Generalized Parton Distributions Program at COMPASS

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On behalf of COMPASS Collaboration

QCD Evolution 2015

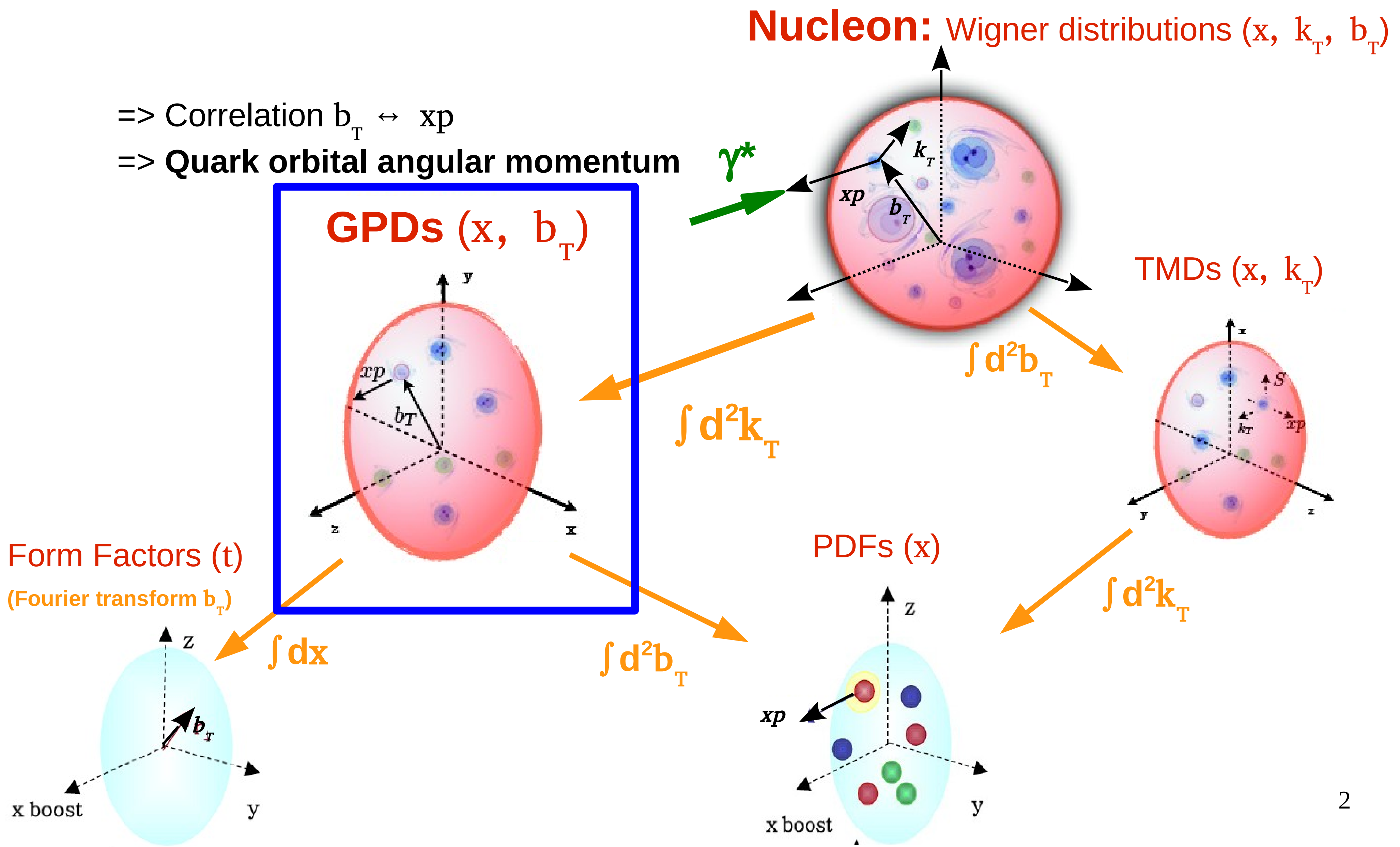
Thomas Jefferson National Accelerator Facility

(May 26-30 2014)

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

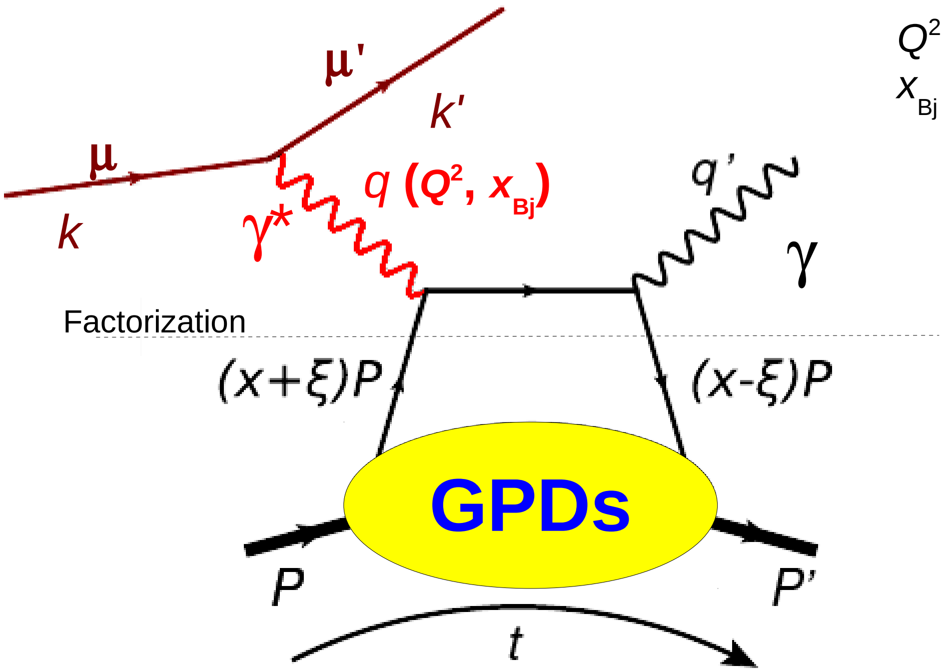
=> Correlation $b_T \leftrightarrow xp$

=> **Quark orbital angular momentum**



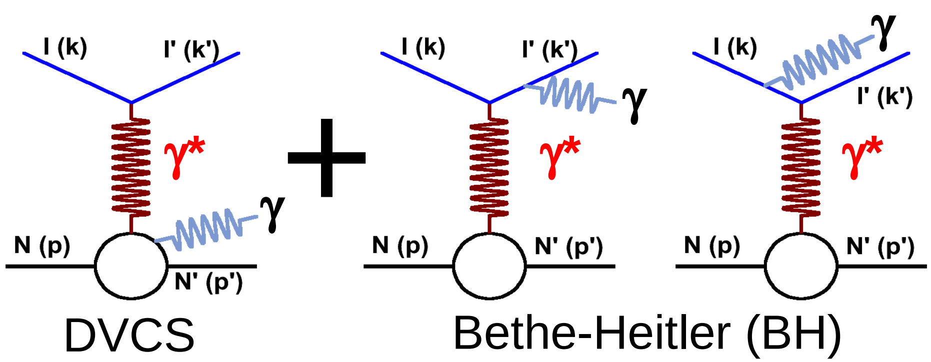
Accessing GPDs : Exclusive processes

DVCS: μ*p* → μ*p*γ, HEMP



$Q^2 = -(k-k')^2$
$x_{Bj} = Q^2/2p\cdot(k-k')$

DVCS: *Interference* with **Bethe-Heitler**

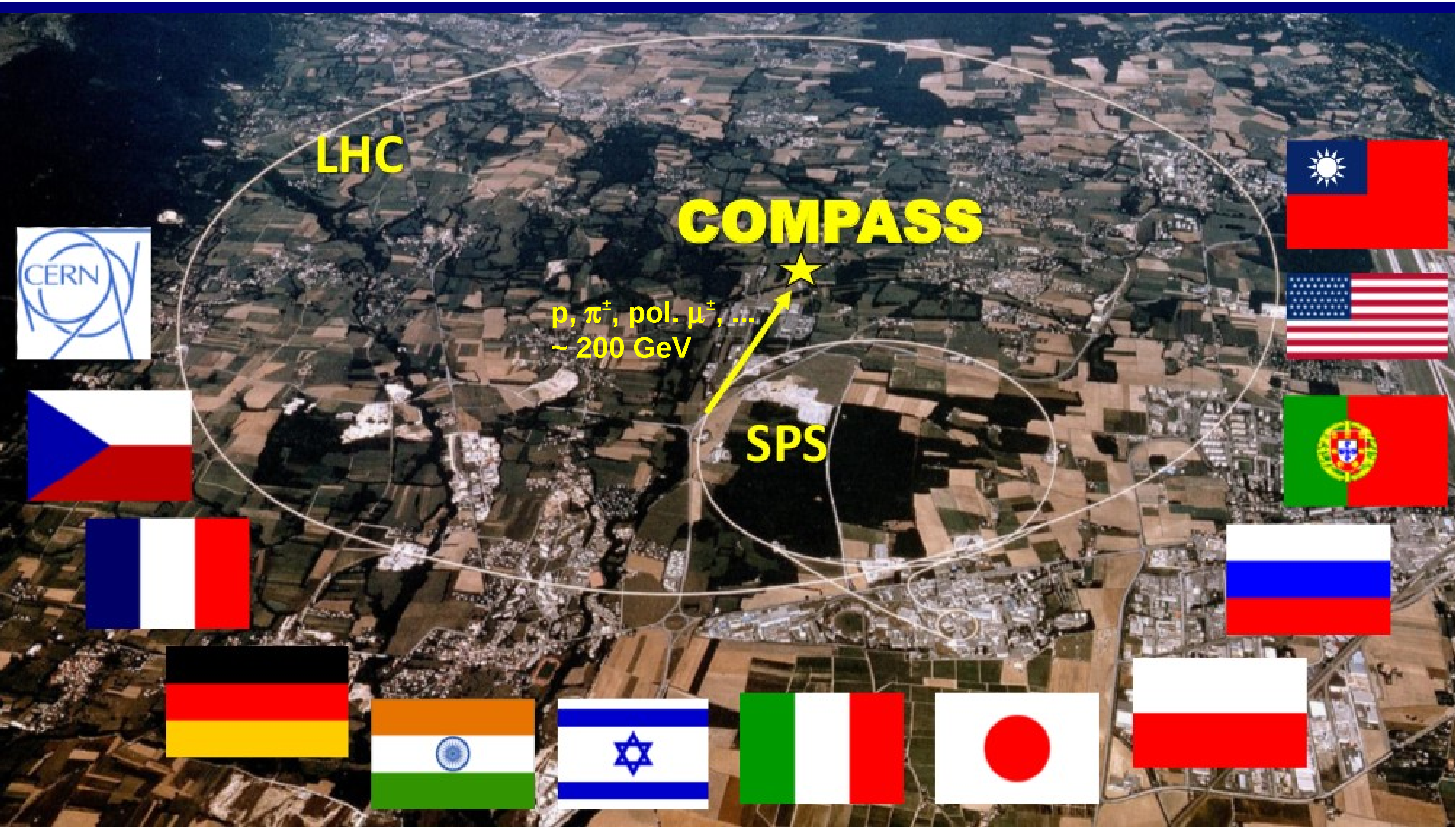


4 Chiral-even GPDs: ***H***, ***E***, $\tilde{H}, \tilde{E}$

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

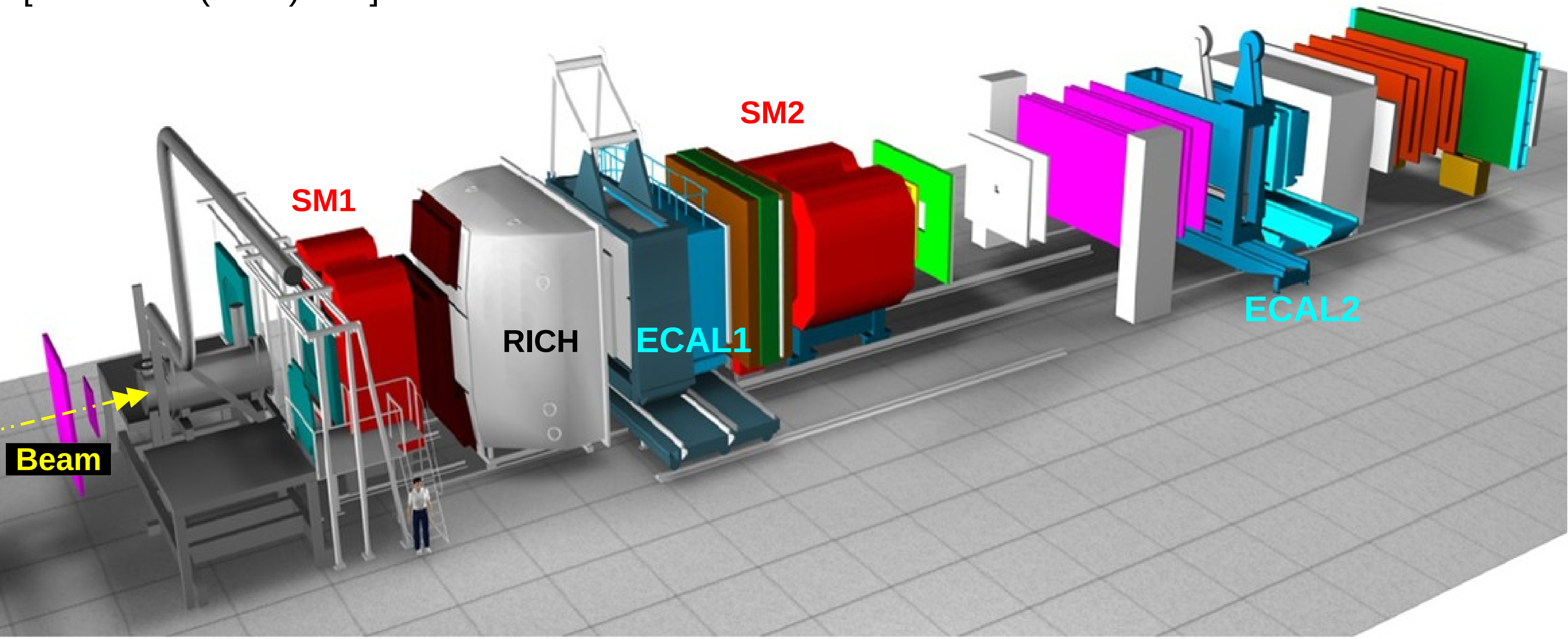
Factorization proved for:
$Q^2 \to \infty$, $t \ll Q^2$, x_{Bj} **finite**
(*Bjorken regime*)

