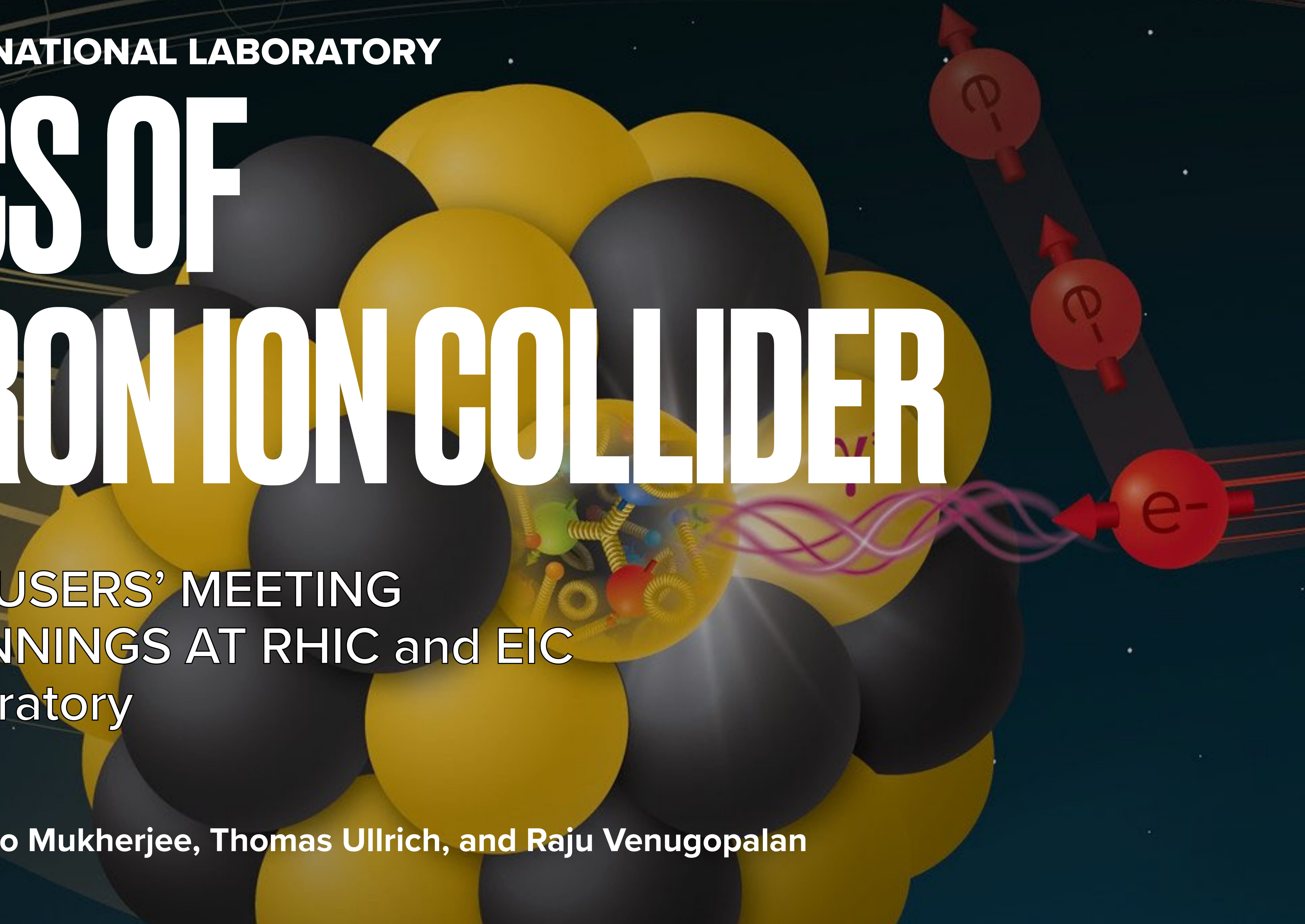
Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

BJÖRN SCHENKE - BROOKHAVEN NATIONAL LABORATORY

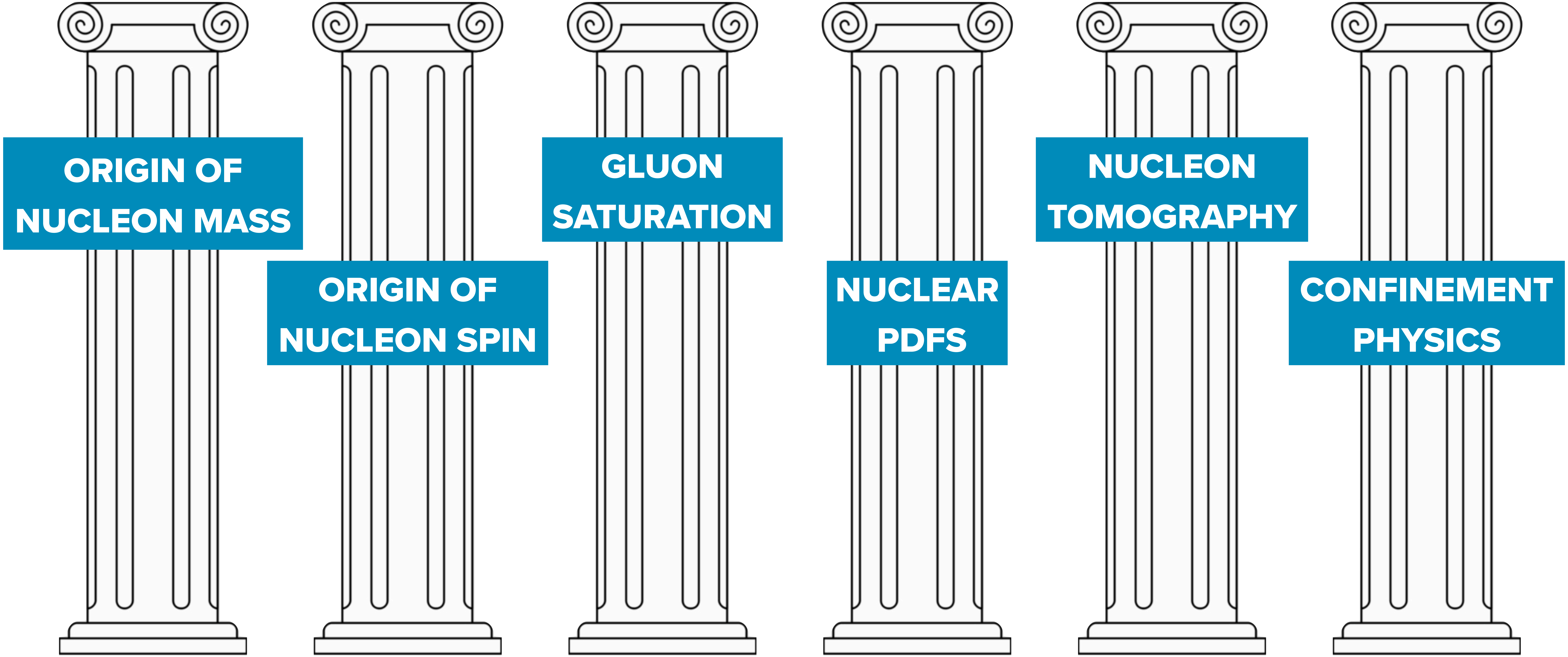
# THE PHYSICS OF THE ELECTRON ION COLLIDER



2023 RHIC/AGS ANNUAL USERS’ MEETING
CELEBRATING NEW BEGINNINGS AT RHIC and EIC
Brookhaven National Laboratory
08/04/2023

Many thanks to Yoshitaka Hatta, Swagato Mukherjee, Thomas Ullrich, and Raju Venugopalan

# PILLARS OF EIC SCIENCE



ORIGIN OF NUCLEON MASS

ORIGIN OF NUCLEON SPIN

GLUON SATURATION

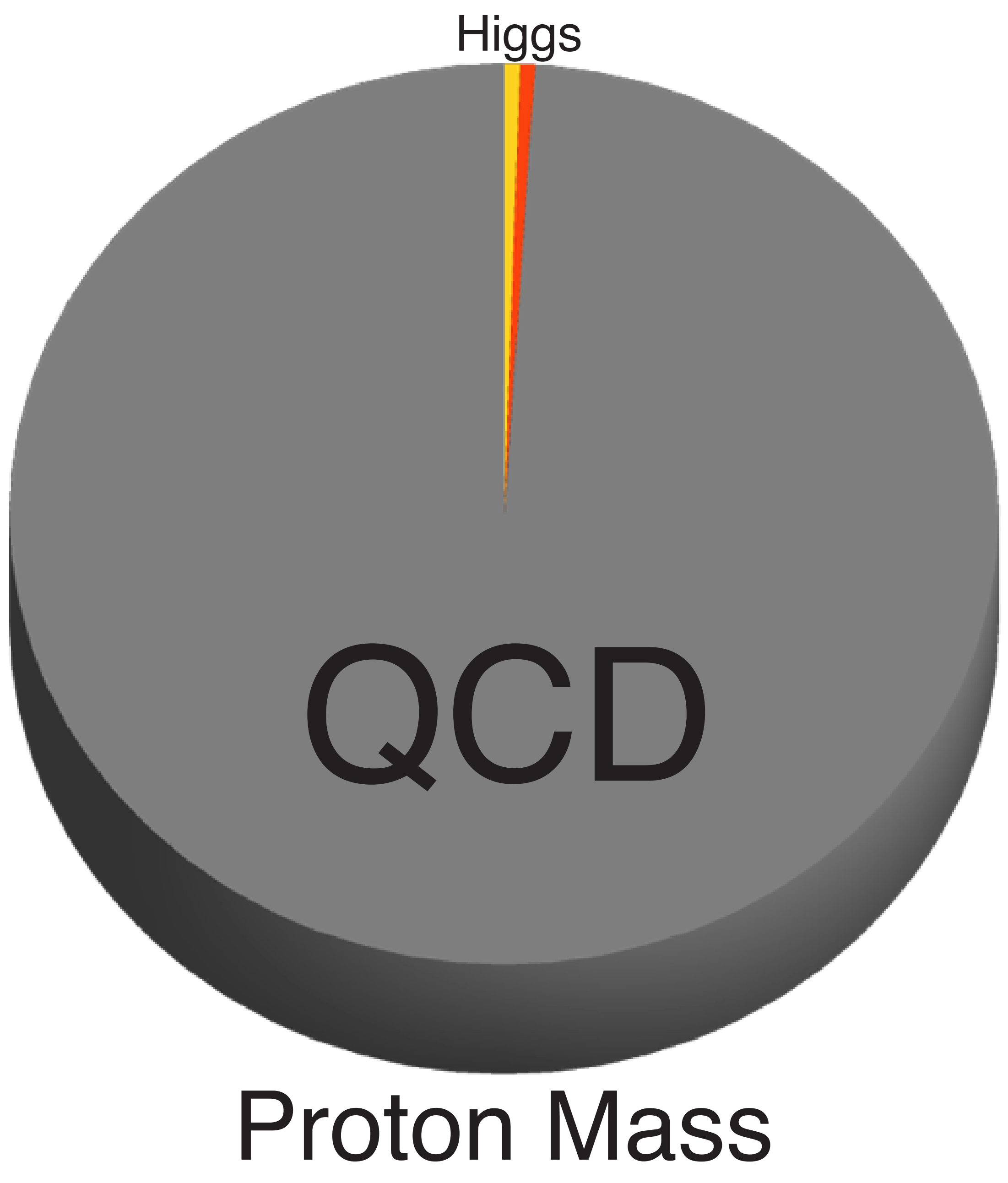
NUCLEAR PDFS

NUCLEON TOMOGRAPHY

CONFINEMENT PHYSICS

# PROTON MASS PUZZLE

The Higgs is responsible for quark masses that make up ~ 2% of the nucleon mass

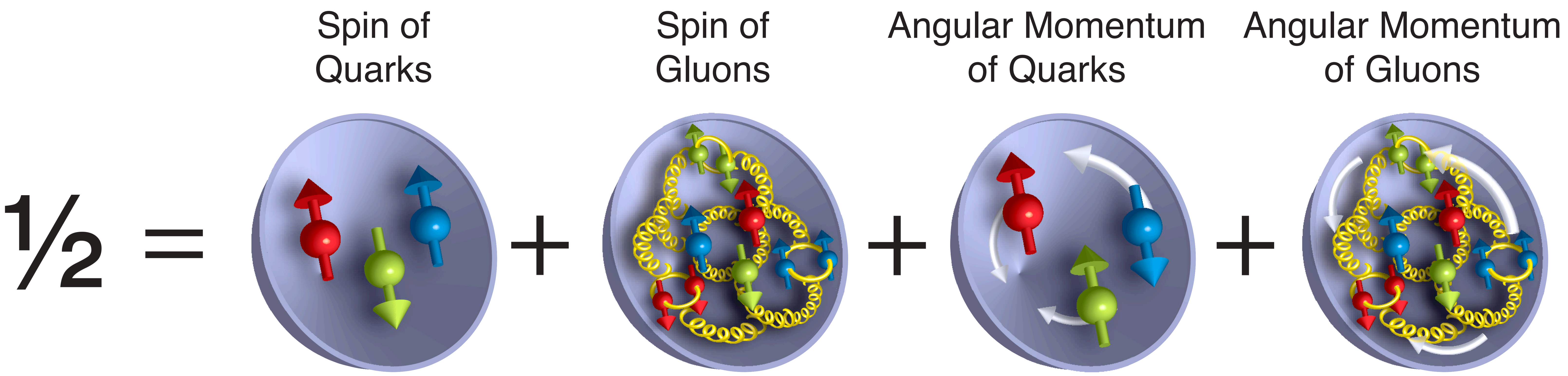


How do the interactions of massless gluons and almost massless quarks generate the proton mass?

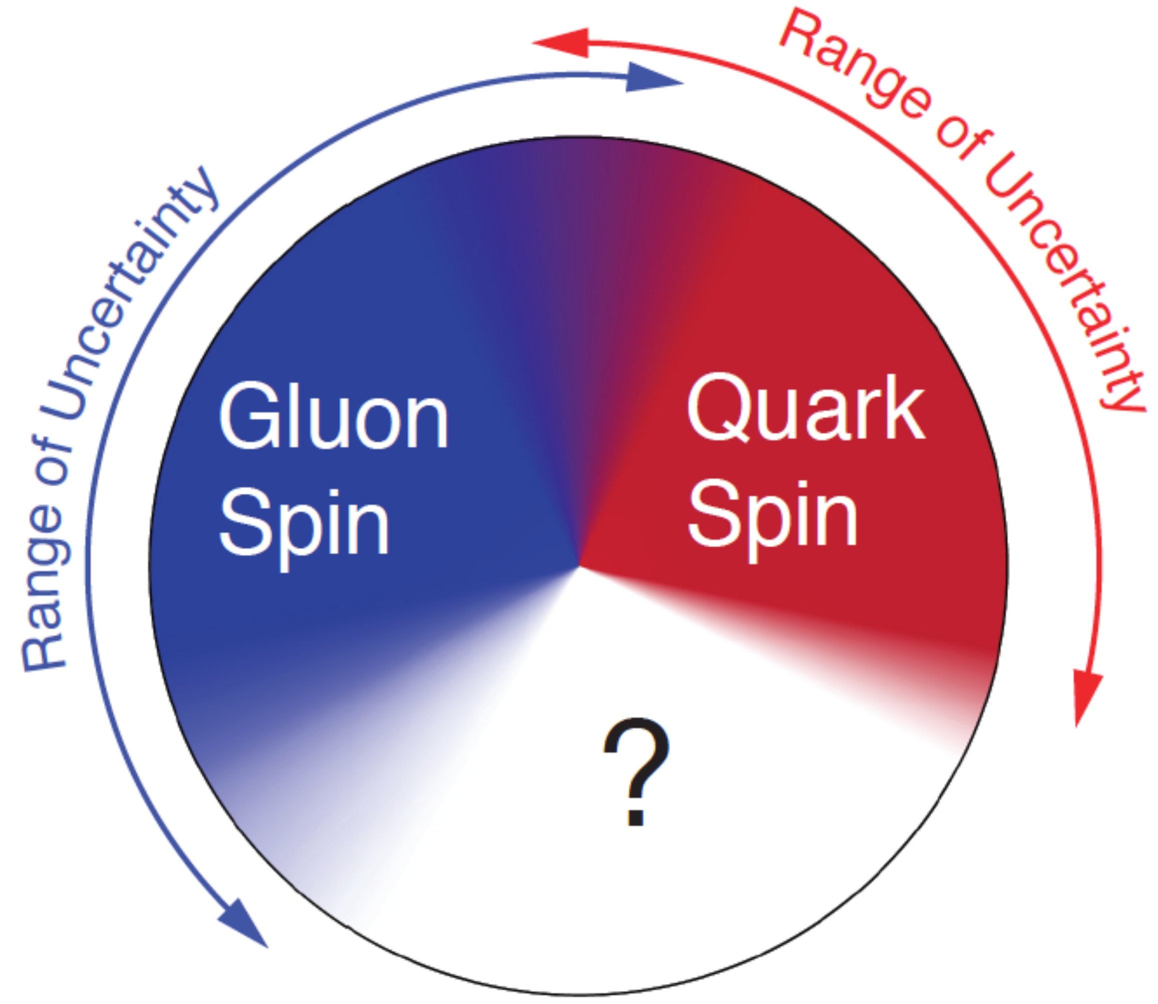
What does the energy momentum tensor of a proton look like?

# PROTON SPIN PUZZLE

How can we understand the spin of the proton within QCD?



½ = Spin of Quarks + Spin of Gluons + Angular Momentum of Quarks + Angular Momentum of Gluons

