COMPASS transverse spin physics program and plans for GPD measurements

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on behalf of the COMPASS Collaboration

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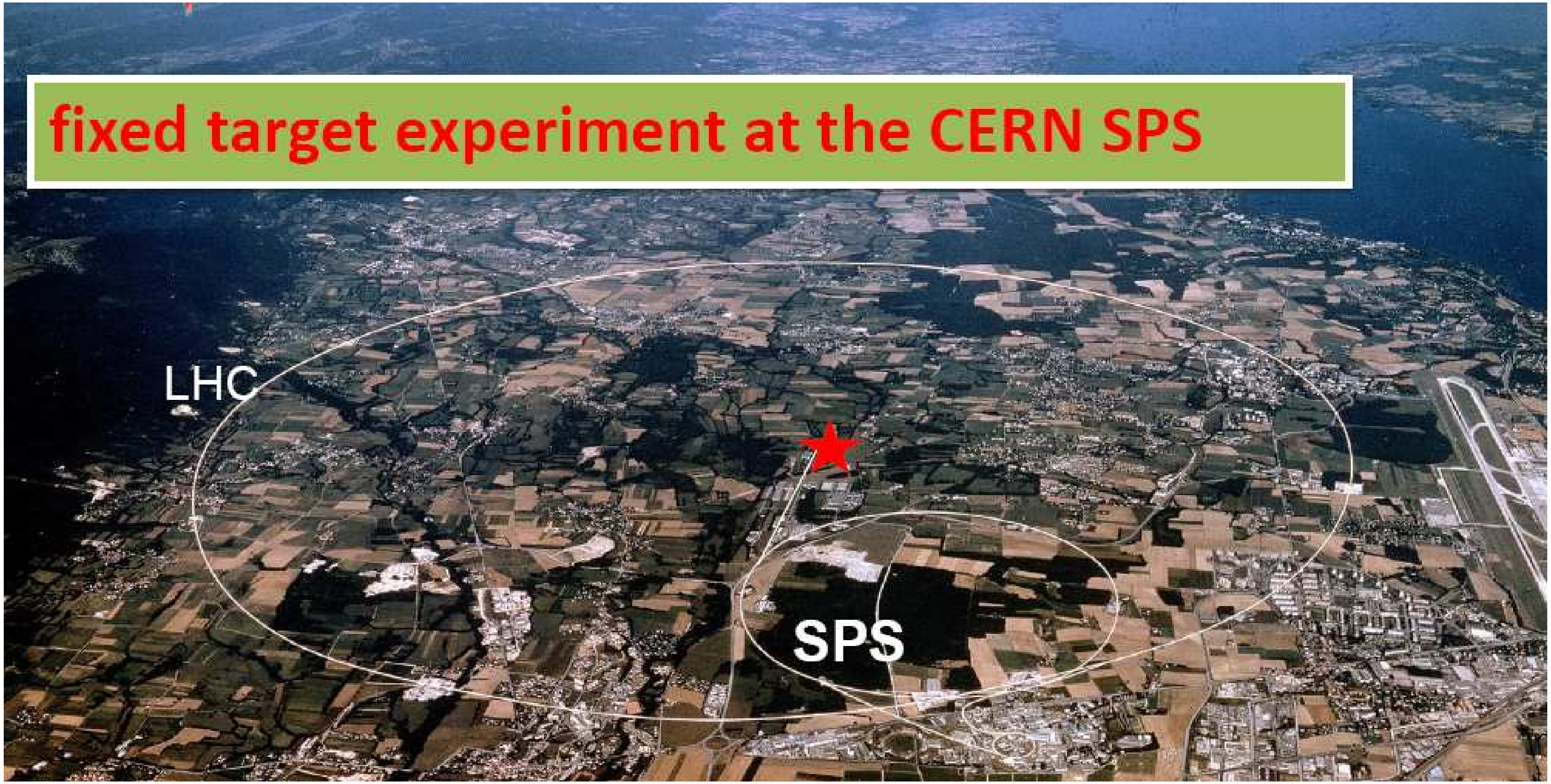
Outline

- COMPASS experiment
- New results with transversely polarised protons and deuterons
- Planned GPD measurements and results from DVCS test runs
- Conclusions

♠ Planned DY measurements at COMPASS $\rightarrow$ talk by IhnJea Choi

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

wide physics program carried on using both muon and hadron beam



COMPASS spectrometer

NIM A 577 (2007) 455

- **high energy beams**
- **large angular acceptance**
- **broad kinematical range**

two stages spectrometer

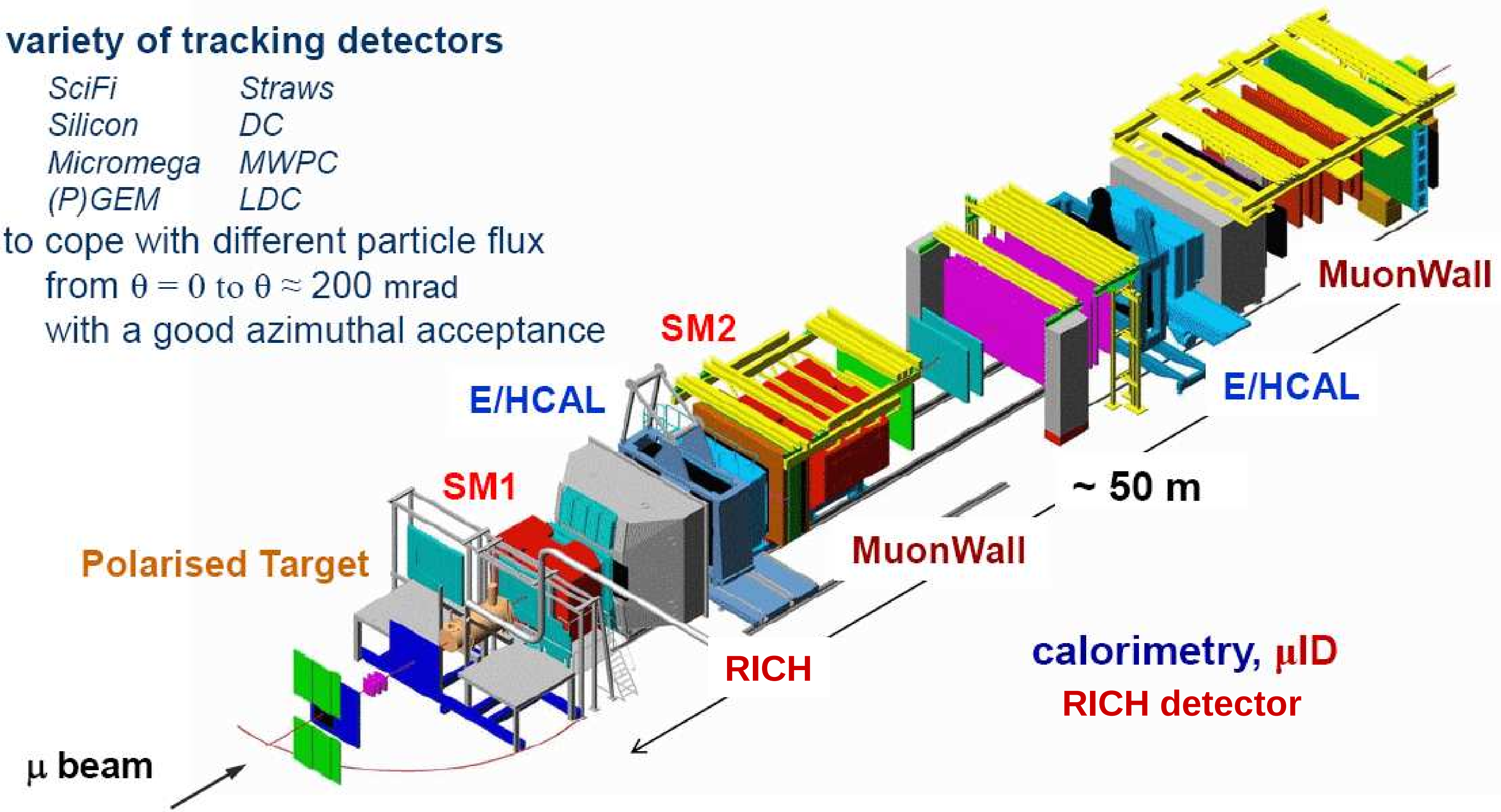
Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

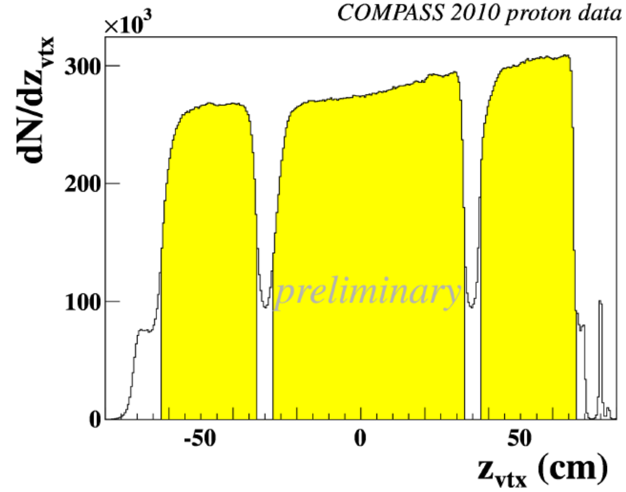
variety of tracking detectors

SciFi	*Straws*
Silicon	*DC*
Micromega	*MWPC*
(P)GEM	*LDC*

to cope with different particle flux
from $\theta = 0$ to $\theta \approx 200$ mrad
with a good azimuthal acceptance

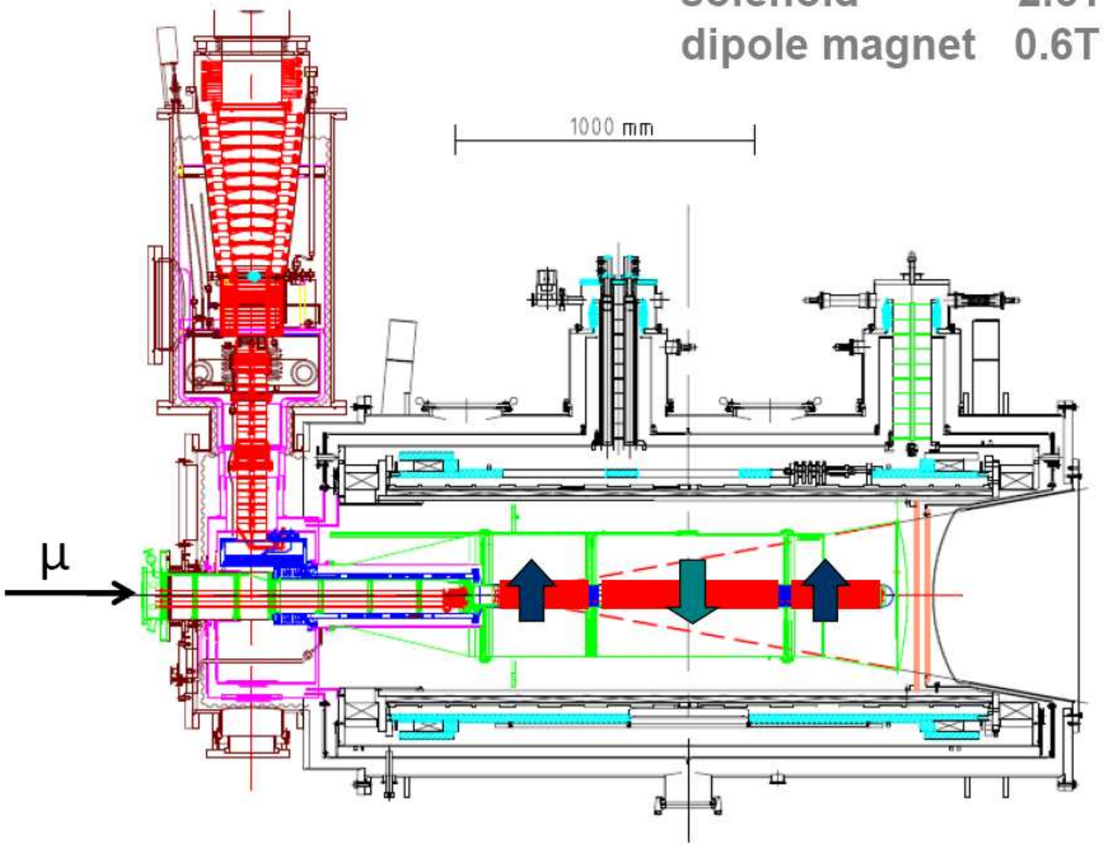


COMPASS polarised target



^{3}He – ^{4}He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T



acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

transverse spin reversed every several days

COMPASS data taking

2002
2003 160 GeV μ L & T polarised deuteron target (^{6}LiD)
2004

2005 CERN shutdown, new large apperture PT magnet, 2 => 3 PT cells

2006 160 GeV μ L polarised deuteron target (^{6}LiD)

2007 160 GeV μ L & T polarised proton target (NH_3)

2008 190 GeV hadron beams LH_2 and nuclear targets
2009 hadron spectroscopy & Primakoff reactions

2010 160 GeV μ T polarised proton target (NH_3)

2011 200 GeV μ L polarised proton target (NH_3)

2012 Primakoff (taking data now) + DVCS run (since October)

New results with transversely polarised protons and deuterons

- Sivers asymmetry — p (2010)

  Sivers TMD, related to quarks OAM

  subm. to PL B, hep-ex/1205,5122

- Collins asymmetry — p (2010)

  sensitive to transversity

  subm. to PL B, hep-ex/1205,5121

- Two-hadron azimuthal asymmetry — $\underbrace{\text{d (2002 – 04), p (2007,}}_{\text{PL B 713 (2012) 10}}$ 2010) → prel.

  sensitive to transversity

- Azimuthal asymmetry for exclusive ρ^0 — d (2003 – 04), p (2007, 2010)

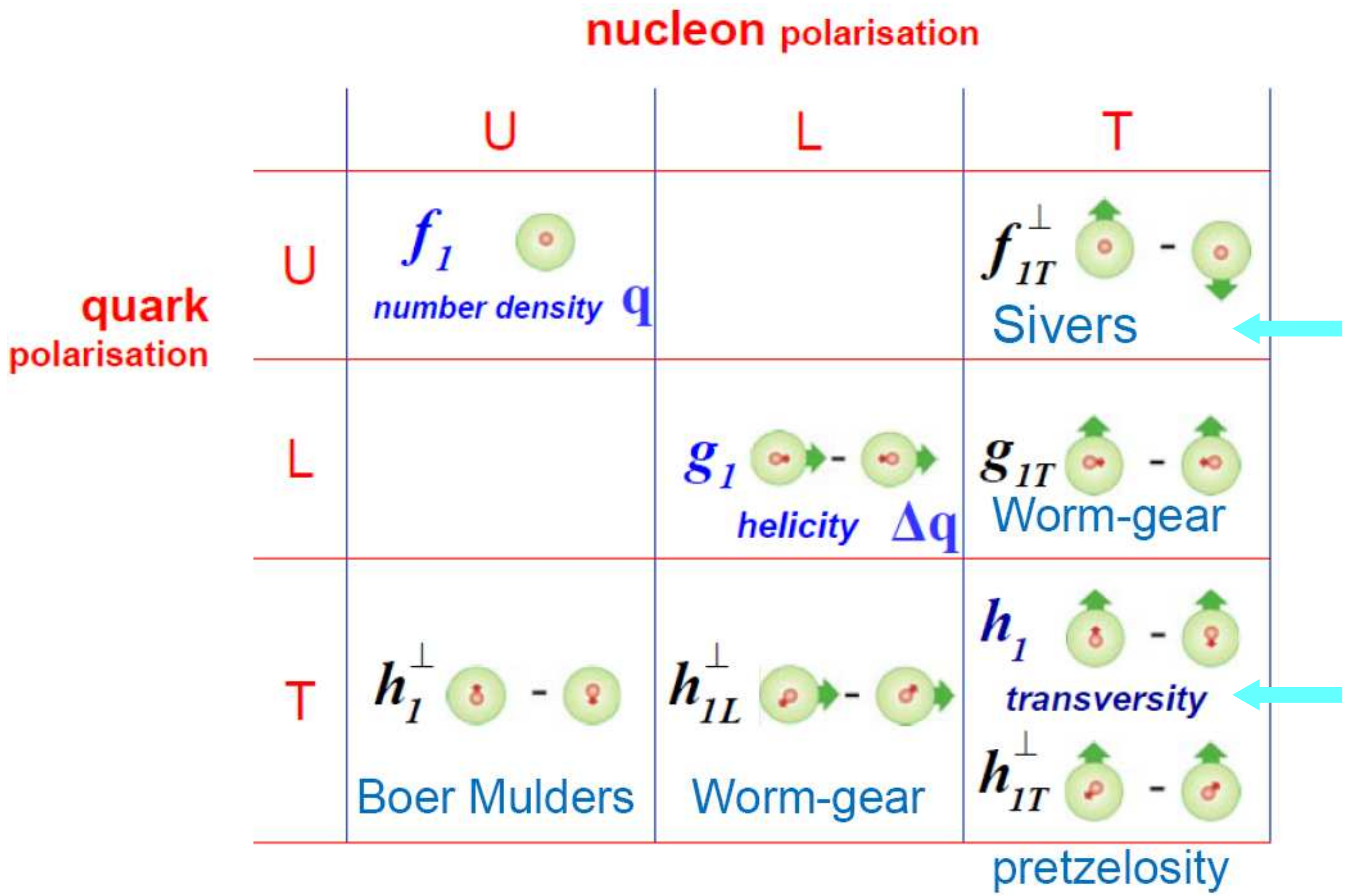
  sensitve to GPDs E => Ji sum rule

  accepted by Nucl. Phys. B

Quark structure of the nucleon

when intrinsic parton transverse momentum not neglected

8 TMD PDFs needed for complete description of the nucleon structure

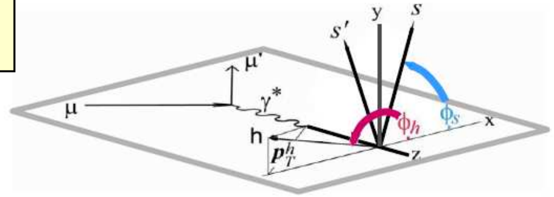


upon integration over transverse momentum only f_1, g_1 and h_1 survive

transversity (h_1) is chiral-odd => in contrast to f_1 and g_1 cannot be measured in inclusive DIS

possible in SIDIS, if coupled to a non-zero chiral-odd fragmentation function

SIDIS cross section



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\;\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$h_1^\perp H_1^\perp$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\;\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$h_{1L}^\perp H_1^\perp$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\;\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\;F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\;\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$f_{1T}^\perp D_1$

$$+\,|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$h_{1T}^\perp H_1^\perp$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$h_1 H_1^\perp$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\;\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\;\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$g_{1T} D_1$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\;\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\;\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\;\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

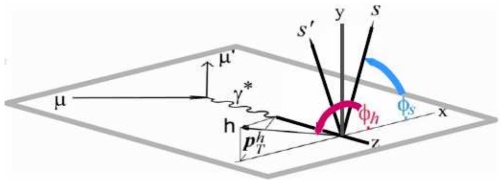
18 structure functions
14 azimuthal modulations
all measured in COMPASS

