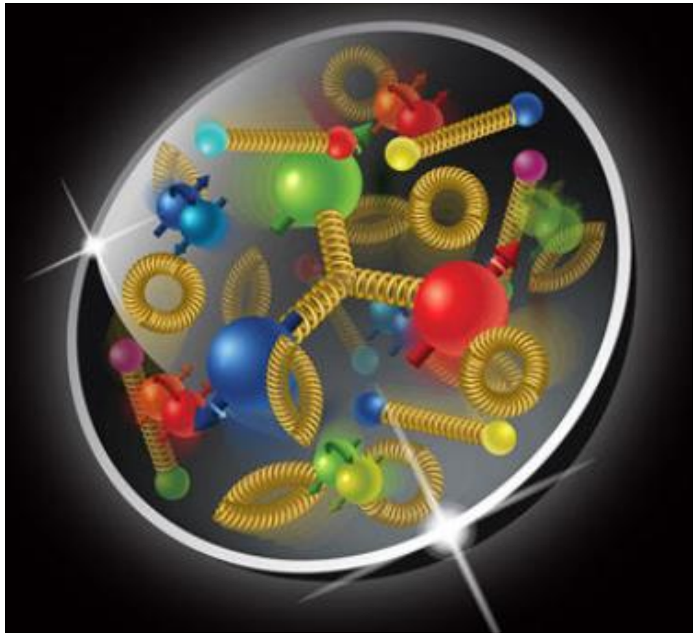



## Lesson II: Hadronic scale, experimental point of view:

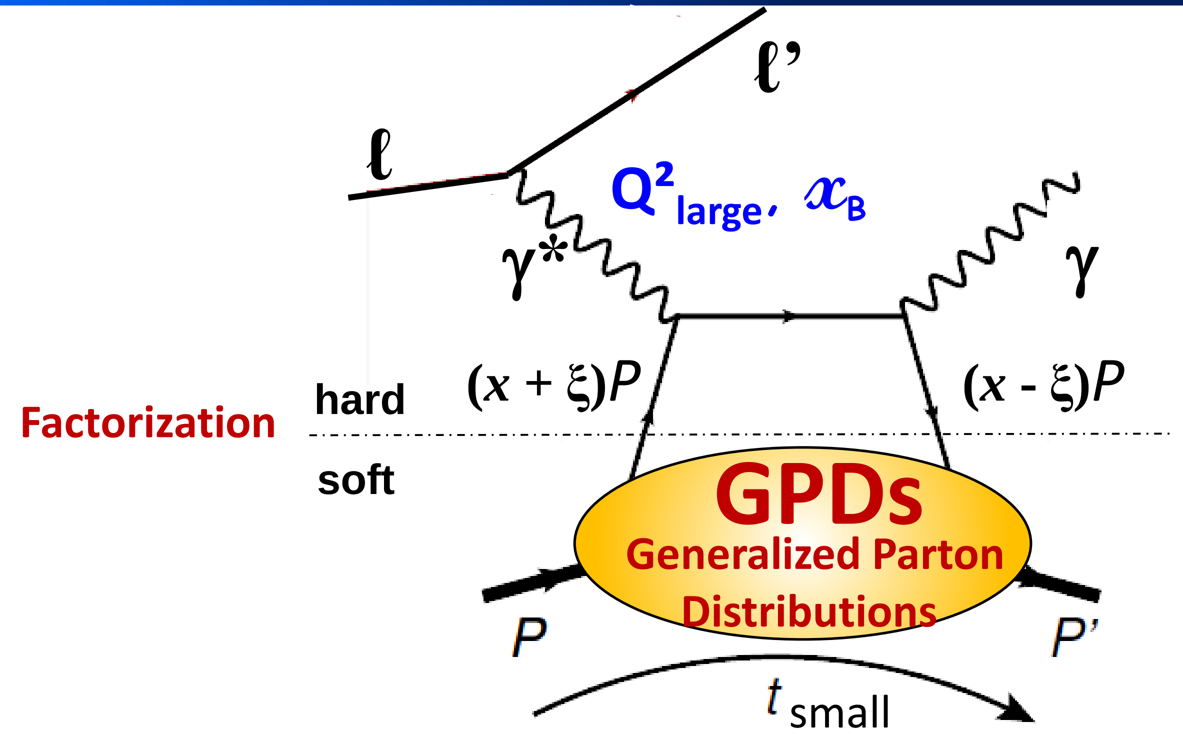
# From high-energy lepton scattering to nucleon pressure

**After the introduction of the different types of experiments to reveal the nucleon structure, the focus is on Exclusive Reactions related to GPDs:**

- → **Compton Form Factors measurements**
  - ✓ **Correlation between position and momentum of partons**
  - ✓ **Angular momentum and nucleon pressure**

*Nicole d'Hose (Irfu, CEA Université Paris-Saclay)*

# Deeply virtual Compton scattering (DVCS)



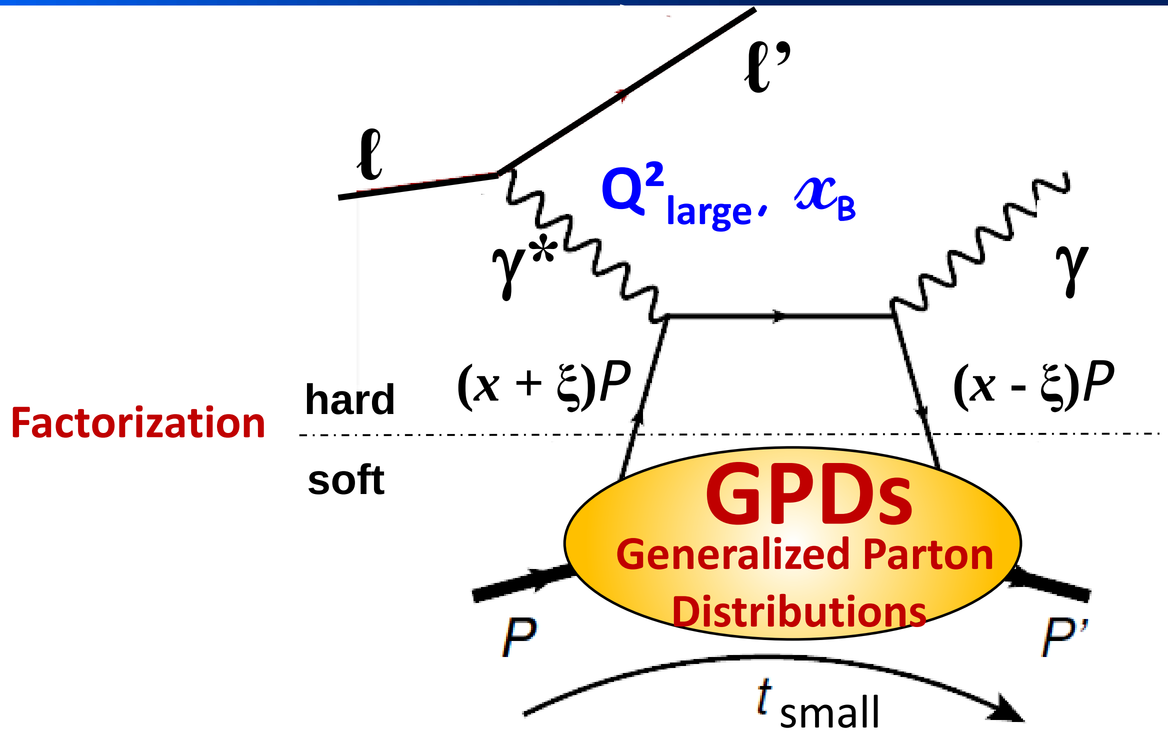

**D. Mueller** *et al*, Fortsch. Phys. 42 (1994)
**X.D. Ji**, PRL 78 (1997), PRD 55 (1997)
**A. V. Radyushkin**, PLB 385 (1996), PRD 56 (1997)


Dieter Mueller


Xiang-Dong Ji


Anatolii Radyushkin

# Deeply virtual Compton scattering (DVCS)




**D. Mueller** *et al*, Fortsch. Phys. 42 (1994)
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**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:

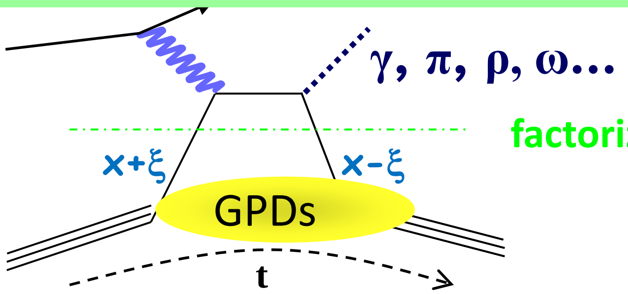
x: average
ξ: transferred
} quark longitudinal momentum fraction

t: proton momentum transfer squared
related to $b_\perp$ via Fourier transform

The variables measured in the experiment:

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

# GPDs and the other observables

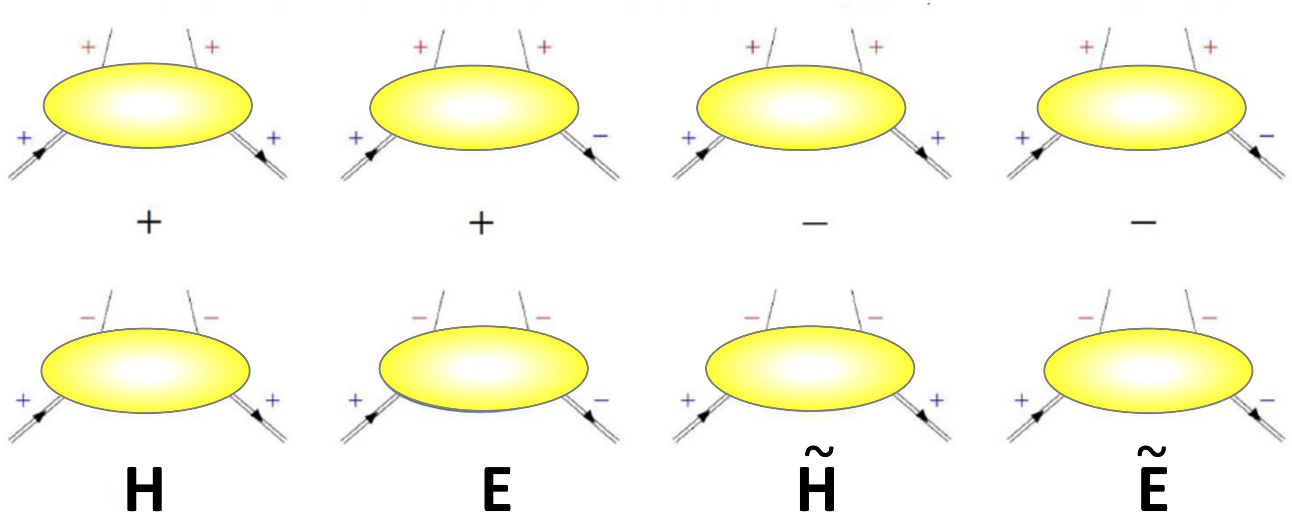



The observables are integrals of GPDs over x

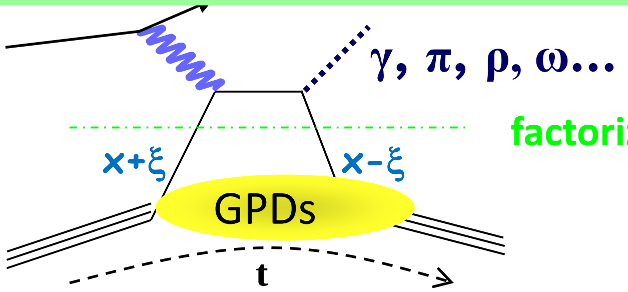
$H, \tilde{H}, E, \tilde{E}(x,\xi,t)$

4 chiral-even GPDs

It exists also
4 chiral-odd GPDs
(not discussed in this talk)



# GPDs and the other observables

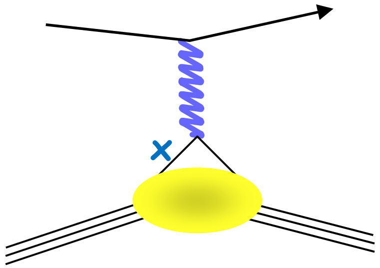



The observables are integrals of GPDs over x

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

4 chiral-even GPDs

Elastic 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***

$\int \tilde{H}_f(x,\xi,t)dx = g_A^f(t)$ ***Axial FF***

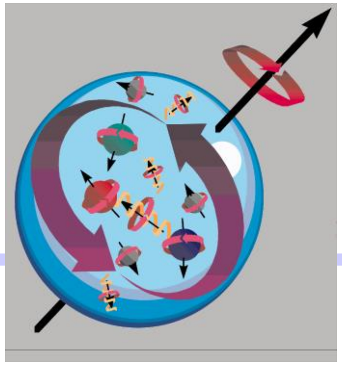
$\int \tilde{E}_f(x,\xi,t)dx = h_A^f(t)$ ***PseudoScalar FF***

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

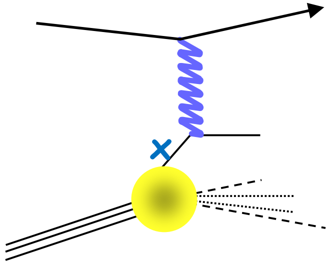
***Ji's Sum Rule***

$½ = J_q + J_g$

$½ = ½\,\Delta\Sigma + L_q + J_q$



"ordinary" parton density



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

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

# GPDs and 3D imaging

**mapping in the transverse plane**

**Impact parameter distribution**

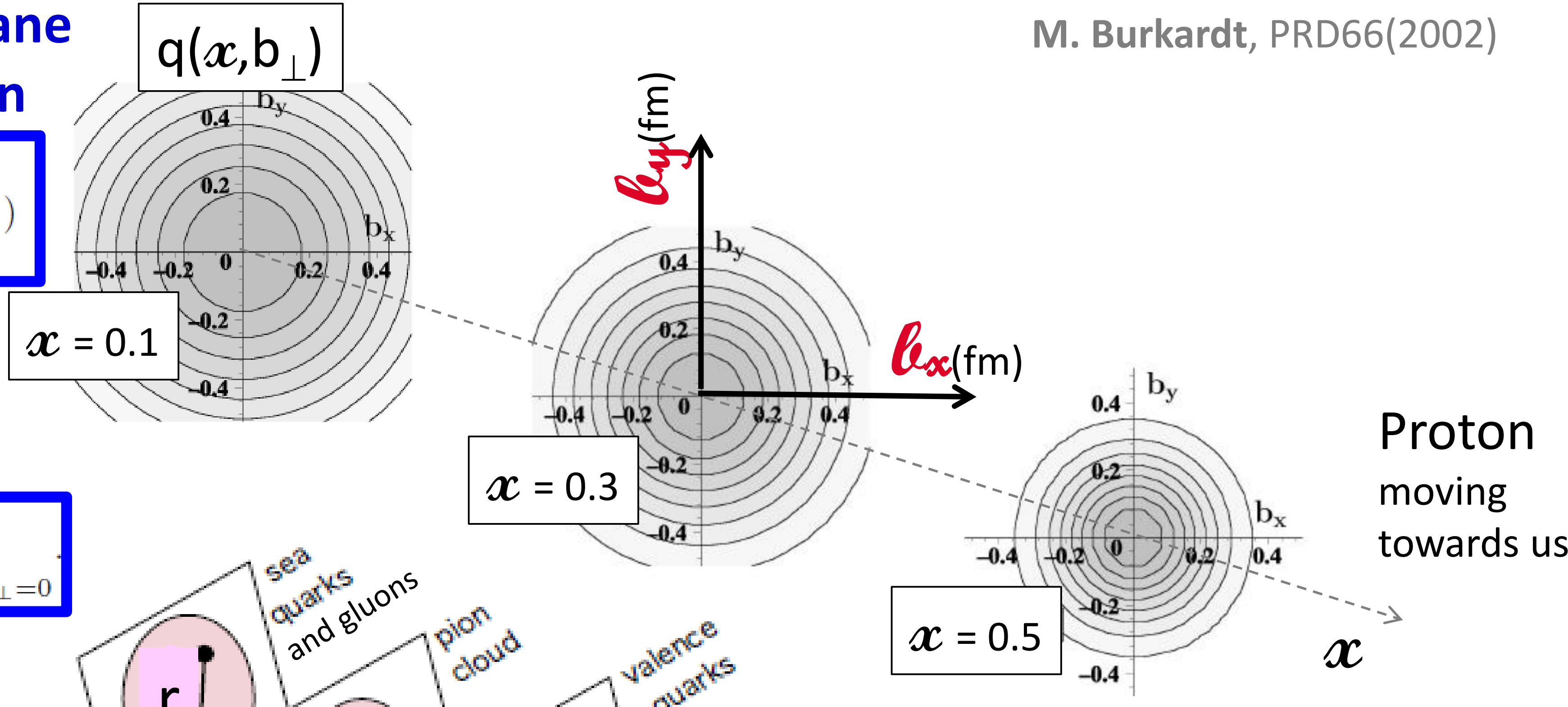
$$q_f(x,b_\perp)=\int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp\cdot b_\perp} H_f(x,0,-\Delta_\perp^2)$$

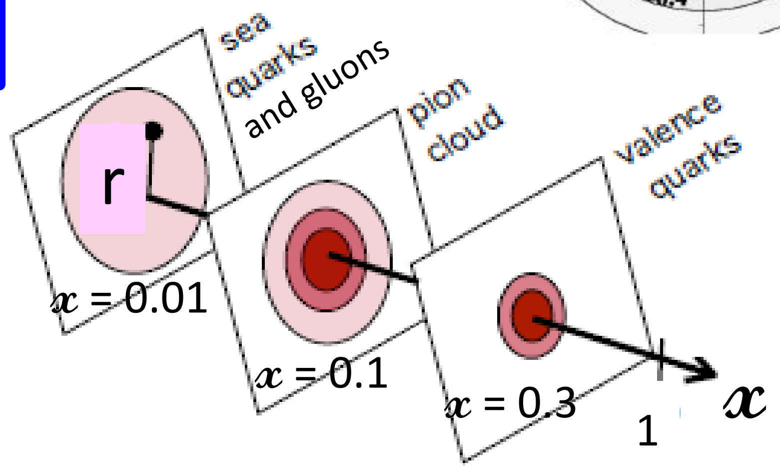
$$\langle b_\perp^2\rangle^q(x) = -4\frac{\partial}{\partial \Delta_\perp^2}\ln H_-^q(x,0,-\Delta_\perp{}^2)\Big|_{\Delta_\perp=0}$$

$t=-\Delta_L^2 - \Delta_\perp^2$

At $\xi=0$ ➔ $\Delta_L^2 = 0$

**M. Burkardt**, PRD66(2002)

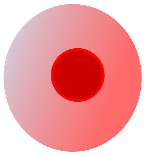



Correlation between the spatial distribution of partons and the longitudinal momentum fraction

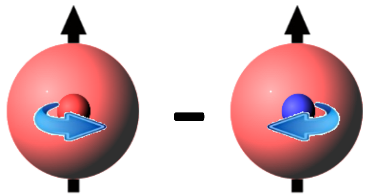
# GPDs and Energy-Momentum Tensor and Confinement

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



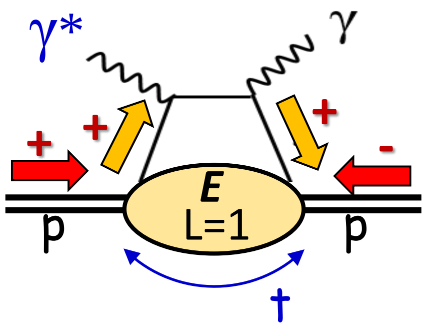
"Elusive"

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

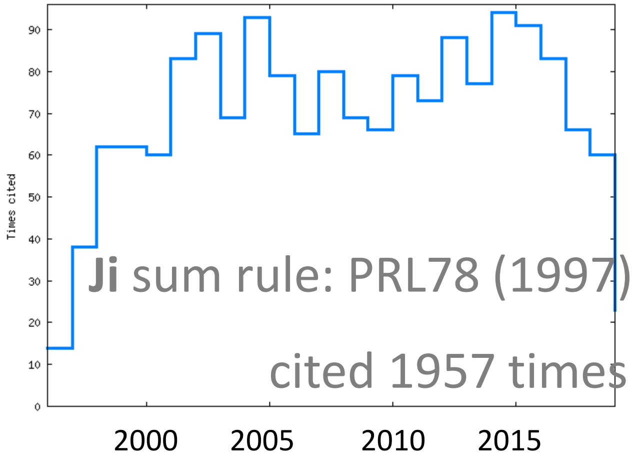


**Sivers:** quark $k_T$ & nucleon transv. spin

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




**Relation to OAM**



# GPDs and Energy-Momentum Tensor and Confinement

*GPDs can provide an experimental answer by exploiting their equivalence to the gravitational form factors of the nucleon energy-momentum-tensor (fundamental nucleon properties)*

mass & energy distribution

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

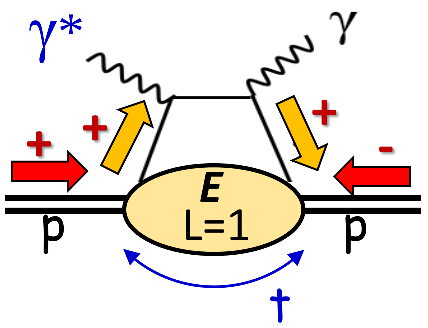
$$\int_{-1}^{1} dx\, x\, E^a(x,\xi,t) = 2J^a(t) - A^a(t) - \xi^2 d_1^{\,a}(t)$$

Angular momentum distribution

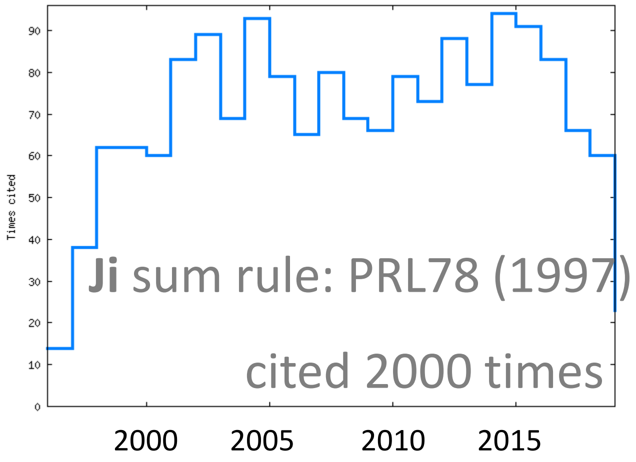
Force & Pressure distribution

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

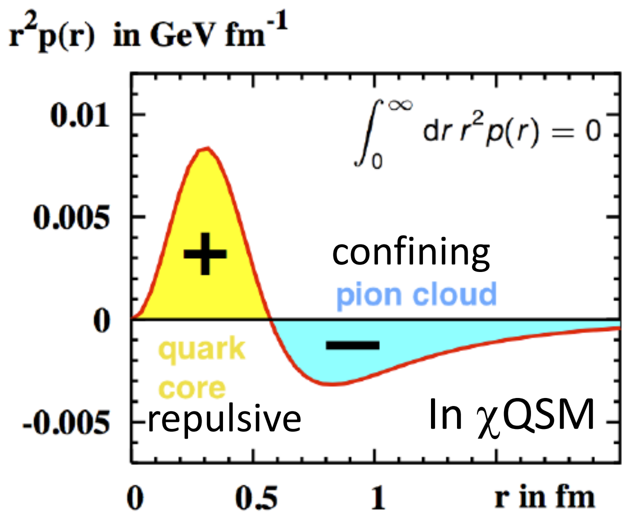
$$2J^q = \lim_{t\to 0} \int x\, (H^q(x,\xi,t) + E^q(x,\xi,t))\, dx$$




**Relation to OAM**

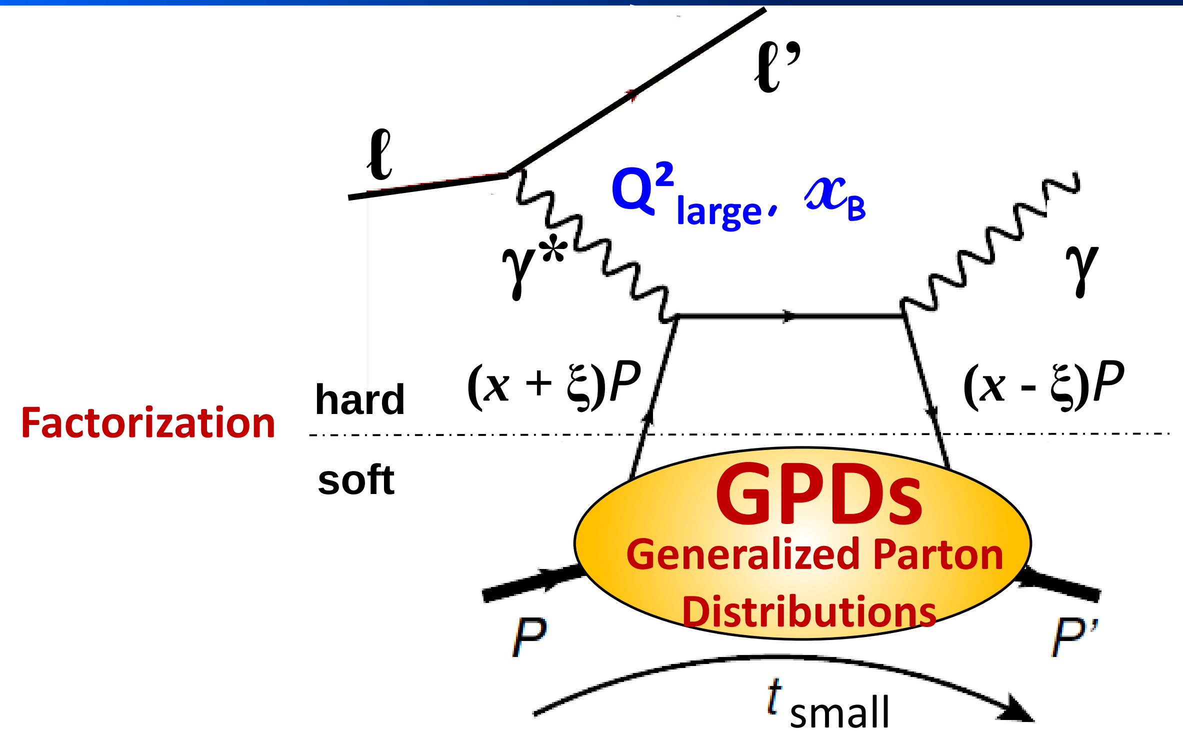



**Pressure Distribution**

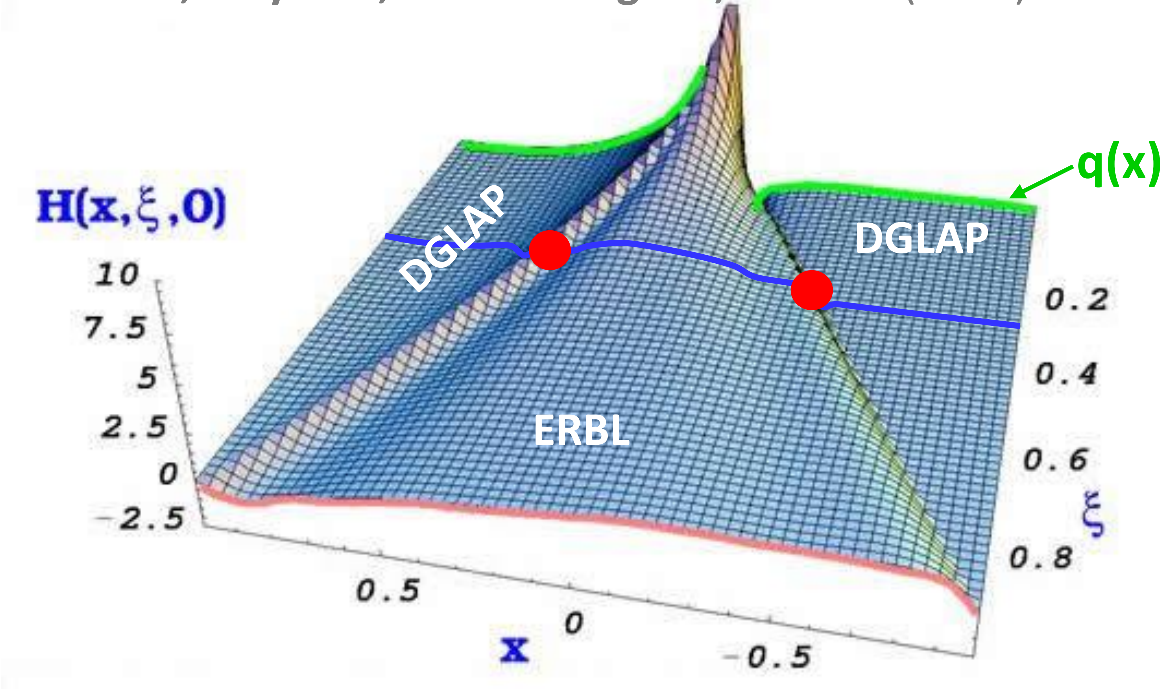



The pion field provides the confining pressure at the proton periphery (pions are the Goldstone bosons of the spontaneous chiral symmetry breaking)

