STRONG-2020 ANNUAL MEETING (2022)

WP23-JRA5 GPD-ACT

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WP23 - JRA5 GPD-ACT: GENERALIZED PARTON DISTRIBUTIONS

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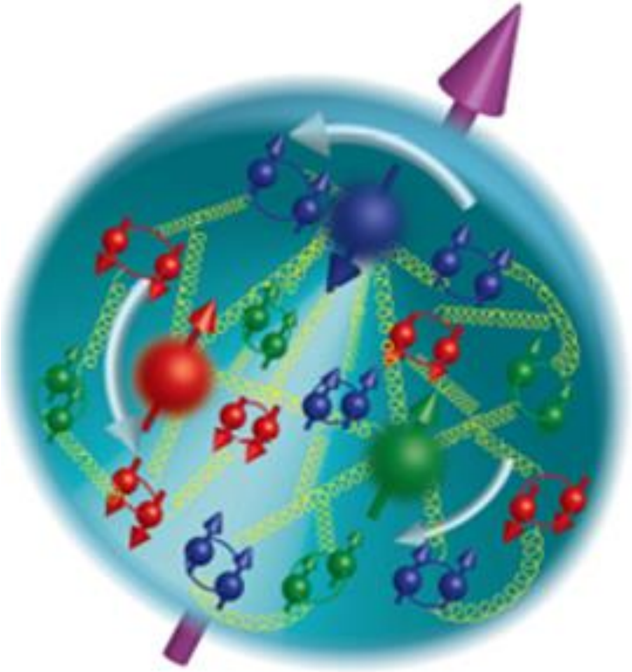

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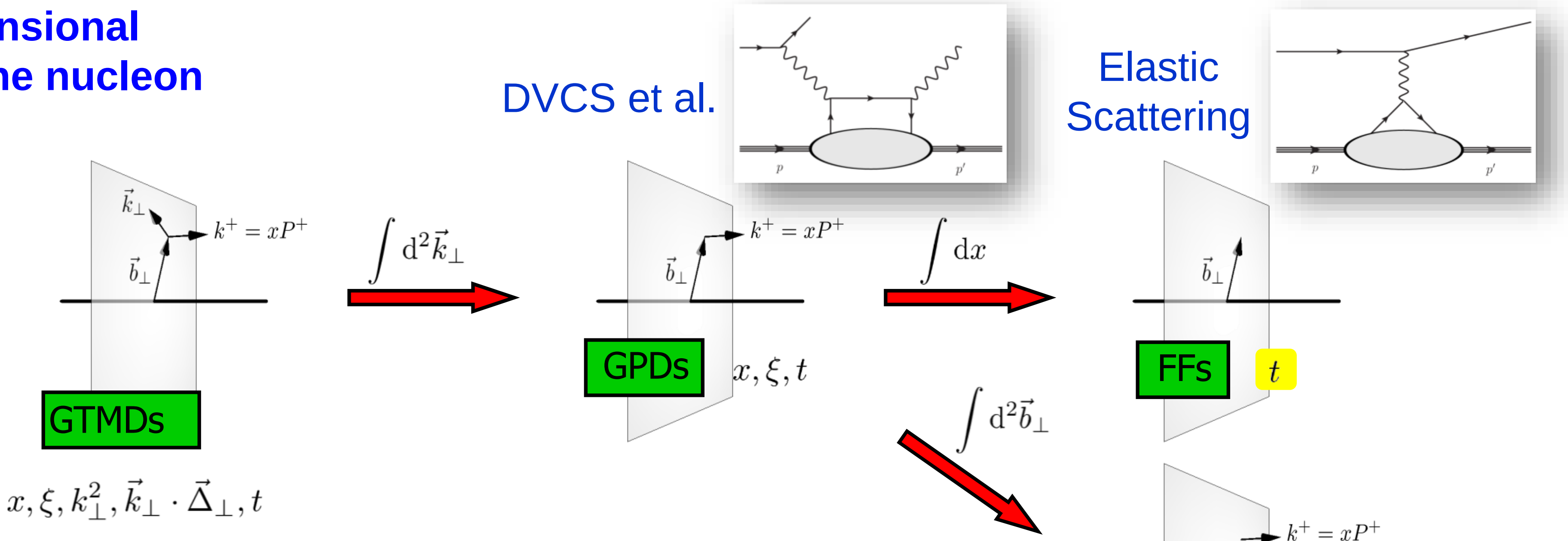
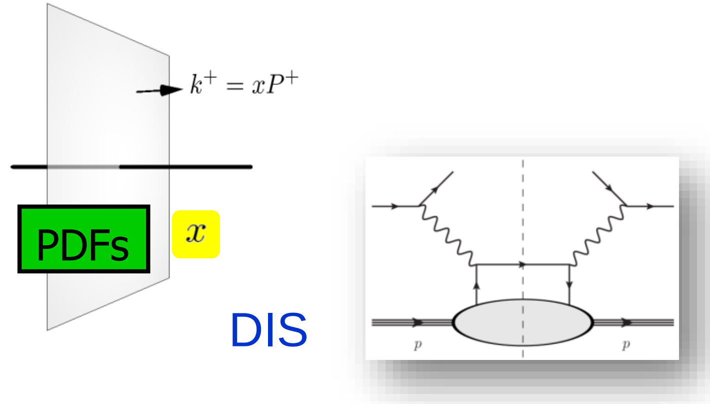
GENERALIZED PARTON DISTRIBUTIONS (GPD)

Multidimensional mapping of the nucleon

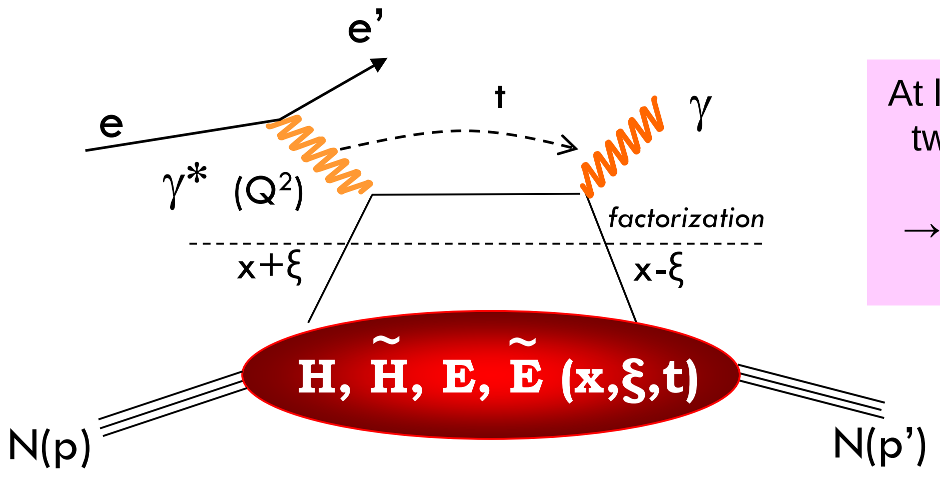




Generalized Parton Distributions:

- Fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space
- Accessible in **hard exclusive** reactions (DVCS, DVMP, TCS,…)

DEEPLY VIRTUAL COMPTON SCATTERING AND INTEREST OF GPDS



At leading order QCD, twist 2, chiral-even, quark sector
→ **4 GPDs for each quark flavor**

DVCS allows access to 4 complex GPDs-related quantities:
Compton Form Factors CFF(x,t)

$$T^{DVCS} \sim P\int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi} dx \pm i\pi GPDs(\pm\xi,\xi,t) + \ldots$$

$$Re\mathcal{H}_q = e_q^2 P \int_0^{+1} \left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right] dx$$

$$Im\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right]$$

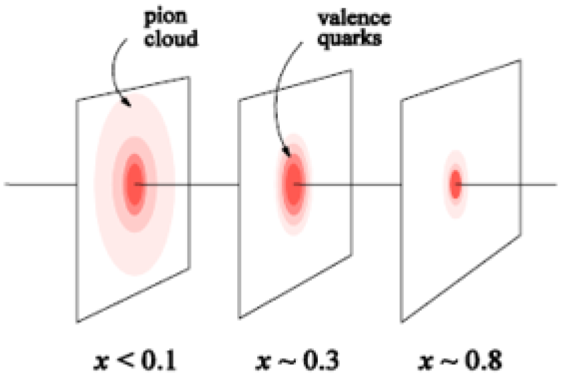
Quark angular momentum (Ji's sum rule)

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0) + E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

