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

Bridge junior faculties

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

Other talks: + Z. Yu

Postdocs

- Fatma Aslan (JLab)
- 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 ✔

No-perturbative Method

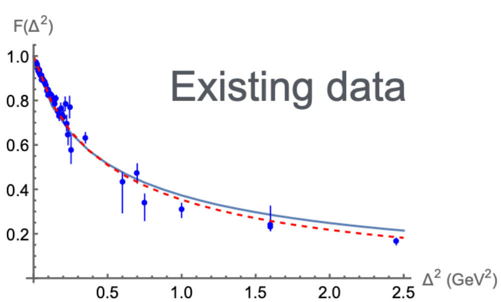
Quark counting, Drell-Yan-West, Pion Wave Function

Modern derivation of D-Y W relation between $\lim_{x\to1} q(x)$ and $F(\Delta^2)$

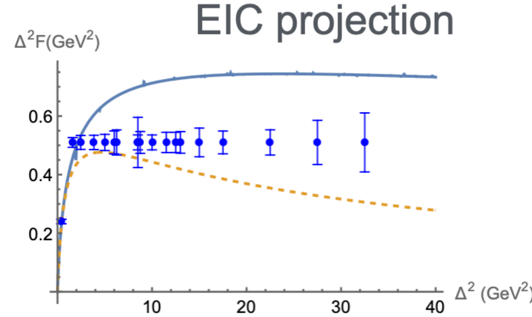
Alberg, Miller
2403.03356 (hep-ph)

- 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 $\lim_{x\to1} q(x) = (1-x)^n \to F(\Delta^2) \sim \frac{\log(\Delta^2)}{(\Delta^2)^{(n+1)/2}}$



EIC projection



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

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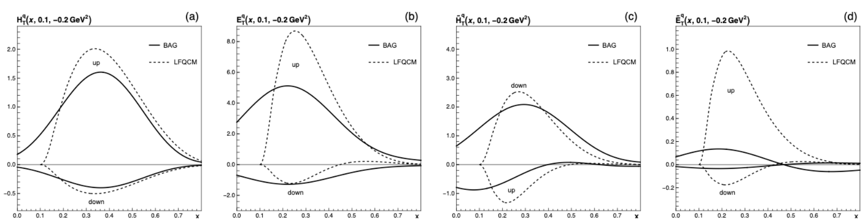
model study: chiral-odd GPDs of the nucleon $H_T^q(x,\xi,t)$, $E_T^q(x,\xi,t)$, $\tilde{H}_T^q(x,\xi,t)$, $\tilde{E}_T^q(x,\xi,t)$

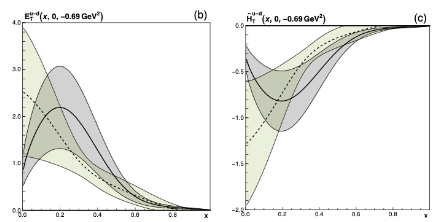
- *first model study in bag model: $H_T^q(x,\xi,t) \neq 0$ and others $= 0$ Scopetta, PRD72, 117502 (2005)*
- *but all 4 chiral-odd GPDs $\neq 0$ in lightfront constituent quark model (LFCQM) Pasquini et al (2005) and in all other quark models used since that. Why do quark models disagree so much?*
-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

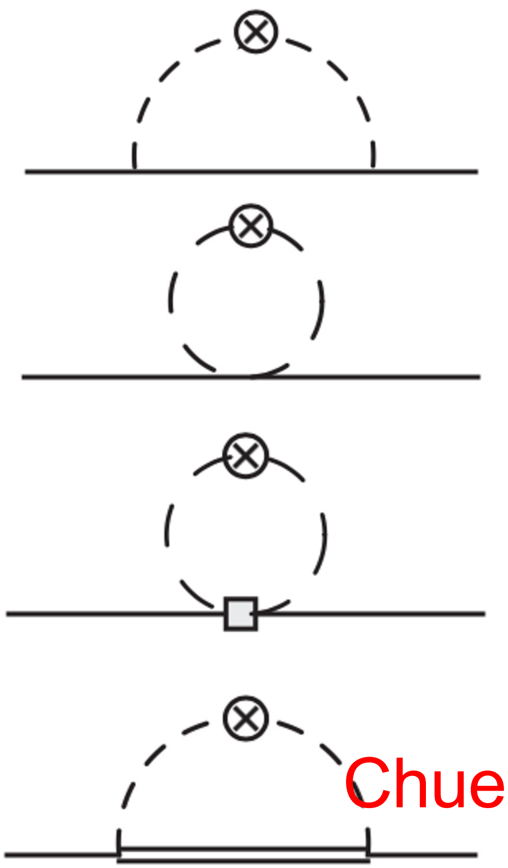
chiral-odd GPDs difficult to measure (e.g. two-vector-meson-production) EIC(?)

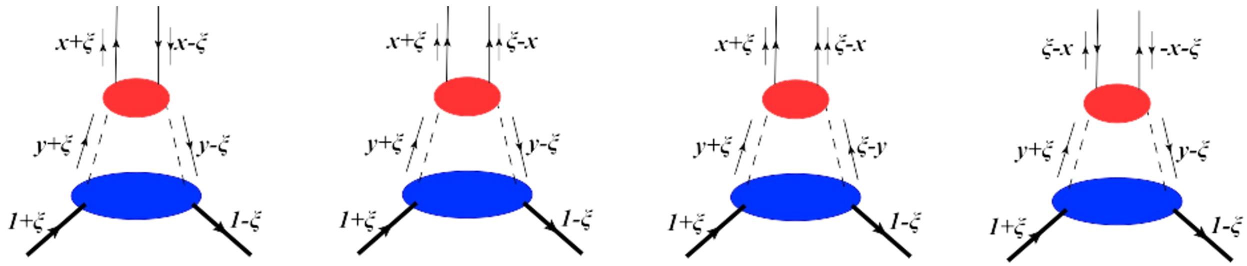
model studies & comparisons of model results & confront with lattice → insightful lessons

