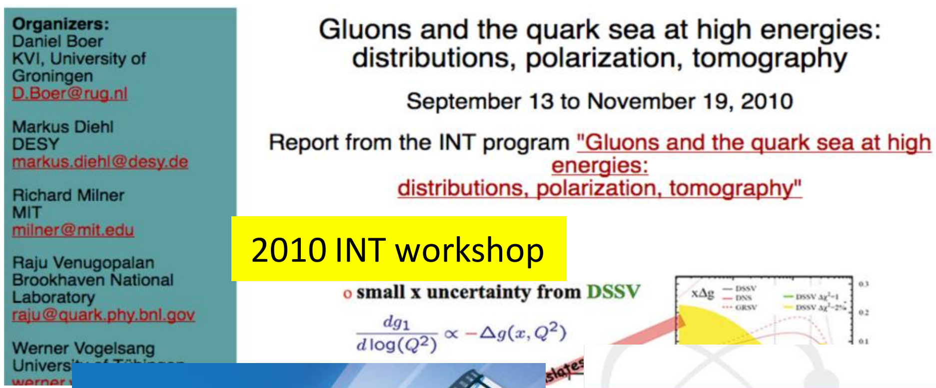
The Science of the Electron-Ion Collider

Yoshitaka Hatta
(BNL)

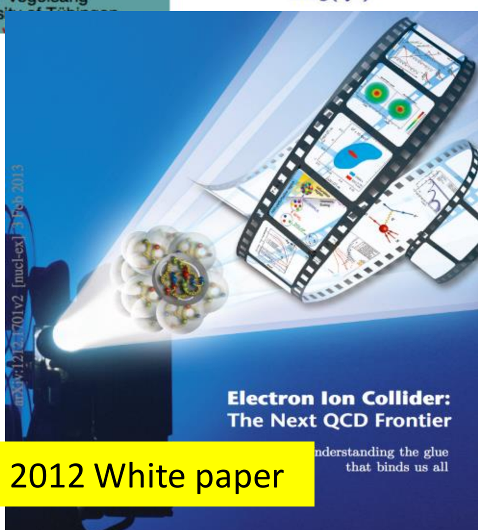
Electron-Ion Collider (EIC)

A future (2029~) high-luminosity polarized ep, eA collider dedicated to the study of the nucleon and nucleus structure.

Center-of-mass energy	$20 \lesssim \sqrt{s} \lesssim 140\,\mathrm{GeV}$
Luminosity	$\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



2010 INT workshop

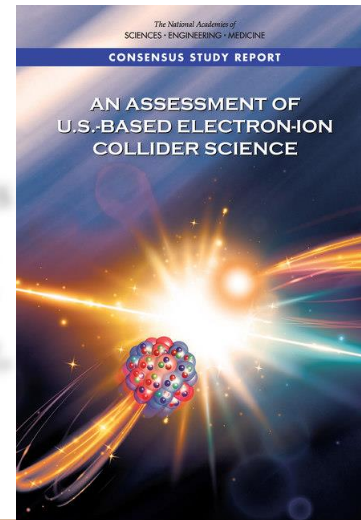


2012 White paper

2015 NSAC Long Range Plan

2018 NAS report

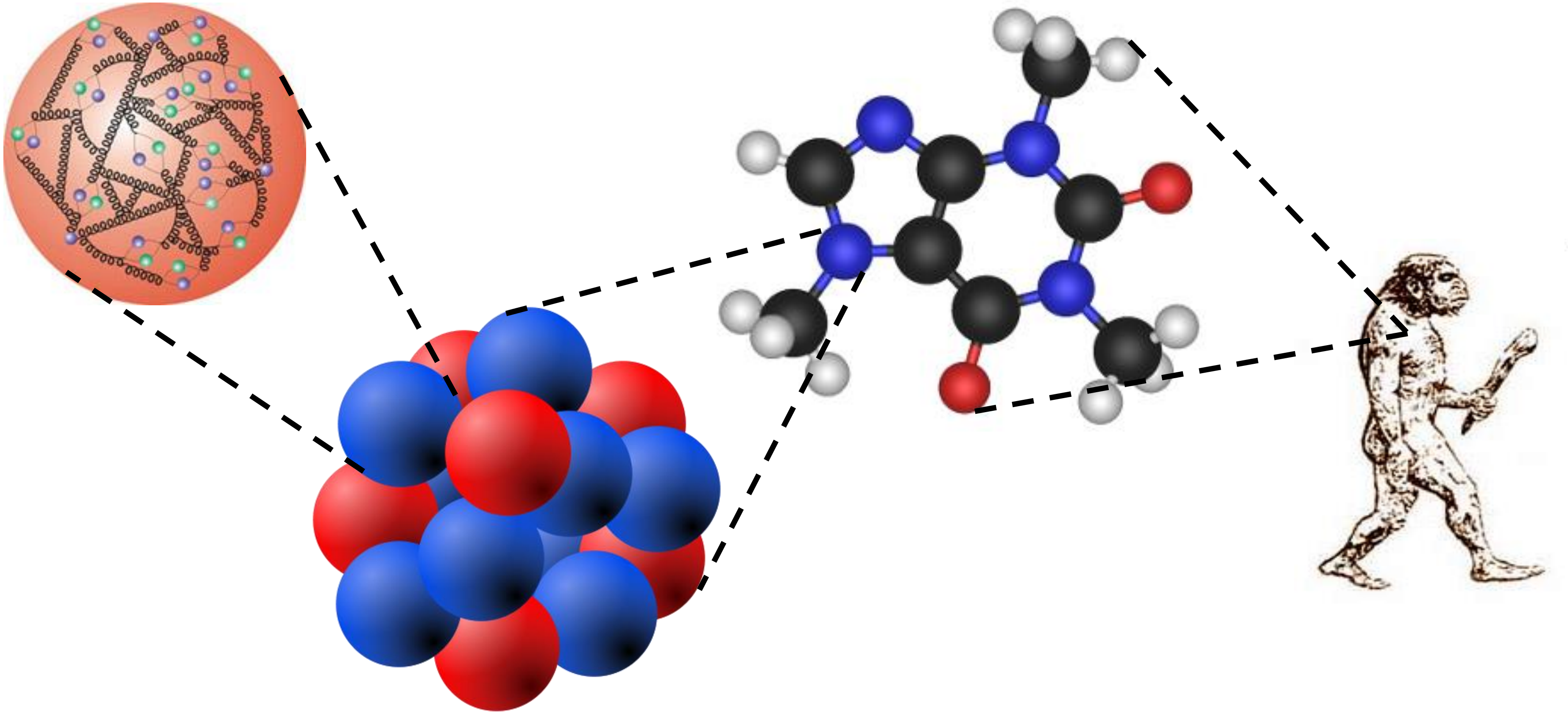
"The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."



2018 INT workshop

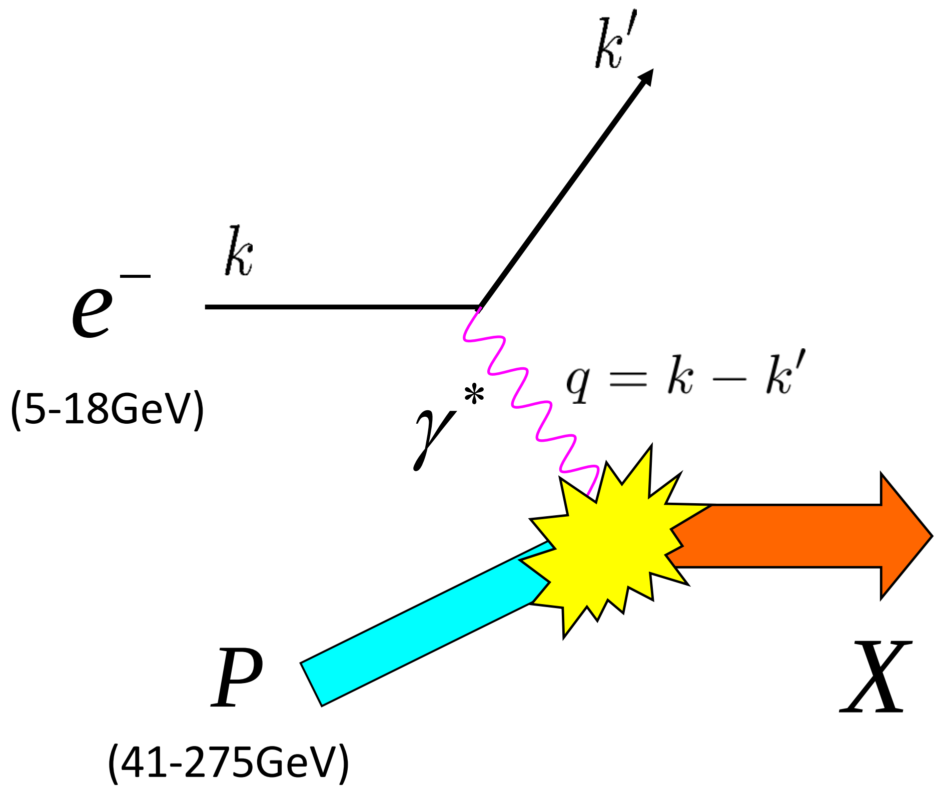
Understand the glue that binds us all

Nucleons and nuclei—the fundamental building blocks of the visible universe. Understand their structure in QCD, namely, in terms of quarks and gluons.



Especially the role of gluons—the `least understood' particle in the Standard Model. How do they give rise to the nucleon's mass, spin, etc?

Experiment at EIC: Deep Inelastic Scattering (DIS)



Two most important kinematic variables

$$Q^2 = -q^2$$ photon virtuality (resolution)

$$x = \frac{Q^2}{2P \cdot q}$$ Bjorken variable (inverse energy)

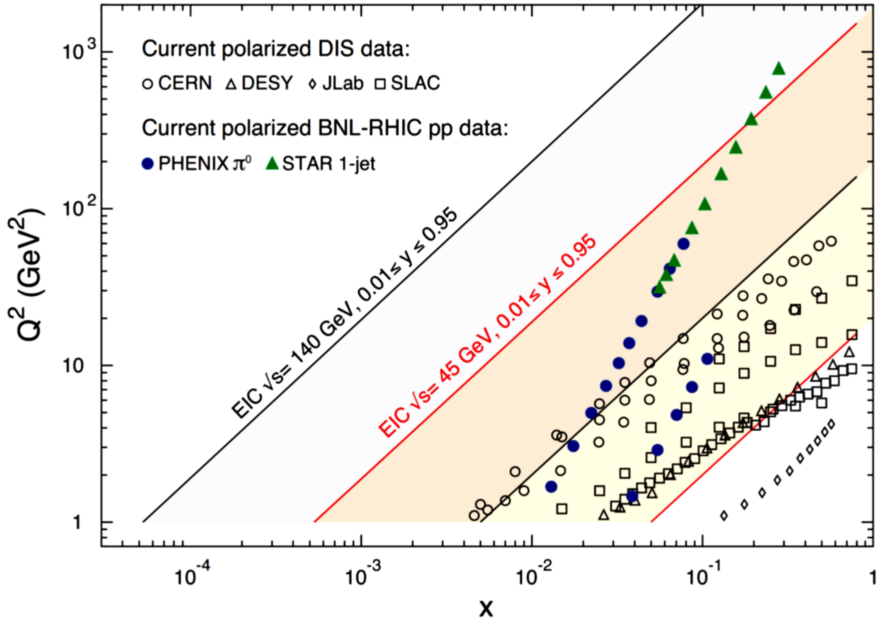
$$\approx \frac{E_{parton}}{E_{proton}}$$

Proton, deuteron, helium, gold…any nucleus of your choice!

