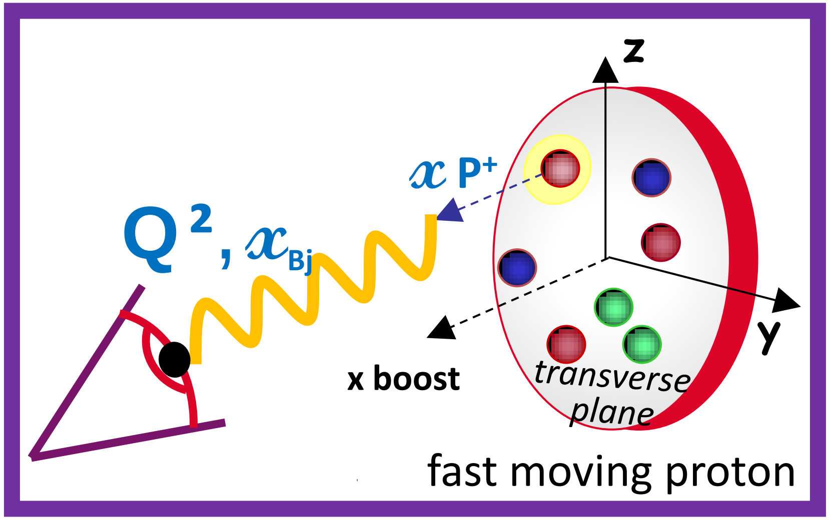
3-Dimensional Structure of the Nucleon from Hard Exclusive Processes

an overview of the Worlwide Program

Nicole d'Hose, CEA-Saclay, France

CEA - Saclay

Proton picture: 1D



Parton Distribution Functions
PDFs (x)

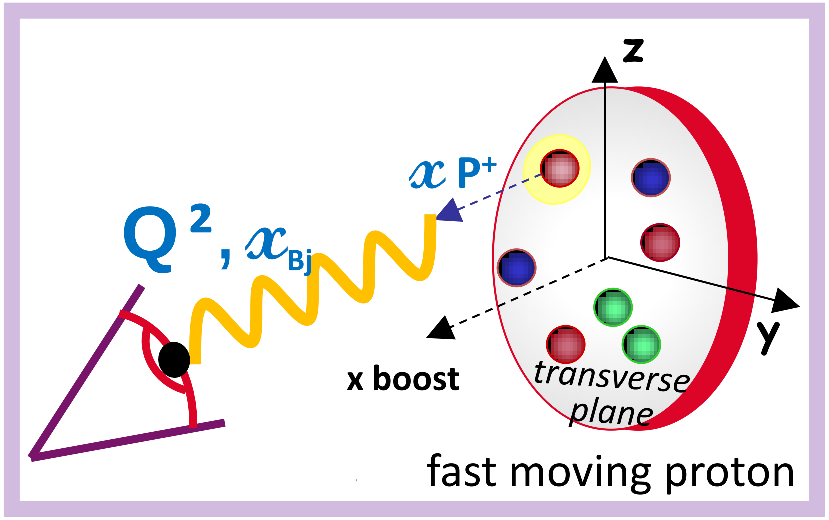
Longitudinal momentum

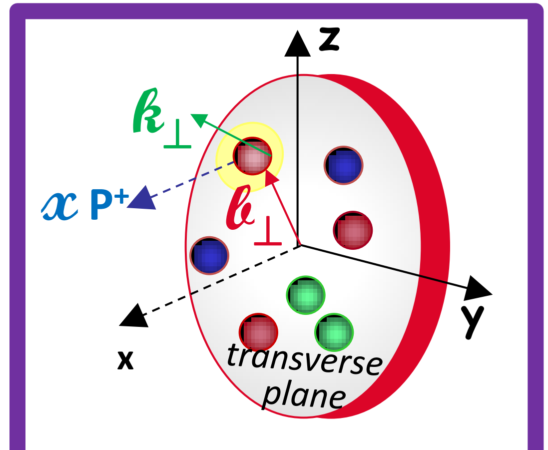
$q(x)$ or $f_1^q(x)$

Longitudinal spin

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

Proton picture: 1D → 1+2D





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

Quantum tomography of the nucleon

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

$\int db_\perp$ → 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 $h_1(x)$

← $\int dk_\perp$

Transverse momentum

8 TMDs ($x, k_\perp$)

accessible
in SIDIS *and* Drell-Yan

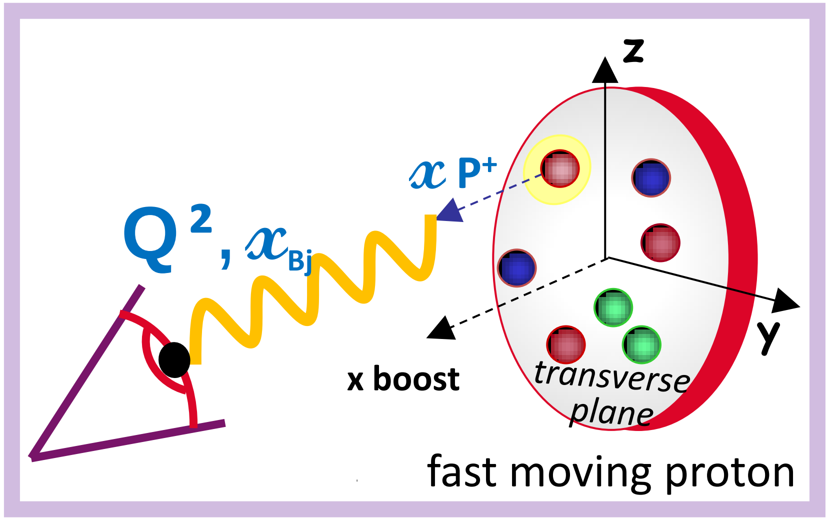
Transverse position

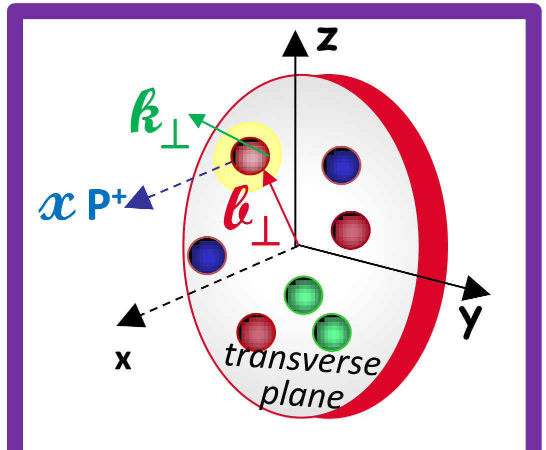
8 GPDs ($x, b_\perp$) → $\int dx$ → Form Factors

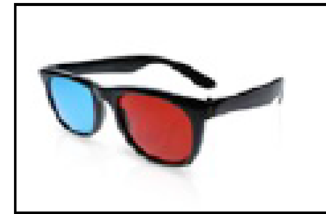
accessible
in **exclusive reactions**

DVCS: Deeply Virtual Compton Scattering
HEMP: Hard Exclusive Meson Production

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 $h_1(x)$

$t \to 0$ (GPDs → PDFs)

$\int dk_\perp$ (TMDs → PDFs)

Transverse momentum

8 TMDs $(x, k_\perp)$

Sivers,
the most famous TMD

Transverse position

8 GPDs $(x, b_\perp)$

H (x, x', t)

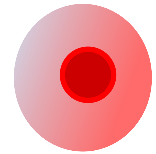
E (x, x', t)

$\int dx$ → Form Factors

holy grail for OAM

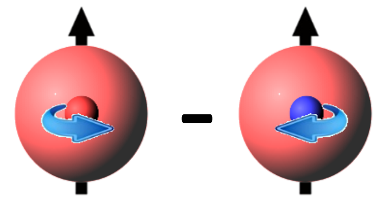
4 chiral-even GPDs (+ 4 chiral-odd GPDs)

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



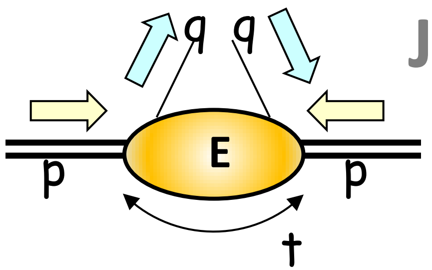
"Elusive"

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



Sivers: quark k_T & nucleon transv. Spin

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



Ji sum rule: PRL78 (1997) cited 1302 times

Relation to OAM

\+ their partner for polarised quarks

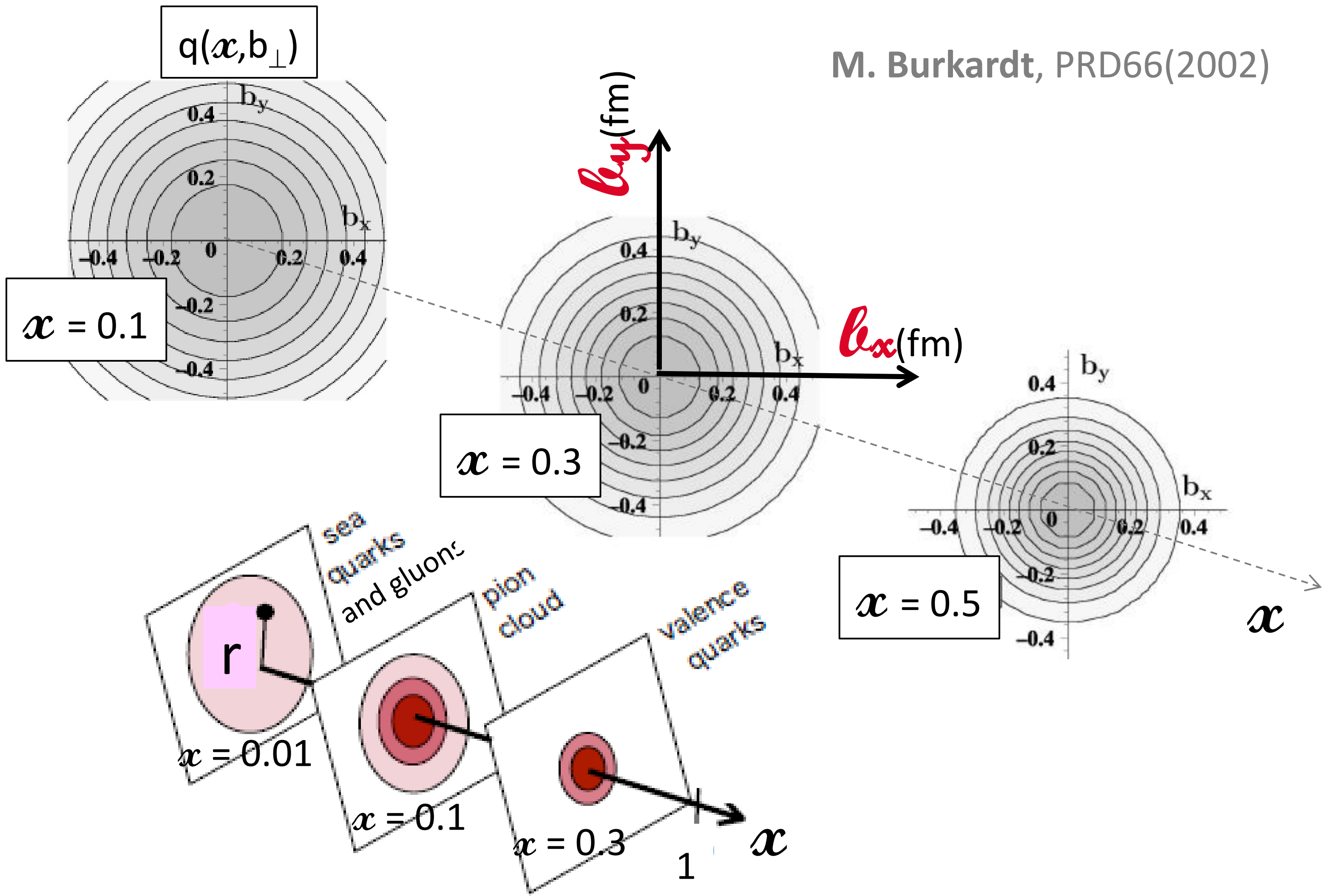
$\tilde{\mathbf{H}}(x, \xi, t) \xrightarrow{t \to 0} \Delta q(x)$ or $g_{1L}(x)$

$\tilde{\mathbf{E}}(x, \xi, t) \longleftrightarrow g_{1T}(x, k_T)$

(+ 4 chiral-odd GPDs)

3D imaging: mapping in the transverse plane

Proton
moving
towards us

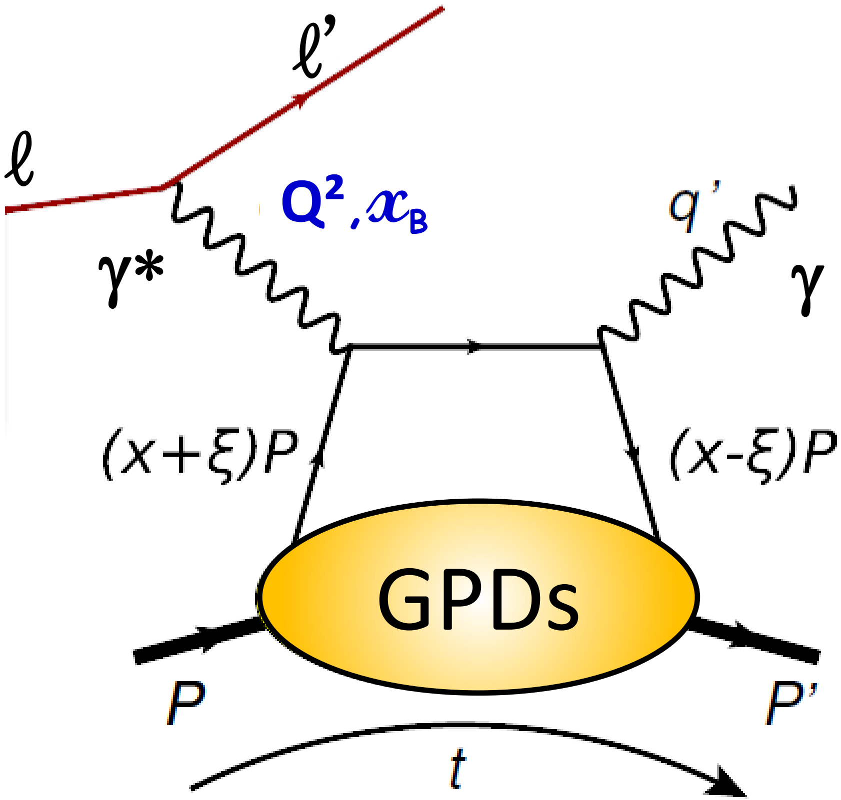


M. Burkardt, PRD66(2002)

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

Deeply virtual Compton scattering (DVCS)

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



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

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

Definition of variables:

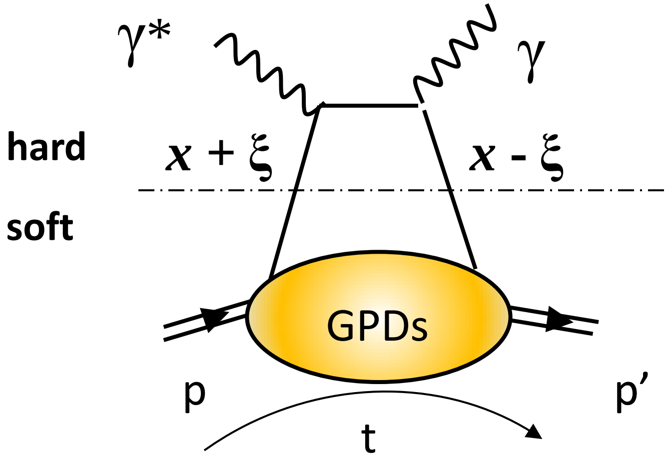
x: average long. momentum

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

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

Exclusive reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):



