# Spin physics at EIC

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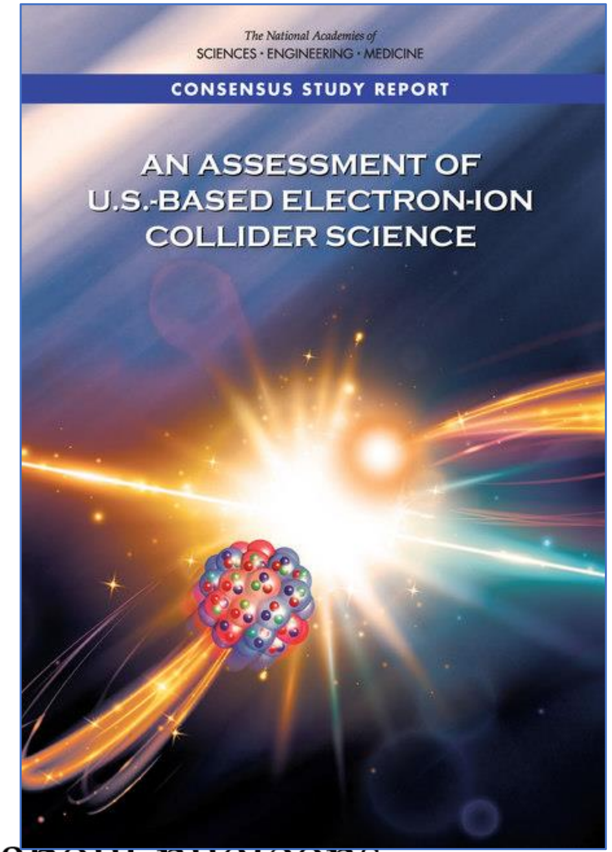
BNL/RIKEN BNL

CFNS workshop: EIC theory in the next decade, MIT, Sept. 20-22, 2022

# Outline

NAS report (2018)

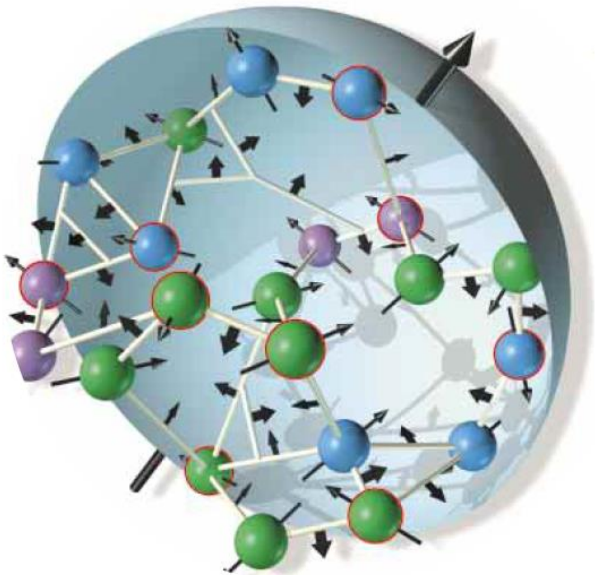



- Longitudinal spin
- Proton spin from GPDs
- Transverse single spin asymmetry

**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?

# The proton spin problem



The proton has spin ½.

The proton is not an elementary particle.

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

Jaffe-Manohar sum rule

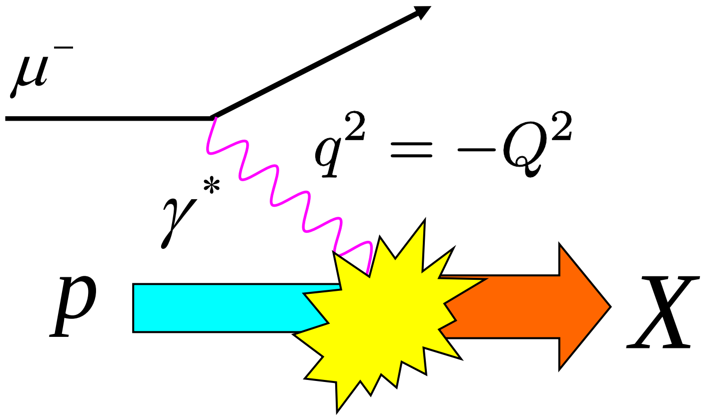
$$= \frac{1}{2}\Delta\Sigma + L^q_{kin} + J_g$$

Ji sum rule

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

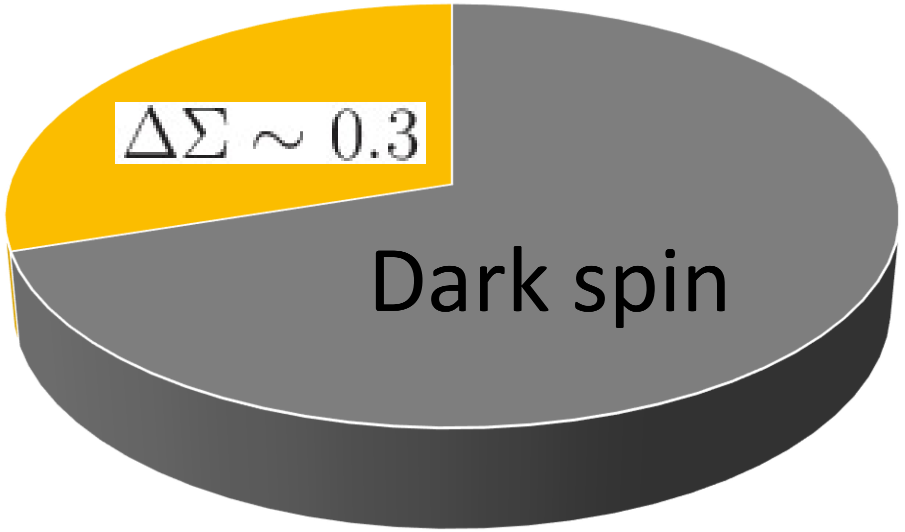
# $\Delta\Sigma$ from polarized DIS

Longitudinal double spin asymmetry in polarized DIS




$$A_{LL} = \frac{\mu^\uparrow p^\downarrow - \mu^\uparrow p^\uparrow}{\mu^\uparrow p^\uparrow + \mu^\uparrow p^\downarrow} \sim \left(1 + \frac{\sigma_L}{\sigma_T}\right) \frac{2x g_1}{F_2}$$

$$\int_0^1 dx g_1(x) = \frac{1}{9}\underline{(\Delta u + \Delta d + \Delta s)} + \frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s) + \mathcal{O}(\alpha_s)$$



