COMPASS-II

Dubna (LPP and LNP),
Moscow (INR, LPI, State University),
Protivinoo

CERN

Bochum, Bonn (ISKP & PI),
Erlangen,
Freiburg, Mainz,
München TU

Warsawa (NCBJ),
Warsawa (TU)
Warsawa (U)

Yamagata

USA (UIUC)

Praha

Lisboa

Saclay

Burden, Calcutta

Tel Aviv

Torino (University,INFN),
Trieste (University,INFN)

Taipei (AS)

COMPASS-II

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2010–014
SPSC-P-340
May 17, 2010

- **DVCS (GPD)** and simultaneously **SIDIS on proton (FF, TMDs)** — **2016/17, ...**
- **TMDs in $\pi^- + p^\uparrow$ Drell-Yan:** — **2014/15, ...**
- ***Pion (and kaon) polarizabilities*** — ***2012***

COMPASS-II Proposal

Approved by CERN RB in December 2010

The COMPASS Collaboration

wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

GPDs

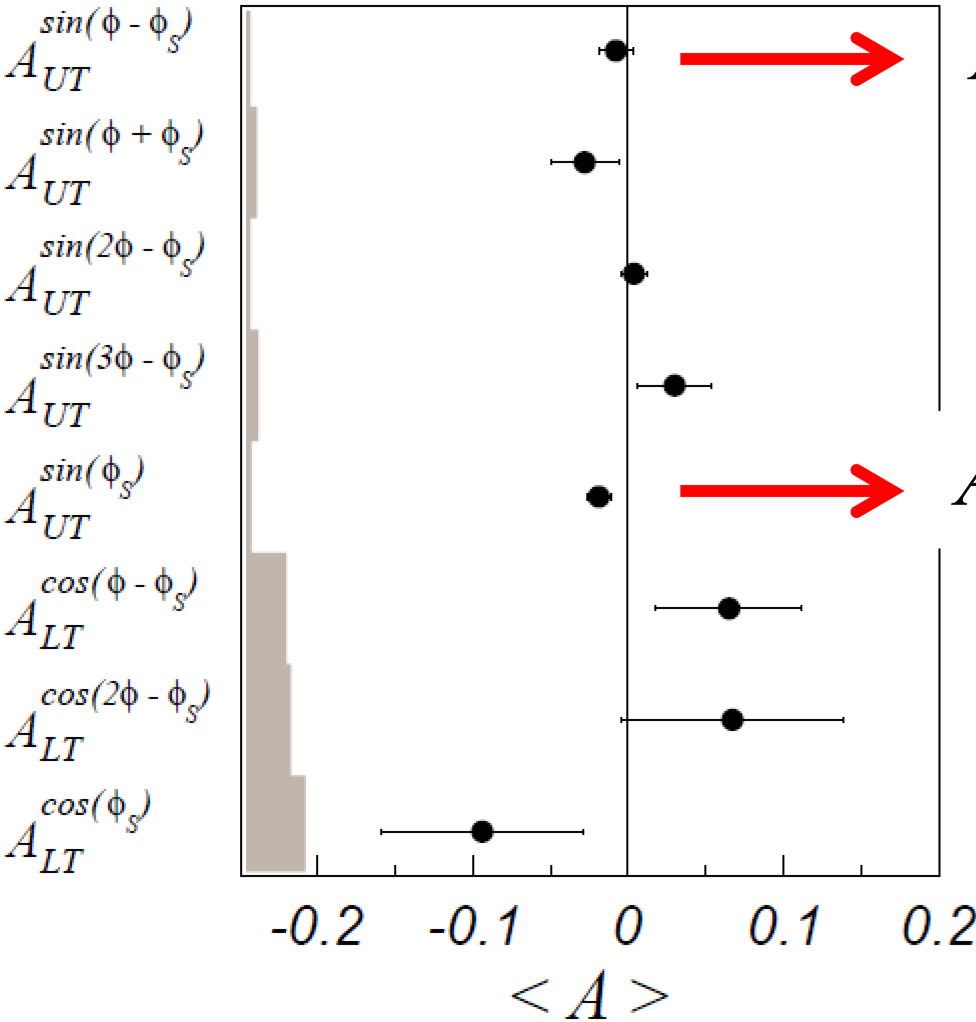
GPD program at COMPASS

- **Transverse target asymmetry for exclusive ρ^0 production with polarized NH3 target**

2007, 2010 data

Transverse spin asymetry for exclusive ρ^0 production with polarized NH3 target

NEW RESULTS



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

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

$\mathcal{H}_T$ could be not small

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

GPD program at COMPASS

- Transverse target asymmetry for exclusive ρ^0 production
  with polarized NH3 target

2007, 2010 data

- DVCS and Hard Exclusive Meson Production
  with LH_2 target + RPD and $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ 160 GeV beams
  to constrain GPD H
  to study the transverse proton size

