XVII International Workshop on Hadron Structure and Spectroscopy

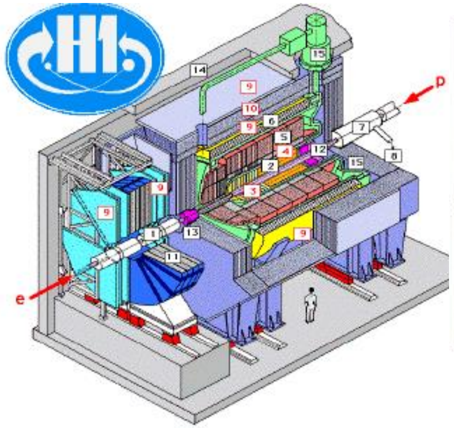
Trieste

16-18 November 2020

Experimental overview of exclusive reactions (related to GPDs)

Nicole d'Hose, CEA Université Paris-Saclay

Past & present for exclusive experiments at small t: $\ell p \rightarrow \ell' p' \gamma$ or meson




Collider mode e-p: forward fast proton

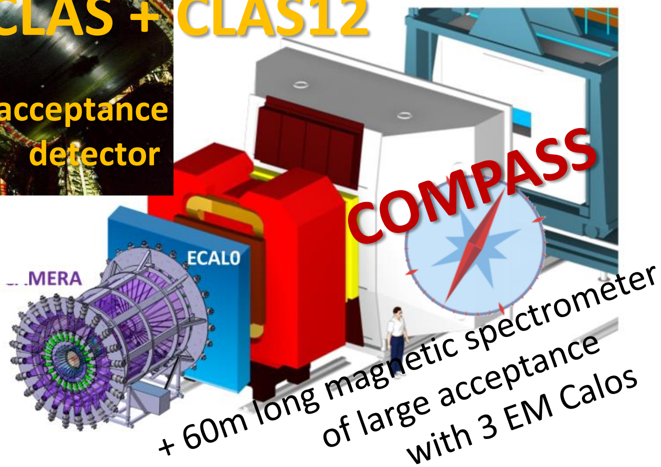
HERA: **H1** and **ZEUS**
Polarised **27 GeV** e-/e+
Unpolarized **920 GeV** proton
~ *Full event reconstruction (proton in Roman Pots)*

Fixed target mode: slow recoiling proton

HERMES: Polarised **27** GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector

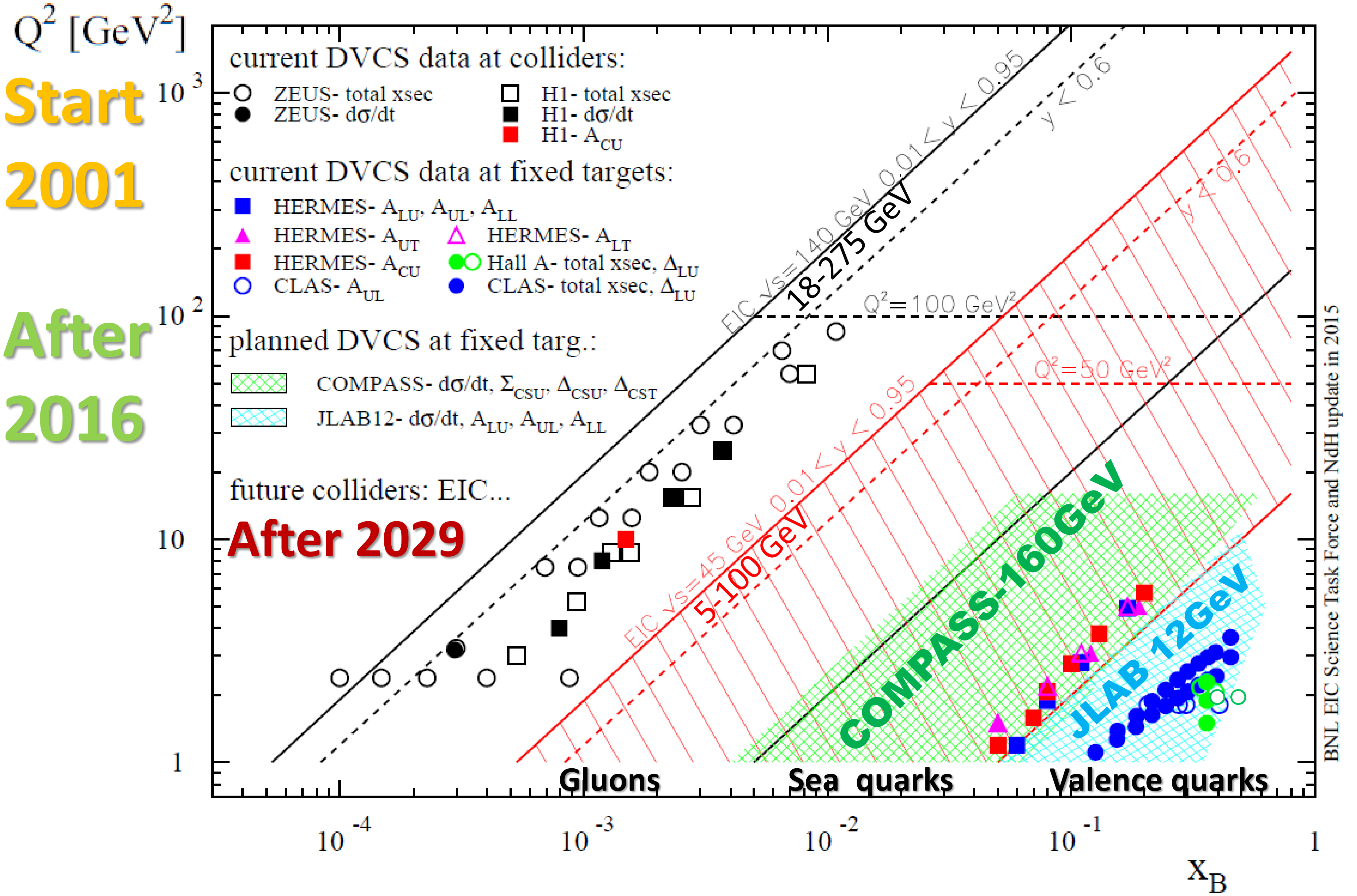
Jlab: Hall A, C, CLAS, CLAS12 High Luminosity Polar. **6** & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique (A,C) and complete detection (CLAS)

COMPASS @ CERN: Polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
with recoil detection



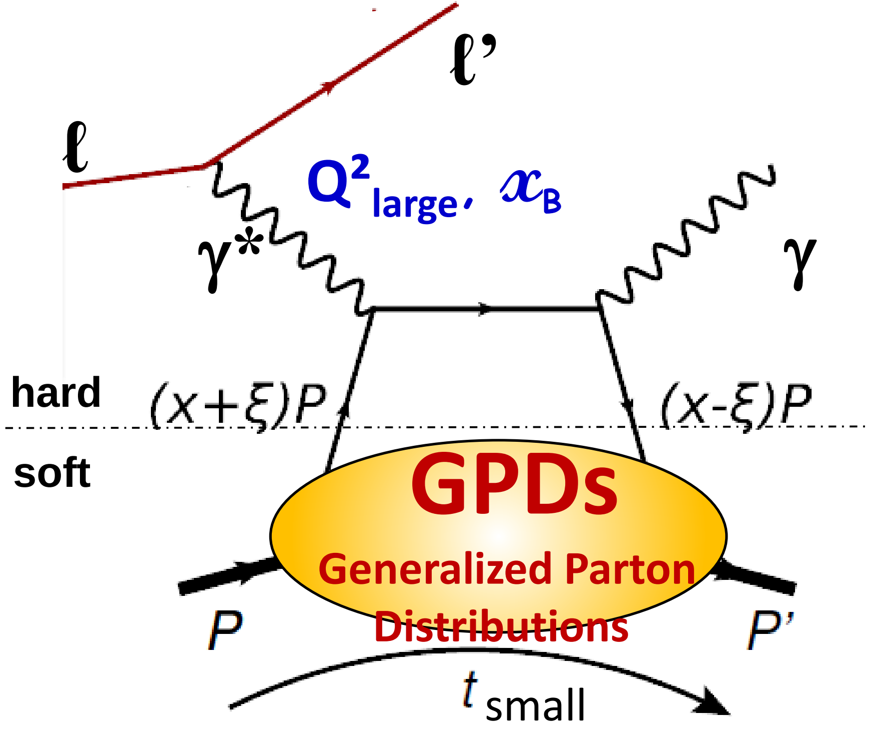
Rejection of background: SIDIS, exclusive π^0/DVCS, dissociation of the proton

Past and future experiments for DVCS ℓp→ ℓ'p'γ



Deeply virtual Compton scattering (DVCS)

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)



DVCS: **ℓp→ ℓ' p' γ**
the golden channel
because it interferes with
the Bethe-Heitler process

also meson production
ℓp→ ℓ' p' π, ρ, ω or **ϕ** or **J/ψ...**

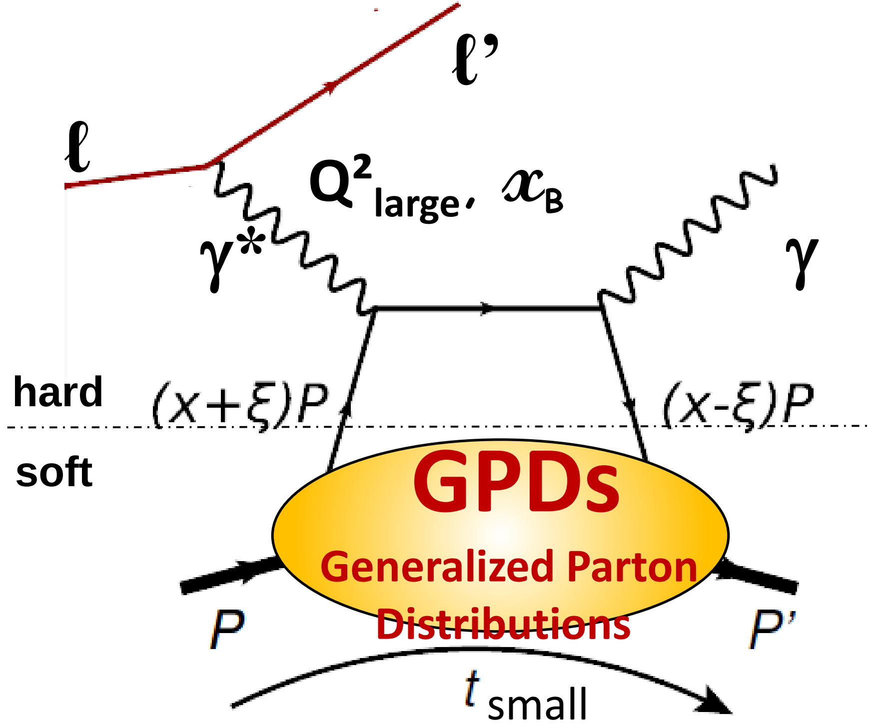
The GPDs depend on the following variables:

- x: average long. momentum
- ξ: long. mom. difference
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

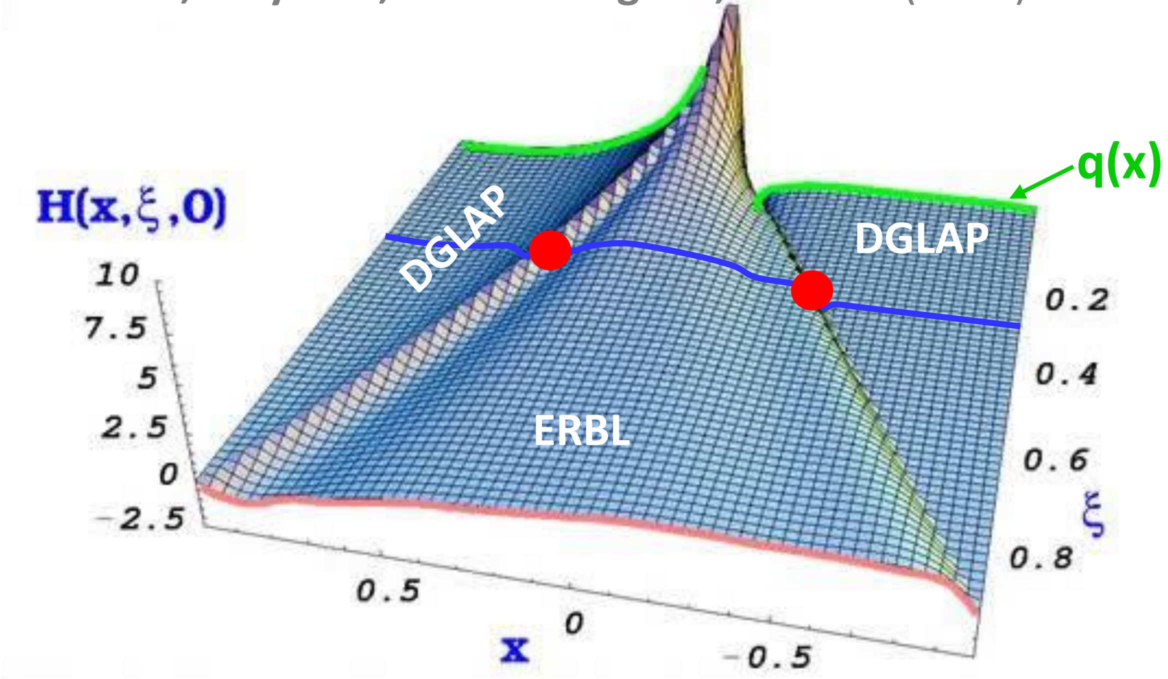
The variables measured in the experiment:

E_ℓ, Q^2, $x_B \sim 2\xi/(1+\xi)$,
t (or $\theta_{\gamma^*\gamma}$) and ϕ (ℓℓ' plane/γγ* plane)

Deeply virtual Compton scattering (DVCS)



Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



The amplitude DVCS at LT & LO in α_S (GPD **H**) :

Real part Imaginary part

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

t, ξ fixed

In an experiment we measure

Compton Form Factor $\mathcal{H}$

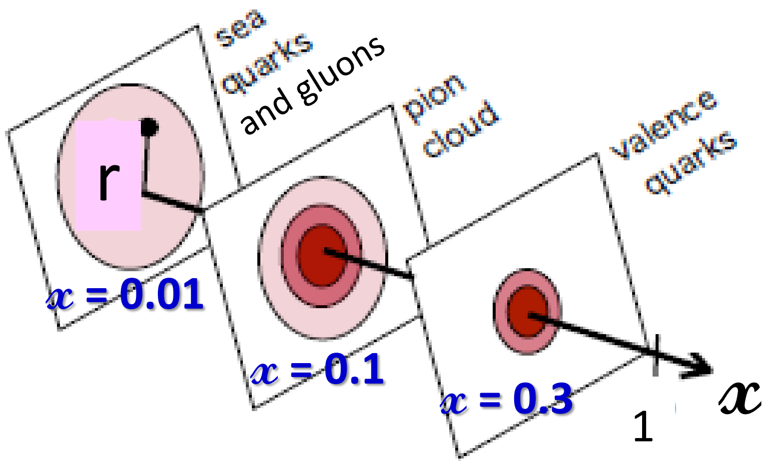
$$Re\mathcal{H}(\xi,t) = \pi^{-1}\int dx \frac{Im\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

Deeply virtual Compton scattering (DVCS)

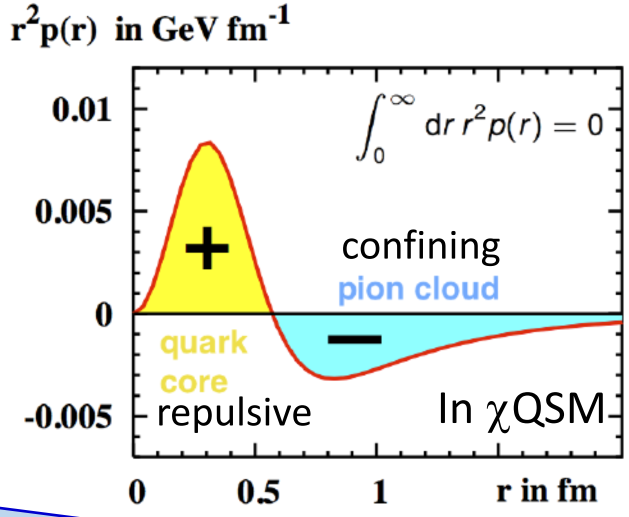
M. Burkardt, PRD66(2002)

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

Mapping in the transverse plane



Pressure Distribution



FT of $H(x, \xi=0,t)$

The amplitude DVCS at LT & LO in α_s (GPD **H**) :

Real part Imaginary part

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

t, ξ fixed

In an experiment we measure

Compton Form Factor $\mathcal{H}$

$$\mathcal{Re}\mathcal{H}(\xi,t) = \pi^{-1}\int dx \frac{Im\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