A Bacchetta et al., 2006

Sivers asymmetries from 2010 run

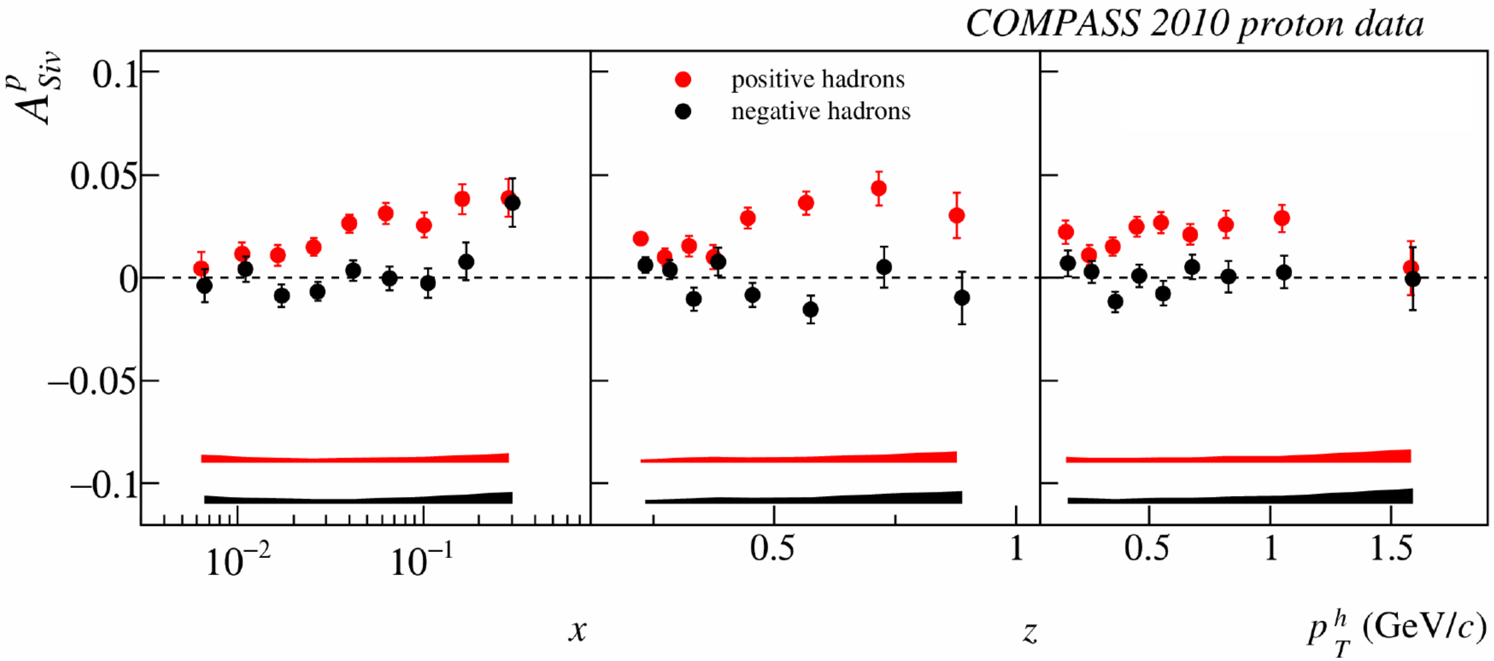
$$N_h^{\pm}(\Phi_S) = N_h^0(1 \pm A_S^h \sin(\Phi_S))$$

with $\Phi_S = \phi_h - \phi_s$



$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 f_{1T}^{\perp q}(x, k_\perp^2) \otimes D_{1,q}(z, p_\perp^2)}{\sum_q e_q^2 f_1^q(x, k_\perp^2) \otimes D_{1,q}(z, p_\perp^2)}$$

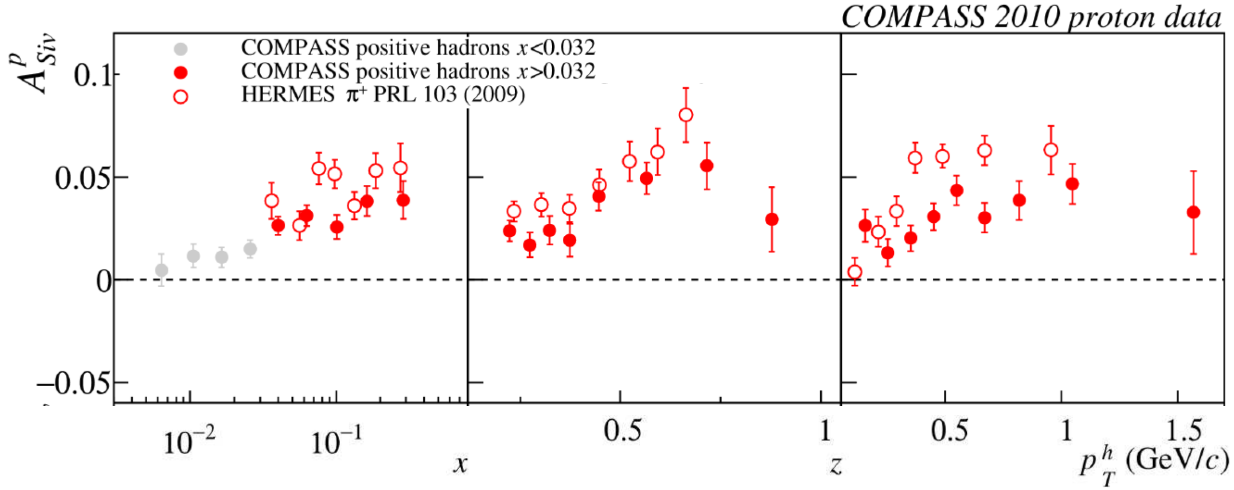
P_T – target polarisation, f – dilution factor

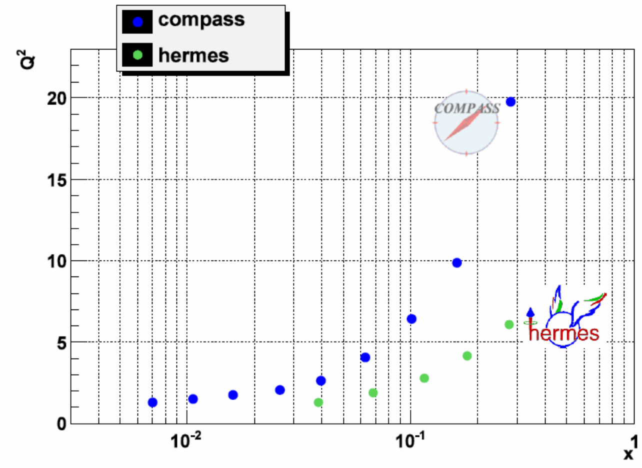


- positive asymmetry for h+ , stays positive well below the valence region (down to $x \approx 10^{-2}$)
- for h^- the asymmetry compatible with zero
- good agreement with 2007 published results, significant reduction of statistical uncertainty

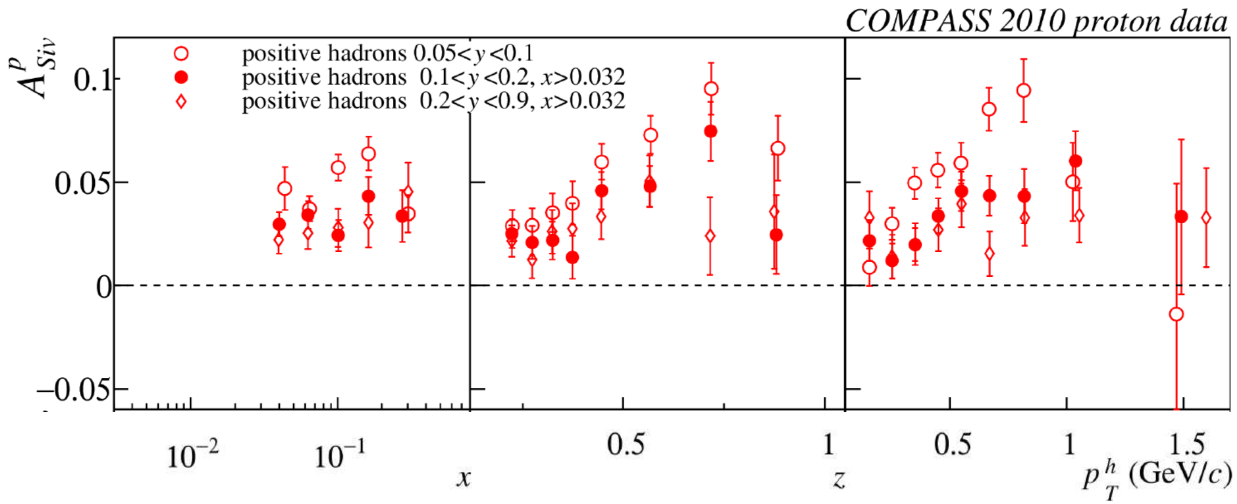
More on kinematic dependence of Sivers asymmetry

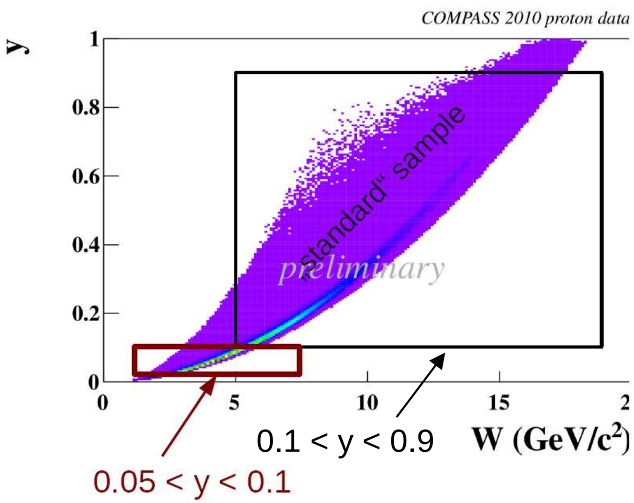
comparison to HERMES





asymmetries in different *y* ranges





clear increase of Sivers asymmetry for h⁺ at low Q^2 and *y* (or *W*)

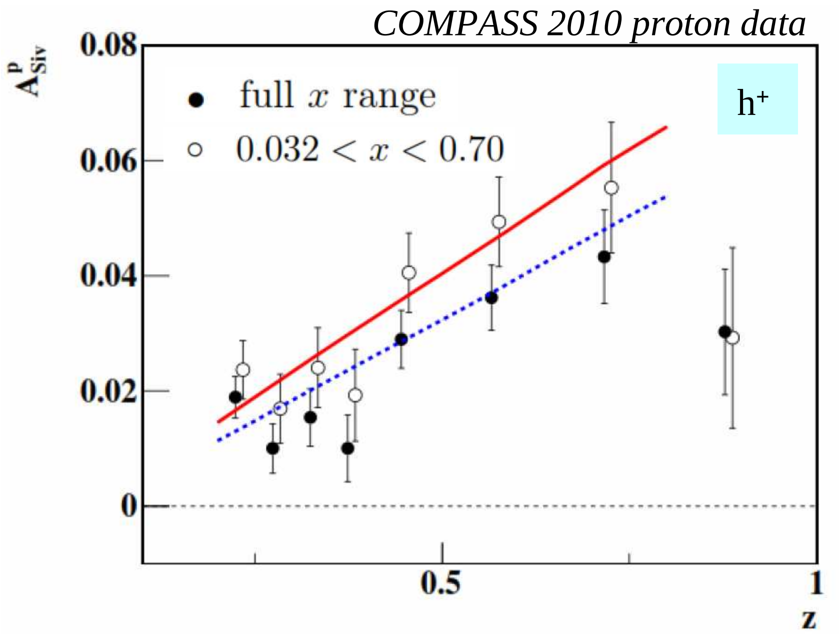
not shown are asymmetries for h⁻, no significant dependence and compatible with zero

Comparison to model predictions

predictions from S.M. Aybat, A. Prokhudin and T.C. Rogers (arXiv:1112.4423)

Sievers asymmetry evaluated for HERMES range using Sievers function of M. Anselmino et al. (arXiv:1107.4446)

and then evolved to COMPASS kinematic region



good agreement (apart of highest z ?)

current TMD approach foresees a strong Q^2-dependence of the Sievers function

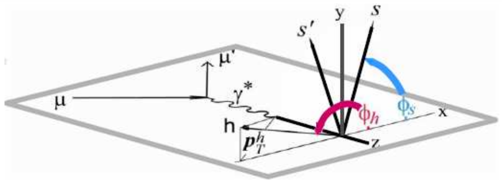
M. Anselmino, M. Boglione and S. Melis (arXiv:1204.1239) Q^2-dependent global fit to HERMES, COMPASS deuteron and COMPASS 2007 proton data reproduces them well

high precision of COMPASS 2010 proton results expected to improve significantly future global fits of Sivers function

Collins asymmetries from 2010 run

$$N_h^{\pm}(\Phi_C) = N_h^0(1 \pm A_C^h \sin(\Phi_C))$$

with $\Phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi$

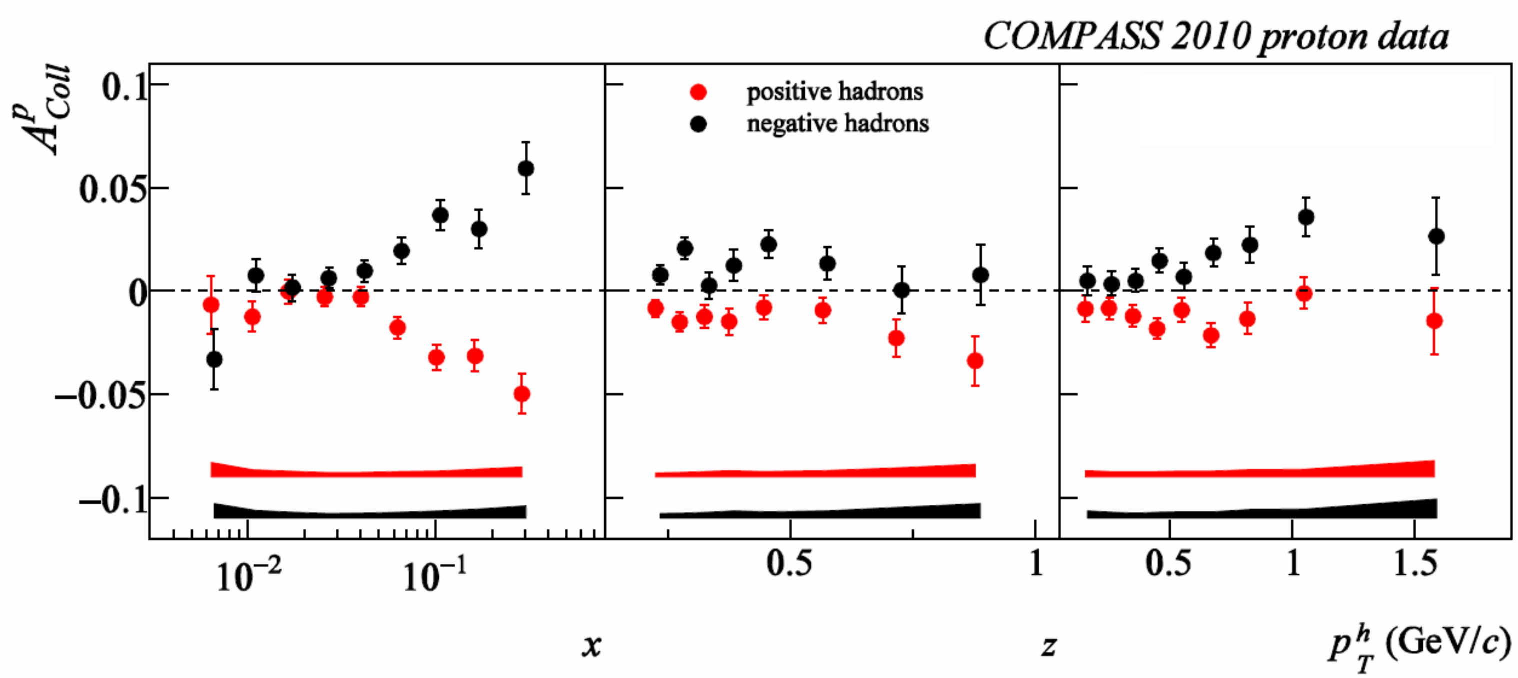


$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 h_1^q(x, k_\perp^2) \otimes H_{1,q}^\perp(z, p_\perp^2)}{\sum_q e_q^2 f_1^q(x, k_\perp^2) \otimes D_{1,q}(z, p_\perp^2)}$$

Collins FF

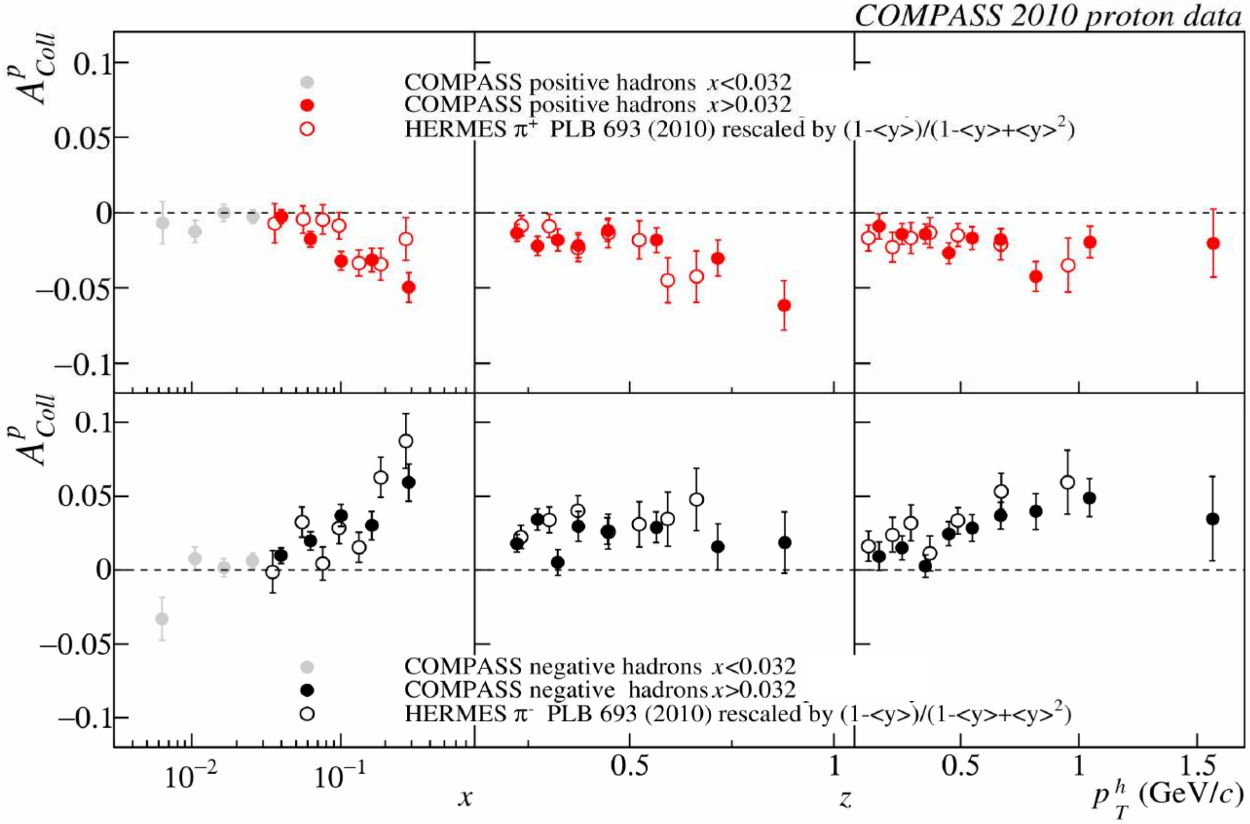
P_T – target polarisation, f – dilution factor