Nucleon tomography

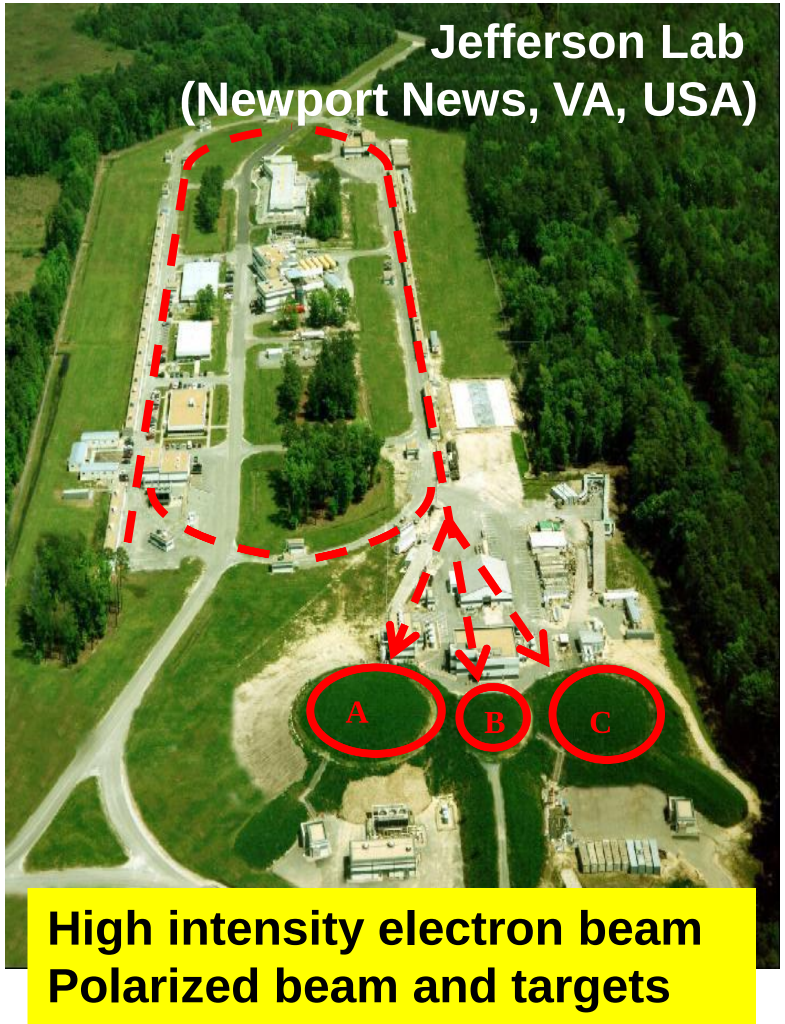
$$q(x,b_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x,b_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} \tilde{H}(x,0,-\Delta_\perp^2)$$



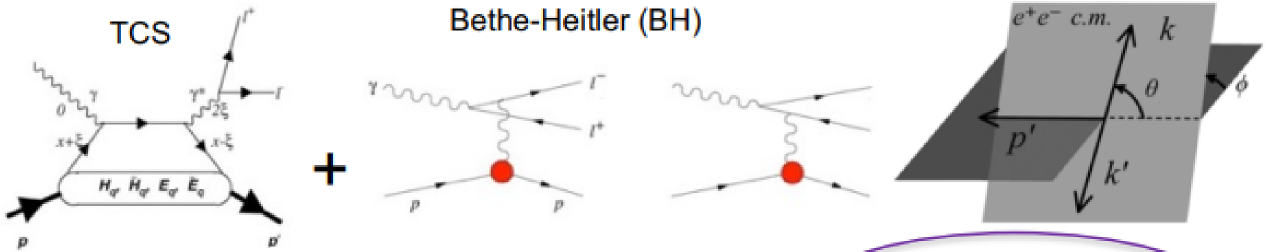
JRA5 GPD-ACT: OBJECTIVES

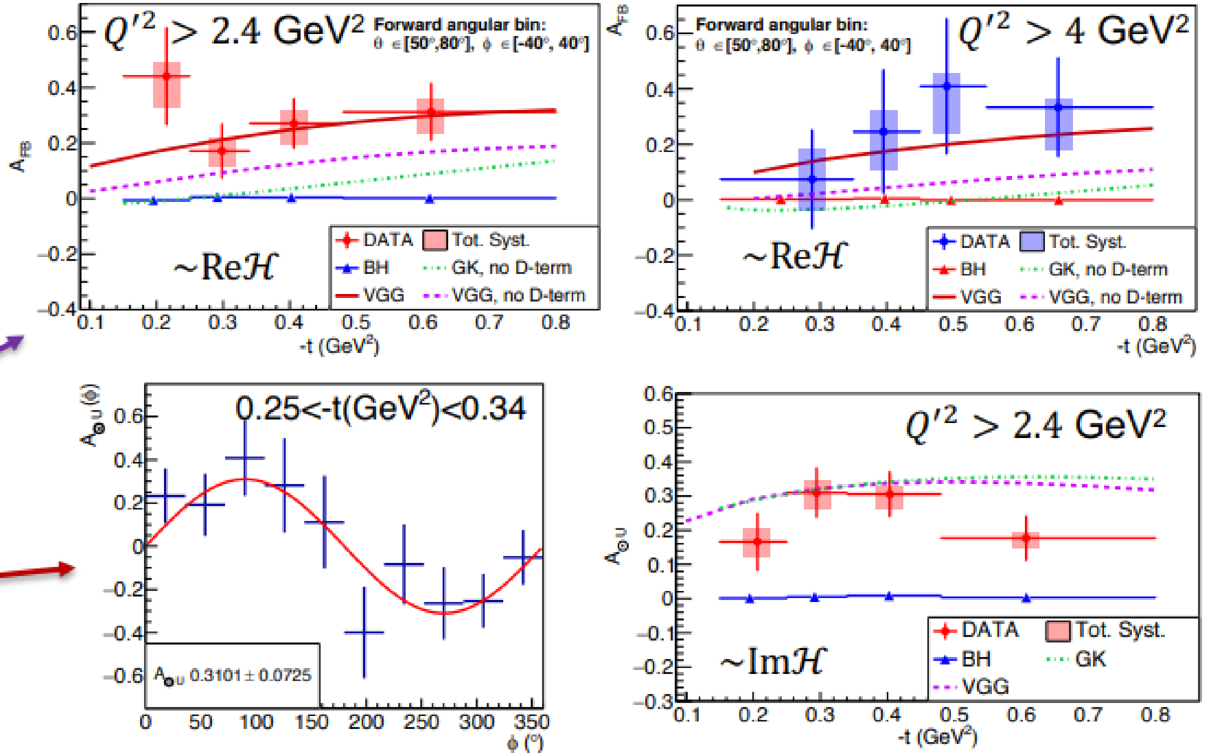
- Analysis of GPD experiments at **JLab@6 GeV** and of DVCS and DVMP with a recoil detector **at COMPASS**
- Preparation, data taking, and analysis of new experiments for **JLab@12GeV** (nDVCS, nuclear DVCS, TCS, DDVCS)
- Producing projections for GPD experiments to propose for the Electron Ion Collider (EIC)
- Building models of GPDs (standard twist-2, but also twist-3 and transversity GPDs), using also the constraints obtained by lattice QCD calculations
- Improved theoretical studies, including higher order and higher twist corrections
- Both experimental and theoretical efforts will be combined in **extraction of GPD information by fits to the data**.



CLAS12: FIRST MEASUREMENT OF TIMELIKE COMPTON SCATTERING

TCS – time-reversal symmetric process to DVCS:
incoming photon is real, and the outgoing photon has large time-like virtuality.





