Accessing the Generalized Parton Distributions

INTT mini-workshop at NCU
November 17, 2023

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Outline & Confession

1. Introduction
2. Review
3. sPHENIX possibilities?

In this presentation, I blatantly took a lot of materials from great talks presented by Andrey Kim, Dariah Sokhan, Stepan Stepanyan, Nicole d'Hose, Ronan McNulty and many others

3D Description of Proton

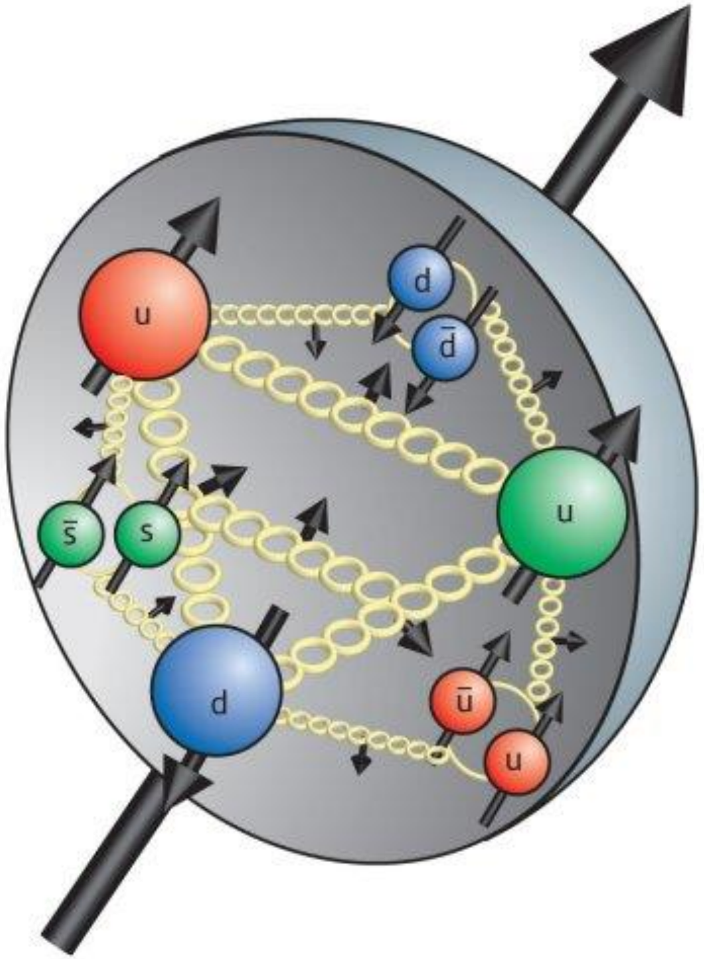
Les Demoiselles d'Avignon, Pablo Picasso

Beyond the Longitudinal Description

Origin of proton mass?

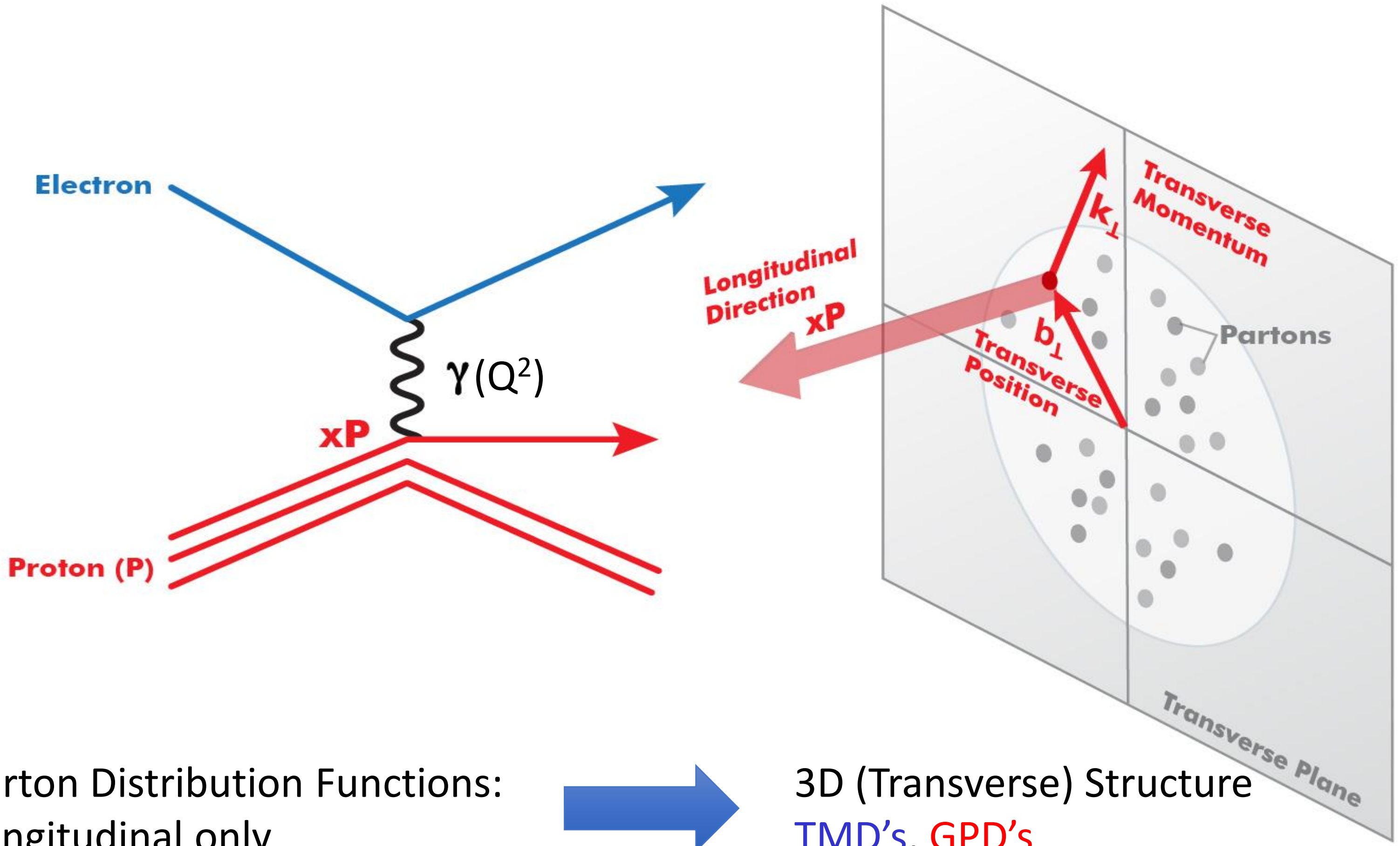
Origin of proton spin?

3D Imaging?



- After decades of study, we are now better equipped, both theoretically and experimentally, to decrypt the multidimensional structure of proton
  → Gain more insights into the questions regarding the fundamental properties of proton

Beyond the Longitudinal Description

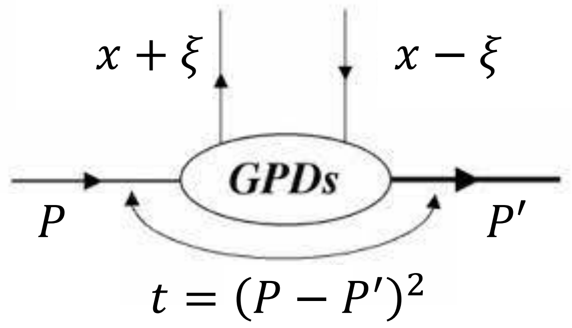


Parton Distribution Functions:
Longitudinal only

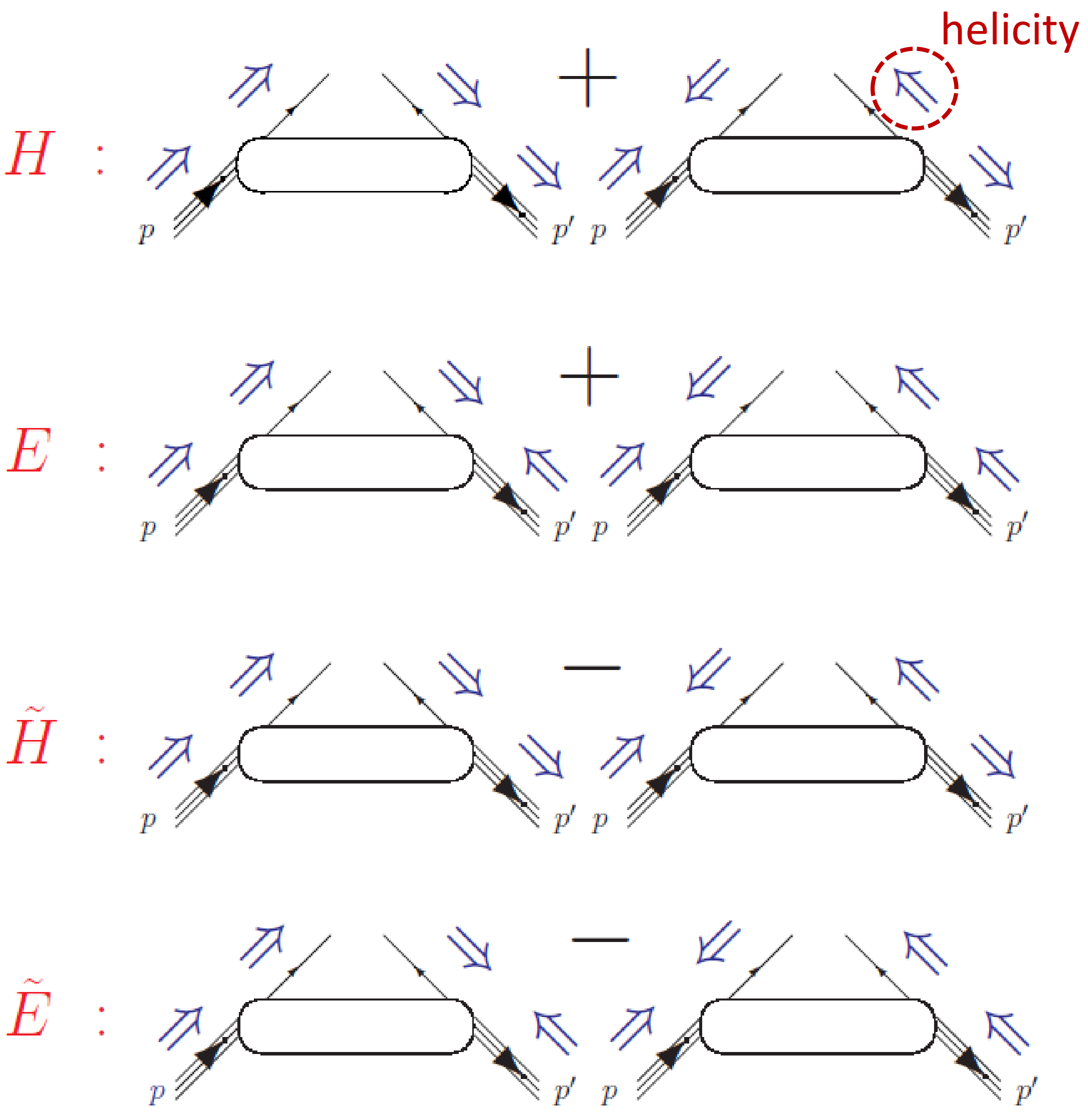
3D (Transverse) Structure
TMD's, GPD's

- Transverse Momentum Dependent Distributions (TMD): $k_{\perp}$
- Generalized Parton Distributions (GPD): $b_{\perp}$

Generalized Parton Distributions (GPDs)



- At fixed Q^2 , the GPDs depend on the following variables:
  - x: average longitudinal momentum fraction
  - ξ: longitudinal momentum difference
  - t: four momentum transfer
    (correlated to $b_\perp$ via Fourier transform)



- A total of 8 GPDs for a specific parton

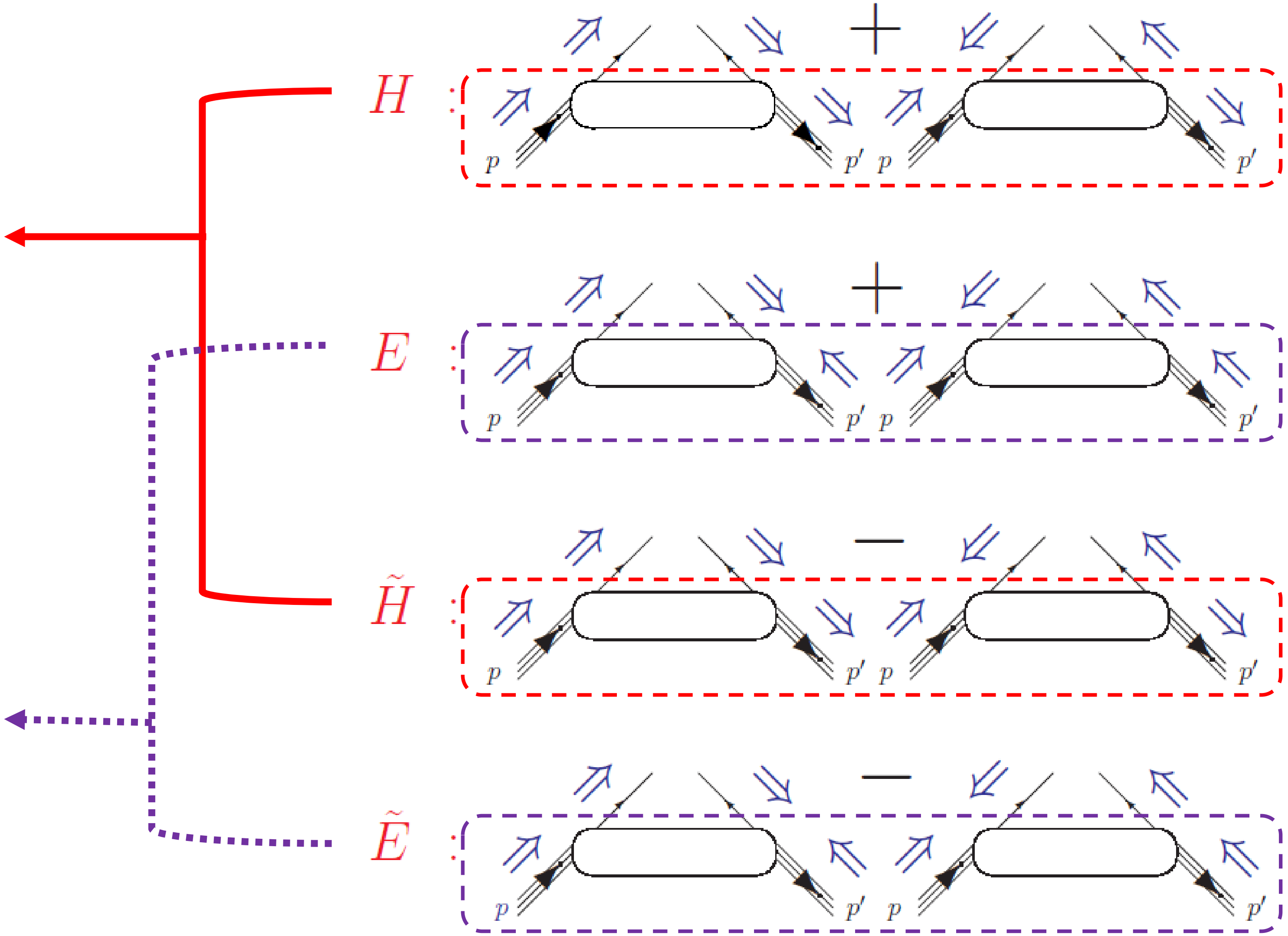
4 Chiral-even (parton helicity unchanged): $H, E, \tilde{H}, \tilde{E}$

4 Chiral-odd (parton helicity changed): $H_T, E_T, \tilde{H}_T, \tilde{E}_T$

Generalized Parton Distributions (GPDs)

Proton helicity unchanged

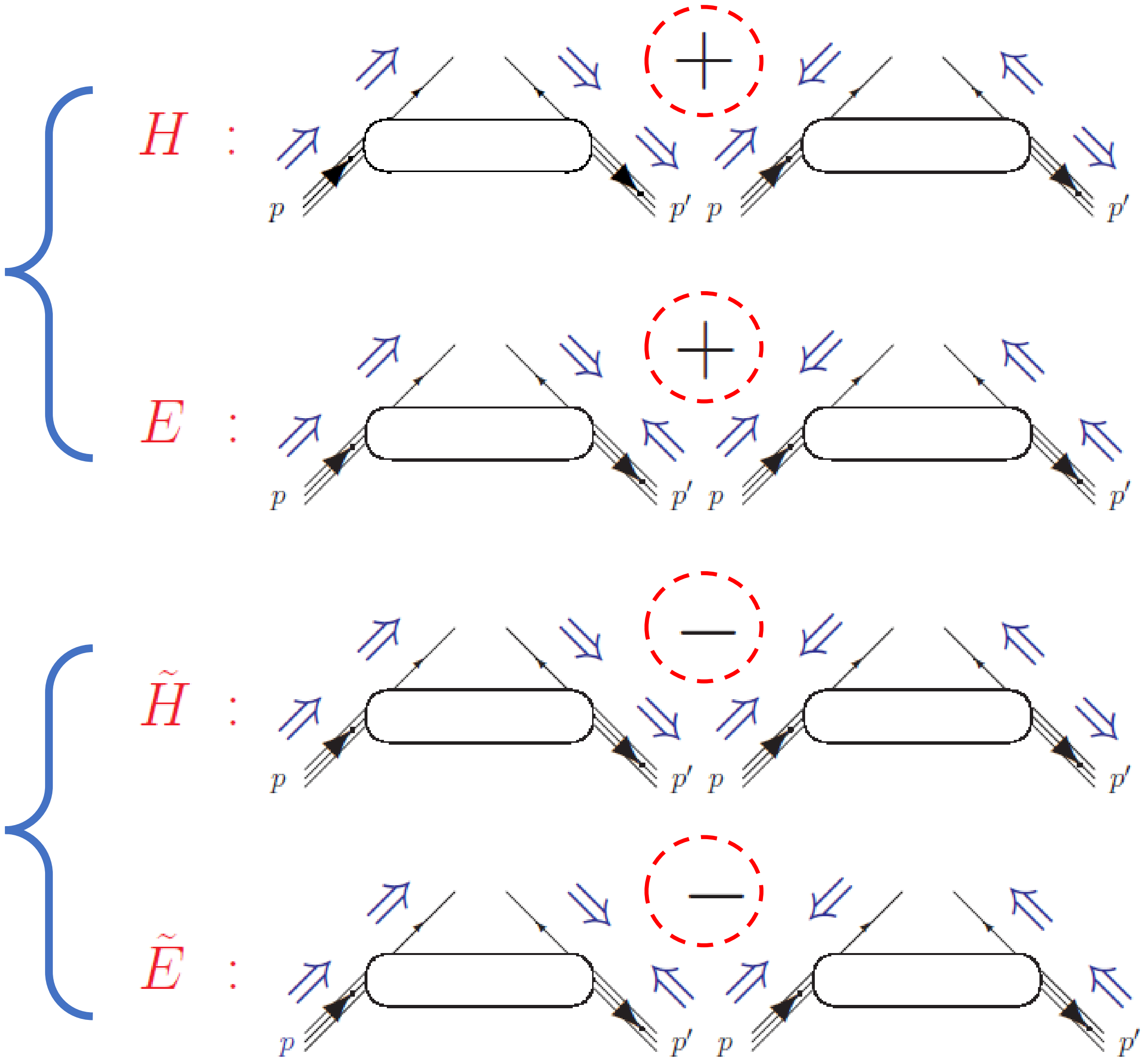
Proton helicity changed



Generalized Parton Distributions (GPDs)

Average over quark helicity
→ Unpolarized

Difference of quark helicity
→ Polarized



Generalized Parton Distributions (GPDs)

Unpolarized

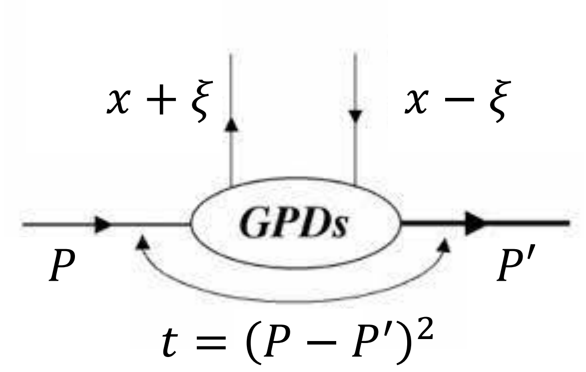
$H_f(x,0,0) = q_f(x)$

$\tilde{H}_f(x,0,0) = \Delta q_f(x)$

Polarized

$\xi = t = 0$

PDFs



First Moment

Form Factors

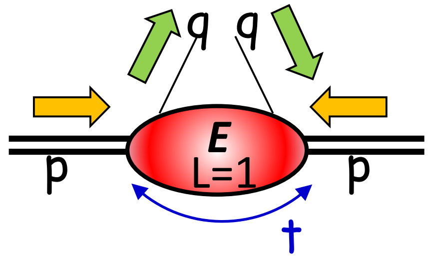
$\int H_f(x,\xi,t)dx = F_1^f(t)$ ***Dirac FF***

$\int E_f(x,\xi,t)dx = F_2^f(t)$ ***Pauli FF***

➢ **GPDs embody both PDFs and FFs**

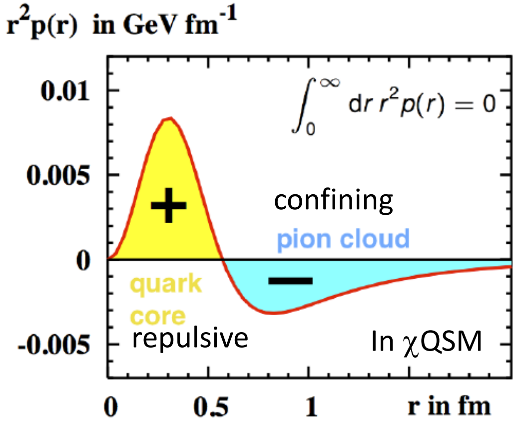
Provides information on the interesting properties of the nucleon.

