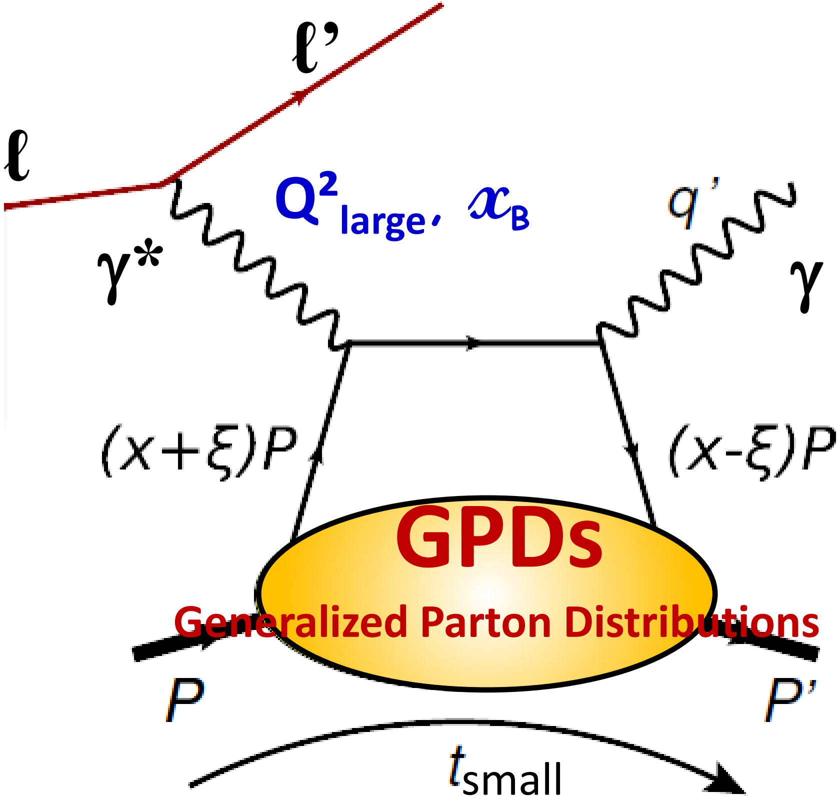
DVCS OVERVIEW

Workshop New Vistas in Low-Energy precision Physics (LEPP)

Nicole d'Hose, Mainz, 5 April 2016

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)



Definition of variables:

x: average long. momentum

ξ: long. mom. difference $\simeq x_B/(2-x_B)$

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

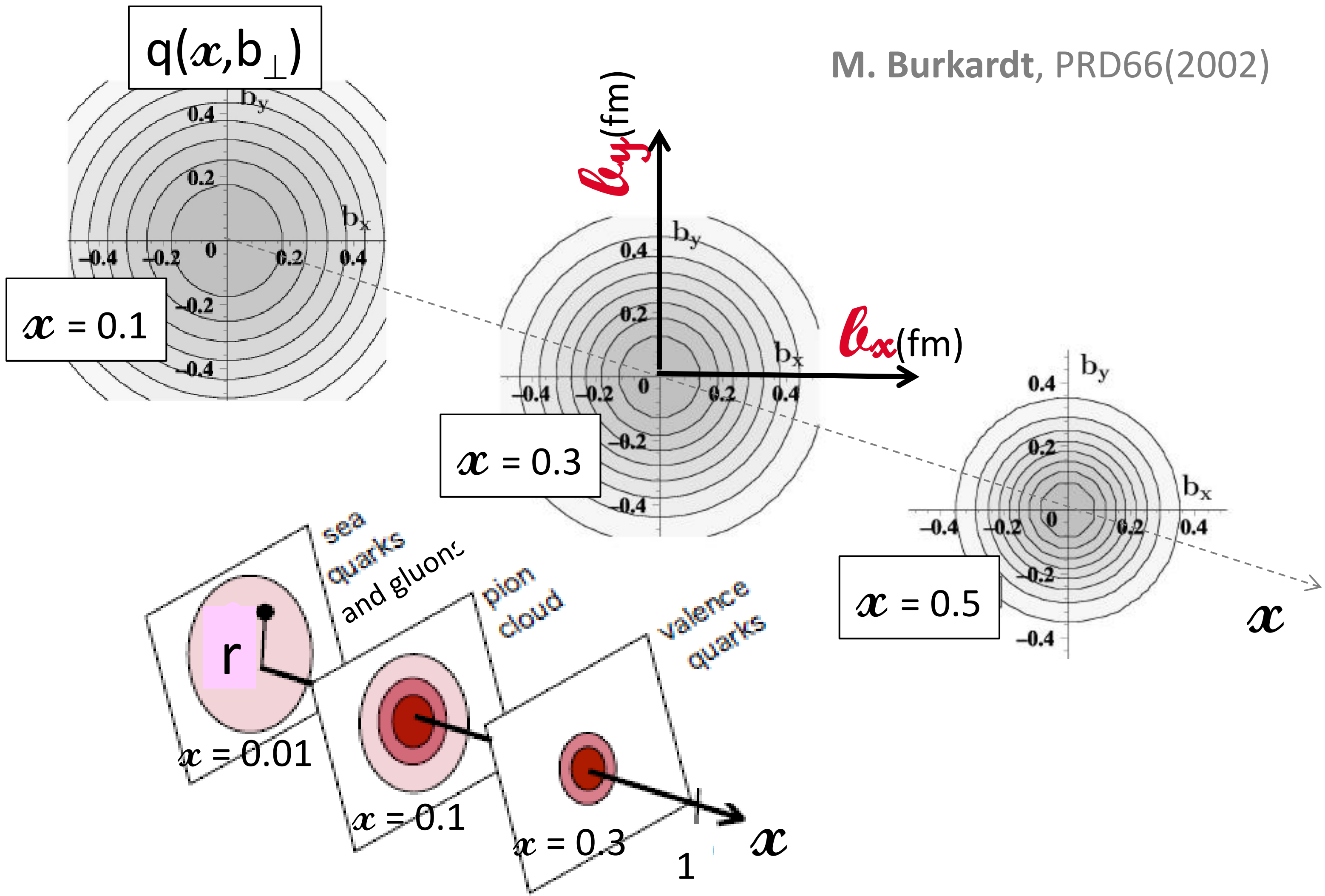
DVCS: $\ell p \rightarrow \ell' p' \gamma$
the golden channel
because its interferes with
the Bethe-Heitler process

also meson production
$\ell p \rightarrow \ell' p' \pi, \rho$ or **ϕ** or **J/ψ...**

3D imaging: mapping in the transverse plane

Proton
moving
towards us

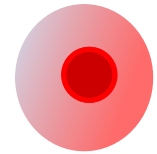
M. **Burkardt**, PRD66(2002)



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

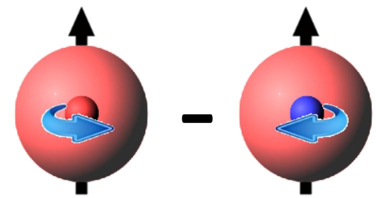
The 2 most famous GPDs

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



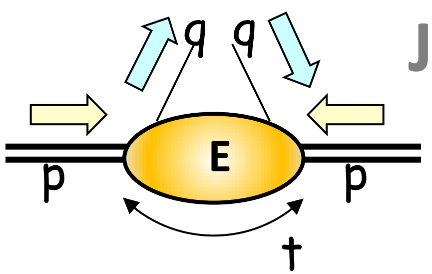
"Elusive"

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



Sivers: quark k_T & nucleon transv. Spin

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



Ji sum rule: PRL78 (1997) cited 1404 times

Relation to OAM

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}$$

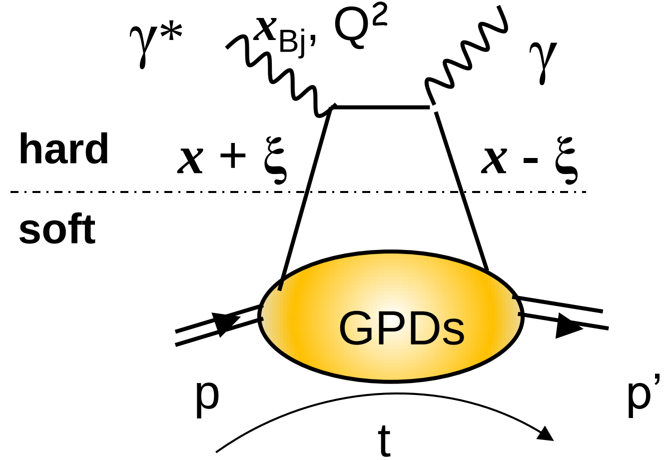
Jaffe and Manohar
NPB337 (1990)

$\tfrac{1}{2}\Delta\Sigma \sim 0.15$ well know from DIS/SIDIS

$\Delta G \sim 0.2$ known from DIS/pp

$\mathcal{L}$ unknown

Compton Form Factors are measured in DVCS

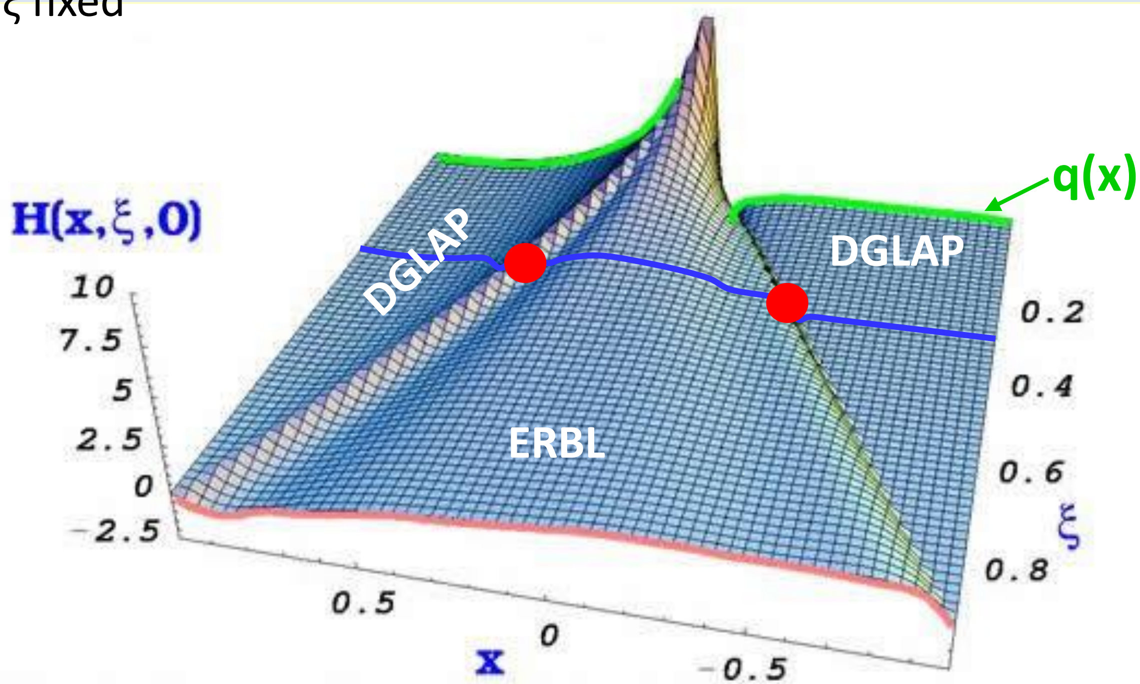


The amplitude DVCS at LT & LO in α_S:

Real part **Imaginary part**

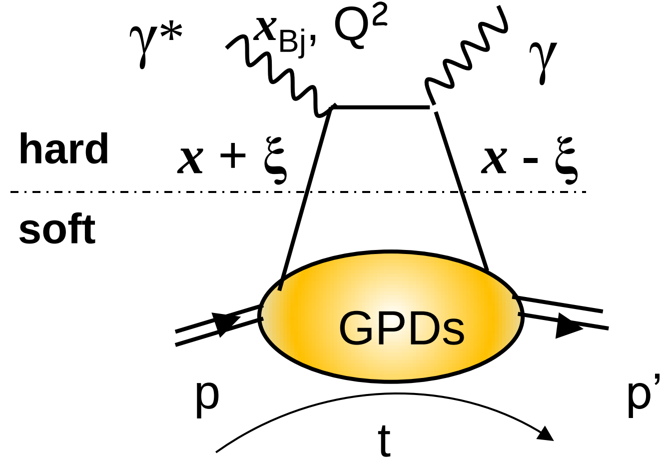
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\,\pi\, H(x=\pm\xi,\xi,t)$$

t, ξ fixed



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)

