EIC science : ep reactions

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BNL & RIKEN BNL

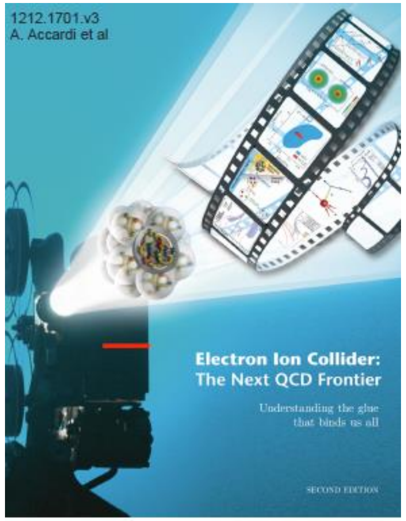
Town hall meeting, Sept.23-25, 2022, MIT

Scientific goals of EIC

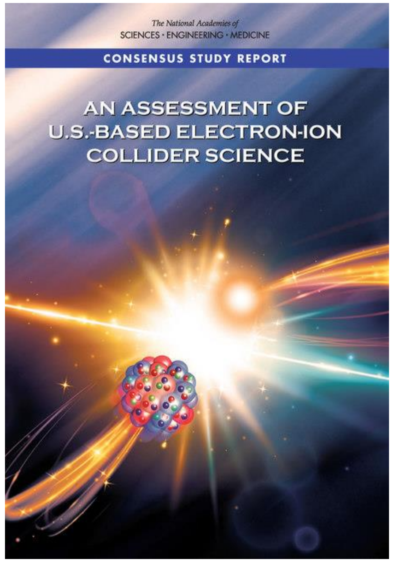
Finding 1: An EIC can uniquely address three profound questions about nucleons-protons—and how they are assembled to form the nuclei of atoms:

- 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? → talk by Stasto

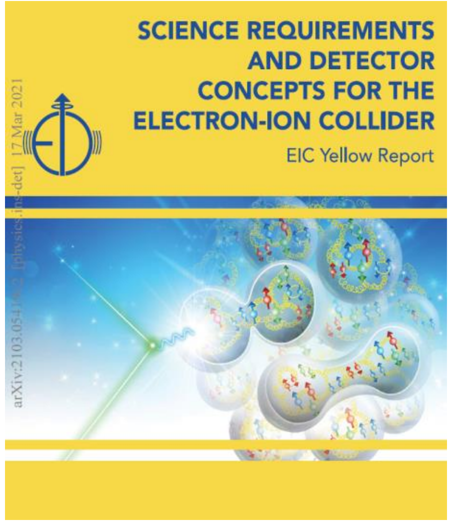
White paper



NAS report



Yellow report



Scientific goals of EIC

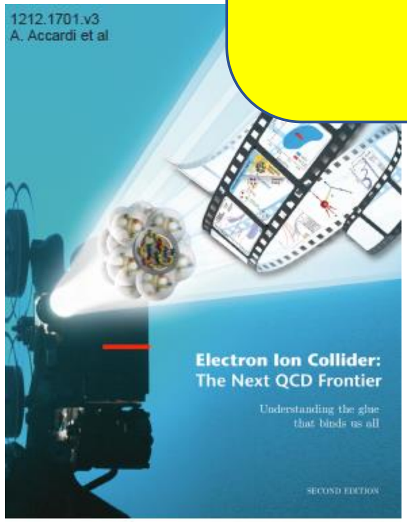
Finding 1: An EIC can uniquely address three profound questions about nucleons-protons—and how they are assembled to form the nuclei of atoms:

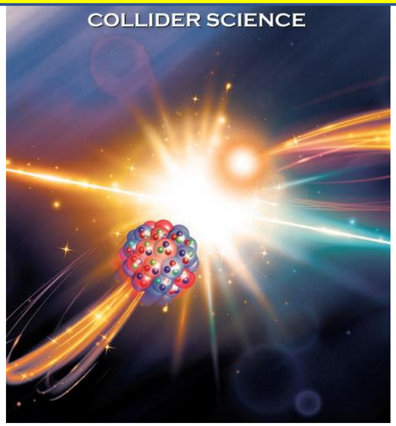
- How does
- How doe
- What are

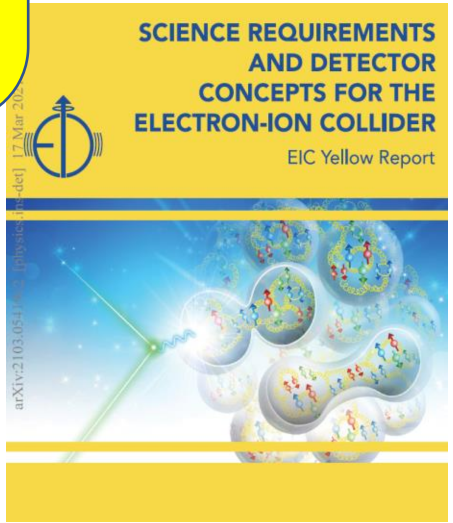
→ talk by Stasto

The era of precision QCD study of nucleon and nuclear structures in the next >20 years!

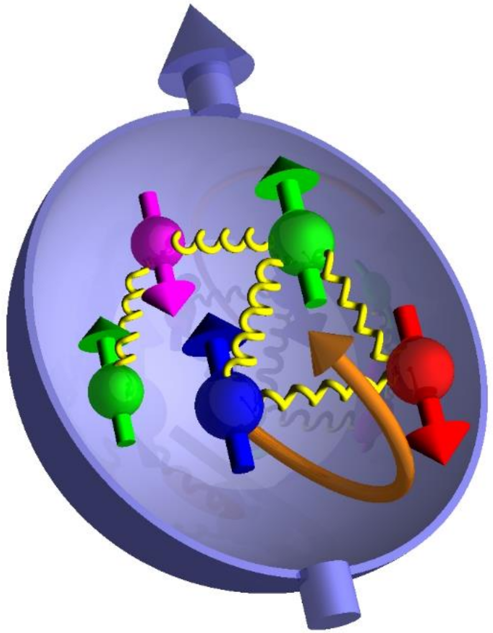
White paper







Proton spin problem



The proton has spin ½.

