Exclusive meson production at COMPASS

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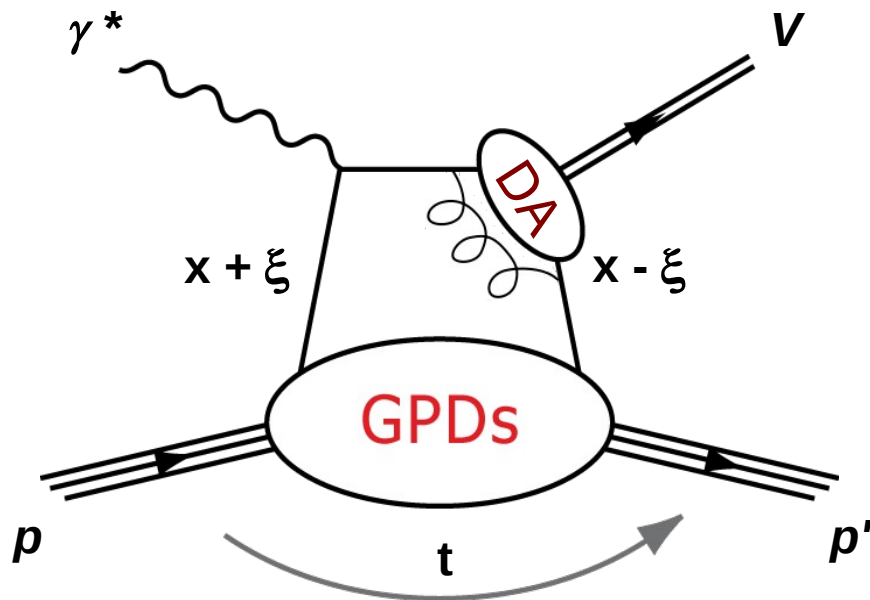*National Centre for Nuclear Research, Warsaw*

on behalf of the COMPASS Collaboration

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects
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Outline

- GPD formalism

- COMPASS experiment

- Transverse target spin asymmetries for incoherent exclusive ρ^0 production

- Projections for COMPASS-II

- Summary and outlook

GPD formalism

Hard Exclusive Meson Production
$$\gamma^* p \to V p'$$

collinear factorization strictly proven only for
longitudinal γ^*

Chiral-even GPDs
helicity of parton unchanged

$$H^{q,g}(x,\xi,t) \qquad E^{q,g}(x,\xi,t)$$
$$\widetilde{H}^{q,g}(x,\xi,t) \qquad \widetilde{E}^{q,g}(x,\xi,t)$$

Chiral-odd GPDs (*not accessed in DVCS*)
helicity of parton changed

$$H_T^{q,g}(x,\xi,t) \qquad E_T^{q,g}(x,\xi,t)$$
$$\widetilde{H}_T^{q,g}(x,\xi,t) \qquad \widetilde{E}_T^{q,g}(x,\xi,t)$$

Flavour separation for GPDs
example:

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

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

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

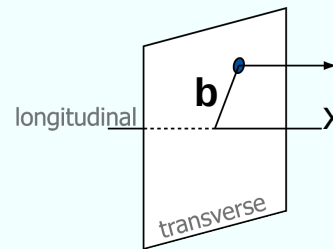- contribution from gluons at the same order of α_s as from quarks

GPD formalism – highlights

Nucleon tomography:　　　　　　　　　　　　　　　　*(unpolarized target, COMPASS-II)*

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

longitudinal　**b**　x

transverse

0.001　　0.01　　0.1

x

Total angular momentum:　　　　　　　　　　　　　　　*(polarized target, COMPASS)*

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

The cross section formula for exclusive meson production

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

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

$$
\quad - P_\ell\,\sqrt{\varepsilon(1-\varepsilon)}\,\sin\phi\,\text{Im}\,(\sigma^{++}_{+0} + \sigma^{--}_{+0})
$$

$$
\quad - S_L\left[\varepsilon\sin(2\phi)\,\text{Im}\,\sigma^{++}_{+-} + \sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi\,\text{Im}\,(\sigma^{++}_{+0} - \sigma^{--}_{+0})\right]
$$

$$
\quad + S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma^{++}_{++} - \sigma^{--}_{++}\right) - \sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\text{Re}\,(\sigma^{++}_{+0} - \sigma^{--}_{+0})\right]
$$

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

$$
\quad \left. + \sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\text{Im}\,\sigma^{+-}_{+0} + \sqrt{\varepsilon(1+\varepsilon)}\,\sin(2\phi - \phi_S)\,\text{Im}\,\sigma^{-+}_{+0}\right]
$$

$$
\quad + S_T P_\ell\left[\sqrt{1-\varepsilon^2}\,\cos(\phi - \phi_S)\,\text{Re}\,\sigma^{+-}_{++}\right.
$$

$$
\quad \left. - \sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\text{Re}\,\sigma^{+-}_{+0} - \sqrt{\varepsilon(1-\varepsilon)}\,\cos(2\phi - \phi_S)\,\text{Re}\,\sigma^{-+}_{+0}\right].
$$

σ^{ij}_{mn}: spin-dependent photoabsorption cross section or interference term

$$
\sigma^{ij}_{mn}\left(x_B, Q^2, t\right) \propto \sum \left(A^i_m\right)^* A^j_n
$$

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

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

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

5 transverse target spin asymmetries and 3 transverse target double spin asymmetries

