

# Status of DVCS analysis at COMPASS and elsewhere

Nicole d'Hose, CEA Université Paris-Saclay



IWHSS18,  
XV International Workshop  
on Hadron Structure  
and Spectroscopy  
March 19-21, 2018,  
Bonn, Germany

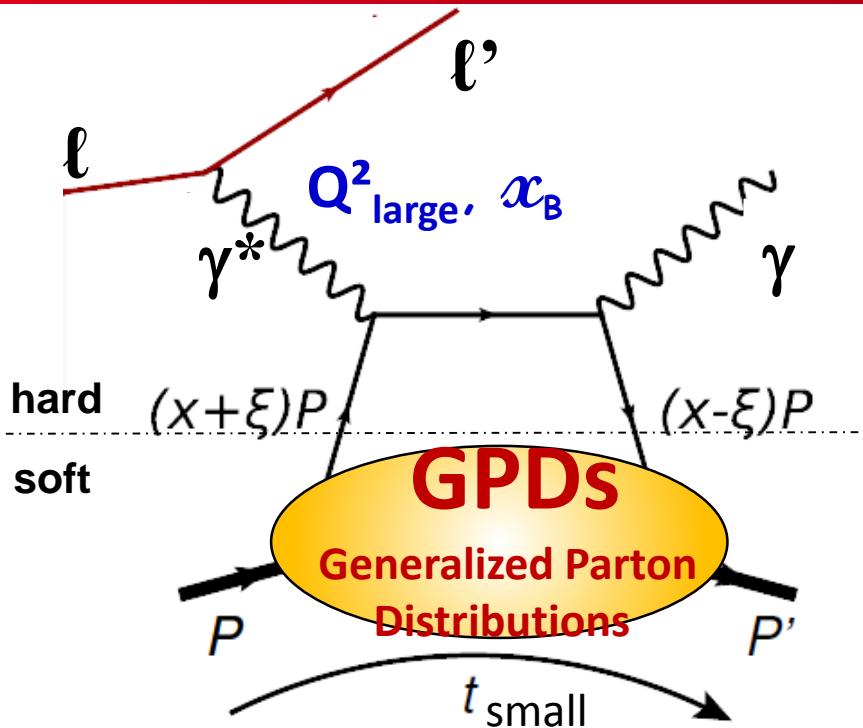


Physikalisches  
Institut



UNIVERSITÄT BONN

# 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:  $\ell p \rightarrow \ell' p' \gamma$   
the golden channel  
because it interferes with  
the Bethe-Heitler process  
  
also meson production  
 $\ell p \rightarrow \ell' p' \pi, \rho, \omega$  or  $\phi$  or  $J/\psi \dots$

The GPDs depend on the following variables:

$x$ : average long. momentum

$\xi$ : long. mom. difference

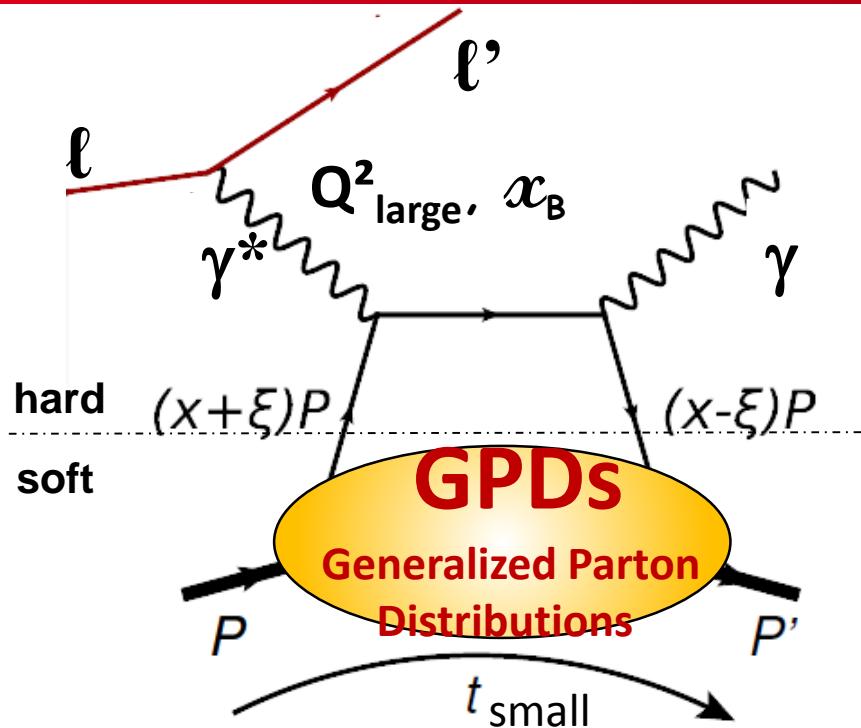
$t$ : four-momentum transfer  
related to  $b_\perp$  via Fourier transform

The variables measured in the experiment:

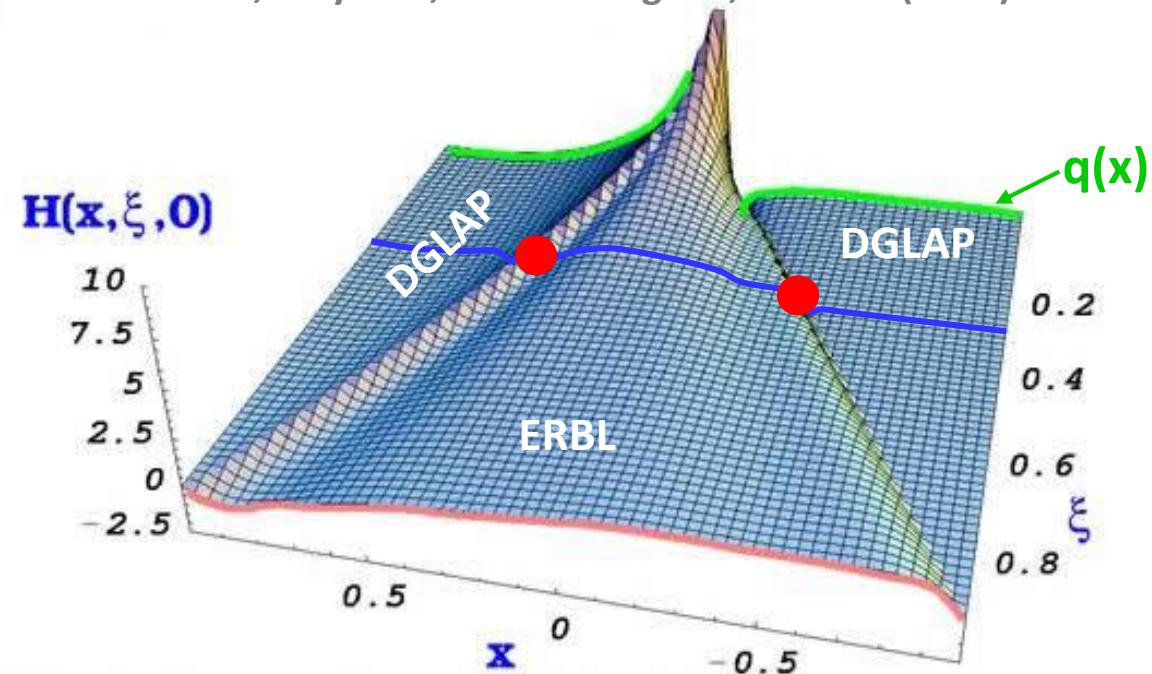
$E_\ell, Q^2, x_B \sim 2\xi/(1+\xi),$

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

# Deeply virtual Compton scattering (DVCS)



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



The amplitude DVCS at LT & LO in  $\alpha_s$ :

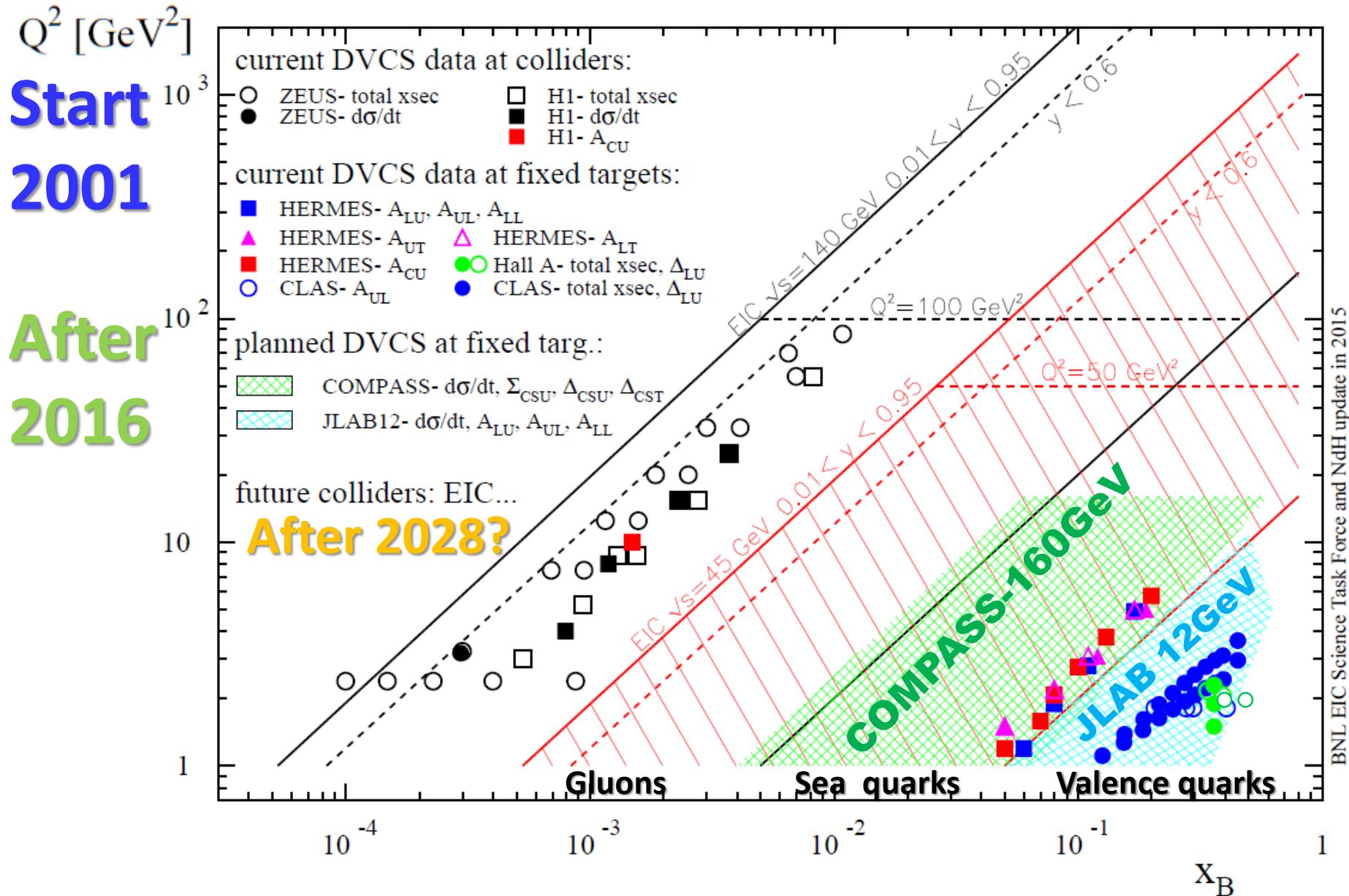
$$\mathcal{H} = \int_{t, \xi \text{ fixed}}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\varepsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(x \pm \xi, x, t)$$

GPD  $H$ , Compton Form Factor  $\mathcal{H}$

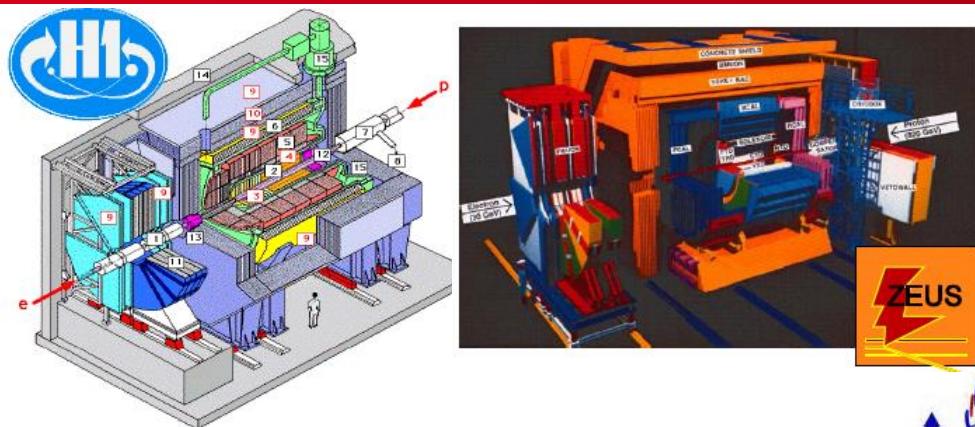
$$\text{Real part} \quad \text{Imaginary part}$$

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

# The past and future DVCS experiments



# The past and present experiments



## Fixed target mode slow recoil 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** High lumi, 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**  $\mu^+/\mu^-$   
p target, (Trans) polarised target  
*with recoil detection*

*Rejection of background: SIDIS, exclusive  $\pi^0/DVCS$ , dissociation of the proton*

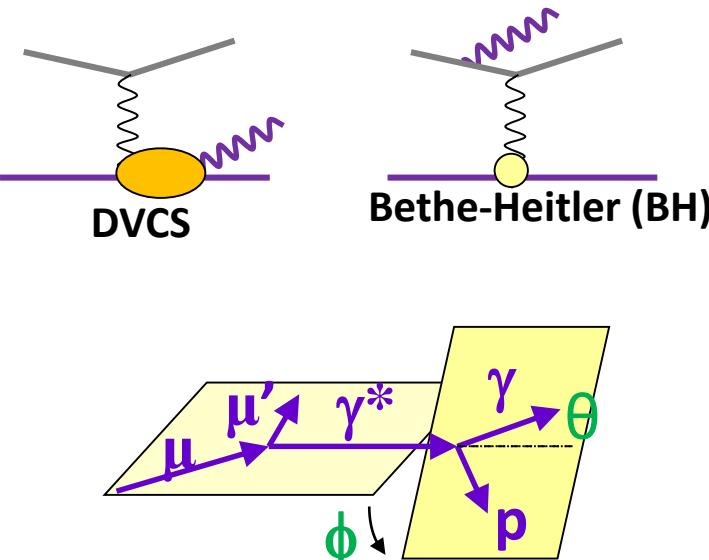
## Collider mode e-p forward fast proton

**HERA: H1 and ZEUS**

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

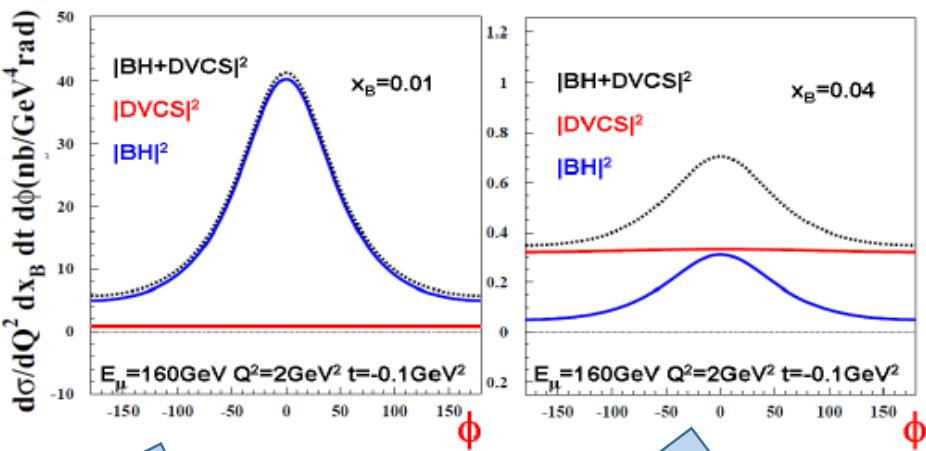


# DVCS and Impact of the beam energy



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

$E_\ell = 160 \text{ GeV}$



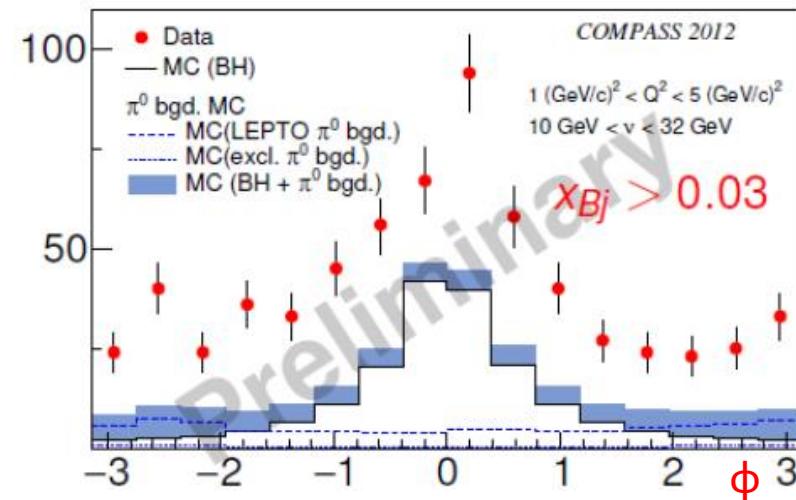
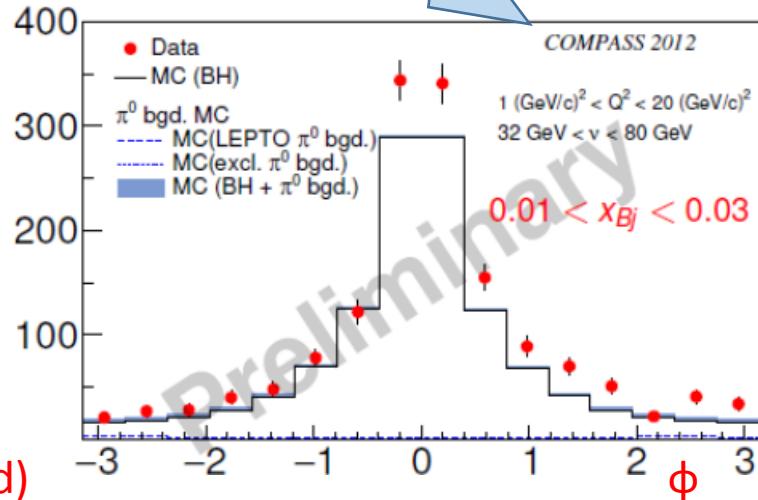
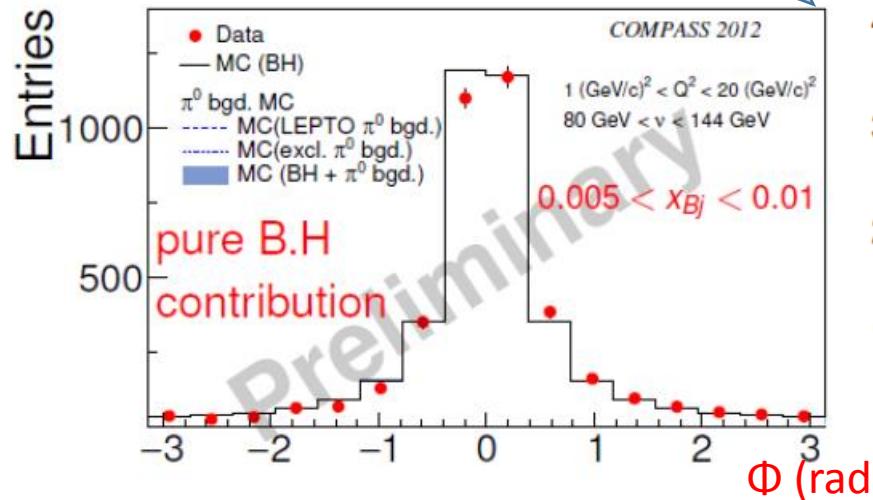
BH dominates  
Reference yield

