Exclusive Reactions at High Momentum Transfer
An Experimental Point of View

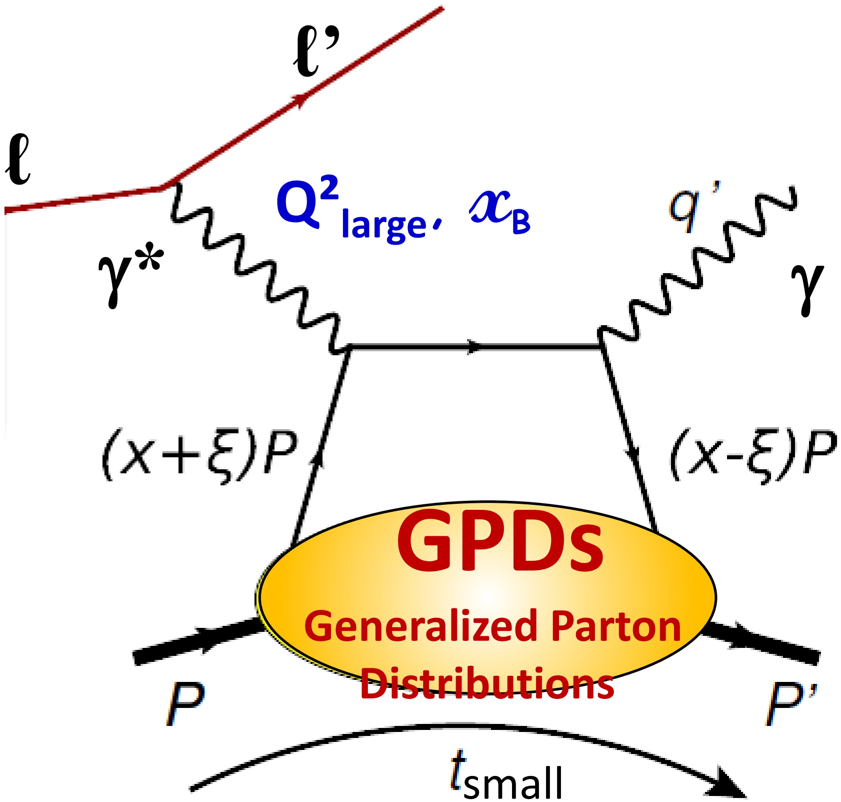
Nicole d'Hose – CERN & CEA Saclay

Photonuclear Reactions
Gordon Research Conference

Holderness, 10 August 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)



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...

The GPDs depend on the following 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

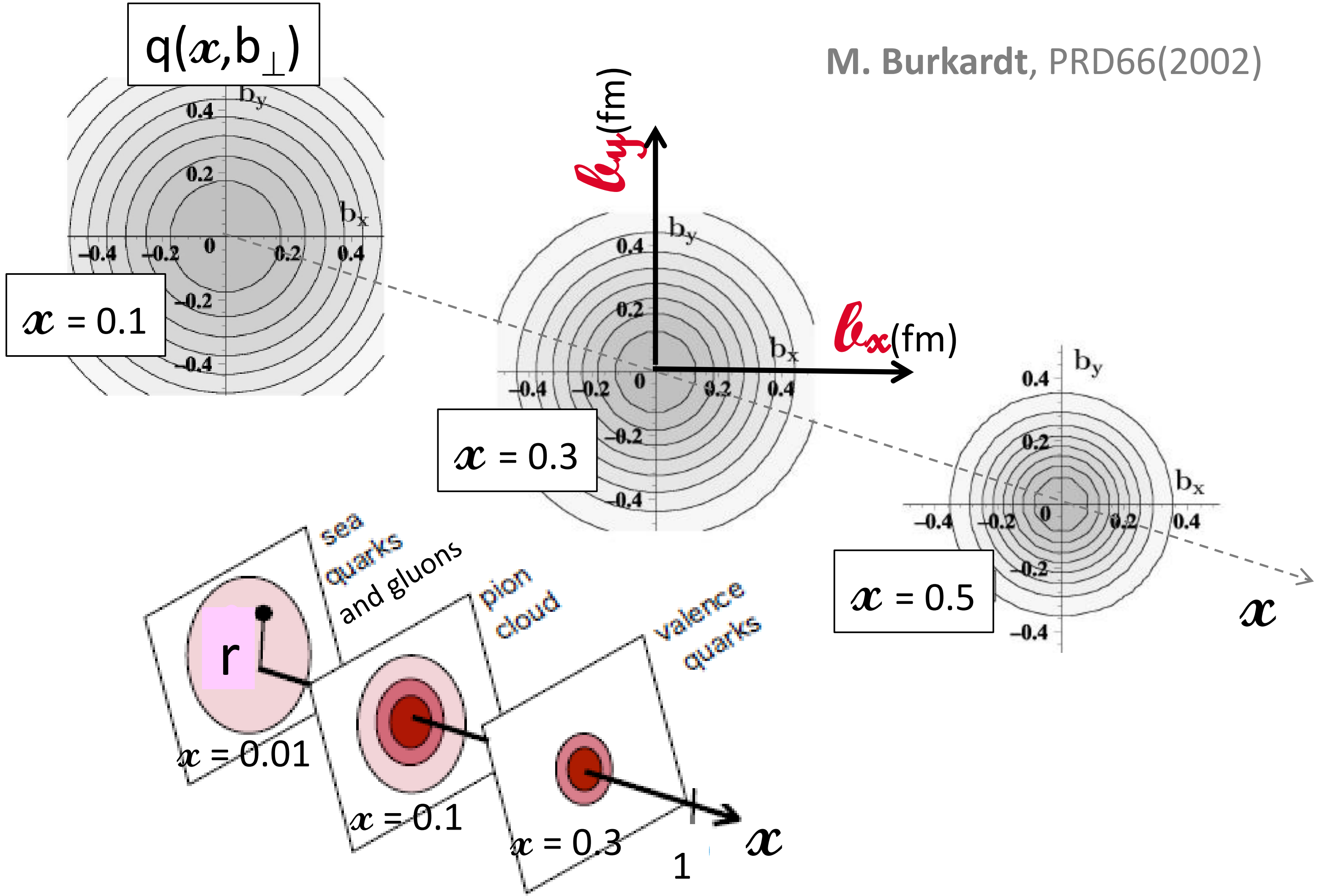
The variables measured in the experiment:

E_ℓ, Q^2, $x_B \sim 2\xi/(1+\xi)$,
t (or $\theta_{\gamma^*\gamma}$) and ϕ

3D imaging: mapping in the transverse plane

Proton
moving
towards us

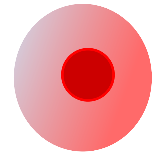
M. Burkardt, PRD66(2002)



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

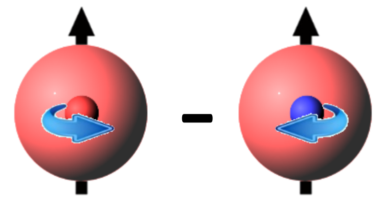
The 2 most famous GPDs

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



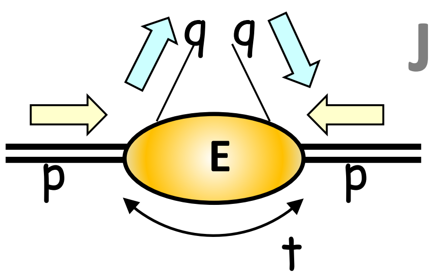
"Elusive"

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



Sivers: quark k_T & nucleon transv. Spin

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



Ji sum rule: PRL78 (1997) cited 1404 times

Relation to OAM

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

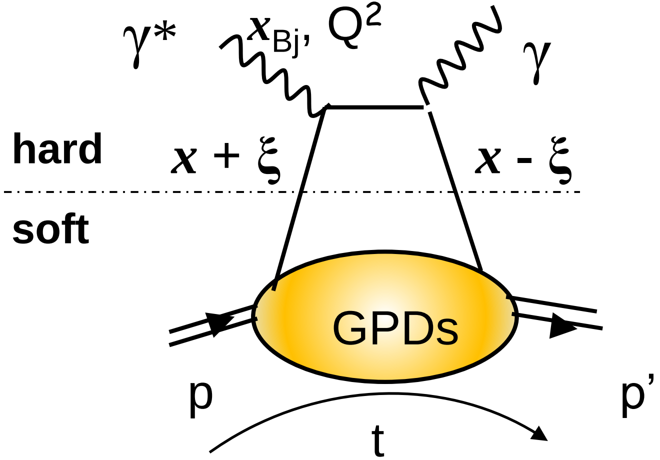
Jaffe and Manohar
NPB337 (1990)

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

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

$\mathcal{L}$ unknown

Compton Form Factors are measured in DVCS

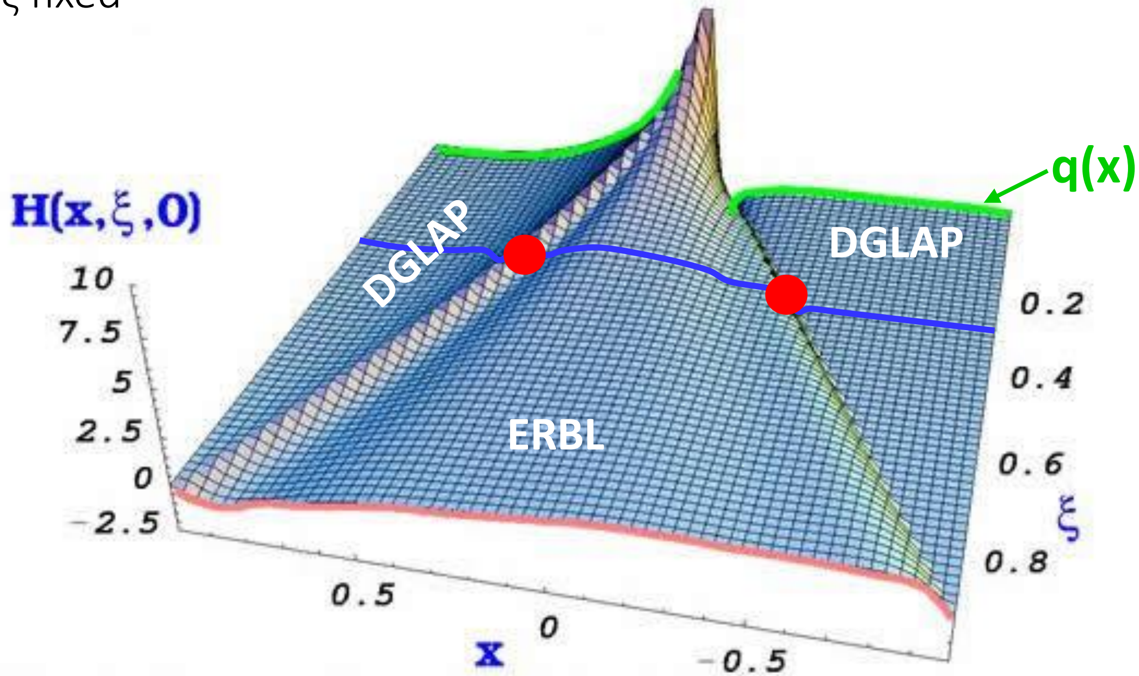


The amplitude DVCS at LT & LO in α_S:

Real part **Imaginary part**

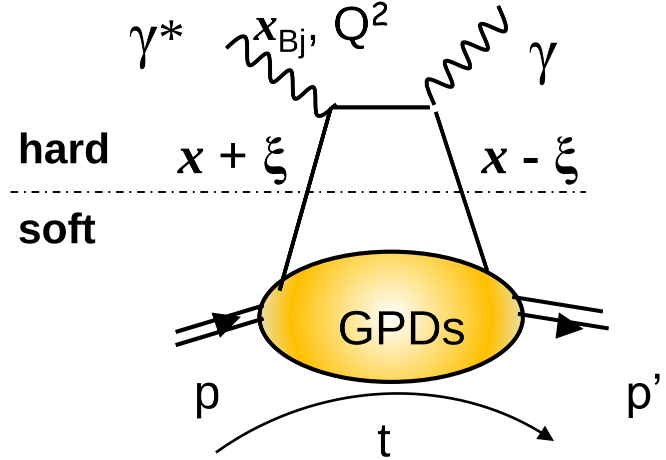
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\,\pi\, H(x=\pm\xi,\xi,t)$$

t, ξ fixed



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)

Compton Form Factors are measured in DVCS



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

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \mathcal{D}(t)$$

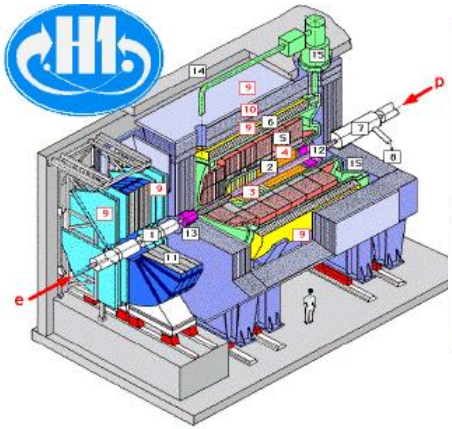
Im part measured in
Single Spin measurements:
Beam Spin or **Target Spin Asym**