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

$$A_{UT}^{\sin(\varphi+\varphi_s)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{+-}}{\sigma_0}$$

$$A_{UT}^{\sin(2\varphi-\varphi_s)} = -\frac{\mathrm{Im}\,\sigma_{+0}^{-+}}{\sigma_0}$$

$$A_{UT}^{\sin(3\varphi-\varphi_s)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{-+}}{\sigma_0}$$

$$A_{UT}^{\sin\varphi_s} = -\frac{\mathrm{Im}\,\sigma_{+0}^{+-}}{\sigma_0}$$

$$A_{LT}^{\cos(\varphi-\varphi_s)} = \frac{\mathrm{Re}\,\sigma_{++}^{+-}}{\sigma_0}$$

$$A_{LT}^{\cos\varphi_s} = -\frac{\mathrm{Re}\,\sigma_{+0}^{+-}}{\sigma_0}$$

$$A_{LT}^{\cos(2\varphi-\varphi_s)} = -\frac{\mathrm{Re}\,\sigma_{+0}^{-+}}{\sigma_0}$$
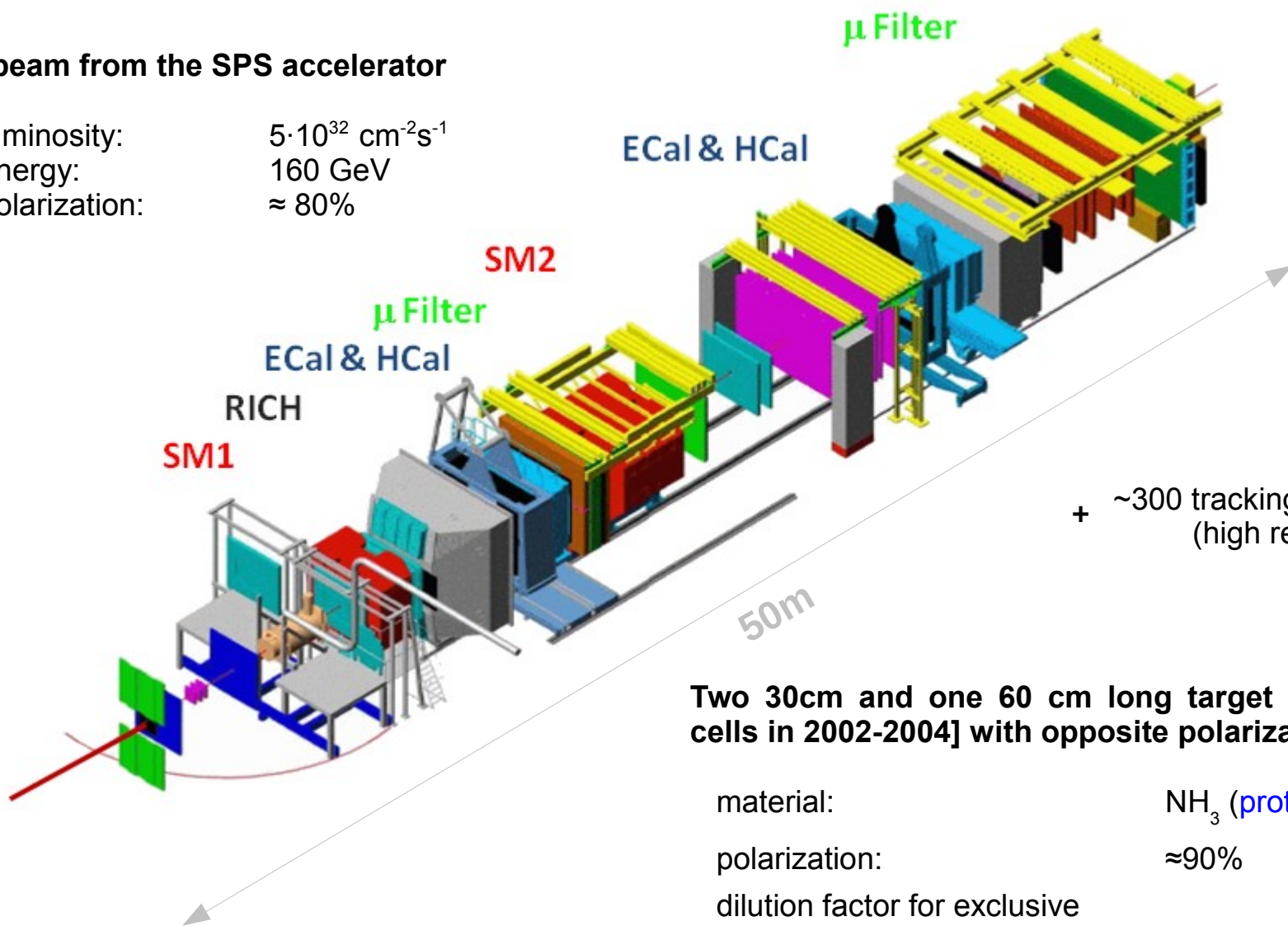
unpolarized cross section

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

μ Filter

ECal & HCal

μ⁺ beam from the SPS accelerator

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

SM2

μ Filter

ECal & HCal

RICH

SM1

50m

+ ~300 tracking detector planes
(high redundancy)