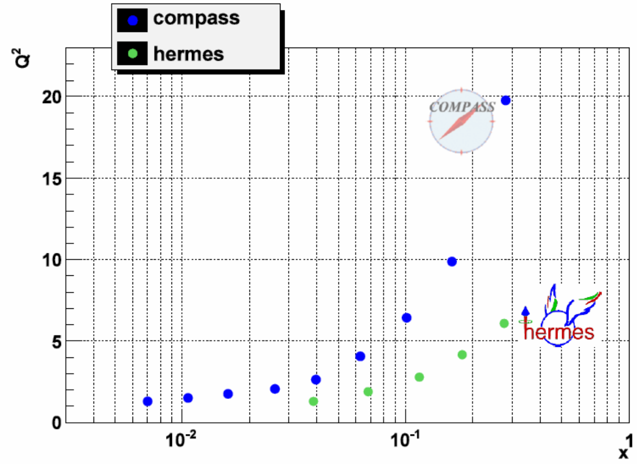
D_{nn} – spin transfer coeff. from initial to struck quark



- in valence region mirror symmetry wrt hadron charge => $H^\perp_{1,fav} \approx - H^\perp_{1,unf}$ (Collins FF)
- at small-x range (< 0.03), not covered by HERMES, asymmetries compatible with zero
- confirm published results from 2007 with statistical uncertainties improved by factor ~ 2

Comparison to HERMES and Q^2 dependence



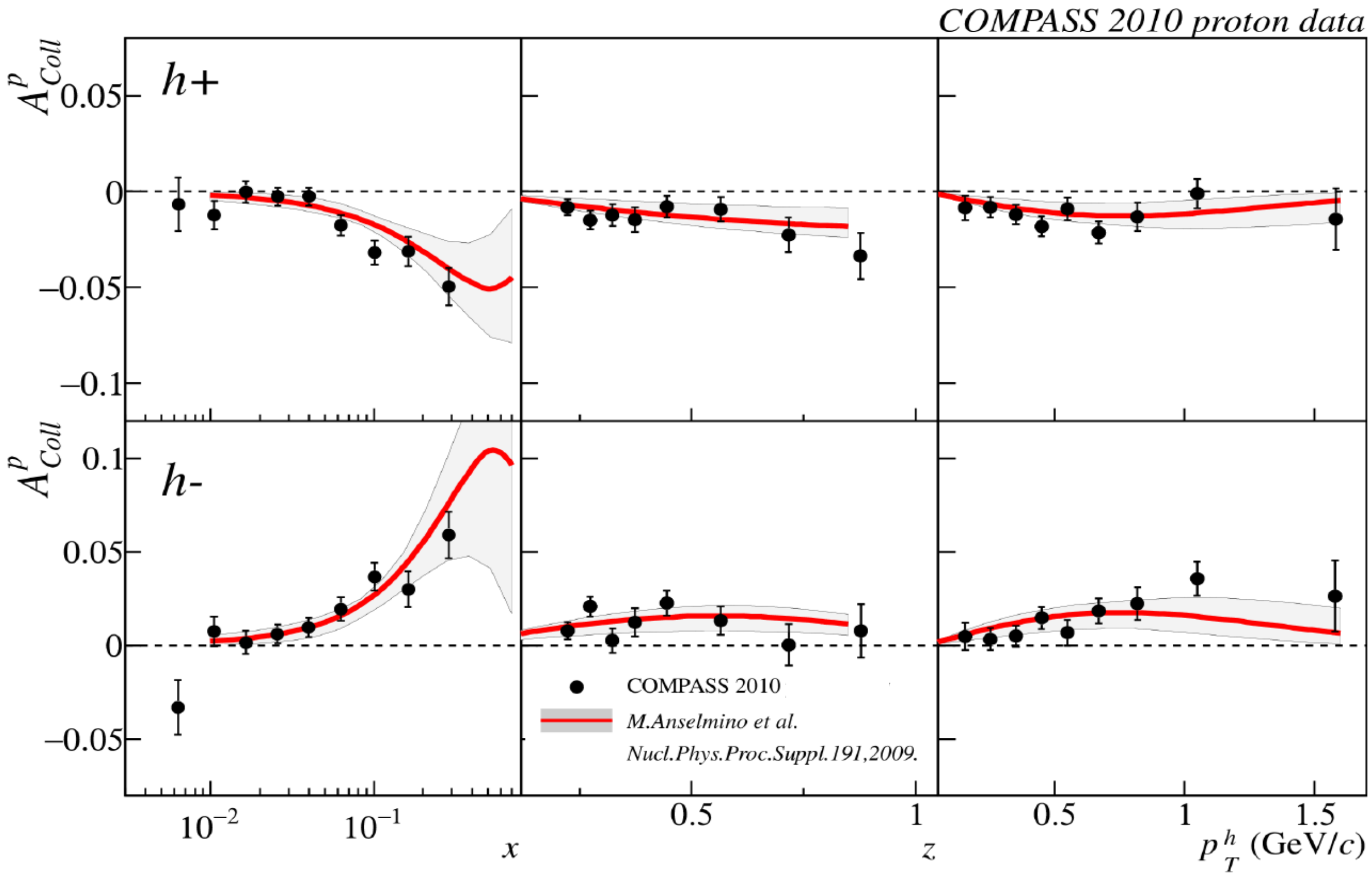


- in overlap region good agreement with HERMES
- non-trivial result; at COMPASS $<Q^2>$ larger by a factor 2-3

→ weak Q^2> dependence of the Collins asymmetry

Comparison to model predictions

predictions from the fit (Anselmino at al.) to HERMES p, COMPASS d and Bell e^+e^- data



observed agreement supports the weak Q^2 dependence
of the Collins FF assumed in the model

Two-hadron asymmetries

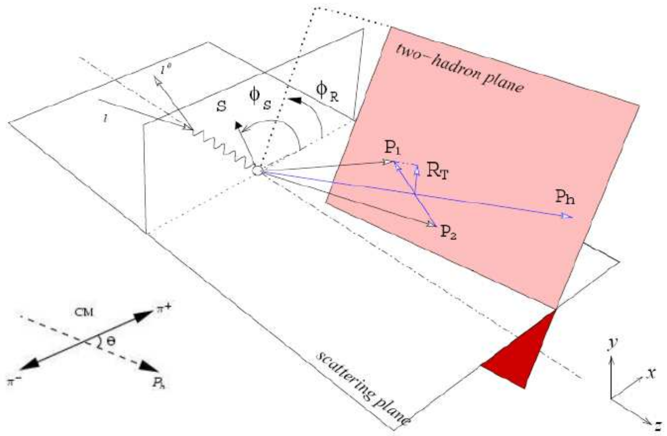
$l\ p^{\uparrow} \rightarrow l\ h_1\ h_2\ X$

alternative method to access transversity, valid within framework of collinear factorization

fragmentation of transversely polarised quark into two unpolarised hadrons

$$N_{2h}^{\pm}(x,z,y,M_h^2,\cos\theta,\Phi_{RS}) = N_{2h}^{0}(1 \pm f\ P_T\ D_{nn}\ A_{UT}^{\sin\Phi_{RS}}\ \sin\theta\ \sin\Phi_{RS})$$

with $\Phi_{RS} = \Phi_R + \Phi_S - \pi$



P_T – target polarisation, f – dilution factor

D_{nn} – transverse spin transfer coeff.

Interference FF

$$A_{UT}^{\sin\Phi_{RS}} = \frac{|\mathbf{p_1}-\mathbf{p_2}|}{2M_h} \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1,q}^{\sphericalangle}(z,M_h^2,\cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z,M_h^2,\cos\theta)}$$

Selection of events (for 2010)

DIS cuts common with single hadron analysis

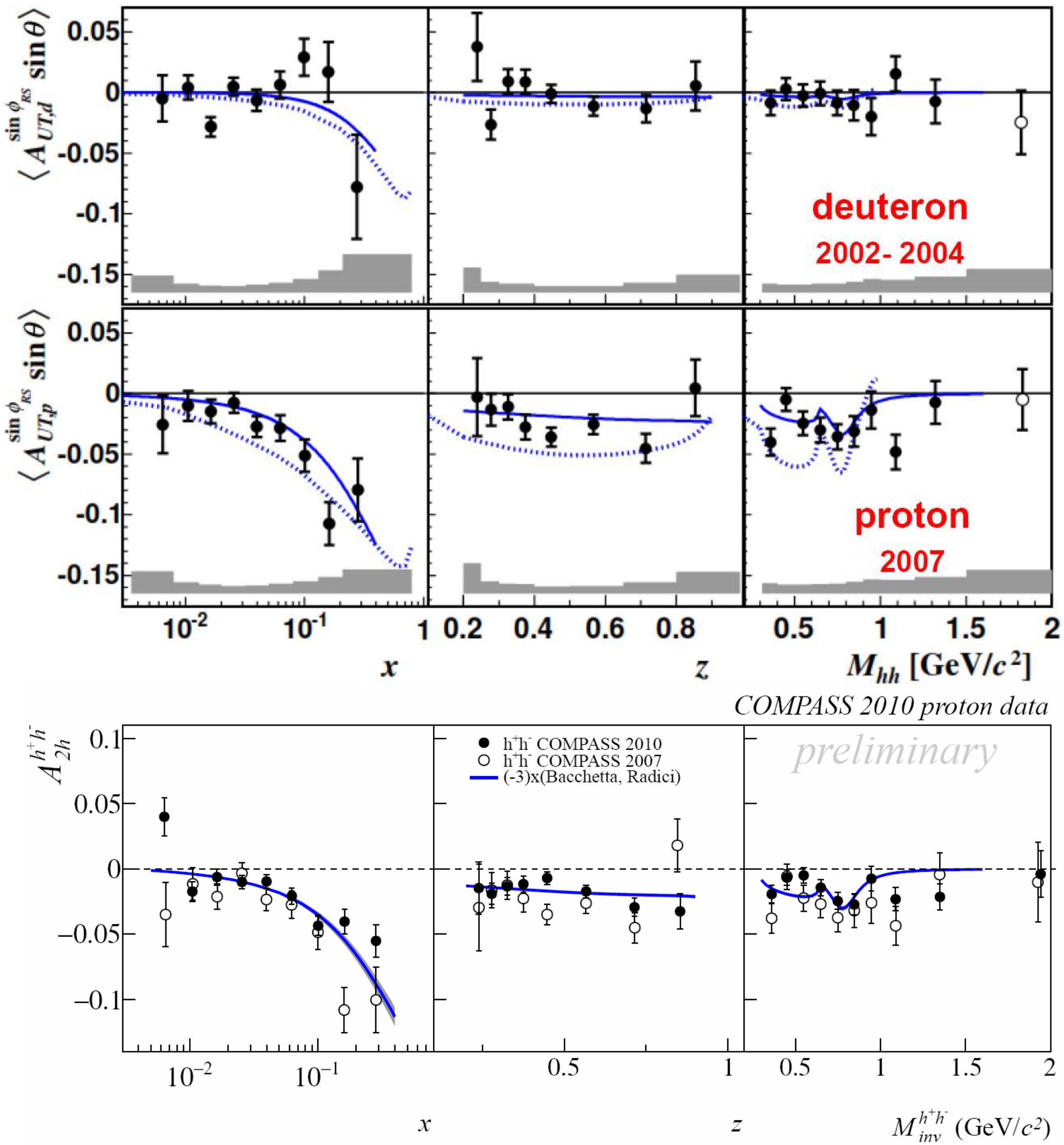
- $Q^2 > 1\ (\mathrm{GeV}/c)^2$
- $0.1 < y < 0.9$
- $W > 5\ \mathrm{GeV}/c^2$
- spectrometer acceptance: $0.003 < x_{bj} < 0.7$

cuts specific for 2-hadron analysis

- Vertex with at least **3** outgoing tracks.
  $\hookrightarrow$ All h^+h^- pair combinations are taken into account
- $z > 0.1$ for each hadron
- $x_F > 0.1$ for each hadron
- $E_{miss} > 3$ GeV for each pair
- $\mathbf{R_T} > 0.07\ \mathrm{GeV}/c$ for each pair

Results for two-hadron asymmetries

PLB 713 (2012) 10



Bacchetta et al. hep-ph/0708037

Ma et al. PR D77 (2008) 14035

- for deuteron compatible with 0
- for proton large negative asymmetries in valence region

  compatible with 0 at $x < 0.03$
- no strong dependence on z and M_{hh}
- good agreement between 2007 and 2010 data

  in 2010 data significantly reduced uncertainties
- good agreement with HERMES in common kinematic region

  wider kinematic range in x, z and M_{hh} at COMPASS
- reasonable agreement with models of Bacchetta and Ma

Extraction of valence quarks transversity from two-hadron asymmetries

using Interference FF from Belle and following approach of Bacchetta, Courtoy and Radici

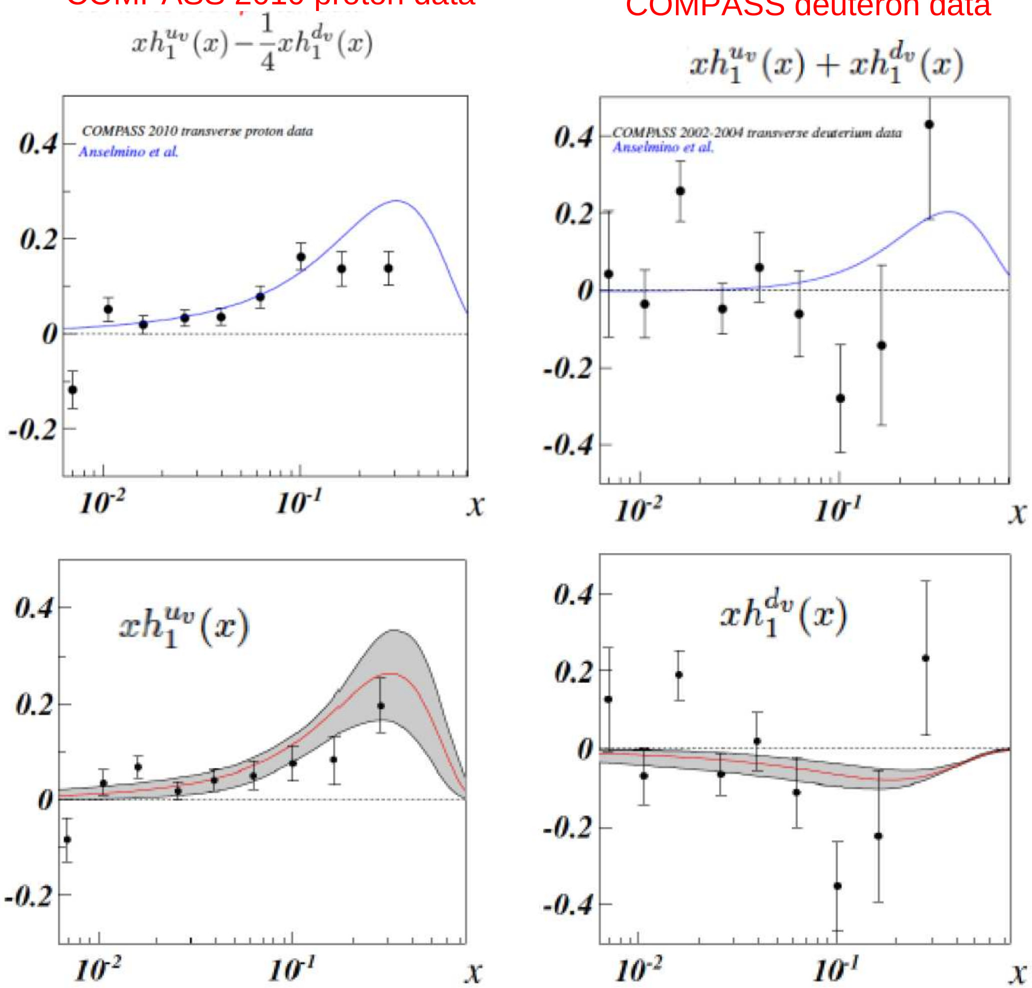
PRL 107:012001,2001

transversity of u_v and d_v extracted from COMPASS deuteron and 2010 proton data

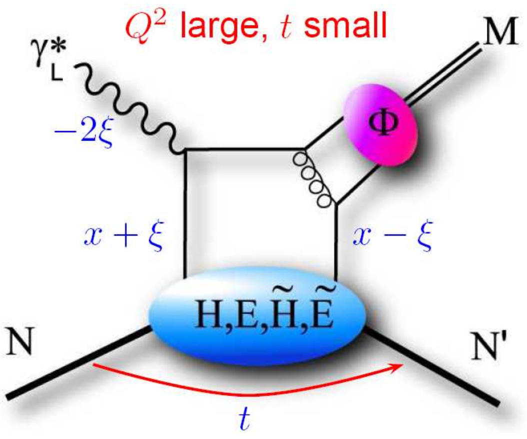
C. Elia, PhD thesis, Trieste 2011

COMPASS 2010 proton data

COMPASS deuteron data



Hard Exclusive Meson Production and GPDs



- 4 Generalised Parton Distributions (GPDs)
  for each quark flavour and for gluons
  GPDs depend on 3 variables: x, ξ, t
- collinear factorisation proven only for σ_L
  σ_T suppressed by $1/Q^2$
- quarks and gluons enter at the same order of α_S
- for vector mesons (ρ, ω, φ): H, E
  non-flip nucleon helicity flip

separation wrt quark flavours and gluons

ρ^0	2/3 u + 1/3 d + 3/8 g
ω	2/3 u – 1/3 d + 3/8 g
ϕ	s, g
ρ^+	u–d
J/ψ	g

LT observables in VM exclusive meson production relevant for GPDs

for longitudinal γ^*

unpolarised cross section $(\sigma_{00}^{++} \equiv \sigma_L)$

$$\frac{d\sigma_{00}^{++}}{dt} = (1-\xi^2)\,|\,\underline{H_M}\,|^2 - (\xi^2 + \frac{t}{4M_p^2})\,|\,E_M\,|^2 - 2\xi^2\,\mathrm{Re}\,(E_M^* H_M)$$

transverse target spin dependent cross section

$$\frac{1}{2}\left(\frac{d\sigma_{00}^{\uparrow\uparrow}}{dt} - \frac{d\sigma_{00}^{\downarrow\downarrow}}{dt}\right) = -\mathrm{Im}\frac{d\sigma_{00}^{+-}}{dt} = \Gamma'\sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\mathrm{Im}(\underline{E_M^*} H_M)$$

access to GPD E
related to orbital momentum

$H_M\,,\,E_M$ are weighted sums of convolutions of the GPDs $H^{q,g}\,,\,E^{q,g}$ with hard scattering kernel and meson DA

weights depend on contributions of various quark flavours and of gluons to the production of meson M

$$\Gamma' = \frac{\alpha_{\mathrm{em}}}{Q^6}\,\frac{x_B^2}{1-x_B}$$

$$\xi = \frac{x_B}{2-x_B}, \qquad -t_0 = \frac{4\xi^2 M_p^2}{1-\xi^2}$$

(large Q^2 approximation)

Give access to the orbital angular momentum of quarks

$$\boxed{\frac{1}{2}\int_{-1}^{1} dx\; x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] \stackrel{t\to 0}{=} J_q \;=\; \frac{1}{2}\Delta\Sigma + L_q}$$

