Exclusive meson production at COMPASS

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on behalf of the COMPASS experiment

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Outline

- Theoretical framework (GPD formalism)
- COMPASS experiment
- Transverse target spin asymmetry for incoherent exclusive ρ^0 production
- Exclusive π^0 production
- GPDs at COMPASS-II
- Summary and outlook

GPD formalism

GPDs (Generalized Parton Distributions):

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

where:

x: average longitudinal momentum fraction of the parton

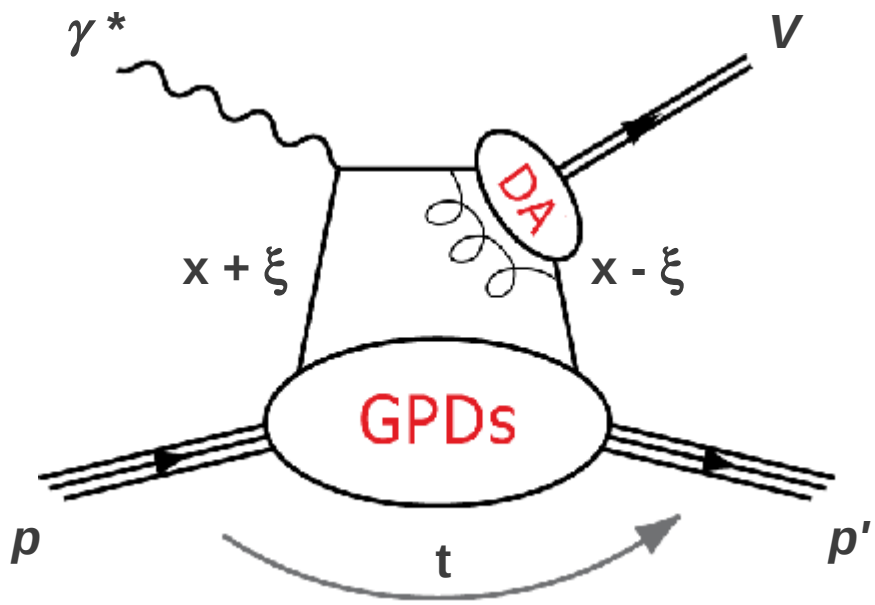
2ξ: longitudinal momentum fraction transferred by the parton

$$\xi \approx \frac{x_{Bj}}{2 - x_{Bj}}$$

t: squared momentum transferred to the target nucleon

Deeply Virtual Meson Production

$\gamma^* p \rightarrow V p'$



(factorization strictly proven only for longitudinal γ^*)

Dependence of meson production on different GPDs:

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

- *DVMP can be used as quark flavor filter*
- *contribution from gluons at the same order of α_s as from quarks*

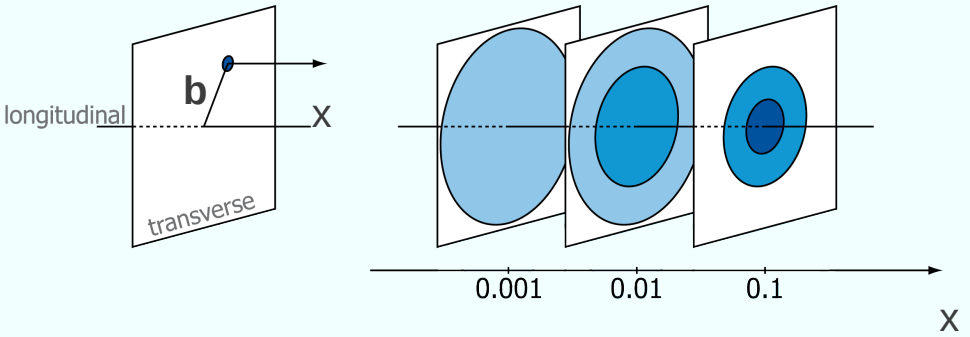
Nucleon tomography:

3D parton distribution function:

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

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*

Cross-section for exclusive meson production (only relevant elements are shown):

$$\left[\frac{\alpha}{8\pi^3}\frac{y^2}{1-\epsilon}\frac{1-x_{Bj}}{x_{Bj}}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}\,dQ^2\,dt\,d\phi\,d\phi_s}\simeq\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\epsilon\,\sigma_{00}^{++}-S_T\,Im\left(\sigma_{++}^{+-}+\epsilon\,\sigma_{00}^{+-}\right)\sin\left(\phi-\phi_s\right)+\ldots$$

$$\simeq\sigma_0\cdot\left(1+S_T\,A_{UT}^{\sin(\phi-\phi_s)}\sin\left(\phi-\phi_s\right)\right)+\ldots$$

where:

