EIC theory overview

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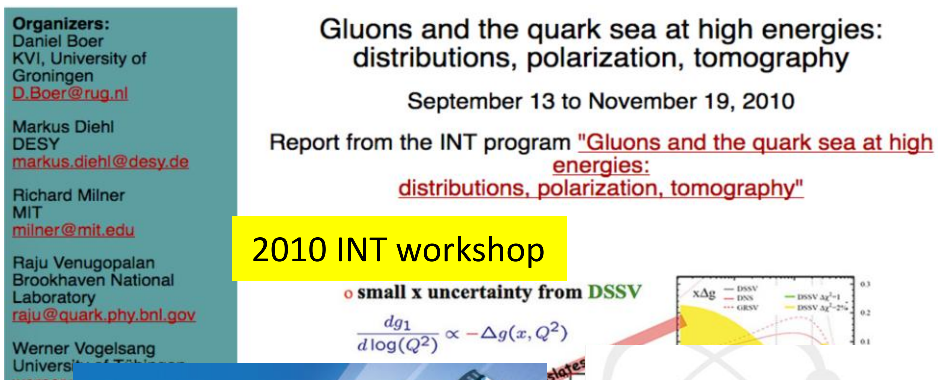
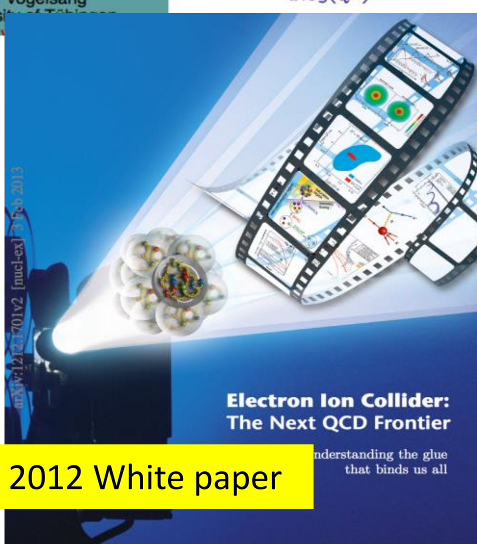
Electron-Ion Collider (EIC)

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

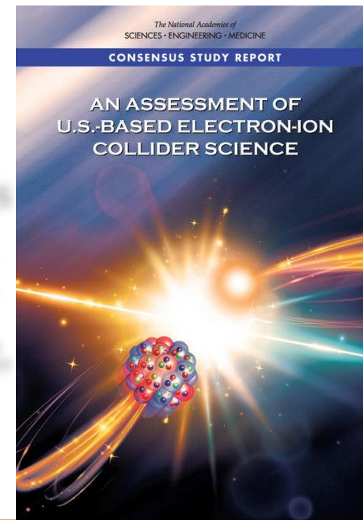


2012 White paper

2015 NSAC Long Range Plan

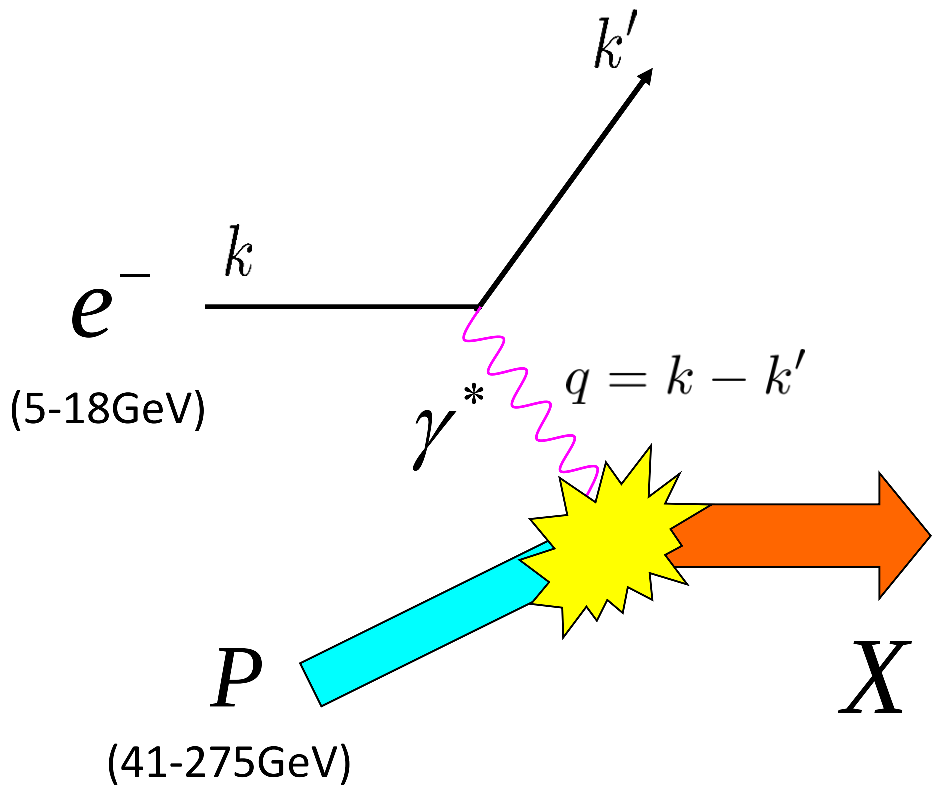
2018 NAS report

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



2018 INT workshop

Experiment at EIC: Deep Inelastic Scattering (DIS)



Two most important kinematic variables

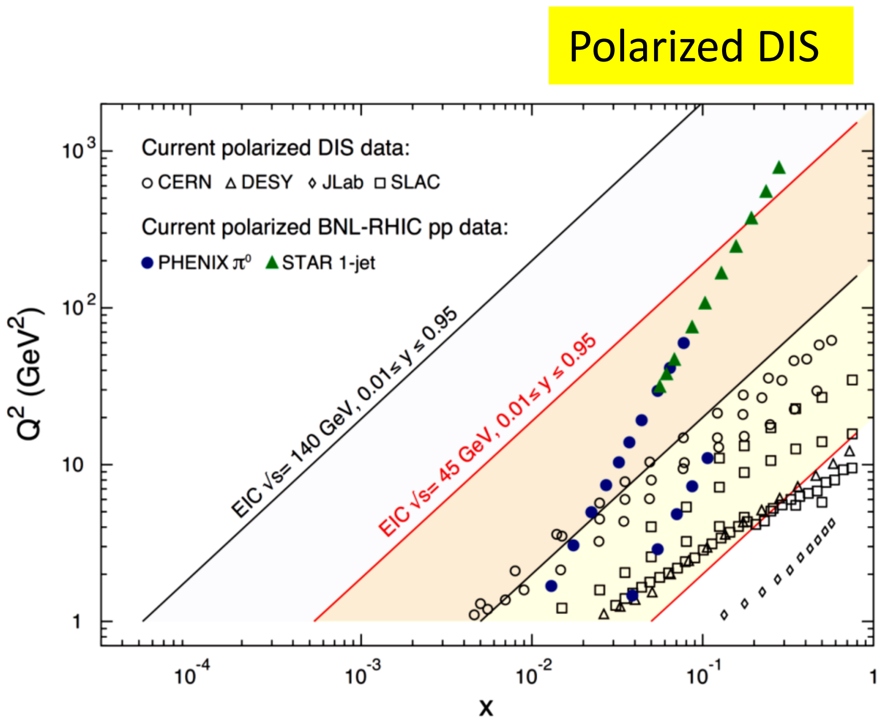
$$Q^2 = -q^2$$ photon virtuality (resolution)

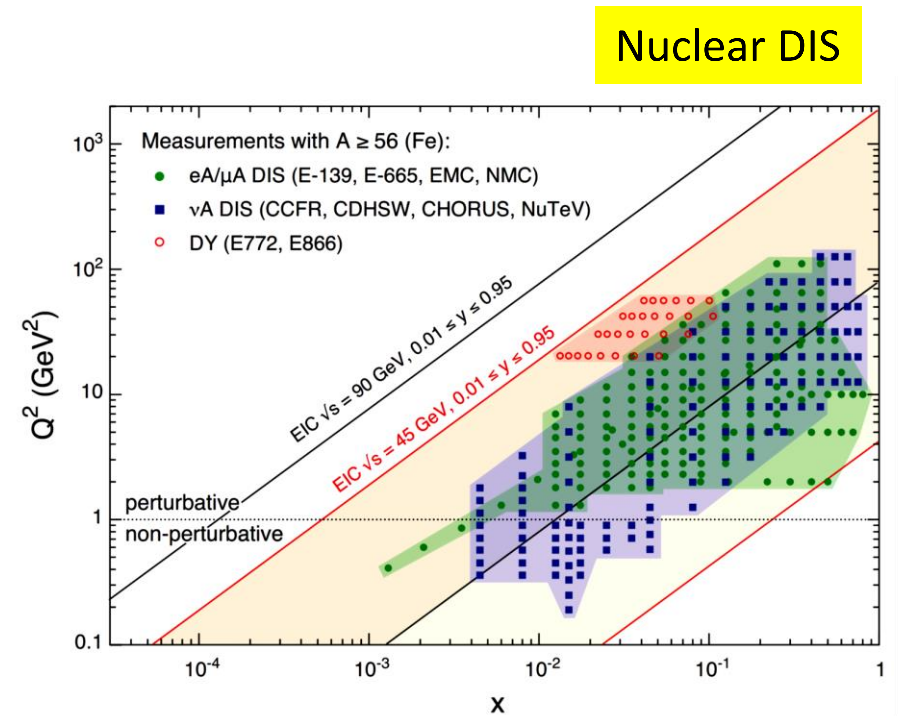
$$x = \frac{Q^2}{2P \cdot q} \approx \frac{E_{parton}}{E_{proton}}$$ Bjorken variable (inverse energy)

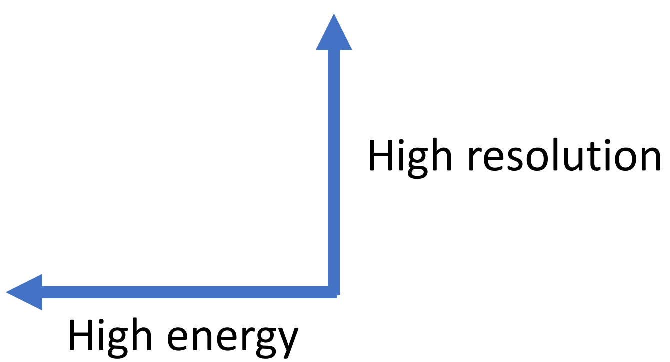
Proton, deuteron, helium, gold…any nucleus of your choice!

Electron, proton and light nuclei can be polarized.

