Theory Opportunities at the EIC

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EIC Science: from quark/gluon to cosmo

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are partons inside the nucleon distributed in both momentum and position space?
- What happens to the gluon density in nucleons and nuclei at small *x*? Does it saturate at high energy, giving rise to gluonic matter with universal properties in all nuclei (and perhaps even in nucleons)?
- How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions generate nuclear binding?
- Do signals from beyond-the-standard-model physics manifest in electron-proton/ion collisions? If so, what can we learn about the nature of these new particles and forces?

EIC Whitepaper for LRP
QCD Whitepaper, 2303.02579

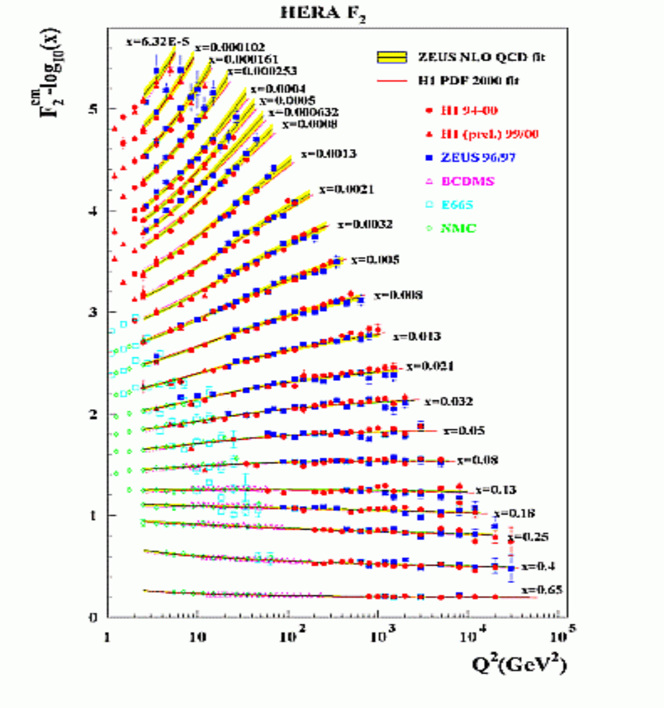
Theory opportunities

- Precision computations and phenomenology developments toward a global analysis to extract nucleon/nucleus structure from various observables
- New observables, new structure, new dynamics

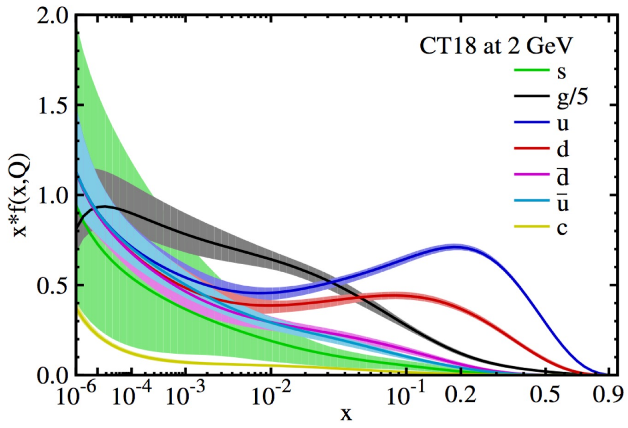
QGT Collaboration

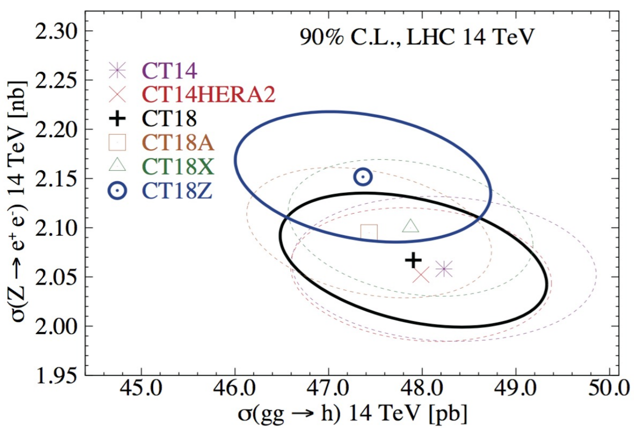
Talks this afternoon

A center piece of EIC science: parton physics



+LHC Data…

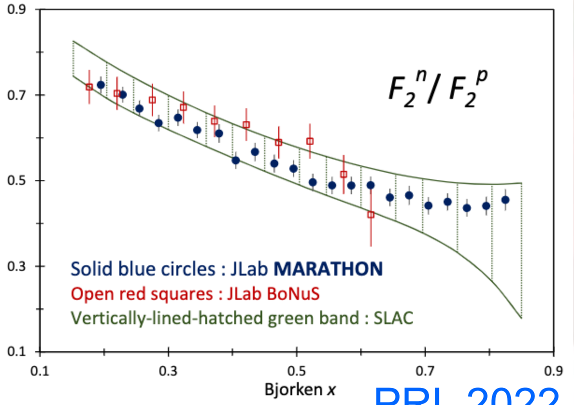




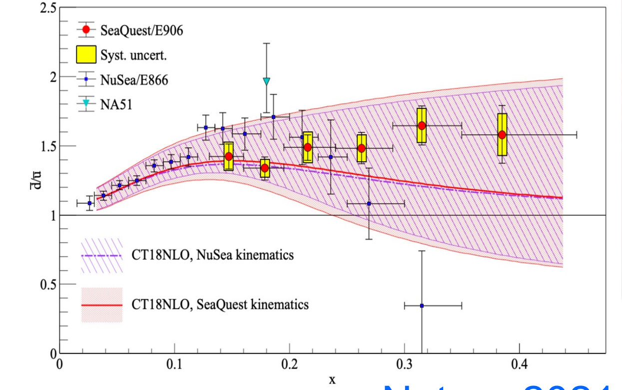
1912.10053

Small and large x

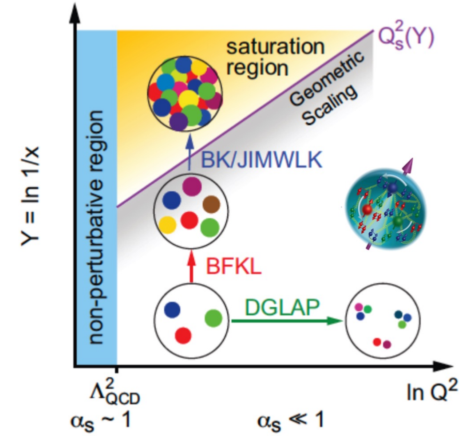
- Flavor structure of quark distributions at large-x is one of remaining puzzles
  - Plays an important role to understand nuclear physics as well, such as nucleon-nucleon short range correlation, …
- How (polarized) gluon/quark distributions behavior at smaller and smaller x (in proton and big nuclei)? A fundamental question



