Spin Density Matrix Elements in hard exclusive light vector meson muoproduction at COMPASS

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on behalf of the COMPASS Collaboration

University of Illinois at Urbana-Champaign

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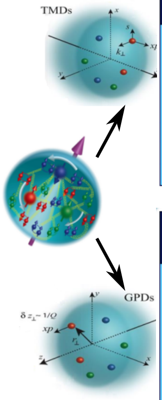


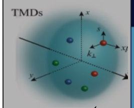
Nucleon Polarisation	Quark Polarisation: Unpolarised (U)	Longitudinally polarised (L)	Tranversely polarised (T)
U	$f_1^q(x, \mathbf{k_T^2})$		$h_1^{q\perp}(x, \mathbf{k_T^2})$
L		$g_1^q(x, \mathbf{k_T^2})$	$h_{1L}^{q\perp}(x, \mathbf{k_T^2})$
T	$f_{1T}^{q\perp}(x, \mathbf{k_T^2})$	$g_{1T}^{q\perp}(x, \mathbf{k_T^2})$	$h_{1T}^{q}(x, \mathbf{k_T^2})$ Transversity $h_{1T}^{q\perp}(x, \mathbf{k_T^2})$ Pretzelosity

Nucleon Polarisation	Quark Polarisation: Unpolarised (U)	Longitudinally polarised (L)	Tranversely polarised (T)
U	H		$\bar{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

Nucleon is a complex object

Most comprehensive description provided by universal non perturbative functions:

- Transverse Momentum Dependent PDFs
- Generalised Parton Distributions



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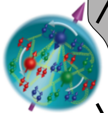

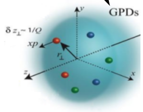

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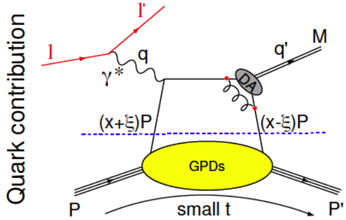
This talk: GPDs

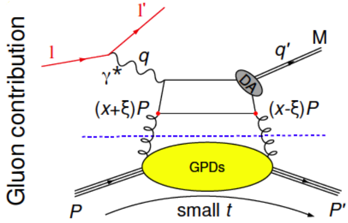
- Encode usual PDF and Form factors
- 4 Chiral-even: $H^{q,g}$, $E^{q,g}$, $\tilde{H}^{q,g}$, $\tilde{E}^{q,g}$
  parton helicity non-flip
- 4 Chiral-odd: $H_T^{q,g}$, $\tilde{H}_T^{q,g}$, $E_T^{q,g}$, $\tilde{E}_T^{q,g}$
  parton helicity flip

Accessible via:

$\Rightarrow$ DVCS talk by A. Koval for COMPASS results

$\Rightarrow$ **Deeply virtual meson production**





Factorization proven for σ_L
σ_T suppressed by $1/Q^2$

Kinematics of reaction:

- x: average longitudinal momentum fraction
  $\rightarrow$ not accessible
- ξ: half longitudinal momentum fraction exchanged between initial and final parton $\sim x_B/(2-x_B)$
- t: four-momentum transfer to target
- $Q^2 = -q^2$: photon virtuality

Interest for vector mesons:

- Sensitive to gluon GPDs (same order in α_S): H & E
- Provide different flavour combinations, *e.g.:*

Diehl, Vinnikov, PLB 609 (2005)

- $F_\rho = \frac{1}{\sqrt{2}}(\frac{2}{3}F^u + \frac{1}{3}F^d + \frac{3}{4}F^g/x)$
- $F_\omega = \frac{1}{\sqrt{2}}(\frac{2}{3}F^u - \frac{1}{3}F^d + \frac{1}{4}F^g/x)$
- $F_\phi = -\frac{1}{3}F^s + \frac{1}{4}F^g/x$

$\Rightarrow$ **COMPASS can measure ρ, ω, ϕ, J/ψ**

Spin density matrix elements of vector mesons

Bilinear combinations of the helicity amplitudes F

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

helicity of vector meson V

helicities of virtual photon γ and nucleon N

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

$$\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} = \varrho^{U}_{\lambda_\gamma \lambda'_\gamma} + P_b\, \varrho^{L}_{\lambda_\gamma \lambda'_\gamma}$$

- Helicity amplitudes, F, describe transitions $\lambda_\gamma, \lambda_N \to \lambda_V, \lambda_{N'}$ depend on W, Q^2, p_T^2
- $\rho_{\lambda_V,\lambda'_V}$ decomposes into 9 matrices $\rho^{\alpha}{}_{\lambda_V,\lambda'_V}$ depending on the photon pol. states: Transv. polarised (α=0-3), Long. polarised (α=4), Inter. polarised (α=5-8)