The COMPASS experiment:
Large acceptance spectrometer for hadronic physics at CERN



The COMPASS experiment:
Experimental setup

[NIM A577 (2007) 455]



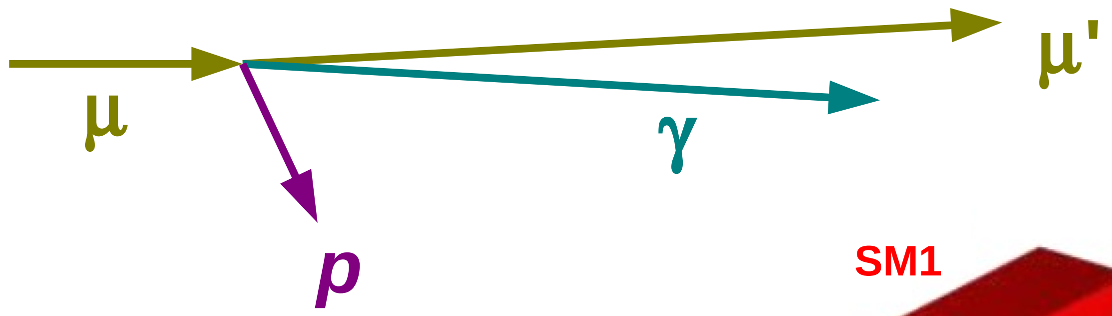
*** Tracking: DCs, GEMs, MM,... + 2 dipole magnets ($|\vec{p}|$);**

*** ECals + HCals (*E*);**

*** RICH (PID);**

Additional setup for DVCS
(and other exclusive channels)

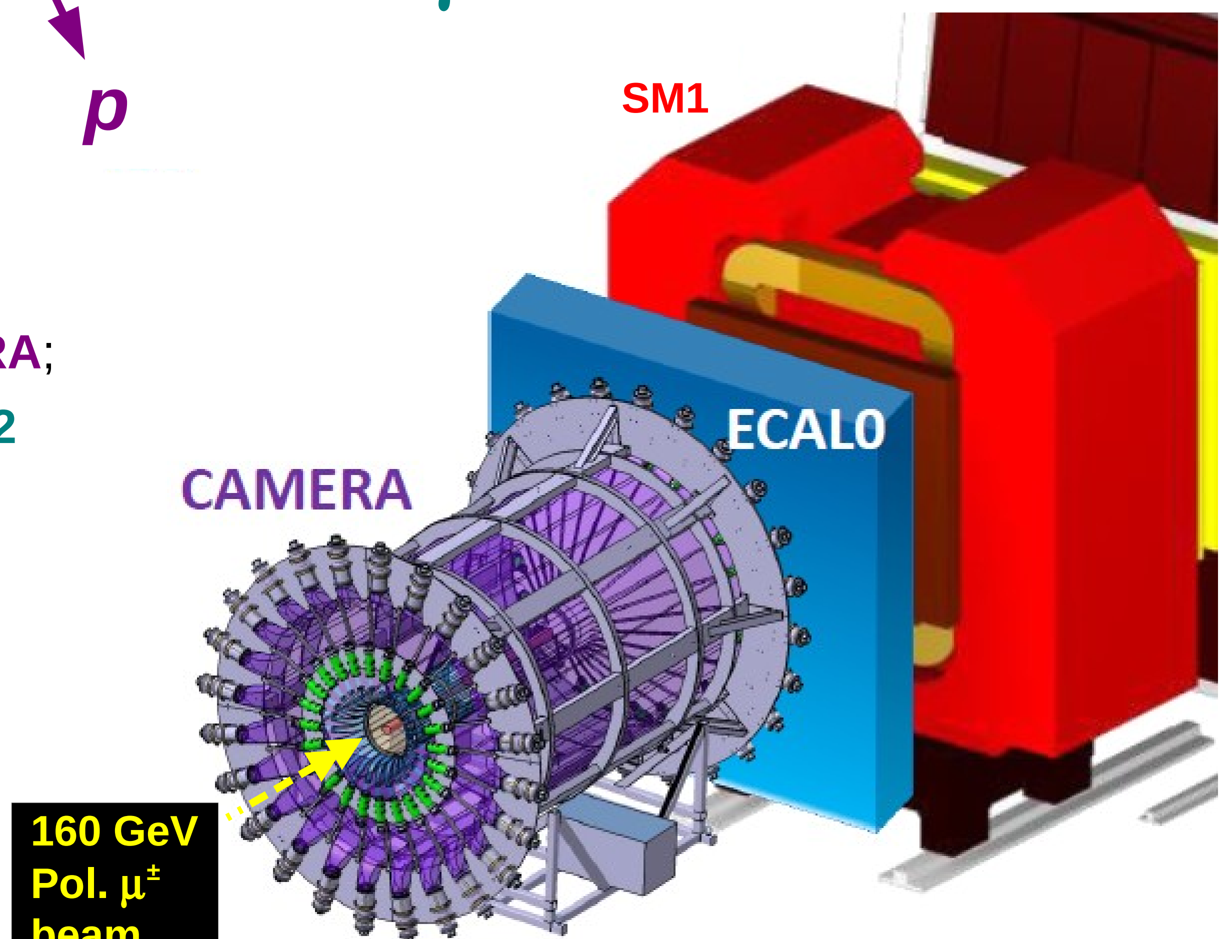
$\mu p \rightarrow \mu p \gamma$



Target: 2.5m LH_2;

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

γ: ECAL0 (cover higher x_{Bj}), **1**, **2**



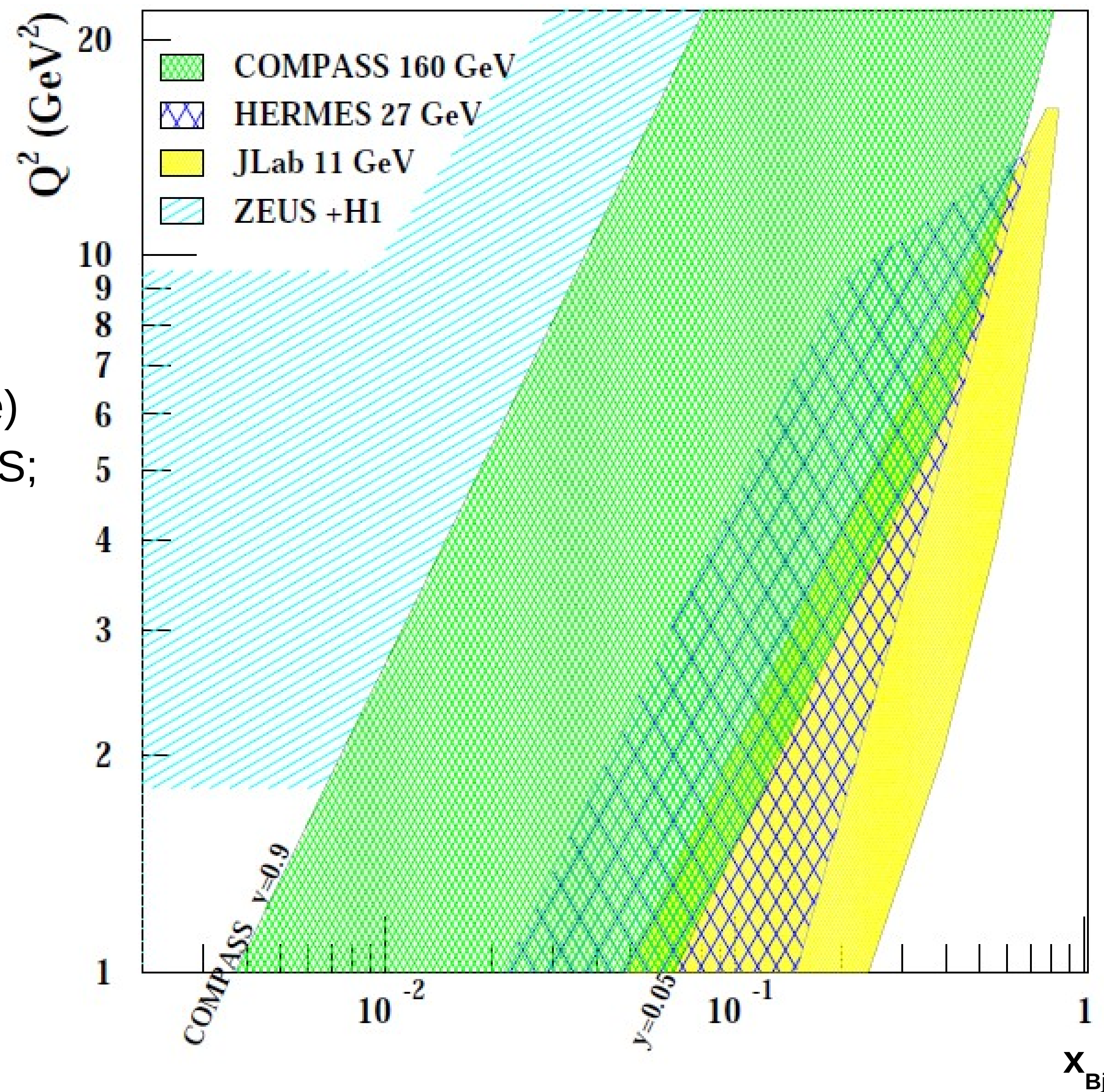
Compass assets for GPD study

Both $\vec{\mu}^{+}$ and $\overleftarrow{\mu}^{-}$ available
(*currently unique*);

GPDs in ***large*** kinematic region
(0.005 < x_{Bj} < ~0.3)
=> *Complementary* of **JLab** (valence)
DESY: ZEUS, H1, (gluons), HERMES;

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)



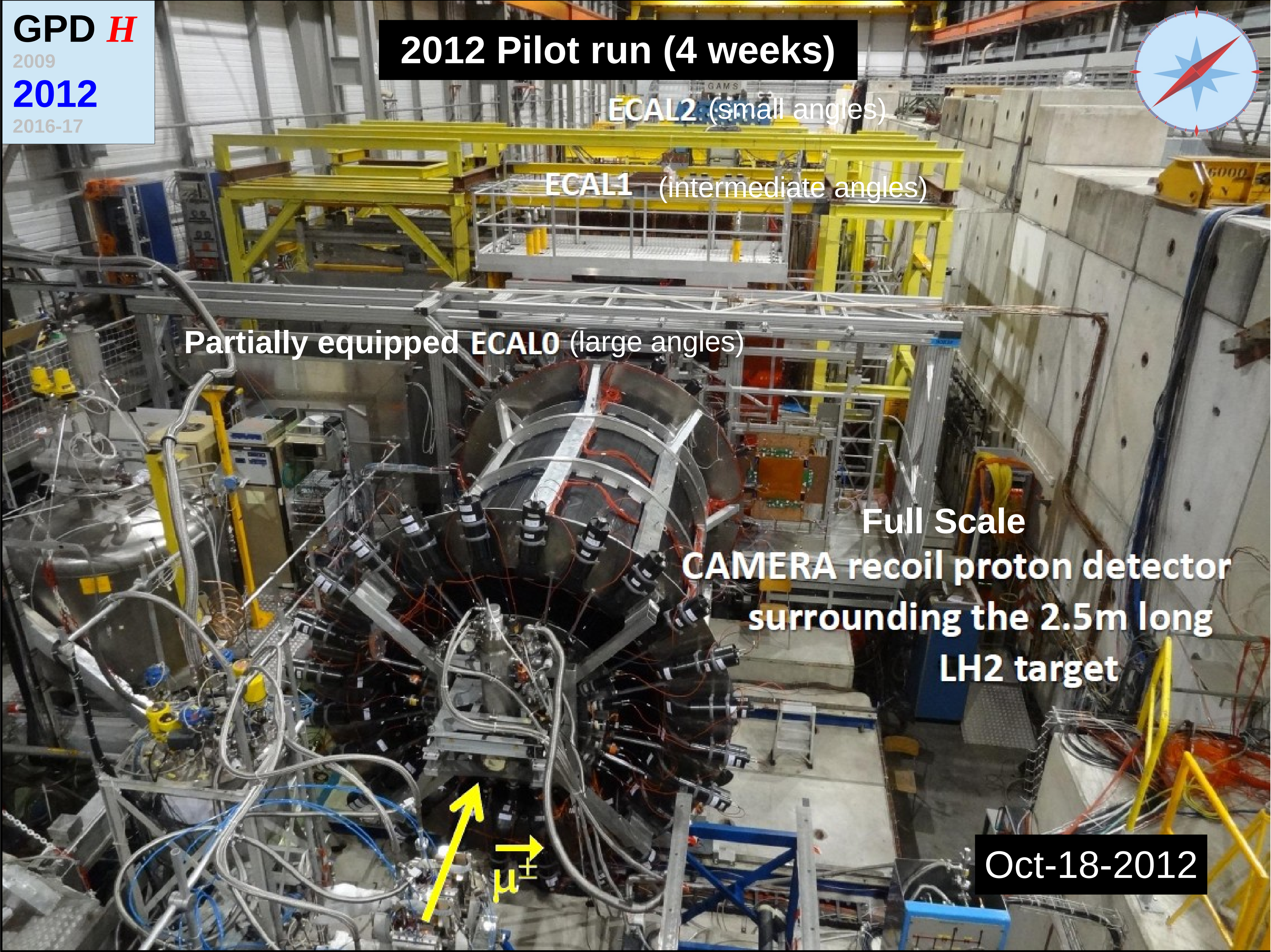
DVCS on unpolarized p:

Study of GPD *H*

2009: Test run

2012: Pilot run

2016-17: Data run



GPD H
2009
2012
2016-17
2012 Pilot run (4 weeks)
ECAL2 (small angles)
ECAL1 (intermediate angles)
Partially equipped ECAL0 (large angles)
Full Scale
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
μ±
Oct-18-2012

