GPD program at COMPASS

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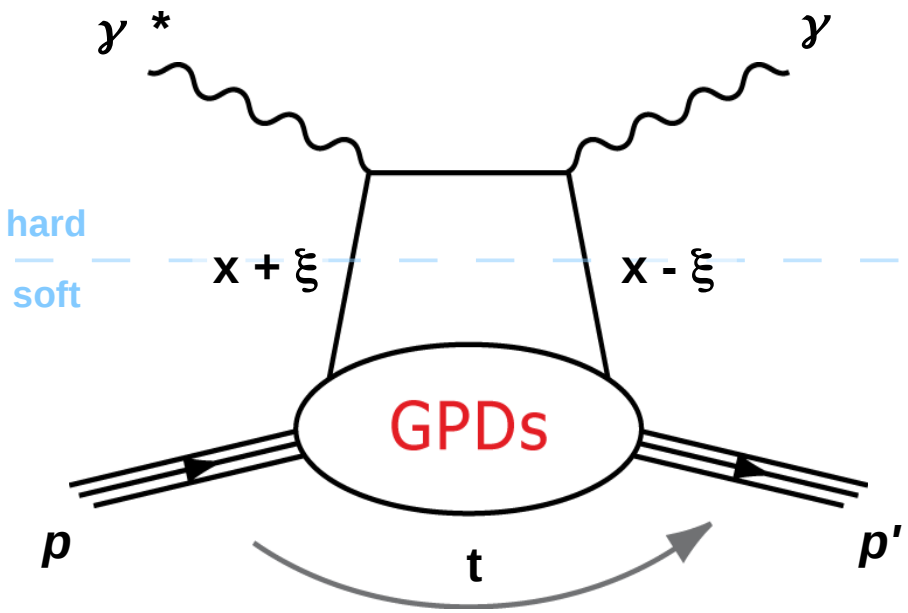
Outline

- GPD formalism
- COMPASS experiment
- Deeply Virtual Compton Scattering
- Transverse target spin asymmetry for incoherent exclusive ρ^0 production
- GPD program at COMPASS-II
- Summary and outlook

Deeply Virtual Compton Scattering
$\gamma^* p \to \gamma p'$



factorization for large Q^2 and $-t < 1$ (GeV/c)^2
$|t|/Q^2 << 1$

GPDs (Generalized Parton Distributions):

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
for retained proton helicity	*for changed proton helicity*	

where:

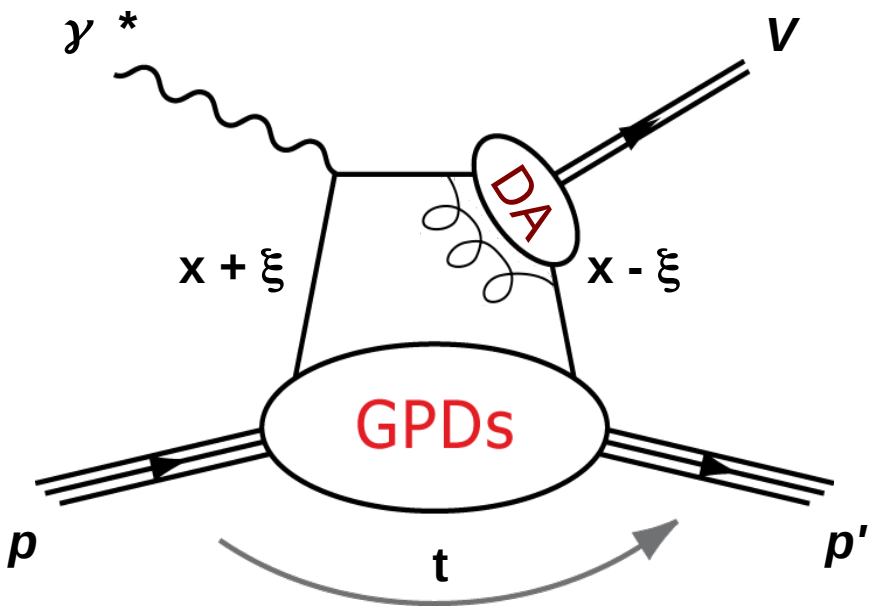
x: average longitudinal momentum fraction of the parton

2ξ: longitudinal momentum fraction transferred by the parton

$$\xi \approx \frac{x_B}{2 - x_B}$$ (in the Bjorken limit)

t: squared four-momentum transferred to the target nucleon

***D**eeply **V**irtual **M**eson **P**roduction*
$\gamma^* p \to V p'$



factorization strictly proven only for longitudinal γ^*

Dependence of meson production on different GPDs:

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for vector mesons*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for pseudoscalar mesons*

for example:

$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{8}E^g\right)$$

$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{8}E^g\right)$$

$$E_{\varphi} = -\frac{1}{3}E^s - \frac{1}{8}E^g$$

- *contribution from gluons at the same order of α_s as from quarks*

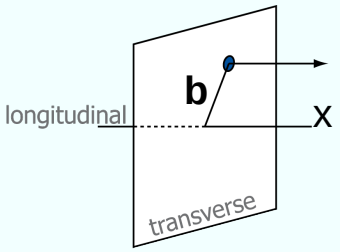
Nucleon tomography:

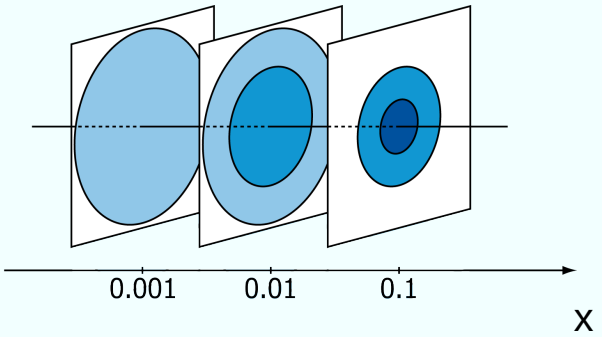
3D parton distribution function:

$$q(x,\boldsymbol{b}) = (2\pi)^{-2} \int d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{b}\cdot\boldsymbol{\Delta}} H^q(x,0,t=-\boldsymbol{\Delta}^2)$$

where:

$\boldsymbol{b}$: impact parameter





Total angular momentum:

$$\int_{-1}^{1} dx\, x\,[H^q(x,\xi,0) + E^q(x,\xi,0)] = 2J^q$$ (Ji's sum rule)

where:

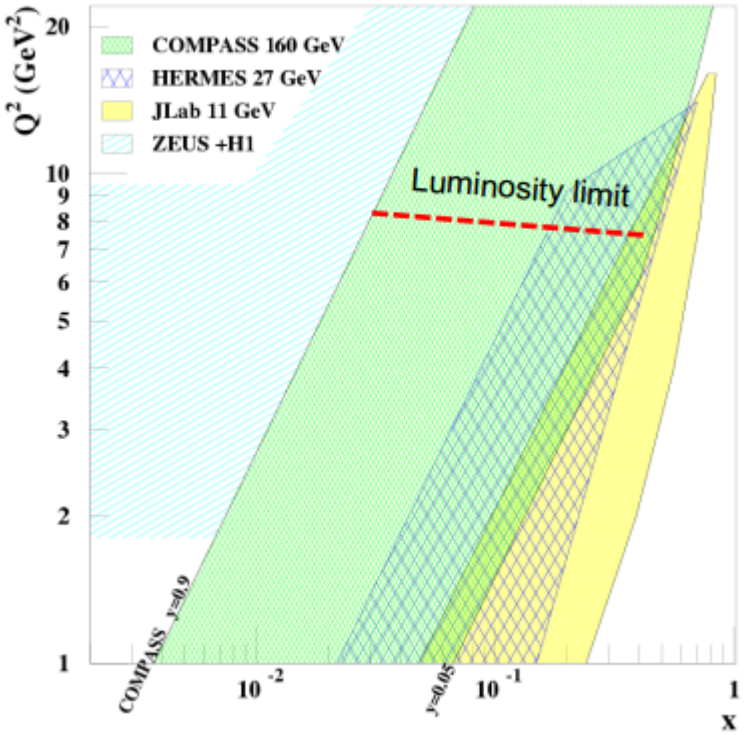
$$J^q = L^q + S^q$$

angular momentum conservation law ⇒ *if proton helicity is changed* ($E^q, \widetilde{E}^q \neq 0$) *orbital angular momentum must be involved*

What makes COMPASS unique for GPD measurement?

The GPD program at COMPASS explores intermediate x_{Bj} and large Q^2 range

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

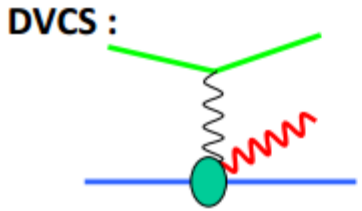


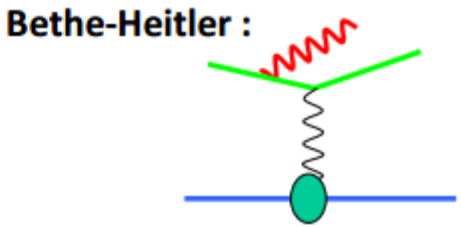
$L = 10^{32}$ cm^{-2} s^{-1}
(with 2.5 m long LH target)

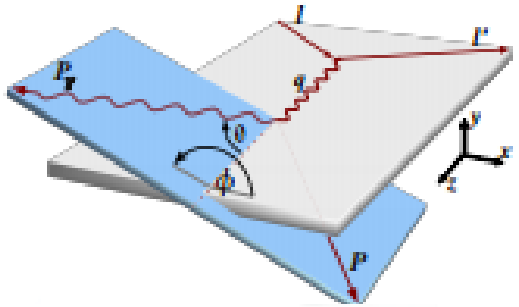
$Q^2 < 8$ GeV^2

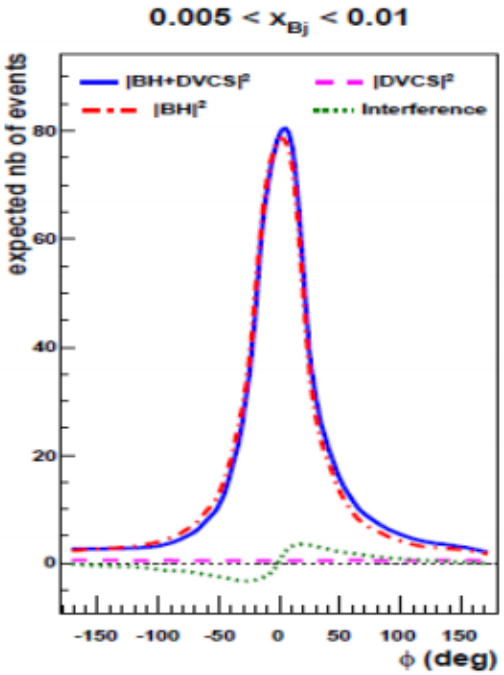
$\sim 10^{-2} < x_{Bj} < \sim 10^{-1}$

In kinematic region covered by COMPASS access DVCS cross section (in high x_{Bj} region) and DVCS amplitude (in intermediate x_{Bj} region) through the interference with BH

