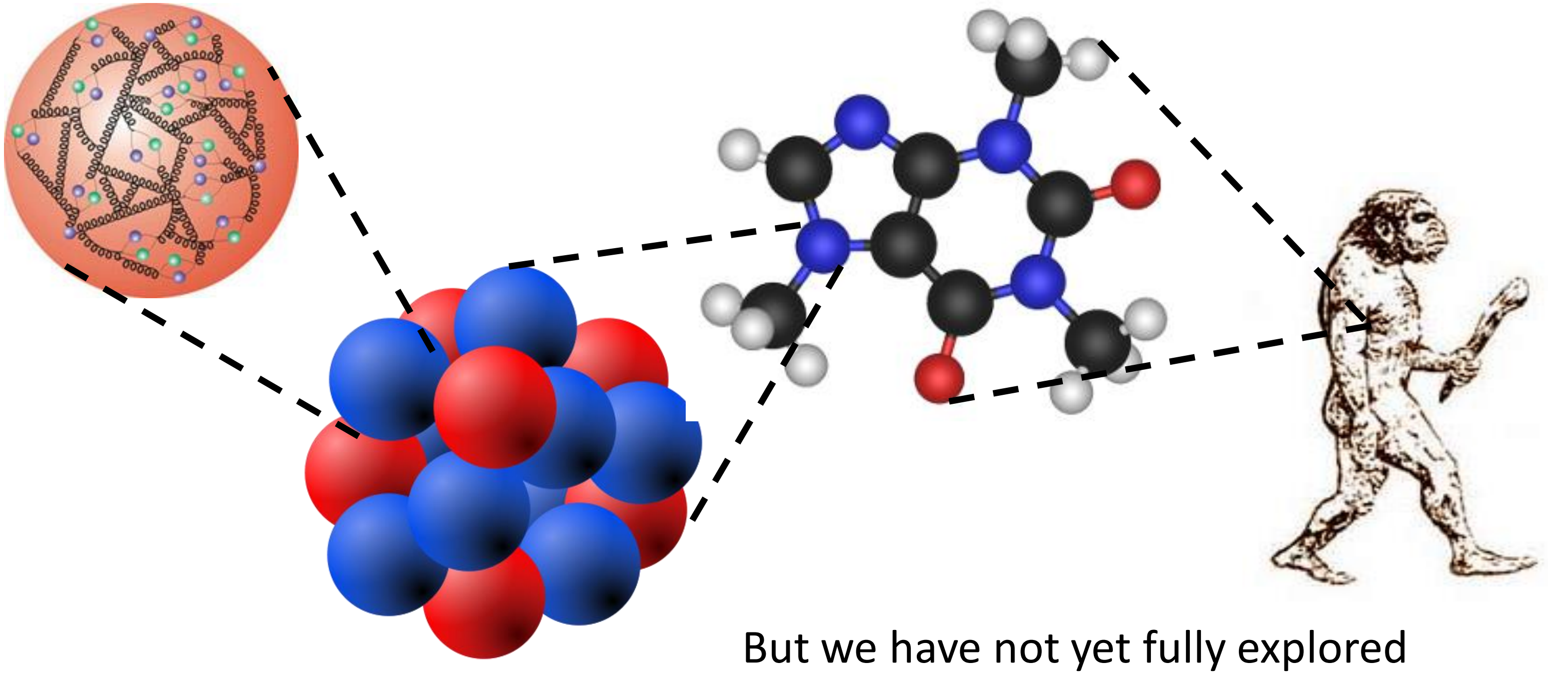
EIC theory overview

Yoshitaka Hatta
Brookhaven National Laboratory

Understanding the glue that binds us all

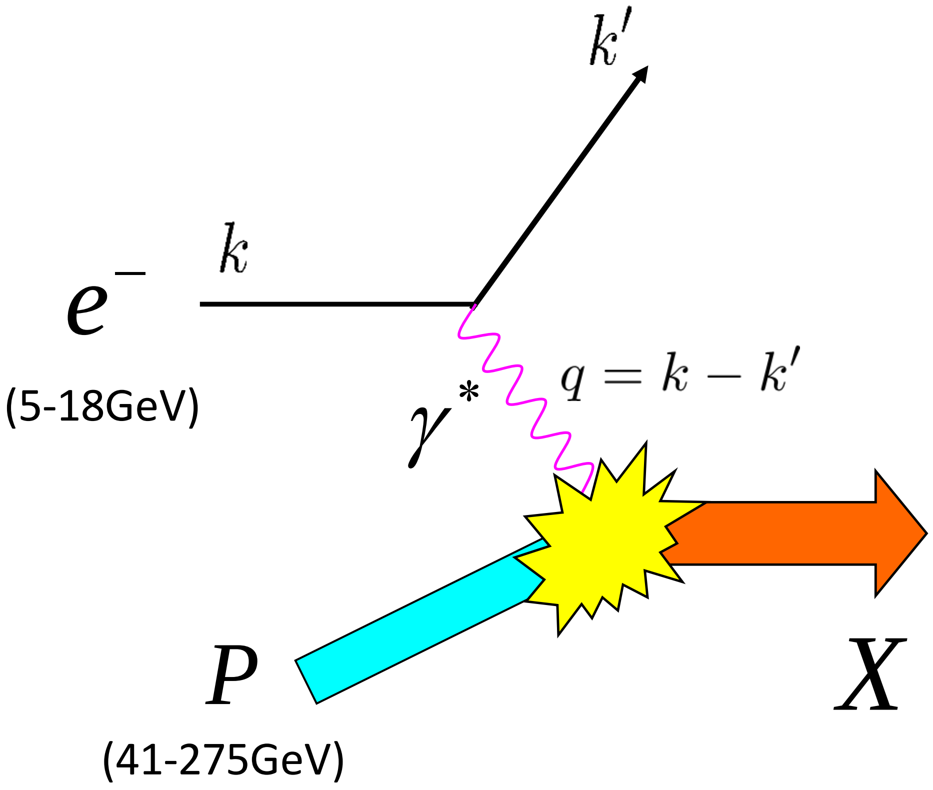
Since the discovery of quarks, DIS has been instrumental to our understanding of the smallest building blocks of our universe.



But we have not yet fully explored
the structure of nucleon/nuclei.
There are still lots of things to be learned.

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)

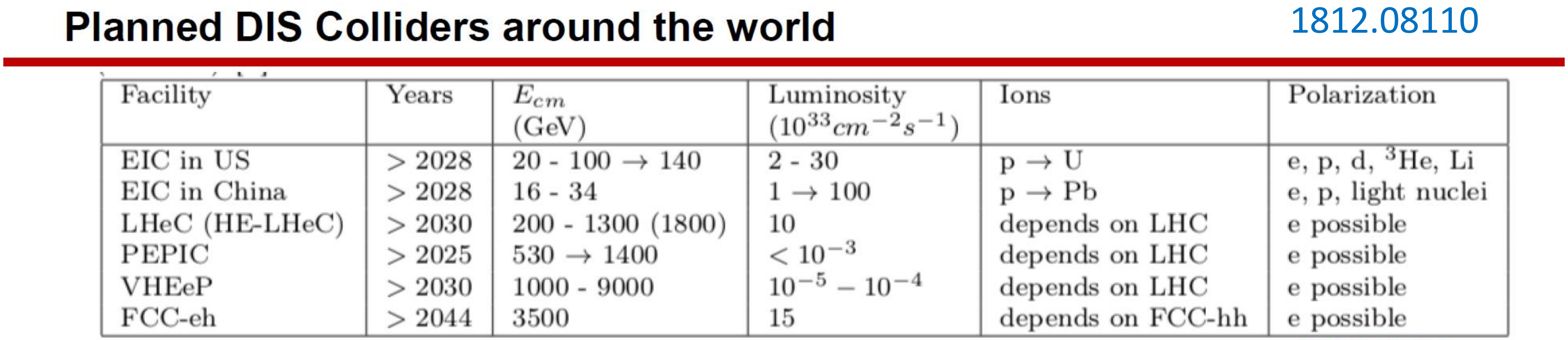
$$x = \frac{Q^2}{2P \cdot q} \approx \frac{E_{parton}}{E_{proton}}$$

Bjorken variable
(inverse energy)

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

Electron, proton and light nuclei can be polarized.

Future DIS experiments worldwide



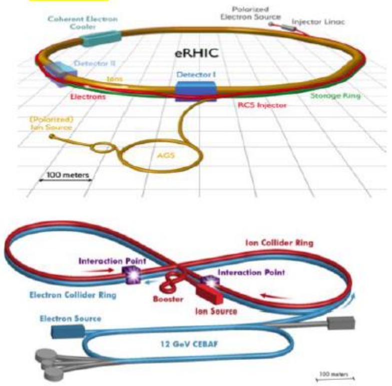
Planned DIS Colliders around the world

1812.08110

Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	20 - 100 → 140	2 - 30	p → U	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	1 → 100	p → Pb	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	530 → 1400	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

