Q2C quarks cosmos

APRIL MEETING 2019

April 13-16, 2019 Denver, Colorado

The World Wide Experimental Programs to Decode Generalized Parton Distributions (GPDs)

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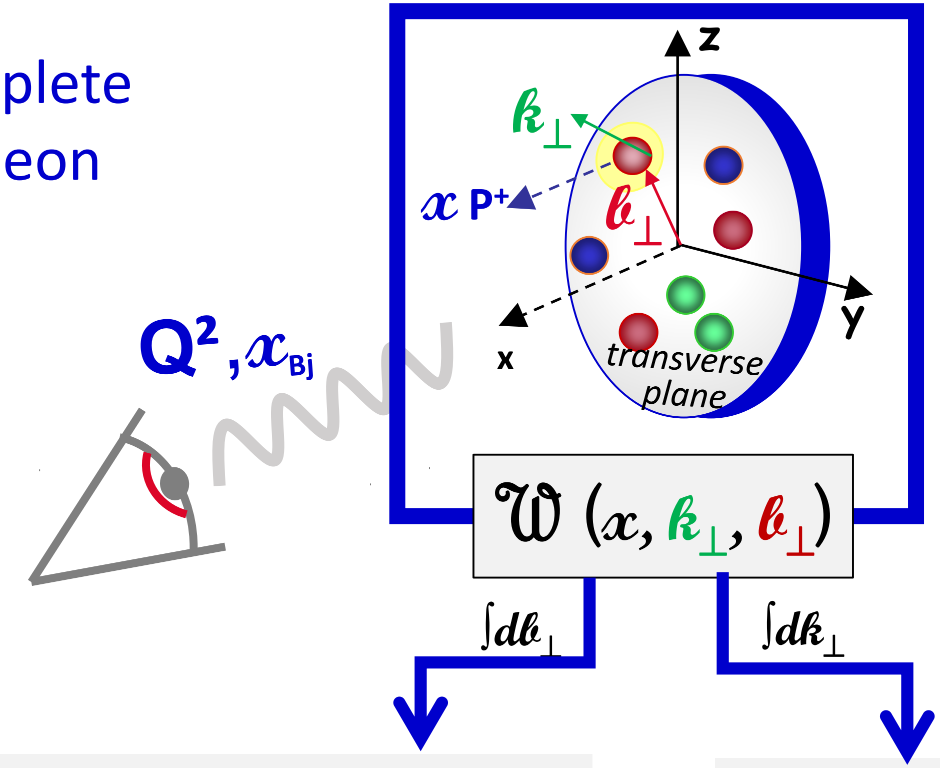
The proton is a fascinating objet

The nucleons (proton and neutron) are the most important building block of our universe.
They are complex system of strongly interacting quarks and gluons.
They make up nearly 90% of the (normal) matter in the universe.
Elementary quarks contribute only few percent to the proton’s mass.
Test the fundamental theory: Quantum ChromoDynamics (QCD)

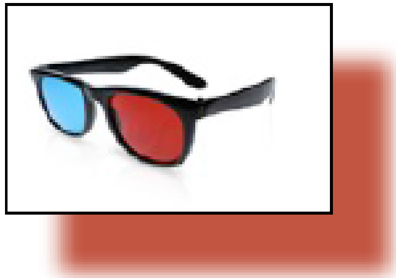
What is the origin of its mass?
What is the origin of confinement ?
Where does the spin of the nucleon come from?
How are the forces distributed in space to make the proton a stable particle?

Proton picture: from 1D to (1+ 2)D

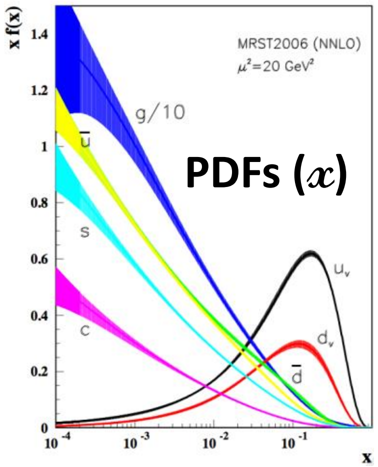
going to the most complete description of the nucleon



Quantum tomography of the nucleon



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



Transverse momentum

f $(x, k_\perp)$
8 TMDs

accessible in SIDIS *and* Drell-Yan

$\int dk_\perp$

Transverse position

q $(x, b_\perp)$
8 GPDs

$\int dx$ → Form Factors

$\int db_\perp$

PDFs (x)

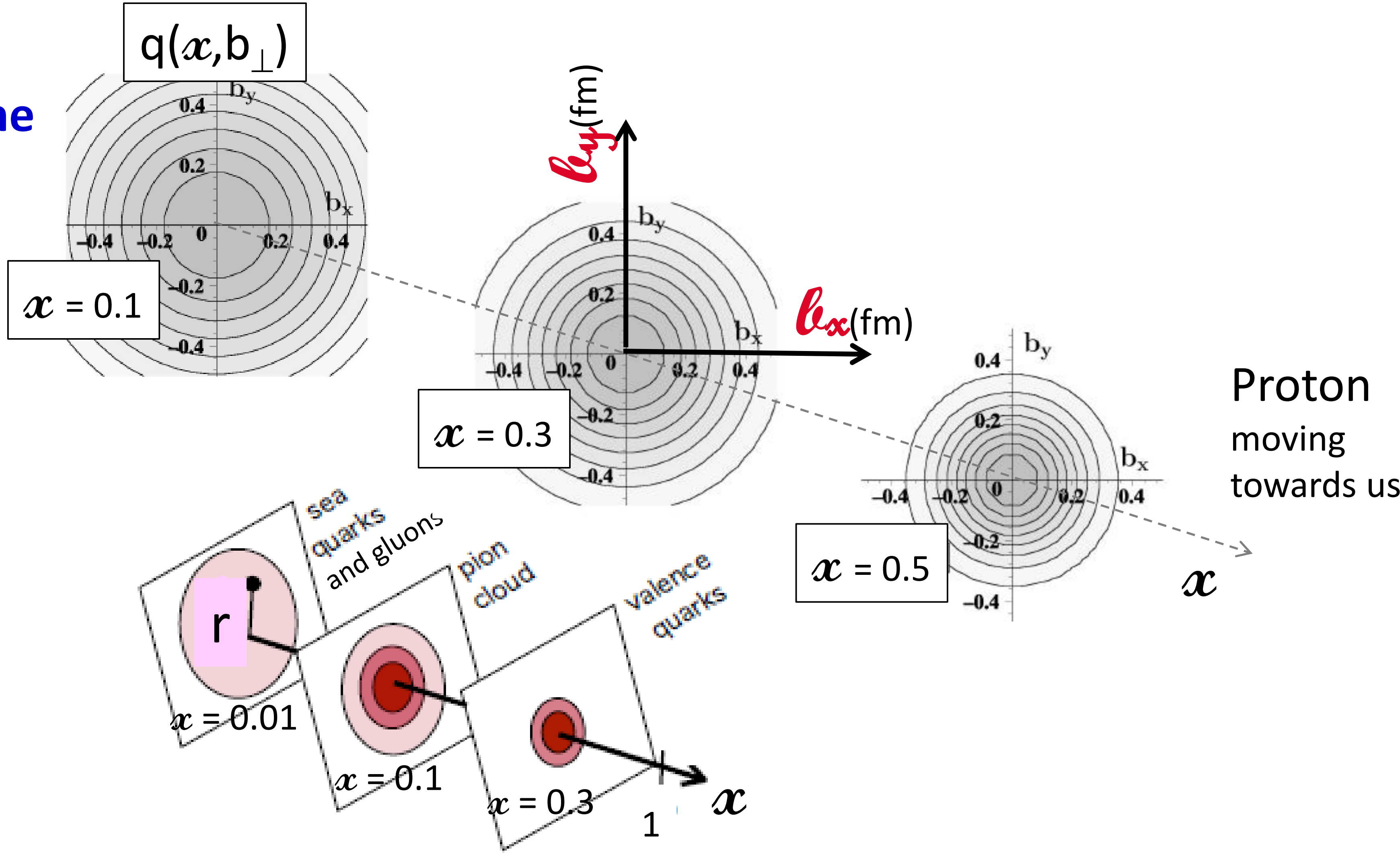
accessible in **exclusive reactions**

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

GPDs and 3D imaging

M. Burkardt, PRD66(2002)

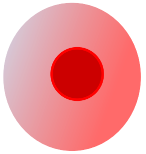
mapping in the transverse plane
Impact parameter distribution



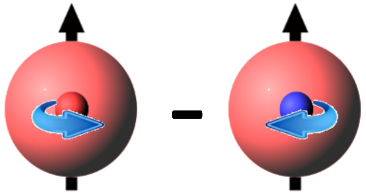
Correlation between the spatial distribution of partons
and the longitudinal momentum fraction

GPDs and Energy-Momentum Tensor and Confinement

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

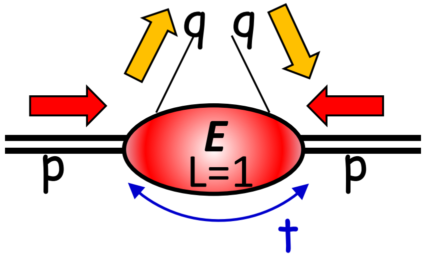


"Elusive"
$\mathbf{E}^q(x, \xi, t) \longleftrightarrow f_{1T}(x, k_T)$

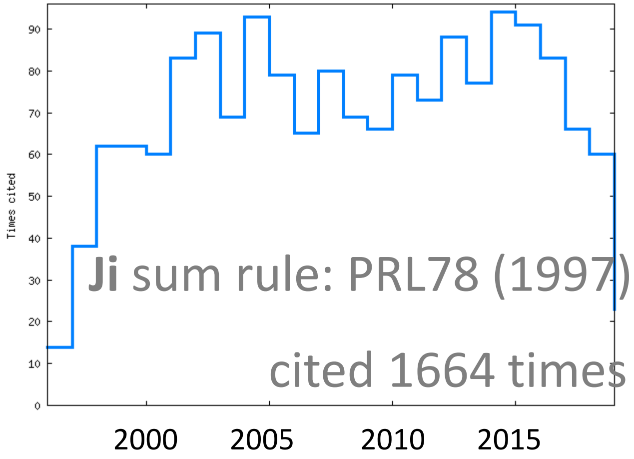


Sivers: quark k_T & nucleon transv. spin

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



Relation to OAM



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)

mass & energy distribution

$$\int_{-1}^{1} dx\, x\, H^a(x,\xi,t) = A^a(t) + \xi^2 d_1^a(t)$$

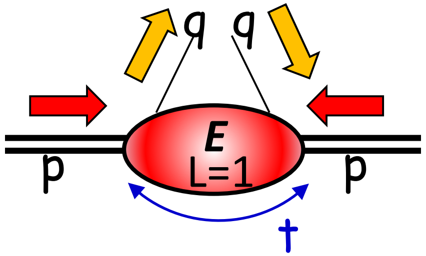
$$\int_{-1}^{1} dx\, x\, E^a(x,\xi,t) = 2J^a(t) - A^a(t) - \xi^2 d_1^a(t)$$

Angular momentum distribution

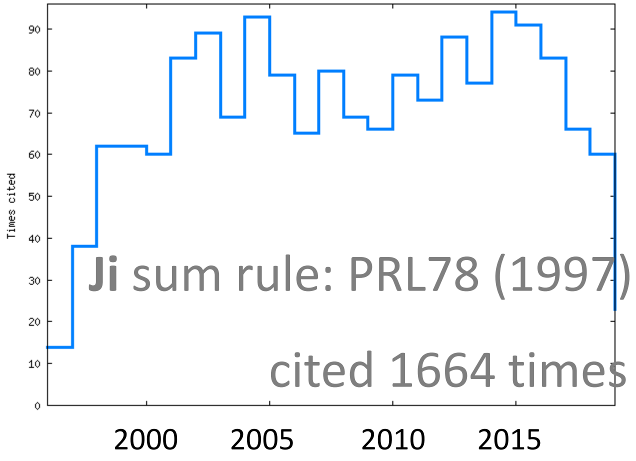
Force & Pressure distribution

M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

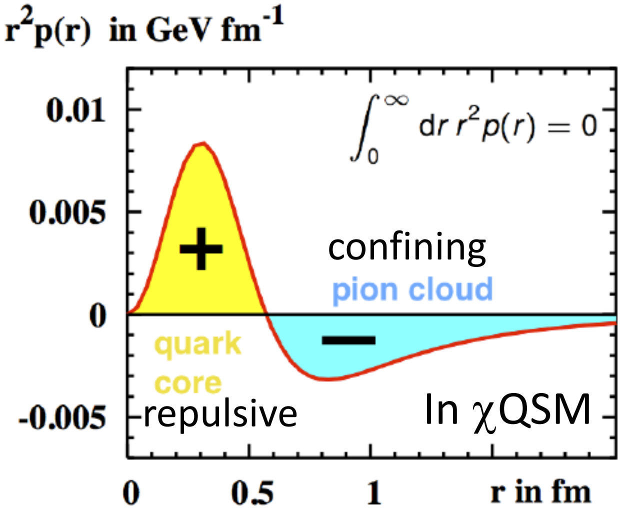
$$2J^q = \lim_{t\to 0} \int x\,(H^q(x,\xi,t) + E^q(x,\xi,t))\,dx$$



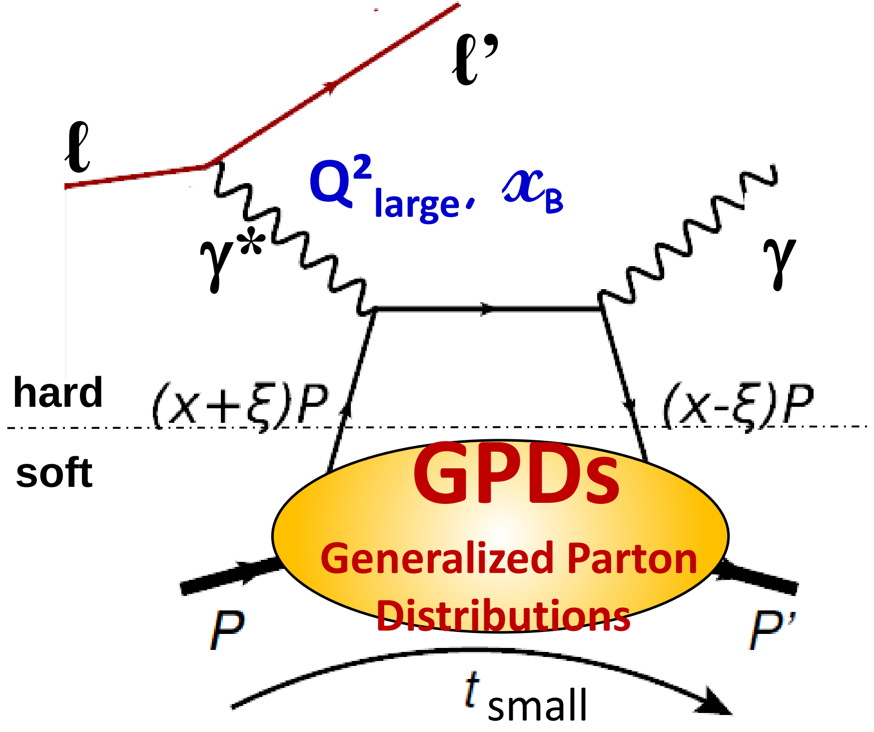
Relation to OAM



Pressure Distribution



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 it interferes with
the Bethe-Heitler process

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

The GPDs depend on the following variables:

x: average long. momentum

ξ: long. mom. difference

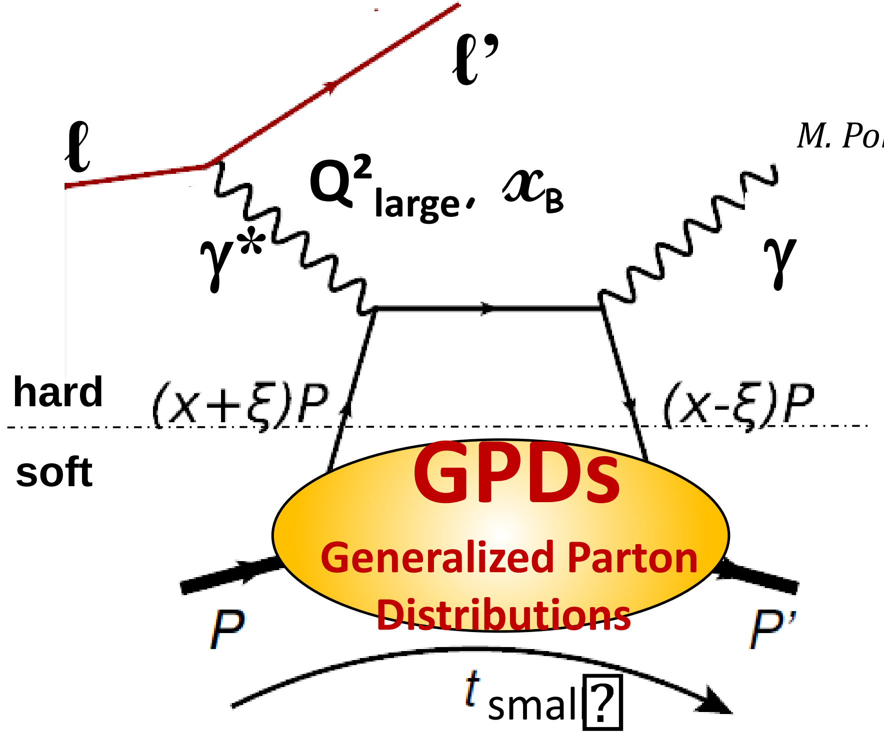
t: four-momentum transfer
related to $b_\perp$ via Fourier transform

The variables measured in the experiment:

E_ℓ, Q^2, $x_B \sim 2\xi/(1+\xi)$,

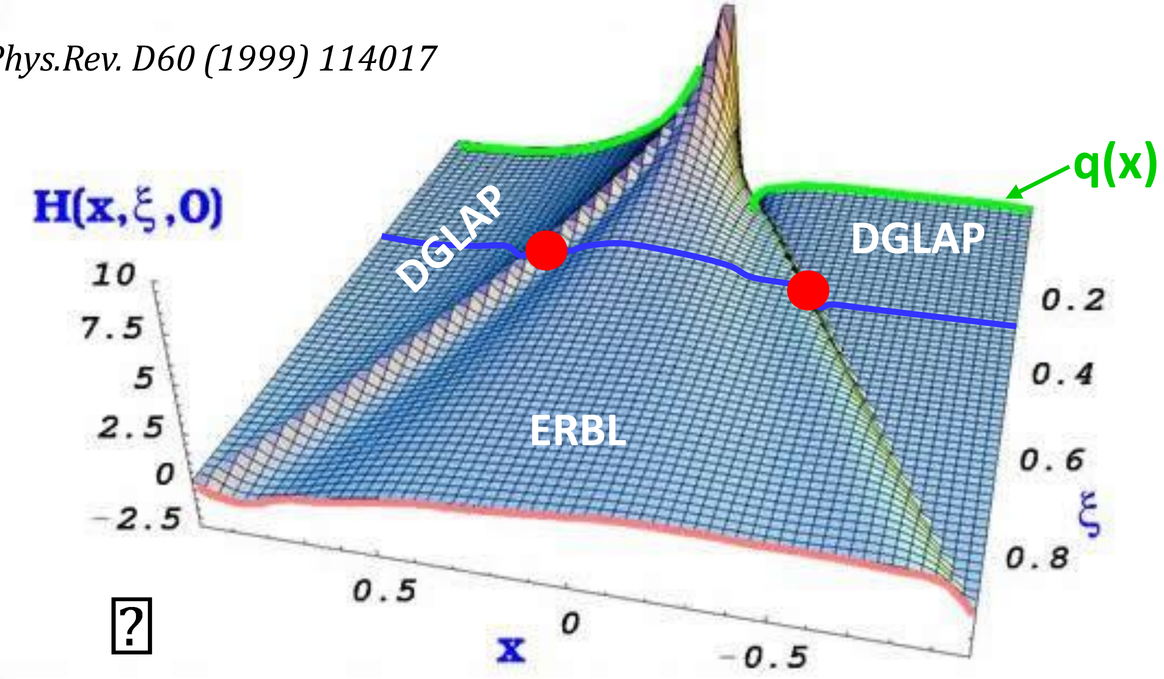
t (or $\theta_{\gamma^*\gamma}$) and ϕ (ℓℓ' plane/γγ* plane)

Deeply virtual Compton scattering (DVCS)



From Goeke, Polyakov, Vanderhaeghen, PNPP47 (2001)

M. Polyakov , C. Weiss, Phys.Rev. D60 (1999) 114017



The amplitude DVCS at LT & O in α_S (GPD **H**) :

