EIC theory overview

Yoshitaka Hatta

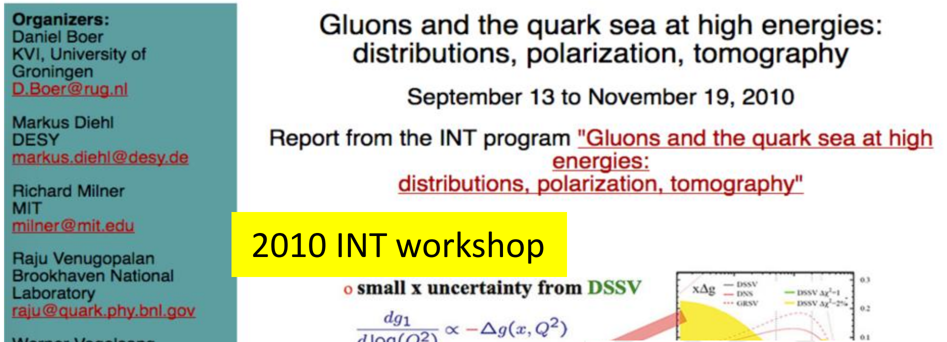
(BNL)

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 $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



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Gluons and the quark sea at high energies: distributions, polarization, tomography

September 13 to November 19, 2010

Report from the INT program "Gluons and the quark sea at high energies: distributions, polarization, tomography"

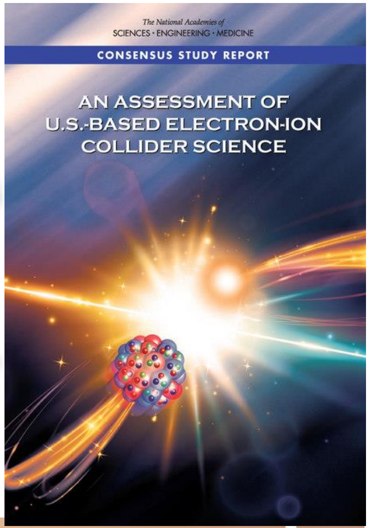
o small x uncertainty from DSSV

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

2010 INT workshop

2018 NAS report

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



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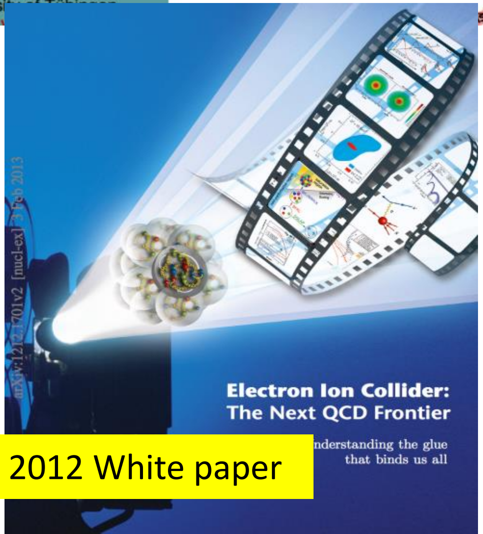
CONSENSUS STUDY REPORT

AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE



Electron Ion Collider: The Next QCD Frontier

nderstanding the glue that binds us all

2012 White paper

REACHING FOR THE HORIZON

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

2015 NSAC Long Range Plan

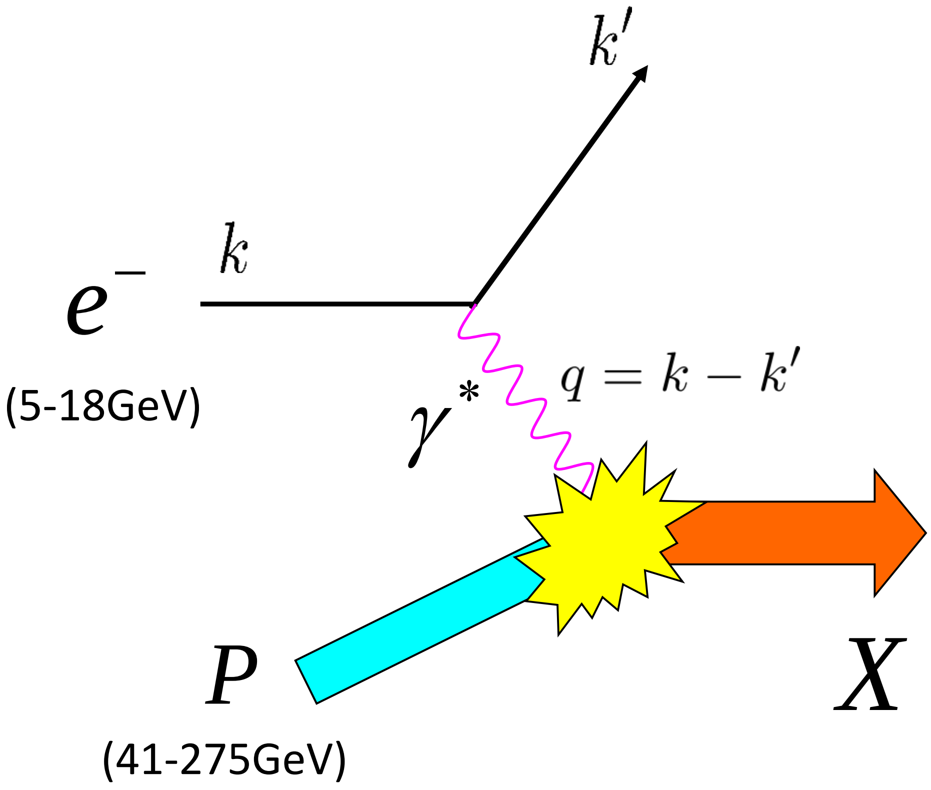
OCTOBER 1 – NOVEMBER 16, 2018 • SEATTLE, WASHINGTON

PROBING NUCLEONS AND NUCLEI IN HIGH ENERGY COLLISIONS

Dedicated to the Physics of the Electron Ion Collider

2018 INT workshop

Experiment at EIC: Deep Inelastic Scattering (DIS)



Two most important kinematic variables

$$Q^2 = -q^2$$

photon virtuality (resolution)

$$x = \frac{Q^2}{2P \cdot q} \approx \frac{E_{parton}}{E_{proton}}$$

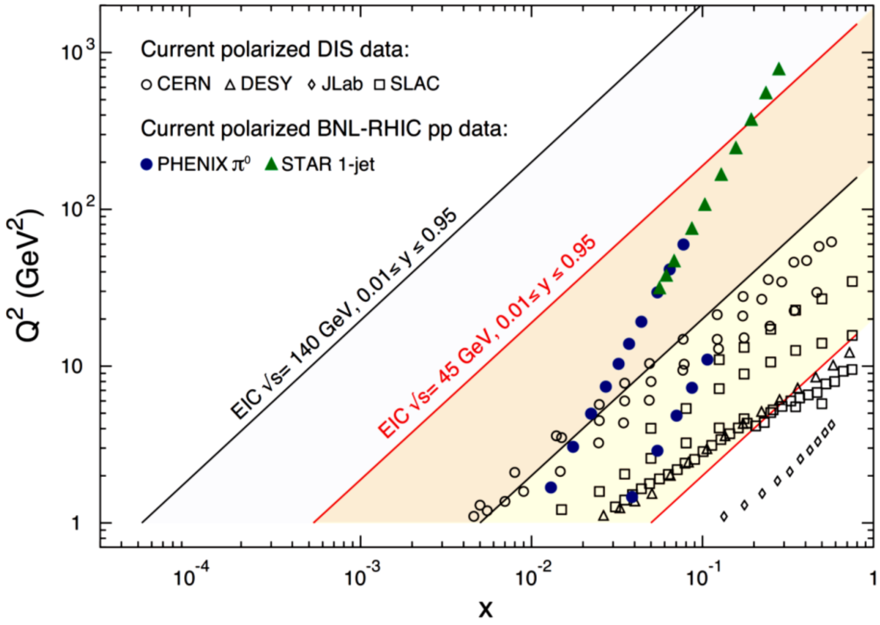
Bjorken variable (inverse energy)

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

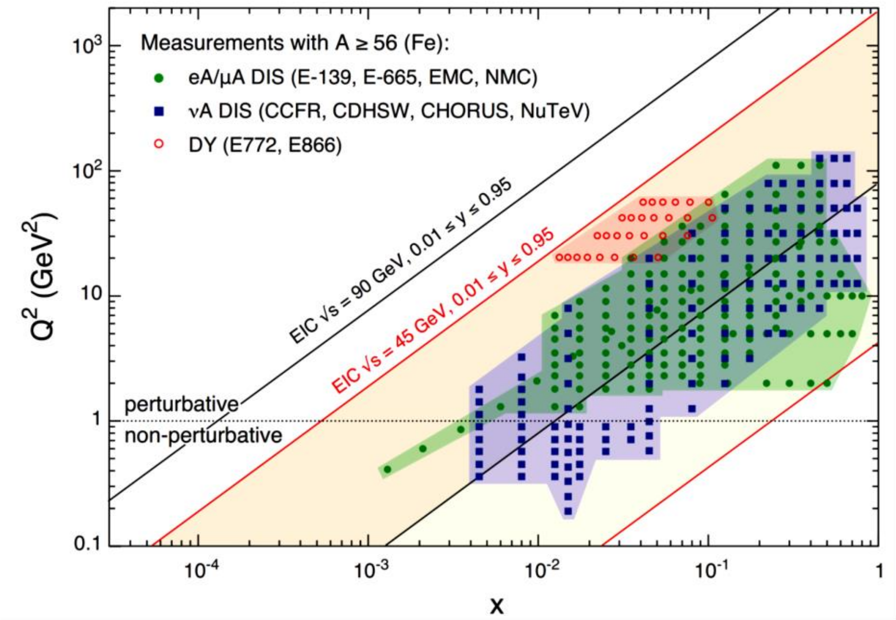
Electron, proton and light nuclei can be polarized.