# Helicity pQCD precision frontier

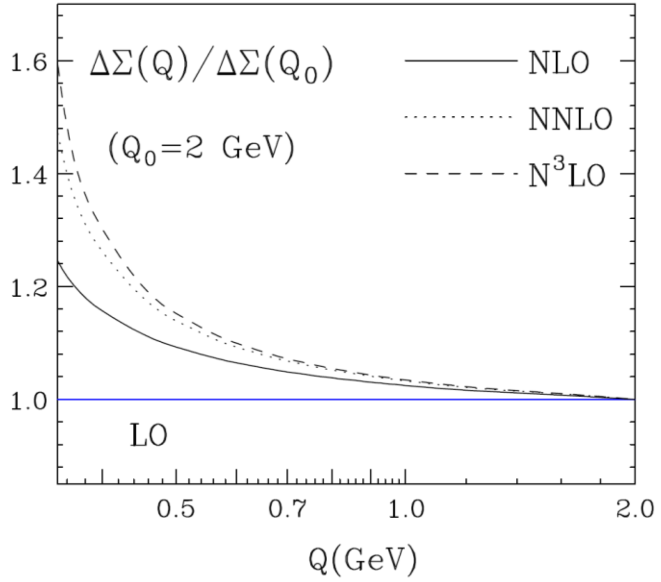
→ talk by Vogelsang

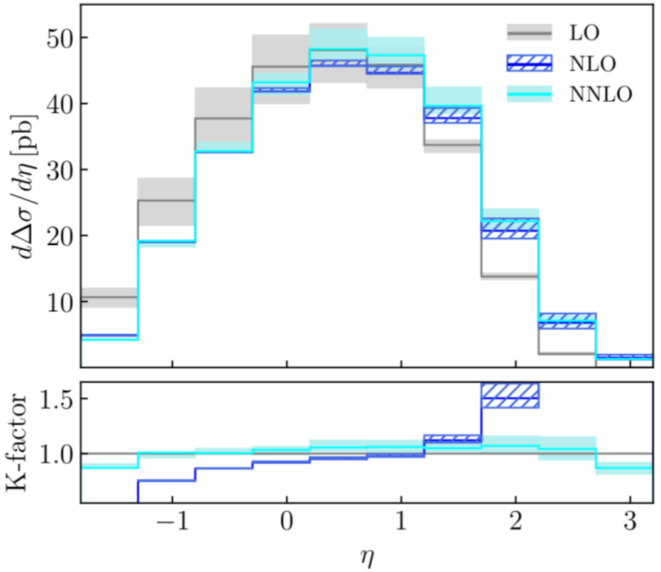
4-loop evolution of $\Delta\Sigma$
De Florian, Vogelsang (2019)

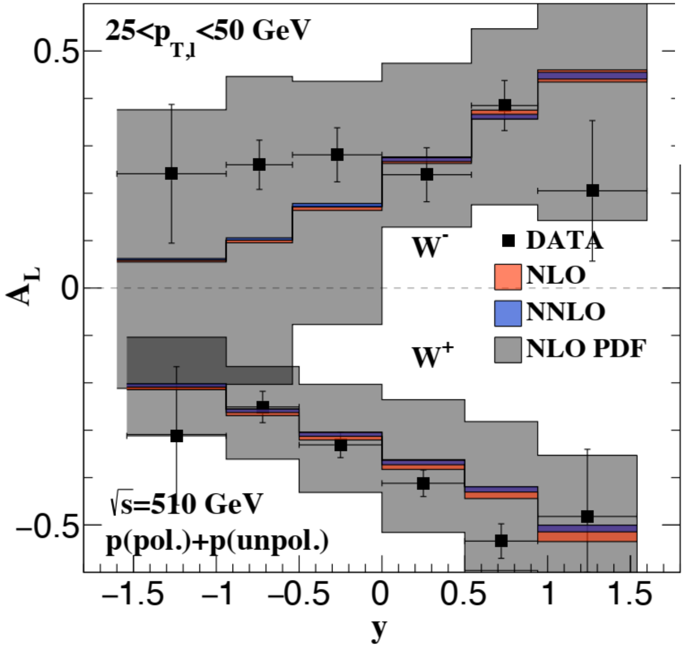
NNLO jet production in polarized DIS
Borsa, de Florian, Pedron (2020)

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)



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

→ talk by Sato

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++

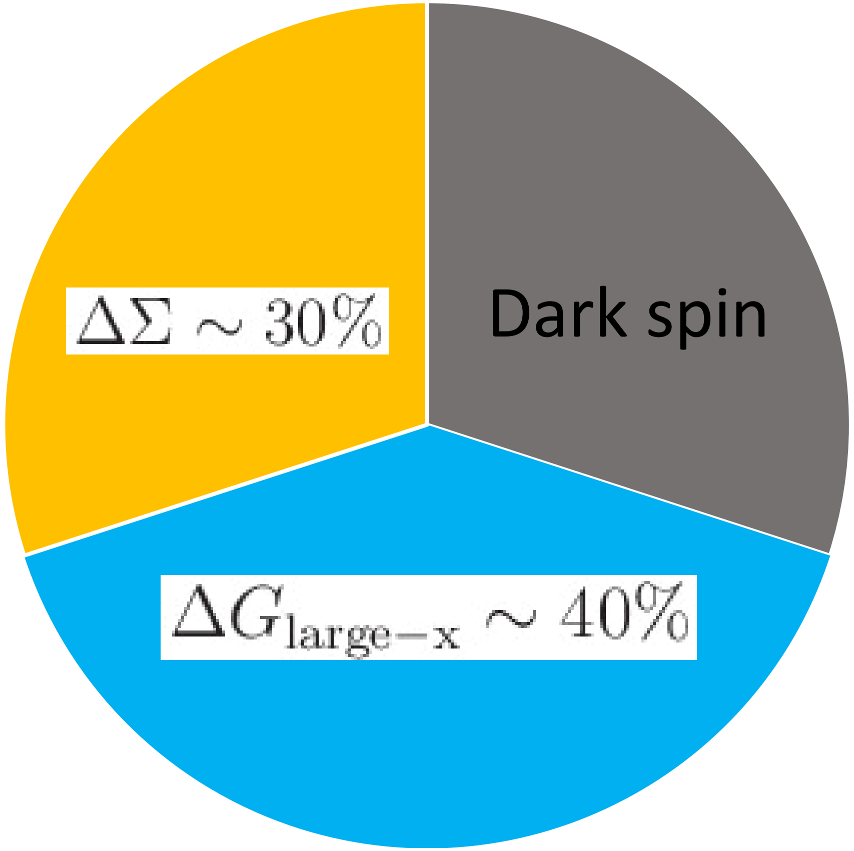
$\int_{0.05}^{0.2} dx\Delta g(x,Q^2=10\text{GeV}^2) = 0.17 +- 0.06$ NNPDFpol1.1

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

Huge uncertainty from the small-x region → EIC

Renewed interest in helicity-dependent small-x resummation
Kovchegov, Pitonyak, Sievert (2016~)

