GPD measurements at COMPASS

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On behalf of the COMPASS collaboration

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Duke University, Durham, North Carolina, USA

CHARLES UNIVERSITY
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and physics

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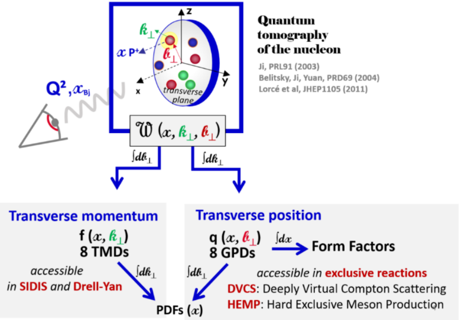
Outline

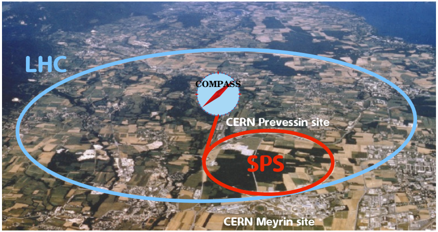
Introduction: GPDs



		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\tilde{H}_T + E_T = \bar{E}_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

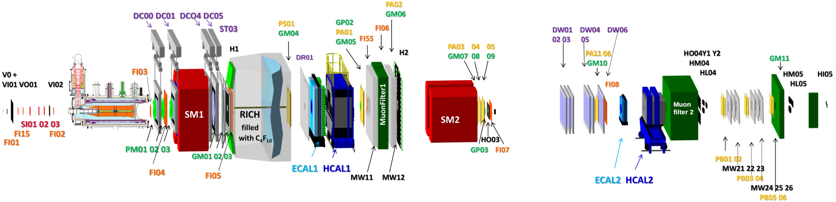
- 4 chiral-even, 4 chiral-odd (subscript T).
- 2 T-odd $(E, \bar{E}_T)$.

Introduction: COMPASS



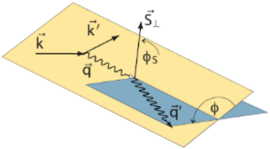
- M2 beamline of CERN's SPS.
- 24 institutes, 13 countries.

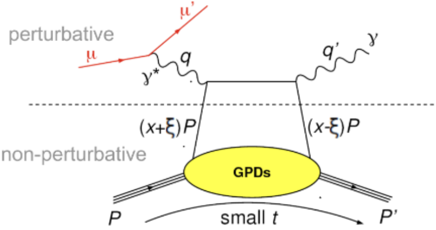
- SIDIS with 160 GeV (200 GeV) μ^+ beam and longitudinally/transversely-polarised proton (NH_3) or deuteron (^6LiD) target
  A. Martin (Wed, TMDs),
  G. Reicherz (Wed, Polarised targets),
  B Parsamyan (Thu, plenary)
- Hadron spectroscopy with hadron beams and nuclear targets.
- Drell–Yan with 190 GeV π^- beam and $p^\uparrow$ (NH_3), Al, W targets.
  V. Andrieux (Wed, TMDs),
  A. Vijayakumar (poster).
- Hard exclusive processes and SIDIS with 160 GeV/c $\mu^\pm$ beam and liquid H_2 target.
  This talk and SIDIS on Tue in TMDs.



2022 setup with $^6LiD^\uparrow$ target: Experiments concluded, now in analysis phase.

Outline





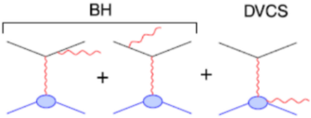
- $q = (p_\mu - p_{\mu'})$: 4-momentum of virtual photon
- $Q^2 = -q^2$: virtual photon virtuality
- $t = (p_P - p_{P'})^2$: 4-momentum transfer to nucleon squared
- x: average longitudinal momentum fraction
- ξ: half of longitudinal momentum fraction transfer

Deeply virtual Compton scattering

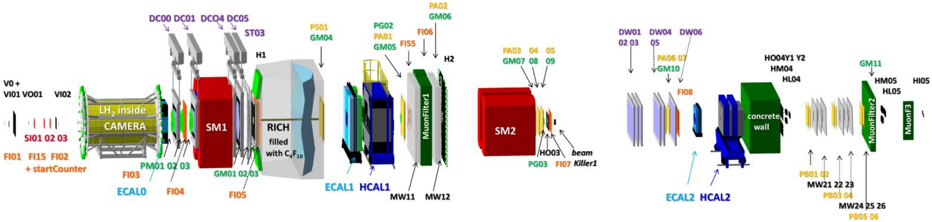
- GPDs appear in the cross-sections via Compton form-factors

$$\mathcal{H}(\xi, t) = \mathcal{P}\int_{-1}^{1} \mathrm{d}x \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\pm\xi, t).$$

