QGT: Theory Highlights and Perspectives

★ Specialization in designing and using effective field theories, chiral perturbation theory, perturbative QCD, and models of QCD

★ Hadron structure-related investigations, e.g., QCD factorization, factorization breaking effects, lepton-nucleon interactions, light-front gauge topology

[SCET/Theory]: S. Fleming, T. Mehen, I. Stewart;
[Instanton]: E. Shuryak, I. Zahed;
[ChEFT]: J. Goity, C. Weiss;
[CPM]: P. Schweitzer;
[Small-x]: A. Metz, F. Salazar, F. Yuan

Bridge junior faculties

Postdocs

- Fatma Aslan (University of Connecticut)
- Adam Freese (University of Washington, now JLab)
- Yuxun Guo (LBL)
- Jun-Young Kim (JLab)
- Kyle Lee (MIT)

Graduate students

- Sarah Blask (University of Arizona)
- Brean Maynard (University of Connecticut)
- Jinghong Yang (University of Maryland)
- Ignacio Castelli, Chris Cocuzza (Temple University)

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QUARK-GLUON TOMOGRAPHY COLLABORATION

Milestones

Year 1:

- [SCET] Analyze factorization for exclusive quarkonia production at leading power for all regions using SCET and NRQCD, including the large and small Q2 regions and quarkonia production at threshold ✔
- [Instanton] Apply the light-front Hamiltonian method to compute the GPDs, explore the nucleon spin/mass sum rule, and help to unveil the parton correlation due to strong interaction non-perturbative physics ✔

Year 2:

- [Small-x] Make quantitative connection of the GPD factorization formalism to the CGC/color-dipole formalism for various exclusive processes ✔
- [CPM] Apply the Covariant Parton Model to the GPDs of quark and gluons, eventually the parton Wigner distributions ✔

Year 3:

- [SCET] Use SCET to investigate factorization at subleading power in DVCS, including hadron mass corrections and the factorization and resummation of potential endpoint singularities

Year 4:

- [ChEFT] Perform large-Nc analysis of hard exclusive pion production with N->\Delta transitions and a combined chiral and 1/Nc analysis of nucleon energy-momentum tensor form factors ✔
- [Small-x] Quantitative study of hard diffractive dijet and di-hadron production at future EIC and explore novel processes to probe the quark/gluon Wigner distribution in the valence and moderate x region ✔

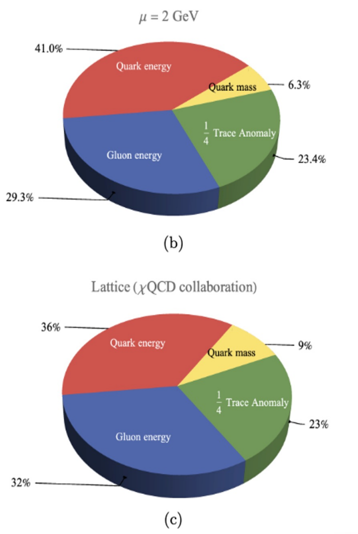
Year 5:

- [SCET] Study relativistic corrections and other subleading effects in heavy quarkonia production for cases where such corrections are likely to be important ✔