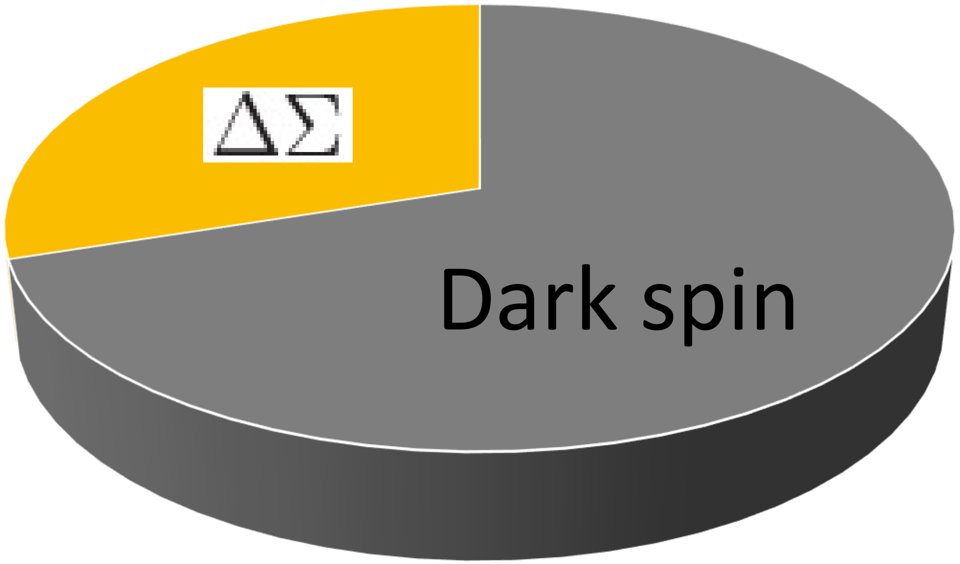
The proton is not an elementary particle.

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

Quarks' helicity

Gluons' helicity

Orbital angular Momentum (OAM)



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

$\Delta\Sigma \sim 0.3$ from polarized DIS experiments

Evidence of nonzero gluon helicity $\Delta G = \int_0^1 dx \Delta G(x)$

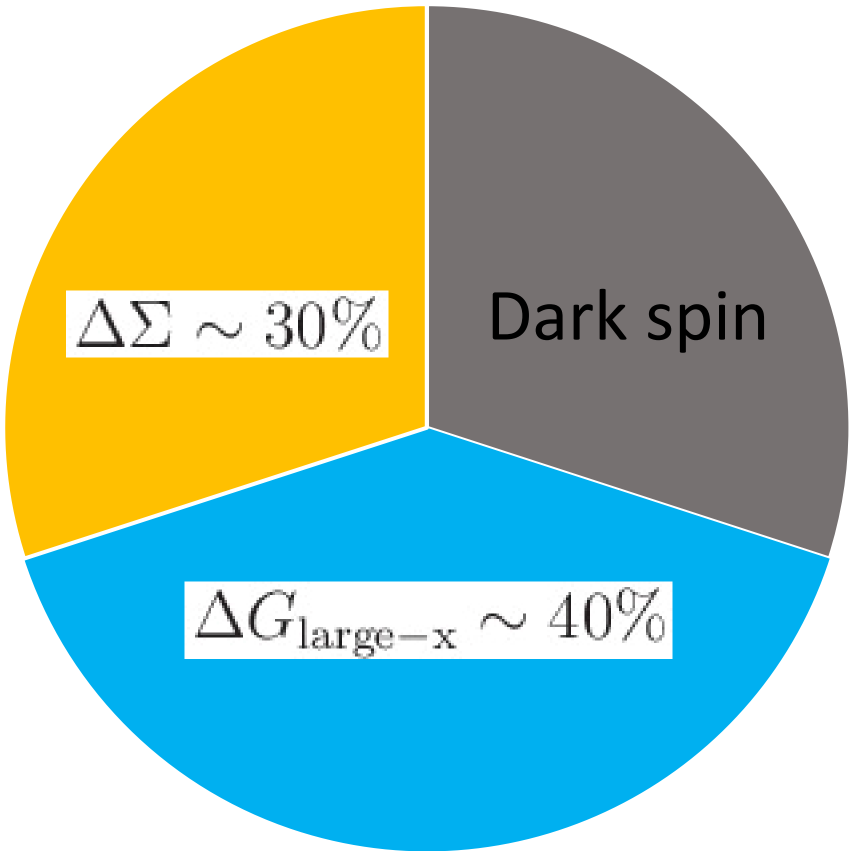
→ talk by Vogelsang

A major achievement of the RHIC spin program!

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

$$\int_{0.05}^{0.2} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.17 \pm 0.06$$ NNPDF

$$\int_{0.05}^{1} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.23 \pm 0.03$$ JAM



Huge uncertainty from the small-x region → EIC

Renewed interest in helicity-dependent small-x resummation
→ talk by Kovchegov

Does the remaining spin (~30%) come from the small-x region of $\Delta G(x)$?

An elephant in the room: Orbital angular momentum

At small-x, helicity and OAM cancel.

There might be a sizable contribution to ΔG from the small-x region.

But there will be even larger L_g from the same x-region with an opposite sign.

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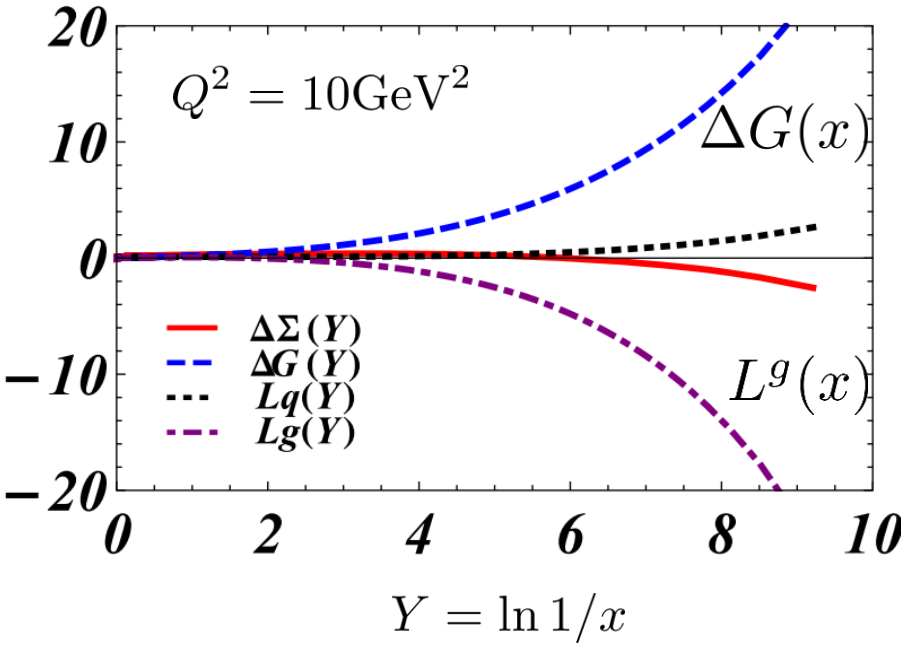
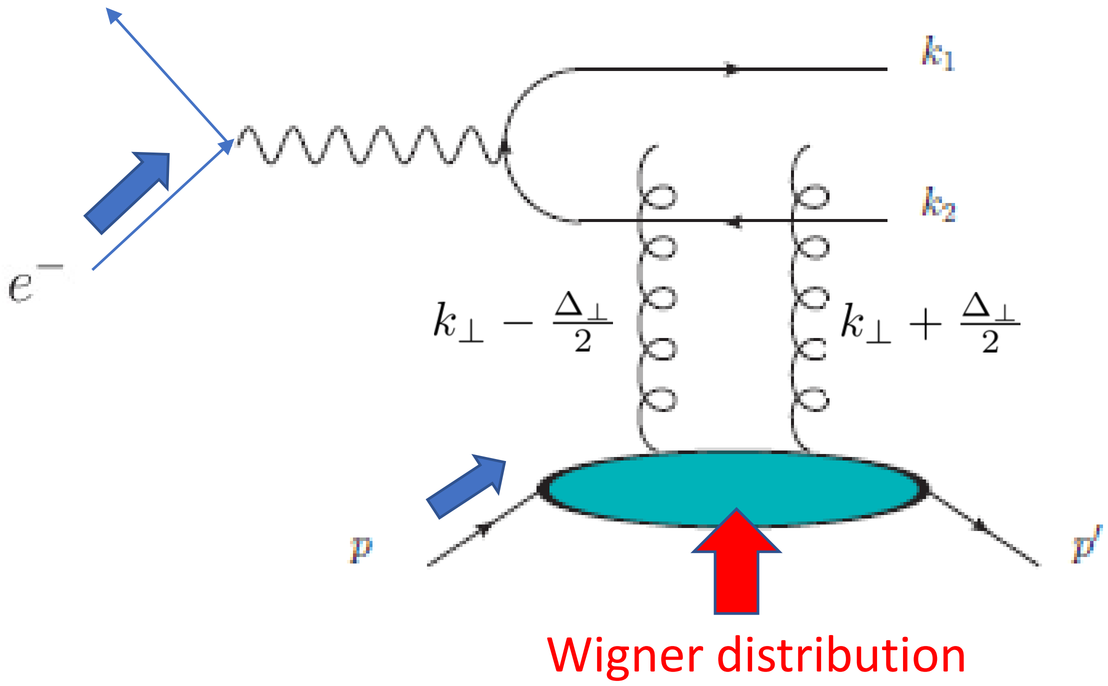


