Generalized Parton Distributions at COMPASS : Present results and future perspectives

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On behalf of COMPASS Collaboration

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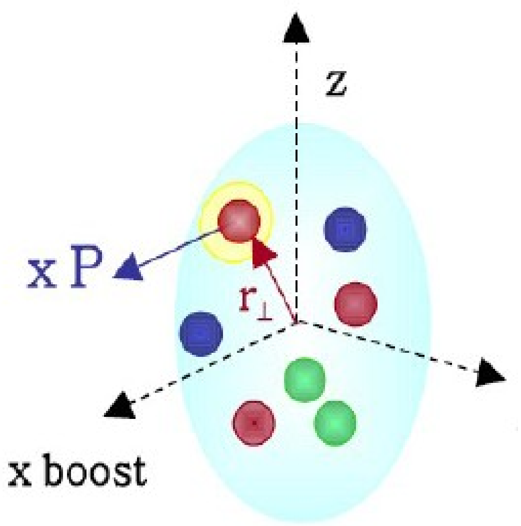
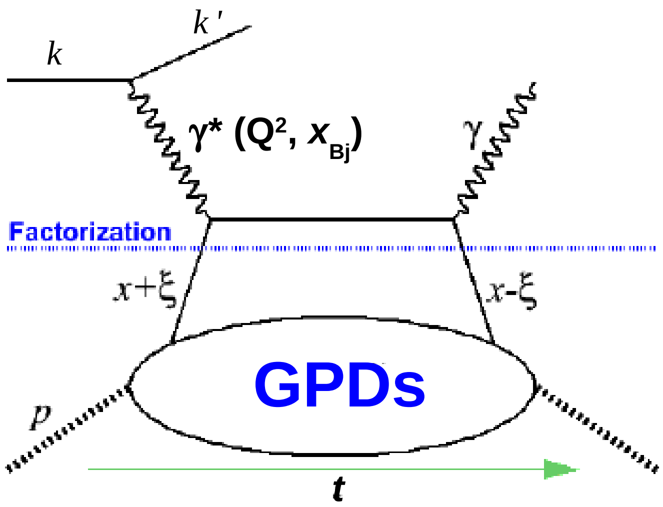
Generalized Parton Distributions (GPDs) :
3D Structure of nucleon



Exclusive production (DVCS, DVMP)



=> Correlation $r_\perp \leftrightarrow$ xP

=> **Quark orbital angular momentum**

4 Chiral-even GPDs: H, E, $\tilde{H}, \tilde{E}$

+ 4 chiral-odd: $H_T, E_T, \tilde{H}_T, \tilde{E}_T$

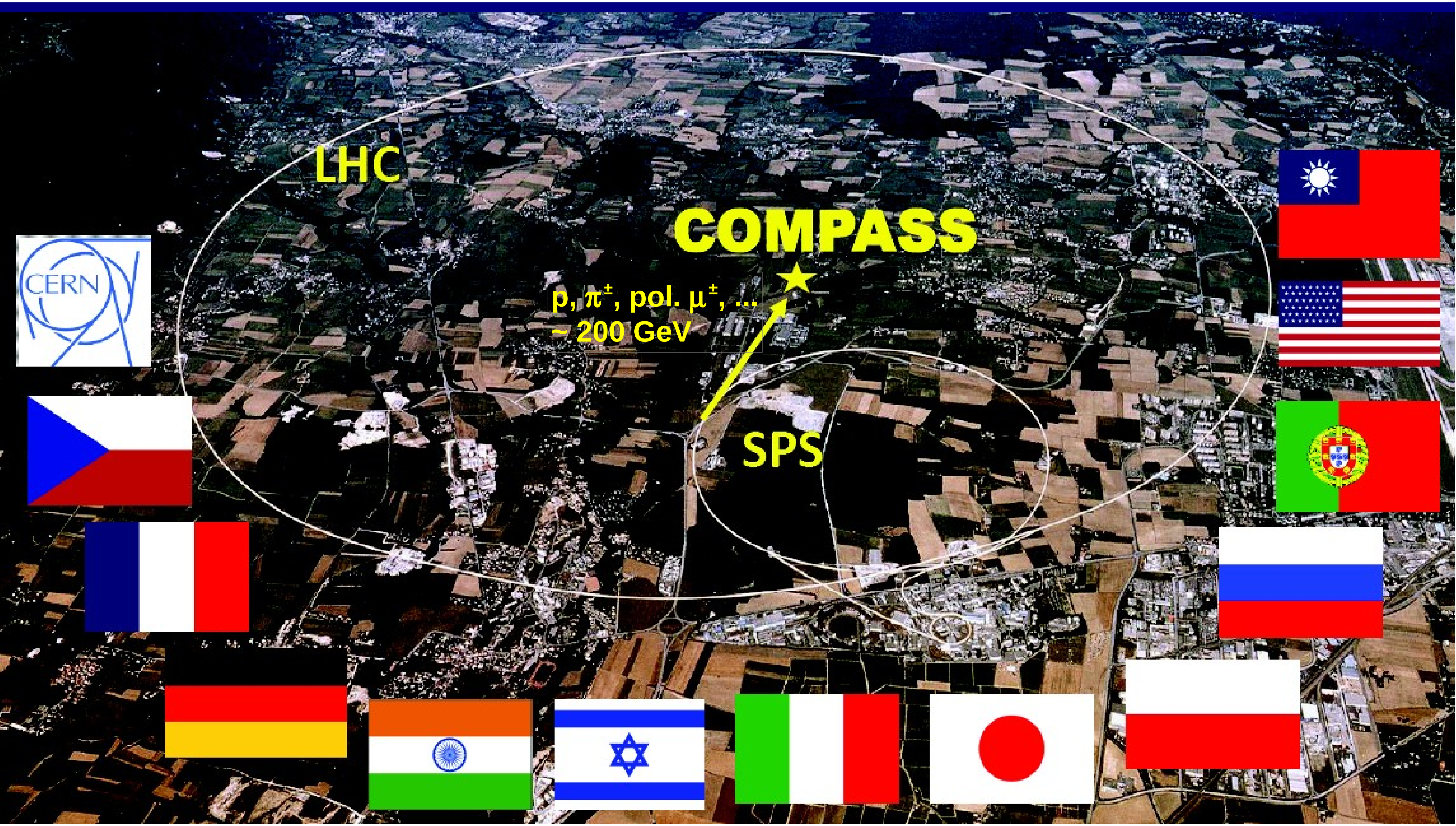
Factorization proved for:

$Q^2 \to \infty$, $t \ll Q^2$, x_{Bj} **finite**

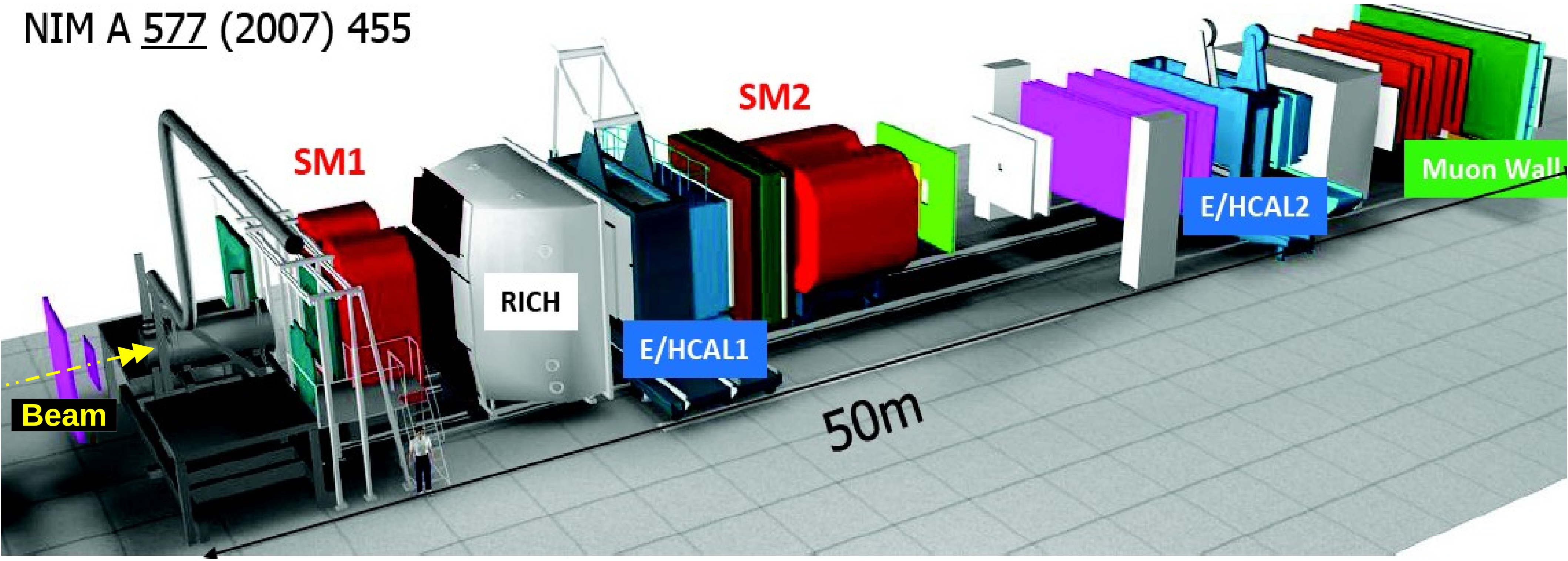
(*Bjorken regime*)

The COMPASS experiment:

Large acceptance spectrometer for hadronic physics at CERN



The COMPASS experiment:
Experimental setup

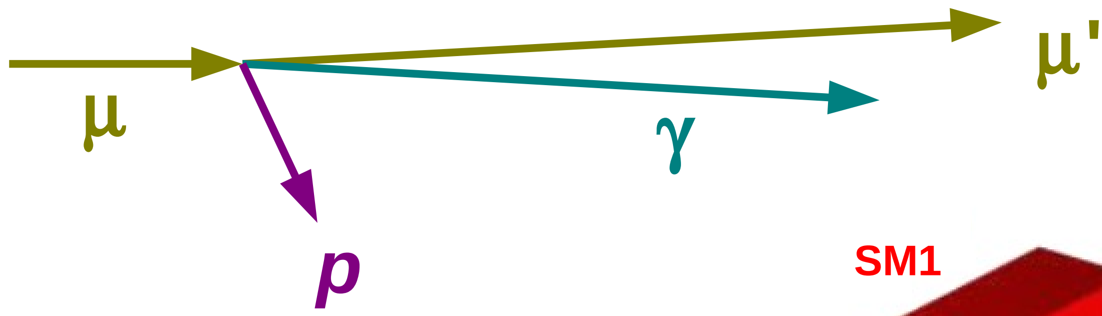


*** Tracking: DCs, GEMs, MM + 2 dipoles ($|\vec{p}|$);**

*** Particle ID: RICH + Ecals (E);**

Additional setup for DVCS
(and other exclusive channels)

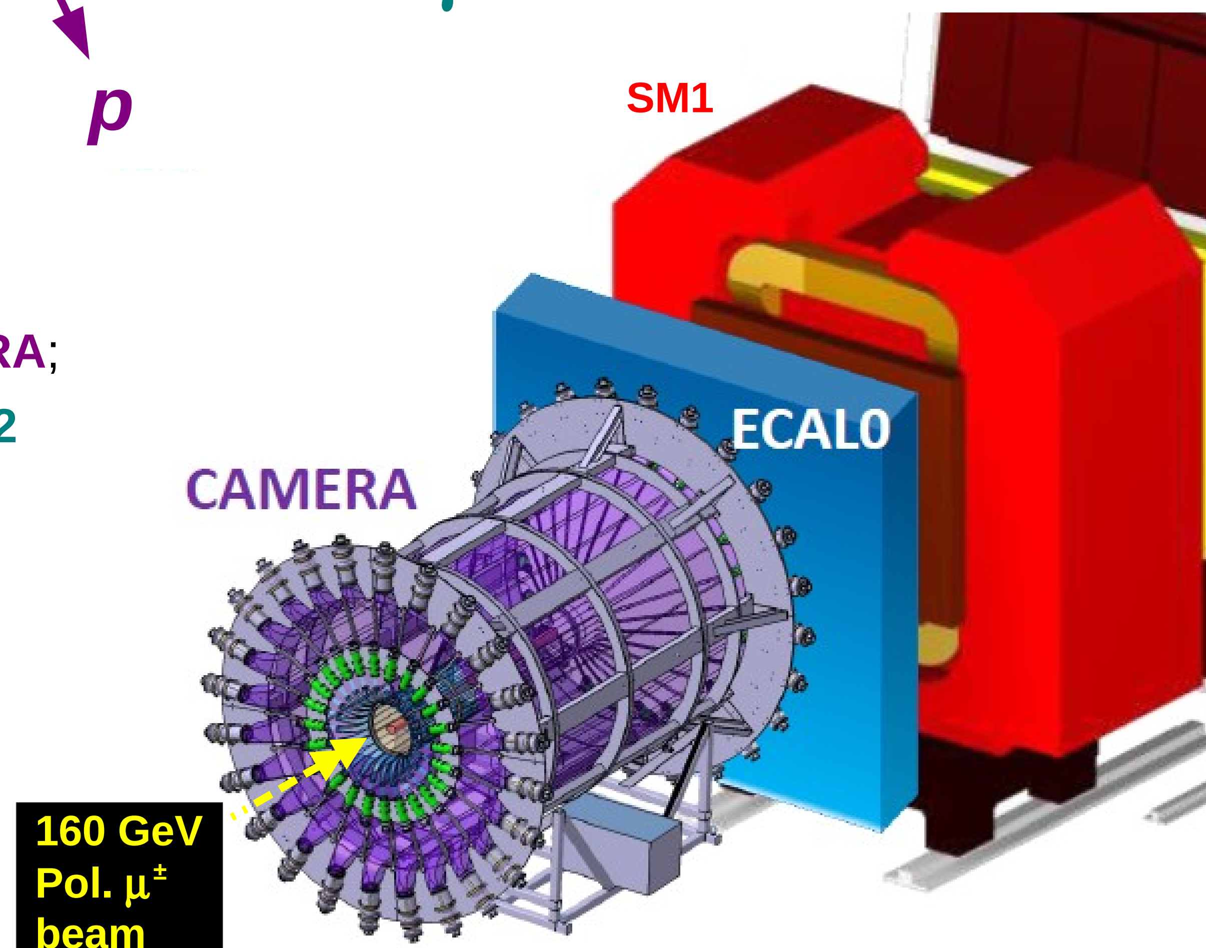
$\mu p \rightarrow \mu p \gamma$



Target: 2.5m LH_2;

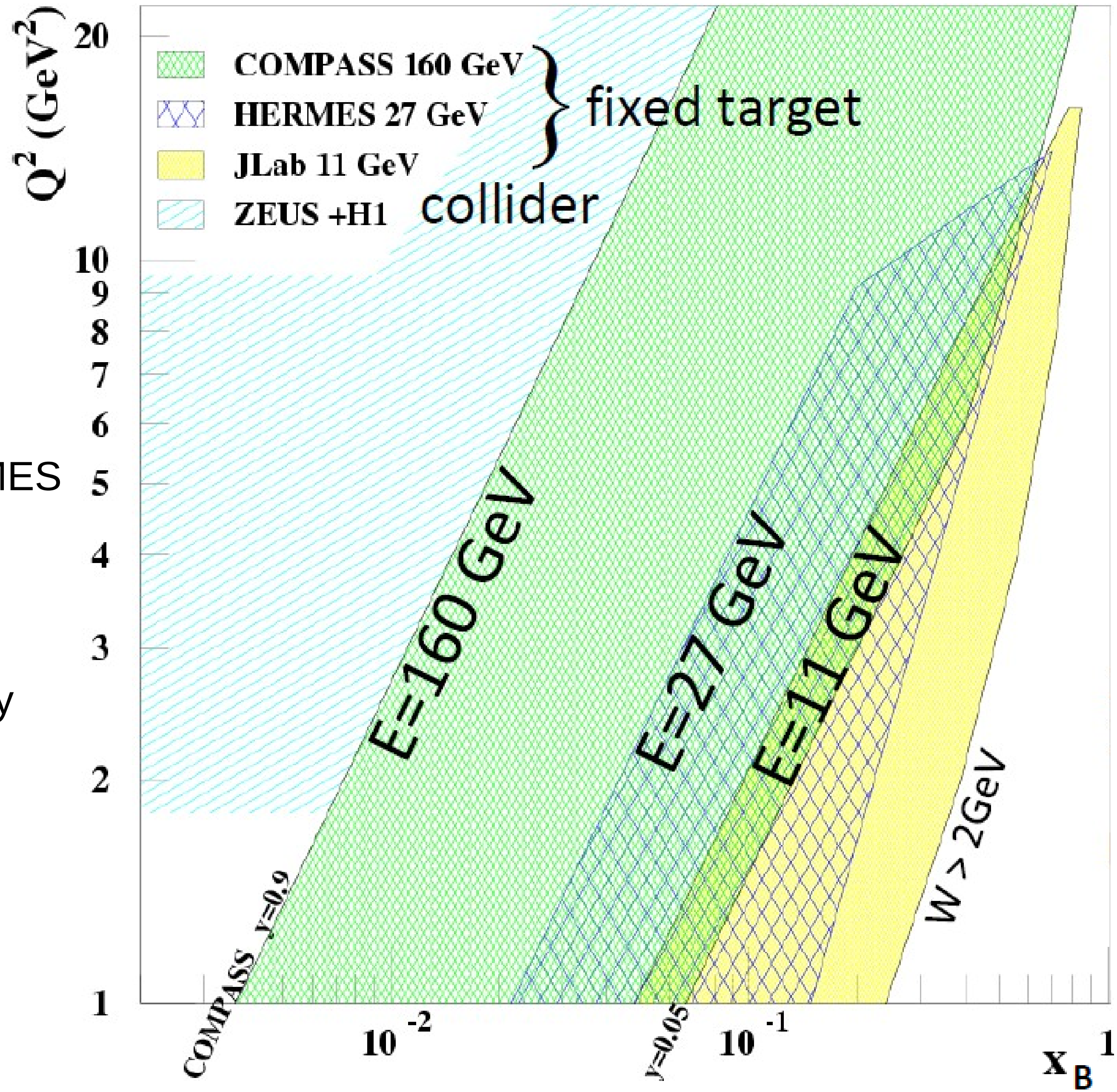
***p_{Recoil}*: 4m ToF detector CAMERA**;

γ: ECAL0 (cover higher x_B), **1**, **2**



Compass assets for GPD study

- *Both* $\vec{\mu}^+$ and $\overleftarrow{\mu}^-$ available (*currently unique*);
- GPDs in ***large*** kinematic region **(0.005 < x_{Bj} < ~0.3)**
  => *Complementary* of
  DESY :ZEUS, H1, (gluons), HERMES
  Jefferson Lab (valence);
- COMPASS + Jefferson Lab:
  only current facilities for GPD study before future Electron-Ion Collider;
- Versatile: Capable to record DVCS *and* DVMP (π^0, ρ, ω, ϕ)



DVCS on unpolarized p:

Study of GPD *H*

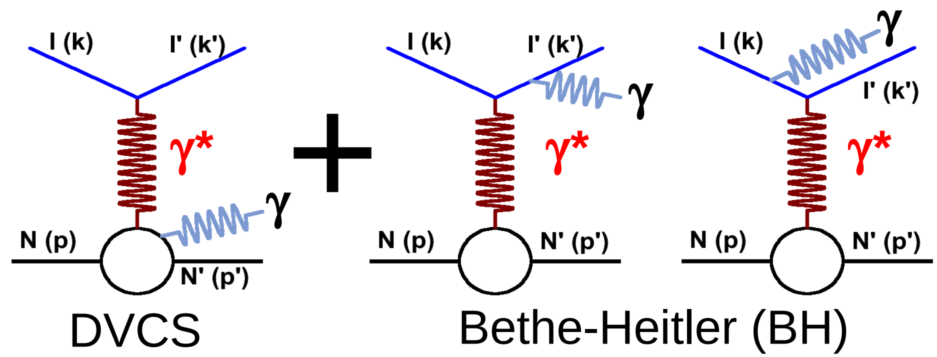
2009: Test run
2012: Pilot run
2016-17: Data run