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

Polyakov, PLB 555 (2003) 57-62

Real part measured in
Unpolarized x- sect,
Beam Charge Asymmetry,
or **Double Spin Asymmetries**

The past and future experiments



Collider mode e-p forward fast proton

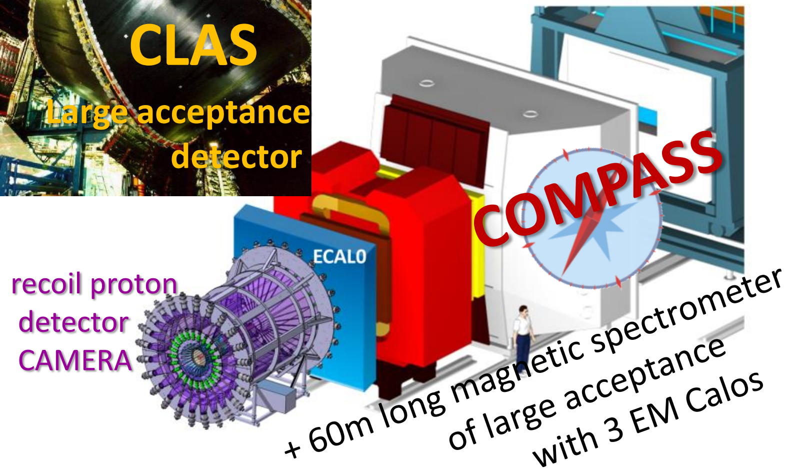
HERA: **H1** and **ZEUS**
Polarised 27 GeV e-/e+
Unpolarized 920 GeV proton
~ Full event reconstruction

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 measurement of t

$t = (p-p')^2 = (q-q')^2$

$|t|_{min} \sim m_p^2 x_B^2 / (1-x_B)$ if $x_B/Q \ll 1$

Fixed target mode slow recoil proton

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

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

with recoiling proton

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

Better resolution at small t

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

Collider mode e-p forward fast proton

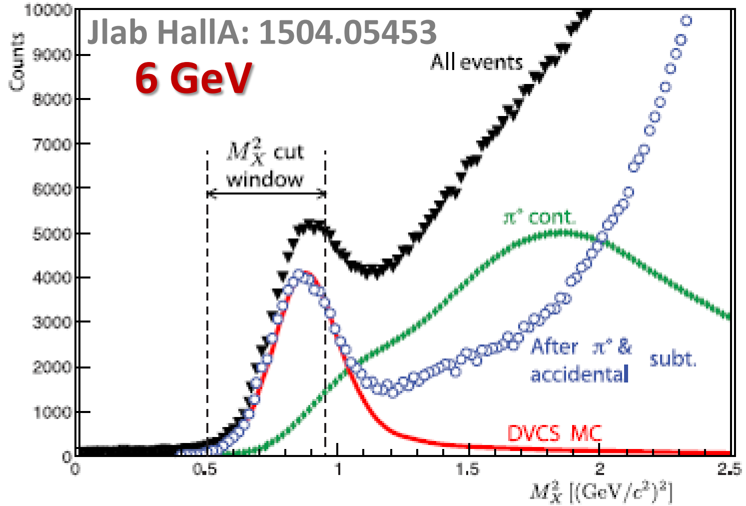
$t = (p-p')^2$ need detection of the fast proton at forward angle close to the beam with dedicated detectors as « Roman Pot »

Ex: Jlab	$x_B = 0.3$	$|t|_{min} \sim 0.1\ GeV^2$	$|t|_{min\ exp} \sim 0.1\ GeV^2$
COMPASS	$x_B = 0.01$	$|t|_{min} \sim 10^{-4}\ GeV^2$	$|t|_{min\ exp} \sim 0.06\ GeV^2$
EIC	$x_B = 0.0001$	$|t|_{min} \sim 10^{-8}\ GeV^2$	we need to measure very small $|t|$

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

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

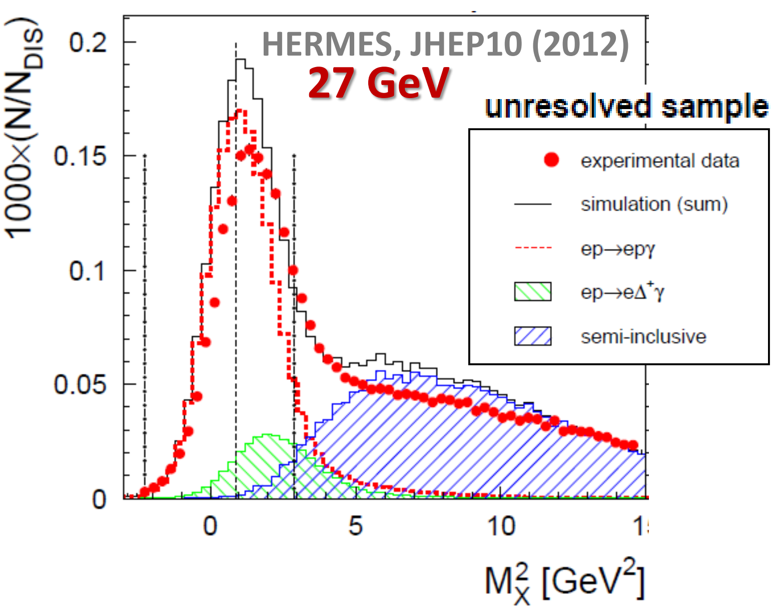
ΔM_x^2 increases with the beam energy !

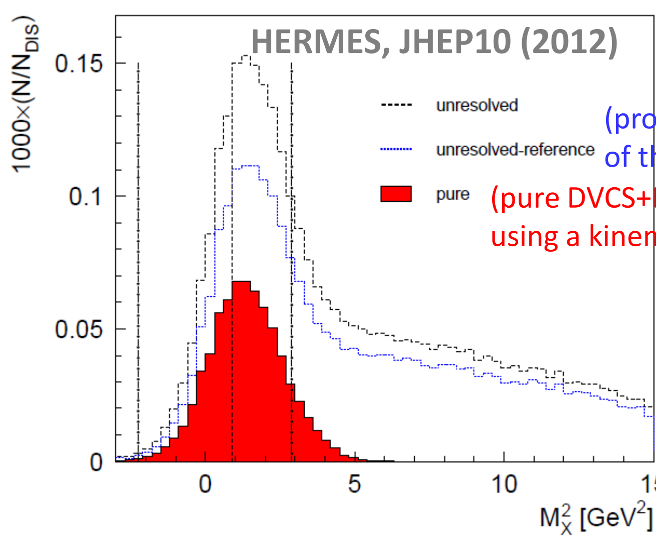


$\ell p \rightarrow \ell' + \gamma\ (+p')$ for DVCS + BH

Contamination from π^0 decay:

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





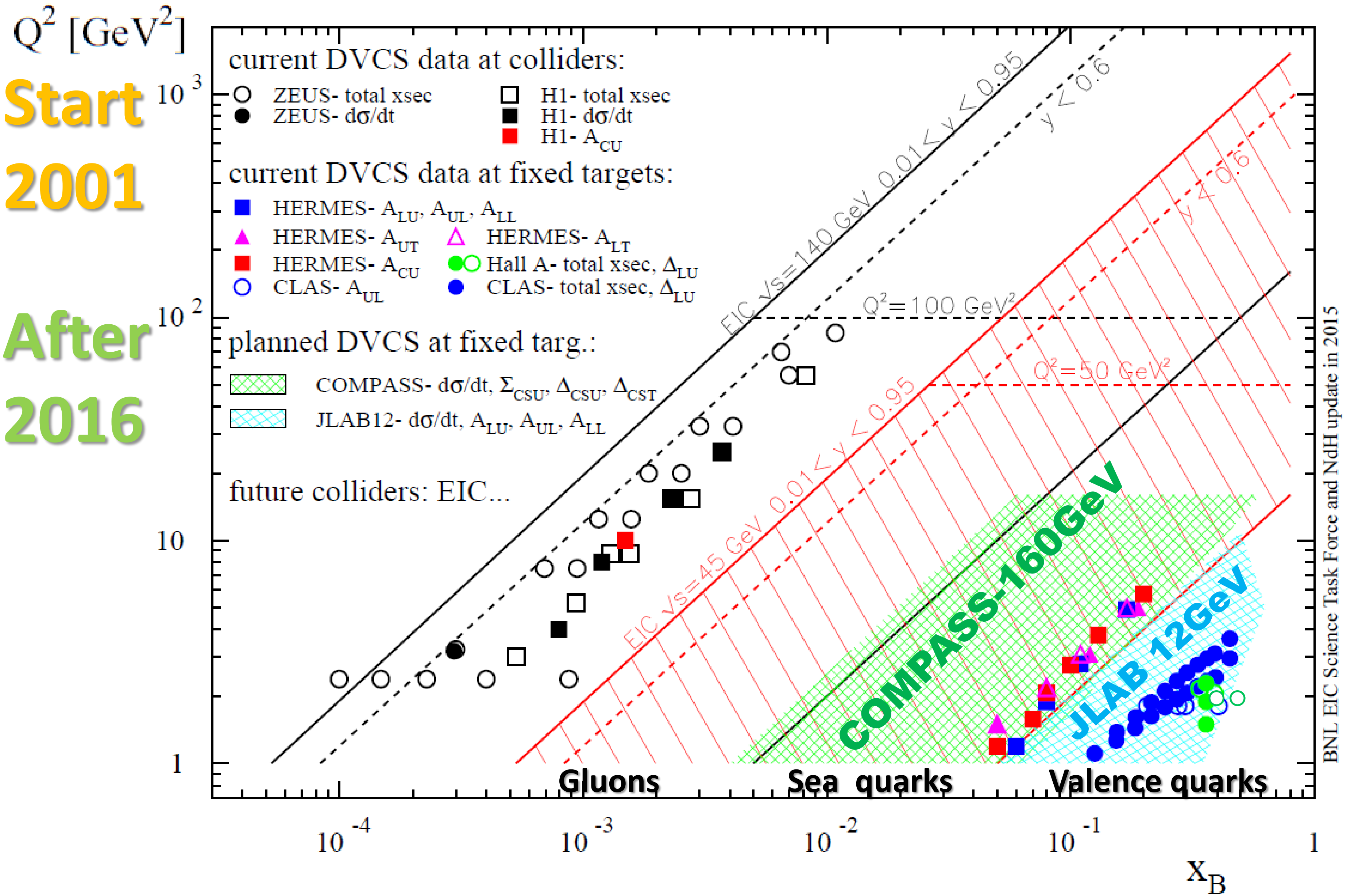
(proton in the acceptance of the recoil detector)

(pure DVCS+BH using a kinematic fit)