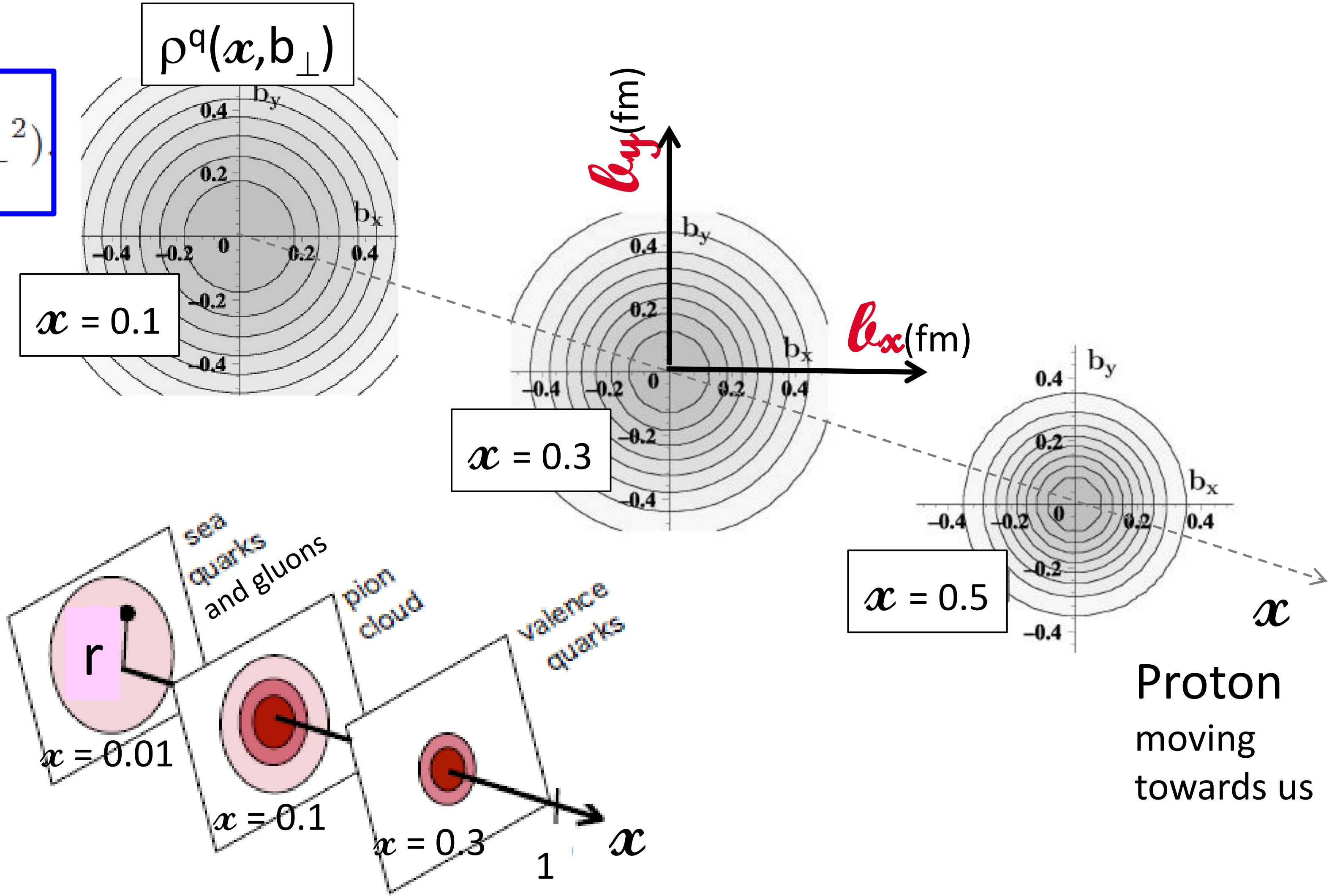
D-term $d_1(t)$

GPDs and 3D imaging

M. Burkardt, PRD66(2002)

$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\boldsymbol{\Delta}_\perp} H_-^q(x, 0, -\boldsymbol{\Delta}_\perp{}^2)$$

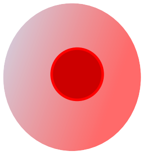
mapping in the transverse plane
Impact parameter distribution



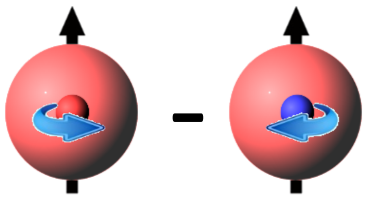
Correlation between the spatial distribution of partons and the longitudinal momentum fraction

GPDs and Energy-Momentum Tensor and Confinement

$\mathbf{H}^q(x, \xi, t) \xrightarrow{t \to 0} q(x)$ or $f_1(x)$

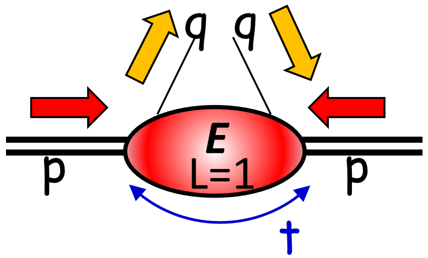


"Elusive"
$\mathbf{E}^q(x, \xi, t) \longleftrightarrow f_{1T}(x, k_T)$

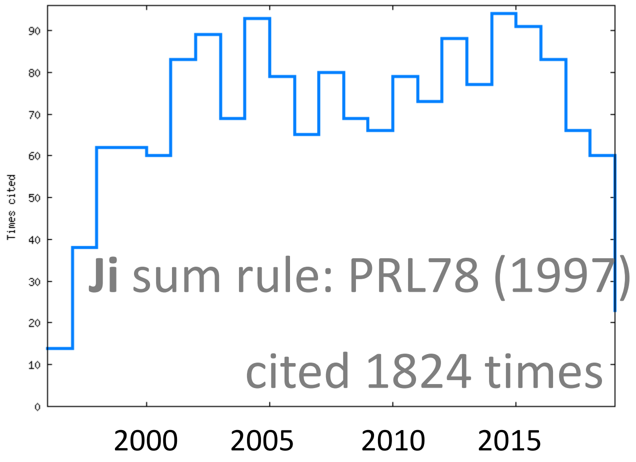


Sivers: quark k_T & nucleon transv. spin

$$2J^q = \lim_{t\to 0} \int x\,(\mathbf{H}^q(x, \xi, t) + \mathbf{E}^q(x, \xi, t))\,dx$$



Relation to OAM



mass & energy distribution

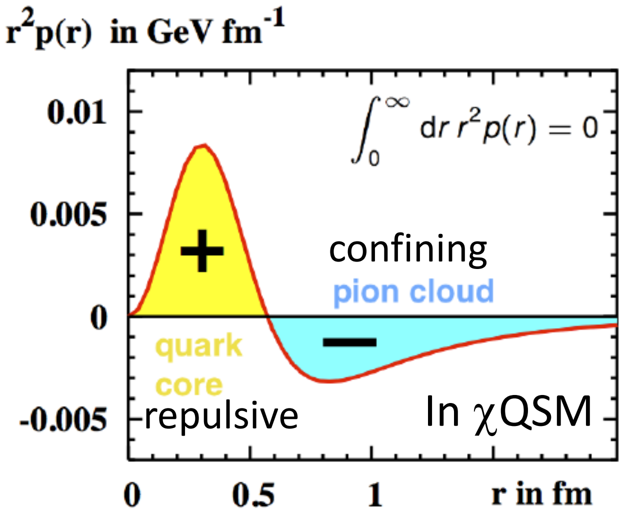
$$\int_{-1}^{1} dx\, x\, H^a(x, \xi, t) = A^a(t) + \xi^2 d_1^a(t)$$
$$\int_{-1}^{1} dx\, x\, E^a(x, \xi, t) = 2J^a(t) - A^a(t) - \xi^2 d_1^a(t)$$

Angular momentum distribution

Force & Pressure distribution

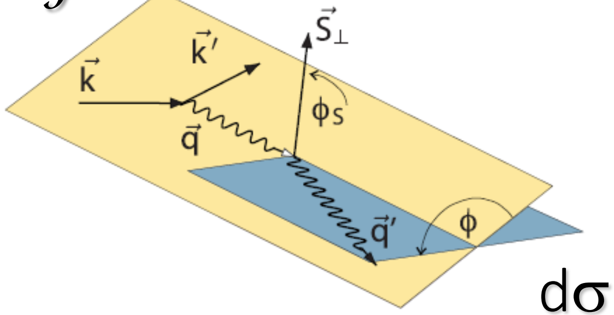
M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

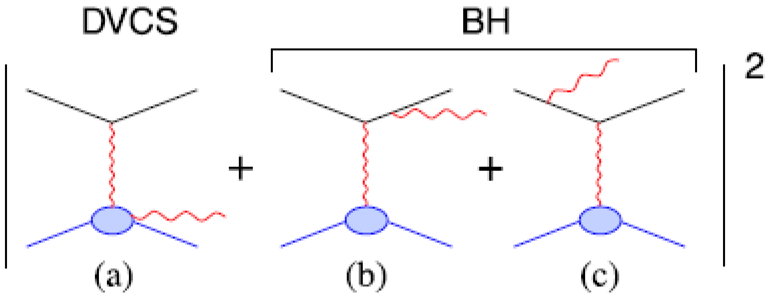
Pressure Distribution



Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

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

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

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

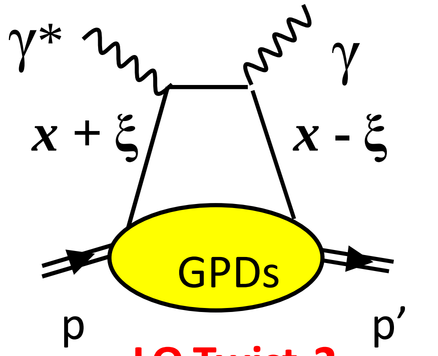
$$\text{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

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

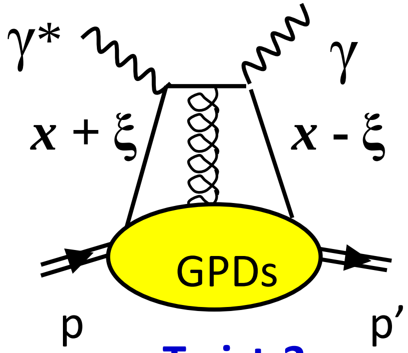
Changing P_ℓ ➔ $s_1^I = Im\ \mathcal{F}$

Changing $e_\ell P_\ell$ ➔ $c_1^I = Re\ \mathcal{F}$

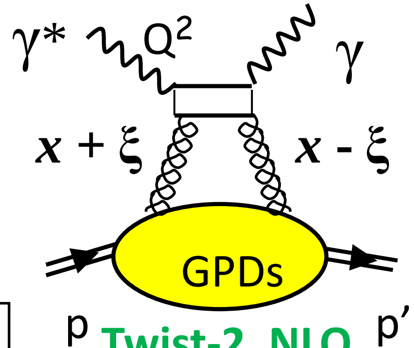
$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + t/4m^2 F_2\mathcal{E}$



LO,Twist-2

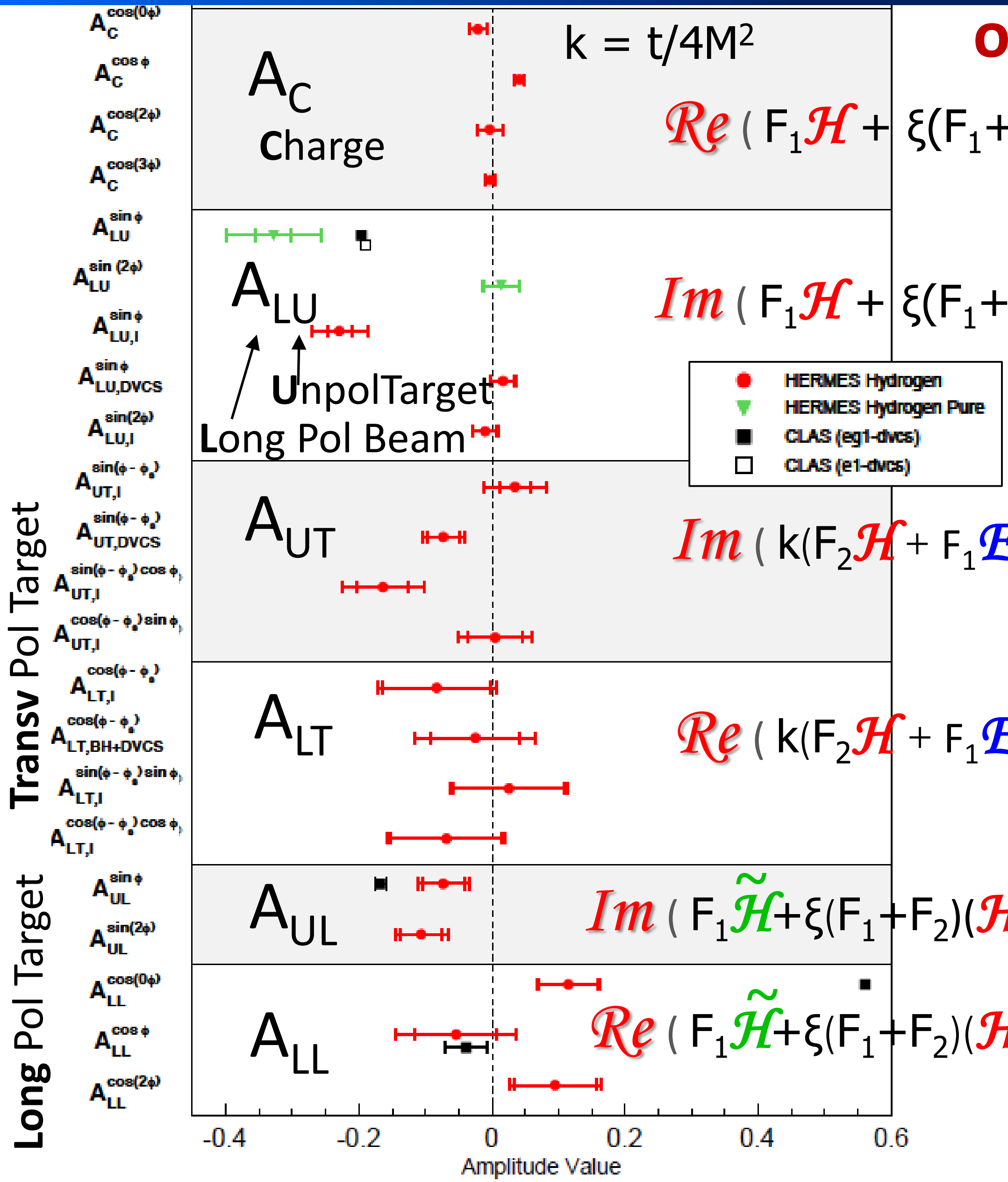


Twist-3



Twist-2, NLO
double helicity flip

2001-2012: A complete set of DVCS asymmetries at Hermes



on the proton

$\mathcal{R}e\,(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E})$

$\mathcal{I}m\,(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E})$

} $\mathcal{H}$

$\mathcal{I}m\,(k(F_2\mathcal{H} + F_1\mathcal{E}))$

$\mathcal{R}e\,(k(F_2\mathcal{H} + F_1\mathcal{E}))$

} $\mathcal{E}$

$\mathcal{I}m\,(F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \xi/(1+\xi)\mathcal{E}))$

$\mathcal{R}e\,(F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \xi/(1+\xi)\mathcal{E}))$

} $\tilde{\mathcal{H}}$

HERMES 27 GeV 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)

Note: **the neutron** allows

- ✓ flavor decomposition
- ✓ access to $\mathcal{E}$

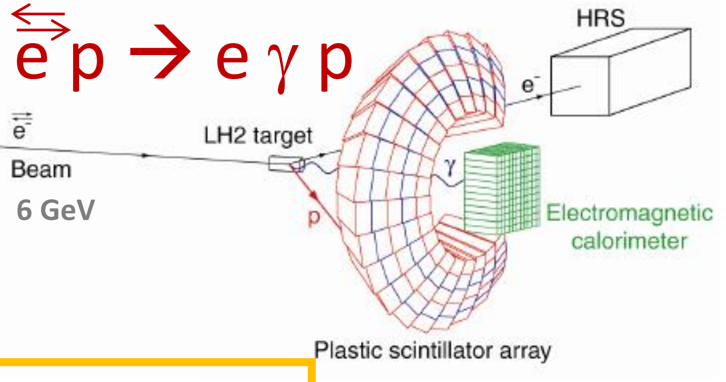
2004-2015: Beam Spin Sum and Diff for DVCS - HallA

E00-110 pioneer experiment in 2004 with magnetic spectrometer

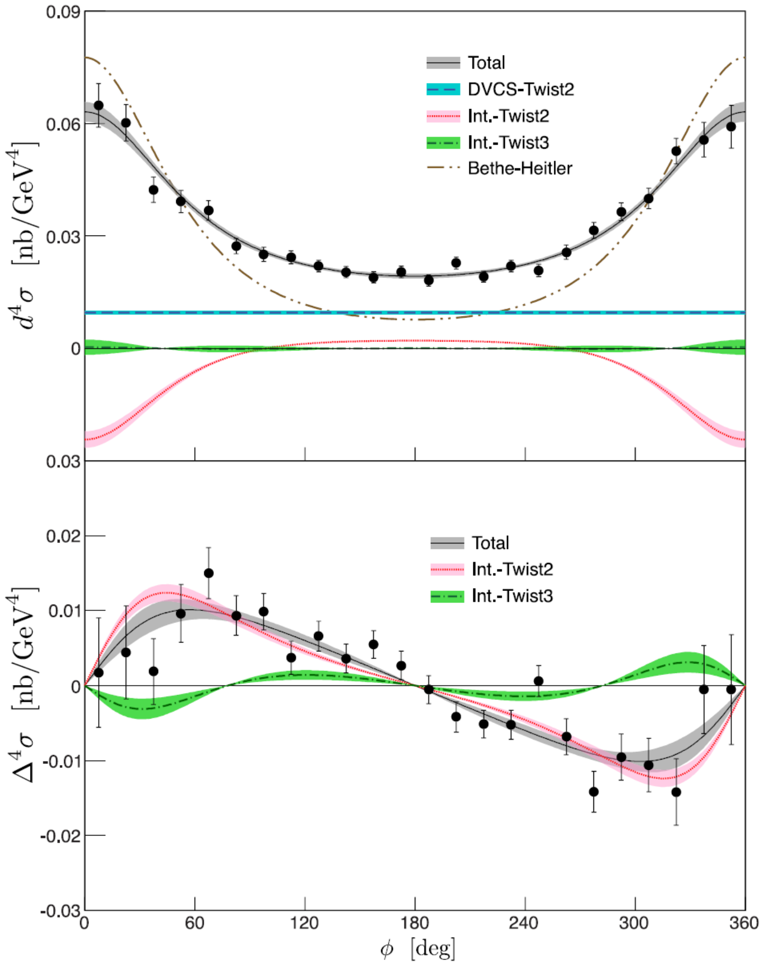
x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV^2 First analysis: Munoz et al. PRL97, 262002 (2006)

x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2 Final analysis: Defurne et al., PRC92, 055202 (**2015**)

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



x_B=0.36, Q^2= 2.3 GeV^2, -t= 0.32 GeV^2



Unpolarized cross section

$$d\sigma^{\leftarrow} + d\sigma^{\rightarrow} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Re}\, I$$
$$\longrightarrow d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$+ c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

Helicity Dependent cross section

$$d\sigma^{\leftarrow} - d\sigma^{\rightarrow} \propto d\sigma^{DVCS}_{pol} + \mathrm{Im}\, I$$
$$\longrightarrow s_1^{DVCS}\sin\phi + s_1^I\sin\phi + s_2^I\sin 2\phi$$

