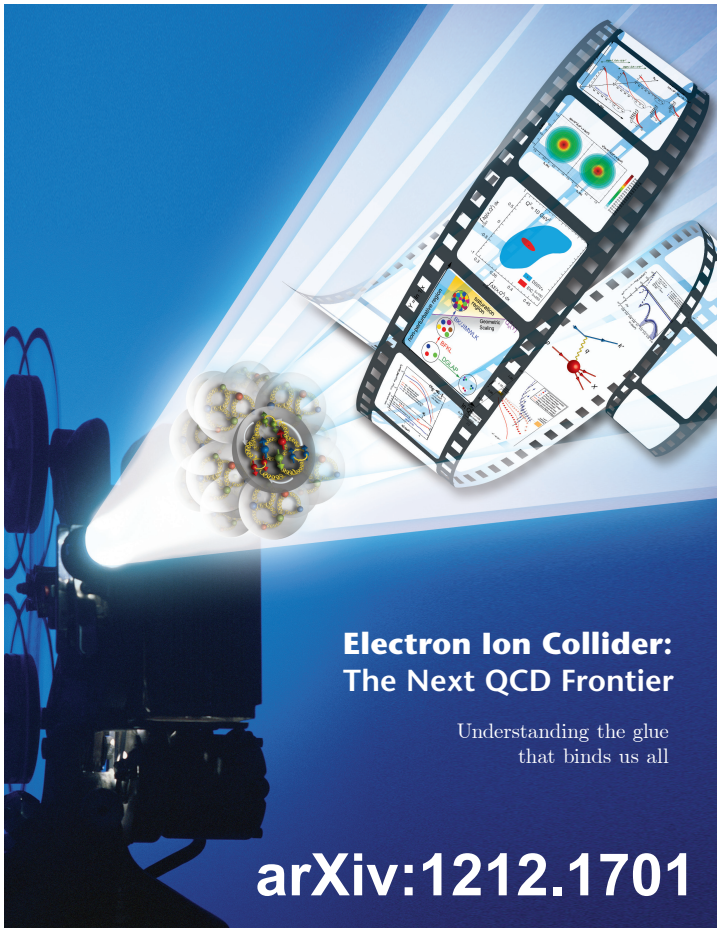
The Glue That Binds Us All

Probing Gluonic Matter With the World's First Electron-Ion Collider

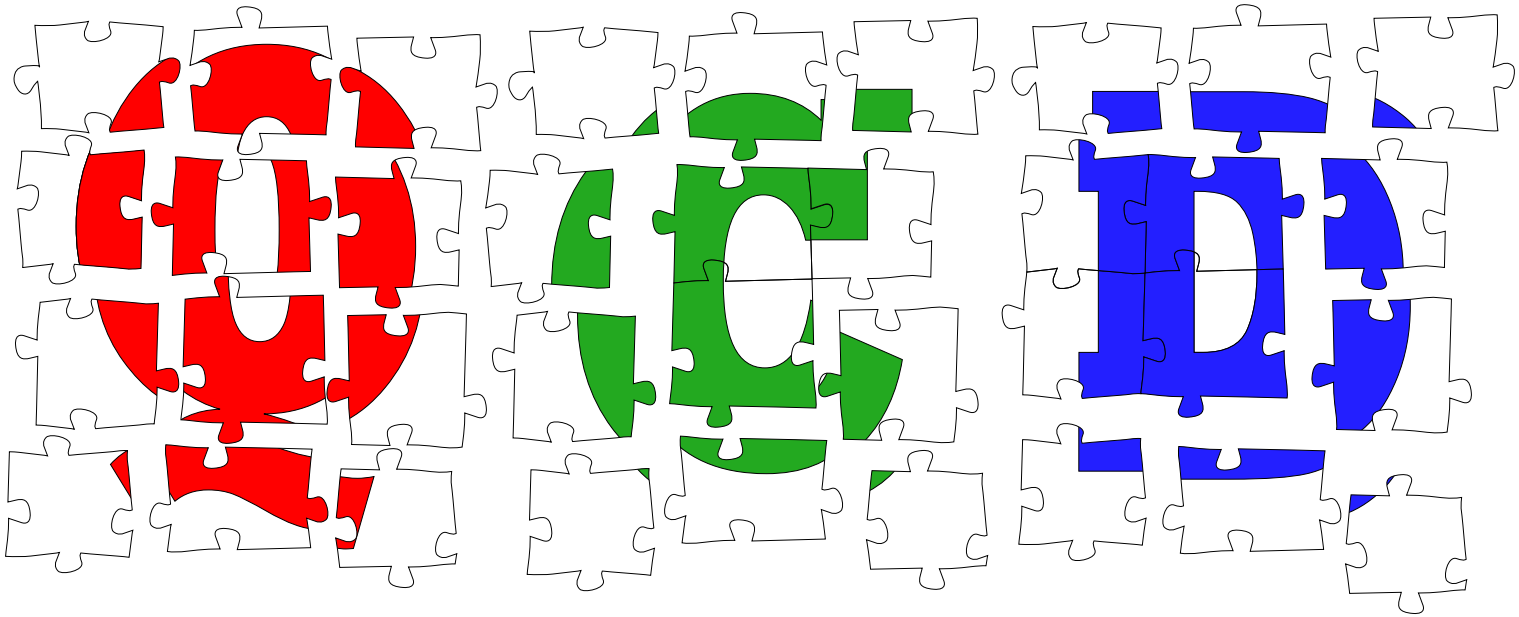


Thomas Ullrich

2013 RHIC & AGS Annual Users' Meeting, June 26, 2013

U.S. DEPARTMENT OF ENERGY | Office of Science
BROOKHAVEN NATIONAL LABORATORY

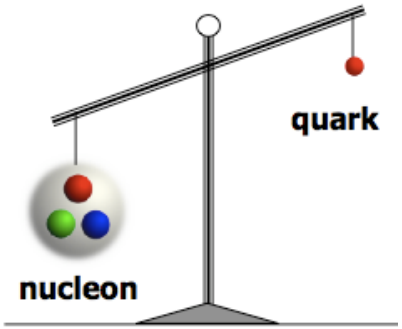
Three Puzzles of QCD



... that motivate an Electron-Ion Collider

The Hadronic Mass Puzzle

How do fundamental quarks and gluons make up mass of visible matter?



m_q ~ 10 MeV (from Higgs field)
m_N ~ 1000 MeV

Quarks carry only ~1% of proton mass

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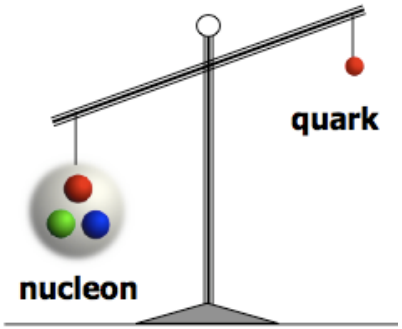

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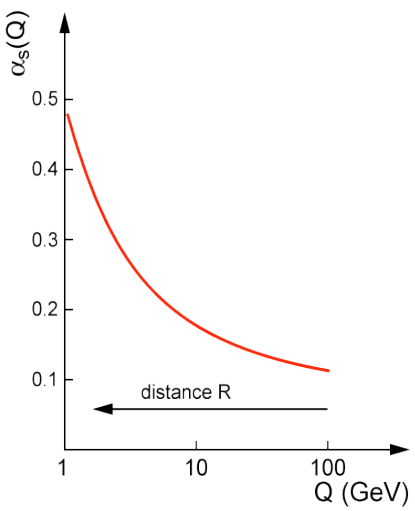
Answer can come only from Quantum Chromodynamics

Understanding QCD ?

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

- "Emergent" Phenomena not evident from Lagrangian
- Asymptotic Freedom
  - $\alpha_s(Q^2) \sim 1 / \log(Q^2/\Lambda^2)$
  - in vacuum (Q ~ 1/R)



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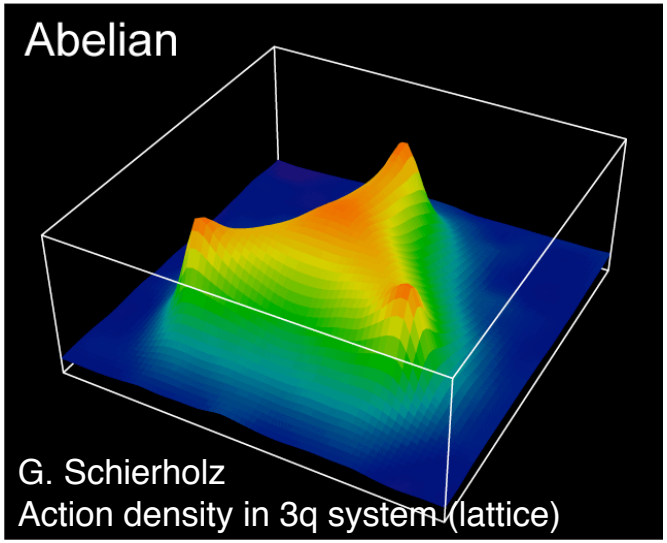

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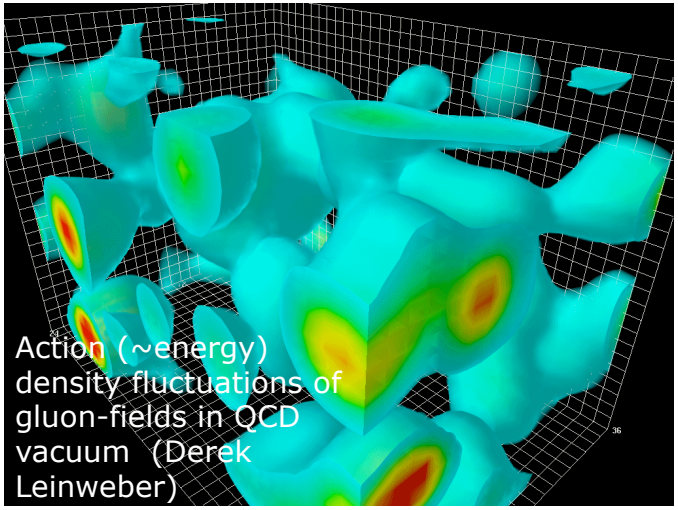
- Gluons & their self-interaction
  - Determine essential features of strong interactions



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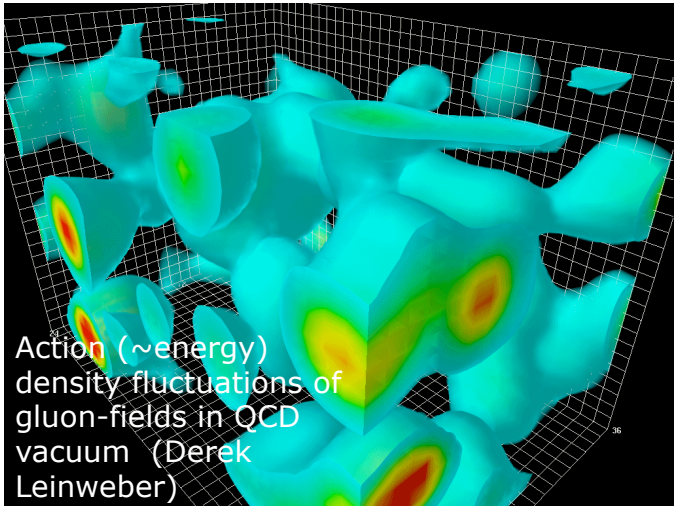
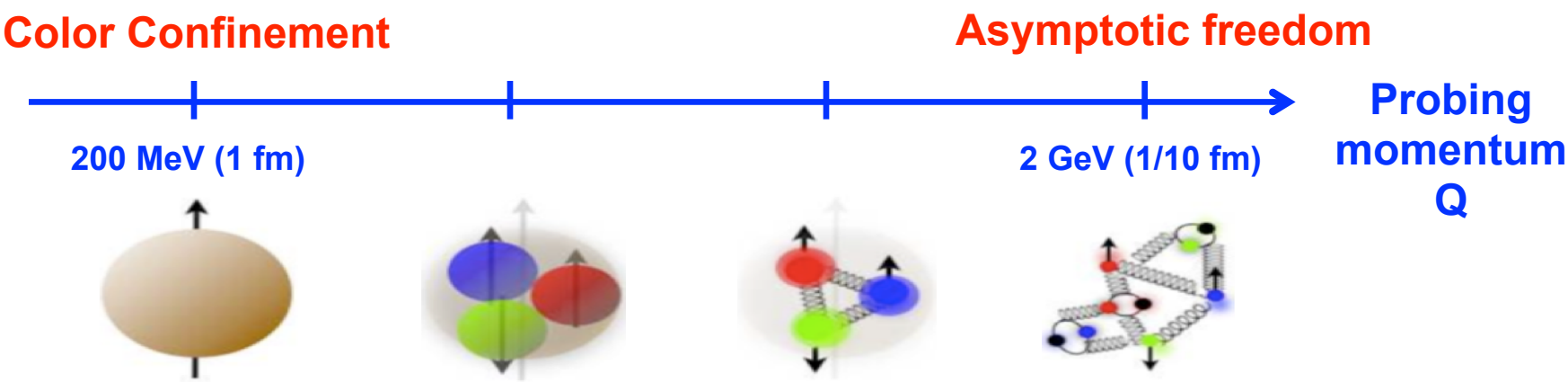


Despite this dominance, the **properties of gluons** in matter remain largely unexplored

The Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain “spin” of a proton/hadron?

Spin of proton is ½ independent of the scale we look at it:



- After 20% years effort
  - quarks (valence and sea): ~30% of proton spin
  - gluons (latest RHIC data): ~20% of proton spin in limited range

Understanding Proton Spin ?

If we do not understand the proton spin,
we do not understand QCD

It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

$$\frac{1}{2} = \overbrace{\frac{1}{2}\Delta\Sigma + L_q}^{\text{Quarks}} + \overbrace{\Delta G + L_g}^{\text{Gluons}}$$

$$\text{Note}: \Delta F = \int \Delta f(x) dx$$

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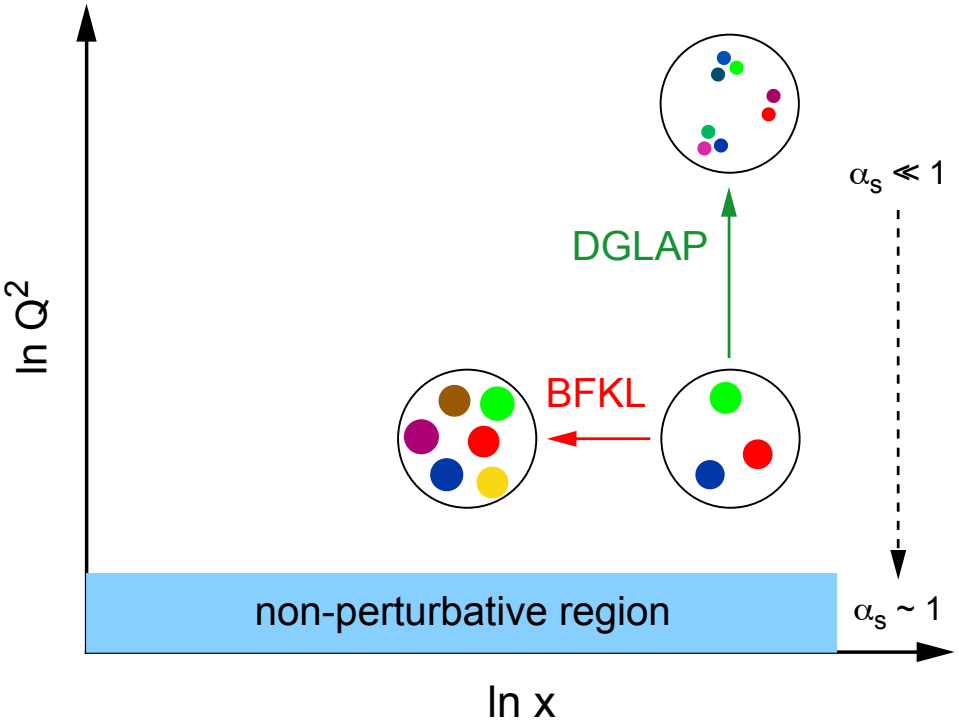
- How are quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- How to quantify the role of orbital motion?

N.B. Spin of proton is scale independent, decomposition is not!