Analysis of 2012 data: selection of $\mu p \rightarrow \mu p \gamma$

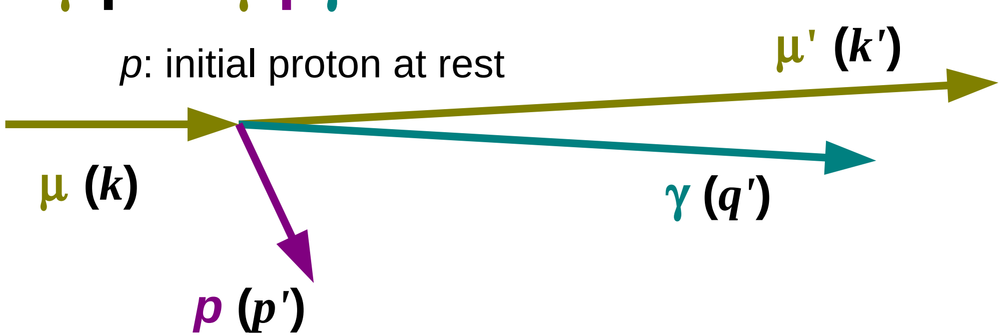
Reconstructed vertices (**1μ**, **1μ'**) **in target volume**;

Only **1** high energy photon with E > **4**, **5**, **10** GeV in Ecal **0**, **1**, **2**;

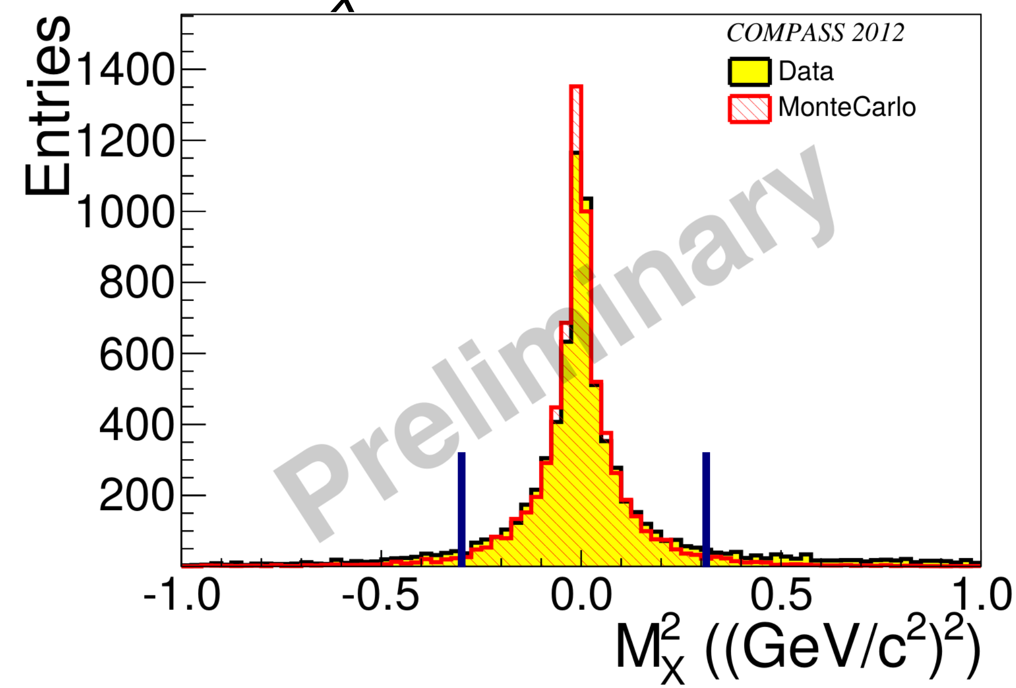
At least **1** proton reconstructed in CAMERA (compatible with vertex);

All particles reconstructed:
exclusivity conditions to clean combinatorial:
1 - cut on $\mathbf{M_X^2}$;
2 - cut on Δφ (next slide);
3 - cut on $\Delta p_\perp$ (next slide);

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



$$M_X^2 = (k+p-k'-q'-p')^2$$



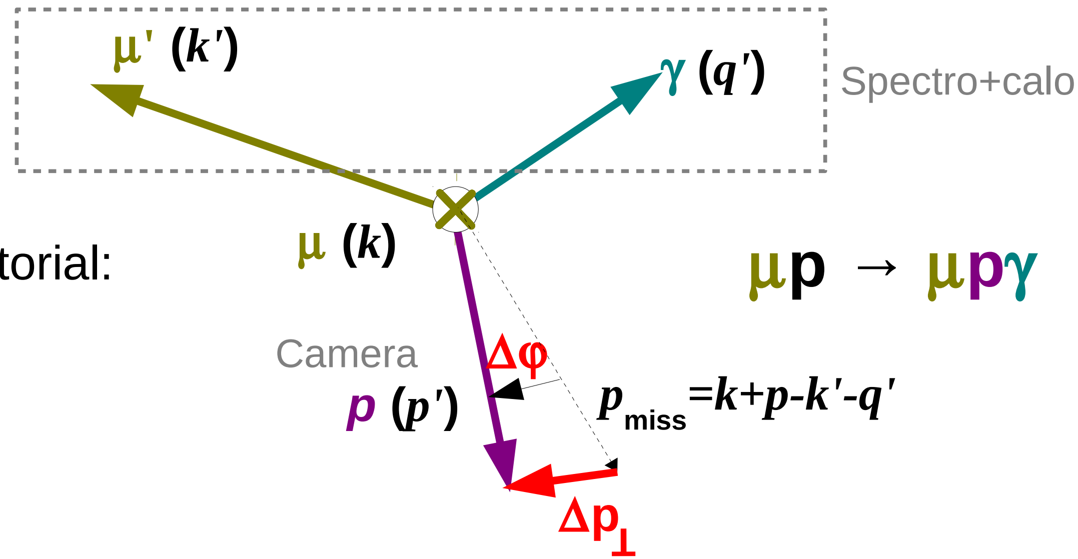
GPD H

2009

2012

2016-17

Analysis of 2012 data: selection of $\mu p \rightarrow \mu p \gamma$

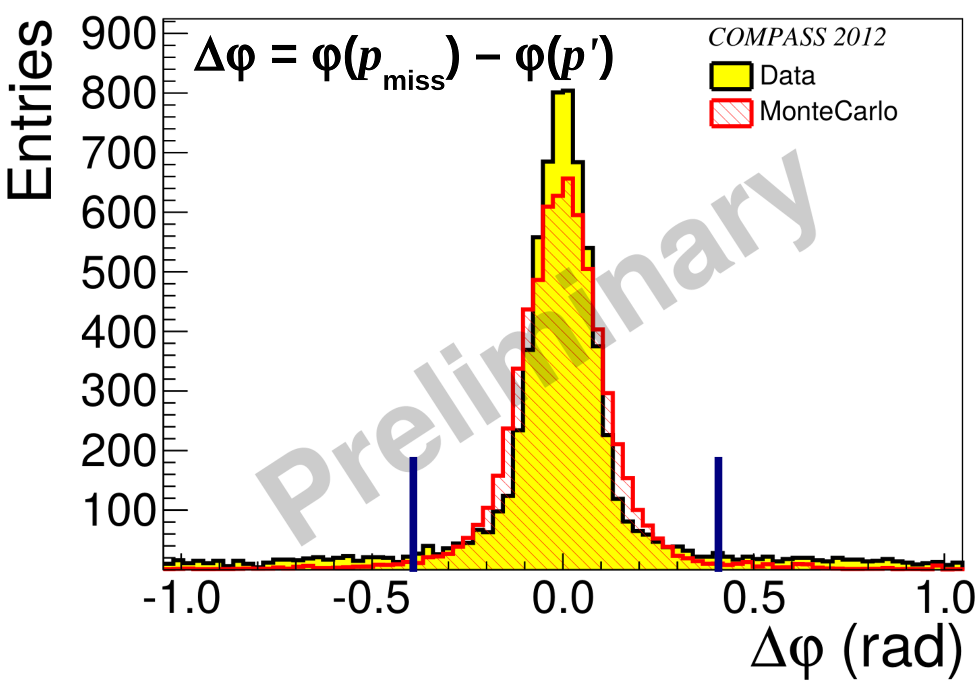


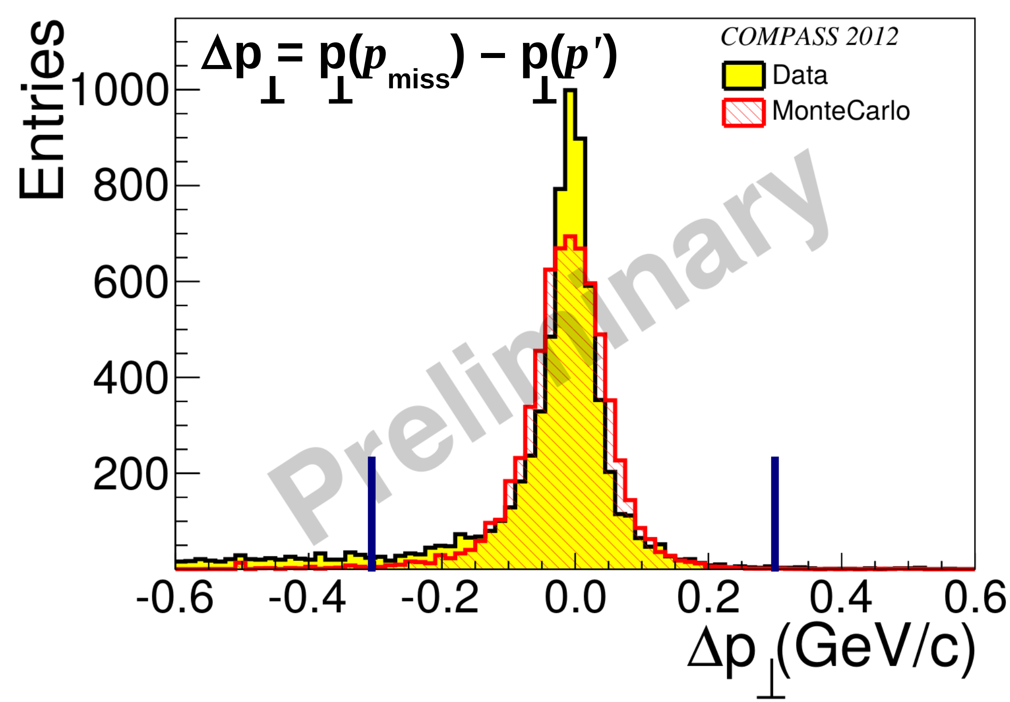
All particles reconstructed:
exclusivity conditions to clean combinatorial:

1 - cut on M_X^2;

2 - cut on $\Delta\varphi$;

3 - cut on $\Delta p_\perp$;





Analysis of 2012 data: π^0 subtraction

π^0: main background source for $\mu p \rightarrow \mu p \gamma$.

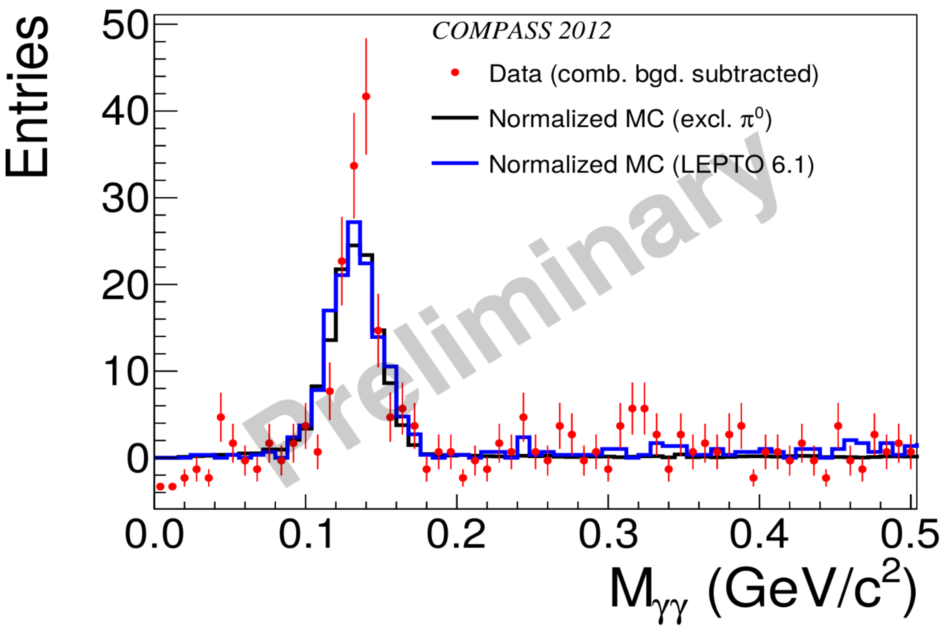
2 possible cases:
- "visible" π^0 (both γ detected, easy to reject);
- "invisible" (1 γ undetected, estimated with MC);

"Visible" π^0 contamination evaluated combining ***exclusive*** γ ***candidates*** with all **low energy** γ in the event.