Compton Form Factors are measured in DVCS



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t, ξ fixed

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

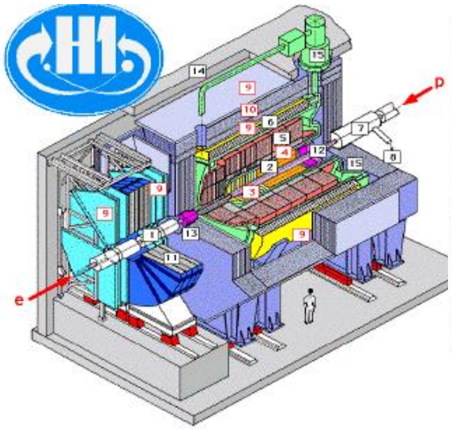
$\mathcal{D}$ term related to the Energy-Momentum Tensor :

Polyakov, PLB 555 (2003) 57-62

Im part measured in
Beam Spin
or **Target Spin** asymmetries

Real part measured in
Beam Charge asymmetry
or Int. term in DVCS **x- sect.**

The past and future experiments



Collider mode e-p forward fast proton

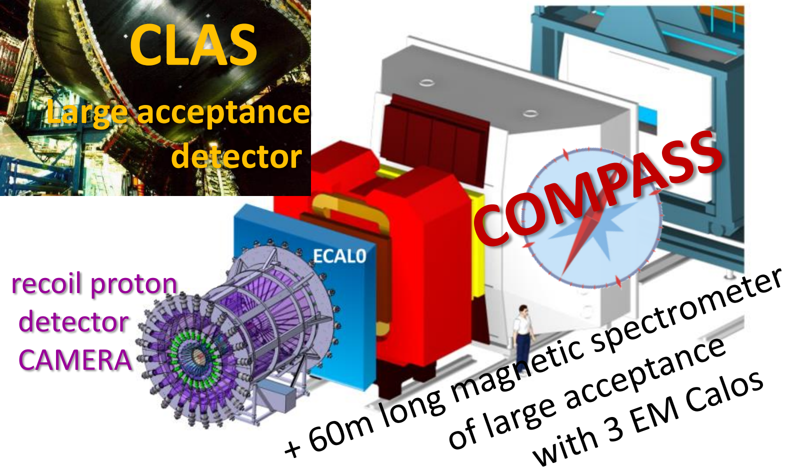
HERA: **H1** and **ZEUS**
Polarised 27 GeV e-/e+
Unpolarized 920 GeV proton
~ Full event reconstruction

Fixed target mode slow recoil proton

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

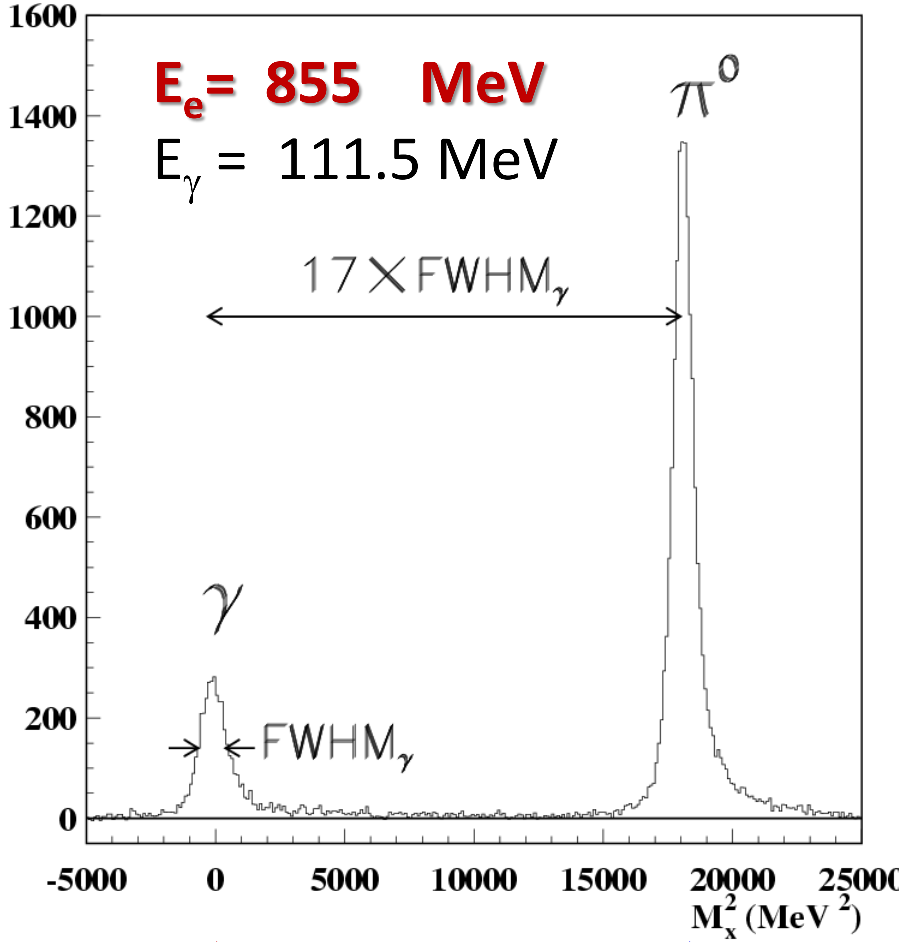
Jlab: Hall A, C, CLAS High lumi, polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique

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



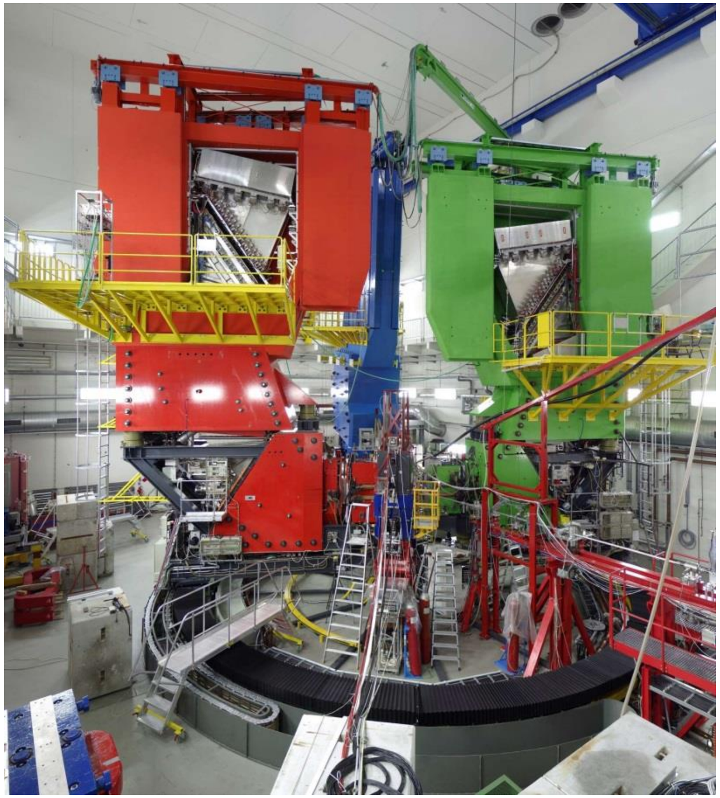
Exclusivity : $\ell\, p \rightarrow \ell + \gamma + p$

$M_x^2 = (P_\ell + P_p - P_{\ell'} - P_{p'})^2$



$ep \rightarrow e'\, p'\, \gamma$ $\quad$ $ep \rightarrow e'\, p'\, \pi^0$

VCS @ MAMI 1995



Very good separation due to the excellent resolutions

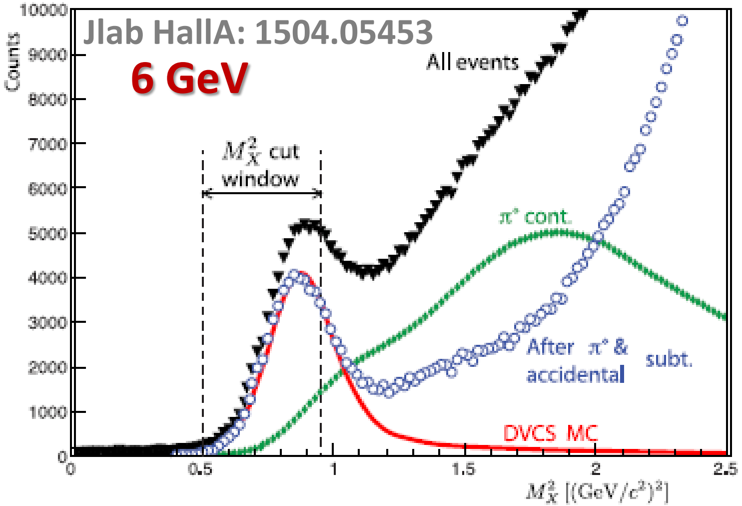
Beam $\Delta E_e/E_e = 10^{-4}$

Spectros $\Delta P/P = 10^{-4}$ $\quad \Delta\theta < 3$mrad

Exclusivity : ℓ p → ℓ + γ + p

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

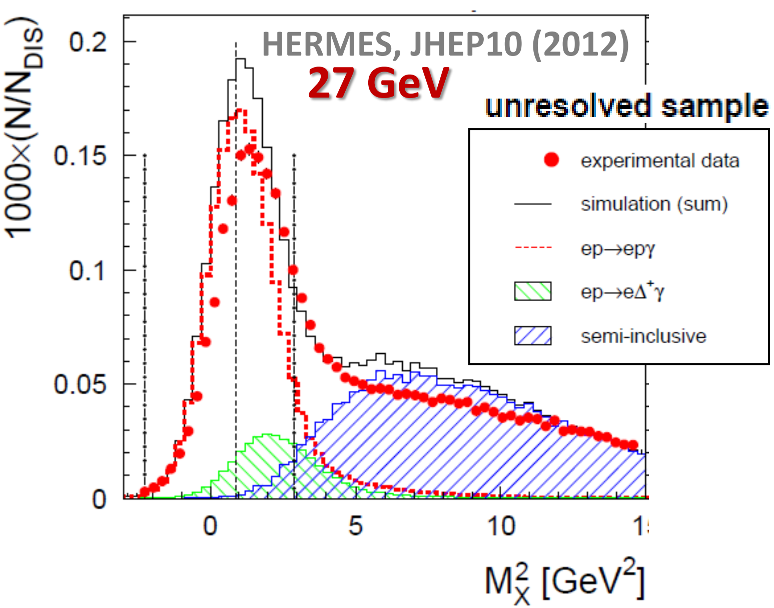
ΔM_x^2 increases with the beam energy !