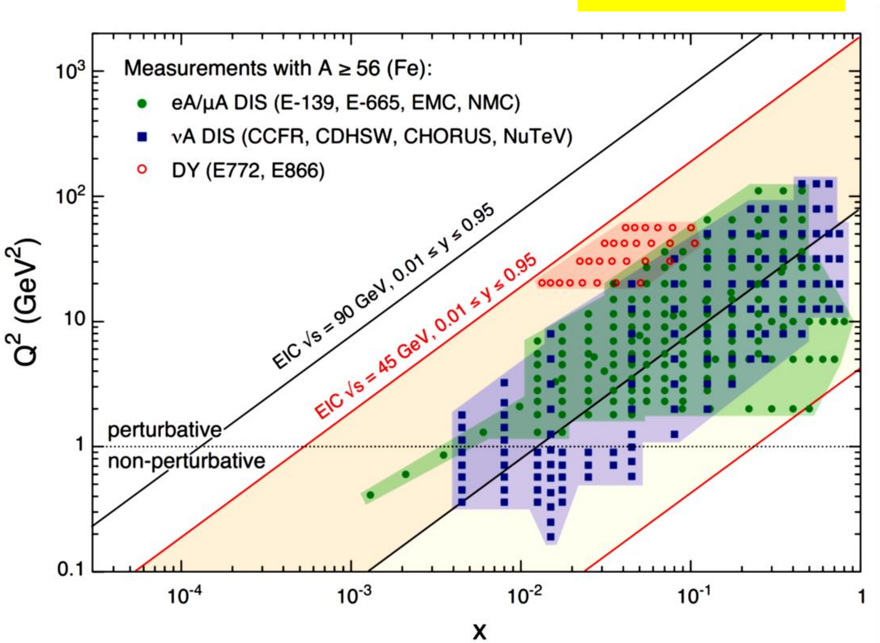
Electron, proton and light nuclei can be polarized.

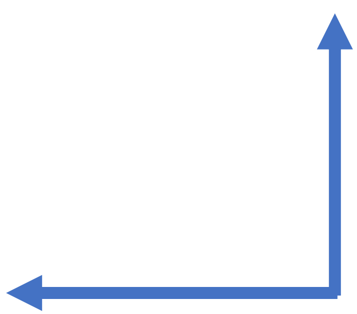
EIC Kinematical coverage

Polarized DIS



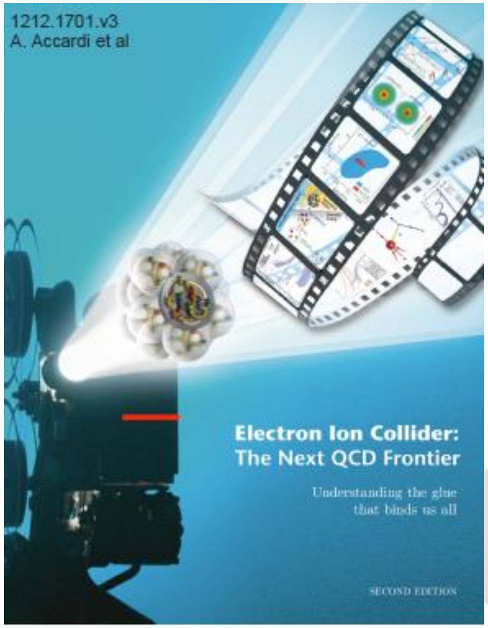
Nuclear DIS





Unprecedented coverage in kinematics.
Tremendous physics opportunities!

Scientific goals of EIC



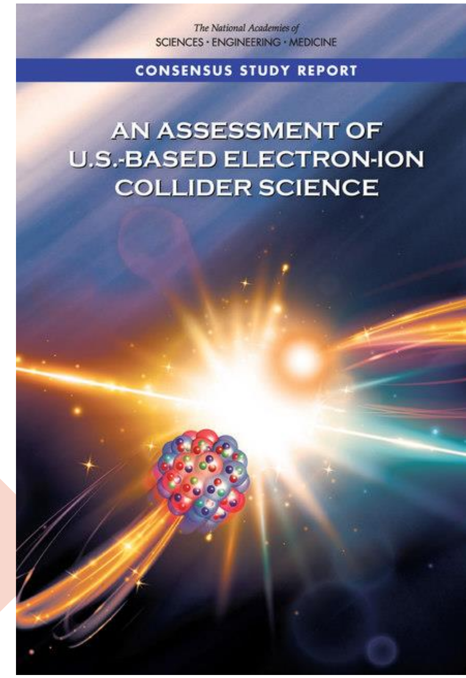
White paper
arXiv:1212.1701

Origin of nucleon mass

Origin of nucleon spin

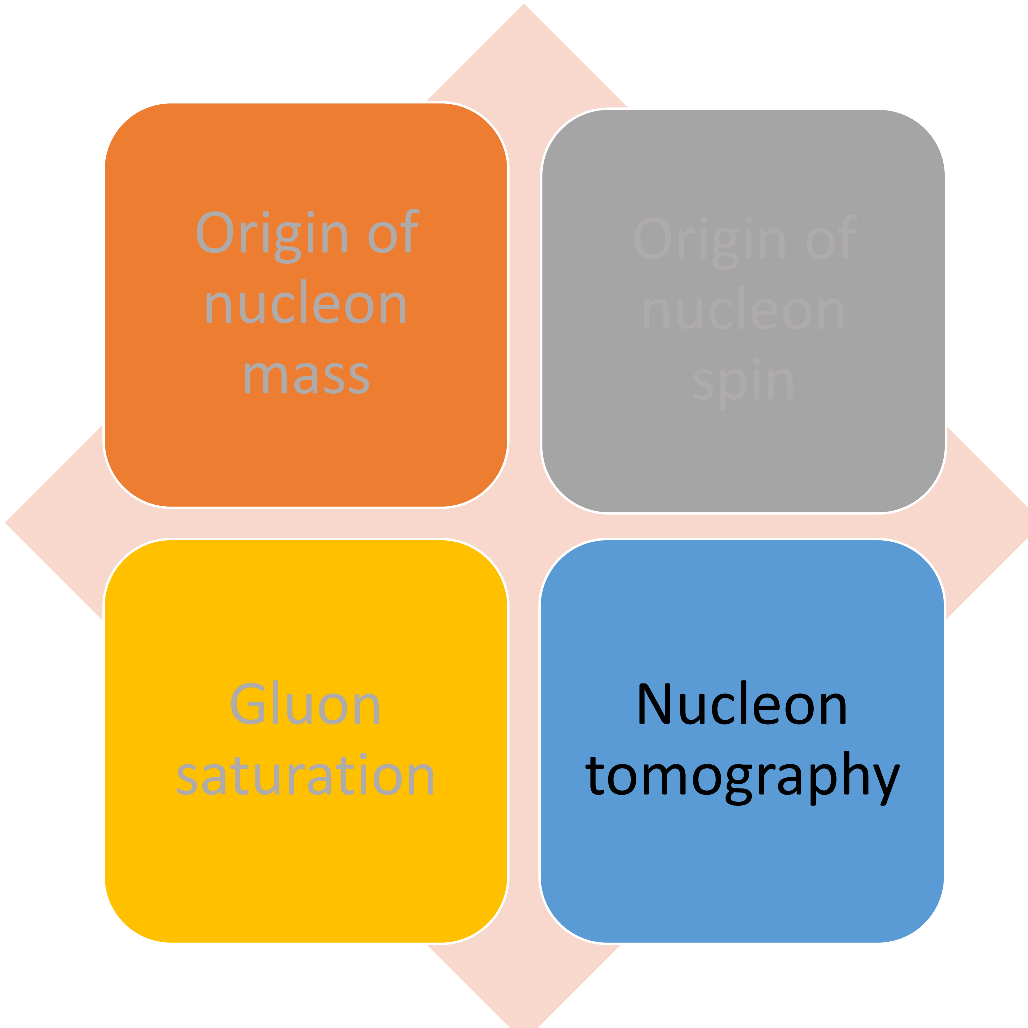
Gluon saturation

Nucleon tomography

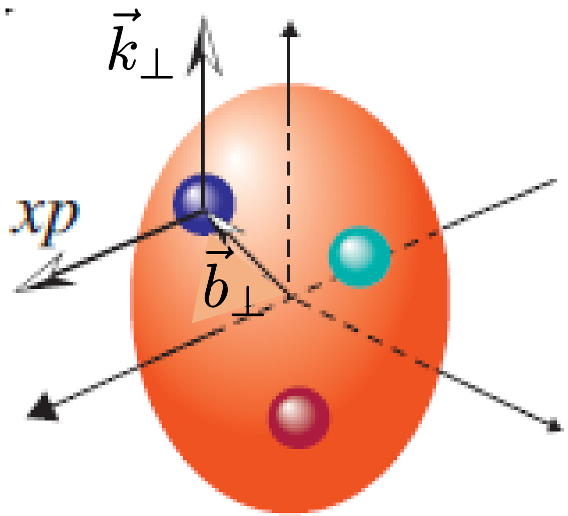


NAS report
July 2018

Scientific goals of EIC



Multi-dimensional tomography



$$u(x) = \int \frac{dz^-}{4\pi} \langle P|\bar{u}(0)\gamma^+ u(z^-)|P\rangle$$

Ordinary parton distribution functions (PDF) can be viewed as the 1D tomographic image of the nucleon

The nucleon is much more complicated!
Partons also have transverse momentum $\vec{k}_\perp$
and are spread in impact parameter space $\vec{b}_\perp$

