Results on deeply virtual exclusive processes from COMPASS

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Prospects for extraction of GPDs
from global fits of current and future data

Heavy Ion Laboratory, Warsaw, 22-25 January 2019

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- Transverse extension of partons in the proton
- Hard exclusive π^0 production
- SDMEs for exclusive ω meson production
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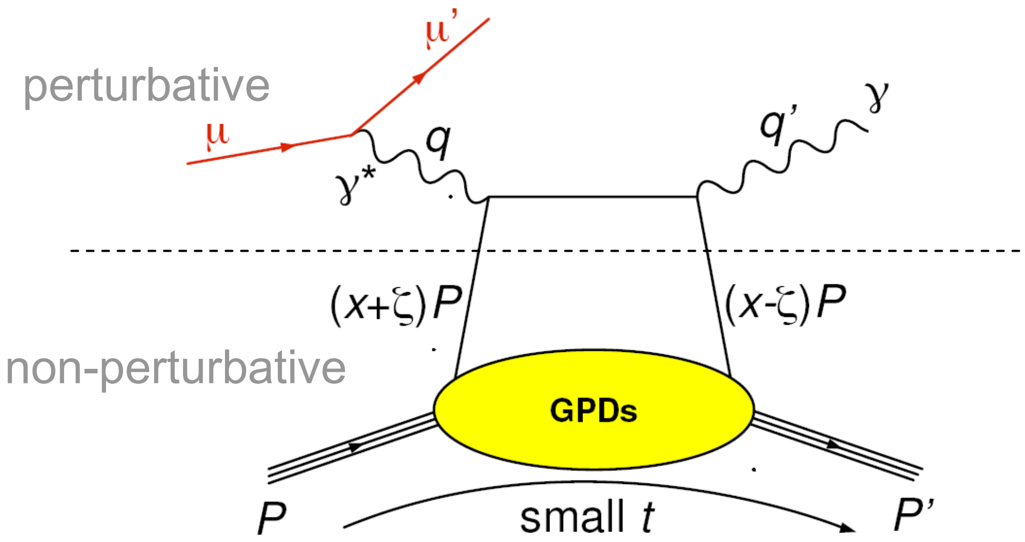
- Summary and outlook

Generalised Parton Distributions (GPDs)

- Provide comprehensive description of 3-D partonic structure of the nucleon
  one of the central problems of non-perturbative QCD
- GPDs can be viewed as correlation functions between different partonic states
- ‘Generalised’ because they encompass 1-D descriptions by PDFs or by form factors

(the simplest) example: Deeply Virtual Compton Scattering (DVCS)

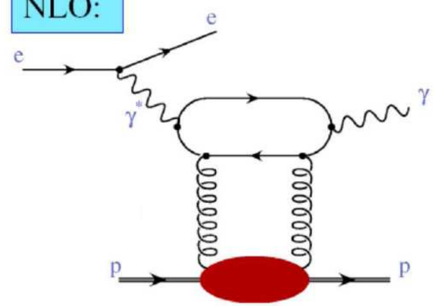


Factorisation for large Q^2 and | t | ‹‹ Q^2

4 GPDs for each **quark flavour**

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

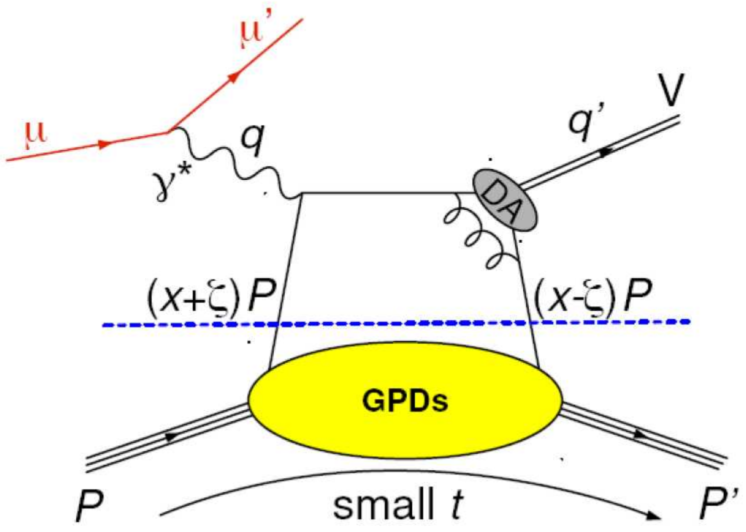
NLO:



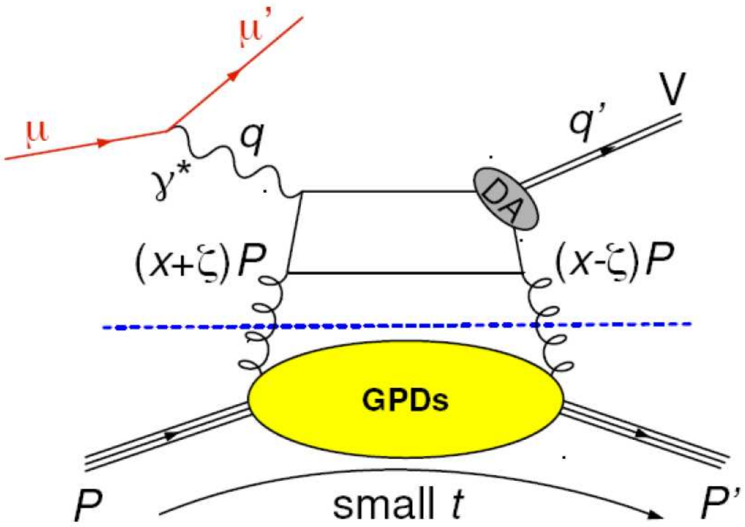
for DVCS **gluons** contribute at higher orders in α_s

GPDs and Hard Exclusive Meson Production

quark contribution



for VMs also gluon contribution



Chiral-even GPDs
helicity of parton unchanged

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

Chiral-odd GPDs
helicity of parton changed (not probed by DVCS)

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

Flavour separation for GPDs
example:

$$\mathcal{E}_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}\mathcal{E}^{u(+)} + \frac{1}{3}\mathcal{E}^{d(+)} + \frac{3}{4}\mathcal{E}^{g}/x\right)$$

$$\mathcal{E}_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}\mathcal{E}^{u(+)} - \frac{1}{3}\mathcal{E}^{d(+)} + \frac{1}{4}\mathcal{E}^{g}/x\right)$$

$$\mathcal{E}_{\phi} = -\frac{1}{3}\mathcal{E}^{u(+)} + \frac{1}{4}\mathcal{E}^{g}/x)$$

Diehl, Vinnikov, PLB 609 (2005) 286

COMPASS experiment at CERN

Basic ingredients of versatile COMPASS experimental setup

❖ **unique secondary beam line M2 from the SPS**

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

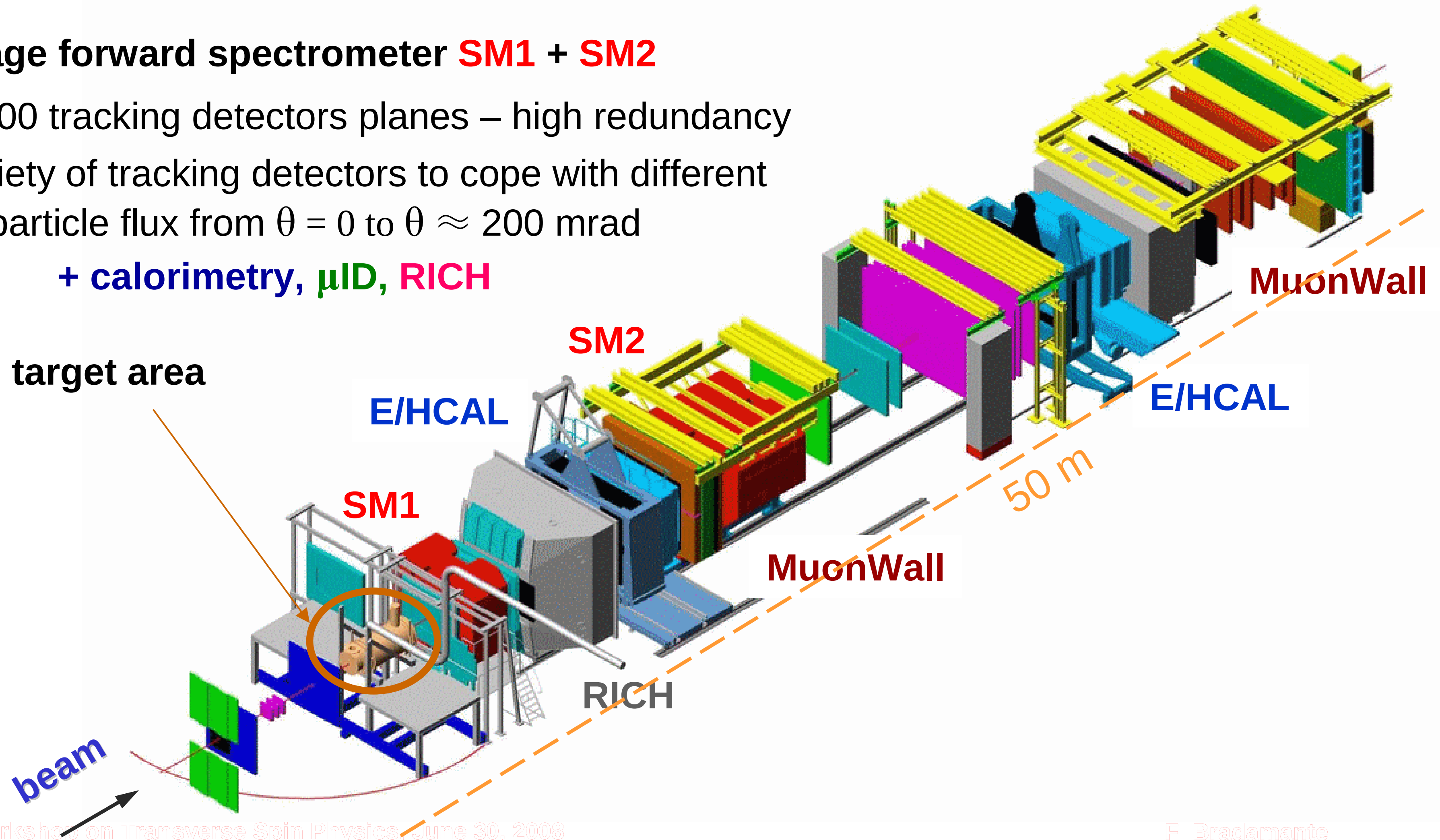
❖ **two-stage forward spectrometer SM1 + SM2**