The Low-x Puzzle



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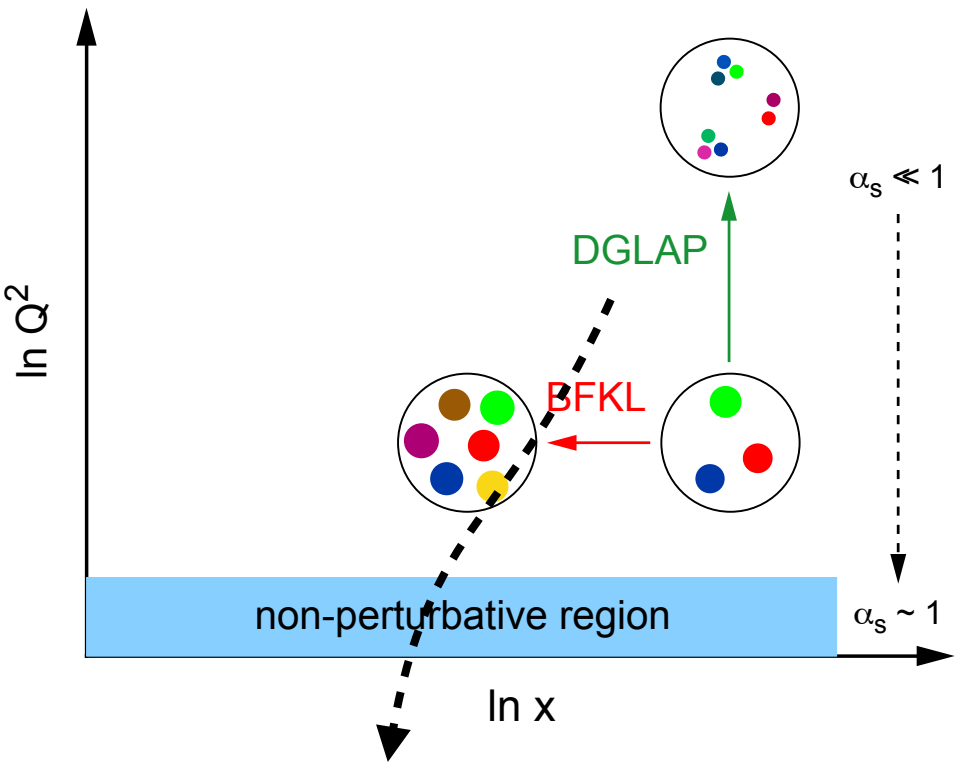

pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA, RHIC, LHC, Tevatron)

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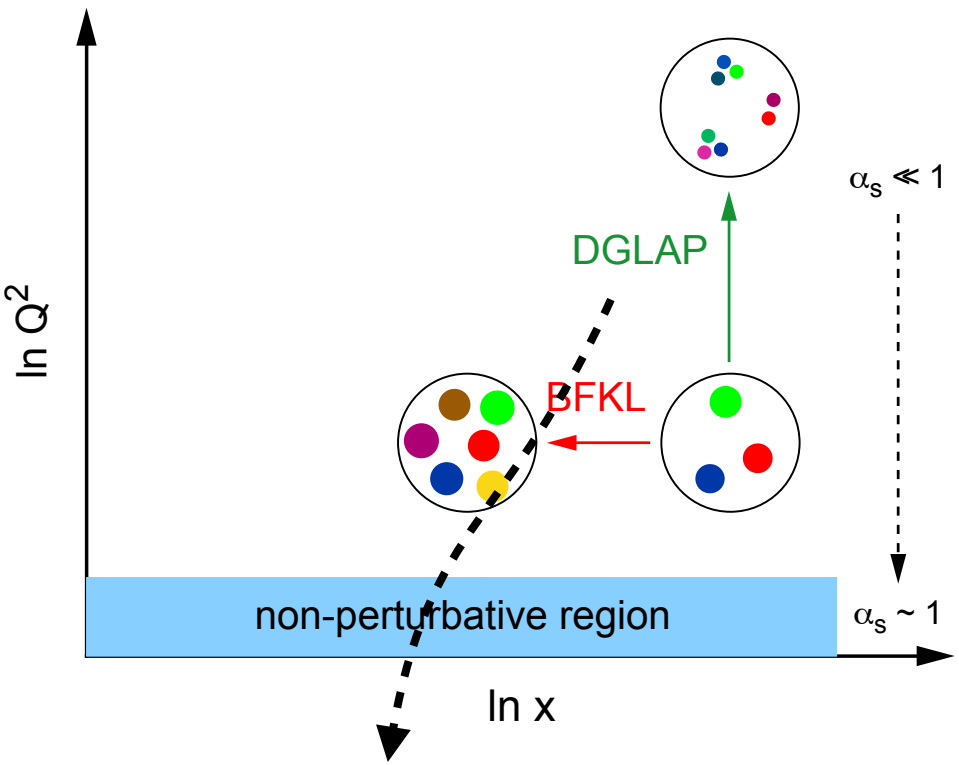

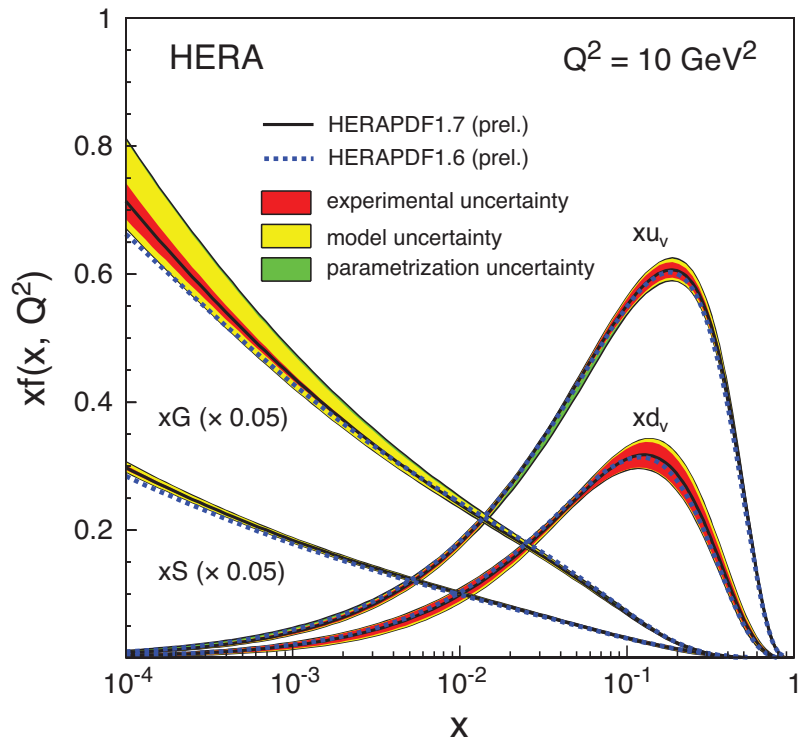

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PDF: glue dominates for x < 0.1

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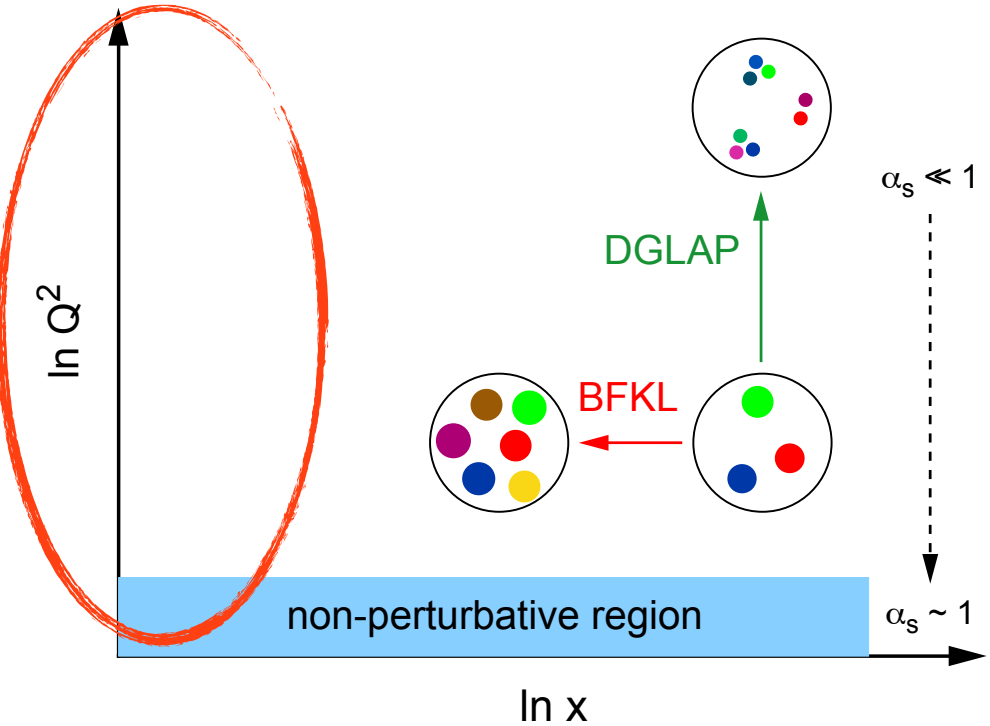
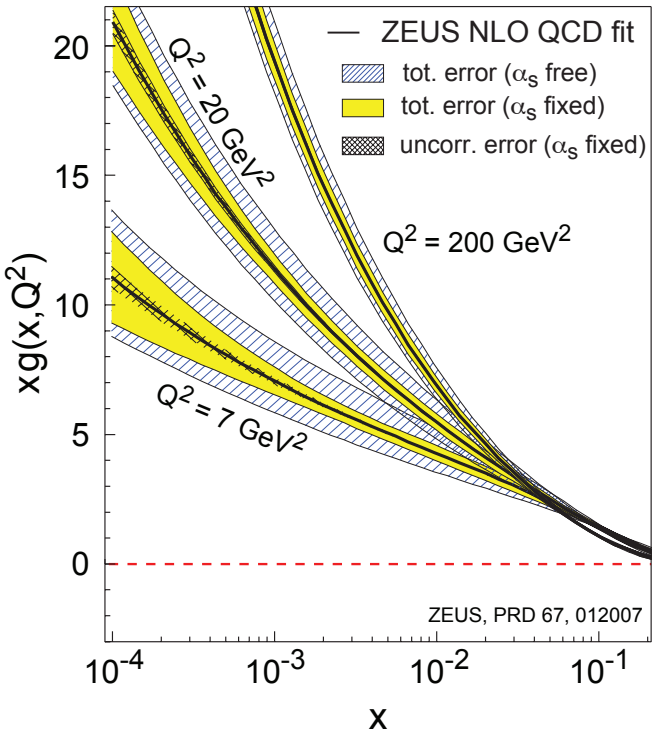
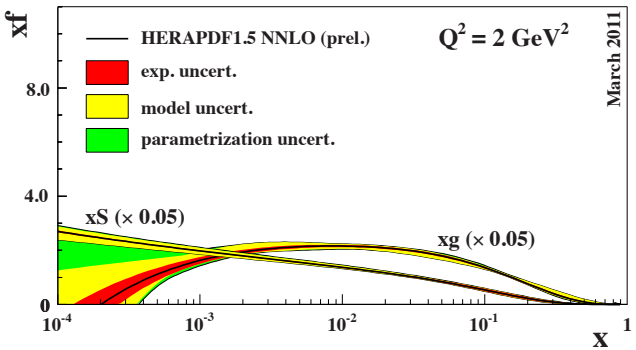




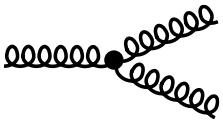


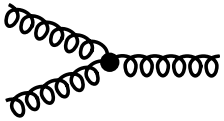
Issues with linear DGLAP/BFKL:

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

$G(,Q^2)$ must saturate ⇒ how?

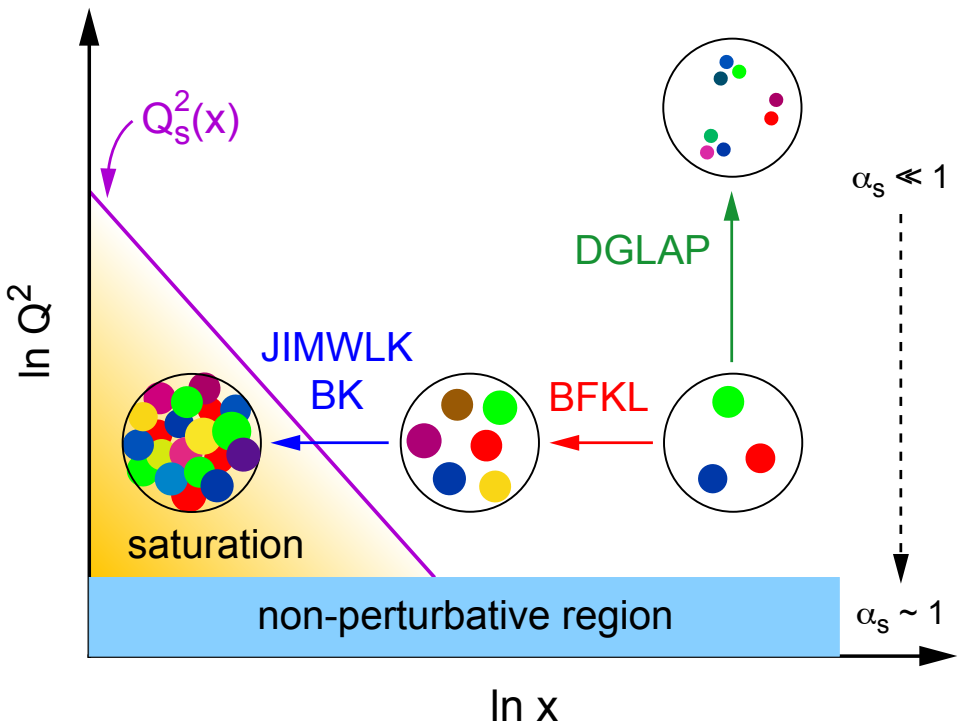
Understanding Low-x ?

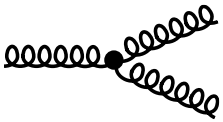
BFKL: 

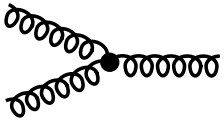
BK adds: 

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

Understanding Low-x ?



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?

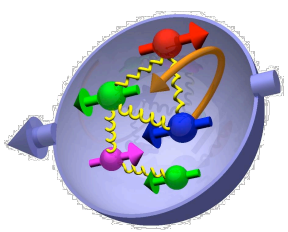
Electron-Ion Collider

Investigate with precision universal dynamics of gluons

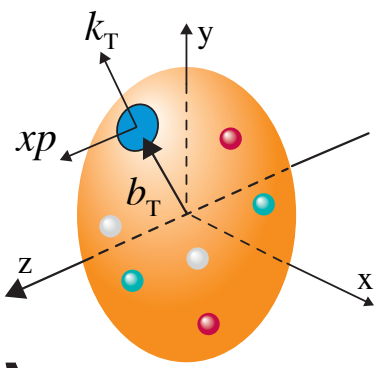
Twin central themes:

- Probing the momentum-dependence of **gluon** densities and the onset of saturation in nucleons and nuclei
- Mapping the transverse spatial and spin distributions of partons in the **gluon**-dominated regime

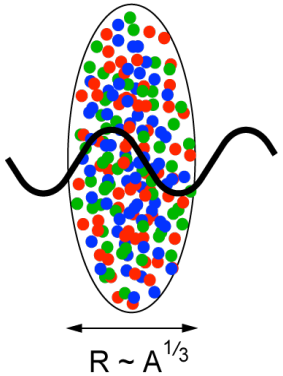
Spin Physics



Imaging



High-Parton Density Physics



proton

nuclei

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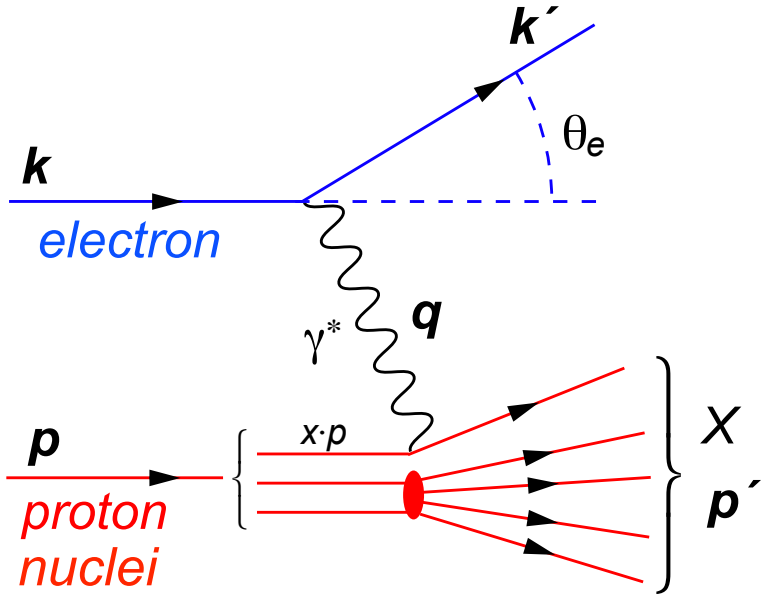
Requirements:

- Collider $\Rightarrow$ Kinematic reach well into gluon-dominated regime
- Electron beams $\Rightarrow$ Use unmatched precision of the electromagnetic interaction
- Polarized e&p beams $\Rightarrow$ Correlations of gluon distributions with the nucleon spin
- Heavy ion beams $\Rightarrow$ Amplification of saturation scale