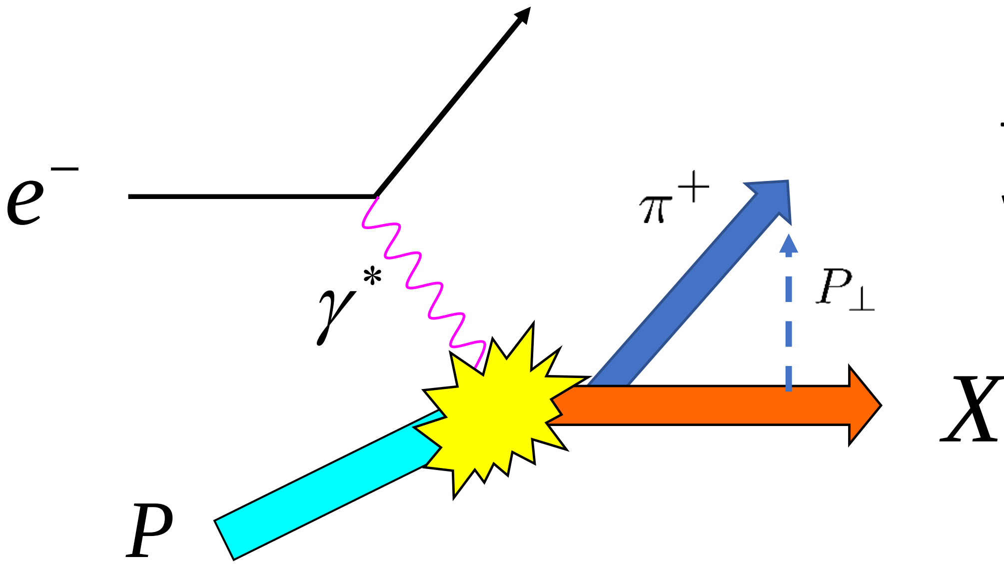
$u(x)$ →

$u(x, \vec{k}_\perp)$ Transverse momentum dependent distribution (TMD) 3D tomography

$u(x, \vec{b}_\perp)$ Generalized parton distribution (GPD) 3D tomography

$u(x, \vec{b}_\perp, \vec{k}_\perp)$ Wigner distribution 5D tomography

Semi-inclusive DIS



Tag one hadron species
with fixed transverse momentum $P_\perp$

When $P_\perp$ is small, TMD factorization

Collins, Soper, Sterman;
Ji, Ma, Yuan,…

$$\frac{d\sigma}{dP_\perp} = H(\mu)\int d^2q_\perp d^2k_\perp f(x,k_\perp,\mu,\zeta)D(z,q_\perp,\mu,Q^2/\zeta)\delta^{(2)}(zk_\perp + q_\perp - P_\perp) + \cdots$$

TMD PDF TMD FF

Open up a new class of observables where perturbative QCD is applicable!

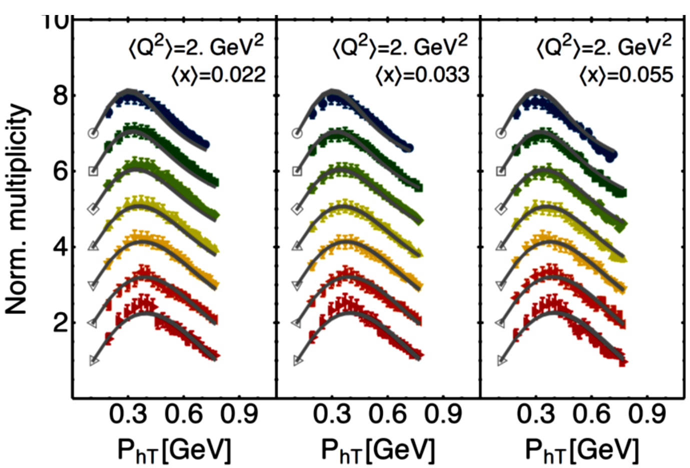
TMD global analysis

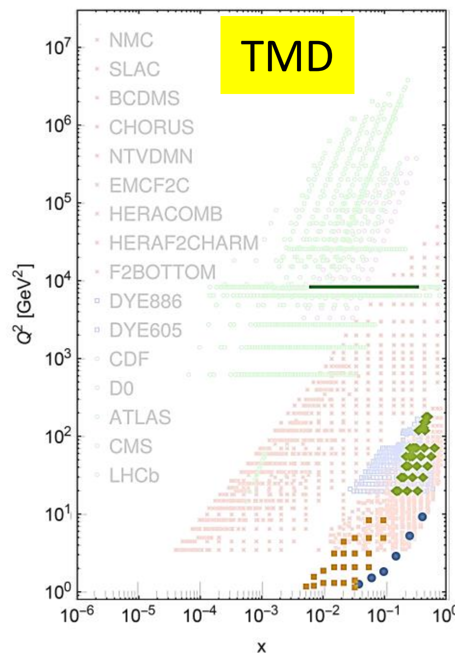
Global analysis of TMD based on ~8000 data points from SIDIS, Drell-Yan.

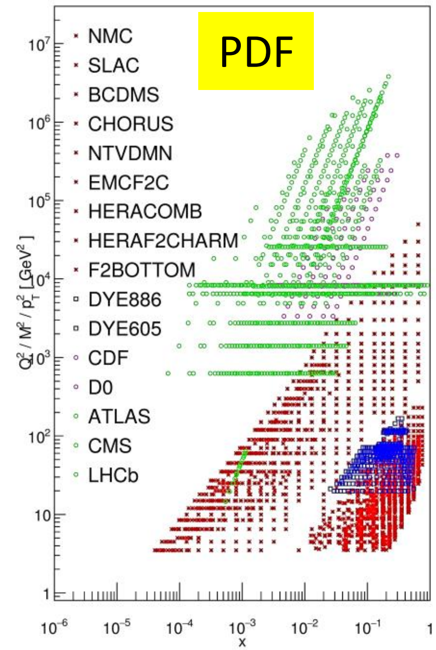
Bacchetta, Delcarro, Pisano, Radici, Signori (2017)

arTeMiDe   state-of-the-art (NNLO+NNLL) implementation   Scimemi, Vladimirov (2017)

TMDlib   public library   Hautmann, Jung, Mulders,…







Still in its infancy. Fully blossoms in the EIC era!

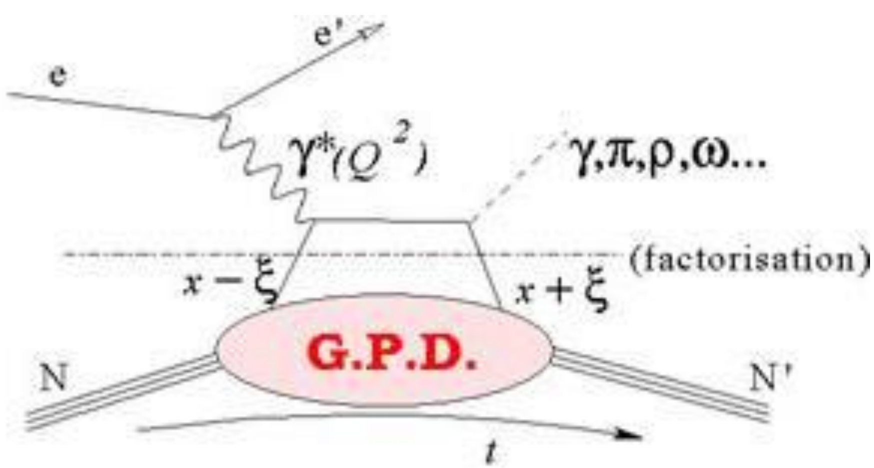
Generalized parton distributions (GPD)

$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu \psi(y^-)|PS\rangle$$

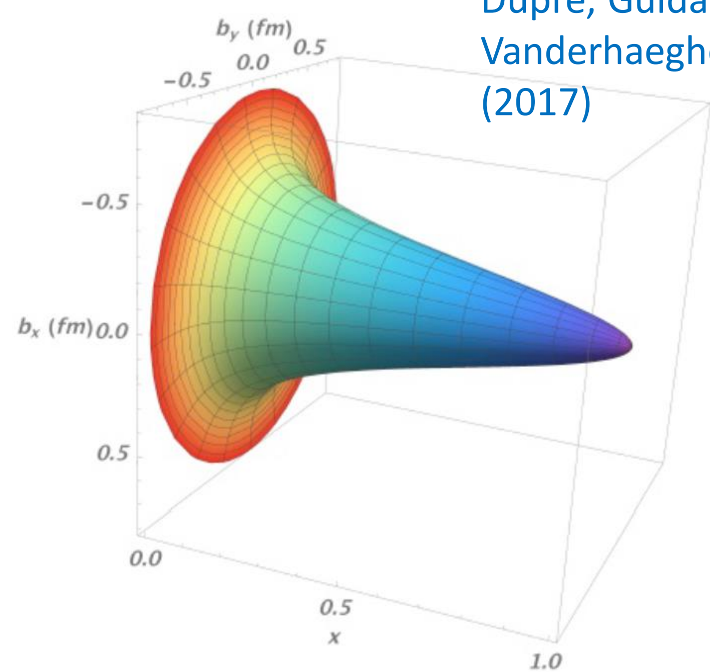
$$= H_q(x,\Delta)\bar{u}(P'S')\gamma^\mu u(PS) + E_q(x,\Delta)\bar{u}(P'S')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}u(PS) \qquad \Delta = P' - P$$

Fourier transform → Distribution of partons in impact parameter space $b_\perp$

Measurable in
Deeply Virtual Compton Scattering (DVCS)



Dupre, Guidal, Vanderhaeghen (2017)



Towards measuring GPD E at the EIC

Ji sum rule for proton spin $$\frac{1}{2} = J_q + J_g$$

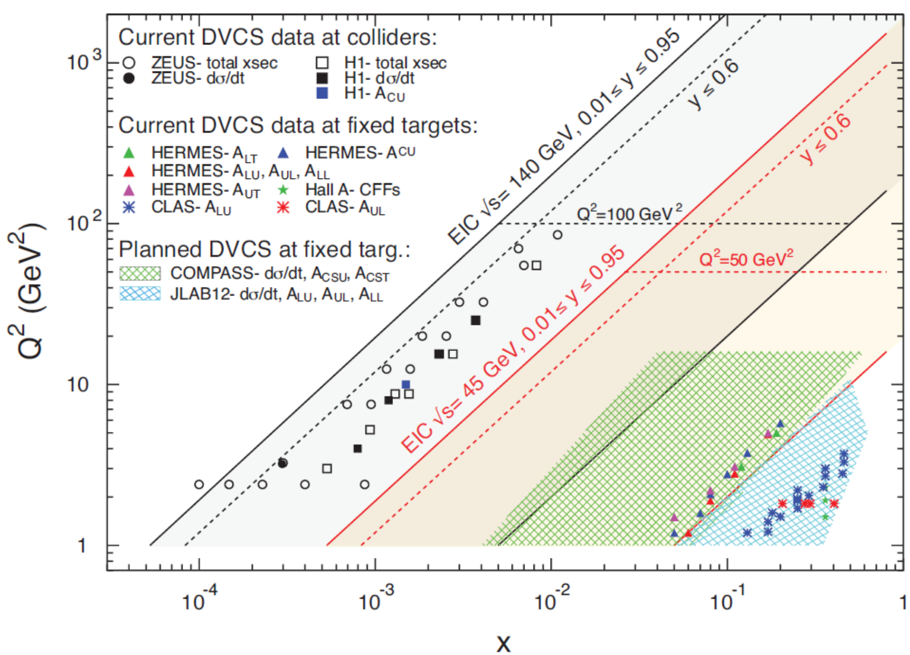
$$J_q = \frac{1}{2}\int dx(H_q(x) + E_q(x)) \qquad J_g = \frac{1}{4}\int dx(H_g(x) + E_g(x))$$

Currently very little is known about E_q, nothing about E_g from experiments.