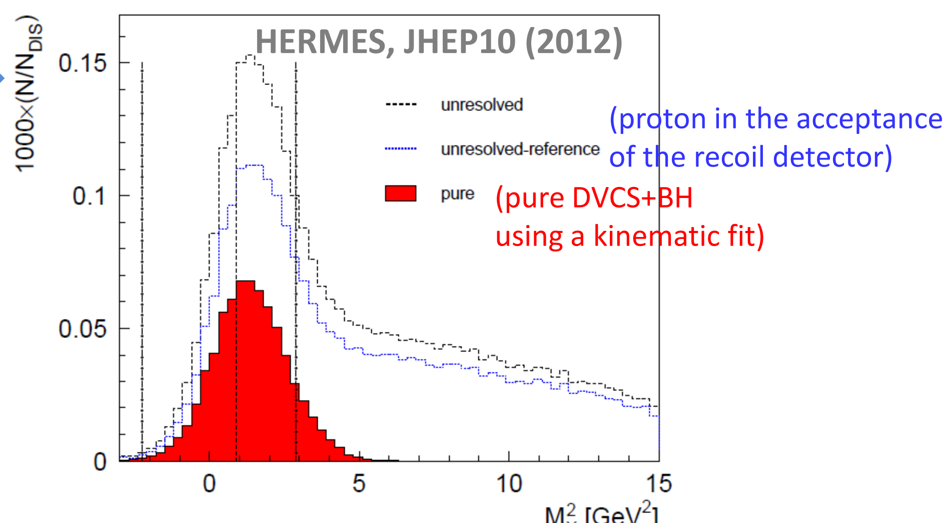


$\ell p \rightarrow \ell' + \gamma\ (+p')$ for DVCS + BH

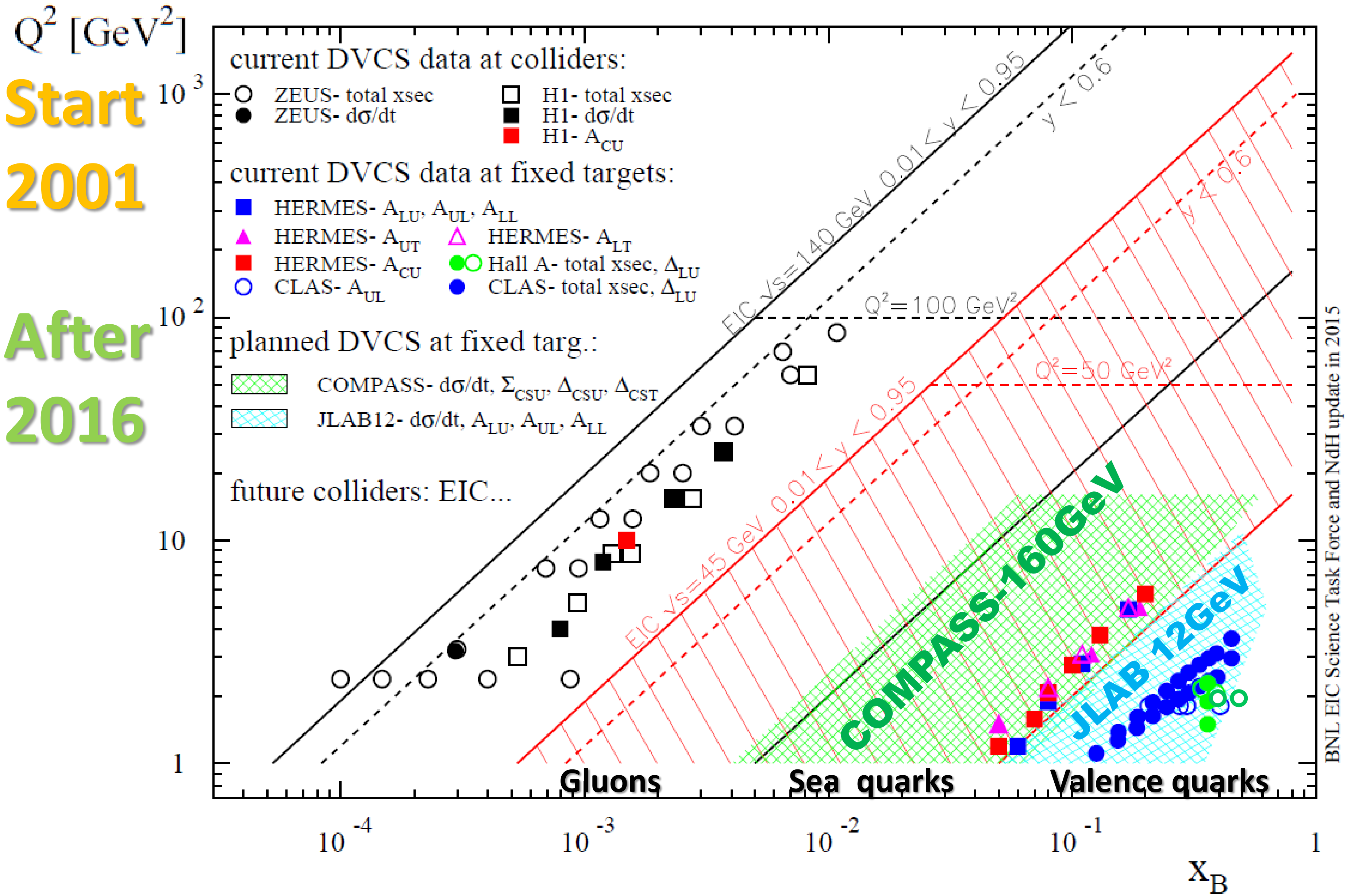
Contamination from π^0 decay:

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

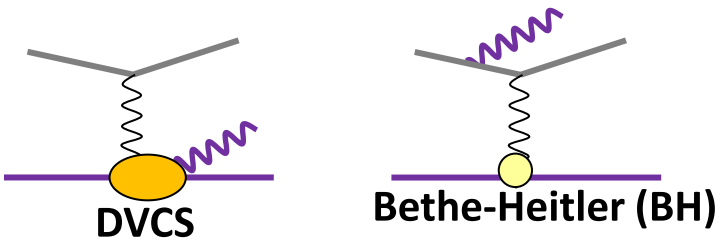


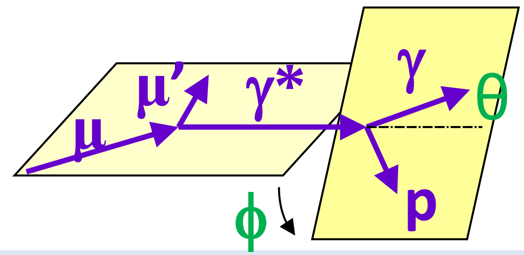


The past and future DVCS experiments

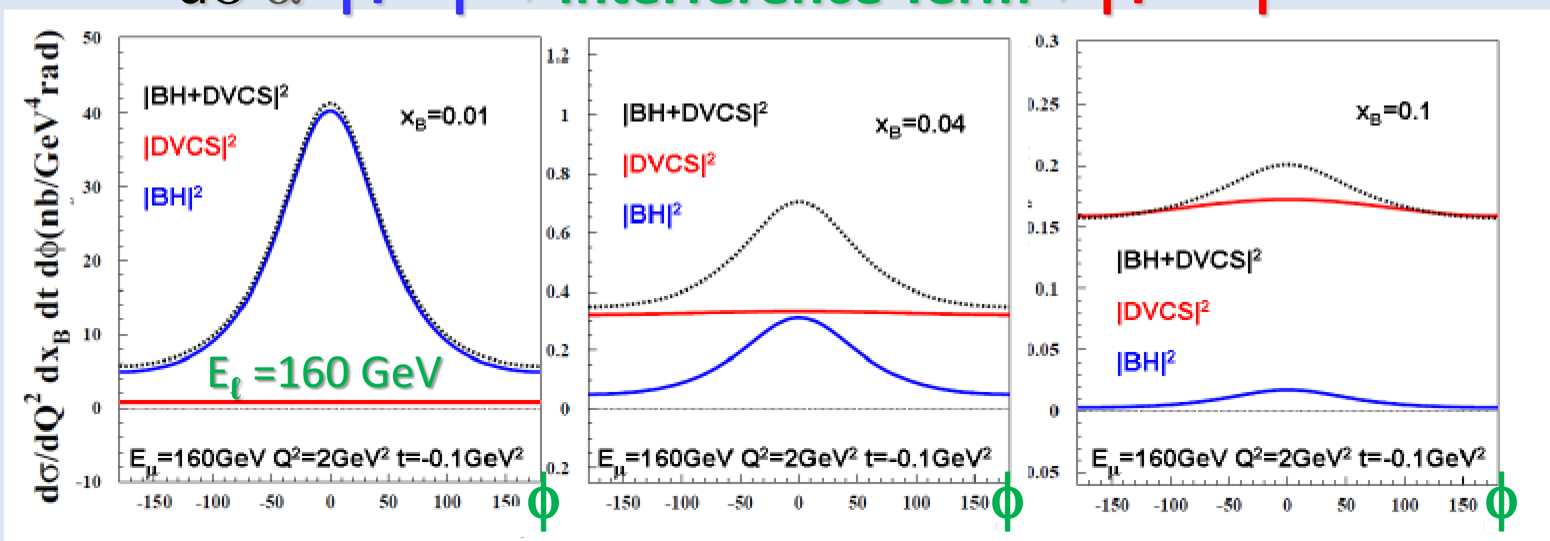


Impact of the beam energy for DVCS





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



BH dominates
Reference yield

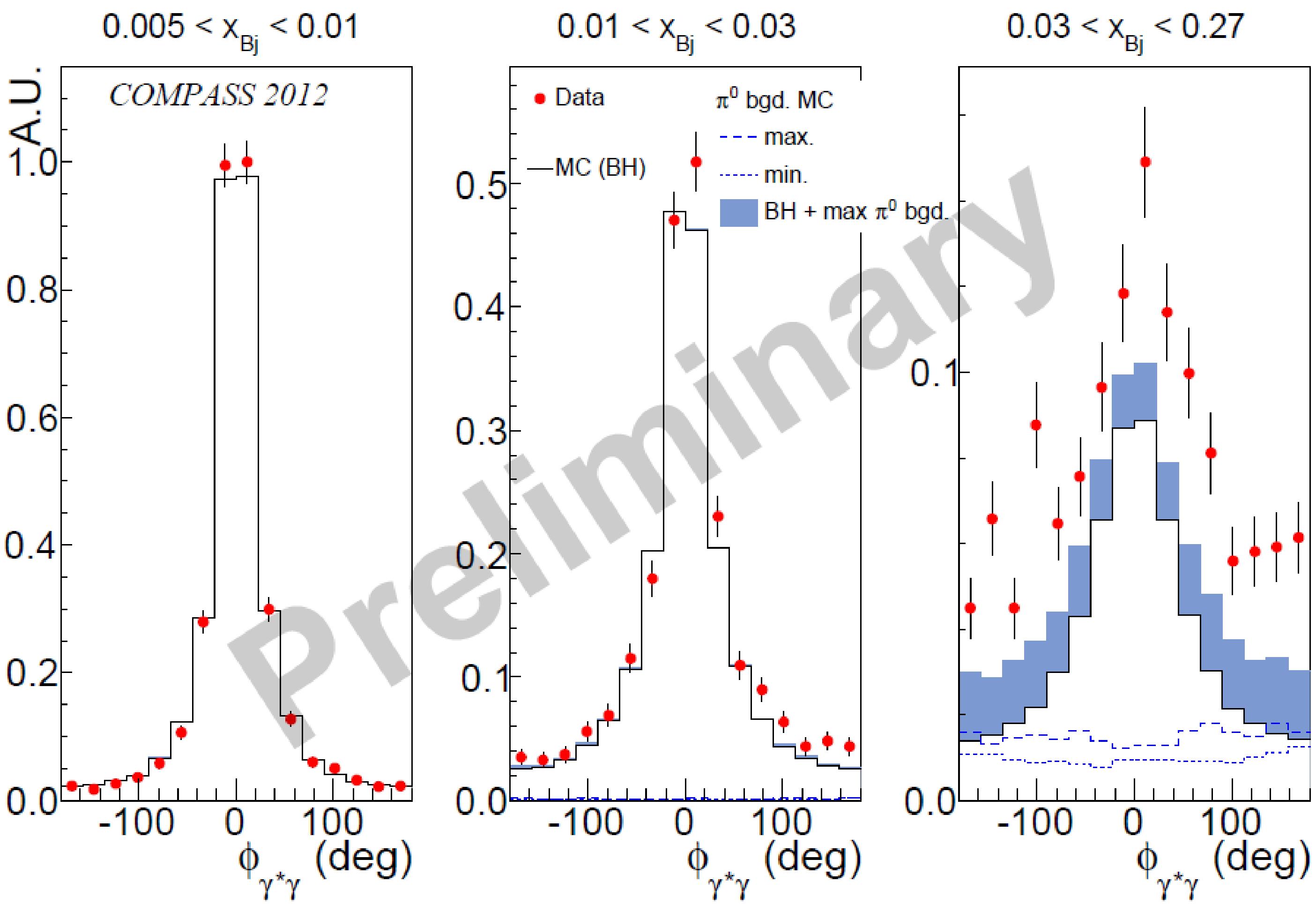
DVCS ampl. via interference
Jlab, HERMES, H1, COMPASS

DVCS dominates - Study of $d\sigma^{DVCS}/dt$
Only for H1, ZEUS, COMPASS

DVCS and BH contributions @ COMPASS

$\mu^{\overleftarrow{+}}$ and $\mu^{\overrightarrow{-}}$

160 GeV



Pilot run in 2012

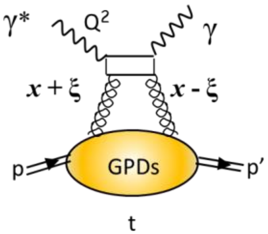
- ✓ Dominant Bethe-Heitler process clearly visible at small x_{Bj}
- ✓ Maximum π^0 background (from exclusive and SIDIS π^0 production) estimated in blue
- ✓ The data at large x_{Bj} show an excess compared to BH+Background (for pure DVCS)