Real part Imaginary part

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

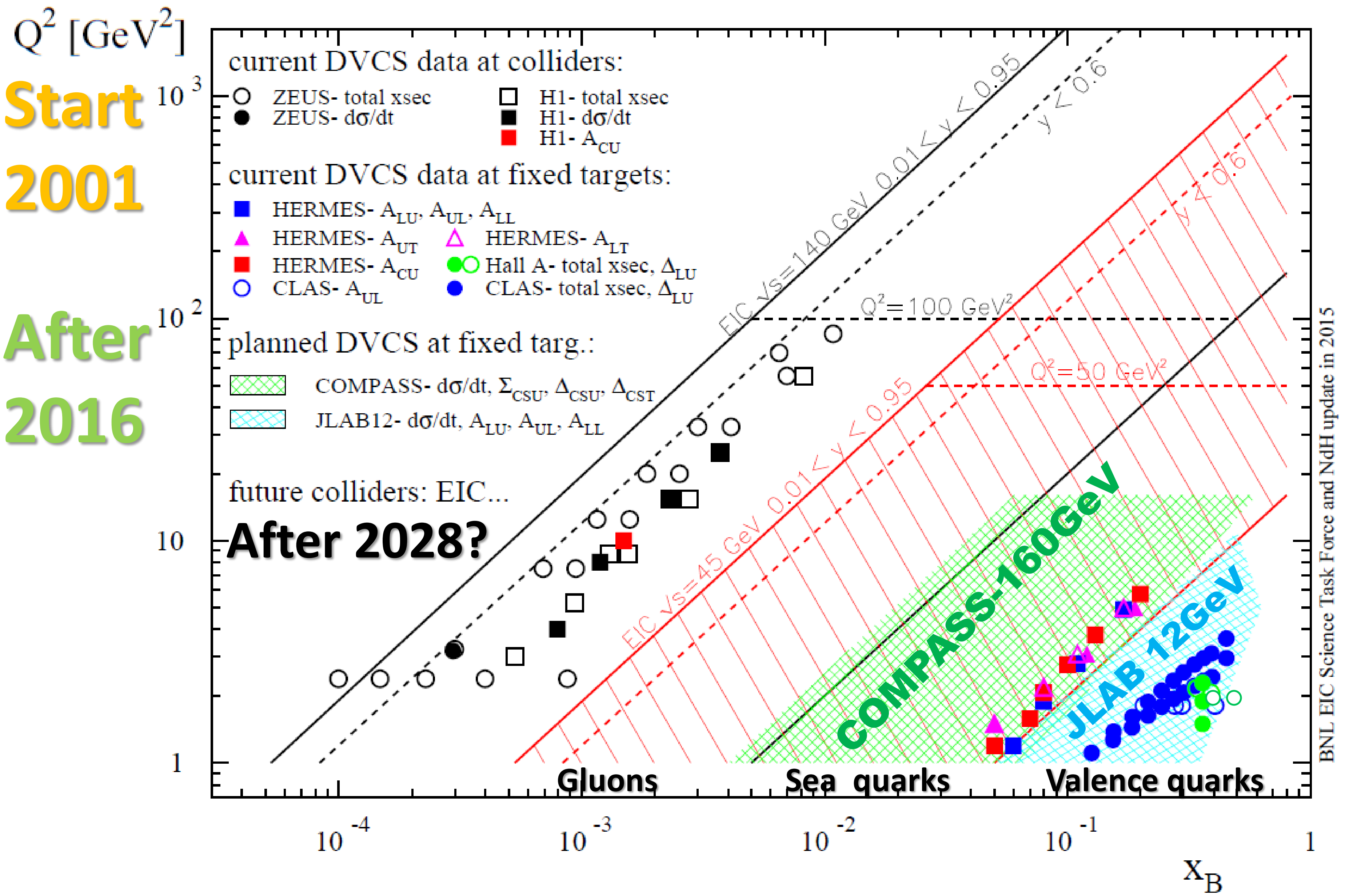
t, ξ fixed

In an experiment we measure

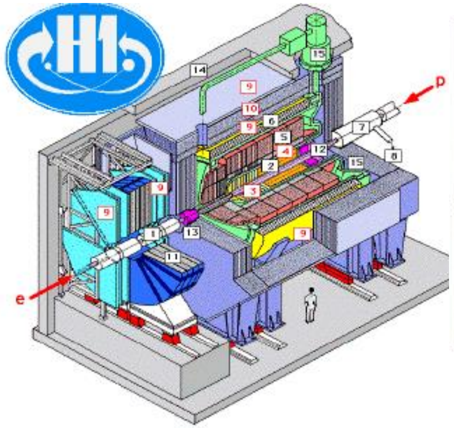
Compton Form Factor $\mathcal{H}$

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

The past and future DVCS experiments



The past and present experiments



Collider mode e-p forward fast proton

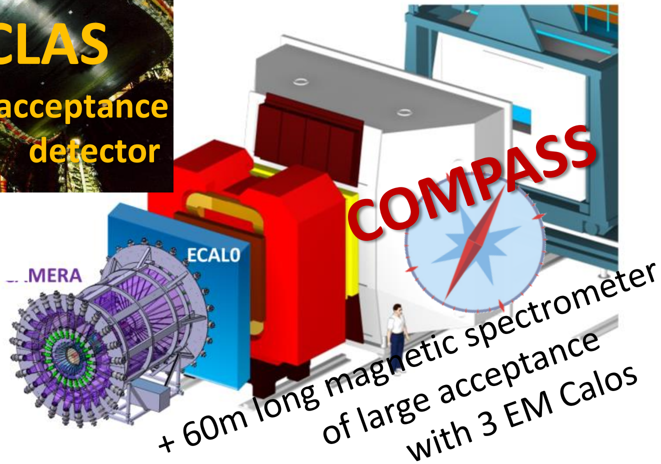
HERA: **H1** and **ZEUS**
Polarised **27 GeV** e-/e+
Unpolarized **920 GeV** proton
~ *Full event reconstruction*

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 Luminosity Polar. **6** & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique (A,C) and complete detection (CLAS)

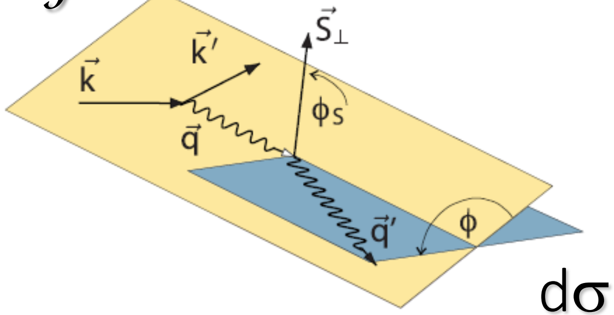
COMPASS @ CERN: Polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
with recoil detection

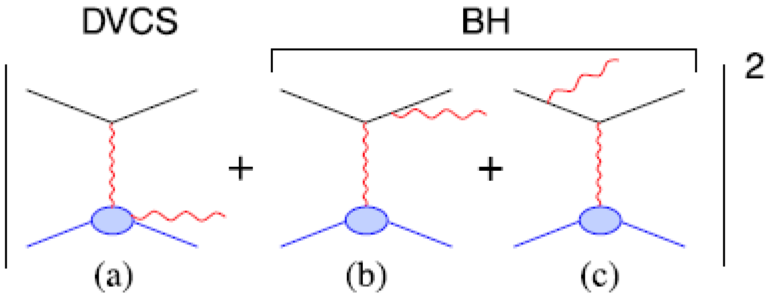


Rejection of background: SIDIS, exclusive π^0/DVCS, dissociation of the proton

Deeply Virtual Compton Scattering

lepton (P_ℓ , e_ℓ) and ϕ



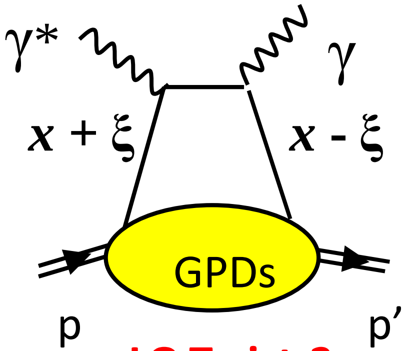


$d\sigma =$ $|T^{BH}|^2$ + $|T^{DVCS}|^2$ + Interference Term

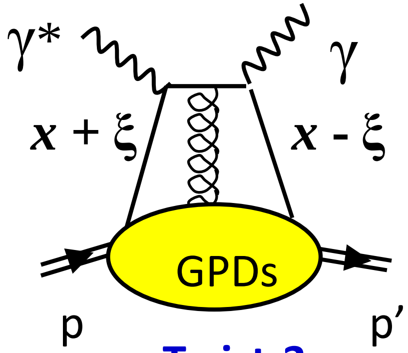
$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell \,\mathrm{Im}\, I\right)$$

Well known

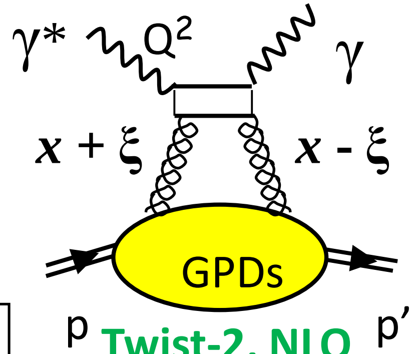
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$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



LO,Twist-2



Twist-3



Twist-2, NLO
double helicity flip

Changing P_ℓ ➔ $s_1^I = \mathrm{Im}\, \mathcal{F}$

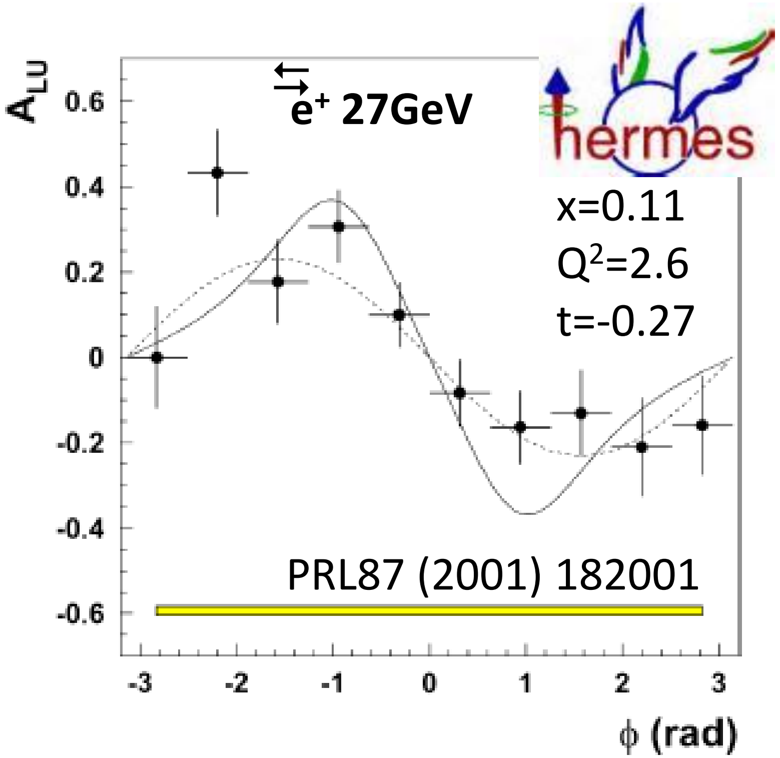
Changing $e_\ell P_\ell$ ➔ $c_1^I = \mathrm{Re}\, \mathcal{F}$

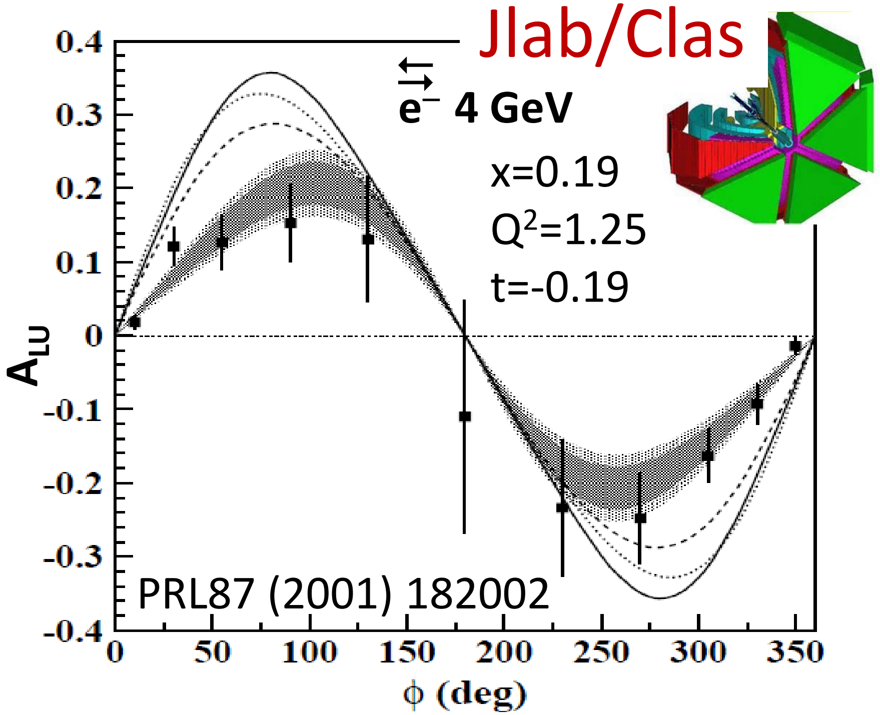
$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} + t/4m^2 F_2 \mathcal{E}$

2001: First DVCS Beam Spin Asymmetries at Hermes and Jlab

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

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



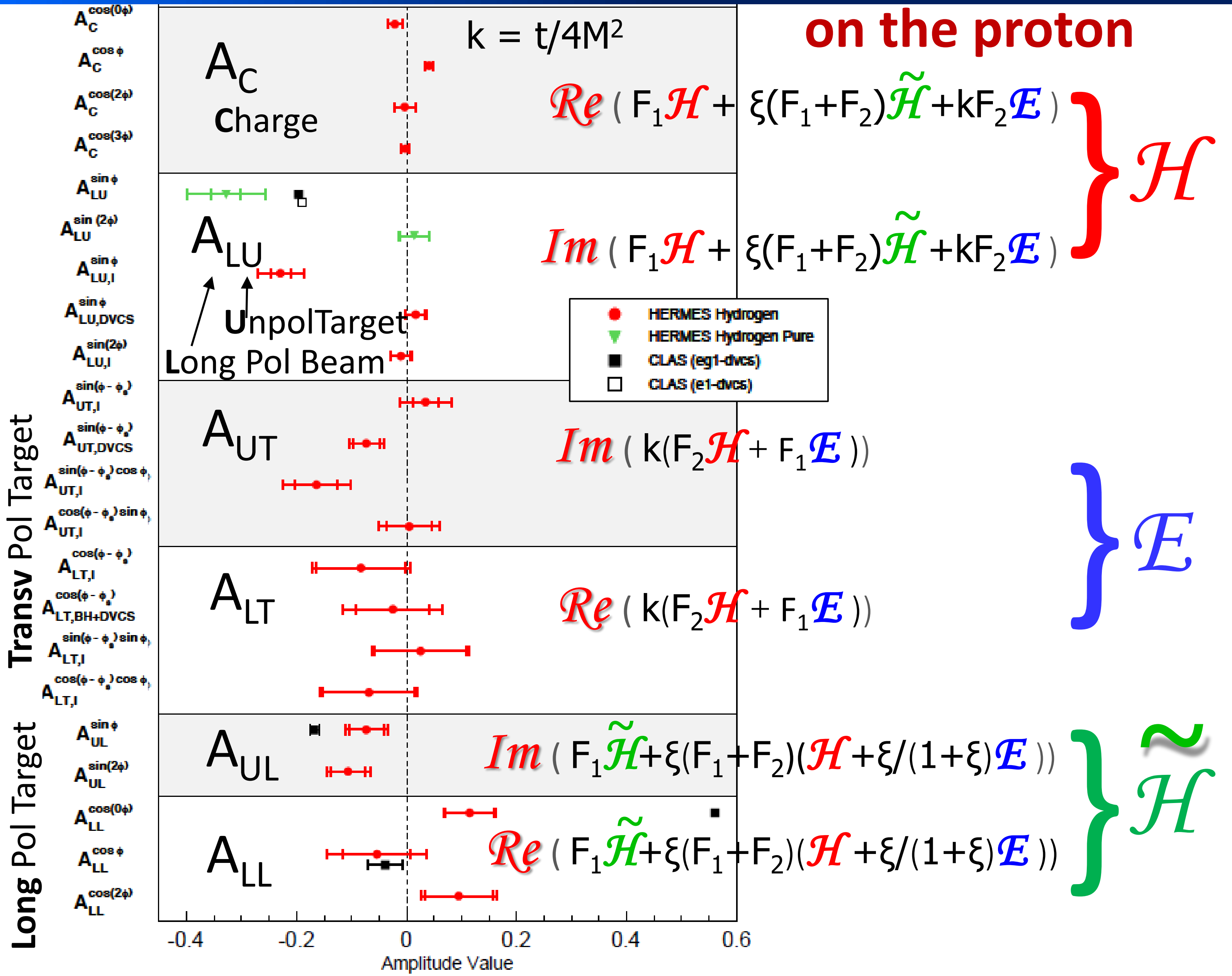


Validate the dominance of the handag contribution

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

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

2001-2012: A complete set of DVCS asymmetries at Hermes



HERMES 27 GeV provided
a complete set of observables

- 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)

Note: **the neutron** allows

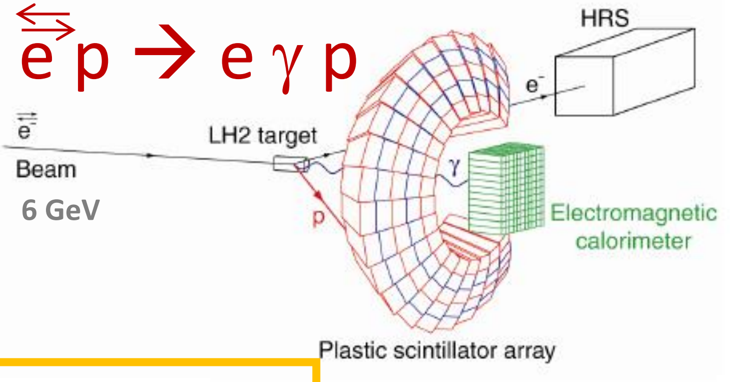
- ✓ flavor decomposition
- ✓ access to $\mathcal{E}$

2004-2016: Beam Spin Sum and Diff of DVCS - HallA

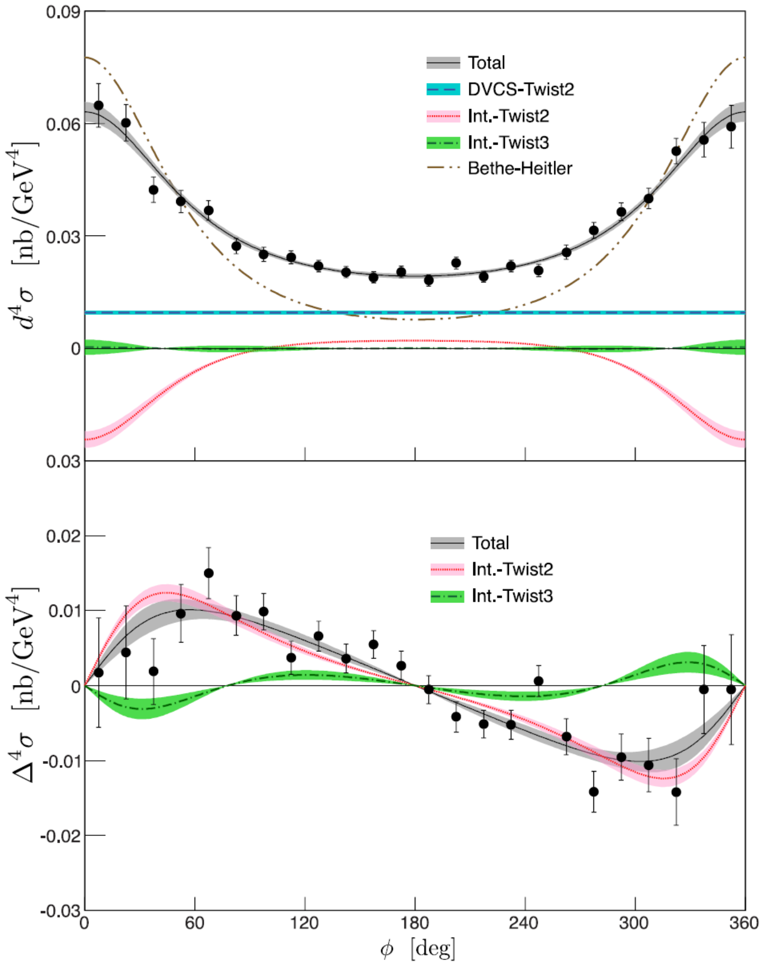
E00-110 pioneer experiment in 2004 with magnetic spectrometer