If $\Delta G(x) \sim \frac{1}{x^\alpha}$, then $L_g(x) \approx -\frac{2}{1+\alpha}\Delta G(x)$ Boussarie, YH, Yuan (2019)

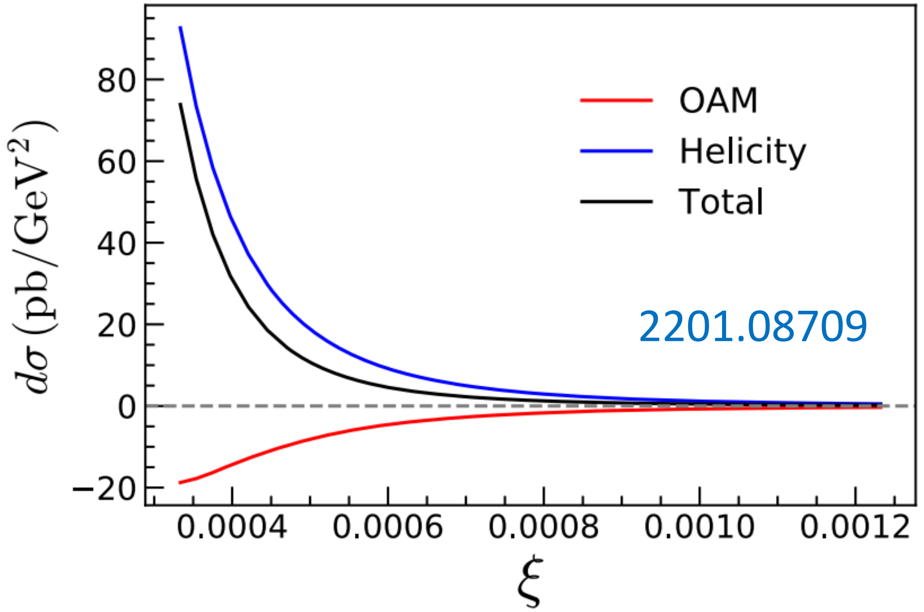
Helicity is only half of the story. Can EIC seriously address OAM?

OAM from single/double spin asymmetries in dijet production at EIC

Ji, Yuan, Zhao (2016) (single)
Bhattacharya, Boussarie, YH (2022) (double)

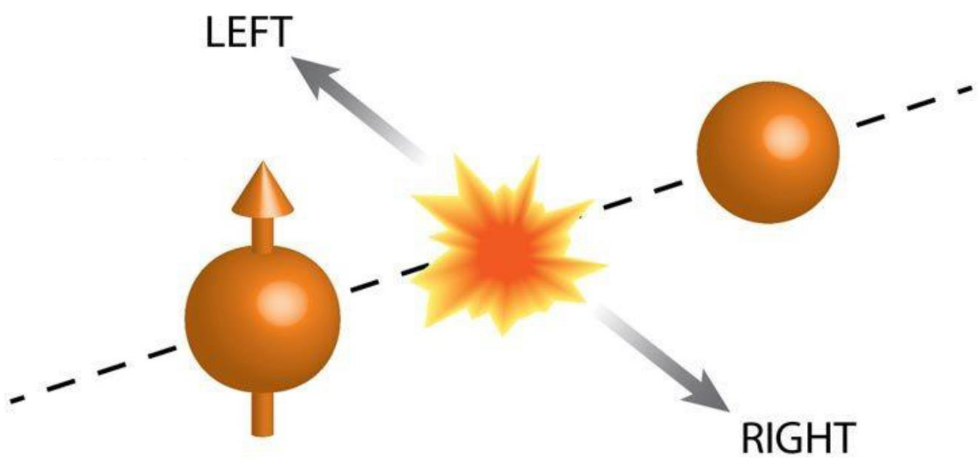


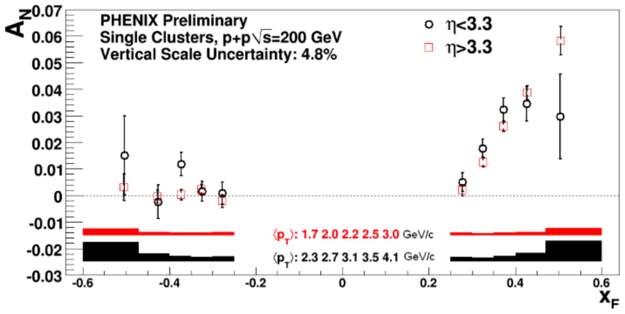
$$L^{q,g} = \int dx \int d^2b_\perp d^2k_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z W^{q,g}(x, \vec{b}_\perp, \vec{k}_\perp)$$