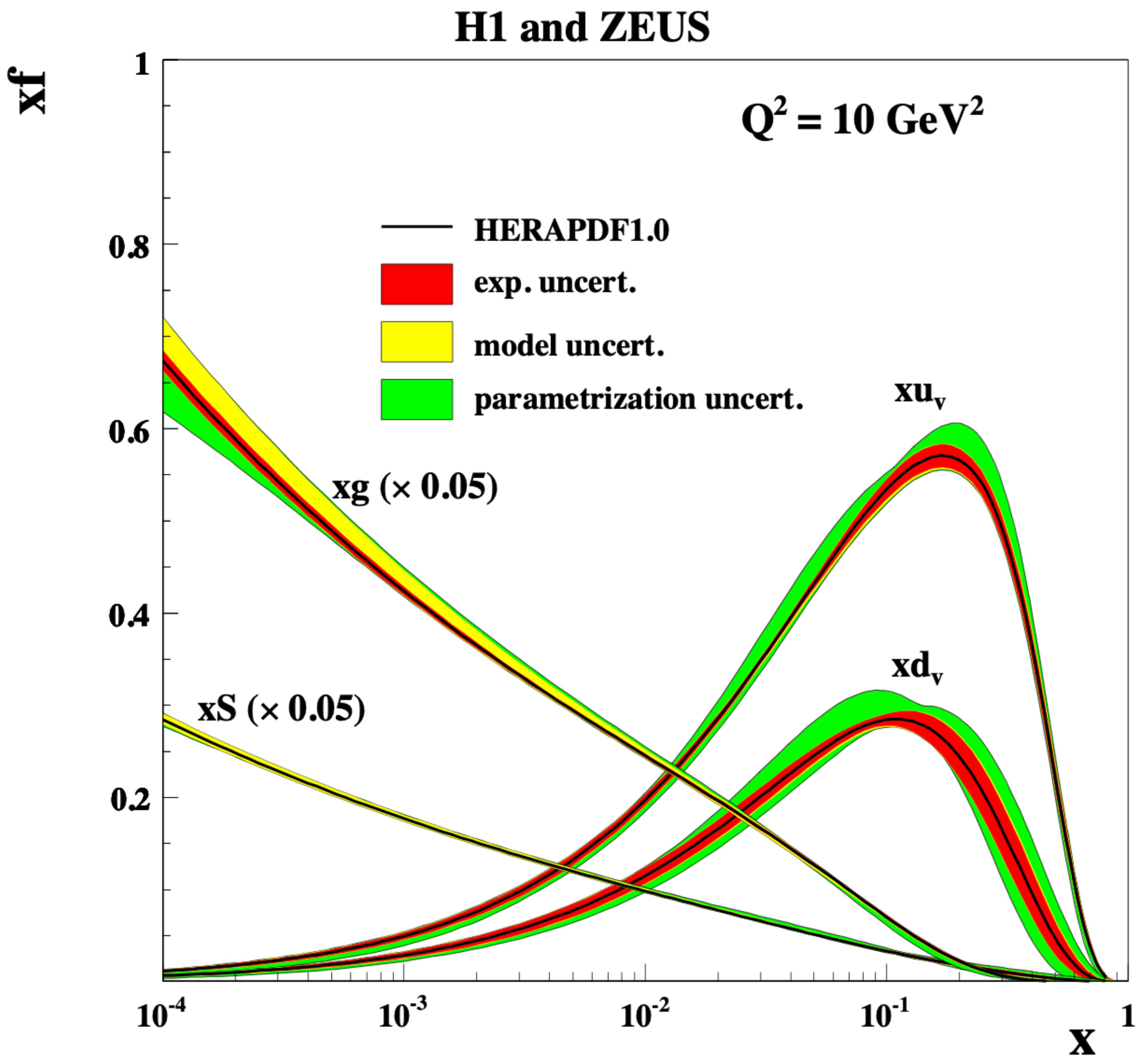


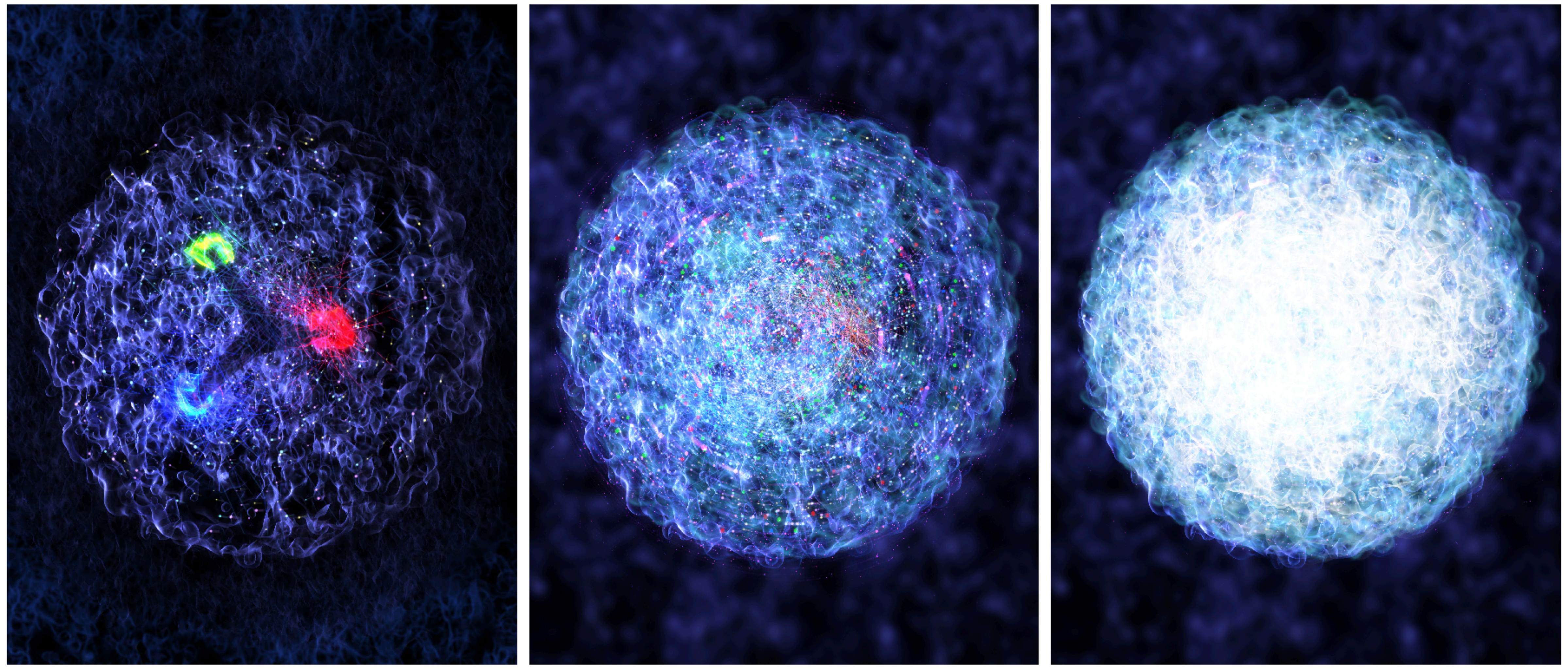
What we know:

- Quarks (valence and sea): ~30% of spin in limited x-range
- Gluons (latest RHIC data): ~40% of spin in limited x-range
- Where is the rest?

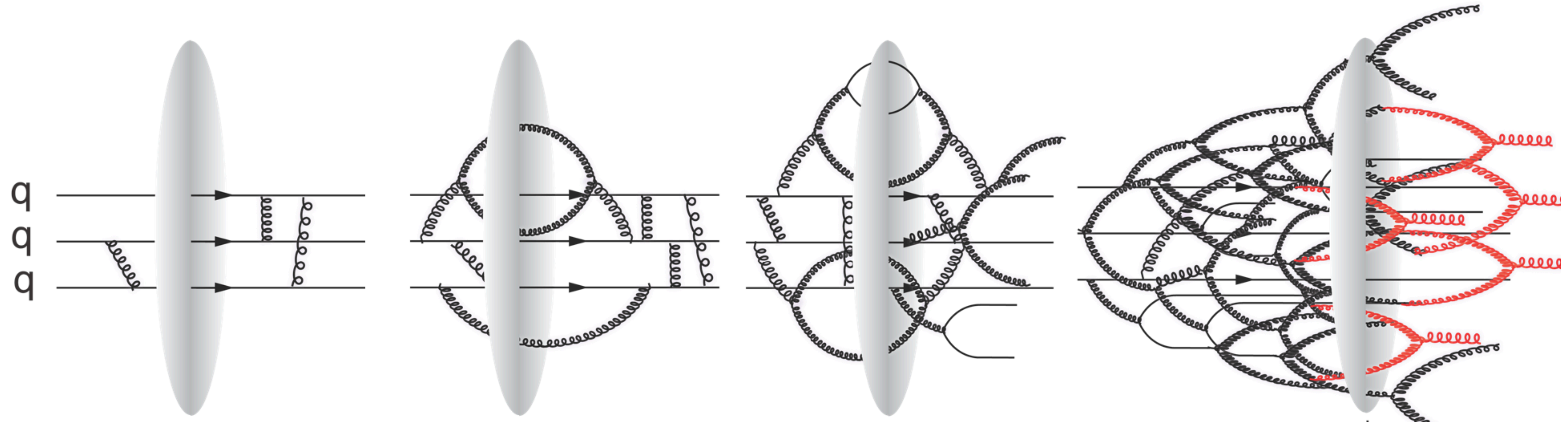
# GLUON SATURATION

Number of gluons grows with decreasing $x$





Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.



BUT: Recombination will balance gluon splittings

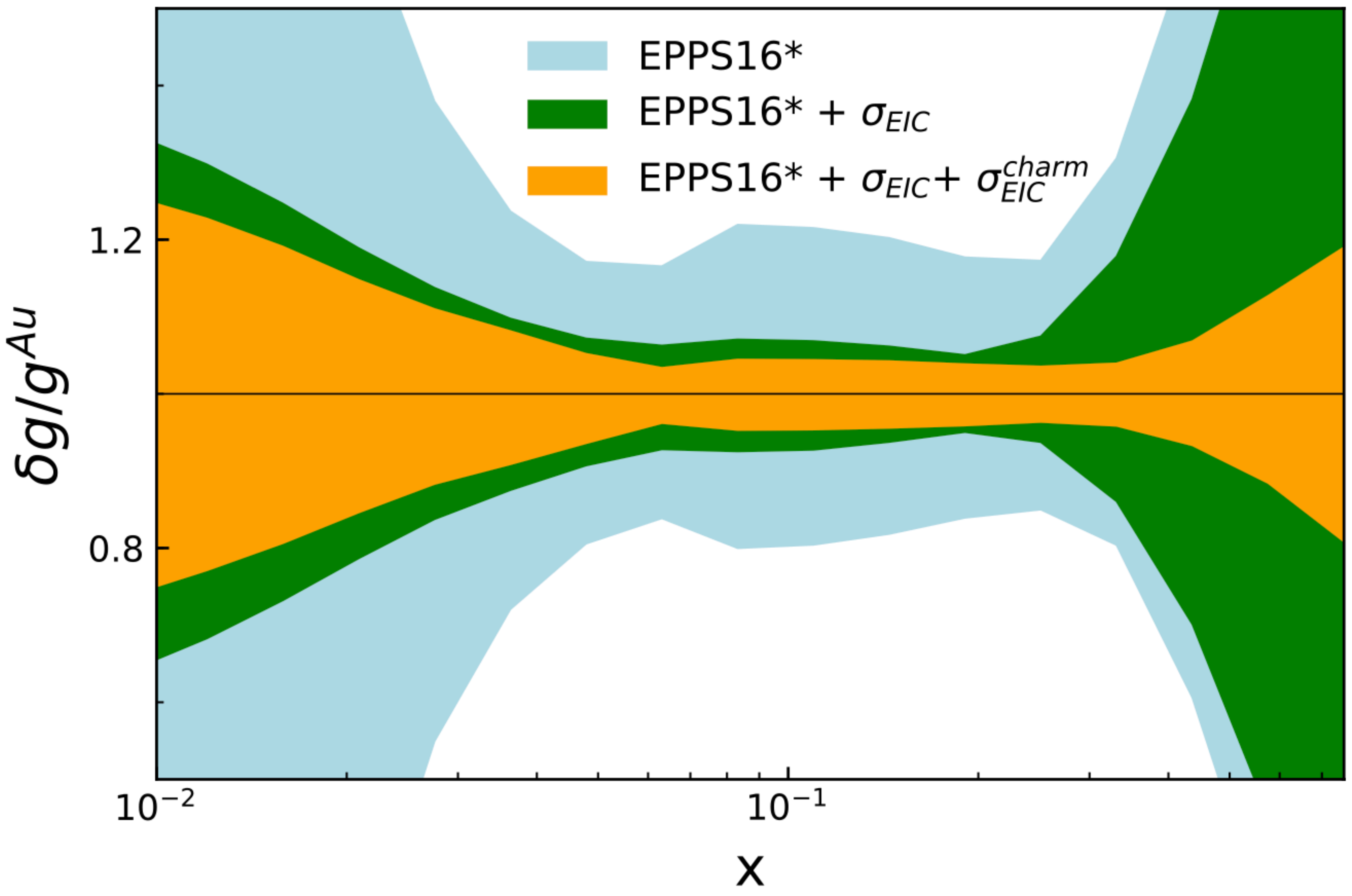
Non-linear evolution at low $x$ and low to moderate $Q^2$

Saturation of gluon density characterized by scale $Q_s(x)$

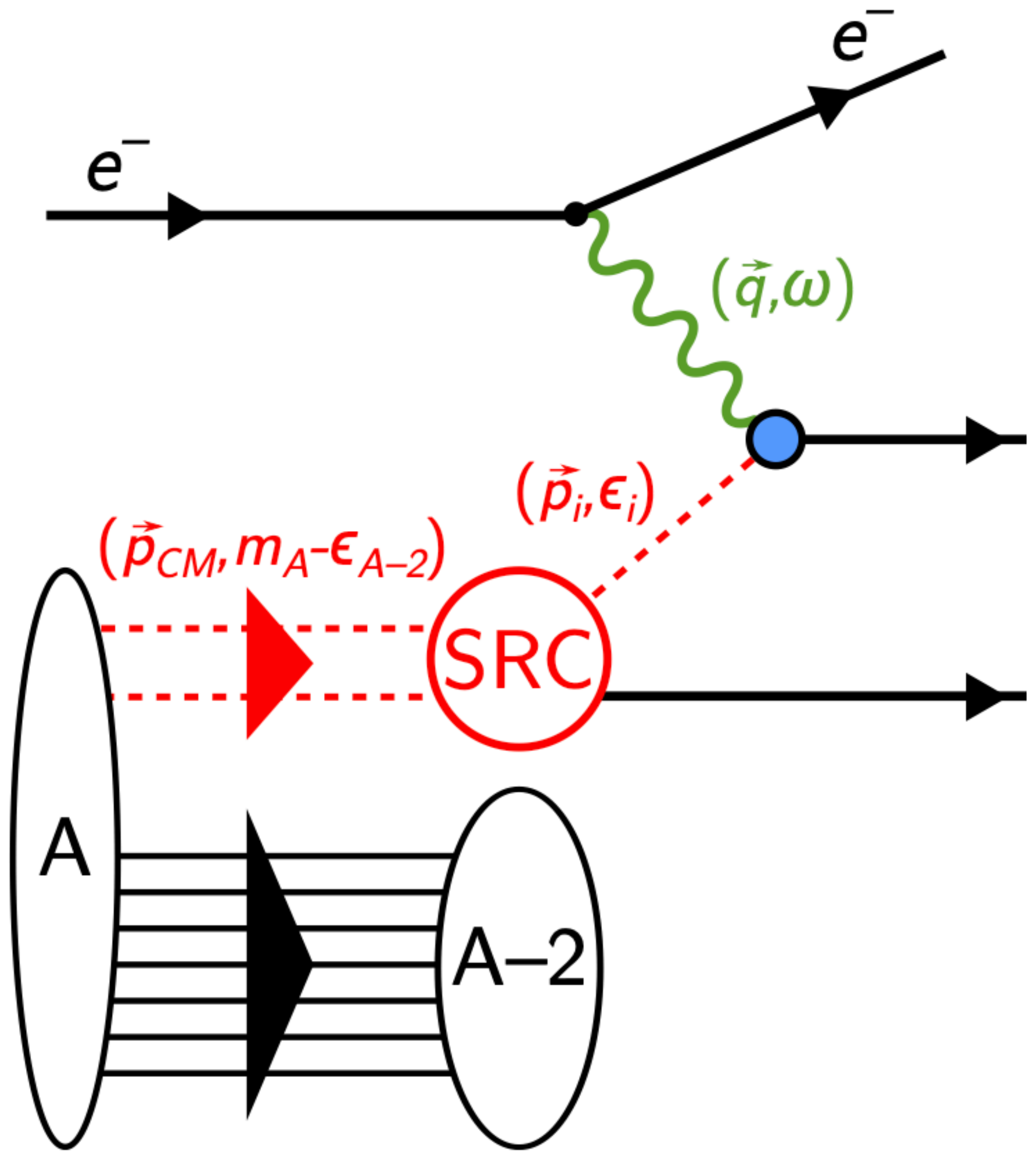
Can we find evidence for gluon saturation in the data?

# NUCLEAR PDFS

Relative uncertainty bands for the gluon distributions in gold nuclei at $Q^2 = 1.69\,\mathrm{GeV}^2$

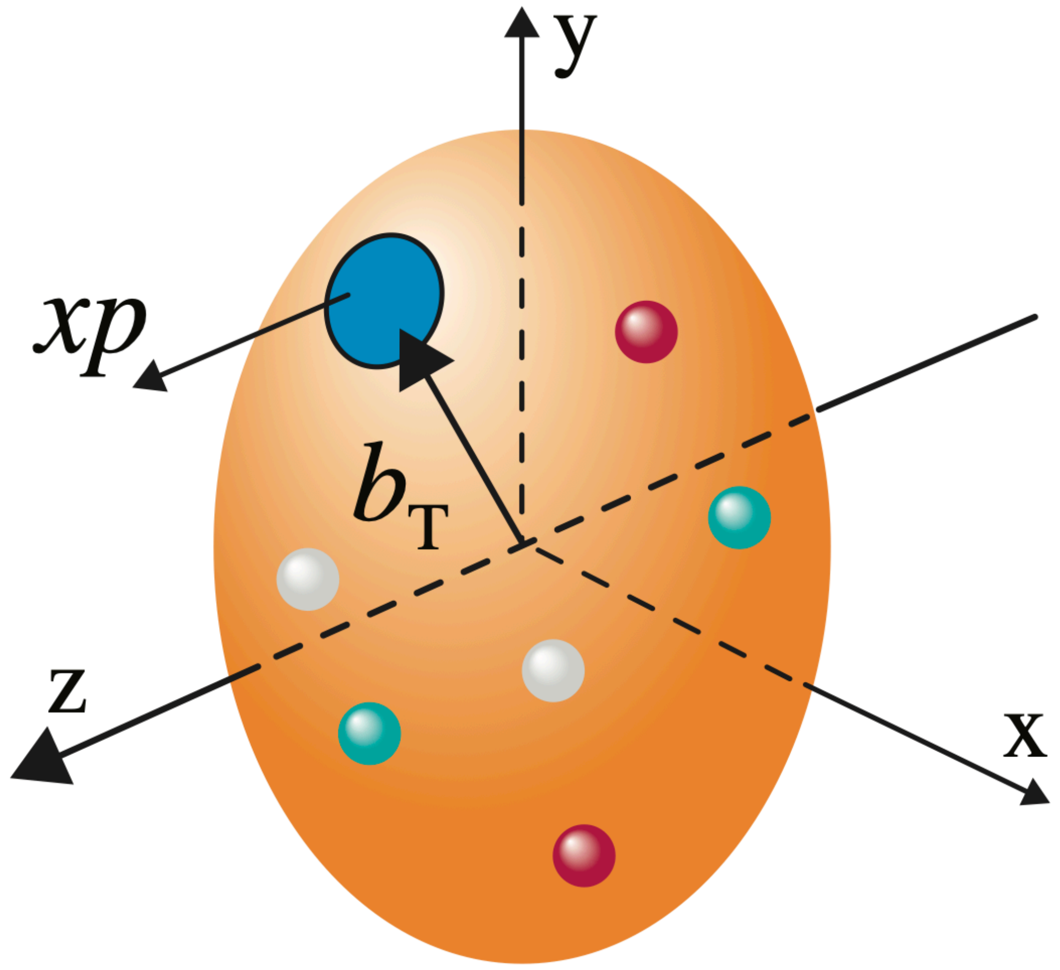


EIC will also help understand Short Range Correlations in nuclei: Scatter electron from one nucleon in a correlated pair and detect its spectator correlated partner



# 3D IMAGING

$W(x, b_T, k_T)$



Mother of all functions describing the structure of the proton:

5D Wigner Function: $W(x, b_T, k_T)$

*longitudinal momentum fraction* ↗ ↑ ↖ *transverse momentum*

*transverse position*

The Wigner distribution was considered not measurable

Recent efforts indicate opportunities via diffractive dijet measurements

**Y. Hatta, B.-W. Xiao, F. Yuan, Phys. Rev. Lett. 116, 202301 (2016)** for gluon Wigner function at small $x$

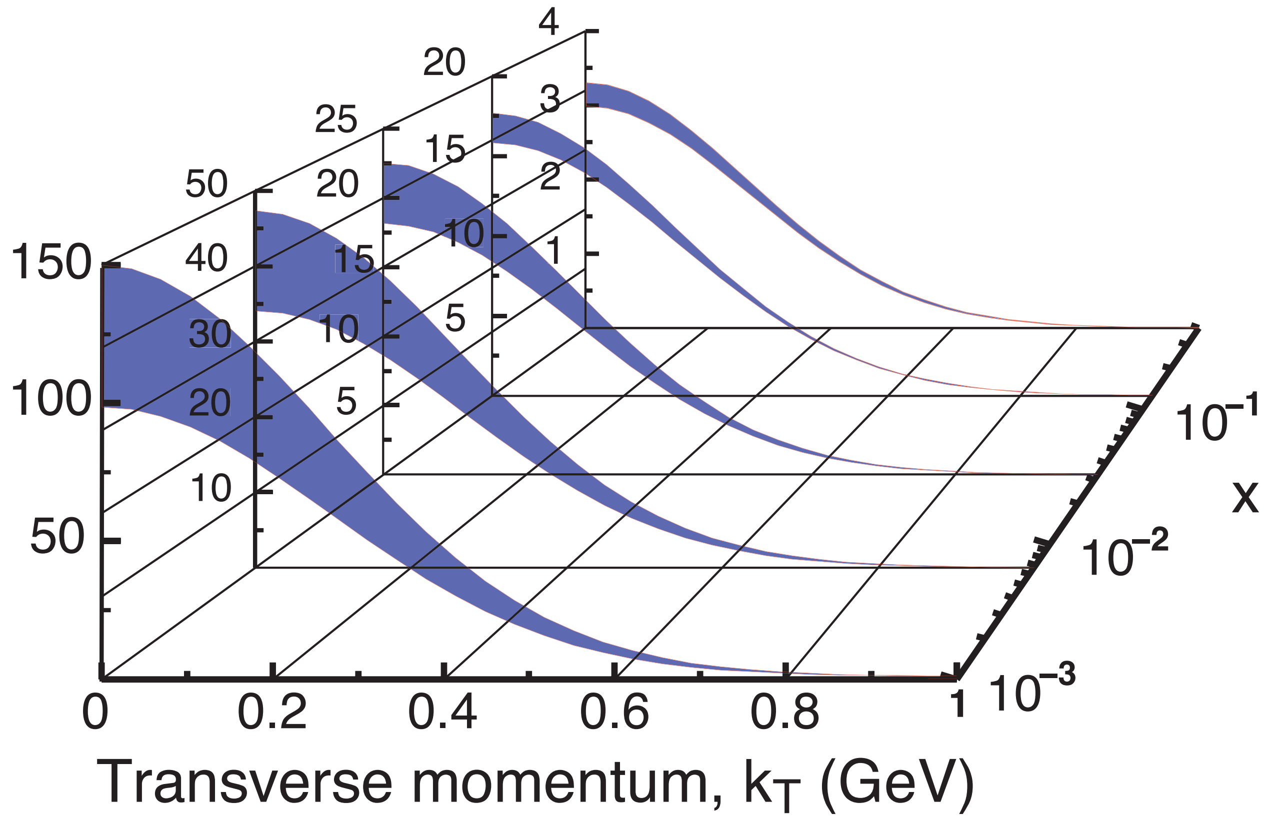
# 3D IMAGING

$W(x, b_T, k_T)$

$\int d^2 b_T$

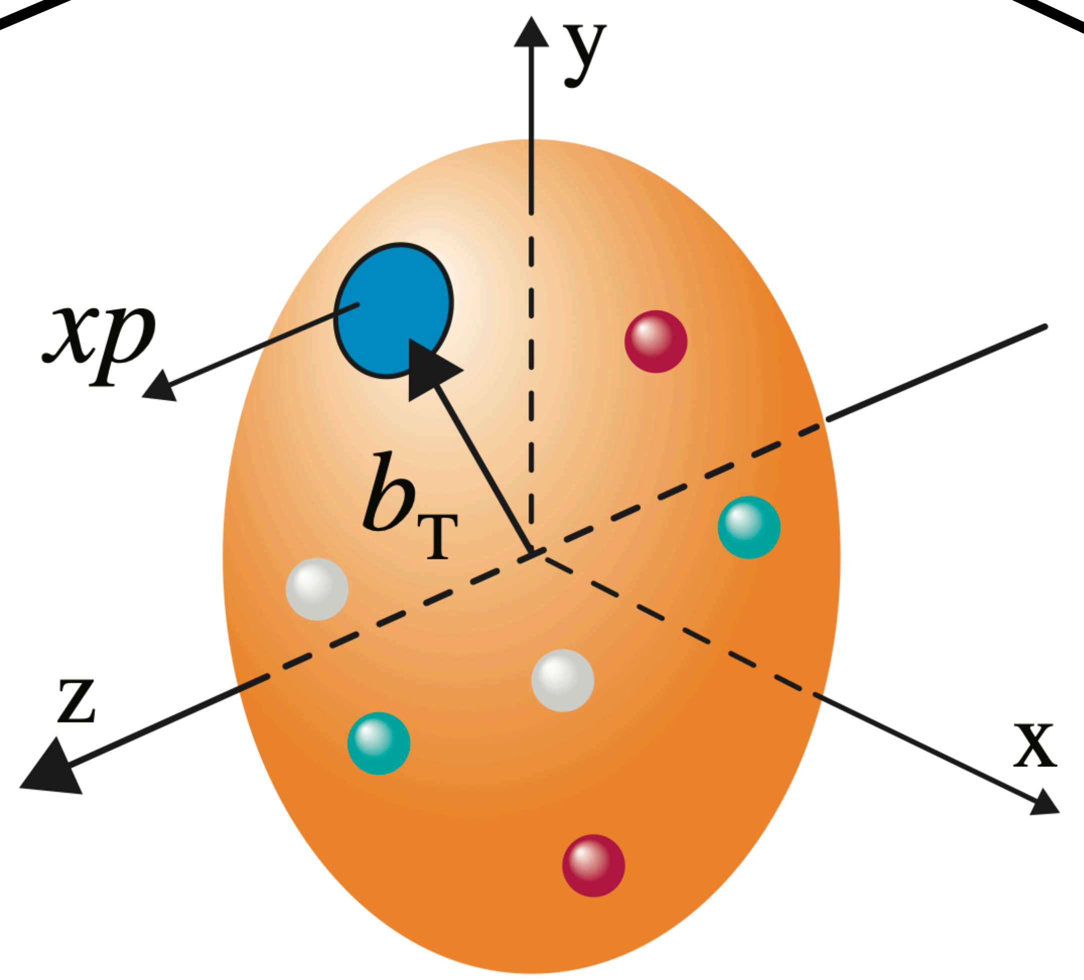
*Momentum space*

$f(x, k_T)$



Spin-dependent
transverse momentum dependent PDF

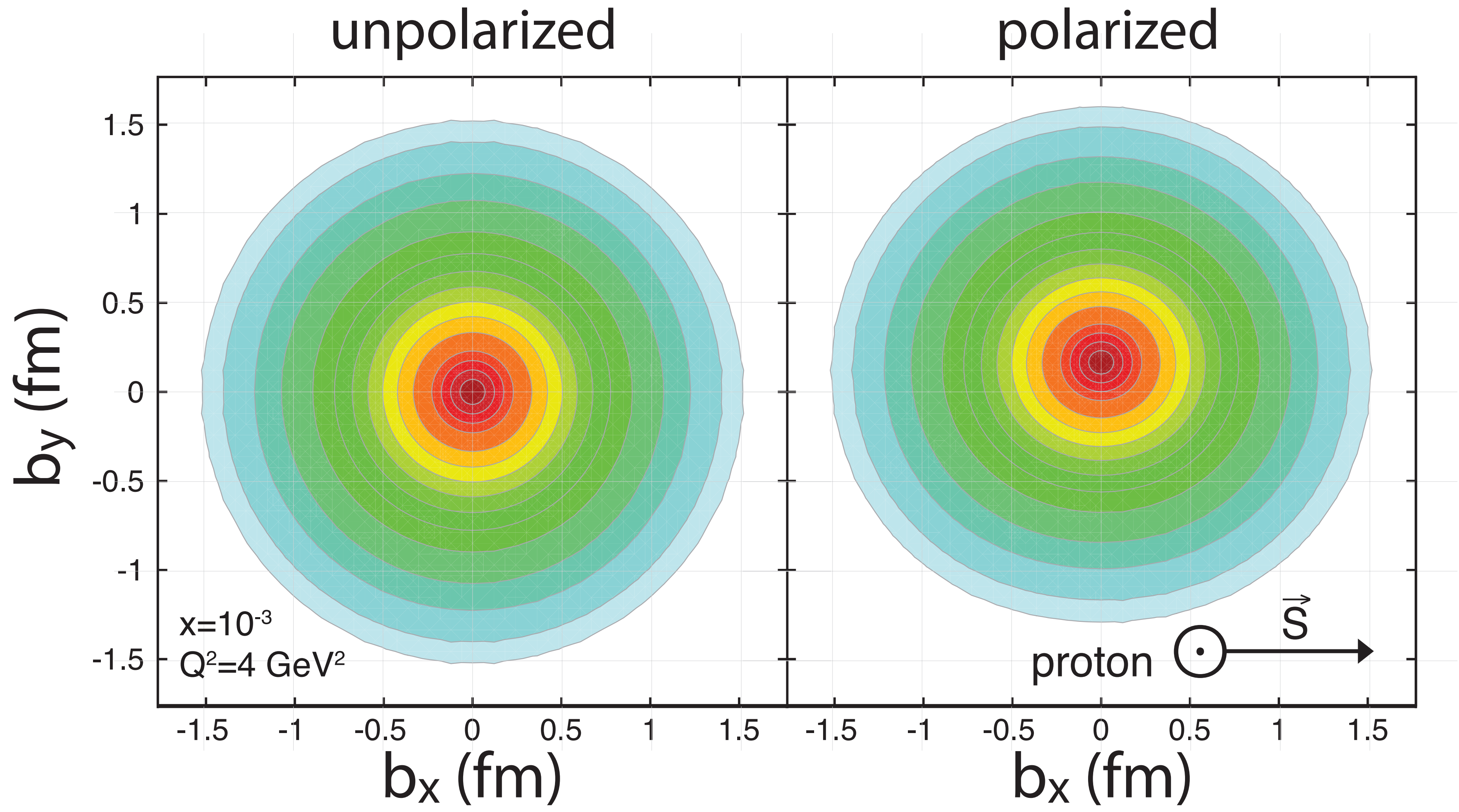
*Transverse Momentum Distributions (TMDs)*



$\int d^2 k_T$

*Coordinate space*

$f(x, b_T)$



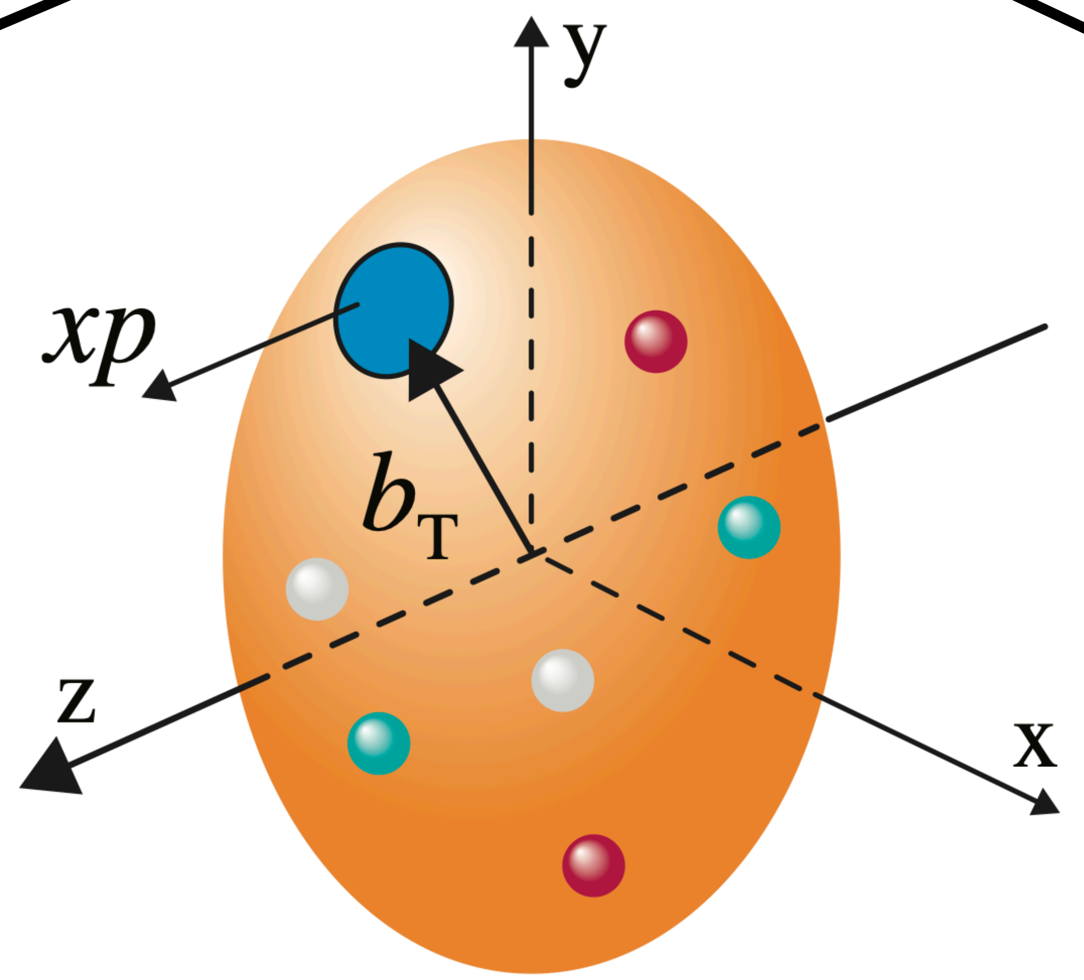
Spin and impact parameter dependent PDF

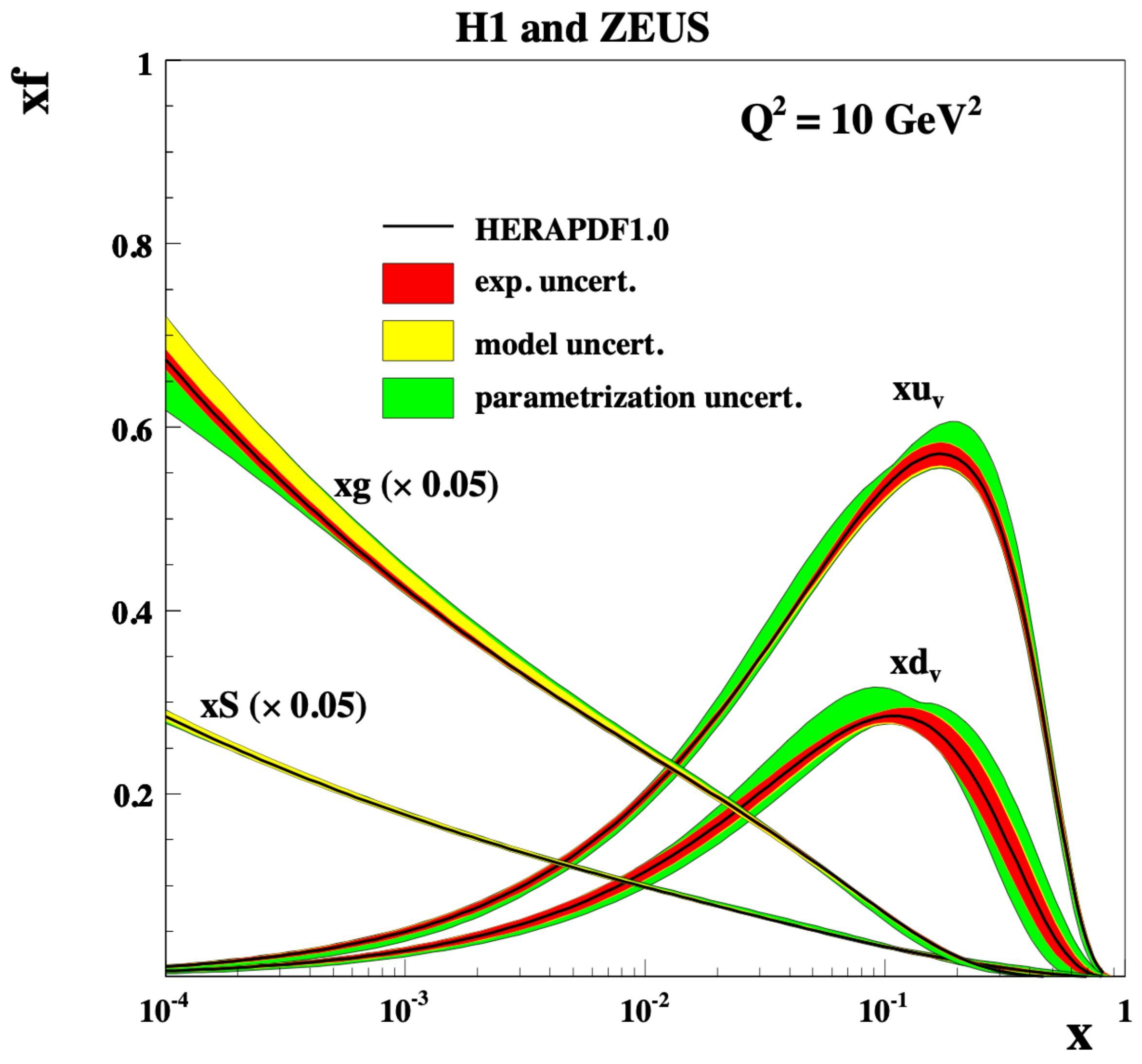
# 3D IMAGING

*Momentum space*

*Coordinate space*

$$\begin{tikzcd}
 & W(x, b_T, k_T) \arrow[dl, "\int d^2 b_T"'] \arrow[dr, "\int d^2 k_T"] & \\
f(x, k_T) \arrow[dr, "\int d^2 k_T"'] & & f(x, b_T) \arrow[dl, "\int d^2 b_T"] \\
 & f(x) &
\end{tikzcd}$$



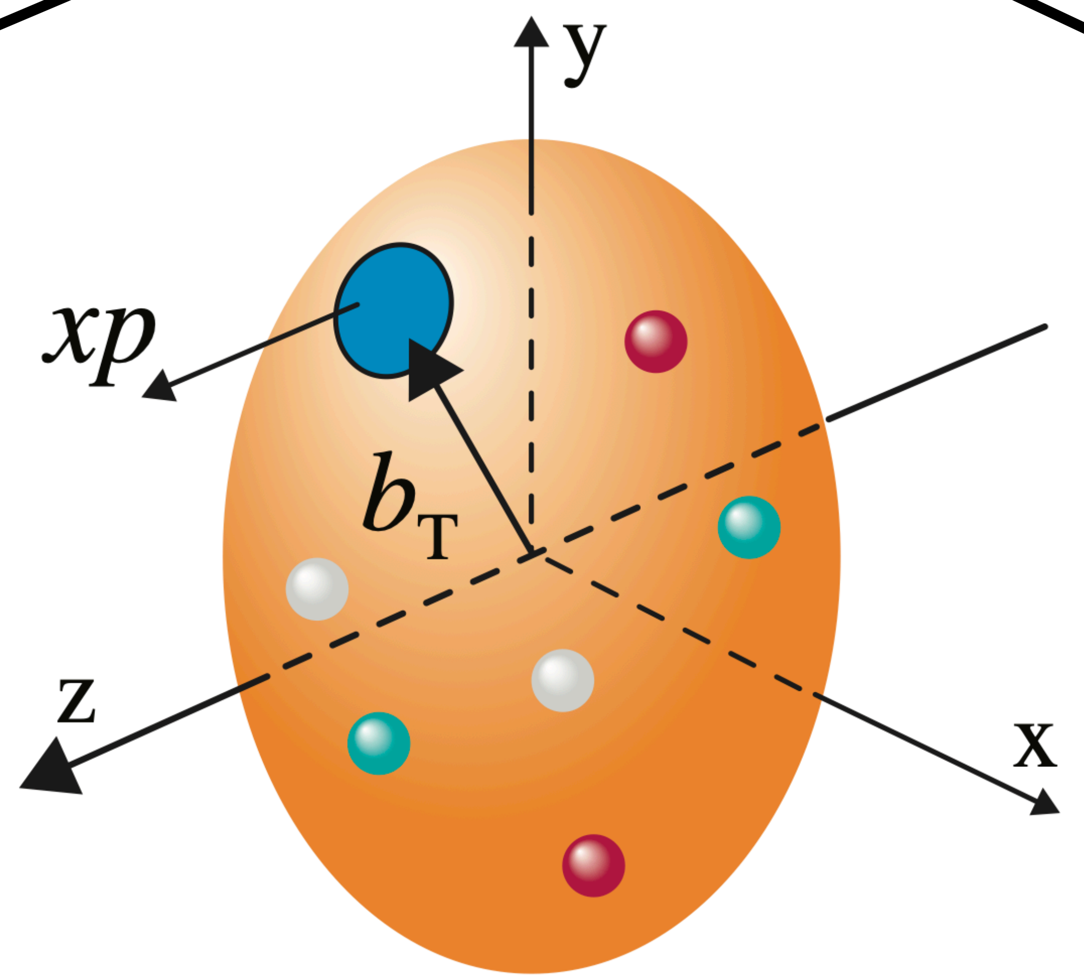


*Parton densities*

# 3D IMAGING

*Momentum space*

*Coordinate space*



$$\begin{tikzcd}
& & W(x, b_T, k_T) \arrow[dll, "\int d^2b_T"'] \arrow[drr, "\int d^2k_T"] & & \\
f(x, k_T) \arrow[drr, "\int d^2k_T"'] & & & & f(x, b_T) \arrow[dll, "\int d^2b_T"] \arrow[d, "b_T \leftrightarrow t\ \text{Fourier}"] \\
& & f(x) & & H(x,0,t) \arrow[d, "\int dx"'] \\
& & & & F(t)
\end{tikzcd}$$