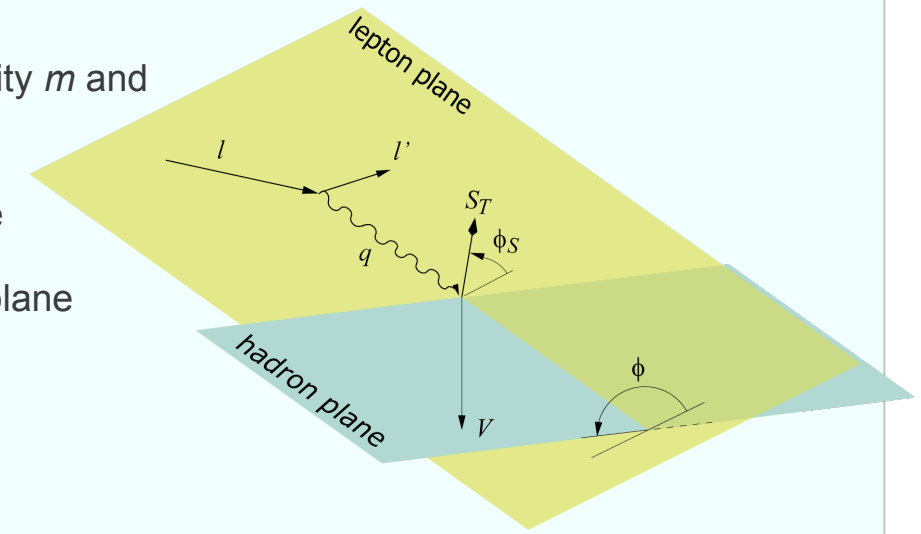
σ_{mn}^{ij}: spin-dependent photoabsorption cross section or interference terms

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

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

ϕ: azimuthal angle between lepton plane and hadron plane

ϕ_s: azimuthal angle between target spin vector and lepton plane



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

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

$$\epsilon=\left(1-y-\frac{1}{4}y^2\gamma^2\right)/\left(1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2\right)$$

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

For vector mesons:

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

unpolarized cross section

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

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

transverse target spin asymmetry

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

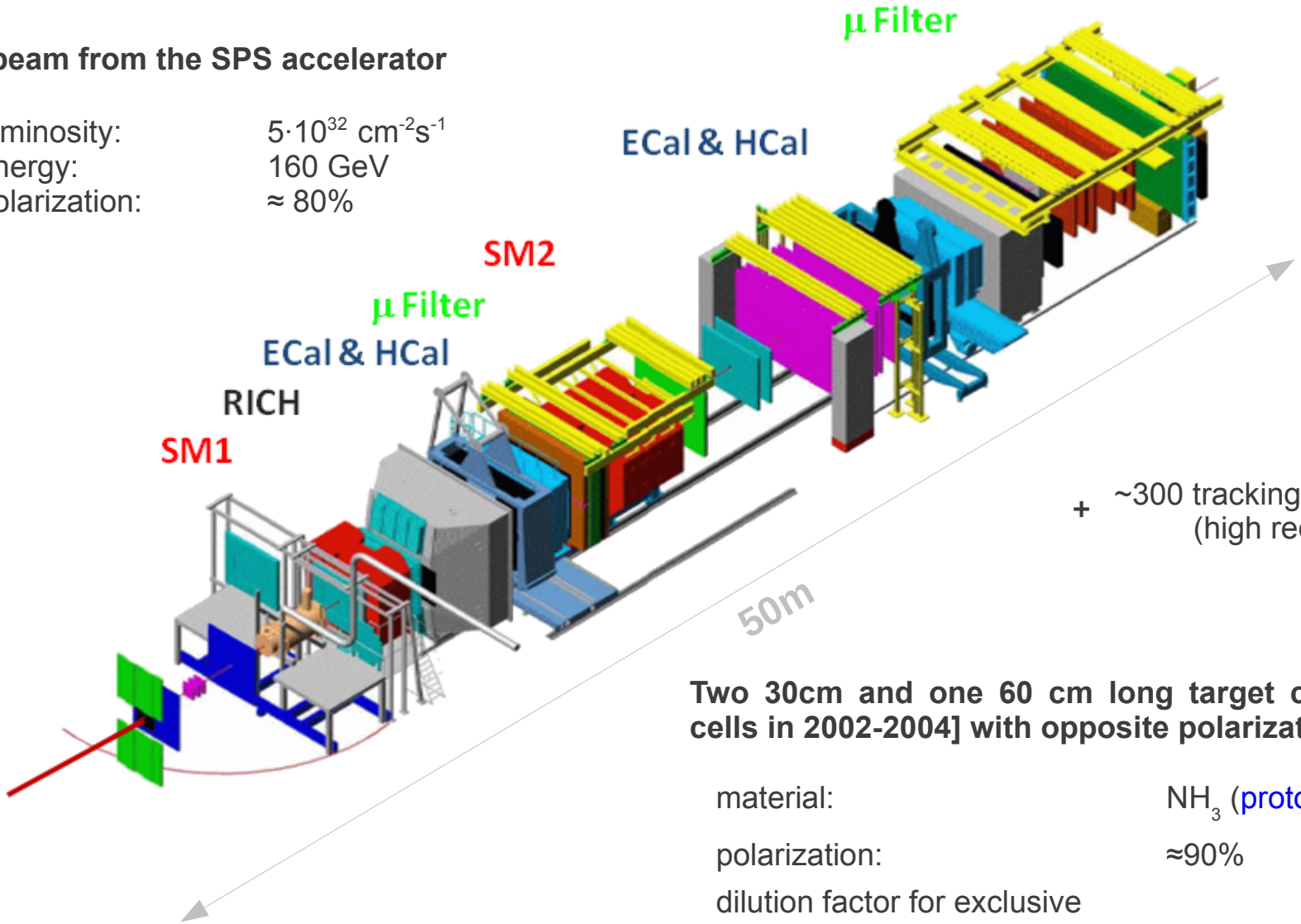
where:

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

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

μ^+ beam from the SPS accelerator

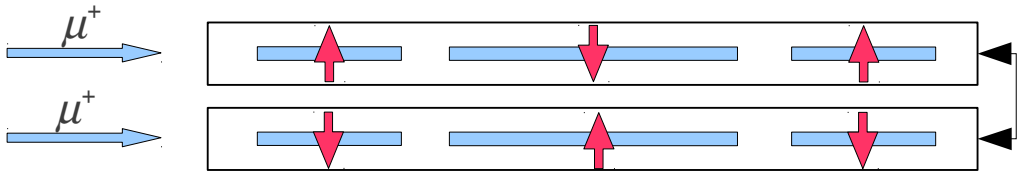
luminosity:	$5 \cdot 10^{32}$ cm^{-2}s^{-1}
energy:	160 GeV
polarization:	≈ 80%



\+ ~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

$$\mu N \to \mu N \rho^0 \quad \rho^0 \to \pi^+ + \pi^-$$

Used data:

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

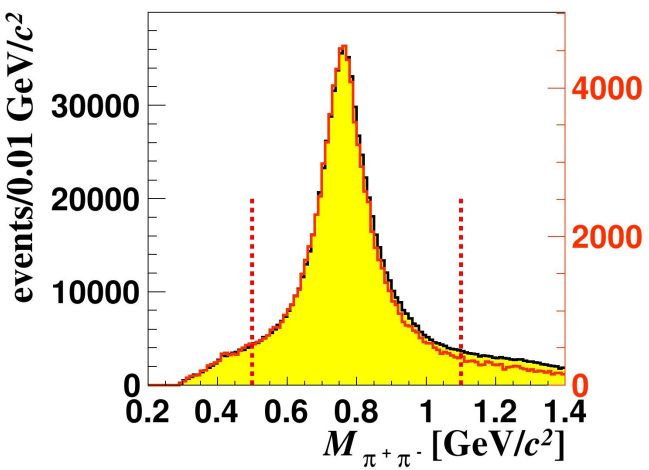
Topology:

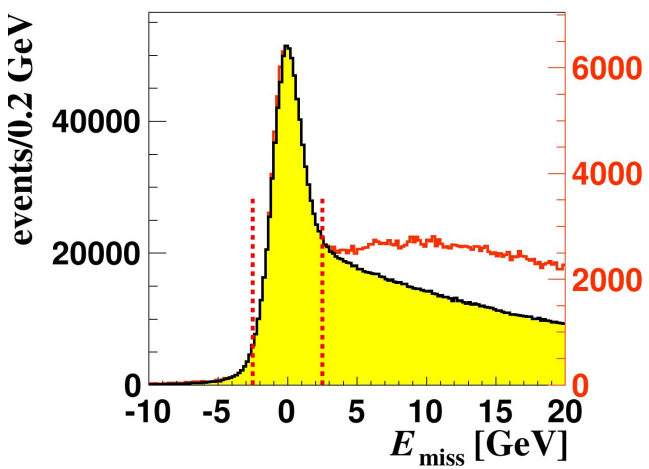
only incoming and outgoing muon tracks,
two hadron tracks of opposite charges in PV

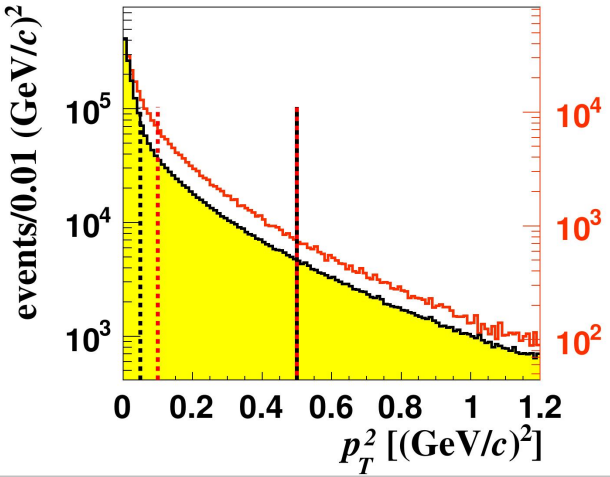
Kinematics domain:

- $Q^2 > 1$ (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*

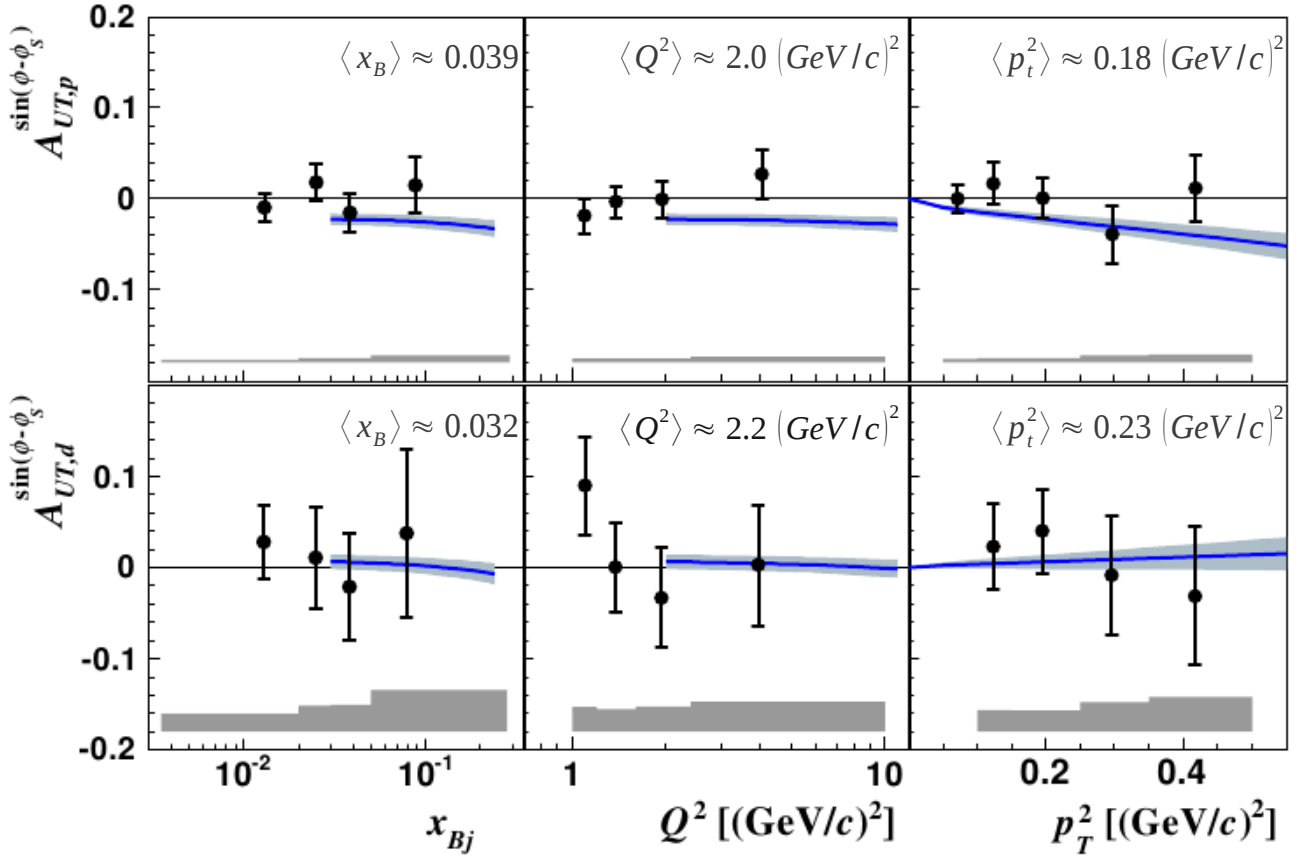
To suppress non-exclusive background

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

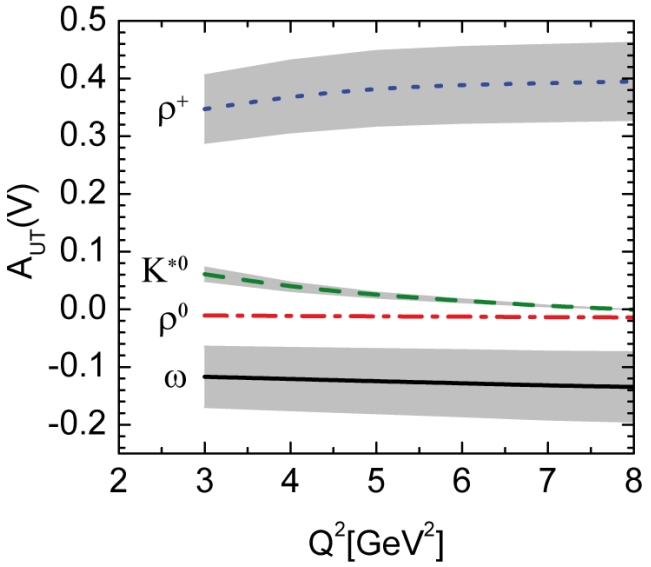
Asymmetry extracted for each kinematic bin from a fit of the number of signal events (i.e. after correction for SIDIS background) in 12 bins of ϕ-ϕ_S for each of the two target cells and polarization state (+,-)

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

COMPASS results
(*Nucl. Phys. B 865 1 (2012)*)



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
- reasonable agreement with predictions of the GPD model of Goloskokov - Kroll
- 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

Exclusive π^0 production

$$\mu N \rightarrow \mu N \pi^0 \hookrightarrow \gamma + \gamma$$

Used data:

2009 DVCS test run with 40cm LH target and

1m Recoil Proton Detector

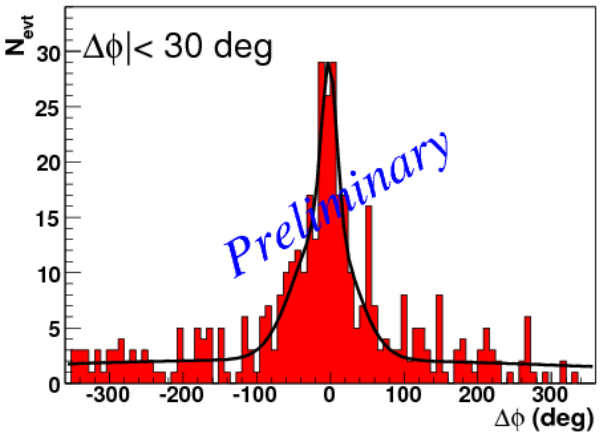
Topology:

only incoming and outgoing muon tracks in PV +

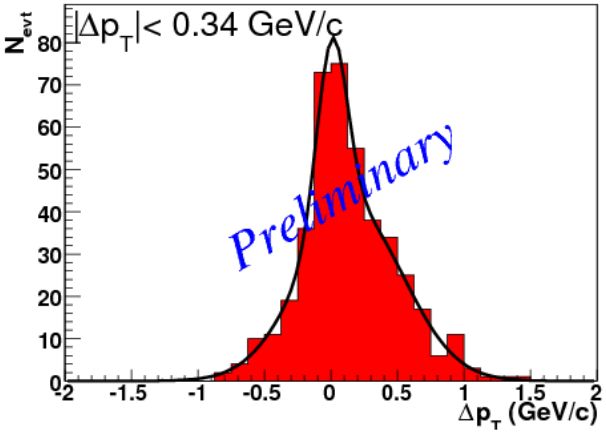
only two photons in first ECAL with E > 5GeV

- $Q^2 > 1$ GeV

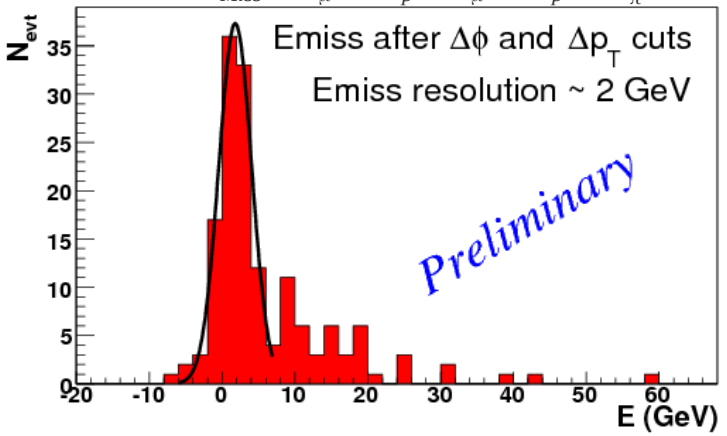
$\Delta\phi = \phi_{Miss} - \phi_{RPD}$

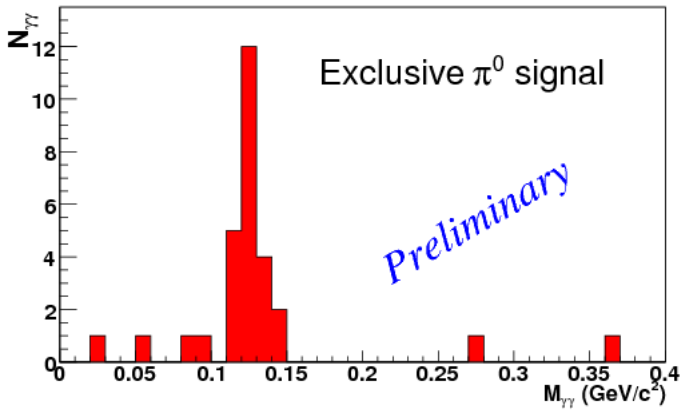


$\Delta p_T = p_{T\,Miss} - p_{T\,RPD}$



$E_{Miss} = E_\mu + M_p - E_{\mu'} - E_{p'} - E_{\pi^0}$





23 exclusive π^0 events (more than expected)

Production sensitive to GPDs $\tilde{H}$, $\tilde{E}$ and H_T, E_T

In progress calculation of cross section

Future GPD program at COMPASS-II

Stage 1 - proposal approved by CERN

- 2012 pion and kaon polarisabilities (Primakoff) + commissioning and test for GPD program (with LH + RPD)
- 2013 long SPS shutdown
- 2014 Drell-Yann measurement with transversely polarized protons (NH_3 target)
- 2015-2016 GPD + SIDIS (with LH + RPD)

Stage 2 - subject of addendum to the proposal

- > 2016 additional year of Drell-Yann measurement
- > 2016 GPD with transversely polarized target (NH_3) and RPD
- > 2016 hadron spectroscopy