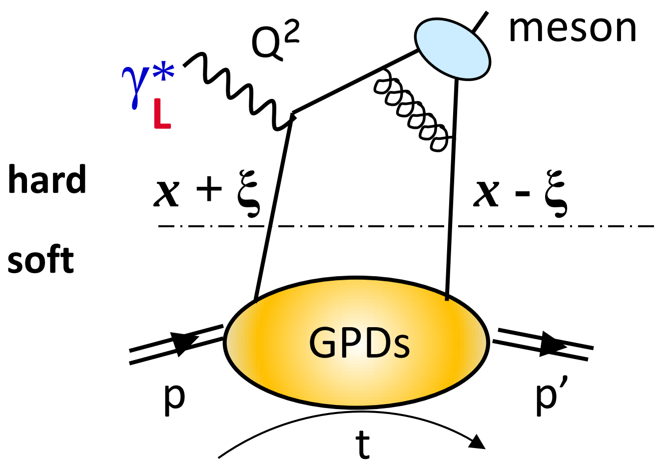
Factorisation:

Collins *et al.*

Q^2 large

$t << Q^2$

Hard Exclusive Meson Production (HEMP):



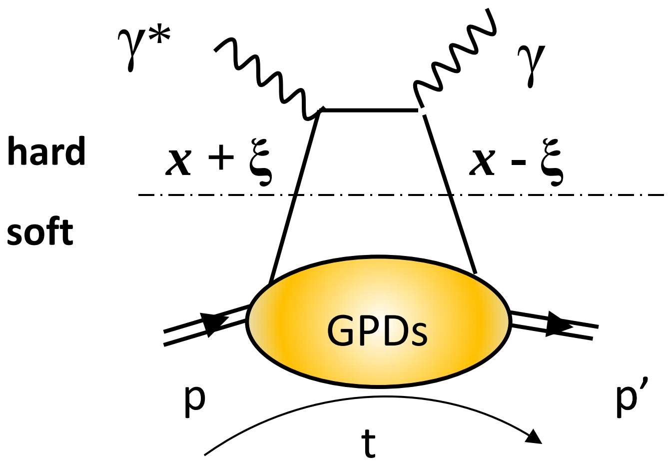
+ γ^*_L

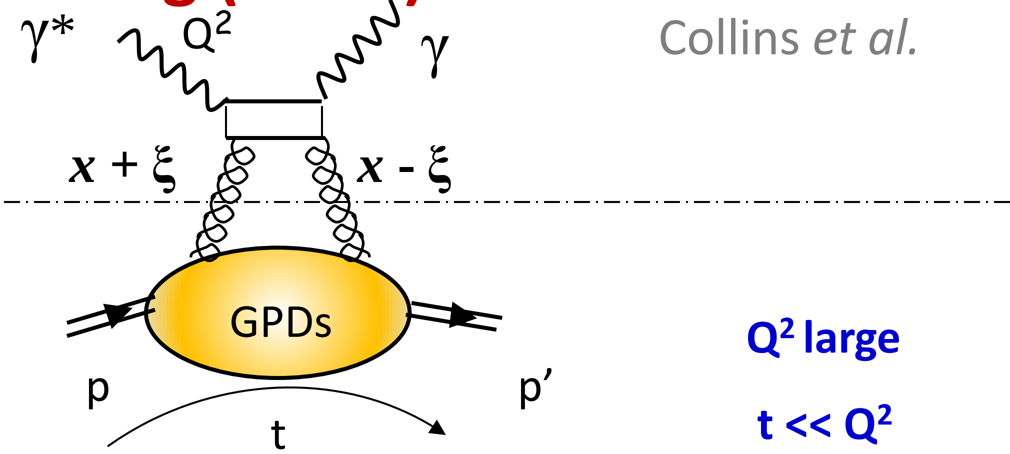
Meson wave funct.
Large power corr. & NLO
Very slow scaling

Quark contribution

Exclusive reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):



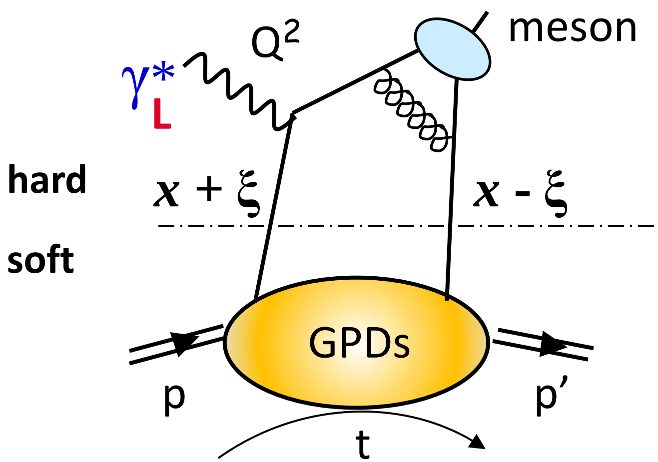


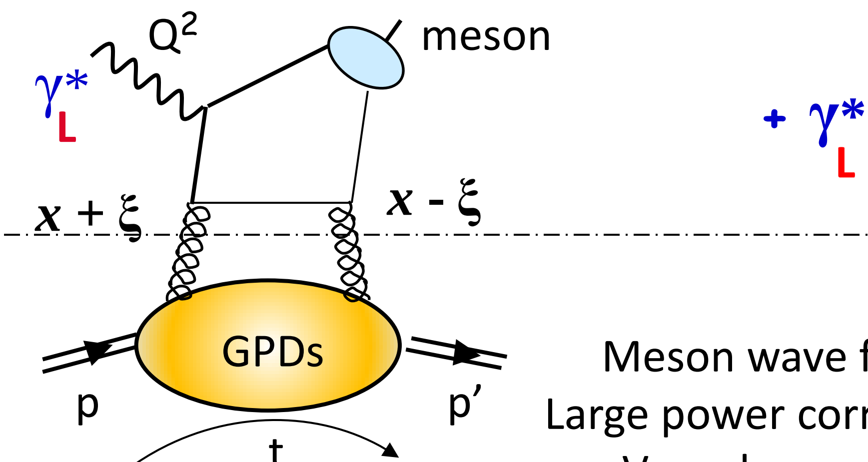
Factorisation:
Collins *et al.*

Q^2 large

$t << Q^2$

Hard Exclusive Meson Production (HEMP):





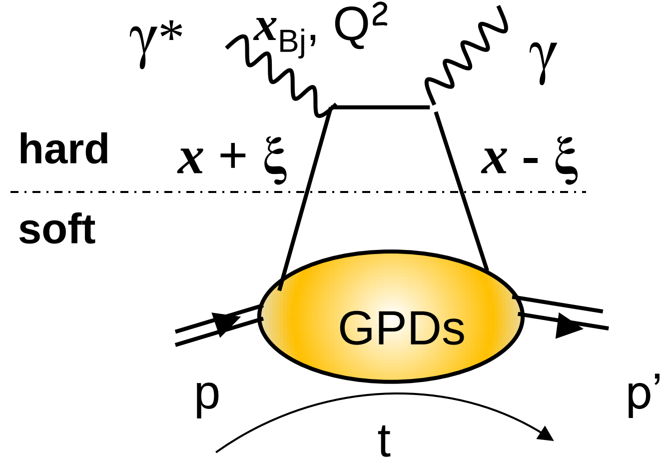
+ γ^*_L

Quark contribution

Gluon contribution

Meson wave funct.
Large power corr. & NLO
Very slow scaling

Compton Form Factors are measured in DVCS

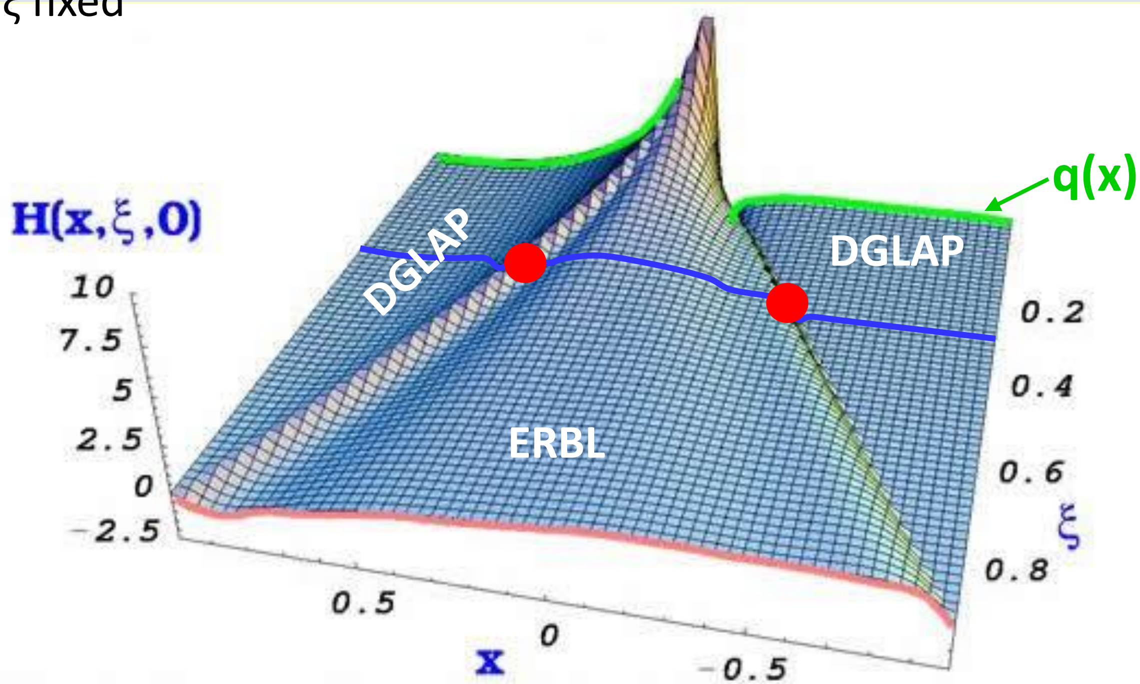


The amplitude DVCS at LT & LO in α_S:

Real part **Imaginary part**

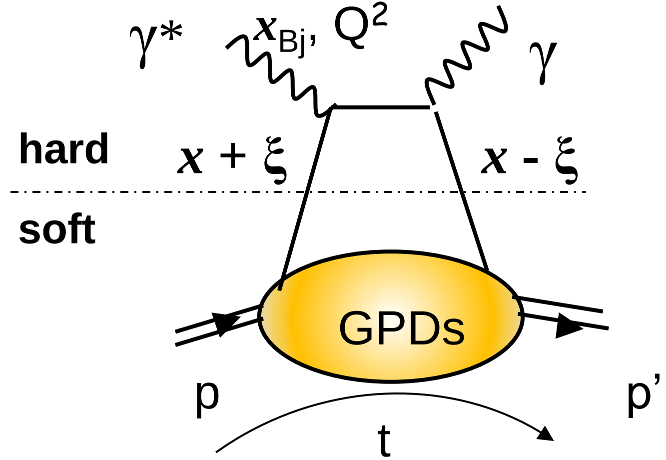
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\,\pi\, H(x=\pm\xi,\xi,t)$$

t, ξ fixed



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)

Compton Form Factors are measured in DVCS



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

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

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.**

HEMP → filter of GPDs and flavors

Hard Exclusive Meson Production (HEMP):

Vector meson production $(\rho,\omega,\phi, J/\psi\ldots)$ $\Rightarrow$ H & E

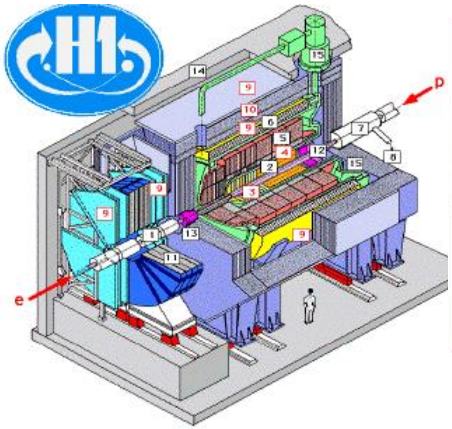
Pseudo-scalar production $(\pi,\eta\ldots)$ $\Rightarrow$ $\tilde{H}$ & $\tilde{E}$

$$H\rho^0 = 1/\sqrt{2}\,(2/3\,H^u + 1/3\,H^d + 3/8\,H^g)$$

$$H\omega = 1/\sqrt{2}\,(2/3\,H^u - 1/3\,H^d + 1/8\,H^g)$$

$$H\phi = -1/3\,H^s - 1/8\,H^g$$

The past and future experiments



Collider mode e-p forward fast proton

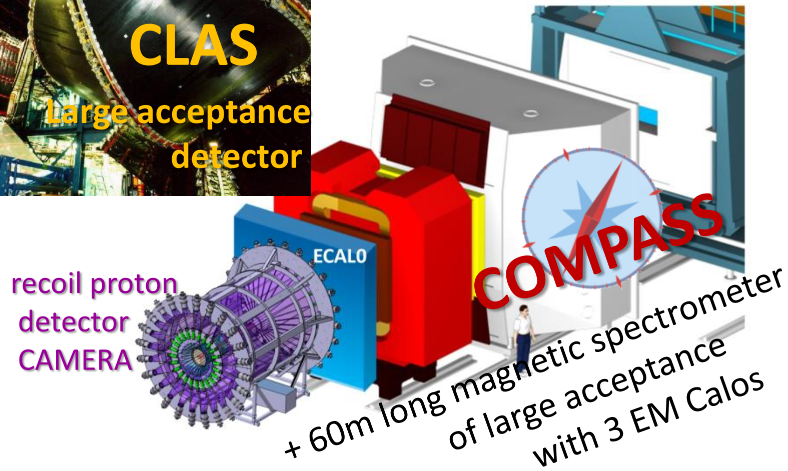
HERA: **H1** and **ZEUS**
Polarised 27 GeV e-/e+
Unpolarized 920 GeV proton
~ Full event reconstruction

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

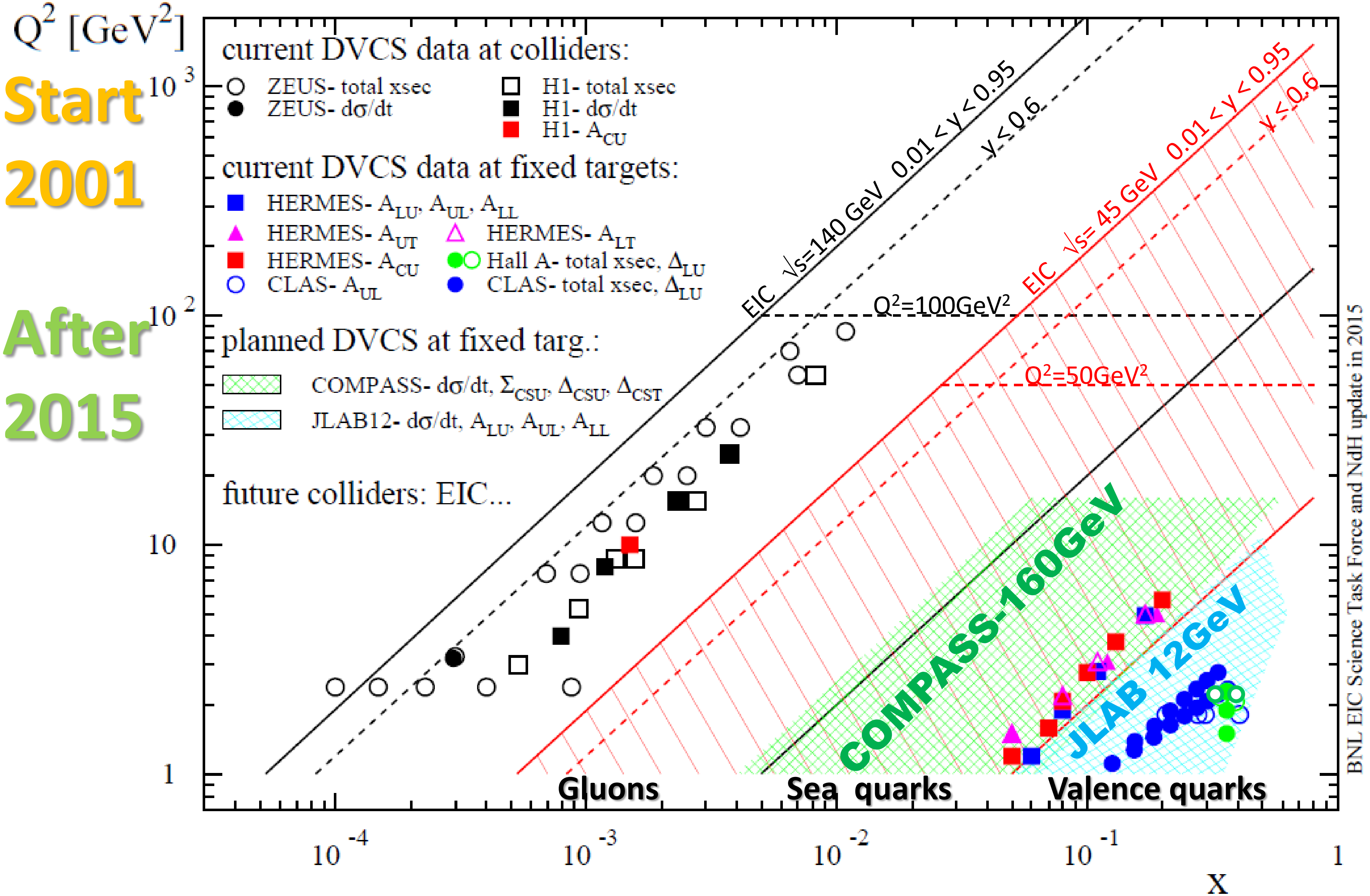
COMPASS @ CERN: Polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
with recoil detection