→ **Further DVCS/Interference separation with different beam energies with 2010 data**

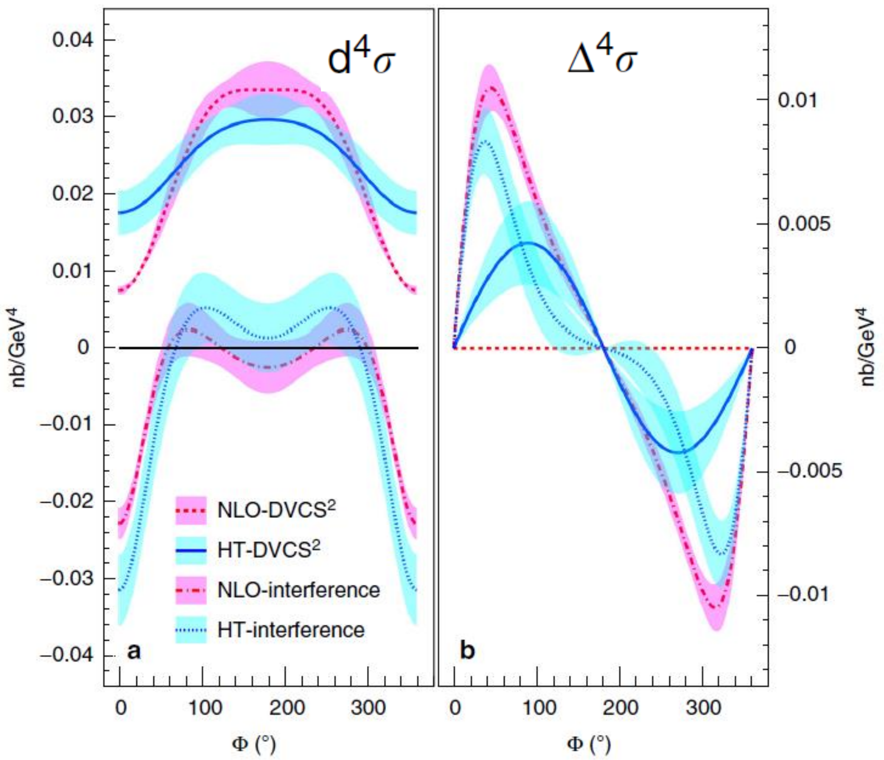
2010-2017: Beam Spin Sum and Diff for DVCS - HallA

E07-007 Hall-A experiment in 2010 with magnetic spectrometer

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

x_B=0.36, Q^2= 1.75 GeV^2, -t= 0.30 GeV^2

Ebeam=5.55 GeV



Unpolarized cross section

$$d^4\sigma \quad d\sigma^{\leftarrow} + d\sigma^{\rightarrow} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Re}\, I$$
$$\longrightarrow d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$+ c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

Helicity Dependent cross section

$$\Delta^4\sigma \quad d\sigma^{\leftarrow} - d\sigma^{\rightarrow} \propto d\sigma^{DVCS}_{pol} + \mathrm{Im}\, I$$
$$\longrightarrow s_1^{DVCS}\sin\phi + s_1^I\sin\phi + s_2^I\sin 2\phi$$

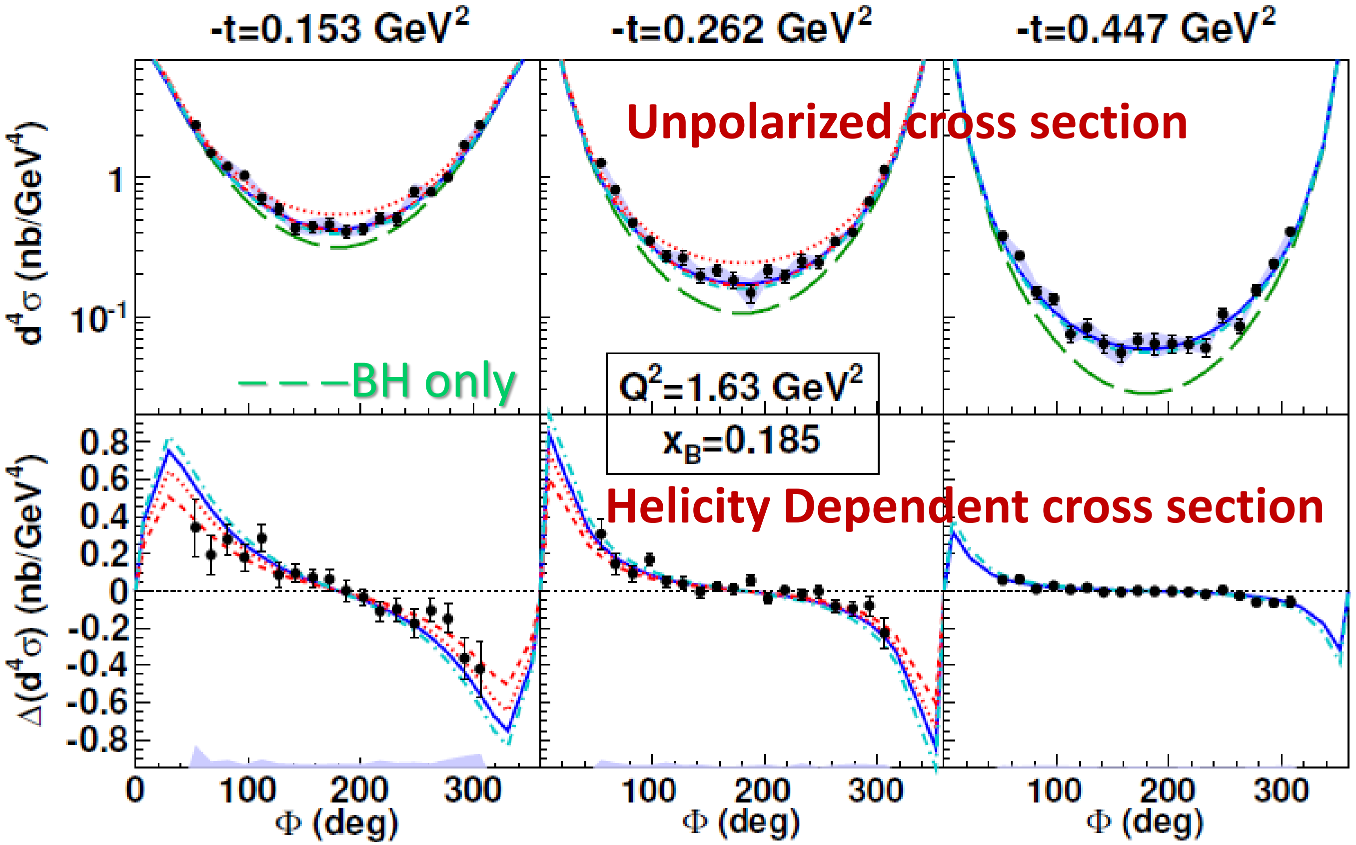
2 solutions: higher-twist OR next-to-leading order

2005-2018: Beam Spin Sum and Diff for DVCS - CLAS

21 bins in (x_B, Q^2) or 110 bins (x_B, Q^2 t) 3 months data taken in 2005

Girod et al. PRL100 (2008), Jo et al. PRL115 (**2015**), Hirlinger Saylor et al. PRC98 (**2018**)

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



models:

VGG Vanderhaeghen, Guichon, Guidal
PRL80(1998),PRD60(1999), PPNP47(2001), PRD72(2005)
1rst model of GPDs improved regularly

KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)
using the **GK** model
Goloskokov, Kroll, EPJC42,50,53,59,65,74

for GPD adjusted on the hard exclusive meson production at small x_B
''universality'' of GPDs

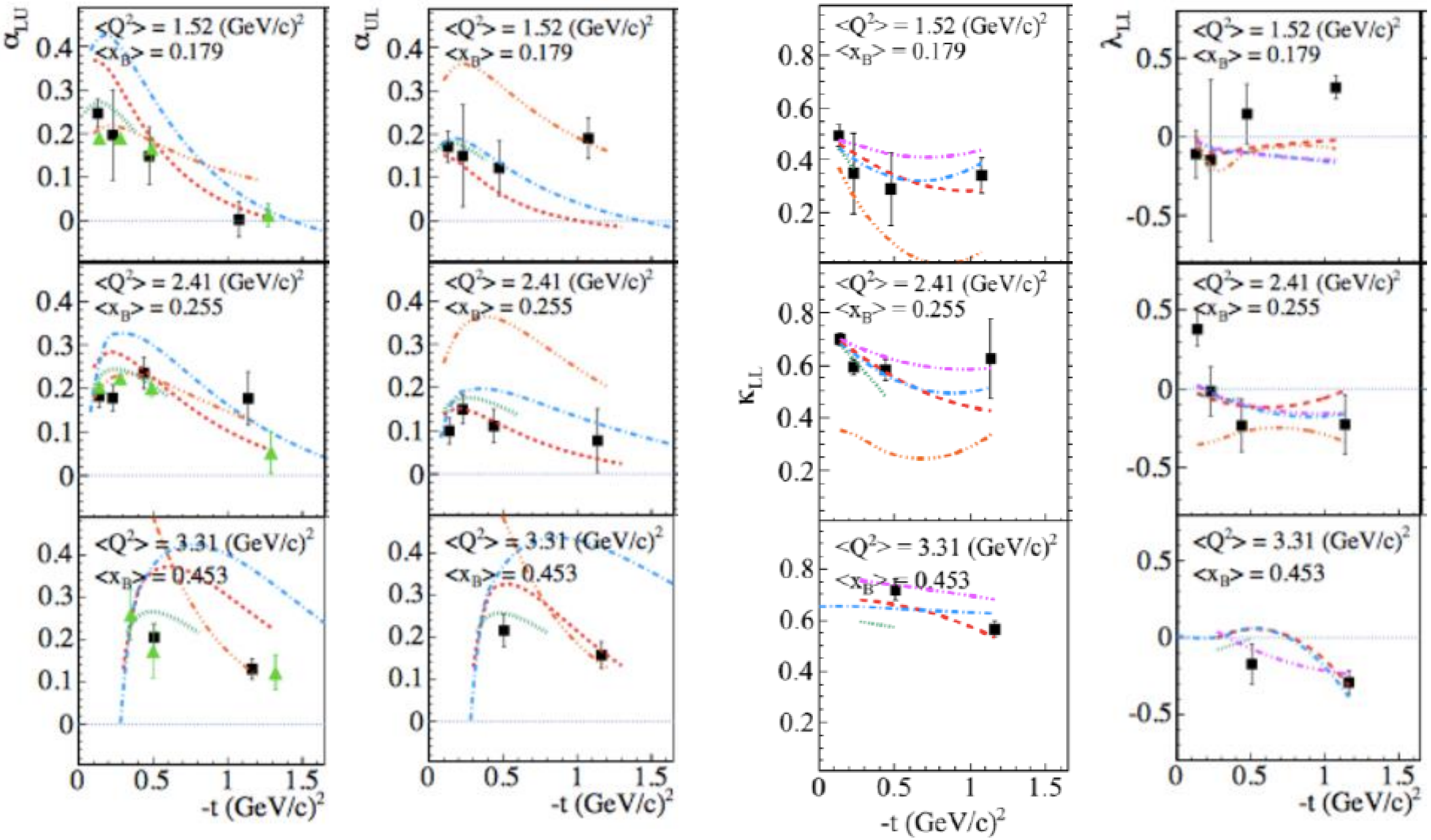
KM10a – – – **(KM10 ....)** Kumericki, Mueller, NPB (2010) 841
Flexible parametrization of the GPDs based on both a Mellin-Barnes representation and dispersion integral which entangle skewness and t dependences
Global fit on the world data ranging from H1, ZEUS to HERMES, JLab

2009-2015: Single Spin and Double Spin - CLAS

$$A_{LU\,(UL)} = \frac{\alpha_{LU(UL)} \sin\phi}{1+\beta\cos\phi} \qquad A_{LL} = \frac{\kappa_{LL} + \lambda_{LL}\cos\phi}{1+\beta\cos\phi}$$

2009: Longitudinally polarized NH3 target

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



Seder et al. PRL114, 032001 (2015)

Pisano et al. PRD91, 052014 (2015)

- CLAS A_{LU} on H_2
- data
- VGG Vanderhaeghen, Guichon, Guidal
- KMM Kumericki, Mueller, Murray
- GK Goloskokov, Kroll
- GGL Goldstein, Gonzalez, Luiti
- BH

→ nucleon tomography in the valence domain

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

Im$\mathcal{H}$, **Re$\mathcal{H}$**, Im$\mathcal{E}$, Re$\mathcal{E}$, **Im$\tilde{\mathcal{H}}$**, **Re$\tilde{\text{H}}$**, Im$\tilde{\mathcal{E}}$, Re$\tilde{\mathcal{E}}$

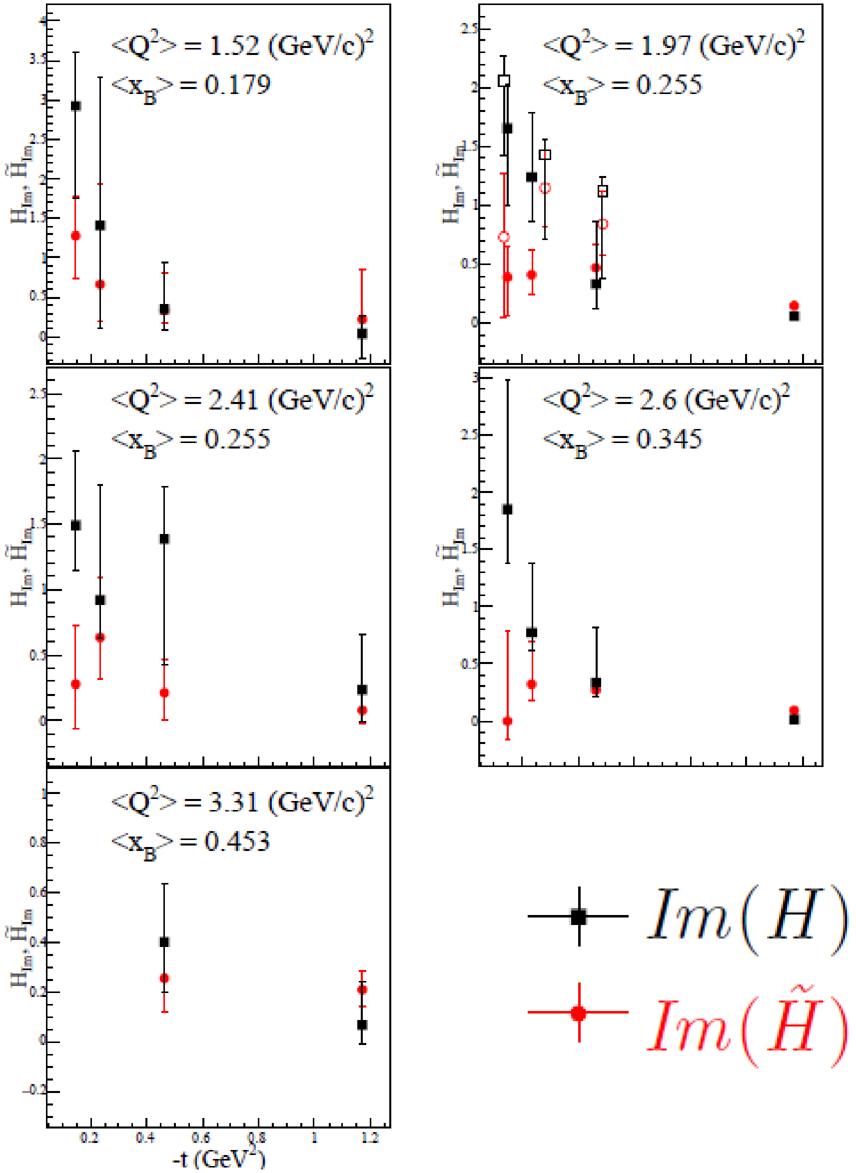
$$H(x,0,0) = q(x) \qquad \tilde{H}(x,0,0) = \Delta q(x)$$

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

$Im(H)$ → electromagnetic charge distribution

$Im(\tilde{H})$ → axial charge distribution

Axial charge is more concentrated than electromagnetic charge



Seder et al. PRL114, 032001 (**2015**)

Pisano et al. PRD91, 052014 (**2015**)

➔ nucleon tomography in the valence domain

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

Dupré, Guidal, Nicolai, Vanderhaeghen, PRD95, 011501(R)(**2017**)
Eur.Phys.J. A53 (**2017**)

$s_1^I = Im\, F_1 \mathcal{H}$ is the best constrained

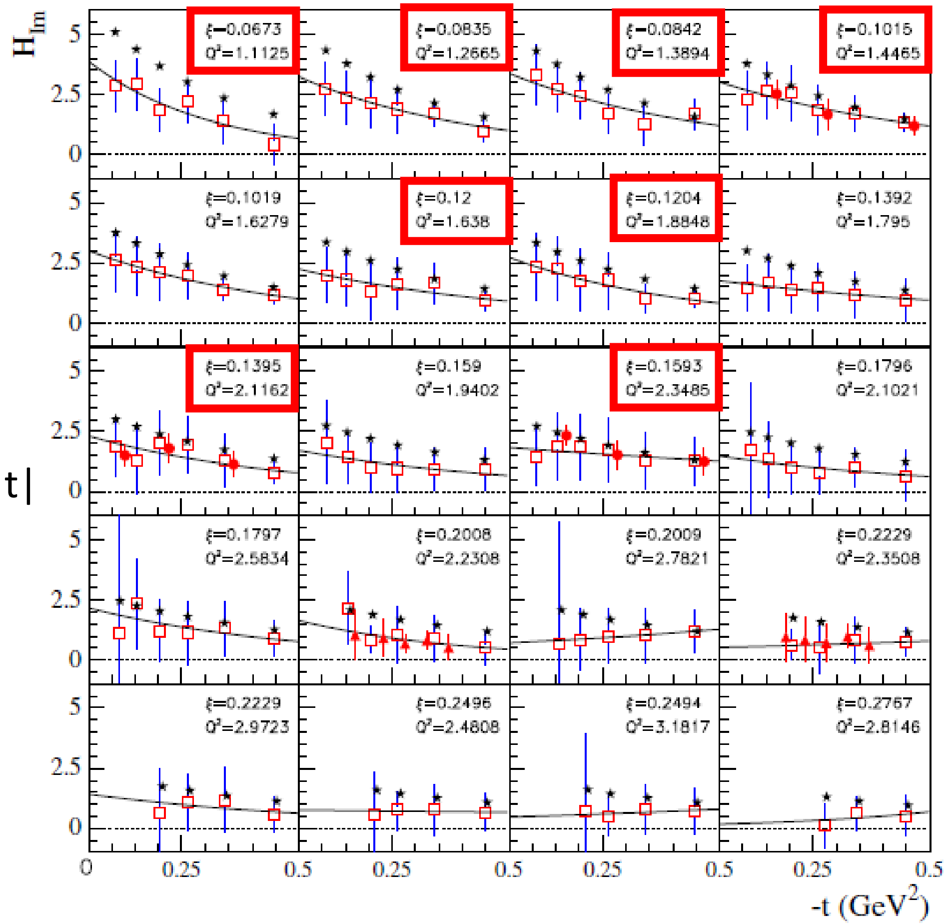
$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp} H_-^q(x, 0, -\mathbf{\Delta}_\perp{}^2).$$

$$\langle b_\perp^2\rangle^q(x) = -4\frac{\partial}{\partial \mathbf{\Delta}_\perp^2} \ln H_-^q(x, 0, -\mathbf{\Delta}_\perp{}^2)\Big|_{\mathbf{\Delta}_\perp=0}.$$