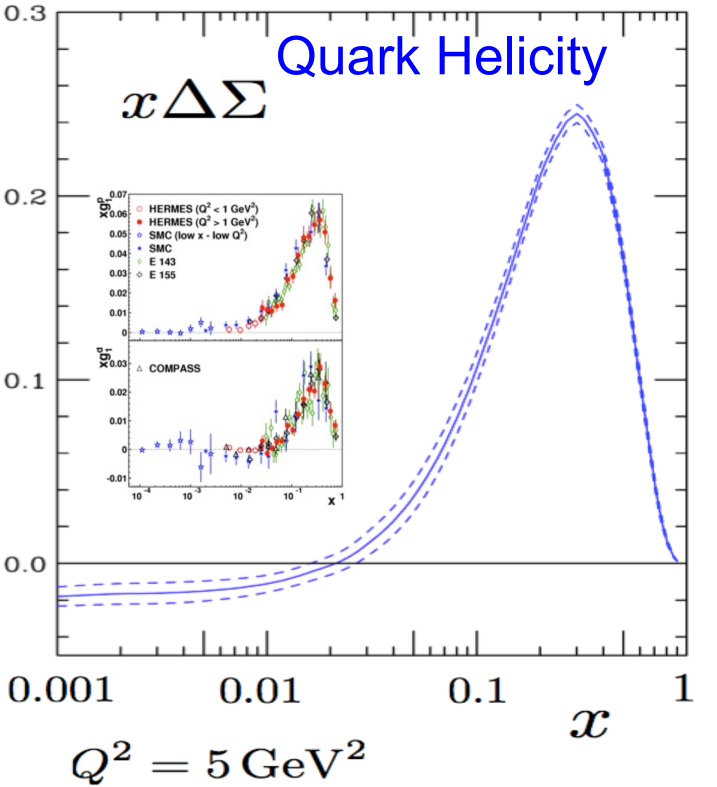
PRL 2022

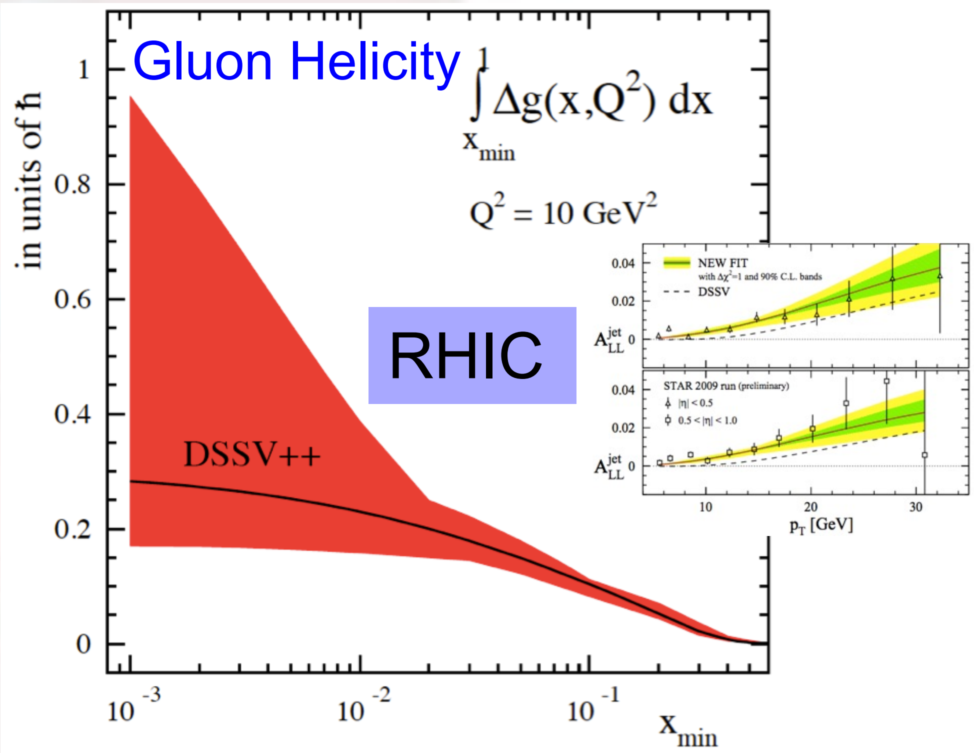


Nature 2021



Parton distributions in a polarized nucleon

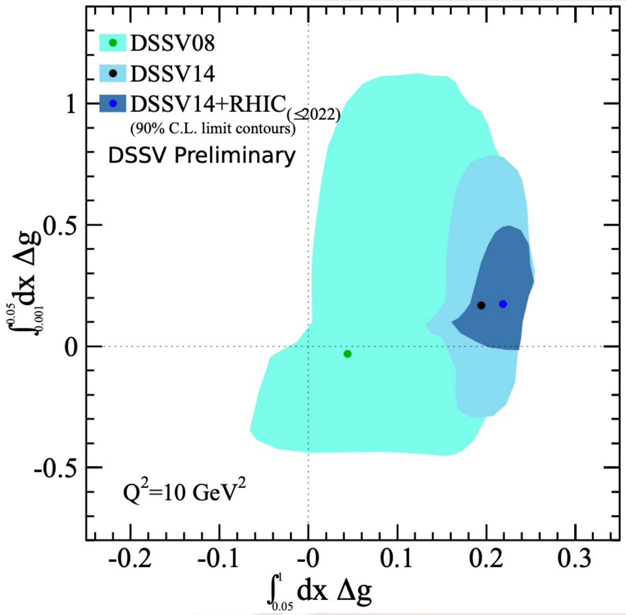


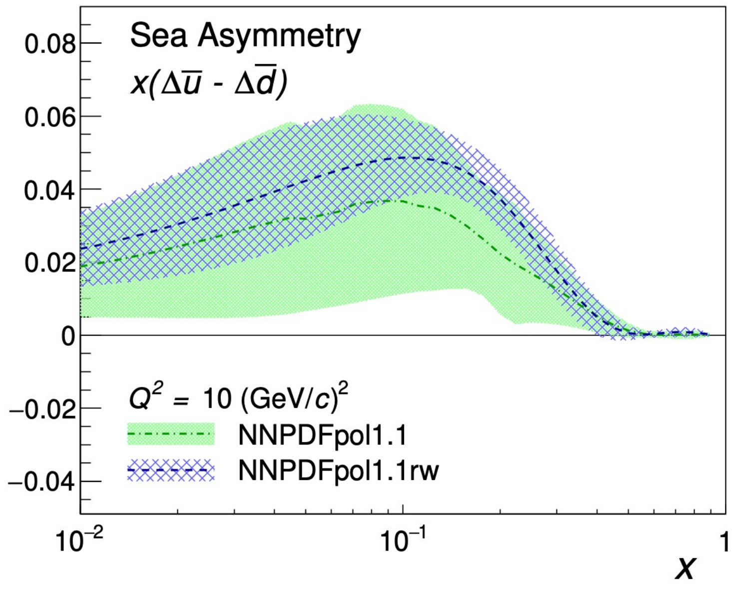


de Florian-Sassot-Stratmann-Vogelsang, 2014

See also, NNPDF, NPB887, 276 (2014)

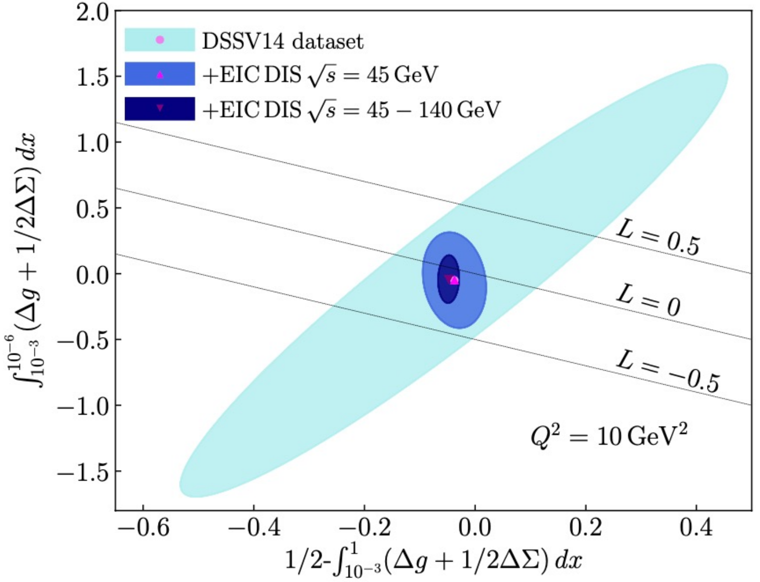
Updates from RHIC spin experiments

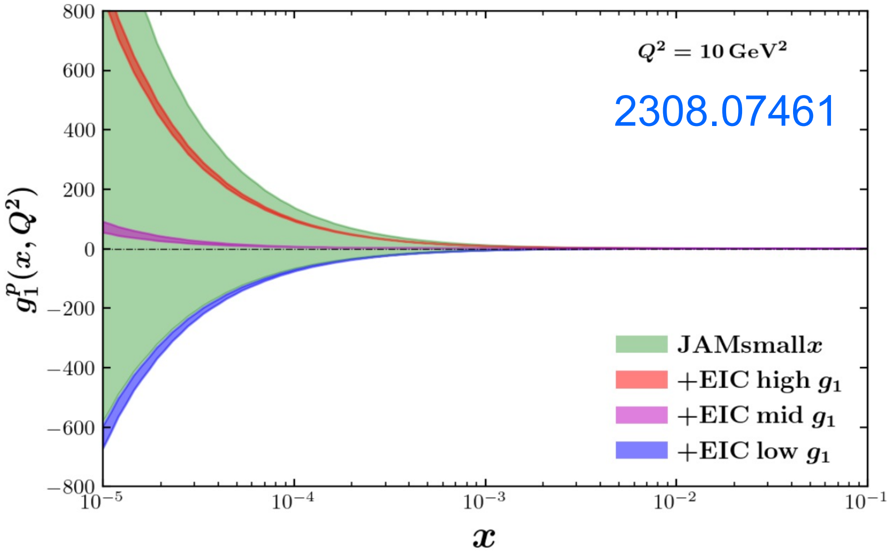




RHIC spin coll., 2302.00605

EIC Science: Proton spin



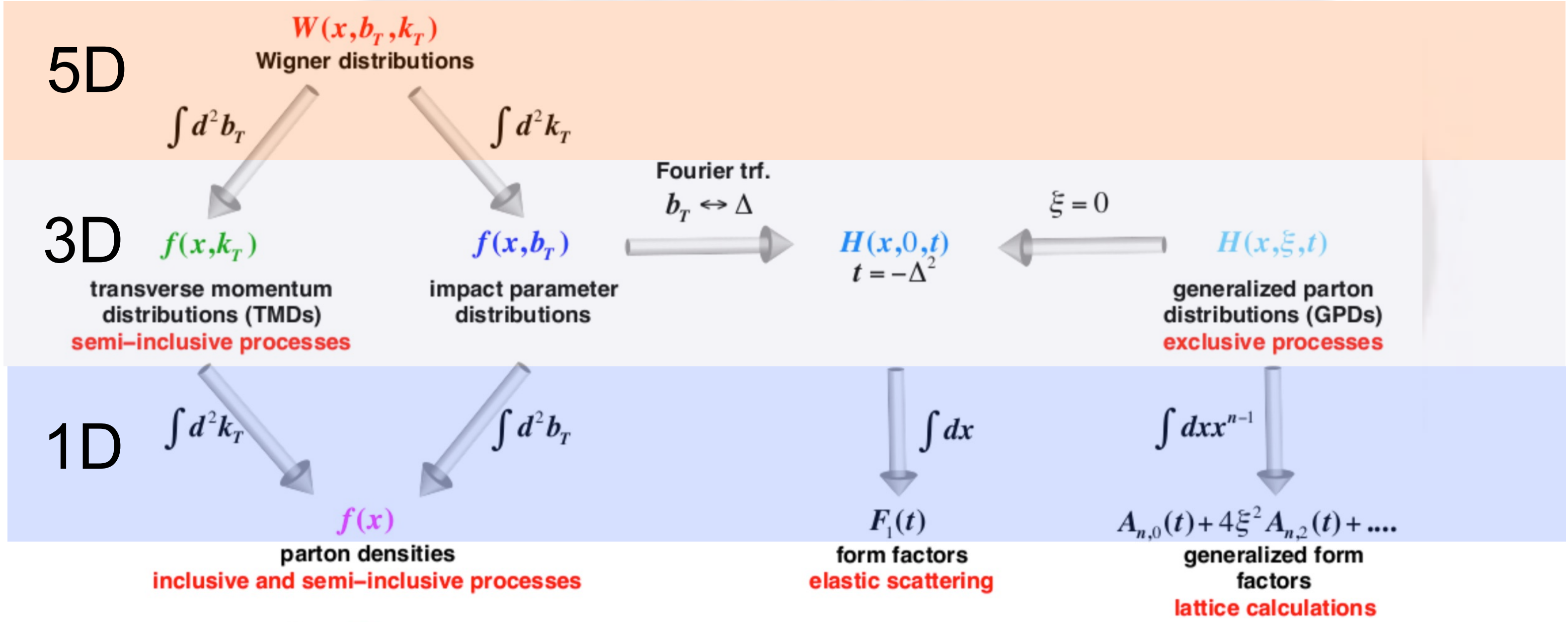


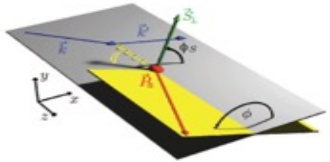
More analyses and comparison between the collinear DGLAP and small-x extrapolation are needed

