Recent results from COMPASS on the GPD program

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- COMPASS experiment
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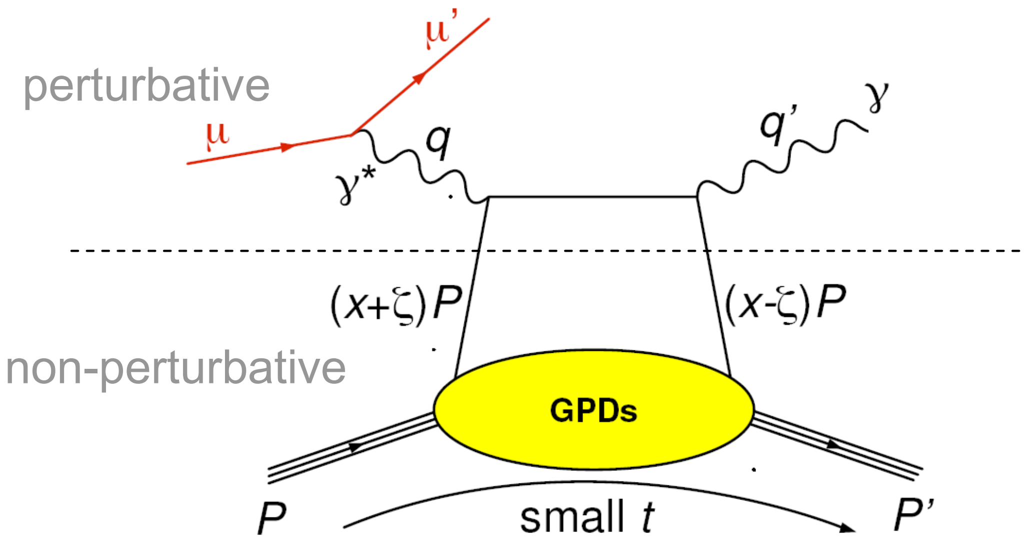
Generalised Parton Distributions (GPDs)

- 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

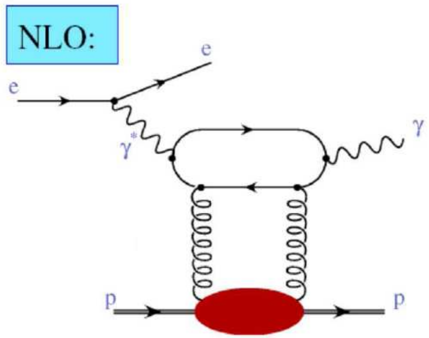
(the simplest) example: Deeply Virtual Compton Scattering (DVCS)



Factorisation for large Q^2 and $|t| \ll Q^2$

4 GPDs for each **quark flavour**

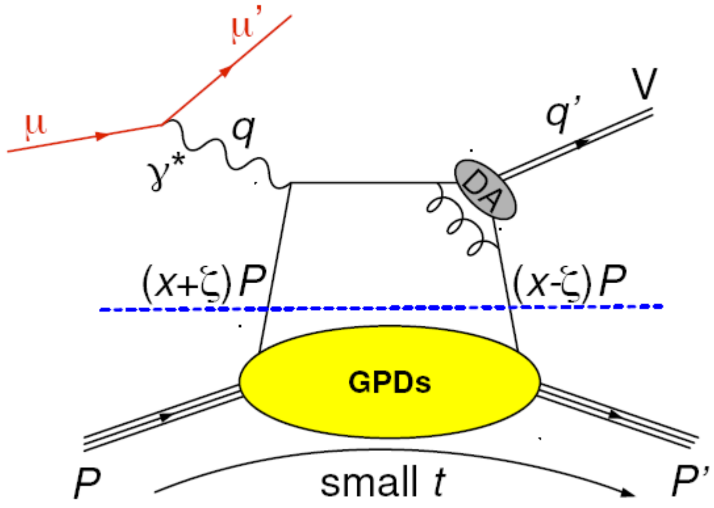
$H^q(x,\xi,t)$	$E^q(x,\xi,t)$
$\tilde{H}^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$



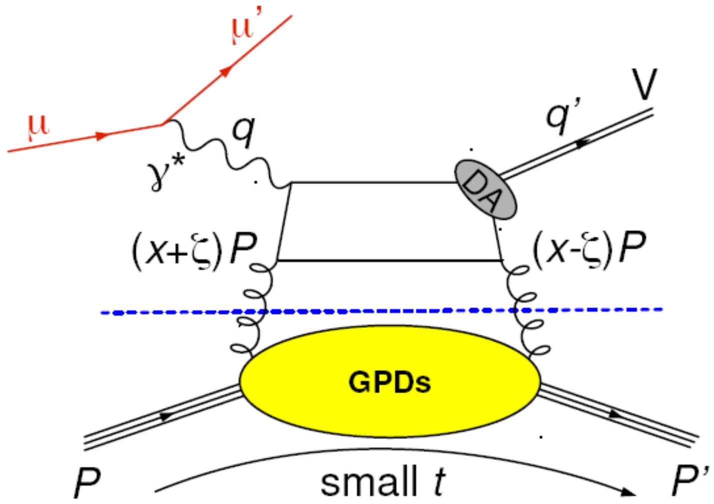
for DVCS **gluons** contribute at higher orders in α_s

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

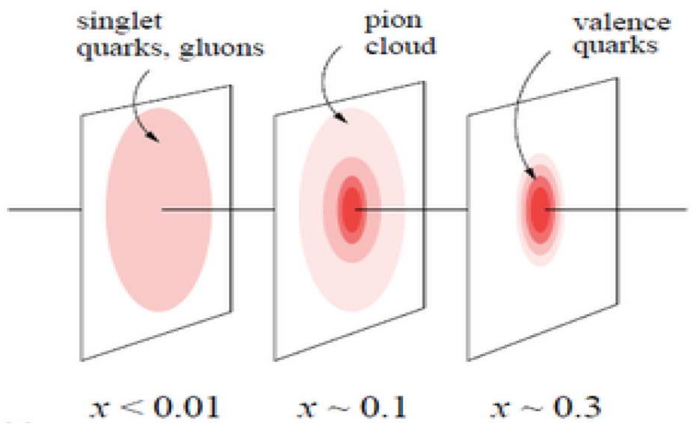
- *contribution from gluons at the same order of α_s as from quarks*

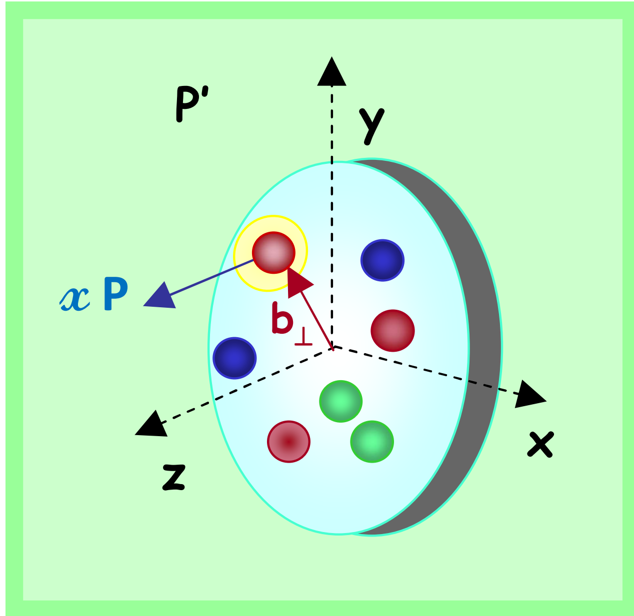
Two most attractive goals of the GPD program

- **3D tomography via GPD *H***

$$H(x, \xi=0, t) \rightarrow H(x, b_\perp) \sim \rho(x, b_\perp)$$

probability interpretation (Burkardt)





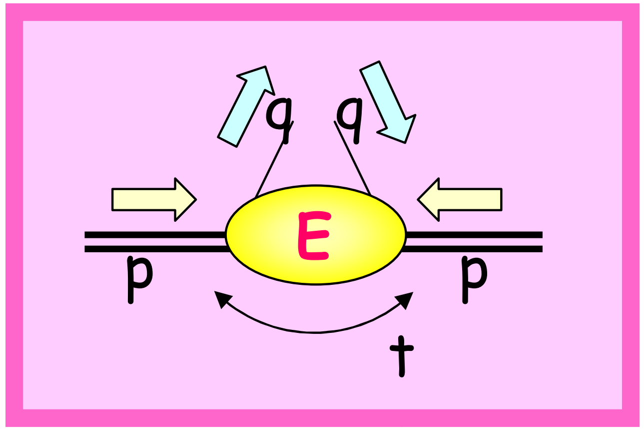
- **Contribution to the nucleon spin puzzle**

