

Exclusive meson production at COMPASS



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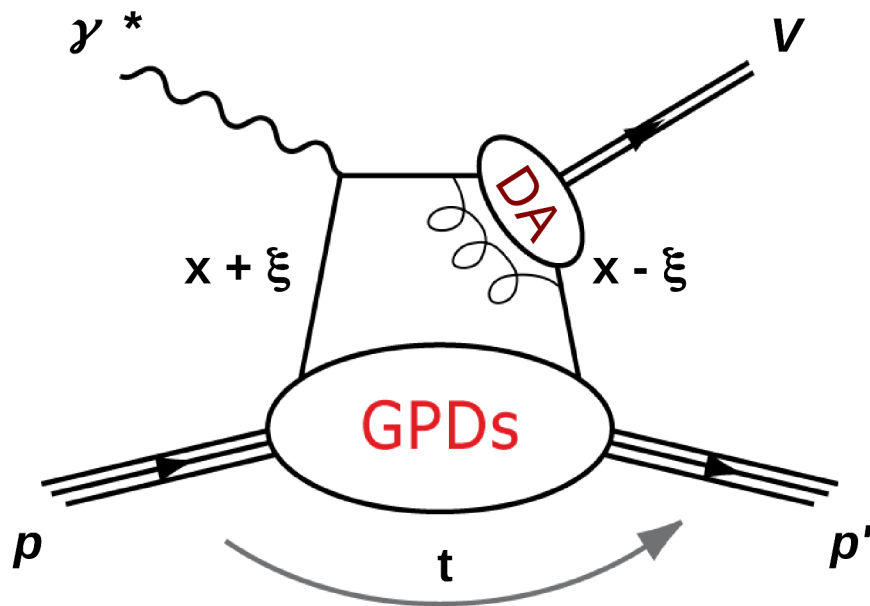


XV WORKSHOP ON HIGH ENERGY SPIN PHYSICS

Dubna, 8 – 12 October 2013

- GPD formalism
- COMPASS experiment
- Transverse target spin asymmetries for incoherent exclusive ρ^0 production
- Projections for COMPASS-II
- Summary and outlook

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



collinear factorization strictly proven only for longitudinal γ^*

Chiral-even GPDs

helicity of parton unchanged

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

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

$$\tilde{H}^{q,g}(x, \xi, t)$$

$$\tilde{E}^{q,g}(x, \xi, t)$$

Chiral-odd GPDs (not accessed in DVCS)

helicity of parton changed

$$H_T^{q,g}(x, \xi, t)$$

$$E_T^{q,g}(x, \xi, t)$$

$$\tilde{H}_T^{q,g}(x, \xi, t)$$

$$\tilde{E}_T^{q,g}(x, \xi, t)$$

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

Nucleon tomography:

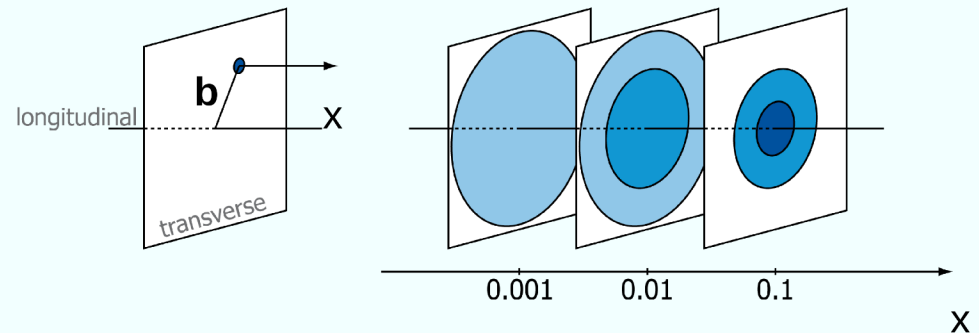
(unpolarized target, COMPASS-II)

3D parton distribution function:

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

where:

\mathbf{b} : impact parameter



Total angular momentum:

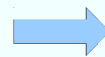
(polarized target, COMPASS)

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

where:

$$J^q = \cancel{L^q} + S^q$$

*angular momentum
conservation law*



*if proton helicity is changed orbital
angular momentum must be involved*

The cross section formula for exclusive meson production

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

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

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

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

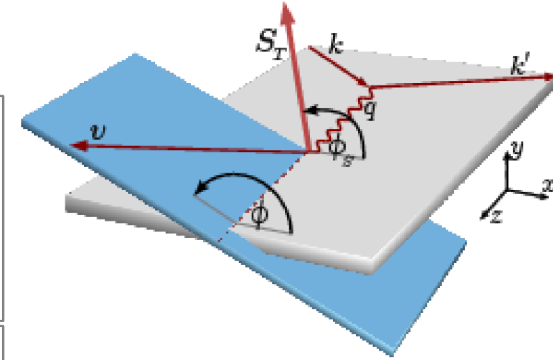
$$+ S_L P_\ell \left[\sqrt{1-\varepsilon^2} \frac{1}{2} (\sigma_{++}^{++} - \sigma_{++}^{--}) - \sqrt{\varepsilon(1-\varepsilon)} \cos \phi \operatorname{Re} (\sigma_{+0}^{++} - \sigma_{+0}^{--}) \right]$$

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

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

$$+ S_T P_\ell \left[\sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) \operatorname{Re} \sigma_{+-}^{+-} \right.$$