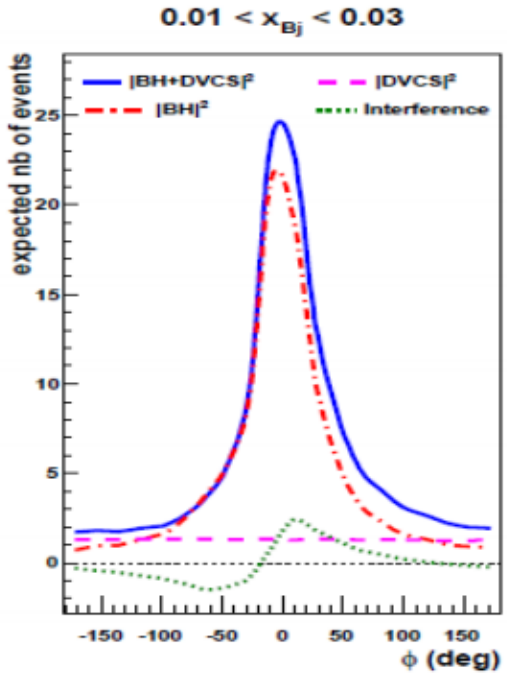




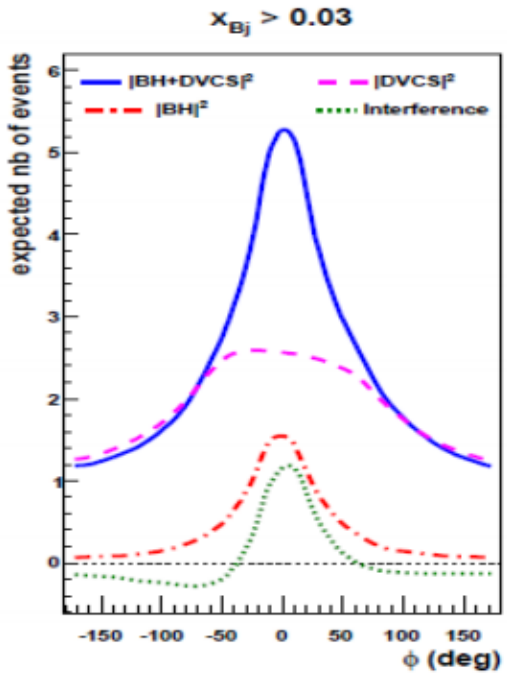




Low x_{Bj} region
Cross-check for predictions



Intermediate x_{Bj} region
Access to DVCS amplitude through BH+DVCS interference



High x_{Bj} region
Access to DVCS cross section

What makes COMPASS unique for GPD measurement?

For several years COMPASS will be unique due to availability of lepton beams of both charges

- μ+ and μ- beams with opposite polarization (80%)
- nominal beam momentum between 100 GeV/c and 190 GeV/c

DVCS + BH with $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ polarized beams and unpolarized target

$$d\sigma_{\mu p\to\mu\gamma} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, Re\,T^{DVCS} + e_\mu P_\mu\, a^{BH}\, Im\,T^{DVCS}$$

Opposite beam charge and polarization - sum:

$$S_{CU,U} = d\sigma^{+-} + d\sigma^{-+} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu\, a^{BH}\, Im\,T^{DVCS}\right)$$

$$c_0^{DVCS} + c_1^{DVCS}\cos\varphi + c_2^{DVCS}\cos 2\varphi \qquad s_1^{int}\sin\varphi + s_2^{int}\sin 2\varphi$$

$$d\sigma/d|t| \qquad Im(F_1\mathcal{H})$$

Opposite beam charge and polarization - difference:

$$D_{CU,U} = d\sigma^{+-} - d\sigma^{-+} = 2\left(P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, Re\,T^{DVCS}\right)$$

$$s_1^{DVCS}\sin\varphi \qquad c_0^{int} + c_1^{int}\cos\varphi + c_2^{int}\cos 2\varphi + c_3^{int}\cos 3\varphi$$

$$Re(F_1\mathcal{H})$$

Leading Twist

GPD program at COMPASS

- DVCS test runs in 2008 (1.5 days) and 2009 (10 days)
  - with unpolarized 40 cm LH target and small recoil proton detector
  - to demonstrate feasibility of DVCS measurement

- Vector Meson production from 2002 – 2011 data
  - with longitudinally/transversely polarized proton/deuteron targets
  - deuteron target unique for COMPASS
  - large statistics but without recoil proton detector
  - early results on spin dependance of DVMP

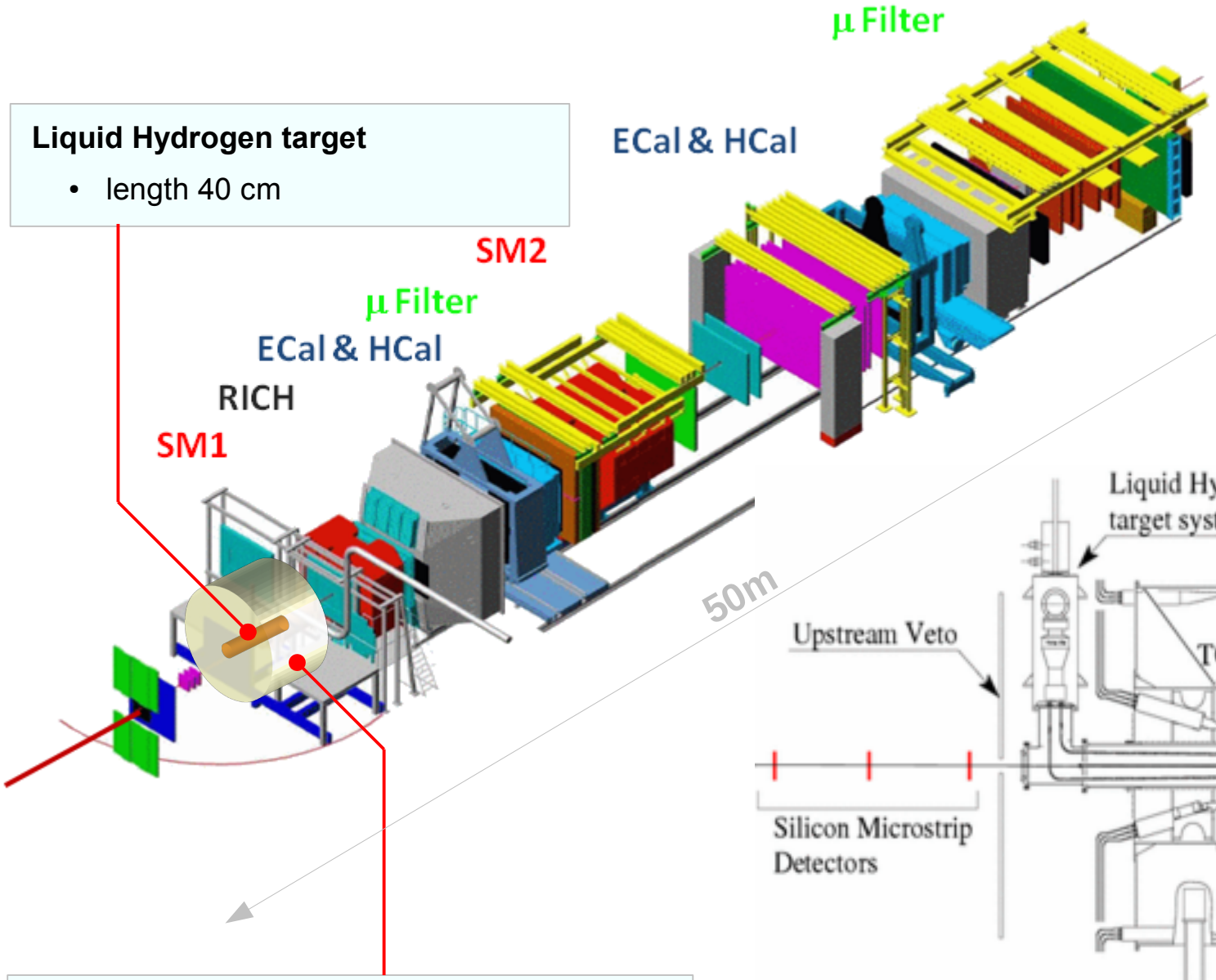
- GPD at COMPASS-II (part 1, approved) in 2012 (30 days) and 2016-2017
  - with unpolarized 2.5 m LH target and large recoil proton detector
  - with optimized setup of the spectrometer (enlarged acceptance for photon detection)
  - access to GPD H

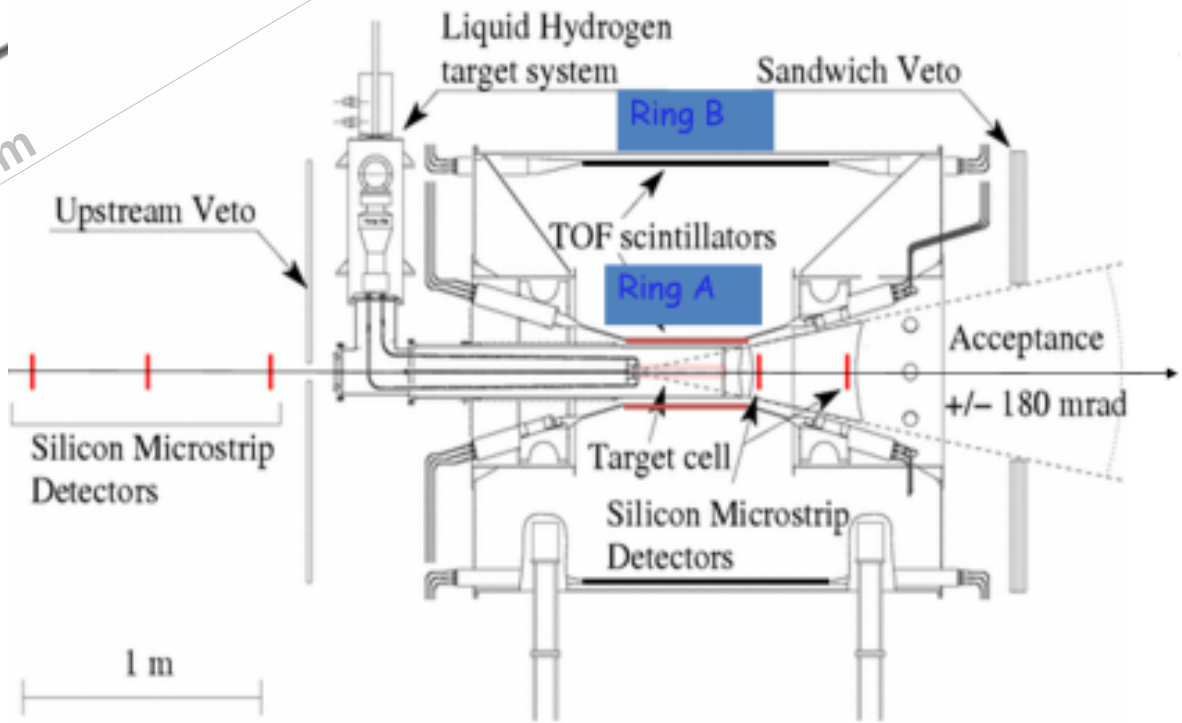
- GPD at COMPASS-II (part 2, future addendum)
  - with polarized ammonia target and large recoil proton detector
  - access to GPD E