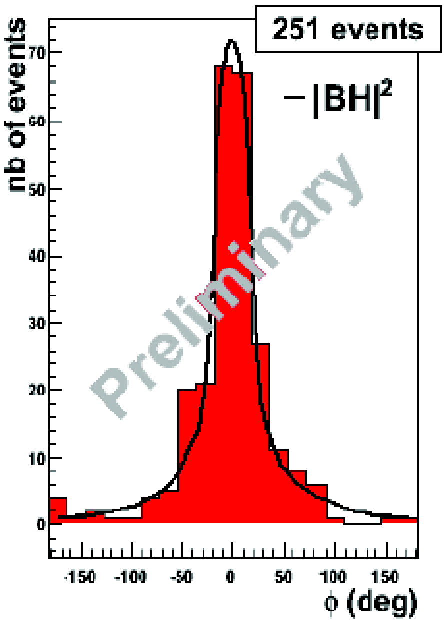
GPD **H**
2009
2012
2016-17

DVCS Test run

(10 days, 40 cm LH_2 target, short RPD, No Ecal0)

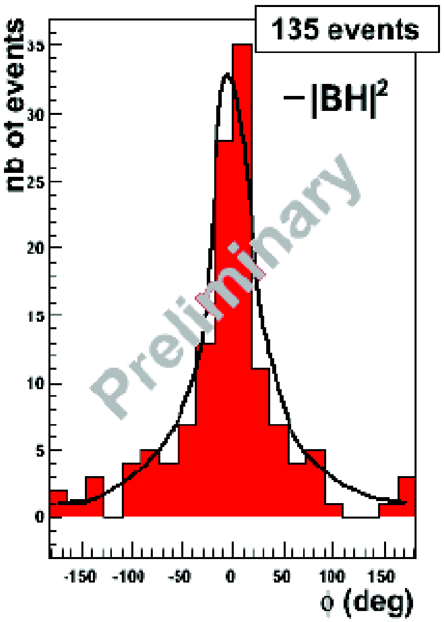
$$\sigma^{ep\to ep\gamma} \propto |BH|^2 + |DVCS|^2 + 2|BH||DVCS|$$





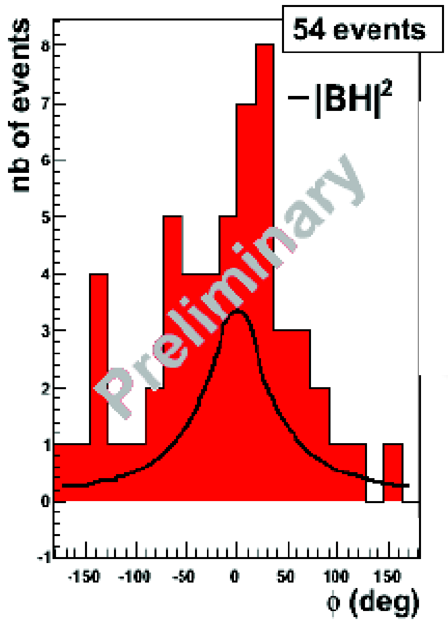
(0.005 < x_{Bj} < 0.01)

BH dominant,
DVCS negligible



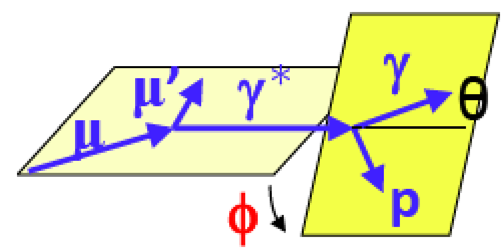
(0.01 < x_{Bj} < 0.03)

DVCS-BH
interference

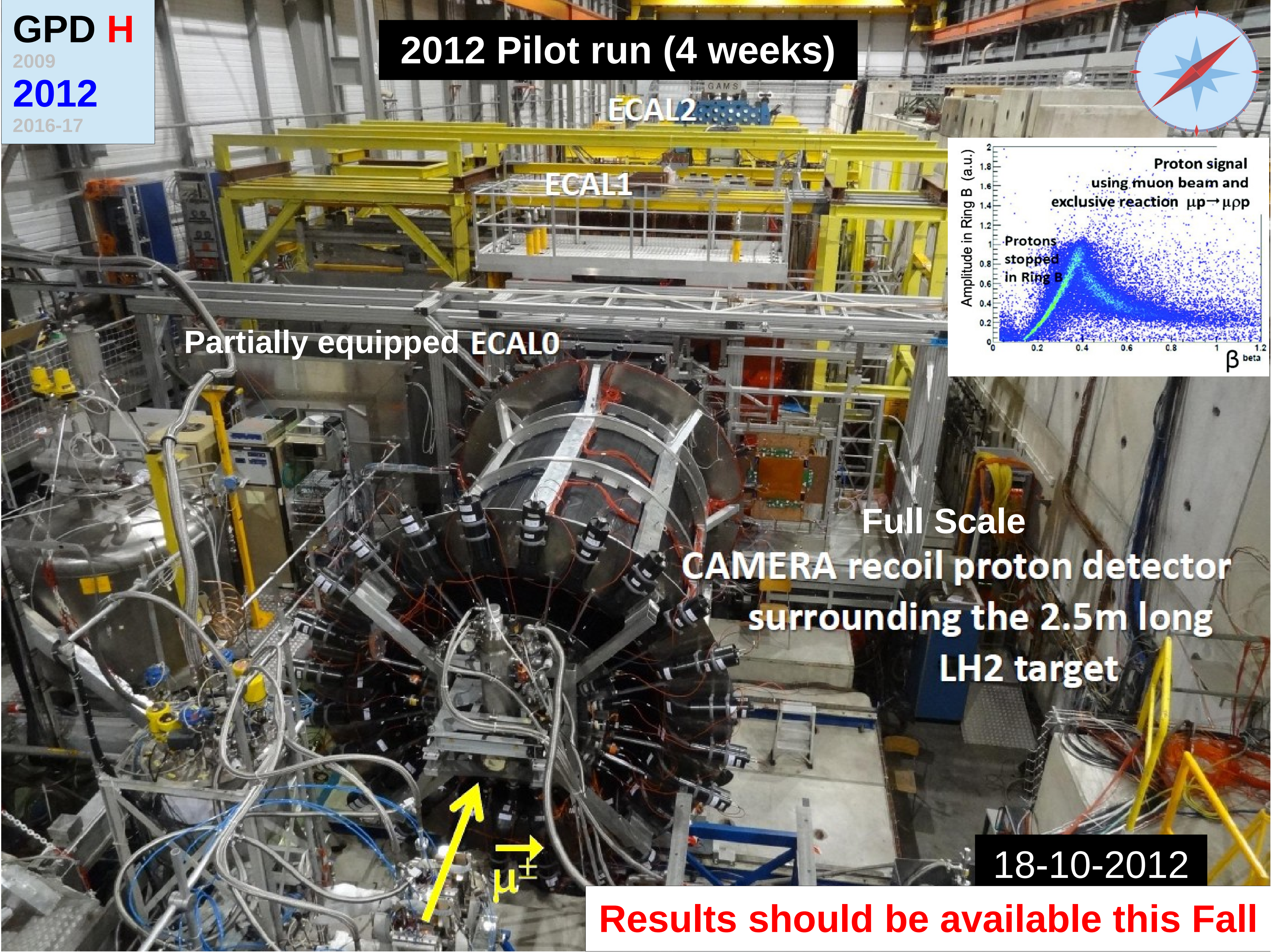


(x_{Bj} > 0.03)