"Invisible" π^0 contamination estimated with **2** MC simulations:
- **semi-inclusive** contribution (LEPTO);
- **exclusive** contribution (HepGen/π^0);

MC normalized with "visible" π^0 peak in DVCS.
2 extreme cases considered:

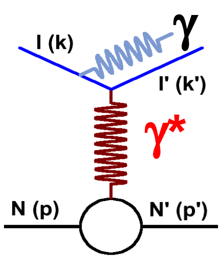
Fully **semi-inclusive** background → lower limit
Fully **exclusive** background → upper limit

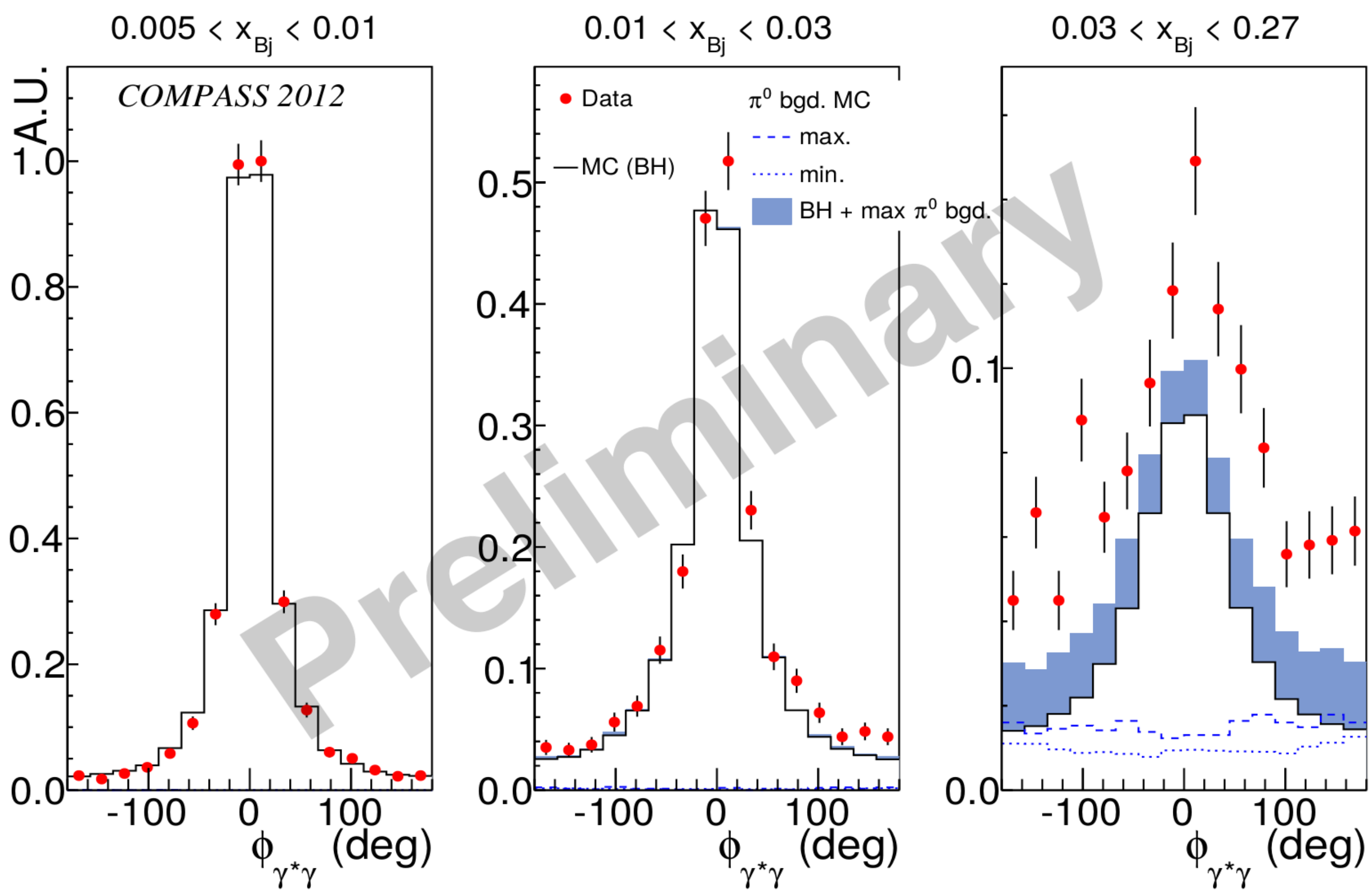


GPD *H*
2009
2012
2016-17

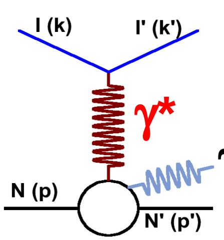
Analysis of 2012 data: Preliminary results + Next steps...

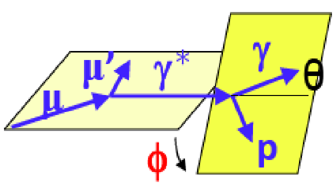
Low x_{Bj}:
Bethe-Heitler





Higher x_{Bj}:
DVCS signal





=> Simultaneous $\boldsymbol{ep \rightarrow ep\pi^0}$ analysis;

=> $\boldsymbol{\pi^0}$ **cross section** + improved π^0 subtraction;

=> **DVCS cross section *t* dependence**.

Next steps:
WORK IN PROGRESS

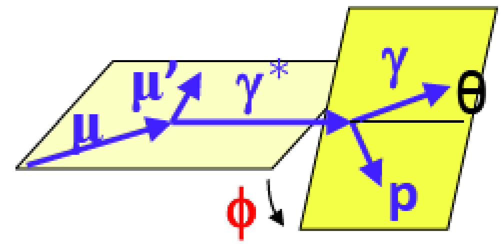
Compass GPD program

DVCS on H_2 target: Study of GPD H

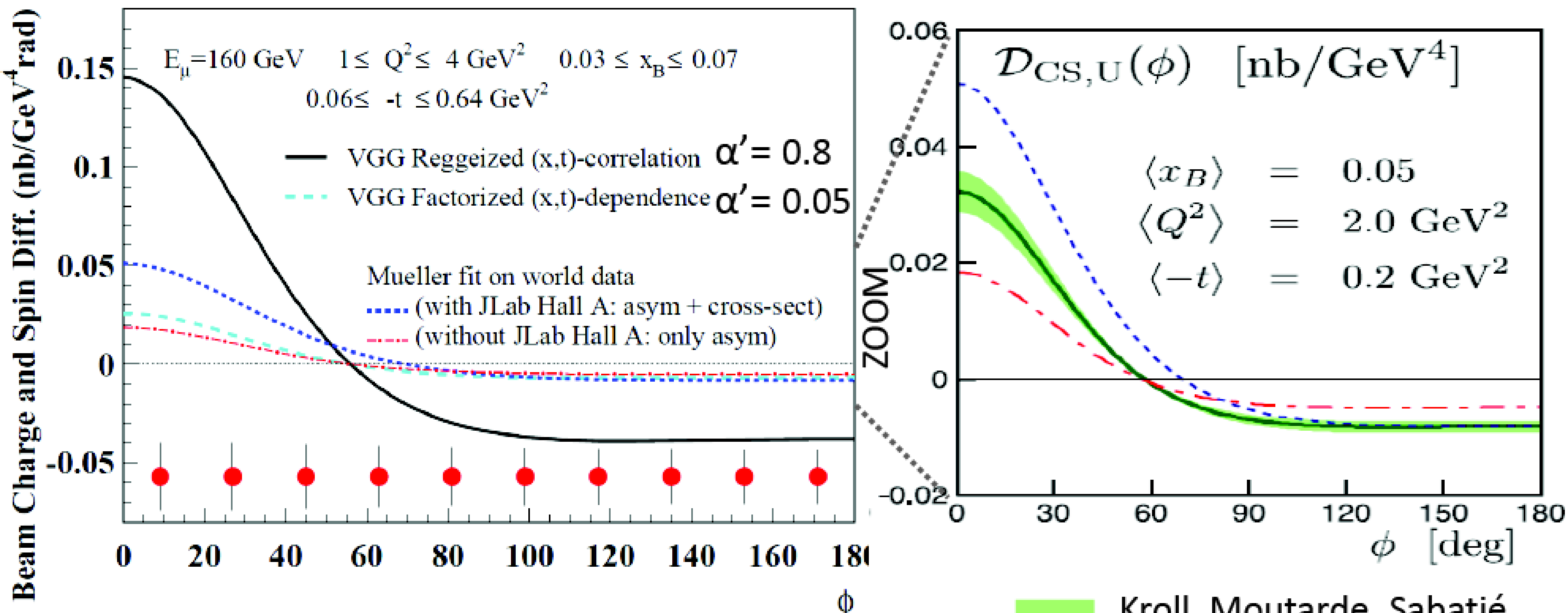
Spin and **charge** cross section **Difference** (Currently *unique* COMPASS feature)

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

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



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

Compass GPD program

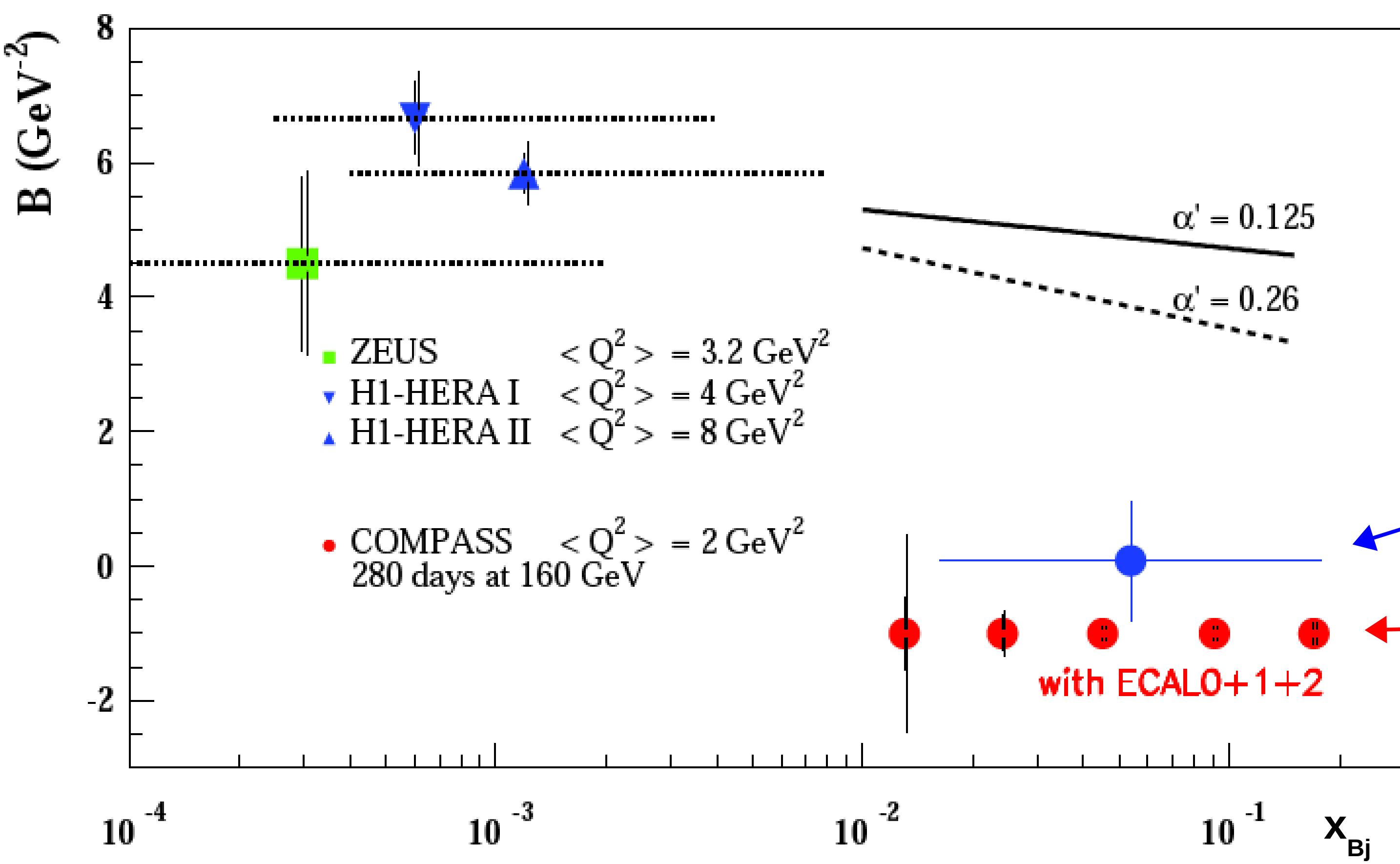
DVCS on H_2 target: Study of GPD $\mathcal{H}$ + Proton size

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

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

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

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



$$B(x_{Bj}) = ½ <r_\perp^2>$$

4 weeks in 2012
(*projection*)

2 years of data
(2016-17)

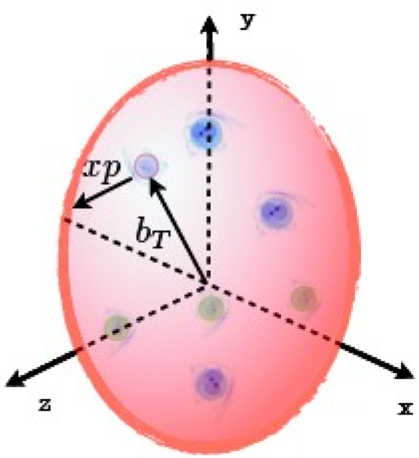
DVCS, DVMP on *polarized* $p^{(\uparrow\downarrow)}$:

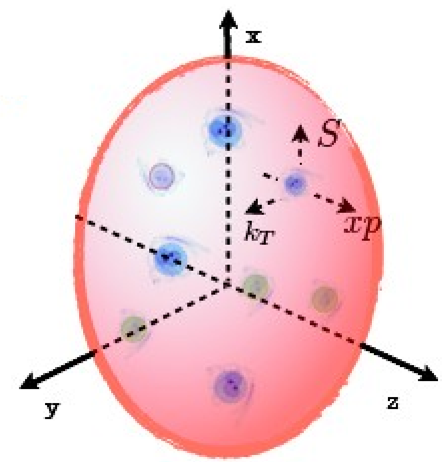
Study of GPD *E*

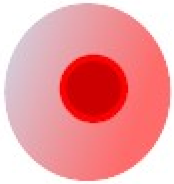
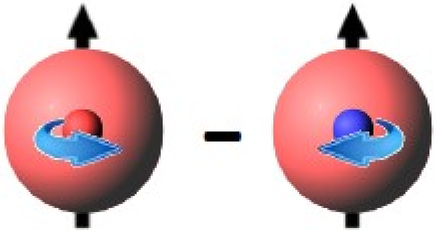
2007-10: $\mu p^{\uparrow\downarrow} \rightarrow \mu p \rho$

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

GPDs (x, b_T) TMDs (x, k_T)