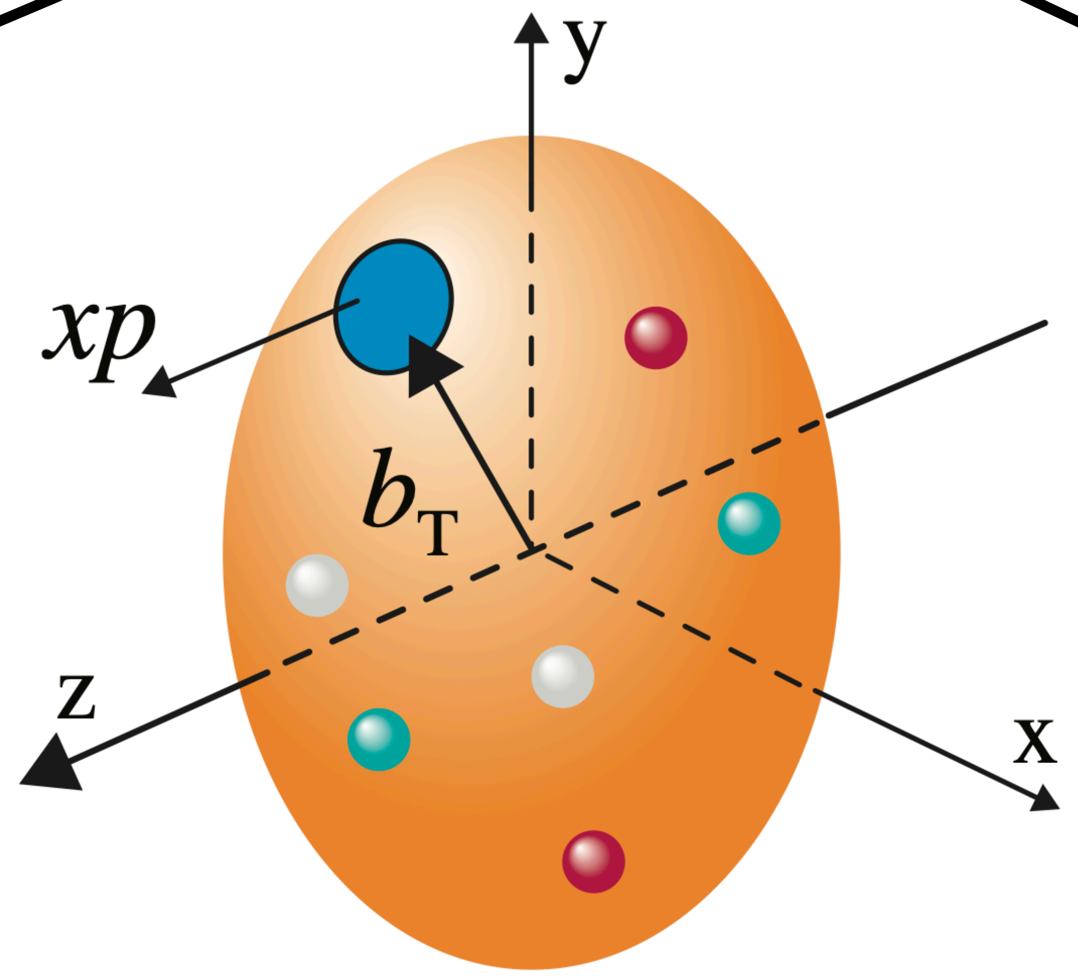
*Form factor*

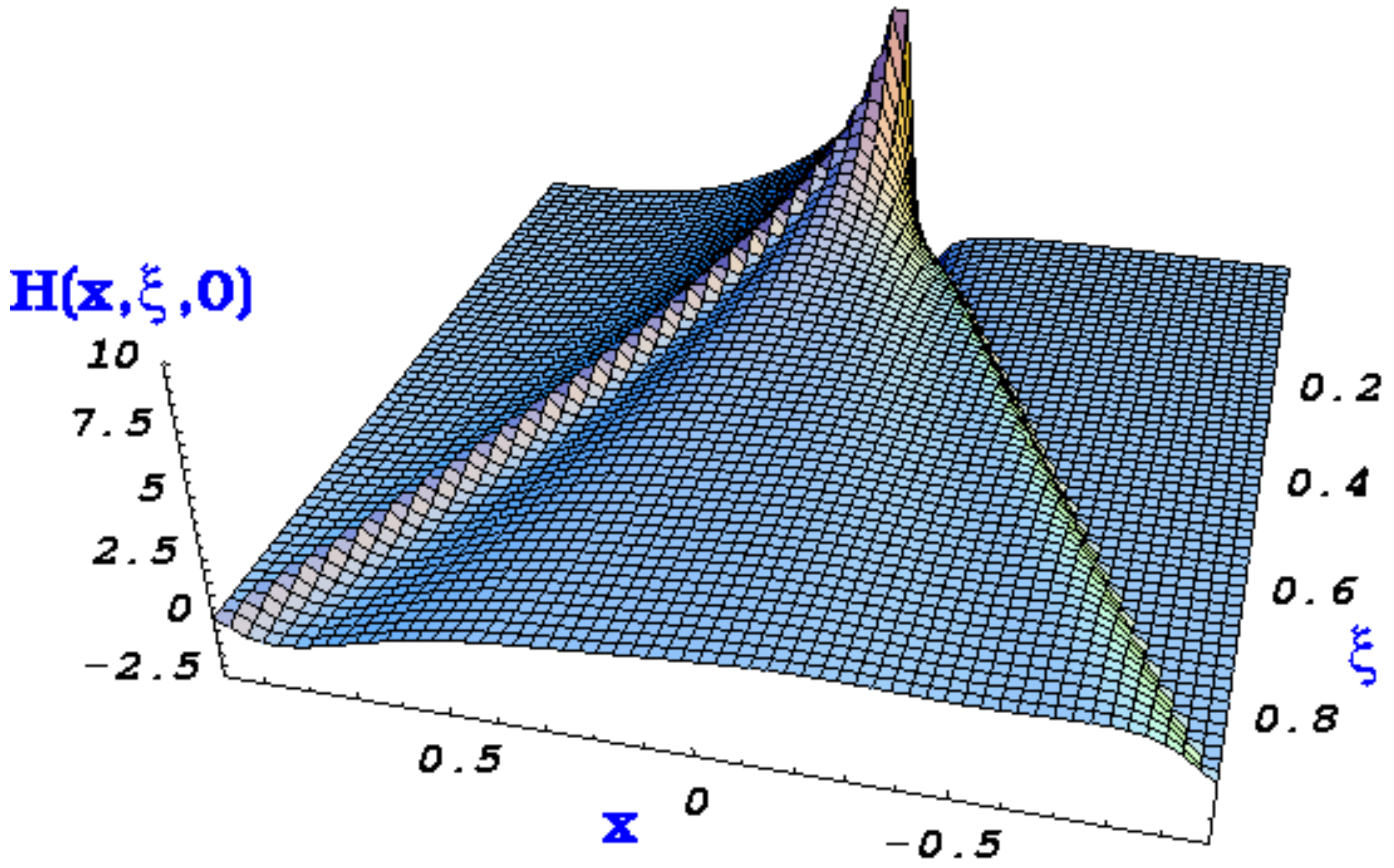
# 3D IMAGING

*Momentum space*

*Coordinate space*

$$\begin{tikzcd}
 & W(x, b_T, k_T) \arrow[dl, "\int d^2b_T"'] \arrow[dr, "\int d^2k_T"] & \\
f(x, k_T) \arrow[dr, "\int d^2k_T"'] & & f(x, b_T) \arrow[dl, "\int d^2b_T"] \arrow[d, "b_T \leftrightarrow t", "\text{Fourier}"'] \\
 & f(x) & H(x,0,t) \arrow[d, leftrightarrow, dotted] \\
 & & H(x, \xi, t)
\end{tikzcd}$$





*Generalized Parton Distribution (GPD)*

# PROTON MASS AND ENERGY MOMENTUM TENSOR

X.-D. Ji, Phys.Rev.D 55 (1997) 7114-7125 , also see e.g. M. V. Polyakov, P. Schweitzer, 1805.06596

current quark mass

kinetic energy of quarks and gluons

QCD trace anomaly

Proton mass: $M = M_q + M_g + M_m + M_a$ (not unique)

These $M_i$ can be computed using forward matrix elements of $T_i^{00}$ (e.g. lattice results from ETMC and $\chi$QCD)

Experimentally, only off-forward matrix elements $\langle P' | T^{\mu\nu} | P \rangle$ can be measured:

$$\langle P' | T^{\mu\nu} | P \rangle = \bar{u}(P') \left[ A(t)\gamma^{(\mu}\bar{P}^{\nu)} + B(t)\frac{\bar{P}^{(\mu} i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} \right] u(P)$$

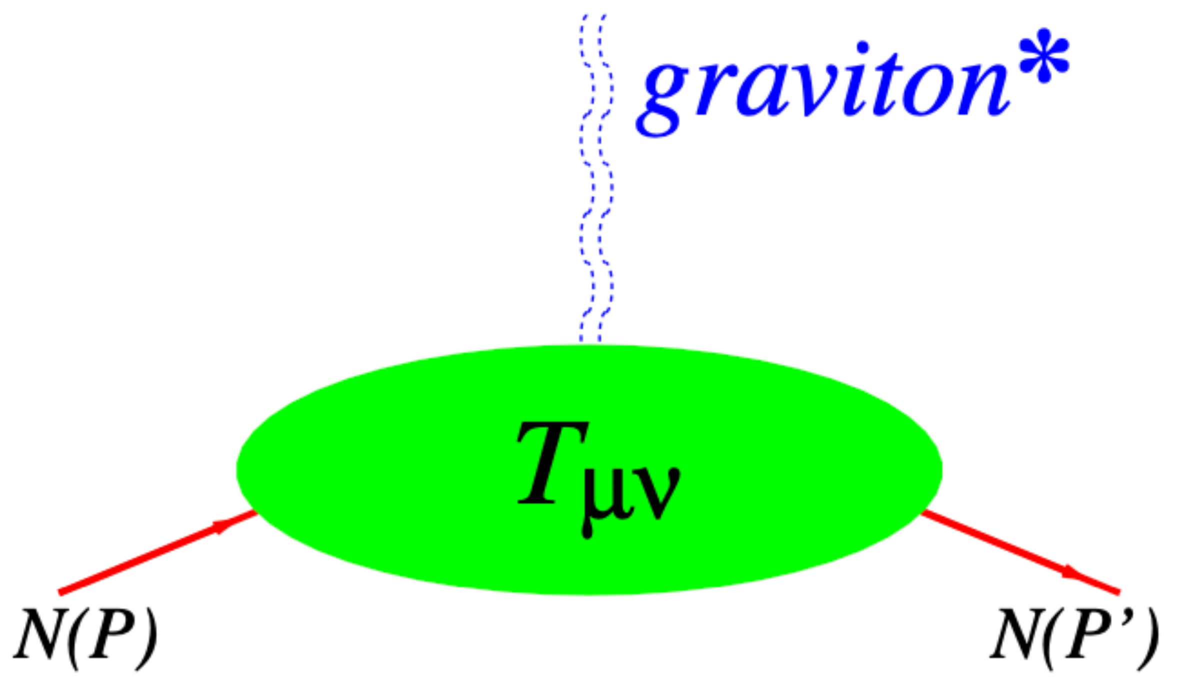
where $\bar{P}^\mu = (P^\mu + P'^\mu)/2$ and $\Delta^\mu = P'^\mu - P^\mu$

$A(0)$ and $B(0)$ are constrained by theoretical considerations

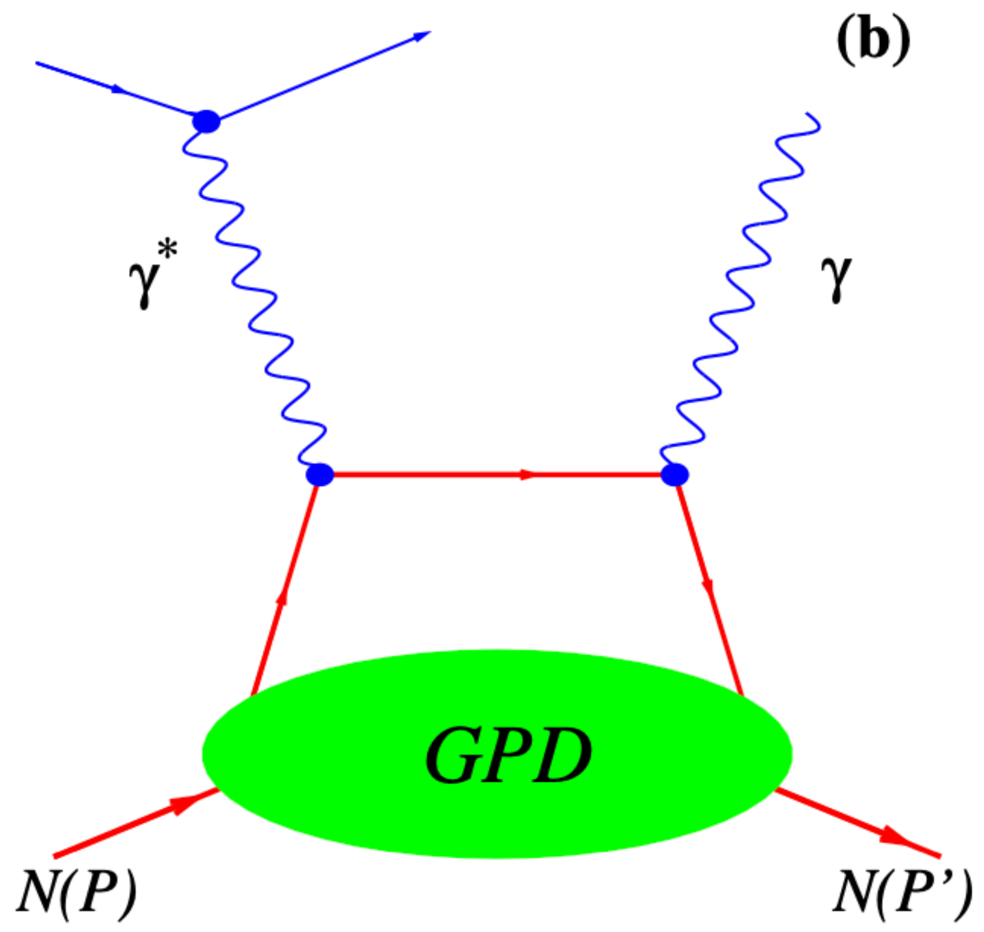
$D$-term $D = D(0)$ must be determined experimentally; related to stress tensor and internal forces

# MEASURING GRAVITATIONAL FORM FACTORS

Measure $T^{\mu\nu}$ form factors:



**(impractical)**



**DVCS**

$$D = D_q + D_g$$

Quark $D_q$ can be extracted from GPDs measured in Deeply Virtual Compton Scattering (DVCS)

**I. V. Anikin and O. V. Teryaev**
**Phys. Rev. D 76, 056007 (2007)**

graviton spin=2

$$\int_{-1}^{+1} dx\, x^{(2-1)}\, \underbrace{H(x,\xi,t)}_{\text{GPD}} = \underbrace{A(t) + \xi^2 D(t)}_{\text{GFFs}}$$

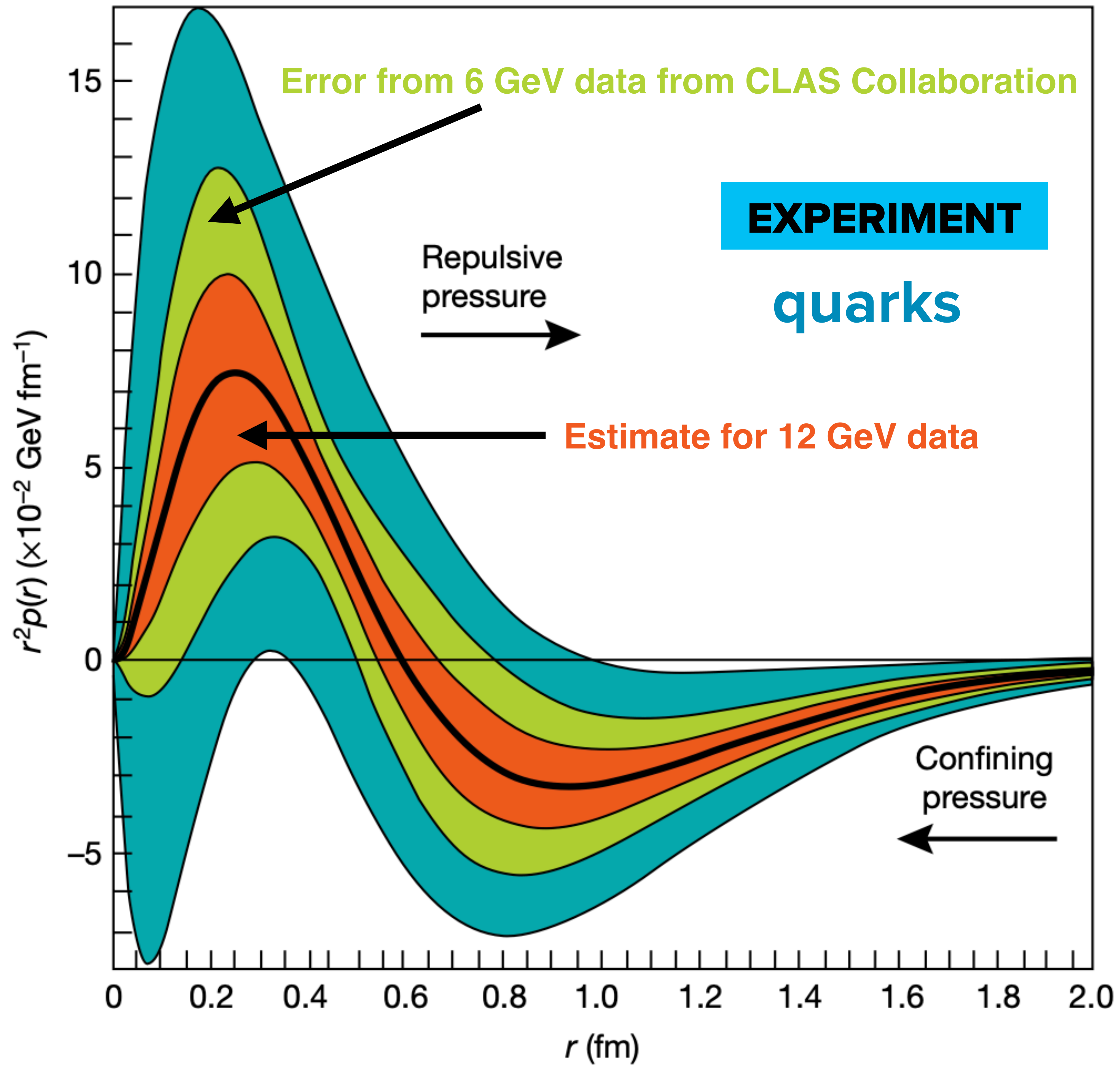
$$\int_{-1}^{+1} dx\, x\, \underbrace{E(x,\xi,t)}_{\substack{\text{GPD}\\ \text{(nucleon helicity flip)}}} = \underbrace{B(t) - \xi^2 D(t)}_{\text{GFFs}}$$

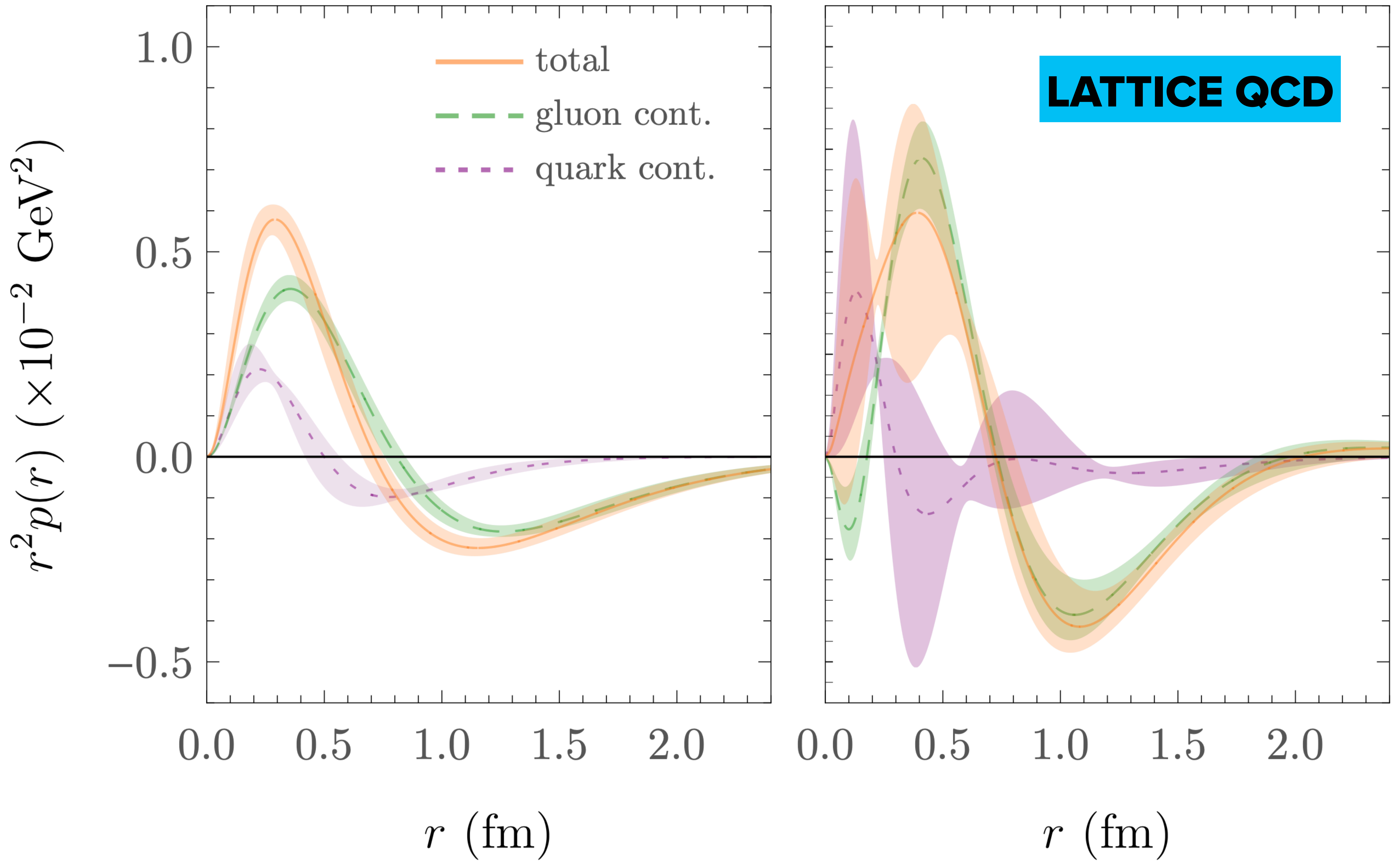
Threshold vector meson production also provides access to D-terms, especially $D_g$ and $D_s$

Connection to gluon GFF better for heavier vector mesons and higher $Q^2$: EIC has advantage!