  (convolution GPD ⊗ hard process).
- Sensitive to
  - H (unpolarised proton target),
  - $E, \tilde{H}, \tilde{E}$ (neutron or polarised targets).
- Interference with Bethe–Heitler process.

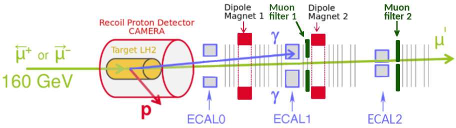


DVCS: Experimental setup



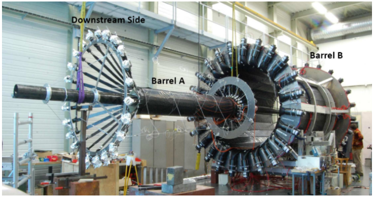
- 160 GeV/c beam
  μ^+: $P_{\mu^+} \approx -80\%$ (from $\pi^+ \to \mu^+ \nu_\mu$)
  μ^-: $P_{\mu^-} \approx +80\%$ (from $\pi^- \to \mu^- \bar{\nu}_\mu$)
- 2.5 m long liquid H target.
- 2-stage magnetic spectrometer.
- CAMERA, ECAL0, ECAL1, ECAL2.
- 2012 pilot run (1 month)
  - Published results [PLB 793 (2019) 188]
- 2016–2017 runs
  - Larger ECAL0.
  - 10× more statistics.
  - The same μ^+ and μ^- beam intensity.
  - Preliminary results using 1/3 statistics.

Event selection:



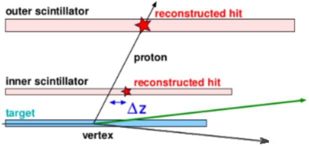
- $\mu p \to \mu' p' \gamma$
- $E_\gamma > 4, 5, 10$ GeV in ECAL 0, 1, 2.

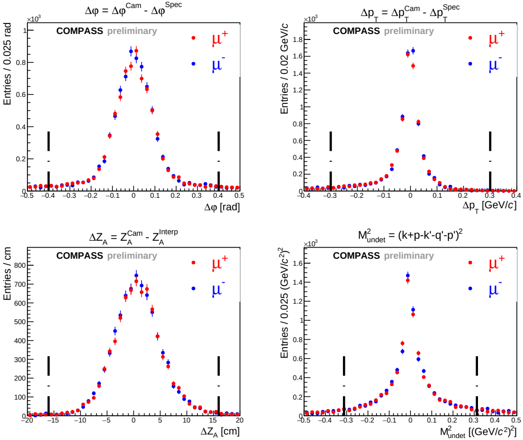
DVCS: Exclusivity with CAMERA



CAMERA recoil proton detector

- Exclusive $\mu p \to \mu' p' \gamma$:
- $|\Delta p_{\mathrm{T}}| < 0.3$ GeV/c,
- $|\Delta\phi| < 0.4$ rad,
- $|\Delta z_{\mathrm{A}}| < 16$ cm,
- $|M_X^2| < 0.3$ (GeV/c^2)^2
- Over-constrained measurement – Kinematic fit performed
- $\chi^2_{\mathrm{fit}} < 10$.





DVCS cross section in bins of t, ϕ, Q^2, ν:

$$\left\langle \frac{d\sigma_{\text{DVCS}}}{d|t|d\phi dQ^2 d\nu} \right\rangle^{\pm}_{t_i\phi_j Q^2_k \nu_l} = \frac{1}{\mathcal{L}^{\pm}\Delta t_i \Delta\phi_j \Delta Q^2_k \Delta\nu_l}\left[\left(a^{\pm}_{ijkl}\right)^{-1}\left(\texttt{data} - \text{BH}_{\text{MC}} - \pi^0_{\text{MC}}\right)\right]$$

- $a^{\pm}_{ijkl}$ Acceptance ≈ 40% and flat
- BH_{MC} Exclusive single photon MC sample
- π^0_{MC} π^0 MC sample (background estimation)

- 160 GeV/c beam
- $Q^2 \in (1, 10)$ $(\text{GeV}/c)^2$
- $|t| \in (0.08, 0.64)$ $(\text{GeV}/c)^2$
- Bethe–Heitler (BH) background:
  - Well known – QED MC.
  - Checked in BH-dominated region of $\nu \in (80, 144)$ GeV.
  - Subtracted in the DVCS region of $\nu \in (10, 32)$ GeV.