COMPASS experiment at CERN – 2008/2009 setup

Liquid Hydrogen target

- length 40 cm





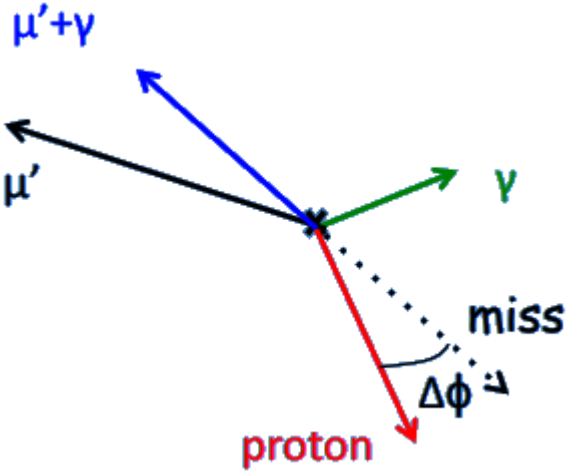
Recoil Proton Detector

1m long ToF barrel of two scintillator layers
recoil proton ID by ToF and ΔE

2008/2009 DVCS selections

- PV vertex with incoming (μ) and only one outgoing (μ') tracks
- only one high energy photon
- only one proton in RPD with p < 1 GeV/c

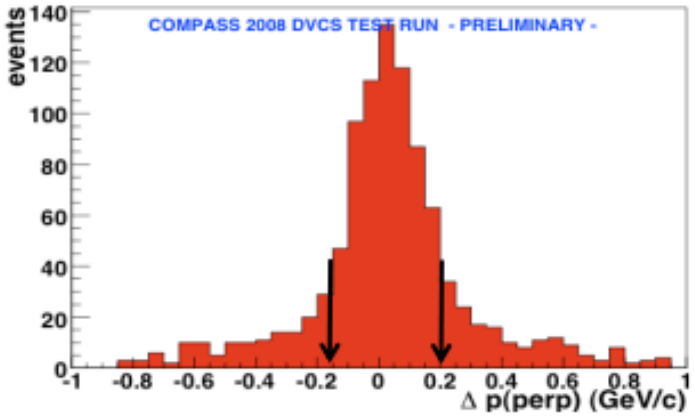
- exclusivity cuts in transverse plane
  $|\Delta p_T| < 0.2$ GeV
  $|\Delta\phi| < 41$ deg

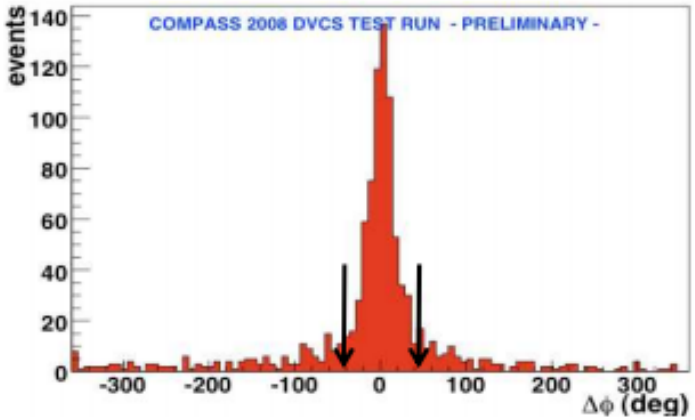


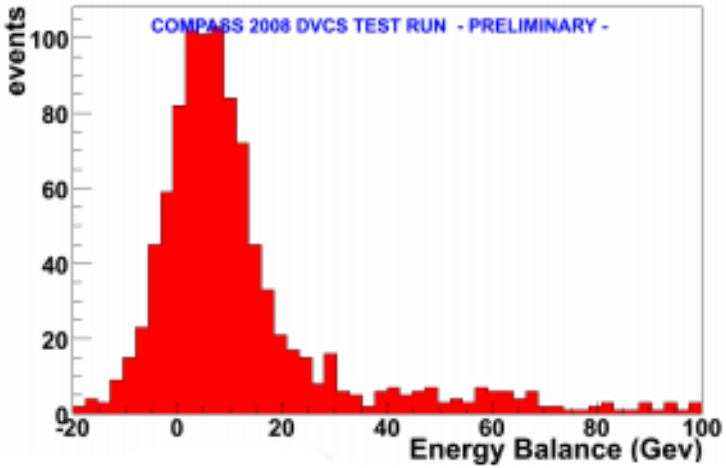
transverse plane

- cut on energy ballance (Emiss)
Emiss = Eμ + Mp – (Eμ' + Ep' + Eγ)
|Emiss| < 20 GeV

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







2008/2009 DVCS results

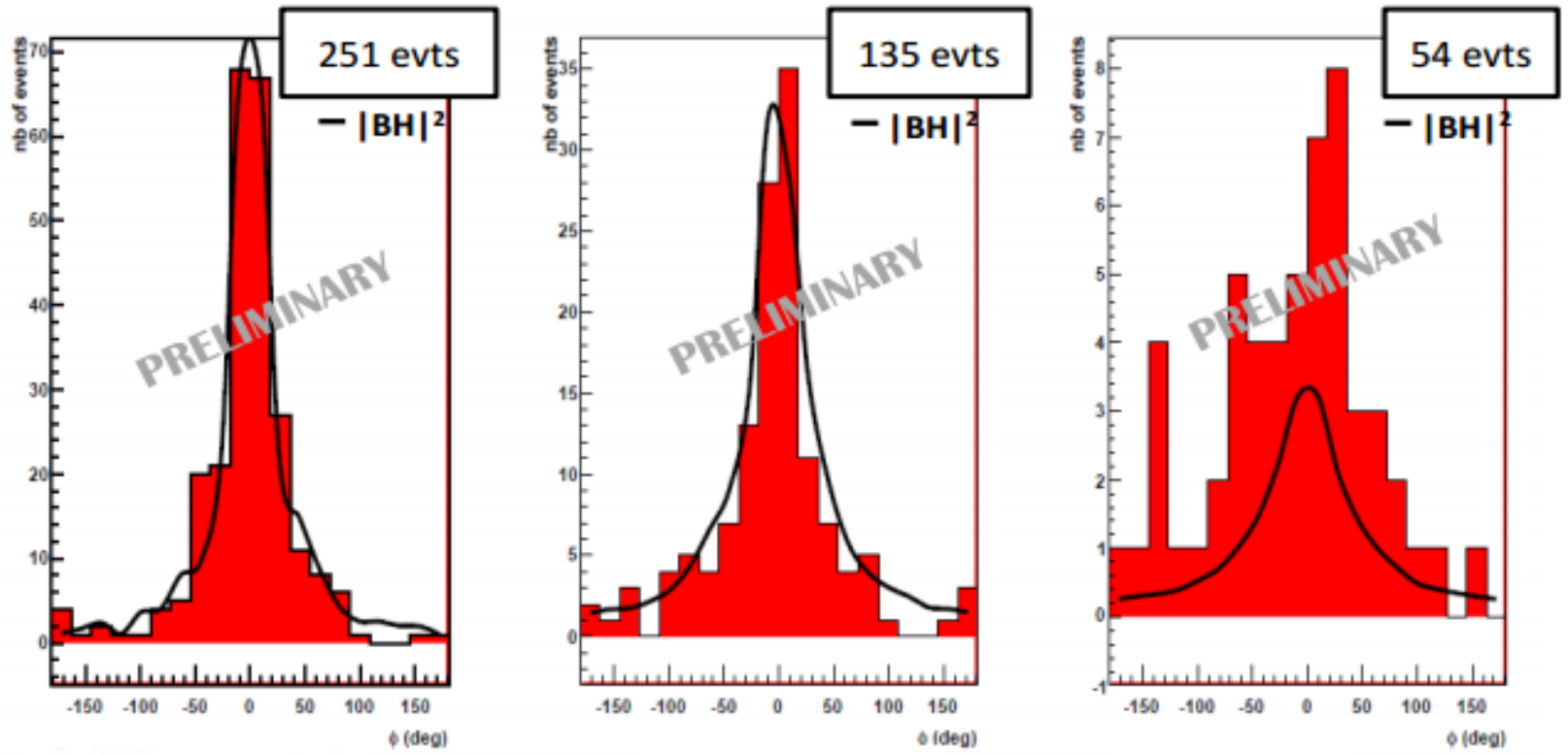
2008 test run 1.5 day

- observation of exclusive single photon production
- confirmed global efficiency ε = 10% assumed in simulations

2009 test run 10 days

- observation of DVCS and BH

$0.005 < x_{Bj} < 0.01$ $0.01 < x_{Bj} < 0.03$ $0.03 > x_{Bj}$



- BH prediction normalized to low x_{Bj} bin
- Excess in high x_{Bj} bin is an indication of DVCS

The cross section formula for exclusive meson production

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\phi_S}$$

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

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

$$-S_L\left[\varepsilon\sin(2\phi)\,\mathrm{Im}\,\sigma_{+-}^{++}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

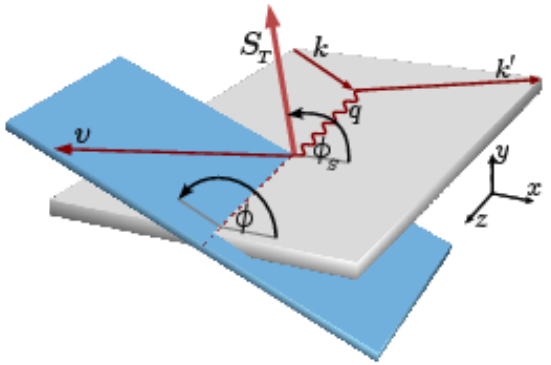
$$+S_LP_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

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

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

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

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



σ_{mn}^{ij}: spin-dependent photoabsorption cross section or interference terms

$$\sigma_{mn}^{ij}\left(x_B,Q^2,t\right)\propto\sum_{spins}\left(A_m^i\right)^*A_n^j$$

