Status and Prospects of the Experimental Investigation on GPDs

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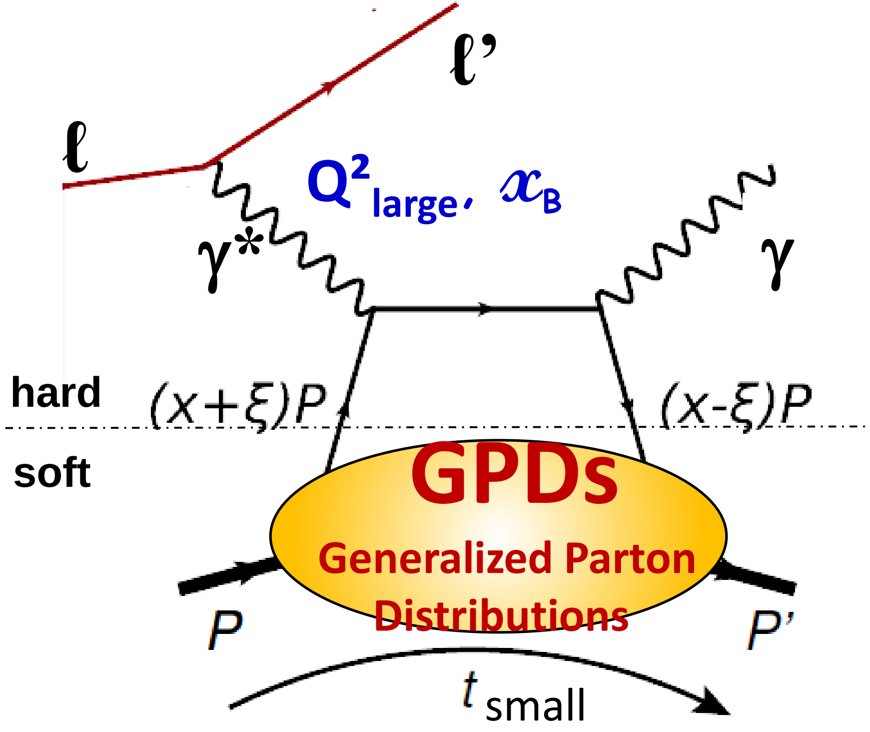
Deeply virtual Compton scattering (DVCS) and DVMP



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
$\ell p \rightarrow \ell' p' \pi, \rho$ 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

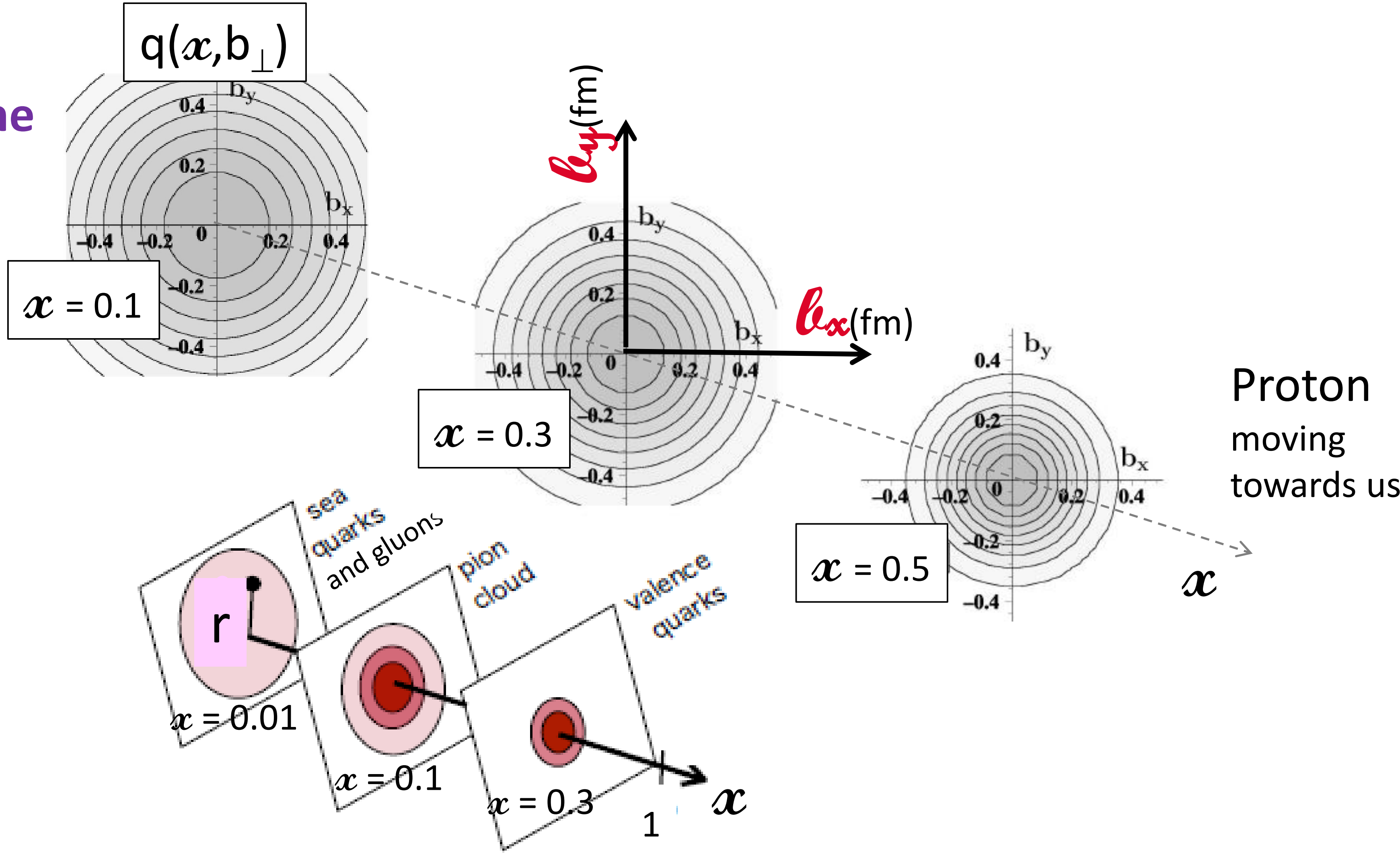
The variables measured in the experiment:

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

GPDs and 3D imaging

M. Burkardt, PRD66(2002)

mapping in the transverse plane
Impact parameter distribution

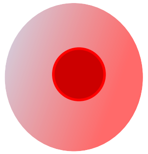


Correlation between the spatial distribution of partons and the longitudinal momentum fraction

GPDs and Energy-Momentum Tensor and Confinement

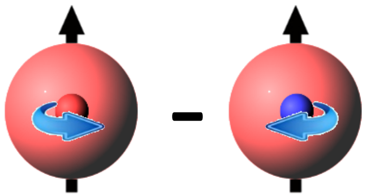
GPDs can provide an experimental answer by exploiting their equivalence to the gravitational form factors of the nucleon energy-momentum-tensor (fundamental nucleon properties)

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



"Elusive"

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



Sivers: quark k_T & nucleon transv. spin

mass & energy distribution

$$\int dx\, x\, H^q(x,\xi,t) = A^q(t) + \frac{4}{5}\xi^2 d_1^q(t)$$

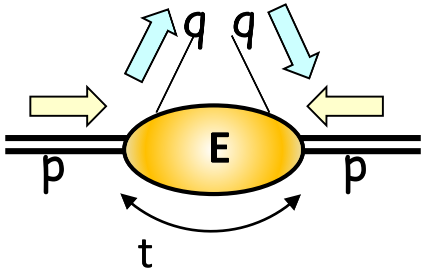
$$\int dx\, x\, E^q(x,\xi,t) = B^q(t) - \frac{4}{5}\xi^2 d_1^q(t)$$

Angular momentum distribution

Force & Pressure distribution

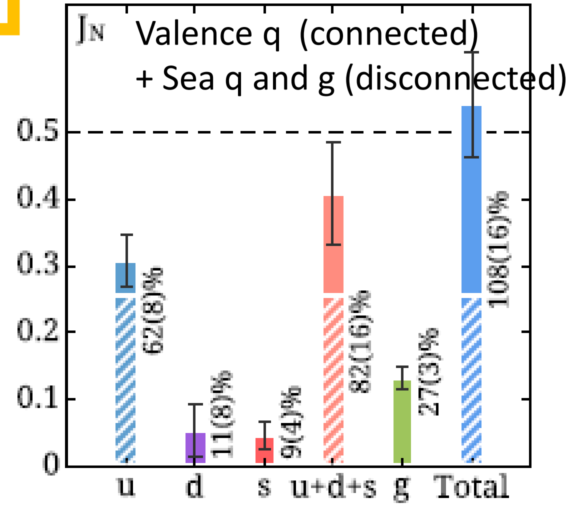
$$2J^q = \lim_{t\to 0} \int x\,(\boldsymbol{H}^q(x, \xi, t) + \boldsymbol{E}^q(x, \xi, t))\, dx$$

Ji sum rule: PRL78 (1997) cited 1504 times

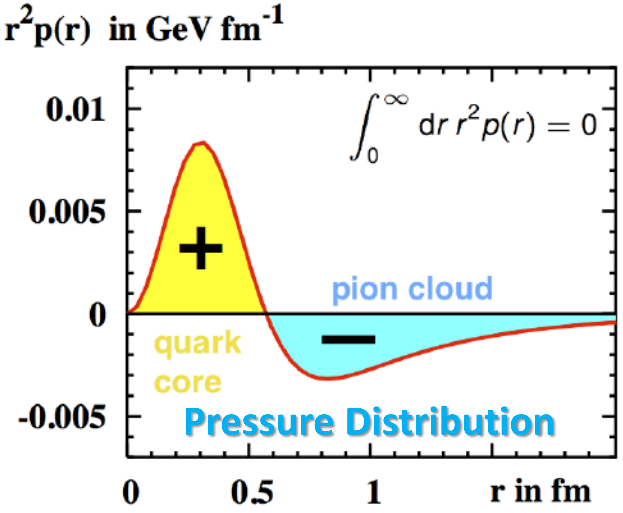


Relation to OAM

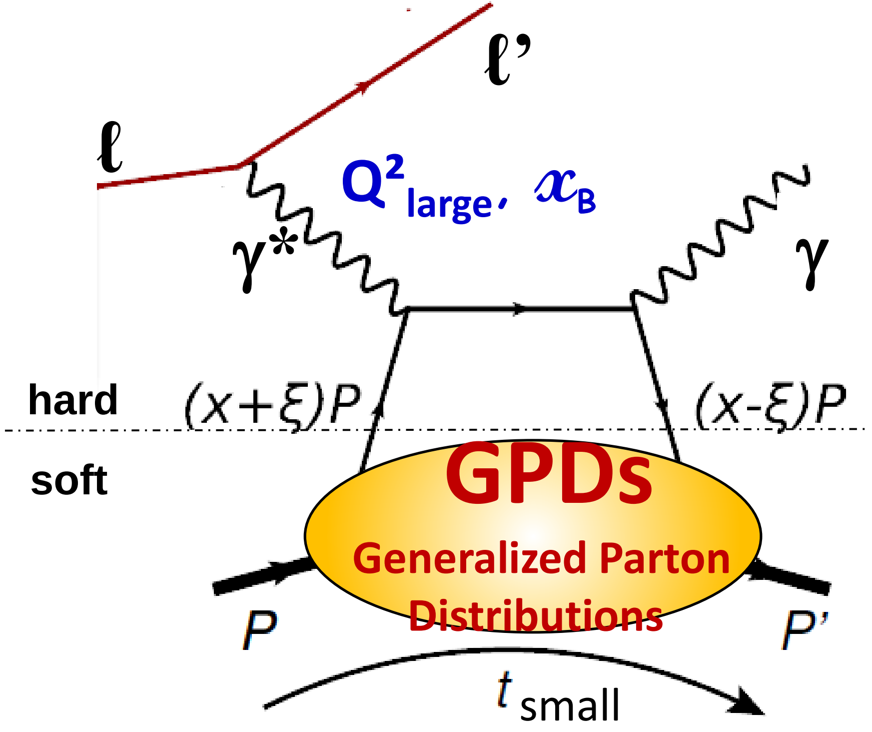
Lattice ArXiv:1706.02973
Alexandrou et al.
$\frac{1}{2}\Delta\Sigma = 0.20$
$L^q = 0.21$
$J^g = 0.13$



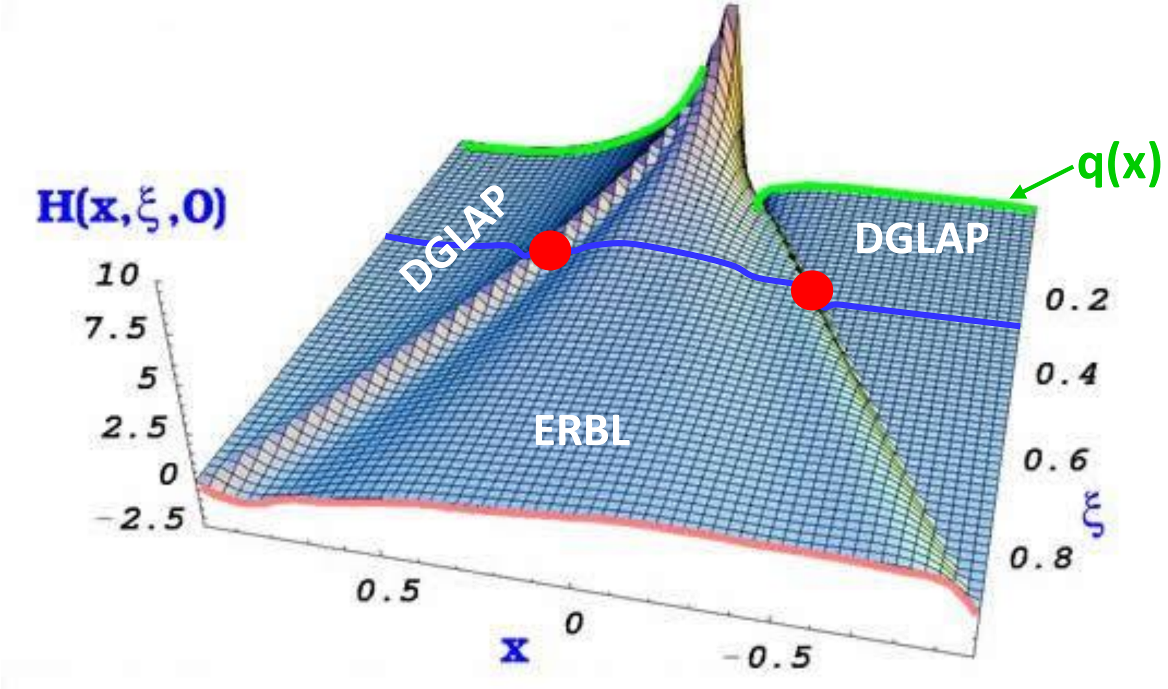
M. Polyakov, P. Schweitzer



Deeply virtual Compton scattering (DVCS)



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



The amplitude DVCS at LT & LO in α_S:

Real part **Imaginary part**

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

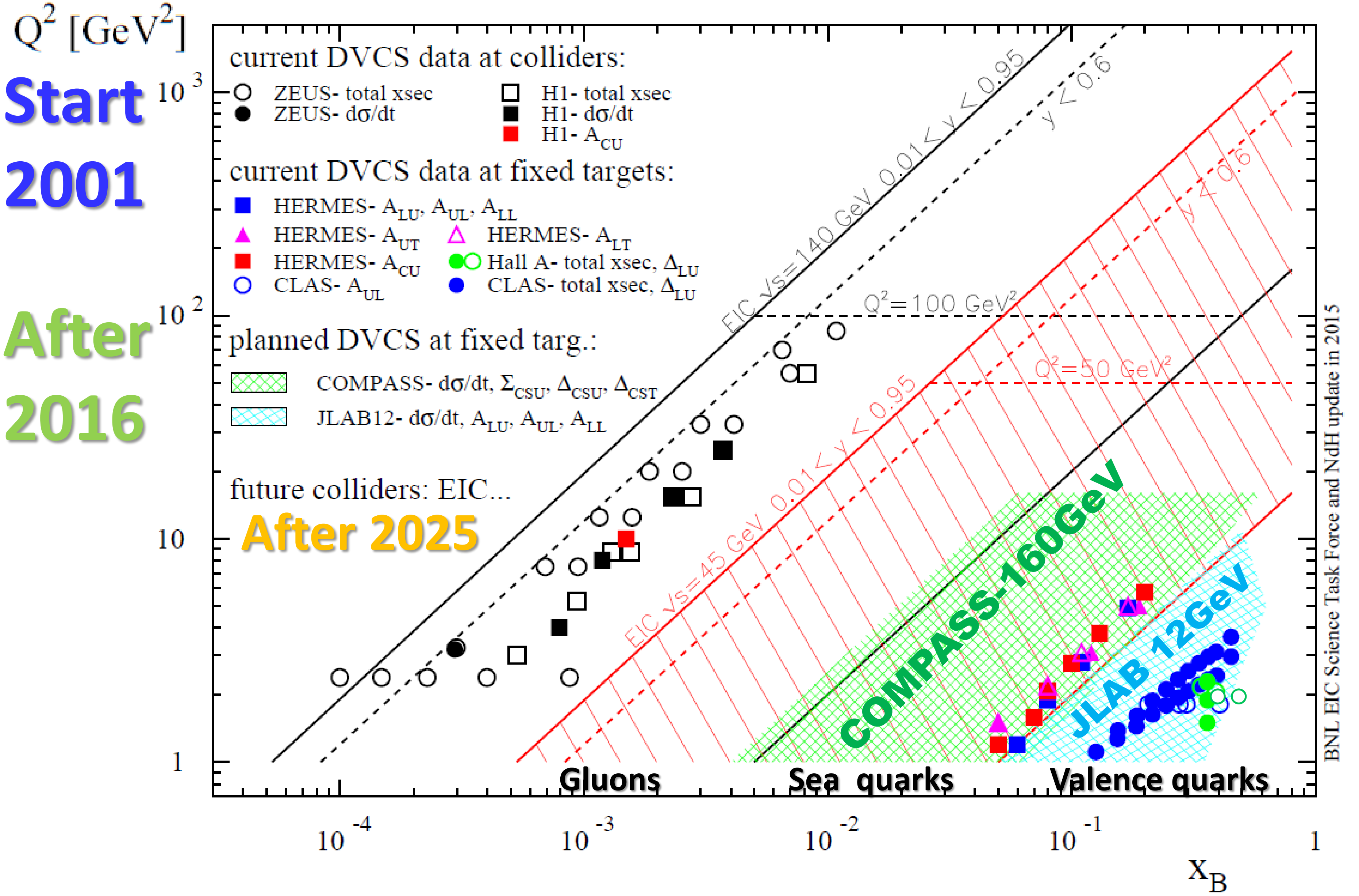
t, ξ fixed

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

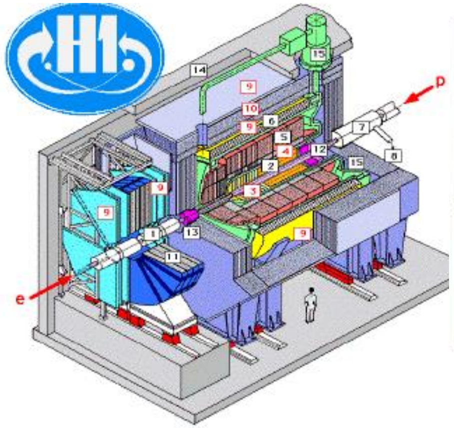
The past and future DVCS experiments

Start 2001

After 2016



The past and present experiments



Collider mode e-p forward fast proton

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

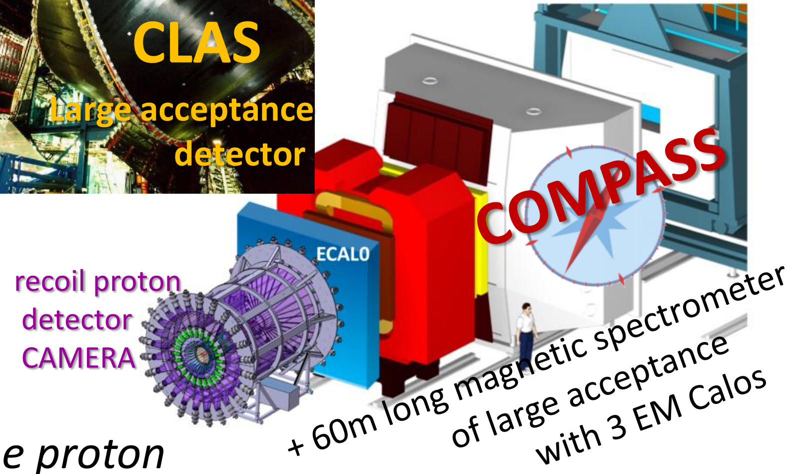
Examples for EIC

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

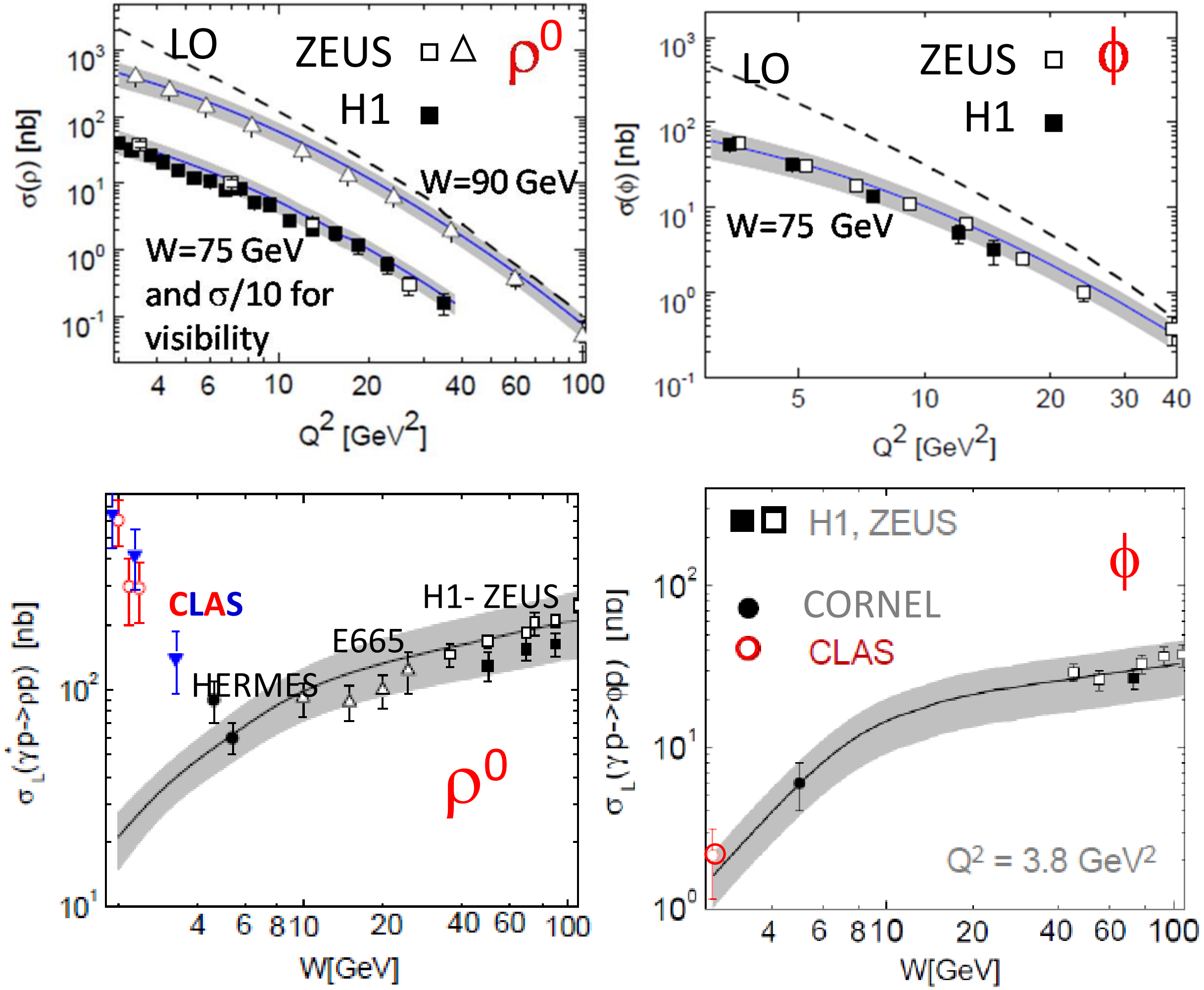
Jlab: Hall A, C, CLAS High lumi, polar. **6** & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique (A,C) and complete detection (CLAS)

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

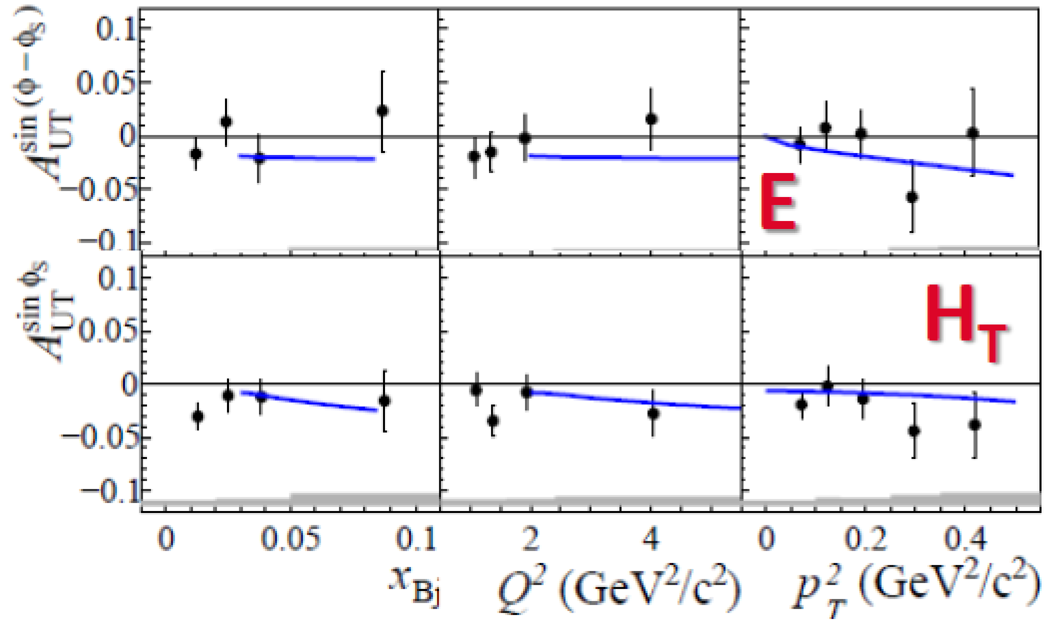


Rejection of background: SIDIS, exclusive π^0/DVCS, dissociation of the proton

Exclusive Meson production for GPD models



ρ^0 ($\rightarrow \pi^+\pi^-$) production at COMPASS
with Transversely Polarized Target

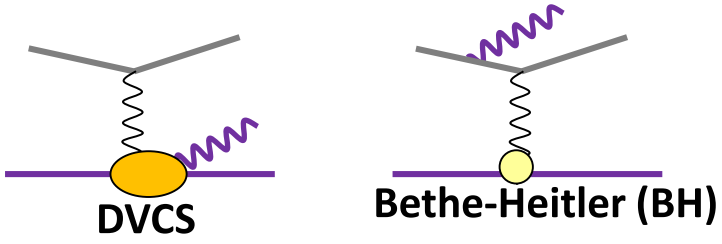


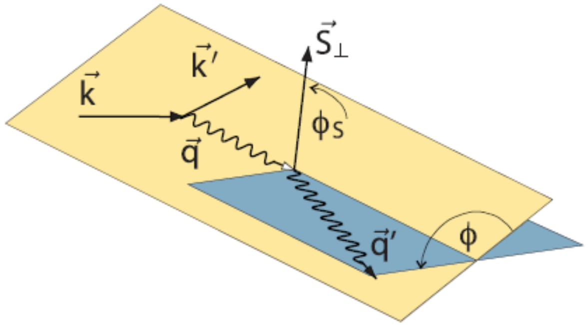
GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small x_B (or large W)