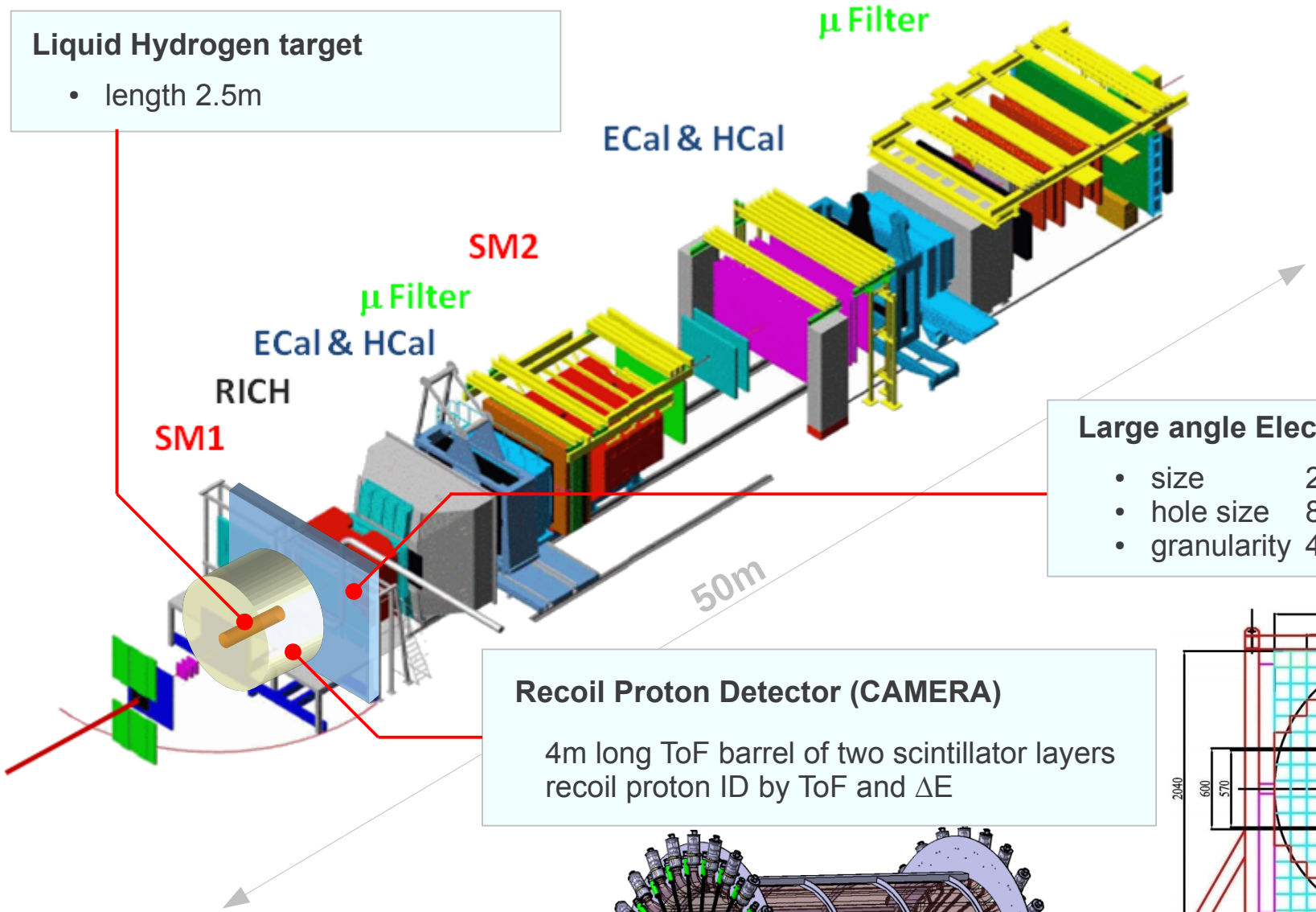
The GPD program at COMPASS will explore intermediate x_{Bj} (0.01-0.10) and large Q^2 (up to ~15 GeV^2) range

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 charge

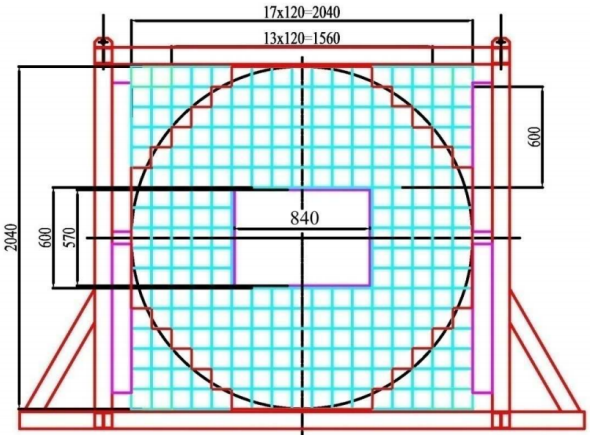
Liquid Hydrogen target

- length 2.5m



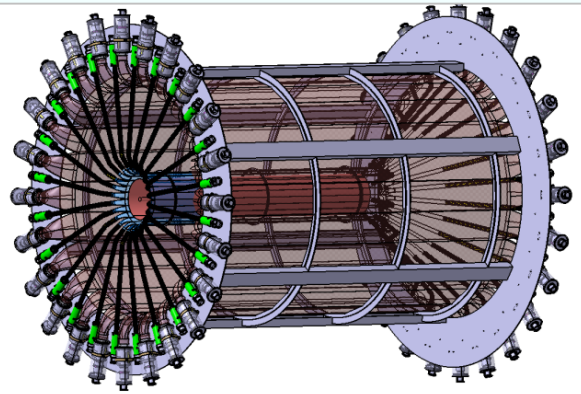
Large angle Electromagnetic Calorimeter

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



Recoil Proton Detector (CAMERA)