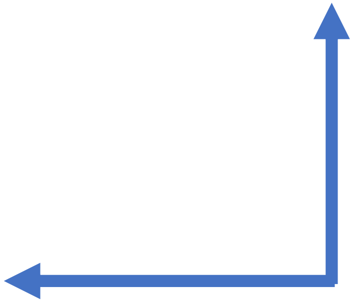
EIC Kinematical coverage

Polarized DIS



Nuclear DIS



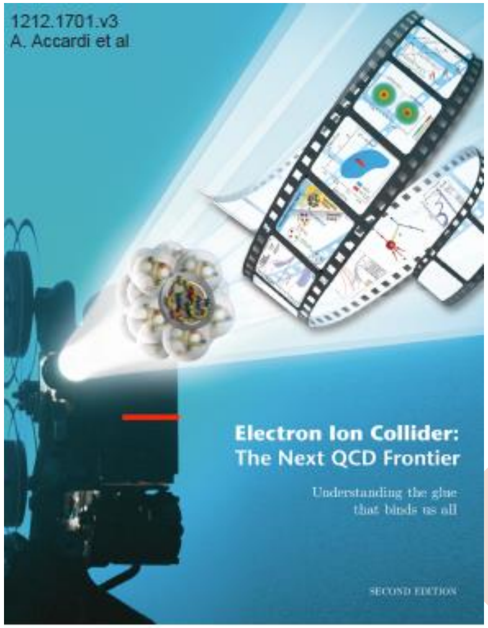


High resolution

High energy

Unprecedented coverage in kinematics.
Tremendous physics opportunities!

Scientific goals of EIC



1212.1701.v3
A. Accardi et al

Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

SECOND EDITION

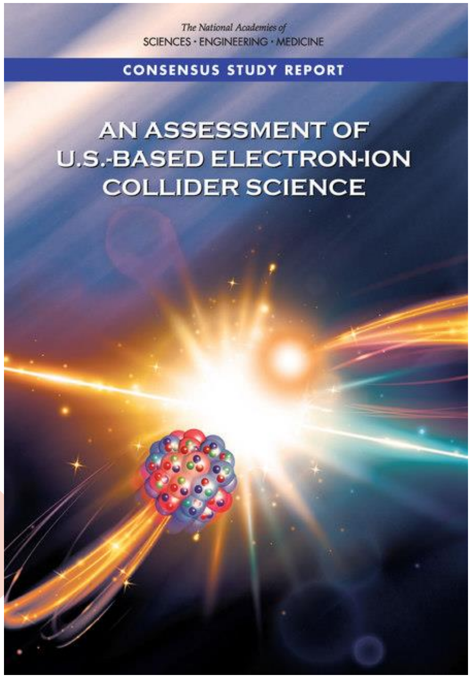
White paper
arXiv:1212.1701

Origin of nucleon mass

Origin of nucleon spin

Gluon saturation

Nucleon tomography



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AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

NAS report
July 2018

Scientific goals of EIC

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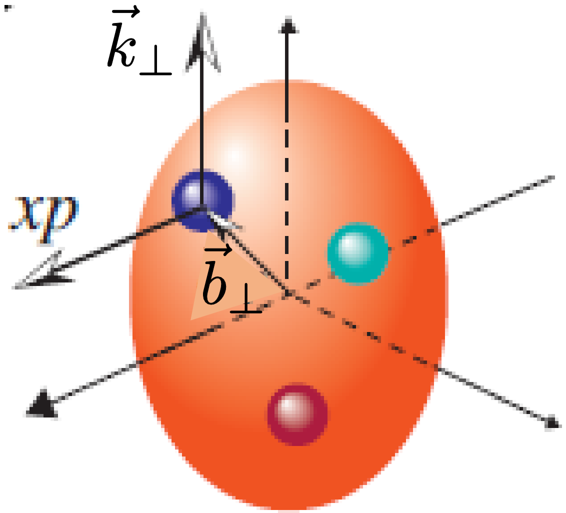
Multi-dimensional tomography



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

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

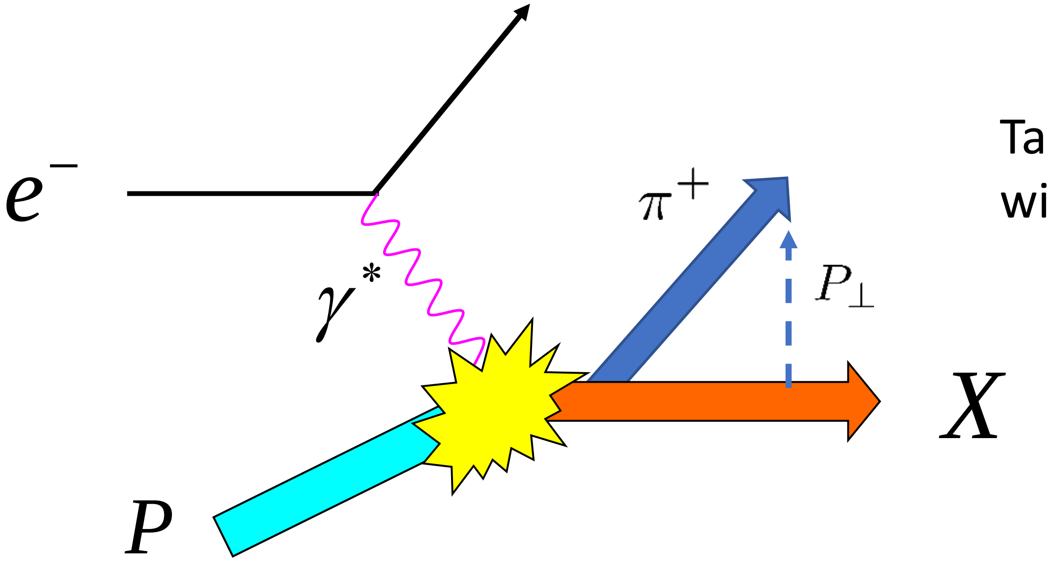
$u(x, \vec{b}_\perp)$ Generalized parton distribution (GPD)

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,…

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

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

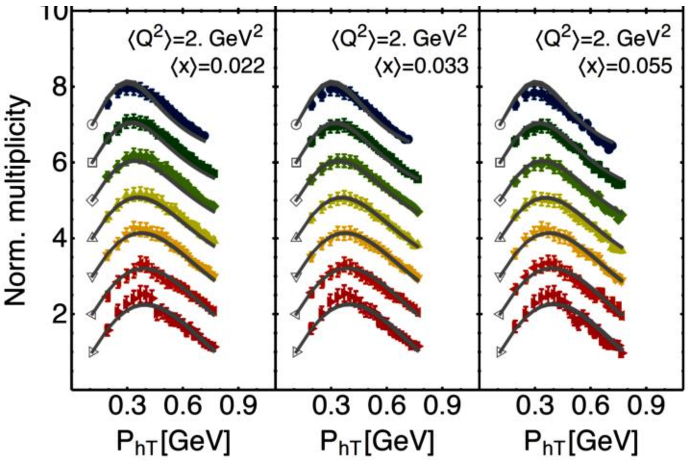
TMD global analysis

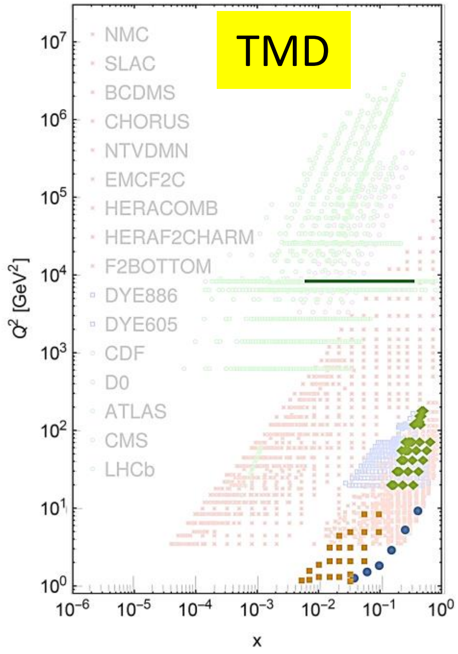
Global analysis of TMD based on ~8000 data points from SIDIS, Drell-Yan.

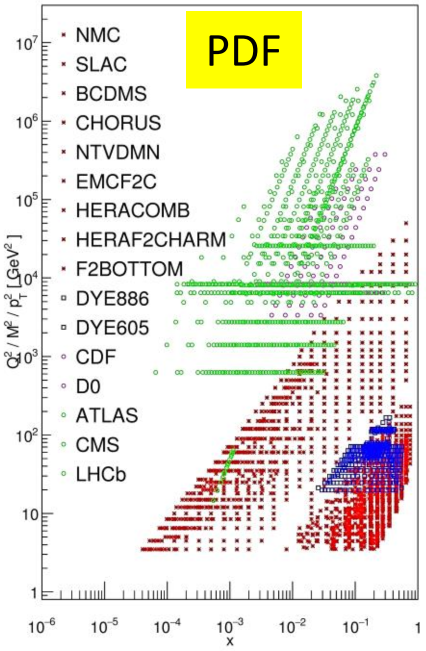
Bacchetta, Delcarro, Pisano, Radici, Signori (2017)

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

TMDlib public library Hautmann, Jung, Mulders,…



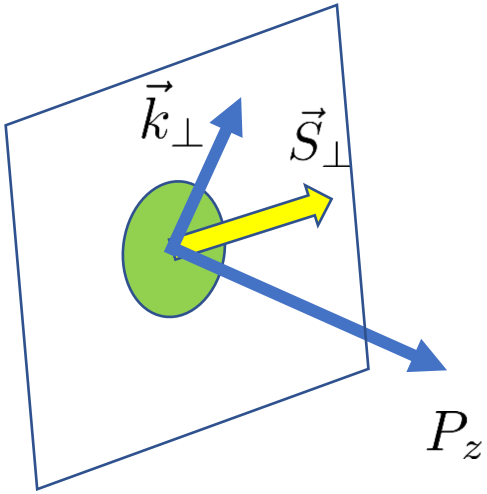




Still in its infancy. Fully blossoms in the EIC era!