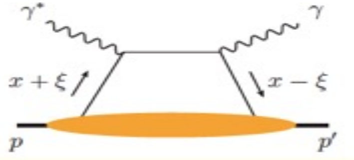
Looking for parton orbital angular

3D Imaging of the Nucleon

❑ Wigner distributions (Belitsky, Ji, Yuan)



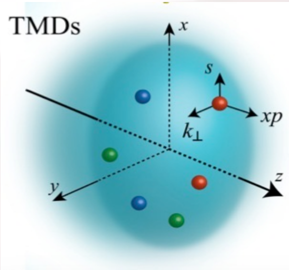


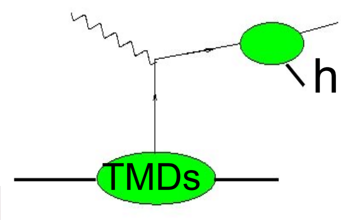


BERKELEY LAB

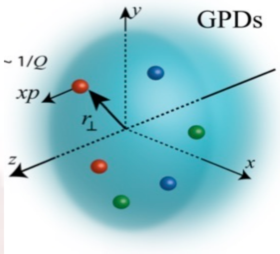
Zoo of TMDs & GPDs

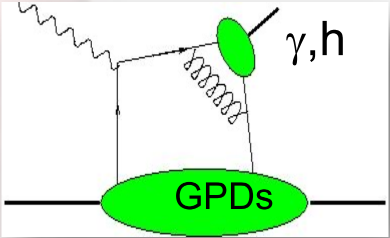
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$





	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



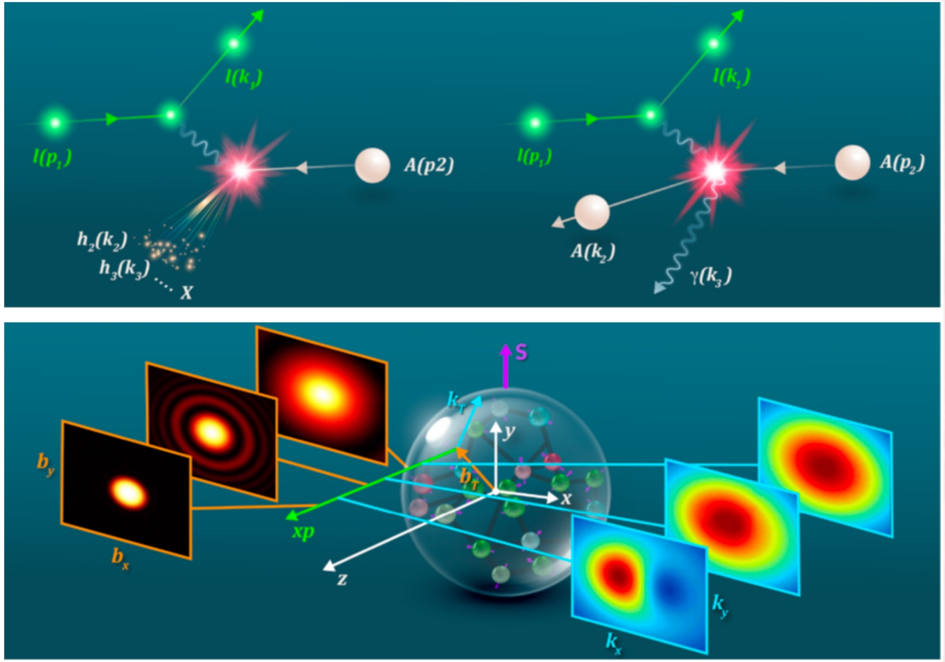


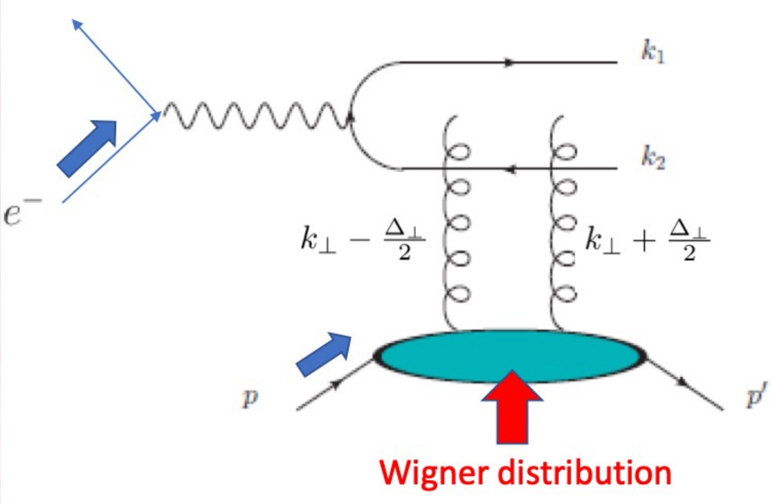
- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of x_B, t, Q^2** (GPD) and **x_B, P_T, Q^2 , z** (TMD)

What can we learn

- 3D Imaging of partons inside the nucleon (non-trivial correlations)
  - Try to answer more detailed questions as Rutherford was doing 100 years ago
- QCD dynamics involved in these processes
  - Transverse momentum distributions: universality, factorization, evolutions,…
  - Small-x: BFKL vs Sudakov?

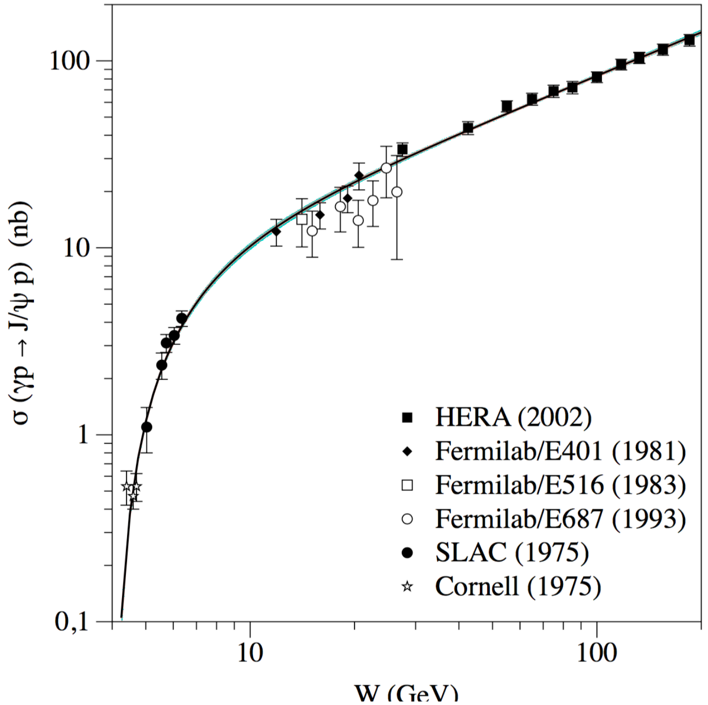
Nucleon tomography and parton OAM

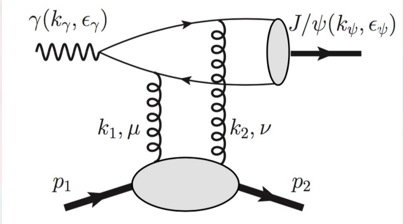


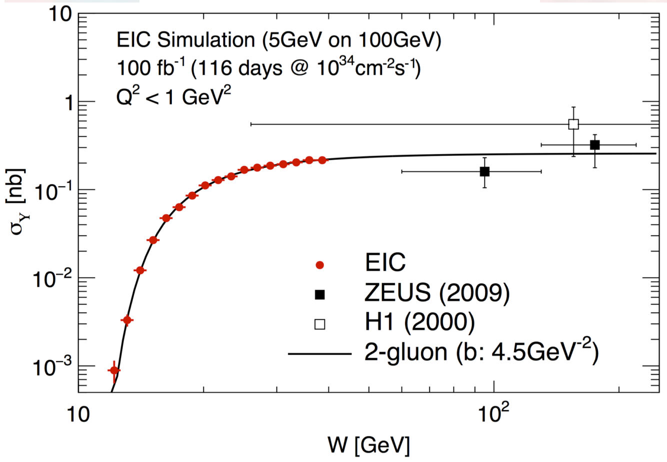


Probe the gluon OAM through spin asymmetries in exclusive dijet process:
Ji,Yuan,Zhao (2016)
Bhattacharya, Boussarie, Hatta (2022)

Gluon landscape from future EIC, e.g., through diffractive quarkonium production







- Cover energy range from threshold to high energy
- Potential to have detailed study of gluon GPDs

Gryniuk, Vanderhaeghen 1806.08205 Joosten, Meziani, 1802.02616

TMDs at small-x

- Consistency between the collinear TMD definitions and the small-x dipole calculations have been established
  - Dominguez-Marquet-Xiao-Yuan 2011
- They are the most studied subjects in small-x phenomenology: inclusive, semi-inclusive processes
- Unique predictions of the TMDs from small-x formalism
  - Significant linear polarization for the gluon (Metz-Zhou 2011)
  - Spin (of hadron) dependence offers nontrivial QCD dynamics (Zhou et al, 2015; Kovchegov et al, 2016-2021)