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

by constraining GPD *H* and *E*

$$J^q = 1/2 \cdot \lim_{t\to 0} \int_{-1}^{+1} x[H^q(x,\xi,t) + E^q(x,\xi,t)]dx$$

GPD *E* related to the orbital angular momentum



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

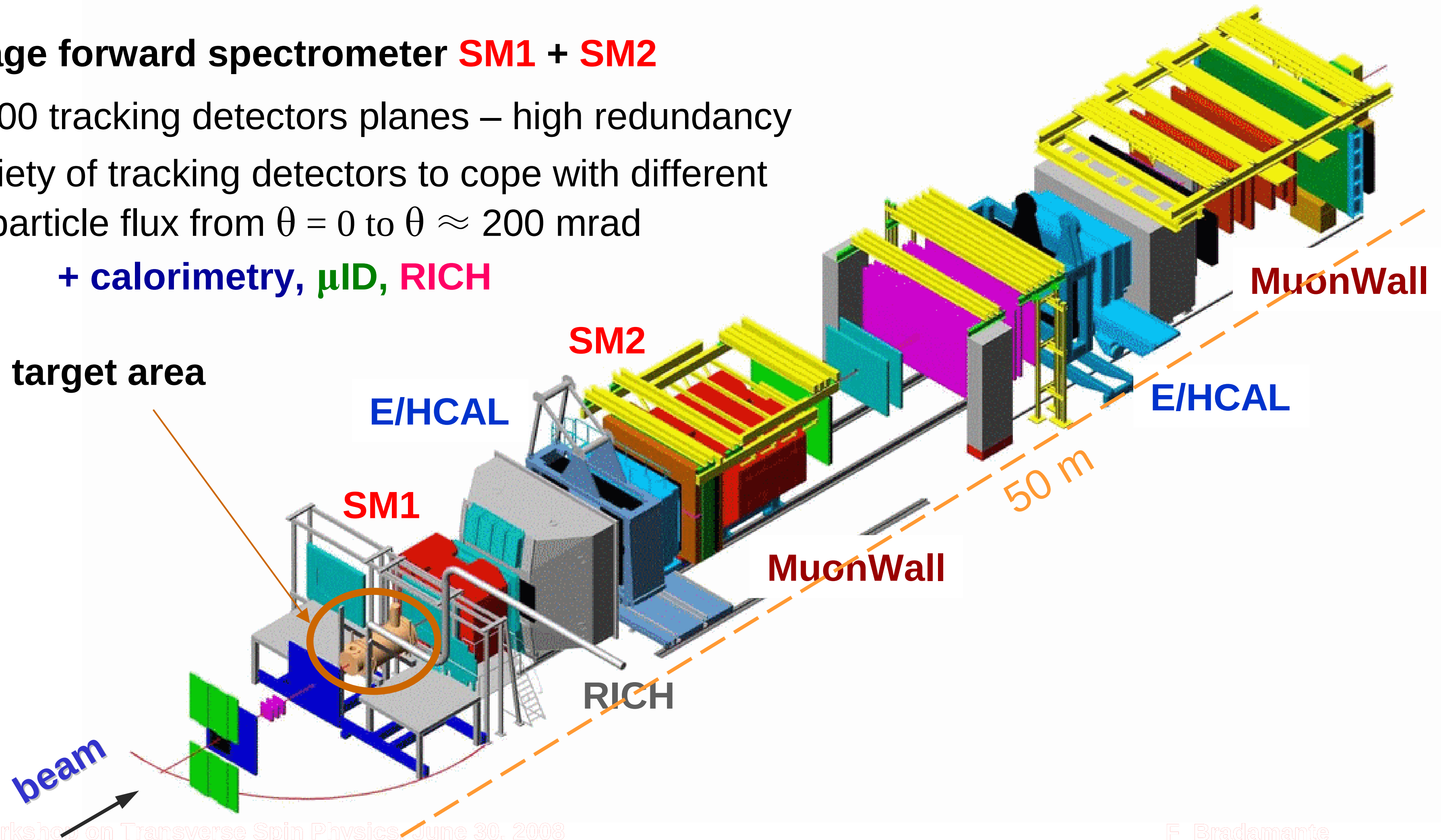
- **two-stage forward spectrometer SM1 + SM2**

  ≈ 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**

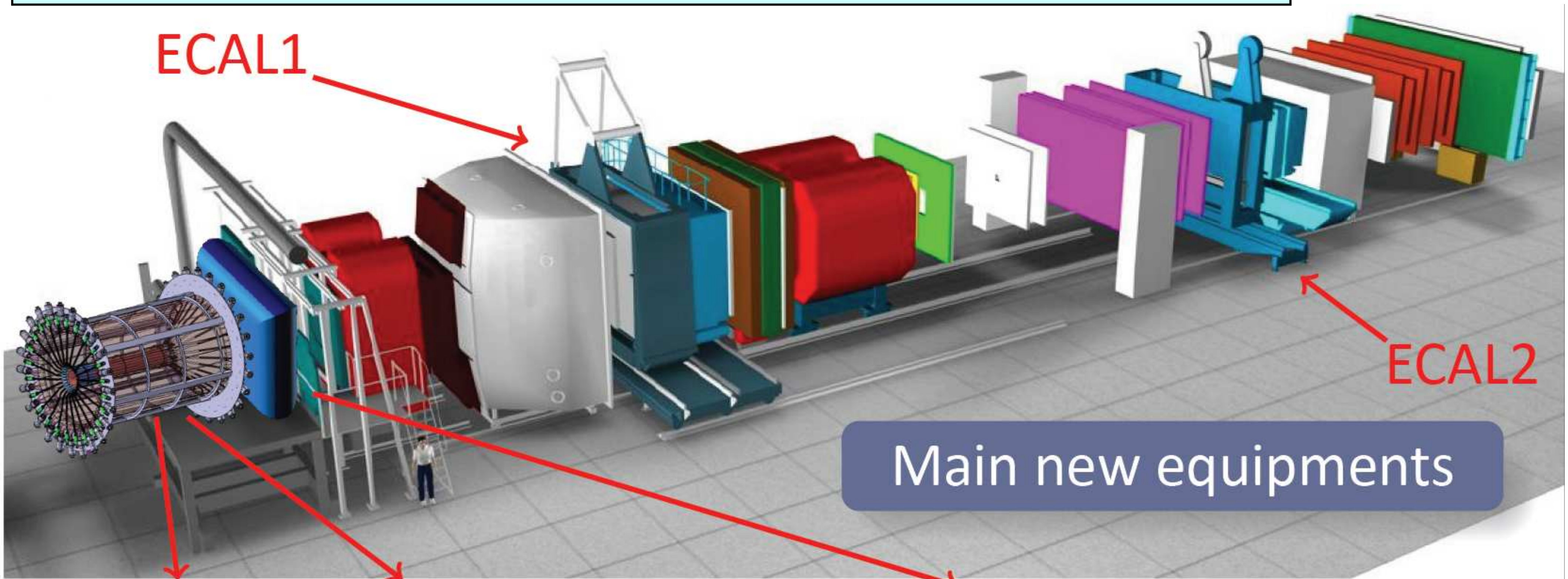


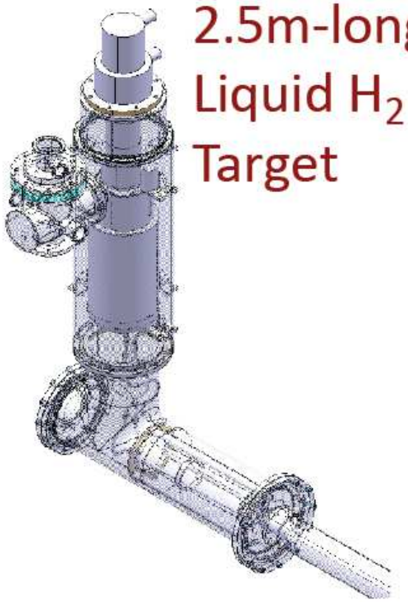
Physics programs

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; 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)

