COMPASS results on hard exclusive muoproduction

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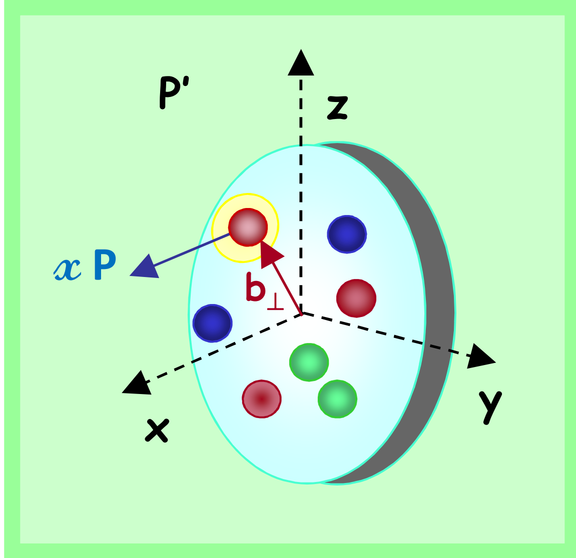
Main goals of the GPD program

- GPD a 3-dimensional image of the partonic structure of the nucleon

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

probability interpretation (Burkardt)



this talk

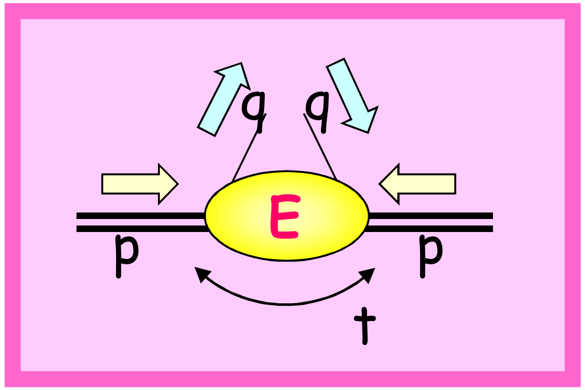
➢ t-dependence of pure DVCS cross section on unpolarised protons

- Contribution to the nucleon spin puzzle

  GPD E related to the orbital angular momentum

$$2J_q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$$

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$



this talk

➢ Exclusive vector meson production on transversely polarised protons and deuterons

COMPASS experiment at CERN

Two basic ingredients of versatile COMPASS experimental setup

- **secondary beam line M2 from the SPS**

  delivers:
  - high energy polarised μ^+ or μ^- beams
  - negative or positive hadron beams

- **two-stage forward spectrometer SM1 + SM2**

  ≈ 300 tracking detectors planes – high redundancy

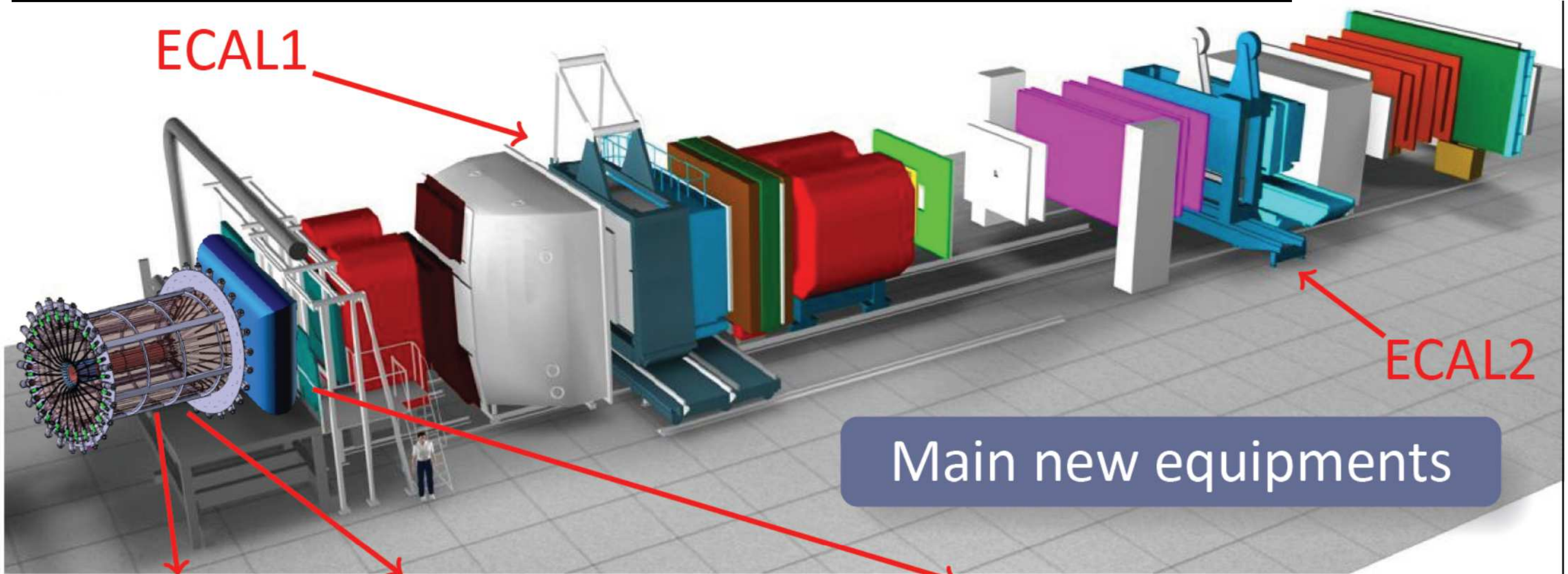
  variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx$ 200 mrad

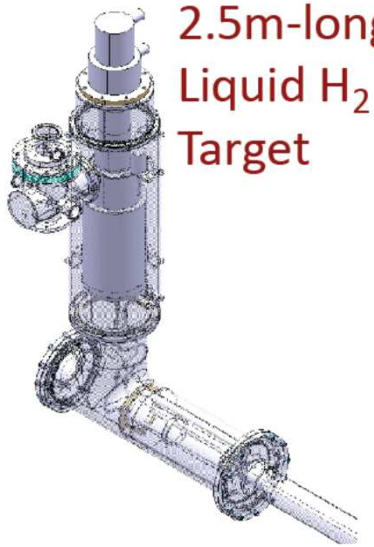
  + calorimetry, μID, RICH

A flexibility to carry out a diverse physics programs by modifying mainly the target region

- spin structure of nucleons; polarised muon-nucleon scattering
- hadron spectroscopy in diffractive and central hadron production
- Primakoff reactions and test of chiral perturbative theory
- polarised and unpolarised Drell-Yan scattering
- GPD studies; DVCS and hard exclusive meson production

The COMPASS set-up for the GPD program (starting from 2012)

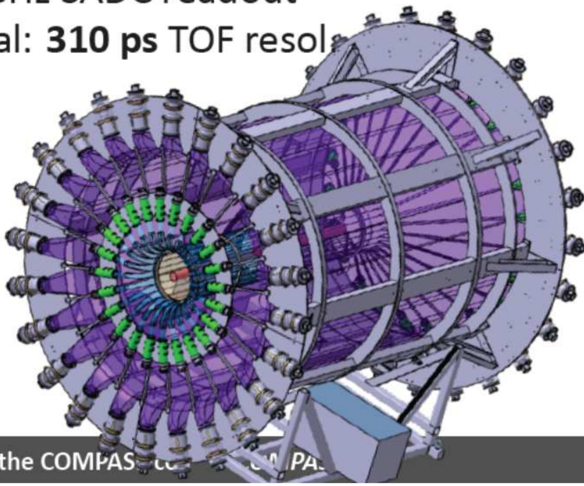




2.5m-long Liquid H_2 Target

Target TOF System

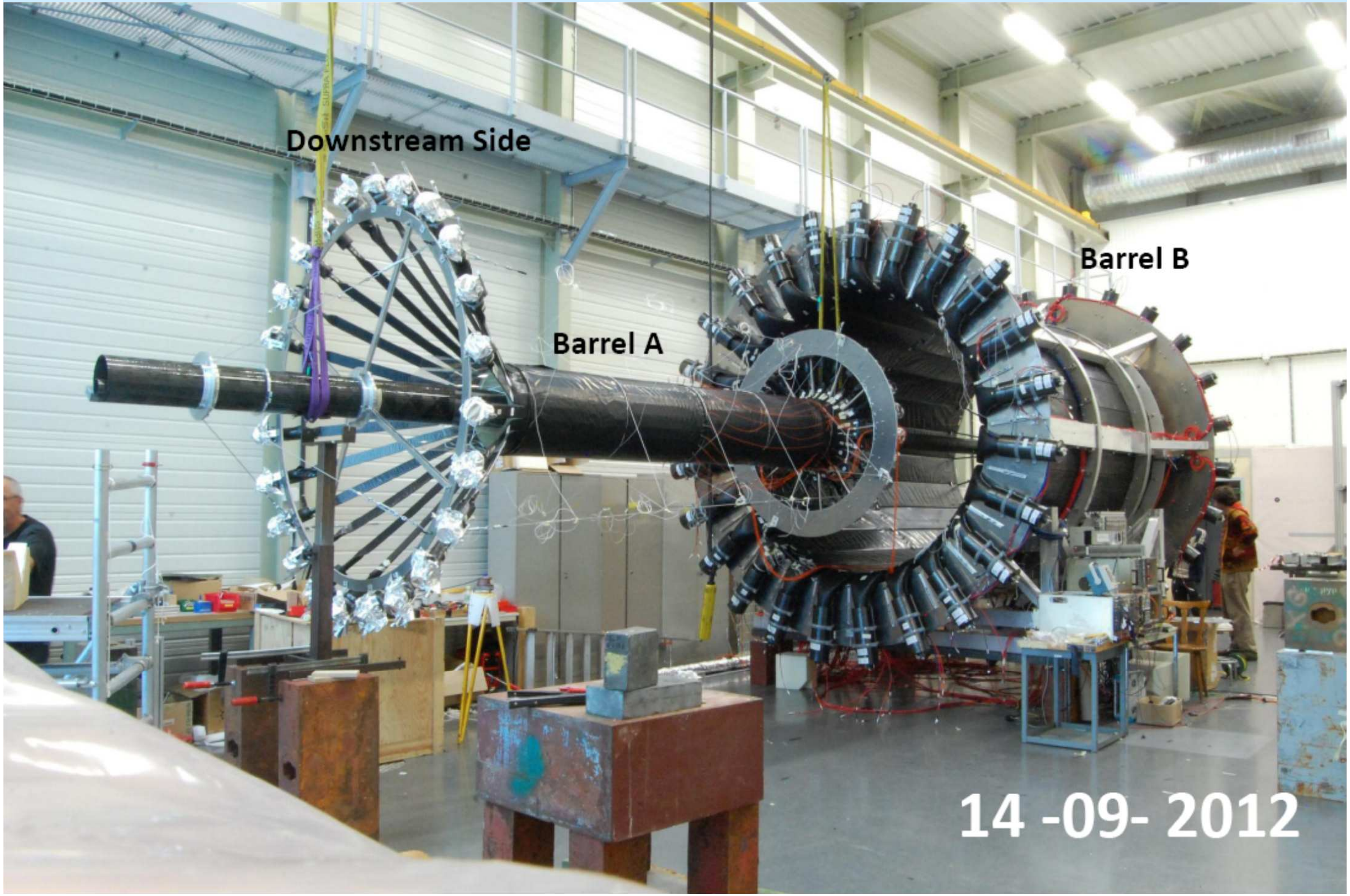
24 inner & outer scintillators
1 GHz SADC readout
goal: **310 ps** TOF resol



