Deeply Virtual Meson Production in muon scattering

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Next-generation GPD studies with exclusive meson production at EIC

CFNS Stony Brook, 4 – 6 June 2018

COMPASS experiment at CERN

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

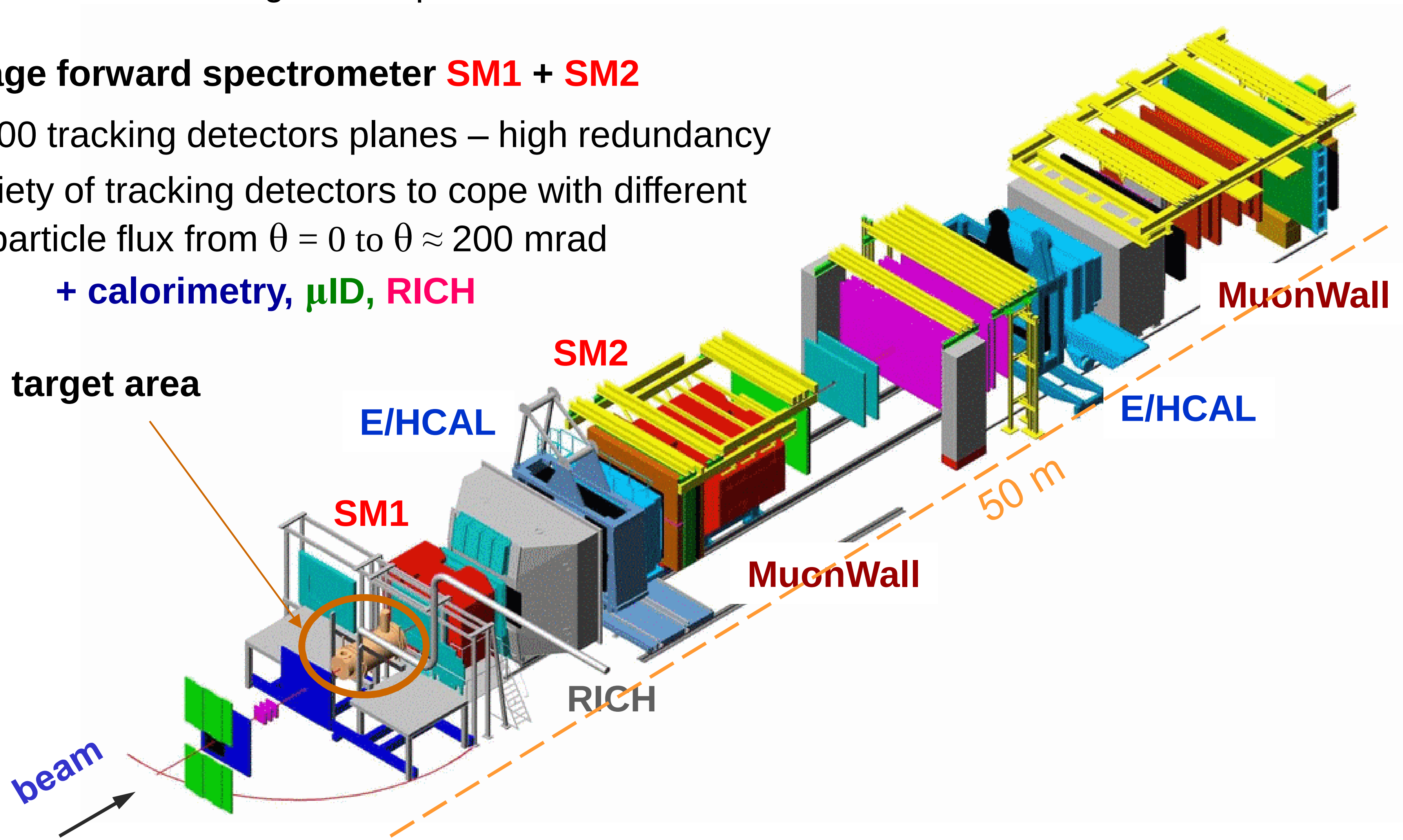
- **two-stage forward spectrometer SM1 + SM2**

  ≈ 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

- **flexible target area**



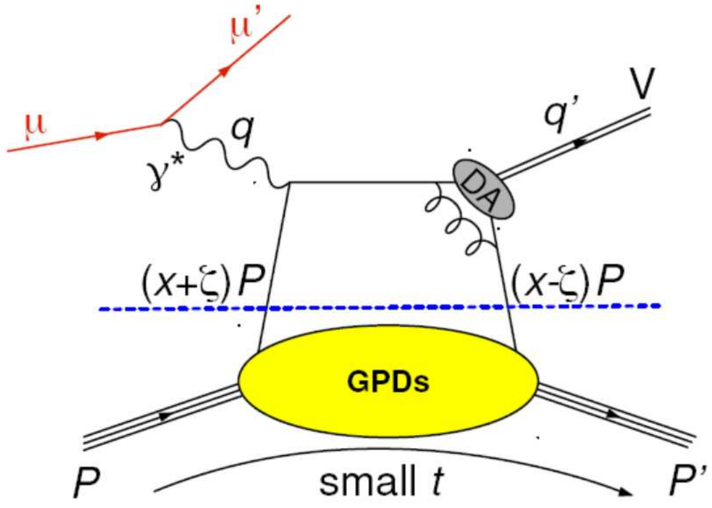
Physics programs

A flexibility to carry out a diverse physics programs
by using different beams and modifying mainly the target region

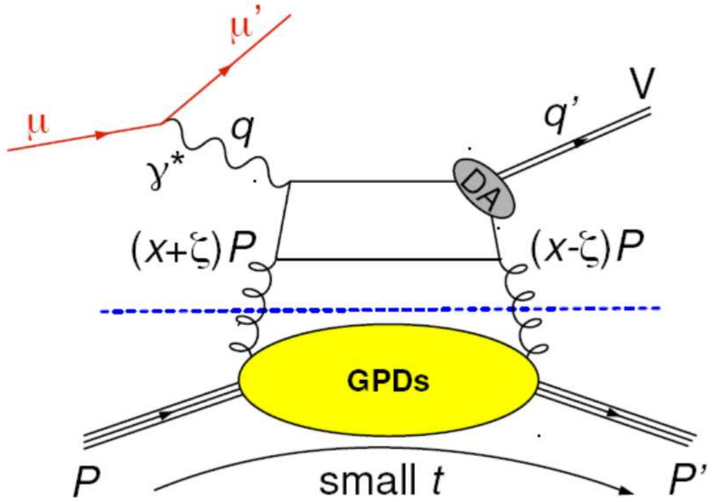
- spin structure of the nucleons; polarised muon-nucleon scattering
- hadron spectroscopy in diffractive and central hadron production
- Primakoff reactions and test of chiral perturbative theory
- polarised and unpolarised Drell-Yan scattering
- GPD studies; DVCS and hard exclusive meson production

GPDs and Hard Exclusive Meson Production

quark contribution



gluon contribution



- factorisation proven only for σ_L
  σ_T suppressed by $1/Q^2$
- wave function of meson (DA)
  additional non-perturbative term

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

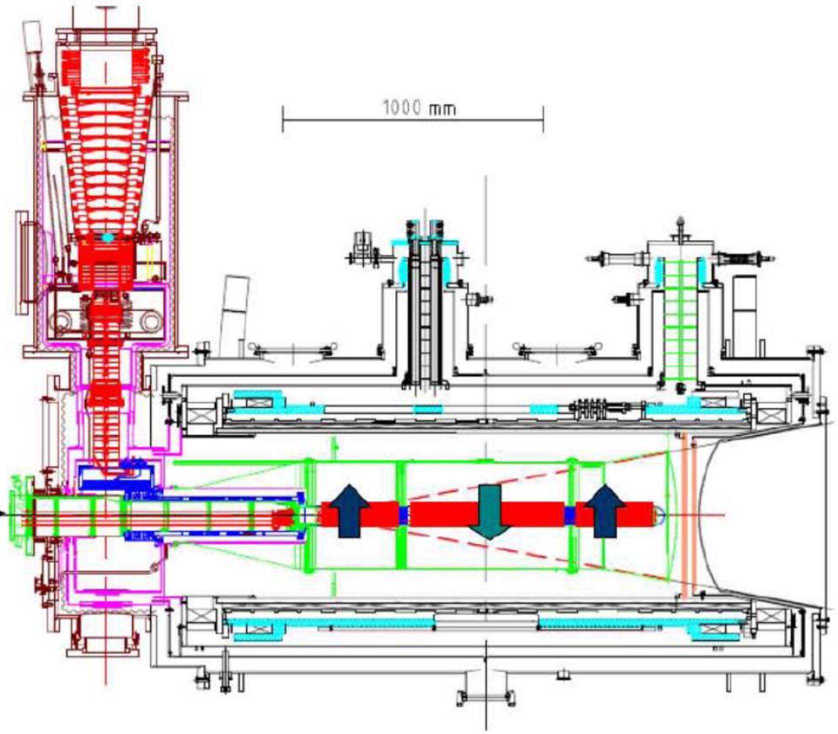
- *contribution from gluons at the same order of α_s as from quarks*

Exclusive ρ^0 and ω production

on transversely polarised protons and deuterons

COMPASS polarised target

μ



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

solenoid 2.5 T

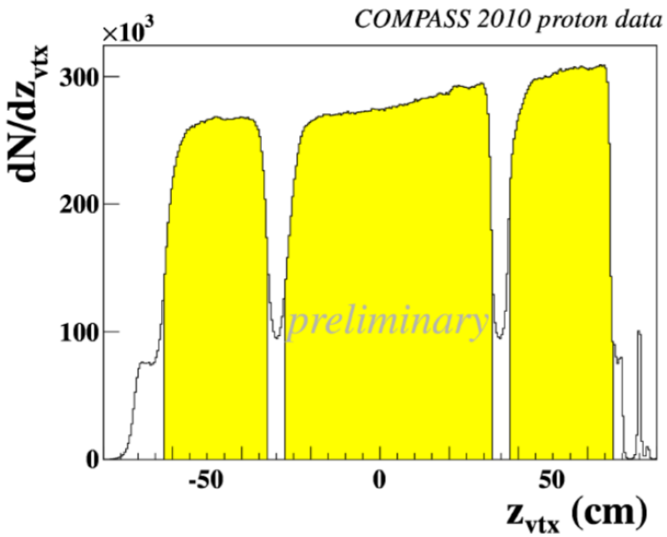
dipole magnet 0.6 T

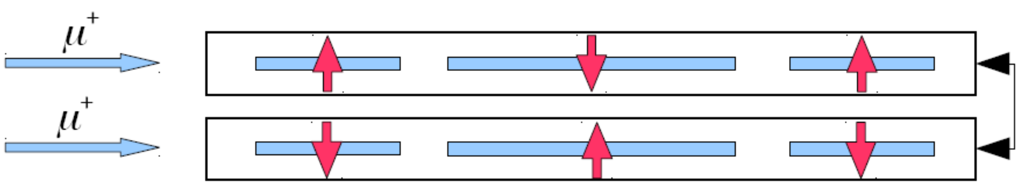
μ^+ polarisation ≈ -80%

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}**

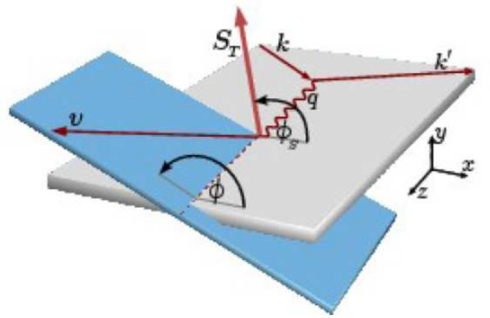




Microwave reversal every week

Spin-dependent cross section for exclusive meson leptoproduction

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



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

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

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

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

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

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

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

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

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 $\gamma^* p \to V p'$ with photon helicity *m* and target proton helicity *i*

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

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

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’

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

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

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

Transversely polarised proton target (NH_3) (2007,2011)
Transversely polarised deuteron target (^{6}LiD) (2003-2004)