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

quark and gluon contributions (GPDs **H, E, H_T**) and beyond leading twist

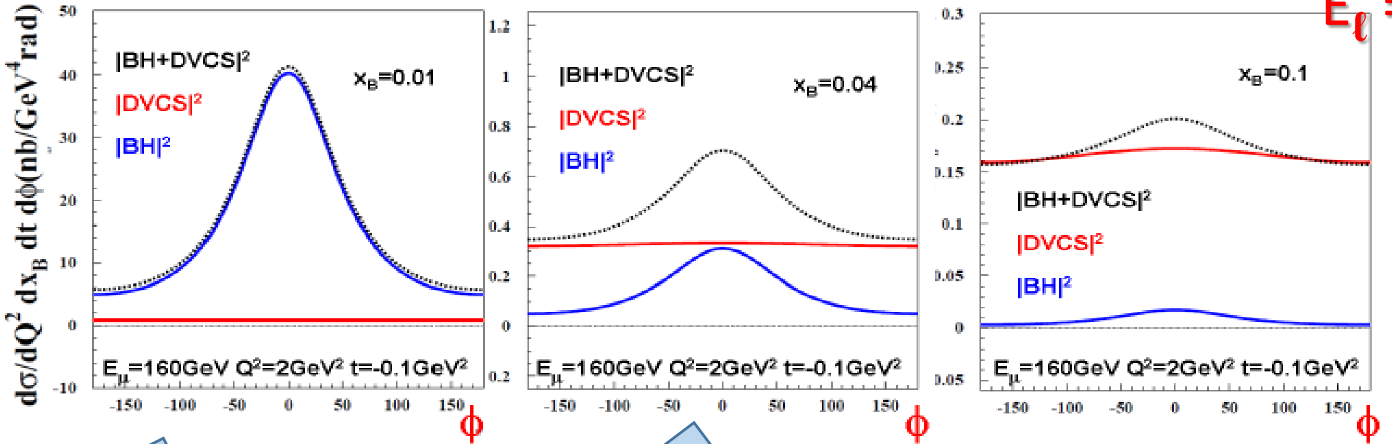
DVCS and Impact of the beam energy





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

E_ℓ =160 GeV



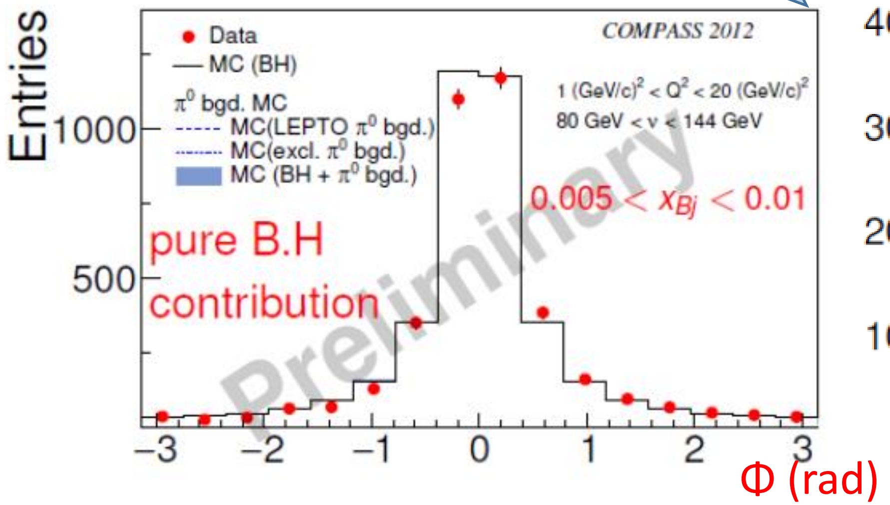
BH dominates
Reference yield

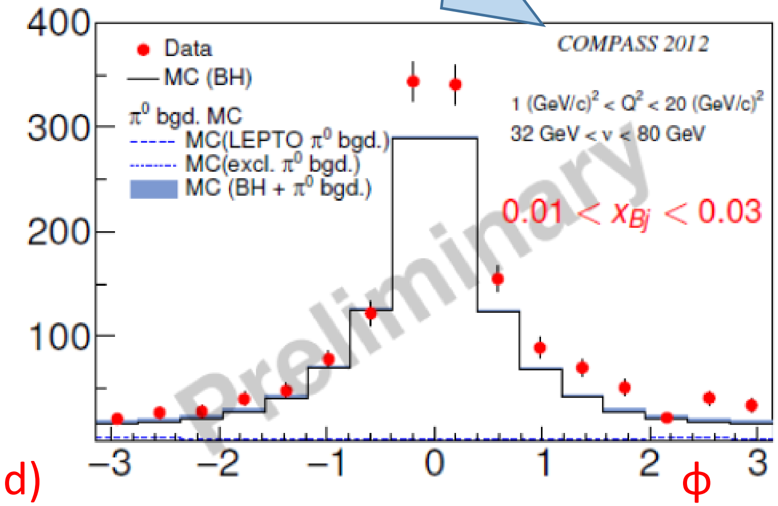
DVCS ampl. via interference

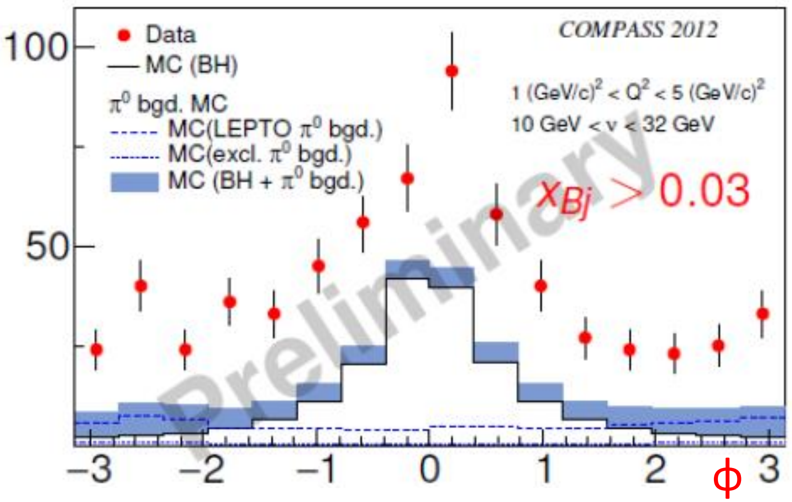
Jlab, HERMES,
H1, COMPASS

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

Only for H1, ZEUS, COMPASS





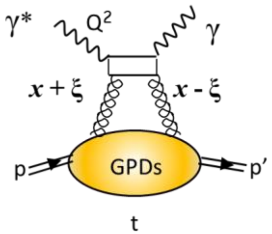


Study of t-dependence of the pure DVCS cross-section ($\gamma^* p \to \gamma p$)

Gluon imaging @ HERA

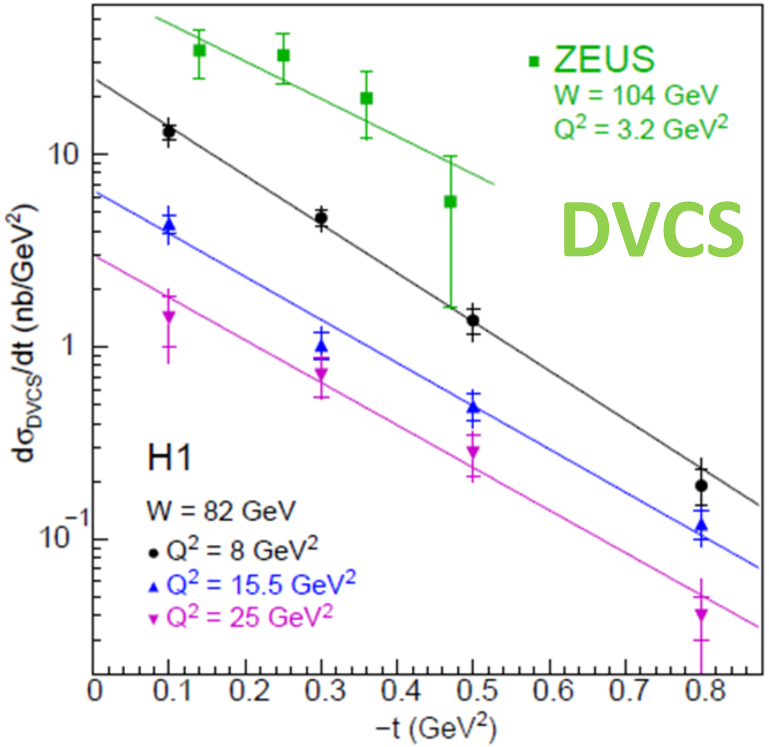
$d\sigma^{DVCS}/dt = e^{-B|t|}$

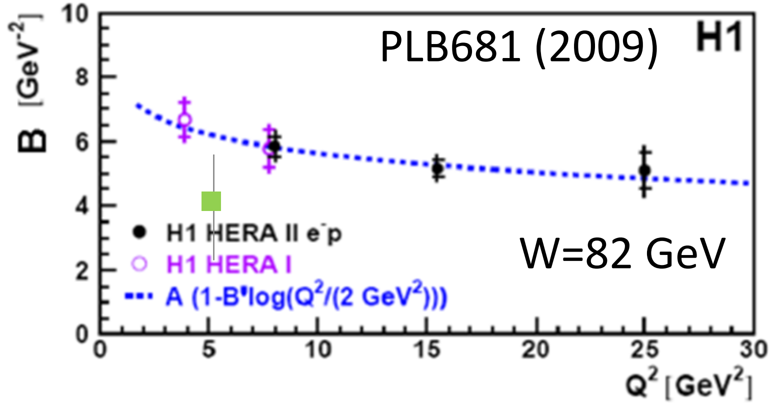
B is related to the transversed size of the scattering objects

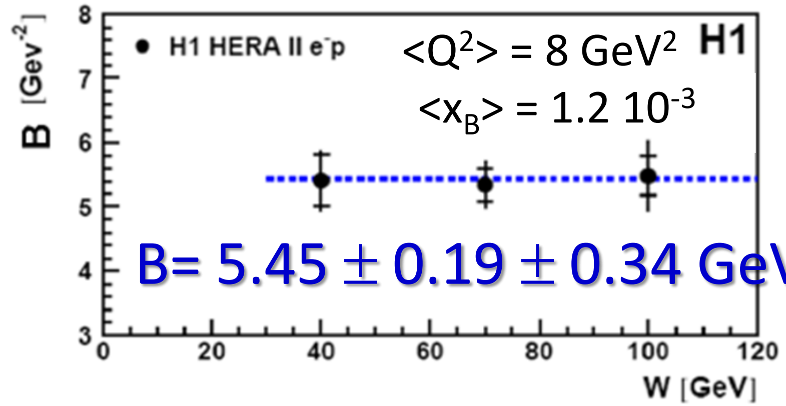


ZEUS-H1
Data collected
1995-2007

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







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

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

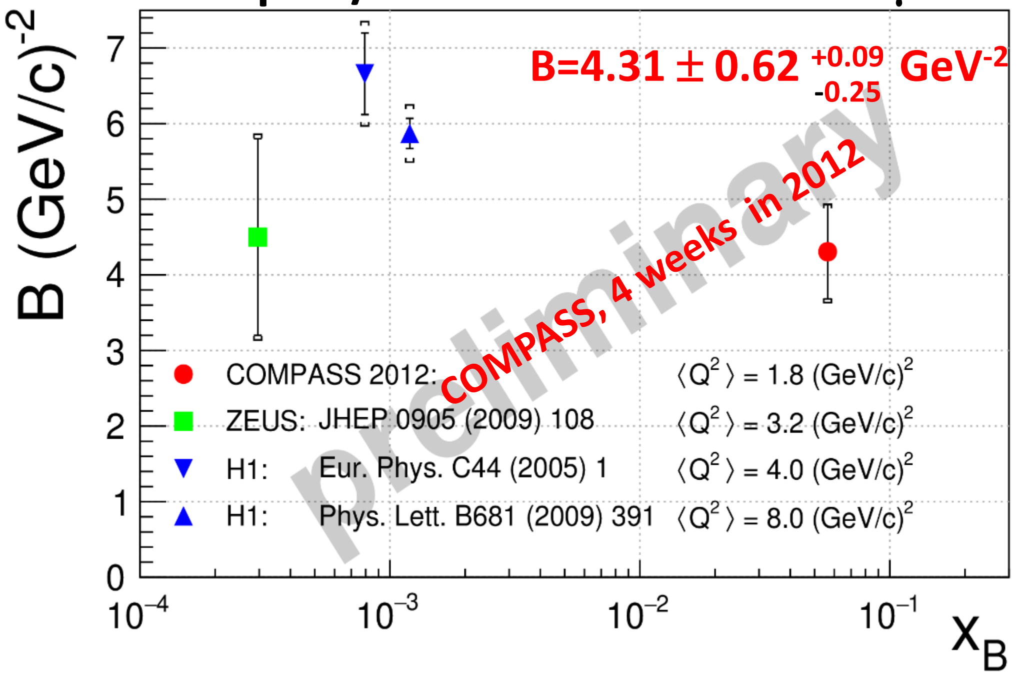
$\sqrt{<r_\perp^2>}$ = **0.65 ± 0.02 fm**

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

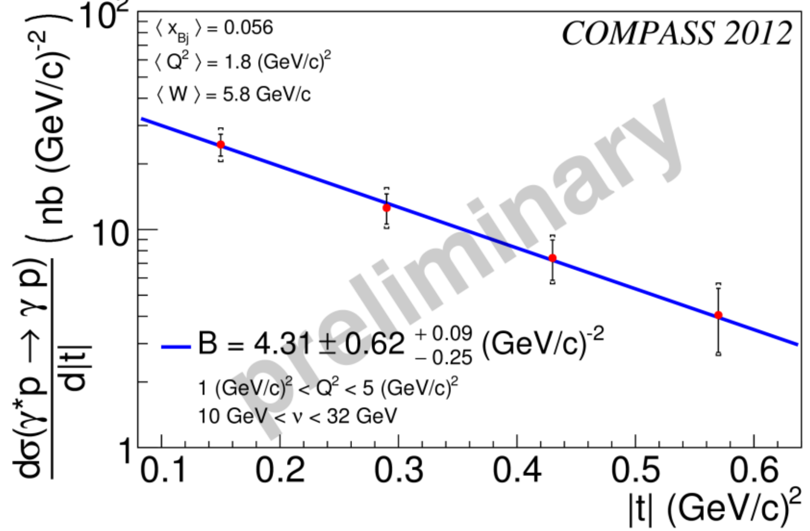
not to $\sqrt{4\frac{d}{dt}G_E^p} = 0.72 \pm 0.01$ fm

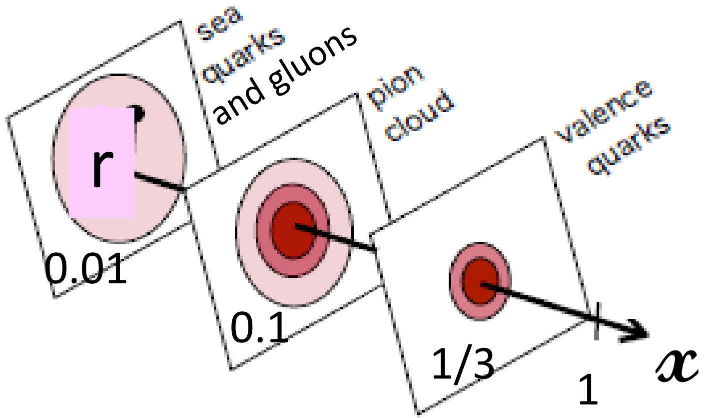
Sea quark imaging @ COMPASS

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

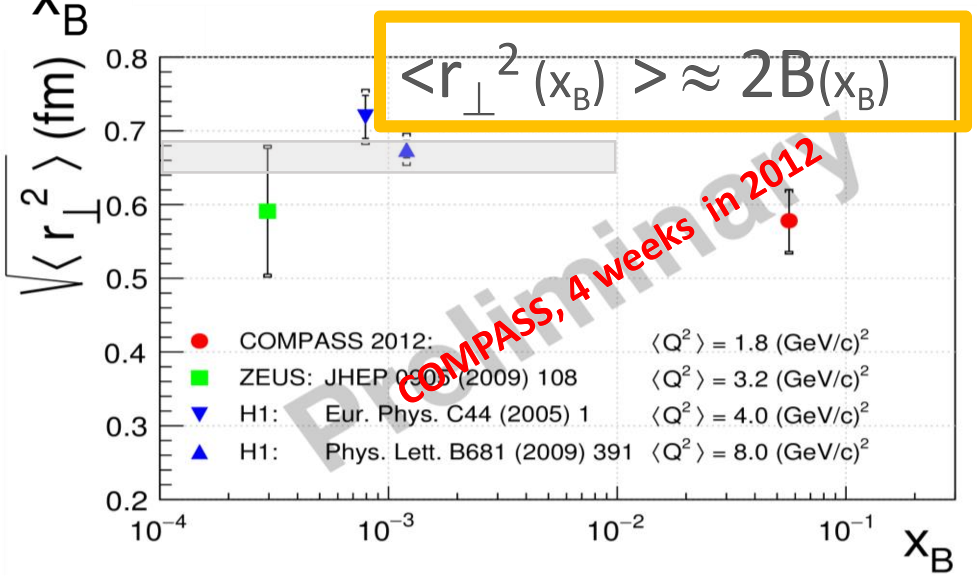


$d\sigma^{DVCS}/dt = e^{-B|t|}$

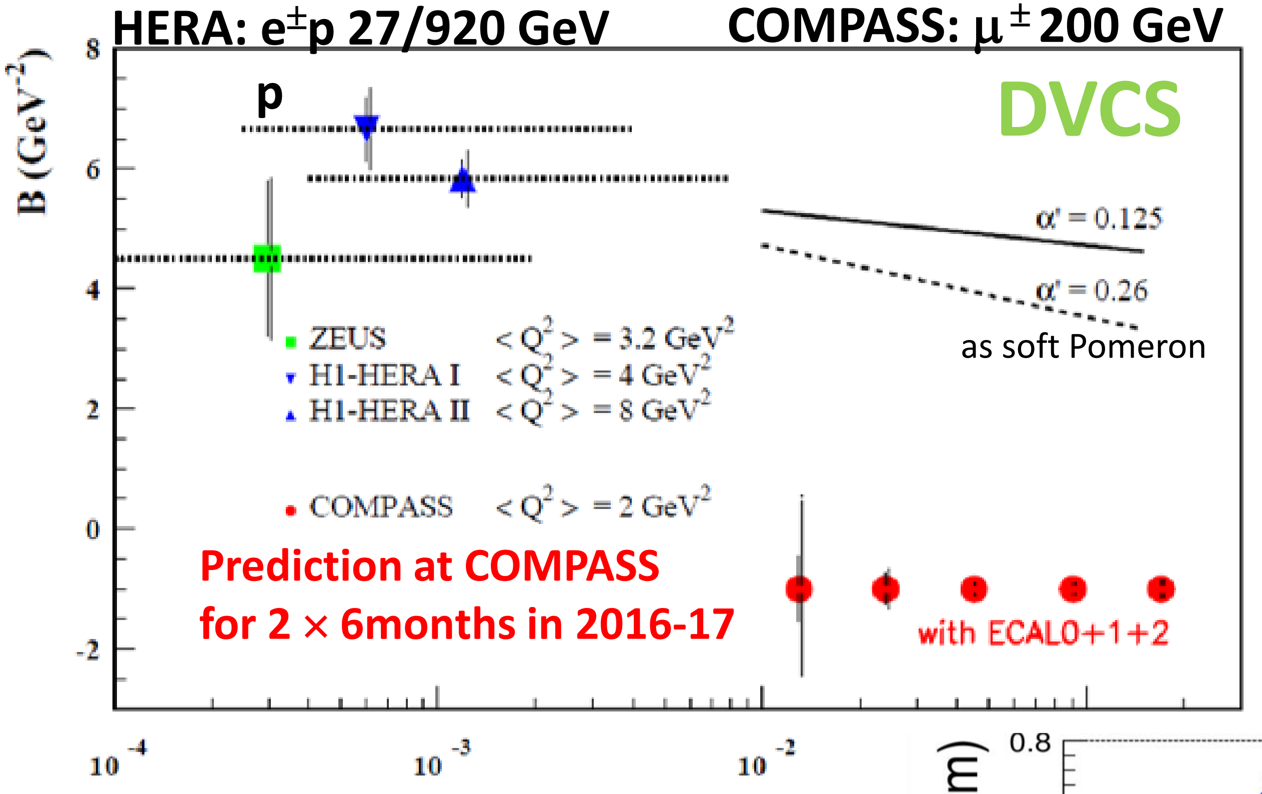




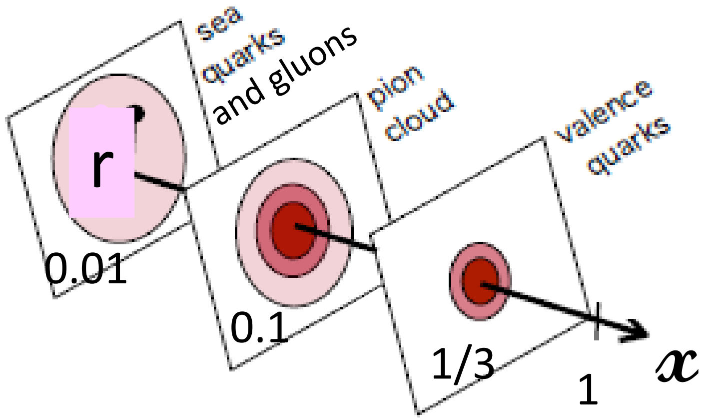
$\langle r_\perp^2 (x_B) \rangle \approx 2B(x_B)$



