

EIC theory overview

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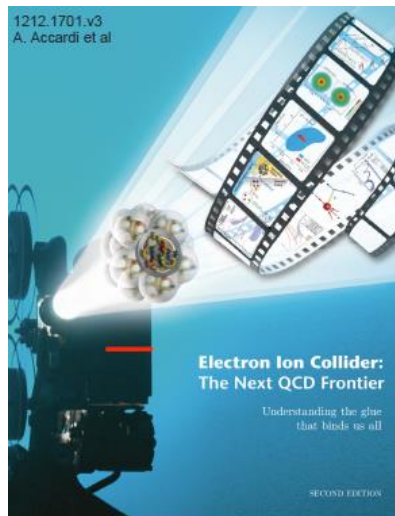
MENU2026, October 19-23, 2026, Stony Brook

Scientific goals of EIC

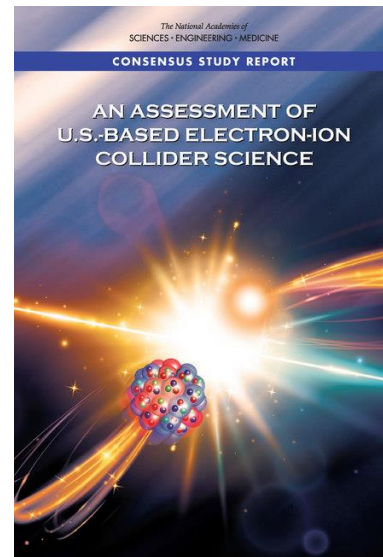
Finding 1: An EIC can uniquely address three profound questions about nucleons—protons—and how they are assembled to form the nuclei of atoms:

- 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?

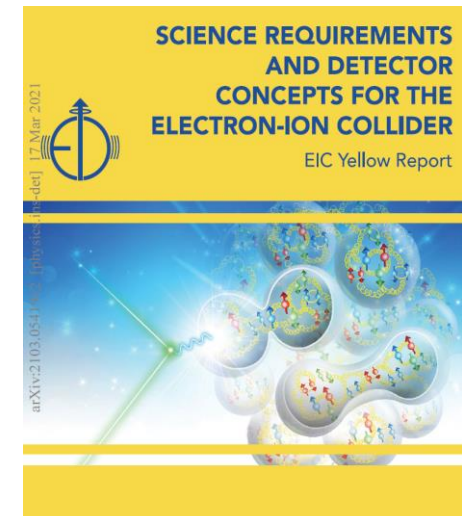
White paper



NAS report



Yellow report

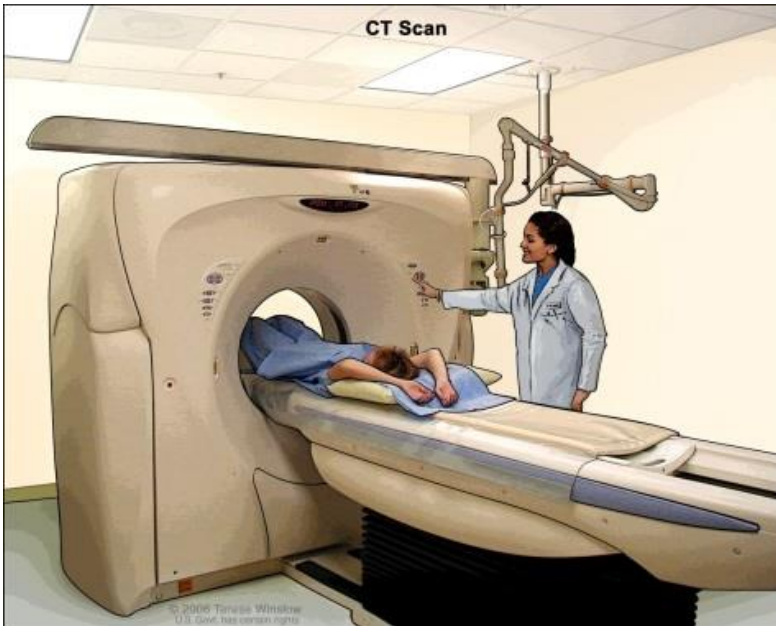
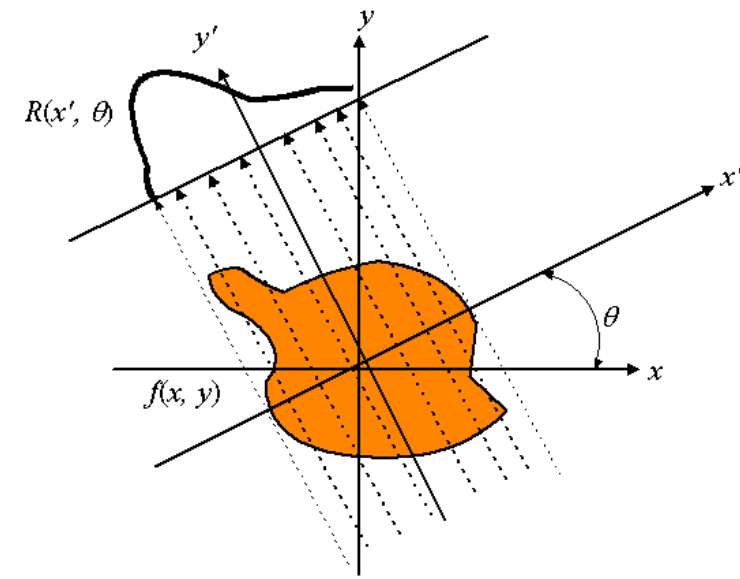


Contents

- Tomography (TMD and GPD)
- Spin (longitudinal and transverse spin)
- Small-x
- Quantum tomography

Tomography

(TMD, GPD)

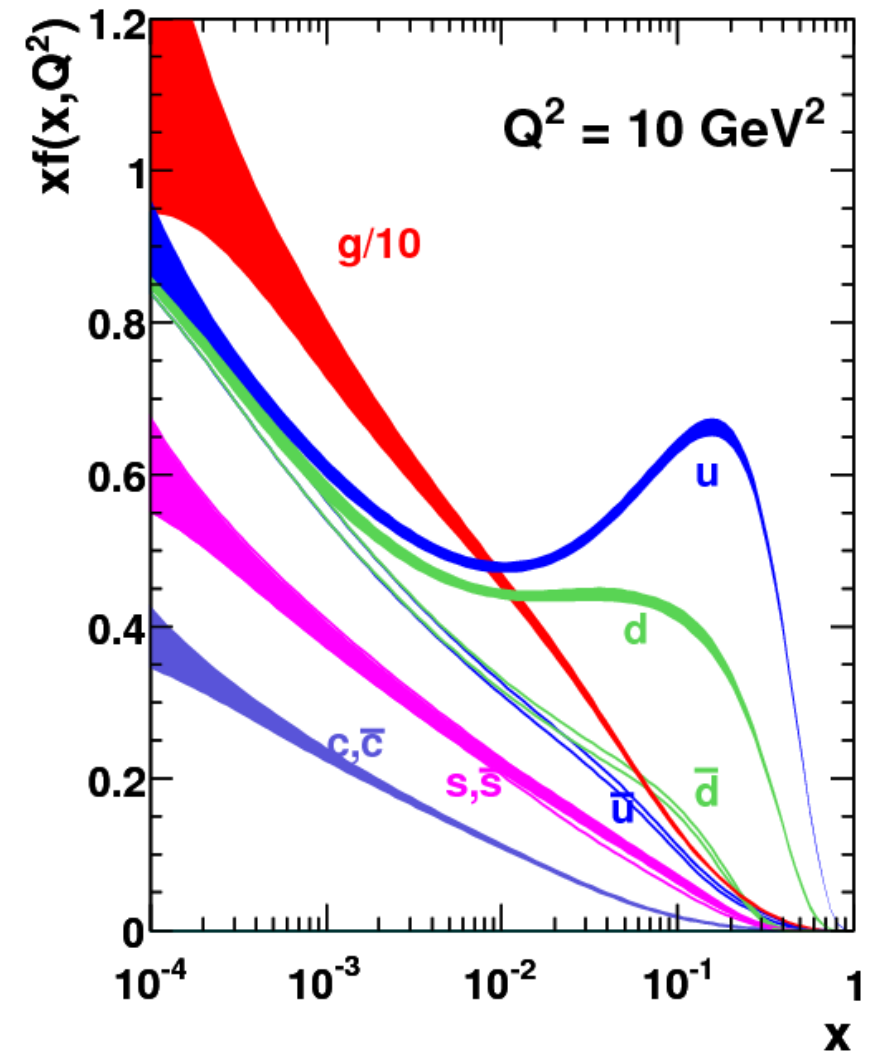
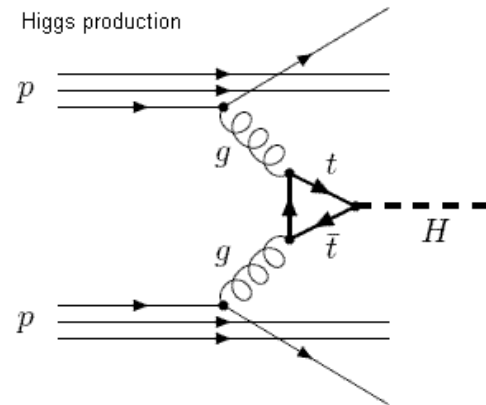


Parton distribution function

$$u(x) = \int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle P | \bar{u}(-z^-/2) \gamma^+ u(z^-/2) | P \rangle$$

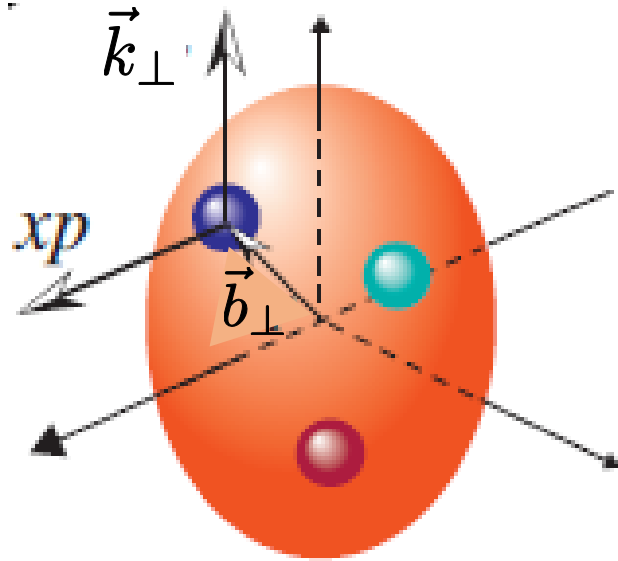
Number distribution of up quarks
with momentum fraction x inside the proton

QCD factorization $\sigma = \sigma_0 \otimes g(x_1) \otimes g(x_2)$

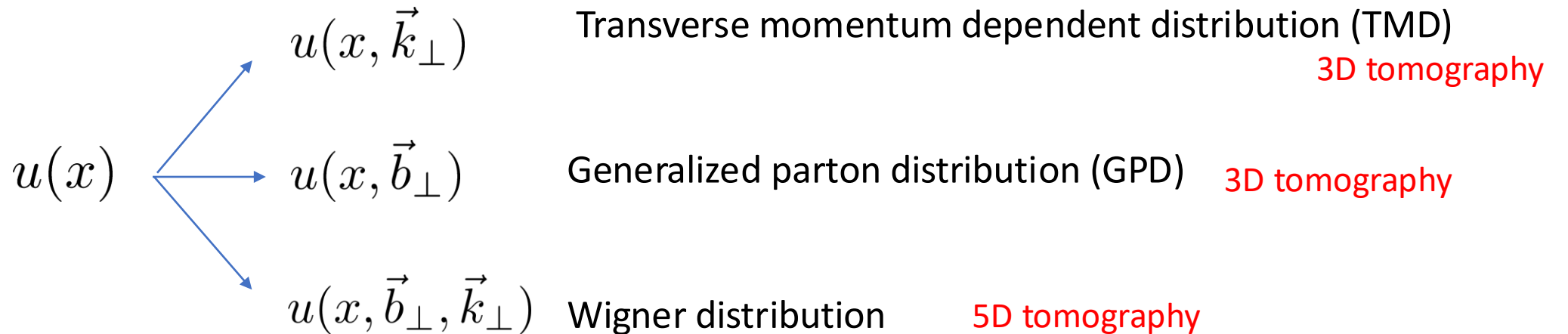


Universality of PDF—the **same** function can be used for different processes.
Fundamental to the predictive power of pQCD

Multi-dimensional tomography



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



Semi-inclusive DIS

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

When $P_{\perp}$ is small, **TMD factorization**

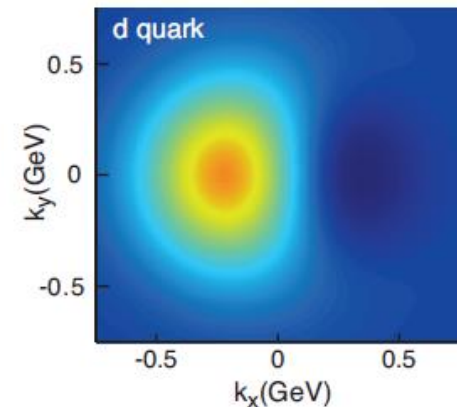
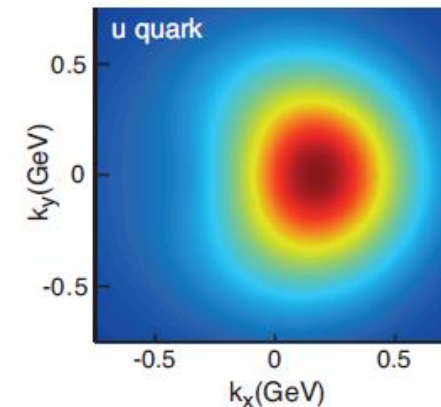
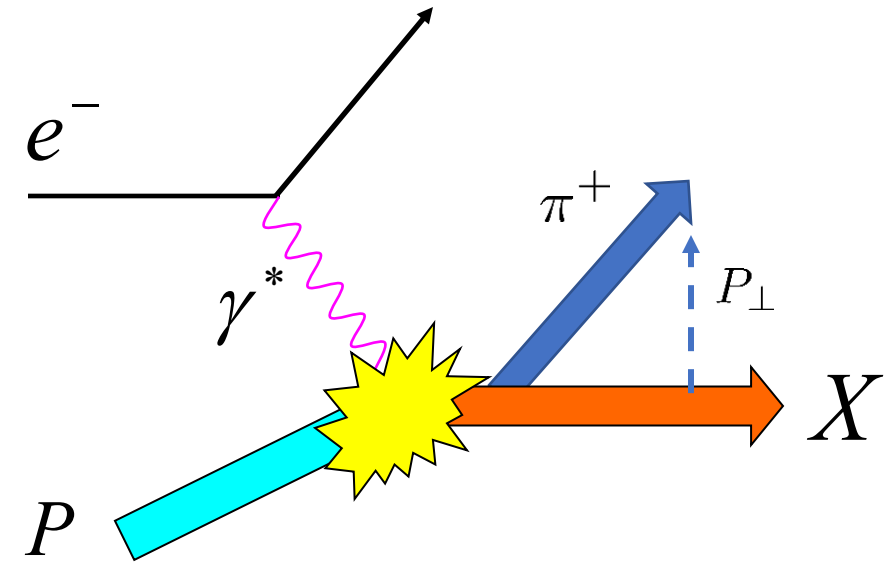
Collins, Soper, Sterman; Ji, Ma, Yuan;...

$$\frac{d\sigma}{dP_{\perp}} = H \otimes \underbrace{f(x, \mathbf{k}_{\perp})}_{\text{TMD PDF}} \otimes \underbrace{D(z, \mathbf{q}_{\perp})}_{\text{TMD FF}}$$

Open up a new class of observables where pQCD is applicable.