Small-x gluon distribution with TMD resummation

Mueller-Xiao-Yuan, 2012;Xiao-Yuan-Zhou 2016
Caucal-Salazar-Schenke-Venugopalan 2022-23
Paels-Altinoluk-Beuf-Marquet 2022

$$xG^{(1)}(x,k_\perp,\zeta_c=\mu_F=Q)$$

→ Hard scale entering TMD Factorization, e.g., Higgs

$$-\frac{2}{\alpha_S}\int\frac{d^2x_\perp d^2y_\perp}{(2\pi)^4}e^{ik_\perp\cdot r_\perp}\mathcal{H}^{WW}(\alpha_s(Q))e^{-S_{sud}(Q^2,r_\perp^2)}$$
$$\times\mathcal{F}^{WW}_{Y=\ln 1/x}(x_\perp,y_\perp)\ ,$$

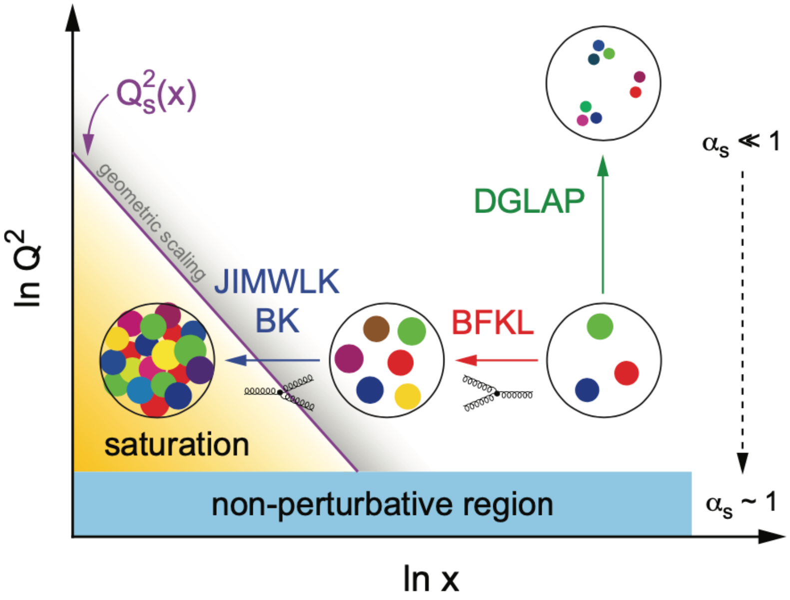
Small-x evolution

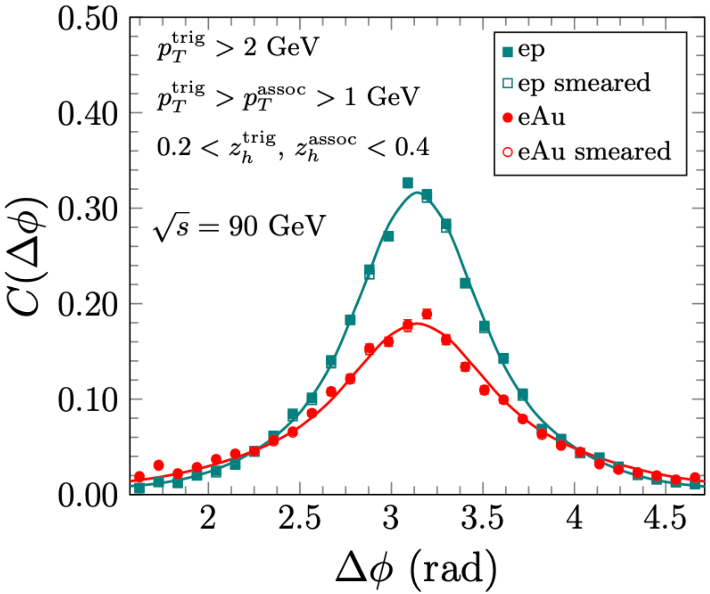
Pert. corrections

Sudakov resum.

Prediction Power!!

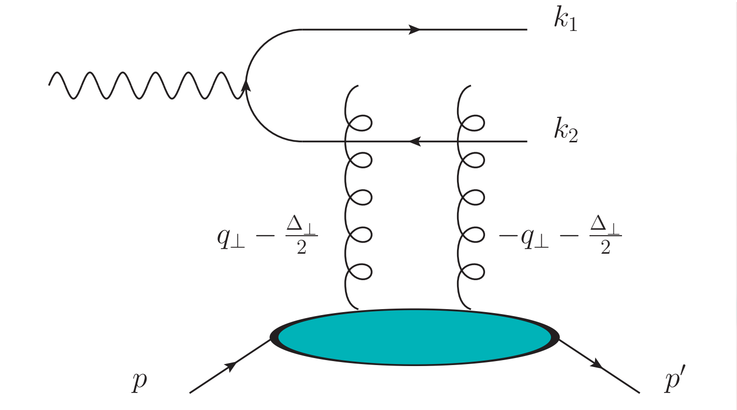
Key observable: dijet/dihadron at EIC



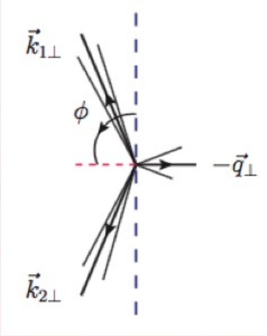


Zheng-Aschenauer-Lee-Xiao, 1403.2413; see also,
Caucal-Salazar-Schenke-Stebel-Venugopalan, 2308.00022

Directly measure the gluon Wigner distribution?



Hatta-Xiao-Yuan,1601.01585



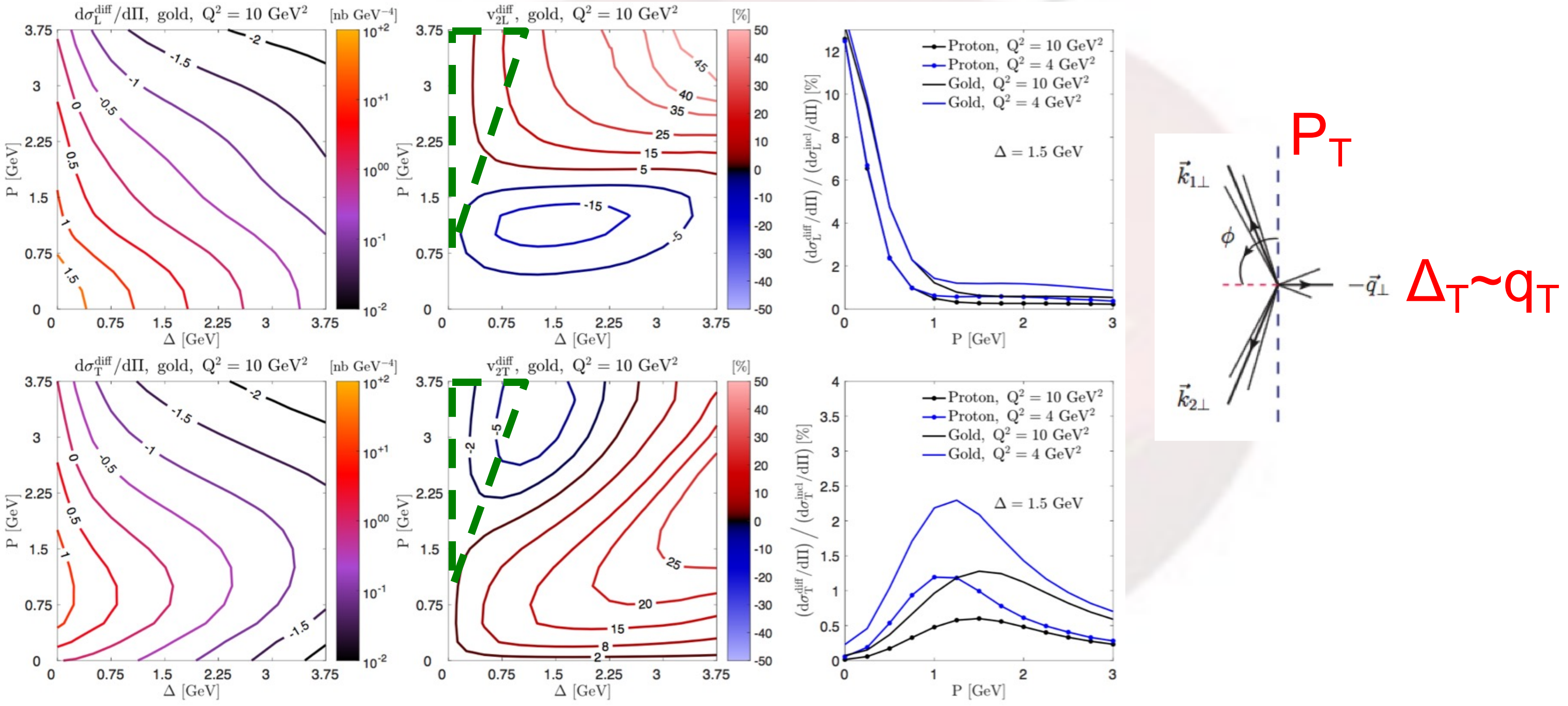
cos(2ϕ) anisotropy

- In the Breit frame, by measuring the recoil of final state proton, one can access Δ_T. By measuring jets momenta, one can approximately access q_T.
- The diffractive dijet cross section is proportional to the square of the Wigner distribution → nucleon/nucleus tomography

$$x\mathcal{W}_g^T(x,|\vec{q}_\perp|,|\vec{b}_\perp|) + 2\cos(2\phi)x\mathcal{W}_g^\epsilon(x,|\vec{q}_\perp|,|\vec{b}_\perp|)$$