DVCS: Kinematic domain, Bethe–Heitler

DVCS cross section in bins of t, ϕ, Q^2, ν:

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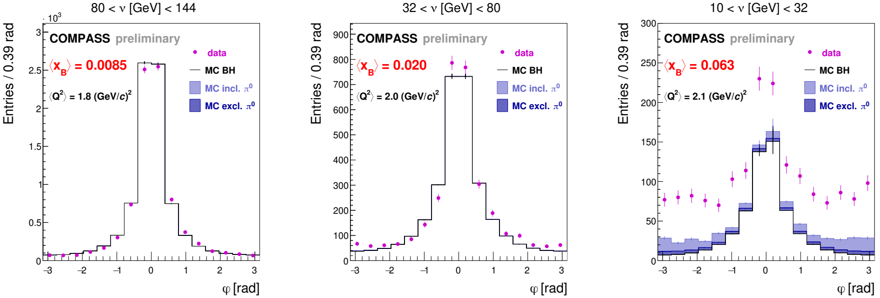

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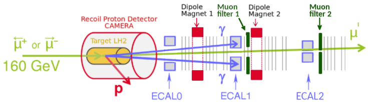


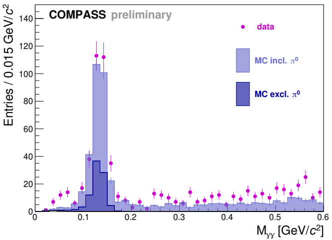
Visible π^0 background

- Both γ detected.
- Rejected in event selection.
- Used to normalize π^0 MC

Non-visible π^0 background

- Only one γ detected.
- Subtracted using π^0 MC.
- Inclusive (LEPTO) and exclusive (HEPGEN) MC.

Visible π^0 candidates



Measurement as a function of $|t|$, integrating over ϕ:

$$\mathrm{d}\sigma^{\overset{+}{\leftarrow}} + \mathrm{d}\sigma^{\overset{-}{\rightarrow}} = 2[\mathrm{d}\sigma^{BH} + \mathrm{d}\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I]$$
$$= 2[\mathrm{d}\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi\,]$$

subtracted — All the other terms are cancelled in the integration over ϕ

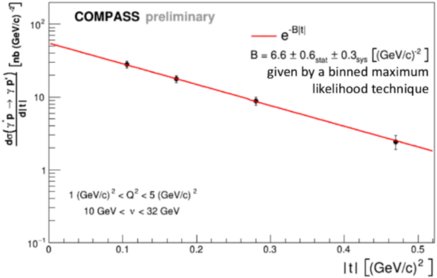
c_0^{DVCS}: related to the Compton form-factor $\mathcal{H}$.

In Compass kinematics ($\frac{2\xi}{1+\xi} = x_B \approx 0.06,$):

- Dominance of Im$\mathcal{H}$ (97% in GK model, 94% in KM model)
- $c_0^{\mathrm{DVCS}} \propto (\mathrm{Im}\mathcal{H})^2$
- $\mathcal{H}$: related to the GPD H (at LT and LO): $\mathcal{H}(x,t) = \mathcal{P}\int_{-1}^{1} \mathrm{d}x \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\pm\xi, t)$.
- $q(x, b_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{b}_\perp\cdot\boldsymbol{\Delta}_\perp} H(x, 0, -\Delta_\perp^2)$

$$\langle b_\perp^2\rangle = \frac{\int \mathrm{d}^2 b_\perp b_\perp^2\, q(x,b_\perp)}{\int \mathrm{d}^2 b_\perp\, q(x,b_\perp)} = -4\frac{\partial}{\partial t}\ln H(x,0,t)\Big|_{t=0}$$

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-B|t|} = e^{-\frac{1}{2}\langle b_\perp^2\rangle |t|}$$