# Deeply virtual Compton scattering (DVCS)




Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)




The amplitude DVCS at LT & LO in $\alpha_s$ (GPD **H**) :

Real part Imaginary part

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

In an experiment we measure

Compton Form Factor $\mathcal{H}$

$$Re\mathcal{H}(\xi,t) = \pi^{-1}\int_0^1 dx\, \frac{2x\; Im\mathcal{H}(x,t)}{x^2-\xi^2} + \Delta(t)$$

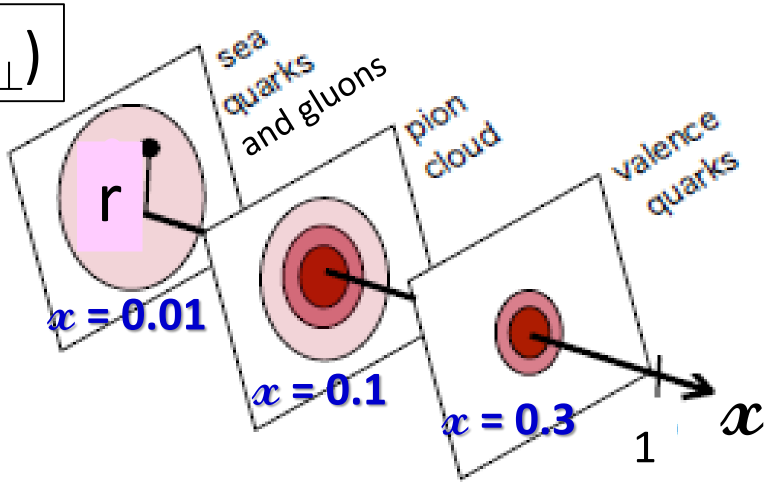
# Deeply virtual Compton scattering (DVCS)

**M. Burkardt**, PRD66(2002)

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

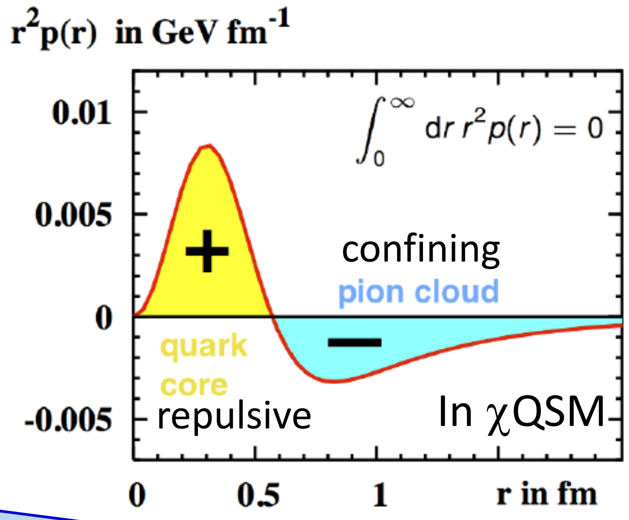
## Mapping in the transverse plane

$q(x, b_\perp)$




FT of H(x, ξ=0,t)

## Pressure Distribution

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In an experiment we measure

Compton Form Factor $\mathcal{H}$

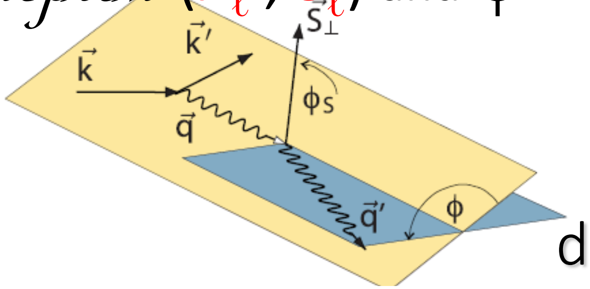
$$\mathcal{R}e\mathcal{H}(\xi,t) = \pi^{-1}\int_0^1 dx\, \frac{2x\, Im\mathcal{H}(x,t)}{x^2-\xi^2} + \Delta(t)$$

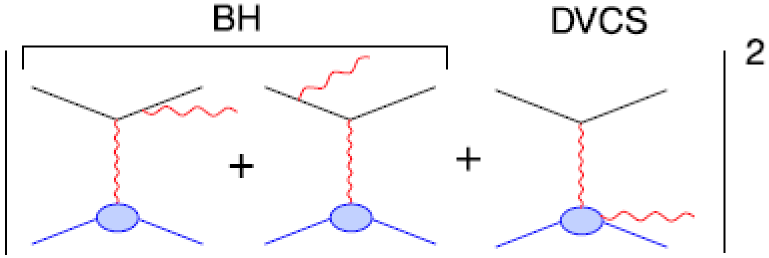
D-term

$d_1(t)$

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$



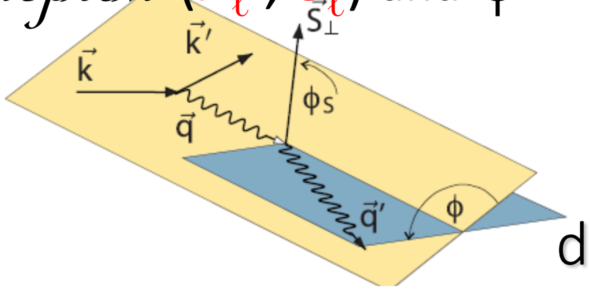

$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

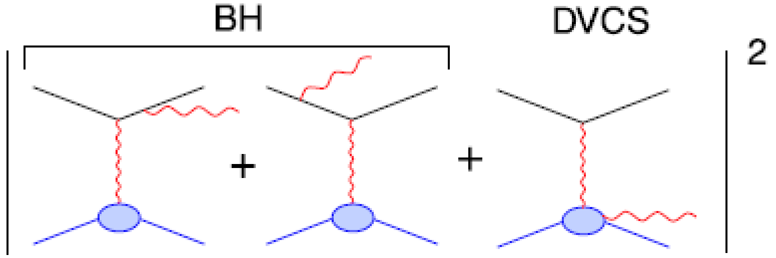
$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell \, d\sigma^{DVCS}_{pol}\right) + (e_\ell \mathrm{Re}\, I + e_\ell P_\ell \, \mathrm{Im}\, I)$$

Well known

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$

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

Well known

**With unpolarized target:**

Belitsky, Müller, Kirner, NPB629 (2002)

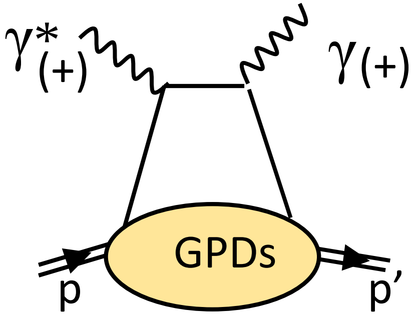
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH} \cos\phi + c_2^{BH} \cos 2\phi$$

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

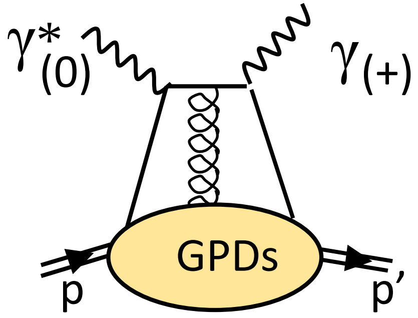
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS} \sin\phi$$

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

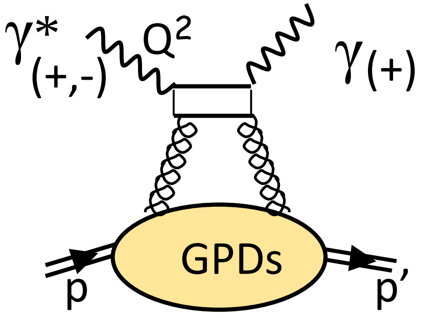
$$\mathrm{Im}\, I \propto s_1^I \sin\phi + s_2^I \sin 2\phi$$




**LO,Twist-2**



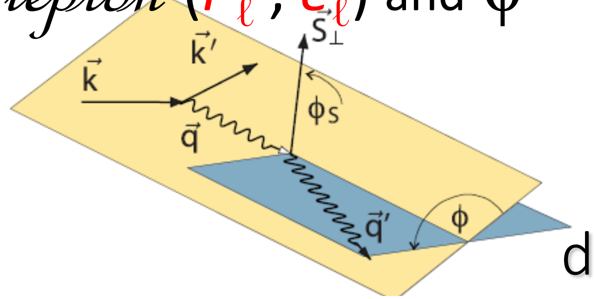

**HT,Twist-3**
suppressed by 1/Q

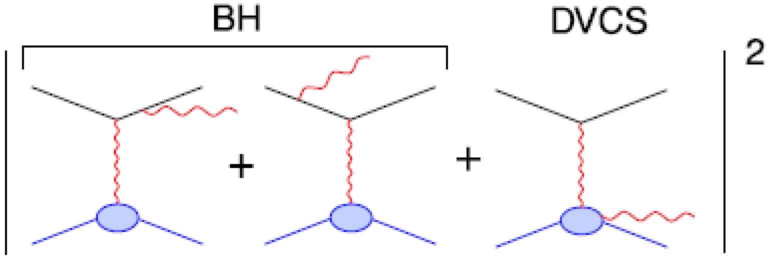



**NLO,Twist-2**
**double helicity flip**
suppressed by $\alpha_s$

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$




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

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

Well known

**With both $\overleftarrow{e^-}$ and $\overrightarrow{e^-}$ beams we can build:**

**❶ beam spin diff**

$$\Delta \equiv d\sigma^{\leftarrow} + d\sigma^{\rightarrow}$$

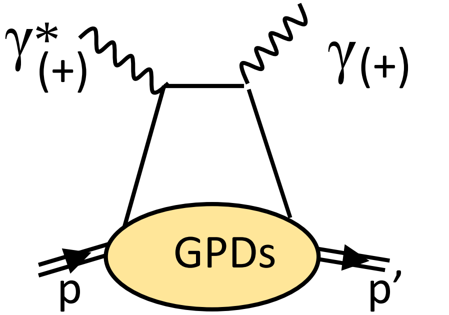
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

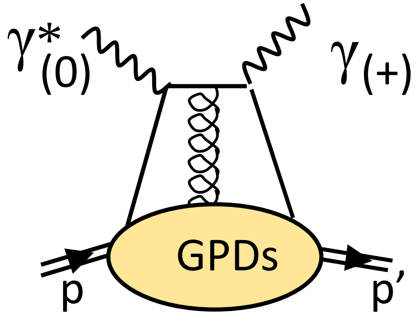
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

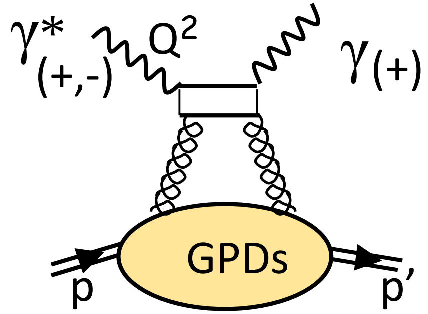
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$




LO,Twist-2




HT,Twist-3
suppressed by 1/Q




NLO,Twist-2
double helicity flip
suppressed by $\alpha_s$

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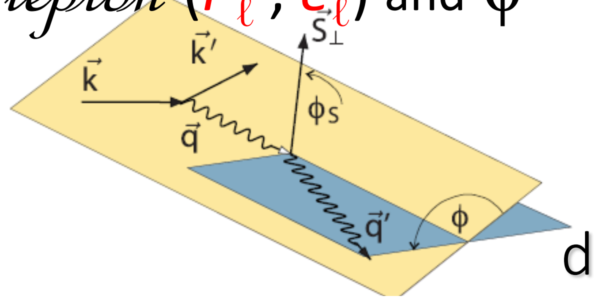
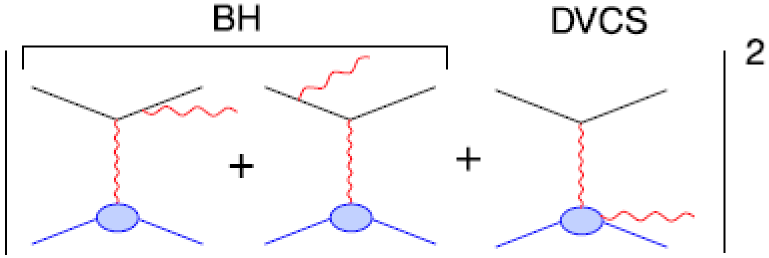
*lepton* ($P_\ell$ , $e_\ell$) and $\phi$

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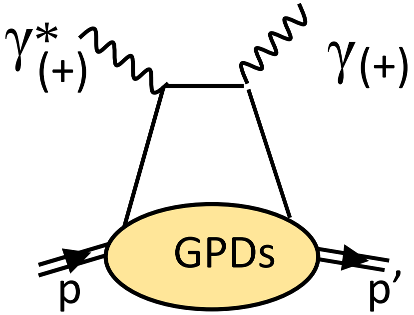
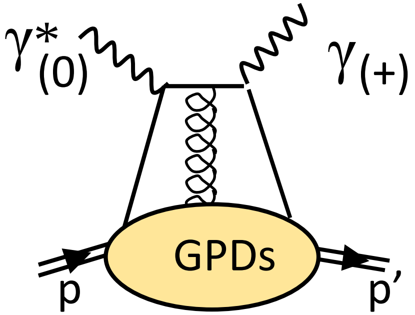
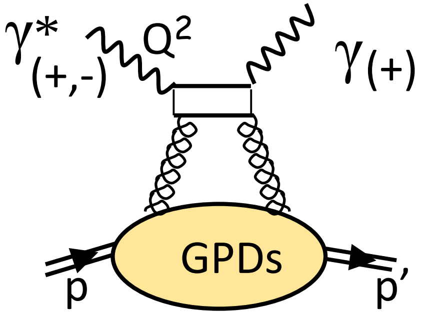
Well known




LO,Twist-2




HT,Twist-3
suppressed by 1/Q




NLO,Twist-2
double helicity flip
suppressed by $\alpha_S$

**With both $\overleftarrow{e^-}$ and $\overrightarrow{e^-}$ beams we can build:**

❶ **beam spin diff**

$$\Delta \equiv d\sigma^{\leftarrow} + d\sigma^{\rightarrow}$$

❷ **beam spin sum**

$$\Sigma \equiv d\sigma^{\leftarrow} + d\sigma^{\rightarrow}$$

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

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

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

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

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

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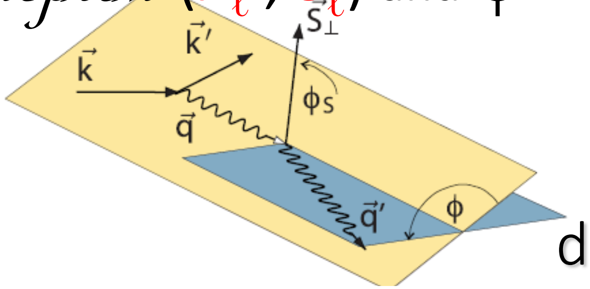
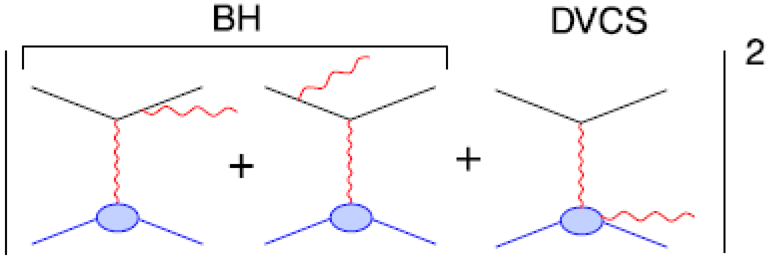
*lepton* ($P_\ell$ , $e_\ell$) and $\phi$




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

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Well known

**With both $\mu^{\overleftarrow{+}}$ and $\mu^{\overrightarrow{-}}$ beams we can build:**

**❶ beam charge-spin sum**

$$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

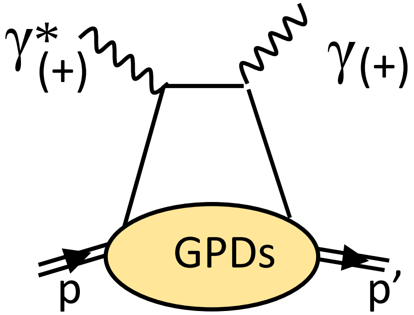
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

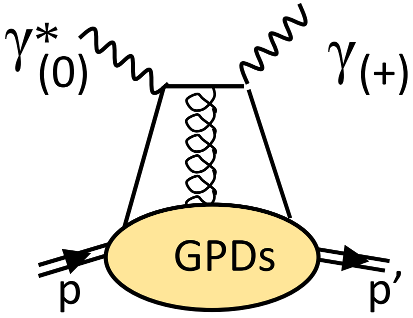
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

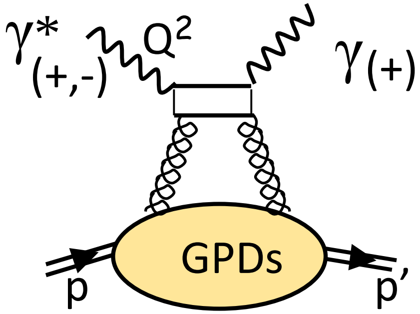
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$




LO,Twist-2



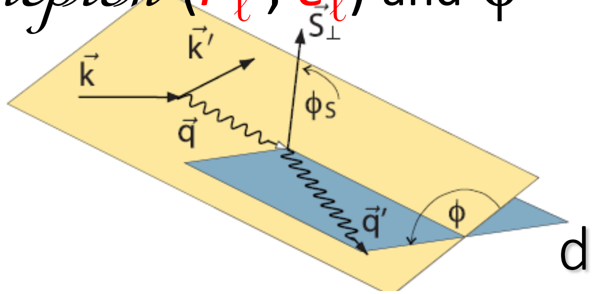

HT,Twist-3
suppressed by 1/Q

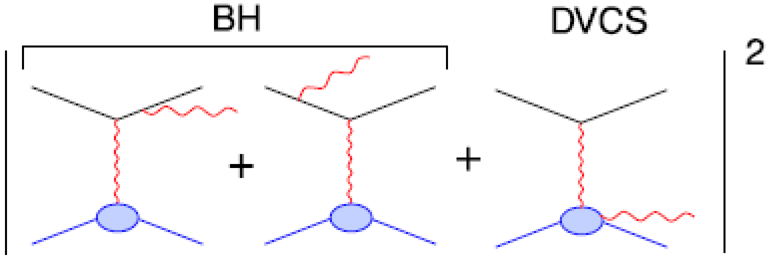



NLO,Twist-2
double helicity flip
suppressed by $\alpha_S$

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$




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

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

Well known

**With both $\mu^{\overleftarrow{+}}$ and $\mu^{\overrightarrow{-}}$ beams we can build:**

**❶ beam charge-spin sum**

$$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

**❷ difference**

$$\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$$

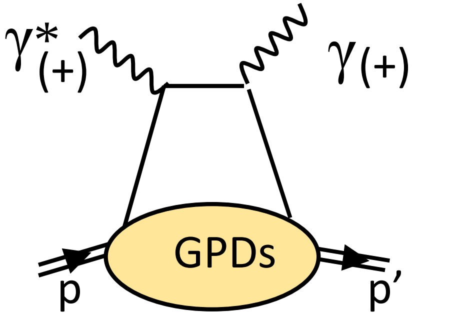
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

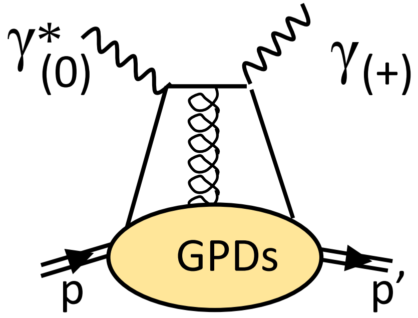
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

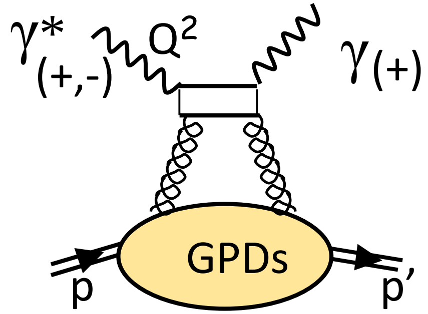
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$




LO,Twist-2

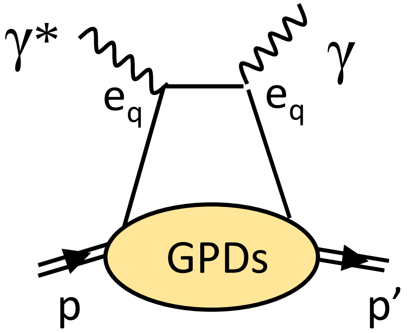



HT,Twist-3
suppressed by 1/Q




NLO,Twist-2
double helicity flip
suppressed by $\alpha_s$

# Deeply virtual Compton scattering (DVCS)




**With unpolarized target,**
**playing with beam charge and polarisation,**
**we can reach:**

$s_1^I \propto Im\, \mathcal{A}$

$c_1^I \propto Re\, \mathcal{A}$

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

$x_B \sim 2\xi/(1+\xi)$

t small; $t/Q^2 < 0.2$

| | proton | neutron |
|---|---|---|
| F1 (t=0)= | 1 | 0 |
| F2 (t=0)= | +1.79 | -1.91 |

**with a proton target** $\mathcal{A} \rightarrow F_1\mathcal{H}$ at small t and $x_B$ for proton

**with a "neutron" target** $F_2\mathcal{E}$ is maximized ★★

$\mathcal{F}$ for $\mathcal{H}$ or $\tilde{\mathcal{H}}$ or $\mathcal{E}$ $\mathcal{F}^q$ for quark flavor in the proton $\mathcal{F}^u = \mathcal{F}_p^u = \mathcal{F}_n^d$

$$\mathcal{F}_{proton} = 4/9\ \mathcal{F}^u + 1/9\ \mathcal{F}^d + 1/9\ \mathcal{F}^s$$
$$\mathcal{F}_{neutron} = 4/9\ \mathcal{F}^d + 1/9\ \mathcal{F}^u + 1/9\ \mathcal{F}^s$$

$e_u^2$ $e_d^2$ $e_s^2$

**u-d flavor separation of GPD contributions (s <<)**

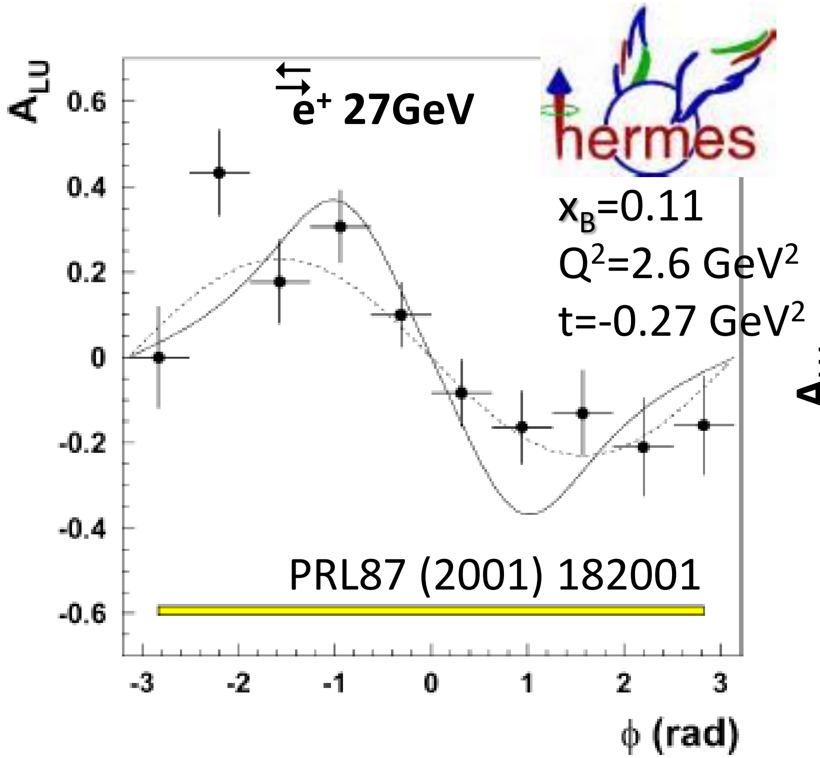
$$\mathcal{F}^u = 9/15\,[\,4\,\mathcal{F}_{proton} - \mathcal{F}_{neutron}\,]$$
$$\mathcal{F}^d = 9/15\,[\,4\,\mathcal{F}_{neutron} - \mathcal{F}_{proton}\,]$$

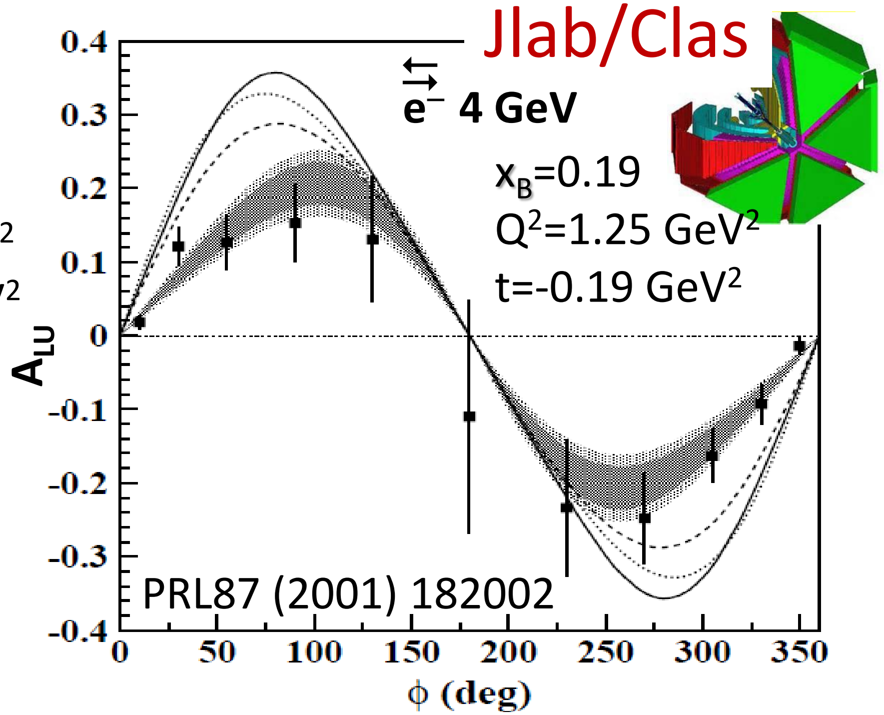
★★

# 2001: First DVCS Beam Spin Asymmetries at Hermes and Jlab

$$\frac{d\sigma^{\leftarrow} - d\sigma^{\rightarrow}}{d\sigma^{\leftarrow} + d\sigma^{\rightarrow}} \propto 2[d\sigma^{DVCS}_{pol} + \mathrm{Im}\, I] \xrightarrow{L.T.} s_1^I \sin\phi$$

$s_1^I = Im\,\mathcal{A}$



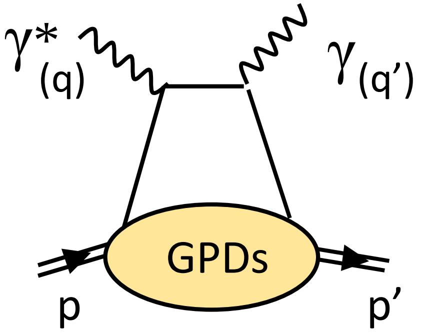

Validate the dominance of the handag contribution

Fit and **VGG** model: Vanderhaeghen, Guichon, Guidal,...