Universality up to a sign

Sivers function for the transversely polarized nucleon



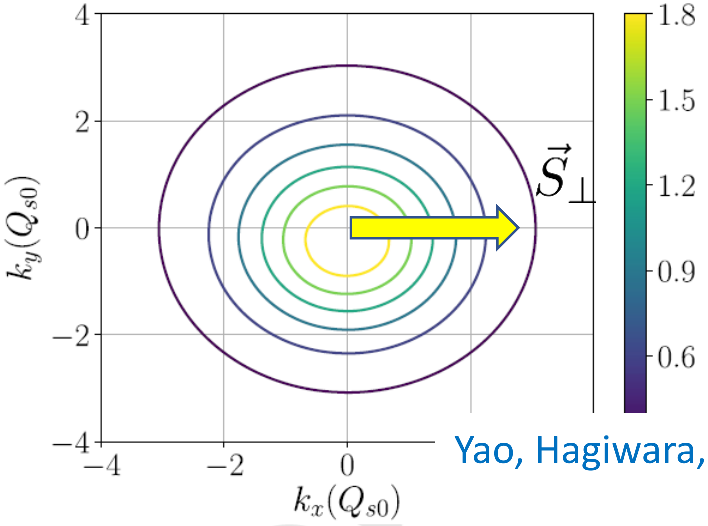
$$\sim \vec{k}_\perp \times \vec{S}_\perp f_{1T}^\perp(x, k_\perp)$$

Azimuthal anisotropy of parton distribution, responsible for single spin asymmetry

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

EIC can probe the gluon Sivers function for the first time.

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



Yao, Hagiwara, YH (2019)

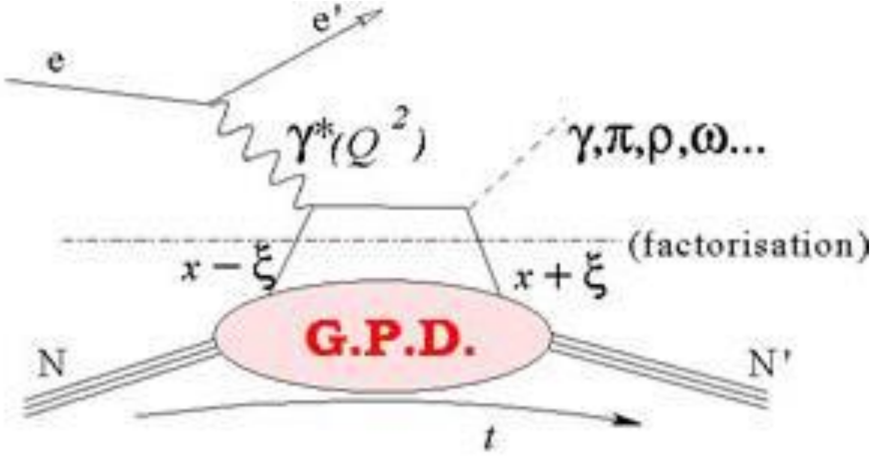
Generalized parton distributions (GPD)

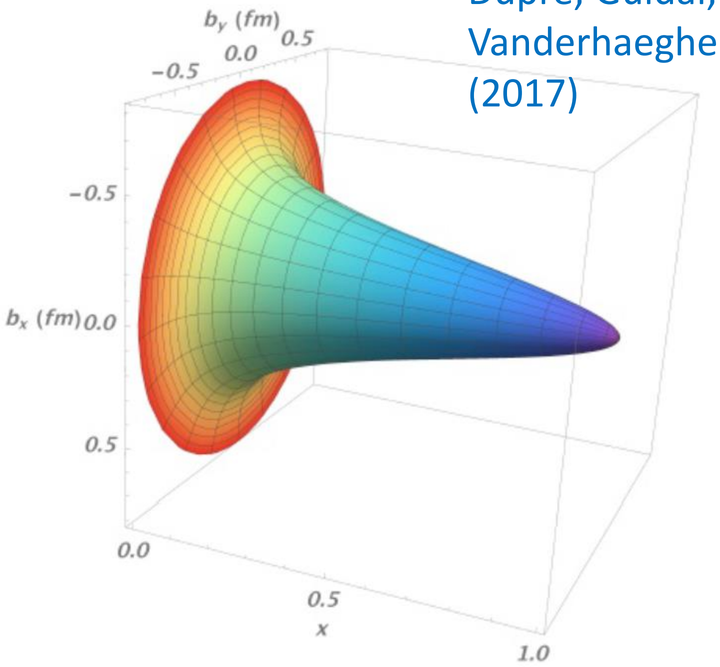
$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu\psi(y^-)|PS\rangle$$

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

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

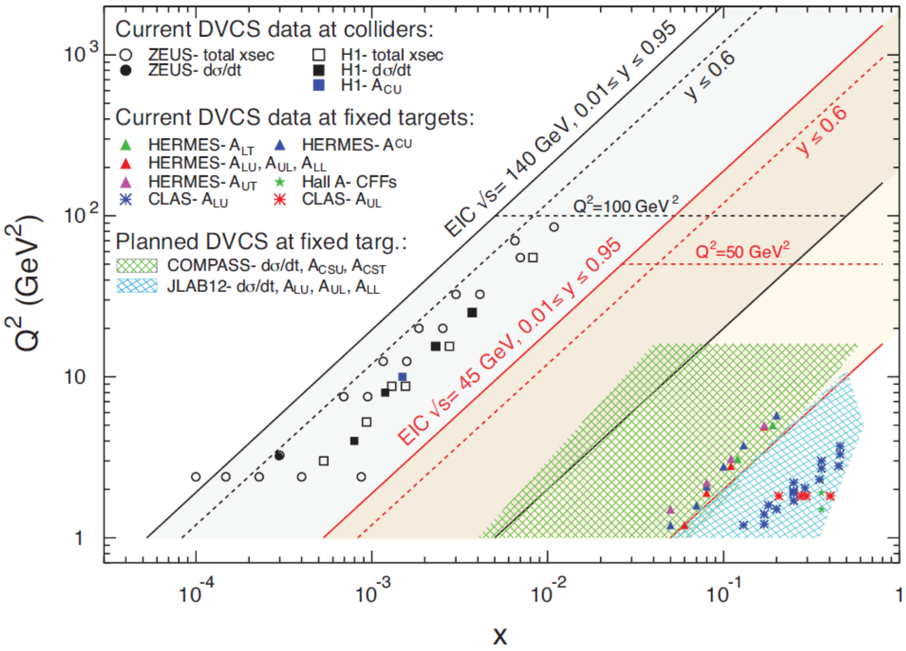
$$J_q = \frac{1}{2}\int dx(H_q(x) + E_q(x)) \qquad J_g = \frac{1}{4}\int dx(H_g(x) + E_g(x))$$

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

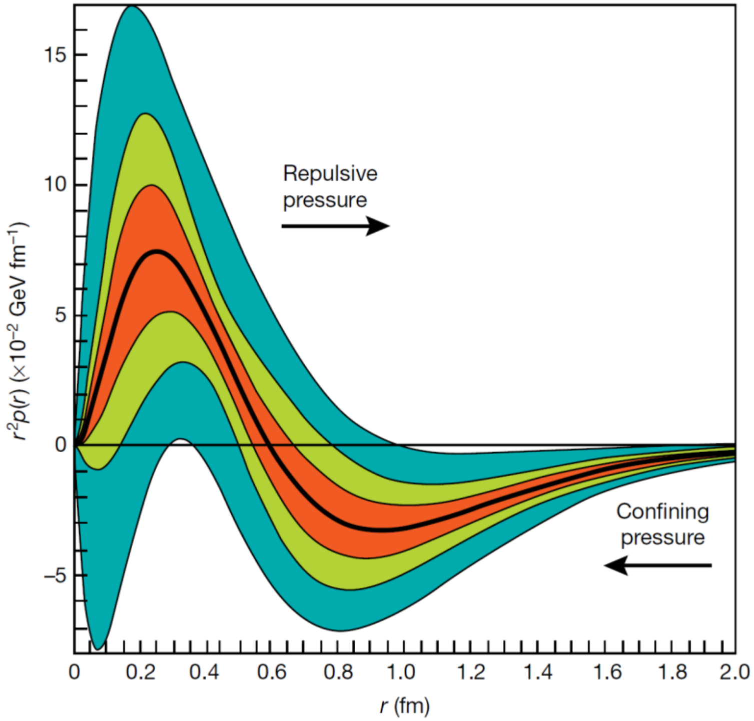
$$\langle P'|T^{ij}|P\rangle \sim (\Delta^i\Delta^k - \delta^{ik}\Delta^2)D(t)$$

Burkert, Elouadrhiri, Girod (Nature, 2018)

