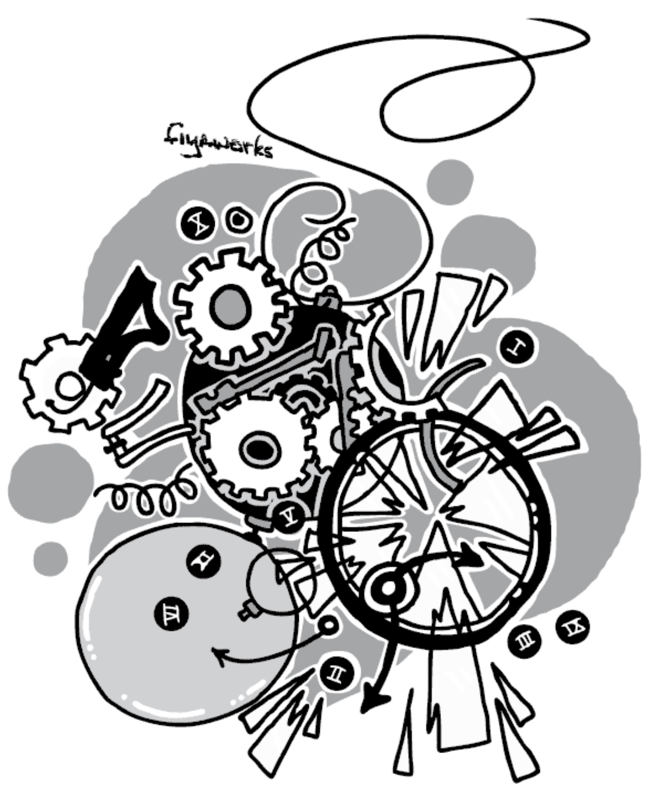


…HIC will …-x than …ward

…eater …regime

Scattering of protons on protons is like colliding Swiss watches to find out how they are built.