≈ 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**

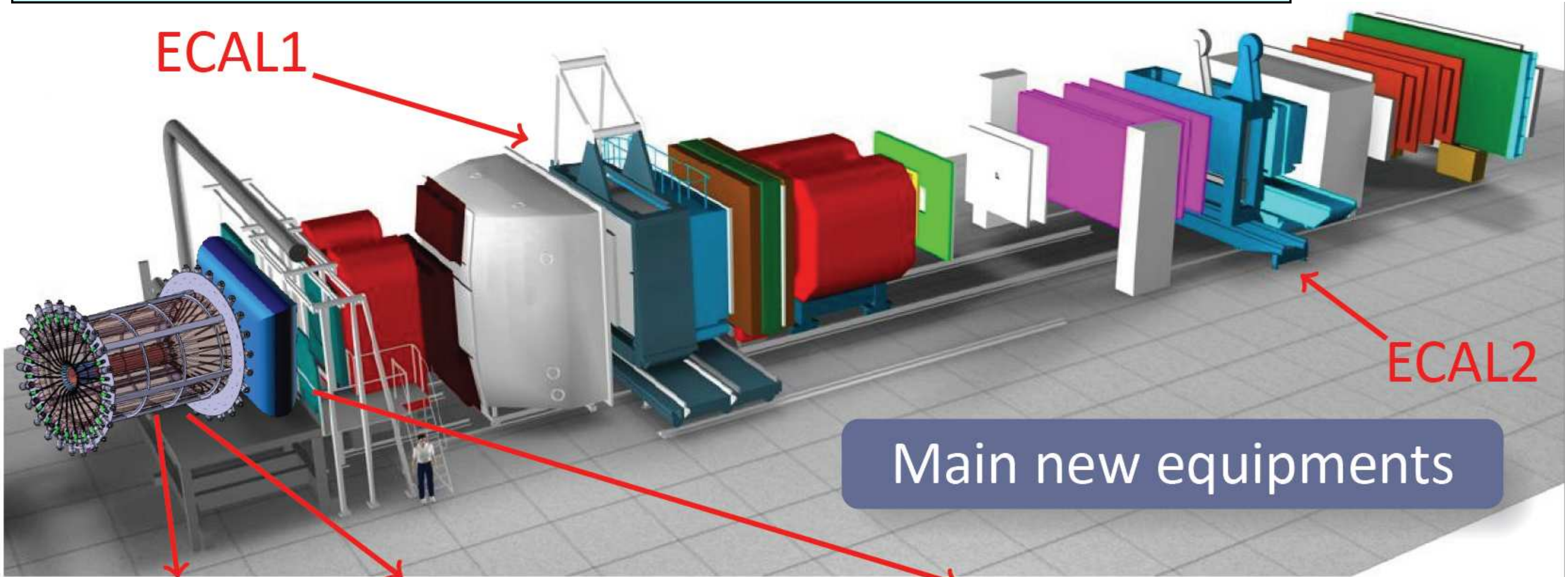


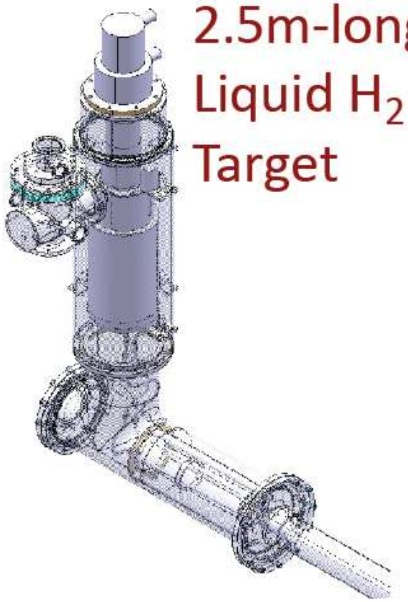
Physics programs

Flexibility of the setup to carry out a diverse physics programs
by using different beams and modifying mainly the target region

- spin structure of the nucleons and TMD studies
- 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)

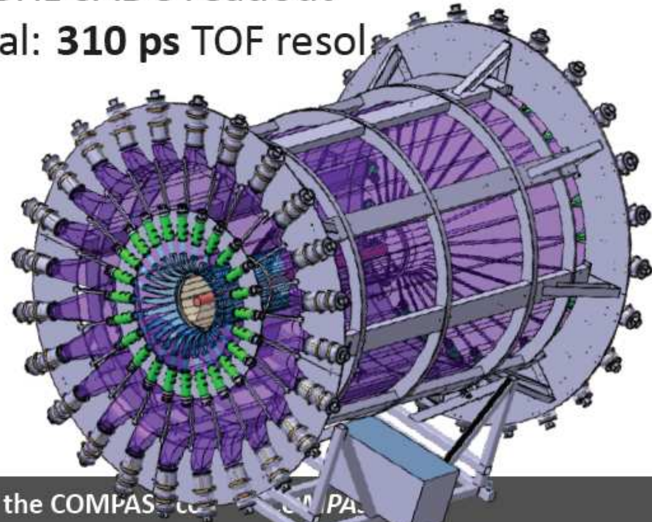




2.5m-long Liquid H_2 Target

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.

Transverse Extension of Partons in the Proton probed by Deeply Virtual Compton Scattering

Selection of exclusive single photon events

sample for t-slope extraction

μ, μ' and vertex in the target volume

1 GeV² < Q² < 5 GeV²,   10 GeV < ν < 32 GeV

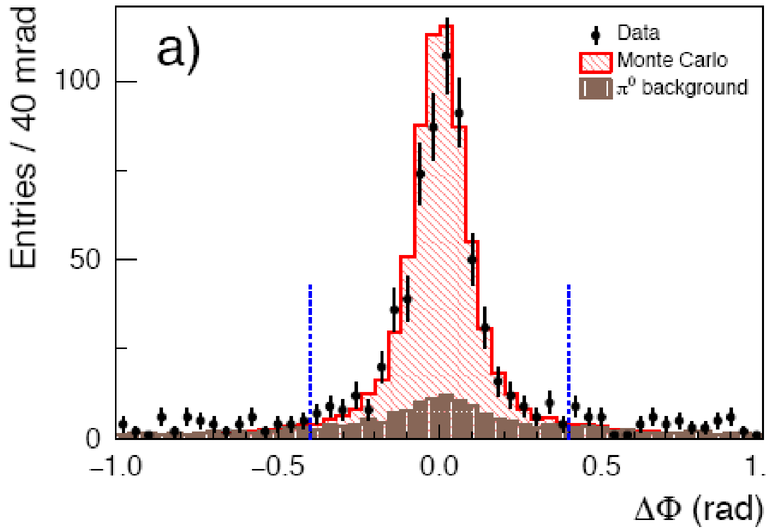
0.08 GeV² < | t | < 0.64 GeV²

1 single photon with energy above DVCS threshold ← $E_{Ecal(0,1,2)}$ > (4,5,10) GeV

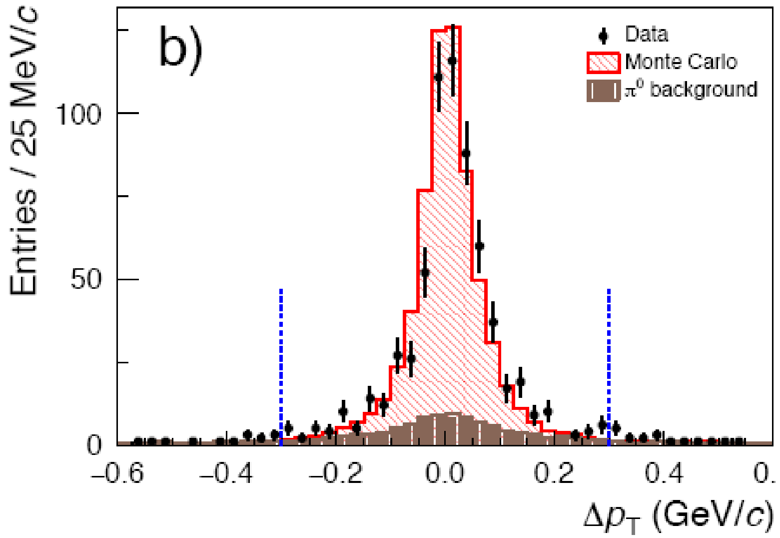
Overconstrained kinematics => a number of „exclusivity cuts" allows to select the exclusive sample

Examples:

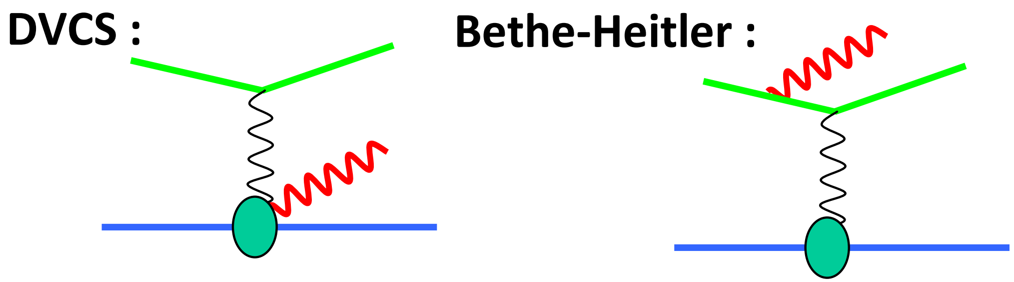
$$\Delta\Phi = \Phi^{p}_{meas} - \Phi^{p}_{pred}$$



$$\Delta p_T = p^{p}_{T,meas} - p^{p}_{T,pred}$$



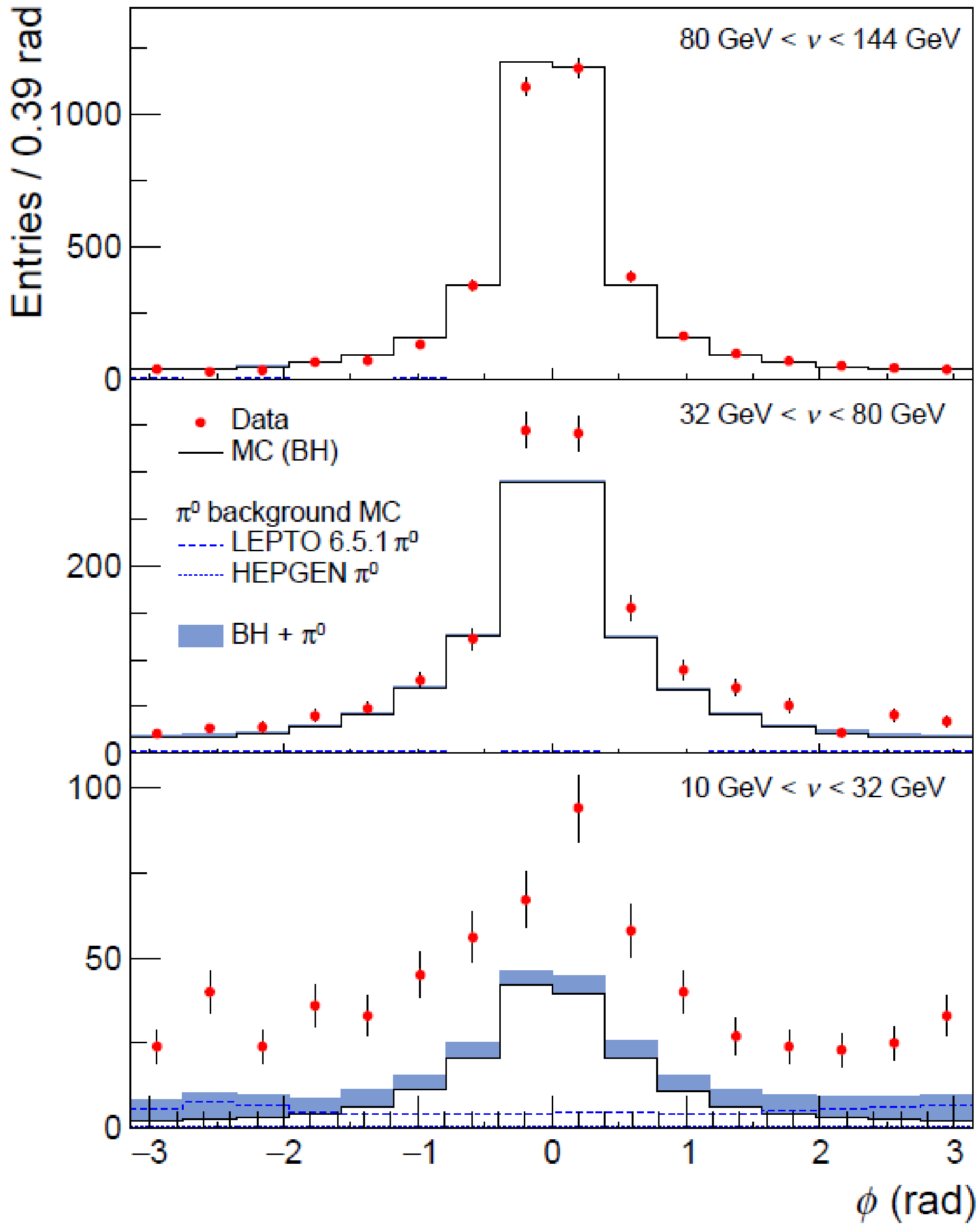
Exclusive single photon production cross section