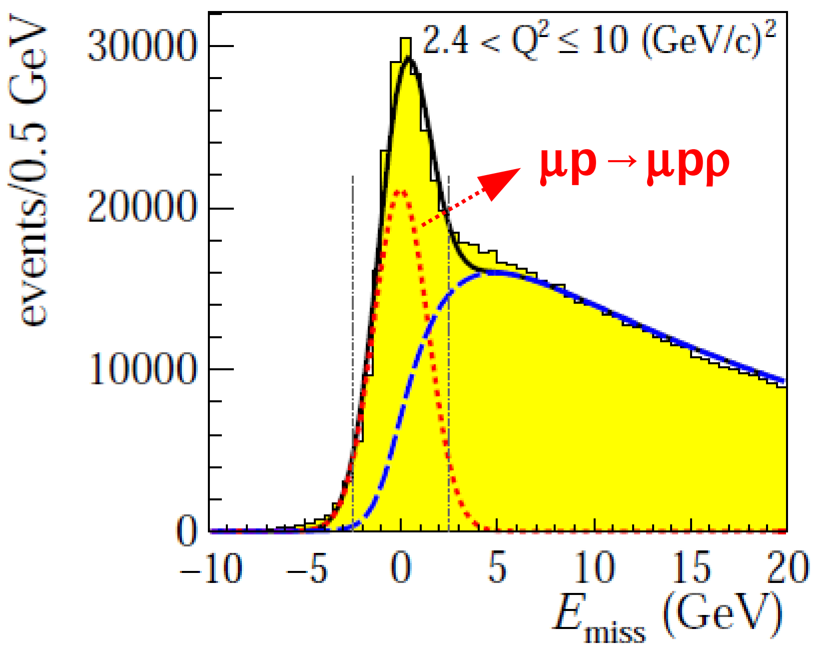
	GPD		TMD	
$\gamma^*_L p^\uparrow \to \rho_L p^\uparrow$	H	<=>	q (PDF)	
$\gamma^*_L p^\uparrow \to \rho_L p^\downarrow$	E	<=>	$f_{1T}^{\perp}$	
	Nucleon spin flip		**Sivers** Quark k_T, Transversely pol. nucleon	

μp → μpV on *transversely polarized* proton target

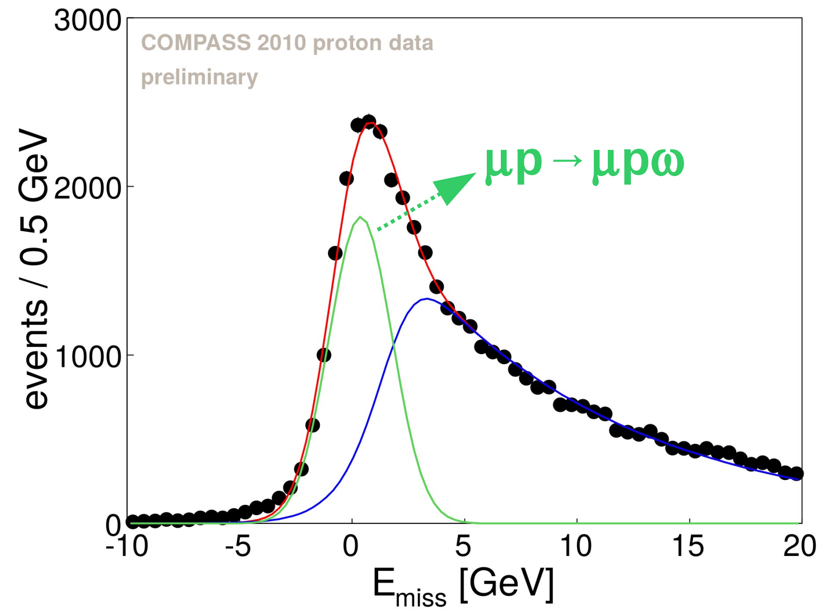
“Phase I” COMPASS setup; *No Recoil Proton Detector*

=> exclusivity ensured by a “missing mass” technique;

$H^{\uparrow\downarrow}(\mu, \mu' \pi^+\pi^-)X \equiv p$



$H^{\uparrow\downarrow}(\mu, \mu' \pi^+\pi^-\pi^0)X \equiv p$



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

GPD E

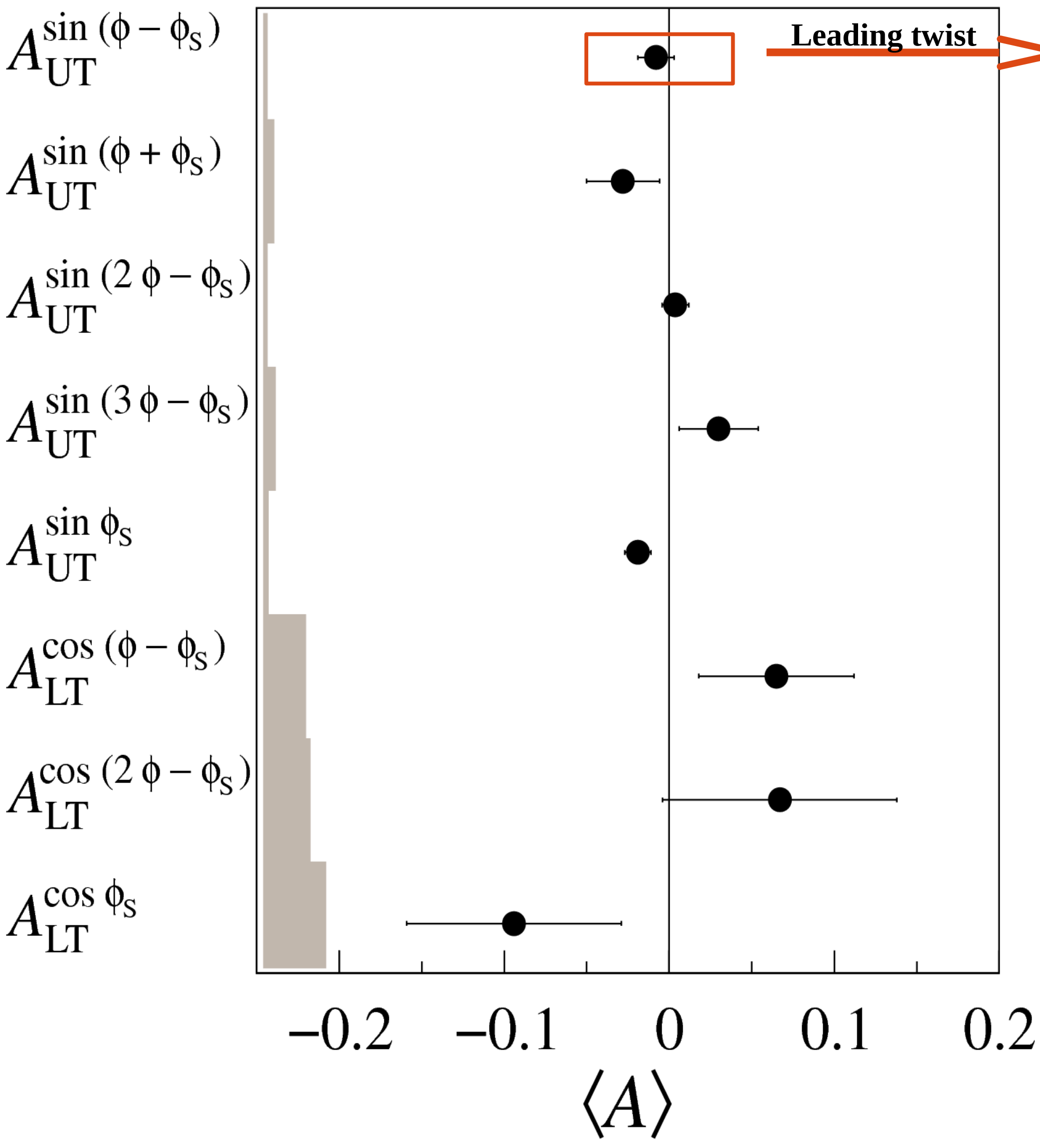
2007-10

> 2018

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

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

W = 8.1 GeV, p_T^2 = 0.2 (GeV/c)^2, Q^2 = 2.2 (GeV/c)^2

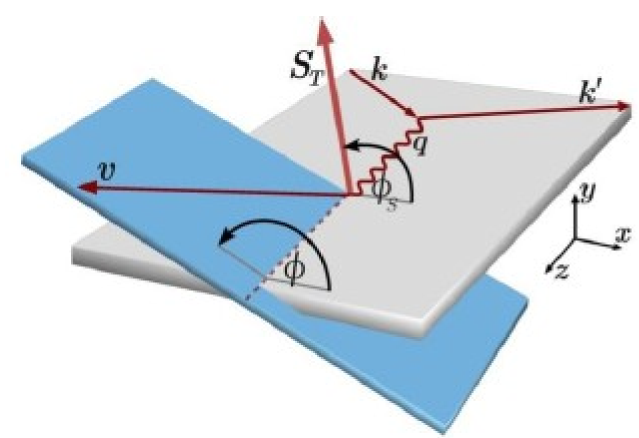


$A_{UT}^{\sin(\phi-\phi_s)} \propto Im(\mathcal{E}^* \mathcal{H})$ => small

- **E**(ρ,p) α 2/3 **E**^{u}+ 1/3 **E**^{d} +3/8 **E**^{g};

- *Cancellation* between **gluon** and **sea** quark contributions:
  E(ρ,p) α 2/3 **E**$^{u\,val}$+ 1/3 **E**$^{d\,val}$
  => **E**$^{u\,val}$ **~ -E**$^{d\,val}$.