Electron-Ion Collider



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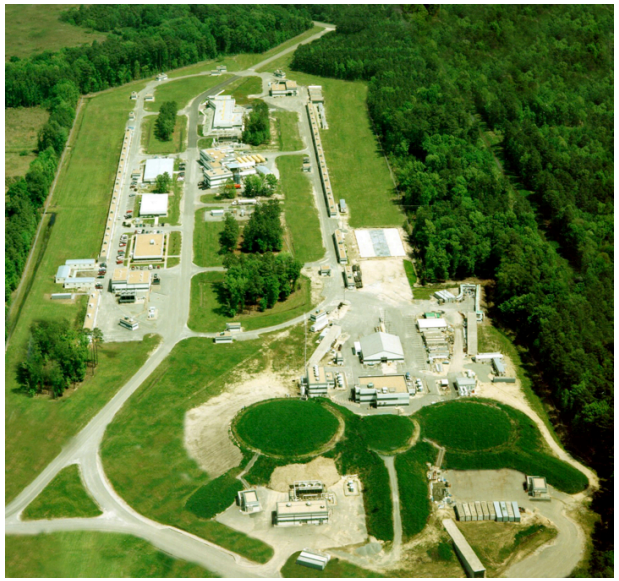
Two concepts to realize EIC in the US

eRHIC at BNL

- RHIC + new electron machine

MEIC at JLab

- CEBAF + new hadron machine

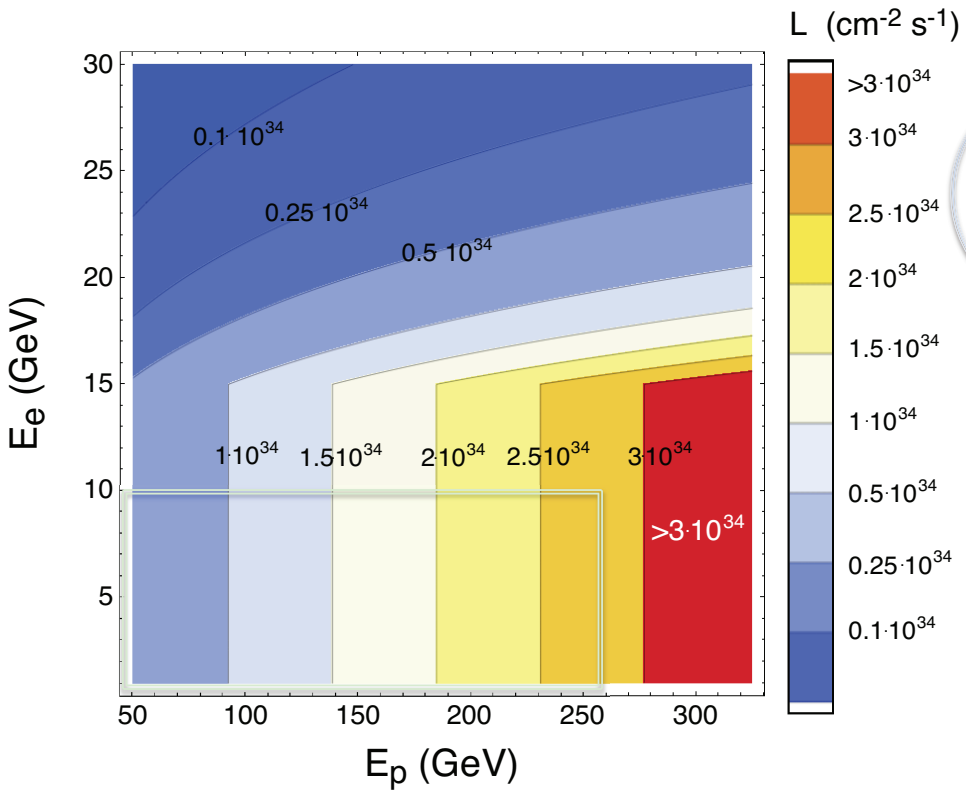


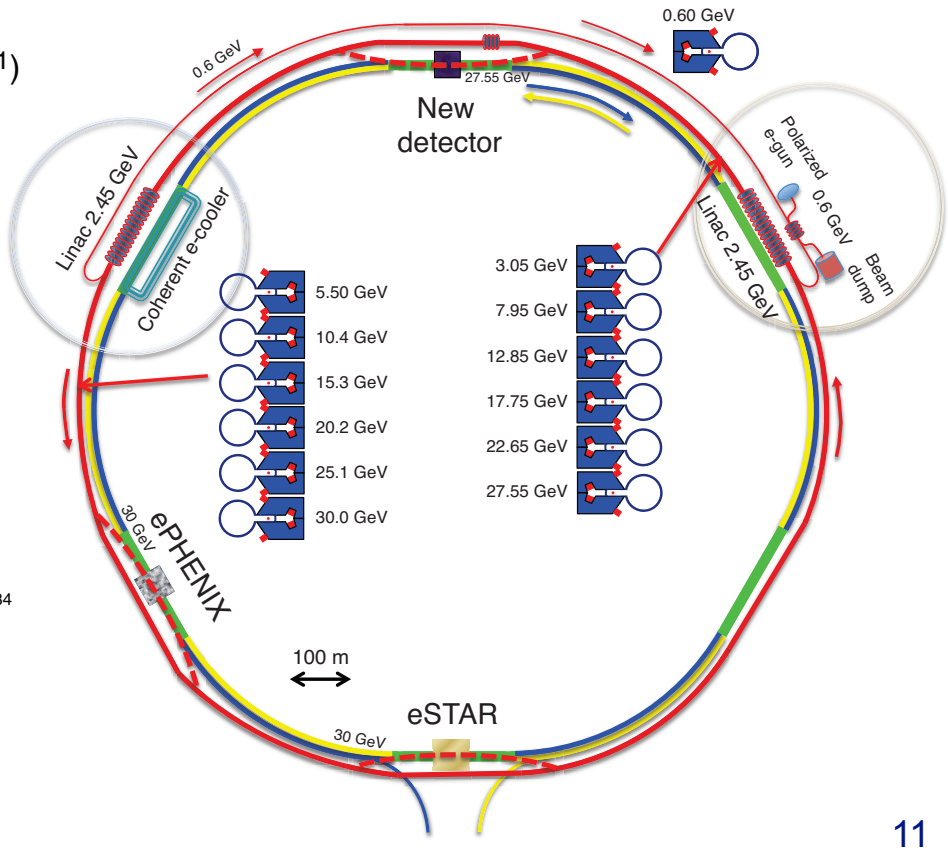
- Realization (2012 version):
  Stage I ($\sqrt{s}$=40-70 GeV), Stage II ($\sqrt{s}$ > 100 GeV)
- Maximum utilization of past and current investments

N.B.: LHeC/CERN **not** included in 2013 HEP European Strategy Plan

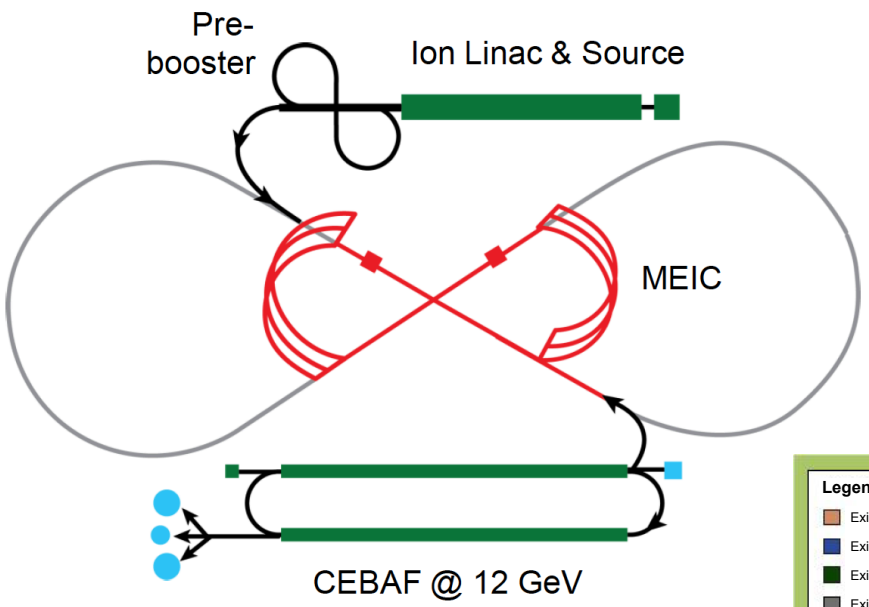
eRHIC Design

- 5 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- Single pass allows for large collision disruption of electron bunch, potential for high luminosity (~ 10^{34} cm^{-2} s^{-1}), and full electron polarization transparency





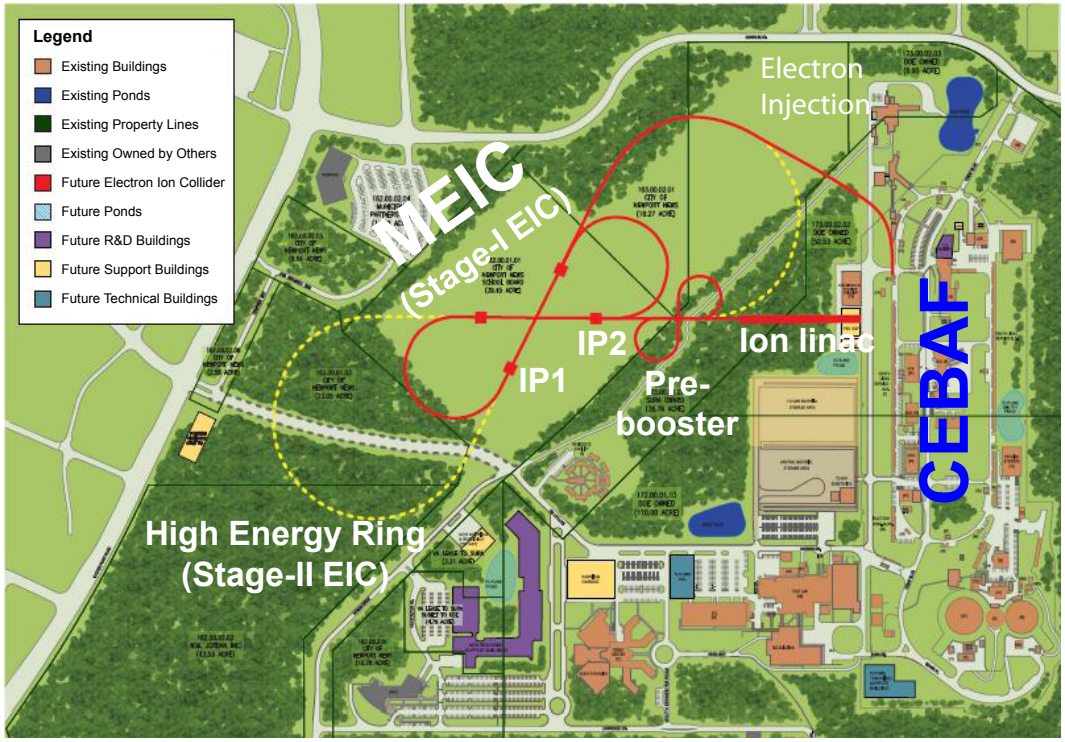
MEIC Design



- Figure-8 Ring-Ring Collider
  - No multi-pass Energy-Recovery Linac (ERL)
  - Regular electron cooling

Stage-I (MEIC)

- $\sqrt{s}$ = 13 – 70 GeV
- E_e = 3 – 12 GeV
- E_p = 15 – 100 GeV
- E_{Pb} = up to 40 GeV/A
- Longitudinal and transverse polarization of light ions (p, d, ^{3}He)

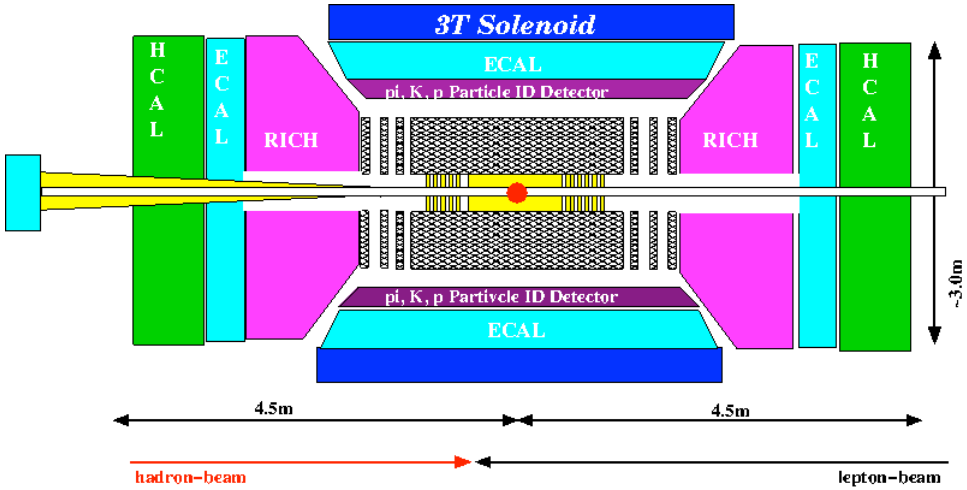


Evolving Detector Concepts

Wide physics program puts stringent requirements on detector performance

- High acceptance -5 < η < 5
- Good PID (π,K,p and lepton) and vertex resolution
- Same rapidity coverage for tracking and calorimeter
  - Good momentum resolution, lepton PID
- Low material density because of low scattered lepton p
  - Minimal multiple scattering and bremsstrahlung
- Very forward electron and proton/ neutron detection
- Fully integrated in machine IR design

eRHIC:



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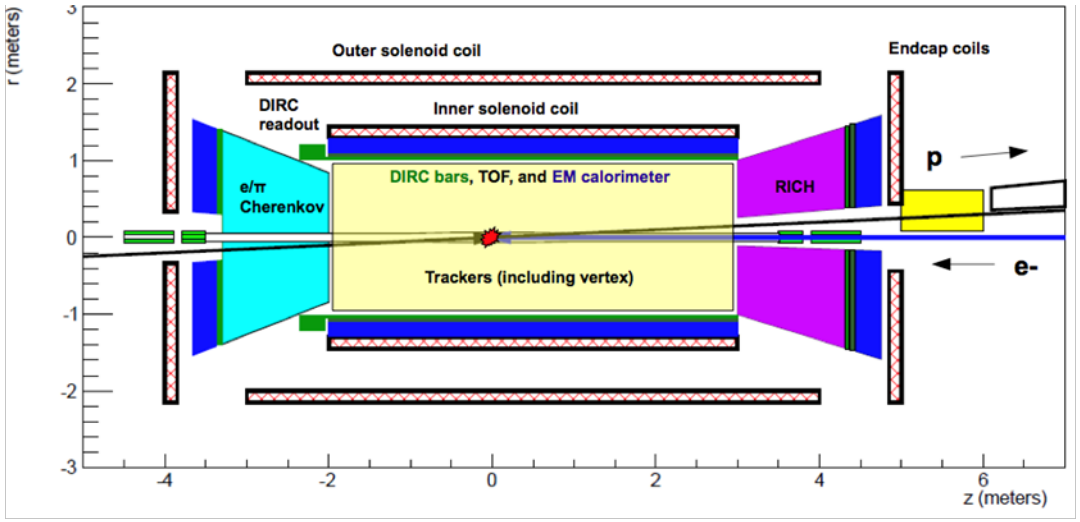
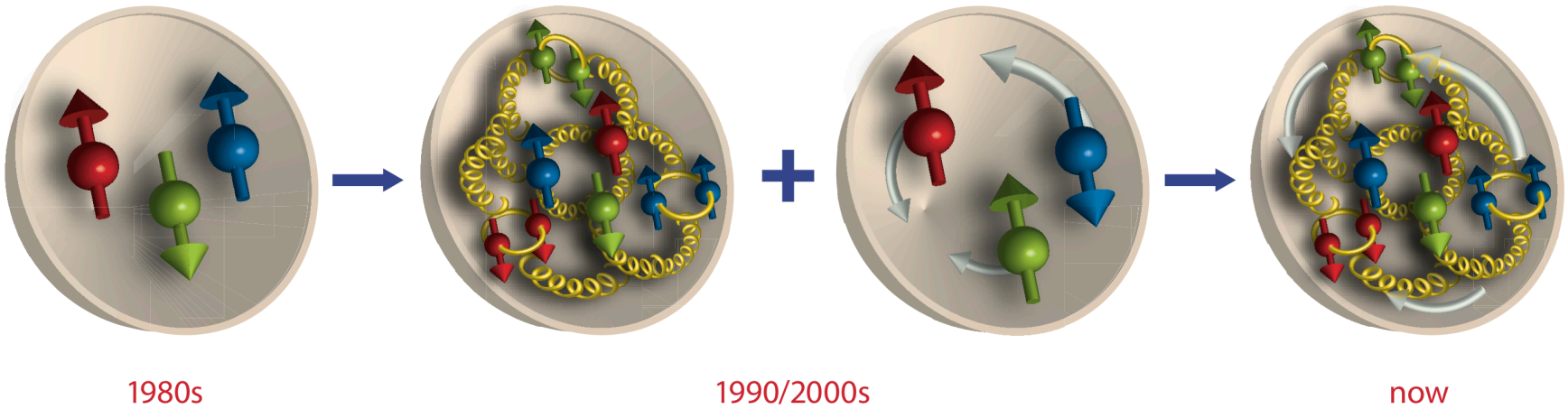
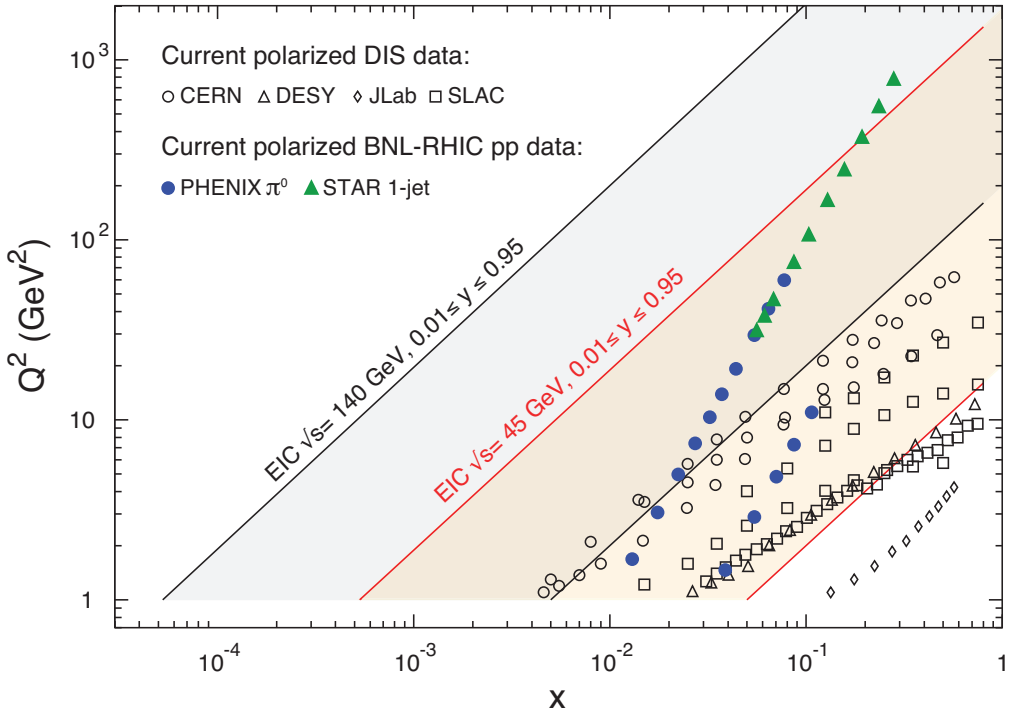