R. Feynman

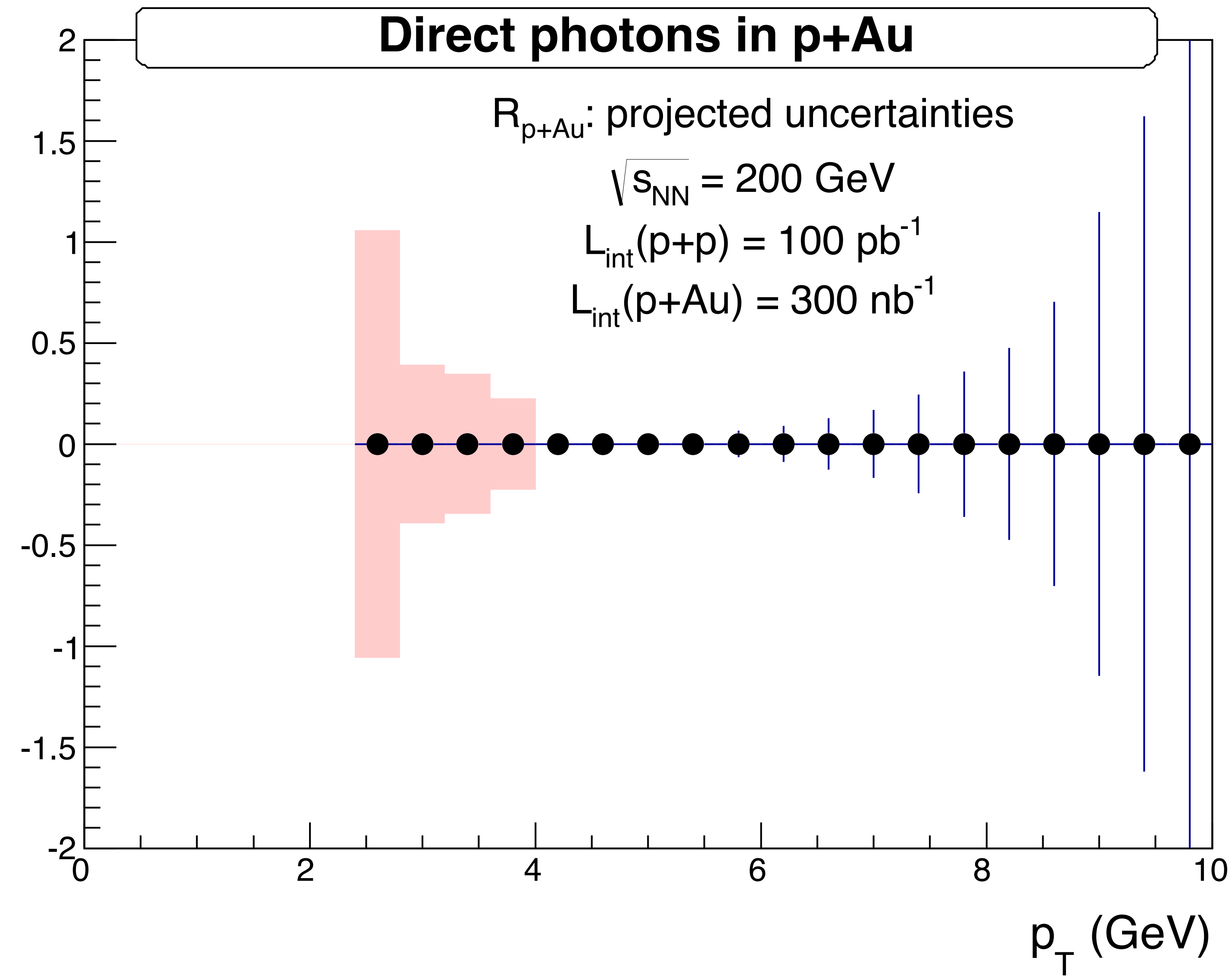


Important measurements in p+A

- di-hadron correlations will be a benchmark measurement, as in d+A and e+A and will measure the same physics

Important measurements in p+A

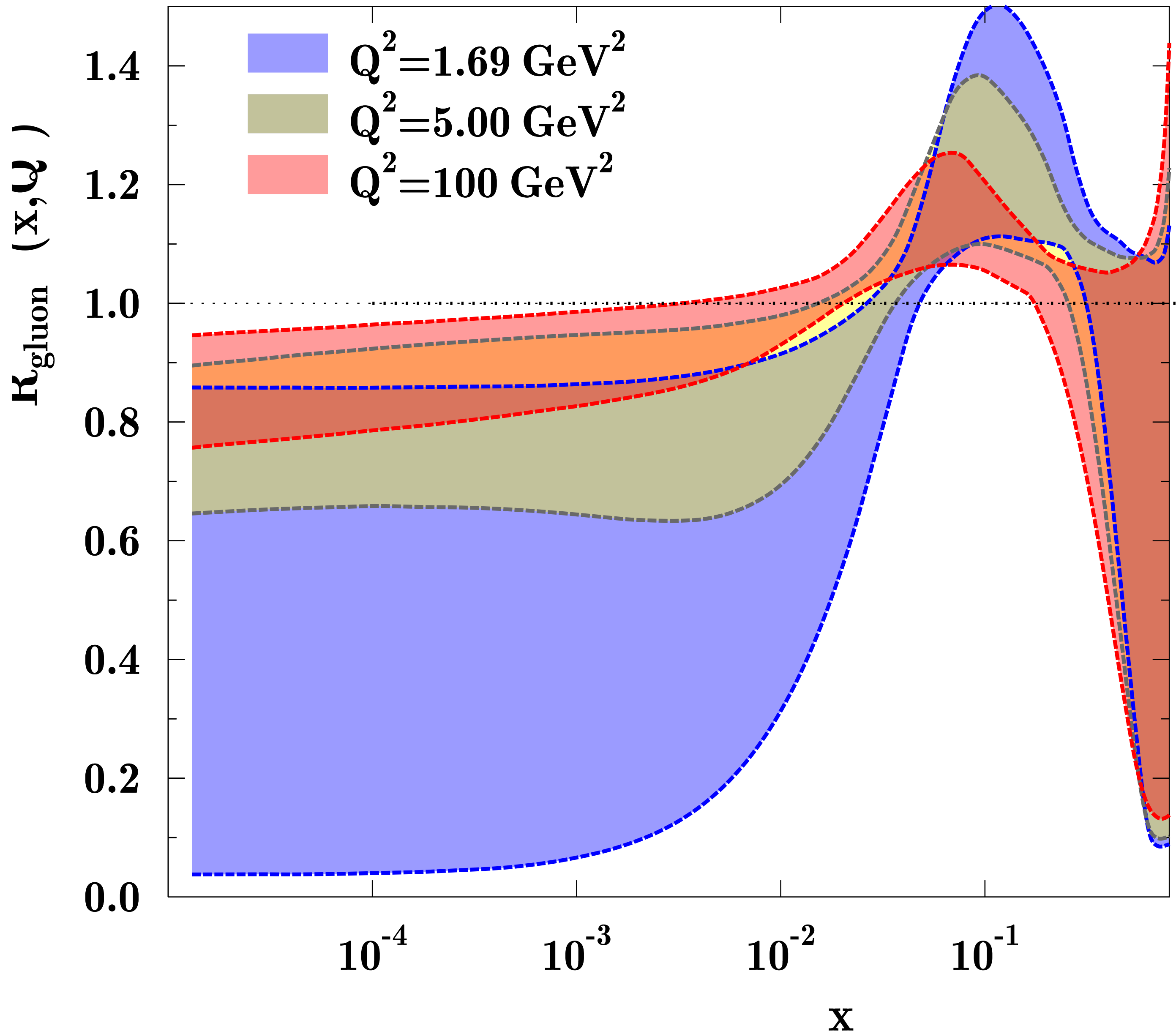
- di-hadron correlations will be a benchmark measurement, as in d+A and e+A and will measure the same physics
- R_{pA} of direct photons is a key measurement as there is no strong interaction in the final state
  - ➡ R_{pA} can be measured in STAR with the FMS for $3<\eta<4$
  - ➡ The issue is that it only probes large Q^2