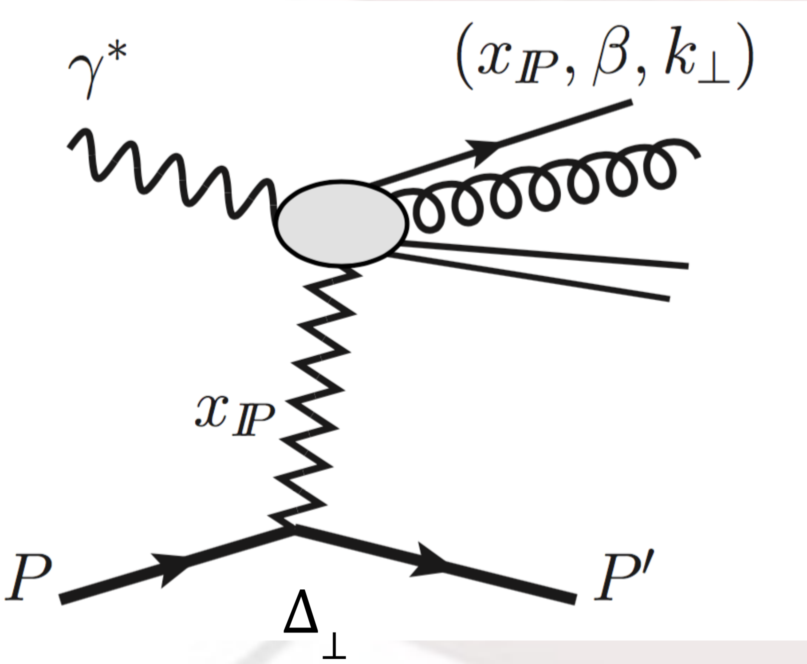
Anisotropy ~ few %

This has generated a lot of interests…



CGC calculations: Mäntysaari-Mueller-Salazar-Schenke, 1912.05586, 1902.05087; Mäntysaari-Roy-Salazar-Schenke 2011.02464

New avenue: semi-inclusive diffractive DIS



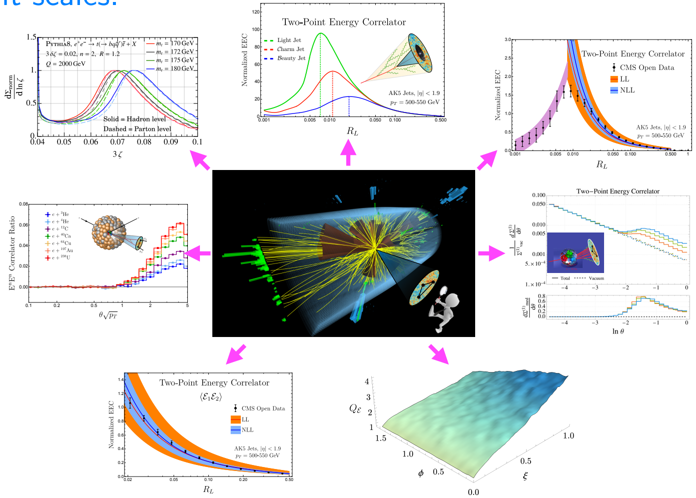
- Flavor dependence in the diffractive PDFs
- TMD dependence can be measured and correlation between $k_\perp$ and $\Delta_\perp$ too

Iancu-Mueller-Triantafyllopoulos, 2112.06353;
Hatta-Xiao-Yuan, 2205.08060;
Hatta-Yuan, work in progress.

Very new idea: Energy-energy correlators

Intrinsic and Emergent Scales at Colliders

- QCD is an extraordinarily rich theory involving both Intrinsic and Emergent scales.



- We can discuss all of them in a common language of correlators.

Ian Moult's HIT Seminar

HIT@LBL Seminar March 16, 2023 26 / 43

Phenomenological applications to the collider physics by Moult, Zhu, et al., in recent years

- Provides a unique access to hadronization process in heavy ion collisions and EIC,

talk by Wenqing Fan

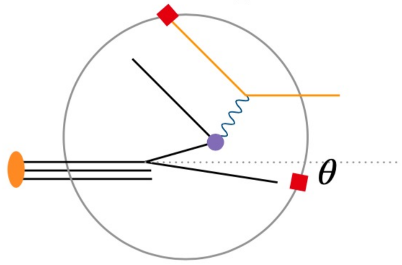
Hadron structure: nucleon energy correlator

$$f_{q,EEC}(x,\theta) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi E_P} e^{ixp^+y^-} \frac{\gamma^+}{2} \langle p | \bar{\psi}(0) \mathcal{E}(\theta) \mathcal{L} \psi(y^-) | p \rangle$$

$$= \sum_X \sum_{i \in X} \frac{E_i}{E_P} \delta(\theta_i^2 - \theta^2) \delta((1-x)p^+ - p_X^+) \frac{\gamma^+}{2} \langle p | \bar{\psi}(0) | X \rangle \langle X | \mathcal{L} \psi(0) | p \rangle$$

Liu, Zhu, 2209.02080

$$x_B = \frac{Q^2}{2P \cdot q}$$



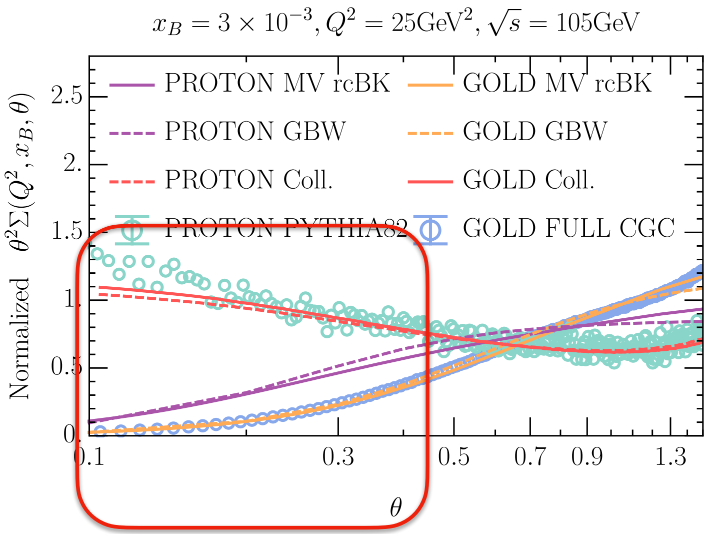
$$\Lambda_{QCD} \ll Q\theta \ll Q$$

$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma}\left(\frac{x_B}{z}, Q^2, \mu\right) f_{\mathrm{EEC}}(z, \theta, \mu)$$

$$\propto \int \frac{dz}{z} \hat{\sigma}\left(\frac{x_B}{z}\right) \frac{1}{\theta^2} \int \frac{d\xi}{\xi} (1 - \frac{z}{\xi}) P(\frac{z}{\xi}) [\xi f(\xi)]$$

- θ-distribution solely determined by f_{EEC}
- In the collinear factorization:
  - $d\Sigma / d\ln\mu = P \otimes \Sigma$, solely determined by the vacuum splitting function
  - $\Sigma \sim \theta^{-2}$ at LO, $\Sigma \sim \theta^{-2+\gamma[\alpha_s]}$ to all orders

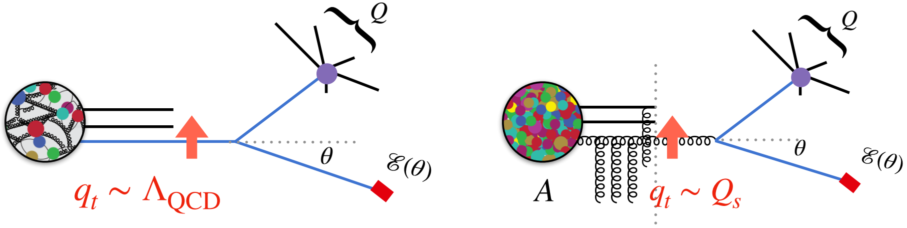
Application to the gluon saturation



NEEC as evident portal to the onset of gluon saturation

Gluon saturation at small x

- Saturation scale $q_t \sim Q_s \gg \Lambda_{\rm QCD}$



$q_t \ll Q\theta$ Ignored $\quad \theta Q \gg \Lambda_{\rm QCD} \quad$ $q_t \sim Q\theta$ kept