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$$\langle b_\perp^2\rangle = \frac{\int \mathrm{d}^2 b_\perp b_\perp^2 q(x,b_\perp)}{\int \mathrm{d}^2 b_\perp q(x,b_\perp)} = -4\frac{\partial}{\partial t}\ln H(x,0,t)\Big|_{t=0}$$

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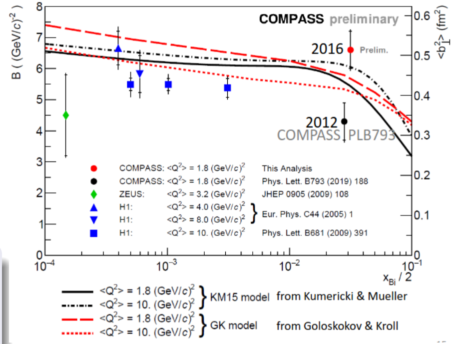
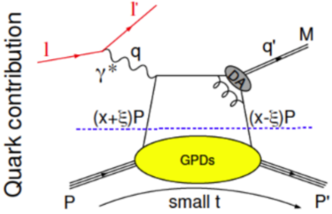
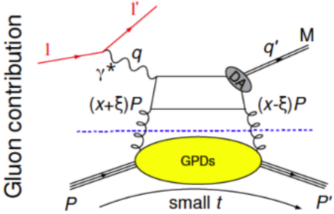


2016: preliminary, 1/3 of available statistics.

- Re-analysis of 2016 data is being finalised → publication soon.
- Study the ϕ-dependence
  - $s_1^{\mathrm{I}} \propto$ Im$\mathcal{H}$ → further constrain transverse extension of partons.
- Cross-section difference to be extracted
  - $\mathrm{d}\sigma^+ - \mathrm{d}\sigma^- \propto \mathrm{Re}\mathcal{F} \propto$ Re$\mathcal{H}$ → related to D-term and pressure distribution.
- 2017 data analysis starting.
- Study the x_{B}-dependence → tomography.
- Analysis slowed down recently due to lack of people.
- New groups interested in GPD analyses joined COMPASS recently.

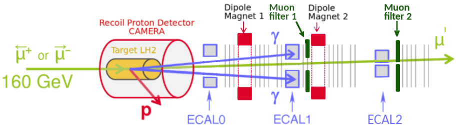




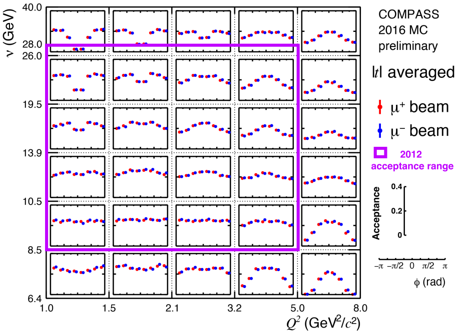
- Factorisation (collinear) proven only for longitudinally polarised γ^*.
- Phenomenological models postulating $k_\perp$-factorisation.
- Flavour separation possible thanks to different quark content of mesons.
- Pseudoscalar mesons
  - At leading twist: sensitive to $\tilde{H}, \tilde{E}, H_\mathrm{T}, \bar{E}_\mathrm{T}$.
- Vector mesons
  - Gluons and quarks enter at the same order of α_S
  - Sensitive to $H, E, H_\mathrm{T}, \bar{E}_\mathrm{T}$.

π^0 production: Event selection

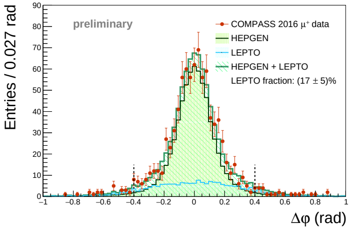
- 2012 pilot run (1 month)
  - Published results [PLB 805 (2020) 135454]
- 2016–2017 runs
  - Larger ECAL0.
  - $10\times$ more statistics.
  - The same μ^+ and μ^- beam intensity.
  - Preliminary results using 1/3 statistics.