only two hadron tracks of opposite charge associated to the primary vertex

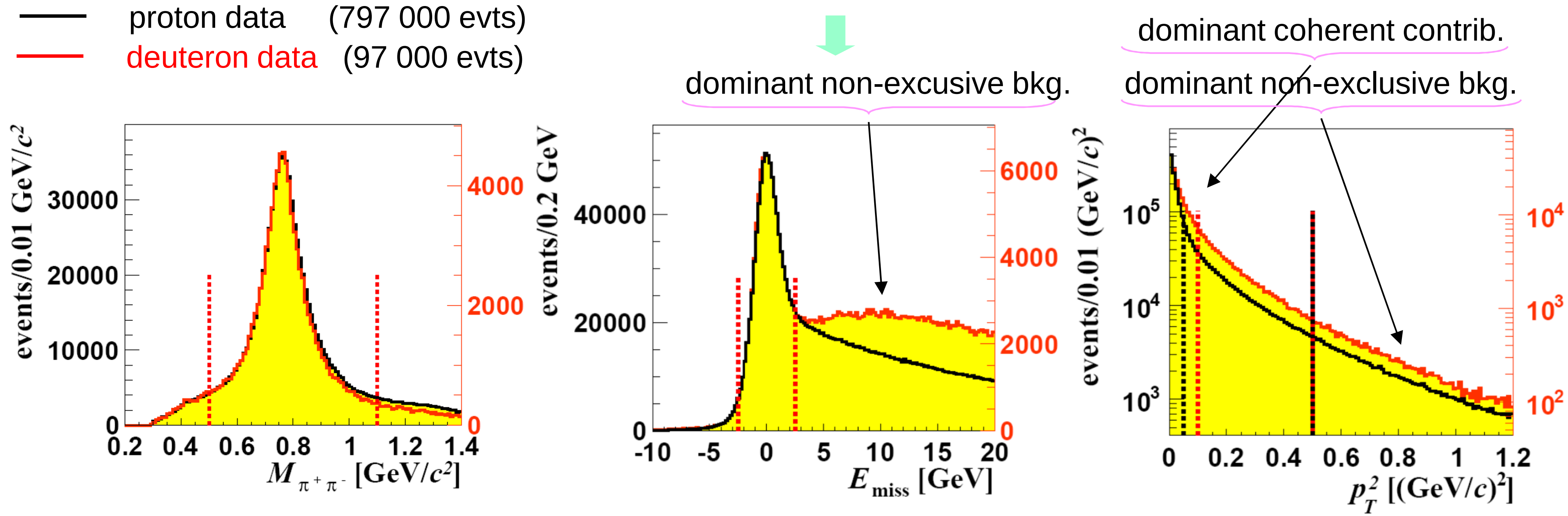
note: there was no RPD for these data

DIS cuts

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

cuts specific for exclusive ρ^0 analysis

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



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

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

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

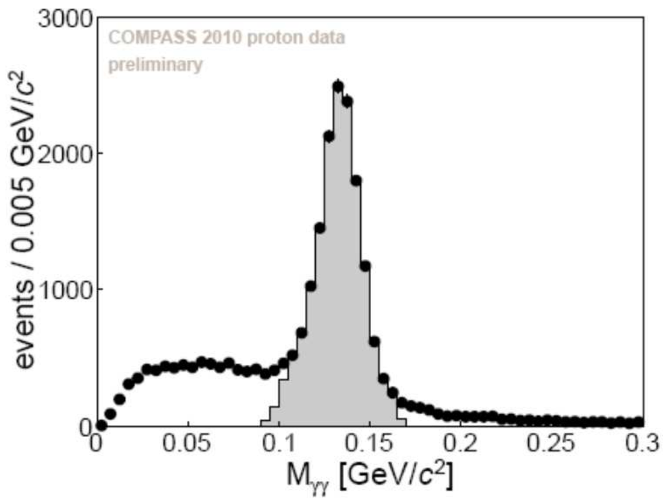
$\hookrightarrow \gamma + \gamma$

Transversely polarised proton target (NH_3), 2010 data

note: there was no RPD 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



$1 < Q^2 < 10$ GeV²

$0.1 < y < 0.9$

$0.003 < x < 0.35$

$W > 5$ GeV

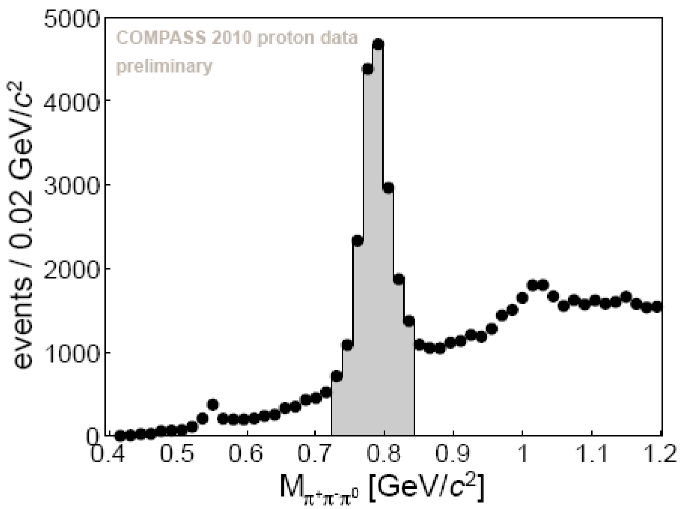
After all selections and cuts

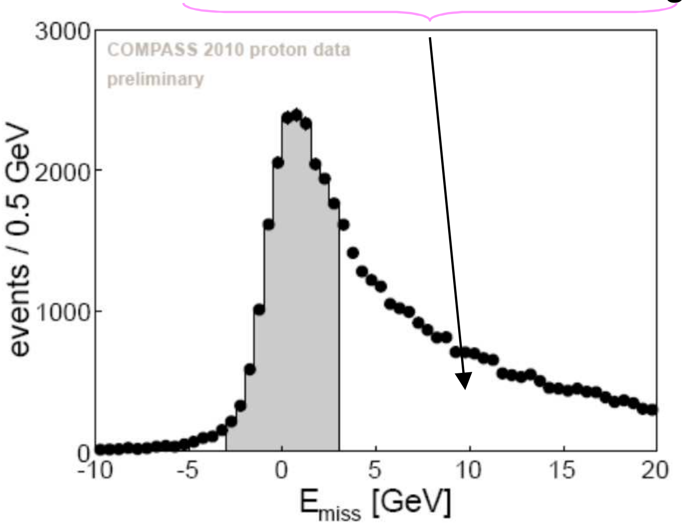
≈ 19 000 evts

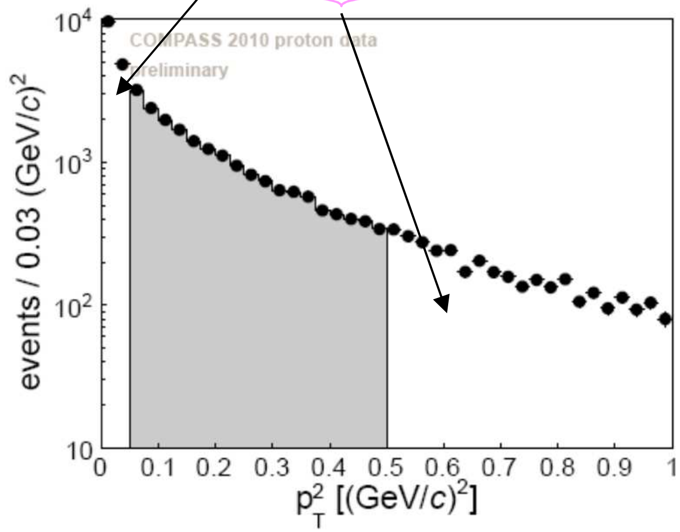
dominant coherent contrib.

dominant non-excusive bkg.

dominant non-exclusive bkg.



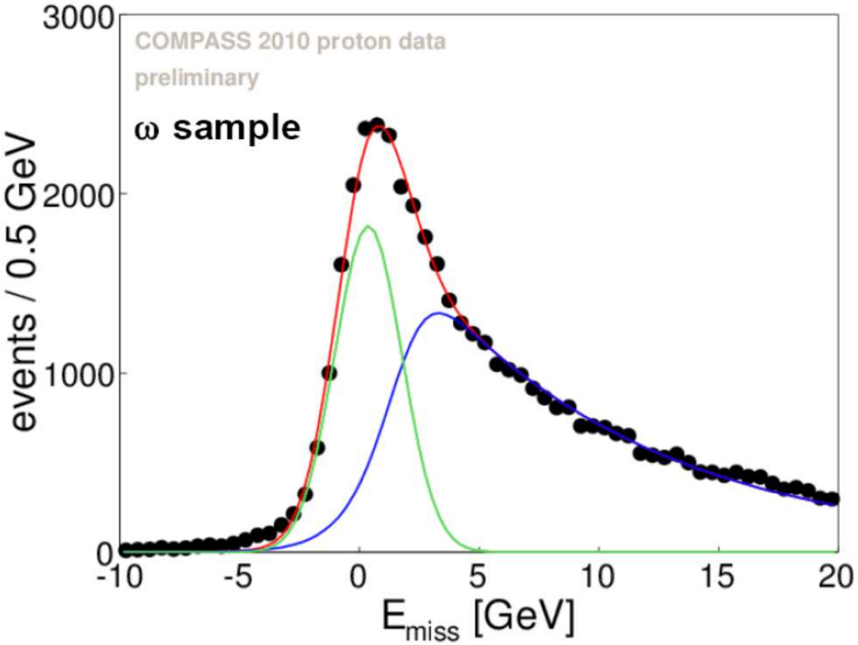




Extraction of asymmetries and subtraction on non-exclusive background

- 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 ($h^+h^+\gamma\gamma$ + $h^-h^-\gamma\gamma$)

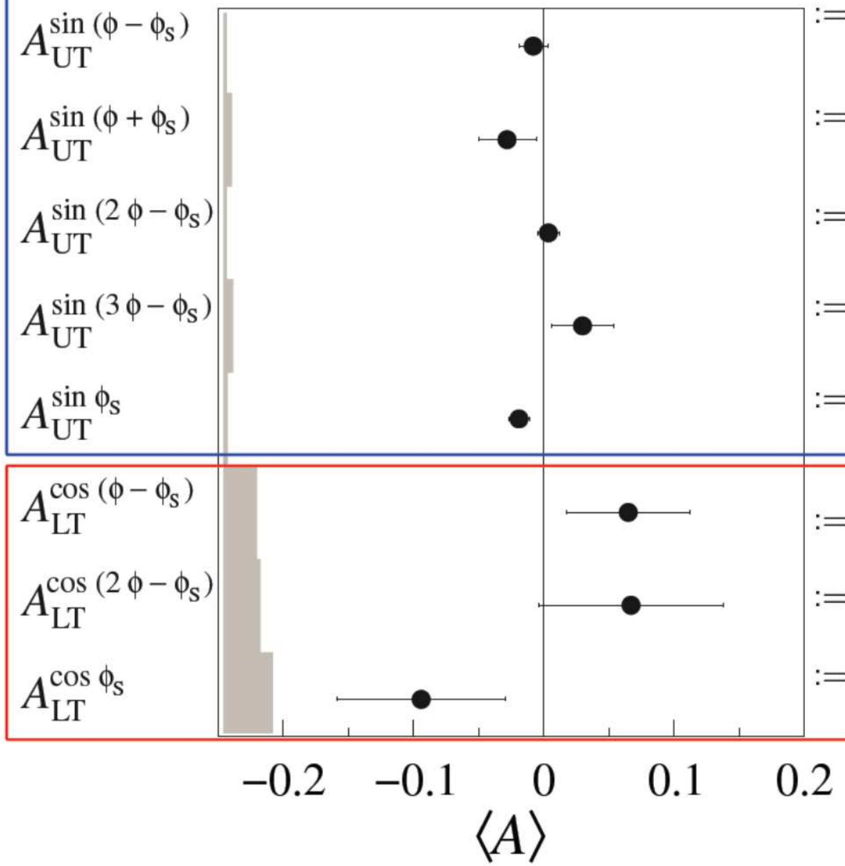
$$w(E_{miss}) = \frac{N_{RD}^{h+h+\gamma\gamma}(E_{miss}) + N_{RD}^{h-h-\gamma\gamma}(E_{miss})}{N_{MC}^{h+h+\gamma\gamma}(E_{miss}) + N_{MC}^{h-h-\gamma\gamma}(E_{miss})}$$

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

Transverse target spin asymmetries for exlusive ρ^0 production on $p^\uparrow$

PLB 731 (2014) 19

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



$$:= \mathrm{Im}(\sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-})/\sigma_0 \propto -\mathrm{Im}\left[\epsilon \mathcal{E}_{LL}^* \mathcal{H}_{LL} + \mathcal{E}_{TT}^* \mathcal{H}_{TT} - \frac{1}{2}\overline{\mathcal{E}}_{T,LT}^* \mathcal{H}_{T,LT}\right],$$

$$:= \mathrm{Im}(\sigma_{+-}^{+-})/\sigma_0 \propto \mathrm{Im}\left[\overline{\mathcal{E}}_{T,LT}^* \mathcal{H}_{T,LL}\right],$$

$$:= \mathrm{Im}(\sigma_{+-}^{-+})/\sigma_0 \propto -\mathrm{Im}\left[\overline{\mathcal{E}}_{T,LT}^* \mathcal{E}_{LL}\right],$$

$$:= \mathrm{Im}(\sigma_{+0}^{+-})/\sigma_0 = 0,$$

$$:= \mathrm{Im}(\sigma_{+0}^{-+})/\sigma_0 \propto \mathrm{Im}\left[\mathcal{H}_{T,LT}^* \mathcal{H}_{LL} - \overline{\mathcal{E}}_{T,LT}^* \mathcal{E}_{LL}\right],$$

5 single spin asymmetries

$$:= \mathrm{Re}(\sigma_{++}^{+-})/\sigma_0 \propto \mathrm{Re}\left[\overline{\mathcal{E}}_{T,LT}^* \mathcal{H}_{T,LT} - 2\mathcal{E}_{TT}^* \widetilde{\mathcal{H}}_{TT}\right],$$

$$:= \mathrm{Re}(\sigma_{+0}^{+-})/\sigma_0 \propto \mathrm{Re}\left[\overline{\mathcal{E}}_{T,LT}^* \mathcal{H}_{T,LT} - 2\mathcal{E}_{TT}^* \widetilde{\mathcal{H}}_{TT}\right],$$

$$:= \mathrm{Re}(\sigma_{+0}^{-+})/\sigma_0 \propto \mathrm{Re}\left[\mathcal{H}_{T,LT}^* \mathcal{H}_{LL} - \overline{\mathcal{E}}_{T,LT}^* \mathcal{E}_{LL}\right].$$

3 double spin asymmetries

$\sim E$, $\sim H$, $\sim H_T$, $\sim \overline{E}_T = 2\widetilde{H}_T - E_T$, $\sim \widetilde{H}$

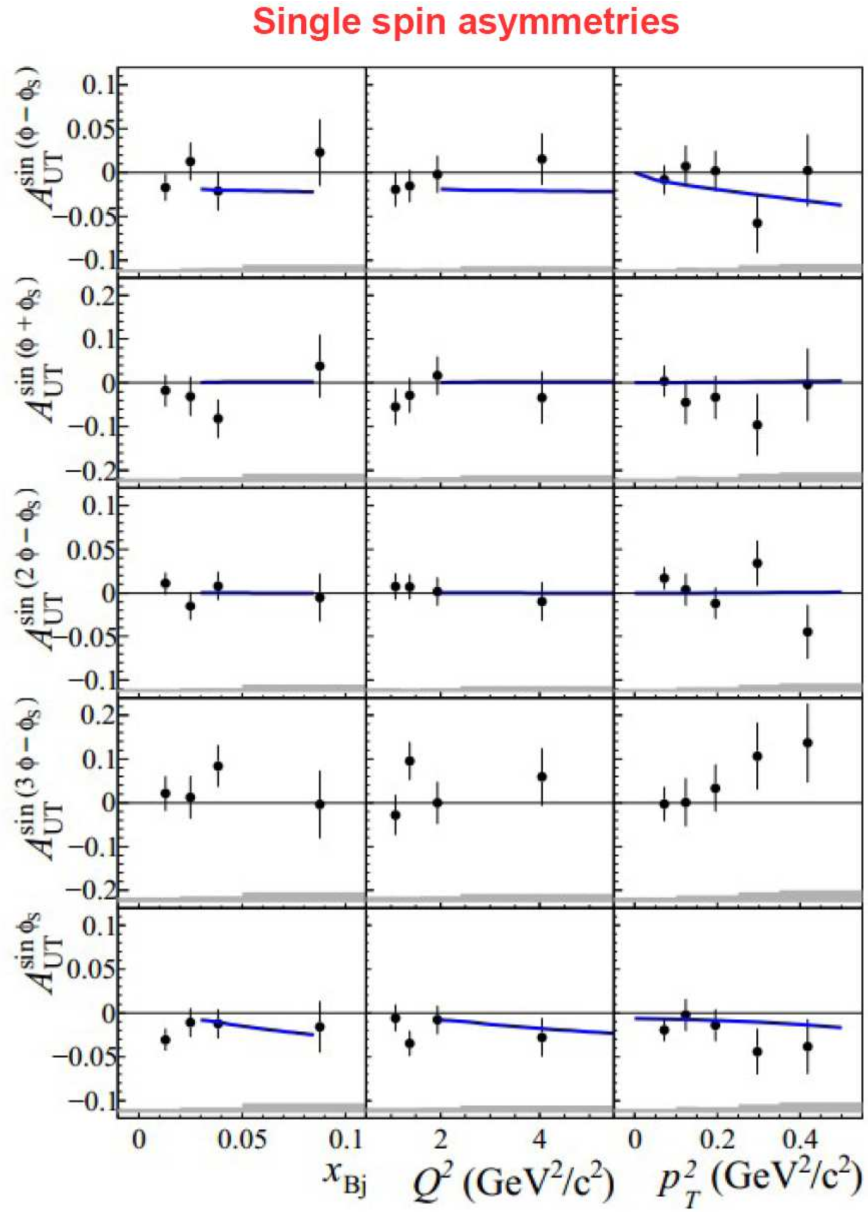
- asymmetries small, compatible with 0, except

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

- indication of H_T, 'transversity' GPD, contribution

$H_T(x, 0, 0) = h_1(x)$

Transverse target spin asymmetries for exlusive ρ^0 production on $p^\uparrow$



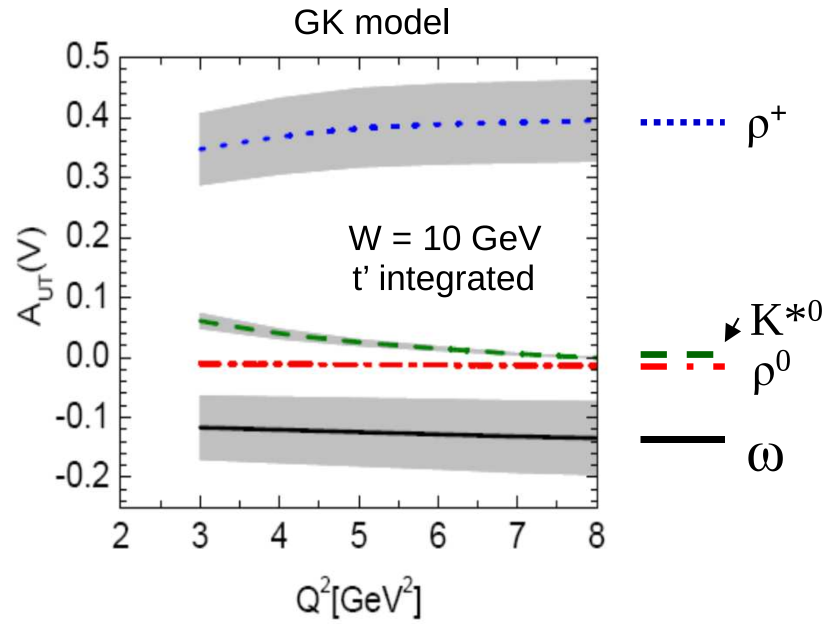
predictions of GPD model of Goloskokov-Kroll