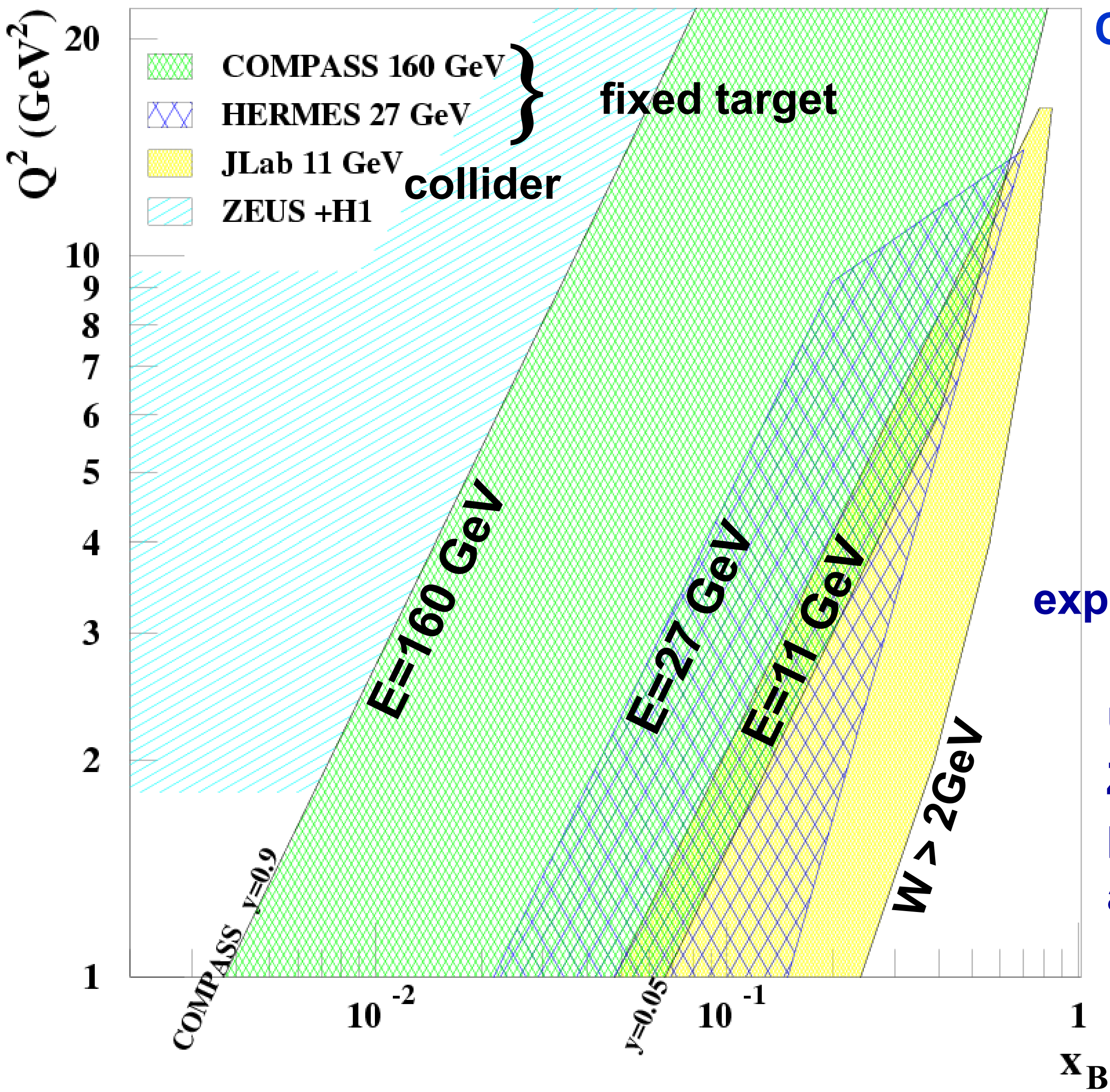
test runs 2009,2012

COMPASS II 2016/17

- DVCS and Hard Exclusive Meson Production
  with proton (NH_3) target + RPD and $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ 160 GeV beams
  to constrain GPD E

future

Kinematic domain (Q^2, x_B) for GPDs



COMPASS unique for GPDs

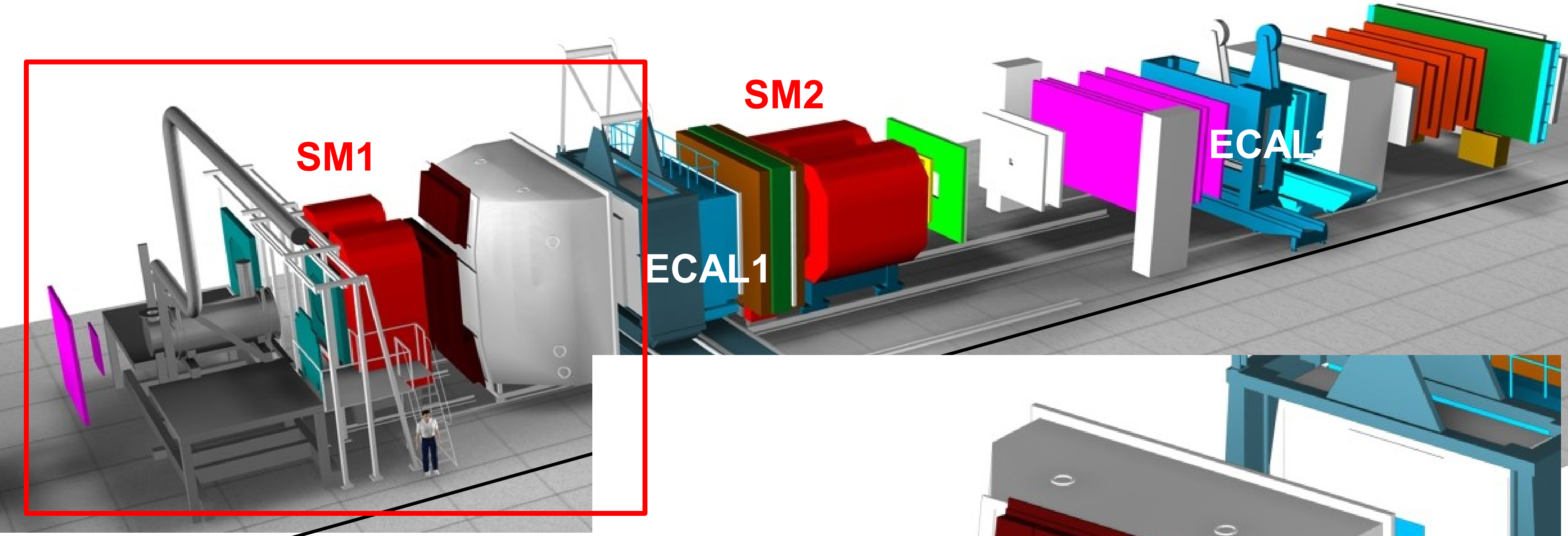
CERN muon beam

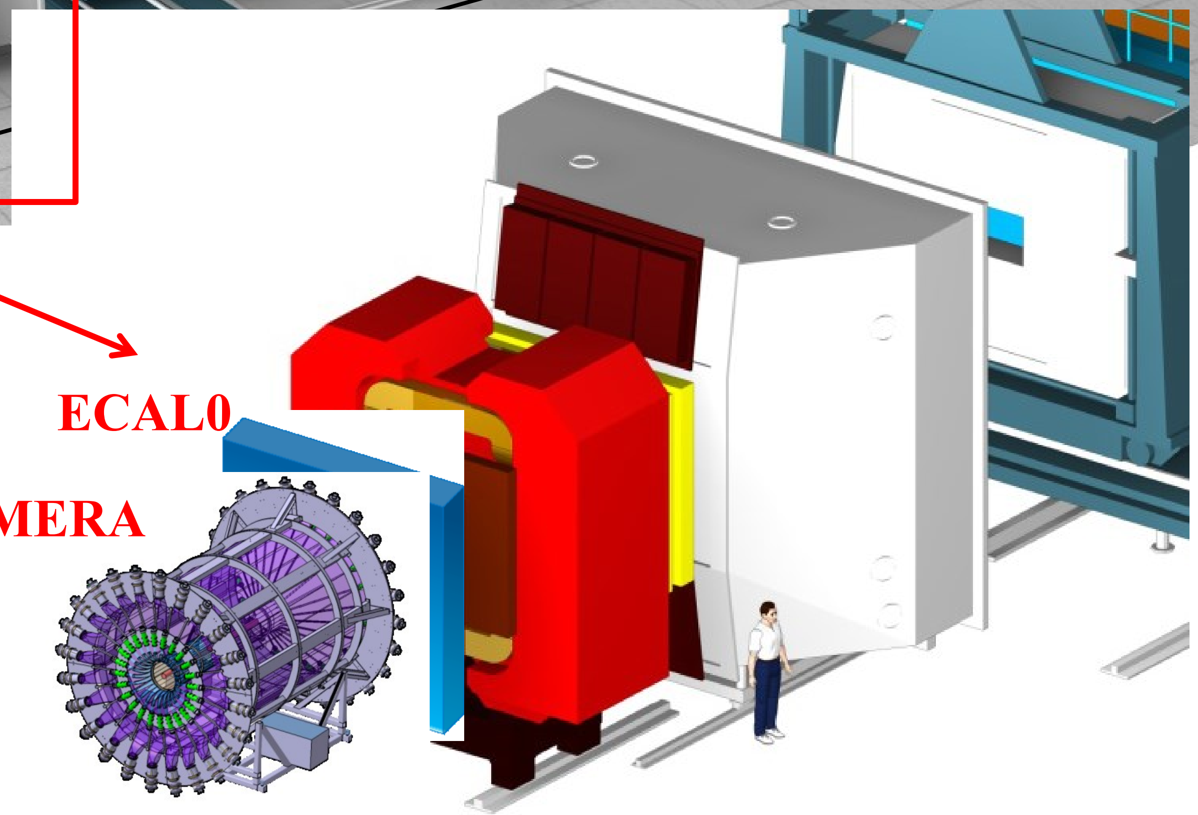
- 100 - 190 GeV
- $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available
- 80% Polarisation
- 4.6 10^8 μ^+