DVCS significant



DVCS not flat ar large x
→ Necessity of ECAL0

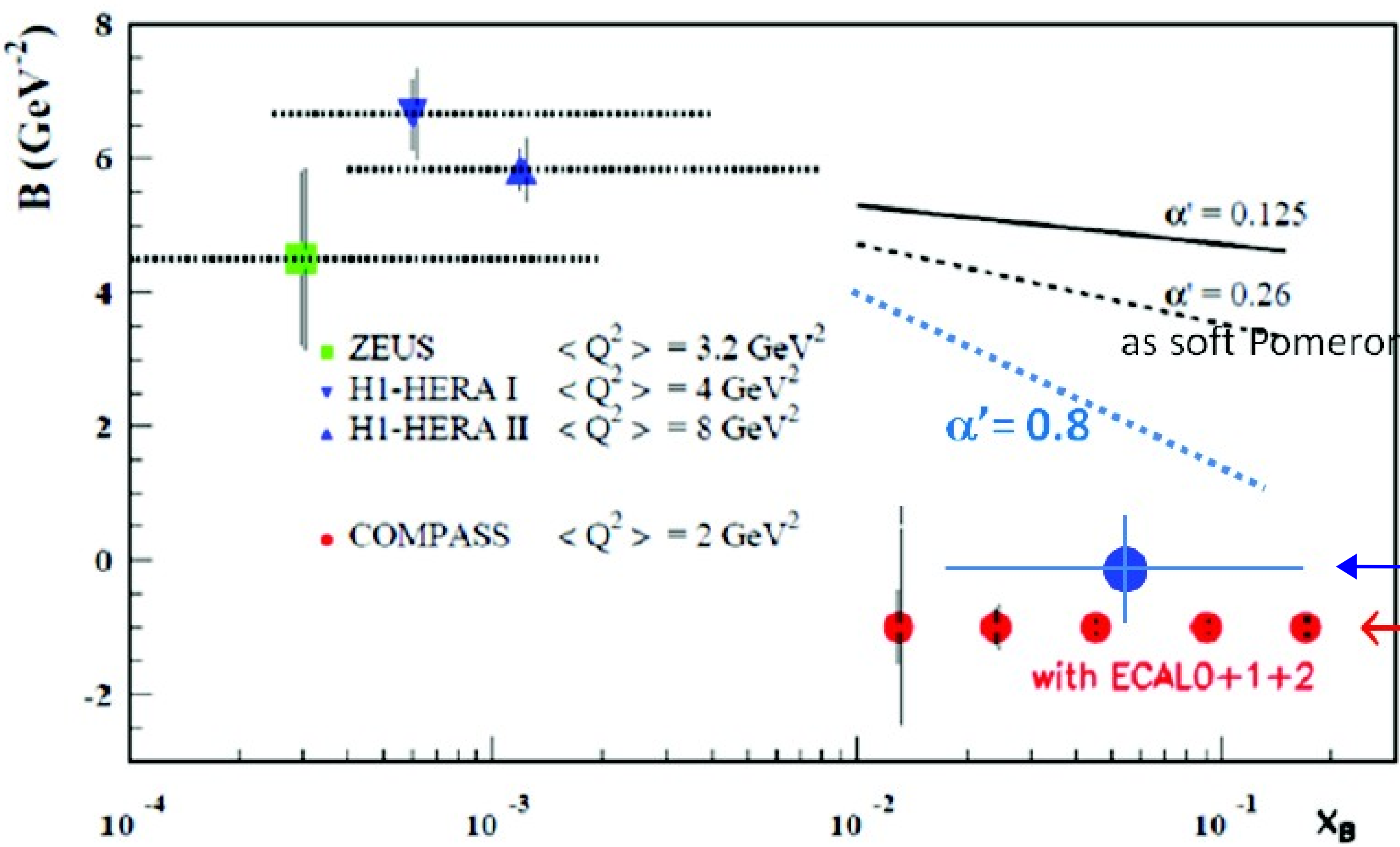

GPD H
2009
2012
2016-17
2012 Pilot run (4 weeks)
ECAL2
ECAL1
Partially equipped ECAL0
Proton signal
using muon beam and
exclusive reaction μp→μρp
Protons
stopped
in Ring B
Amplitude in Ring B (a.u.)
β beta
Full Scale
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
μ±
18-10-2012
Results should be available this Fall

Compass GPD program

DVCS on H_2 target: Proton size; Study of GPD H

Spin and **charge** cross section **Sum** (Currently *unique* COMPASS feature)

$$S_{CS,U} \equiv d\sigma(\overleftarrow{\mu}^{+}) + d\sigma(\overrightarrow{\mu}^{-}) \rightarrow d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$



$B(x_{Bj}) = ½ <r_\perp^2>$

4 weeks in 2012

2 years of data **(2016-17)**

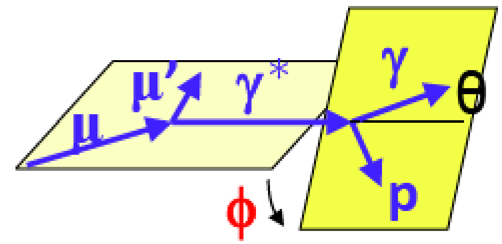
GPD **H**
2009
2012
2016-17

Compass GPD program
DVCS on H_2 target: Study of GPD H

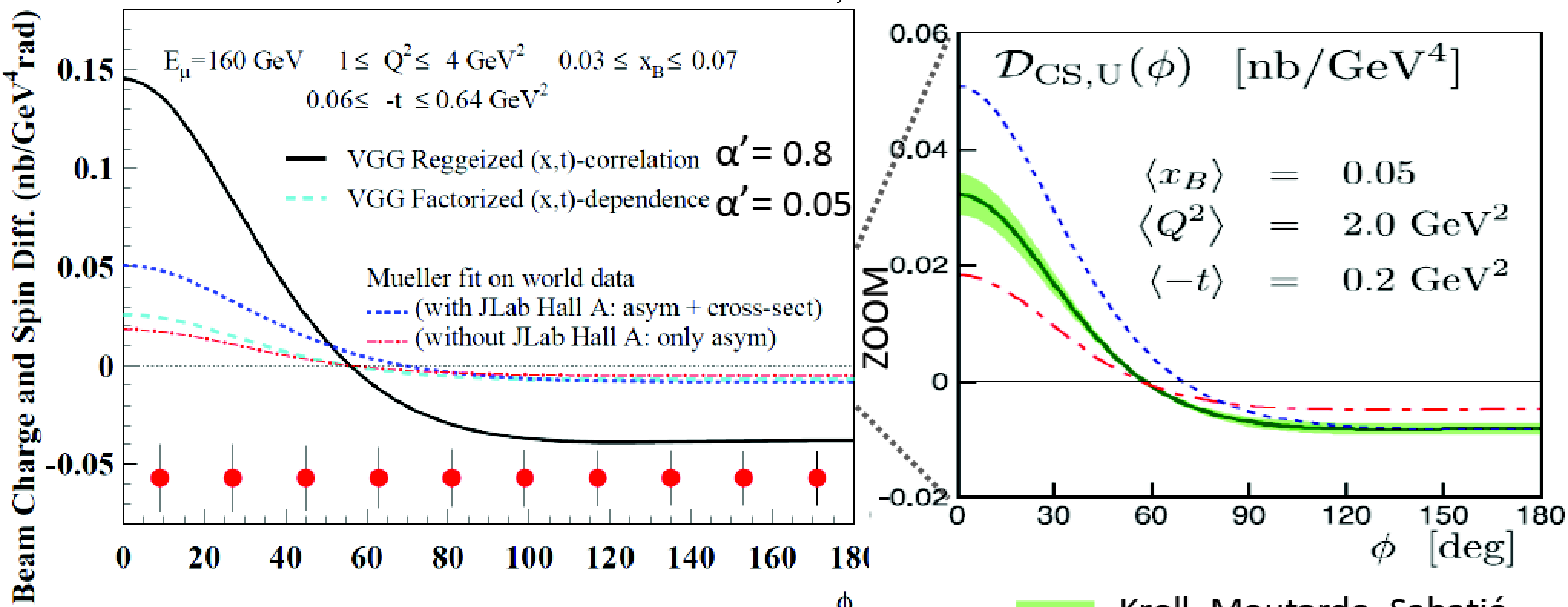
Spin and **charge** cross section **Difference** (Currently *unique* COMPASS feature)

$$\mathbf{D}_{CS,U} \equiv d\sigma(\overset{\rightarrow}{\mu}^{+}) - d\sigma(\overset{\leftarrow}{\mu}^{-}) \propto c_0^{Int} + c_1^{Int}\cos(\phi)$$

$$c_1^{Int} \propto \mathrm{Re}(F_1 \mathcal{H})$$



CFFs $\mathcal{H}$ accesed through ϕ modulation of $\mathbf{D}_{CS,U}$



Predictions for 2 years of data taking (2016-17)

Kroll, Moutarde, Sabatié
EPJC 73 (2013) 2278

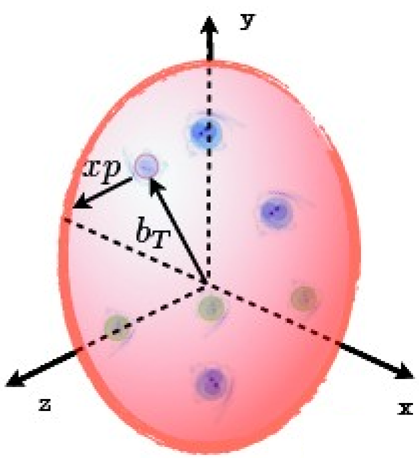
DVCS, DVMP on *polarized* $p^{(\uparrow\downarrow)}$:

Study of GPD *E*

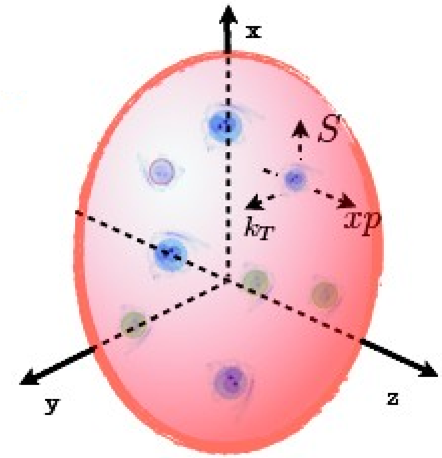
2007-10: $\mu p^{\uparrow\downarrow} \rightarrow \mu p \rho$

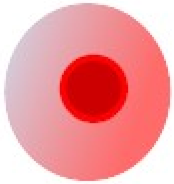
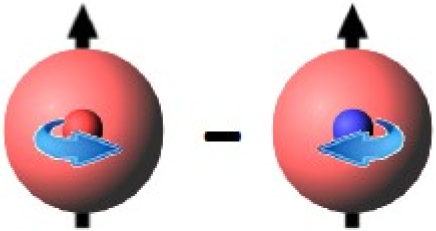
> 2018: $\mu p^{\uparrow\downarrow} \rightarrow \mu p \gamma$

GPDs (x, b_T)



TMDs (x, k_T)

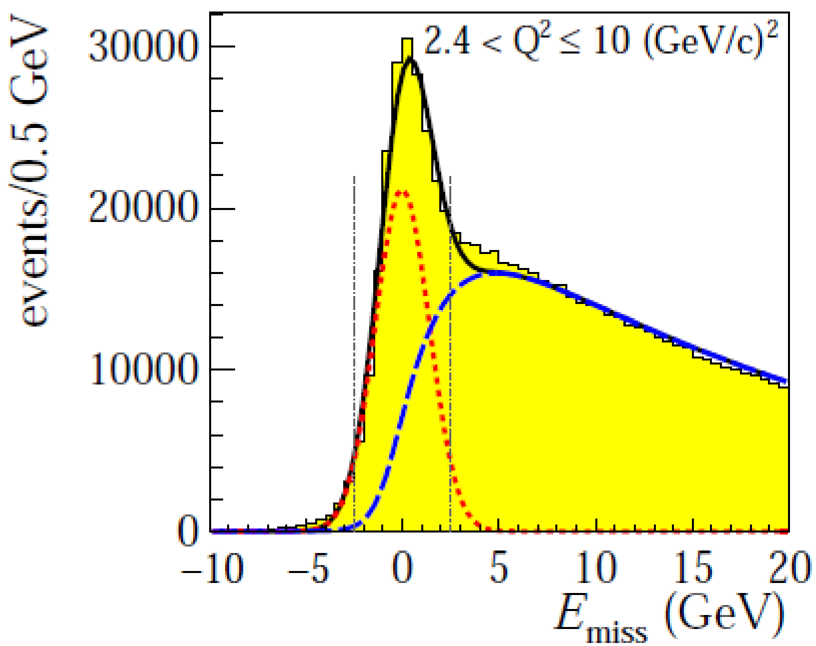


	GPD		TMD	
$\gamma^*_L\, p^{\uparrow} \rightarrow \rho_L\, p^{\uparrow}$	H	<=>	q (PDF)	
$\gamma^*_L\, p^{\uparrow} \rightarrow \rho_L\, p^{\downarrow}$	E	<=>	$f_{1T}^{\perp}$	
	Nucleon spin flip		**Sivers** Quark k_T, Transversely pol. nucleon	