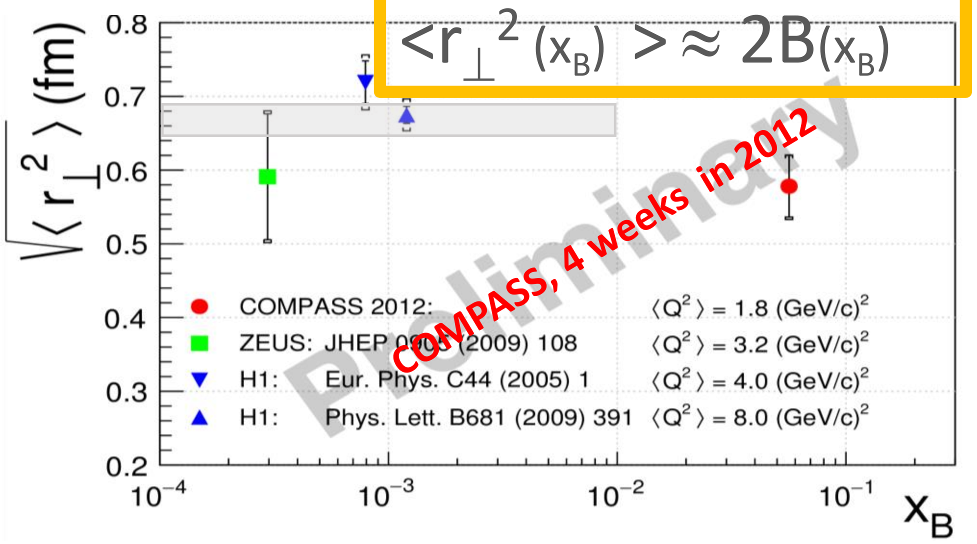
Sea quark imaging @ COMPASS



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

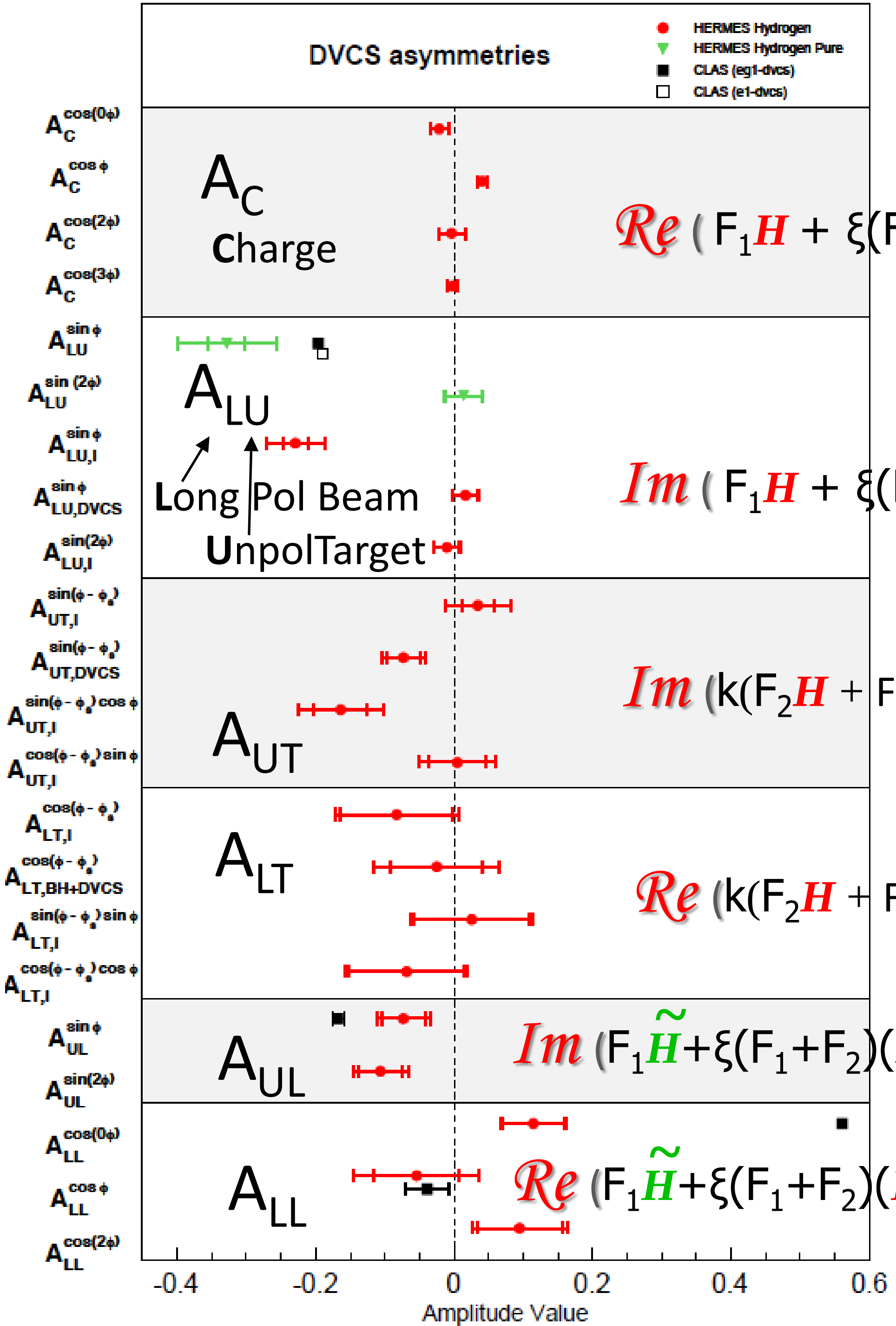


$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$



Study of DVCS-BH interference

A complete set of observables for DVCS



Results on the proton

$Re\,(F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E)$

$Im\,(F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E)$

} H

$Im\,(k(F_2 H + F_1 E)\})$

$Re\,(k(F_2 H + F_1 E)\})$

} E

$Im\,(F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)$

$Re\,(F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)$

} $\tilde{H}$

$k = t/4M^2$

Asymmetry measurements

HERMES 27 GeV provided
a complete set of obersvables

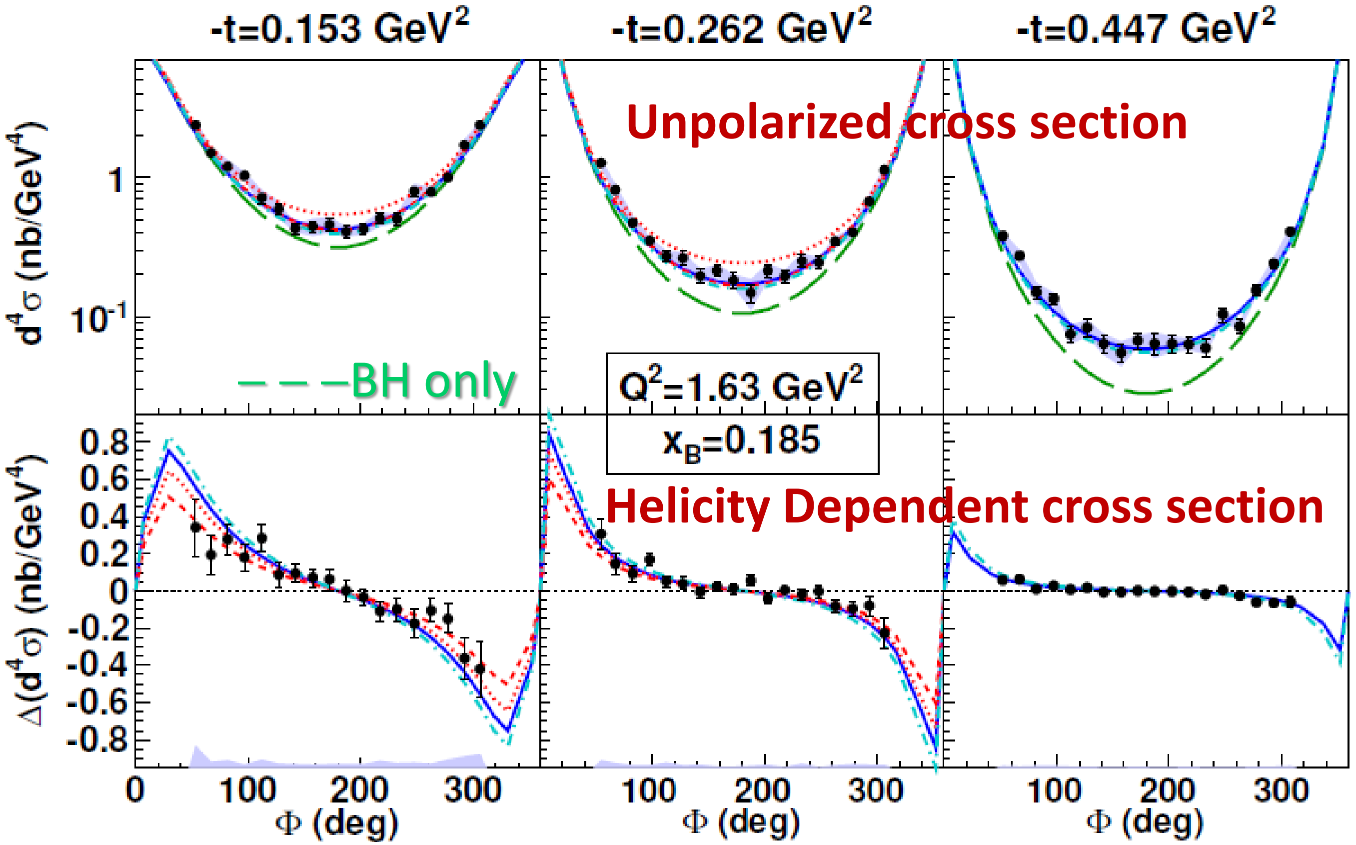
- 1995: start of data taking
- 2001: 1st DVCS publication as CLAS & H1
- 2007: end of data taking
- 2012: still important publications
  - *JHEP 07 (2012) 032 A_C A_{LU}*
  - *JHEP10(2012) 042 A_{LU}*
  - *with recoil detection (2006-7)*

\+ 1998-2017 JLAB 6 GeV
Very precise data

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)

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



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
constant evolution

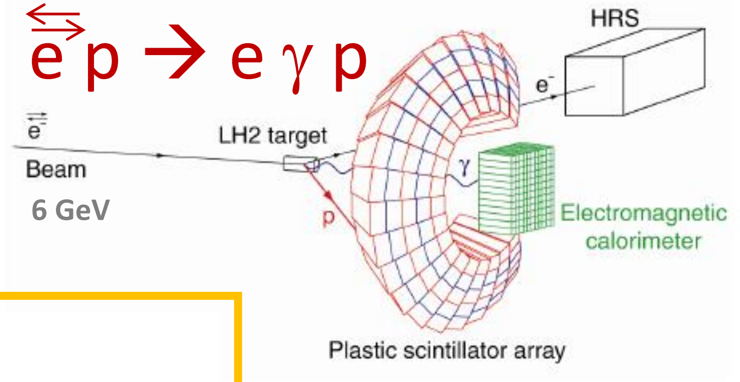
KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)
using the **GK** model
Goloskokov, Kroll, EPJC42,50,53,59,65,74
for GPD adjusted on the hard exclusive meson production at small x_B
"universality" of GPDs

Beam Spin Sum and Diff of DVCS - HallA

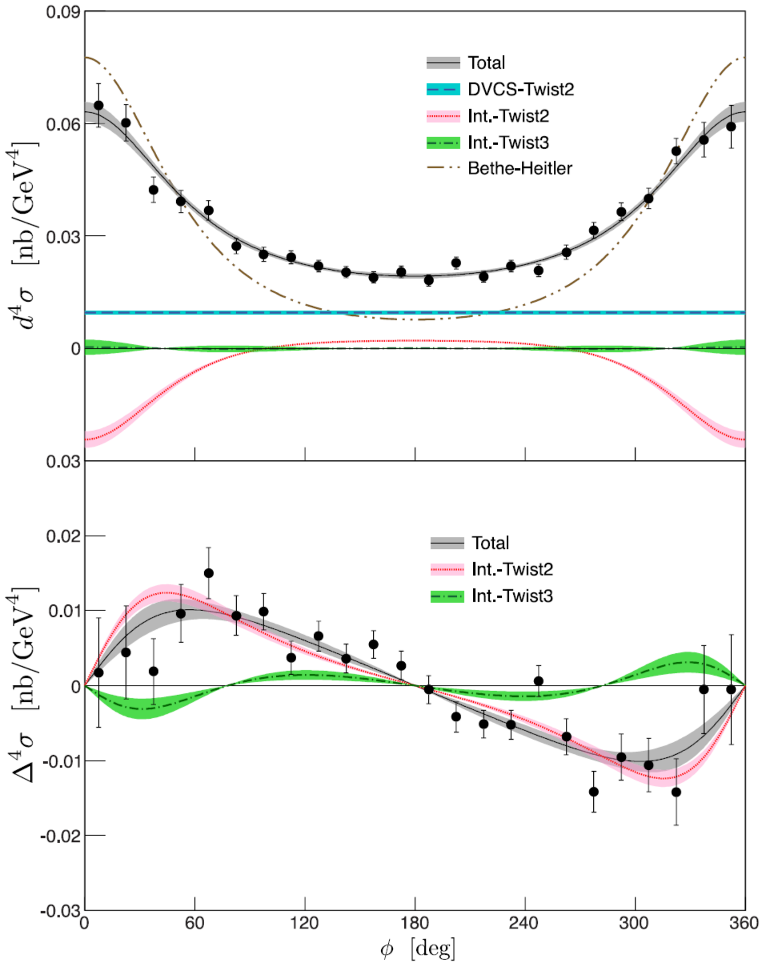
E00-110 pioneer experiment in 2004 with magnetic spectrometer

x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV^2 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

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

Helicity Dependent cross section

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

Further separation with different beam energies (2010 data)