EIC Kinematical coverage

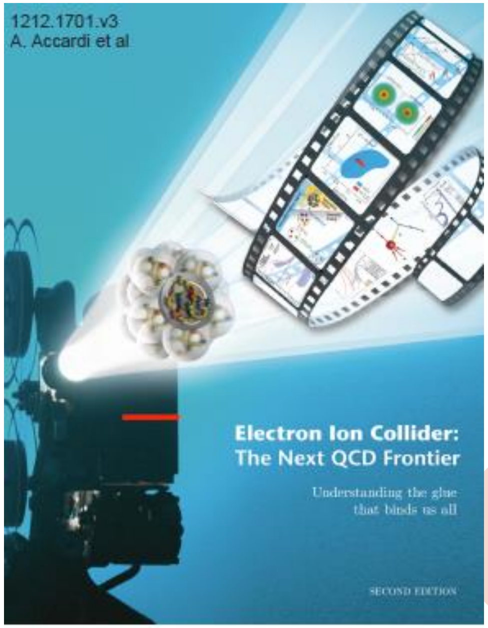






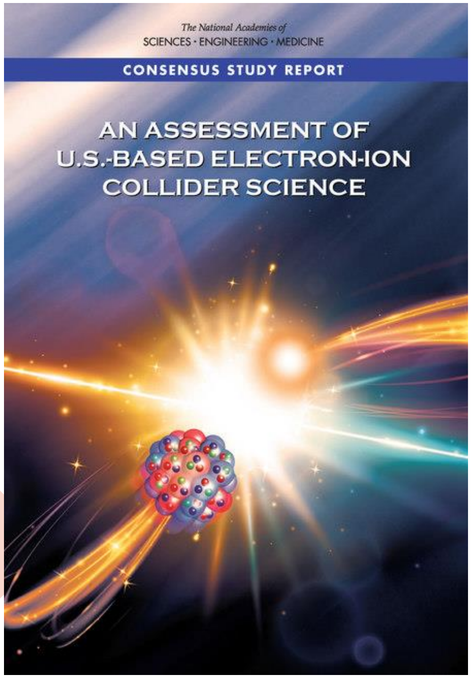
Unprecedented coverage in kinematics.
Tremendous physics opportunities!

Scientific goals of EIC



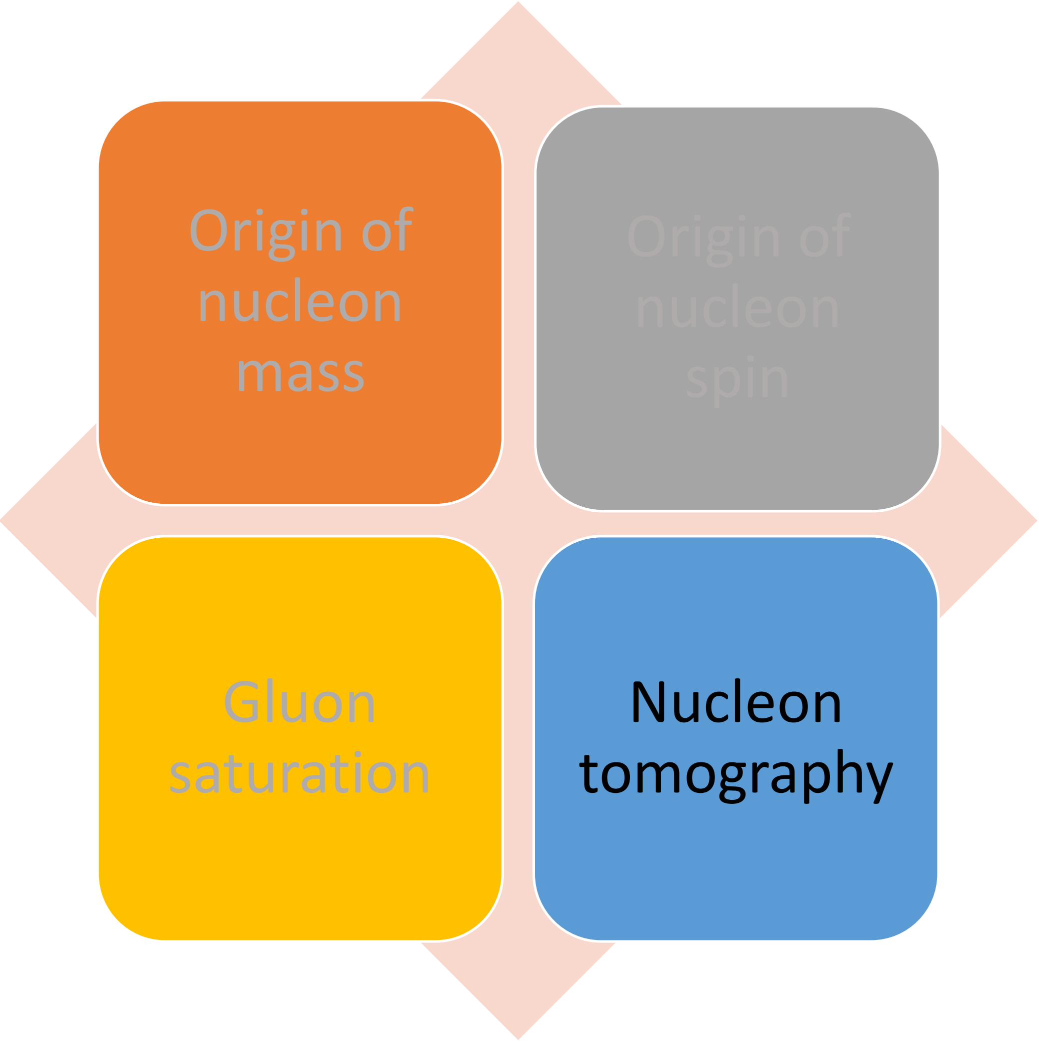
White paper
arXiv:1212.1701

- Origin of nucleon mass
- Origin of nucleon spin
- Gluon saturation
- Nucleon tomography

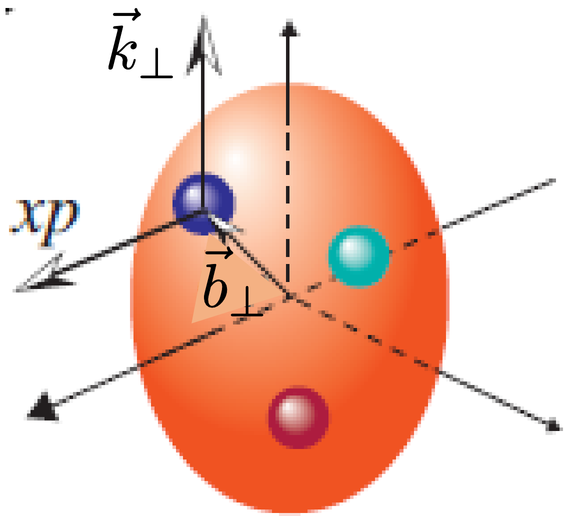


NAS report
July 2018

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

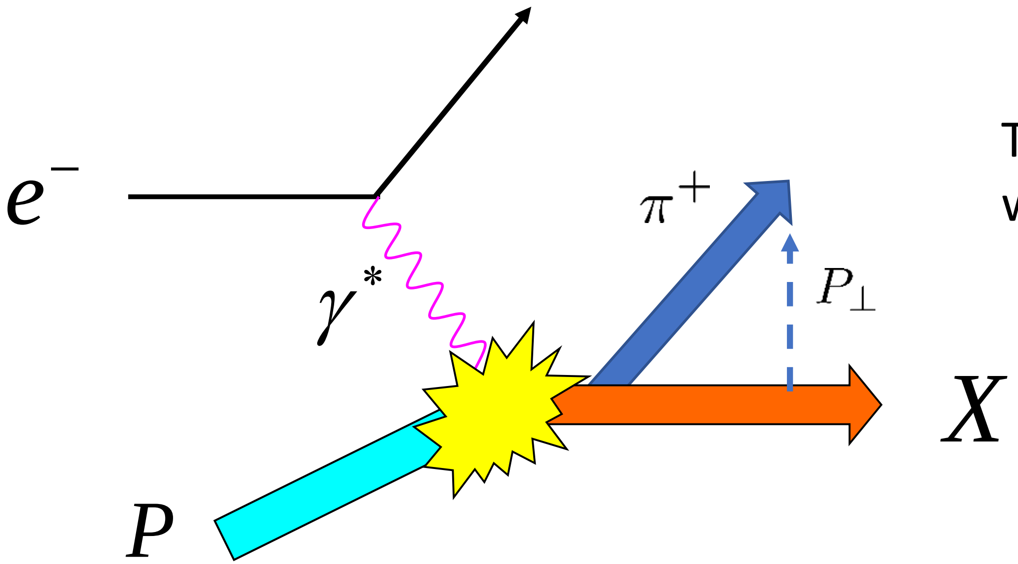
$u(x, \vec{b}_\perp)$ Generalized parton distribution (GPD)

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 evolution

Define Fourier transform $$\int d^2k_\perp e^{ik_\perp r_\perp} f(k_\perp \ldots) = f(r_\perp \ldots)$$

RG equation

$$\frac{\partial}{\partial \ln \mu} f(x, r_\perp, \mu, \zeta) = \gamma_F f(x, r_\perp, \mu, \zeta)$$

Known to three loops
Moch, Vermeseren, Vogt (2005)

Collins-Soper equation

$$\frac{\partial}{\partial \ln \zeta} f(x, r_\perp, \mu, \zeta) = -\mathcal{D}(r_\perp) f(x, r_\perp, \mu, \zeta)$$

Recently computed to three loops!
Li, Zhu (2017); Vladimirov (2017)

Computable from lattice QCD at large $r_\perp$
Ebert, Stewart, Zhao (2018)

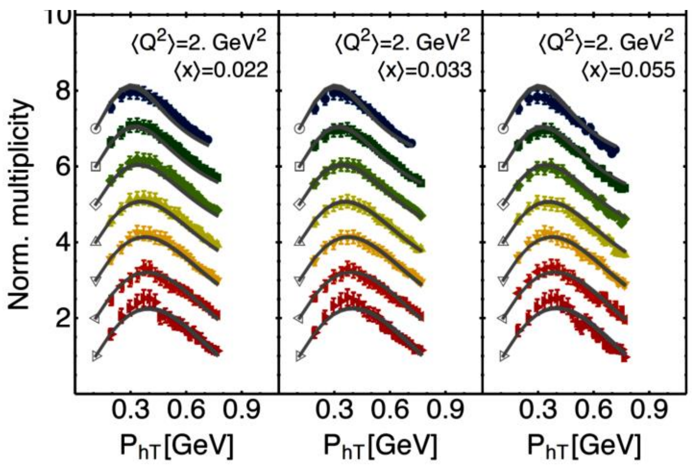
TMD global analysis

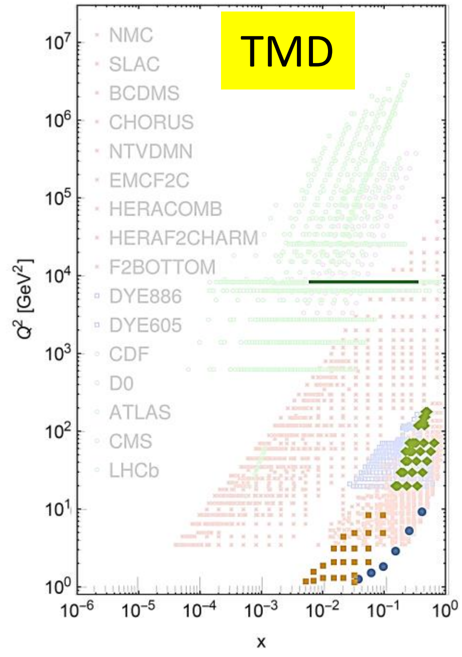
Global analysis of TMD based on ~8000 data points from SIDIS, Drell-Yan.