Ji's sum rule

So far GPD E poorly constrained by data (mostly by Pauli form factors)

Exclusive ρ^0 production on $p^\uparrow$ and $d^\uparrow$ at COMPASS

$\boxed{\mu\, N \rightarrow \mu\, \rho^0\, N}$

i.e. incoherent process

Transversely polarised proton target (NH_3), 2007, 2010
Transversely polarised deuteron target (^6LiD), 2003-2004

note: there was no RPD for these data

only two tracks of opposite charge associated to the primary vertex

DIS cuts

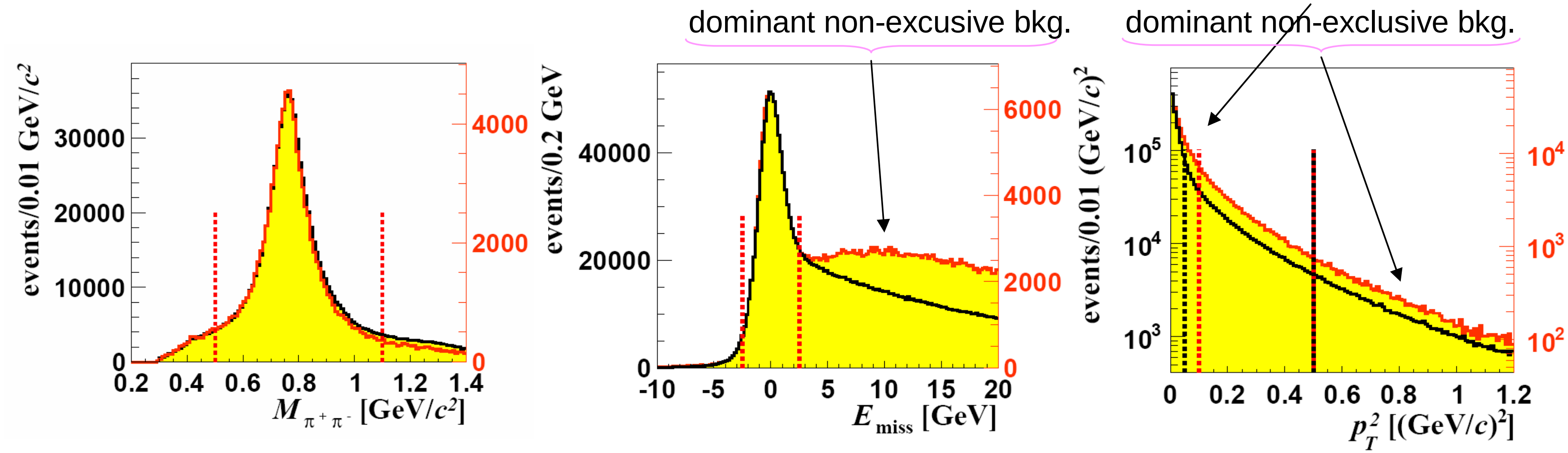
$1 < Q^2 < 10$ GeV^2
$0.1 < y < 0.9$
$W > 5$ GeV

cuts specific for exclusive ρ^0 analysis

$0.5 < M_{\pi\pi} < 1.1$ GeV
$-2.5 < E_{miss} < 2.5$ GeV
$E_{\rho 0} > 15$ GeV
$0.05 < p_T^2 < 0.5$ GeV^2 [NH_3]
$0.1 < p_T^2 < 0.5$ GeV^2 [^6LiD]

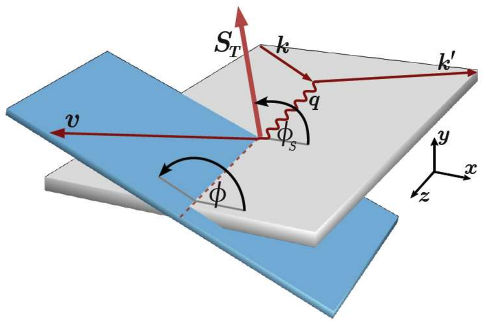
$E_{miss} = (M_X^2 - M_p^2)/(2M_p)$

proton data (797 000 evts)
deuteron data (97 000 evts)



TTS asymmetry $A_{UT}^{\sin(\phi-\phi s)}$ for exlusive ρ^0 production from COMPASS

$\mu\, N \rightarrow \mu\, \rho^0\, N$



$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\epsilon}\frac{1-x_{Bj}}{x_{Bj}}\frac{1}{Q^2}\right]^{-1}\frac{\mathrm{d}\sigma}{\mathrm{d}x_{Bj}\mathrm{d}Q^2\mathrm{d}t\mathrm{d}\phi\mathrm{d}\phi_s} \simeq$$

$$\underbrace{\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\epsilon\sigma_{00}^{++}}_{\text{unpolarised cross section}} - S_T \sin(\phi-\phi_s)\,\mathrm{Im}\left(\sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-}\right)+\ldots$$

$$\boxed{A_{UT}^{\sin(\phi-\phi_s)} = -\frac{\mathrm{Im}(\sigma_{++}^{+-}+\epsilon\,\sigma_{00}^{+-})}{\frac{1}{2}(\sigma_{++}^{++}+\sigma_{++}^{--})+\epsilon\,\sigma_{00}^{++}}}$$

number of exclusive events
after bin-by-bin correction for SIDIS background

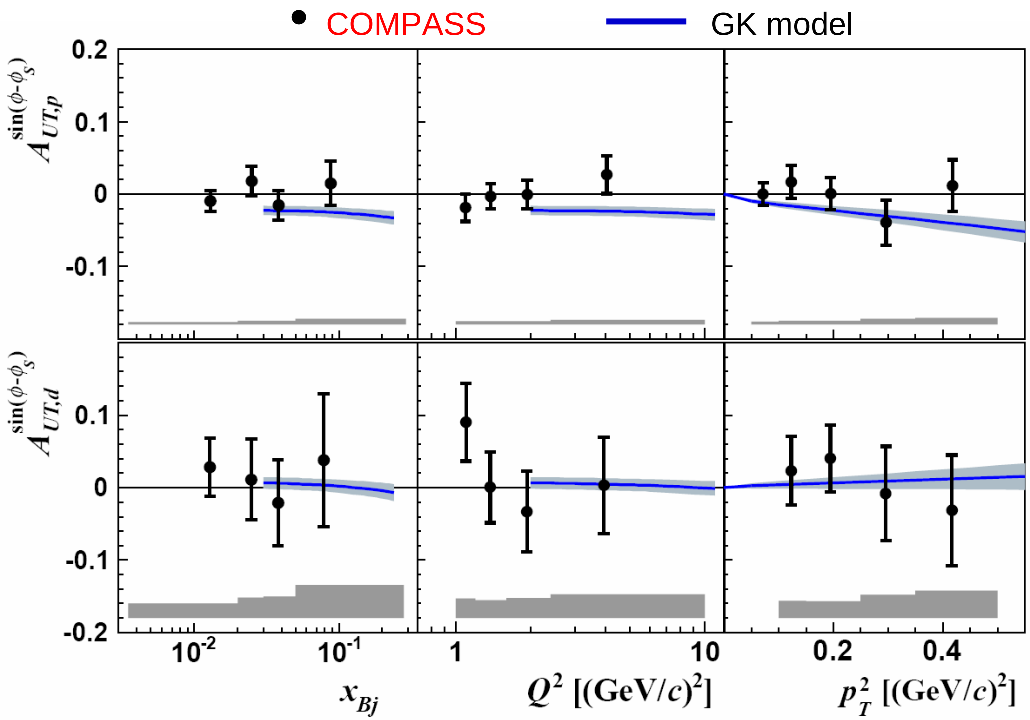
$$\boxed{N(\phi-\phi_S) = F\,n\,a\,\sigma_0\left(1 \pm f\,|P_T|\,A_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S)\right)}$$

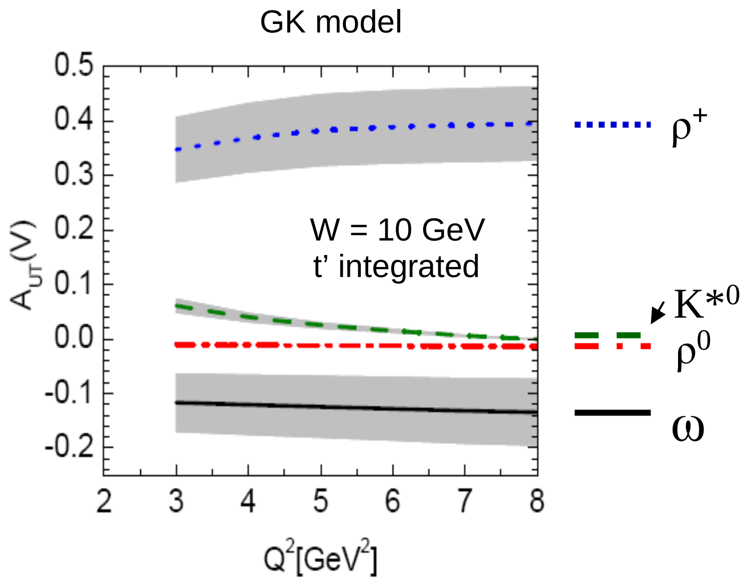
F – flux, n – number of nucleons, a – acceptance, σ_0 – unpolarised cross section
f – dilution factor, P_T – target transverse polarisation

asymmetry extracted form a fit of the number of events in 12 bins of ϕ - ϕ_s
for each of the two(*) target cells and polarisation state (+,-)

(*) for 3-cell target used for proton data (2007, 2010) upstream and downstream ones were combined

Results on $A_{UT}^{\sin(\phi-\phi s)}$ for exlusive ρ^0 production from COMPASS





- $A_{UT}^{\sin(\phi-\phi s)}$ for transversely polarised protons and deuterons compatible with 0
- for the proton agreement with HERMEs results
  COMPASS results with statistical errors improved by factor 3 and extended kinematic range
- for the deuteron the first measurement
- reasonable agreement with predictions of the GPD model of Goloskokov - Kroll

[EPJ C59 (2009) 809]

small values expected due to approximate cancellation of contributions from E^u and E^d, $E^u \approx -E^d$

$E^p_{\rho 0} \sim \frac{2}{3} E^u + \frac{1}{3} E^d + \frac{3}{8} E^g$ vs. $E^p_{\omega} \sim \frac{2}{3} E^u - \frac{1}{3} E^d + \frac{3}{8} E^g$ (cf. upper-right plot)

COMPASS-II

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

- Generalized Parton Distributions (GPD)
- Drell-Yan
- Pion (and kaon) Polarizabilities

COMPASS-II Proposal

Approved December 2010, first measurements 2012

The COMPASS Collaboration

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

Future GPD program in context of COMPASS-II time lines

Part of the COMPASS-II proposal scheduled presently by CERN

- 2012: pion and kaon polarisabilities (Primakoff) + comissioning and test run for DVCS
- 2013: long SPS shutdown
- 2014: Drell-Yann measurements with transversely polarised protons (NH_3 target)
- 2015-2016: stage 1 of GPD program and in parallel SIDIS (LH target)

Further subjects to be pursued at COMPASS-II > 2016

- ✓ additional year of Drell-Yann measurements
- ✓ stage 2 of GPD program (transversely polarised target and RPD)
- ✓ hadron program (spectroscopy in diffractive and central production)

The GPDs in the next several years

- H1, ZEUS, HERMES, JLab 6 GeV provided/providing first results

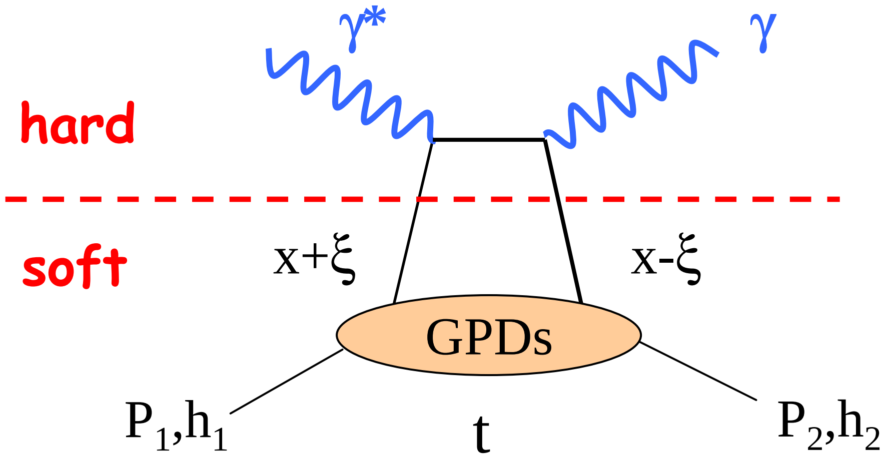
- The **energy upgrade** of the **CEBAF** accelerator will allow access to the **high x_B** region which requires **large luminosity**.

- The **GPD** project at **COMPASS** will explore **intermediate x_B** (0.01-0.10) and **large Q^2** (up to ~8(16) GeV^2) range

  COMPASS will be **the only experiment in this range** before availability of new colliders

  for several years COMPASS **unique** due to availability of lepton **beams of both charges**

Generalized Parton Distributions and DVCS



Factorisation:
Q^2 large, $-t<1$ GeV^2

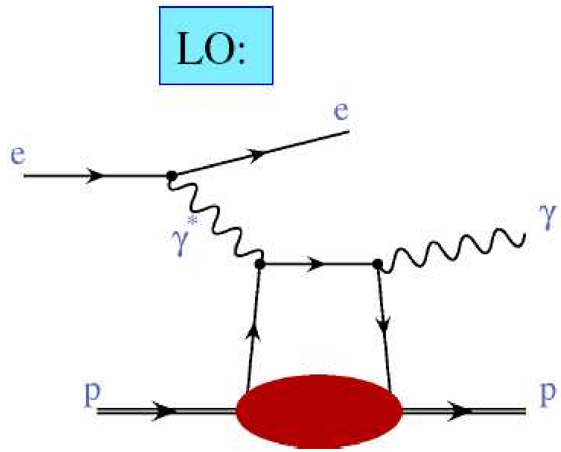
$$\xi = \frac{x_B}{2 - x_B}$$

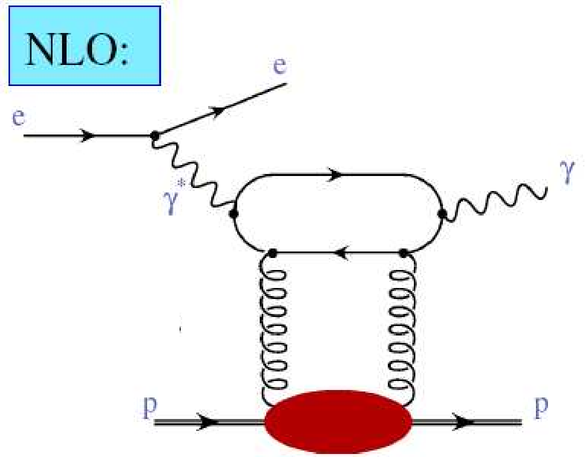
P_i, h_i – proton momentum and helicity

4 Generalised Parton Distributions : $H, E, \tilde{H}, \tilde{E}$ depending on 3 variables: x, ξ, t

for each quark flavour and for gluons

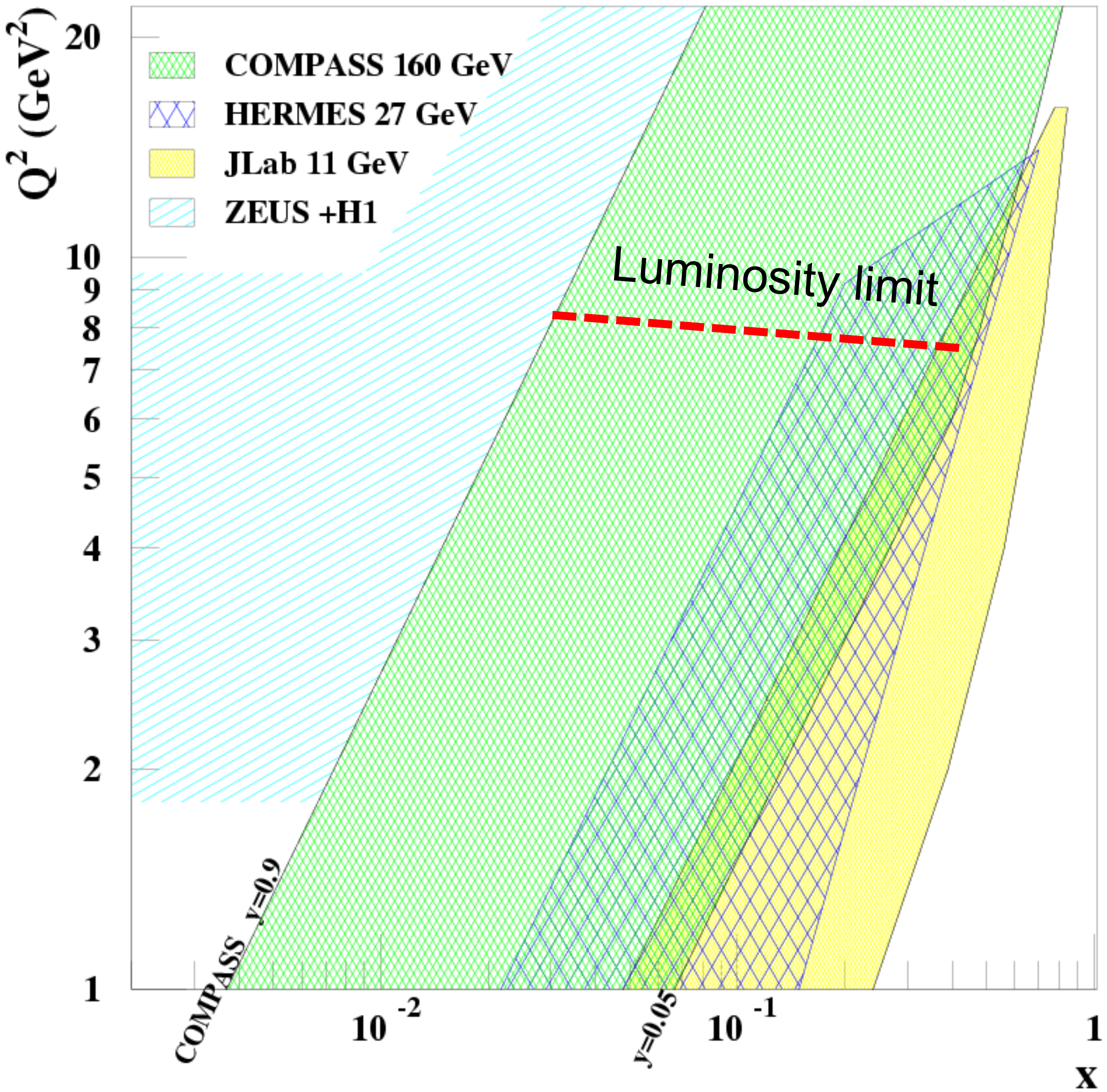
for DVCS gluons contribute at higher orders in α_s





COMPASS kinematical coverage for DVCS

CERN SPS high energy polarised muon beam 100/190 GeV



with a 2.5m long LH_2 target
$L = 10^{32}$ cm^{-2} s^{-1}

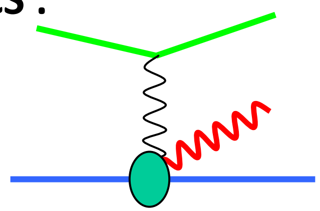
$Q^2 \rightarrow$ 8 GeV^2
$\rightarrow$ 16 GeV^2 if luminosity increased by factor 4