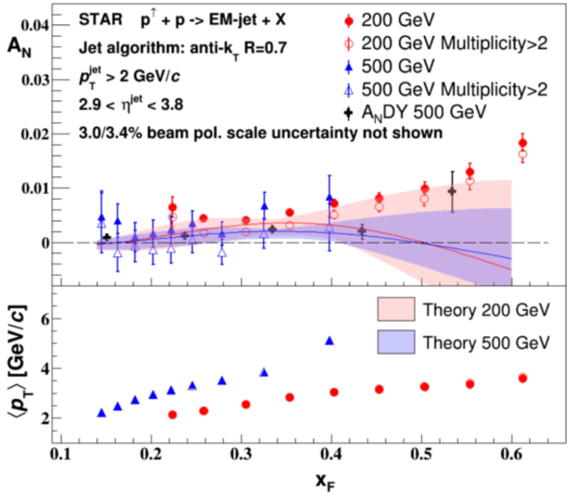


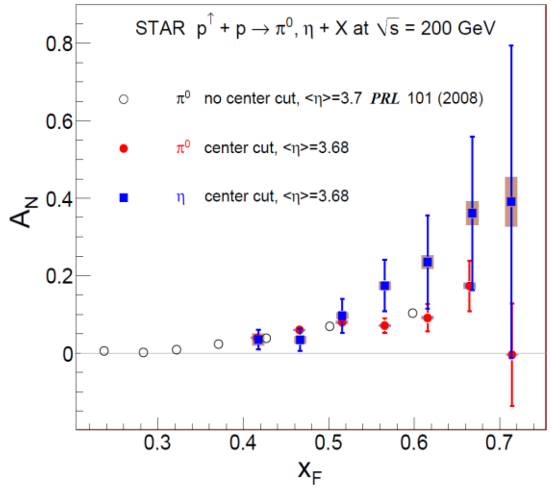
5D tomography encoded in the Wigner distribution
—Holy grail of the nucleon structure
Can be explored at the EIC for the first time!

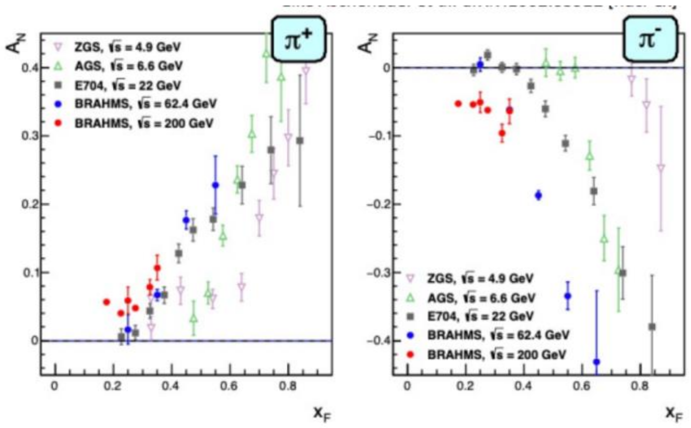
Transverse Single Spin Asymmetry (SSA)











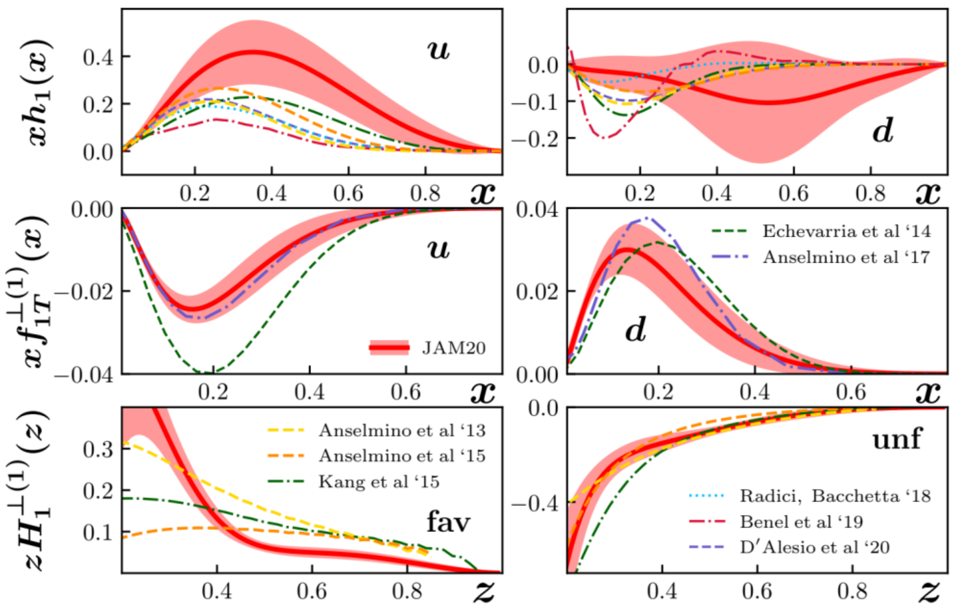
Production of hadrons are left-right asymmetric.
Discovered in the 70's, not fully understood yet.

Asymmetry can be as large as 20-30% in hadron collisions.

Many origins (Sivers&Collins functions, twist-3 quark-gluon correlator,…)

Global analysis of SSA

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

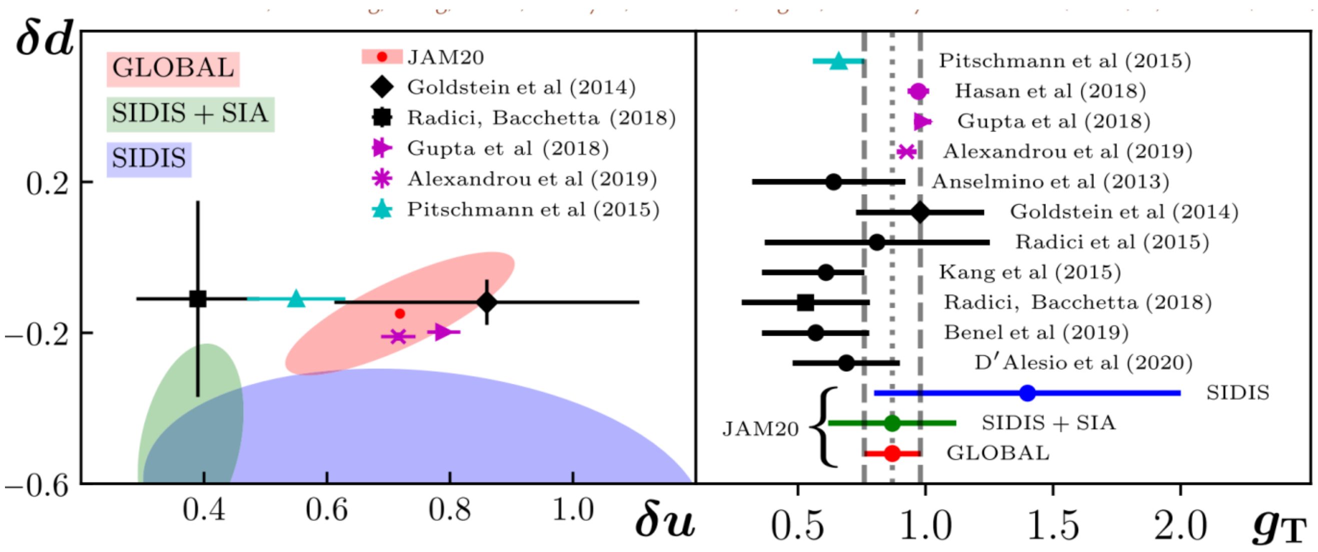


Simultaneous fit of

e+e- (BELLE, BaBar, BESIII)
SIDIS (COMPASS, HERMES, Jlab) ← input from EIC in future
Drell-Yan (COMPASS, STAR)
pp (STAR, PHENIX, BRAHMS)