Nonlocal chiral contributions to GPDs of the proton at nonzero skewness:

arXiv:2406.03412v1 [hep-ph]; PRD in press

Z. Gao, F. He, C.-R. Ji, W. Melnitchouk, Y. Salamu, and P. Wang

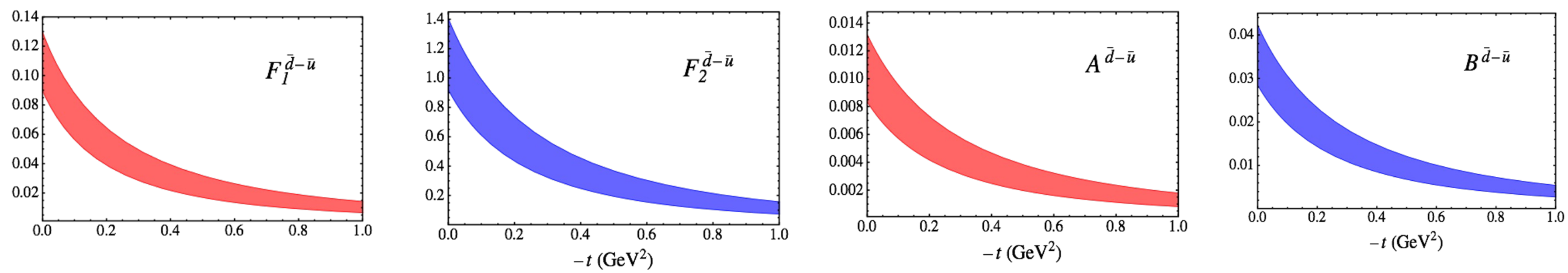


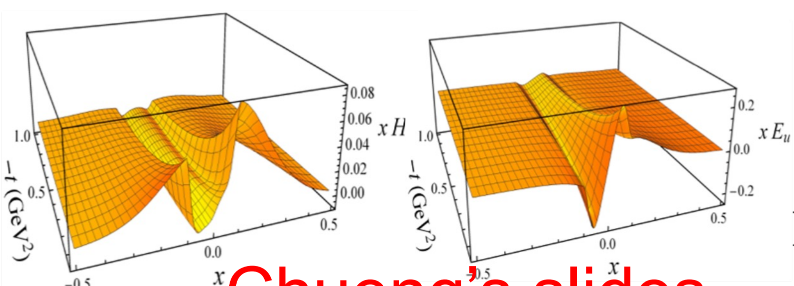


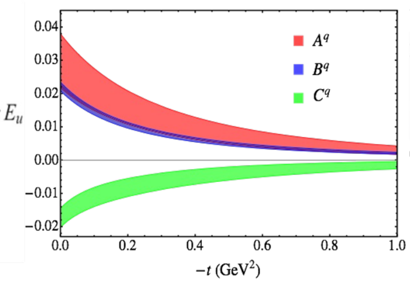
$$H_q^{(\mathrm{rbw})}(x,\xi,t) = \begin{cases} \displaystyle\int_x^1 \frac{\mathrm{d}y}{y} f_{\phi B}^{(\mathrm{rbw})}(y,\xi,t)\, H_{q/\phi}\Big(\frac{x}{y},\frac{\xi}{y},t\Big), & [\xi < x < y] \\ \displaystyle\int_\xi^1 \frac{\mathrm{d}y}{y} f_{\phi B}^{(\mathrm{rbw})}(y,\xi,t)\, H_{q/\phi}\Big(\frac{x}{y},\frac{\xi}{y},t\Big), & [x < \xi < y] \\ \displaystyle\int_{-\xi}^{\xi} \frac{\mathrm{d}y}{2y} f_{\phi B}^{(\mathrm{rbw})}(y,\xi,t)\frac{1}{\pi}\int_{s_0}^{\infty}\mathrm{d}s\,\frac{\mathrm{Im}\Phi_{q/\phi}\big(\frac{1}{2}(1+\frac{x}{\xi}),\frac{1}{2}(1+\frac{y}{\xi}),s\big)}{s-t+i\epsilon}, & [|x|,|y| < \xi] \\ \displaystyle\int_{-x}^1 \frac{\mathrm{d}y}{y} f_{\phi B}^{(\mathrm{rbw})}(y,\xi,t)\, H_{q/\phi}\Big(\frac{x}{y},\frac{\xi}{y},t\Big), & [\xi < -x < y < 1] \end{cases}$$

Chueng's slides

- **Nonlocal generalization of the effective Lagrangian provides systematic finite range regularization**
- **Nonzero skewness provides testing ground for the theory via polynomiality condition**
- **Extension to gravitational form factors, A, B and D=4C**







Chueng's slides

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Review

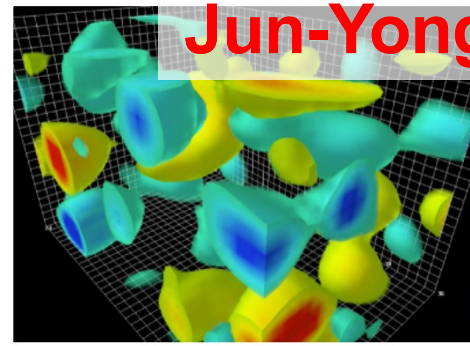
Nucleon form factors and parton distributions in nonlocal chiral effective theory

P. Wang [a,b,*], Fangcheng He [c], Chueng-Ryong Ji [d], W. Melnitchouk [e]

Gluonic structure from topological fields

Ismail's talk
Jun-Yong's talk

Instanton vacuum: Topological gauge fields → chiral symmetry breaking → nonperturbative gluonic structure. Effective description using semiclassical approx, parametric expansion. Complementary to LQCD



Instanton effects in twist-3 GPDs

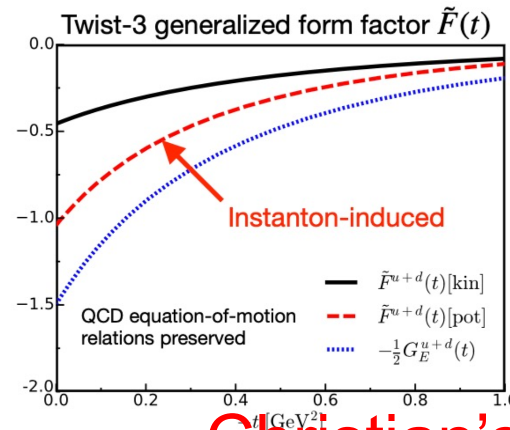
Large instanton effects in twist-3 QCD operators. QCD gauge interaction converted to effective spin-flavor interaction. Numerous implications for hadron structure