$\sim 10^{-2} < x < \sim 10^{-1}$

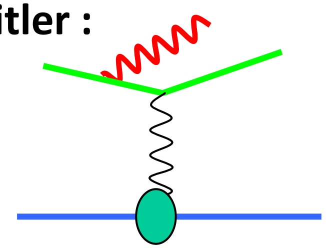
$x \rightarrow$ 0.20 with extension of present calorimetry

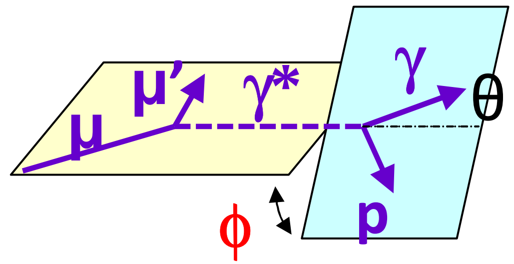
Interplay of DVCS and BH at 160 GeV

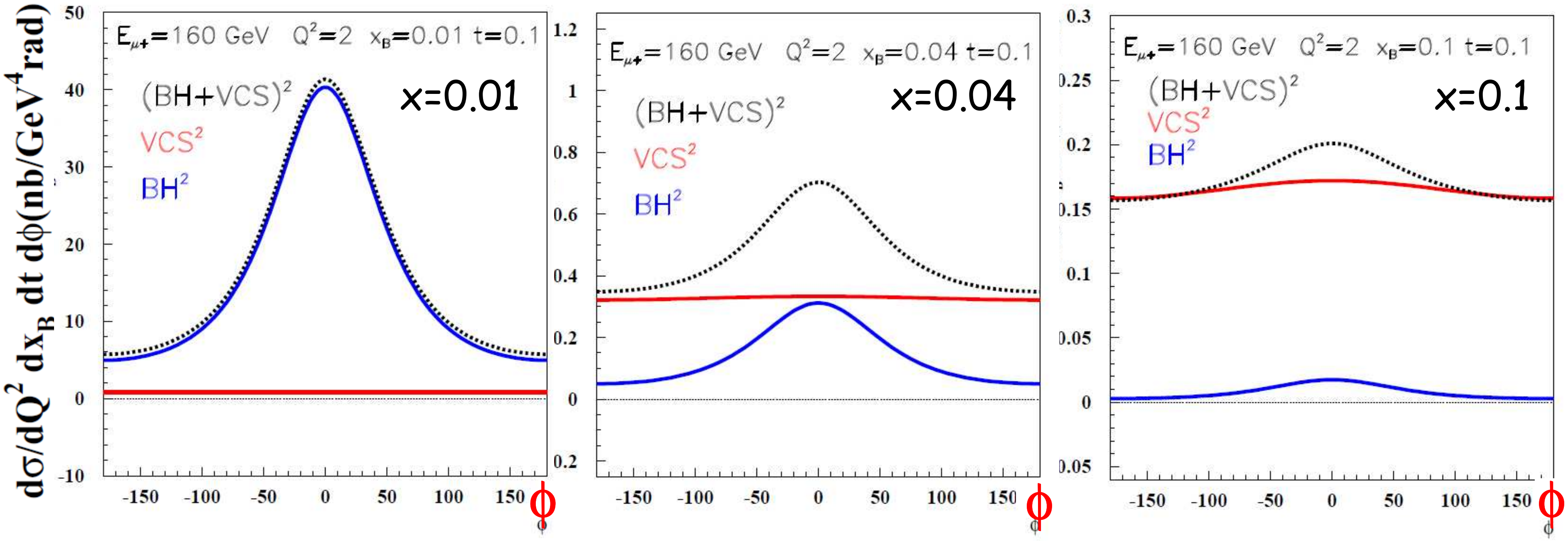
DVCS :



Bethe-Heitler :







BH dominates

BH and DVCS at the same level

DVCS dominates

excellent reference yield

access to DVCS amplitude through the interference

study of $d\sigma^{DVCS}/dt$

‘Stage 1’ of COMPASS GPD program

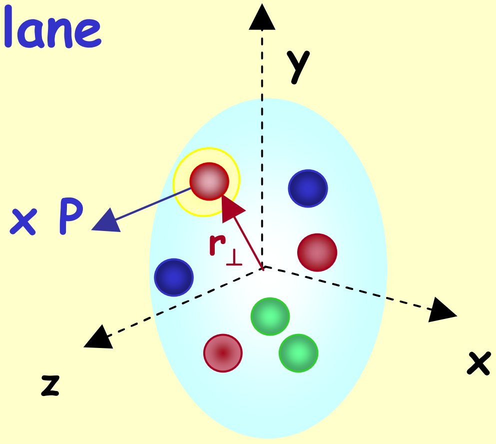
DVCS and HEMP with unpolarised proton target

to constrain GPD H

- **GPD - 3-dimensional picture of the partonic nucleon structure or spatial parton distribution in the transverse plane**

$$H(x,\ \xi=0,\ t) \rightarrow H(x,\ r_{x,y})$$

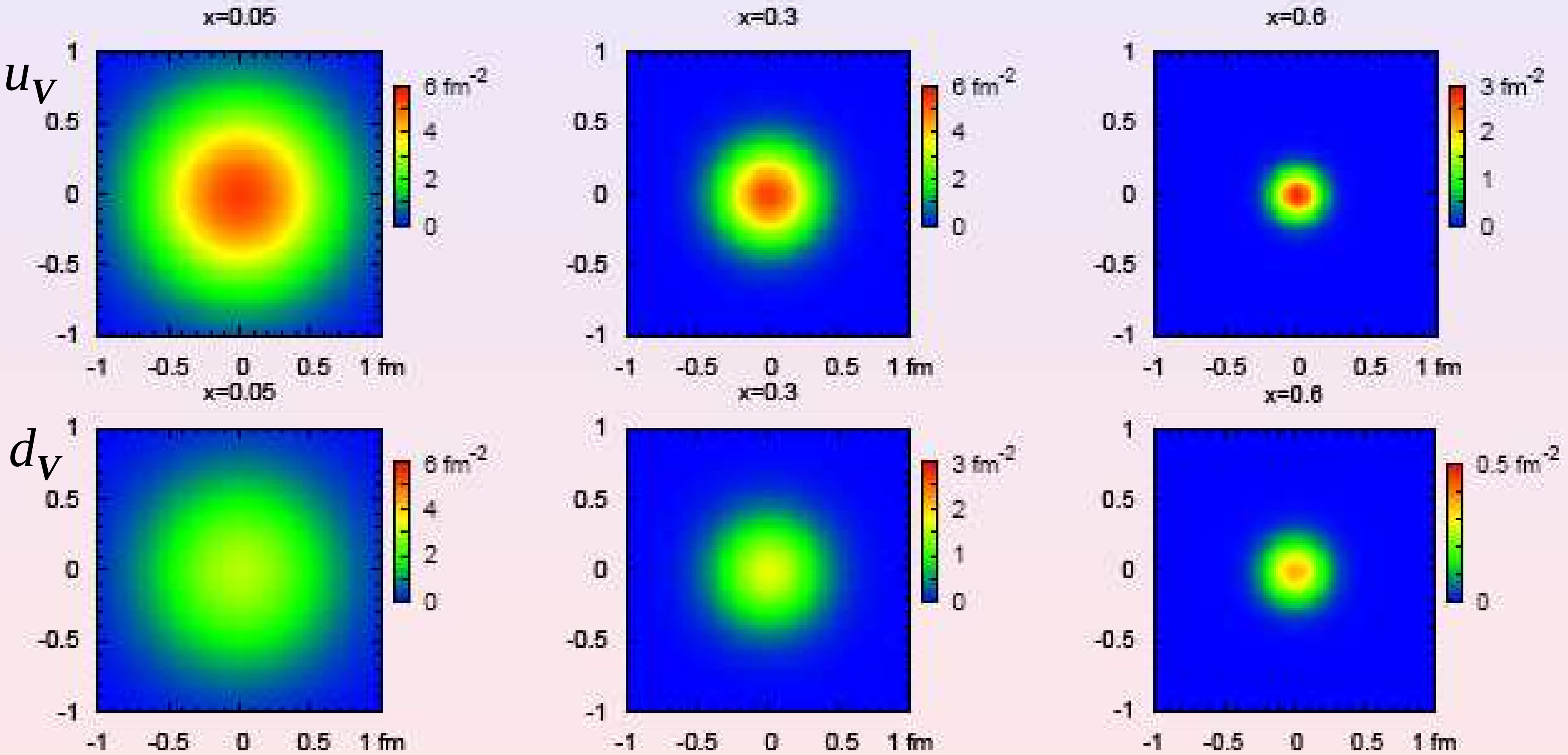
probability interpretation
Burkardt



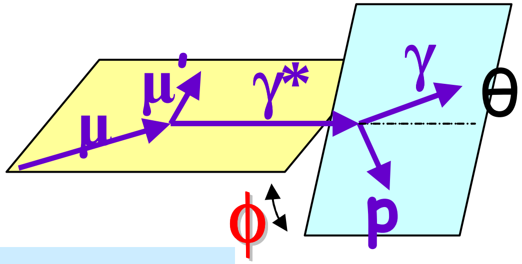
Nucleon tomography from fits to elastic form factors

from GPD fits to $F_{1,2}^{p,n}$ Diehl, Feldmann, Jakob, Kroll – (2005)

valence quarks unpolarized proton



DVCS + BH with μ+↓ and μ-↑ beams
and unpolarized proton target



$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}{}_{unpol} + P_\mu\, d\sigma^{DVCS}{}_{pol}$$
$$+ e_\mu\, a^{BH}\, \mathcal{R}e\, T^{DVCS} + e_\mu P_\mu\, a^{BH}\, \mathcal{I}m\, T^{DVCS}$$

Beam Charge & Spin Difference

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) = 2(e_\mu\, a^{BH}\, \mathcal{R}e\, T^{DVCS} + P_\mu\, d\sigma^{DVCS}{}_{pol})$$

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi$$

$$s_1^{DVCS}\sin\phi$$

Beam Charge & Spin Sum

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) = 2(\underline{d\sigma^{BH}} + d\sigma^{DVCS}{}_{unpol} + e_\mu P_\mu\, a^{BH}\, \mathcal{I}m\, T^{DVCS})$$

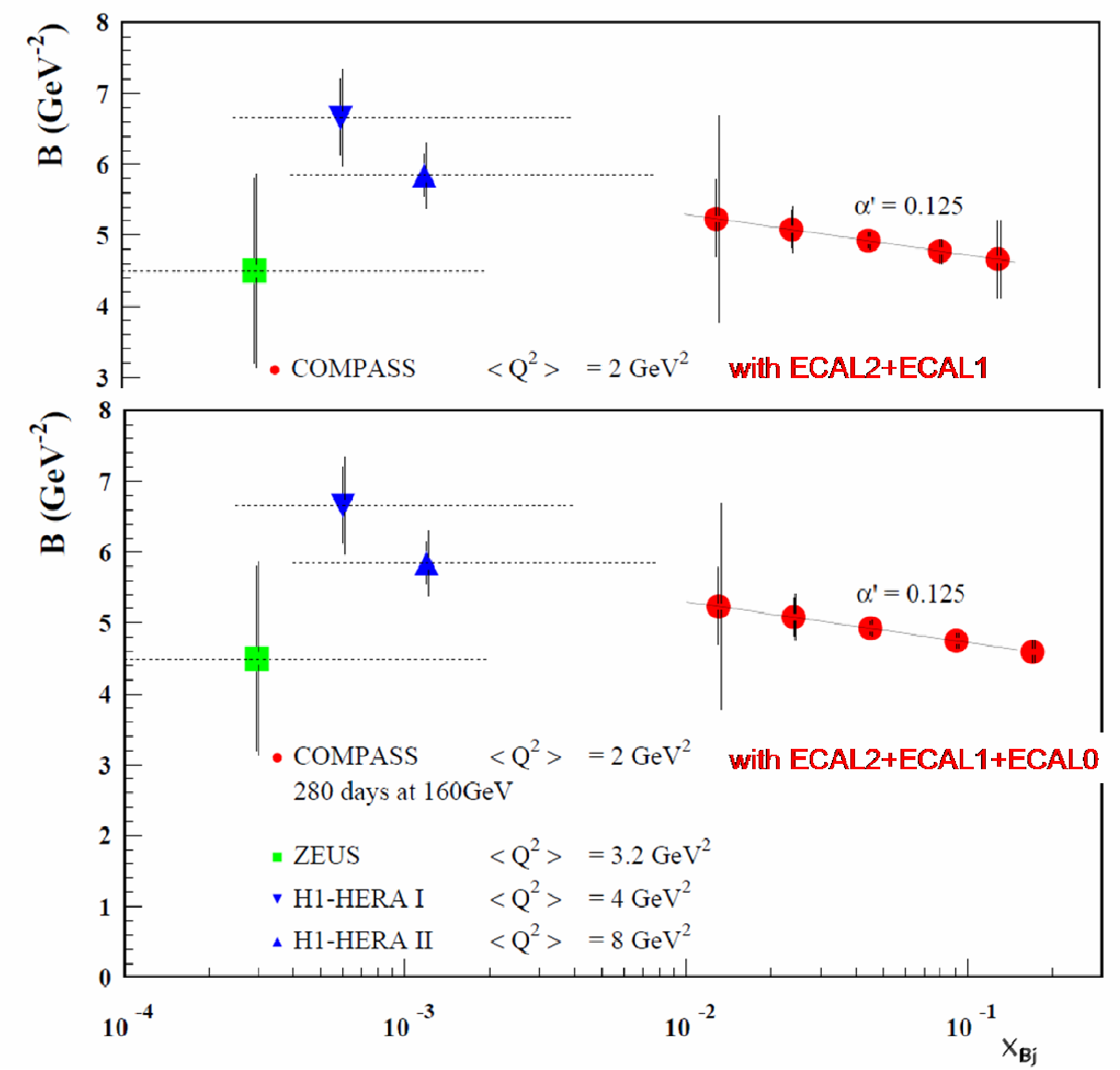
$$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

$$s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi$$

t-slope measurement for DVCS; relevant for nucleon 'tomography'

Using $\mathcal{S}_{CS,U}$, integrating over ϕ and subtracting BH $\longrightarrow$ $d\sigma_{DVCS}/dt \sim \exp(-B|t|)$

'tomography': $B(x) \Leftrightarrow \langle r_T^2 \rangle(x)$



FFS model

adapted for COMPASS (by AS)

assumed

$$\boxed{B(x) = b_0 + 2\,\alpha' \ln(x_0/x)}$$

with $\alpha' = 0.125\ \mathrm{GeV}^{-2}$

160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
L = 1222pb^{-1}

$0.06 < |t| < 0.64\ \mathrm{GeV}^2$

assumed 3% systematic error on extracted DVCS c.s.

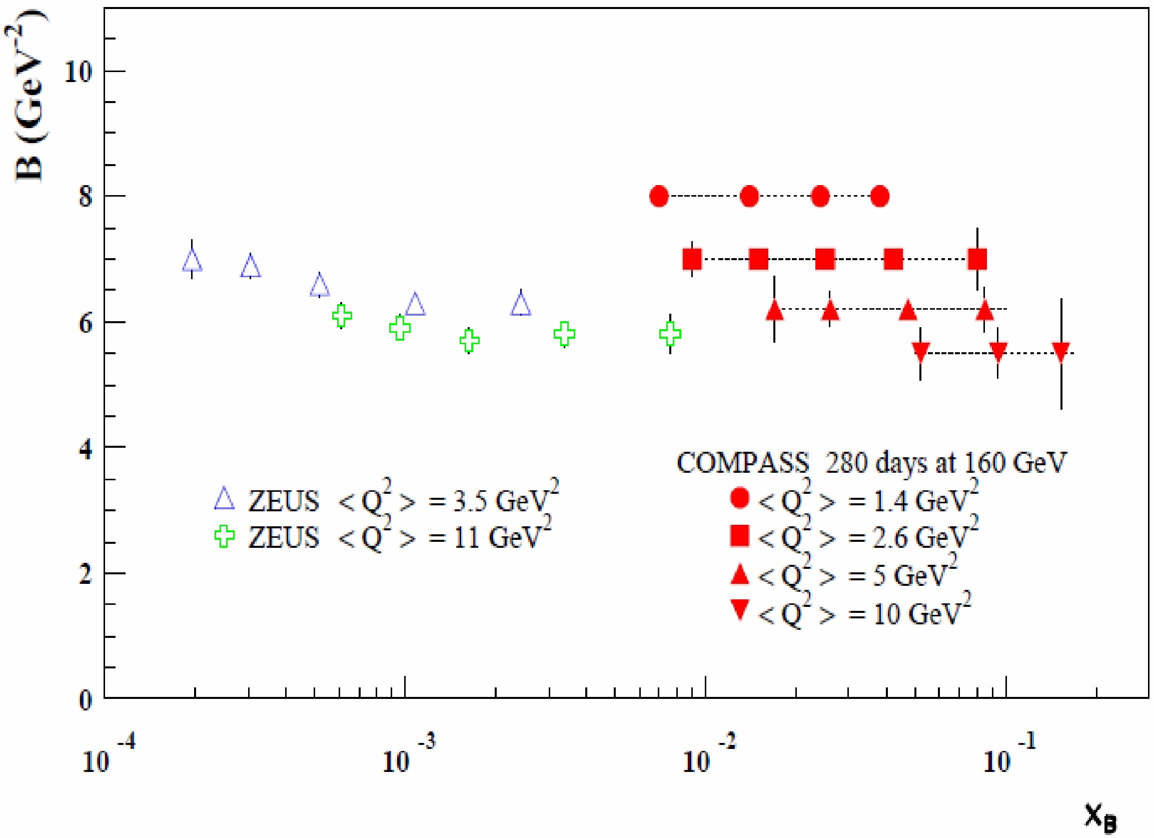
t-slope measurement for exclusive ρ^0 production

$$d\sigma_{\gamma N \rightarrow \rho N}/dt \quad \sim \quad \exp(-B|t|)$$

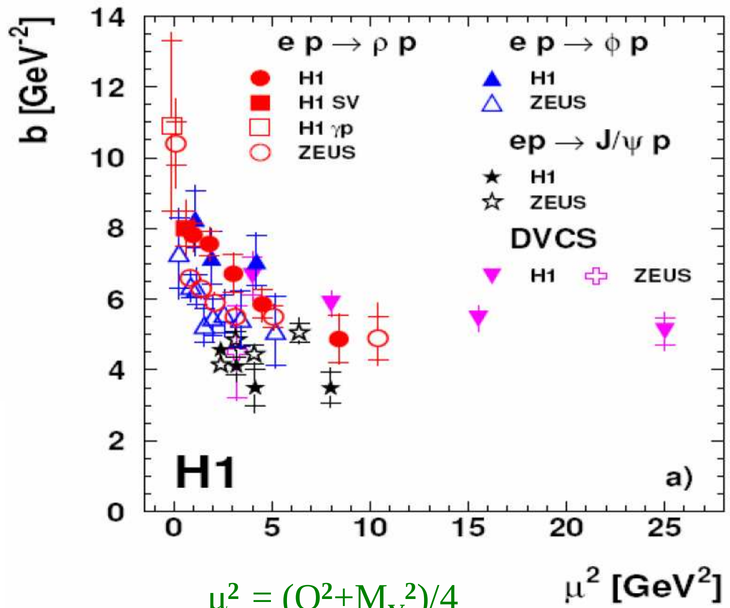
model by AS with normalisation to Goloskokov and Kroll