At EIC, we can get a handle on E_q.

Aschenauer, Fazio, Kumericki, Muller (2013)

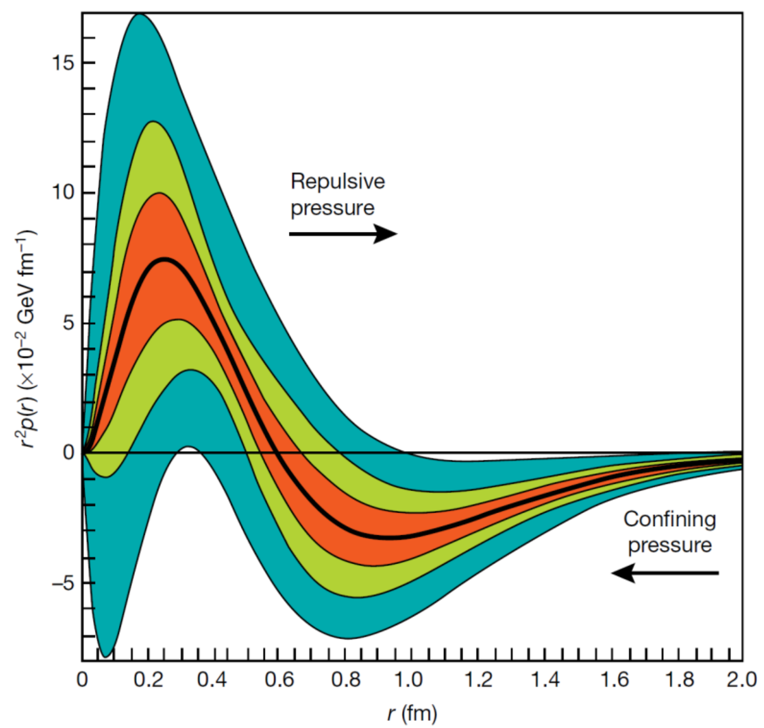
E_g is still challenging, but EIC is the only hope.



D-term: the last global unknown

$$\langle P'|T^{ij}|P\rangle \sim (\Delta^i\Delta^k - \delta^{ik}\Delta^2)D(t)$$

Burkert, Elouadrhiri, Girod (Nature, 2018)



$D(t=0)$ is a conserved charge of the nucleon, just like mass and spin!

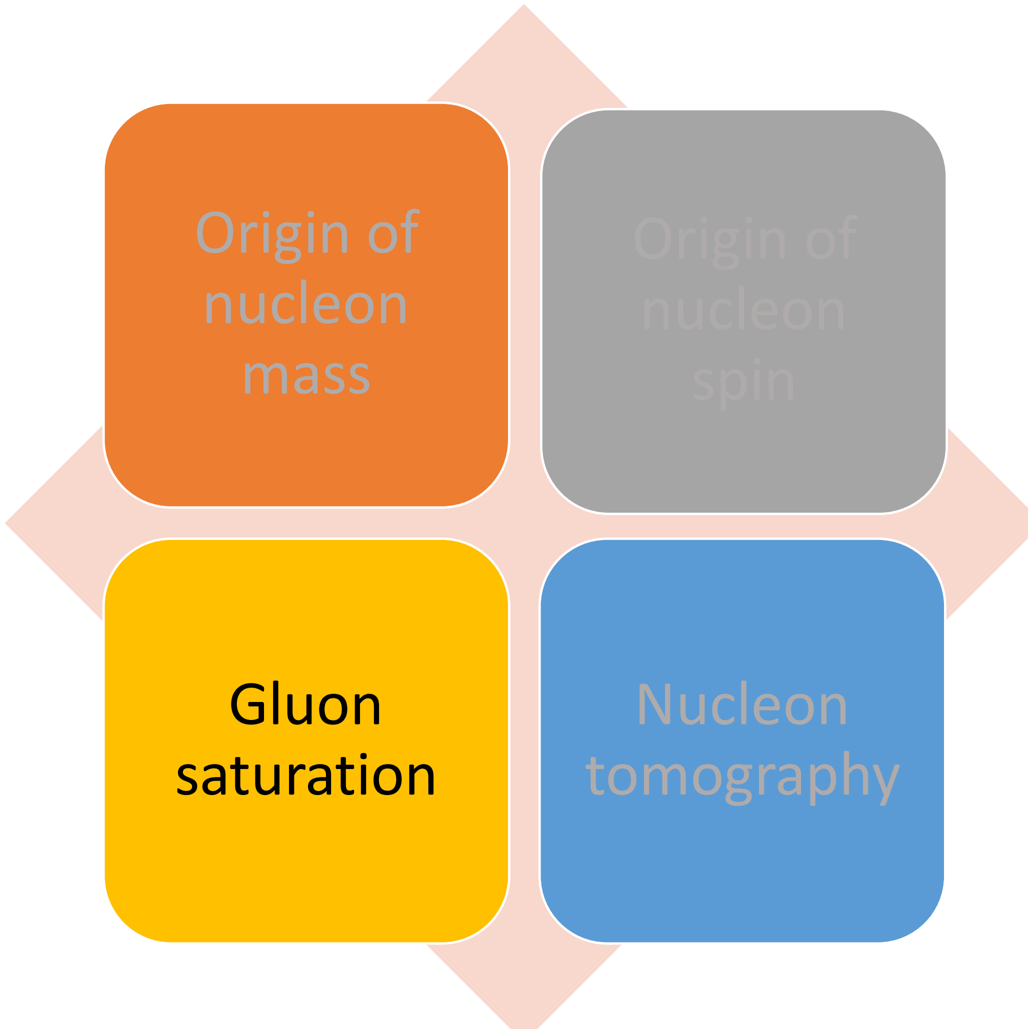
Related to the radial pressure distribution inside a nucleon   Polyakov, Schweitzer,...

$$T^{ij}(r) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right)s(r) + \delta^{ij}p(r)$$

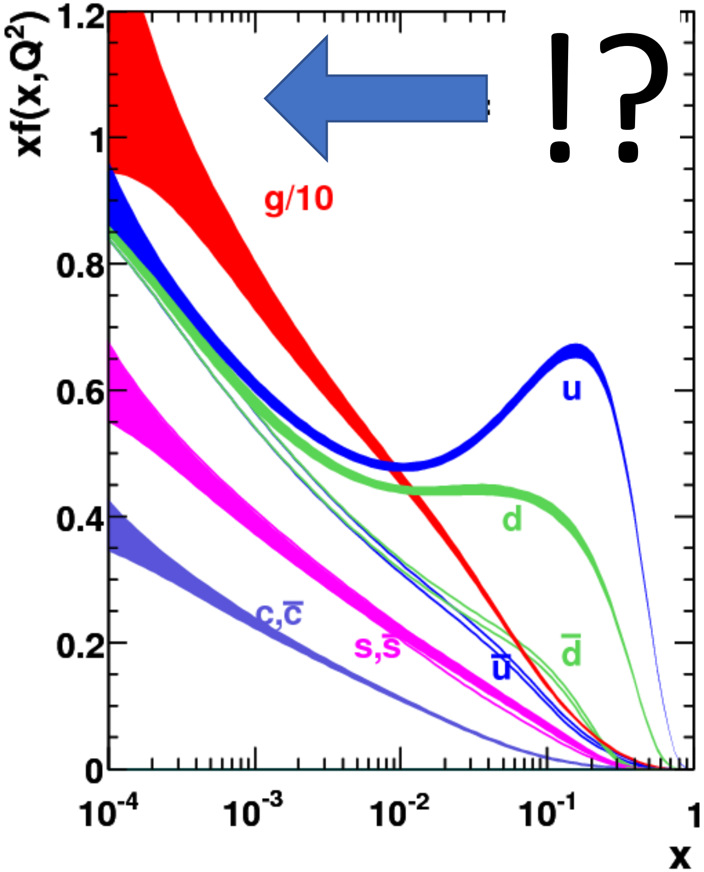
First extraction at Jlab, large model dependence.
Need significant lever-arm in Q^2 to disentangle various moments of GPDs

→ EIC

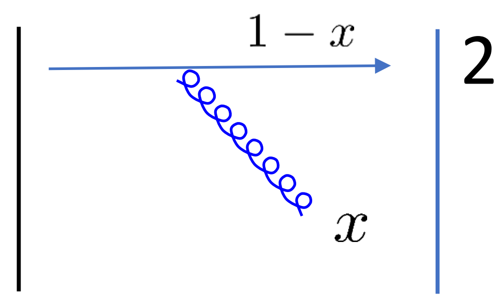
Scientific goals of EIC



QCD at small-x



Probability to emit a soft gluon diverges



$$\propto \frac{1}{x}$$

A myriad of small-x gluons
in a high energy hadron/nucleus!

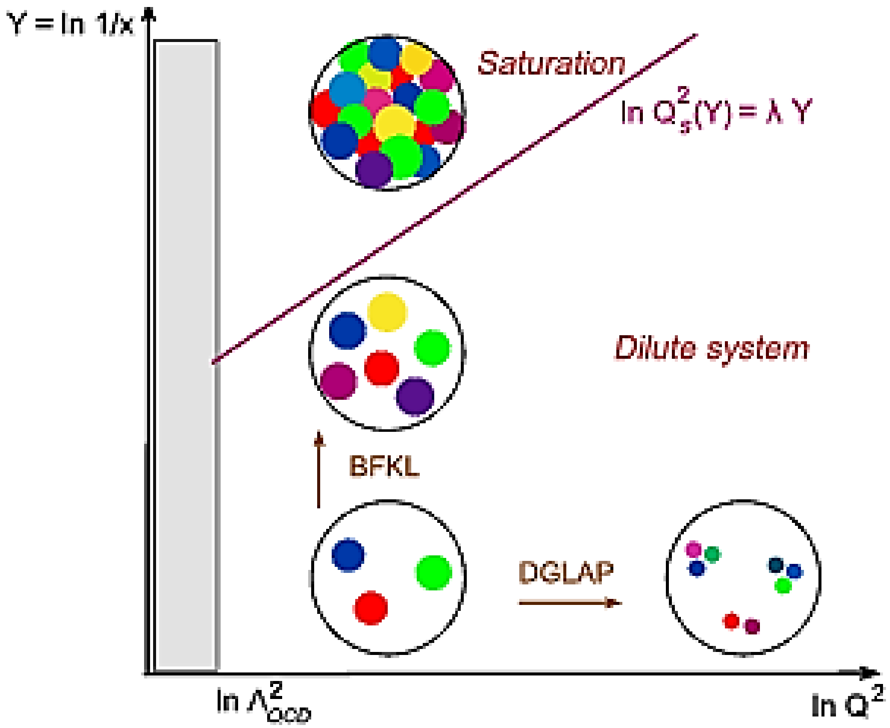
as predicted by BFKL
(Balitsky-Fadin-Kuraev-Lipatov)

$$\sum_n \frac{1}{n!}\left(\alpha_s \ln 1/x\right)^n \sim \left(\frac{1}{x}\right)^{\alpha_s}$$

Gluon saturation

The gluon number eventually saturates, forming the universal QCD matter at high energy called the Color Glass Condensate.