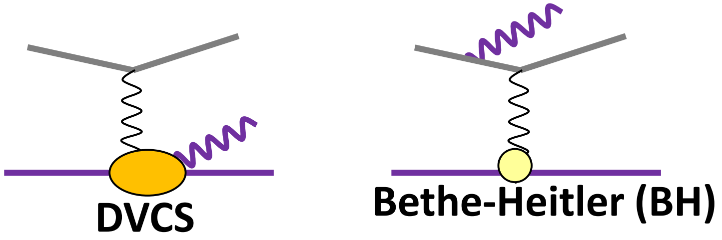
The past and future DVCS experiments

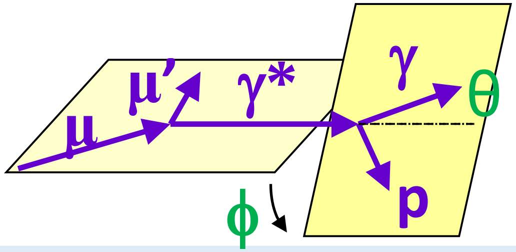
Start 2001

After 2016

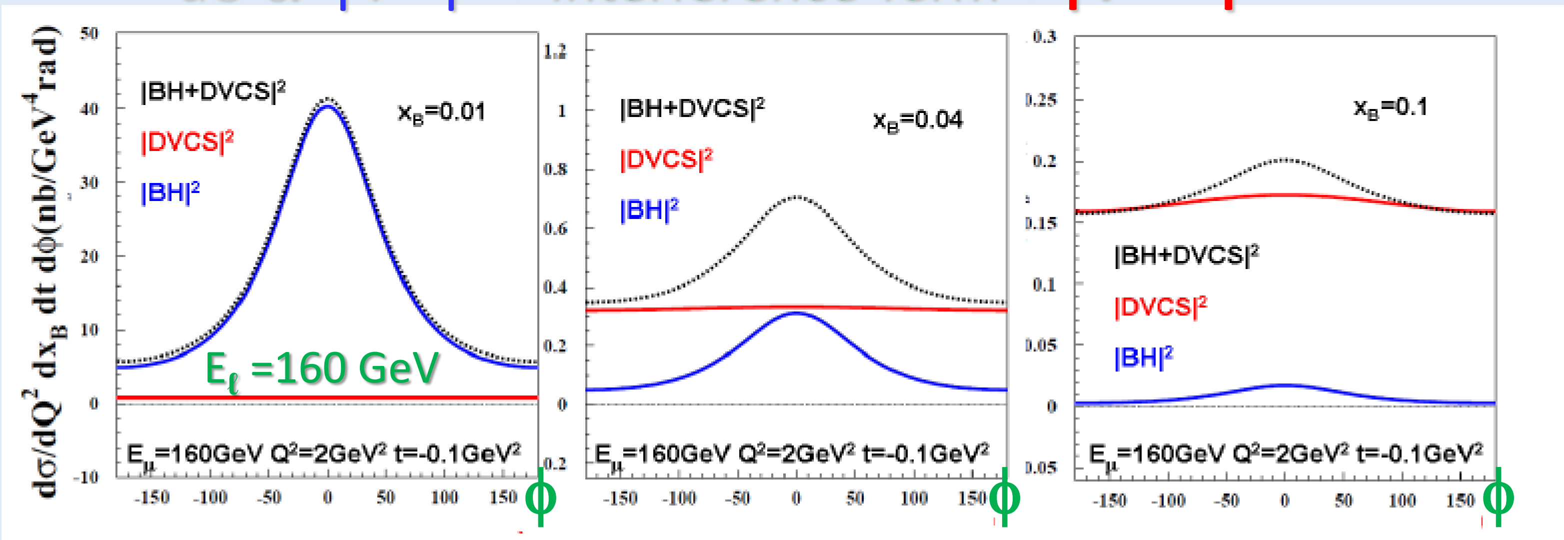


Impact of the beam energy for DVCS





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



BH dominates
Reference yield

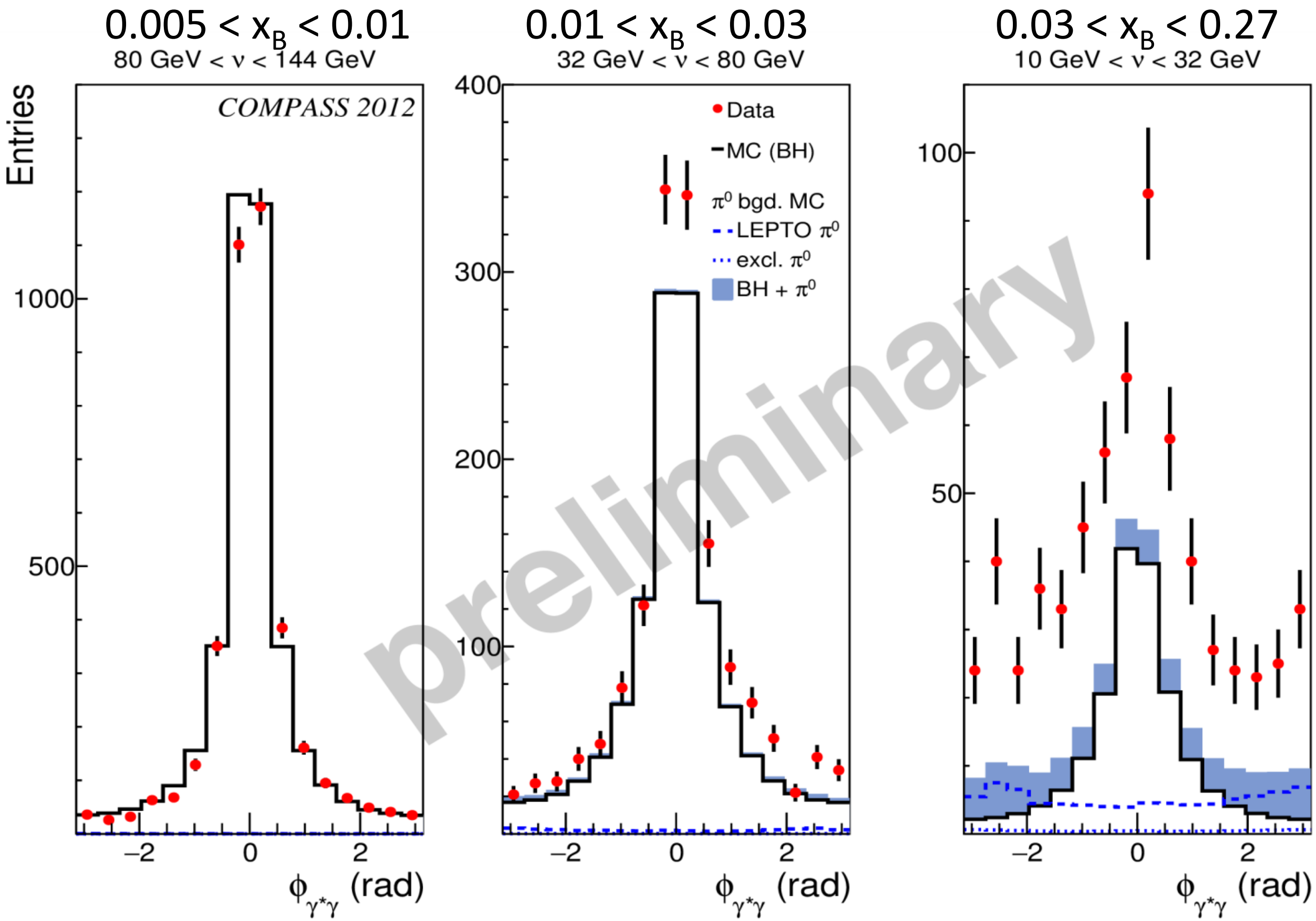
DVCS ampl. via interference
Jlab, HERMES, H1, COMPASS

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

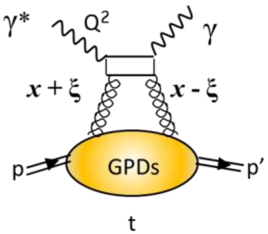
- ✓ Dominant Bethe-Heitler process clearly visible at small x_{Bj}
- ✓ Maximum π^0 background (from exclusive and SIDIS π^0 production) estimated in blue
- ✓ The data at large x_{Bj} show an excess compared to BH+Background (for pure DVCS)

COMPASS is taking DVCS data during 2 years (2016 and 2017)

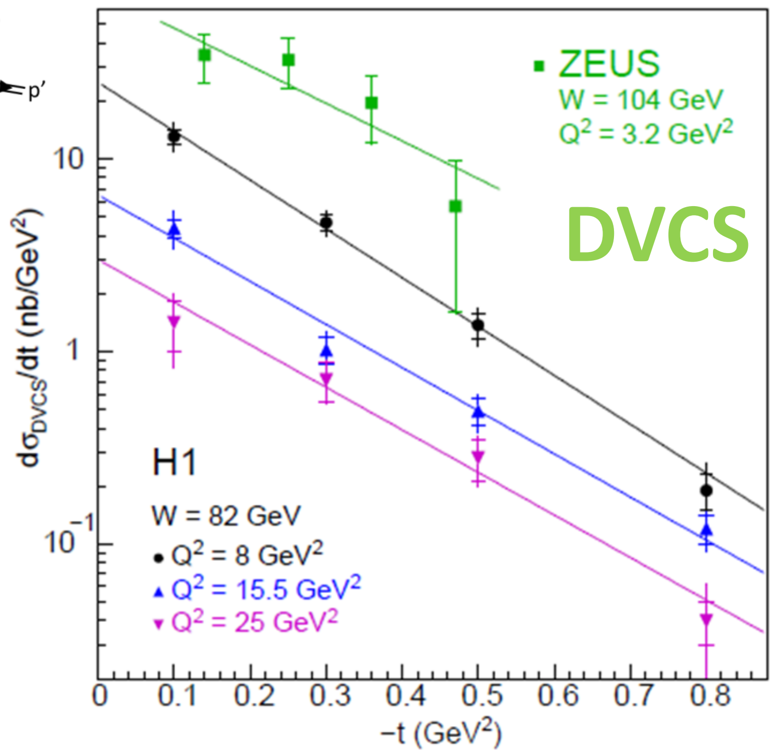
Gluon imaging @ HERA

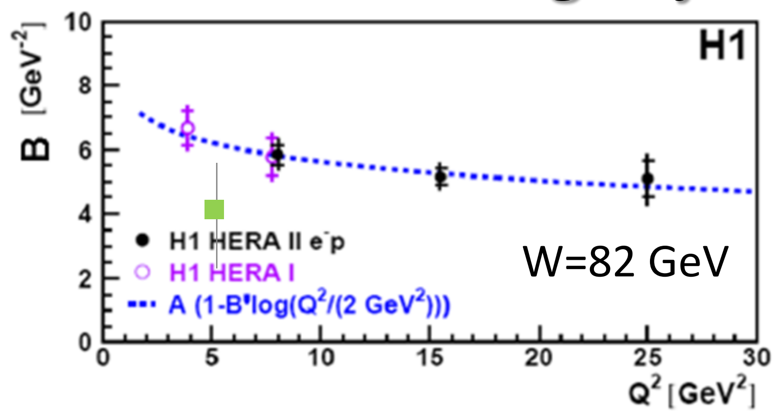
$d\sigma^{DVCS}/dt = e^{-B|t|}$

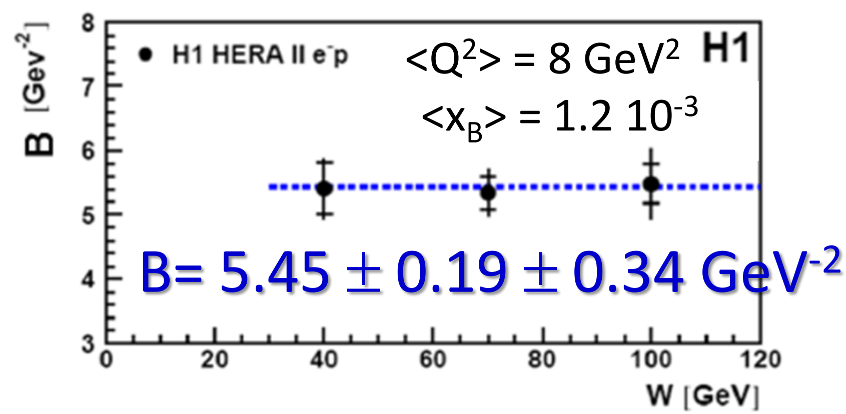
B is related to the transversed size of the scattering objects



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







$B = 5.45 \pm 0.19 \pm 0.34\ \text{GeV}^{-2}$

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

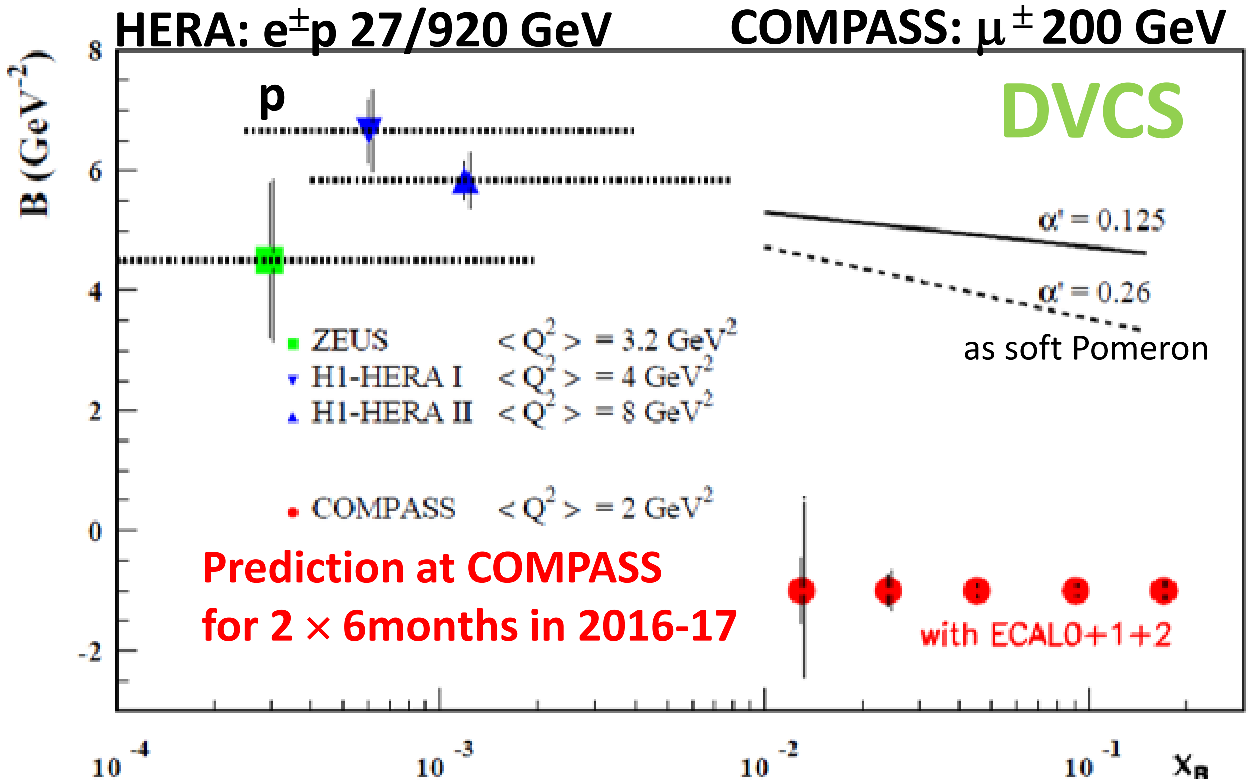
$\sqrt{< r_\perp^2 >}$ = **0.65 ± 0.02 fm**