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

x_B=0.34, x_B=0.39 Q^2= 2.1 GeV^2 Final analysis: Defurne et al., PRC92, 055202 (2015)



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



Unpolarized cross section

$$d\sigma^{\leftarrow} + d\sigma^{\rightarrow} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Re}\, I$$
$$\longrightarrow d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$+ c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

Helicity Dependent cross section

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

→ Further DVCS/Interference separation with different beam energies (with 2010 data)

2010-2017: Beam Spin Sum and Diff of DVCS - HallA

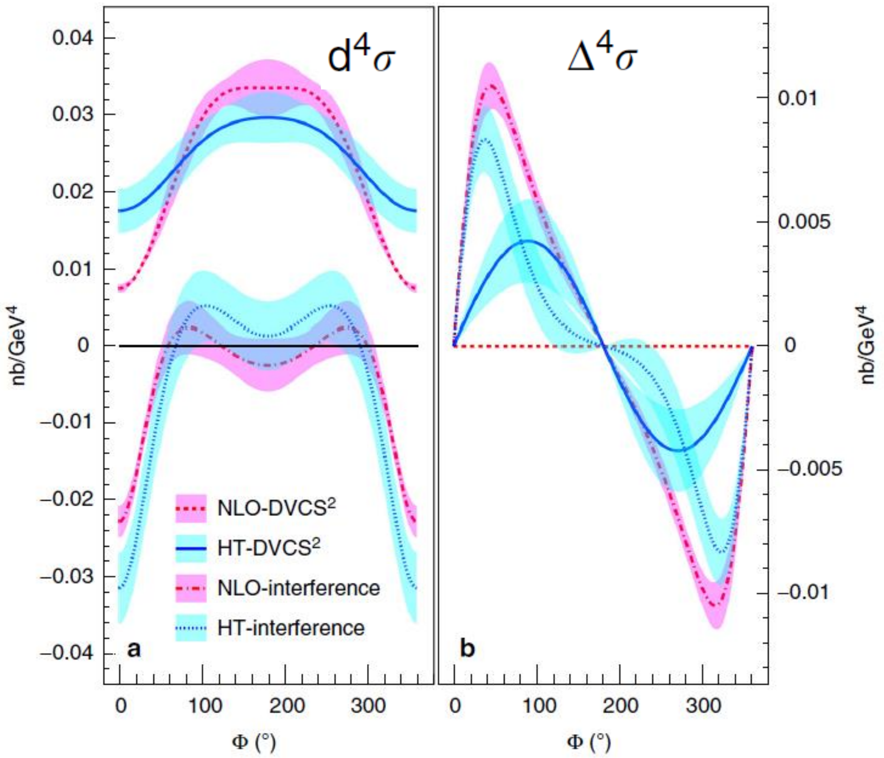
E07-007 Hall-A experiment in 2010 with magnetic spectrometer

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

nature COMMUNICATIONS

x_B=0.36, Q^2= 1.75 GeV^2, -t= 0.30 GeV^2

Ebeam=5.55 GeV



Unpolarized cross section

$$d^4\sigma \quad d\sigma^{\leftarrow} + d\sigma^{\rightarrow} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Re}\, I$$

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

$$+ c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

Helicity Dependent cross section

$$\Delta^4\sigma \quad d\sigma^{\leftarrow} - d\sigma^{\rightarrow} \propto d\sigma^{DVCS}_{pol} + \mathrm{Im}\, I$$

$$\longrightarrow s_1^{DVCS}\sin\phi + s_1^I\sin\phi + s_2^I\sin 2\phi$$

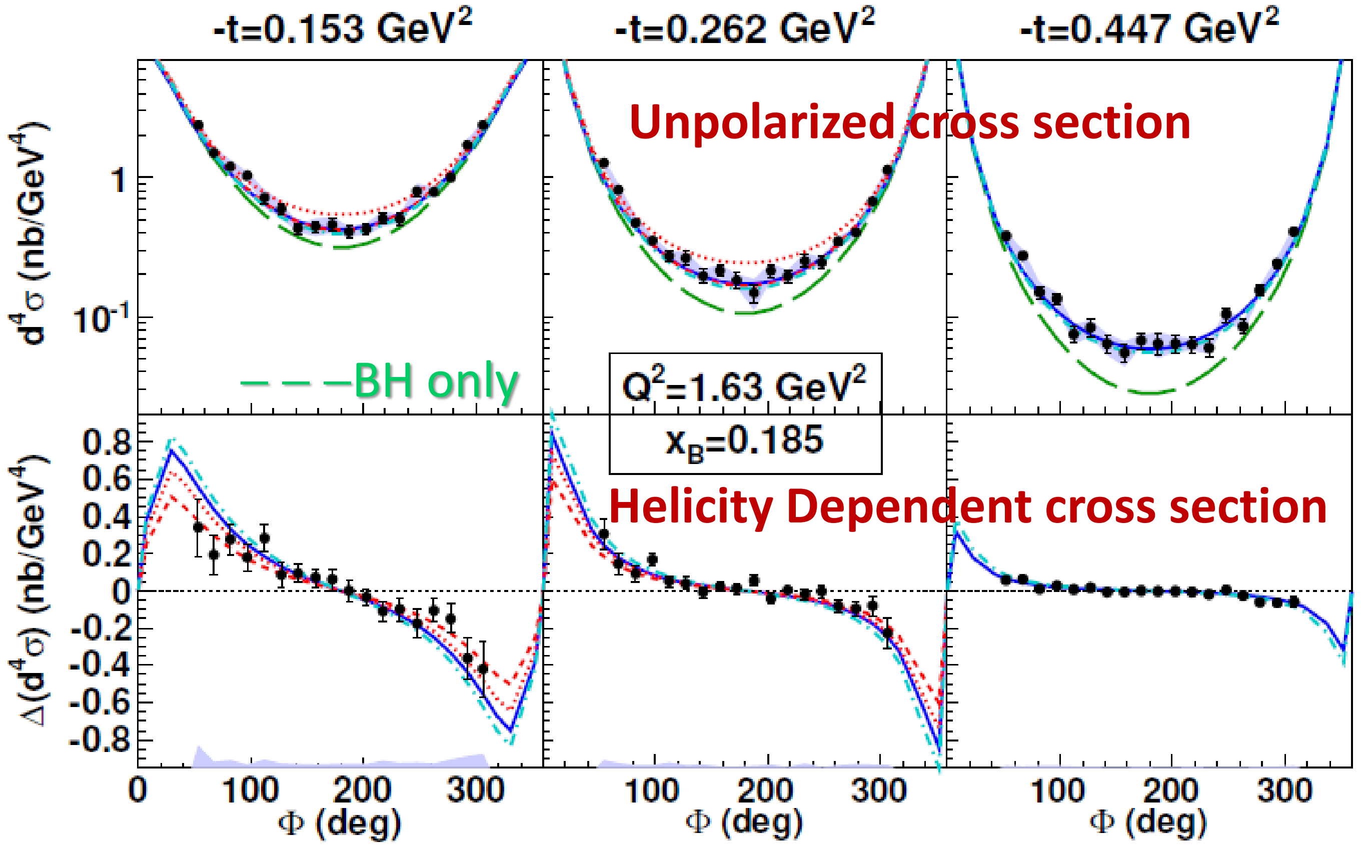
2 solutions: higher-twist OR next-to-leading order

2005-2015: 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

Girod et al. PRL100 (2008) 162002, 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 improved regularly

KMS12 Kroll, Moutarde, Sabatié, EPJC73 (2013)

using the **GK** model Goloskokov, Kroll, EPJC42,50,53,59,65,74

for GPD adjusted on the hard exclusive meson production at small x_B

"universality" of GPDs

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

→ nucleon tomography in the valence domain

Fit of 8 CFFs at L.O and L.T.
(Im$\mathcal{H}$, Re$\mathcal{H}$, Im$\mathcal{E}$, Re$\mathcal{E}$, Im$\tilde{\mathcal{H}}$, Re$\tilde{\mathcal{H}}$, Im$\tilde{\mathcal{E}}$, Re$\tilde{\mathcal{E}}$)

$$H(x,0,0) = q(x)$$

$$\int_{-1}^{+1} H dx = F_1$$

—— VGG model

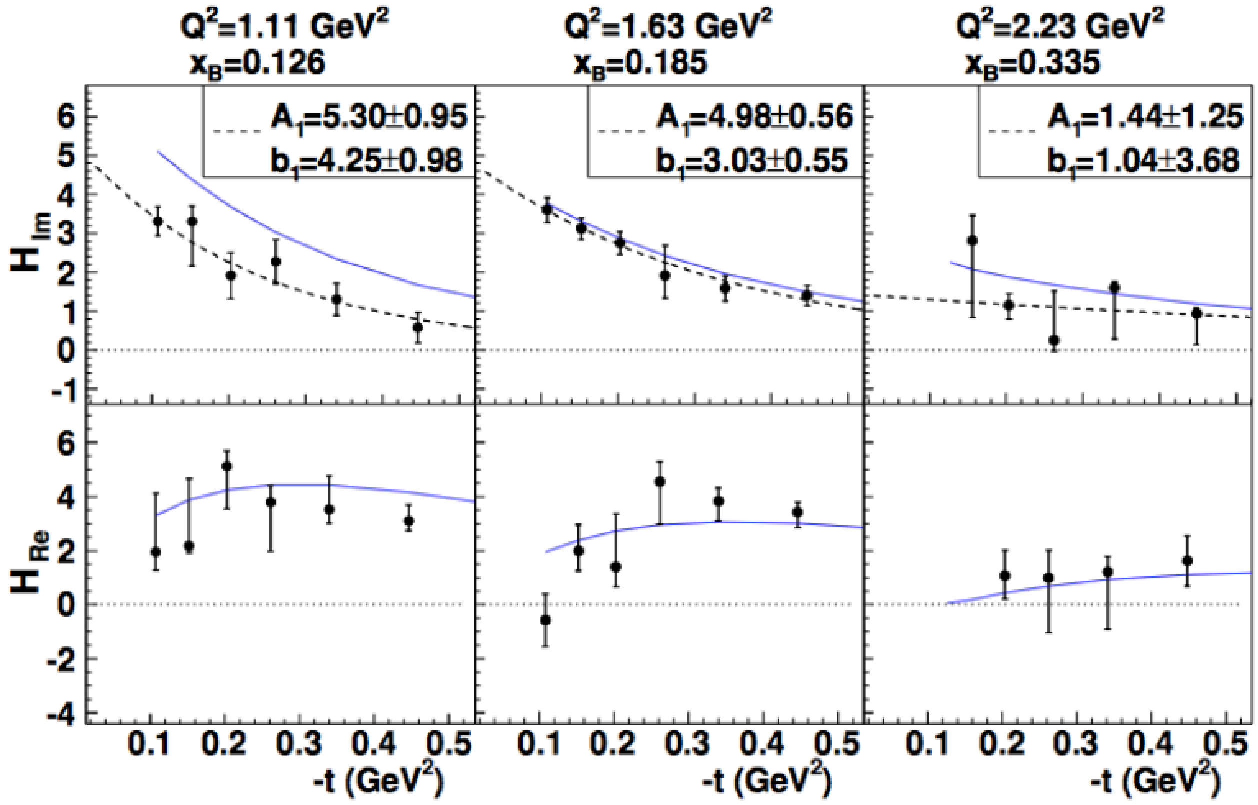
----- Fit Im$\mathcal{H}$ = A $e^{-B|t|}$

B gives information on the transverse extension of the partons

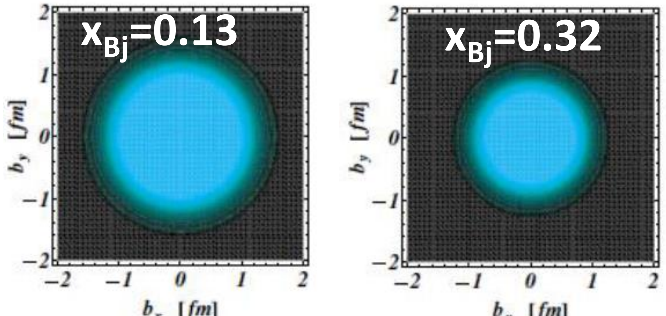
B becomes smaller at higher x_{Bj}

Valence quarks at centre
Sea quarks spread out towards the periphery

Jo et al. PRL115, 212003 (2015)



Guidal, Moutarde, Vanderhaeghen, PNPP 76 (2013)



2009-2015: Single Spin and Double Spin - CLAS

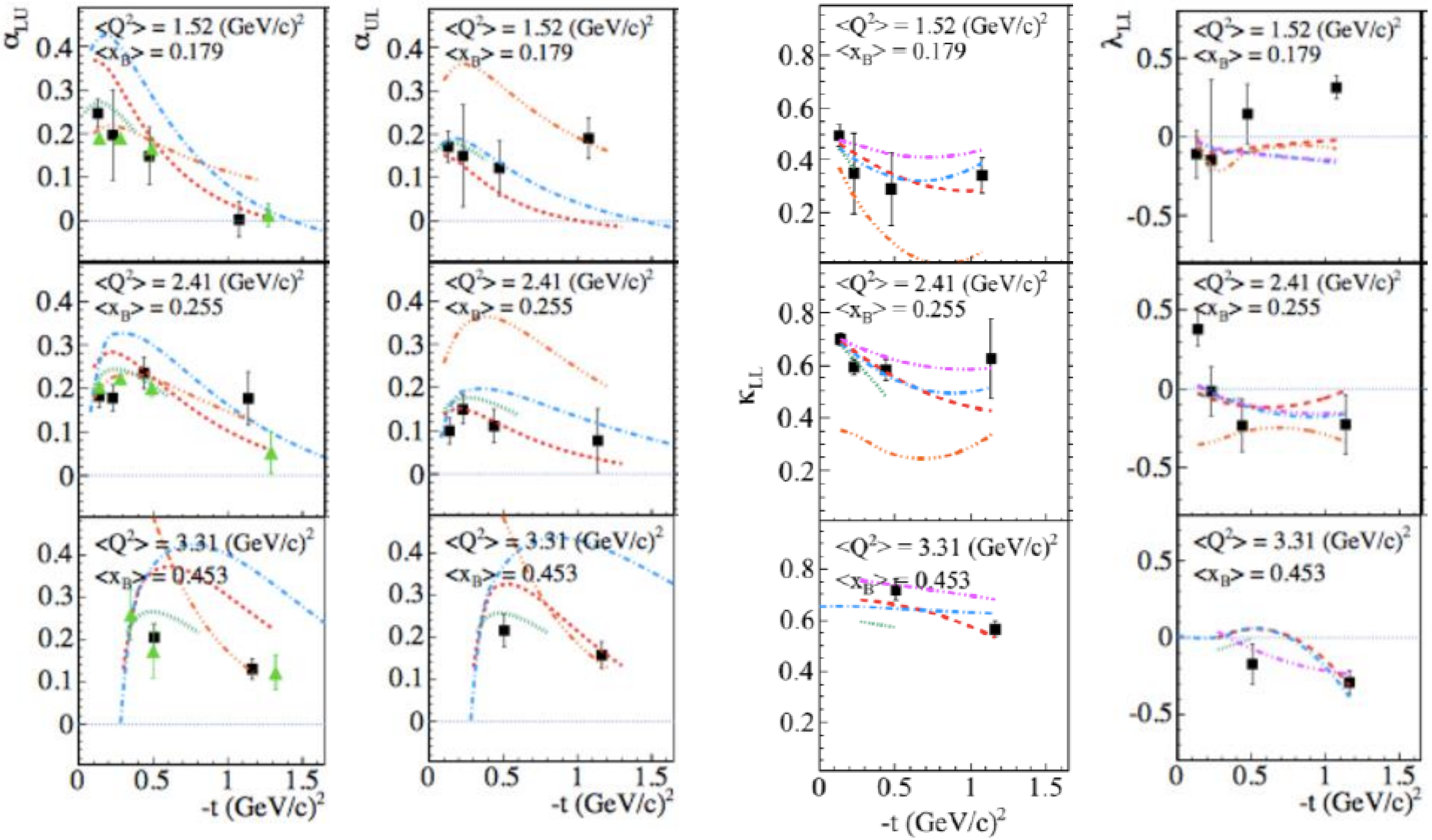
$$A_{LU\,(UL)} = \frac{\alpha_{LU(UL)} \sin\phi}{1+\beta\cos\phi} \qquad A_{LL} = \frac{\kappa_{LL}+\lambda_{LL}\cos\phi}{1+\beta\cos\phi}$$

2009: Longitudinally polarized NH3 target

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

Seder et al. PRL114, 032001 (2015)

Pisano et al. PRD91, 052014 (2015)



- CLAS A_{LU} on H_2
- data
- VGG Vanderhaeghen, Guichon, Guidal
- KMM Kumericki, Mueller, Murray
- GK Goloskokov, Kroll
- GGL Goldstein, Gozalez, Luiti
- BH

➔ nucleon tomography in the valence domain

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

($Im\mathcal{H}$, $Re\mathcal{H}$, $Im\mathcal{E}$, $Re\mathcal{E}$, $Im\tilde{\mathcal{H}}$, $Re\tilde{H}$, $Im\tilde{\mathcal{E}}$, $Re\tilde{\mathcal{E}}$)

$$H(x,0,0) = q(x) \qquad \tilde{H}(x,0,0) = \Delta q(x)$$

$$\int_{-1}^{+1} H dx = F_1 \qquad \int_{-1}^{+1} \tilde{H}\, dx = G_A$$

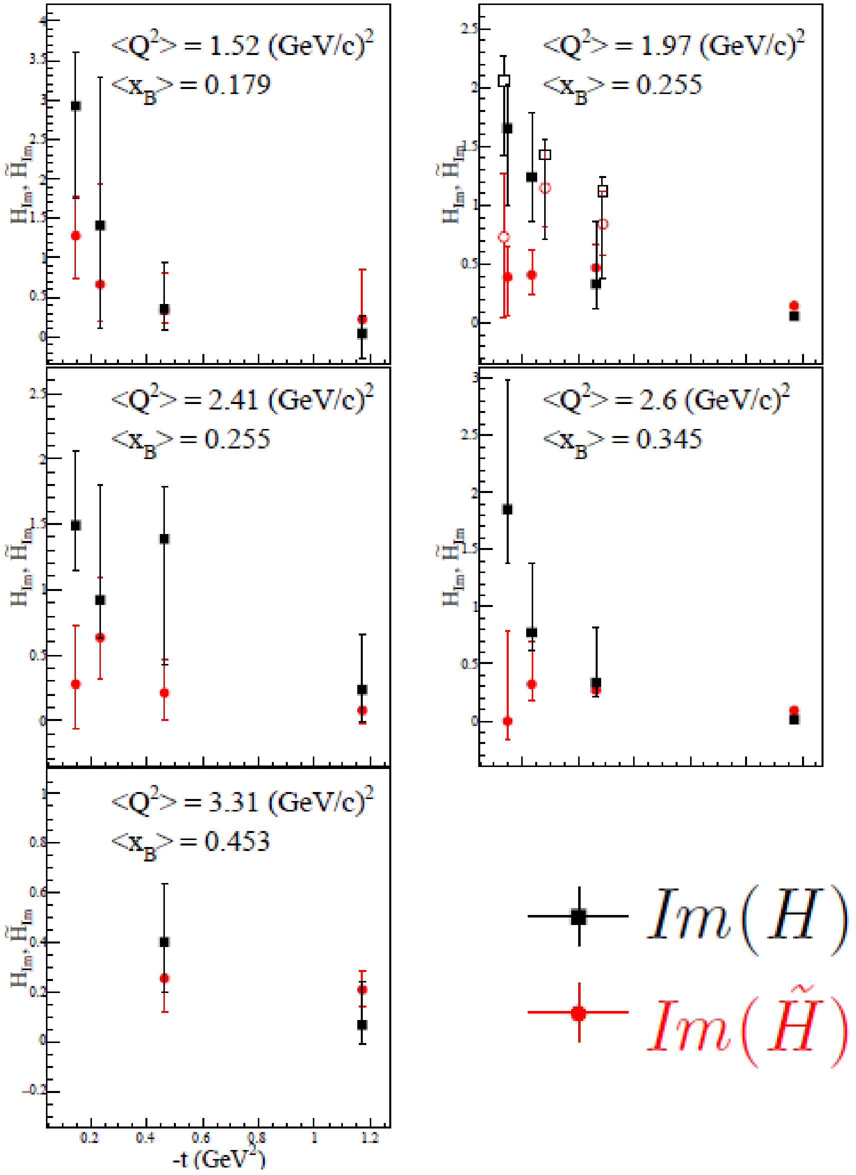
$Im(H)$ ➔ electromagnetic charge distribution

$Im(\tilde{H})$ ➔ axial charge distribution

Axial charge is more concentrated than electromagnetic charge

Seder et al. PRL114, 032001 (2015)

Pisano et al. PRD91, 052014 (2015)