A_m^i: amplitude for subprocess $\gamma^*\,p\rightarrow V\,p'$ with photon helicity *m* and target proton helicity *i*

$$\epsilon=\frac{1-y-\frac{1}{4}y^2\gamma^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2}$$

$$\gamma=2x_{Bj}M_p/Q$$

Access to GPDs through exclusive meson production

For vector mesons:

$$\frac{1}{\Gamma'}\frac{d\sigma_{00}^{++}}{dt} = (1-\xi^2)|\mathcal{H}_M|^2 - \left(\xi^2 + \frac{t}{4M_p^2}\right)|\mathcal{E}_M|^2 - 2\xi^2 Re(\mathcal{E}_M^* \mathcal{H}_M)$$

unpolarized cross section

$$\sigma_0 = \frac{1}{2}\left(\sigma_{++}^{++} + \sigma_{++}^{--}\right) + \epsilon\sigma_{00}^{++} \equiv \sigma_T + \epsilon\sigma_L$$

$$\frac{1}{\Gamma'} Im\frac{d\sigma_{00}^{+-}}{dt} = -\sqrt{1-\xi^2}\frac{\sqrt{t_0 - t}}{M_p} Im(\mathcal{E}_M^* \mathcal{H}_M)$$

transverse target spin asymmetry

$$A_{UT}^{\sin(\varphi-\varphi_s)} = -\frac{Im\left(\sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-}\right)}{\sigma_0}$$

where:

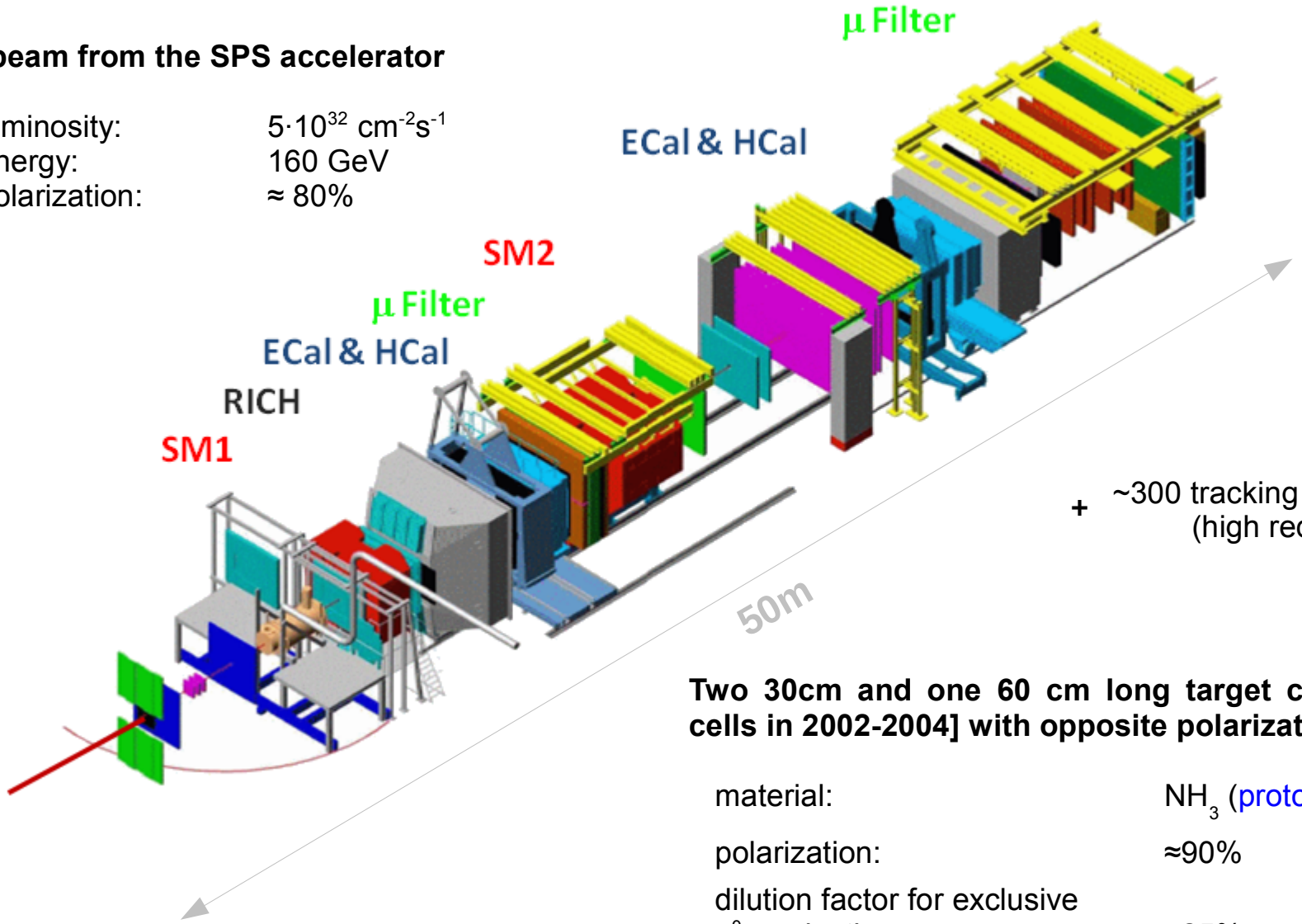
$\mathcal{H}_M, \mathcal{E}_M$ are convolutions of the GPDs $H^{q,g}, E^{q,g}$ with hard scattering kernel and meson DA

$$\Gamma' = \frac{\alpha_{em}}{Q^6}\frac{x_B^2}{1-x_B} \qquad -t_0 = \frac{4\xi^2 M_P^2}{1-\xi^2} \qquad \xi \approx \frac{x_B}{2-x_B}$$

COMPASS experiment at CERN – setup with transversely polarized target

μ^+ beam from the SPS accelerator

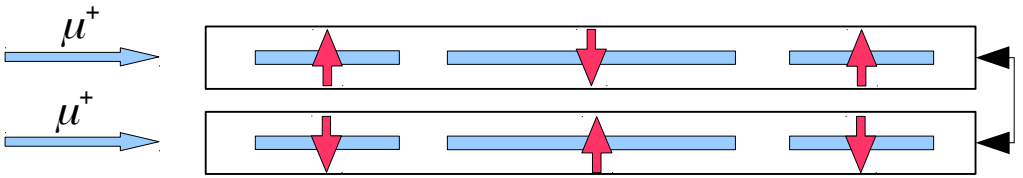
luminosity:	$5 \cdot 10^{32}$ cm^{-2}s^{-1}
energy:	160 GeV
polarization:	≈ 80%



+ ~300 tracking detector planes (high redundancy)

Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization

material:	NH_3 (protons)	[^{6}LiD (deuterons)]
polarization:	≈90%	[≈50%]
dilution factor for exclusive ρ^0 production:	≈25%	[≈44%]



Microwave reversal every week

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

$$\mu N \rightarrow \mu N \rho^0 \quad (\rho^0 \rightarrow \pi^+ + \pi^-)$$

Used data:

2003 – 2004 (deuterons)
2007, 2010 (protons)
} *for transverse target polarization*

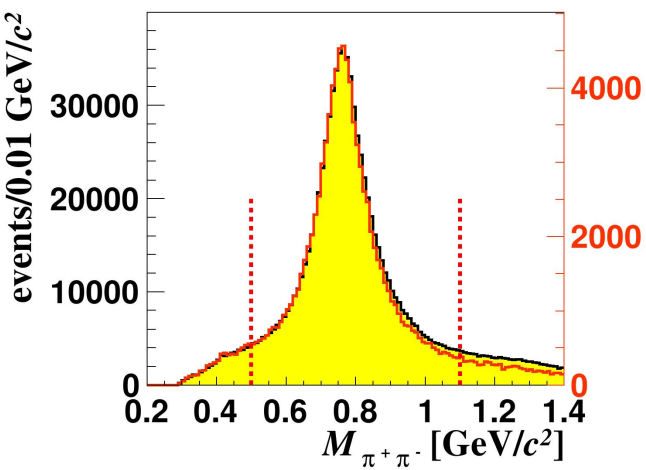
Topology:

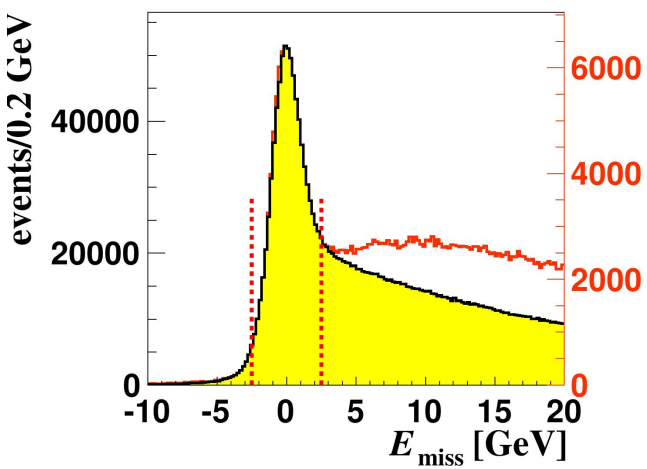
only incoming and outgoing muon tracks,
two hadron tracks of opposite charges in PV

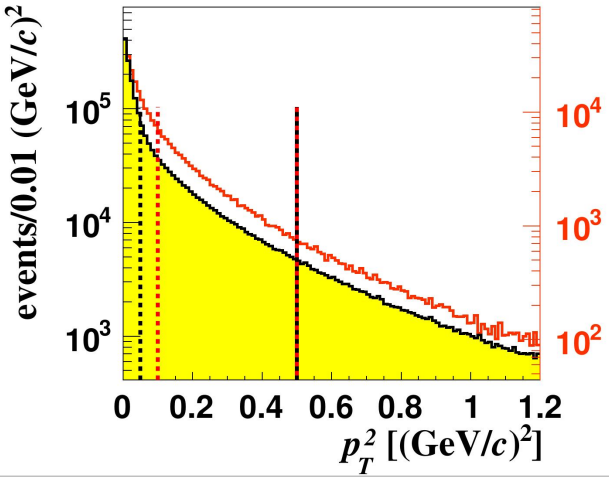
Kinematics domain:

- $Q^2 > 1$ (GeV/c)^2
- $W > 5$ GeV
- $0.1 < y < 0.9$
- $0.003 < x_{Bj} < 0.35$

proton data (~797 000 events) — deuteron data (~97 000 events)