J.-Y. Kim, C. Weiss, Phys. Lett. B 848 (2024) 138387 [INSPIRE]

Twist-3 spin-orbit correlations in nucleon

Large instanton effects in twist-3 spin-orbit correlations. Qualitiative change from quark model expectations

J.-Y. Kim, H.-Y. Won, H.-C. Kim, C. Weiss, arXiv:2403.07186



Trace anomaly and pion gravitational form factors

Trace anomaly from "topological compressibility" of QCD vacuum. Low-energy theorems from broken scale invariance

W.-Y. Liu, E. Shuryak, C. Weiss, I. Zahed, arXiv:2405.14026

Christian's slide

Theory and Phenomenology

QGT Topical Collaboration Meeting

QUARK-GLUON TOMOGRAPHY COLLABORATION

A New Look to Azimuthal Modulations and Extraction of GPDs in DVCS

Zhite Yu
(Jefferson Lab, Theory Center)

In collaboration with Jianwei Qiu and Nobuo Sato

PRD 107 (2023) 014007
arXiv: 2409.06882
papers in preparation

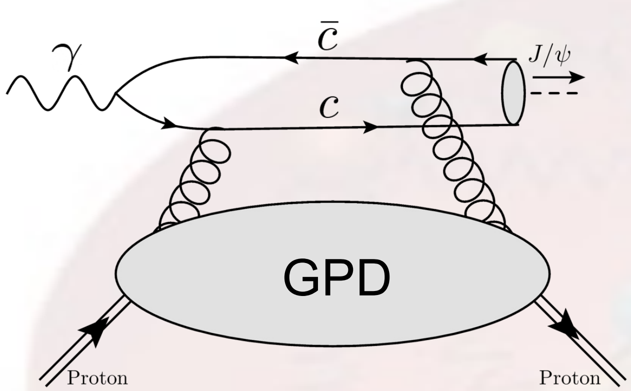
Sep/13/2024
JLab CEBAF

Jefferson Lab

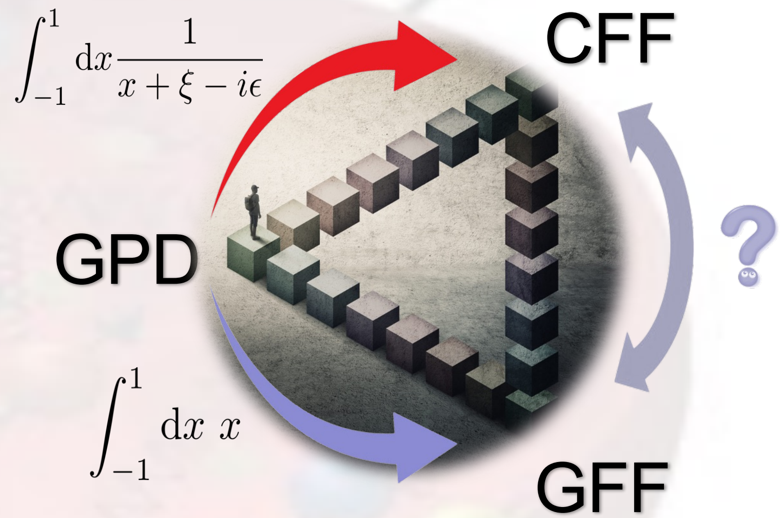
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

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.

Complementary to high energy scattering: Yuxun's talk

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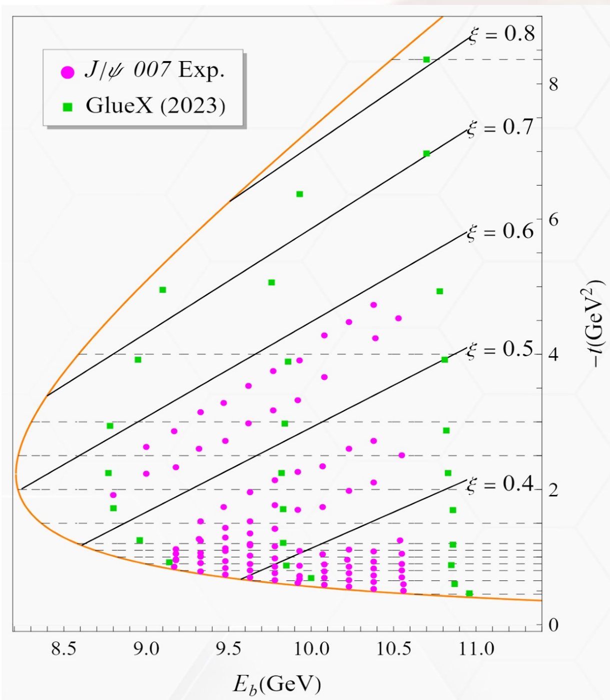
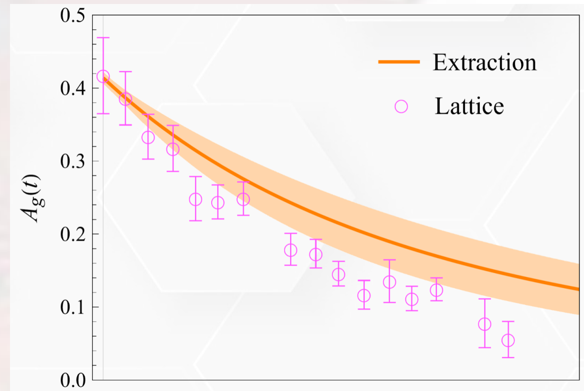
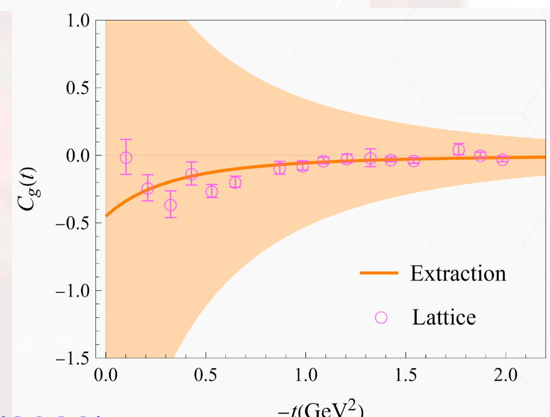
What current data tell us