2 solutions: higher-twist

or next-to-leading order

arXiv:1703.09442 submited to nature COMMUNICATIONS

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

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

□ CLAS σ and Δσ

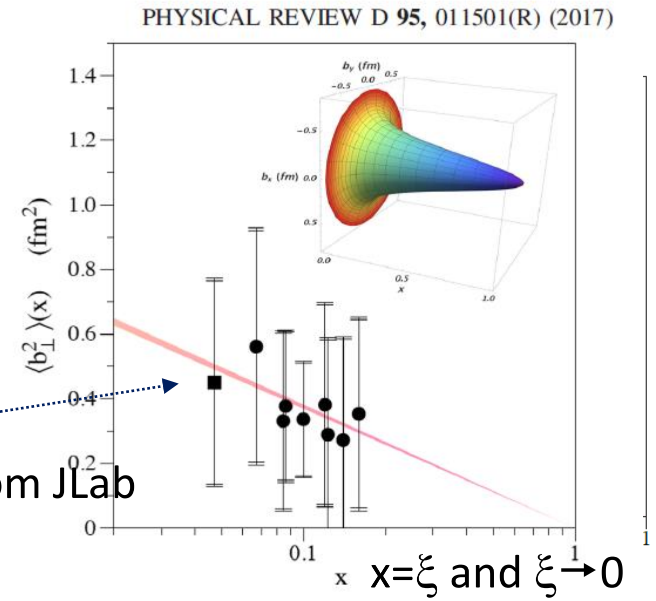
▲ HallA σ and Δσ

● CLAS A_{UL} and A_{LL}

★ VGG model

— Fit $A\, e^{-B'|t|}$

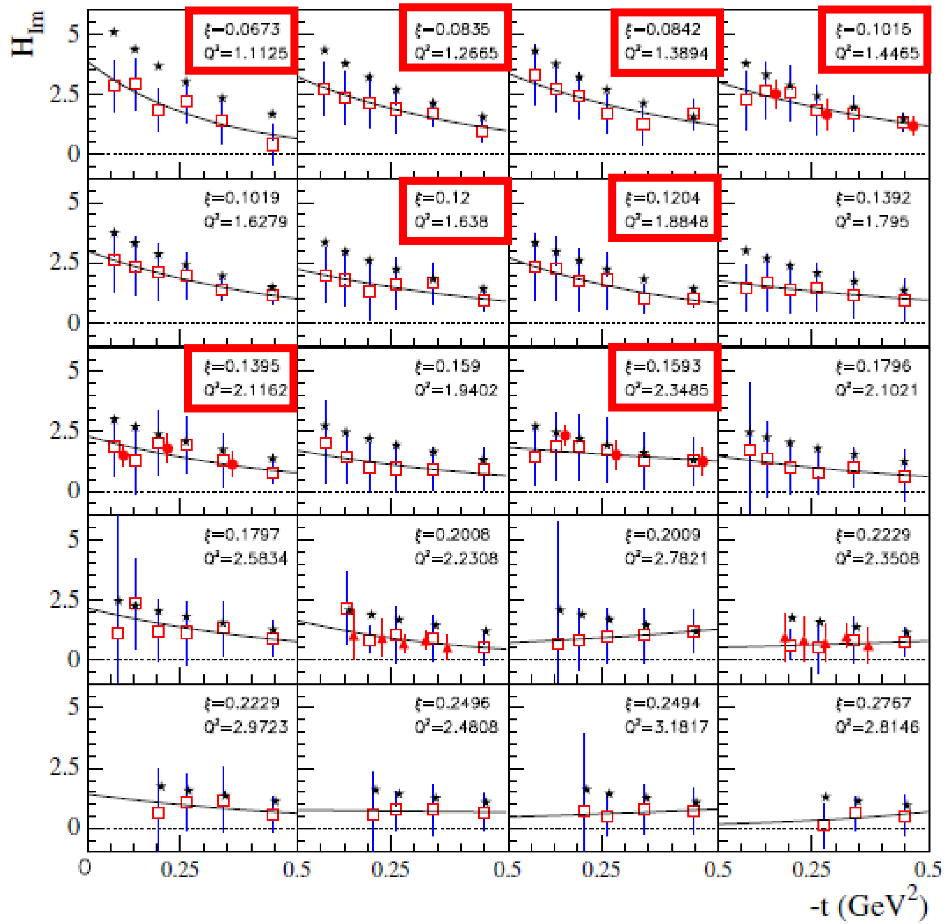
$< b_\perp^2 > \approx 4 B'$



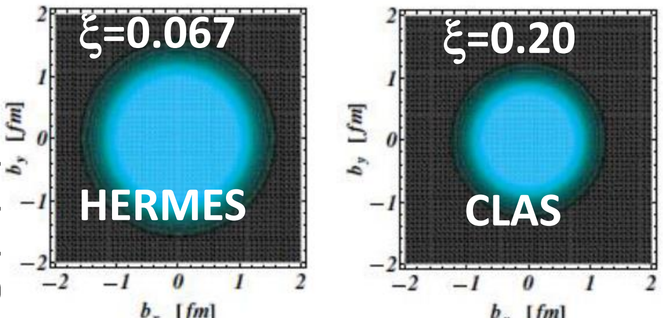
HERMES

+ 8 points from JLab

x=ξ and ξ→0



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

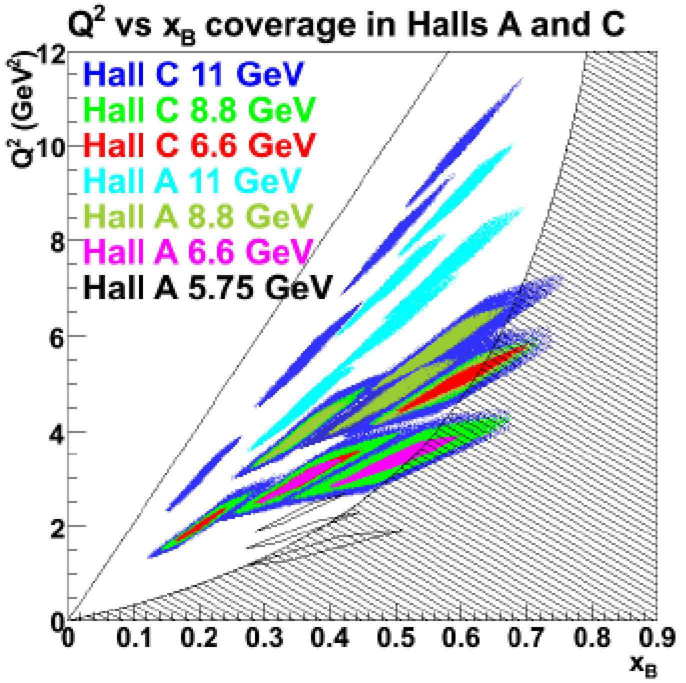


Future Beam Spin Sum and Diff @JLab12

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

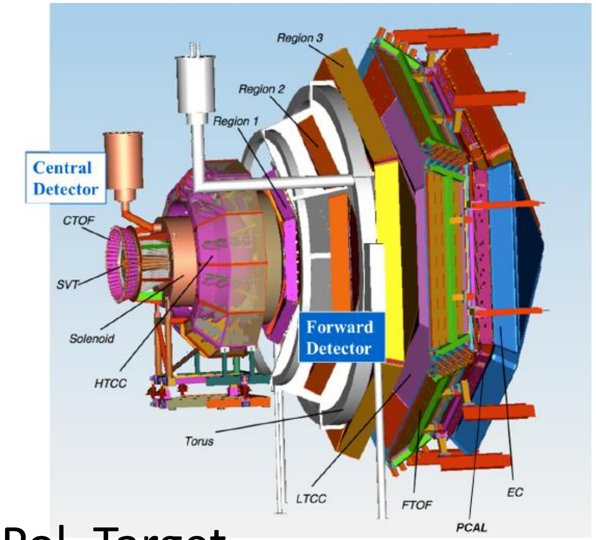
Exp. 2010: run E07-007
2016-17: Hall A: E12-06-119
~2018: Hall C: E12-13-010