➔Lumi= 10^{32} cm^{-2} s^{-1}
with 2.5m LH2 target

explore the
intermediate x_{Bj} region
uncovered region between
ZEUS+H1 & HERMES + Jlab
before new colliders may be available

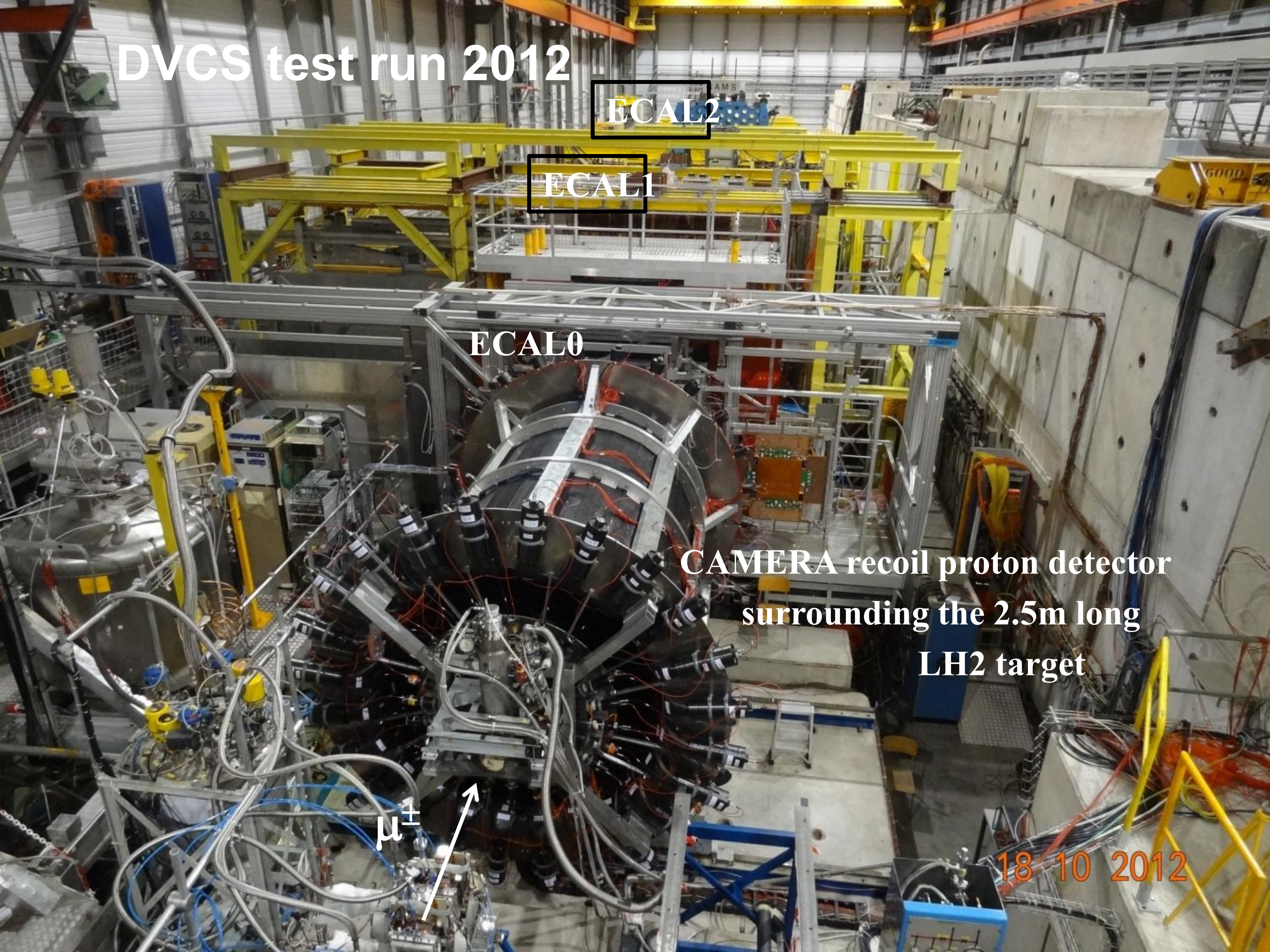
experimental apparatus





new equipements

- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0


DVCS test run 2012
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
μ±
18 10 2012