PRL80(1998), PRD60(1999), PPNP47(2001), PRD72(2005)

# Precise t measurement (related to $b_\perp$) $|t| << Q^2$

$t = (p-p')^2 = (q-q')^2 < 0$ $|t|_{min} \sim m_p^2 x_B^2 / (1-x_B)$ if $x_B/Q << 1$




## Fixed target mode slow recoil proton

with forward outgoing photon ($\theta_{\gamma^*\gamma}$ in the Lab)

$$t = (q-q')^2 = -Q^2 - 2E_\gamma(\nu - q\cos\theta_{\gamma^*\gamma}) = \frac{-Q^2 - 2\nu(\nu - q\cos\theta_{\gamma^*\gamma})}{1 + 1/m_p(\nu - q\cos\theta_{\gamma^*\gamma})}$$

with recoiling proton

$$t = (p-p')^2 = 2m_p(m_p - E_p)$$

Better resolution at small t
But $|t|_{min\ exp}$ to escape target cell to be detected

if both detection use of kinematical fit

| | | |
|---|---|---|
| $\|t\|=0.064$ GeV$^2$ | $P_p$=255 MeV/c | $E_p$=0.972 GeV |
| $\|t\|=0.6$ GeV$^2$ | $P_p$=838 MeV/c | $E_p$=1.257 GeV |

## Collider mode e-p forward fast proton

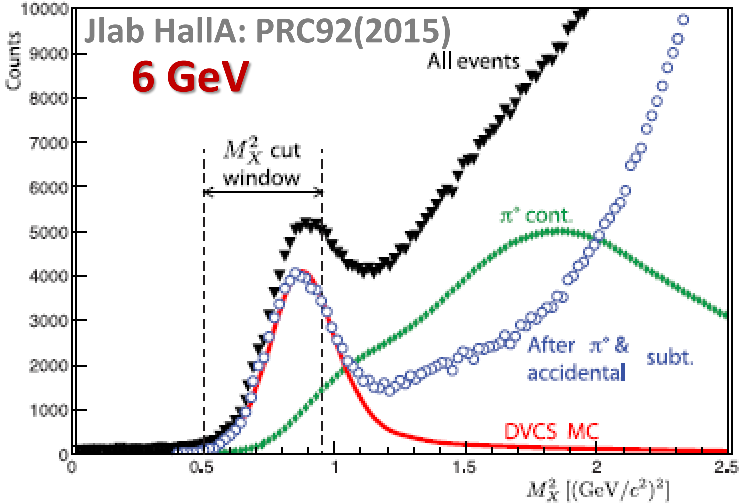
$t = (p-p')^2$ need detection of the fast proton at forward angle very close to the beam with dedicated detectors as ''Roman Pot''

Ex: Jlab $x_B = 0.1, 0.2, 0.36$ $|t|_{min} \sim 0.01, 0.044, 0.16$ GeV$^2$ $|t|_{min\ exp} \sim 0.064$ GeV$^2$
COMPASS $x_B = 0.01$ $|t|_{min} \sim 10^{-4}$ GeV$^2$

EIC $x_B = 0.0001$ $|t|_{min} \sim 10^{-8}$ GeV$^2$ need a dedicated detector in the forward direction

# Selection of the exclusive process $\ell\, p \rightarrow \ell + \gamma + p_{slow}$

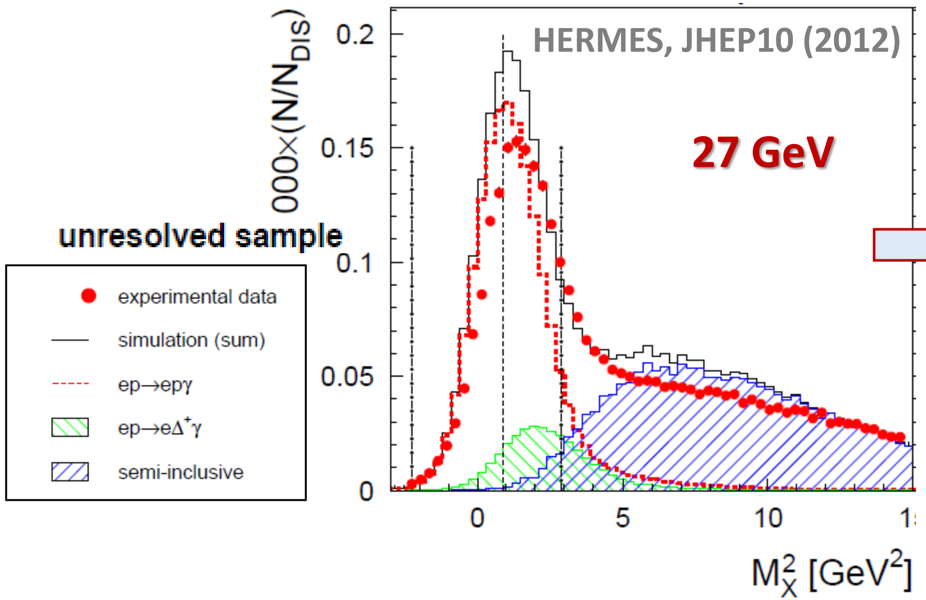
**If the slow recoiling proton is not detected, building of Missing Mass** $M_x^2 = (P_\ell + P_p - P_{\ell'} - P_\gamma)^2$




$\ell p \rightarrow \ell' + \gamma\ (+p')$ for DVCS + BH

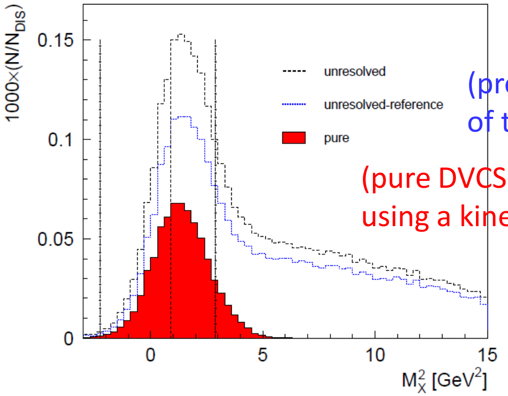
Contamination from $\pi^0$ decay:

- $\ell p \rightarrow \ell' + \gamma\ (+\gamma + p')$ exclusive $\pi^0$
- $\ell p \rightarrow \ell' + \gamma\ (+\gamma + p' + \ldots)$ SIDIS $\pi^0$
- $\ell p \rightarrow \ell' + \gamma\ (+\Delta^+)$ associated DVCS + BH




Ee ↗ $M_x^2$ resolution ↗

necessity to detect all the particles



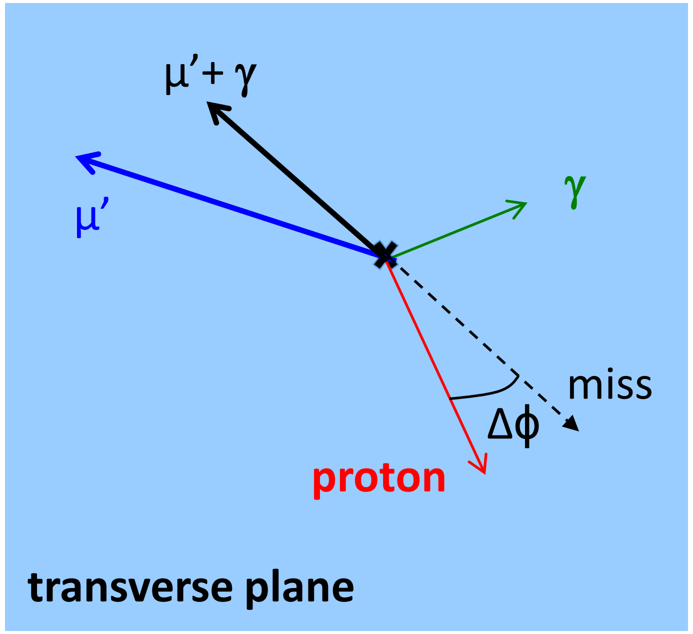

(proton in the acceptance of the recoil detector ➔ |t| > 0.064 GeV²) Drawback

(pure DVCS+BH using a kinematic fit) Advantage

# Selection of the exclusive process $\ell\, p \to \ell + \gamma + p_{slow}$

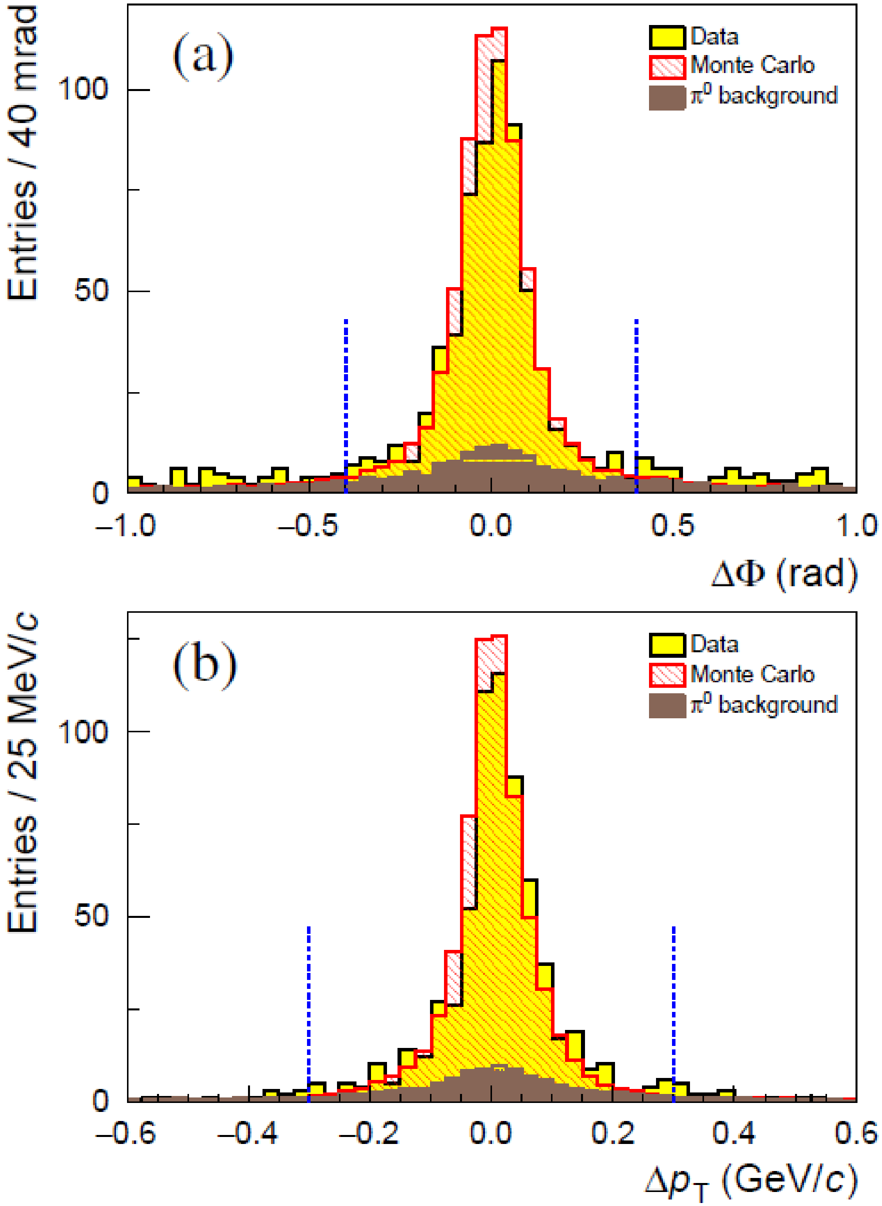
Take benefit of the overconstrained kinematics

Pmiss = Pμ - Pμ’ - Pγ compared to
the direct measurement of proton momentum




$\Delta\Phi = \Phi^{spectr} - \Phi^{RPD}$

$\Delta p_T = p_T^{spectr} - p_T^{RPD}$



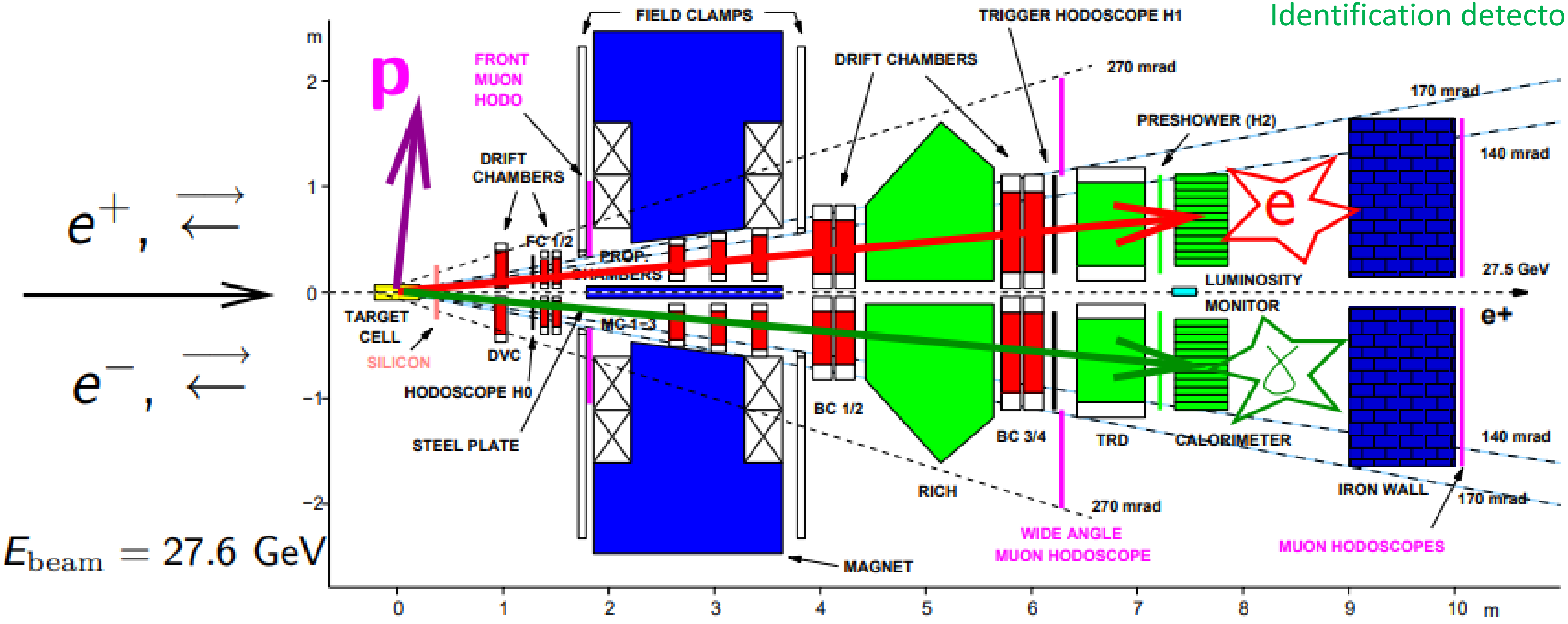
# Experimental Setup at Hermes

$e^{\pm}N \rightarrow e^{\pm}N\gamma$

$N \in \{p,d\}$

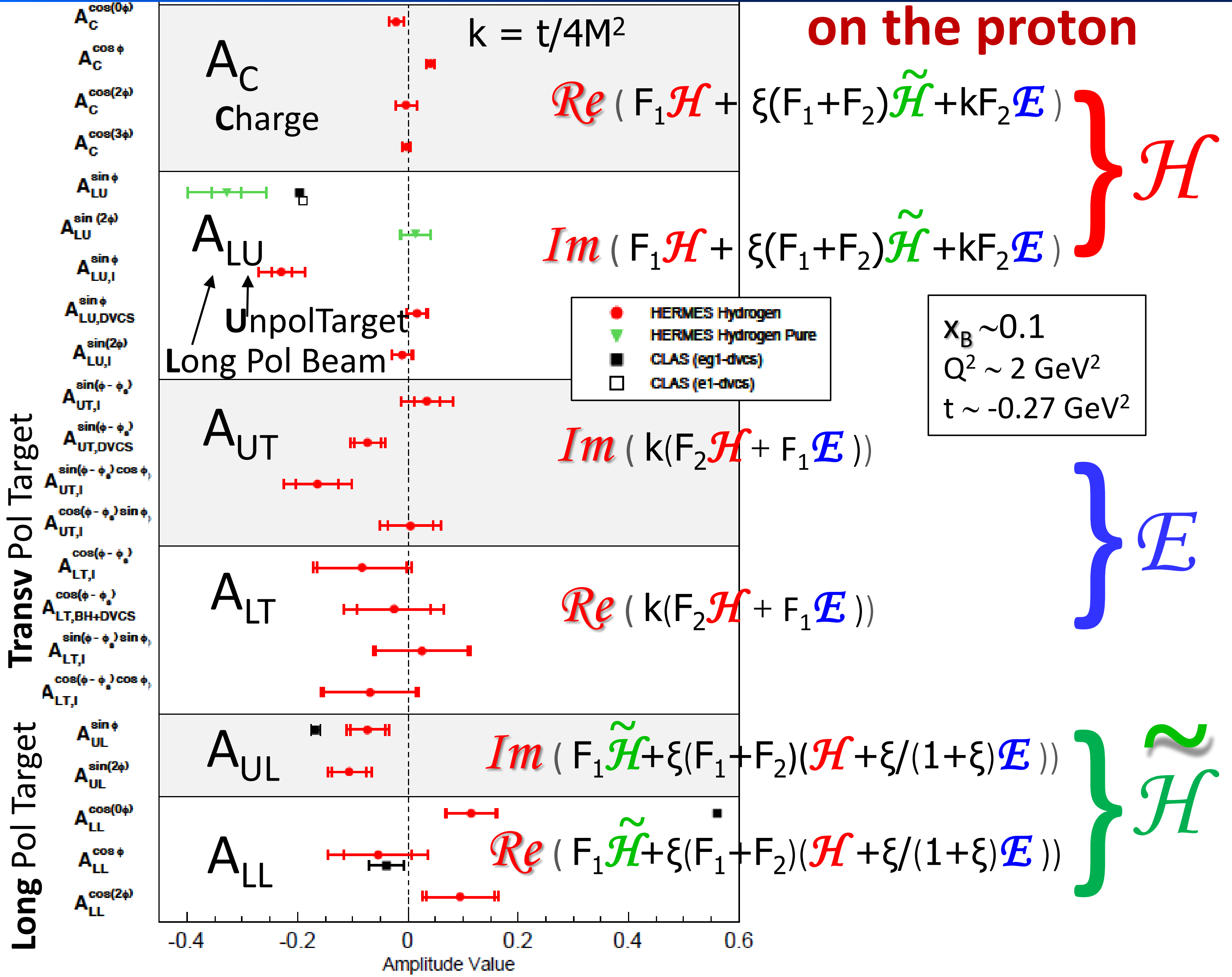
**Internal gas target**
Hydrogen: unpolarised, long and transversely polarised
Deuterium: unpolarised

Tracking detectors
Identification detectors




$E_{\mathrm{beam}} = 27.6\ \mathrm{GeV}$

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



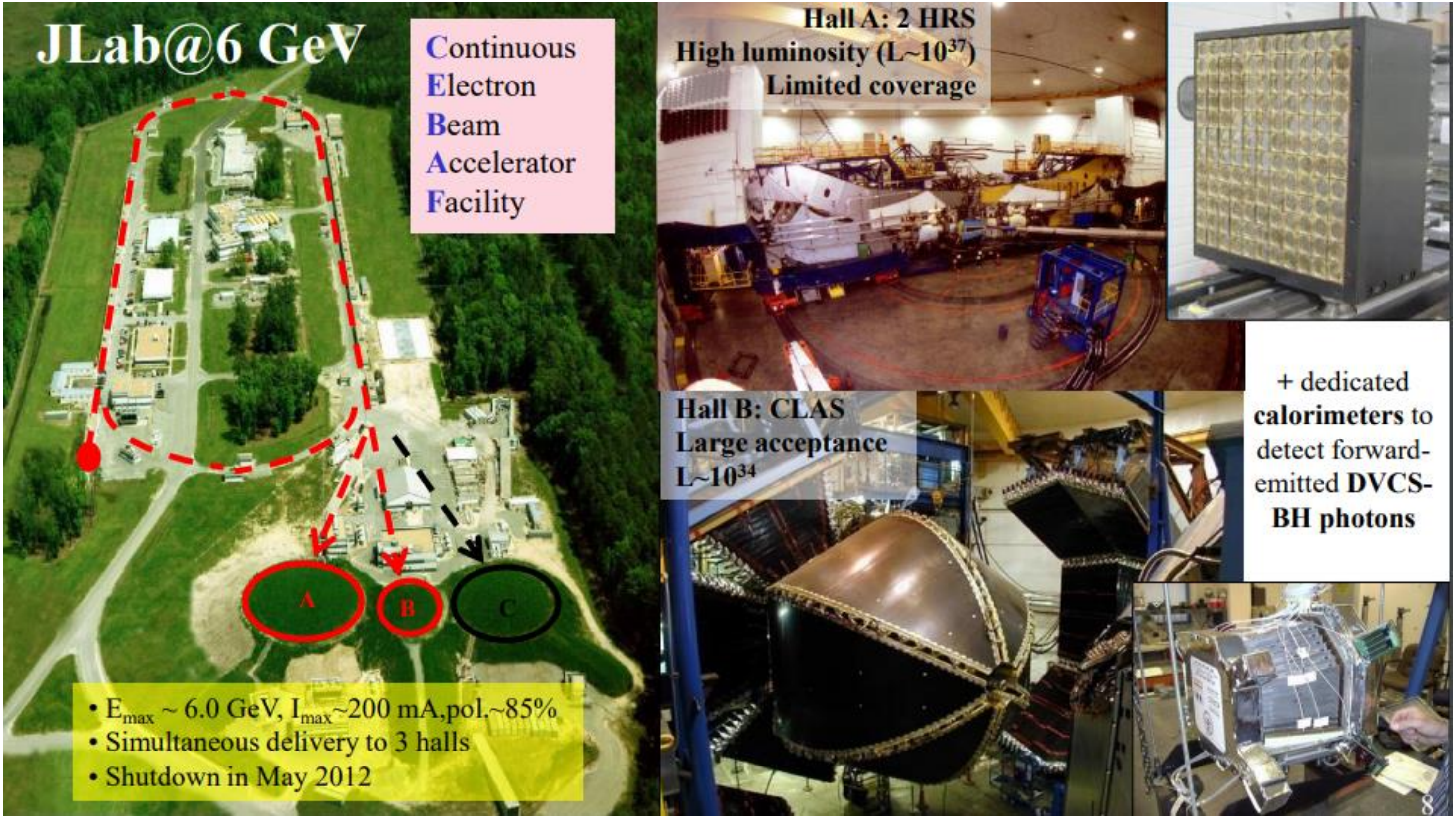

HERMES 27 GeV provided a complete set of observables

- 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: DVCS off **the neutron** allows:

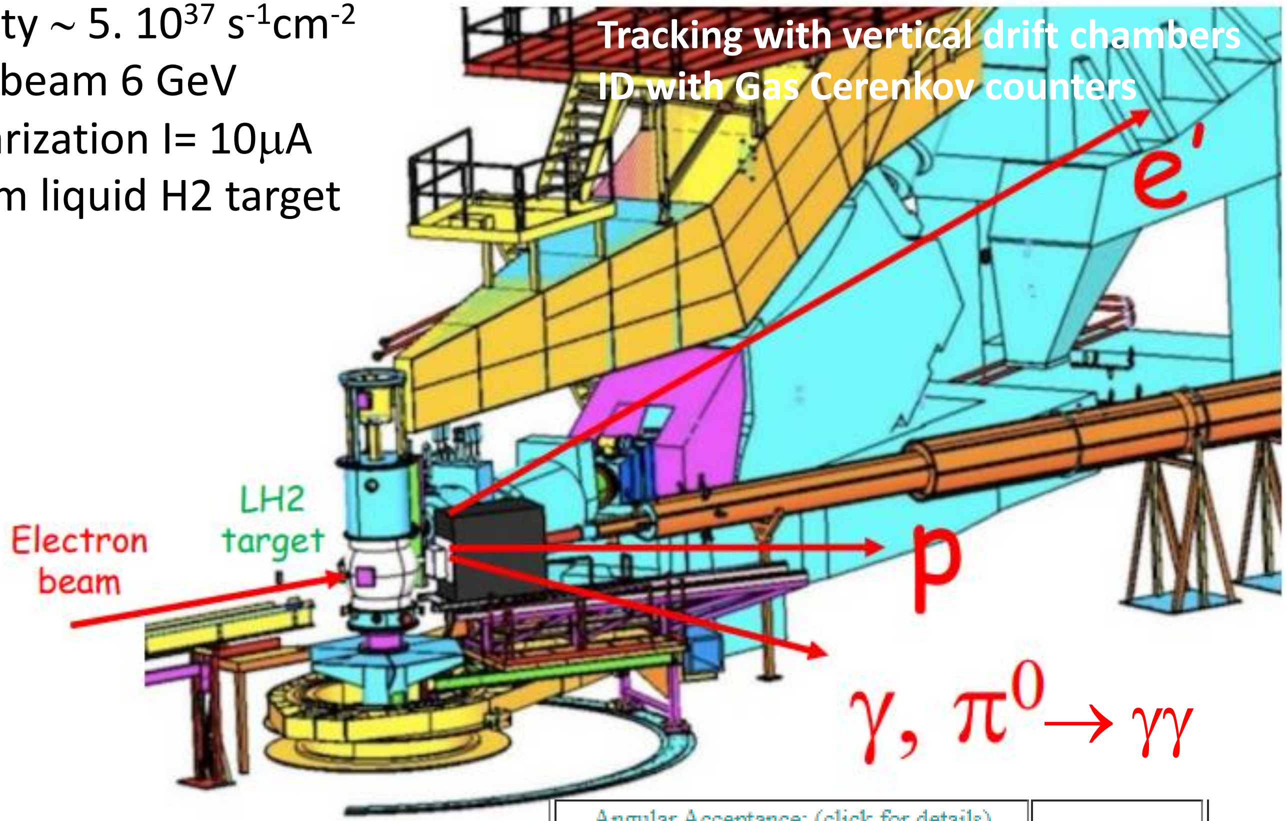
- ✓ access to $\mathcal{E}$
- ✓ flavor decomposition