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

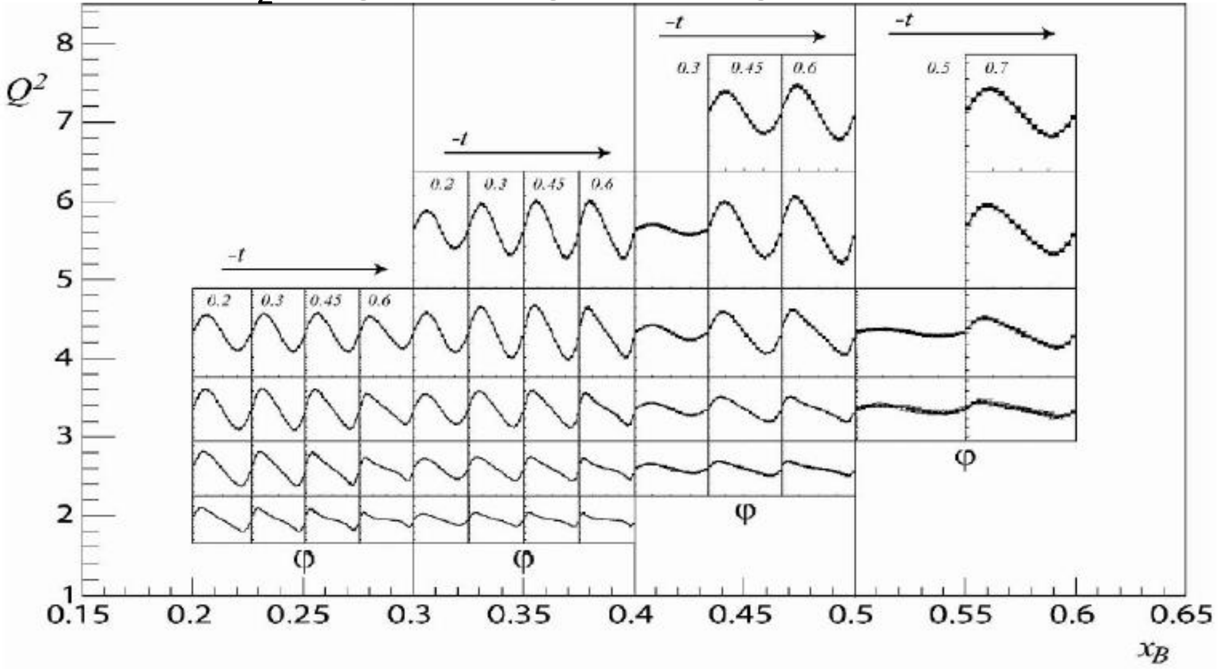


with CLAS12
In 2017

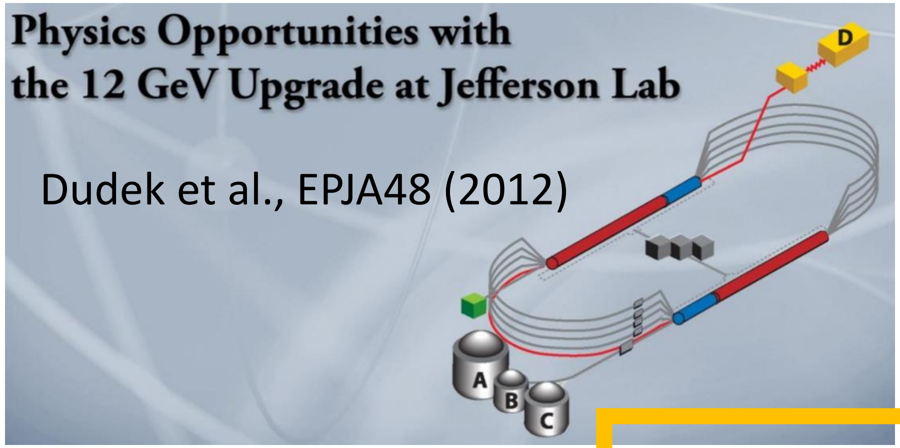
E12-06-119

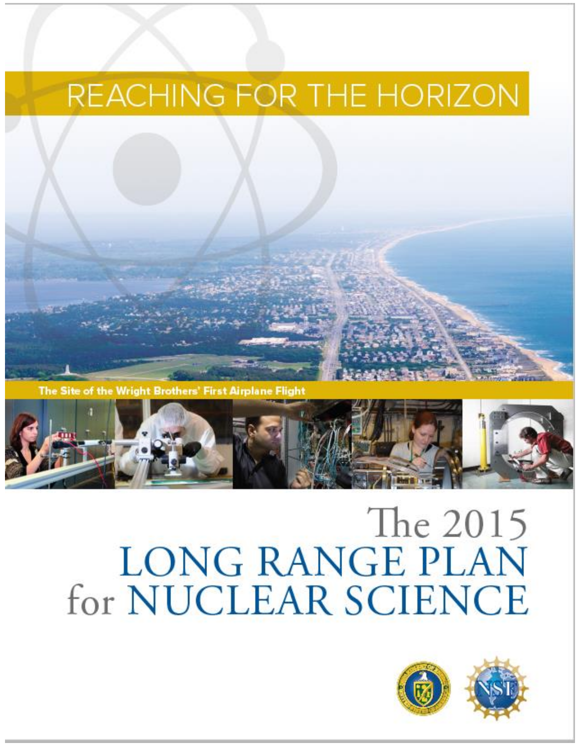


LH_2 Target & Long. Pol. Target



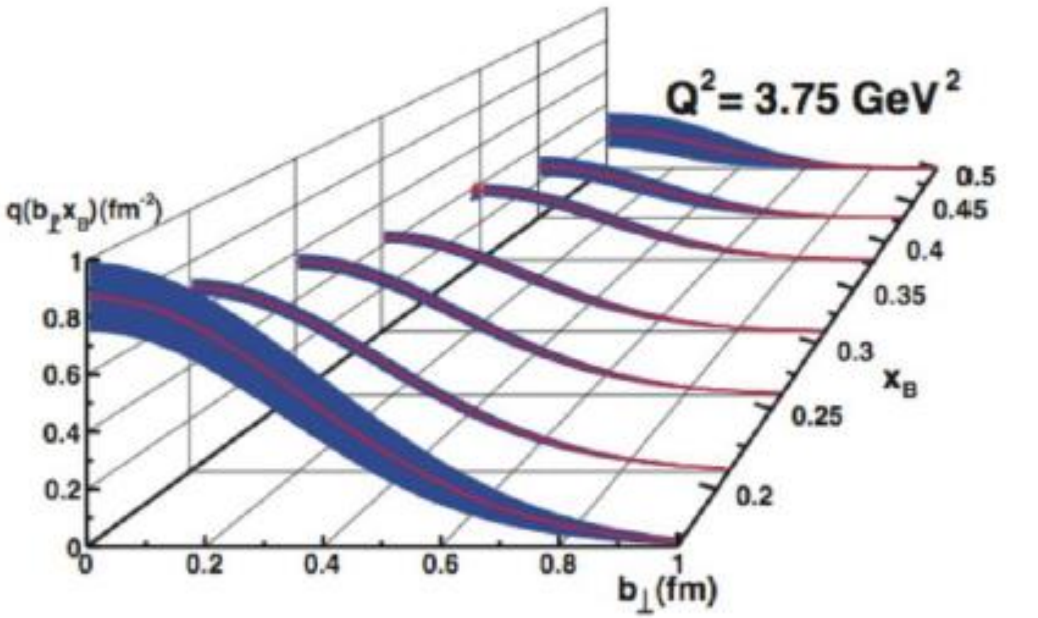
Future Beam Spin Sum and Diff @JLab12





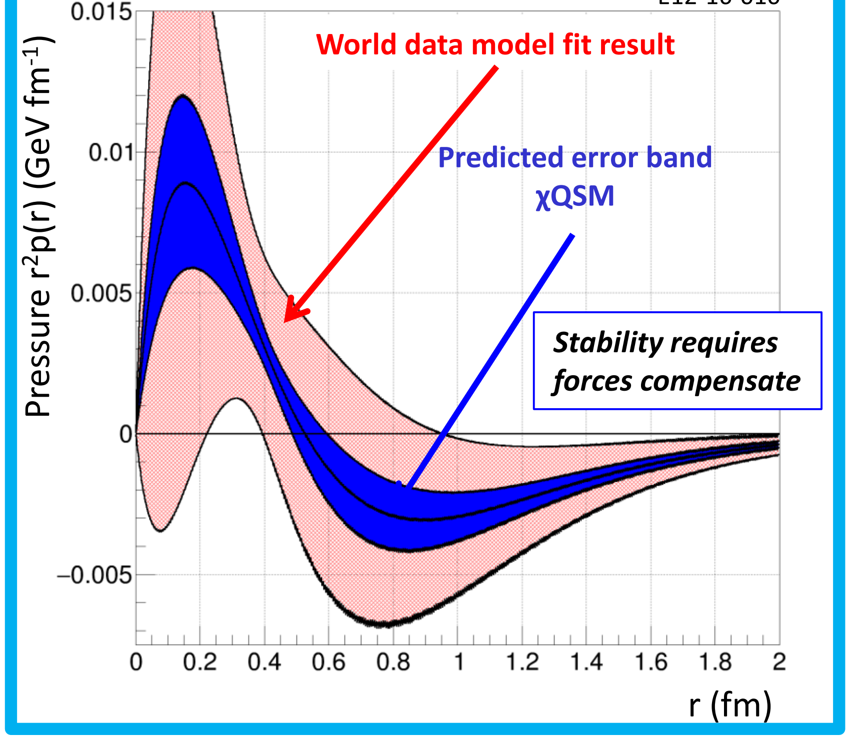
Projection for Jlab 12 GeV

Transverse profile



Pressure Distribution

E12-06-119
E12-16-010

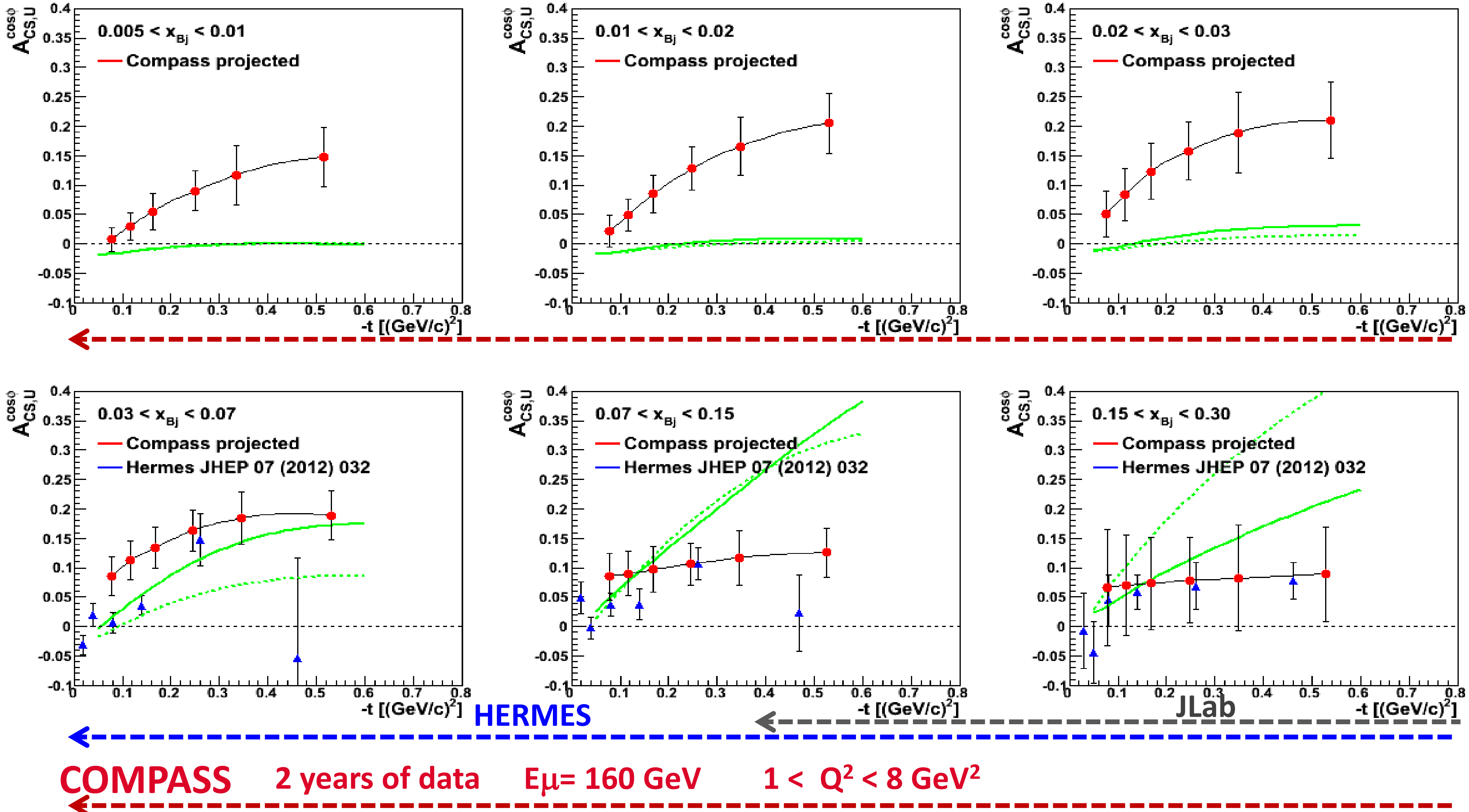


Beam Charge and Spin Diff. @ COMPASS

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

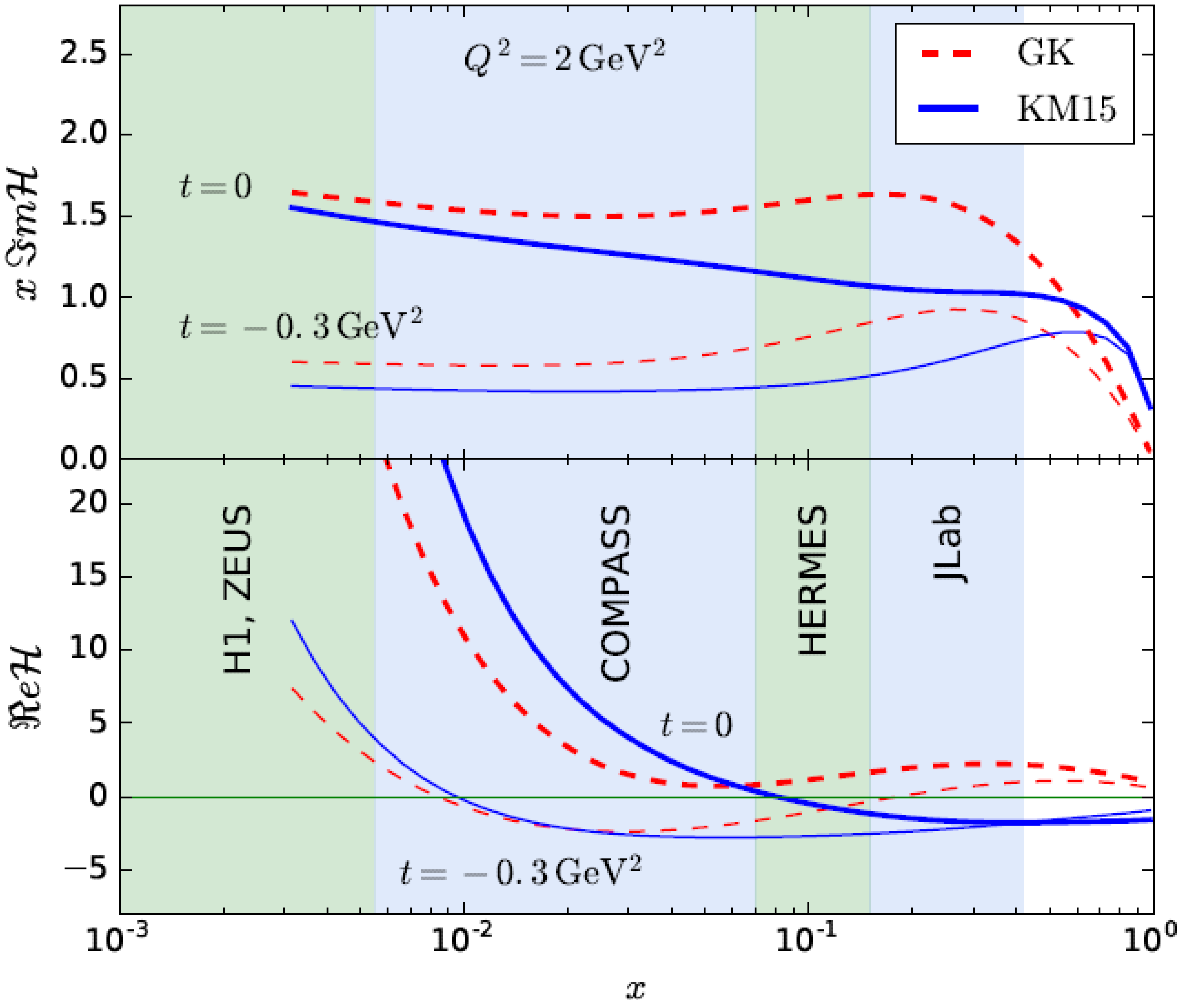
Predictions with
VGG and **D.Mueller KM10**

$Re\,\mathcal{H}$ > 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

Present knowledge of the GPD H in global analysis



Im H
is rather
well known

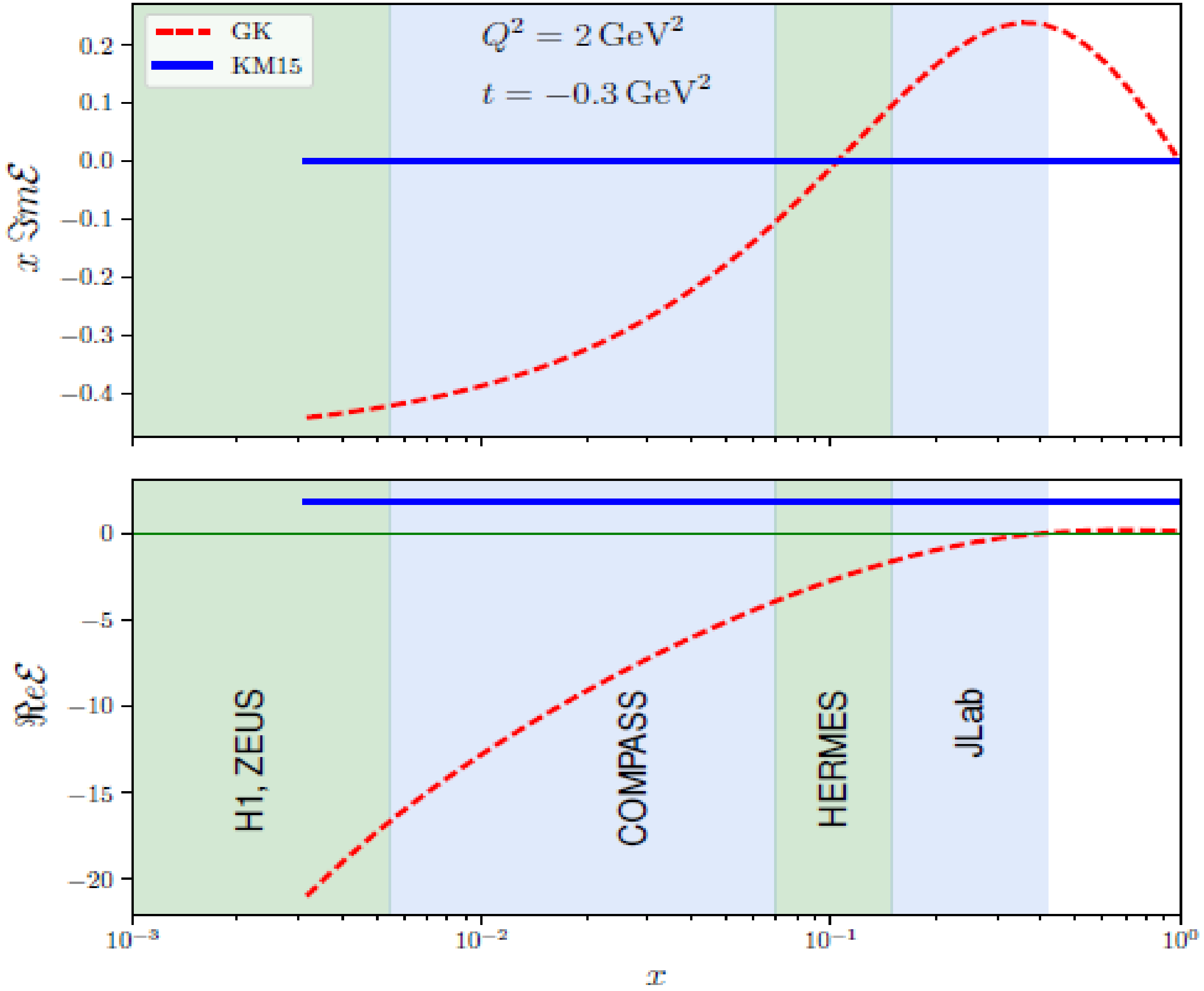
Re H linked
to the ***d term***
is still poorly
constrained

KM15 K Kumericki and D Mueller arXiv:1512.09014v1

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

Present knowledge of the GPD E in global analysis

Figure made by D. Mueller and K. Kumericki



Im E
is rather unknown

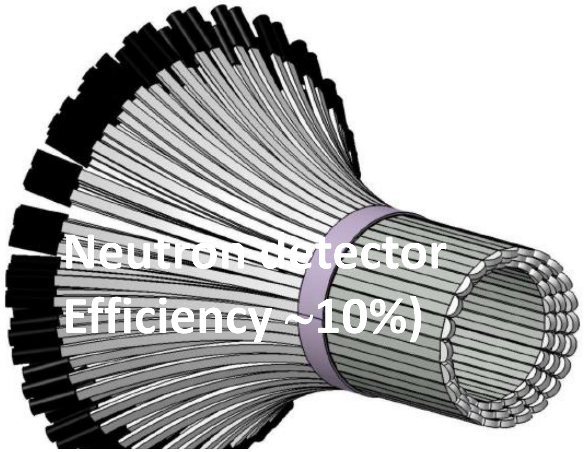
Re E
is rather unknown

KM15 K Kumericki and D Mueller arXiv:1512.09014v1
GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