**D. Kharzeev, H. Satz, A. Syamtomov, G. Zinovjev, Eur.Phys.J.C9:459-462 (1999); Y. Hatta, A. Rajan, D.-L. Yang, Phys.Rev.D 100 (2019), 014032; K. A. Mamo, I. Zahed, Phys.Rev.D 101 (2020), 086003; Y. Guo, X.-D. Ji, Y. Liu, Phys.Rev.D 103 (2021) 9, 096010; Y. Hatta, M. Strikman, Phys.Lett.B 817 (2021) 136295**

# PRESSURE DISTRIBUTION IN THE PROTON FROM D(t)





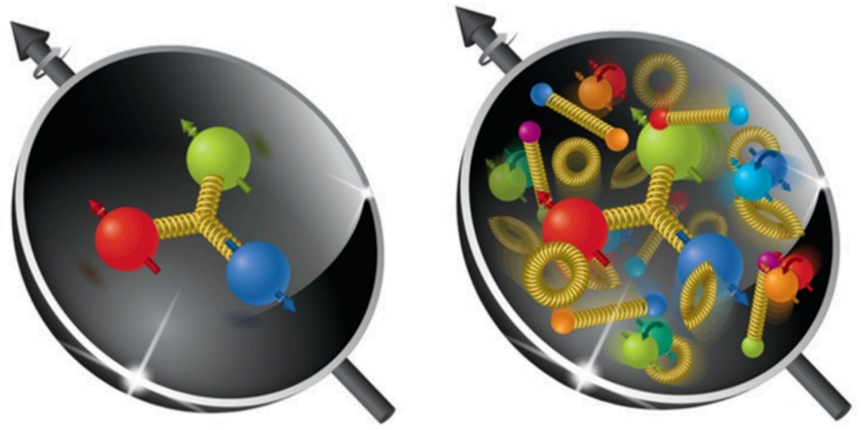
**Extraction from LQCD using two different methods**

P. E. Shanahan, W. Detmold, Phys. Rev. Lett. 122, 072003 (2019)

V. D. Burkert, L. Elouadrhiri, F. X. Girod, Nature 557, 396–399 (2018)

**Gluon GFFs:** B.Duran et al., Nature 615 (2023) 7954, 813-816

# PROTON SPIN



GPDs can also teach us about quark and gluon contributions to the proton spin:

$$J_{q,g} = \frac{1}{2}\int_0^1 dx\, x\,(H_{q,g}(x) + E_{q,g}(x))$$

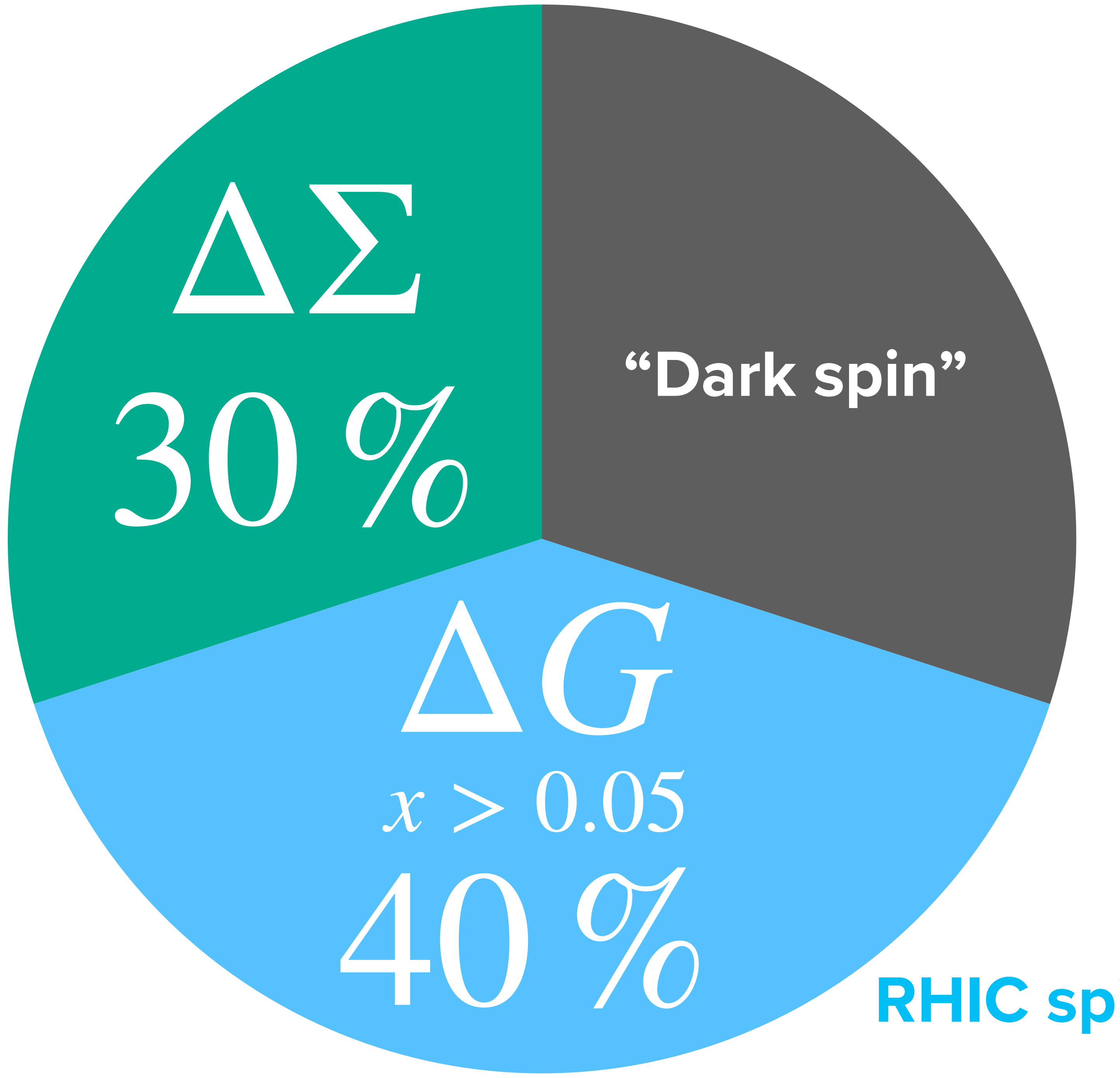
with $\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q^{\mathrm{kin}} + J_g$

X.-D. Ji, Phys.Rev.D 55 (1997) 7114-7125

Alternative spin sum rule:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

R. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)



RHIC spin program

Missing spin could come from $\Delta G$ at small $x$ and orbital angular momentum (OAM)

At small $x$ OAM has been computed:
It can have opposite sign to the helicities

Y. Hatta, D.-J. Yang, Phys.Lett.B 781 (2018) 213-219

OAM from Wigner function, from diffractive dijets

C. Lorce, B. Pasquini, Phys.Rev.D 84 (2011) 014015
Y. Hatta, Phys.Lett.B 708 (2012) 186-190
X.-D. Ji, F. Yuan, Y. Zhao, Phys.Rev.Lett. 118 (2017) 19, 192004

# PROTON SPIN

Get quark and gluon helicities by measuring the **proton's spin structure function** $g_1(x, Q^2)$ in the inclusive process $e + p \to e' + X$ with longitudinally polarized $e$ and $p$ beams

$$g_1(x,Q^2) \simeq \frac{1}{2}\sum e_q^2(\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2))$$

quark and anti-quark spin

$$\frac{dg_1(x,Q^2)}{d\log Q^2} \propto \Delta g(x,Q^2)$$

gluon spin

$$\frac{1}{2}\left[\frac{d^2\sigma^{\rightleftarrows}}{dxdQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dxdQ^2}\right] \simeq \frac{4\pi\alpha^2}{Q^4} y(2-y)\, g_1(x,Q^2)$$

The structure function $g_1(x, Q^2)$ presently is terra incognita for $x < 0.004$ and $Q^2 > 1\,\mathrm{GeV}^2$

Theory also needs better control at small $x$: **Helicity evolution equations**

Y. V. Kovchegov, D. Pitonyak, M. D. Sievert, JHEP 01 (2016) 072

Computations including the **chiral anomaly** of QCD indicate that $g_1$ is governed by QCD **topological sphaleron transitions** at small $x$ → strong quenching of $g_1$ with decreasing $x$

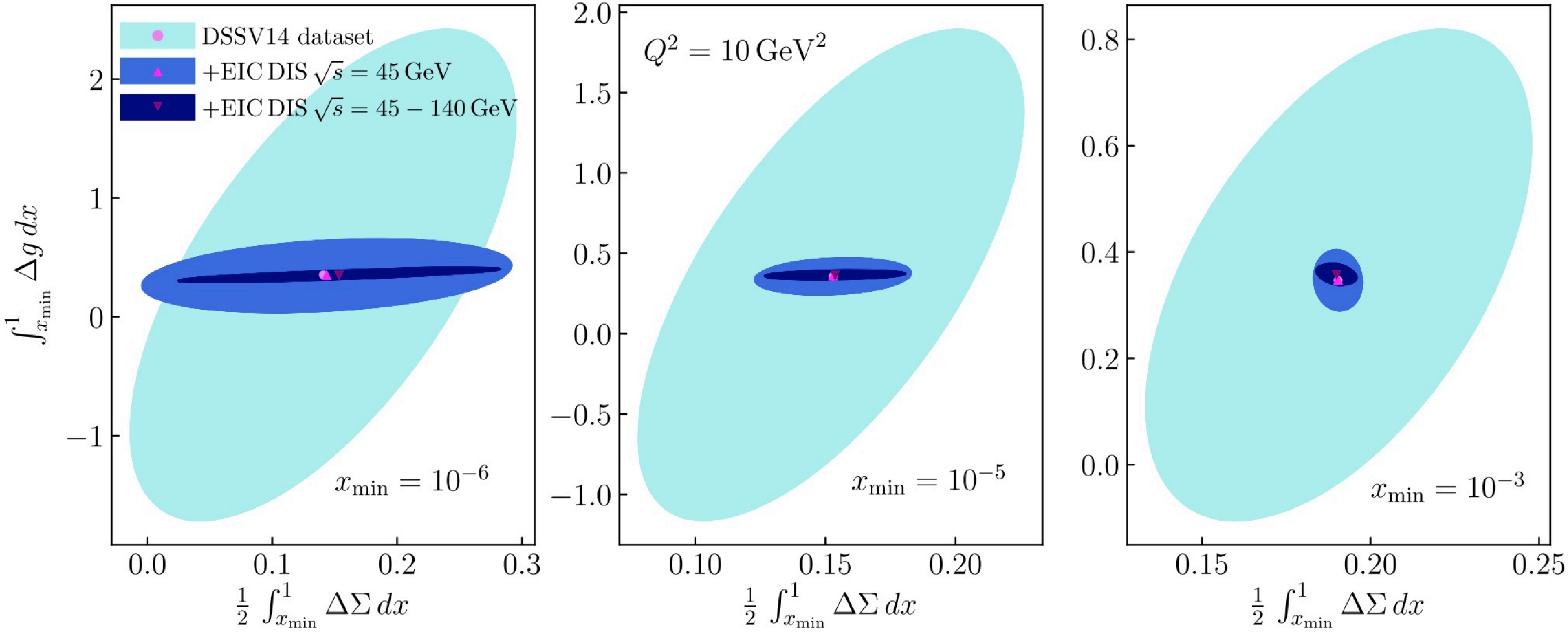
A. Tarasov, R. Venugopalan, Phys.Rev.D 105 (2022) 1, 014020

If observed at EIC: **First evidence for a topological phenomenon** conjectured to play a key role in the generation of matter-antimatter asymmetry in the early universe

# CONSTRAINING QUARK AND GLUON HELICITY DISTRIBUTIONS

decreasing $x$

gluons



quarks

**SEE TALK BY Y. HATTA, TUE, 9AM, FOR MORE ON SPIN @ EIC**

# GLUON SATURATION

New DOE Topical Theory Collaboration
to advance calculations
and connect to experiment
with goal of finding gluon saturation

SURGE
COLLABORATION

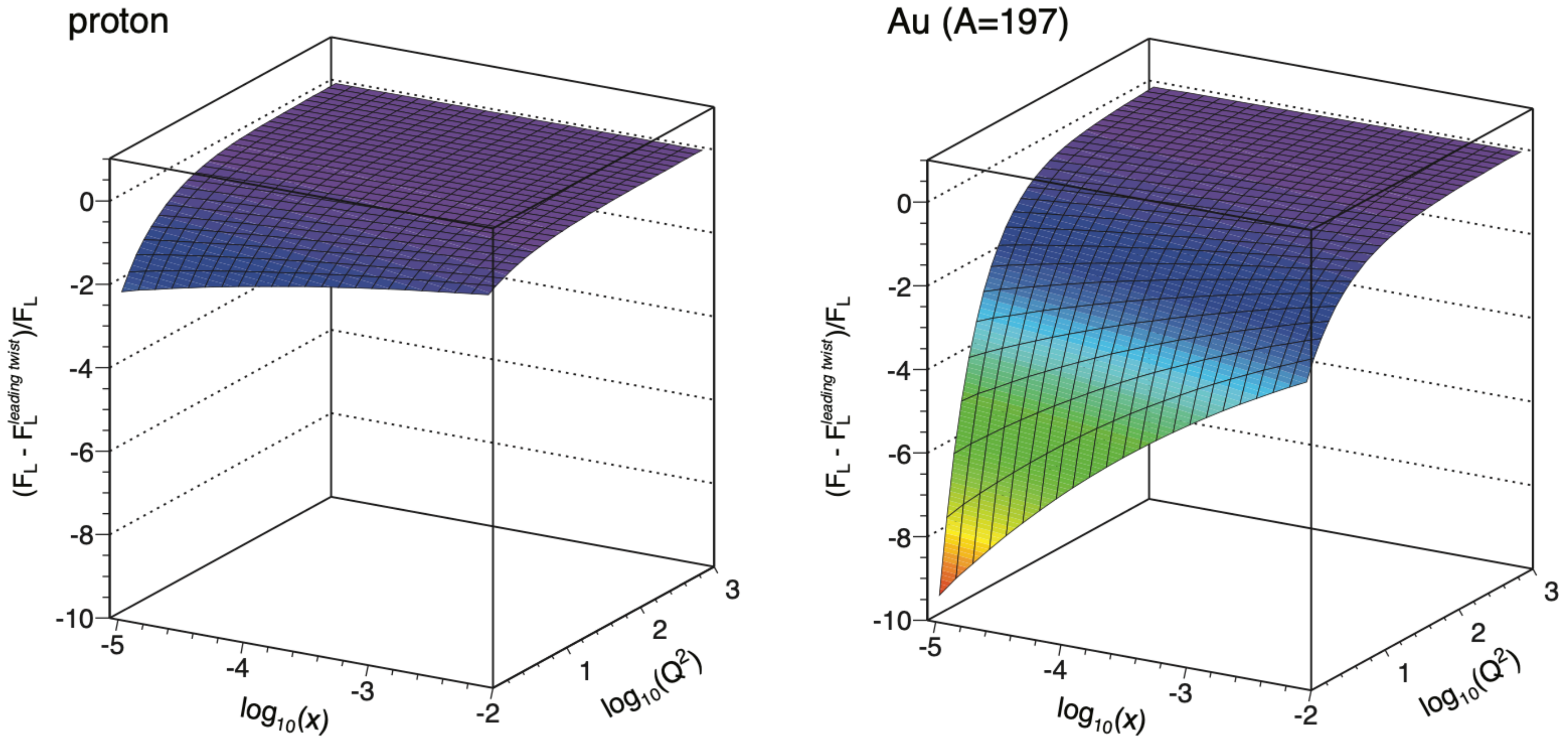
Observables that are sensitive to saturation:

- Inclusive: Structure functions
- Semi-inclusive: dihadron, dijet correlations
- Diffractive processes: e.g. ratio of diffractive and total cross-section, vector meson production, diffractive dijet production, …

**for a recent review:** A. Morreale, F. Salazar, Universe 7 (2021) 8, 312 • e-Print: 2108.08254

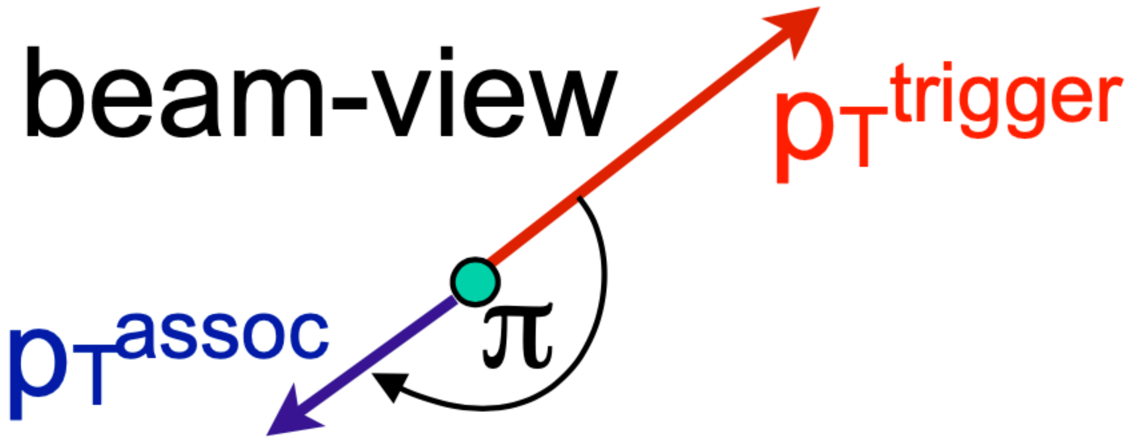
For **nuclei** at the EIC, saturation effects on structure functions should become more prominent