# Experimental Setup at JLab

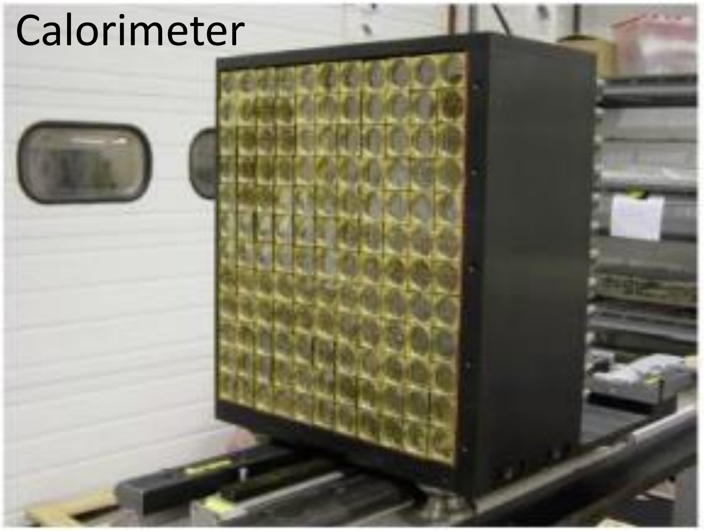


# Experimental Setup at Jlab -HallA

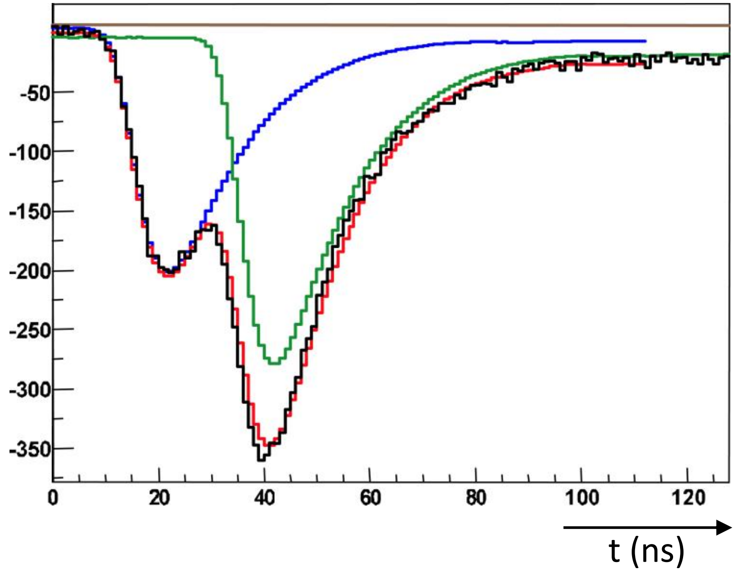
Luminosity ~ 5. $10^{37}$ $s^{-1}cm^{-2}$
electron beam 6 GeV
76% polarization I= 10μA
on a 15cm liquid H2 target




11 x 12 array of 3 x 3 x 18.6 cm3 PbF2 crystals




Calorimeter signal with a 1GHz sampler




| | |
|---|---|
| Momentum Range | 0.3 - 4.0 GeV/c |
| Configuration | QQDQ |
| Bend Angle | 45° |
| Optical Length | 23.4 m |
| Momentum Acceptance | +/- 4.5% |
| Momentum Resolution (FWHM) | 1 x $10^{-4}$ |

| | |
|---|---|
| Angular Acceptance: (click for details)<br>Horizontal<br>Vertical | <br>+/- 28 mr<br>+/- 60 mr |
| Solid Angle:<br>(rectangular approximation)<br>(elliptical approximation) | <br>6.7 msr<br>5.3 msr |
| Angular Resolution: (FWHM)<br>Horizontal<br>Vertical | <br>0.6 mr<br>2.0 mr |

# 2004-2016: Beam Spin Sum and Diff of DVCS - HallA

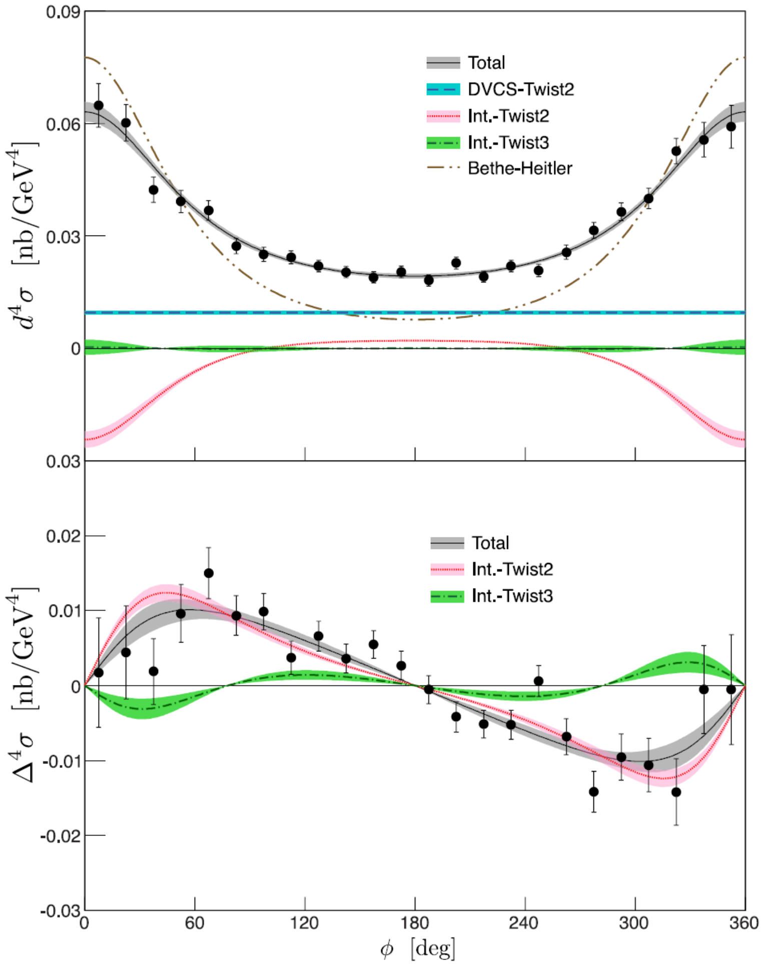
E00-110 **pioneer experiment in 2004** with magnetic spectrometer

$x_B$=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$^2$

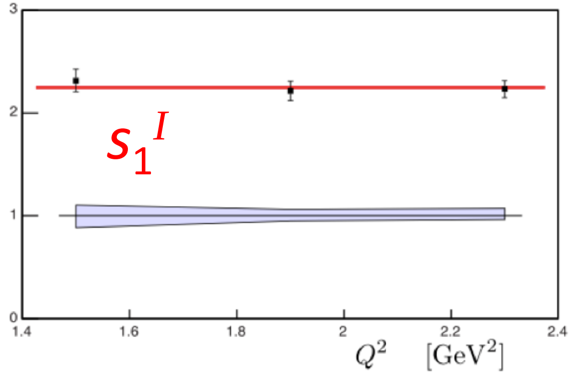



## Unpolarized cross section

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

## 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 of DVCS - HallA

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

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

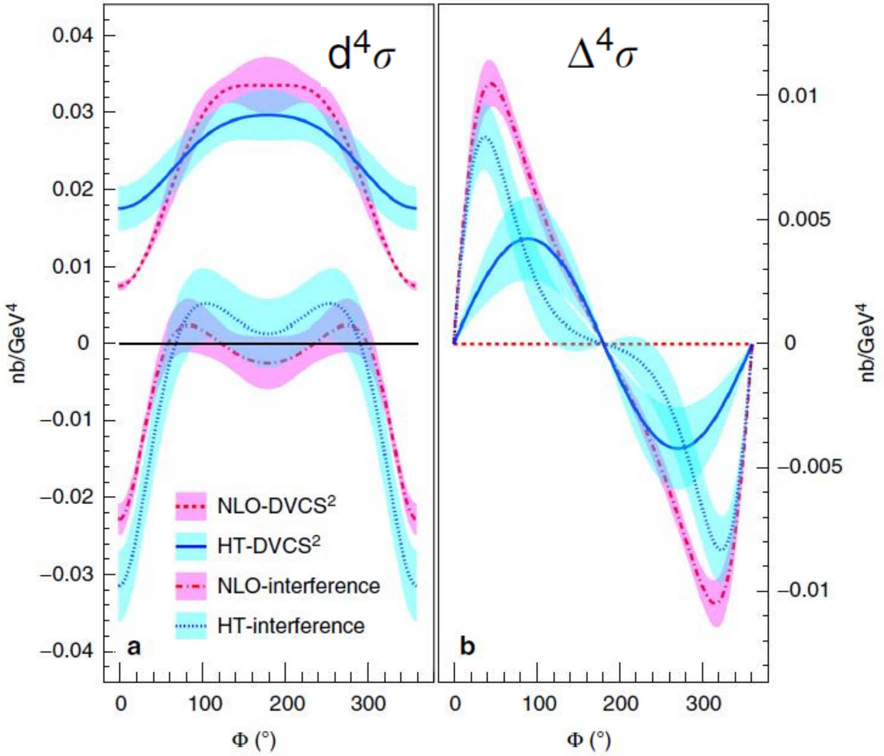
nature COMMUNICATIONS

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

Ebeam=5.55 GeV (fit also uses data at 4.455 GeV)

**Beam energy dependence study at fixed $x_B$ and $Q^2$**

- Separate DVCS from Int terms, $C_0^{DVCS}$ from $C_0^I$
- Separate HT and NLO from LT coefficients




## Unpolarized cross section

$$d^4\sigma = d\sigma^{\leftarrow} + d\sigma^{\rightarrow} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Re}\, I$$

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

$$+ c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

## Helicity Dependent cross section

$$\Delta^4\sigma = d\sigma^{\leftarrow} - d\sigma^{\rightarrow} \propto d\sigma^{DVCS}_{pol} + \mathrm{Im}\, I$$

$$\longrightarrow s_1^{DVCS}\sin\phi + s_1^I\sin\phi + s_2^I\sin 2\phi$$

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

# 2010-2017: Beam Spin Sum and Diff of DVCS - HallA

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

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

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**Beam energy dependence study at fixed $x_B$ and $Q^2$**

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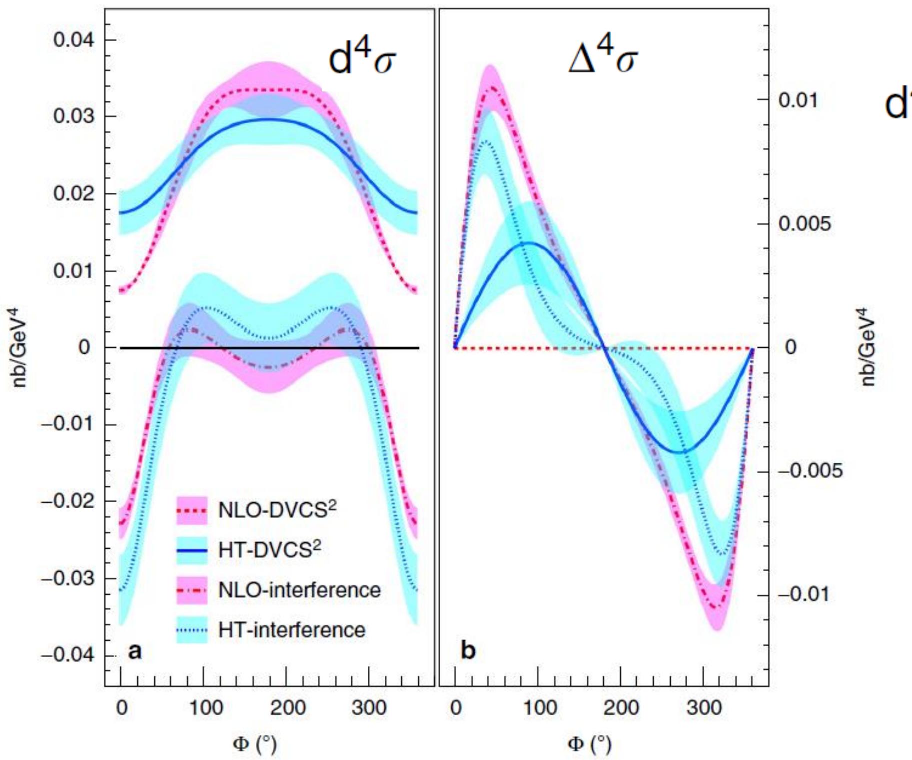
- Separate HT and NLO from LT coefficients




**Unpolarized cross section**

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

**Helicity Dependent cross section**

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

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

# today: Beam Spin Sum and Diff of DVCS - HallA @12GeV

E12-06-114 Hall-A experiment
in 2014-2016 with magnetic spectrometer

Georges et al., PRL128 (2022) 252002

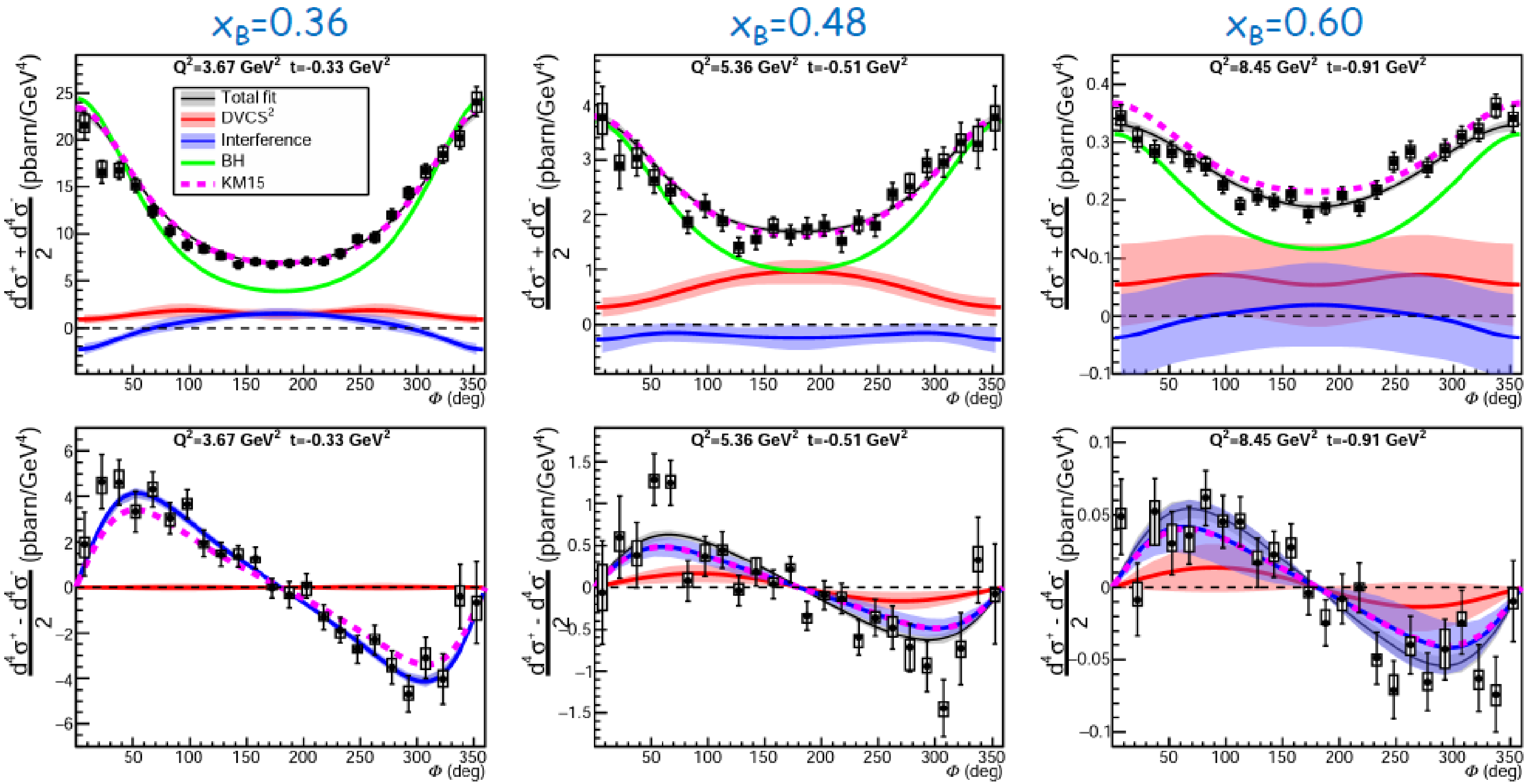
| Setting | Kin-36-1 | Kin-36-2 | Kin-36-3 | Kin-48-1 | Kin-48-2 | Kin-48-3 | Kin-48-4 | Kin-60-1 | Kin-60-3 |
|---|---|---|---|---|---|---|---|---|---|
| $x_B$ | | 0.36 | | | 0.48 | | | 0.60 | |
| $E_b$ (GeV) | 7.38 | 8.52 | 10.59 | 4.49 | 8.85 | 8.85 | 10.99 | 8.52 | 10.59 |
| $Q^2$ (GeV$^2$) | 3.20 | 3.60 | 4.47 | 2.70 | 4.37 | 5.33 | 6.90 | 5.54 | 8.40 |
| $E_\gamma$ (GeV) | 4.7 | 5.2 | 6.5 | 2.8 | 4.7 | 5.7 | 7.5 | 4.6 | 7.1 |
| $-t_{min}$ (GeV$^2$) | 0.16 | 0.17 | 0.17 | 0.32 | 0.34 | 0.35 | 0.36 | 0.66 | 0.70 |

Measurements for
**3 high $x_B$=0.36, 0.48, 0.60**
at 2 or 3 or 4 high $Q^2$ (or $E_{beam}$)
in 3 or 5 bins in t
in 24 bins in φ.

Fit for constant (xB, t) using different beam energies (and $Q^2$) to separate DVCS$^2$, Interf. and BH

Formalism: Braun-Manashov-Müller-Pirnay, PRD 89, 074022 (2014)

**Prediction:**
KM15: global fit of the world data
K. Kumericki and D. Mueller,
*EPJ Web Conf.* 112 (2016) 01012



# today: Beam Spin Sum and Diff of DVCS - HallA @12GeV

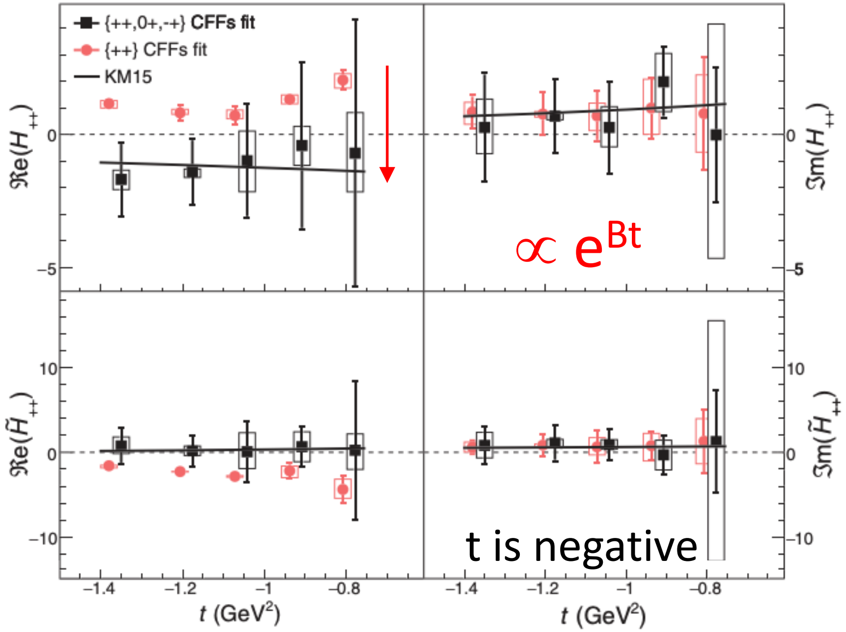
Fit for constant **($x_B$, t)** using different beam energies (but also different $Q^2$) of

- 24 CFF $(H, \tilde{H}, E, \tilde{E}) \otimes (\Re e, \Im m) \otimes (++, 0+, -+)$
- or only 8 CFF $(H, \tilde{H}, E, \tilde{E},) \otimes (\Re e, \Im m) \otimes (++)$

➔Importance of considering all CFFs when extracting helicity-conserving CFFs

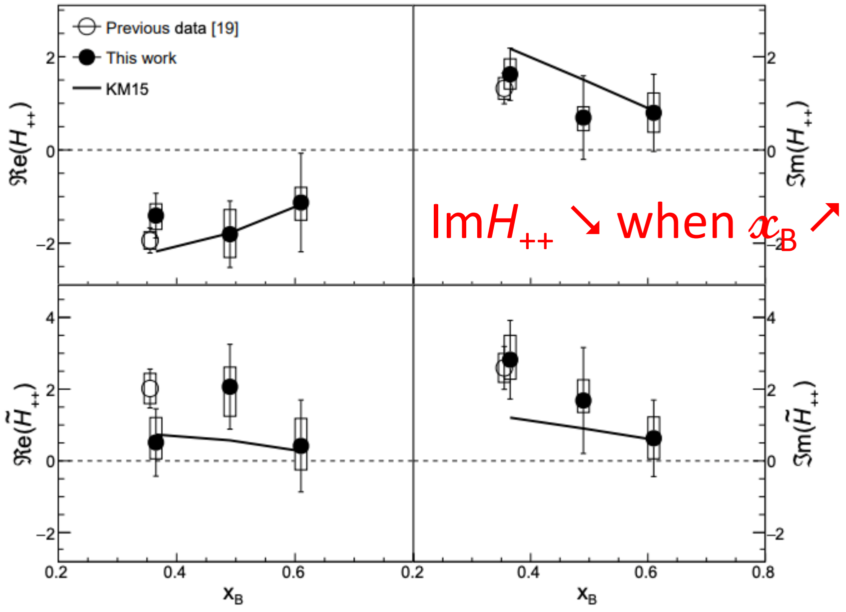
Results for the better known CFFs $H_{++}$ and $\tilde{H}_{++}$

**$x_B$=0.6**

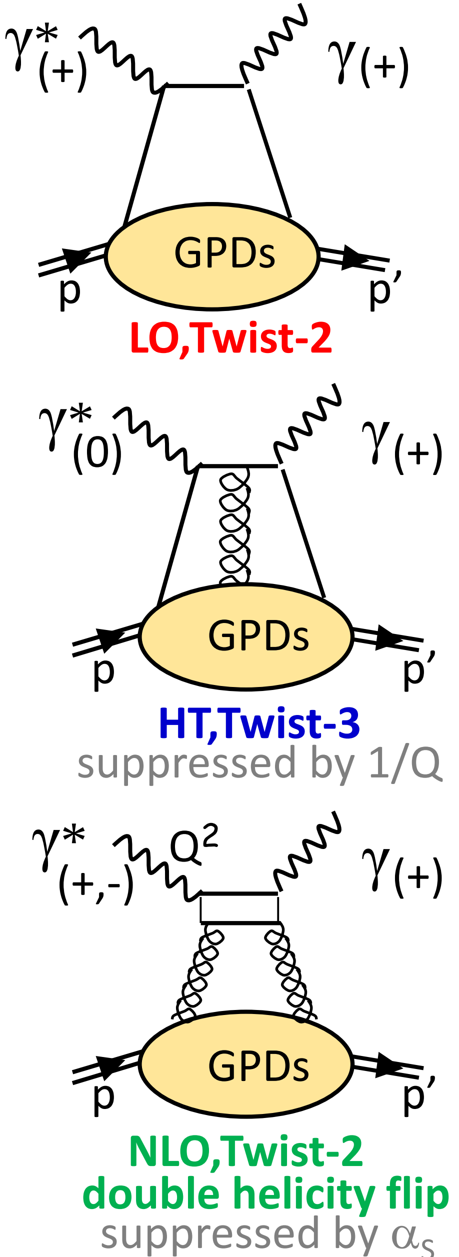



Georges et al., PRL128 (2022) 252002

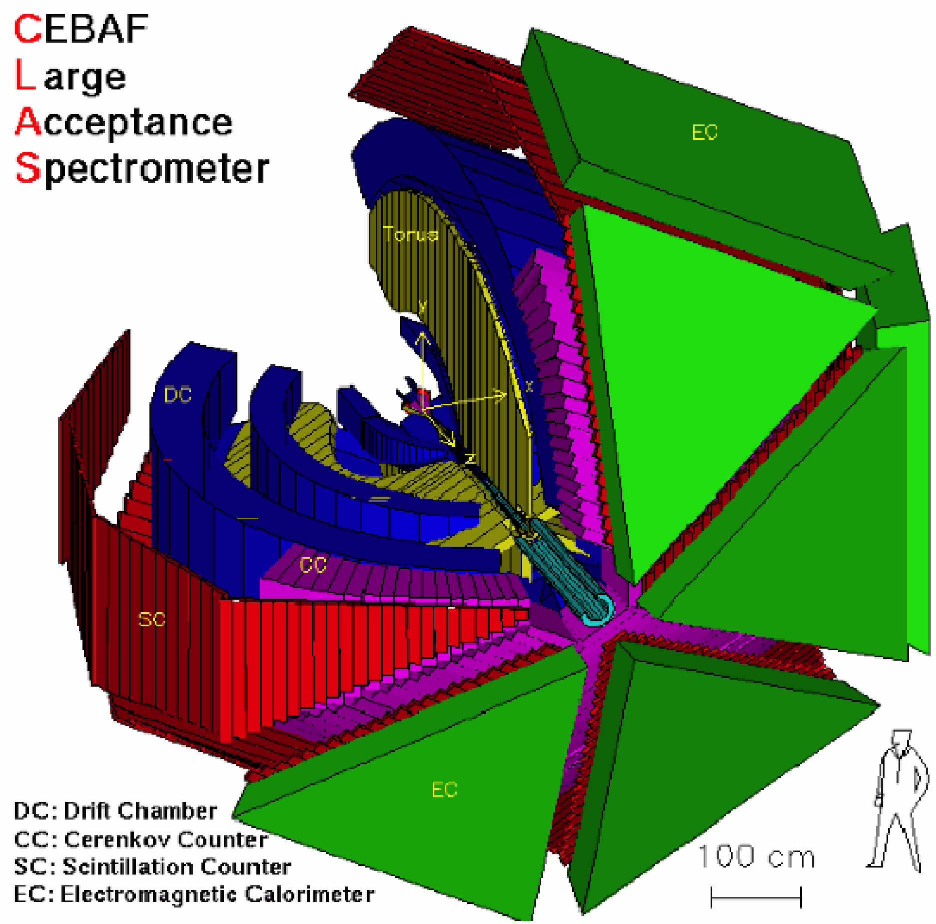
$H_{++}$ and $\tilde{H}_{++}$ averaged over t