➢ **Mapping the transverse plane distribution of parton**
➢ **Pressure distribution inside nucleon**
➢ **Angular momentum of parton**



$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

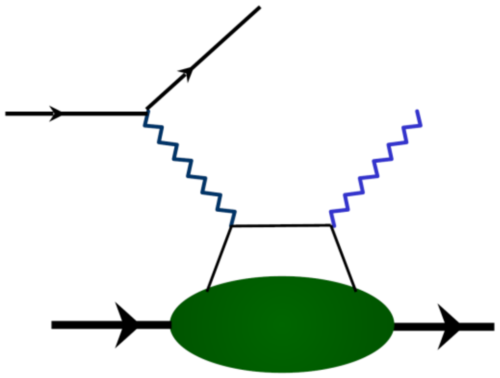
Ji's Sum Rule



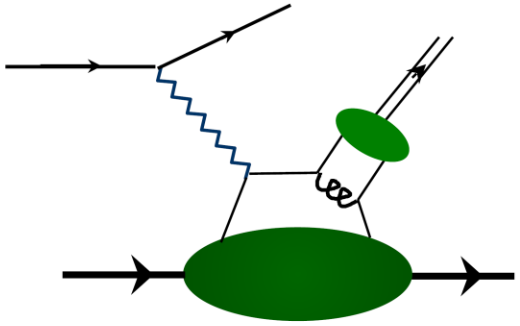
M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Exclusive Process

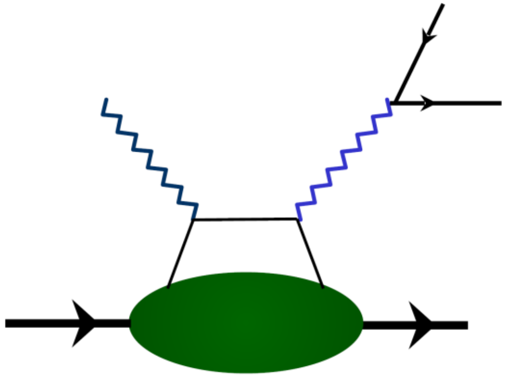
- ➢ Use exclusive processes, where all final state particles are “detected”, to access the muliti-variable dependence of GPDs, and constrain the GPD parameterization with measurements in various phase space.
- ➢ Processes:
  - Deeply Virtual Compton Scattering (DVCS)
  - Deeply Virtual Meson Production (DVMP)
  - Time-like Compton Scattering (TCS)
  - Double DVCS (DDVCS)
  - …



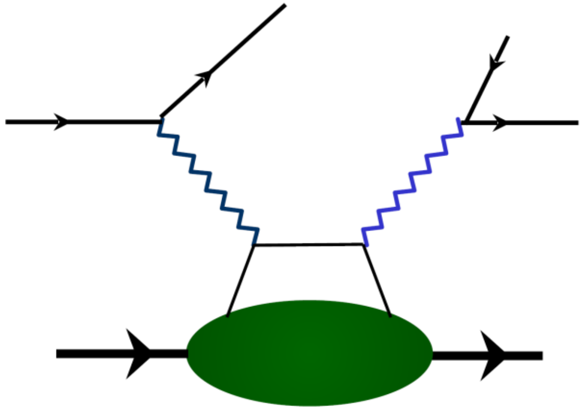
DVCS



DVMP

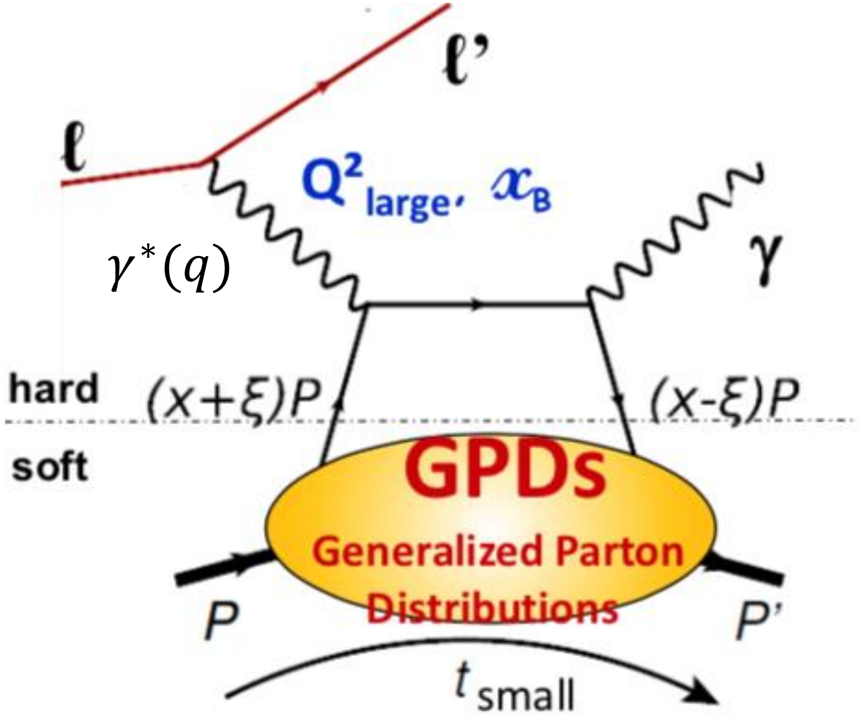


TCS



DDVCS

Deeply Virtual Compton Scattering



DVCS: $\boldsymbol{l + p \rightarrow l' + p' + \gamma}$

- Exclusive production of a single photon in the final state

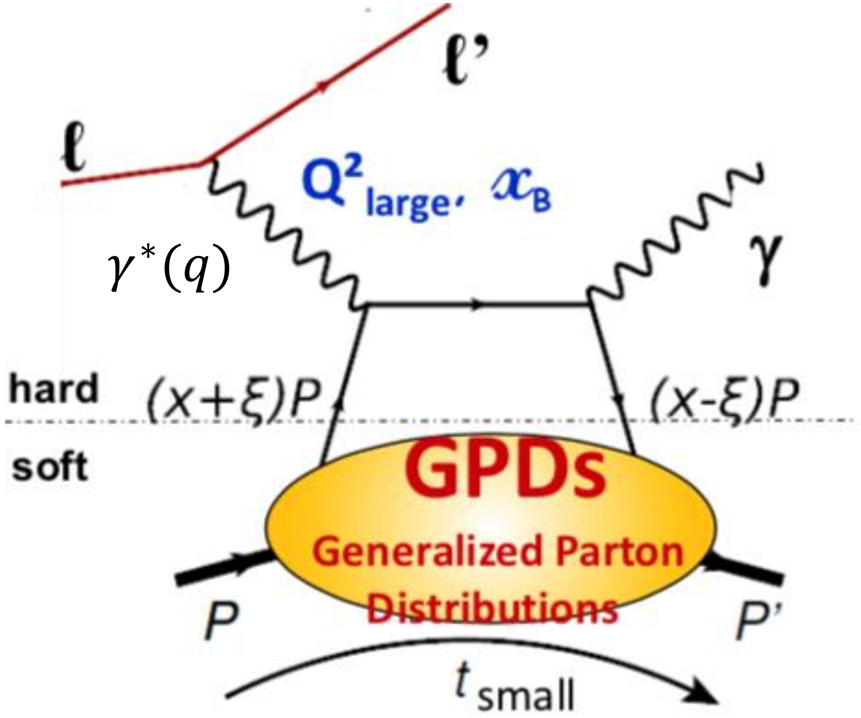
D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

Dieter Mueller

Xiang-Dong Ji

Anatolii Radyushkin

Deeply Virtual Compton Scattering



The variables measured in the experiment:

E_ℓ, Q^2, $x_B \sim 2\xi/(1+\xi)$,

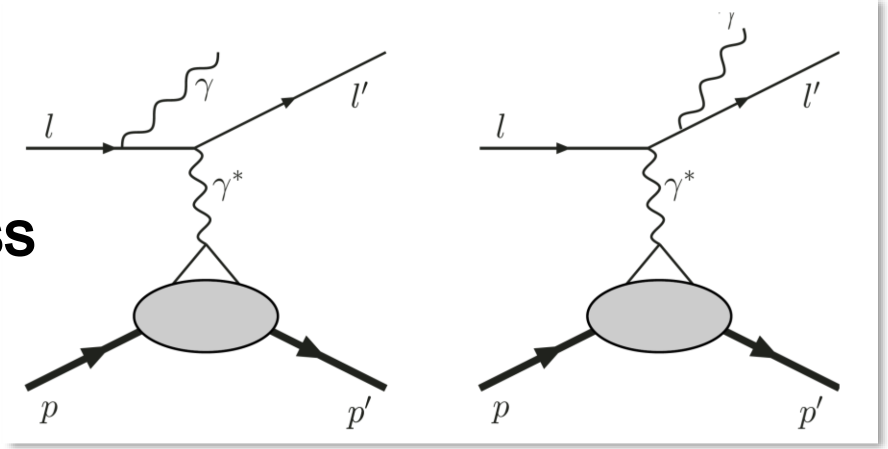
t (or $\theta_{\gamma^*\gamma}$) and ϕ ($\ell\ell'$ plane/$\gamma\gamma^*$ plane)

$x_B = \frac{Q^2}{2P\cdot q}$ → Bjorken scaling variable

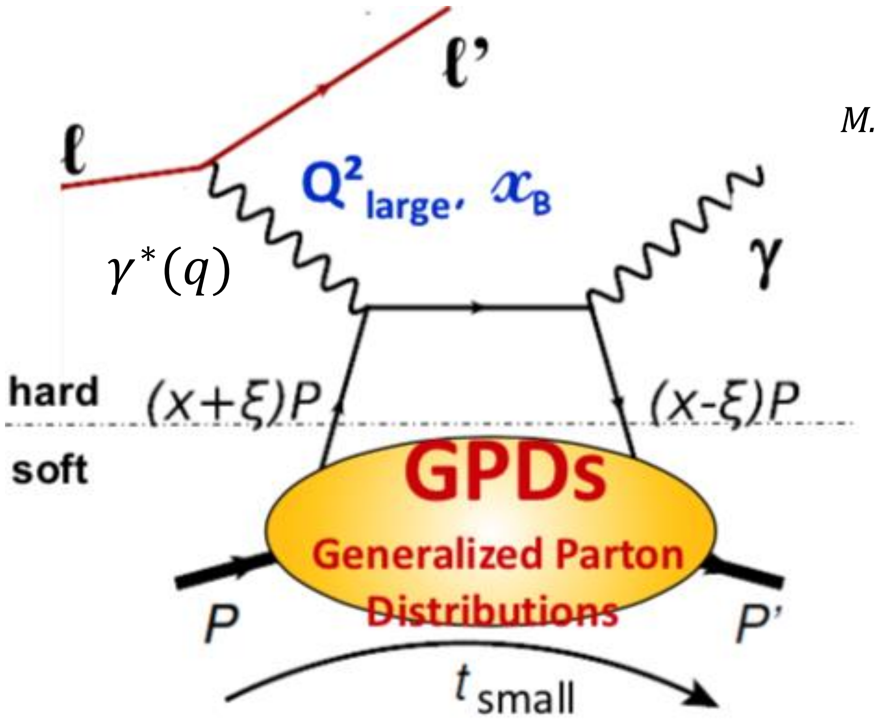
DVCS: $l + p \rightarrow l' + p' + \gamma$

- DVCS is regarded as the golden channel and gives access to four chiral-even GPDs $H, \widetilde{H}, E, \widetilde{E}(x, \xi, t)$. Its interference with the well-understood Bethe-Heitler process gives access to more info.

BH Process

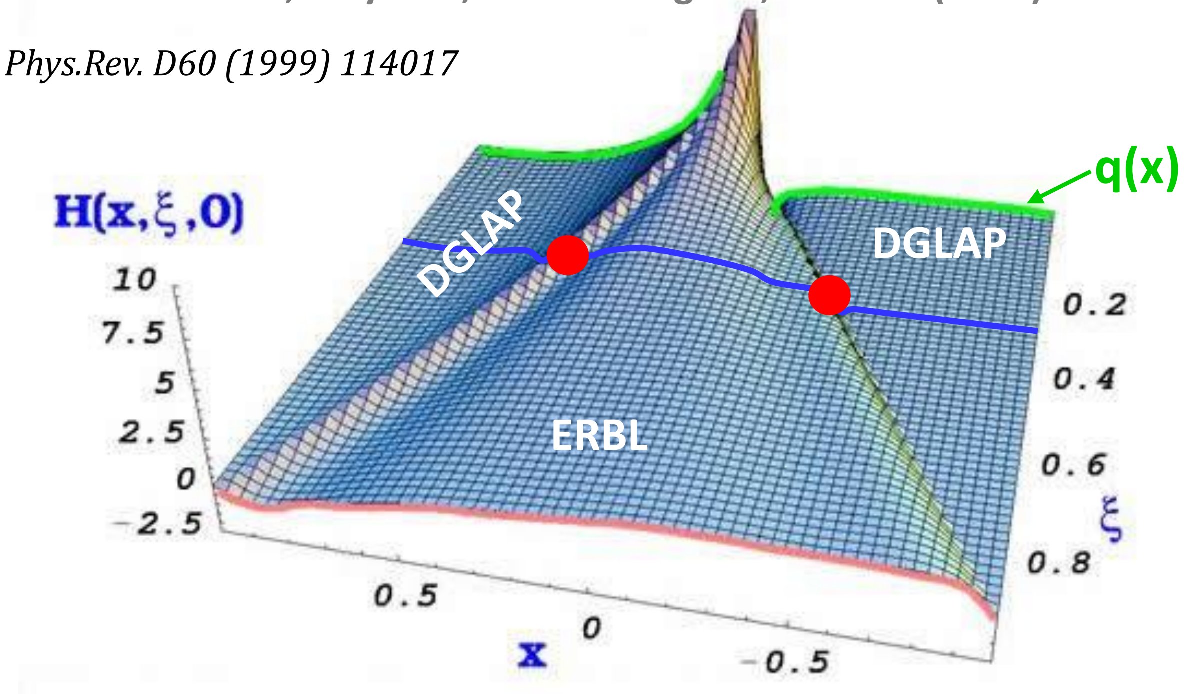


Compton Form Factors (CFFs)



From Goeke, Polyakov, Vanderhaeghen, PNPP47 (2001)

M. Polyakov , C. Weiss, Phys.Rev. D60 (1999) 114017



CFF — GPD

REAL part — Imaginary part

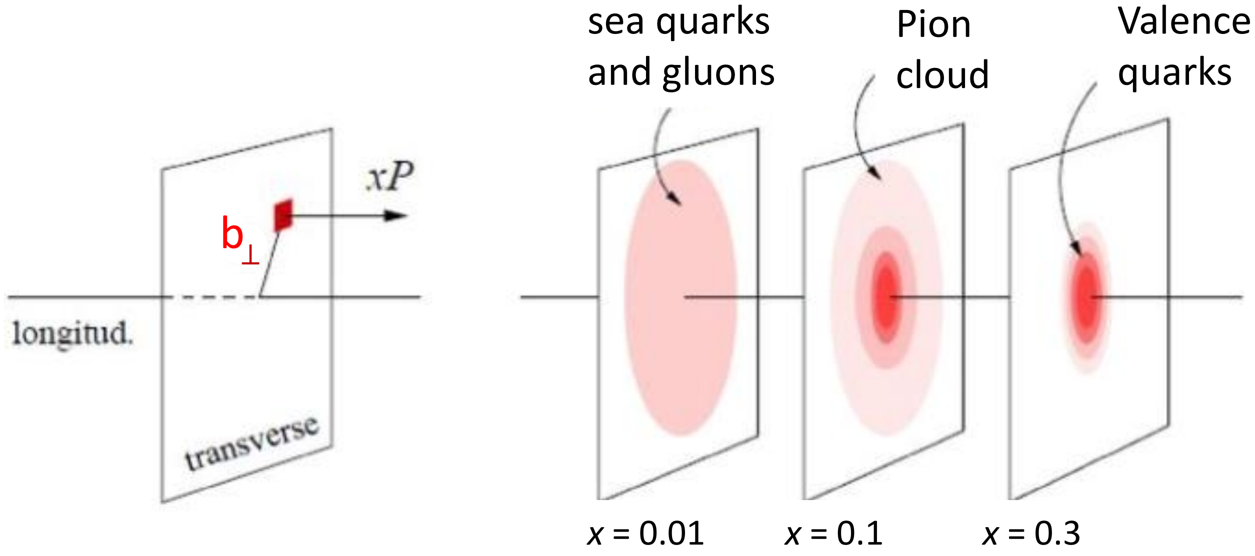
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

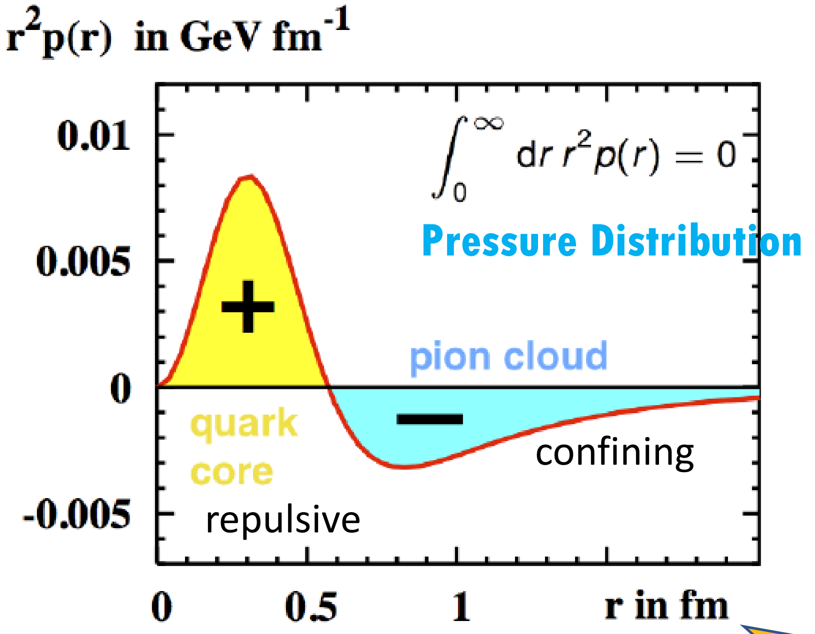
Transverse Imaging and Pressure Distribution

Mapping in the transverse plane

Fit $A\, e^{-B|t|}$ $\langle b_\perp^2 \rangle \approx 4B$



M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)



FT of H(x, ξ=0,t)

CFF GPD

REAL part Imaginary part

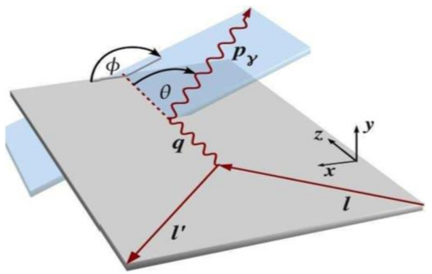
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

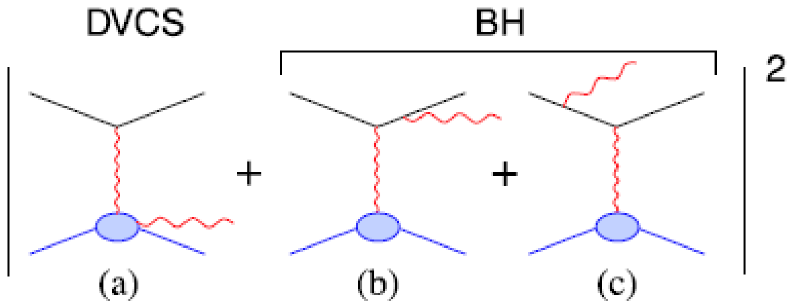
$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

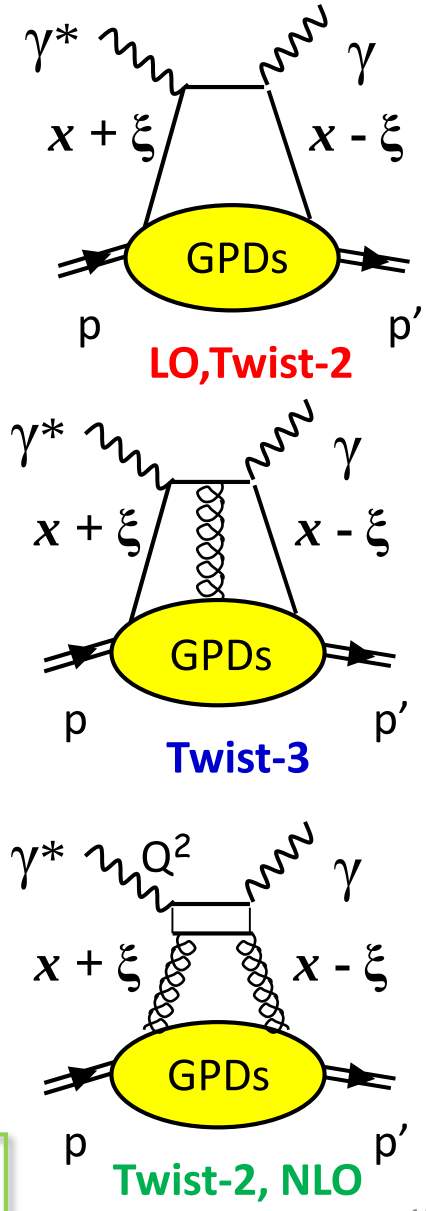
D-term $d_1(t)$

Polarized Beam & Unpolarized Target

- Experimental access by cross-sections and spin asymmetries







$$\frac{d^4\sigma(\ell p \to \ell p\gamma)}{dx_B dQ^2 d|t| d\phi} = \underbrace{d\sigma^{BH}}_{\text{Well known}} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell \mathrm{Im}\, I\right)$$

$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

Change P_ℓ → $s_1^I = Im\, \mathcal{F}$

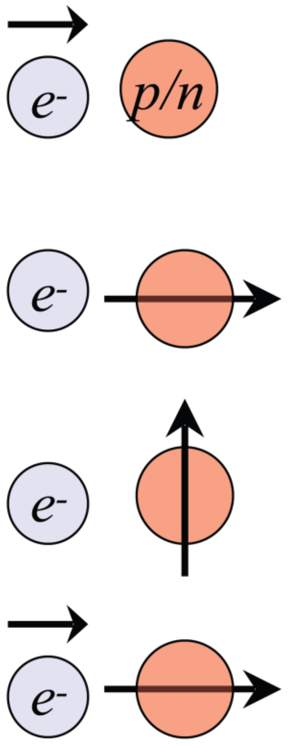
Change e_ℓ, P_ℓ → $c_1^I = Re\, \mathcal{F}$

$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} + t/4m^2 F_2\mathcal{E}$

Sensitivity to CFFs

➢ The target polarization can be explored as well.

Beam, target polarisation



For example:

$$\Delta\sigma_{LU} \sim \sin\phi\, \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E)\, d\phi \quad\rightarrow\quad Im\{\boldsymbol{H}_\mathbf{p}, \tilde{H}_p, E_p\} \quad Im\{H_n, \tilde{H}_n, \boldsymbol{E}_\mathbf{n}\}$$

$$\Delta\sigma_{UL} \sim \sin\phi\, \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + \ldots)\, d\phi \quad\rightarrow\quad Im\{\boldsymbol{H}_\mathbf{p}, \boldsymbol{\tilde{H}}_\mathbf{p}\} \quad Im\{\boldsymbol{H}_\mathbf{n}, E_n, \tilde{E}_n\}$$

$$\Delta\sigma_{UT} \sim \cos\phi\, \Im(\frac{t}{4M^2}(F_2 H - F_1 E) + \ldots) d\phi \quad\rightarrow\quad Im\{\boldsymbol{H}_\mathbf{p}, \boldsymbol{E}_\mathbf{p}\} \quad Im\{\boldsymbol{H}_\mathbf{n}\}$$

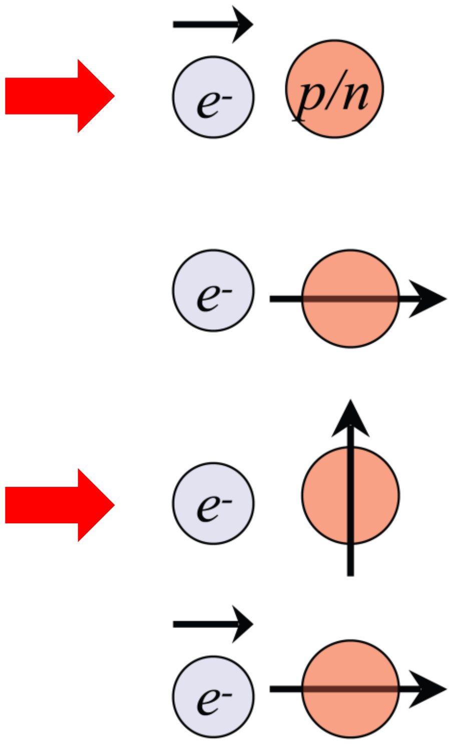
$$\Delta\sigma_{LL} \sim (A + B\cos\phi)\, \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + \ldots) d\phi \quad\rightarrow\quad Re\{\boldsymbol{H}_\mathbf{p}, \boldsymbol{\tilde{H}}_\mathbf{p}\} \quad Re\{\boldsymbol{H}_\mathbf{n}, E_n, \tilde{E}_n\}$$

Proton	Neutron

Sensitivity to CFFs

➢ The target polarization can be explored as well.