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

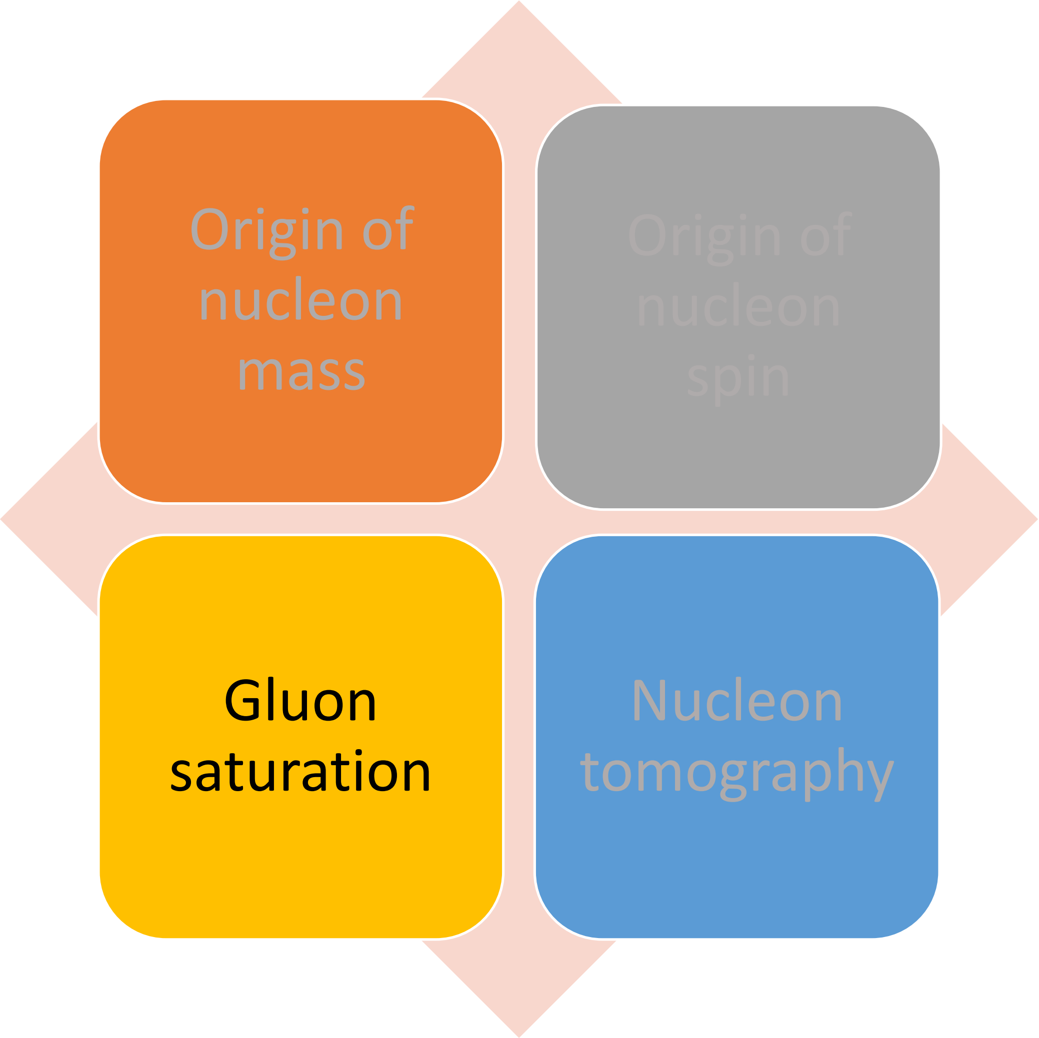
Related to the radial `pressure’ inside a nucleon   Polyakov, Schweitzer,…

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



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



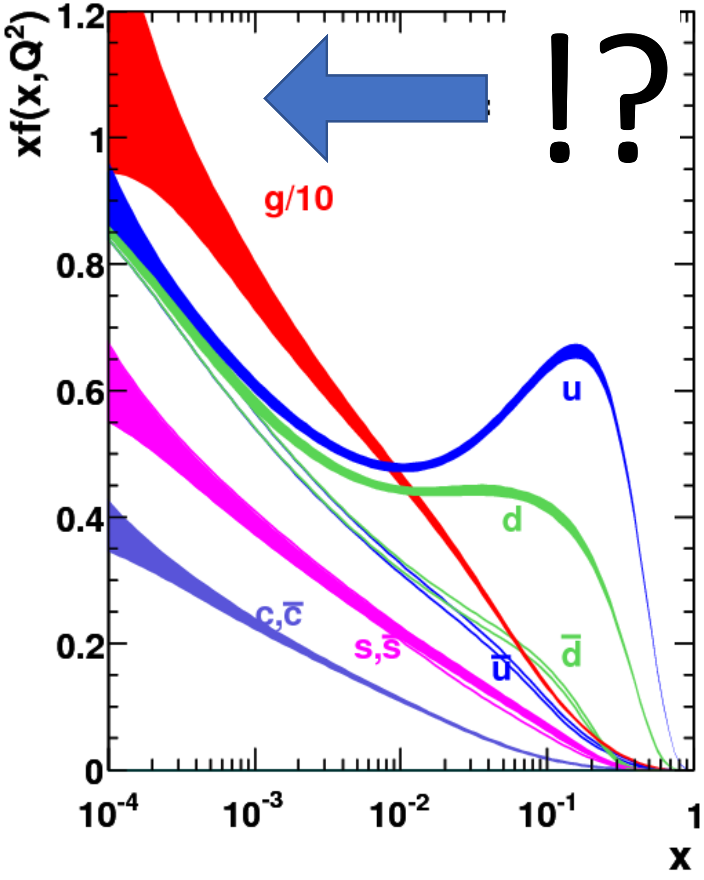
Origin of nucleon mass

Origin of nucleon spin

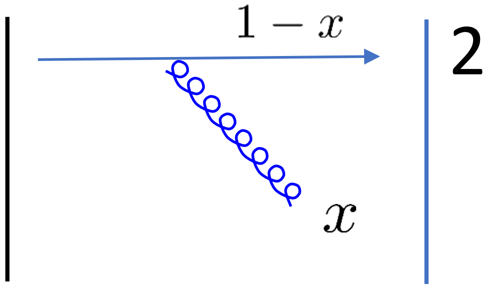
Gluon saturation

Nucleon tomography

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!

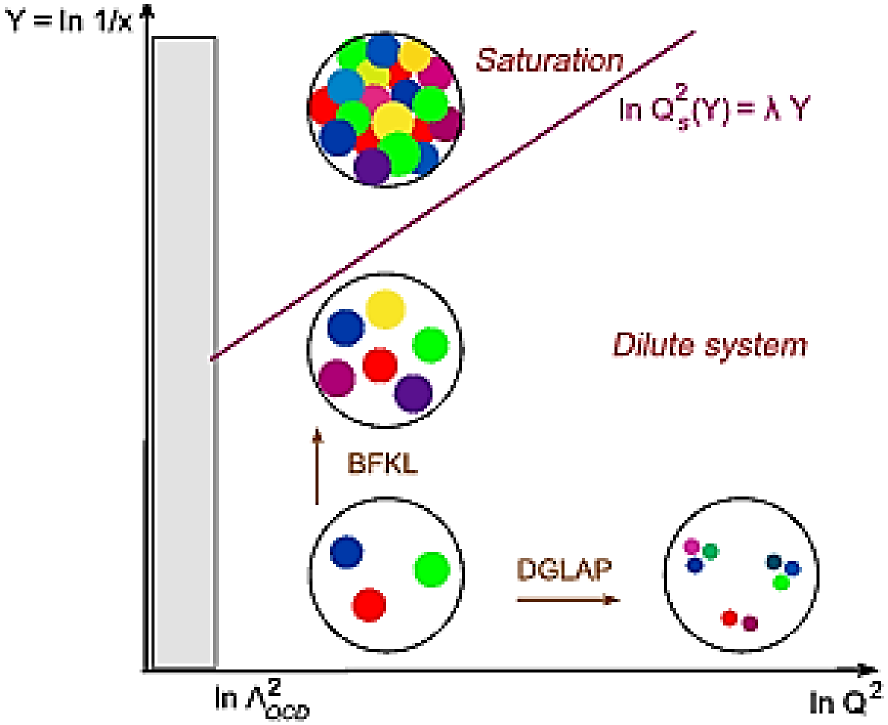
as predicted by BFKL
(Balitsky-Fadin-Kuraev-Lipatov)

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

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

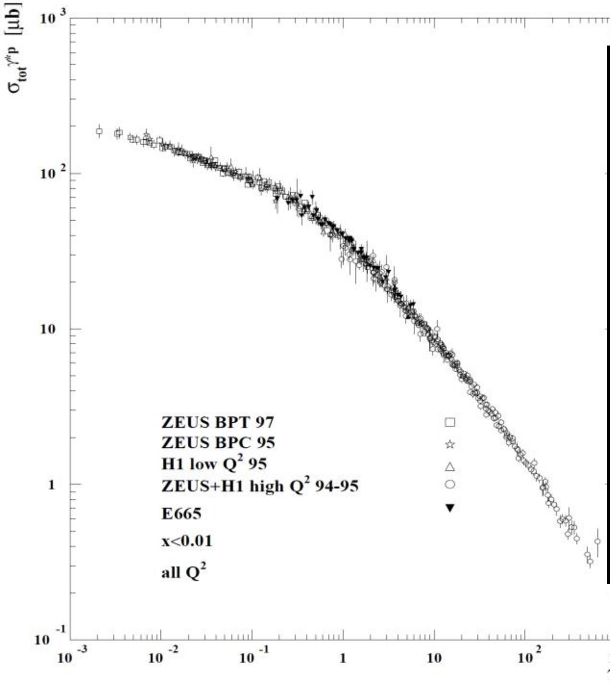
$$\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2$$

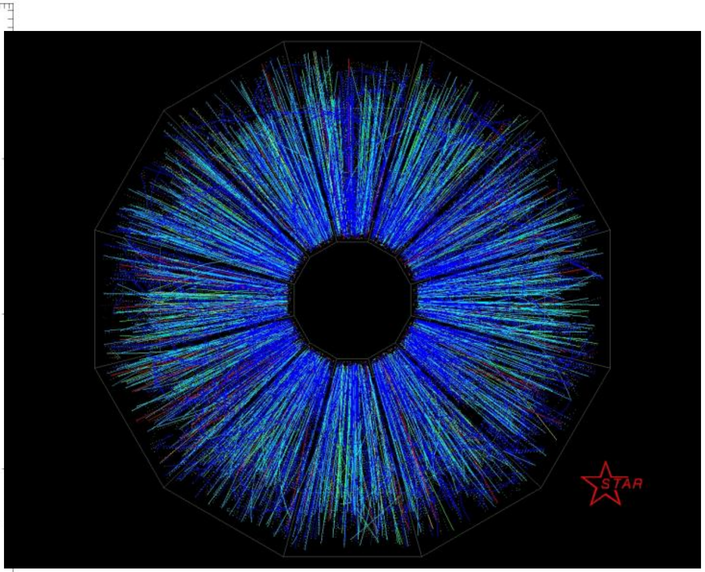
The saturation momentum

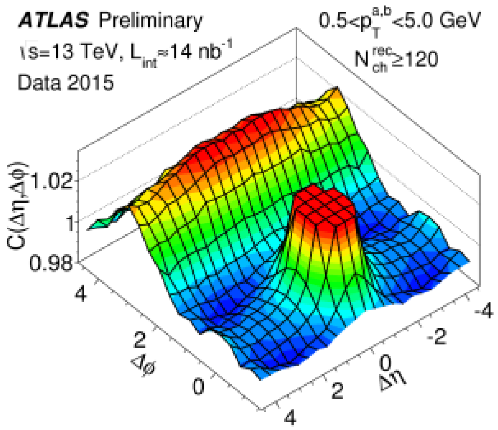
$$Q = Q_s(x) \gg \Lambda_{QCD}$$

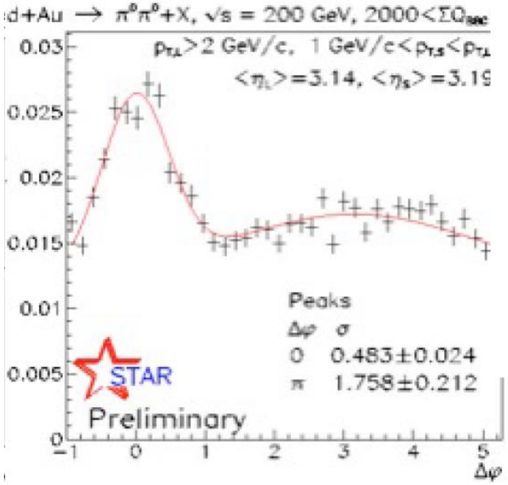
High density, but weakly coupled many-body problem