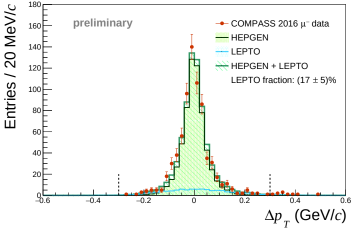


- $\mu p \to \mu' p' \pi^0$
  $\pi^0 \to \gamma\gamma$
- E_γ thresholds in ECAL 0, 1, 2.
- Exclusivity with CAMERA:
  - $|\Delta\varphi| < 0.4$ rad,
  - $|\Delta p_T| < 0.3$ GeV/c,
  - $|\Delta z_A < 16|$ cm,
  - $M_X^2 < 0.3\ (\mathrm{GeV}/c^2)^2$
- Kinematic fit
- $\chi^2_{\mathrm{fit}} < 10$
- Kinematic domain:
  - $\nu \in (6.4, 40)$ GeV,
  - $Q^2 \in (1, 8)\ (\mathrm{GeV}/c)^2$,
  - $|t| \in (0.08, 0.64)$ GeV/c.



Improved acceptance with respect to 2012.

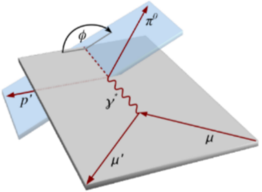




Non-exclusive background

- π^0 from deep inelastic scattering.
- Simulated by LEPTO MC.
- Exclusive π^0 simulated by HEPGEN MC.
- Mix of HEPGEN and LEPTO fitted to exclusivity distributions in the data.
- Result: $(17 \pm 5)\%$ of nonexclusive background.

π^0 production: Results



$$\frac{d\sigma^{\mu^+ p\to\mu' p^+ \pi^0}}{dt d\phi} + \frac{d\sigma^{\mu^- p\to\mu' p^- \pi^0}}{dt d\phi} = \frac{\Gamma(Q^2,\nu)}{2\pi}$$

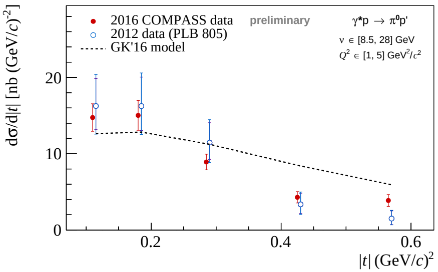
$$\times \left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$

$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$

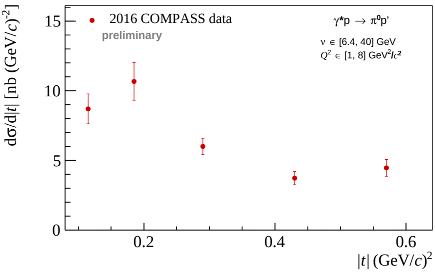
$\frac{d\sigma_T}{dt} \propto |\langle H_T\rangle|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2$

$\frac{\sigma_{TT}}{dt} \propto \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$

$\frac{\sigma_{LT}}{dt} \propto \frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$



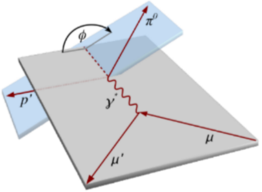
Cross section in 2012 kinematic range.
GK16 model: Goloskokov–Kroll (2016),
Other models: Goldstein–Gonzalez–Liuti, PRD91 (2015)



Cross section in enlarged kinematic domain.

New 2016 preliminary results [K. Lavičková, IWHSS 2023, Prague] (using 1/3 statistics):
Statistical uncertainty shown, the systematic one is 10% to 20% (in low cross section bins).

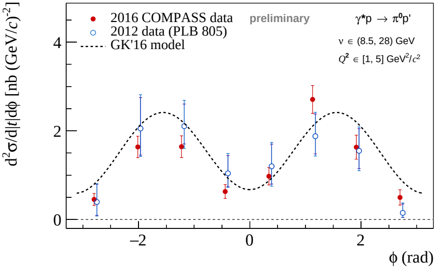
π^0 production: Results



$$\frac{d\sigma^{\mu^+ p\to\mu' p^+ \pi^0}}{dt d\phi} + \frac{d\sigma^{\mu^- p\to\mu' p^- \pi^0}}{dt d\phi} = \frac{\Gamma(Q^2,\nu)}{2\pi}$$

$$\times \left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$

$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$ | $\frac{d\sigma_T}{dt} \propto |\langle H_T\rangle|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2$ | $\frac{\sigma_{TT}}{dt} \propto \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$ | $\frac{\sigma_{LT}}{dt} \propto \frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$



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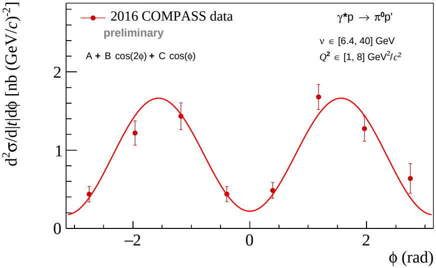

Cross section in enlarged kinematic domain.
Large $\cos 2\phi$ modulation – the role of $\bar{E}_T$

New 2016 preliminary results [K. Lavičková, IWHSS 2023, Prague] (using 1/3 statistics):
Statistical uncertainty shown, the systematic one is 10% to 20% (in low cross section bins).