Provides a vivid picture of hadron structure in momentum space

Variety of novel phenomena due to intrinsic transverse momentum



TMD becoming precision science

Hadronic tensor, fully factorized form

hard part

$$\begin{aligned}
 W^{\mu\nu} = & \frac{8\pi^3 z_A z_B}{Q^2} \sum_{f, j_A, j_B} H_f^{\mu\nu}(Q; g(\mu_Q), \mu_Q) \int \frac{d^2 b_T}{(2\pi)^2} e^{-i q_{hT} \cdot b_T} \\
 & \times \int_{z_A}^1 \frac{d\hat{z}_A}{\hat{z}_A^3} d_{H_A/j_A}(\hat{z}_A; \mu_b) \tilde{C}_{j_A/f}\left(\frac{z_A}{\hat{z}_A}, b_*; \mu_b^2, \mu_b, g(\mu_b)\right) \\
 & \times \int_{z_B}^1 \frac{d\hat{z}_B}{\hat{z}_B^3} d_{H_B/j_B}(\hat{z}_B; \mu_b) \tilde{C}_{j_B/\bar{f}}\left(\frac{z_B}{\hat{z}_B}, b_*; \mu_b^2, \mu_b, g(\mu_b)\right) \\
 & \times \exp[-g_{H_A/f}(z_A, b_T) - g_{H_B/\bar{f}}(z_B, b_T)] \\
 & \times \exp\left[-\ln \frac{Q^2 z_A z_B}{m_A m_B} g_K(b_T) + \ln \frac{Q^2}{\mu_b^2} \tilde{K}(b_*; \mu_b)\right] \\
 & \times \exp\left\{\int_{\mu_b}^{\mu_Q} \frac{d\mu'}{\mu'} \left[2\gamma_D(g(\mu'); 1) - \ln \frac{Q^2}{(\mu')^2} \gamma_K(g(\mu'))\right]\right\}
 \end{aligned}$$

matching to collinear PDF/FF

Accuracy	$H, \mathcal{J}$	$\Gamma_{\text{cusp}}(\alpha_s)$	$\gamma_H^q(\alpha_s)$	$\gamma_r^q(\alpha_s)$	$\beta(\alpha_s)$
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 ³ LL	2-loop	4-loop	3-loop	3-loop	4-loop
N ³ LL'	3-loop	4-loop	3-loop	3-loop	4-loop
N ⁴ LL	3-loop	5-loop	4-loop	4-loop	5-loop
N ⁴ LL'	4-loop	5-loop	4-loop	4-loop	5-loop

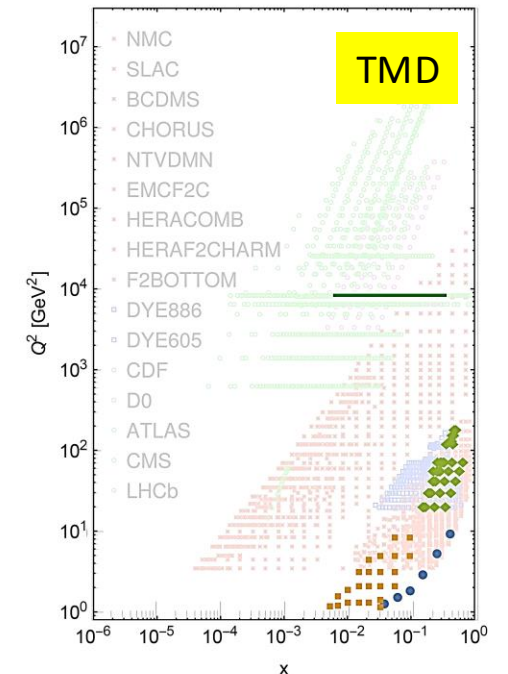
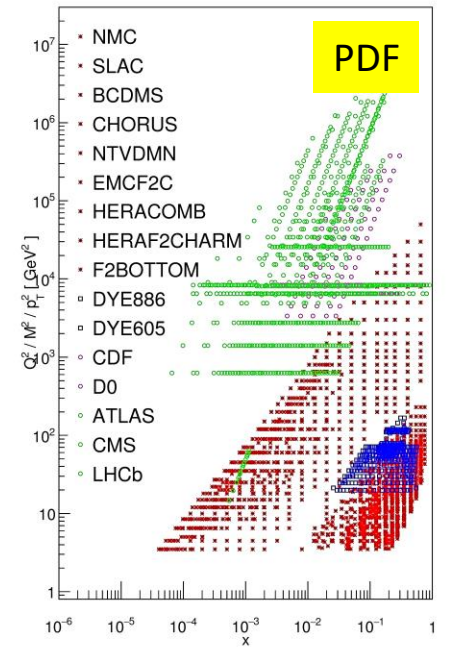
QCD evolution

Duhr, Mistlberger, Vita (2022)

TMD global analysis

Talk by Granger

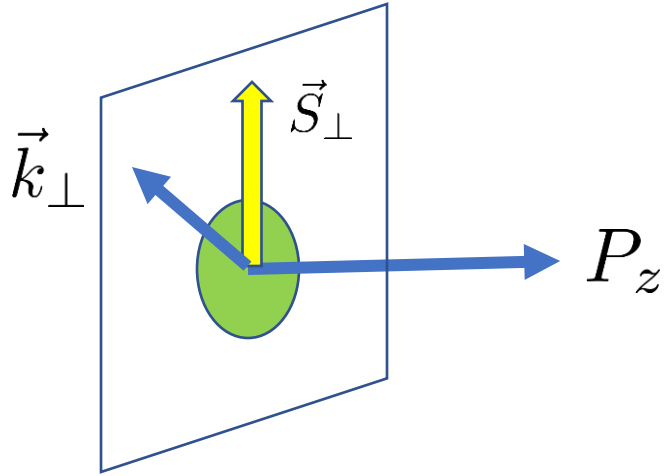
	Accuracy	SIDIS	DY	N of points	χ^2/N_{data}	Flavor Dependence
Pavia 2017 Bacchetta, Delcarro, et al., JHEP 06 (2017)	NLL	✓	✓	8059	1.55	✗
SV 2019 Scimemi, Vladimirov, JHEP 06 (2020)	N^3LL^-	✓	✓	1039	1.06	✗
MAPTMD22 Bacchetta, Bertone, et al., JHEP 10 (2022)	N^3LL^-	✓	✓	2031	1.06	✗
MAPTMD24 Bacchetta, Bertone, et al., JHEP 08 (2024)	N^3LL	✓	✓	2031	1.08	✓
ART25 Moos, Scimemi, et al., JHEP 11 (2025)	N^3LL^+	✓	✓	1209	1.05	✓



Available phase space still limited. Fully blossoms in the EIC era!

Universality up to a sign

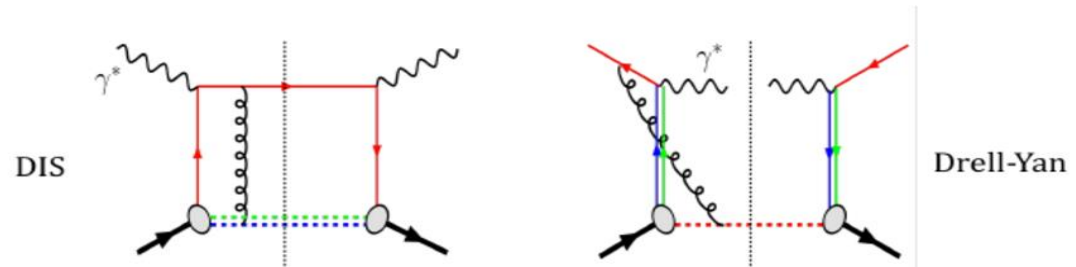
Sivers function for the transversely polarized nucleon



$$q(x, \vec{k}_\perp) = q(x, |k_\perp|) + \vec{S}_\perp \times \vec{k}_\perp f_{1T}(x, |k_\perp|)$$

→ Single spin asymmetry

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



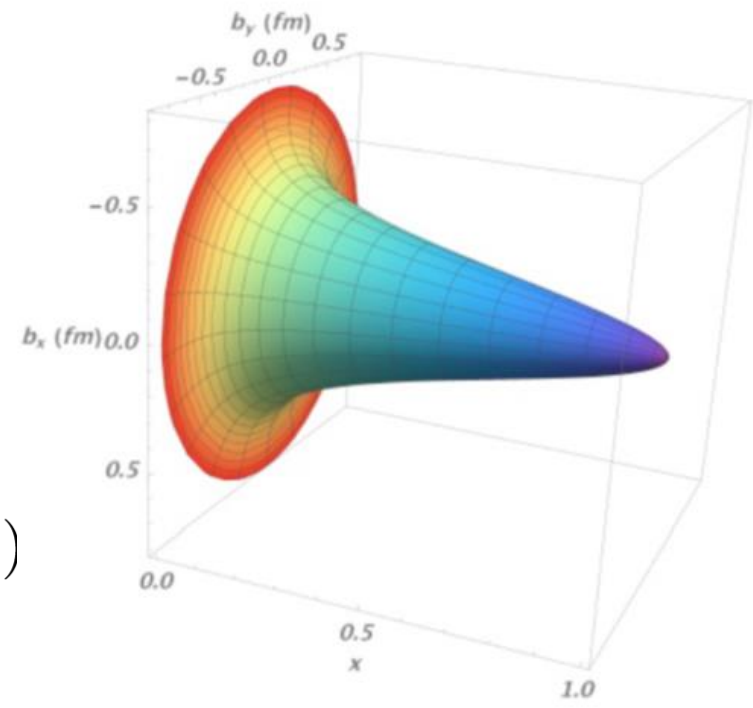
EIC will probe **gluon** Sivers function for the first time.
(connection to QCD **odderon**)

Generalized parton distributions

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

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

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



First moment $\rightarrow$ electromagnetic form factors

$$\int_{-1}^1 dx H_q(x, \eta, t) = F_1^q(t)$$

Fourier transform

$\rightarrow$ parton distribution in impact parameter space

$$H_q(x, t = -\vec{\Delta}_\perp^2) \rightarrow H_q(x, \vec{b}_\perp)$$

Ji sum rule for the nucleon spin

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

Deeply Virtual Compton Scattering (DVCS)

QCD factorization of Compton **amplitudes**

$$\mathcal{A} \sim \int_{-1}^1 dx \frac{1}{x - \xi + i\epsilon} H(x, \xi, t)$$

EIC offers an unprecedented kinematical coverage of DVCS

Curse of dimensionality: More variables, more severe inverse problem. [Talks by Kriesten, Choudhary](#)