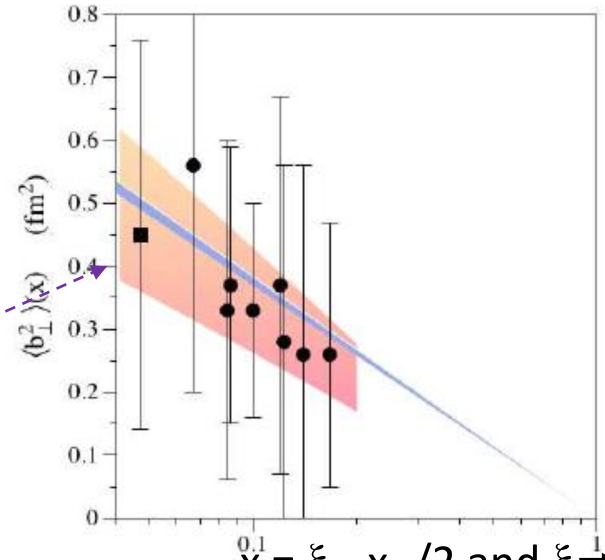
$< b_\perp{}^2 > \approx 4\,B$

— Fit

$Im\mathcal{H} = A\, e^{-B|t|}$



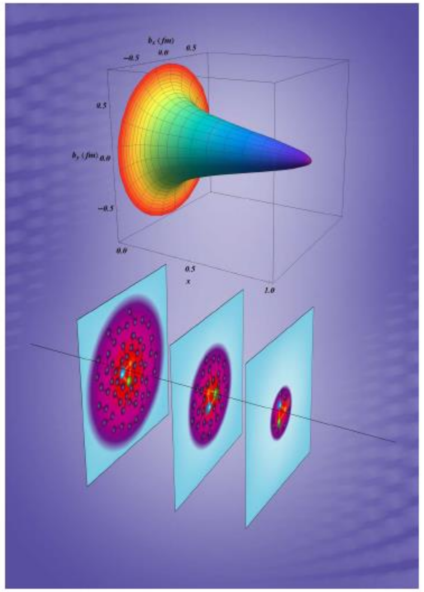
- □ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}
- ★ VGG model



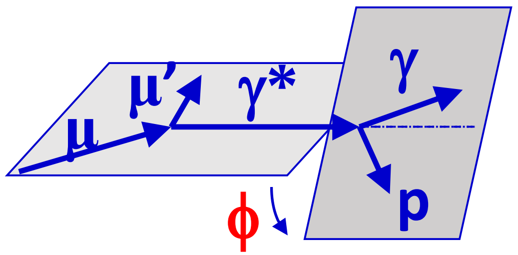
HERMES

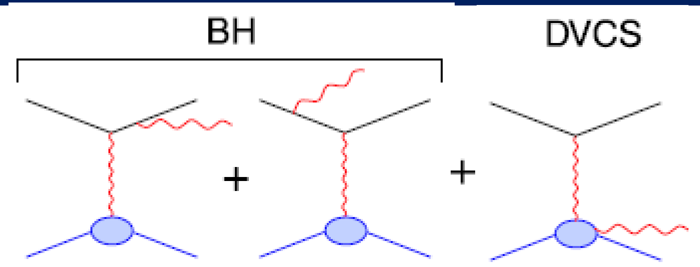
+ 8 data from JLab

$x = \xi \sim x_{Bj}/2$ and $\xi \to 0$



2012-2019: Beam Charge & Spin Sum for DVCS - COMPASS



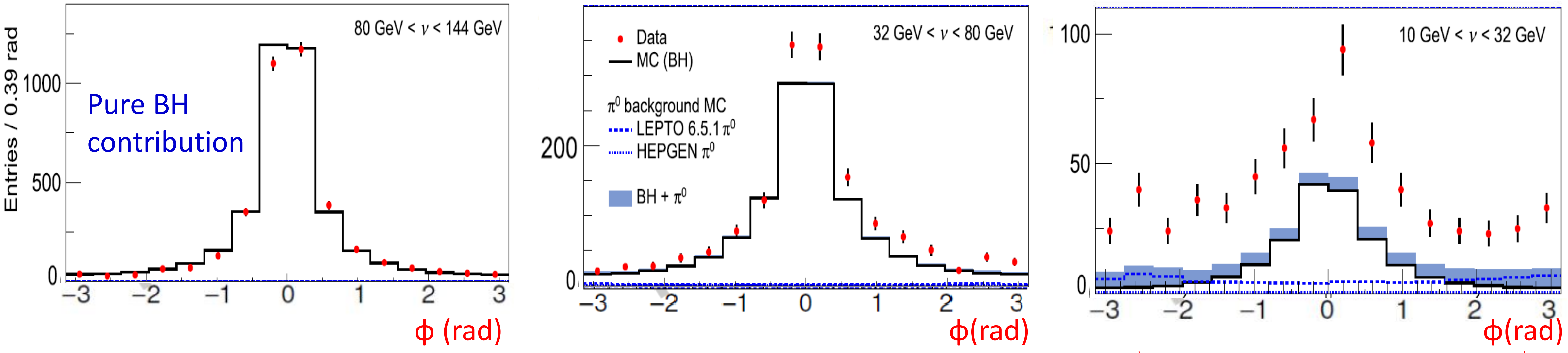


$\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams of 160 GeV

$$S_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

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

$0.005 < x_{Bj} < 0.01$ | $0.01 < x_{Bj} < 0.03$ | $x_{Bj} > 0.03$



MC: — BH normalisation based on integrated luminosity
π° background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

DVCS > BH

COMPASS PLB793 (**2019**) 188-194

2012-2019: Beam Charge & Spin Sum for DVCS - COMPASS

At COMPASS using polarized positive and negative muon beams:

when DVCS > BH

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I]$$

$$= 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi]$$

calculable
can be subtracted

All the other terms are cancelled in the integration over ϕ

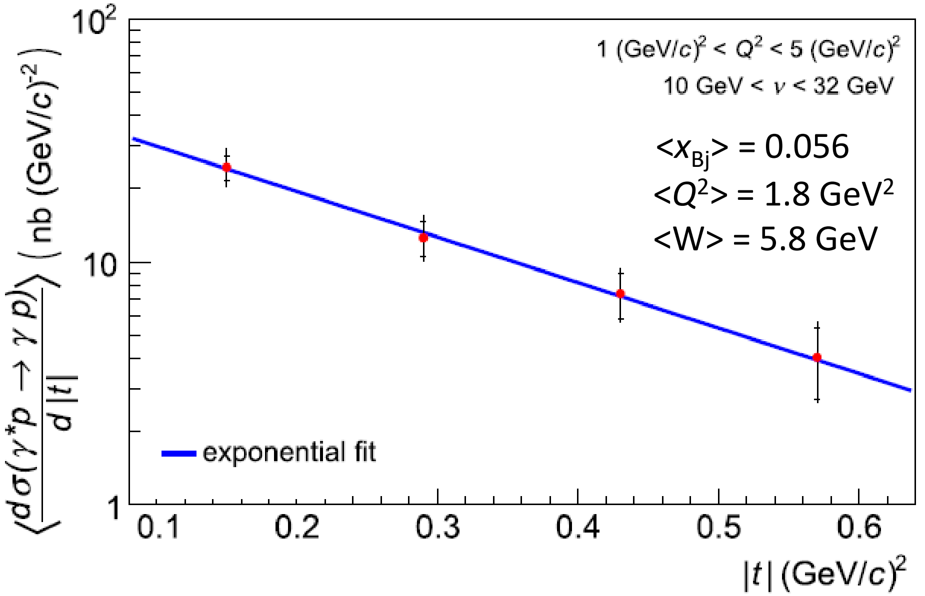
$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS}$$

$$B = (4.3 \pm 0.6_{\text{stat}} \,{}^{+0.1}_{-0.3}\big|_{\text{sys}})\ (\text{GeV}/c)^{-2}$$

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

$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \,{}^{+0.01}_{-0.02}\big|_{\text{sys}} \pm 0.04_{\text{model}})\ \text{fm}$$

COMPASS PLB793 (2019) 188-194



→ nucleon tomography in the gluon and sea quark domains

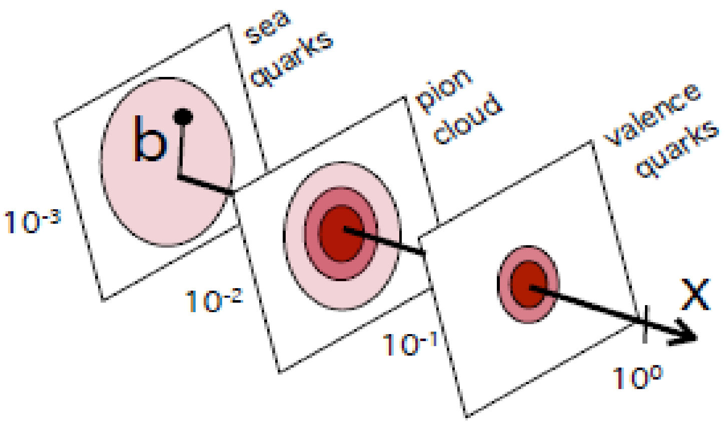
$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$

At COMPASS: $\langle x_{Bj}\rangle = 0.056$;;
t varies from 0.08 to 0.64 GeV^2

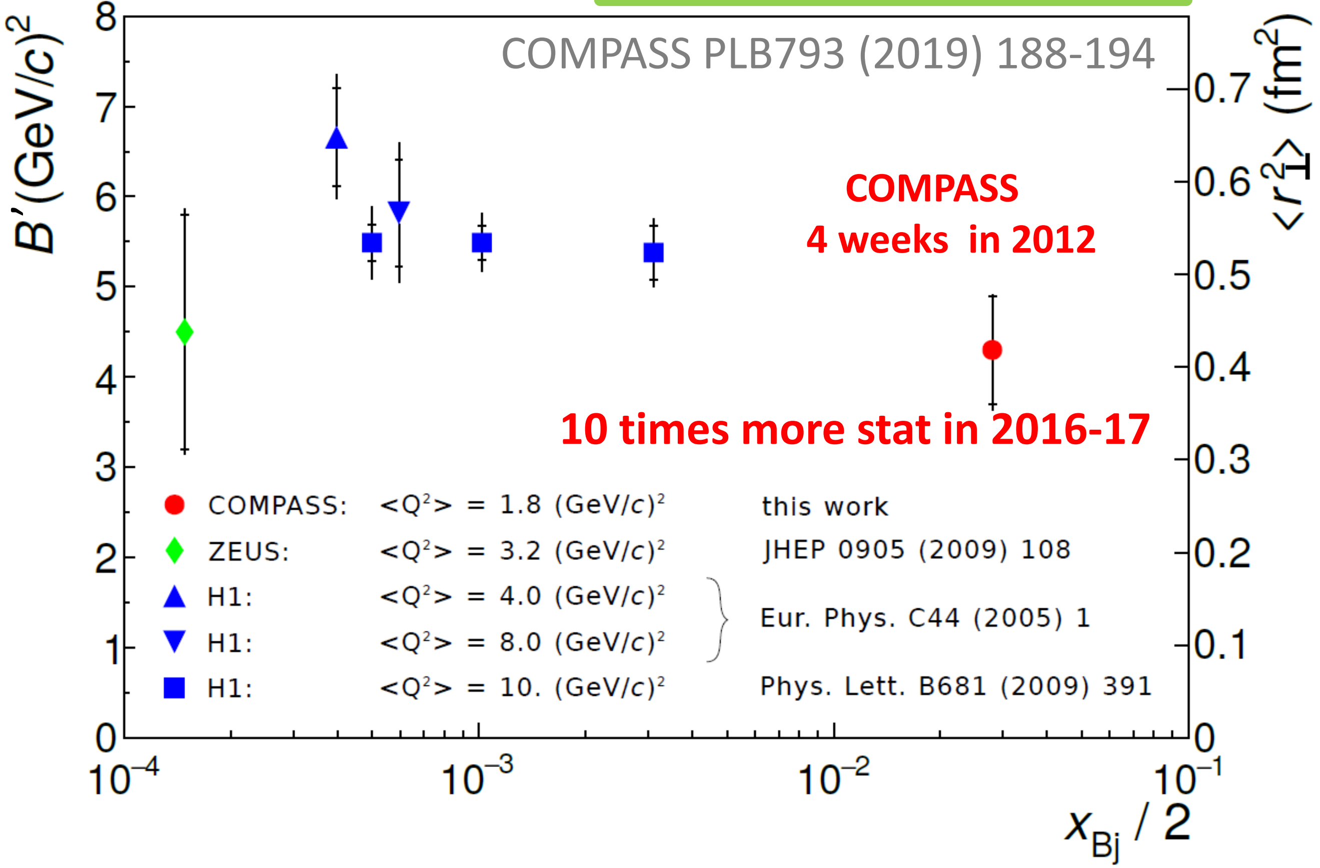
At small x_{Bj} and small t:

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) - \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$

Dominance of *Im$\mathcal{H}$*
(with respect of *Re$\mathcal{H}$* and other *CFFs*)



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



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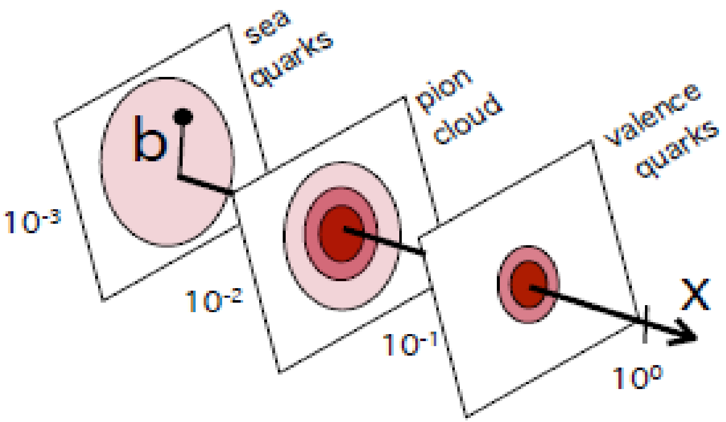

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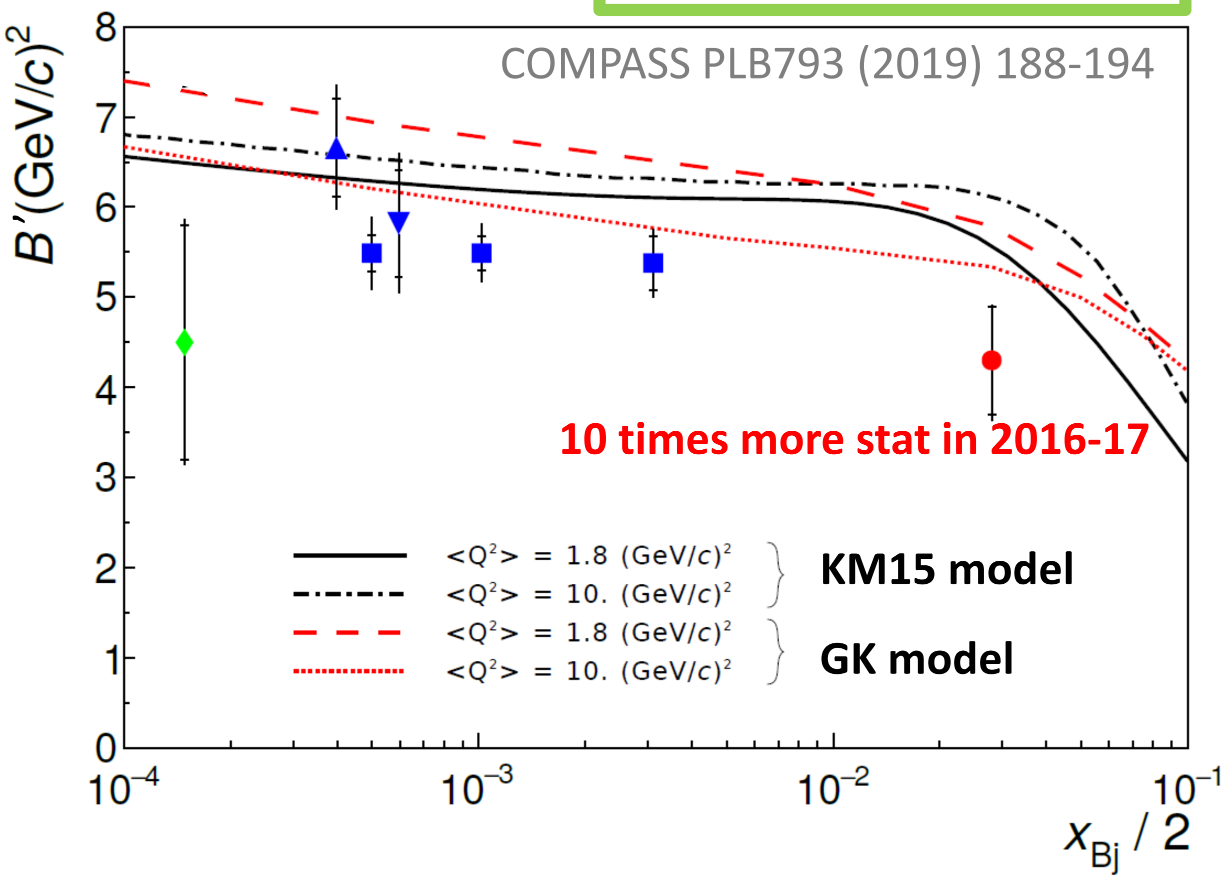