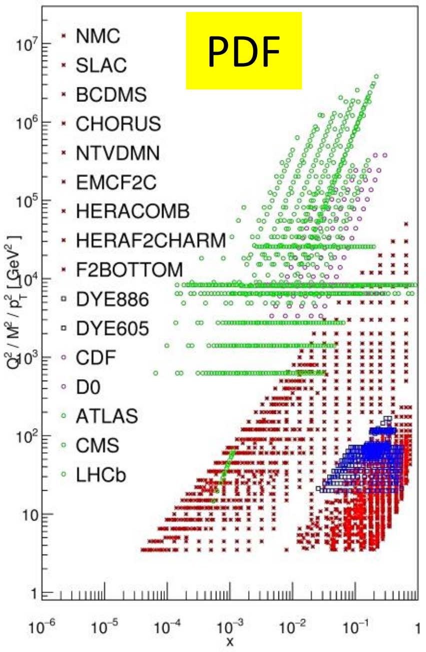
Bacchetta, Delcarro, Pisano, Radici, Signori (2017)

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

TMDlib public library Hautmann, Jung, Mulders,…



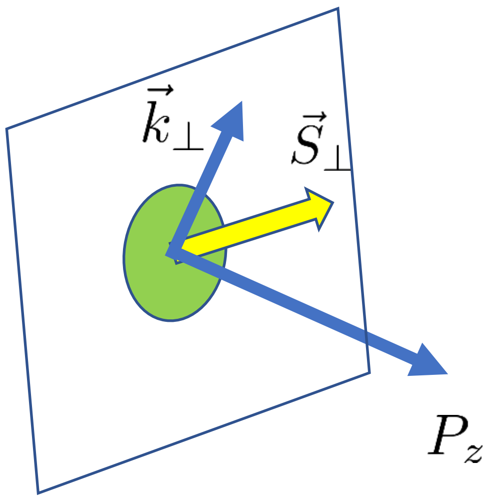


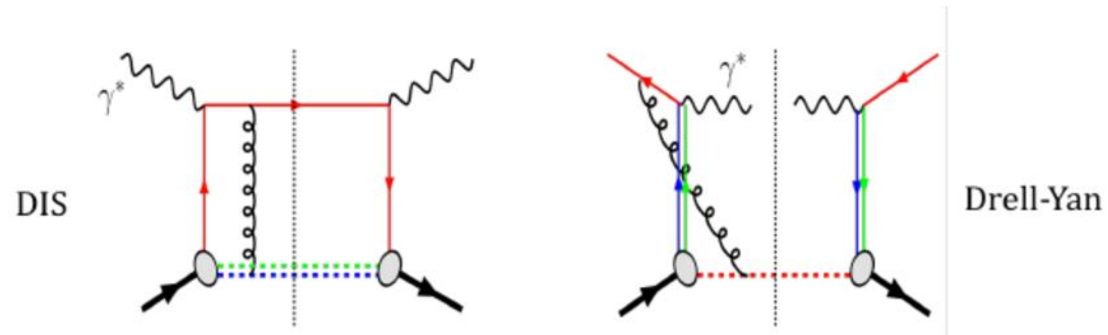


Still in its infancy. Fully blossoms in the EIC era!

Universality up to a sign

Sivers function $f_{1T}^{\perp}(x, k_{\perp})$ for the transversely polarized nucleon





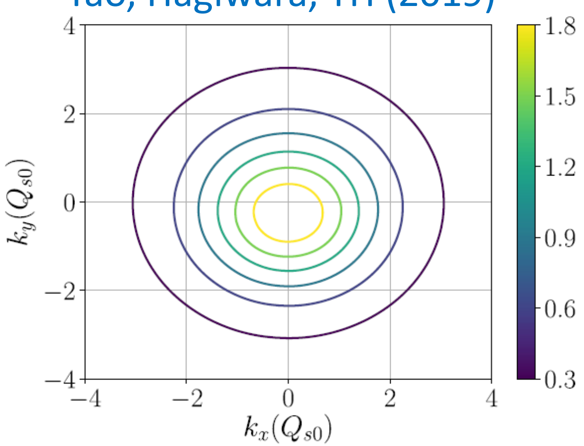
The same function, but with opposite signs in DIS and Drell-Yan. (Collins, 2002)

Experimental tests at RHIC and Compass, to be continued at EIC.

EIC can also probe gluon Sivers function from open charm single spin asymmetry

Zheng, Aschenauer, Lee, Xiao, Bao (2018)

Yao, Hagiwara, YH (2019)



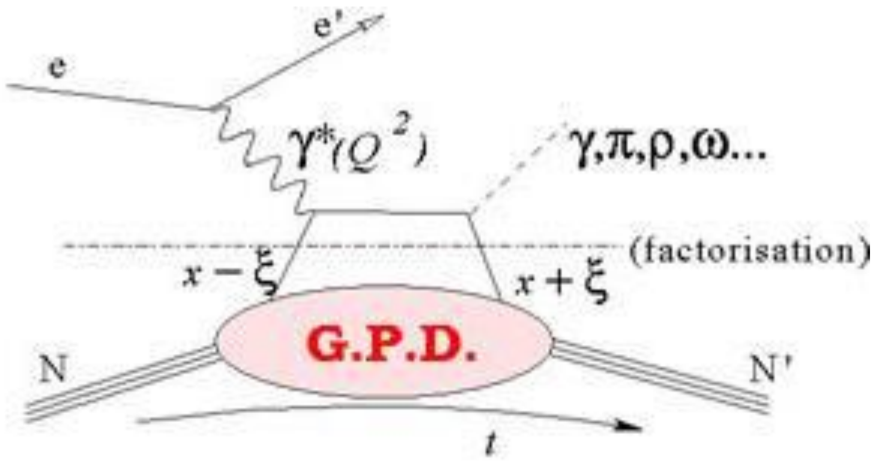
Generalized parton distributions (GPD)

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

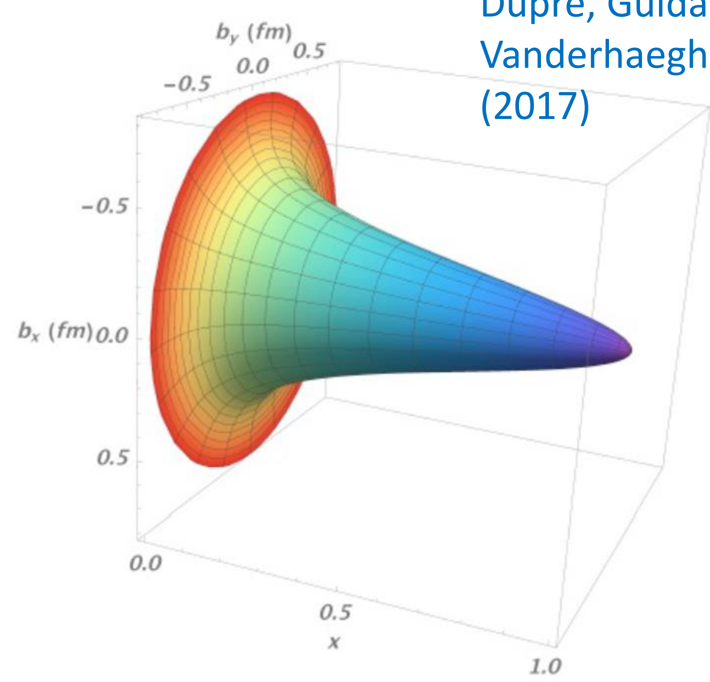
$$= H_q(x,\Delta)\bar{u}(P'S')\gamma^\mu u(PS) + E_q(x,\Delta)\bar{u}(P'S')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}u(PS) \qquad \Delta = P' - P$$

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 $\frac{1}{2} = J_q + J_g$

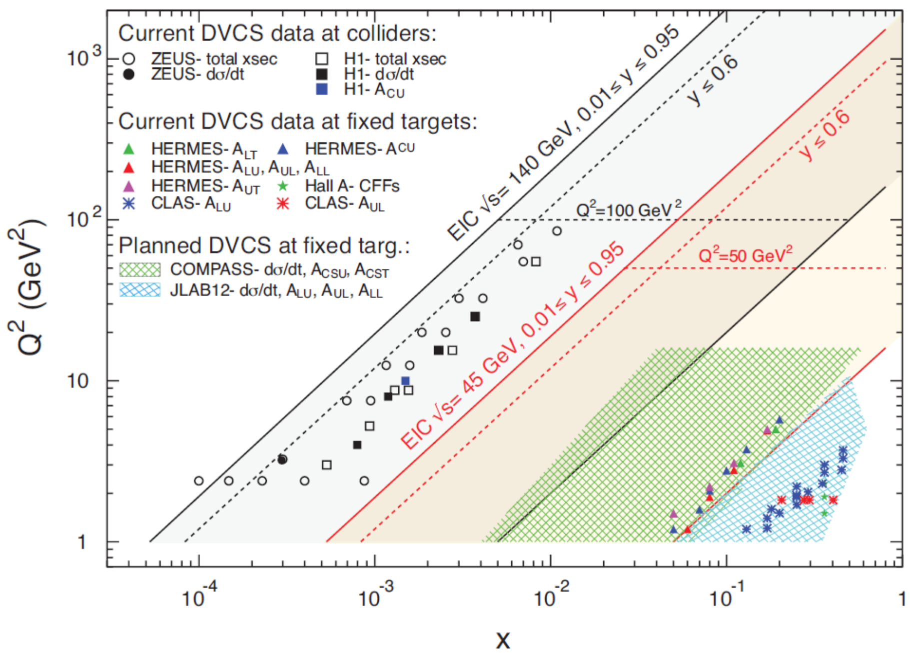
$$J_q = \frac{1}{2}\int dx x(H_q(x) + E_q(x)) \qquad J_g = \frac{1}{4}\int dx x(H_g(x) + E_g(x))$$

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

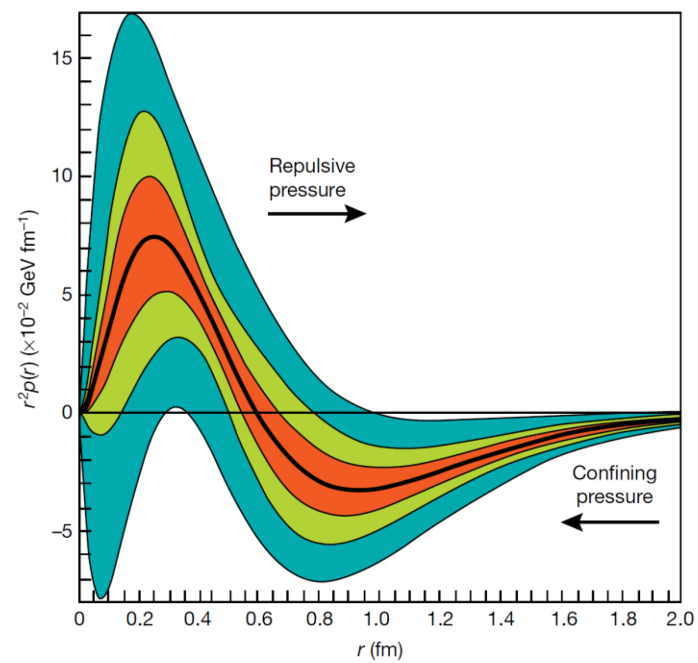
Burkert, Elouadrhiri, Girod (Nature, 2018)