SIDIS

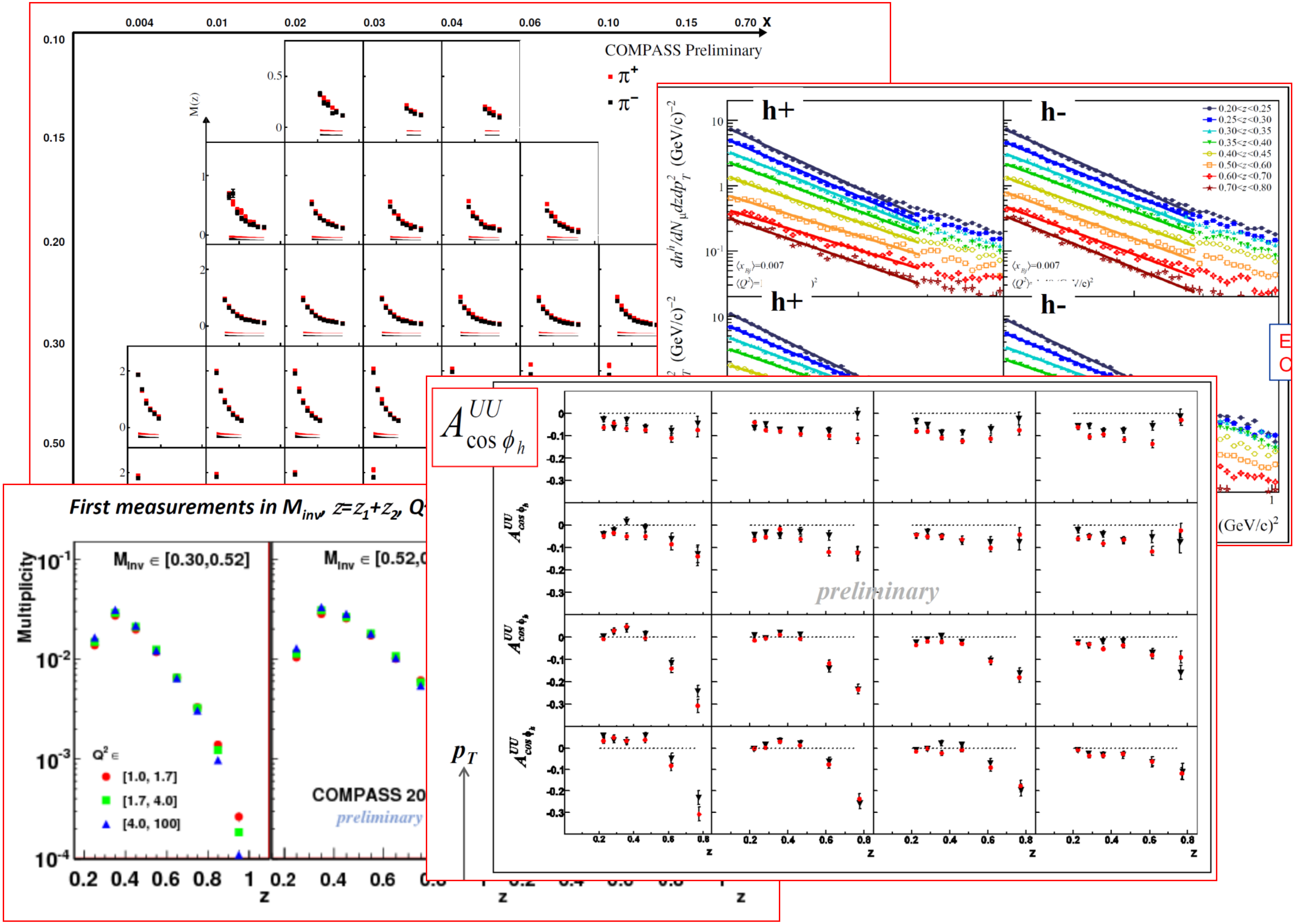
SIDIS

i.e. **hadron multiplicities vs z and p_t^2**

dihadron multiplicities

and

azimuthal asymmetries



unpolarised deuteron

SIDIS

i.e. **hadron multiplicities vs z and p_t^2**
dihadron multiplicities
and
azimuthal asymmetries

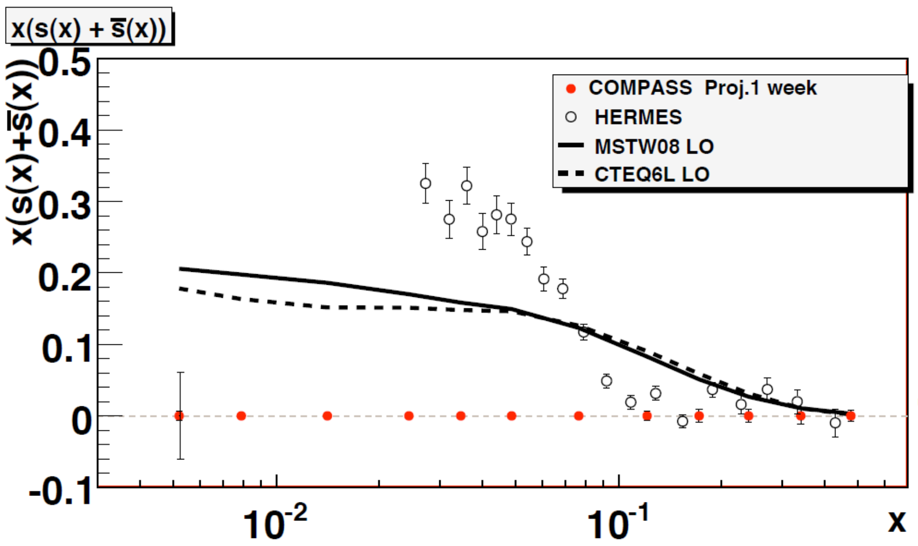
on the 2.5 m long LH_2 target

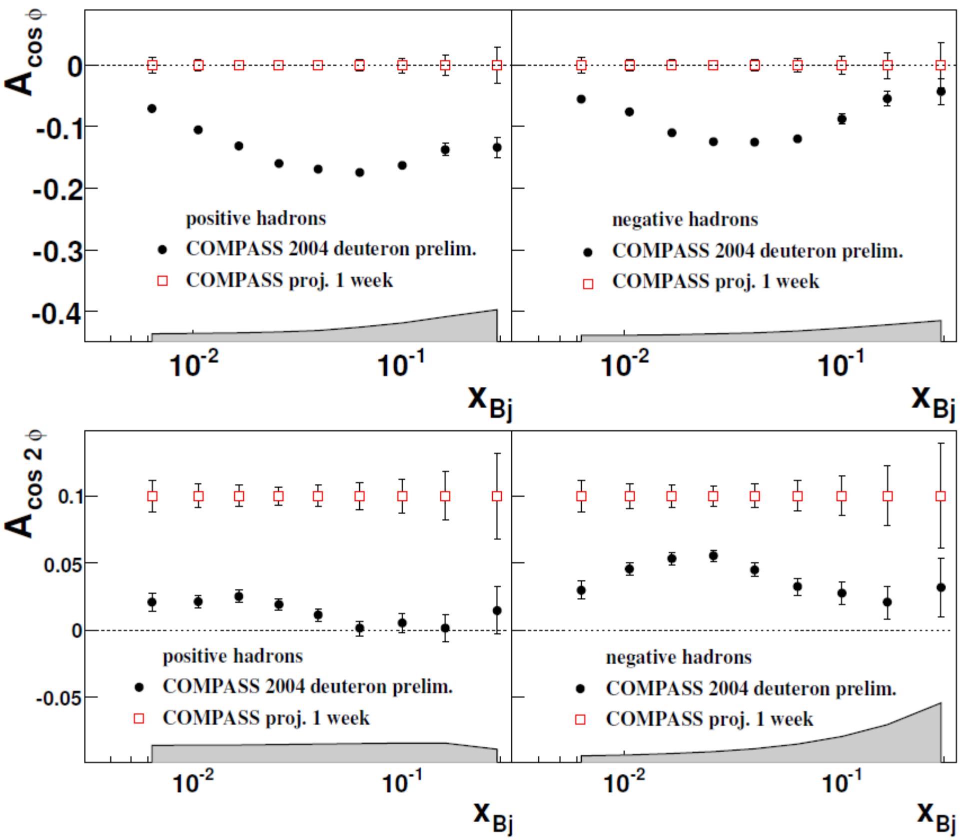
taking advantage of the spectrometer consolidation and upgrades which are ongoing
trackers, RICH

SIDIS

160 GeV/c, 2.5 m long LH_2 target

1 week of data taking

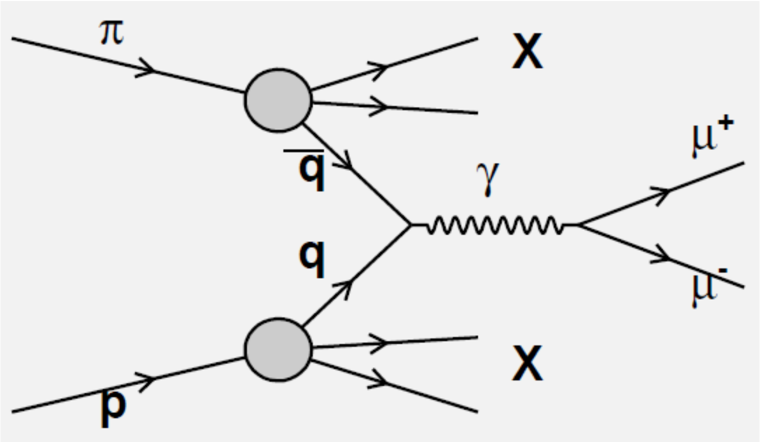




polarised Drell - Yan

test run in 2009

polarised Drell - Yan



complementary to SIDIS:

cross-sections:

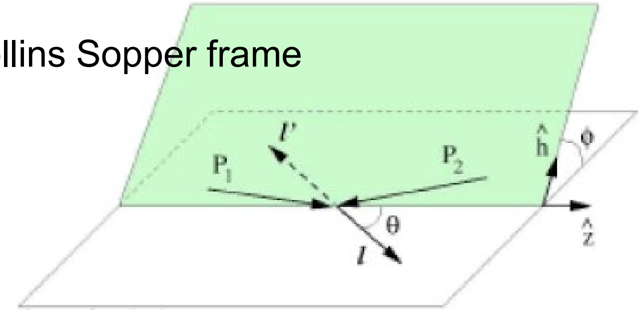
SIDIS: convolution of a TMD PDFs with FFs

DY: convolution of 2 TMD PDFs

$$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X \quad \rightarrow \quad \sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$$

polarised Drell - Yan

Collins Sopper frame



$$
\frac{d\sigma}{d^4q\,d\Omega} = \left[\frac{\alpha^2}{Fq^2}\left(F_{UU}^1 + F_{UU}^1\right)\left(1 + A_{UU}^1 \cos^2\theta\right)\right] \times
$$

$$
\left\{
\begin{array}{l}
1 + \cos\varphi \times D_{[\sin 2\theta]} A_{UU}^{\cos\varphi} + \cos(2\varphi) \times D_{[\sin^2\theta]} A_{UU}^{\cos(2\varphi_h)} + \\
S_L \left[\sin\varphi \times D_{[\sin 2\theta]} A_{UL}^{\sin\varphi} + \sin(2\varphi) \times D_{[\sin^2\theta]} A_{UL}^{\sin(2\varphi)} \right] + \\
\mathbf{S}_T \left[
\begin{array}{l}
\sin\varphi_S \times \left(D_{[1]} A_{UT}^{\sin\varphi_S} + D_{[\cos^2\theta]} \tilde{A}_{UT}^{\sin\varphi_S} \right) + \\
\sin(\varphi - \varphi_S) \times \left(D_{[\sin 2\theta]} A_{UT}^{\sin(\varphi-\varphi_S)} \right) + \\
\sin(\varphi + \varphi_S) \times \left(D_{[\sin 2\theta]} A_{UT}^{\sin(\varphi+\varphi_S)} \right) + \\
\sin(2\varphi - \varphi_S) \times \left(D_{[\sin^2\theta]} A_{UT}^{\sin(2\varphi-\varphi_S)} \right) + \\
\sin(2\varphi + \varphi_S) \times \left(D_{[\sin^2\theta]} A_{UU}^{\sin(2\varphi_h+\varphi_S)} \right)
\end{array}
\right] +
\end{array}
\right\}
$$

$(\text{B.-M.})_\pi \otimes (\text{B.-M.})_p$

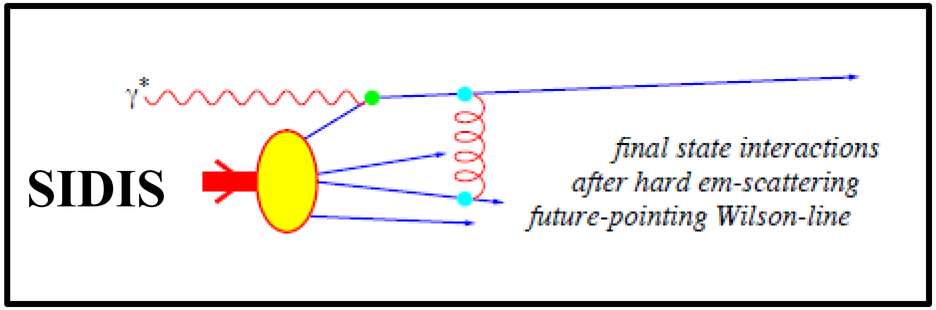
$(f_1)_\pi \otimes (\text{Sivers})_p$

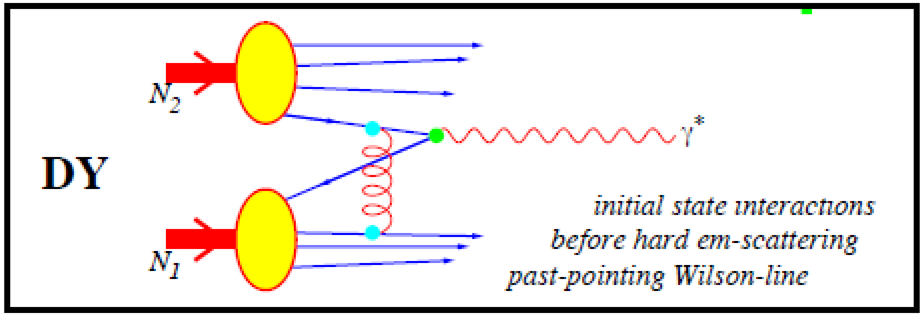
$(\text{B.-M.})_\pi \otimes (\text{Transv.})_p$