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



Measurement of t-slope for exclusive ρ^0 production

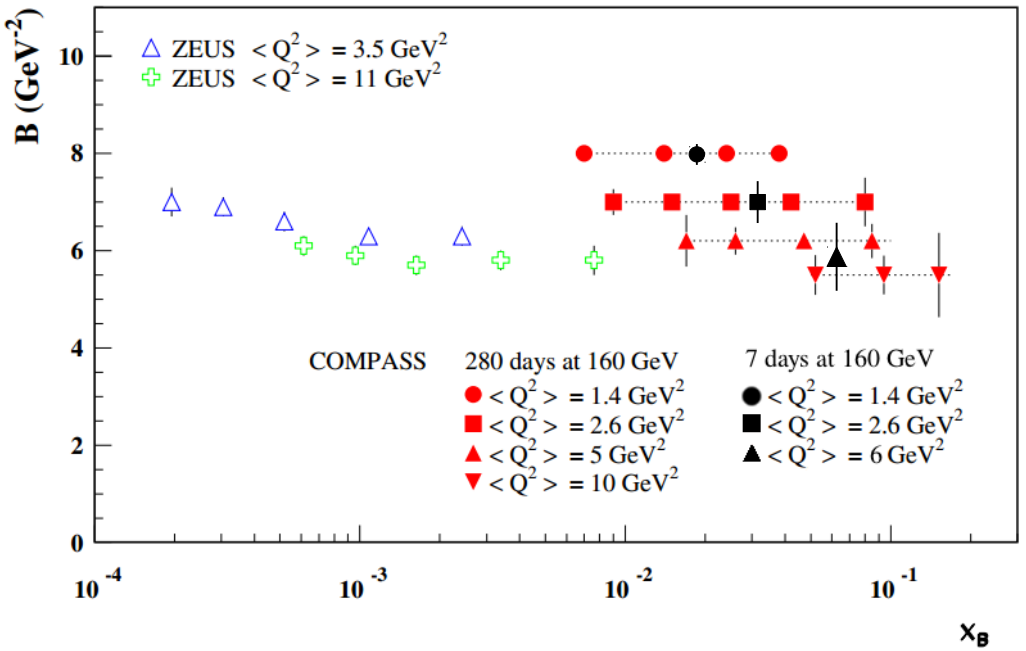
sensitive to transverse size of nucleon – meson system
(*at large Q^2 mostly sensitive to transverse size of nucleon* $r_\perp$)

- 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

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

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



Summary and outlook

- Exclusive meson production → flavor separation for GPDs

- Transverse target spin asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ for exclusive ρ^0 production was measured both for protons and deuterons
- Asymmetries are small, compatible with 0
- Results compatible with HERMES experiment and with GPD predictions by S. V. Goloskokov and P. Kroll
- In progress measurement for ϕ and ω

- Exclusive π^0 production has been observed
- Production sensitive to GPDs $\tilde{H}$, $\tilde{E}$ and H_T, E_T
- In progress calculation of cross section

- GPD program will be continued at COMPASS-II
- Data taking in 2012 (pilot) and 2015-2016 with LH target, RPD and new ECAL
- Example of foreseen results → t-slope for exclusive ρ^0 production
- Measurement with transversely polarized target (NH_3) with RPD is considered