Key Measurements:
Spin and Three-Dimensional Structure of the Nucleon



Polarized inclusive deep-inelastic scattering



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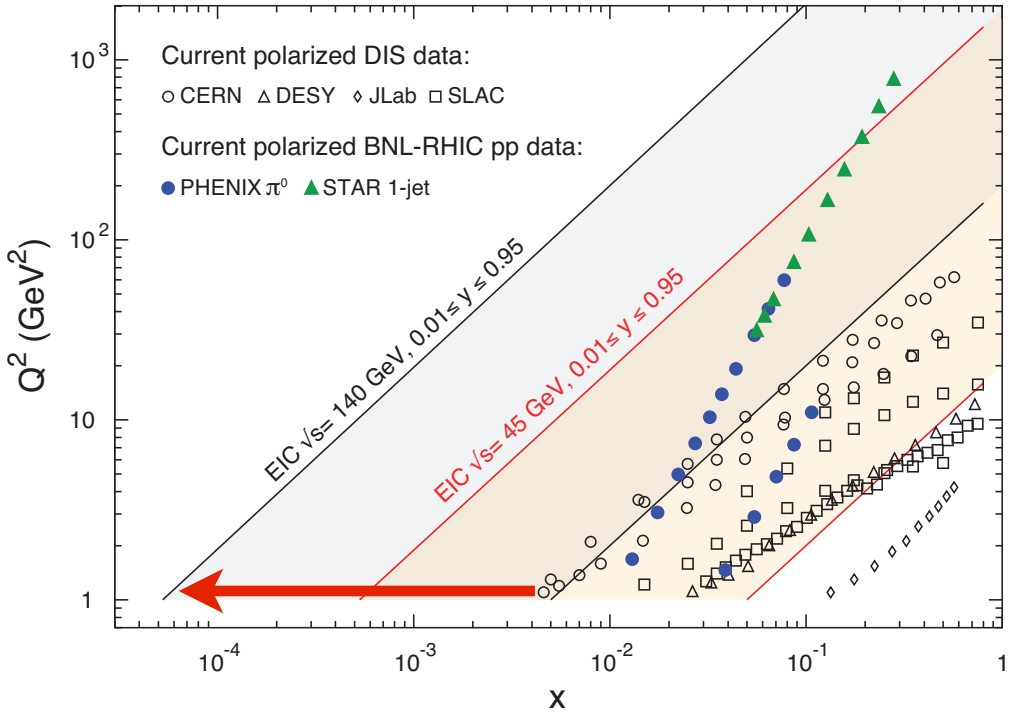

- gain two decades in x ⇒ get into the region where gluons and sea quarks dominate

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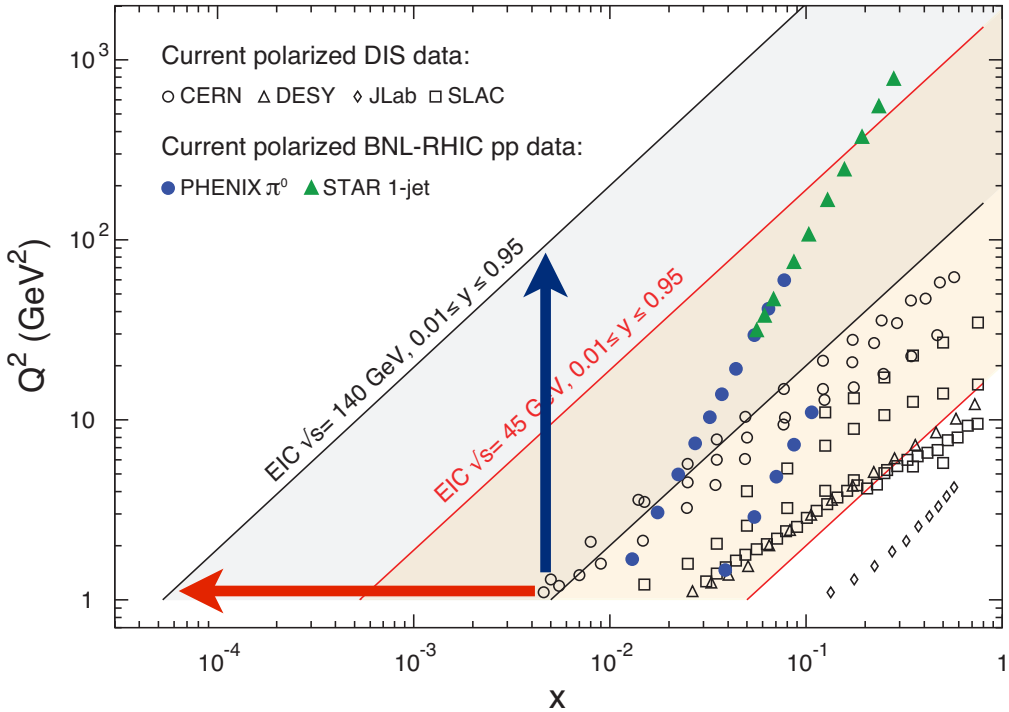

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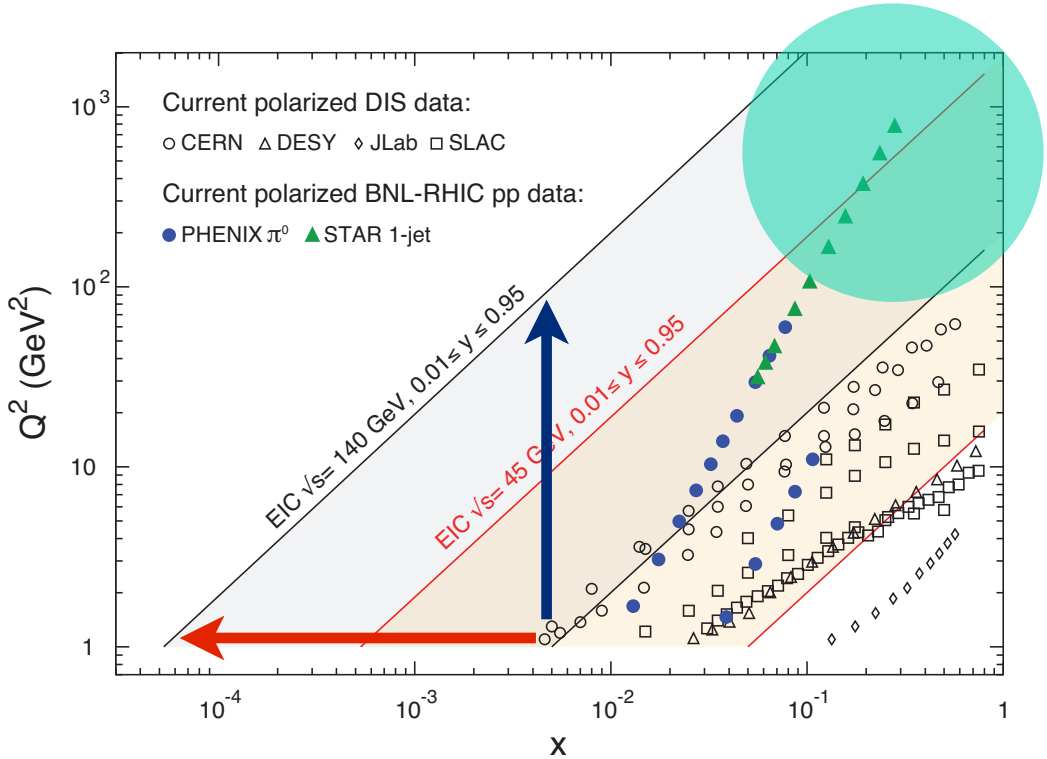
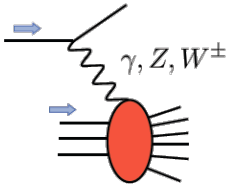
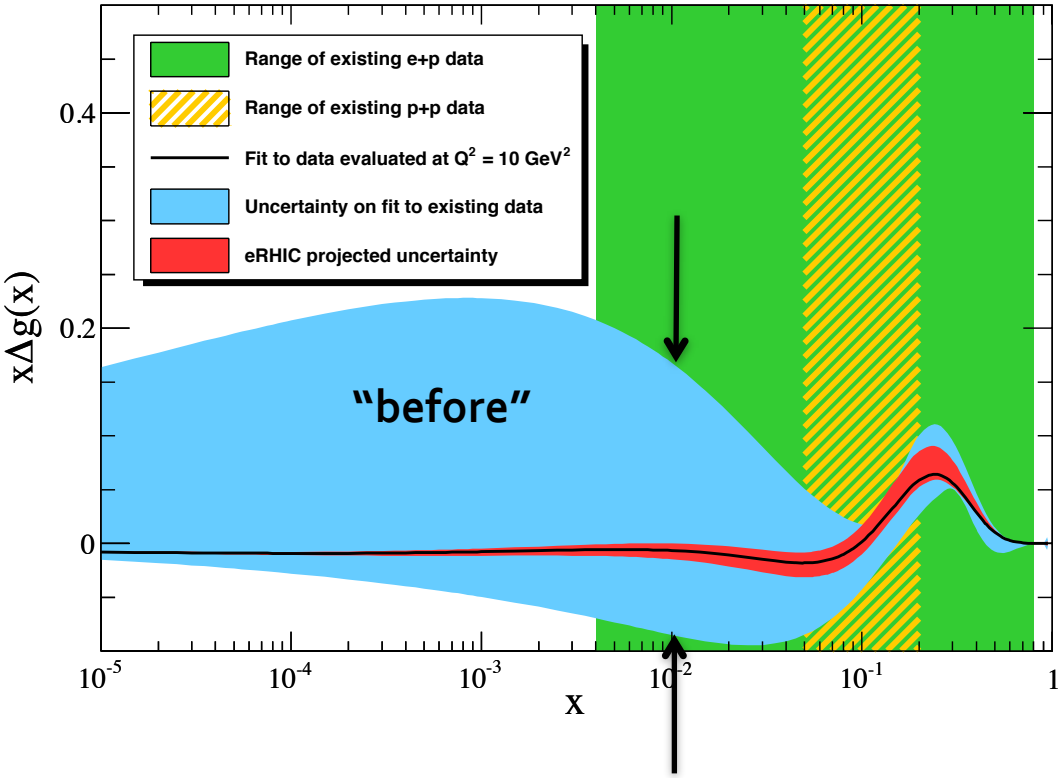


- gain two decades in x ⇒ get into the region where gluons and sea quarks dominate
- cover large Q^2 range for each x ⇒ study "scaling violations" ⇒ gluon density
- can reach large Q^2 (at medium-to-large x) ⇒ access to electroweak effects



Impact of EIC on $\Delta g_f(x,Q^2)$



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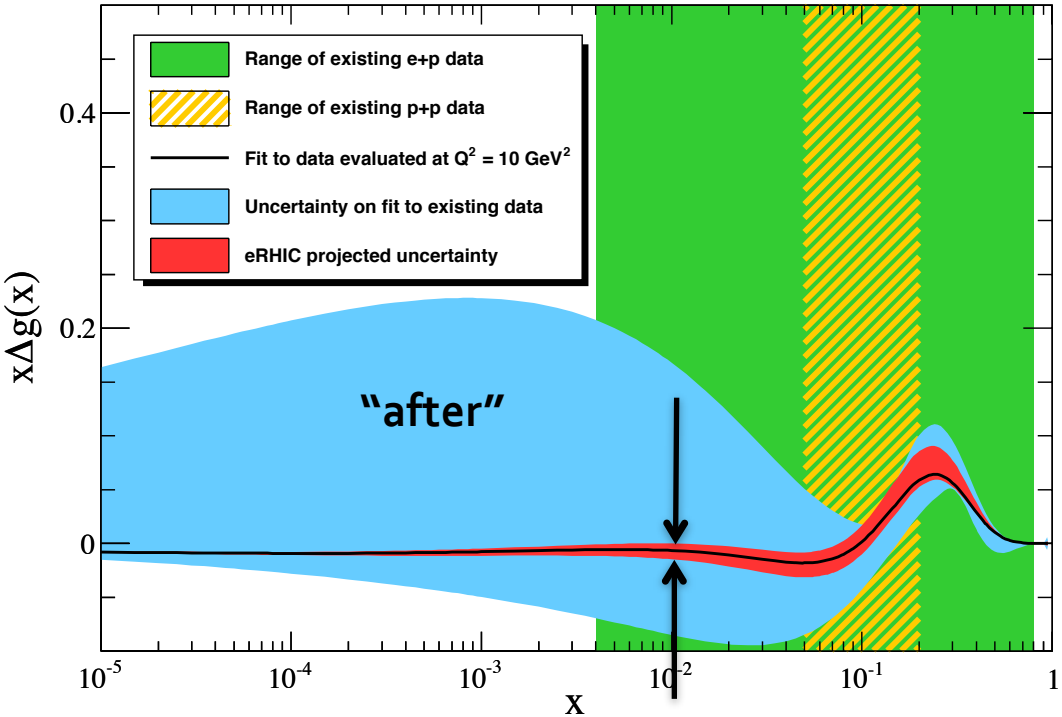

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- EIC - Inclusive DIS: dramatic reduction of uncertainties in ΔG

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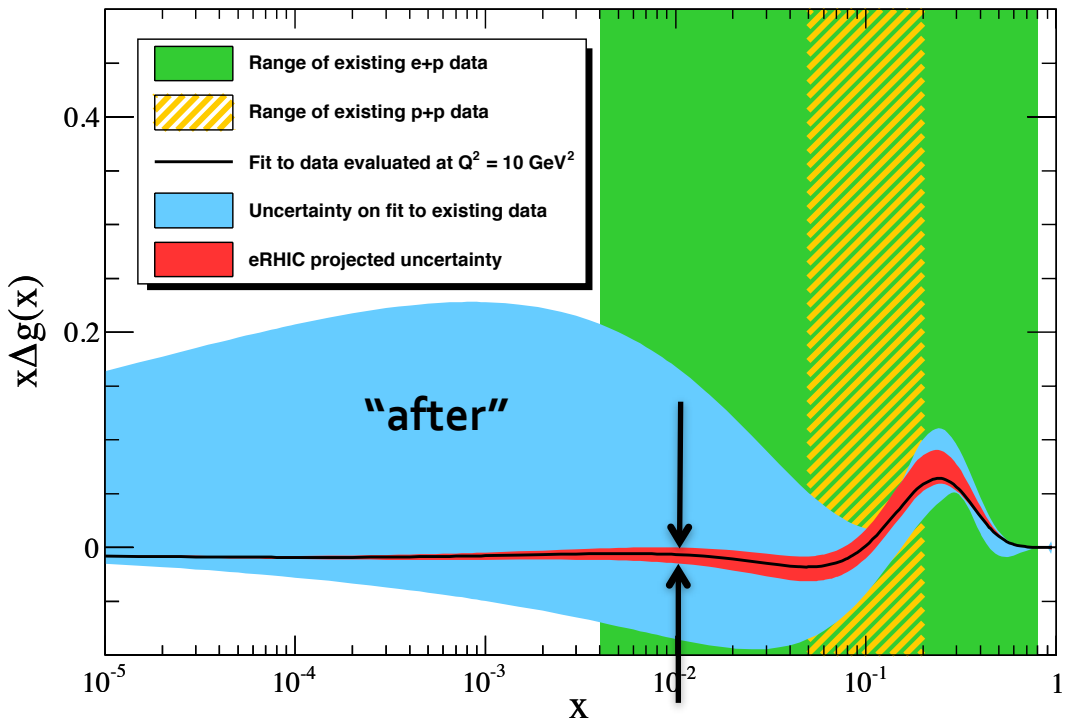