COMPASS ready to take DVCS data in 2016 and 2017

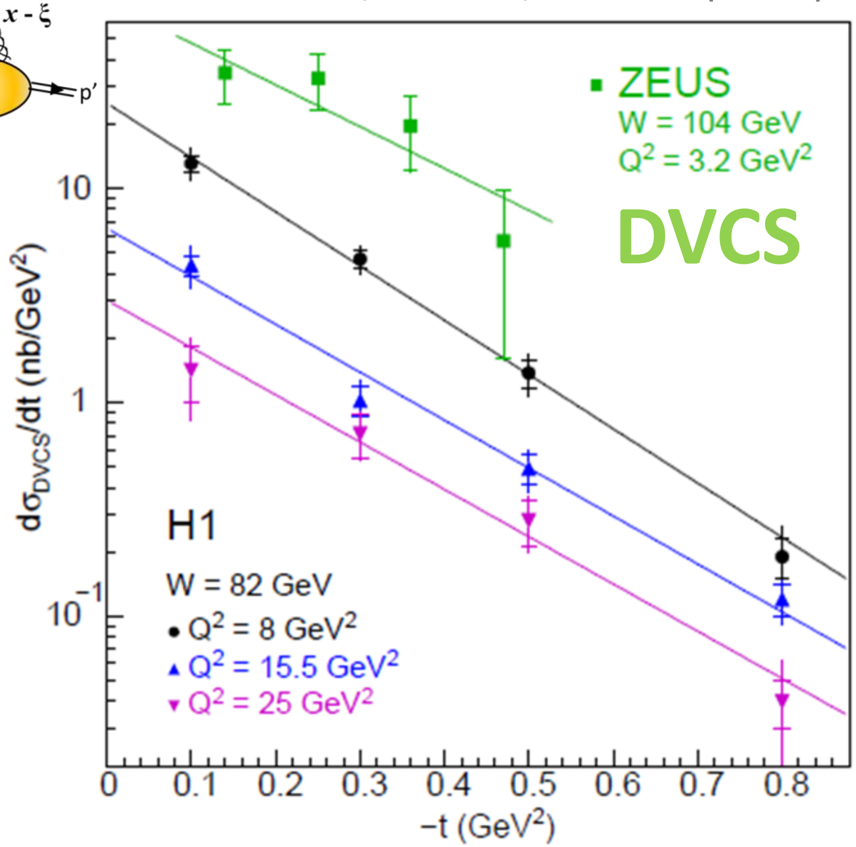
Gluon imaging @ HERA

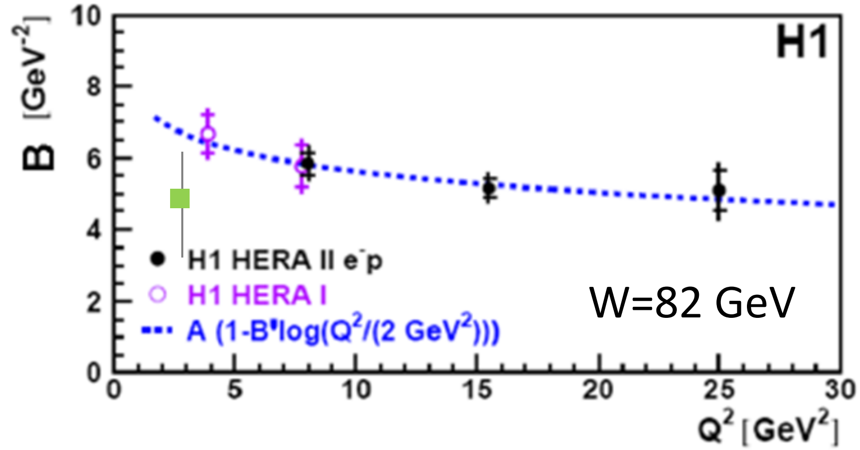
$d\sigma^{DVCS}/dt = e^{-B|t|}$

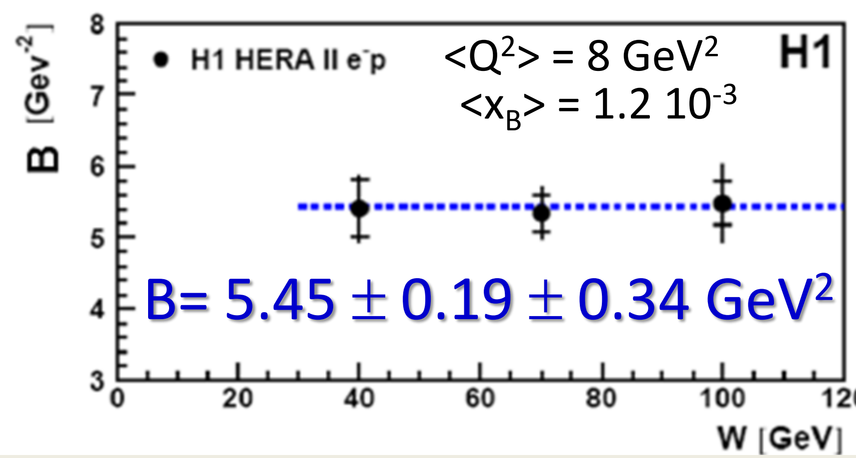
B is related to the transversed size of the scattering objects



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



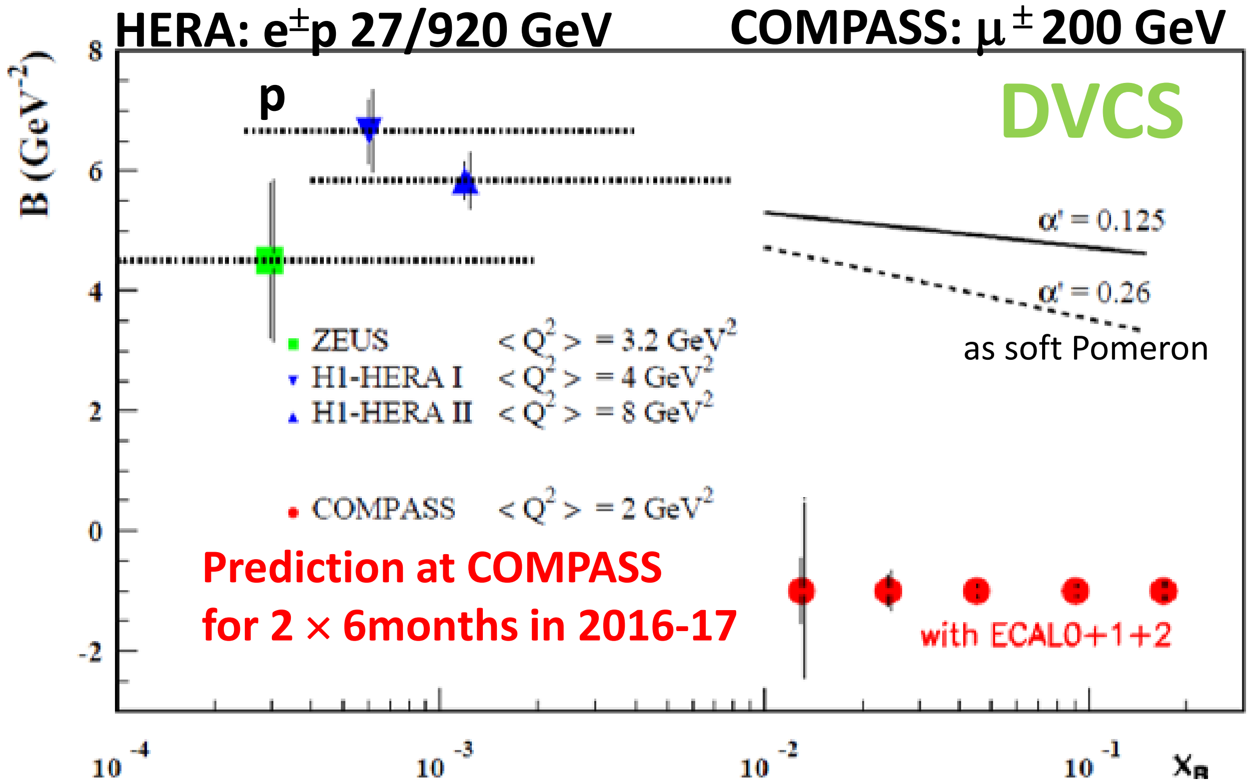




$< r_\perp^2 > \approx 2B$

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

Sea quark imaging @ COMPASS



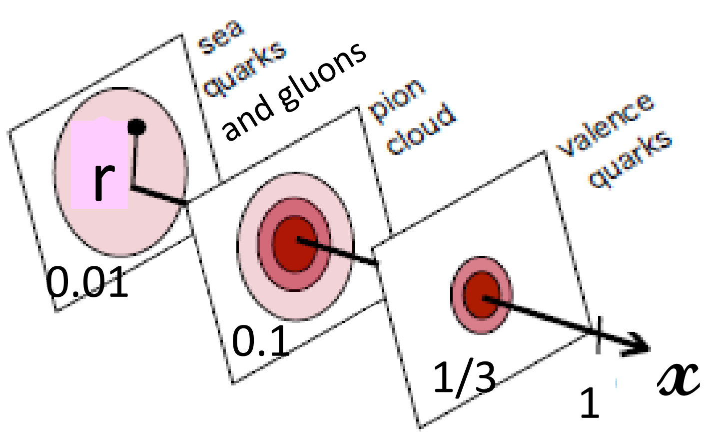
$d\sigma^{DVCS}/dt = e^{-B|t|}$

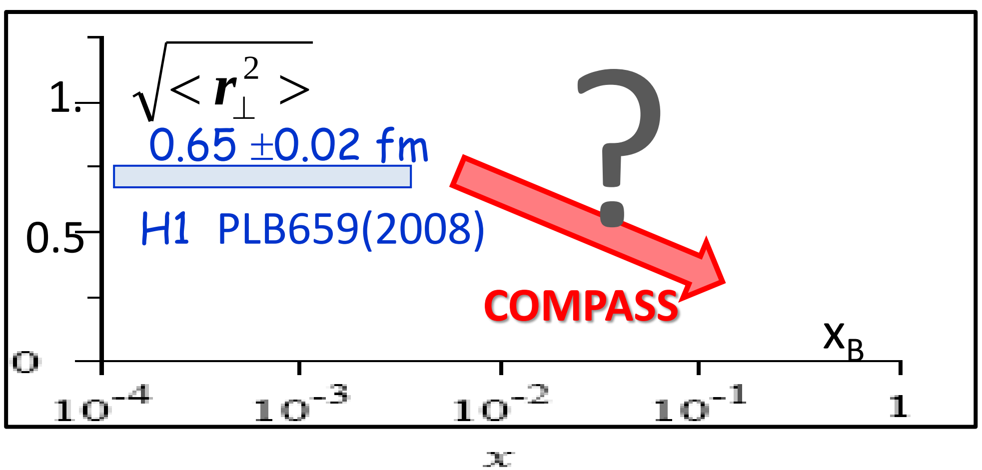
ansatz inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

α' slope of Regge traject

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





DVCS-BH interference on the proton

→ *Im* DVCS with BSA or Beam Spin difference

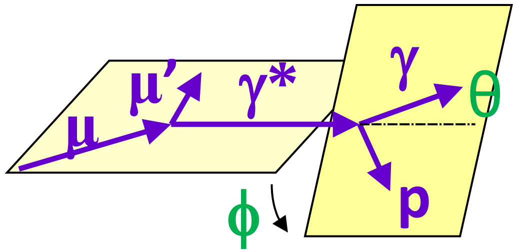
→ *Re* DVCS with BCA or Beam Charge difference

→ mainly constrains on the GPD H

Azimuthal dependence of BH+DVCS

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

Well known



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

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

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

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

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

Twist-2 >>

■ Twist-3,

■ Twist-2

double helicity flip for gluons

$s_1^I = Im \; \mathcal{F}$ $\qquad c_1^I = Re \; \mathcal{F}$

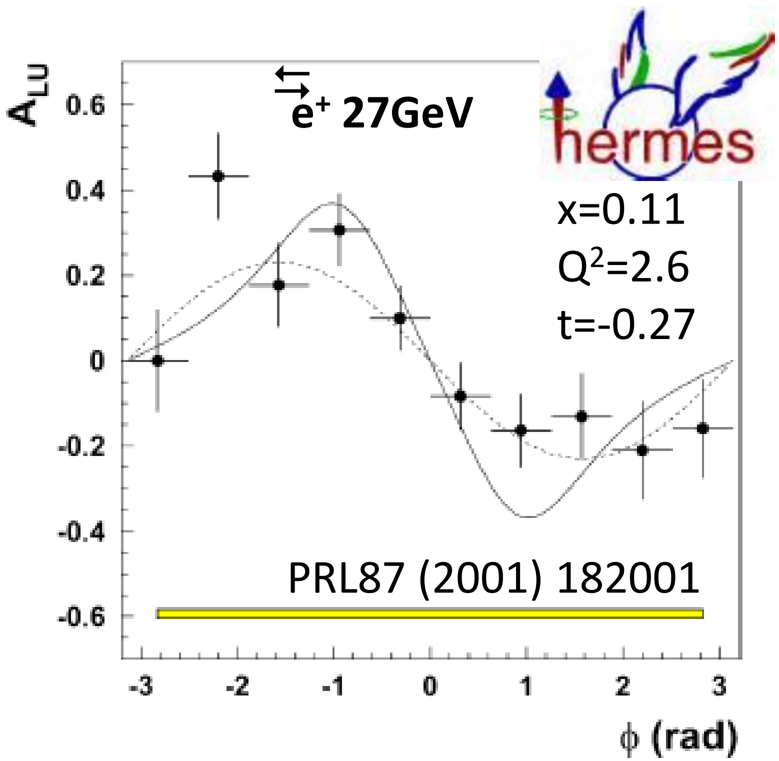
$\mathcal{F} = F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} - t/4m^2 \, F_2\mathcal{E}$ $\xrightarrow{\text{at small } x_B}$ $F_1\mathcal{H}$ for proton