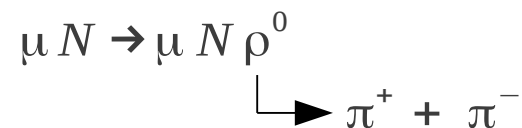**Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization**

material:	NH$_3$ (protons)	[^{6}LiD (deuterons)]
polarization:	≈90%	[≈50%]
dilution factor for exclusive ρ^0 production:	≈25%	[≈44%]

μ⁺

μ⁺

Microwave reversal every week

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

Used data:

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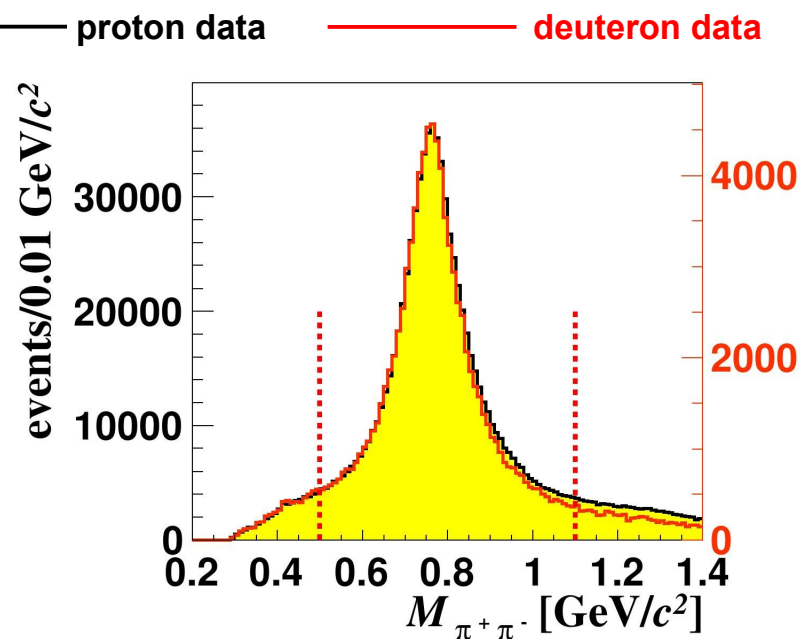2007, 2010   (protons) ⎰ *target polarization*

$$\mu\,N \rightarrow \mu\,N\,\rho^0$$
$$\hookrightarrow \pi^+ + \pi^-$$

Kinematics domain:

- $1\ (GeV/c)^2 < Q^2 < 10\ (GeV/c)^2$
- $W > 5$ GeV

- $0.1 < y < 0.9$
- $0.003 < x_{Bj} < 0.35$

Topology:

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

—— **proton data**   —— **deuteron data**

Invariant mass

Pion mass is assumed for each
outgoing hadron track

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

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

Missing energy and energy of ρ^0 candidate
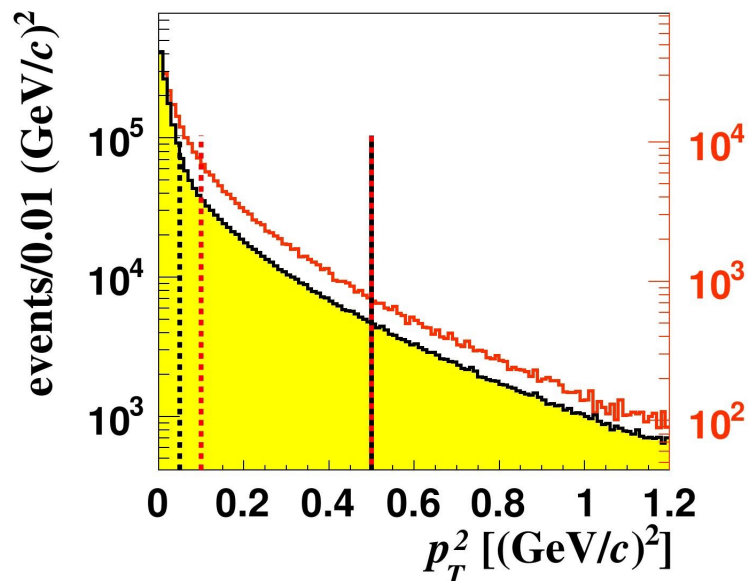
- Check if the proton is intact

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

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

- Check if $E_{\rho^0} > \nu_{min}$ (minimal energy of γ^* allowed by the kinematic cuts)

$$E_{\rho^0} > 15\ GeV$$

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

To remove coherent production off target nuclei

$$0.05 < p_T^2\ (GeV/c)^2 \quad \text{for protons}$$
$$0.1 < p_T^2\ (GeV/c)^2 \quad \text{for deuterons}$$