Liu, XL, Pan, Yuan, Zhu, 2301.01788

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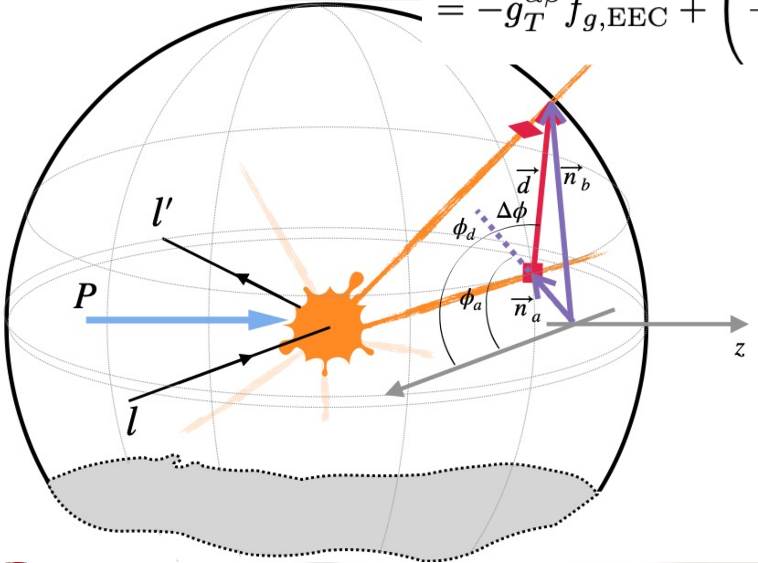
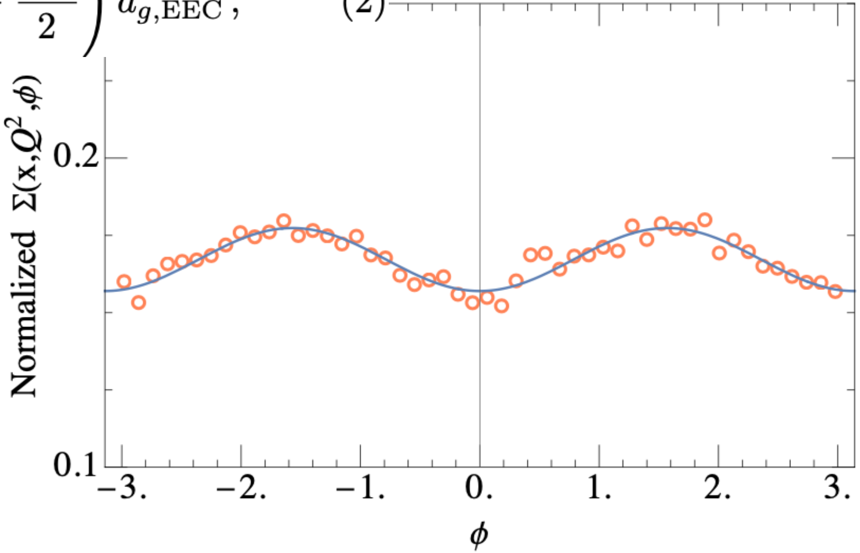
Cos(2ϕ) to probe the linearly polarized gluon

$$f_{g,\mathrm{EEC}}^{\alpha\beta}(x,\vec{n}_a) = \int \frac{dy^-}{4\pi x P^+} e^{-ixP^+\frac{y^-}{2}} \times \langle P|\mathcal{F}^{+\alpha}(y^-)\,\mathcal{L}^\dagger[\infty,y^-]\hat{\mathcal{E}}(\vec{n}_a)\mathcal{L}[\infty,0]\mathcal{F}^{+\beta}(0)|P\rangle = -g_T^{\alpha\beta} f_{g,\mathrm{EEC}} + \left(\frac{n_{a,T}^\alpha n_{a,T}^\beta}{n_{a,T}^2} - \frac{g_T^{\alpha\beta}}{2}\right) d_{g,\mathrm{EEC}}\,, \quad (2)$$



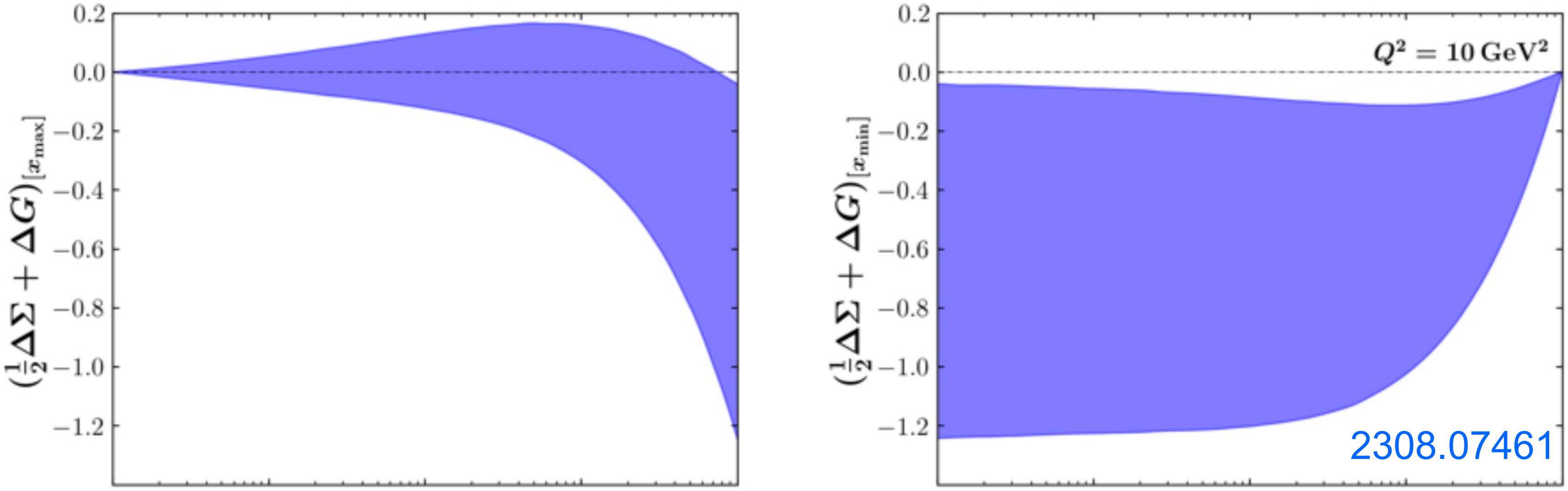


Li-Liu-Yuan-Zhu, to appear

Looking forward…

- Other exciting developments in recent years
  - Jet physics, machine learning applications, nucleon-nucleon short range correlations, …
- Both theory and experiment efforts are needed to push forward the EIC science program now and in the future
- With next generation of theorists in the pipeline, we expect more developments that will excite the community for the EIC physics

Back-up

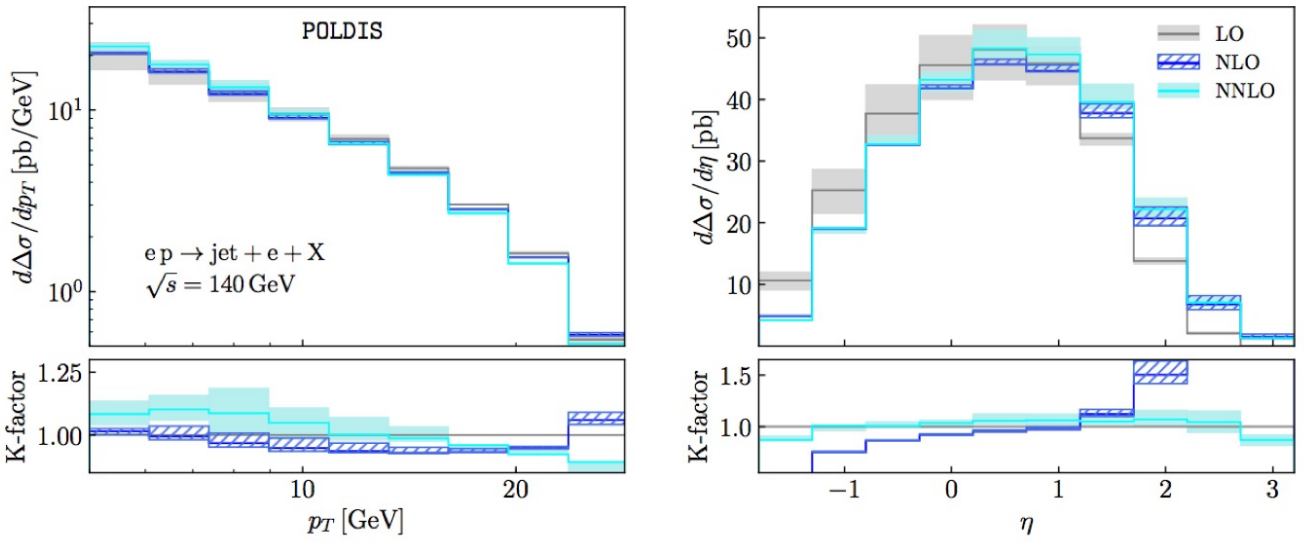


0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
$(\frac{1}{2}\Delta\Sigma + \Delta G)_{[x_{max}]}$
$(\frac{1}{2}\Delta\Sigma + \Delta G)_{[x_{min}]}$
$Q^2 = 10\,\mathrm{GeV}^2$
2308.07461

Jet @EIC has been very active in recent years

- Contribute to explore
  - Spin/tomography of nucleon
  - Small-x gluon saturation
  - Hard probe interaction with cold nuclei matter
- QCD dynamics in precision study
  - E.g., jet substructure to measure α_s, jet algorithms, jet angularity, hadronization, etc.
- Observables:
  - Leading jet/hadron, dijet/dihadron, jet substructure, …

Inclusive jet: state of art



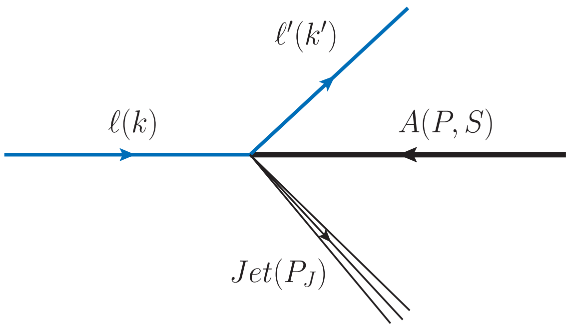
Will contribute to a global fit of parton helicity distributions in the EIC-era

Benchmark measurements:

Borsa-de Florian-Pedron, PRL 2020, 2005.10705, 2010.07354

See also: Hinderer, Schlegel, Vogelsang, 1703.10872; Boughezal, Petriello, Xing,1704.05457, 1806.07311; Page, Chu, Aschenauer, 1911.00657