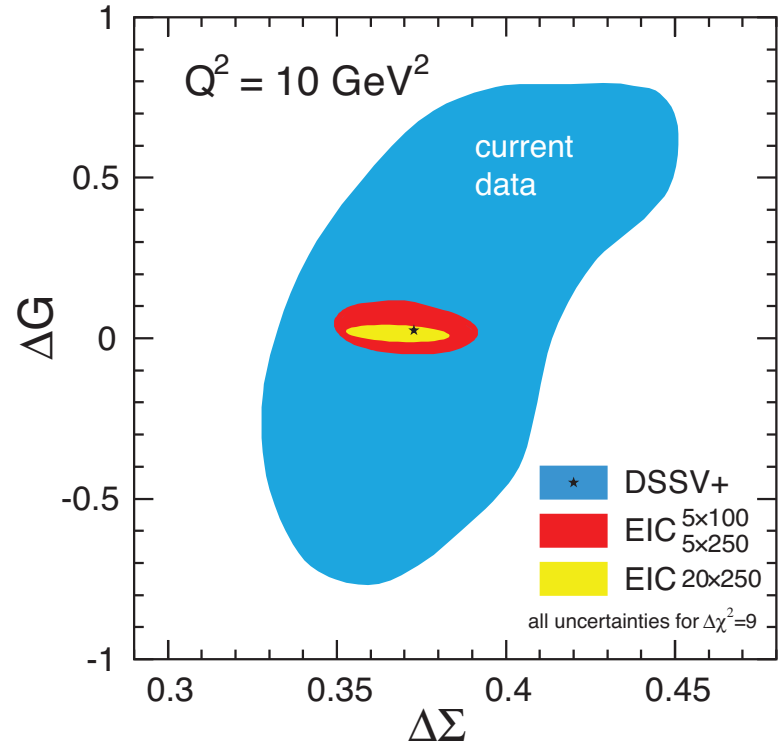

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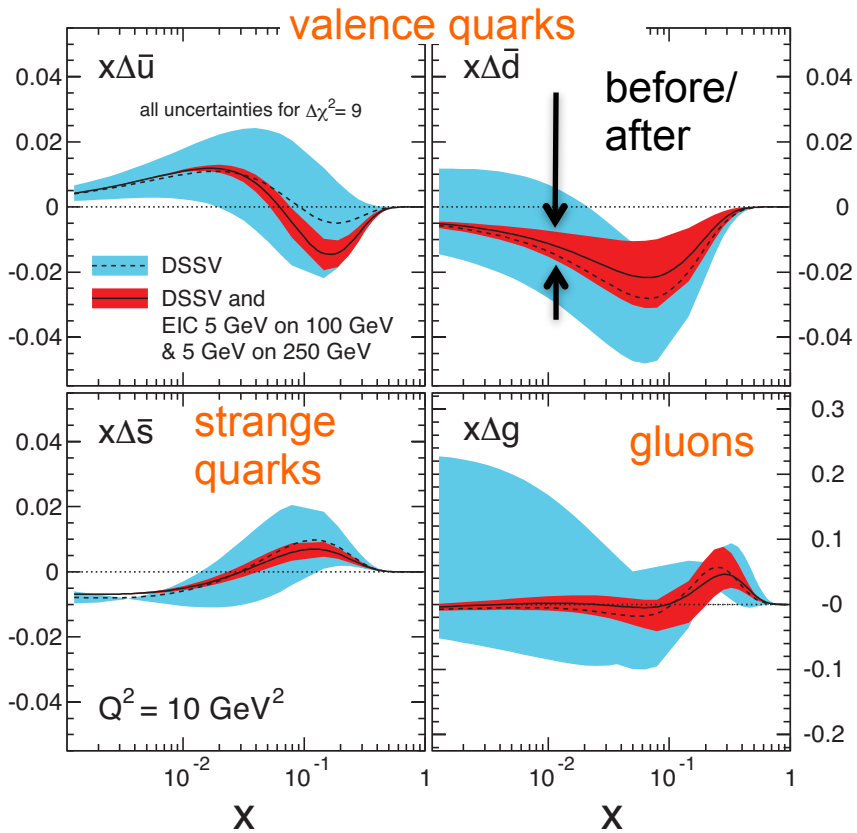
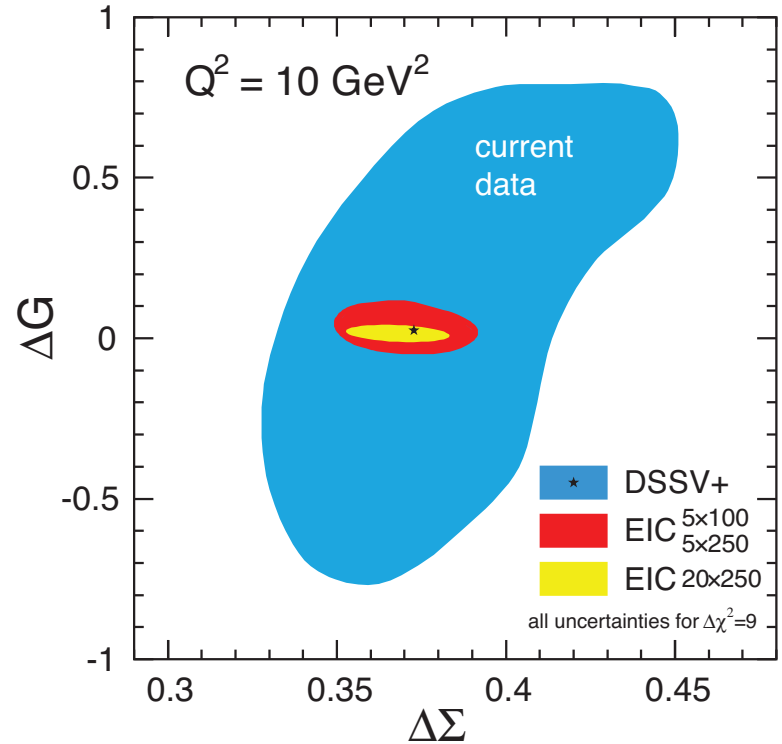
- EIC - Inclusive DIS: dramatic reduction of uncertainties in ΔG

Impact of EIC on $\Delta g_f(x,Q^2)$





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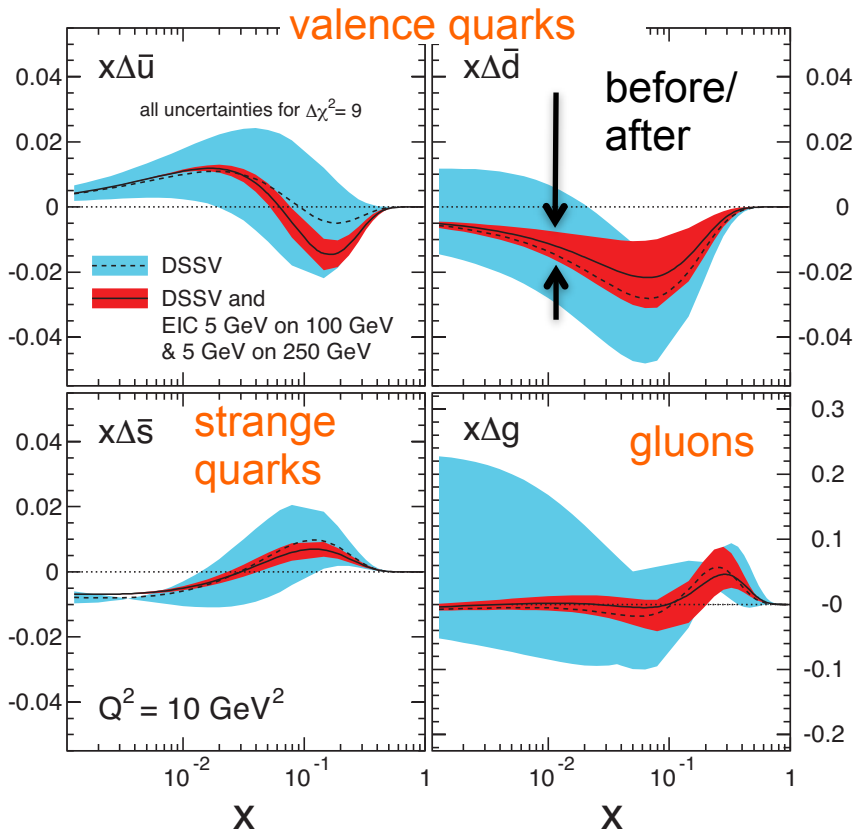
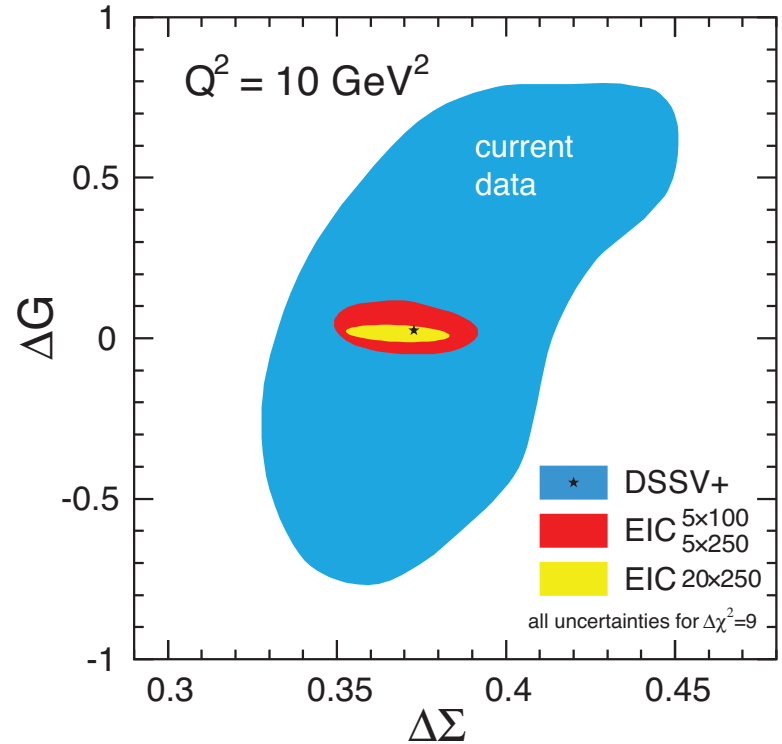


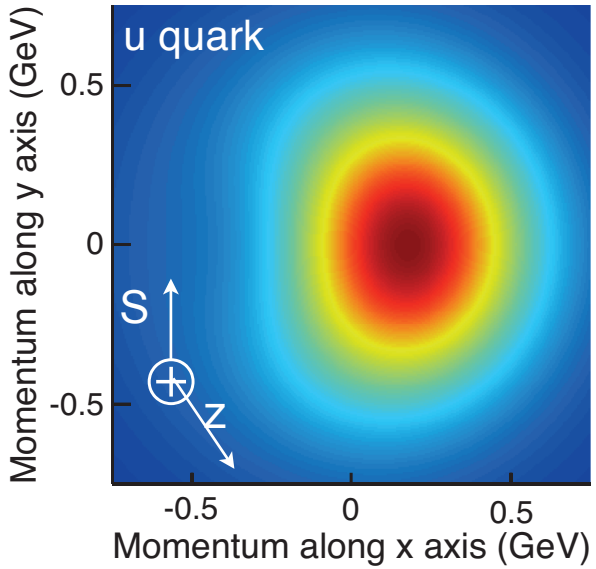


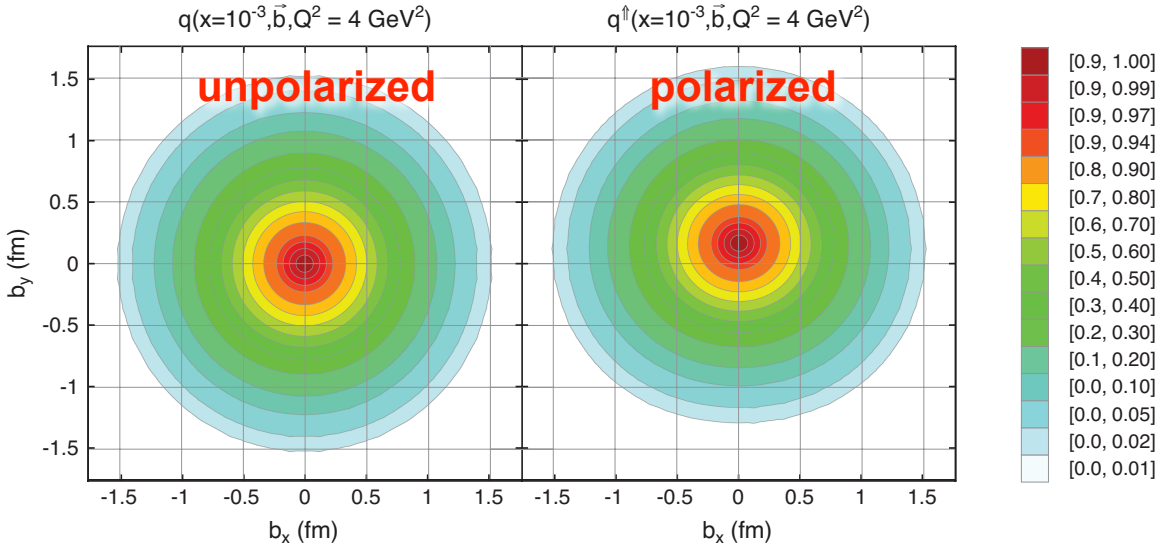
- Present uncertainties at small x as large as twice the proton spin
- EIC - Inclusive DIS: dramatic reduction of uncertainties in ΔG
- EIC - Semi-inclusive DIS: flavor separated distributions

Decisive impact on understanding of proton spin

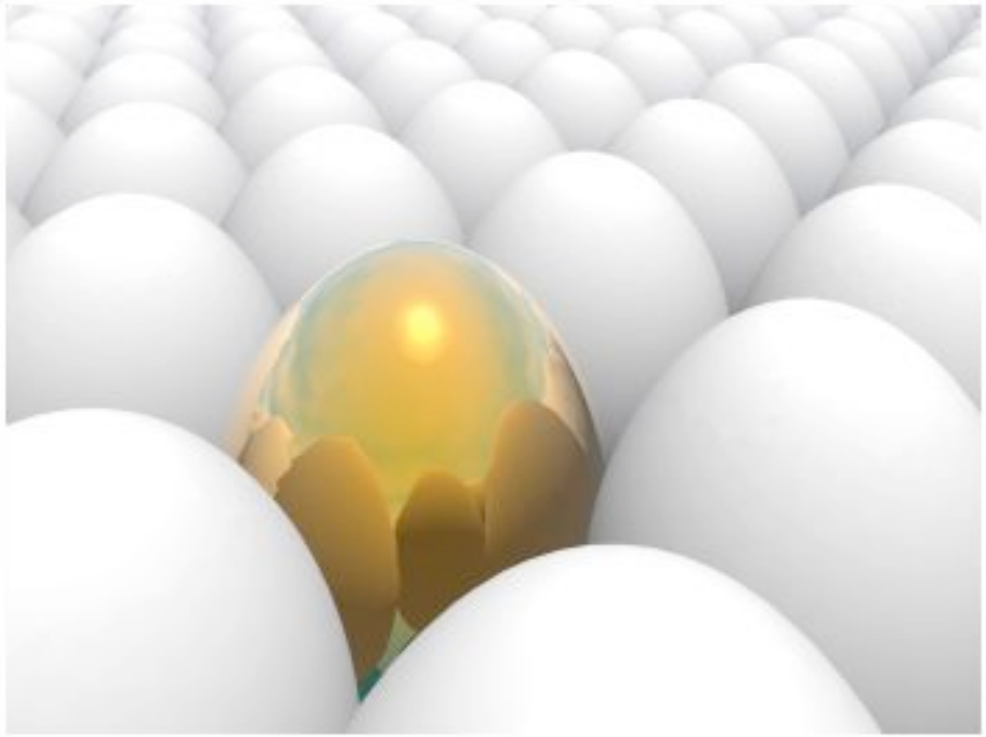
Imaging at EIC: TMDs & GPDs

- Transverse Momentum Distributions (TMD):
  - 2D+1 picture in momentum space (k_T)
- Generalized Parton Distributions (GPD):
  - 2D+1 picture in coordinate space (b_T)

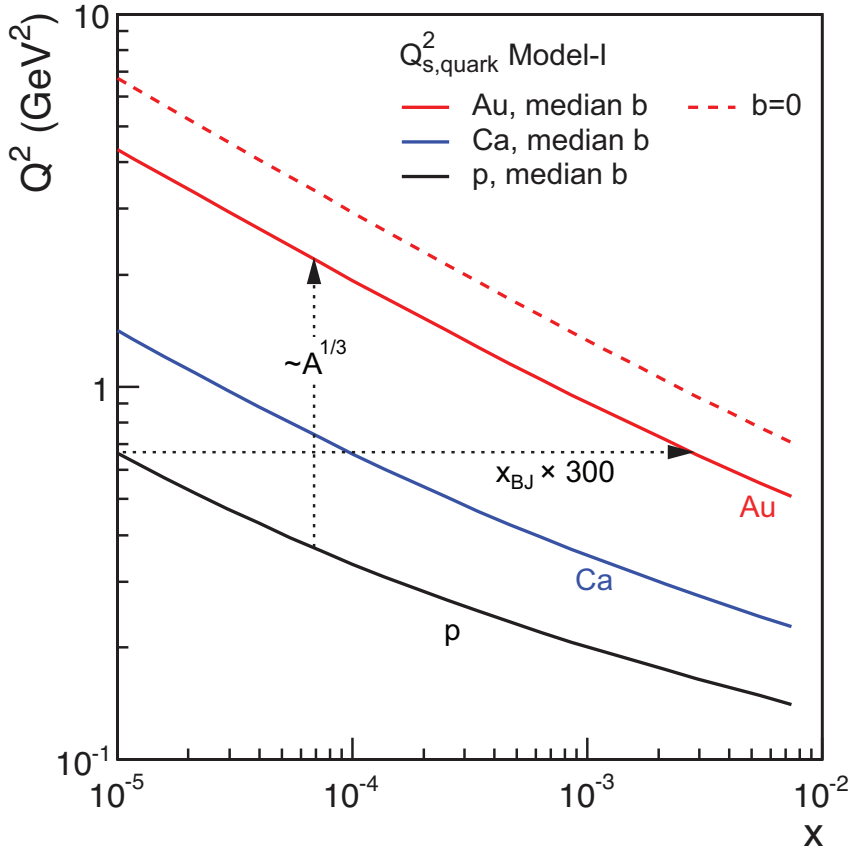


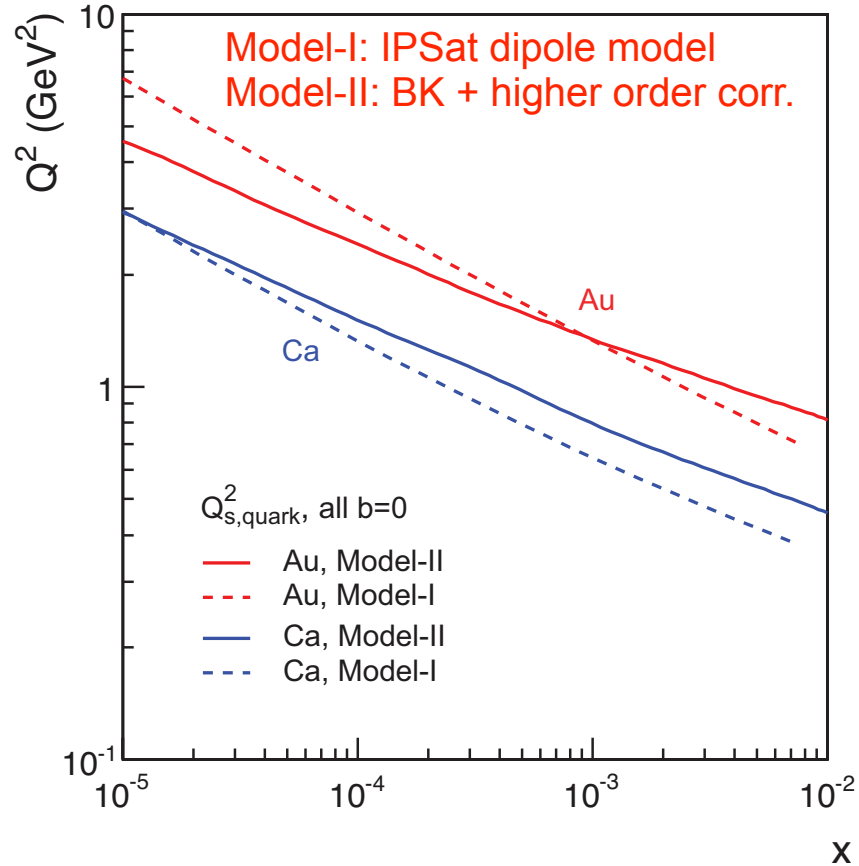


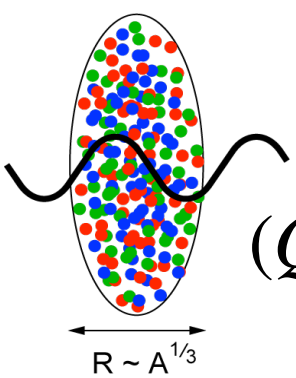
Key Measurements:
Low-x Physics in eA, the Physics of Strong Color Fields