General formula for cross-section including beam and target polarization

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

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

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

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

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

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

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

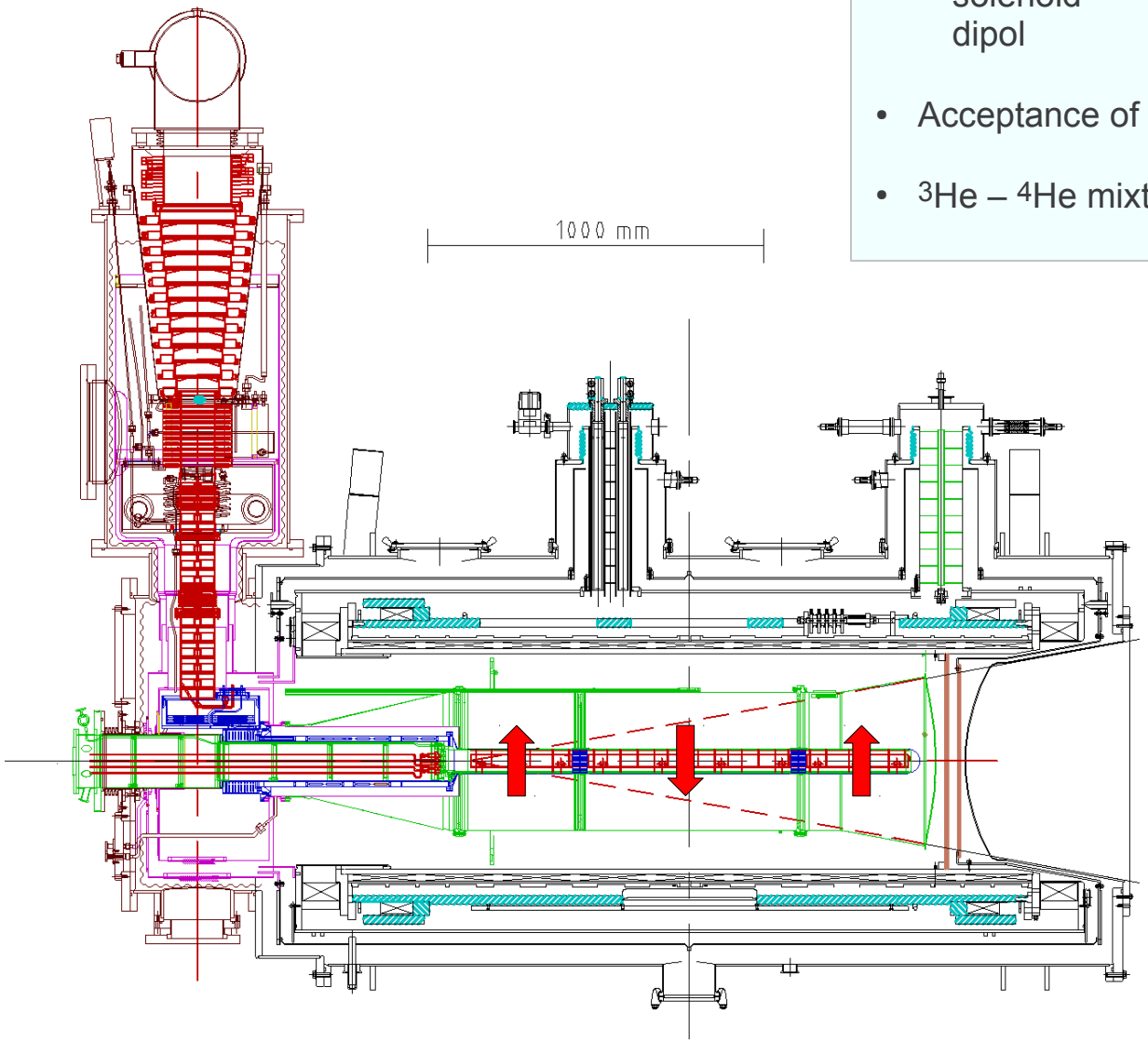
$$+S_TP_\ell\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}\right.$$

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

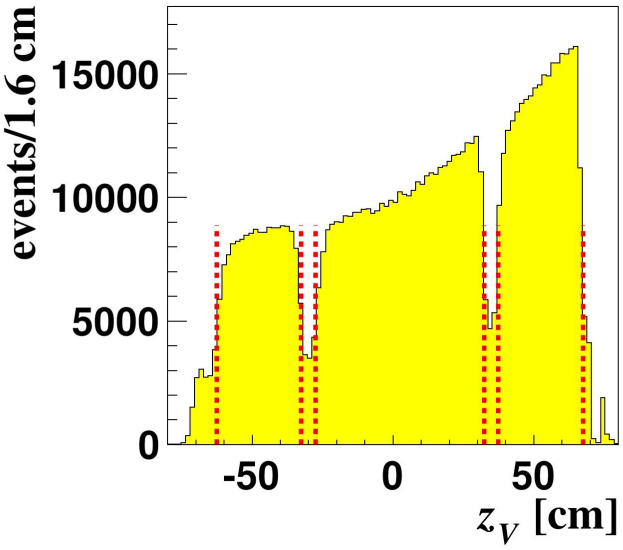
$$\epsilon=\frac{1-y-\frac{1}{4}y^2\gamma^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2}\qquad \gamma=2x_{Bj}M_P/Q$$

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)

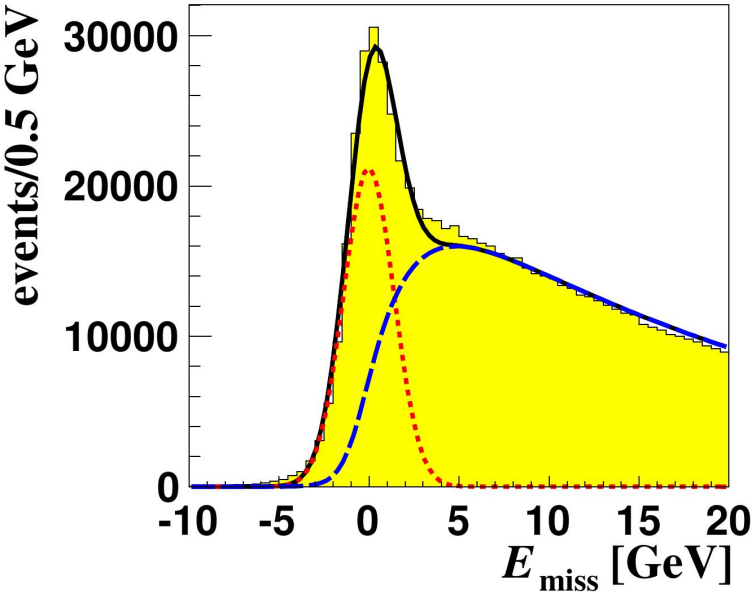


position of PV along the beam direction for incoherent exclusive ρ^0 production



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)