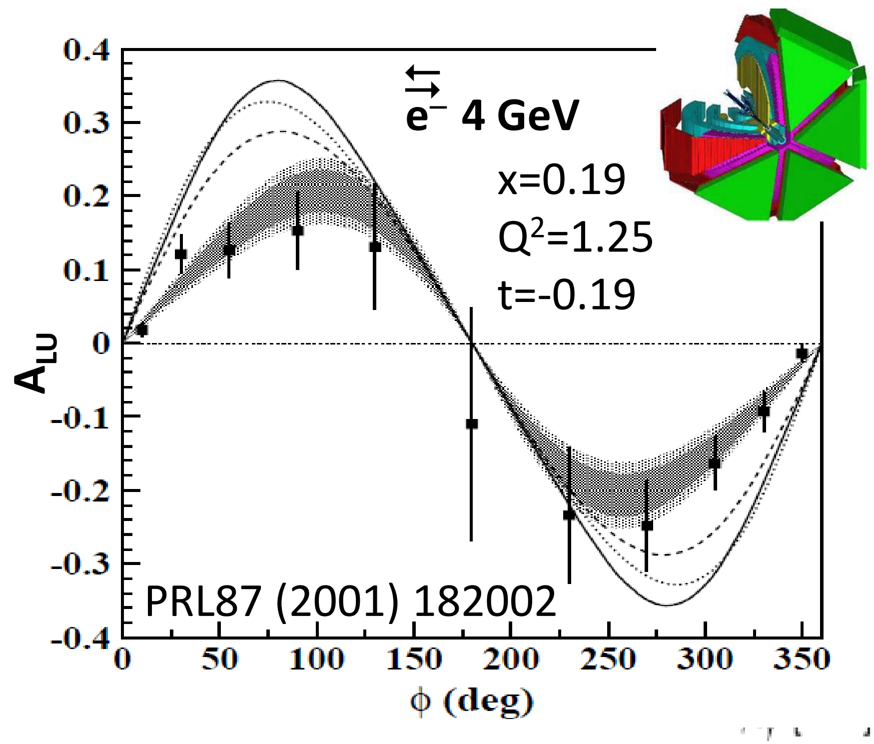
NB: to extract $\mathcal{E}$ use a neutron (deuteron) target or a transversely pol. target

to extract $\tilde{\mathcal{H}}$ use a longitudinally polarized target

First Beam Spin Asymmetries in 2001

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





Validate the dominance of the handag contribution

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

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

Beam Spin Sum and Diff of DVCS - HallA

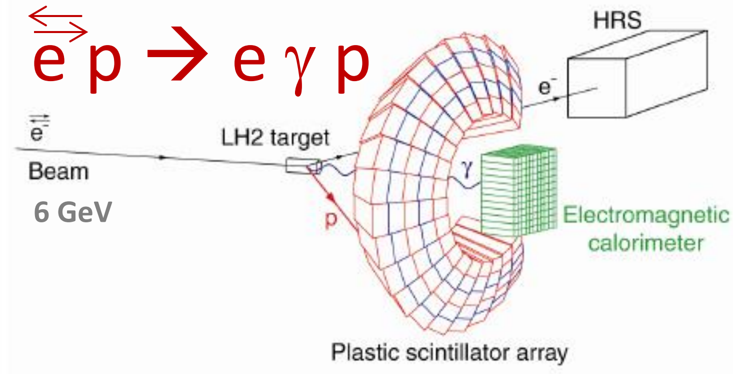
E00-110 pioneer experiment with magnetic spectrometer

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

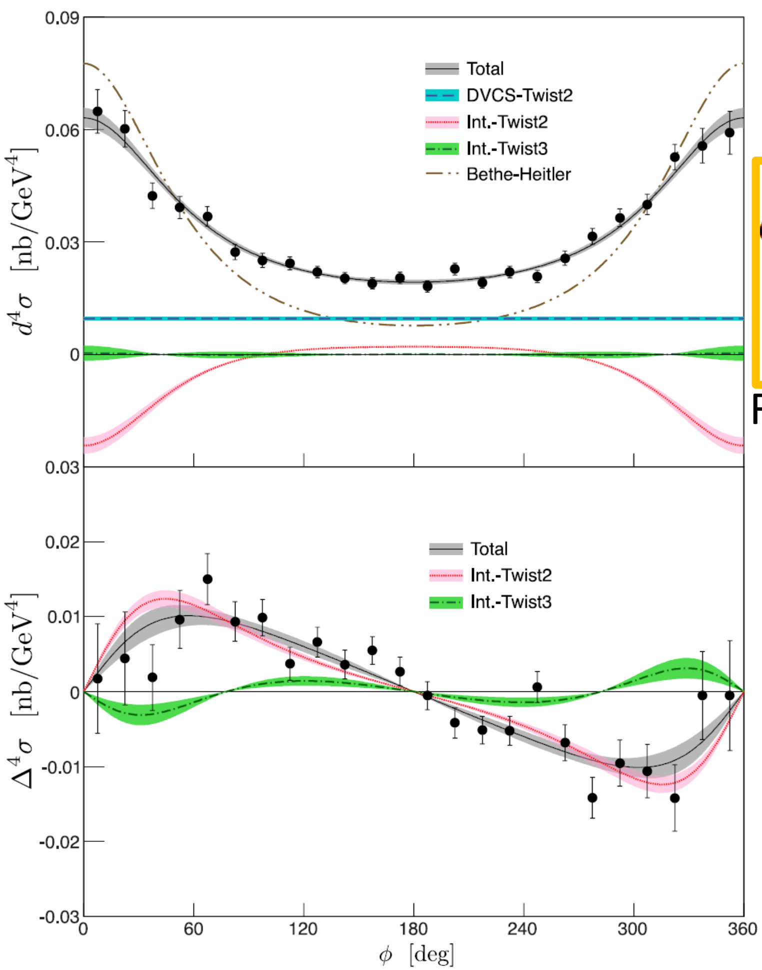
x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2 Defurne et al. arXiv: 1504.05453

new improved analysis

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



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



Unpolarized cross section

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

Further separtion ➔ need of different ε or beam energies

Helicity dependent cross section

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

These results supersede the previous publication

Beam Spin Sum and Diff of DVCS - HallA

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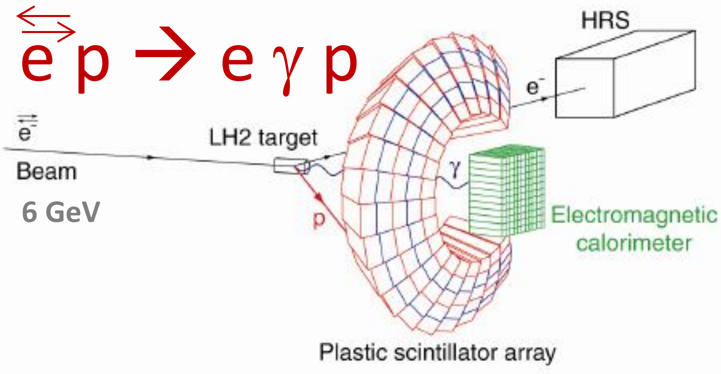
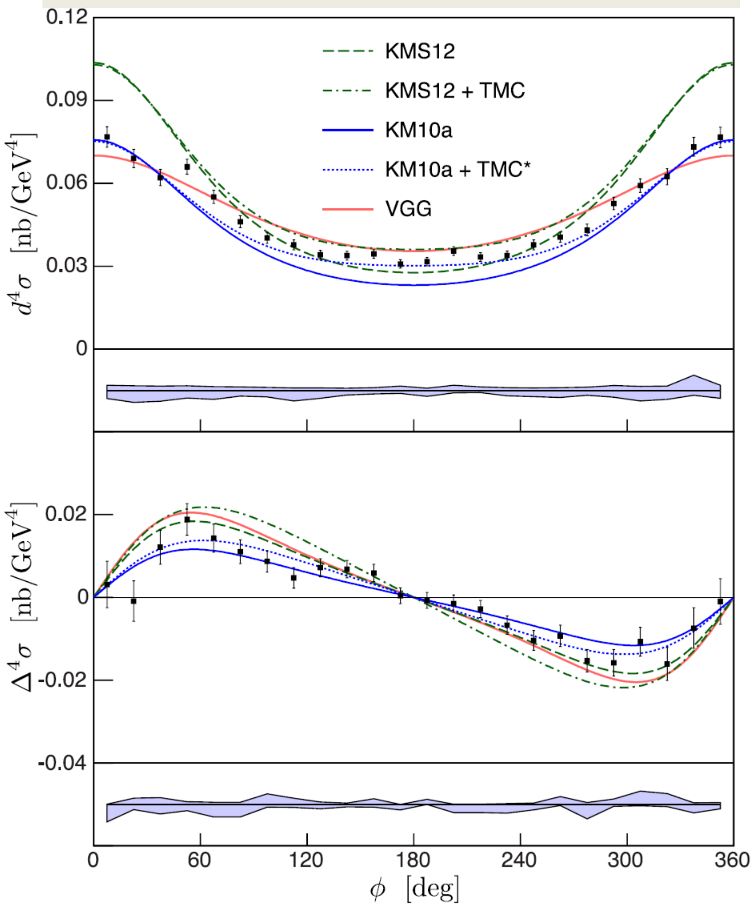


x_B=0.36, Q^2= 1.9 GeV^2, -t= 0.23 GeV^2



Comparison to models:

VGG popular model of GPD

KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)
using the **GK** model of GPD adjusted on
the hard exclsuive meson production at small x_B
"universality" of GPD

KM10a fit including all the world DVCS data
from HERA to HERMES and JLab

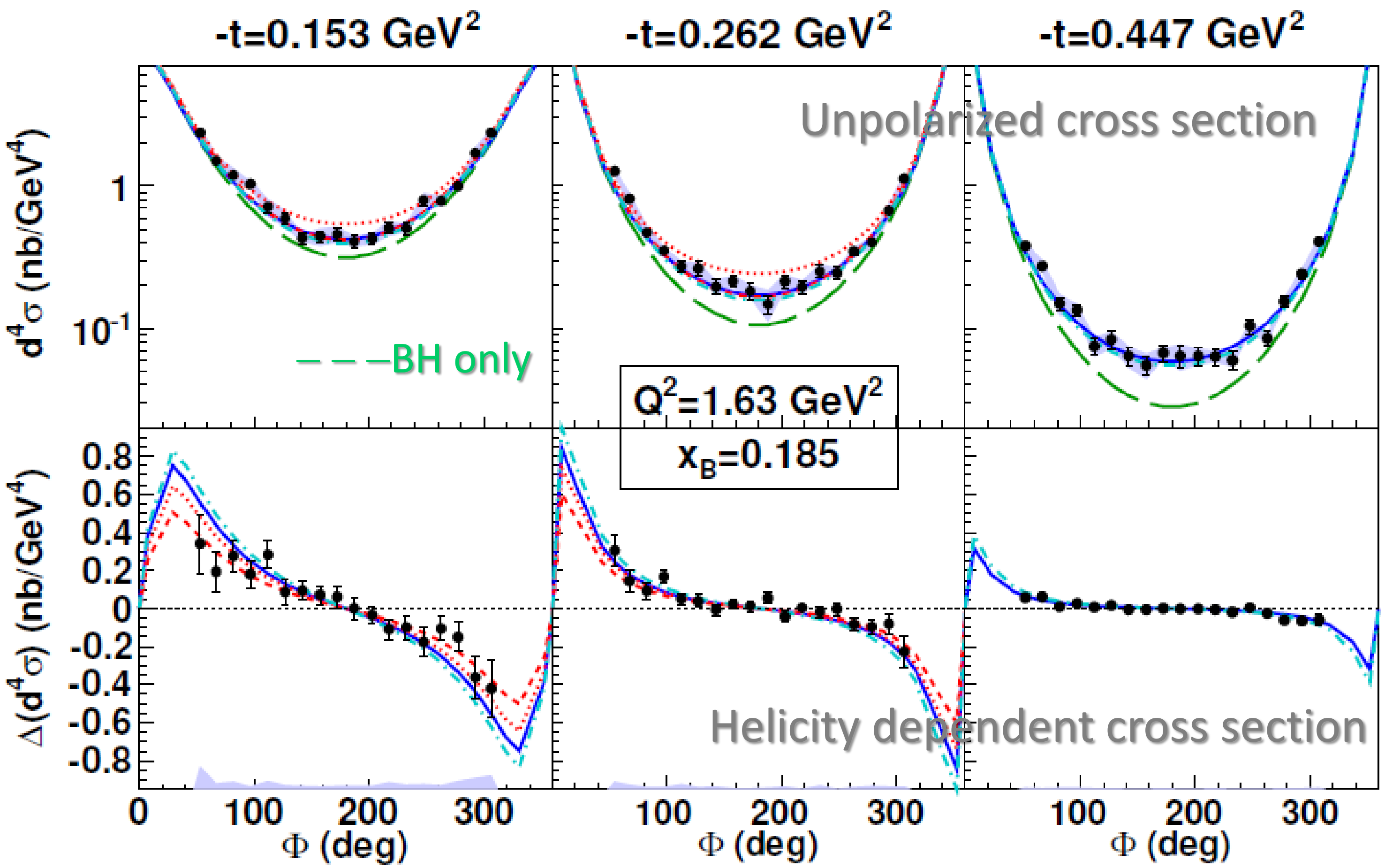
Difficulties to reproduce the total cross section at ϕ=180°

+ TMC twist-4 corrections for kinematic effects due to
target-mass and finite-t,Braun et al., PRD79 (2014)

Beam Spin Sum and Diff of DVCS - CLAS

21 bins in (x_B, Q^2) or 110 bins (x_B, Q^2 t)
- Girod et al. PRL100, 162002 (2008)
- Jo et al. arXiv: 1504.02009 new analysis

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



models:

VGG

KMS12

KM10a – – –

KM10 ....
old fit including
the first data set
of Jlab HallA

Valence quark imaging at Jlab

Fit of only two CFFs at L.O and L.T.