π^0 production: Outlook

- The 2016 analysis is being finalised $\rightarrow$ publication soon.
- Comparison with theory predictions, once they are available in our kinematic domain.
- 2017 data analysis starting.
- Study the ν, x_B or Q^2 dependence.
- Cross-section difference $(\mathrm{d}\sigma^{+} - \mathrm{d}\sigma^{-}) \rightarrow \sin$ modulation amplitude.

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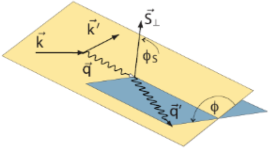
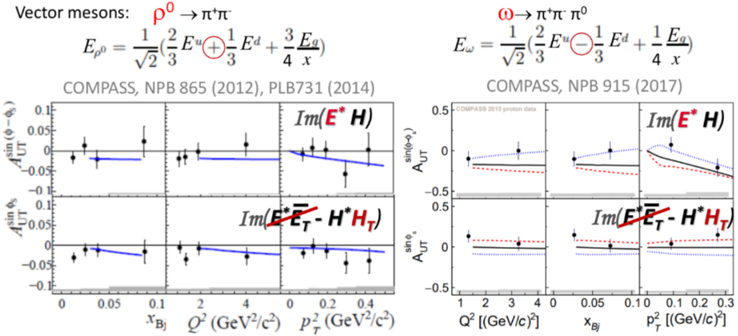
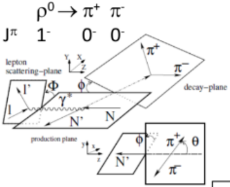


- $\mu p \to \mu' p' \rho^0$ and $\mu p \to \mu' p' \omega$
  $\rho^0 \to \pi^+\pi^-$ $\quad\quad \omega \to \pi^+\pi^-\pi^0$
- No recoil proton detector.
- Exclusivity imposed via energy conservation.
- Target: transversely polarised p (H in NH_3).



- Contribution of pion pole important for ω, as $\Gamma(\omega \to \pi^0\gamma) \approx 9\,\Gamma(\rho^0 \to \pi^0\gamma)$

Spin density matrix elements (SDMEs) – parametrize experimental angular distributions of vector meson production on unpolarised target:



$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + P_b\mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$$

15 'unpolarized' and 8 'polarized' SDMEs

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

$$\mathcal{W}^L(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\left(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\right)$$
$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\left(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\right)$$
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ε close to 1,
small $\mathcal{W}^L$
no L/T separation

Vector mesons: SDMEs

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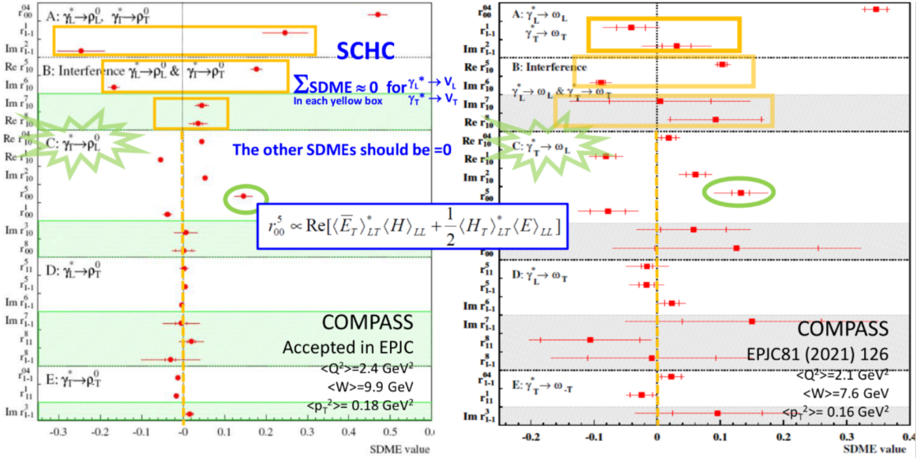
PRIMUS



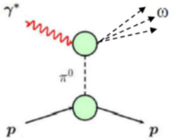
- 2012 data with LH target, not using CAMERA here (to access low t).
- s-channel helicity conservation model (SCHC): $\lambda_\gamma = \lambda_V$
  Sum of SDMEs in the yellow boxes should be 0, all others 0.