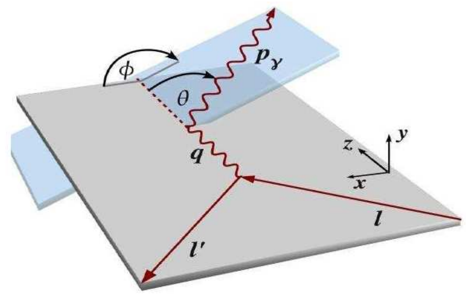


cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu \, d\sigma^{DVCS}_{pol} + e_\mu \, a^{BH} \, \mathcal{Re}\, A^{DVCS} + e_\mu \, P_\mu \, a^{BH} \, \mathcal{Im}\, A^{DVCS}$$

Azimuthal distributions for single γ events





BH dominates

excellent reference yield

BH and DVCS at the same level

access to DVCS amplitude through the interference

DVCS dominates

study of $d\sigma^{DVCS}/dt$

Extraction of $d\sigma^{DVCS}/dt$

- measure $d\sigma := \frac{d^4\sigma^{\mu p}}{dQ^2 d\nu dt d\phi}$ for μ^+ and μ^- beams

- sum of μ^+ and μ^- cross sections $2d\sigma \equiv d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2(d\sigma^{BH} + d\sigma^{DVCS} - |P_\mu| d\sigma^I)$

P_μ *beam polarisation*

$$d\sigma^{DVCS} \propto \frac{1}{y^2 Q^2}(c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi)$$

$$d\sigma^I \propto \frac{1}{x_{Bj} y^3 t P_1(\phi) P_2(\phi)}(s_1^I \sin\phi + s_2^I \sin 2\phi)$$

- subtract calculable BH cross sections and integrate over ϕ

$$\frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt} = \int_{-\pi}^{\pi} d\phi\,(d\sigma - d\sigma^{BH}) \propto c_0^{DVCS}$$

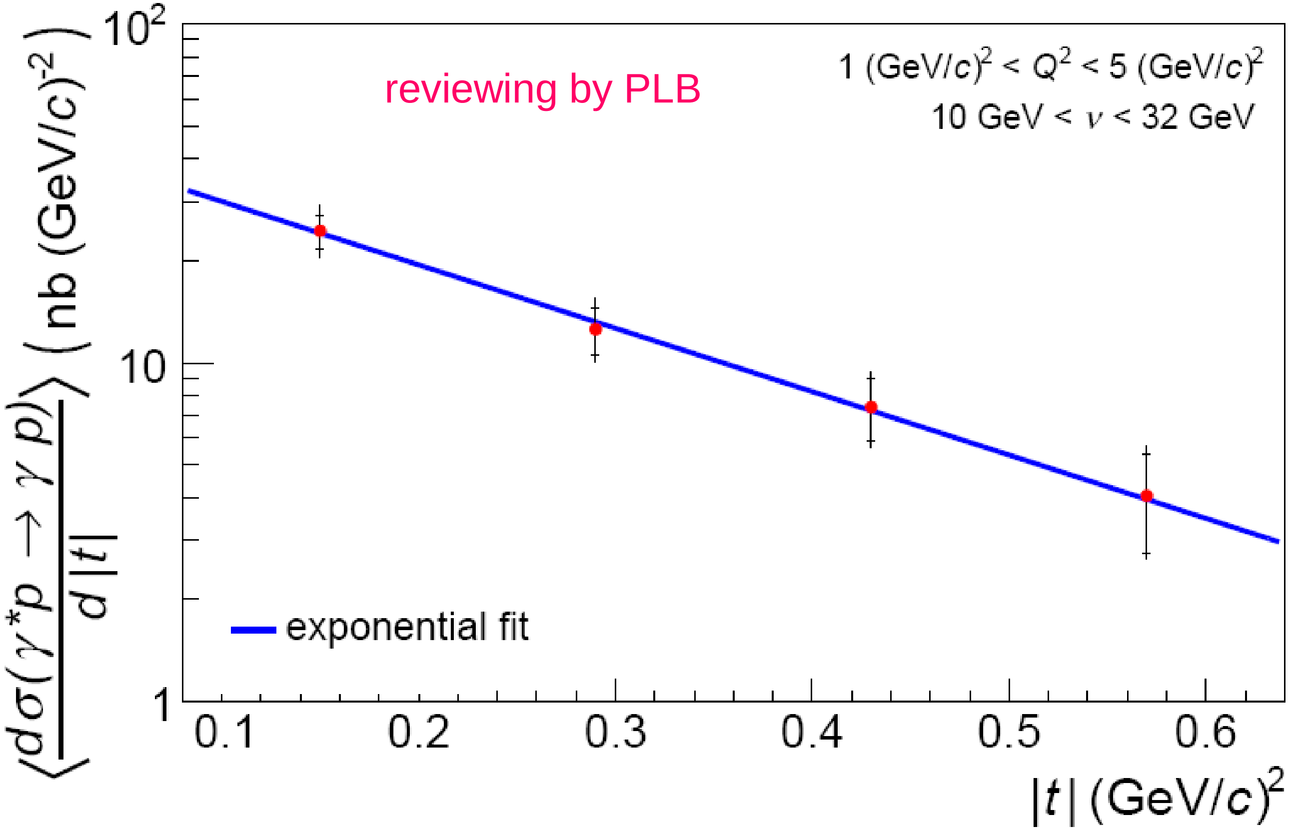
- convert into cross section for virtual-photon scattering

$$\frac{d\sigma^{\gamma^* p}}{dt} = \frac{1}{\Gamma(Q^2, \nu, E_\mu)} \frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt}$$

Γ *transverse virtual photon flux*

DVCS cross section and t-slope

from 4 weeks of 2012 commissioning data



$$B = (4.3 \pm 0.6_{\text{stat}} \, {}^{+\,0.1}_{-\,0.3}\big|_{\text{sys}}) \; (\text{GeV}/c)^{-2}$$

$$\langle W \rangle = 5.8\,\text{GeV}/c^2, \;\; \langle Q^2 \rangle = 1.8\,(\text{GeV}/c)^2 \text{ and } \langle x_{\text{Bj}} \rangle = 0.056$$

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

(*) $$\langle r_\perp^2(x_{Bj})\rangle \approx 2\langle B(x_{Bj})\rangle \hbar^2$$

how good is this approximation ?

Strict determination of $\langle r_\perp^2 \rangle$ requires (M. Burkardt)

i) measurement of t-dependence of the imaginary part of CFF $\mathcal{H}$

ii) skewness ξ = 0

spin- and ϕ-independent DVCS cross section $\propto c_0^{DVCS}$

for small x_{Bj} $c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$ (BMK)

Systematic uncertainties on $\langle r_\perp^2 \rangle$ when using (*) ('model' uncertainty)

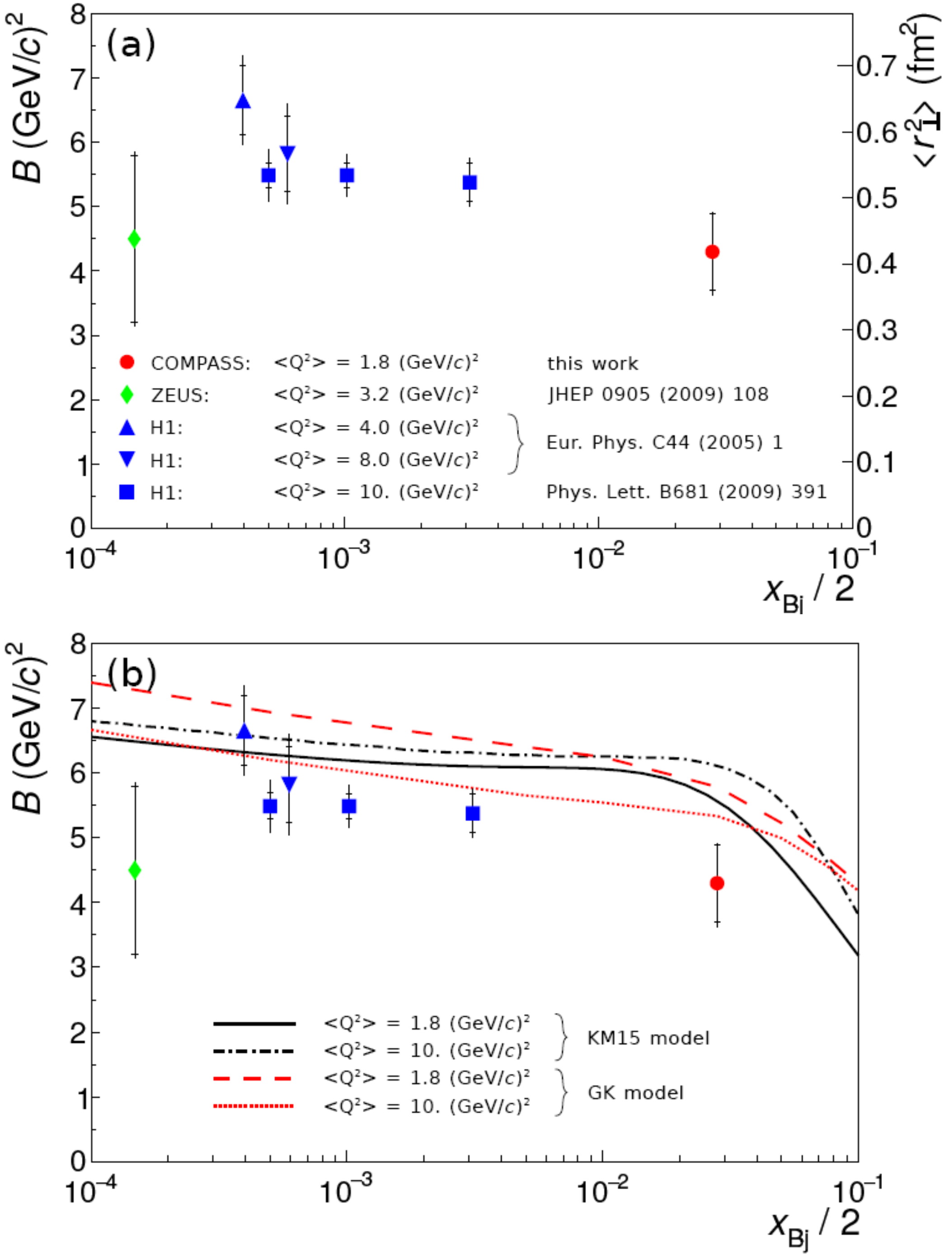
a) correction due to contributions of real part of $\mathcal{H}$ and other GPDs → ± 0.03

b) correction due to assumption ii) → ± 0.02

Estimates based on models {
- GK model in PARTONS framework
- Kumerički – Müller model

$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\rm stat} \,{}^{+\,0.01}_{-\,0.02}\big|_{\rm sys} \pm 0.04_{\rm model})\ {\rm fm}$$

Comparison to HERA and model predictions



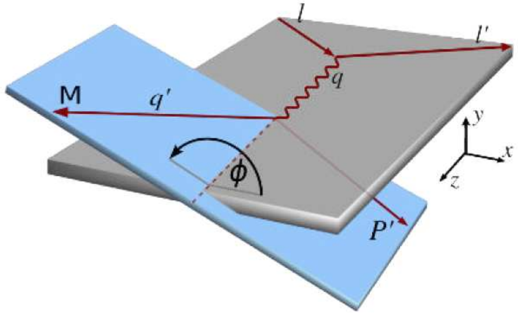
a hint for shrinking with increasing x_{Bj}

weak Q^2 dependence of B (3 – 13%)