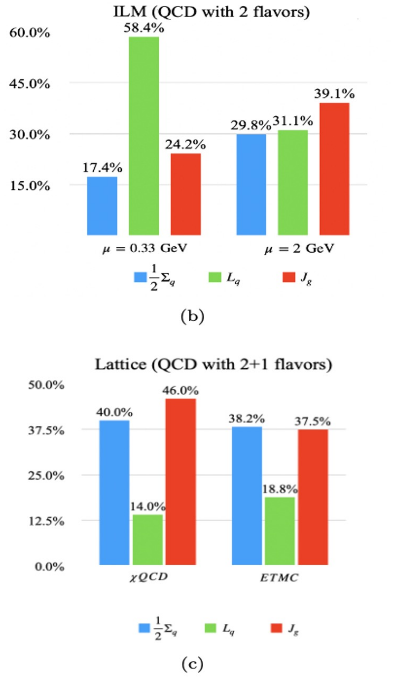
Work in progress ✔ Toward finishing ✔

Recent hightlights: deep insight from non-perturbative method

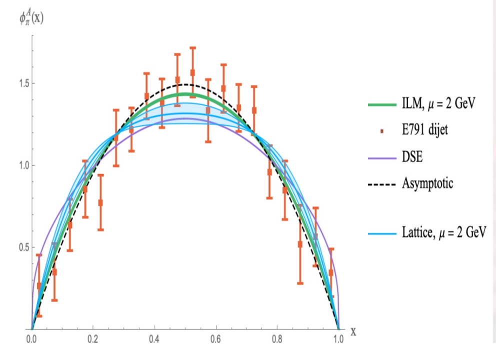
Proton mass



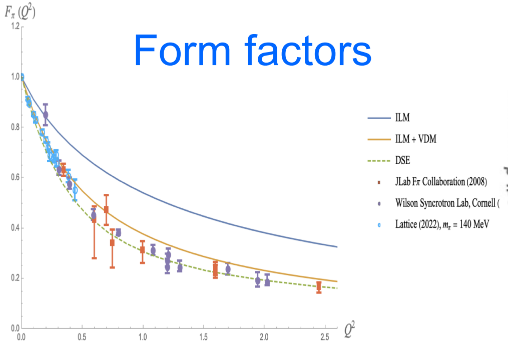
Proton spin



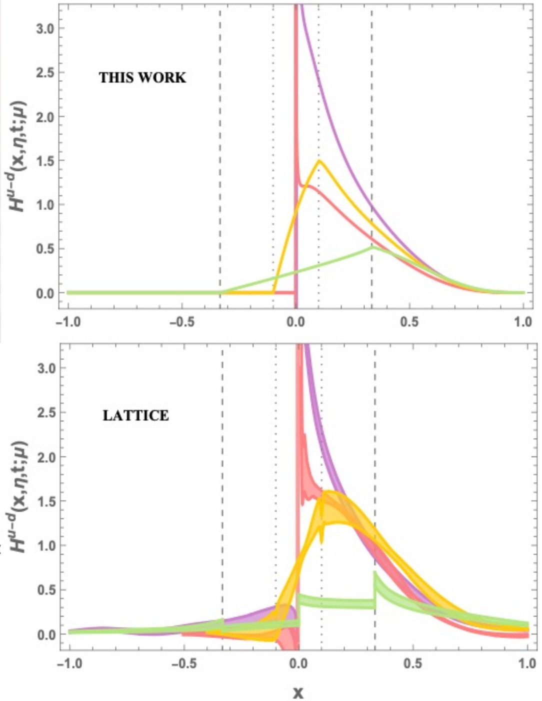
Parton Distributions



Form factors



GPDs



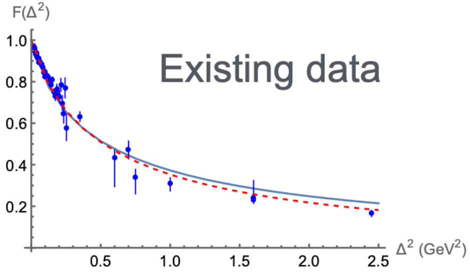
Stony Brook Group, Shuryak, Zahed et al., 2404.13245,.05112,.03875,.03047, 2403.18700, 2401.12162,.09318, …

Quark counting, Drell-Yan-West, Pion Wave Function

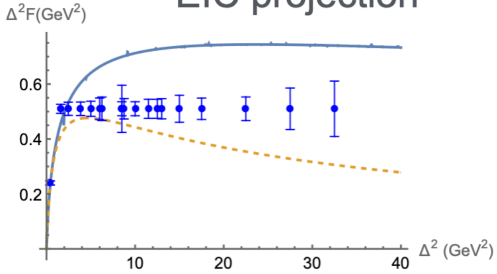
Modern derivation of D-Y W relation between $\lim_{x\to 1} q(x)$ and $F(\Delta^2)$