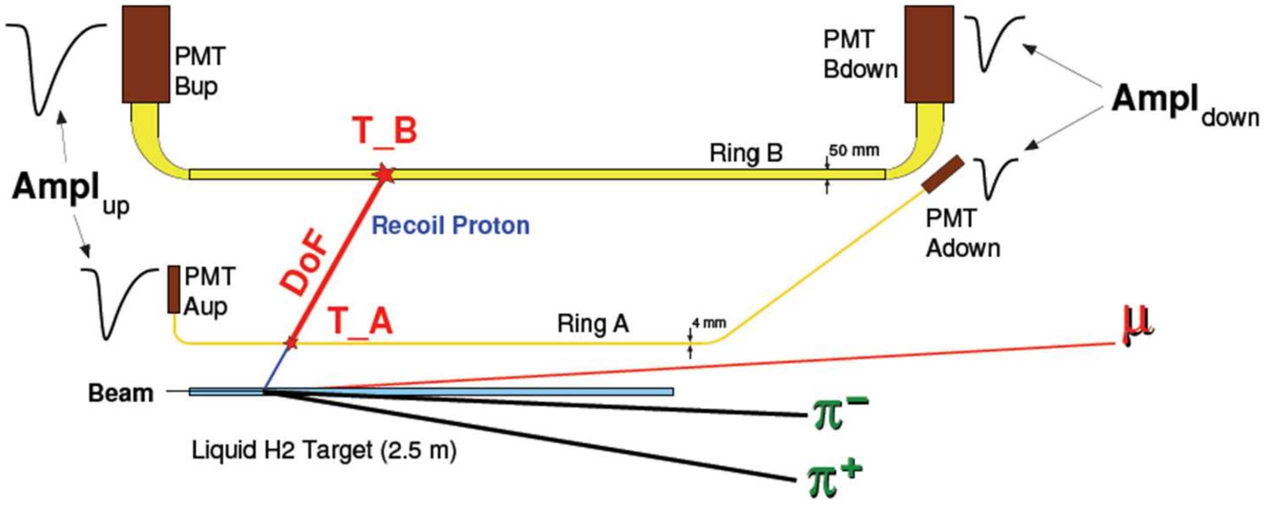
ECAL0 Calorimeter

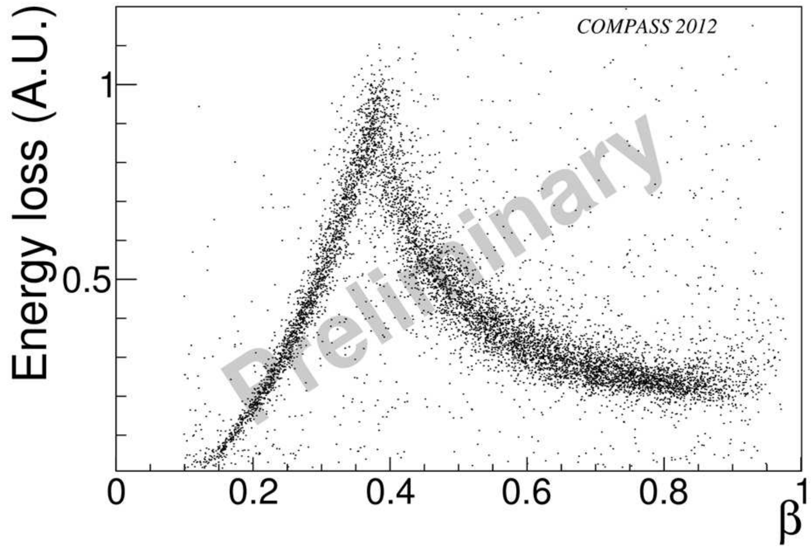
Shashlyk modules + MAPD readout
$\sim 2 \times 2$ m^2, $\sim$2200 ch.

Mounting of Recoil Proton Detector ('CAMERA') in clean area at CERN



Recoil particle reconstruction in CAMERA





$E_{loss} \sim \sqrt{(Ampl_{up} \times Ampl_{down})}$

$z_{A,B} \sim (t_{up} - t_{down})_{A,B}$

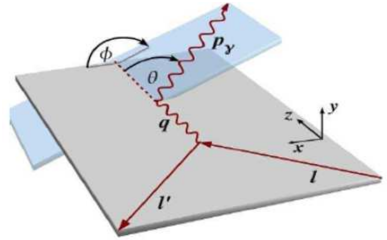
$ToF = (t_{up} + t_{down})_{A,B}$

$\beta = DoF / ToF$

counting rate: > 5 MHz in ring A
~ 1 MHz in ring B

- Proton signature clearly visible after exclusivity selections

Extraction of DVCS cross section and amplitude



Beam Charge & Spin Sum

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

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

$c_0^{DVCS} \longrightarrow d\sigma^{DVCS}/dt$

$s_1^{Int} \longrightarrow Im(F_1 \mathcal{H})$

$Im\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$

Beam Charge & Spin Difference

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

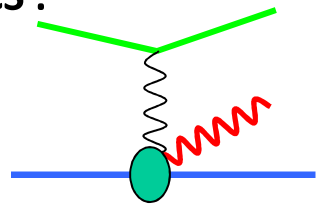
$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi \qquad s_1^{DVCS}\sin\phi$$

$c_{0,1}^{Int} \rightarrow Re(F_1 \mathcal{H})$

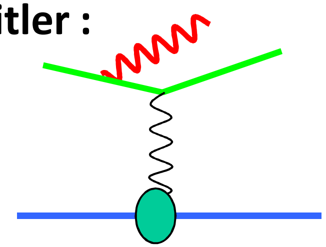
$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

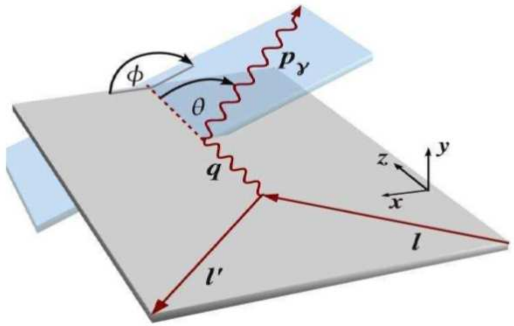
Interplay of DVCS and BH at 160 GeV

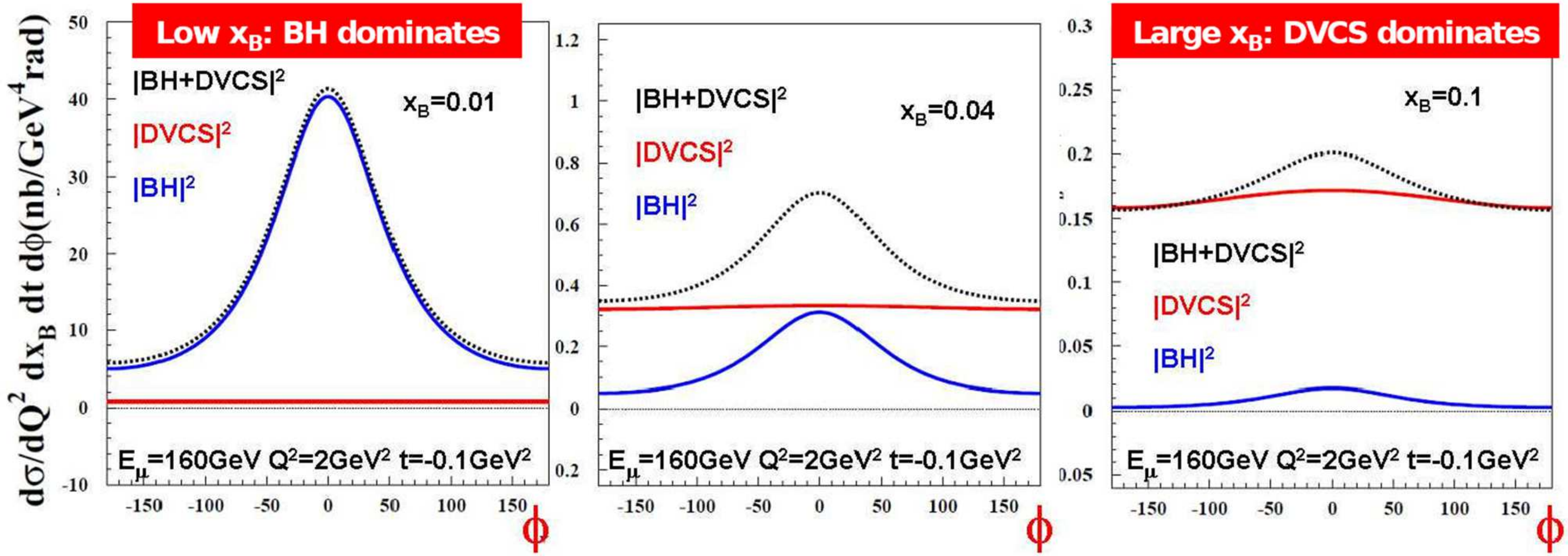
DVCS :



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 $d\sigma^{DVCS}/dt$

Selection of exclusive single photon events

sample for t-slope extraction

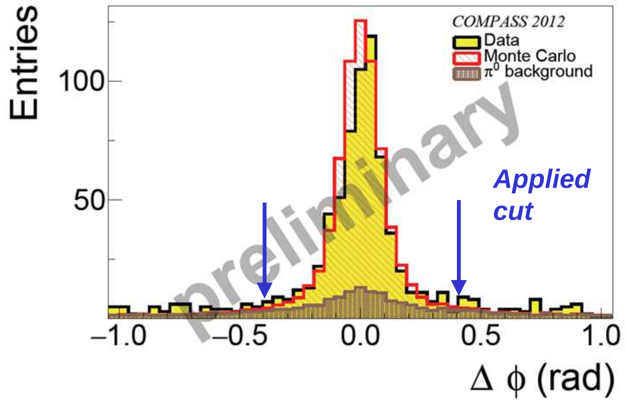
- reconstructed vertex in the target volume
- 1 GeV² < Q² < 5 GeV², 10 GeV < ν < 32 GeV →
- 0.08 GeV² < | t | < 0.64 GeV²
- 1 single photon with energy above DVCS threshold ← $E_{Ecal(0,1,2)}$ > (4,5,10) GeV

'extended' sample

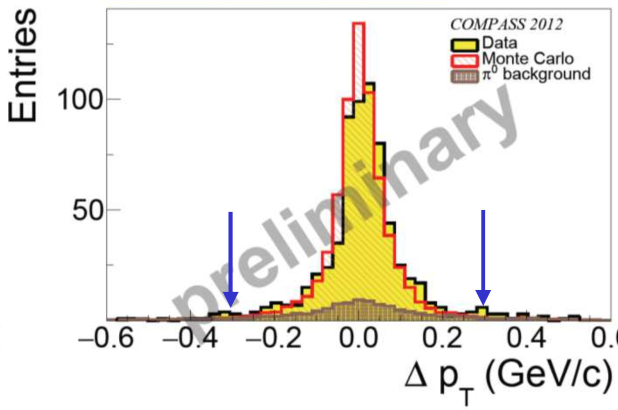
for cross checks: beam flux, π^0 background

1 GeV² < Q² < 20 GeV², 8 GeV < ν < 144 GeV

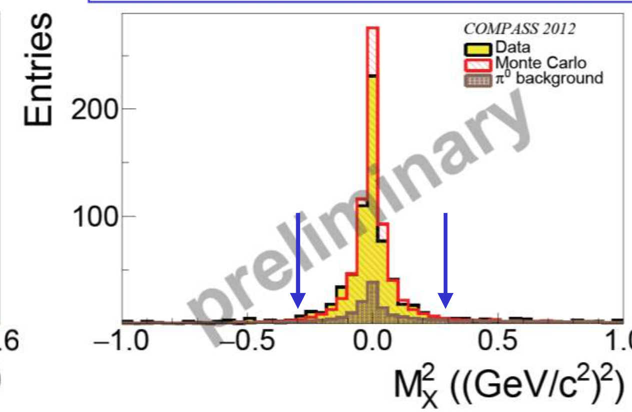
$$\Delta\varphi = \varphi^{prot}_{meas} - \varphi^{prot}_{recon}$$

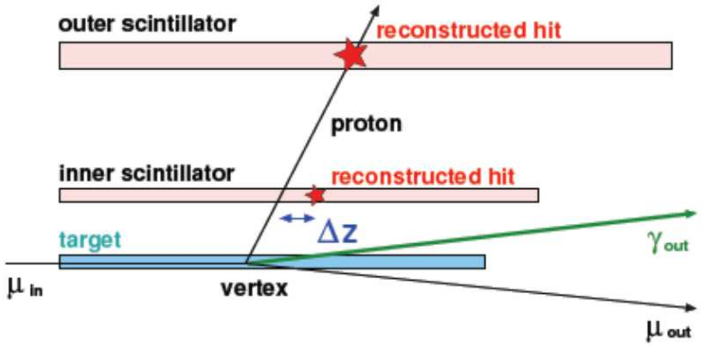


$$\Delta p_{\perp} = p^{prot}_{\perp,meas} - p^{prot}_{\perp,recon}$$

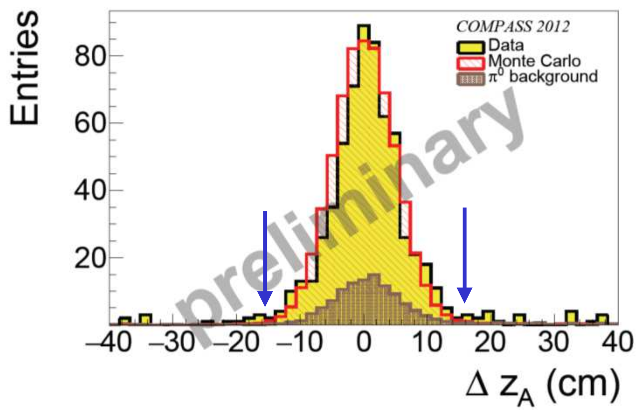


$$M_X^2 = (p^{\mu}_{in} + p^{p}_{in} - p^{\mu}_{out} - p^{p}_{out} - p^{\gamma})^2$$