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

$D(t=0)$ 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

$D(t) = D_q(t) + D_g(t)$ can be separately computed on a lattice
Hagler et al. (2007); Shanahan, Detmold (2018)

Pressure from quark and gluon subsystems

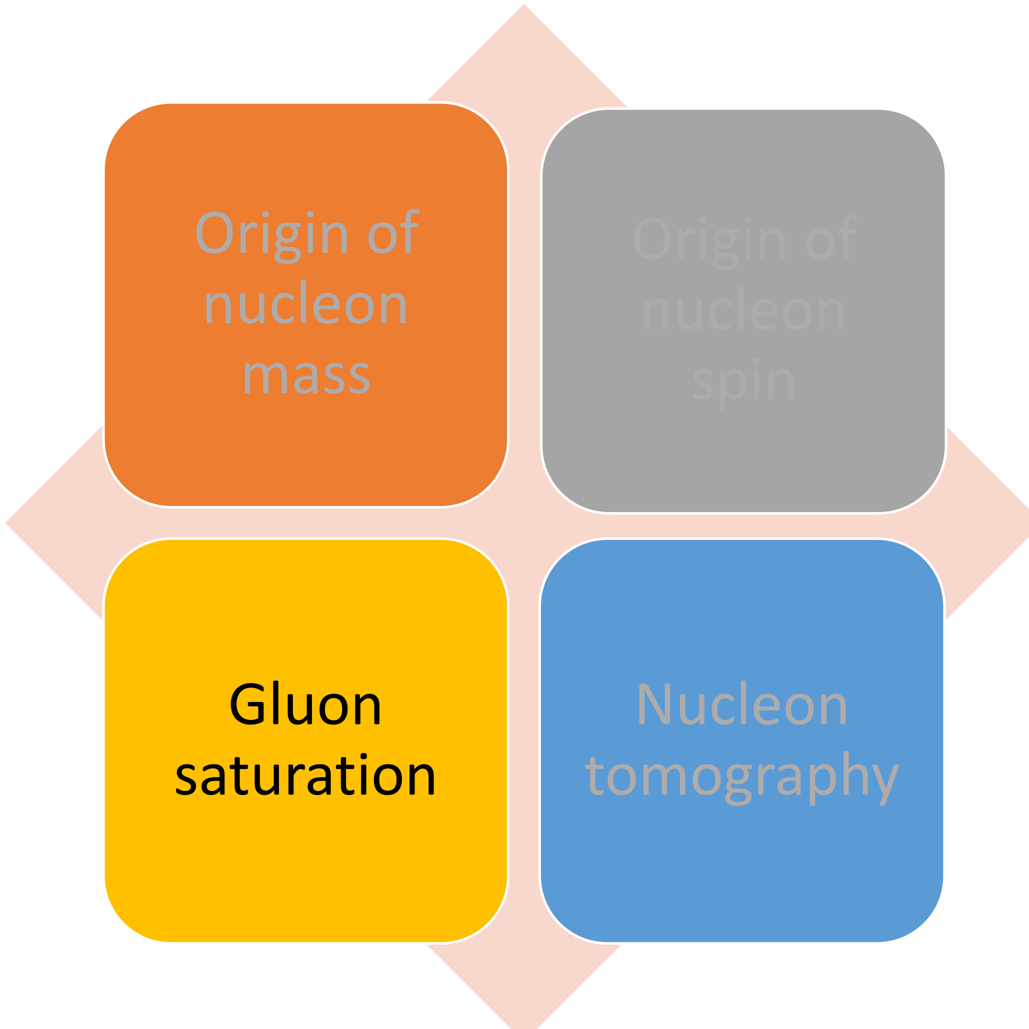
$$p_{q,g}(r) = \frac{1}{6Mr^2}\frac{d}{dr}r^2\frac{d}{dr}D_{q,g}(r) - M\bar{C}_{q,g}(r)$$

$$\begin{aligned}
\bar{C}_q^R(\mu) = & -\frac{1}{4}\left(\frac{n_f}{4C_F+n_f}+\frac{2n_f}{3\beta_0}\right)+\frac{1}{4}\left(\frac{2n_f}{3\beta_0}+1\right)\frac{\langle P|\left(m\bar{\psi}\psi\right)_R|P\rangle}{2M^2} \\
& -\frac{4C_F A_q^R(\mu_0)+n_f\left(A_q^R(\mu_0)-1\right)}{4(4C_F+n_f)}\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\frac{8C_F+2n_f}{3\beta_0}} \\
& +\frac{\alpha_s(\mu)}{4\pi}\left[\frac{n_f\left(-\frac{34C_A}{27}-\frac{49C_F}{27}\right)}{4\beta_0}+\frac{\beta_1 n_f}{6\beta_0^2}\right. \\
& \left.+\frac{1}{4}\left(\frac{n_f\left(\frac{34C_A}{27}+\frac{157C_F}{27}\right)}{\beta_0}+\frac{4C_F}{3}-\frac{2\beta_1 n_f}{3\beta_0^2}\right)\frac{\langle P|\left(m\bar{\psi}\psi\right)_R|P\rangle}{2M^2}\right]+\cdots, \\
\simeq & -0.146-0.25\left(A_q^R(\mu_0)-0.36\right)\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\frac{50}{81}}-0.01\alpha_s(\mu) \\
& +(0.306+0.08\alpha_s(\mu))\frac{\langle P|\left(m\bar{\psi}\psi\right)_R|P\rangle}{2M^2},
\end{aligned}$$

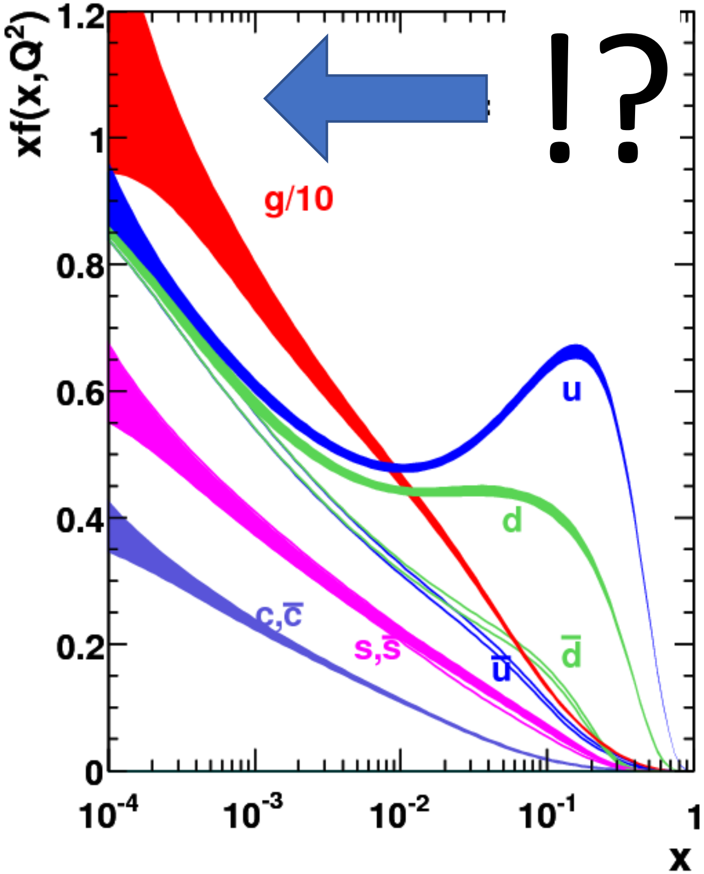
Value of $\bar{C}_{q,g}(\Delta=0)$ completely fixed by the trace anomaly

YH, Rajan, Tanaka (2018)

Scientific goals of EIC

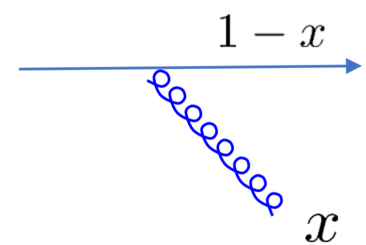


QCD at small-x



Probability to emit a soft gluon diverges

$$\left| \; \text{(emission diagram)} \; \right|^2 \propto \frac{1}{x}$$



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

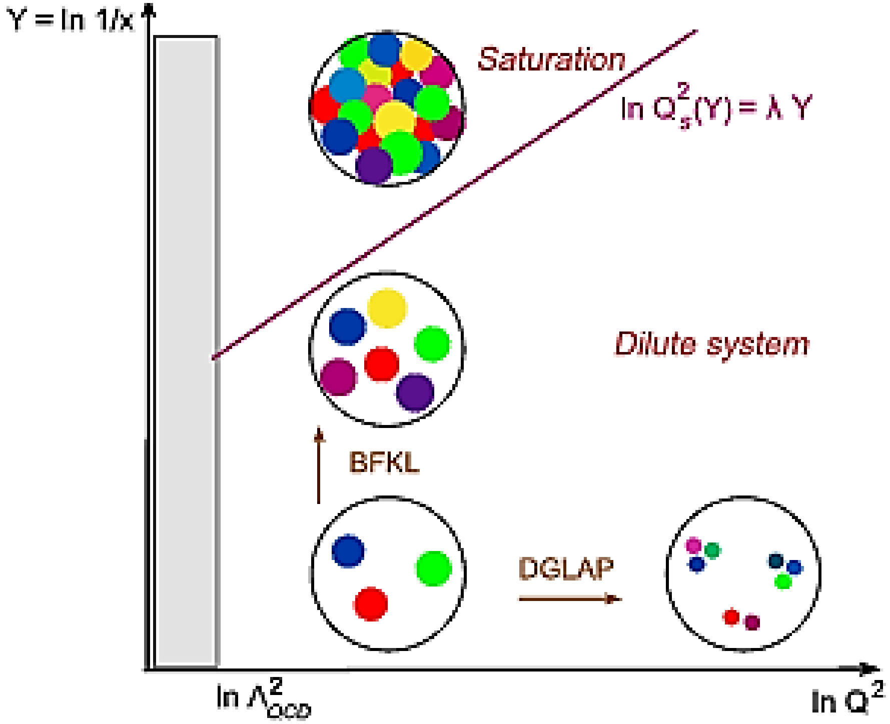
as predicted by BFKL
(Balitsky-Fadin-Kuraev-Lipatov)