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 $\Delta G$ 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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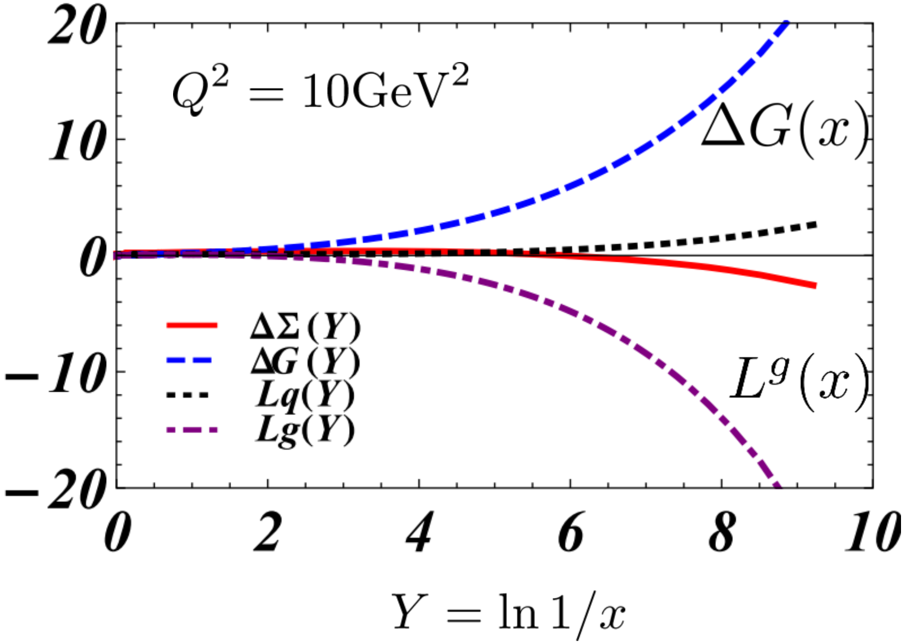



If $\Delta G(x) \sim \frac{1}{x^\alpha}$, then $L_g(x) \approx -\frac{2}{1+\alpha}\Delta G(x)$ Boussarie, YH, Yuan (2019)

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

# OAM and the Wigner distribution

Wigner/GTMD distribution
Phase space distribution of partons in QCD

Belitsky, Ji, Yuan (2004);
Meissner, Metz, Schlegel (2009)

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

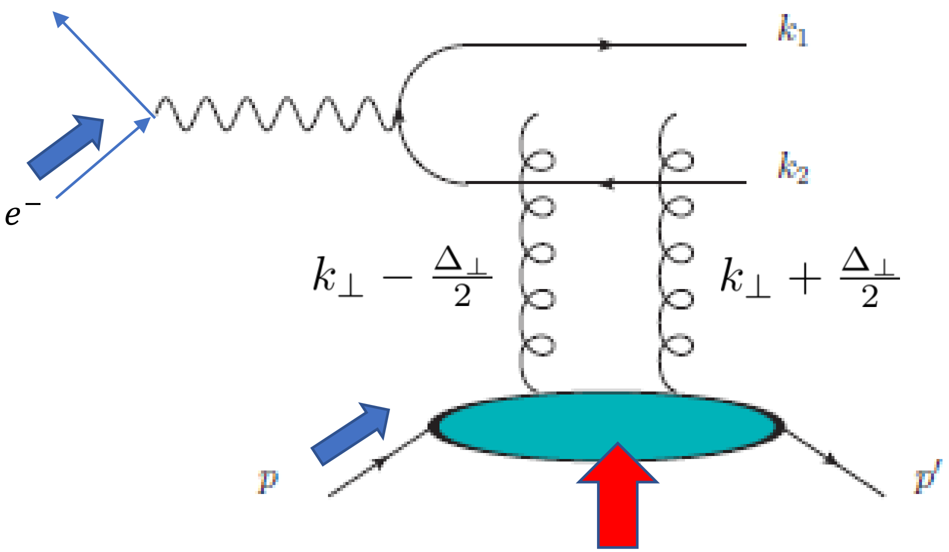
Define

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

Lorce, Pasquini (2011);
YH (2011);
Lorce, Pasquini, Xiong, Yuan (2011)
Ji, Xiong, Yuan (2012)
Engelhardt (2017) (lattice simulation)

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

# Longitudinal single/double spin asymmetries in dijet production




Wigner distribution

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

Expand the amplitude to linear order in $k_\perp$ (twist-3 effect)

$$\int d^2k_\perp k_\perp^i W_g(k_\perp, \Delta_\perp) \sim \epsilon^{ij}\Delta_\perp^j L_g$$

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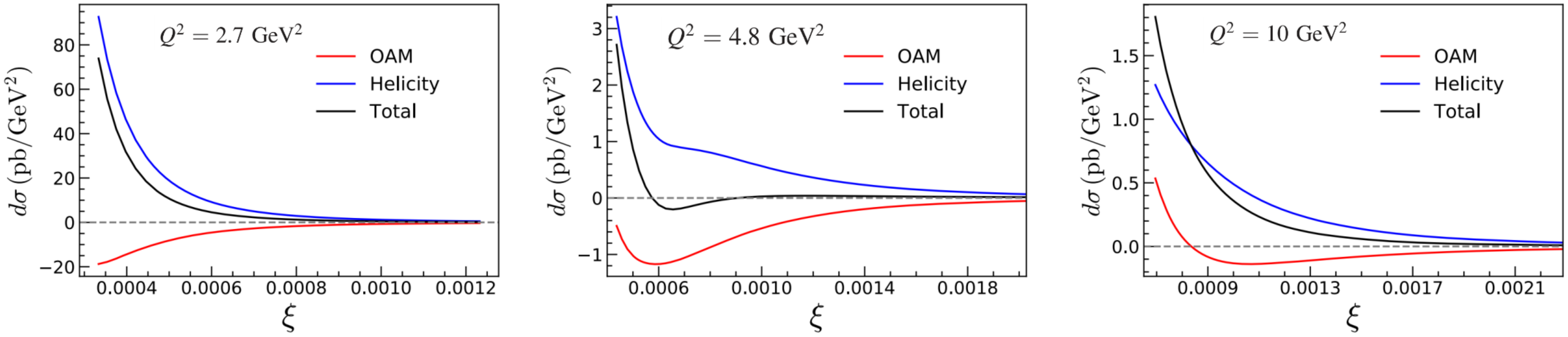
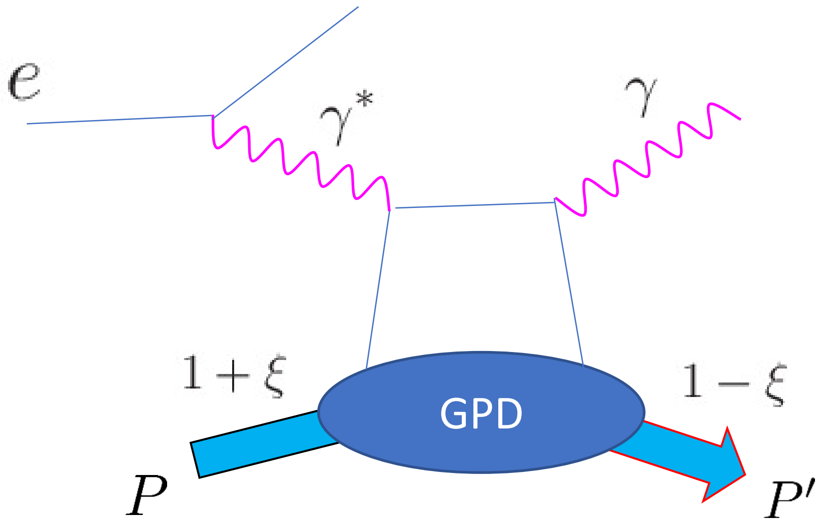