A polarized p+p and p+A program for the next years - The STAR Collaboration

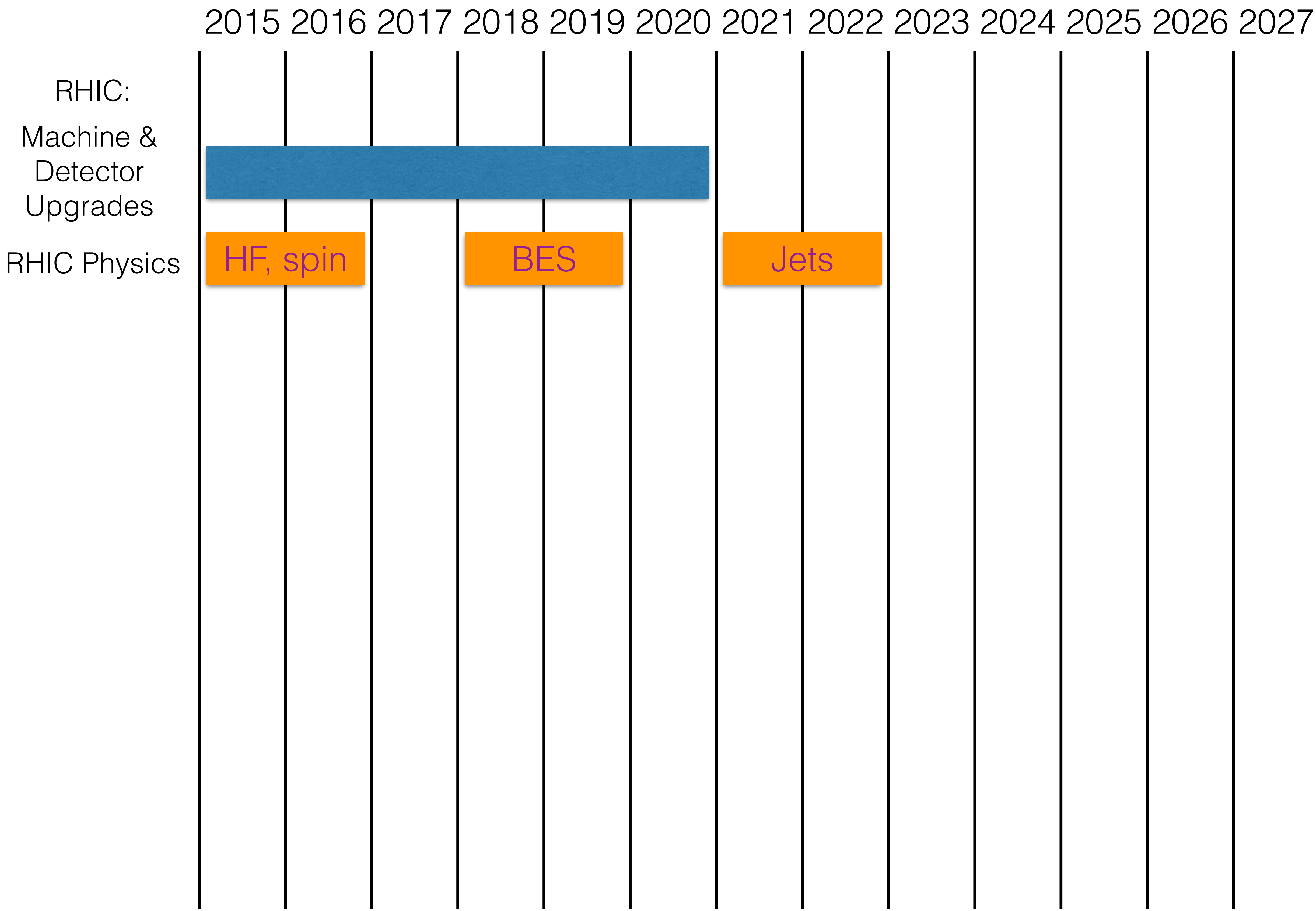
Important measurements in p+A

- di-hadron correlations will be a benchmark measurement, as in d+A and e+A and will measure the same physics
- R_{pA} of direct photons is a key measurement as there is no strong interaction in the final state
  - ➡ R_{pA} can be measured in STAR with the FMS for $3<\eta<4$
  - ➡ The issue is that it only probes large Q^2
    - Nuclear PDFs are relatively well constrained at high Q^2