$(\text{B.-M.})_\pi \otimes (\text{Pretz.})_p$

Test of universality

the T-odd Boer-Mulders and Sivers functions are process dependent





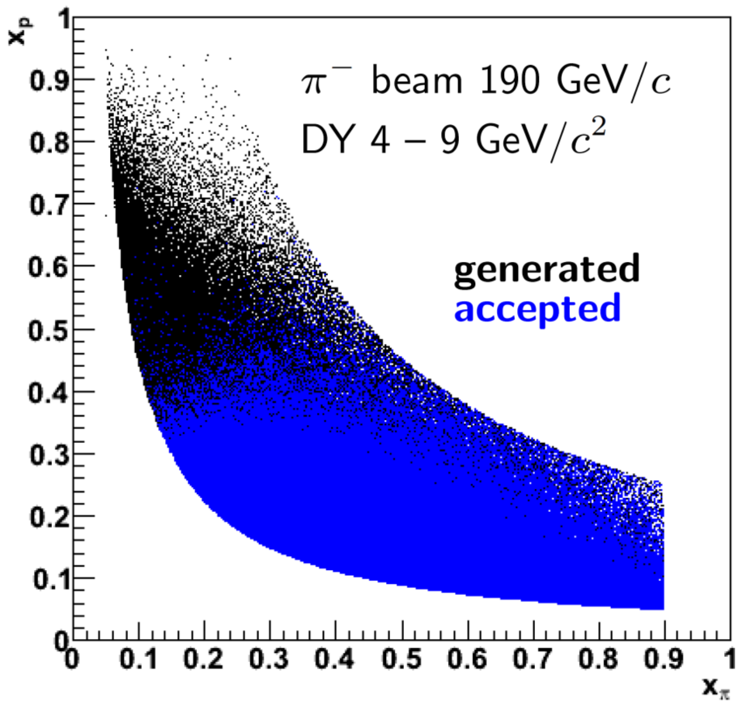
and are expected to change sign

Boer-Mulders $$h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)$$

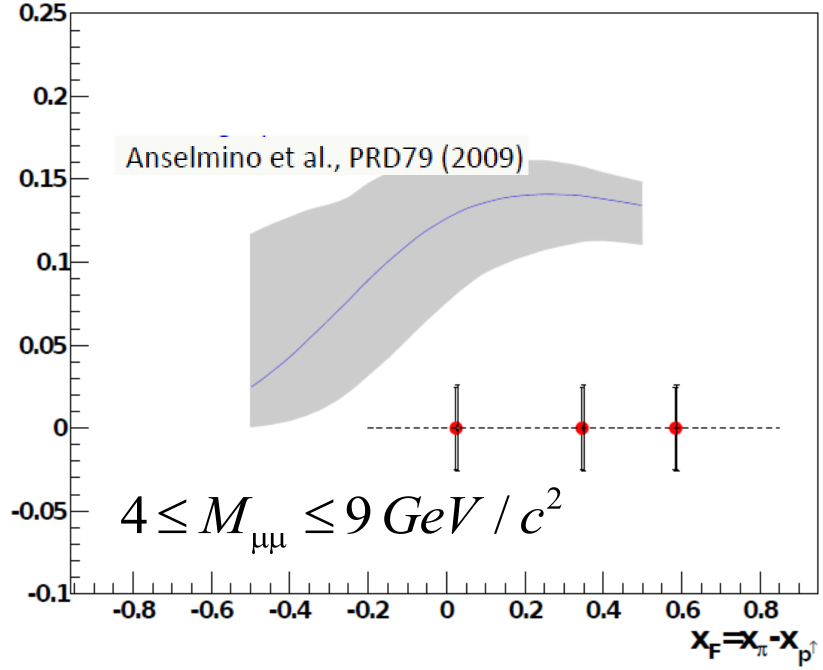
Sivers $$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

polarised Drell - Yan

acceptance



$A_T^{\sin\phi_s}$ statistical errors

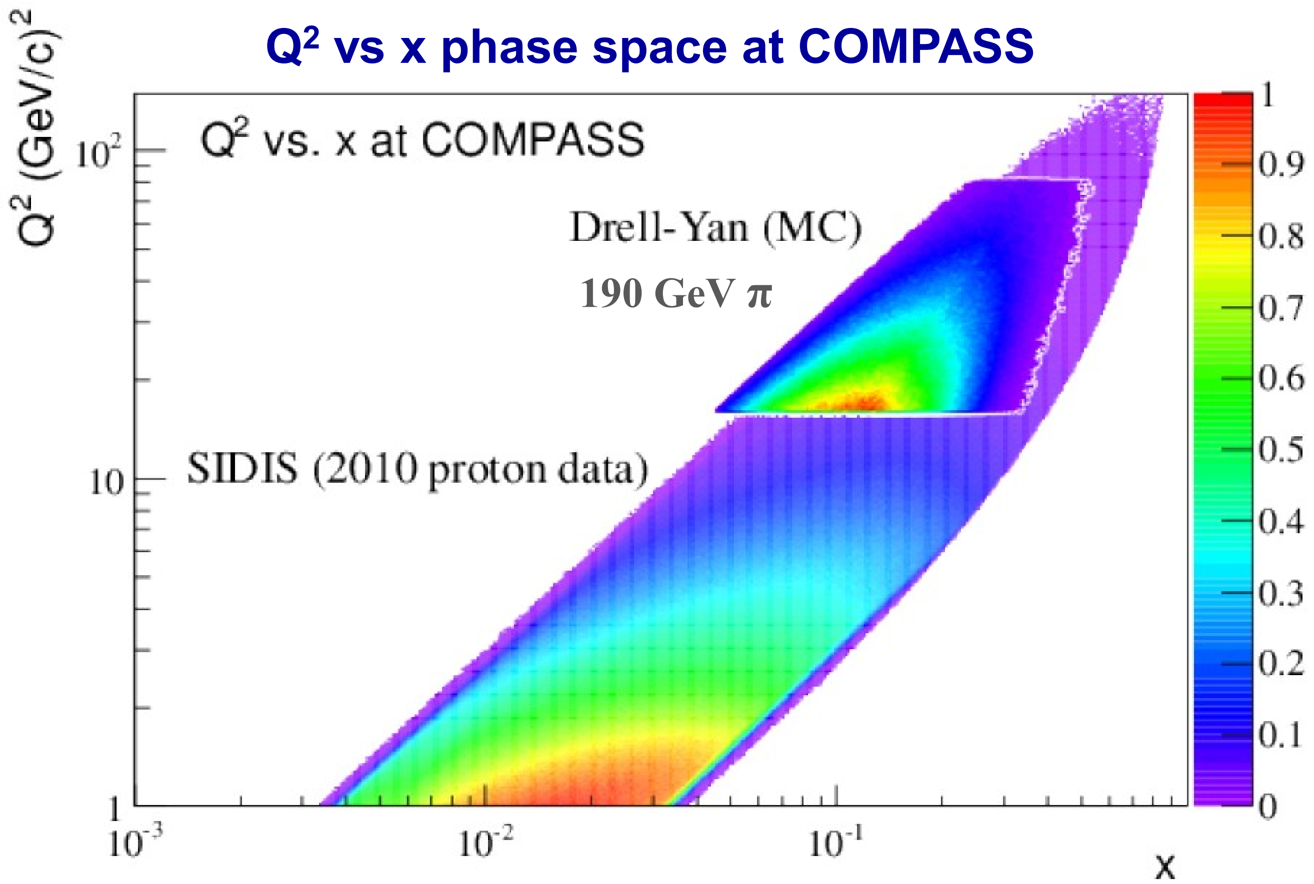


2 years data taking (1y = 140d)
$6 \cdot 10^8$ π/spill (9.6s/48s duty cycle)
1.1m transv pol. NH_3 target
Lumi=$1.2 \cdot 10^{32}$ $cm^{-2}s^{-1}$

polarised Drell - Yan

and many ideas for
other measurements
in 2015 and after

Q² vs x phase space at COMPASS



the phase spaces of the two processes overlap

→ consistent extraction of TMD DPFs in the same region

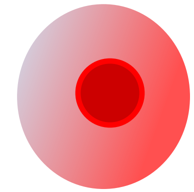
COMPASS-II

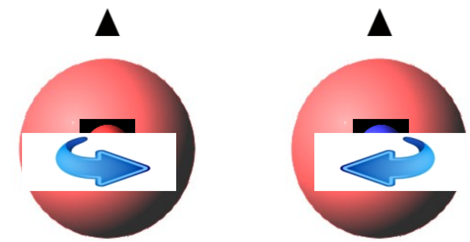
- **a lot of interesting results are expected in few years !!**

With DVCS and exclusive ρ production

Chiral-even GPDs

σ $\quad H \rightarrow q$



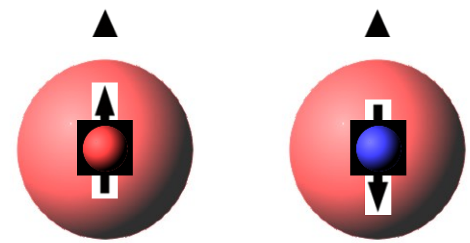


$A_{UT}^{\sin(\phi - \phi_S)}$ $\quad E \leftrightarrow f_{1T}^{\perp}$

Sivers correlates

quark k_T and nucleon spin (transv. pol. N)