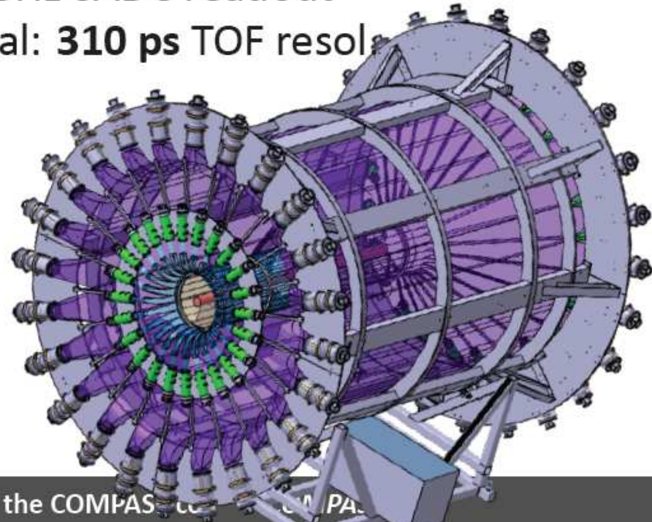




2.5m-long Liquid H_2 Target

Target TOF System

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



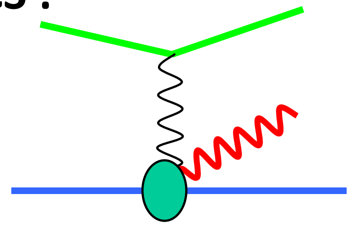
ECAL0 Calorimeter

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

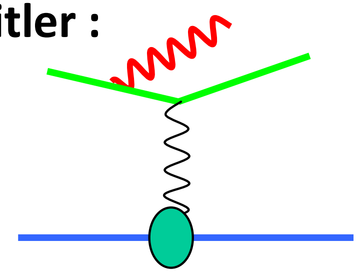
Transverse Extension of Partons in the Proton probed by Deeply Virtual Compton Scattering

Exclusive single photon production cross section

DVCS :



Bethe-Heitler :



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

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

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

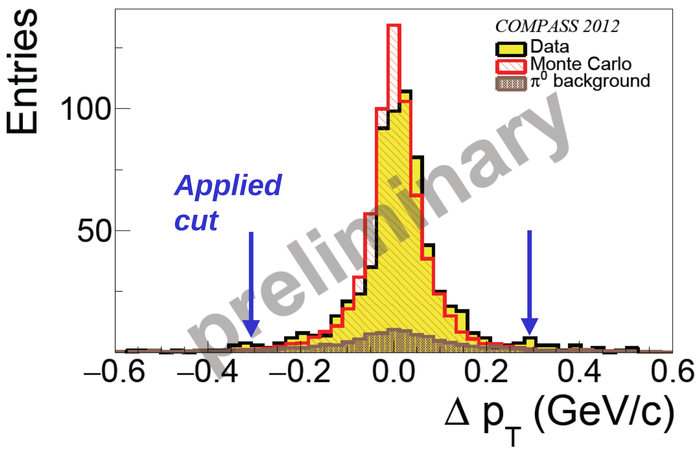
0.08 GeV² < | t | < 0.64 GeV²

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

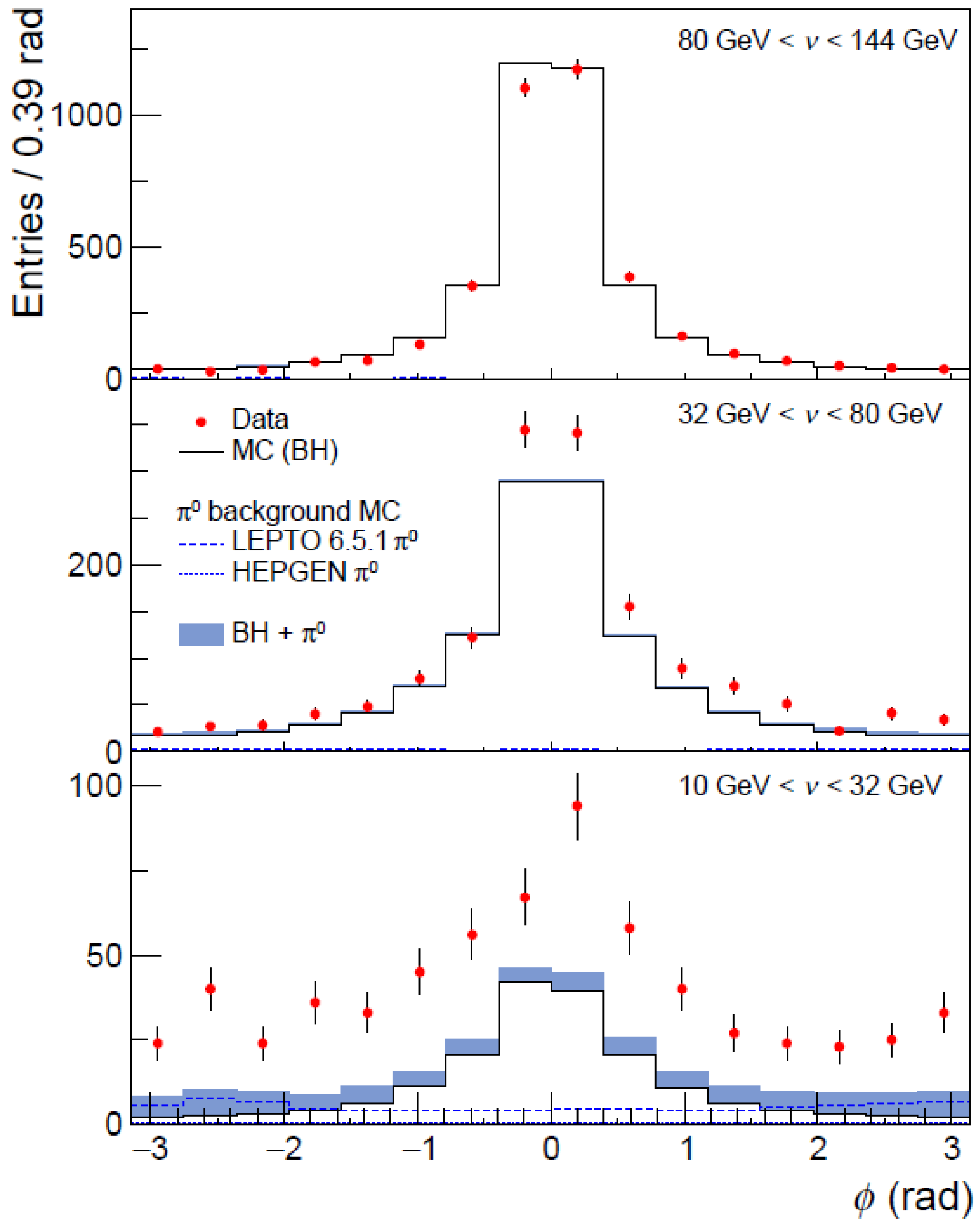
Overconstrained kinematics => a number of „exclusivity cuts” allows to select the exclusive sample

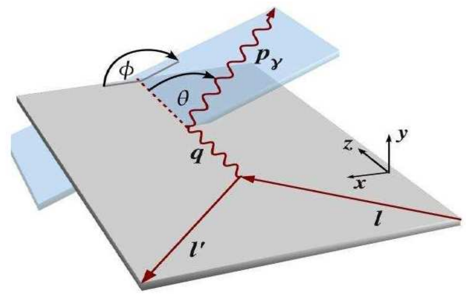
$$\Delta p_{\perp} = p^{prot}_{\perp,meas} - p^{prot}_{\perp,recon}$$

Example:



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 $d\sigma := \dfrac{d^4\sigma^{\mu p}}{dQ^2 d\nu dt d\phi}$ for either μ^+ or μ^- beam

- 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*

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

$$d\sigma^I \propto \frac{1}{x_{\mathrm{Bj}}y^3tP_1(\phi)P_2(\phi)}(s_1^I \sin\phi + s_2^I \sin 2\phi)$$