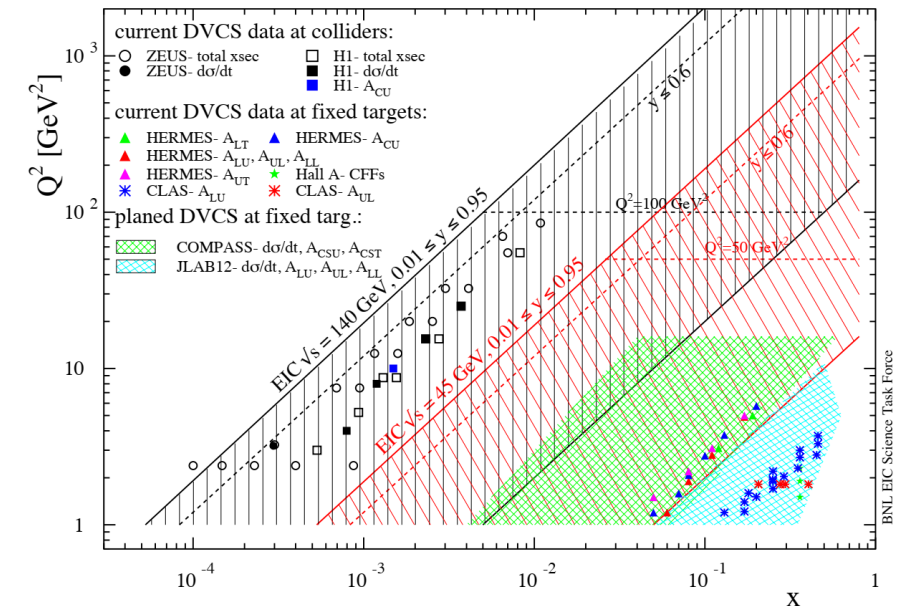
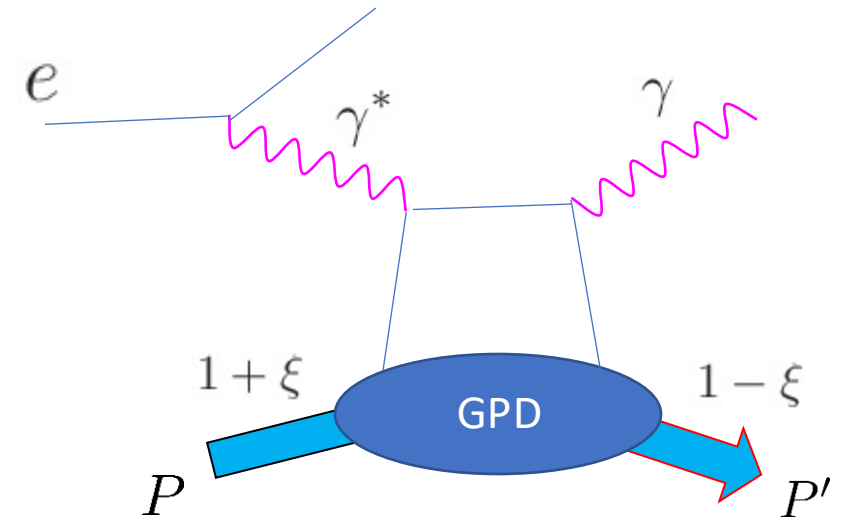
Yet, significant theory progress

3-loop evolution [Braun, Manashov, Moch, Strohmeier \(2019\)](#)

2-loop coefficient functions [Braun, Ji, Schoenleber \(2022\)](#)

Quark GPD E_q within reach.
Gluon GPD E_g challenging even at EIC

[Talks by Jevons, Lee](#)



Gravitational form factors

Talks by Tanaka, Gao, Freese, Yang, Liu

Second moment of GPDs

$$\int_{-1}^1 dx x H_q(x, \eta, t) = A_2^q(t) + \eta^2 D^q(t)$$

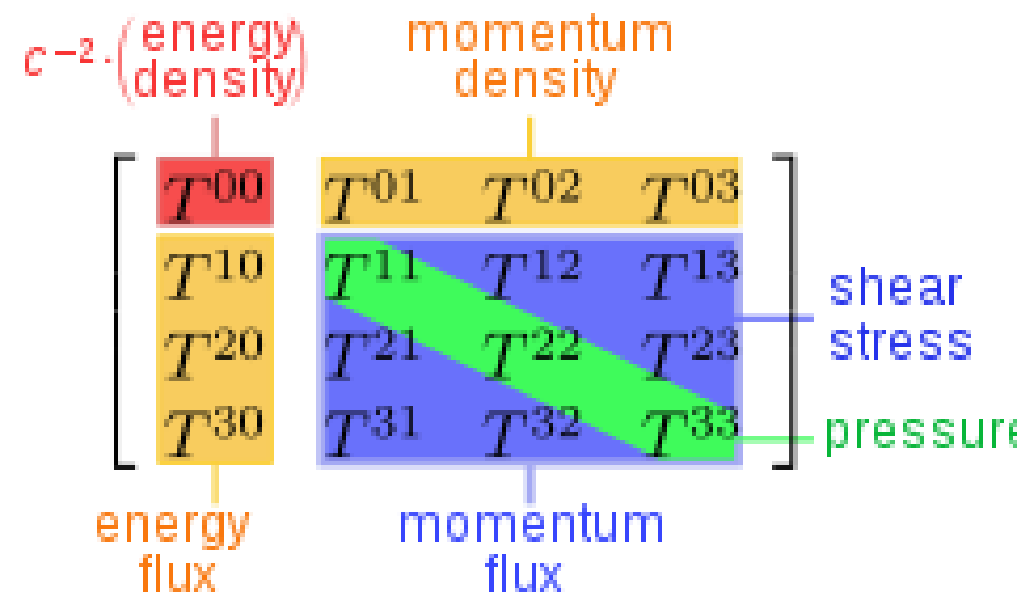
Form factors of the QCD **energy momentum tensor**

$$\langle P' | T^{\mu\nu} | P \rangle = \bar{u}(P') \left[A(t) \gamma^{(\mu} \bar{P}^{\nu)} + B(t) \frac{\bar{P}^{(\mu} i \sigma^{\nu)\alpha} \Delta_\alpha}{2M} + D(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{4M} \right] u(P)$$

$$A(0) = 1, \quad B(0) = 0 \quad D(0) = ??$$

Study of hadron masses

⊂ Study of energy momentum tensor



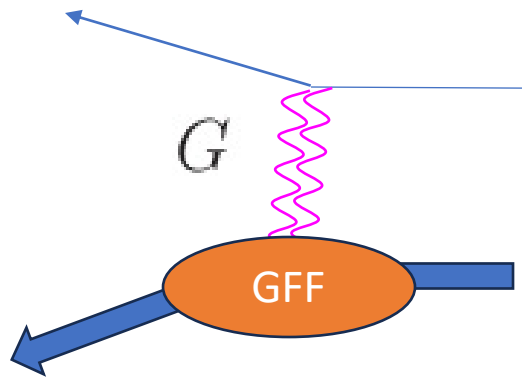
Experimental study of GFFs?

Elemag form factors: 70+ years of history, still highly active, several future experiments

Gravitational form factors: Just the beginning, we can make history!

Direct measurement impossible:

Graviton exchange enormously suppressed below the **Planck** energy



$$\frac{d\sigma}{dt} \sim G_N^2 \frac{s^2}{t^2}$$

$$G_N \sim 1/M_P^2$$

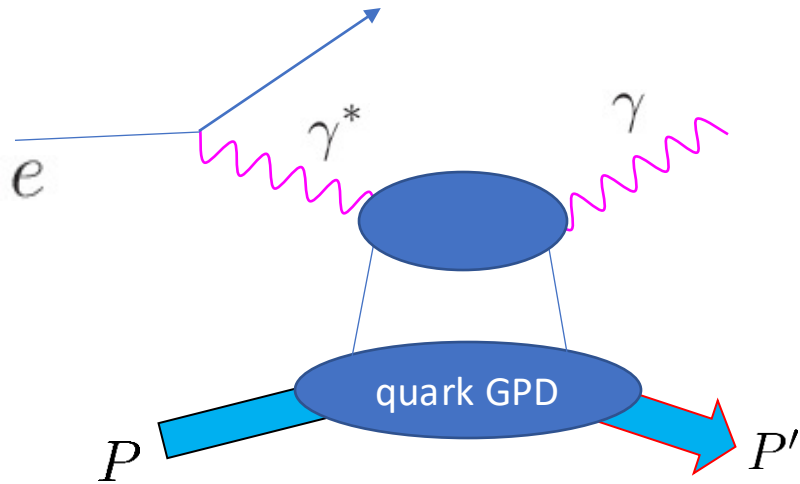
$$M_P \sim 10^{19} \text{ GeV}$$

But theorists are bad losers...

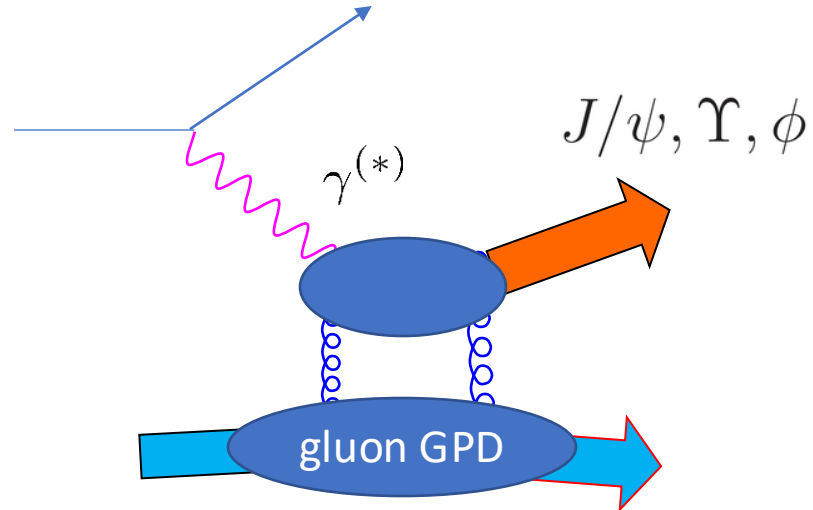
Accessing GFFs at JLab and EIC

Talks by Mamo, Singh

DVCS



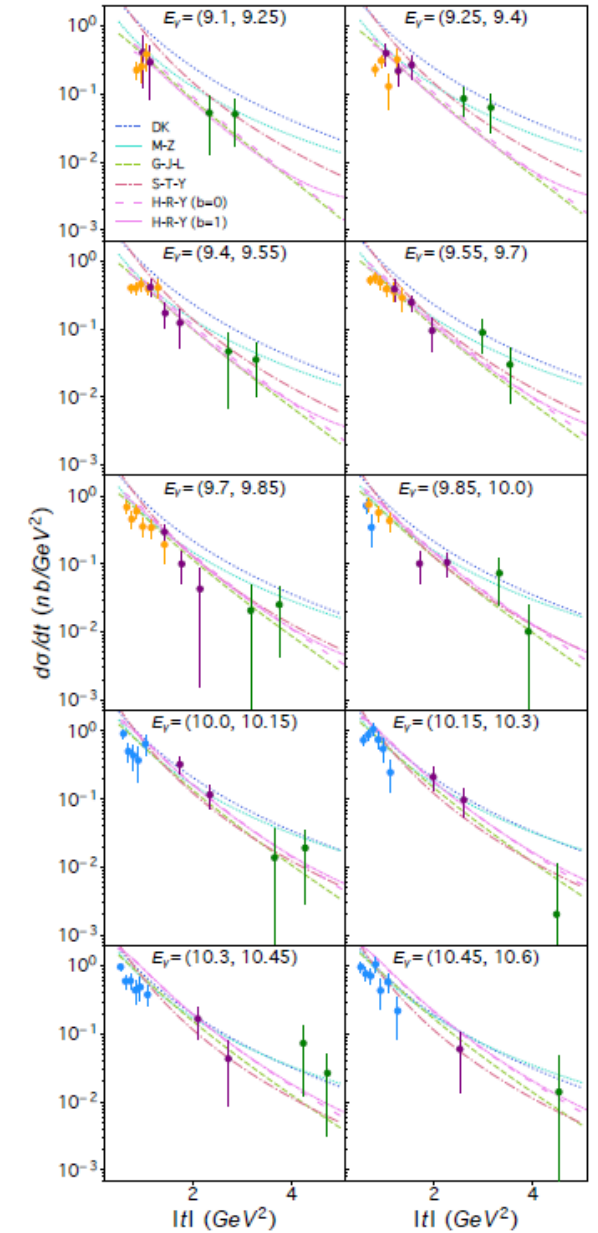
Heavy vector meson production near threshold



1 graviton $\approx$ 2 photons or 2 gluons

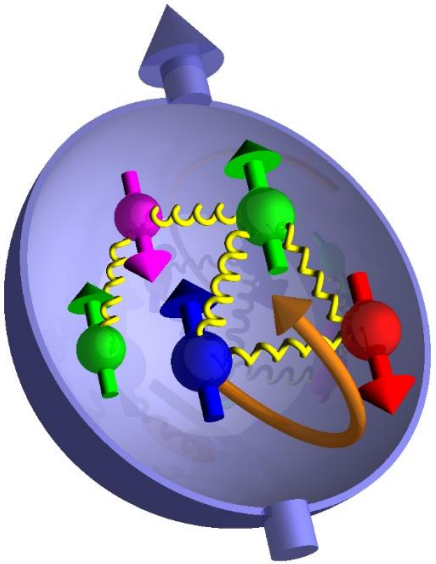
$$1+1=2$$

??



Duran et al. 2207.05212

Proton spin



The proton spin problem

The proton has spin $\frac{1}{2}$.

The proton is not an elementary particle.