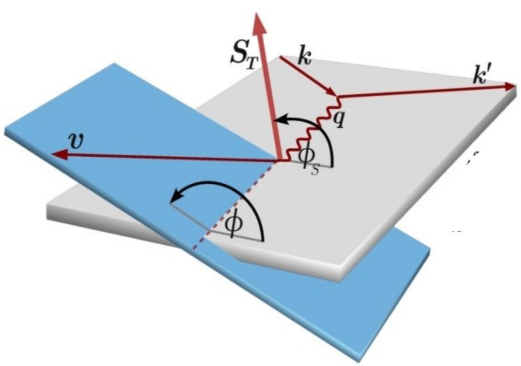
Chiral-odd GPDs

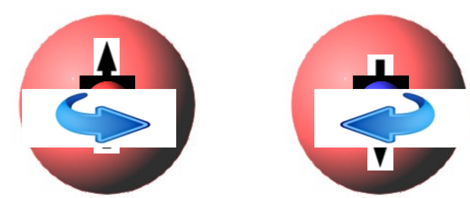


$A_{UT}^{\sin(\phi_S)}$ $\quad H_T \leftrightarrow h_1$

Transversity correla

quark spin and nucleon spin (transv. pol. N)





$\overline{E}_T = 2\widetilde{H}_T + E_T \leftrightarrow h_1^{\perp}$

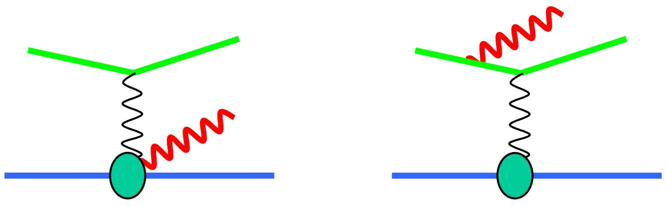
Boer-Mulders correlates

quark k_T and quark transverse spin (unpol N)

DVCS

can be separated from BH and constrain the GPD *H*

e.g. using cross-sections for different lepton (μ) beam charge & spin (e_μ & P_μ)



Charge & Spin difference and sum:

$$\mathcal{S} = d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + \mathrm{Im}\, I)$$

$$\mathcal{D} = d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} = 2(d\sigma_0^{DVCS} + \mathrm{Re}\, I)$$

Im and Re related to:

$$H(x = \xi, \xi, t)$$

$$\mathcal{P} \int dx\, H(x, \xi, t)/(x - \xi)$$

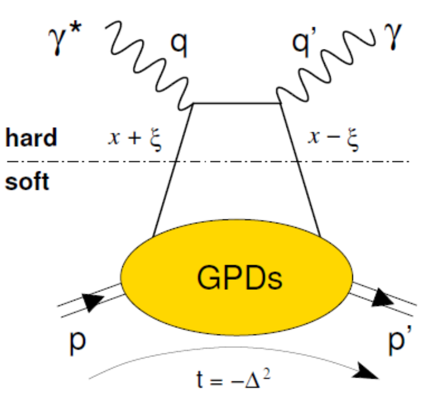
DVCS & transverse proton size

distance $\langle r_\perp^2 \rangle$ between struck quark and spectator c.m.
given by *t*-slope of DVCS cross-section σ_0 (as function of x_{Bj}, LO)

$$\frac{d\sigma_0^{DVCS}}{dt} \propto \exp(-B(x_B)|t|)$$

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

- Reminder $\mathcal{S} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + Im\, I)$
- Subtract BH from $\mathcal{S}$, integrate over $\phi \rightarrow \sigma_0$
- H1 found 0.65 ± 0.02 fm at $x_{Bj} \approx 10^{-3}$

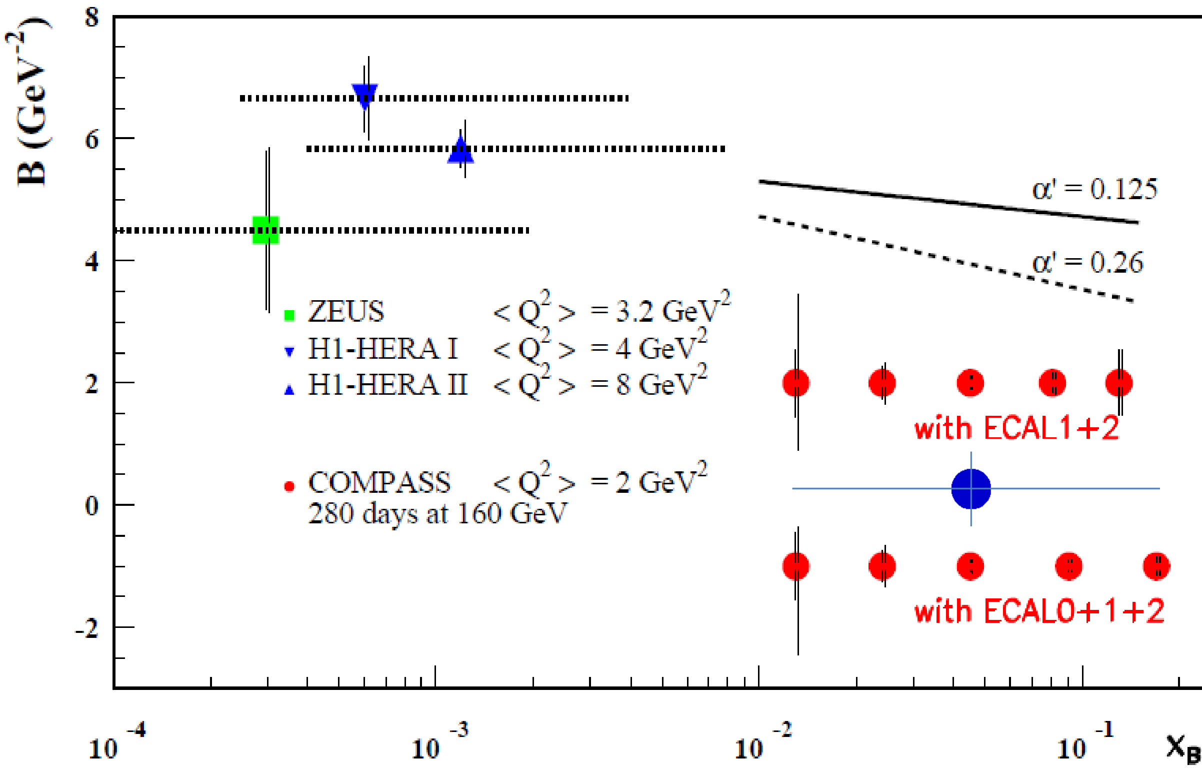


Parametrisation

$$B(x_B) = B_0 + 2\alpha' \log \frac{x_0}{x_B}$$

DVCS & transverse proton size

- COMPASS-II projection, 2 years of data taking ●, pilot run 2012 ●
- x_B region unique to COMPASS
- transition from HERA → HERMES/JLab