With ξ > *0.5*
data



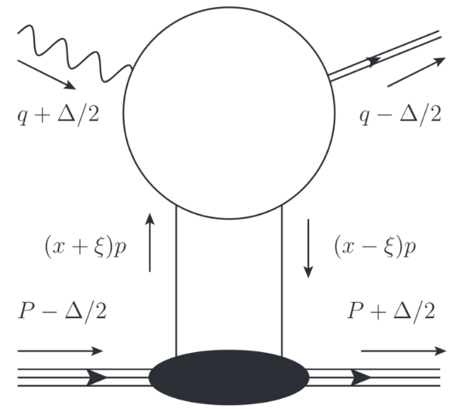


Guo et. al. Phys. Rev. D 108, 034003 (2023)
Lattice: Pefkou et. al. Phys. Rev. D 105, 054509 (2022),
Phys. Rev. Lett. 132, 251904 (2024)

Gluon GPDs from exclusive J/ψ production

Jyotirmoy Roy@Duke

- Matrix elements factorization: (1) photon transition to heavy quarkonium state, (2) gluon GPDs coupling to nucleon states



$$T^{\mu\nu} = \int_{-1}^{1} \frac{dx}{x} \left[C_{\perp,g}\left(\xi/x, Q^2\right) g_{\perp}^{\mu\nu} + C_{L,g}\left(\xi/x, Q^2\right) l^{\mu\nu} \right] \left(\frac{\langle O_1 \rangle_V}{m^3} \right)^{1/2} \frac{F^g(x,\xi)}{x} + \dots$$

- Calculation of (1) using NRQCD factorization to NLO [Ivanov et. al. (2004), Chen and Qiao (2019), Flett et. al. (2021)]

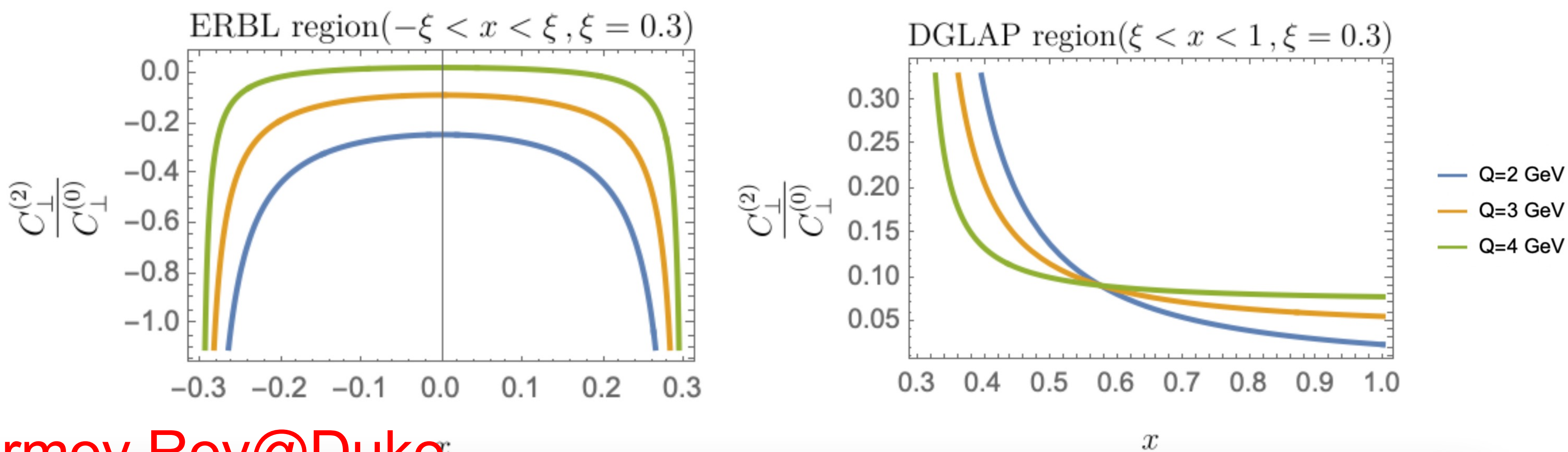
- Relativistic corrections can be large: ${}^3S_1$ decay to lepton pair $> 100\,\%$ [Bodwin and Petelli (2002)], gluon fragmentation to spin-triplet $\sim 40\,\%$ color-octet, $\sim 50\,\%$ color-singlet [Bodwin and Lee (2004)], etc.

- Relativistic corrections in exclusive HVM production leads to double poles in the matching coefficient

Earlier works:
Hoodbhoy, 1998
Lappi et al 2020

$$C^{(0)}_{\perp,g}\left(\xi/x, Q^2\right) \sim \frac{1}{(x-\xi)(x+\xi)}, \qquad C^{(2)}_{\perp,g}\left(\xi/x, Q^2\right) \sim \frac{1}{(x-\xi)^2(x+\xi)^2}$$

- Principal value prescription applicable in the leading calculation fails for the relativistic correction. The region $x = \pm\,\xi$ is sensitive to soft partons and therefore the small light-cone components of the partons needs to be considered in this region