$\mu p \to \mu p\rho$ on *transversely polarized* proton target

"Phase I" COMPASS setup; *No Recoil Proton Detector*

=> $\mu p \to \mu p\rho$ detected in $H^{\uparrow\downarrow}(\mu, \mu'\,\pi^+\pi^-)X \equiv p$;
=> exclusivity ensured by a "missing mass" technique;

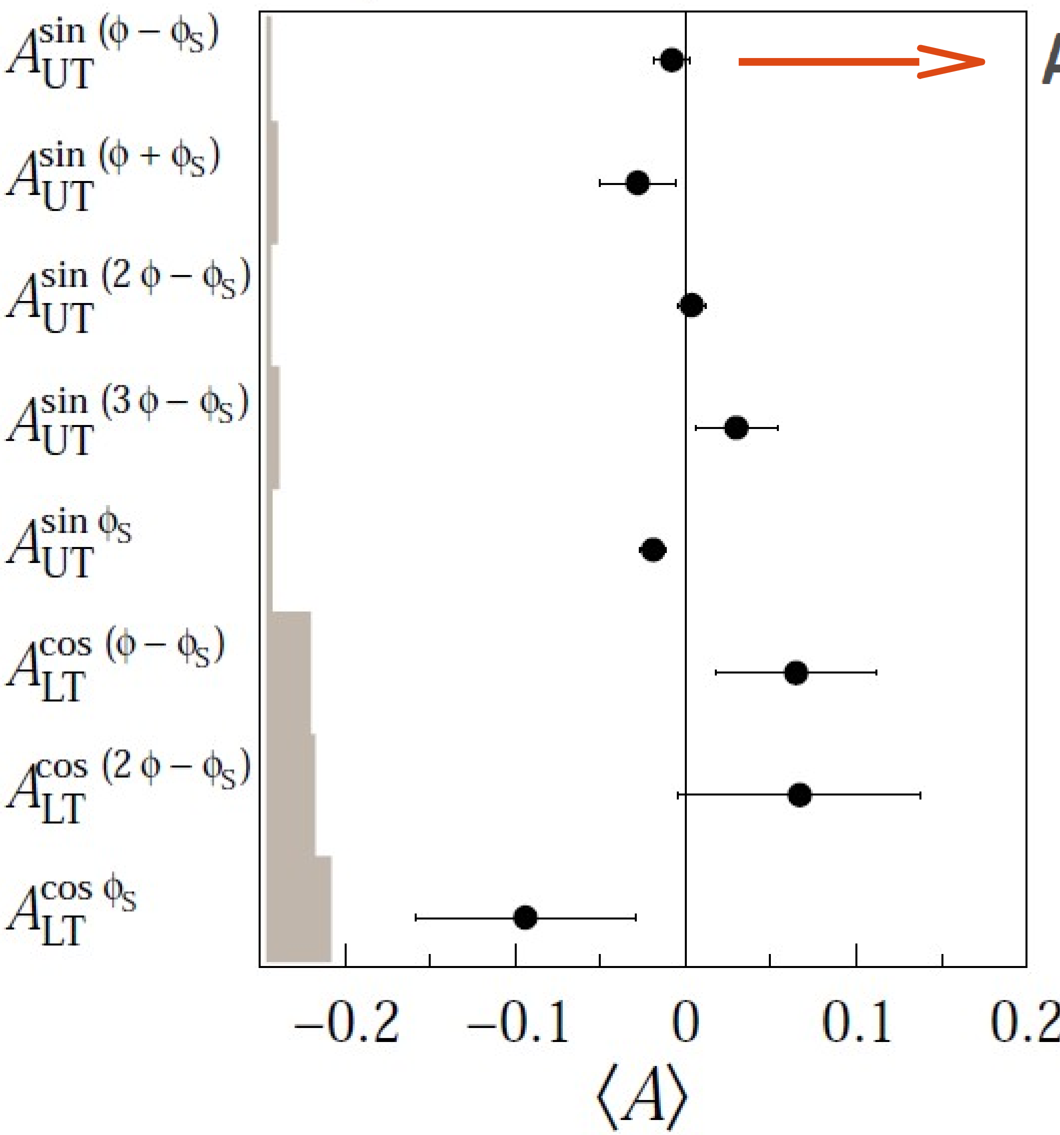


$$E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$$

Transverse Target spin asymmetries for $\mu p^{\uparrow\downarrow} \rightarrow \mu p \rho$

[COMPASS Coll., PL**B731**, 19-26 (2014)]

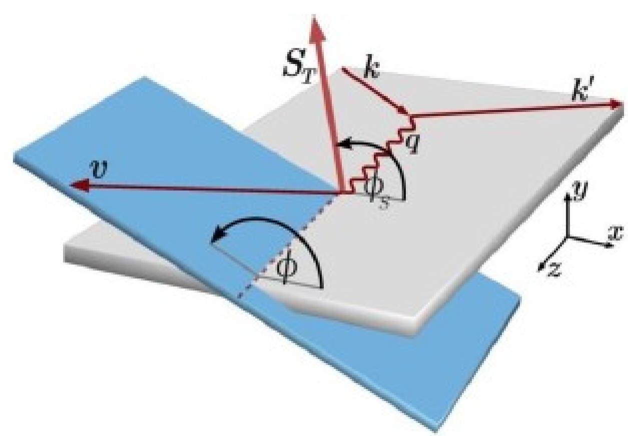
$W = 8.1\ \mathrm{GeV}/c^2,\ p_T^2 = 0.2\ (\mathrm{GeV}/c)^2,\ Q^2 = 2.2\ (\mathrm{GeV}/c)^2$



$A_{UT}^{\sin(\phi-\phi_s)} \propto Im(\mathcal{E}^* \mathcal{H})$ => small

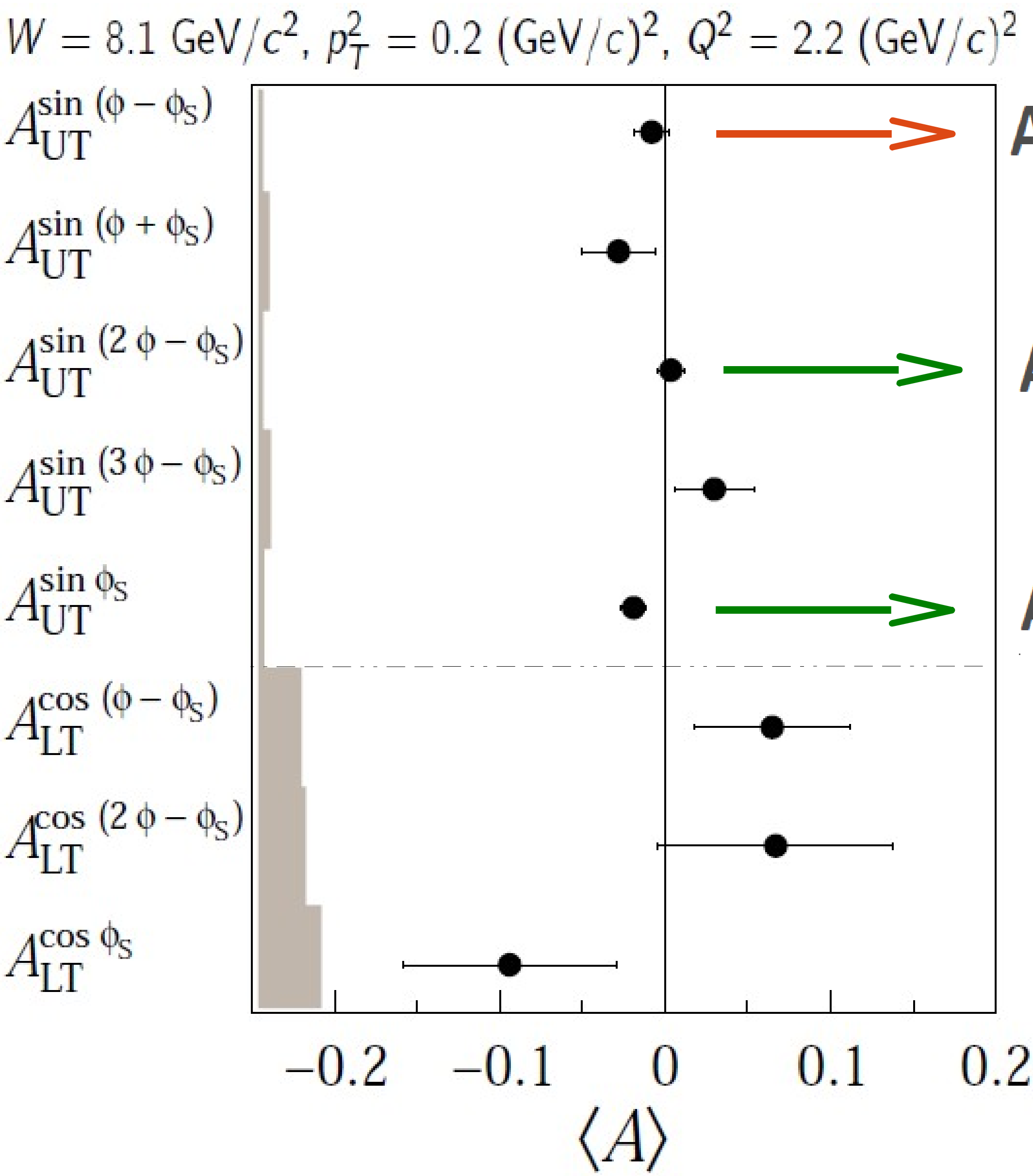
- **E**(ρ,p) α 2/3 $\mathbf{E^u}$+ 1/3 $\mathbf{E^d}$ +3/8 $\mathbf{E^g}$;
- *Cancellation* between **gluon** and **sea** quark contributions;
- $\mathbf{E^{u\ val} \sim -E^{d\ val}}$.