Gribov, Levin, Ryskin (1980); Mueller, Qiu (1986); McLerran, Venugopalan (1993)



Gluons overlap when

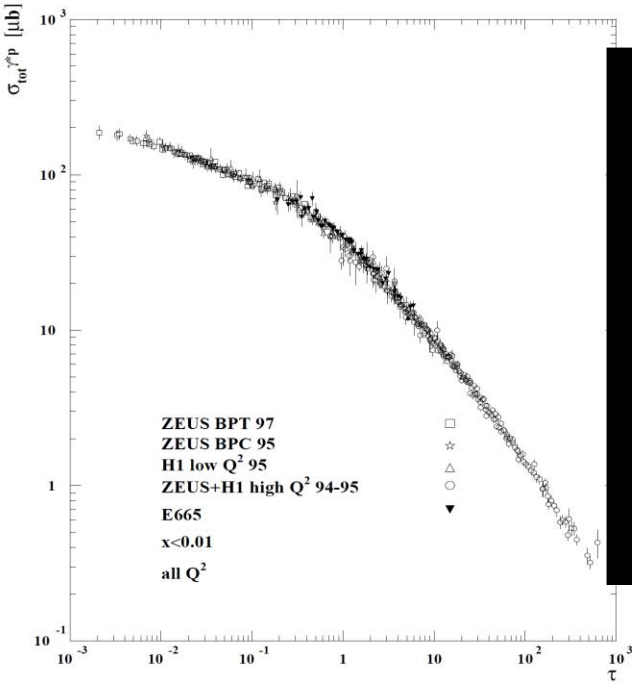
$$\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2$$

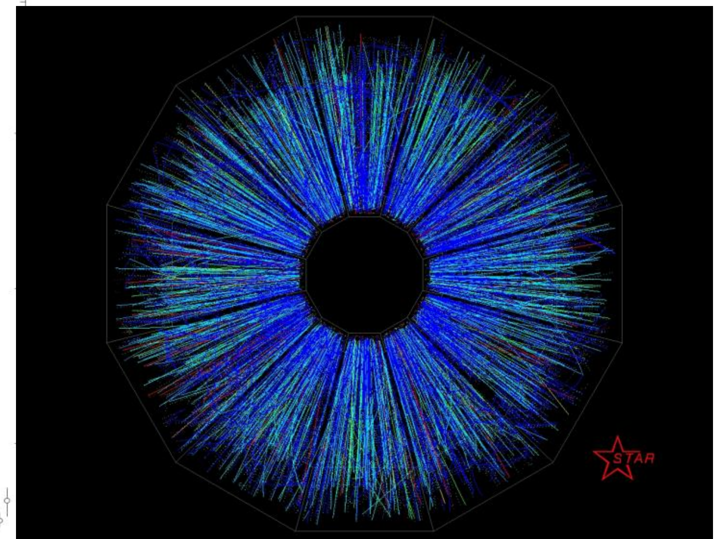
The saturation momentum

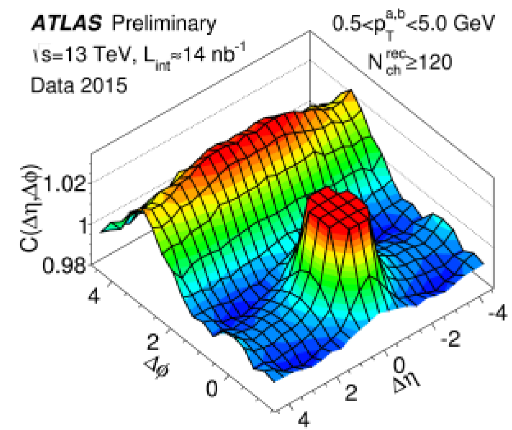
$$Q = Q_s(x) \gg \Lambda_{QCD}$$

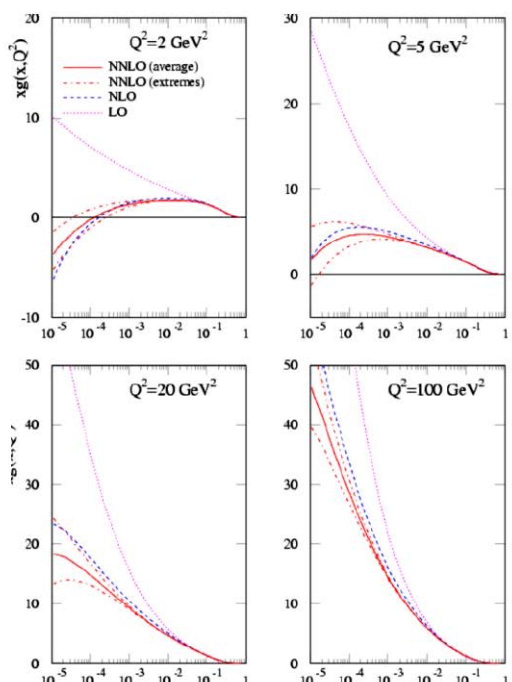
High density, but weakly coupled many-body problem

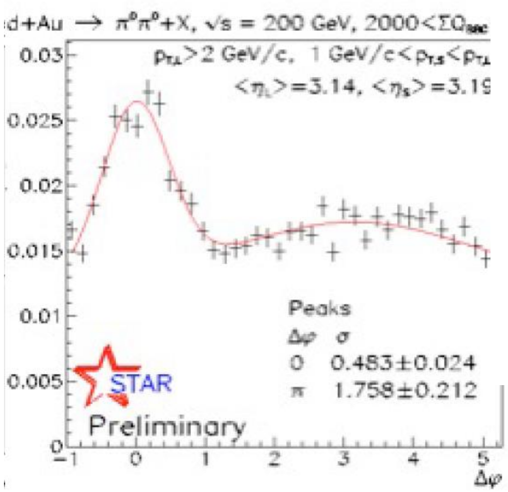
Has saturation been observed at HERA, RHIC, LHC?

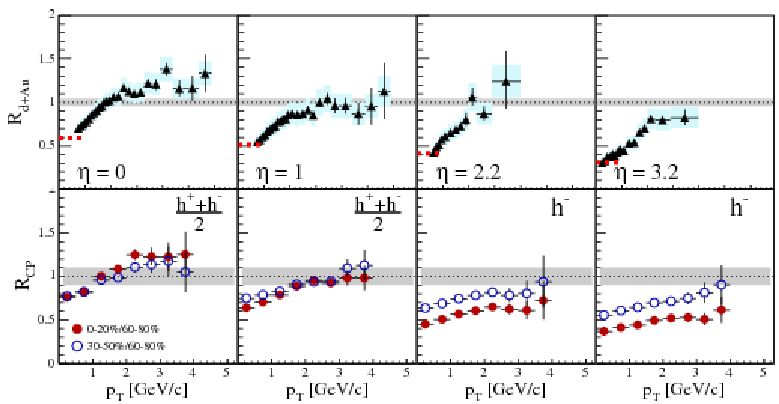








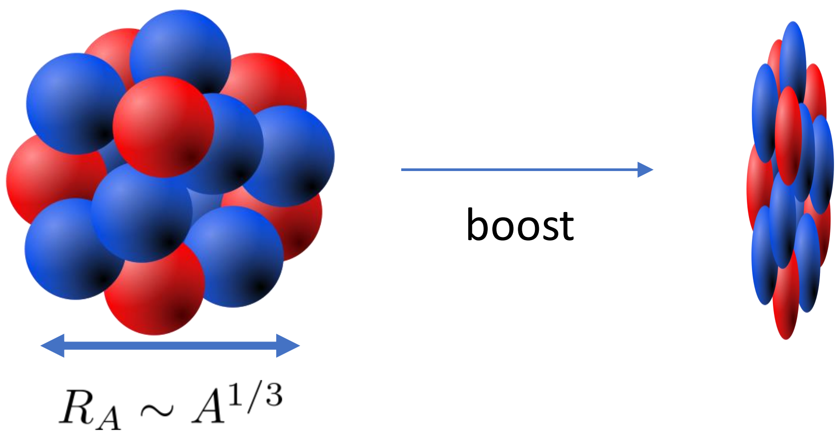




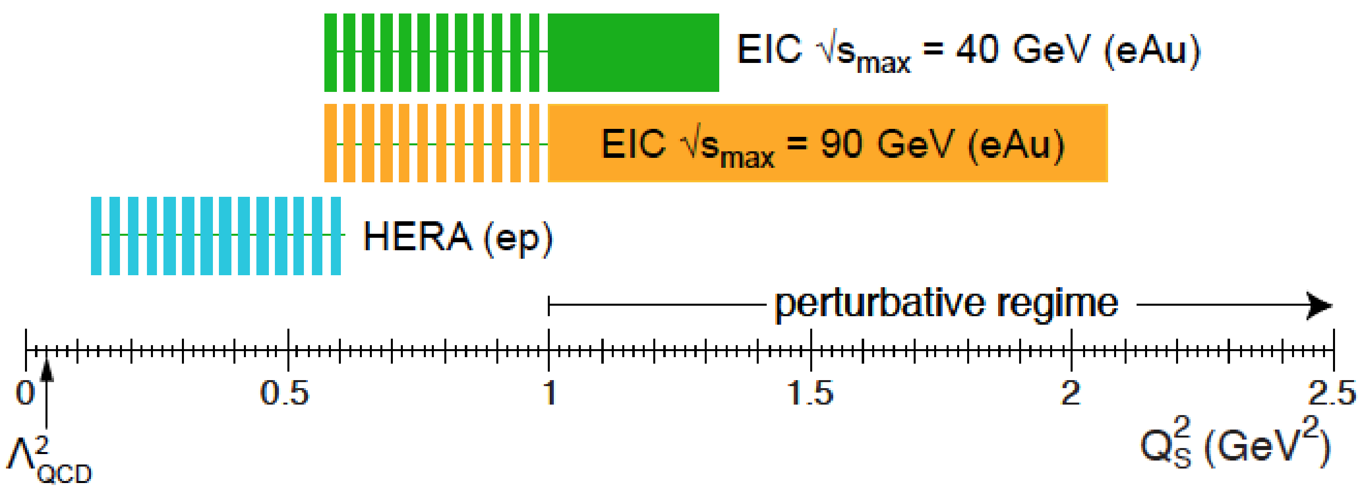
eA collision at EIC : ideal place to study saturation

No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)