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

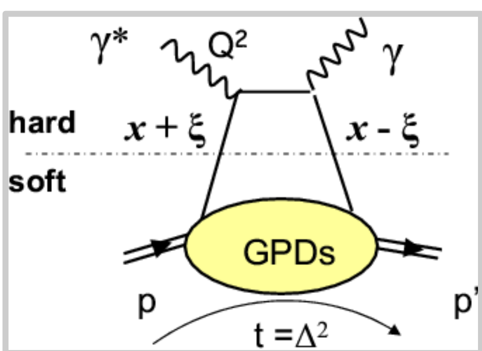
Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\rightarrow\mu p\gamma)} = \sout{d\sigma^{BH}} + \sout{d\sigma^{DVCS}}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

$$+\, e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} \qquad \sout{+\, e_\mu P_\mu}\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int}\cos\phi \qquad c_{0,1}^{Int} \sim \mathcal{R}e(F_1\mathcal{H})$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int}\sin\phi \qquad s_1^{Int} \sim \mathcal{I}m(F_1\mathcal{H})$$



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

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

Note: dominance of H at COMPASS kinematics

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\to\mu p\gamma)} = \cancel{d\sigma^{BH}} + \cancel{d\sigma^{DVCS}_{unpol}} + P_\mu\, d\sigma^{DVCS}_{pol}$$

$$+\, e_\mu\, a^{BH}\, \mathcal{Re}\, A^{DVCS} \quad \cancel{+\, e_\mu P_\mu}\, a^{BH}\, \mathcal{Im}\, A^{DVCS}$$

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int}\cos\phi \qquad c_{0,1}^{Int} \sim \mathcal{Re}(F_1\mathcal{H})$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int}\sin\phi \qquad s_1^{Int} \sim \mathcal{Im}(F_1\mathcal{H})$$

Angular decomposition of sum and diff of the DVCS cross section

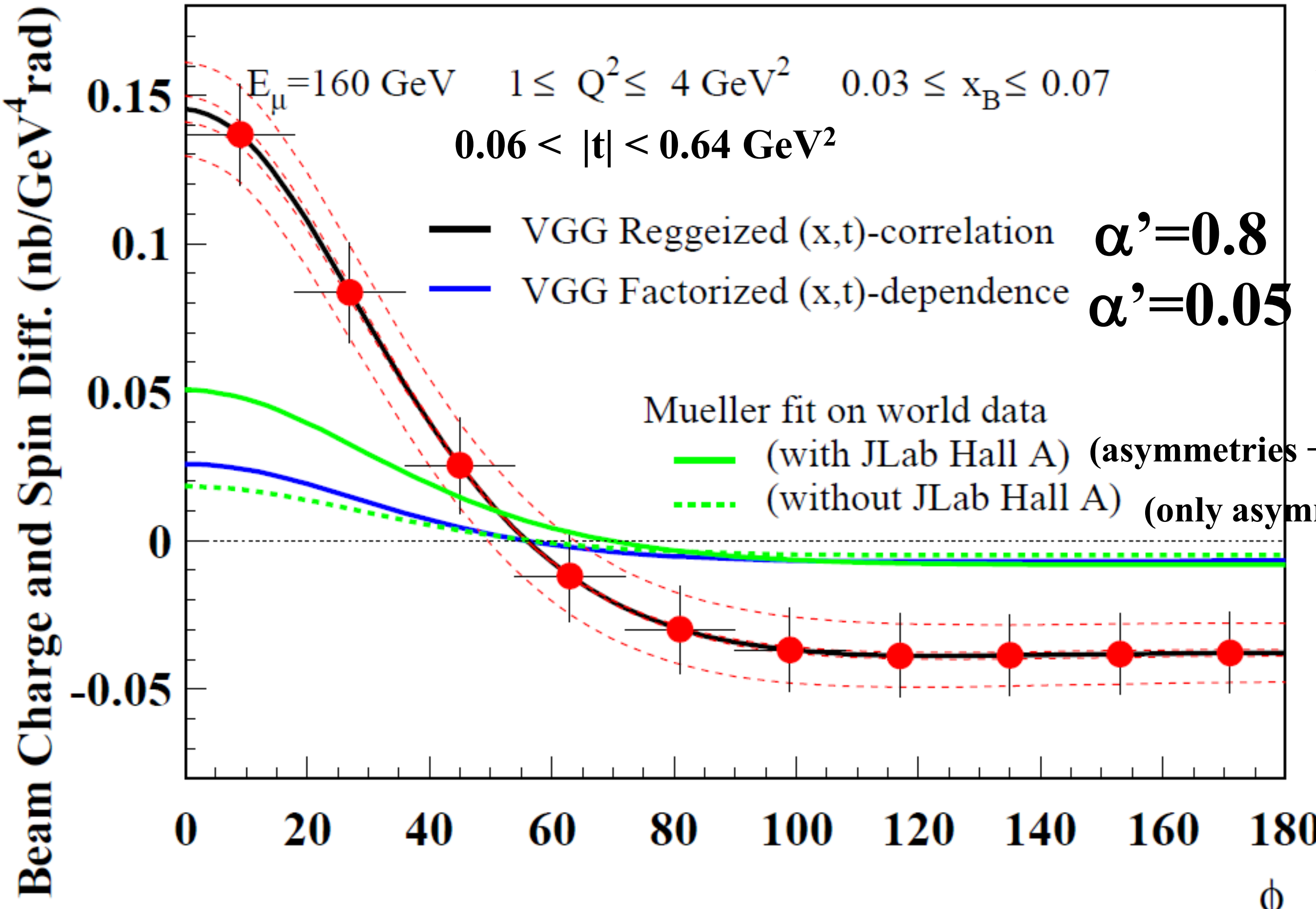
will provide umambiguous way to separate

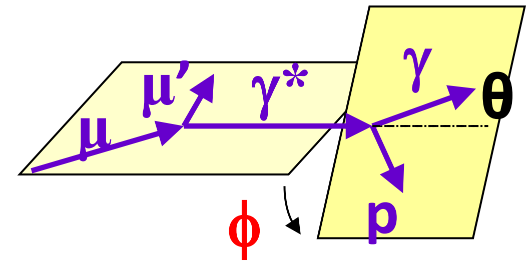
the *Re* and *Im* of the *Compton Form Factors*

from higher twist contributions

Beam Charge and Spin Difference (using $\mathcal{D}_{CS,U}$)

Comparison to different models





2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

High precision beam flux and acceptance determination

Systematic error bands assuming a 3% charge-dependent effect between μ+ and μ-   (control with inclusive evts, BH…)

Beam Charge and Spin Difference over the kinematic domain

Statistics and Systematics

$\text{Diff} = (N_{BH}+N_{DVCS})^{+} / a^{+} - (N_{BH}+N_{DVCS})^{-} / a^{-}$

$a = \text{lumi} \times \text{acceptance}$

$\Delta\text{Diff}_{Syst} = \Delta a / a_{\text{charge dependent}} \times \text{Sum}$

~3% (hypothesis)

$\Delta\text{Diff}_{Stat} = 1/\sqrt{(N_{BH}+N_{DVCS})} \times \text{Sum}$