Hard exclusive π^0 production on unpolarised protons
and chiral-odd GPDs

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

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

def. $\bar{E}_T = 2\tilde{H}_T + E_T$

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

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

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

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

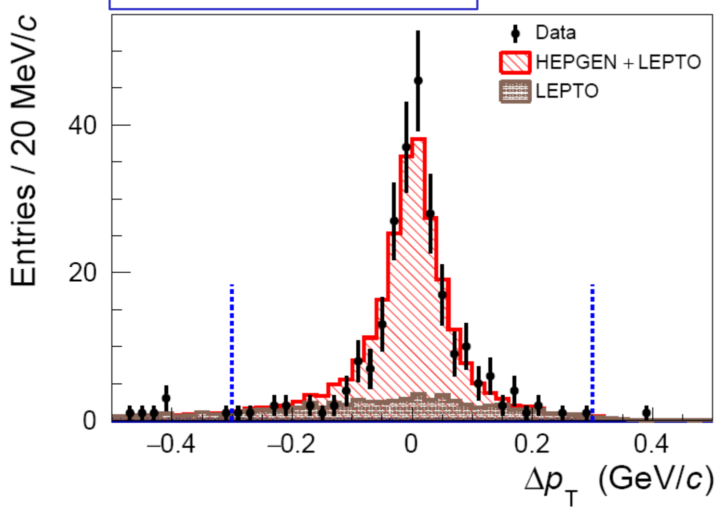
Selection of exclusive π^0 production events

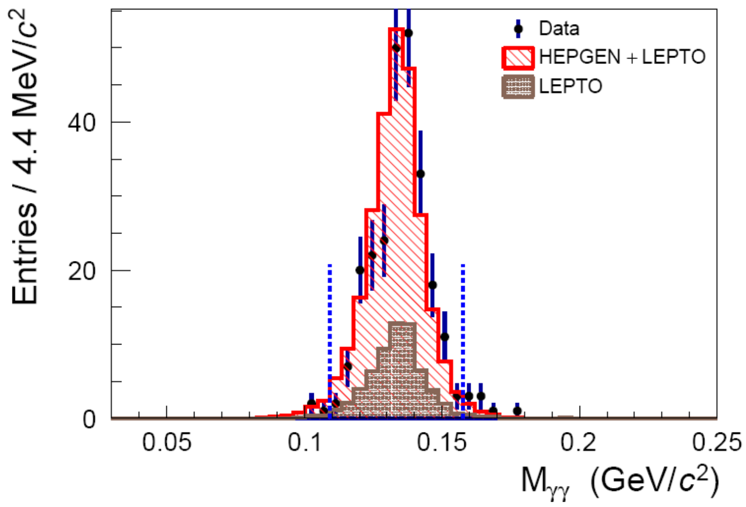
- μ, μ' and vertex in the target volume
- 1 GeV² < Q² < 5 GeV², 8.5 GeV < ν < 28 GeV
- 0.08 GeV² < | t | < 0.64 GeV²
- two photons with invariant mass consistent with π^0

Overconstrained kinematics => a number of „exclusivity cuts" allows to select the exclusive sample

example

$$\Delta p_T = p^p_{T,meas} - p^p_{T,pred}$$





background fraction $(29^{+\ 2}_{-\ 6}|_{\text{sys}})\%$

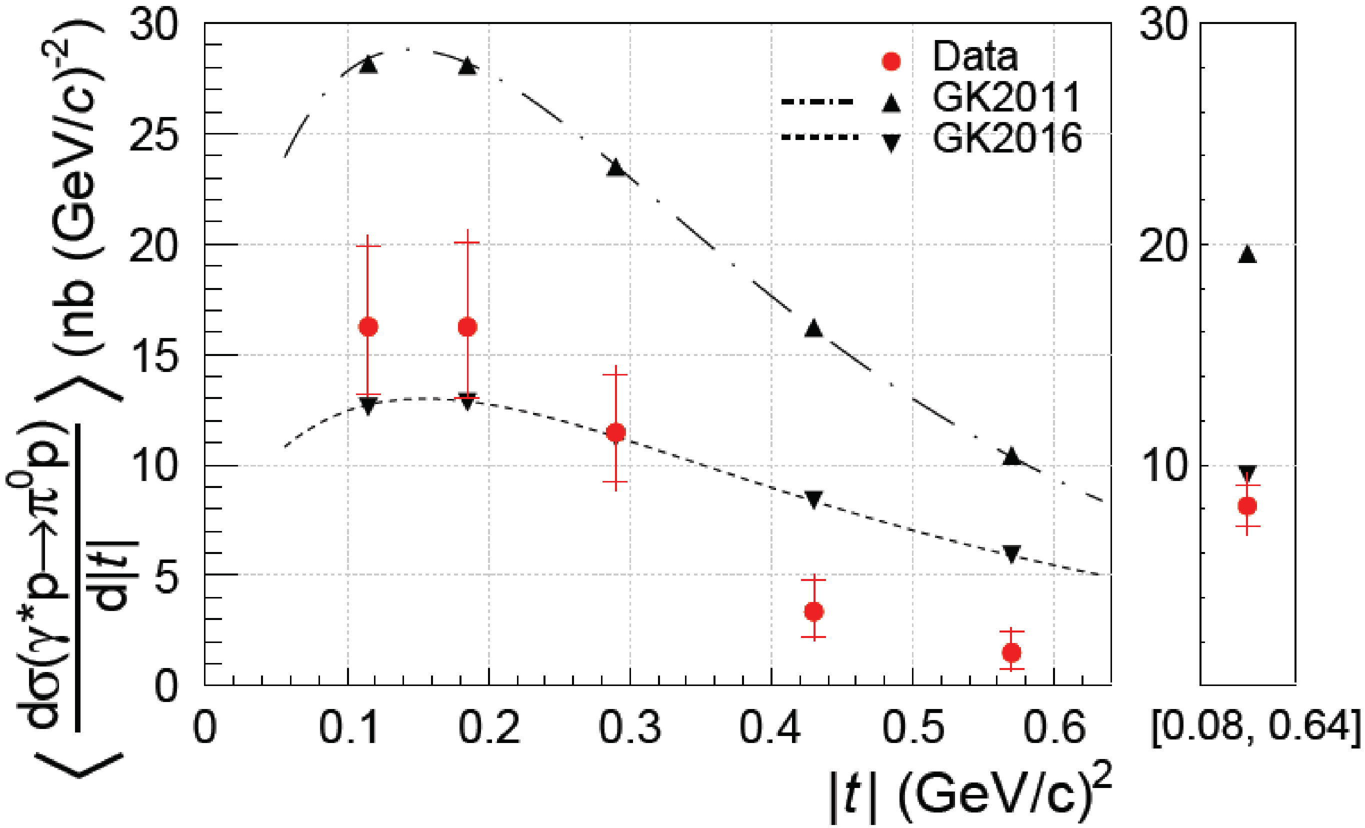
<u>kinematic fit</u> applied to determine the most precise particle kinematics and enhance purity of the sample

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

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt}$$

An impact of $\bar{E}_T$ contribution in $\frac{d\sigma_T}{dt}$

to be subm. to PLB



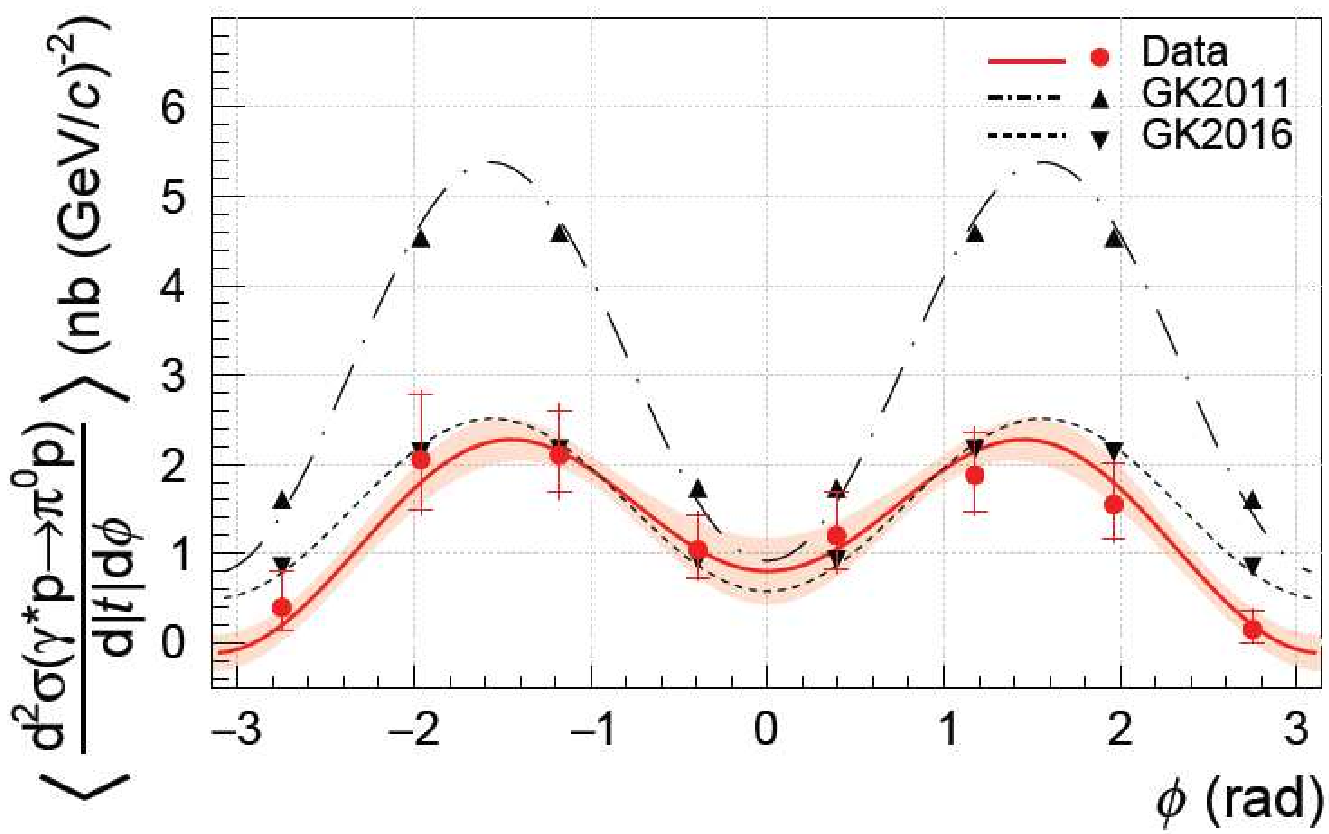
$\langle Q^2 \rangle = 2.0\ (\mathrm{GeV}/c)^2$, $\langle \nu \rangle = 12.8\ \mathrm{GeV}$,

$\langle x_{Bj} \rangle = 0.093$ and $\langle -t \rangle = 0.256\ (\mathrm{GeV}/c)^2$

First measurement at low ξ

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

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



$$\left\langle \frac{d\sigma_T}{d|t|} + \epsilon\frac{d\sigma_L}{d|t|} \right\rangle = (8.1 \pm 0.9_{stat}{}^{+\,1.1}_{-\,1.0}|_{sys})\frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{d|t|} \right\rangle = (-6.0 \pm 1.3_{stat}{}^{+\,0.7}_{-\,0.7}|_{sys})\frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{LT}}{d|t|} \right\rangle = (1.4 \pm 0.5_{stat}{}^{+\,0.3}_{-\,0.2}|_{sys})\frac{nb}{(GeV/c)^2}$$

Large impact of $\overline{E}_T$ visible in $\frac{d\sigma_{TT}}{dt} \sim \overline{E}_T$

positive result for $\frac{d\sigma_{LT}}{dt}$

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)