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

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

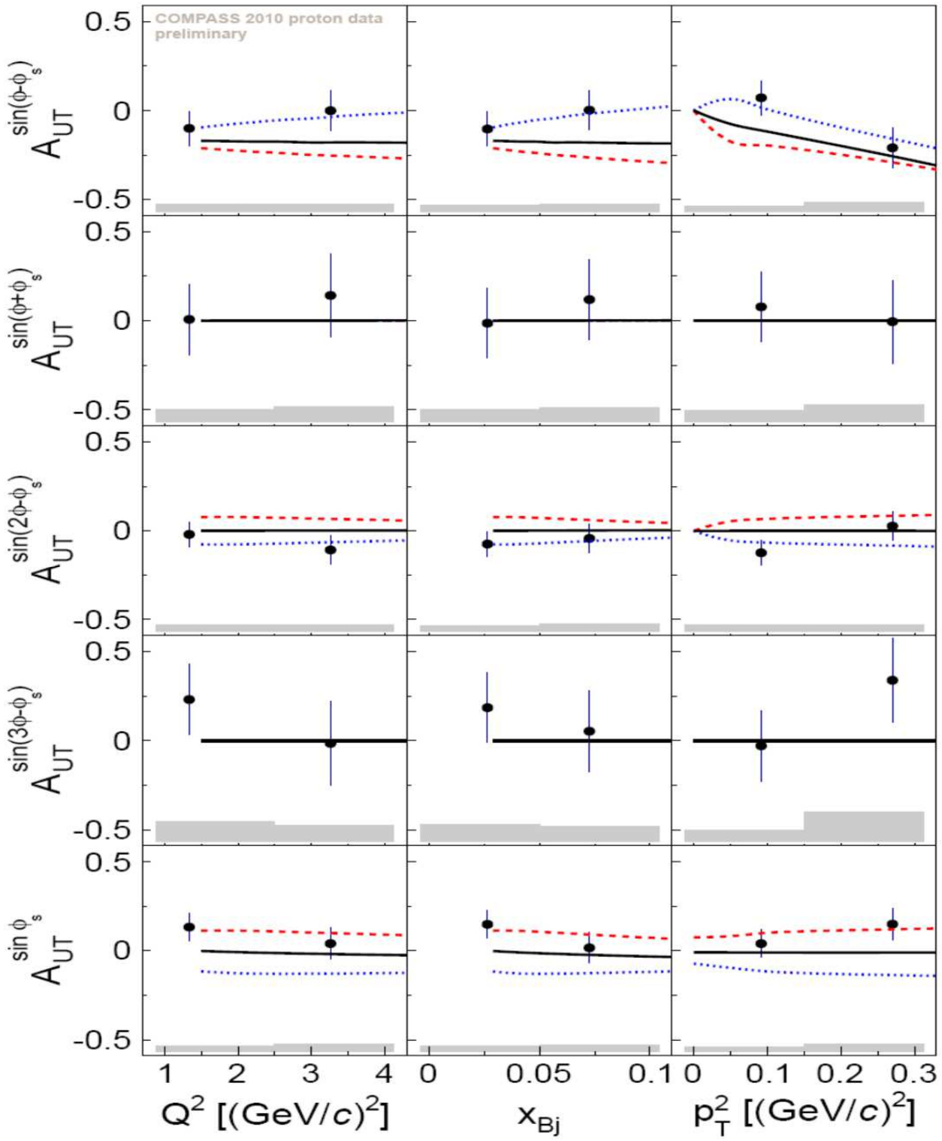
its small values due to approximate cancellation of contributions from E^u and E^d, $E^u \approx -E^d$

- larger effects 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

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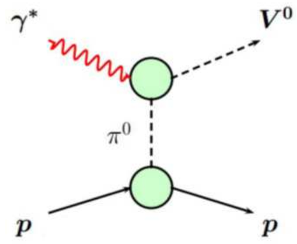
comparison to modified GPD model of GK

with added π^0 pole exchange



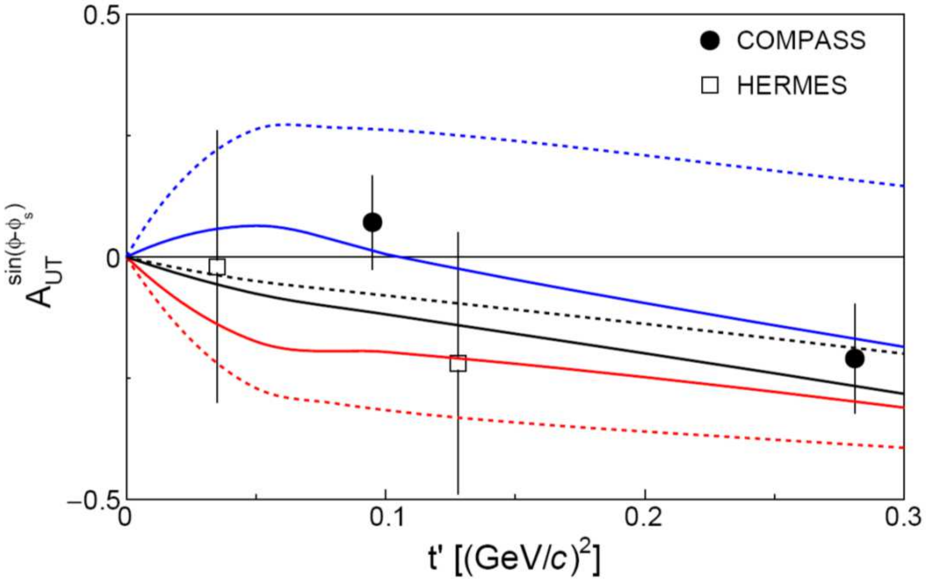
EPJ A50 (2014) 146

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.
- (solid) no pion pole
- (dashed) positive πω form factor
- (dotted) negative πω form factor

- 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 πω form factor
blue solid line	blue dotted line	negative πω 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

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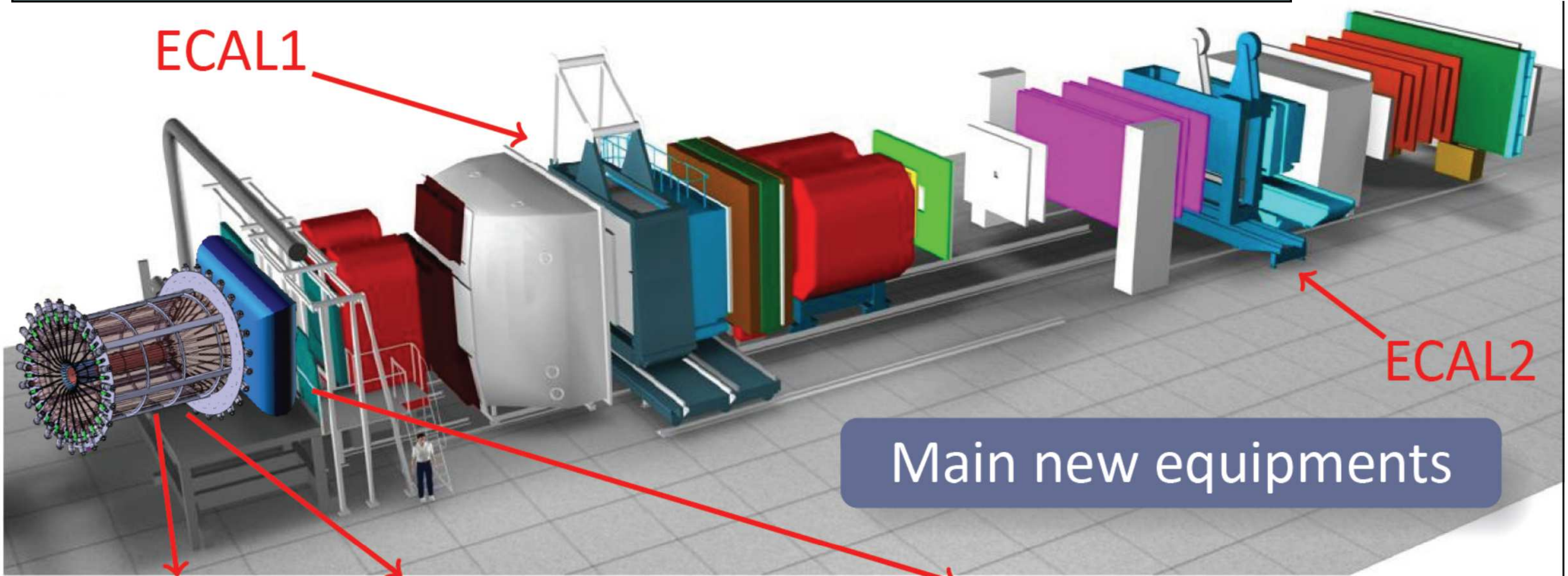
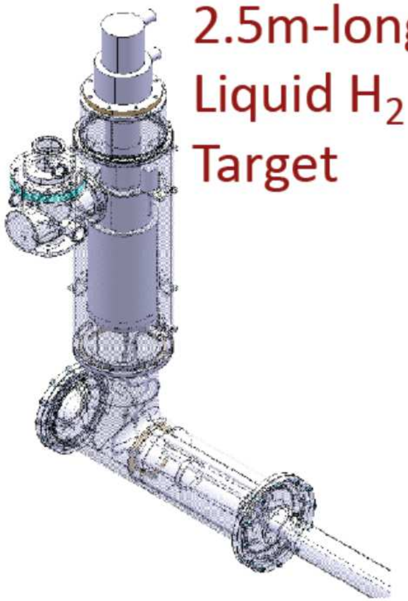
✓ Future measurements at JLab12 **EPJ A48 (2012) 187**

expected to resolve the issue of πω transition form factor

Hard exclusive π^0 production on unpolarised protons

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

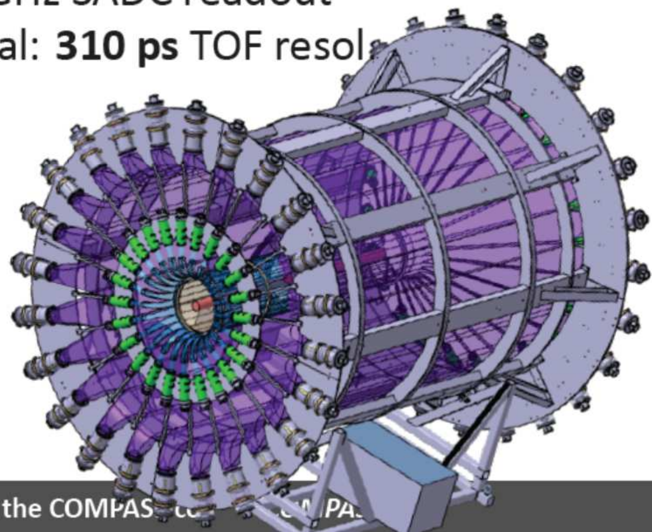




2.5m-long Liquid H_2 Target

Target TOF System

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

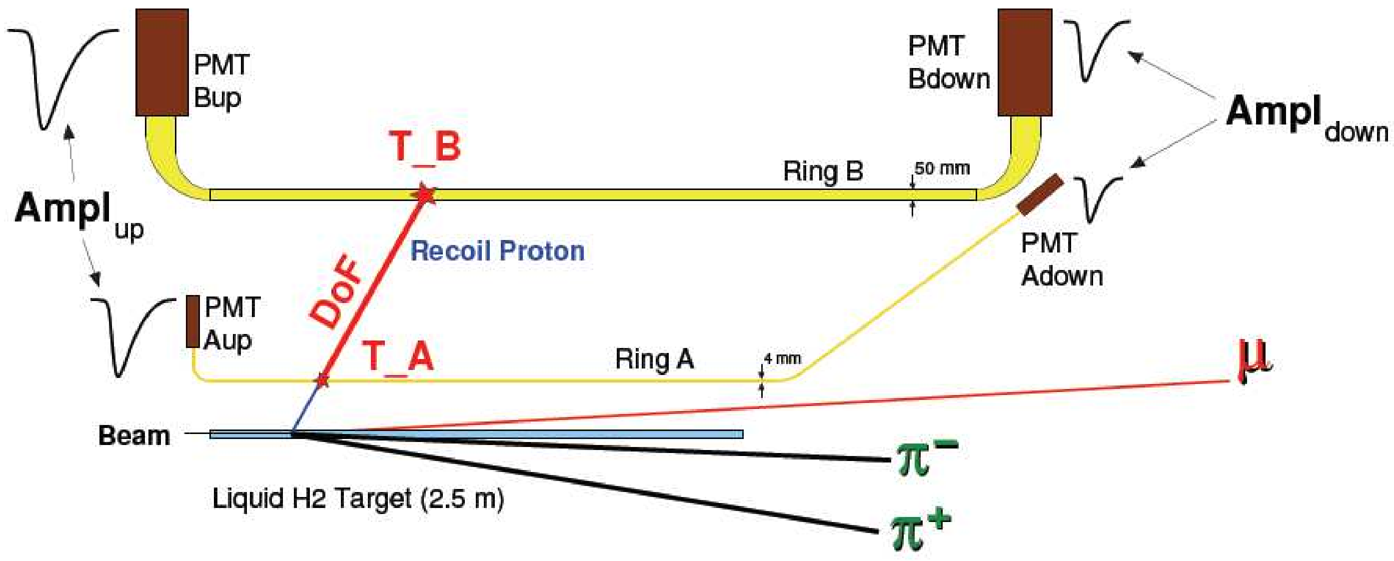


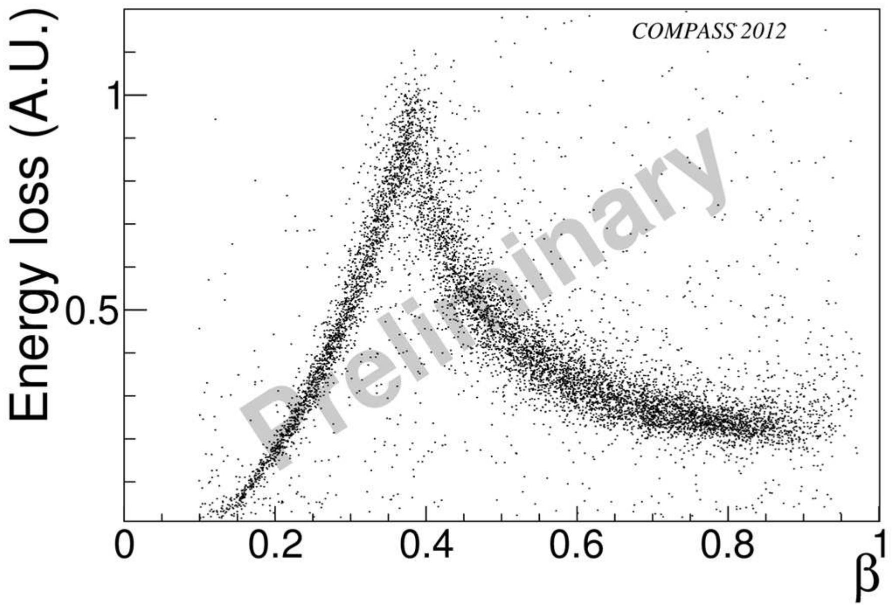
ECAL0 Calorimeter

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





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

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

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

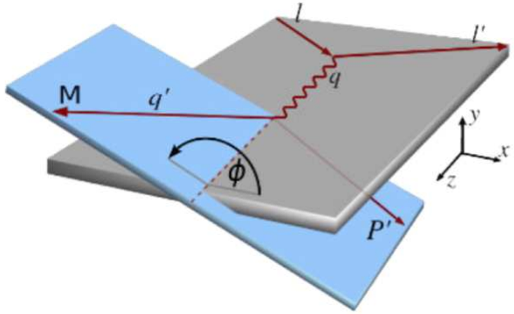
$\beta = DoF / ToF$

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

- Proton signature clearly visible after exclusivity selections

Exclusive π^0 production on unpolarised protons

$$\left[\frac{\alpha_{em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_{Bj}}{x_{Bj}}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}\,dQ^2\,dt\,d\phi}=$$



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

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

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

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

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 γ^* p → V p' with photon helicity *m* and target proton helicity *i*

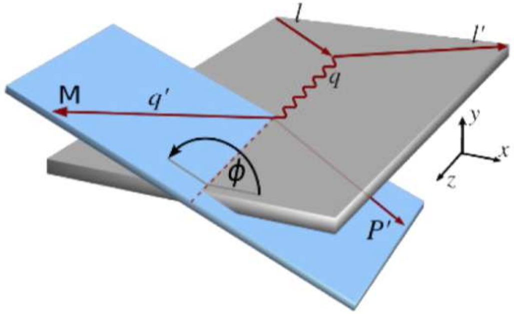
muon polarisation dependence cancels in $S_{CS,U}=[d\sigma(\mu^{+})+d\sigma(\mu^{-})]/2$

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

~~$-P_l\sqrt{\varepsilon(1-\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma_{+0}^{++}+\sigma_{+0}^{--})$~~

GPDs in exclusive π^0 production on unpolarised protons

$$\frac{d^2\sigma}{dt\,d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$



$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

leading twist
at JLAB only few% of $\frac{d\sigma_T}{dt}$

other contributions arise from coupling
of chiral-odd (quark helicity-flip) GPDs to twist-3 pion amplitude