DVCS ampl. via interference

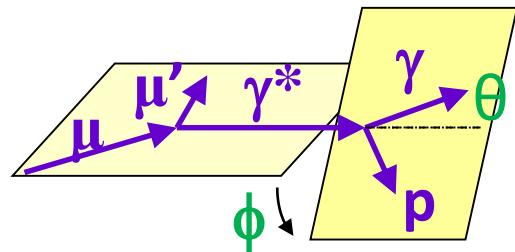
Jlab, HERMES,  
H1, COMPASS

DVCS dominates - Study of  $d\sigma^{\text{DVCS}}/dt$

Only for H1, ZEUS, COMPASS



# Study of azimuthal dependence of DVCS+BH



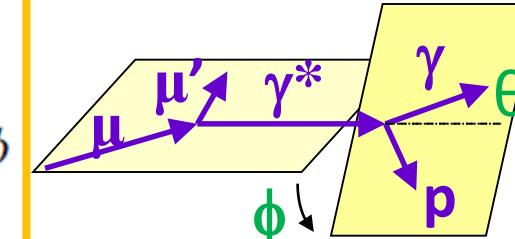
# Azimuthal dependence of BH+DVCS with Unpol Target

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

Well known

Up to Twist-3

$d\sigma^{BH}$	$\propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi$
$d\sigma_{unpol}^{DVCS}$	$\propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi$
$d\sigma_{pol}^{DVCS}$	$\propto s_1^{DVCS} \sin \phi$
$\text{Re } I$	$\propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$
$\text{Im } I$	$\propto s_1^I \sin \phi + s_2^I \sin 2\phi$

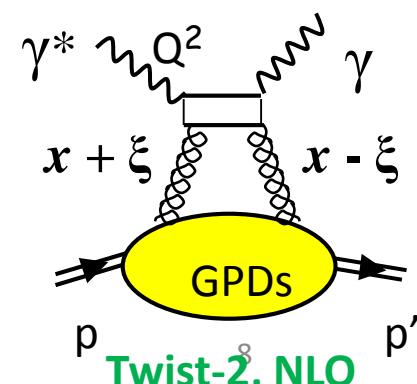
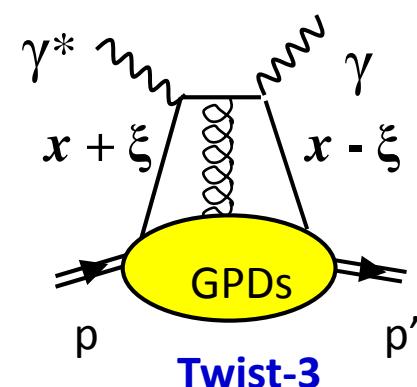
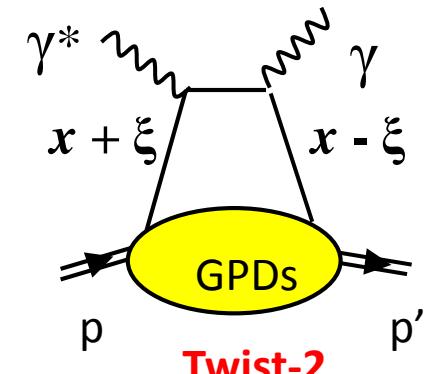


Twist-2 >>

■ Twist-3,

■ Twist-2

double helicity flip  
for gluons (NLO)



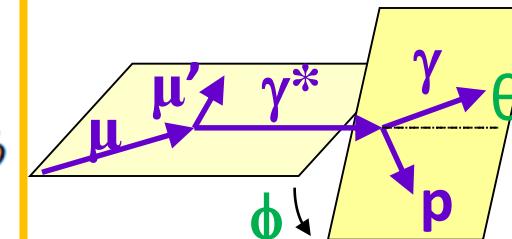
# Azimuthal dependence of BH+DVCS with Unpol Target

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

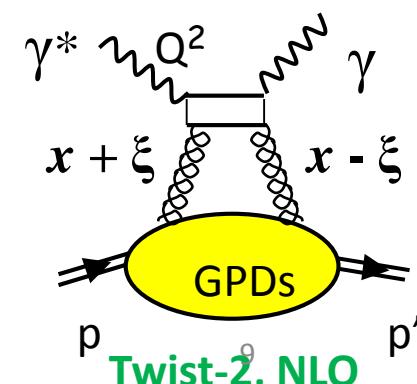
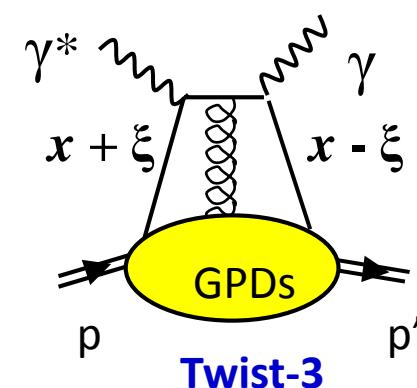
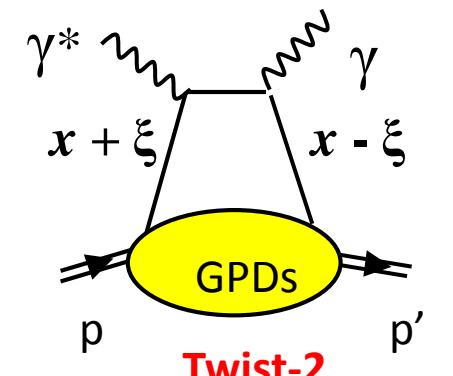
Well known

$\Sigma$   
 $\Sigma$   
 $\Delta$   
 $\Sigma$   
 $\Delta$   
 $\leftrightarrow$   
 $e^-$

$d\sigma^{BH}$	$\propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi$
$d\sigma_{unpol}^{DVCS}$	$\propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi$
$d\sigma_{pol}^{DVCS}$	$\propto s_1^{DVCS} \sin \phi$
$\text{Re } I$	$\propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$
$\text{Im } I$	$\propto s_1^I \sin \phi + s_2^I \sin 2\phi$



Twist-2 >>  
■ Twist-3,  
■ Twist-2  
 double helicity flip  
 for gluons (NLO)



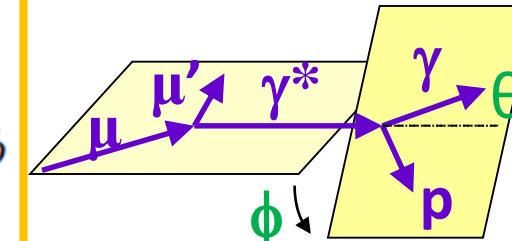
# Azimuthal dependence of BH+DVCS with Unpol Target

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

Well known

$\Sigma$	$\Sigma$
$\Sigma$	$\Sigma$
$\Delta$	$\Delta$
$\Sigma$	$\Delta$
$\Delta$	$\Sigma$
$\leftrightarrow$	$\leftrightarrow$
e-	$\mu^\pm$

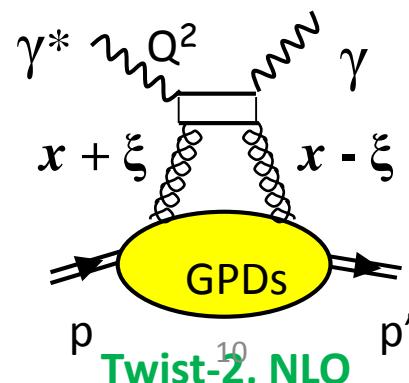
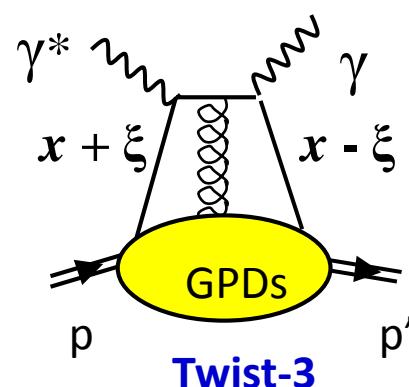
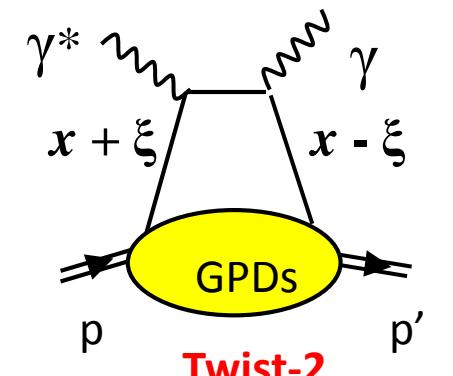
$d\sigma^{BH}$	$\propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi$
$d\sigma_{unpol}^{DVCS}$	$\propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi$
$d\sigma_{pol}^{DVCS}$	$\propto s_1^{DVCS} \sin \phi$
$\text{Re } I$	$\propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$
$\text{Im } I$	$\propto s_1^I \sin \phi + s_2^I \sin 2\phi$



Twist-2 >>

- Twist-3,
- Twist-2

double helicity flip  
for gluons (NLO)



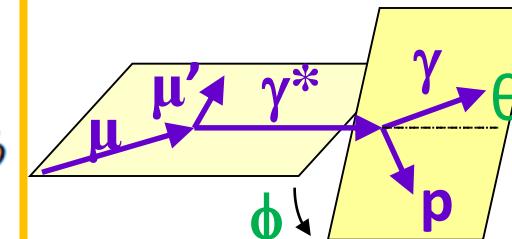
# Azimuthal dependence of BH+DVCS with Unpol Target

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

Well known

$\Sigma$	$\Sigma$
$\Sigma$	$\Sigma$
$\Delta$	$\Delta$
$\Sigma$	$\Delta$
$\Delta$	$\Sigma$
$\leftrightarrow$	$\leftrightarrow$
e-	$\mu^\pm$

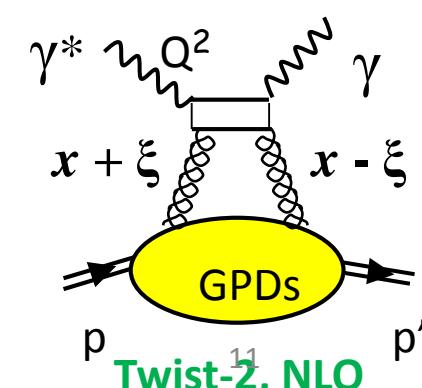
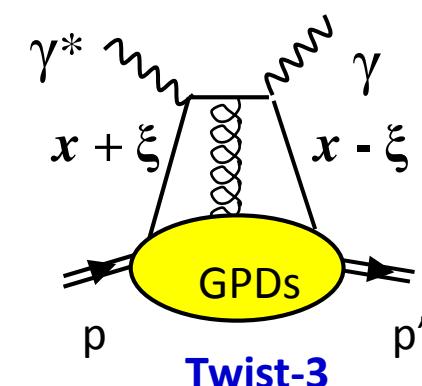
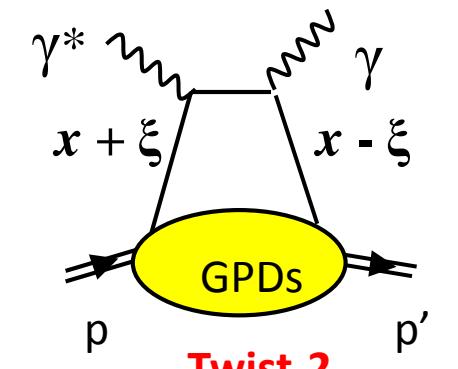
$d\sigma^{BH}$	$\propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi$
$d\sigma_{unpol}^{DVCS}$	$\propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi$
$d\sigma_{pol}^{DVCS}$	$\propto s_1^{DVCS} \sin \phi$
$\text{Re } I$	$\propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$
$\text{Im } I$	$\propto s_1^I \sin \phi + s_2^I \sin 2\phi$



Twist-2 >>

- Twist-3,
- Twist-2

double helicity flip  
for gluons (NLO)



$$s_1^I = \text{Im } \mathcal{F} \quad c_1^I = \text{Re } \mathcal{F}$$

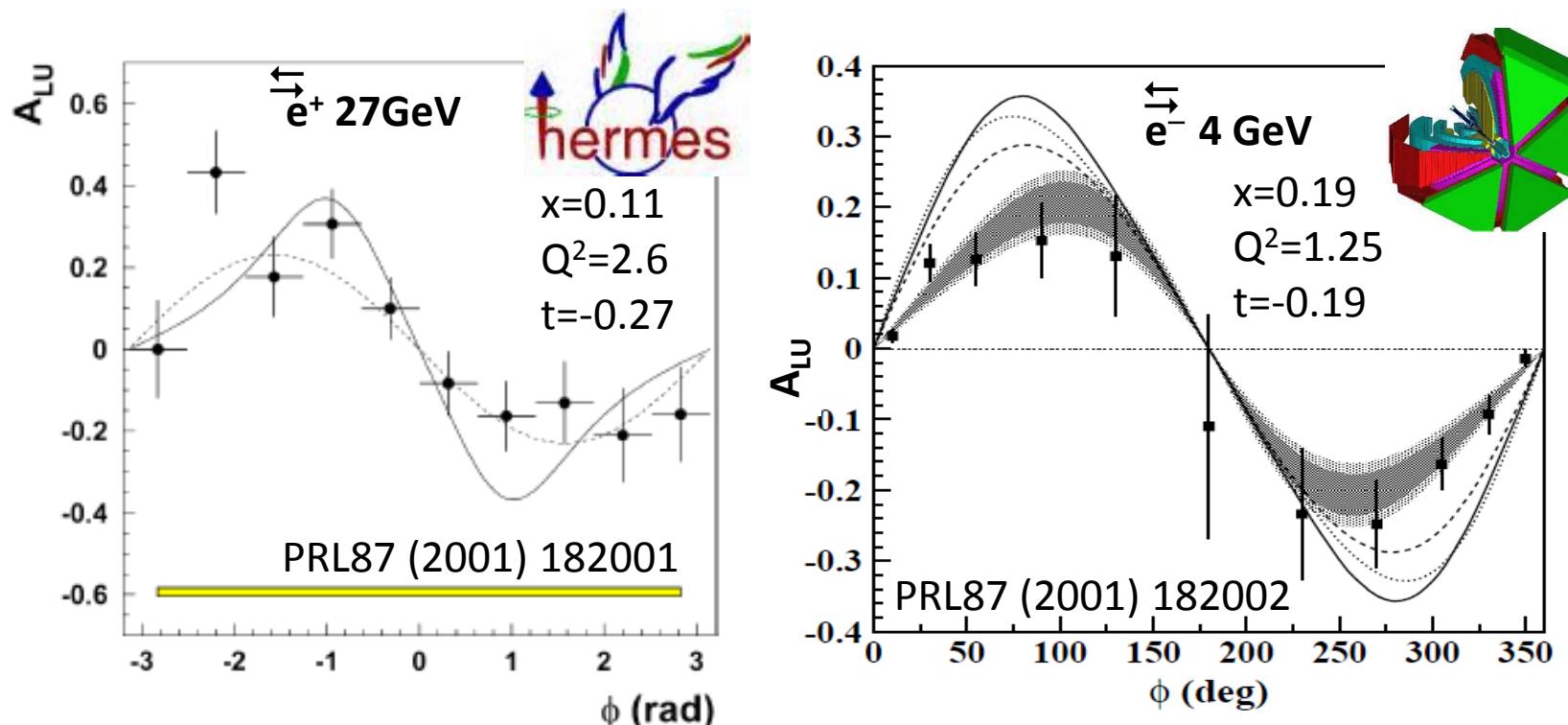
$$\mathcal{F} = F_1 \mathcal{H} + \xi(F_1 + F_2) \tilde{\mathcal{H}} - t/4m^2 F_2 \mathcal{E} \quad \text{at small } x_B \rightarrow F_1 \mathcal{H} \quad \text{for proton}$$

NB: to extract  $\mathcal{E}$  use a neutron (deuteron) target or a transversely pol. target  
 to extract  $\tilde{\mathcal{H}}$  use a longitudinally polarized target

# **Measurement of asymmetries (DVCS+BH)**

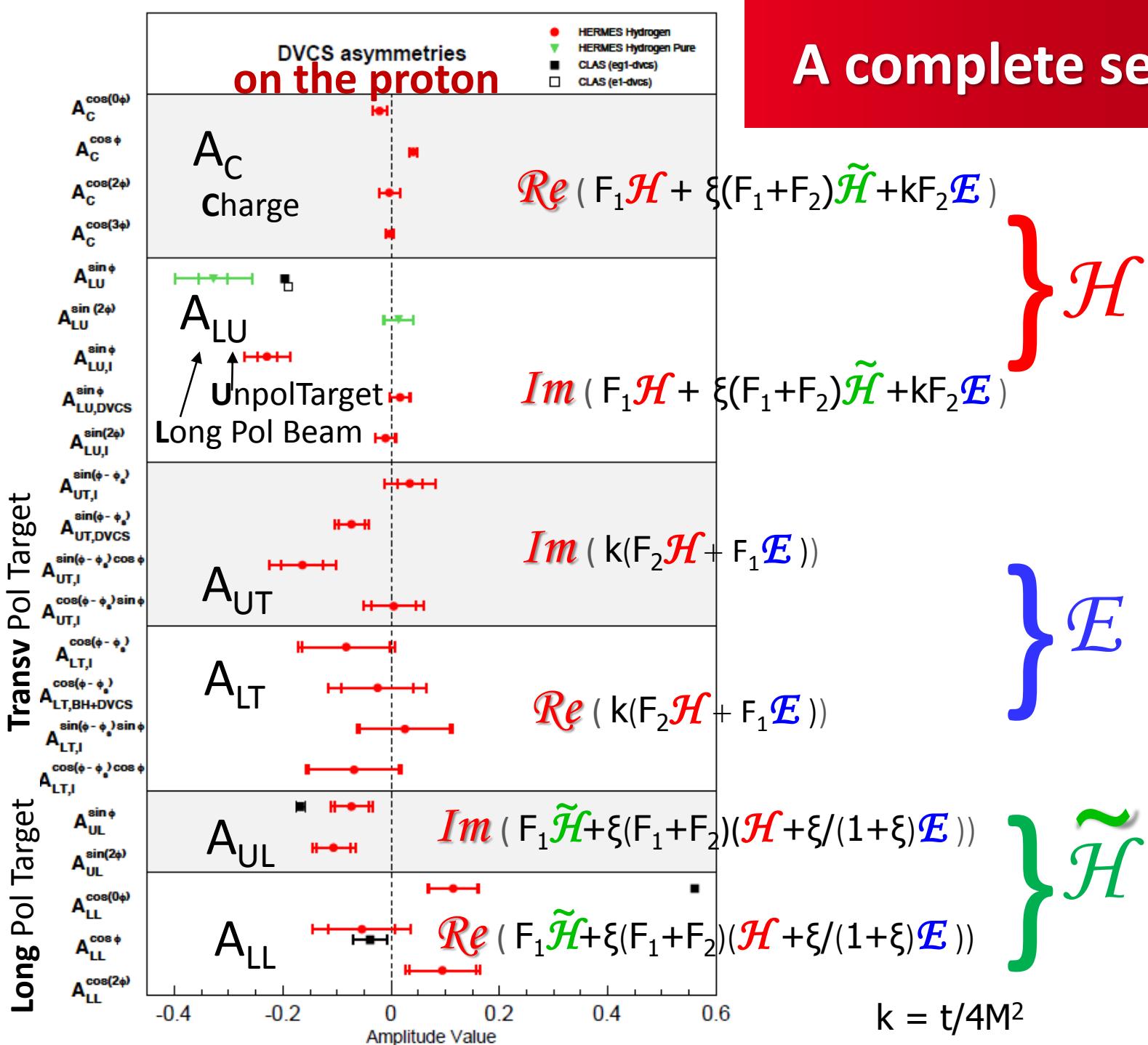
# First Beam Spin Asymmetries in 2001

$$d\sigma^{\leftarrow} - d\sigma^{\rightarrow} = 2[d\sigma_{pol}^{DVCS} + \text{Im } I] \xrightarrow{L.T.} s_1^I \sin \phi$$



Validate the dominance of the handag contribution

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



# A complete set of asymmetries for DVCS

HERMES 27 GeV provided  
a complete set of observables

- 1995: start of data taking
- 2001: 1<sup>st</sup> 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)*