➔ nucleon tomography in the valence domain

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

Dupré, Guidal, Nicolai, Vanderhaeghen,
PRD95, 011501(R)(2017)
Eur.Phys.J. A53 (2017)

$s_1^{\,I} = \ Im\ F_1\mathcal{H}$ is the best constrained

$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp} H^q_-(x, 0, -\mathbf{\Delta}_\perp{}^2).$$

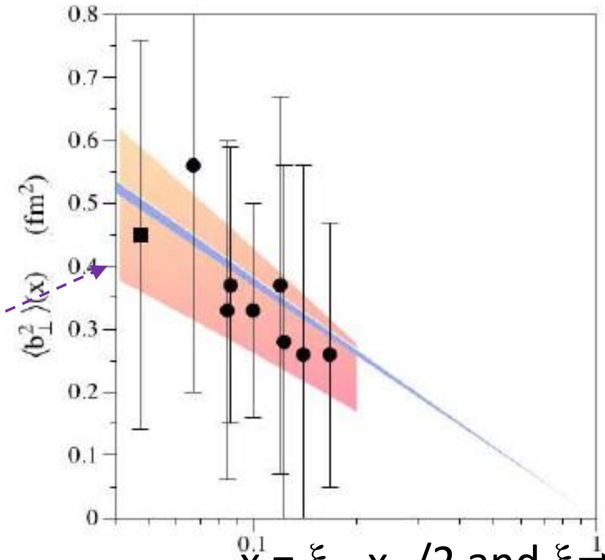
$$\langle b_\perp^2\rangle^q(x) = -4\frac{\partial}{\partial\mathbf{\Delta}_\perp^2} \ln H^q_-(x, 0, -\mathbf{\Delta}_\perp{}^2)\Big|_{\mathbf{\Delta}_\perp=0}.$$

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

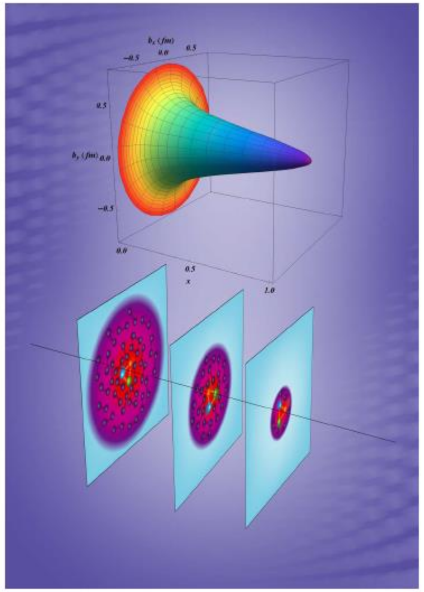
— Fit $A\ e^{-B|t|}$

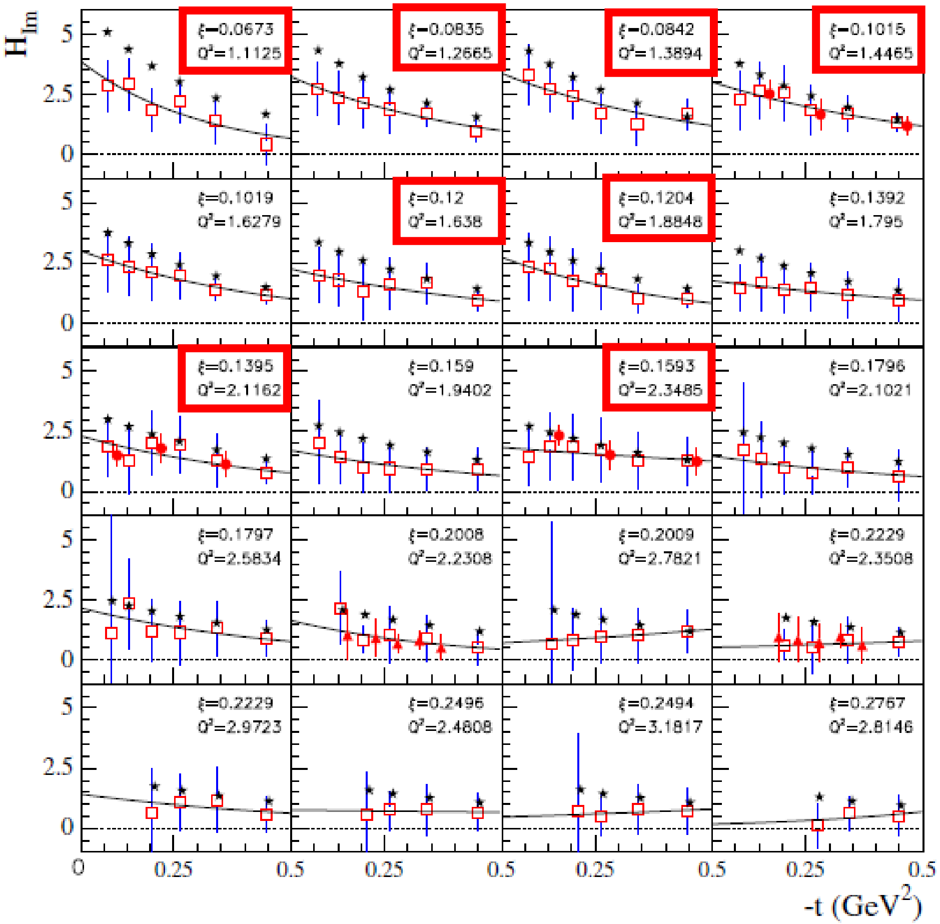
HERMES

\+ 8 data from JLab



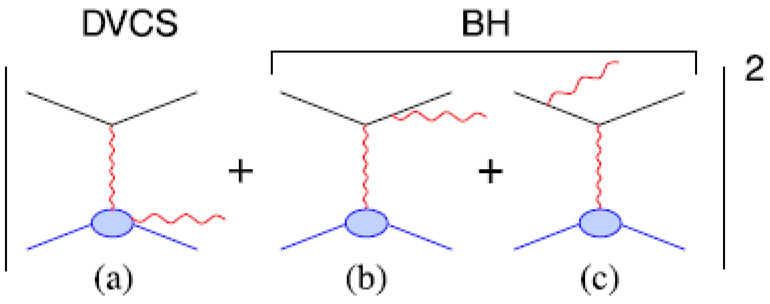
$x = \xi \sim x_{Bj}/2$ and $\xi \rightarrow 0$

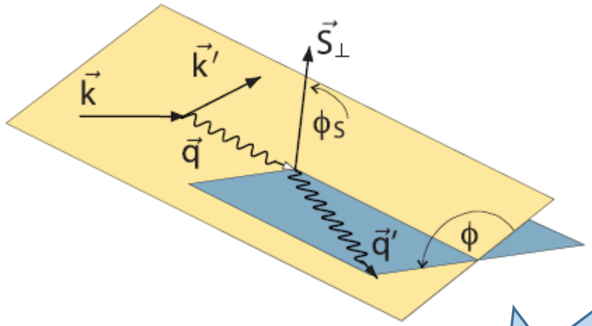




□ CLAS σ and Δσ
▲ HallA σ and Δσ
● CLAS A_{UL} and A_{LL}
★ VGG model

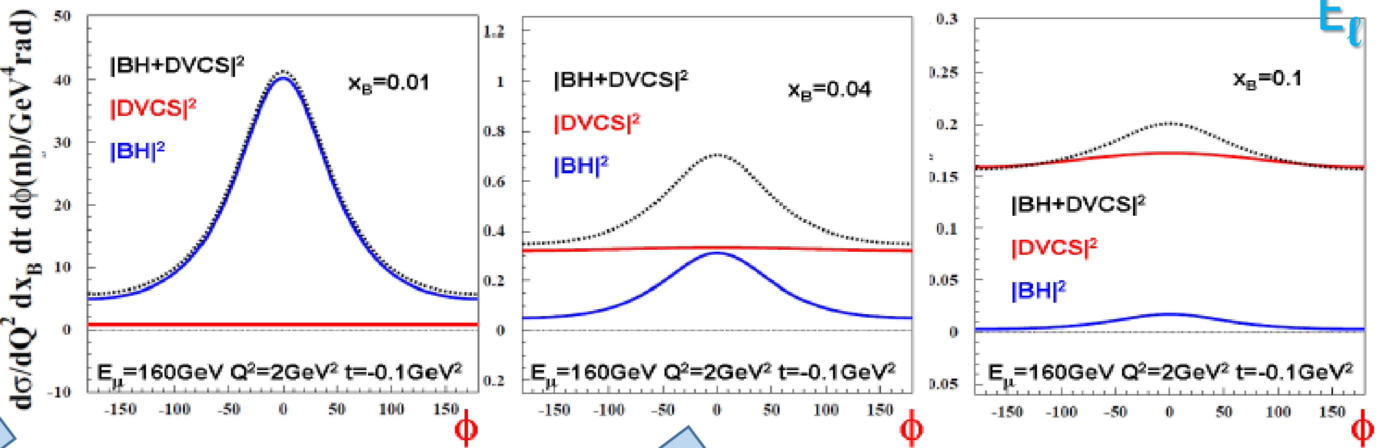
DVCS at higher beam energy





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

E_ℓ =160 GeV



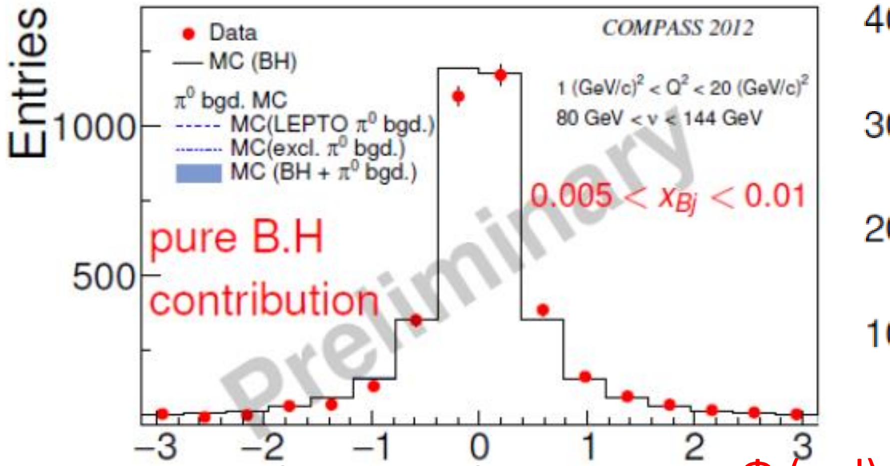
BH dominates
Reference yield

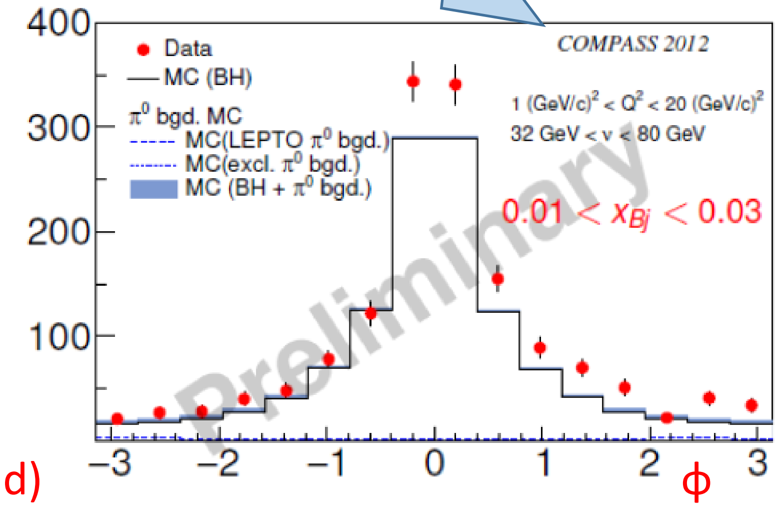
DVCS ampl. via interference

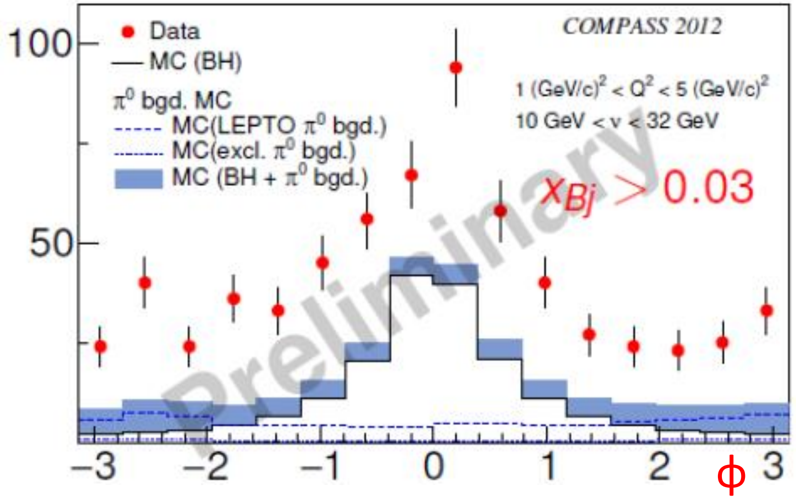
Jlab, HERMES,
H1, COMPASS

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

Only for H1, ZEUS, COMPASS







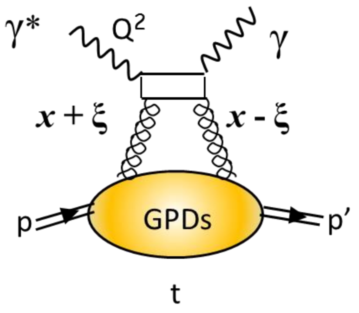
COMPASS 4 weeks 2012 pilot run

→ nucleon tomography in the gluon domain at HERA

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

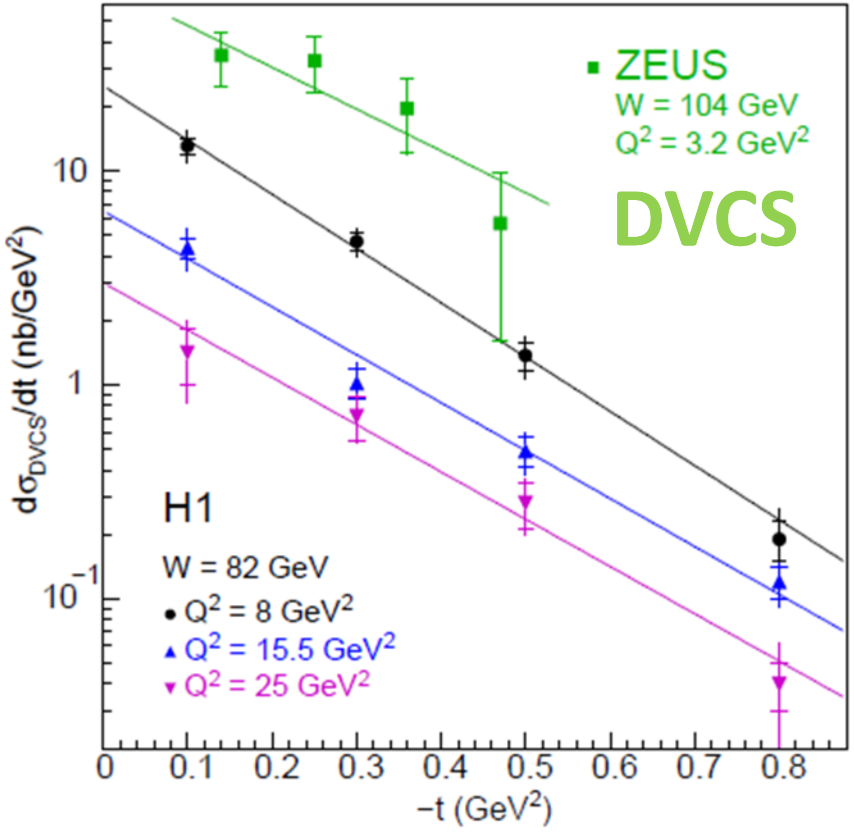
B' is related to the transversed size of the scattering object