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



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

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

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

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

$$\gamma = 2x_B M_p / Q$$

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

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

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

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

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

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

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

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

$$A_{LT}^{\cos(2\varphi - \varphi_s)} = -\frac{\text{Re} \sigma_{+0}^{-+}}{\sigma_0}$$

unpolarized cross section

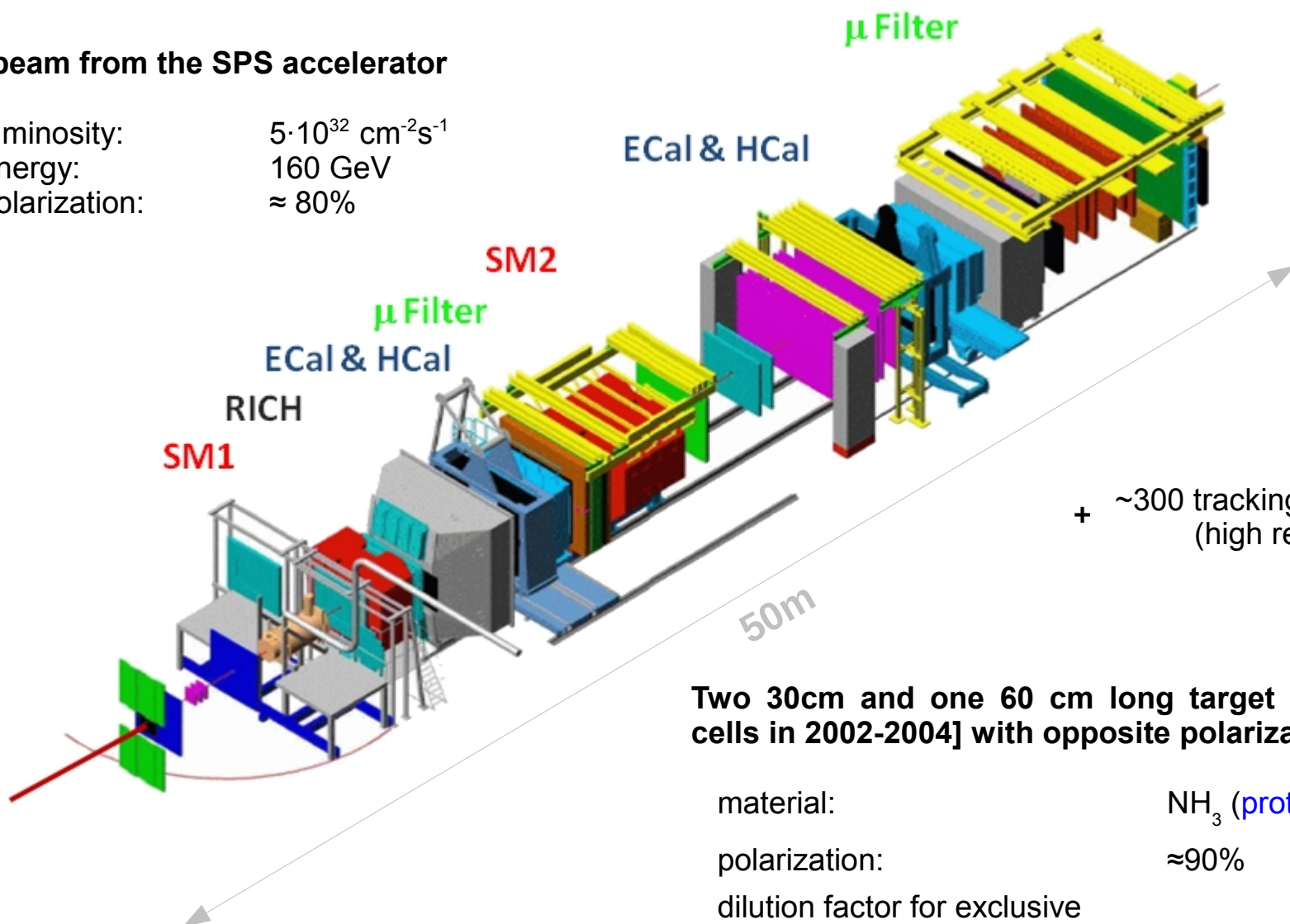
$$\sigma_0 = \frac{1}{2}(\sigma_{++}^{++} + \sigma_{++}^{--}) + \epsilon \sigma_{00}^{++} = \sigma_L + \epsilon \sigma_T$$

COMPASS experiment at CERN – setup with transversely polarized target



μ^+ beam from the SPS accelerator

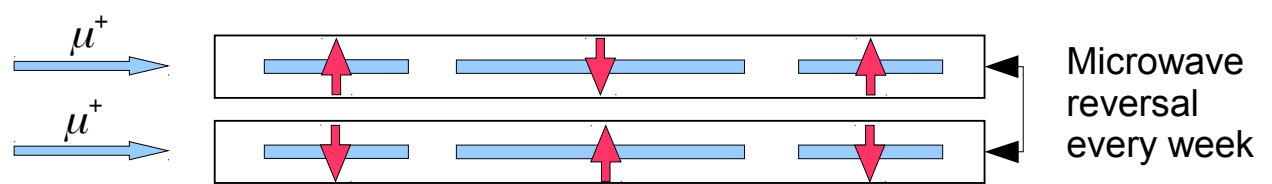
luminosity: $5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
 energy: 160 GeV
 polarization: $\approx 80\%$



+ ~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

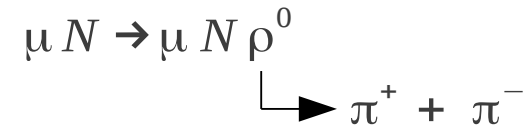
material:	NH ₃ (protons)	[⁶ LiD (deuterons)]
polarization:	$\approx 90\%$	[$\approx 50\%$]
dilution factor for exclusive ρ^0 production:	$\approx 25\%$	[$\approx 44\%$]



Transverse target spin asymmetry for incoherent exclusive ρ^0 production

Used data:

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

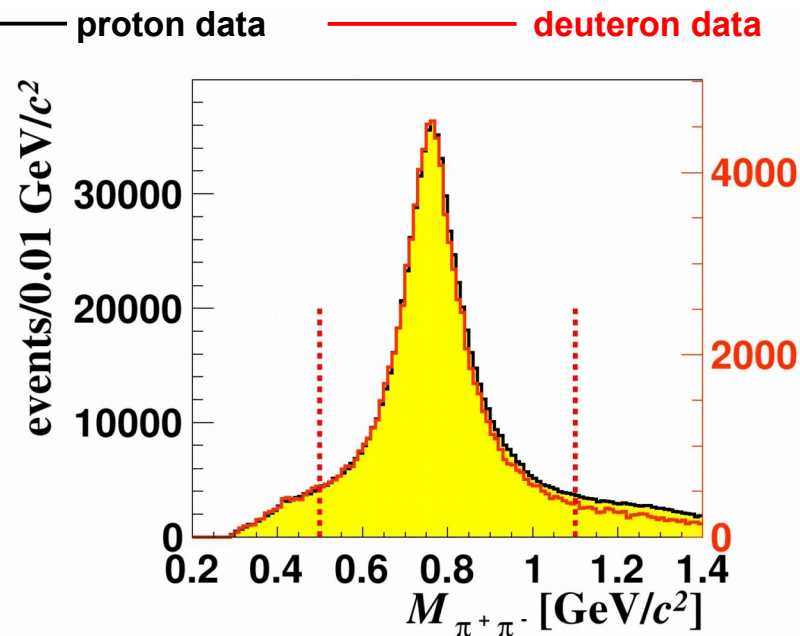


Kinematics domain:

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

Topology:

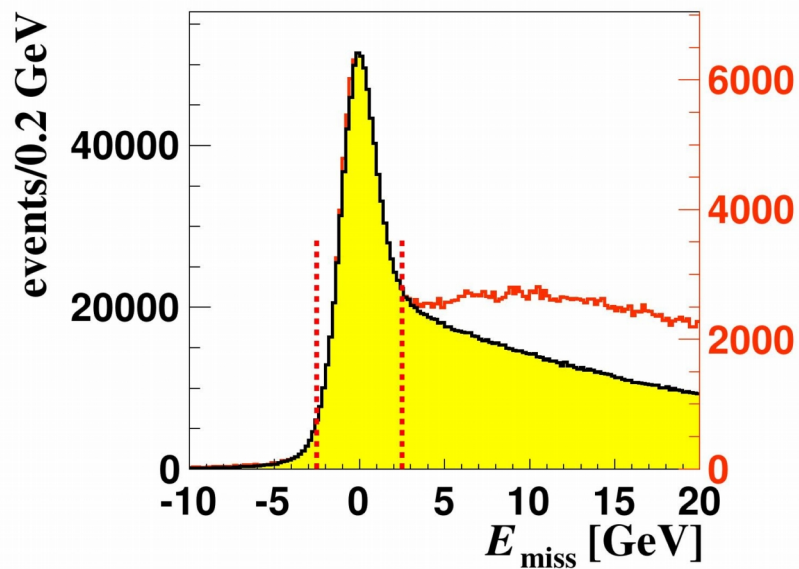
only incoming and outgoing muon tracks,
two hadron tracks of opposite charges in PV



Invariant mass

Pion mass is assumed for each outgoing hadron track

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



Missing energy and energy of ρ^0 candidate

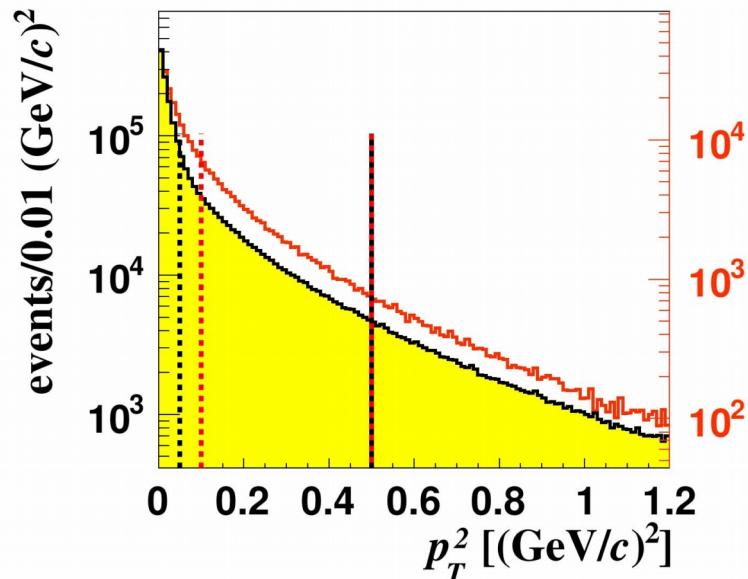
- Check if the proton is intact

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

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

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

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



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

To remove coherent production off target nuclei

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

$$0.01 < p_T^2 (\text{GeV}/c)^2 \text{ for deuterons}$$

To suppress non-exclusive background

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

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

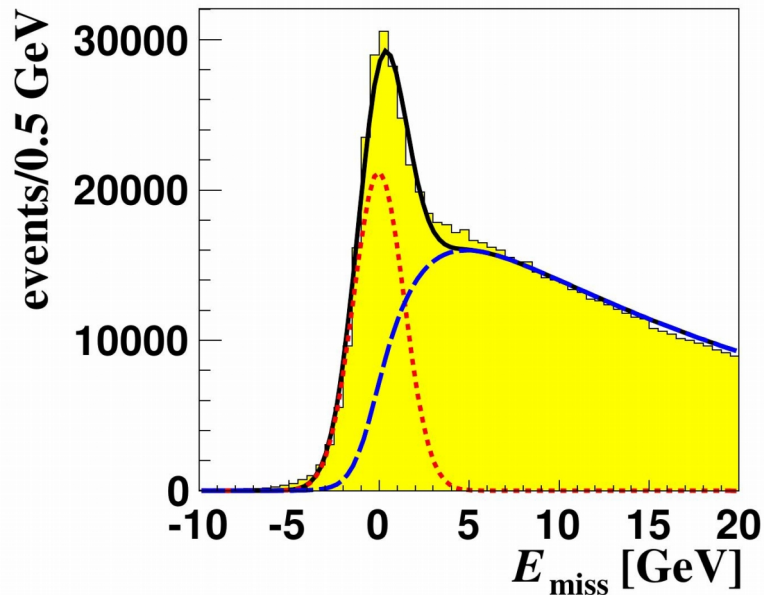
Extraction:

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 (+,-) \rightarrow 4 input 2D matrices

Background rejection:

for each kinematic bin, target cell and polarization state



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

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

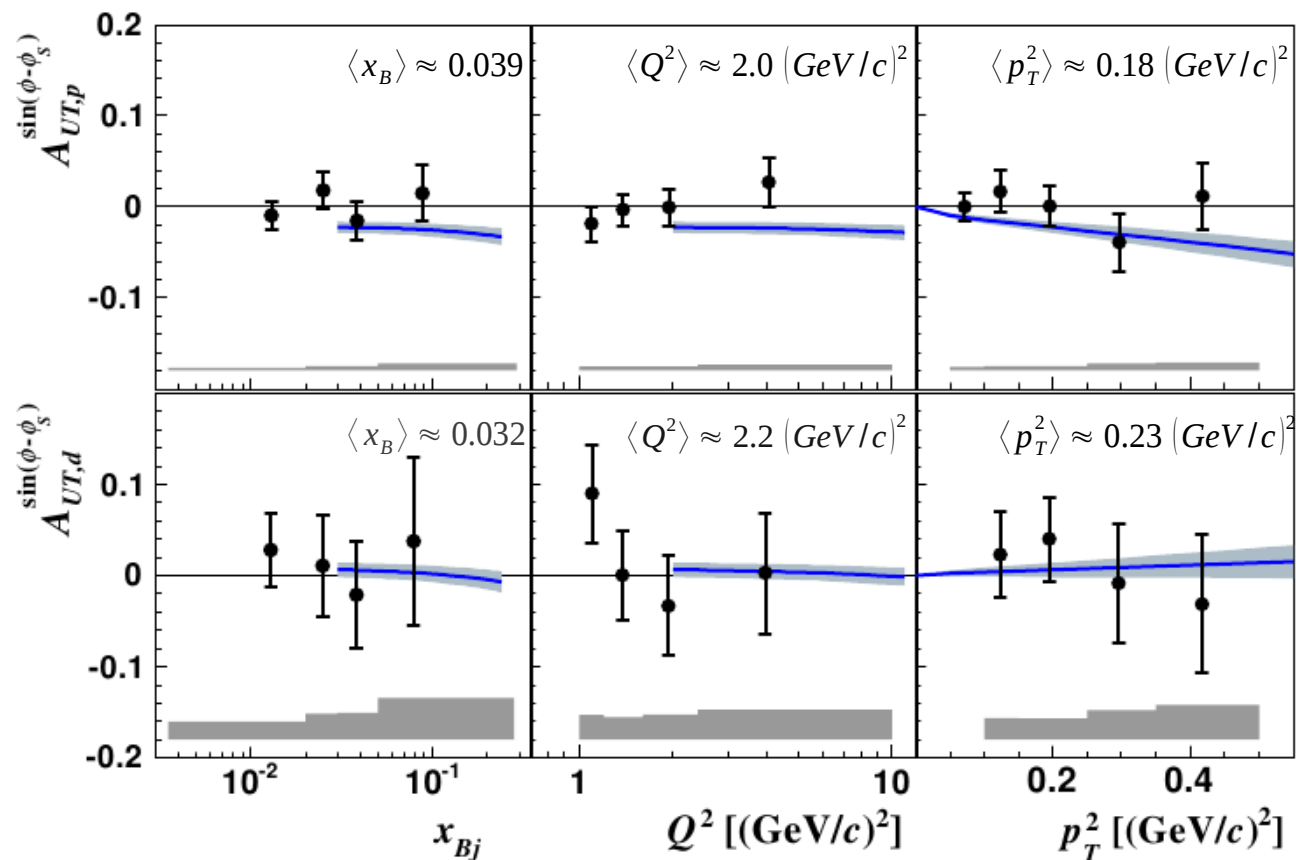
MC weighted using agreement between real data and MC for wrong charge combination sample ($h^+h^+ + h^-h^-$)

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

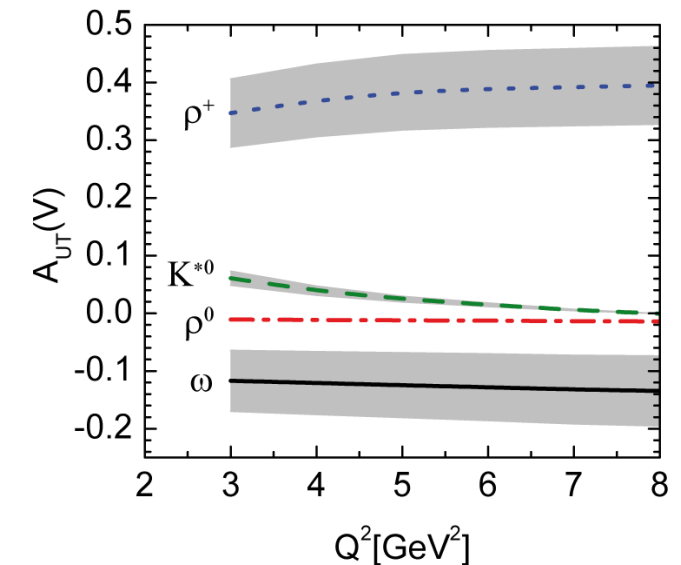
Normalization of MC to the real data using two component fit
Gaussian function (signal) + shape from MC (bkg)