Jyotirmoy Roy@Duke

Explore New Opportunities

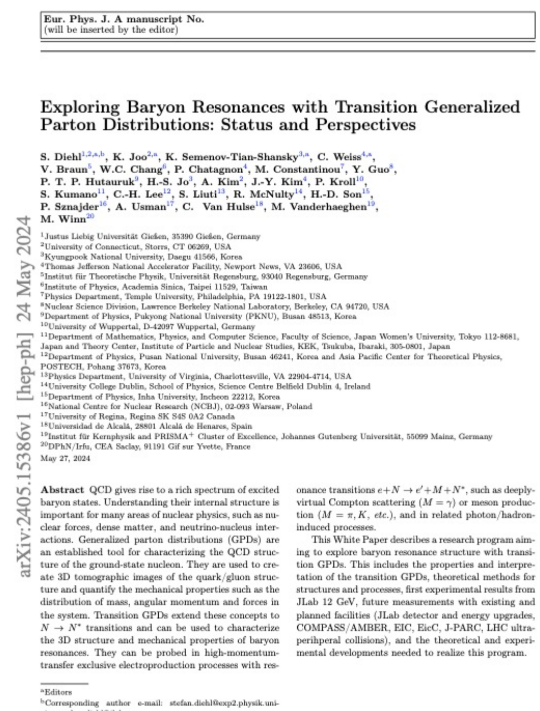
Transition GPD program

GPDs with N → πN, Δ, N* transitions: Explore 3D structure of baryon resonances in QCD

Sampled in exclusive processes with N → πN transitions at JLab12, first results coming

White Paper produced with leadership and contributions from QGT members

C. Weiss (editor), M. Constantinou, Y. Guo, J.-Y. Kim et al., arXiv:2405.15386



Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

Exploring Baryon Resonances with Transition Generalized Parton Distributions: Status and Perspectives

S. Diehl[1,2,a,b], K. Joo[2,a], K. Semenov-Tian-Shansky[3,a], C. Weiss[4,a], V. Braun[5], W.C. Chang[6], P. Chatagnon[4], M. Constantinou[7], Y. Guo[8], P. T. P. Hutauruk[9], H.-S. Jo[3], A. Kim[2], J.-Y. Kim[4], P. Kroll[10], S. Kumano[11], C.-H. Lee[12], S. Liuti[13], R. McNulty[14], H.-D. Son[15], P. Sznajder[16], A. Usman[17], C. Van Hulse[18], M. Vanderhaeghen[19], M. Winn[20]

[1]Justus Liebig Universität Gießen, 35390 Gießen, Germany
[2]University of Connecticut, Storrs, CT 06269, USA
[3]Kyungpook National University, Daegu 41566, Korea
[4]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[5]Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany
[6]Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
[7]Physics Department, Temple University, Philadelphia, PA 19122-1801, USA
[8]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[9]Department of Physics, Pukyong National University (PKNU), Busan 48513, Korea
[10]University of Wuppertal, D-42097 Wuppertal, Germany
[11]Department of Mathematics, Physics, and Computer Science, Faculty of Science, Japan Women's University, Tokyo 112-8681, Japan and Theory Center, Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, 305-0801, Japan
[12]Department of Physics, Pusan National University, Busan 46241, Korea and Asia Pacific Center for Theoretical Physics, POSTECH, Pohang 37673, Korea
[13]Physics Department, University of Virginia, Charlottesville, VA 22904-4714, USA
[14]University College Dublin, School of Physics, Science Centre Belfield Dublin 4, Ireland
[15]Department of Physics, Inha University, Incheon 22212, Korea
[16]National Centre for Nuclear Research (NCBJ), 02-093 Warsaw, Poland
[17]University of Regina, Regina SK S4S 0A2 Canada
[18]Universidad de Alcalá, 28801 Alcalá de Henares, Spain
[19]Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg Universität, 55099 Mainz, Germany
[20]DPhN/Irfu, CEA Saclay, 91191 Gif sur Yvette, France

May 27, 2024

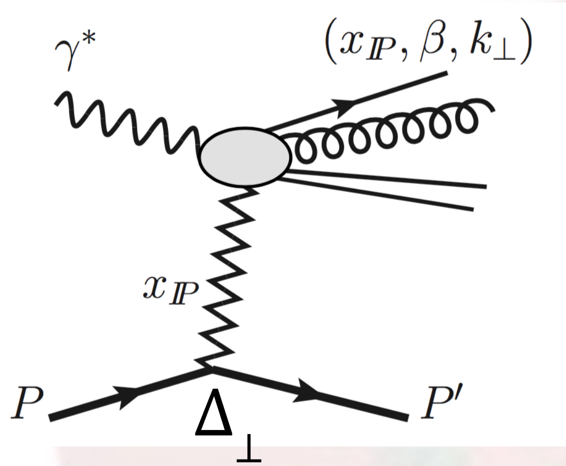
Abstract QCD gives rise to a rich spectrum of excited baryon states. Understanding their internal structure is important for many areas of nuclear physics, such as nuclear forces, dense matter, and neutrino-nucleus interactions. Generalized parton distributions (GPDs) are an established tool for characterizing the QCD structure of the ground-state nucleon. They are used to create 3D tomographic images of the quark/gluon structure and quantify the mechanical properties such as the distribution of mass, angular momentum and forces in the system. Transition GPDs extend these concepts to $N \to N^*$ transitions and can be used to characterize the 3D structure and mechanical properties of baryon resonances. They can be probed in high-momentum-transfer exclusive electroproduction processes with resonance transitions $e + N \to e' + M + N^*$, such as deeply-virtual Compton scattering ($M = \gamma$) or meson production ($M = \pi, K$, *etc.*), and in related photon/hadron-induced processes.

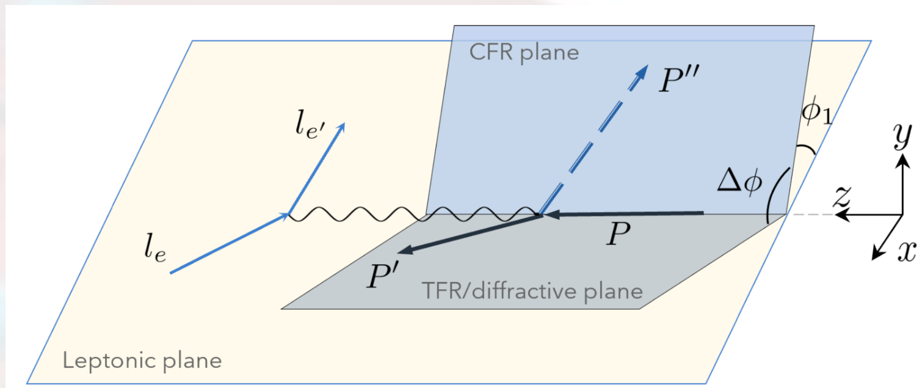
This White Paper describes a research program aiming to explore baryon resonance structure with transition GPDs. This includes the properties and interpretation of the transition GPDs, theoretical methods for structures and processes, first experimental results from JLab 12 GeV, future measurements with existing and planned facilities (JLab detector and energy upgrades, COMPASS/AMBER, EIC, EicC, J-PARC, LHC ultraperihperal collisions), and the theoretical and experimental developments needed to realize this program.