vertex pointing

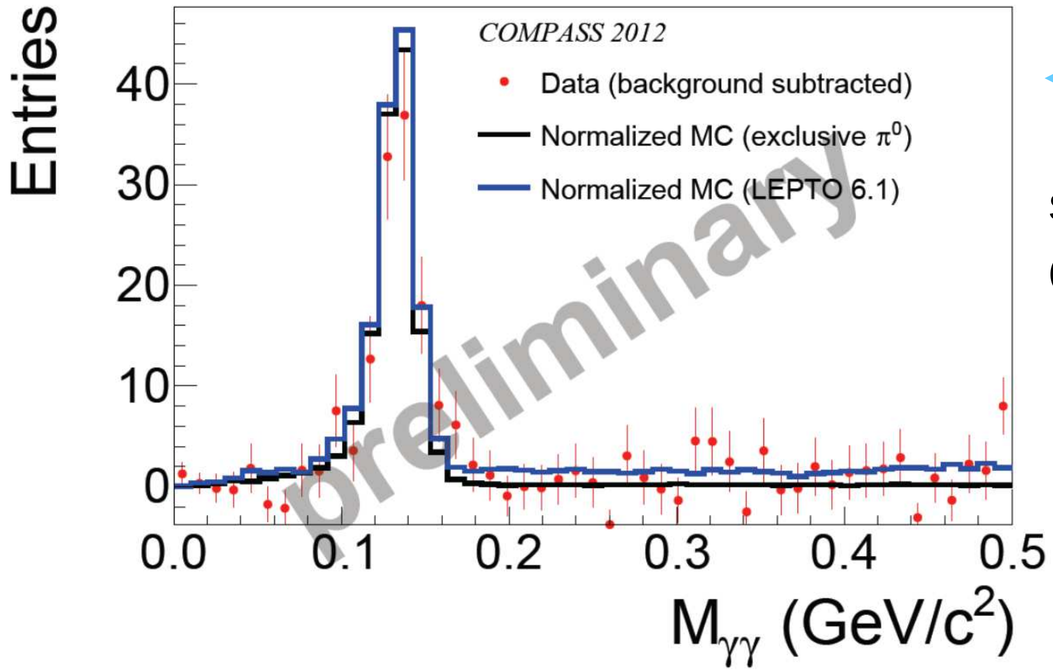


Estimate of π^0 background

Major source of background for exclusive photon events

Two cases:

- Visible; detected second γ (below DVCS threshold) => events rejected from final sample
- Invisible; one γ lost => estimated from MC normalised to π^0 peak for 'visible' sample



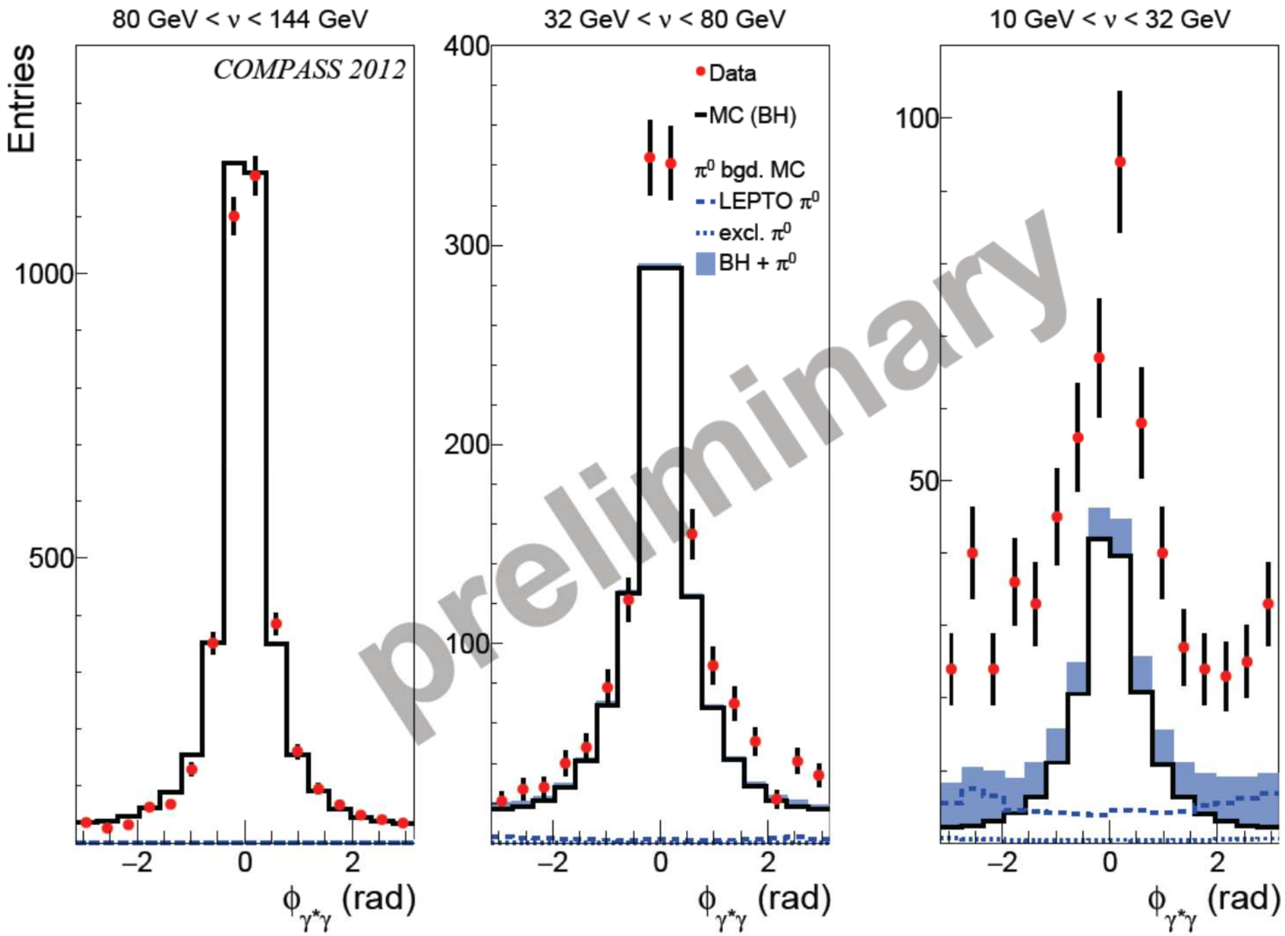
'Visible' sample

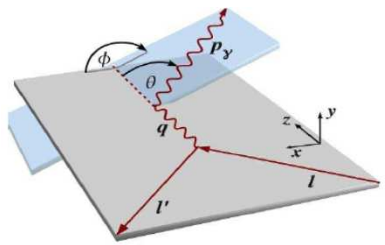
Semi-inclusive (LEPTO MC) or exclusive (HEPGEN MC based on Goloskokov-Kroll model) π^0 contribution normalised to $M_{\gamma\gamma}$ peak

'Invisible' sample

Relative contributions from both processes to π^0 background estimated from combined fits to the distributions of 'exclusivity variables' (M_X^2, $\Delta\phi$, Δp_T) and $E_{miss} = \nu - E_\gamma + t/(2m_p^2)$

Exclusive γ production from 2012 DVCS comissioning run





for normalization of BH MC to the data beam flux measurement used

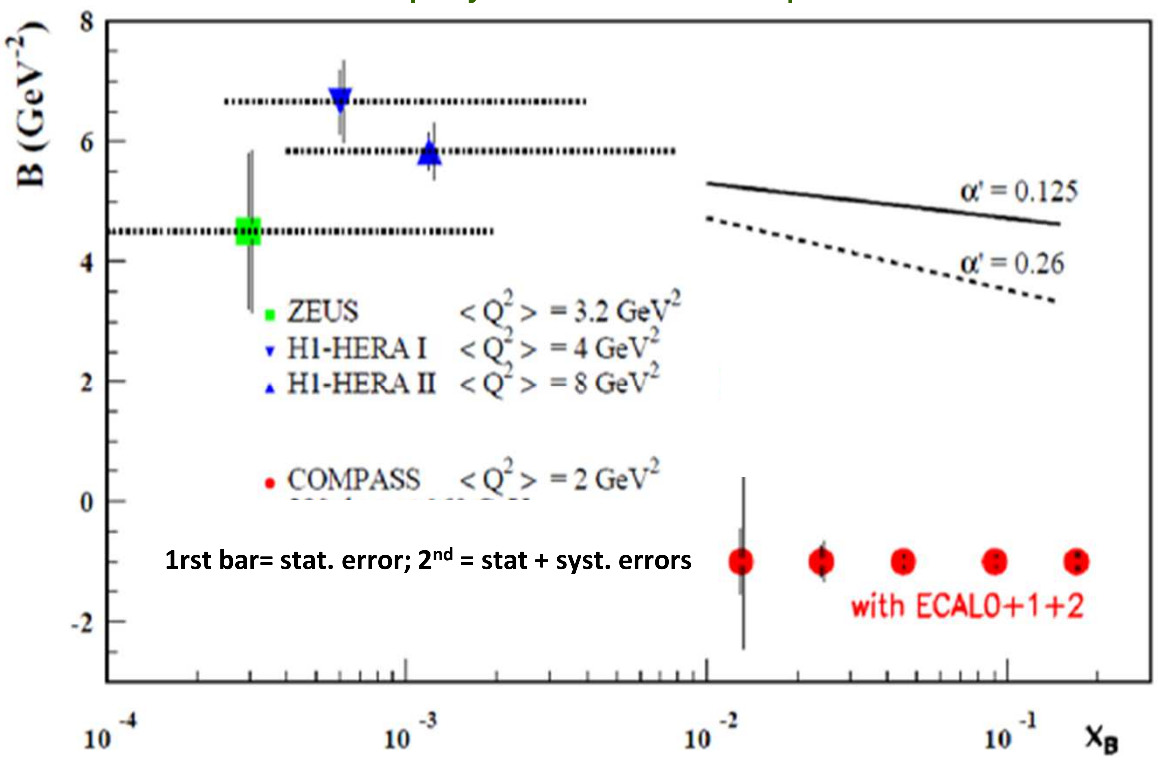
- dominant BH process at large ν (small x_{BJ}) clearly visible
- shape of ϕ distribution reproduced well by MC
- estimates of π^0 background contributing at small ν (large x_{BJ})
- at small ν (large x_{BJ}) an excess of DVCS events above BH + background

Transverse imaging of the proton using $d\sigma^{DVCS}/dt$

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

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

COMPASS-II projections for B-slope uncertainties



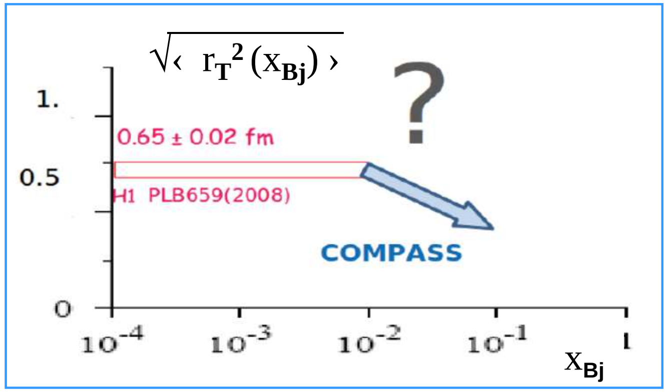
ansatz at small x_B
inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