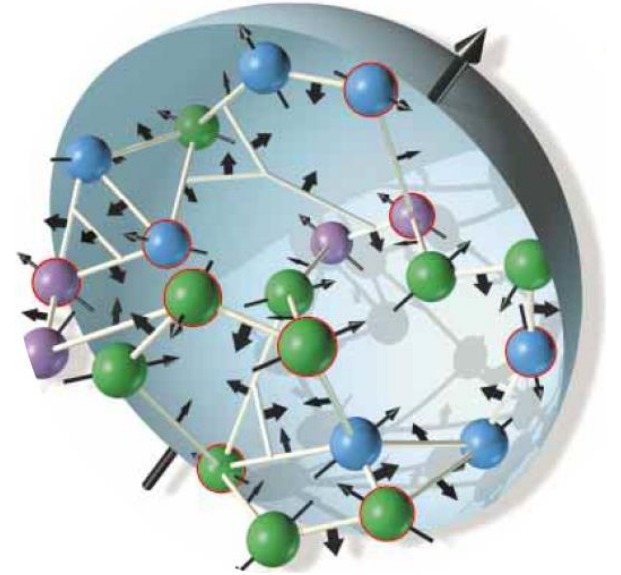
➔

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

Jaffe-Manohar sum rule

Ji sum rule

$\Delta\Sigma = 0.25 \sim 0.3$ reasonably well constrained from polarized DIS



$$\Delta G = \int_0^1 dx \Delta G(x) \text{ from polarized pp}$$

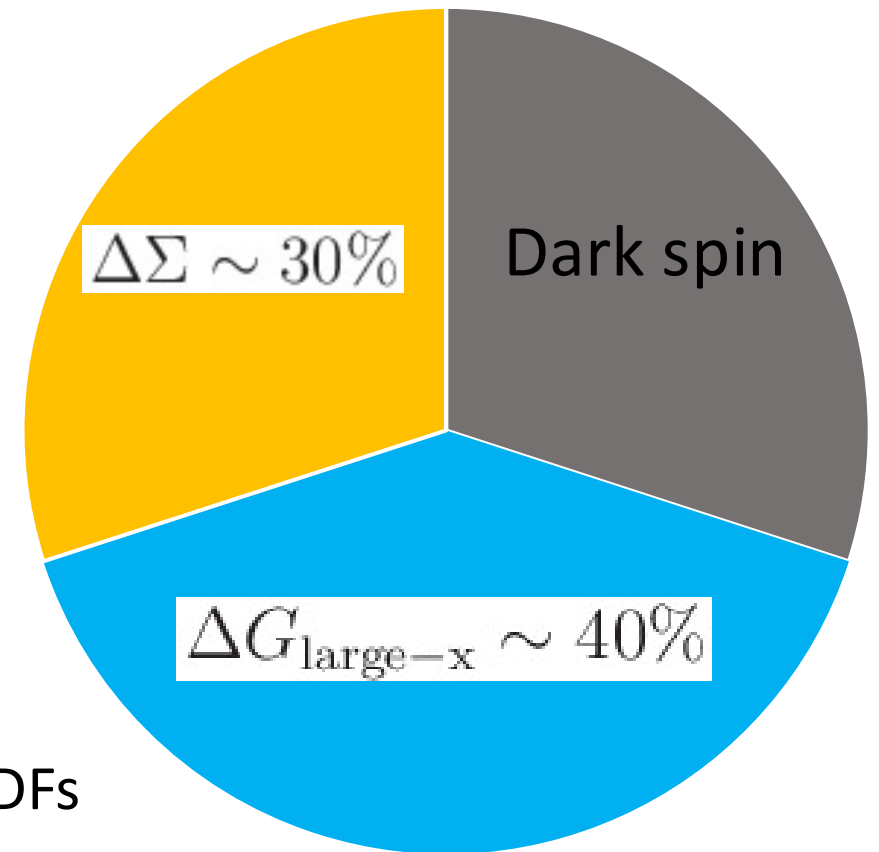
A major achievement of the RHIC spin program!

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

[Kovchegov, Sievert, Pitonyak \(2015\)](#) + many works



Helicity pQCD precision frontier

4-loop evolution of $\Delta\Sigma$

De Florian, Vogelsang (2019)

NNLO jet production in polarized DIS

Borsa, de Florian, Pedron (2020)

NNLO longitudinal spin asymmetry of W at RHIC

Boughezal, Li, Petriello (2021)

3-loop Wilson coefficients for $g_1(x)$

Blumlein, Marquard, Schneider, Schonwald (2022)

4-loop small-x anomalous dimension

Borden, Kovchegov (2023)

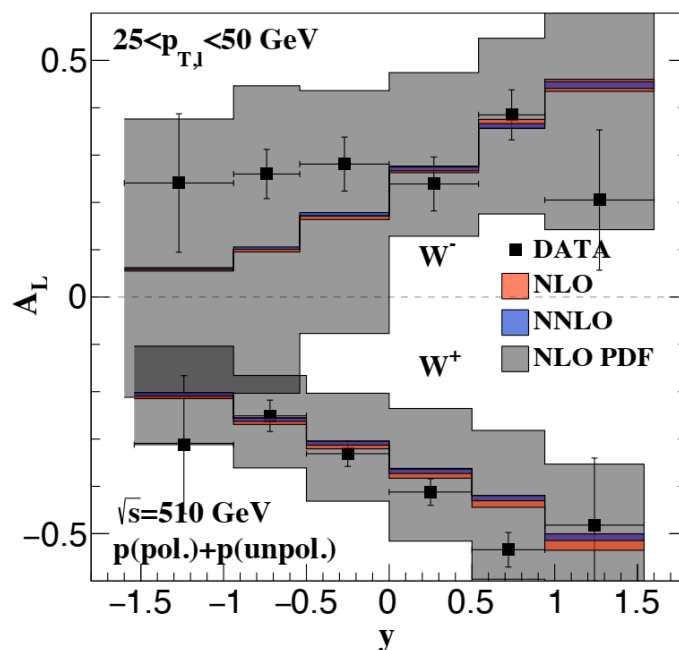
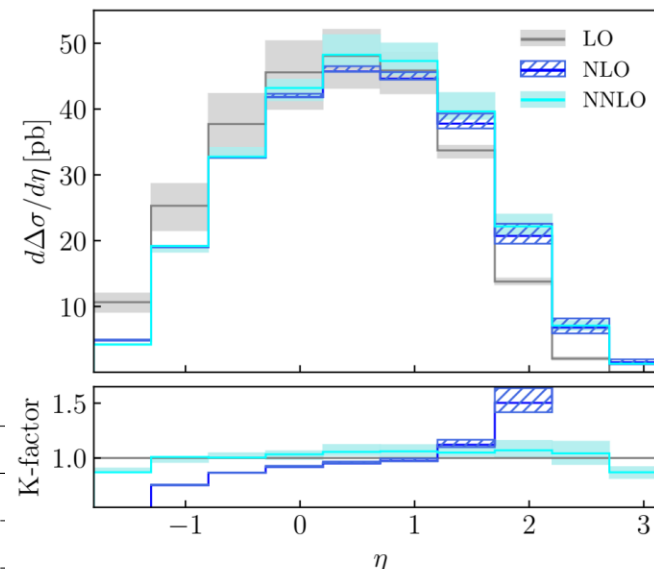
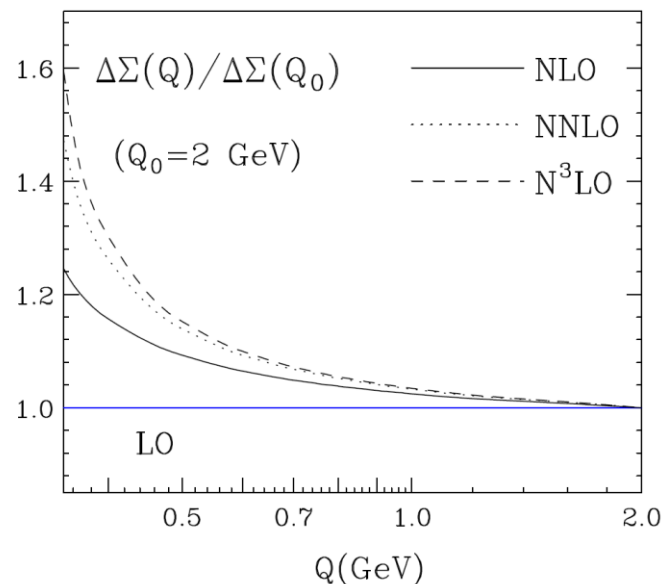
NNLO polarized SIDIS

Bonino, Gehrmann, Lockner, Schonwald (2024,2025)

Goyal, Lee, Moch, Pathak, Rana, Ravindran (2024,2025)

NNNLO polarized SIDIS

Dong, Fan, Gao, Li, Shao, Zhou, Zhu (2026)



NNLO global analysis for helicity PDF

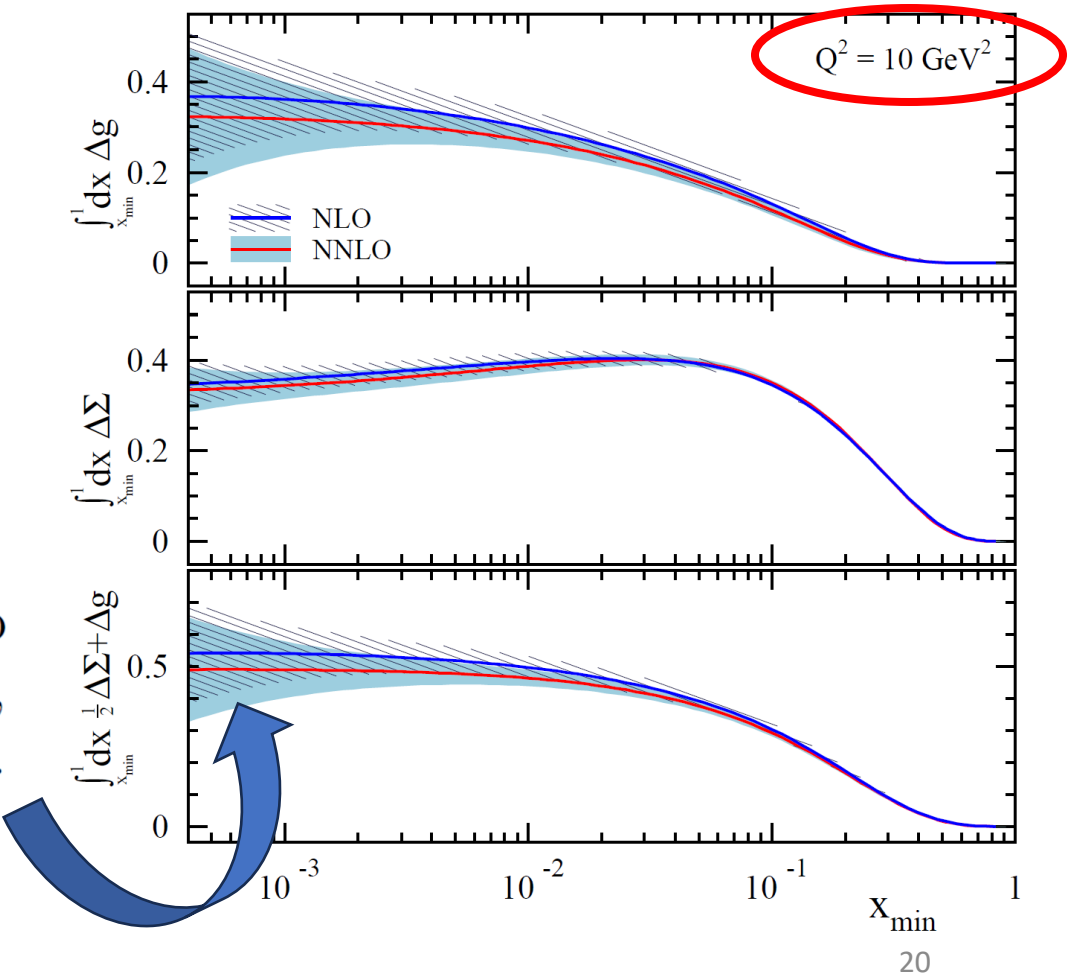
Bertone, Chiefa, Nocera (2024)

Borsa, de Florian, Sassot, Stratmann, Vogelsang (2024)

TABLE I. Partial and total χ^2 obtained in the fits

	Total	DIS	SIDIS	pp-jets	pp-pions	pp-W
NLO	627.2	302.7	127.6	111.1	63.5	22.3
NNLO	607.5	294.3	122.9	104.0	66.0	20.3
Data points	673	368	114	91	78	22

of the integrals. Remarkably, when combining the two contributions according to their role for the proton spin, one finds a result approaching 1/2 toward lower $x_{\min}$.



An elephant in the room: Orbital angular momentum

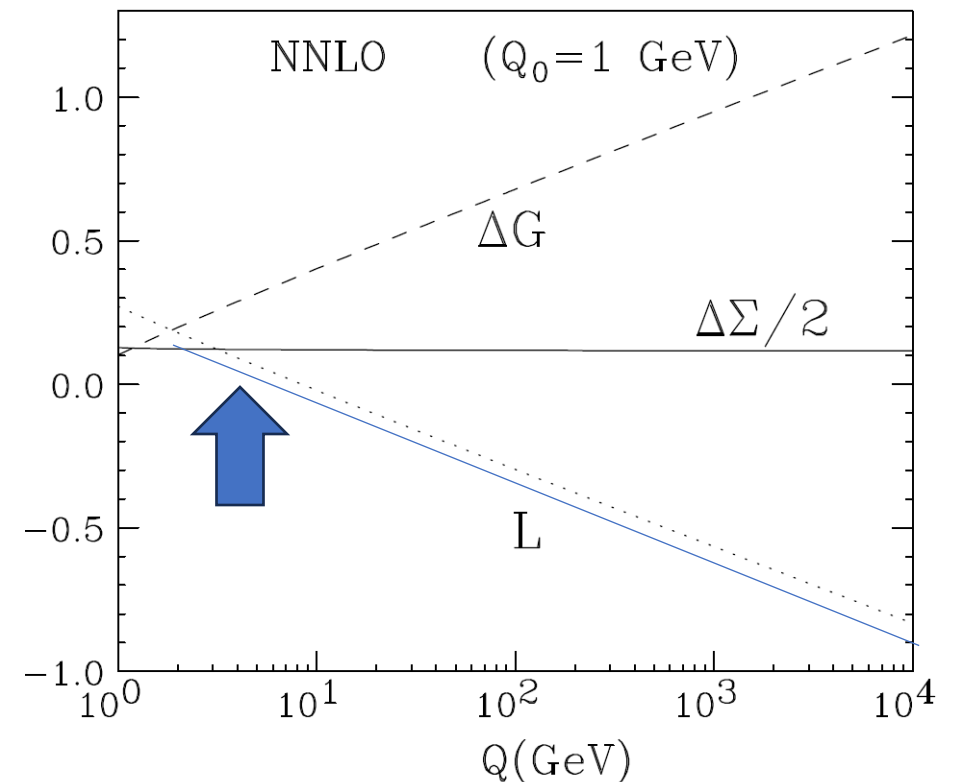
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

No experimental measurement of OAM so far
Spin sum rule cannot be complete
without understanding OAM

Helicity is not a conserved quantity.
Even if OAM is zero at one scale,
it is nonzero at other scales.