# Proton spin from GPDs



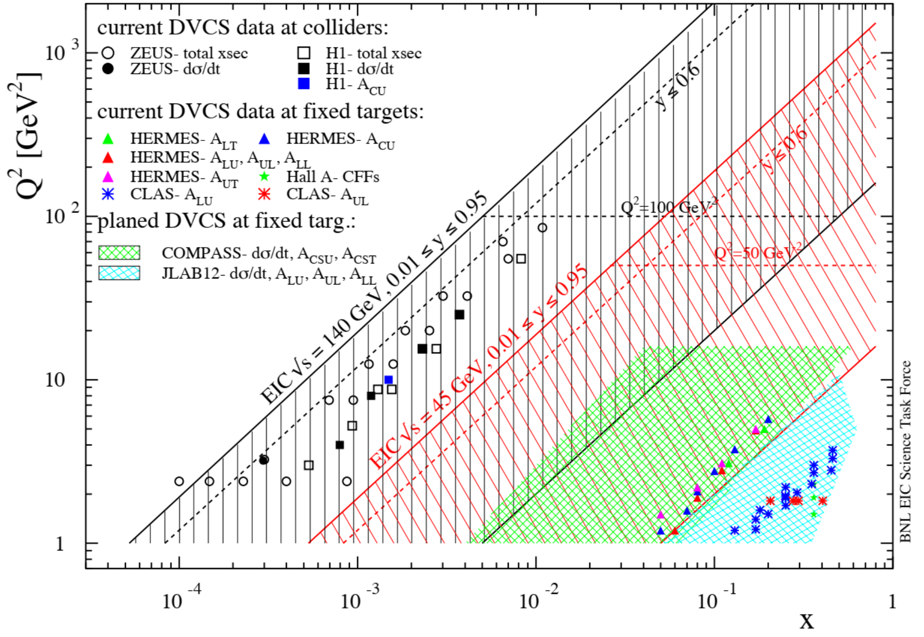

Ji sum rule

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

Extract the generalized parton distributions (GPDs) from
Deeply Virtual Compton Scattering (DVCS) and other exclusive processes

$$i\int d^4y e^{iqy}\langle P'|T\{J^\mu(y)J^\nu(0)\}|P\rangle$$

$$= g_\perp^{\mu\nu}\int\frac{dx}{2}\left(\frac{1}{x+\xi-i\epsilon}+\frac{1}{x-\xi+i\epsilon}\right)H_q(x,\xi,\Delta)\bar{u}(P')\gamma^+u(P)+\cdots$$




EIC offers an unprecedented kinematical coverage of DVCS and other exclusive processes. New era of GPD studies.

# GPD theory challenges for EIC

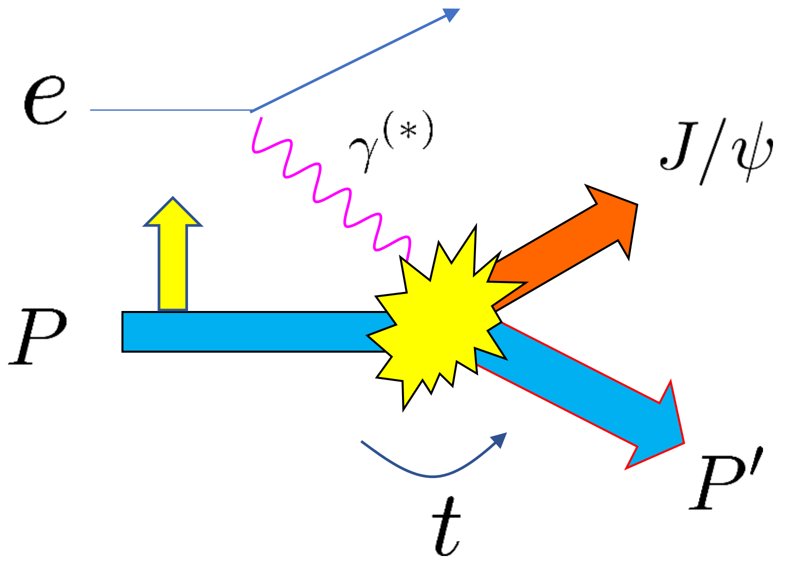
- Higher order pQCD calculations

  3-loop nonsinglet evolution kernel  Braun, Manashov, Moch, Strohmaier (2017)
  2-loop singlet coefficient function  Braun, Ji, Schoenleber (2022)

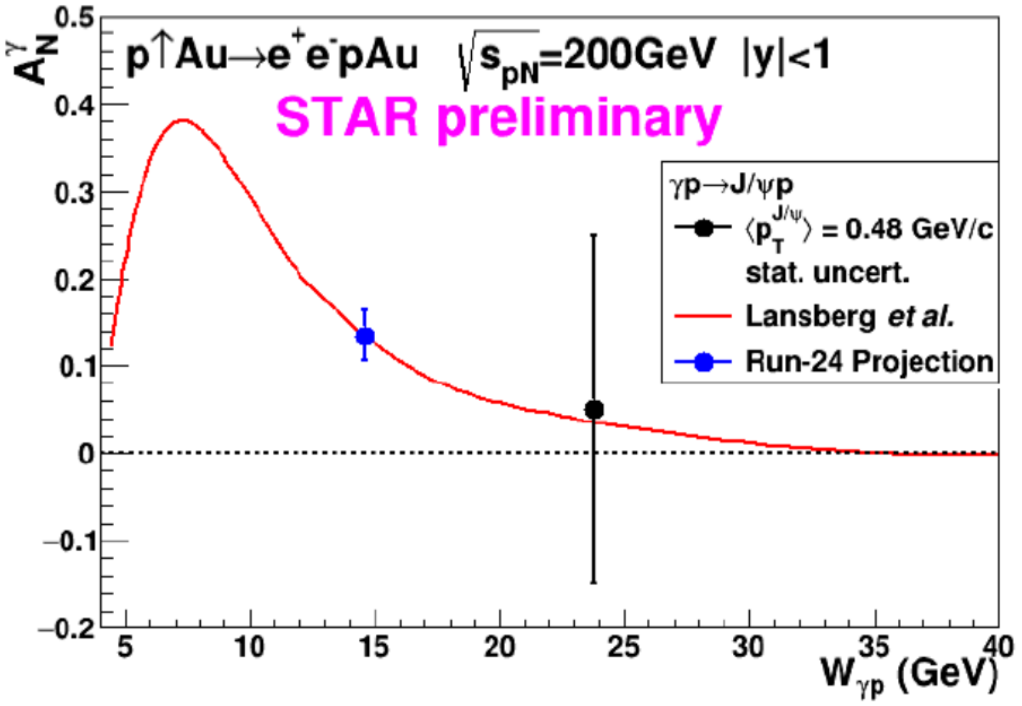
- NLO global analysis  Kumericki, et al.
- Extraction of x-dependence → talk by Qiu
- GPD from lattice QCD → talk by Constantinou
- Extraction of the `D-term'
- Extraction of GPD E's, especially gluon GPD $E_g(x)$