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

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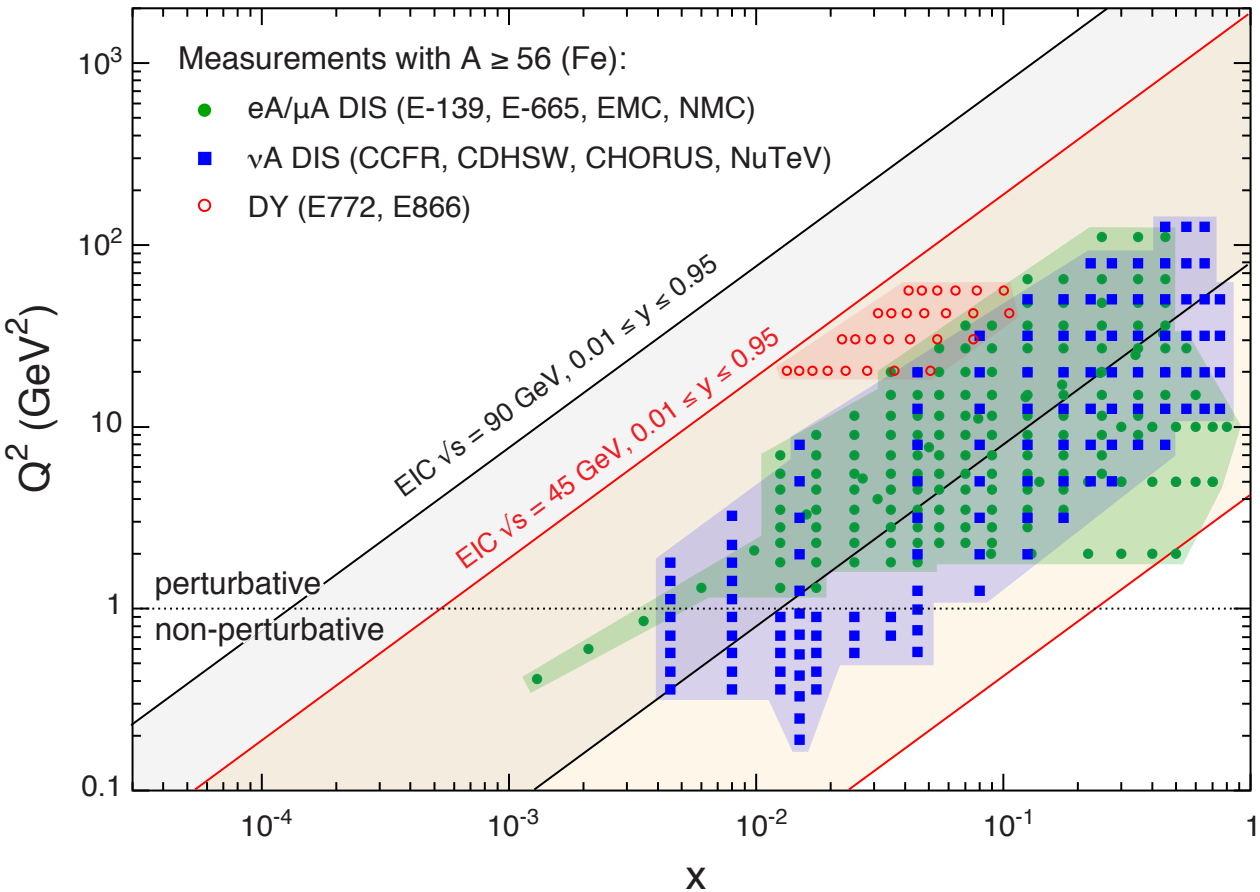

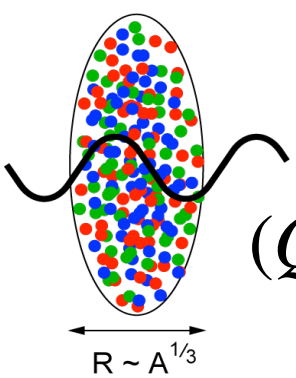

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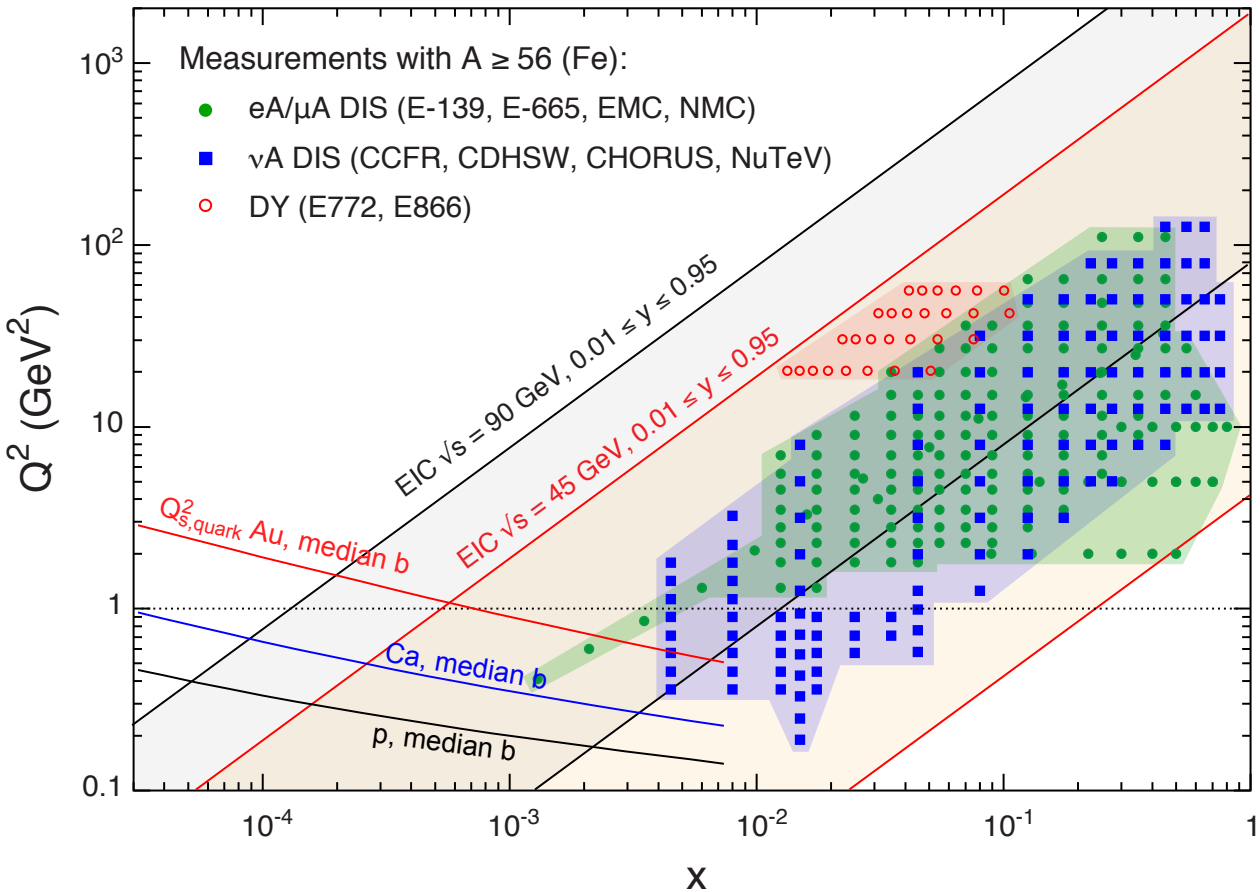

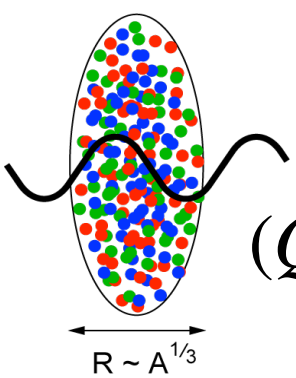

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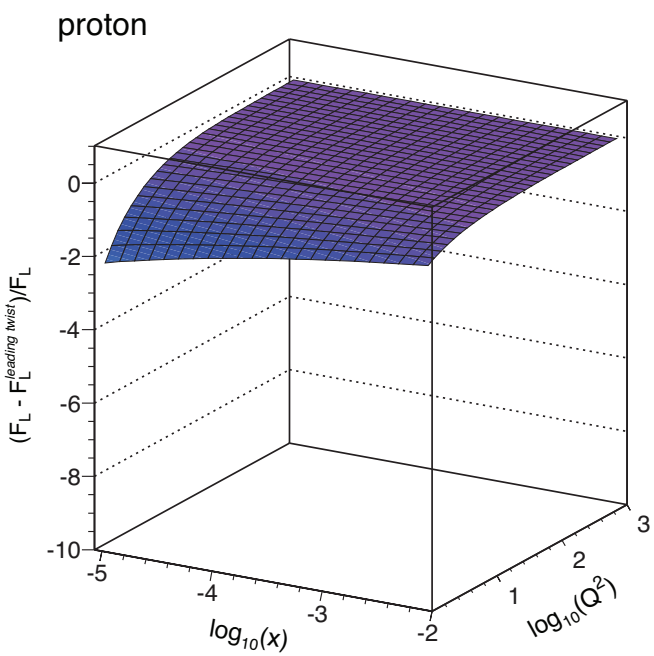
Inclusive DIS in eA: Nuclear PDFs

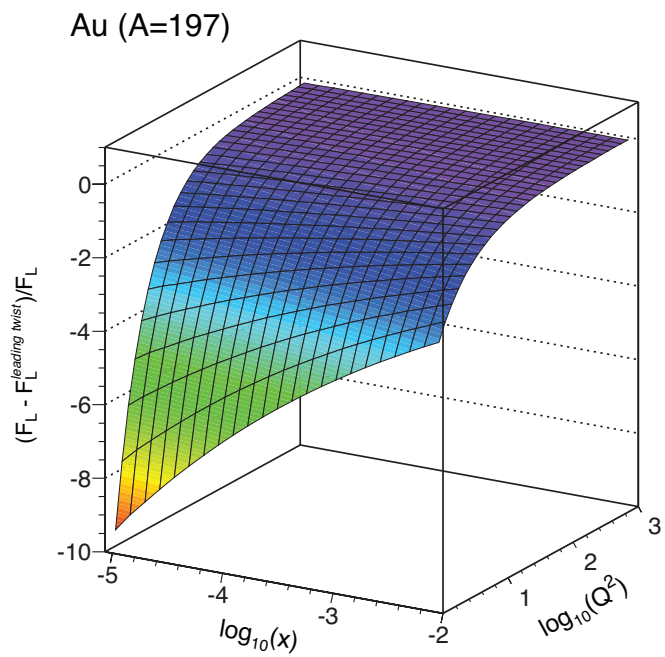
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

gluon

- Expect strong non-linear effects in F_L

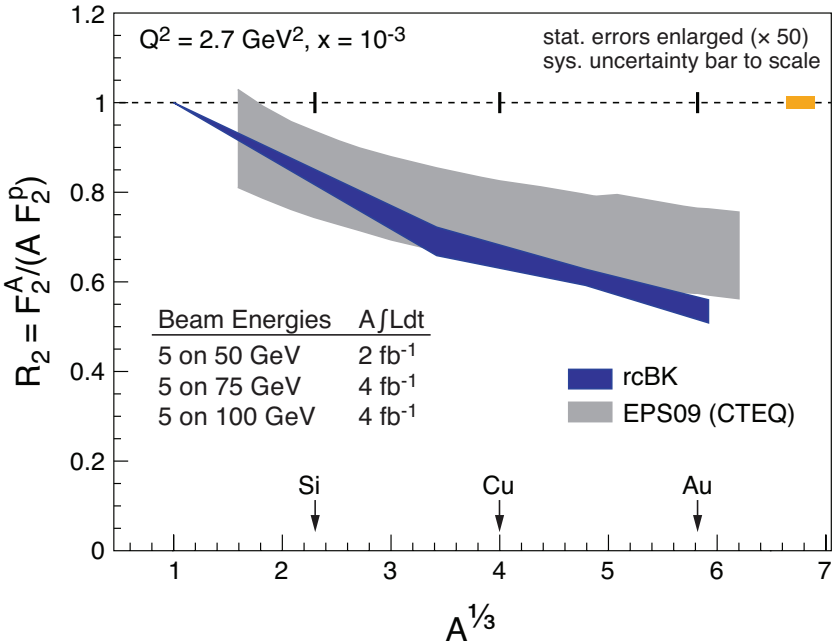


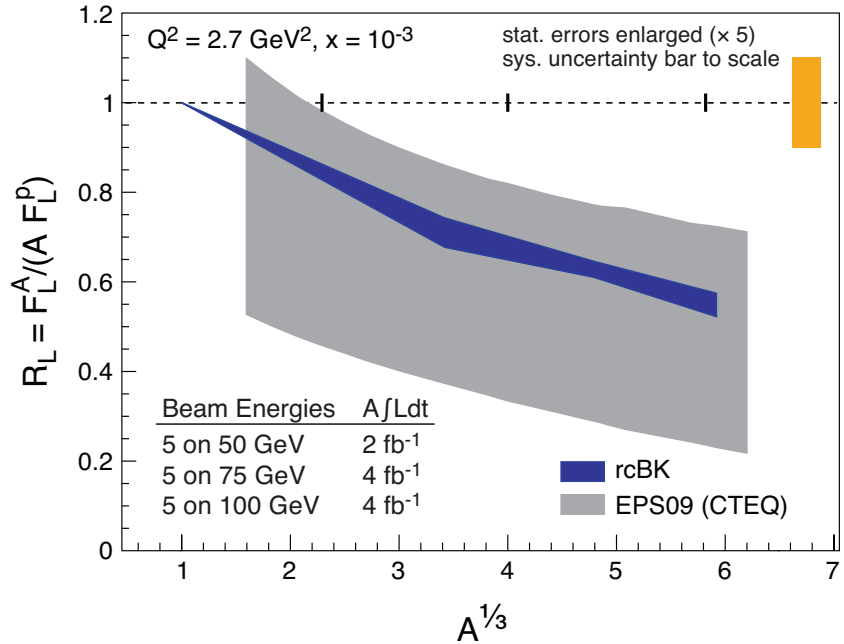


Relative contributions of higher twist effects to F_L amplified in eA

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

Inclusive DIS in eA: Nuclear PDFs

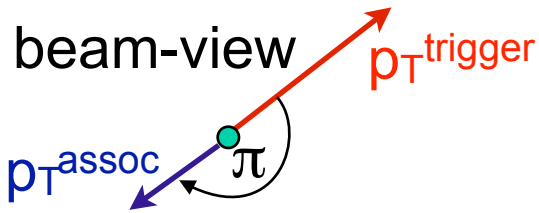




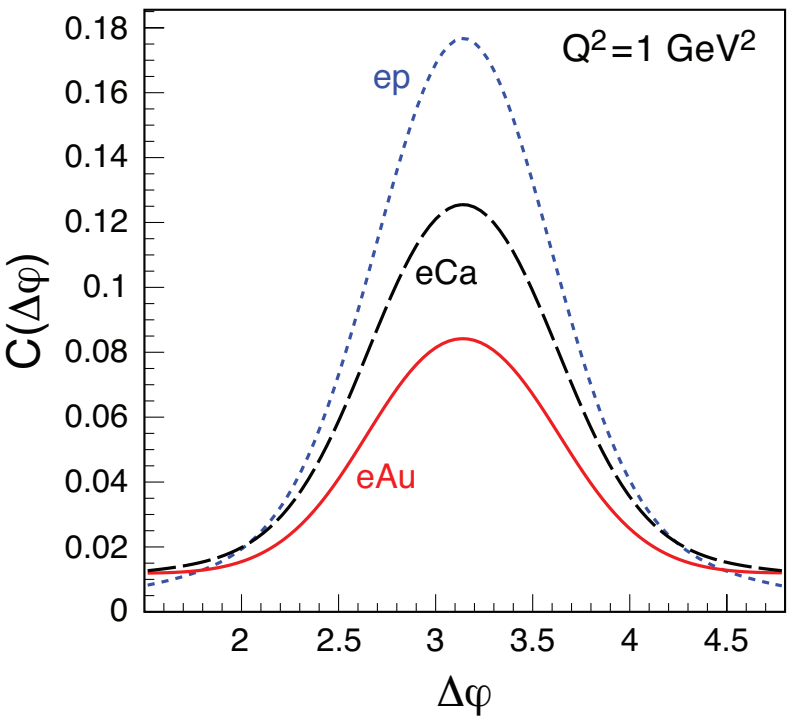
- measurement of F_L requires running at different $\sqrt{s}$
- F_2, F_L: negligible stat. error, systematics dominated
- A dependence helps to discriminate between linear and non-linear (saturation) models
- Precision nPDF: Huge impact on pA, AA physics