→ D-term and Pressure distribution in the proton

Δ(t) subtraction constant of the DVCS dispersion relation:

$$\mathrm{Re}\mathscr{H}(\xi,\ t) = \Delta(t) + \frac{1}{\pi}\,\mathrm{P.V.}\int_0^1 dx\left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right)\mathrm{Im}\mathscr{H}(x,\ t)$$

Relation with D(z,t), the D-term of the GPD $-1 < z = \frac{x}{\xi} < 1$

& with d_1^q, the proton gravitational FF (the spherical Bessel transform of the pressure):

$$\Delta(t) = 2\sum_q Q_q^2 \int_{-1}^{1} \mathrm{d}z \frac{D_q(z,t)}{1-z} = 4\sum_q Q_q^2\left(d_1^q(t) + \ldots\right),\ q = u, d, \ldots$$

next order terms <<

Q is the quark charge

With assumptions, considering only u and d quarks:

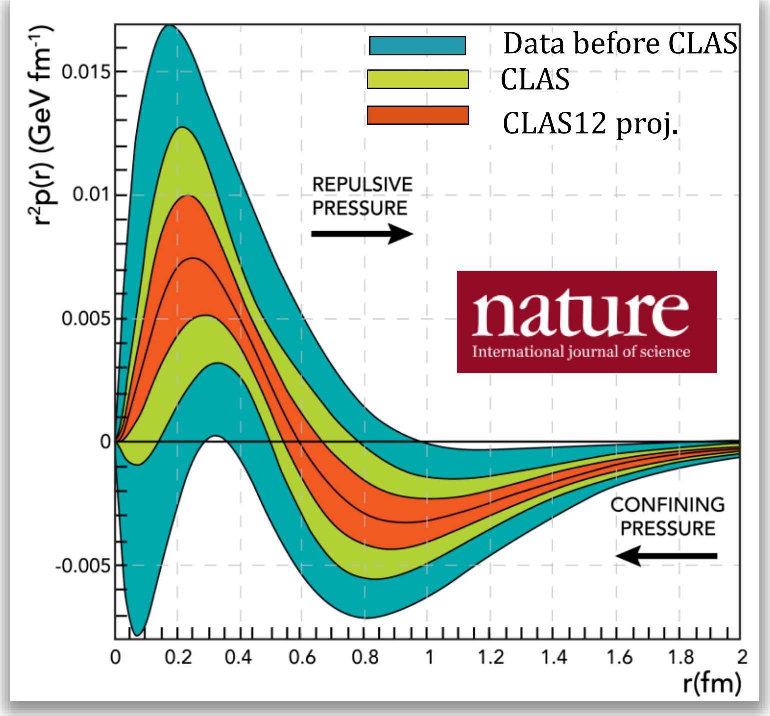
$$d_1^Q(t) = \frac{9}{10}\Delta(t)$$

The spherical Bessel transform of the pressure :

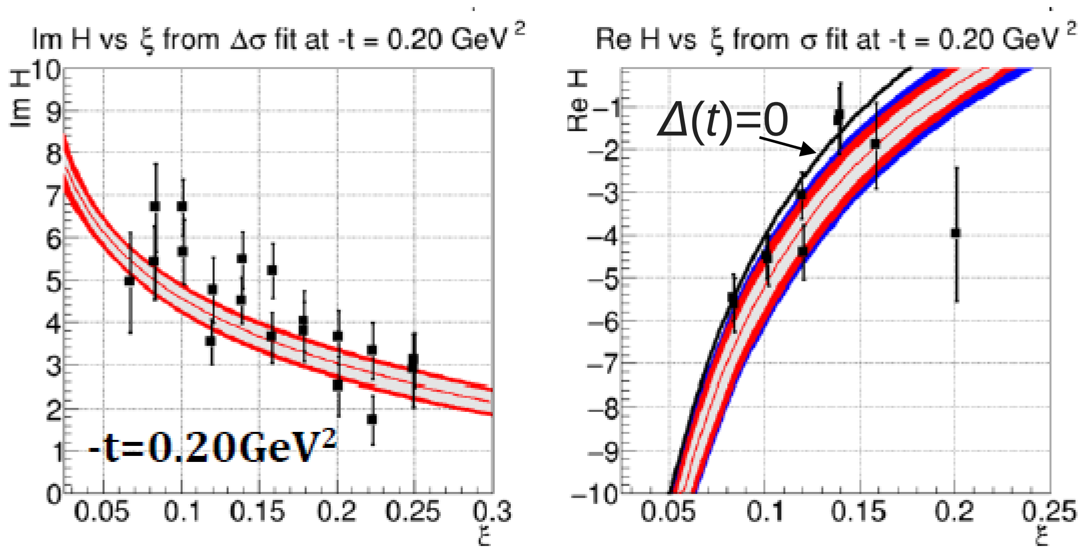
$$d_1(t) \propto \int \mathrm{d}^3\mathbf{r}\, \frac{j_0(r\sqrt{-t})}{2t}\, p(r)$$

M.V. Polyakov, Phys. Lett. B555 (2003) 57

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



➔ D-term and Pressure distribution in the proton



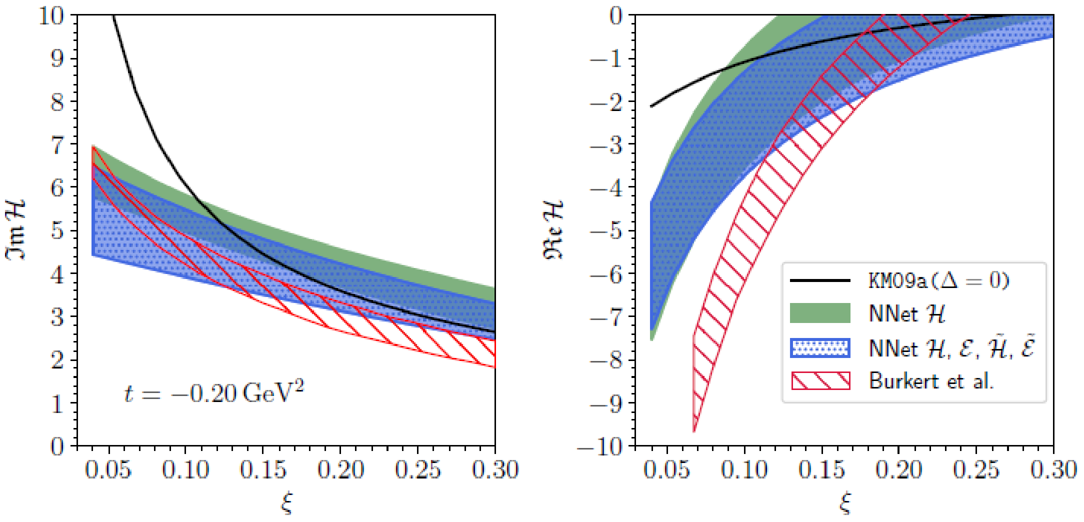
V. Burkert et al., Nature 557, 396-399 (**2018**)

acurate $\Delta(t)$ to determine D-term and pressure
within some assumptions

$\Delta(t=0)$ = -1.63 ± 0.11 ± 0.24

This is a critical result,
required for dynamical stability of the proton.
Deeply rooted in chiral symmetry breaking.

however improvement of uncertainties
Using flexible parametrization by neural networks



K. Kumericki, Nature 570, E1–E2 (**2019**)

$\Delta(t)$ = 0.78 ± 1.5 (statistical uncertainty)
with almost no dependence on t

➔ D-term and pressure consistent with 0
➔ waiting for more data sensitive to Re H
(importance of $\mu^{\pm}$ at COMPASS and e^{+} at JLab)

next future: Beam Charge and Spin Diff @ COMPASS

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} \xrightarrow{L.T.} c_0^I + c_1^I \cos\phi$$

$$c_1^I = Re\, F_1 \mathcal{H}$$

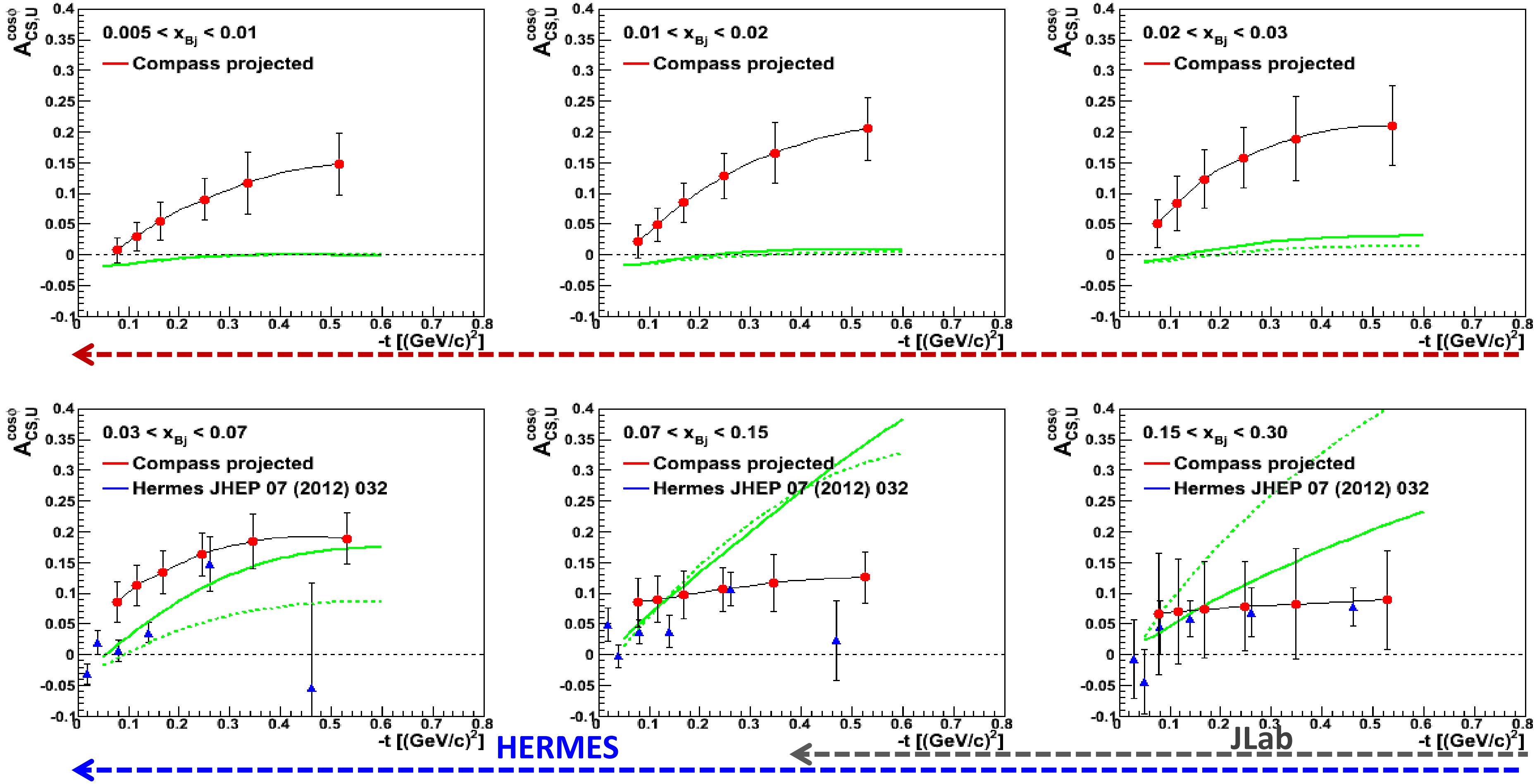
$Re\,\mathcal{H}$ > 0 at H1
< 0 at HERMES
Value of x_B for the node?

Predictions with VGG and KM10

2016-17: 2x 6 months of data taking

Analysis on going

Impact on the D-term



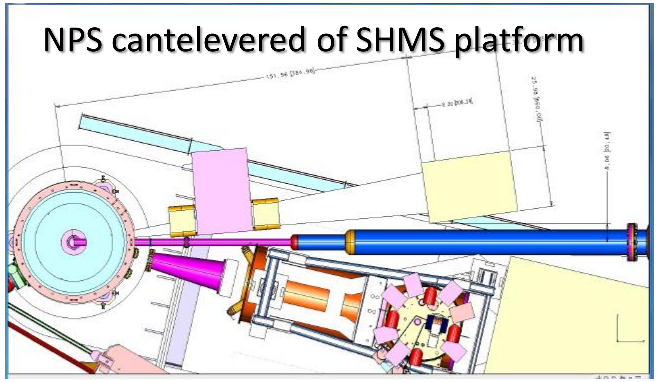
COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV²

next future: Beam Spin Sum and Diff @ JLab12

with high resolution magnetic spectrometer + Calorimeter in Halls A and C

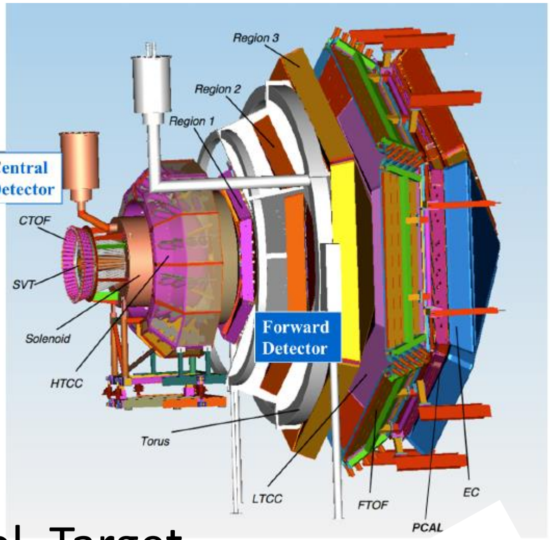
done in 2016-17: Hall A: E12-06-114
>2021: Hall C: E12-13-010

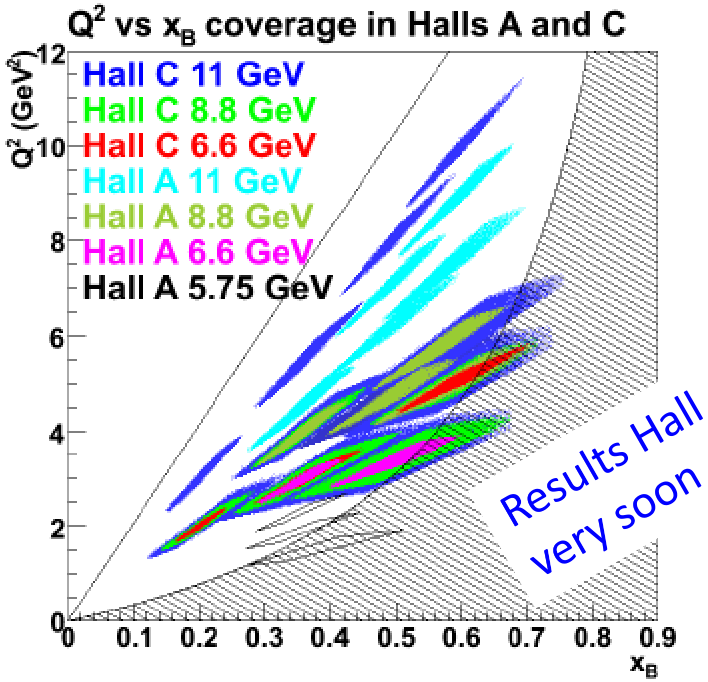
Different beam energies for a Rosenbluth-like DVCS^2/Interf. separation



with CLAS12

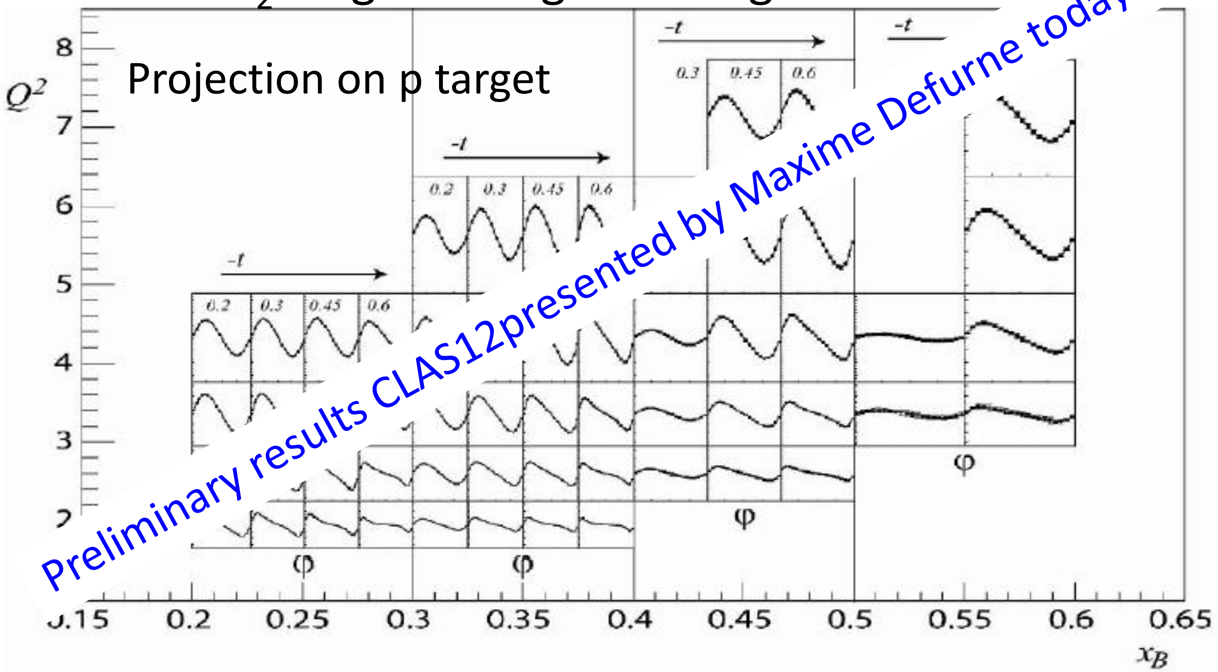
E12-06-119
2018-19: LH2
2020: Long Pol Target