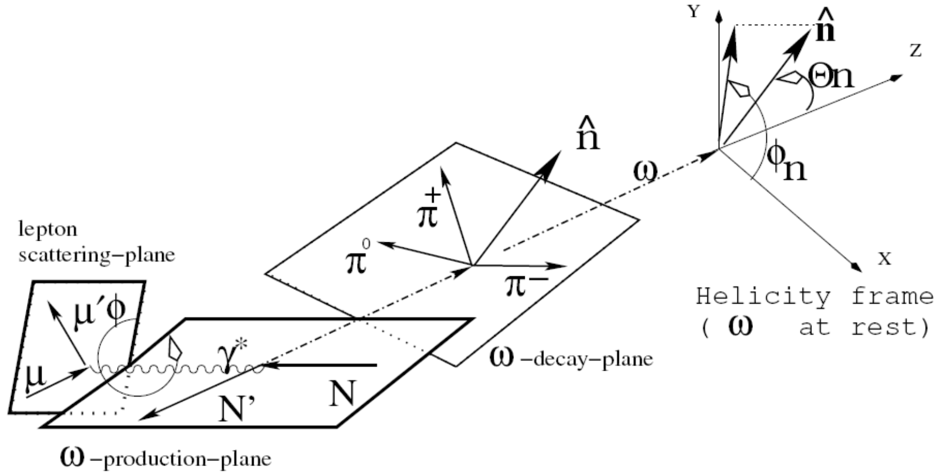
- tests of GPD models
  - e.g. for SCHC-violating transitions $\gamma_T \rightarrow V_L$ test sensitivity to GPDs with exchanged-quark helicity flip (transversity GPDs)

Experimental access to SDMEs

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

SDMEs: „amplitudes" of decomposition of W^{U+L} in the sum of terms of different angular dependences

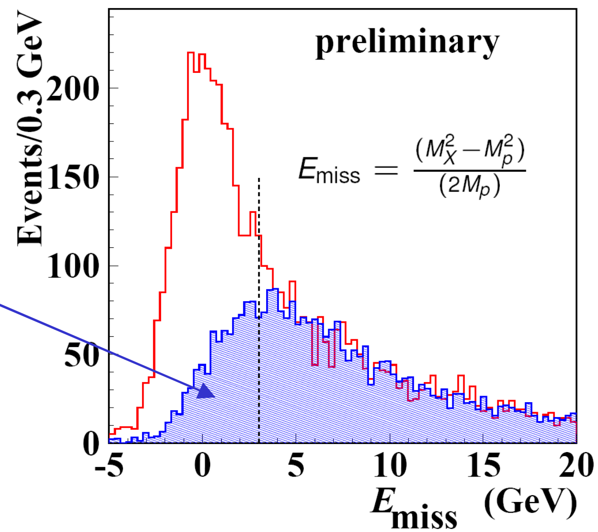
[K. Schilling and G. Wolf, Nucl. Phys. B61, 381 (1973)]



15 unpolarised SDMEs (in W^U) and 8 polarised (in W^L)

<u>Extraction of SDMEs</u>

Unbinned ML fit to experimental W^{U+L}
taking into account
- total acceptance
- fraction of background in the signal window
- anglar distribution of background W^{U+L}_{bkg} (determined either from LEPTO MC or real data side band)



Results on SDMEs for exclusive ω production at COMPASS

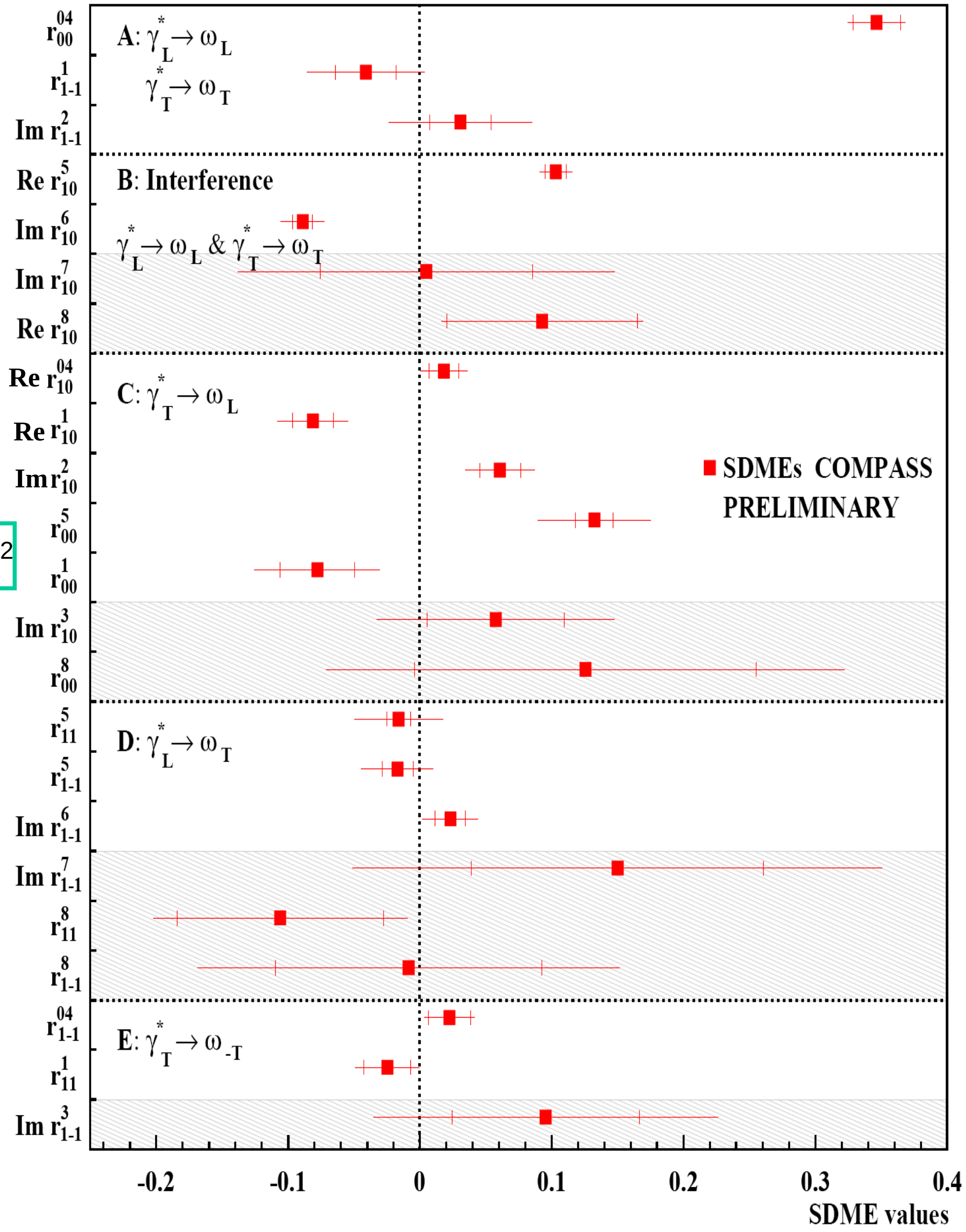
1 GeV² < Q² < 10 GeV²

5 GeV < W < 20 GeV

0.01 GeV² < p_T^2 < 0.5 GeV²

< Q²> = 2.13 GeV², <W> = 7.6 GeV, < p_T^2 > = 0.16 GeV²

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



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

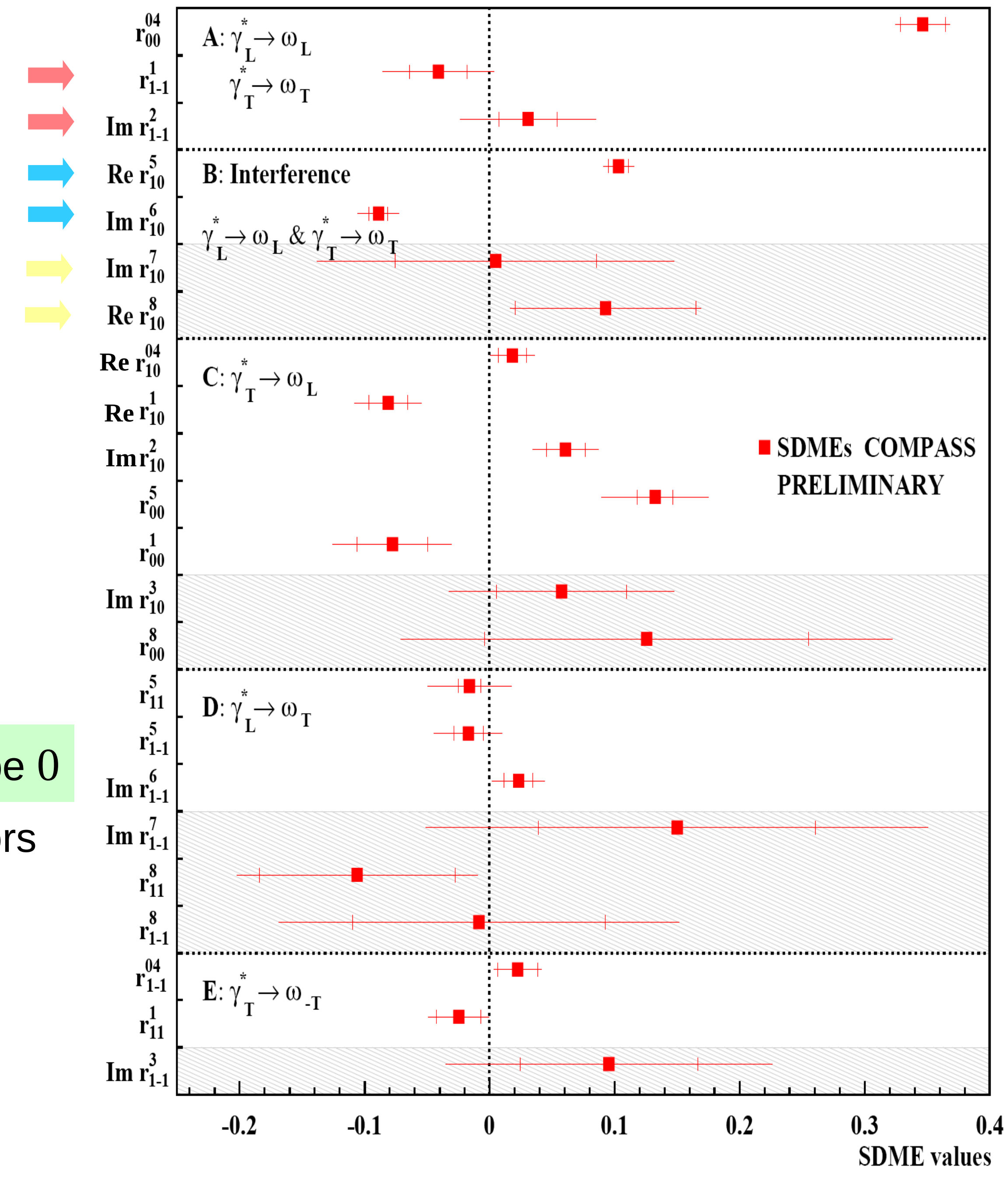
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

  = - 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 $\gamma^*_T \to \omega_L$