$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right]$$

Incoming photon polarization

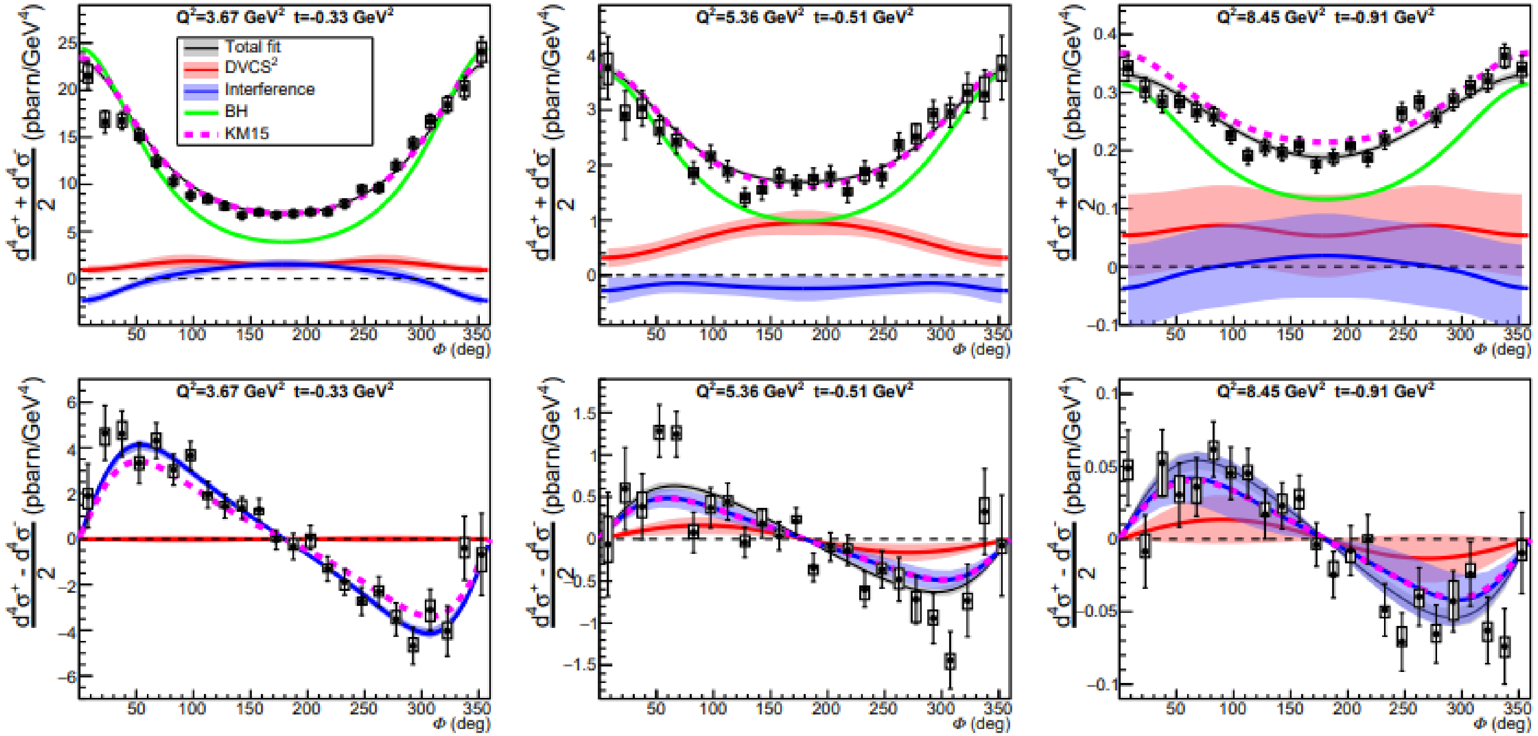
$$-\lambda\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right].$$

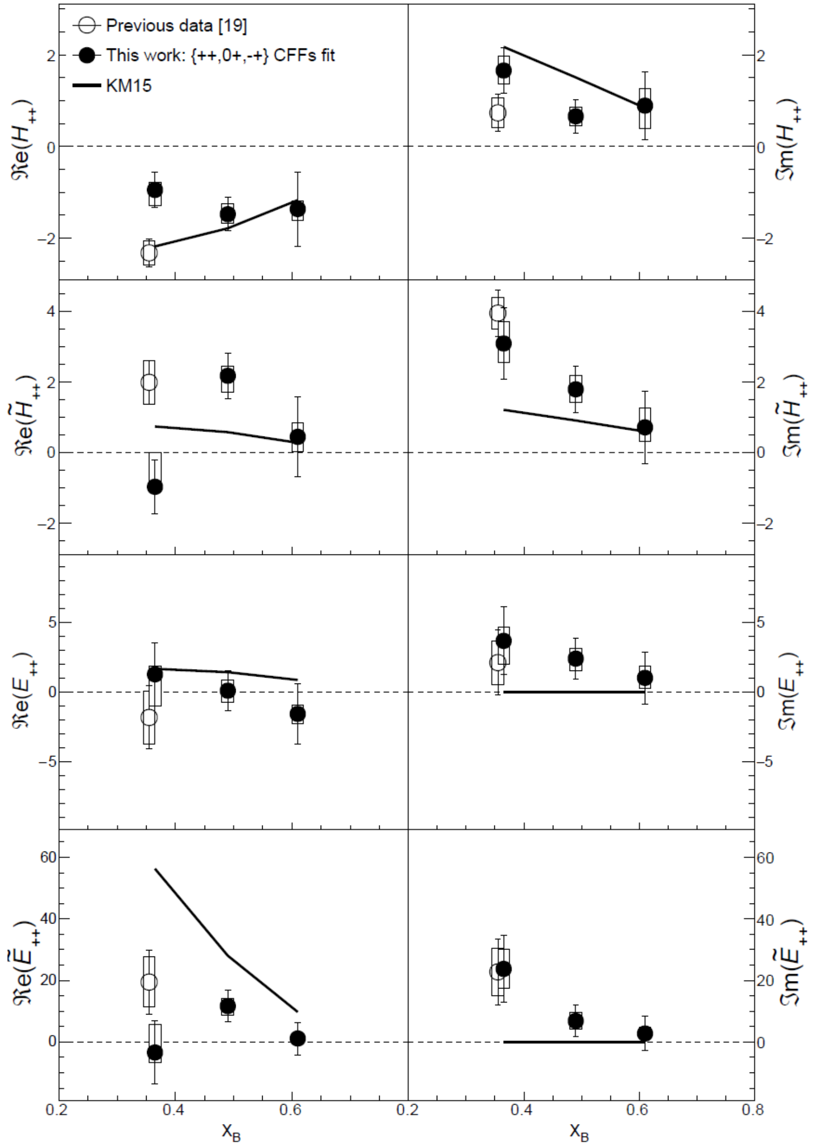
$\gamma p \rightarrow \gamma^* p \rightarrow e^+ e^- p$

Phys. Rev. Lett. 127, 262501 (2021)

- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and **probes the universality of GPDs**
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $D_q(t)$ that relates to the **mechanical properties of the nucleon** (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.

HALL-A: HIGH-PRECISION CROSS SECTIONS FOR DVCS ON THE PROTON

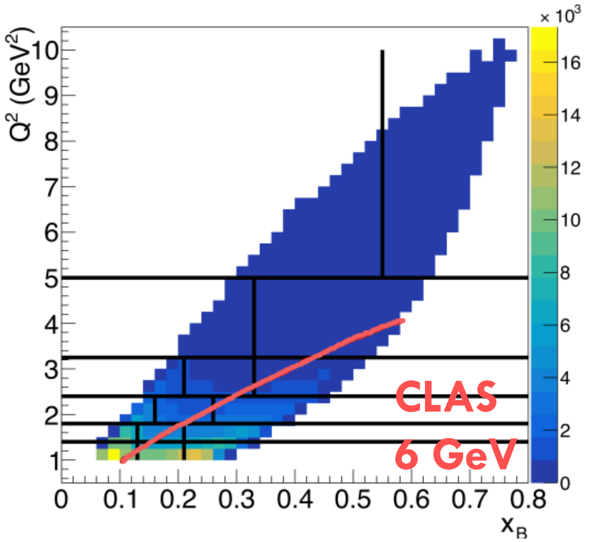




- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Separation of BH, DVCS^2, Interference terms
- Sensitivity to all 4 Compton Form Factors

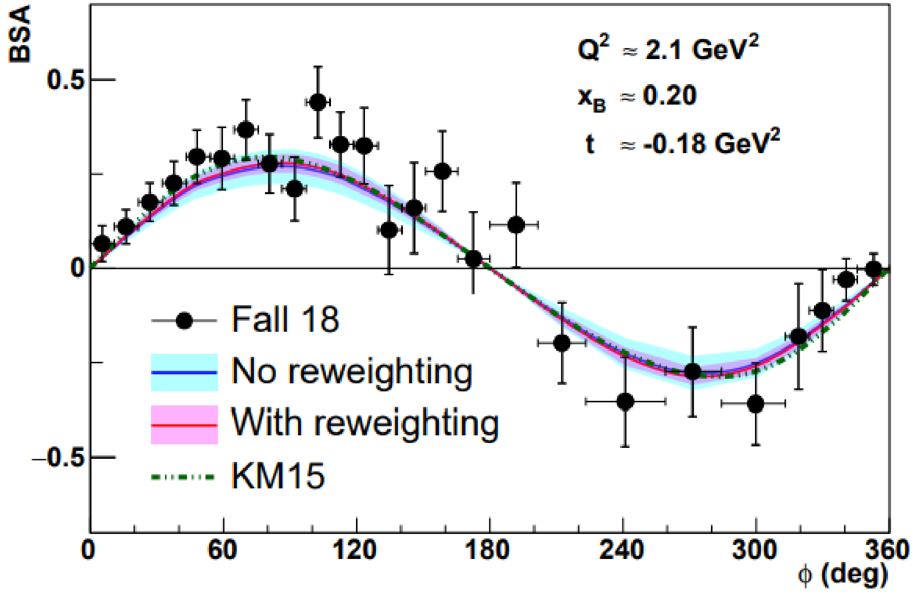
Phys. Rev. Lett. 128, 252002 (2022)