- subtract calculable BH cross sections and integrate over ϕ

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

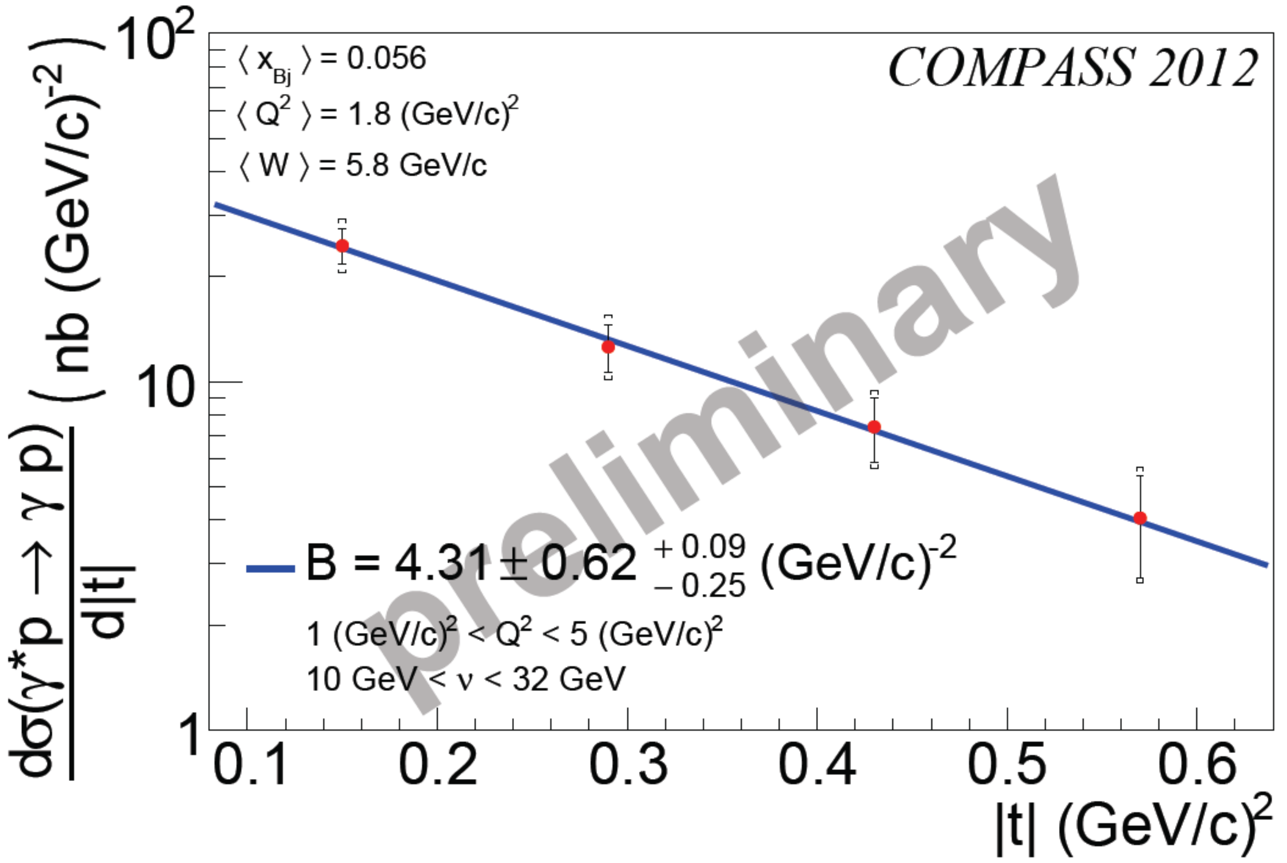
- convert into cross section for virtual-photon scattering

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

Γ *transverse virtual photon flux*

DVCS cross section and t-slope

from 4 weeks of 2012 commissioning data



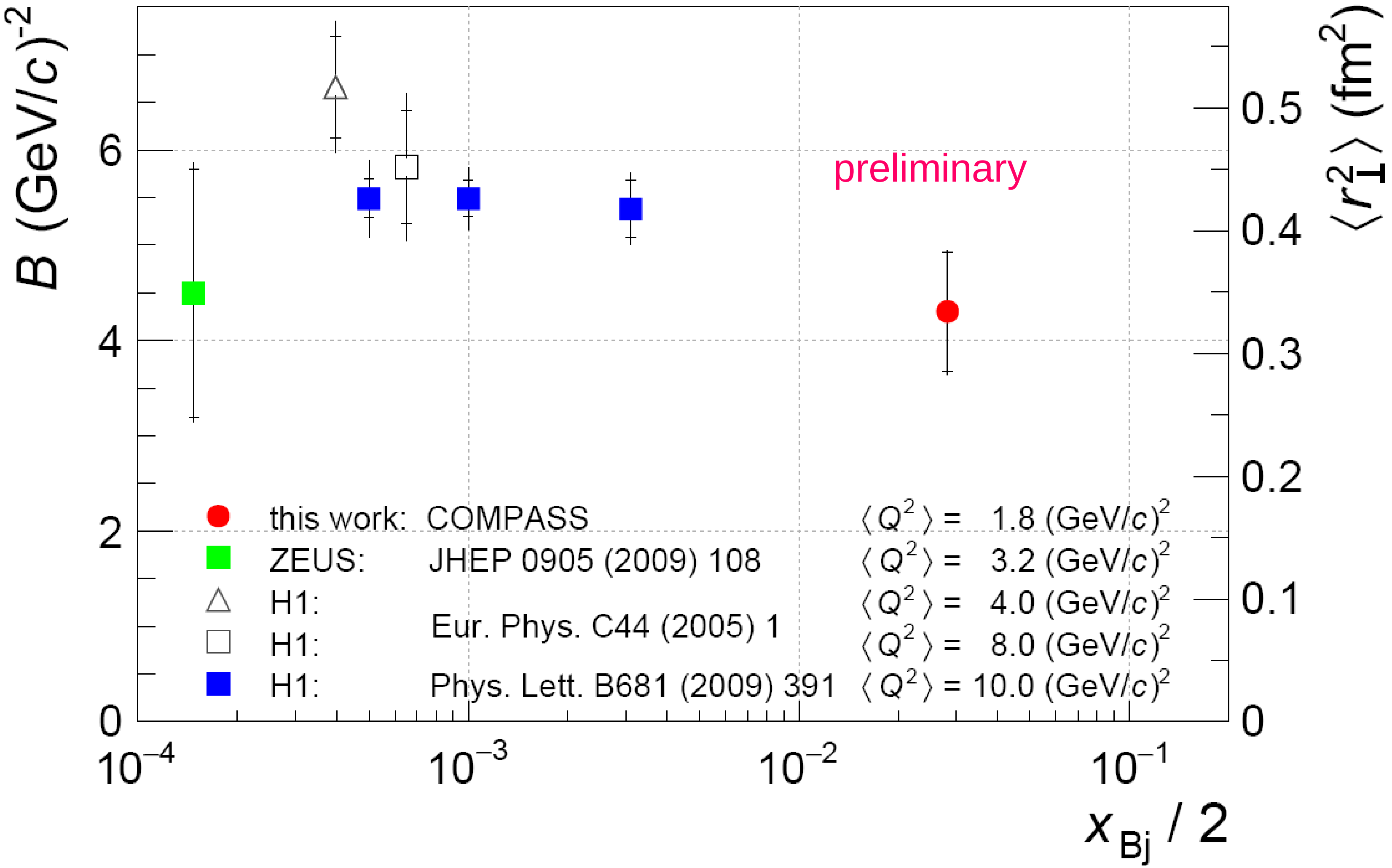
the first measurement of B-slope for DVCS at x_{Bj} above HERA range

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

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

$d\sigma_{DVCS}/dt \sim \exp(-B|t|)$ → 'tomography': $B(x_{Bj}) \sim \langle r_T^2 \rangle (x_{Bj})$

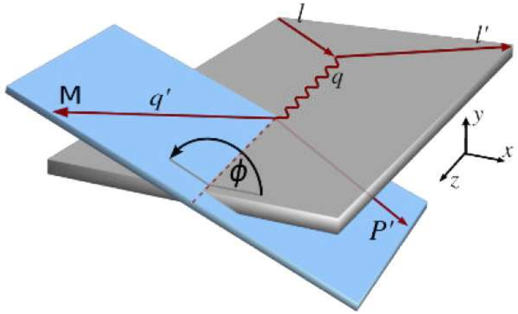
$$\langle r_\perp^2(x_{Bj})\rangle = 2\langle B(x_{Bj})\rangle \hbar^2$$