to be compared to

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

$$\sqrt{4\frac{d}{dt}G_E^p} = 0.72 \pm 0.01\ \text{fm}$$

Sea quark imaging @ COMPASS



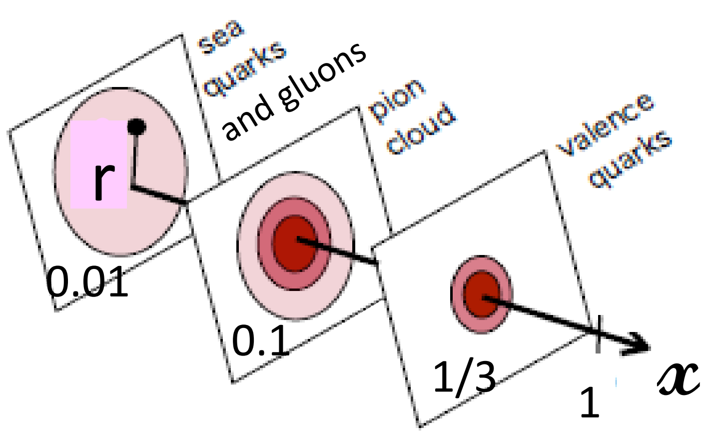
$d\sigma^{DVCS}/dt = e^{-B|t|}$

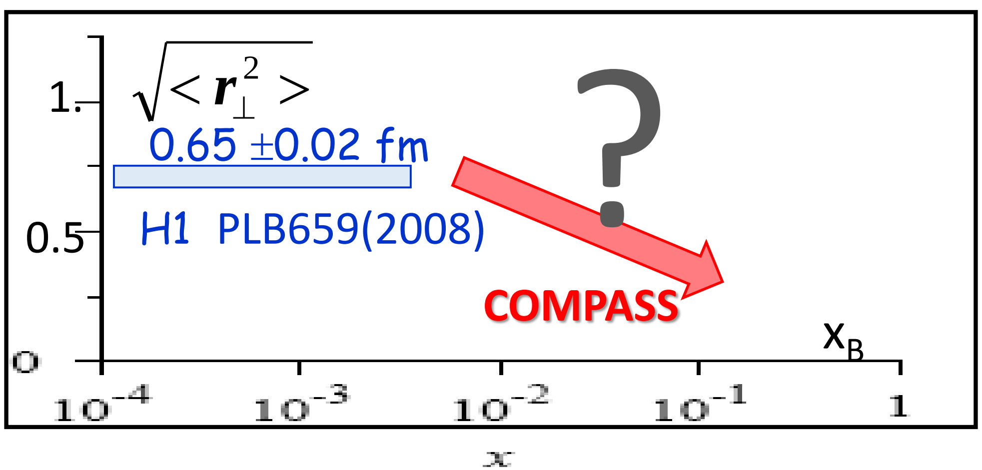
ansatz inspired by
Regge Phenomenology:

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

α' slope of Regge traject

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

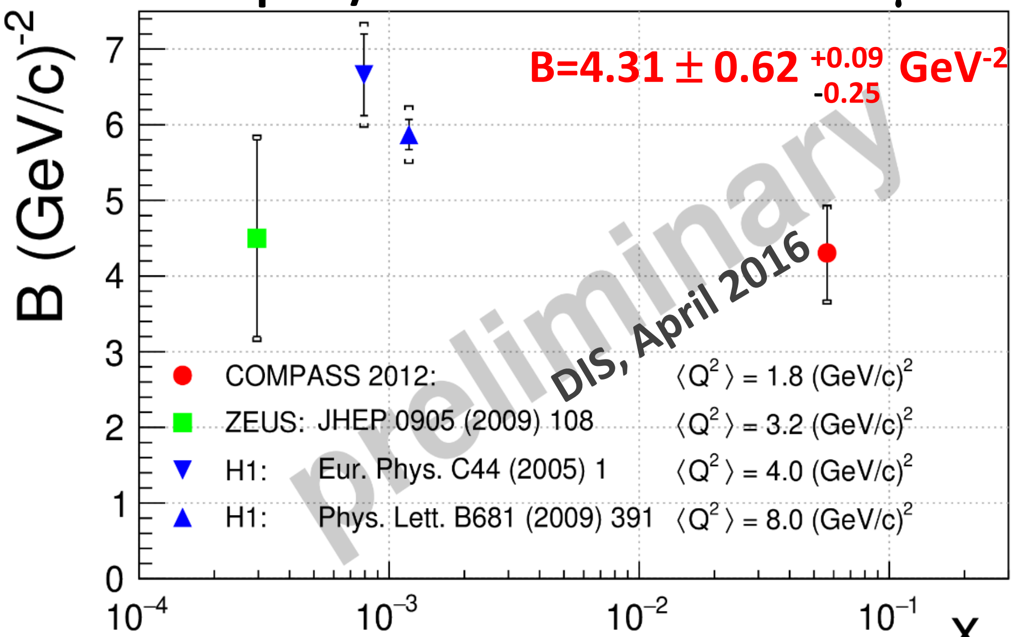


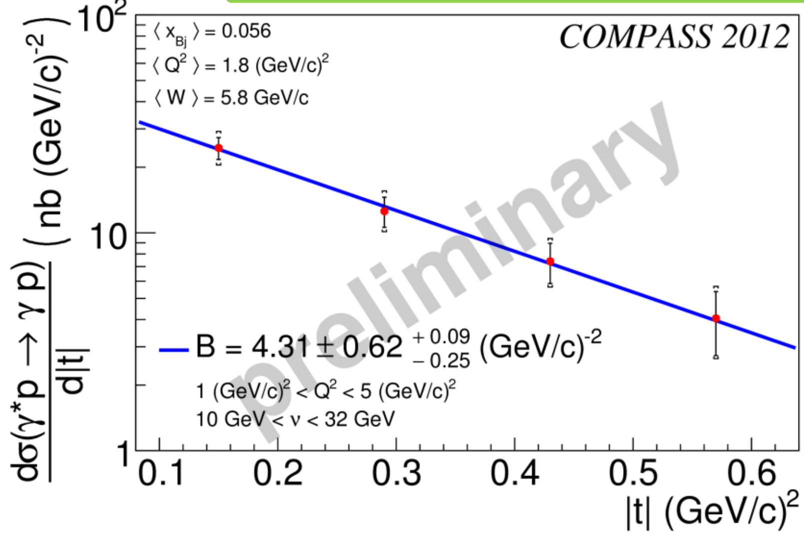


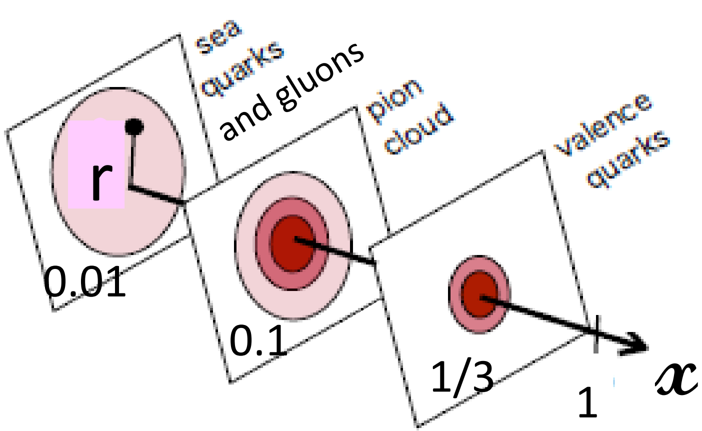
Sea quark imaging @ COMPASS

HERA: $e^{\pm}p$ 27/920 GeV **COMPASS: $\mu^{\pm}$ 200 GeV**

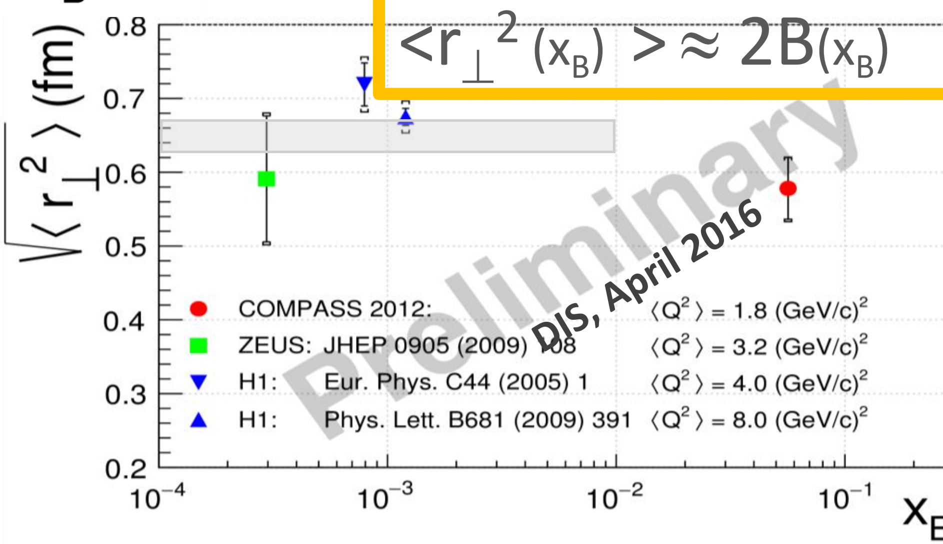
$$d\sigma^{DVCS}/dt = e^{-B|t|}$$







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



DVCS-BH interference on the proton

→ $\mathcal{Im}$ DVCS with Beam Helicity Dependent X-sect.

→ $\mathcal{Re}$ DVCS with Beam Charge Difference and Unpolarized X-section

→ 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

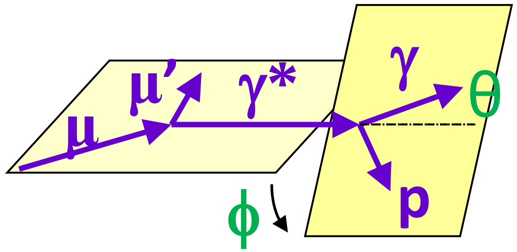
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

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

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

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



Twist-2 >>

■ Twist-3,

■ Twist-2 double helicity flip for gluons

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

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

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

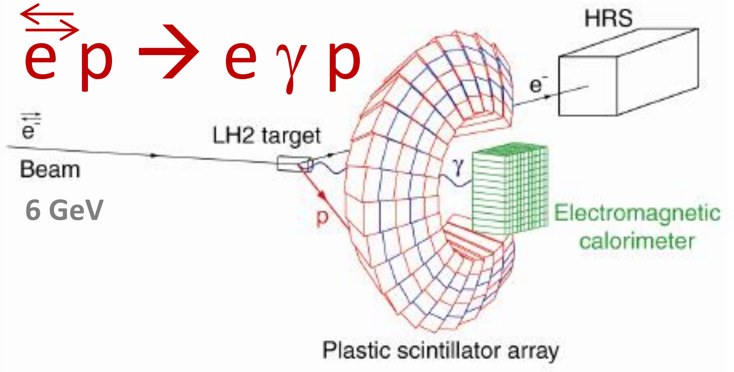
to extract $\tilde{\mathcal{H}}$ use a longitudinally polarized target