Beam, target polarisation

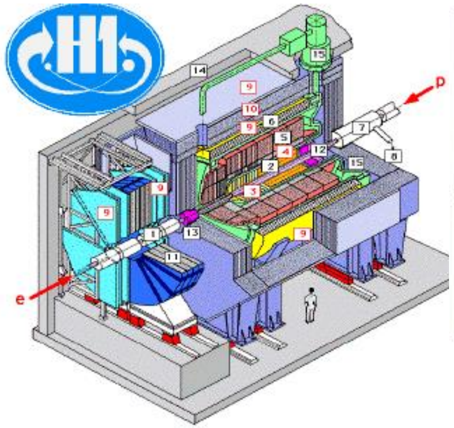


For example:

		Proton / Neutron
$\vec{e}^-$, p/n	$\Delta\sigma_{LU} \sim \sin\phi\, \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E)\, d\phi$	$Im\{H_p, \tilde{H}_p, E_p\}$ $Im\{H_n, \tilde{H}_n, E_n\}$
e^-, longitudinal target	$\Delta\sigma_{UL} \sim \sin\phi\, \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + \ldots)\, d\phi$	$Im\{H_p, \tilde{H}_p\}$ $Im\{H_n, E_n, \tilde{E}_n\}$
e^-, transverse target	$\Delta\sigma_{UT} \sim \cos\phi\, \Im(\frac{t}{4M^2}(F_2 H - F_1 E) + \ldots) d\phi$	$Im\{H_p, E_p\}$ $Im\{H_n\}$
$\vec{e}^-$, longitudinal target	$\Delta\sigma_{LL} \sim (A + B\cos\phi)\, \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + \ldots) d\phi$	$Re\{H_p, \tilde{H}_p\}$ $Re\{H_n, E_n, \tilde{E}_n\}$

➢ **Neutron target: flavor decomposition & access to *E***

The Past and Present Experiments



e-p Collider forward fast proton

- **HERA**: **H1** and **ZEUS**

Polarised **27 GeV** e-/e+
Unpolarized **920 GeV** proton
~ ***Full event reconstruction***

Fixed target mode slow recoil proton

- **HERMES:** Polarised **27** GeV e-/e+

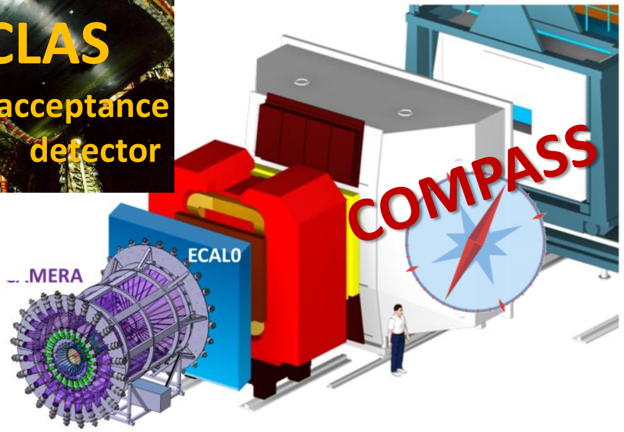
Long., Trans. polarised p, d target
Missing mass technique, 2006-09 with recoil detector

- **Jlab: Hall A, C, CLAS** High Luminosity Polar. **6** & **12 GeV e-**

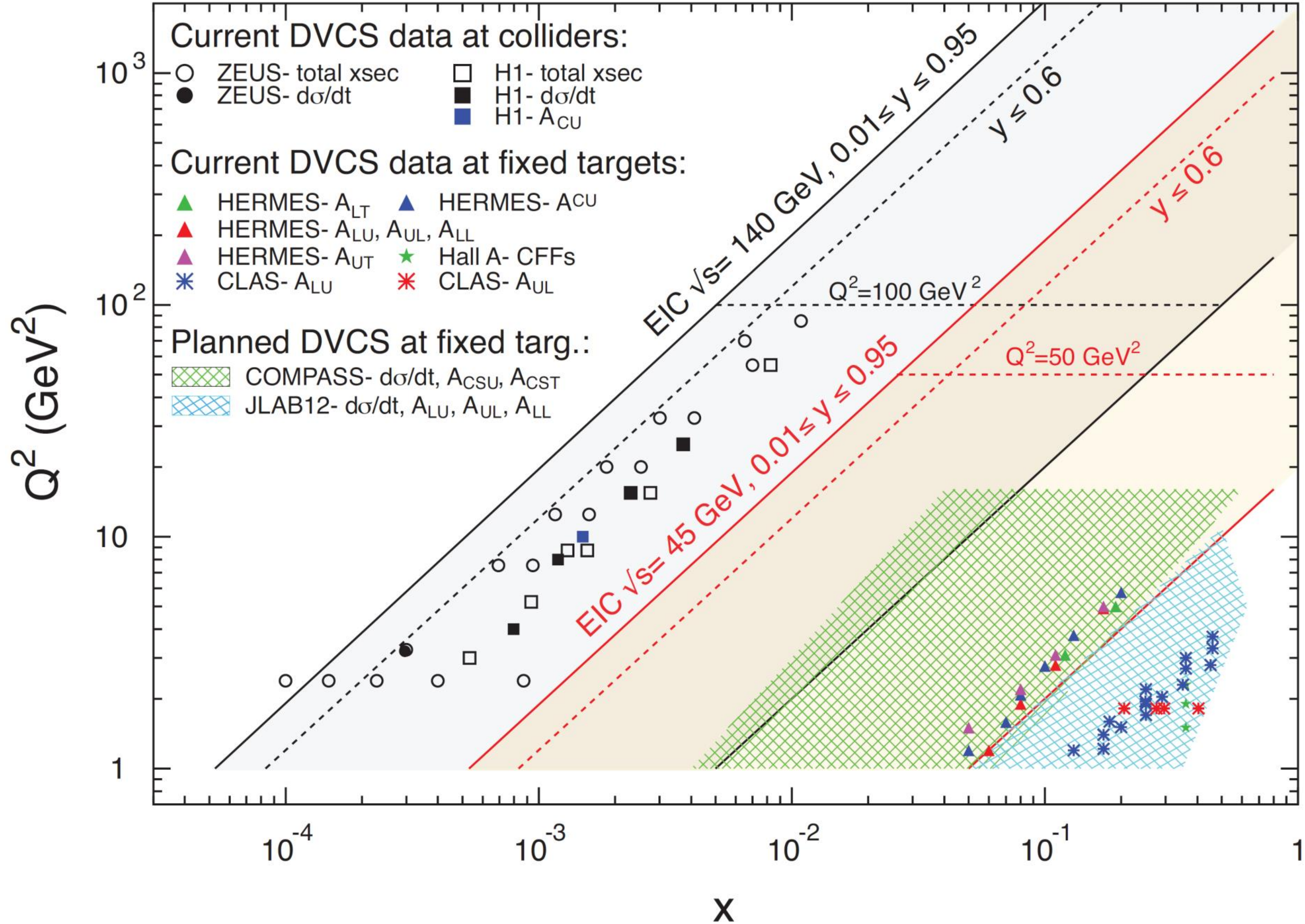
Long., (Trans.) polarised p, d target
Missing mass technique (A,C) and complete detection (CLAS)

- **COMPASS @ CERN:** Polarised **160 GeV μ+/μ-**

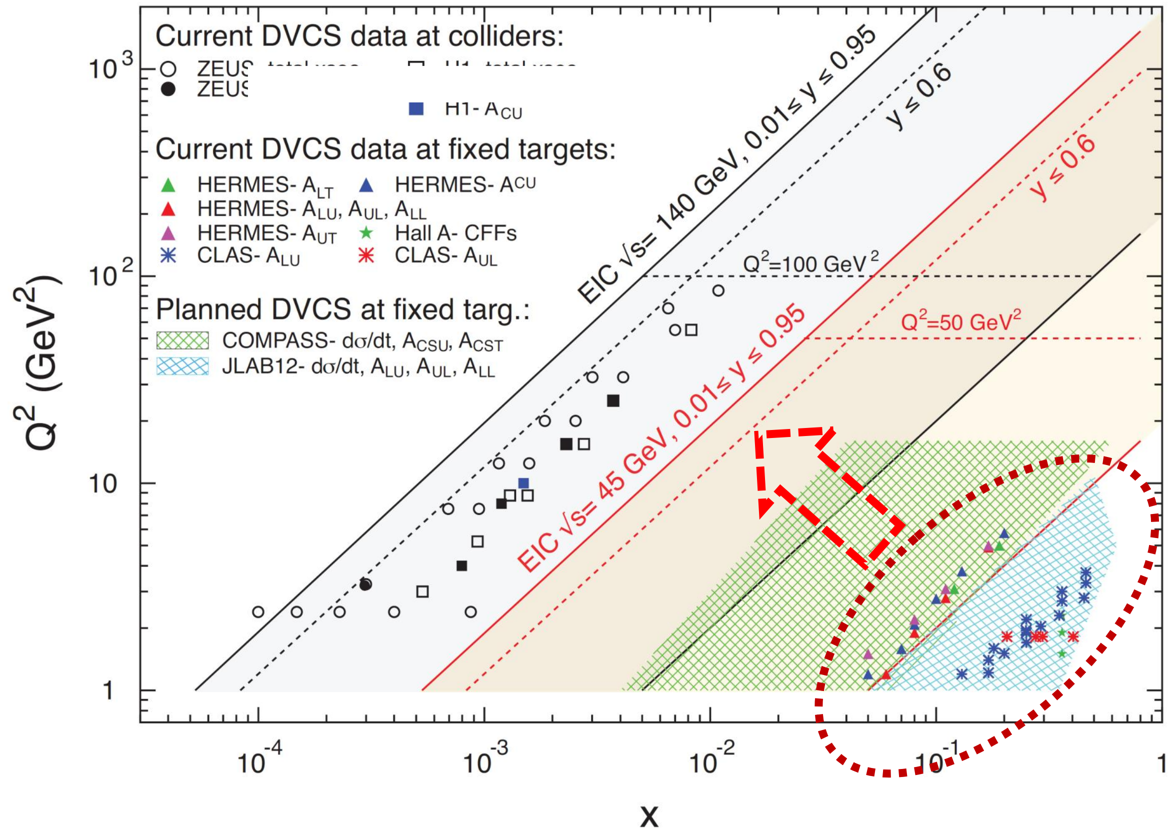
p target, (Trans.) polarised ***target with recoil p detection***



Landscape – Global Programs of DVCS

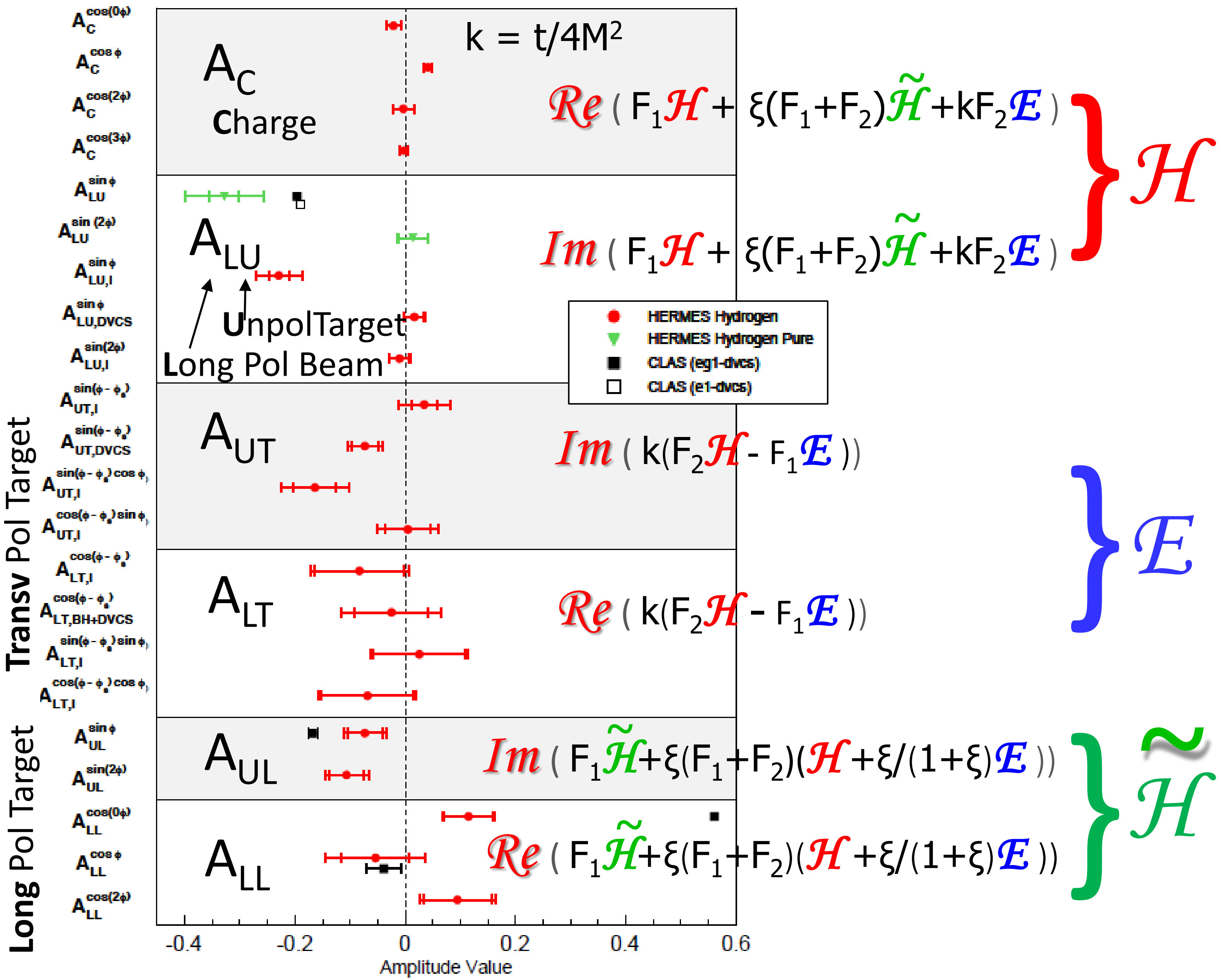


DVCS Measurements



Starting with lower energy – intermediate to high xB

A complete set of DVCS asymmetries at Hermes



HERMES provided a complete set of observables

2001: 1st DVCS publication as CLAS & H1

2007: end of data taking

2012: still important publications

JHEP 07 (2012) 032 A_C A_{LU}

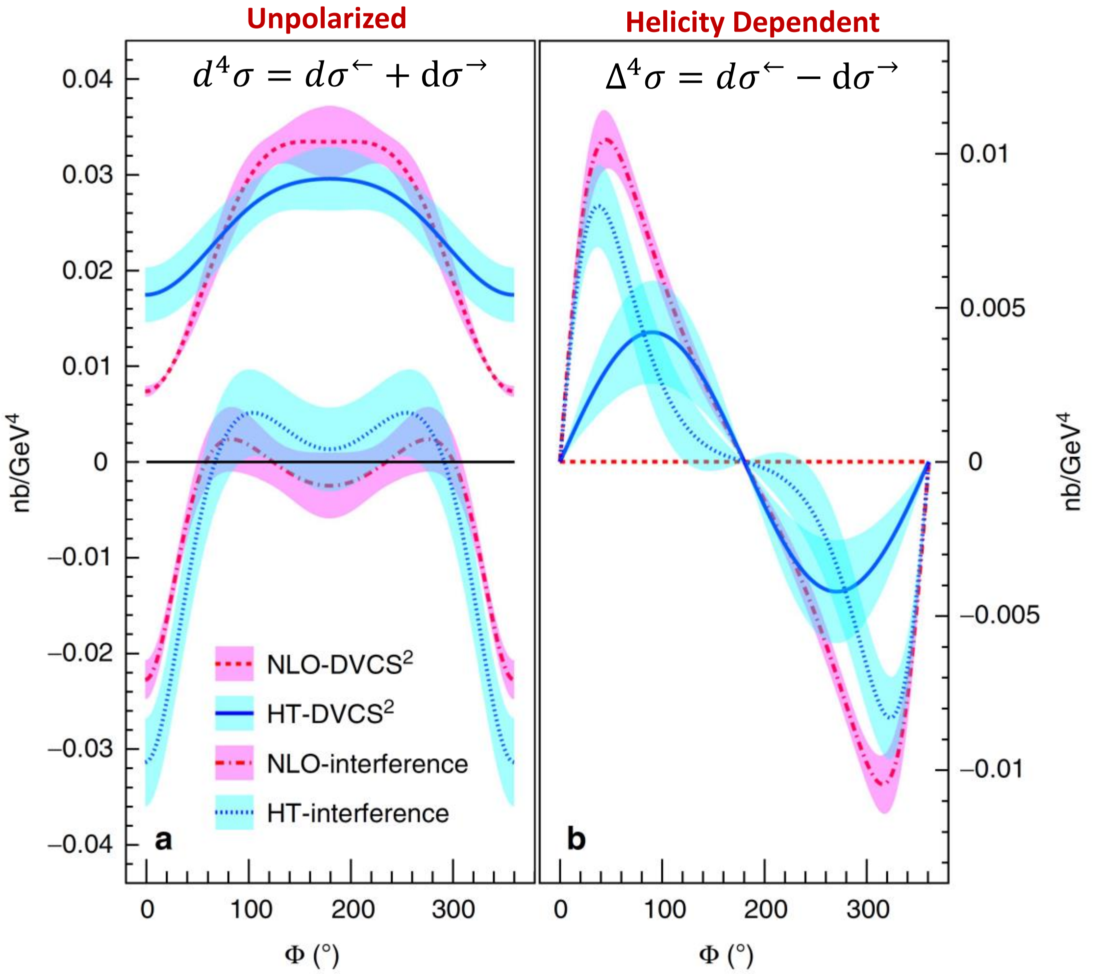
JHEP10(2012) 042 A_{LU}

with recoil detection (2006-7)

- Electron & positron beams on proton
- Beam energy of 27.6 GeV
- Luminosity $\leq 10^{31}\ cm^{-2}s^{-1}$
- Most data within:
  $0.05 \leq x_B \leq 0.2$
  $2\ GeV^2 \leq Q^2 \leq 6\ GeV^2$

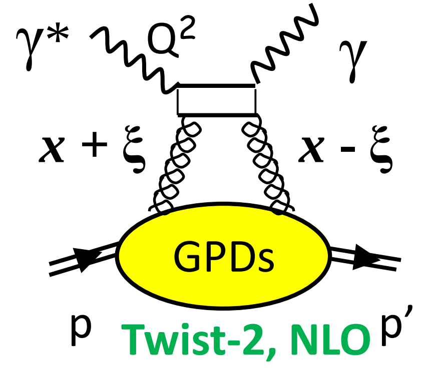
Beam Spin Sum and Diff of DVCS at JLab Hall A

- After the pioneering E00-110 in 2004 at Hall-A, the E07-007 experiment in 2010
- High precision cross-section measurement in a small kinematic region: Generalized Rosenbluth separation of the DVCS^2 (scales as E_e^2) and the BH-DVCS interference (scales as E_e^3) terms. NLO and/or higher-twist improve model agreement



$\overleftrightarrow{e}\, p \rightarrow e\, \gamma\, p$

- E_e: 4.5 & 5.6 GeV
- Q^2: 1.5, 1.9, 2.3 GeV^2 at fixed x_B: 0.36

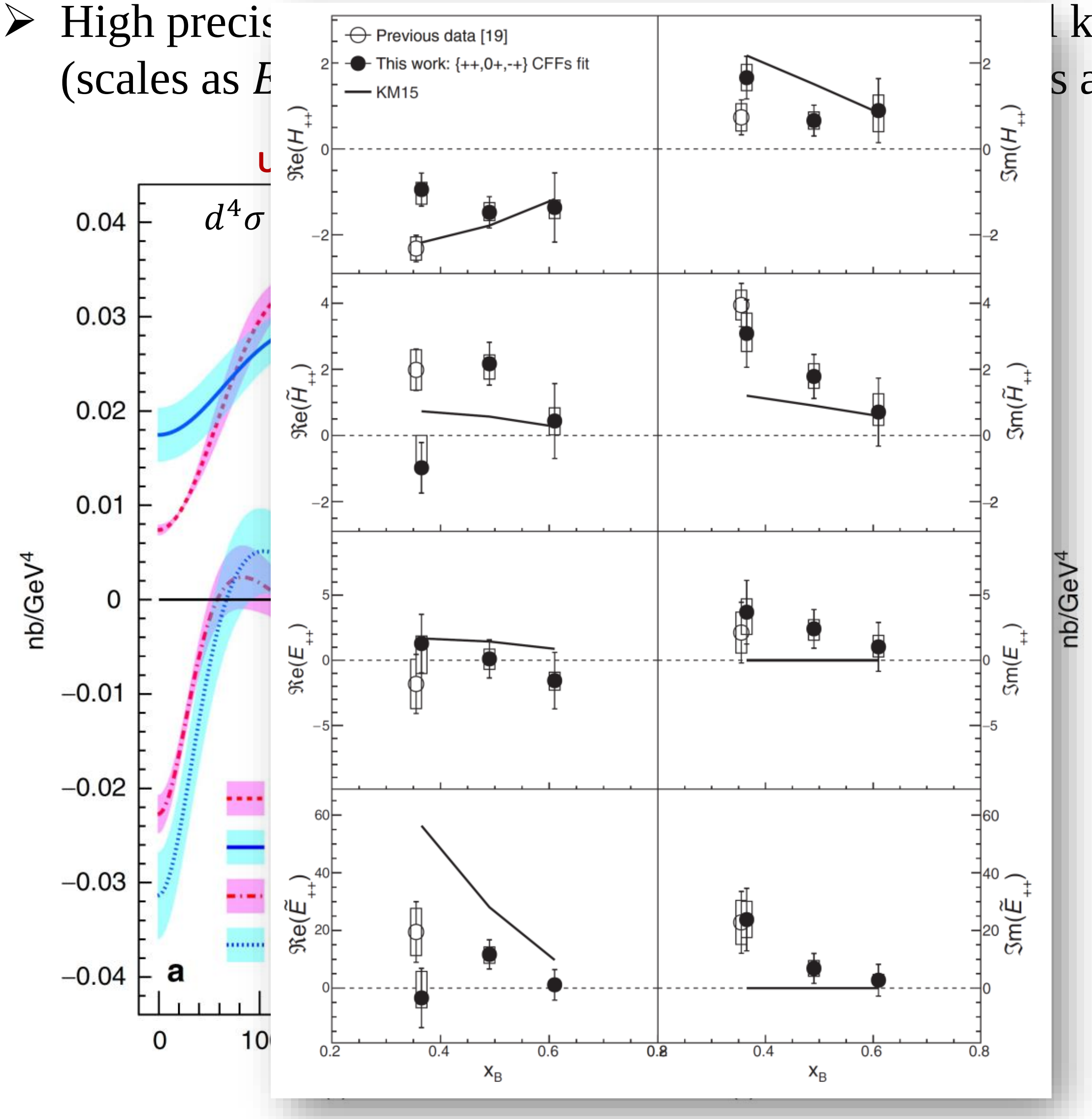


- Two scenarios: **higher-twist** or **next-to-leading order**
- Significant differences between pure DVCS and interference contributions.
- Sensitivity to gluons.
- Separation of HT and NLO effects requires scans across wider ranges of Q^2 and beam energy → JLab 12

Defurne et al., Nature Communications 8 (2017) 1408

Beam Spin Sum and Diff of DVCS at JLab Hall A

- After the pioneering E00-110 in 2004 at Hall-A, the E07-007 experiment in 2010
- High precis… kinematic region: Generalized Rosenbluth separation of the DVCS[2] (scales as E… s as E_e^3) terms. NLO and/or higher-twist improve model agreement