EPPSU DIS Input

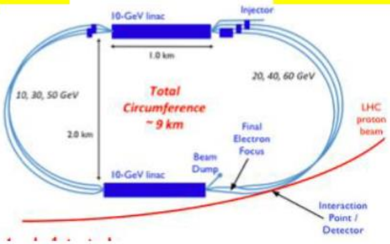
EIC



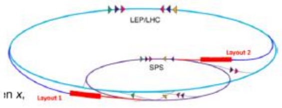
EicC

LHeC

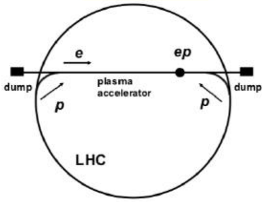
FCC-eh



PEPIC

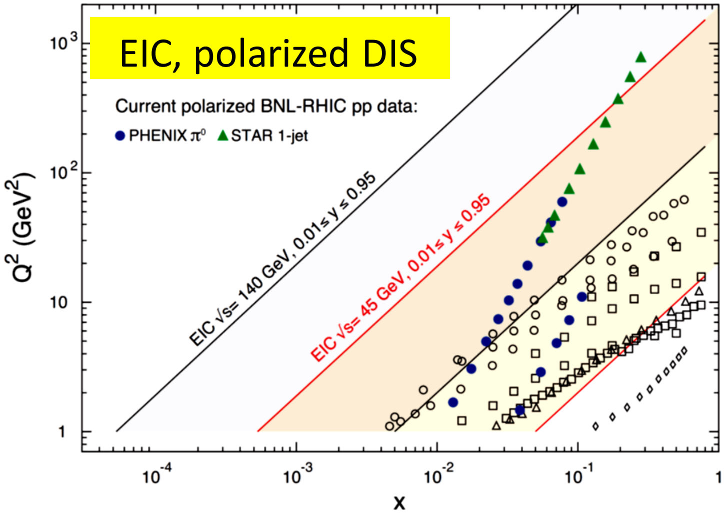


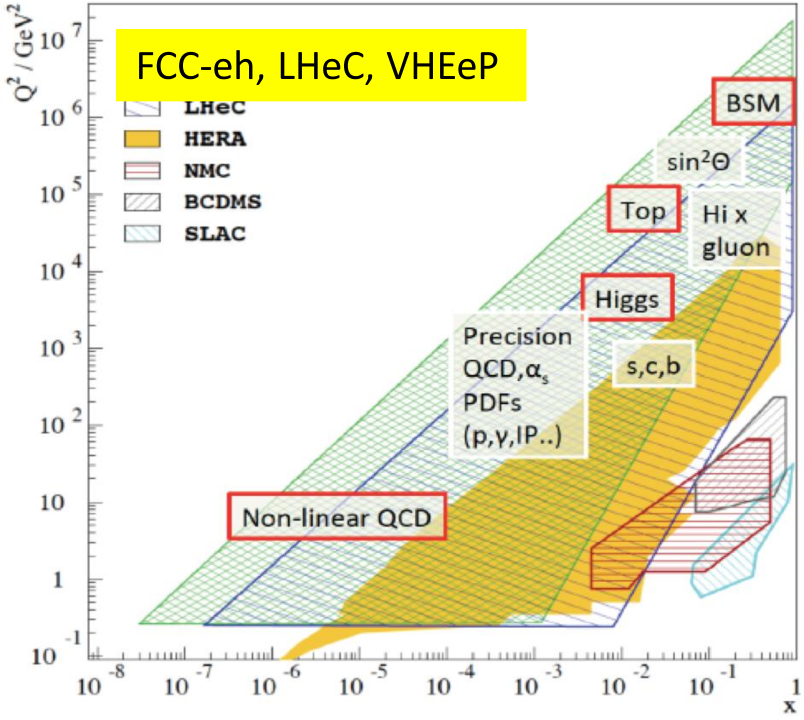
VHEeP

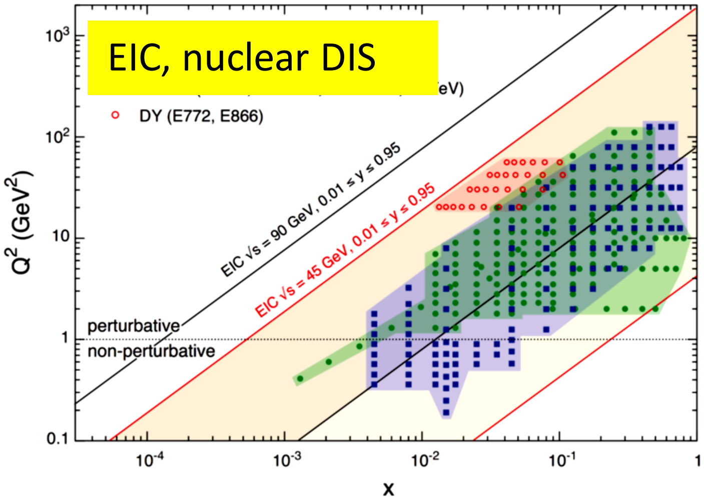


The era of precision study of nucleon and nuclear structures in the next 25~30 years.

Exploring *terra incognita*



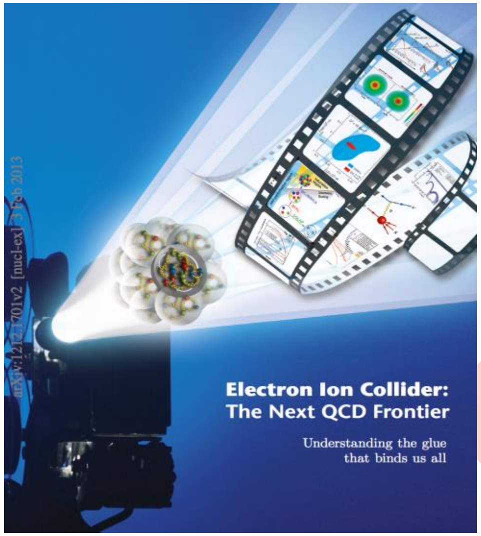




Unprecedented coverage in kinematics.
Tremendous physics opportunities.

Scientific goals of EIC

White paper
arXiv:1212.1701



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

arXiv:1212.1701v2 [nucl-ex] 3 Feb 2013

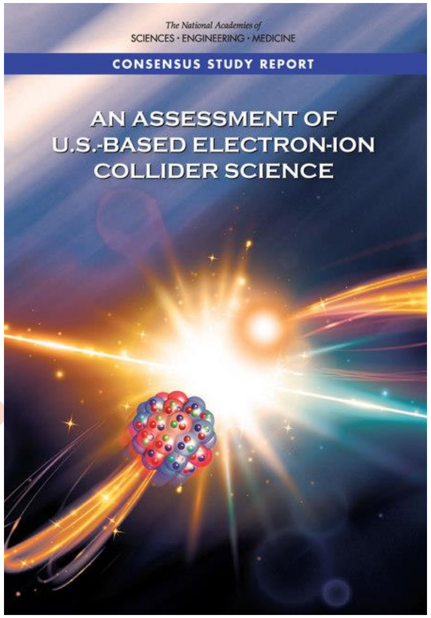
Origin of nucleon mass

Origin of nucleon spin

Gluon saturation

Nucleon tomography

NAS report
(2018/07)



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

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

Scientific goals of EIC

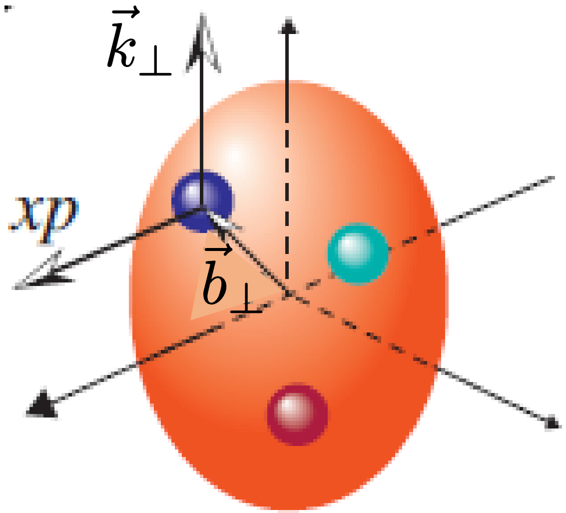
Origin of nucleon mass

Origin of nucleon spin

Gluon saturation

Nucleon tomography

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

PDF family tree

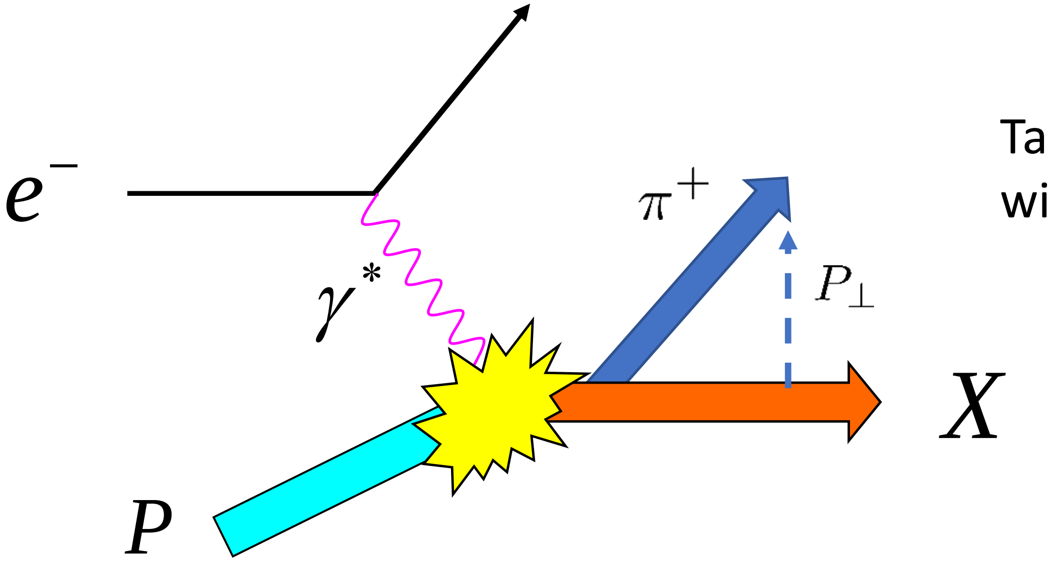
Wigner distribution—the `mother’ distribution

Belitsky, Ji, Yuan (2003)

$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2 z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P-\frac{\Delta}{2}|\bar{q}(-z/2)\gamma^+ q(z/2)|P+\frac{\Delta}{2}\rangle$$

$$\begin{tikzcd}
 & W(x,\vec{k}_\perp,\vec{b}_\perp) \arrow[dl, "\int d\vec{b}_\perp"'] \arrow[dr, "\int d\vec{k}_\perp"] & & \\
\text{TMD}\quad f(x,\vec{k}_\perp) \arrow[dr, "\int d\vec{k}_\perp"'] & & \text{GPD}\quad f(x,\vec{b}_\perp) \arrow[dl, "\int d\vec{b}_\perp"] \arrow[dr, "\int dx"] & \\
 & \underset{\text{PDF}}{f(x)} \arrow[dr, "\int dx"'] & & F(\vec{b}_\perp)\quad \text{Form factor} \arrow[dl, "\int d\vec{b}_\perp"] \\
 & & \underset{\text{charge}}{Q} &
\end{tikzcd}$$

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 is becoming precision physics

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

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

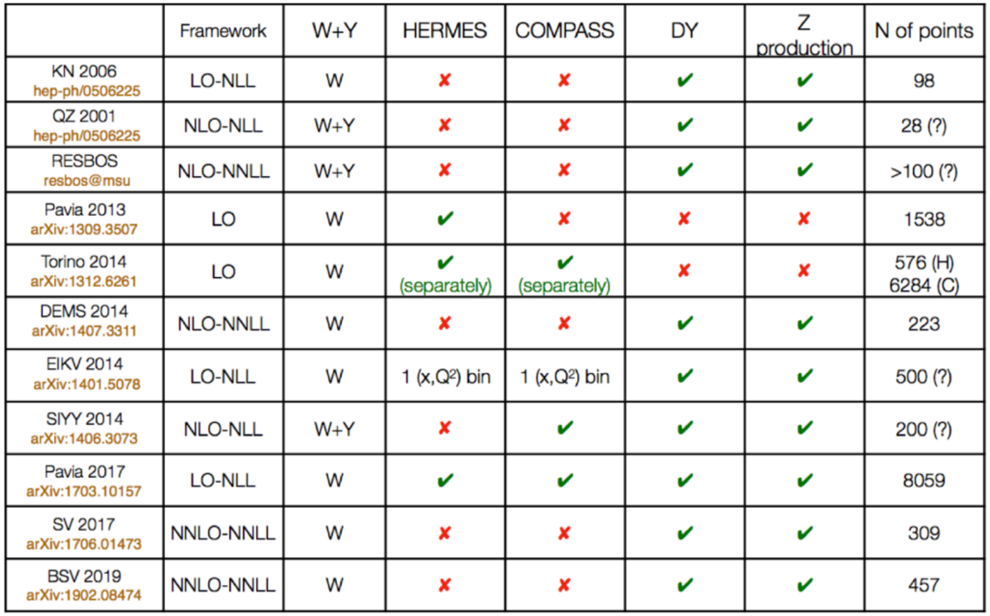
Recently computed to three loops

Li, Zhu (2017); Vladimirov (2017)