Results Hall A expected very soon

LH_2 Target & Long. Pol. Target



Preliminary results CLAS12presented by Maxime Defurne today

2007-8: GPD E from Jlab 6 GeV and HERMES

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

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

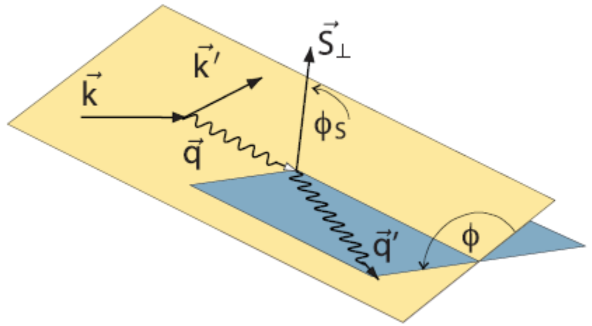
analysis still on going for a Hall-A experiment done in 2010

Note: neutron target ➔ quark flavor separation

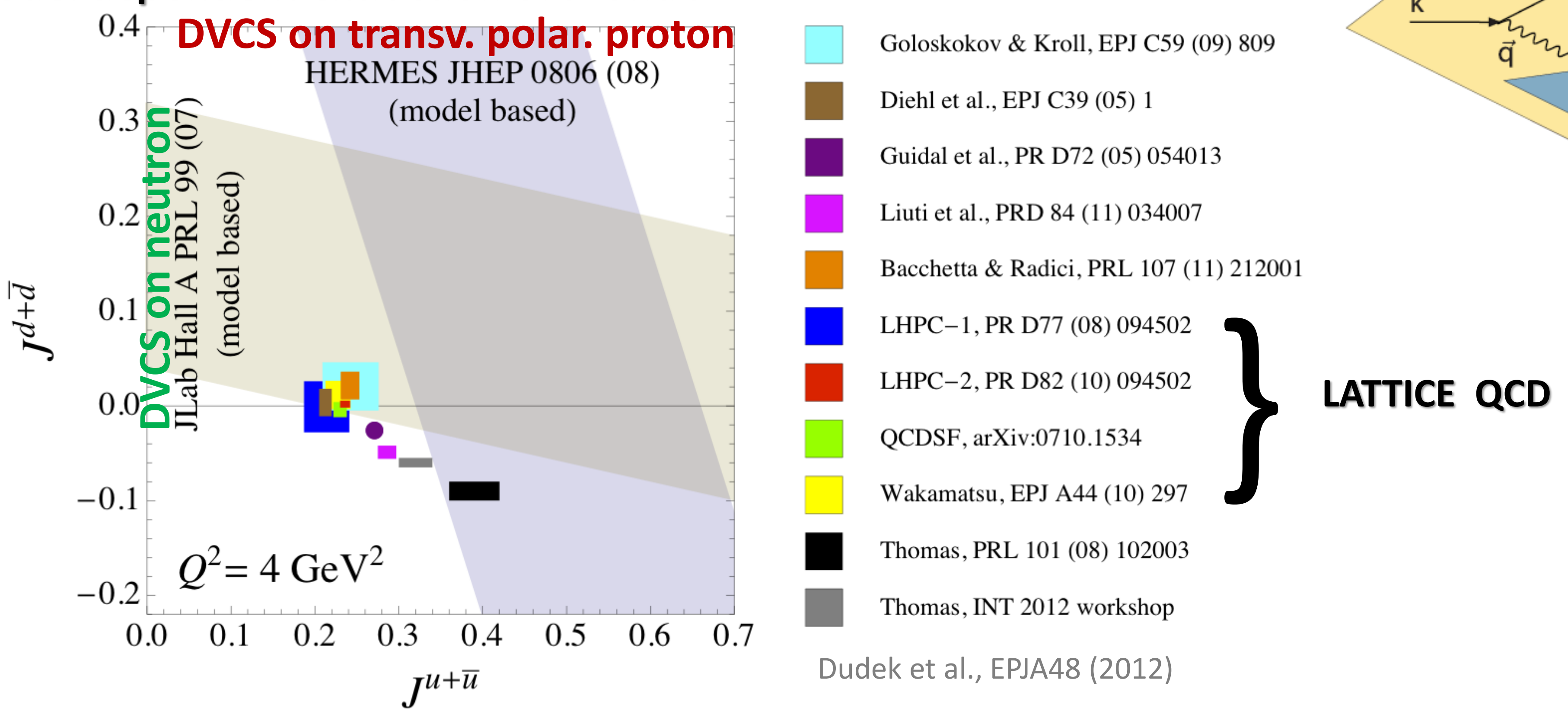
$\vec{\ell}\, p^{\uparrow} \rightarrow \ell\, p\, \gamma$

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

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



Model dependent extraction of J^u and J^d



Dudek et al., EPJA48 (2012)

next future: GPD E @ JLab12 with CLAS12

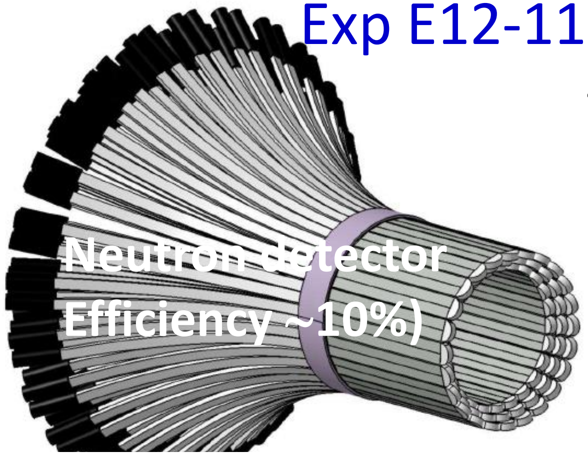
$\ell\, d \rightarrow \ell\, n\, \gamma\, (p)$

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

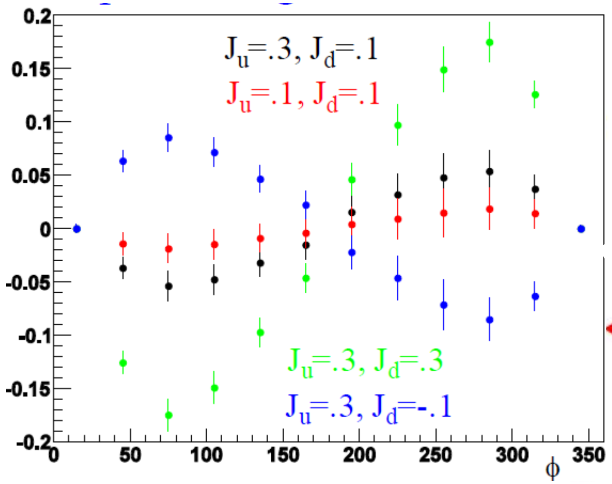
Exp E12-11-003: DVCS on the neutron

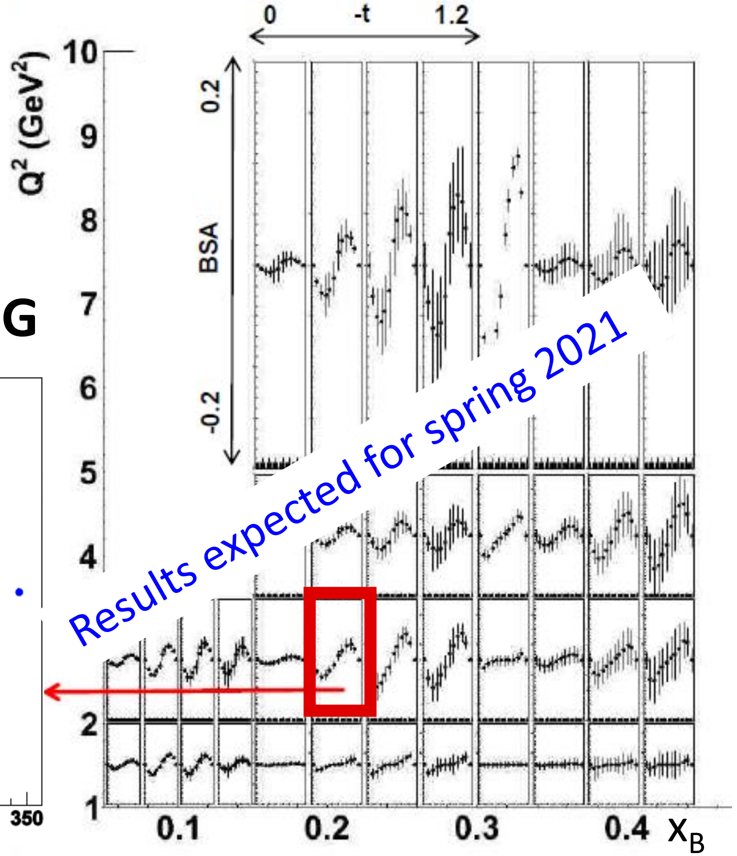
2019-20: 90 days on LD2 target

Lumi= 10^{35} cm^{-2} s^{-1}/nucleon



Model prediction using VGG





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

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

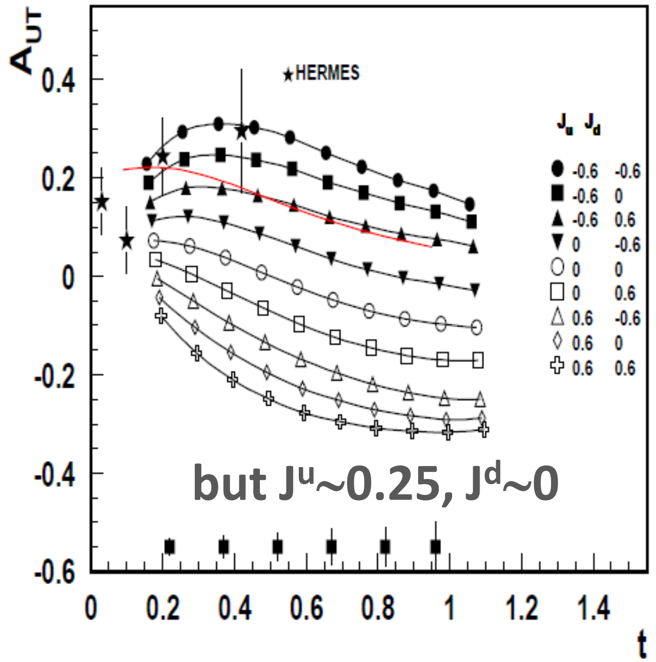
$$\Delta\sigma_{LT}^{\sin(\phi-\phi_s)\cos\phi} = -\, t/4m^2\; Re\,(F_{2p}\,\mathcal{H} - F_{1p}\,\mathcal{E})$$

Exp E12-12-010: DVCS on a transversely polarized HD-Ice target

Pol H = 60% Pol D = 35%

2021: 110 days on HD-Ice target

Lumi= 5 x 10^{33} cm^{-2} s^{-1}/nucleon



2010-2020 : DVCS off the neutron in Hall A @ 6 GeV

nature physics

ℓ d → ℓ n γ (p)

Flavor separation of CFFs when combined with p-DVCS

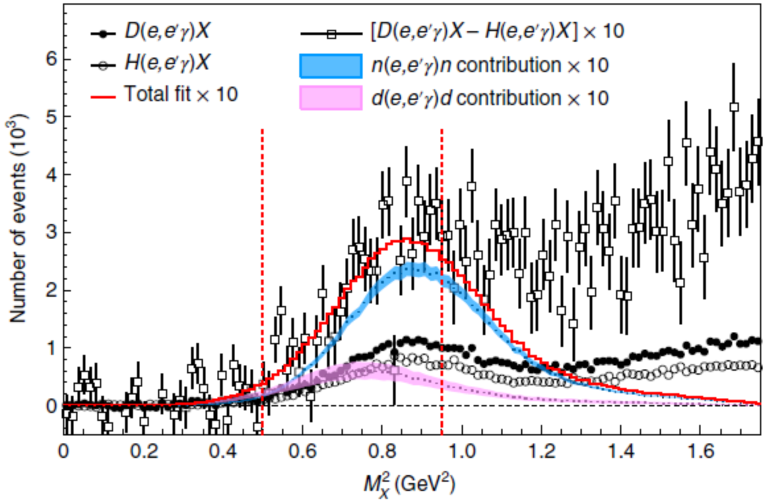
Benali et al., Nature Physics 16, 191-198 (**2020**)

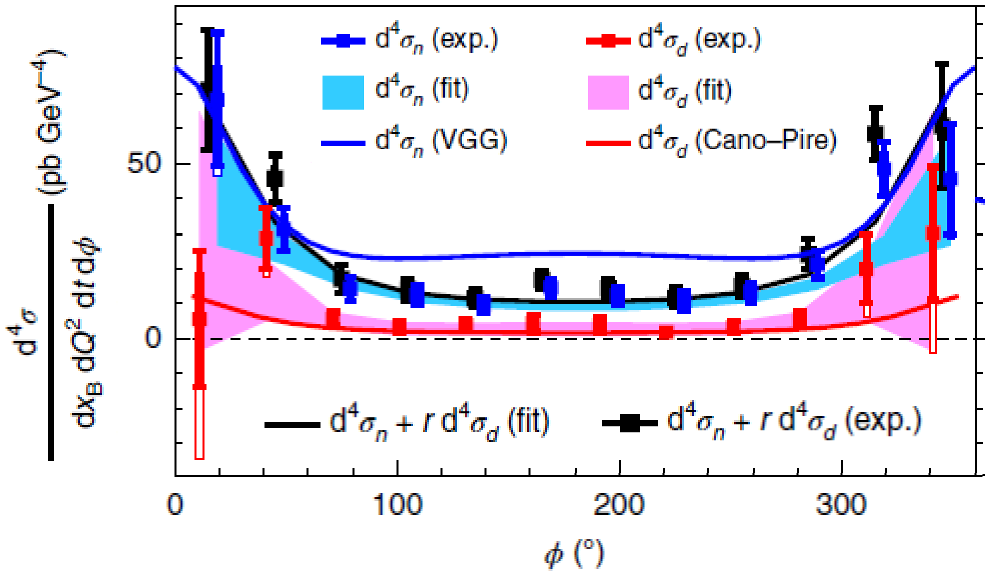
Coherent deuteron

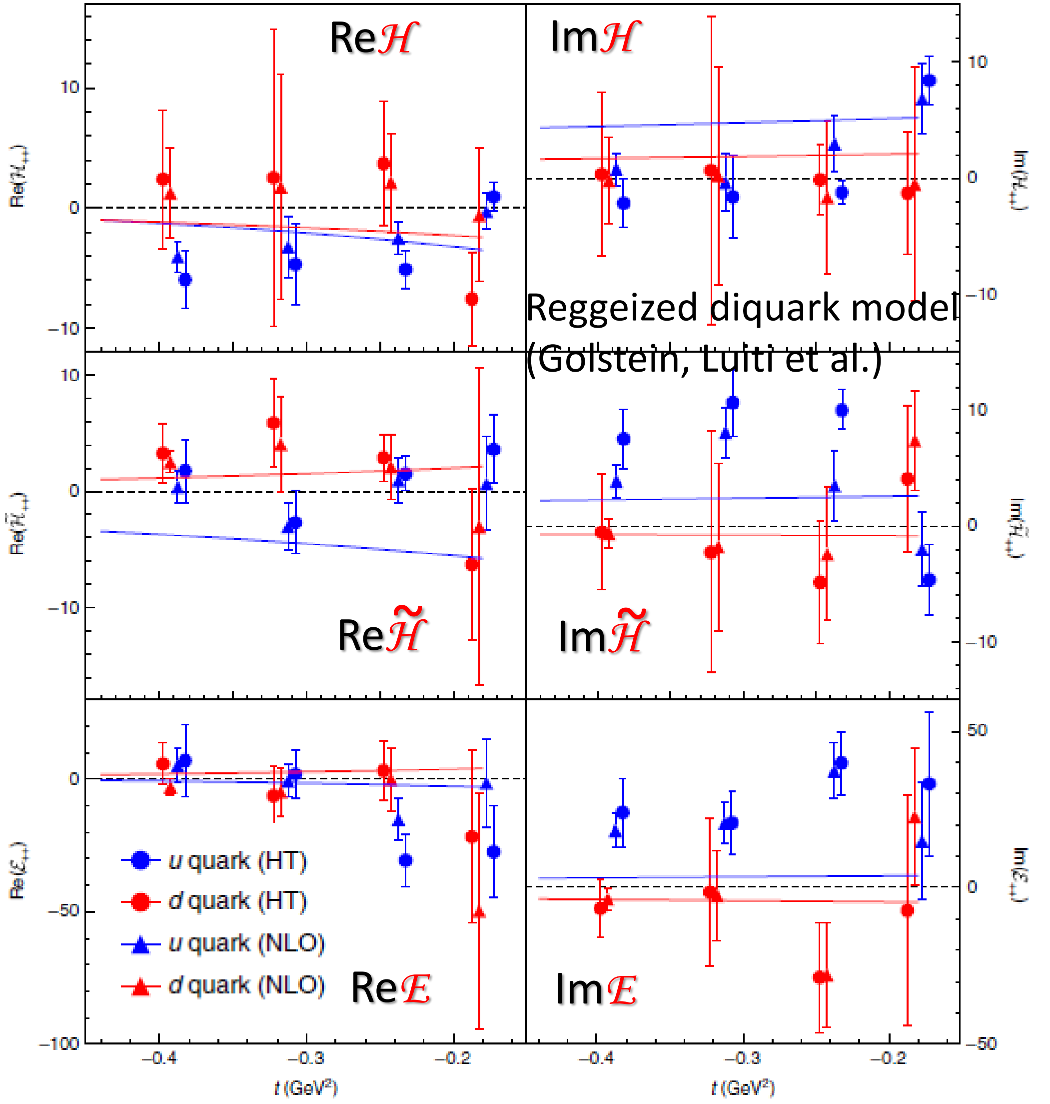
+

quasi-free neutron

DVCS χsections off LD2



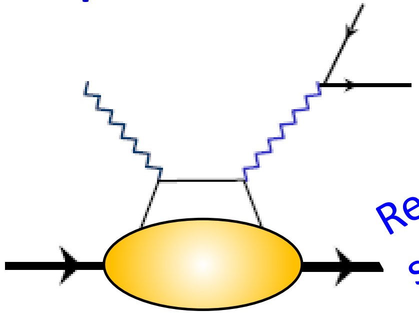




Reggeized diquark model (Golstein, Luiti et al.)