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

An impact of $\bar{E}_T$ should be visible in $\frac{\sigma_{TT}}{dt}$

and in a dip at small t' of $\frac{d\sigma_T}{dt}$

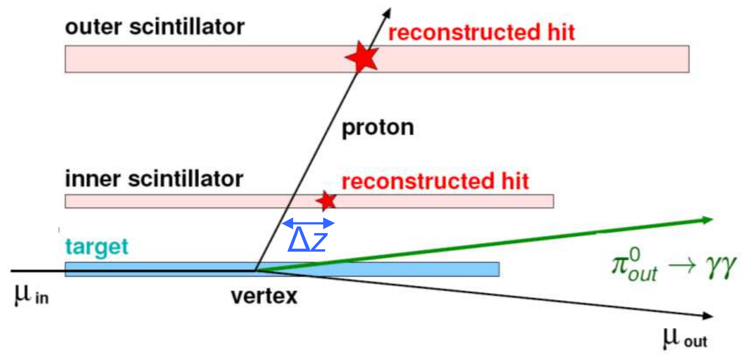
Selection of exclusive π^0 events

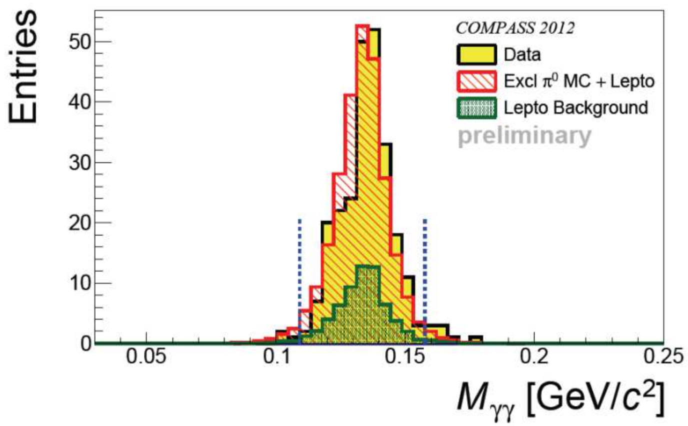
reconstructed vertex in the target volume

1 GeV² < Q² < 5 GeV²,   8.5 GeV < ν < 28 GeV

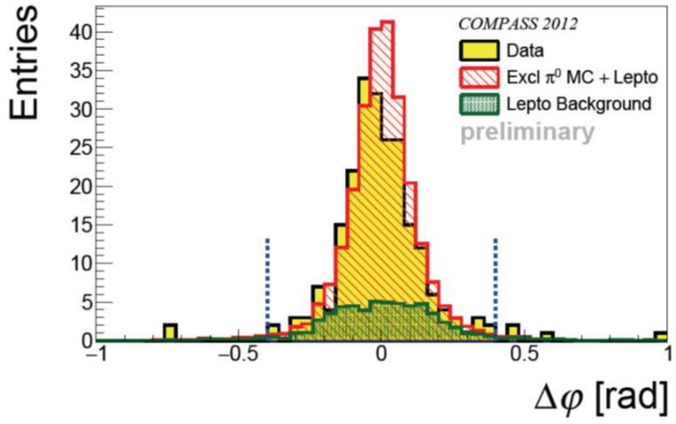
0.08 GeV² < | t | < 0.64 GeV²

two photons

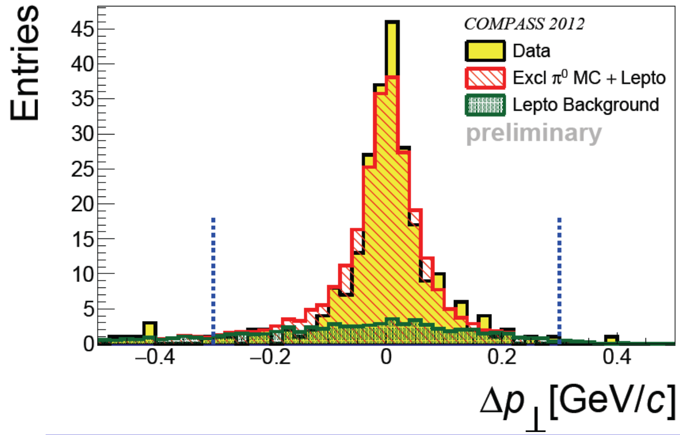




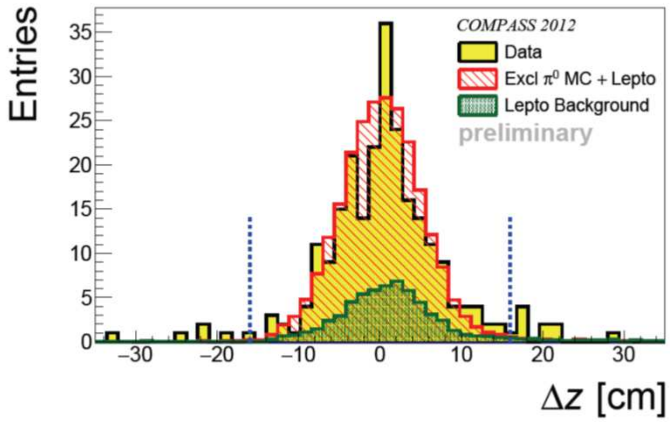
$\Delta\varphi = \varphi^{prot}_{meas} - \varphi^{prot}_{recon}$



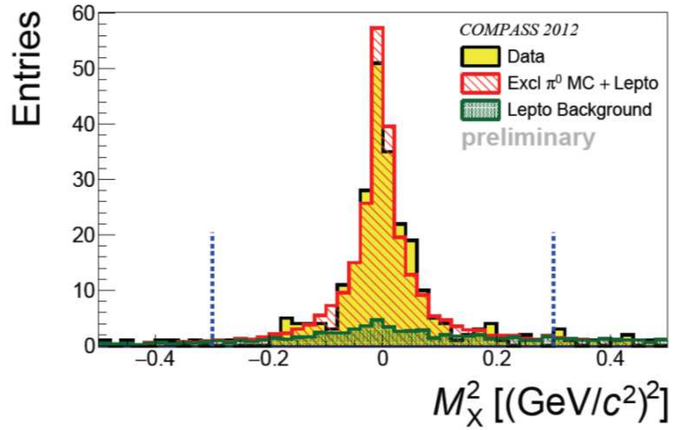
$\Delta p_{\perp} = p^{prot}_{\perp,meas} - p^{prot}_{\perp,recon}$



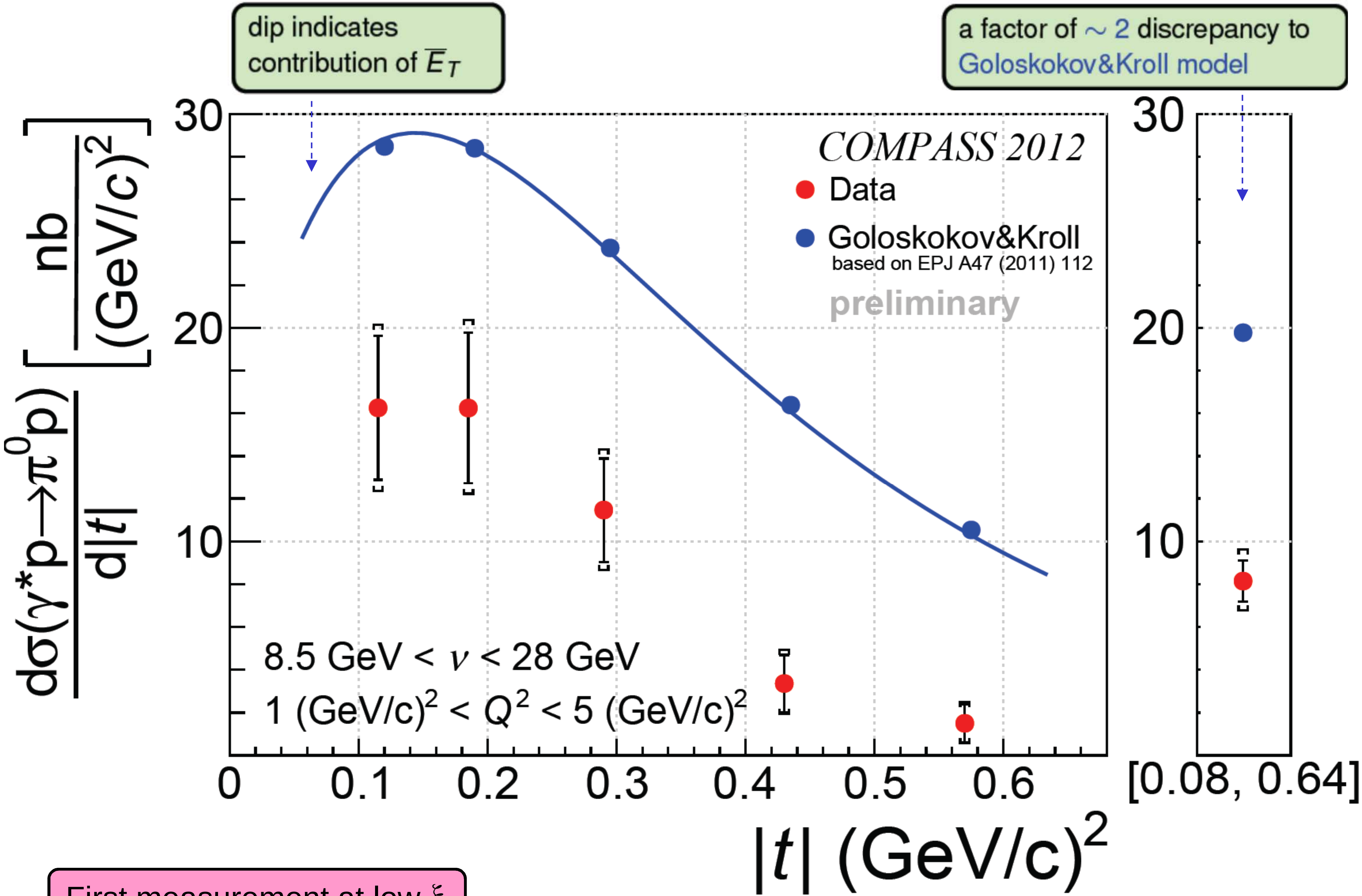
vertex pointing



$M_X^2 = (p^{\mu}_{in} + p^{p}_{in} - p^{\mu}_{out} - p^{p}_{out} - p^{\pi^0})^2$



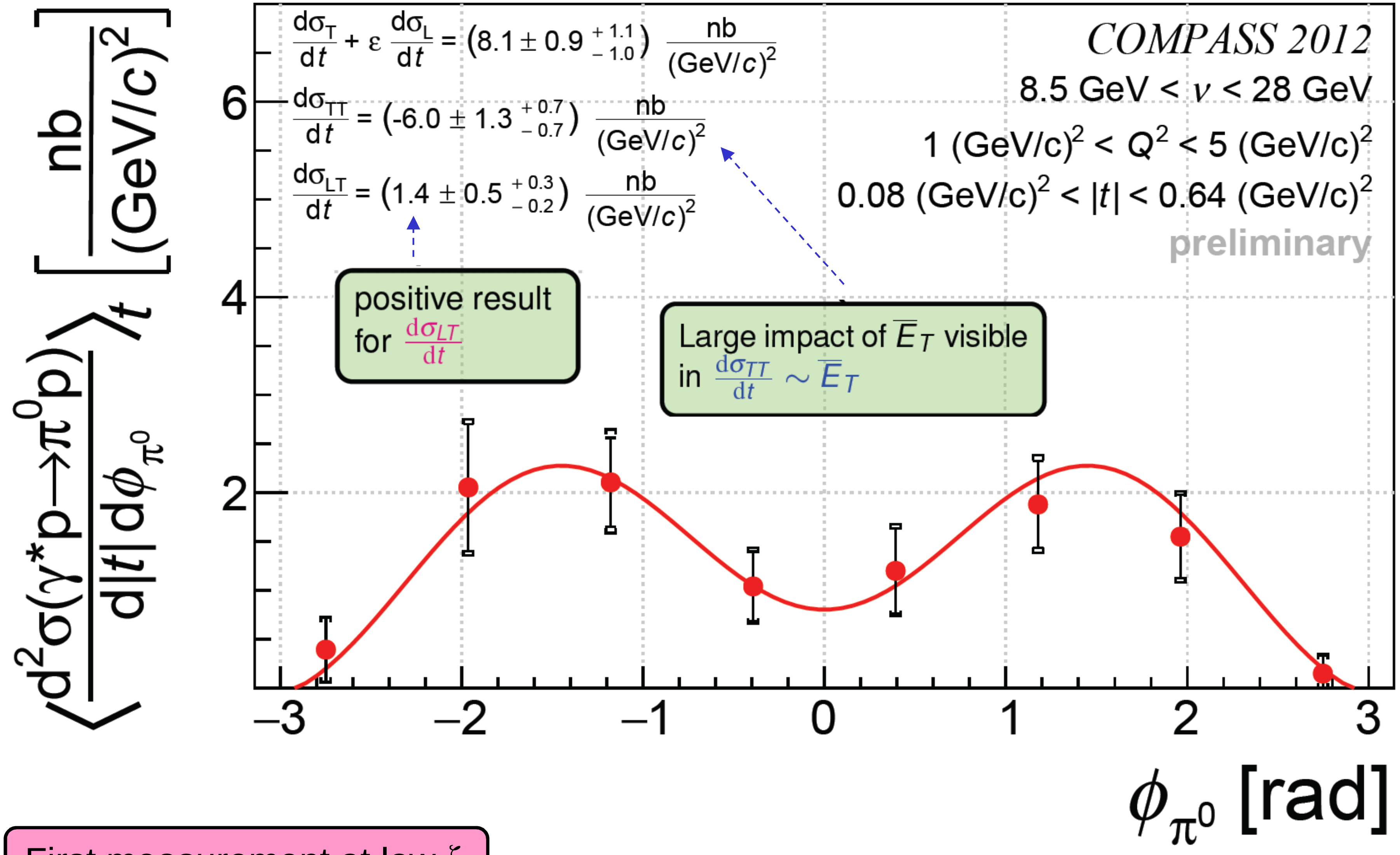
Exclusive π^0 production cross sections as a function of $|t|$



First measurement at low ξ

Exclusive π^0 production cross sections as a function of ϕ

$$\frac{d^2\sigma}{dt\,d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$



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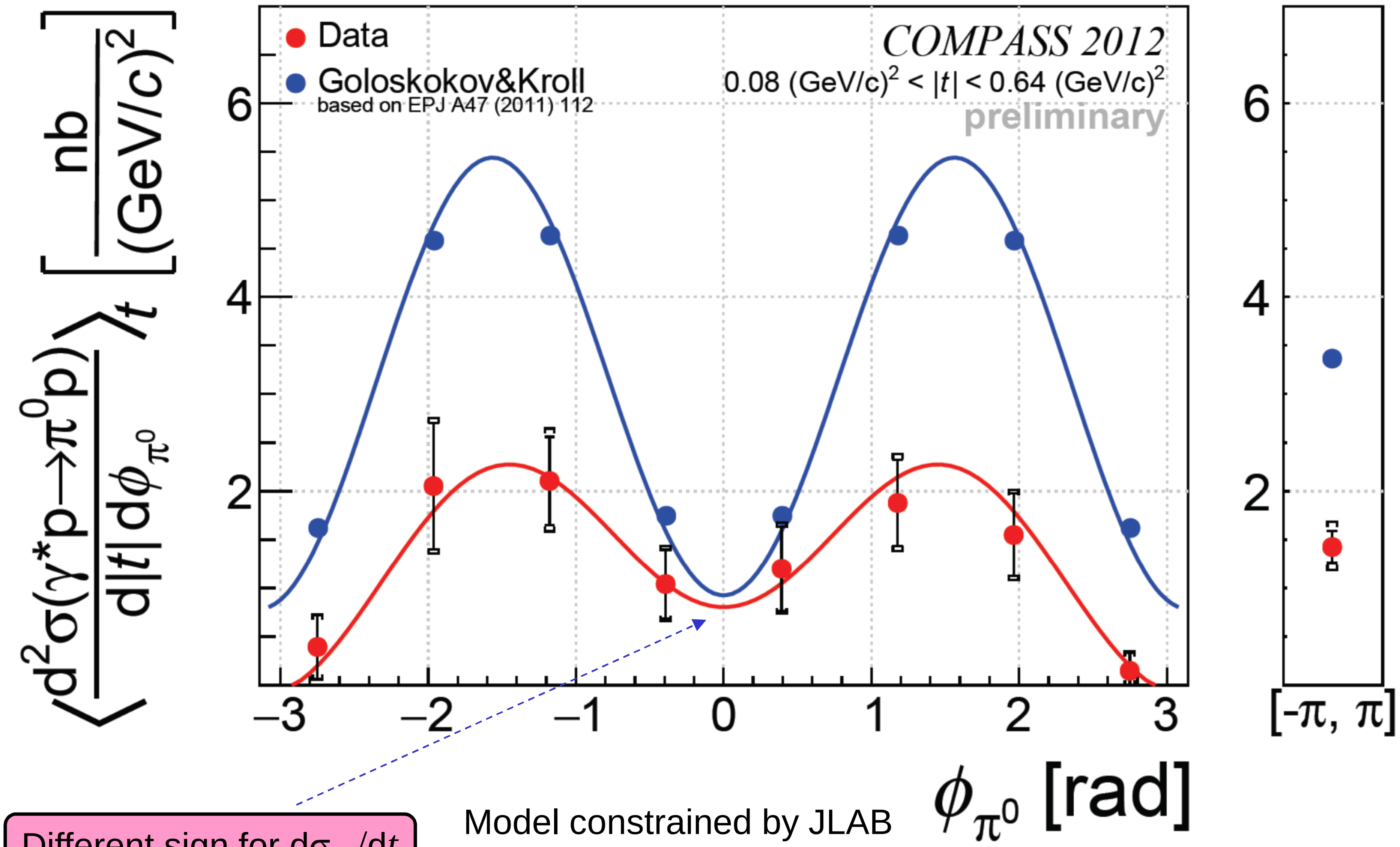
Exclusive π^0 production cross sections as a function of ϕ

$$\frac{d^2\sigma}{dt\,d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$



Different sign for $d\sigma_{LT}/dt$

Model constrained by JLAB data with $d\sigma_{LT}/dt \leq 0$

Spin Density Matrix Elements

for exclusive ω meson production on unpolarised protons

Vector meson spin-density matrix ρ(V)

helicity of vector meson V

helicities of virtual photon γ and nucleon N

photon spin density matrix ($\mu \rightarrow \mu+\gamma^*$); calculable on QED

$$\rho_{\lambda_V \lambda'_V} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