# GPD $E_g$ from $J/\psi$ single spin asymmetry

Koempel, Kroll, Metz, Zhou (2012)
Lansberg, Massacrier, Szymanowski, Wagner (2018)




$$A_N \sim \frac{Im(\mathcal{H}_g^* \mathcal{E}_g)}{|\mathcal{H}_g|^2}$$




Will be measured by the STAR collaboration in UPC
Can be continued at the EIC

Large- $W_{\gamma p}$ tail → Constrain the small-x behavior

$$xE_g(x) \sim \left(\frac{1}{x}\right)^{4\ln 2\bar{\alpha}_s}$$

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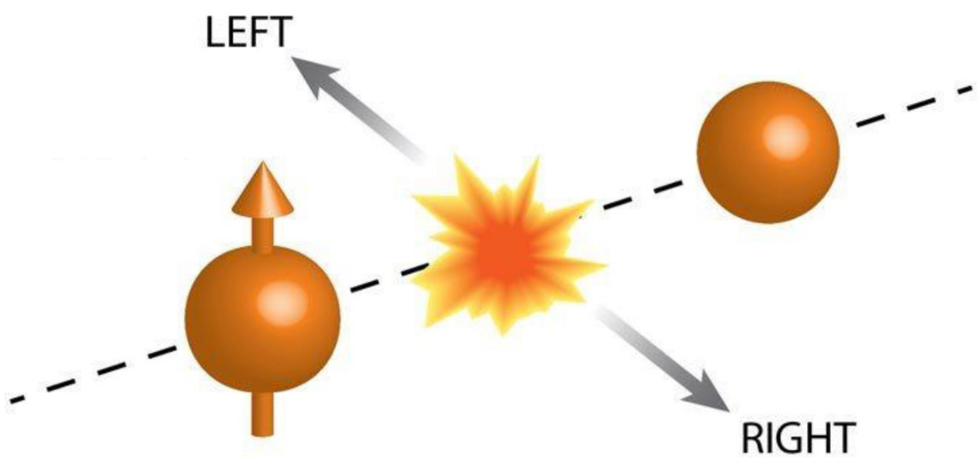
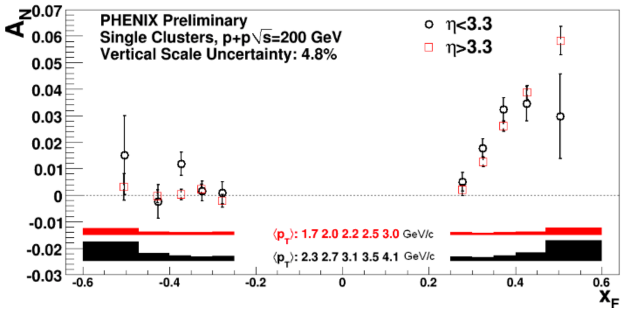
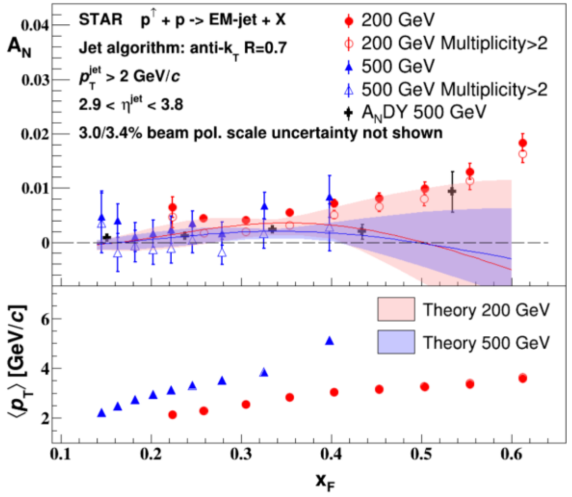
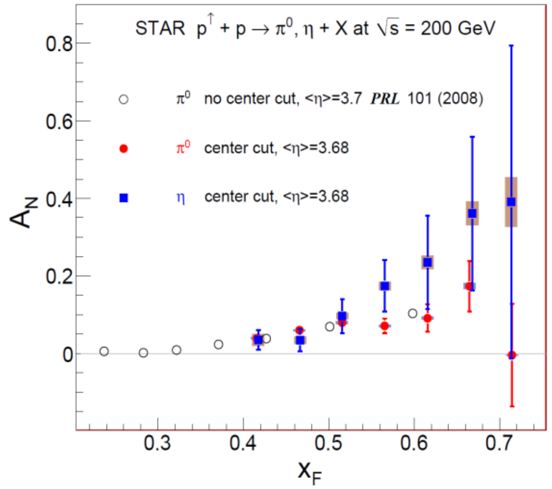
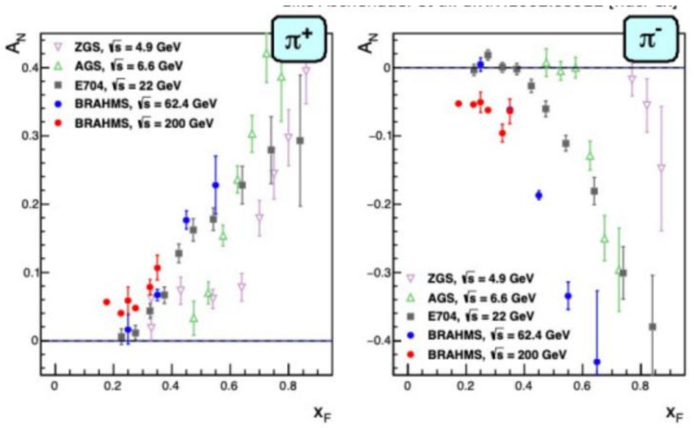
# Transverse Single Spin Asymmetry (SSA)




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

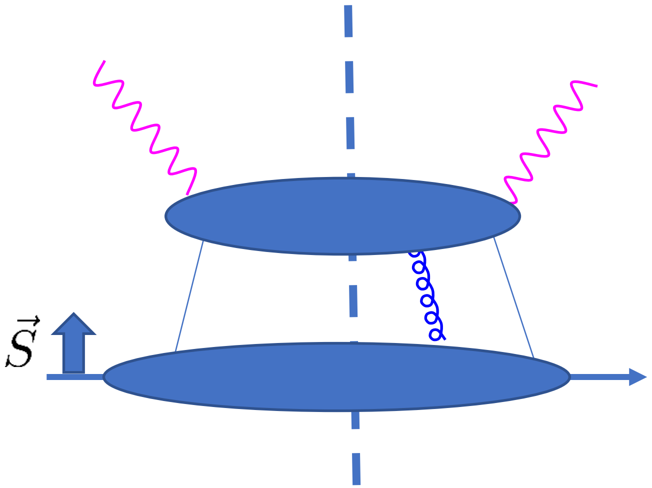
Asymmetry can be as large as 20-30% in hadron collisions.