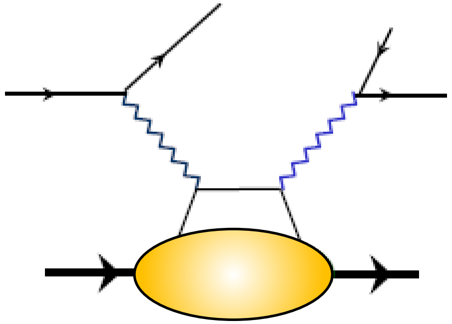
And other paths to get GPDs

Study of protons and neutrons



Results expected soon

Time Like Compton Scattering



Double DVCS

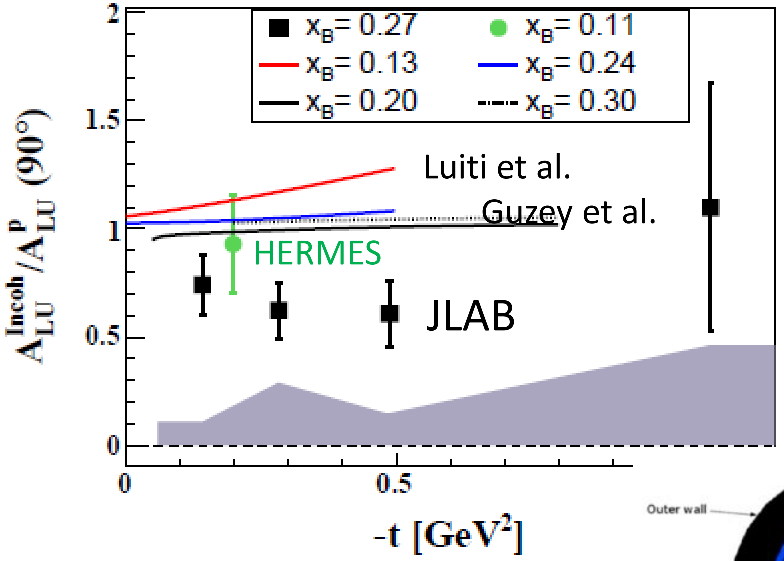
Projects which start to be explored
with the high lumnosity of JLab12
(in Hall-C or with CLAS12 and Solid)

Study of nuclei

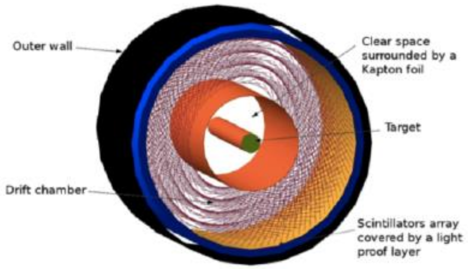
(HERMES, JLab6, JLab12)

First measurement on He4: Hattawy, PRL 119 (**2017**)
Spin 0 target, one chiral even GPD

Off bound protons: Hattawy, PRL 123(**2019**)
Ratio of the bound to the free proton at ϕ=90°

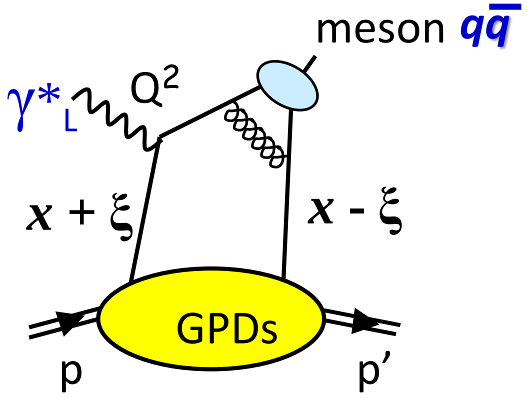


Other projects with the
recoil detecteur ALERT

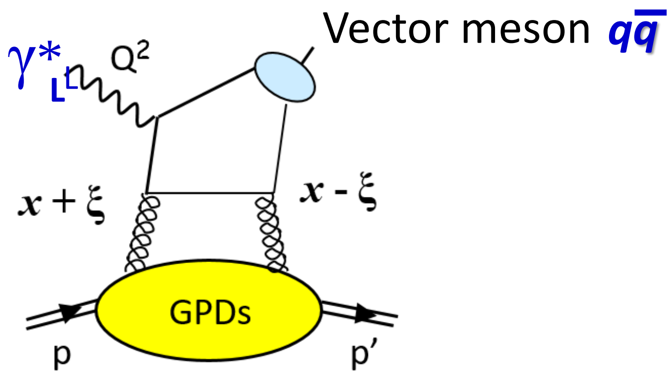


GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution at the same order in α_S



The meson wave function
Is an additional non-perturbative term

4 chiral-even GPDs: helicity of parton unchanged

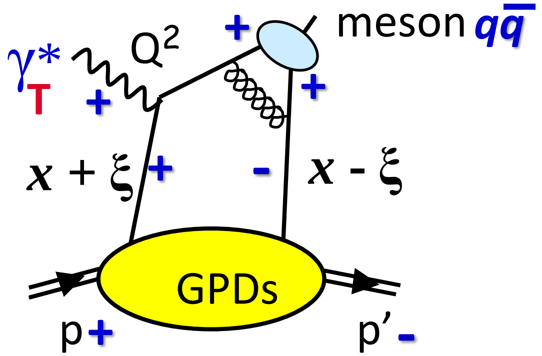
$H^q(x, \xi, t)$	$E^q(x, \xi, t)$	**For Vector Meson**
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$	**For Pseudo-Scalar Meson**

+ 4 chiral-odd or transversity GPDs: helicity of parton changed
(not possible in DVCS)

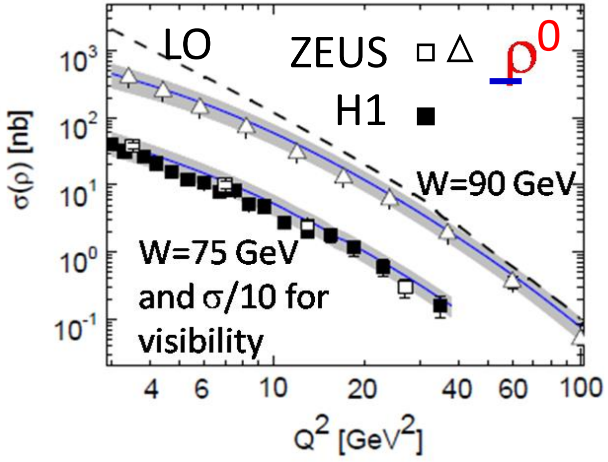
$H^q_T(x, \xi, t)$	$E^q_T(x, \xi, t)$	$\bar{E}^q_T = 2\,\tilde{H}^q_T + E^q_T$
$\tilde{H}^q_T(x, \xi, t)$	$\tilde{E}^q_T(x, \xi, t)$	(as Boer-Mulders)

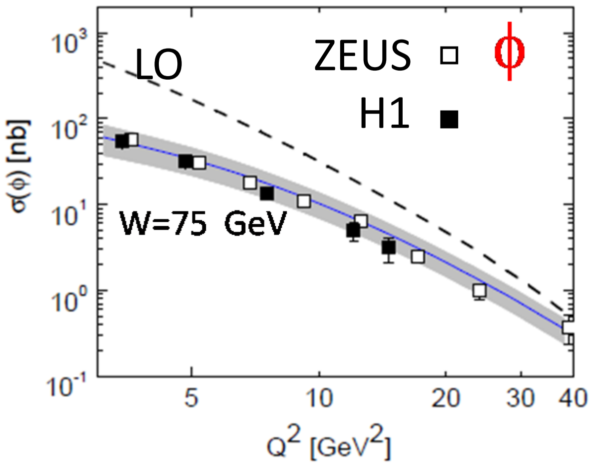
Factorisation proven only for σ_L
σ_T is asymptotically suppressed by $1/Q^2$ but large contribution observed
model of σ_T with transversity GPDs - divergencies regularized by k_T of q and $\bar{q}$ and Sudakov suppression factor

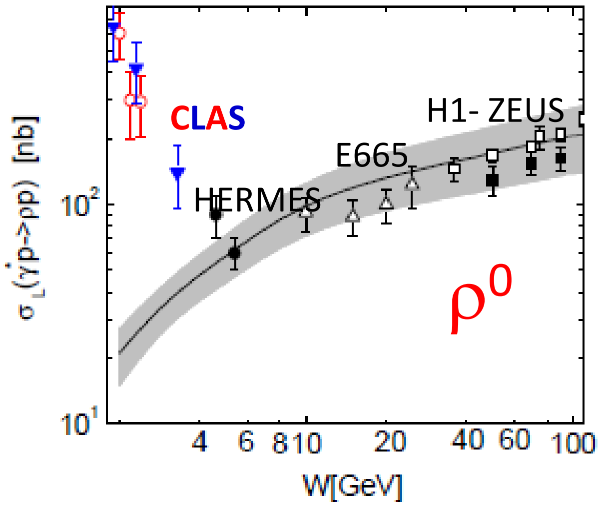
$\mathfrak{M}_{0-,++}$ sensitive to H^q_T
and to a twist-3 meson wave function

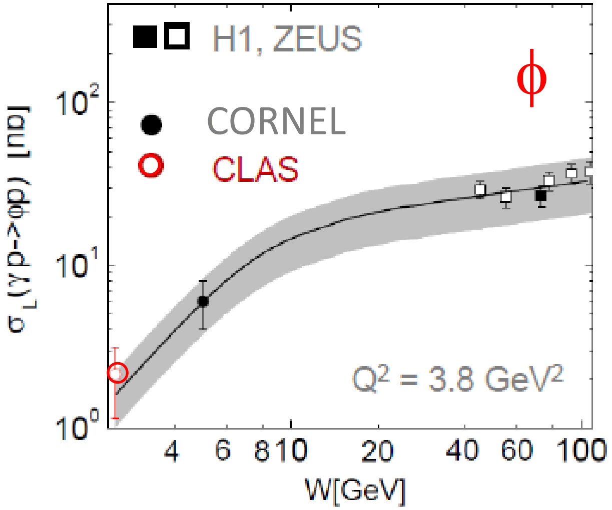


GPDs and Hard Exclusive Vector Meson Production



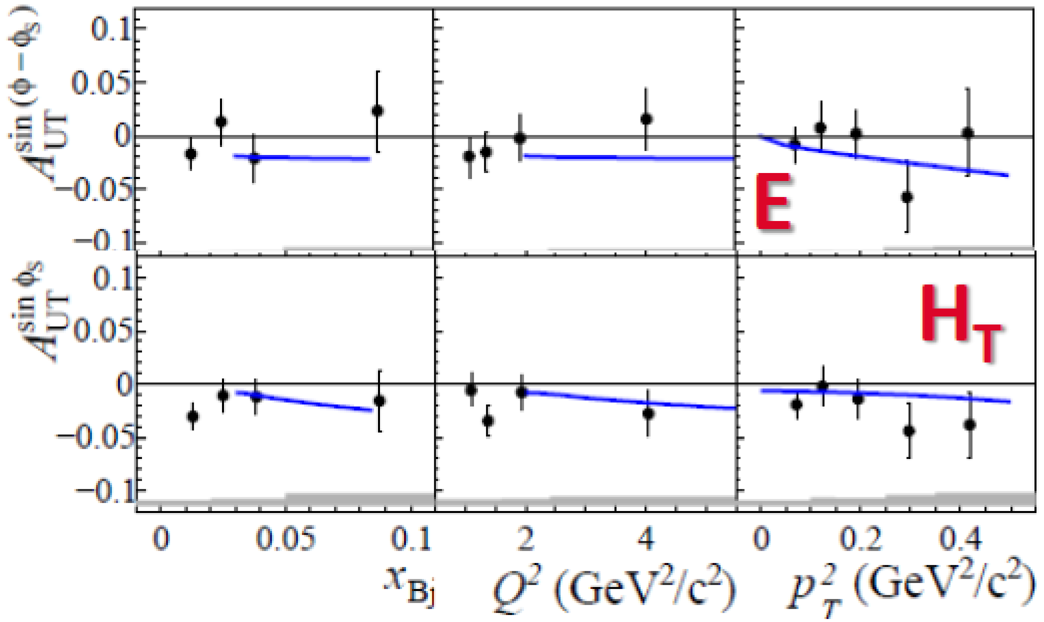






ρ^0 ($\rightarrow \pi^+\pi^-$) production at COMPASS
with Transversely Polarized Target

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

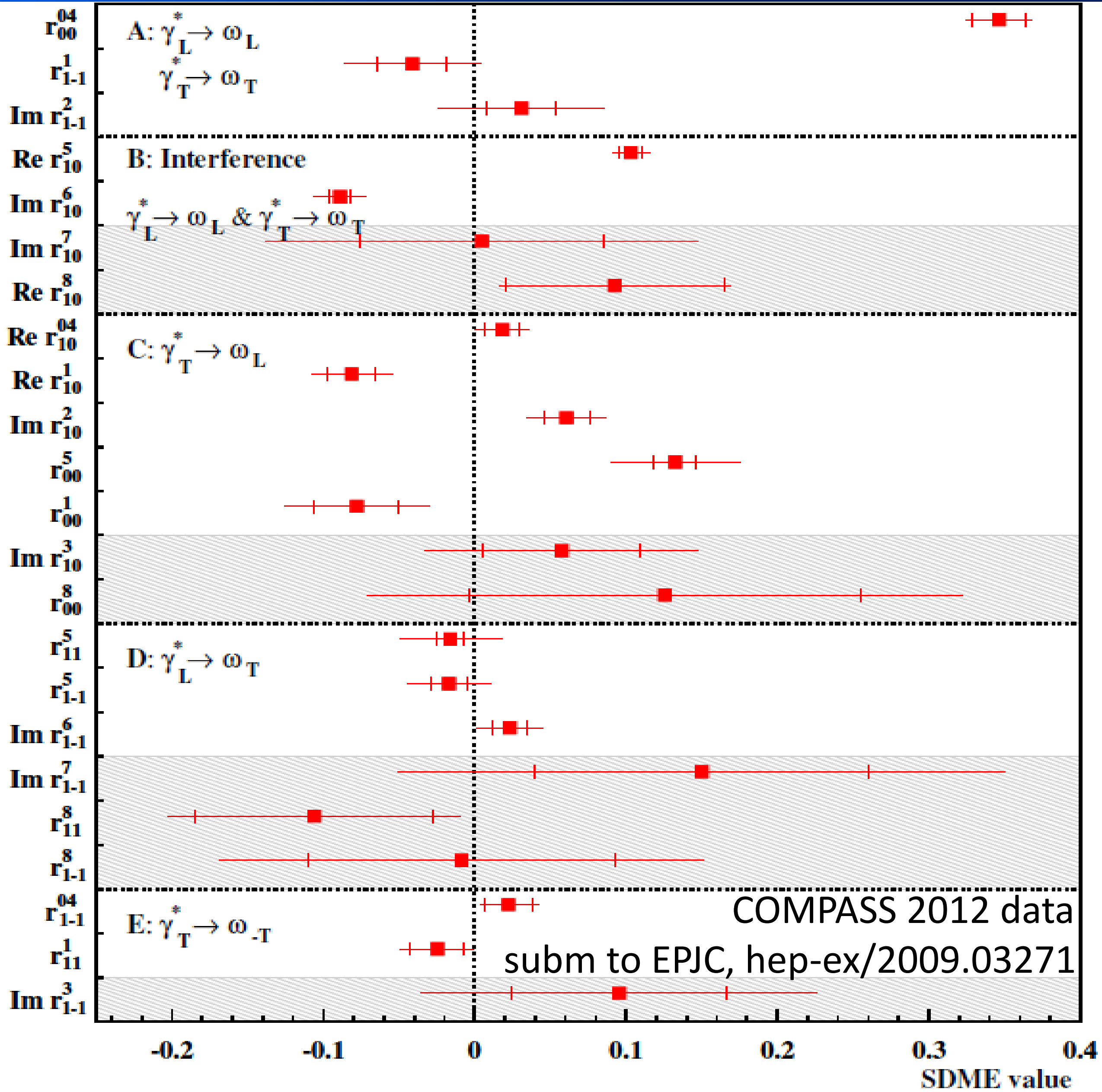


GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small x_B (or large W)

dominant (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

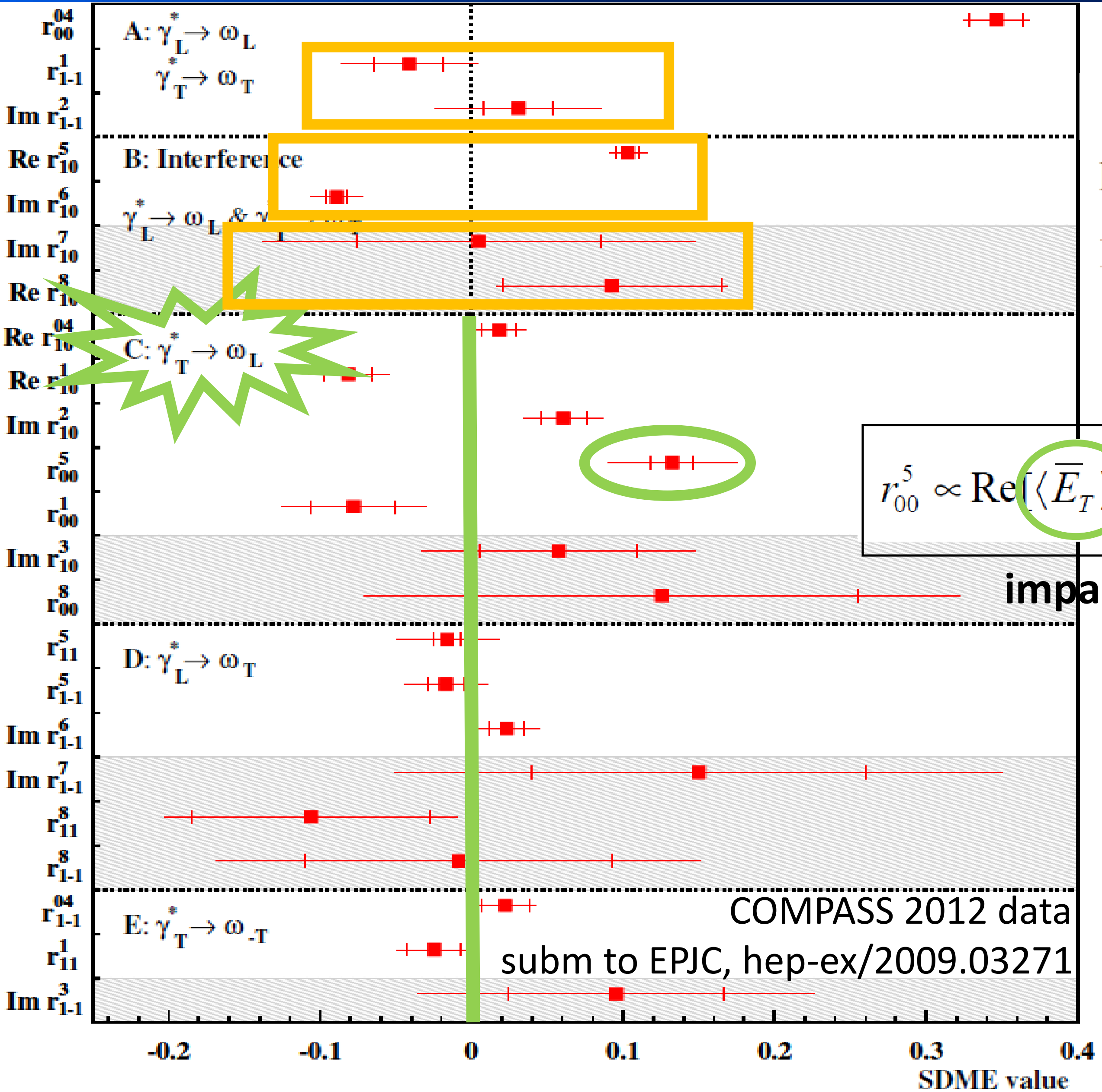
GPDs and Hard Exclusive ω Vector Meson Production