J. Bartels, K. Golec-Biernat, and L. Motyka
Phys. Rev. D81, 054017 (2010)

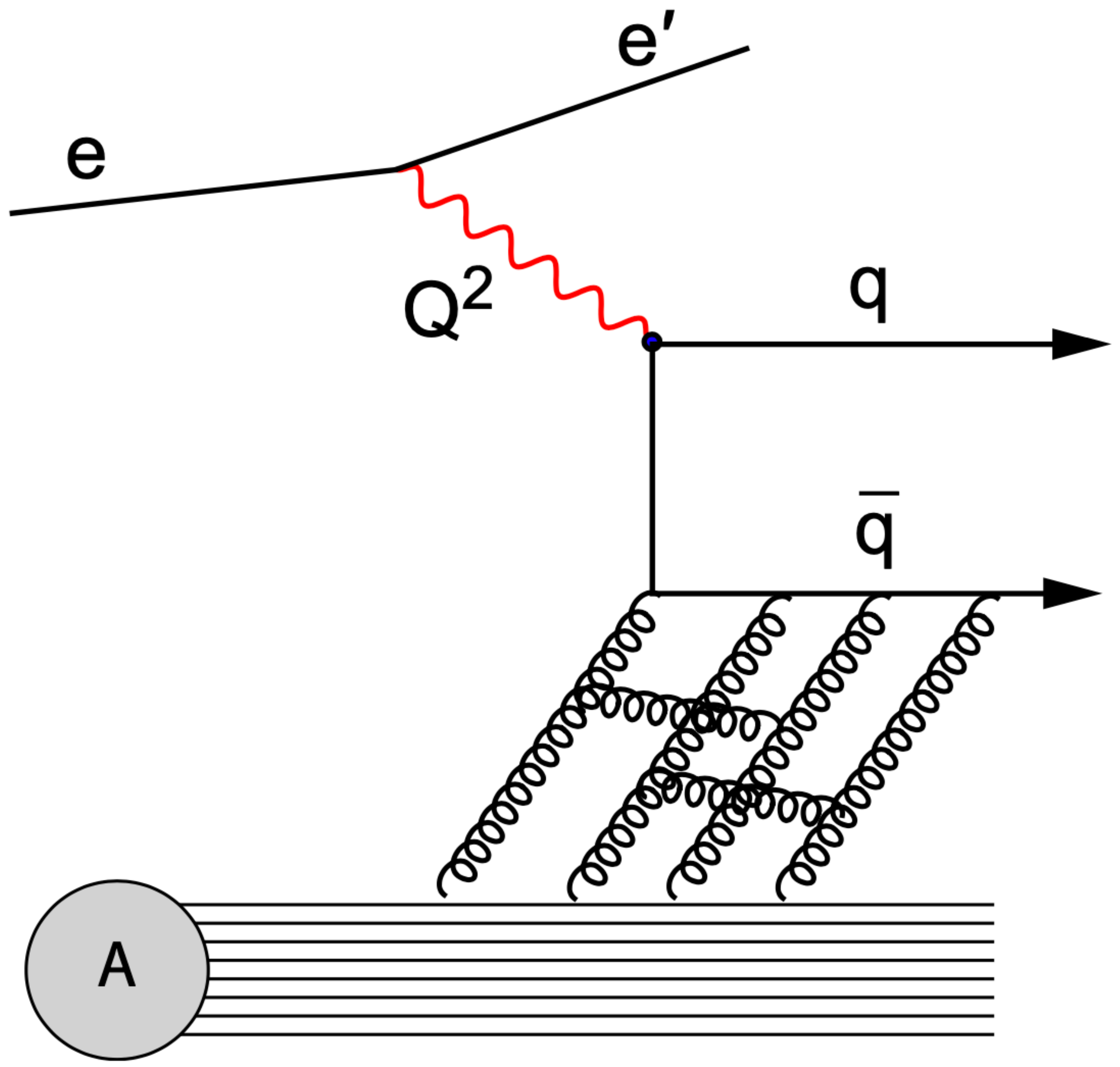


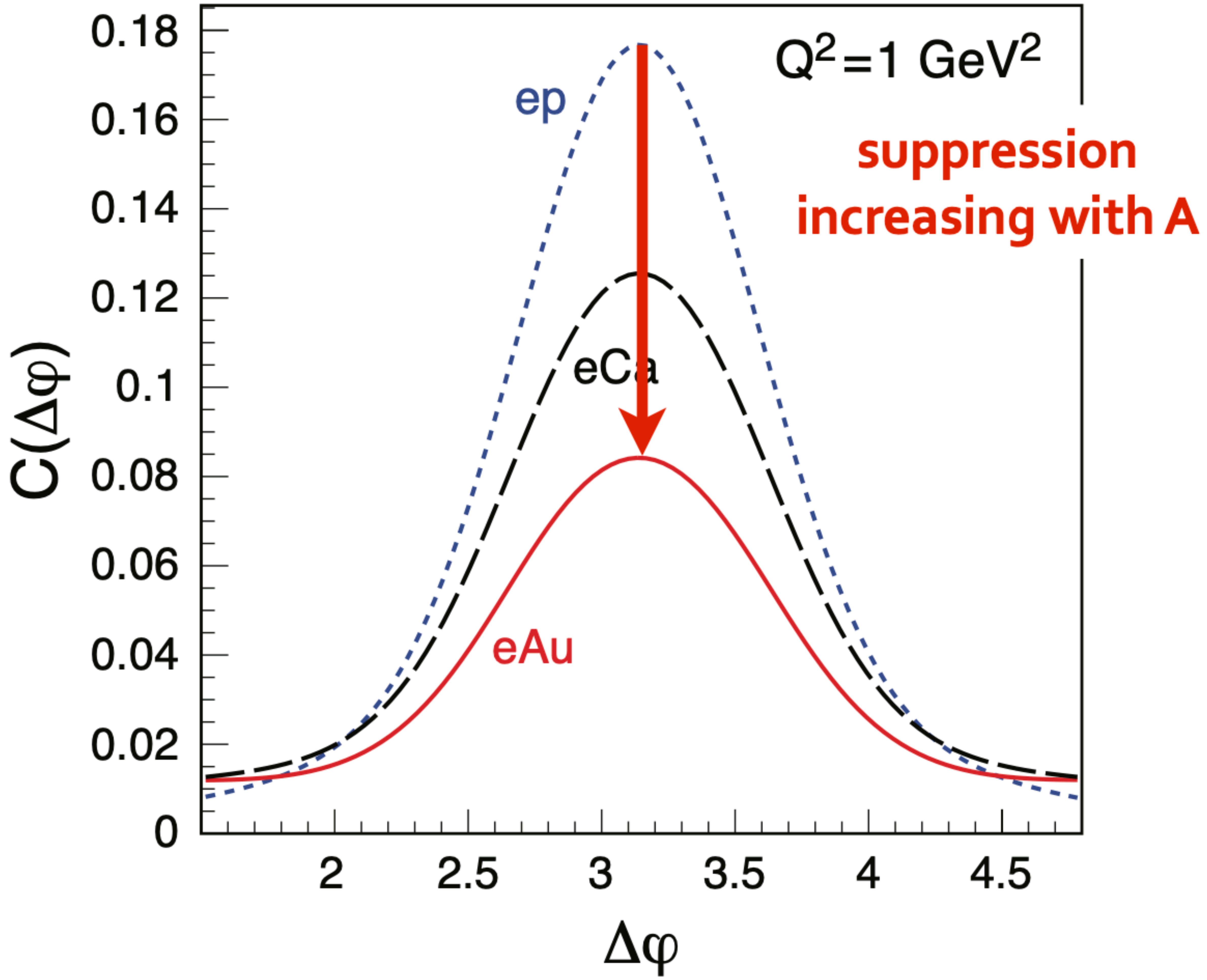
# DOUBLE-INCLUSIVE DIS

C. Marquet, B. -W. Xiao and F. Yuan, Phys. Lett. B 682 (2009) 207
L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, Phys. Rev. D 89, 074037 (2014)



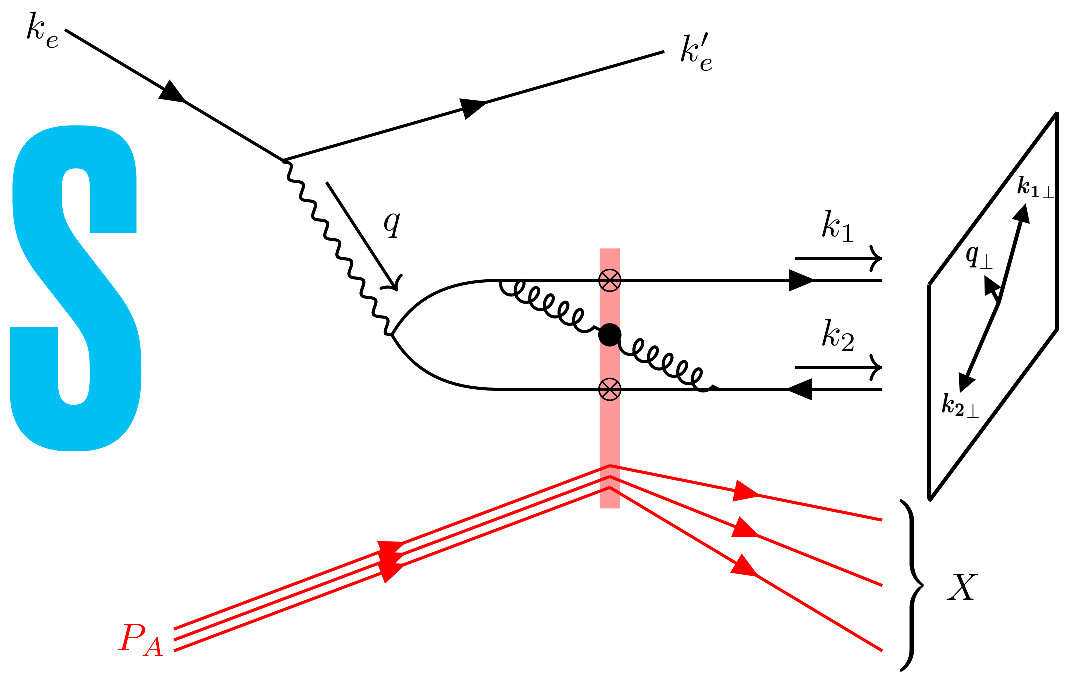
Back-to-back peak suppressed more in larger nuclei as momentum imbalance $\sim Q_s$





Broadening is also affected by soft gluon radiation (Sudakov effect)

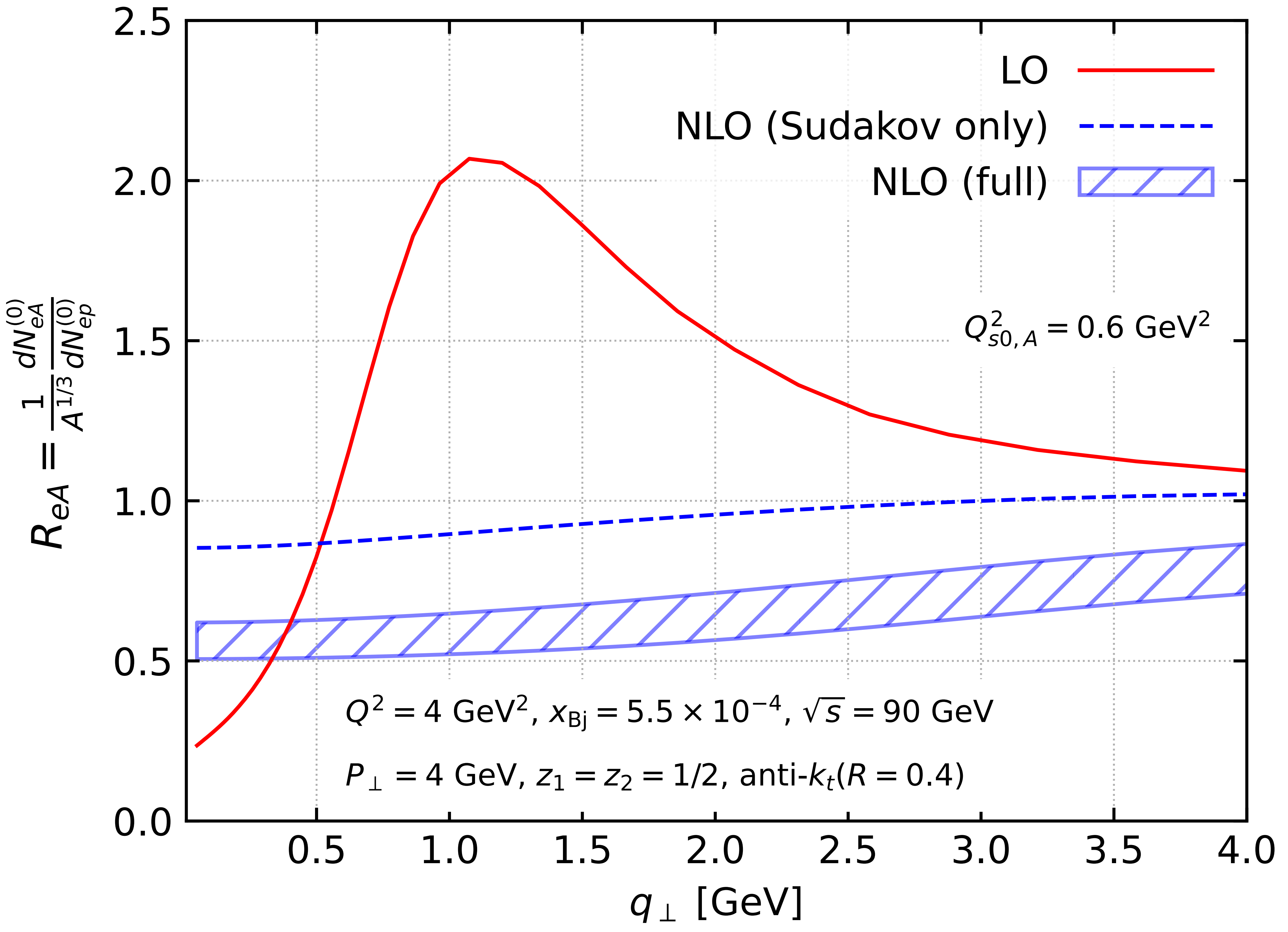
# NEXT TO LEADING ORDER CALCULATIONS



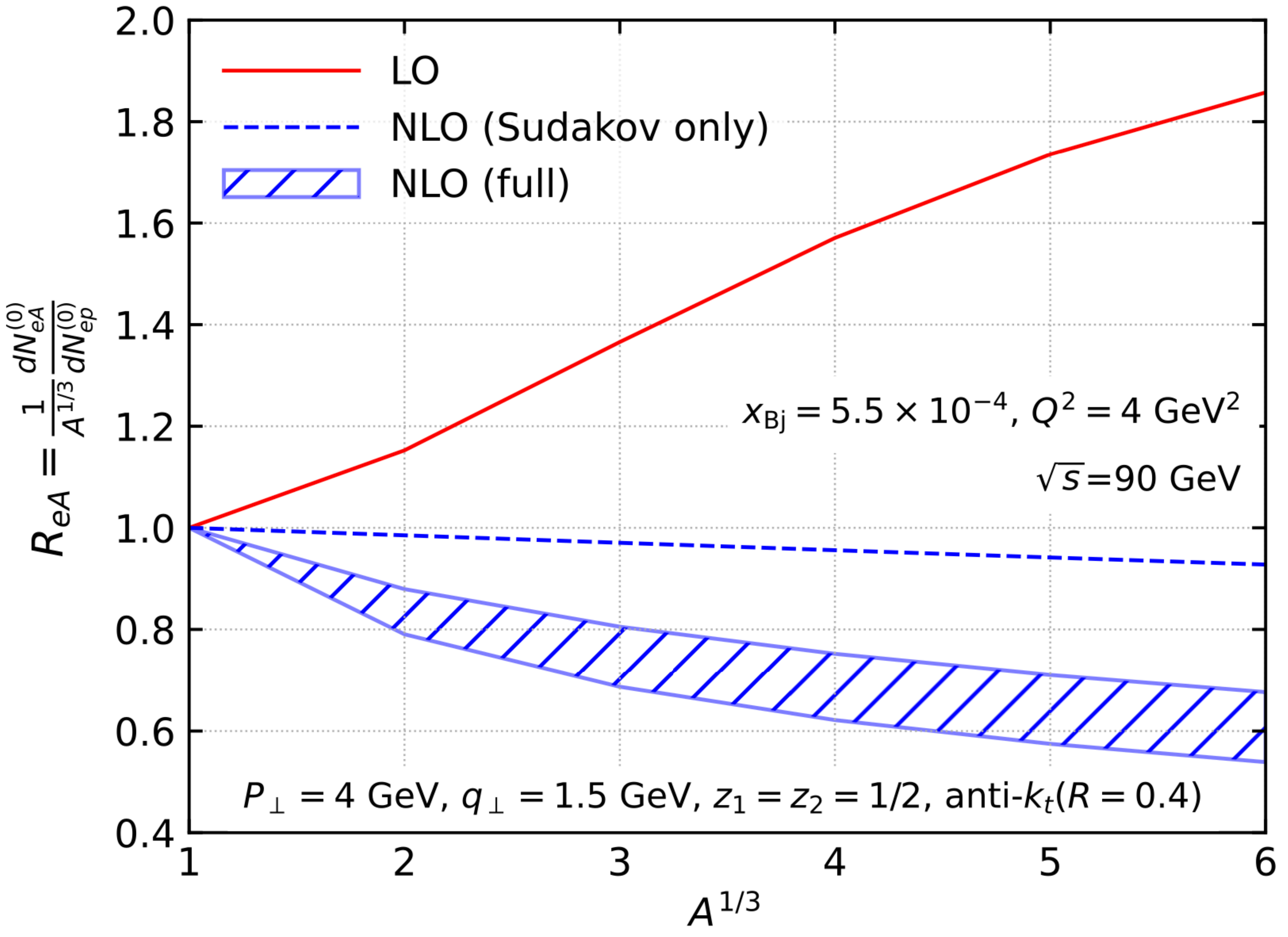
Calculations of saturation effects are advancing to NLO

Example: Inclusive dijet production and modification of the back-to-back peak in the CGC

**P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan, arXiv:2308.00022**

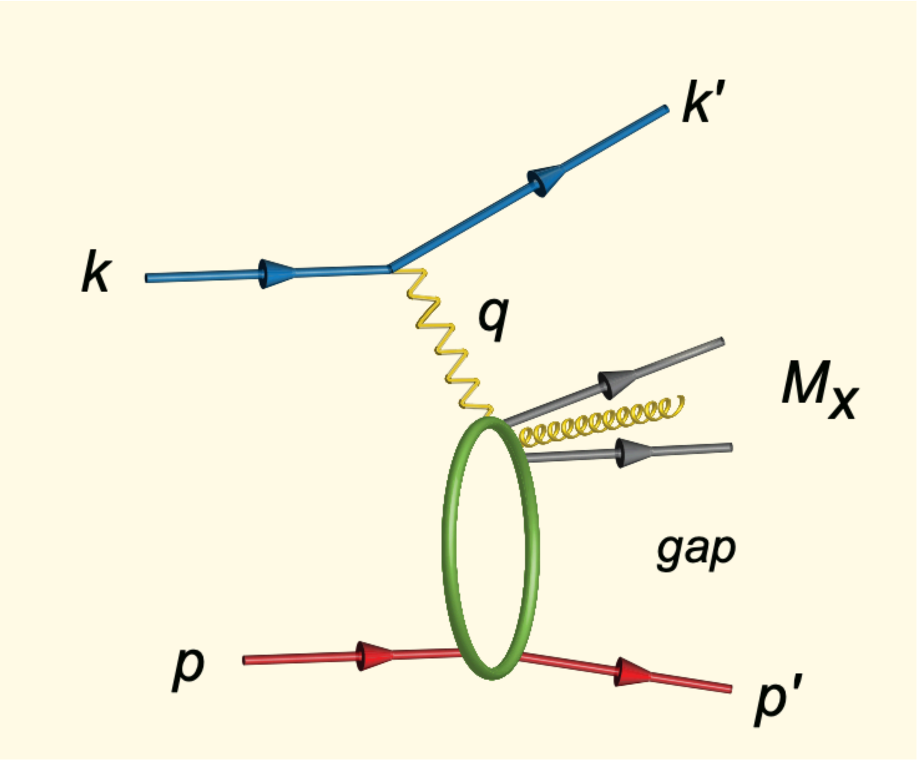


Ratio showing the modification in a large nucleus over expectation from scaled proton target



Modification as a function of nuclear mass number

# DIFFRACTIVE PROCESSES



Diffractive events are characterized by rapidity gap

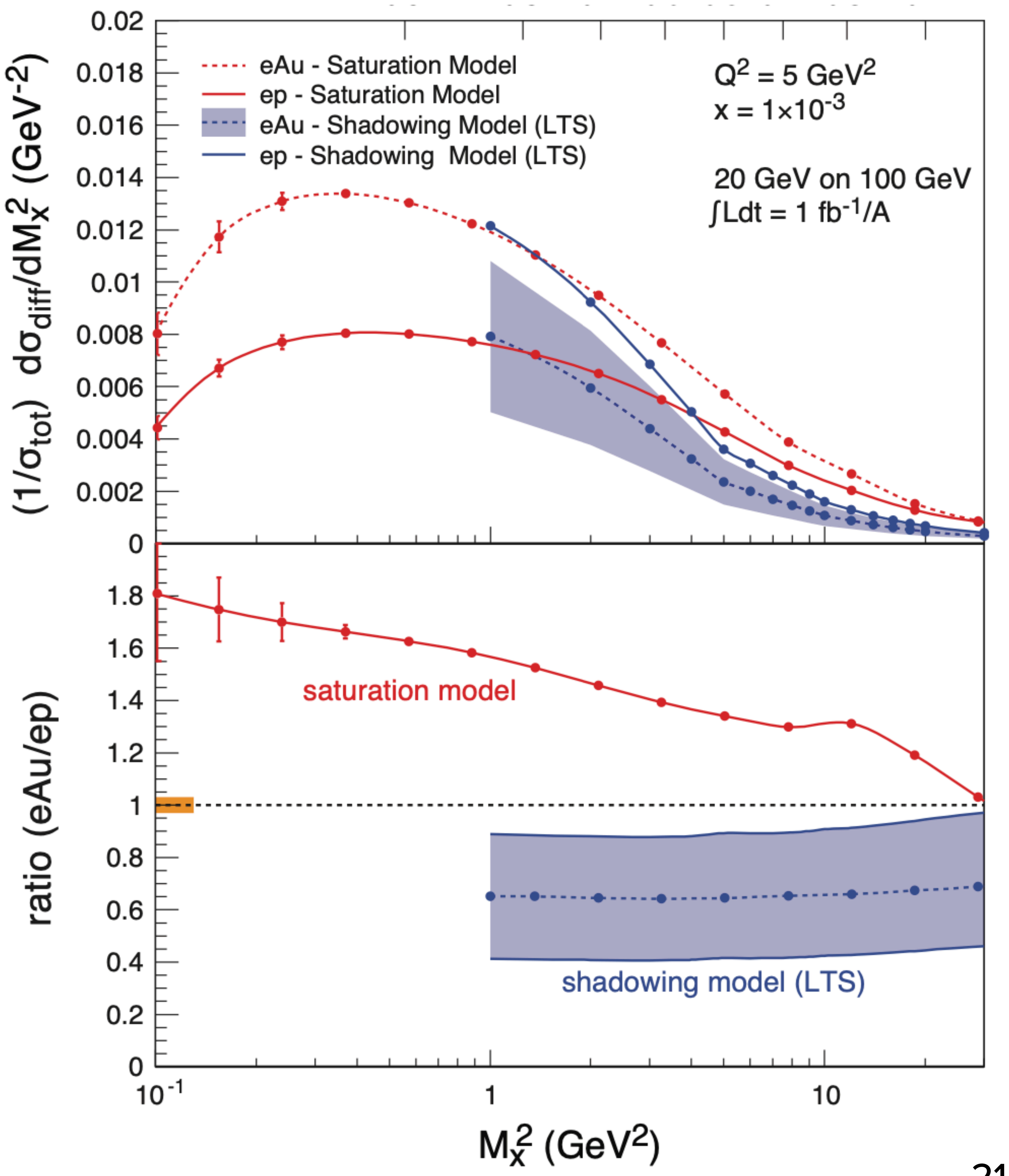
Neutral color exchange requires at least two-gluons → enhanced sensitivity to gluon saturation