[COMPASS Coll., NP**B865** 1, 20 (2012)]



Transverse Target spin asymmetries for $\mu p^{\uparrow\downarrow} \rightarrow \mu p \rho$

[COMPASS Coll., PL**B731**, 19-26 (2014)]



$A_{UT}^{\sin(\phi - \phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$

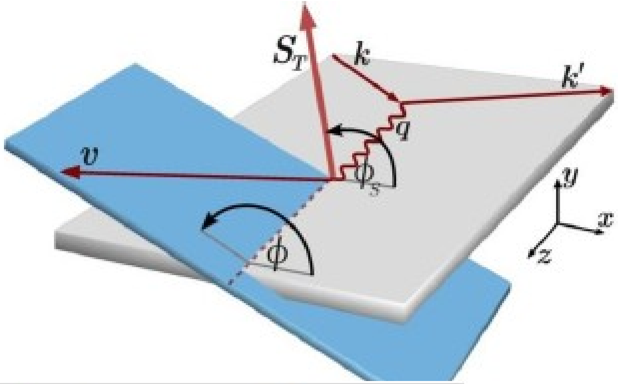
$A_{UT}^{\sin(2\phi - \phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T)$

$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

=> H_T **not small**

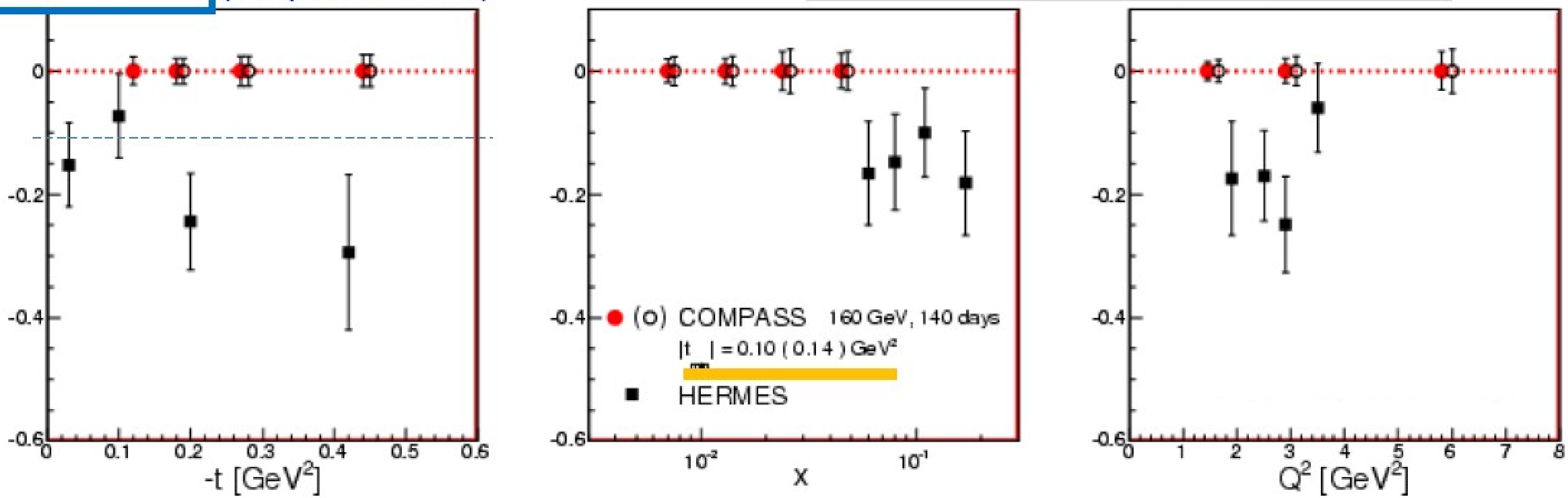
DVCS on *transversely polarized* proton target

$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow})$$
$$\propto Im(F_2\mathcal{H} - F_1\mathcal{E})\ \sin(\phi-\phi_S)\cos\phi$$



$A^{\sin(\phi-\phi_s)\cos\phi}_{CS,T}$ **related to H and E** (only stat .error)

2 years of data 160 GeV muon beam
1.2 m polarised NH_3 target ε_{global} = 10%



Conclusion and outlook

COMPASS offers **unique** features for the study of GPDs:

* Both $\overrightarrow{\mu}^{+}$ and $\overleftarrow{\mu}^{-}$ beams;

* Large kinematic range (complementary JLab / DESY / EIC);

Very encouraging existing results;

- 2009: DVCS test run;
- 2007-2010: $\mu p^{\uparrow\downarrow} \rightarrow \mu p \rho$;
- 2012: DVCS pilot run => results available soon;

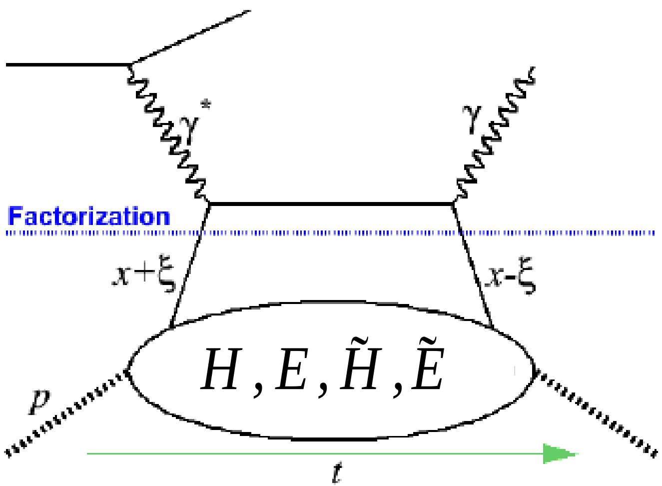
Two years DVCS run (2016-2017)

=> required accuracy for good constraint on observables

Experimental access to GPDs :
Exclusive processes

Deeply Virtual Compton Scattering (DVCS)

ep → ***ep*****γ**: $\sigma = f\left(H, E, \tilde{H}, \tilde{E}\right)$



Hard Exclusive Meson Production ***ep*** → ***ep h***

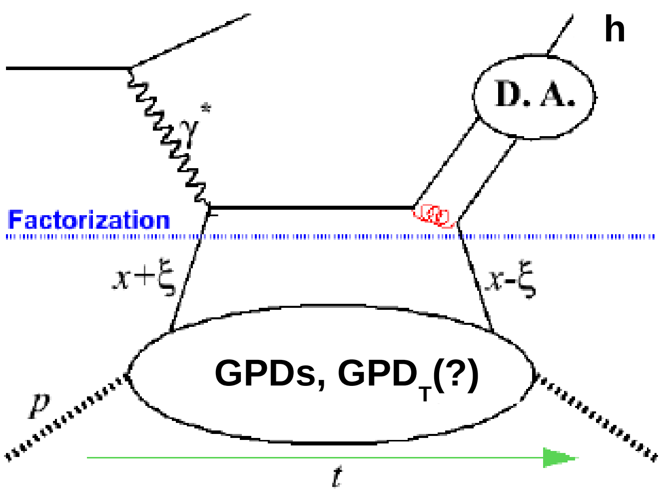
Factorization proved for **longitudinal** polarization γ^*_L.

Vectors (ρ, ϕ...): $\sigma_L = f\left(H, E\right)$ (VGG)

$\sigma_T = f\left(\tilde{H}_T, \tilde{E}_T\right)$ (GK)

Pseudoscalar (π^0, ...): $\sigma_L = f\left(\tilde{H}, \tilde{E}\right)$ (VGG)

$\sigma_T = f\left(H_T, E_T\right)$ (GK)



VGG: [Vanderhaeghen, Guichon, Guidal, PR**D60**, 094017, 1999]

GK: [Goloskokov, Kroll, EPJ**A47**, 112, 2011;
EPJ**C74**, 2725, 2014]

Generalized Partons Distributions (GPDs)

4 "chiral-even" GPDs :

$H(x,\xi,t)$ → $q(x)$ (PDFs)

(limite "forward" → t=0)

$\tilde{H}(x,\xi,t)$ → $\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$ (Polarized PDFs)

$E, \tilde{E}(x,\xi,t)$ Nucleon spin-flip

$$\int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t) \qquad \int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t)$$

$$\int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t) \qquad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = g_P(t)$$

→ FFs

$$\int_{-1}^{1} dx\, x[H_q(x,\xi,0) + E_q(x,\xi,0)] = 2J_q$$

→ Ji sum rule :
Access to **total angular momentum** of quarks

[Ji, PRL**78**, 610, 1997]

Compass GPD program

DVCS on H_2 target: Proton size; Study of GPD H

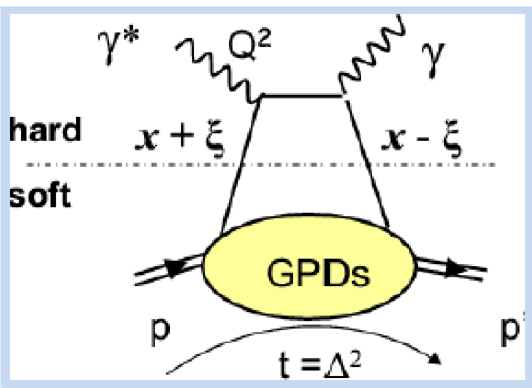
Spin and **charge** cross section **Sum** (Currently *unique* COMPASS feature)

$$S_{CS,U} \equiv d\sigma(\overrightarrow{\mu}^{+}) + d\sigma(\overleftarrow{\mu}^{-}) \rightarrow s_1^{Int}\sin(\phi) + s_2^{Int}\sin(2\phi)$$

$$s_1^{Int} \propto \mathrm{Im}(F_1\mathcal{H})$$

$$D_{CS,U} \equiv d\sigma(\overrightarrow{\mu}^{+}) - d\sigma(\overleftarrow{\mu}^{-}) \propto c_0^{Int} + c_1^{Int}\cos(\phi)$$

$$c_1^{Int} \propto \mathrm{Re}(F_1\mathcal{H})$$



$\xi \sim x_B / (2-x_B)$

$$Im\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

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

Re part of the *Compton Form Factors* linked to the *D term*

Energy-Momentum Tensor : Polyakov, PLB 555 (2003) 57-62

Spin and **charge** cross section **Sum** (Currently *unique* capability of COMPASS)

$$\mathbf{S_{CS,U}} \equiv \mathbf{d\sigma}(\mu^{+\leftarrow}) + \mathbf{d\sigma}(\mu^{-\rightarrow}) = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \Im m I\right)$$

$$S_{CS,U} = 2\frac{\Gamma(x_{Bj}, Q^2, t)}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left(c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi)\right)$$

$$+2\frac{e^6}{y^2 Q^2}\left(c_0^{DVCS} + c_1^{DVCS}\cos(\phi) + c_2^{DVCS}\cos(2\phi)\right)$$

$$+2 e_\mu P_\mu \frac{e^6}{x_{Bj} y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left(s_1^I \sin(\phi) + s_2^I \sin(2\phi)\right)$$

can be extracted

$$s_1^I \propto \Im m\left(F_1 \mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

dominant

$$\Im m\mathcal{H}(\xi,t,Q^2) \stackrel{LO}{=} \pi\sum_f e_f^2\left(H^f(\xi,\xi,t,Q^2) \mp H^f(-\xi,\xi,t,Q^2)\right)$$