Beam Spin Sum and Diff of DVCS - HallA

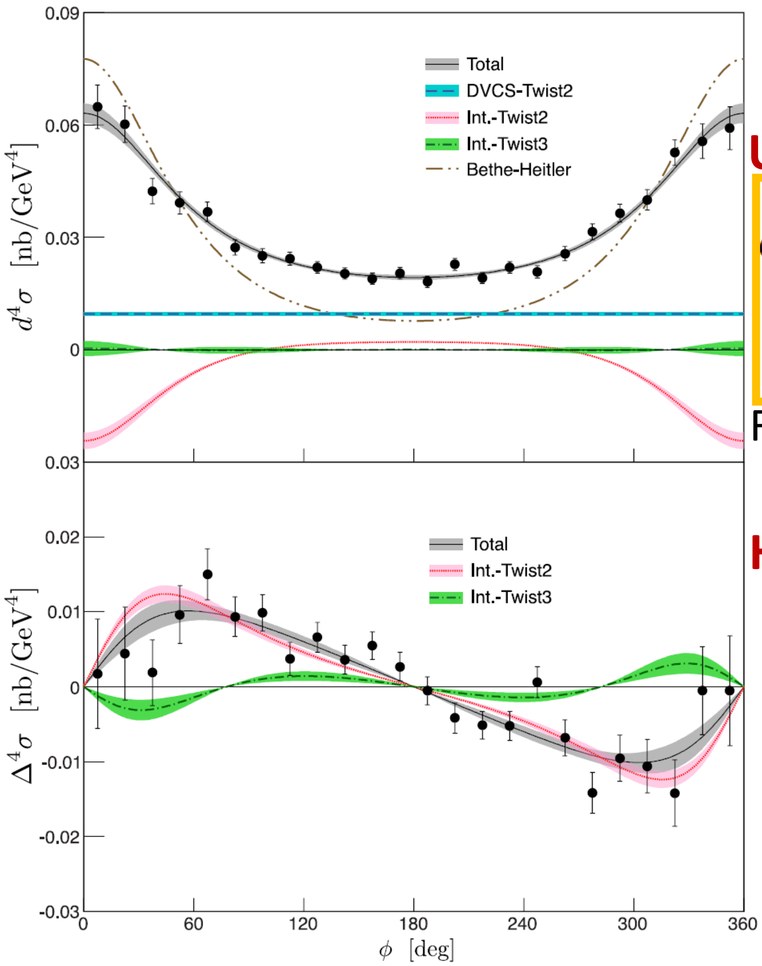
E00-110 pioneer experiment with magnetic spectrometer

x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV^2 Defurne et al. PRC92, 055202 (2015)

x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2



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



Unpolarized cross section

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

Further separation ➔ need of different ε or beam energies

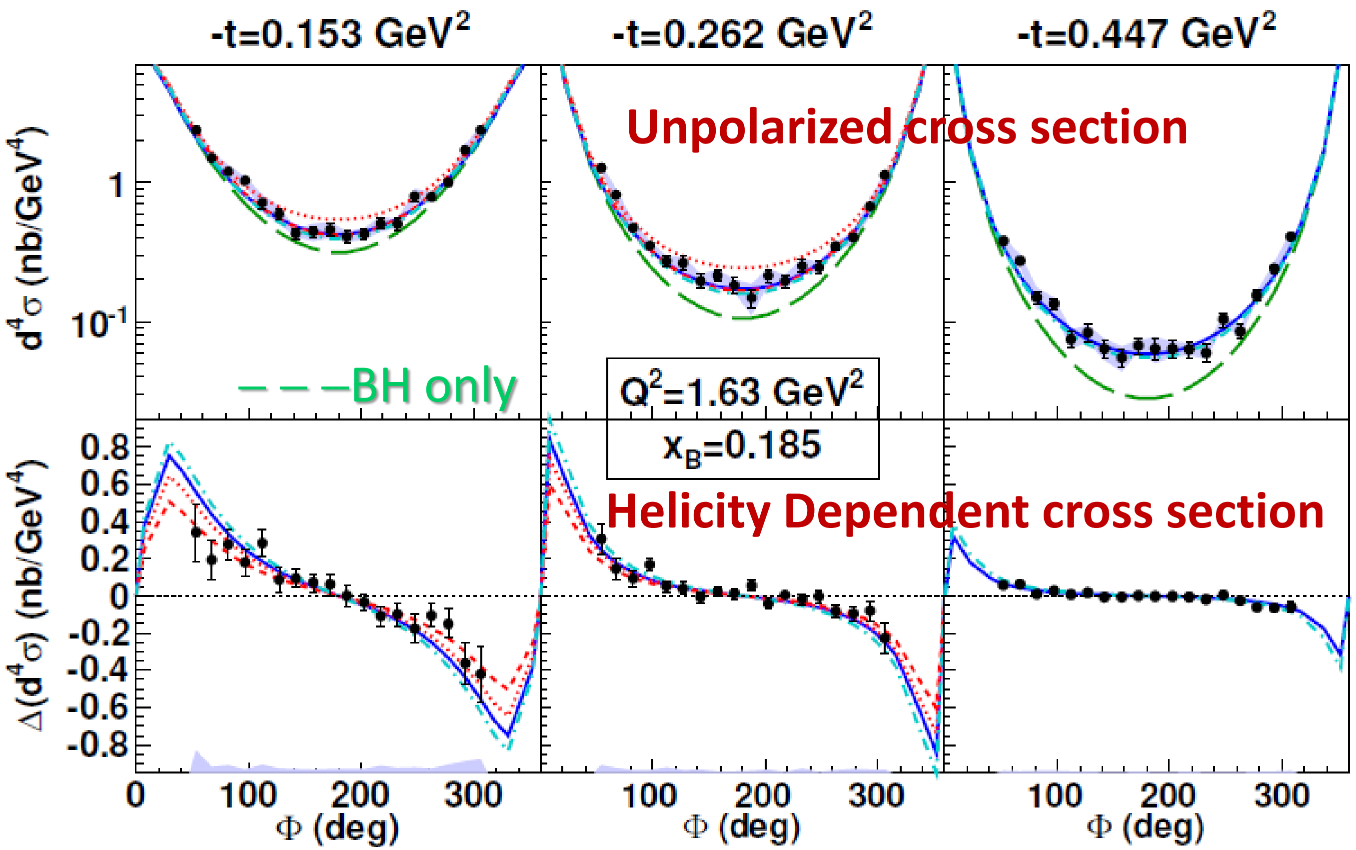
Helicity Dependent cross section

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

Beam Spin Sum and Diff of DVCS - CLAS

21 bins in (x_B, Q^2) or 110 bins (x_B, Q^2 t)
- Jo et al. PRL115, 212003 (2015)

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



models:

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

KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)
using the **GK** model
Goloskokov, Kroll, EPJC42,50,53,59,65,74
for GPD adjusted on the hard exclusive meson production at small x_B
"universality" of GPDs

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

Valence quark imaging at Jlab

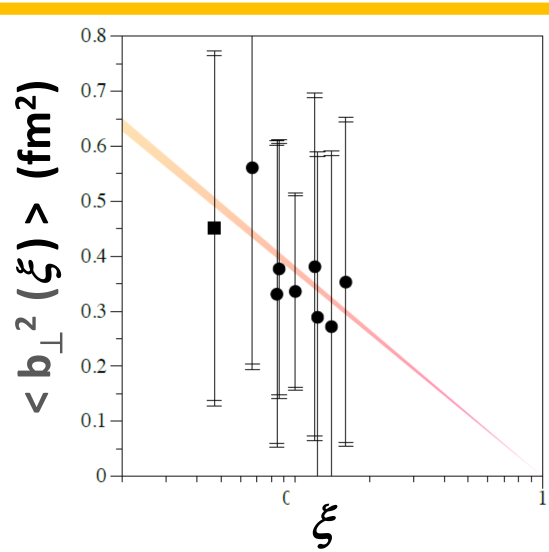
Fit of 8 CFFs at L.O and L.T.

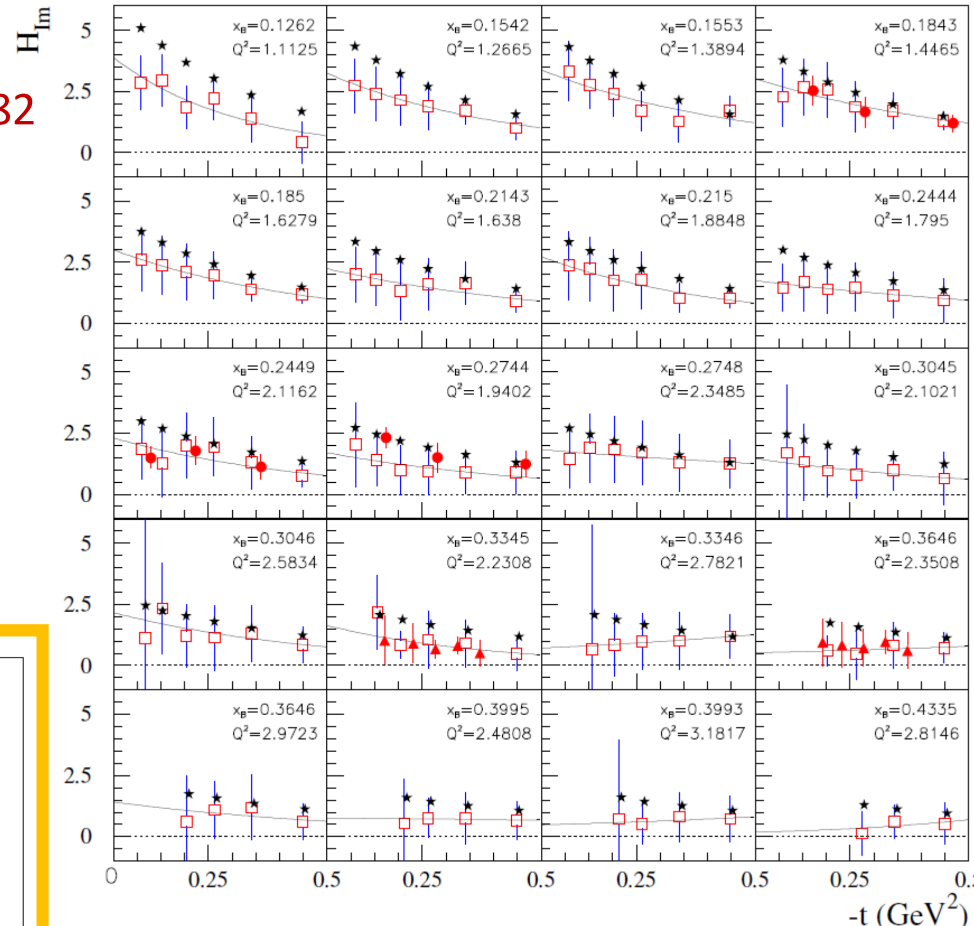
Dupré, Guidal, Vanderhaeghen, arXiv: 1606.0782

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

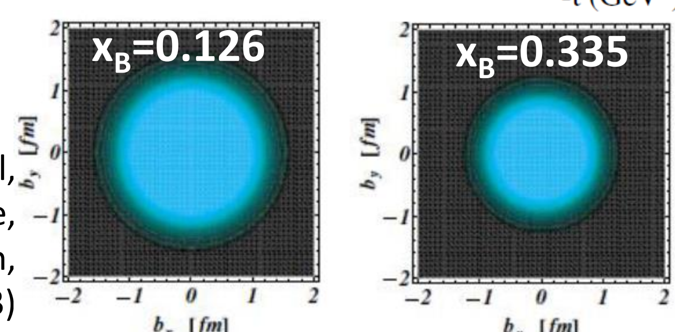
- □ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}
- ★ VGG model
- — Fit $A\, e^{-B'|t|}$

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





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



Valence quark imaging at Jlab

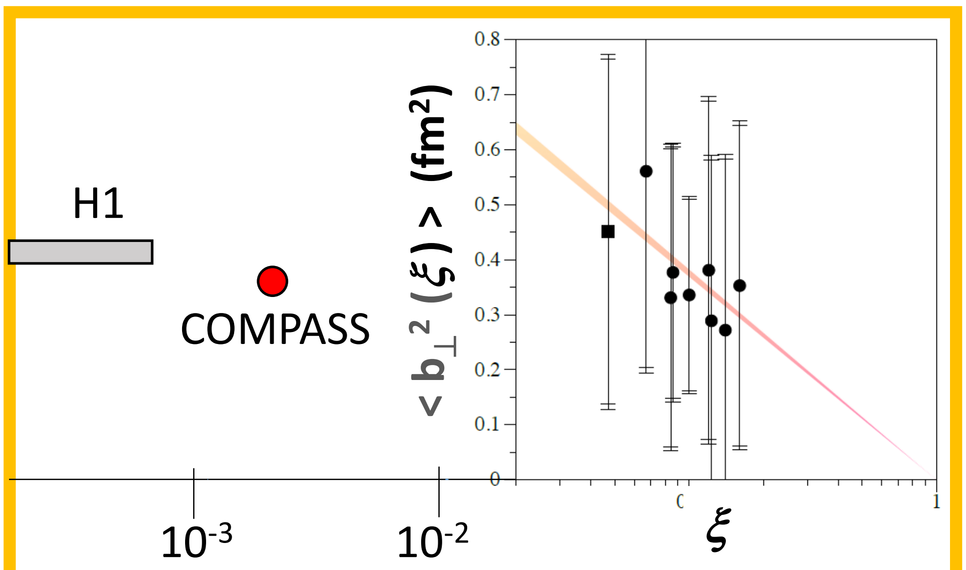
Fit of 8 CFFs at L.O and L.T.