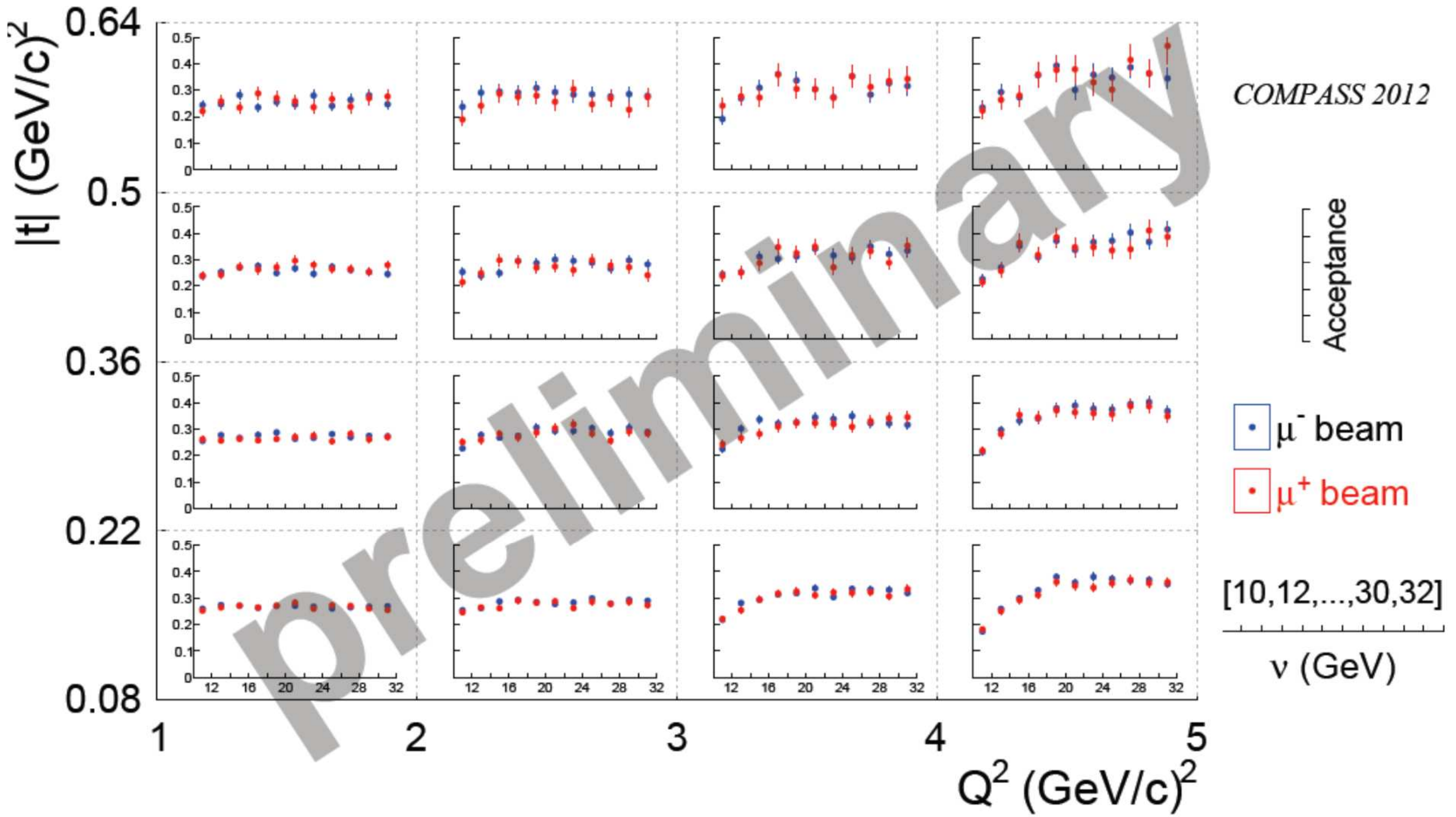
α' slope of Regge traject.

Predictions from COMPASS-II proposal
for 40 weeks in 2016-17

- From 4 weeks of 2012 commissioning data
  the first measurement of B-slope for DVCS
  an x_{Bj} above HERA range



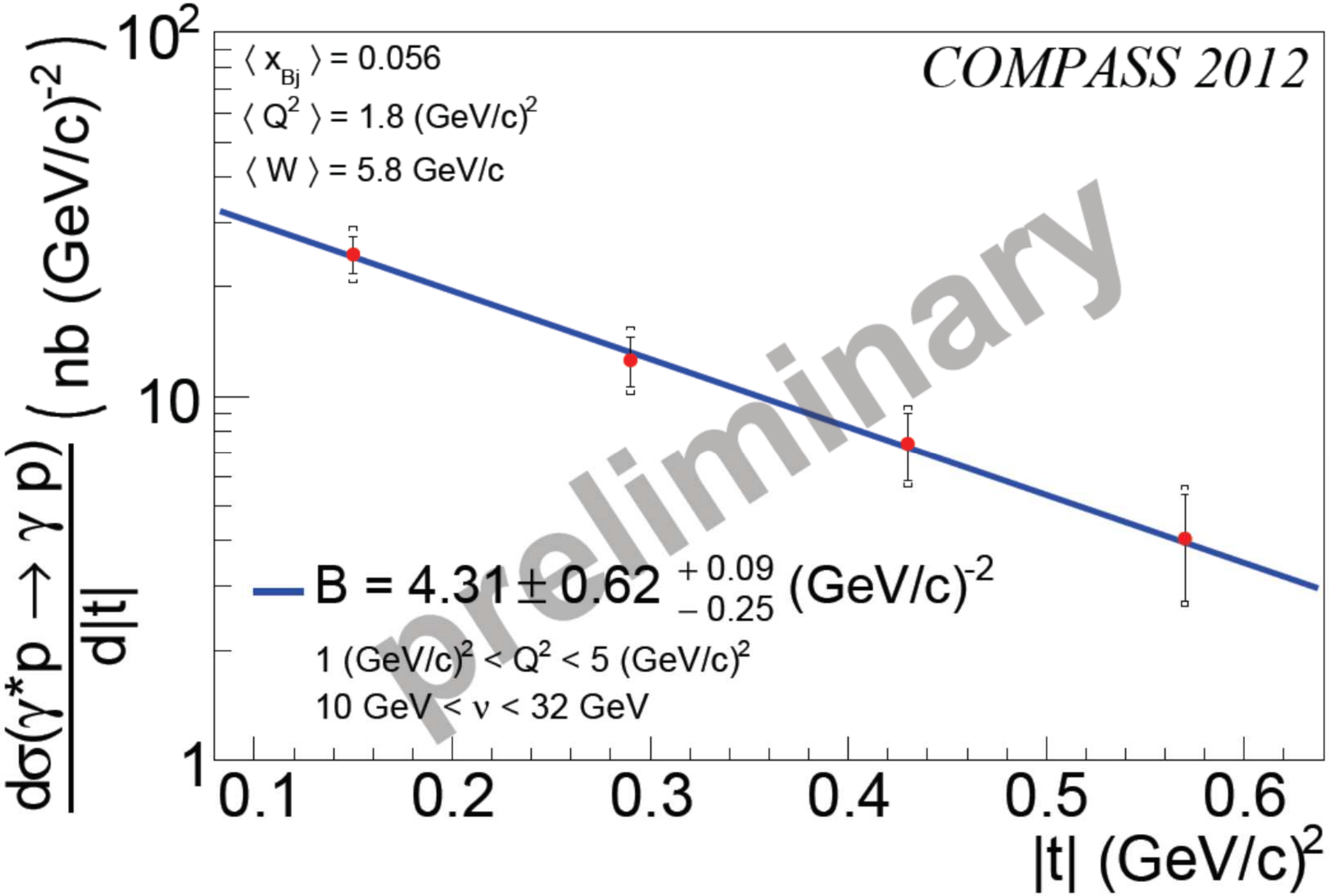
COMPASS acceptance for DVCS



Binning of acceptance in Q^2, ν and $|t|$

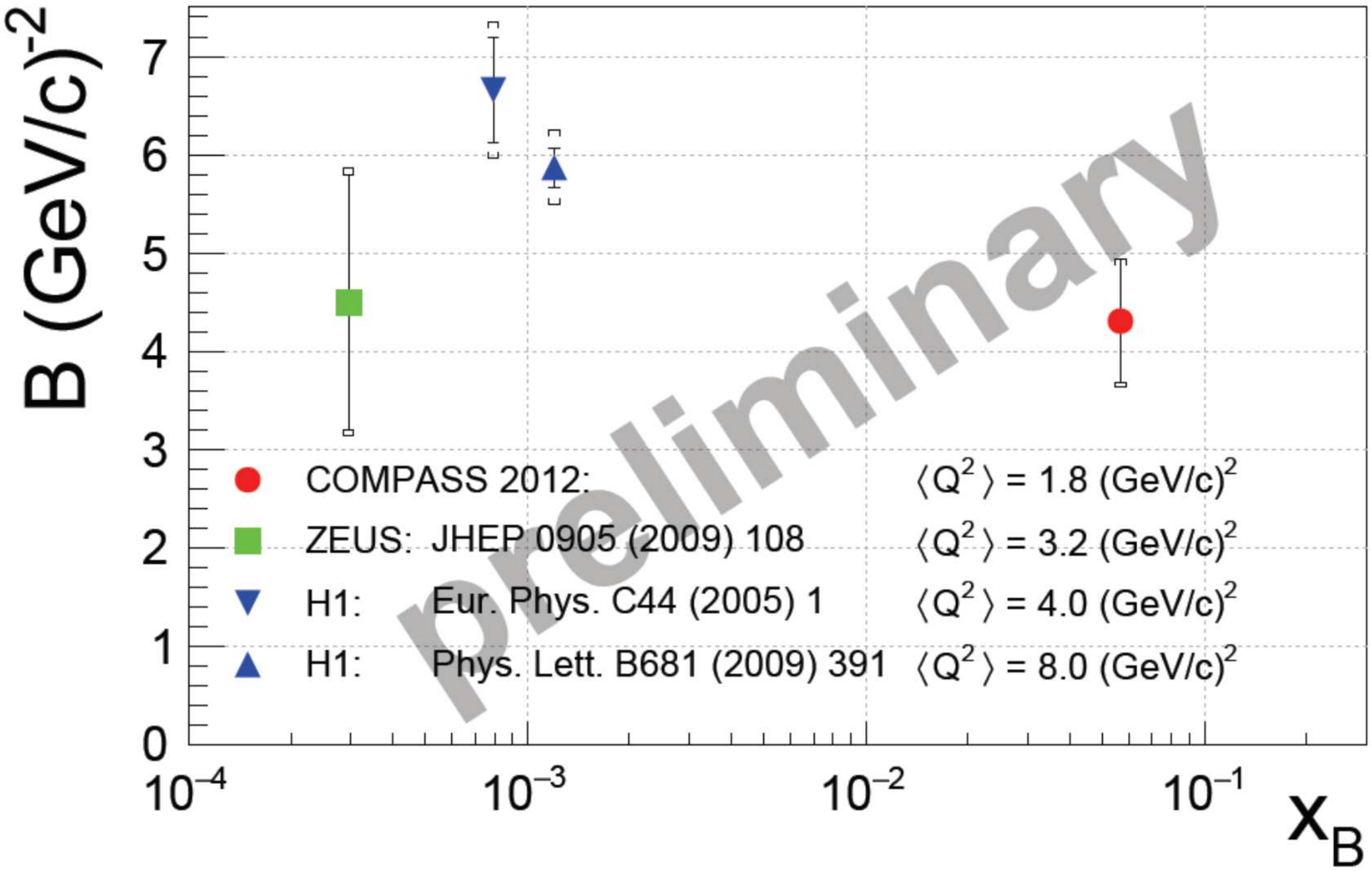
recall: $$\frac{d^3\sigma^{\mu p}}{dQ^2 d\nu\, dt} = \Gamma \frac{d\sigma^{\gamma^* p}}{dt}$$ with the virtual photon flux $\Gamma = \Gamma\,(Q^2, \nu)$

DVCS cross section and t-slope

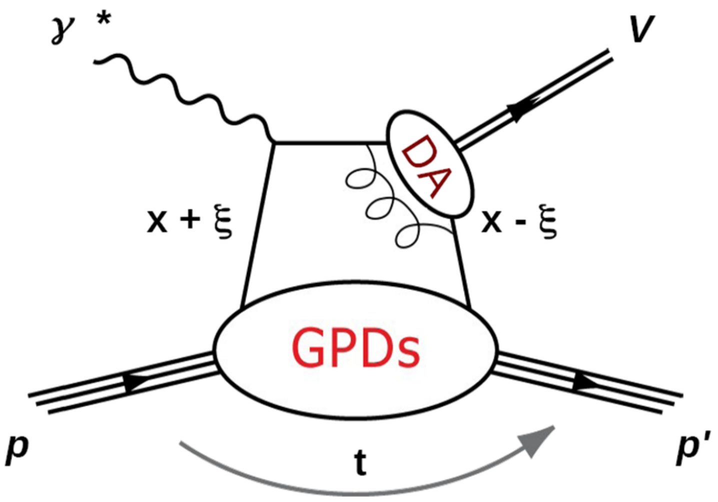


Comparison of t-slope B to HERA results

Model independent result



GPDs and Hard Exclusive Meson Production



- factorisation proven only for σ_L
  σ_T suppressed by $1/Q^2$
- wave function of meson (DA)
  additional non-perturbative term
- at $Q^2 \approx$ few GeV² higher order pQCD terms important

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
helicity of parton changed (not probed by DVCS)

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

Flavour separation for GPDs
example:

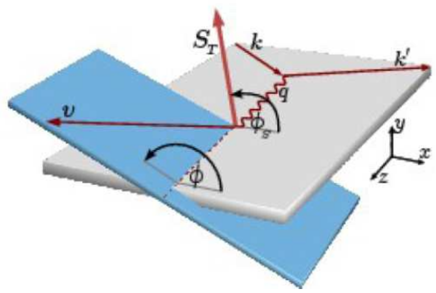
$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^{u(+)} + \frac{1}{3}E^{d(+)} + \frac{3}{4}E^g / x\right)$$
$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^{u(+)} - \frac{1}{3}E^{d(+)} + \frac{1}{4}E^g / x\right)$$
$$E_{\phi} = -\frac{1}{3}E^{s(+)} + \frac{1}{4}E^g / x$$

Diehl, Vinnikov PLB, 2005

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

Spin-dependent cross section for exclusive meson leptoproduction

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



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

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

$$- S_T\left[\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}\right.$$
$$\left.+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\right]$$

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

σ_{mn}^{ij}: helicity-dependent photoabsorption cross sections and interference terms

$$\sigma_{mn}^{ij}\left(x_B, Q^2, t\right) \propto \sum \left(M_m^i\right)^* M_n^j$$