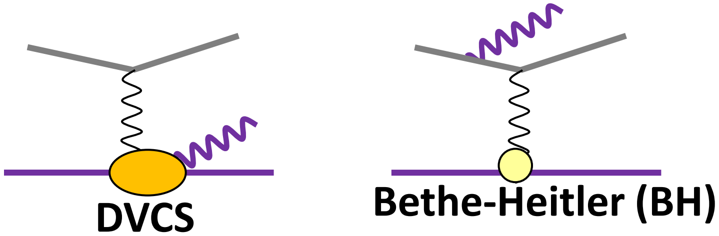
The past and future DVCS experiments

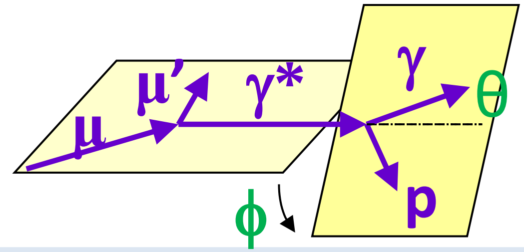
Start 2001

After 2015

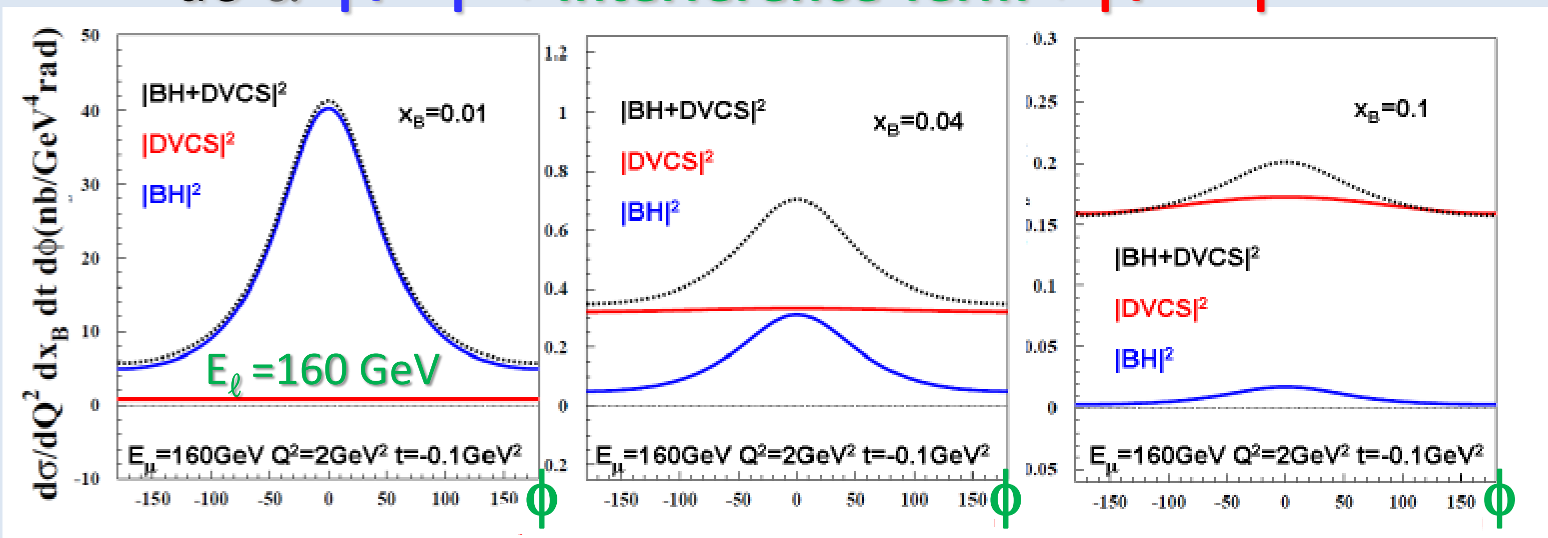


Impact of the beam energy for DVCS





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



BH dominates	DVCS ampl. via interference	DVCS dominates - Study of $d\sigma^{DVCS}/dt$
Reference yield	Jlab, HERMES, H1, COMPASS	Only for H1, ZEUS, COMPASS

‘pure’ DVCS and exclusive meson x-sections

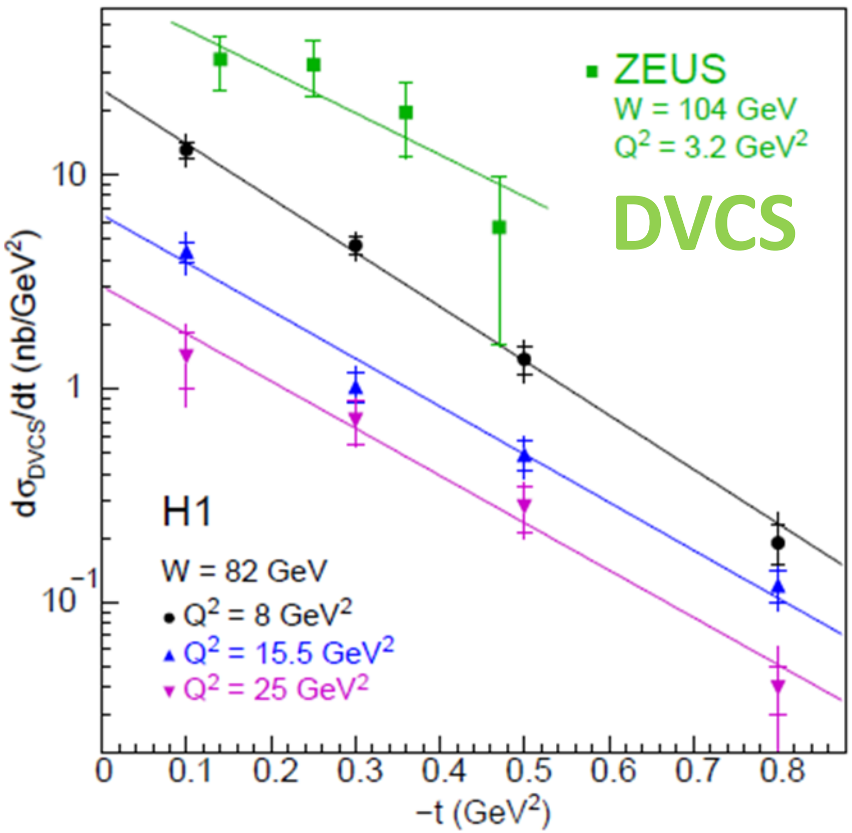
interpretated with ‘’universal’’ GPDs

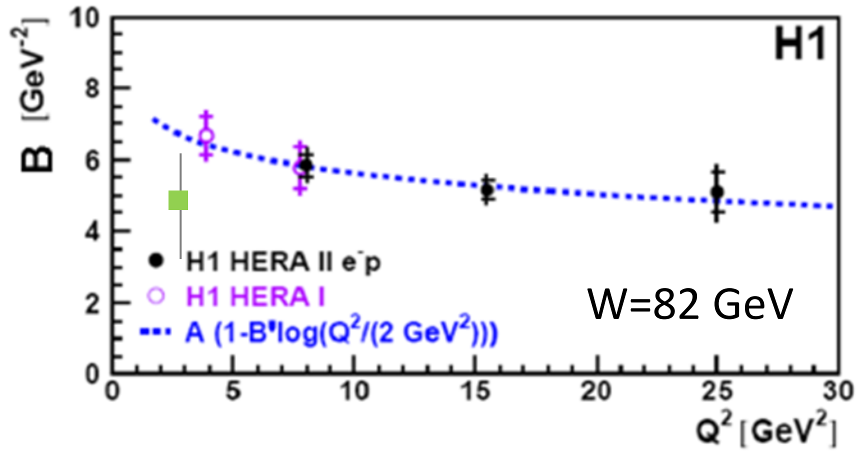
Gluon imaging @ HERA

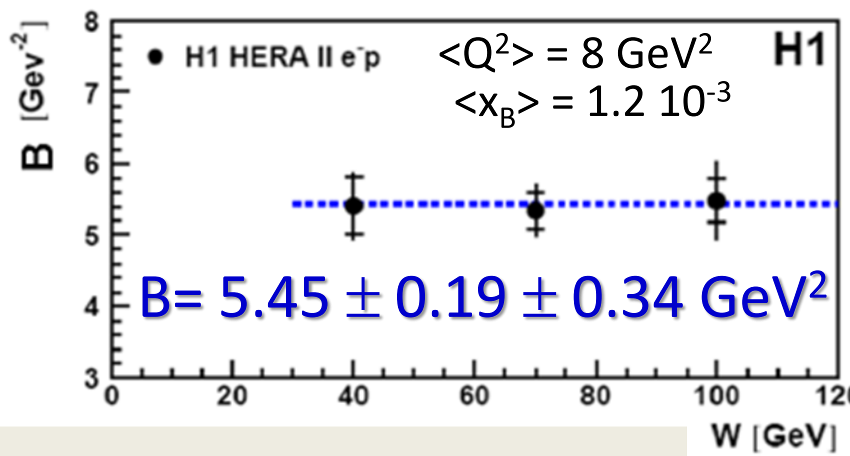
$d\sigma^{DVCS}/dt = e^{-B|t|}$

B is related to the transversed size of the scattering objects

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



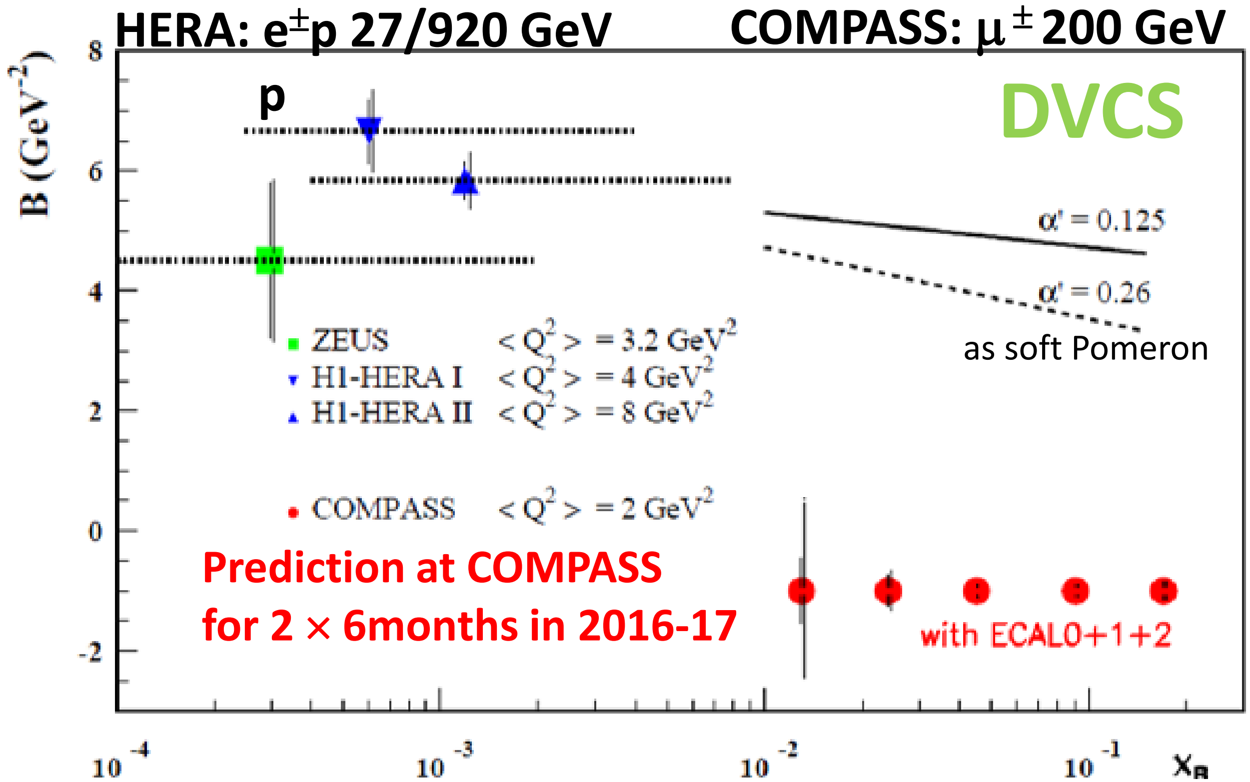




$<r_\perp^2(x_B)> \approx 2B(x_B)$

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

Sea quark imaging @ COMPASS



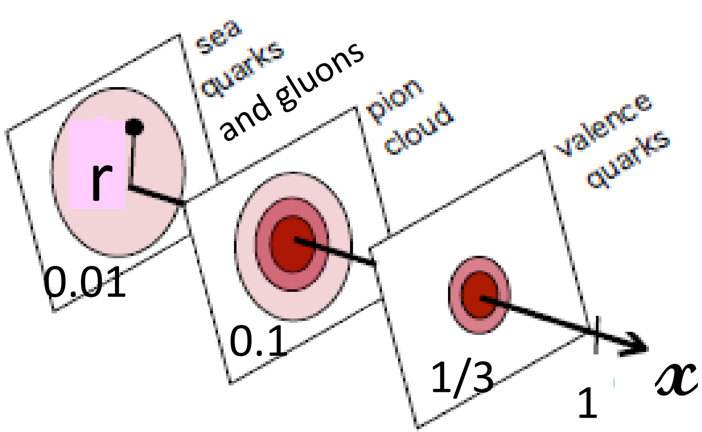
$d\sigma^{DVCS}/dt = e^{-B|t|}$

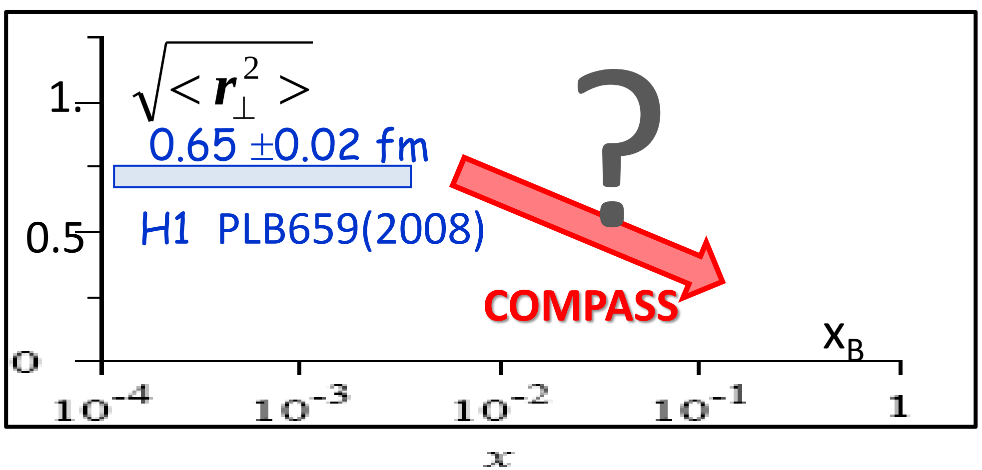
ansatz inspired by Regge Phenomenology:

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

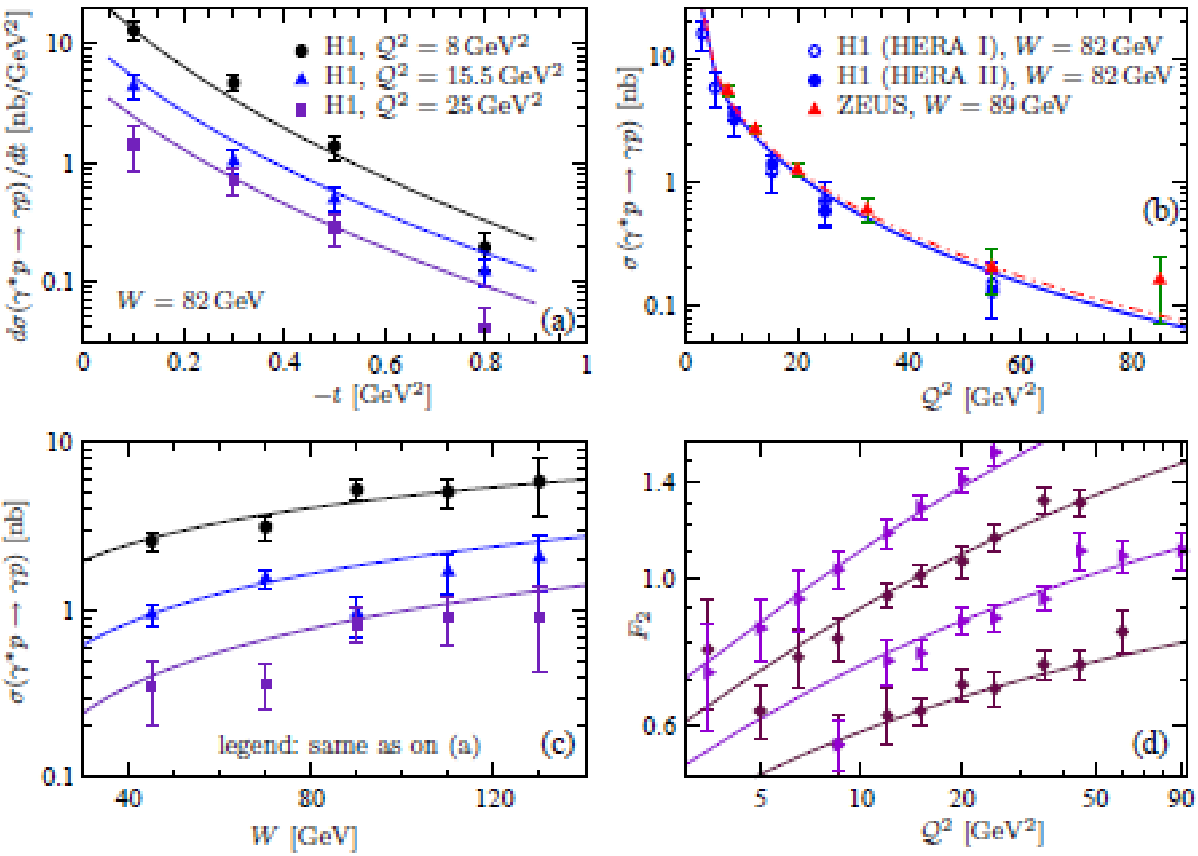
α' slope of Regge traject

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





KM10 model constrained by DVCS



KM10: Kumericki, Mueller, NPB (2010) 841

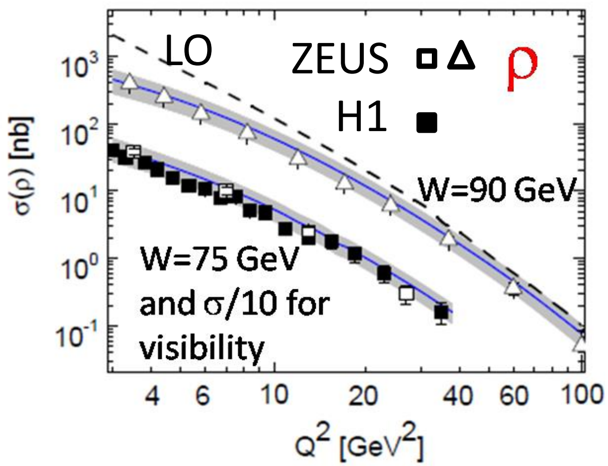
- Flexible parametrization of the GPDs based on both a Mellin-Barnes representation and dispersion integral which entangle skewness and t dependences
- Global fit on the world data ranging from H1, ZEUS to HERMES, JLab

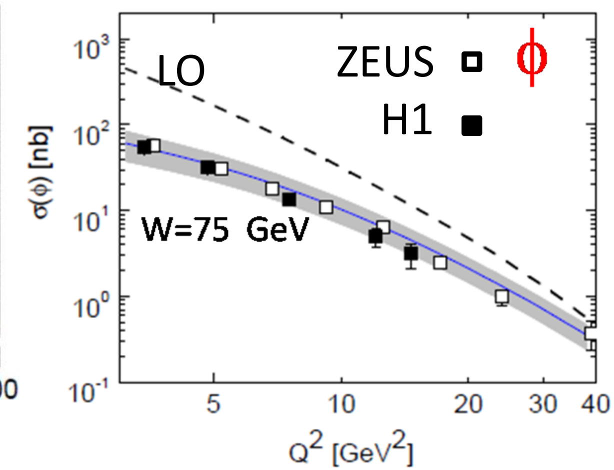
GK model constrained by HEMP

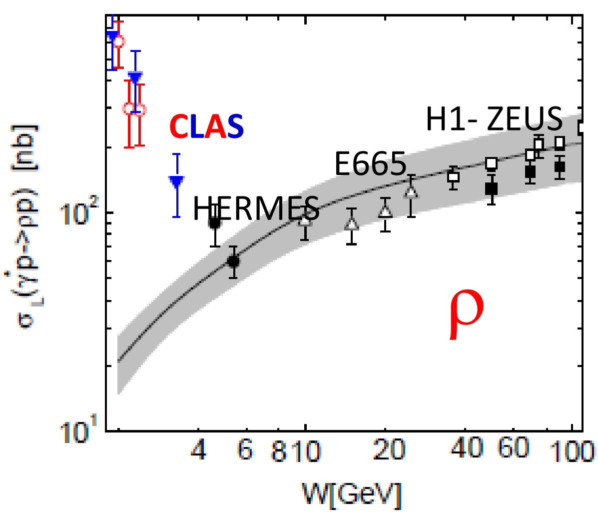
GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small x_B (or large W)

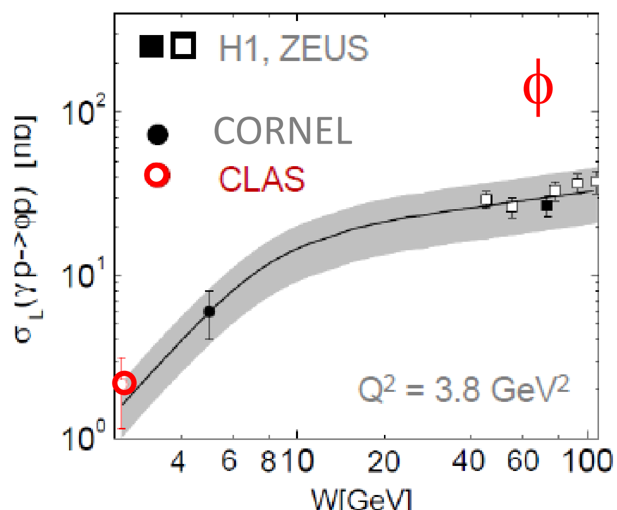
dominant (longitudinal) **$\gamma_L^* \, p \rightarrow M \, p$** and transv. polar. **$\gamma_T^* \, p \rightarrow M \, p$**

quark and gluon contributions and beyong leading twist









DVCS-BH interference on the proton

→ *Im* DVCS with BSA or Beam Spin difference

→ *Re* DVCS with BCA or Beam Charge difference

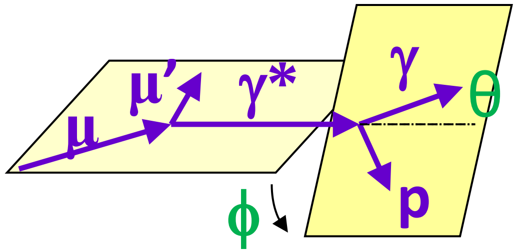
→ mainly constrains on the GPD H

Azimuthal dependence of BH+DVCS

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

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

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

$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - t/4m^2 F_2\mathcal{E}$ $\xrightarrow{\text{at small } x_B}$ $F_1\mathcal{H}$ 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 → see Angela Biselli's talk tomorrow

Beam Spin Sum and Diff of DVCS - HallA

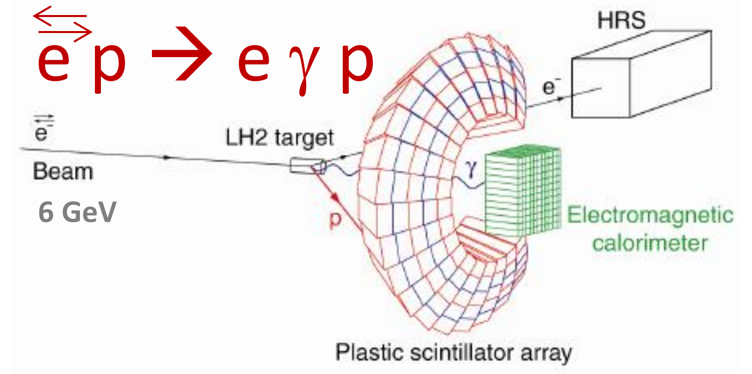
E00-110 pioneer experiment with magnetic spectrometer

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

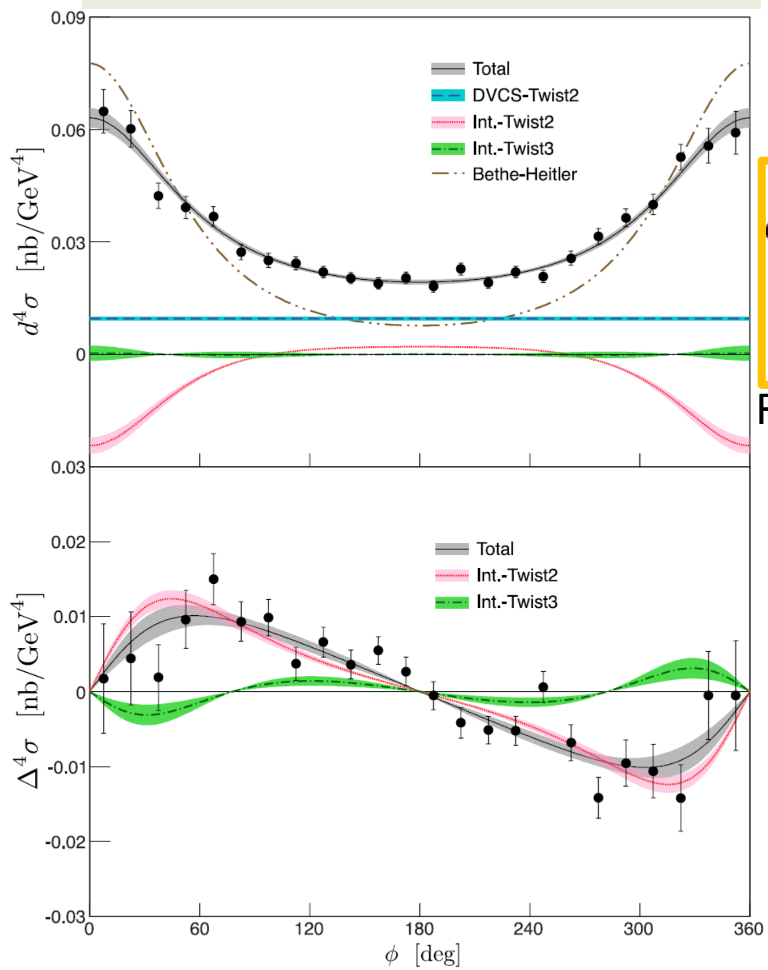
x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2 Defurne et al. arXiv: 1504.05453

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

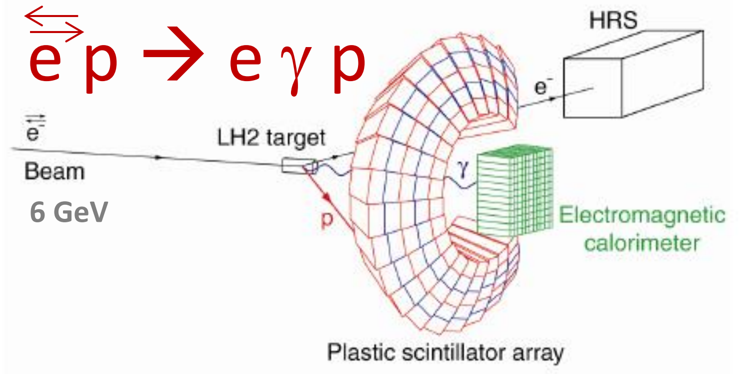
E00-110 pioneer experiment with magnetic spectrometer

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

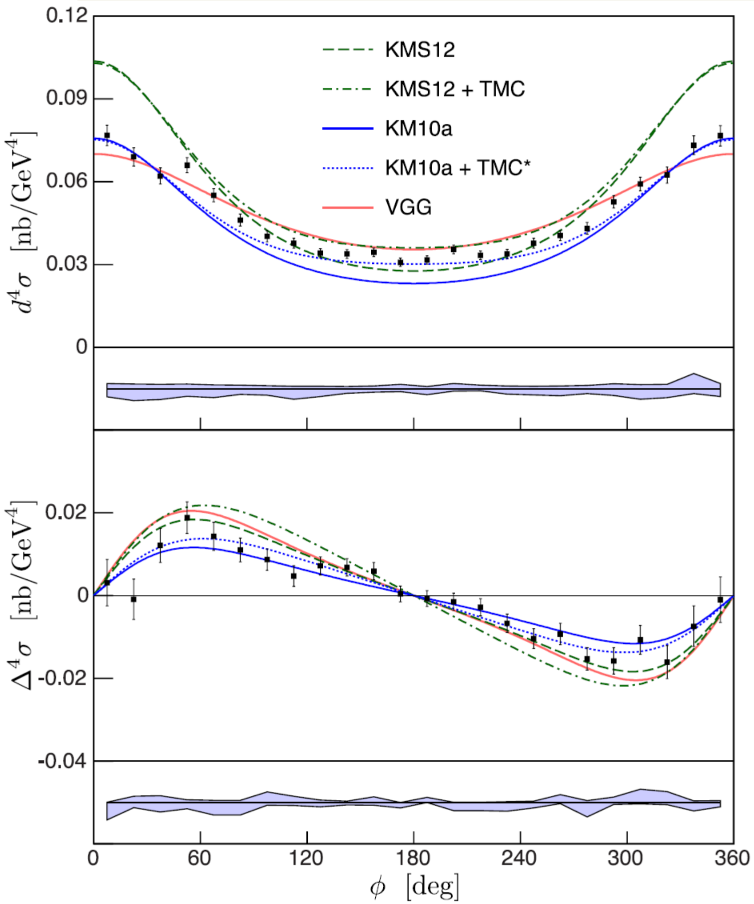
x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2 Defurne et al. arXiv: 1504.05453

new improved analysis

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



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



Comparison to models:

VGG 1rst model of GPD

KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)
with the GPD from GK model
(not adapted for the valence quark region)

KM10a fit including all the world DVCS data
except the previous x- sections of Hall A