GPD E at Jlab 11 GeV with CLAS12

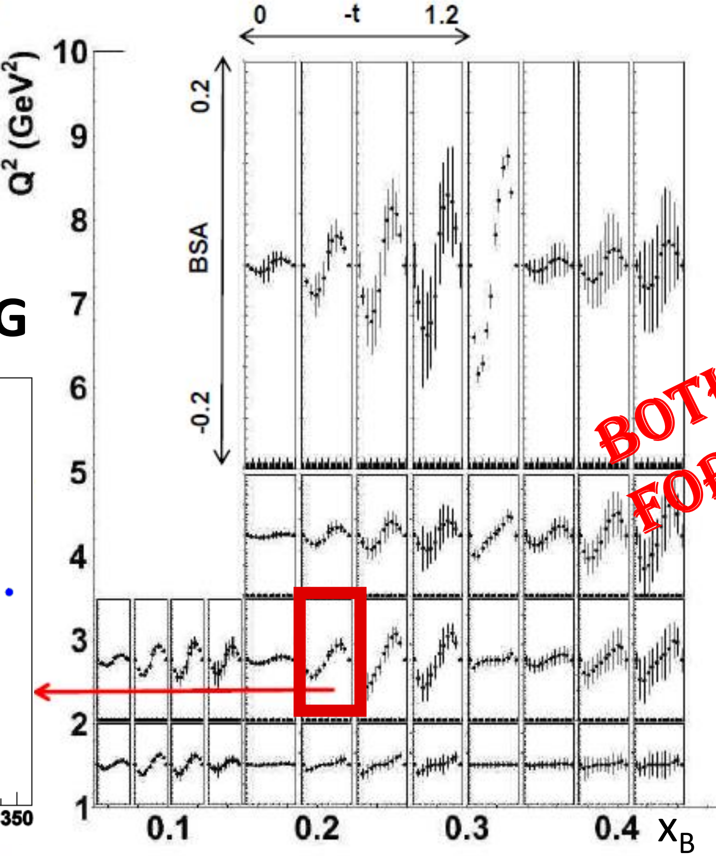
Exp E12-11-003: DVCS on the neutron

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

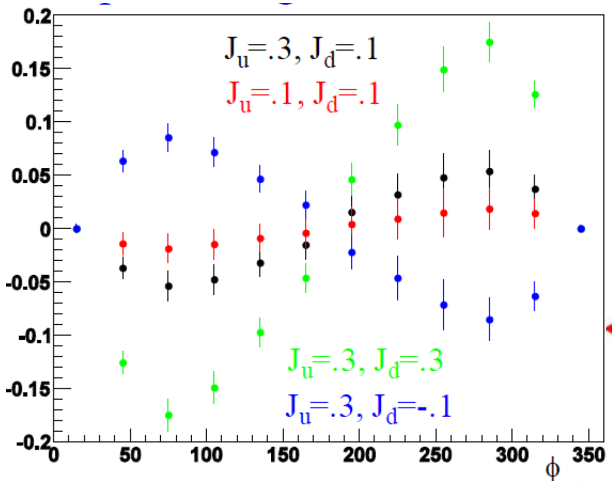


90 days on LD2 target

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



Model prediction using VGG



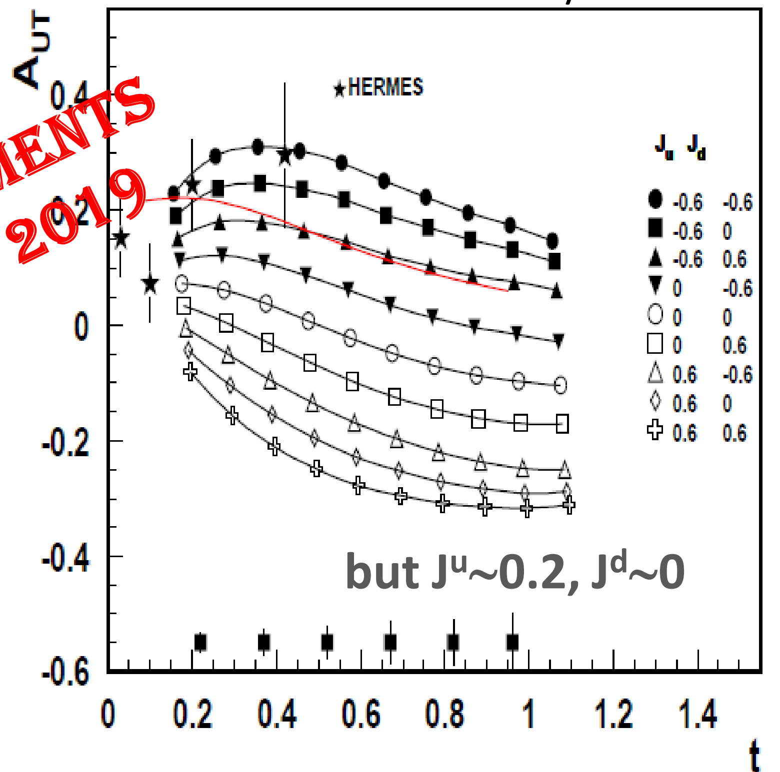
Exp E12-12-010: DVCS on a transversely polarized HD-Ice target Pol H = 60% Pol D = 35%

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

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

110 days on HD-Ice target

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



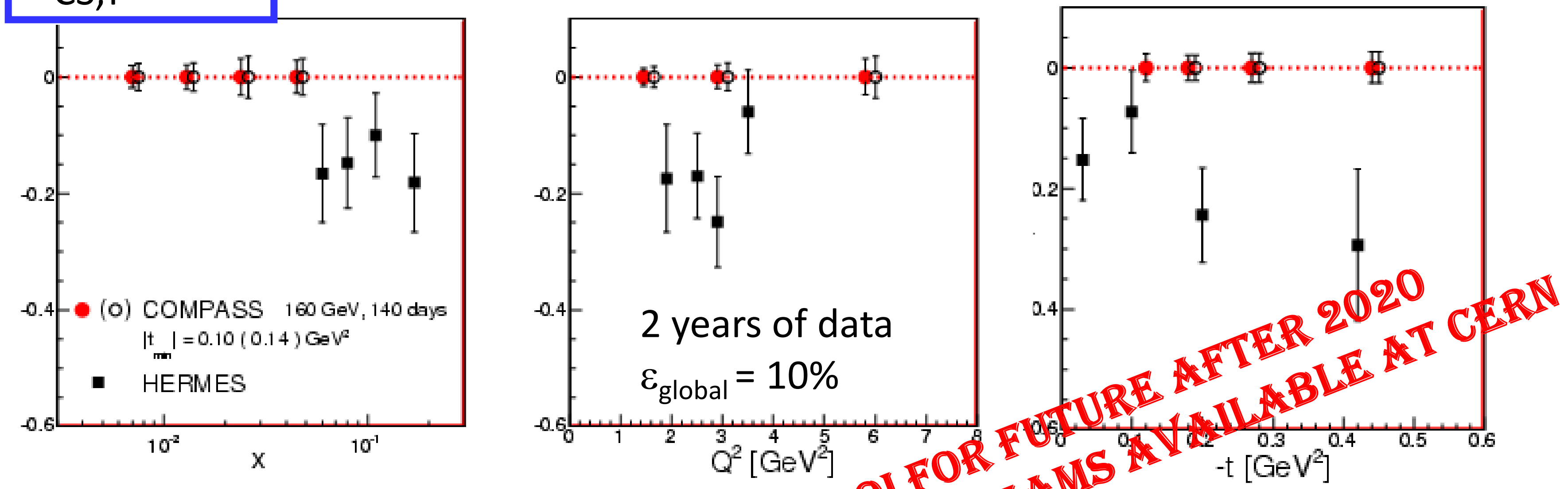
BOTH EXPERIMENTS FORESEEN IN 2019

GPD E at COMPASS 160 GeV with μ+ and μ -

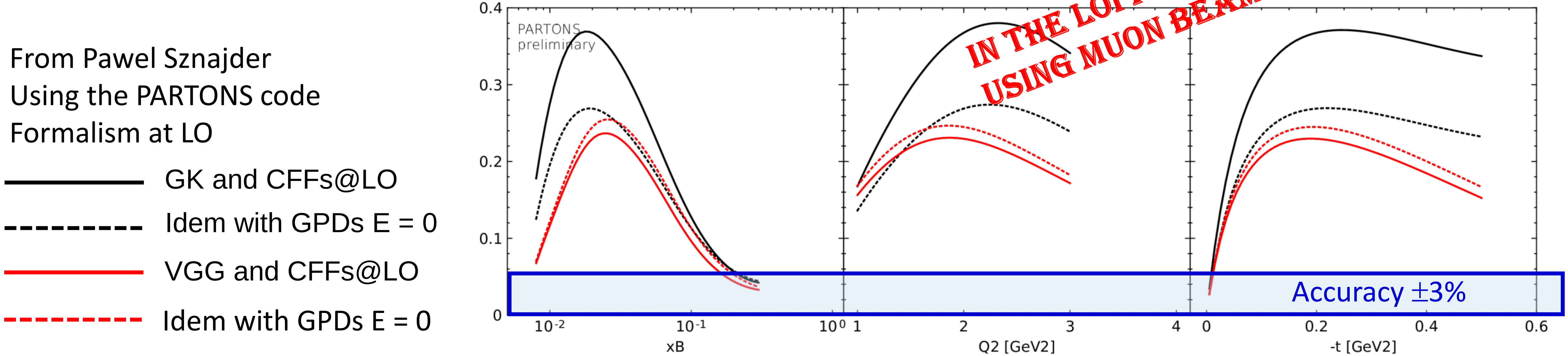
$\mathcal{D}_{CS,T} \equiv \sigma_T(\mu^{+\downarrow}) - \sigma_T(\mu^{-\uparrow})$

$\propto Im(F_2\mathcal{H} - F_1\mathcal{E}) \sin(\phi-\phi_s)\cos\phi$

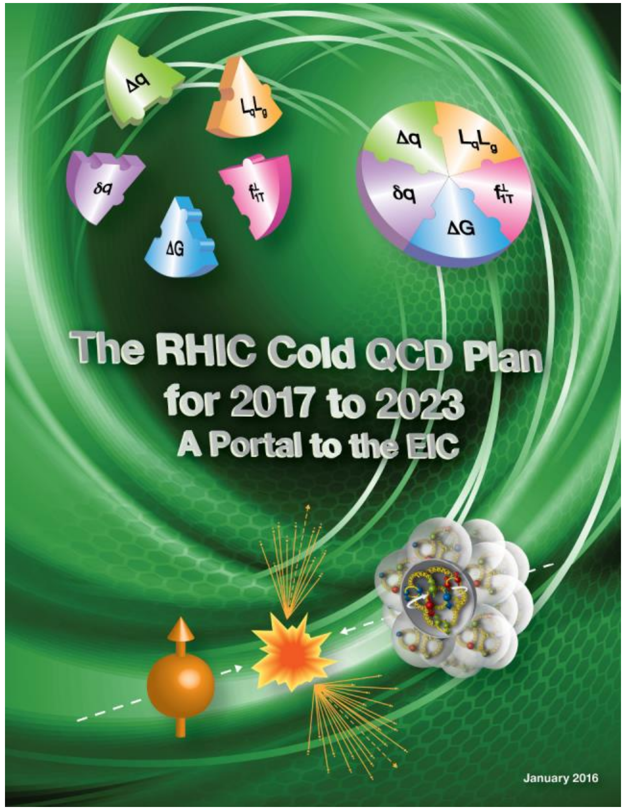
$A_{CS,T}^{\sin(\phi-\phi_s)\cos\phi}$ DVCS on a 1.2m long transversely polarized NH_3 target



From Pawel Sznajder
Using the PARTONS code
Formalism at LO



GPD E_{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_{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/ψ in ultra-peripheral $p^{\uparrow}$+p collisions (UPC) [99]. The measurement is at a fixed Q^2 of 9 GeV^2 and $10^{-4} < x < 10^{-1}$. A nonzero asymmetry would be the first signature of a nonzero 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/ψ in 2017 ($p^{\uparrow}$ p @ 510 GeV) and 13k in 2023 ($p^{\uparrow}$ Au @ 200 GeV)

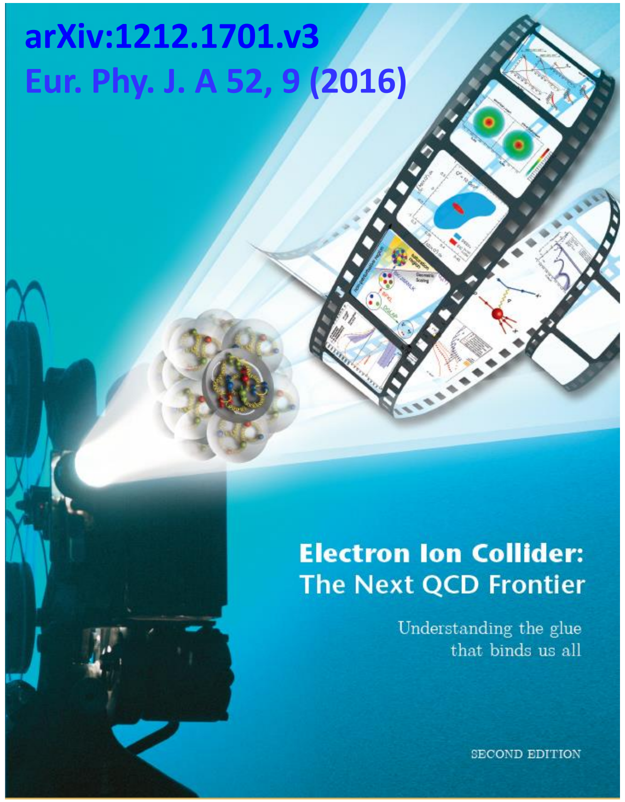
Important input for the photoproduction of J/ψ at EIC

Key measurements for imaging partons with EIC

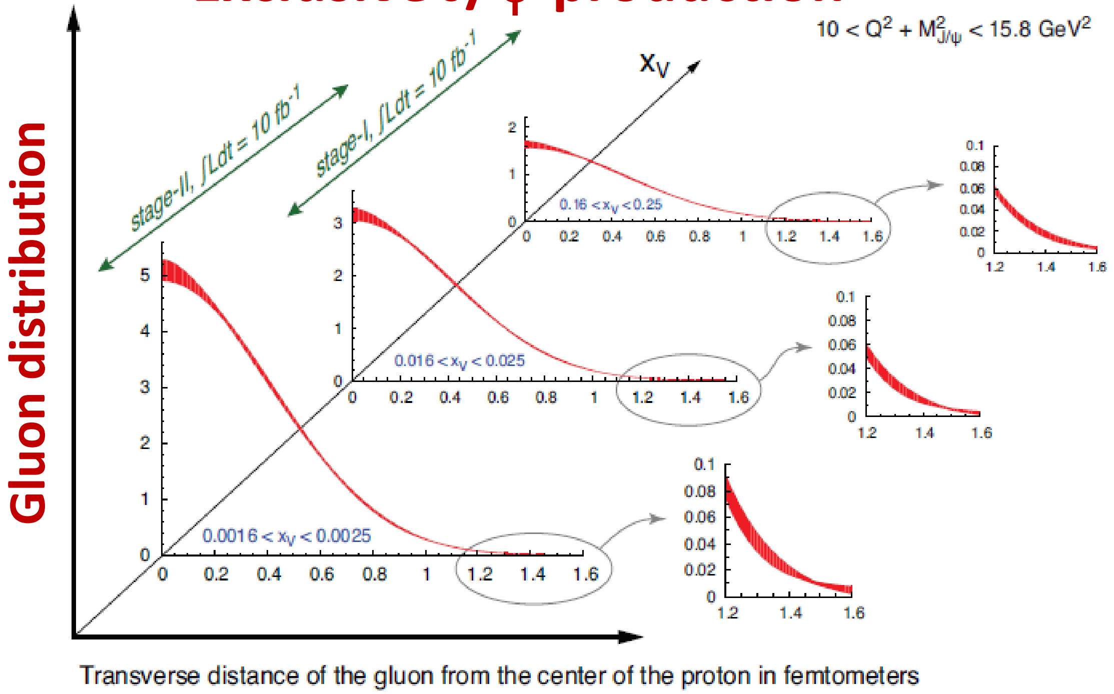
Stage 2
Ee=20 GeVEp=250 GeV

Stage 1
Ee=5 GeVEp=100 GeV

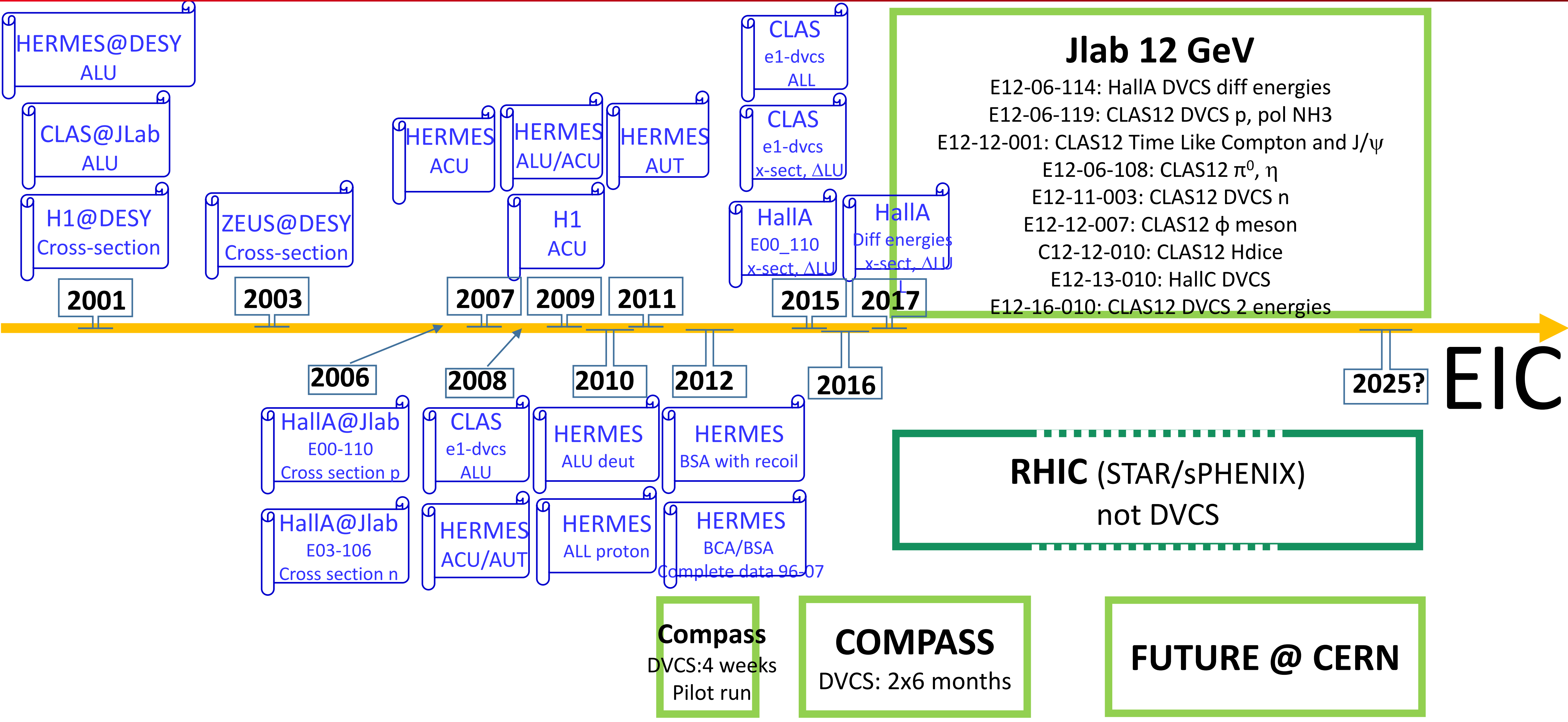
Deliverables	Observables	What we learn	Requirements
GPDs of sea quarks and gluons	DVCS and $J/\Psi, \rho^0, \phi$ production cross section and polarization asymmetries	transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations	$\int dt\, L \sim 10$ to $100\,\mathrm{fb}^{-1}$; 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 π^+, K and ρ^+, K^*	dependence on quark flavor and polarization	