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

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

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

Azimuthal asymmetries of cross section for exclusive meson leptoproduction

5 single spin asymmetries

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

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

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

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

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

3 double spin asymmetries

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

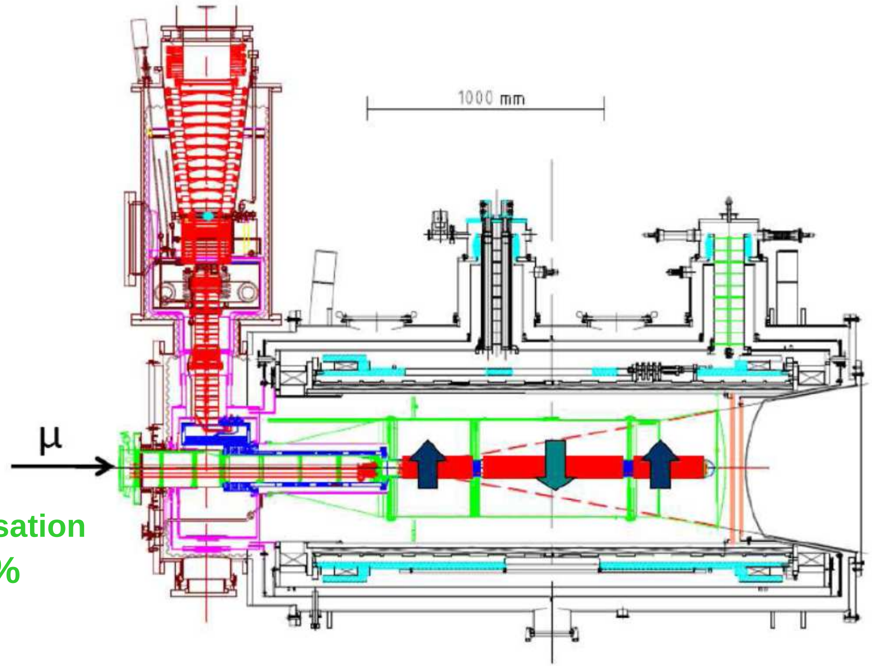
$$A_{LT}^{\cos(2\varphi-\varphi_s)} = -\frac{\mathrm{Re}\,\sigma_{+0}^{-+}}{\sigma_0}$$

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

σ_0 - ‘unpolarised cross section’

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

COMPASS polarised target



^{3}He - ^{4}He dilution refrigirator (T~50 mK)

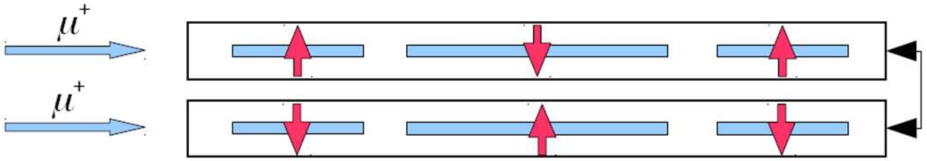
solenoid 2.5 T
dipole magnet 0.6 T

μ^+ polarisation ≈ -80%

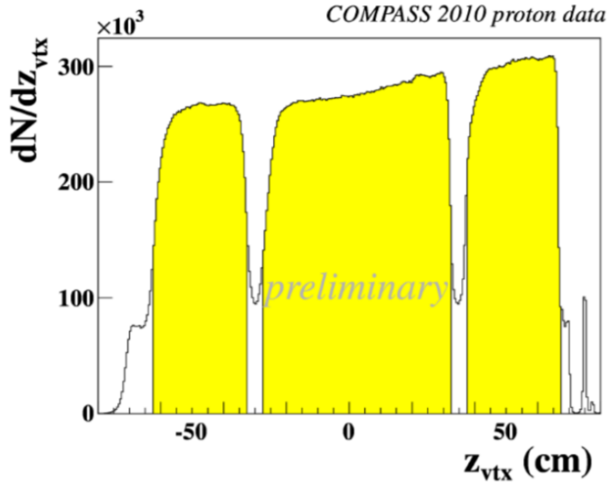
Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization

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

Luminosity $5\cdot10^{32}$ cm^{-2}s^{-1}



Microwave reversal every week



Exclusive ω production on $p^{\uparrow}$ at COMPASS

(Selections similar for ρ^0 sample)

$\mu N \rightarrow \mu \omega N$

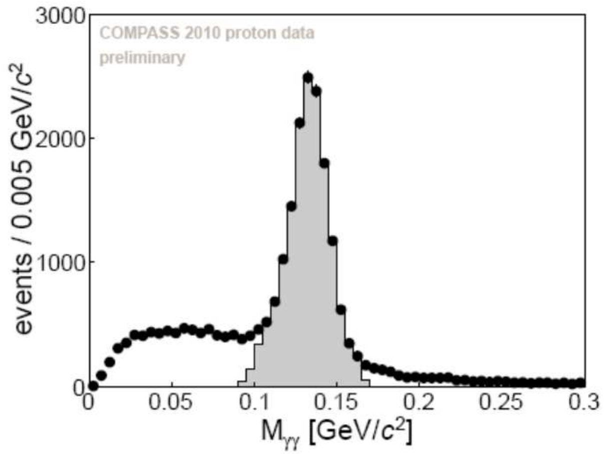
$\hookrightarrow \pi^+ \pi^- \pi^0$

$\hookrightarrow \gamma + \gamma$

Transversely polarised proton target (NH_3), 2010 data

note: there was no Recoil Detector for these data

only two hadron tracks of opposite charge associated to the primary vertex
only two ECAL clusters time-correlated with beam and not associated to a charged particle



$|M_{\pi\pi\pi} - M_\omega^{PDG}| < 0.07$ GeV
$-3 < E_{miss} < 3$ GeV
$E_\omega > 14$ GeV
$0.05 < p_T^2 < 0.5$ GeV²

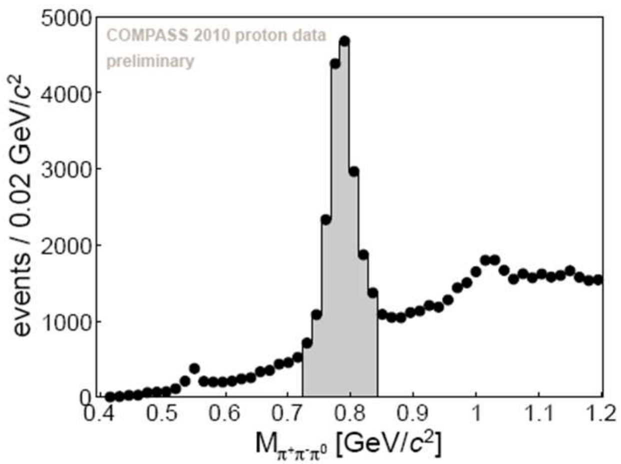
$1 < Q^2 < 10$ GeV²
$0.1 < y < 0.9$
$0.003 < x < 0.35$
$W > 5$ GeV

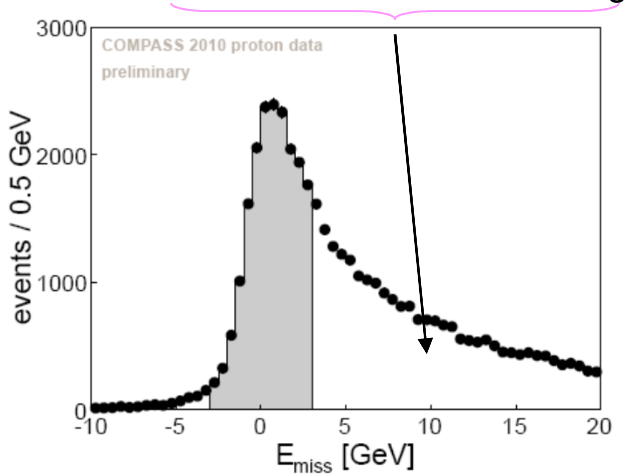
$E_{miss} = (M_X^2 - M_p^2)/(2M_p)$

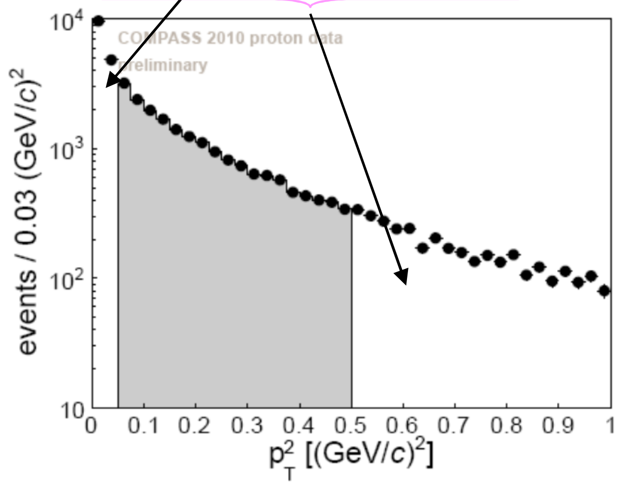
dominant non-excusive bkg.

dominant coherent contrib.

dominant non-exclusive bkg.



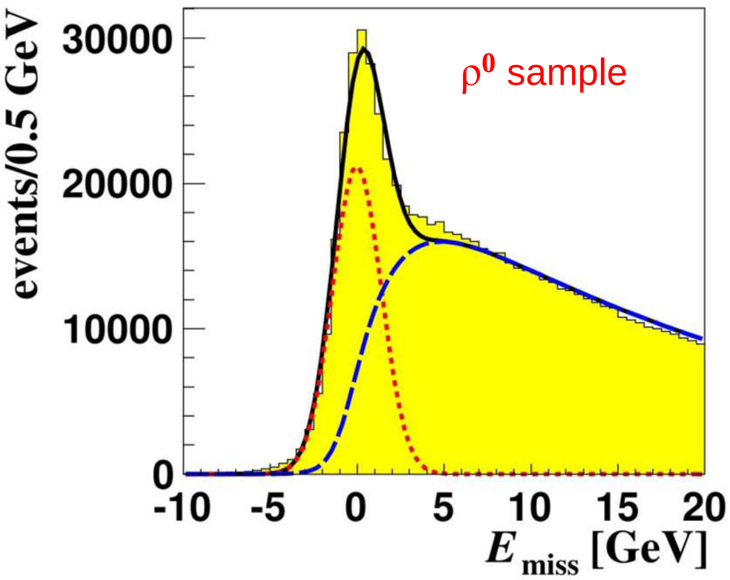




Extraction of asymmetries and subtraction of non-exclusive background

- ρ^0 analysis
  - 1D (deuteron) and 2D (proton) binned maximum likelihood estimator with subtraction of background in (φ, φ_S) bins
- ω analysis
  - Unbinned maximum likelihood estimator with simultaneous fit of signal and background asymmetries

Background rejection:
For each target cell and polarization state



shape of semi-inclusive background from MC
(LEPTO with COMPASS tuning + simulation of spectrometer response + reconstruction as for real data)

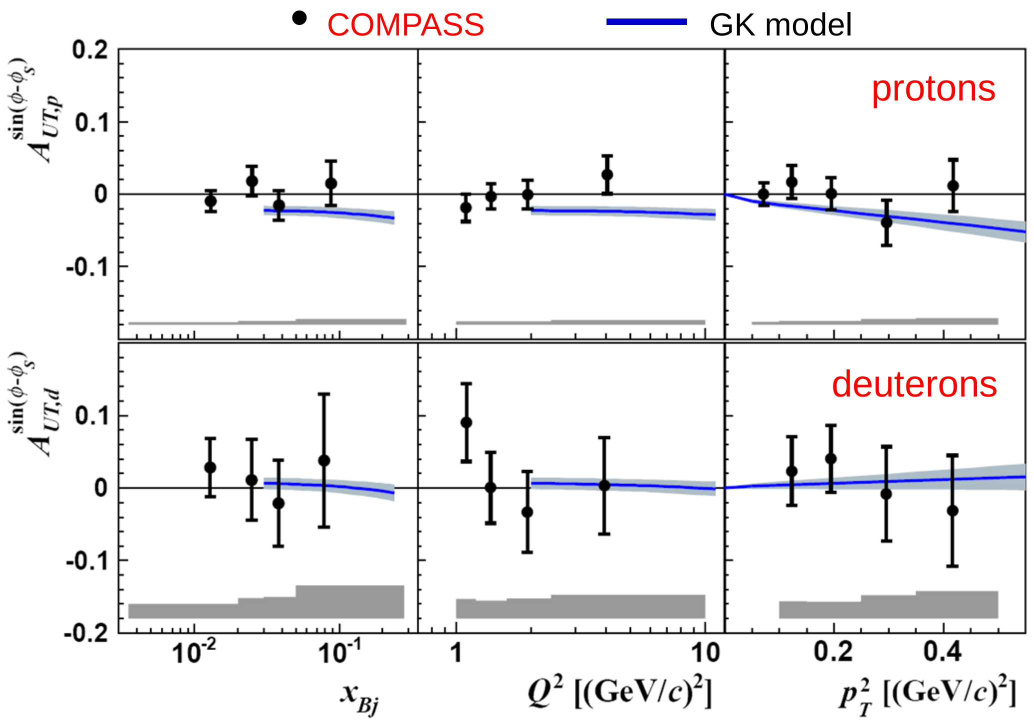
MC weighted using ratio between real data and MC for wrong charge combination sample ($h^+h^+\gamma\gamma$ + $h^-h^-\gamma\gamma$)