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

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

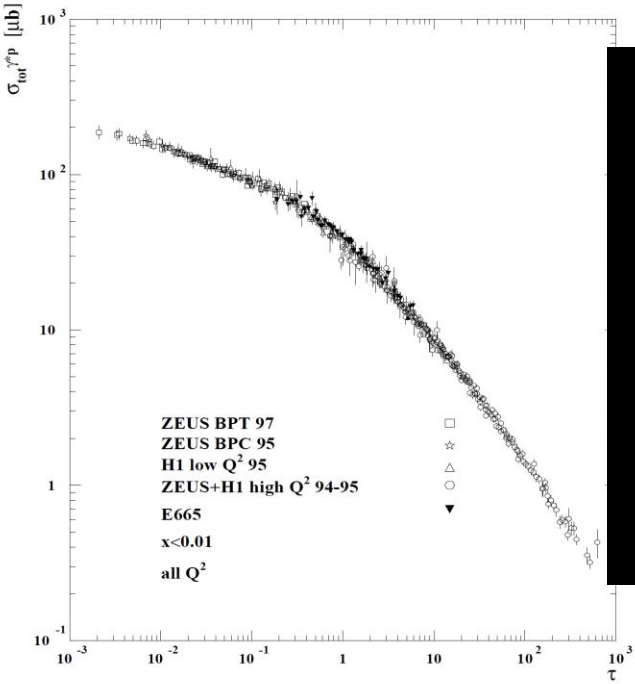
$$\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2$$

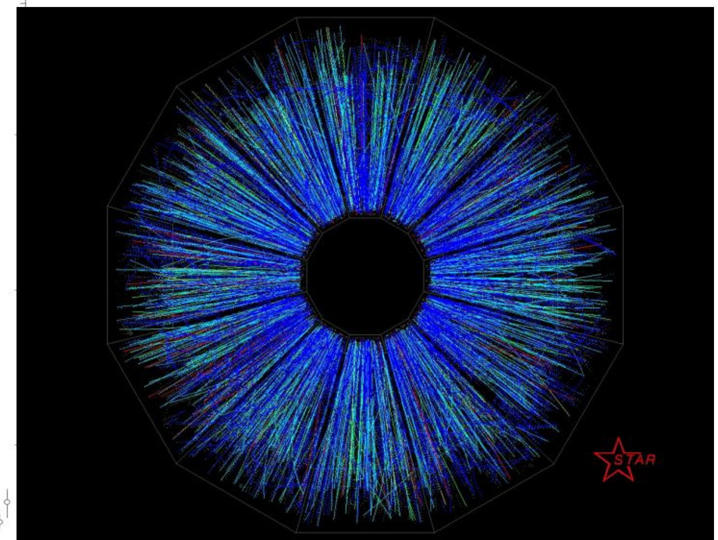
The saturation momentum

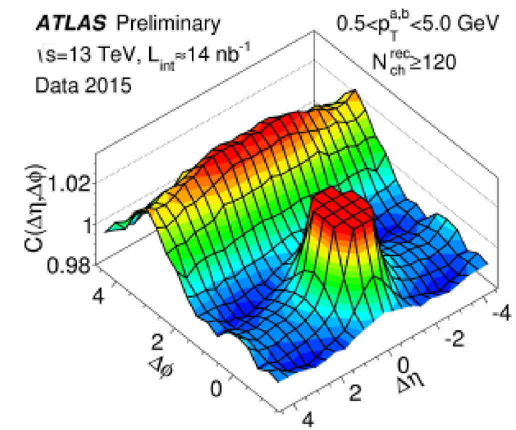
$$Q = Q_s(x) \gg \Lambda_{QCD}$$

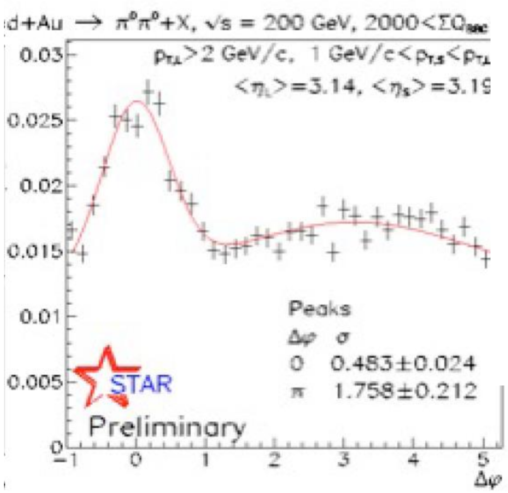
High density, but weakly coupled many-body problem

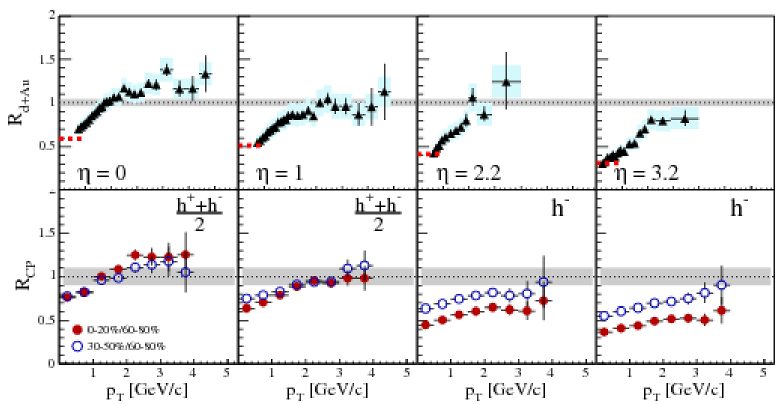
Has saturation been observed at HERA, RHIC, LHC?

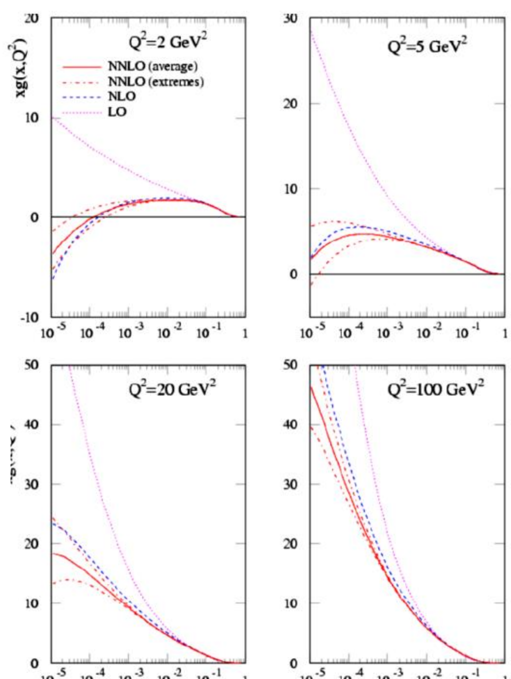








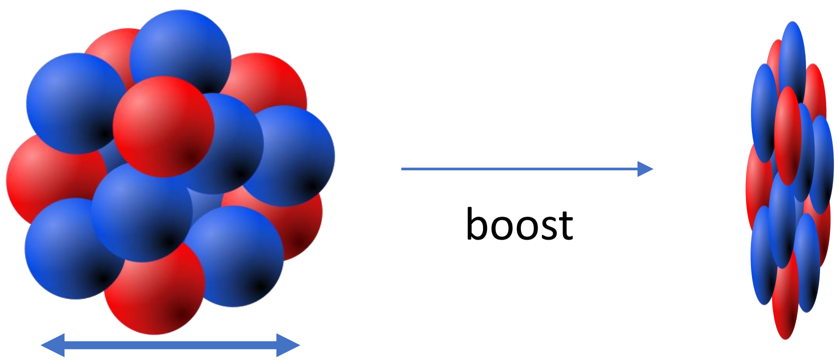




eA collision at EIC : ideal place to study saturation

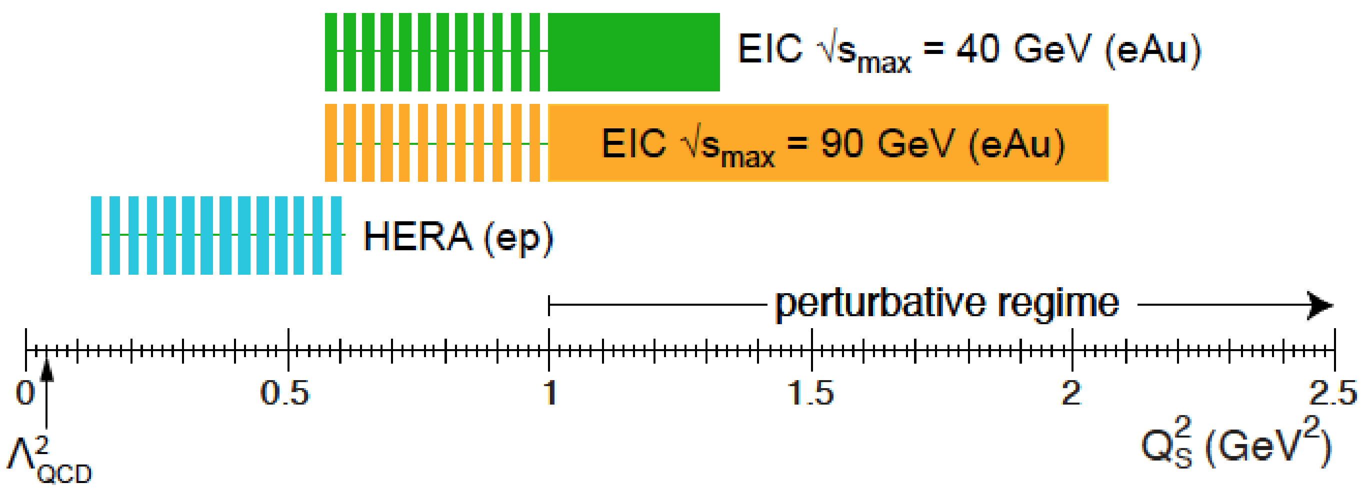
No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)



$R_A \sim A^{1/3}$

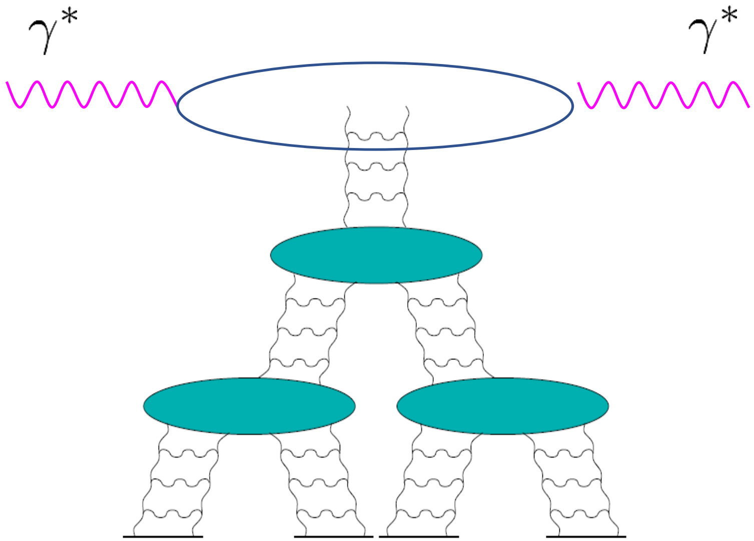
$$Q_s^2 \propto A^{1/3}$$



BK-JIMWLK equation

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

Photon-nucleus scattering
at high energy



$\equiv S$

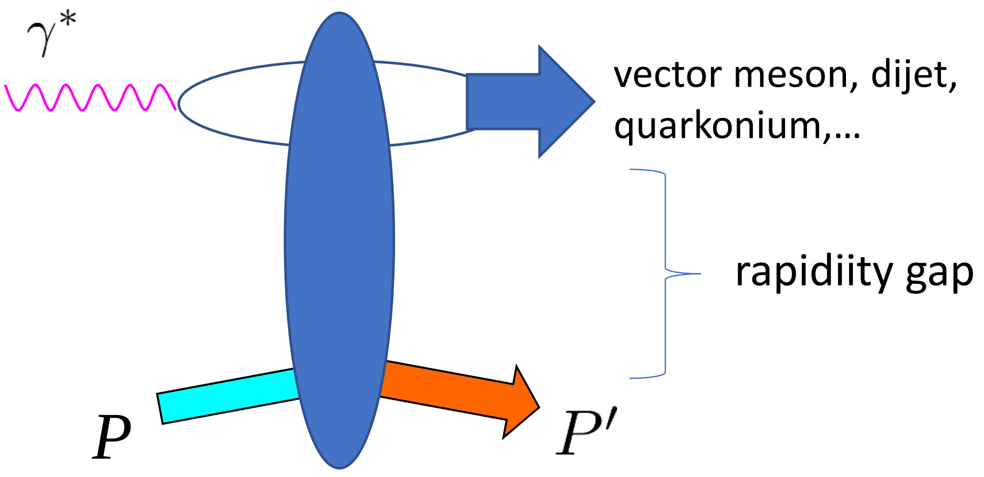
Leading Logarithmic (LL) evolution of the scattering amplitude with energy