Computable from lattice QCD at large $r_\perp$

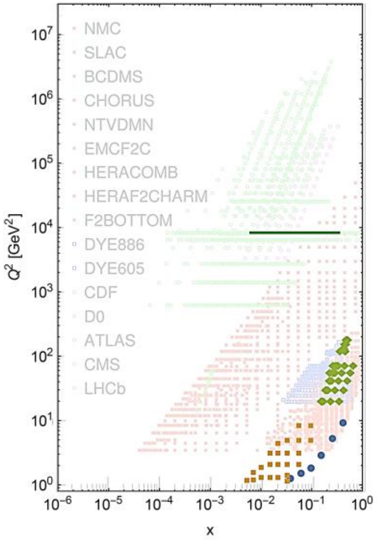
Ebert, Stewart, Zhao (2018)

TMD global analysis

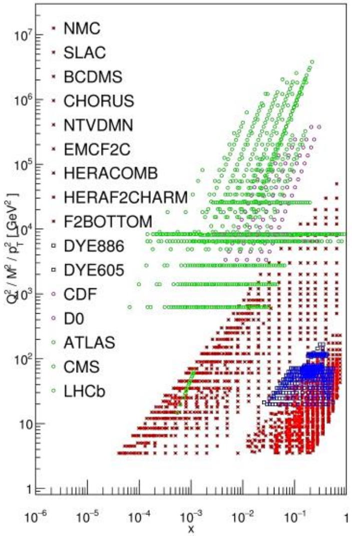


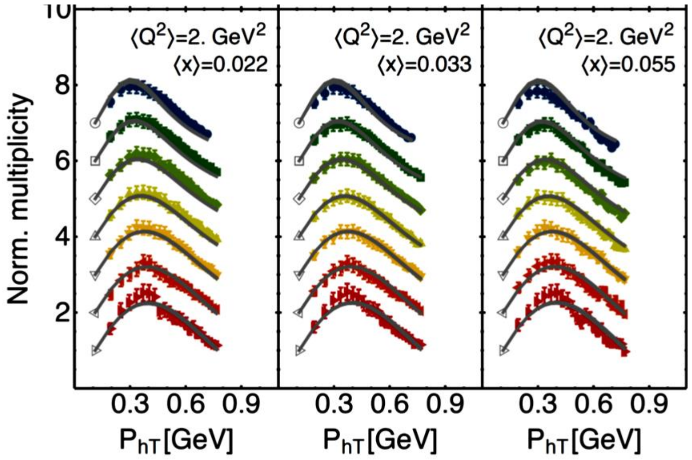
	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	457

TMD



PDF



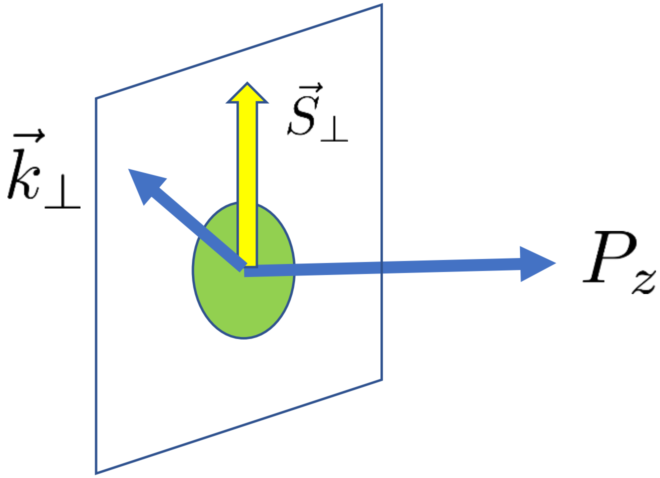


Still in its infancy.

Fully blossoms in the EIC era!

Universality up to a sign

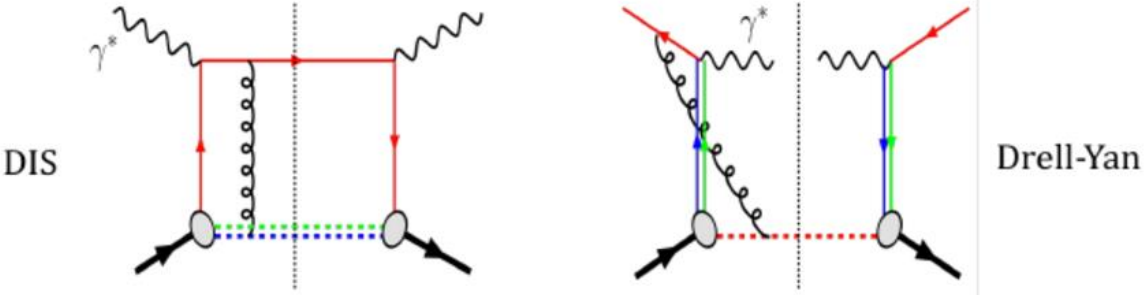
Sivers function for the transversely polarized nucleon



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

→ Single spin asymmetry

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



Experimental test at Compass and RHIC. Continue at EIC.
EIC can also probe gluon Sivers function from open charm SSA.

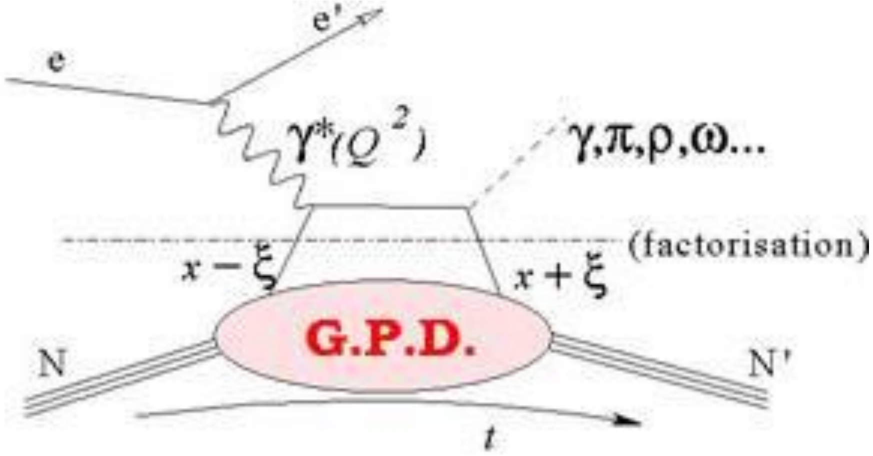
Generalized parton distributions (GPD)

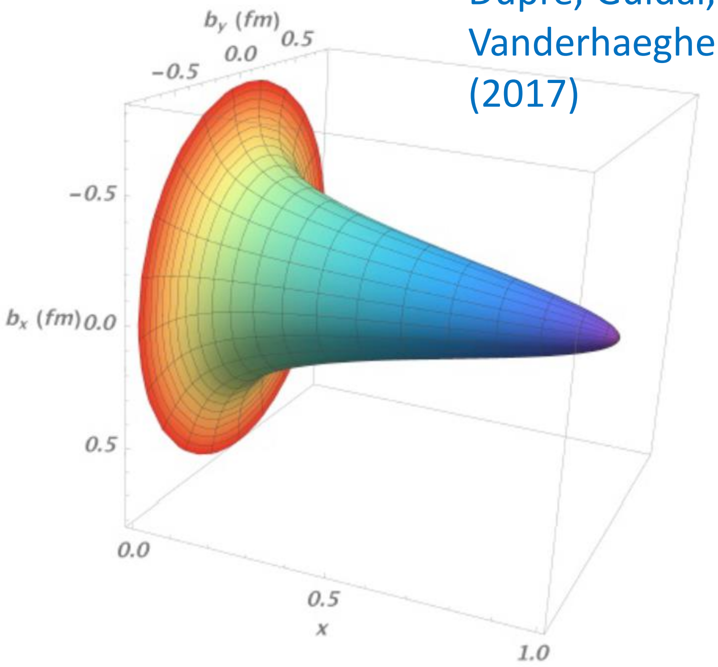
$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu \psi(y^-)|PS\rangle$$

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

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

Measurable in
Deeply Virtual Compton Scattering (DVCS)

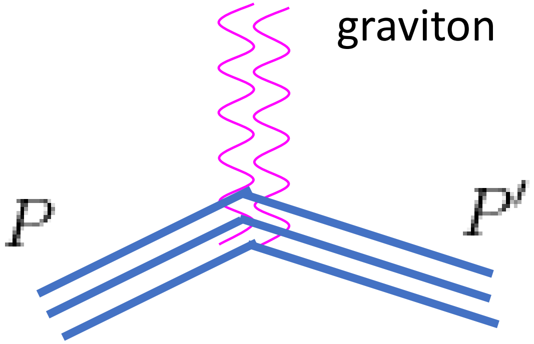




Dupre, Guidal, Vanderhaeghen (2017)

Nucleon gravitational form factors

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\left[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M}\right.$$
$$\left. + D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}Mg^{\mu\nu}\right]u(P)$$



All the form factors are interesting and measurable!