[a]Editors
[b]Corresponding author e-mail: stefan.diehl@exp2.physik.uni-giessen.de, sdiehl@jlab.org

Christian's slide

New avenue: semi-inclusive and inclusive diffractive DIS





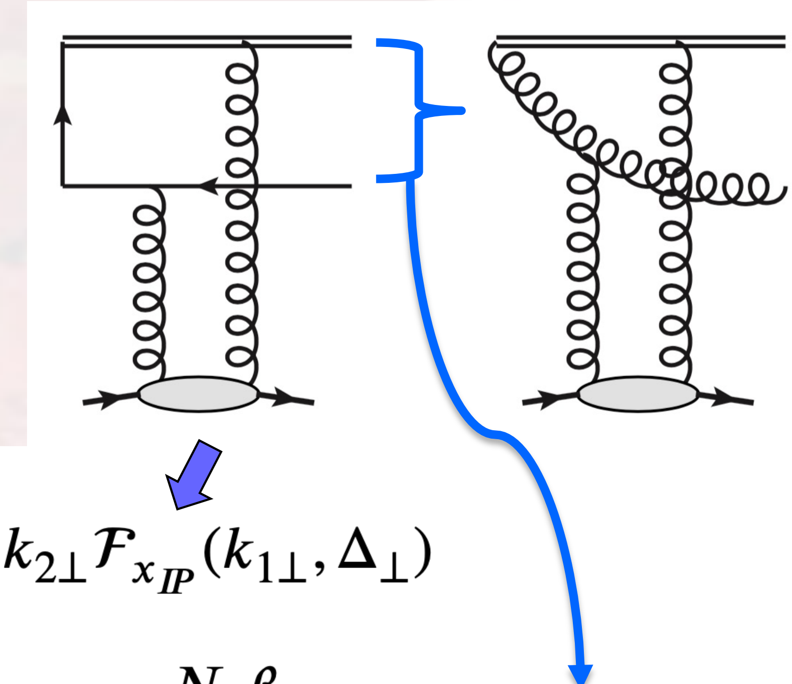
Factorization: Kyle's talk

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 $\Delta_\perp$
- More handle on the GPD extractions

Compute the diffractive PDFs at small-x

- Definition is similar to TMDs for inclusive processes
- Requires large rapidity gap/color-singlet exchange



$$x\frac{d\, f_q^D(\beta, k_\perp; x_{I\!P})}{dY_{I\!P}\, dt\, d\phi_\Delta} = \int d^2k_{1\perp} d^2k_{2\perp} \mathcal{F}_{x_{I\!P}}(k_{1\perp}, \Delta_\perp)$$

$$\times \mathcal{F}_{x_{I\!P}}(k_{2\perp}, \Delta_\perp) \frac{N_c \beta}{(2\pi)^2} \mathcal{T}_q(k_\perp, k_{1\perp}, k_{2\perp})$$

Summarize the leading TMD DPDFs

Elliptic:

$$x\frac{df_{q\epsilon}^{D}(\beta,k_\perp;x_{I\!P})}{dY_{I\!P}\,dt\,d\phi_\Delta}=\frac{N_c\beta\Delta_\perp^2}{16(1-\beta)^2}\Gamma^q\Gamma_\epsilon^q\cos(2\phi_k-2\phi_\Delta)$$

Sivers:

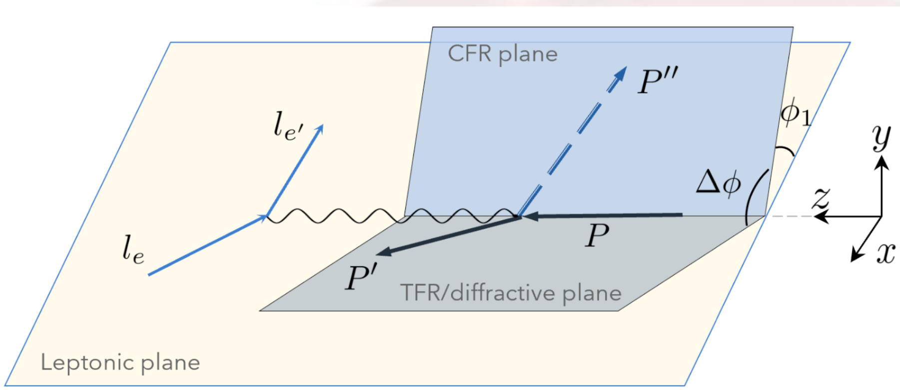
$$x\frac{df_{1Tq}^{D\perp}(\beta,k_\perp;x_{I\!P})}{dY_{I\!P}\,dt}=\frac{\pi N_c\beta}{8(1-\beta)^2}\Gamma^q\Gamma_{S_\perp}^q$$

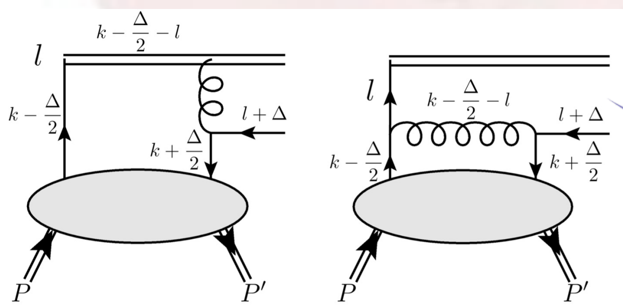
No linearly polarized gluon TMD DPDF!!