$\propto$

Spin and **charge** cross section **Difference** (Currently *unique* capability of COMPASS)

$$\mathbf{D}_{CS,U} \equiv \mathbf{d}\sigma(\mu^{+\leftarrow}) - \mathbf{d}\sigma(\mu^{-\rightarrow}) = 2\left(P_\mu d\sigma_{pol}^{DVCS} + e_\mu \Re e\, I\right)$$

$$D_{CS,U} = +2\mathrm{P}_\mu \frac{e^6}{y^2 Q^2}\left(s_1^{DVCS}\sin(\phi)\right)$$

$$+2e_\mu \frac{e^6}{x_{Bj} y^3 t\, \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left(c_0^I + c_1^I\cos(\phi) + \left\{c_2^I\cos(2\phi) + c_3^I\cos(3\phi)\right\}\right)$$

can be extracted

$$c_1^I \propto \Re e\left(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4\mathrm{M}^2}F_2\mathcal{E}\right)$$

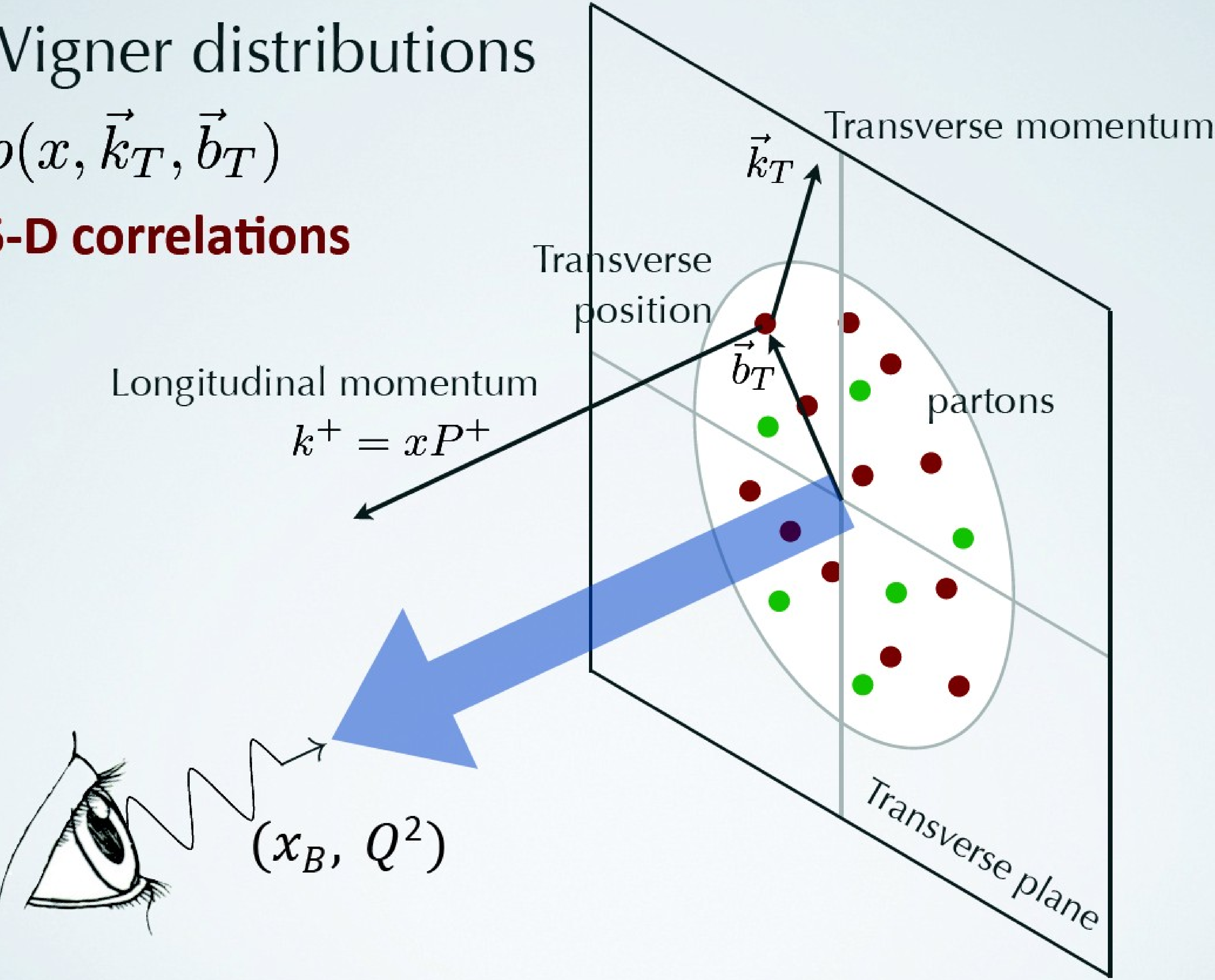
dominant

$$\Re e\,\mathcal{H}(\xi,t,Q^2) \overset{LO}{=} \pi\sum_f e_f^2\left[\mathcal{P}\int_{-1}^{1} dx\, H^f(x,\xi,t,Q^2)\left(\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right)\right]$$

Wigner distributions

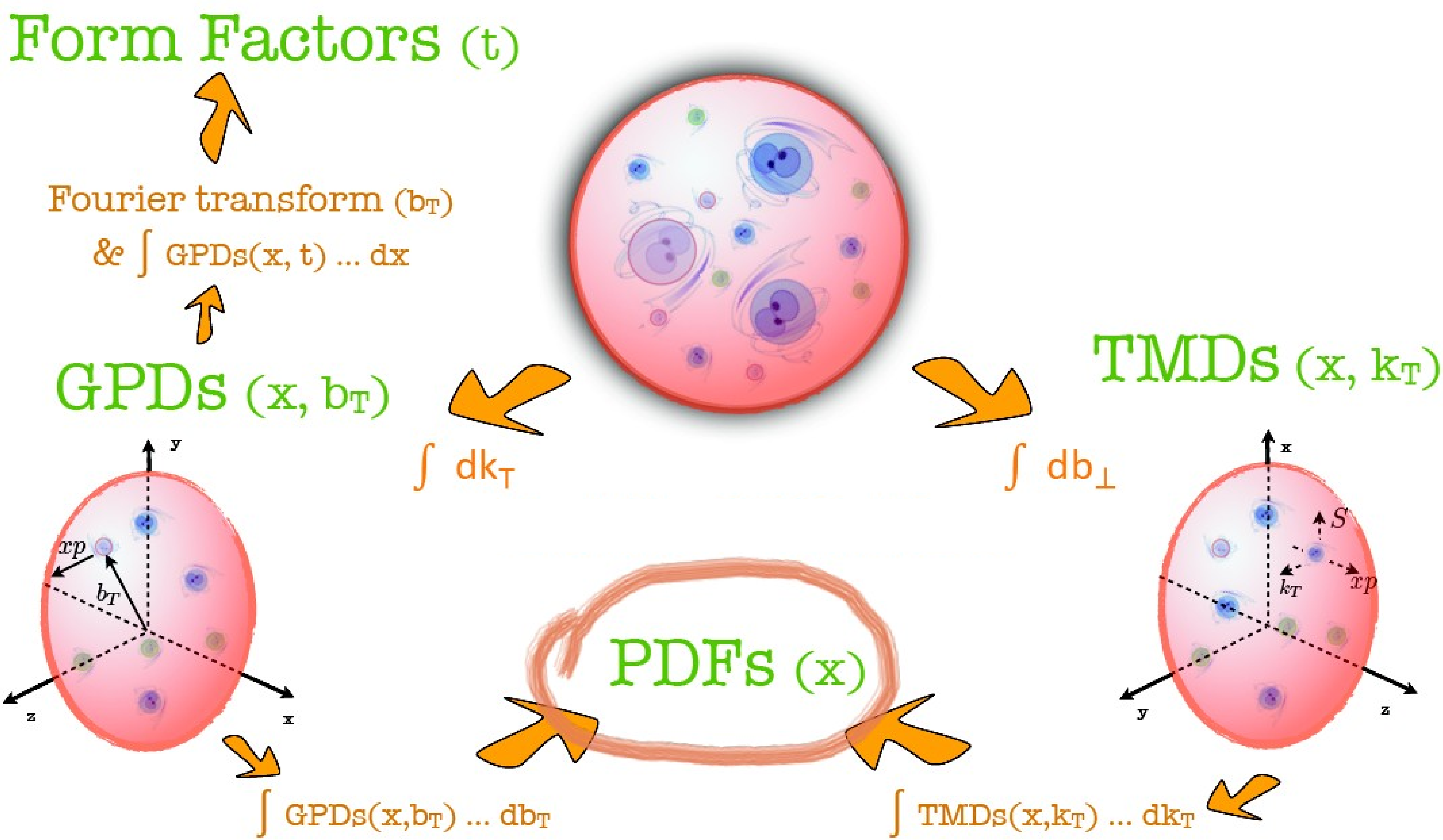
$\rho(x, \vec{k}_T, \vec{b}_T)$

5-D correlations



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Towards a 3D Picture of the Nucleon…