Exclusive J/ψ production



DVCS publications and data taking over the years



Conclusions

Jlab 12 GeV will perfectly investigate the valence quarks at large x_B

COMPASS with high energy muon beams at CERN and RHIC 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
- to prepare the next generation of leading new experiments at EIC

Jlab 12 GeV

E12-06-114: HallA DVCS diff energies
E12-06-119: CLAS12 DVCS p, pol NH3
E12-12-001: CLAS12 Time Like Compton and J/ψ
E12-06-108: CLAS12 π^0, η
E12-11-003: CLAS12 DVCS n
E12-12-007: CLAS12 ϕ meson
C12-12-010: CLAS12 HDice
E12-13-010: HallC DVCS
E12-16-010: CLAS12 DVCS 2 energies

2016 | 2017 | 2025? | EIC

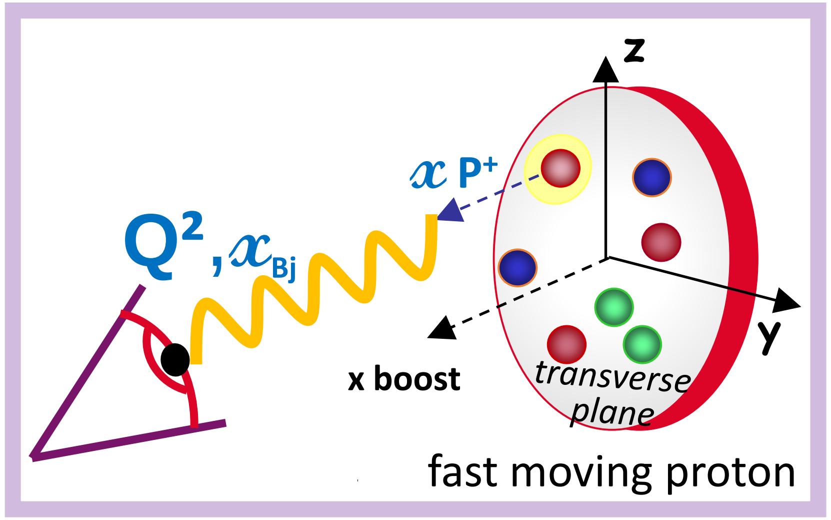
RHIC (STAR/sPHENIX)

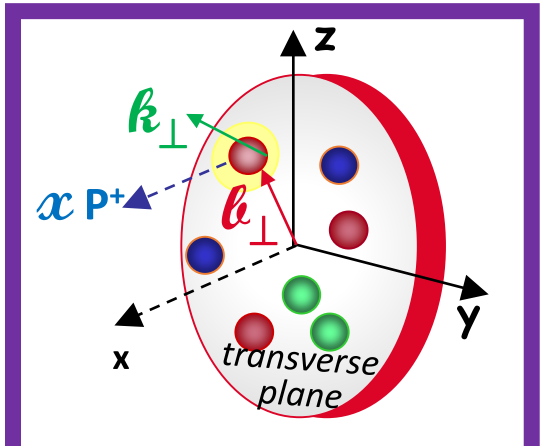
COMPASS
DVCS: 2x6 months

FUTURE @ CERN
M2 beam line

Proton picture: 1D → 1+2D

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

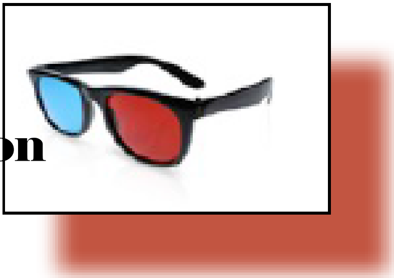




$\mathcal{W}(x, k_\perp, b_\perp)$

$\int db_\perp$ $\int dk_\perp$

Quantum tomography of the nucleon



The Wigner functions offer unprecedented insight into confinement and *chiral symmetry breaking*

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

Impact param. q(x, $b_\perp$)

8 GPDs (x, ξ, t)

accessible
in **exclusive reactions**

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

$\int dx$ → Form Factors

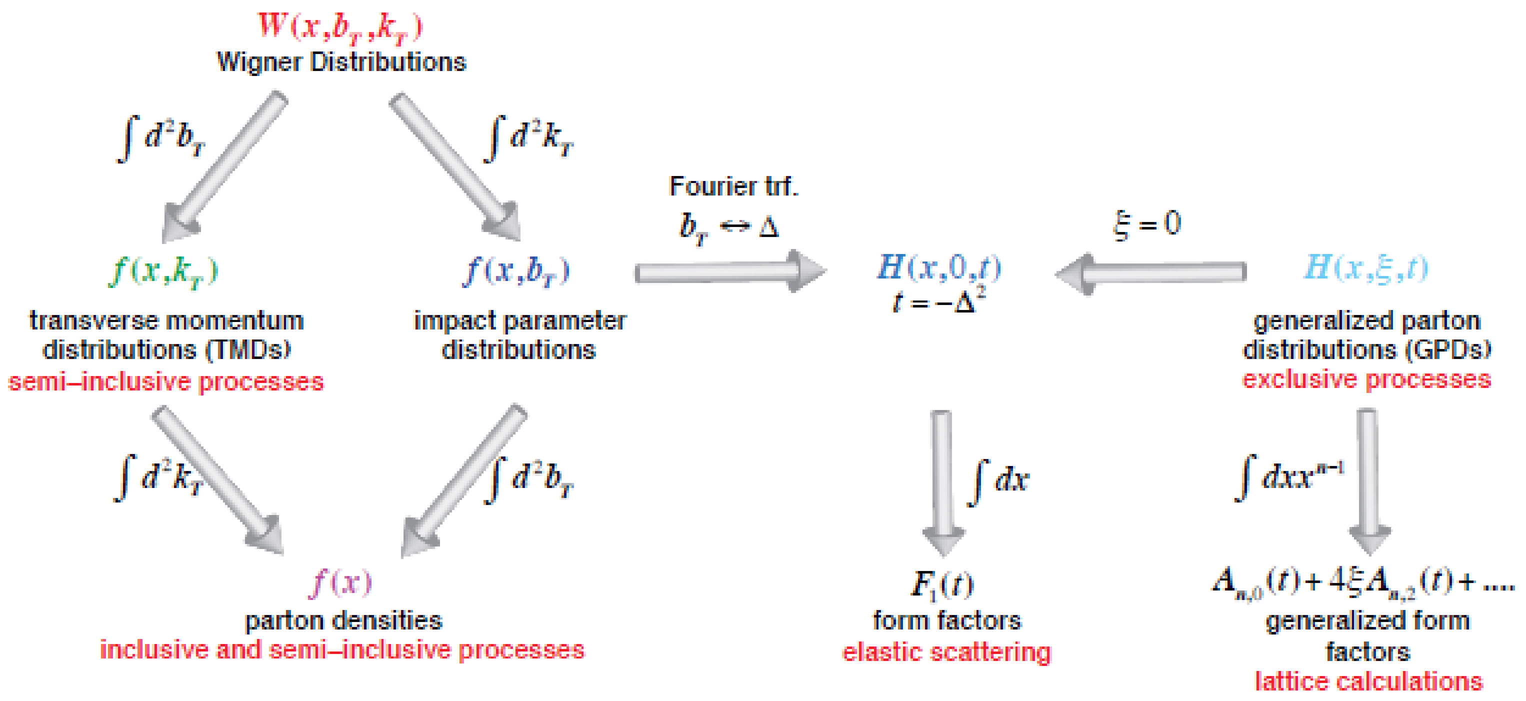
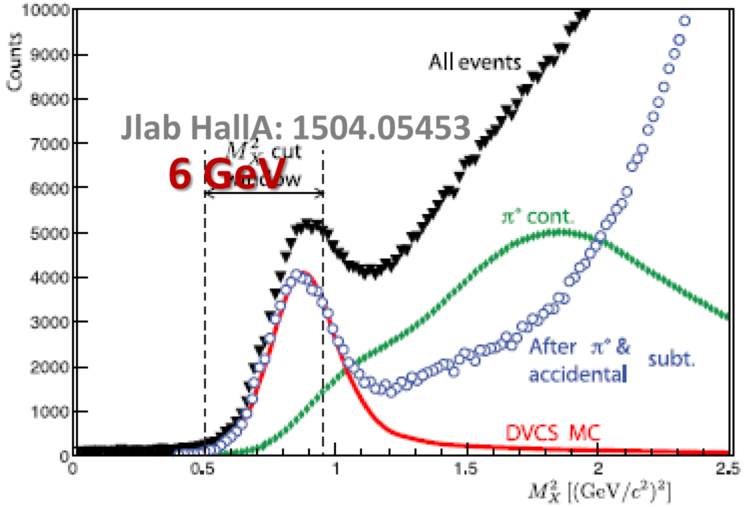
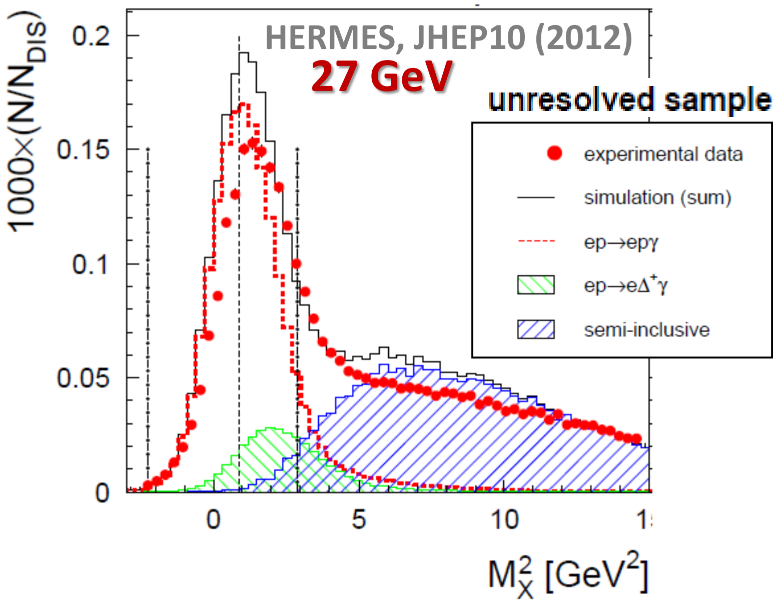


Figure 2.2: Connections between different quantities describing the distribution of partons inside the proton. The functions given here are for unpolarized partons in an unpolarized proton; analogous relations hold for polarized quantities.

Exclusivity : $\ell\, p \rightarrow \ell + \gamma$ (or ρ^0) + p

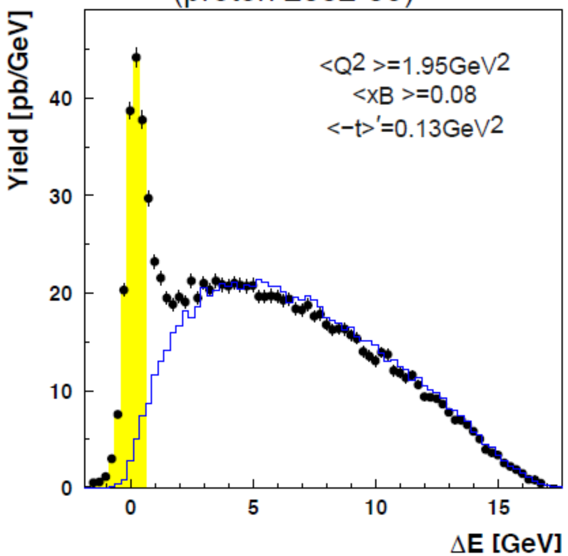




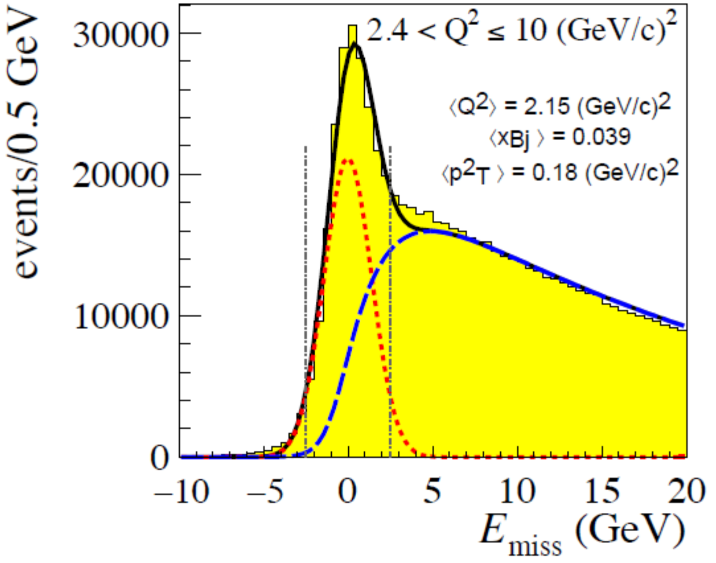
$$M_x^2 = (P_\ell + P_p - P_\ell - P_\gamma)^2$$

ΔM_x^2 increases with the beam energy !

HERMES exclusive ρ^0
(proton 2002-05)



COMPASS exclusive ρ^0
(proton 2007/10)



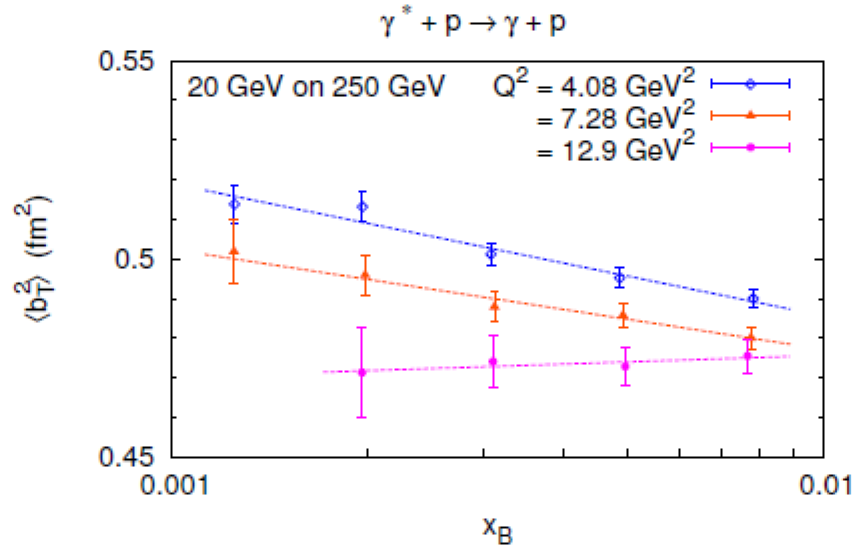


Figure 2.22: Average values of b_T^2 obtained from the DVCS cross section in different bins of x_B and Q^2. The assumed luminosity is as for the left panels of figure 2.21.