To suppress non-exclusive background

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

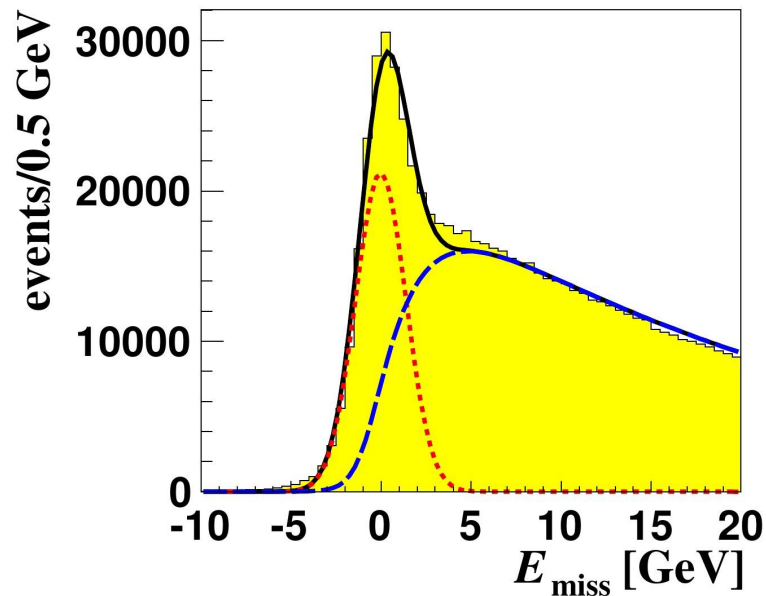# Transverse target spin asymmetry for incoherent exclusive ρ^0 production

Extraction:
for each kinematic bin

All 8 asymmetries extracted together from a fit of the number of signal events in ϕ, ϕ_s bins for each of the target cell (U+D, C) and polarization state (+,-) → 4 input 2D matrices

Background rejection:
for each kinematic bin, target cell and polarization state

Background asymmetry probed in 7 GeV < E_{miss} < 20 GeV region

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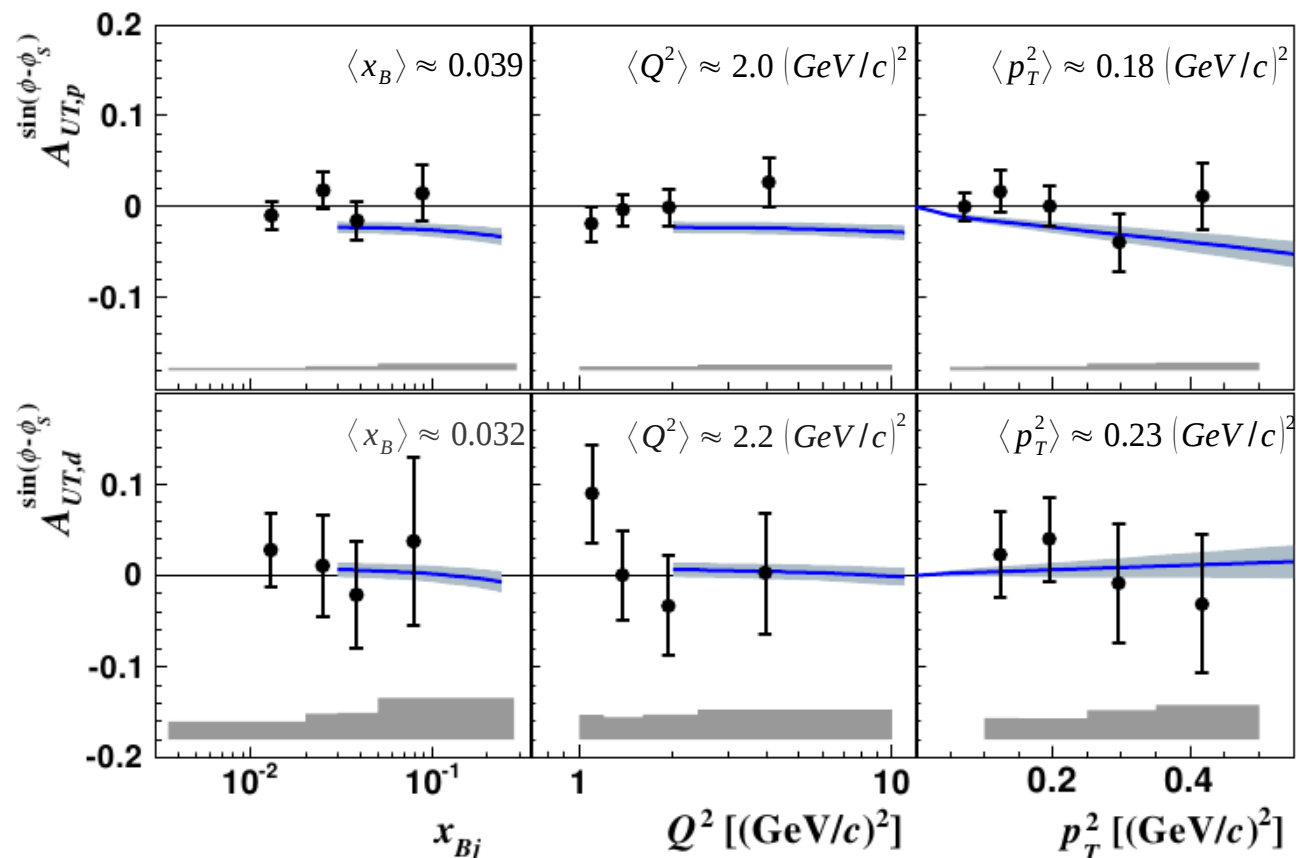*(lepto with COMPASS tuning + simulation of spectrometer response + data reconstruction)*