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

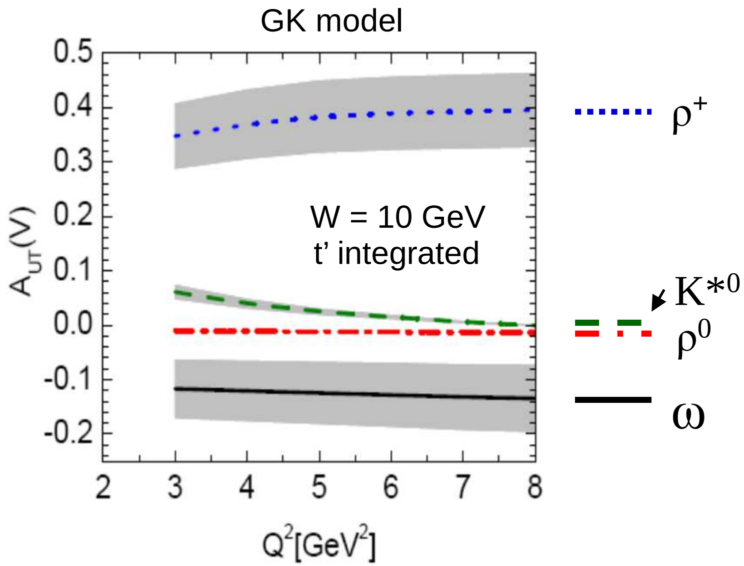
Normalization of MC to the real data using two component fit
Gaussian function (signal) + shape from MC (bkg)

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

→ **NPB 865 (2012) 1**



$A_{UT}^{sin(\phi-\phi_s)}$ contains twist-2 terms depending on $E^{q,g}$



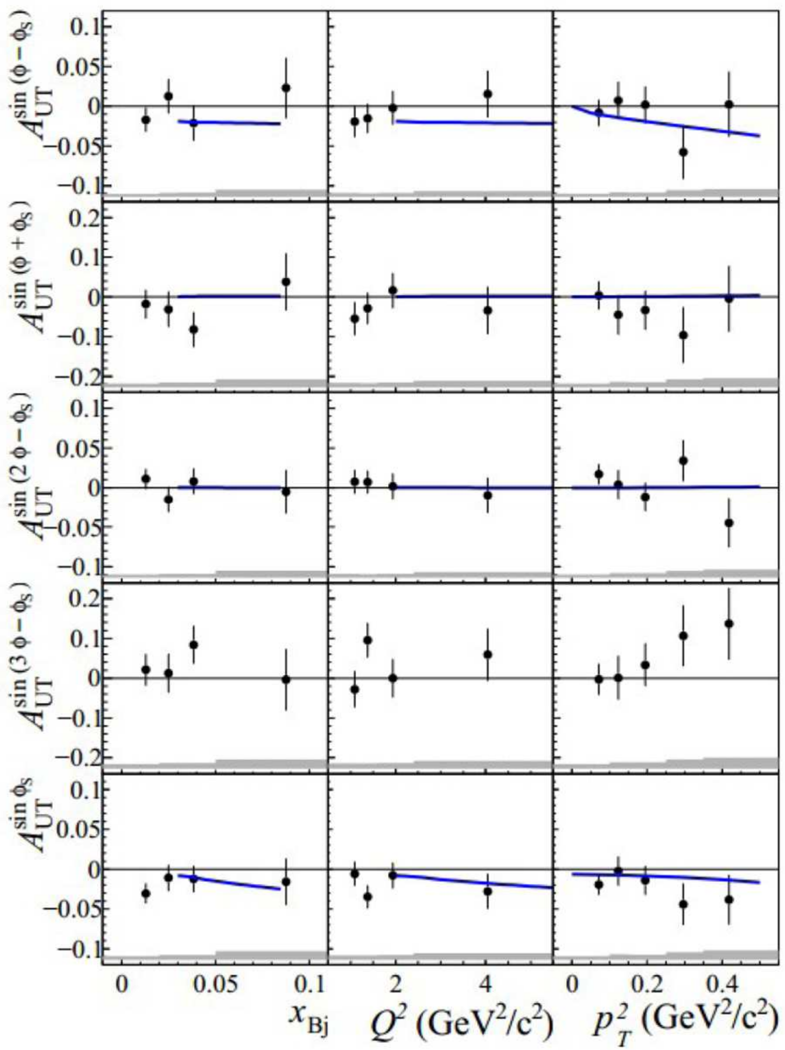
- $A_{UT}^{\sin(\phi\text{-}\phi s)}$ for transversely polarised protons and deuterons small, compatible with 0
- for the proton agreement with HERMES results
  COMPASS results with statistical errors improved by factor 3 and extended kinematic range
- for the deuteron the first measurement
- reasonable 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, $E^u \approx -E^d$

(cf. upper-right plot)

Complete set of transverse target spin asymmetries for exlusive ρ^0 production on $p^\uparrow$

Single spin asymmetries



$\langle x_{Bj} \rangle = 0.039$, $\langle Q^2 \rangle = 2.0$ GeV²
$\langle p_T^2 \rangle = 0.18$ GeV², $\langle W \rangle = 8.1$ GeV²

- Improved method of extraction (2D)
- Simultaneous extraction of
  5 single spin asymmetries and
  3 double spin asymmetries
  for transversely polarised protons

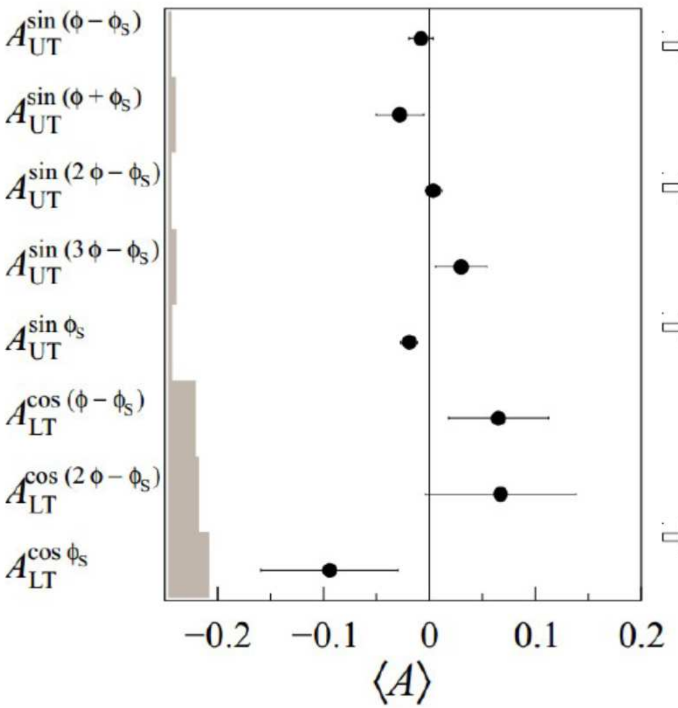
→ **PLB 731 (2014) 19**

—— predictions of GPD model of Goloskokov-Kroll

- reasonable agreement with GK model
  (also for not-shown double spin asym.)

Connection between azimuthal asymmetries and GPDs

exlusive ρ^0 production on $p^\uparrow$



~E ~H ~E ~H ~H_T ~$\bar{E}_T$

$$\Rightarrow A_{UT}^{\sin(\varphi-\varphi_s)}\sigma_0 = -2\,Im[\epsilon M^*_{0-,0+} M_{0+,0+} + M^*_{+-,++} M_{++,++} + \frac{1}{2} M^*_{0-,++} M_{0+,++}]$$

~$\bar{E}_T$ ~E

$$\Rightarrow A_{UT}^{\sin(2\varphi-\varphi_s)}\sigma_0 = -Im[M^*_{0+,++} M_{0-,0+}]$$

~H_T ~H ~$\bar{E}_T$ ~E

$$\Rightarrow A_{UT}^{\sin(\varphi_s)}\sigma_0 = -Im[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}]$$

~H_T ~H ~$\bar{E}_T$ ~E

$$\Rightarrow A_{LT}^{\cos(\varphi_s)}\sigma_0 = -Re[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}]$$

M_{Vp',γ^*p} helicity amplitudes
σ_0 unpolarised cross section
$H_T(x, 0, 0) = h_1(x)$
$\bar{E}_T = 2\tilde{H}_T - E_T$

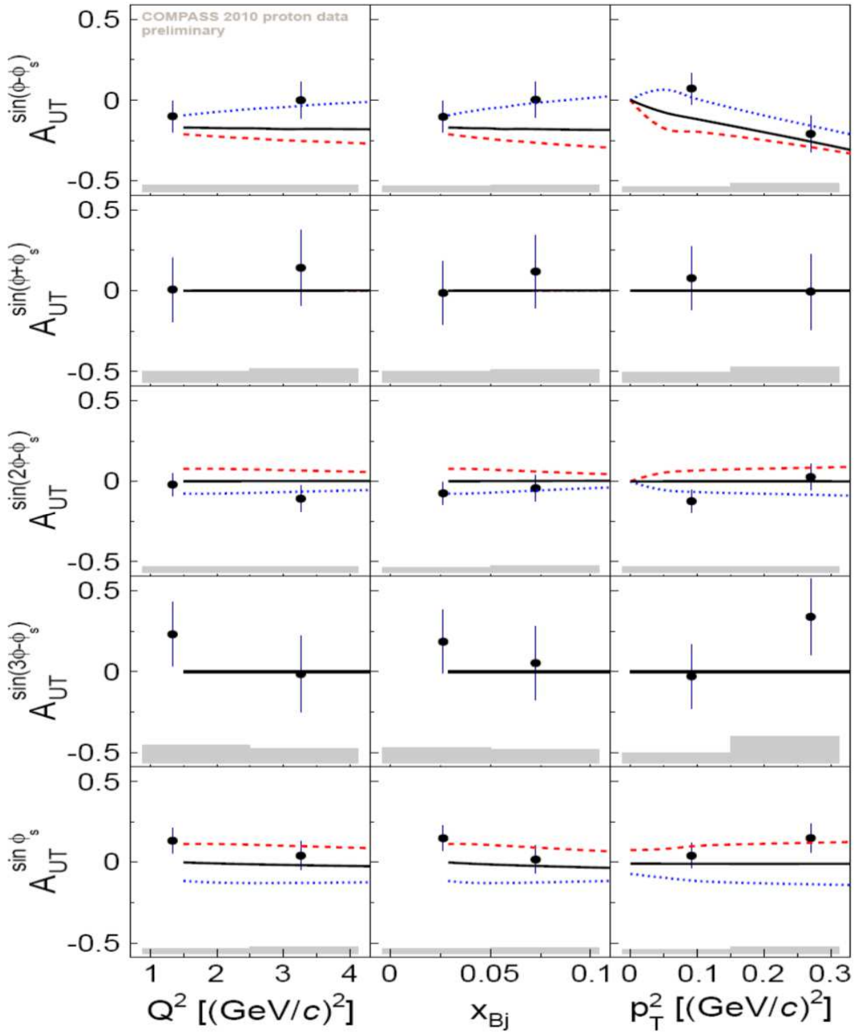
- asymmetries small, compatible with 0, except

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

- indication of H_T, 'transversity' GPD, contribution
- larger effects for some asymmetries expected for exclusive ω production

Azimuthal asymmetries for exlusive ω production on p↑

Single spin asymmetries

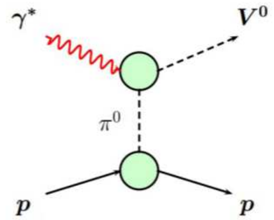


$\langle x_{Bj} \rangle = 0.049$, $\langle Q^2 \rangle = 2.2$ GeV²
$\langle p_T^2 \rangle = 0.17$ GeV², $\langle W \rangle = 7.1$ GeV²