# **Measurement of sum and diff of cross sections (DVCS+BH)**

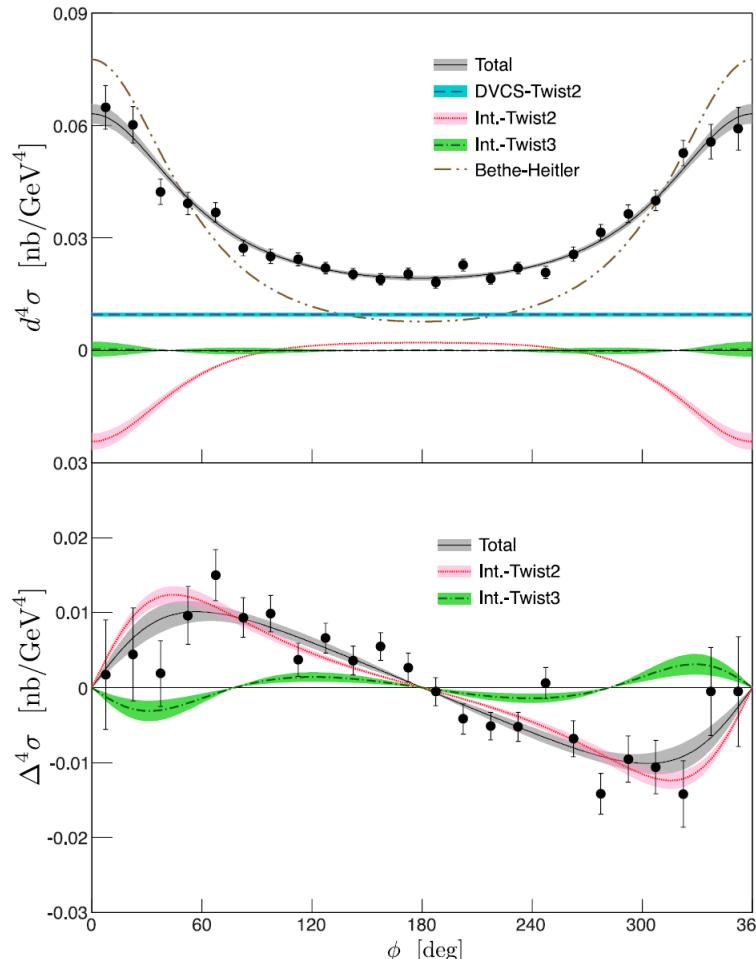
# Beam Spin Sum and Diff of DVCS - HallA

E00-110 pioneer experiment in 2004 with magnetic spectrometer

$x_B = 0.36$   $Q^2 = 1.5, 1.9, 2.3 \text{ GeV}^2$

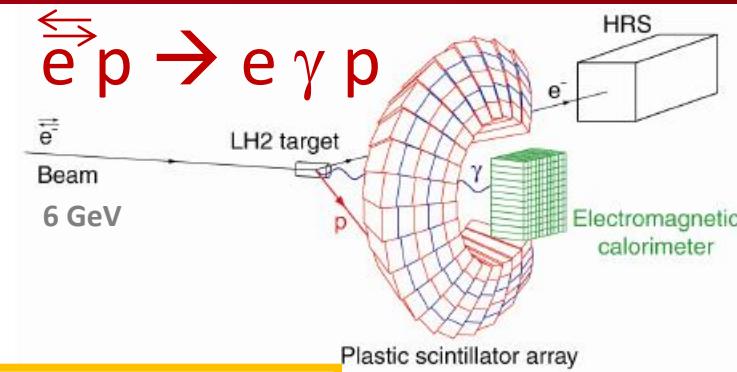
$x_B = 0.34, x_B = 0.39$   $Q^2 = 2.1 \text{ GeV}^2$

$x_B = 0.36, Q^2 = 2.3 \text{ GeV}^2, -t = 0.32 \text{ GeV}^2$



First analysis: Munoz et al. PRL97, 262002 (2006)

Final analysis: Defurne et al., PRC92, 055202 (2015)



## Unpolarized cross section

$$\begin{aligned} d\sigma^\leftarrow + d\sigma^\rightarrow &\propto d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + \text{Re } I \\ &\rightarrow d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \\ &\quad + c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \end{aligned}$$

## Helicity Dependent cross section

$$\begin{aligned} d\sigma^\leftarrow - d\sigma^\rightarrow &\propto d\sigma_{vol}^{DVCS} + \text{Im } I \\ &\rightarrow s_1^{DVCS} \sin \phi + s_1^I \sin \phi + s_2^I \sin 2\phi \end{aligned}$$

→ Further separation with  
different beam energies (2010 data)

# Beam Spin Sum and Diff of DVCS - HallA

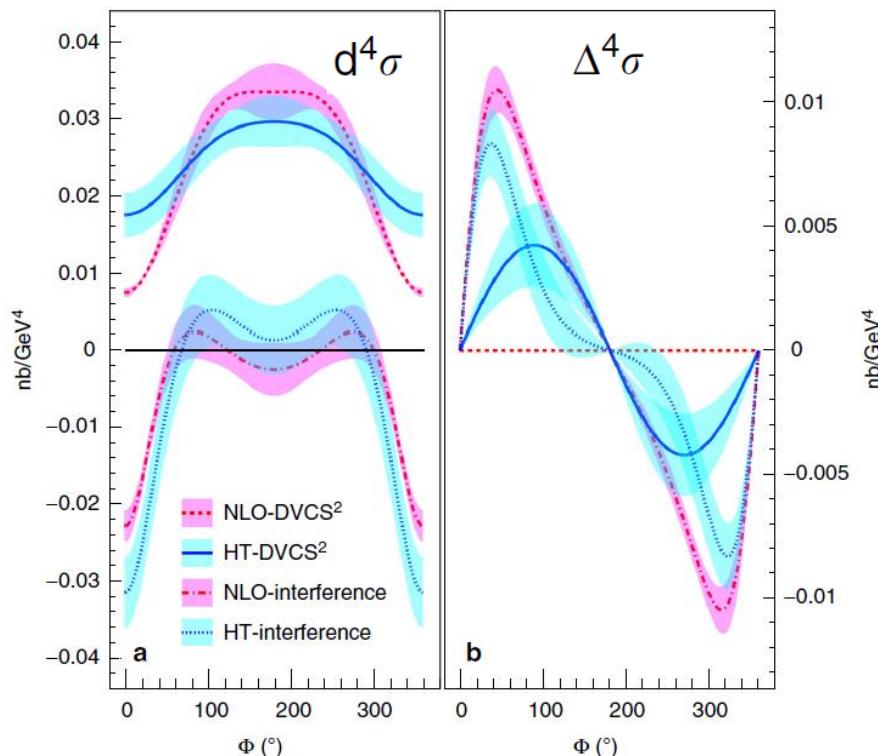
E07-007 Hall-A experiment in 2010 with magnetic spectrometer

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



$x_B=0.36$ ,  $Q^2= 1.75 \text{ GeV}^2$ ,  $-t= 0.30 \text{ GeV}^2$

Ebeam=5.55 GeV



## Unpolarized cross section

$$\begin{aligned} d^4\sigma & d\sigma^\leftarrow + d\sigma^\rightarrow \propto d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + \text{Re } I \\ & \longrightarrow d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \\ & + c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \end{aligned}$$

## Helicity Dependent cross section

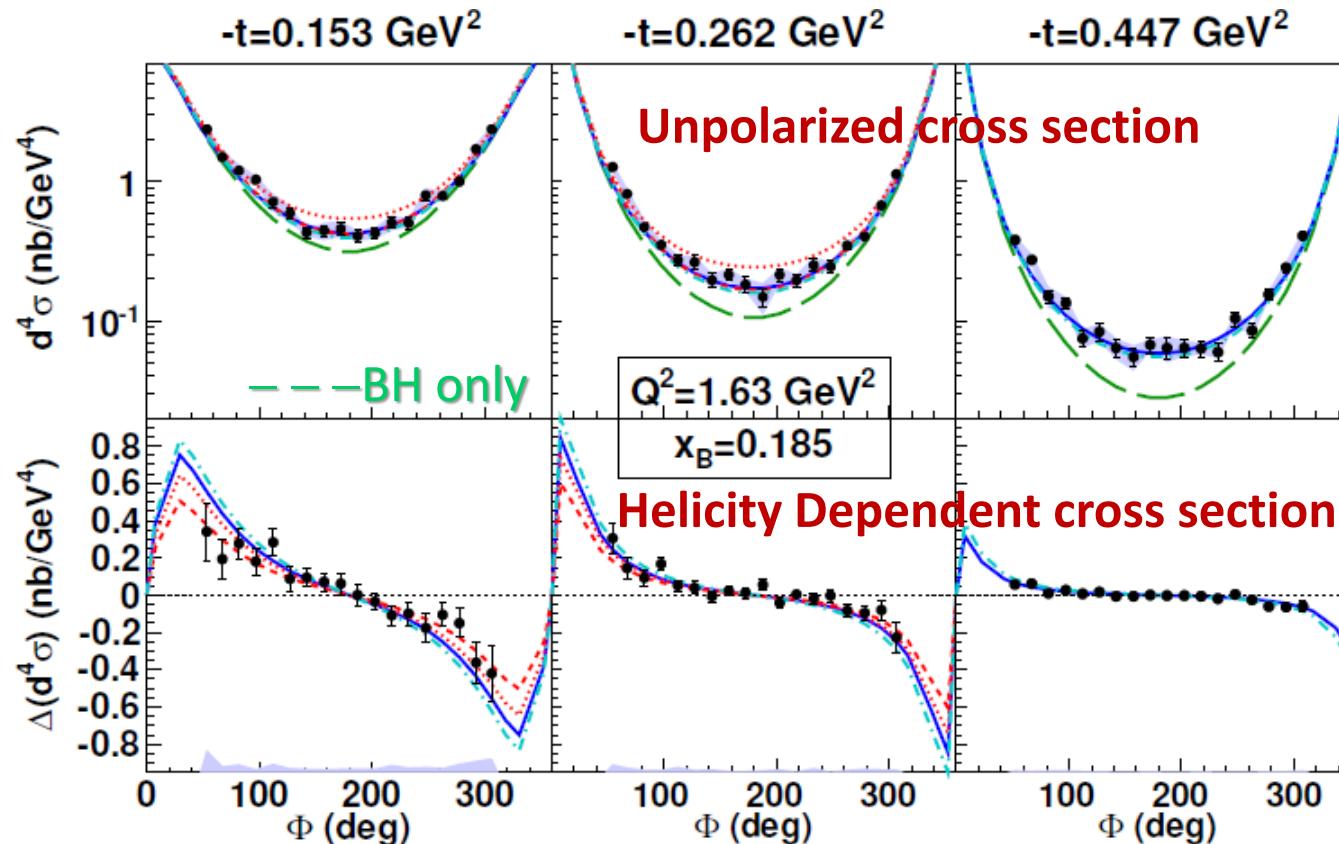
$$\begin{aligned} \Delta^4\sigma & d\sigma^\leftarrow - d\sigma^\rightarrow \propto d\sigma_{pol}^{DVCS} + \text{Im } I \\ & \longrightarrow s_1^{DVCS} \sin \phi + s_1^I \sin \phi + s_2^I \sin 2\phi \end{aligned}$$

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

# 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 - Jo et al. PRL115, 212003 (2015)



**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**

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

# Valence quark imaging at Jlab and HERMES

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

Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

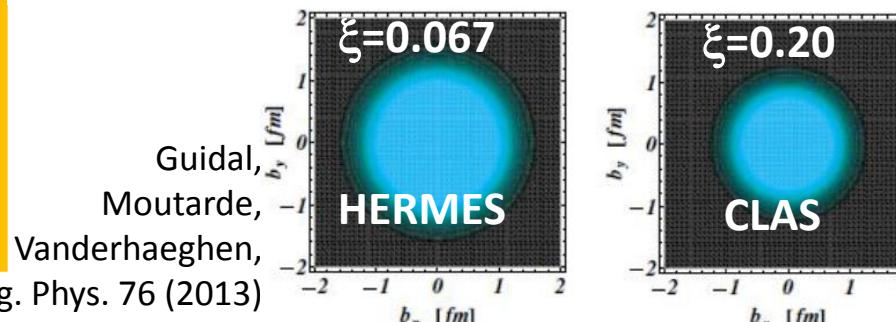
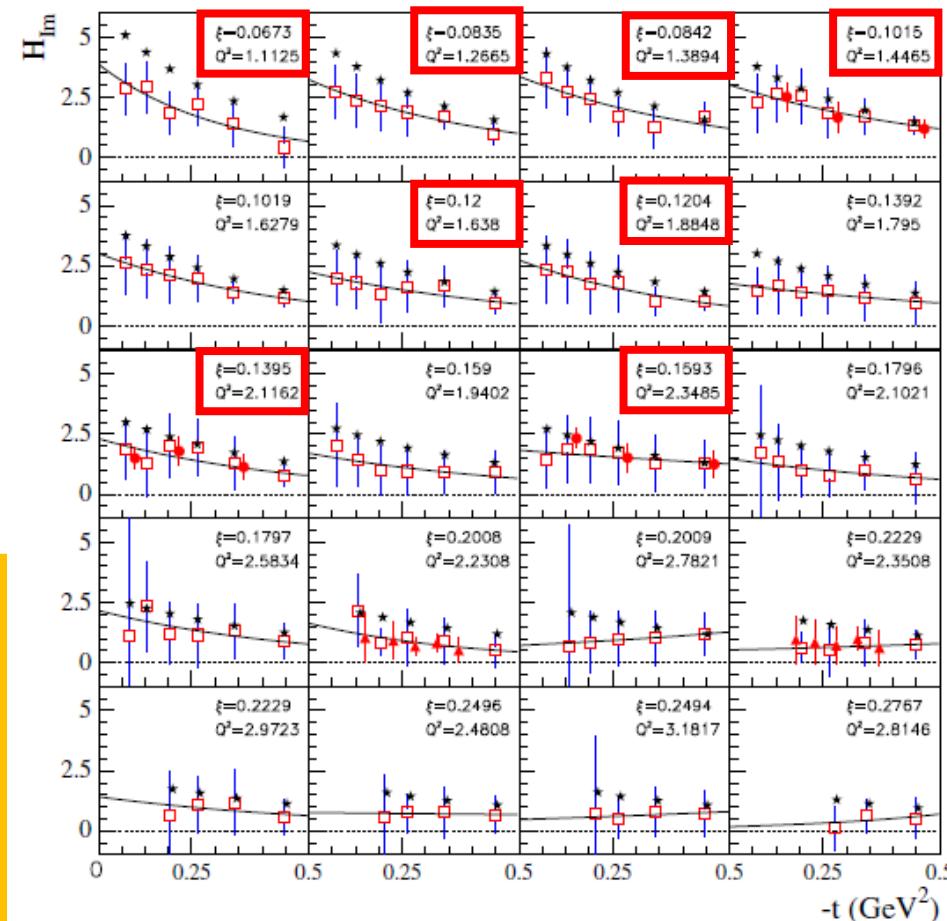
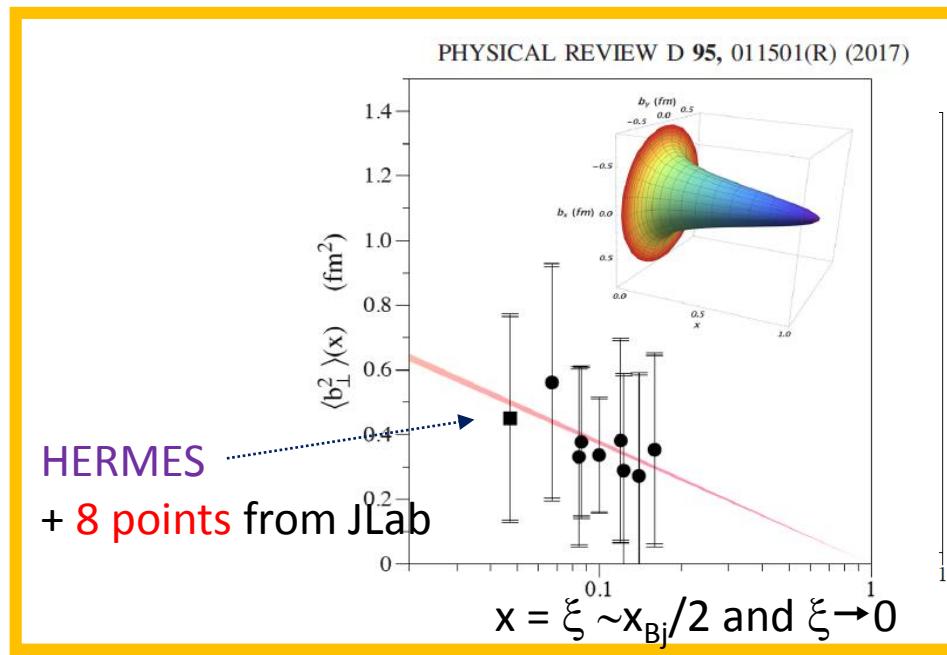
Dupré, Guidal, Nicolai, Vanderhaeghen, arXiv: 1704.07330

$$S_1^I = \text{Im } F_1 \mathcal{H}$$

- CLAS  $\sigma$  and  $\Delta\sigma$
- ▲ HallA  $\sigma$  and  $\Delta\sigma$
- CLAS  $A_{UL}$  and  $A_{LL}$
- ★ VGG model

— Fit A  $e^{-B|t|}$

$$\langle b_\perp^2 \rangle \approx 4 B$$



# **Measurement of the integrated DVCS cross sections at high lepton energy (when BH is not dominant)**

# Measurement of the integrated DVCS cross sections at high lepton energy (when BH is not dominant)

At COMPASS with polarized positive and negative muon beams:

$$\begin{aligned}
 S_{cs,U} &\equiv d\sigma^{\leftarrow} + d\sigma^{\rightarrow} = 2[d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + \text{Im } I] \\
 &= 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin \phi + s_2^I \sin 2\phi]
 \end{aligned}$$