$A_{q,g}$	Momentum fraction
$B_{q,g}$	Ji sum rule
$D_{q,g}$	\`Pressure' and \`shear' inside proton
$\bar{C}_{q,g}$	Mass, pressure

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

$$J_q = \frac{1}{2}\int dx(H_q(x) + E_q(x))$$

D-term: the last global unknown

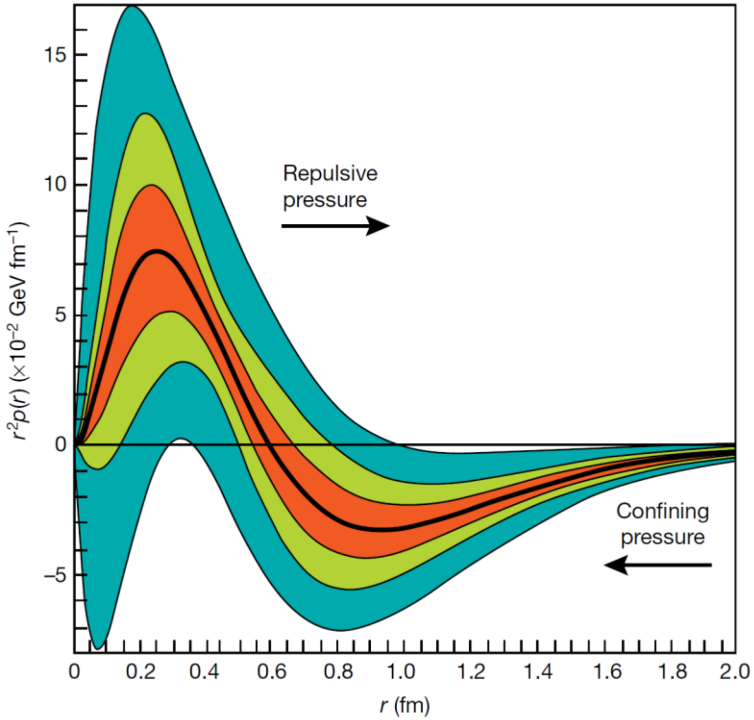
$$\langle P'|T^{ij}|P\rangle \sim (\Delta^i\Delta^k - \delta^{ik}\Delta^2)D(t)$$

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

Related to the radial pressure distribution inside a nucleon

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

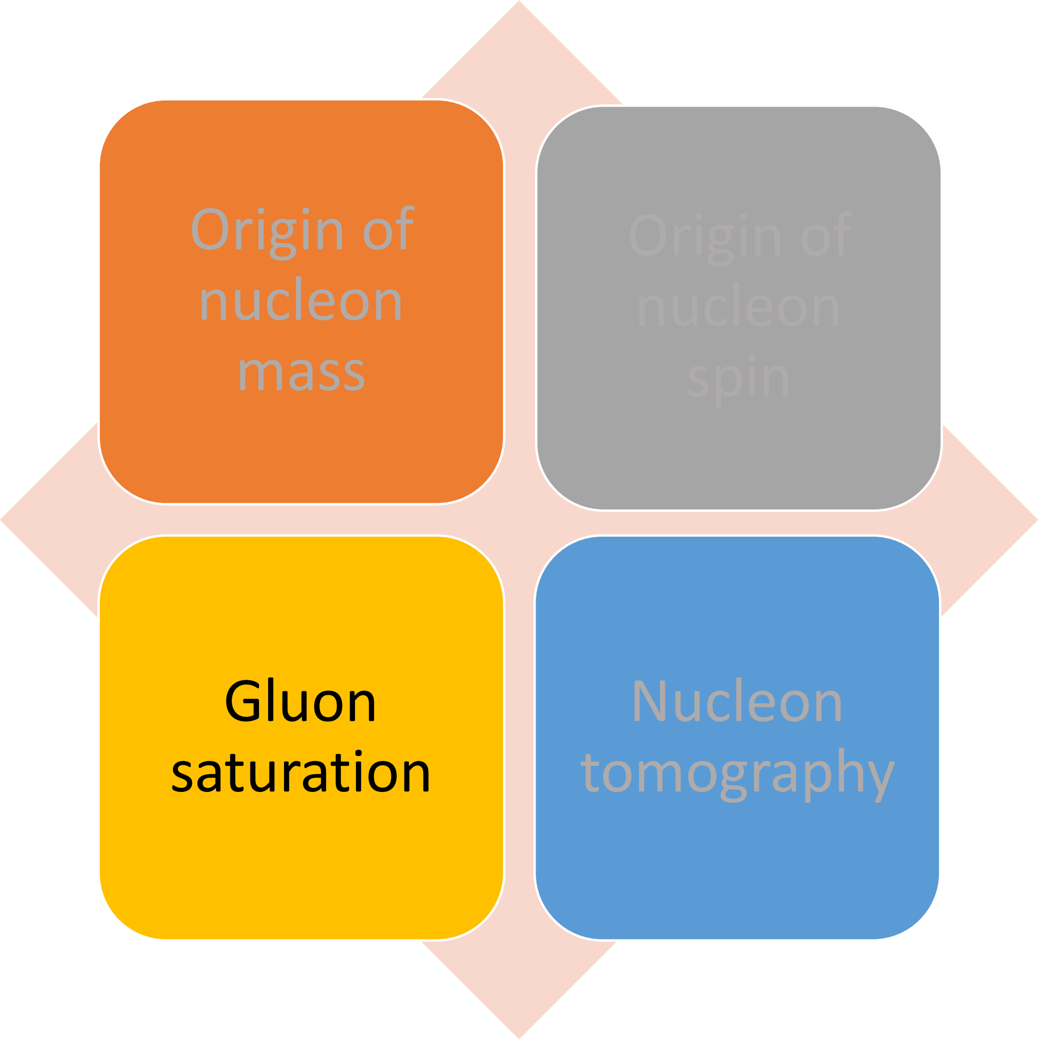
Burkert, Elouadrhiri, Girod (2018)



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



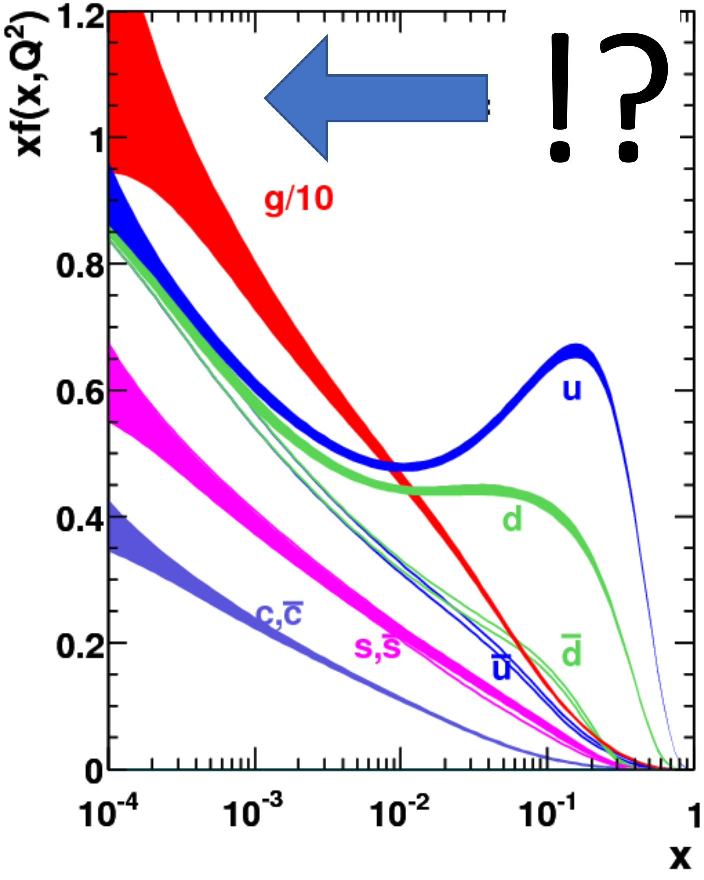
Origin of nucleon mass

Origin of nucleon spin

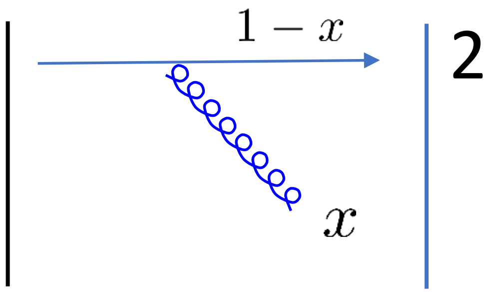
Gluon saturation

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!

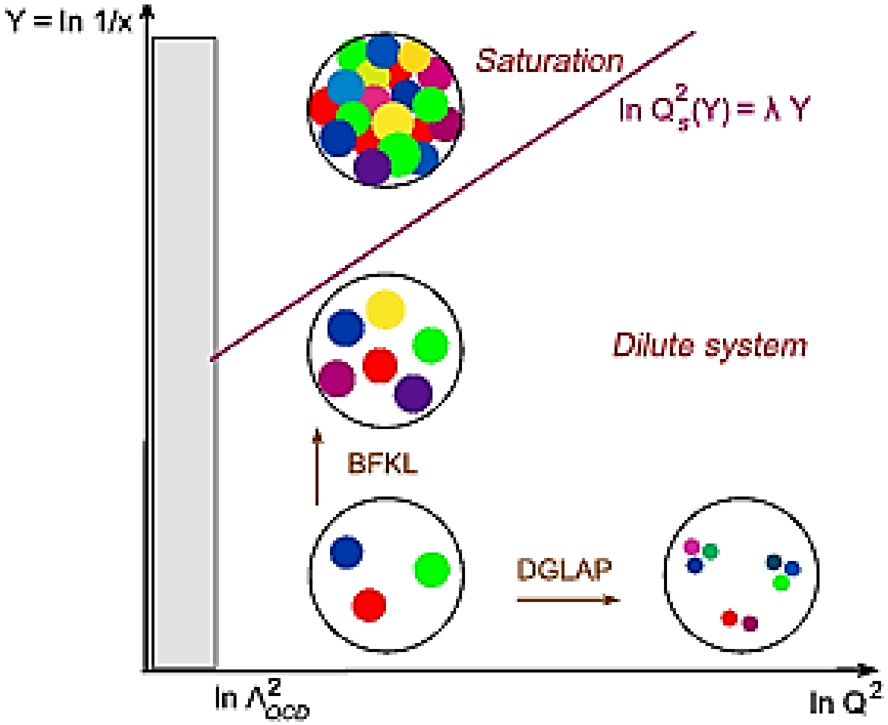
as predicted by BFKL
(Balitsky-Fadin-Kuraev-Lipatov)

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

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

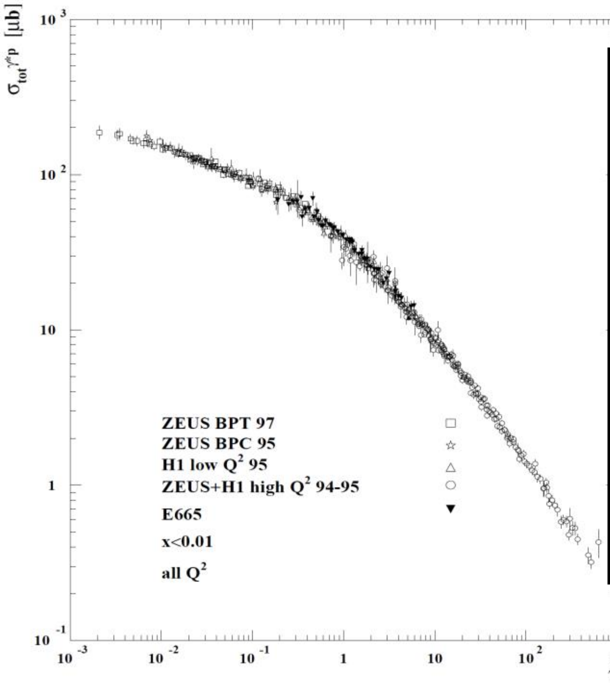
$$\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2$$