- new result, to be published
- unbinned maximum likelihood method
- extraction of 8 transverse spin asymmetries

comparison to modified GPD model of GK

with added π^0 pole exchange



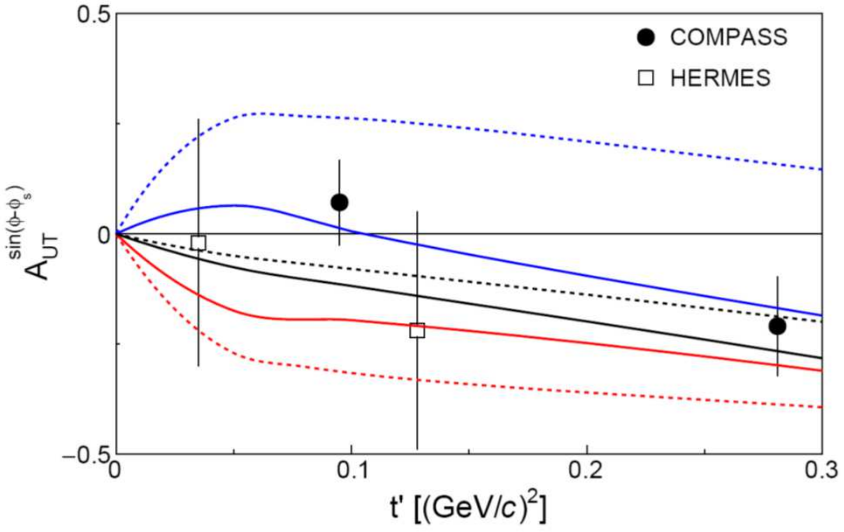
EPJ A50 (2014) 146

parameters constrained by HERMES SDMEs for ω
except sign of πω transition form factor
more sensitivity in azimuthal asymmetries

GK predictions for COMPASS, private com.
- no pion pole (solid black line)
- positive πω form factor (dashed red line)
- negative πω form factor (dotted blue line)

- when 'global' comparison to the data
  no clear preference for any version

Comparison to HERMES asymmetries for ω production on p↑



COMPASS <W> = 8 GeV	HERMES <W> = 4.8 GeV	← **EPJ C75 (2015) 600**
black solid line	black dotted line	no pion pole
red solid line	red dotted line	positive $\pi\omega$ form factor
blue solid line	blue dotted line	negative $\pi\omega$ form factor

✓ Note: contribution of pion pole decreases with W

→ each experiment to be compared to corresp. predictions

✓ COMPASS uncertainties smaller by a factor > 2

✓ within large errors combined HERMES data compatible with all 3 scenarios

(authors conclusion 'data favor a positive $\pi\omega$ transition form factor')

✓ Future measurements at JLab12 **EPJ A48 (2012) 187**

expected to resolve the issue of $\pi\omega$ transition form factor

COMPASS-II time lines

Part of the COMPASS-II proposal approved and scheduled by CERN

- 2012: pion and kaon polarisabilities (Primakoff) + comissioning and pilot run for DVCS
- 2013-2014: long SPS/LHC shutdown
- 2014-2015: Drell-Yan measurements with transversely polarised protons (NH_3 target)
- 2016-2017: stage 1 of GPD program and in parallel SIDIS (LH target)
- 2018: Drell-Yan measurements with transversely polarised protons (NH_3 target)

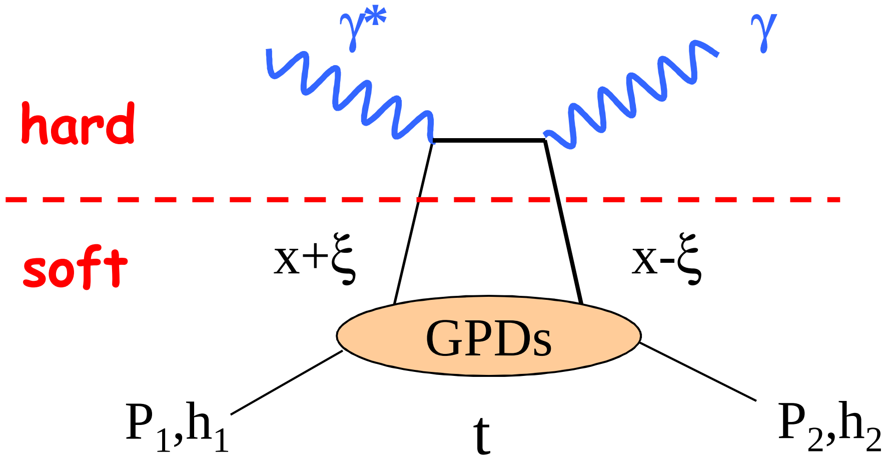
Measurements to be pursued at COMPASS-II > 2020 (subject to a new proposal)

- ✓ stage 2 of GPD program with transversely polarised NH_3 target and RPD
- ✓ SIDIS (high statistics) from transversely polarised deuteron and proton targets
- ✓ Drell-Yan on transversely polarised deuterons, unpolarised protons and nuclear targets
- ✓ hadron spectroscopy program with high-intensity separated kaon and antiproton beams


Thank you !

Backup

Generalized Parton Distributions and DVCS



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

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

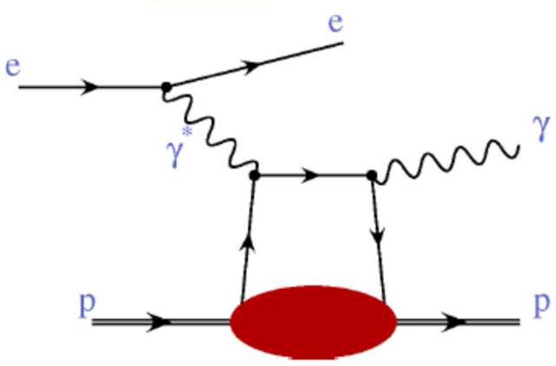
P_i, h_i – proton momentum and helicity

4 Generalised Parton Distributions : $H, E, \tilde{H}, \tilde{E}$ (chiral even)
for each quark flavour and for gluons

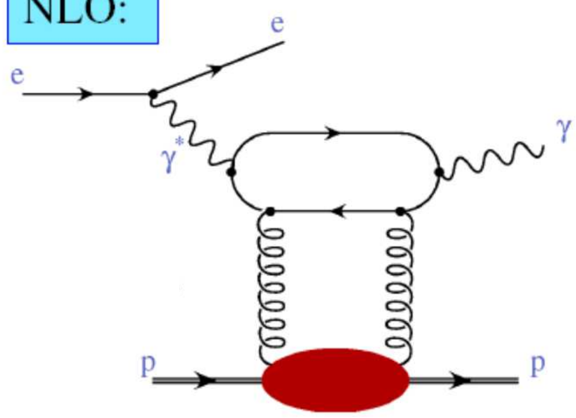
depend on 3 variables: x, ξ, t

for DVCS gluons contribute at higher orders in α_s

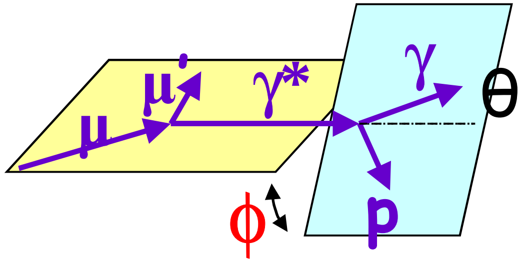
LO:



NLO:



Azimuthal dependence of exclusive photon xsec.



from Belitsky, Kirchner, Müller :
polarized beam off unpolarized target

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

$$d\sigma^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)}\left(c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right)$$ ← Known expression

$$d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2Q^2}\left(c_0^{DVCS} + c_1^{DVCS}\cos\varphi + c_2^{DVCS}\cos 2\varphi\right)$$

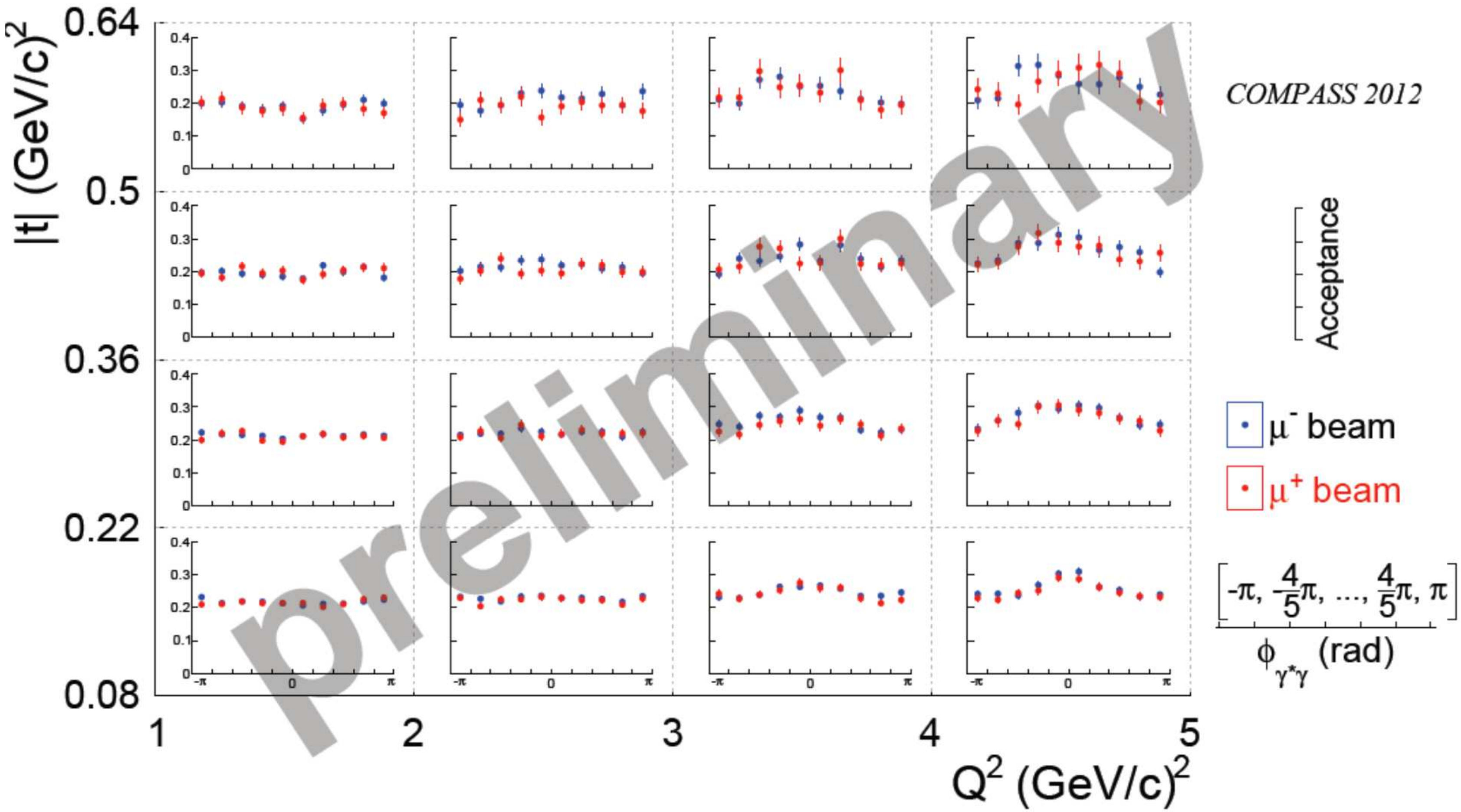
$$P_\mu \times \quad d\sigma^{DVCS}_{pol} = \frac{e^6}{y^2Q^2}\left(s_1^{DVCS}\sin\varphi\right)$$

$$e_\mu \times \quad a^{BH}\,\Re e\, A^{DVCS} = \frac{e^6}{xy^3 t P_1(\varphi)P_2(\varphi)}\left(c_0^{Int} + c_1^{Int}\cos\varphi + c_2^{Int}\cos 2\varphi + c_3^{Int}\cos 3\varphi\right)$$

$$e_\mu P_\mu \times \quad a^{BH}\,\Im m\, A^{DVCS} = \frac{e^6}{xy^3 t P_1(\varphi)P_2(\varphi)}\left(s_1^{Int}\sin\varphi + s_2^{Int}\sin 2\varphi\right)$$

Twist-2 >> Twist-3 Twist-2 gluon

COMPASS acceptance for DVCS (1)



Symmetric acceptance in ϕ leads to cancellation of the interference terms when integrated over ϕ

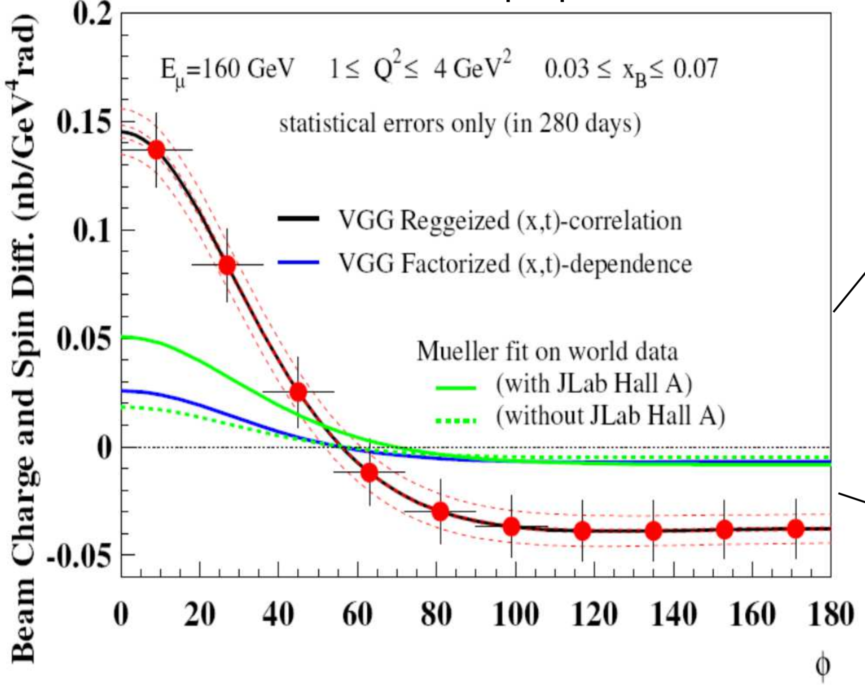
Beam Charge&Spin Difference of cross sections