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

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

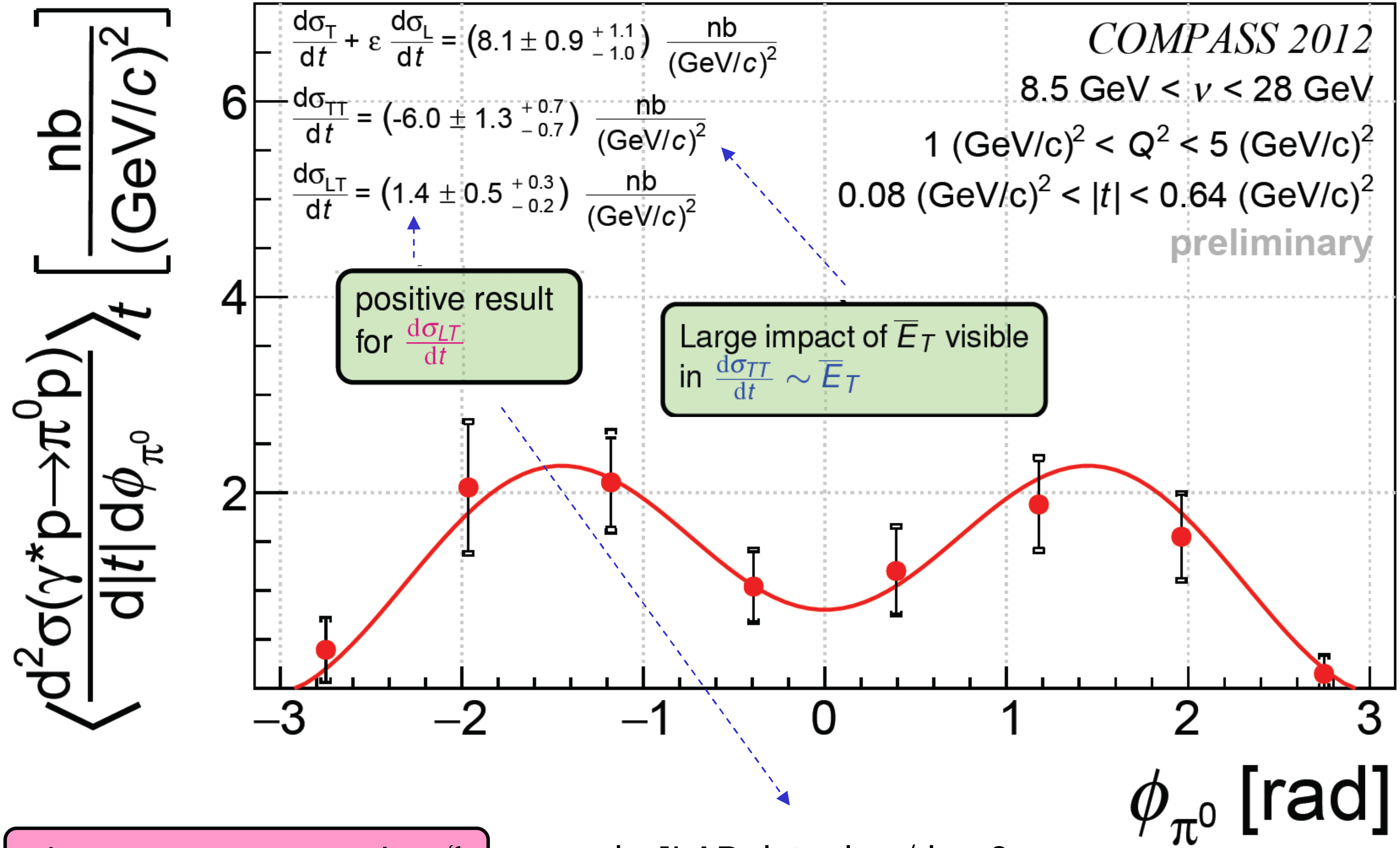
$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