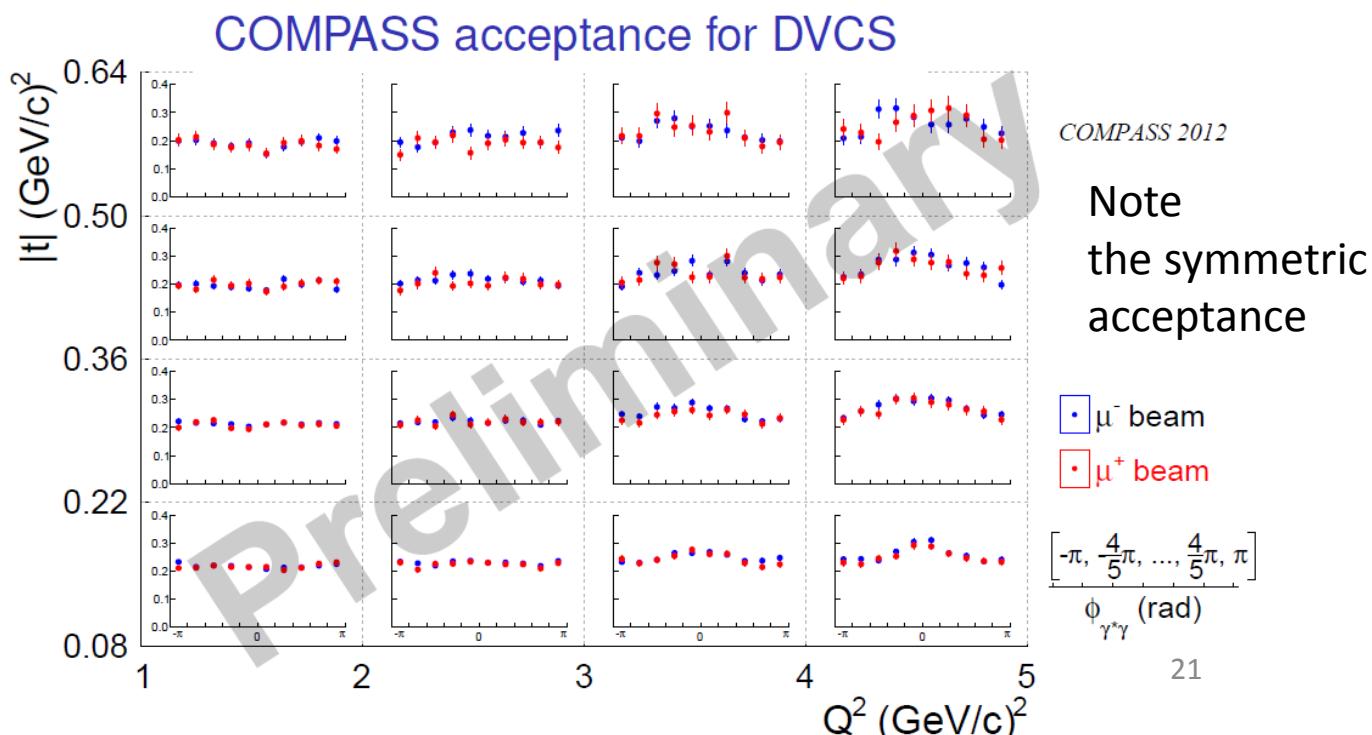
calculable  
 can be subtracted

All the other terms are cancelled in the integration over phi

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

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

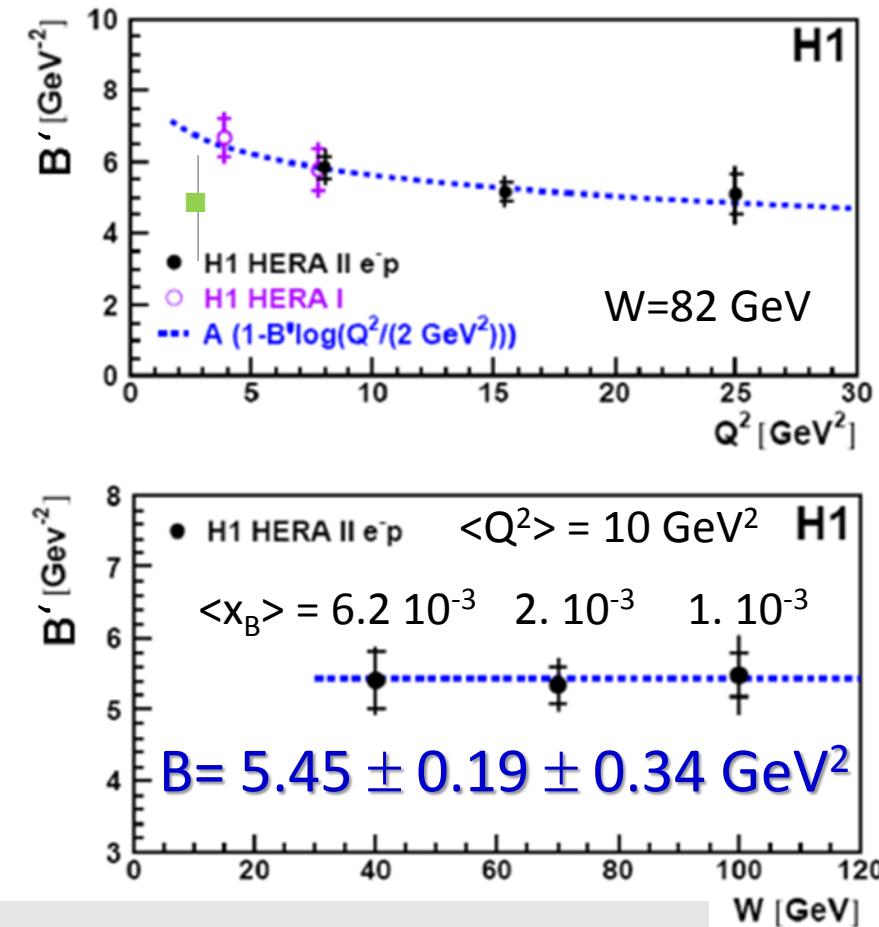
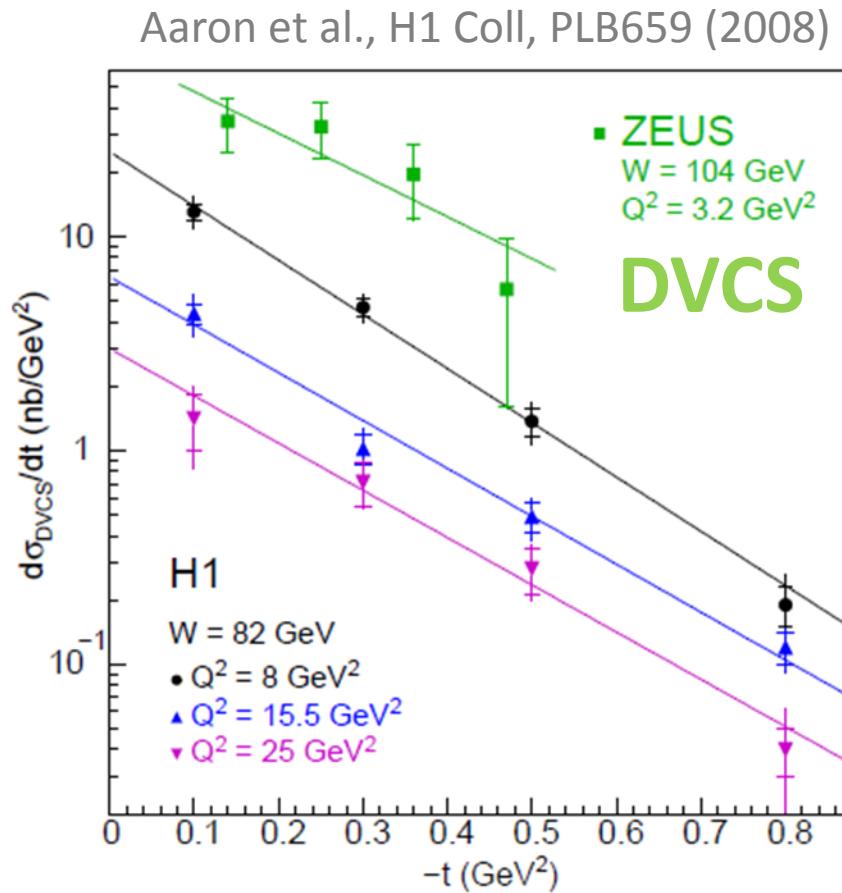
Flux for transverse virtual photons



# Gluon or sea quark imaging @ HERA

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

$B'$  is related to the transversed size of the scattering objects

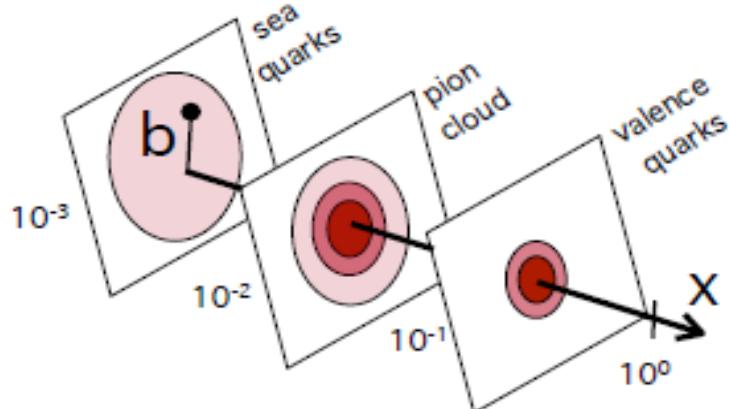
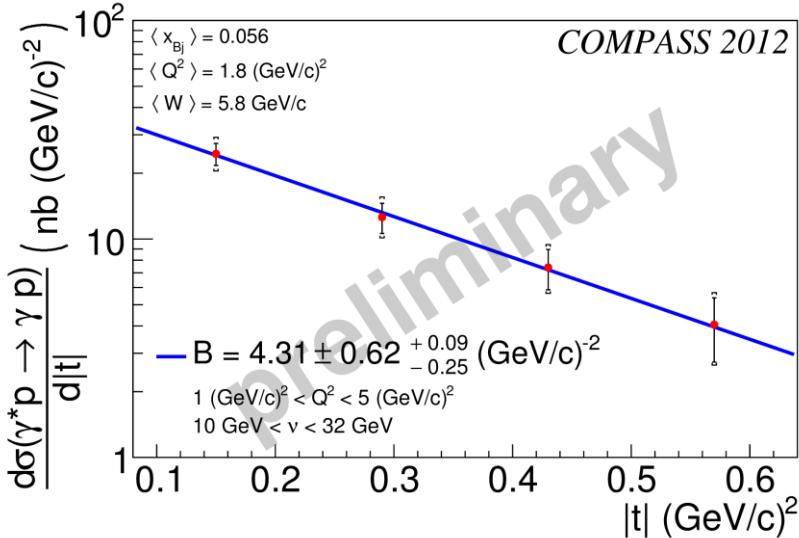


$$\langle r_\perp^2(x_B) \rangle \approx 2 B'(x_B)$$

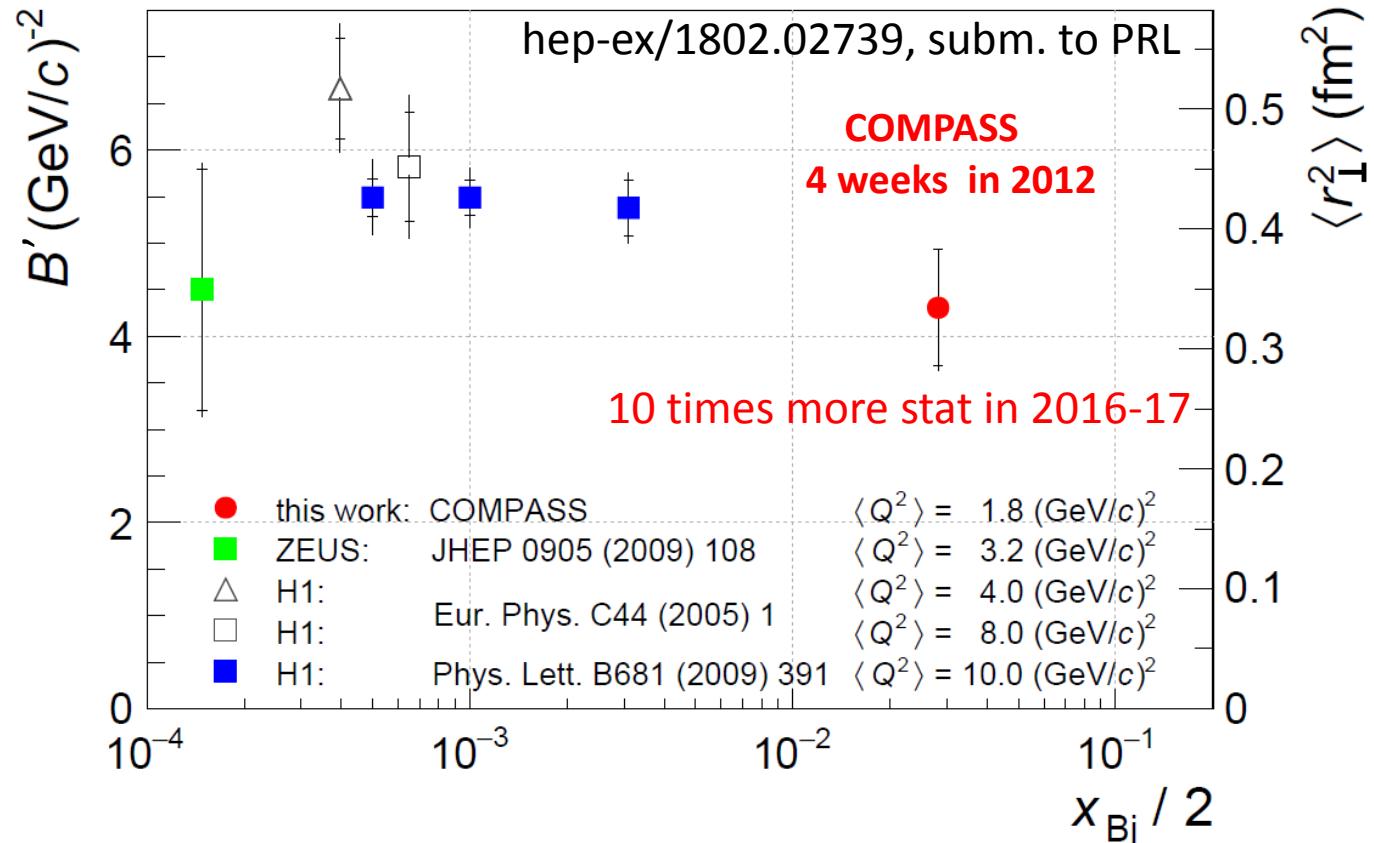
$$\sqrt{\langle r_\perp^2 \rangle} = 0.65 \pm 0.02 \text{ fm}$$

# Sea quark imaging @ COMPASS

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



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



$$B' = (4.31 \pm 0.62_{\text{stat}} \pm 0.09_{\text{sys}}) (\text{GeV}/c)^{-2}$$

$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}}) \text{ fm}$$

# proton tomography or parton distributions in transv plane

**Unpol. DVCS x-section** mostly sensitive to  
 $\text{Im} \mathcal{H}(\xi, t) \propto H(\xi, \xi, t)$  and  $\xi \sim x_B/2$

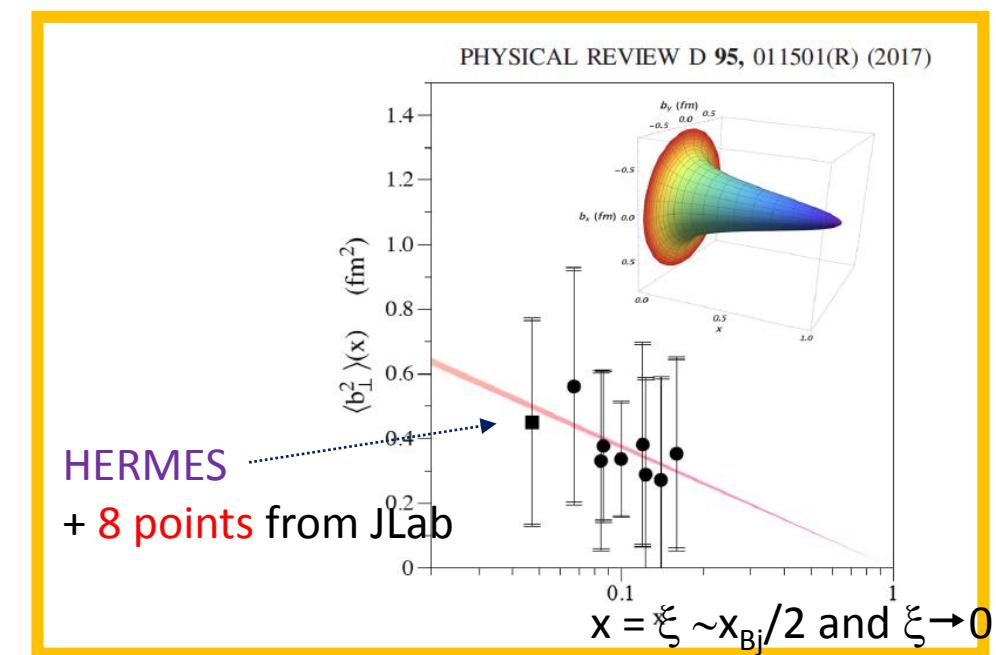
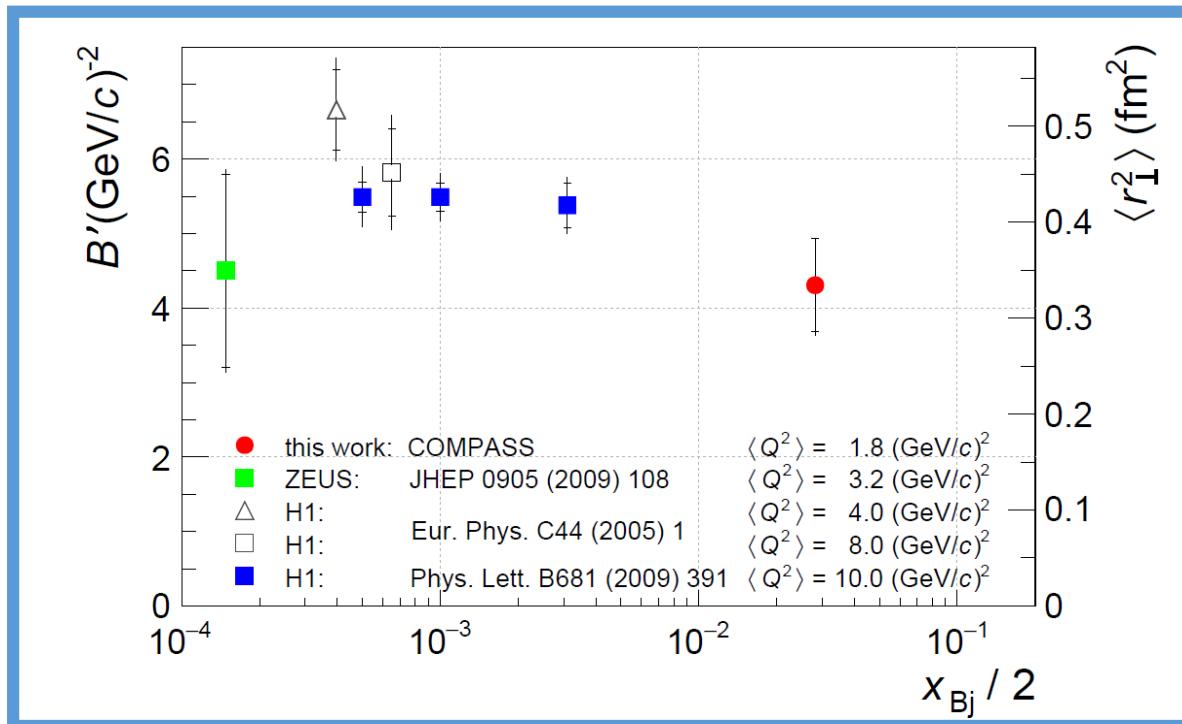
$$\langle b_\perp^2(x) \rangle^f = -4 \frac{\partial}{\partial t} \ln H^f(x, 0, t) \Big|_{t=0}$$

$$d\sigma_{\text{DVCS}}/dt \propto e^{-B'|t|} \rightarrow \langle r_\perp^2(x_B) \rangle \approx 2B'(x_B)$$

$$H(x, 0, t) \propto e^{-B_0(x)|t|} \quad \langle b_\perp^2(x) \rangle = 4B_0(x)$$

$$H(x = \xi, \xi, t) \propto e^{-B(\xi)|t|} \quad \langle r_\perp^2(\xi) \rangle = 4B(\xi)$$

Model dependent



# **What will come in the next Future?**

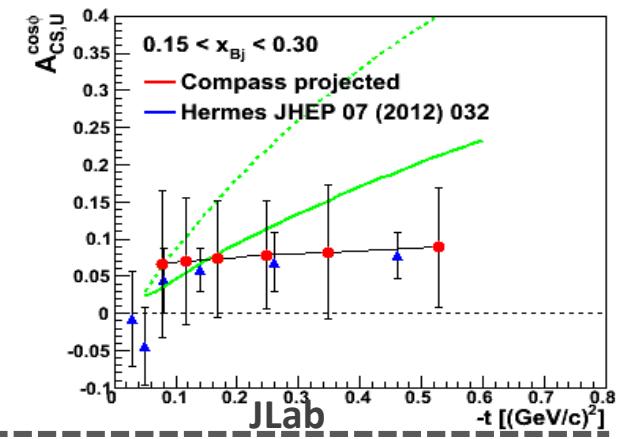
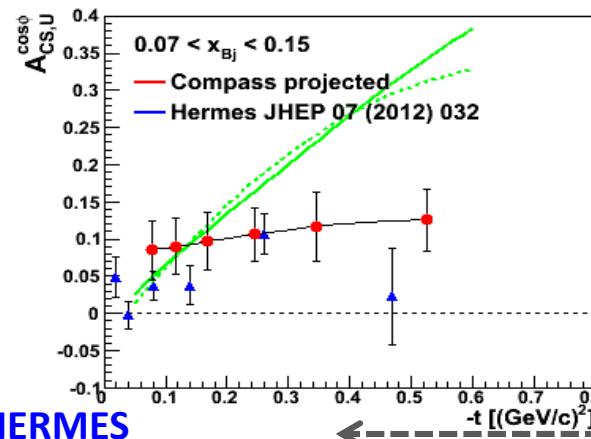
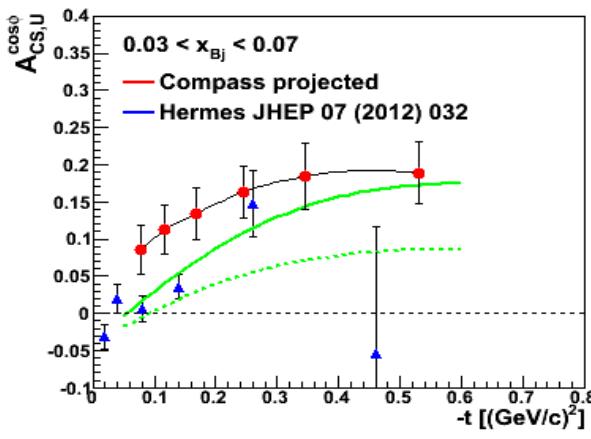
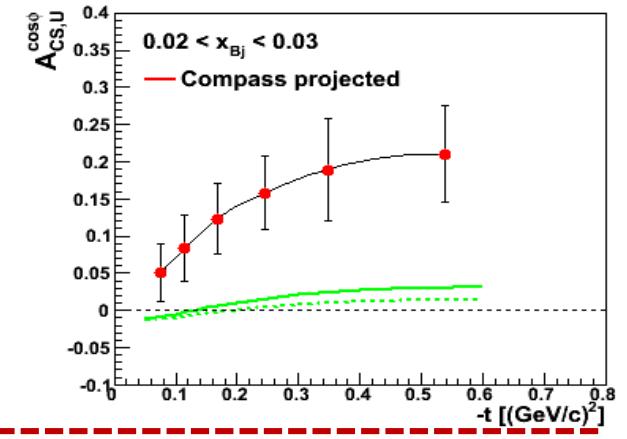
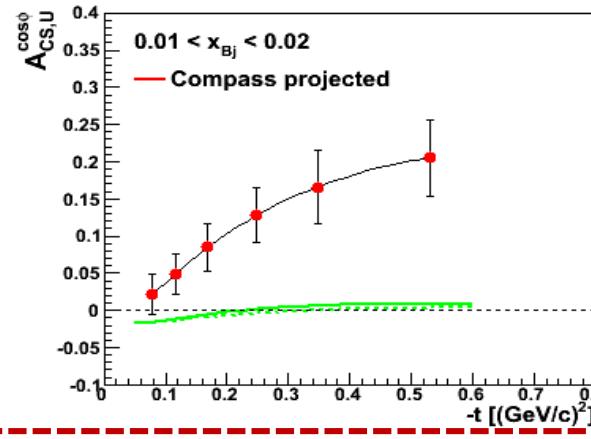
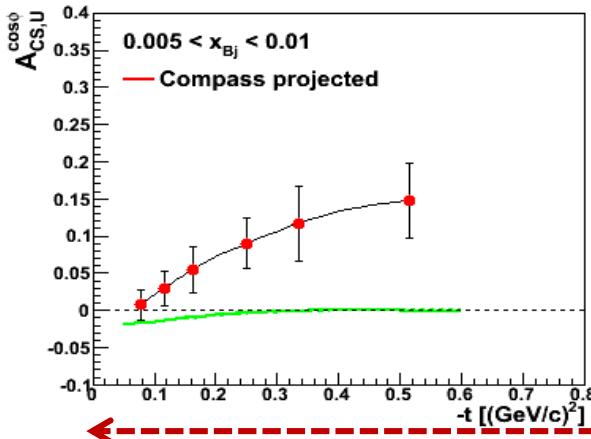
# Beam Charge and Spin Diff. @ COMPASS