Invariant mass

Pion mass is assumed for each outgoing hadron track

$$0.5 < M_{\pi\pi} < 1.1\ GeV/c^2$$

Missing energy

Check if the proton is intact

$$E_{miss} = \frac{M_x^2 - M_p^2}{2M_p} \in (-2.5,\ 2.5)\ GeV$$

$E_{miss} = 0$ is the signature of exclusivity

Squared transverse momentum of ρ^0 candidate w.r.t. γ^*

To remove coherent production off target nuclei

$0.05 < p_t^2\ (GeV/c)^2$ *for protons*

$0.01 < p_t^2\ (GeV/c)^2$ *for deuterons*

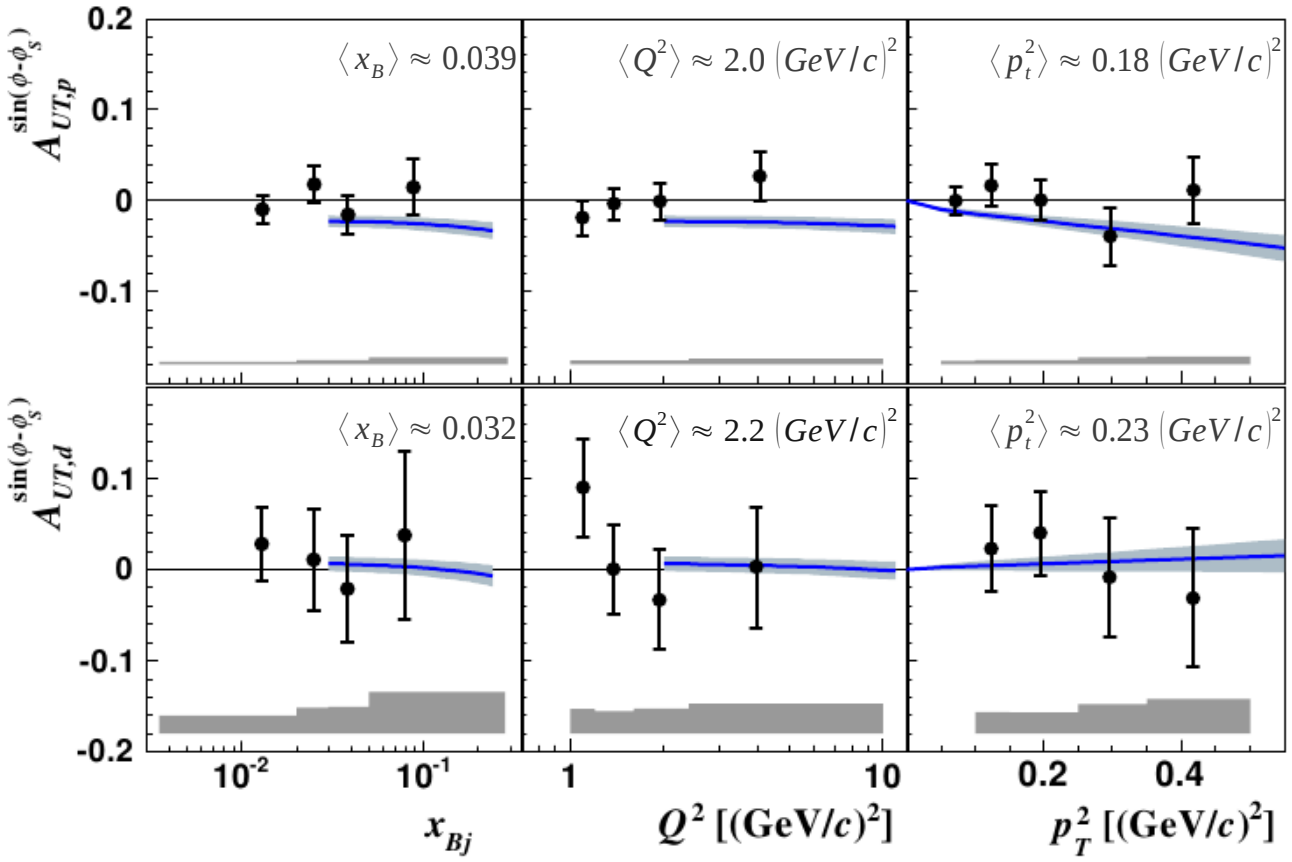
To suppress non-exclusive background

$p_t^2 < 0.5\ (GeV/c)^2$

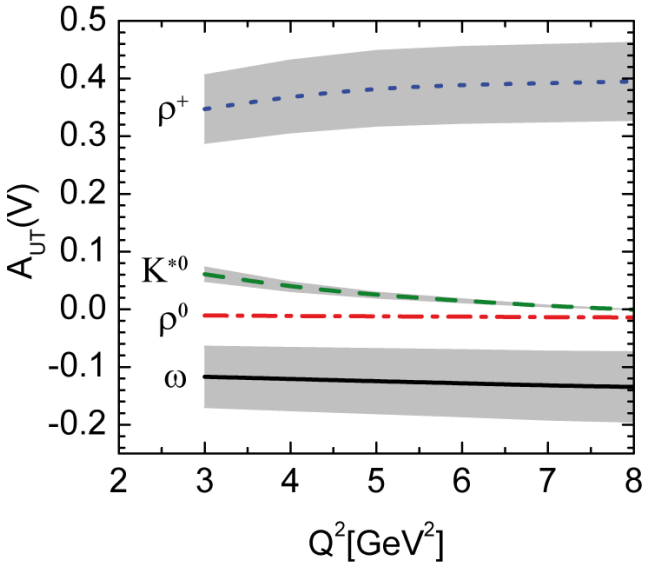
Asymmetry extracted for each kinematic bin from a fit of the number of signal events (i.e. after correction for SIDIS background) in azimuthal angle bins for each of the target cell and polarization state (+,-)

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

COMPASS results
(*Nucl. Phys. B 865 1*)



Goloskokov and Kroll
(*Eur. Phys. J. C 59 4 (2009)*)



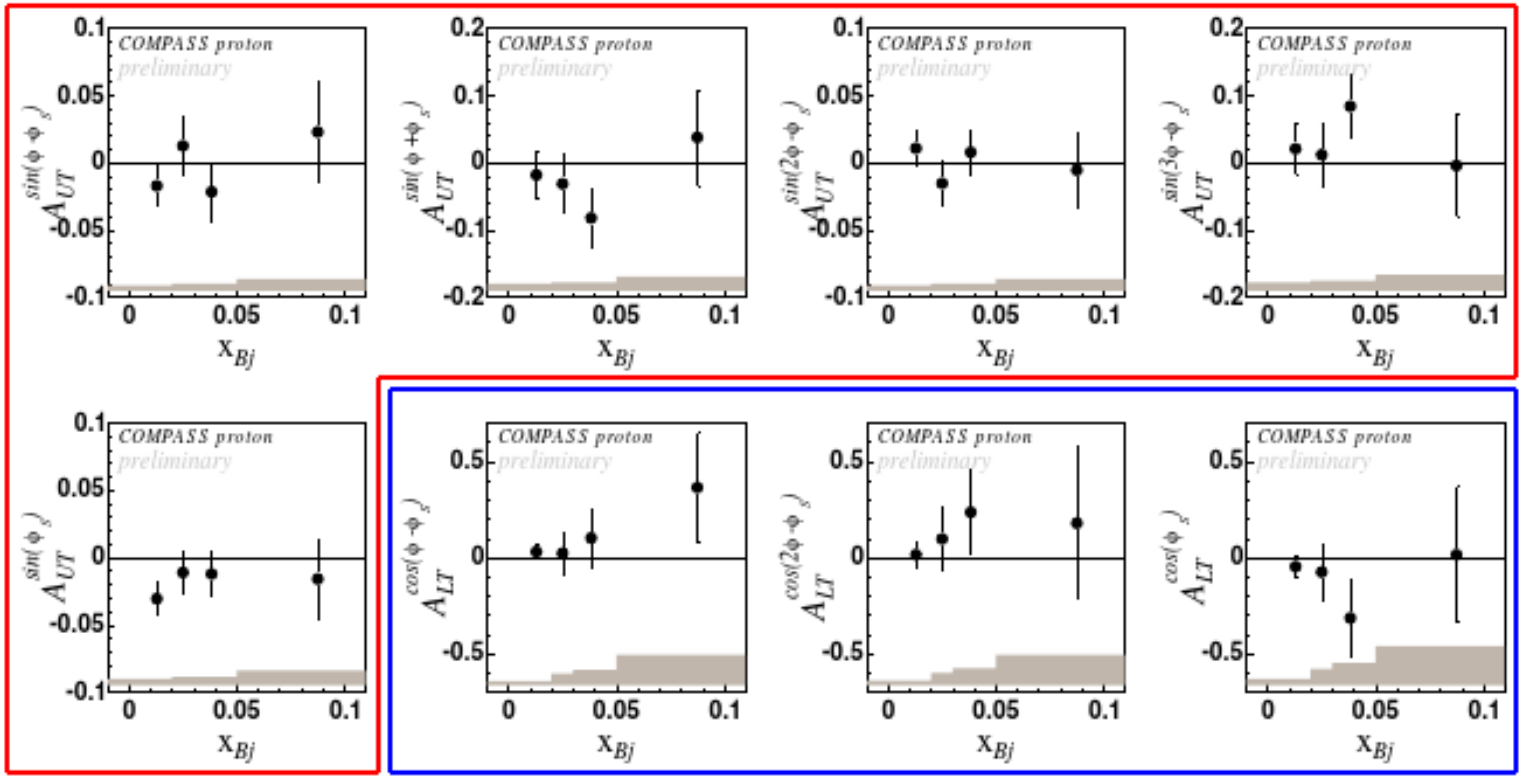
- "handbag model"
- GPDs constrained by CTEQ6 parametrization and nucleon form factors
- power corrections due to transverse quarks momenta
- predictions both for γ^*_L and γ^*_T

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

Transverse target spin asymmetry for incoherent exclusive ρ⁰ production

- New results for 5 transverse target spin asymmetries and 3 transverse target double spin asymmetries for proton target