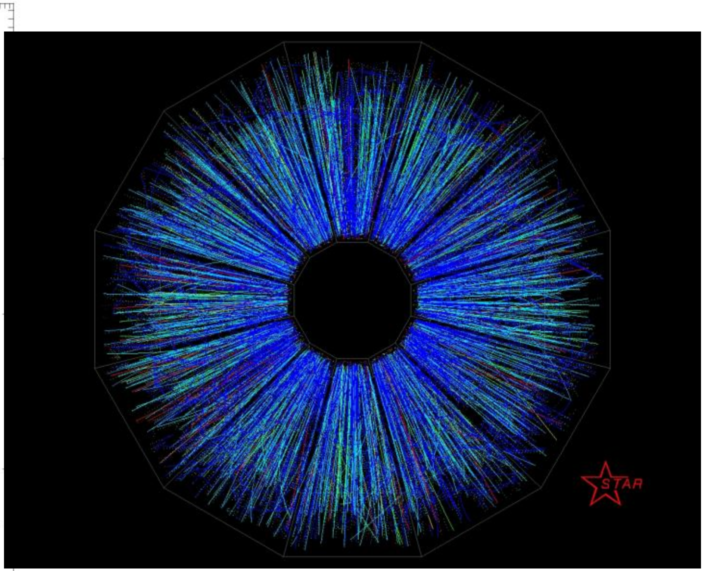
The saturation momentum

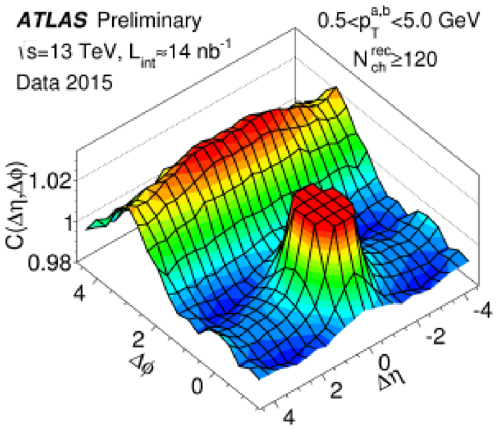
$$Q = Q_s(x) \gg \Lambda_{QCD}$$

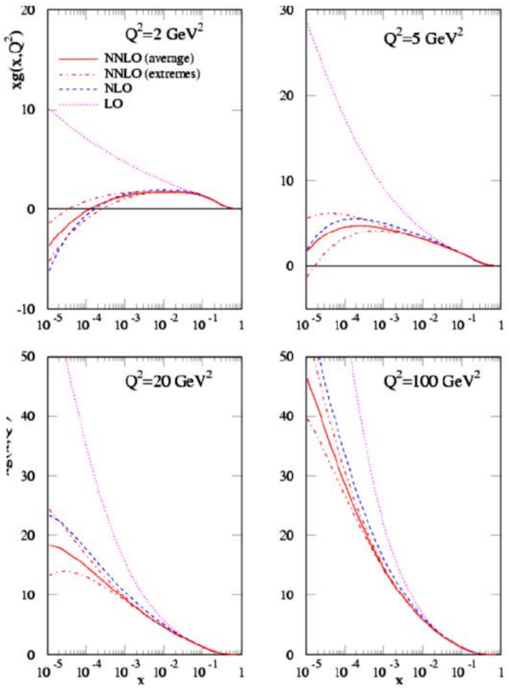
High density, but weakly coupled many-body problem

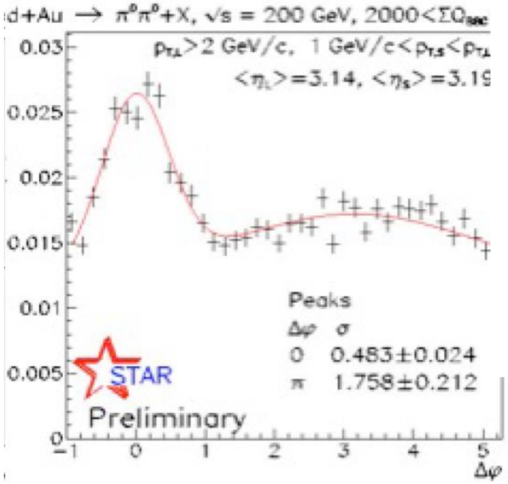
Has saturation been observed at HERA, RHIC, LHC?

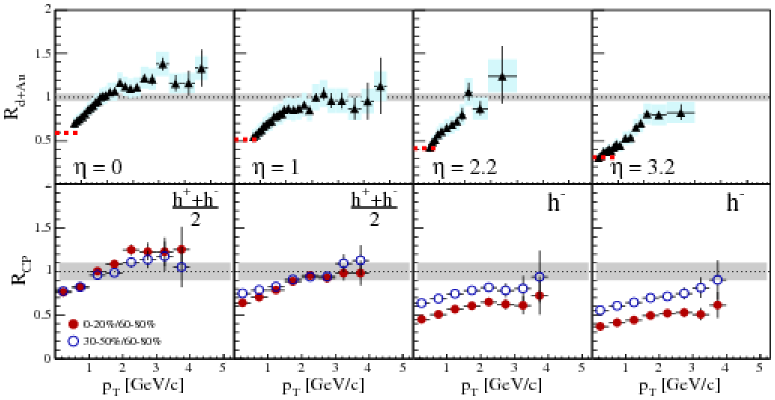








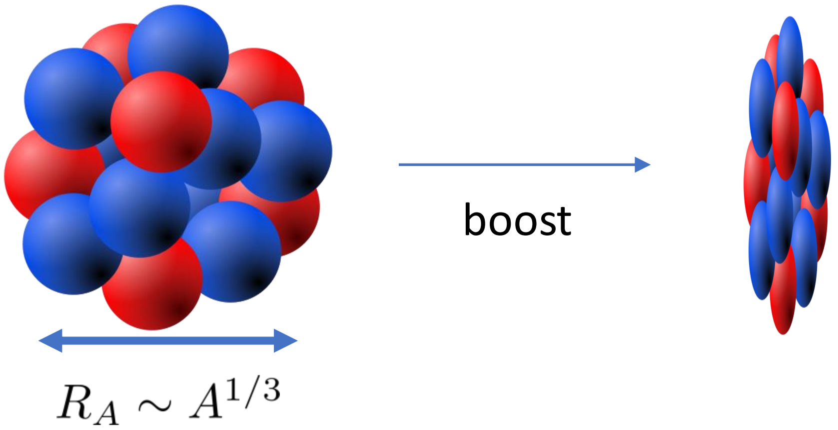




eA collision at EIC : Dream machine for saturation

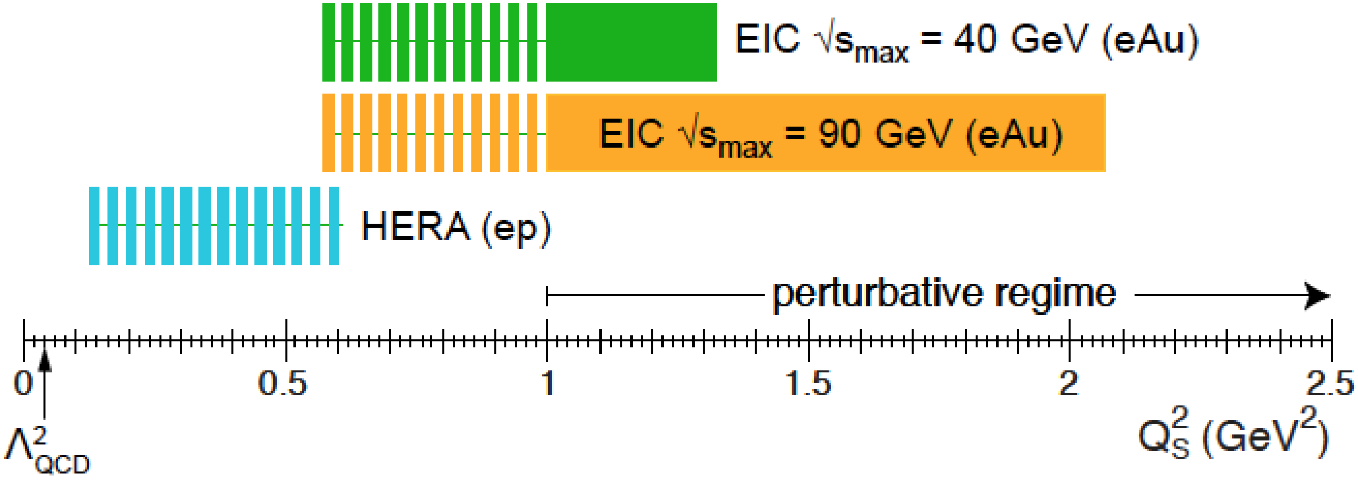
No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)

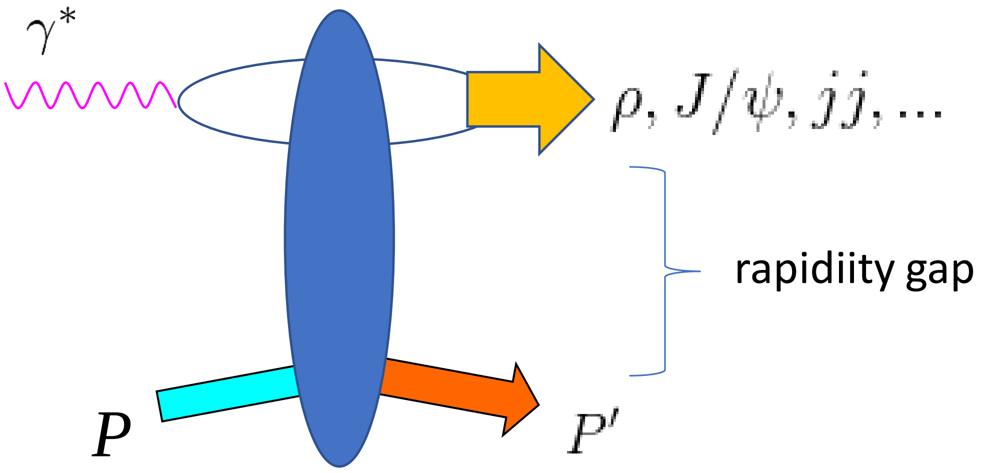


$R_A \sim A^{1/3}$

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



Golden channel for saturation: Diffraction



Cross sections proportional to the square of the gluon distribution

→ More sensitive to saturation

- Total diffraction Kowalski, Lappi, Marquet, Venugopalan (2008)

\`Day 1 prediction' $\left.\frac{\sigma_{diff}}{\sigma_{tot}}\right|_{eA} \approx 20\% > \left.\frac{\sigma_{diff}}{\sigma_{tot}}\right|_{ep}$ Nucleus stays intact in every 1 out of 5 events!