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) =$$

$$c_0^{Int} + c_1^{Int} \cos\phi + c_2^{Int} \cos 2\phi + c_3^{Int} \cos 3\phi + s_1^{DVCS} \sin\phi$$

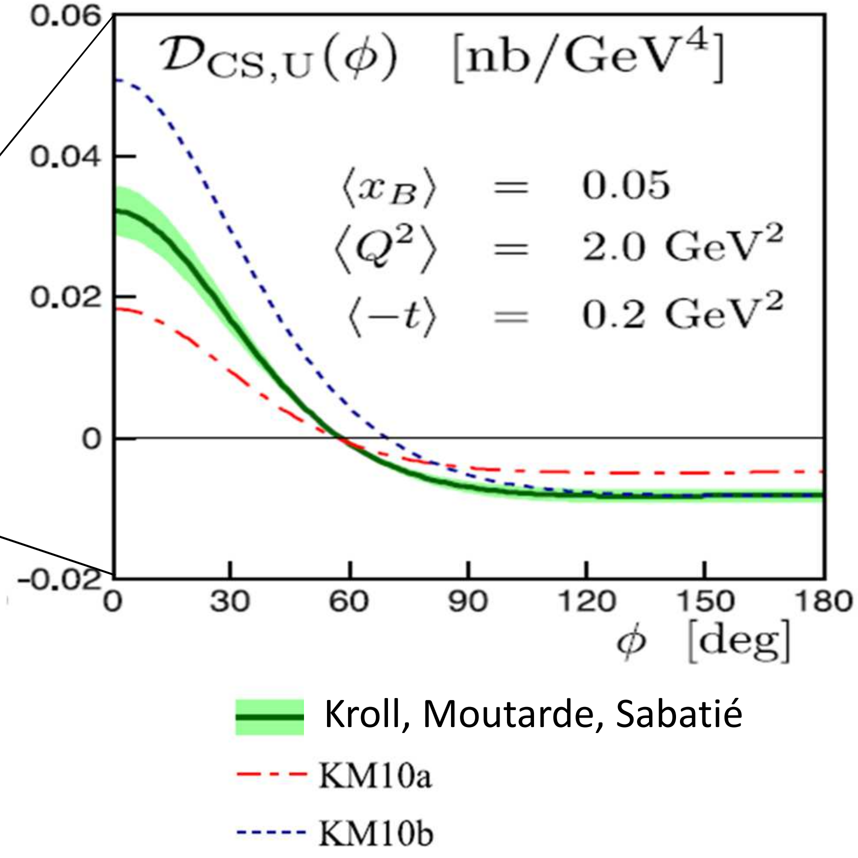
$$c_{0,1}^{Int} \rightarrow \mathcal{R}e(F_1 \mathcal{H})$$

COMPASS-II proposal



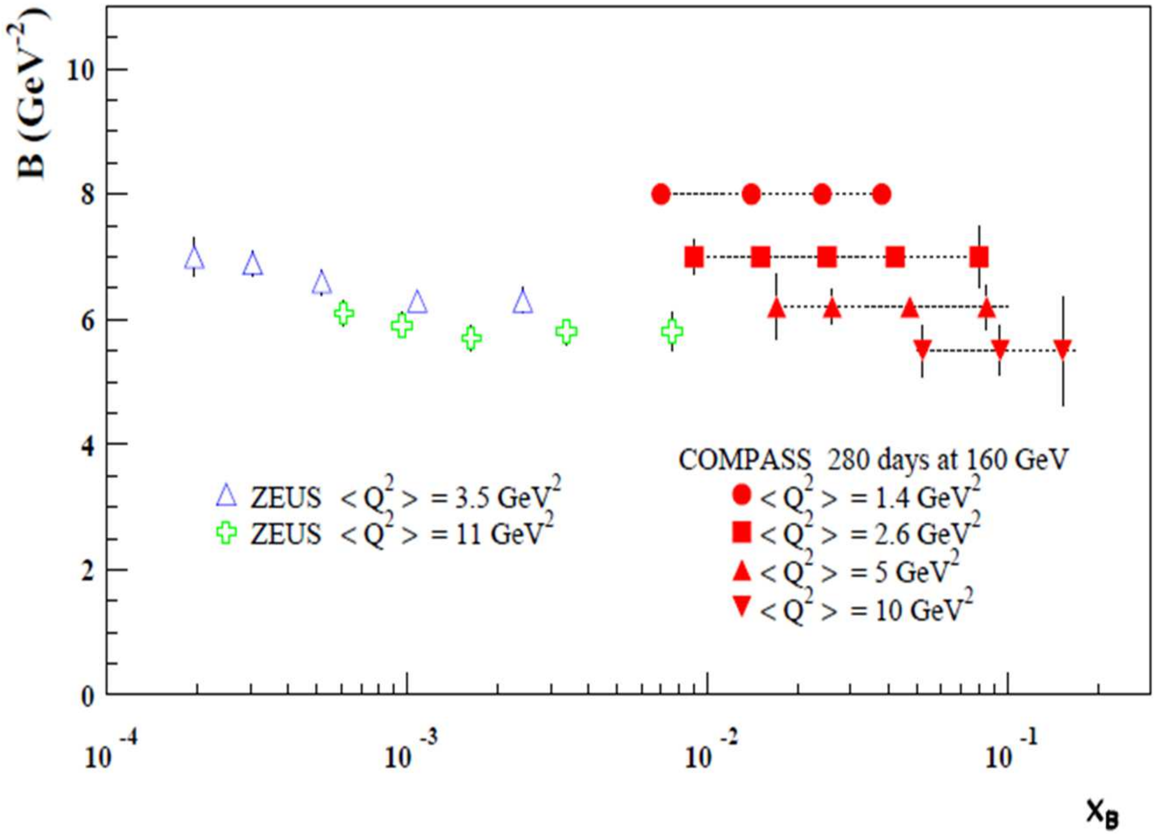
Systematic error: 3% mostly due to luminosity measurements for μ^+ and μ^-

Kroll, Moutarde and Sabatié



t-slope measurement for exclusive ρ^0 production

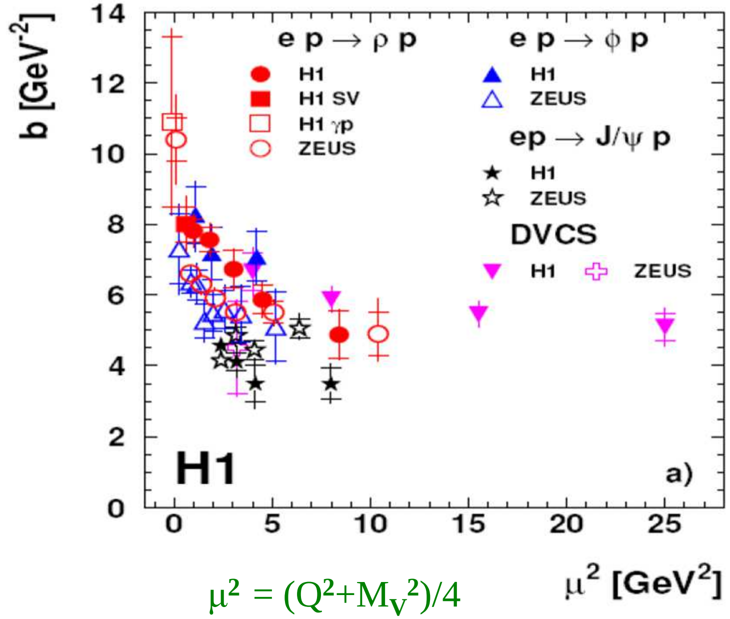
$$d\sigma_{\gamma N \to \rho N}/dt \;\sim\; \exp(-B|t|)$$



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

$0.06 < |t| < 0.64$ 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)

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

$\mu N \to \mu \rho^0 N$

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 hadron tracks of opposite charge associated to the primary vertex

DIS cuts

$1 < Q^2 < 10$ GeV^2

$0.1 < y < 0.9$

$0.003 < x < 0.35$

$W > 5$ 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]

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

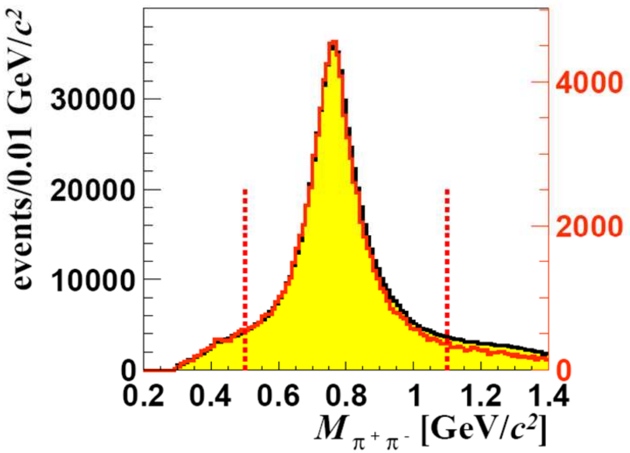
proton data (797 000 evts)

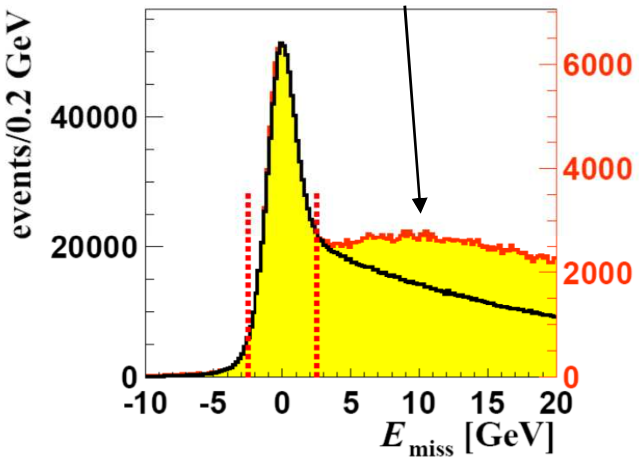
deuteron data (97 000 evts)

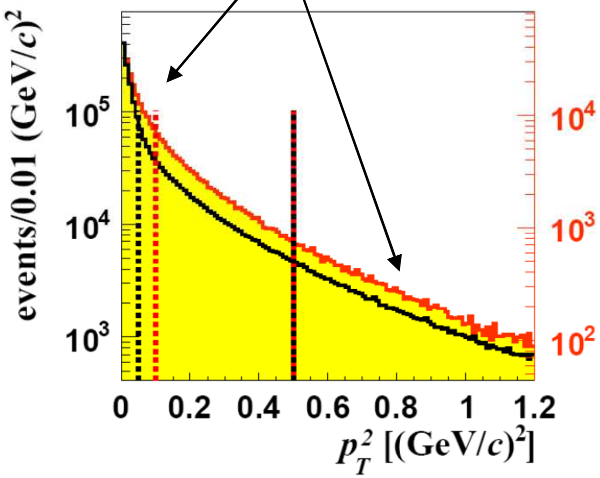
dominant non-excusive bkg.

dominant coherent contrib.

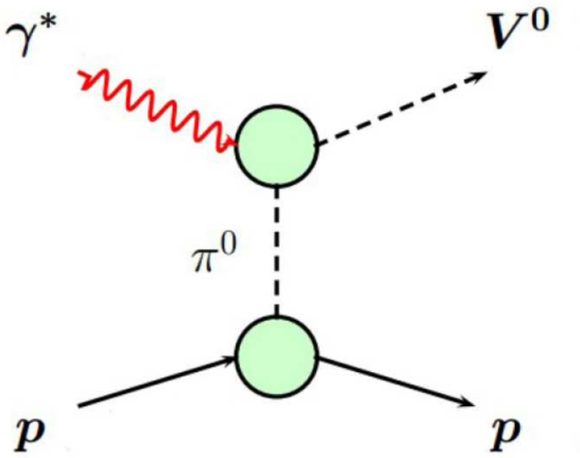
dominant non-exclusive bkg.







Role of pion exchange



- Effect known since early photoproduction experiments
- At COMPASS kinematics:
  - small for ρ^0 production
  - sizable for ω production
- Unnatural parity exchange process
  → impact on helicity-dependent observables
- Crucial for description of SDMEs for excl. ω production
  → Goloskokov and Kroll, Eur. Phys. J. A50 (2014) 9, 146
- Sign of $\pi\omega$ form factor not resolved from SDMEs data
  → azimuthal asymmetries more sensitive