Can EIC access OAM information?

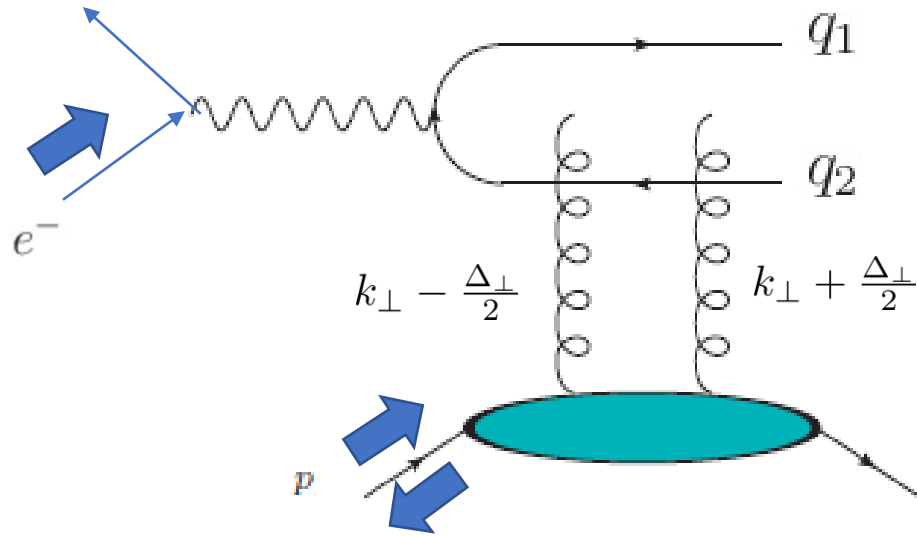
de Florian, Vogensang (2019)



Longitudinal double spin asymmetry in exclusive dijet production

Bhattacharya, Boussarie, YH (2022,2024);
Kovchegov, Manley (2024)
Zardo Becker, et al. 2608.25120

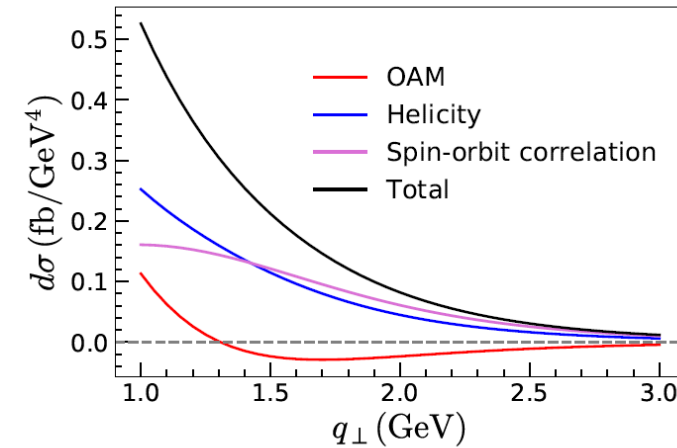
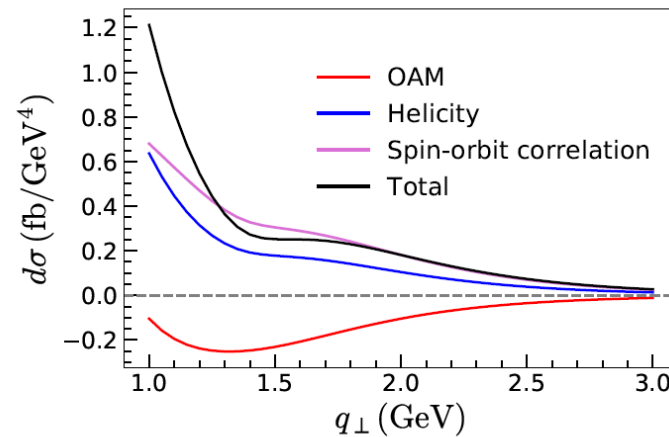
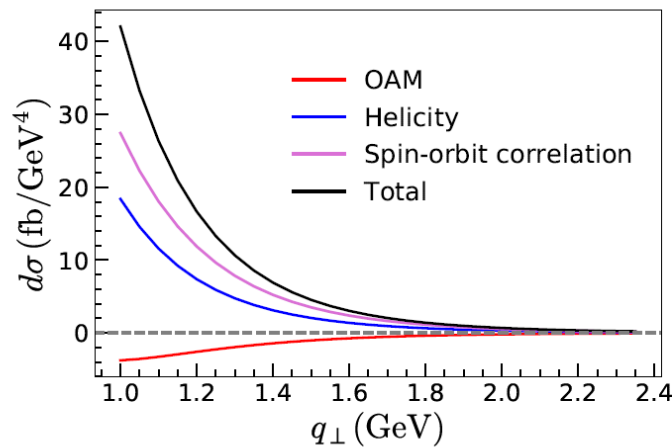
Talk by Manley



$$L^z \sim b_{\perp} \times k_{\perp}$$

$$d\sigma^{h_p h_l} \sim h_p h_l \cos(\phi_{l_{\perp}} - \phi_{\Delta_{\perp}}) \text{Re}(iA_L^{2*} A_T^{3i} - iA_T^{2i*} A_L^3)$$

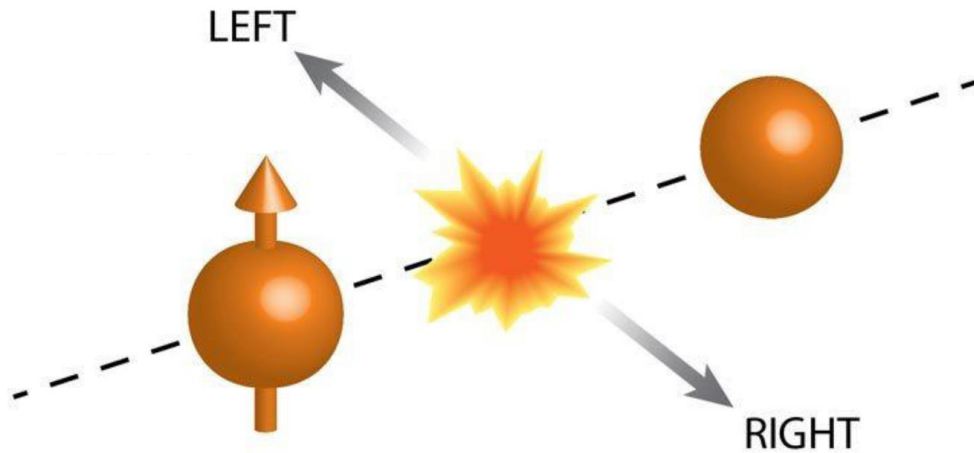
Sensitive to the gluon OAM at small-x



2404.04209

Transverse Single Spin Asymmetry (SSA)

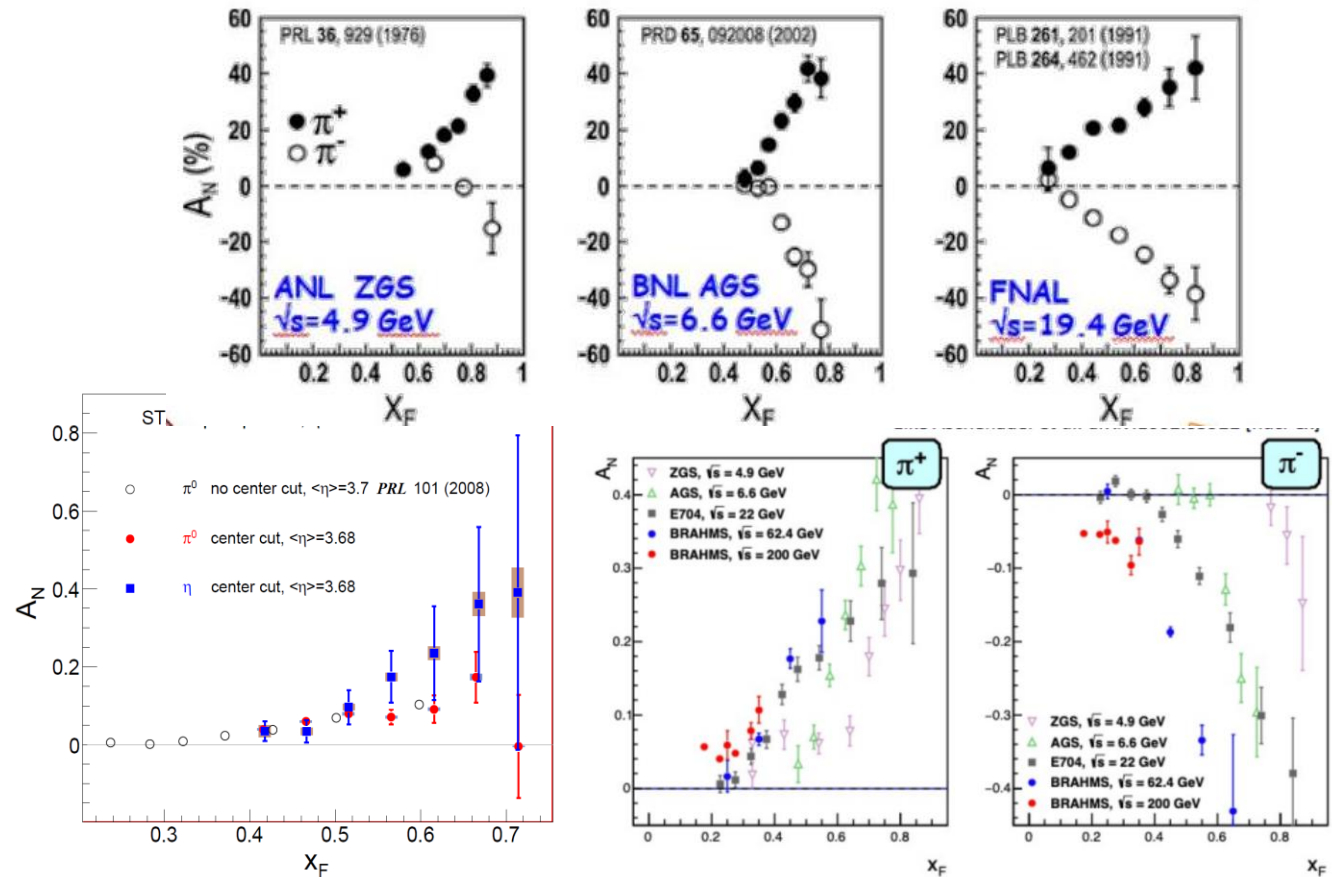
Talks by Zurek, Kelleher, Schnell, Surrow



Production of hadrons is left-right asymmetric

$$d\sigma \sim S_{\perp} \times P_{hT} \sim \sin(\phi_{S_{\perp}} - \phi_{P_{hT}})$$

$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$



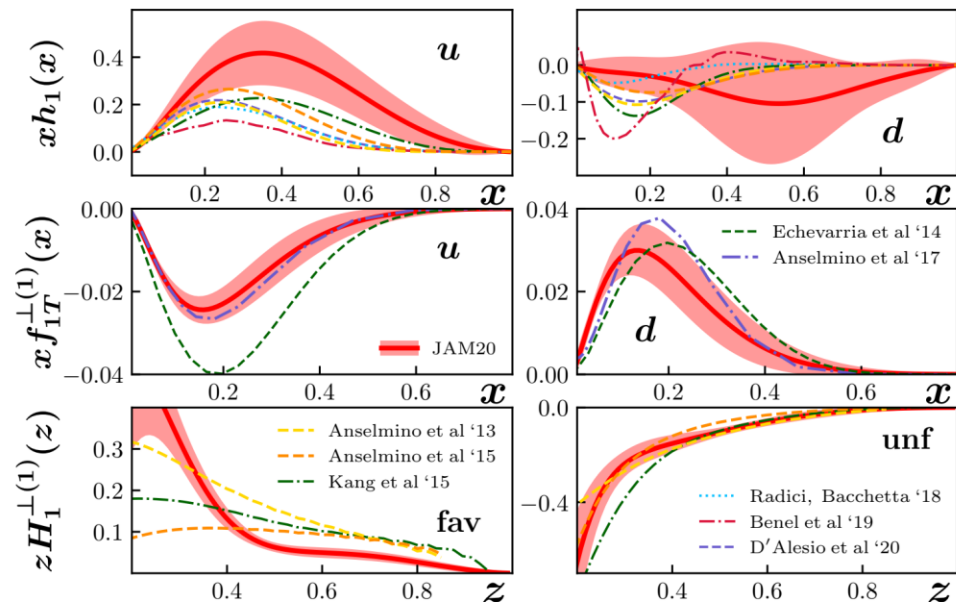
40+ years puzzle in QCD

Many explanations.

Which mechanism dominates and why?