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

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

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

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



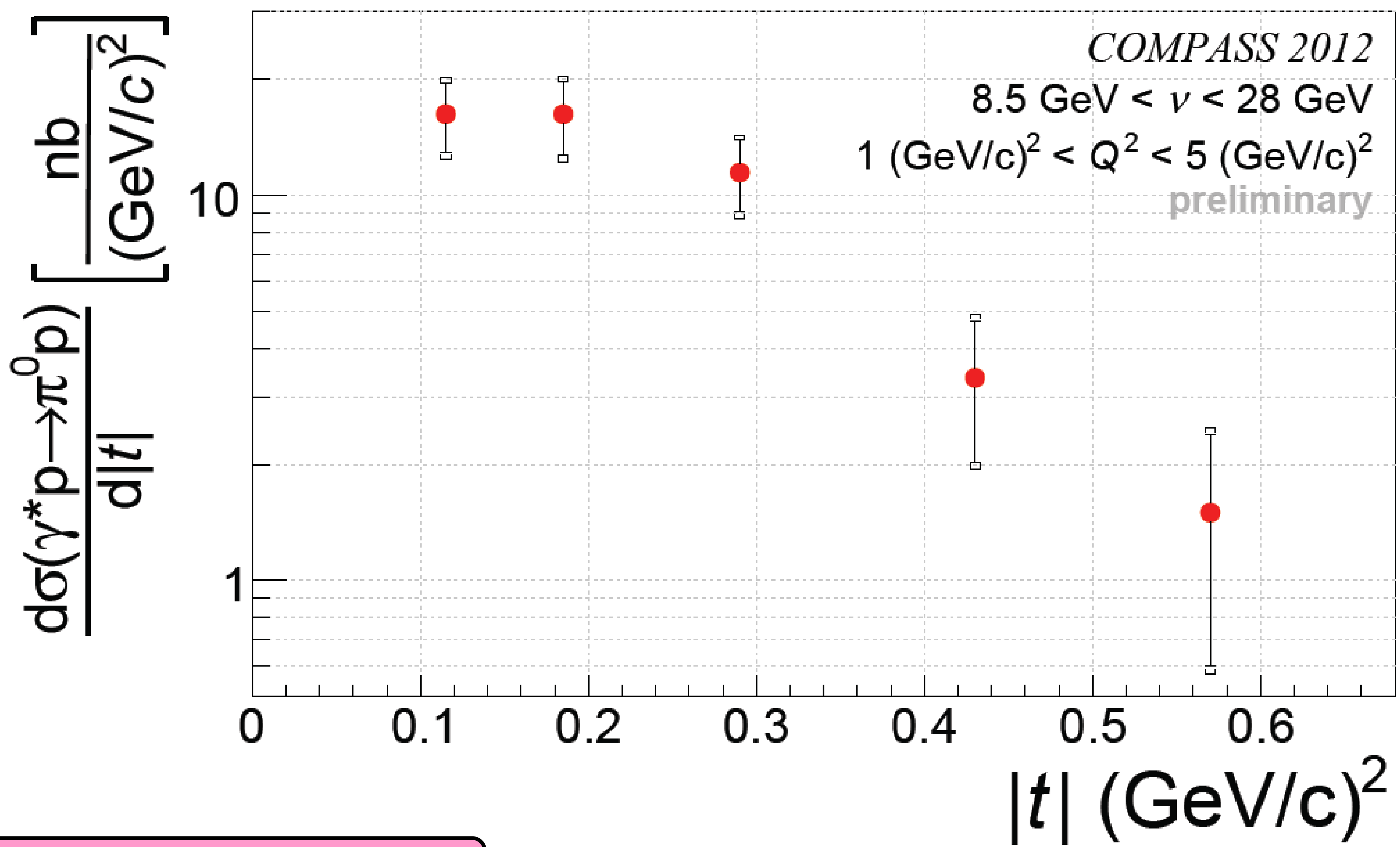
First measurement at low ξ

in JLAB data $d\sigma_{LT}/dt \le 0$

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

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

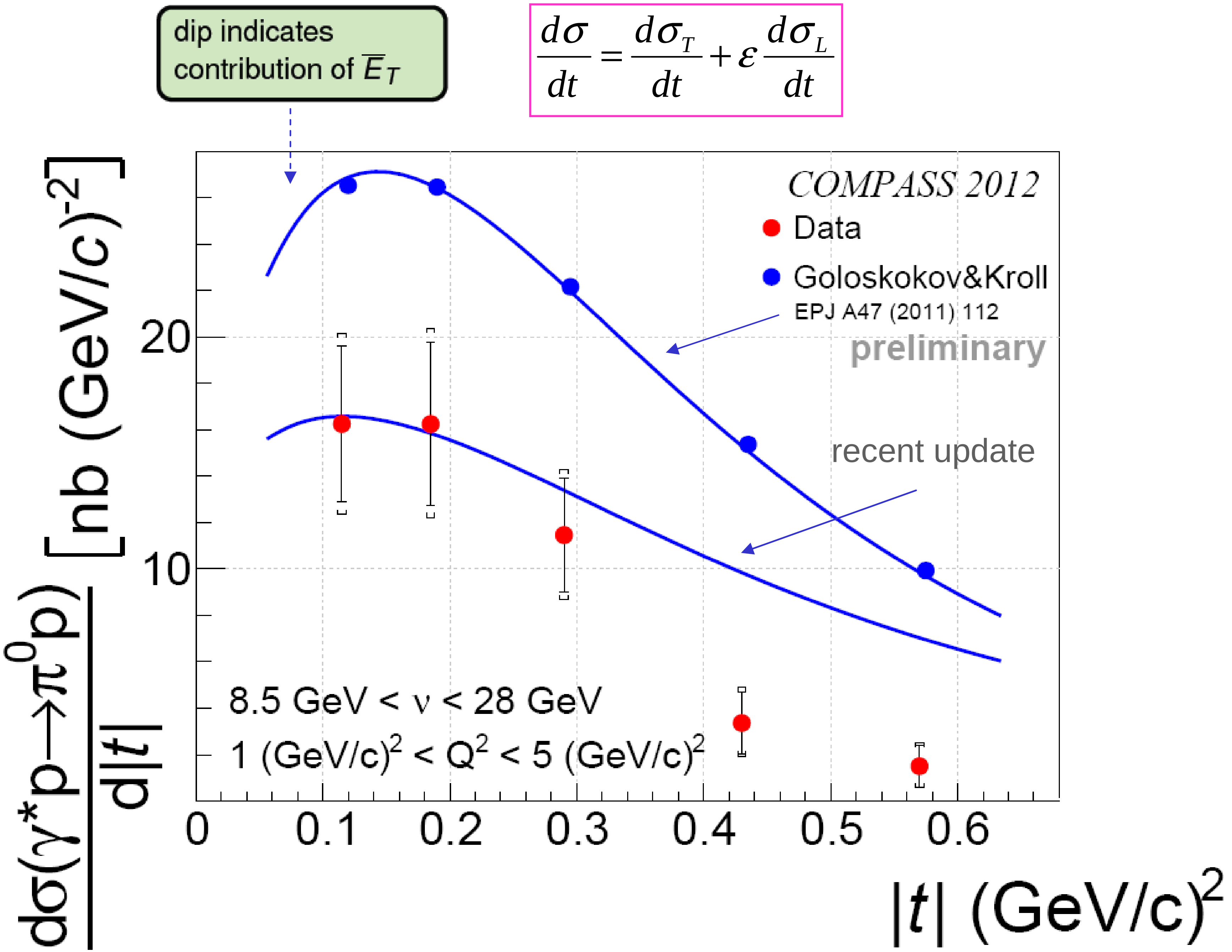
An impact of $\bar{E}_T$ contribution in $\frac{d\sigma_T}{dt}$



First measurement at low ξ

Impact of COMPASS measurements on the fenomenology

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



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)

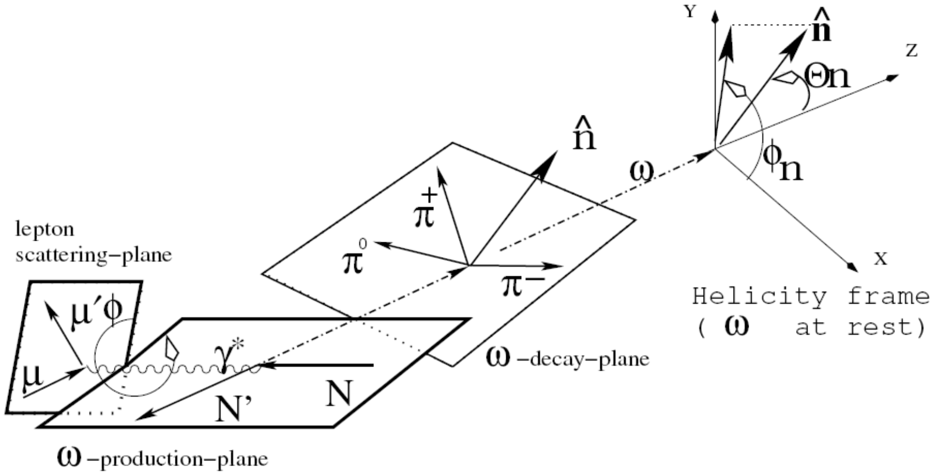
Experimental access to SDMEs

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

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)