Alberg, Miller
2403.03356 (hep-ph)

- Much current interest in these properties for the pion, to be measured by JLab and EIC
- MA & GM did modern version of the relation - new non-perturbative technique to derive model wave functions $\lim_{x\to 1} q(x) = (1-x)^n \rightarrow F(\Delta^2) \sim \frac{\log(\Delta^2)}{(\Delta^2)^{(n+1)/2}}$

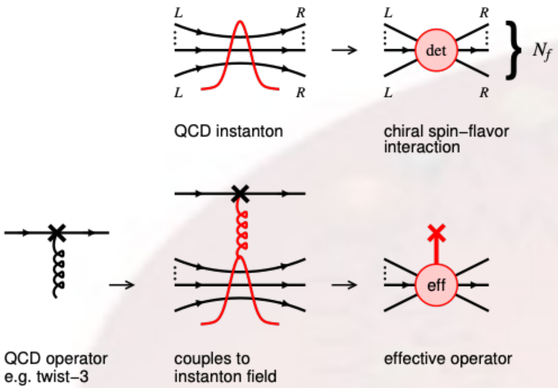


EIC projection



- Two models agree with existing data for low Δ^2, disagree strongly at higher Δ^2 to be measured in future experiments

Instanton effects in twist-3 GPDs



Topological gauge fields - instantons

Observed/studied extensively in Lattice QCD simulations

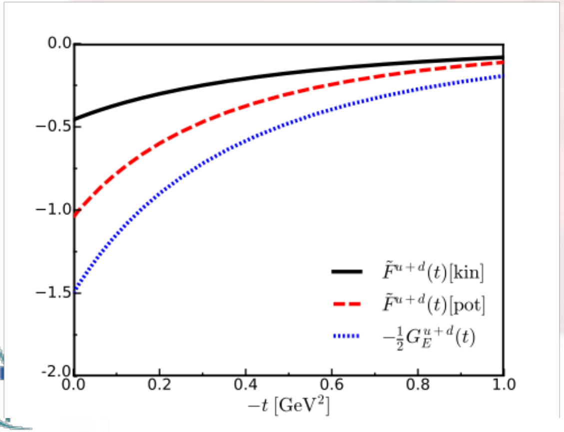
Induce effective chiral spin-flavor interactions

Convert QCD operators to effective chiral operators
at nonpertubative scale $1/\rho \sim 0.6$ GeV

Instanton effects in twist-3 GPDs

QCD twist-3 operator $\bar{\psi}\,\gamma^{[\alpha}i\,\nabla^{\beta]}\psi,\qquad \nabla^{\beta} \equiv \partial^{\beta} - iA^{\beta}$

Large effect from instanton fields,
strong twist-3 quark-gluons correlations in GPDs
J.-Y. Kim, C. Weiss, Phys. Lett. B 848 (2024) 138387 [INSPIRE]



Impact on quark spin-orbit correlations in nucleon
J.-Y. Kim, H.-Y. Won, H.-C. Kim, C. Weiss, arXiv:2403.07186

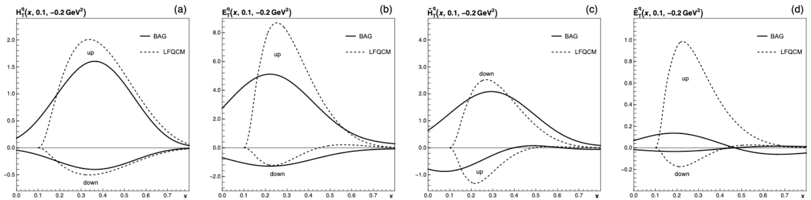
Systematic approach to non-perturbative gauge fields available for GPD theory

model study: chiral-odd GPDs of the nucleon $H_T^q(x,\xi,t)$, $E_T^q(x,\xi,t)$, $\tilde{H}_T^q(x,\xi,t)$, $\tilde{E}_T^q(x,\xi,t)$