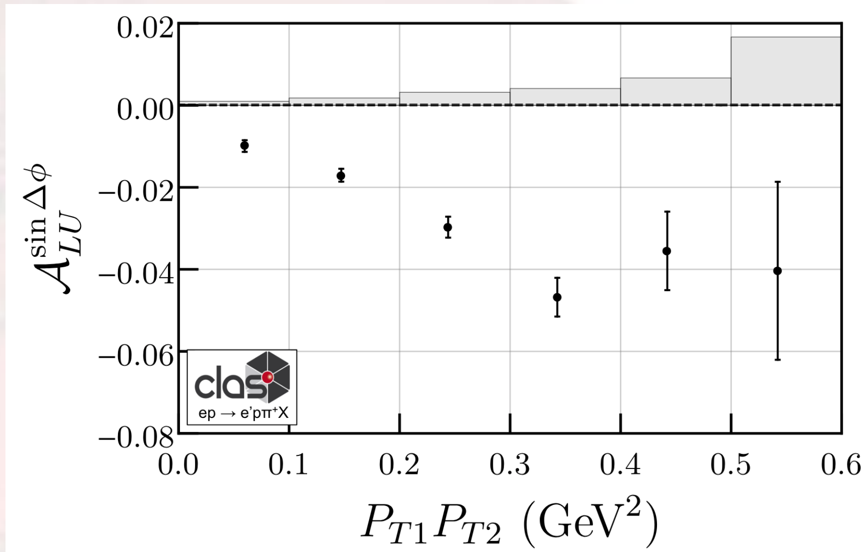
contrast to the non-diffractive case (Metz-Zhou 2011)

Extend to the moderate and large-x

Motivated by a recent JLab exp.



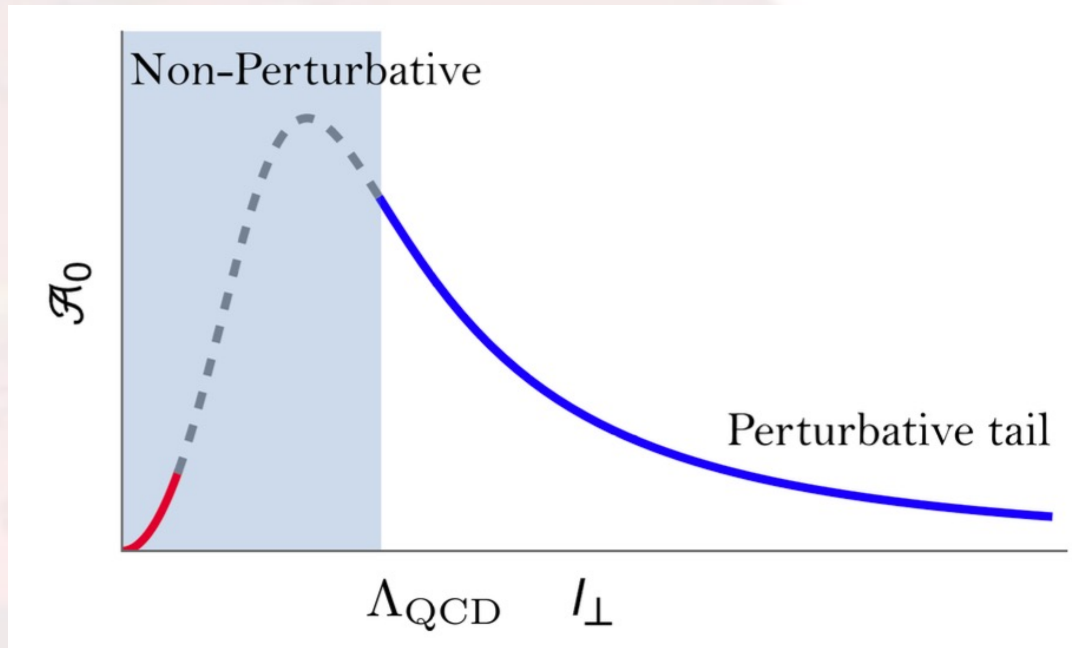




CLAS Coll., 2208.05508

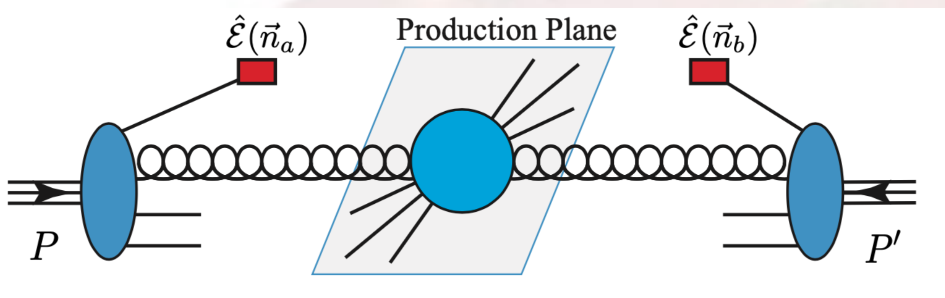
Transition between pert. to non-pert.

- At low transverse momentum, power corrections become important and will modify the transverse momentum dependence
- Applying GTMD will help transition from pert. to non-pert. region

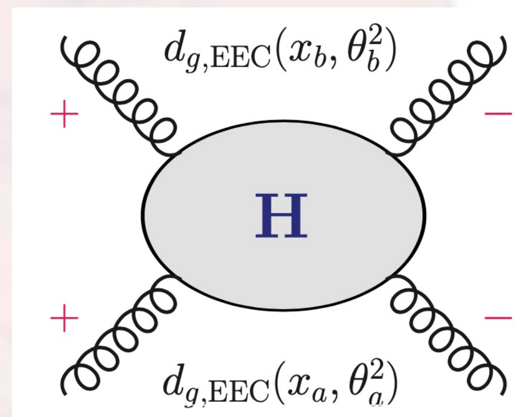


Gluon Tomography from Different Perspective: Spinning gluon at the LHC

Guo, Liu, Yuan, Zhu, arXiv: 2406.05880
Guo, Liu, Yuan, arXiv: 2408.14693



$$\Sigma(Q^2;\theta_{a,b},\phi)$$
$$= \int d\Omega \left\{ x_a f_{g,\mathrm{EEC}}\left(x_a,\theta_a^2\right) x_b f_{g,\mathrm{EEC}}\left(x_b,\theta_b^2\right)\hat{\sigma}_0 \right. \quad (3)$$
$$\left. + x_a d_{g,\mathrm{EEC}}\left(x_a,\theta_a^2\right) x_b d_{g,\mathrm{EEC}}\left(x_b,\theta_b^2\right)\hat{\sigma}_2(Q^2)\cos(2\phi) \right\} ,$$