(von Neuman)

F helicity amplitudes; describe transitions $\lambda_\gamma, \lambda_N \rightarrow \lambda_V, \lambda'_N$, depend on W, Q^2 and p_T

Helicity amplitudes allows:

- test of s-channel helicity conservation ($\lambda_\gamma = \lambda_V$)
- decomposition into Natural (N) Parity and Unnatural (U) Parity exchange amplitudes

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

  - in Regge framework NPE: $J^P = (0^+, 1^-, \ldots)$ (pomeron, ρ, ω, a_2 … reggeons)
    UPE: $J^P = (0^-, 1^+, \ldots)$ (π, a_1, b_1… reggeons)

- tests of GPD models
  - e.g. for SCHC-violating transitions $\gamma_T \rightarrow V_L$ test sensitivity to GPDs with exchanged-quark helicity flip (transversity GPDs)

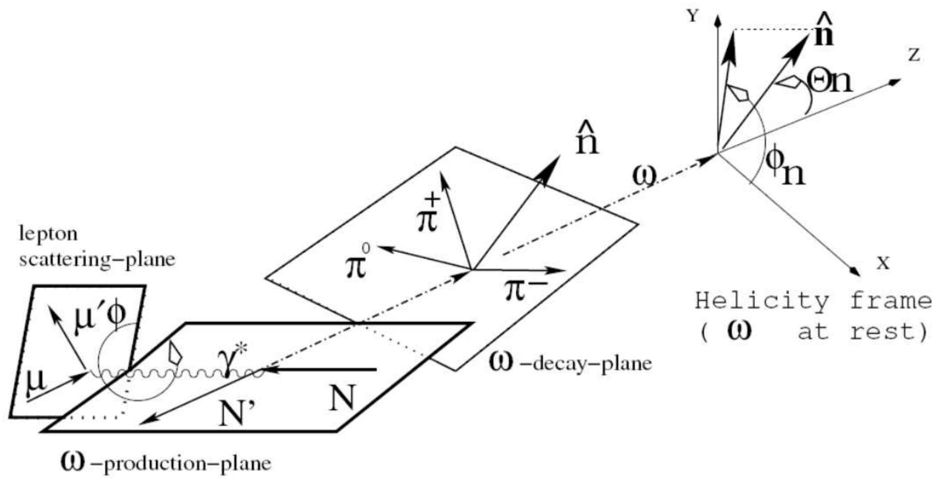
Experimental access to SDMEs

$$W^{U+L}(\Phi,\phi,\cos\Theta) = W^{U}(\Phi,\phi,\cos\Theta) + P_B W^{L}(\Phi,\phi,\cos\Theta) \propto \frac{d\sigma}{d\Phi\, d\phi\, d\cos\Theta}$$

$$W^U = \frac{3}{8\pi^2}\Big[\frac{1}{2}(1 - r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00} - 1)\cos^2\Theta - \sqrt{2}\mathrm{Re}(r^{04}_{10})\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi$$
$$- \epsilon\cos 2\Phi\left(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}(r^{1}_{10})\sin 2\Theta\cos\phi - r^{1}_{1-1}\sin^2\Theta\cos 2\phi\right)$$
$$- \epsilon\sin 2\Phi\left(\sqrt{2}\mathrm{Im}(r^{2}_{10})\sin 2\Theta\sin\phi + \mathrm{Im}(r^{2}_{1-1})\sin^2\Theta\cos\phi\right)$$
$$+ \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(r^{5}_{11}\sin^2\Theta + r^{5}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}(r^{5}_{10})\sin 2\Theta\cos\phi - r^{5}_{1-1}\sin^2\Theta\, cos2\phi\right)$$
$$+ \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\left(\sqrt{2}\mathrm{Im}(r^{6}_{10})\sin 2\Theta\sin\phi + \mathrm{Im}(r^{3}_{1-1})\sin^2\Theta\sin 2\phi\right)\Big]$$

$$W^L = \frac{3}{8\pi^2}\Big[\sqrt{1-\epsilon^2}\left(\sqrt{2}\mathrm{Im}(r^{3}_{10})\sin 2\Theta\sin\phi + \mathrm{Im}(r^{3}_{1-1})\sin^2\Theta\sin 2\phi\right)$$
$$+ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\left(\sqrt{2}\mathrm{Im}(r^{7}_{10})\sin 2\Theta\sin\phi + \mathrm{Im}(r^{7}_{1-1})\sin^2\Theta\sin 2\phi\right)$$
$$+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^{8}_{11}\sin^2\Theta + r^{8}_{00}\cos^2\Theta$$
$$- \sqrt{2}\mathrm{Re}(r^{8}_{10})\sin 2\Theta\cos\phi$$
$$- r^{8}_{1-1}\sin^2\Theta\cos 2\phi\Big)\Big]$$

[K. Schilling and G. Wolf, Nucl. Phys. B61, 381 (1973)]



Selection of exclusive ω sample for SDMEs analysis

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

↳ $\pi^+\ \pi^-\ \pi^0$

↳ $\gamma + \gamma$

Liquid hydrogen target, data from 2012 from 4-week test run with RPD

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

$0.1 < y < 0.9$

$W > 5$ GeV

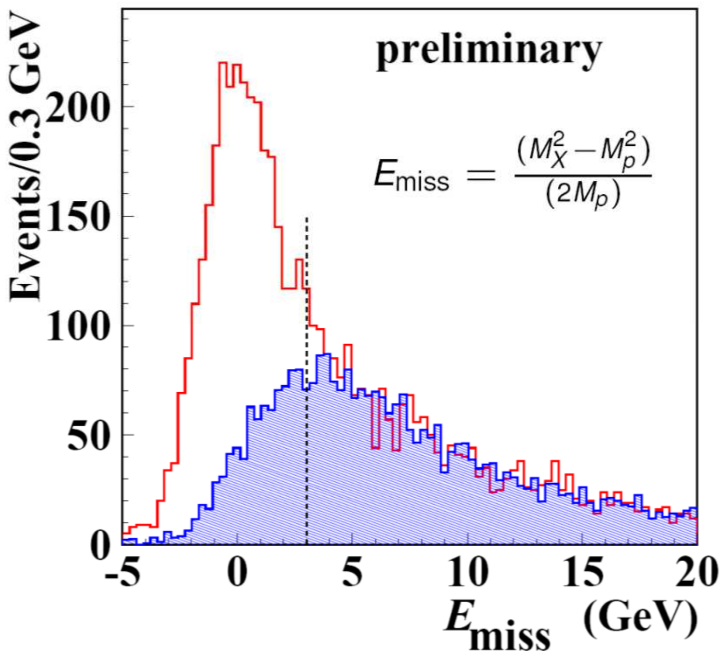
$|E_{miss}| < 3$ GeV

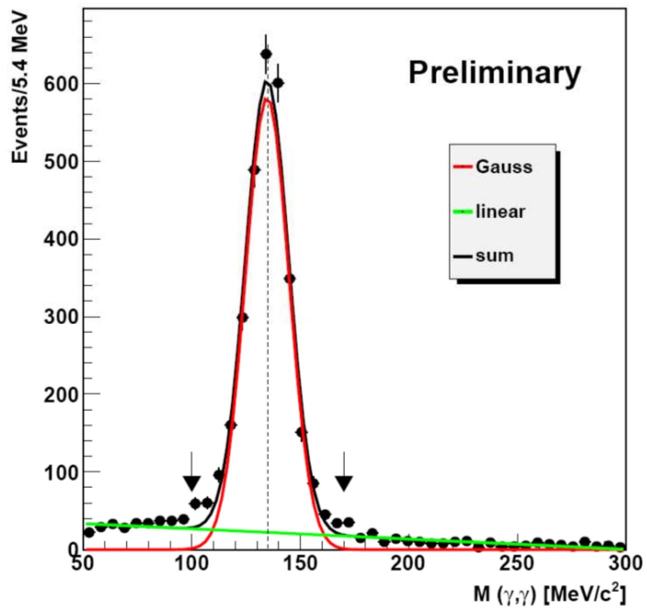
$0.01 < p_T^2 < 0.5$ (GeV/c)^2

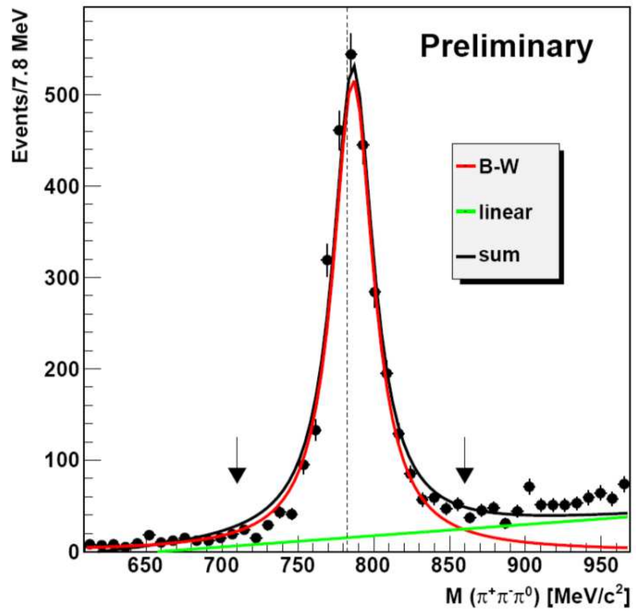
After all selections and cuts

≈ 3 000 evts

RPD not included in selections







Results on SDMEs for exclusive ω production at COMPASS

- Extraction of SDMES $\vec{r}$:
  unbinned ML fit of exp. angular distribution to

$$L(\vec{r}) = a \cdot W^{U+L}(\vec{r}) + f_{bgd} \cdot a \cdot W^{U+L}(\vec{r}_{bgd})$$

- Acceptance, reconstruction-efficiency and detection-probabilities $a(\Phi, \phi, \cos\Theta, Q^2, \nu, \ldots)$:

  HEPGEN++ MC (Golosgokov & Kroll model)

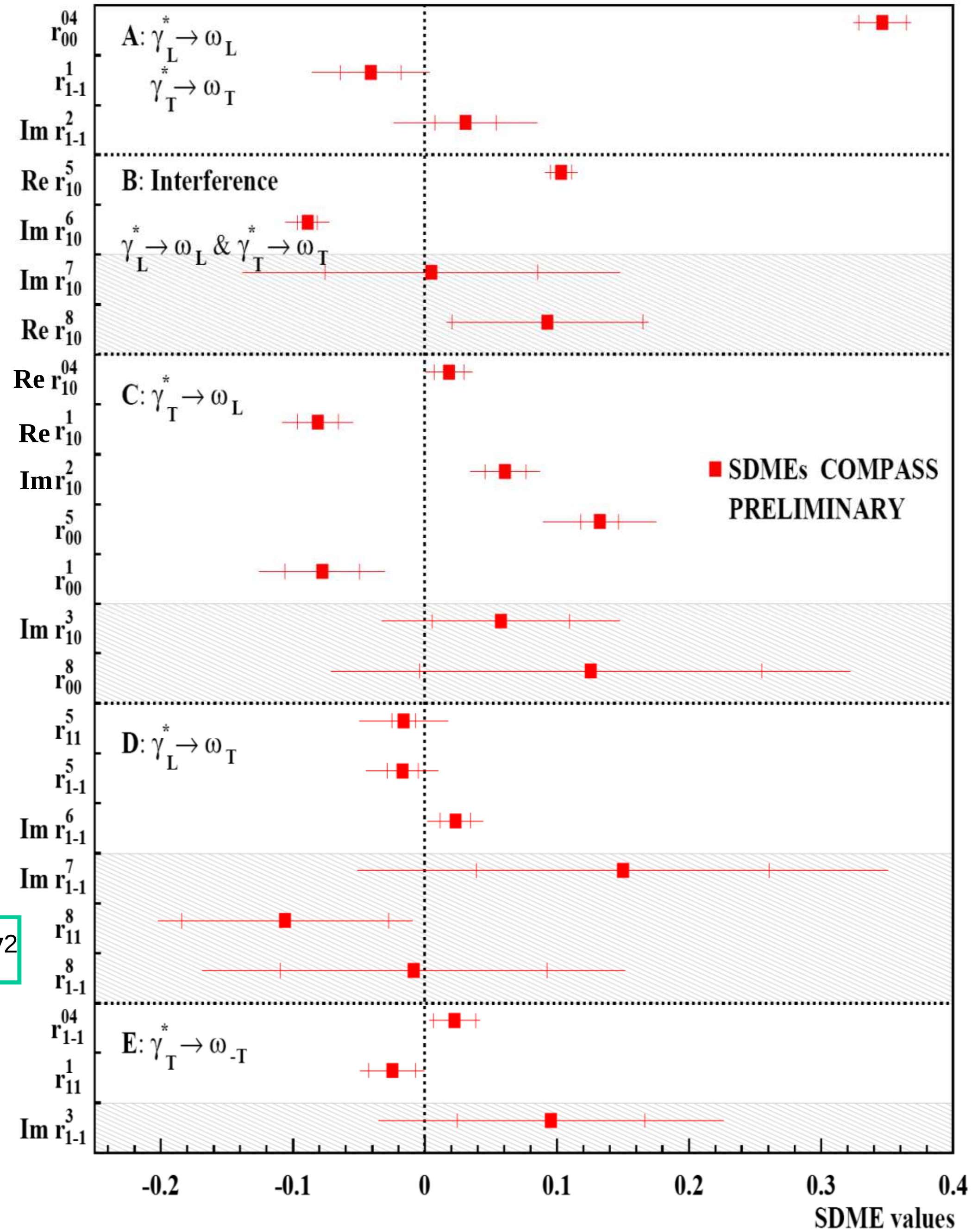
- Semi-inclusive background fraction f_{bgd} and bgd. SDMEs $\vec{r}_{bgd}$:

  LEPTO MC/ real data side-bands

15 unpolarisedd and 8 polarised SDMEs

< Q^2> = 2.13 GeV^2, <W> = 7.6 GeV, <p_T^2> = 0.16 GeV^2

- ➢SDMEs grouped in clasess: A, B, C, D, E corresponding to different helicity transitions
- ➢SDMEs dependent on beam polarisation shown within shaded areas



Kinematic dependences of all SDMEs in the backup

Tests of s-channel helicity conservation

SCHC ($\lambda_\gamma = \lambda_V$)

SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$

  = - 0.010 ± 0.032 ± 0.047 OK

- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$

  = 0.014 ± 0.011 ± 0.013 OK

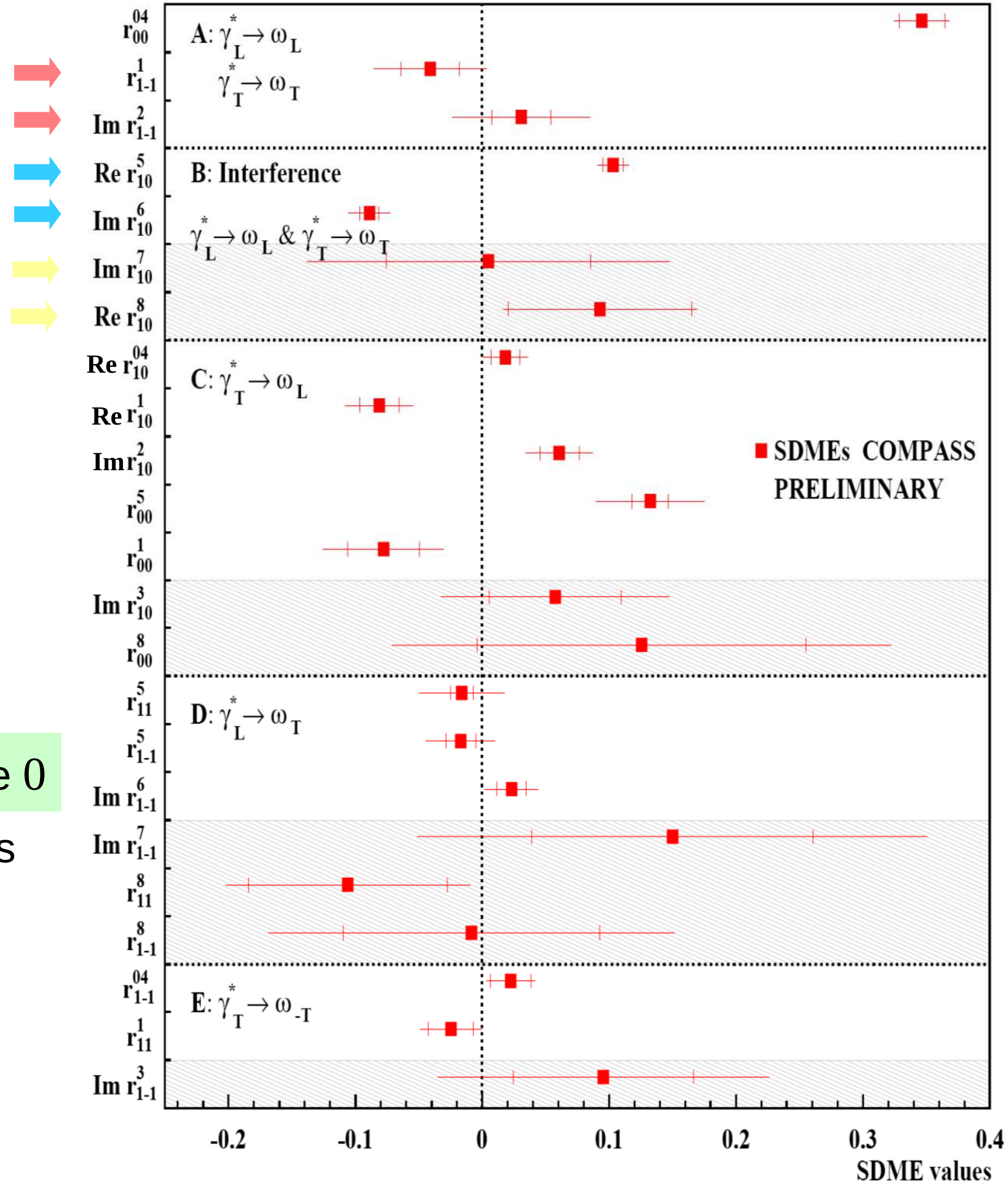
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

  = - 0.088 ± 0.110 ± 0.196 OK

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \omega_T$ and $\gamma^*_T \to \omega_{-T}$ OK within errors

not obeyed for transitions $\gamma^*_T \to \omega_L$

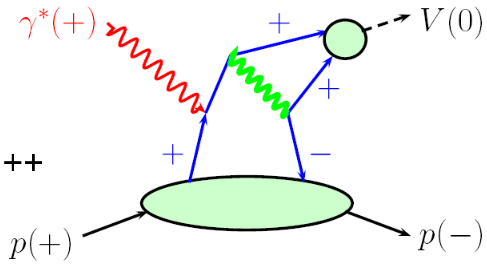


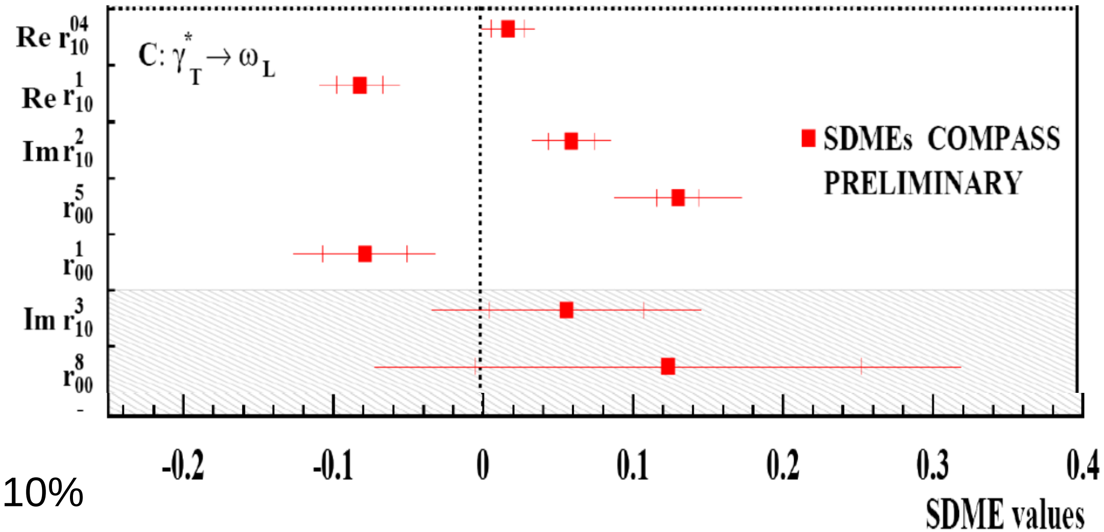
Transitions $\gamma^*_T \rightarrow \omega_L$

possible GPD interpretation **Goloskokov and Kroll, EPJC 74 (2014) 2725**

contribution of amplitudes depending on transversity GPDs $H_T, \bar{E}_T = 2\tilde{H}_T + E_T$

example ➡ graph for amplitude $F_{0-,++}$



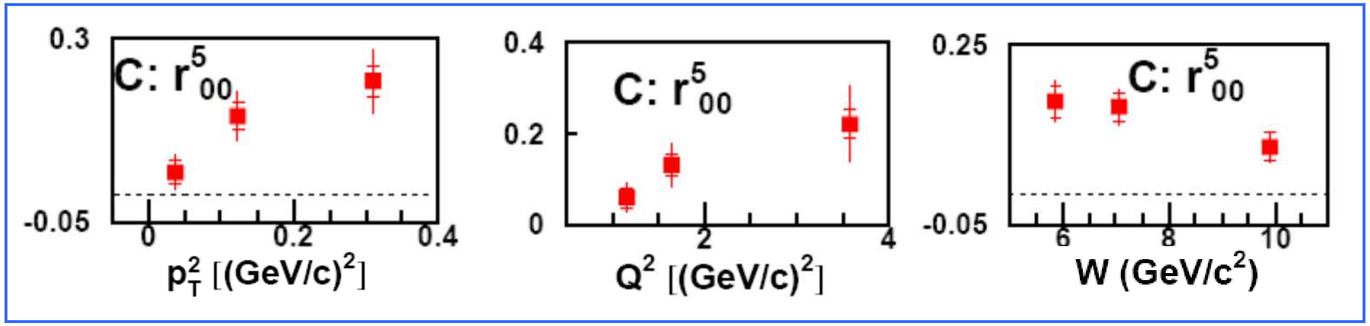


- $r^1_{00} \propto |\langle \bar{E}_T \rangle^*_{LT} \langle \bar{E}_T \rangle_{LT}|^2$

  $(-1) \cdot r^1_{00}$ partial cross section from $F_{0+,++}$, ≈ 10%

- $r^5_{00} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$

COMPASS preliminary



- $\mathrm{Re}\, r^{04}_{10} \approx -\mathrm{Re}\, r^1_{10} \approx \mathrm{Im}\, r^2_{10} \quad \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle^N_{TT} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle^N_{TT}]$

'tension' at 2σ level

OK within errors

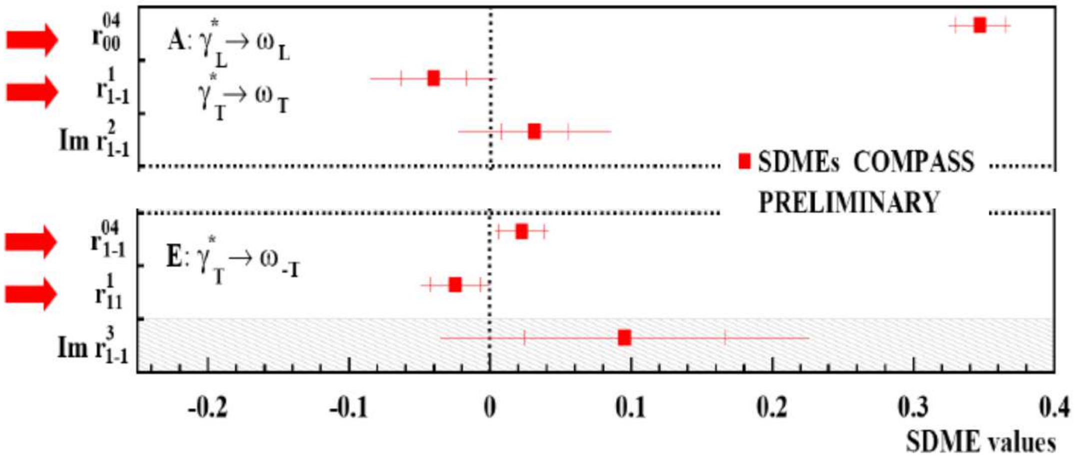
Unnatural parity exchange contribution

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1}$$

$$= \sum_{\lambda_N \lambda'_N} \frac{4\epsilon |U_{1\lambda'_N 0\lambda_N}|^2 + 2|U_{1\lambda'_N 1\lambda_N} + U_{-1\lambda'_N 1\lambda_N}|^2}{N}$$

numerator depends only on UPE amplitudes

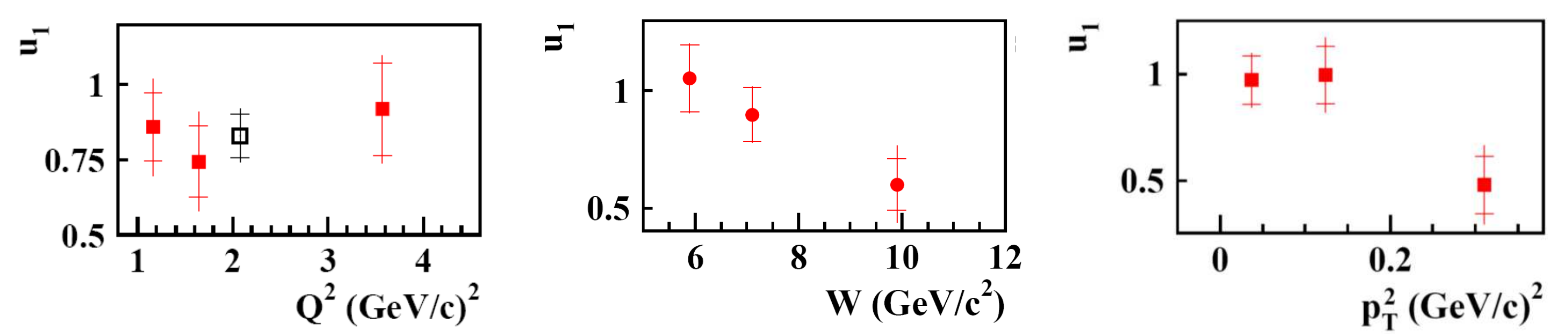
$u1 > 0 \implies$ UPE contribution



GPD interpretation **Goloskokov and Kroll, EPJA 50 (2014) 146**

contribution of amplitudes depending on helicity GPDs $\tilde{E}, \tilde{H}$ the former parameterised predominantly by **pion-pole exchange**

COMPASS preliminary



- decrease of UPE contribution with increasing W
- decrease of UPE with increasing p^2_T (?)

qualitative agreement with predictions from pion-pole exchange

Results expected in the near future

➢ from the data collected in 2016+2017

with LH_2 target, RPD and wide-angle electromagneric calorimetry

collected statistic ~ 10 larger than from 2012 test run

undergoing or planned analyses of hard exclusive meson production:

- differential cross section for π^0 vs. Q^2, ν (W), t(p_T^2), ϕ
- differential cross sections and SDMEs for VMs vs. Q^2, ν (W), t (p_T^2)

➢ from the data to be collected in 2021

with transversely polarised ^{6}LiD (deuteron) target (no RPD)

Addendum to realised COMPASS-II proposal

primary goal transversity in SIDIS on transv. pol. deuterons

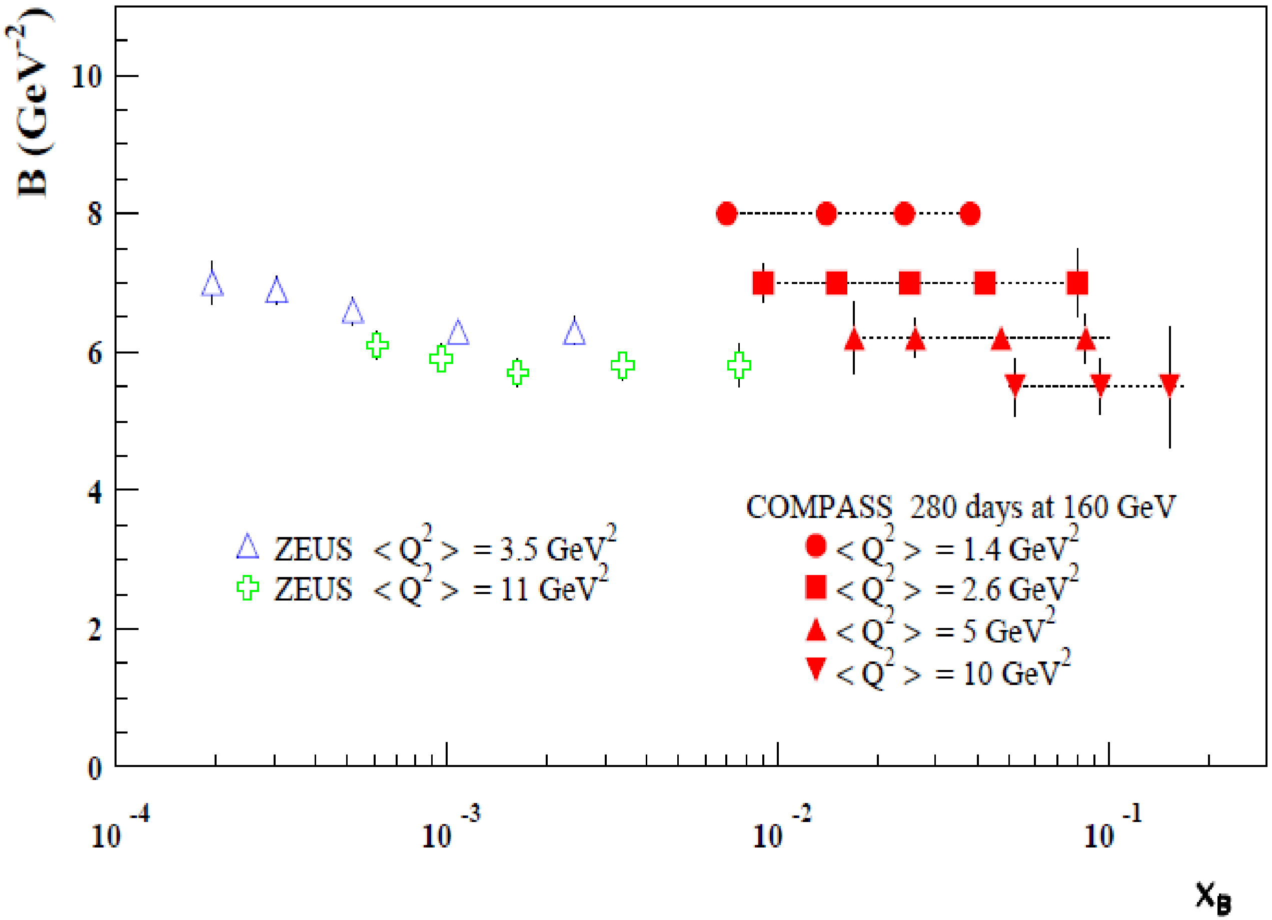
- transverse target spin asymmetries for exclusive ρ^0 and ω production

  expected statistical uncertainties similar to those

  for presented results from NH_3 (proton) target example: **t-slope measurement for exclusive ρ^0 production**