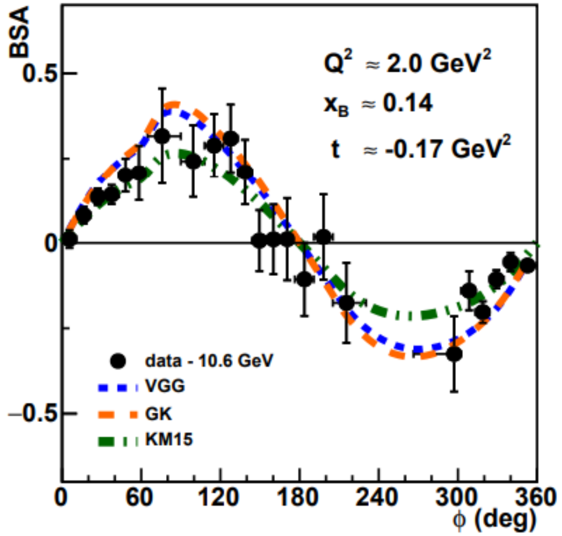
CLAS12: BEAM SPIN ASYMMETRY FOR DVCS ON THE PROTON

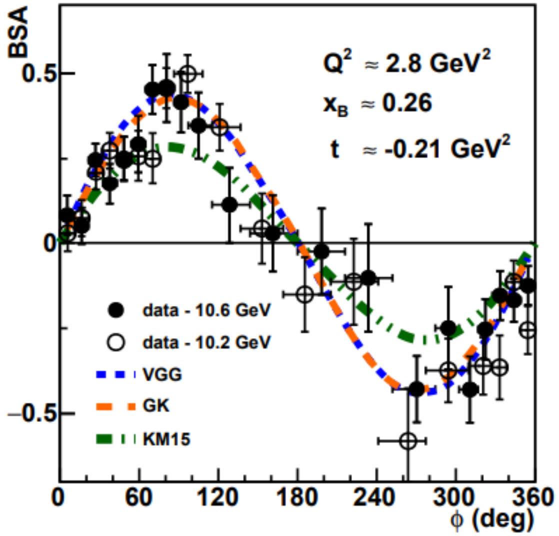


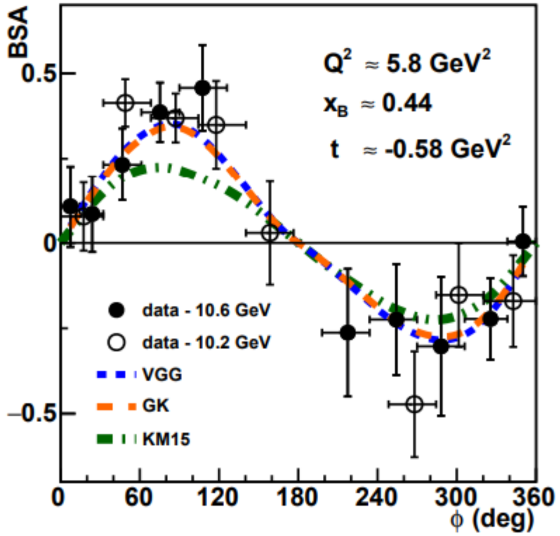
$\vec{e}p \rightarrow ep\gamma$

- Polarized beam (86%) E=10.6 GeV; unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits









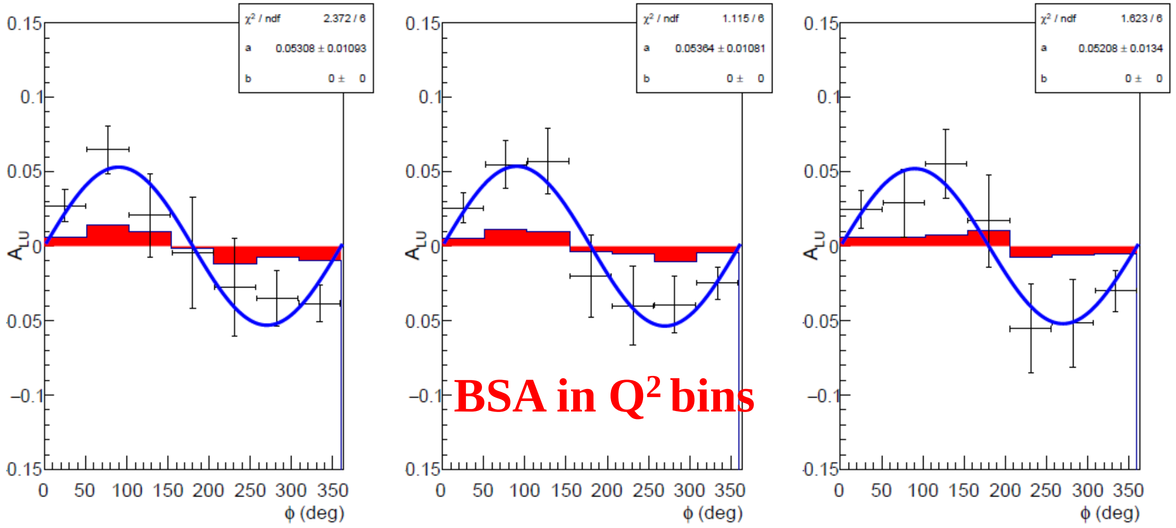
Examples of kinematics only accessible with ~10.6-GeV beam

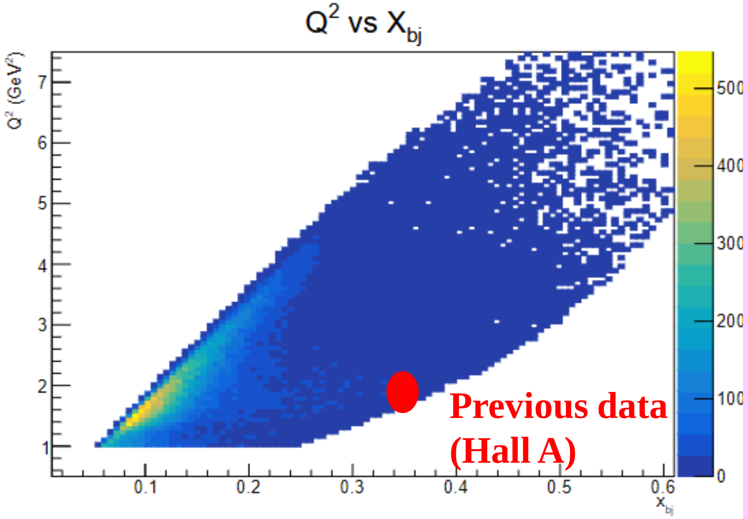
To be submitted to PRL for publication in two weeks (final stage of Collaboration review)

CLAS12: BEAM SPIN ASYMMETRY FOR NEUTRON DVCS

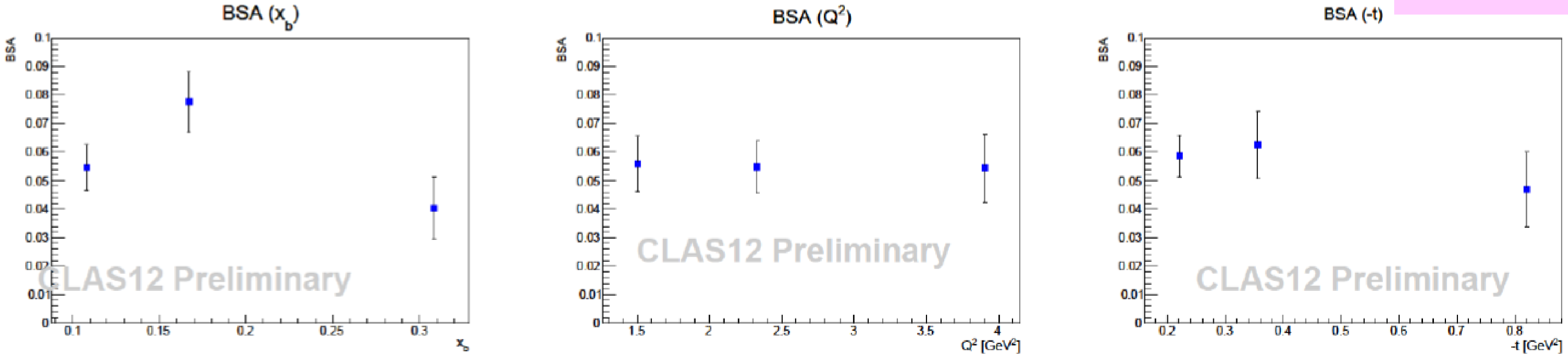
$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}$