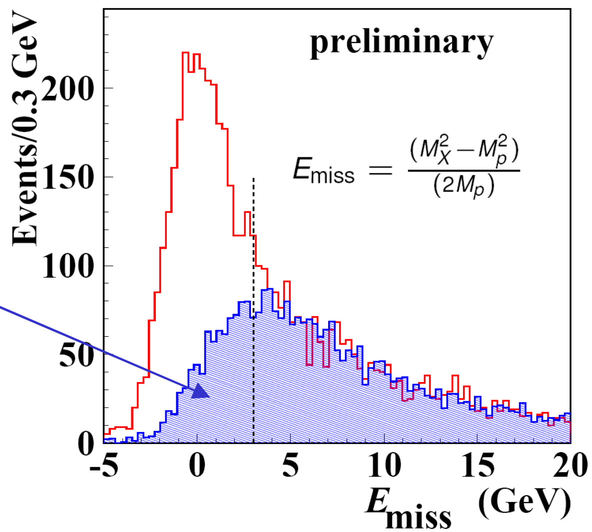


Extraction of SDMEs

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

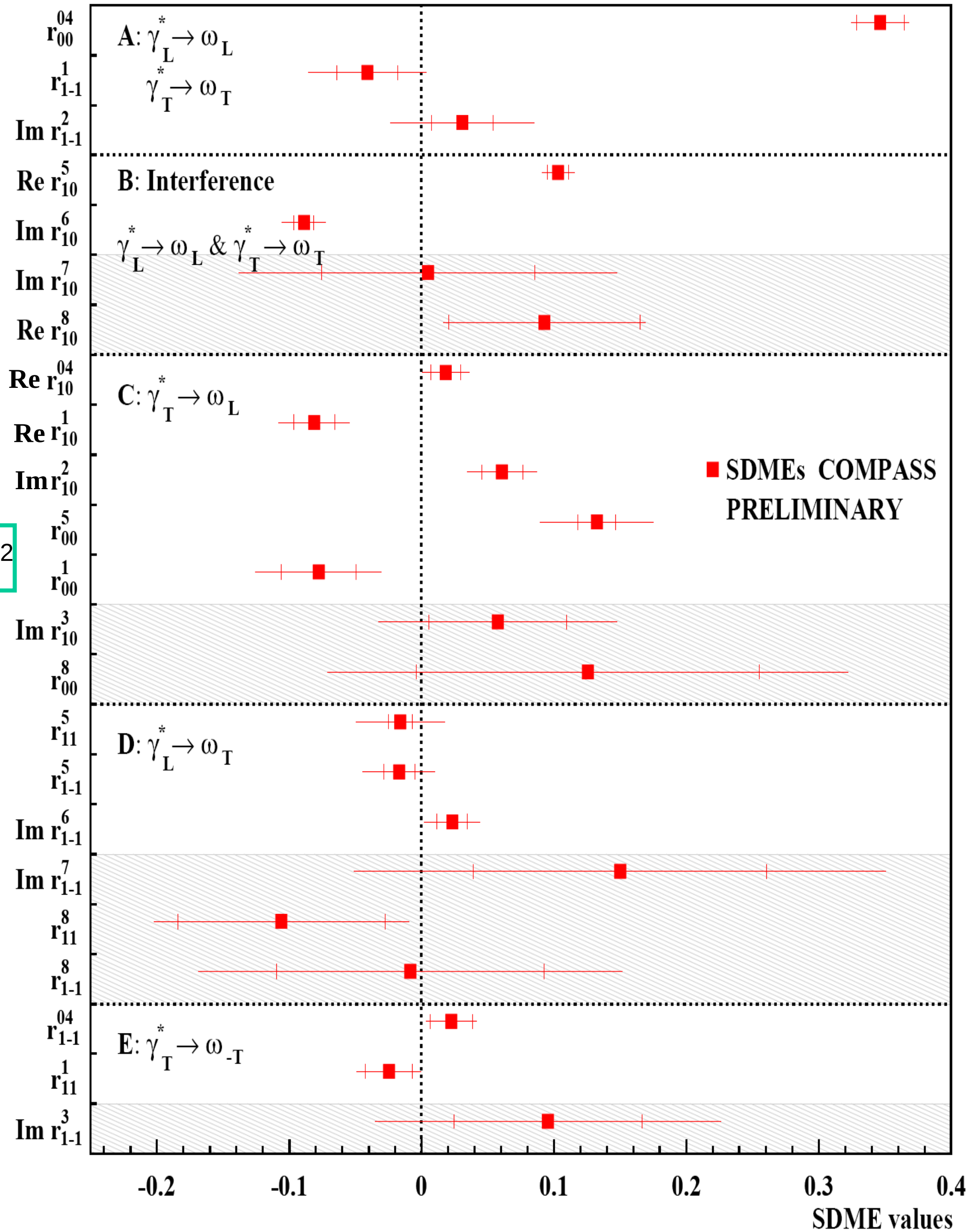
1 GeV² < Q² < 10 GeV²

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

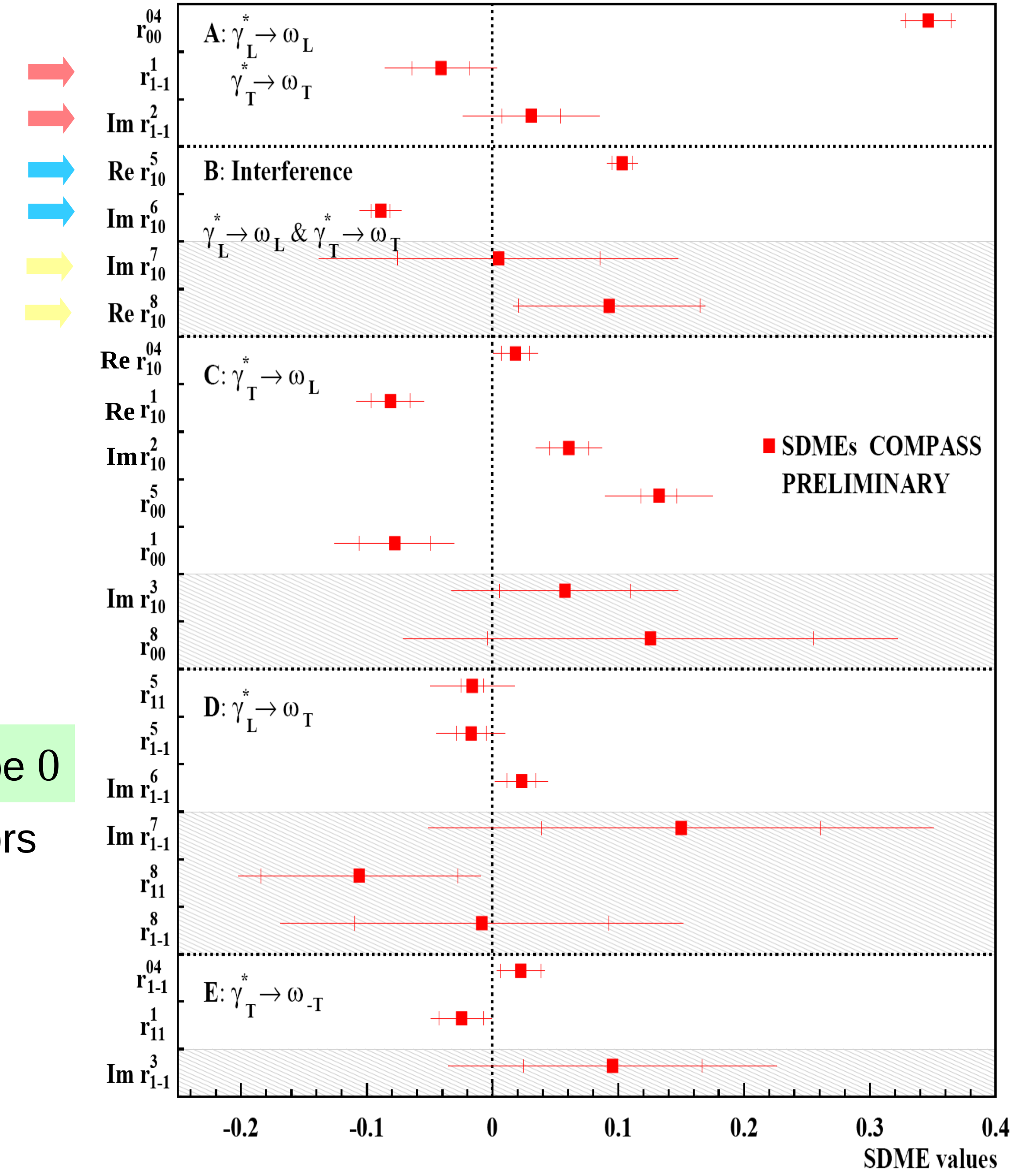
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

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



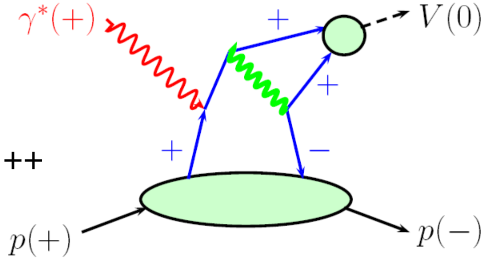
Transitions $\gamma^*_T \to \omega_L$

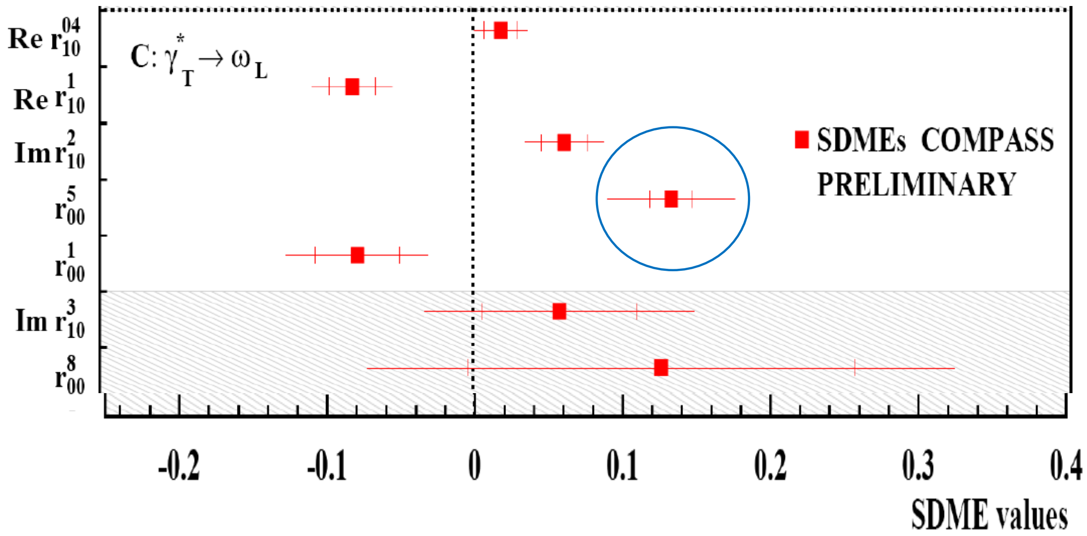
possible GPD interpretation **Goloskokov and Kroll, EPJC 74 (2014) 2725**