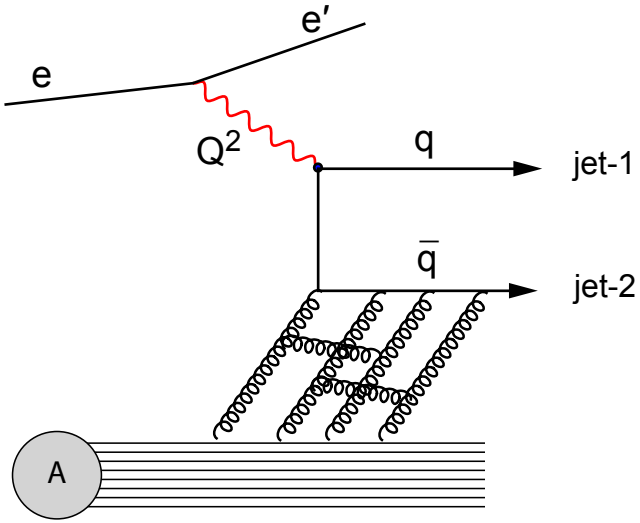
Semi-inclusive DIS: eA Dihadron Correlations

Simple Measurement



Theory: Saturation





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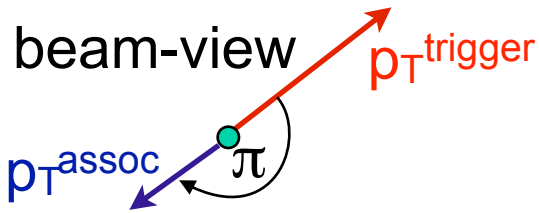

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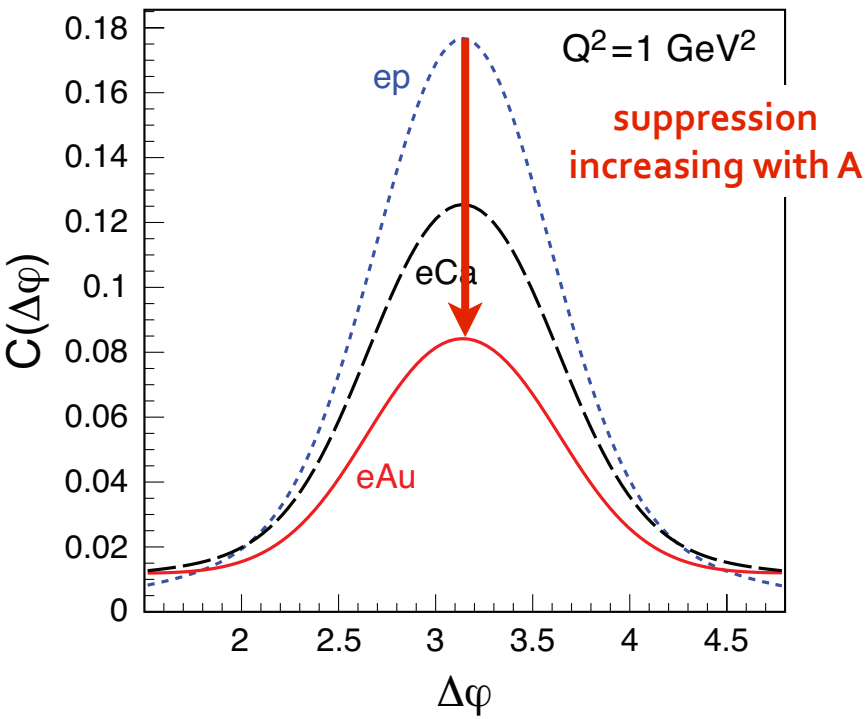

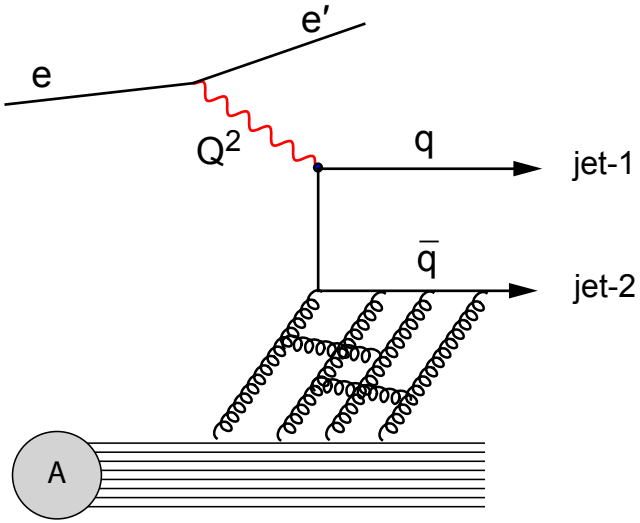

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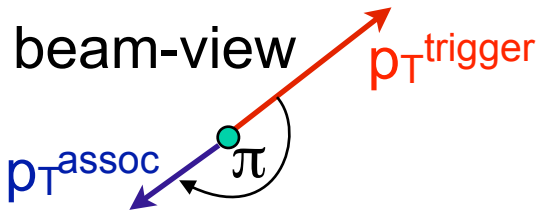

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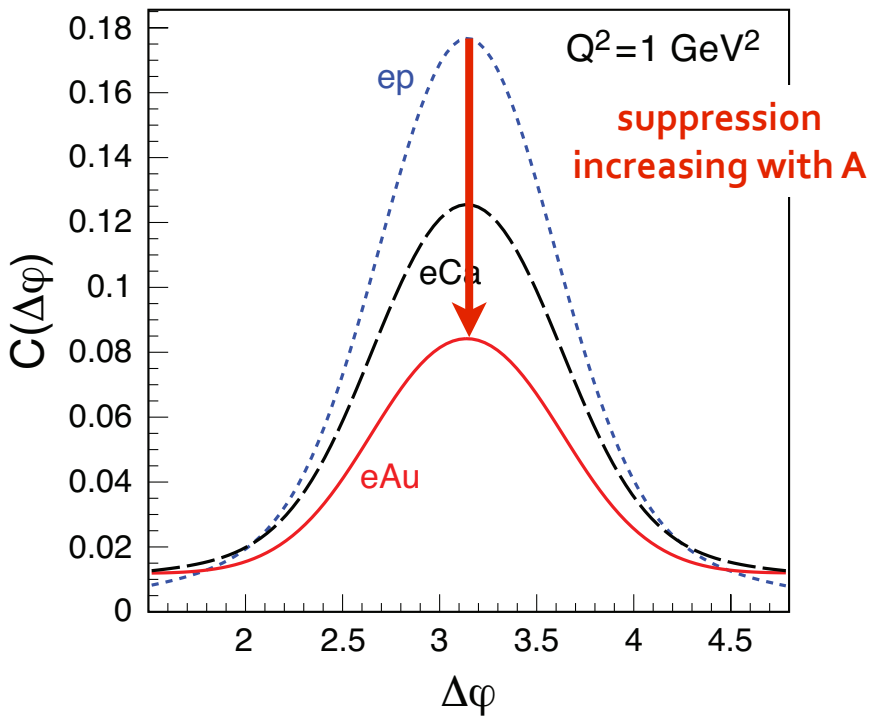
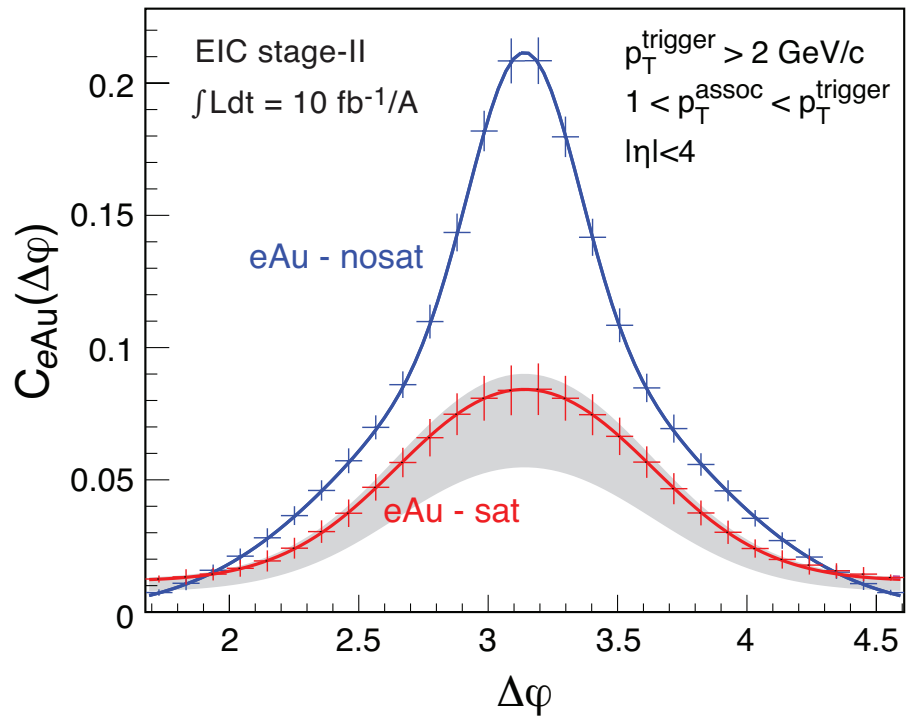


Exp: Saturation versus "conventional" scenario



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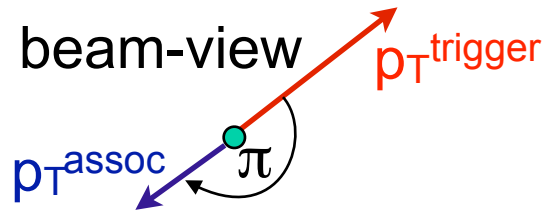

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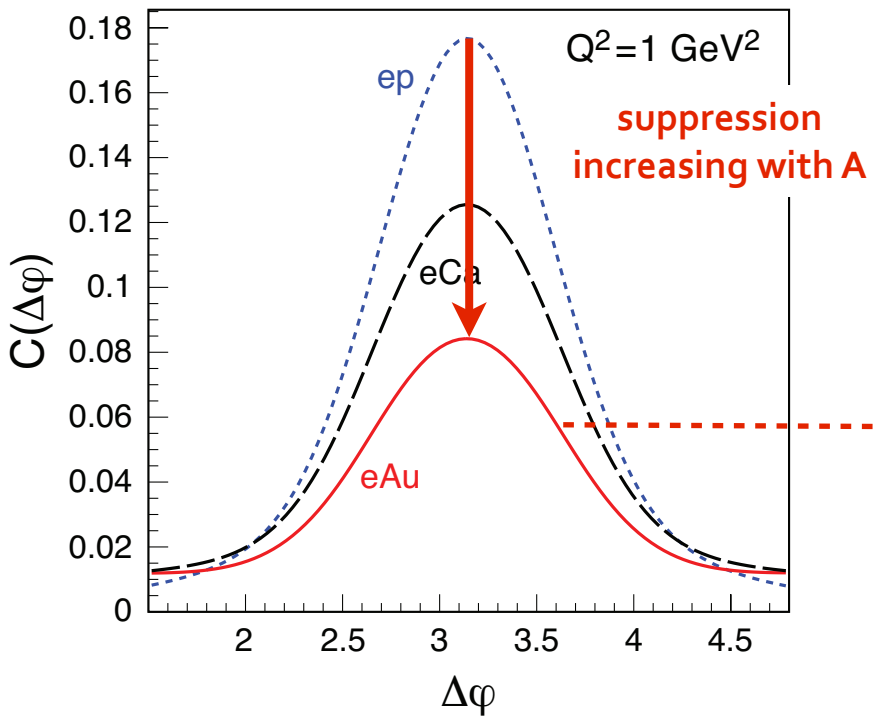

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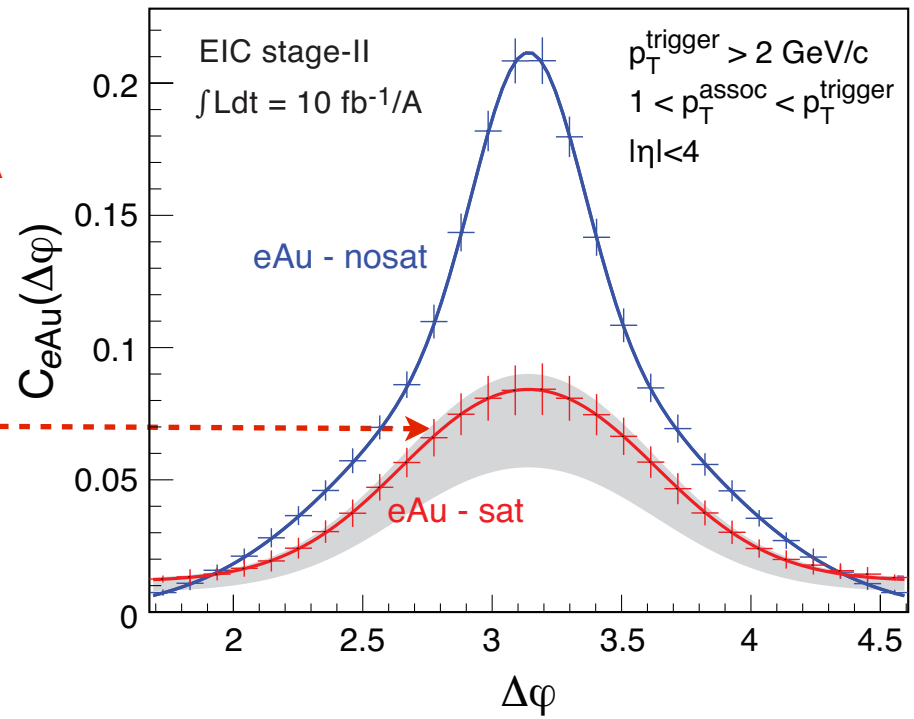

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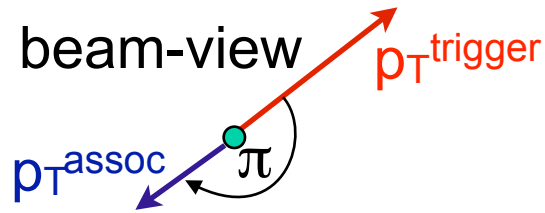

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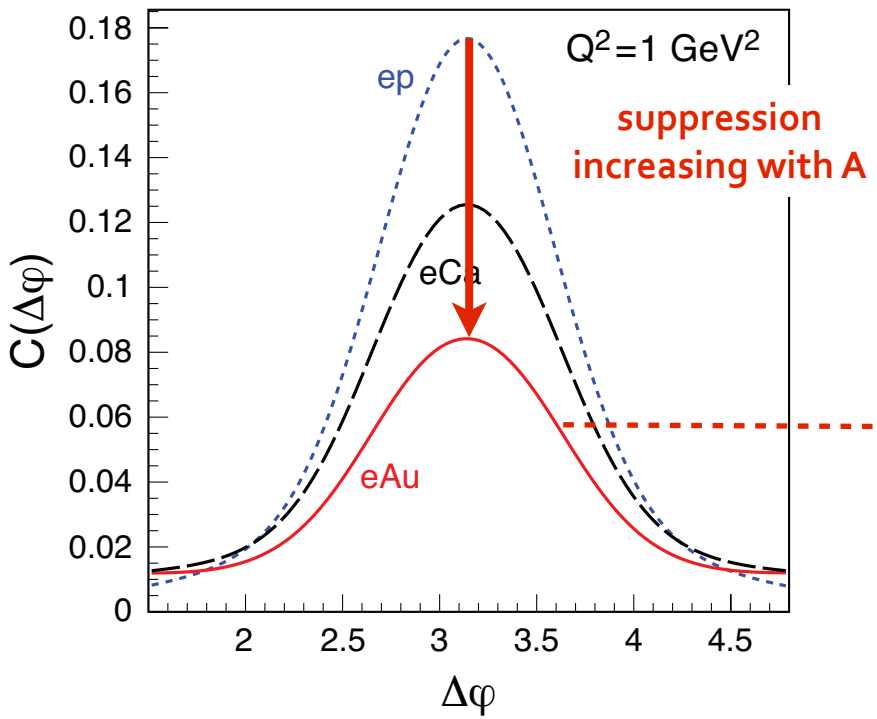