$\vec{e}d \rightarrow en\gamma(p)$

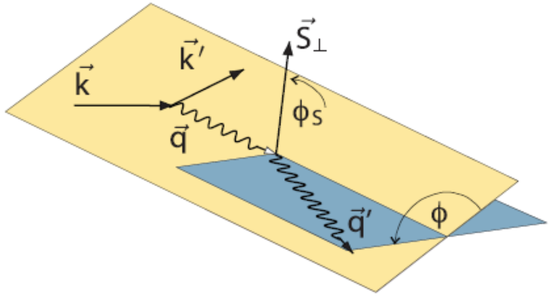


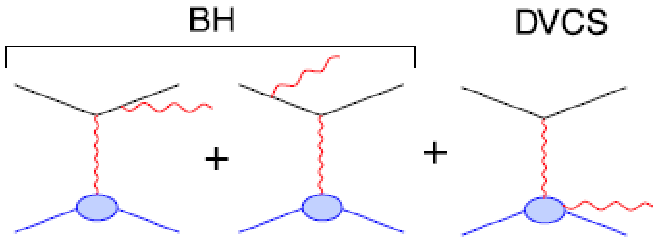


- LD2 target, ~10.4 GeV beam energy
- Scan of the BSA on a wide phase space
- Reaching the high Q^2- high x_B region
- Exclusivity thanks to **detection of the active neutron** → small systematics
- Analysis undergoing internal review
- Publication in early 2023



COMPASS 2016: DVCS+BH CROSS SECTION AT E=160 GEV

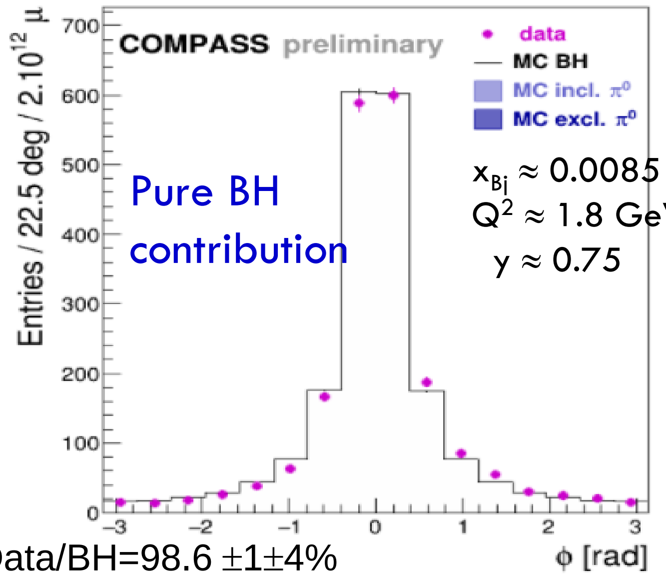




$$\Sigma = d\sigma(\overleftarrow{\mu}^{+}) + d\sigma(\overrightarrow{\mu}^{-})$$

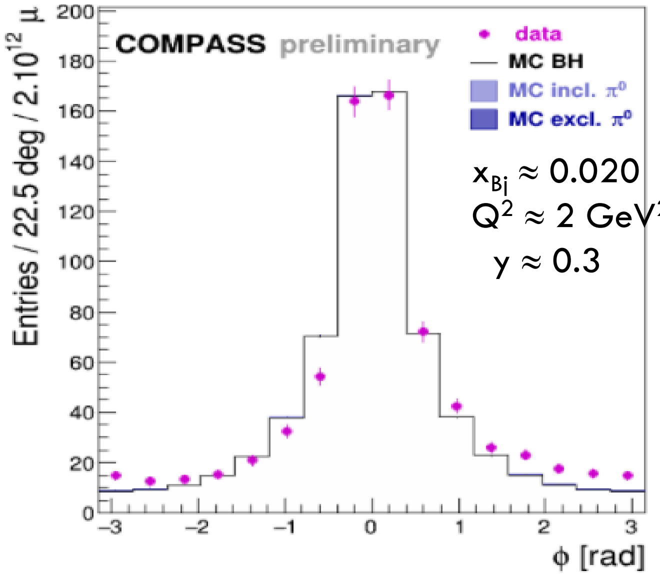
$$d\sigma \,\alpha\, |T^{BH}|^2 + \text{Interference Term} + |T^{DVCS}|^2$$

$80 < \nu\,[\text{GeV}] < 144$

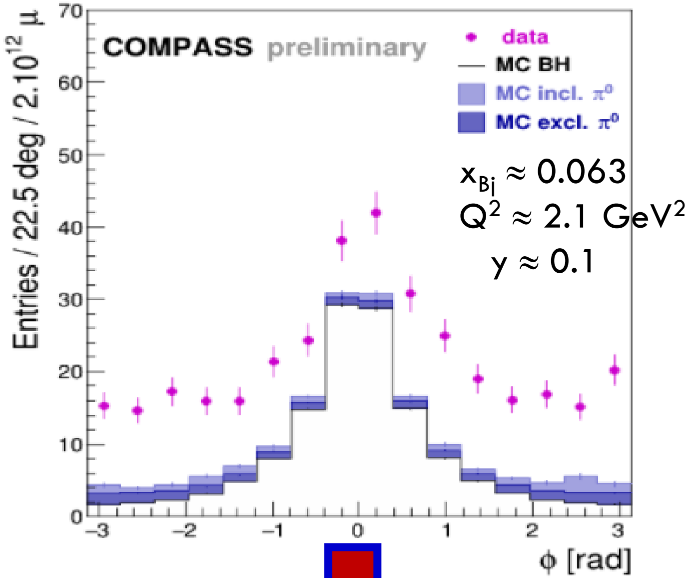


Data/BH=98.6 ±1±4%

$32 < \nu\,[\text{GeV}] < 80$



$10 < \nu\,[\text{GeV}] < 32$



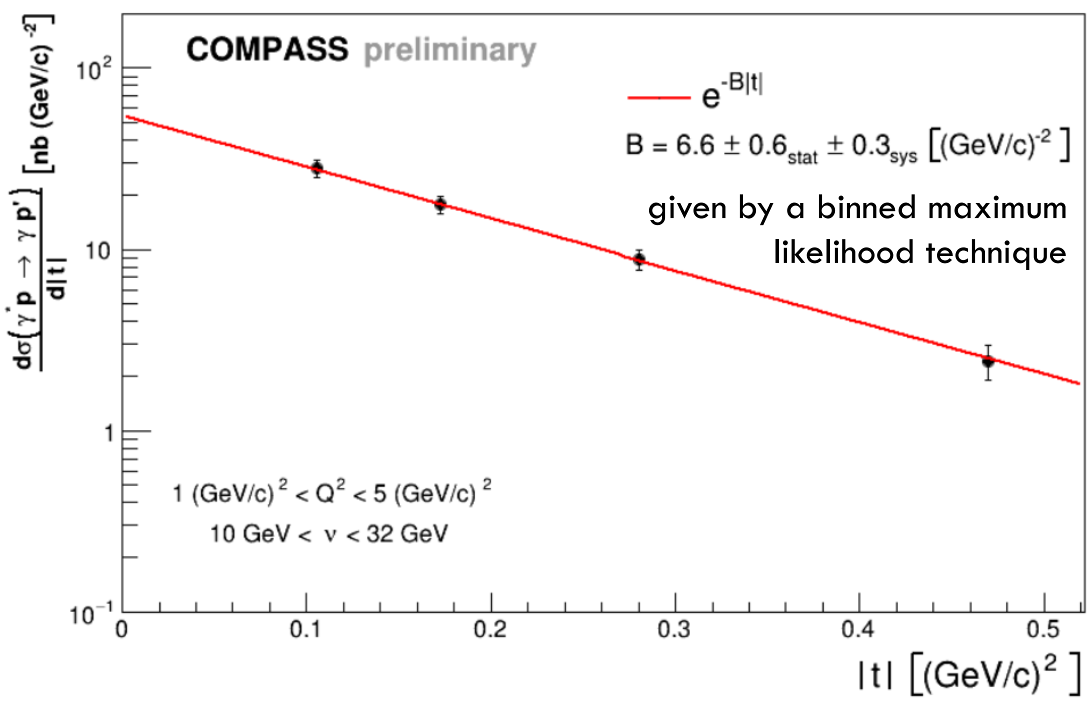
DVCS above the BHcontrib.