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

example ➡

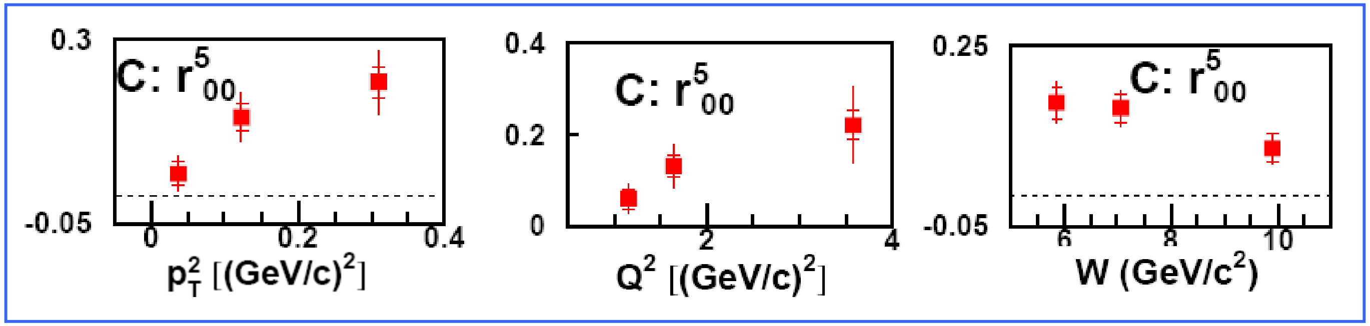
graph for amplitude $F_{0-,++}$





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

COMPASS preliminary



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

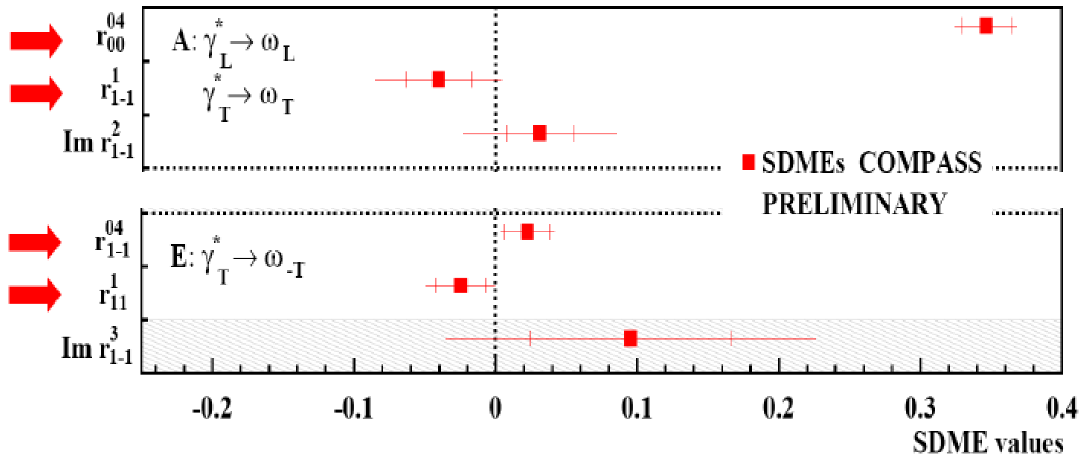
Unnatural parity exchange contribution

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

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

numerator depends only on UPE amplitudes

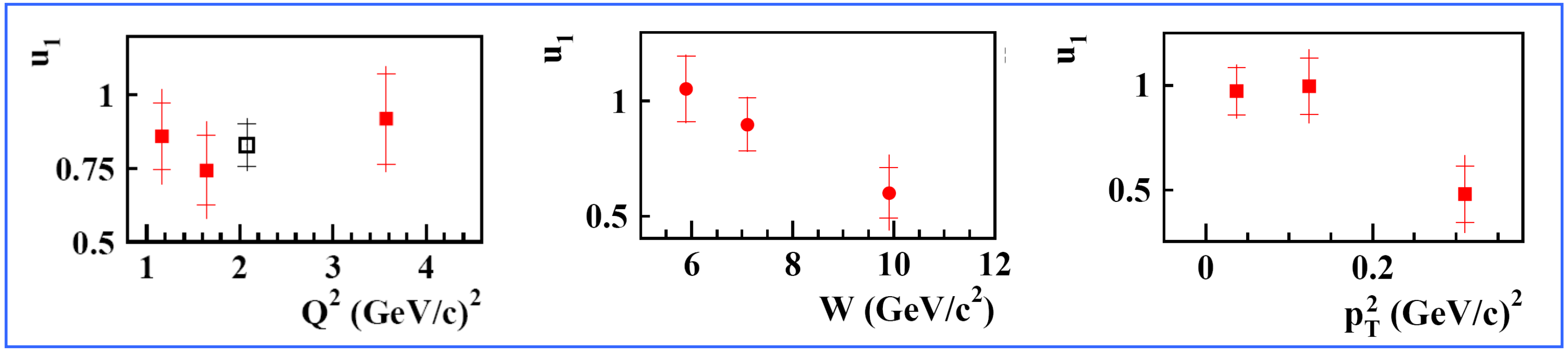
$u1 > 0 \implies$ UPE contribution



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

Summary and outlook

- shown results from comissioning „DVCS test run" in 2012

  - t-slope of DVCS cross section, *first at x_{BJ} above HERA range*
    decrease of the proton transverse radius with increasing x_{Bj}
  - measurement of exclusive π^0 lepto-production, *first above JLAB energies*
    significant role of twist-3 contributions with chiral-odd GPDs
  - SDMEs of exclusive ω lepto-production
    structure in terms of helicity amplitudes => constraints on GPD models

- 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)

Thank you

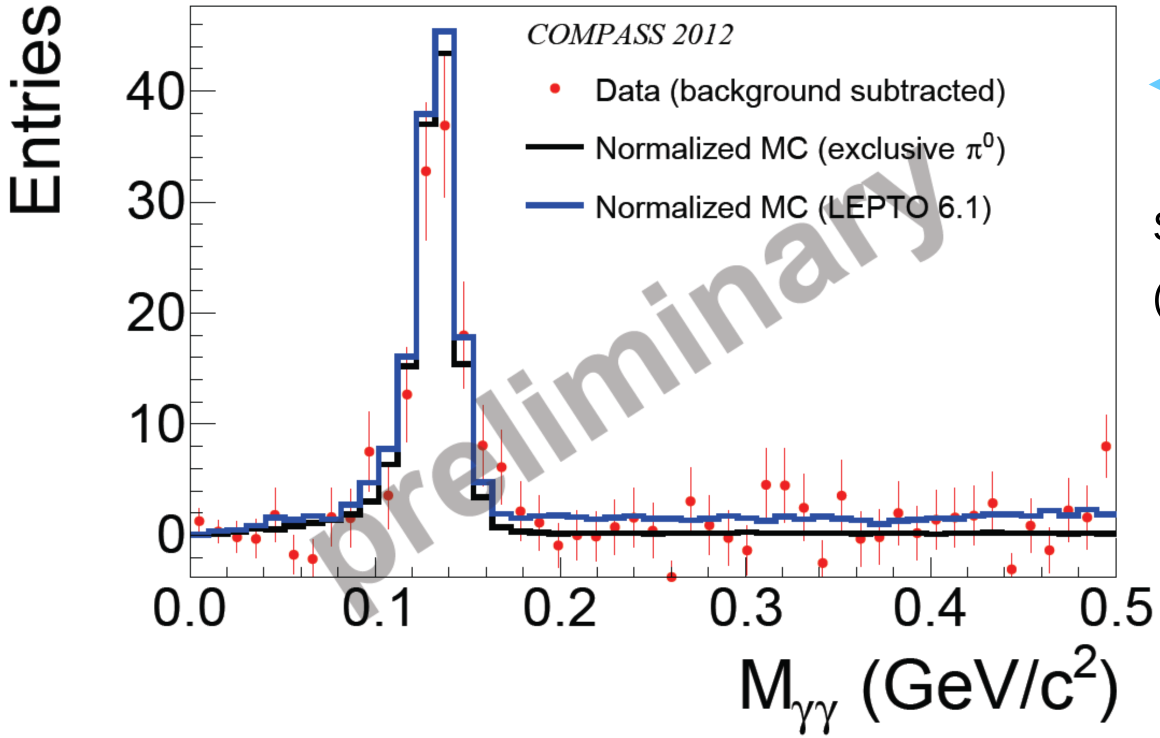
Supplementary material

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

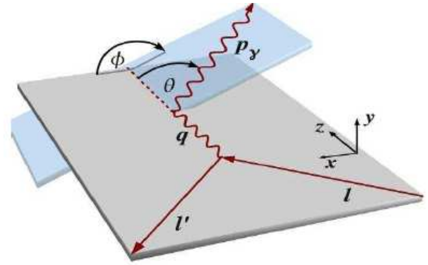
Semi-inclusive (LEPTO MC) or exclusive (HEPGEN MC based on Goloskokov-Kroll model) π^0 contribution normalised to $M_{\gamma\gamma}$ peak

'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

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

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

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

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