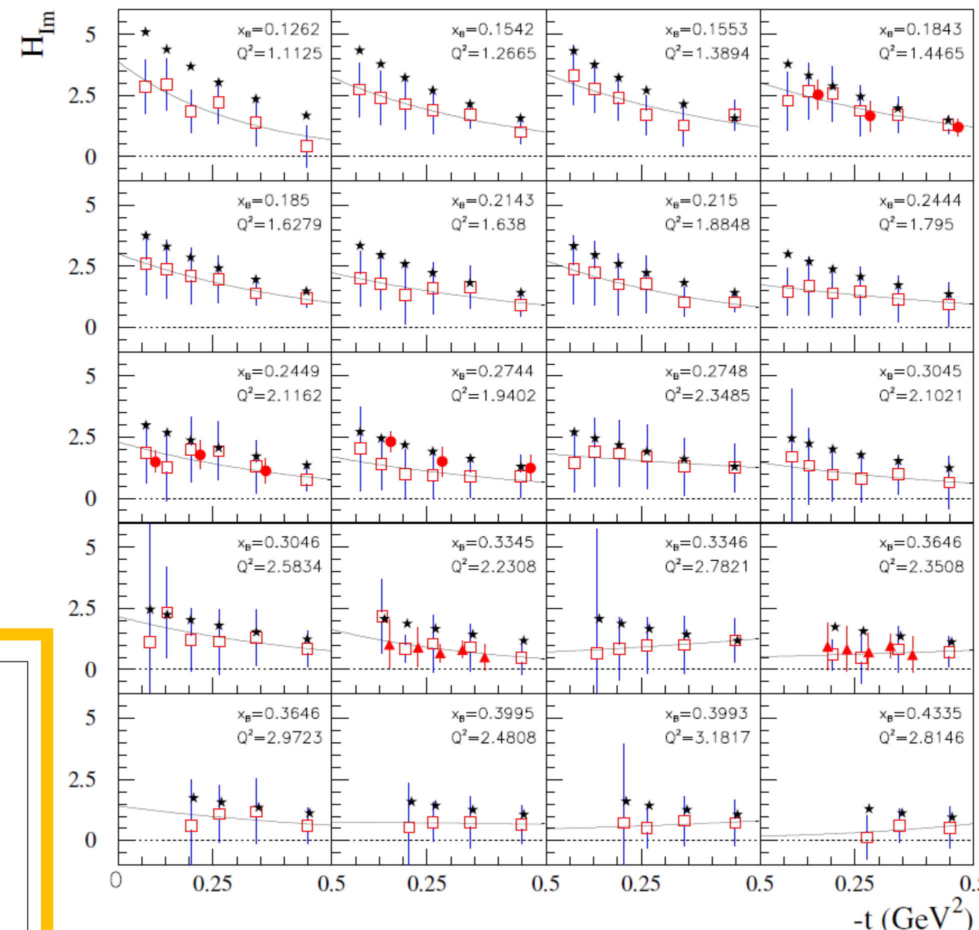
Dupré, Guidal, Vanderhaeghen, arXiv: 1606.07ﾑ

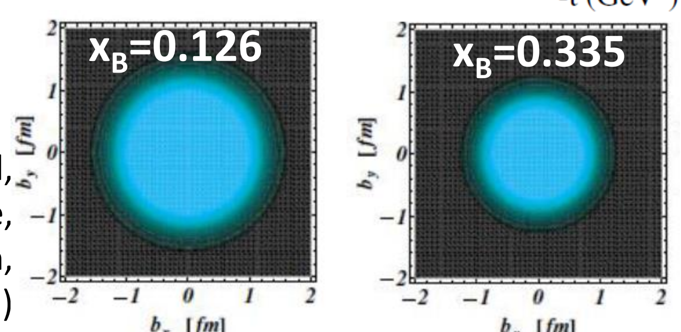
$s_1^I = Im\, F_1 \mathcal{H}$

- □ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}
- ★ VGG model
- — Fit $A\, e^{-B'|t|}$

$< b_\perp^2 > \approx 4B'$







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

Future Beam Spin Sum and Diff @JLab12

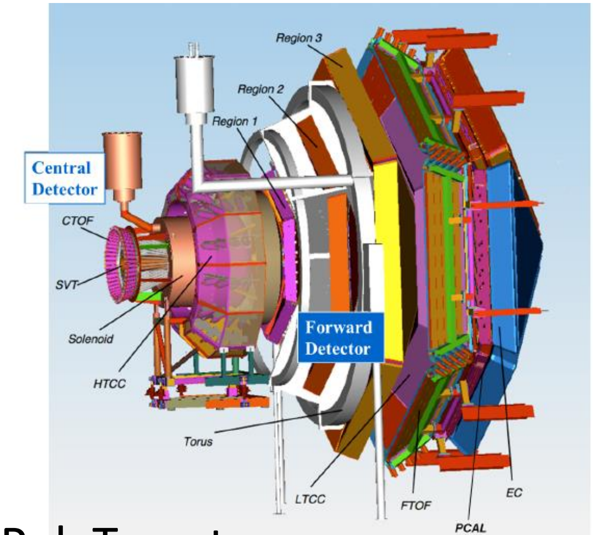
with high resolution magnetic spectro-meter+ Calorimeter in Halls A and C

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

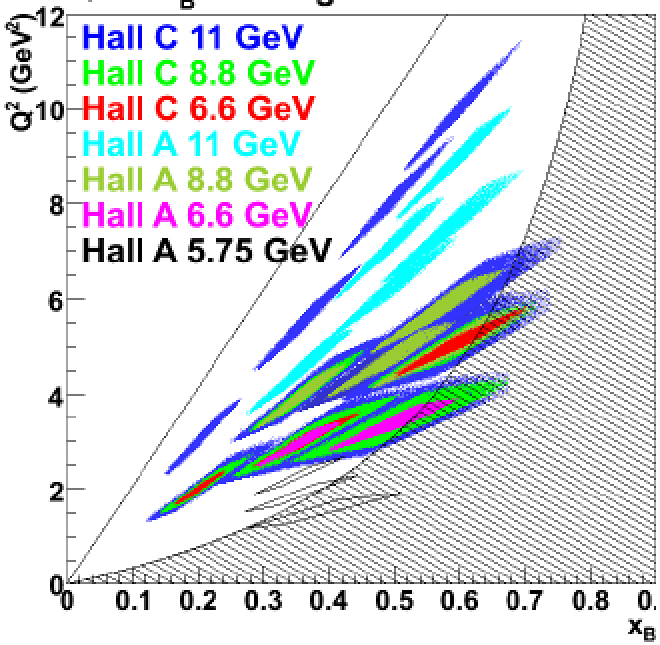
Different beam energies for a Rosenbluth-like $DVCS^2$/Interf. separation

with CLAS12
In 2016

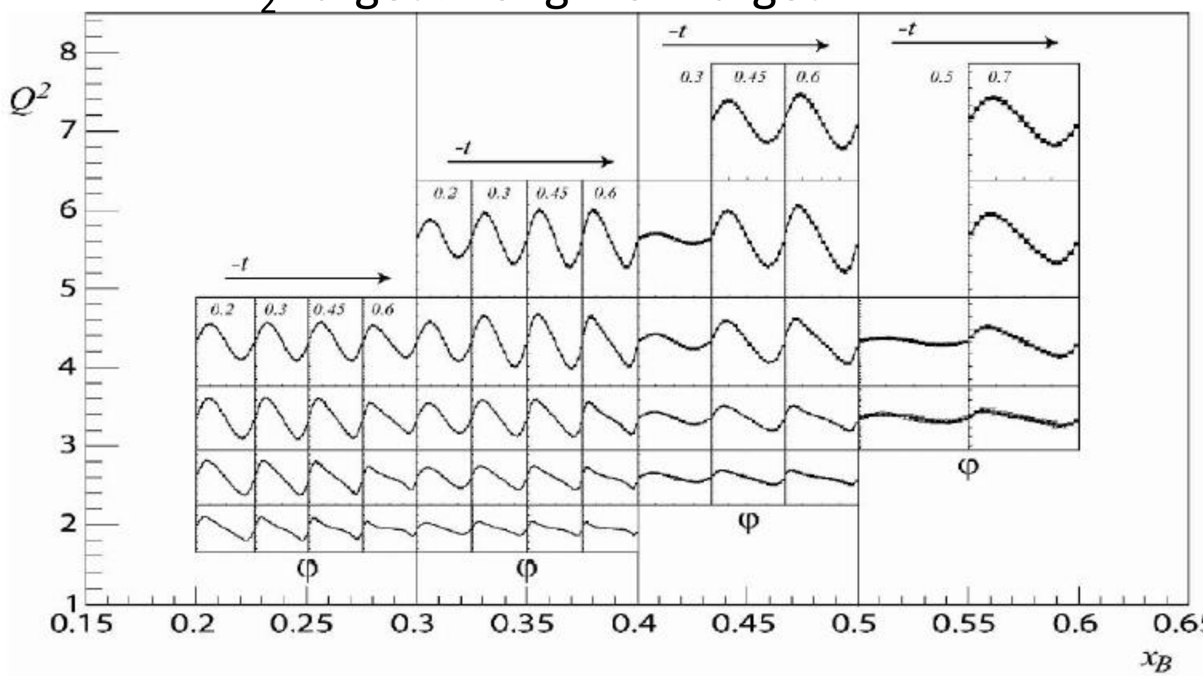
E12-06-119



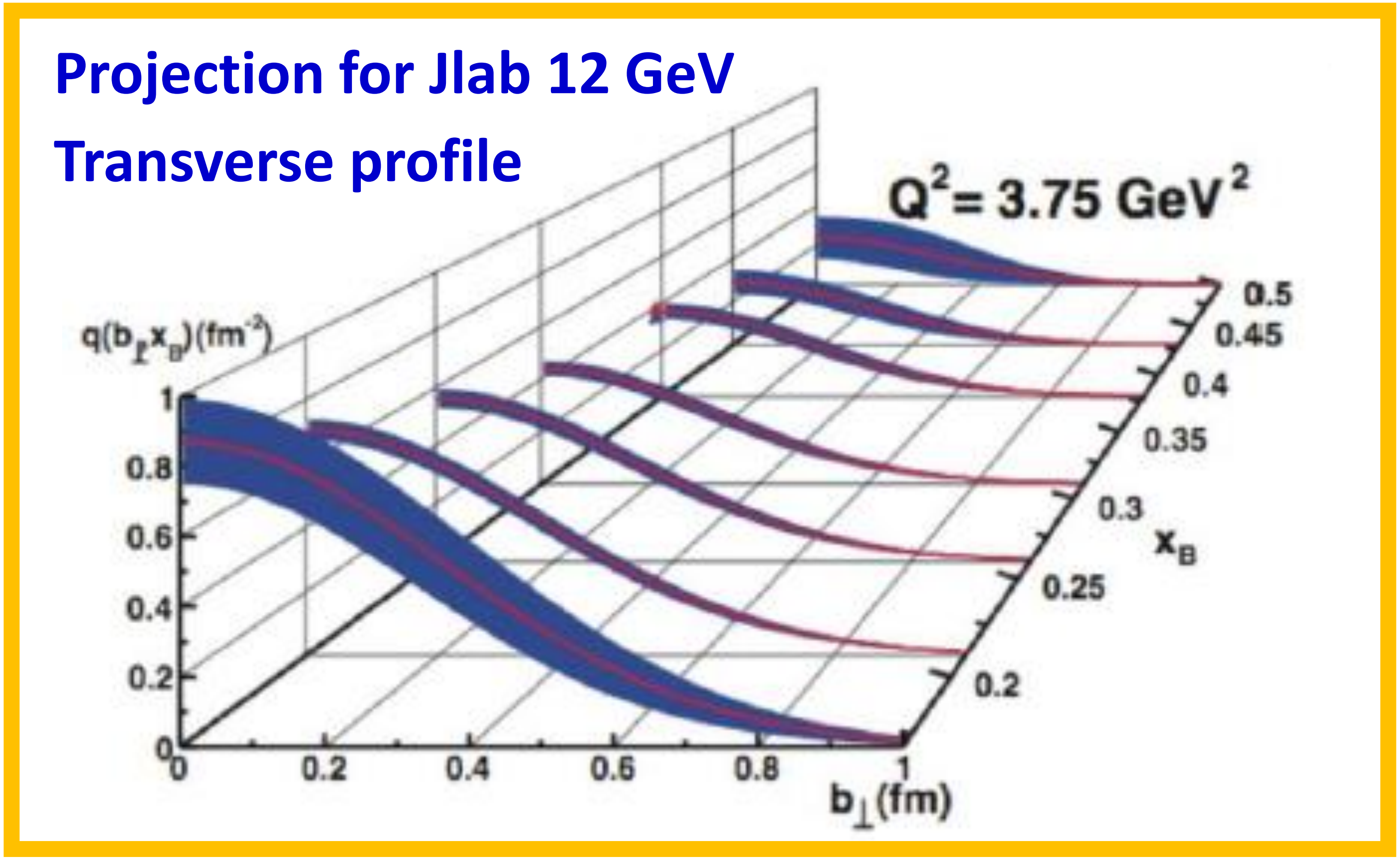
Q^2 vs x_B coverage in Halls A and C



LH_2 Target & Long. Pol. Target



Future Beam Spin Sum and Diff @JLab12



Dudek et al., EPJA48 (2012)