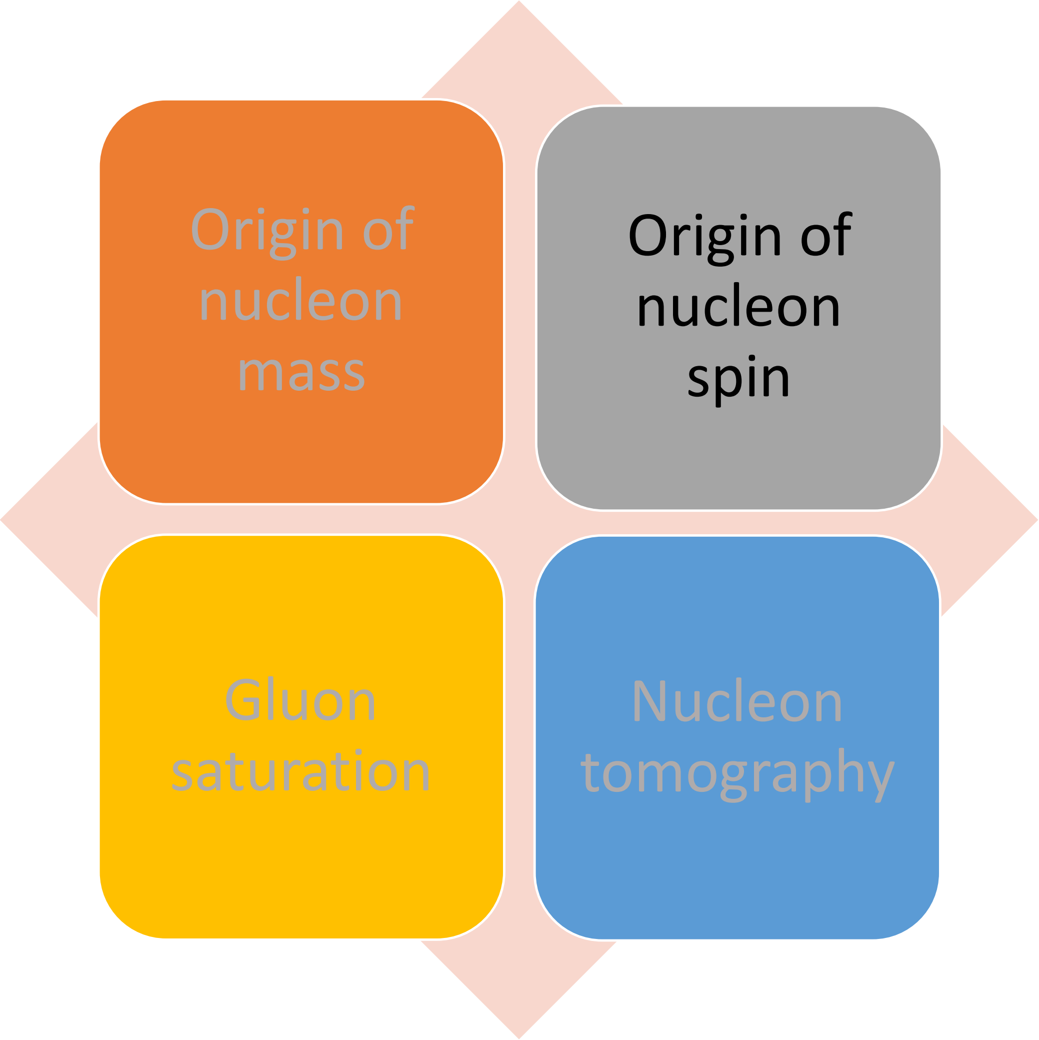
- Incoherent diffraction→ Partonic fluctuations inside the proton (Good-Walker)

Schenke, Mantysaari (2016)

- Exclusive diffractive dijet → Wigner distribution

YH, Xiao, Yuan (2016); Boussarie, Grabovsky, Szymanowski, Wallon (2016); Mantysaari, Mueller, Schenke (2019)

Scientific goals of EIC



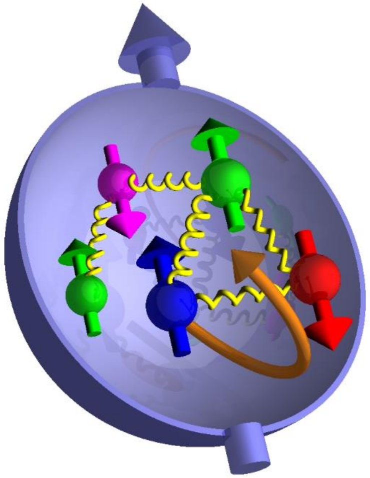
Origin of nucleon mass

Origin of nucleon spin

Gluon saturation

Nucleon tomography

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

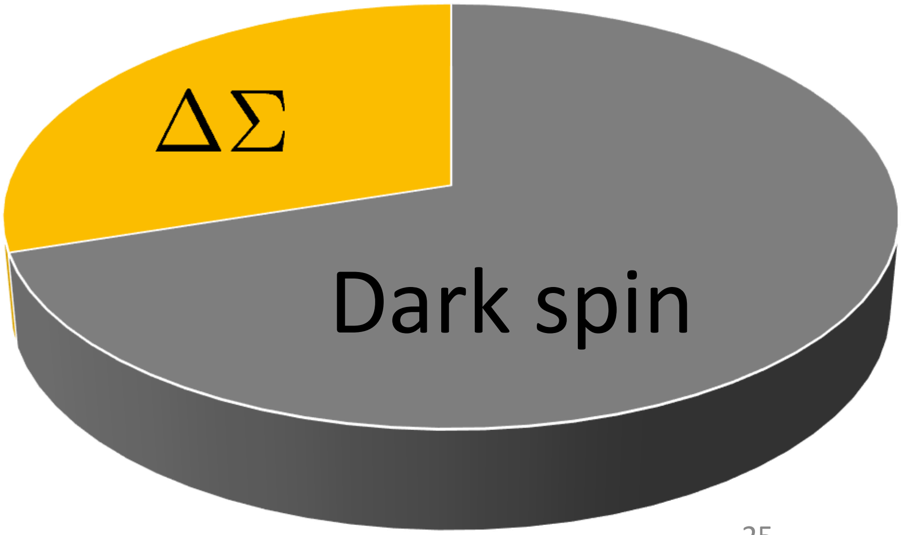
`Spin crisis’

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 value from NLO QCD global analysis

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



Evidence of nonzero ΔG

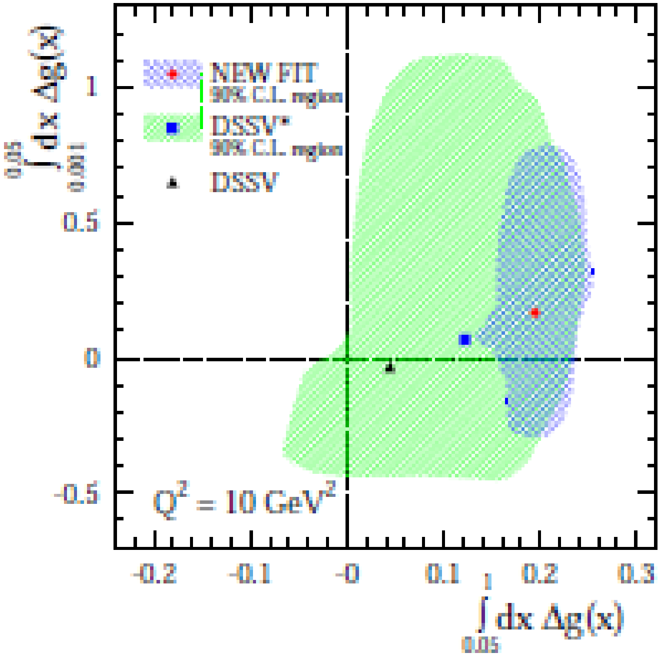
Global analysis including the RHIC pp data

$$\int_{0.05}^{1} dx\Delta g(x,Q^2=10\mathrm{GeV}^2) = 0.20^{+.06}_{-.07} \qquad \text{DSSV++}$$

$$\int_{0.05}^{0.2} dx\Delta g(x,Q^2=10\mathrm{GeV}^2) = 0.17\text{+-}0.06 \qquad \text{NNPDFpol1.1}$$

$$\int_{0.001}^{0.8} dx\Delta g(x,Q^2 = 1\ \mathrm{GeV}^2) = 0.5\text{+-}0.4 \qquad \text{JAM15}$$

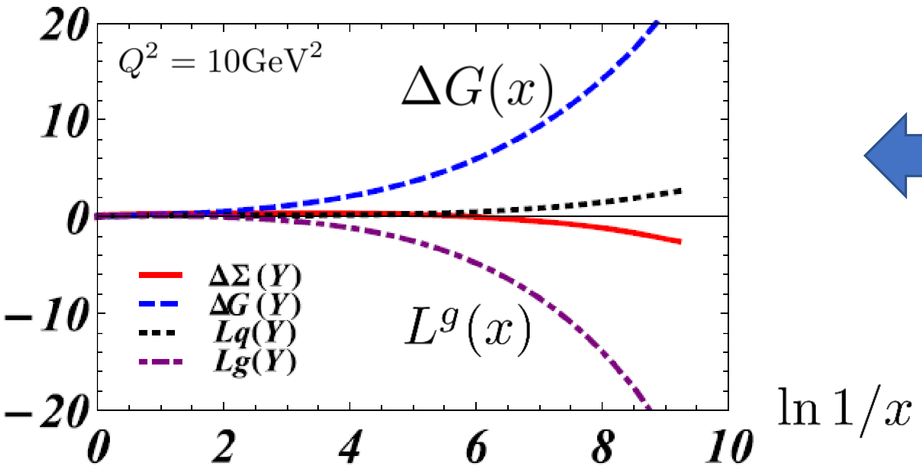
Huge uncertainty from the small-x region



EIC will pin down the value of ΔG

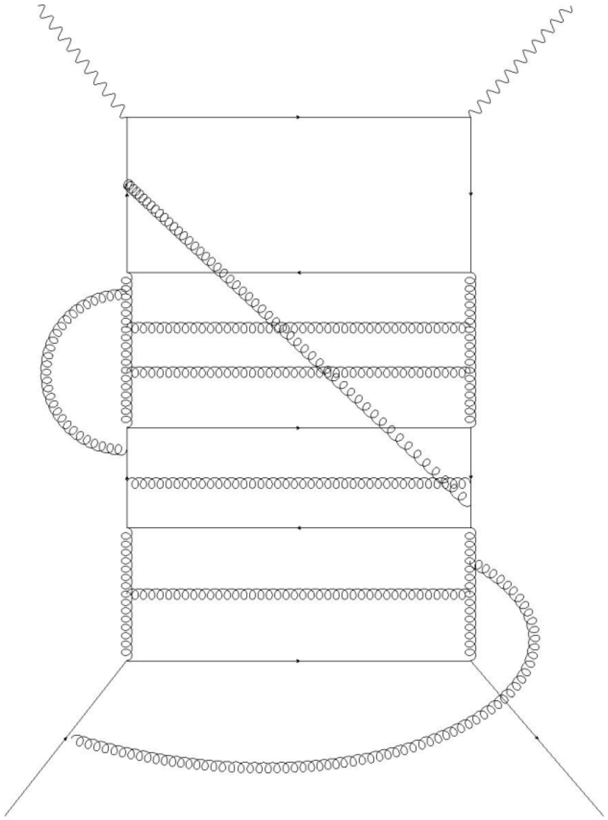
… finally solve the spin puzzle? No!