160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
L = 1222pb^{-1}

$0.06 < |t| < 0.64$ GeV^2



At large Q^2 slope B sensitive mostly to the nucleon size



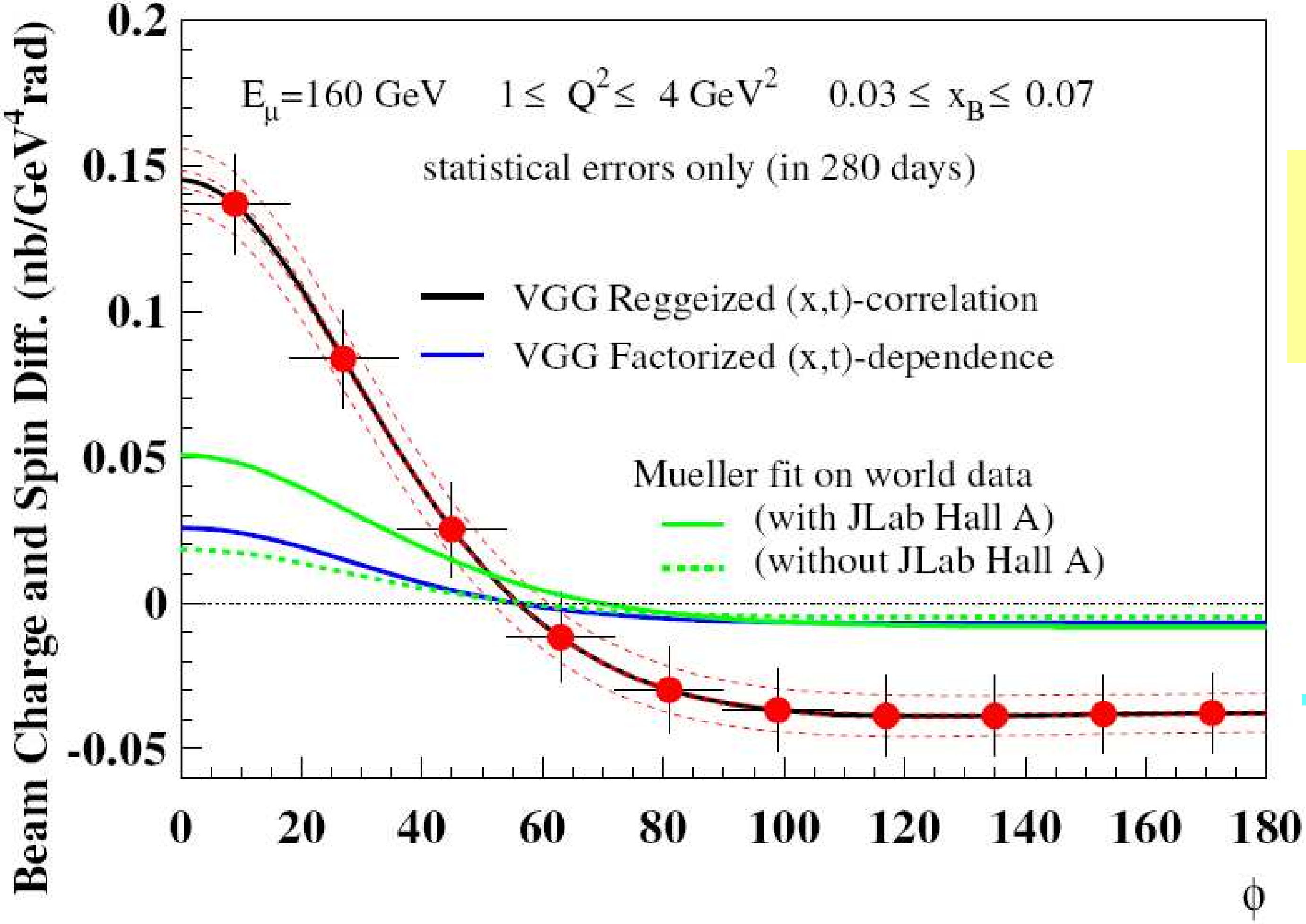
$\mu^2 = (Q^2+M_V^2)/4$
(= Q^2 for DVCS)

Beam Charge&Spin Difference of cross sections

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) = 2(e_\mu\, a^{BH}\, \mathcal{R}e\, T^{DVCS} + P_\mu\, d\sigma^{DVCS}{}_{pol})$$

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi$$

$$s_1^{DVCS}\sin\phi$$



160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
L = 1222pb^{-1}

0.06 < |t| < 0.64 GeV^2

$$\ldots + c_1^{Int}\cos\varphi + \ldots$$

$\Rightarrow \mathcal{R}e(F_1\mathcal{H})$

Sensitivity of COMPASS; cosϕ modulation

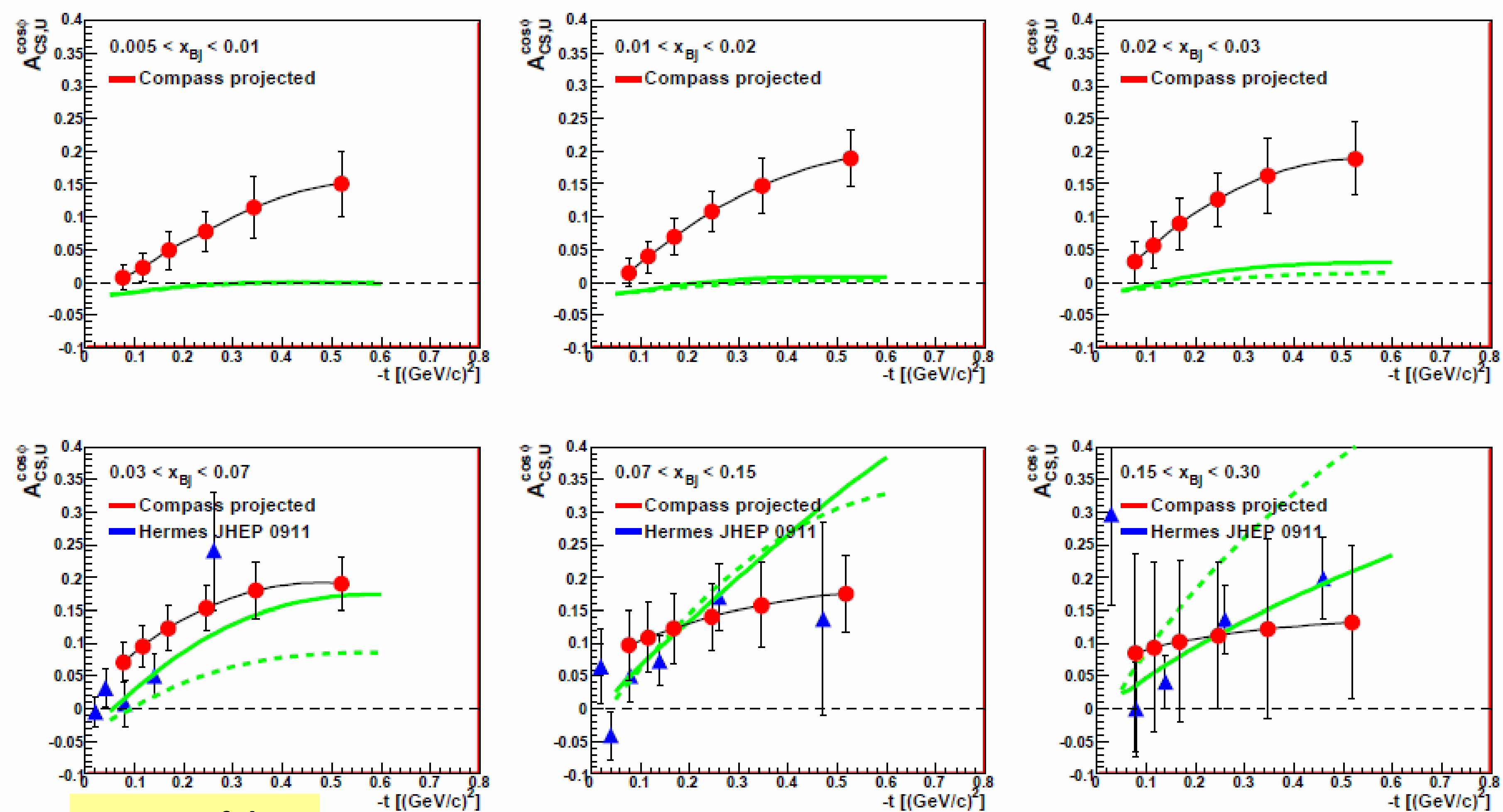
$BCSA = \mathcal{D}_{CS,U} / \mathcal{S}_{CS,U} = A_0 + A^{\cos\phi}_{CS,U} \cos\phi + A_2 \cos 2\phi$

$A^{\cos\phi}_{CS,U}$ => c_1^{Int} $\boxed{\Rightarrow \mathcal{R}e(F_1\mathcal{H})}$

Mueller's fits to world data

VGG

$\mathcal{R}e(F_1\mathcal{H})$ > 0 at H1
< 0 at HERMES/JLab
Value of x_B for the node?



2 years of data

with ECAL2 + ECAL1 + ECAL0

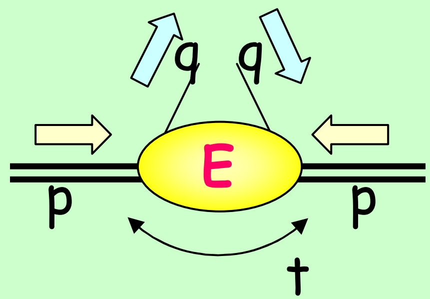
‘Stage 2’ of COMPASS GPD program

DVCS and HEMP with transversely polarised proton target (NH_3)

to constrain GPD E

- **Contribution to the nucleon spin puzzle**

E related to the orbital angular momentum



$$J_q = \frac{1}{2} \int x \left(H^q(x,\xi,0) + E^q(x,\xi,0)\right) dx$$

Sensitivity to GPD E

the most promissing Transverse Target Spin asymmetry

$$A^{D}_{CS,T} \text{ (or } A_{UT}) \ ^{\sin(\phi-\phi s)\cos\phi} \longrightarrow c_{1,\mathrm{T}-}^{Int}$$

COMPASS HERMES

$$c_{1,T-}^{Int} \propto -\frac{M}{Q}\mathrm{Im}\left\{\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E}-4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right]\right.$$
$$\left.+x_B\xi\left[F_1(\mathcal{H}+\mathcal{E})-(F_1+F_2)(\widetilde{\mathcal{H}}+\frac{t}{4M^2}\widetilde{\mathcal{E}})\right]\right\}$$

Study of azimuthal asymmetries from transversely polarized NH_3 target is a part of Phase 2 of COMPASS GPD program

example: COMPASS projections for

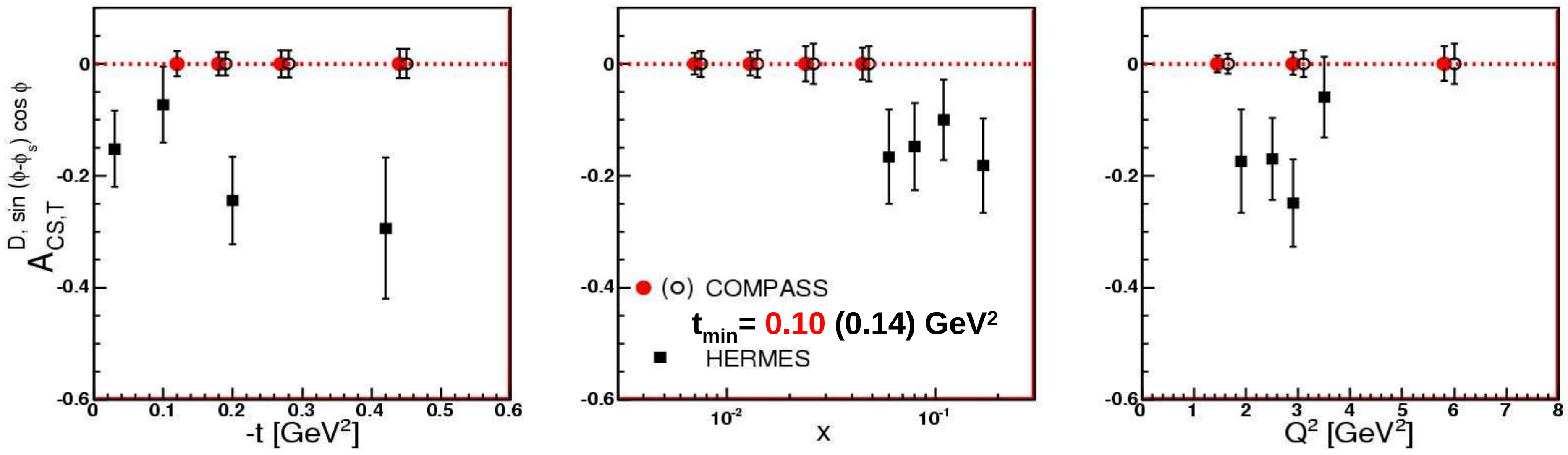
$$A^{D}_{CS,T}{}^{\sin(\phi-\phi s)\cos\phi}$$

160 GeV muon beam
1.2m NH_3 target
ε_{global} = 10%, 280 days
ECAL1+ECAL2 only

for $\mu\, p^{\uparrow} \rightarrow \mu\, \gamma\, p$
dilution factor f=0.26

FFS model
adapted for COMPASS (by AS)

0.10 (0.14) < |t| < 0.64 GeV^2



Typical statistical errors of TTS azimuthal asymmetries:

projections for COMPASS ≈ 0.03

for HERMES ≈ 0.08

DVCS test runs in 2008-2009

with COMPASS ‘hadron’ set-up

Goal: evaluate feasibility to detect DVCS/BH in the COMPASS setup

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

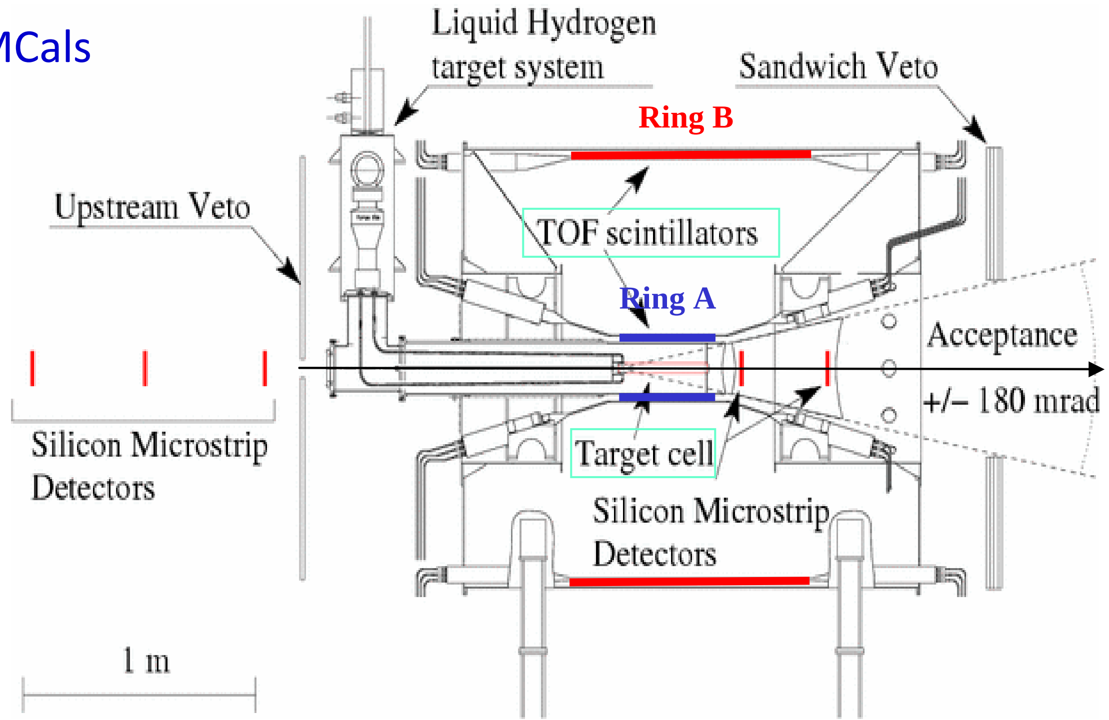
LH 40 cm

in the small RPD

in EMCals

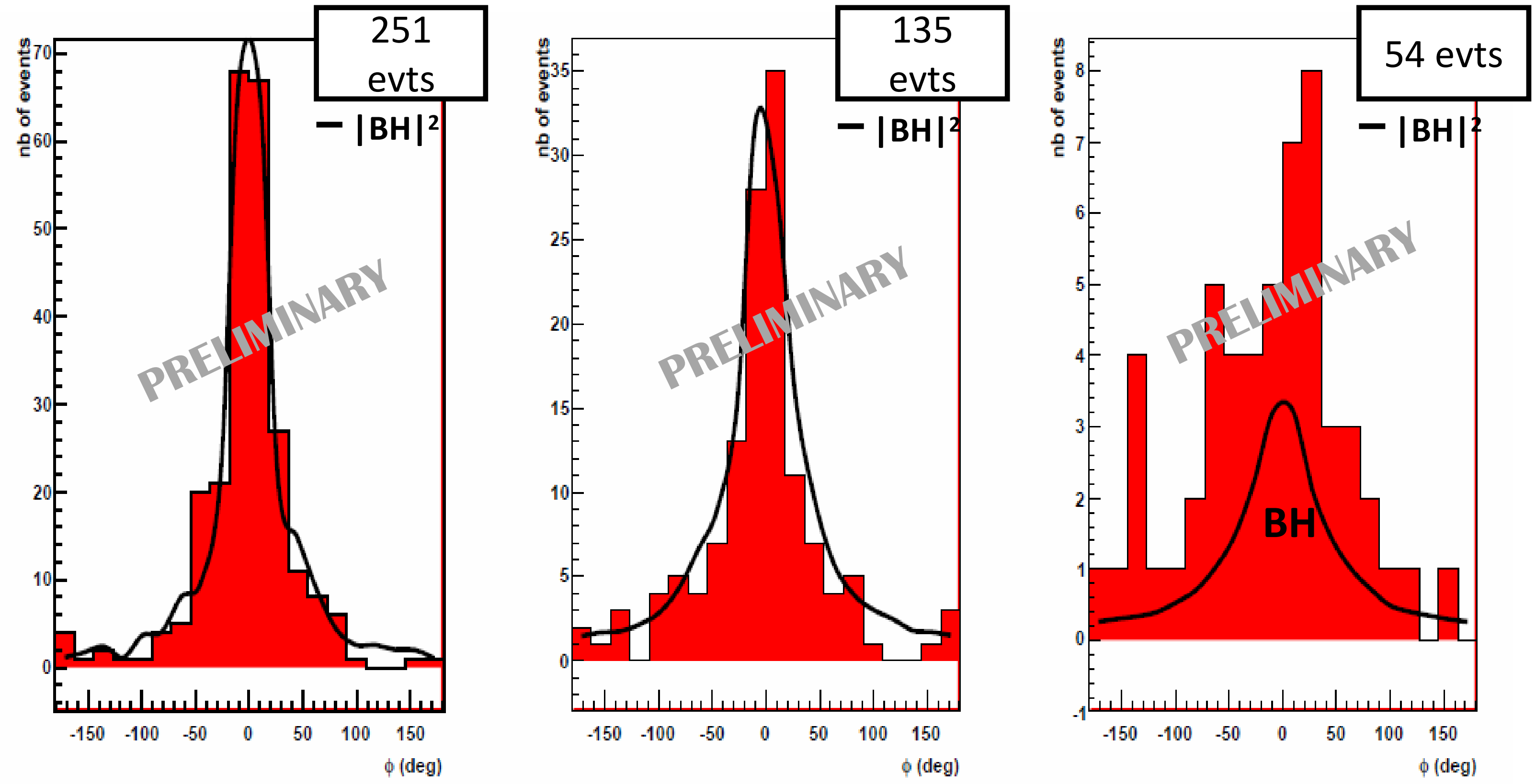
- Target: 40 cm LH_2
- Recoil Detector (1 m long)
- ECAL1 & ECAL2

target region



Short: 1.5 day in 2008 and 10 days in 2009 of 160 GeV muon beam (μ^+ and μ^-)