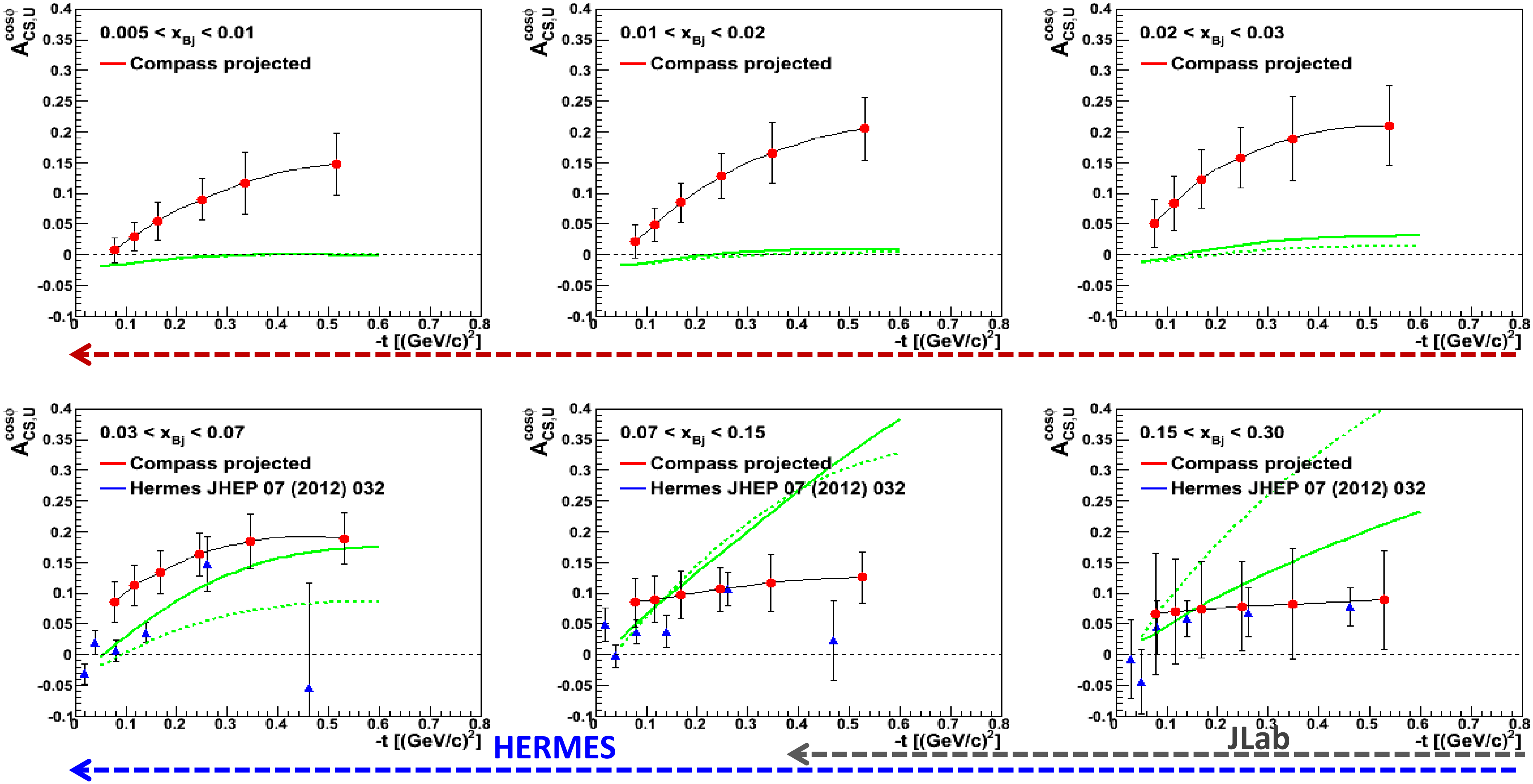
The 2015 Long Range Plan for Nuclear Science

Beam Charge and Spin Diff. @ COMPASS

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

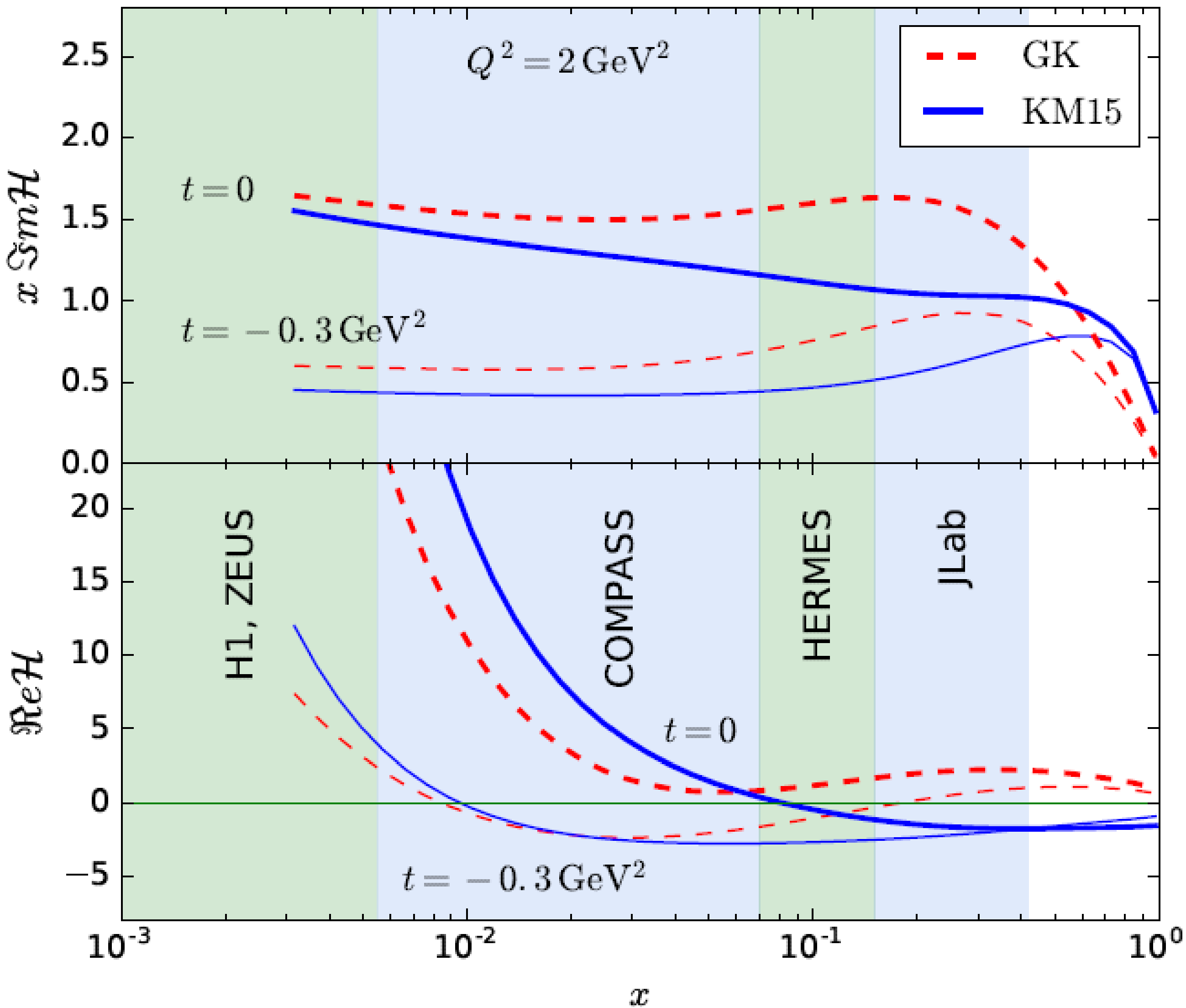
Predictions with
VGG and D.Mueller KM10

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



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

Impact of DVCS @ COMPASS in global analysis ?



Im H
Is it rather well known ?

Re 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

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

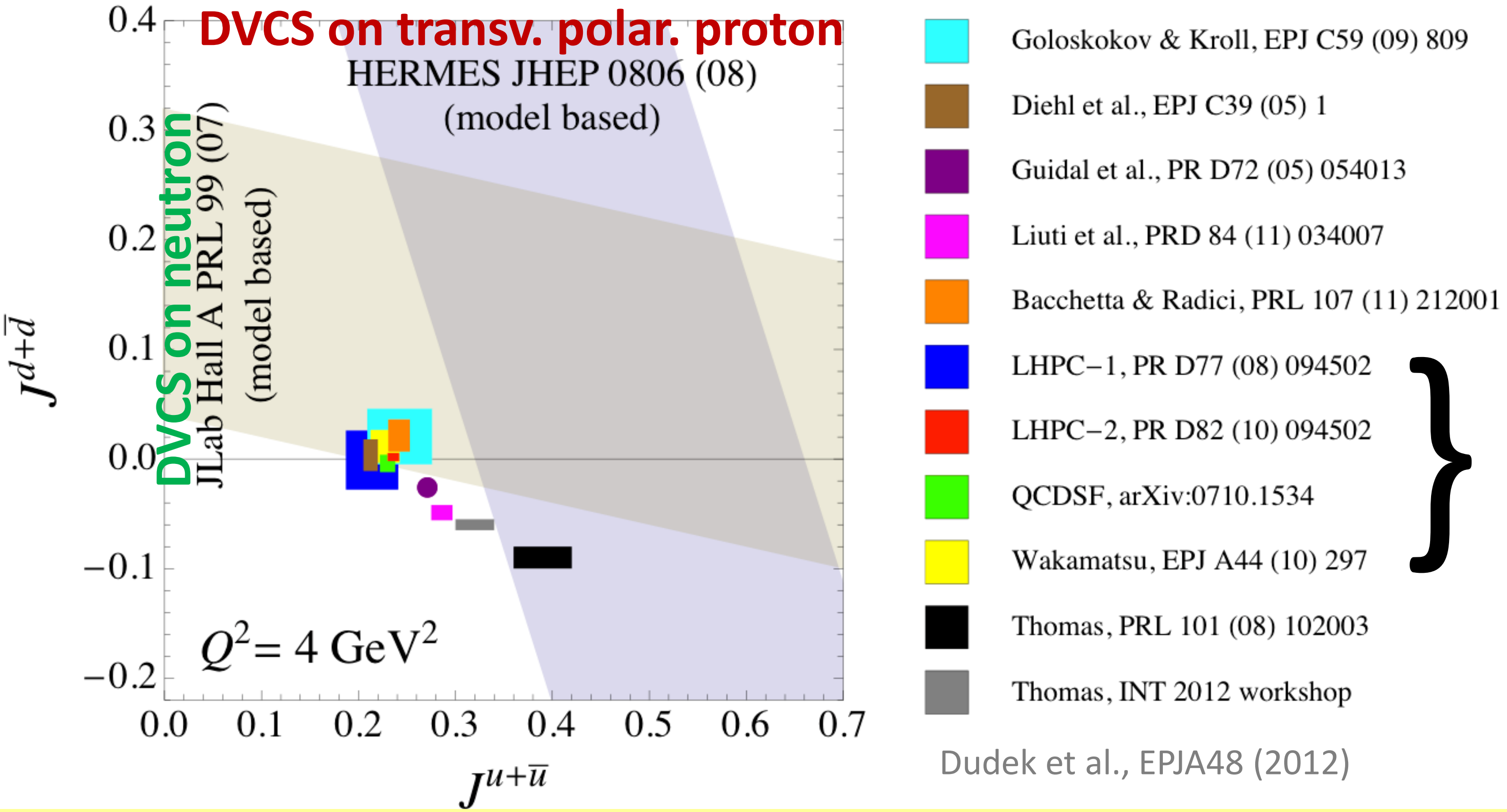
$\Delta\sigma_{LU} \sim Im\, (F_{1n}\, \mathcal{H} - F_{2n}\, \mathcal{E})$

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

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

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

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)