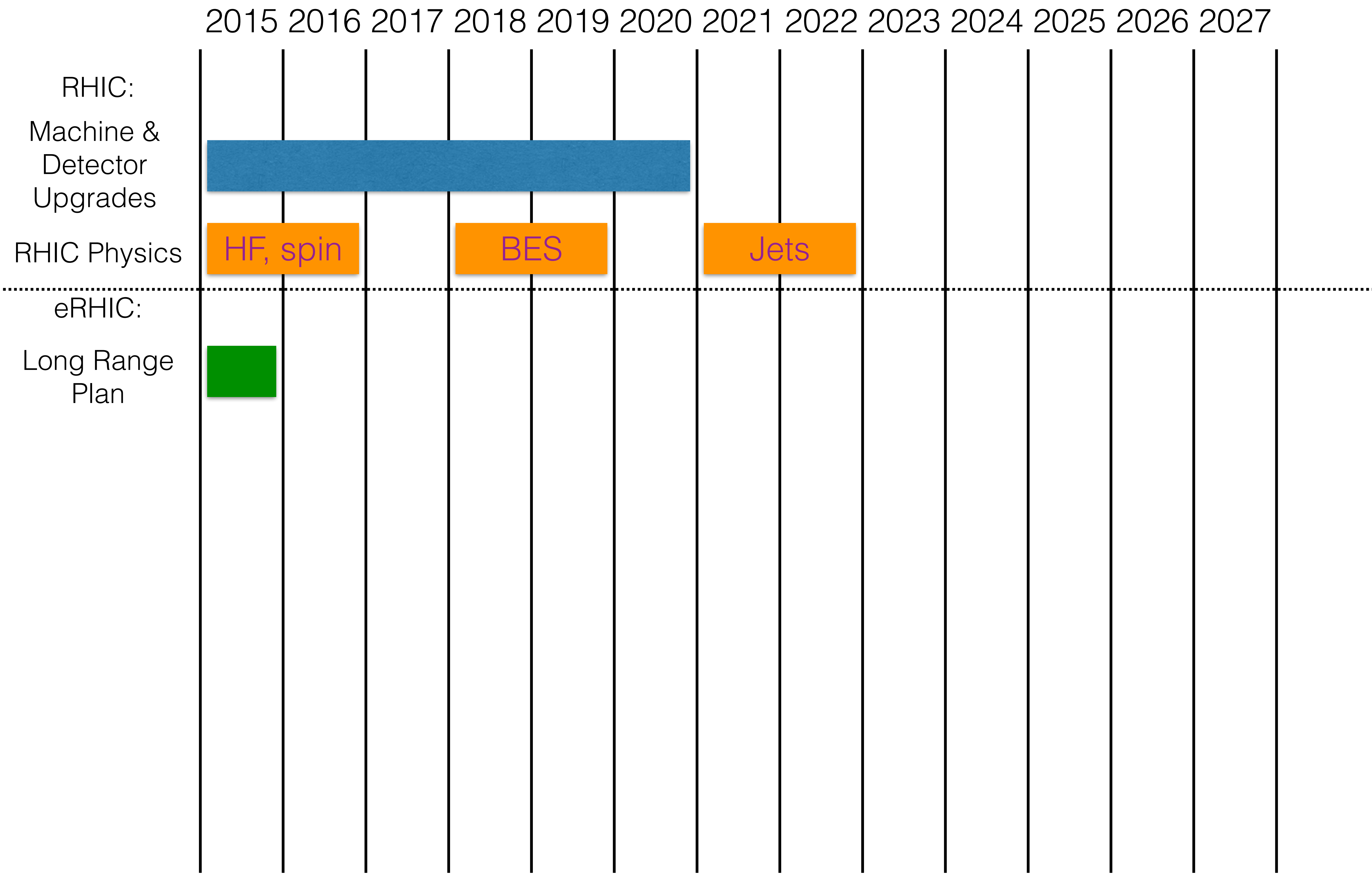


EPS09 - H. Paukkunen

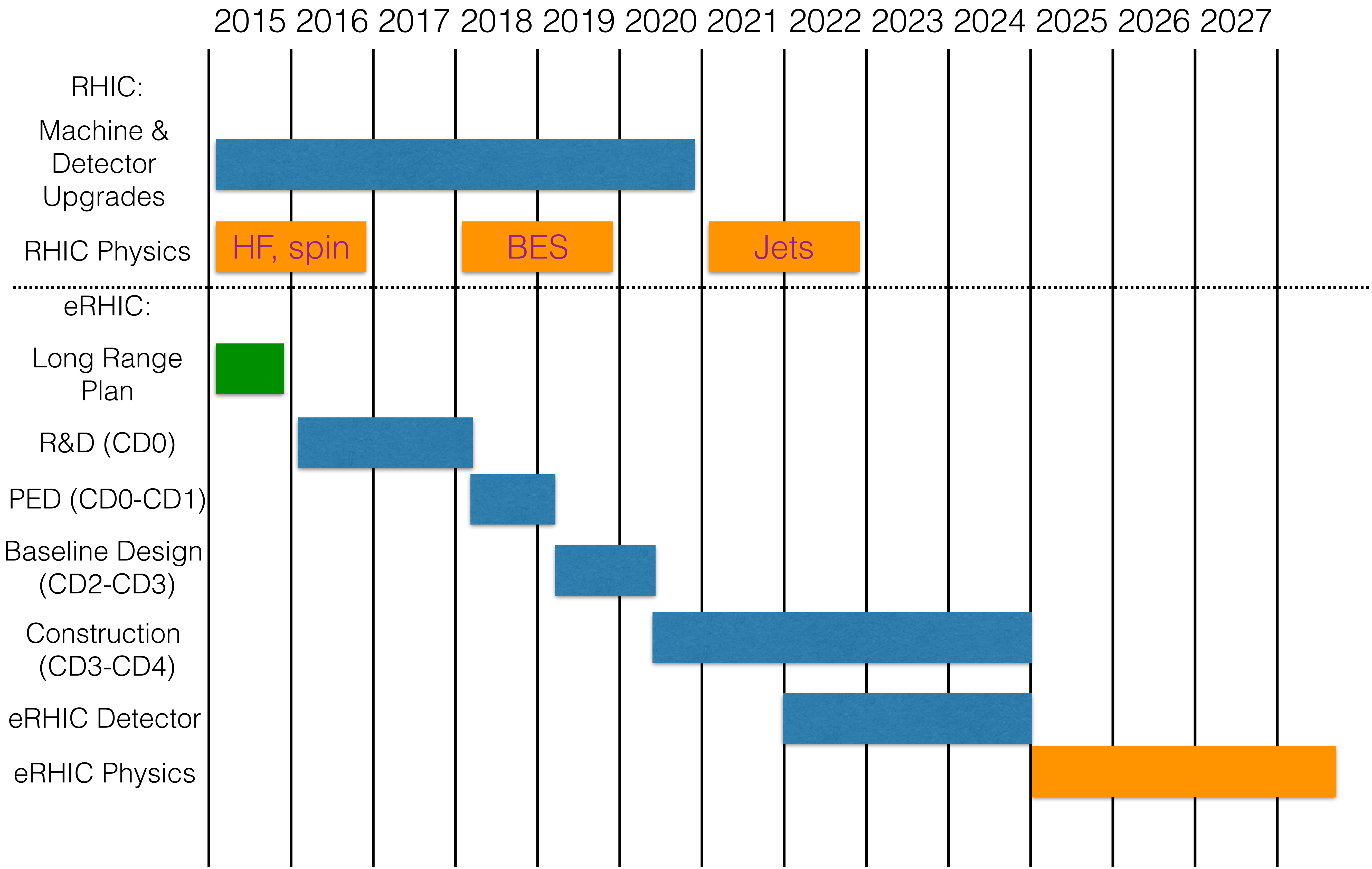
Timescale of eRHIC construction



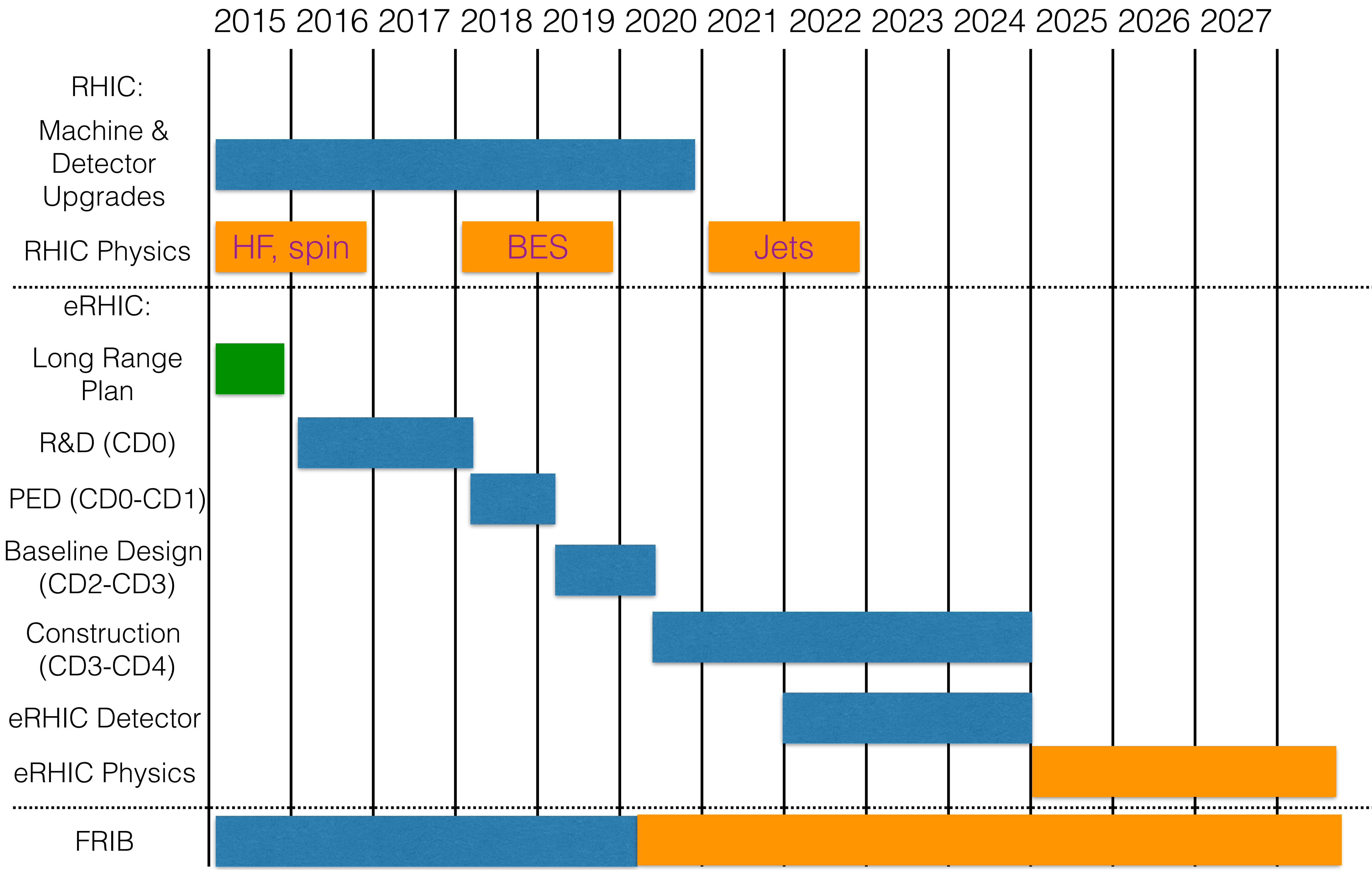
Timescale of eRHIC construction



Timescale of eRHIC construction



Timescale of eRHIC construction



Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
  - ➡ Low-x - structure functions: Measure the properties of gluons where saturation is the dominant governing phenomena
  - ➡ Low-x - diffraction: Can gain access to the initial wave function through vector meson production
  - ➡ di-Hadron Correlations: Analogue measurement to p/d+A, but less uncertainties on the measurement

Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
    - Low-x - structure functions: Measure the properties of gluons where saturation is the dominant governing phenomena
    - Low-x - diffraction: Can gain access to the initial wave function through vector meson production
    - di-Hadron Correlations: Analogue measurement to p/d+A, but less uncertainties on the measurement
- Other important observables not discussed due to time limitations:
    - Higher-x: Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization

Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
    - Low-x - structure functions: Measure the properties of gluons where saturation is the dominant governing phenomena
    - Low-x - diffraction: Can gain access to the initial wave function through vector meson production
    - di-Hadron Correlations: Analogue measurement to p/d+A, but less uncertainties on the measurement
- Other important observables not discussed due to time limitations:
    - Higher-x: Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization
- Understanding the role of gluons in nuclei is crucial to understanding RHIC and LHC results

Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
  - ➡ Low-x - structure functions: Measure the properties of gluons where saturation is the dominant governing phenomena
  - ➡ Low-x - diffraction: Can gain access to the initial wave function through vector meson production
  - ➡ di-Hadron Correlations: Analogue measurement to p/d+A, but less uncertainties on the measurement
- Other important observables not discussed due to time limitations:
  - ➡ Higher-x: Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization
- Understanding the role of gluons in nuclei is crucial to understanding RHIC and LHC results
  - ➡ A detailed write-up of the 2010 INT EIC programme is on the ArXiv: 1108.1713
  - ➡ An updated EIC White Paper (not just e+A), expounding on the INT programme has been released to the community ArXiv: 1212.1701.
  - ➡ A Design Study document for eRHIC has also been released: ArXiv: 1409.1633

Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
  - Low-x - structure functions: Measure the properties of gluons where saturation is the dominant governing phenomena
  - Low-x - diffraction: Can gain access to the initial wave function through vector meson production
  - di-Hadron Correlations: Analogue measurement to p/d+A, but less uncertainties on the measurement

entire science programme is uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

- A detailed write-up of the 2010 INT EIC programme is on the ArXiv: 1108.1713
- An updated EIC White Paper (not just e+A), expounding on the INT programme has been released to the community ArXiv: 1212.1701.
- A Design Study document for eRHIC has also been released: ArXiv: 1409.1633