Exclusive γ production from 2009 DVCS test run



$0.005 < x_B < 0.01$ $\quad$ $0.01 < x_B < 0.03$ $\quad$ $x_B > 0.03$

$\epsilon_{\mu p \to \mu' \gamma p} \approx 35\%$

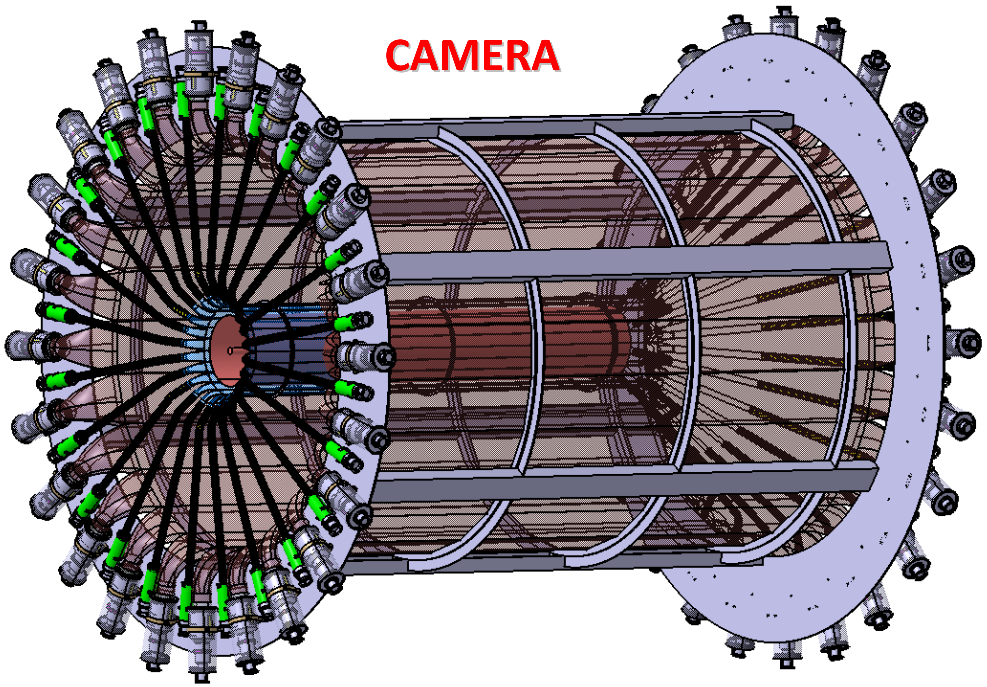
$\times (0.8)^4$ for SPS + COMPASS avail. + trigger eff + dead time

$\varepsilon_{global} \approx 0.14$ confirmed $\varepsilon_{global} = 0.1$ assumed for COMPASS-II projections

54 evts ≈ 20 BH
+ 22 DVCS
+ about 12 γ from π^0
upper limit

New developments - target and recoil detector

CAMERA

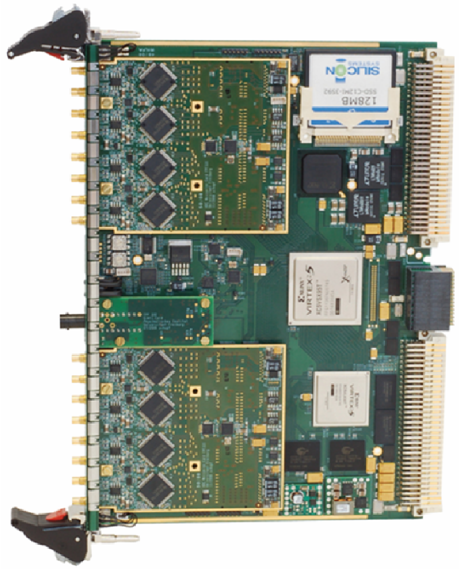


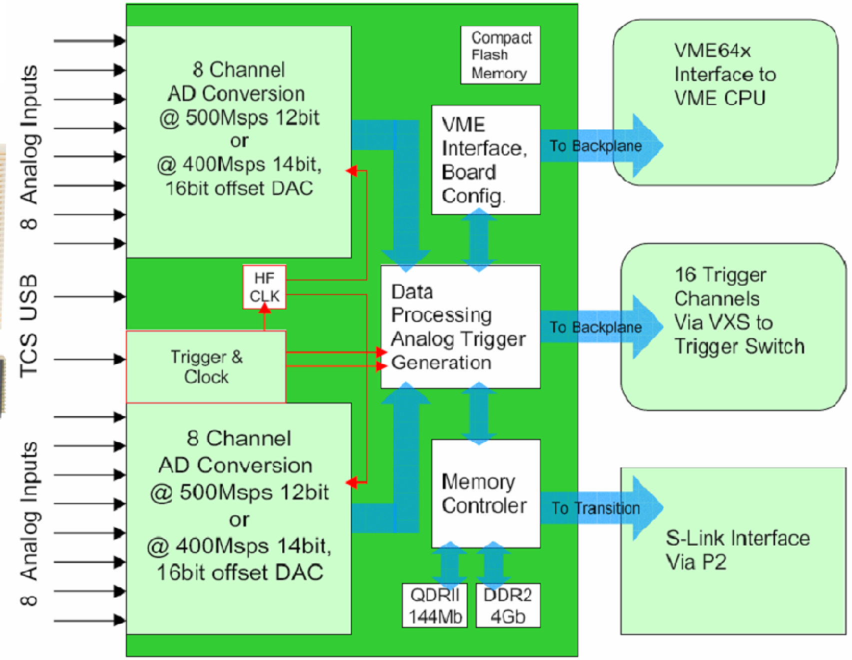
- 2.5m long LH target
- 4m long ToF barrel
  of 2 scintillator layers
- recoil proton ID by ToF and ΔE
- ≈ 300 ps time resolution
- full scale prototype tested

high occupancy due to δ rays

GANDALF project:

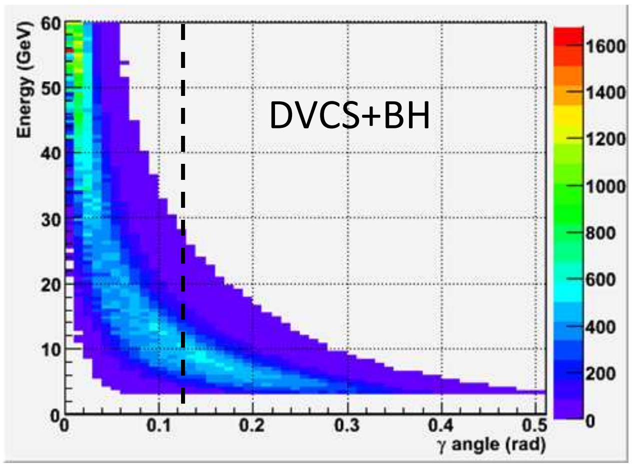
- 1 GHz digitsation of PMT signal to cope with high rate
- resolution > 10 ENOB
- self triggered

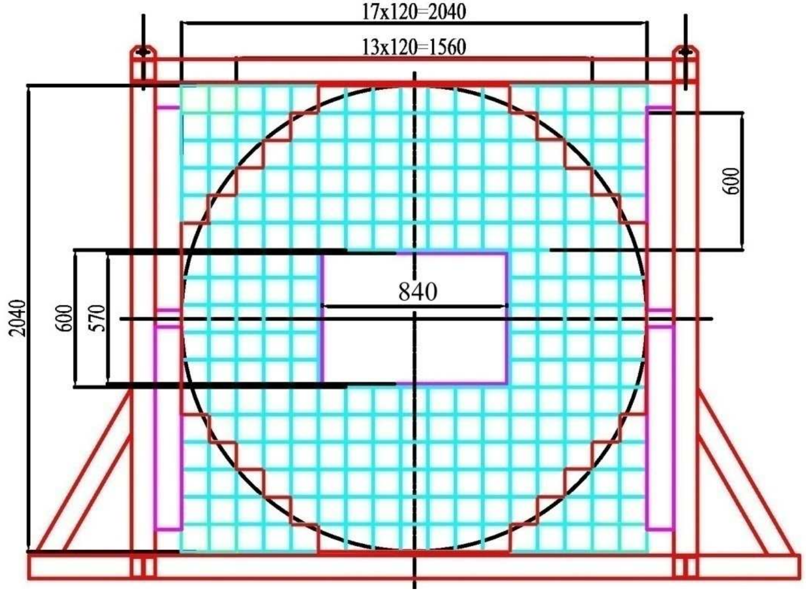




New developments - large-angle electromagnetic calorimeter ECAL0

existing
ECAL1&2





ECAL0 location and specifications

ECAL0 located downstream of CAMERA

- transverse size 204x204 cm^2 (approx.)
  modules arranged in a circular array of 1.02 m radius
- hole size 84x60 cm^2
- granularity 4x4 cm^2
- energy range 0.1 - 30 GeV
- polar angle range 0.15-0.5 rad.
- energy resolution ~ (5-7)%/sqrt(E)
- time resolution 0.5-0.6 ns
- thickness ≾ 50 cm
- insensitive to magnetic field

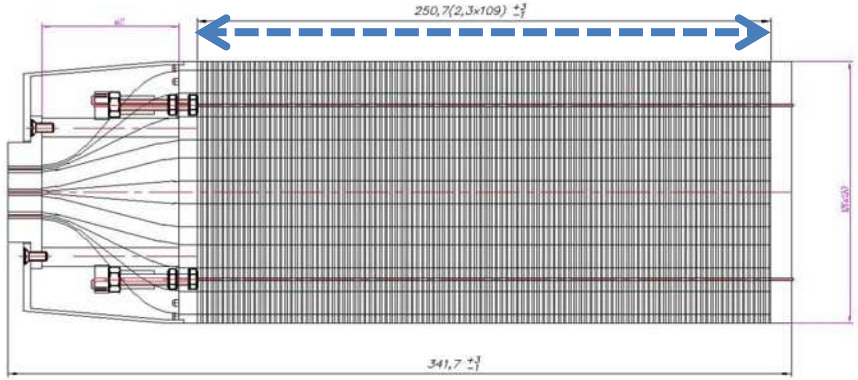
Total:	194	9-cell modules
	1746	MAPDs and read out channels
	the weight about 6 tons	

ECAL0 module

<u>Module</u>:
- size is 12x12 cm^2
- 9 cells, size is 4x4 cm^2
- 9 light collection systems
- 9 MAPDs
- 9 MSADC channels
- Temperature stabilization system (Peltier element, electronics)
- 9 Amplifiers
- Control system (LED, Laser)
- Power supply

ECAL0 cell

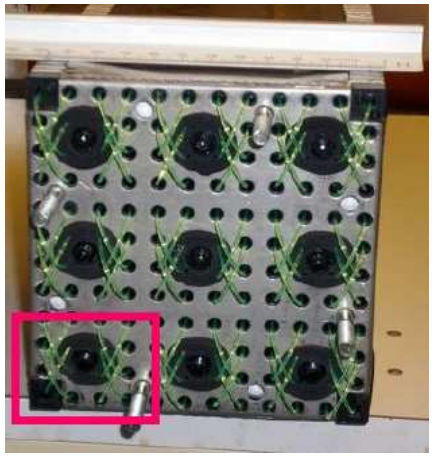
252mm or 15 radiation length

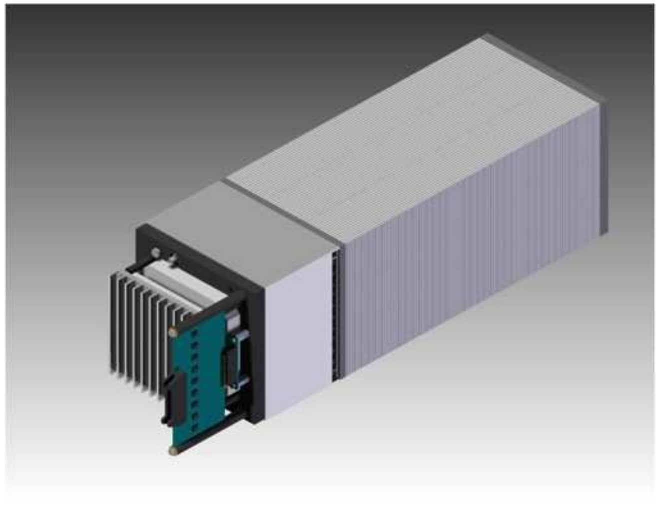


shashlyk technology
109 plates made of Sc 1.5 mm /Pb 0.8 mm

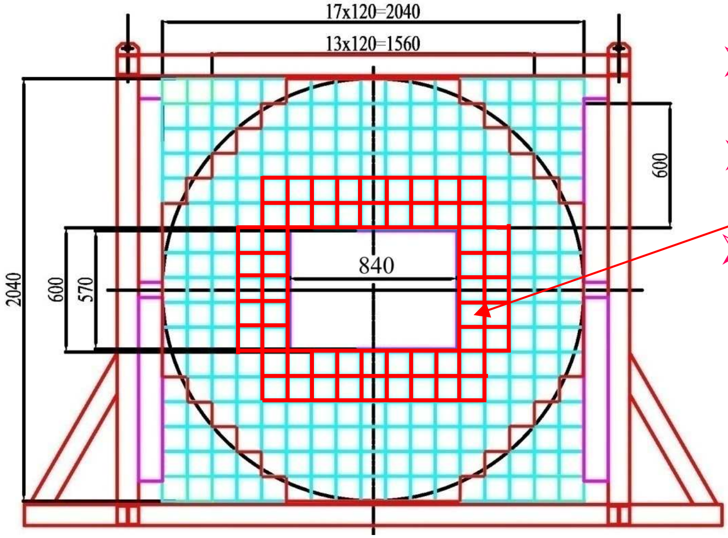
Micropixel Avalanche Photo Diodes
3 x 3 mm^2, number of pixels ~ 135 000

module for tests in 2011





Start of GPD program of COMPASS-II in 2012 - ‘dress rehearsal’

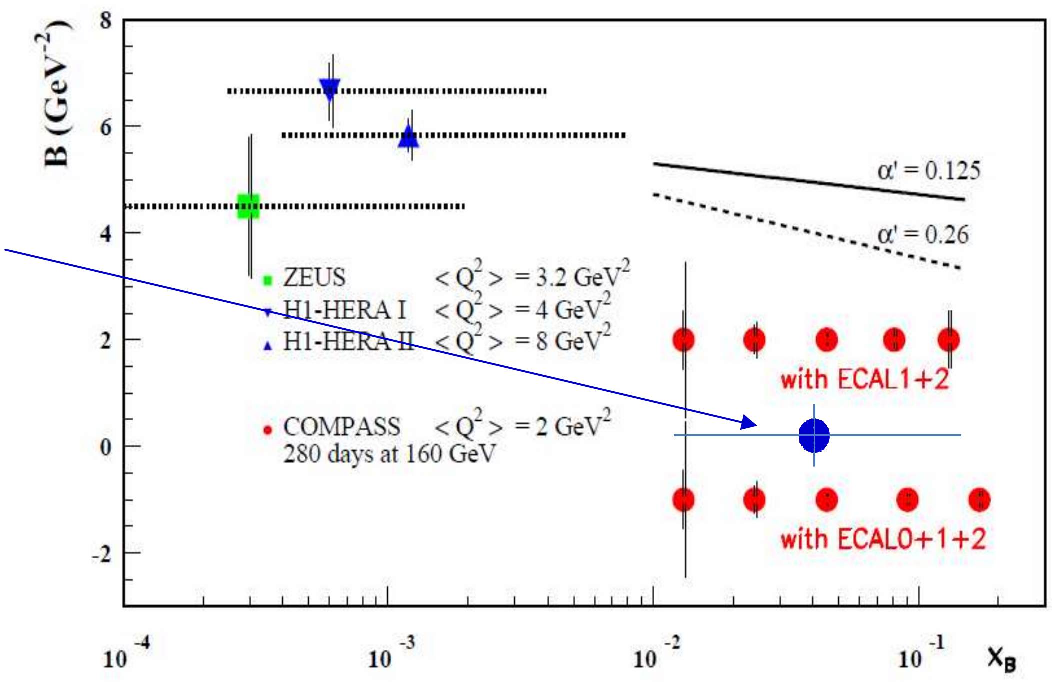


- 2.5m LH target and CAMERA ready by September 2012
- reduced ECAL0 (56 modules) ready in September 2012
- 6 weeks of comissioning and DVCS data taking

after 18 weeks of Primakoff measurements
which is the main goal in 2012

- projection for a physics result

from 1 week of DVCS test in 2012
1/40 of the complete statistics



Complete GPD program of Stage 1 with complete ECAL0 is scheduled for 2015-2016

Summary-I , new results on transverse spin asymmetries

- COMPASS full set of data for transversely polarised targets available
  - ✓ polarised deuterons, ^{6}LiD target, 2002-2004
  - ✓ polarised protons, NH3 target 2007 and 2010

- All azimuthal spin asymmetries for deuteron compatible with zero
  - ✓ approximate cancellation of u- and d-quark contributions
  - ✓ important for global fits to disentangle different flavour contributions

- Collins and two-hadron asymmetries for proton
  - ✓ h^+ and h^- Collins asymmetries in valence region large and of opposite sign

    no strong dependence on Q^2 / y (LT)
  - ✓ two-hadron asymmetry large in valence region, no strong dependence on M_{hh}

- Sivers asymmetries for proton
  - ✓ large asymmetry for h^+ dependence on Q^2 / y (Q^2 evolution ?)