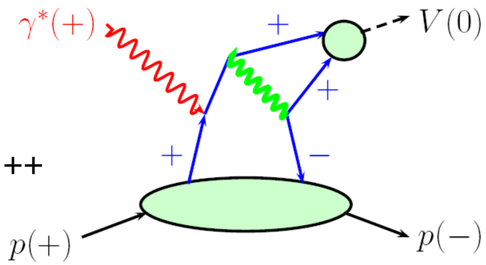


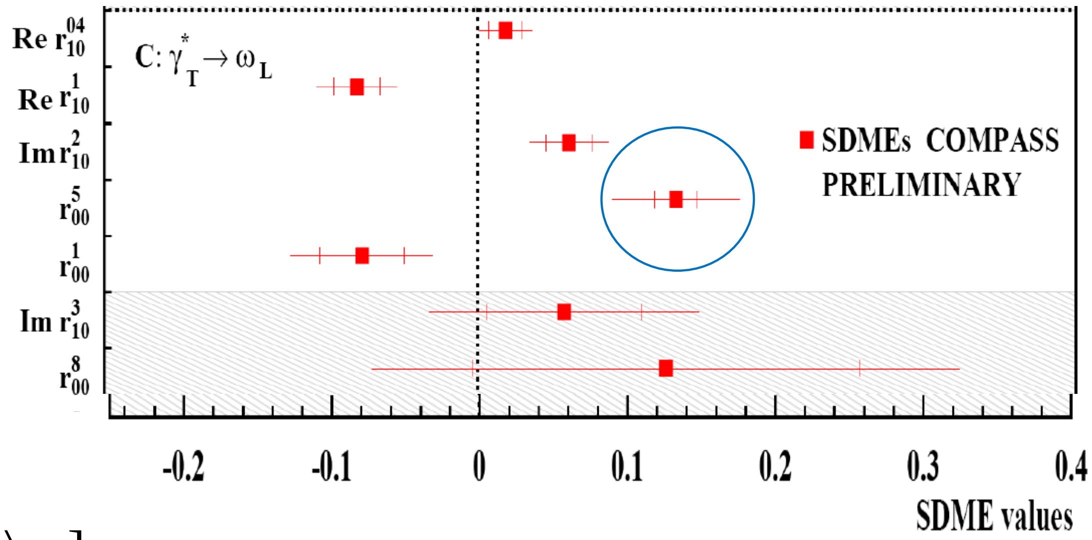
Transitions $\gamma^*_T \to \omega_L$

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

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

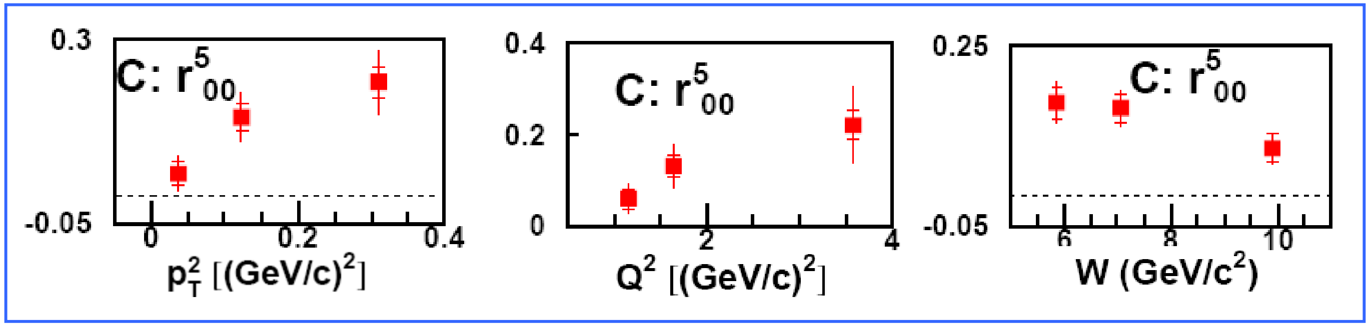
example ➡ graph for amplitude $F_{0-,++}$





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

COMPASS preliminary

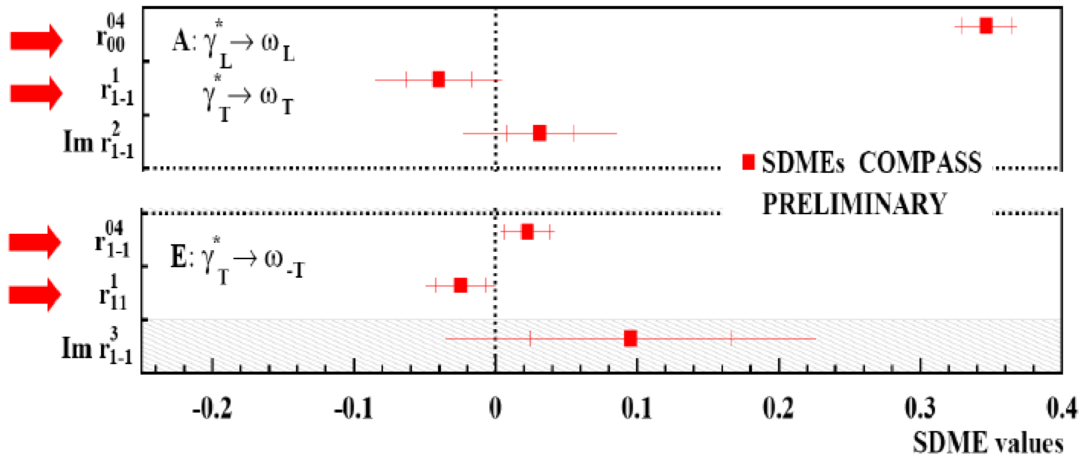


interplay of interference of transversity GPDs $H_T, \bar{E}_T = 2\tilde{H}_T + E_T$ with GPDs H and E, respectively

Unnatural parity exchange contribution

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

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



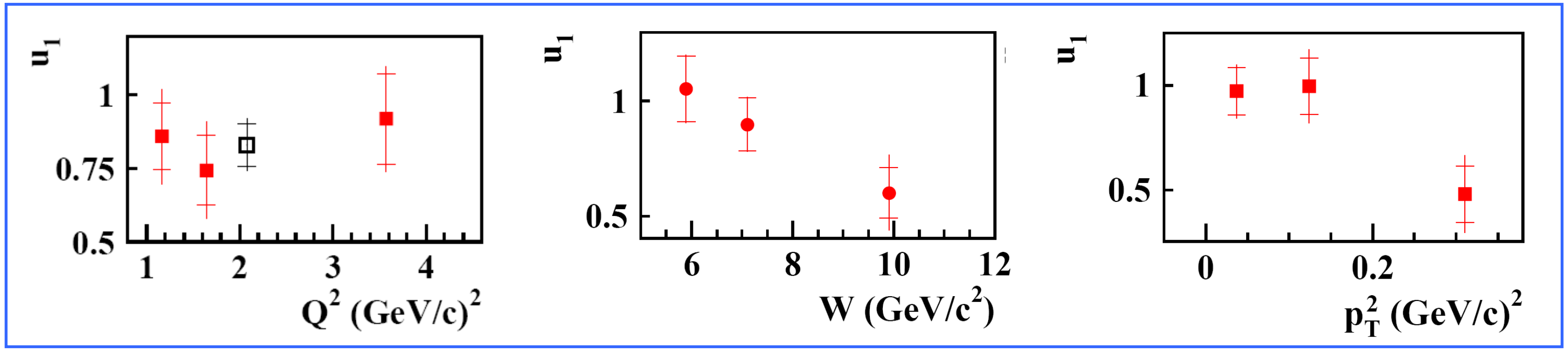
numerator depends only on UPE amplitudes

$u1 > 0 \implies$ UPE contribution

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

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

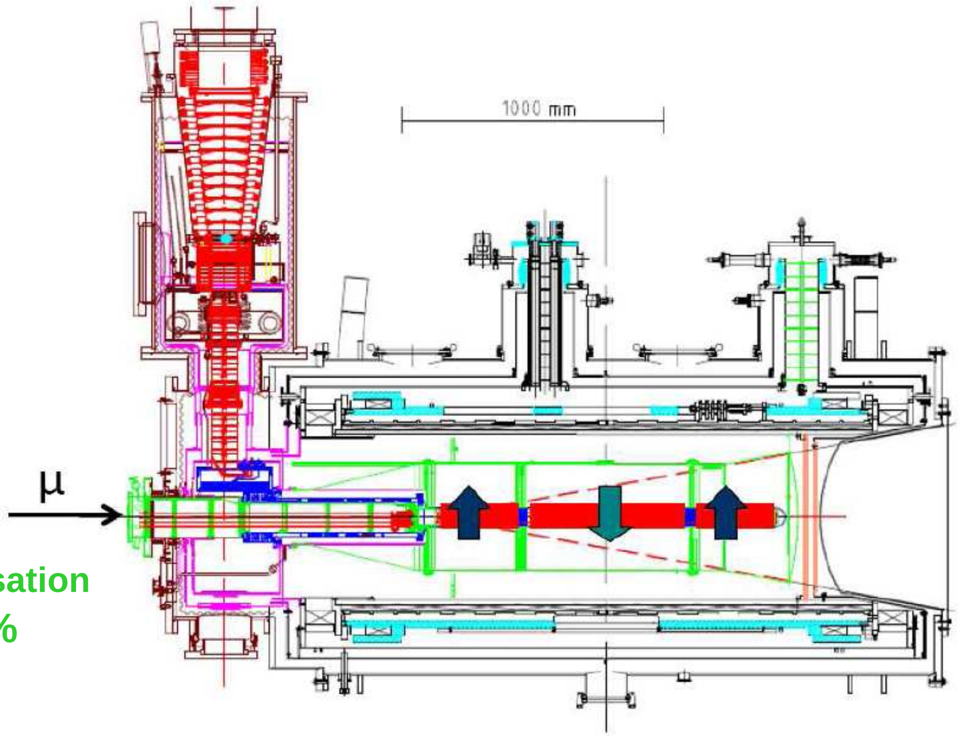
COMPASS preliminary



- decrease of UPE contribution with increasing W
  still non-negligible contribution from pion-pole exchange even at W = 10 GeV/c^2

Transverse target spin asymmetries for exclusive ρ^0 and ω production

COMPASS polarised target



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

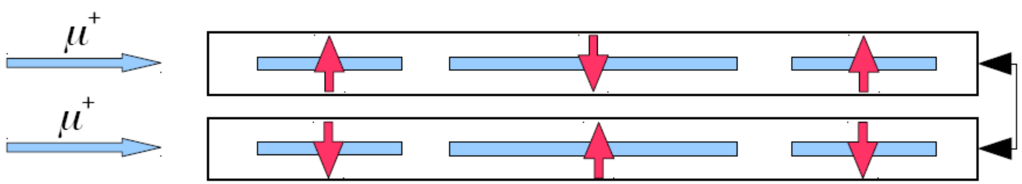
solenoid	2.5 T
dipole magnet	0.6 T

μ^+ polarisation
≈ -80%

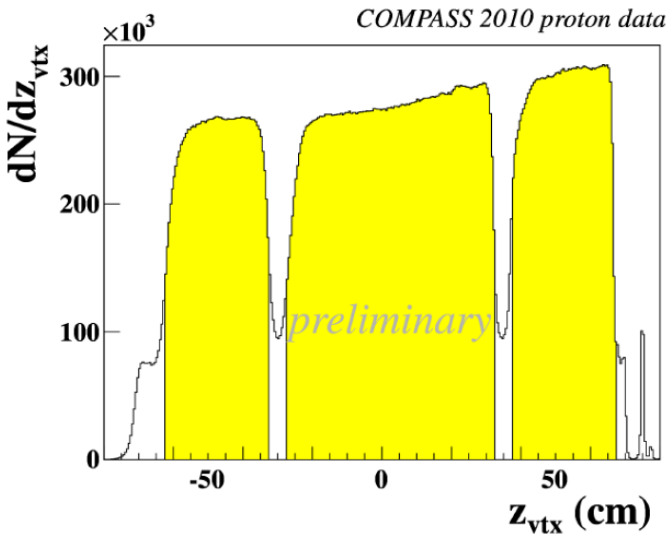
Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization

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



Spin-dependent cross section for exclusive meson leptoproduction

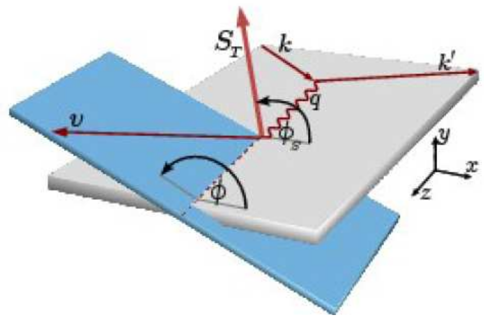
$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\epsilon}\frac{1-x_{Bj}}{x_{Bj}}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}dQ^2dtd\phi d\phi_s}$$