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)

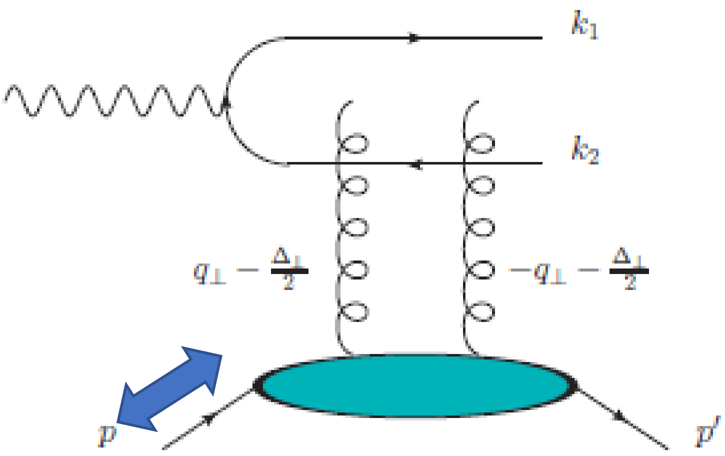
Measuring OAM at EIC

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

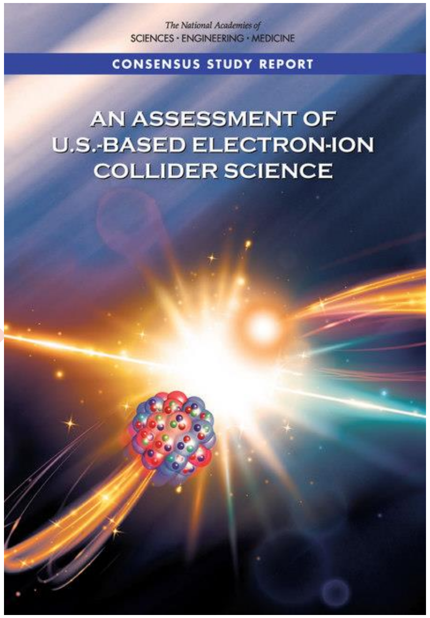
Origin of nucleon mass

Origin of nucleon spin

Gluon saturation

Nucleon tomography

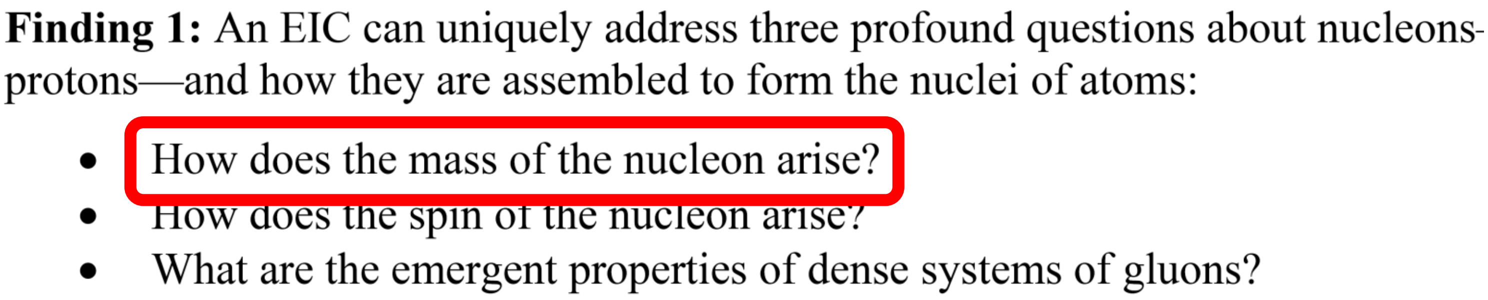
NAS report (2018/07)



The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

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

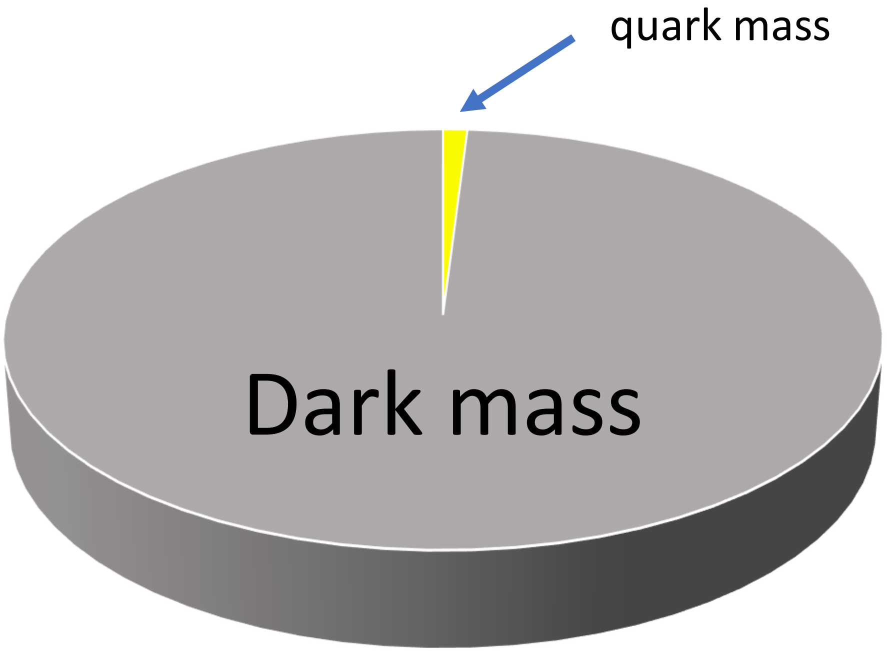


Finding 1: An EIC can uniquely address three profound questions about nucleons-protons—and how they are assembled to form the nuclei of atoms:

- 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

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

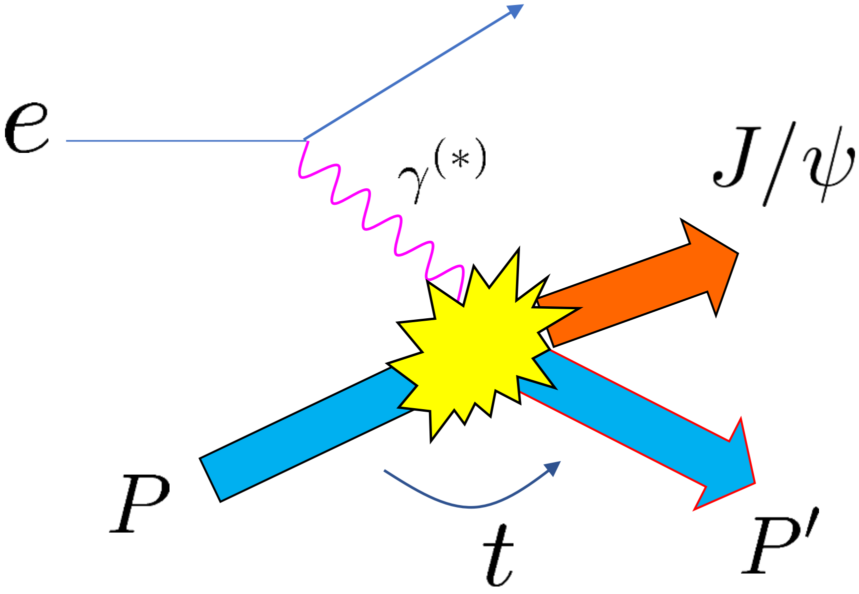
$$\boxed{T^{\mu}_{\mu} = \frac{\beta(g)}{2g}F^2 + m(1+\gamma_m(g))\bar{q}q}$$

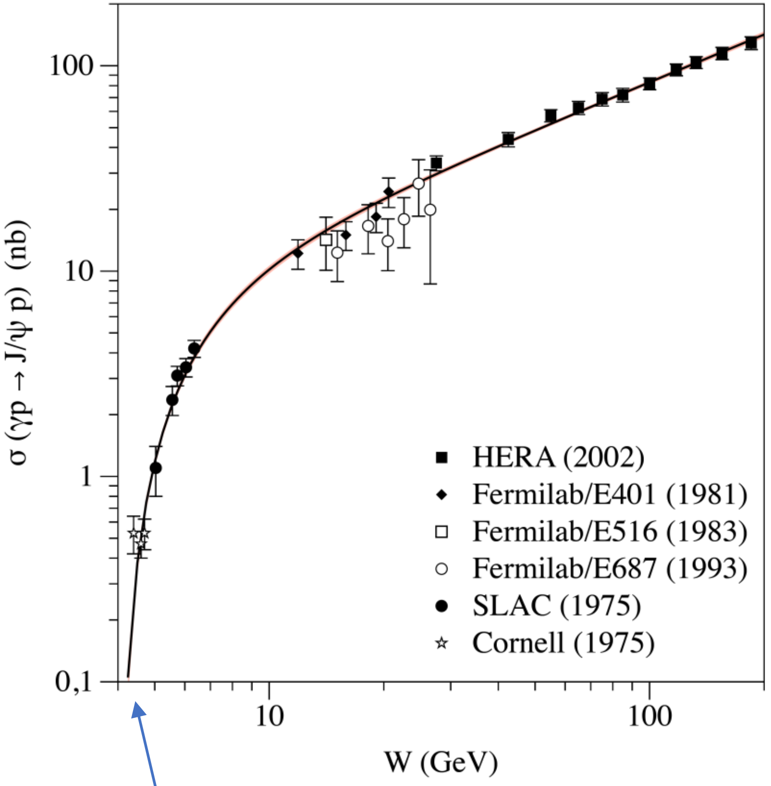
$$\langle P|T^{\mu}_{\mu}|P\rangle = 2M^2$$

Photo-production of J/ψ near threshold

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

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





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

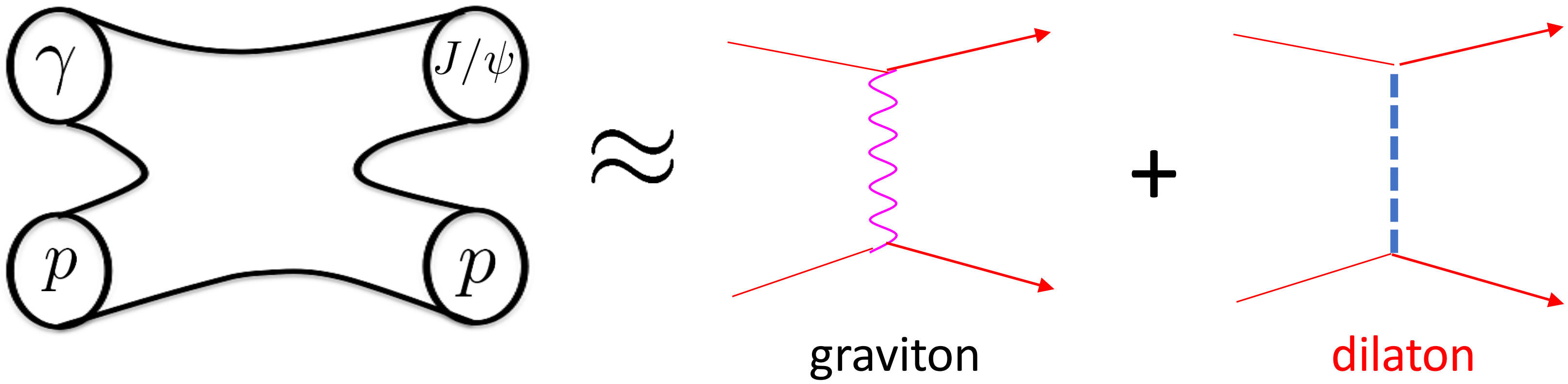
Straightforward to measure.
Ongoing experiments at Jlab.