Already 40 years of history. What’s big at EIC?

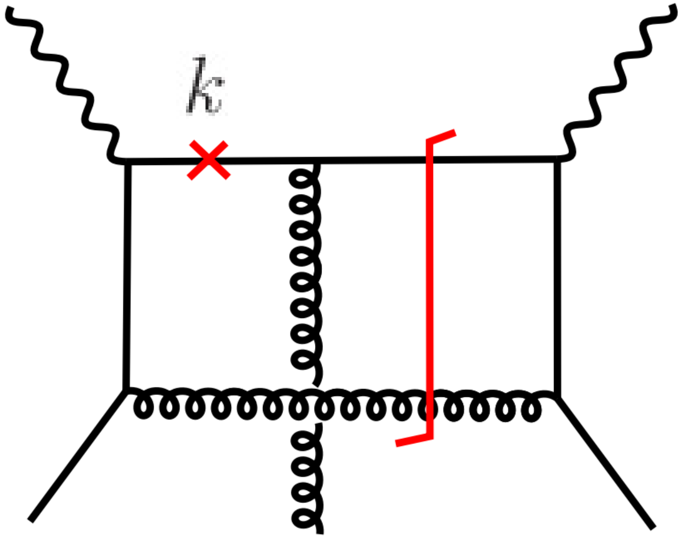
# Quest for a phase

Find part of the cross section linear in spin $\vec{S}$ → interference terms

$d\sigma \sim$




$+\ c.c.$




Naively purely imaginary, vanish after adding the c.c. part

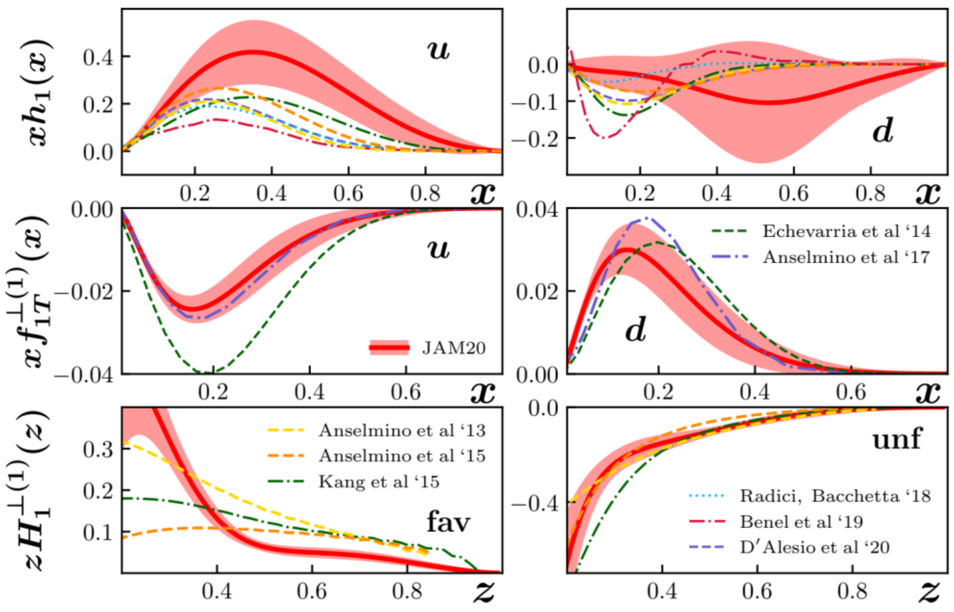
An extra factor of $i$ is needed to make the asymmetry nonzero.

$$\frac{1}{k^2+i\epsilon} = \frac{\mathrm{P}}{k^2} - i\pi\delta(k^2)$$

The problem is, there are many sources of $i$ . Typically requires twist-3 PDFs and FFs $\langle \bar{q}Fq\rangle, \langle FFF\rangle$

# Global analysis of SSA

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

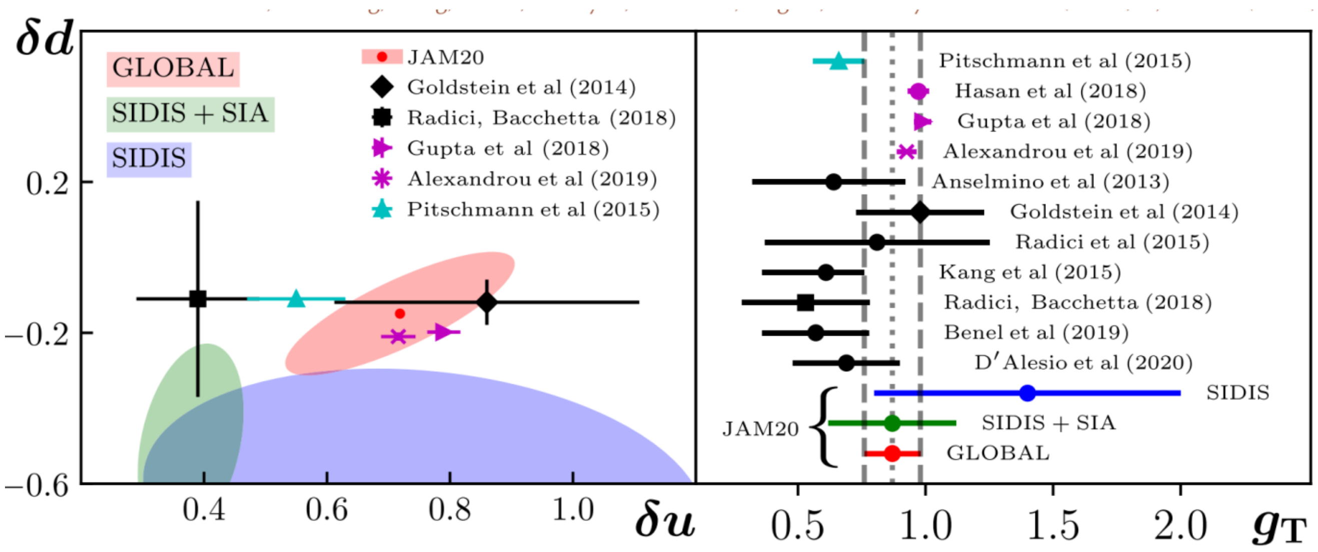



Simultaneous fit of

- 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.