$\phi = \phi_a - \phi_b$

Two simple examples: Higgs, Top pair

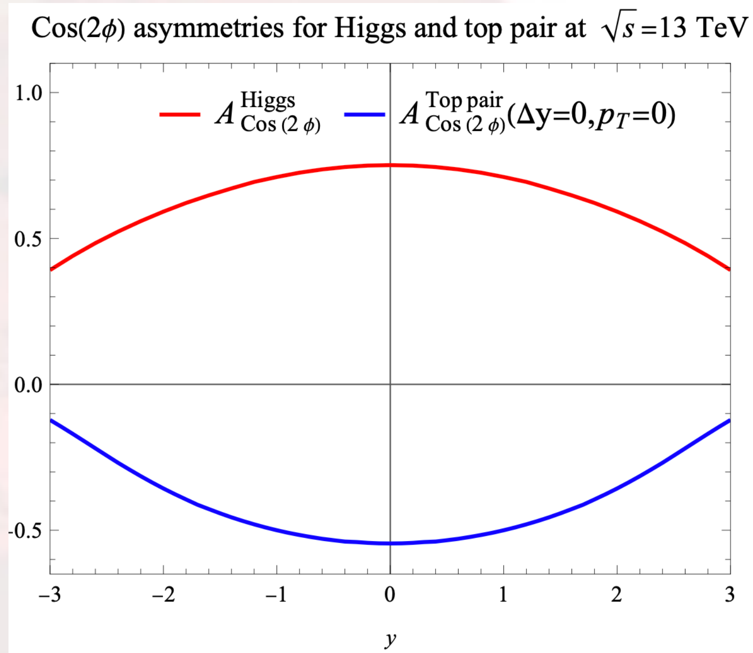
Higgs couples to the spinning gluon directly

$$\hat{\sigma}_2 = \hat{\sigma}_0 = \pi g_\phi^2/64$$

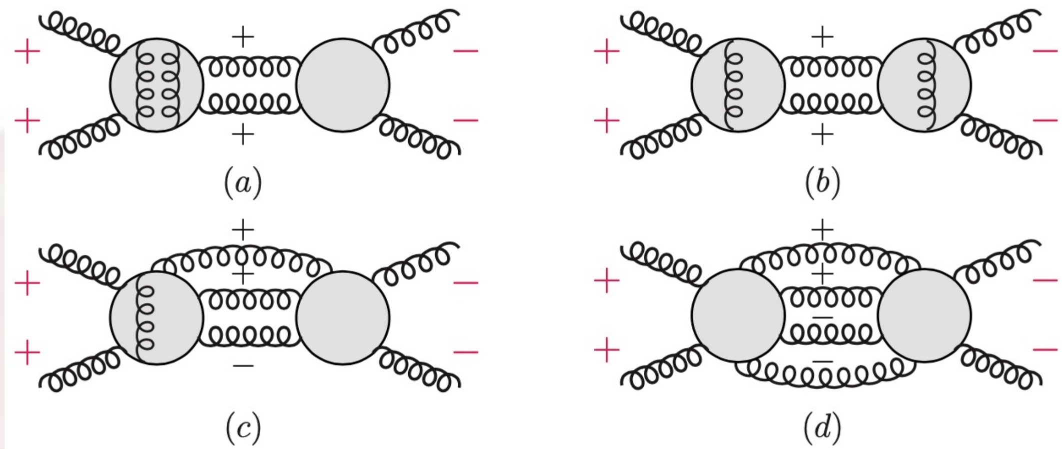
Top quark pair is different

$$\hat{\sigma}_0 = \frac{\alpha_s^2\pi}{\hat{s}^2}\left[\frac{1}{6}\frac{1}{\hat{t}_1\hat{u}_1} - \frac{3}{8}\frac{1}{\hat{s}^2}\right]\left[\hat{t}_1^2 + \hat{u}_1^2 + 4m_t^2\hat{s} - \frac{4m_t^4\hat{s}^2}{\hat{t}_1\hat{u}_1}\right]$$

$$\hat{\sigma}_2 = \frac{\alpha_s^2\pi}{\hat{s}^2}\left[\frac{3}{8}\frac{1}{\hat{s}^2} - \frac{1}{6}\frac{1}{\hat{t}_1\hat{u}_1}\right]\frac{2m_t^4\hat{s}^2}{\hat{t}_1\hat{u}_1}\,, \tag{7}$$

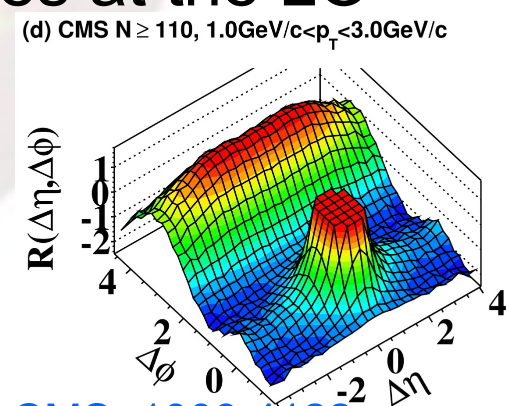


Different story for jet production: a power counting rule



- Helicity structure from QCD processes: (1) $\cos(2\phi)$ vanishes for dijet at LO and NLO; (2) vanishes at the LO for three-jet; (3) for four-jet, it is a LO effect

Number of Jets	2	3	≥ 4
$\langle\cos(2\phi)\rangle$ asymmetry	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(1)$



CMS, 1009.4122

Future looks bright: on track to finish 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 ✔

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