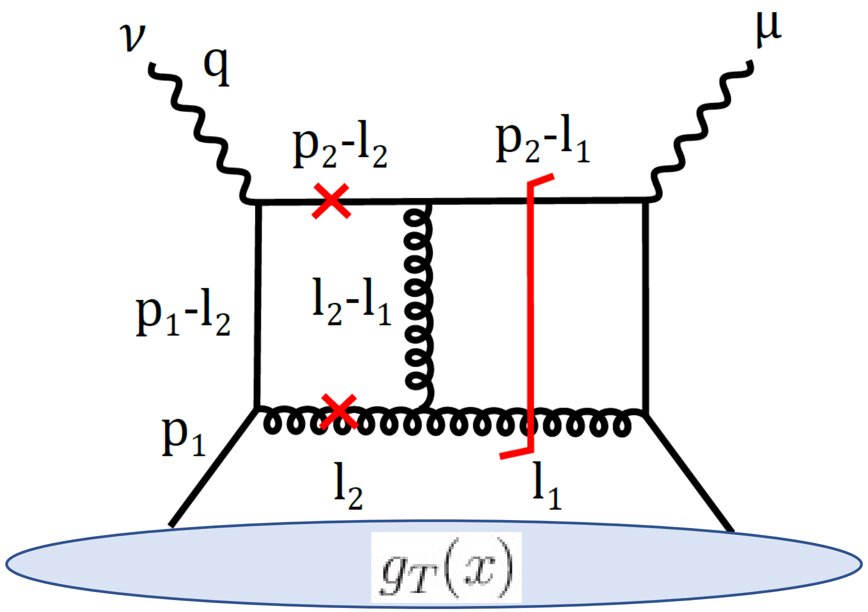
At the moment, the only viable way to generate O(10%) asymmetry seems to be twist-3 FFs convoluted with the transversity distribution.

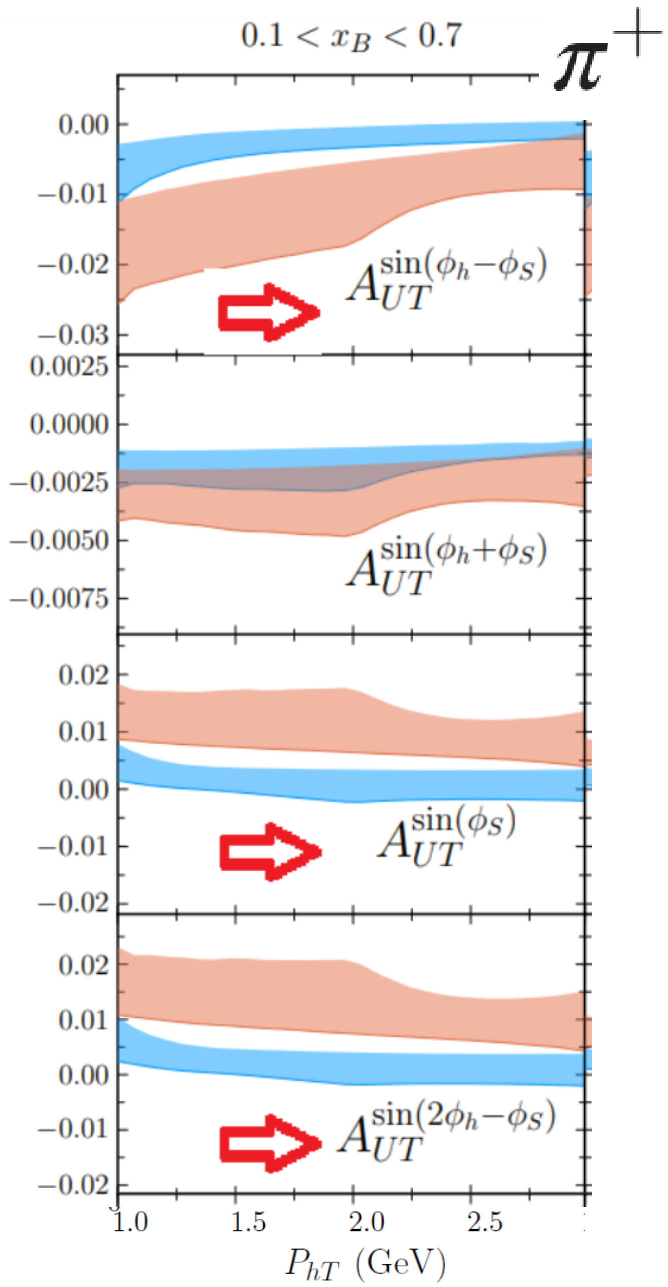
→ Constraints on the nucleon tensor charge.



Breaking the myth of `tiny pQCD contribution'

Benic, YH, Kaushik, Li (2021)





Perturbative contributions at SSA start at 2-loop, believed to be negligible for 40 years.

This will no longer be the case at the EIC!

Spin asymmetries from higher order pQCD could be systematically studied at EIC

cf. Abele, Aicher, Piacenza, Schafer, Vogelsang (2022)

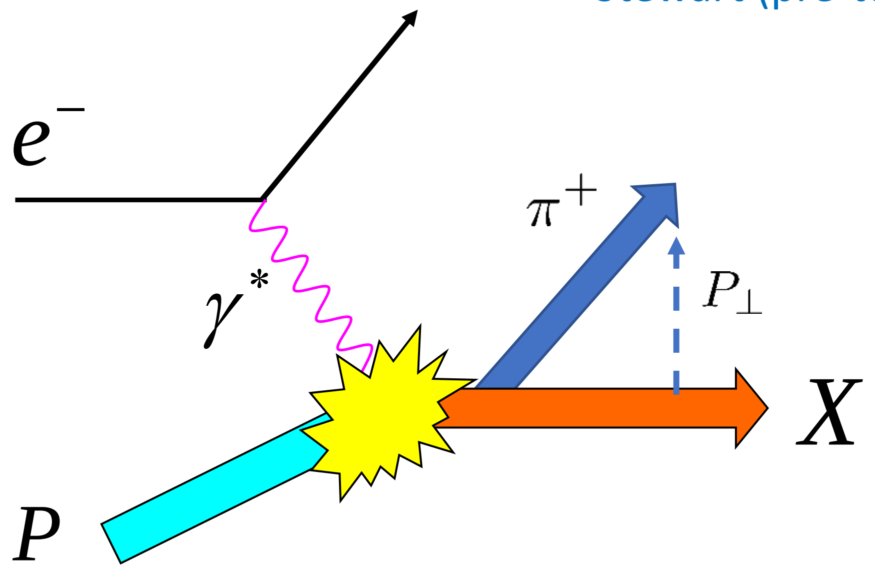
Semi-inclusive DIS

→ talk by Kang, Zhao (lattice), Stewart (pre-town)