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

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)

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

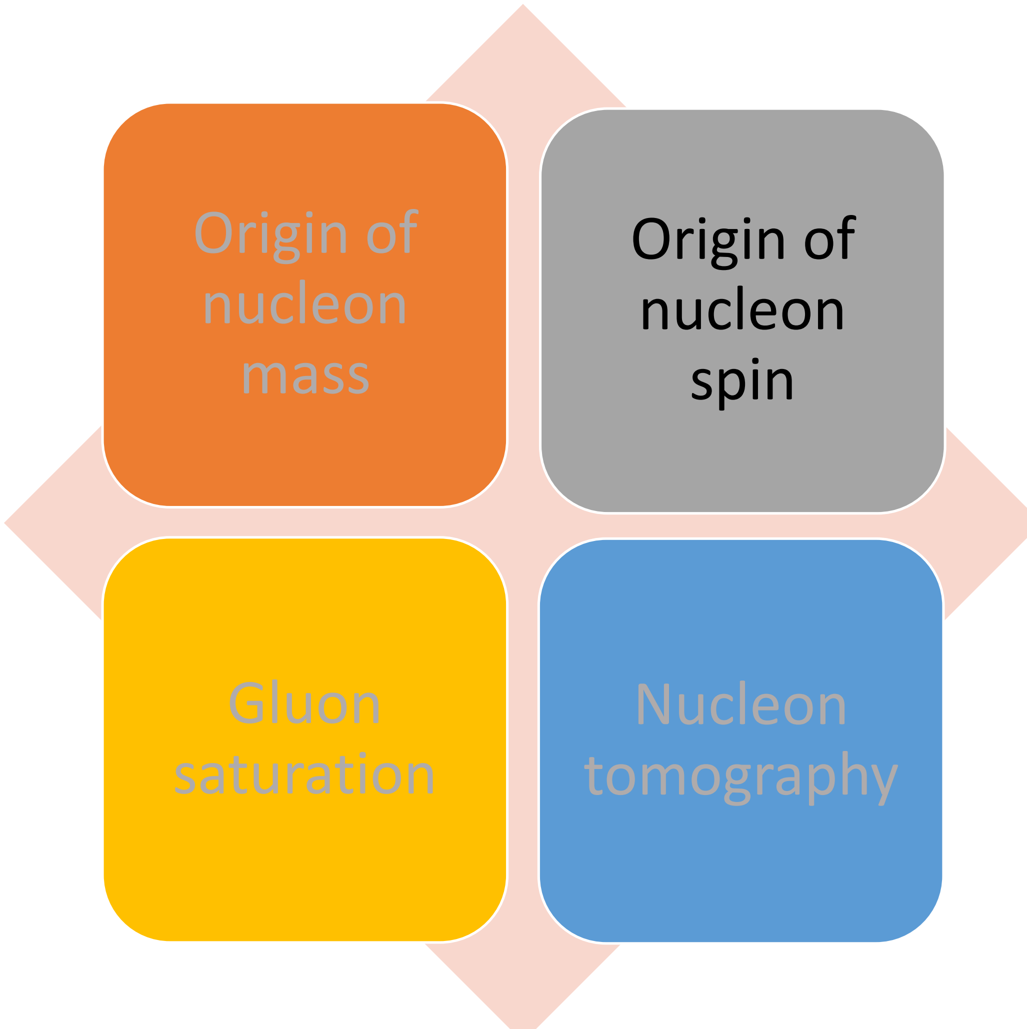
Nucleus stays intact in every 1 out of 5 events!

Recently extended to NLO for dijet, vector meson…

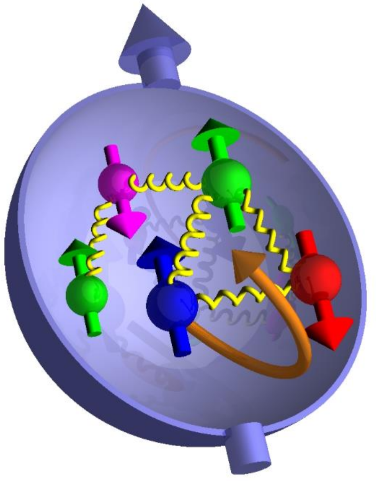
Boussarie, Grabovsky, Szymanowski, Wallon (2016)

Can access also the Wigner distribution   YH, Xiao, Yuan (2016)
Mantysaari, Mueller, Schenke 1902.05087

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

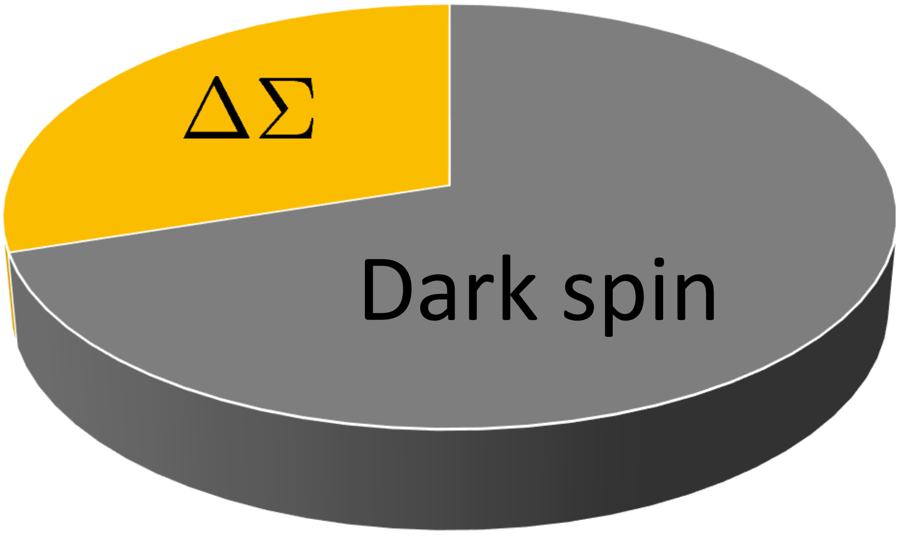
$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14 \;\; !?$$

Recent values from NLO global analysis

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

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

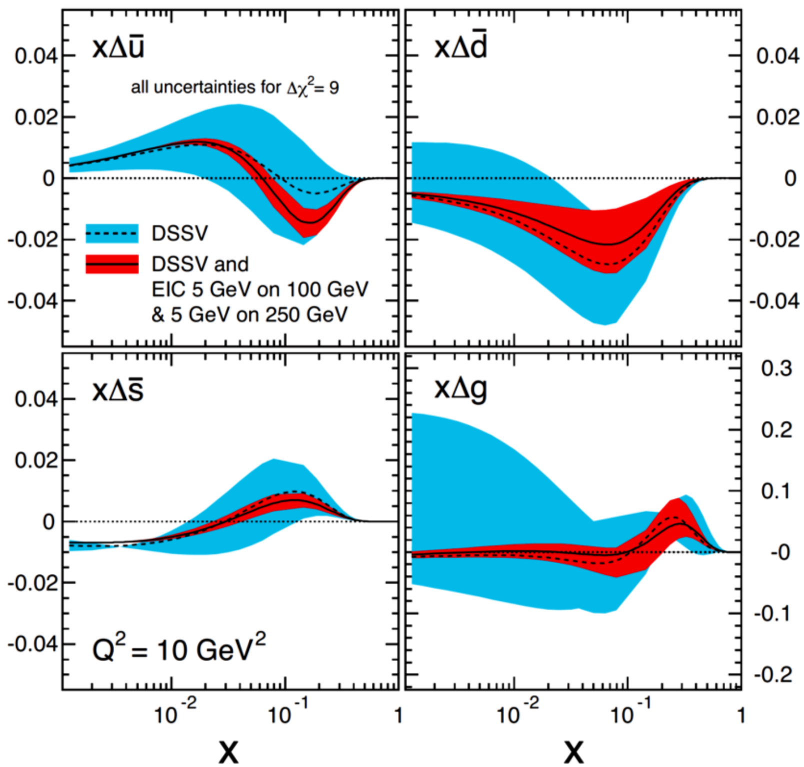
DeFlorian, Sassot, Stratmann, Vogelsang (2014)