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

$$w(E_{miss}) = \frac{N_{MC}^{h+h+}(E_{miss}) + N_{MC}^{h-h-}(E_{miss})}{N_{RD}^{h+h+}(E_{miss}) + N_{RD}^{h-h-}(E_{miss})}$$
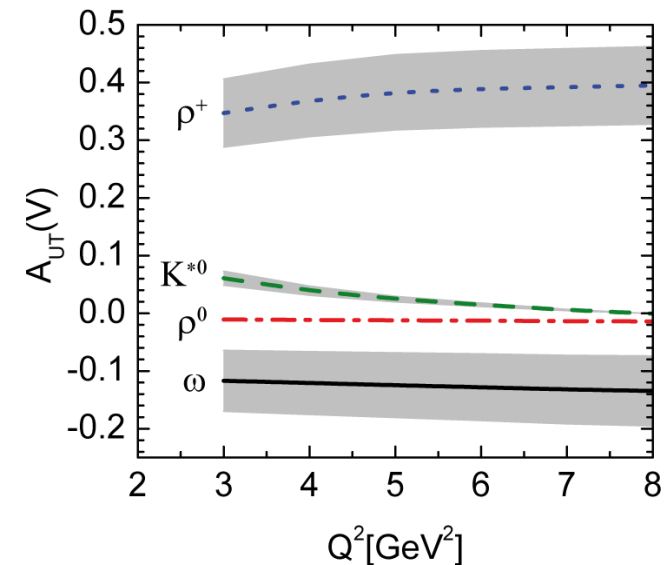
Normalization of MC to the real data using two component fit
Gaussian function (signal) + shape from MC (bkg)

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

COMPASS results
(NPB 865 (2012) 1)

Goloskokov and Kroll
(EPJC 59 (2009) 809)

- "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 ρ^0 production

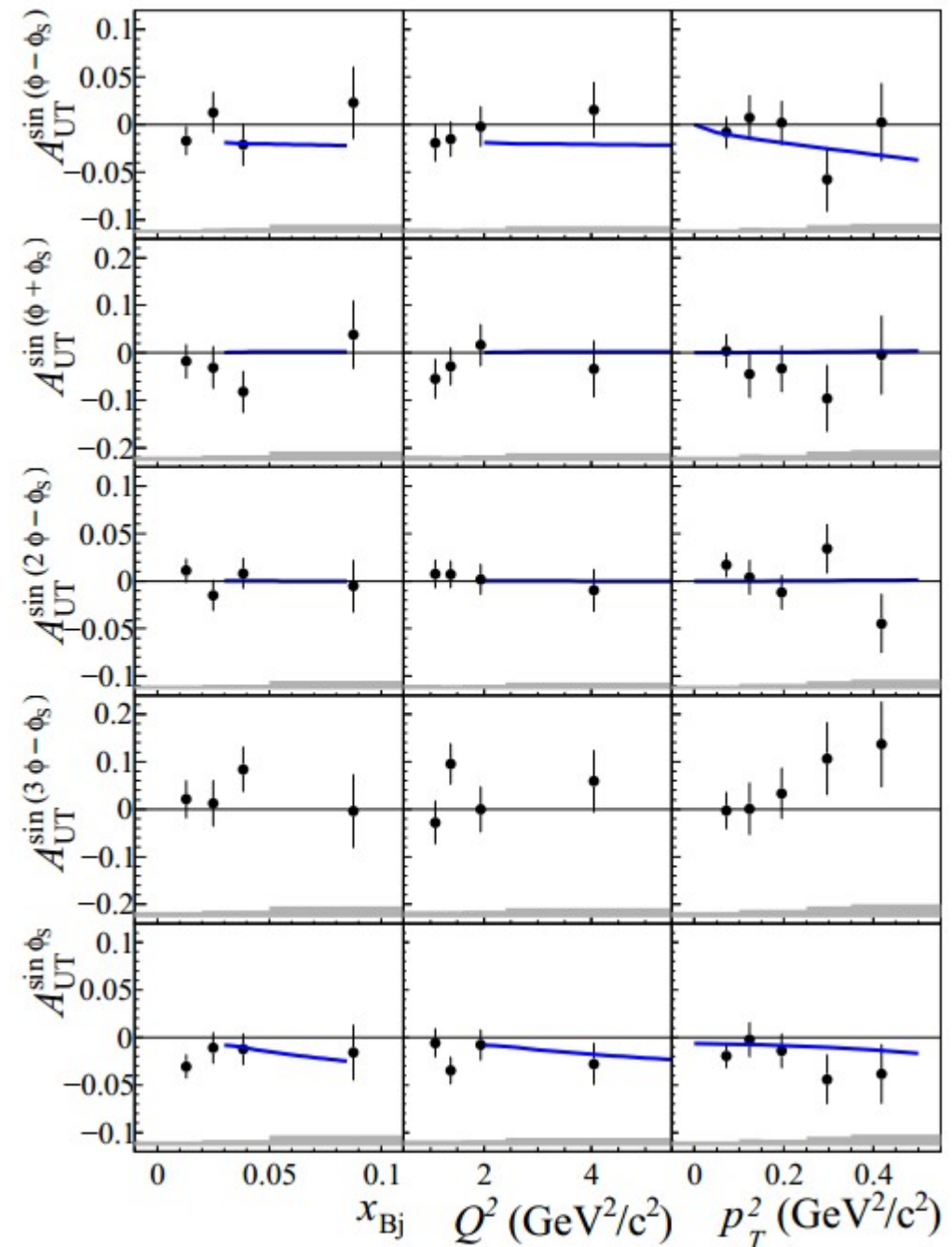**Single spin asymmetries**

New results $\rightarrow$ **PLB 731 (2014) 19**

- Improved method of extraction (2D)

- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0 \, (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18 \, (GeV/c)^2$