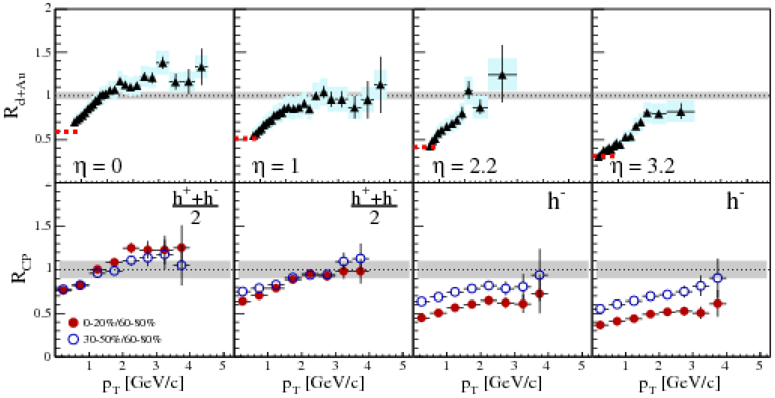
Has saturation been observed at HERA, RHIC, LHC?

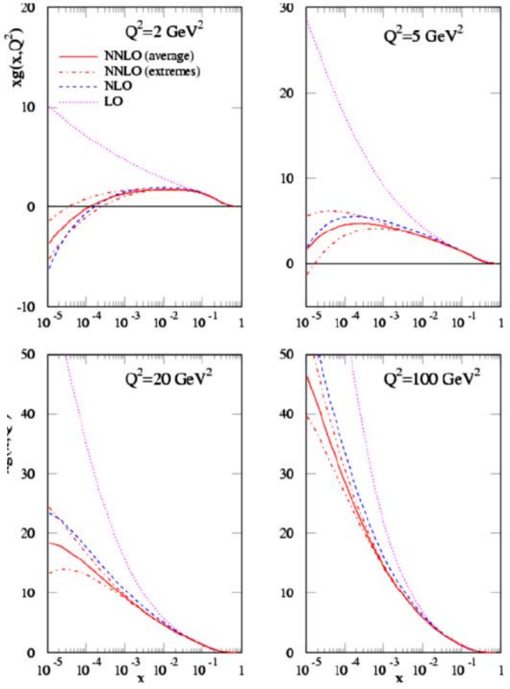








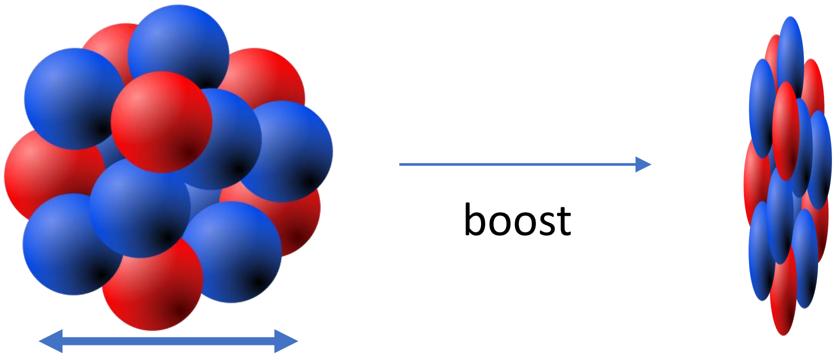




eA collision at EIC : ideal place to study saturation

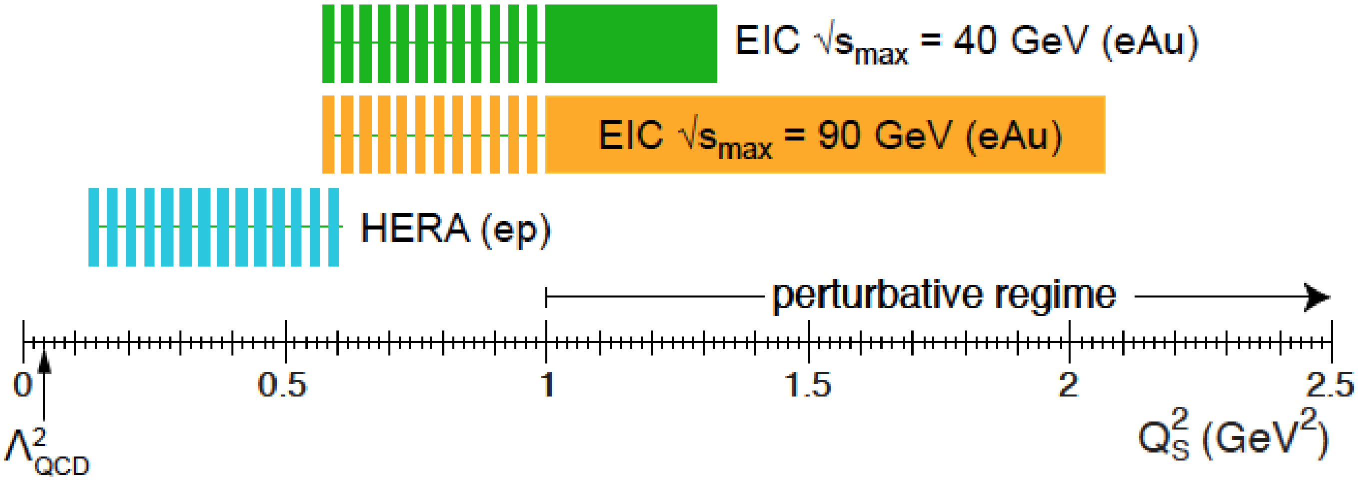
No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)

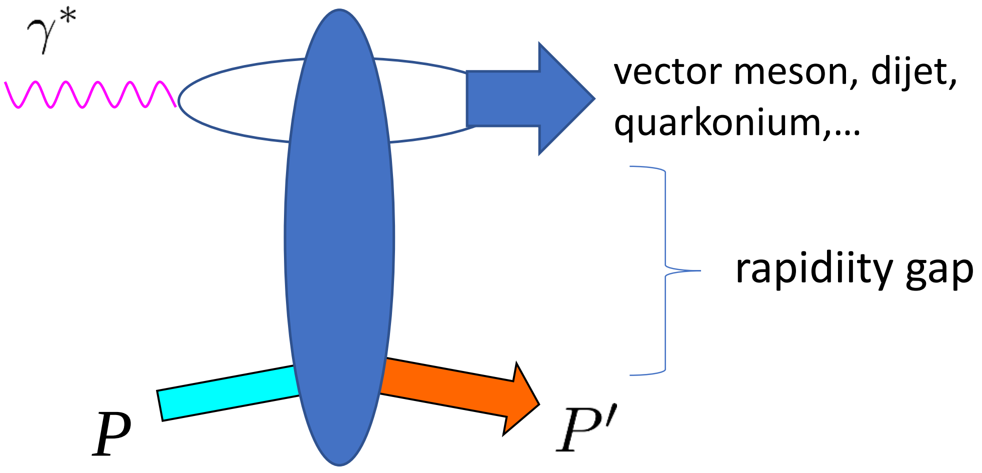


$R_A \sim A^{1/3}$

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



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)

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

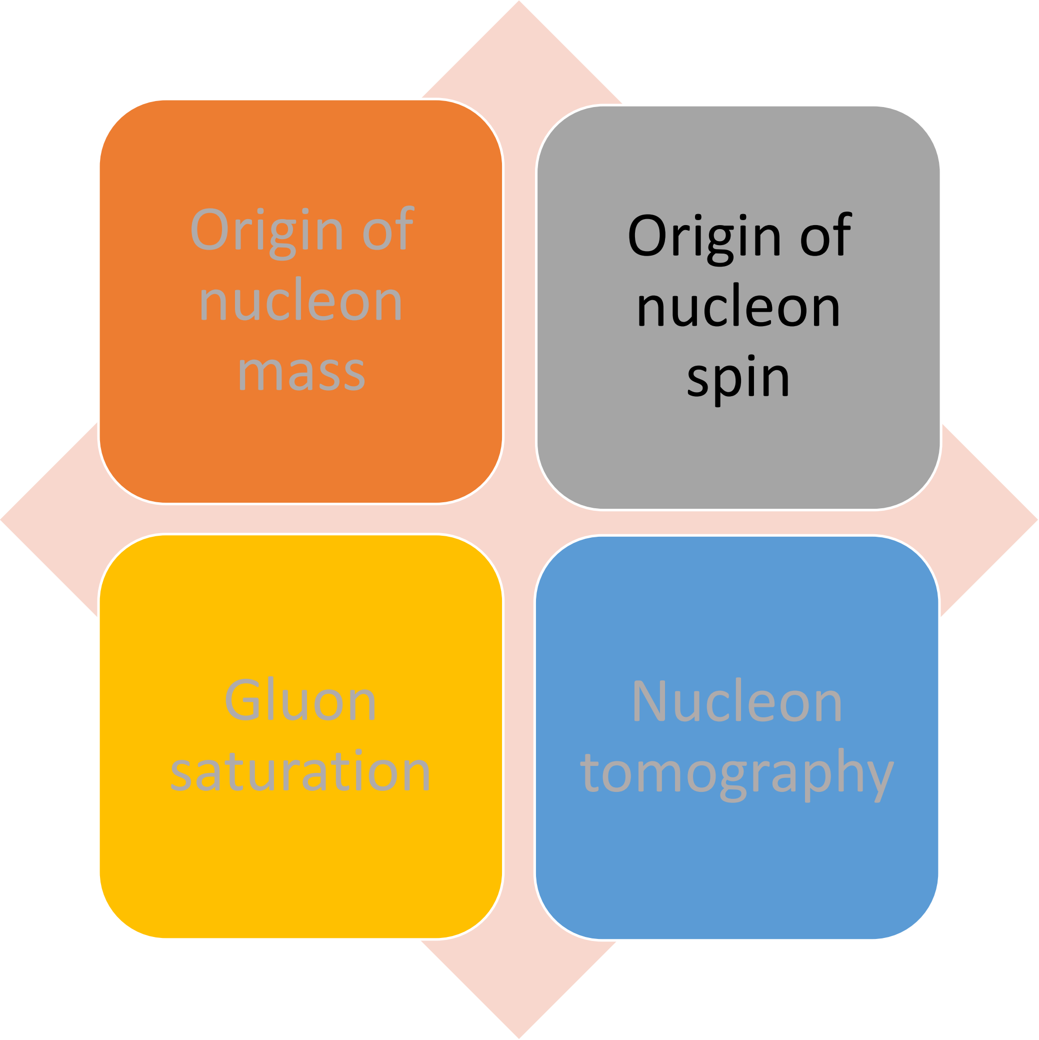
Nucleus stays intact in every 1 out of 5 events!