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

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

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

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



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

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

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

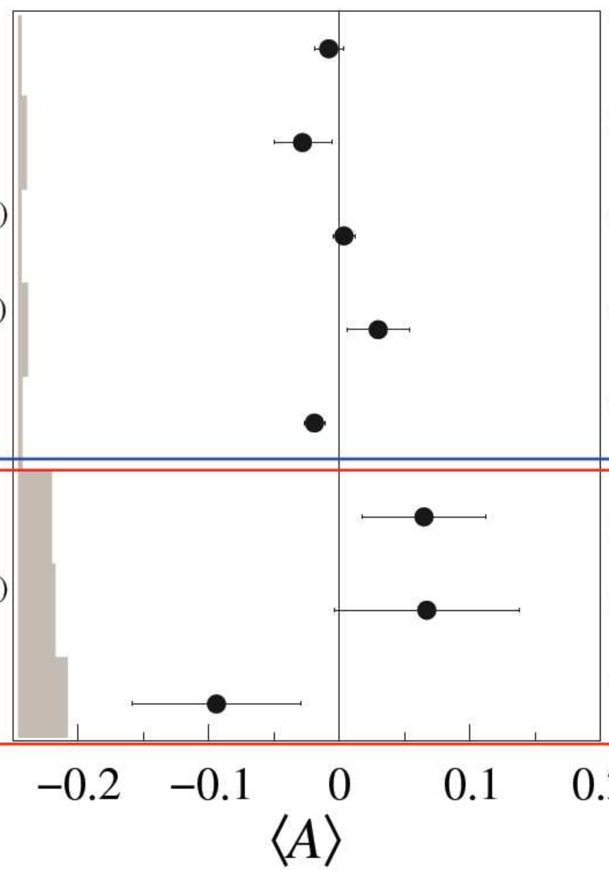
$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2 y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2 y^2}$$

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

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

PLB 731 (2014) 19

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



$A_{UT}^{\sin(\phi-\phi_S)} := \mathrm{Im}(\sigma^{+-}_{++} + \varepsilon\sigma^{+-}_{00})/\sigma_0 \propto -\mathrm{Im}\left[\varepsilon \mathcal{E}^*_{LL}\mathcal{H}_{LL} + \mathcal{E}^*_{TT}\mathcal{H}_{TT} - \frac{1}{2}\bar{\mathcal{E}}^*_{T,LT}\mathcal{H}_{T,LT}\right]$,

$A_{UT}^{\sin(\phi+\phi_S)} := \mathrm{Im}(\sigma^{+-}_{+-})/\sigma_0 \propto \mathrm{Im}\left[\bar{\mathcal{E}}^*_{T,LT}\mathcal{H}_{T,LL}\right]$,

$A_{UT}^{\sin(2\phi-\phi_S)} := \mathrm{Im}(\sigma^{-+}_{+-})/\sigma_0 \propto -\mathrm{Im}\left[\bar{\mathcal{E}}^*_{T,LT}\mathcal{E}_{LL}\right]$,

$A_{UT}^{\sin(3\phi-\phi_S)} := \mathrm{Im}(\sigma^{+-}_{+0})/\sigma_0 = 0$,

$A_{UT}^{\sin\phi_S} := \mathrm{Im}(\sigma^{-+}_{+0})/\sigma_0 \propto \mathrm{Im}\left[\mathcal{H}^*_{T,LT}\mathcal{H}_{LL} - \bar{\mathcal{E}}^*_{T,LT}\mathcal{E}_{LL}\right]$,

5 single spin asymmetries

$A_{LT}^{\cos(\phi-\phi_S)} := \mathrm{Re}(\sigma^{+-}_{++})/\sigma_0 \propto \mathrm{Re}\left[\bar{\mathcal{E}}^*_{T,LT}\mathcal{H}_{T,LT} - 2\mathcal{E}^*_{TT}\tilde{\mathcal{H}}_{TT}\right]$,

$A_{LT}^{\cos(2\phi-\phi_S)} := \mathrm{Re}(\sigma^{+-}_{+0})/\sigma_0 \propto \mathrm{Re}\left[\bar{\mathcal{E}}^*_{T,LT}\mathcal{H}_{T,LT} - 2\mathcal{E}^*_{TT}\tilde{\mathcal{H}}_{TT}\right]$,

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

3 double spin asymmetries

$\sim E$, $\sim H$, $\sim H_T$, $\sim \bar{E}_T = 2\tilde{H}_T - E_T$, $\sim \tilde{H}$

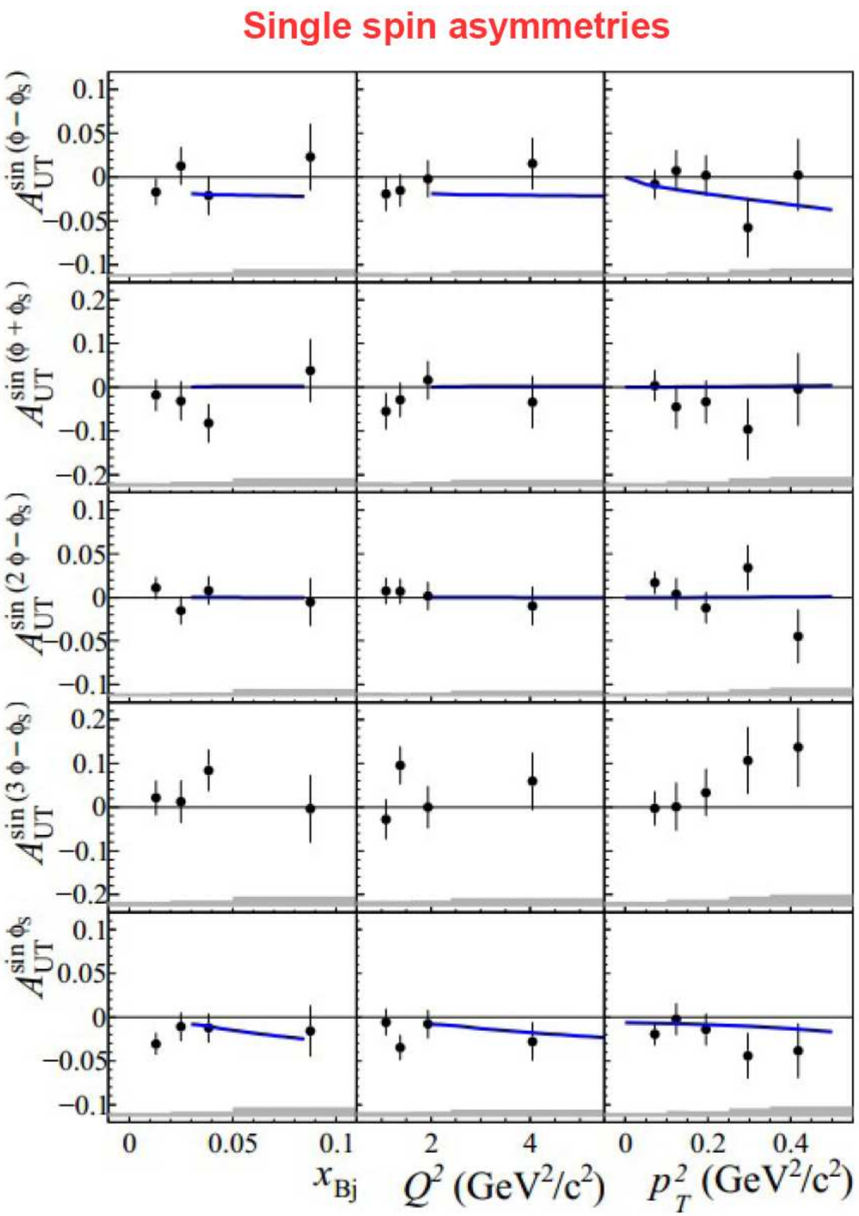
- asymmetries small, compatible with 0, except

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

- indication of transversity GPD H_T contribution

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

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



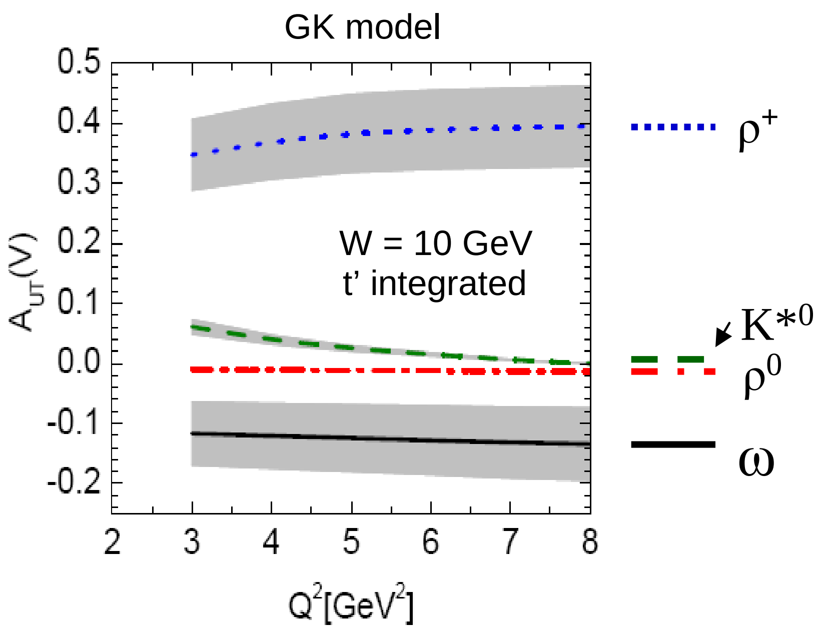
predictions of GPD model of Goloskokov-Kroll

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

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

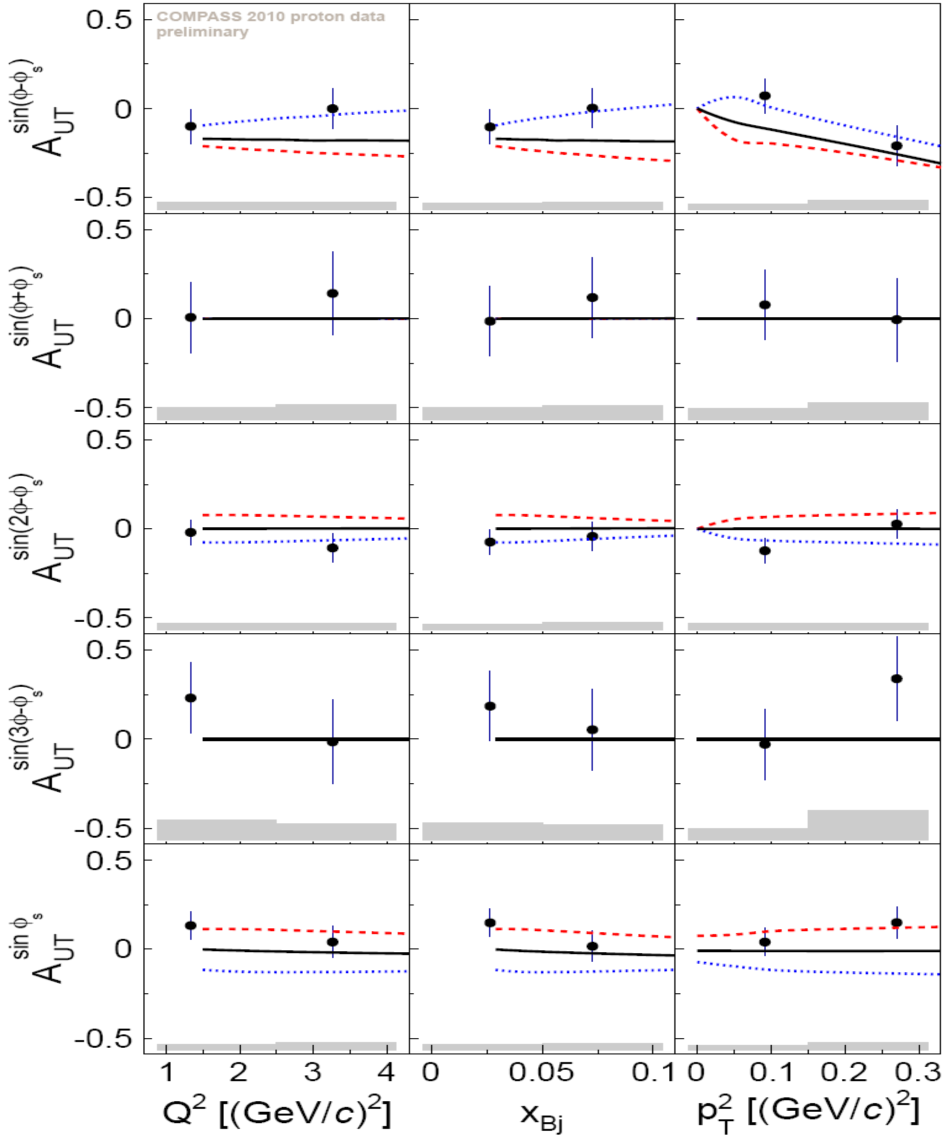
its small values due to approximate cancellation of contributions from E^u and E^d, $E^u \approx -E^d$