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

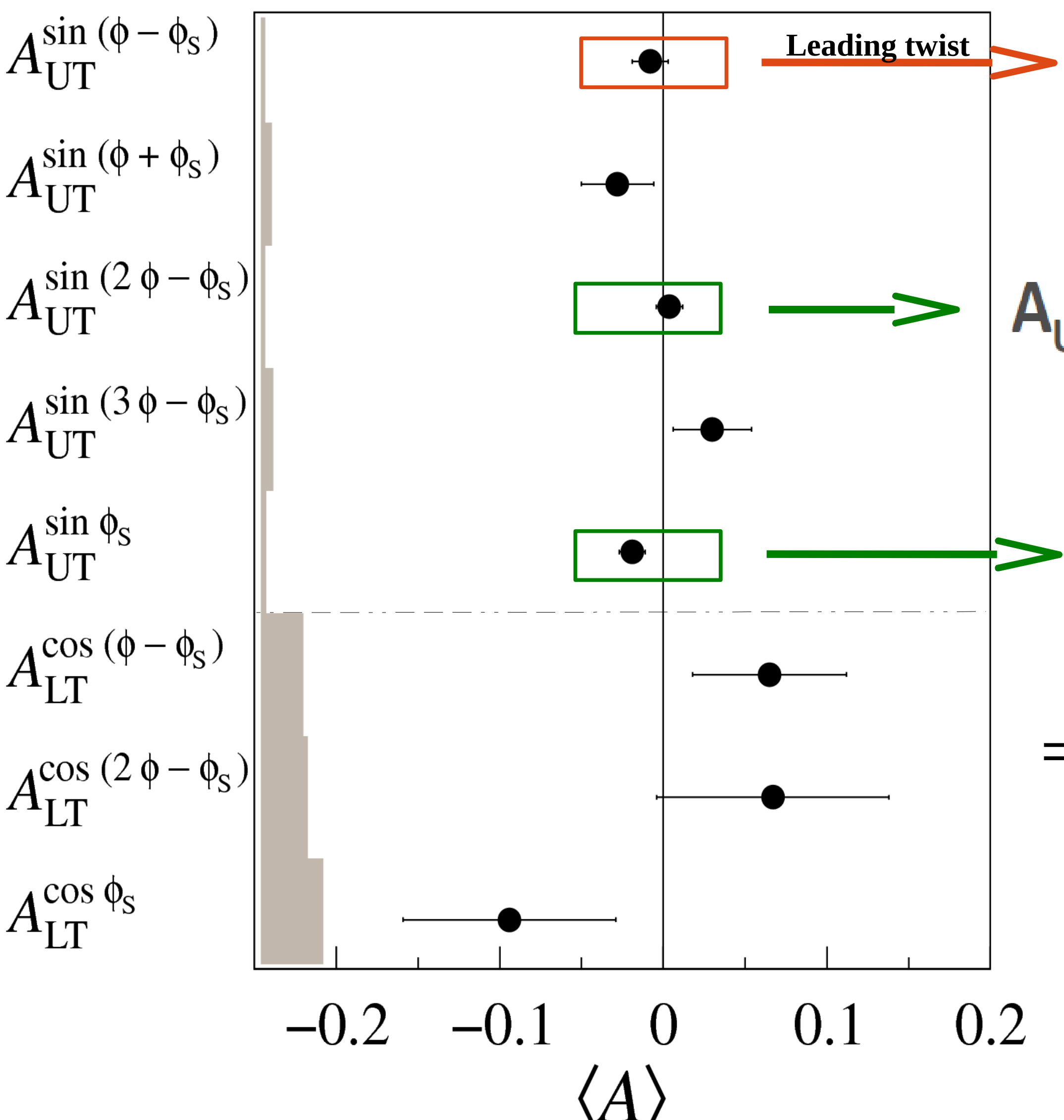


ω *should be more promising*

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

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

W = 8.1 GeV, p_T^2 = 0.2 (GeV/c)^2, Q^2 = 2.2 (GeV/c)^2



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

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

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

=> H_T **not small**

GPD E

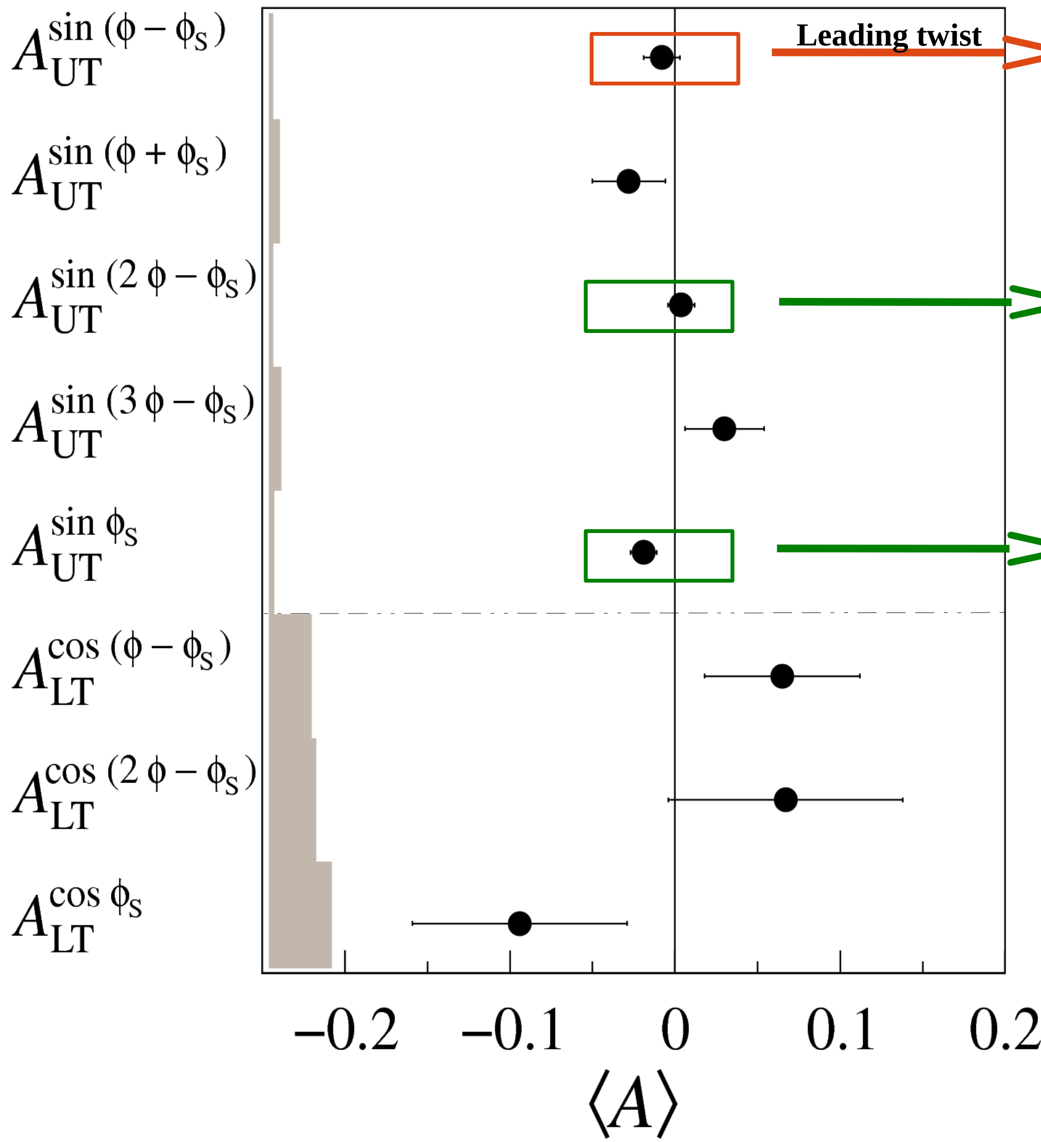
2007-10

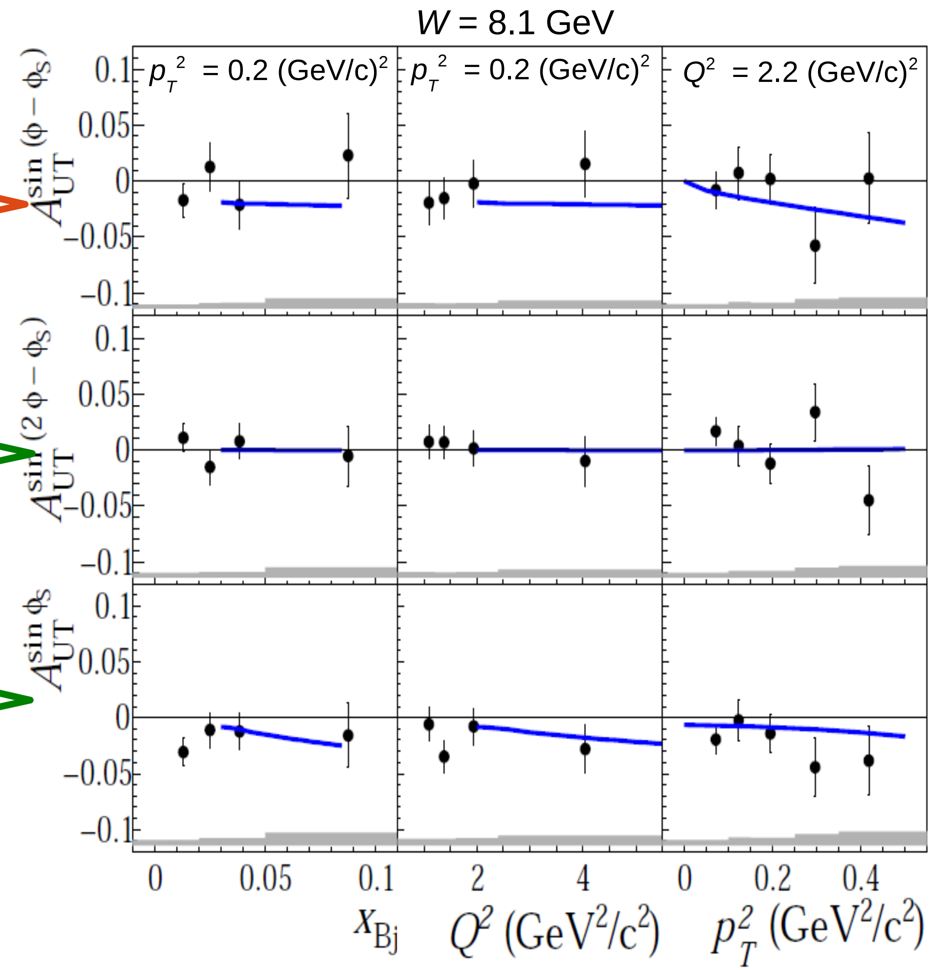
> 2018

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

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

W = 8.1 GeV, p_T^2 = 0.2 (GeV/c)^2, Q^2 = 2.2 (GeV/c)^2



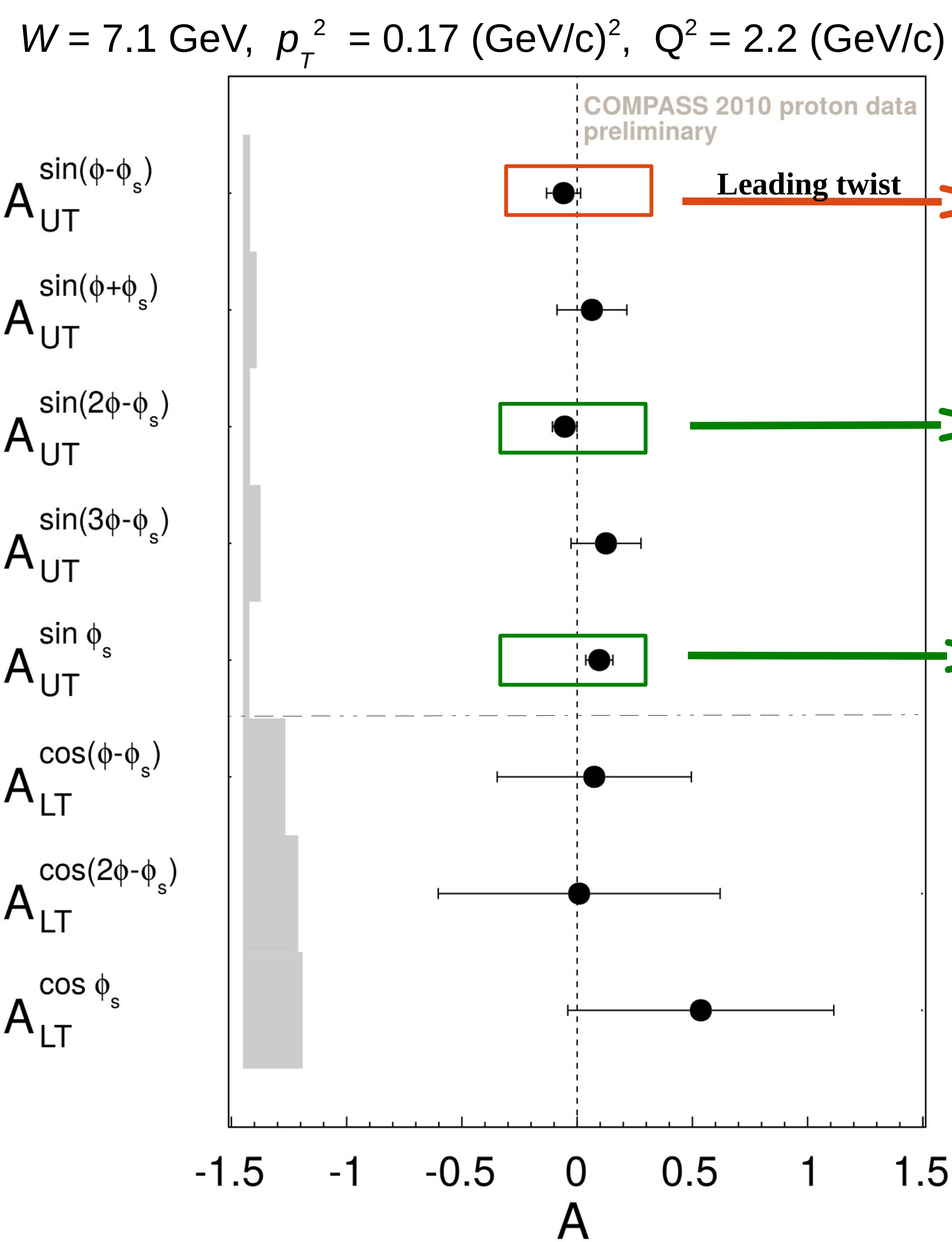


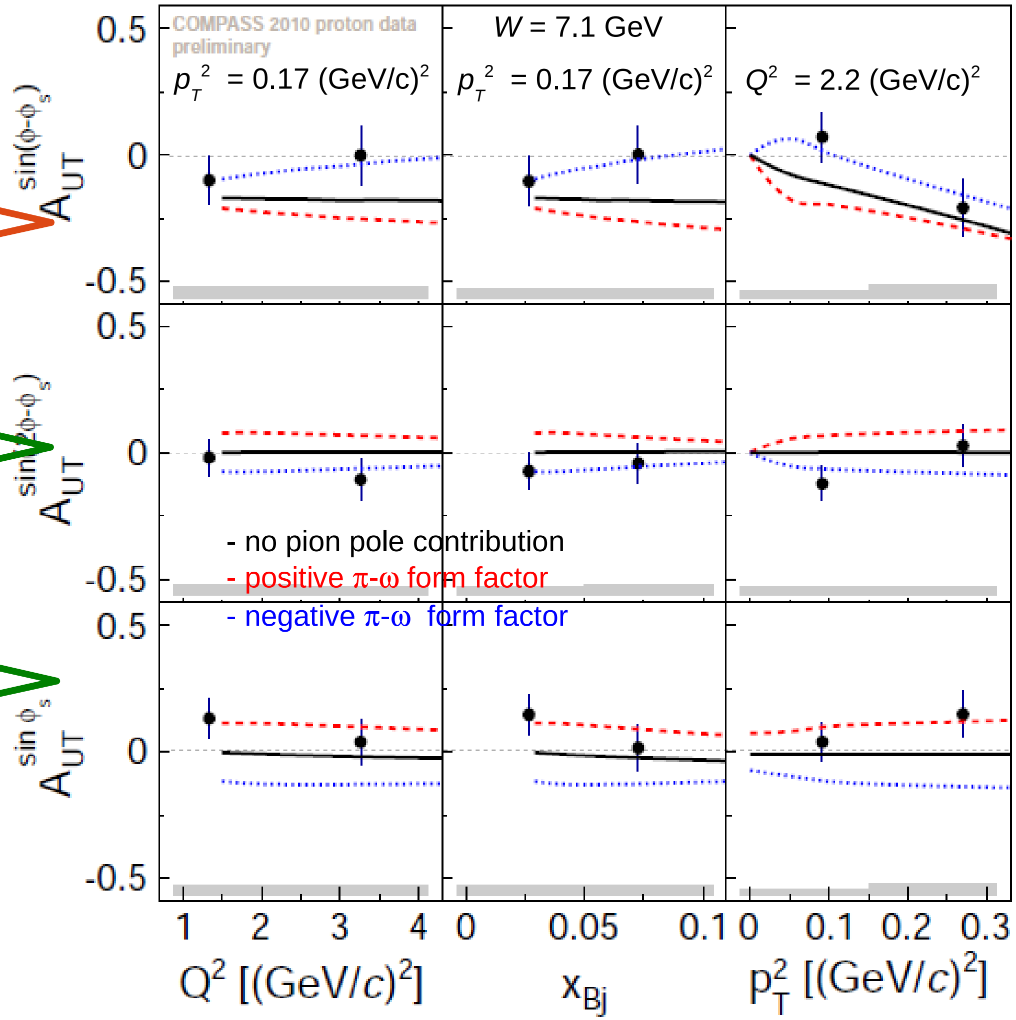
described by GPDs: E, H_T

Model:

[Goloskokov-Kroll: Eur.Phys.J. C74, 2725 (2014)]

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



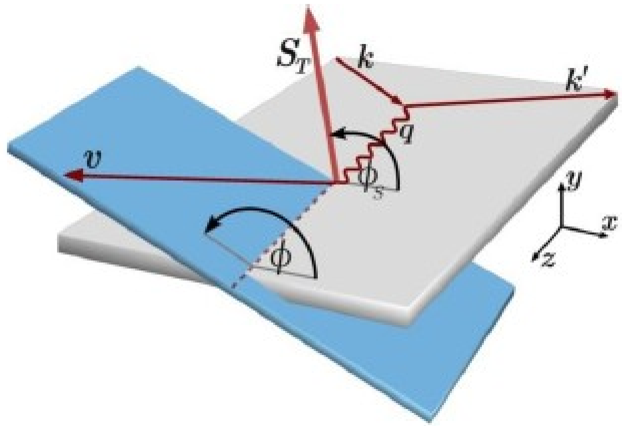


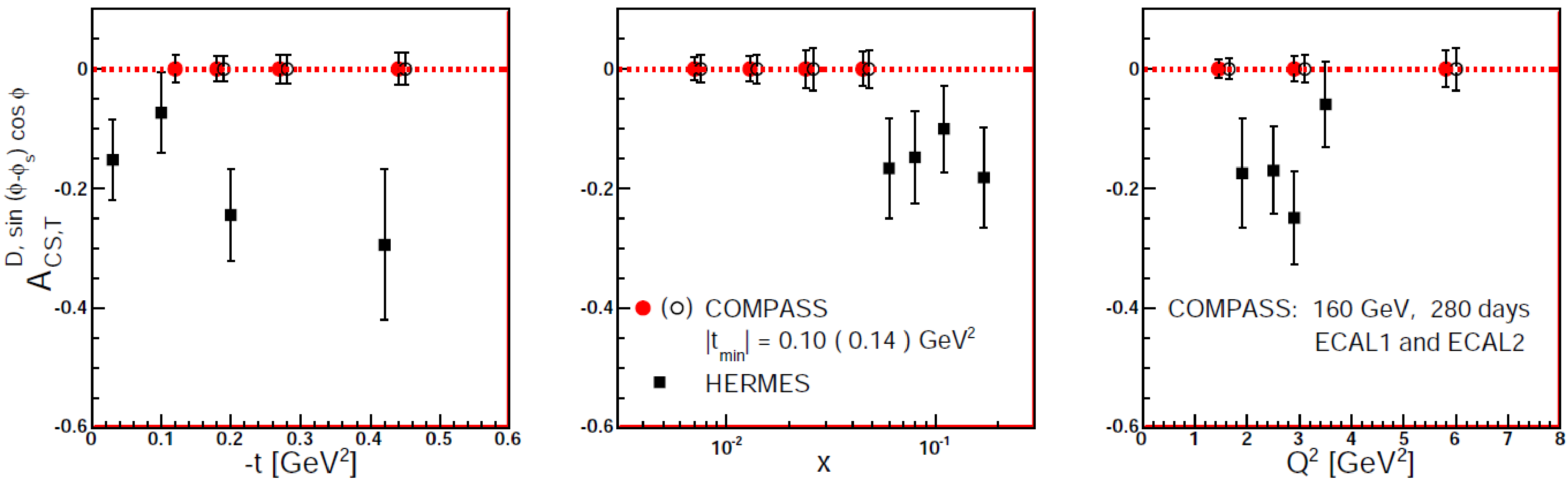
Dominated by pion pole contribution

Model:
[Goloskokov-Kroll: Eur.Phys.J. A50, 146 (2014)]