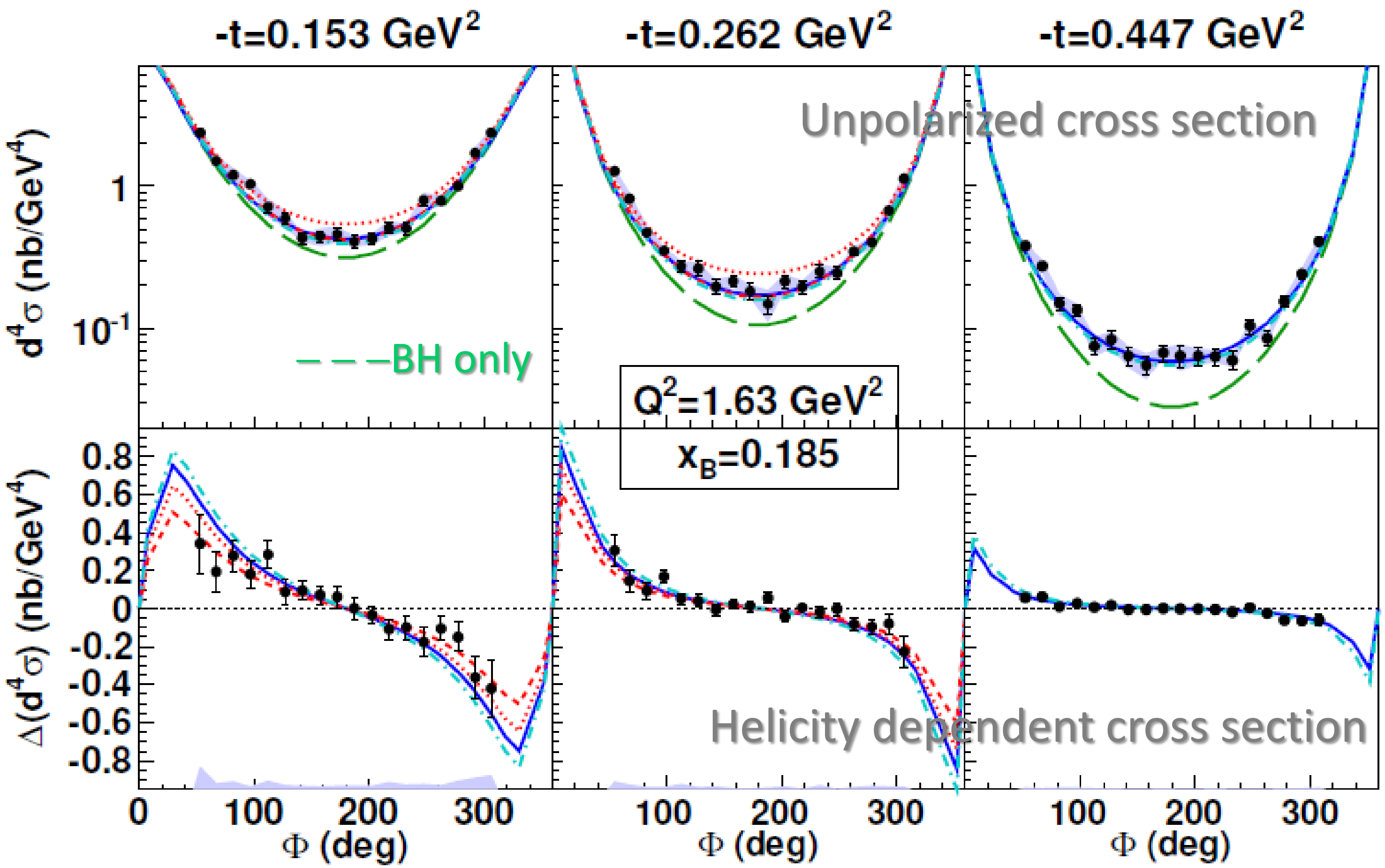
Difficulties to reproduce the total cross section at ϕ=180°

+ 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 – – –
all data
except 1st σ HallA

KM10 ....
all data including
1st σ Hall A

Large statistical uncertainties at large x_B and lack of ϕ=180° coverage for a definitive comparison with HallA

Valence quark imaging at Jlab

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

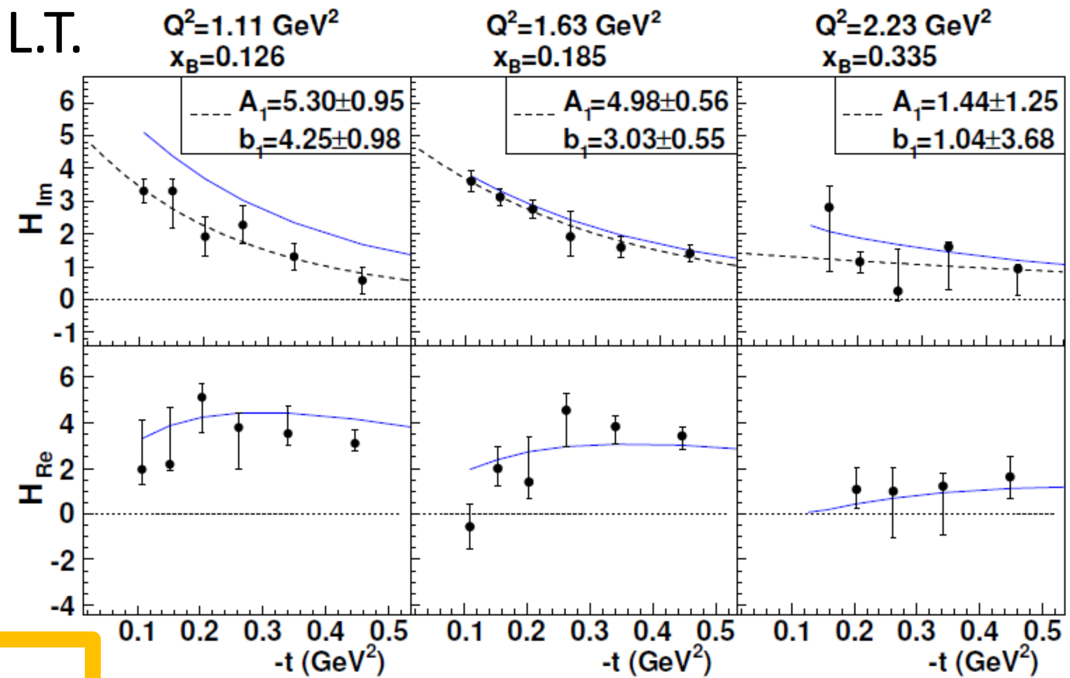
Jo et al. arXiv: 1504.02009

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

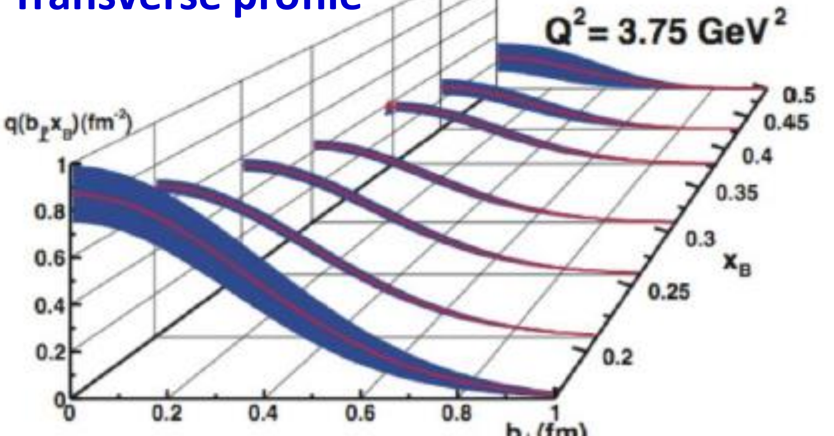
$$c_1^I = Re\ F_1\mathcal{H}$$

VGG model

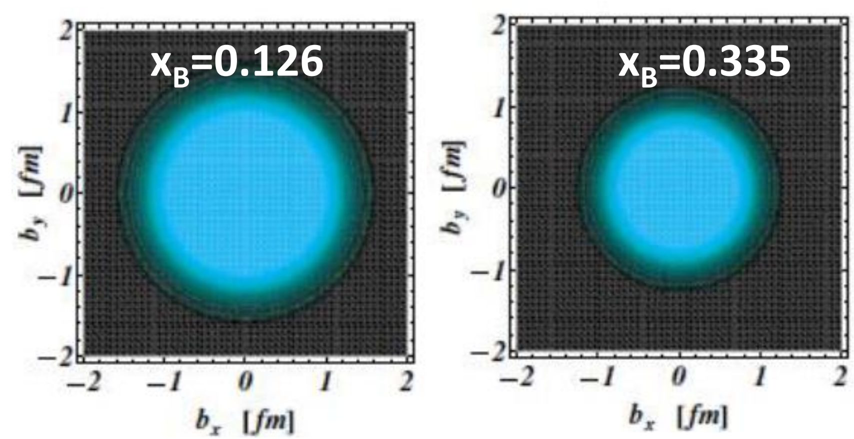
Fit $A\ e^{-b|t|}$



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

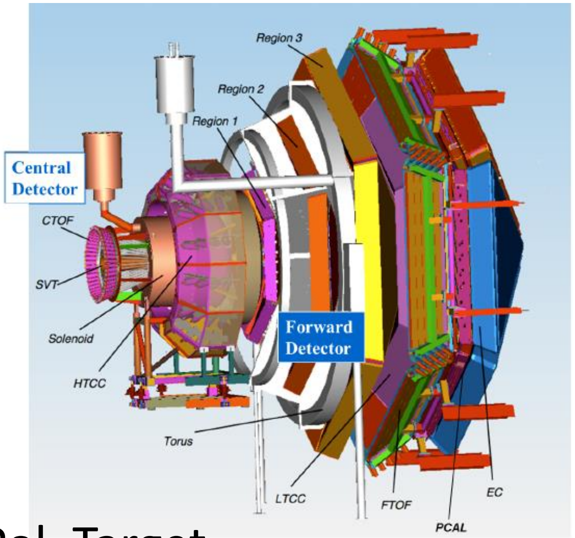
with high resolution magnetic spectrometer+ Calorimeter in Halls A and C

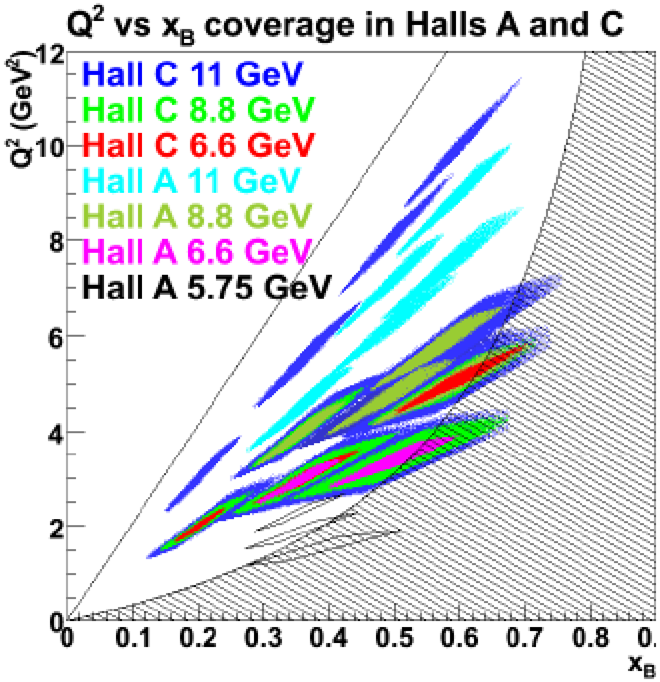
Exp. 2010: run E07-007
Now 2015: Hall A
~2018: Hall C