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

COMPASS results
(*NPB 865 (2012) 1.*)



Goloskokov and Kroll
(*EPJC 59 (2009) 809.*)



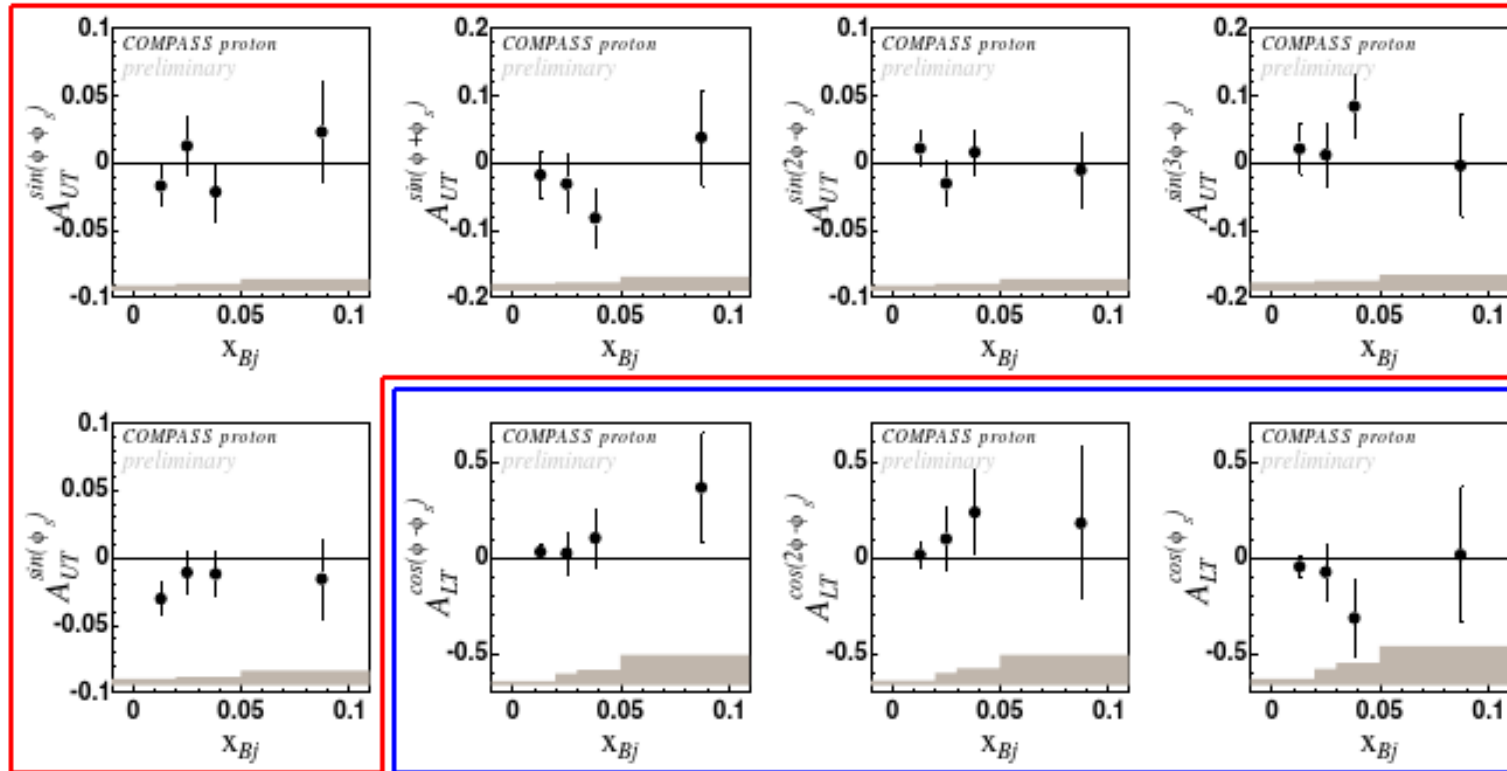
- “handbag model”
- GPDs constrained by CTEQ6 parametrization and nucleon form factors
- power corrections due to transverse quarks momenta
- predictions both for γ_L^* and γ_T^*

- $A_{UT} \sin(\phi-\phi_S)$ 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