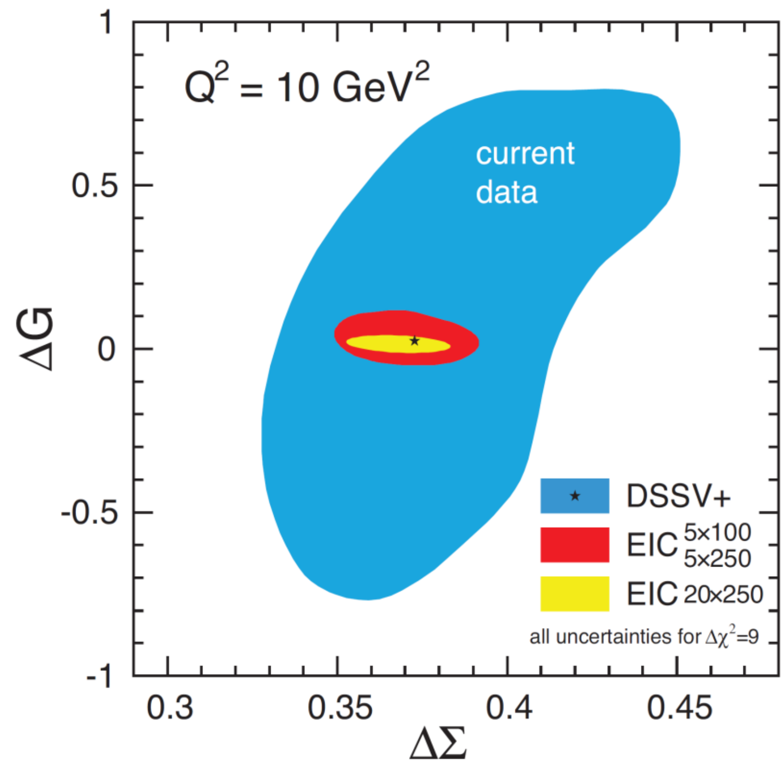


Warning: Huge uncertainties from the small-x region

Helicity measurements at EIC

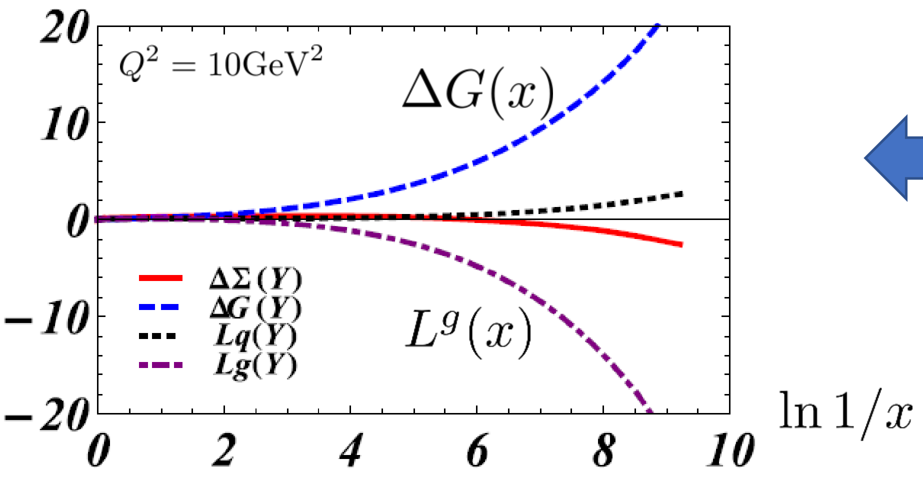
After one-year of data taking at EIC...



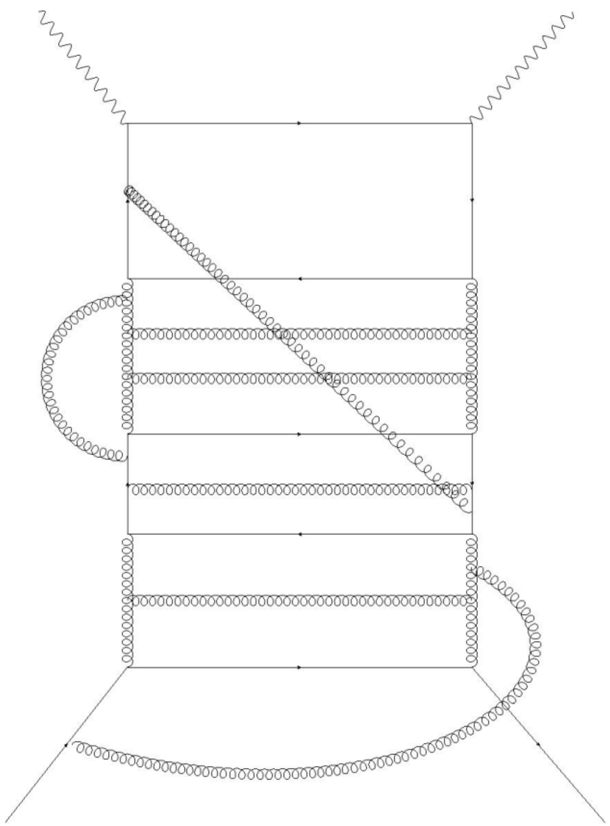


Wider coverage in x and Q^2... finally solve the spin puzzle? No!

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 $(\alpha_s \ln^2 1/x)^n$ by InfraRed Evolution Equation

Kirschner, Lipatov (1983)
Bartels, Ermolaev, Ryskin (1996)

Generalized to OAM

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

Boussarie, YH, Yuan (2019)

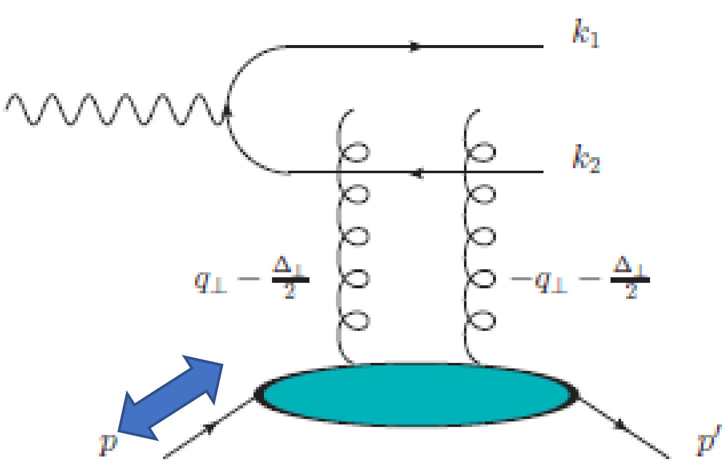
Measuring OAM at EIC

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

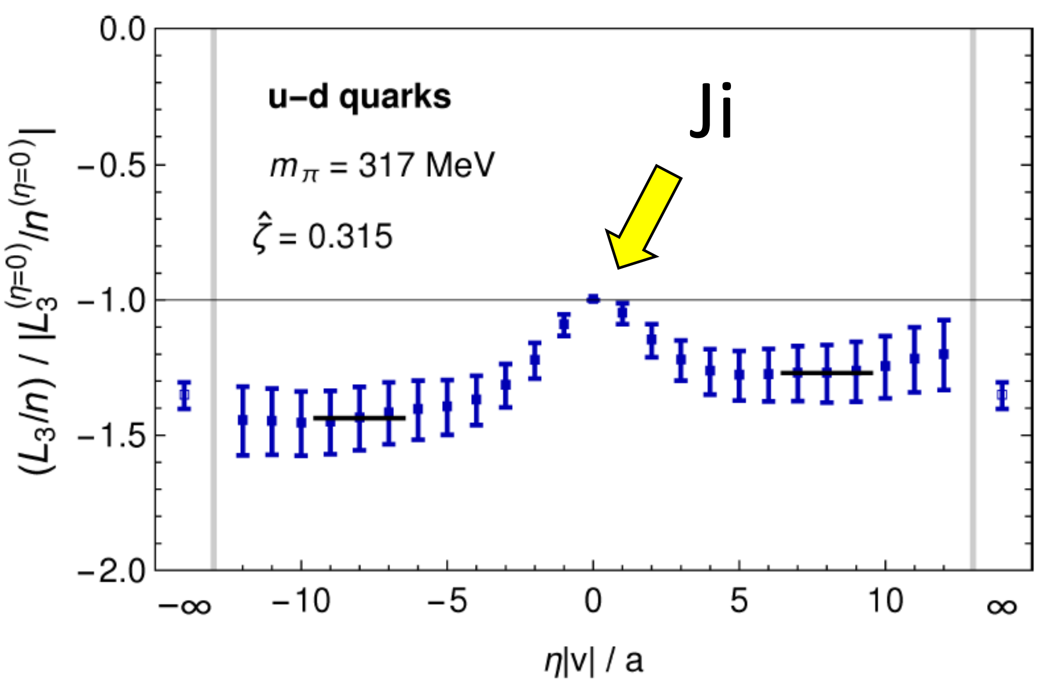
Need more work, more new ideas!

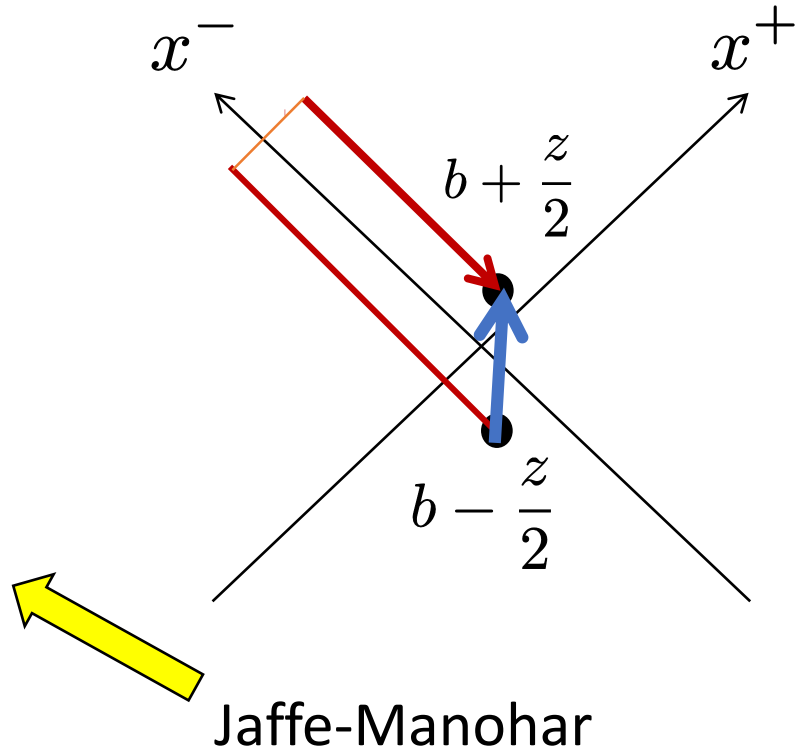
OAM from lattice QCD

Engelhardt (2017)

Jaffe-Manohar OAM from staple Wilson line YH (2011)

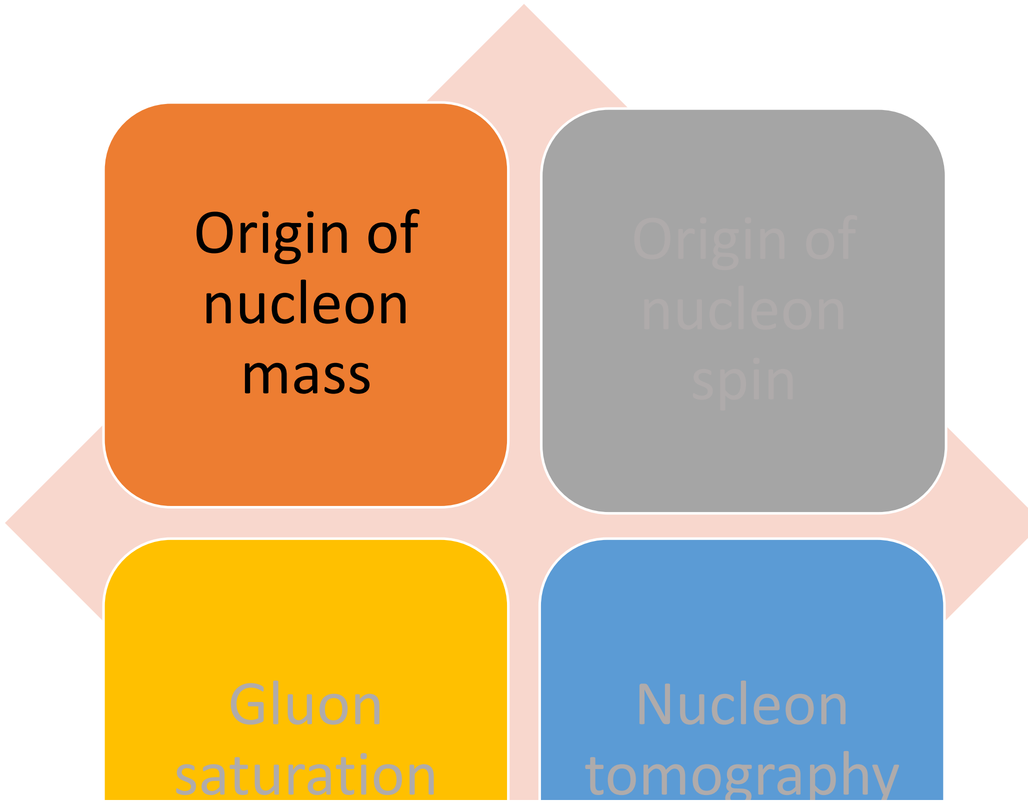
Ji's OAM from straight Wilson line Ji, Xiong, Yuan (2012)