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

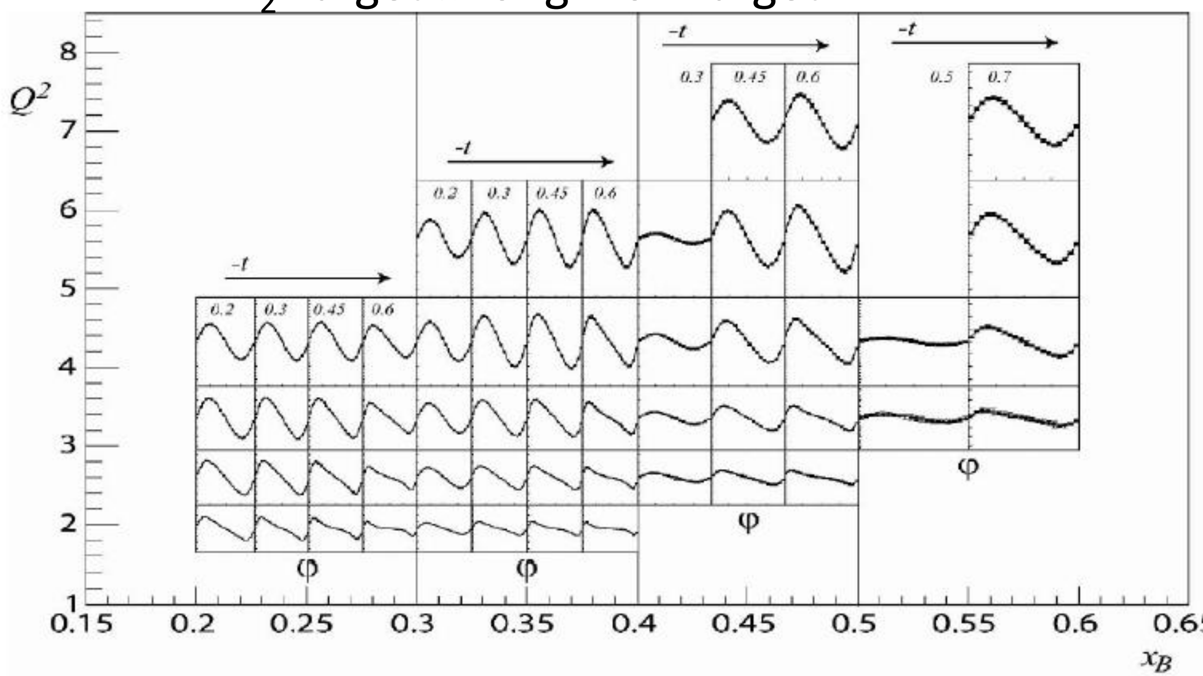
with CLAS12
In 2016

E12-06-119





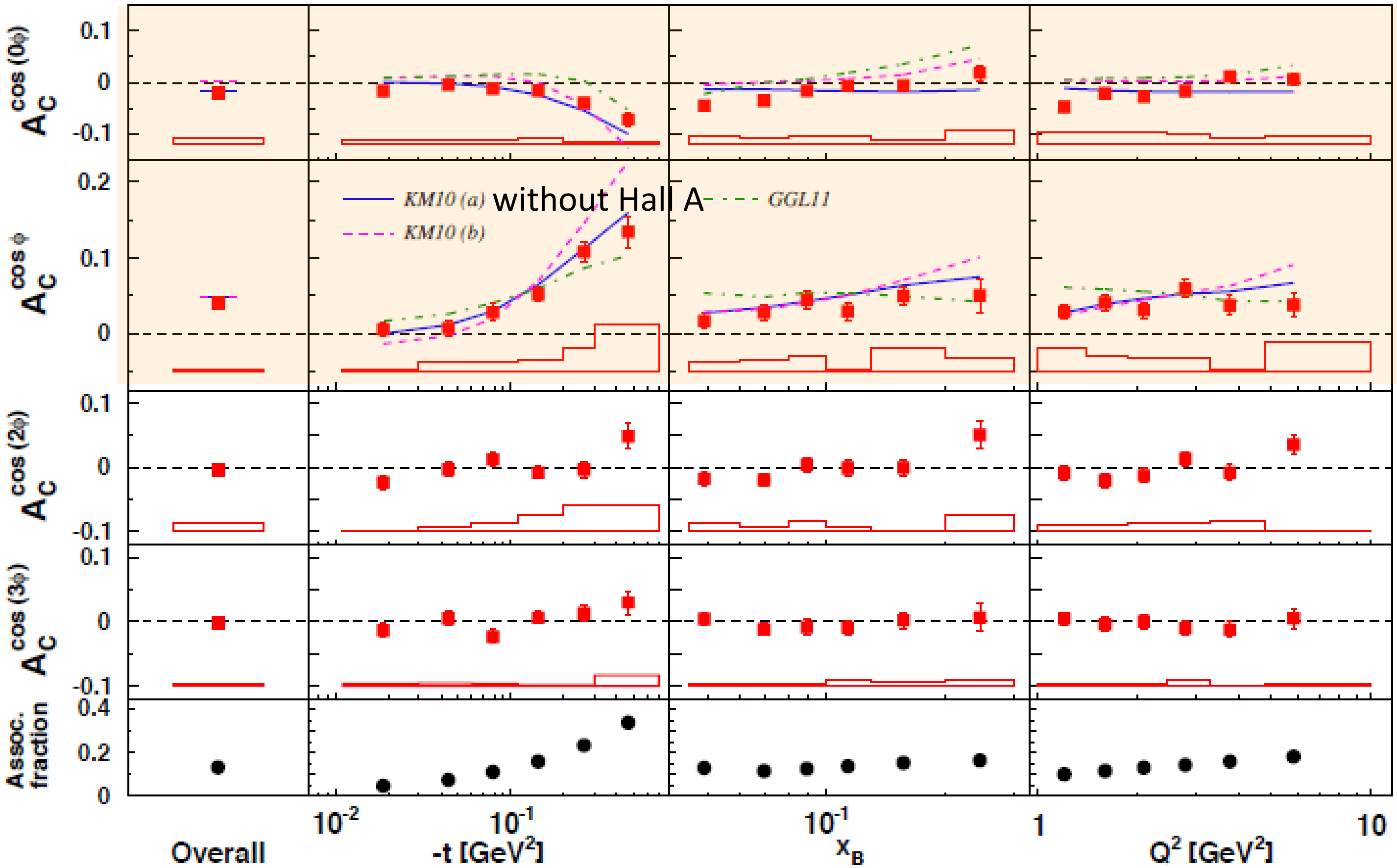
LH_2 Target & Long. Pol. Target



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

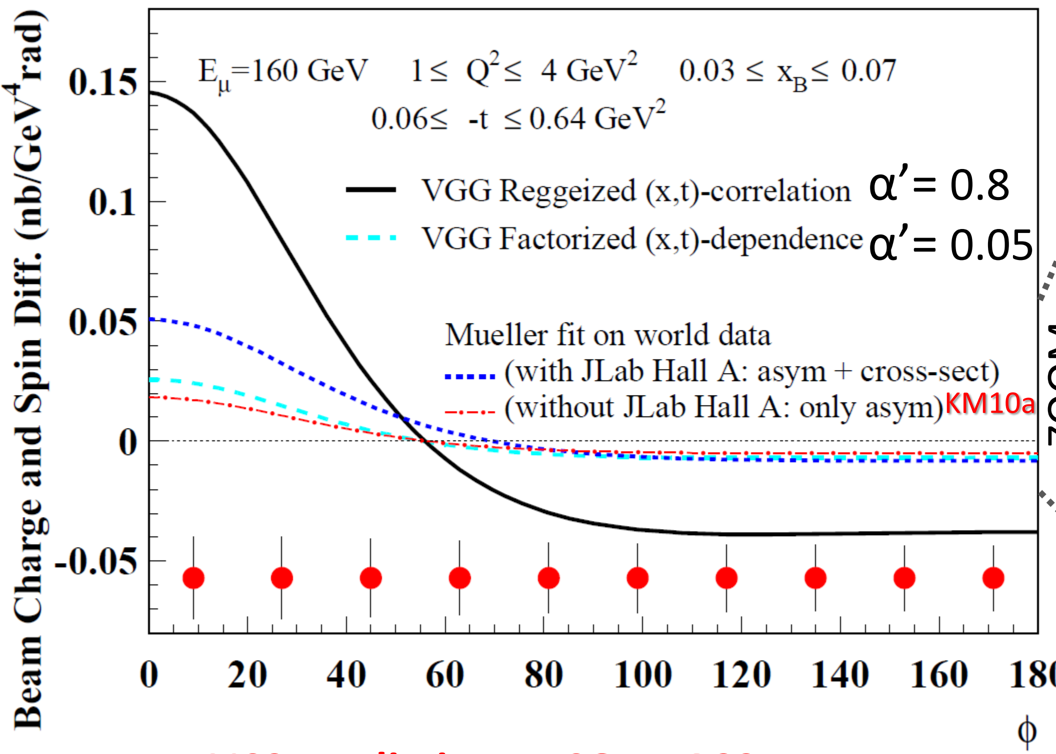
*G. Goldstein, J. Hernandez and S. Liuti, **Phys. Rev. D84** (2011)*

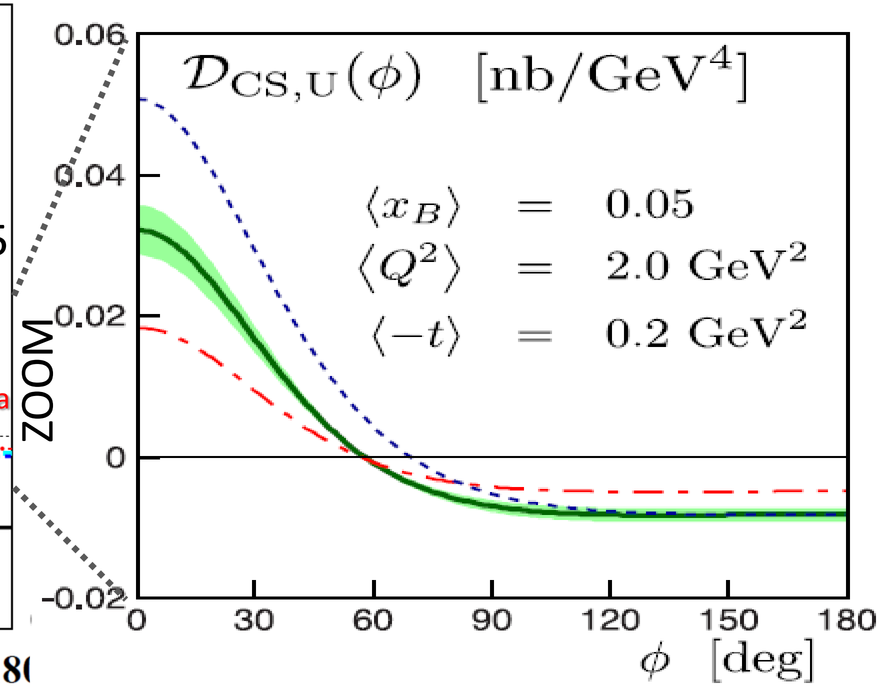
Beam Charge and Spin Diff. @ COMPASS

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

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

Comparison to different models





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

KM10a (without Hall A)

KM10b

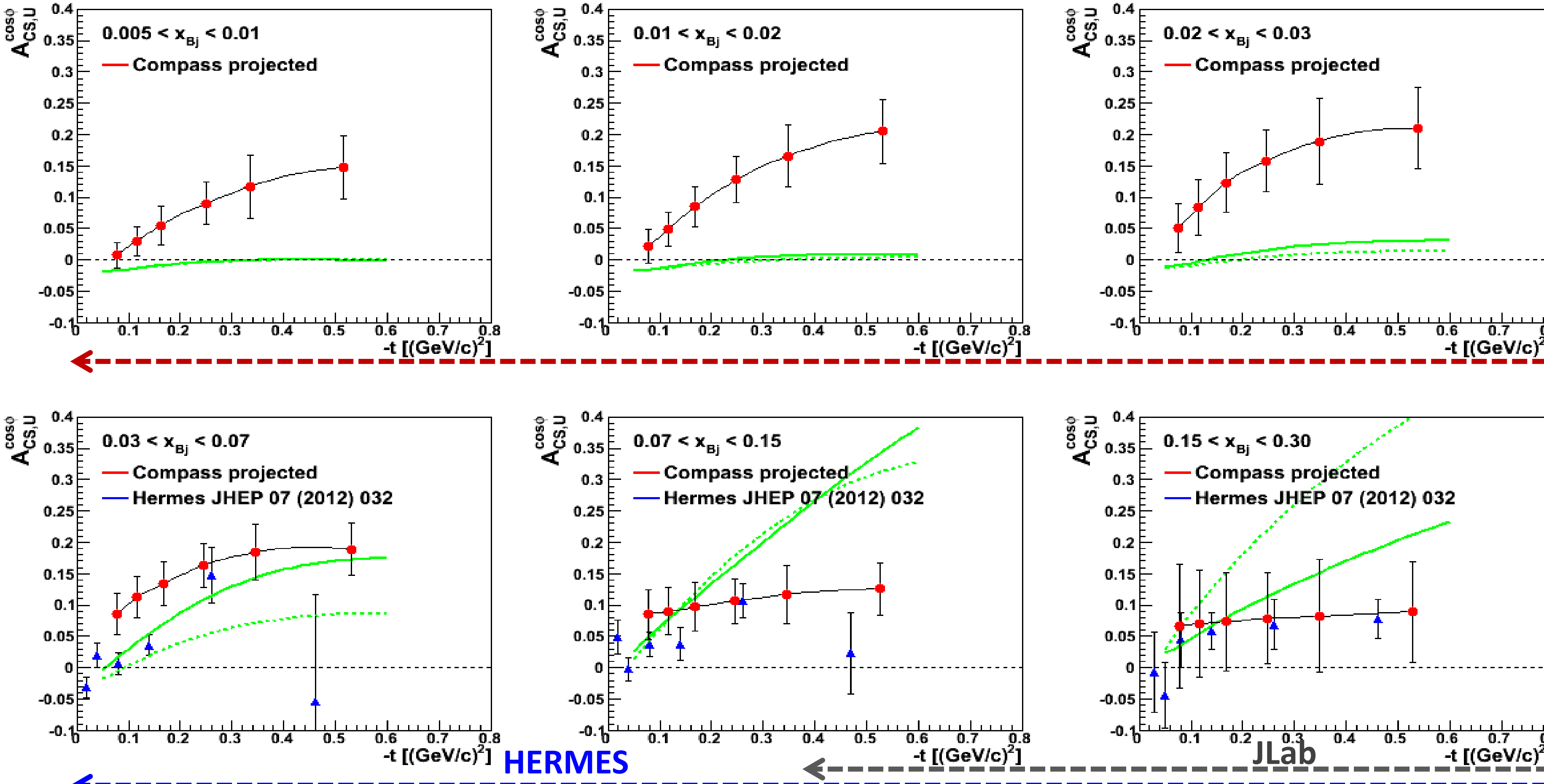
DVCS Prediction at COMPASS
For 2 × 6months in 2016-17

Beam Charge and Spin Diff. @ COMPASS

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

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

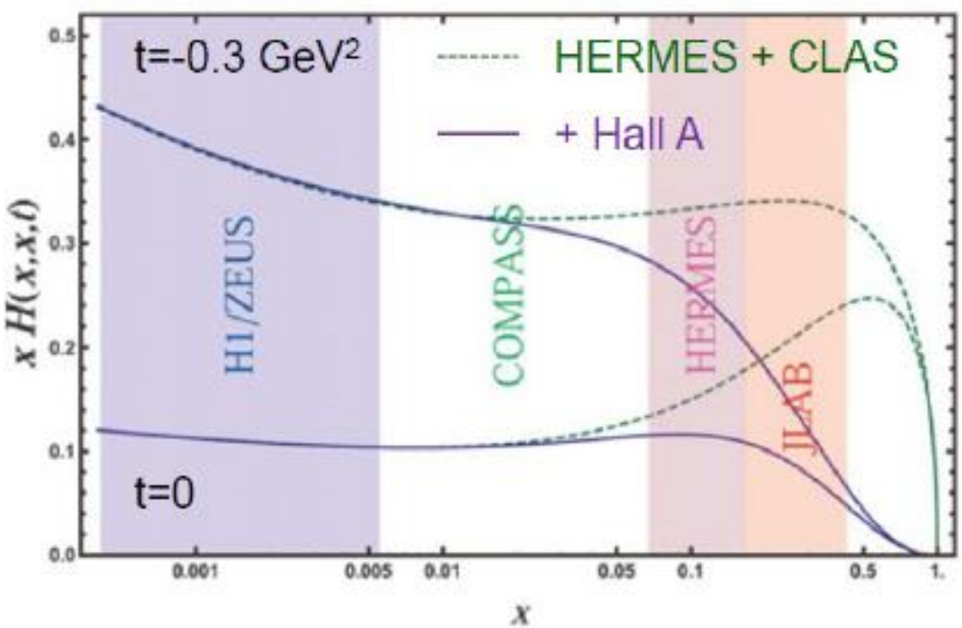
$Re\,\mathcal{H}$ > 0 at H1
< 0 at HERMES
Value of x_B for the node?



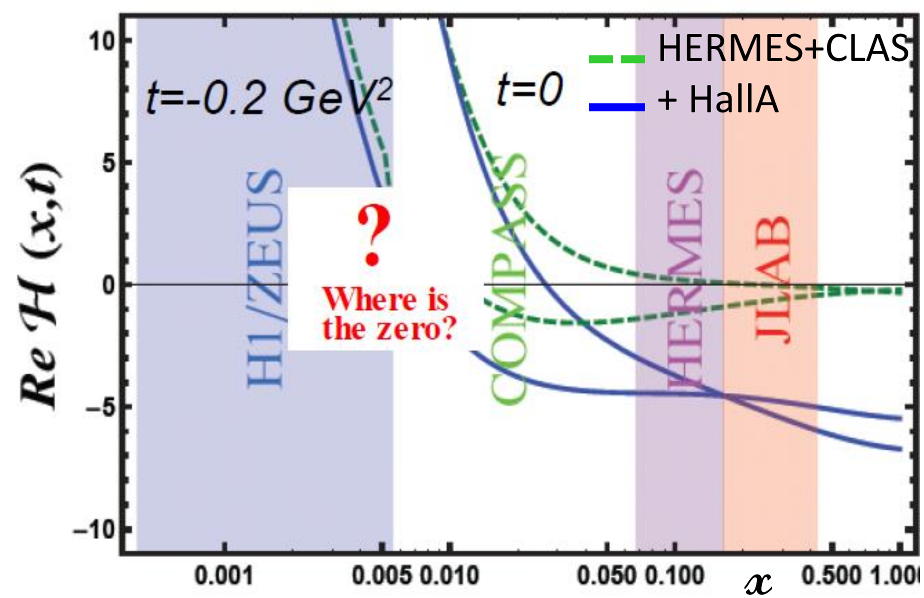
COMPASS 2 years of data E_μ= 160 GeV 1 < Q^2 < 8 GeV^2 with ECAL2 + ECAL1 + ECAL0

Impact of DVCS @ COMPASS in global analysis ?