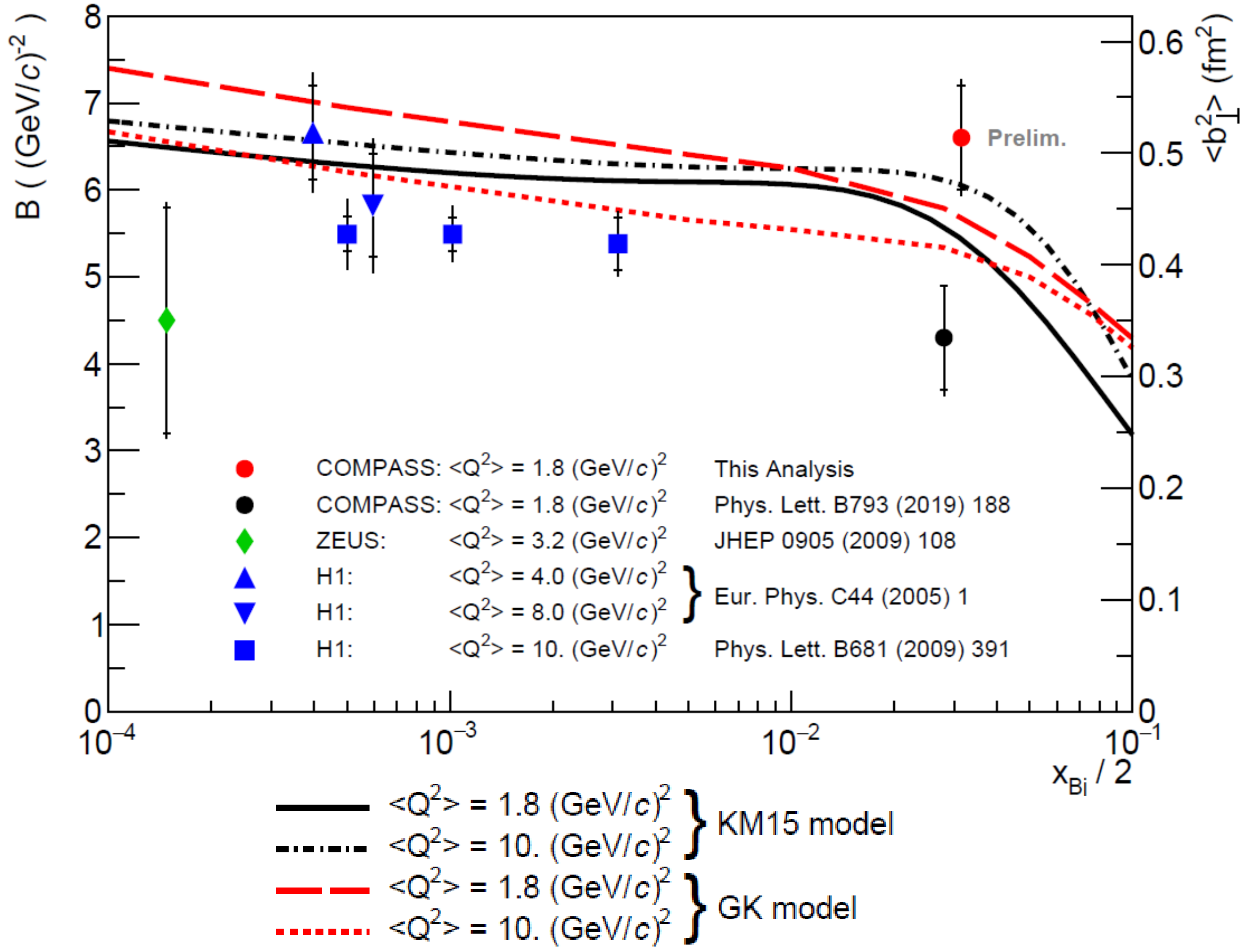
MC: BH contribution evaluated for the integrated luminosity
π° background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

COMPASS 2012-2016 TRANSVERSE EXTENSION OF PARTONS IN THE SEA QUARK RANGE

$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$ $\langle b_\perp^2(x)\rangle \approx 2B(\xi)$

2012 statistics = Ref
2016 analysed statistics = 2.3 × Ref
2016+2017 expected statistics = 10 × Ref





3σ difference between 2012 and 2016 data

- more advanced analysis with 2016 data
- π^0 contamination with different thresholds
- binning with 3 variables (t,Q^2,ν) or 4 variables (t,ϕ,Q^2,ν)

COMPASS 2012 – 2016: EXCLUSIVE π^0 PRODUCTION ON UNPOLARIZED PROTON

$\mu^\pm p \rightarrow \mu^\pm \pi^0 p$

$F\pi^0 = 2/3 F^u + 1/3 F^d$

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

COMPASS
Q^2=2.0 GeV^2
x_B=0.093
|t|~ 0.26 GeV^2
ε close to 1

$$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

$$\frac{d\sigma_T}{dt} \propto \left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{TT}}{dt} \propto \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{LT}}{dt} \propto \frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^* \langle\tilde{E}\rangle\right]$$

$$\left\langle\frac{d\sigma_T}{d|t|} + \epsilon\frac{d\sigma_L}{d|t|}\right\rangle = (8.2 \pm 0.9_{stat}\,{}^{+\,1.2}_{-\,1.2}|_{sys})\frac{nb}{(GeV/c)^2}$$

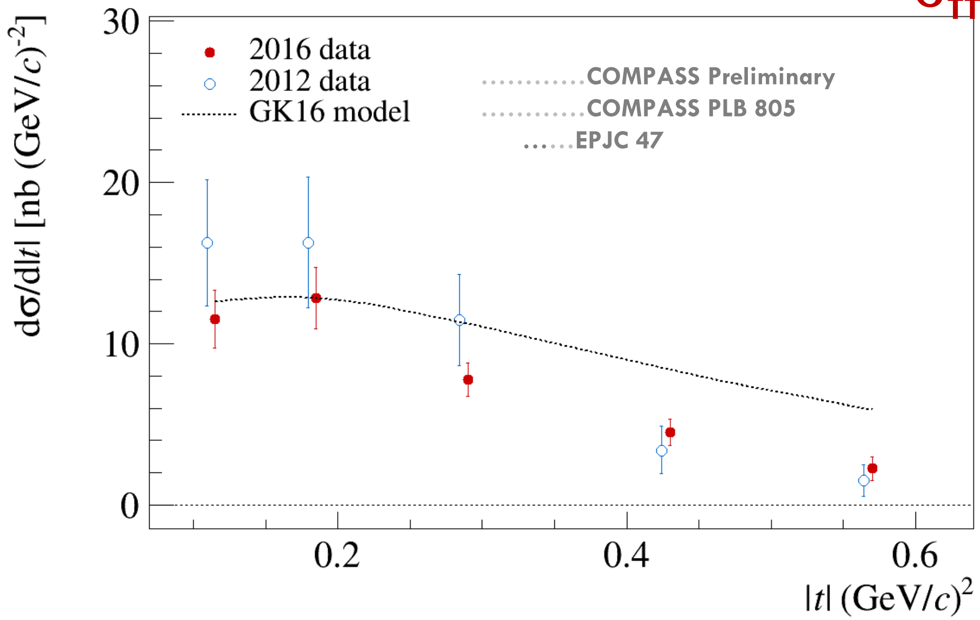
$$\left\langle\frac{d\sigma_{TT}}{d|t|}\right\rangle = (-6.1 \pm 1.3_{stat}\,{}^{+\,0.7}_{-\,0.7}|_{sys})\frac{nb}{(GeV/c)^2}$$