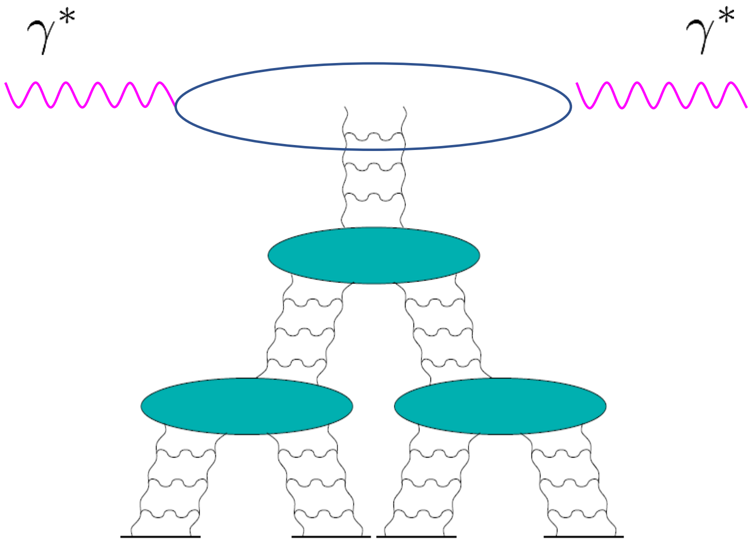
$$Q_s^2 \propto A^{1/3}$$



BK-JIMWLK equation

Balitsky
Kovchegov
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

Photon-nucleus scattering at high energy



$\equiv S$

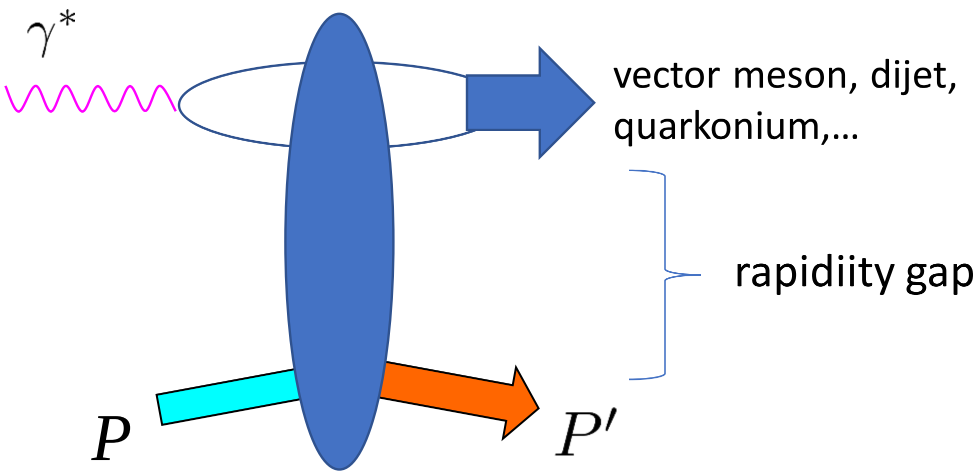
Leading Logarithmic (LL) evolution of the scattering amplitude with energy

$$\frac{\partial}{\partial \ln 1/x} S(r_\perp) = \frac{N_c \alpha_s}{2\pi} \int d^2 r_\perp \frac{r_\perp^2}{z_\perp^2 (r_\perp - z_\perp)^2} \left(S(z_\perp) S(z_\perp - r_\perp) - S(r_\perp) \right)$$

Extension to NLL Balitsky, Chirilli (2008)
Even to NNLL? Caron-Huot (2016)

State-of-the-art: NLL' + NLO

Golden channel for saturation: Diffraction



Cross sections proportional to the square of the gluon distribution

→ More sensitive to saturation

`Day 1 prediction' Kowalski, Lappi, Marquet, Venugopalan (2008)

$$\left.\frac{\sigma_{diff}}{\sigma_{tot}}\right|_{eA} \approx 20\% > \left.\frac{\sigma_{diff}}{\sigma_{tot}}\right|_{ep}$$

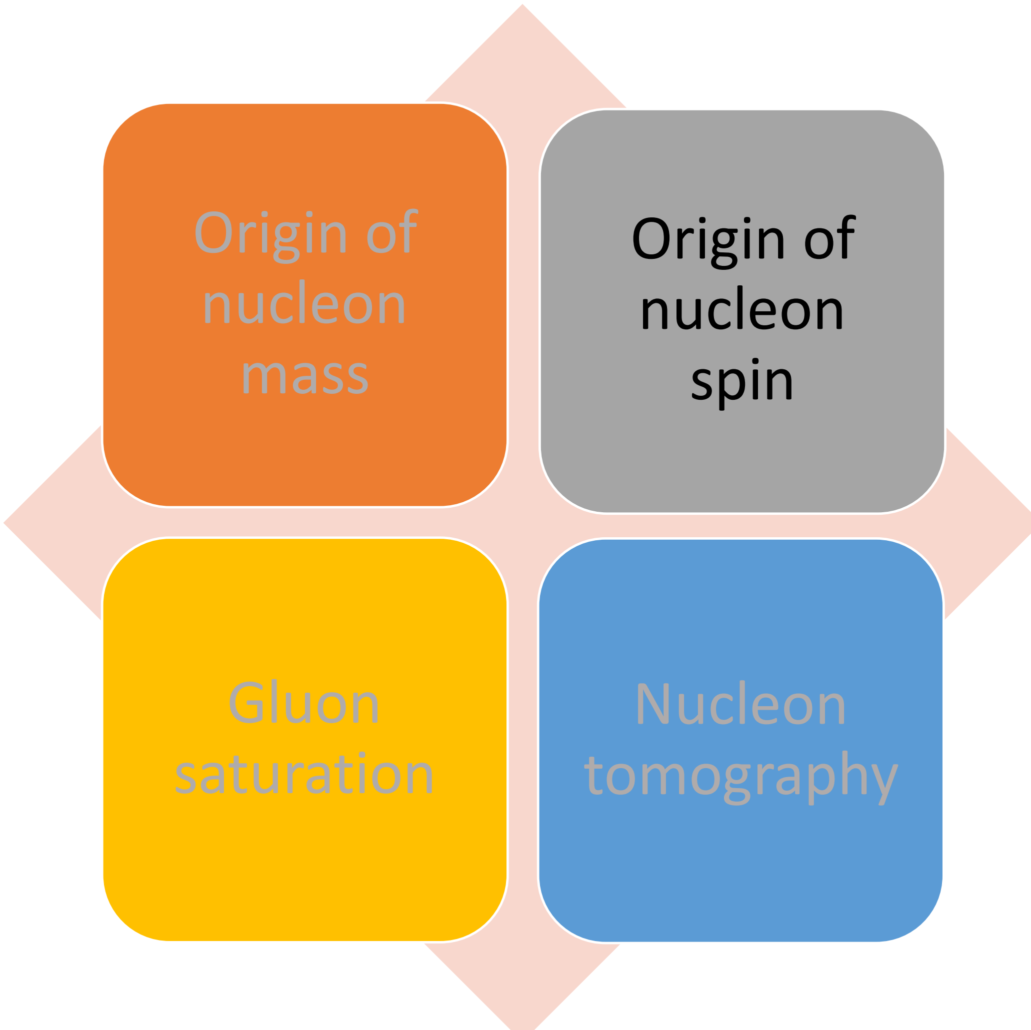
Nucleus stays intact in every 1 out of 5 events!

Recent trend: Expand in scope and reach out to other topics of EIC

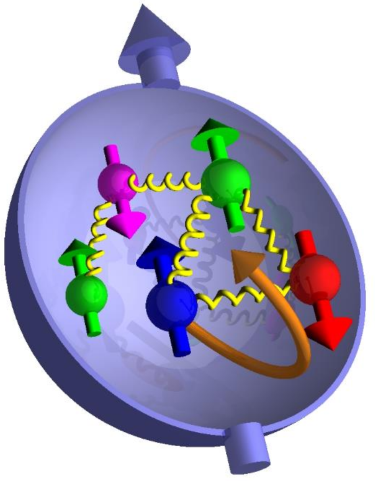
Small-x and saturation physics strongly connected to

TMD, GPD, Wigner, spin, jets, integrability, AdS/CFT, entanglement entropy,…

Scientific goals of EIC



Proton spin decomposition



The proton has spin ½.
The proton is not an elementary particle.

Jaffe-Manohar sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Quarks' helicity

Gluons' helicity

Orbital angular Momentum (OAM)

$\Delta\Sigma = 1$ in the quark model

Spin crisis

In 1987, EMC (European Muon Collaboration) announced a very small value of the quark helicity contribution

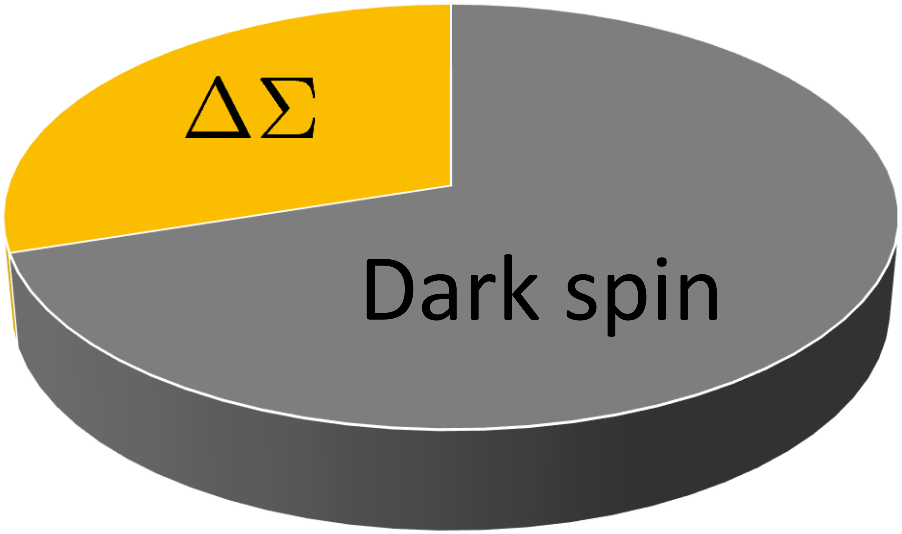
$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14 \ \ !?$$

Recent values from NLO global analysis

$$\Delta\Sigma = 0.25 \sim 0.3$$

$$\int_{0.05}^{1} dx \Delta G(x, Q^2) \approx 0.2 \pm^{0.06}_{0.07}$$

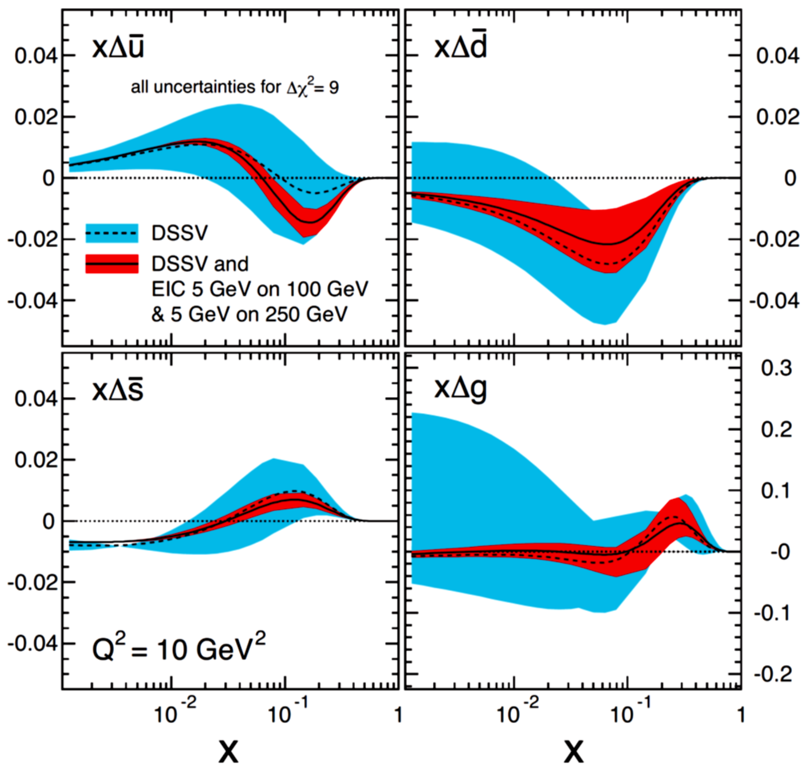
DeFlorian, Sassot, Stratmann, Vogelsang (2014)