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

When $P_\perp$ is small, TMD factorization

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



$$\frac{d\sigma}{dP_\perp} = H \otimes f(x, k_\perp) \otimes D(z, q_\perp)$$

TMD PDF TMD FF

Accuracy	$H, \mathcal{J}$	$\Gamma_{\rm cusp}(\alpha_s)$	$\gamma_H^q(\alpha_s)$	$\gamma_r^q(\alpha_s)$	$\beta(\alpha_s)$
LL	Tree level	1-loop	–	–	1-loop
NLL	Tree level	2-loop	1-loop	1-loop	2-loop
NLL′	1-loop	2-loop	1-loop	1-loop	2-loop
NNLL	1-loop	3-loop	2-loop	2-loop	3-loop
NNLL′	2-loop	3-loop	2-loop	2-loop	3-loop
N^3LL	2-loop	4-loop	3-loop	3-loop	4-loop
N^3LL′	3-loop	4-loop	3-loop	3-loop	4-loop
N^4LL	3-loop	5-loop	4-loop	4-loop	5-loop
N^4LL′	4-loop	5-loop	4-loop	4-loop	5-loop

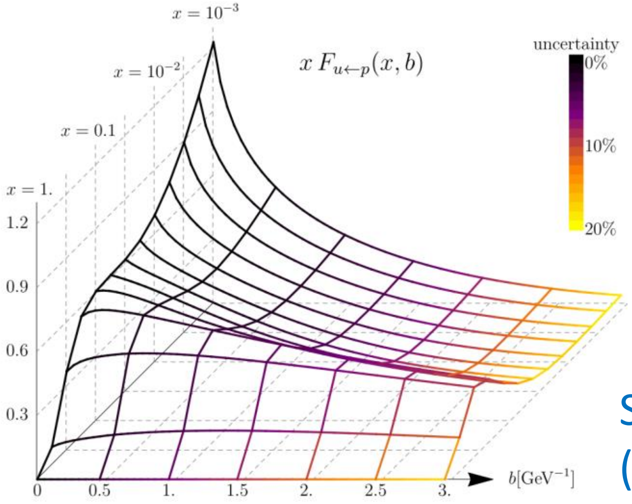
Duhr, Mistlberger, Vita (2022)

Open up a new class of observables where perturbative QCD is applicable.
Variety of novel phenomena due to intrinsic transverse momentum
(i.e., Sivers function)

Significant recent developments in theory and lattice.
TMD is already precision science!

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,Q²) bin	1 (x,Q²) 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



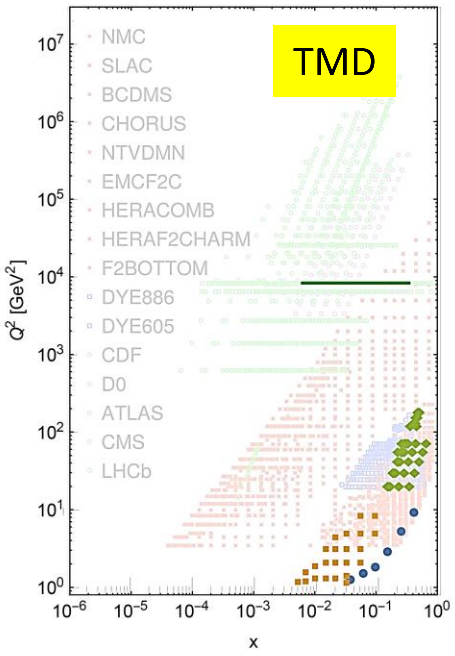
Scimemi, Vladimirov (2019)

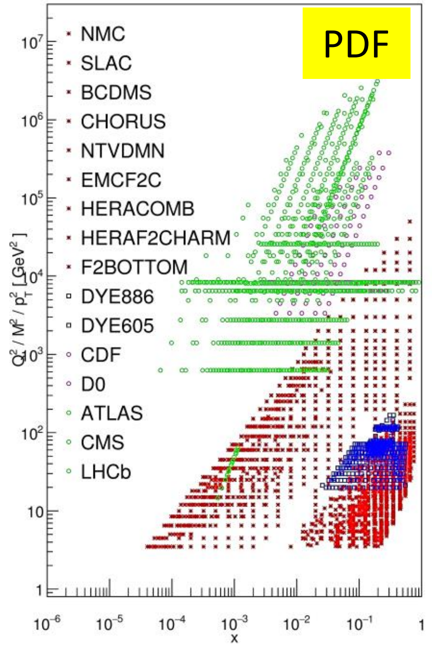
Uncertainties in W-boson mass partly coming from TMD

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$-6 \leq M_{W^+} \leq 9\ \text{MeV}$$
$$-4 \leq M_{W^-} \leq 7\ \text{MeV}$$

Bacchetta, et al. (2018)





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

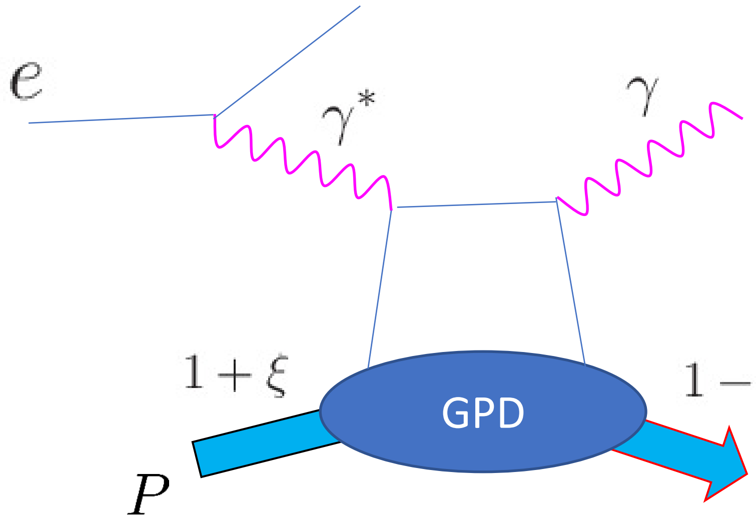
Generalized parton distributions

→ talk by Constantinou (lattice), Qiu (pre-town)