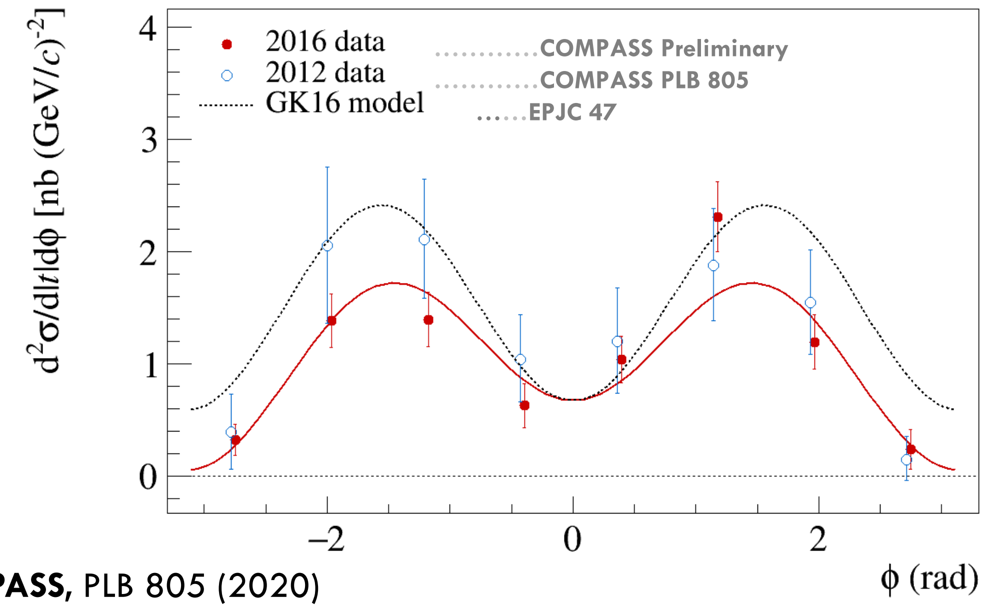
$$\left\langle\frac{d\sigma_{LT}}{d|t|}\right\rangle = (1.5 \pm 0.5_{stat}\,{}^{+\,0.3}_{-\,0.2}|_{sys})\frac{nb}{(GeV/c)^2}$$

PLB 805 (2020)

σ_{TT} large - impact of $\bar{E}_T$

σ_{LT} small but significantly positive as at CLAS

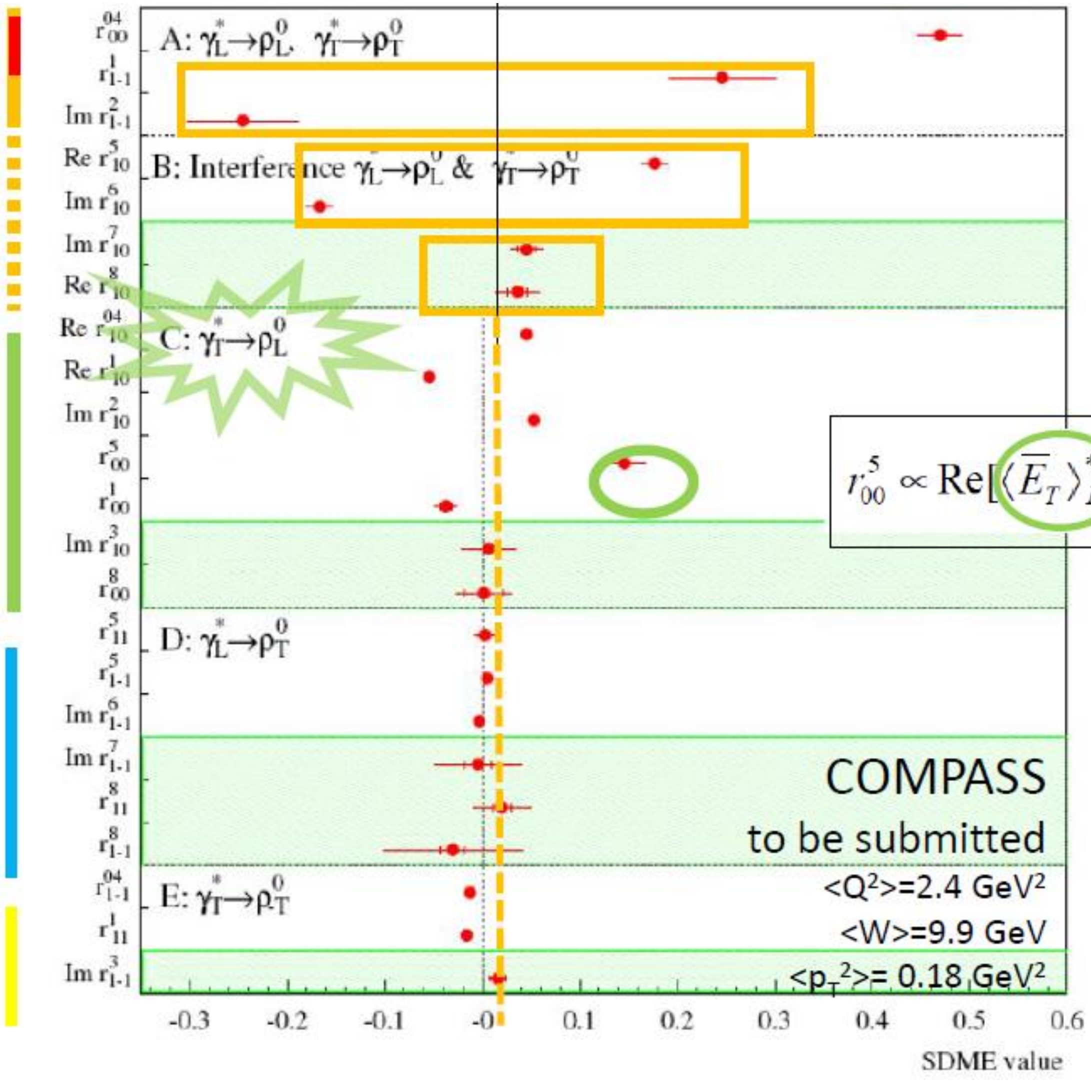




Data: **COMPASS,** PLB 805 (2020)

Models: **GK** Kroll Goloskokov EPJC47 (2011) Also **GGL:** Golstein Gonzalez Liuti PRD91 (2015)

COMPASS 2012: EXCLUSIVE RHO0 PRODUCTION ON UNPOLARIZED PROTON



If SCHC ($\lambda_\gamma = \lambda_V$)

measurements:

$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0 \quad = 0.000 \pm 0.005 \pm 0.003,$$

$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0 \quad = 0.011 \pm 0.002 \pm 0.002,$$

$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0 \quad = 0.009 \pm 0.014 \pm 0.028,$$

All the other SDME in classes C,D, E should be 0

not observed for class C

$$r^5_{00} \propto \mathrm{Re}[\langle \overline{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$$

From Goloskokov and Kroll, EPJC74 (2014) 2725

Spin Density Matrix Elements using the 2012 data

- **Final results – the draft is ready to be submitted to EPJC**
- *Main result:*
- SCHC is not conserved for transition $\gamma^*_T \to V_L$, impact of chiral-odd GPDs H_T and E_T
- In the transition $\gamma^*T \to VT$ dominance of the Natural Parity Exchange GPDs H and E

SDME in Exclusive ϕ muon-production using the 2016 data:

- good progress on the analysis

10 Conference presentations in 2022 for COMPASS (GPD-ACT)

NEWS ON THE THEORY/PHENOMENOLOGY SIDE

First public release of Gepard software

README.md

Tests passing | codecov 82%

Gepard

Synopsis

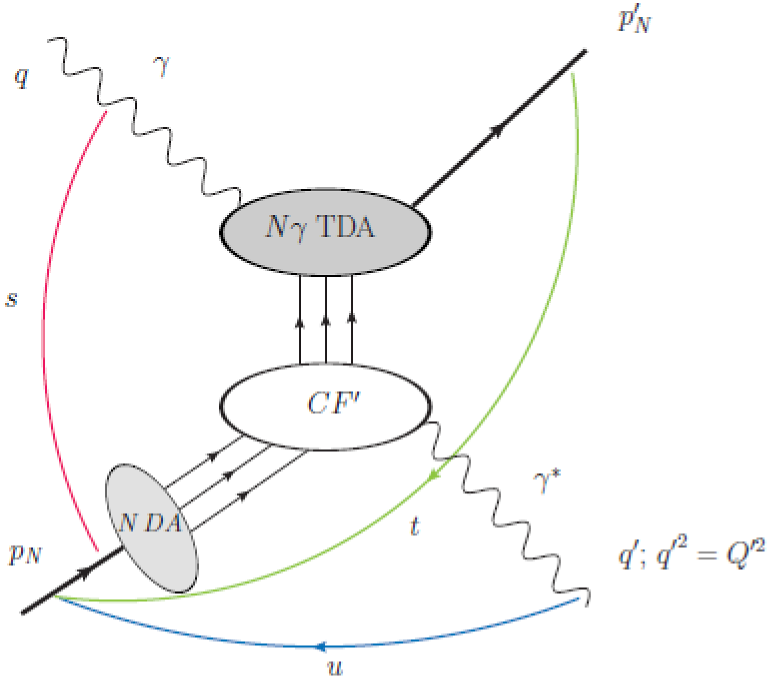
Gepard - tool for studying the 3D quark and gluon distributions in the nucleon

- Modelling Generalized Parton Distributions (GPD) and Compton form factors (CFF).
- Perturbative NLO QCD evolution of GPDs
- Calculation of deeply virtual Compton scattering (DVCS) and deeply virtual meson production (DVMP) observables to NLO accuracy.
- Fitting parametrized models to the experimental data.