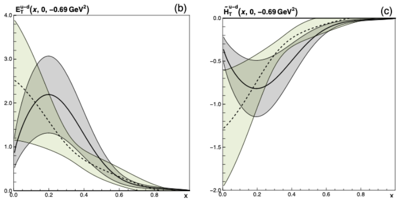
- *first model study in bag model:* $H_T^q(x,\xi,t) \neq 0$ *and others* $= 0$ *Scopetta, PRD72, 117502 (2005)*
- *but all 4 chiral-odd GPDs* $\neq 0$ *in lightfront constituent quark model (LFCQM) Pasquini et al (2005) and in all other quark models used since that. Why do quark models disagree so much?*
- *worth to investigate! General credibility of quark models at risk. Investigated in recent preprint:*

  K. Tezgin, B. Maynard, P. Schweitzer, "Chiral-odd GPDs in bag model," arXiv:2404.11563
- *results:*

  in bag model all 4 chiral-odd GPDs $\neq 0$ *!!*



agreement with other models (LFCQM) at low scale $\mu_0 < 1\,\text{GeV}$
bag model satisfies $\int dx\, \tilde{E}_T^q(x,\xi,t) = 0$ *(most models do not!)*
different quark models credible within $\pm 40\%$ *(except* $\tilde{E}_T^q$*)*



compare to lattice at $\mu = 2\text{GeV}$
but quasi GPDs at $P_z = 1.67\text{GeV}$
(limit $P_z \to \infty$ *not yet possible)*
Alexandrou et al, PRD105 (2022)

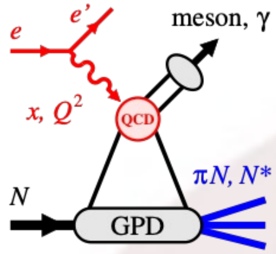
consistent quark model picture emerges (valence x, small $|t|$)

$\tilde{E}_T^q(x,\xi,t)$ difficult for models, and for lattice (small, node at valence-x)

chiral-odd GPDs difficult to measure (e.g. two-vector-meson-production) EIC(?)

model studies & comparisons of model results & confront with lattice $\to$ insightful lessons

N → Δ Transition GPDs

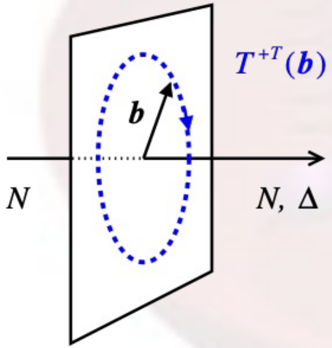


N → N* Transition GPDs new field of research

Sampled in exclusive processes with N → N* transitions @JLab12

New probes of resonance structure: Imaging, mechanical properties

C. Weiss (organizer), Workshop ECT* Trento, 21-25 Aug 2023



QCD angular momentum in N → Δ transitions

Introduced concept of N → Δ transition angular momentum

Estimated transition angular momentum using 1/Nc expansion, connected it with flavor asymmetry J^{u-d} in proton

J.-Y. Kim, H.-Y. Won, J. Goity, C. Weiss, Phys.Lett.B 844, 138083 (2023) [INSPIRE]

N → Δ Transition GPDs

Studied x-dependence, flavor structure in large-Nc soliton model

J.-Y. Kim, Phys.Rev.D 108, 034024 (2023) [INSPIRE]

Lattice QCD	$J^S_{p\to p}$	$J^S_{\Delta^+\to\Delta^+}$	$J^V_{p\to p}$	$J^V_{p\to\Delta^+}$	$J^V_{\Delta^+\to\Delta^+}$
[9] $\mu^2 = 4\,\mathrm{GeV}^2$	0.33*	0.33	0.41*	0.58	0.08
[10] $\mu^2 = 4\,\mathrm{GeV}^2$	0.21*	0.21	0.22*	0.30	0.04
[11] $\mu^2 = 4\,\mathrm{GeV}^2$	0.24*	0.24	0.23*	0.33	0.05
[12] $\mu^2 = 1\,\mathrm{GeV}^2$	–	–	0.23*	0.33	0.05
[13] $\mu^2 = 4\,\mathrm{GeV}^2$	–	–	0.17*	0.24	0.03