arXiv.1901.00843

Scientific goals of EIC



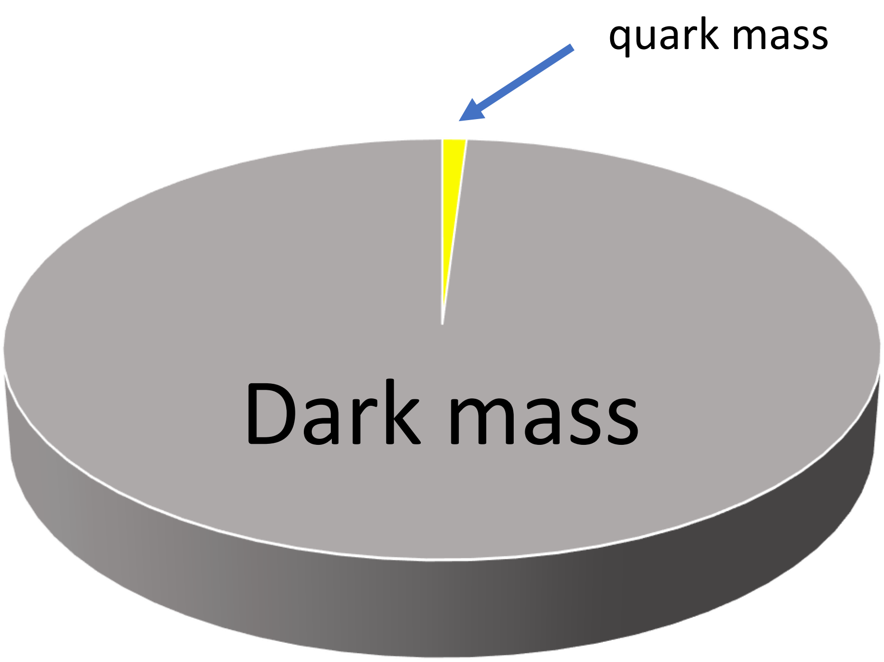
NAS report (2018/07)

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?

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

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

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

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

Can we measure the trace anomaly $\langle P|F^{\mu\nu}F_{\mu\nu}|P\rangle$?

The operator $F^{\mu\nu}F_{\mu\nu}$ is twist-four,
highly suppressed in high energy scattering.

Purely gluonic operator, very difficult to compute in lattice QCD

Instead, we should look at low-energy scattering.

Purely gluonic operator. Use quarkonium as a probe.

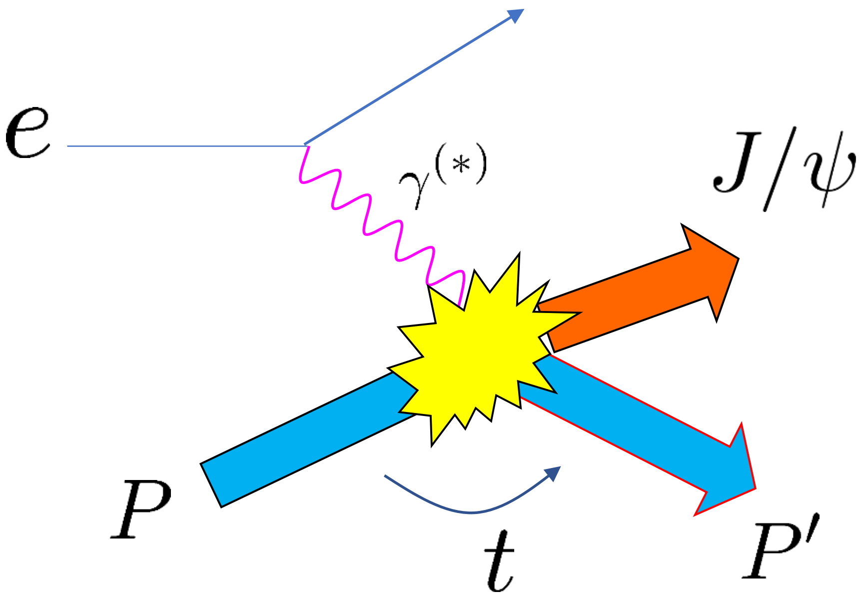
Luke-Manohar-Savage (1992)

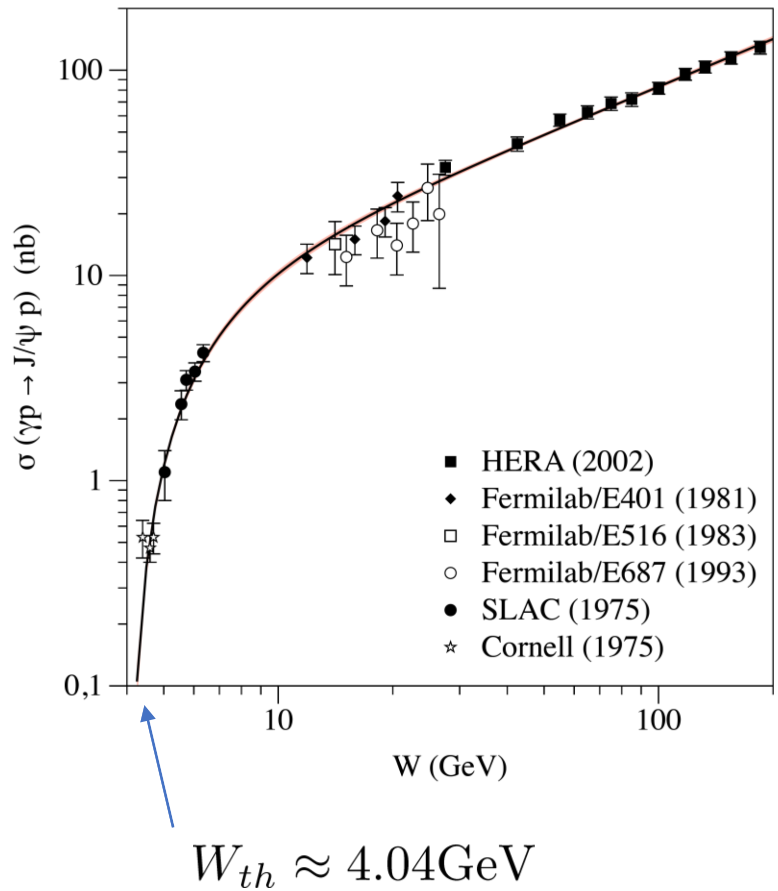
→ J/ψ photo-production near threshold.

Photo-production of J/ψ near threshold

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

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





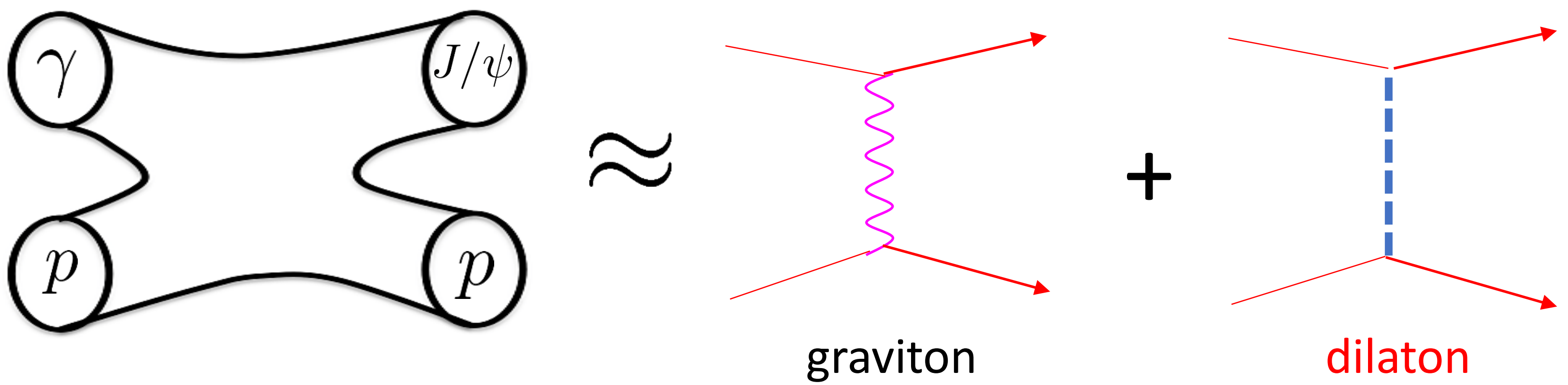
Straightforward to measure.
Ongoing experiments at Jlab.

Difficult to compute from first principles
(need nonperturbative approaches)

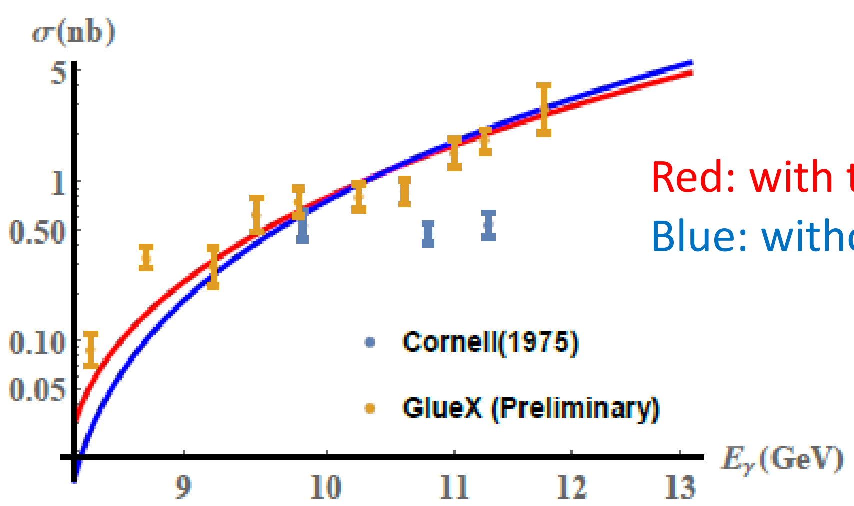
Holographic approach

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 nucleon/nuclei, the fundamental building blocks of the universe.

- Topics not covered include: jets, EMC, short-range correlation, UPC, heavy-quark, etc. etc.

- Great opportunity for lattice QCD. PDF, TMD, GPD, Wigner, DA, form factors,…tons of observables to calculate!