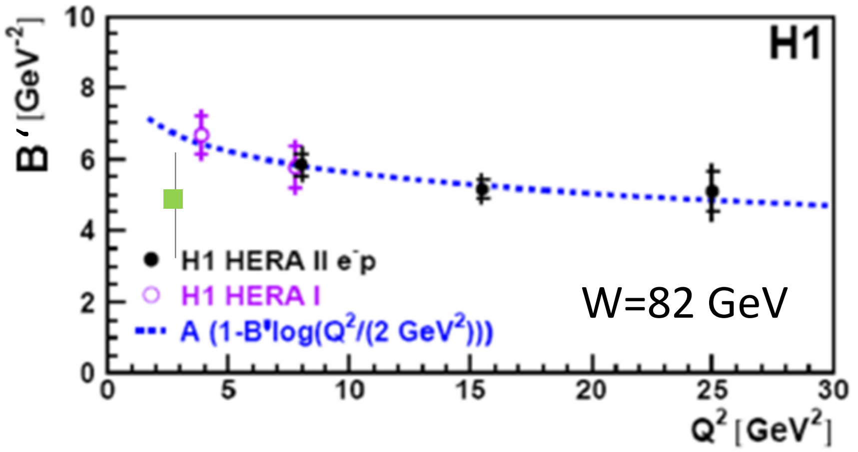
Dominance of *Im*$\mathcal{H}$

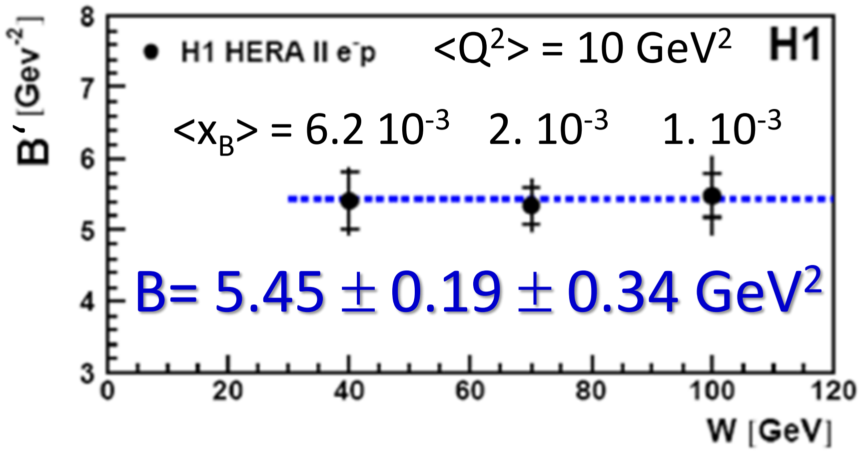


ZEUS-H1
Data collected
1995-2007

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







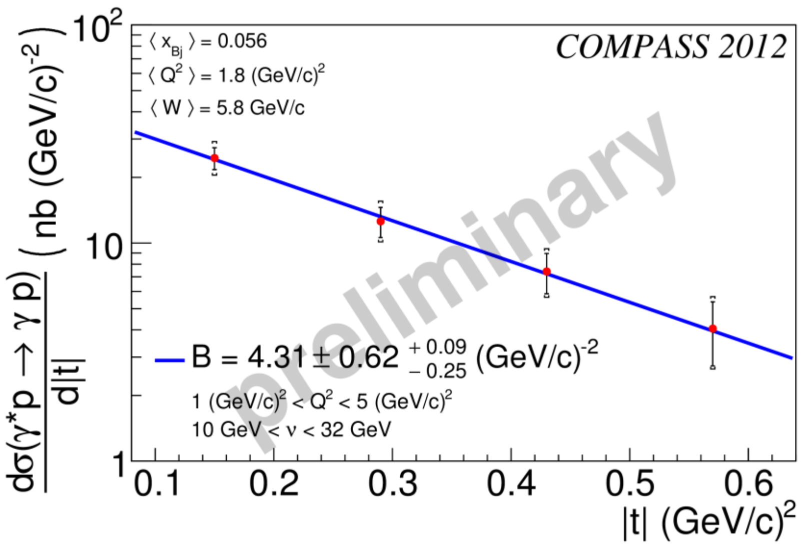
$B = 5.45 \pm 0.19 \pm 0.34\ GeV^2$

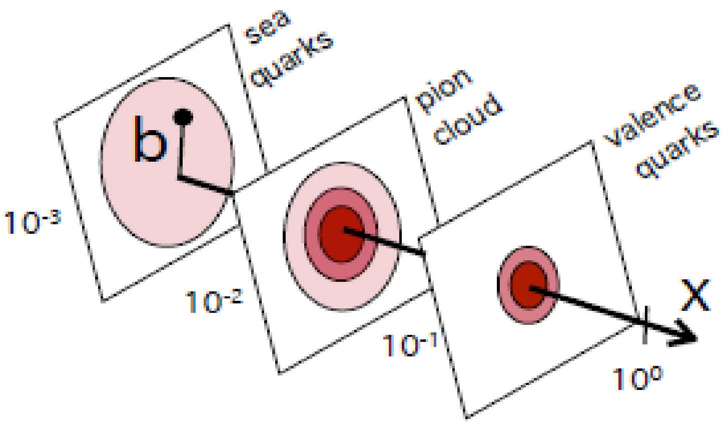
$< r_\perp^2(x_B) > \approx 2 B'(x_B)$

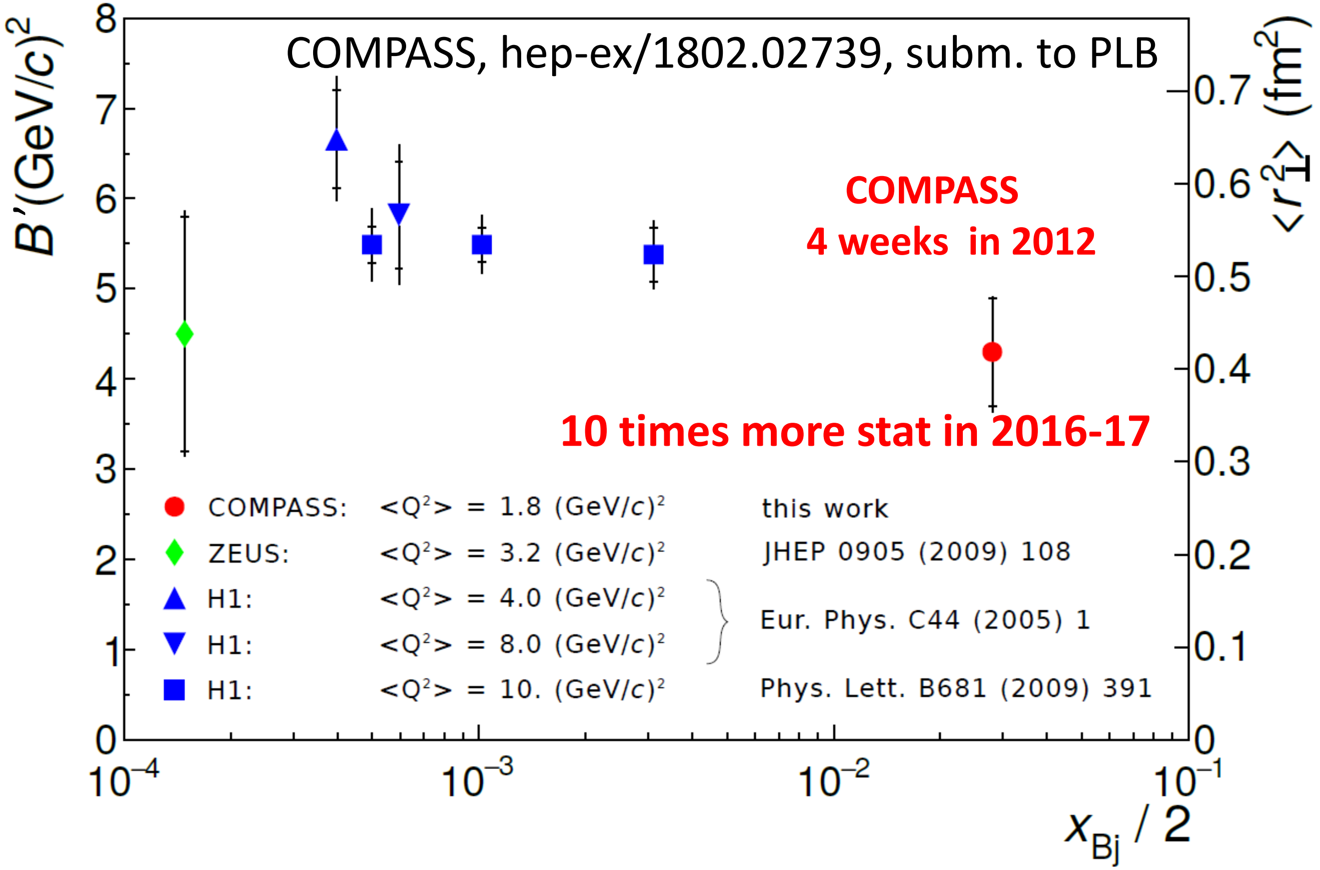
$\sqrt{< r_\perp^2 >} = 0.65 \pm 0.02$ fm to be compared to $\sqrt{4 \frac{d}{dt} F_1^p} \overset{t=0}{=} 0.67 \pm 0.01$ fm

→ nucleon tomography in the sea quark domain at COMPASS

$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$







$$B = (4.3 \pm 0.6_{\text{stat}} \, {}^{+\,0.1}_{-\,0.3}\big|_{\text{sys}}) \; (\text{GeV}/c)^{-2}$$

➔ nucleon tomography in the sea quark domain at COMPASS

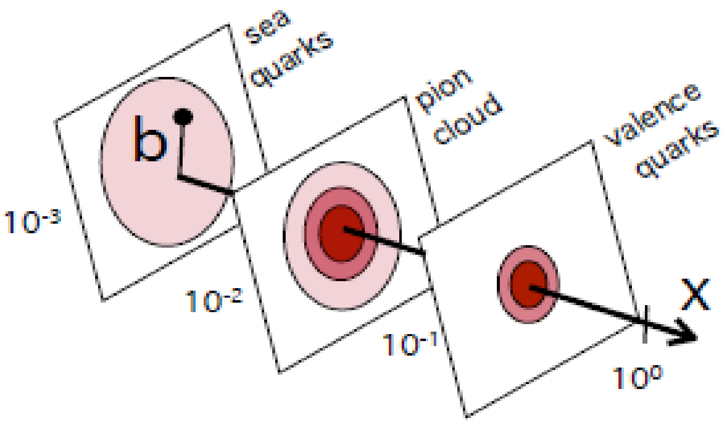
$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$

At COMPASS:
$\langle x_{Bj}\rangle=0.056$; $\langle Q^2\rangle=1.8$ GeV^2;
t varies from 0.08 to 0.64 GeV^2

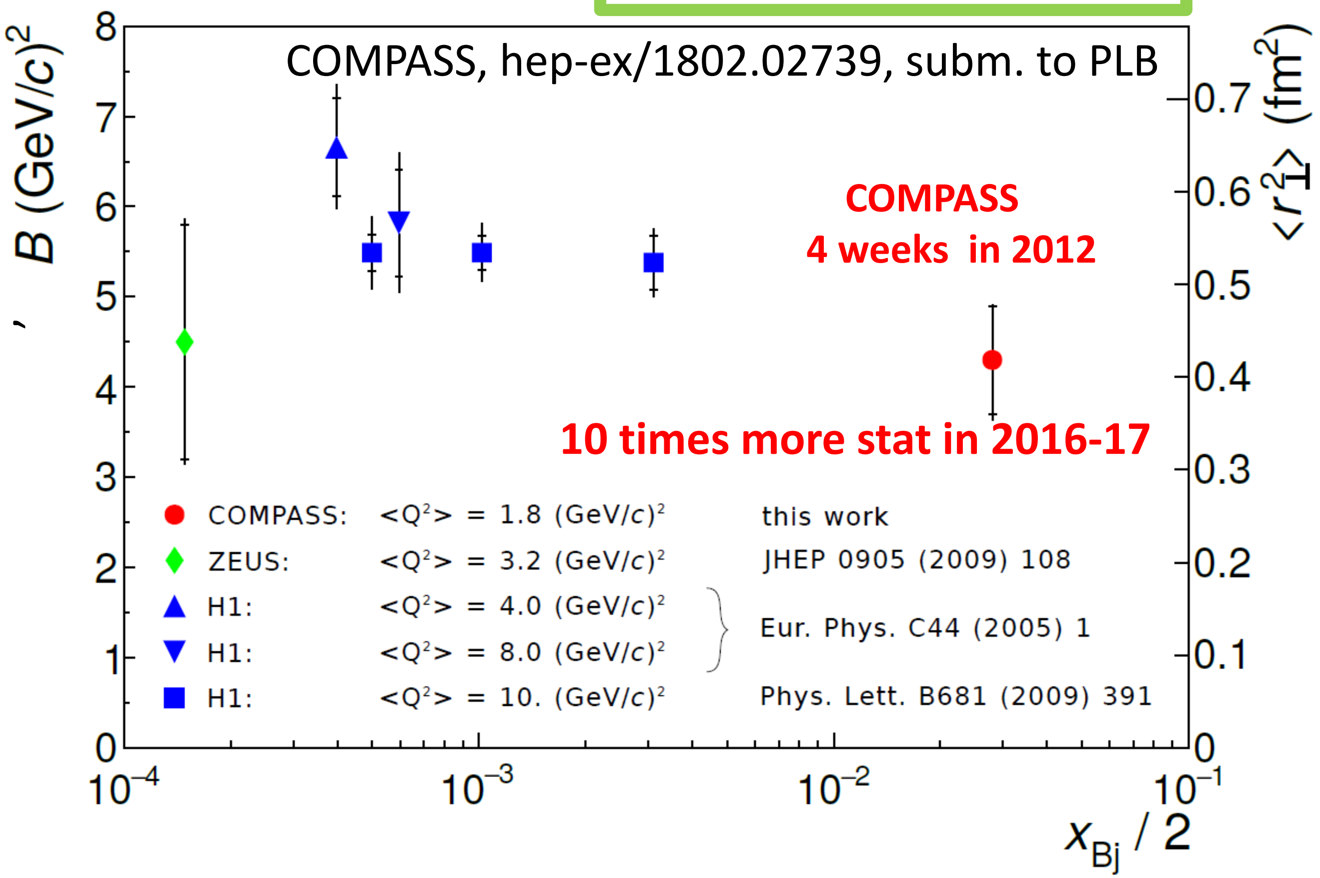
At small x_{Bj} and small t:

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) - \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$

Dominance of *ImH*
(with respect of *ReH* and other *CFF*)



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



$$B = (4.3 \pm 0.6_{stat}\ {}^{+0.1}_{-0.3}|_{sys})\ (\mathrm{GeV}/c)^{-2}$$

$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \pm 0.04_{stat}\ {}^{+0.01}_{-0.02}|_{sys}\ \pm 0.04_{model})\ \mathrm{fm}$$

➔ nucleon tomography in the sea quark domain at COMPASS

$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$

At COMPASS:
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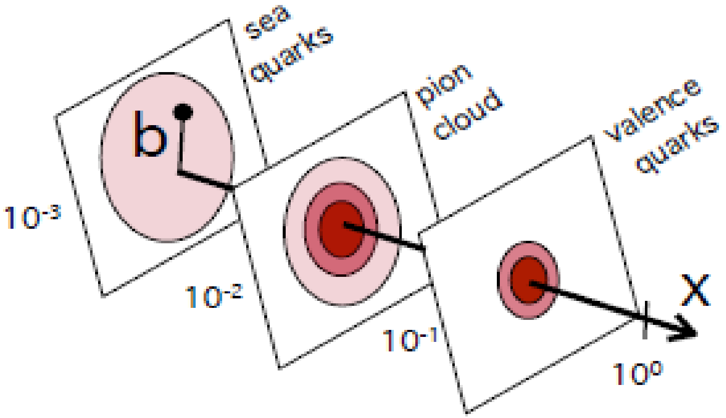
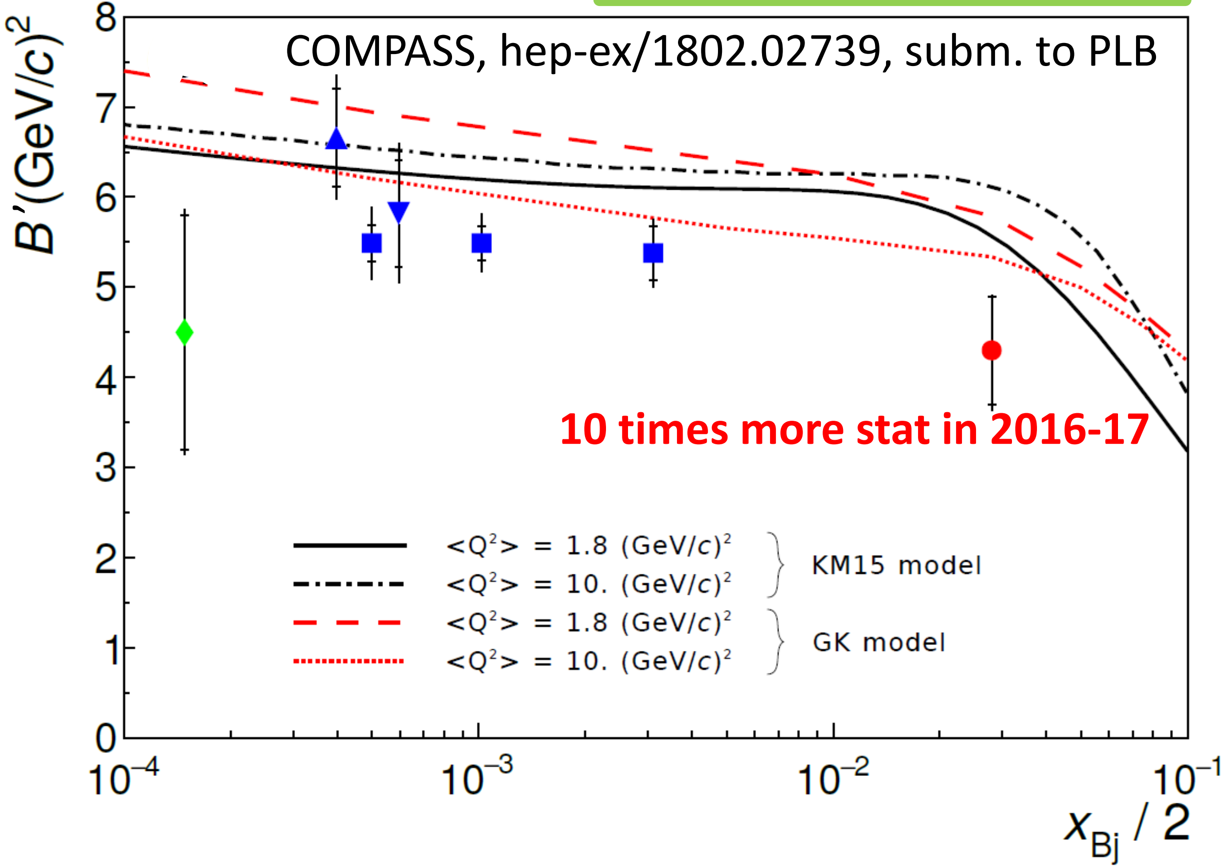


$\langle r_\perp^2(x_B)\rangle \approx 2B'(x_B)$



$$B = (4.3 \pm 0.6_{stat} {}^{+0.1}_{-0.3}|_{sys})\ (\mathrm{GeV}/c)^{-2}$$

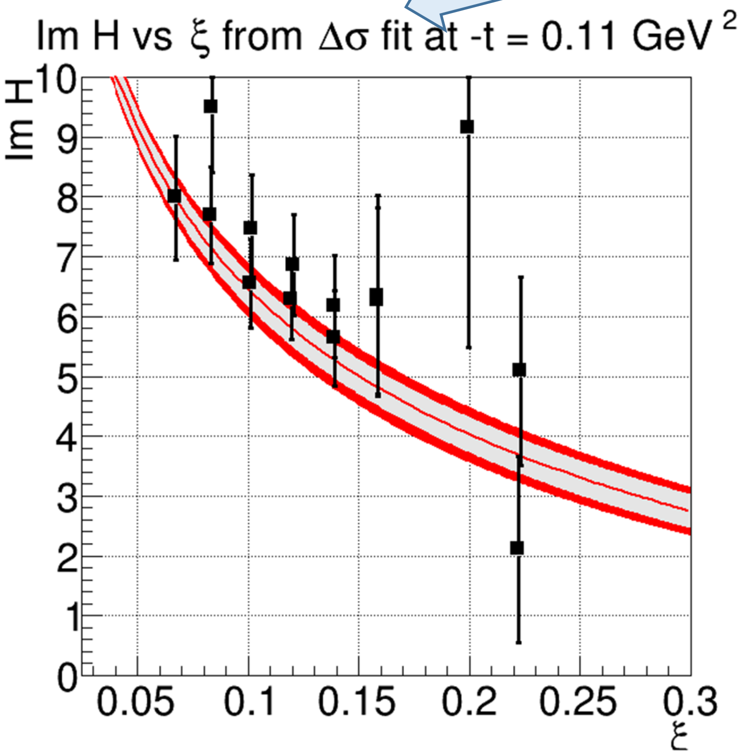
$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \pm 0.04_{stat} {}^{+0.01}_{-0.02}|_{sys} \pm 0.04_{model})\ \mathrm{fm}$$

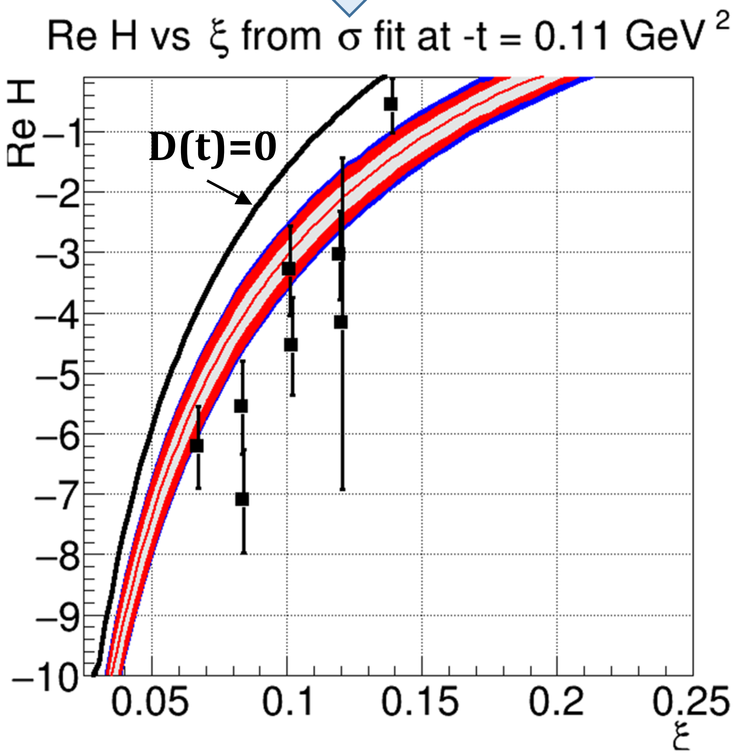
→ D-term and Pressure distribution in the proton

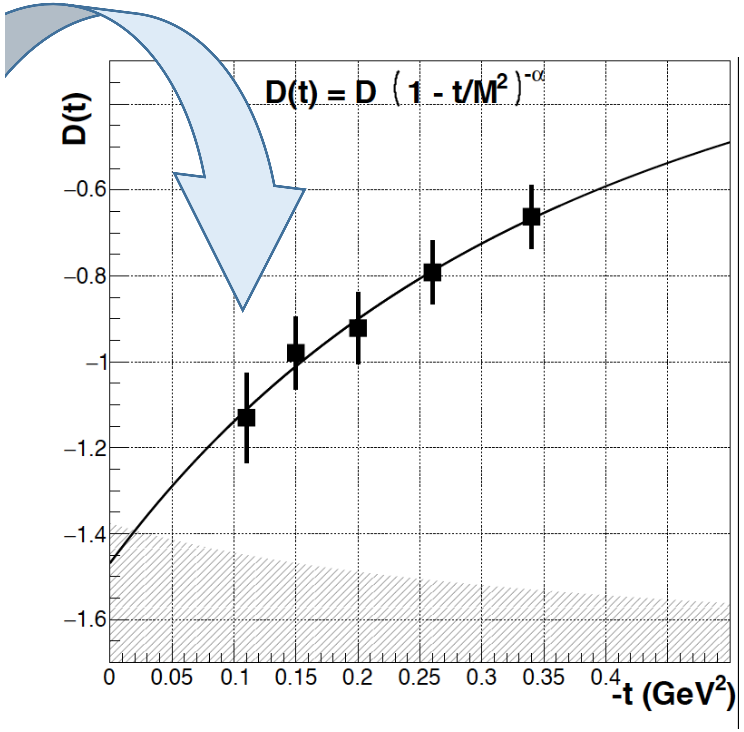
With all the data for Beam Spin Diff and Sum of DVCS - CLAS@Jlab 6 GeV

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

Girod et al. PRL100 (2008) 162002, Jo et al. PRL115, 212003 (2015)







$D^Q(0) < 0$

This is a critical result, required for dynamical stability of the proton.
Deeply rooted in chiral symmetry breaking.