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Synchronization effects on rest frame E&M and EMT densities

Space-time conventions

Instant $(t, \vec{r})$ Light front $(\tau = t + z, x^-, \vec{b})$ Tilted $(\tau, \vec{r})$

- aim of tilting - spatial tomography w. 3 space dimensions

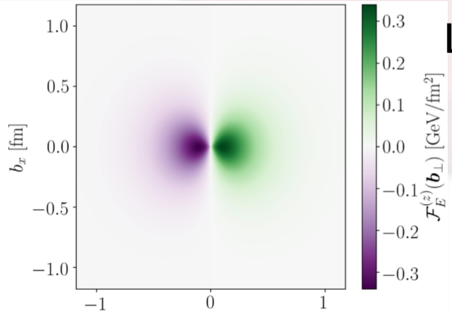
Interpret all 16 components energy-momentum-tensor (EMT $T^{\mu\nu}$

$$Energy\, density : \mathcal{E}(x) = T^{00}(x) - T^{03}(x)$$

$$Energy\, flux\, density\ \vec{\mathcal{F}}(x) = (T^{0i}(x) - T^{i3}(x))\hat{e}_i$$

$$Momentum\, density\ \vec{\mathcal{P}}(x) = -T^0_i(x)\hat{e}_i$$

$$Stress\, tensor\, (momentum\, flux\, densities)\ S^{ij} = -T^i_j(x)$$



Longitudinal energy flux/longitudinally polarized proton

Freese, Miller,
PRD **107**, 074036; **108**, 094026

Ultimate aim: manifest rotational invariance

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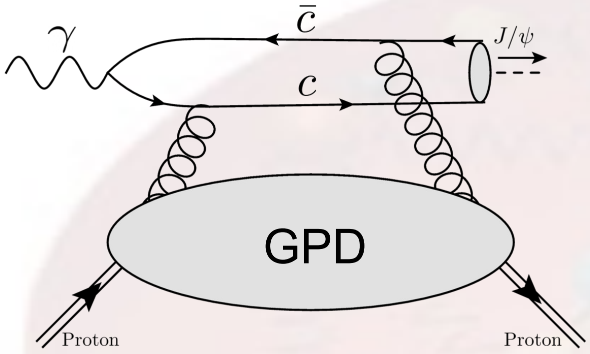
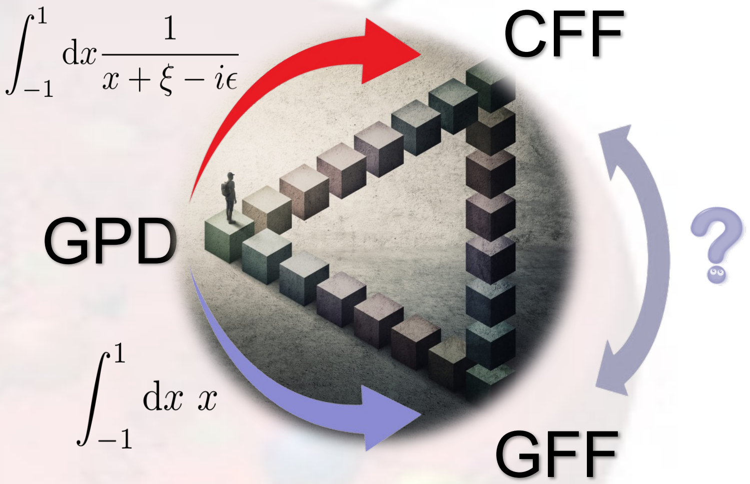
Near-threshold Jpsi photo-production to probe GPDs