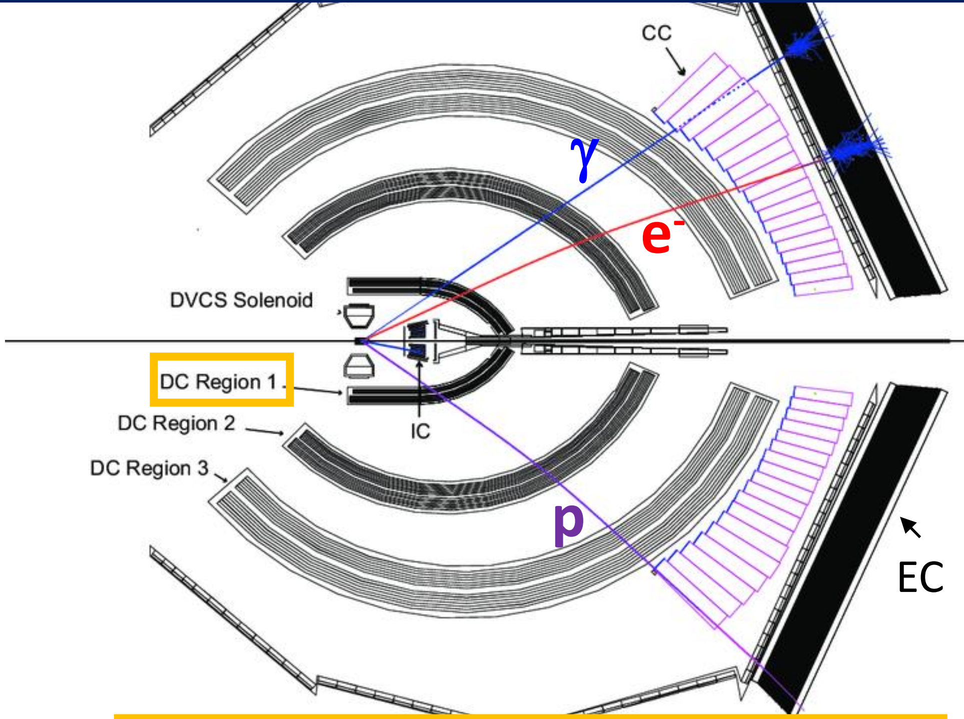


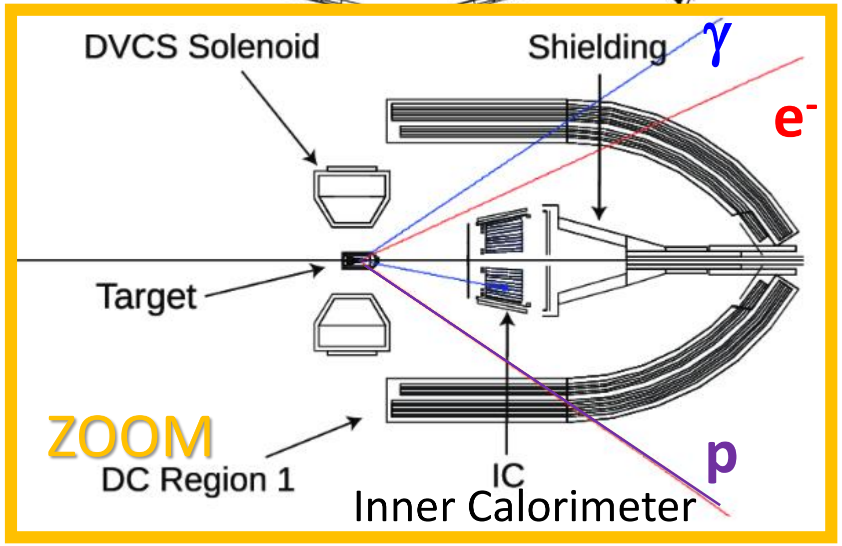

<t>= −0.345, −0.702, −1.050 GeV² at $x_B$= 0.36, 0.48, 0.60



# Experimental Setup at Jlab - CLAS

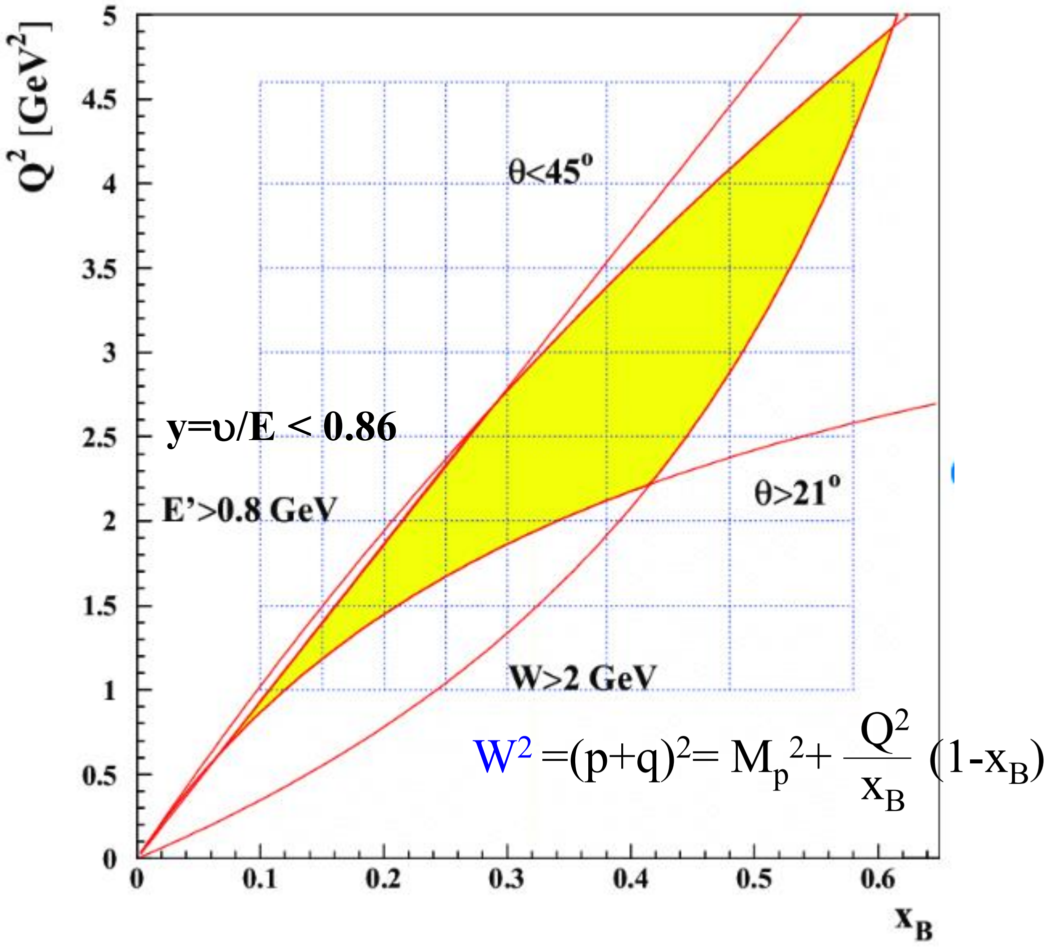


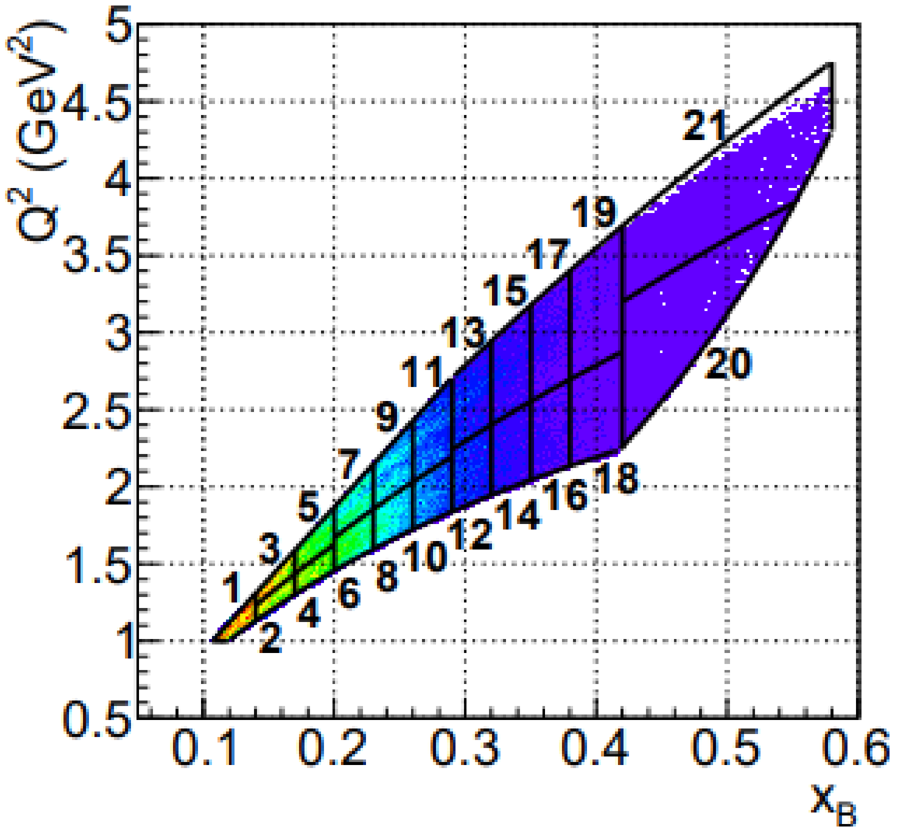
# Experimental Setup at Jlab - CLAS

$Q^2 = 2M_p \upsilon x_B = 2M_p y E x_B = 4 E E' \sin^2 \theta/2$




(Color online) The kinematic coverage and binning as a function of Q 2 and x B. The accepted region (yellow online) is determined by the following cuts: W > 2 GeV, E > 0.8 GeV, 21 • < θ < 45 •. W is the γ * p center-of-mass energy, E is the scattered electron energy, and θ is the electron's polar angle in the laboratory frame. The dotted grid represents the kinematic regions for which the cross sections are calculated and presented.

## At $E_{beam}$ = 6 GeV




21 bins in ($x_B$, $Q^2$) or 110 bins ($x_B$, $Q^2$ t)

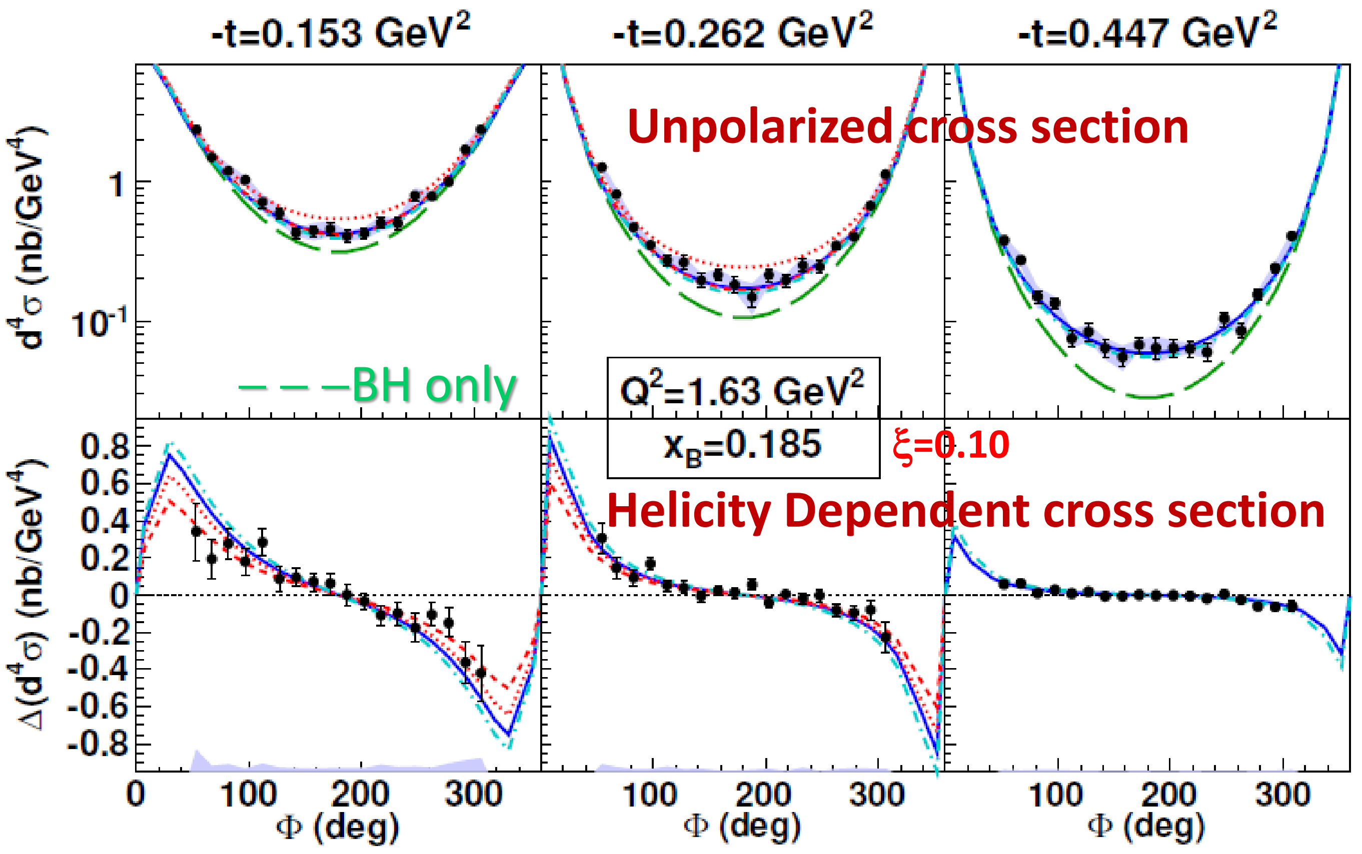
3 months data taken in 2005

# 2005-2015: Beam Spin Sum and Diff of 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) 162002, Jo et al. PRL115, 212003 (2015)

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




**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**

# → nucleon tomography in the valence domain

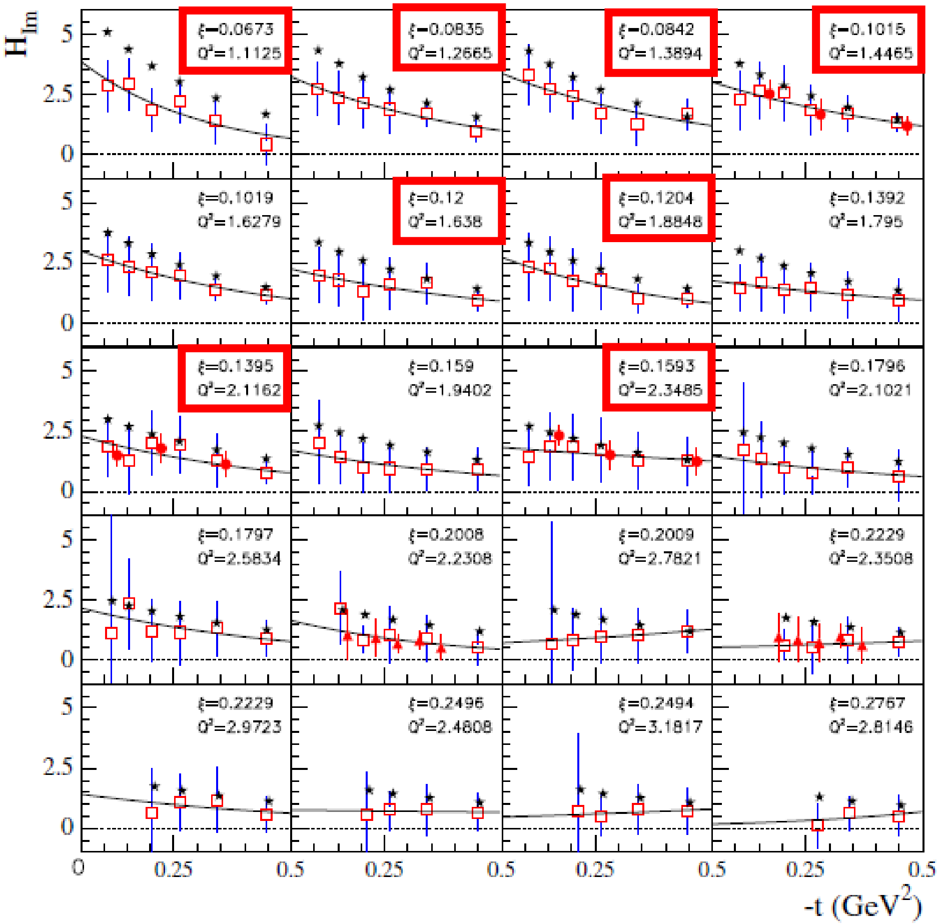
Fit of 8 CFFs at L.O and L.T. Dupré, Guidal, Nicolai, Vanderhaeghen, PRD95, 011501(R)(2017) Eur.Phys.J. A53 (2017)

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

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

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

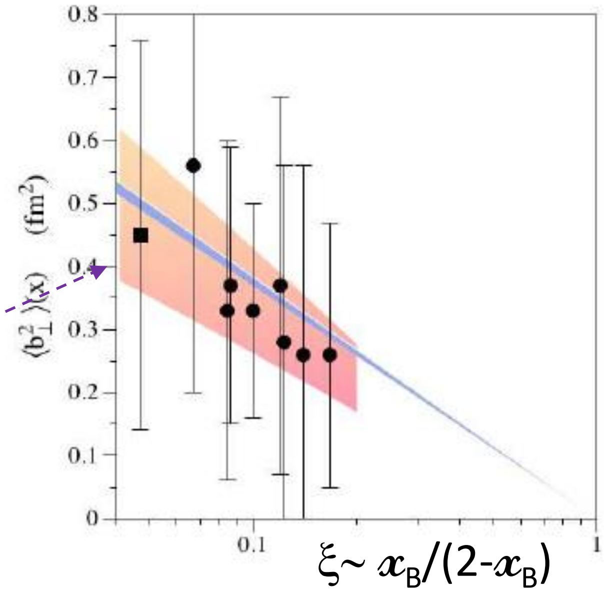
$< b_\perp{}^2 > \;\approx\; 4\,B$

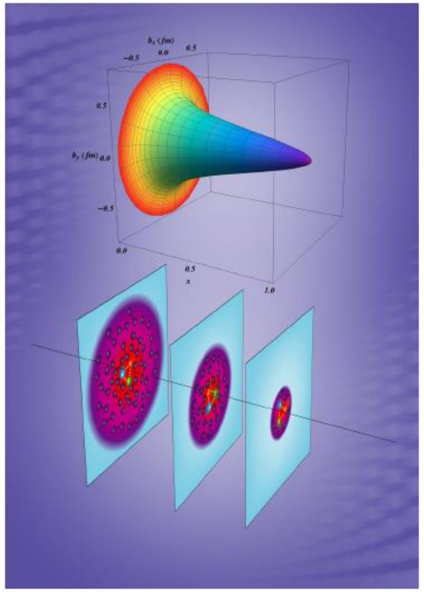



— Fit $A\, e^{-B|t|}$

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

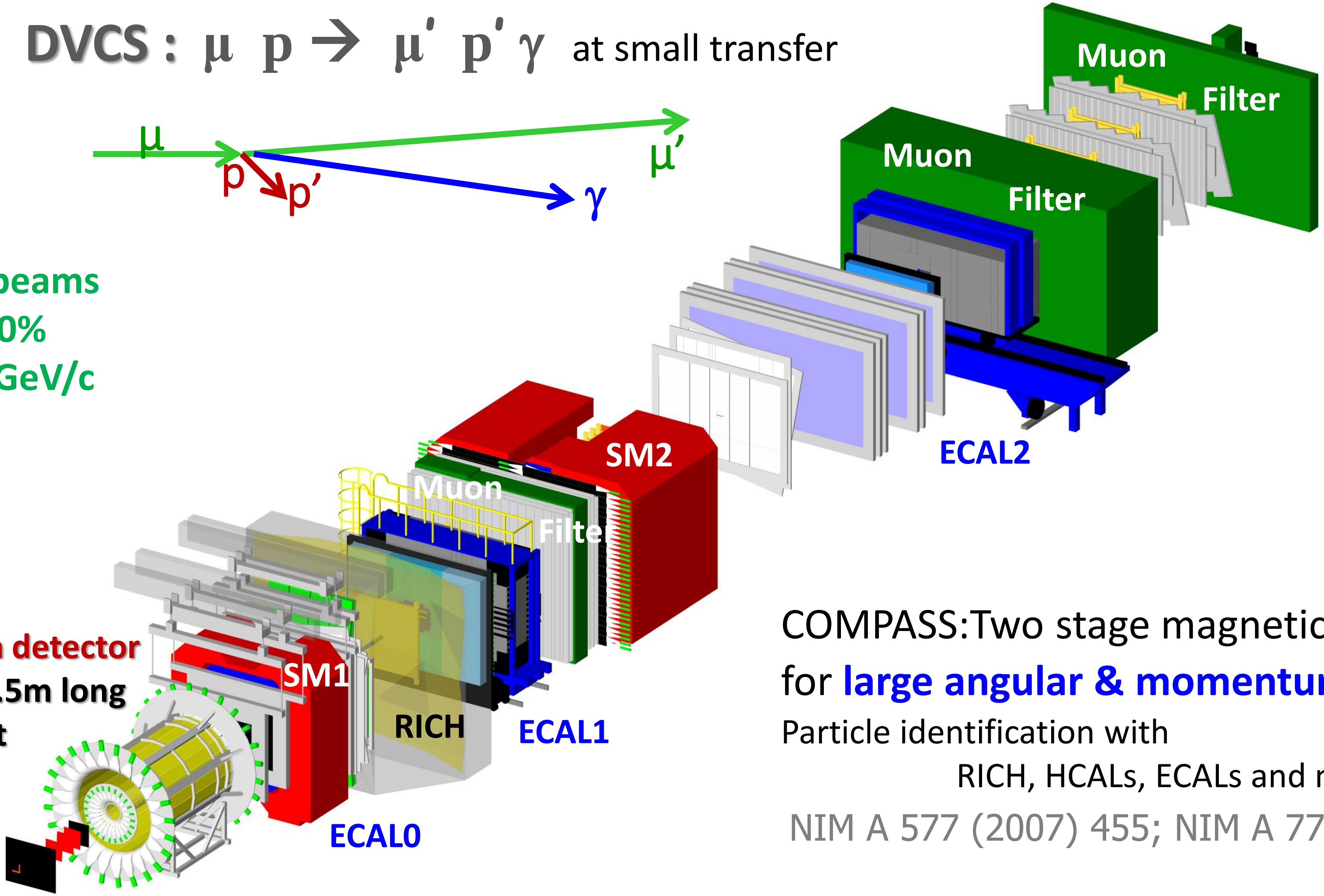
HERMES + 8 data from JLab



# DVCS at higher beam energy 160 GeV

**DVCS :** $\mu\ p \rightarrow \mu'\ p'\ \gamma$ at small transfer



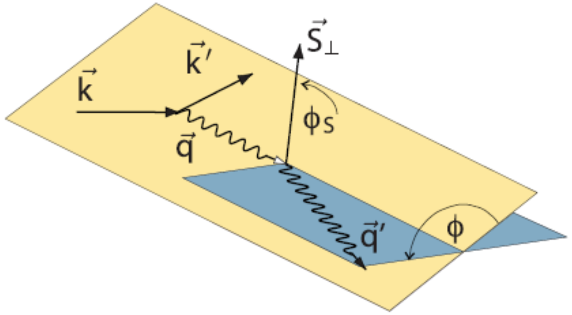

**Both $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams**
**Polarisation ~ ±80%**
**Momentum 160 GeV/c**

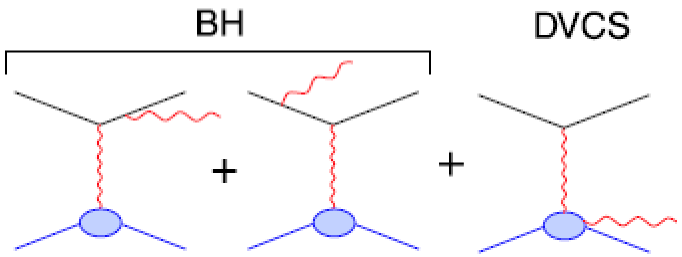
**CAMERA recoil proton detector**
**surrounding the 2.5m long**
**LH2 target**

COMPASS:Two stage magnetic spectrometer
for **large angular & momentum acceptance**
Particle identification with
RICH, HCALs, ECALs and muon filters