Ratio of diffractive and total cross-section in e+p and e+Au collisions →

Clear difference between saturation models and leading twist shadowing (LTS)

A. Accardi et al., EIC White Paper, Eur.Phys.J.A 52 (2016) 9, 268

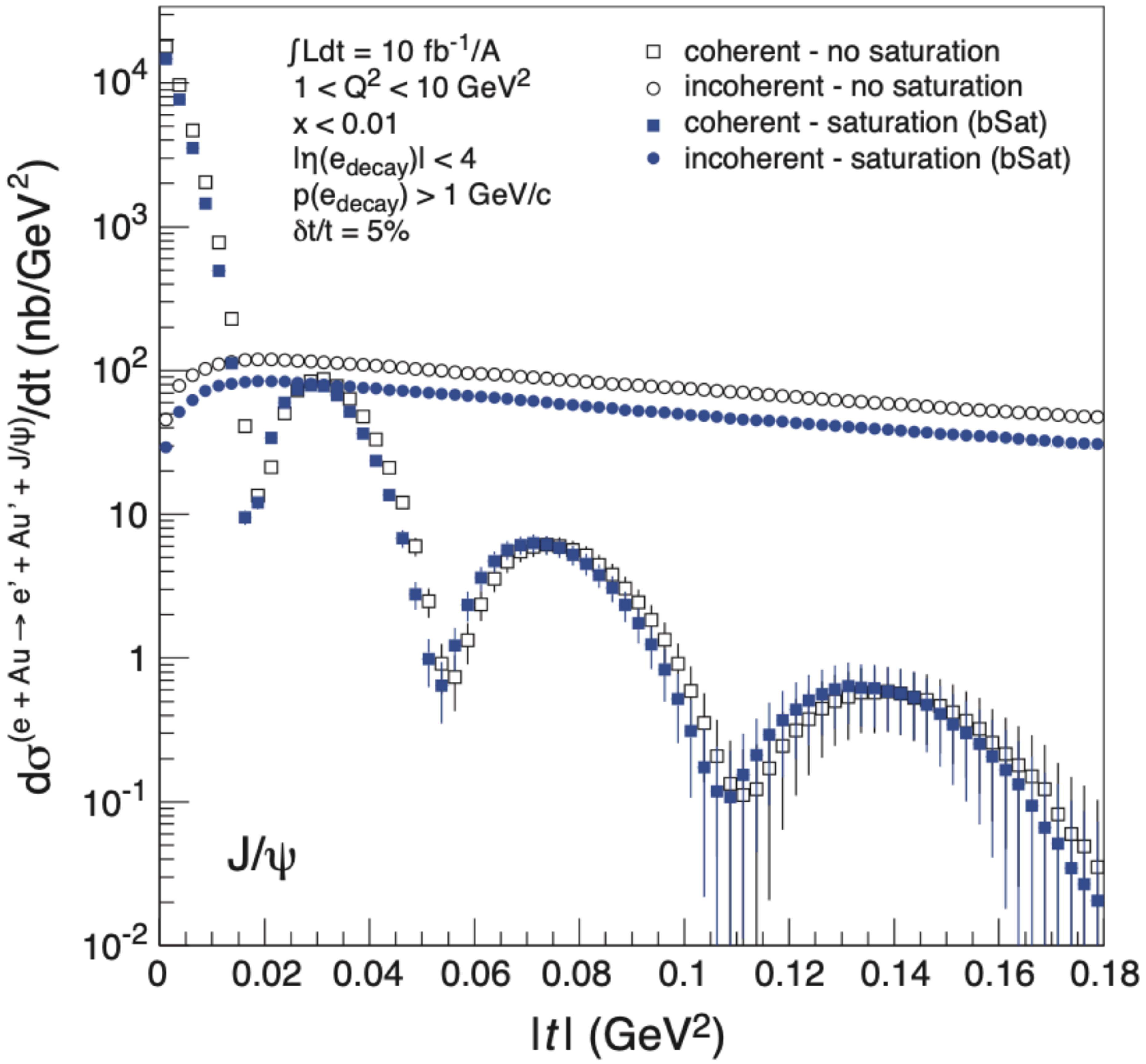
**SEE TALKS BY YURI KOVCHEGOV AND MINJUNG KIM ON TUESDAY MORNING FOR MORE ON DIFFRACTION @ EIC**

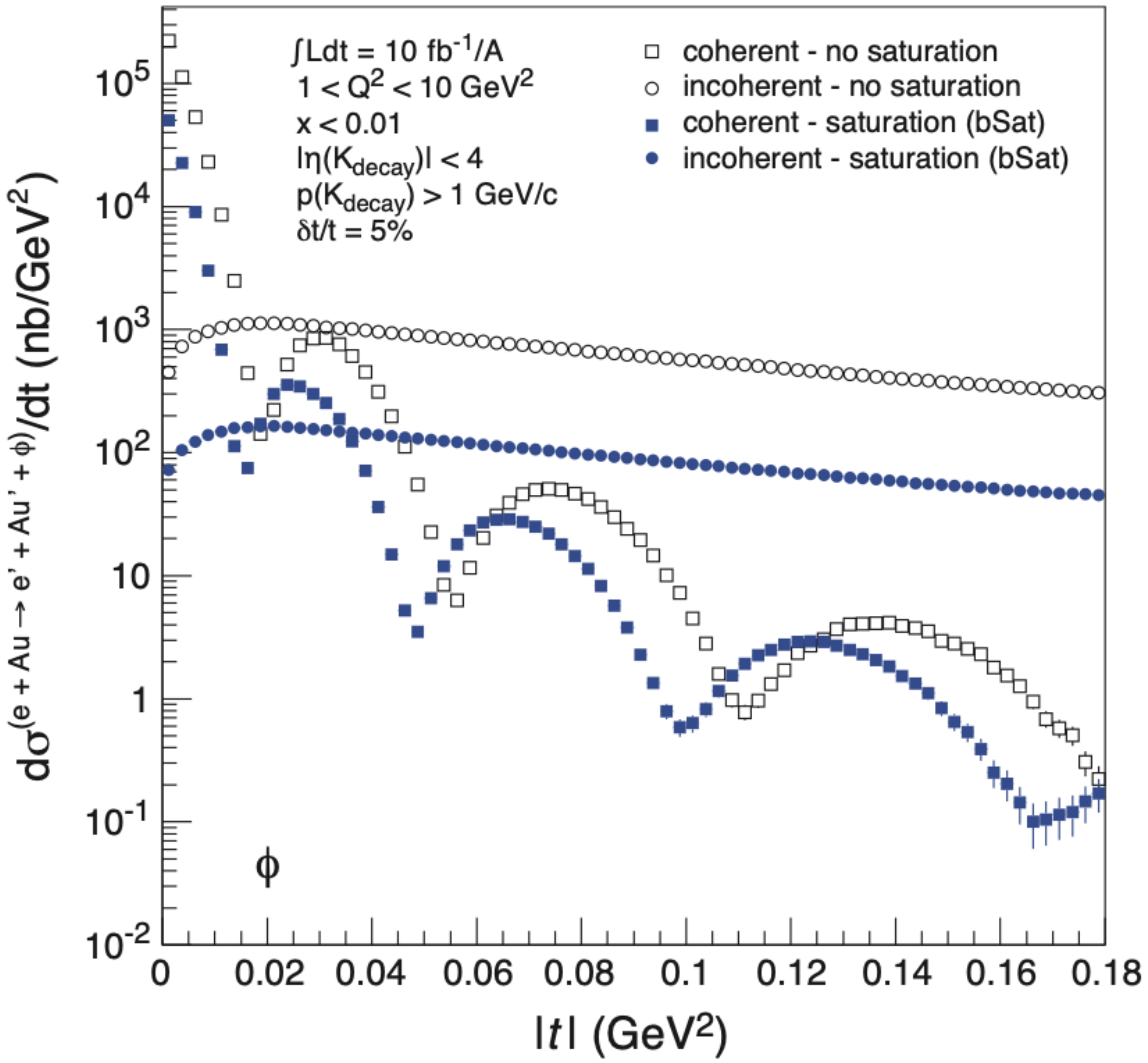


# DIFFRACTIVE VECTOR MESON PRODUCTION

T. Toll, T. Ullrich, Phys.Rev.C 87 (2013) 2, 024913

A. Accardi et al., EIC White Paper, Eur.Phys.J.A 52 (2016) 9, 268

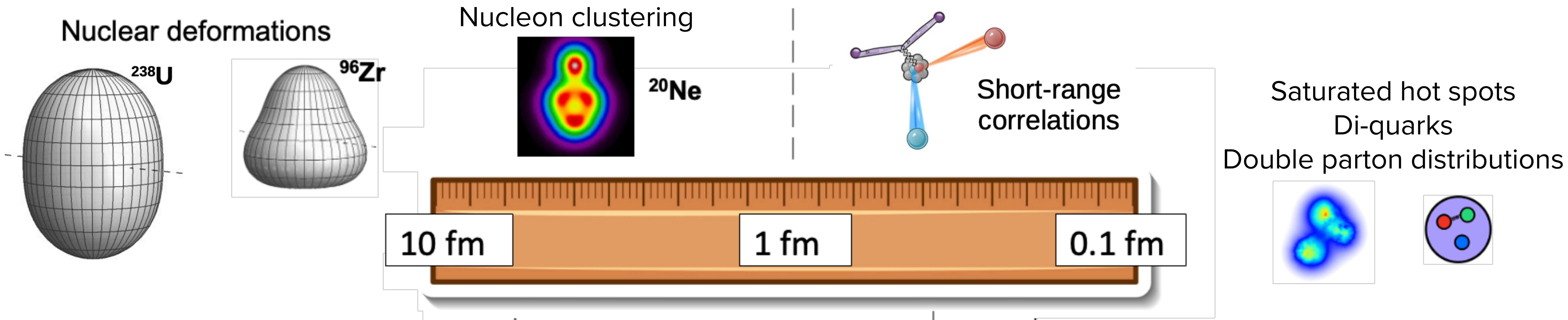




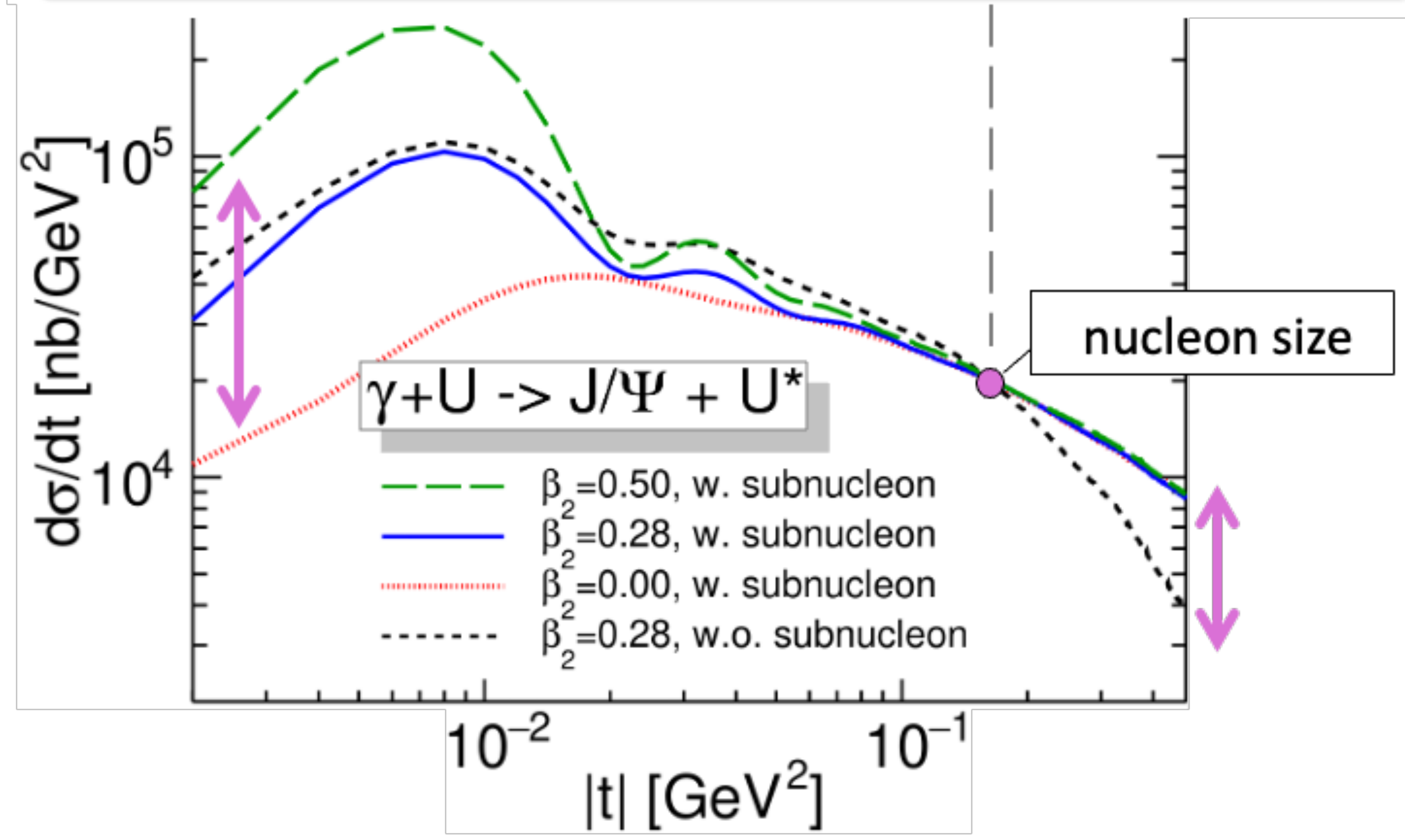
- Sartre event generator (bSat & bNonSat = linearized bSat)
- Big difference for ϕ; less so for J/ψ (larger mass reduces sensitivity to saturation)

# MULTISCALE IMAGING - NUCLEAR STRUCTURE @ EIC

**H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, arXiv:2303.04866, accepted in PRL**



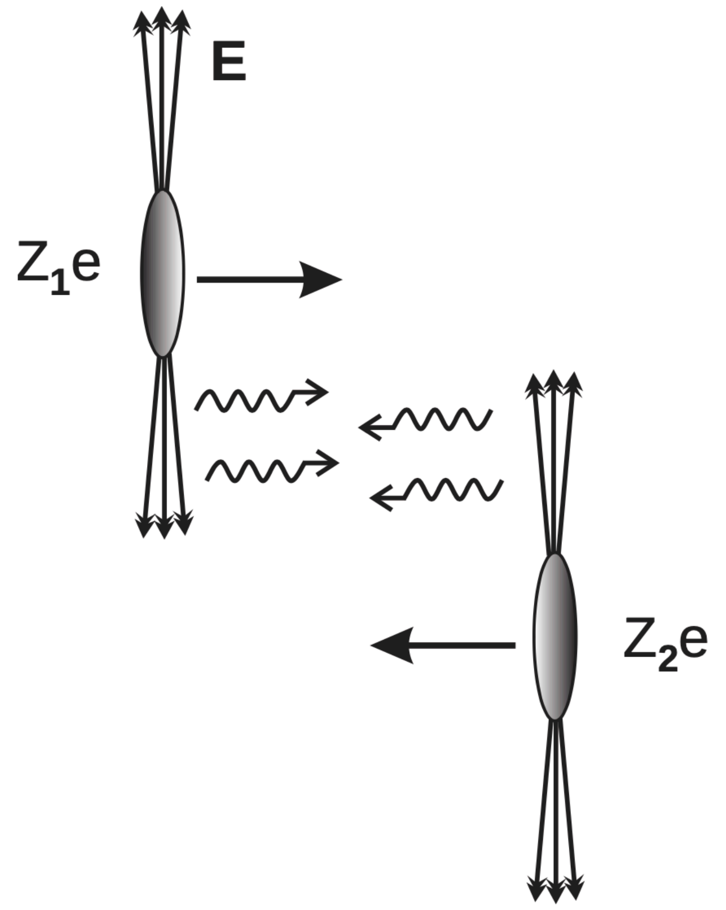
Incoherent diffractive vector meson production is sensitive to fluctuations in the target



The transverse momentum transfer sets the length scale we probe

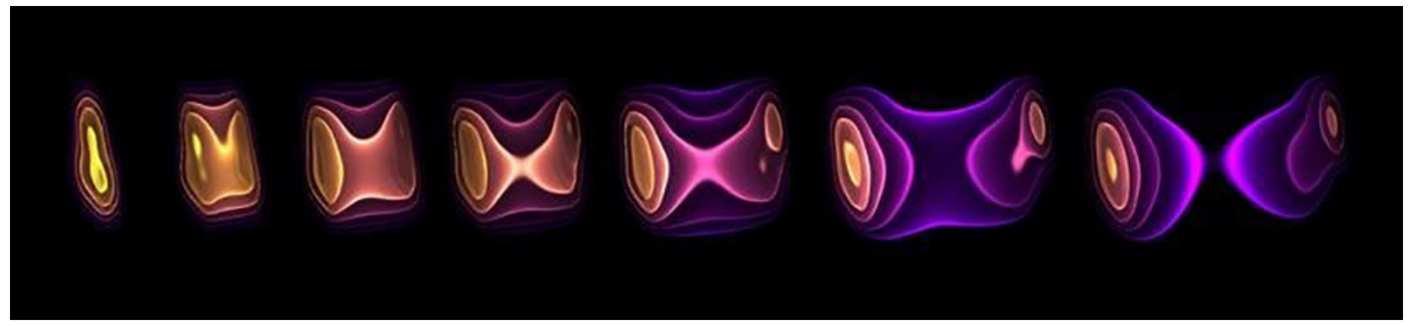
**Illustration by G. Giacalone**

# FLOW IN $\gamma^*$+A COLLISIONS

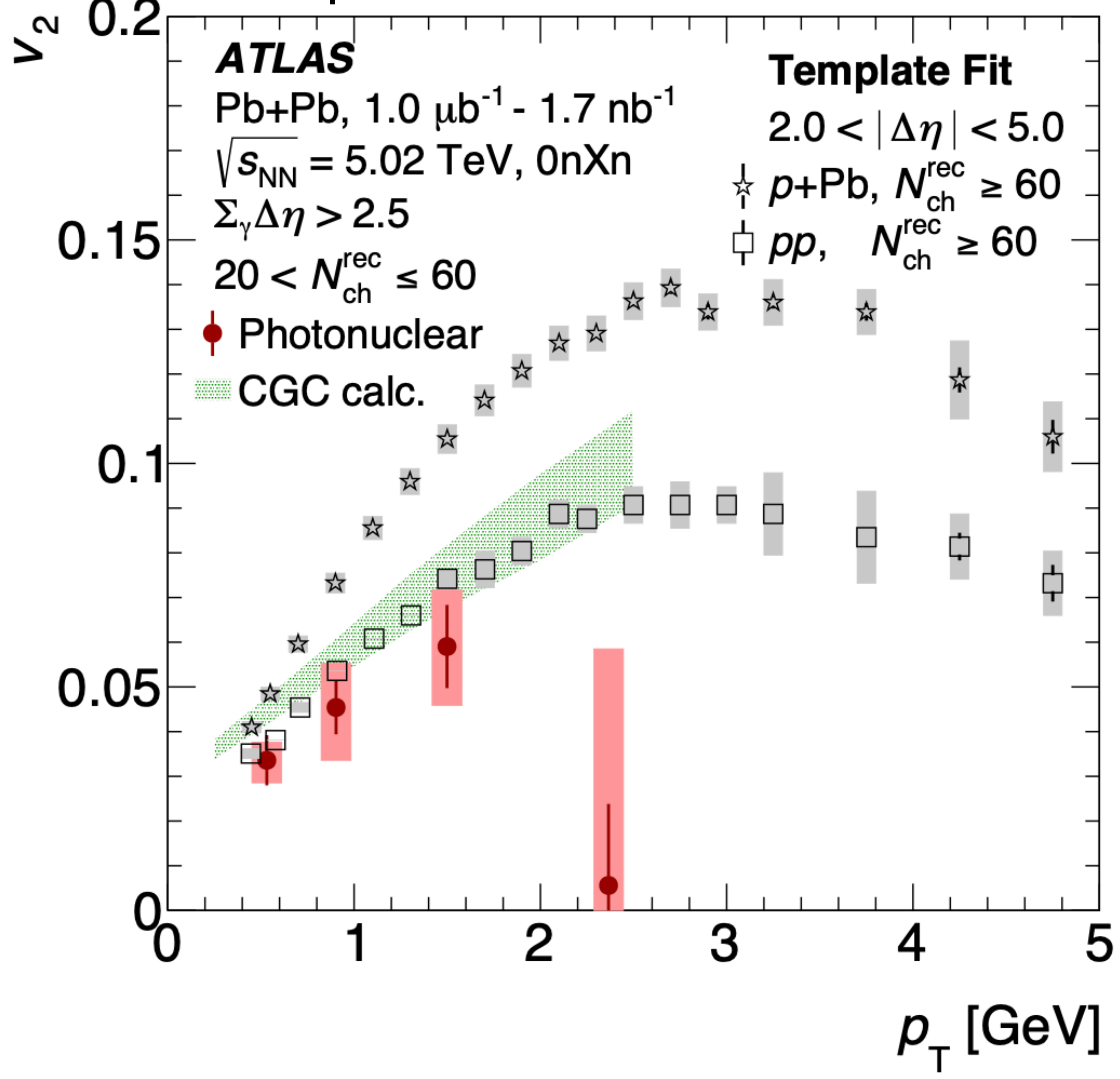


ATLAS has measured $v_2$ in ultra-peripheral collisions (UPC) → photon-nucleus collisions