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\leftarrow^+} - d\sigma^{\leftarrow^-} = 2[d\sigma_{pol}^{DVCS} + \text{Re } I] \xrightarrow{L.T.} c_0^I + c_1^I \cos \phi$$

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

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

Predictions with  
**VGG**  
**D.Mueller KM10**



COMPASS 2 years of data  $E\mu = 160 \text{ GeV}$   $1 < Q^2 < 8 \text{ GeV}^2$

# Future Beam Spin Sum and Diff @JLab12

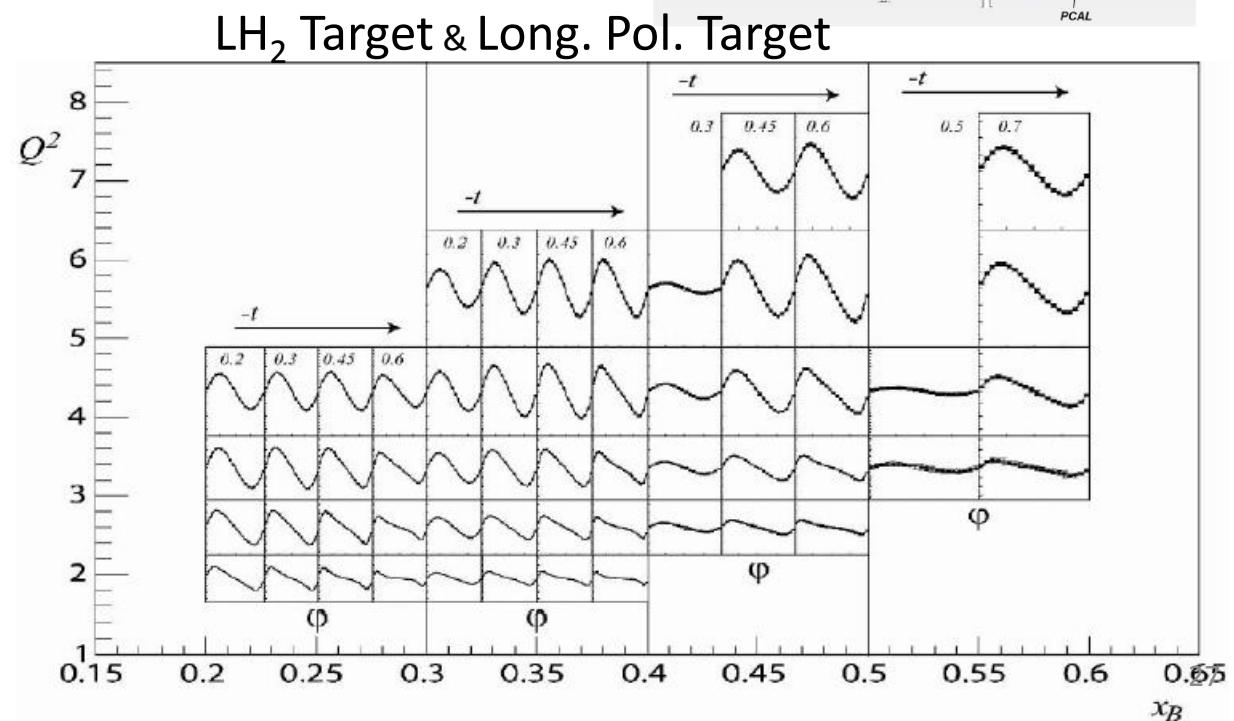
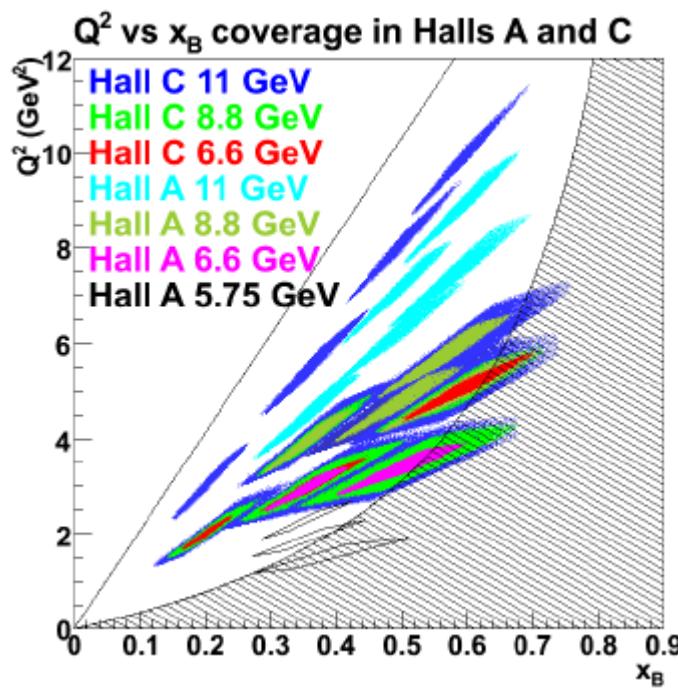
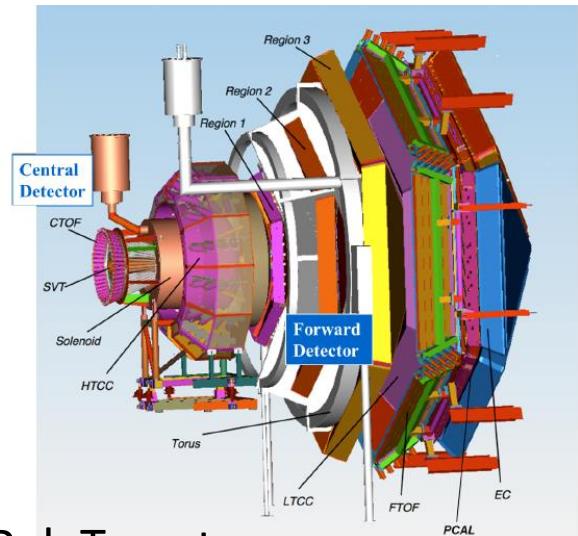
with high resolution magnetic spectrometer  
+ Calorimeter in Halls A and C

done in 2016-17: Hall A: E12-06-119  
~2020: Hall C: E12-13-010

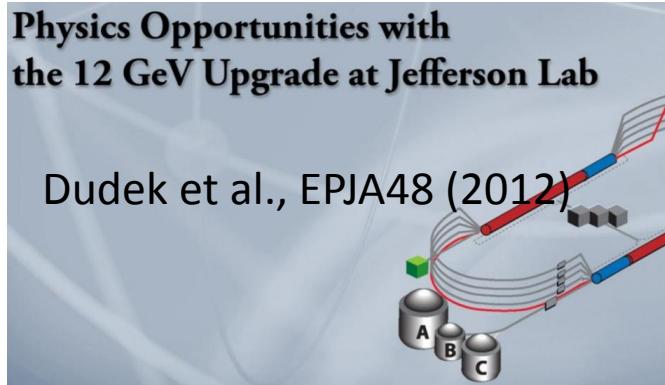
Different beam energies for a  
Rosenbluth-like DVCS<sup>2</sup>/Interf. separation

with CLAS12  
Started now

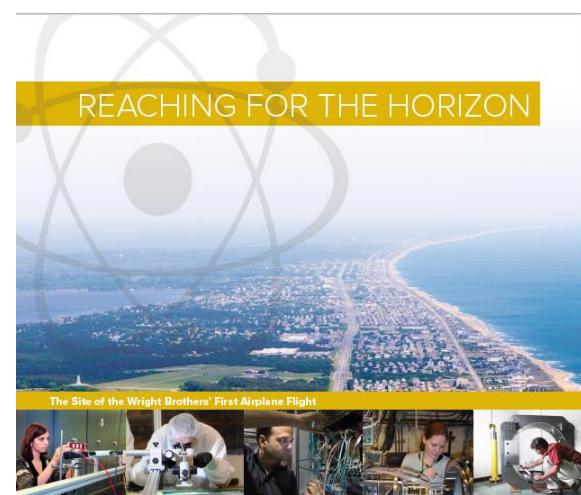
E12-06-119



# Future Beam Spin Sum and Diff @JLab12



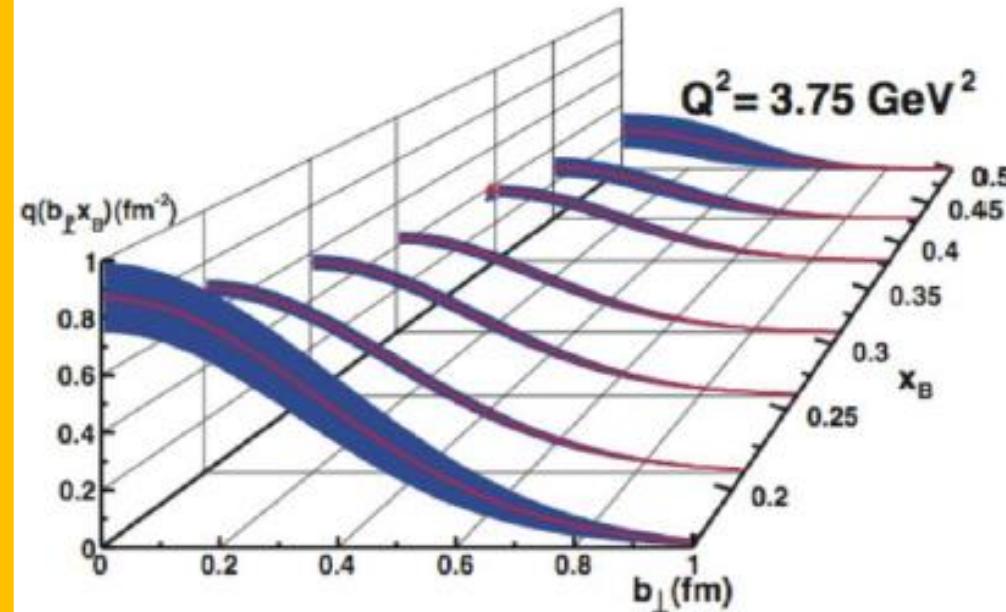
## Projection for Jlab 12 GeV



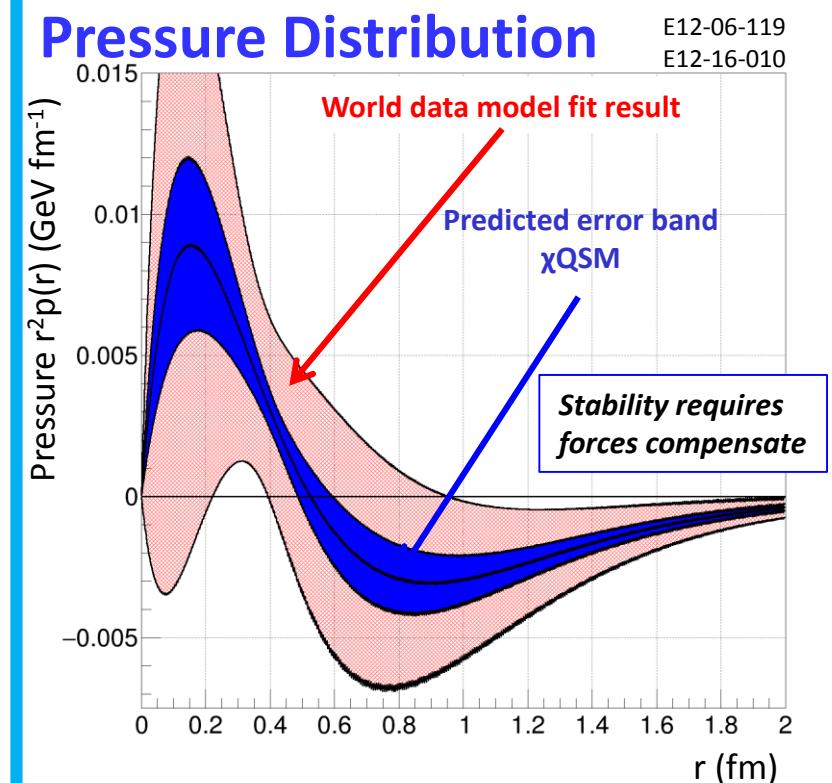
The 2015  
LONG RANGE PLAN  
for NUCLEAR SCIENCE



### Transverse profile



### Pressure Distribution



**And for the GPD E,  
the holy grail for Orbital Angular Momentum?**

# GPD E from Jlab 6 GeV and HERMES

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

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

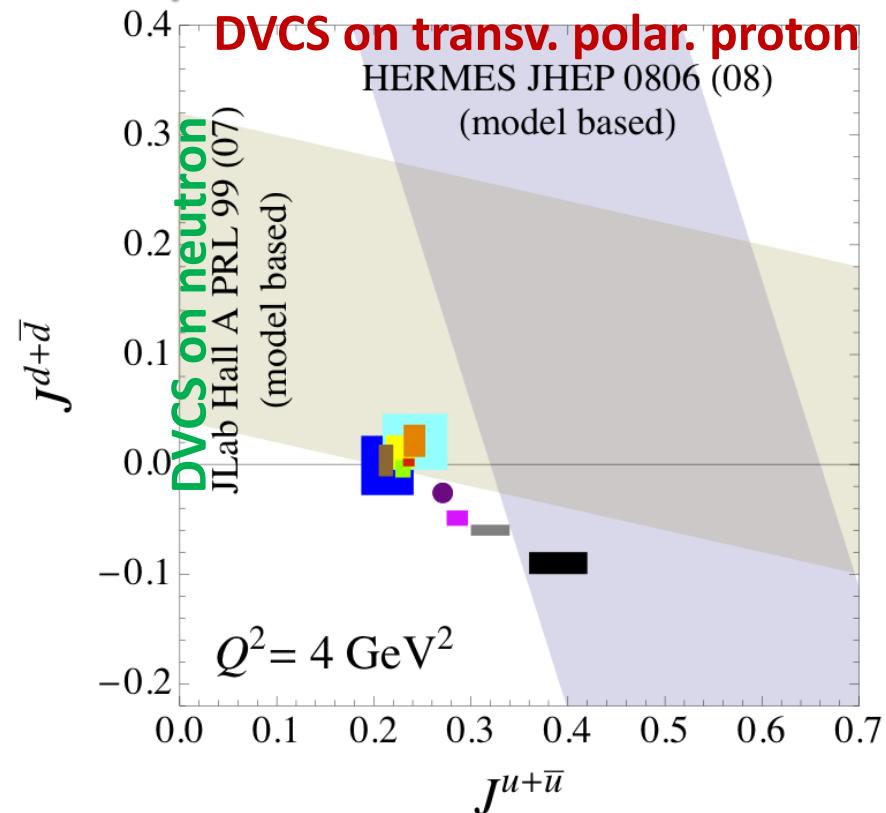
$$\Delta\sigma_{LU}^{\sin\phi} = \text{Im} (F_{1n}\mathcal{H} + \xi(F_{1n} + F_{2n})\tilde{\mathcal{H}} + t/4m^2 F_{2n}\mathcal{E})$$

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

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

analysis still on going for another experiment done in 2010

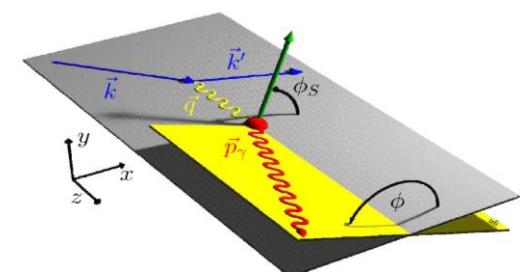
## Model dependent extraction of $J^u$ and $J^d$



- [Light Blue Box] Goloskokov & Kroll, EPJ C59 (09) 809
- [Brown Box] Diehl et al., EPJ C39 (05) 1
- [Purple Box] Guidal et al., PR D72 (05) 054013
- [Magenta Box] Liuti et al., PRD 84 (11) 034007
- [Orange Box] Bacchetta & Radici, PRL 107 (11) 212001
- [Dark Blue Box] LHPC-1, PR D77 (08) 094502
- [Red Box] LHPC-2, PR D82 (10) 094502
- [Yellow Box] QCDSF, arXiv:0710.1534
- [Yellow Box] Wakamatsu, EPJ A44 (10) 297
- [Black Box] Thomas, PRL 101 (08) 102003
- [Grey Box] Thomas, INT 2012 workshop

Dudek et al., EPJA48 (2012)

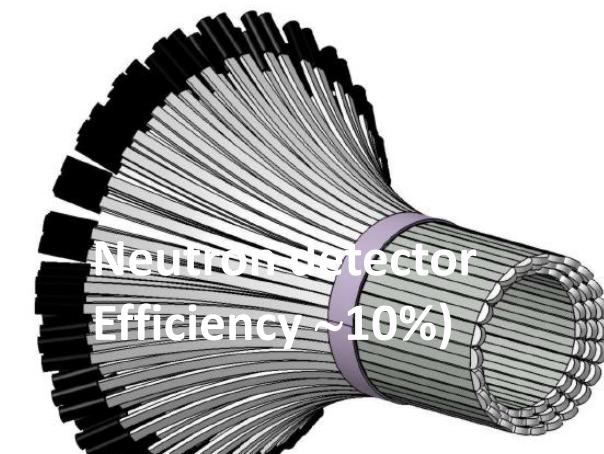
LATTICE QCD



# GPD E at Jlab 11 GeV with CLAS12

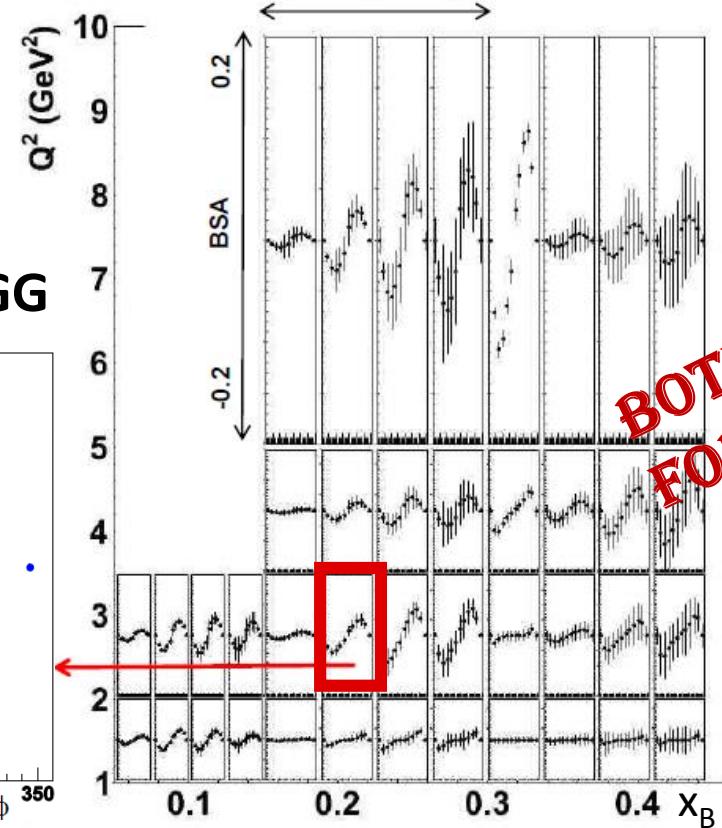
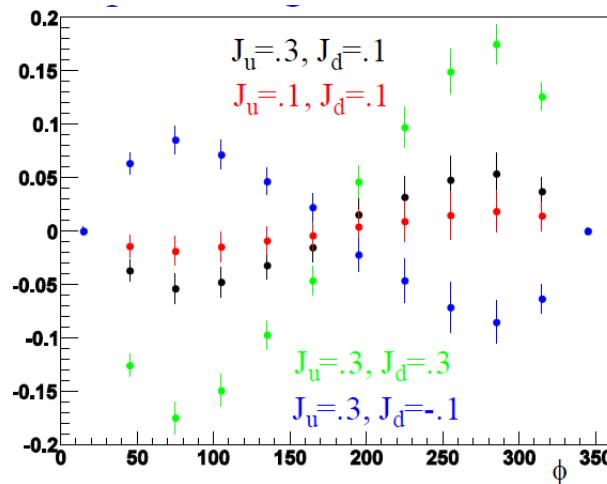
Exp E12-11-003: DVCS on the neutron