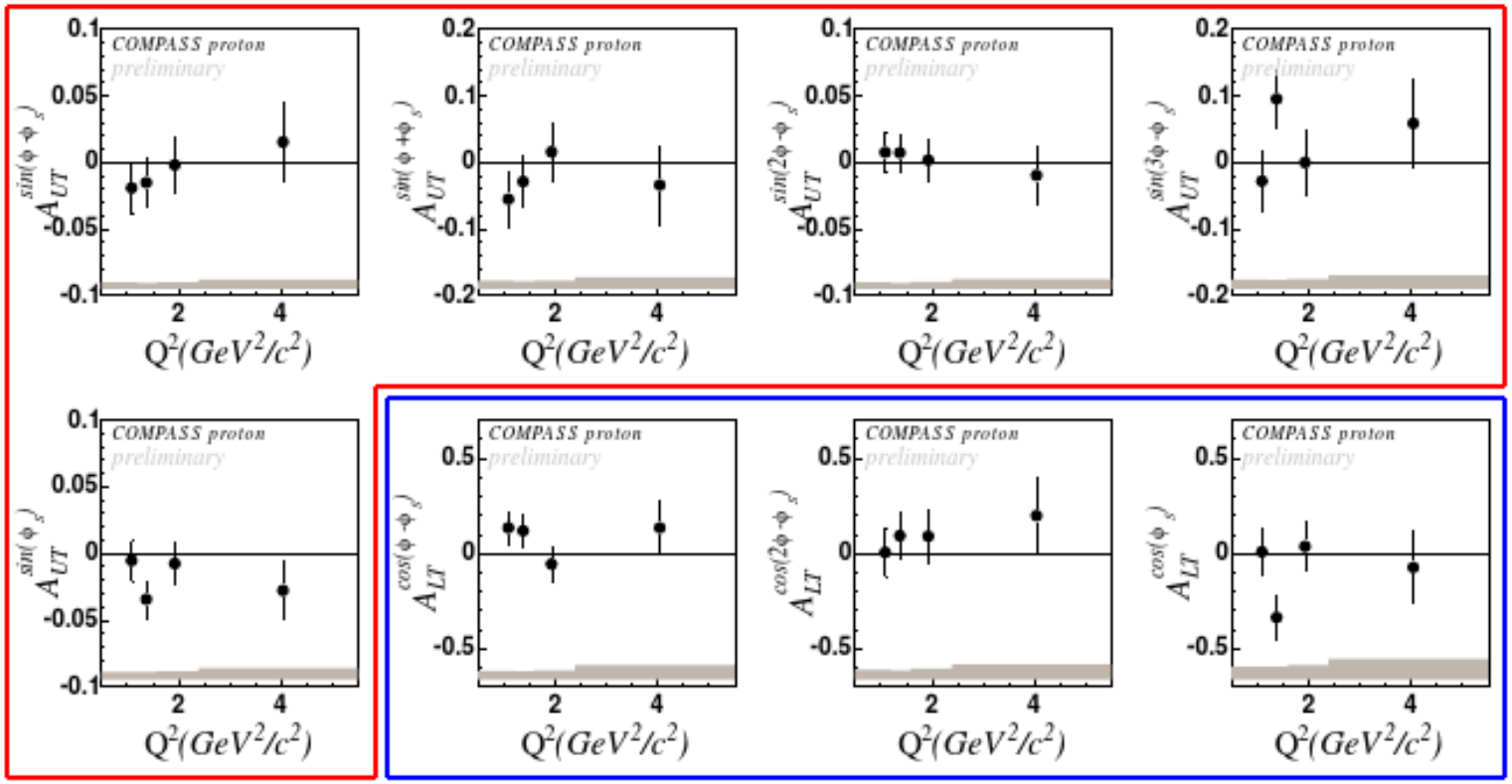
as a function of x_{Bj}



Transverse target spin asymmetry for incoherent exclusive ρ⁰ production

- New results for 5 transverse target spin asymmetries and 3 transverse target double spin asymmetries for proton target

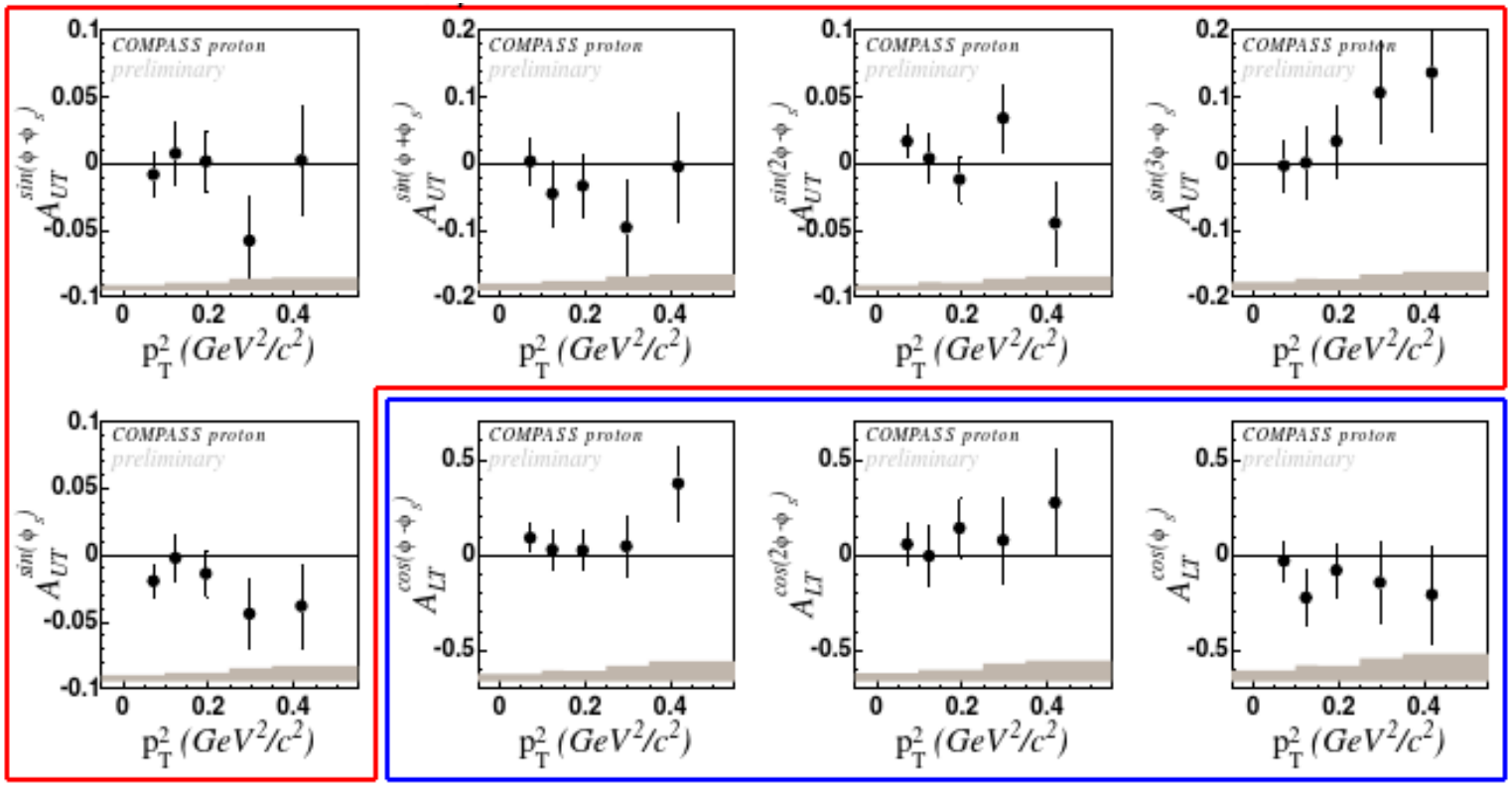
as a function of Q^2



Transverse target spin asymmetry for incoherent exclusive ρ⁰ production

- New results for 5 transverse target spin asymmetries and 3 transverse target double spin asymmetries for proton target

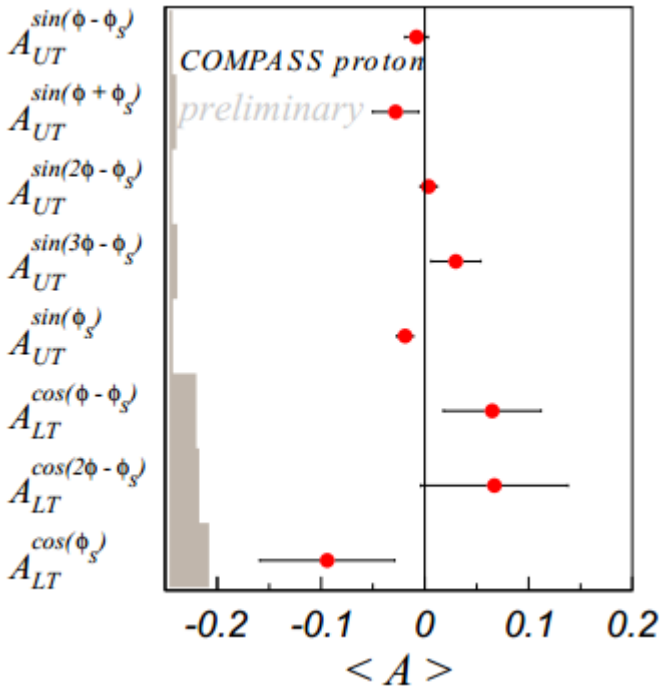
as a function of p_T^2



Transverse target spin asymmetry for incoherent exclusive ρ⁰ production

- All asymmetries small, compatible with 0, except
- $A_{UT}^{\sin(\varphi_S)} = -0.019 \pm 0.008 \pm 0.003$

integrated



Future GPD program at COMPASS-II

Stage 1 - proposal approved by CERN

2012 pion and kaon polarisabilities (Primakoff) + commissioning and short data taking for GPD program (with LH + RPD)

2013 long SPS shutdown

2014-2015 Drell-Yann measurement with transversely polarized protons (NH_3 target) → Stefano, Monday's talk

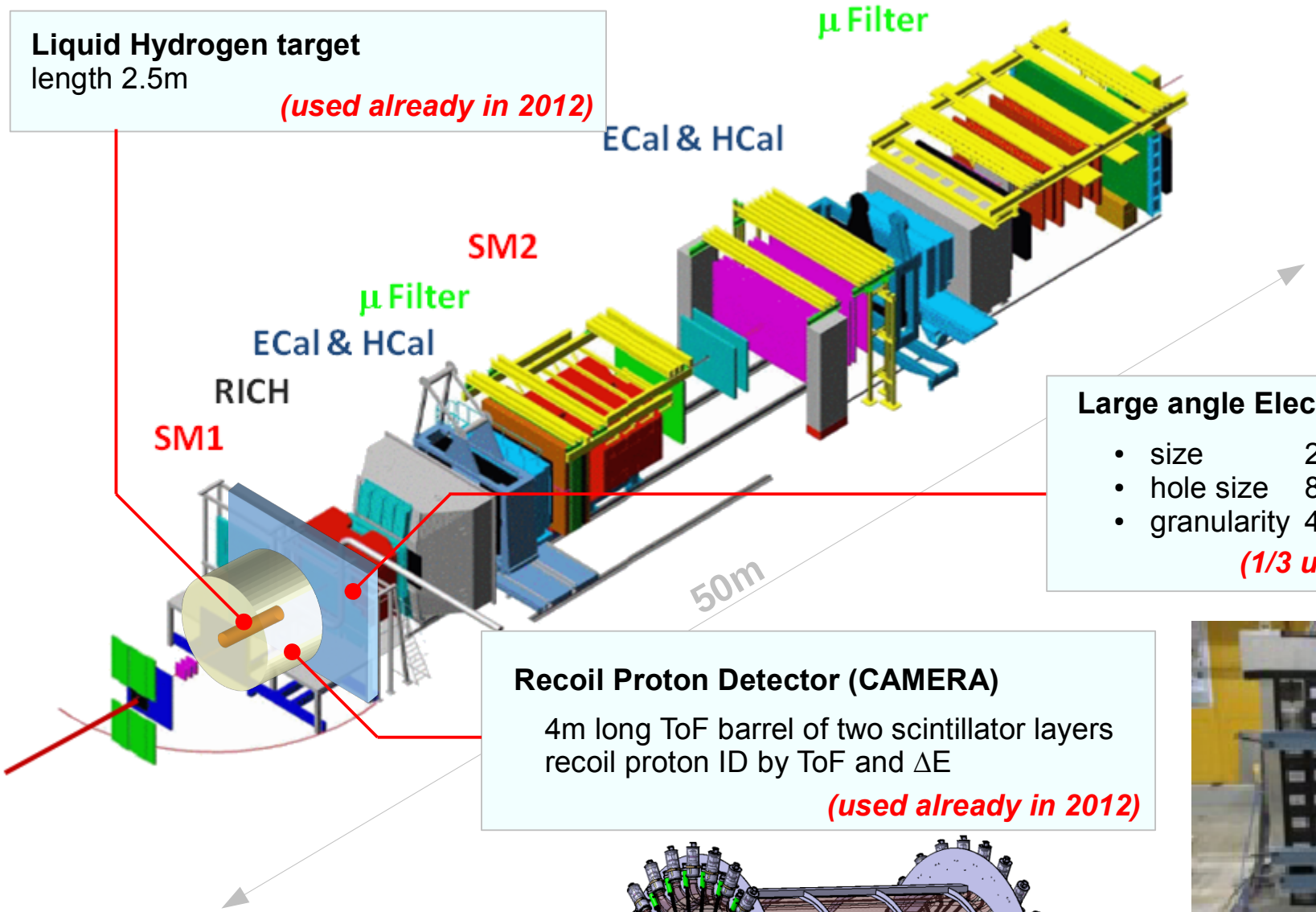
2016-2017 GPD + SIDIS (with LH + RPD)