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



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



- From Müller, COMPASS workshop, Venise, 2010
- Kumericki, Müller, NPB 841 (2010) 1-58
- Müller, Lautenschlager, Passek-Kumericki, Schaefer, arXiv:1310.5394, 125p

Hunting the GPD E, holy grail for OAM

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

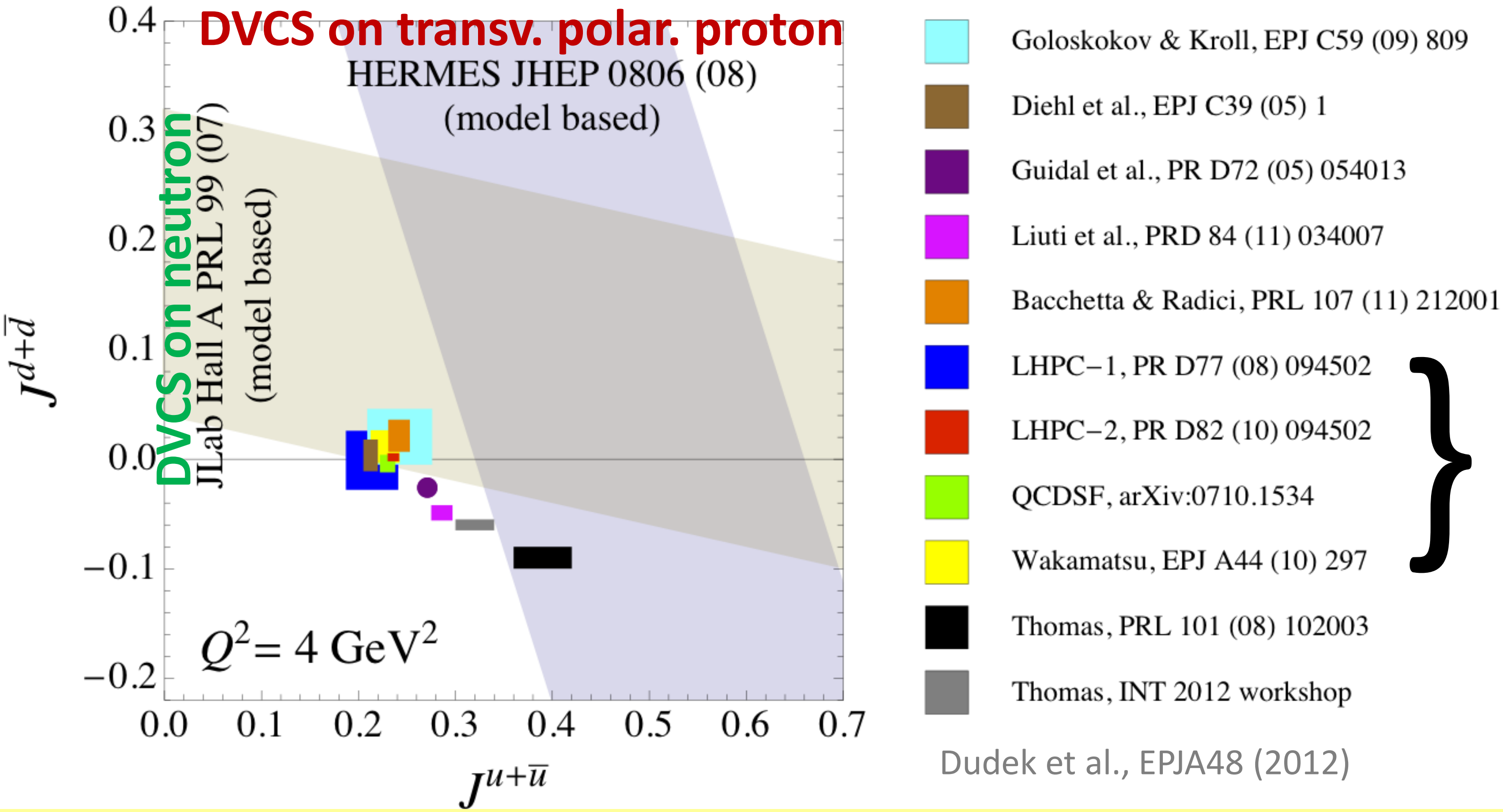
$\Delta\sigma_{LU} \sim Im\,(F_{1n}\,\mathcal{H} - F_{2n}\,\mathcal{E})$

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

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

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

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)

Large contributions of the chiral-odd H_T and $\bar{E}_T$

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

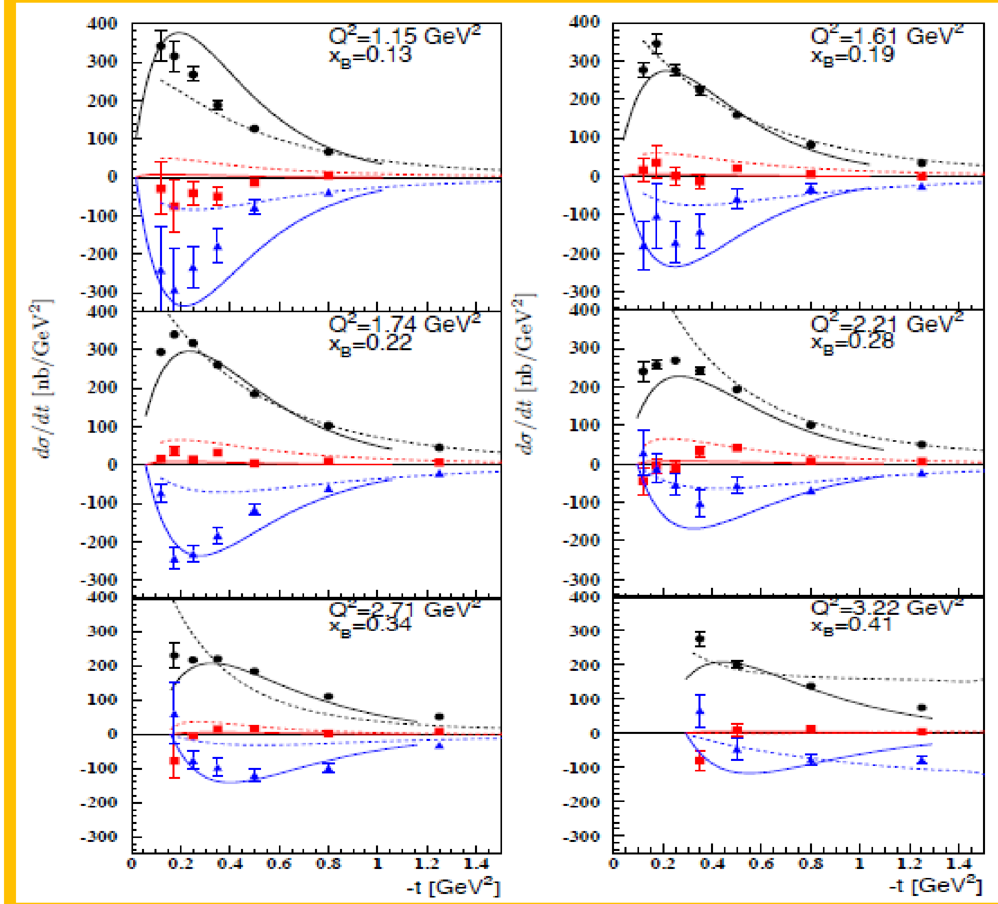
$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\} \approx \text{only a few \% of } \frac{d\sigma_T}{dt}$$

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$



Large impact of E_T
clearly visible in σ_{TT}
and in the dip at small t of σ_T

solid lines : **GK** EPJA47 (2011)
Dotted lines: **GHL** JPG:NPP39 (2012)

CLAS Coll, Bedlinskiy et al., PRC90(2014)2-025205

Only selected results, many others are given in parallel session.

A. Sandacz (COMPASS), B. Seitz (HERMES), A. Biselli, T. Horn, F. Sabatié (Jlab)

Prospects for Time-like Compton Scattering and Double DVCS.

Data in a large kinematic domain are still necessary.

A large theoretical effort remains:

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

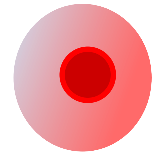
GPD programs with DVCS, HEMP (from light mesons to J/Ψ) are a priority for COMPASS @ CERN, JLab 12 GeV, and for a future electron-proton collider

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

Beyond the chiral-even GPDs → chiral-odd GPDs

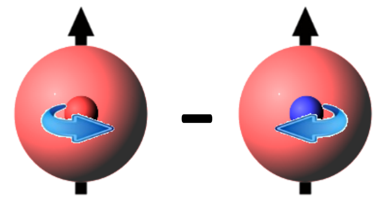
2 of the 4 Chiral-even

$H \leftrightarrow q$ or f_1



$\gamma^*_L\ p \rightarrow \pi^0\ p \quad L=0$

"Elusive" $E \leftrightarrow f_{1T}^{\perp}$



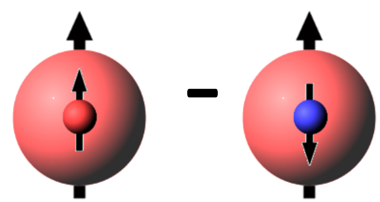
Sivers: quark k_T
& nucleon transv. Spin

$\gamma^*_L\ p^{\uparrow} \rightarrow \pi^0\ p^{\downarrow} \quad L=1$

Ji: $2J^q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

2 of the 4 Chiral-odd

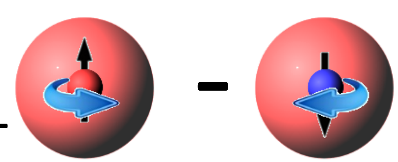
$H_T \leftrightarrow h_1$



Transversity: quark spin
& nucleon transv. spin

$\gamma^*_T\ p^{\uparrow} \rightarrow \pi^0\ p^{\downarrow} \quad L=0$

$\bar{E}_T = 2\tilde{H}_T + E_T \leftrightarrow h_1^{\perp}$



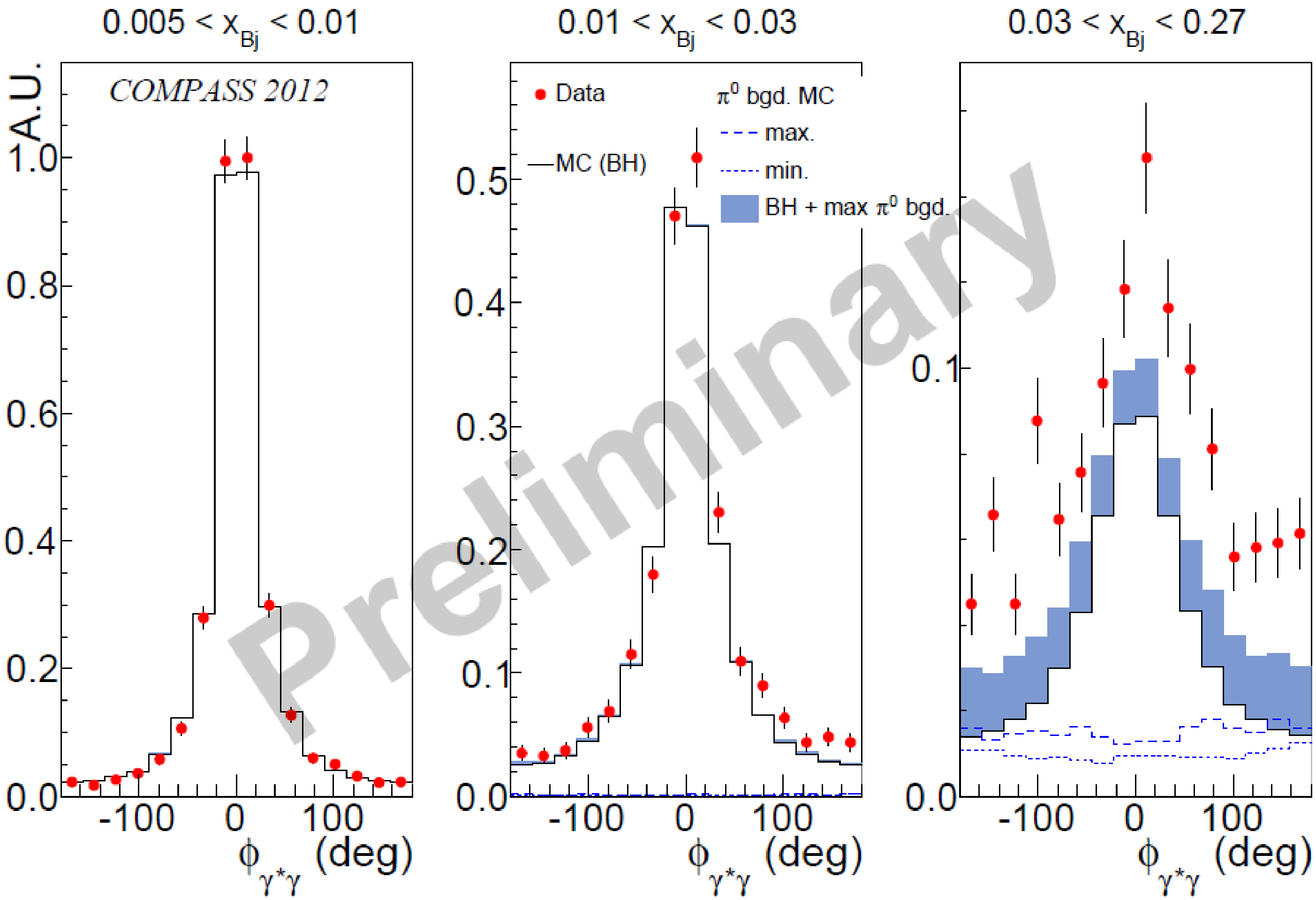
Boer-Mulders: quark k_T
& quark transverse spin

$\gamma^*_T\ p \rightarrow \pi^0\ p \quad L=1$

DVCS and BH contributions @ COMPASS

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

160 GeV



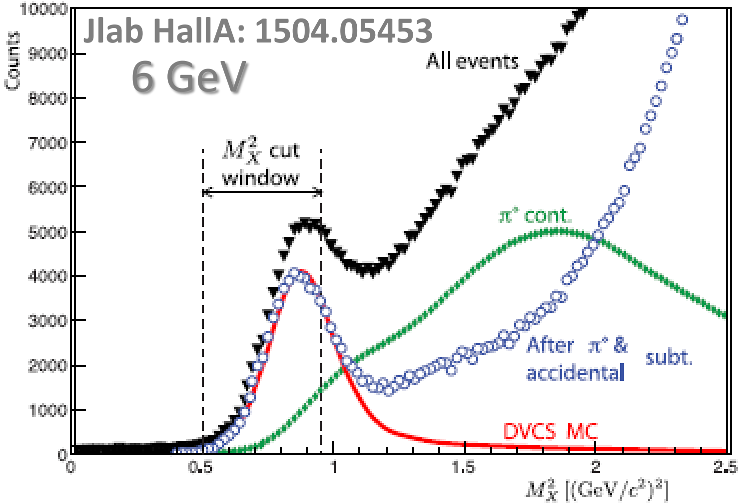
Pilot run in 2012

- ✓ 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 and HEMP data in 2016 and 2017

Exclusivity in fixed target: $\ell\, p \rightarrow \ell + \gamma + p_{slow}$

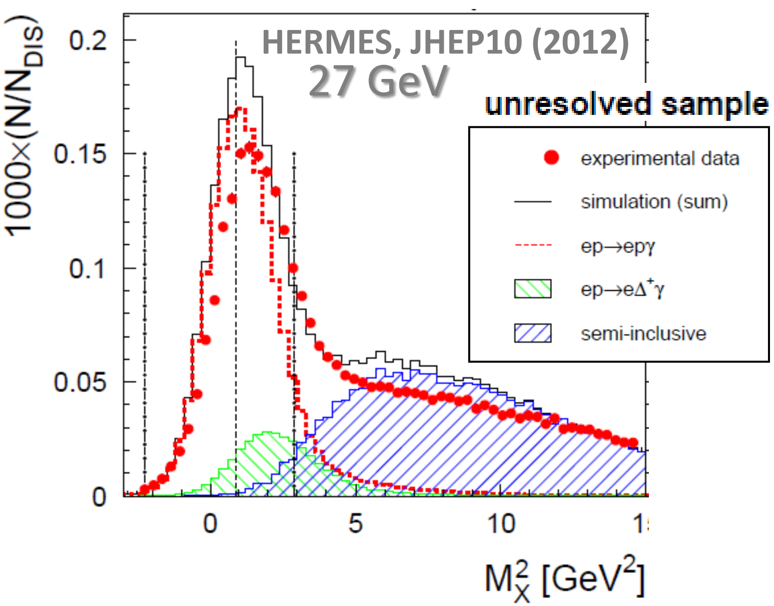
$$M_x^2 = (P_\ell + P_p - P_\ell - P_\gamma)^2$$

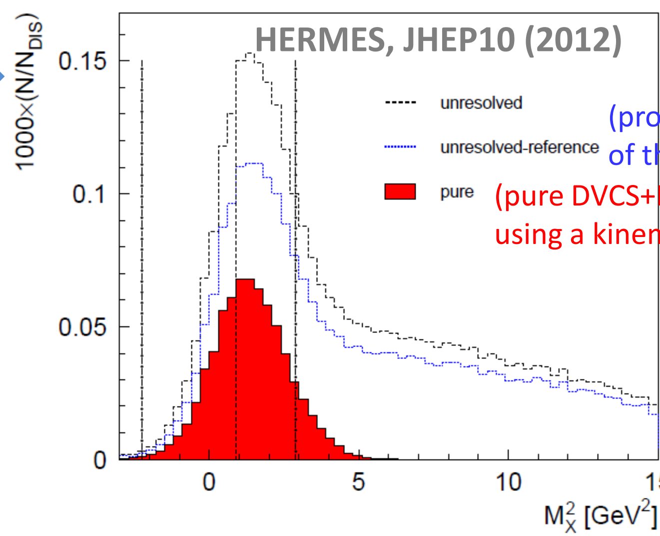


$\ell p \rightarrow \ell' + \gamma$ (+p') for DVCS + BH

Contamination from π^0 decay:

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

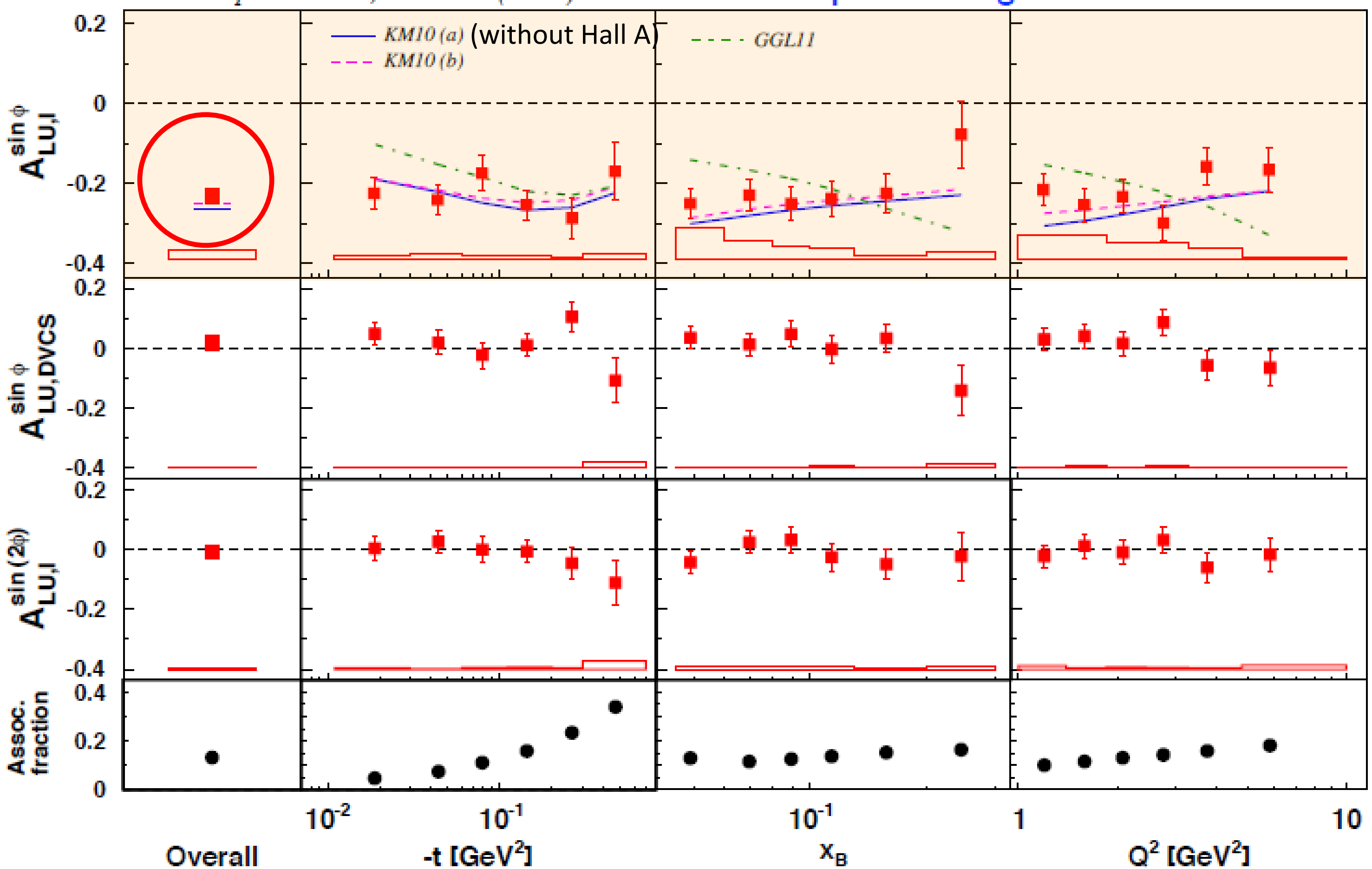




Beam Spin Asymmetry @ HERMES

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

$s_1^I \sin\phi$

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

Twist-3 from DVCS^2

$s_1^{DVCS} \sin\phi$

Twist-3 from *Int*

$s_2^I \sin 2\phi$

resonant fraction ep → eγΔ$^+$

KM10: http://arxiv.org/abs/0904.0458

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

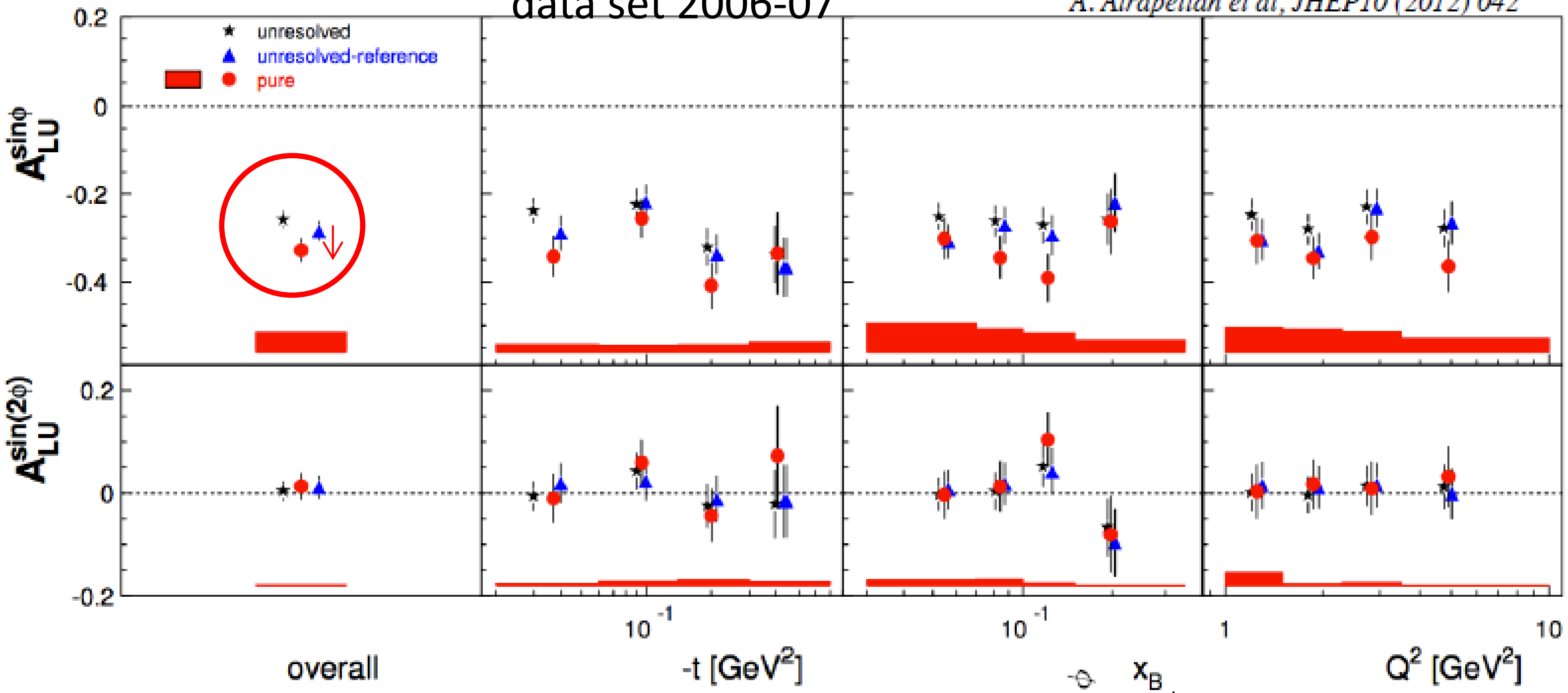
GHL11: another flexible parameterization http://arxiv.org/abs/1012.3776

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

BSA with recoil detector @ HERMES

data set 2006-07

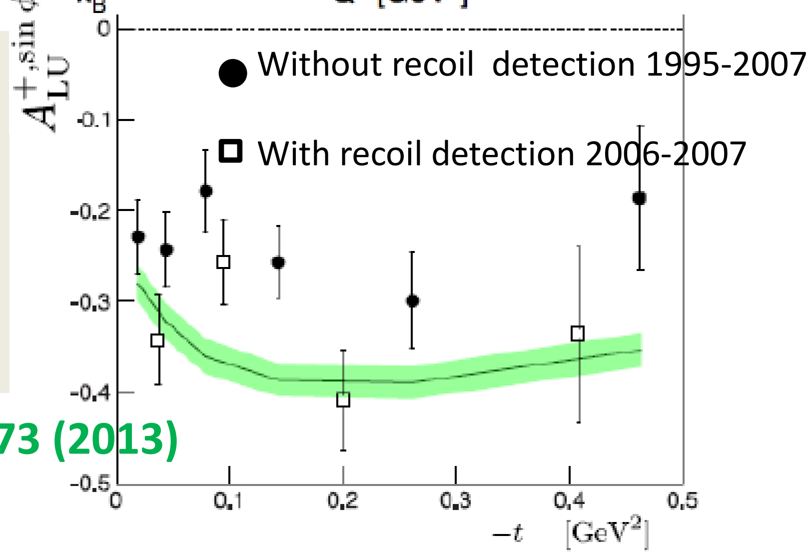
A. Airapetian et al, JHEP10 (2012) 042



High-purity event selection shows that there is only a small influence on the extracted BSA amplitude from events involving an Δ particle (associated DVCS)

The leading asymmetry has increased by 0.054 ± 0.016

Mainly dilution due to the associated DVCS

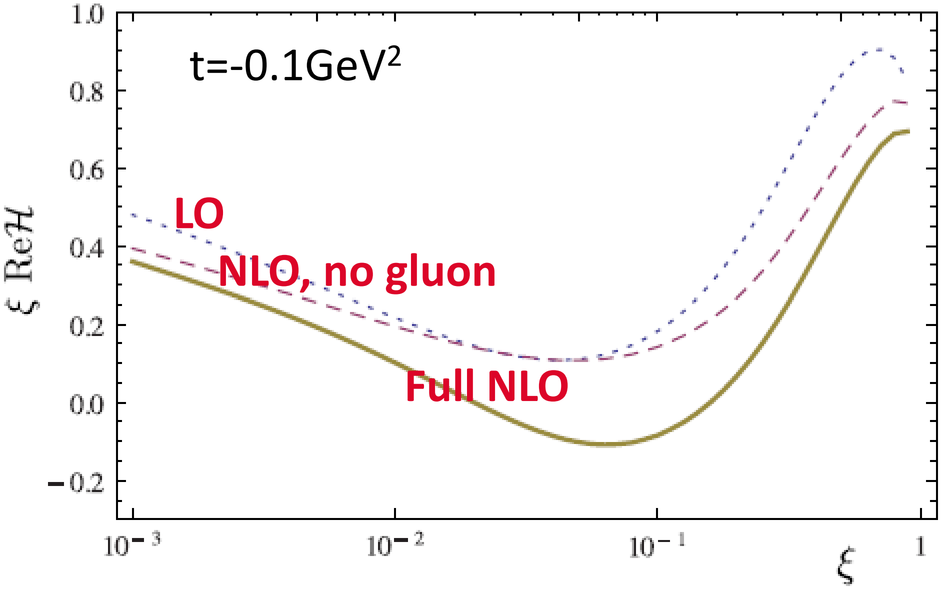


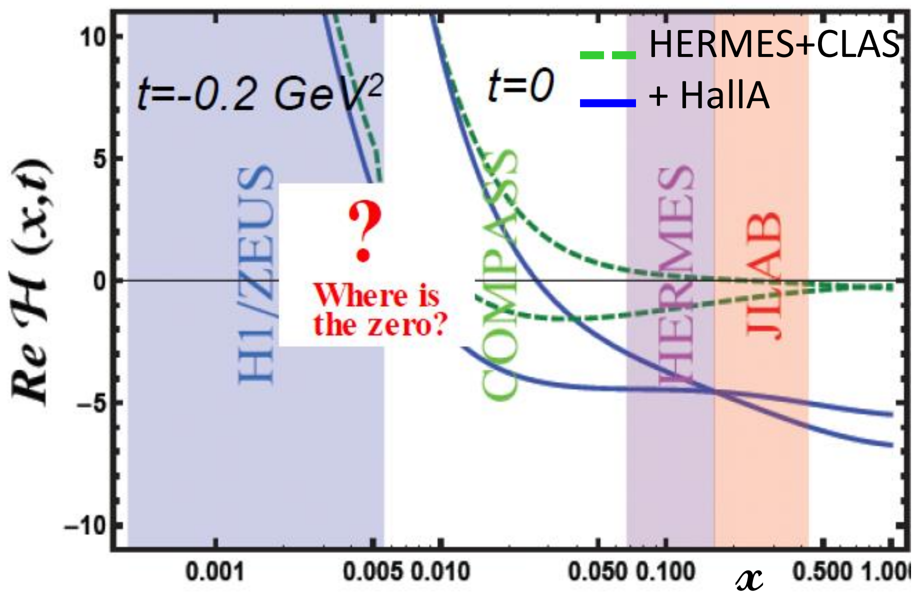
KMS12: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model

Impact of DVCS @ COMPASS in global analysis ?

Better knowledge of *Re* $\mathcal{H}$ linked to the *$\mathcal{D}$ term*

Importance of NLO





- Moutarde, Pire, Sabatié, Szymanowski, Wagner,PRD87(2013) 054029, 15p

- From Müller, COMPASS workshop, Venise, 2010
- Kumericki, Müller, NPB 841 (2010) 1-58
- Müller, Lautenschlager, Passek-Kumericki,
- Schaefer, arXiv:1310.5394, 125p

Bratt et al, LHPC, PRD82 (2010)

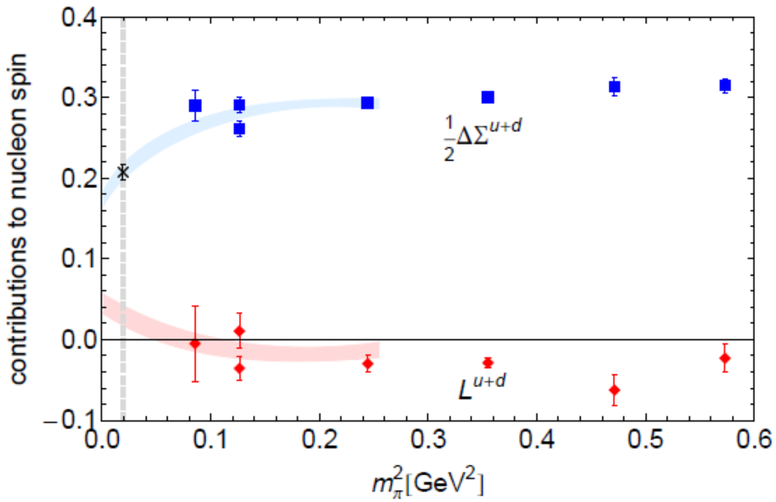


FIG. 44: Total quark spin and orbital angular momentum contributions to the spin of the proton. The cross represents the value from the HERMES 2007 measurement [92]. The error bands are explained in the text. Disconnected contributions are not included.

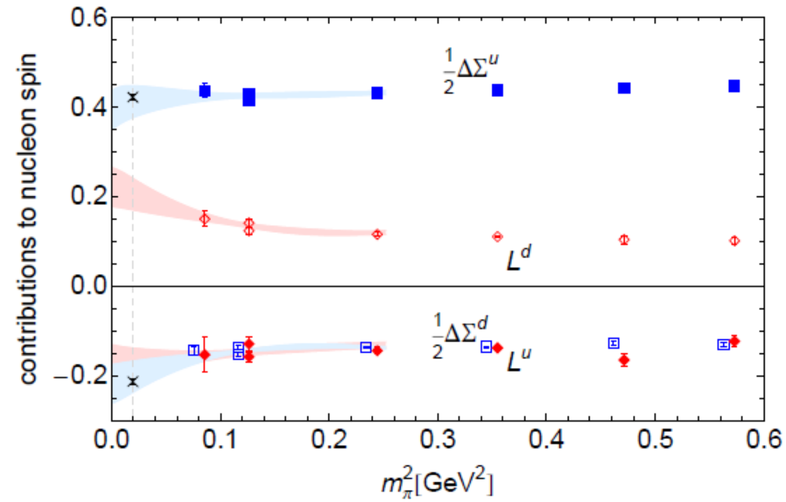


FIG. 45: Quark spin and orbital angular momentum contributions to the spin of the proton for up and down quarks. Filled and open squares denote $\Delta\Sigma^u/2$ and $\Delta\Sigma^d/2$, and filled and open diamonds denote L^u and L^d, respectively. The crosses represent the values from the HERMES 2007 measurement [92]. The error bands are explained in the text. Disconnected contributions are not included.