Non-forward $\Delta = P' - P$ generalization of PDF

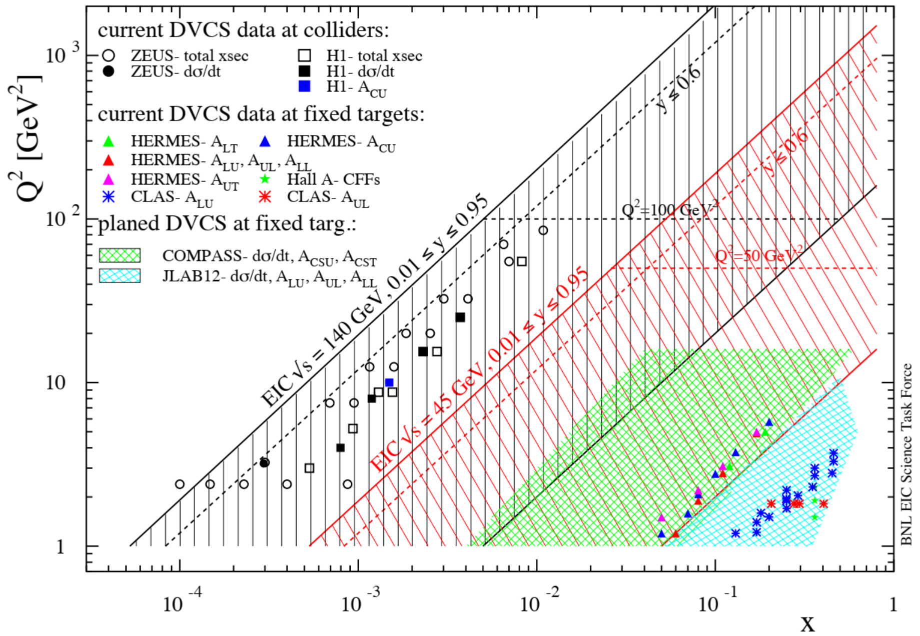
$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu\psi(y^-)|PS\rangle$$

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



Ji sum rule

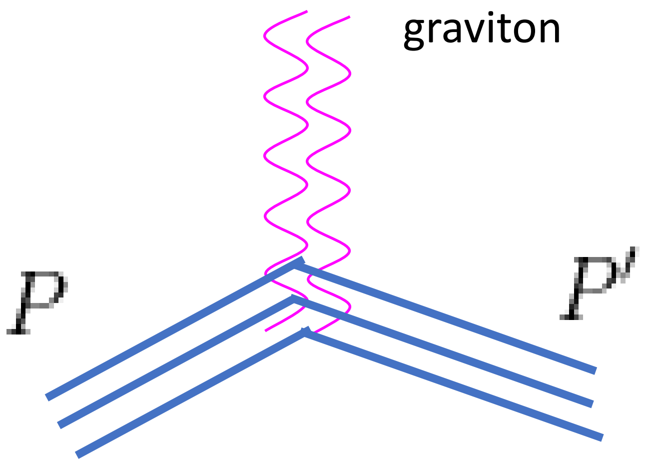
$$J_{q,g} = \frac{1}{2}\int_0^1 dx\, x(H_{q,g}(x) + E_{q,g}(x))$$



EIC offers an unprecedented kinematical coverage of Deeply Virtual Compton Scattering (DVCS).

We will get a handle on quark GPD E_q.
Gluon GPD E_g is still challenging.

Nucleon Gravitational Form Factors (GFF)



Second moment of GPD = gravitational form factors

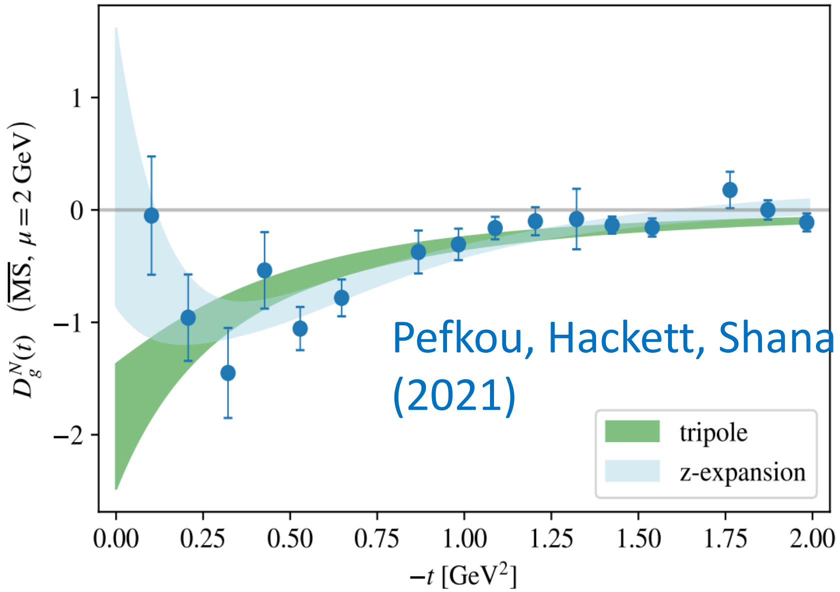
$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\Big[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}Mg^{\mu\nu}\Big]u(P)$$

All the form factors are interesting and measurable!

$A_{q,g}$, $B_{q,g}$ — Ji sum rule $J_{q,g} = \frac{1}{2}(A_{q,g} + B_{q,g})$

$D_{q,g}$ `pressure' inside proton

$\bar{C}_{q,g}$ trace anomaly, gluon condensate



Pefkou, Hackett, Shanahan (2021)

EM form factors → proton charge radius

Gravitational form factors → proton mass radius

Quark D-term from DVCS

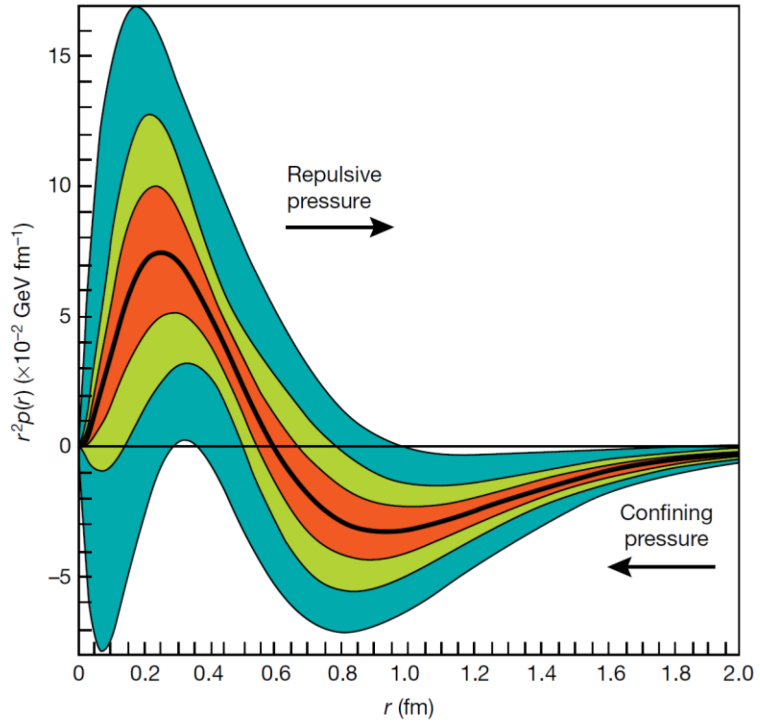
$D(t=0)$ is a conserved charge of the nucleon, just like mass and spin!