Transverse target spin asymmetry for incoherent exclusive ρ^0 production
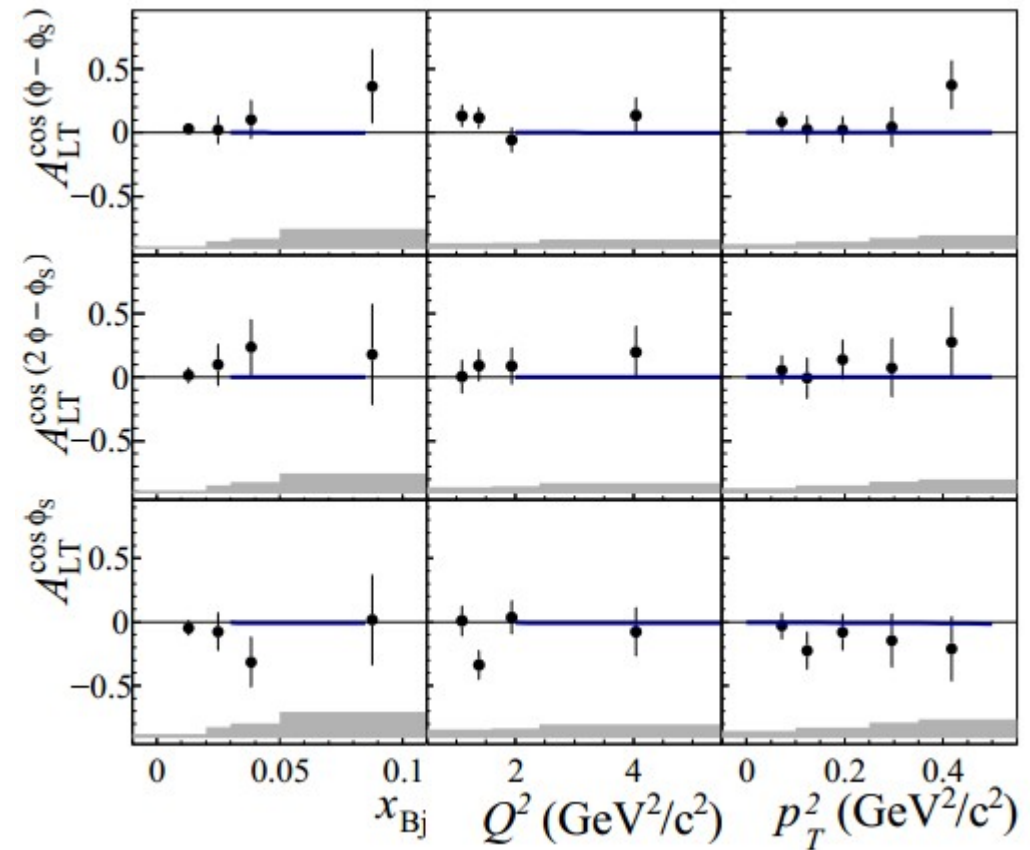
Double spin asymmetries

New results → **PLB 731 (2014) 19**

- Improved method of extraction (2D)

- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

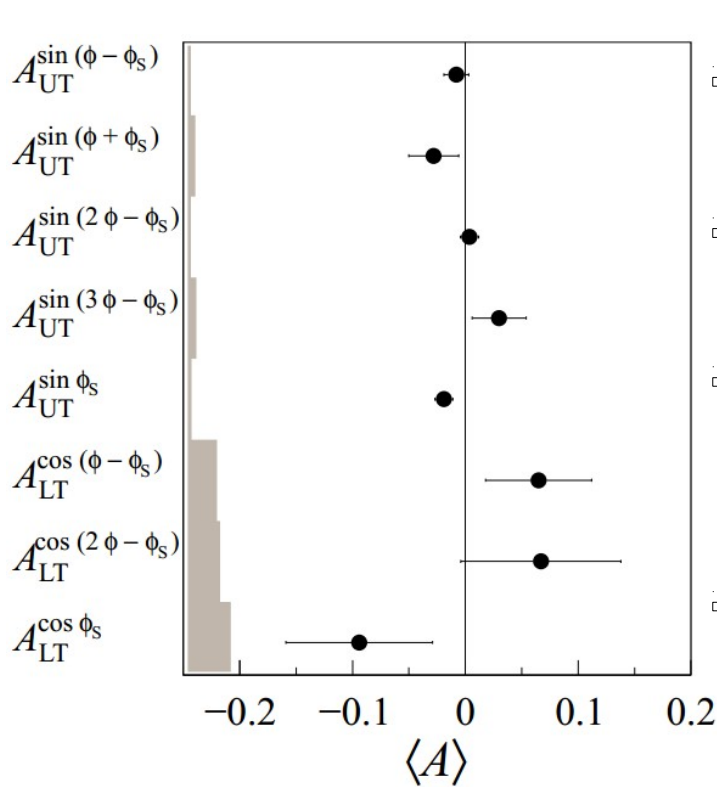$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0 \ (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18 \ (GeV/c)^2$

Transverse target spin asymmetry for incoherent exclusive ρ^0 production - integrated