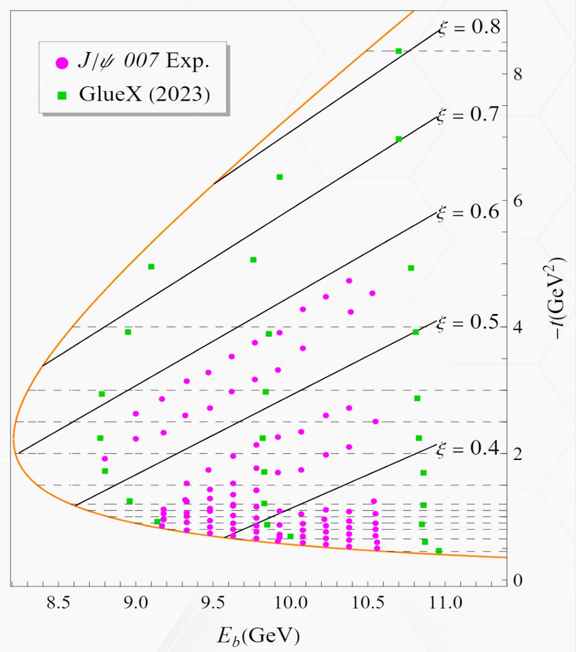


Y. Guo et. al. Phys. Rev. D 103 9, 096010

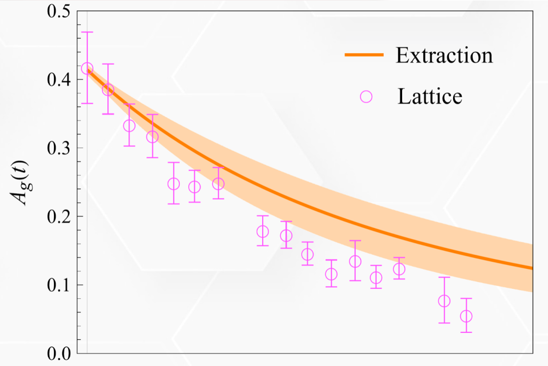


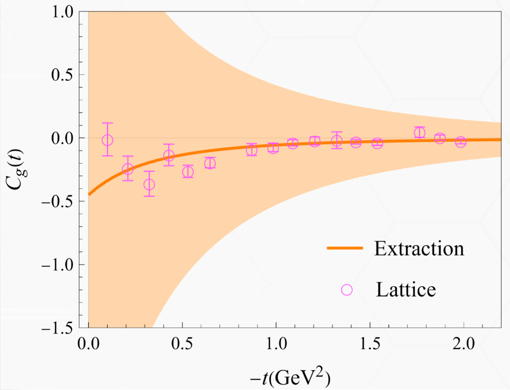
- Will be sensitive to the gluonic Compton form factors (gCFFs)
- We can then extract the GFFs from the gCFFs, utilizing the large skewness kinematics in the near-threshold region in the heavy quark limit.