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



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

Model prediction using VGG



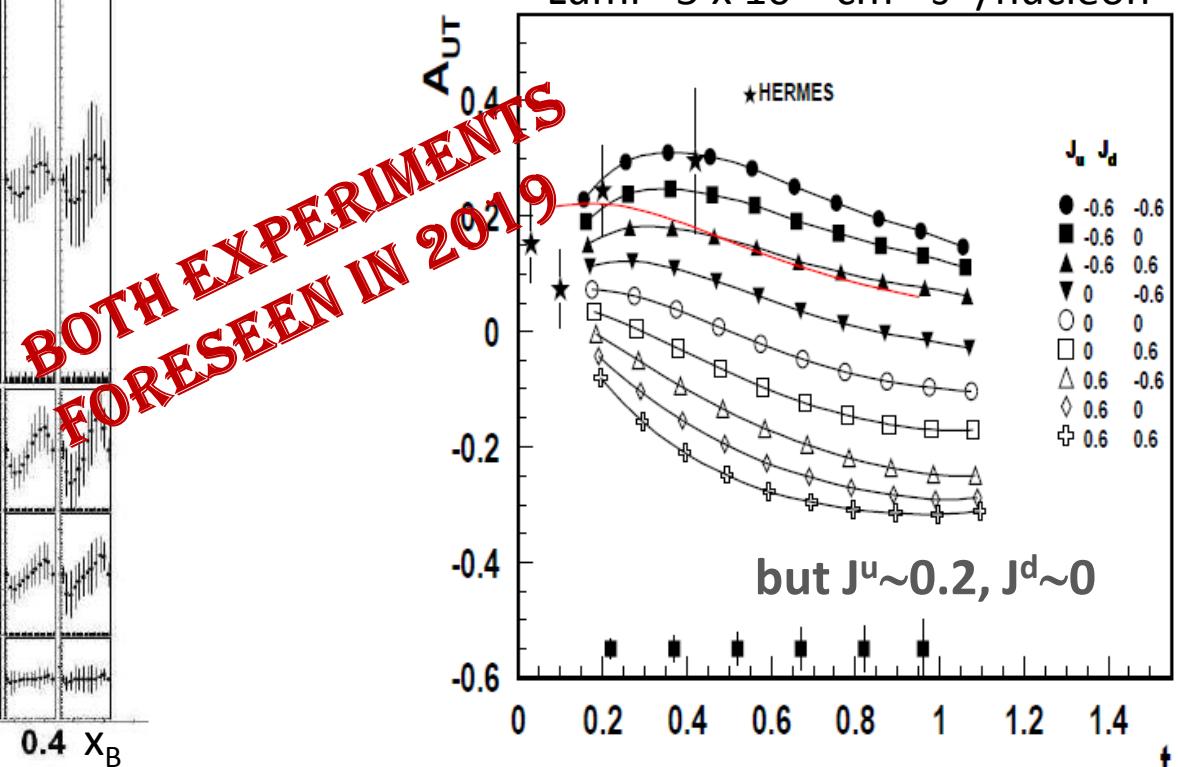
Exp E12-12-010: DVCS on a transversely

polarized HD-Ice target Pol H = 60% Pol D = 35%

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

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

110 days on HD-Ice target  
Lumi=  $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}/\text{nucleon}$



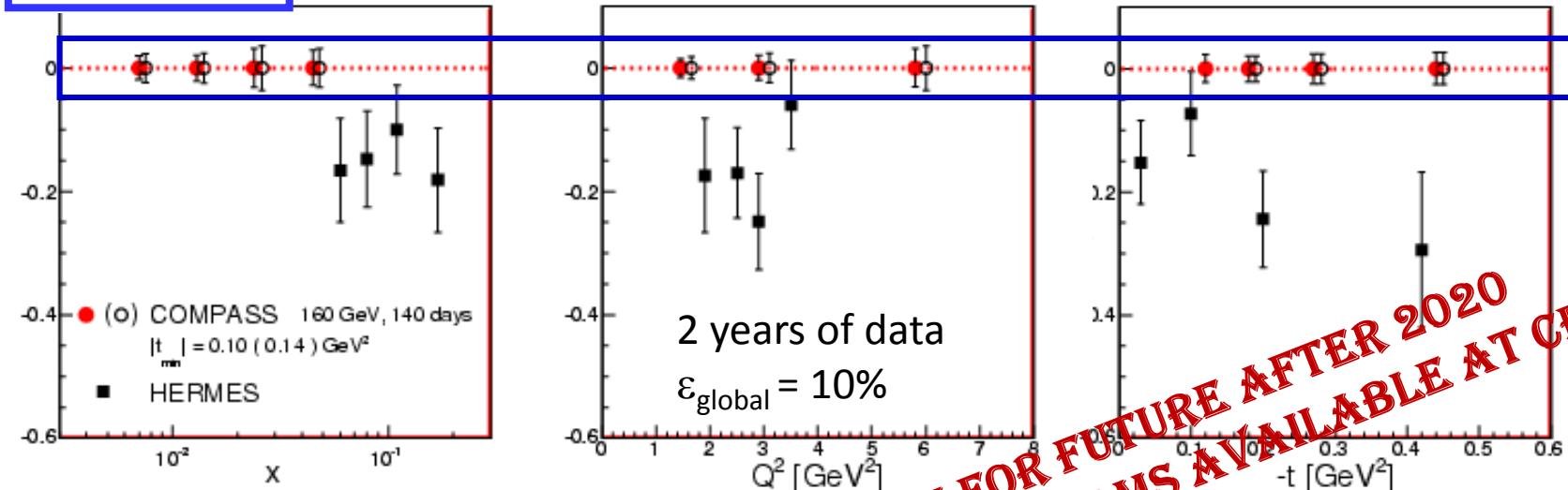
# GPD E at COMPASS 160 GeV with $\mu^+$ and $\mu^-$

$$\mathcal{D}_{CS,T} \equiv \sigma_T(\mu^{+\downarrow}) - \sigma_T(\mu^{-\uparrow})$$

$$\propto \text{Im}(\mathcal{F}_2 \mathcal{H} - \mathcal{F}_1 \mathcal{E}) \sin(\phi - \phi_s) \cos \phi$$

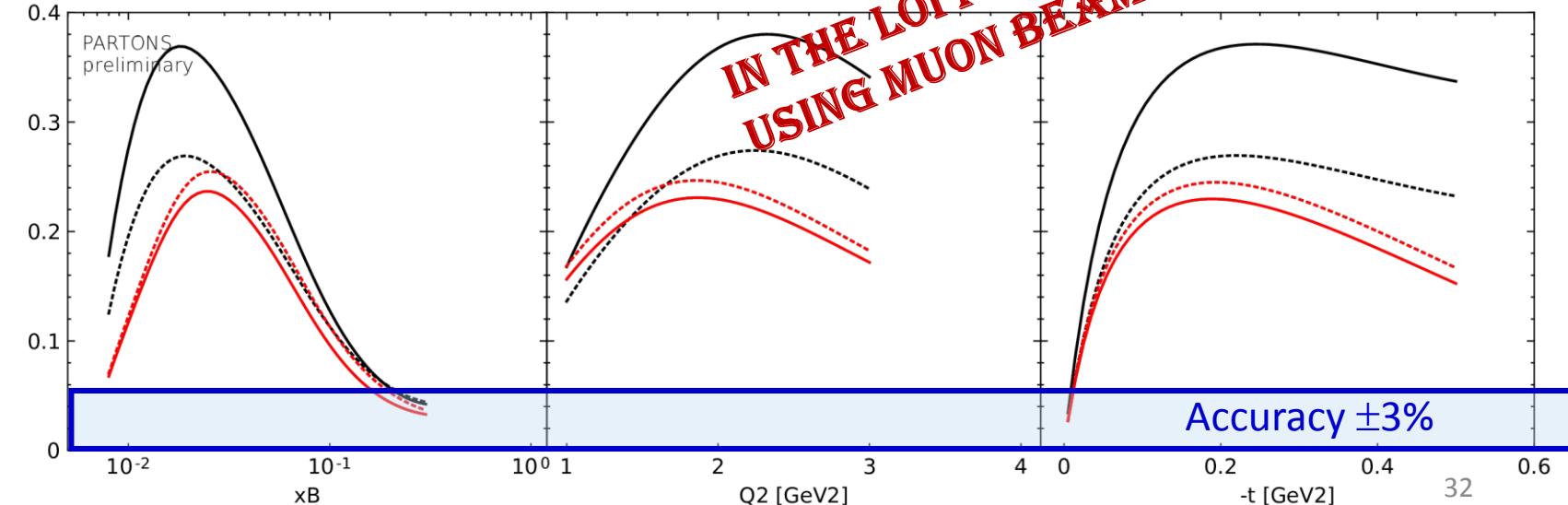
$$A_{CS,T}^{\sin(\phi-\phi_s)\cos\phi}$$

DVCS on a 1.2m long transversely polarized  $\text{NH}_3$  target

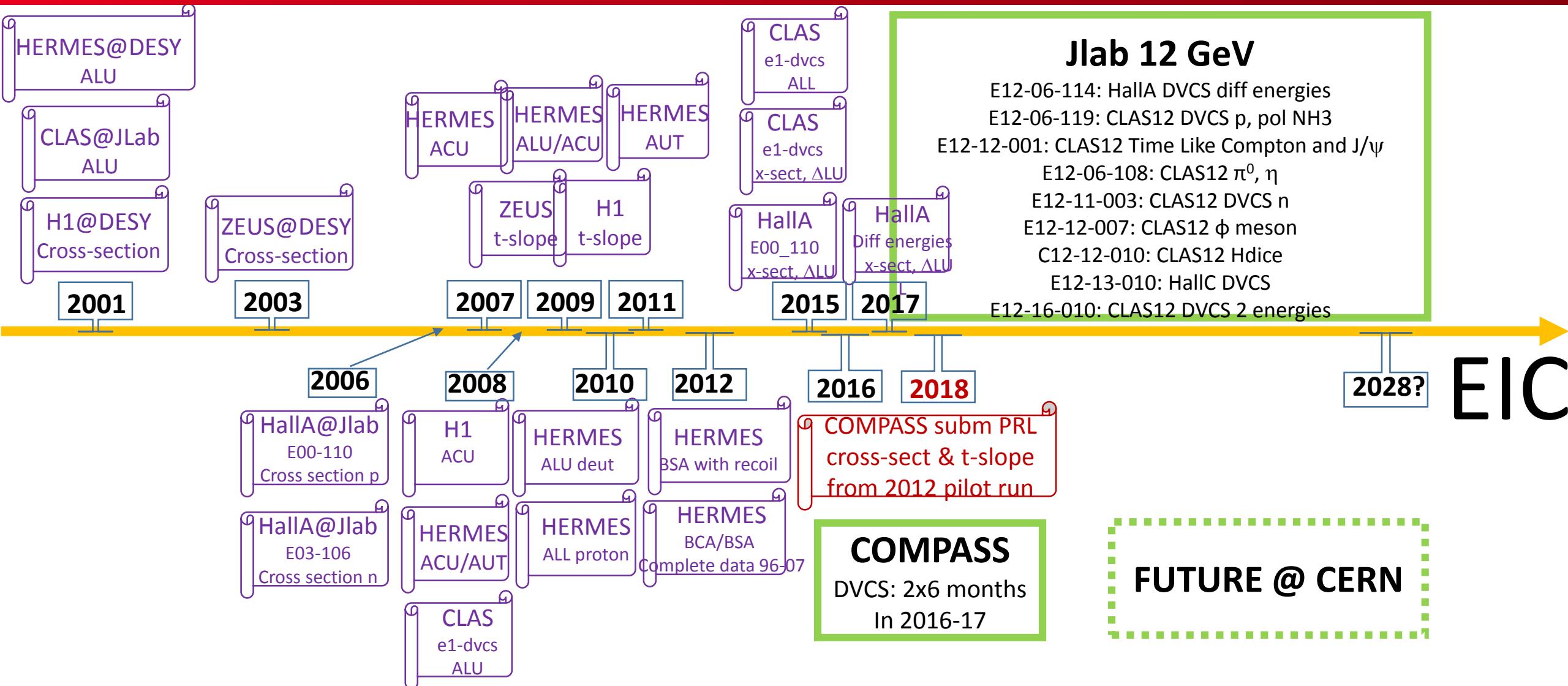


From Paweł Sznajder  
Using the PARTONS code  
Formalism at LO

- GK and CFFs@LO
- - - Idem with GPDs  $E = 0$
- VGG and CFFs@LO
- - - Idem with GPDs  $E = 0$



# DVCS publications and data taking over the years



Not exhaustive list

# Conclusions

DVCS is a very rich and delicate tool to study GPDs, mainly  $H$ ,  $\tilde{H}$  and  $E$ .  
With the BH and the beam energy we can reveal different facets.

However we have not to forget the numerous results with meson production  
(related also to chiral odd or transverse GPDs).

In the next future:

- Jlab 12 GeV will perfectly investigate the valence quarks at large  $x_B$
- COMPASS with high energy muon beams at CERN (and RHIC with Ultra Peripheral Collisions)  
will provide first results of sea quarks and gluons at small  $x_B$

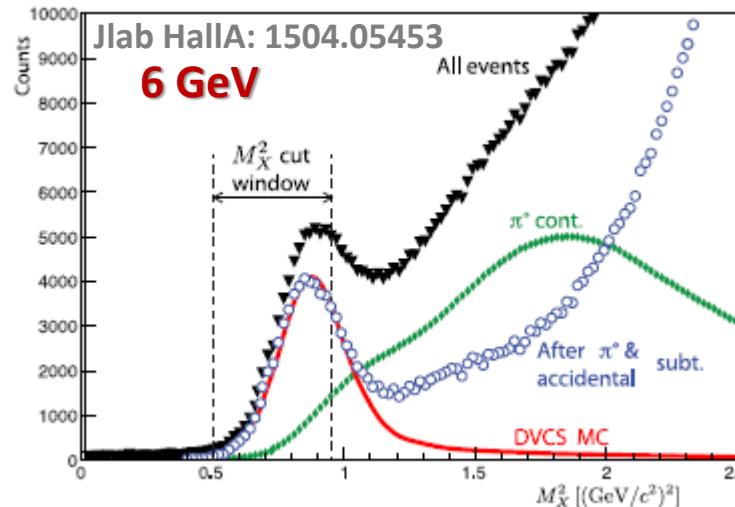
All these facilities are physics opportunities prior EIC to preserve knowledge on state of the art techniques and to prepare the next generation of leading new experiments at EIC



# Exclusivity in fixed target: $\ell^- p \rightarrow \ell^- + \gamma + p_{\text{slow}}$

$$M_x^2 = (P_\ell + P_p - P_\ell - P_\gamma)^2$$

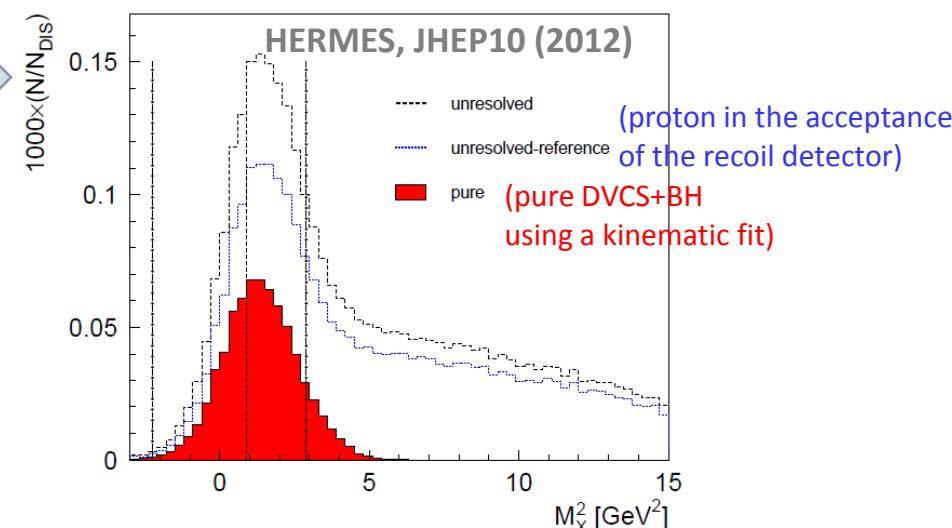
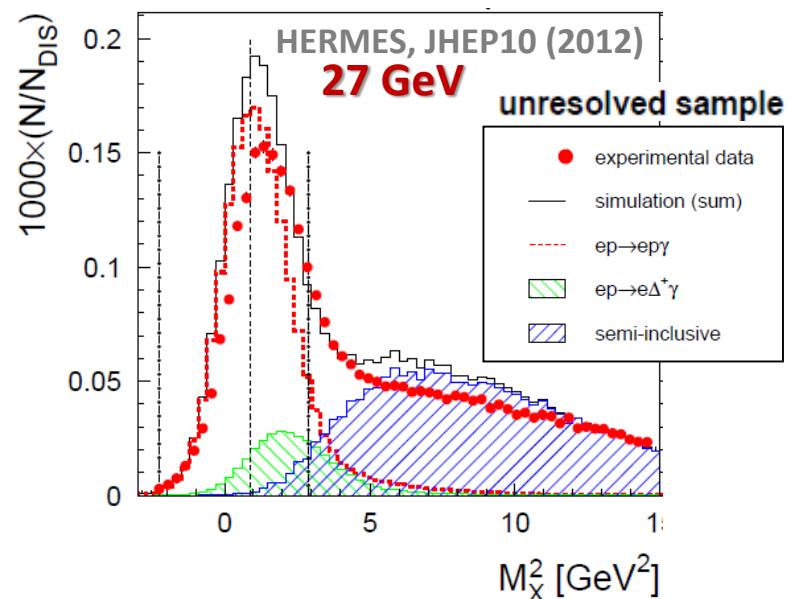
$\Delta M_x^2$  increases with the beam energy !