Global analysis of SSA

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



Simultaneous fit of

e^+e^- (BELLE, BaBar, BESIII)

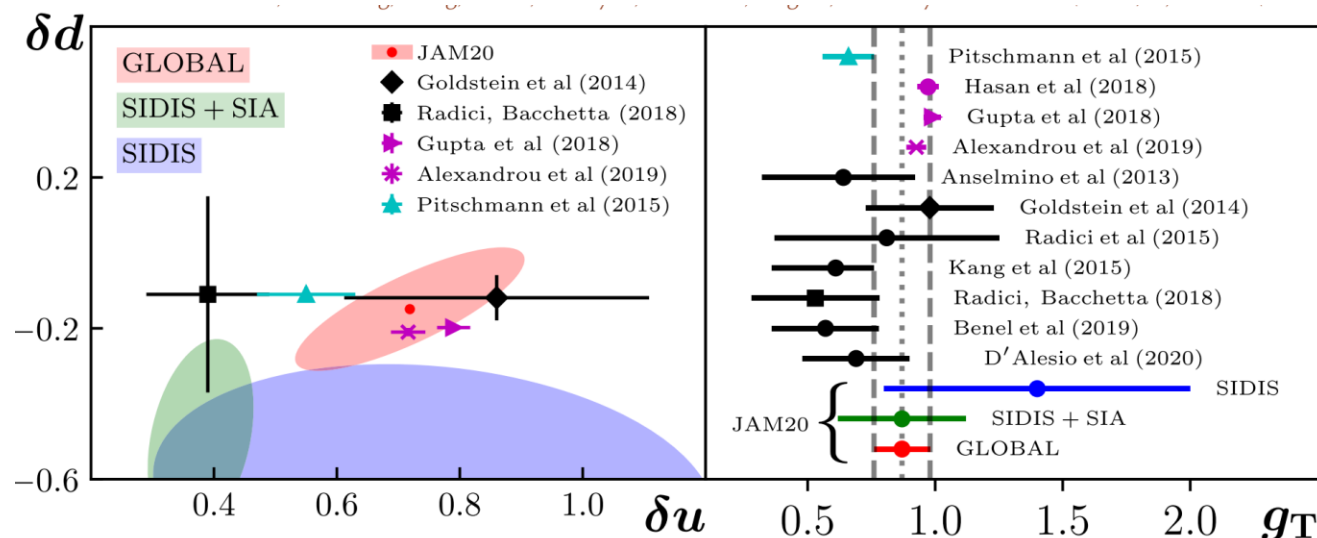
SIDIS (COMPASS, HERMES, Jlab) ← input from EIC in future

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**.
connection to nucleon **Electric Dipole Moment**



BSM physics from spin asymmetries at the EIC

Weinberg operator contribution to proton EDM from polarized DIS

$$f_{abc} \tilde{F}_{\mu\nu}^a F_b^{\mu\alpha} F_{c\alpha}^\nu \quad \text{YH, 2012.01865}$$

Beam/target spin asymmetries $e^\uparrow p \rightarrow eX$ $ep^\uparrow \rightarrow eX$

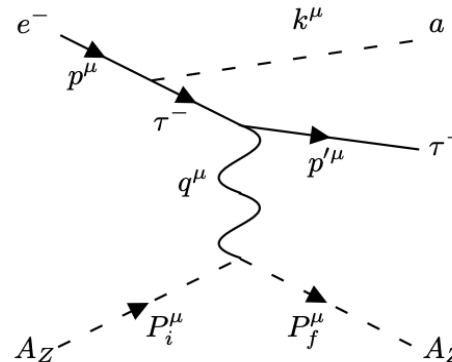
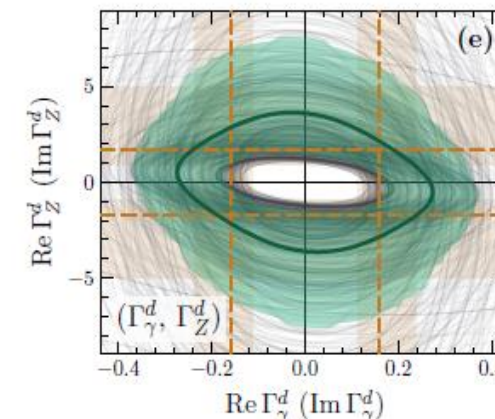
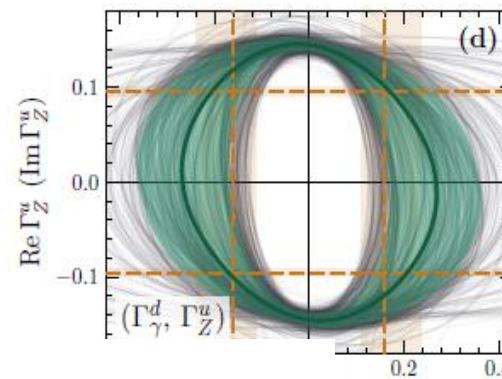
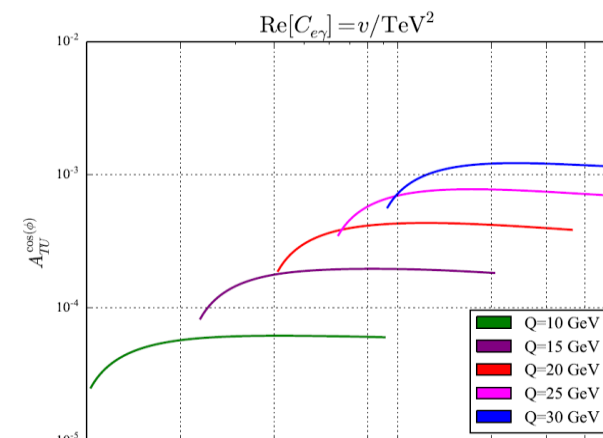
→ Constraints on SMEFT parameters relevant to EDMs

Boughezal, de Florian, Petriello, Vogelsang 2301.02304

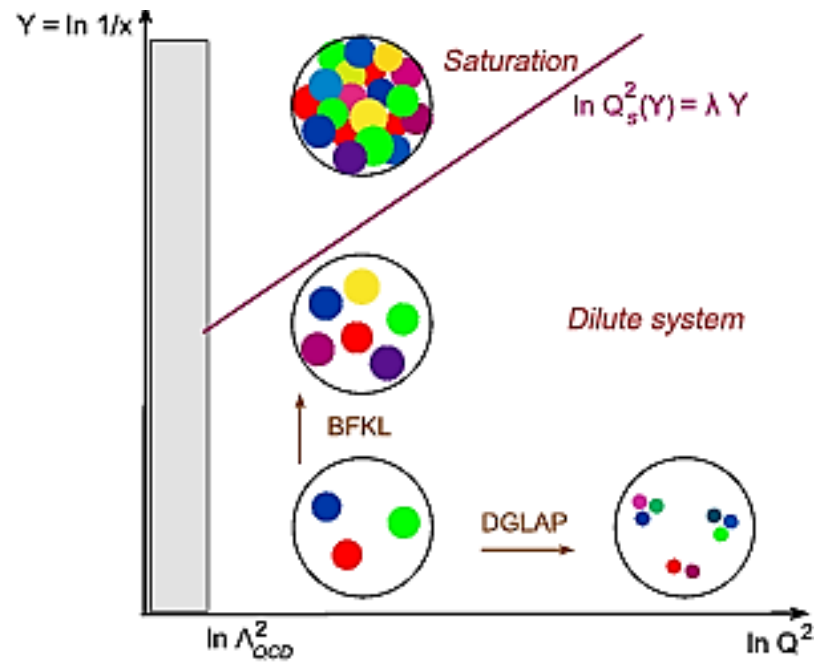
Yu, Dawson 2609.38535

Electron $g - 2$ and EDM from $e^\rightarrow p \rightarrow X$
with flavor-changing axion-like particle (ALP)

Davoudiasl, Marcarelli, Neil, 2402.17821



Gluon saturation

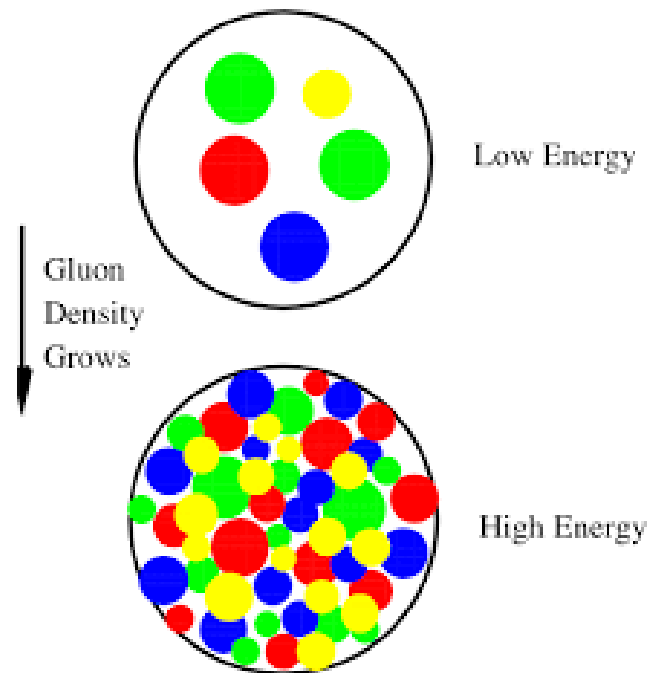


Gluon saturation

Rapid rise of the gluon distribution at $x \ll 1$

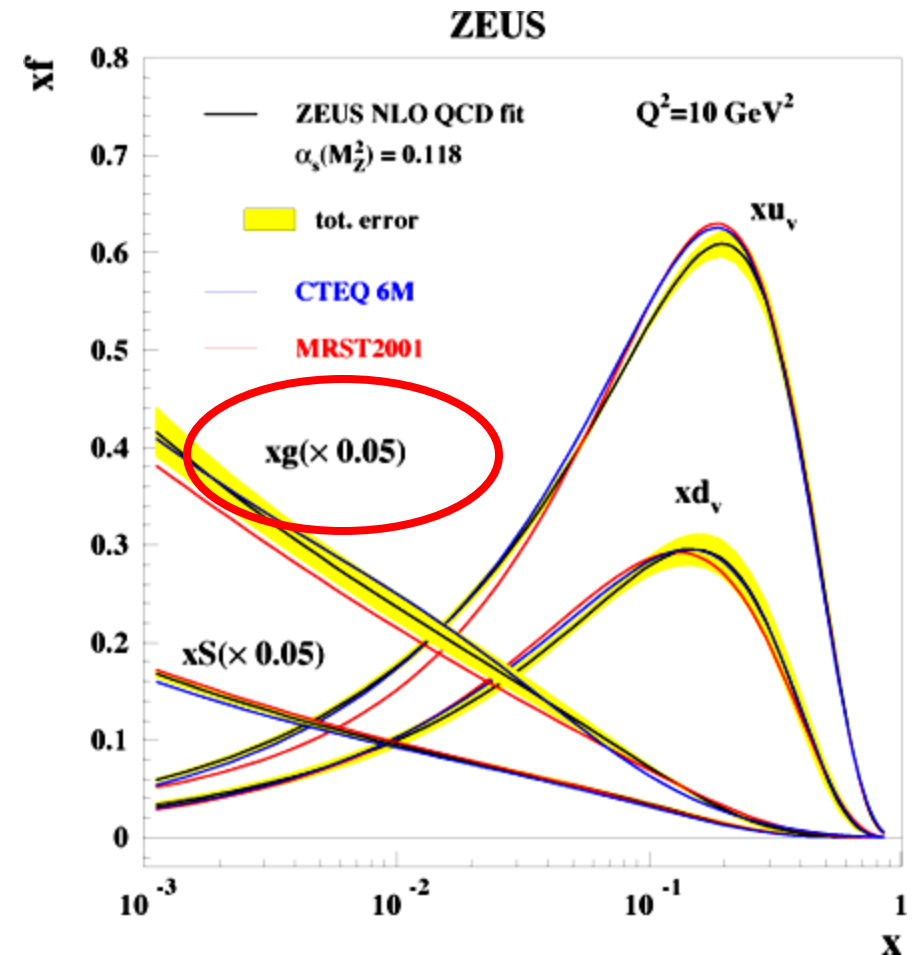
Gluon density eventually saturates due to unitarity.
Gribov, Levin, Ryskin (1980); Mueller, Qiu (1986)