COMPASS
23 SDMEs in 5 classes A, B, C, D, E depending on helicity transitions

SDMEs dependent on beam polarisation shown within shaded areas

GPDs and Hard Exclusive ω Vector Meson Production



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

measurements:

$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0 \quad = -0.010 \pm 0.032 \pm 0.047$$

$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0 \quad = 0.014 \pm 0.011 \pm 0.013$$

$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0 \quad = -0.088 \pm 0.110 \pm 0.196$$

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

not observed for class C

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

From Goloskokov and Kroll, EPJC74 (2014) 2725

impact of $\bar{E}_T$ and H_T

Already clearly observed
in exclusive ρ^0, ω production
with transvers. polar. target
COMPASS 2004-7-10 data

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

GPDs and Hard Exclusive π^0 Production

e p → e π^0 p

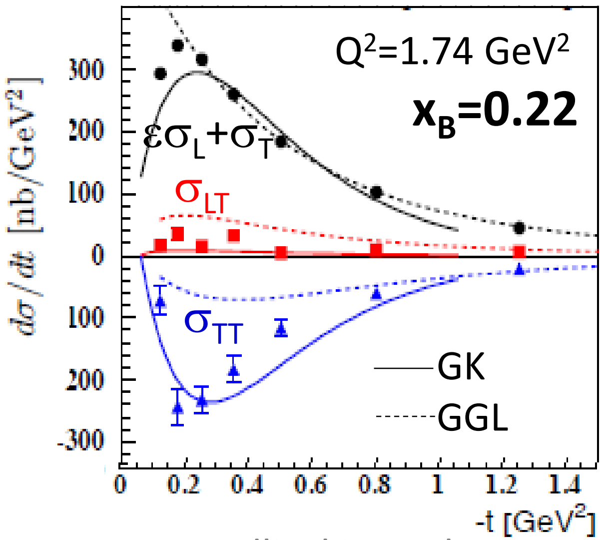
$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

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

Jlab 6 GeV CLAS

σ_{TT} large (impact of $\bar{E}_T$)

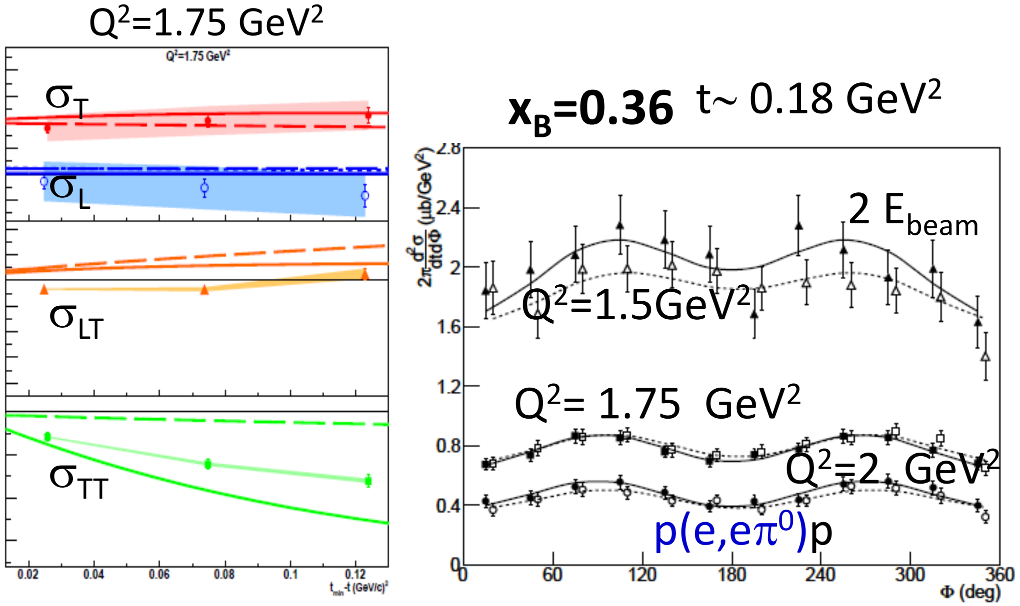
σ_{LT} smaller



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

Jlab 6 GeV Hall-A LH2 target → proton

Different beam energies → L/T separation

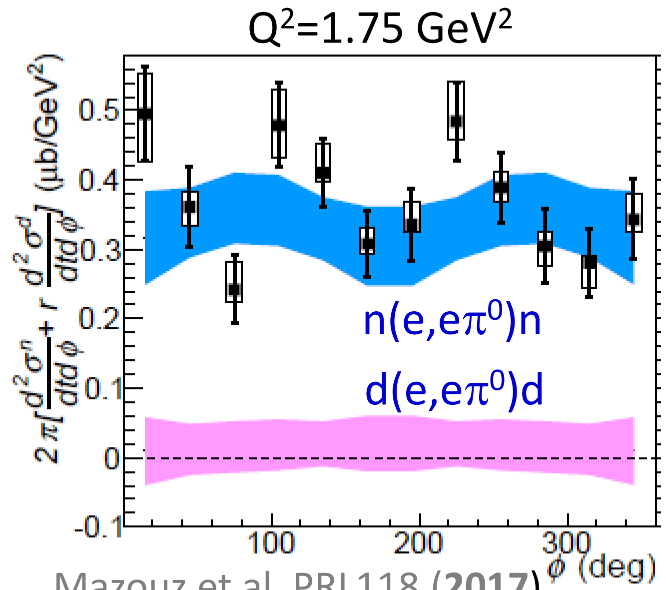


Defurne et al, PRL117 (**2016**)

LD2 target → neutron+deuteron

D(e,eπ^0)X - p(e,eπ^0)p = n(e,eπ^0)n + d(e,eπ^0)d

→ Flavor decomposition on u and d quarks



Mazouz et al, PRL118 (**2017**)

GPDs and Hard Exclusive π^0 Production

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

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

COMPASS

PLB 805 (2020)

Q^2=2.0 GeV^2

x_B=0.093

t~ 0.26 GeV^2

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

$$|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2$$

$$\frac{t'}{16m^2}|\langle\bar{E}_T\rangle|^2$$

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

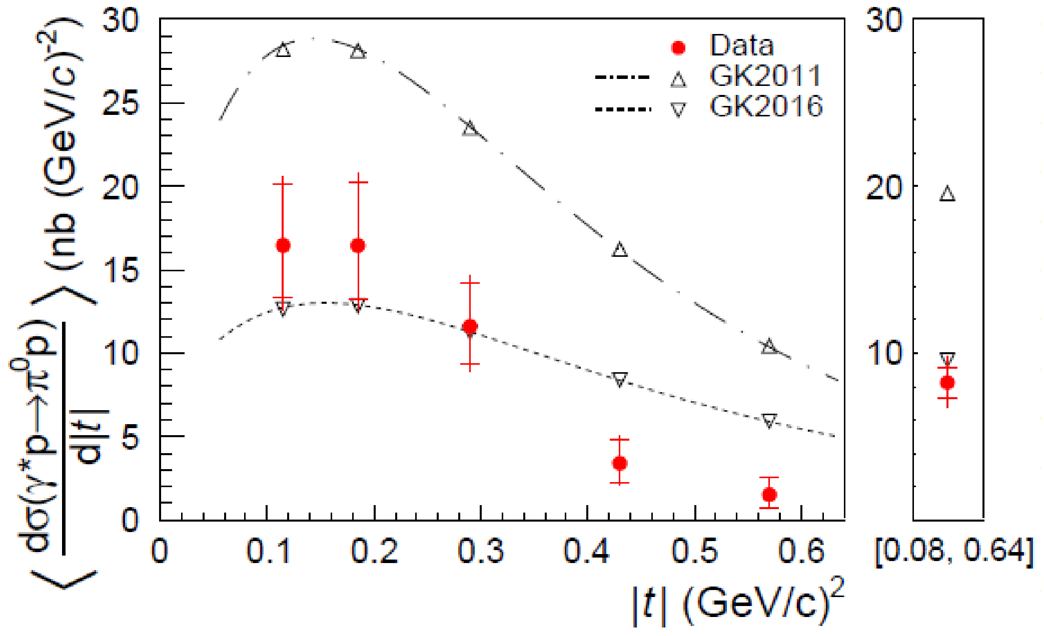
$$\left\langle\frac{d\sigma_T}{d|t|}+\epsilon\frac{d\sigma_L}{d|t|}\right\rangle = (8.2 \pm 0.9_{\rm stat}\,{}^{+\,1.2}_{-\,1.2}|_{\rm sys})\frac{\rm nb}{({\rm GeV}/c)^2}$$

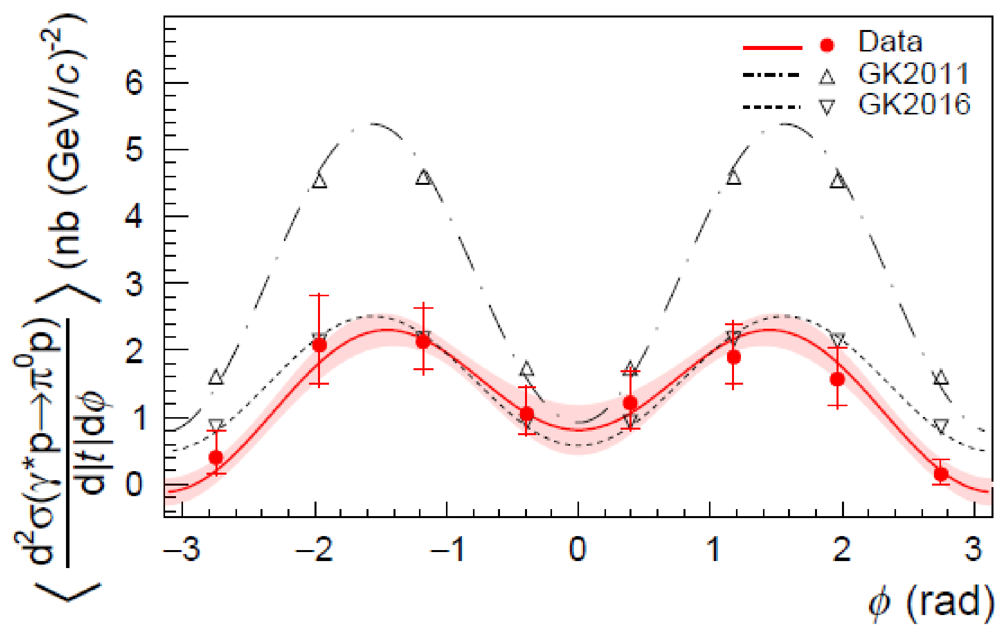
$$\left\langle\frac{d\sigma_{TT}}{d|t|}\right\rangle = (-6.1 \pm 1.3_{\rm stat}\,{}^{+\,0.7}_{-\,0.7}|_{\rm sys})\frac{\rm nb}{({\rm GeV}/c)^2}$$

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

σ_{TT} large (impact of $\bar{E}_T$)

σ_{LT} smaller but significantly positive as at CLAS





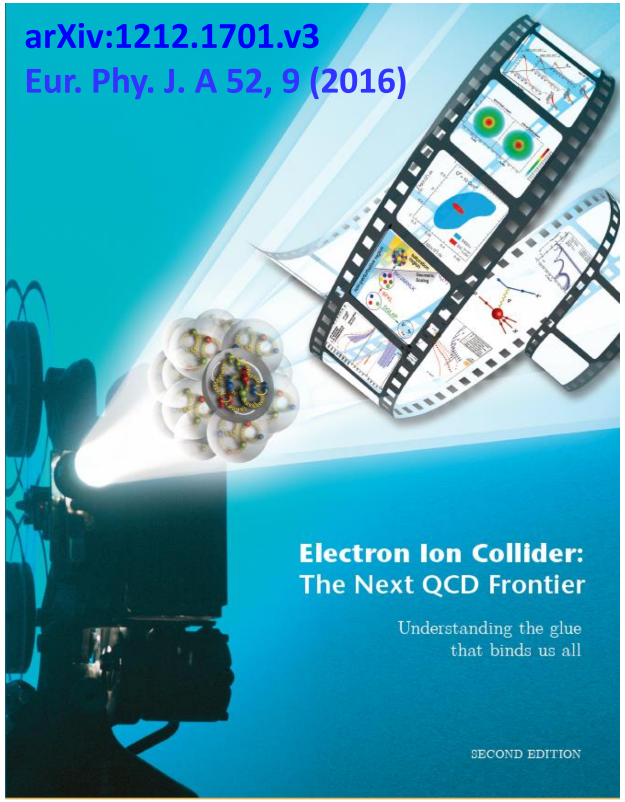
Future: Key measurements for imaging partons with EIC

Stage 2
Ee=20 GeVEp=250 GeV

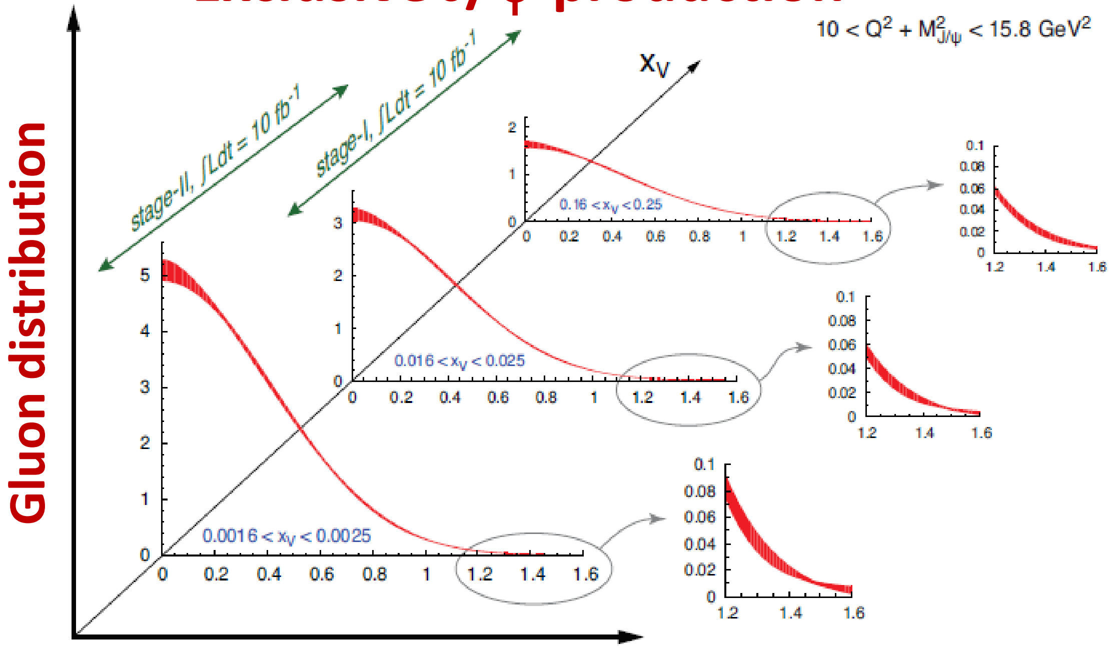
Stage 1
Ee=5 GeVEp=100 GeV

Deliverables	Observables	What we learn	Requirements
GPDs of sea quarks and gluons	DVCS and $J/\Psi, \rho^0, \phi$ production cross section and polarization asymmetries	transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations	$\int dt\, L \sim 10$ to $100\,\text{fb}^{-1}$; Roman Pots; polarized e^- and p beams; wide range of x_B and Q^2; range of beam energies; e^+ beam valuable for DVCS
GPDs of valence and sea quarks	electroproduction of π^+, K and ρ^+, K^*	dependence on quark flavor and polarization	

arXiv:1212.1701.v3
Eur. Phy. J. A 52, 9 (2016)



Exclusive J/ψ production



Conclusions

Not an exhaustive compilation of all results and projections, also JPARC in the game…

Jlab 12 GeV with the high luminosity electron beam is at the beginning of a very exciting time with a high precision era for valence quarks at large x_B

COMPASS, with high energy muon beams at CERN and RHIC with UPC will provide first results of sea quarks and gluons at small x_B

They are the foundations for the preparation of new experiments at EIC

For example preparation of the EIC Yellow Report
for the detector requirement to study DVCS and π^0 using:

- ✓ the PARTONS framework
  with KM20 CFF tables provided by Kumericki
  and GK16 model from Goloskokov and Kroll based on the COMPASS results
- ✓ an update of the MC event generator MILOU developed for H1 and ZEUS