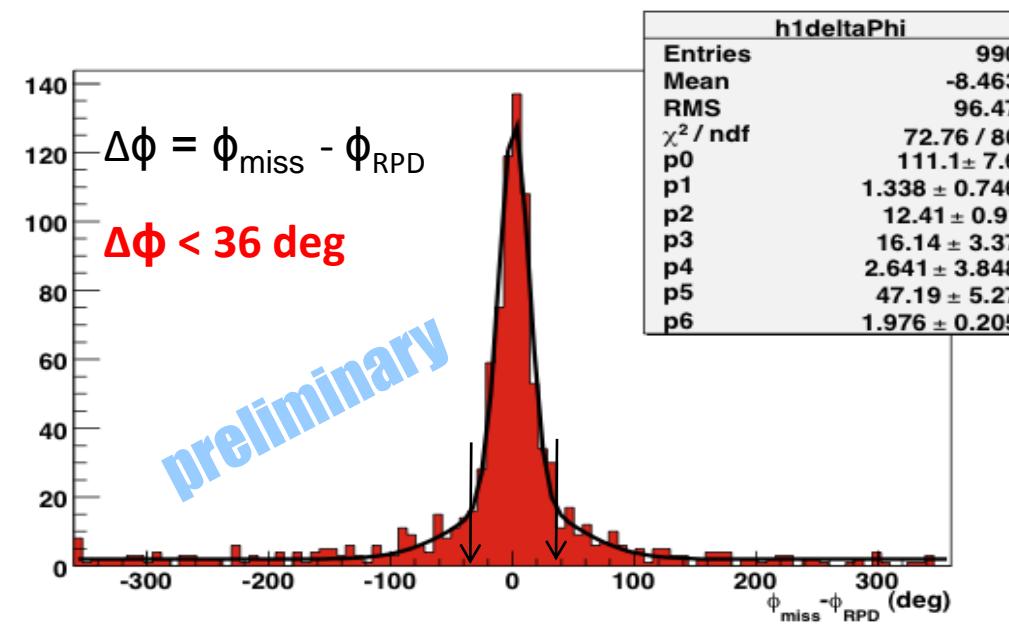
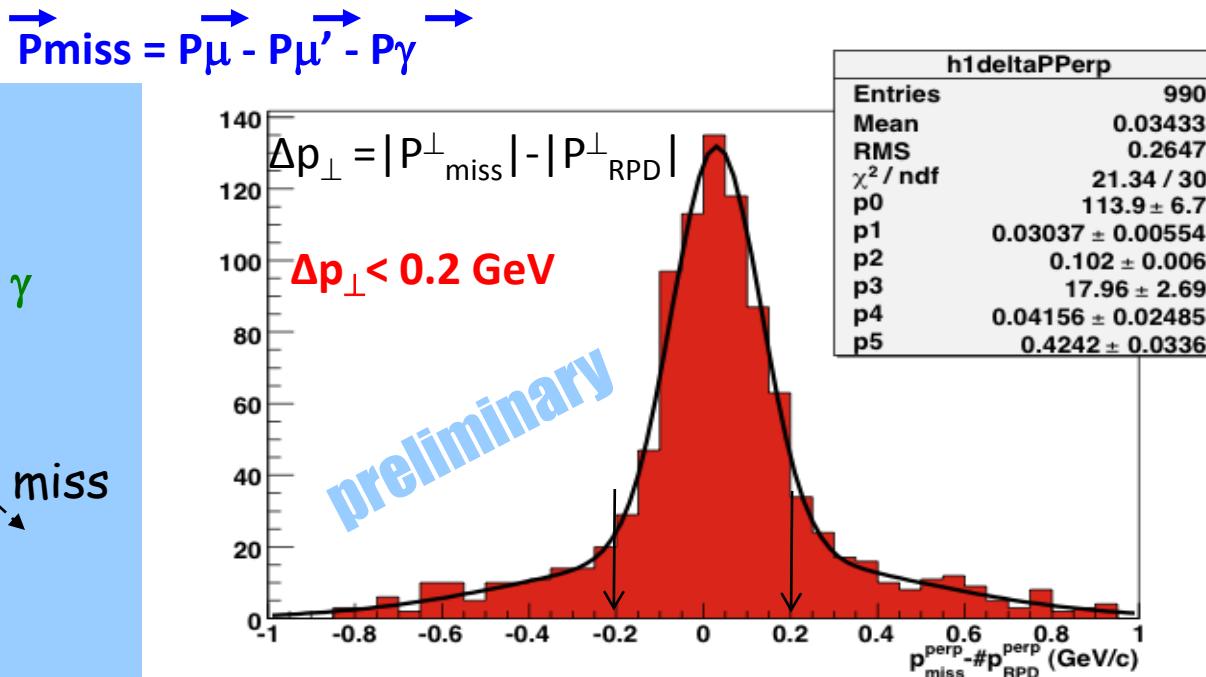
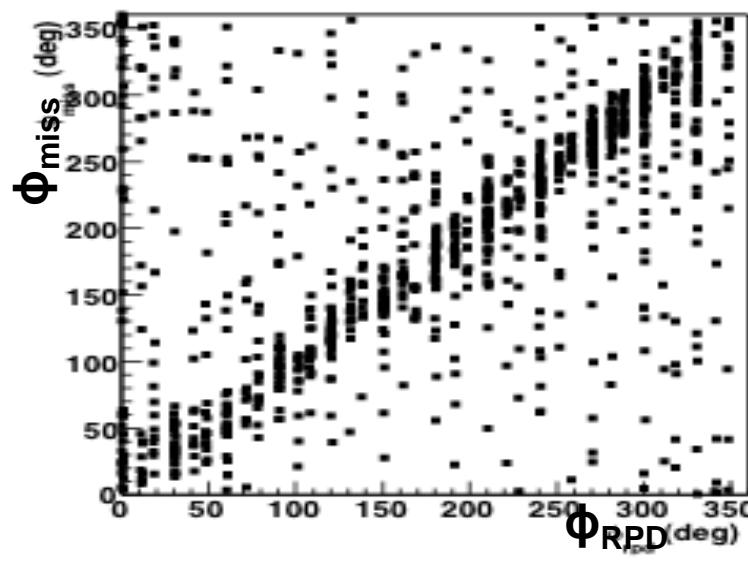
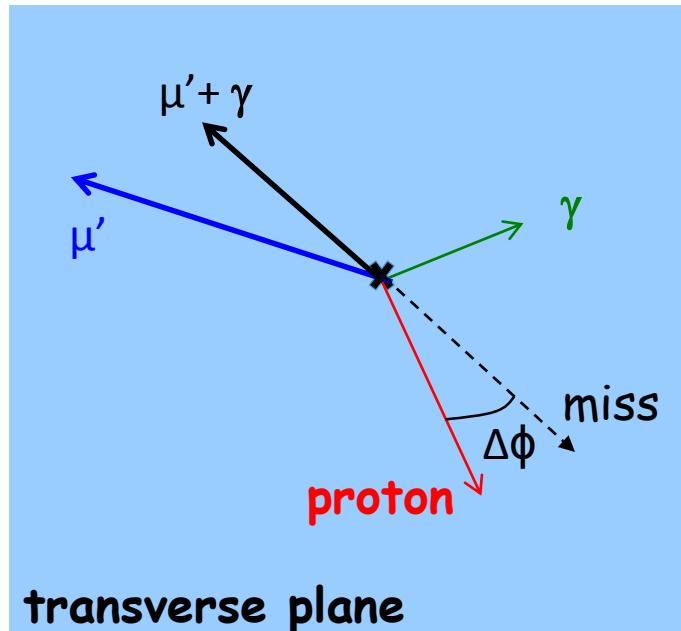
$\ell^- p \rightarrow \ell' + \gamma (+p')$  for DVCS + BH

Contamination from  $\pi^0$  decay:

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

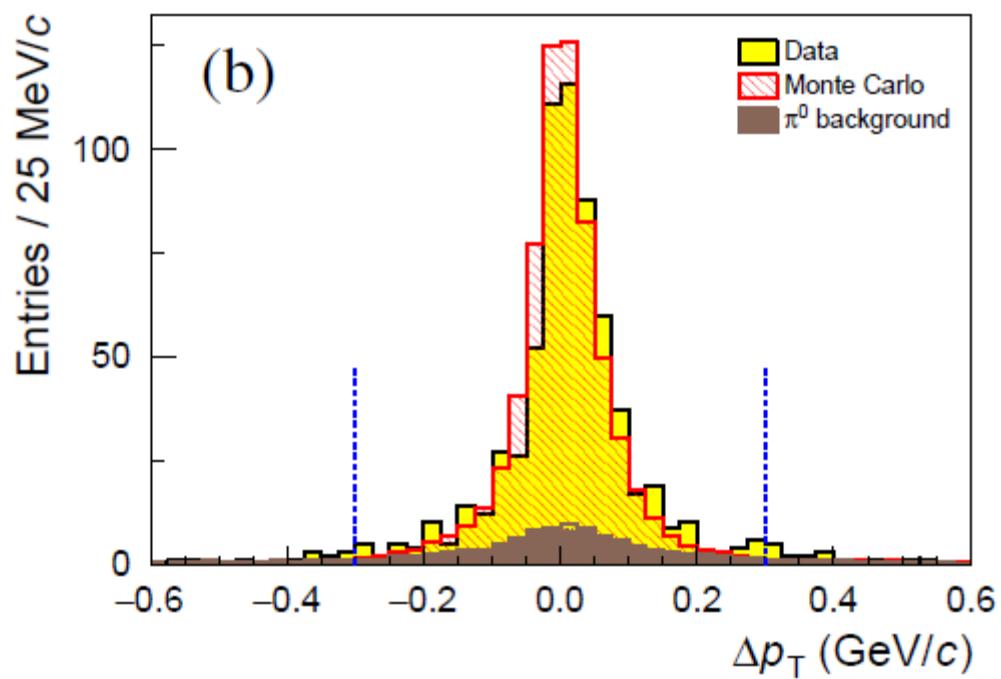
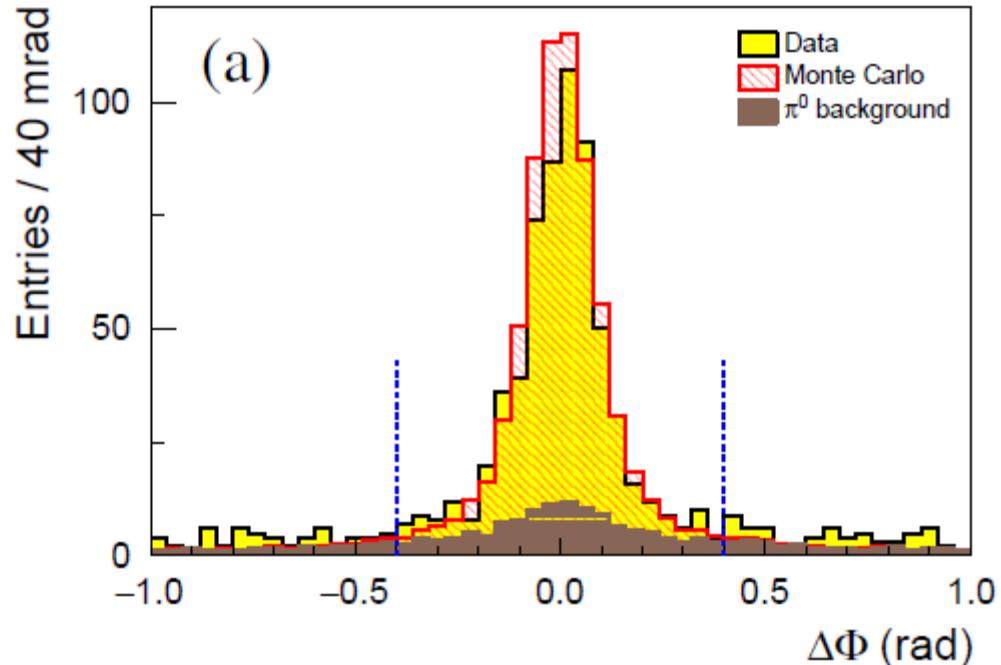


# Kinematic constraints in the transverse plane



COMPASS  
2009 data

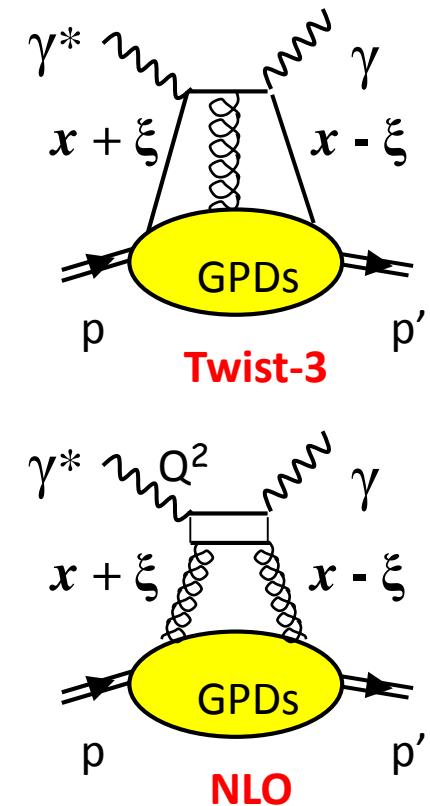
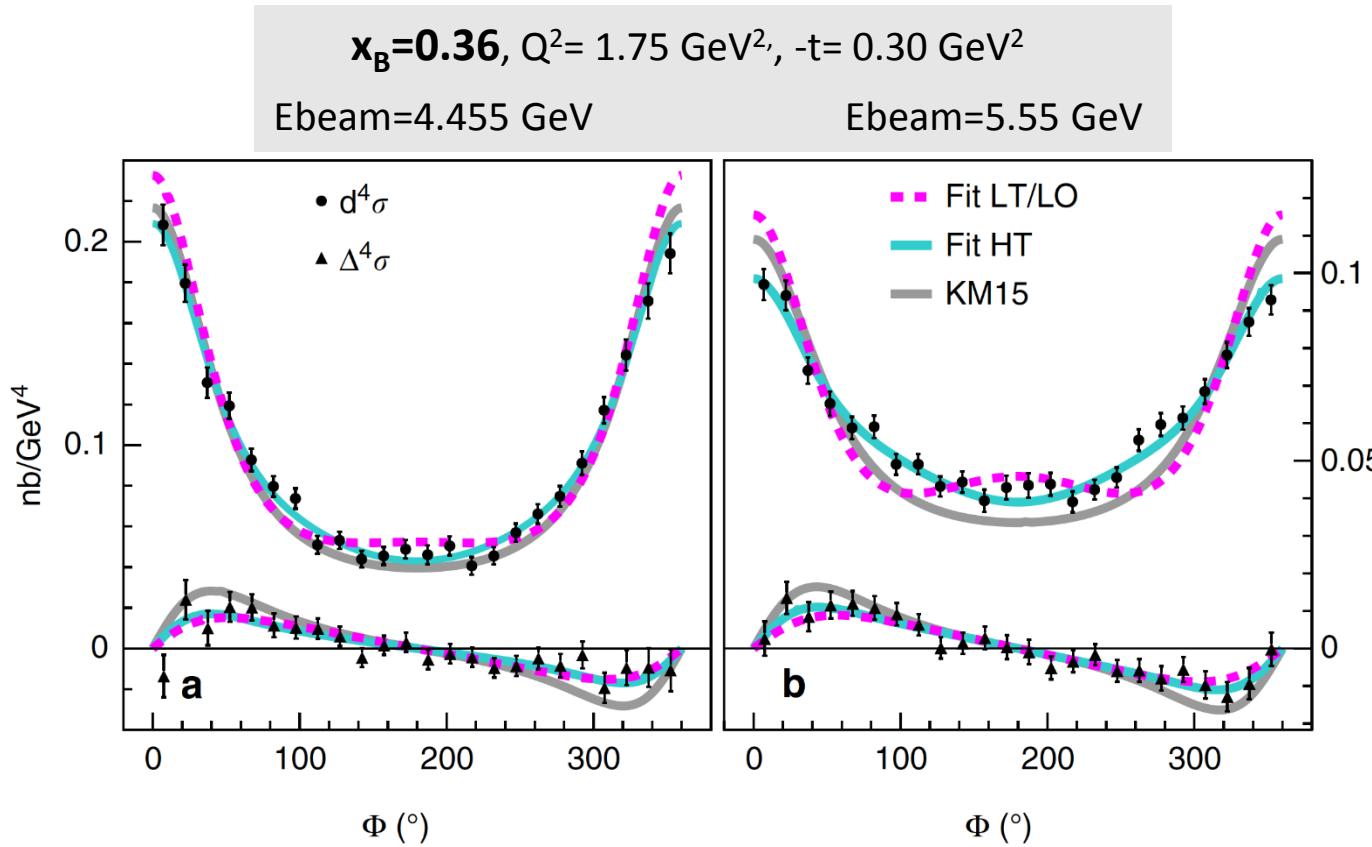
COMPASS 2012 data  
published result in 2017



# Beam Spin Sum and Diff of DVCS - HallA

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

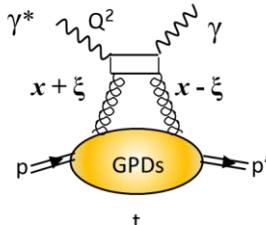
Defurne et al. Nature Communications 8 (2017) 1408, arXiv:1703.09442