Difficult to compute from first principles
(need nonperturbative approaches)

Holographic approach

YH, Yang (2018)

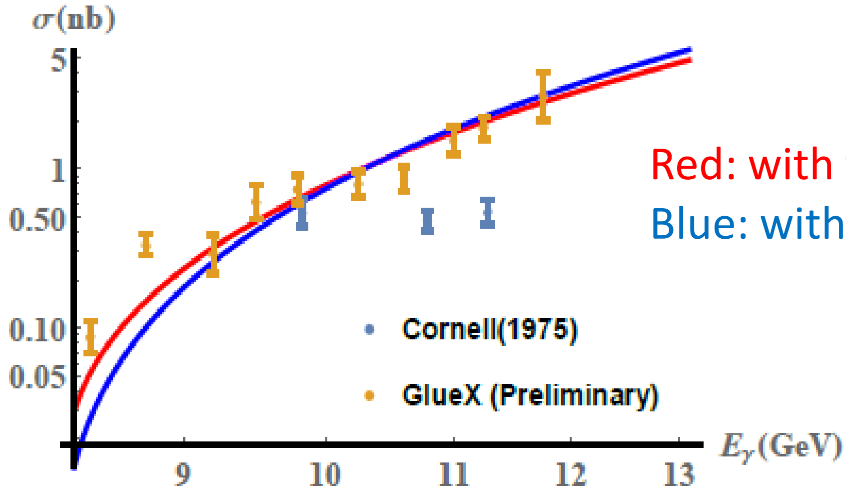
The operator $F^{\mu\nu}F_{\mu\nu}$ is dual to a massless string called dilaton



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

Fit of the latest data from JLab

YH, Rajan, Yang (2019)



Red: with trace anomaly

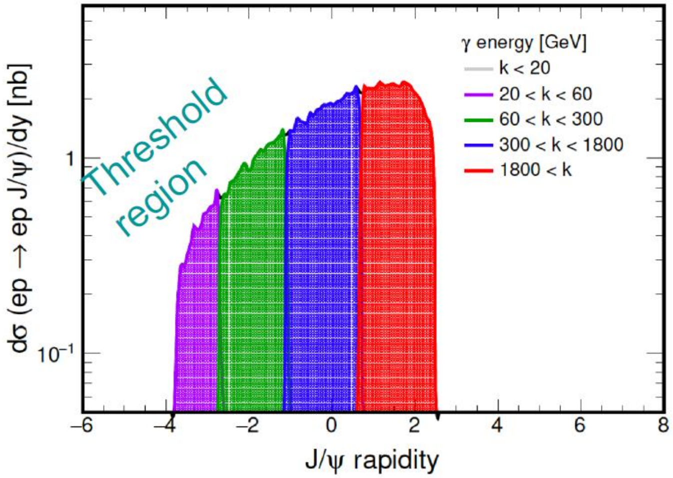
Blue: without trace anomaly

Threshold production at high energy colliders ?

EIC photo-production limit

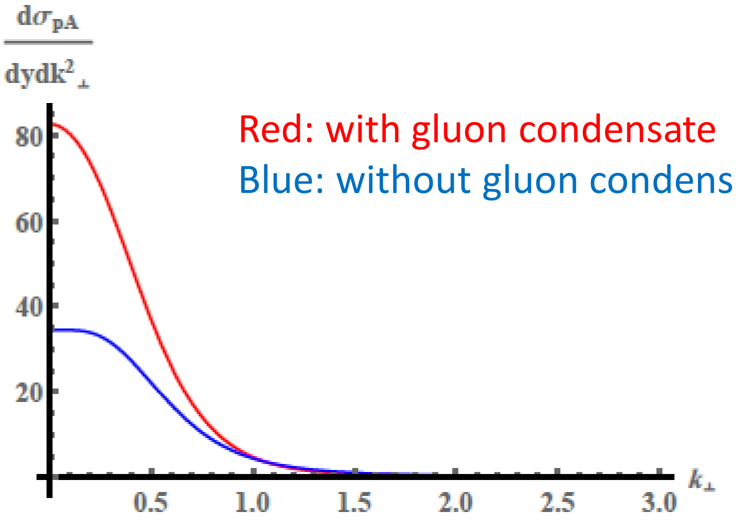
eSTARlight Monte Carlo

Lomnitz, Klein (2018),
Klein, talk at POETIC 2019

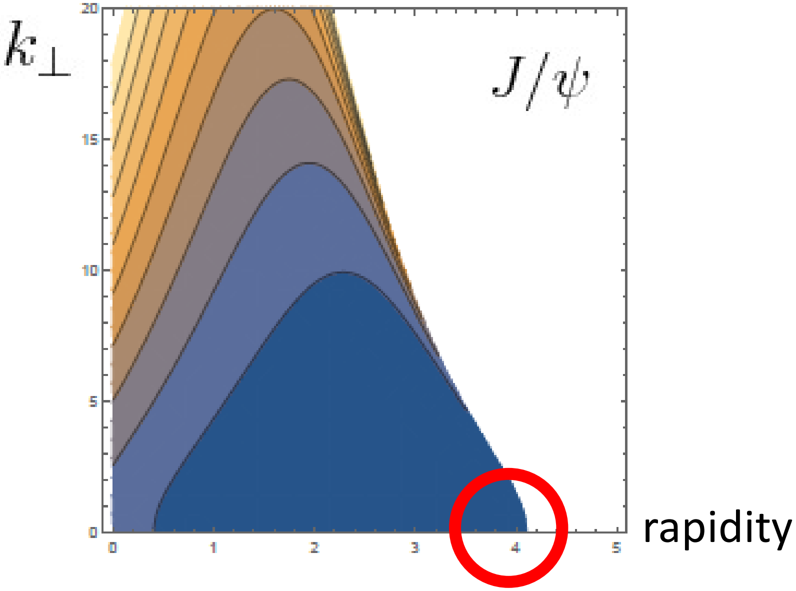


RHIC, Ultra-peripheral pA collisions

YH, Rajan, Yang (2019)



Red: with gluon condensate
Blue: without gluon condensate



Challenging to measure, need forward detectors.

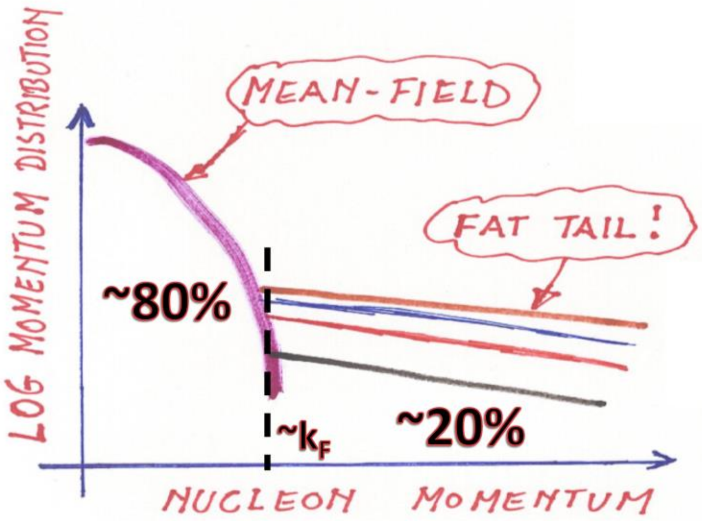
Sub-threshold photo-production of $J/\psi, \Upsilon$

YH, Strikman, Xu, Yuan, 1911.11706

If the target is a nucleus, J/psi can be produced at lower photon energy

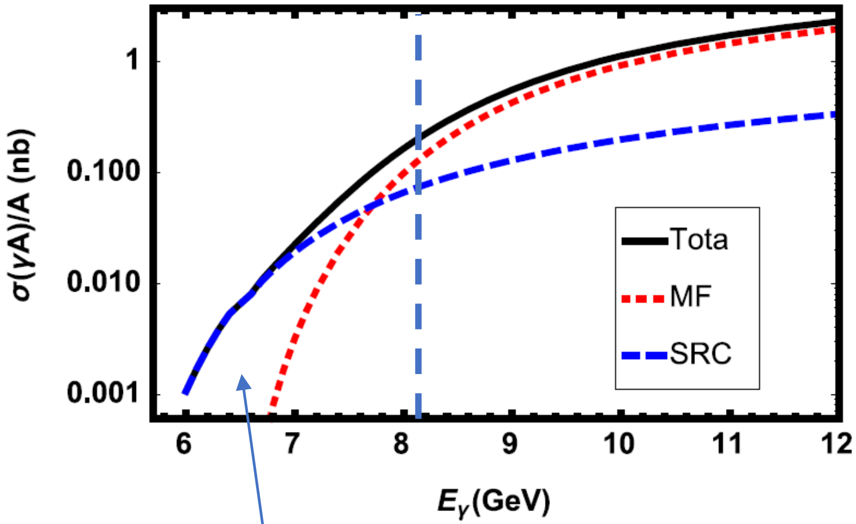
Cross section in this region is sensitive to the
short range correlation
in the target nucleus.

EIC in China ideal for Υ



$E_\gamma = 8.2\,\mathrm{GeV}$

γp threshold



Completely dominated by the SRC contribution

Conclusion

- In 10-15 years from now, DIS machines will be running in the US, China and possibly in Europe.

- Tremendous physics opportunities for theory, experiments, and lattice QCD. Exciting times ahead.