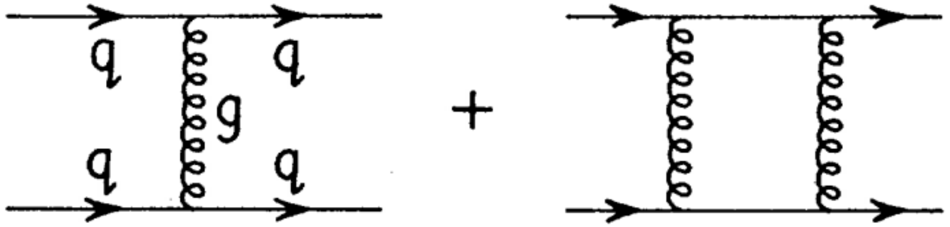
→ Constraints on the nucleon tensor charge.



# Folklore

"Perturbative QCD contribution to SSA is negligible
because it's proportional to the quark mass"

$$A_N \sim \alpha_s \frac{m_q}{p_T \text{ or } \sqrt{s}}$$




Kane, Pumplin, Repko (1978)

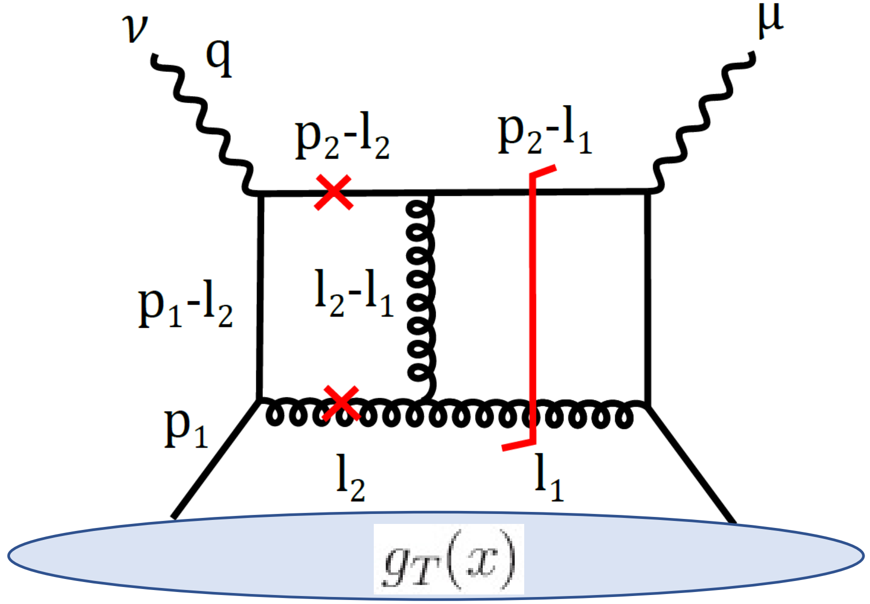
No real pQCD calculation beyond this parametric estimate for 40 years.

What is the coefficient?
More seriously, is this formula valid in the first place?

# pQCD contribution to SSA

Benic, YH, Li, Yang (2019)

Convolute 2-loop diagrams with the $g_T(x)$ distribution




Wandzura-Wilczek approximation

$$g_T(x) = \int_x^1 \frac{dx'}{x'} \Delta q(x') + \cdots$$

quark helicity PDF

SSA solely from collinear twist-two PDFs and twist-two FFs!

$$A_N \sim \alpha_s \frac{M_N}{p_T} \frac{x\Delta q(x)}{q(x)} \quad \text{SIDIS}$$

$$\sim \alpha_s \frac{M_N p_T}{s} \frac{x\Delta q(x)}{q(x)} \quad \text{pp}$$

$$A_N \sim \alpha_s \frac{m_q}{p_T \text{ or } \sqrt{s}}$$

# Breaking the myth of `tiny pQCD contribution'

Benic, YH, Kaushik, Li (2021)

At the EIC, up to 2% asymmetry for

$\sin(\phi_h - \phi_S)$ (Sivers)

$\sin(\phi_S)$

$\sin(2\phi_h - \phi_S)$

No free parameter

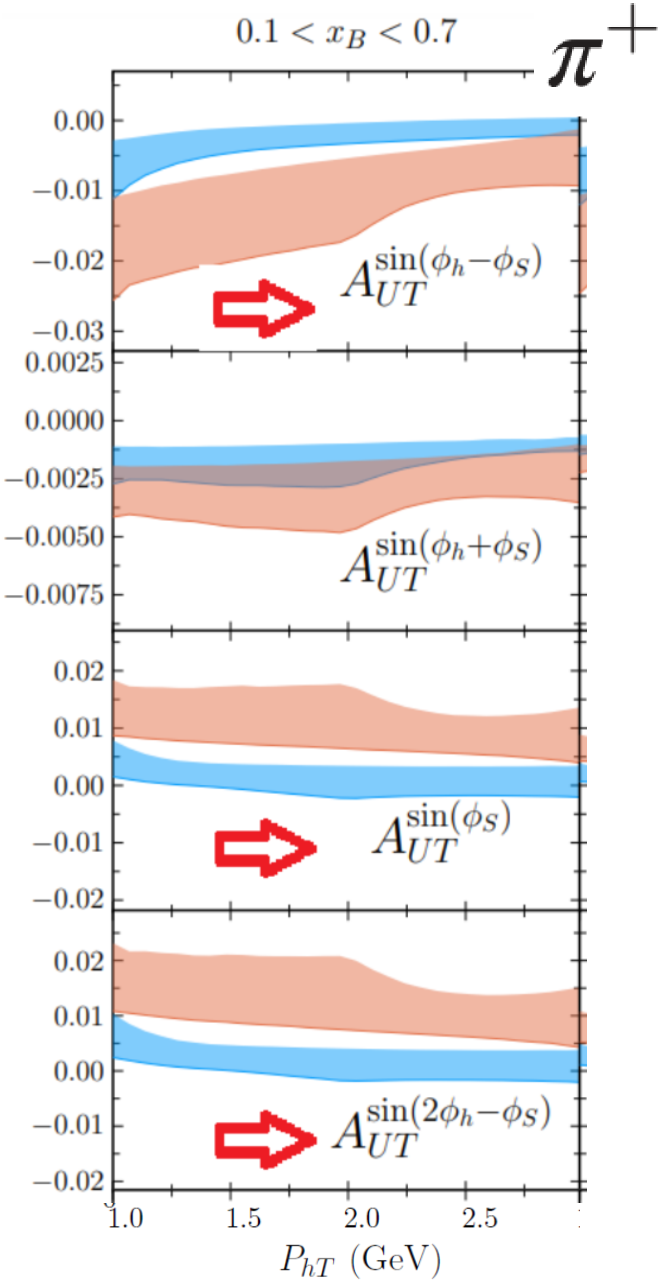
Comparable to predictions from other mechanisms.