$D^Q(0) = -1.47 \pm 0.10 \pm 0.22$

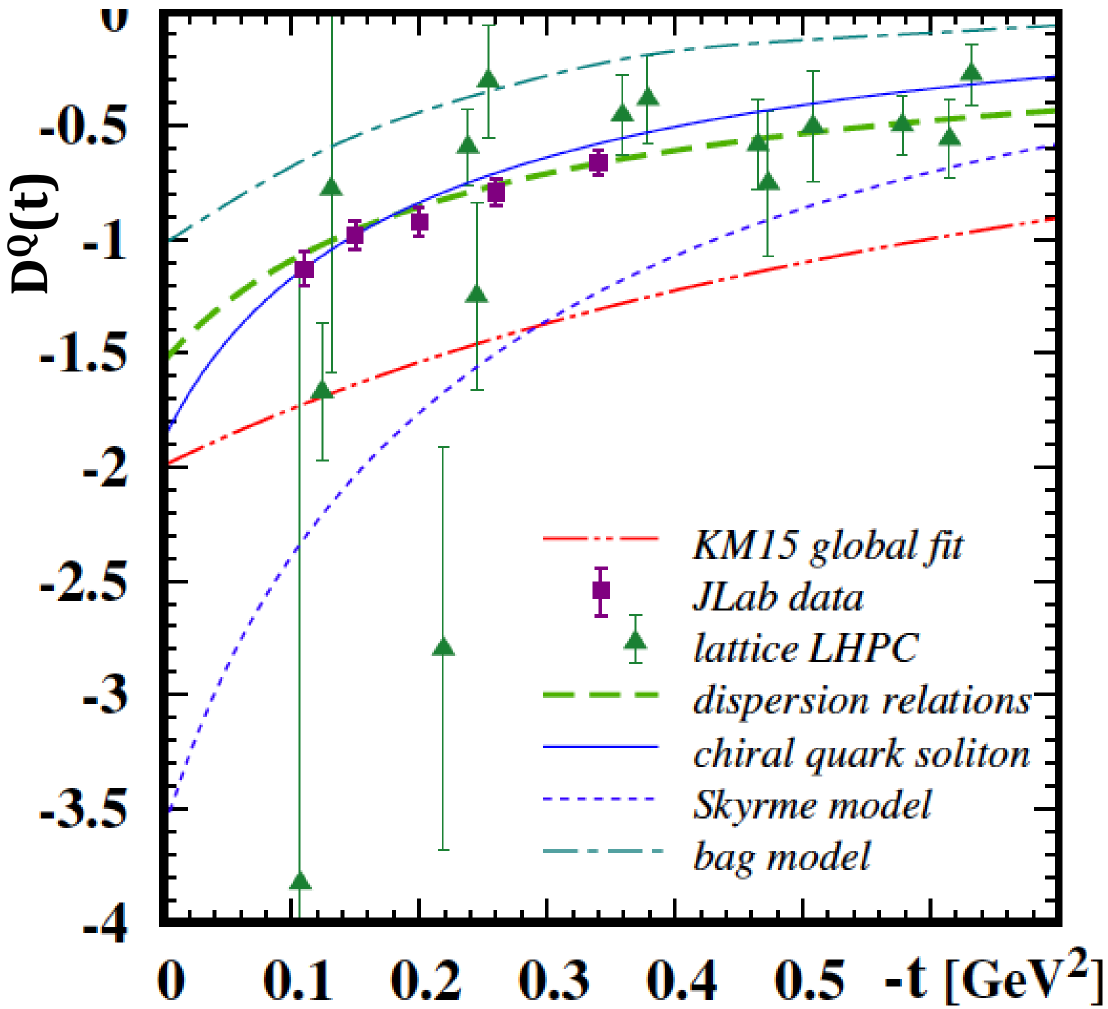
$M^2 = 1.06 \pm 0.10 \pm 0.15$

$\alpha = 2.76 \pm 0.25 \pm 0.50$

D-term and Pressure distribution in the proton

Comparison of $D^Q(t)$ with theories

M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)



Global properties of the Proton

Em:	Q_{prot}	=	$1.602176487(40) \times 10^{-19}$C
	μ_{prot}	=	$2.792847356(23)\mu_N$
Weak:	g_A	=	$1.2694(28)$
	g_p	=	$8.06(0.55)$
Gravity:	M_{prot}	=	$938.272013(23)\,\mathrm{MeV}/c^2$
	J	=	$\frac{1}{2}$
	D	=	-1.47 (10) (22)

➔ D-term and Pressure distribution in the proton

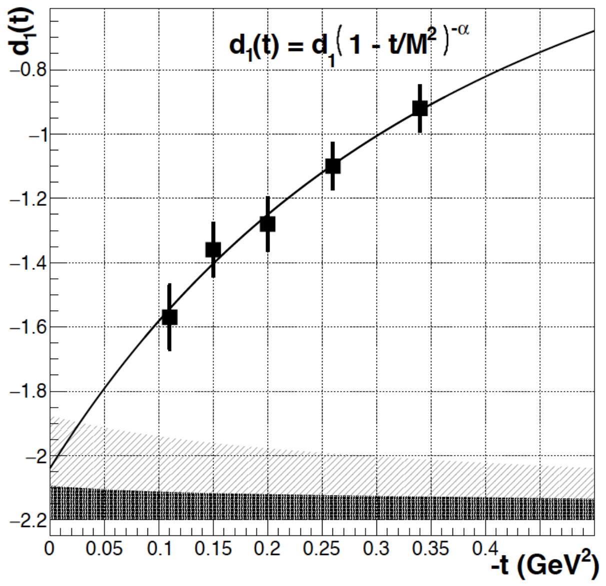
M.V. Polyakov and C. Weiss, Phys.Rev.D60, 114017 (1999)

$$D(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}z \frac{D(z,t)}{1-z} \qquad -1 < z = \frac{x}{\xi} < 1$$

Expansion in Gegenbauer polynomials

$$D(z,t) = (1-z^2)\left[d_1(t) C_1^{3/2}(z) + \cdots\right]$$

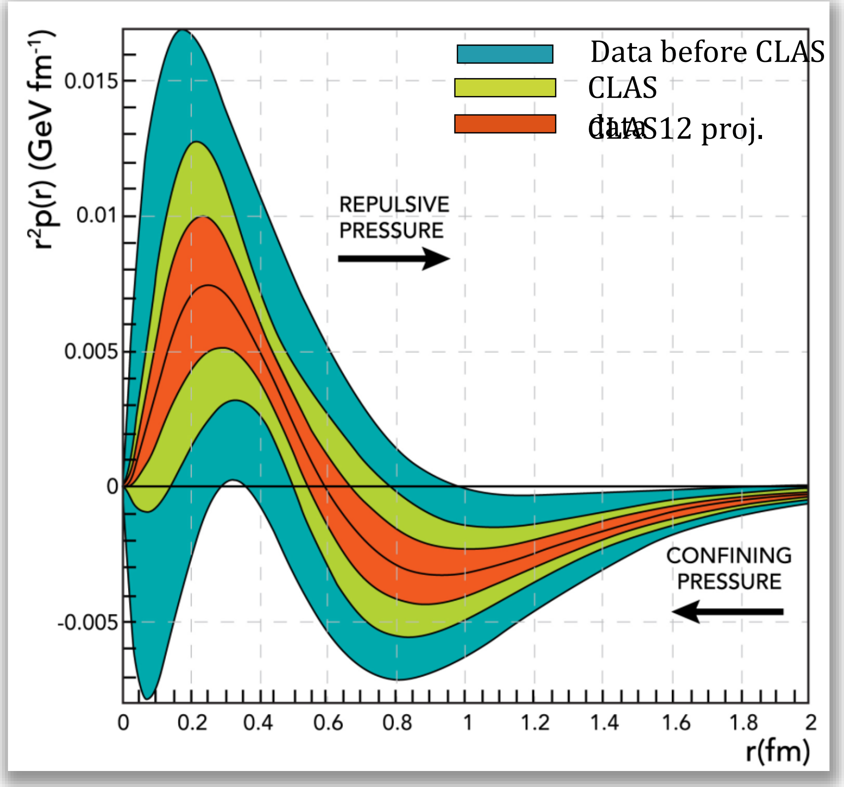
next order terms <<



M.V. Polyakov, Phys. Lett. B555 (2003) 57

With the first spherical Bessel integral

$$d_1(t) \propto \int \mathrm{d}^3\mathbf{r}\, \frac{j_0(r\sqrt{-t})}{2t}\, p(r)$$



Repulsive pressure near center **$p(r=0) \sim 10^{35}$ Pa**

Confining pressure at r > 0.6 fm

nature International journal of science

V.Burkert, L. Elouadrhiri, F.X. Girod
Nature 557 (2018) no.7705, 396-399

Atmospheric pressure: 10^5 Pa

Pressure in the center of neutron stars ~ 10^{34} Pa

next future: Beam Charge and Spin Diff @ COMPASS

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} \xrightarrow{L.T.} c_0^I + c_1^I \cos\phi$$

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

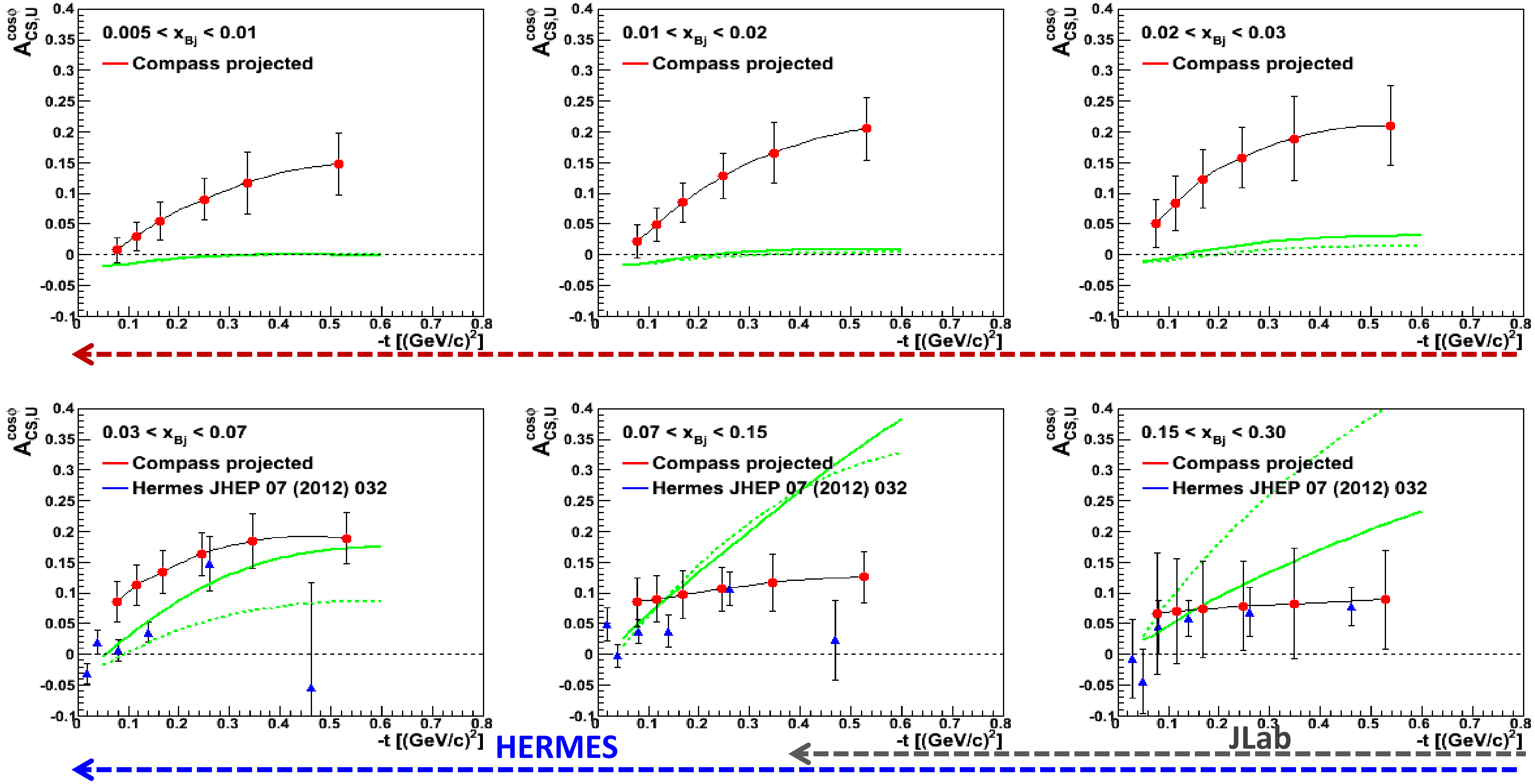
$Re\,\mathcal{H}$ > 0 at H1
< 0 at HERMES
Value of x_B for the node?

Predictions with VGG and KM10

2016-17: 2x 6 months of data taking

Analysis on going

Impact on the D-term



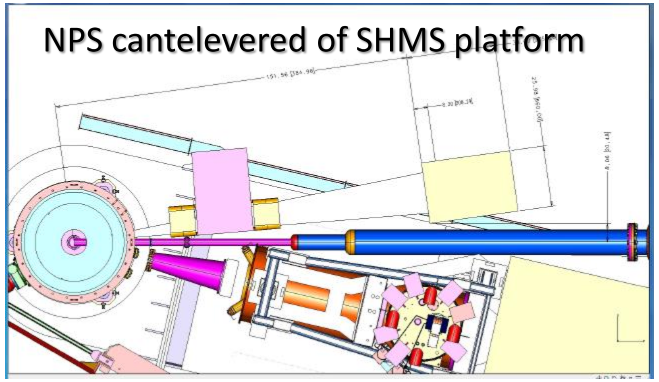
COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2

next future: Beam Spin Sum and Diff @ JLab12

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

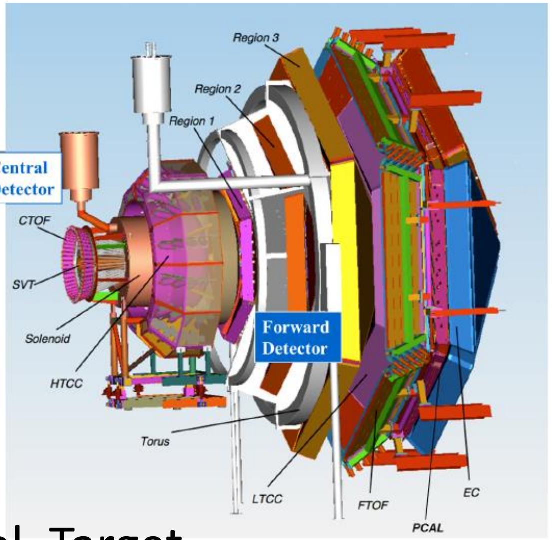
done in 2016-17: Hall A: E12-06-114
~2020: Hall C: E12-13-010

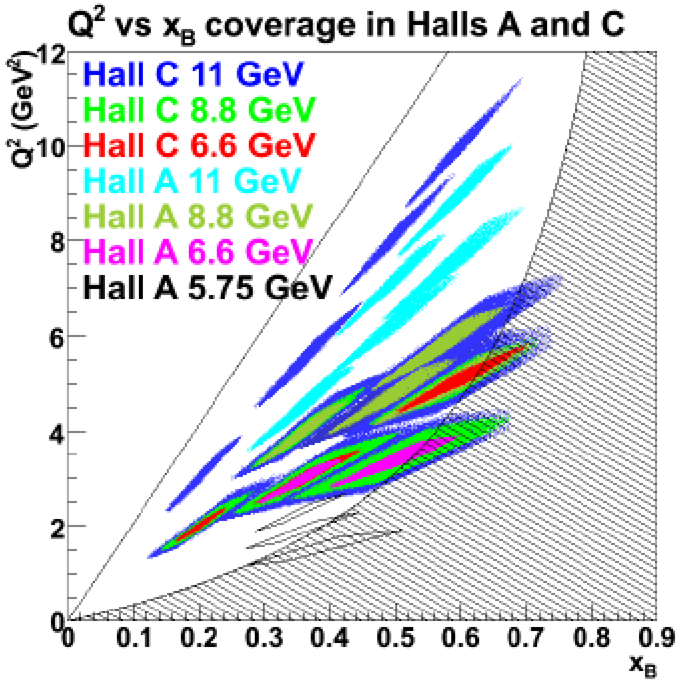
Different beam energies for a Rosenbluth-like DVCS^2/Interf. separation



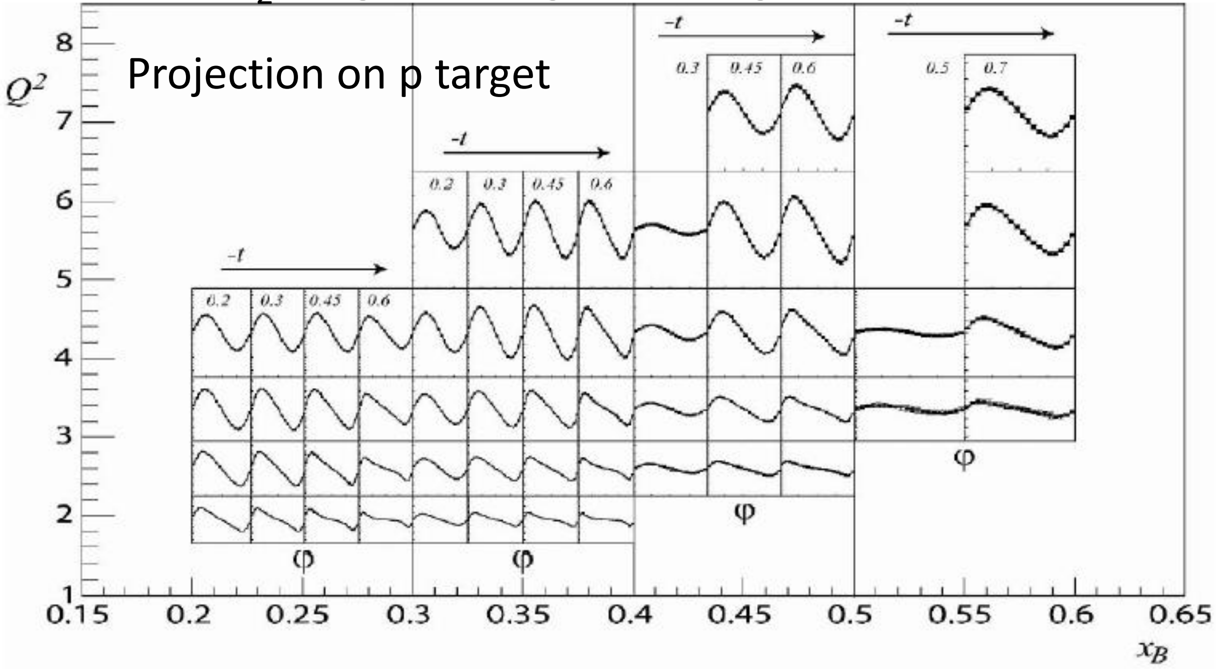
with CLAS12

E12-06-119
2018-19: LH2
2020: Long Pol Target

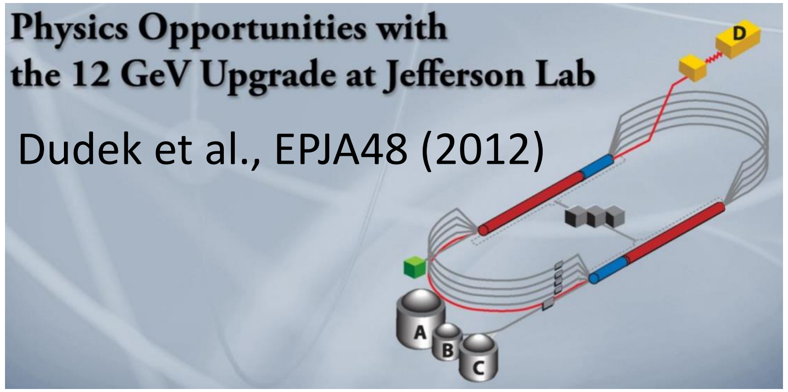




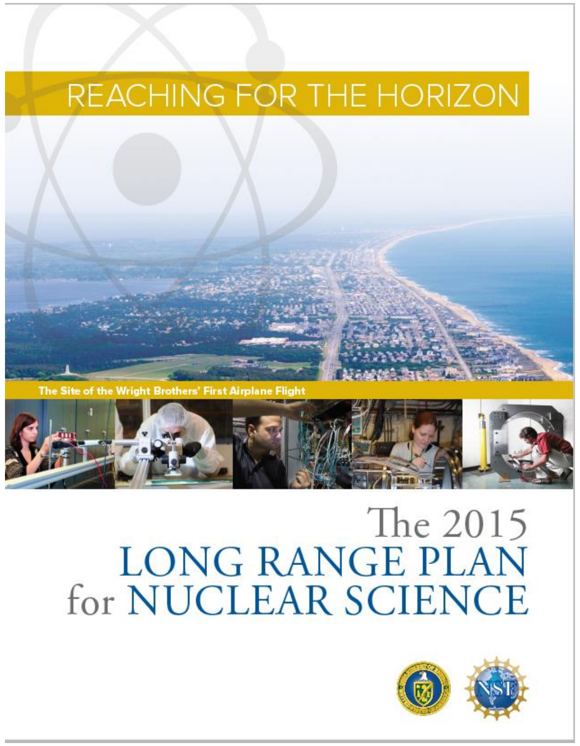
LH_2 Target & Long. Pol. Target



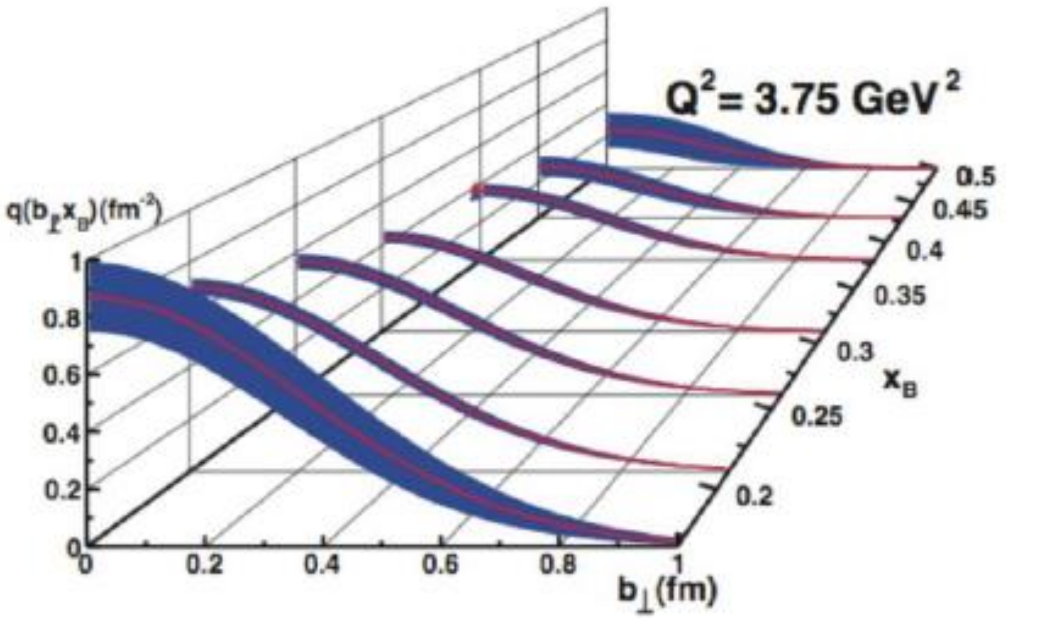
next future: Beam Spin Sum and Diff @ JLab12