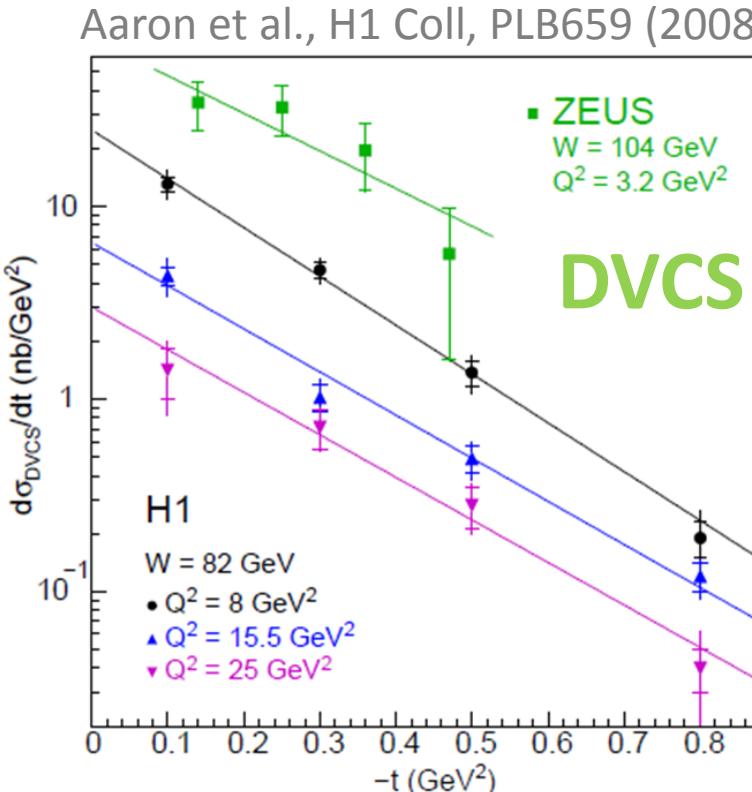
NLO gives the same result **in Cyan**

# Gluon imaging @ HERA

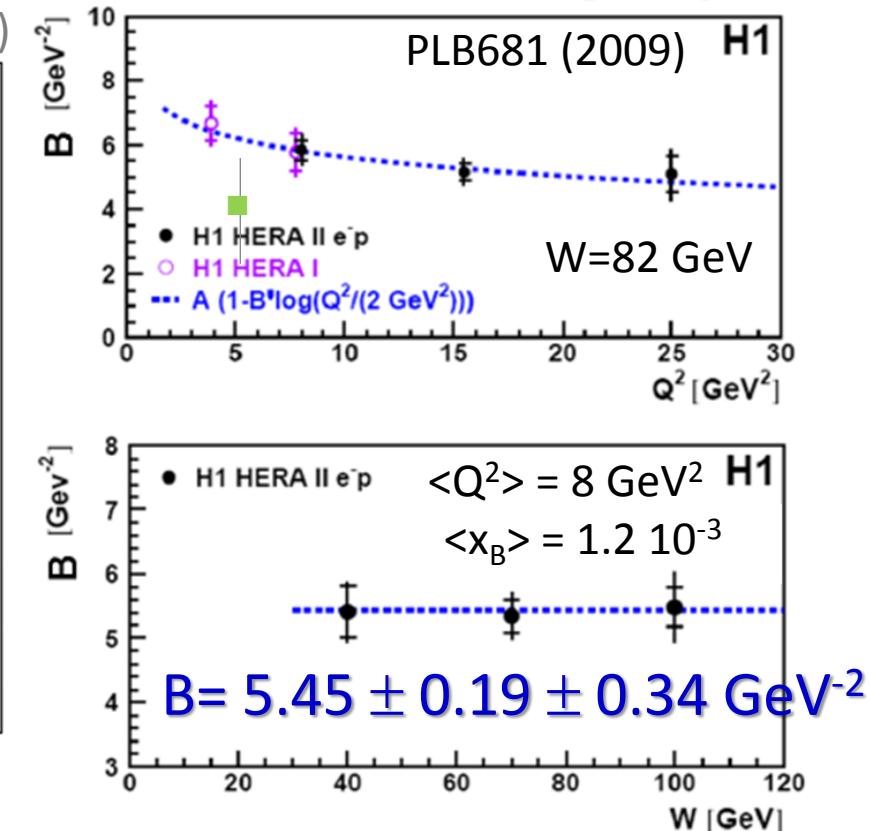
$$d\sigma^{DVCS}/dt = e^{-B|t|}$$



ZEUS-H1  
Data collected  
1995-2007



B is related to the transversed size of the scattering objects



$$\langle r_\perp^2 \rangle \approx 2B$$

$$\sqrt{\langle r_\perp^2 \rangle} = 0.65 \pm 0.02 \text{ fm}$$

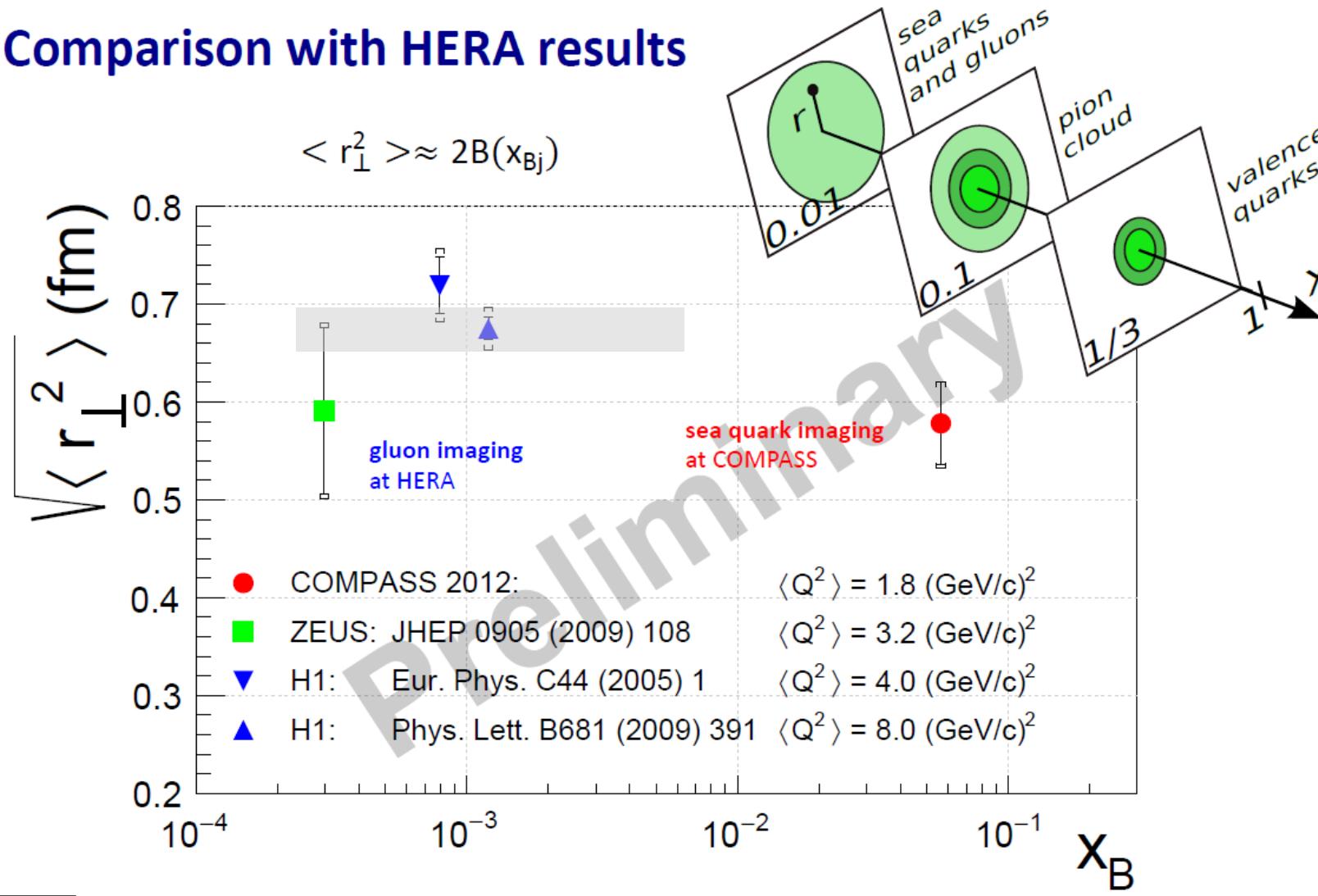
to be compared to

$$\sqrt{\frac{4}{dt} F_1^p} \stackrel{t=0}{=} 0.67 \pm 0.01 \text{ fm}$$

$$\text{not to } \sqrt{\frac{4}{dt} G_E^p} = 0.72 \pm 0.01 \text{ fm}$$

# Proton « radius » measured at COMPASS

## Comparison with HERA results



$$\sqrt{\langle r_{\perp}^2 \rangle} \text{ to be compared to } \sqrt{4 \frac{d}{dt} F_1^p} \Big|_{t=0} = 0.66 \pm 0.01 \text{ fm}$$

$$+ \sqrt{\kappa/m_p^2} \sqrt{4 \frac{d}{dt} G_E^p} \Big|_{t=0} = 0.72 \pm 0.01 \text{ fm}$$

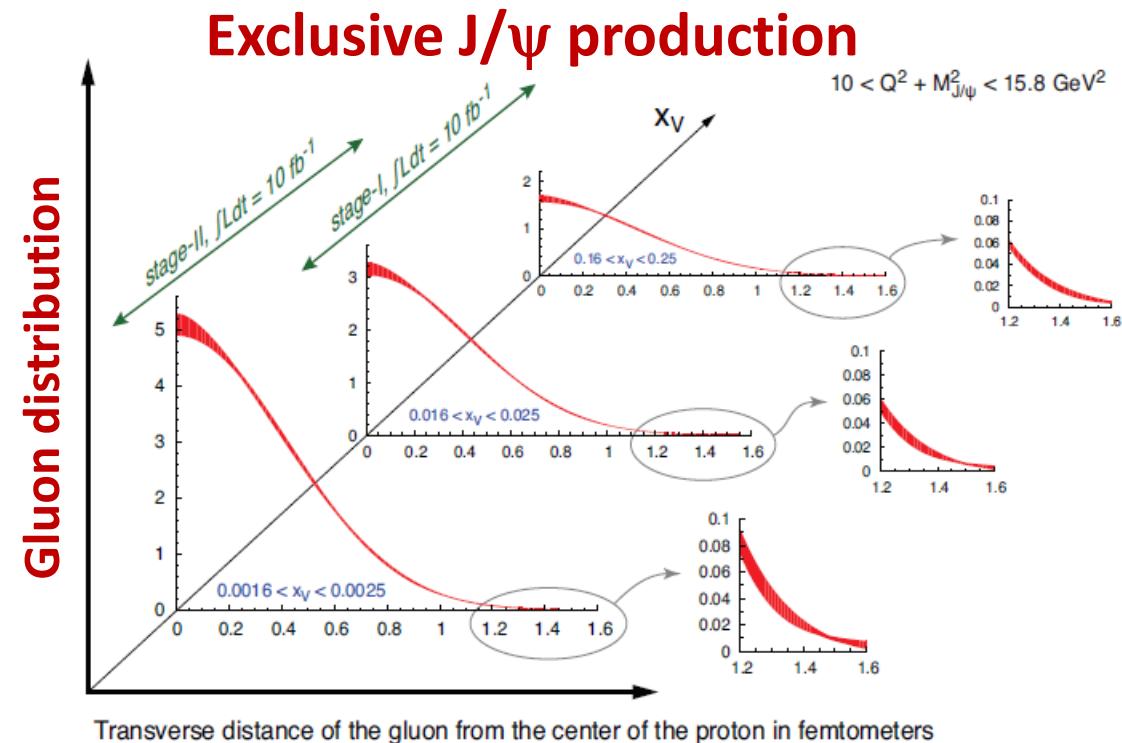
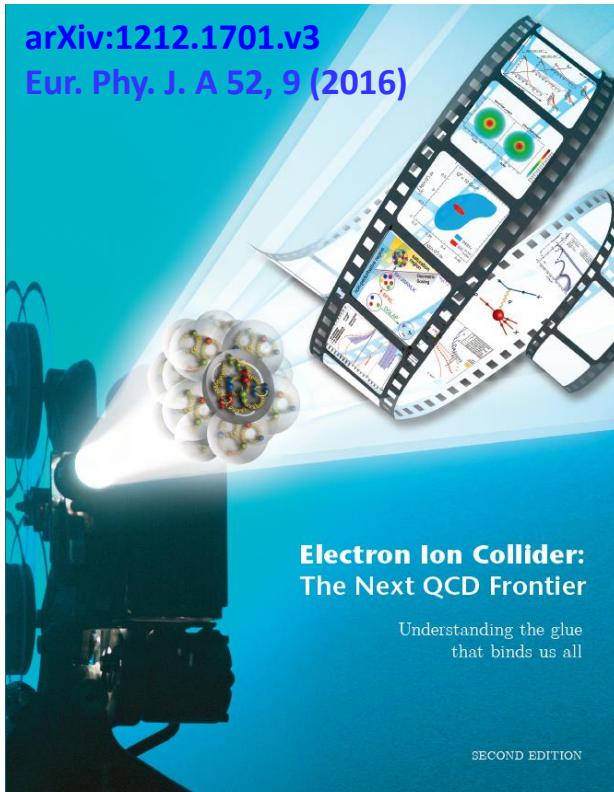
$$r_p = 0.88 \text{ fm}$$

# Key measurements for imaging partons with EIC

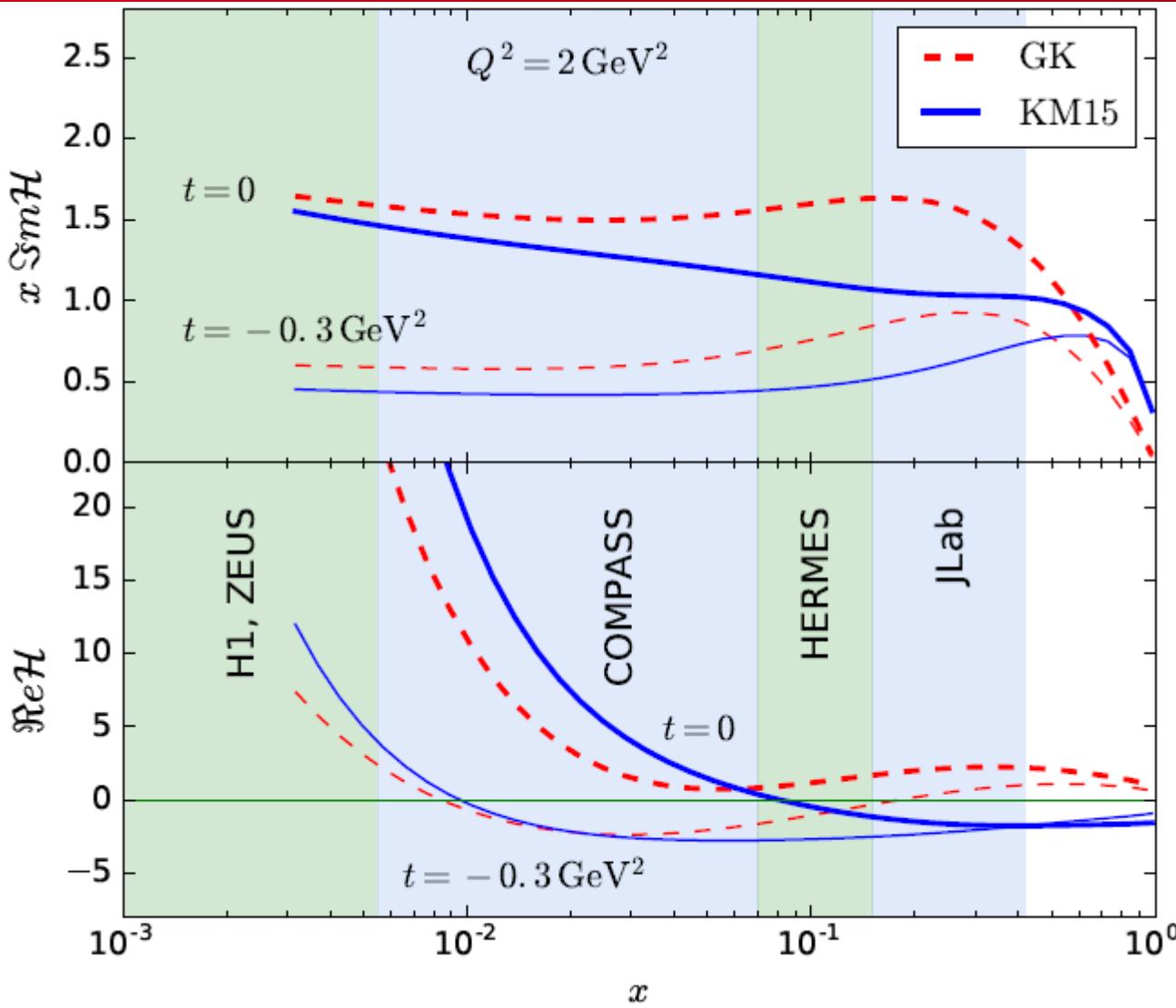
**Stage 2**  
**Ee=20 GeV Ep=250 GeV**

**Stage 1**  
**Ee=5 GeV Ep=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	$\int dt L \sim 10 \text{ to } 100 \text{ fb}^{-1}$ ; 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 $\pi^+, K$ and $\rho^+, K^*$	dependence on quark flavor and polarization	



# Present knowledge of the GPD H in global analysis



$\Im m \mathcal{H}$   
is rather  
well known

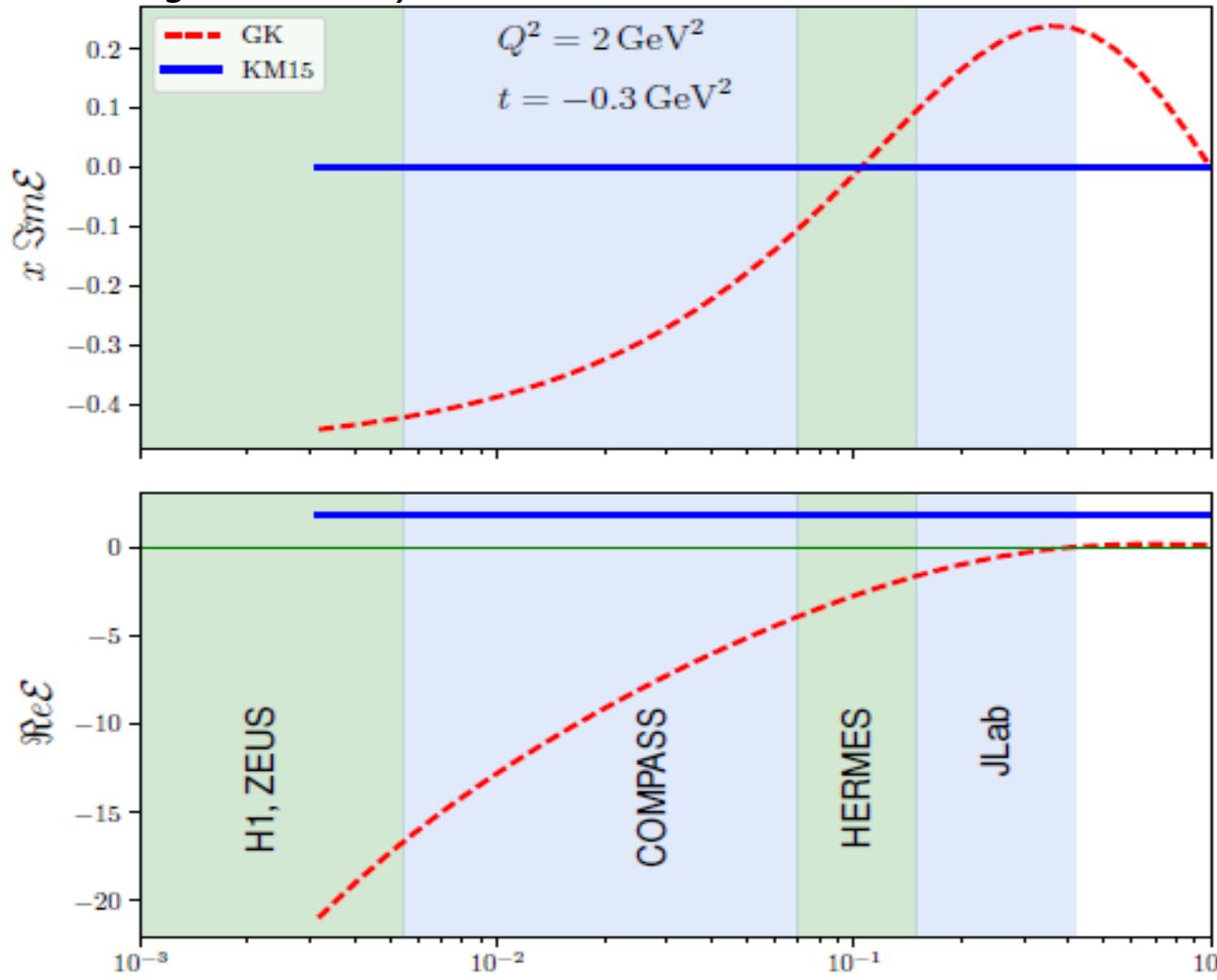
$\Re e \mathcal{H}$  linked  
to the *dterm*  
is still poorly  
constrained

**KM15** K Kumericki and D Mueller [arXiv:1512.09014v1](https://arxiv.org/abs/1512.09014v1)

**GK** S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

# Present knowledge of the GPD E in global analysis

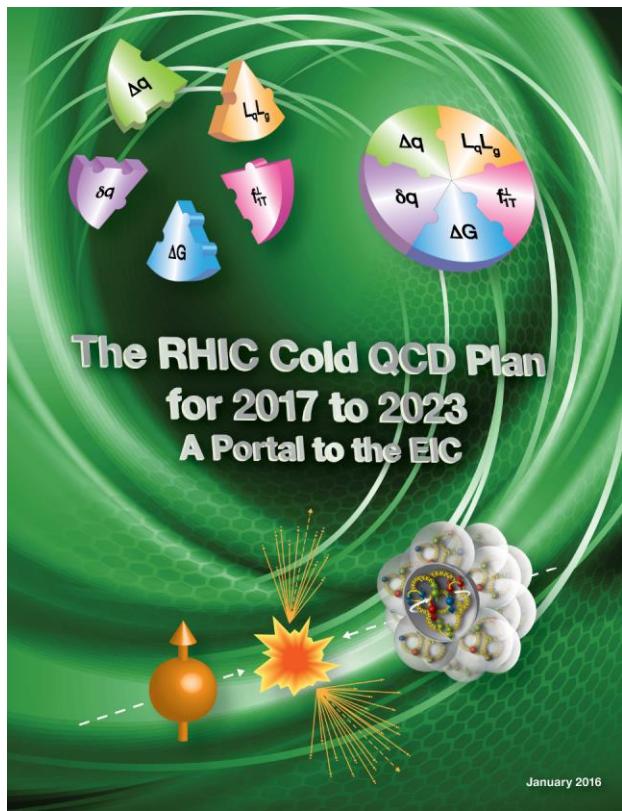
Figure made by D. Mueller and K. Kumericki



$\text{Im } E$   
is rather unknown

$\text{Re } E$   
is rather unknown

# GPD $E_{\text{gluon}}$ at RHIC in 2017 and 2023



## 2.3.1 Run-2017, Run-2023 and Opportunities with a Future Run at 500 GeV

### *Ultra Peripheral Collisions to access the Generalized Parton Distribution $E_{\text{gluon}}$*

Two key questions, which need to be answered to understand overall nucleon properties like the spin structure of the proton, can be summarized as:

- How are the quarks and gluons, and their spins distributed in space and momentum inside the nucleon?
- What is the role of orbital motion of sea quarks and gluons in building the nucleon spin?

..... RHIC, with its capability to collide transversely polarized protons at  $\sqrt{s}=500$  GeV, has the unique opportunity to measure  $A_N$  for exclusive  $J/\psi$  in ultra-peripheral  $p^\dagger + p$  collisions (UPC) [99]. The measurement is at a fixed

$Q^2$  of  $9 \text{ GeV}^2$  and  $10^{-4} < x < 10^{-1}$ . A nonzero asymmetry would be the first signature of a non-zero GPD  $E$  for gluons, which is sensitive to spin-orbit correlations and is intimately connected with the orbital angular momentum carried by partons in the nucleon and thus with the proton spin puzzle. Detecting one of the scattered polarized protons in “Roman Pots” (RP) ensures an elastic process. ....

**11k  $J/\psi$  in 2017 ( $p^\dagger p$  @ 510 GeV) and 13k in 2023 ( $p^\dagger \text{Au}$  @ 200 GeV)**  
**Important input for the photoproduction of  $J/\psi$  at EIC**