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- E_e: 4.5 & 5.6 GeV
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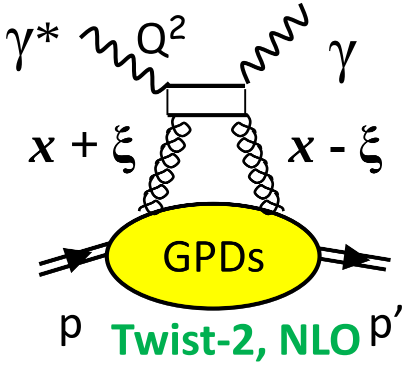


- Two scenarios: higher-twist or next-to-leading order
- Significant differences between pure DVCS and interference contributions.
- Sensitivity to gluons.
- Separation of HT and NLO effects requires scans across wider ranges of Q^2 and beam energy → JLab 12

- First experimental extraction of all four helicity-conserving CFFs

F. Georges et al. (JLab Hall A Collaboration), Phys. Rev. Lett. 128, 252002 (June 2022)

Defurne et al., Nature Communications 8 (2017) 1408

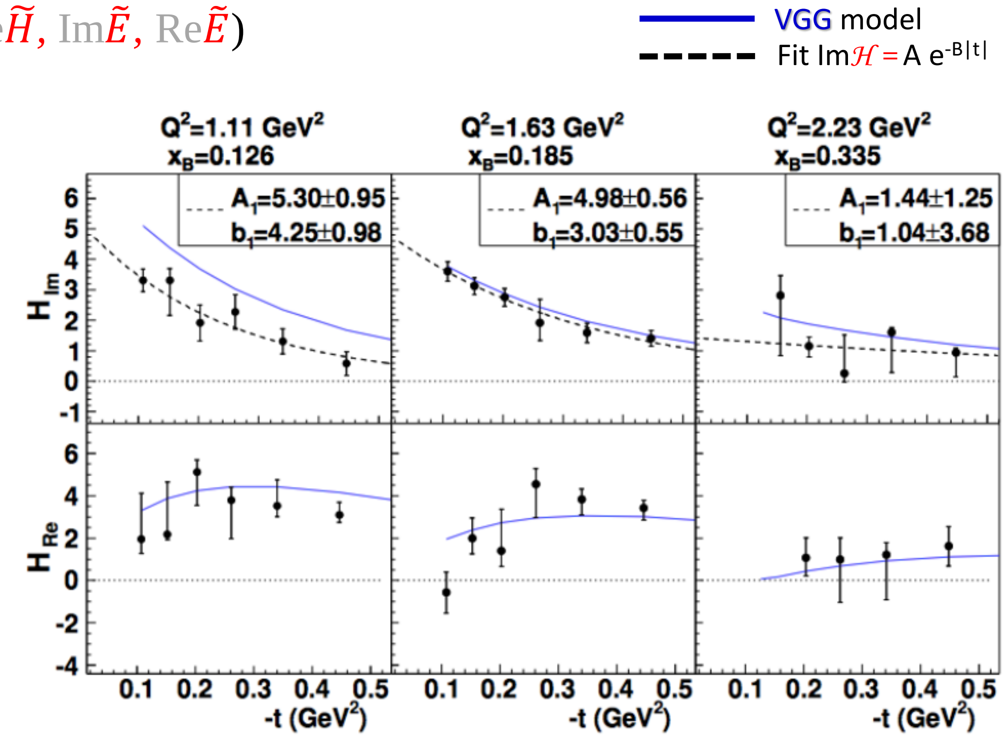
Nucleon Tomography in the Valence Domain with CLAS Data

Fit of 8 CFFs at **L.O.** and **L.T.**

(ImH, ReH, ImE, ReE, Im$\tilde{H}$, Re$\tilde{H}$, Im$\tilde{E}$, Re$\tilde{E}$)

Better Constrained

- Wide kinematic coverage
- Carried out measurements with logitudinally polarized target as well

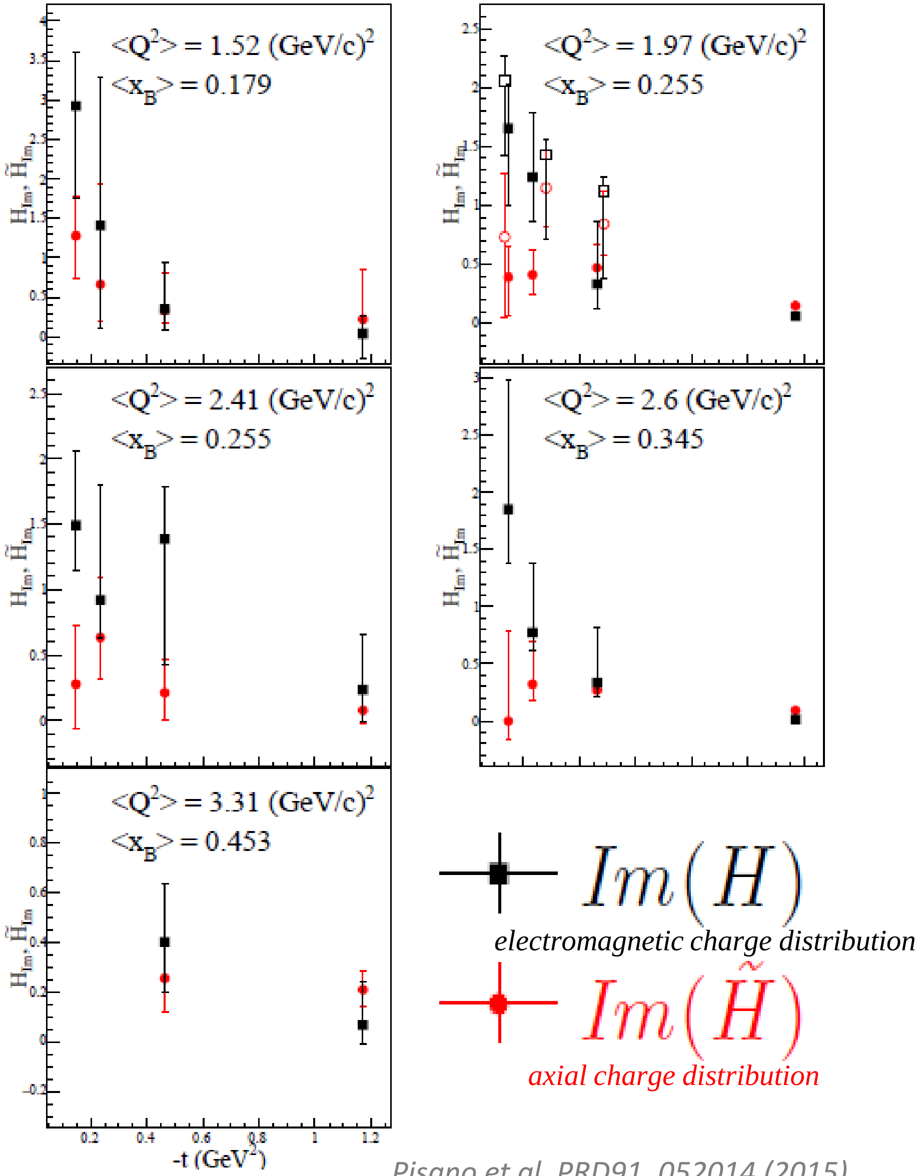


H.-S. Jo et al. (CLAS) PRL115, 212003 (2015) 212003
N. Hirlinger Saylor et al (CLAS) PRC 98 (2018) 045203

$\overleftrightarrow{e}\, p \rightarrow e\, \gamma\, p$

- Valence quarks at centre
- Sea quarks spread out towards the periphery.

$\overleftrightarrow{e}\, \vec{p} \rightarrow e\, \gamma\, p$



- Simultaneous fit to BSA, TSA & DSA → Information on relative distribution of quark momenta (PDFs) and quark helicity, $\Delta q(x)$

$$H(x,0,0) = q(x) \qquad \tilde{H}(x,0,0) = \Delta q(x)$$

$$\int_{-1}^{+1} H dx = F_1 \qquad \int_{-1}^{+1} \tilde{H}\, dx = G_A$$

- Indication that axial charge is more concentrated than electromgnatic charge

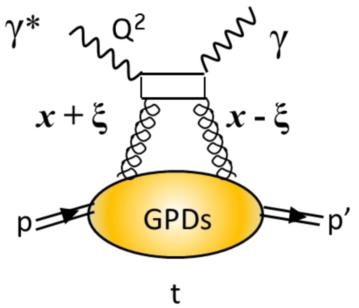
Pisano et al. PRD91, 052014 (2015)
Seder et al. PRL114, 032001 (2015)

Nucleon Tomography in the Gluon Domain at HERA

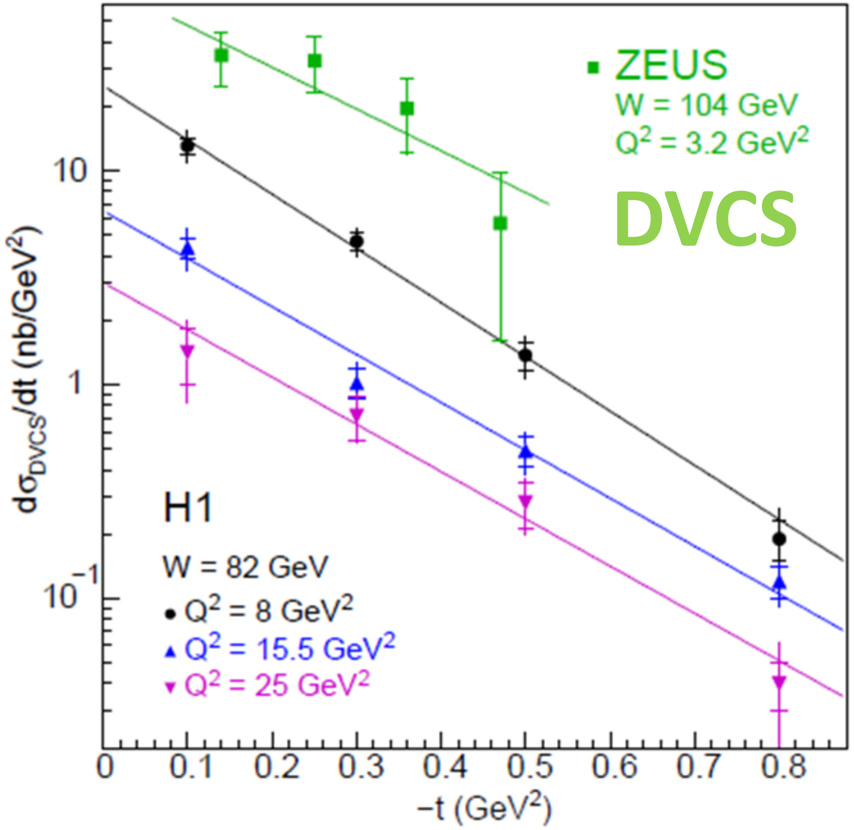
$$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$$

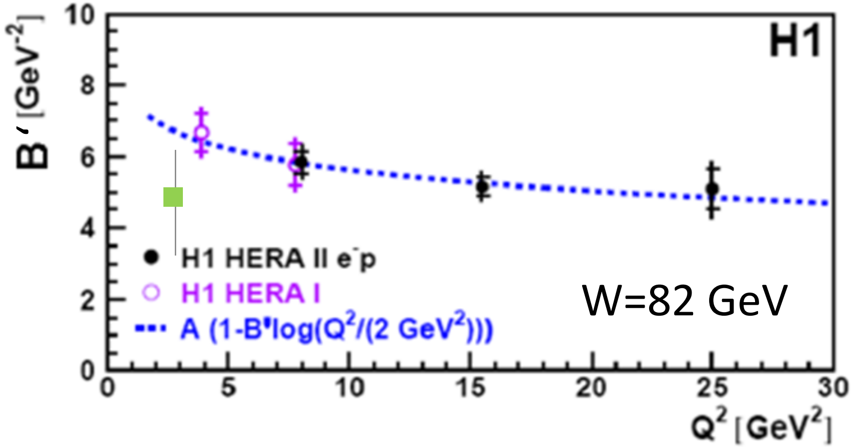
B’ related to the transversed size of the scattering object

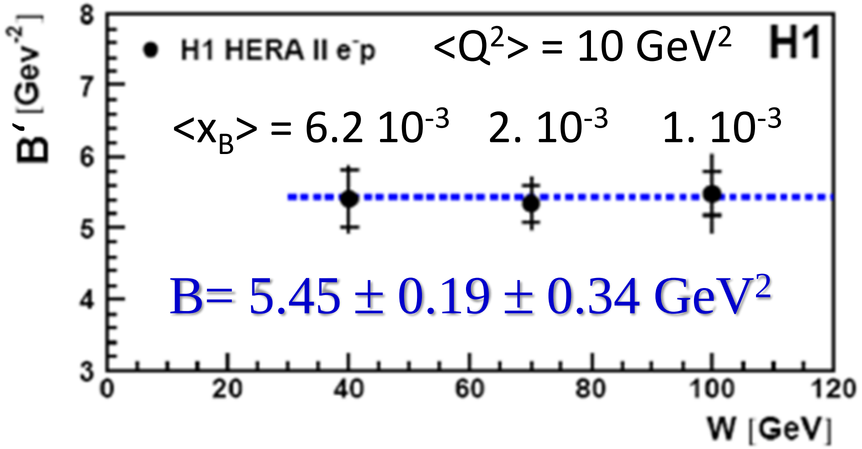
Dominance of $Im\mathcal{H}$



Aaron et al., H1 Coll, PLB659 (2008)







ZEUS-H1

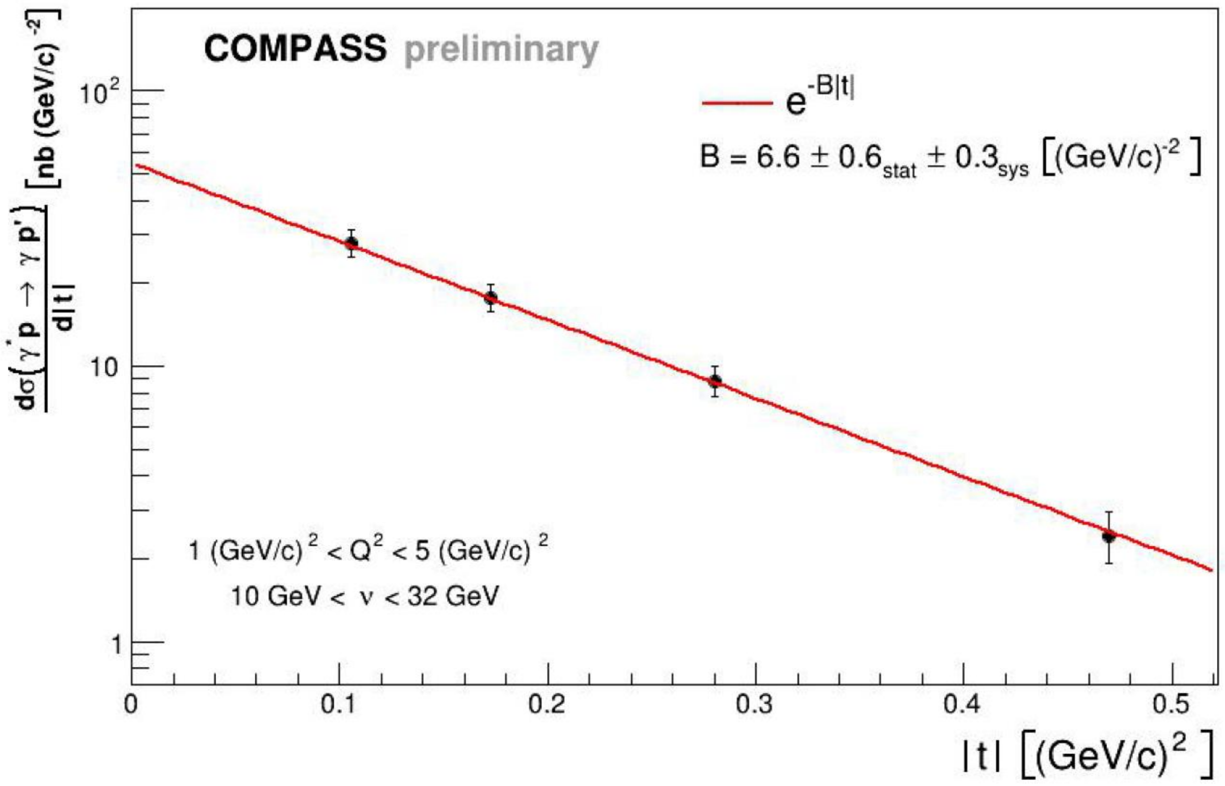
Data collected 1995-2007

$$< r_\perp^2 (x_B) > \approx 2\, B'(x_B)$$

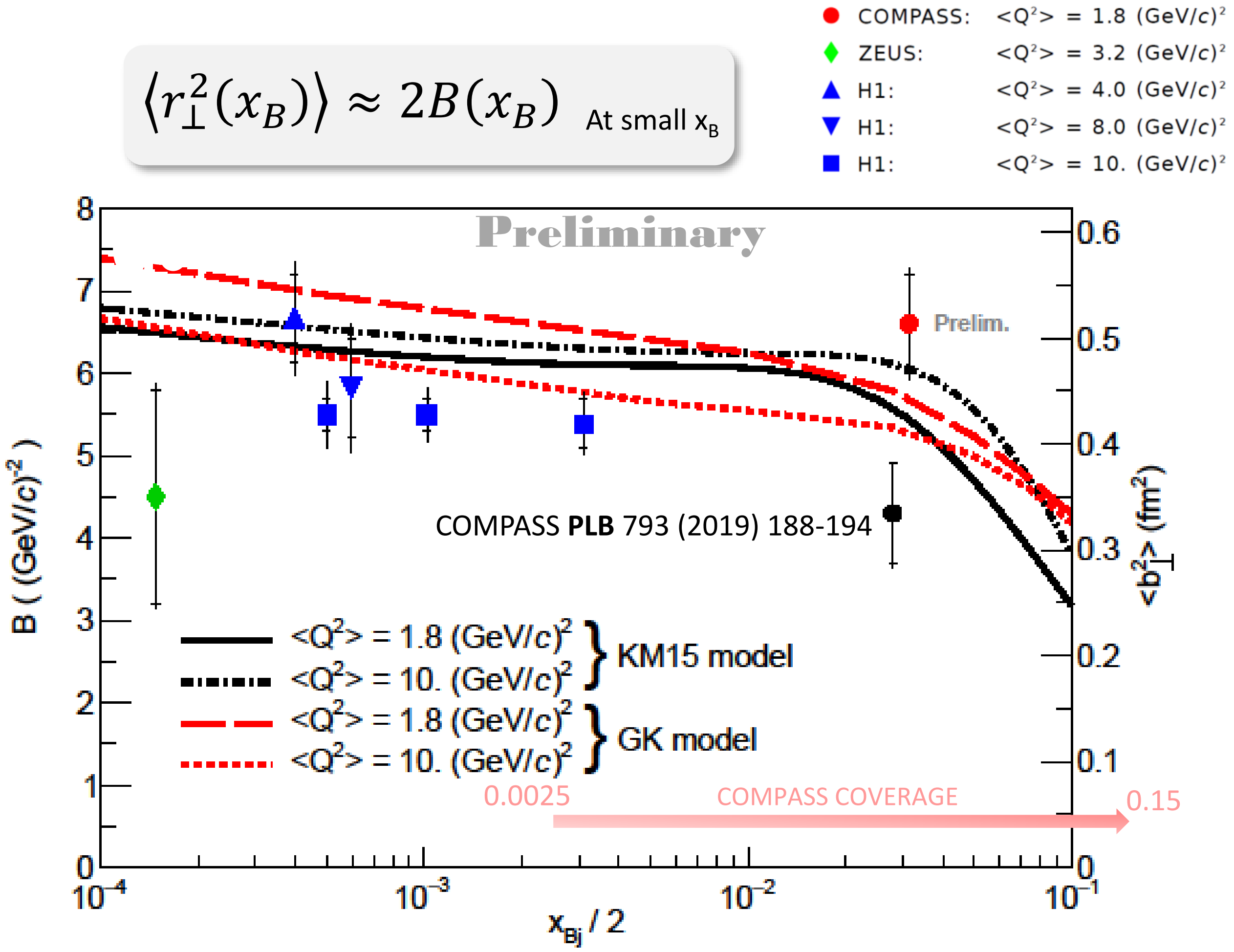
$$\sqrt{< r_\perp^2 >} = 0.65 \pm 0.02 \text{ fm}$$

Nucleon Tomography of COMPASS Preliminary Result

$$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$$



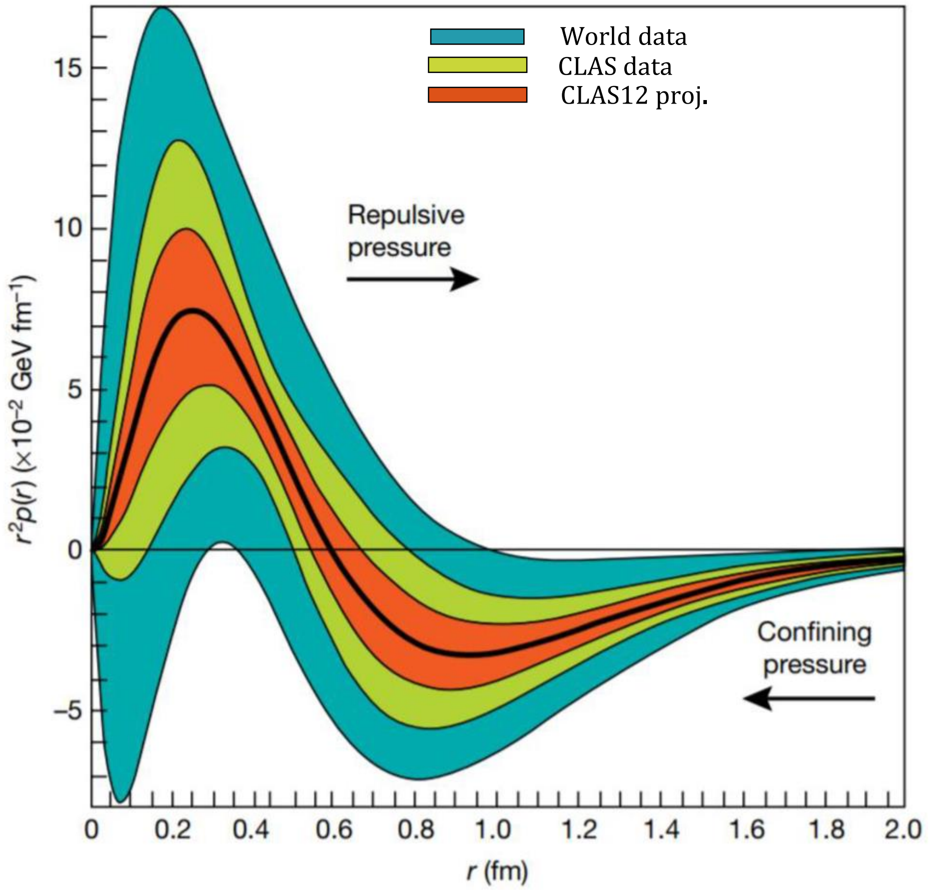
$$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$ At small x_B



- ➢ The transverse-size evolution as a function of x_B → Expect at least 3 x_B bins from full 2016-17 data

GPDs and Pressure Distribution

V. D. Burkert, L. Elouadrhiri, F. X. Girod
Nature **557**, 396-399 (2018)



- **With all the data from beam spin sum and difference of CLAS at 6 GeV**

$\overleftrightarrow{e}\, p \rightarrow e\, \gamma\, p$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r)\mathrm{d}^3 r$$

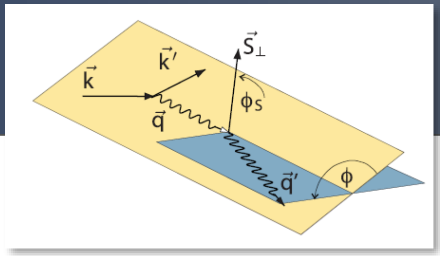
$M_2(t)$: Mass/energy distribution inside the nucleon
$d_1(t)$: Forces and pressure distribution

Bessel Integral relates $d_1(t)$ to the radial pressure p(r).