Recently extended to NLL+NLO for dijet, vector meson…

Boussarie, Grabovsky, Szymanowski, Wallon (2016,2019)

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

Scientific goals of EIC



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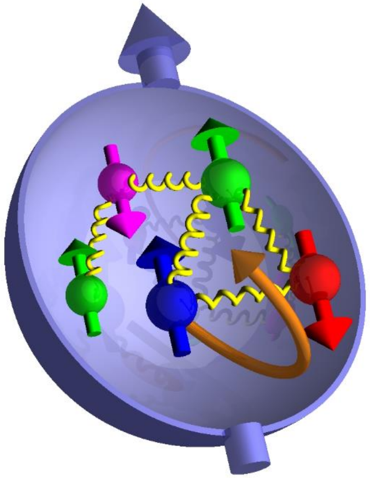
Proton spin decomposition



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

Proton spin crisis

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

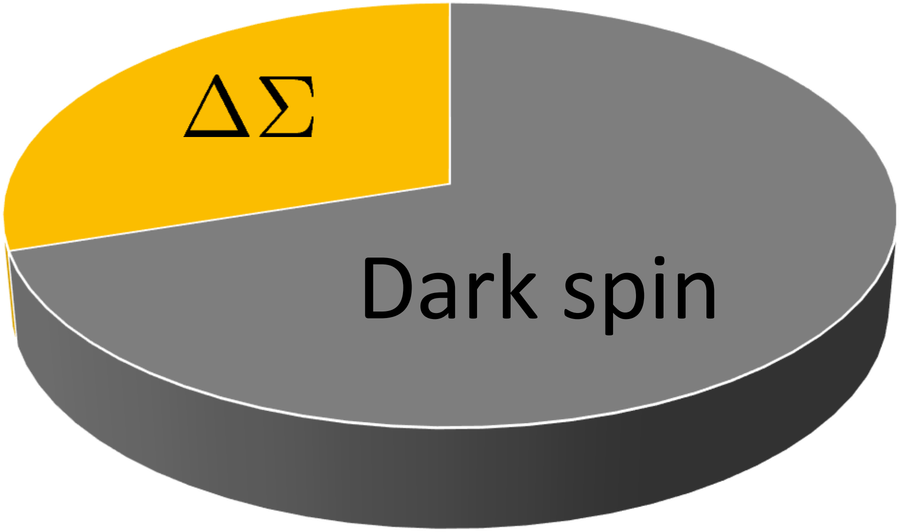
$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14 \ \ !?$$

Recent values from NLO global analysis

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

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

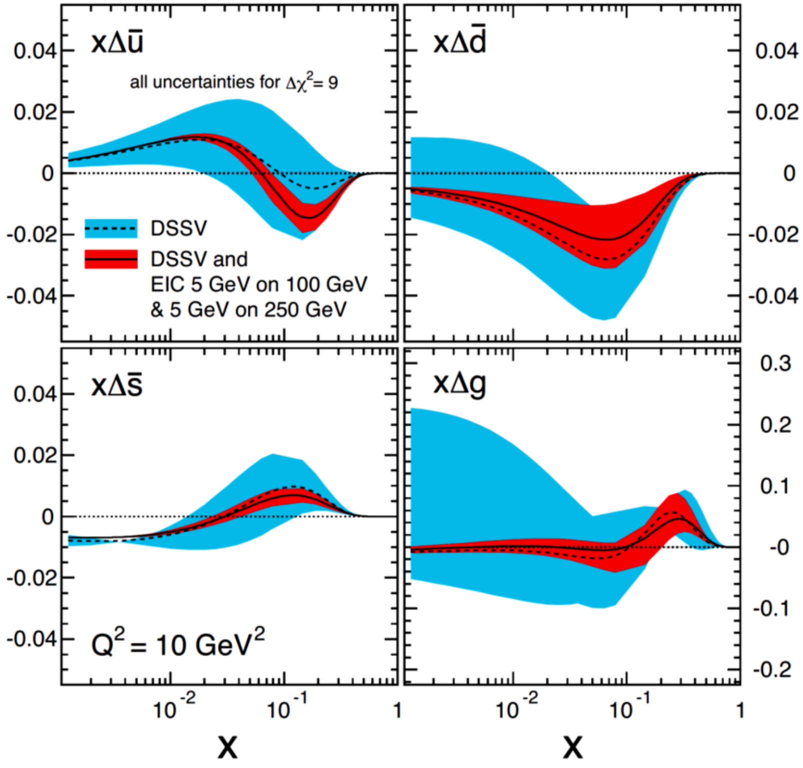
DeFlorian, Sassot, Stratmann, Vogelsang (2014)

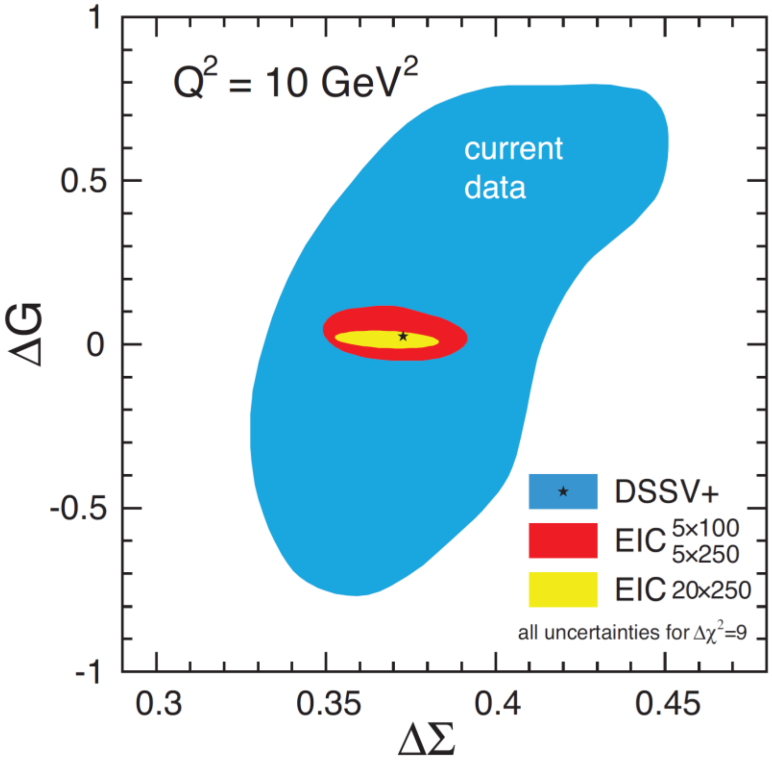


Warning: Huge uncertainties from the small-x region

Helicity measurements at EIC

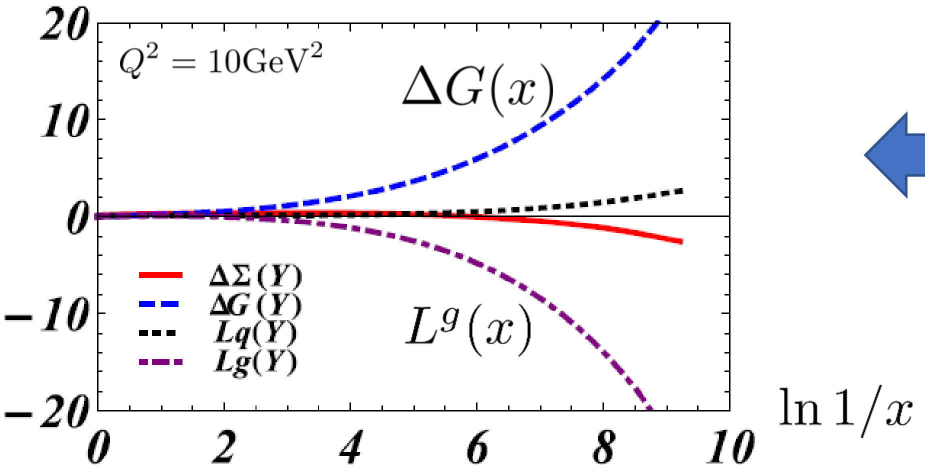
After one-year of data taking at EIC…





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

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

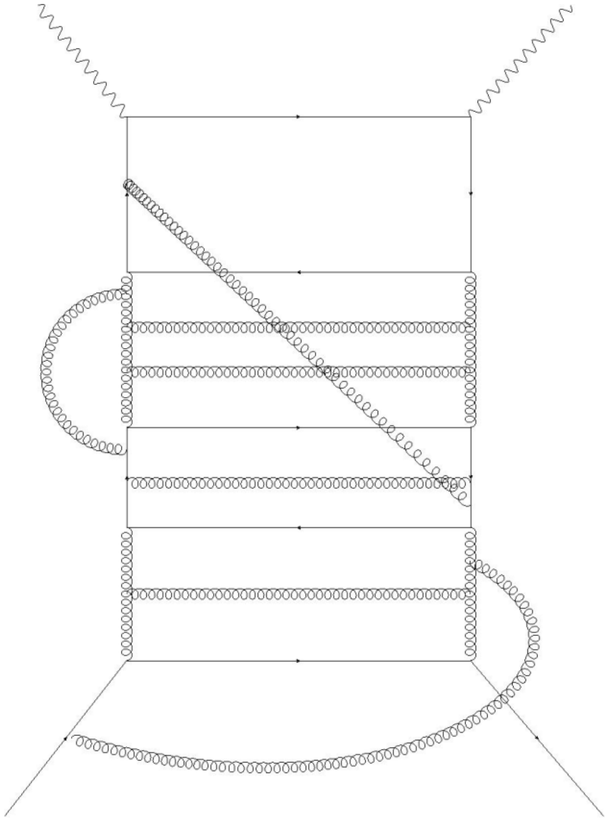


Significant cancellation at small-x from one-loop DGLAP
YH, Yang (2018)