- Transverse Target Spin Asymmetry for exclusive ρ^0 production
  - ✓ both asymmetries for proton and deuteron compatible with zero

    approximate cancellation of contributions of GPD E^u and E^d

Summary-II , on GPD program

- <u>COMPASS has a great potential for GPD physics</u>
  - ✓ unique polarised μ^+ and μ^- beams
  - ✓ favourable kinematic domain (x_{Bj})
- <u>Large projects for new apparatus</u>
  - ✓ 4m RPD + large angle ECAL0 (phase 1)
  - ✓ recoil proton detector incorporated into a large polarised target (phase 2)
- <u>Investigation of GPDs with both DVCS and HEMP on unpolarised nucleons</u>
  - ✓ t-slope of DVCS and HEMP cross section

    → transverse distribution of partons
  - ✓ Beam Charge&Spin sum and difference of DVCS cross sections

    → $\mathcal{R}e\, T^{DVCS}$ and $\mathcal{I}m\, T^{DVCS}$ for the GPD H determination
  - ✓ Production of vector mesons ρ^0, ω, φ … → flavour separation for GPD H
  - ✓ Production of π^0 → sensitivity to GPDs $\tilde{E}$ and $\bar{E}_T$ ($\equiv 2\tilde{H}_T + E_T$)
- <u>Transverse Target Spin Asymmetries for DVCS and hard exclusive VM production</u>

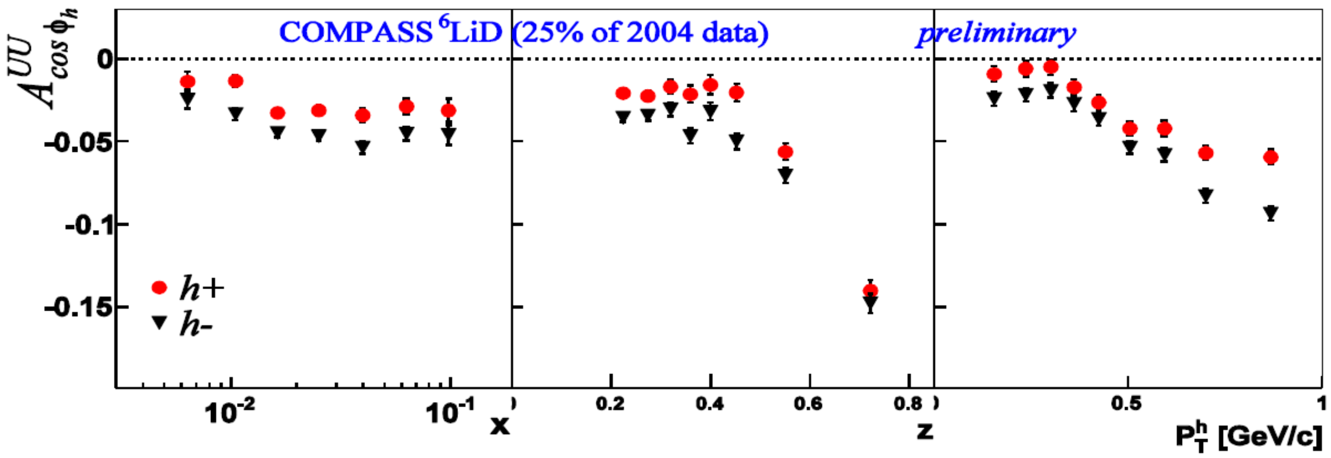
  → GPD E and angular momentum of partons

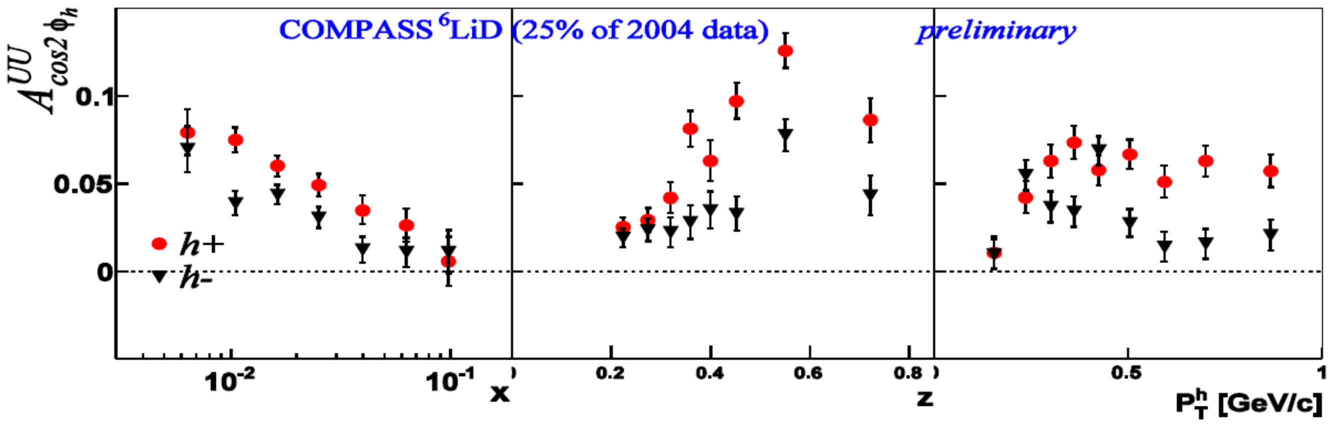
Backup

cosϕ and cos2ϕ modulations $\quad$ ^{6}LiD

$$N(\phi_h) \propto N_0 \cdot (1 + \varepsilon_1 \boxed{A^{UU}_{\cos\phi_h}} \cos\phi_h + \varepsilon_2 \boxed{A^{UU}_{\cos 2\phi_h}} \cos 2\phi_h)$$

$$\langle \cos\phi_h \rangle = \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM} \qquad \langle \cos 2\phi_h \rangle = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$





GPDs properties, links to DIS and form factors

$H^q, \widetilde{H}^q \leftrightarrow h_1 = h_2$ for $\boldsymbol{P_1 = P_2}$ recover usual parton densities

$$H^q(x,0,0) = q(x), \qquad \widetilde{H}^q(x,0,0) = \Delta q(x) \qquad for\ x > 0$$
$$H^q(x,0,0) = -\bar{q}(-x), \qquad \widetilde{H}^q(x,0,0) = \Delta\bar{q}(-x) \qquad for\ x < 0$$

$E^q, \widetilde{E}^q \leftrightarrow h_1 \neq h_2$ no similar relations; these GPDs decouple for $\boldsymbol{P_1 = P_2}$

$E^q, \widetilde{E}^q \neq 0$ **needs** orbital angular momentum between partons

$$\int dx H^q(x,\xi,t) = F_1^q(t) \quad \textbf{Dirac} \qquad \int dx \widetilde{H}^q(x,\xi,t) = g_A^q(t) \quad \textbf{axial}$$

$$\int dx E^q(x,\xi,t) = F_2^q(t) \quad \textbf{Pauli} \qquad \int dx \widetilde{E}^q(x,\xi,t) = g_P^q(t) \quad \textbf{pseudoscalar}$$

Ji's sum rule $\quad \frac{1}{2}\int dx\, x\,(H^q + E^q) = J^q(t)$

$J^q(0)$ **total** angular momentum carried by quark flavour *q*
(helicity and **orbital** part)

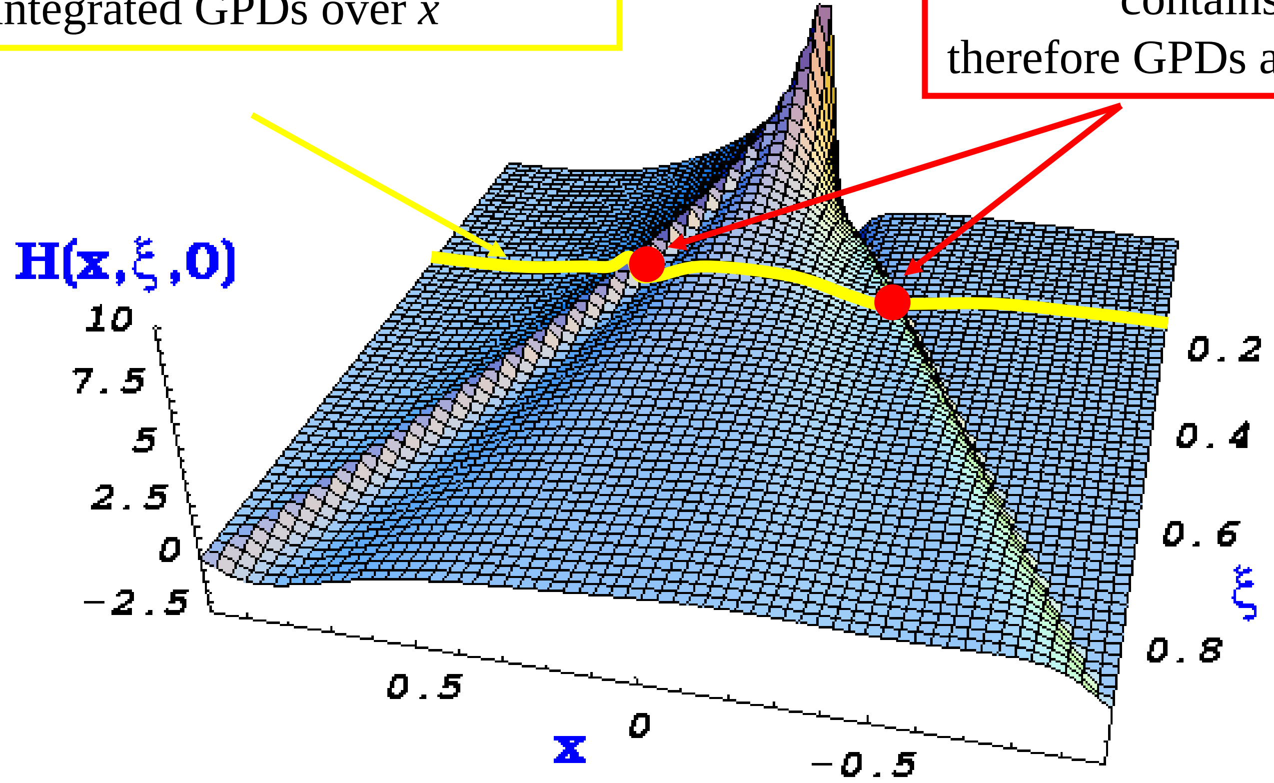
Observables and their relationship to GPDs

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Beam charge asymmetry contains ReT, integrated GPDs over x

Beam or target spin asymmetry contains ImT, therefore GPDs at $x = \xi$ and $-\xi$



Assumptions for the proposal projections

- polarised muon beam with 160 GeV energy
- 48 s SPS period with 9.6 s spill duration
- μ^+ beam intensity 4.6 x 10^8 muons / spill
- 3 times smaller intensity for μ^- beam
- running time 280 days (70 days with μ^+, 210 days with μ^-)
- a) 2.5 m LH target => $\mathcal{L} = 1. \times 10^{32}\ cm^{-2}s^{-1}$ for μ^+ beam

  b) 1.2 m NH_3 target => $\mathcal{L} = 3.4 \times 10^{32}\ cm^{-2}s^{-1}$ for μ^+ beam
- a new recoil proton detector(s) (RPD) surrounding the target(s)
- two existing electromagnetic calorimeters (ECAL1, ECAL2)

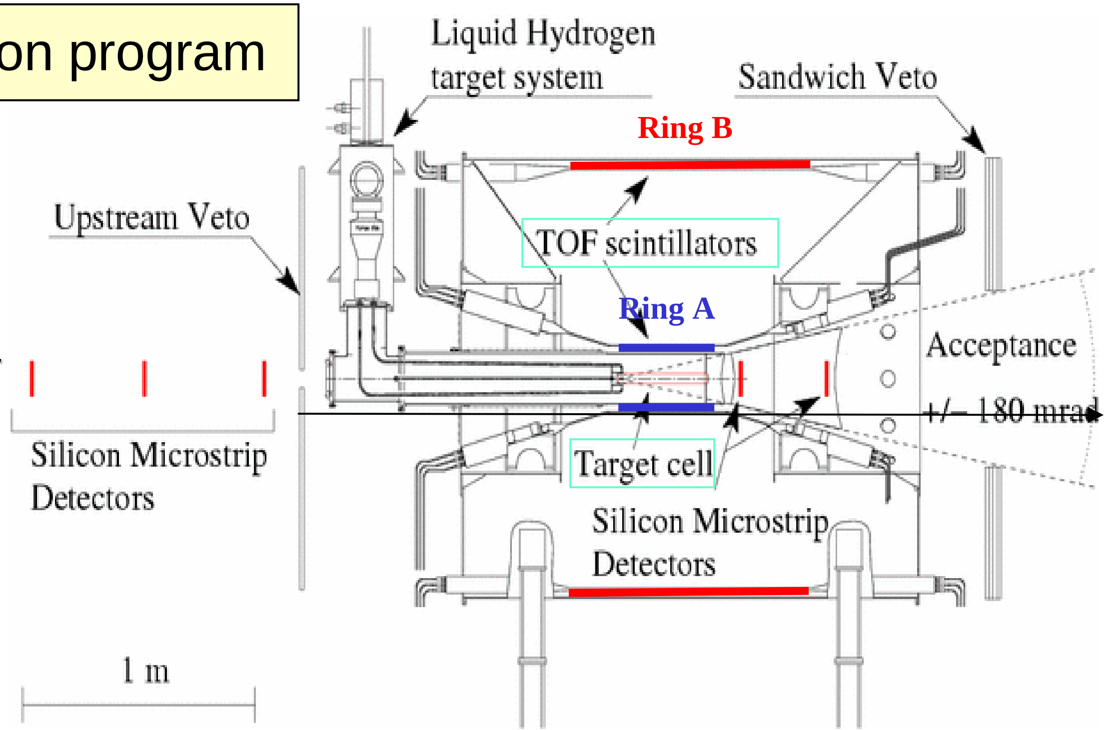
  + additional new large angle calorimeter (ECAL0)
- an overall global efficiency $\varepsilon_{\mathbf{global}} = 0.1$

2 generators for single photon production (BH+DVCS) used:

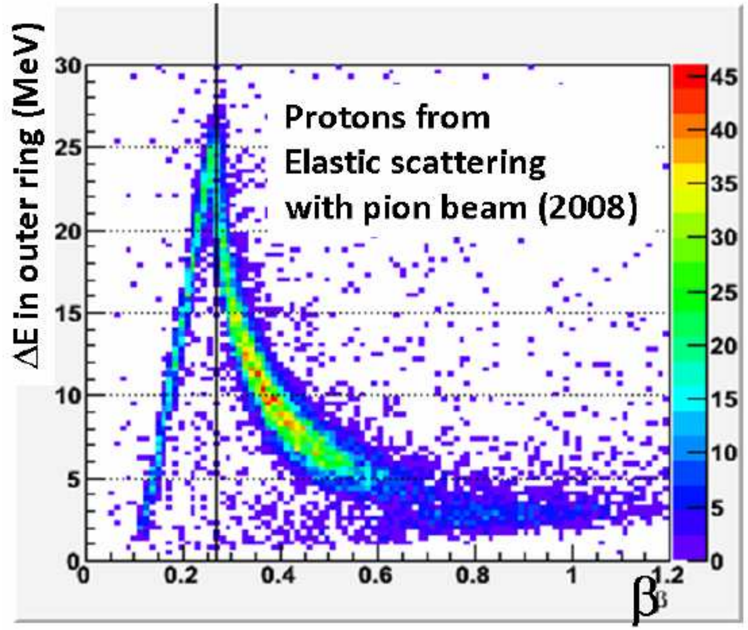
a) VGG code b) FFS model adapted for COMPASS (by AS)

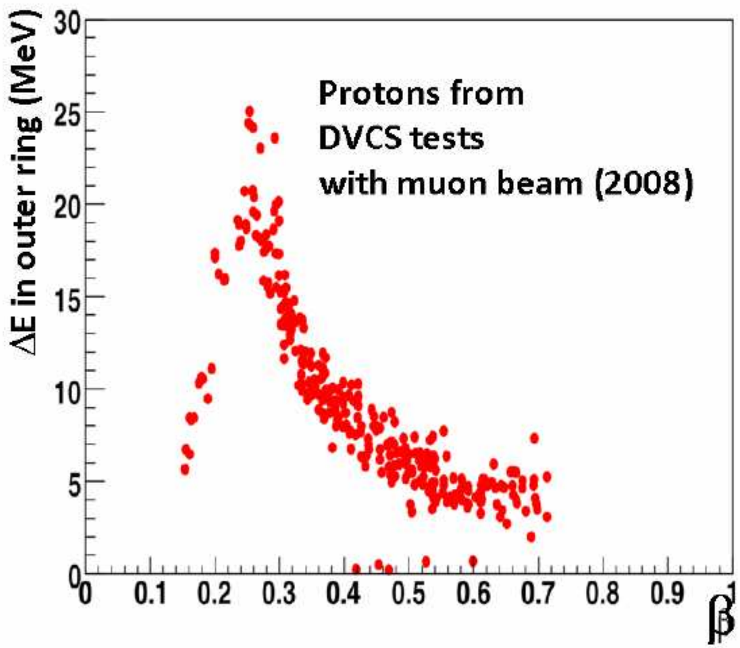
Recoil proton detector for hadron program

Small 1 m long Recoil Proton Detector and a 40cm LH target in 2008/2009



Proton identification in RPD





Selection of single γ events

$$\vec{p}_{miss} = \vec{p}_{\mu} - \vec{p}_{\mu'} - \vec{p}_{\gamma}$$

- one vertex with μ and μ'
- no other charged tracks
- only 1 high energy photon
- 1 proton in RPD with $p < 1$ GeV/c
- exclusivity cuts in transverse plane

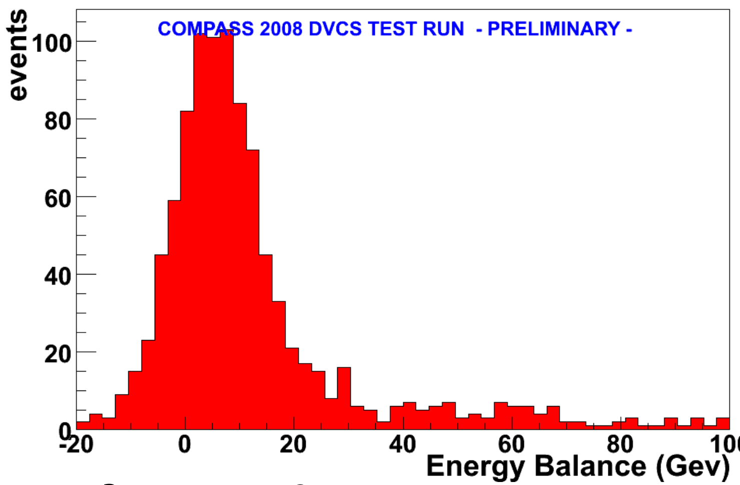
  $|\Delta p_{\perp}| < 0.2$ GeV

  $|\Delta\phi| < 41$ deg

- exclusivity cut on energy ballance (E_{miss})

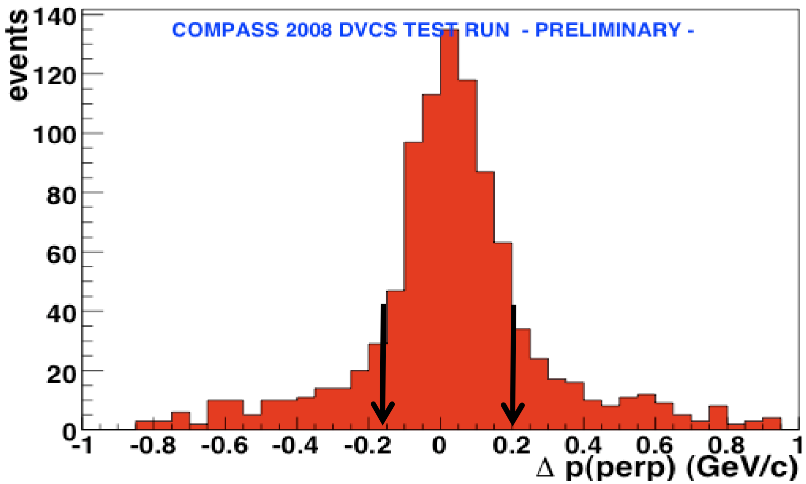
  $E_{miss} = E_{\mu} + M_p - (E_{\mu'} + E_{p'} + E_{\gamma})$

  $|E_{miss}| < 20$ GeV



- $1 < Q^2 < 4$ GeV^2

$\Delta p_{\perp} = |P^{\perp}_{miss}| - |P^{\perp}_{RPD}|$



$\Delta\phi = \phi_{miss} - \phi_{RPD}$