- **Repulsive** pressure near center
  $p(r=0) = 10^{35}$ Pa
- **Confining** pressure at r > 0.6 fm

Atmospheric pressure: 10^5 Pa
Pressure in the center of neutron stars ≤ 10^{34} Pa

GPDs and Nucleon Spin



$\ell\, d \rightarrow \ell\, n\, \gamma\, (p)$

$$\Delta\sigma_{LU}^{\sin\phi} = Im\left(F_{1n}\mathcal{H} + \xi(F_{1n}+F_{2n})\widetilde{\mathcal{H}} + t/4m^2 F_{2n}\mathcal{E}\right)$$

$\vec{\ell}\, p^{\uparrow} \rightarrow \ell\, p\, \gamma$

$$\Delta\sigma_{UT}^{\sin(\phi-\phi s)\cos\phi} = -\, t/4m^2\ Im\left(F_{2p}\mathcal{H} - F_{1p}\mathcal{E}\right)$$

$$\Delta\sigma_{LT}^{\sin(\phi-\phi s)\cos\phi} = -\, t/4m^2\ Re\left(F_{2p}\mathcal{H} - F_{1p}\mathcal{E}\right)$$

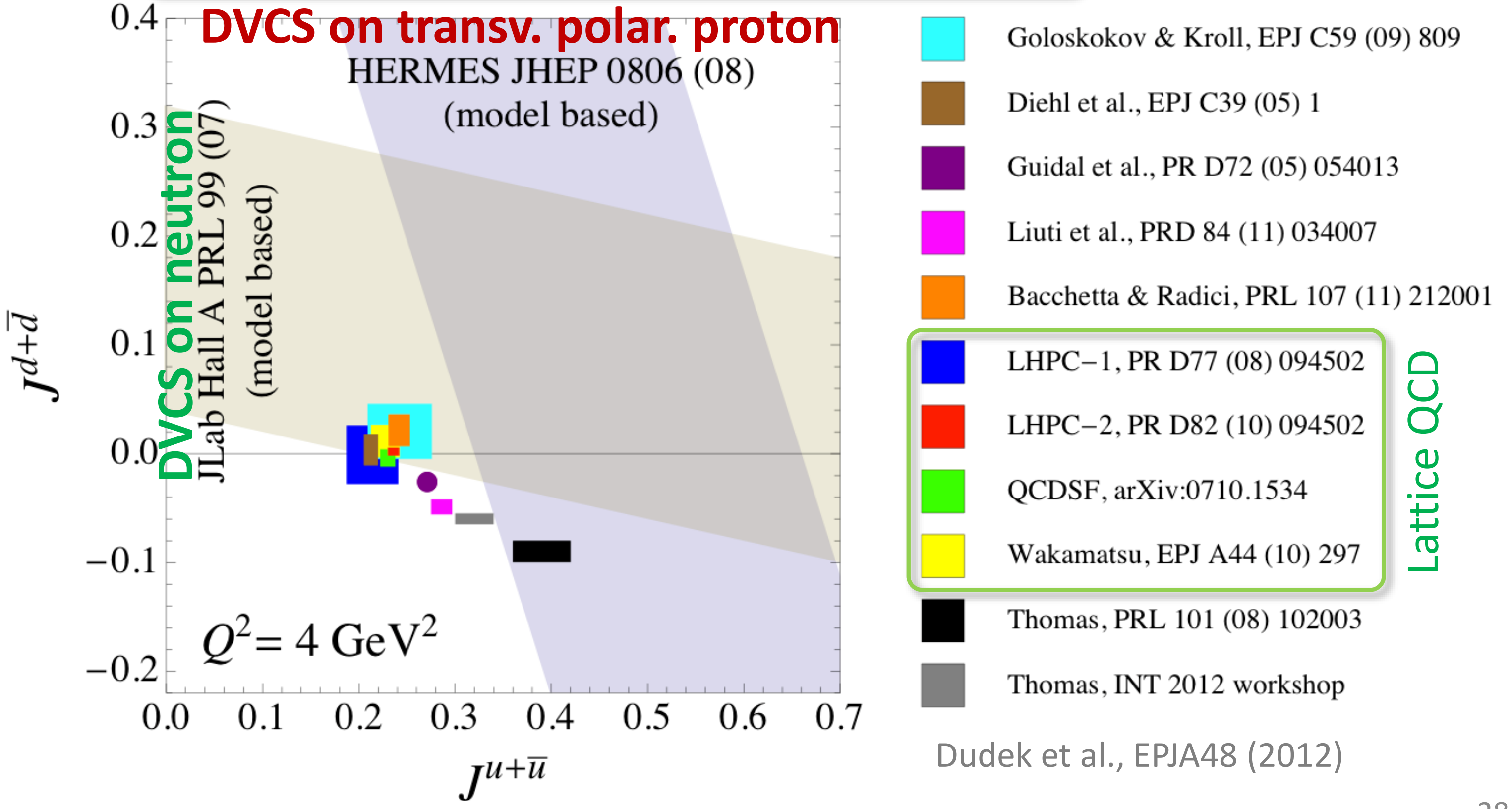
- First experimental constraint on E^q from neutron DVCS beam spin asymmetry at Hall A.

  M. Mazouz *et al*, PRL 99 (2007) 242501

- Provides constraints on orbital angular momentum of quarks

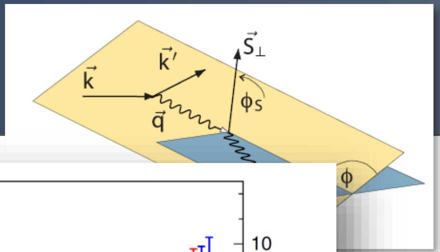
$$J_q = \frac{1}{2}\Sigma_q + L_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

Model dependent extraction of J^u and J^d



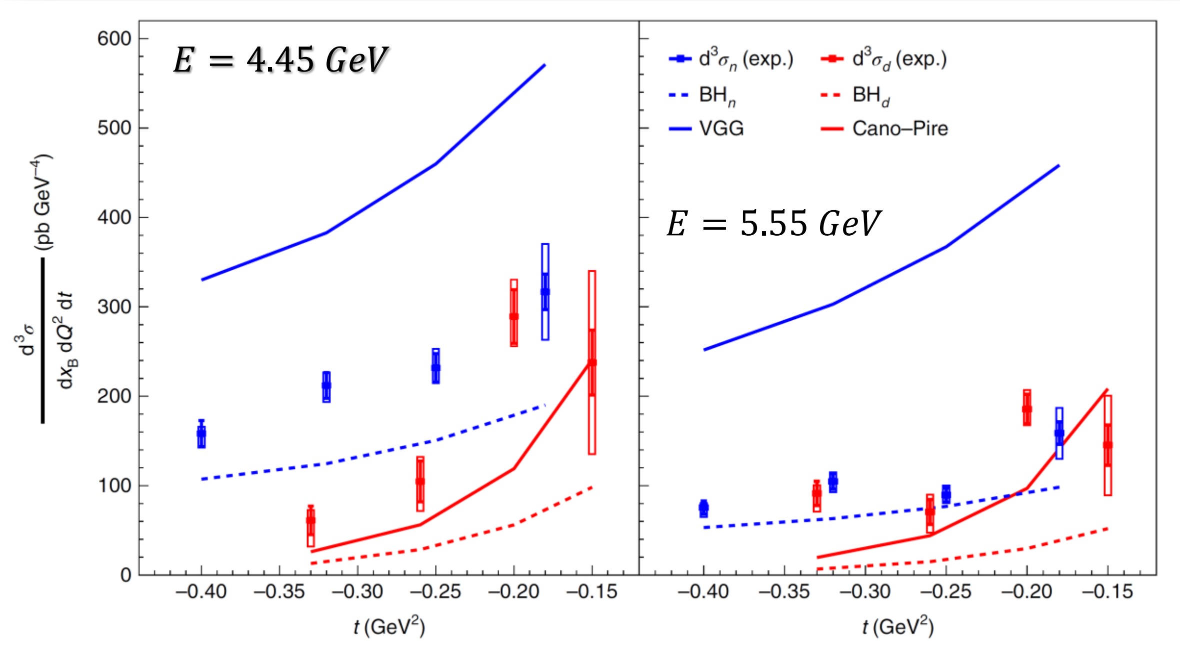
Dudek et al., EPJA48 (2012)

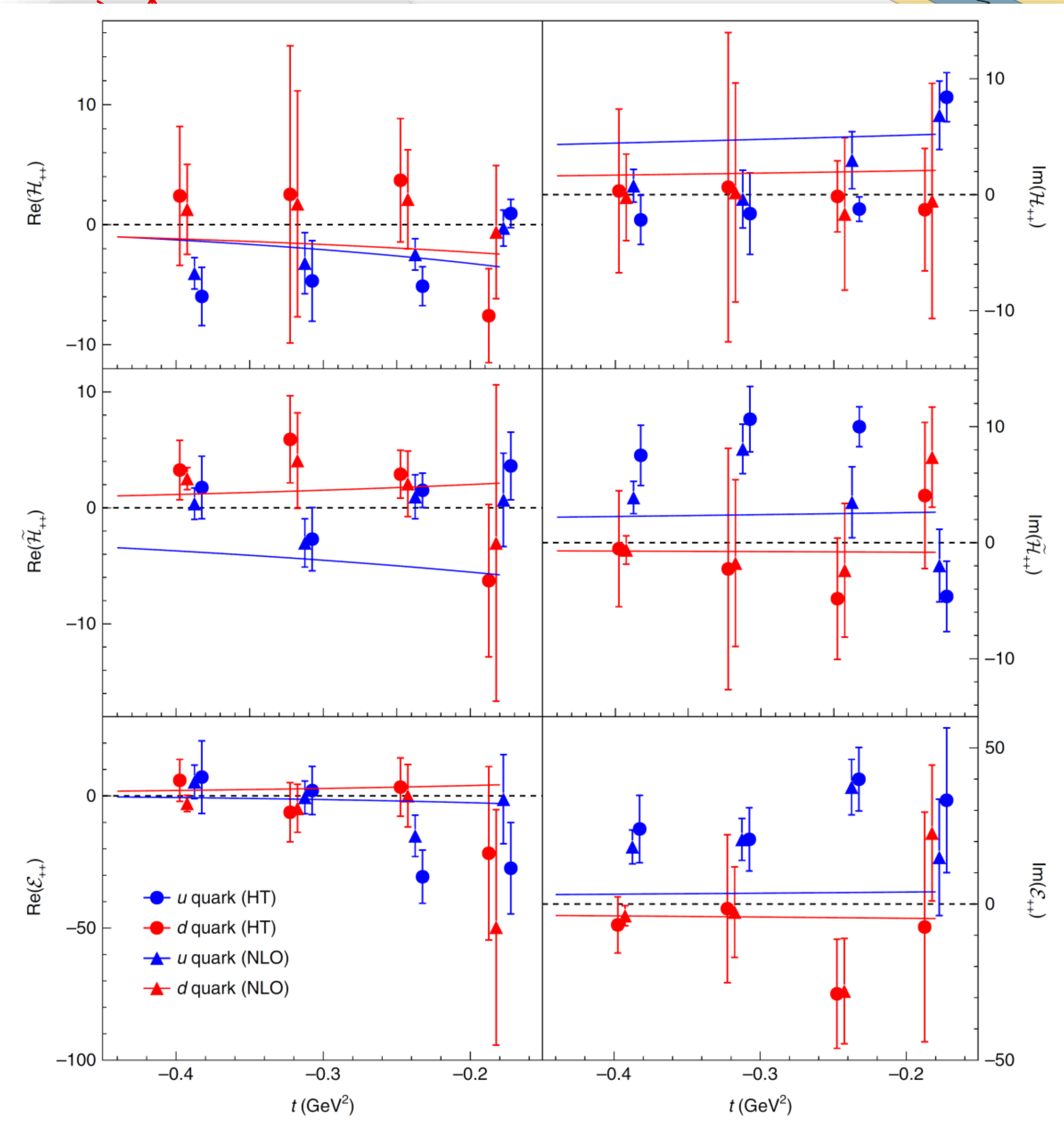
GPDs and Nucleon Spin



ℓ d → ℓ n γ (p)

$$\Delta\sigma_{LU}^{\sin\phi} = Im\,(F_{1n}\mathcal{H} + \xi(F_{1n}+F_{2n})\widetilde{\mathcal{H}} + t/4m^2\, F_{2n}\mathcal{E})$$

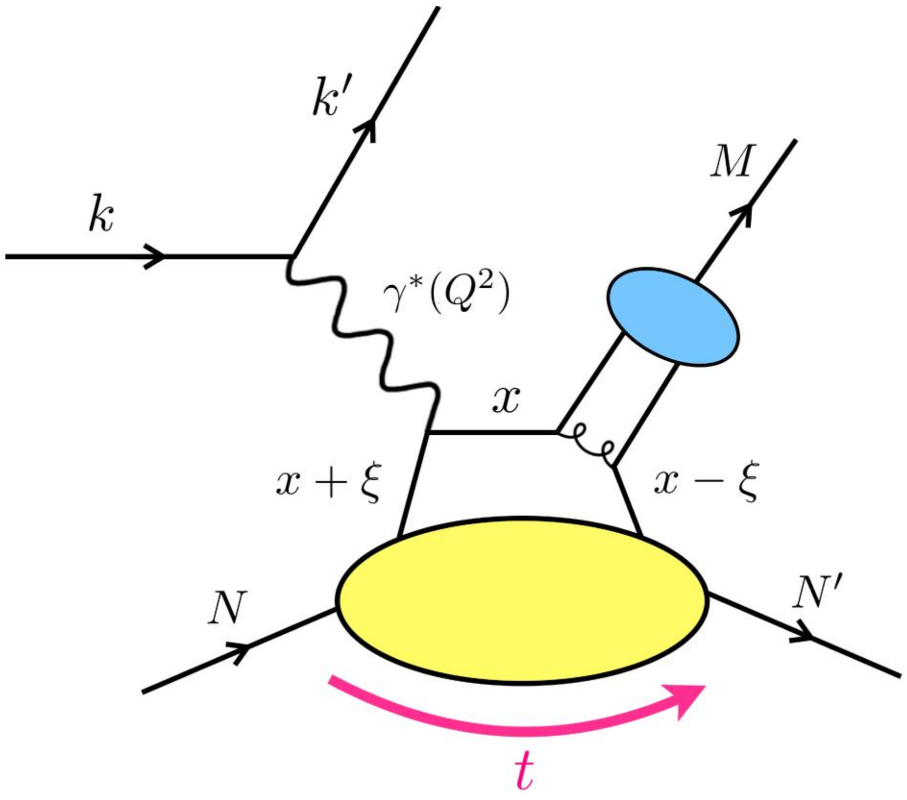




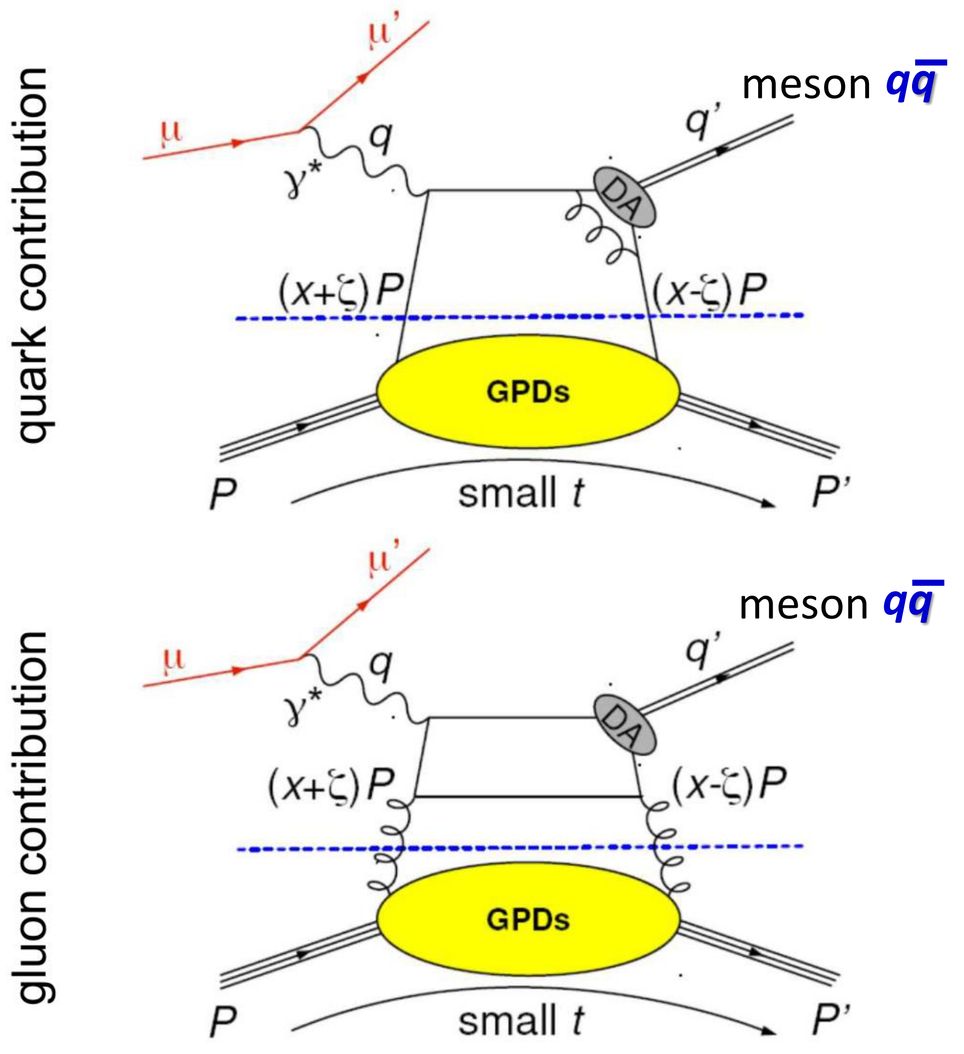
- Recent input from Result of neutron-DVCS at Hall A E08-025 (done on 2010)
- with $E_e = 4.5$ & 5.5 GeV on LD_2 target. $< Q^2 > = 1.75\ GeV^2$, $< x_B > = 0.36$

M. Benali *et al.*, Nature Phys. 16(2), 191 **(2020)**

DVMP



Deeply Virtual Meson Production (DVMP)



4 chiral-even GPDs: helicity of parton unchanged

$H^q(x, \xi, t)$	$E^q(x, \xi, t)$
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$

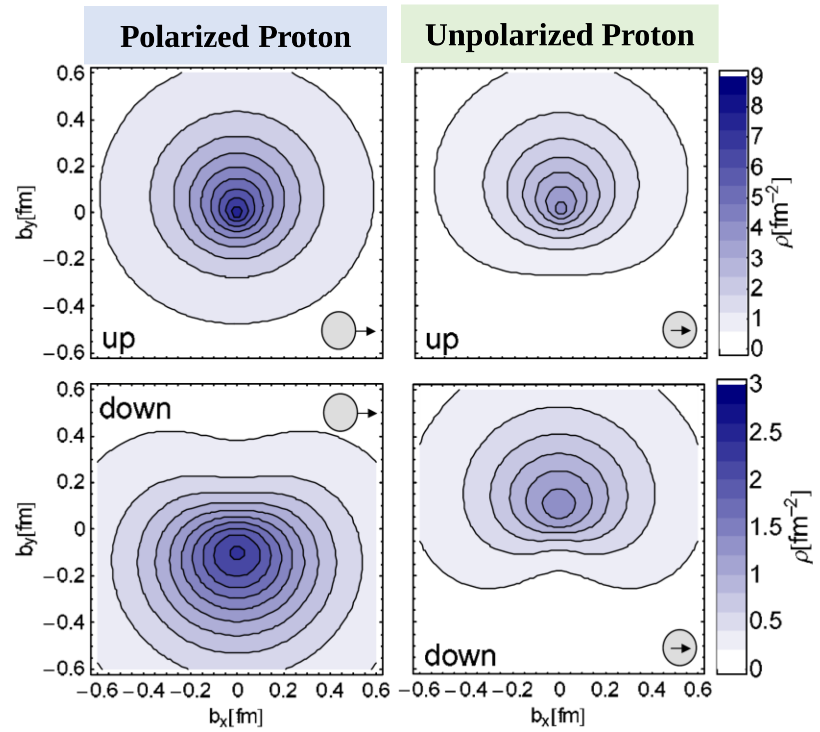
+ 4 chiral-odd or transversity GPDs: helicity of parton changed

$H_T^q(x, \xi, t)$	$E_T^q(x, \xi, t)$	$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$
$\tilde{H}_T^q(x, \xi, t)$	$\tilde{E}_T^q(x, \xi, t)$	

- Universality of GPDs, quark flavor filter
- Ability to probe the chiral-odd GPDs.
- Additional non-perturbative term from meson wave function → more difficult for GPD extraction
- In addition to nuclear structure, provide insights into reaction mechanism

What Can We Learn from Chiral-odd GPDs

		Quark polarization		
		U	L	T
Nucleon polarization	U	H		$\bar{E}_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	H_T, $\tilde{H}_T$



Described by E

Described by $\bar{E}_T = 2\tilde{H}_T + E_T$

Lattice Calculation: Gockeler *PRL* 222001 (2007)

- $\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon
- Chiral-odd GPDs H_T
  - Generalization of transversity distribution $h_1(x)$ → related to the transverse spin structure
  - Tensor charge

GPDs parametrization:

H_T

→ tensor charge: T.Ledwig, A.Silva, H.C. Kim

$\int dx H_T(x, \xi, t)$

→ transversity PDF: M.Anselmino

$H_T(x, \xi = 0, t = 0) = h_1$

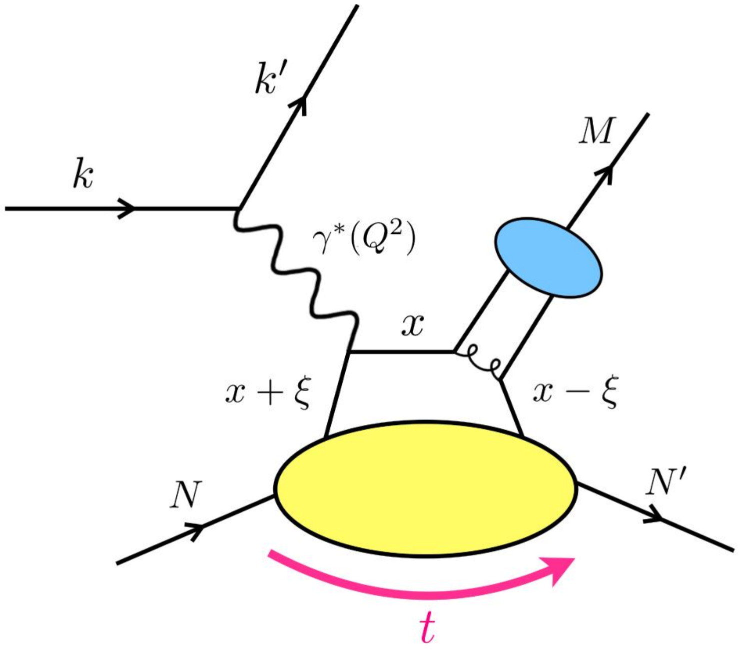
DVMP Structure Functions with Longitudinally Polarized Beam & Target

$$\frac{2\pi}{\Gamma}\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi$$ → Unpolarized

$$+P_b\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$ → Longitudinally polarized beam

$$+P_{tg}\left(\sqrt{\epsilon(1+\epsilon)}\sigma_{UL}^{\sin\phi}\sin\phi + \epsilon\sigma_{UL}^{\sin 2\phi}\sin 2\phi\right)$$ → Longitudinally polarized target

$$+P_b P_{tg}\left(\sqrt{1-\epsilon^2}\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\,\sigma_{LL}^{\cos\phi}\cos\phi\right)$$ → Longitudinally polarized beam and target