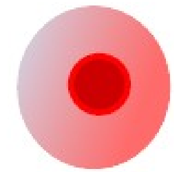


PDFs $\rightarrow \Delta\Sigma, \Delta G$

TMDs, GPDs $\rightarrow \begin{cases} \text{nucleon"tomography"} \\ L_{q,g} \end{cases}$

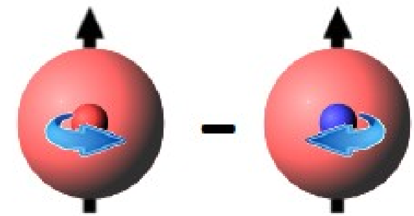
Chiral-even

$H \longleftrightarrow q$



$\gamma^*_L \; p^\uparrow \rightarrow \rho^0_L \; p^\uparrow \quad L=0$

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



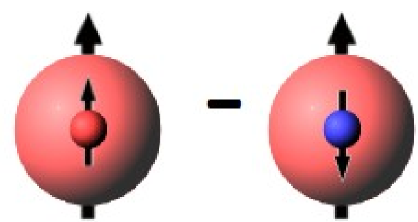
Sivers: quark k_T & nucleon transv. Spin

$\gamma^*_L \; p^\uparrow \rightarrow \rho^0_L \; p^\downarrow \quad L=1$

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

Chiral-odd

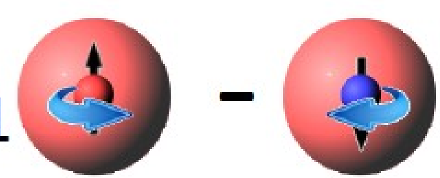
$H_T \longleftrightarrow h_1$



Transversity: quark spin & nucleon transv. spin

$\gamma^*_T \; p^\uparrow \rightarrow \rho^0_L \; p^\downarrow \quad L=0$

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



Boer-Mulders: quark k_T & quark transverse spin

$\gamma^*_T \; p^\uparrow \rightarrow \rho^0_L \; p^\uparrow \quad L=1$

Towards GPD *E*:
μp → μpρ on transversely polarized proton target

$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\varepsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}\,dQ^2\,dt\,d\phi\,d\phi_s}$$

$$= \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++}-\sqrt{\varepsilon(1+\varepsilon)}\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$-P_\ell\sqrt{\varepsilon(1-\varepsilon)}\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

transv. polar. target

$$-S_T\Big[\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}$$

$$+\sqrt{\varepsilon(1+\varepsilon)}\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\Big]$$

transv. polar. target + long. Polar. beam

$$+S_TP_\ell\Big[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}$$

$$-\sqrt{\varepsilon(1-\varepsilon)}\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\Big]$$

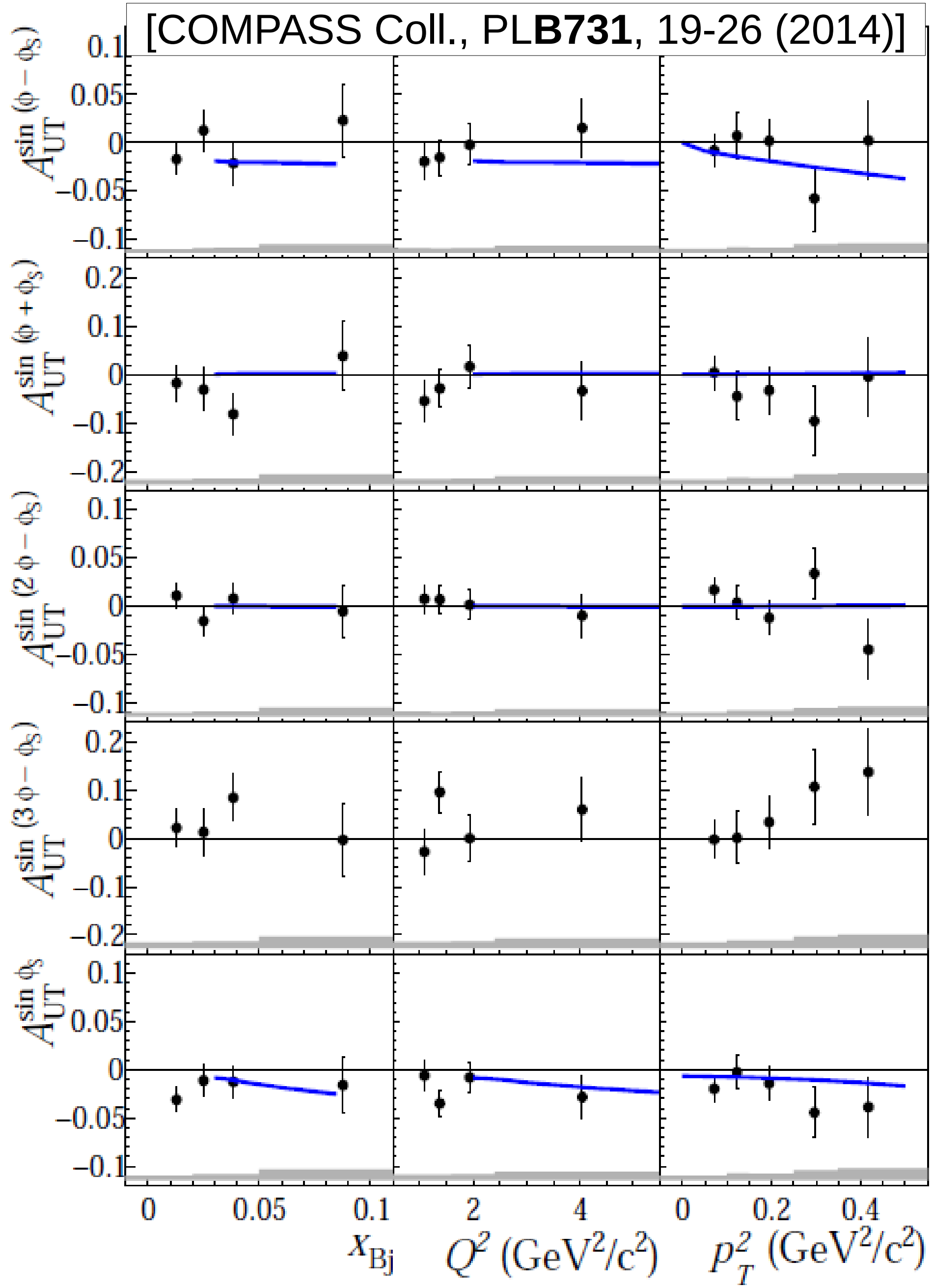
σ^{ij}_{mn}: ij for nucleon helicity, mn for photon helicity

Dominant interference terms:

LL $\quad \gamma^*_L \rightarrow \rho^0_L$

then LT $\quad \gamma^*_T \rightarrow \rho^0_L$

Towards GPD *E*:
Transverse Target spin asymmetries for $\mu p \rightarrow \mu p \rho$



$$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$$

— Calculations by Goloskokov and Kroll [EPJ**C74**, 2725, 2014]

$$A_{UT}^{\sin(2\phi-\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T)$$

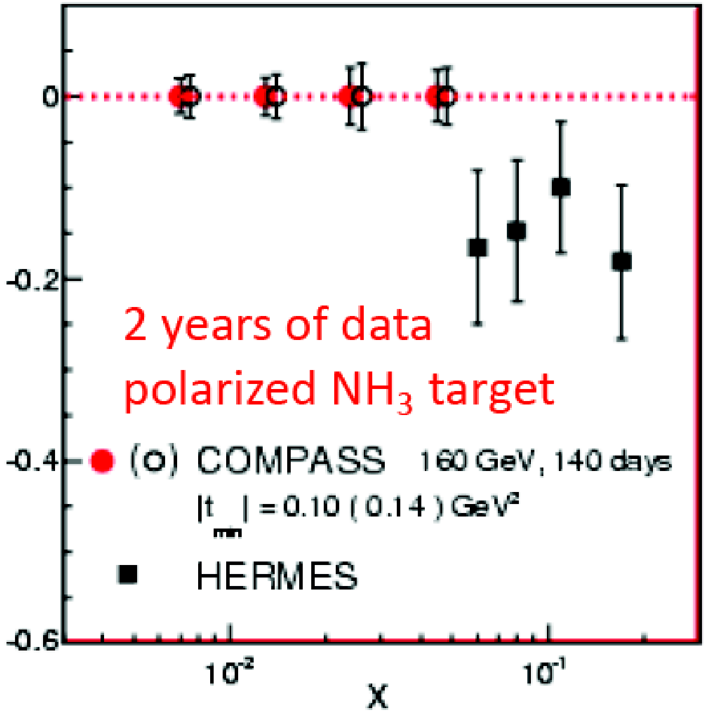
$$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$$

Towards the GPD E

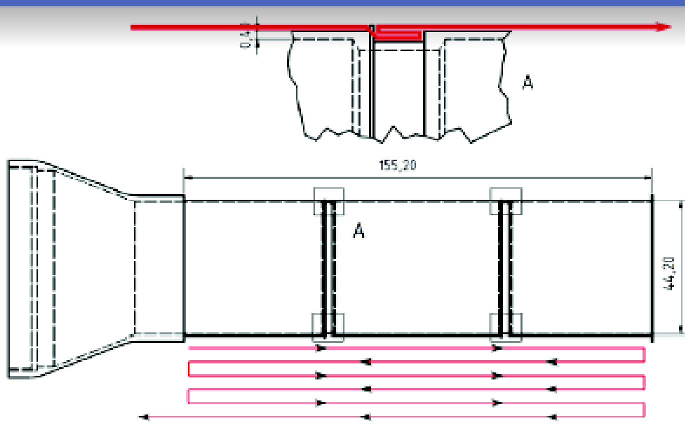
After 2018: DVCS and HEMP on transv. pol. target
and recoil detector

$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow})$$
$$\propto Im(F_2\mathcal{H} - F_1\mathcal{E}) \sin(\phi-\phi_S)\cos\phi$$

$A^{\sin(\phi-\phi_s)\cos\phi}_{CS,T}$



- Update simulations and predictions
  → synergy with approved ANR Parton
- Developments of internal supercond. magnets for polarized targets
  → JRA Kripta application to H2020



Wiring procedure for the inversed notched coil