NIM A 577 (2007) 455; NIM A 779 (2015) 69

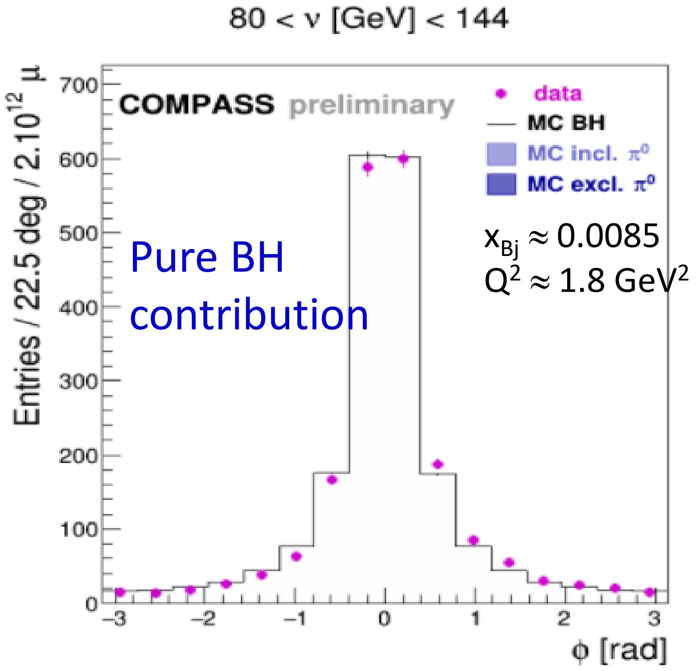
# DVCS at higher beam energy 160 GeV

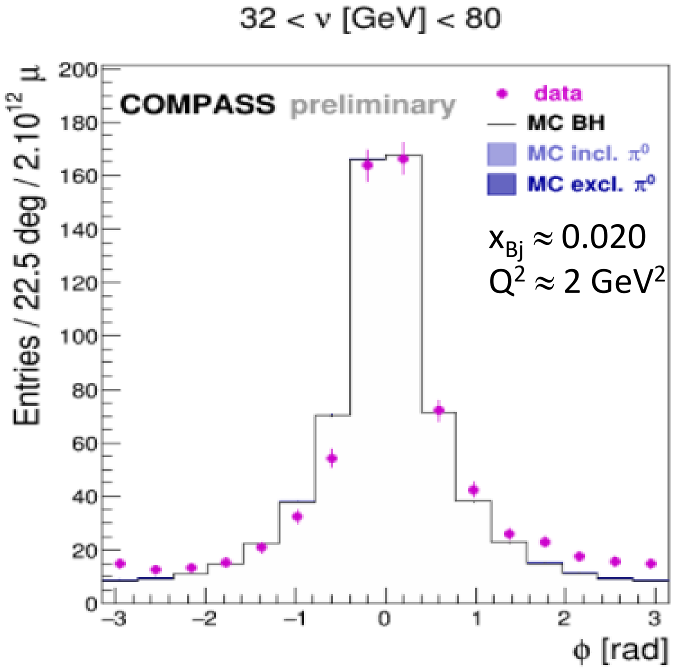


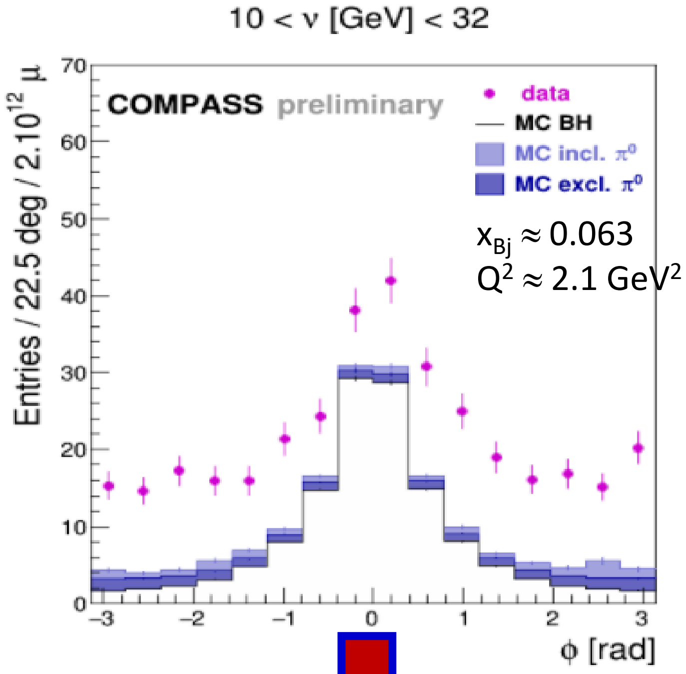




$\Sigma = d\sigma(\overleftarrow{\mu^{+}}) + d\sigma(\overrightarrow{\mu^{-}})$

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




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

**DVCS** above the **BH** contrib.

# 2012-2022: DVCS Beam Charge & Spin Sum - COMPASS

At COMPASS using polarized positive and negative muon beams:

10 < υ < 32 GeV

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

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

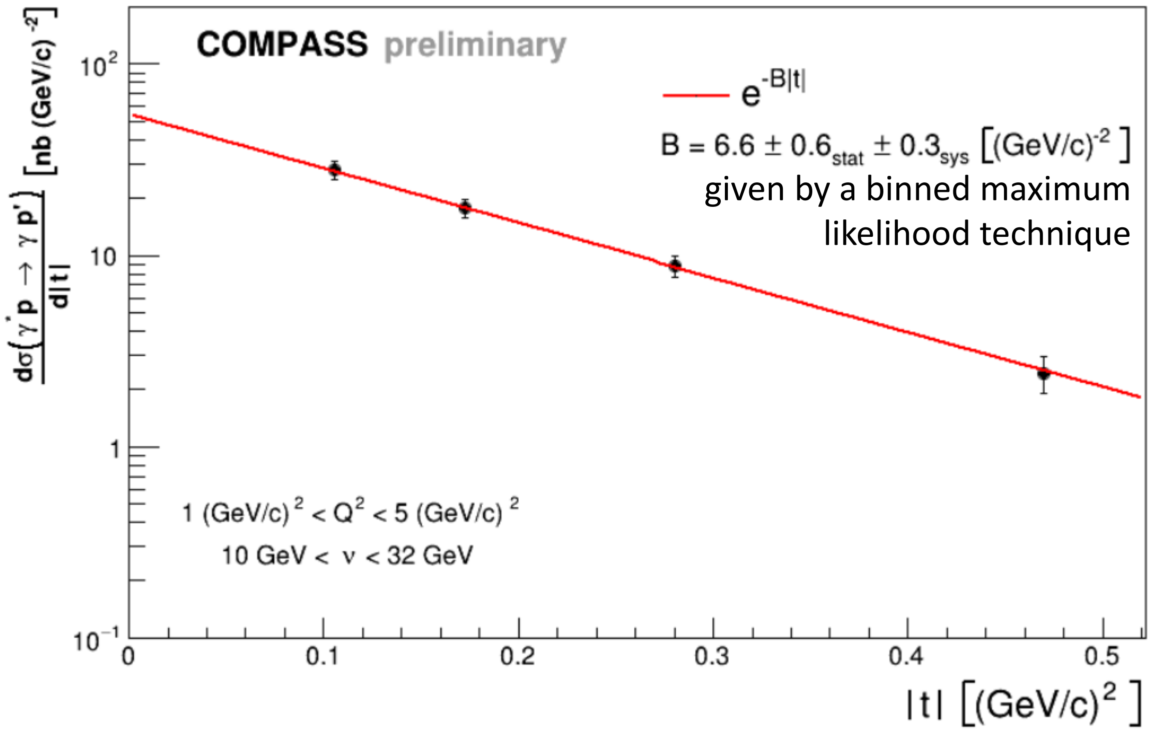
calculable
can be subtracted

All the other terms are cancelled in the integration over $\phi$

$$\frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt} = \int_{-\pi}^{\pi} d\phi\,(d\sigma - d\sigma^{BH}) \propto c_0^{DVCS}$$

$$\frac{d\sigma^{\gamma^* p}}{dt} = \frac{1}{\Gamma(Q^2,\nu,E_\mu)} \frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt}$$

Flux for transverse virtual photons



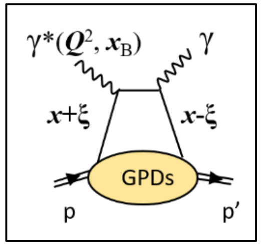
# → nucleon tomography in the sea quark domain at COMPASS

$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$$

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

In the COMPASS kinematics, $x_B \approx 0.06$, dominance of $Im\mathcal{H}$
97% (GK model) 94% (KM model)

$Im\mathcal{H}$ = $H$ (x=ξ, ξ, t)
x = ξ ≈ $x_B$ /2 close to 0

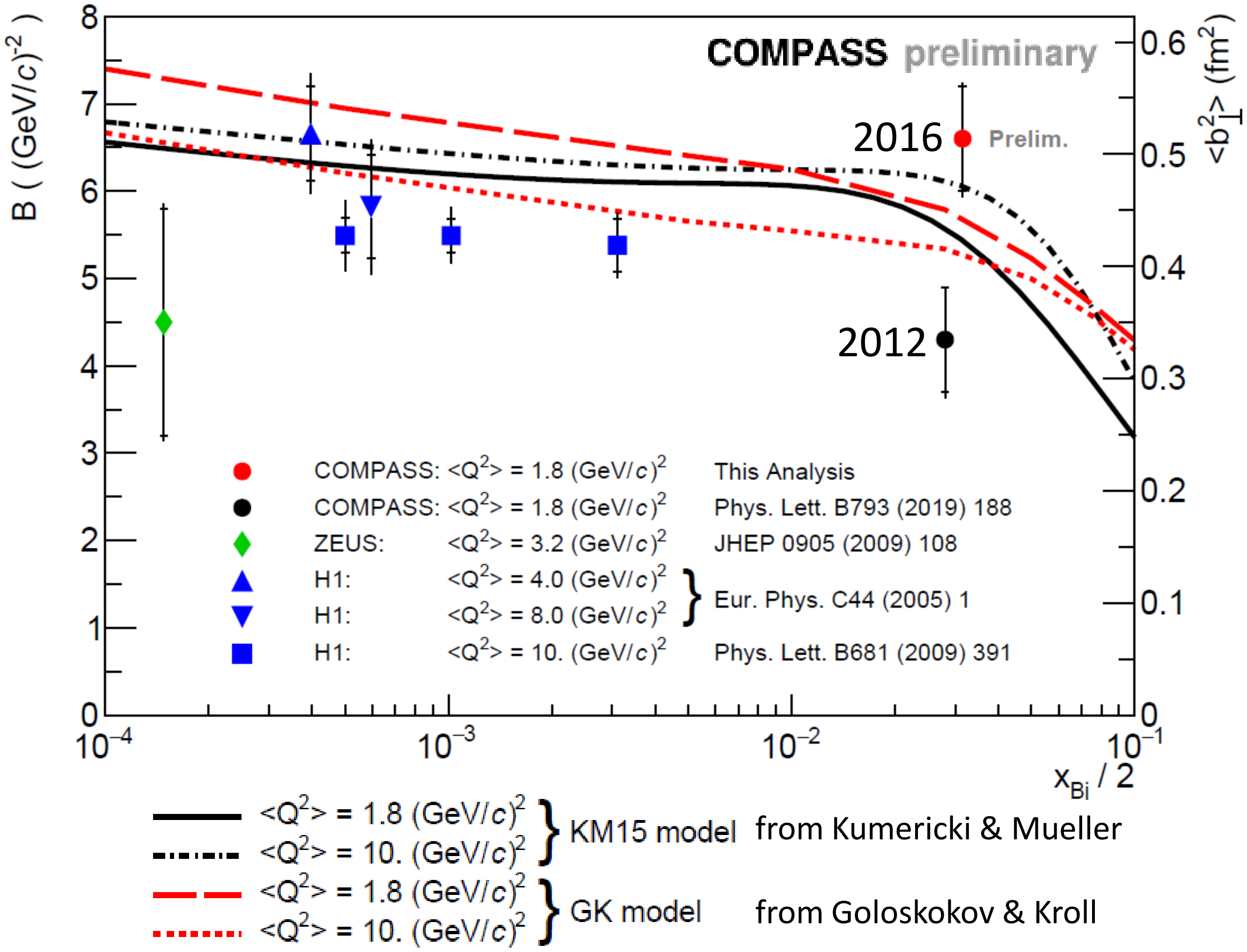



$$q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H^q_-(x, 0, -\mathbf{\Delta}_\perp{}^2).$$

$$\langle b_\perp^2 \rangle_x^f = \frac{\int d^2b_\perp b_\perp^2 q_f(x, b_\perp)}{\int d^2b_\perp q_f(x, b_\perp)} = 4\frac{\partial}{\partial t} \log H^f(x, \xi = 0, t)\Big|_{t=0}$$

$$\langle b_\perp^2(x) \rangle \approx 2B(\xi)$$

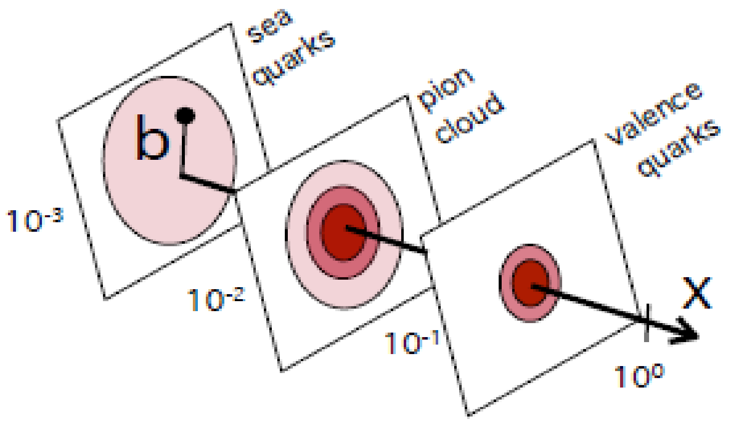
**direct extraction of physical observable**



# ➔ nucleon tomography in the sea quark domain at COMPASS

$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$

$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$



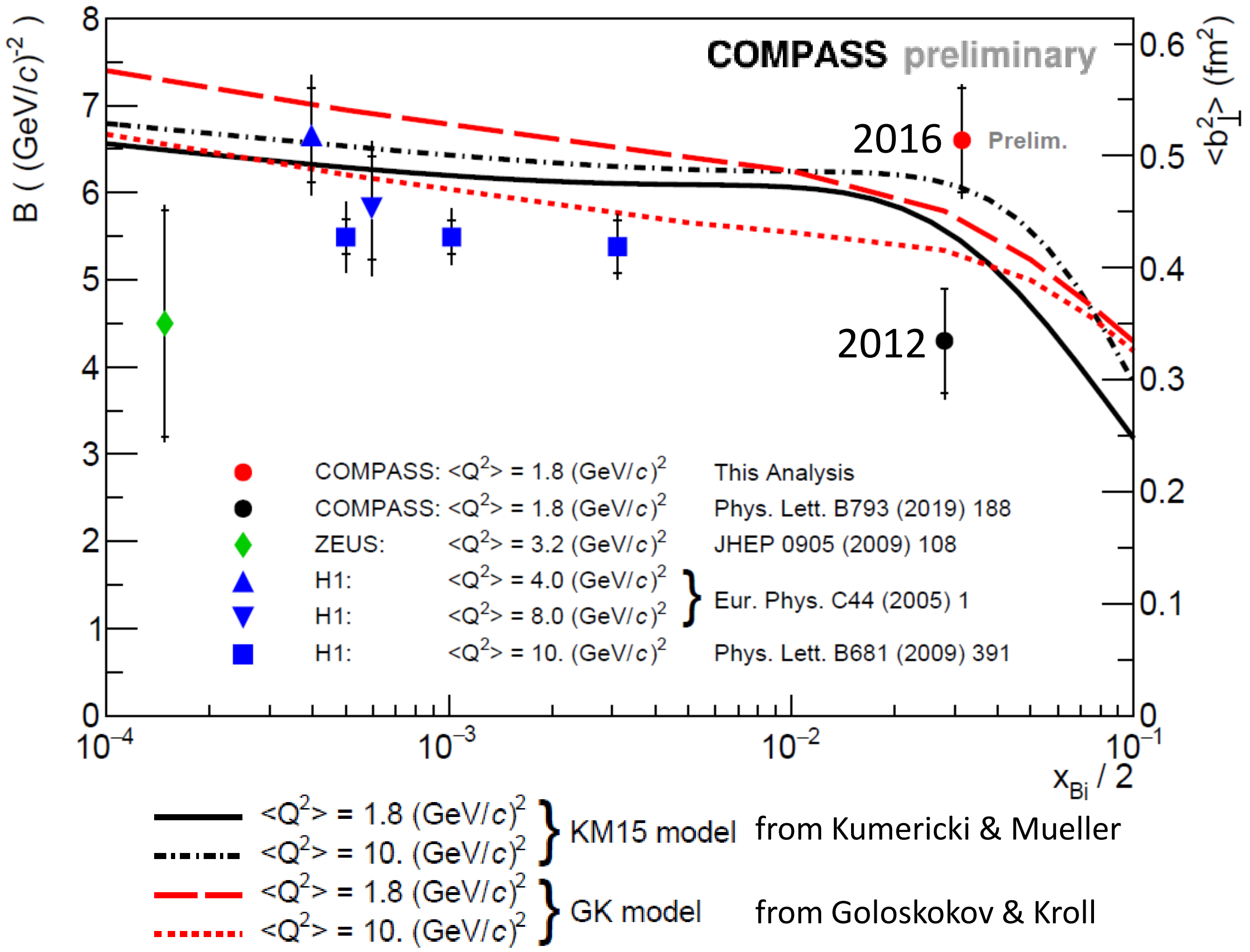

3σ difference between 2012 and 2016 data

- more advanced analysis with 2016 data
- $\pi^0$ contamination with different thresholds
- binning with 3 variables $(t,Q^2,\nu)$ or 4 variables $(t,\phi,Q^2,\nu)$

2012 statistics = Ref

2016 analysed statistics = 2.3 × Ref

2016+2017 expected statistics = 10 × Ref

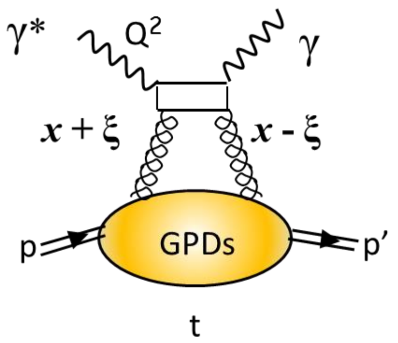


# ➔ nucleon tomography in the gluon domain at HERA

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

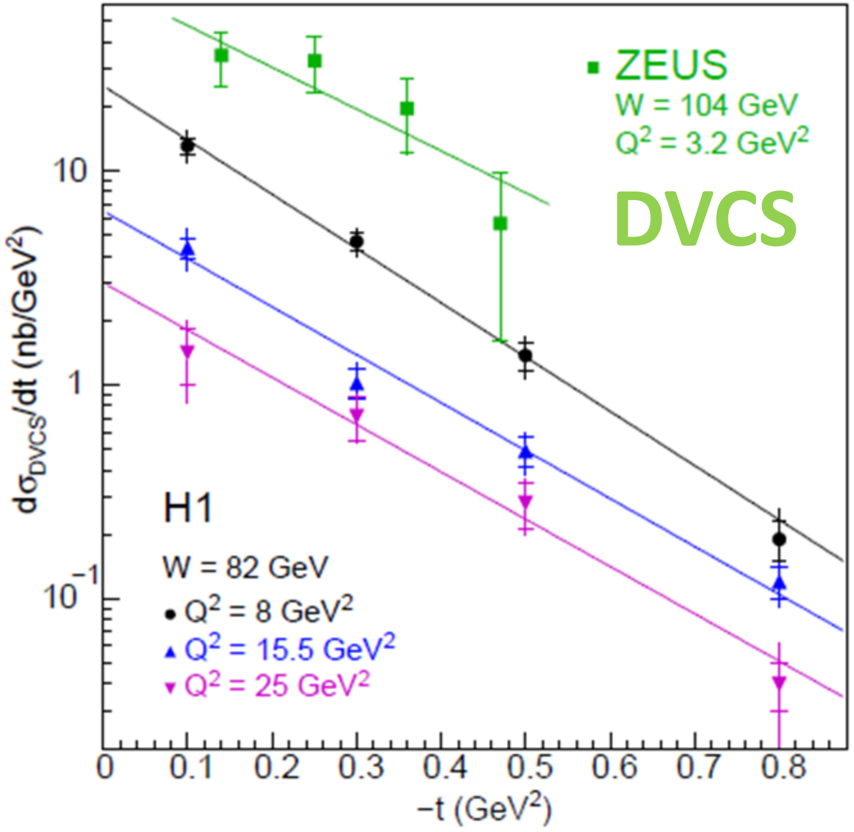
B is related to the transversed size of the scattering object

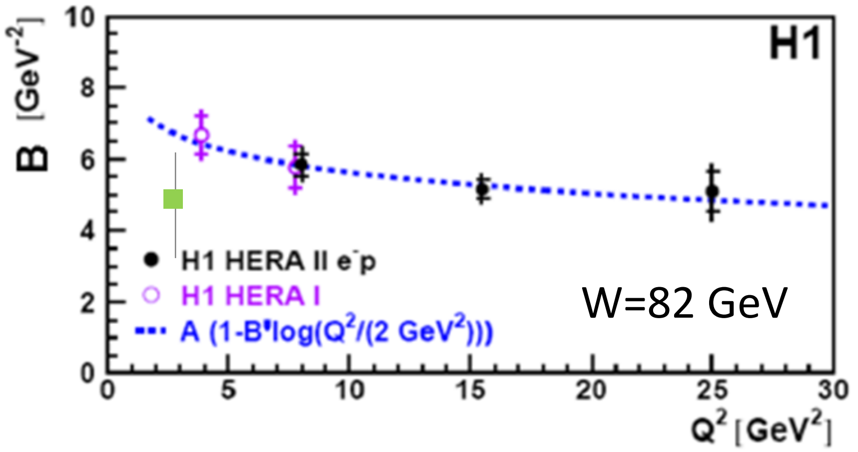
Dominance of $Im\mathcal{H}$

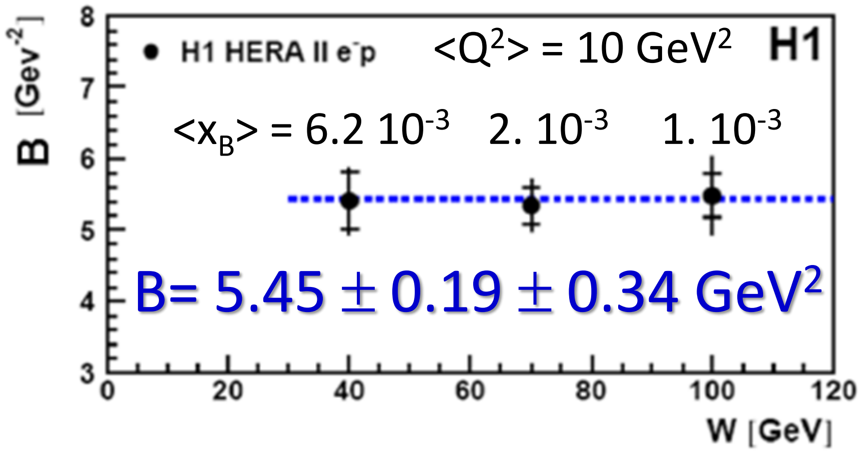



ZEUS-H1
Data collected
1995-2007

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



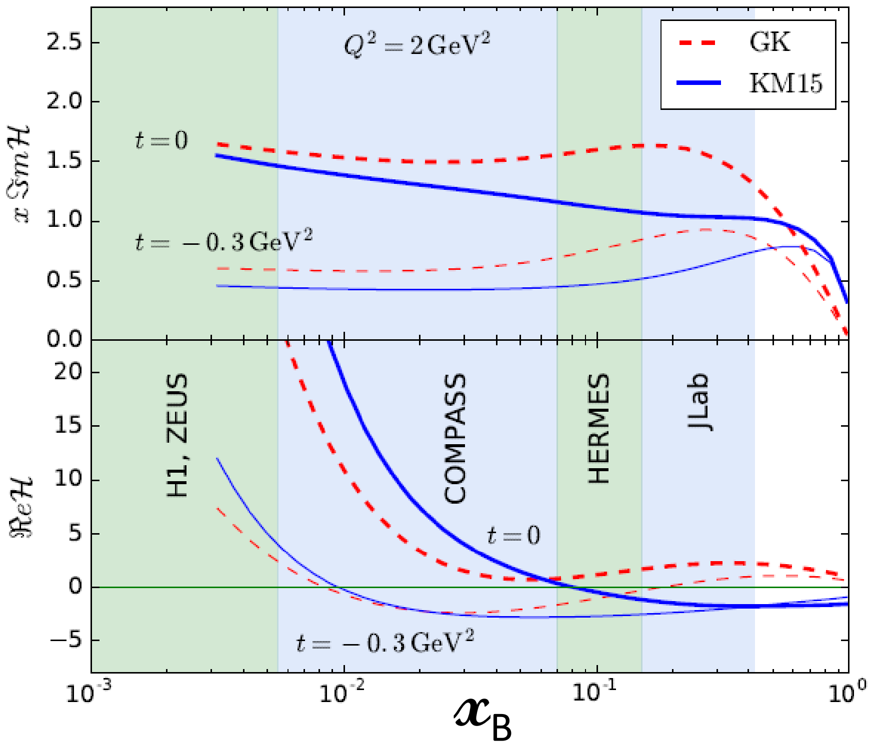

$$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$$

$\sqrt{< b_\perp^2 >}$ = 0.65 ± 0.02 fm to be compared to $\sqrt{4\frac{d}{dt}F_1^p}\overset{t=0}{=}$ 0.67 ± 0.01 fm

# ImH and ReH using global fits of the world data

**Global Fit KM15**
Compared to GK Model GK

Kumericki, Mueller, NPB (2010) 841, private com.