Semi-inclusive processes: lepton-jet correlation



Quark distribution ⊗ soft factor

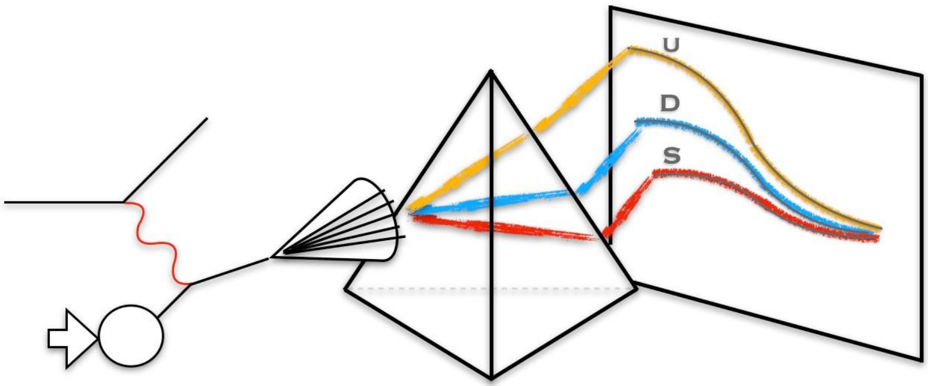
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\rm TMD}(Q,\mu_F) S_J(\lambda_\perp, \mu_F)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp) \ .$$

Liu-Ringer-Vogelsang-Yuan 1812.08077, 2007.12866

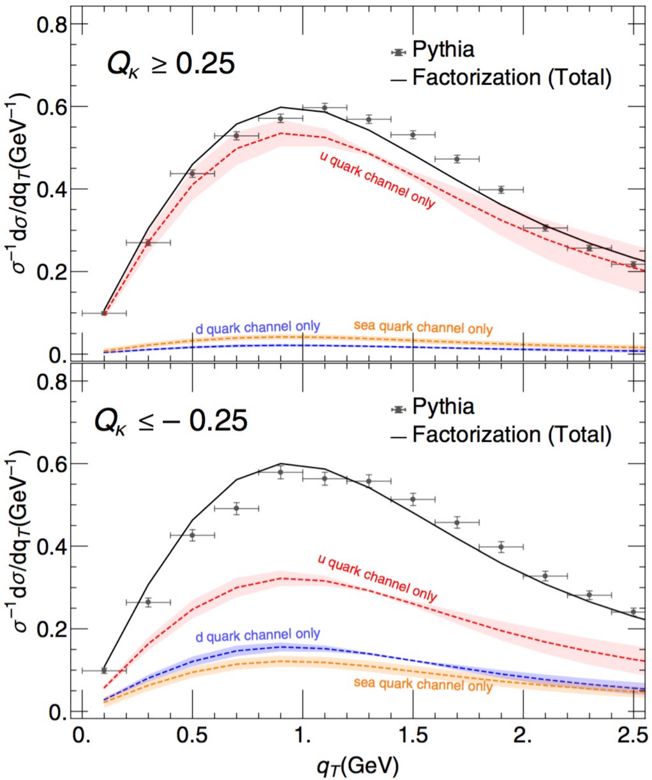
(Lab frame)
Total transverse momentum of the lepton+jet probes the TMD quark distribution

See also, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi, 1807.07573, 1904.04259

Jet Charge: A Flavor Prism for Spin Asymmetries at the Electron-Ion Collider

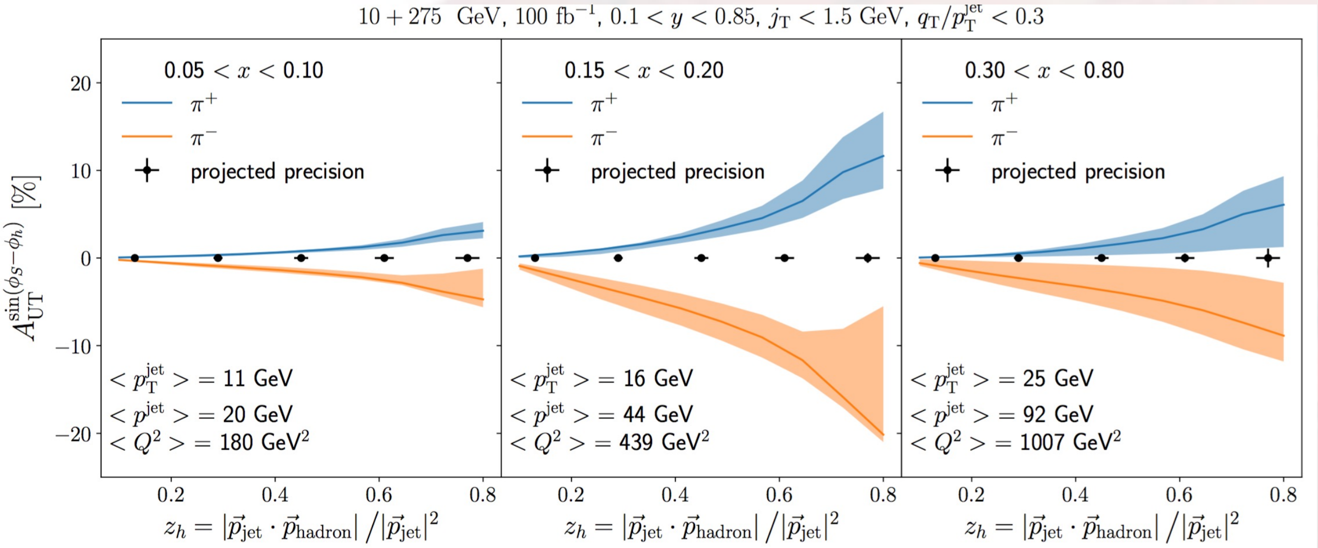


$$Q_\kappa \equiv \sum_{h \in \text{jet}} z_h^\kappa Q_h$$



Kang, Liu, Mantry, Shao, PRL 2020, 2008.00655;
Kang, Larkoski, Yang, PRL2023

TMD fragmentation in jet: Collins asymmetries at EIC



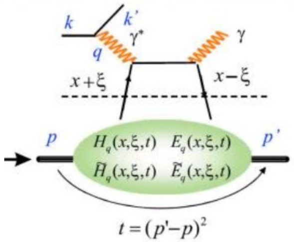
Factorization involves jet axis definition, applying jet thrust as an alternate approach:

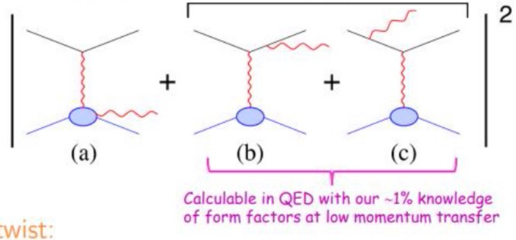
- Kang, Shao, Zhao, 2007.14425
- Boglione, Simonelli, 2011.07366
- Will be studied by Belle II experiments

Arratia, Kang, Prokudin, Ringer, 2007.07281

See also, polarized jet fragmentation functions: Kang, Lee, Zhao, 2005.02398

Access GPDs through exclusive processes





At leading twist:

$$d^5\vec{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH}\cdot T^{DVCS})$$

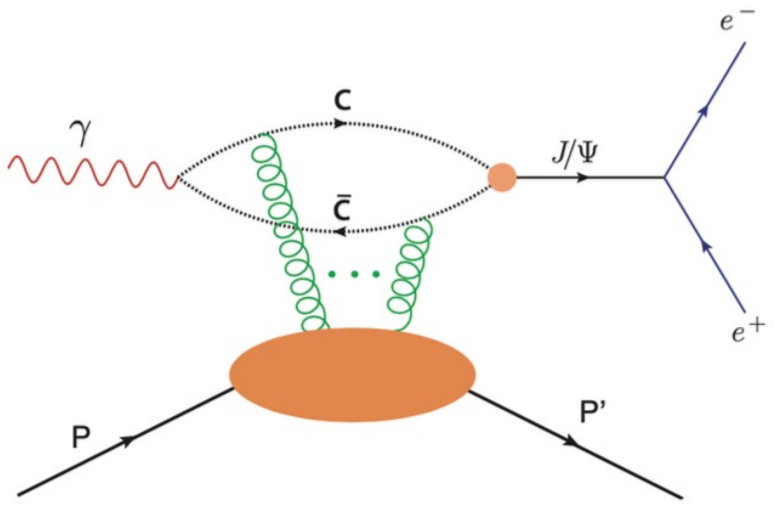
$$d^5\vec{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\,(T^{BH}\cdot T^{DVCS}) + |DVCS|^2$$

$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

Opposite sign for e- & e+

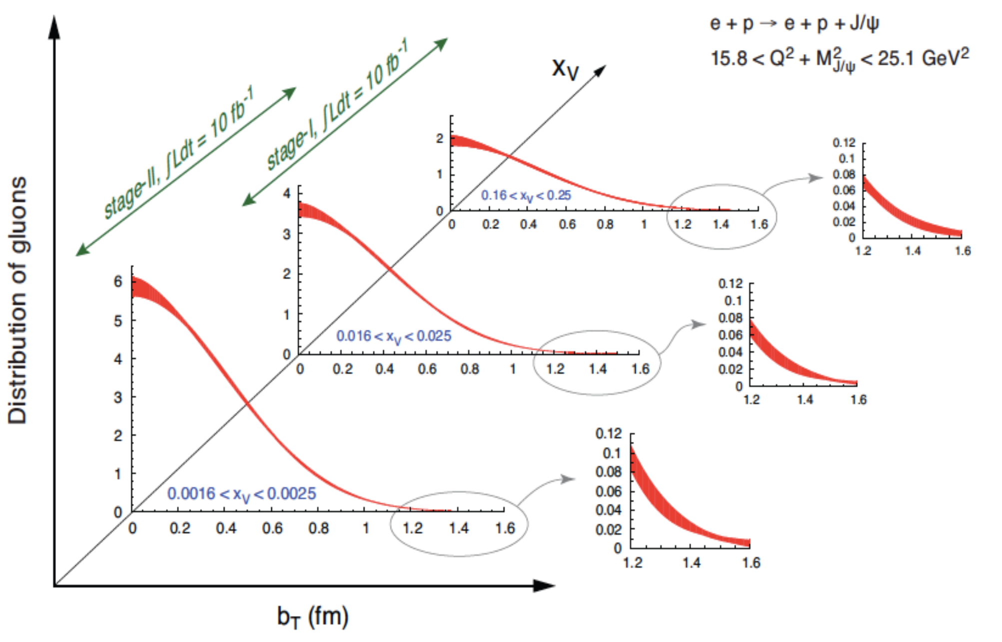
$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