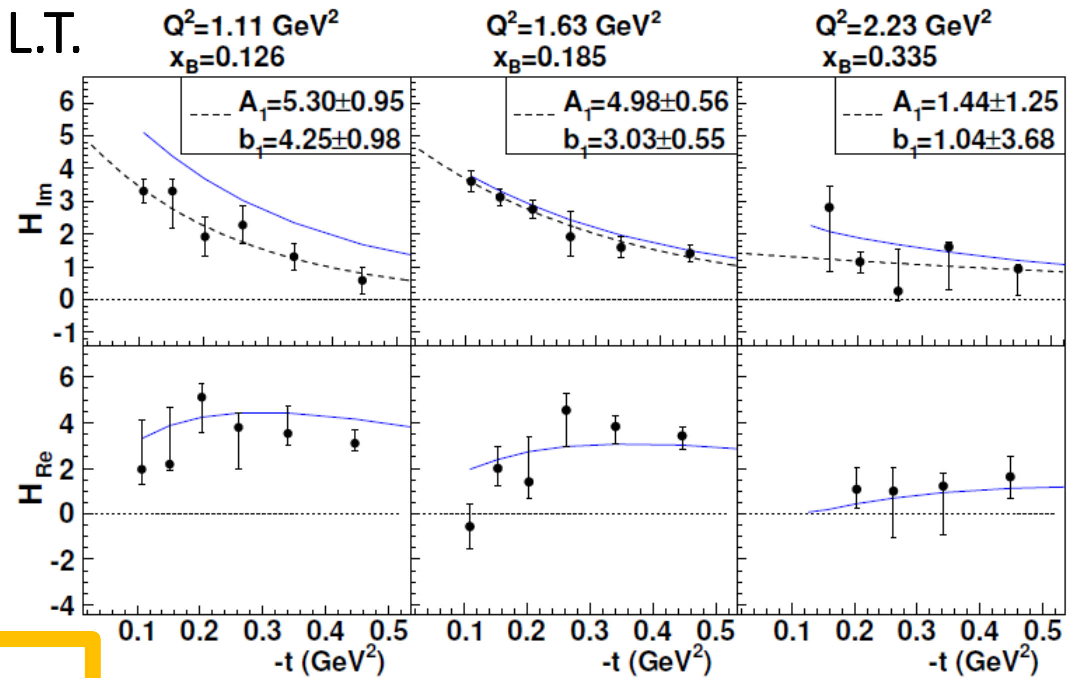
Jo et al. arXiv: 1504.02009

$$s_1^I = Im\, F_1\mathcal{H}$$

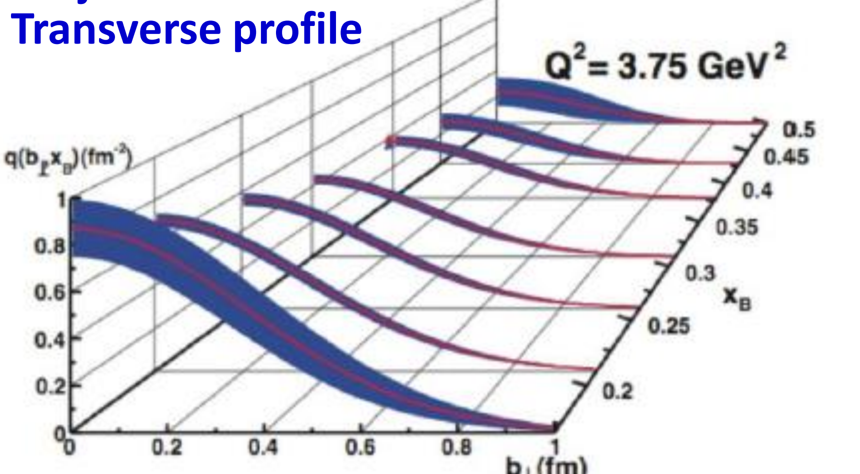
$$c_1^I = Re\, F_1\mathcal{H}$$

VGG model

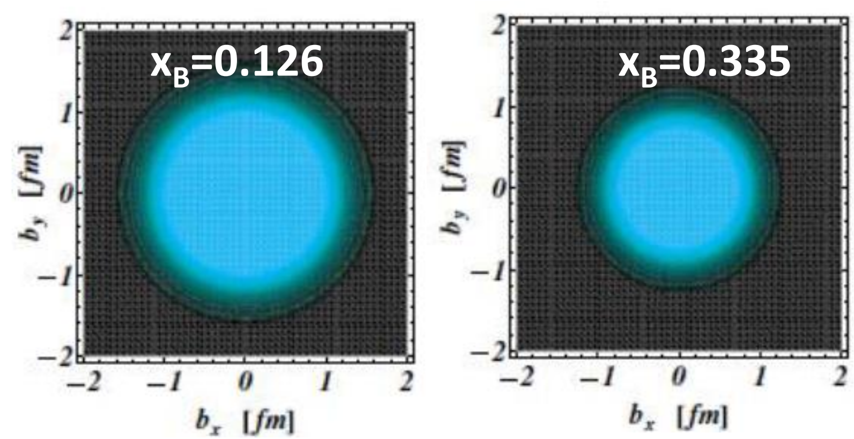
Fit $A\, e^{-b|t|}$



Projection for Jlab 12 GeV
Transverse profile



Dudek et al., EPJA48 (2012)



Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

Future Beam Spin Sum and Diff @JLab12

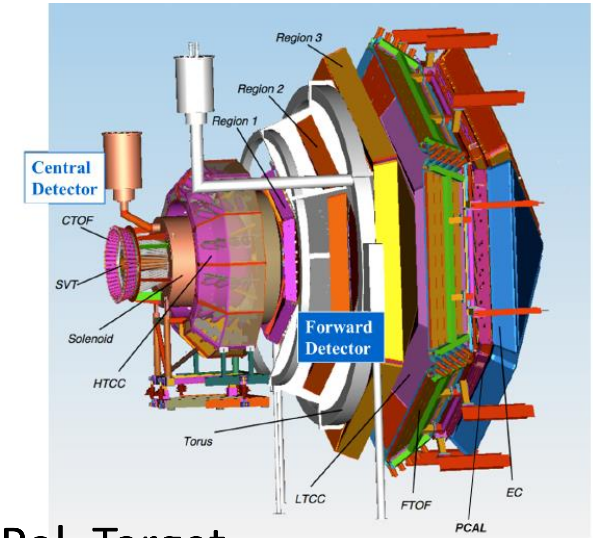
with high resolution magnetic spectro-meter+ Calorimeter in Halls A and C

Exp. 2010: run E07-007
Now 2015: Hall A
~2018: Hall C

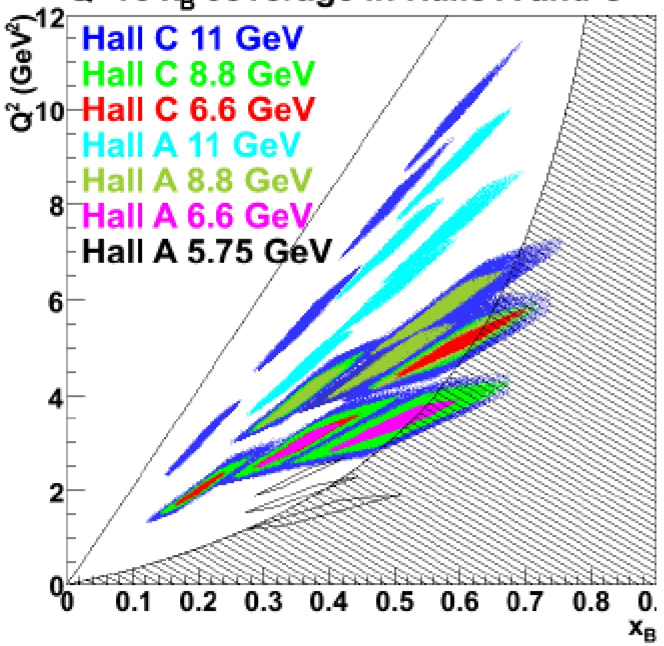
Different beam energies for a Rosenbluth-like DVCS²/Interf. separation