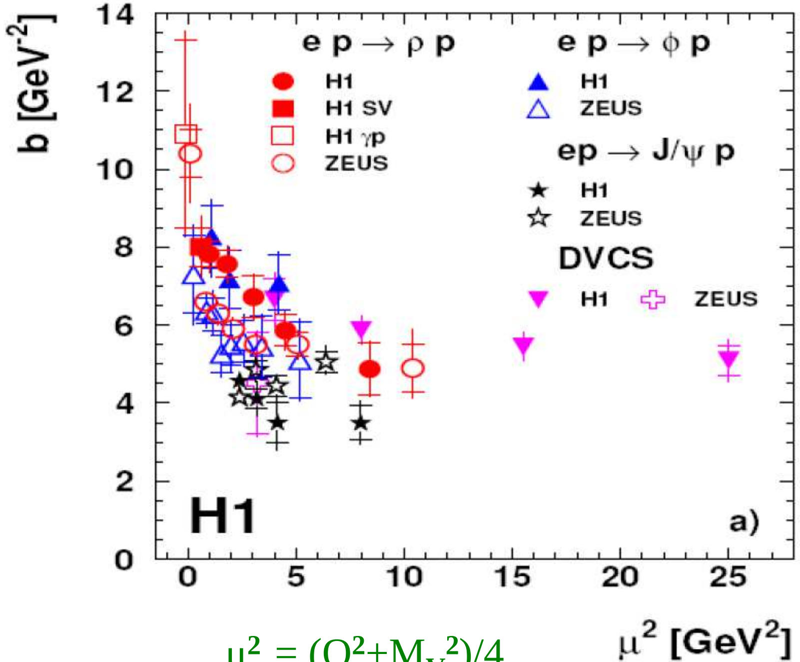
projections for 2 years from COMPASS-II proposal

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



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

… and in a more distant future

Letter of Intent: Fixed-Target Experiment at M2 beam line beyond 2020

to be made public in a couple of weeks

one of proposed measurements

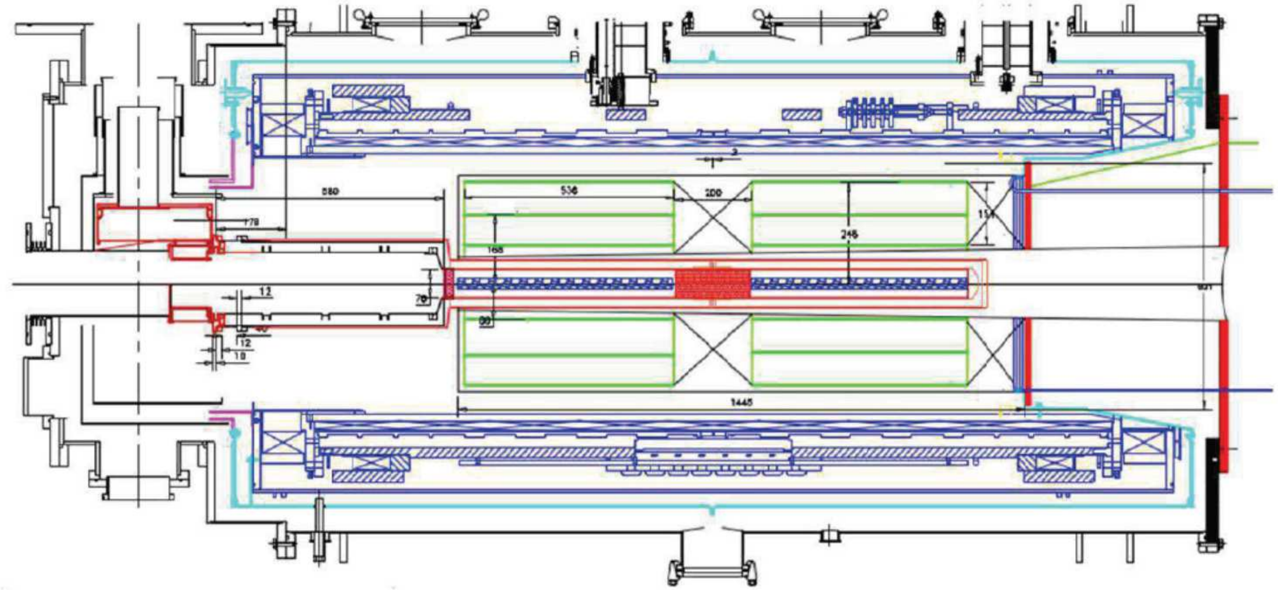
- Exclusive reactions with muon beams and transversely polarised target

primary goal to access GPDs *E* via

- DVCS
- DVMP of VMs with transverse-longitudinal separation

transversely polarised target combined with recoil detector indispensable for both

proposed solution



- 3 concentric barrels of Si pixel det. (in green)
- modified MW cavities
- 2 cells with opposite polarisation MW reversal every week
- material NH_3 (protons)
- polarisation ≈ 90%
- minimal |t| for recoil 0.1(0.14) GeV^2

❖ Expected stat. errors of unseparated $A_{UT}^{\sin(\phi-\phi_S)}$ for exclusive ρ^0 from 280 days of data taking

$\Delta A_{UT}^{\sin(\phi-\phi_S)} \approx 0.042\ (0.048)$ for each of 4 bins in x_{Bj}, Q^2 or p_T^2

DVMP for VMs with transverse-longitudinal γ^* separation

- At twist-2 GPDs related to DVMP observables for longitudinal γ^*

  for vector mesons: ρ^0, ω, f_2, …

$$\frac{1}{\Gamma'}\,\sigma_{00}^{++} = (1-\xi^2)\,|\mathcal{H}_M|^2 - \left(\xi^2 + \frac{t}{4M_p^2}\right)|\mathcal{E}_M|^2 - 2\xi^2\,\mathrm{Re}\,(\mathcal{E}_M^*\mathcal{H}_M) \qquad \Gamma' = \frac{\alpha_{em}}{Q^6}\,\frac{x_B^2}{1-x_B}$$

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

access to GPD E

$\mathcal{H}_\mathcal{M}$, $\mathcal{E}_\mathcal{M}$ are integrals of GPDs H, E appropriate for production of meson $\mathcal{M}$

- Method to separate transverse and longitudinal contributions

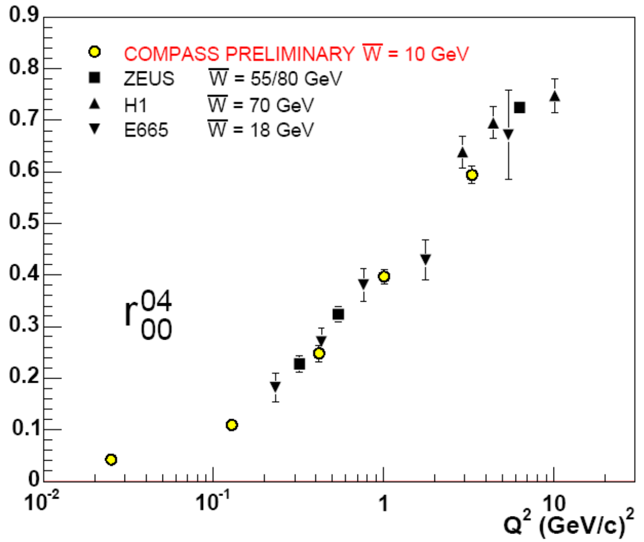
  Rosenbluth separation not feasible for muon beam experiment

  Proposed method employs VM decay angular distribution W and assumption of SCHC

$$W(\cos\vartheta) = \underbrace{r_{00}^{04}\cdot\frac{3}{2}\cos^2\vartheta}_{\rho_L} + \underbrace{(1-r_{00}^{04})\cdot\frac{3}{4}\sin^2\vartheta}_{\rho_T} = \frac{3}{4}[(1-r_{00}^{04}) + (3r_{00}^{04}-1)\cos^2\vartheta]$$

r_{00}^{04} fraction of longitudinal mesons in the sample

found from the fit of W to the data



DVMP for VMs with transverse-longitudinal γ* separation (cont.d)

Basic formula for cross section including dependence on VM decay angles υ and φ

Integrating over azimuthal decay angle φ results in

$$\frac{d\sigma^{ij}_{mn}(\gamma^* p \to \pi^+\pi^- p)}{d(\cos\vartheta)} = \frac{3\cos^2\vartheta}{2}\,\sigma^{ij}_{mn}(\gamma^* p \to \rho_L p) + \frac{3\sin^2\vartheta}{4}\,\sigma^{ij}_{mn}(\gamma^* p \to \rho_T p)$$

Diehl, Sapeta, EPJ C41 (2005) 515

denote for brevity $\tilde{\sigma}^{ij}_{mn} \equiv \frac{d\sigma^{ij}_{mn}(\gamma^* p \to \pi^+\pi^- p)}{d\cos\vartheta}$

SCHC

$$\tilde{\sigma}^{ij}_{++} = \frac{3}{4}\sin^2\vartheta \cdot \sigma^{ij}_{++} \qquad \tilde{\sigma}^{ij}_{00} = \frac{3}{2}\cos^2\vartheta \cdot \sigma^{ij}_{00}$$

- Measure asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ as a function of cos υ

$$A_{UT}^{\sin(\phi-\phi_S)}(\cos\vartheta) = -\frac{\mathrm{Im}[\tilde{\sigma}^{+-}_{++} + \varepsilon\tilde{\sigma}^{+-}_{00}]}{\tilde{\sigma}_0}$$
$$= A_{\gamma T}^{\sin(\phi-\phi_S)}\frac{3}{4}\sin^2\upsilon(1-r^{04}_{00})/W(\cos\vartheta) + A_{\gamma L}^{\sin(\phi-\phi_S)}\frac{3}{2}\cos^2\vartheta\, r^{04}_{00}/W(\cos\vartheta) \qquad (\#)$$

here $A_{\gamma T}^{\sin(\phi-\phi_S)} \equiv -\frac{\mathrm{Im}\,\sigma^{+-}_{++}}{\sigma_T} \qquad A_{\gamma L}^{\sin(\phi-\phi_S)} \equiv -\frac{\mathrm{Im}\,\sigma^{+-}_{00}}{\sigma_L}$

- Extract $A_{\gamma T}^{\sin(\phi-\phi_S)}$ and $A_{\gamma L}^{\sin(\phi-\phi_S)}$ from the fit of Eq. (#) to measured asymmetry $A_{UT}^{\sin(\phi-\phi_S)}(\cos\vartheta)$

Considerations for DVMP at EIC

❖ Goals and ➢ Experimenal requirements

❖ Flavour separation for GPDs H, E

accessed via

- exclusive production of different VMs on protons

  e.g. e p → e' ρ^0 p' vs. e p → e' ω p'

- exclusive production of a given VM on protons and neutrons

  e.g. e p → e' ρ^0 p' vs. e d → e' ρ^0 n p_{spec}

➢ Hermetic detector for tracks and photons with RPs for fast protons

➢ Transverse polarisation of proton beam

❖ Role of GPDs $H_T, \bar{E}_T, \tilde{E}, \tilde{H}$ and higher-twist contributions

accessed via

- exclusive production of PS mesons and flavoured mesons

note that small cross sections et EIC energies and strong ‘competition’ from SIDIS makes the following requirement even stronger than for VMs

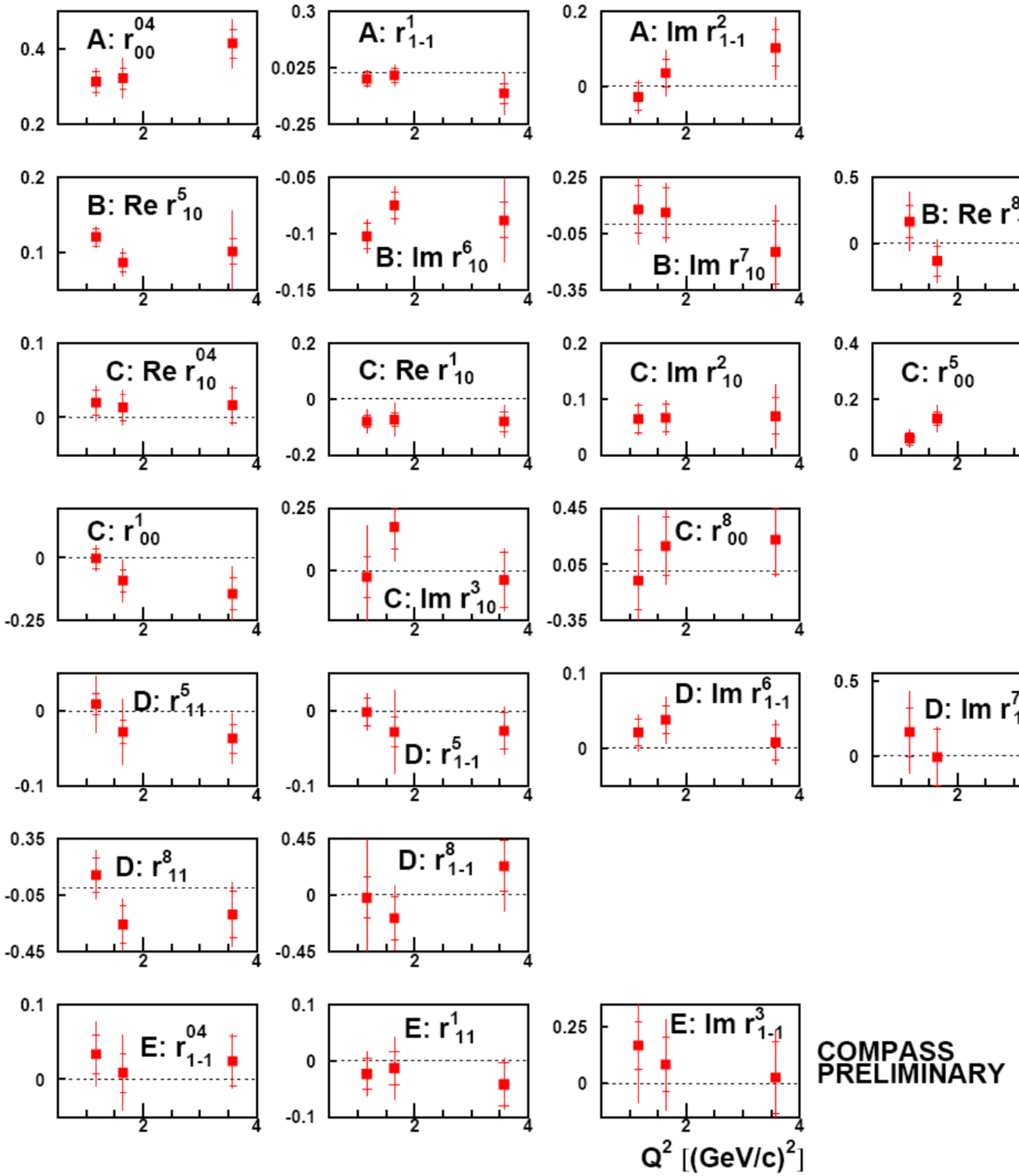
➢ Hermetic detector for tracks and photons with RPs for fast protons