Interpretable as `pressure' and `shear' inside a nucleon

Polyakov, Schweitzer (2018)

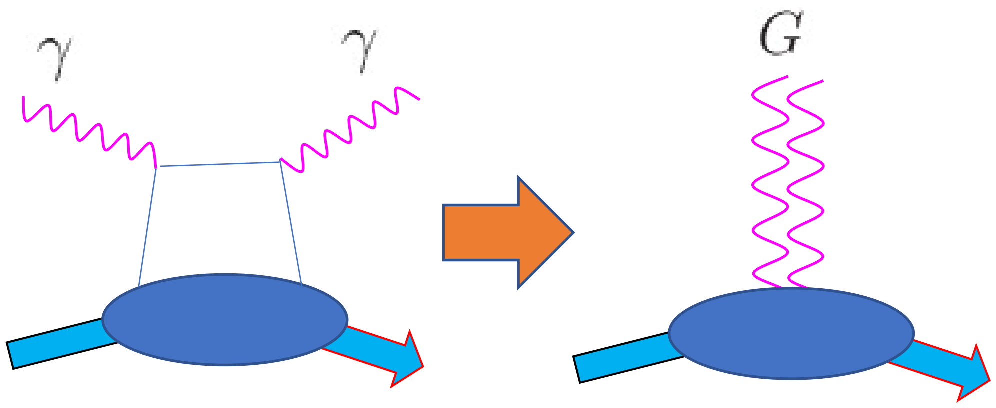
$$T^{ij}(r) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right) s(r) + \delta^{ij} p(r)$$

Burkert, Elouadrhiri, Girod (2018)



u,d-quark D-term can be in principle extracted from DVCS,

1 graviton ≈ 2 photons



However, two-photon state probes not just spin-2, but infinitely many twist-2 operators.

Need a significant lever-arm in Q^2 → EIC

Quarkonium photo- and electro-production near threshold

→ talk by Joosten

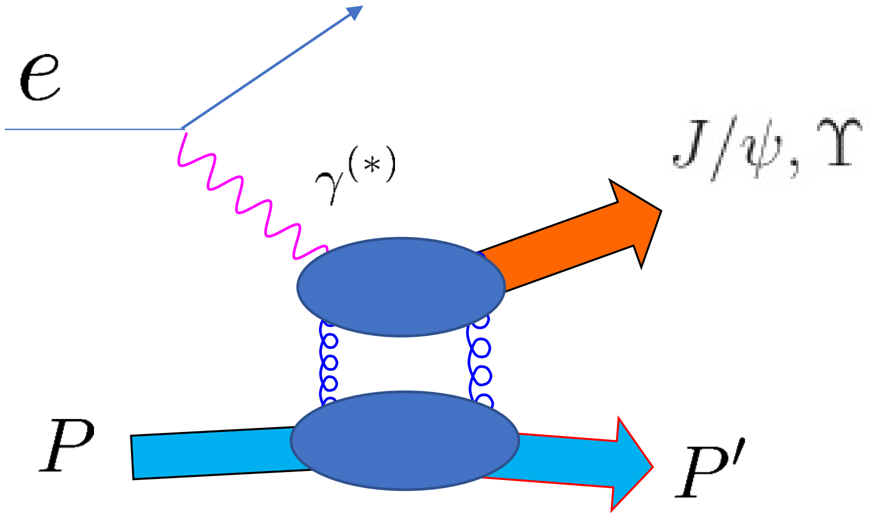
Ongoing experiments at Jlab, future at EIC?

Originally proposed to probe the gluon condensate

$$\langle P|F^{\mu\nu}F_{\mu\nu}|P\rangle$$

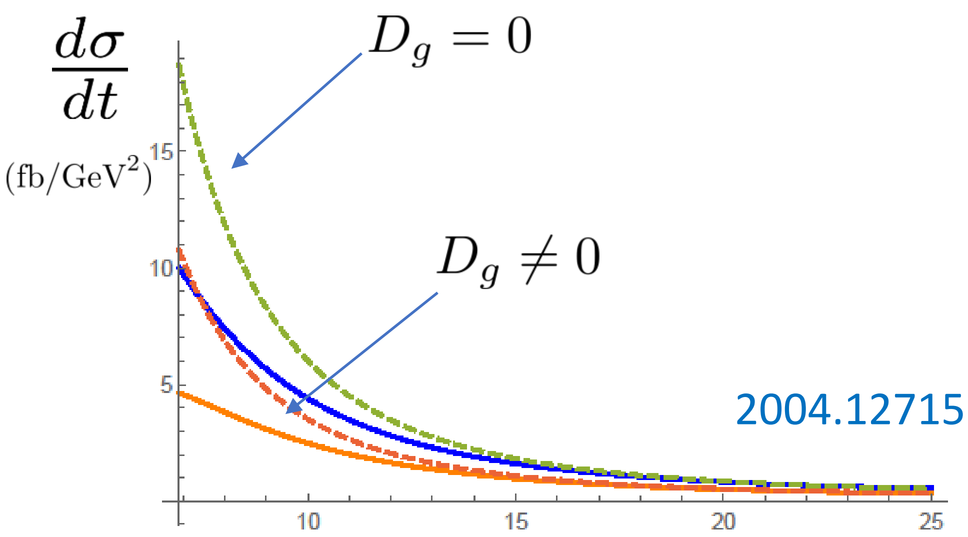
Kharzeev, Satz, Syamtomov, Zinovjev (1998)

→ Origin of proton mass



Recent theory developments have unlocked exciting new directions—gluon GFFs, gluon D-term, mass/mechanical radius, glueballs,…

1 graviton $\approx$ 2 gluons



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So much work has been done for EM form factors over the past 70 years. It's just the beginning for GFFs!

Recommendation for the Long Range Plan

Needs and challenges for EIC theory reviewed at
CFNS workshop: EIC theory in the next decade, Sept. 20-22, 2022, MIT

Organizers: Ian Cloët (ANL), Dmitri Kharzeev (Stony Brook University/BNL), Xiandong Ji (University of Maryland), Peter Petreczky (BNL), Jianwei Qiu (JLab), Phiala Shanahan (MIT), Iain Stewart (MIT), Ivan Vitev (LANL), Feng Yuan (LBNL)

Resolution:

"We recommend the establishment of a national EIC theory alliance to enhance and broaden the theory community needed to advance EIC physics goals and the experimental program.
This theory alliance will develop a diverse workforce through a competitive national EIC theory fellow program and tenure-track bridge positions, including appointments at minority serving institutions."