e.g., Echevarria, Kang, Terry (2020)

Collins asymmetry sub-percent → twist-3 FFs

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

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

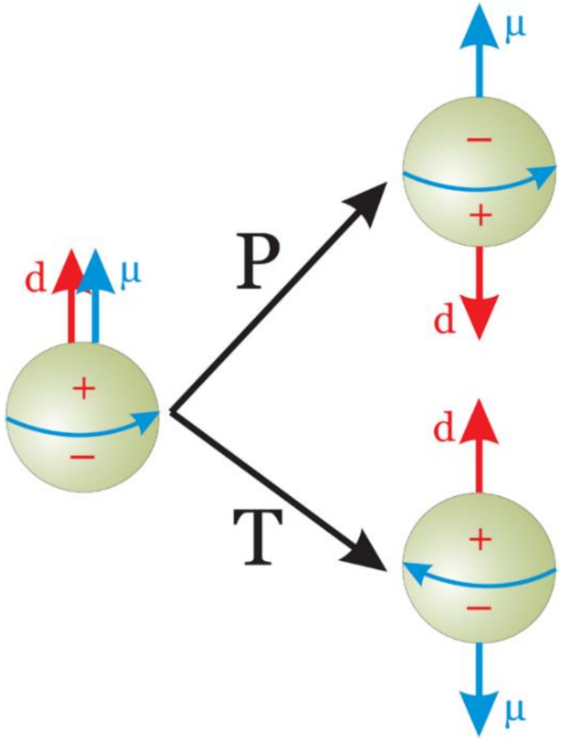


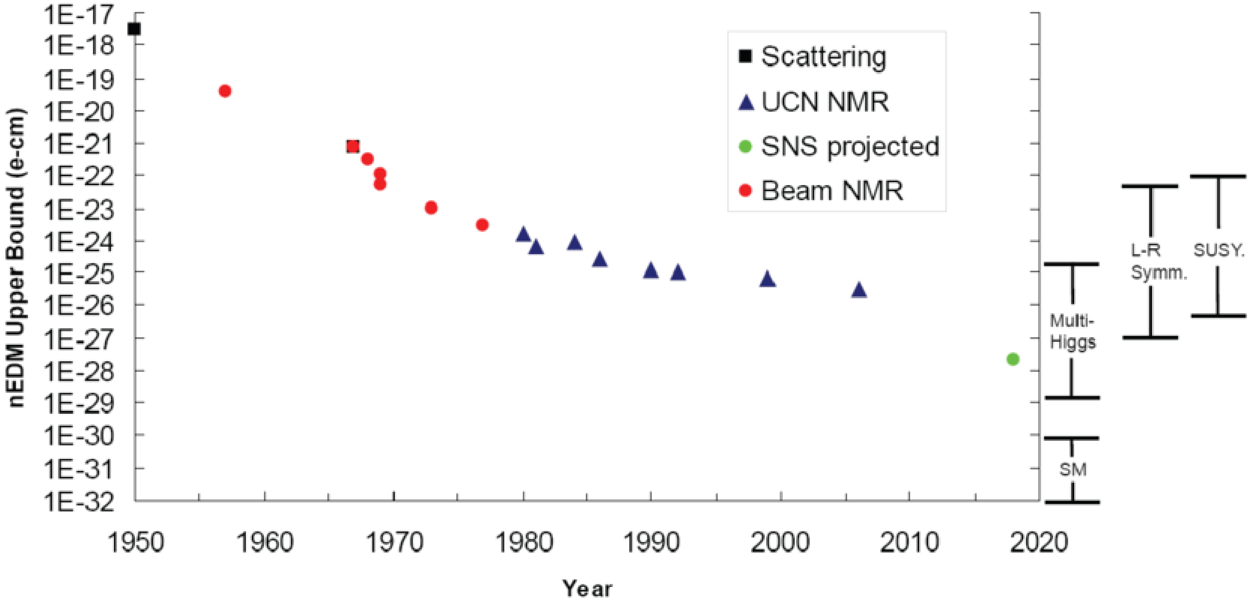
# Nucleon electric dipole moment (EDM)

If nonvanishing, both P and CP are violated.

CKM mechanism gives a too small value of nucleon EDM,

CP violation from BSM physics? Required to explain the baryon number asymmetry in the universe




EDM is a vector, must be proportional to nucleon spin

Is there anything EIC can help?

# Nucleon EDM from polarized DIS

YH (2020)
See, also, Weiss (2021)

Weinberg operator

$$\mathcal{O}_W = g f_{abc} \tilde{F}^a_{\mu\nu} F_b^{\mu\alpha} F^{\nu}_{c\alpha}.$$

Can be induced in QCD via some BSM physics, possible source of CP violation

$$d^{EDM} \sim \mu \frac{\langle p'|w\mathcal{O}_W|p\rangle}{m_N \bar{u}(p') i\gamma_5 u(p)}$$

Bigi, Uraltsev (1990)

magnetic moment

Matrix element related to part of the twist-4 corrections in polarized DIS

$$\int_0^1 g_1^{p,n}(x,Q^2)dx = (\pm\frac{1}{12}g_A + \frac{1}{36}a_8)(1-\frac{\alpha_s}{\pi}+\mathcal{O}(\alpha_s^2)) + \frac{1}{9}\Delta\Sigma(1-\frac{33-8N_f}{33-2N_f}\frac{\alpha_s}{\pi}+\mathcal{O}(\alpha_s^2))$$
$$-\frac{8}{9Q^2}\Big[\{\pm\frac{1}{12}f_3+\frac{1}{36}f_8\}\left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\right)^{-\frac{\gamma^0_{NS}}{2\beta_0}} + \frac{1}{9}f_0\left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\right)^{-\frac{1}{2\beta_0}(\gamma^0_{NS}+\frac{4}{3}N_f)}\Big],$$

New connection between EIC and BSM physics

# Conclusions

- Spin is one of the core sciences of EIC
- Helicity getting more and more precise
- OAM is the key to fulfill the spin sum rule. Lagging far behind in both theory and experiment, but a glimmer of hope.
- Rapid progress in GPD. Extraction of GPD E is a major challenge.
- SSA@EIC: Global analysis & revival of pQCD contributions?
- Many more interesting topics

Spin effects in jets → talk by Kang
TMDs → talk by Stewart, Zhao
Light nuclei → talk by Cosyn
Interplay between small-x and spin physics → talk by Venugopalan, Kovchegov
More connections to BSM physics → talk by Mereghetti
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