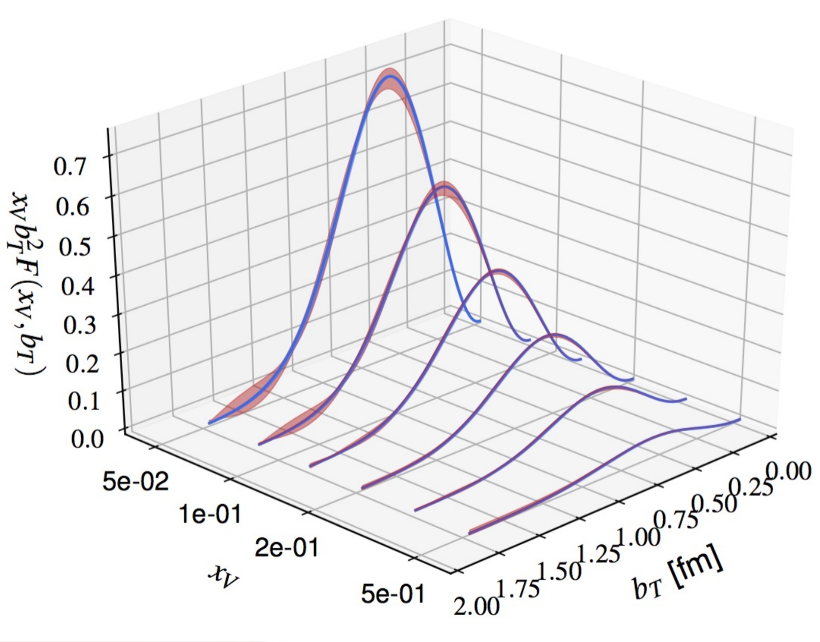
Quark GPDs



Gluon GPDs

Gluon tomography at different x (GPDs)

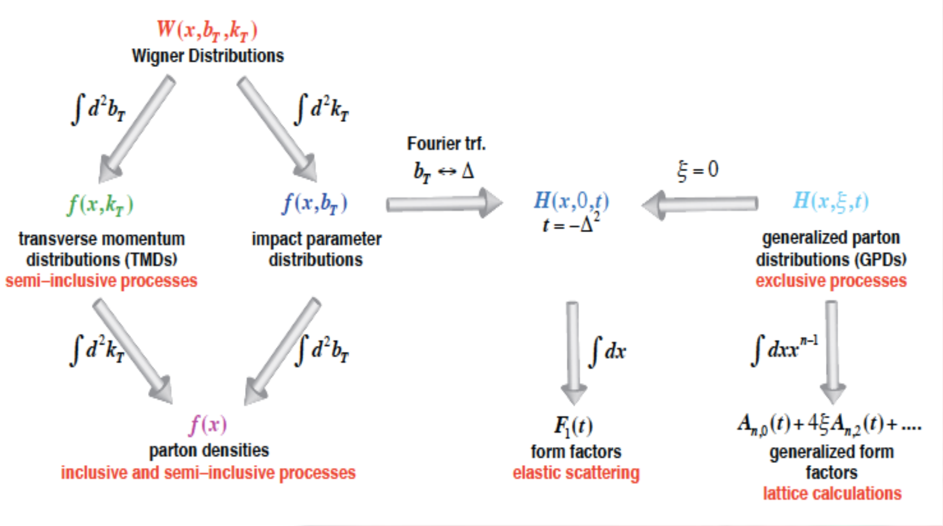




EIC-White paper, arXiv:1212.1701

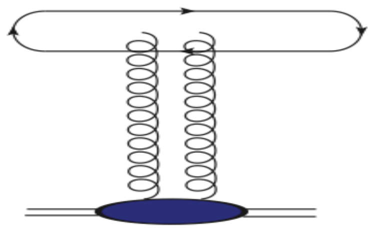
Joosten, Meziani, 1802.02616

Small-x Approximation



Small-x

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\left[U\left(R_\perp\right)U^\dagger\left(R'_\perp\right)\right]\right\rangle_x$$

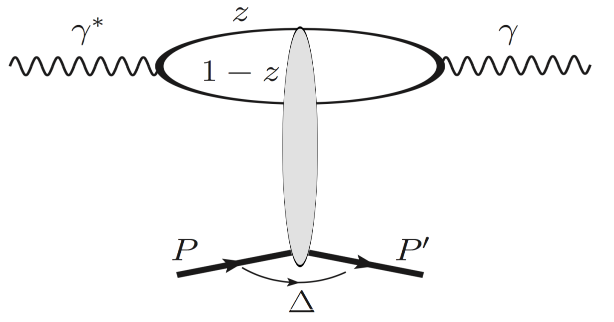


Hatta-Xiao-Yuan,1601.01585
earlier: Mueller, NPB 1999

GPDs at small-x

- Can be studied through exclusive processes: deeply virtual Compton scattering (DVCS), deeply virtual meson production, and various diffractive processes
- For DVCS at small-x, there exists a consistency between the dipole formalism and the collinear GPD framework
  - GPD gluon distribution is directly related to the dipole amplitude, and the GPD quark distribution can be computed
- The cos(2phi) asymmetry in DVCS will provide information on the elliptic gluon distribution at small-x

DVCS and GPDs at small-x



$$\frac{1}{P^+}\int \frac{d\zeta^-}{2\pi} e^{ixP^+\zeta^-}\langle p'|F^{+i}(-\zeta/2)F^{+j}(\zeta/2)|p\rangle$$
$$= \frac{\delta^{ij}}{2} xH_g(x,\Delta_\perp) + \frac{xE_{Tg}(x,\Delta_\perp)}{2M^2}\left(\Delta_\perp^i\Delta_\perp^j - \frac{\delta^{ij}\Delta_\perp^2}{2}\right) +$$

Hoodbhoy-Ji 98
Diehl 01

- Two GPDs at the leading small-x approximation

Gluon GPDs and dipole amplitudes

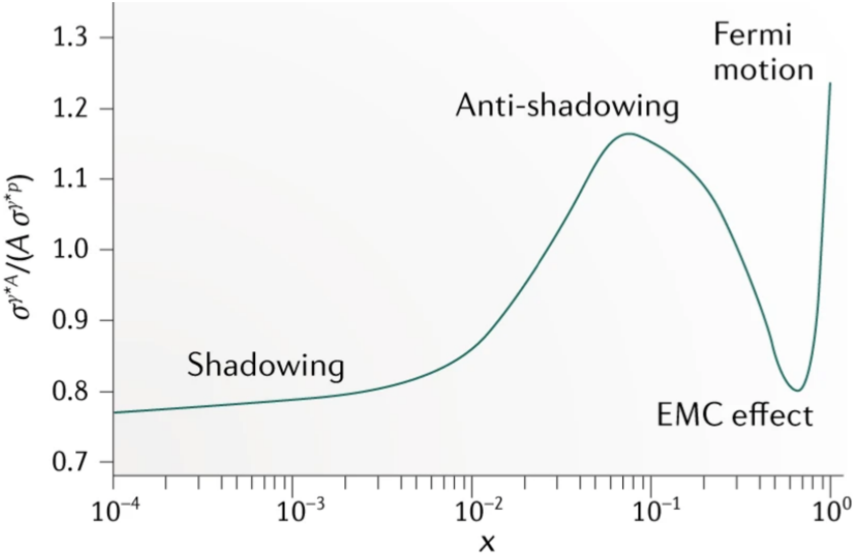
$$xH_g(x,\Delta_\perp) = \frac{2N_c}{\alpha_s}\int d^2q_\perp q_\perp^2 F_0 \,,$$

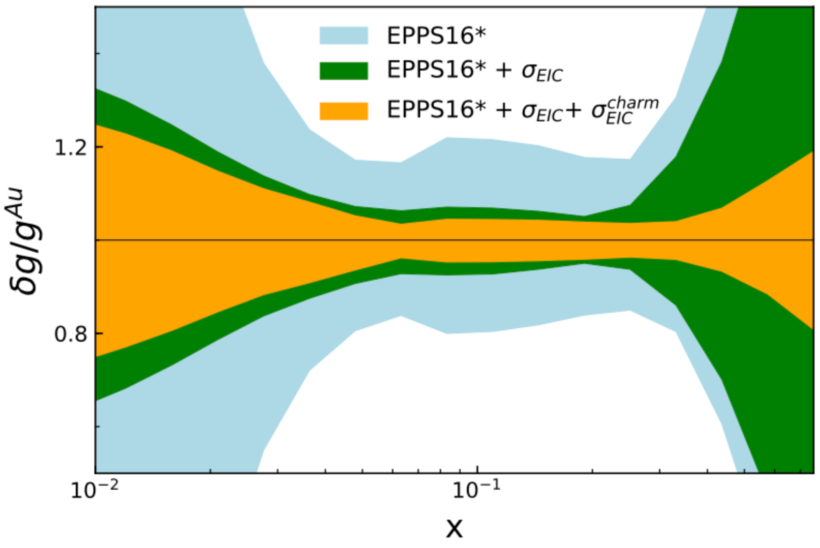
$$xE_{Tg}(x,\Delta_\perp) = \frac{4N_cM^2}{\alpha_s\Delta_\perp^2}\int d^2q_\perp q_\perp^2 F_\epsilon$$

→ Elliptic gluon distribution

Hatta-Xiao-Yuan 1703.02085

Gluon shadowing





Hard probes for cold nuclear effects