- larger effects expected for exclusive **ω** production



Azimuthal asymmetries for exlusive ω production on $p^{\uparrow}$

Single spin asymmetries

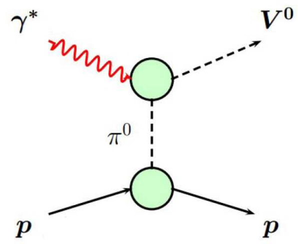


$\langle x_{Bj} \rangle = 0.049$, $\langle Q^2 \rangle = 2.2$ GeV^2
$\langle p_T^2 \rangle = 0.17$ GeV^2, $\langle W \rangle = 7.1$ GeV^2

Nucl. Phys. B 915 (2017) 454

comparison to modified GPD model of GK

with added π^0 pole exchange



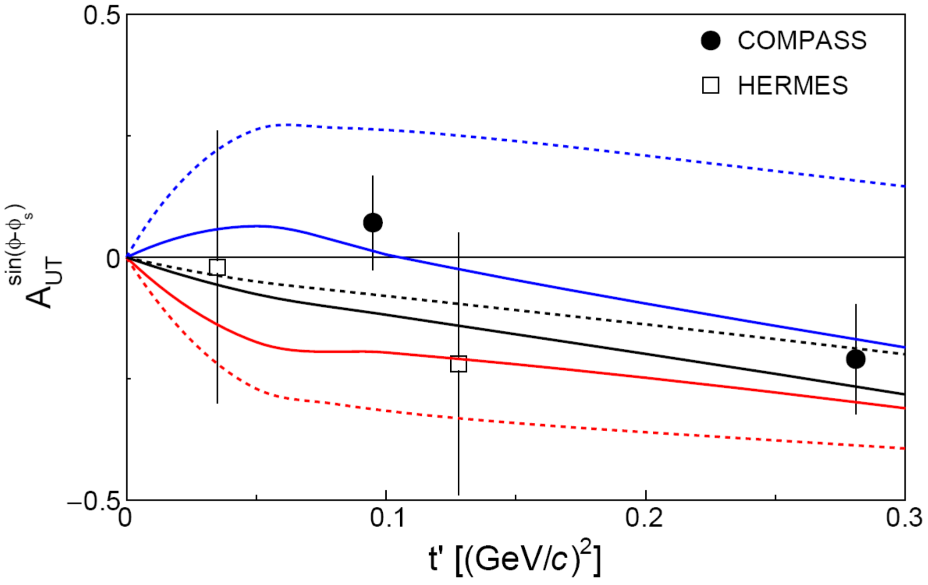
EPJ A50 (2014) 146

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)
- positive πω form factor (dashed red)
- negative πω form factor (dotted blue)

- 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**
solid black line	dotted black line	no pion pole
solid red line	dotted red line	positive πω form factor
solid blue line	dotted blue 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

Prospects to separate GPDs E_u and E_d from TTS asymmetries

Section in PhD thesis of P. Sznajder, Warsaw 2015

In the framework of GK model an attempt to constrain $L^{u\ val}$ and $L^{d\ val}$ using COMPASS $A_{UT}^{sin(\phi - \phi_S)}$ for exclusive ρ^0 and ω production

- ☺ $-L^{u\ val} \approx L^{d\ val} > 0$ (as expected)
- ☺ adding ω result reduces allowed region in ($L^{u\ val}$, $L^{d\ val}$) space
- ☹ constraints are rather weak

  due to limited statistics of COMPASS ω sample (1/40 of that of ρ^0)

A promissing alternative method

Future combined analysis of TTS asymmetries for exclusive ρ^0 production on transversely polarised protons [(1)] and deuterons [(2)]

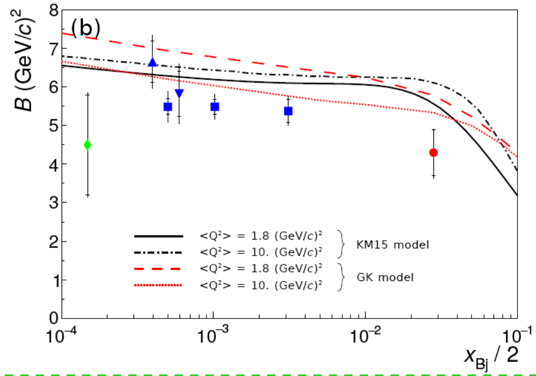
(1) existing measurements

(2) expected results from approved one-year data taking in 2021

Summary

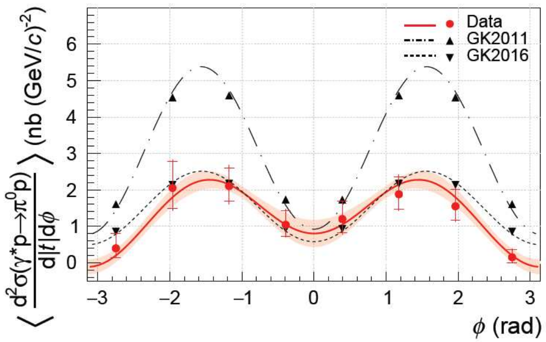
- t-slope of DVCS cross section

  decrease of the proton transverse radius with increasing x_{Bj}



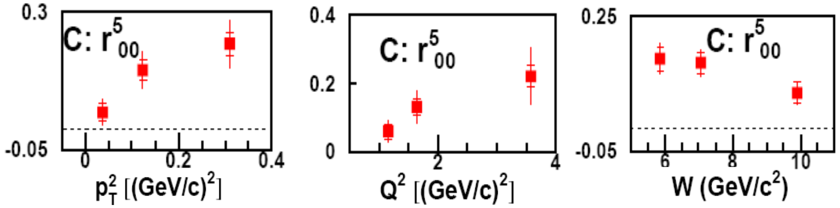
- measurement of exclusive π^0 leptoproduction

  significant role of twist-3 contributions with transversity GPDs



- SDMEs in exclusive ω leptoproduction

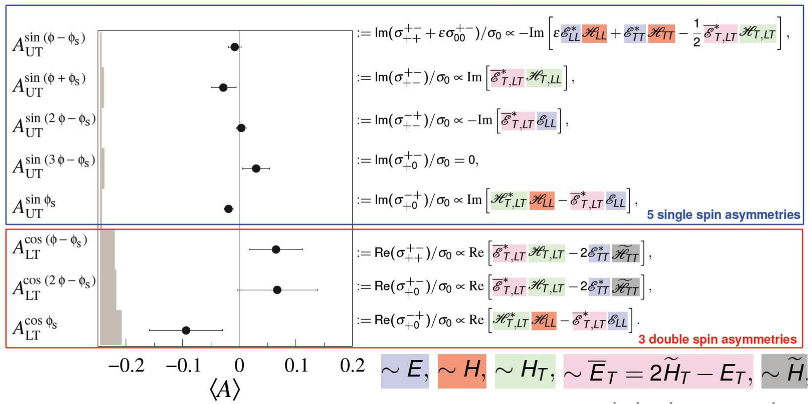
  role of transversity GPDs and UPE



- asymmetries small, compatible with 0 except

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

indication of transversity GPD H_T contribution



Outlook

- results expected from the large data sample collected in 2016+2017

with LH_2 target, RPD and wide-angle electromagneric calorimetry

collected statistic ~ 10 times larger than from 2012 test run

Deeply Virtual Compton Scattering:

- t-dependence of DVCS cross section vs. x_{Bj} („proton tomography")
- mapping GPD H by measurments of real and imaginary parts of DVCS via ϕ-dependence the μ^+ and μ^- cross sections difference and sum

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)

- results expected from the large data sample to be collected in 2021

Hard Exclusive Vector Meson Production on transversely polarised deuterons

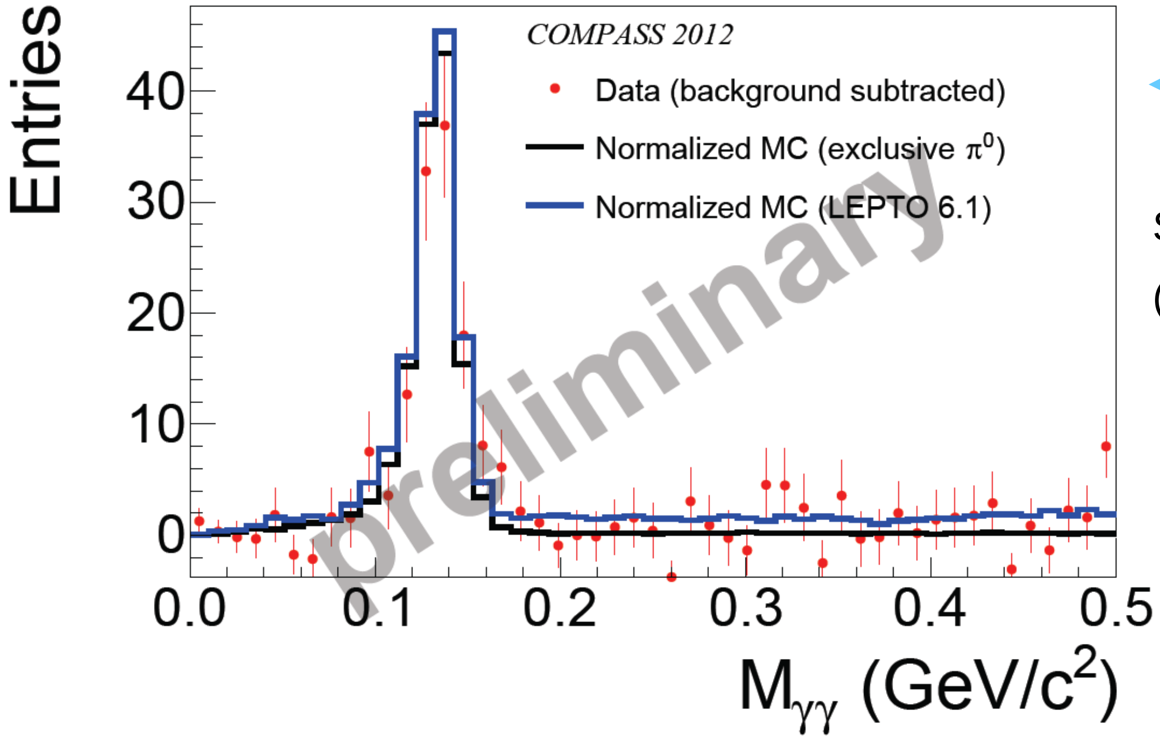
Supplementary material

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)

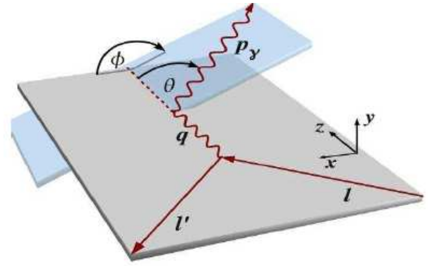
π^0 contribution normalised to $M_{\gamma\gamma}$ peak

'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 $E_{miss} = \nu - E_\gamma + t/(2m_p^2)$

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

Extraction of DVCS cross section and amplitude



Beam Charge & Spin Sum

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

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

$$c_0^{DVCS} \longrightarrow d\sigma^{DVCS}/dt \qquad s_1^{Int} \rightarrow Im(F_1\mathcal{H}) \qquad Im\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

Beam Charge & Spin Difference

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

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

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

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