with CLAS12
In 2016

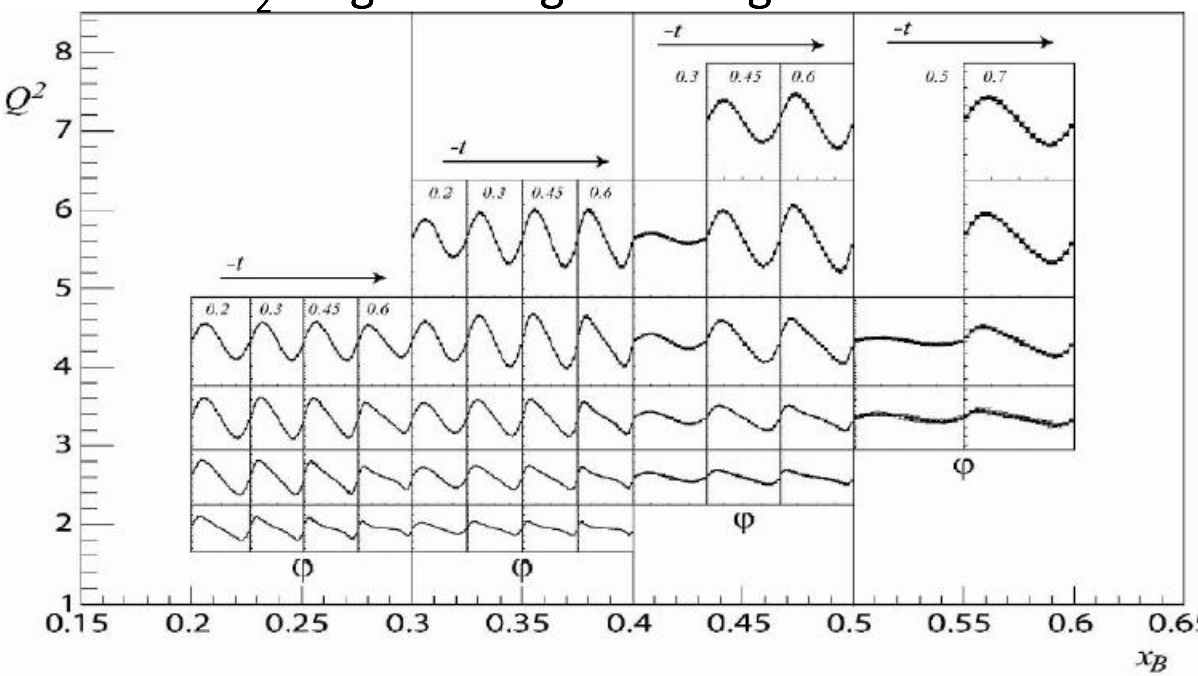
E12-06-119



Q^2 vs x_B coverage in Halls A and C



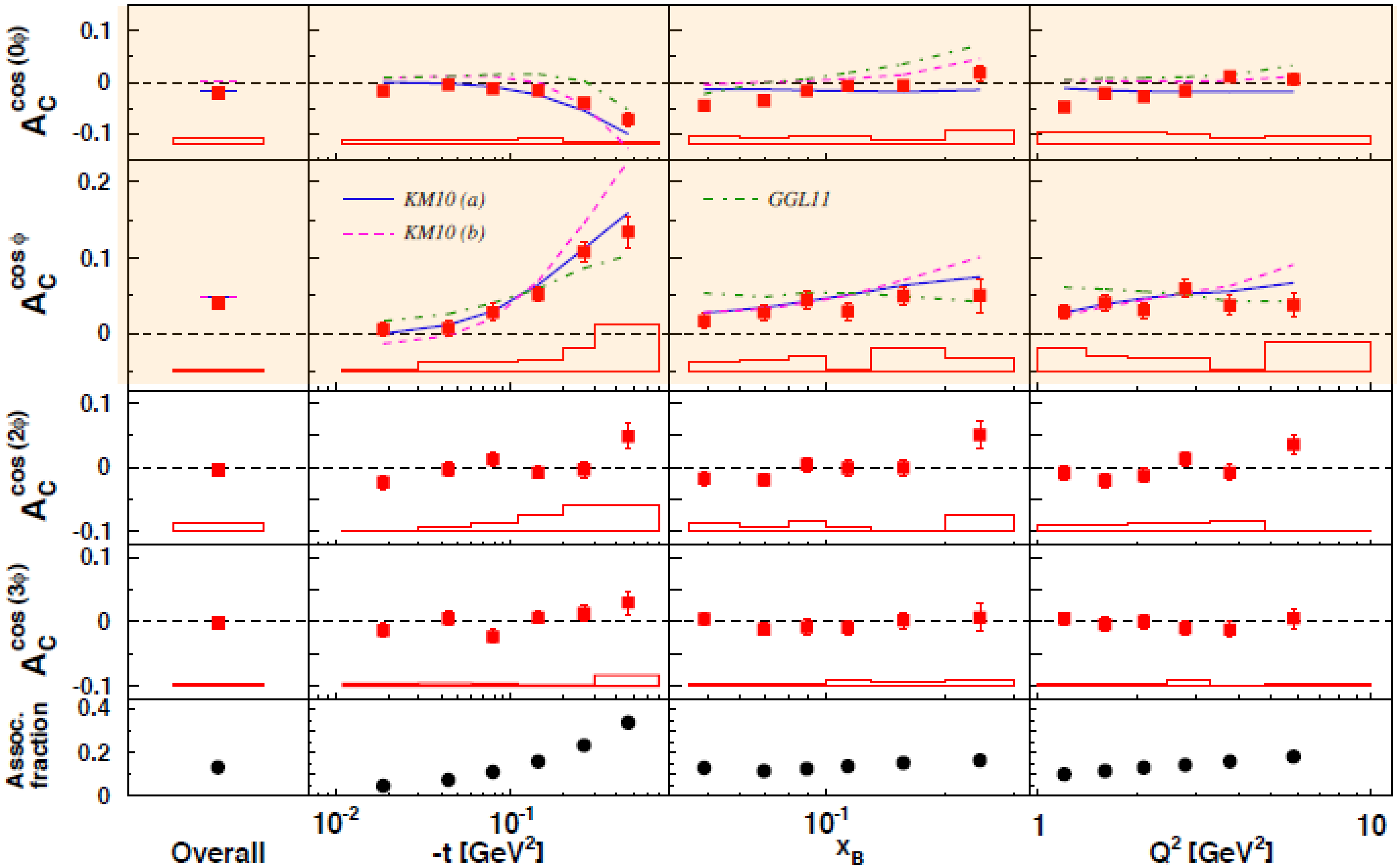
LH₂ Target & Long. Pol. Target



Beam Charge Asymmetry @ HERMES

Complete data set including 2006-07 without recoil detection

A. Airapetian et al, JHEP 07 (2012) 032 http://arxiv.org/abs/1203.6287



Dominant Twist-2

$c_0^I + c_1^I \cos\phi$

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

Twist-3 for Int

$c_2^I \cos 2\phi$

Twist-2 gluons for Int

$c_3^I \cos 3\phi$

resonant fraction

ep → eγΔ$^+$

KM10a: http://arxiv.org/abs/0904.0458

Kumerički and Müller, Nucl. Phys. ***B841*** *(2010)*

GHL11: another flexible parameterization

http://arxiv.org/abs/1012.3776

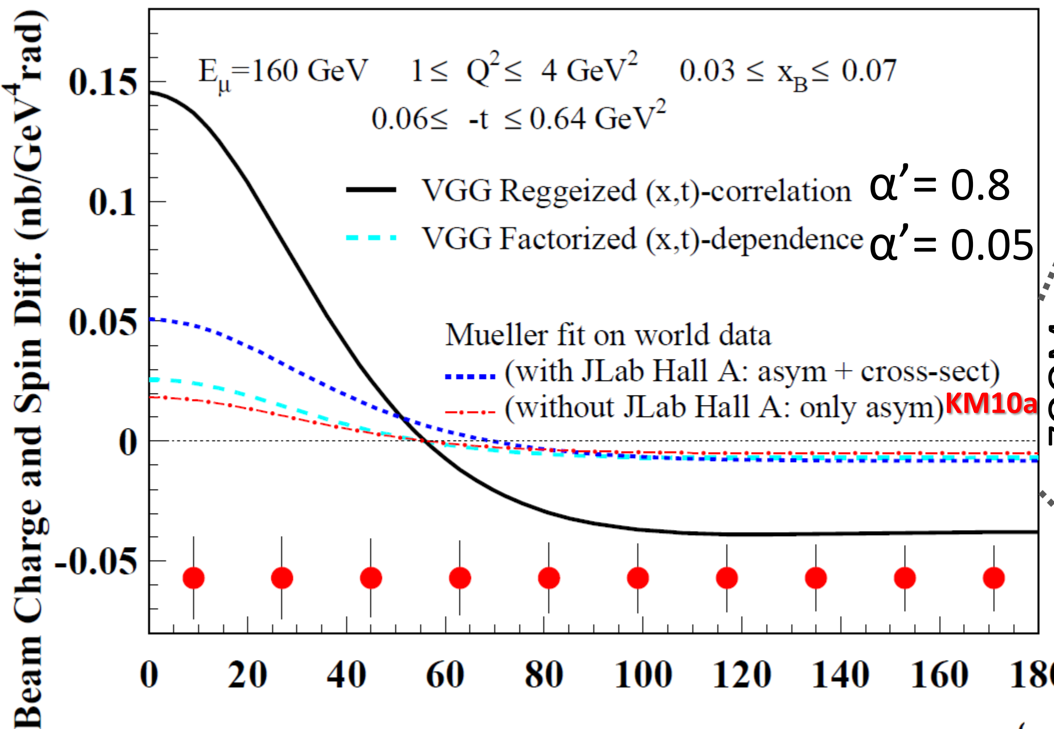
G. Goldstein, J. Hernandez and S. Liuti, ***Phys. Rev. D84*** *(2011)*

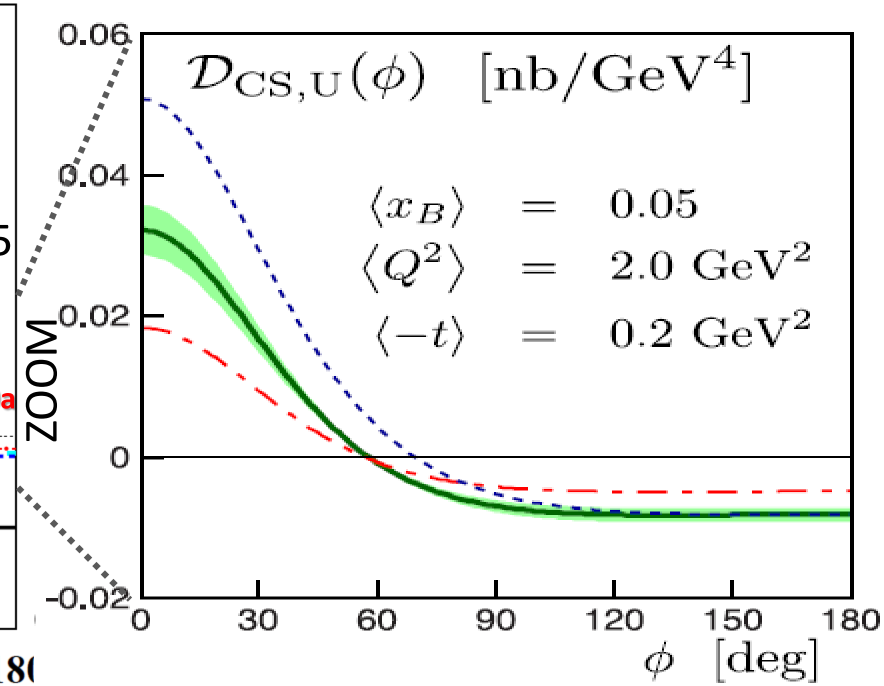
Beam Charge and Spin Diff. @ COMPASS

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

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

Comparison to different models





KMS12: Kroll, Moutarde, Sabatié
EPJC 73 (2013) 2278

KM10a

KM10b (old fit with the 1rst data set Hall A)

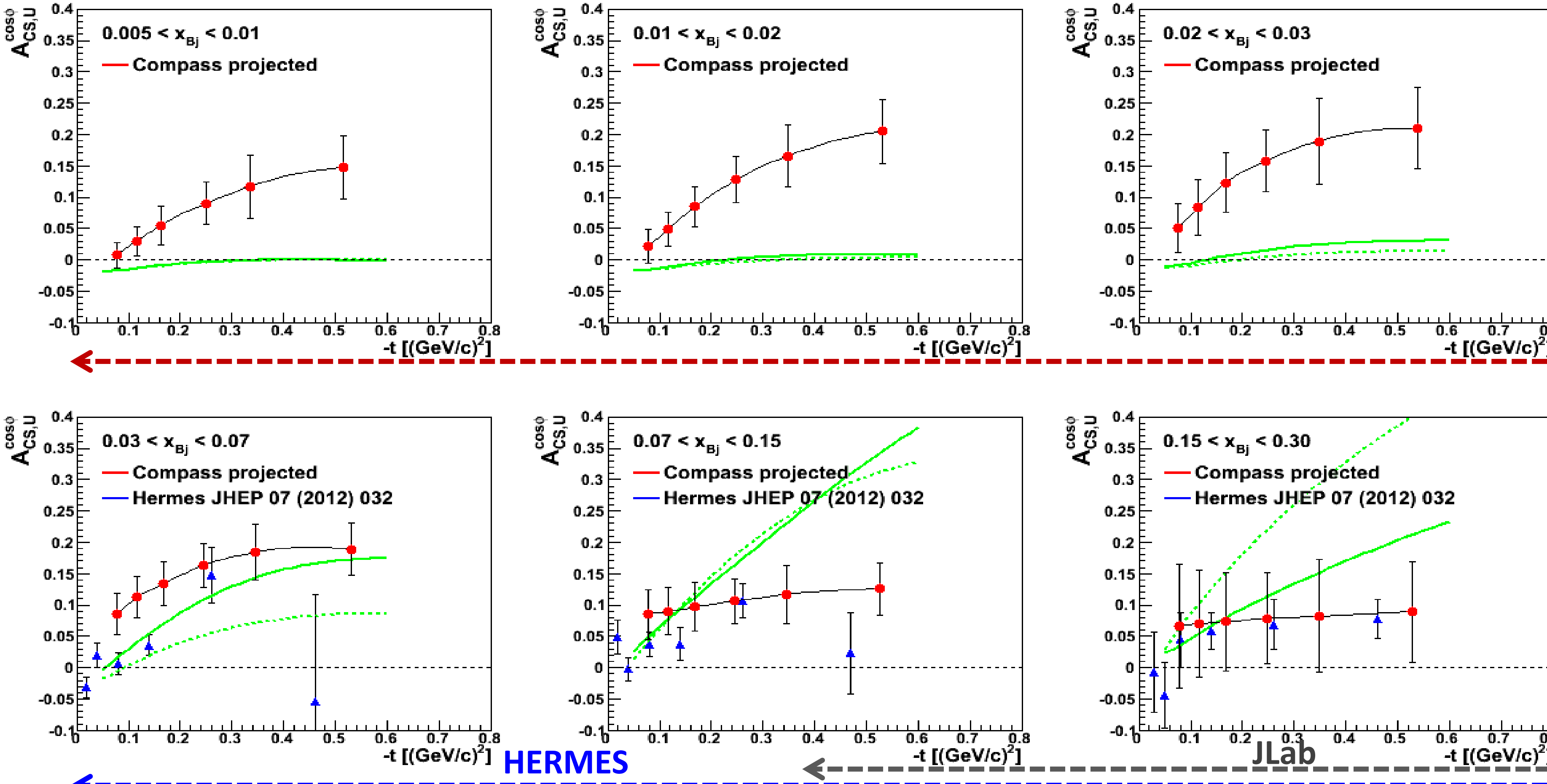
DVCS Prediction at COMPASS
For 2 × 6months in 2016-17