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

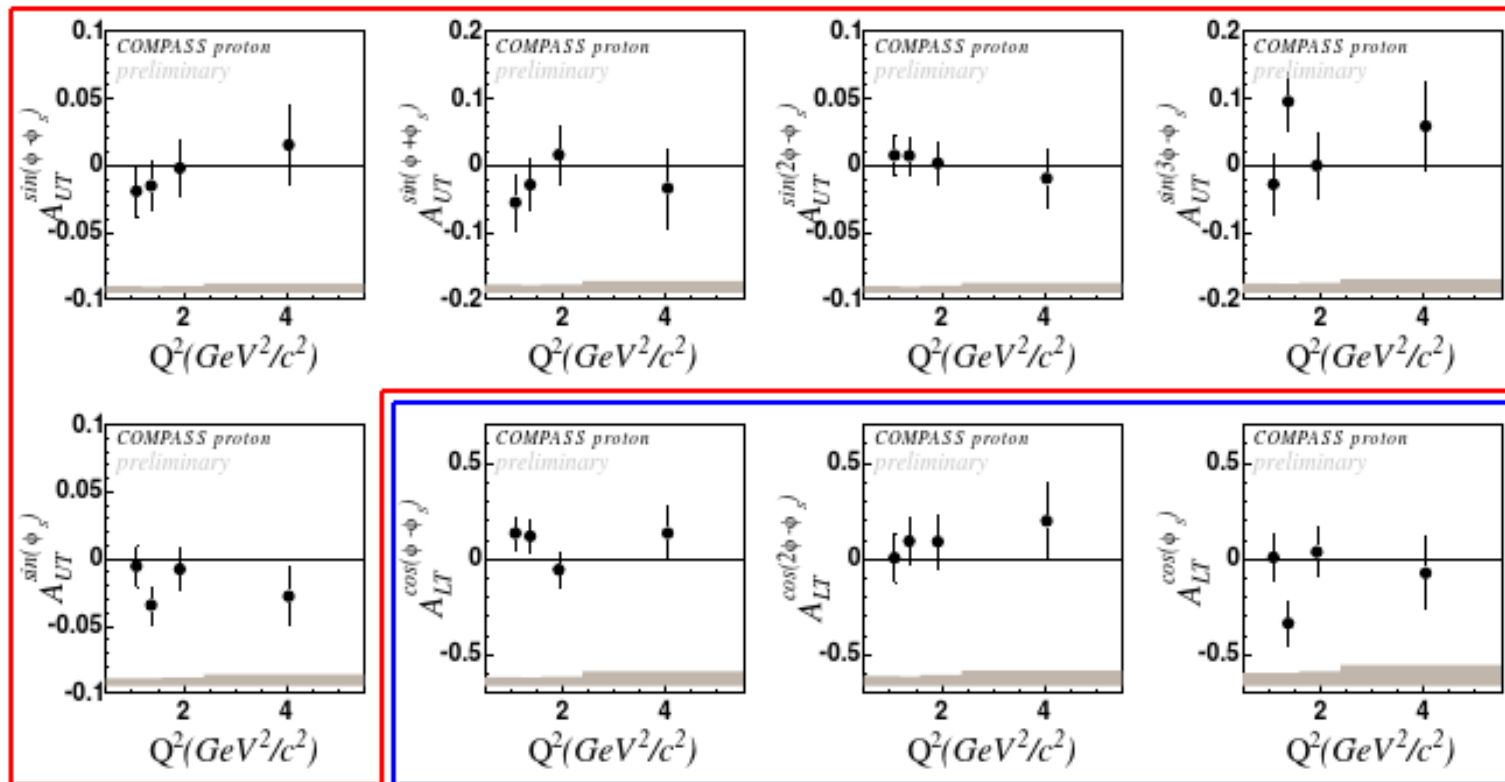
as a function of x_{Bj}



Transverse target spin asymmetry for incoherent exclusive ρ^0 production

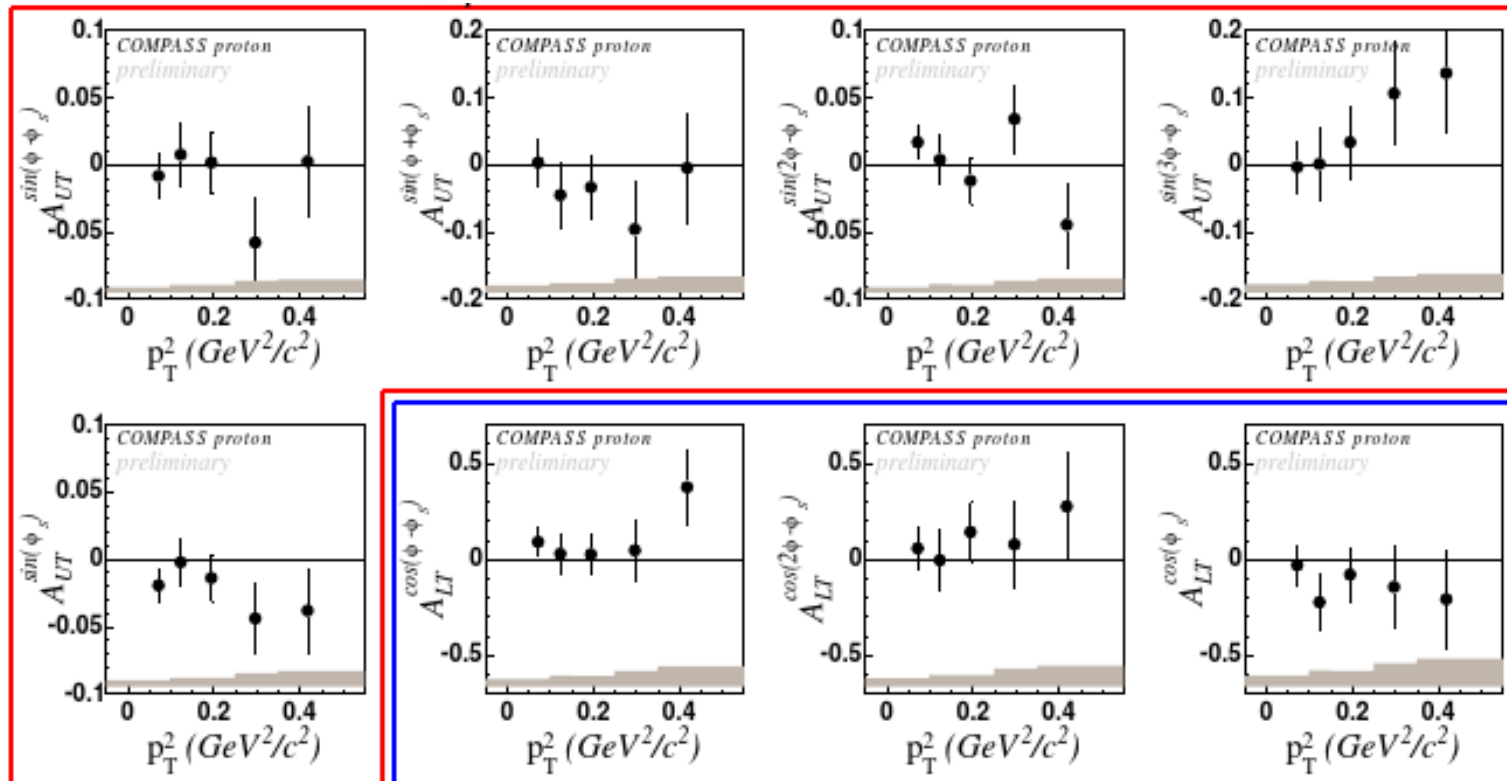
- New results for 5 **transverse target spin asymmetries** and 3 **transverse target double spin asymmetries** for proton target