ATLAS Collaboration, Phys. Rev. C. 104 (2021) 014903

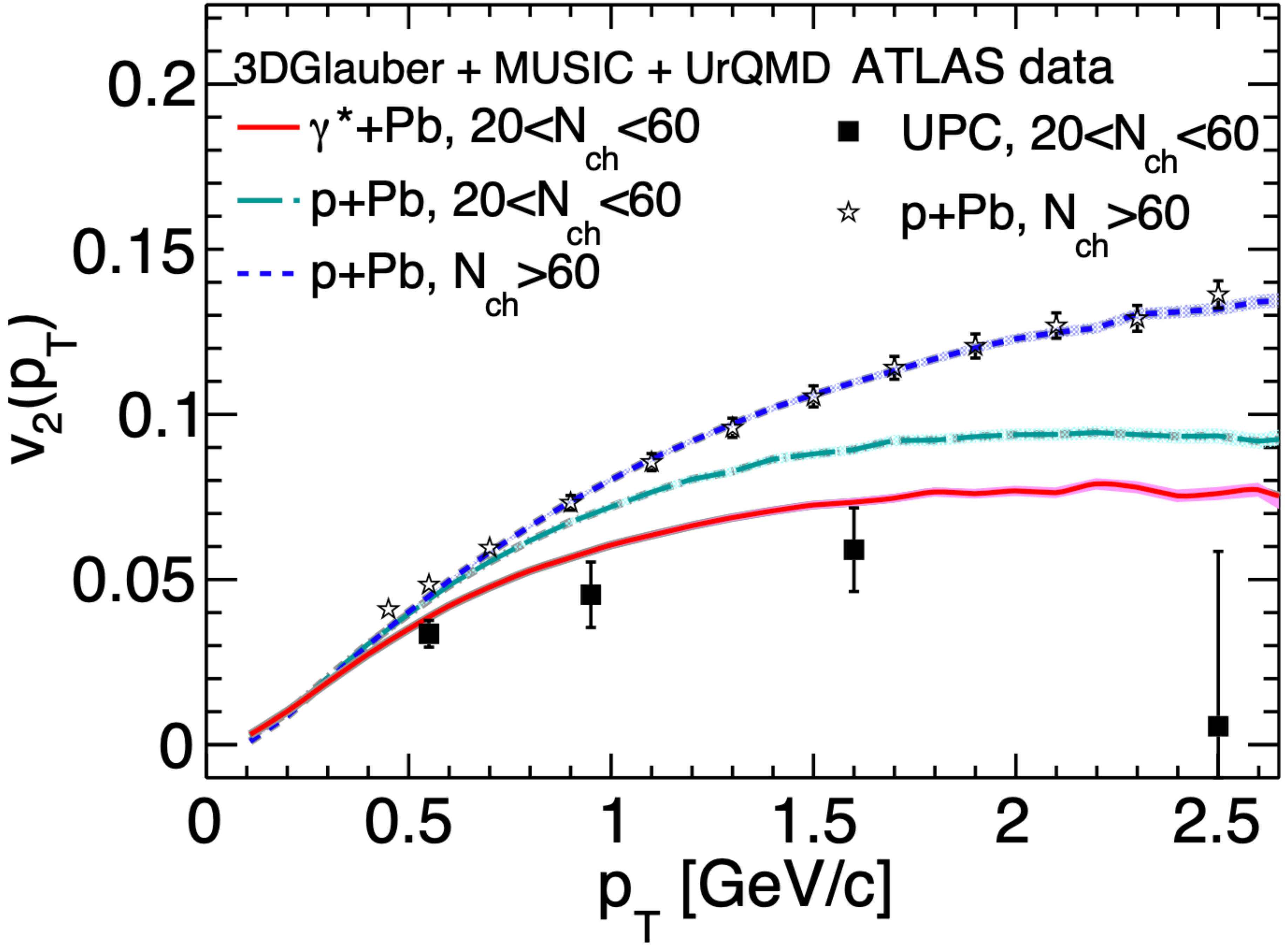


Compared to CGC calculation



Y. Shi, L. Wang, S.-Y. Wei, B.-W. Xiao and L. Zheng
Phys. Rev. D 103 (2021) 054017

Compared to hydrodynamics

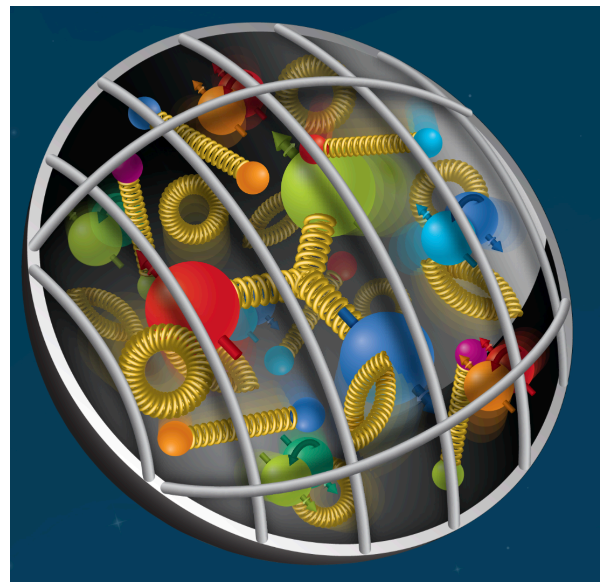


W. Zhao, C. Shen, B. Schenke, 2203.06094

This assumes a vector meson nucleus collision and pressure driven final state interactions

Models predict opposite $Q^2$-dependence. This can be studied at the EIC

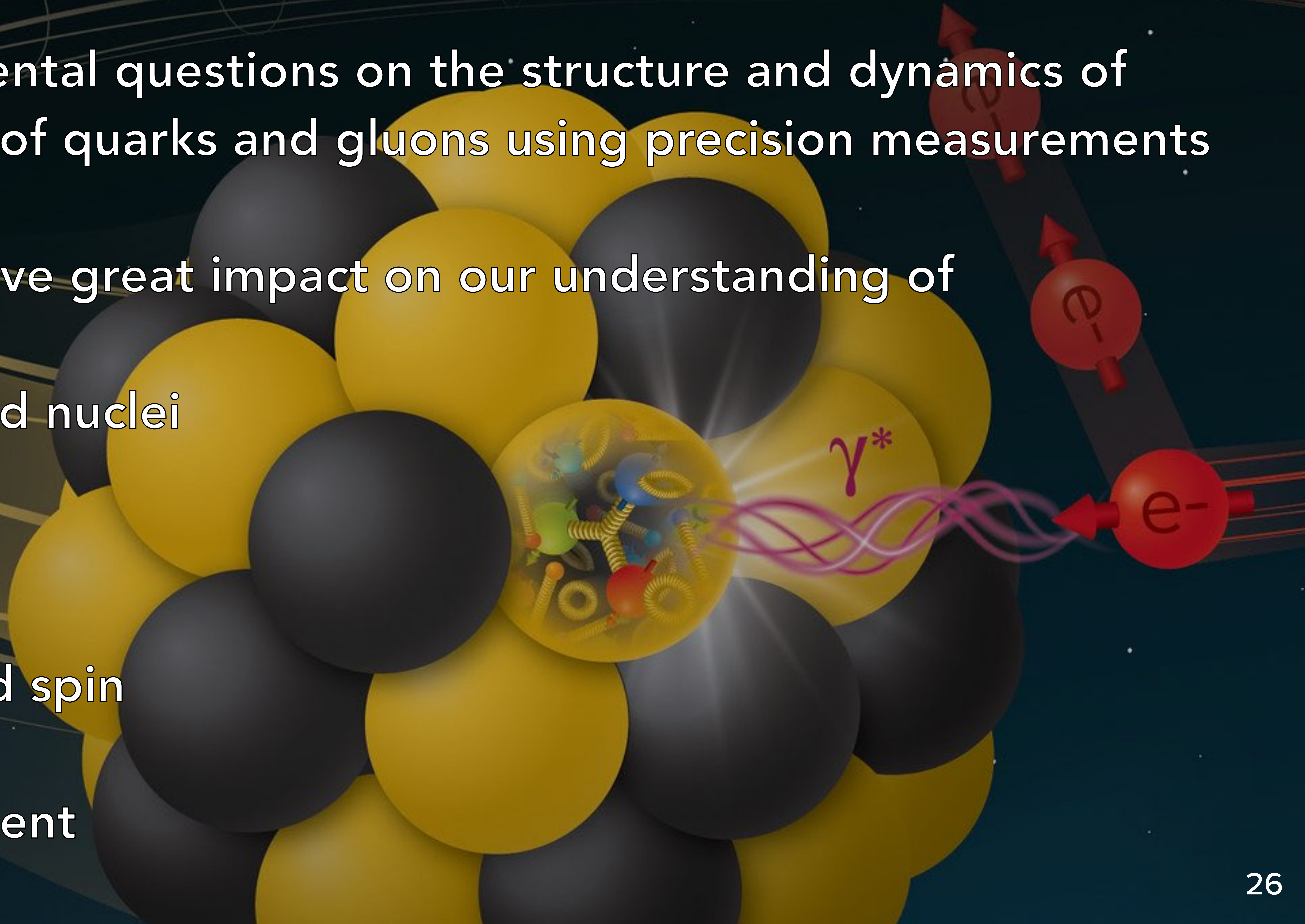
# MORE PHYSICS POTENTIAL AT THE EIC



**SEE TALKS BY KEVIN ADKINS AND JUAN LI, TUE, 11:30 AM, 11:50AM FOR MORE ON JETS (AND HEAVY FLAVOR) @ EIC**

- Study fragmentation and learn about confinement
  - For example using flavor tagging in jets
- Photon PDF
  - Dijet measurements at EIC provide high precision to constrain unpolarized photon PDFs and first measurements of polarized photon PDFs
- Beyond the standard model physics
  - Charged Lepton Flavor Violation
  - Complementarity of the EIC with the LHC in exploring the SMEFT
  - Nucleon electric dipole moment (CP-violation)
  - Probes of anomalous dipole moments at the EIC
- …

# SUMMARY



The EIC will address fundamental questions on the structure and dynamics of nucleons and nuclei in terms of quarks and gluons using precision measurements

Among other topics it will have great impact on our understanding of

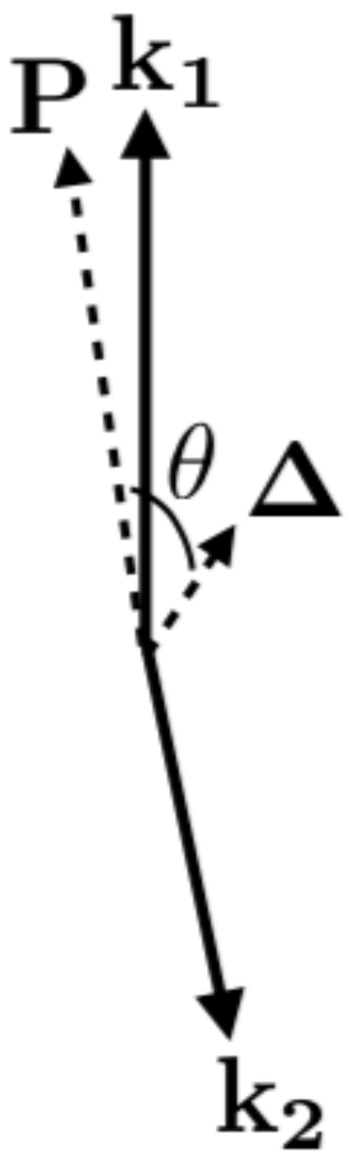
- 3D structure of protons and nuclei
- Gluon saturation
- Origins of proton mass and spin
- Quark and gluon confinement

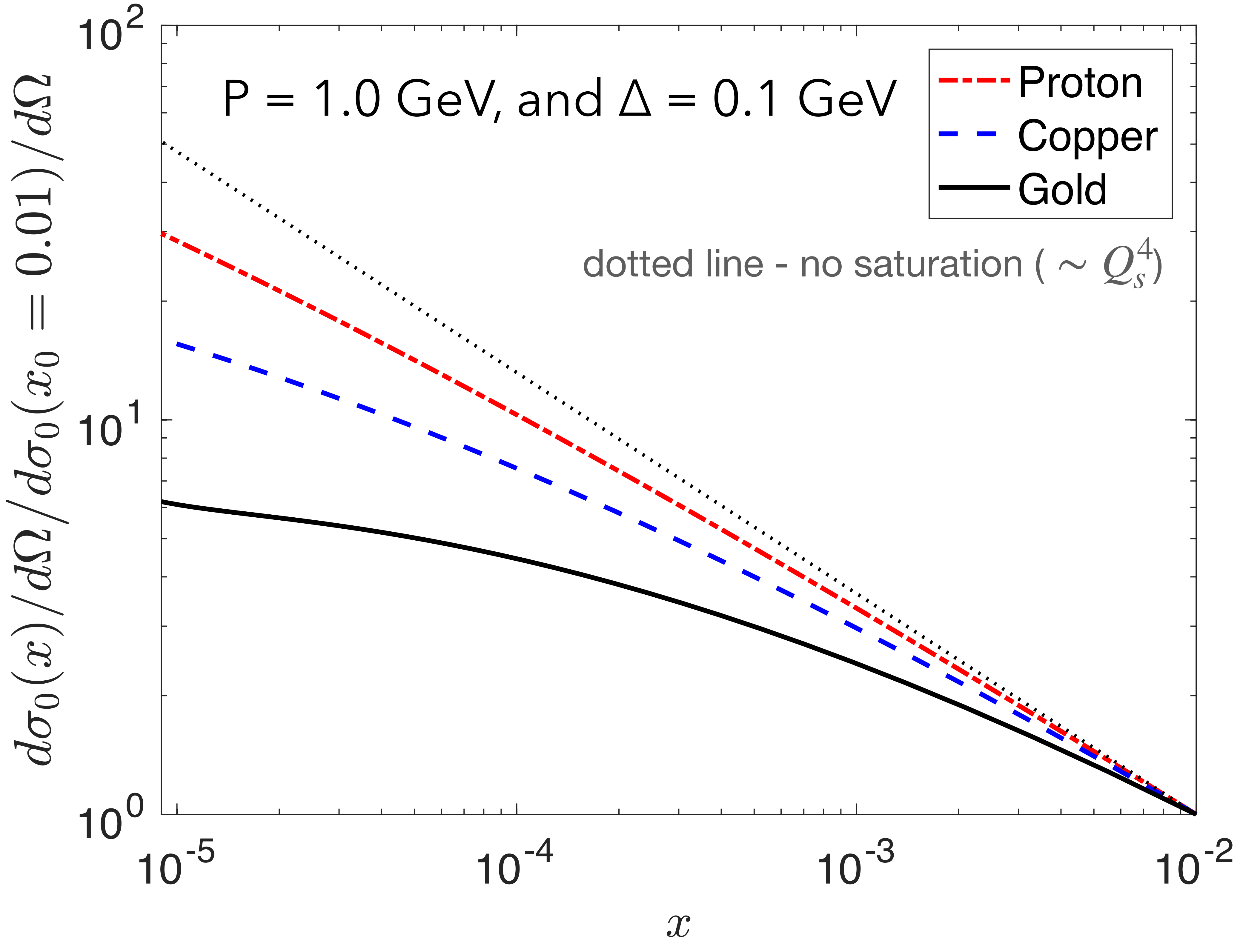
# DIFFRACTIVE DIJET PRODUCTION

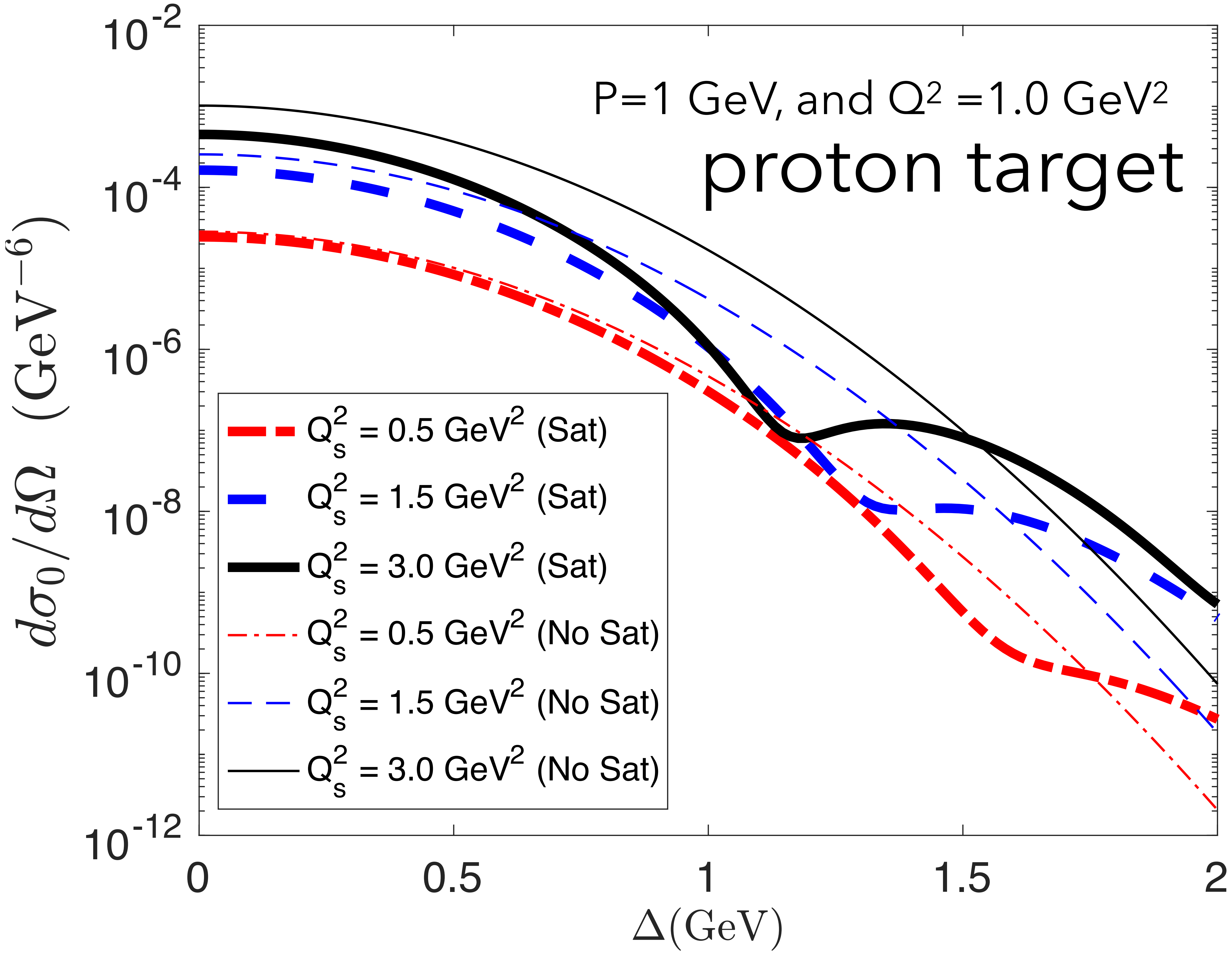
F. Salazar, B. Schenke, Phys.Rev. D100 (2019) 034007

Slow-down of growth of
the cross section for heavv nuclei

Saturation leads to diffractive dip
even for a Gaussian proton
→ shape is modified







also sensitive to the Wigner distribution