$$\pi R^2 \sim \frac{\alpha_s}{Q_s^2} x G(x, Q_s)$$

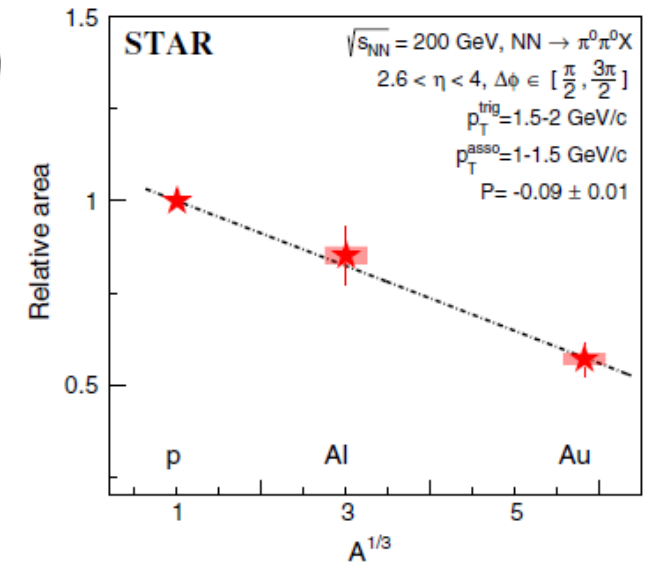
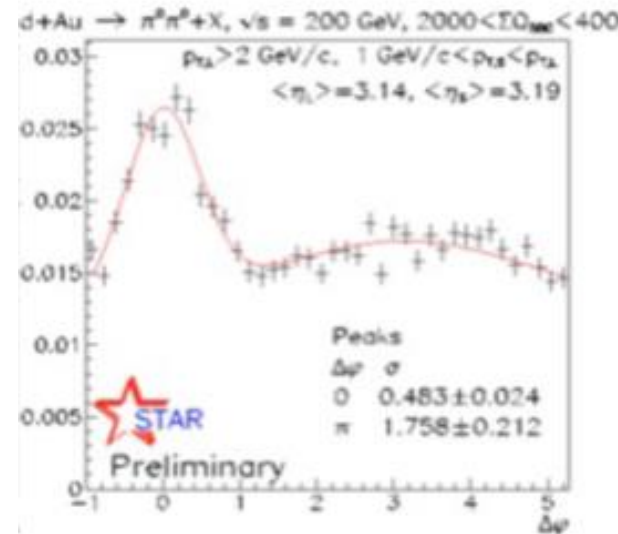
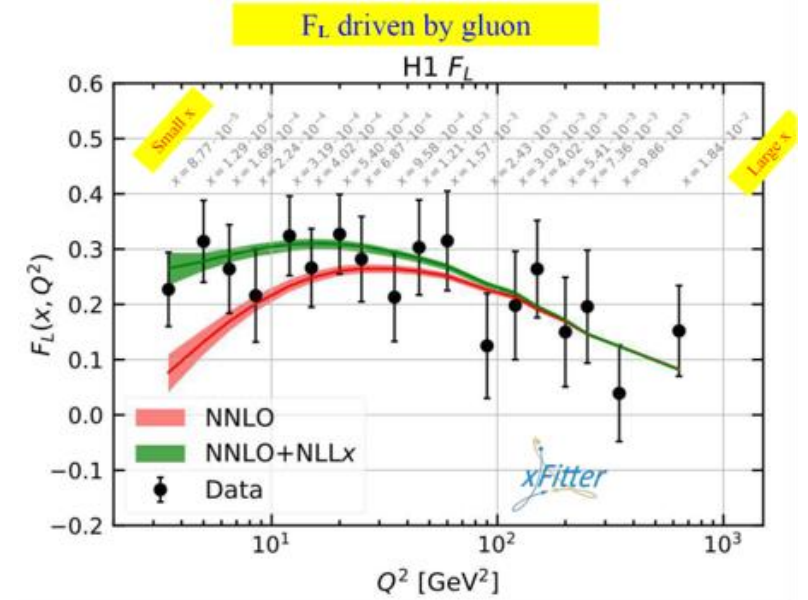
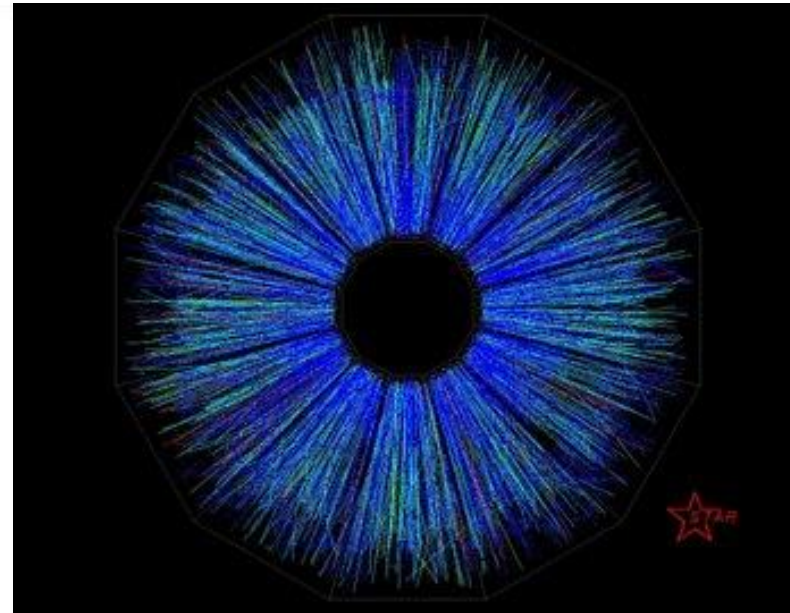
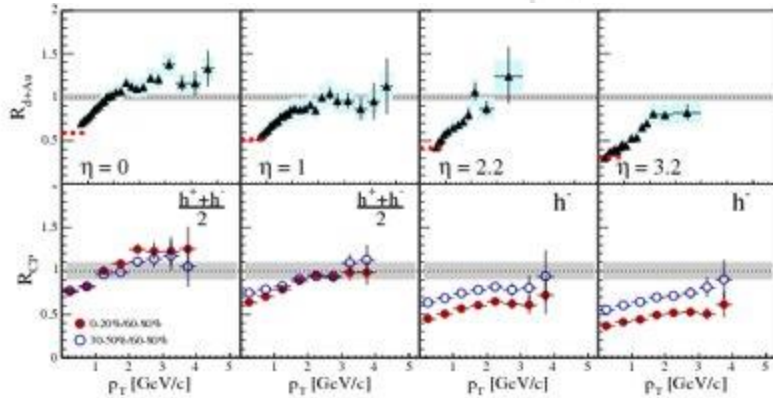
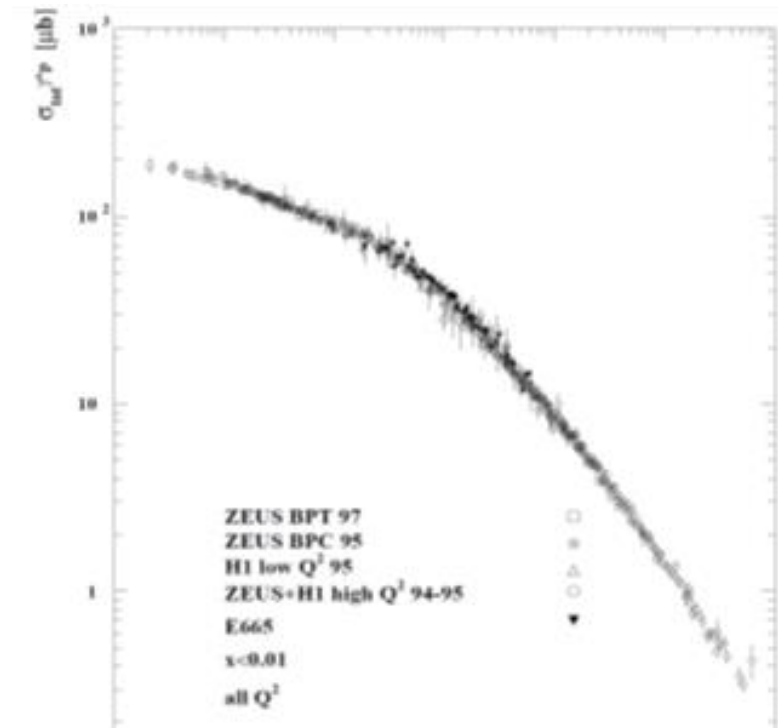


The ultimate state of matter at high energy
→ Color Glass Condensate (CGC).

High density, weakly coupled gluon matter which allows perturbative QCD approaches [McLerran, Venugopalan \(1993\)](#)



Has saturation been observed at HERA, RHIC, LHC?



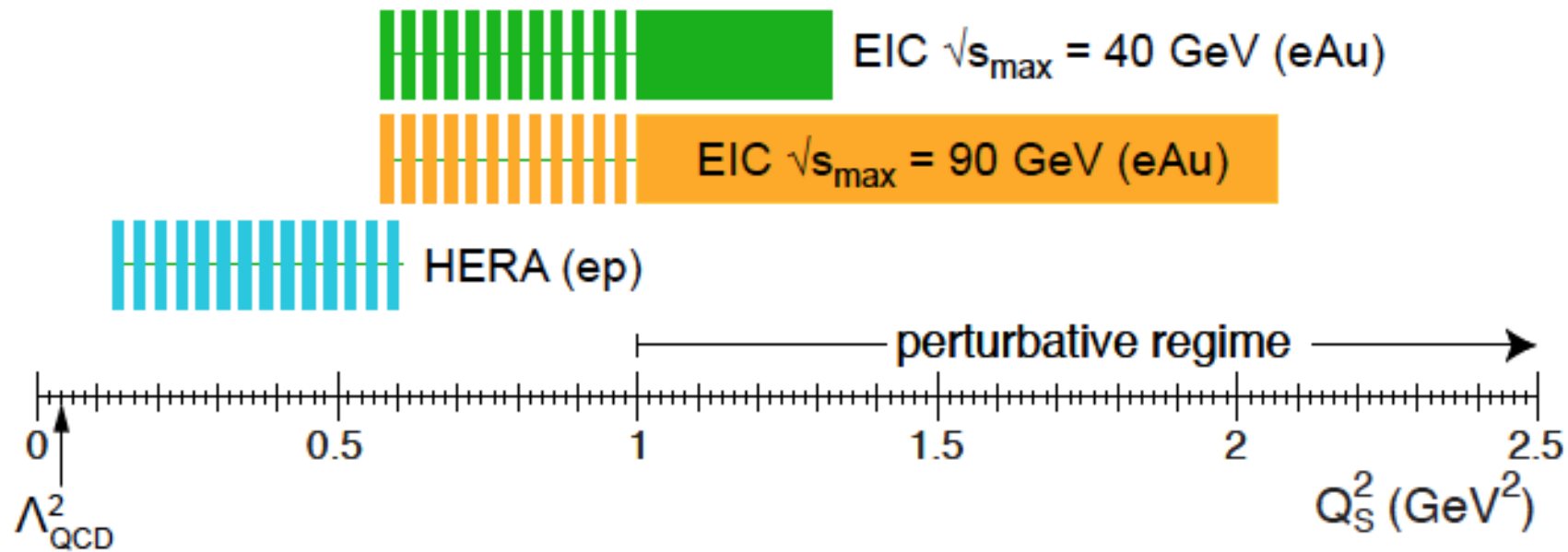
EIC: Dream machine for gluon saturation

CGC characterized by one hard momentum scale, the saturation momentum

Enhanced in a large nucleus $Q_s^2 \propto A^{1/3}$

EIC energy lower than HERA, yet the saturation momentum larger

Electron scattering : less initial state effects



Towards NLO global analysis at small-x

Unambiguous discovery of gluon saturation likely requires NLO global analysis of many observables

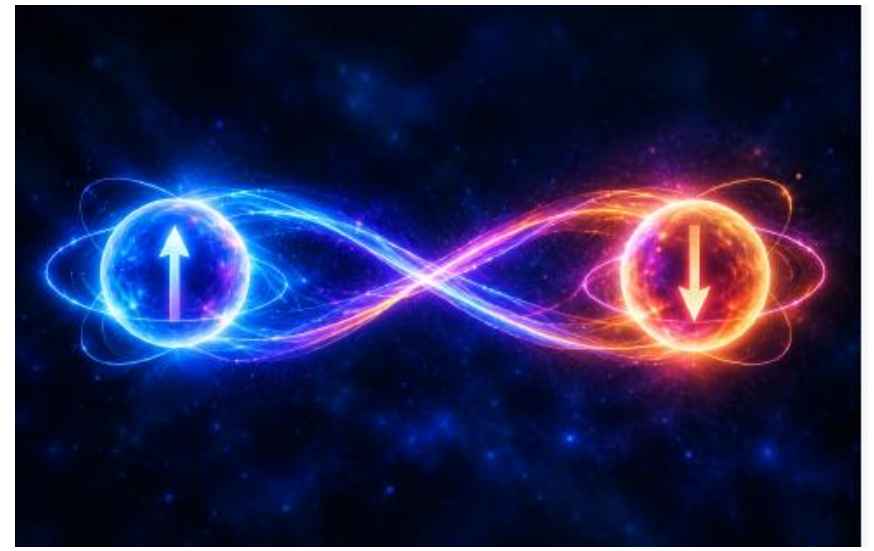
NLO computations, NLL BK-JIMWLK evolution, initial state, event generators,...

Talks by Mehtar-Tani, Tiwari, Yao, Lempert, Chu



Observable	Fixed order	Small-x evolution	Sudakov, threshold	Hadronization	Data
Forward hadrons, p+A	NLO	rcBK, NLO BK	threshold resummed	collinear FF	RHIC, LHC
Dihadrons, dijets, p+A	LO, real NLO	rcBK	Sudakov + NP	collinear FF	STAR, ATLAS (FoCal)
Photon-tagged, p+A	LO	BK-type	Sudakov, showers	FF, none (γ +jet)	PHENIX, ALICE (FoCal)
Heavy-meson pairs, p+A	LO	large- N_c dipoles	Sudakov with mass	heavy-quark FF	LHCb
Dijets, dihadrons, e+A	NLO	kin. constr. JIMWLK	double + single logs	TMD FF	EIC
Hadrons, jets, TFR, e+A	NLO	rcBK	Sudakov, threshold	FF, fracture fns	HERA, EIC
Energy correlators, e+A	LO	rcBK	none (NEC)	none (sum rule)	EIC

Salazar, talk at DNP2026



Quantum tomography

Quantum tomography

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From Wikipedia, the free encyclopedia

Quantum [tomography](#) or **quantum state tomography** is the process by which a quantum state is reconstructed using measurements on an ensemble of identical quantum states.^[1] The source of these states may be any device or system which

Quantum entanglement at the LHC

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SEPTMBER 25, 2024 | 4 MIN READ

‘Spooky Action at a Distance’ Observed in Quarks for the First Time

Physicists report the first observations of quantum entanglement in top and anti-top quarks, the heaviest known fundamental particles and their antimatter counterparts, inside the Large Hadron Collider.

BY DAN GARISTO & NATURE



The ATLAS detector, part of the Large Hadron Collider, sits 100 meters below ground, where it measures various properties of high-energy particles. Maxmillion Brice/CERN

Article

Observation of quantum entanglement with top quarks at the ATLAS detector

<https://doi.org/10.1038/s41586-024-07824-z> The ATLAS Collaboration[✉]

Received: 14 November 2023

Accepted: 12 July 2024

Published online: 18 September 2024

Open access

Entanglement is a key feature of quantum mechanics^{1–3}, with applications in fields such as metrology, cryptography, quantum information and quantum computation^{4–6}. It has been observed in a wide variety of systems and length scales, ranging from the microscopic^{7–13} to the macroscopic^{14–16}. However, entanglement at the highest accessible energy scales. Here we report the observation of quantum entanglement in top–antitop quark events produced in proton–proton collisions at the Large Hadron Collider.