Vector mesons: SDMEs

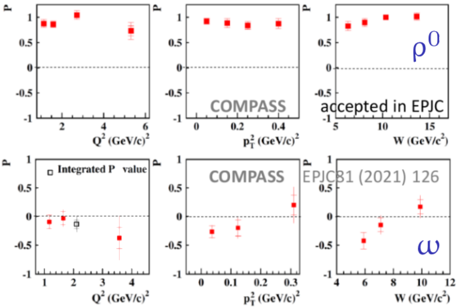
Natural (N) to unnatural (U) parity exchange

$$P = \frac{2r^1_{1-1}}{1 - r^{04}_{00} - 2r^{04}_{1-1}} \approx \frac{d\sigma^N_T(\gamma^*_T \to V_T) - d\sigma^U_T(\gamma^*_T \to V_T)}{d\sigma^N_T(\gamma^*_T \to V_T) + d\sigma^U_T(\gamma^*_T \to V_T)}$$

- NPE: GPDs H, E,
- UPE: GPDs $\tilde{H}, \tilde{E}$ and the pion pole.



Pion pole exchange contributes to UPE,
$\Gamma(\omega \to \pi^0\gamma) \approx 9\,\Gamma(\rho^0 \to \pi^0\gamma)$



ρ^0: $P \approx 1 \to$ dominance of NPE

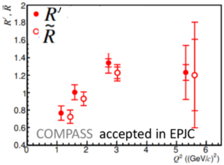
ω: $P \approx 0 \to$ NPE $\approx$ UPE

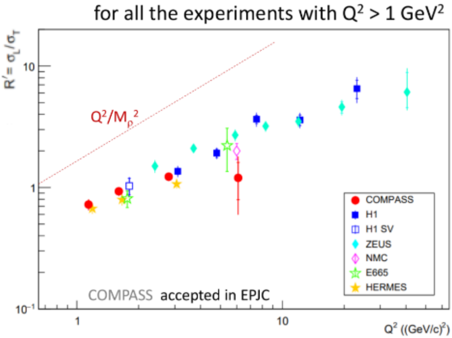
Longitudinal-to-transverse cross section ratio for ρ^0 production

$$R = \frac{d\sigma_L(\gamma^*_L \to V)}{d\sigma_T(\gamma^*_T \to V)}$$

To obtain it from the data:

- Assuming SCHC: $R' = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$ (standard, used by many experiments)
- Assuming only NPE: $\tilde{R}$





Vector mesons: Outlook

- Exclusive ϕ production: ongoing analysis (SMDEs, cross section).
- Exclusive J/ψ production: feasibility studies.

Conclusion

- 2016–2017 data with LH target and 160 GeV/c $\mu^{\pm}$ beam
- Preliminary results using 1/3 of statistics (part of 2016 data)
  - DVCS t-slope of the cross section → transverse extension of partons at $x_B = 0.06$.
  - Deep virtual π^0 production cross-section: new results (6/2023).
    → large contribution of σ_{TT} confirmed – significant role of γ_T and the GPD $\bar{E}_T$.
  - Both measurements are being finalised, to be published soon.
- SDMEs in hard ω production [EPJC (2021) 81 126]
- SDMEs in hard ρ^0 production: Paper accepted to EPJC [hep-ex/2210.16932]
  → Importance of γ_T and the GPD H_T
- ρ^0 and ω production on polarised target [NPB 915 (2017) 454] [PLB B731 (2014) 19]

Outlook:

- 2017 data: starting with new people joining the analysis – promising!
- Extensions of the DVCS and π^0 analyses:
  - Kinematic dependencies (ν, x_B, Q^2),
  - Azimuthal dependence of the DVCS cross section,
  - Cross section difference $d\sigma^+ - d\sigma^-$
- Deep virtual ϕ production cross section and SDMEs: work in progress on 2016 data.
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Thank you for your attention!