What current data tell us



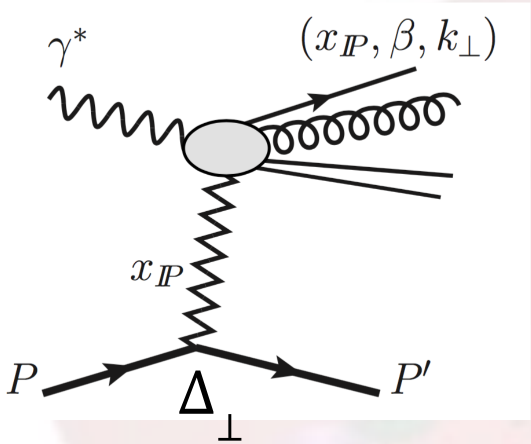
With $\xi > 0.5$ data

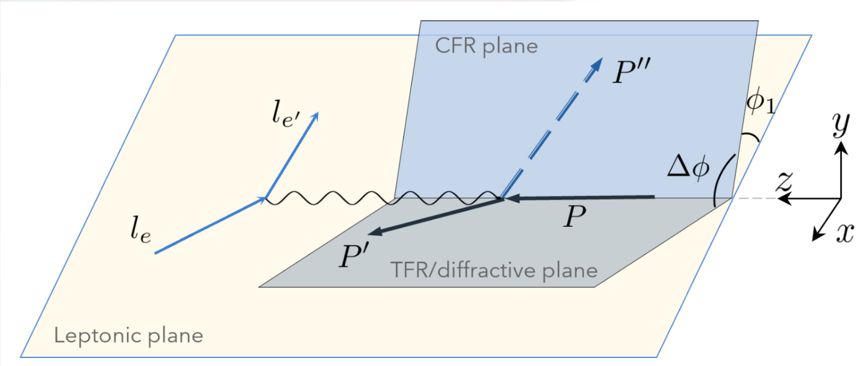




Guo et. al. Phys. Rev. D 108, 034003 (2023)
Lattice: Pefkou et. al. Phys. Rev. D 105, 054509 (2022)

New avenue: semi-inclusive diffractive DIS

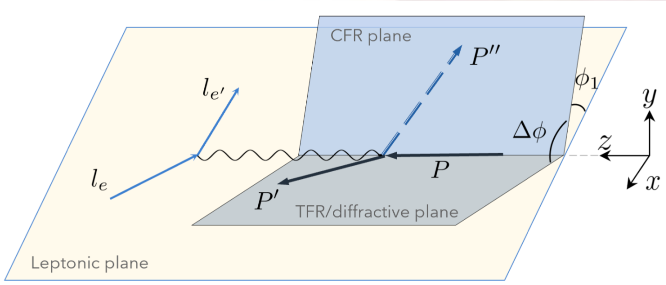


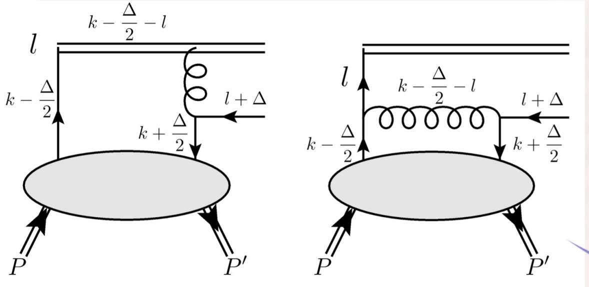


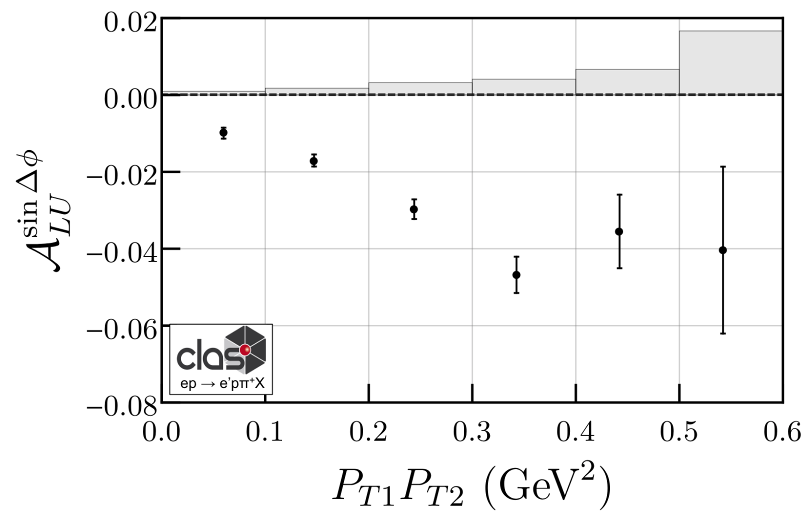
Iancu-Mueller-Triantafyllopoulos, 2112.06353;
Hatta-Xiao-Yuan, 2205.08060, Hatta-Yuan, 2403.19609;
Guo, Yuan, 2312.01008

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

Compute the Diffractive PDFs/Fracture functions, spin asymmetries in semi-inclusive diffractive DIS







CLAS Coll., 2208.05508

Future looks bright: on track to finish milestones

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- [SCET] Analyze factorization for exclusive quarkonia production at leading power for all regions using SCET and NRQCD, including the large and small Q2 regions and quarkonia production at threshold ✔
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Work in progress ✔ Toward finishing ✔

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Quark-Gluon Tomography Collaboration