Observation of quantum entanglement in top quark pair production in proton–proton collision

The CMS Collaboration

CERN, Geneva, Switzerland

E-mail: cms-publication-committee-chair@cern.ch

Received 6 June 2024, revised 18 September 2024
Accepted for publication 23 September 2024
Published 23 October 2024

Quantum Observables for Collider Physics 2026

Apr 20 – 24, 2026
CERN
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Contribution List

Book of Abstracts

Participant List

Code of Conduct

Practical information

Accommodation

Health Insurance, MICA

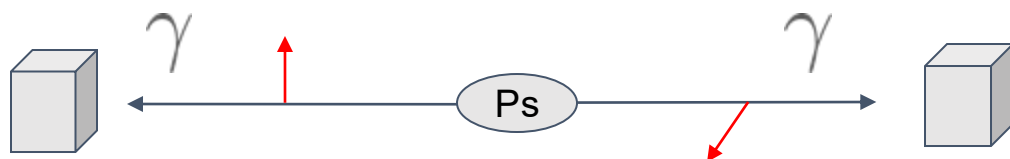
Participant List

101 participants

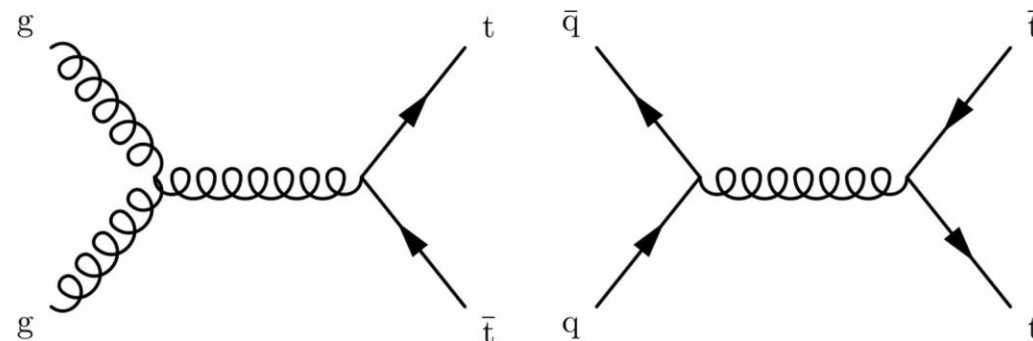
Last Name	First Name	Affiliation
Afik	Yoav	University of Chicago
Arisi	Angelo	Purdue University
Bae	Joonwoo	Korea Advanced Institute of Science and Technology
Barr	Alan	University of Oxford

Entanglement is ubiquitous

Positronium decay into two photons



Top-antitop pair production at the LHC



Elementary particles with spin (photon, electron, quark, proton,...) are **qubits/qutrits**

When produced in pairs, they can be entangled in quantum mechanical sense.

Complete characterization of two-qubit states: **spin density matrix**

$$\rho = \frac{1}{4} (\mathbb{I} \otimes \mathbb{I} + B^a \sigma^a \otimes \mathbb{I} + \bar{B}^b \mathbb{I} \otimes \sigma^b + C^{ab} \sigma^a \otimes \sigma^b)$$

Entanglement, Bell's inequality, etc., encoded in the density matrix.

Spin-spin entanglement at the EIC

Compute the spin density matrix of quark-antiquark pairs produced in electron-proton scattering.

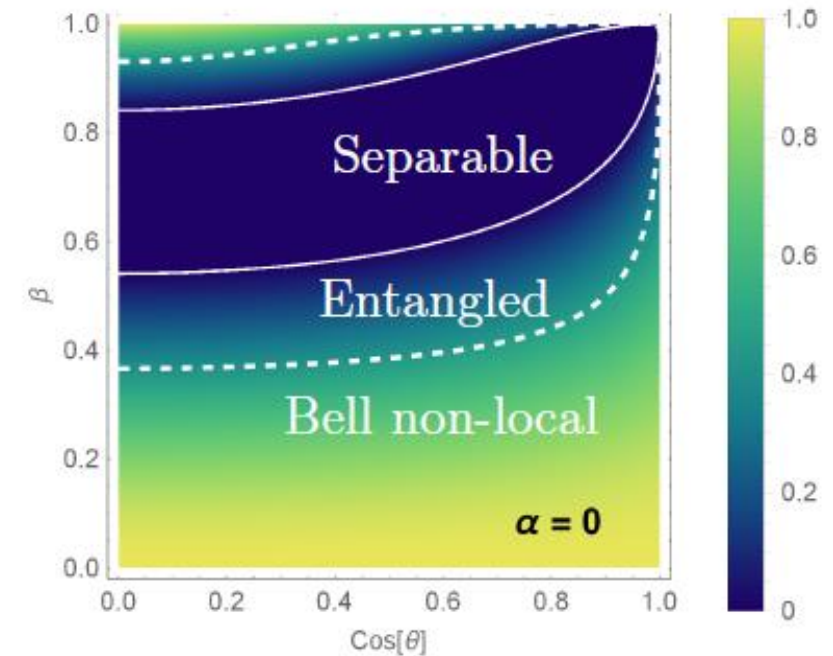
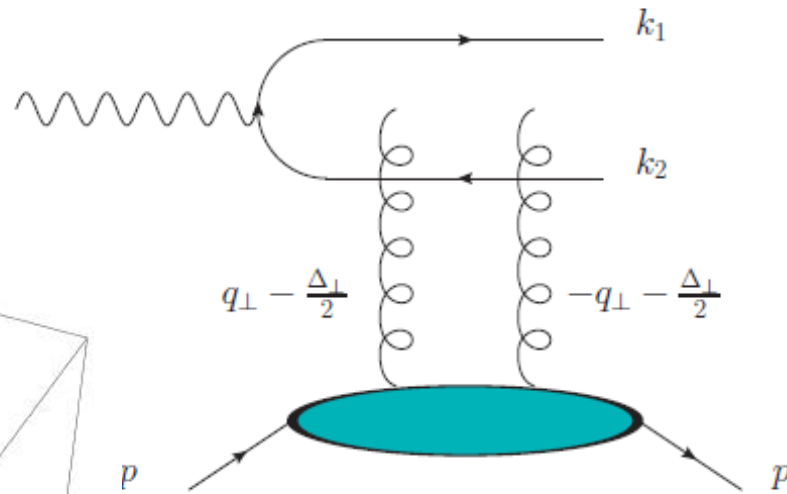
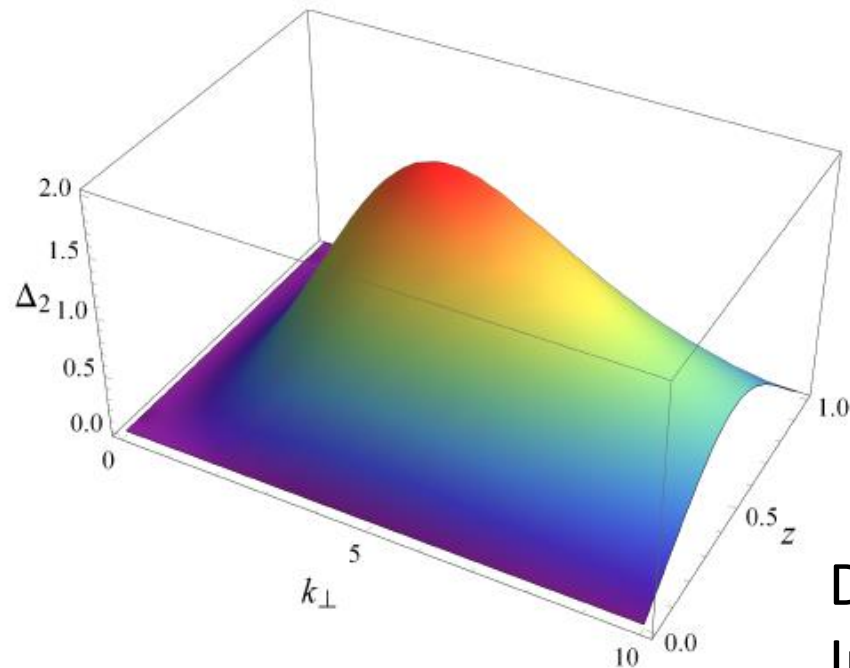
2506.12889, Qi, Guo, Xiao

2509.05267, Fucilla, YH

2510.23773, Cheng, Han, Trifinopoulos

2511.04537, YH, Schoenleber

2604.11697, Fucilla, YH, Xiao



Density matrix depends on TMDs and GPDs.

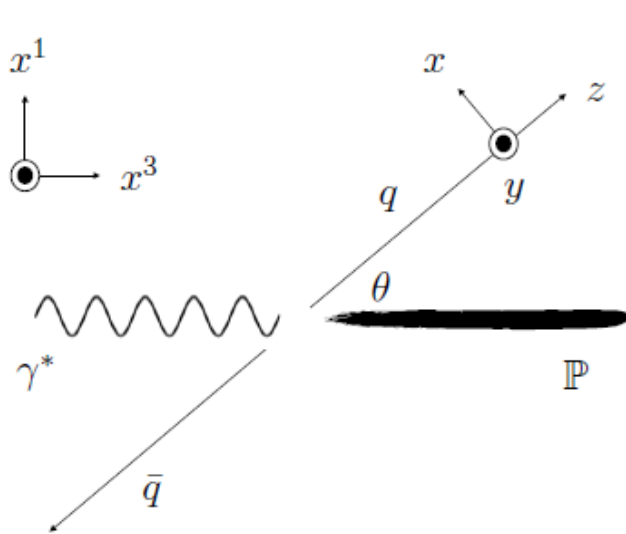
Initial state nucleon structure affects final state entanglement

Quantum tomography at the EIC

Fucilla, Guo, YH, 2609.32800

Quantum tomography: Experimental reconstruction of the complete density matrix

Possible with the help of **Collins and dihadron fragmentation functions**



Maximal entanglement of heavy quarks
modifies Collins asymmetry

$$\cos(\phi + \phi') \rightarrow \cos \phi \cos \phi'$$

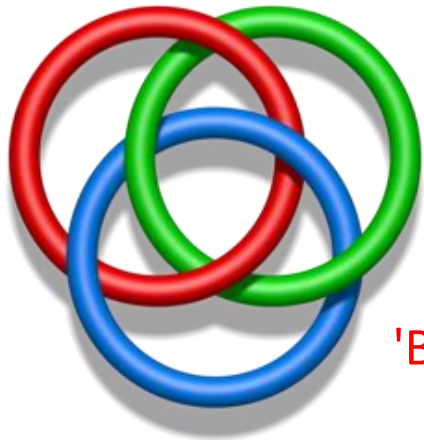
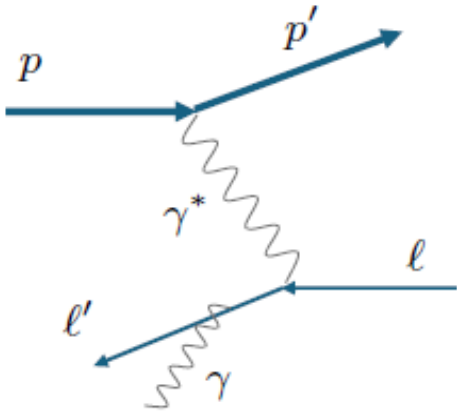
$$\begin{pmatrix} C_{xx} & C_{xy} & C_{xz} \\ C_{yx} & C_{yy} & C_{yz} \\ C_{zx} & C_{zy} & C_{zz} \end{pmatrix}$$

$H_1^\perp \bar{H}_1^\perp$ (points to C_{xx})
 $H_1^\triangleleft \bar{G}_1^\perp$ (points to C_{xz})
 $G_1^\perp \bar{H}_1^\triangleleft$ (points to C_{zx})
 $G_1^\perp \bar{G}_1^\perp$ (points to C_{zz})

3-qubit entanglement in Bethe-Heitler

Cao, Guo, YH, Schoenleber, 2608.18030

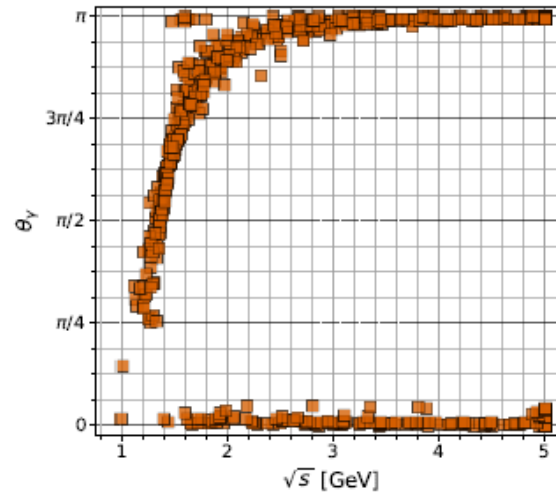
Nuisance in DVCS turned into a factory of **genuine tripartite entanglement**



'Borromean ring'

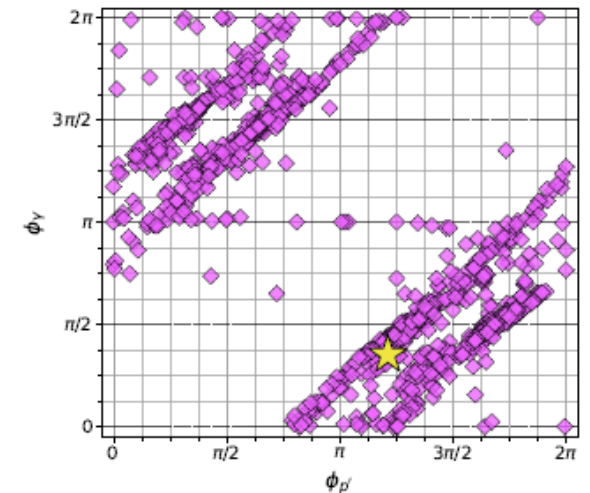
The GHZ state

$$\frac{|+++ \rangle + |-- - \rangle}{\sqrt{2}}$$



The W state

$$\frac{|+-- \rangle + |-+- \rangle + |--+ \rangle}{\sqrt{3}}$$



EIC will produce GHZ and W-states by the thousands!

Conclusions

- EIC opens the era of precision QCD study of nucleon and nuclear structures in the next >30 years
- Significant challenges ahead for both theorists, including lattice QCD, and experimentalist
- Interdisciplinary connections: BSM, QIS, low energy hadron/nuclear,...
- Many more talks during the meeting!