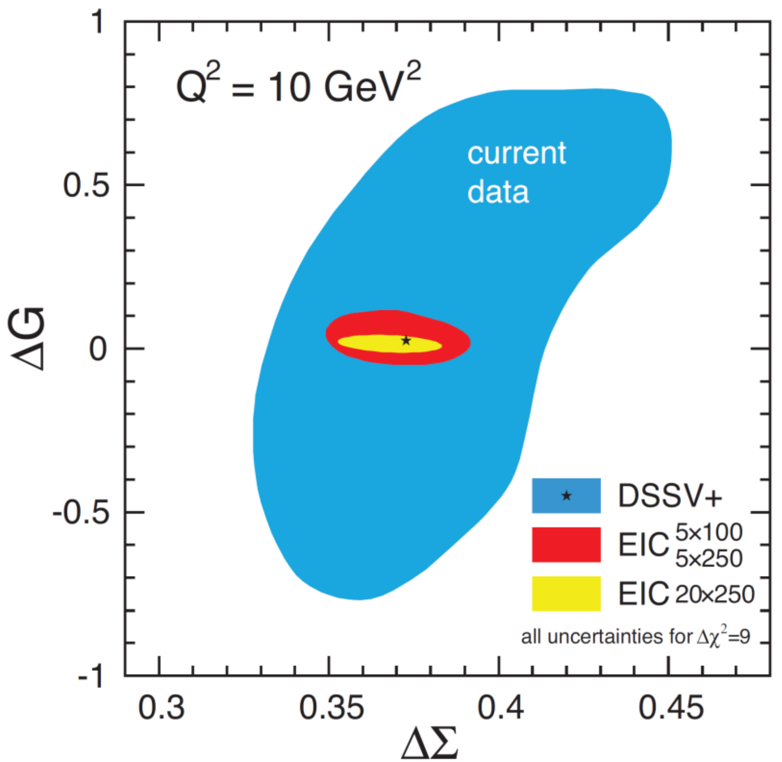


Warning: Huge uncertainties from the small-x region

Helicity measurements at EIC

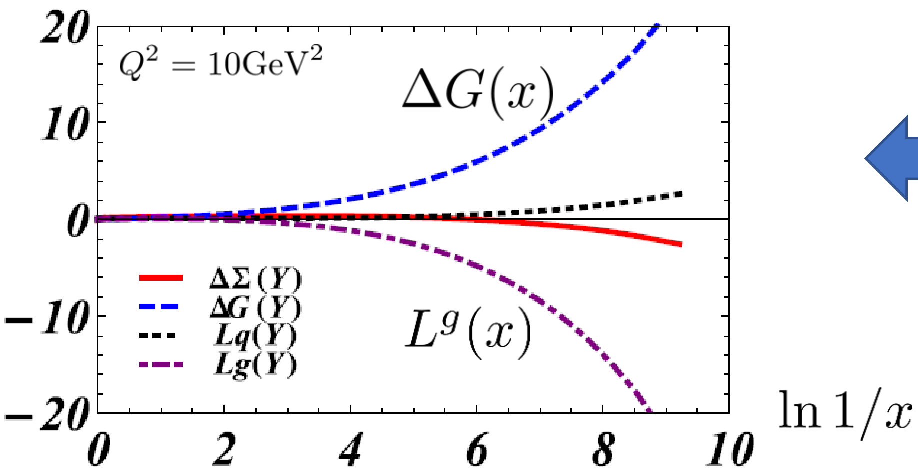
After one-year of data taking at EIC…





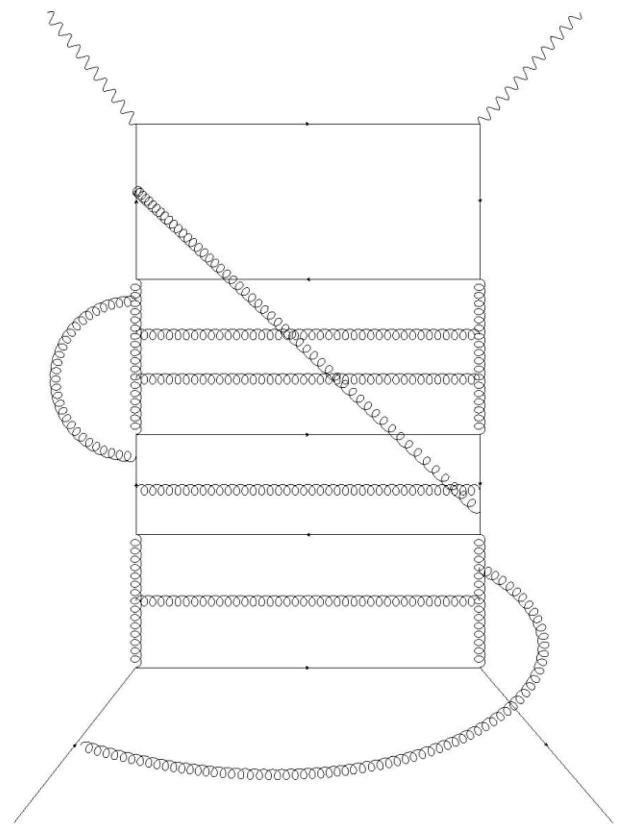
Wider coverage in x and Q^2… finally solve the spin puzzle? No!

Don't forget Orbital Angular Momentum. It's there!



Significant cancellation at small-x from one-loop DGLAP

YH, Yang (2018)



All-loop resummation of small-x double logarithms $(\alpha_s \ln^2 1/x)^n$ gives

$$L_g(x) \approx -2\Delta G(x)$$

Boussarie, YH, Yuan (2019)

see, also, Kovchegov (2019)

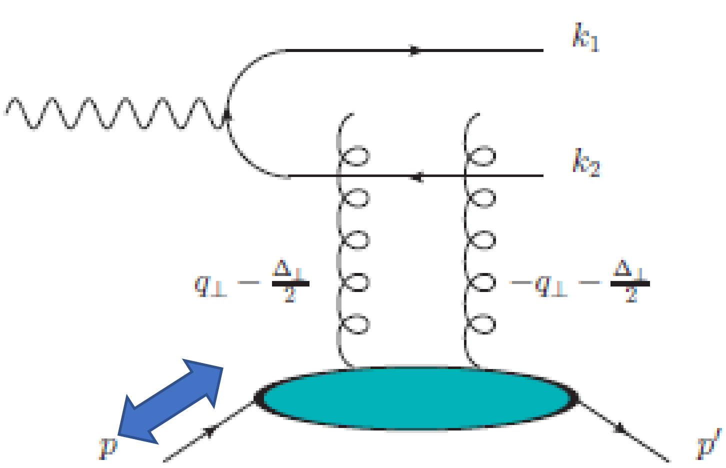
Measuring OAM at EIC

Ji, Yuan, Zhao (2016)
YH, Nakagawa, Xiao, Yuan, Zhao (2016)
Bhattacharya, Metz, Zhou (2017)

Exploit the connection between OAM and the Wigner distribution

$$L^{q,g} = \int dx \int d^2 b_\perp d^2 k_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z W^{q,g}(x, \vec{b}_\perp, \vec{k}_\perp)$$

Longitudinal single spin asymmetry in diffractive dijet production



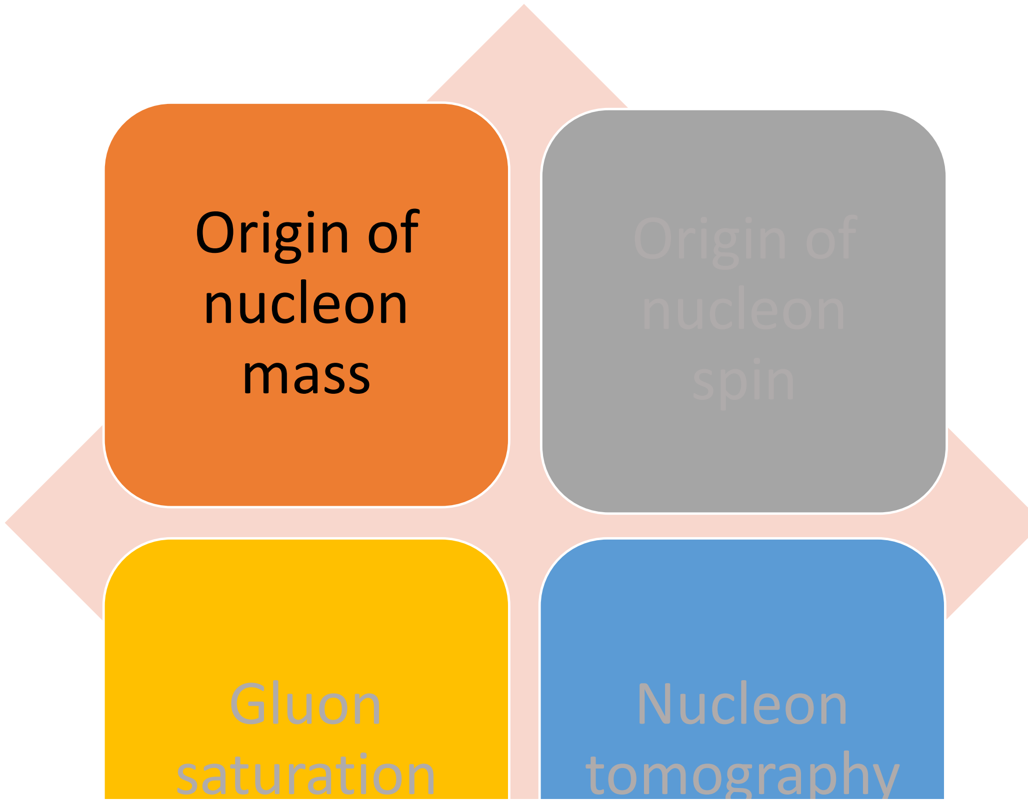
proton recoil momentum

$$\sigma^{\rightarrow} - \sigma^{\leftarrow} \propto \sin(\phi_P - \phi_\Delta)$$

dijet relative momentum

Need more work, more new ideas!