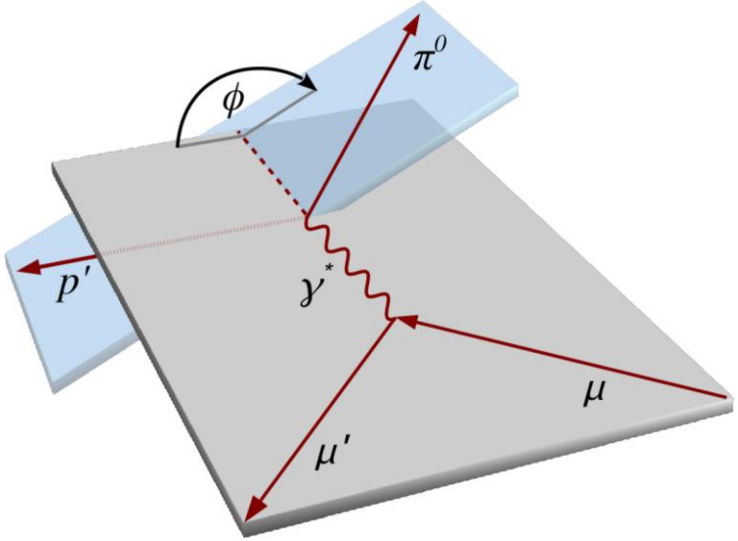
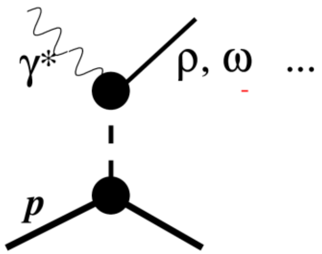


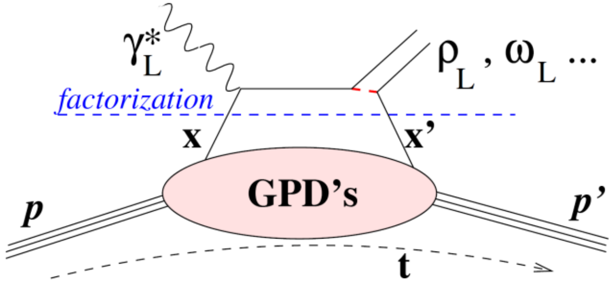
Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

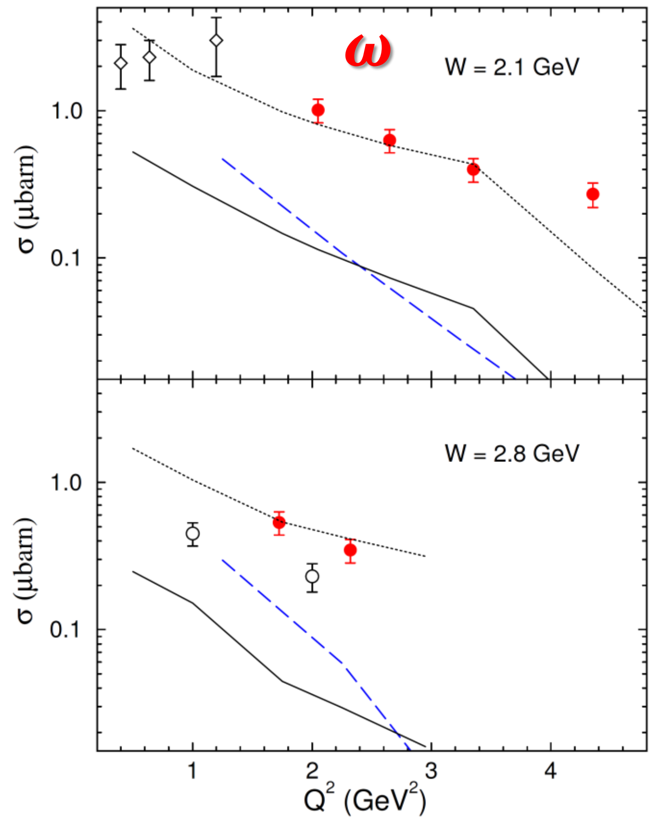
ϵ : degree of longitudinal polarization
P_b: initial lepton polarization
P_{tg}: initial target polarization

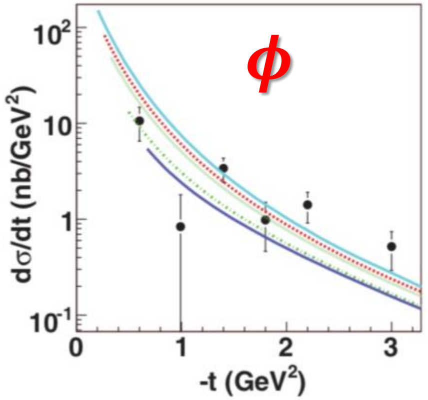
Vector Meson Production at CLAS

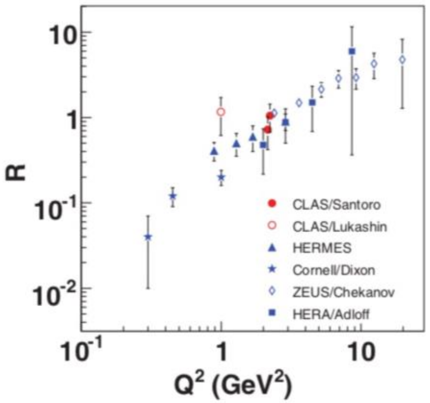
- Pilot analysis of exclusive ω-electroproduction published in EPJ A **24**, 445 (2005), followed by analyses of ϕ, Phys. Rev. C **78**, 025210 (2008), and ρ^0, EPJ A **39**, 5-31 (2009)
- Test two hypotheses → t-channel Regge trajectory exchange on the hadronic level and the handbag diagram approach on the partonic level
- Regge Model favored by data in CLAS kinematics.

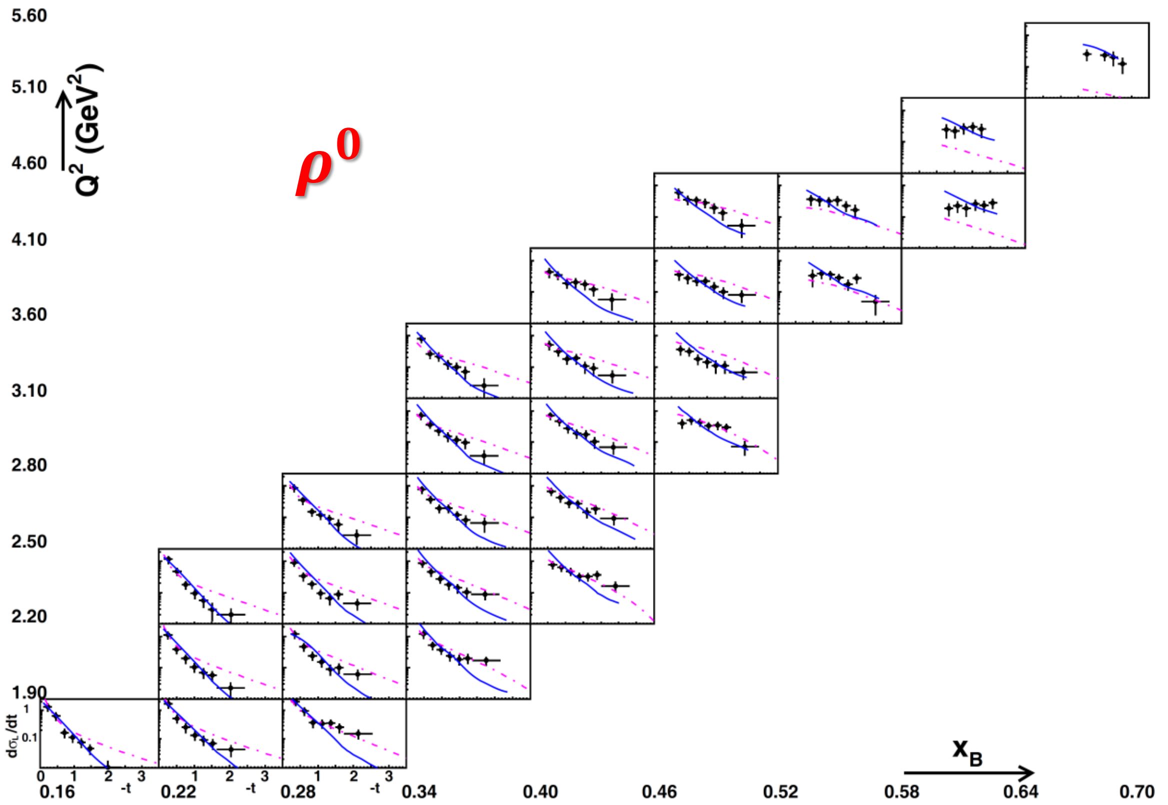




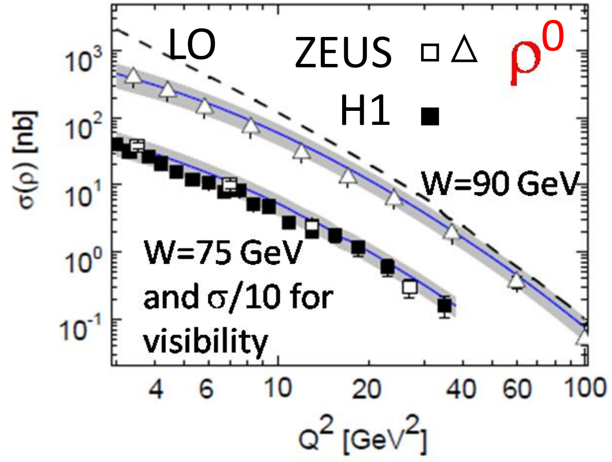


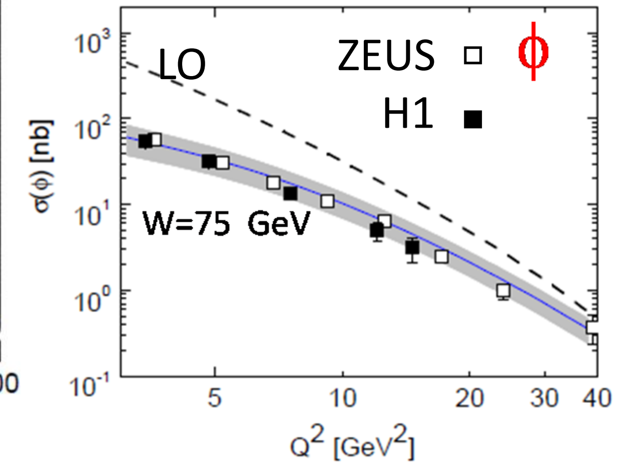


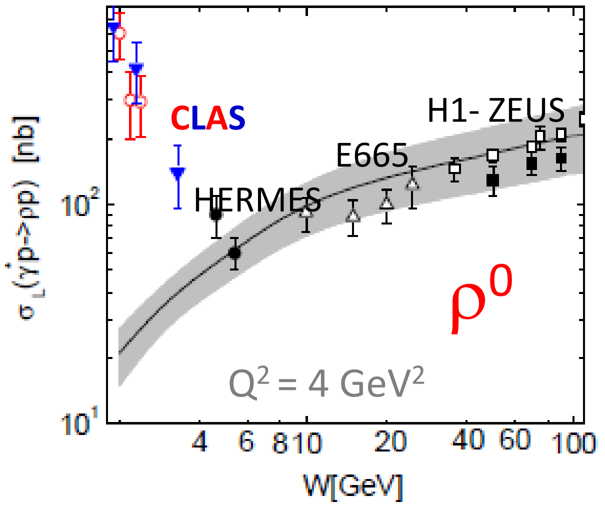


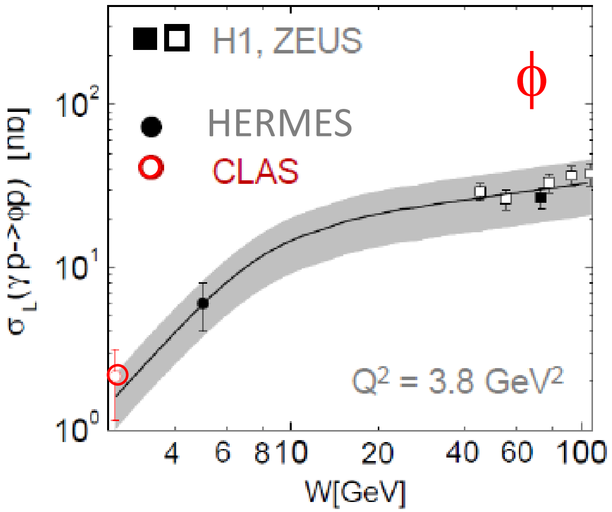


GPDs with Vector Meson Production



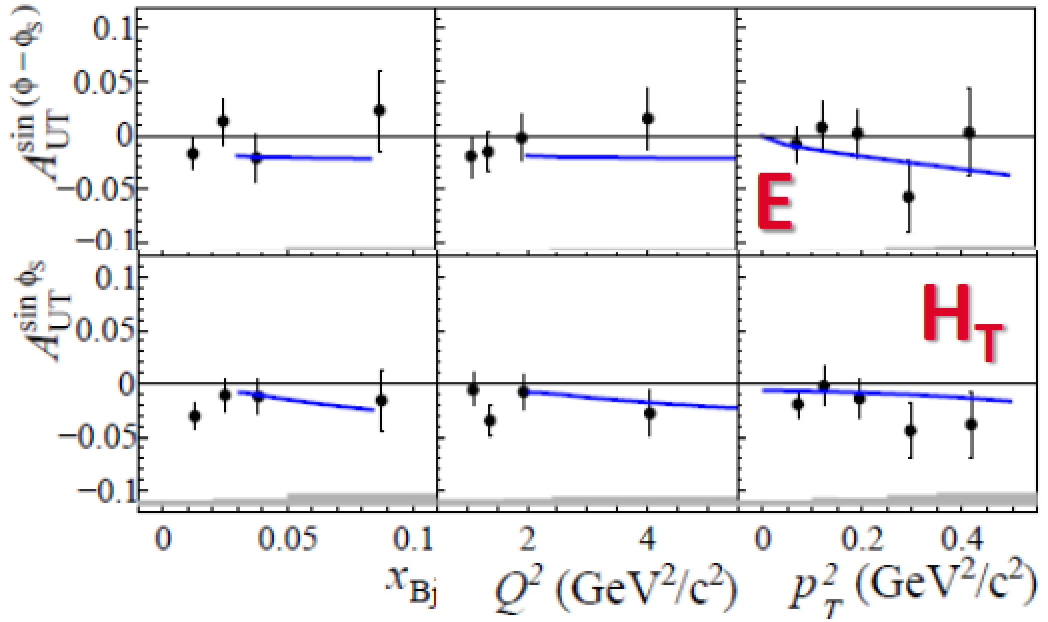






ρ^0 ($\rightarrow \pi^+\pi^-$) production at COMPASS with Transversely Polarized Target

COMPASS, NPB 865 (2012) 1-20, PLB731 (2014) 19

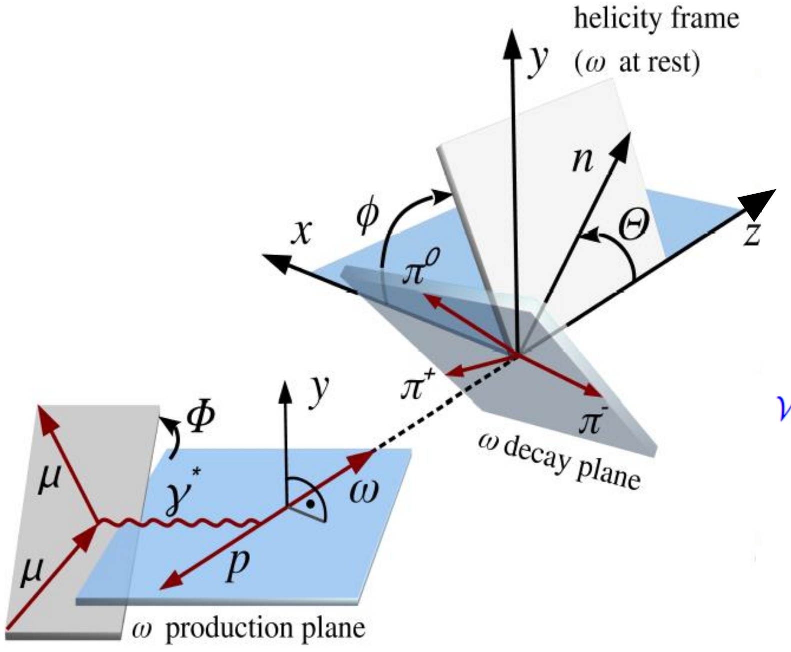


GK Model by Goloskokov, Kroll, constrained by DVMP at small x_B (or large W)

- leading-twist longitudinal $\gamma_L^* \, p \rightarrow M \, p$ and transv. polar. $\gamma_T^* \, p \rightarrow M \, p$
- quark and gluon contributions (GPDs **H, E, H_T**) and beyond leading twist

Vector Meson Production: Spin Density Matrix Elements

Experimental angular distributions



$$\frac{d\sigma}{d\phi\ d\Phi\ d\Theta\ dQ^2\ dx_B\ dt} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\}\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta)$$

$$\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta) = \mathcal{W}^{U}(\Phi, \phi, \cos\Theta) + P_b\mathcal{W}^{L}(\Phi, \phi, \cos\Theta)$$

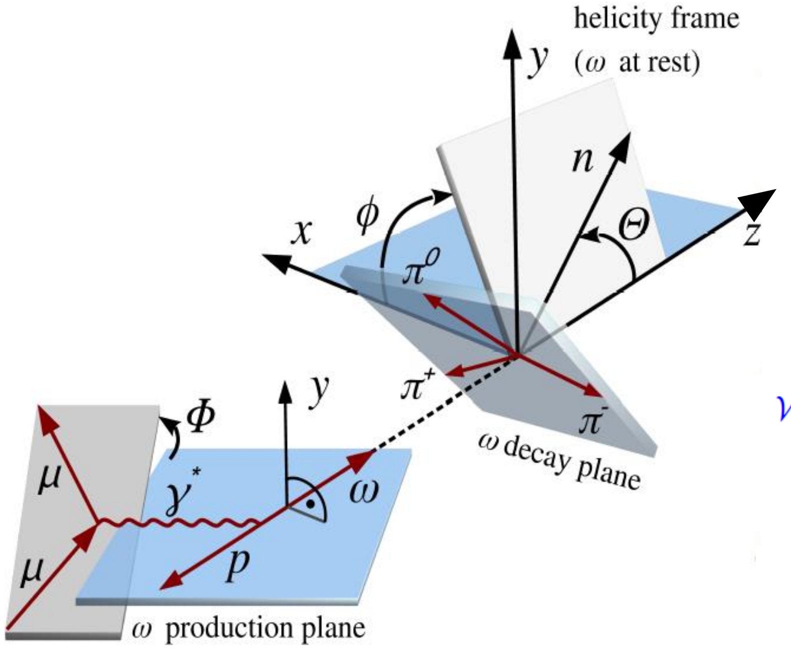
15 unpolarized SDMEs in $\mathcal{W}^U$ and 8 polarized in $\mathcal{W}^L$

$$\mathcal{W}^U(\Phi, \phi, \cos\Theta) = \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1 - r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00} - 1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi$$
$$-\epsilon\cos 2\Phi\Big(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^1_{10}\}\sin 2\Theta\cos\phi - r^1_{1-1}\sin^2\Theta\cos 2\phi\Big)$$
$$-\epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^2_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^2_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^5_{10}\}\sin 2\Theta\cos\phi - r^5_{1-1}\sin^2\Theta\cos 2\phi\Big)$$
$$+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^6_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^6_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],$$

$$\mathcal{W}^L(\Phi, \phi, \cos\Theta) = \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Bigg]$$

Vector Meson Production: Spin Density Matrix Elements

Experimental angular distributions



$$r^1_{00}\sigma_0 \sim \left|\bar{E}_T\right|^2$$

$$r^5_{00}\sigma_0 \sim \mathrm{Re}\left[\langle\bar{E}_T\rangle\langle H\rangle + \langle H_T\rangle\langle E\rangle\right]$$

$$r^8_{00}\sigma_0 \sim \mathrm{Im}\left[\langle\bar{E}_T\rangle\langle H\rangle + \langle H_T\rangle\langle E\rangle\right]$$

$$\begin{aligned}
\mathcal{W}^U(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[&\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi \\
&-\epsilon\cos 2\Phi\Big(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^1_{10}\}\sin 2\Theta\cos\phi - r^1_{1-1}\sin^2\Theta\cos 2\phi\Big) \\
&-\epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^2_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^2_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
&+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^5_{10}\}\sin 2\Theta\cos\phi - r^5_{1-1}\sin^2\Theta\cos 2\phi\Big) \\
&+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^6_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^6_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],
\end{aligned}$$

$$\begin{aligned}
\mathcal{W}^L(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[&\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
&+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
&+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Bigg]
\end{aligned}$$

2012 COMPASS Exclusive ω Prod. On Unpolarized Proton

SCHC ($\lambda_\gamma = \lambda_V$)
(S-Channel Helicity Conservation)

SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$

= - 0.010 ± 0.032 ± 0.047 OK

- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$

= 0.014 ± 0.011 ± 0.013 OK

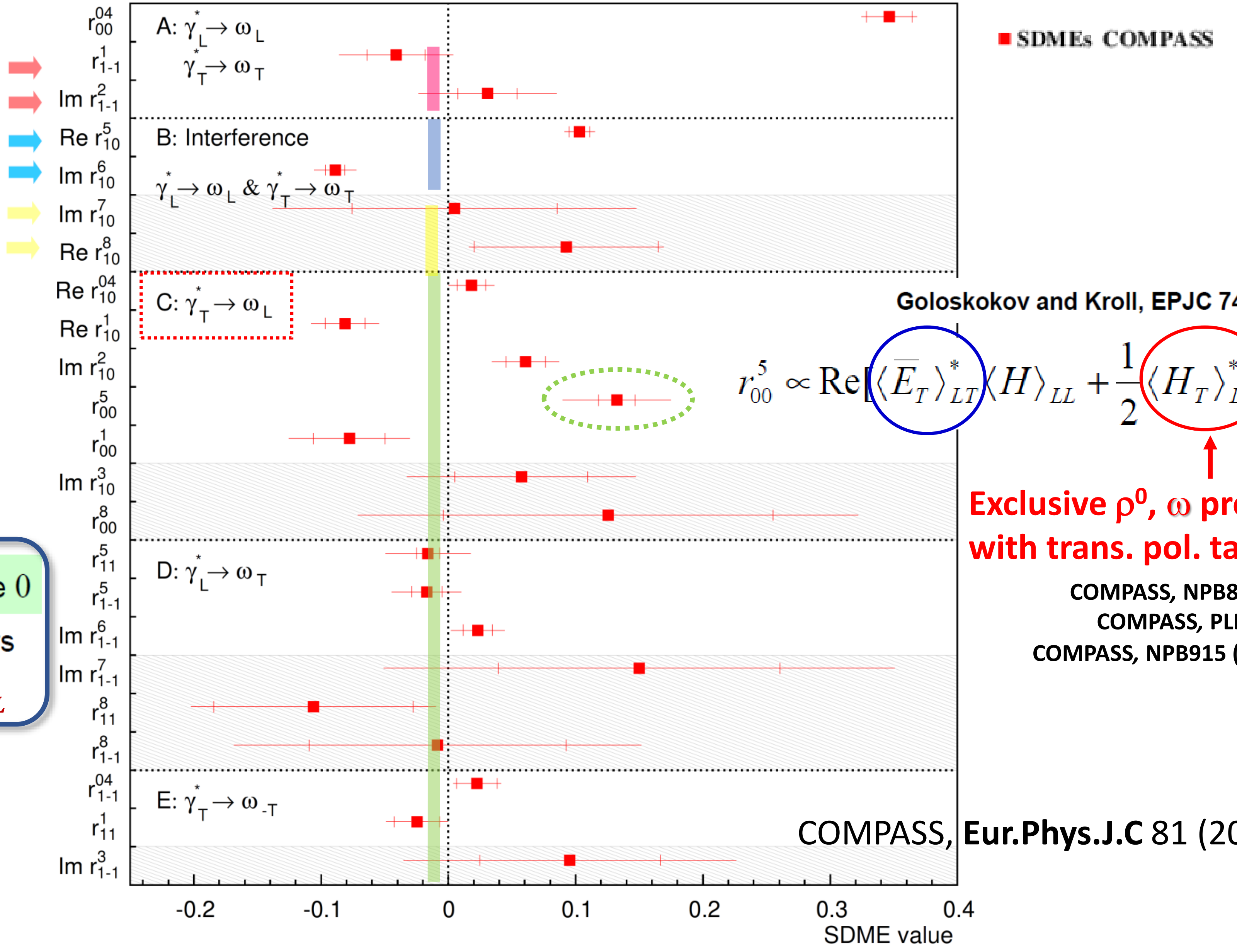
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

= - 0.088 ± 0.110 ± 0.196 OK

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \omega_T$ and $\gamma^*_T \to \omega_{-T}$ OK within errors

NOT OBSERVED for transitions $\gamma^*_T \to \omega_L$



Goloskokov and Kroll, EPJC 74 (2014) 2725

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

Exclusive ρ^0, ω production with trans. pol. target

COMPASS, NPB865 (2012) 1-20
COMPASS, PLB731 (2014) 19
COMPASS, NPB915 (2017) 454-475

COMPASS, **Eur.Phys.J.C** 81 (2021) 126

2012 COMPASS Exclusive ρ^0 Prod. On Unpolarized Proton

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

(S-Channel Helicity Conservation)

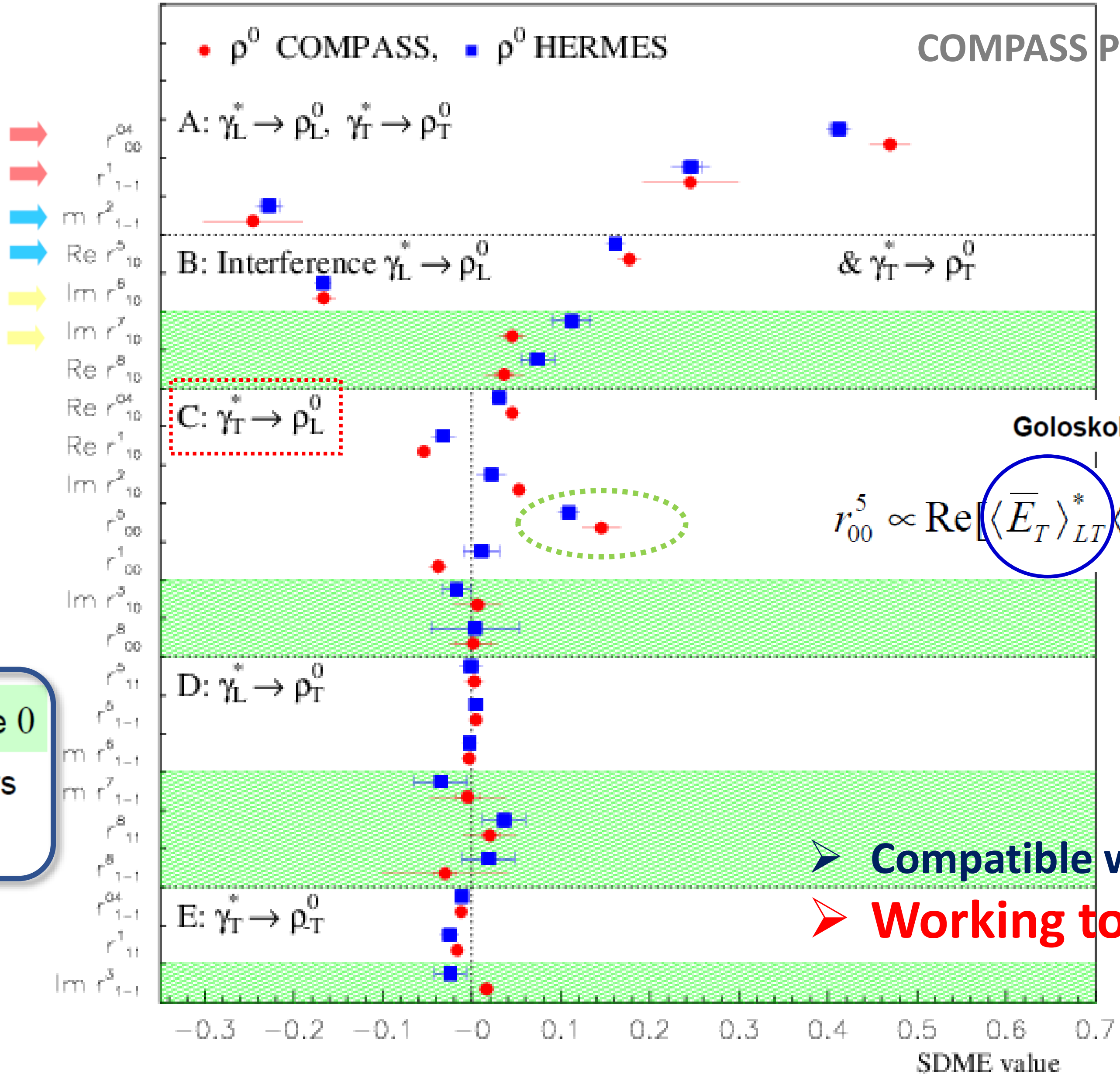
SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$ **OK**
- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$ **OK**
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$ ✓**OK**

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \rho^0_T$ and $\gamma^*_T \to \rho^0_{-T}$ OK within errors

NOT OBSERVED for transitions $\gamma^*_T \to \rho^0_L$



COMPASS Preliminary

Goloskokov and Kroll, EPJC 74 (2014) 2725

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

First term dominates
→ Probes $\overline{E}_T$

- Compatible with HERMES
- **Working towards publication!**

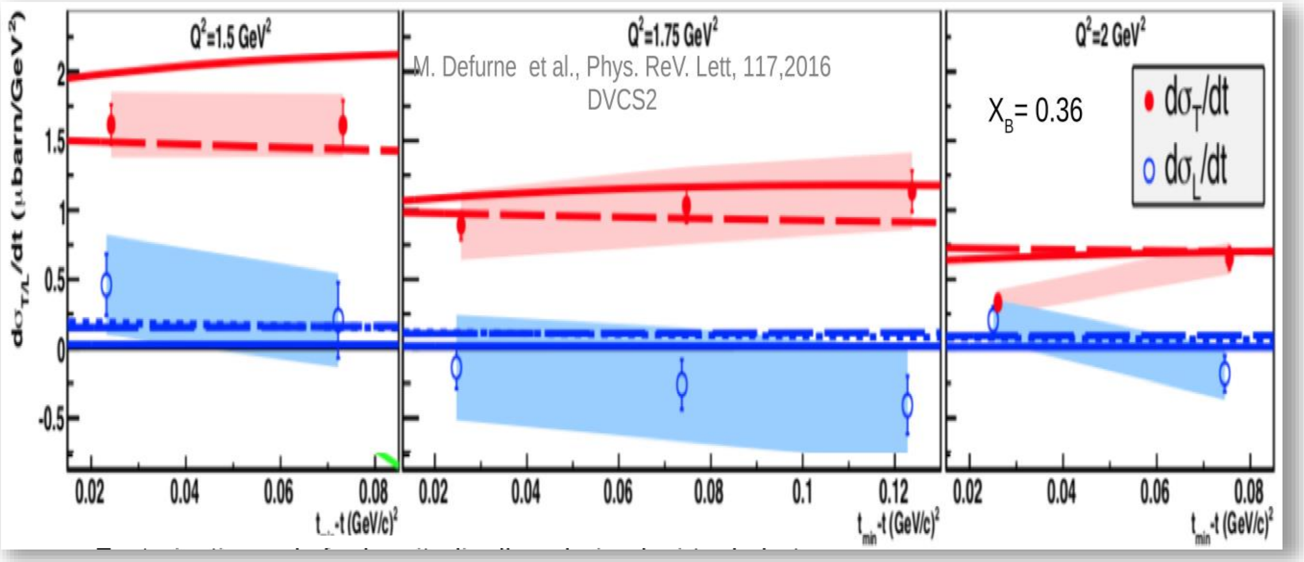
Exclusive π^0 Production

$\ell\, p \rightarrow \ell\, \pi^0\, p$

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{TL'}}{dt}\sin(\phi)\right]$$

- $\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$
- $\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$
- $\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$
- $\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$

$$\bar{E}_T = 2\tilde{H}_T + E_T$$



- Significant transverse contribution:
  Coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude.

—— S. V. Goloskokov and P. Kroll, Eur. Phys. J. C65:137 (2010) - - - - G. R. Goldstein, J. O. Hernandez, S. Liuti, Phys. Rev. D84 (2011)

GPDs and Hard Exclusive π^0 Production

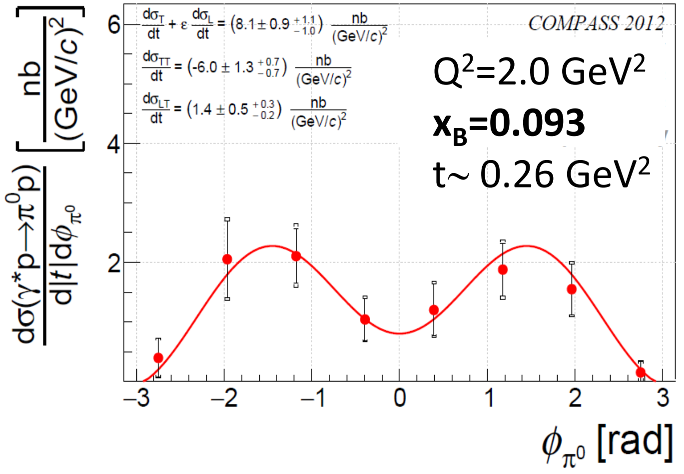
$\ell\, p \rightarrow \ell\, \pi^0\, p$

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

$$\left|\langle \tilde{H} \rangle\right|^2 - \frac{t'}{4m^2}\left|\langle \tilde{E} \rangle\right|^2 \qquad \left|\langle H_T \rangle\right|^2 - \frac{t'}{8m^2}\left|\langle \bar{E}_T \rangle\right|^2 \qquad \frac{t'}{16m^2}\left|\langle \bar{E}_T \rangle\right|^2 \qquad \frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T \rangle^* \langle \tilde{E} \rangle\right]$$

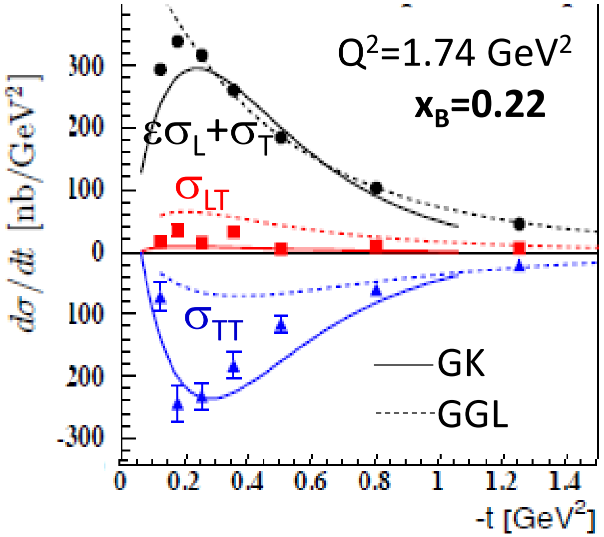
COMPASS 4 weeks 2012 pilot run

COMPASS, PLB 805 (2020) 135454



JLab 6 GeV CLAS

Bedlinskiy et al, PRL109 (2012), PRC90 (2014)



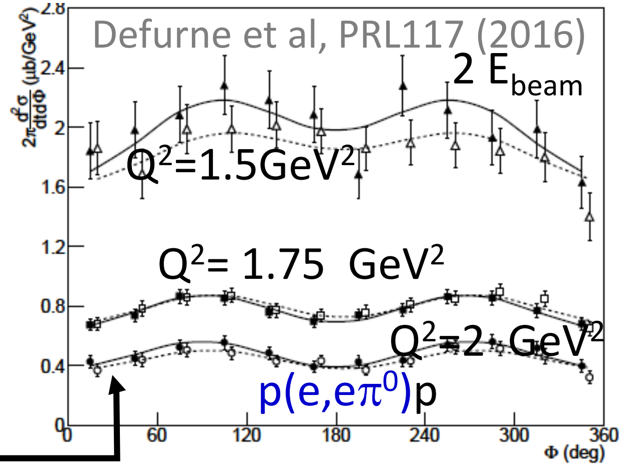
JLab 6 GeV Hall-A

Different beam energies

➔ L/T separation

LH2 target → proton

LD2 target → neutron+deuteron

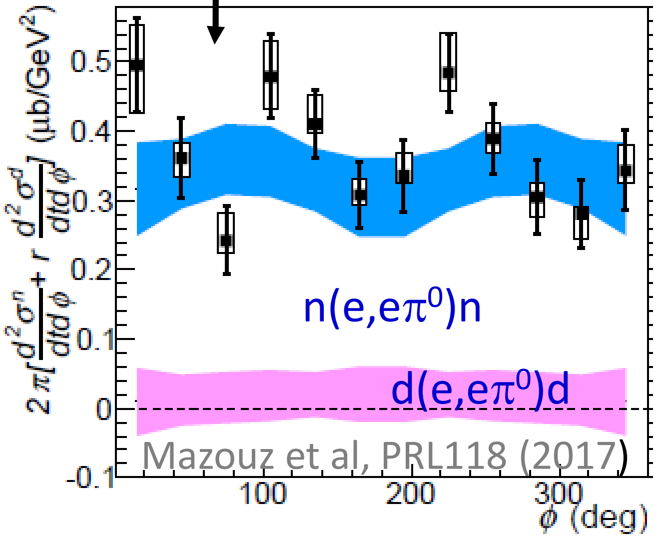


$D(e,e\pi^0)X - p(e,e\pi^0)p = n(e,e\pi^0)n + d(e,e\pi^0)d$

➢ Flavor decomposition

H_T^u and H_T^d

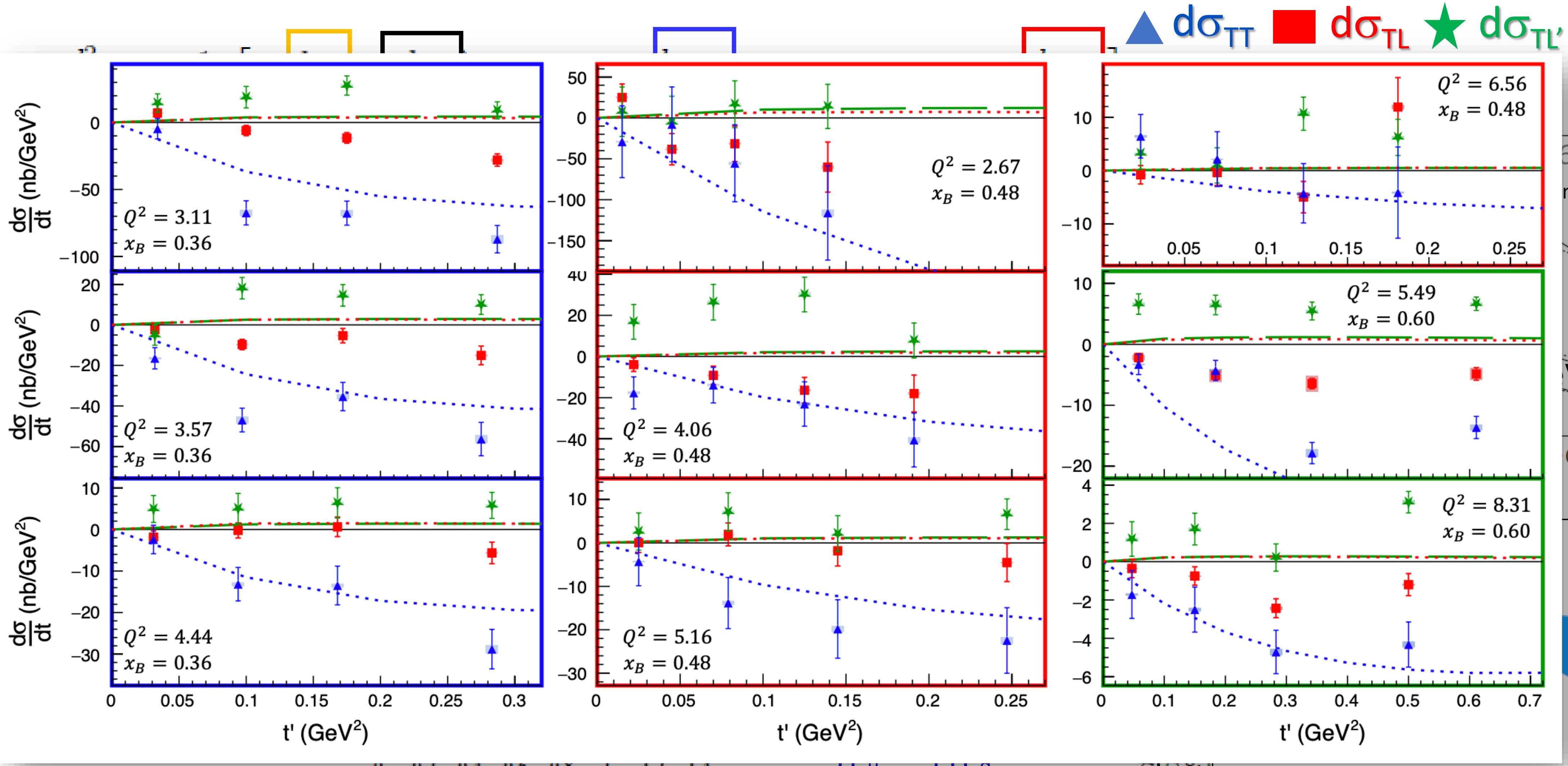
$\bar{E}_T^u$ and $\bar{E}_T^d$



➢ Provide constraints on H_T and $\bar{E}_T$

GPDs and Hard Exclusive π^0 Production

$\ell\, p \rightarrow \ell\, \pi^0\, p$



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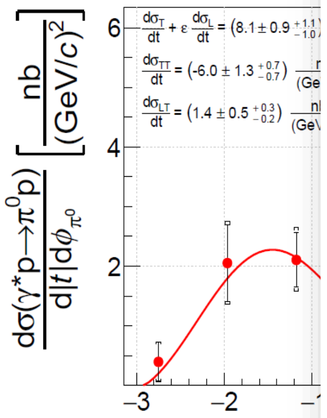
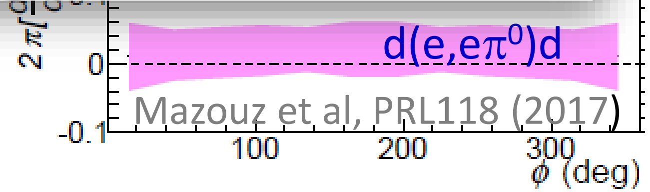


H_T^u and H_T^d

$\bar{E}_T^u$ and $\bar{E}_T^d$



- Recent input from Hall-A E12-06-114, at high x_B over a large Q^2 range

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301 (2021)