- All asymmetries small, compatible with 0, except

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

- Indication of H_T contribution $\rightarrow$ relation with transitivity at forward limit: $H_T(x, 0, 0) = h_1(x)$

$$\Rightarrow A_{UT}^{\sin(\varphi-\varphi_s)}\sigma_0 = -2\,Im\left[\epsilon\,\underset{\sim E}{M^*_{0-,0+}}\,\underset{\sim H}{M_{0+,0+}} + \underset{\sim E}{M^*_{+-,++}}\,\underset{\sim H}{M_{++,++}} + \frac{1}{2}\underset{\sim H_T}{M^*_{0-,++}}\,\underset{\sim \bar{E}_T}{M_{0+,++}}\right]$$

$$\Rightarrow A_{UT}^{\sin(2\varphi-\varphi_s)}\sigma_0 = -Im\left[\underset{\sim \bar{E}_T}{M^*_{0+,++}}\,\underset{\sim E}{M_{0-,0+}}\right]$$

$$\bar{E}_T = 2\widetilde{H}_T - E_T$$

$$\Rightarrow A_{UT}^{\sin(\varphi_s)}\sigma_0 = -Im\left[\underset{\sim H_T}{M^*_{0-,++}}\,\underset{\sim H}{M_{0+,0+}} - \underset{\sim \bar{E}_T}{M^*_{0+,++}}\,\underset{\sim E}{M_{0-,0+}}\right]$$
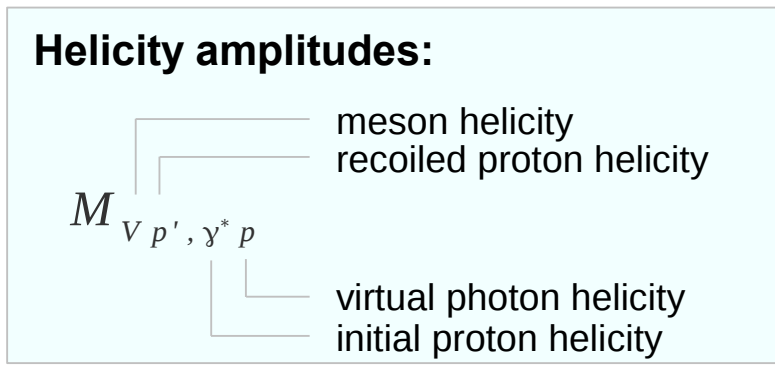
$$\Rightarrow A_{LT}^{\cos(\varphi_s)}\sigma_0 = -Re\left[\underset{\sim H_T}{M^*_{0-,++}}\,\underset{\sim H}{M_{0+,0+}} - \underset{\sim \bar{E}_T}{M^*_{0+,++}}\,\underset{\sim E}{M_{0-,0+}}\right]$$

Plot of asymmetries $A_{UT}^{\sin(\phi-\phi_S)}$, $A_{UT}^{\sin(\phi+\phi_S)}$, $A_{UT}^{\sin(2\phi-\phi_S)}$, $A_{UT}^{\sin(3\phi-\phi_S)}$, $A_{UT}^{\sin\phi_S}$, $A_{LT}^{\cos(\phi-\phi_S)}$, $A_{LT}^{\cos(2\phi-\phi_S)}$, $A_{LT}^{\cos\phi_S}$ vs $\langle A \rangle$ (axis from -0.2 to 0.2)

$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0\ (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18\ (GeV/c)^2$

Helicity amplitudes:

$$M_{V\,p',\,\gamma^*\,p}$$

- meson helicity
- recoiled proton helicity
- virtual photon helicity
- initial proton helicity

Study of exclusive meson production will be continued at COMPASS-II

- 2012 pilot + 2016, 2017 with unpolarized LH target and RPD
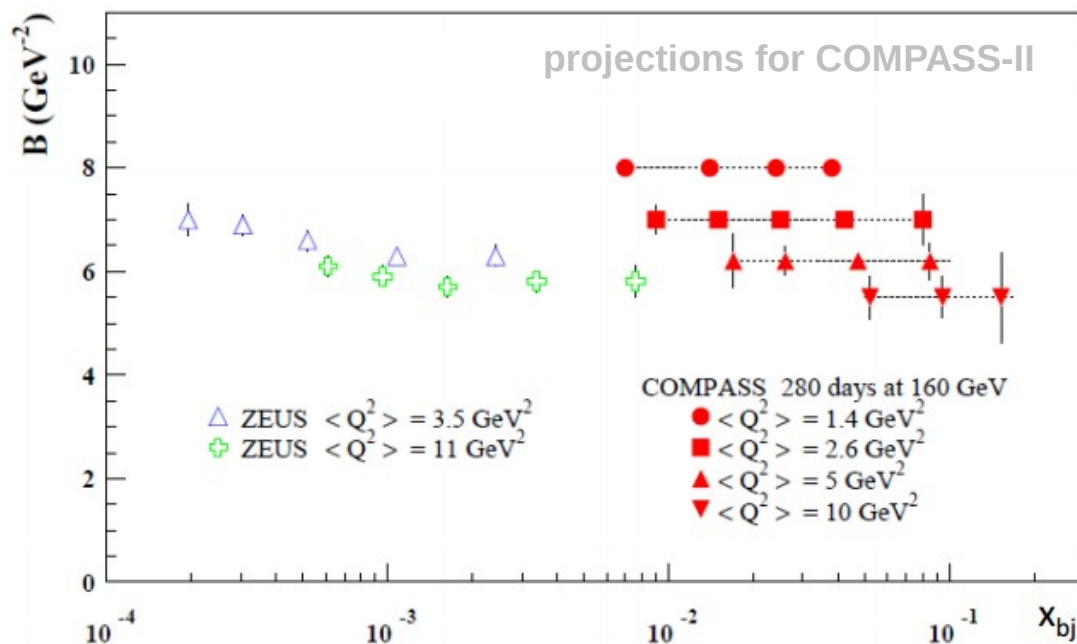- > 2017 with polarized target and RPD (*subject of addendum to the proposal*)