Look for other GPDs: the chiral-odd H_T and $\bar{E}_T$

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

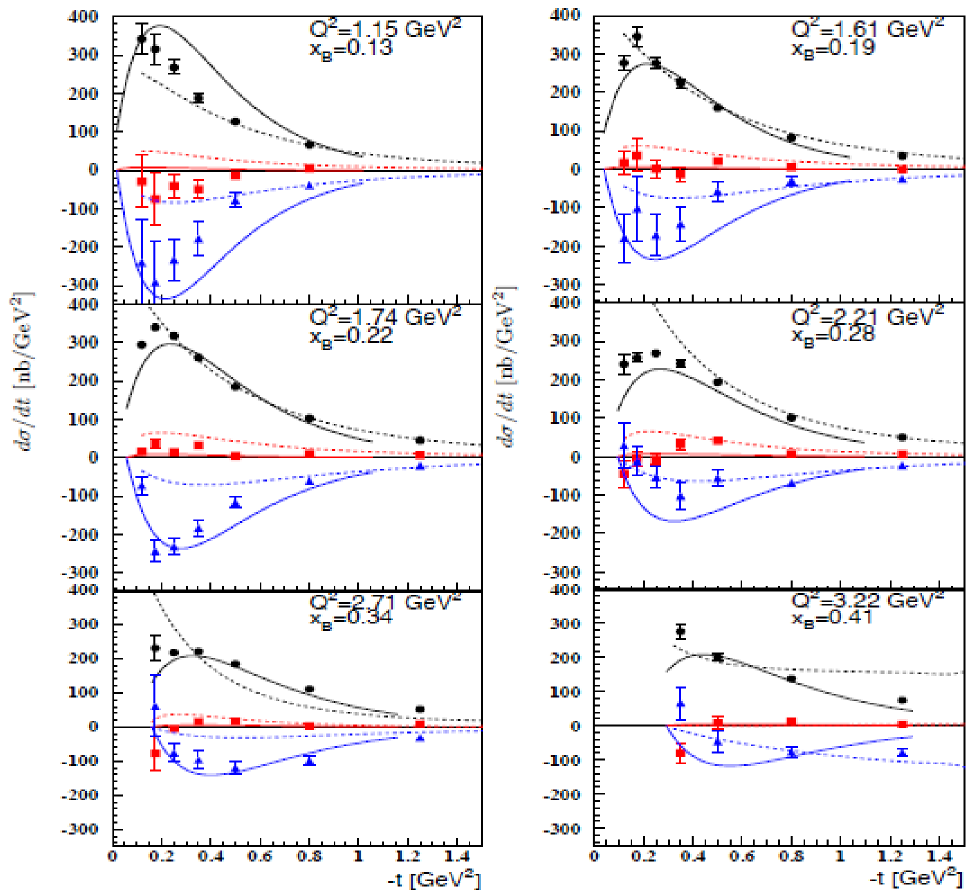
$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

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

Look for other GPDs: the chiral-odd H_T and $\bar{E}_T$

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

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

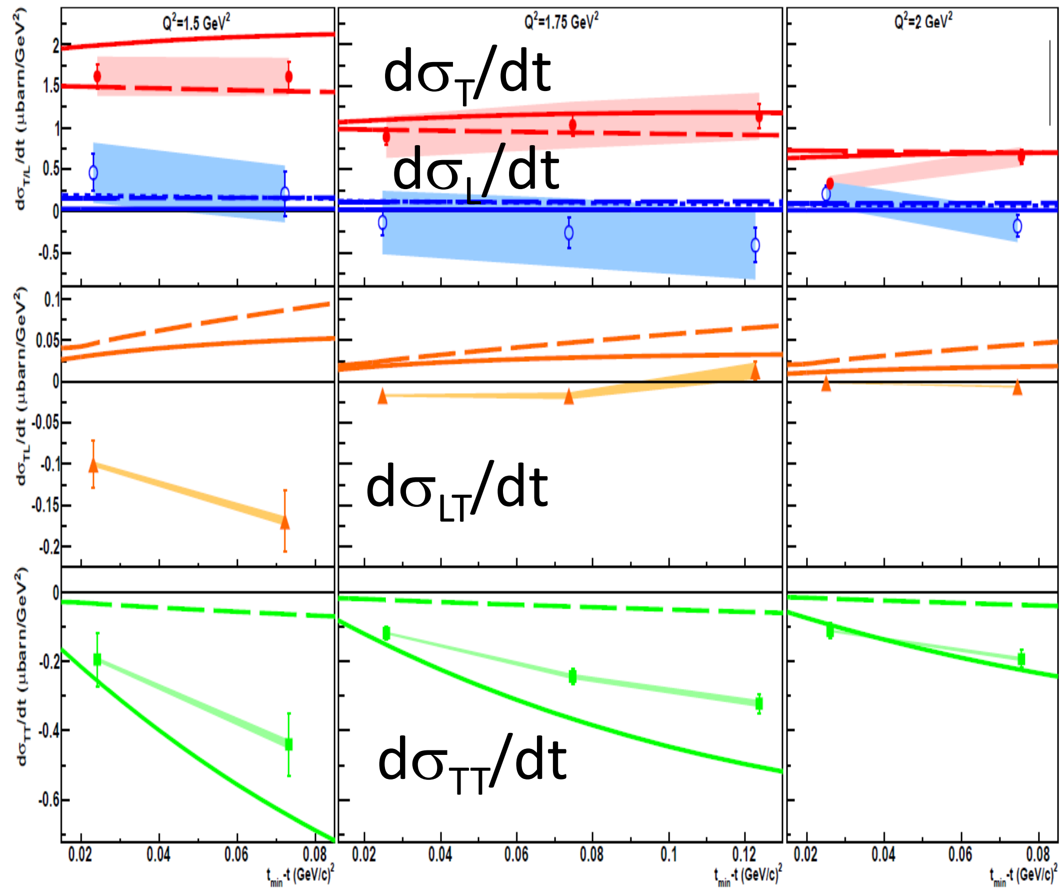
$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\} << \frac{d\sigma_T}{dt}$$

Confirmation -HallA

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

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

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



Large impact of $\bar{E}_T$
clearly visible in σ_{TT}
and in the dip at small t of σ_T

Hall A: σL and σT separation
Defurne et al. ArXiv:1608.01003

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

Only selected results.
A large effort on ρ, ω, ϕ, J/Ψ, π^0,….
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) @ 200GeV, JLab @ 12GeV and for a future electron-proton collider

Transverse imaging at COMPASS

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

$B(x_B) = ½ < r_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by $H(x, \xi=x, t)$

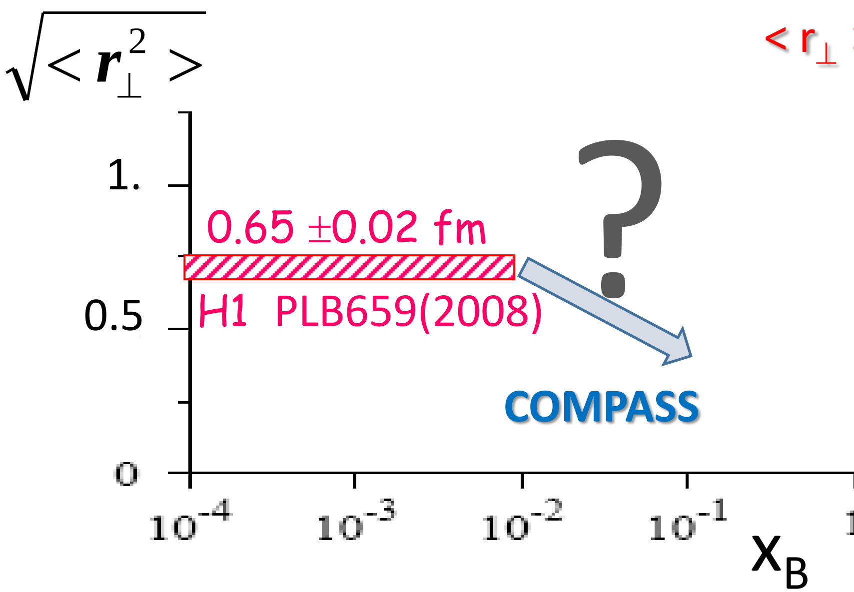
related to $½ < b_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of the nucleon

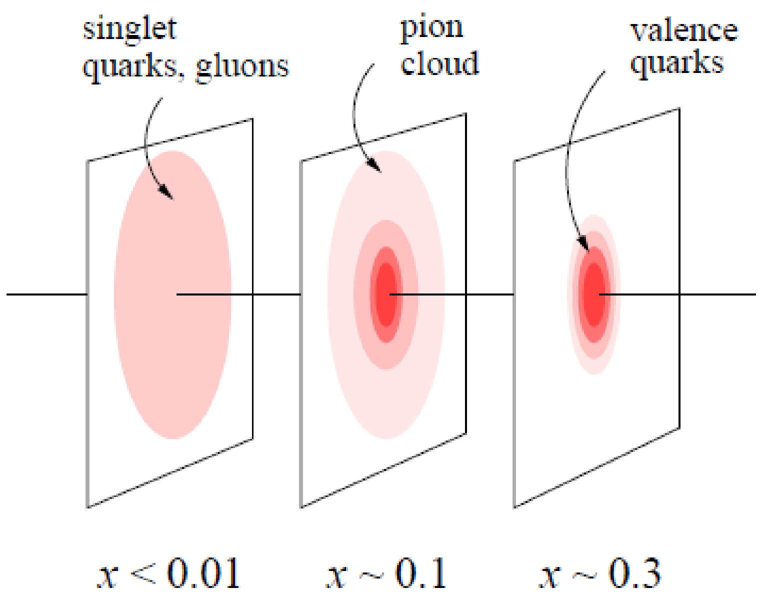
Impact Parameter Representation

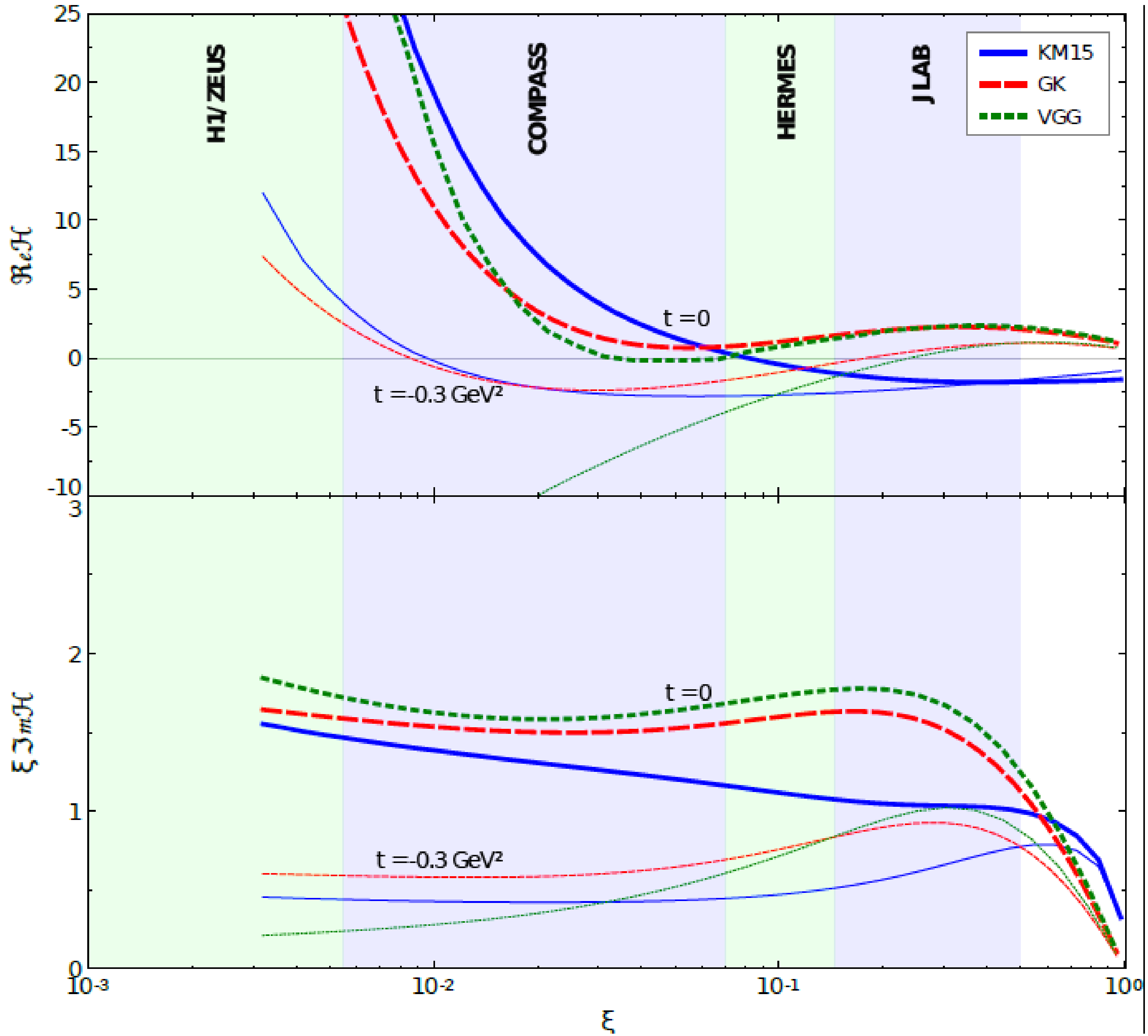
$q(x, b_\perp) \leftrightarrow H(x, \xi=0, t)$

$< r_\perp > \sim < b_\perp > / (1-x)$



Note 0.65 fm $= \sqrt{2/3} \times 0.8$ fm





H1/ ZEUS
COMPASS
HERMES
J LAB
KM15
GK
VGG
t =0
t =-0.3 GeV²
ℜeℋ
ξ ℑmℋ
ξ
25
20
15
10
5
0
-5
-10
3
2
1
0
10-3
10-2
10-1
100