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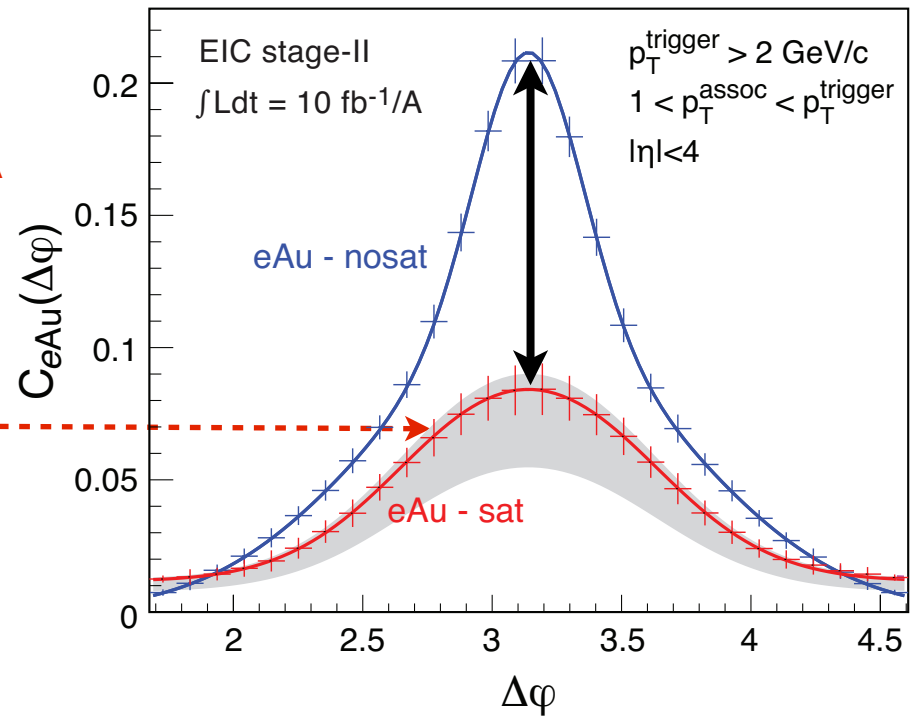
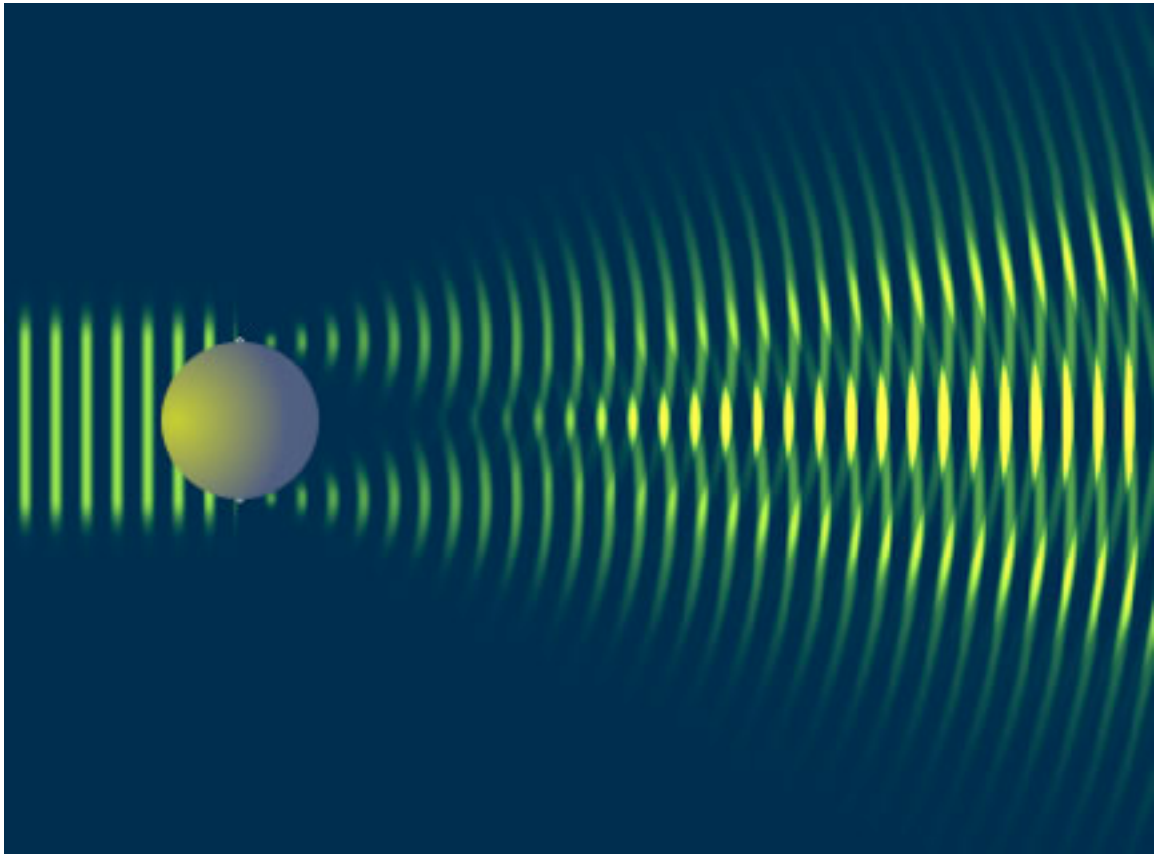


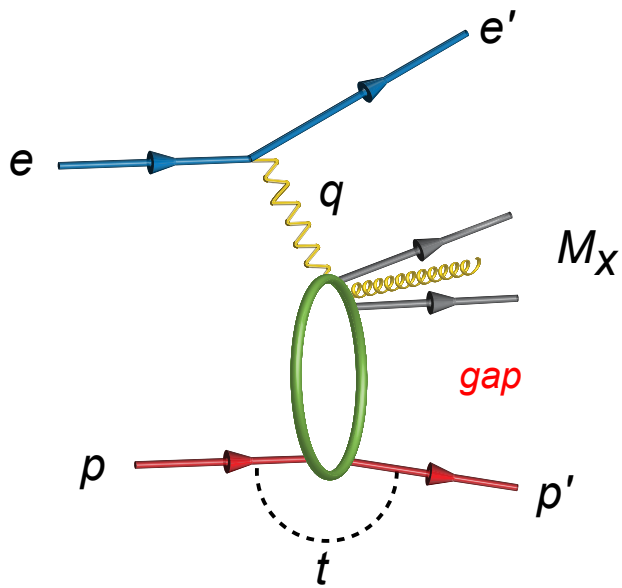
Clear differences between sat and no-sat models

Diffractive Processes in eA



Hard Diffraction: What is It?

HERA: large fraction of diffractive events (15% of total DIS rate)



Close relative of DIS

Need in addition:
t : momentum transfer squared
M_X : mass of diffractive final-state

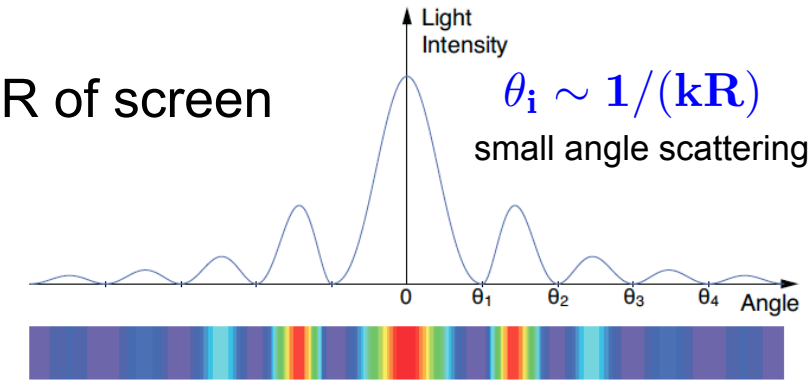
Diffractive event characterized by large **rapidity gap** mediated by **color neutral exchange** (e.g. 2 or more gluons)

Terminology:	**coherent**	**incoherent**
	p/A stays intact	p/A breaks up

- ep: detect intact protons in forward detectors
- eA: need to tag on emitted neutrons from nuclear breakup

Why Is Diffraction So Important?

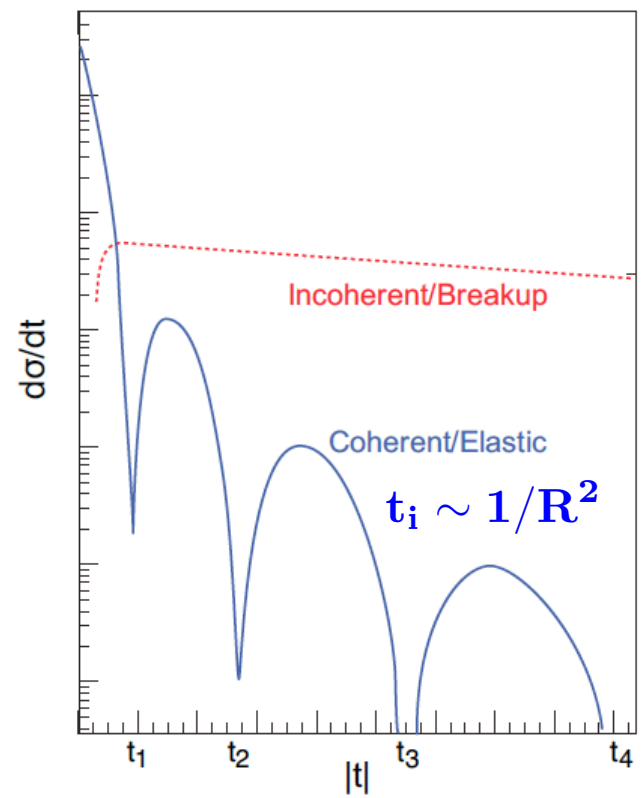
Recall: diffractive pattern in optics
position of minima θ_i related to size R of screen



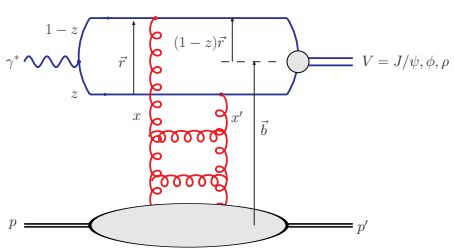
Similarly: in coherent (elastic) scattering
$d\sigma/dt$ resembles diffractive
pattern where $|t| \approx k^2\theta^2$

Crucial differences:

- target not always "black disc"
  - sensitivity to "size" of probe / onset of black disc limit
- incoherent (inelastic) contribution



Strong sensitivity to gluons & saturation



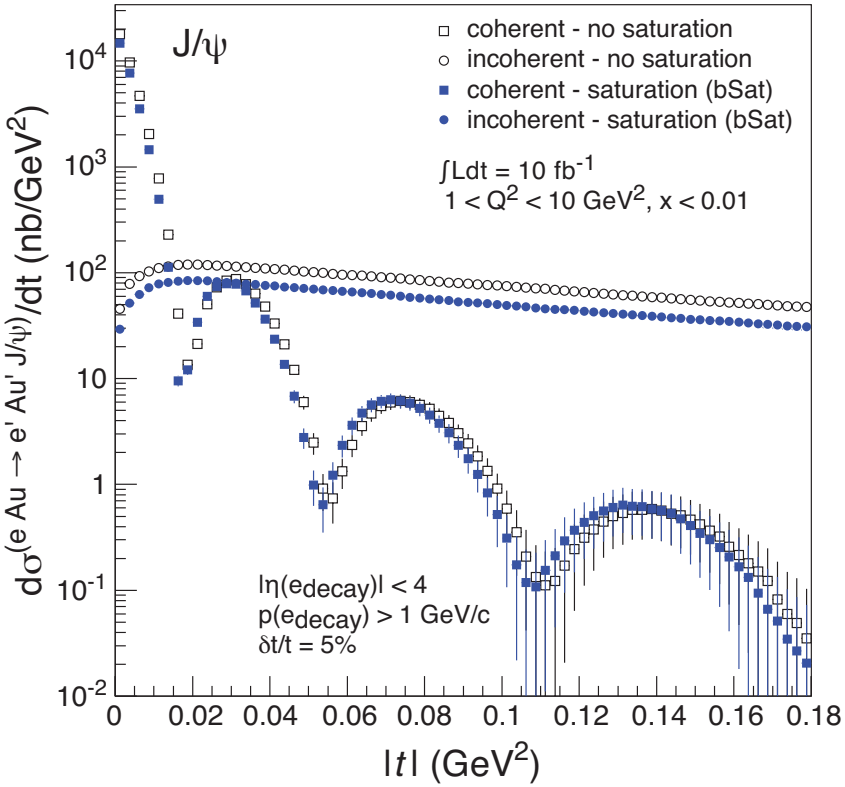
$$d\sigma \sim [g(x)]^2$$

due to required
color-neutral exchange

Bonus: $\frac{d\sigma}{dt}$ $\xleftrightarrow[\text{transform}]{\text{Fourier}}$ **spatial distribution of gluons**

Spatial Gluon Distribution Through Diffraction

- Goal: going after the source distribution of gluons through Fourier transform of dσ/dt
- momentum transfer *t* conjugate to transverse position (b_T)



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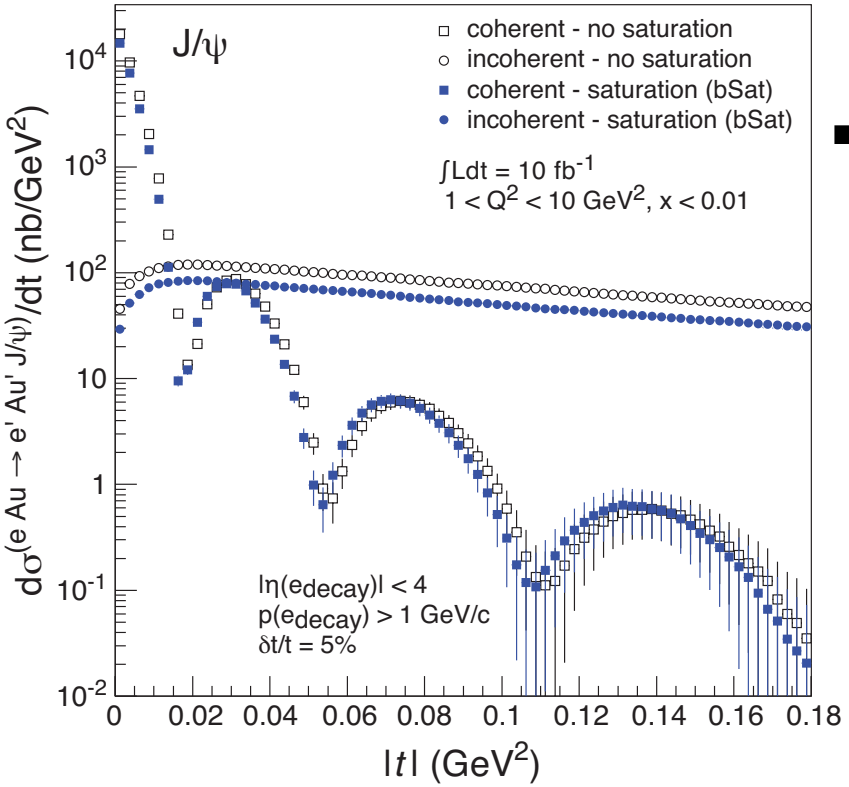

$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

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

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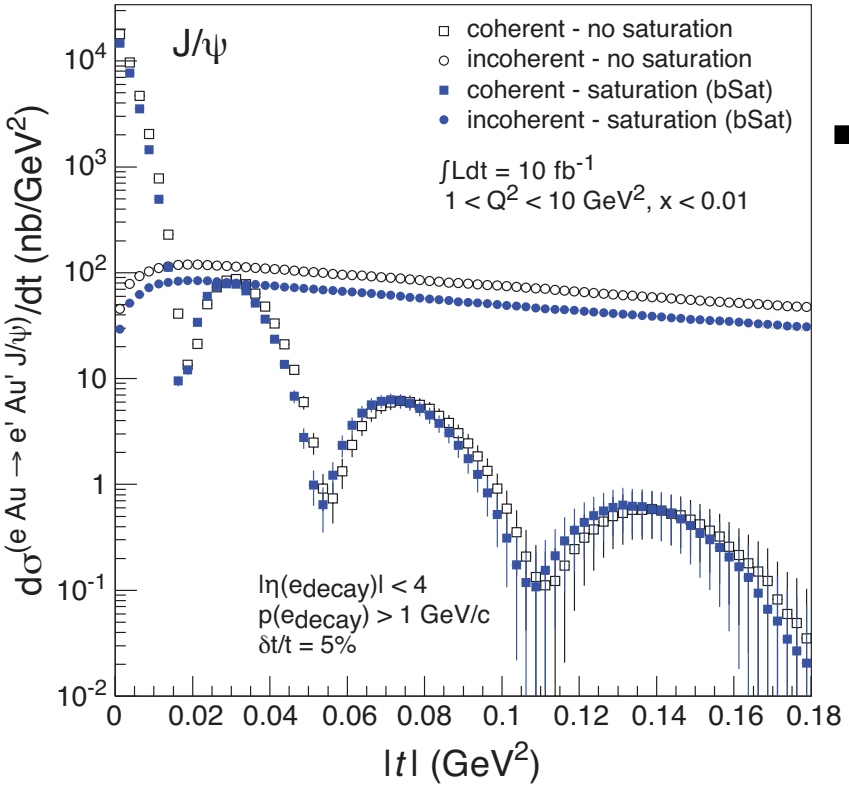

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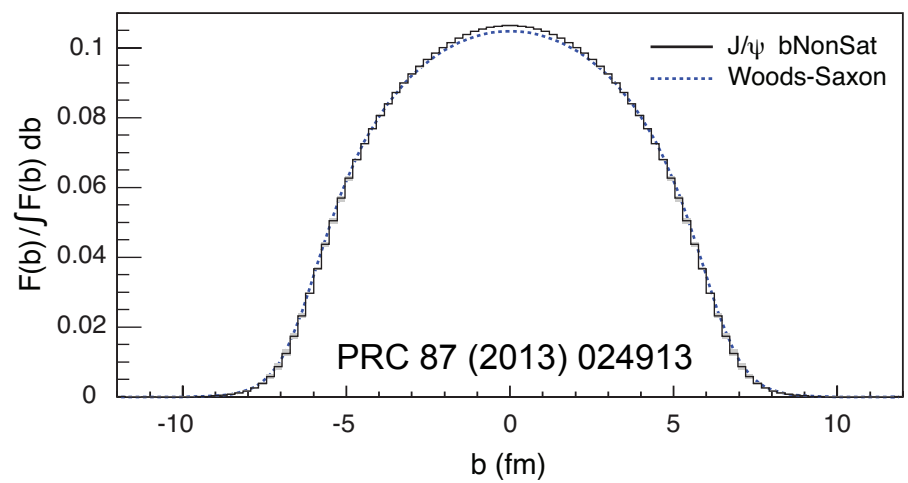

EIC will able to retrieve input distribution with high precision (here Woods-Saxon to test sensitivity)

Take Away Message

The EIC will profoundly impact our understanding of QCD with its high energy, high luminosity eA and polarized ep collisions

- **ep:** precision studies of PDFs, TMDs, and GPDs will lead to the most comprehensive picture of the nucleon ever: its flavor, spin, and spatial structure

- **eA:** unprecedented 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), understand how fast partons interact as they traverse nuclear matter, new insight into fragmentation processes, clarification of the nature of pomerons.

This physics is tied to a future high-energy electron-ion collider
It cannot be done without.