GPDs and Hard Exclusive π^0 Production

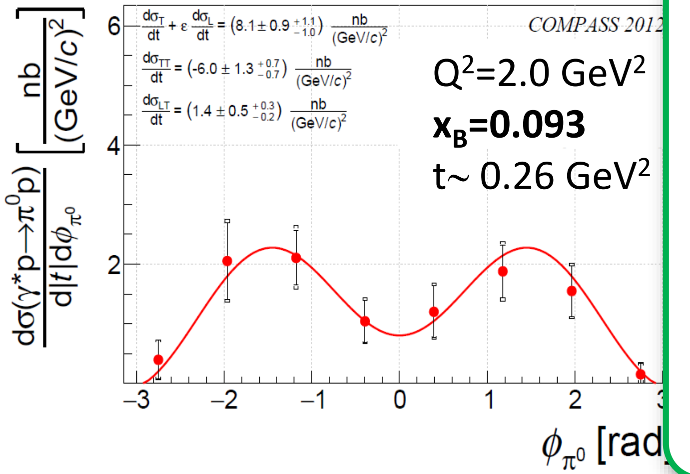
$\ell\, p \rightarrow \ell\, \pi^0\, p$

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}$$

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

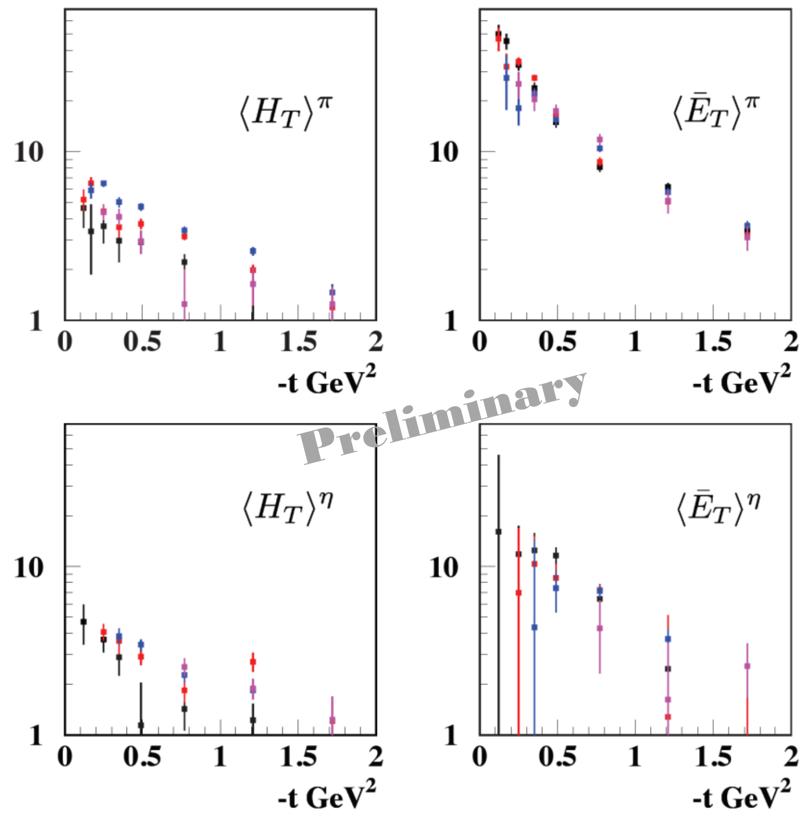
COMPASS 4 weeks 2012 pilot r

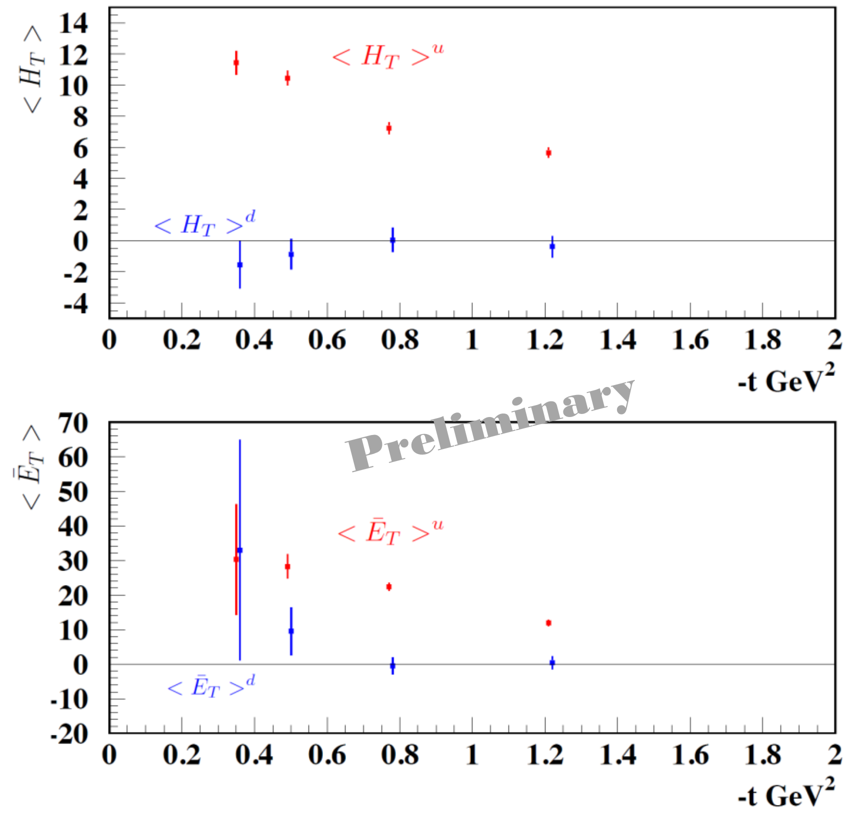
COMPASS, PLB 805 (2020) 135454



➢ Generalized Form Factors

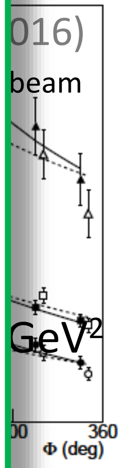
➢ Quark Flavor Decomposition

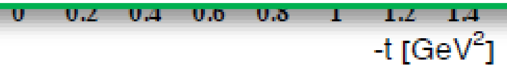




Preliminary attempts using π^0 & η data from CLAS

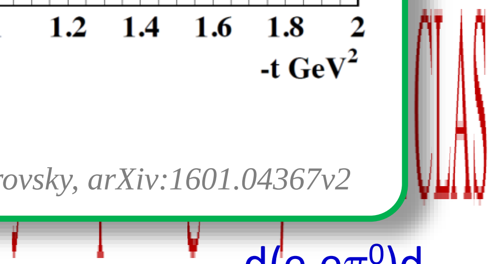
Valery Kubarovsky, arXiv:1601.04367v2





H_T^u and H_T^d

$\bar{E}_T^u$ and $\bar{E}_T^d$



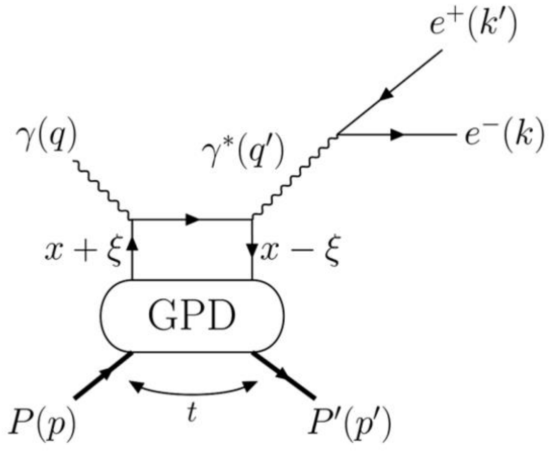
$d(e,e\pi^0)d$

Mazouz et al, PRL118 (2017)

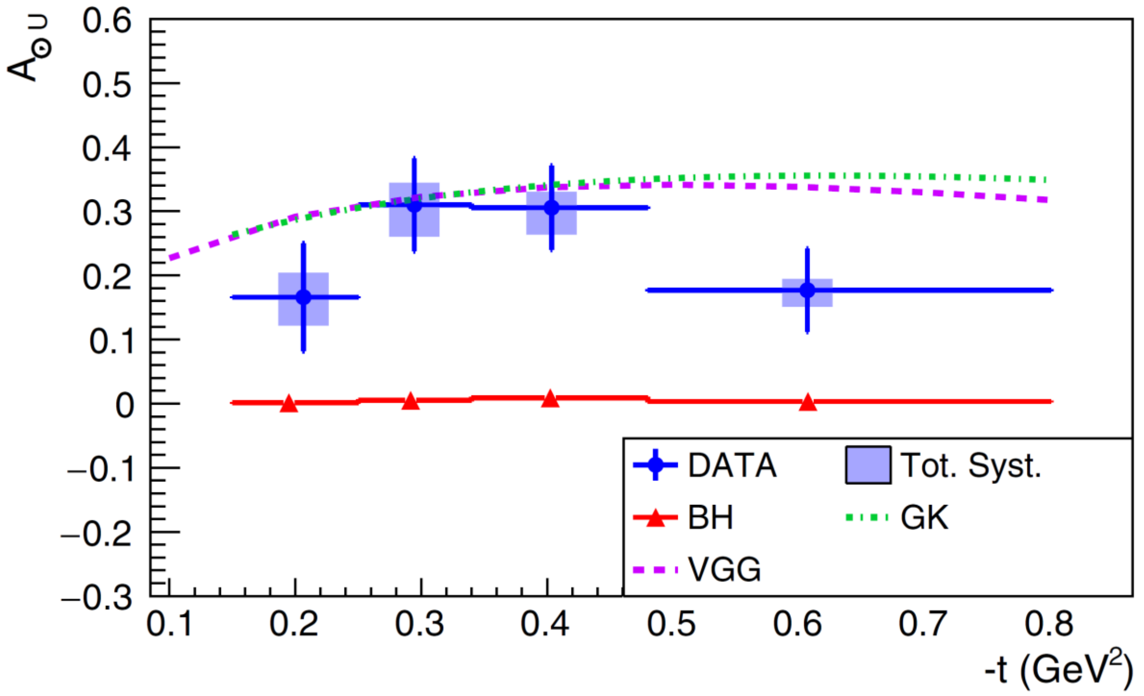
➢ Preliminary attempts using π^0 & η data from CLAS

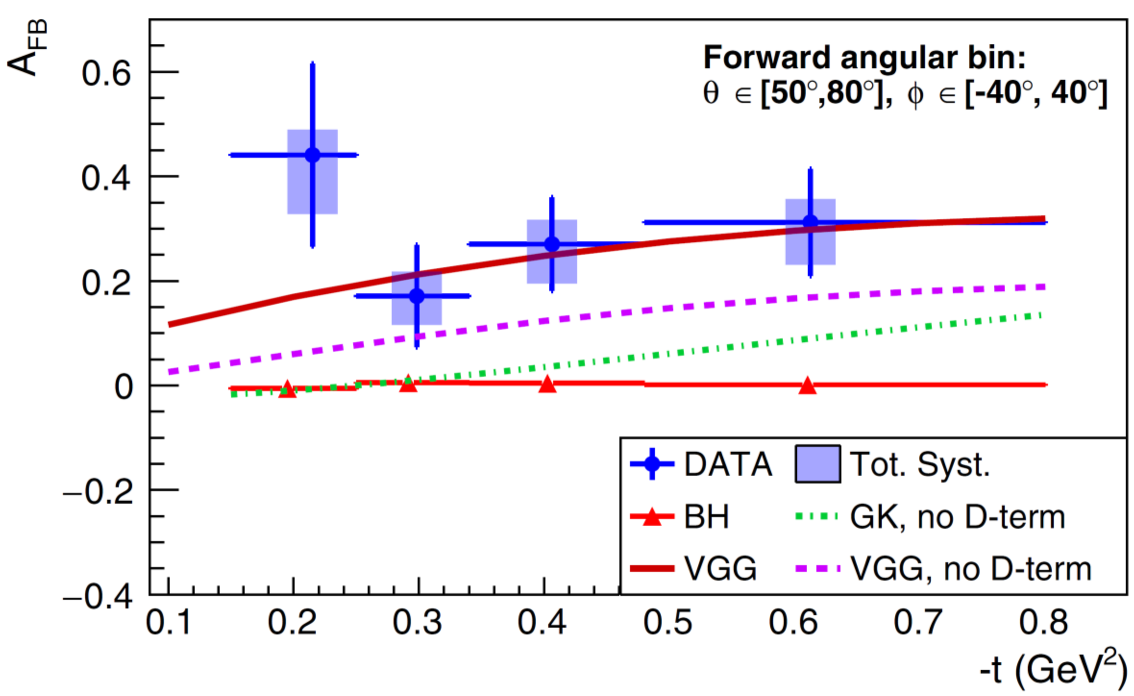
Timelike Compton Scattering (TCS)

- First ever Timelike Compton Scattering Measurement at CLAS
  Phys. Rev. Lett. 127, 262501 (2021)
- Photon polarization asymmetry $A_{\odot U} \sim sin\phi \cdot \mathrm{Im}\widetilde{M}^{--}$ → GPD universality
- Forward backward asymmetry $A_{FB} \sim cos\phi \cdot \mathrm{Re}\widetilde{M}^{--}$ → Access D-term



$$\tilde{M}^{--} = \left[F_1 \mathcal{H} - \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4m_p^2} F_2 \mathcal{E} \right]$$

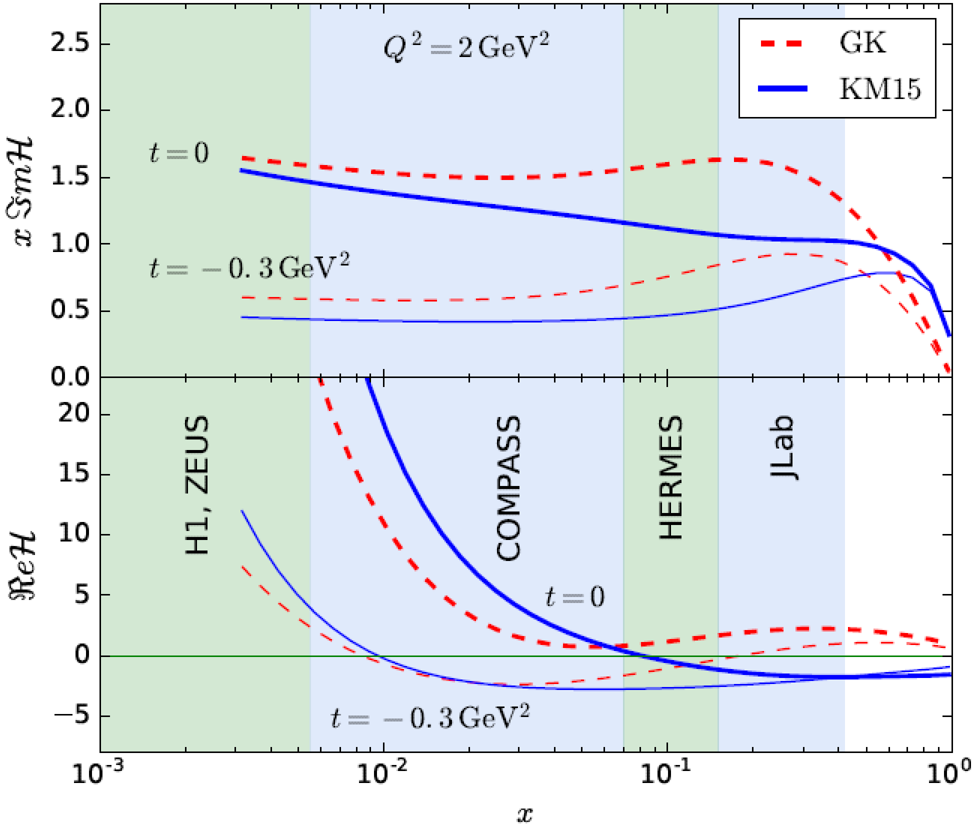




Global Analysis

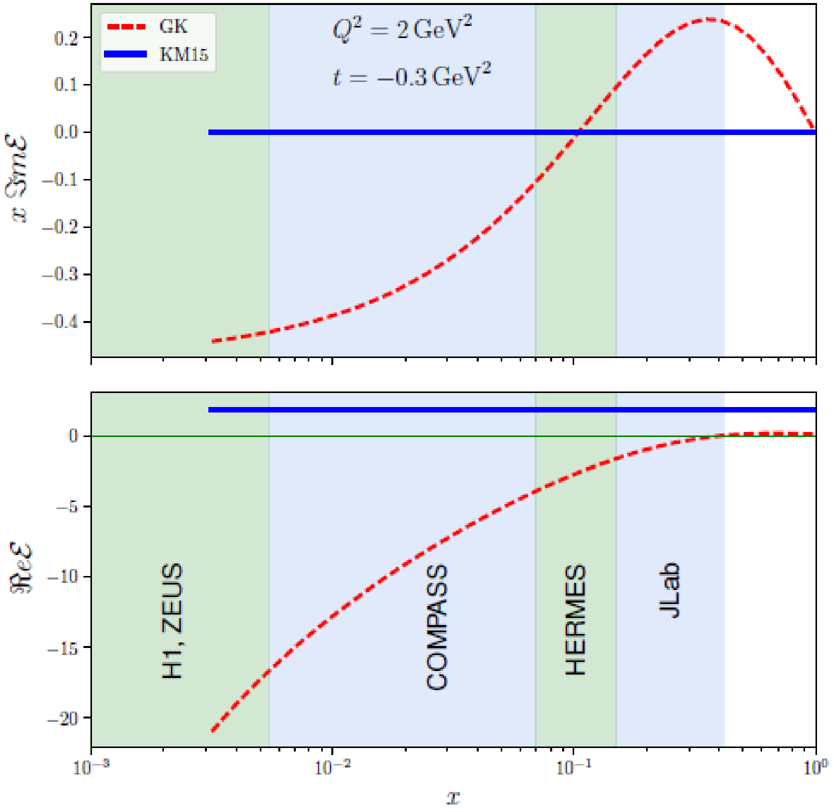
Figures made by D. Mueller and K. Kumericki

KM15 K Kumericki and D Mueller arXiv:1512.09014v1
GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)



Im H
is better known

Re H linked to the *d term* is still poorly constrained



Im E
is fairly unknown

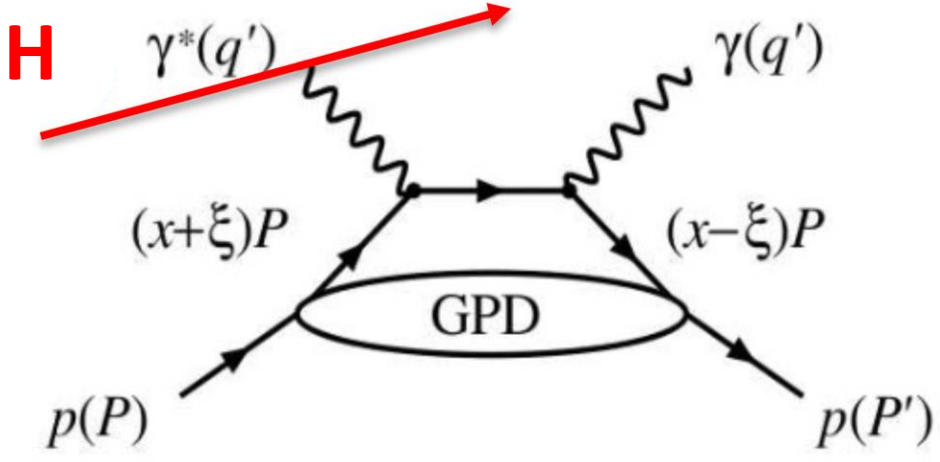
Re E
is fairly unknown

- Very little is known for chiral-odd GPDs as well.
- **More experimental inputs required!**

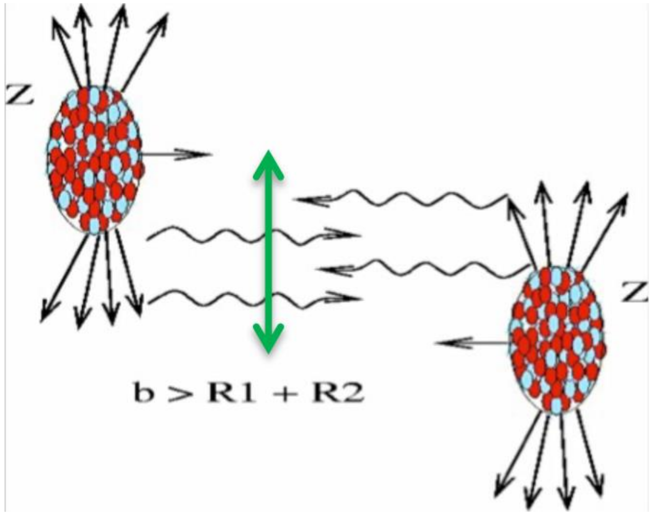
 - Various processes and precise data mapping, with high granularity and phase space wider than what has been covered, are required to fully constrain the entire set of GPDs

Possibilities at sPHENIX?

DVCS & Ultraperipheral Collisions



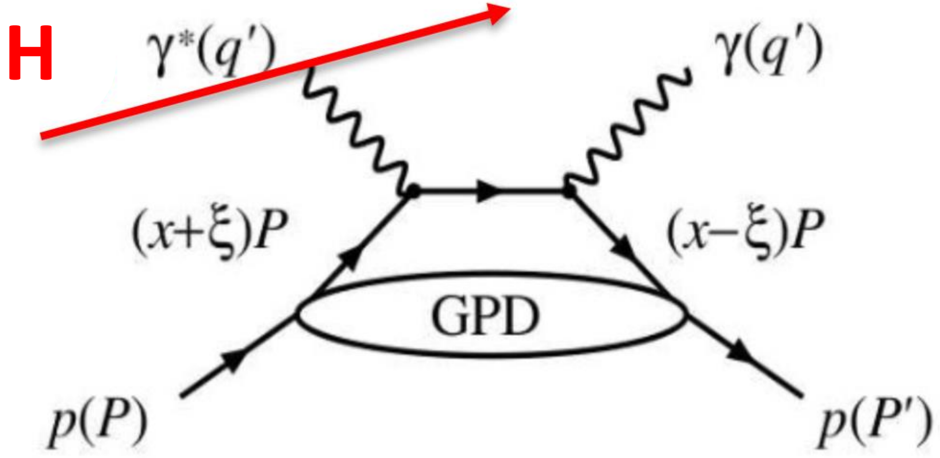
- As discussed already, DVCS has been the workhorse for GPD extraction from **lepton beams.**
- Can the virtual photon come from hadron (**H**)?



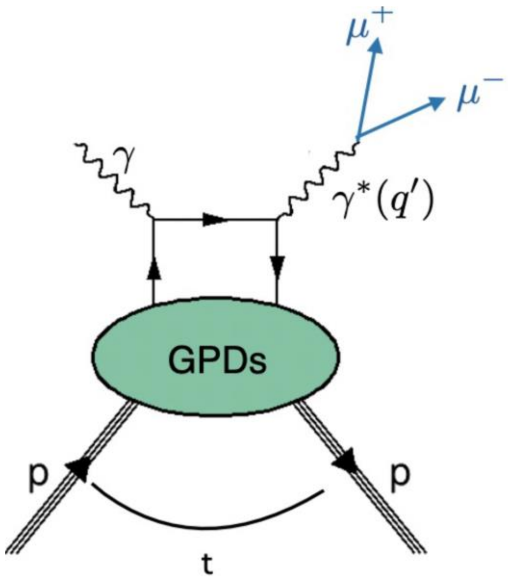
Yes.

- For large Q^2 and small impact parameter, hadronic QCD interaction overshadows DVCS.
- Ultraperipheral collisions (UPC): In general, to ensure no (colorful) QCD interaction, have b > R_1+R_2 (around few fm)
- Large impact parameter → small Q^2

DVCS & Ultraperipheral Collisions

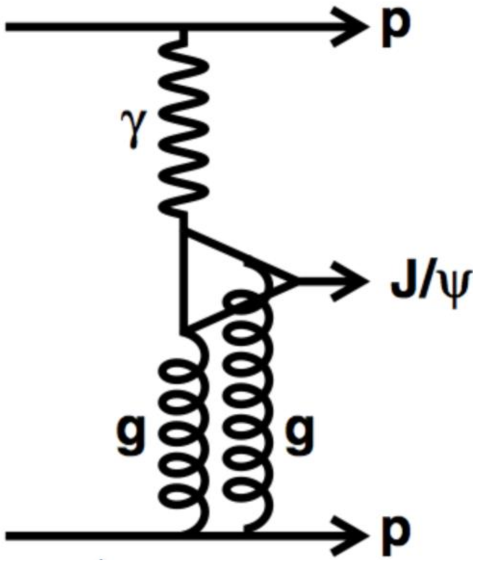


- Can use heavy ions to enhance photon flux.
- Detection of single photon in the final stat:
  - Limitation in acceptance brought by small Q^2?
  - Backgrounds?
  - Difficult/possible?



TCS

- Detection of lepton pairs instead → easier?
- Small cross section could be enhanced by interference with BH?

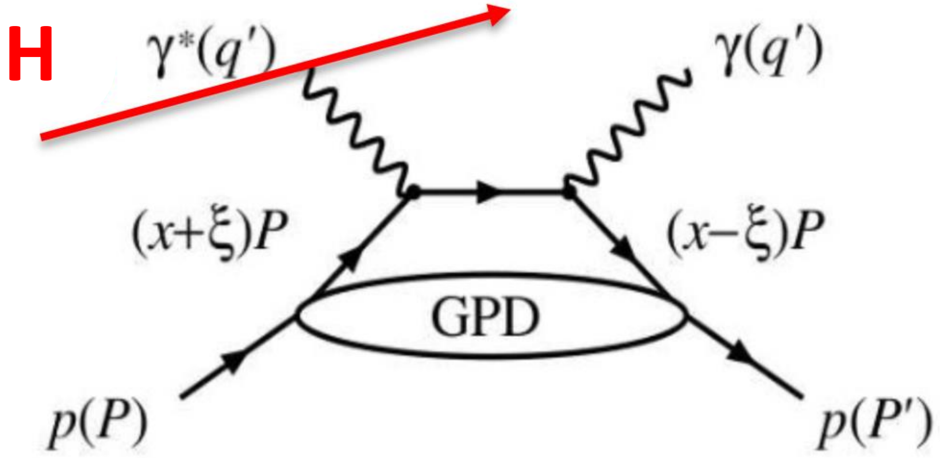


DVMP

- J/Ψ production → Gluon GPDs

- Theoretical understanding/predictions in the sPHENIX kinematics? Other possible channels?

Final Words



- GPD study can provide interesting insights into the nucleon properties. There have been great efforts devoted but we need more data. Although my gut feeling is that it would be quite difficult (if possible), it would be very nice to have inputs from sPHENIX as well.