as a function of Q^2



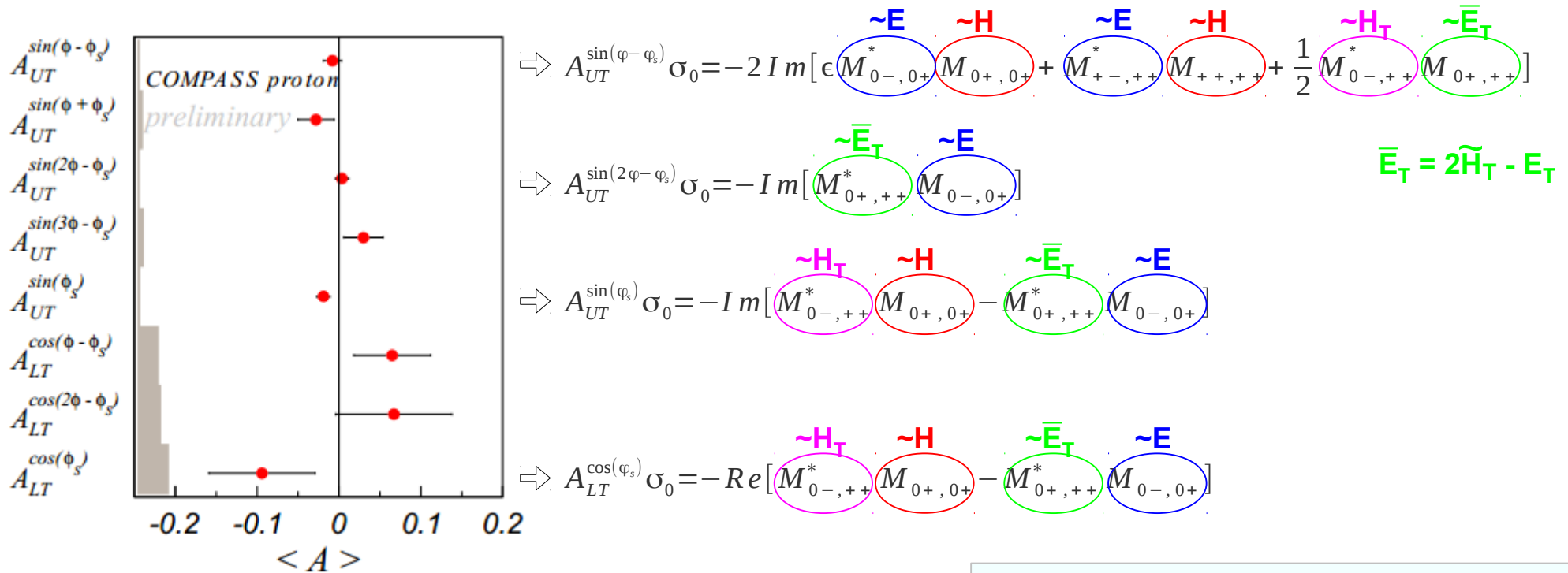
- New results for 5 **transverse target spin asymmetries** and 3 **transverse target double spin asymmetries** for proton target

as a function of p_T^2



Transverse target spin asymmetry for incoherent exclusive 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 that $H_T \neq 0$

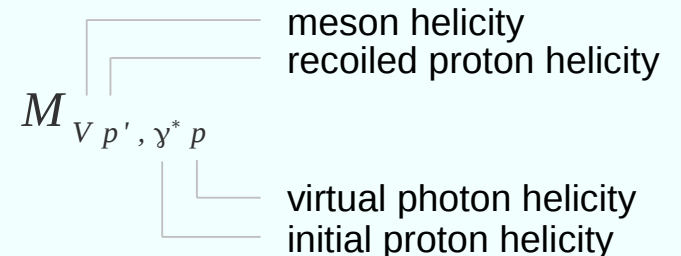


$$\langle x_B \rangle \approx 0.039$$

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

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

Helicity amplitudes:



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*)