Scientific goals of EIC



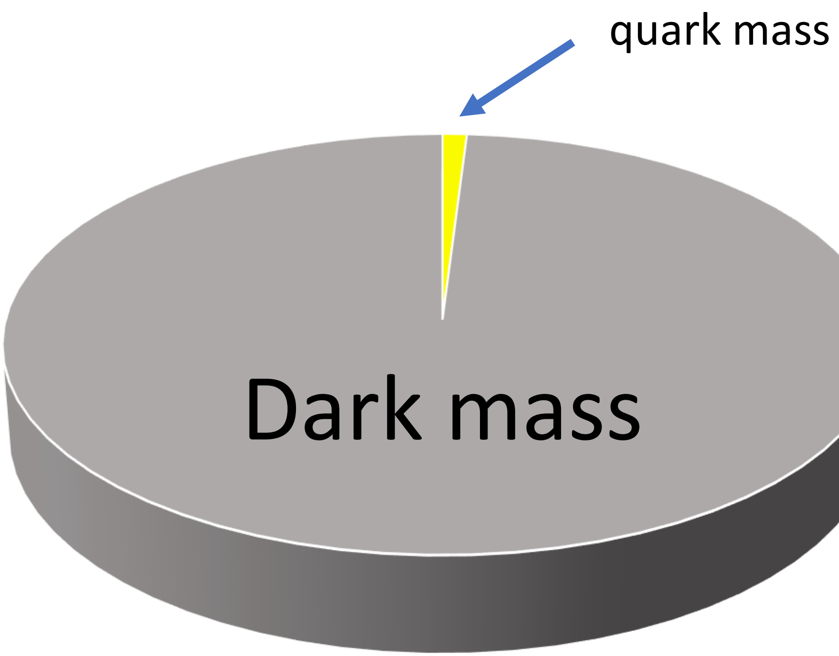
Finding 1: An EIC can uniquely address three profound questions about nucleons-
protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

NAS report
(2018/07)

Proton mass crisis

u,d quark masses add up to ~10MeV, only 1 % of the proton mass!



Higgs mechanism explains quark masses, but not hadron masses!

The trace anomaly

QCD Lagrangian approximately scale (conformal) invariant.
Why is the proton mass nonvanishing in the first place?

Conformal symmetry is explicitly broken by the trace anomaly.

QCD energy-momentum tensor

$$T^{\mu\nu} = -F^{\mu\lambda}F^{\nu}{}_{\lambda} + \frac{\eta^{\mu\nu}}{4}F^2 + i\bar{q}\gamma^{(\mu}D^{\nu)}q$$

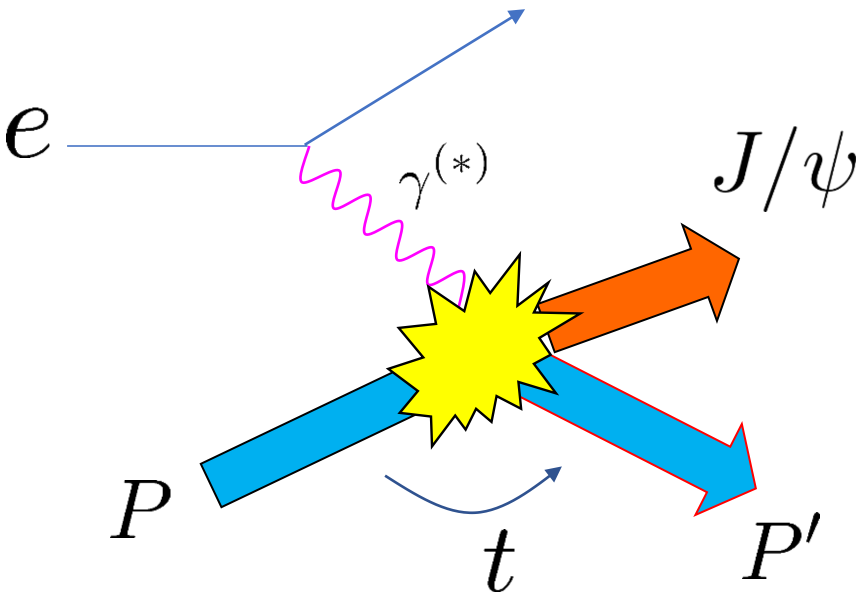
$$T^{\mu}_{\mu} = \frac{\beta(g)}{2g}F^2 + m(1+\gamma_m(g))\bar{q}q$$

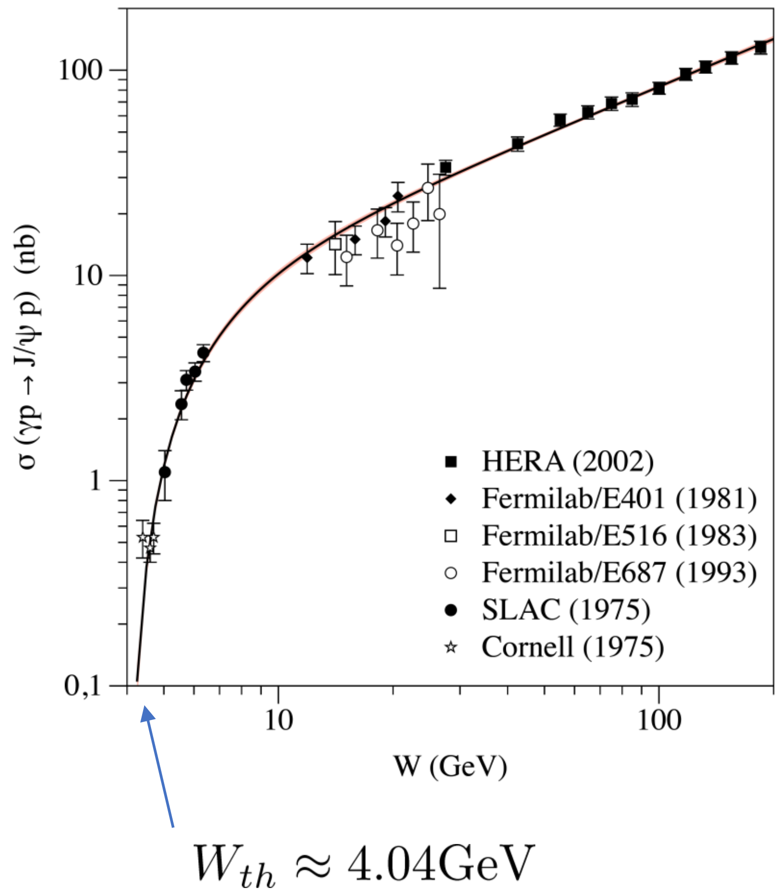
$$\langle P|T^{\mu}_{\mu}|P\rangle = 2M^2$$

Photo-production of J/ψ near threshold

Kharzeev, Satz, Syamtomov, Zinovjev (1998)
Brodsky, Chudakov, Hoyer, Laget (2000)

Sensitive to the matrix element $\langle P'|F^{\mu\nu}F_{\mu\nu}|P\rangle$





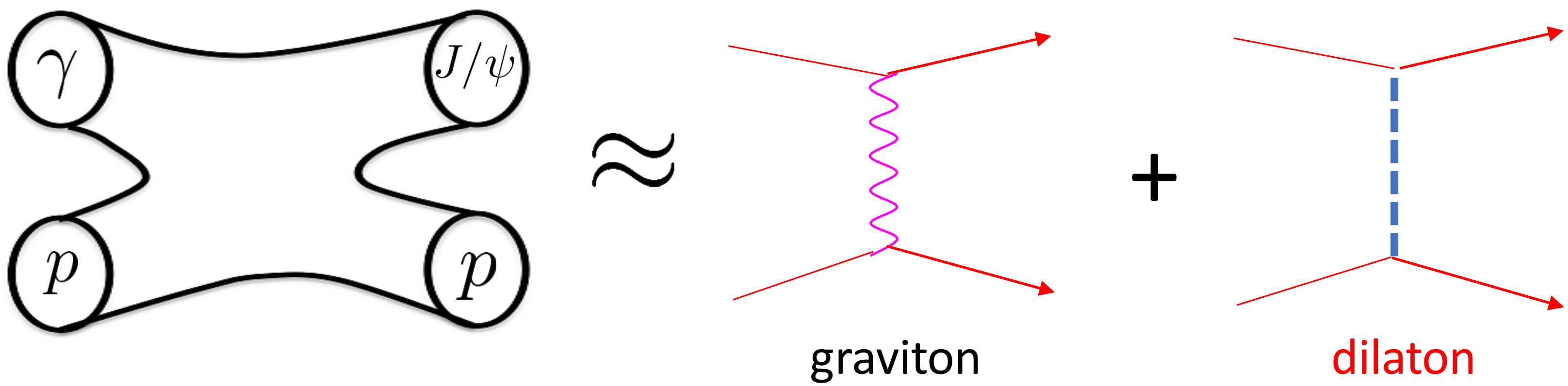
Straightforward to measure.
Ongoing experiments at Jlab.

Difficult to compute from first principles
(need nonperturbative approaches)

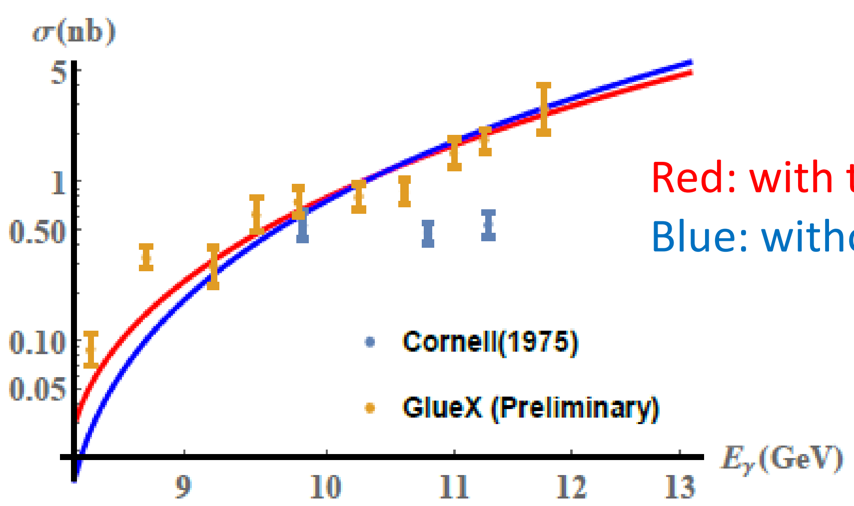
Holographic approach

YH, Yang (2018)

The operator $F^{\mu\nu}F_{\mu\nu}$ is dual to a massless string called dilaton



Suppressed compared to graviton exchange at high energy, but not at very low energy!



Red: with trace anomaly

Blue: without trace anomaly

At EIC, use Υ instead.

The heavier, the better.

Conclusion

- EIC will significantly advance our knowledge of the nucleons/nuclei, the fundamental building blocks of the universe.
- Topics not covered include:

  jets, lattice, EMC and short-range correlation, transverse spin, UPC, nPDF, etc. etc.

The scope of EIC is so broad that everyone can find his/her favorite topics. Everyone welcome.