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)



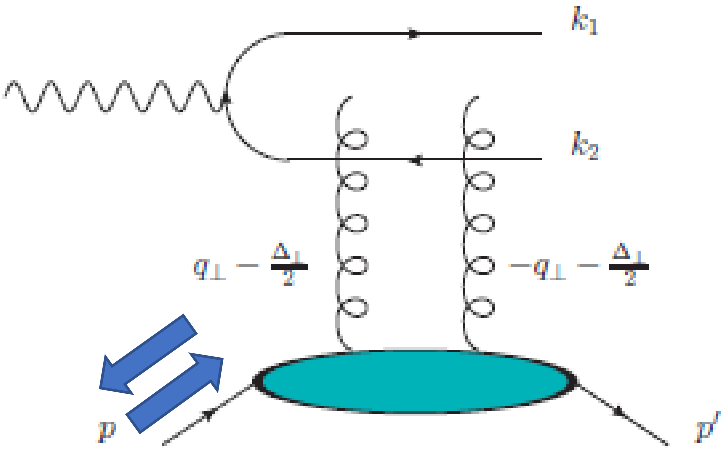
Measuring OAM at EIC

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

Exploit the connection between OAM and the Wigner distribution

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

Longitudinal single spin asymmetry in diffractive dijet production



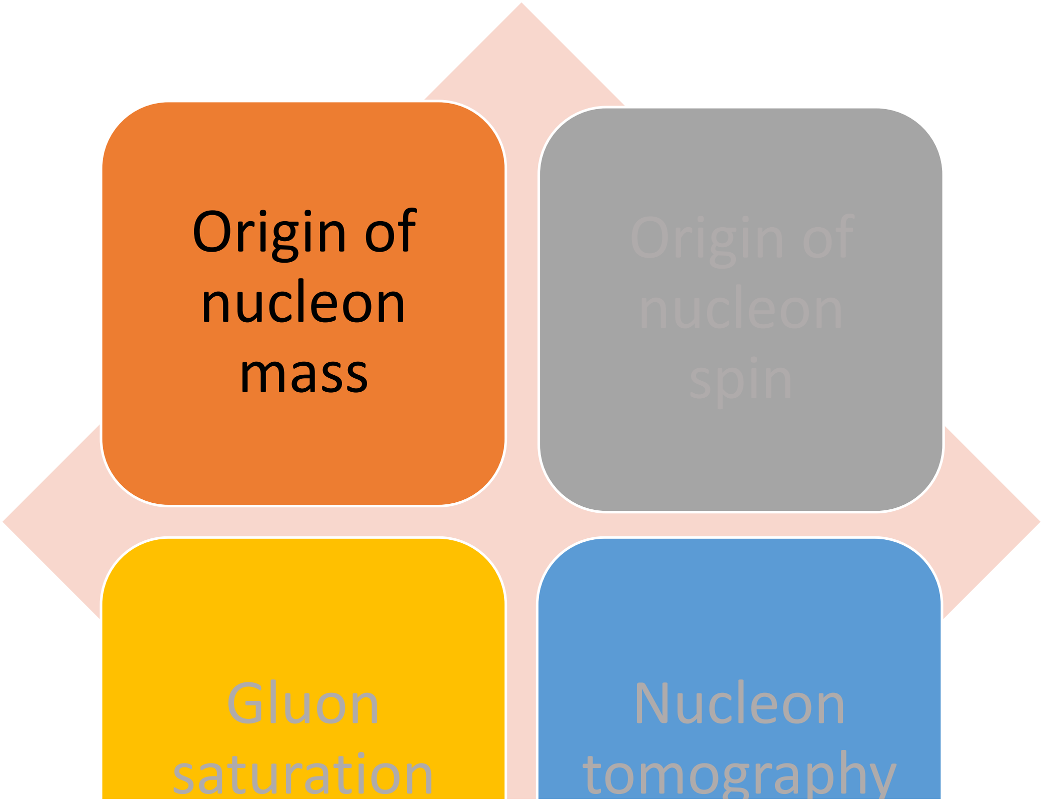
proton recoil momentum

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

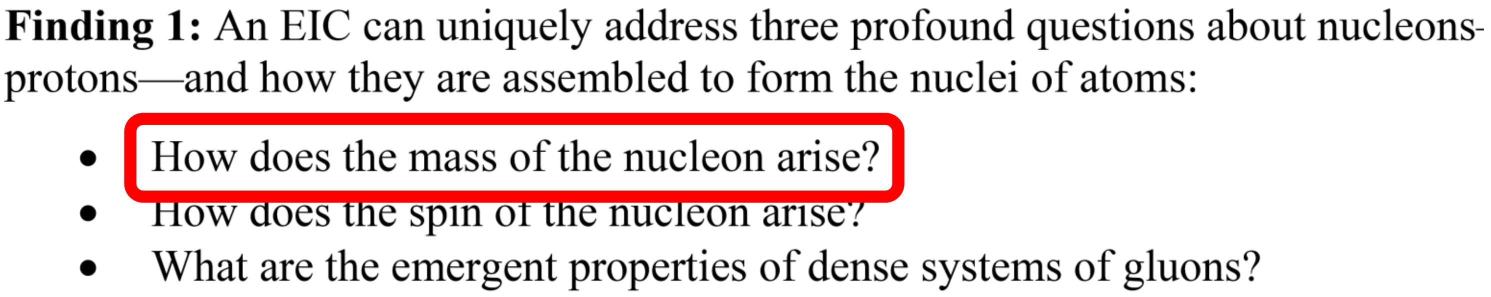
dijet relative momentum

Need more work, more new ideas!

Scientific goals of EIC



NAS report (2018/07)

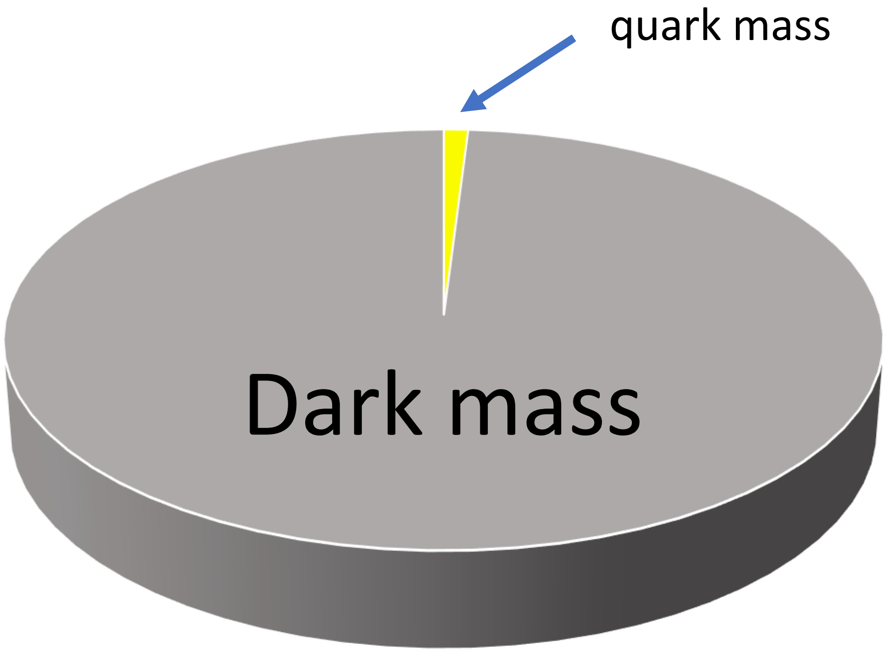


Finding 1: An EIC can uniquely address three profound questions about nucleons- protons—and how they are assembled to form the nuclei of atoms:

- 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

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

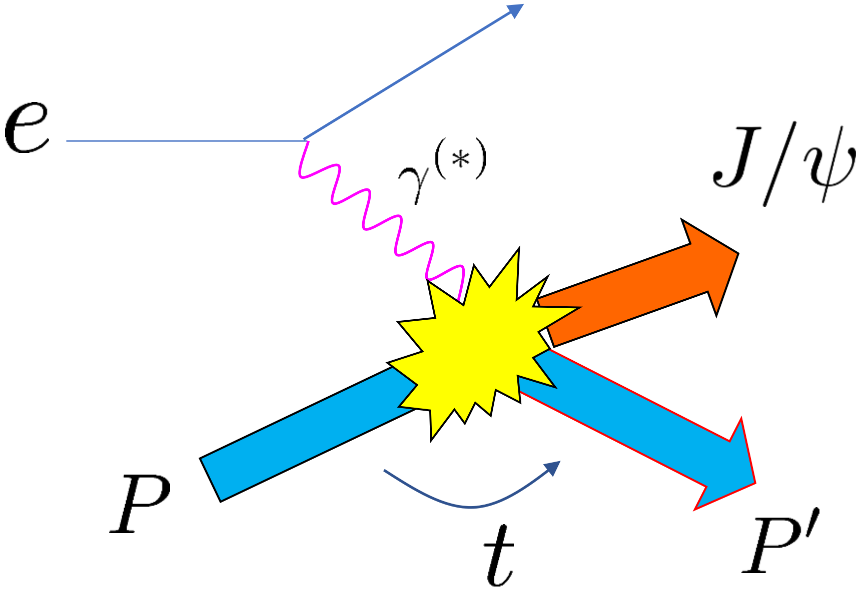
$$\boxed{T^{\mu}_{\mu} = \frac{\beta(g)}{2g}F^2 + m(1+\gamma_m(g))\bar{q}q}$$