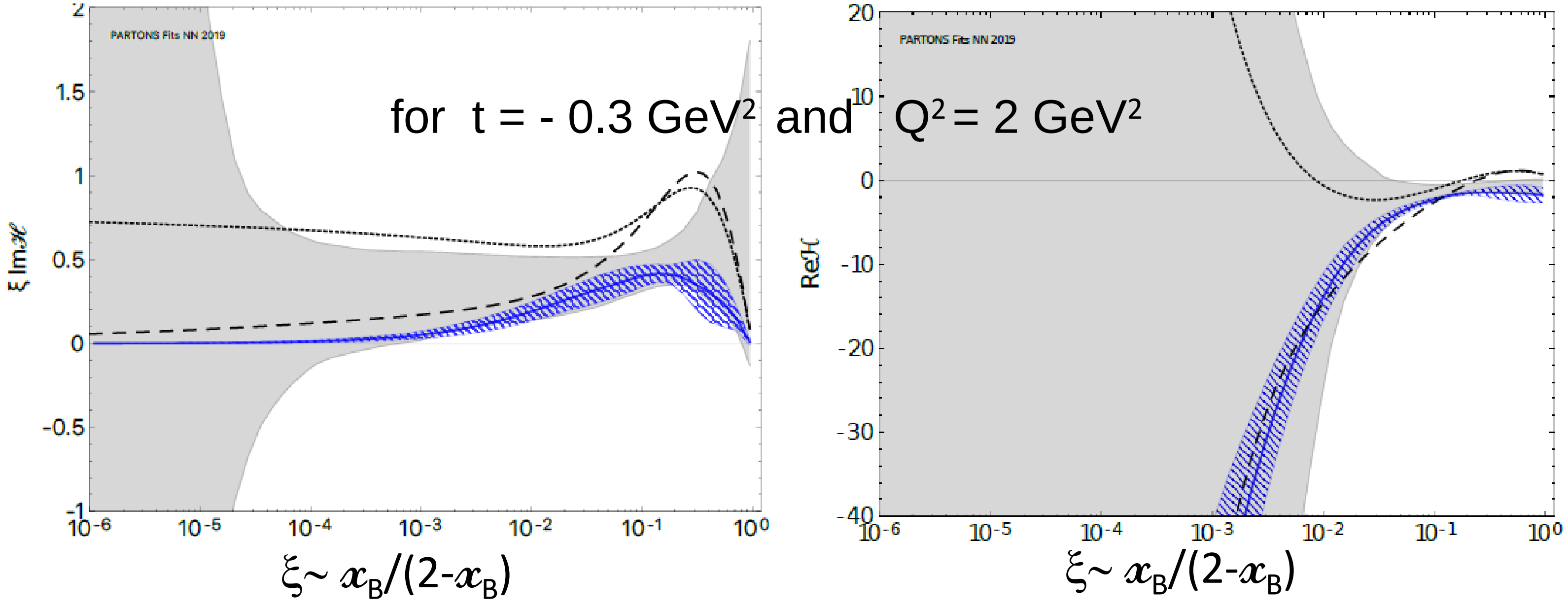



**Global Fits using PARTONS framework**
Compared to GK and VGG Models

Moutarde, Sznajder, Wagner, Eur. Phys. J. C 79 (2019) 7, 614

PARTONS global Fit
PARTONS Neural Network
to reduce the model dependency

...... GK
---- VGG



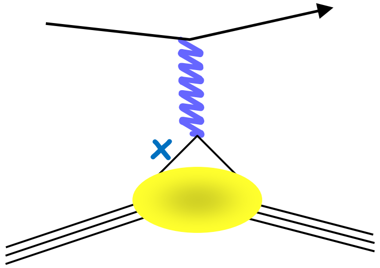

**ReH** is still poorly known (importance of DVCS with $\mu^{\pm}$ at COMPASS, $e^{\pm}$ at JLab or TCS at JLab and EIC)

# Other GPDs

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

4 chiral-even GPDs

Elastic 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***

$$\int \tilde{H}_f(x,\xi,t)dx = g_A^f(t)$$ ***Axial FF***

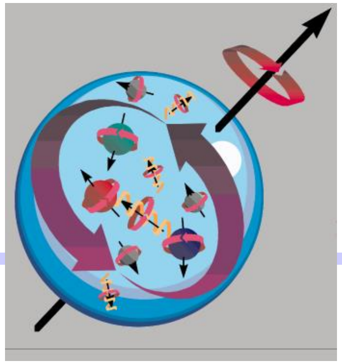
$$\int \tilde{E}_f(x,\xi,t)dx = h_A^f(t)$$ ***PseudoScalar FF***

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

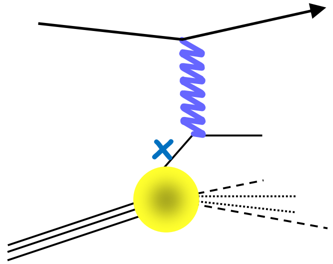
***Ji's Sum Rule***

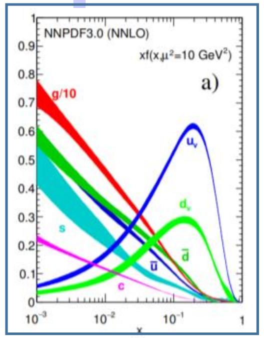
$½ = J_q + J_g$

$½ = ½\, \Delta\Sigma + L_q + J_q$



"ordinary" parton density






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

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

Vector mesons **ρ, ω** or **ϕ** or **J/ψ…**

⇒ **H and E**

Pseudo Scalar Mesons **π, η …**

⇒ $\tilde{\mathbf{H}}$ **and** $\tilde{\mathbf{E}}$

Mesons are also sensitive to chiral-odd GPDs

**Using of a "neutron" target** to get flavor decomposition and insight to **E**

***Pauli FF***

$$F_2^p(0) = \kappa^p = 1.793 \qquad \kappa^u = 2\,\kappa^p + \kappa^n = 1.673\,,$$

$$F_2^n(0) = \kappa^n = -1.913 \qquad \kappa^d = \kappa^p + 2\,\kappa^n = -2.033$$

in the forward limit $(\xi = 0,\ t = 0)$ $\displaystyle\int_{-1}^{+1} dx\, E^q(x) = \kappa^q$

⇒ $J_u$ should be large and $J_d$ small

# 2007-12: GPD E from Jlab 6 GeV and HERMES

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

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

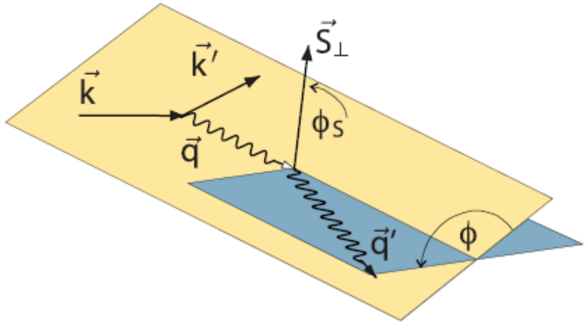
analysis still on going for a Hall-A experiment done in 2010

Note: proton + 'neutron' target ➔ quark flavor separation

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

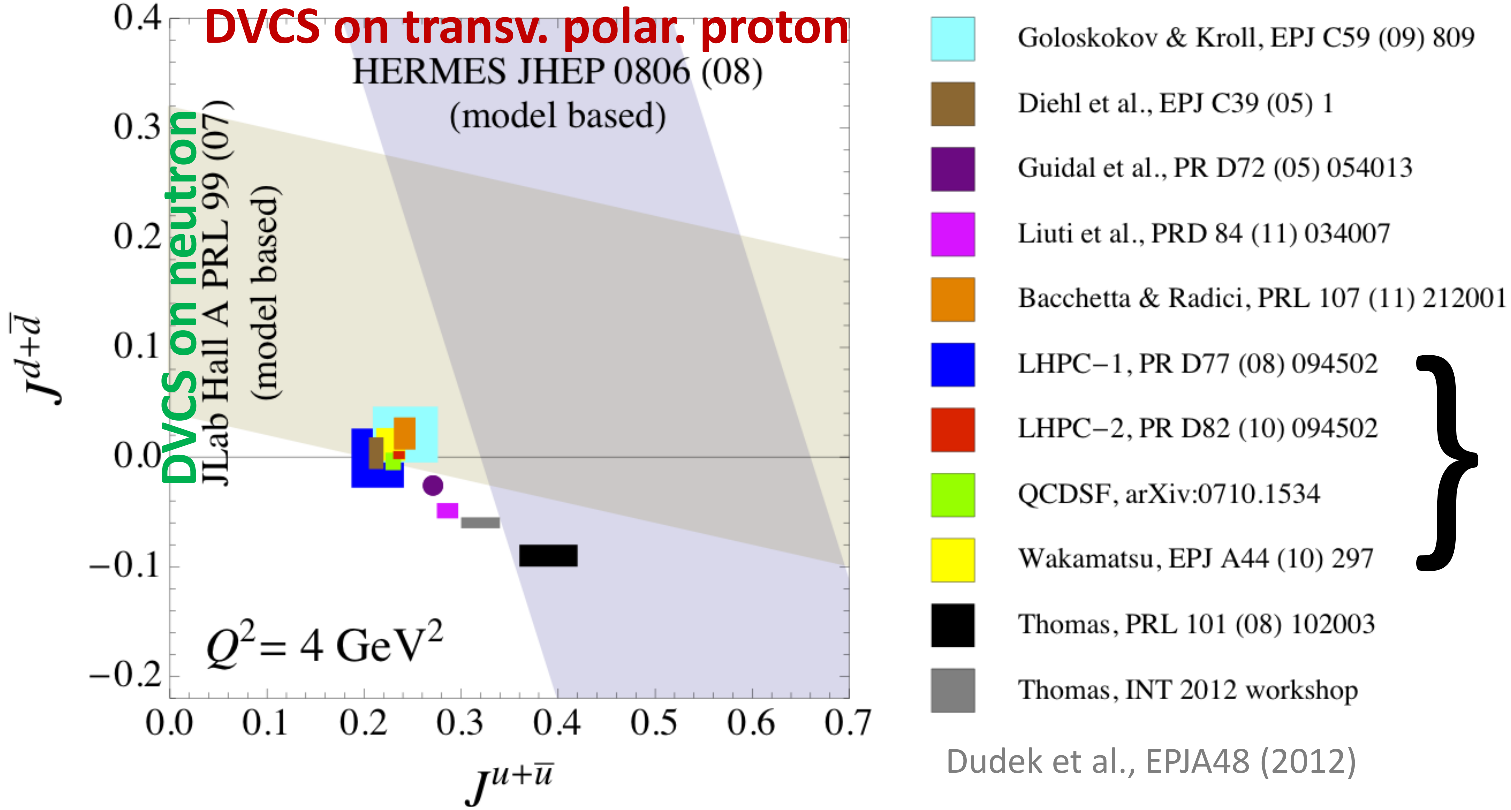
$$\Delta\sigma_{UT}^{\sin(\phi-\phi_s)\cos\phi} = -\,t/4m^2\; Im\,(F_{2p}\,\mathcal{H} - F_{1p}\mathcal{E})$$

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




J=

**Model dependent extraction of $J^u$ and $J^d$**




Dudek et al., EPJA48 (2012)

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

nature physics

## ℓ d → ℓ n γ (p)

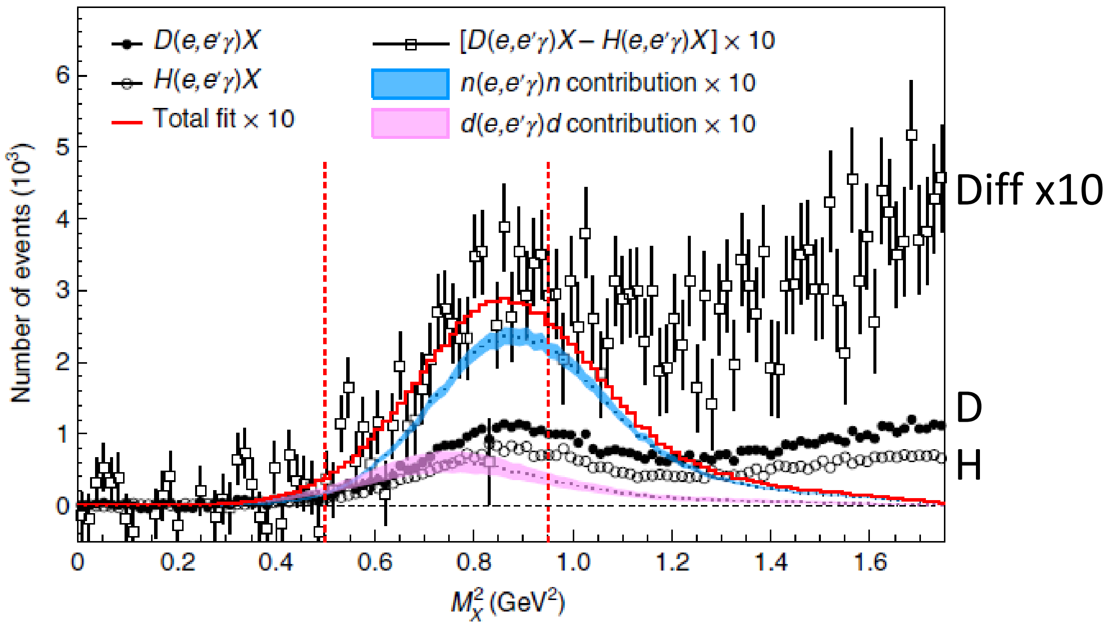
Benali et al., Nature Physics 16, 191-198 (**2020**)

From $LH_2$ target,
Fermi smearing added

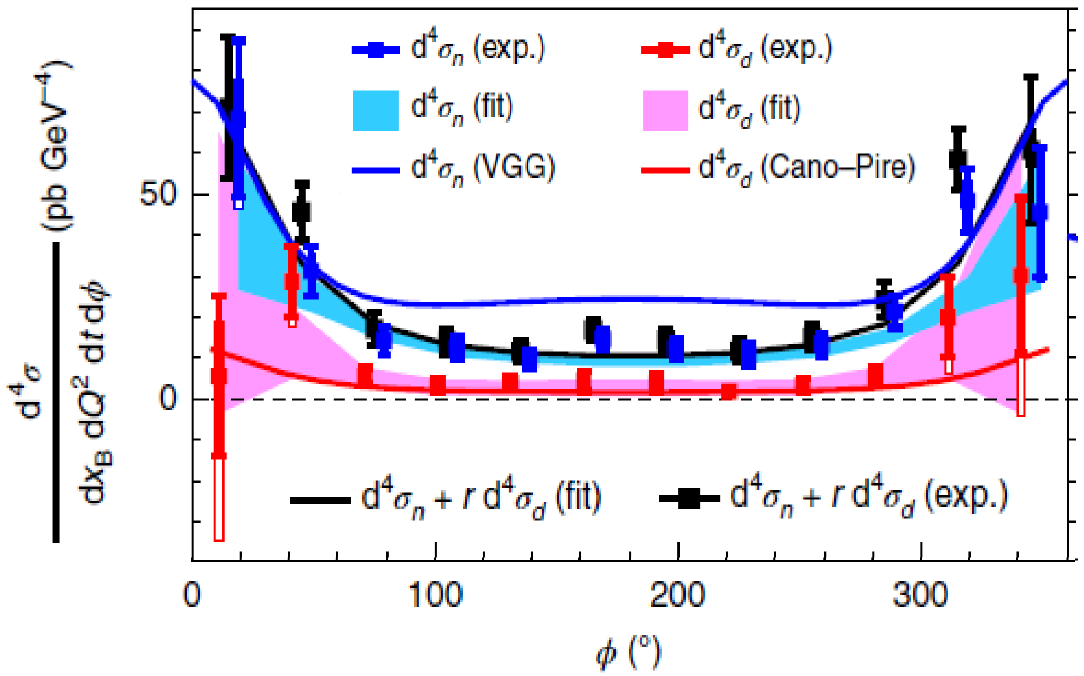
With $LH_2$ target

$$D(e,e'\gamma)X = d(e,e'\gamma)d + n(e,e'\gamma)n + \overbrace{p(e,e'\gamma)p}.$$

**Coherent deuteron + quasi-free neutron + quasi-free proton**




computed for n(e,e'γ)X




ratio of deuteron and neutron acceptance r ≈ 0.5

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

**using ℓ n → ℓ n γ and ℓ p → ℓ p γ**
**fit for each case of 12 CFFs**

2 fits: **HT:** 12 CFFs $(H, \tilde{H}, E) \otimes (\Re e, \Im m) \otimes (+\,+, 0\,+)$

**NLO:** 12 CFFs $(H, \tilde{H}, E) \otimes (\Re e, \Im m) \otimes (+\,+, -\,+)$

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

$\mathcal{F}$ for $\mathcal{H}$ or $\tilde{\mathcal{H}}$ or $\mathcal{E}$

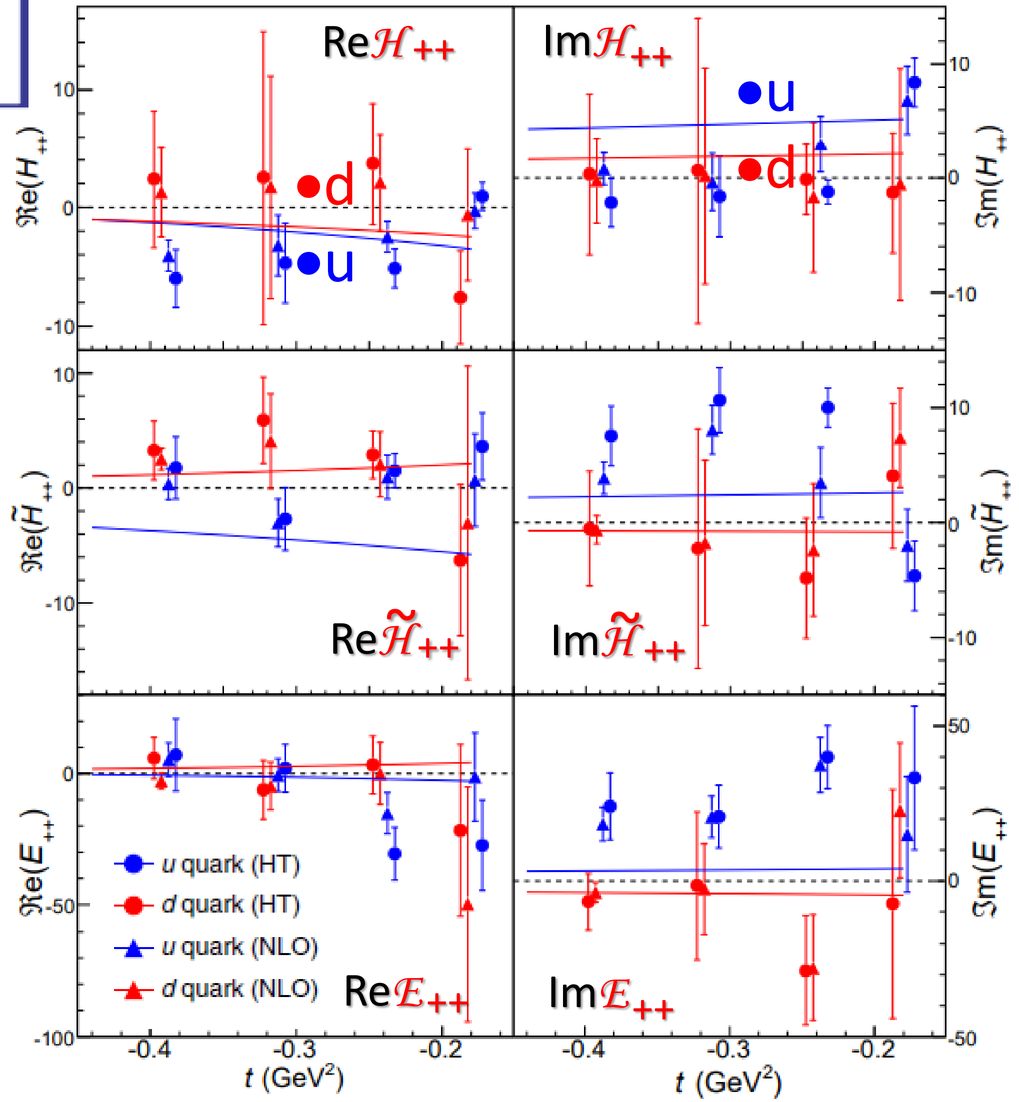
$\mathcal{F}^q$ for quark flavor in the proton $\mathcal{F}^u = \mathcal{F}_p^u = \mathcal{F}_n^d$

**u-d flavor separation of CFF contributions (s <<)**

$$\mathcal{F}^u = 9/15\,[\,4\,\mathcal{F}_{proton} - \mathcal{F}_{neutron}\,]$$
$$\mathcal{F}^d = 9/15\,[\,4\,\mathcal{F}_{neutron} - \mathcal{F}_{proton}\,]$$

nature physics

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

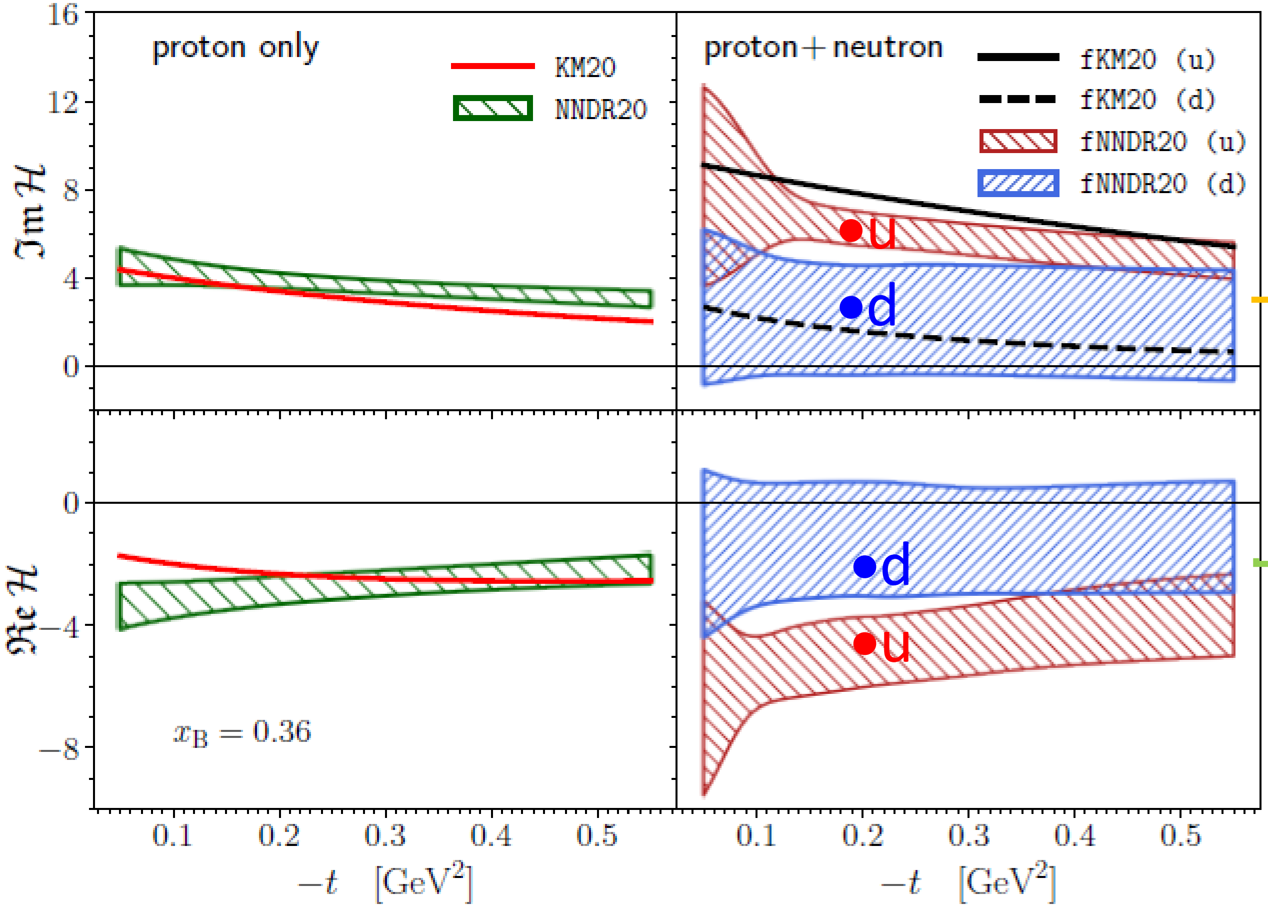



Solid line: Reggeized diquark model (Golstein, Luiti et al.)

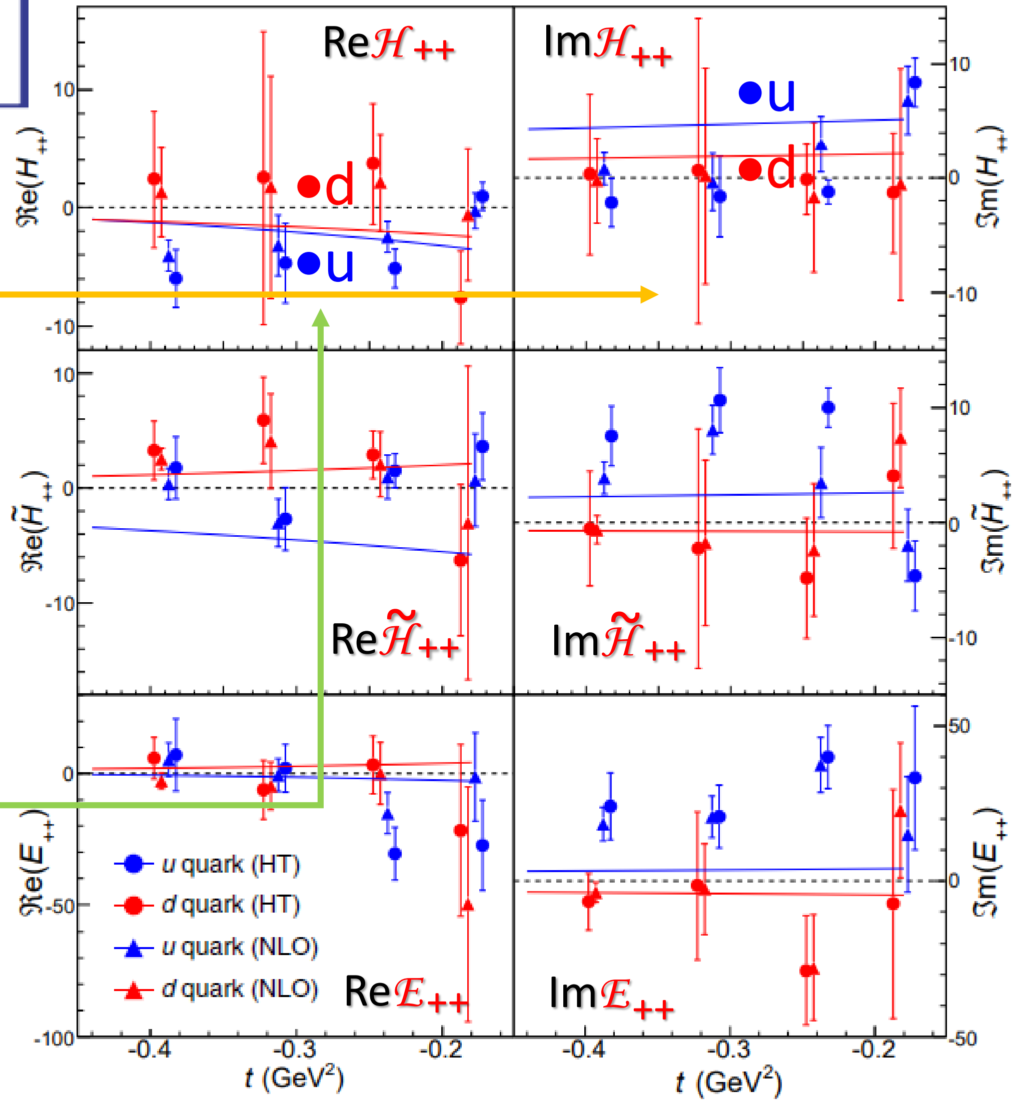
# 2010-2020 : DVCS off the neutron in Hall A @ 6 GeV

## using ℓ n → ℓ n γ and ℓ p → ℓ p γ

Comparison with global fits KM20, NNDR20
Cuic, Kumericki, Schaefer PRL 125 (2020) 232005




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



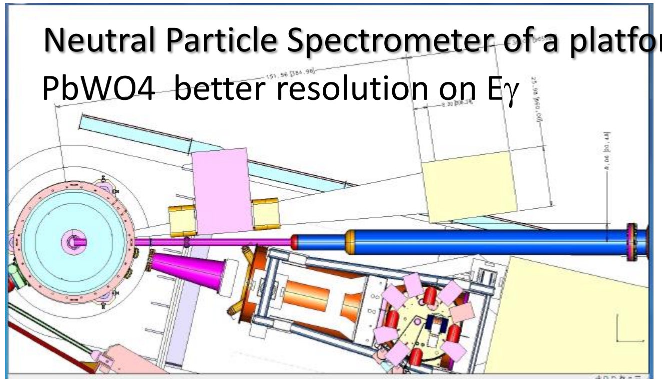

Solid line: Reggeized diquark model (Golstein, Luiti et al.)