Projection for Jlab 12 GeV

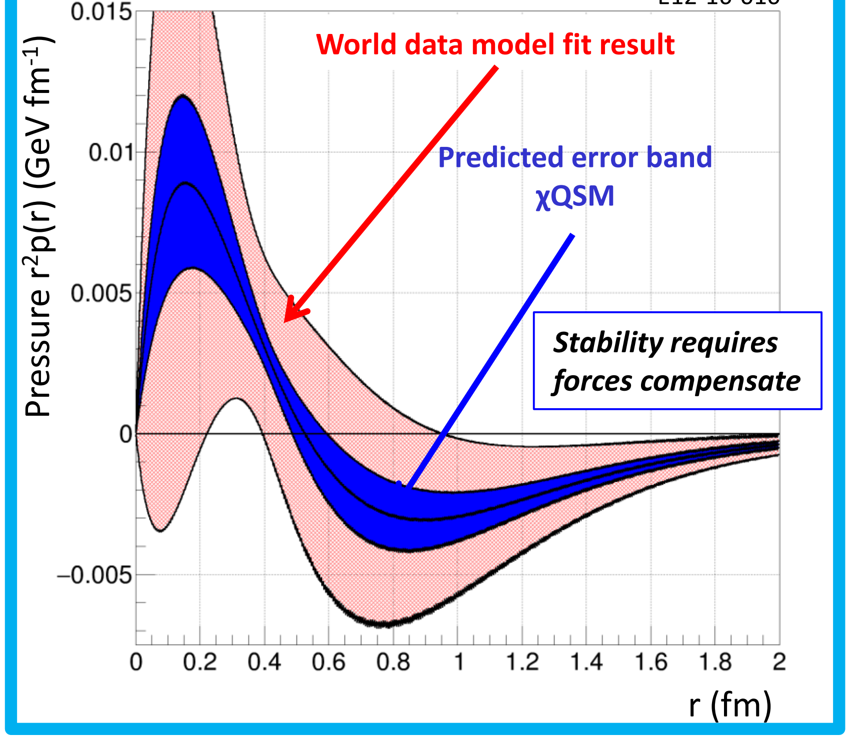


Transverse profile



Pressure Distribution

E12-06-119
E12-16-010



2007-8: GPD E from Jlab 6 GeV and HERMES

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

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

analysis still on going for a Hall-A experiment done in 2010

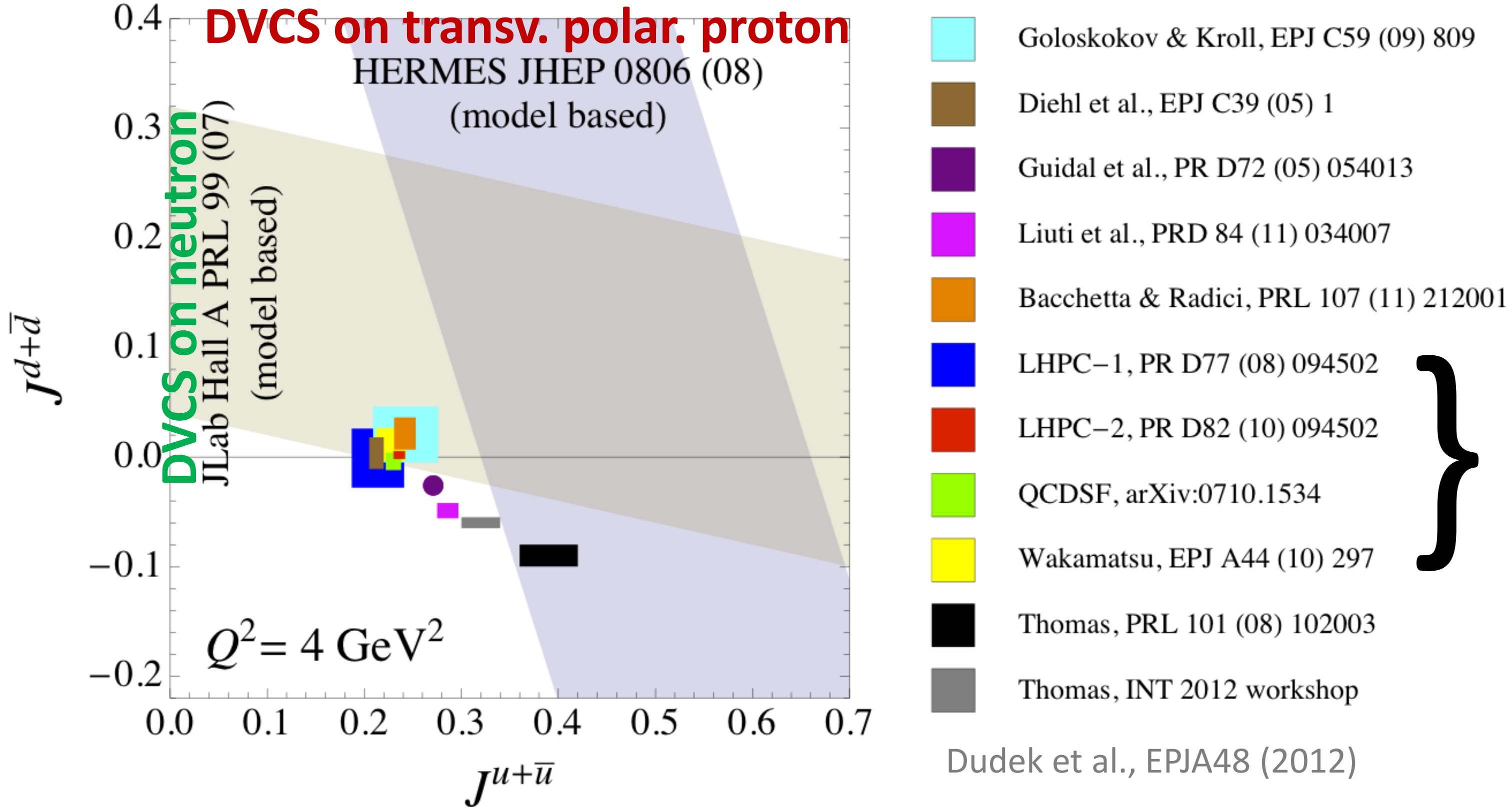
Note: neutron target ➔ quark flavor separation

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

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

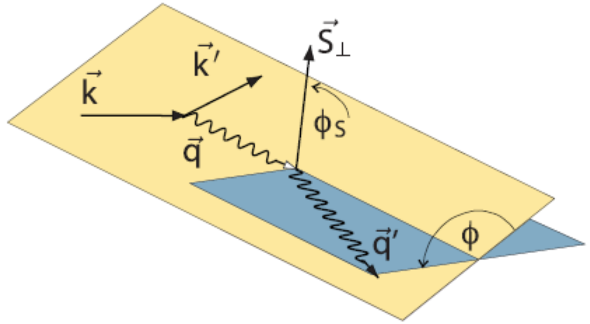
$$\Delta\sigma_{LT}^{\sin(\phi-\phi_s)\cos\phi} = -\, t/4m^2\; Re\,(F_{2p}\,\mathcal{H} - F_{1p}\,\mathcal{E})$$

Model dependent extraction of J^u and J^d



} **LATTICE QCD**

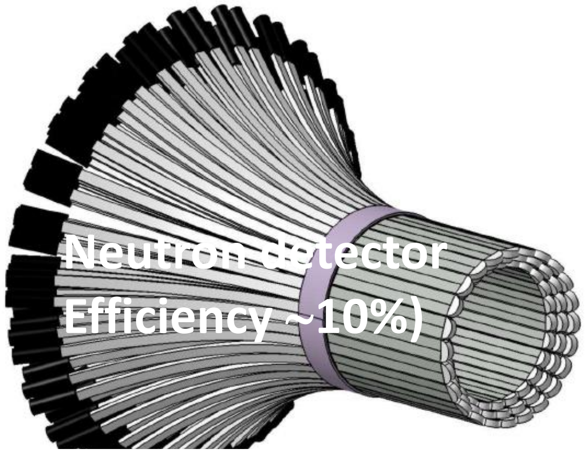
Dudek et al., EPJA48 (2012)



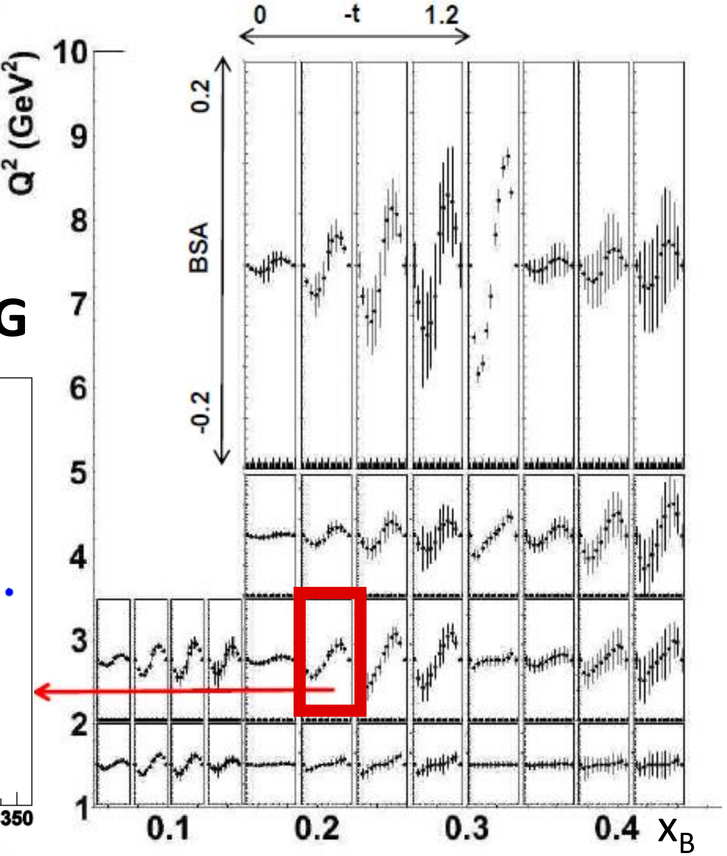
next future: GPD E @ JLab12 with CLAS12

Exp E12-11-003: DVCS on the neutron

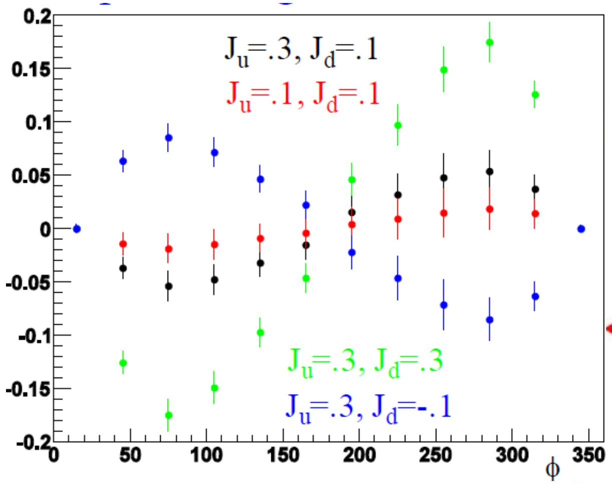
$$\Delta\sigma_{LU}^{\sin\phi} = Im\,(F_{1n}\mathcal{H} + \xi(F_{1n} + F_{2n})\widetilde{\mathcal{H}} + t/4m^2 F_{2n}\mathcal{E})$$



2019: 90 days on LD2 target
Lumi= 10^{35} cm^{-2} s^{-1}/nucleon



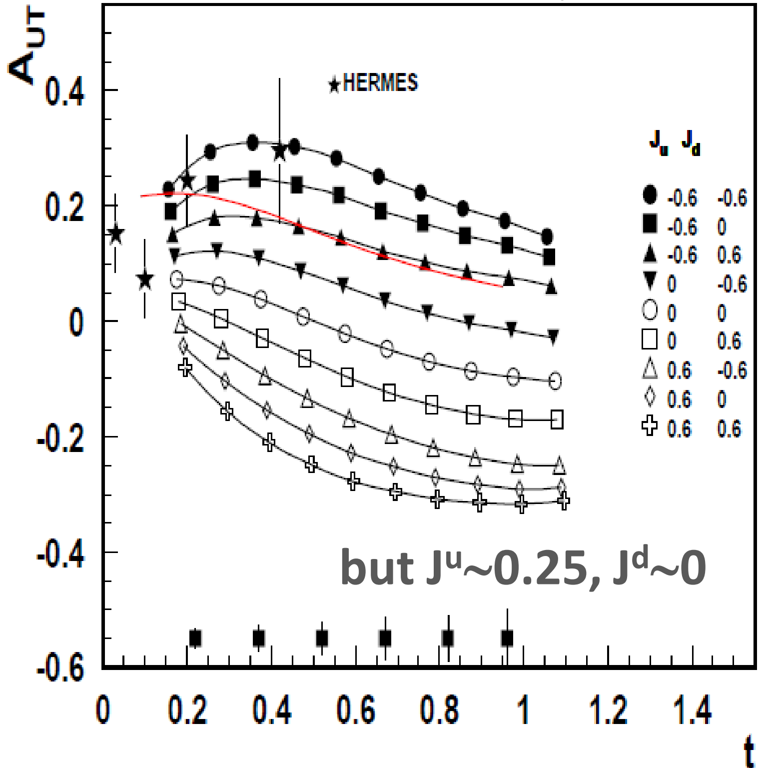
Model prediction using VGG



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

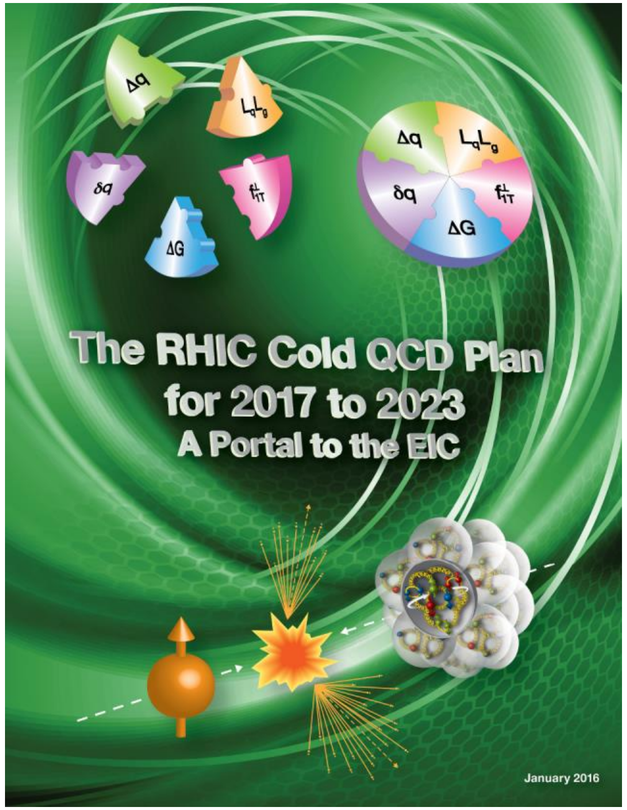
$$\Delta\sigma_{UT}^{\sin(\phi-\phi s)\cos\phi} = -\,t/4m^2\ Im\,(F_{2p}\,\mathcal{H} - F_{1p}\,\mathcal{E})$$
$$\Delta\sigma_{LT}^{\sin(\phi-\phi s)\cos\phi} = -\,t/4m^2\ Re\,(F_{2p}\,\mathcal{H} - F_{1p}\,\mathcal{E})$$

After 2020: 110 days on HD-Ice target
Lumi= 5 x 10^{33} cm^{-2} s^{-1}/nucleon



next future: GPD E_{gluon} @ RHIC in 2017 and 2023

11k J/ψ in 2017 ($p^{\uparrow}$ p @ 510 GeV) analysis on going
13k J/ψ in 2023 ($p^{\uparrow}$ Au @ 200 GeV)
Important input for the photoproduction of J/ψ at EIC



Ultra Peripheral Collisions to access the Generalized Parton Distribution **E_{gluon}**

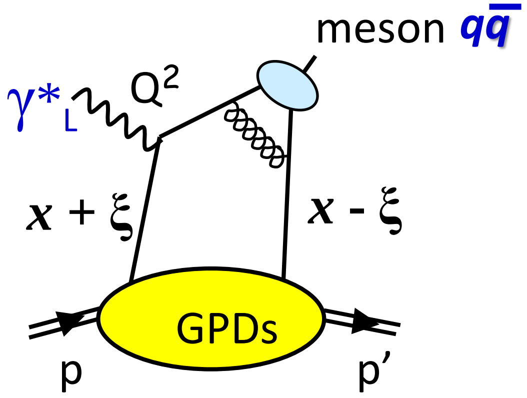
Two key questions, which need to be answered to understand overall nucleon properties like the spin structure of the proton, can be summarized as:

- 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?

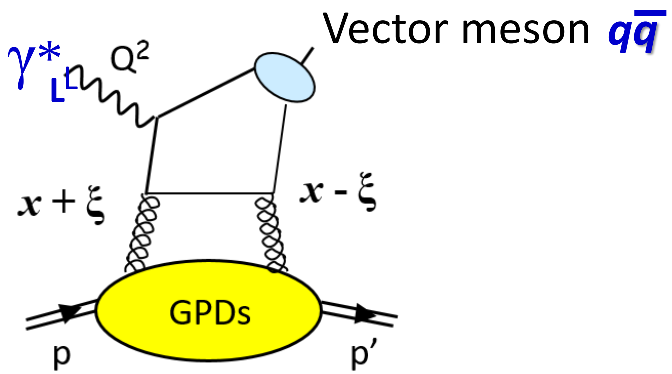
.... RHIC, with its capability to collide transversely polarized protons at $\sqrt{s}$=500 GeV, has the unique opportunity to measure A_N for exclusive J/ψ in ultra-peripheral $p^{\uparrow}$+p collisions (UPC) [99]. The measurement is at a fixed Q^2 of 9 GeV^2 and $10^{-4} < x < 10^{-1}$. A nonzero asymmetry 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. ....

GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution at the same order in α_S



The meson wave function
Is an additional non-perturbative term

4 chiral-even GPDs: helicity of parton unchanged

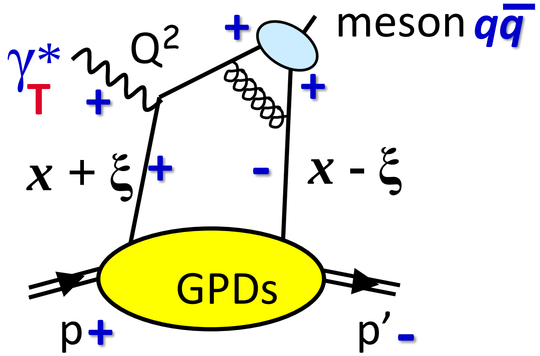
$H^q(x, \xi, t)$	$E^q(x, \xi, t)$	**For Vector Meson**
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$	**For Pseudo-Scalar Meson**

+ 4 chiral-odd or transversity GPDs: helicity of parton changed
(not possible in DVCS)

$H_T^q(x, \xi, t)$	$E_T^q(x, \xi, t)$	$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$
$\tilde{H}_T^q(x, \xi, t)$	$\tilde{E}_T^q(x, \xi, t)$	

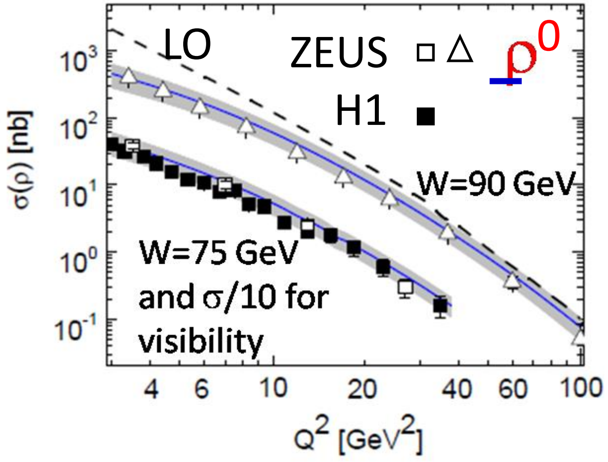
Factorisation proven only for σ_L
σ_T is asymptotically suppressed by $1/Q^2$ but large contribution observed
model of σ_T with transversity GPDs - divergencies regularized by k_T of q and $\bar{q}$ and Sudakov suppression factor

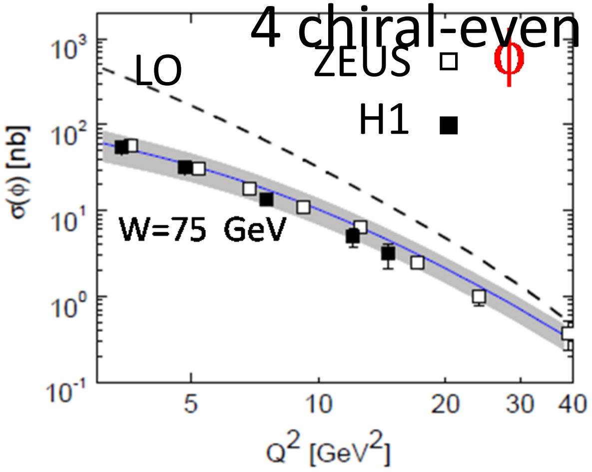
$\mathfrak{M}_{0-,++}$ sensitive to H_T^q
and to a twist-3 meson wave function

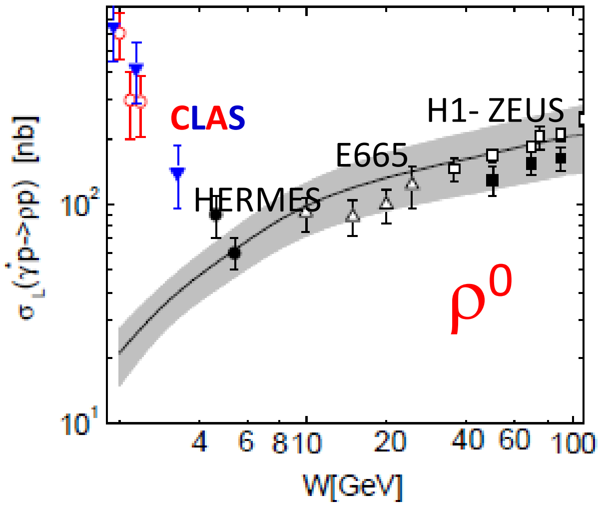


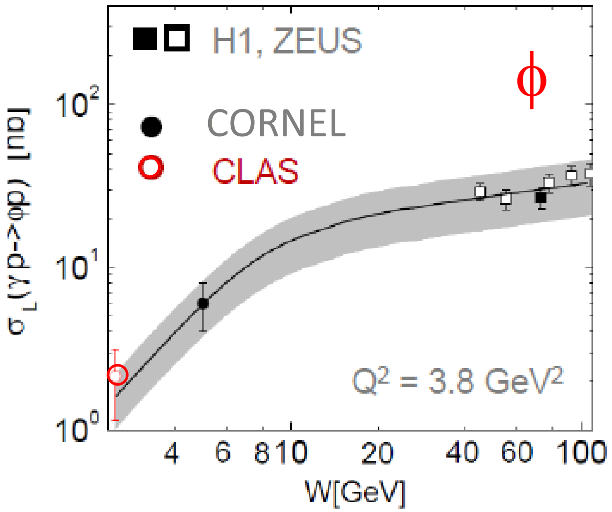
GPDs and Hard Exclusive Meson Production

4 chiral-even GPDs: helicity of parton unchanged



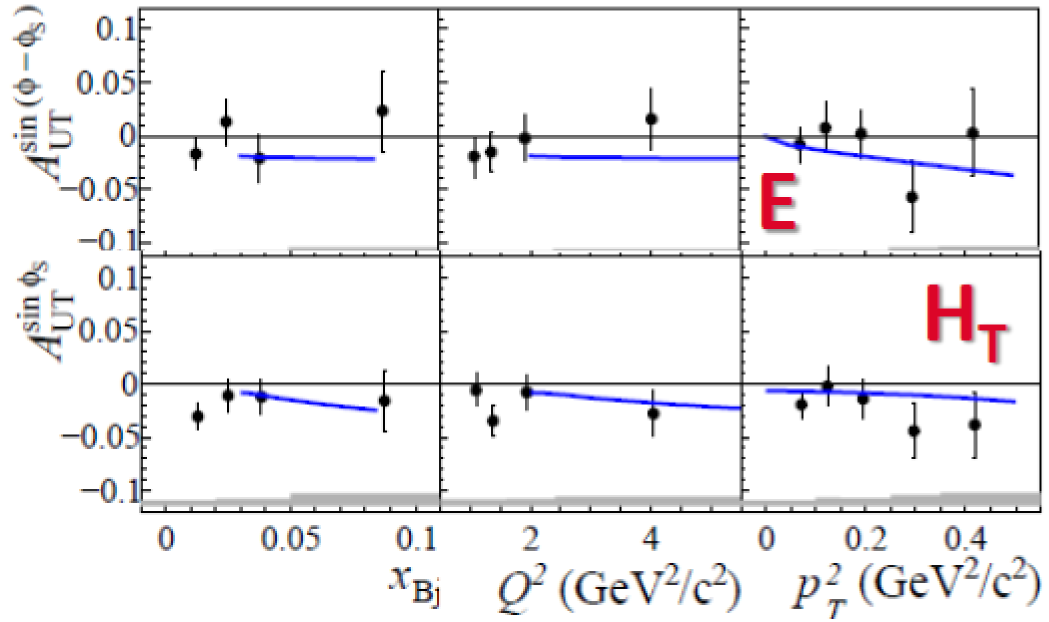






ρ^0 ($\rightarrow \pi^+\pi^-$) production at COMPASS
with Transversely Polarized Target

COMPASS, NPB 865 (2012) 1-20, PLB731 (2014) 19



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

GPDs and Hard Exclusive π^0 Production

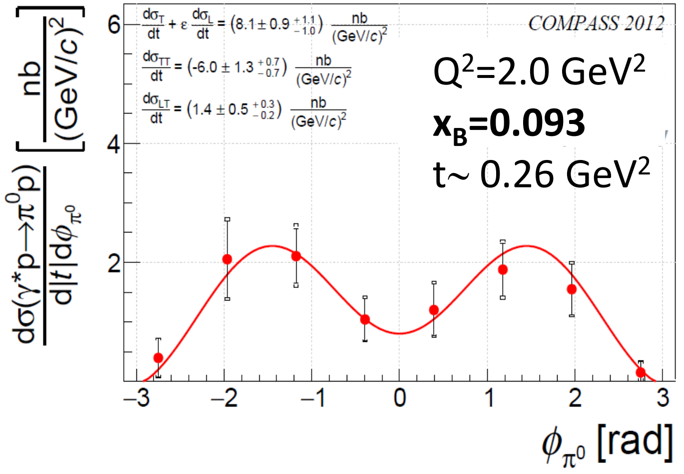
$e\, p \rightarrow e\, \pi^0\, p$

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

$$\left|\langle\tilde{H}\rangle\right|^2-\frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2 \qquad \left|\langle H_T\rangle\right|^2-\frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2 \qquad \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2 \qquad \frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

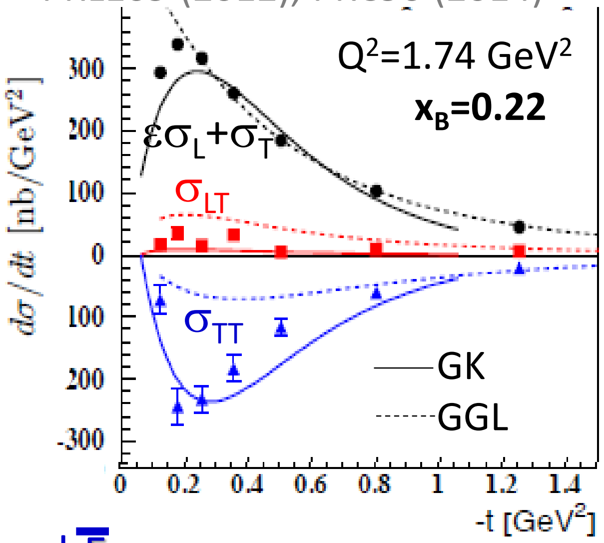
COMPASS 4 weeks 2012 pilot run

hep-ex/1903.12030, subm. to PLB



Jlab 6 GeV CLAS

Bedlinskiy et al, PRL109 (2012), PRC90 (2014)



σ_{TT} large (impact of H_T and $\bar{E}_T$)

σ_{LT} smaller but significantly positive

Jlab 6 GeV Hall-A

Different beam energies

➔ L/T separation

LH2 target ➔ proton

LD2 target ➔ neutron+deuteron

D(e,eπ^0)X - p(e,eπ^0)p = n(e,eπ^0)n + d(e,eπ^0)d

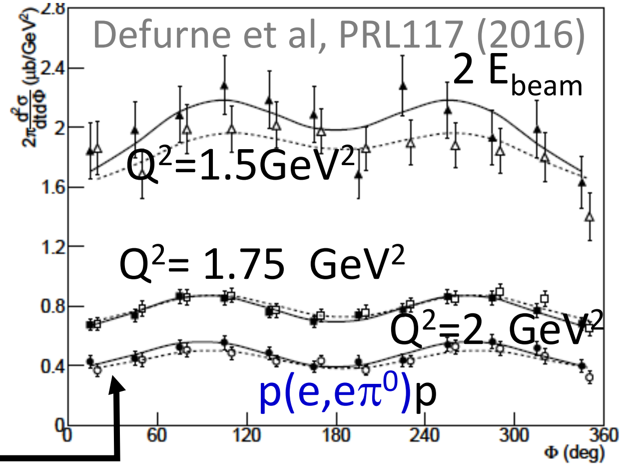
➔ Flavor decomposition

H_T^u and H_T^d

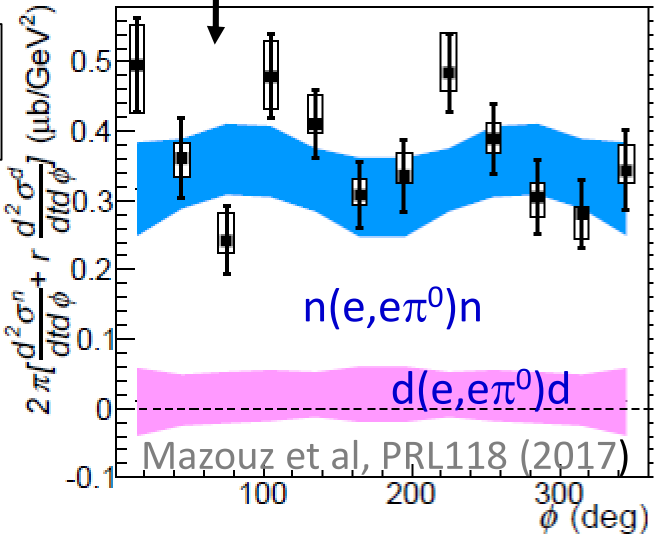
$\bar{E}_T^u$ and $\bar{E}_T^d$

x_B=0.36

t~ 0.18 GeV^2

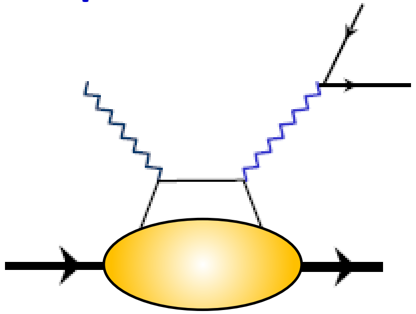


Q^2=1.75 GeV^2

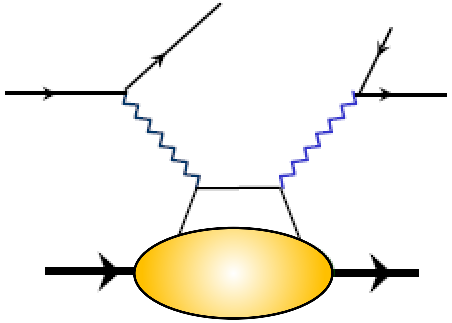


And other paths to get GPDs

Study of protons and neutrons



Time Like Compton Scattering



Double DVCS

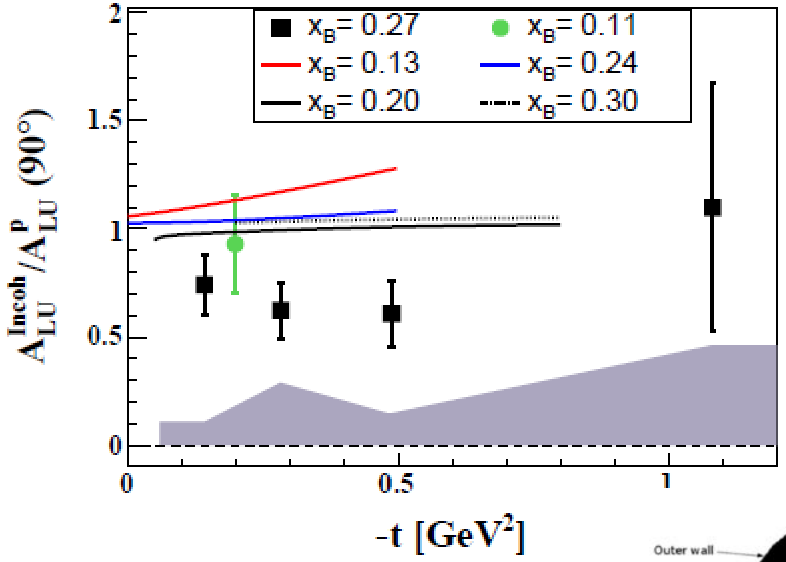
Projects which start to be explored with the high lumnosity of JLab12 (in Hall-C or with CLAS12 and Solid)

Study of nuclei

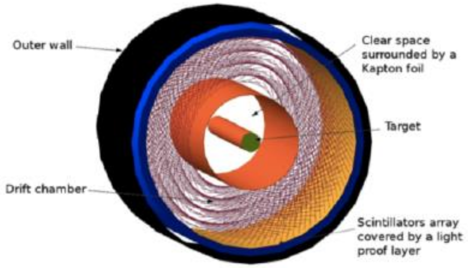
(HERMES, JLab6, JLab12)

First measurement on He4: Hattawy, PRL119 (2017)
Spin 0 target, one chiral even GPD

Off bound protons: Hattawy, arXiv:1812.07628, sub to PRL



Other projects with the recoil detecteur ALERT



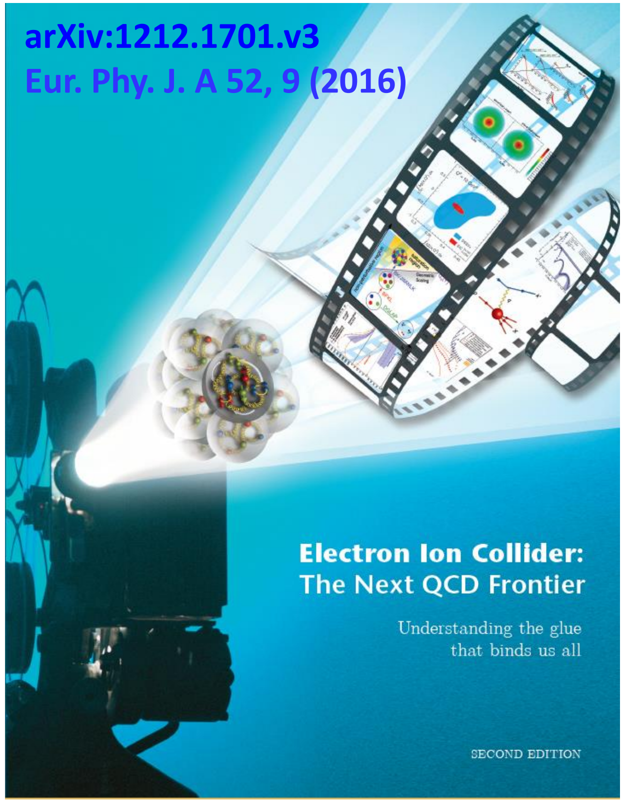
Future: Key measurements for imaging partons with EIC

Stage 2
Ee=20 GeVEp=250 GeV

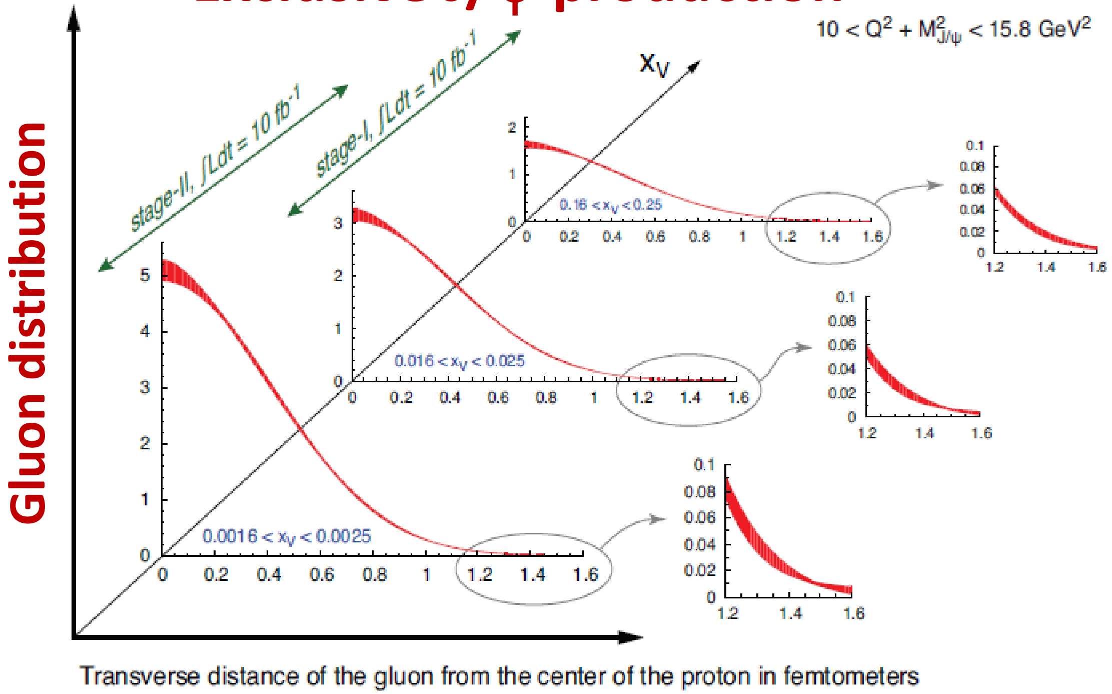
Stage 1
Ee=5 GeVEp=100 GeV

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 $100\, \text{fb}^{-1}$; Roman Pots; polarized e^- and p beams; wide range of x_B and Q^2; range of beam energies; e^+ beam valuable for DVCS
GPDs of valence and sea quarks	electroproduction of π^+, K and ρ^+, K^*	dependence on quark flavor and polarization	

arXiv:1212.1701.v3
Eur. Phy. J. A 52, 9 (2016)



Exclusive J/ψ production



Conclusions

Jlab 12 GeV with the high luminosity electron beam
at the beginning of a very exciting time
For high precision era
For 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

EIC

RHIC (STAR/sPHENIX)

COMPASS
DVCS: 2x6 months

COMPASS++/AMBER
M2 beam line @ CERN