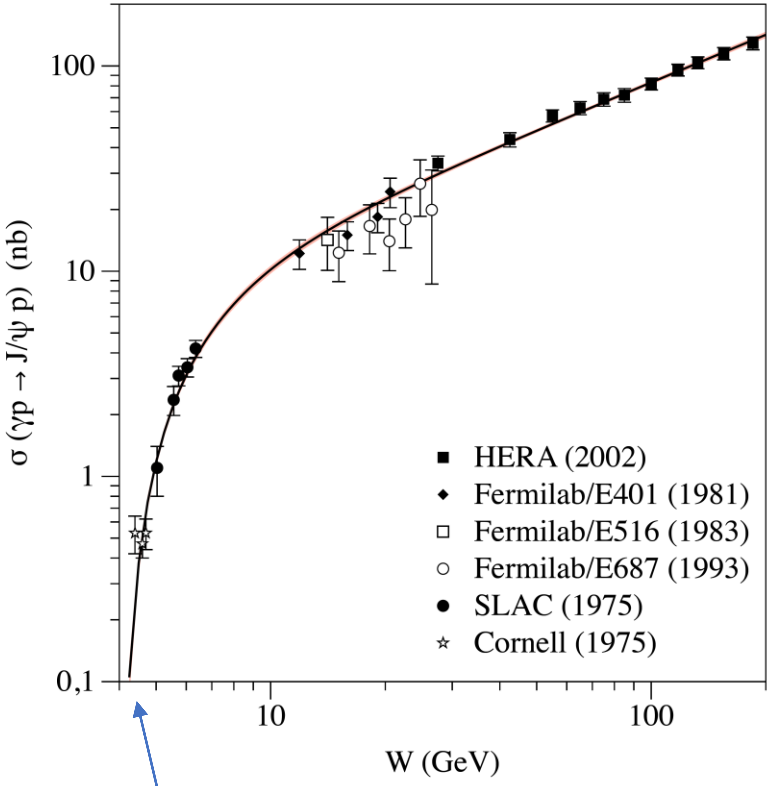
$$\langle P|T^{\mu}_{\mu}|P\rangle = 2M^2$$

Photo-production of J/ψ near threshold

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

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





$W_{th} \approx 4.04\text{GeV}$

Straightforward to measure.
Ongoing experiments at Jlab.

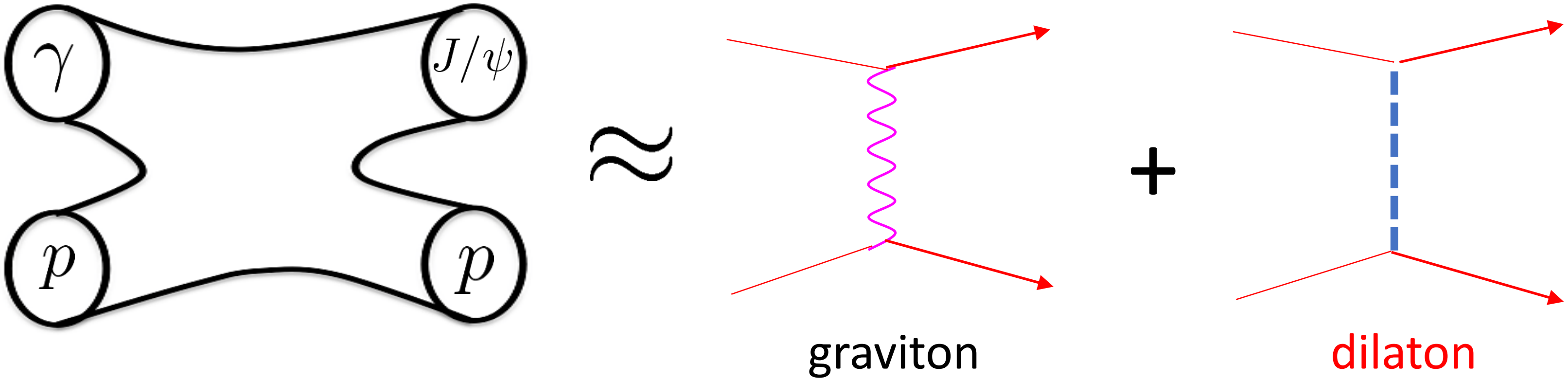
Difficult to compute from first principles
(need nonperturbative approaches)

Holographic approach

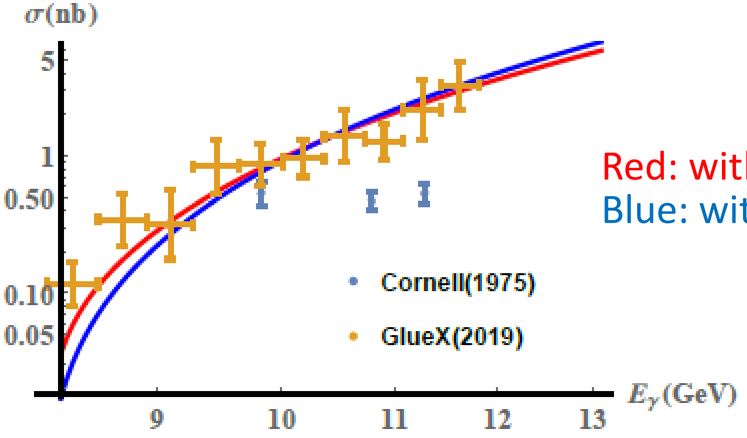
YH, Yang (2018),
YH, Rajan, Yang, 1906.00894 ← NEW!!

Scattering of hadrons $\approx$ scattering of strings in anti-de Sitter

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



Data from the GlueX collaboration
1905.10811 ← NEW!!

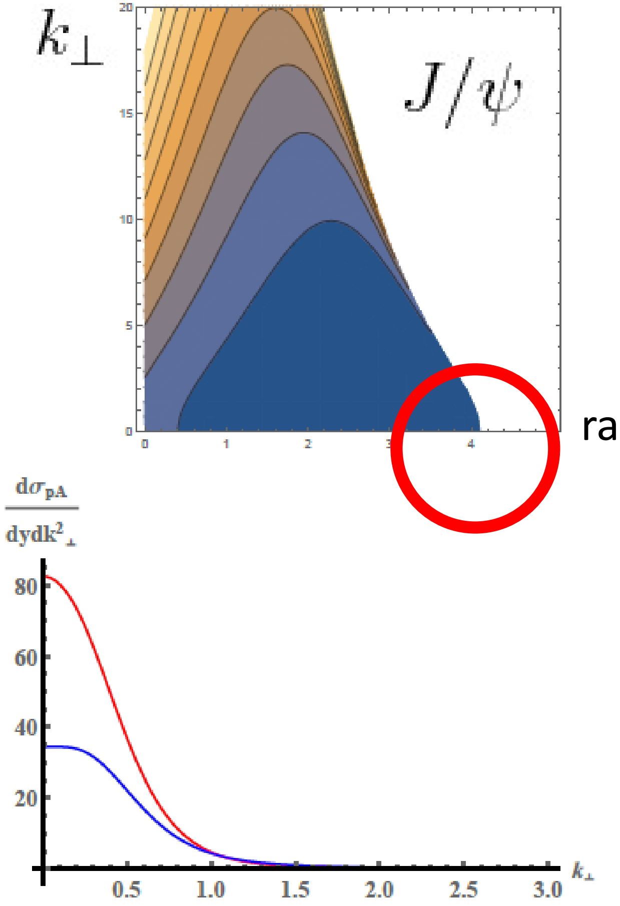


Red: with gluon condensate
Blue: without gluon condnsate

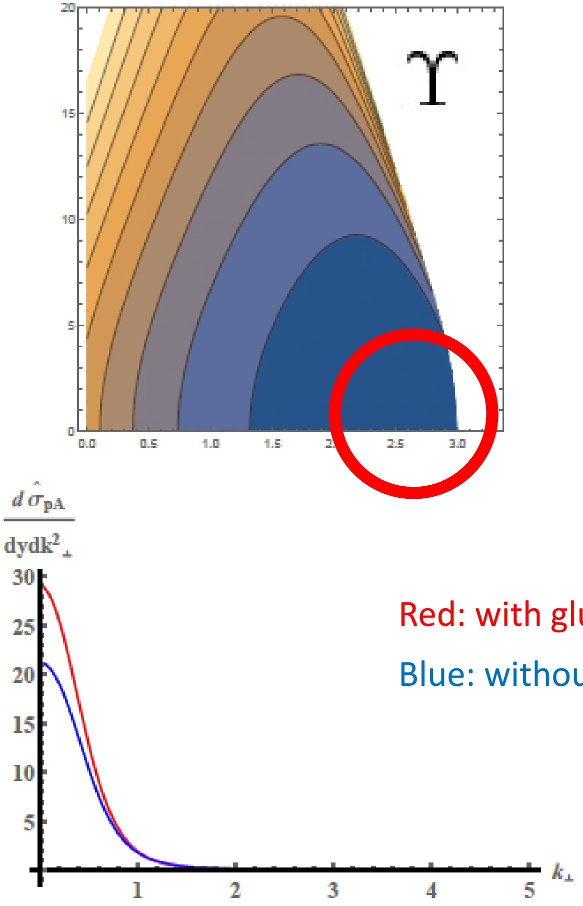
We can do it at RHIC, too!

Near threshold production in ultra-peripheral pA collisions (UPC)

YH, Rajan, Yang, 1906.00894



rapidity



Red: with gluon condensate

Blue: without gluon condndsate

…and in future, at the EIC

Conclusion

- The science of EIC is one of the key future directions of nuclear physics in the US and around the world.
- EIC will significantly advance our knowledge of the nucleons/nuclei, the fundamental building blocks of the universe.
- Topics not covered include:

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

EIC user group
833 members, 177 institutions
(as of Nov.2018)

Let’s join the groundswell.

Exciting times ahead!