# next future: Beam Spin Sum and Diff @ JLab12

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

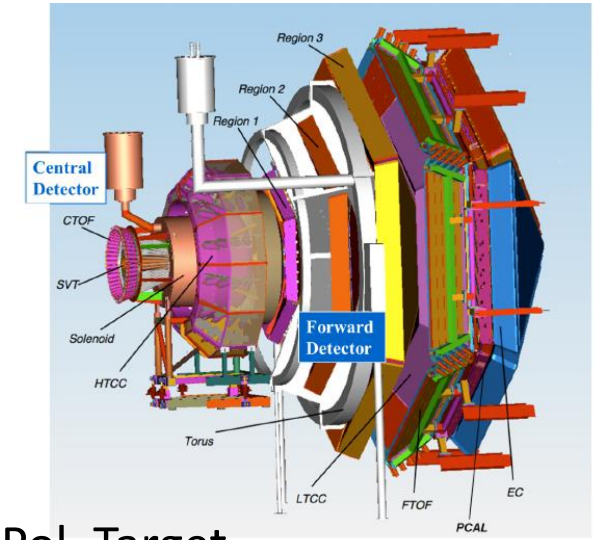
done in 2014-16: Hall A: E12-06-114
2023: Hall C: E12-13-010

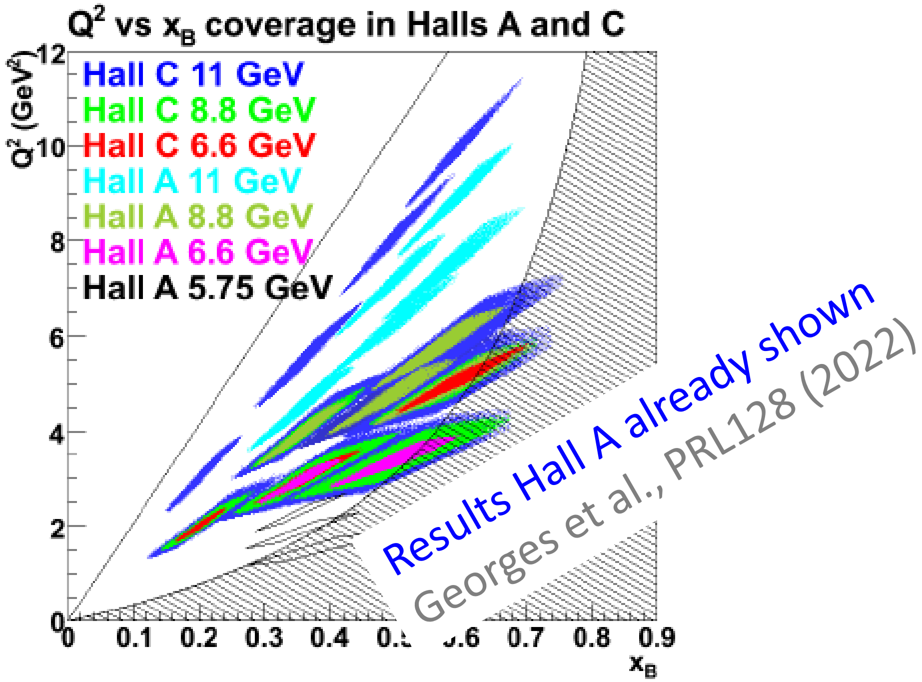
Different beam energies for a DVCS$^2$/Interf/ BH separation



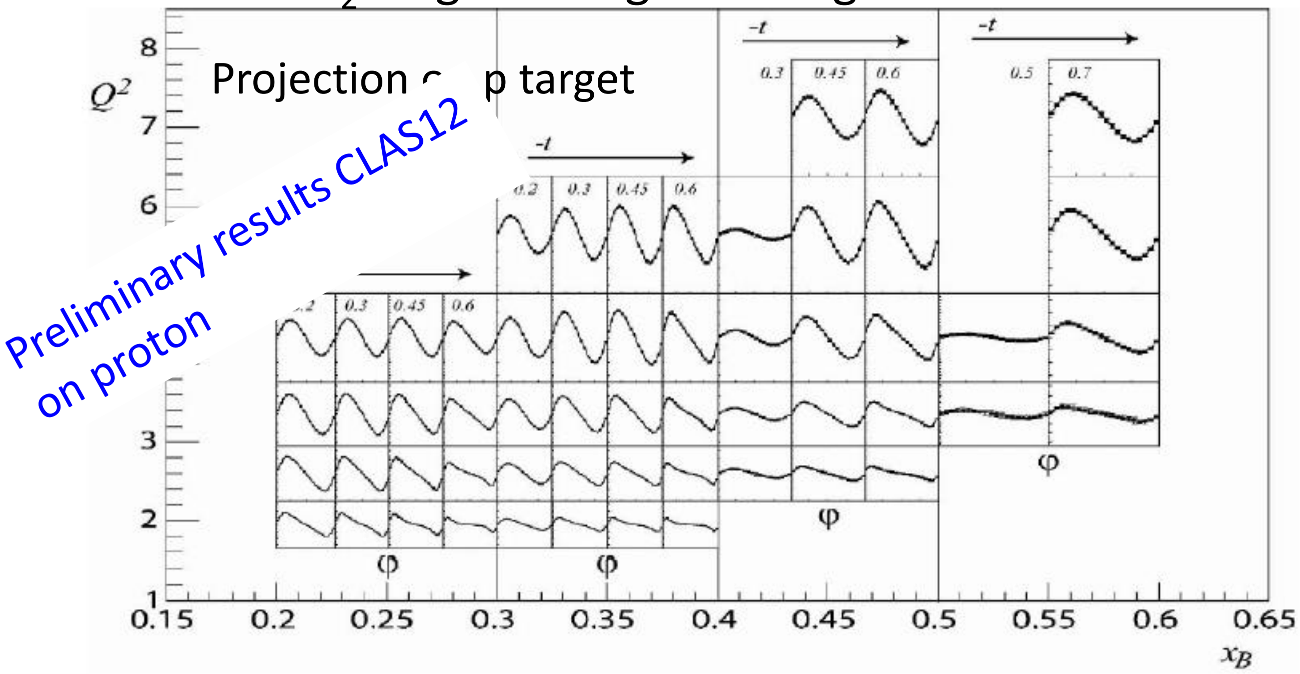

with CLAS12

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



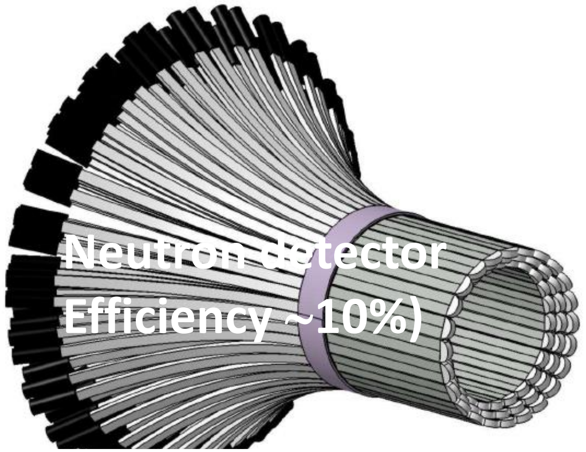

LH$_2$ Target & Long. Pol. Target



# next future: GPD E @ JLab12 with CLAS12

## Exp E12-11-003: DVCS off the neutron with $LD_2$

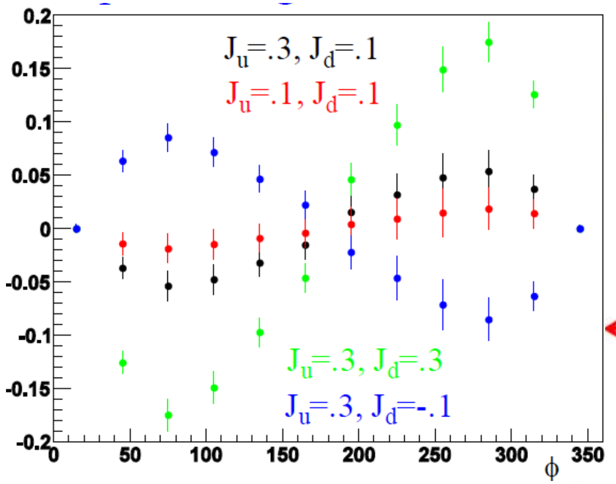
$$\Delta\sigma_{LU}^{\sin\phi} = Im\,(F_{1n}\mathcal{H} + \xi(F_{1n}+F_{2n})\widetilde{\mathcal{H}} + t/4m^2 F_{2n}\mathcal{E})$$

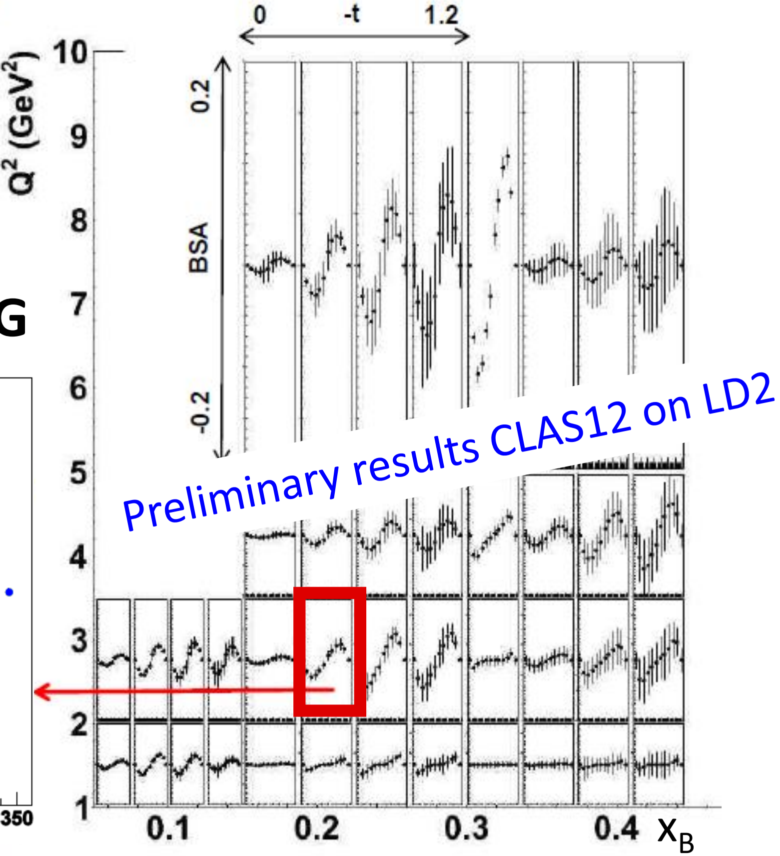



2019: 90 days on LD2 target

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

**Model prediction using VGG**



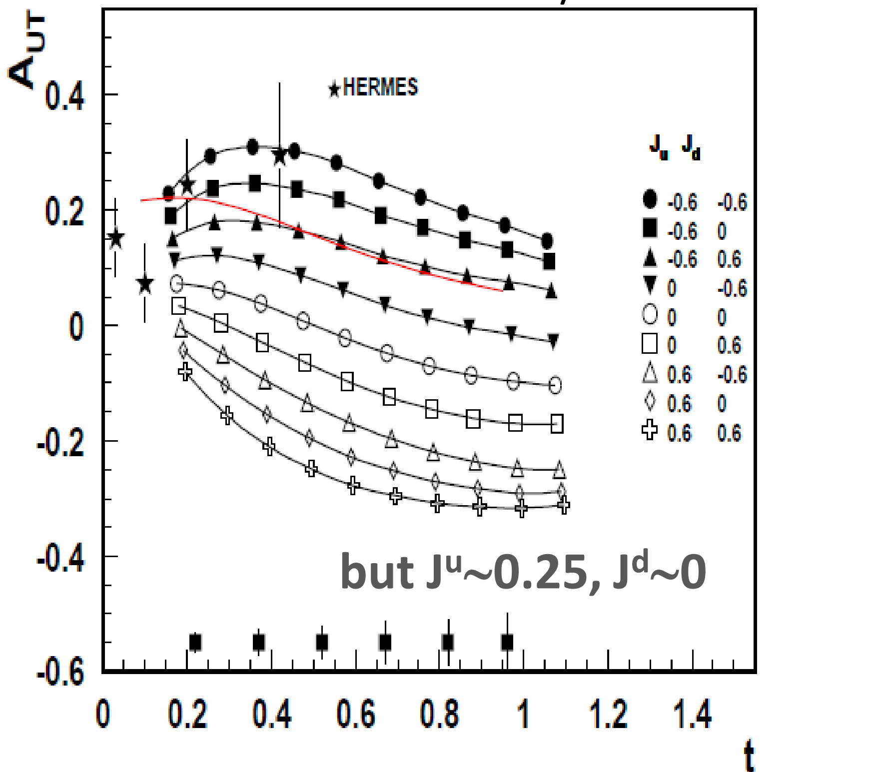

## Exp E12-12-010: DVCS on a transversely polarized HD-Ice target Pol H = 60% Pol D = 35%

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

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

After 2020: 110 days on HD-Ice target

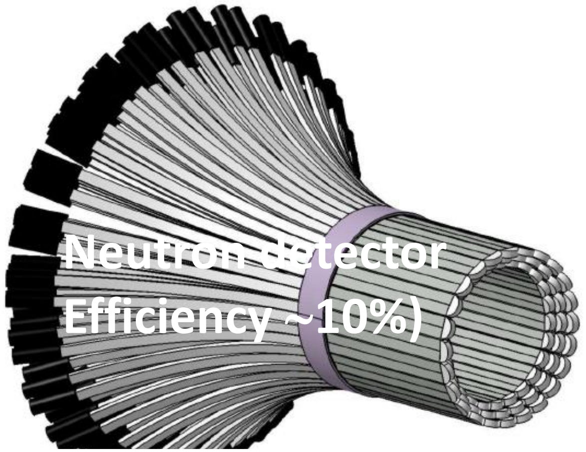
Lumi= 5 x $10^{33}$ $cm^{-2}$ $s^{-1}$/nucleon



# next future: GPD E @ JLab12 with CLAS12

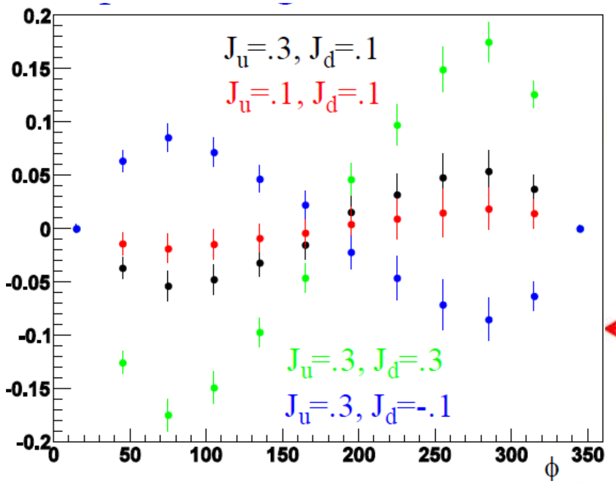
## Exp E12-11-003: DVCS off the neutron with $LD_2$

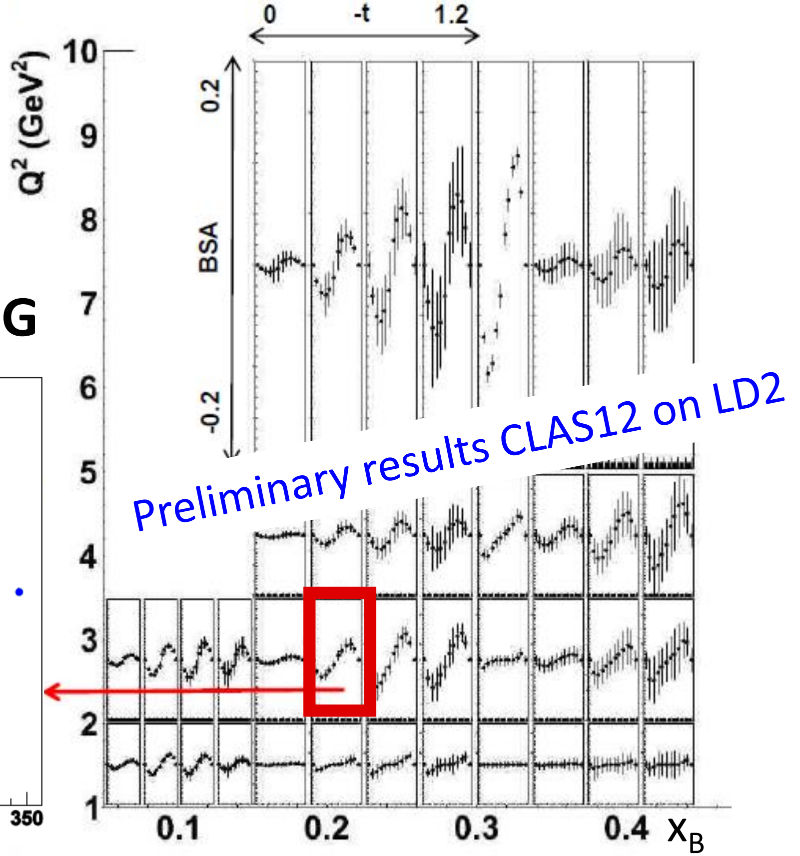
$$\Delta\sigma_{LU}^{\sin\phi} = Im\,(F_{1n}\mathcal{H} + \xi(F_{1n}+F_{2n})\widetilde{\mathcal{H}} + t/4m^2\, F_{2n}\mathcal{E})$$

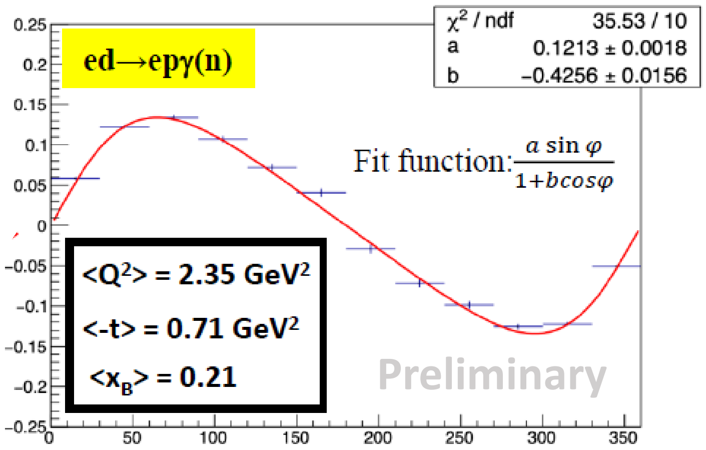


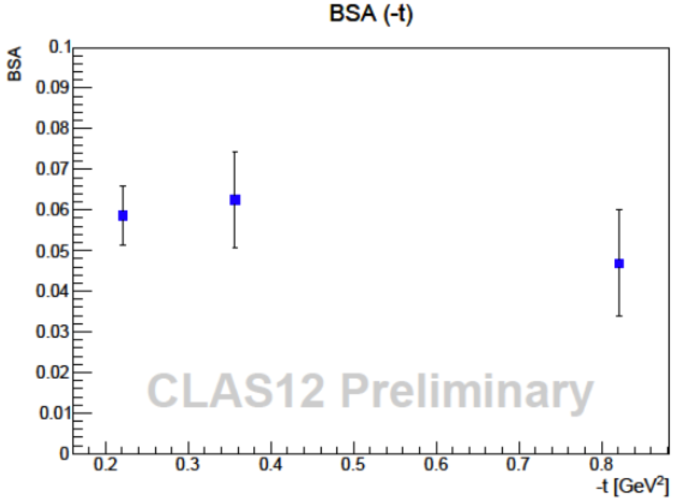

2019: 90 days on LD2 target
Lumi= $10^{35}$ $cm^{-2}$ $s^{-1}$/nucleon

**Model prediction using VGG**



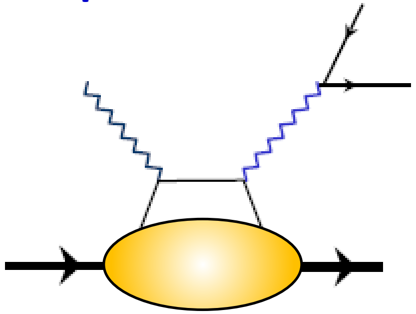



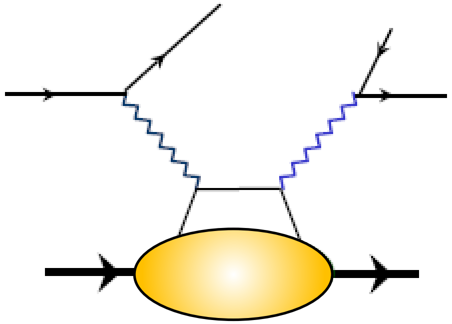
# Other paths to get GPDs with Compton Scattering

## Study of protons and neutrons



Time Like Compton Scattering

Result with CLAS12: Chatagnon et al. PRL127, 262501 **(2021)**



Double DVCS

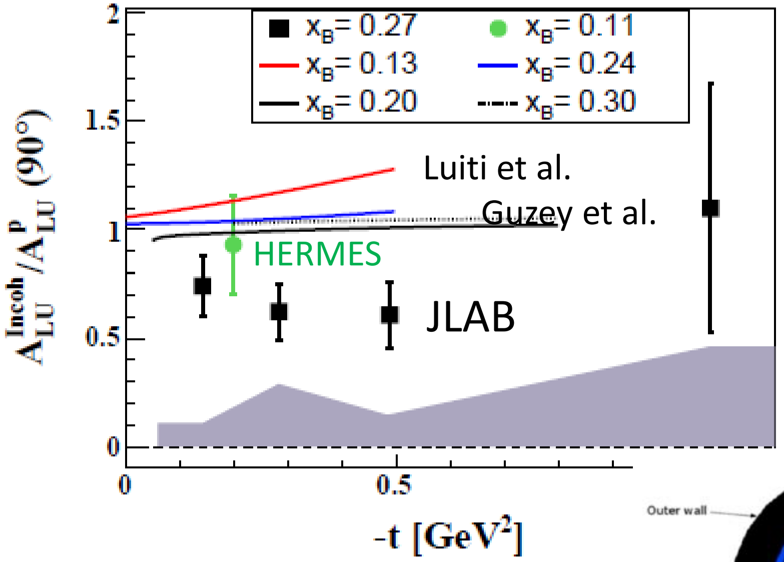
Projects explored with the high luminosity of JLab12
(in Hall-C or with CLAS12 and Solid)

## Study of nuclei

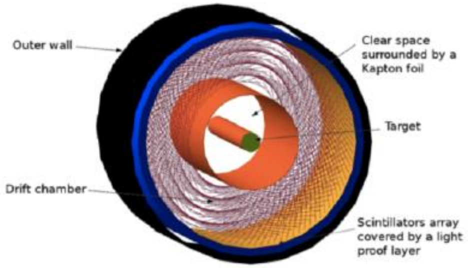
(HERMES, JLab6, JLab12)

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

Off bound protons: Hattawy et al., PRL 123(**2019**)
Ratio of the bound to the free proton at $\phi$=90°




Other projects with the recoil detecteur ALERT

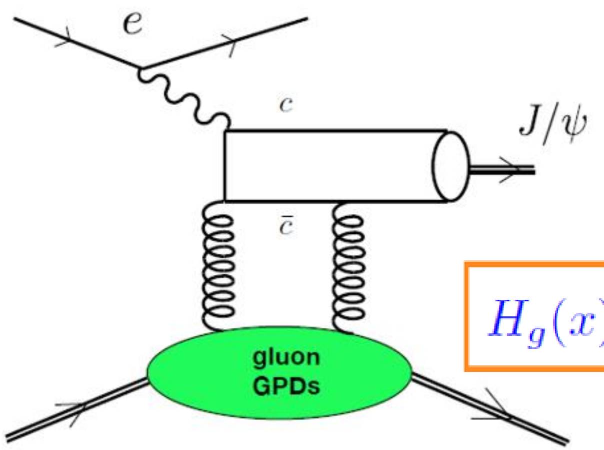


# exclusive J/ψ production at EIC

## mapping in the transverse plane
## Impact parameter distribution

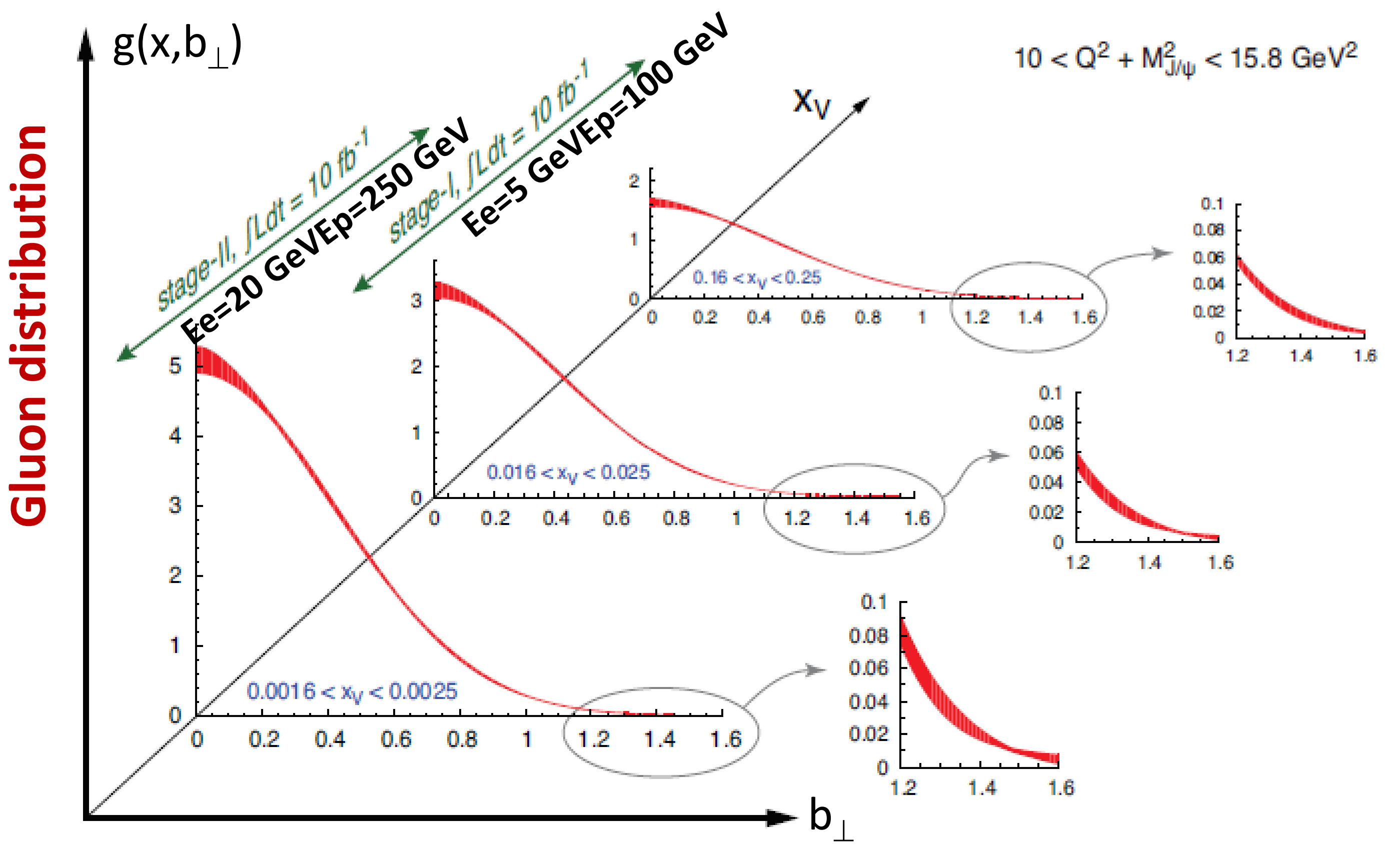
$$q_f(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp \cdot b_\perp} H_f(x, 0, -\Delta_\perp^2)$$

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




$H_g(x), E_g(x)$

## Exclusive J/ψ production




Transverse distance of the gluon from the center of the proton in femtometers

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