DVCS on *transversely polarized* proton target (with *recoil proton detection*)

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





Projections for a future addendum of COMPASS physics program

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: $\mu p^{\uparrow\downarrow} \rightarrow \mu p \rho, \omega$;
- 2012: DVCS pilot run => **promising DVCS signal**;

Two years DVCS run (2016-2017)

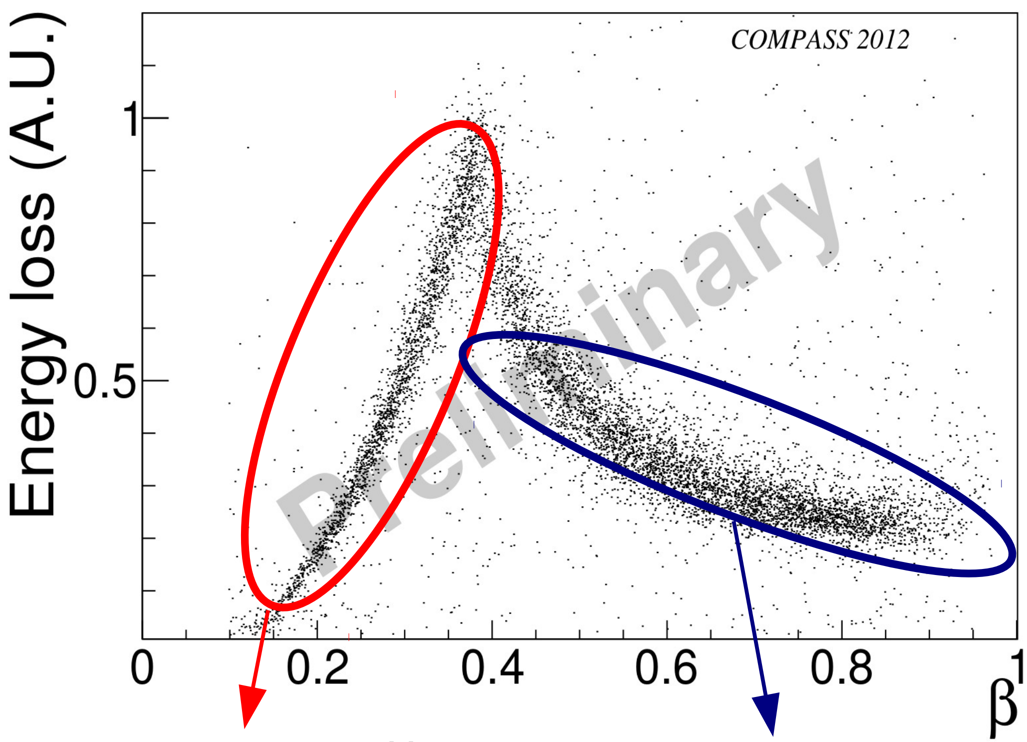
=> Two years for **DVCS** and **HEMP** measurement