Stage 2 - subject of addendum to the proposal

> 2017
- additional year of Drell-Yann measurement
- GPD with transversely polarized target (NH_3) and RPD
- hadron spectroscopy

Future GPD program at COMPASS-II – experimental setup

Liquid Hydrogen target
length 2.5m
(used already in 2012)



Large angle Electromagnetic Calorimeter

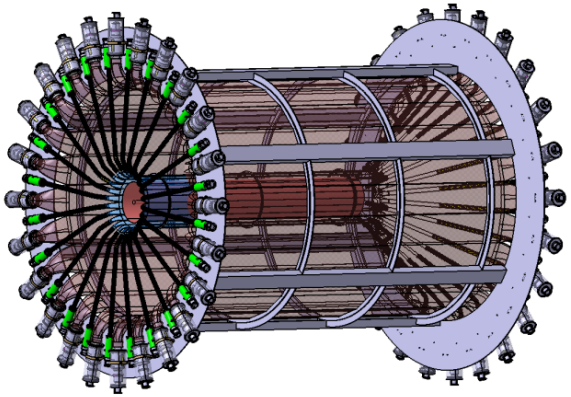
- size 204cm x 204cm x 34cm
- hole size 84cm x 60cm
- granularity 4cm x 4cm

(1/3 used already in 2012)

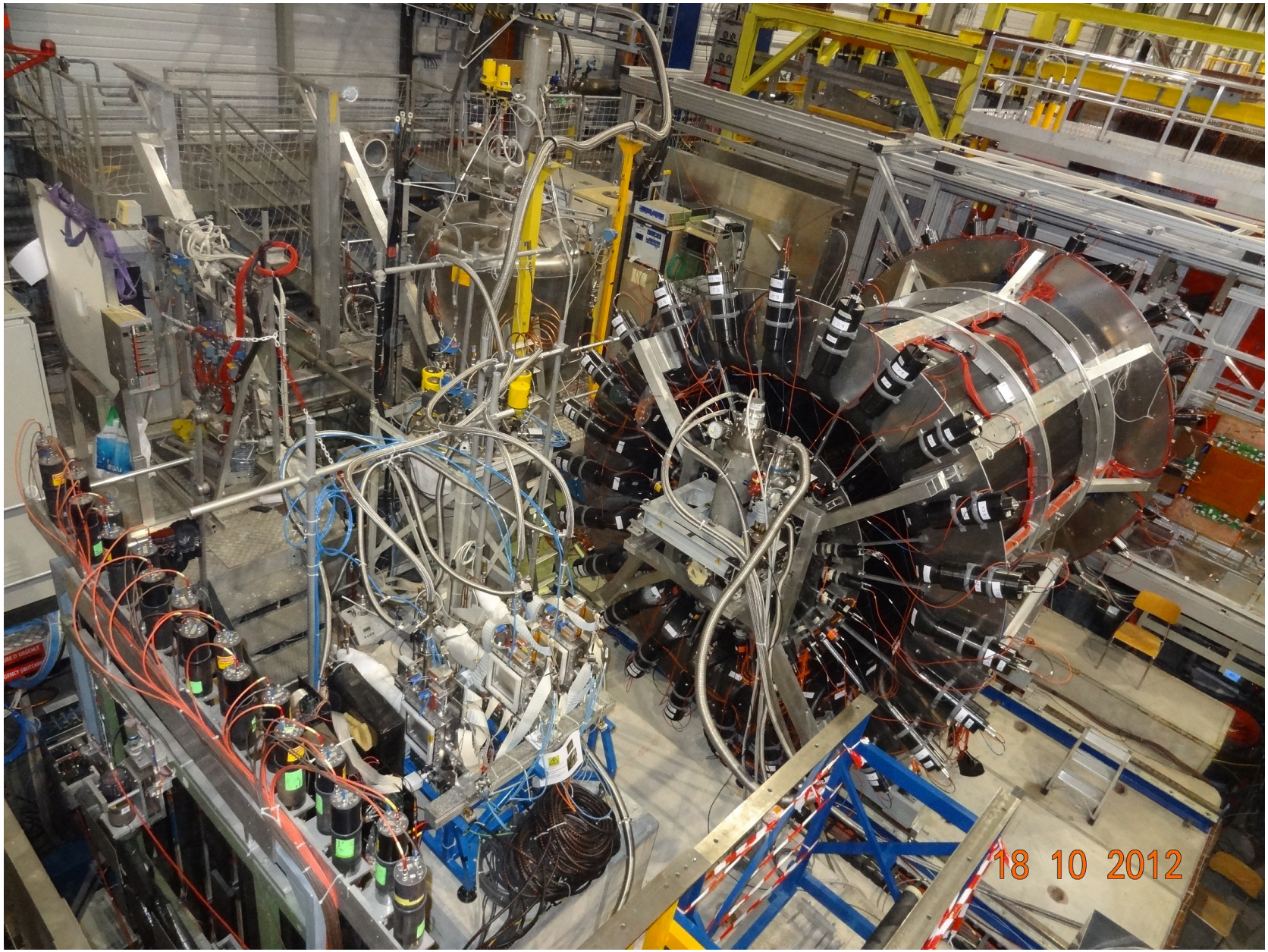
Recoil Proton Detector (CAMERA)

4m long ToF barrel of two scintillator layers
recoil proton ID by ToF and ΔE

(used already in 2012)



Target area during 2012 DVCS data taking



Measurement of t-slope for DVCS production

sensitive to transverse size of nucleon

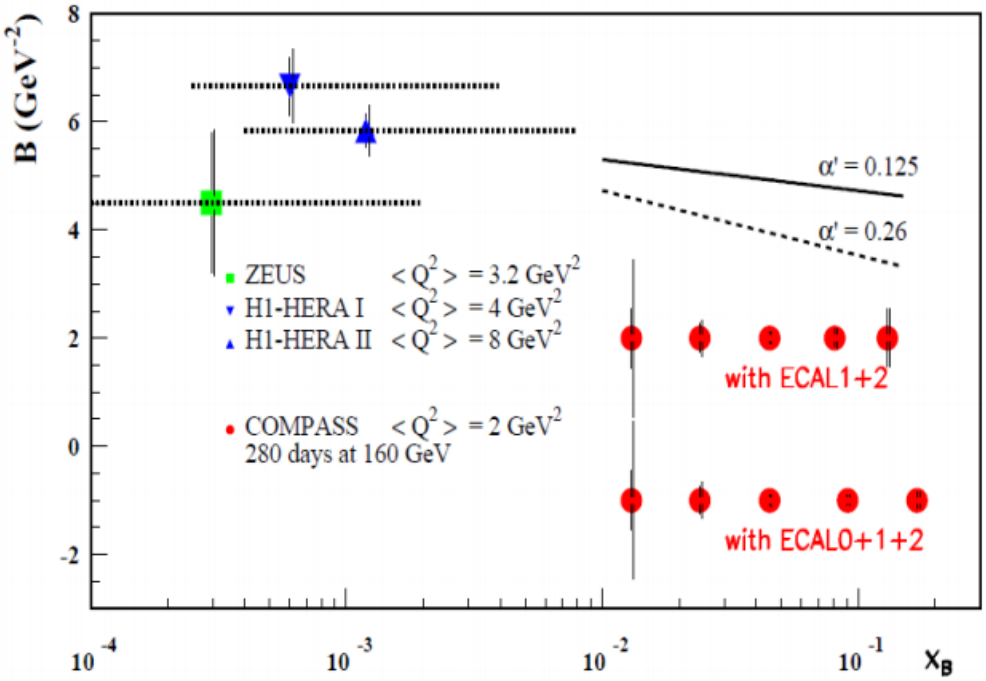
$$\frac{d\sigma}{dt} \sim \exp\left(-b|t|\right)$$

$$b(x_{Bj}) \approx \frac{1}{2}\left\langle r_{\perp}^{2}(x_{Bj})\right\rangle$$

Assumptions for simulations

- 160 GeV muon beam
- global efficiency ε = 10%
- L = 1.2 nb^{-1} (2 years of data taking)

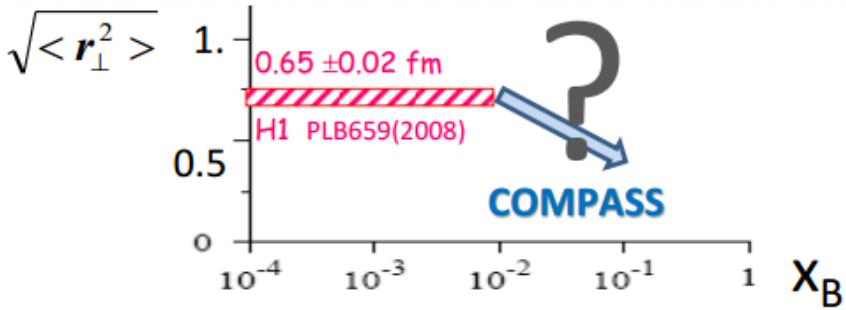
1/10 statistics expected in 2012 pilot run



ansatz at small x_{Bj}:

$b(x_{Bj}) = b_0 + 2\,\alpha' \ln(x_0/x_{Bj})$

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

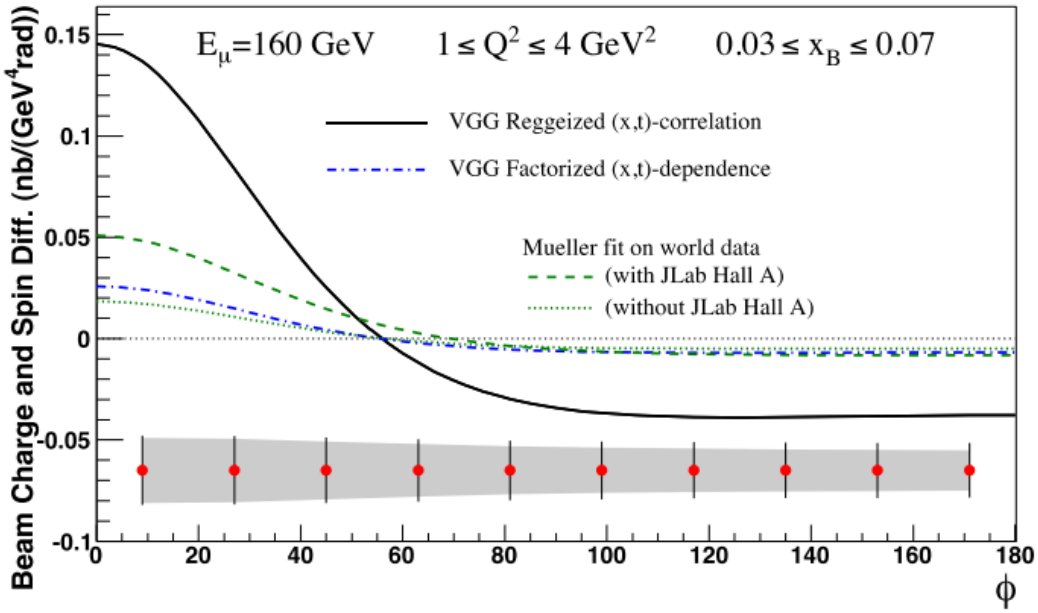


Measurement of difference of cross section for single photon production

$$D_{CU,U} = d\sigma^{+-} - d\sigma^{-+} = 2\left(P_\mu \, d\sigma_{pol}^{DVCS} + e_\mu \, a^{BH} \, ReT^{DVCS}\right)$$

$$s_1^{DVCS} \sin\varphi \qquad c_0^{int} + c_1^{int}\cos\varphi + c_2^{int}\cos 2\varphi + c_3^{int}\cos 3\varphi$$

$$Re\left(F_1 \mathcal{H}\right)$$



Systematic error: 3% charge dependent effect between μ^+ and μ^-

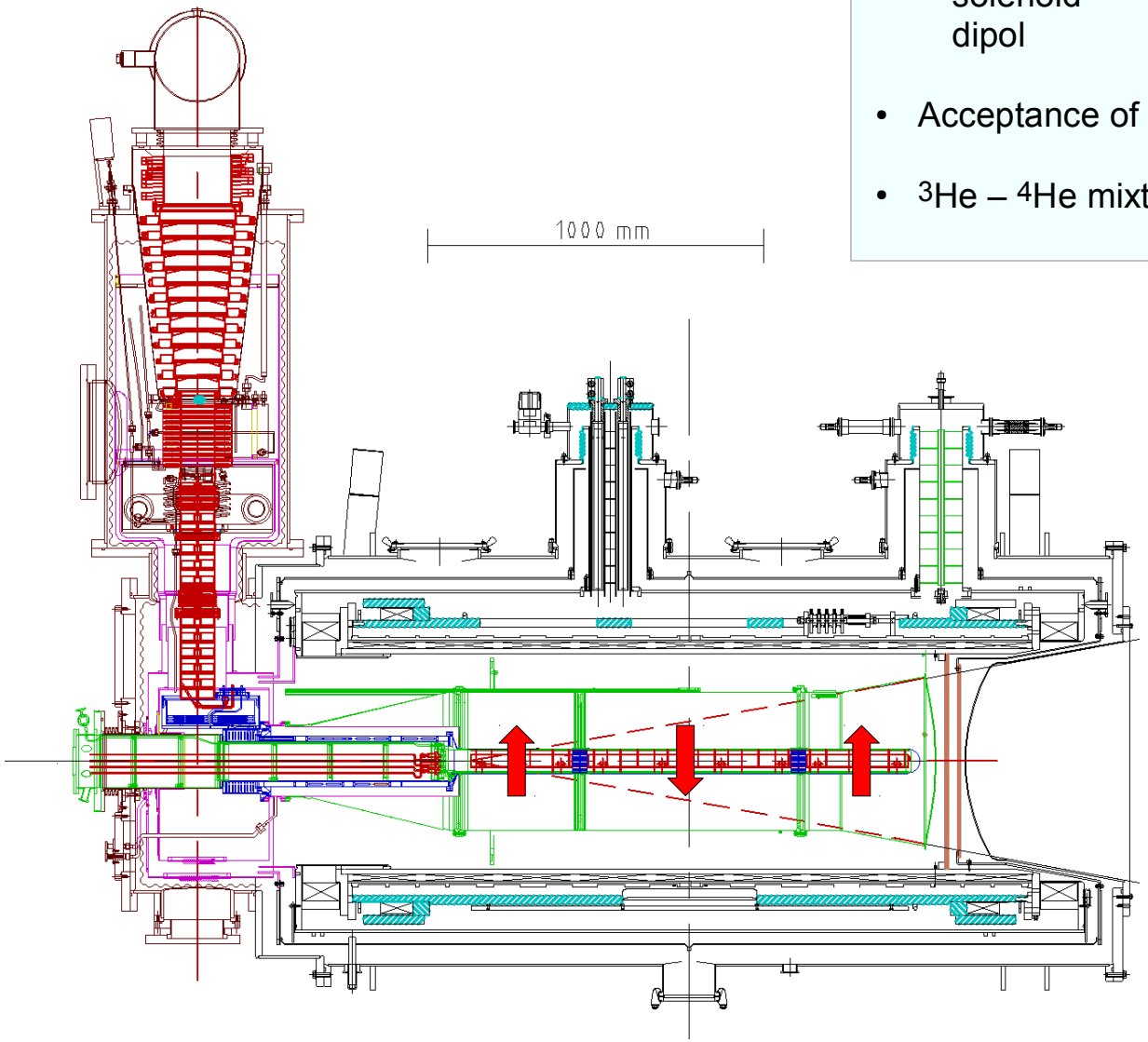
Summary and outlook

- COMPASS is unique to probe GPDs due to covered kinematic region of intermediate x_{Bj} and availability of beams of two charges and polarizations
- COMPASS has proved feasibility to measure DVCS process
- Exclusive meson production → complementary measurement to DVCS, flavor separation for GPDs
- Transverse target spin asymmetries for exclusive ρ^0 production was measured both for protons and deuterons, asymmetries are small, compatible with 0,except

$$A_{UT}^{\sin(\varphi_S)} = -0.019 \pm 0.008 \pm 0.003$$

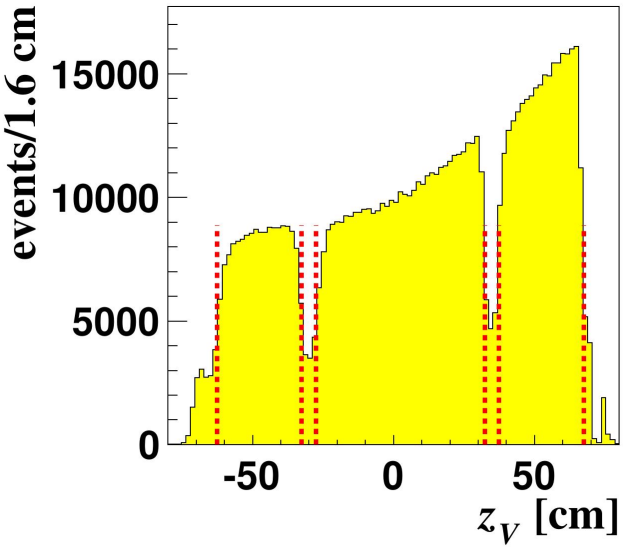
- In progress measurement for ϕ and ω
- GPD program is continued at COMPASS-II

COMPASS polarized target



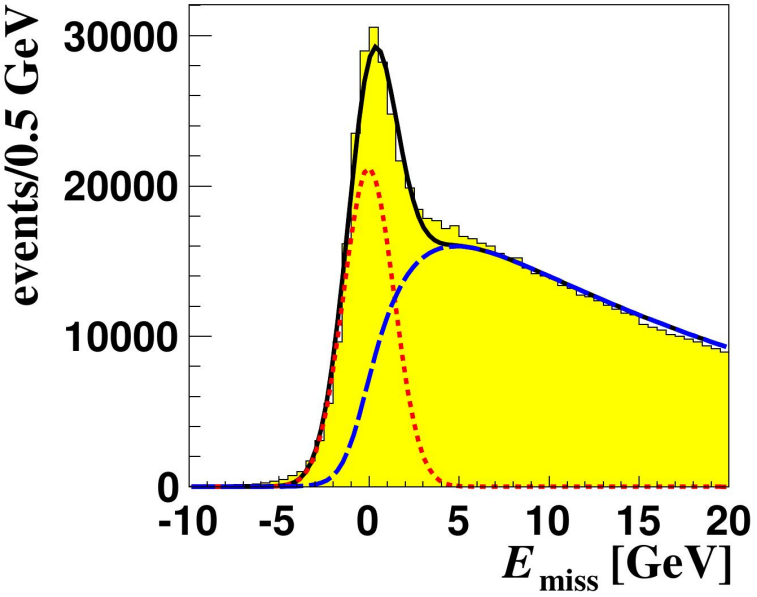
- 3 target cells with opposite polarization
- 2 magnets to hold and rotate polarization
  solenoid 2.5T
  dipol 0.5T
- Acceptance of ±180 mrad for upstream edge
- ^{3}He – ^{4}He mixture used to refrigerate (T~50mK)

position of PV along the beam direction for incoherent exclusive ρ^0 production



Transverse target spin asymmetry for incoherent exclusive ρ^0 production – bkg rejection

For every kinematic bin, bin of φ-φ_s, target cell and polarization state:



shape of semi-inclusive background from MC
(lepto with COMPASS tuning + simulation of spectrometer response + data reconstruction)

MC weighted using agreement between real data and MC for wrong charge combination sample ($h^+h^+ + h^-h^-$)

$$w(E_{miss}) = \frac{N_{MC}^{h+h+}(E_{miss}) + N_{MC}^{h-h-}(E_{miss})}{N_{RD}^{h+h+}(E_{miss}) + N_{RD}^{h-h-}(E_{miss})}$$

Normalization of MC to the real data using two component fit
Gaussian function (signal) + shape from MC (bkg)

Measurement of t-slope for exclusive ρ^0 production

sensitive to transverse size of nucleon – meson system
(*at large Q^2 mostly sensitive to transverse size of nucleon* $r_\perp$)

- Q^2 and ν parametrization of cross section from NMC data normalized to Goloskokov and Krol predictions
- 160 GeV muon beam
- global efficiency ε = 10%
- L = 1.2 nb^{-1} (2 years of data taking)

1/40 statistics expected in 2012 pilot

$$\frac{d\sigma}{dt} \sim \exp(-b|t|)$$

$$b(x_{Bj}) \approx \frac{1}{2}\left\langle r_\perp^2(x_{Bj})\right\rangle$$