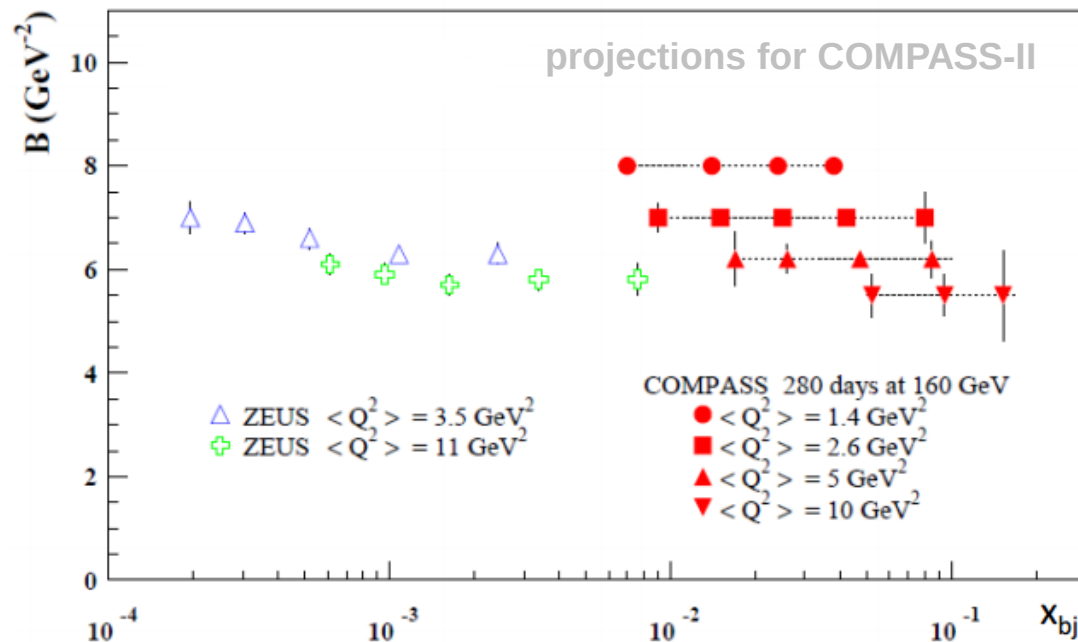
Measurement of t-slope for exclusive ρ^0 production sensitive to transverse size of nucleon – meson system

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

1/40 statistics expected in 2012 pilot

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

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



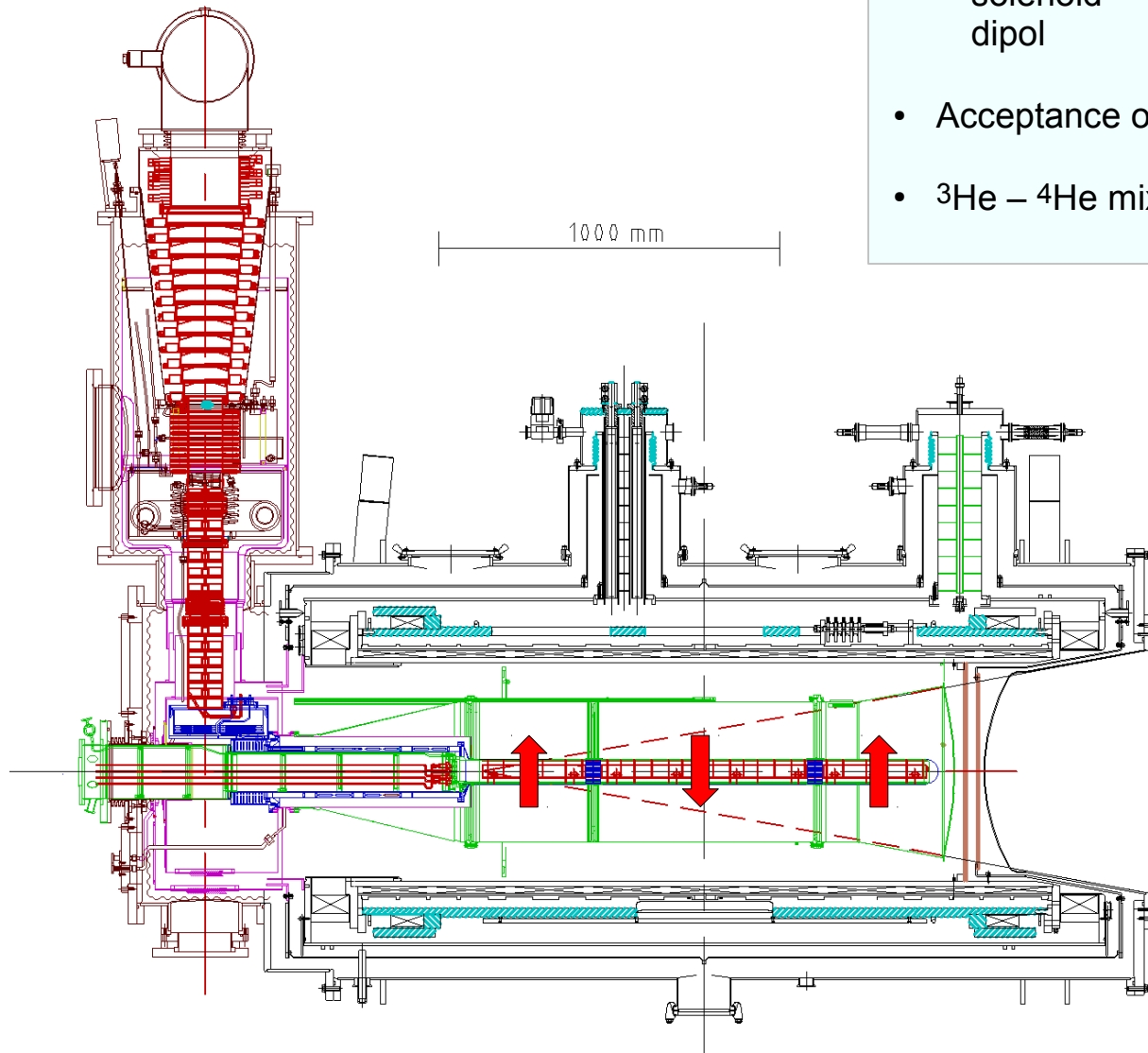
- COMPASS is unique to probe GPDs due to covered kinematic region of intermediate x_{Bj} and availability of beams of two charges and polarizations
- Exclusive meson production \rightarrow complementary measurement to DVCS, flavour separation for GPDs, sensitivity to chiral-odd GPDs
- Transverse target 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 that $H_T \neq 0$
- 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

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
- $^3\text{He} - ^4\text{He}$ mixture used to refrigerate ($T \sim 50\text{mK}$)



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