❖ γ^*_T vs. γ^*_L cross section separation

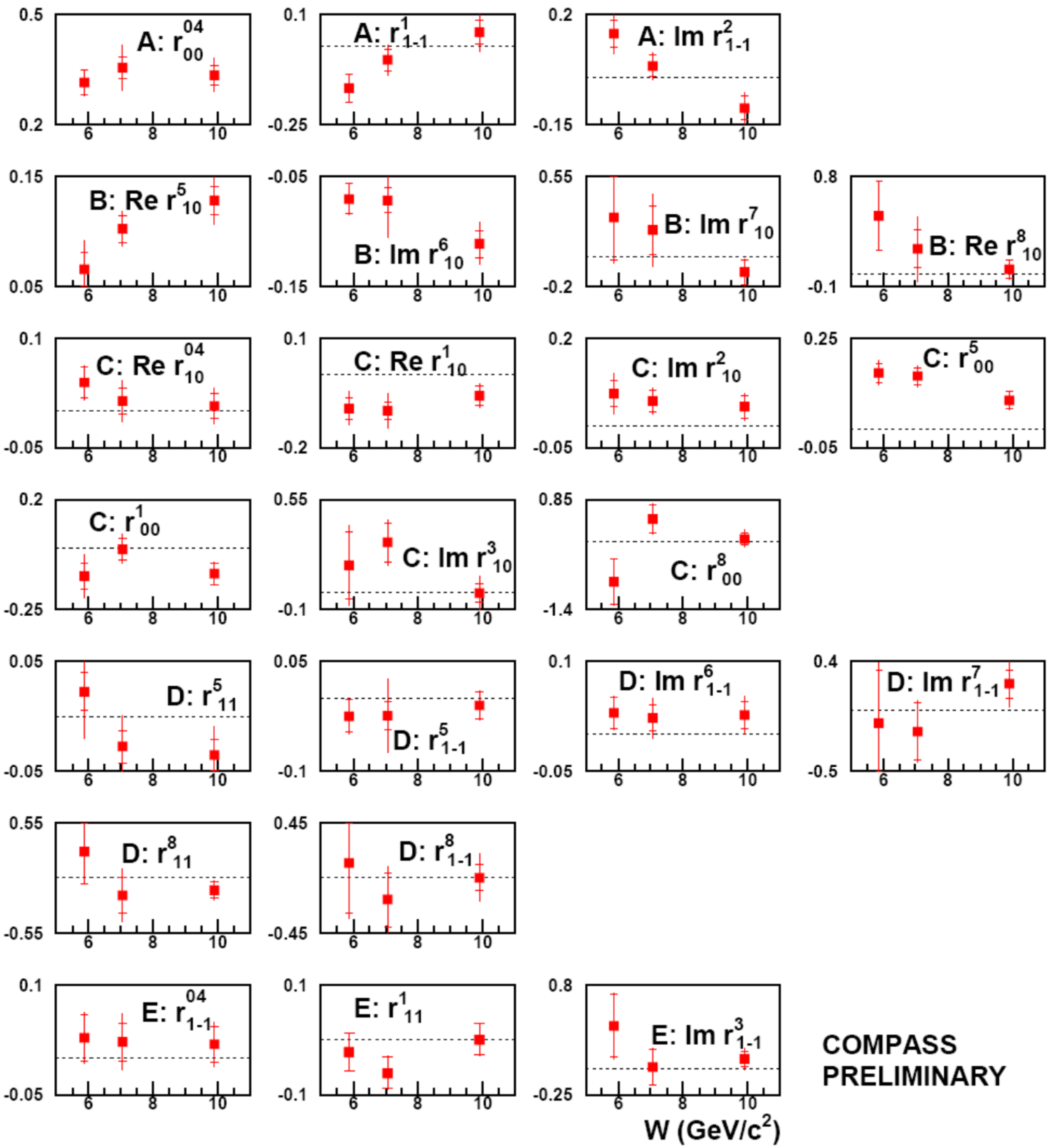
➢ Rosenbluth separation preferable

Backup

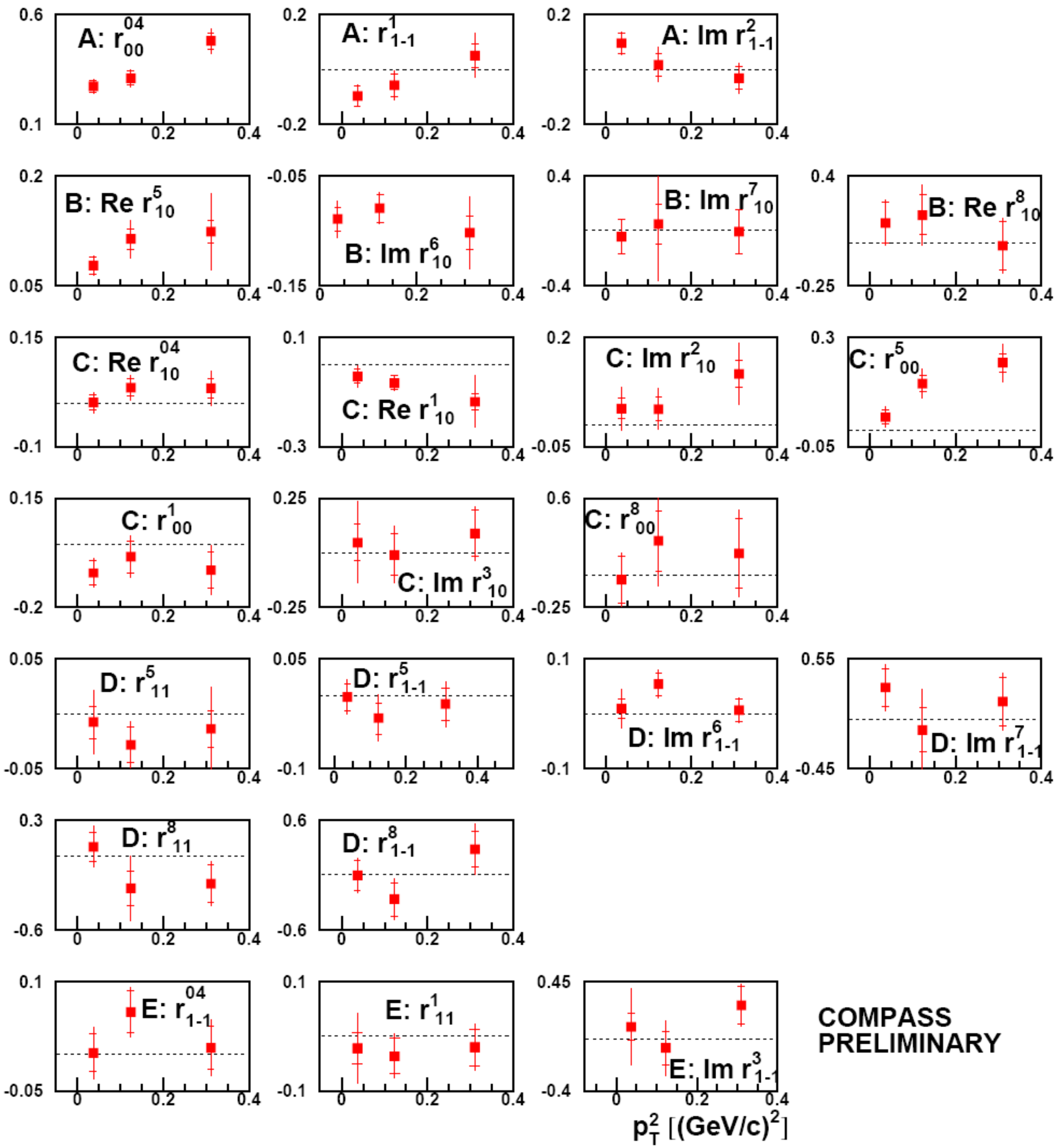
Q^2 dependence of SDMEs for exclusive ω



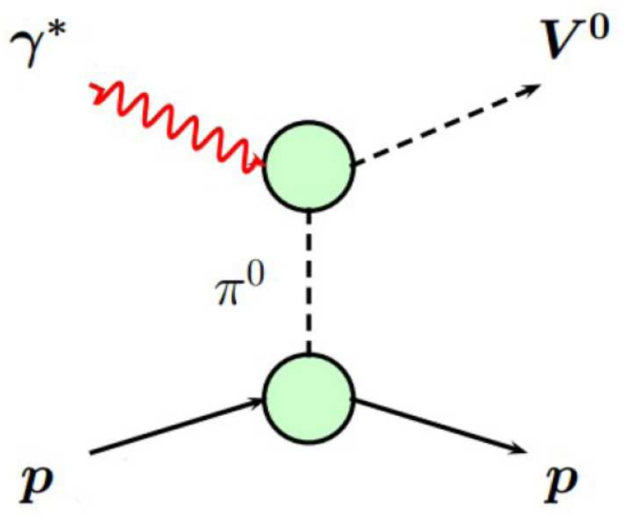
W dependence of SDMEs for exclusive ω



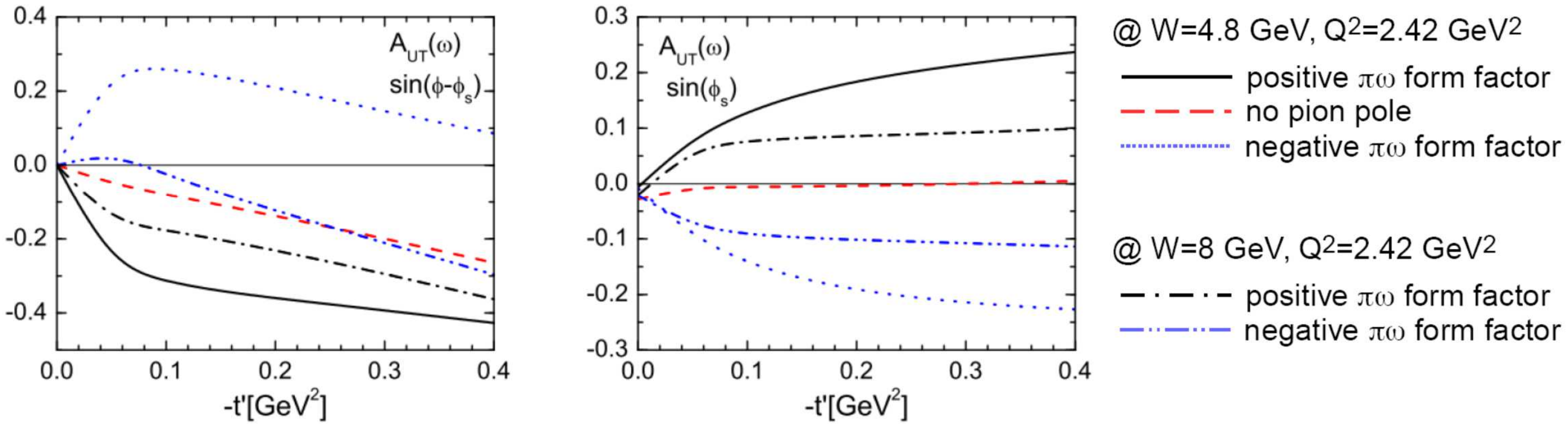
p_T^2 dependence of SDMEs for exclusive ω



Role of pion exchange



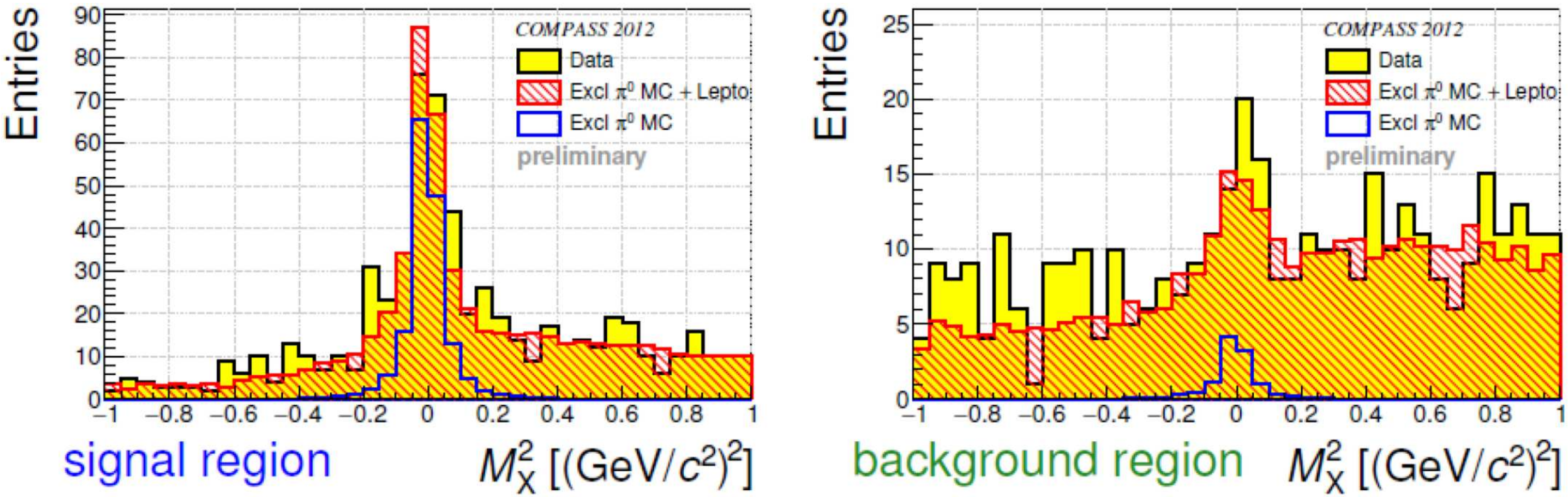
- Effect known since early photoproduction experiments
- At COMPASS kinematics:
  - small for ρ^0 production
  - sizable for ω production
- Unnatural parity exchange process
  → impact on helicity-dependent observables
- Crucial for description of SDMEs for excl. ω production
  → Goloskokov and Kroll,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



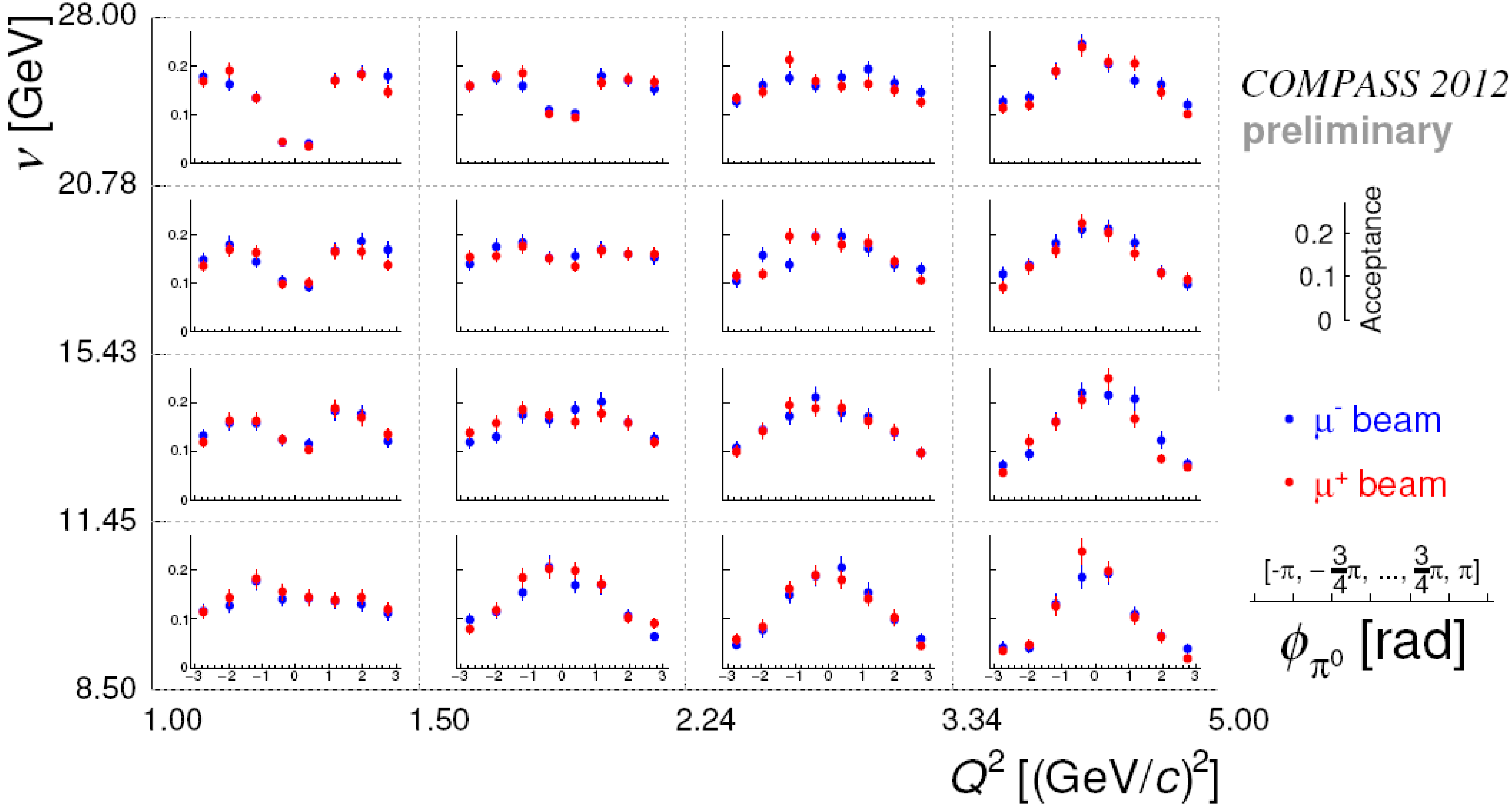
Estimate of SIDIS background

- use LEPTO MC to describe non exclusive background
- use exclusive π^0 MC to describe signal contribution
- find best description of data
  - in signal region (only two photon clusters)
  - in background region (more photon clusters)

$$M_X^2 = (p_{in}^{\mu} + p_{in}^{p} - p_{out}^{\mu} - p_{out}^{p} - p^{\pi^0})^2$$



Acceptance for exclusive π^0 production



4D-Acceptance binning (3D projection shown):

- Q^2 and ν recall: $\frac{d^3\sigma^{\mu p}}{dQ^2 d\nu dt} = \Gamma \frac{d\sigma^{\gamma^* p}}{dt}$

  with the virtual photon flux $\Gamma = \Gamma(Q^2, \nu)$
- $|t|$ and ϕ_{π^0}

Letter of Intent: Fixed-Target Experiment at M2 beam line beyond 2020

➢ Hadron Physics with Standard Muon Beams

- Proton radius measurement using μ -p elastic scattering
- Exclusive reactions with muon beams and transversely polarised target ➡ GPDs *E* via DVCS and DVMP

➢ Hadron Physics with Standard Hadron Beams

- DY and charmonium production with conventional hadron beams
- Spectroscopy with Low-Energy Antiprotons
- Measurements of antimatter production cross section for Dark Matter Search

➢ Hadron Physics with RF-Separated Beams

- Spectroscopy of Kaons
- Drell-Yan physics with high intensity kaon and antiproton beams
- Study of gluon distribution in kaon via prompt photon production
- Primakoff reactions

\+ Sections on: RF-Separated Beam Line and Instrumentation

LoI to be made public in a couple of weeks