Measurement of t-slope for exclusive ρ^0 production
sensitive to transverse size of nucleon – meson system

- Q^2 and ν parametrization of cross section from NMC data normalized to Goloskokov and Kroll 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

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

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

→ *more in:*
The GPD program at COMPASS II
Eva-Maria Kabuss
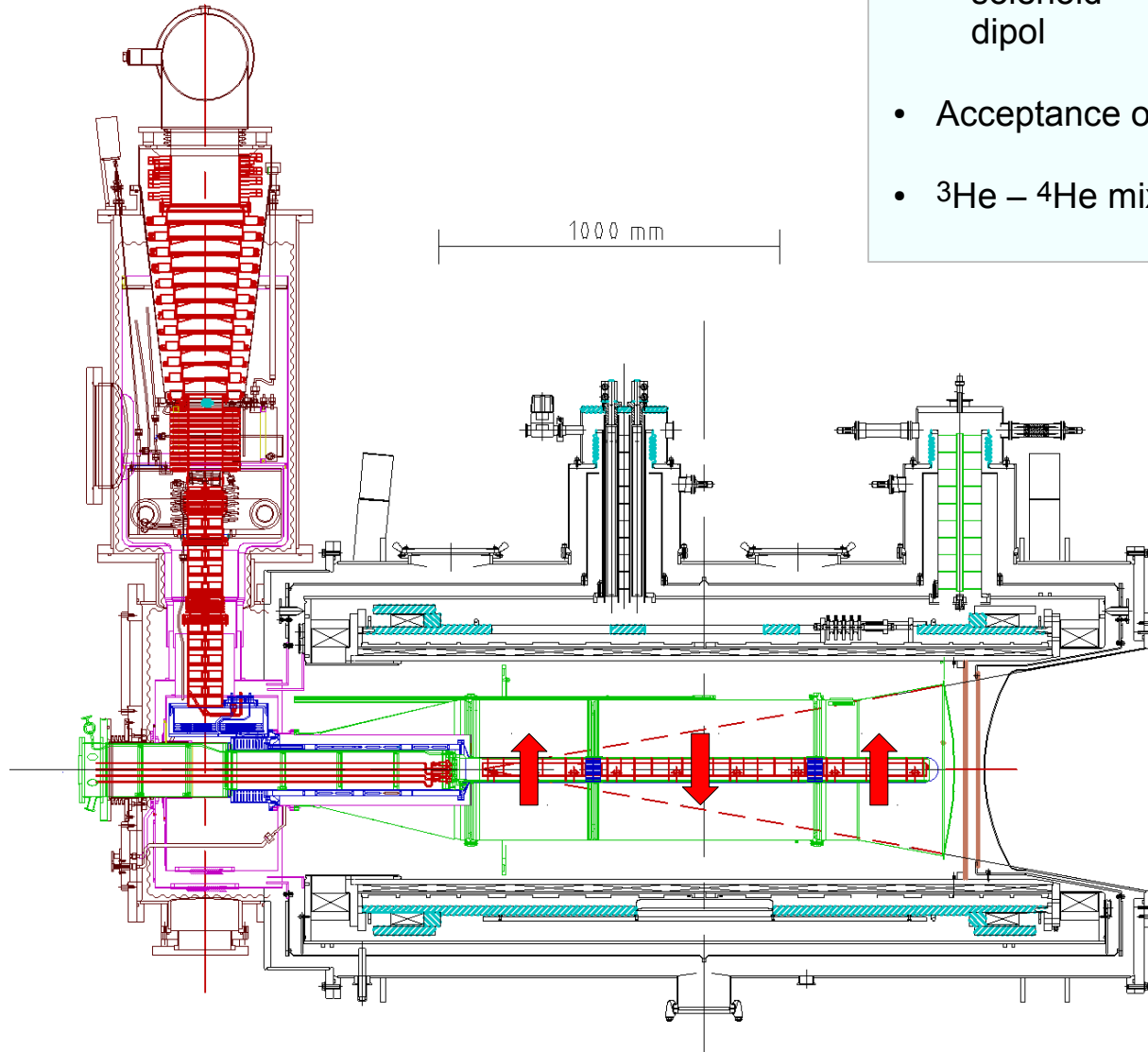Thursday, WG6+WG7 joint session

- COMPASS is unique to probe GPDs due to covered kinematic region of intermediate x_{Bj} and availability of beams of two charges and polarizations

- Exclusive meson production $\rightarrow$ complementary measurement to DVCS, flavour separation for GPDs, sensitivity to chiral-odd GPDs

- Transverse target spin asymmetries for exclusive ρ^0 production was measured for protons, asymmetries are small, compatible with 0, except

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

- Indication of H_T contribution
- Transverse target spin asymmetry $A_{UT}^{\sin(\varphi-\varphi_S)}$ measured for deuterons, asymmetries are small, compatible with 0

- Measurement for ω in progress

- GPD program is continued at COMPASS-II

- 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)

1000 mm

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