NEWS ON THE THEORY/PHENOMENOLOGY SIDE

Backward Timelike Compton scattering

***Backward timelike Compton scattering to decipher the photon content of the nucleon*, Eur. Phys. J. C 82 (2022) 7, 656**



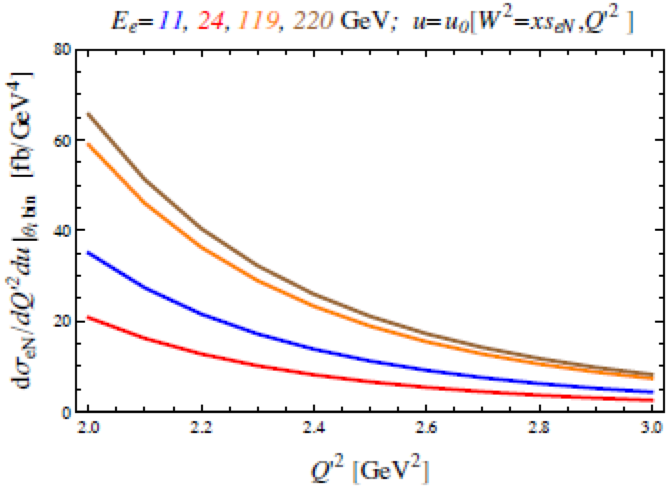
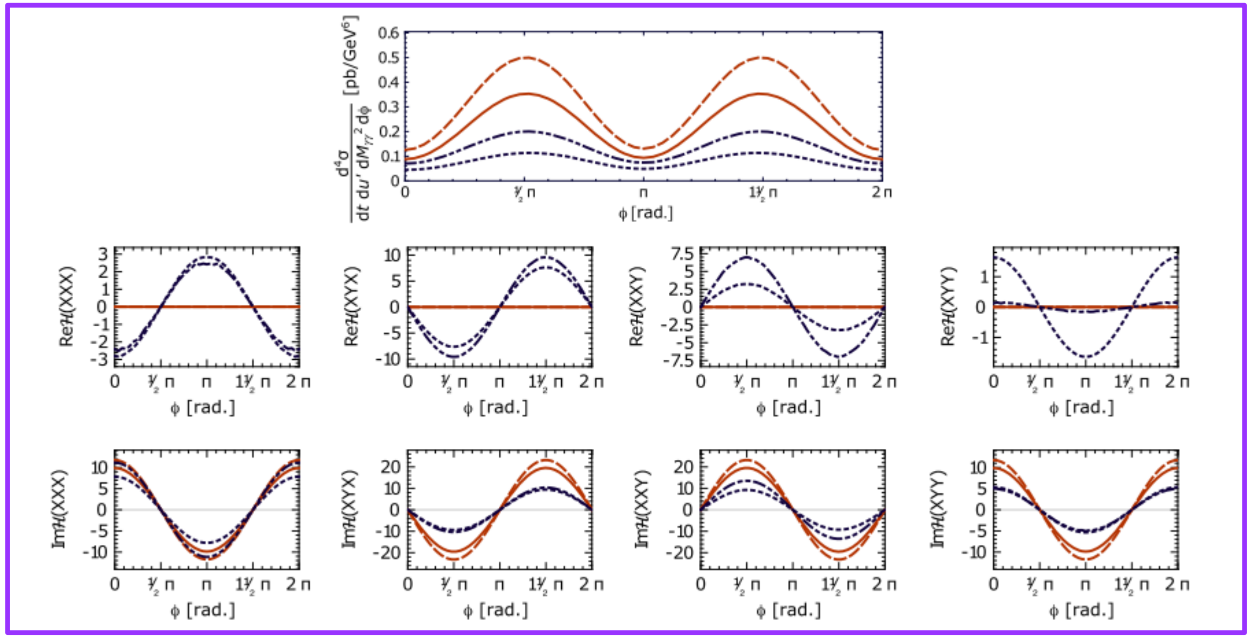


FIG. 9: The electron-nucleon cross section (47) integrated over θ_ℓ as a function of Q'^2 for $u = u_0$ (exactly backward TCS) at electron beam energies E_e corresponding (from down to up) to kinematical conditions of JLab@12, JLab@24 and of EIC and EicC. We employ the VMD-based model for γN TDAs and account for the contribution of $\omega(782)$ meson. We use the set of $G^{V,T}_{\omega NN}$ couplings Bonn 2000 [29] and COZ solution for nucleon DAs as phenomenological input.

NEWS ON THE THEORY/PHENOMENOLOGY SIDE

- *Progress and opportunities in backward angle (u-channel) physics*, Eur. Phys. J. A 57 (2021) 12, 342
- *Collinear factorization of diphoton photoproduction at next to leading order*, Phys. Rev. D 104 (2021) 11, 114006
- *Phenomenology of diphoton photoproduction at next-to-leading order*, Phys. Rev. D 105 (2022) 9, 094025



- *Artificial neural network modelling of generalised parton distributions*, Eur.Phys.J.C 82 (2022) 3, 252
- *Accessing the Pion 3D Structure at US and China Electron-Ion Colliders*, Phys.Rev.Lett. 128 (2022) 20, 202501
- *Pion generalized parton distributions: A path toward phenomenology*, Phys.Rev.D 105 (2022) 9, 094012
- *Revisiting evolution equations for generalised parton distributions*, Eur.Phys.J.C 82 (2022) 10, 888
- *EpIC: novel Monte Carlo generator for exclusive processes*, Eur.Phys.J.C 82 (2022) 9, 819

- "Wide-angle photo- and electroproduction of pions to twist-3 accuracy", Phys. Rev. D 104 (2021) 5, 054040
- "Wide-angle photoproduction of the η′-meson and its gluon content", Phys. Rev. D 105 (2022) 3, 034005
- The pion in the graviton soft-wall model: phenomenological applications, Eur. Phys. J. C 82 (2022) 7, 626

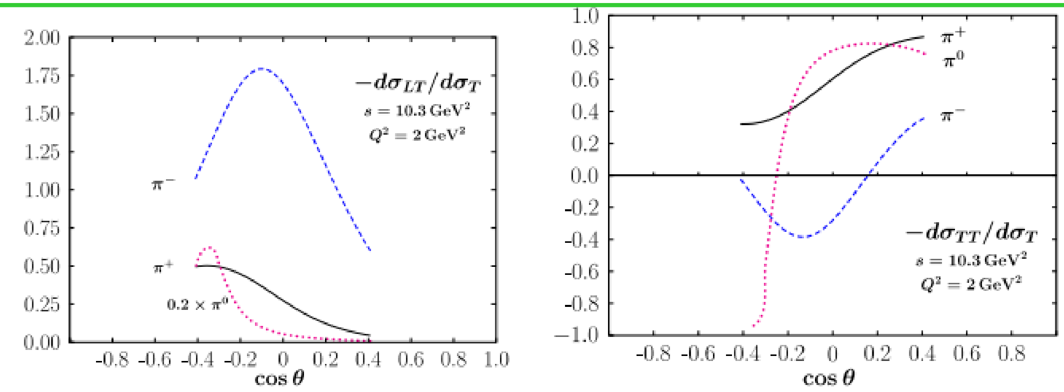


FIG. 9. Predictions for the longitudinal-transverse (left) and transverse-transverse (right) interference cross sections of pion electroproduction vs $\cos\theta$ at at $s = 10.3$ GeV^2 and $Q^2 = 2.0$ GeV^2. The interference cross sections are divided by the corresponding transverse cross section.

CONCLUSIONS

1) A wealth of physics results were obtained since the last year: publication of TCS (CLAS12), pDVCS@HallA; more papers from CLAS on their way; COMPASS progressing on DVMP and DVCS; several theory/phenomenology publications on GPDs; new GPD software available online for modeling and fits to measured observables

2) Modifications of the scientific Work Plan: last year we requested an extension of deadlines for milestones/deliverables for COMPASS, to include the analysis of 2016-2017 data

3) Possibilities/needs of another request for the extension of the project (beyond 30 November 2023): why not, if possible? It could be helpful to continue collaborating, in particular to reinforce the synergy between experiment and theory