GPD *H*
2009
2012
2016-17

Analysis of 2012 data: selection of *ep* → *epγ*

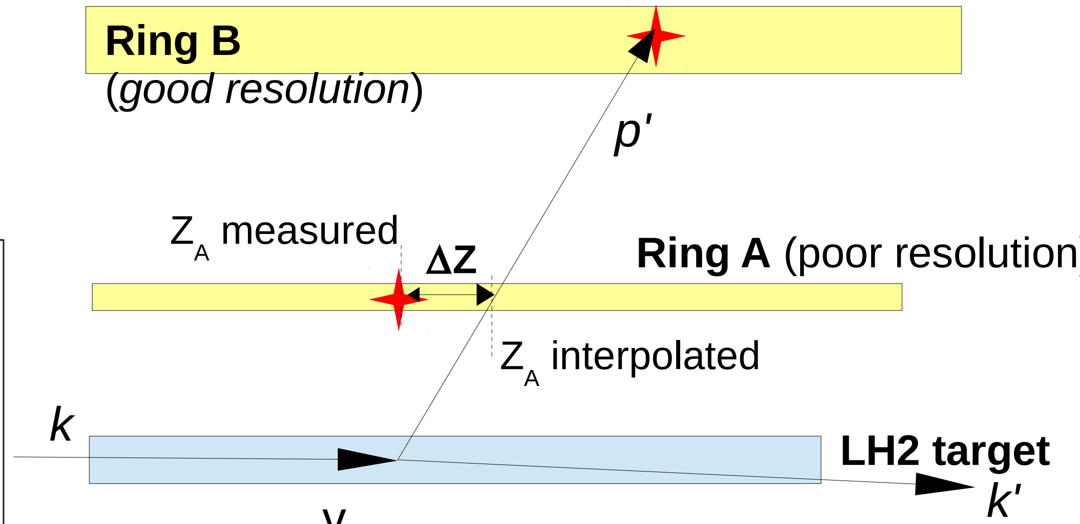
Proton selection

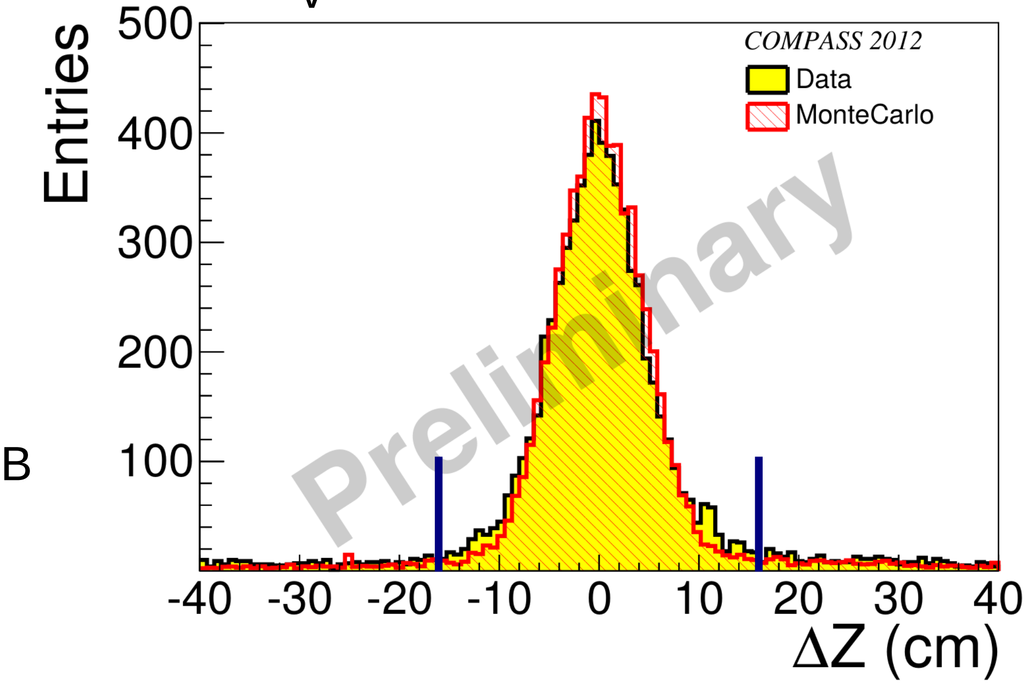
Proton signal in ring B



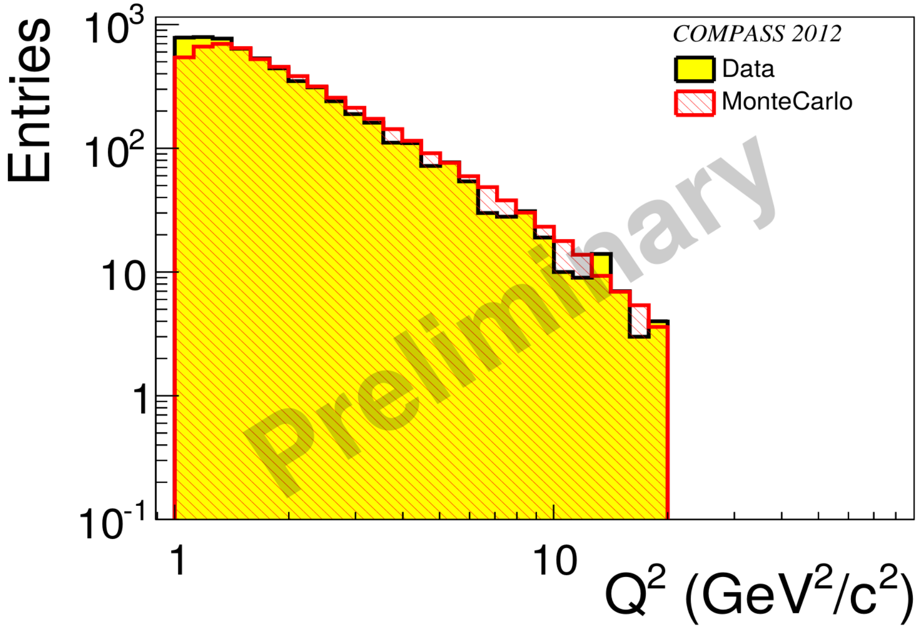
Protons *stopped* in B

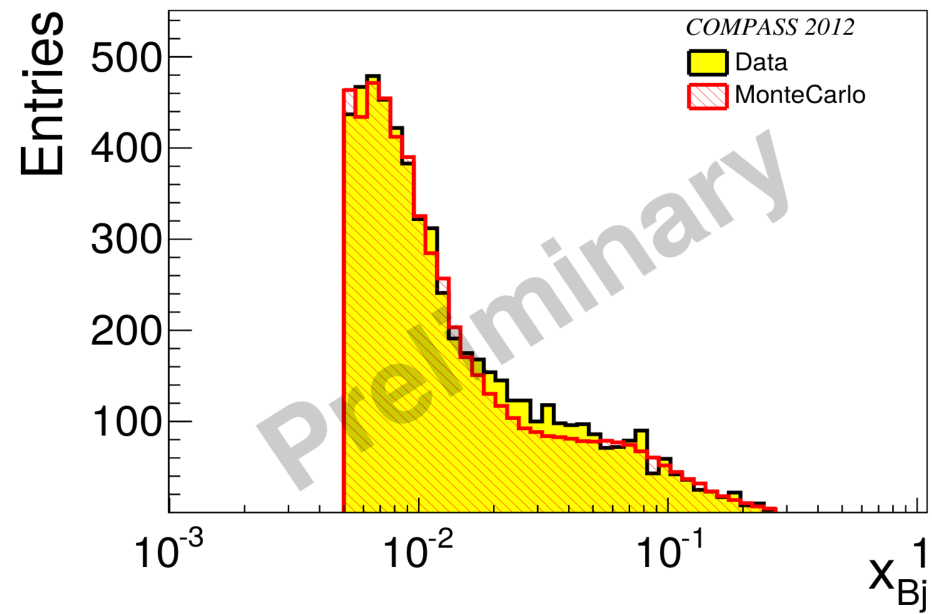
Protons *escaping* ring B

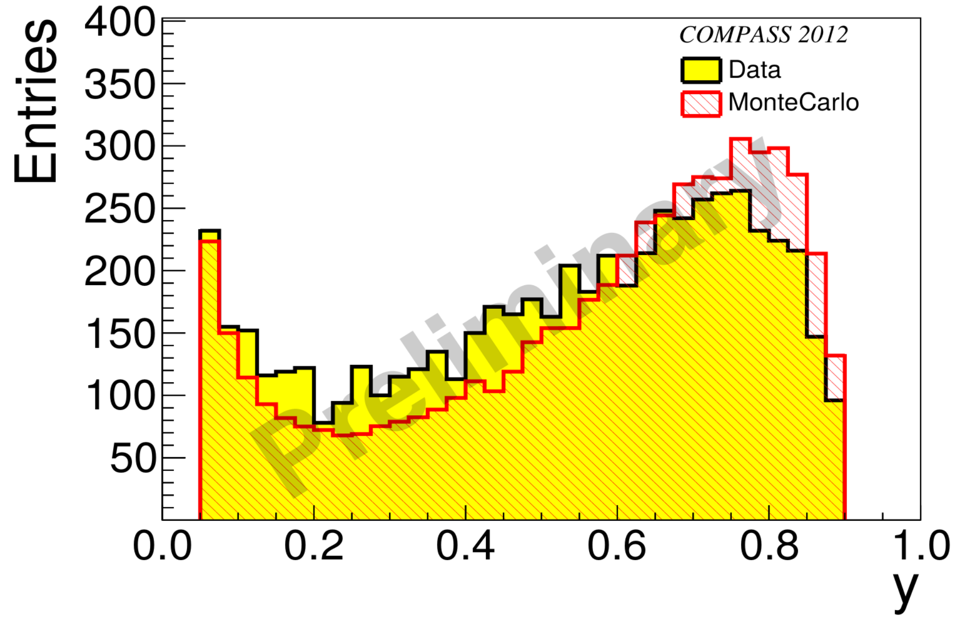




Analysis of 2012 data:
Kinematic coverage





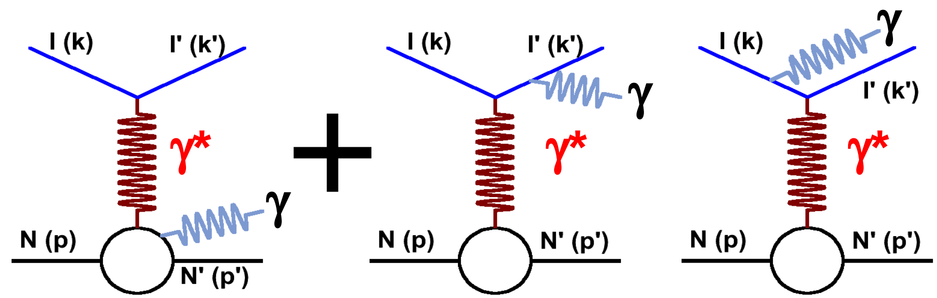


$y = (E_\mu - E_\mu')/E_\mu$

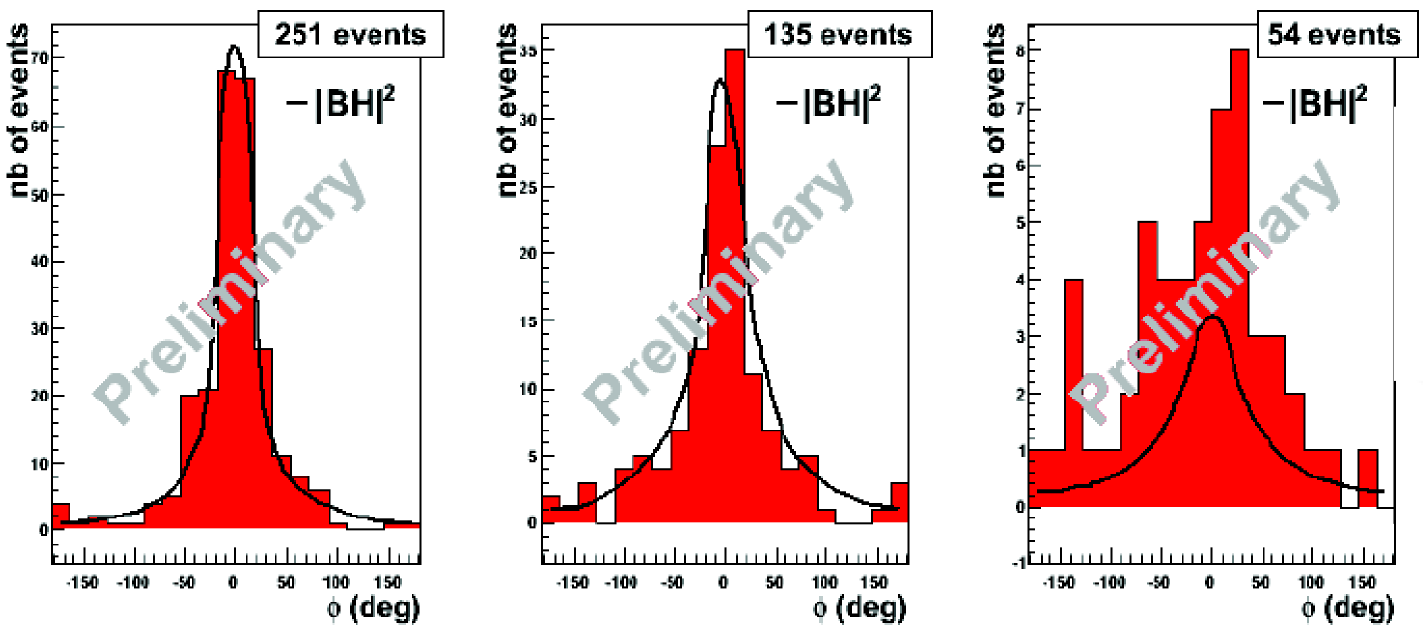
DVCS Test run

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

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



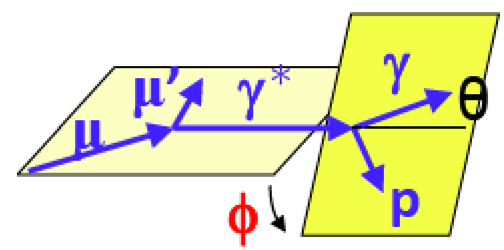
DVCS Bethe-Heitler (BH)



(0.005 < x_{Bj} < 0.01)
BH dominant,
DVCS negligible

(0.01 < x_{Bj} < 0.03)
DVCS-BH
interference

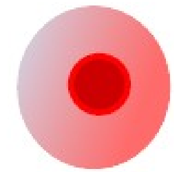
(x_{Bj} > 0.03)
DVCS significant



DVCS not flat ar large x
→ Necessity of ECAL0

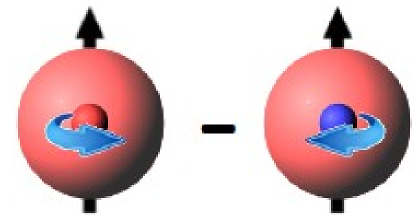
Chiral-even

$H \longleftrightarrow q$



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

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



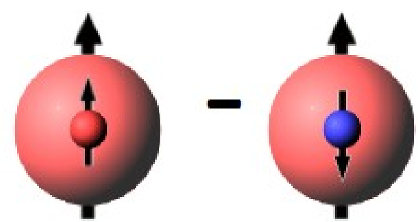
Sivers: quark k_T
& nucleon transv. Spin

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

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

Chiral-odd

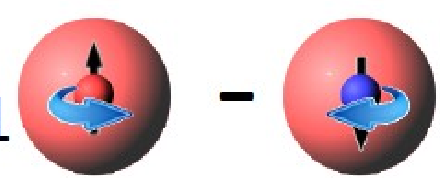
$H_T \longleftrightarrow h_1$



Transversity: quark spin
& nucleon transv. spin

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

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



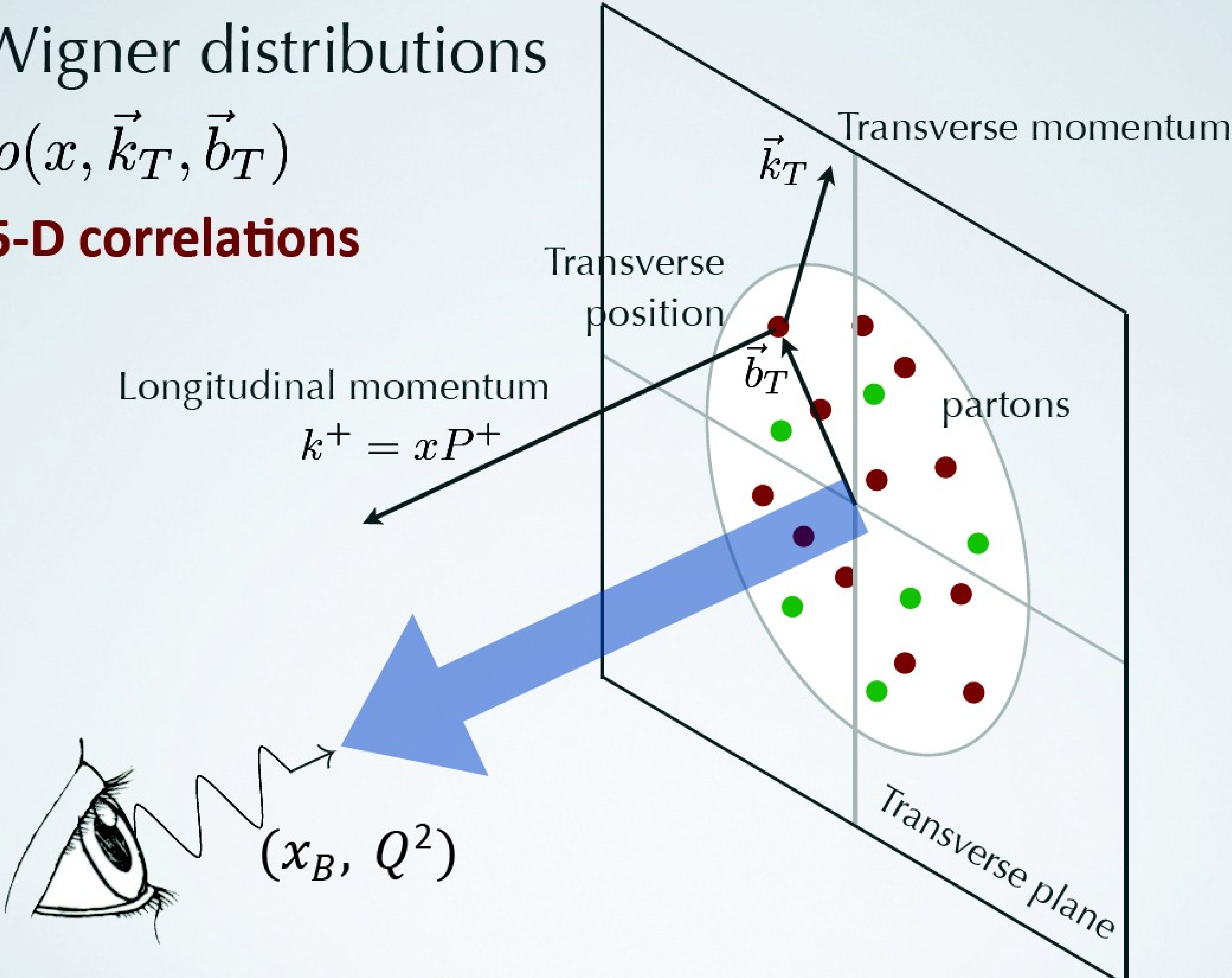
Boer-Mulders: quark k_T
& quark transverse spin

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

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)

Compass GPD program

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

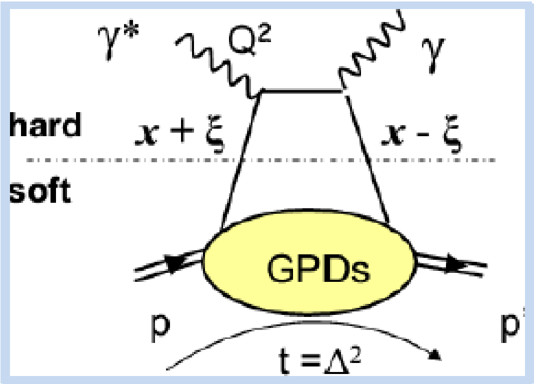
Spin and **charge** cross section **Sum** (Currently *unique* COMPASS feature)

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

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

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

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



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

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

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

Re part of the *Compton Form Factors* linked to the $\mathcal{D}$ *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)

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

$$D_{CS,U} = +2\mathrm{P}_\mu \frac{e^6}{y^2 Q^2}\left(s_1^{DVCS}\sin(\phi)\right)$$
$$+2e_\mu \frac{e^6}{x_{Bj}\, y^3\, t\, \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left(c_0^I + c_1^I\cos(\phi) + \left\{c_2^I\cos(2\phi) + c_3^I\cos(3\phi)\right\}\right)$$

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

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

Towards GPD *E*:

μp → μpρ on transversely polarized proton target

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

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

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

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

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

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

σ_{mn}^{ij} — ij for nucleon helicity, mn for photon helicity

Dominant interference terms:

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

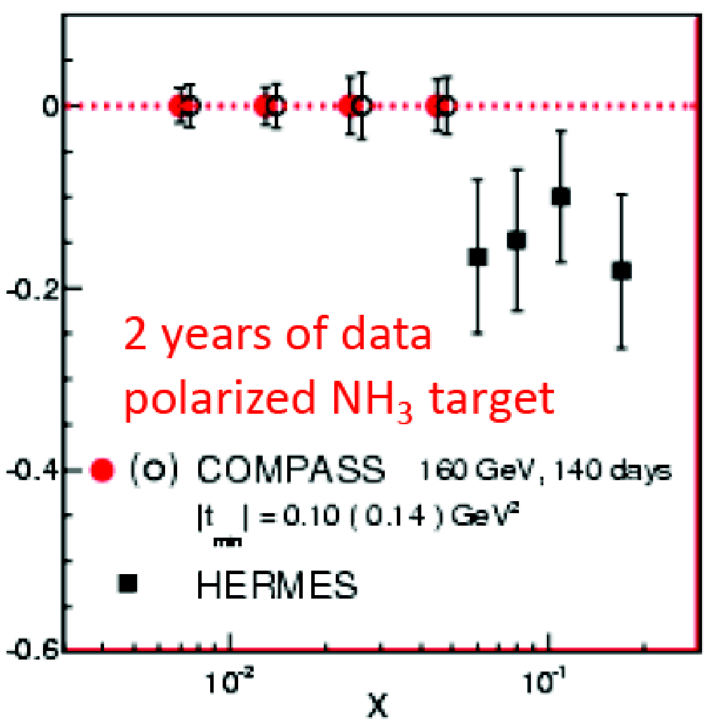
then LT $\quad \gamma^*_T \rightarrow \rho^0_L$

Towards the GPD E

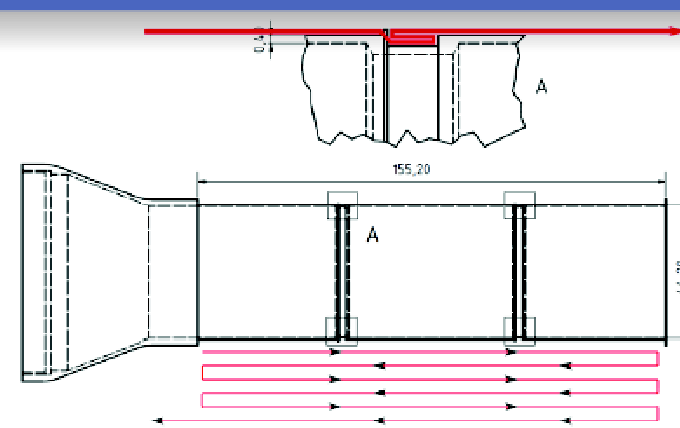
After 2018: DVCS and HEMP on transv. pol. target **and recoil detector**

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

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



- 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