Beam Charge and Spin Diff. @ COMPASS

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

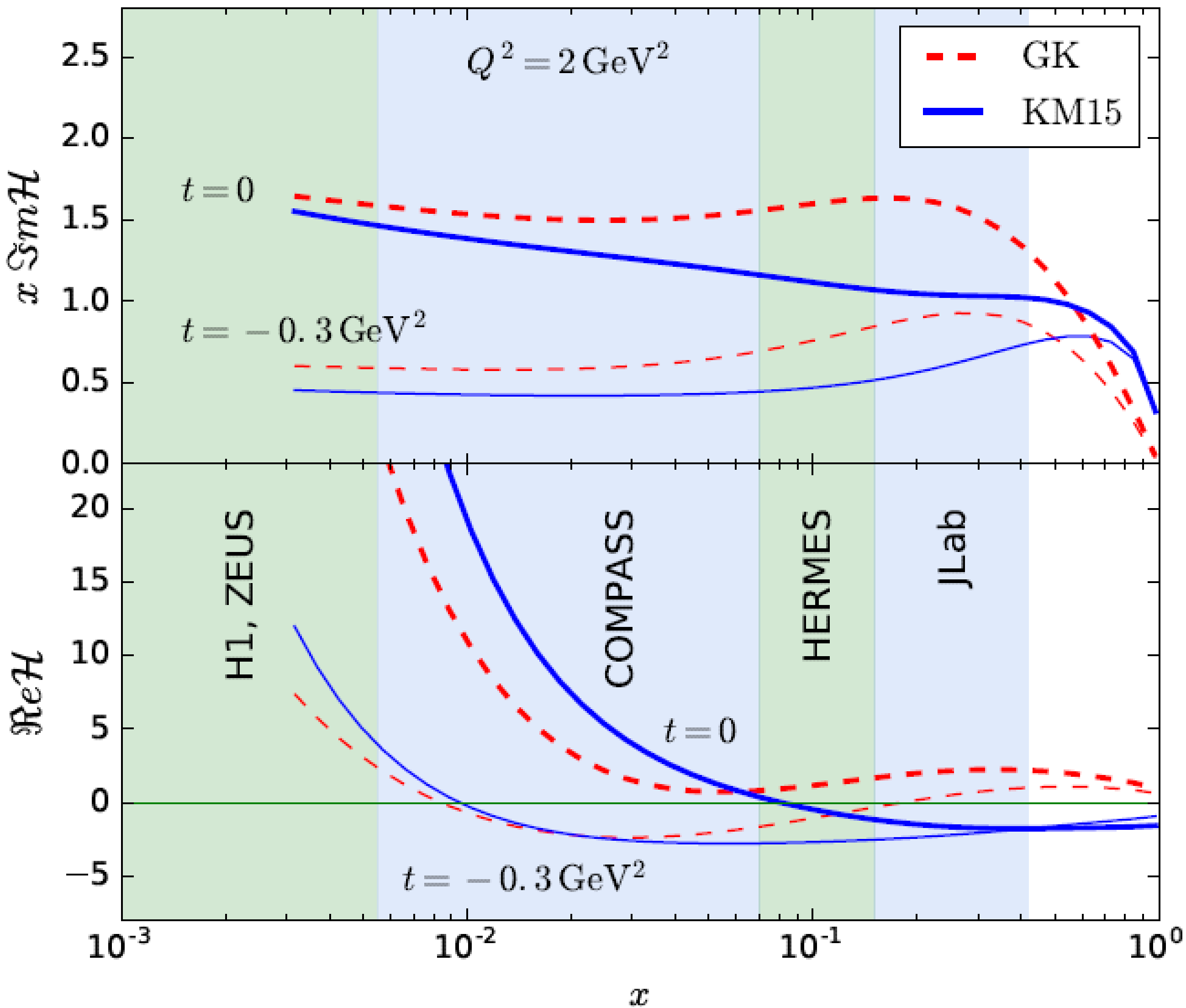
Predictions with
VGG and D.Mueller KM10

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



COMPASS 2 years of data E_μ= 160 GeV 1 < Q^2 < 8 GeV^2 with ECAL2 + ECAL1 + ECAL0

Impact of DVCS @ COMPASS in global analysis ?



Im $\mathcal{H}$

Is it rather well known ?

Re $\mathcal{H}$ linked to the *D term* is still poorly constrained

KM15 K Kumericki and D Mueller arXiv:1512.09014v1

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

Hunting the GPD E, holy grail for OAM

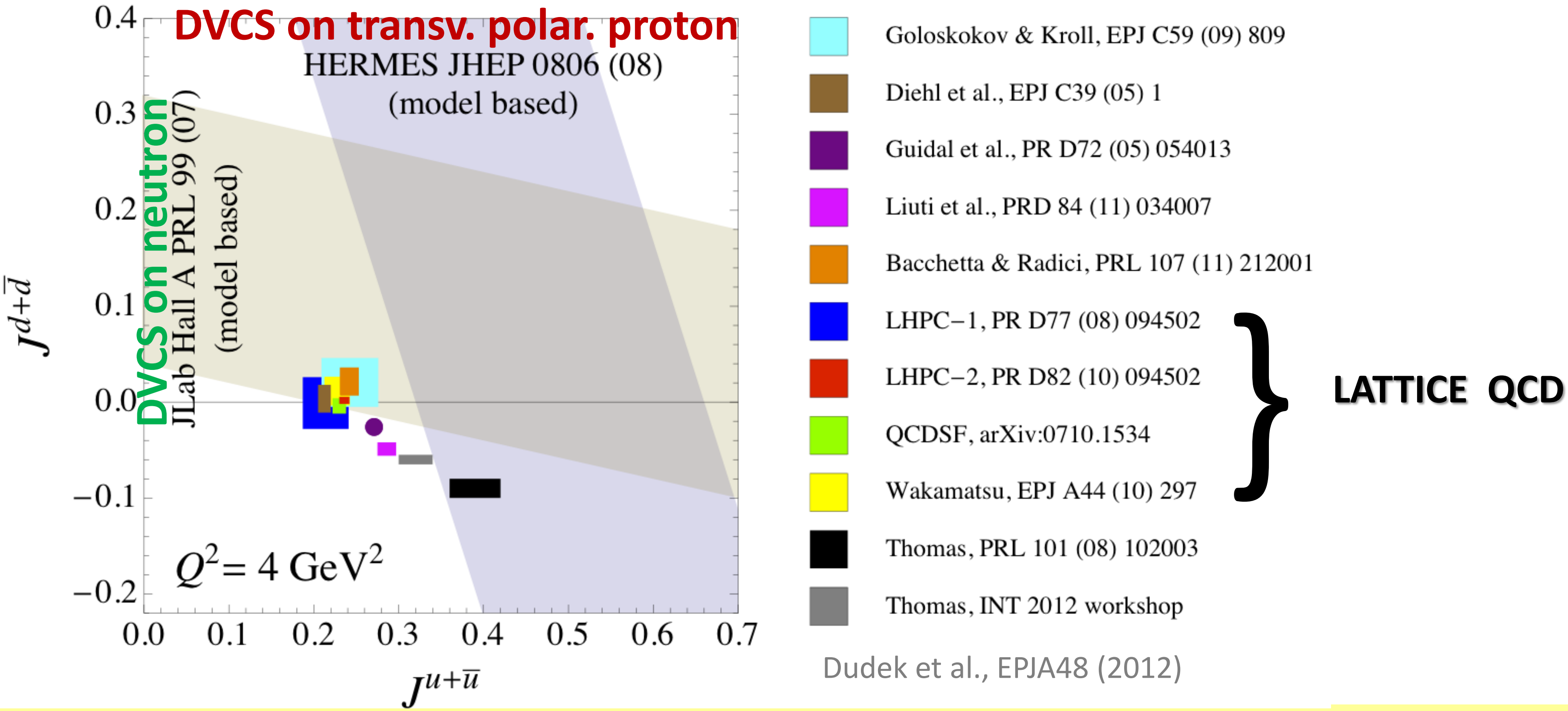
$\vec{\ell}\, d \rightarrow \ell\, n\, \gamma\, (p)$

$$\Delta\sigma_{LU} \sim Im\,(F_{1n}\, \mathcal{H} - F_{2n}\, \mathcal{E})$$

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

$$\Delta\sigma_{UT}^{\sin(\phi-\phi s)\cos\phi} = Im\,(F_2\, \mathcal{H} - F_1 \mathcal{E})$$
$$\Delta\sigma_{LT}^{\sin(\phi-\phi s)\cos\phi} = Re\,(F_2\, \mathcal{H} - F_1 \mathcal{E})$$

Model dependent extraction of J^u and J^d



Dudek et al., EPJA48 (2012)

Future program - under discussion at COMPASS - selected at JLab12 as
"High impact" experiments (CLAS 12 + neutron detector + HDice or ND_3 target)

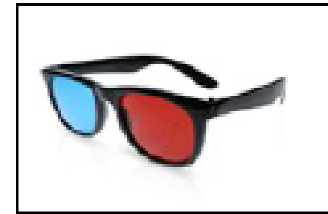
Only selected results.
Prospects for Time-like Compton Scattering and Double DVCS.
Precise Data in a large kinematic domain are necessary.
A large theoretical effort:

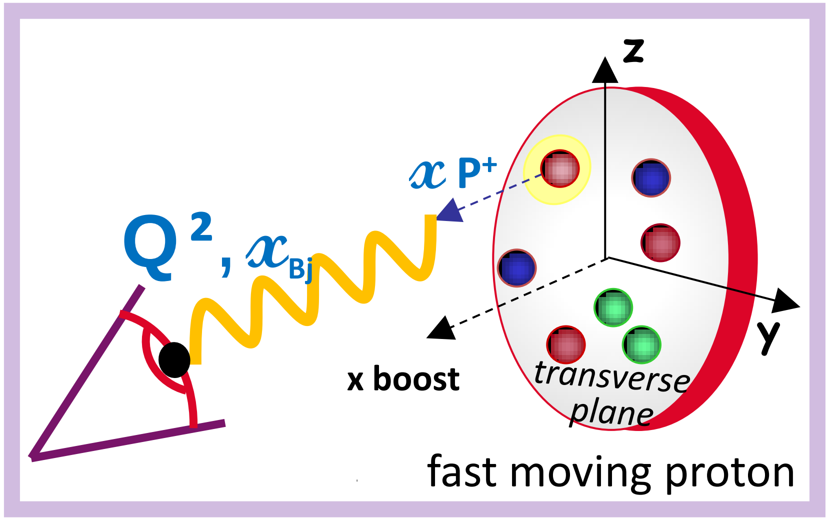
- to extract the GPD information from the experiments
- to still improve the GPD models

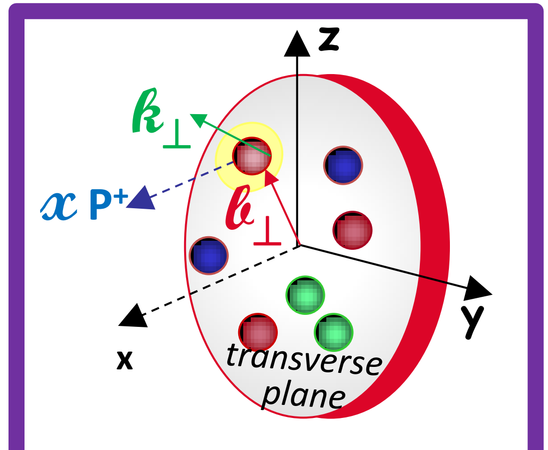
GPD programs with DVCS, HEMP (from light mesons to J/Ψ) are a priority for COMPASS @ CERN, JLab 12 GeV, and for a future electron-proton collider

Understanding the structure of the nucleon is still an exciting and vibrant area of research

Proton picture: 1D → 1+2D







Quantum tomography of the nucleon

Ji, PRL91 (2003)
Belitsky, Ji, Yuan, PRD69 (2004)
Lorcé et al, JHEP1105 (2011)

$\mathcal{W}\,(x, k_\perp, b_\perp)$

$\int db_\perp$ → **Transverse momentum**

$\int dk_\perp$ → **Transverse position**

Parton Distribution Functions
PDFs (x)

Longitudinal momentum

$q(x)$ or $f_1^{\,q}(x)$

Longitudinal spin

$\Delta q(x) = \vec{q}(x) - \overleftarrow{q}(x)$

Transverse spin

$\Delta_T q$ or $h_1(x)$

Transverse momentum

$t \to 0$

$\int dk_\perp$

8 TMDs $(x, k_\perp)$

Sivers,
the most famous TMD

Transverse position

8 GPDs $(x, b_\perp)$

$\int dx$ → Form Factors

$H\,(x, x', t)$
$E\,(x, x', t)$

holy grail for OAM