We actually measure:

$$r^{\alpha}{}_{\lambda_V,\lambda'_V} = S\rho^{\alpha}{}_{\lambda_V,\lambda'_V}(1+\epsilon R)^{-1}, \text{S=1 for } \alpha = 1-3, \text{ S=} \sqrt{R} \text{ for } \alpha = 5-8$$

$$r^{04}{}_{\lambda_V,\lambda'_V} = (\rho^{0}{}_{\lambda_V,\lambda'_V} + \epsilon R \rho^{4}{}_{\lambda_V,\lambda'_V})(1+\epsilon R)^{-1}$$

using K. Schiling and G. Wolf (Nucl. Phys. B 61 (1973) 381) definition in absence of photon $R = \sigma_L/\sigma_T$ separation

ϵ is the virtual photon polarisation parameter

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In GPD models for vector mesons:

$\Rightarrow$ Natural parity exchange amplitudes $\Rightarrow$ H, E: Dominant contribution at LO & LT

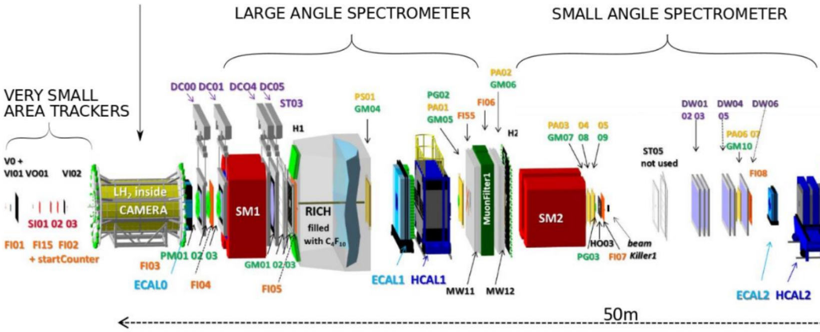
$\Rightarrow$ Unnatural parity exchange amplitudes $\Rightarrow$ $\tilde{H}$, $\tilde{E}$ and pion pole

$\Rightarrow$ s-channel helicity conservation violation: $\gamma_T \to V_L \Rightarrow$ transverse GPDs H_T, $\bar{E}_T$

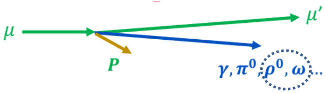
COMPASS apparatus for exclusive reaction measurements

Two-stage spectrometer in NA of CERN SPS

NIMA 577 (2007) 455, NIMA 779 (2015) 69



Reactions:



Beam:

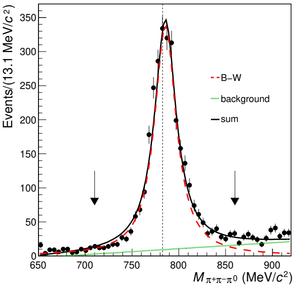
- 160 GeV/c $\mu^{\pm}$ with $P \sim \mp 80\%$ and $I \sim 20$MHz
- 190 GeV/c Hadron beams

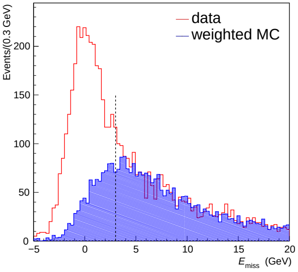
Key elements:

- 2.5m long LH_2 target with recoil detector for DVCS & π^0
- 3 EM Calorimeters
- $\sim$ 400 tracking planes

Event selection of ω

EPJC 81 (2021) 126





Topology: $\mu p \to \mu' p' \omega$

$\hookrightarrow \pi^+\pi^-\pi^0$ BR $\approx$ 89%

$0.71 < M_{3\pi}/(\text{GeV}/c^2) < 0.86$

$\hookrightarrow \gamma\gamma$ BR $\approx$ 99%

$0.1 < M_{\gamma\gamma}/(\text{GeV}/c^2) < 0.17$

Main kinematic selection:

- $1 < Q^2/(\text{GeV}/c)^2 < 10$ $\Leftarrow$ pQCD & minimisation of SIDIS
- $W > 5$ GeV$/c^2$ $\Leftarrow$ suppress resonance region
- $0.01 < p_T^2/(\text{GeV}/c)^2 < 0.5$ $\Leftarrow$ angular resolution & SIDIS bkg
- $0.1 < y < 0.9$ $\Leftarrow$ Poor reconstruction and large radiative corr.

Recoil proton detector limits low p_T^2 of meson $\to$ not used

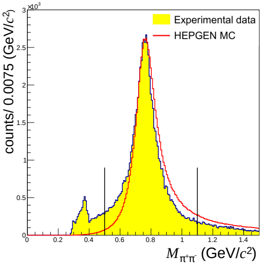
Instead:

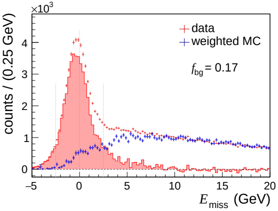
$$|E_{miss}| = \frac{|M_X^2 - M_p^2|}{2M_p} < 3.0 \text{ (GeV)}$$ & subtract SIDIS background

$\Rightarrow$ Final sample: 3,060 events

Event selection of ρ

arXiv:2210.16932, acc. EPJC





Topology $\mu p \to \mu' p' \rho^0$

$\hookrightarrow \pi^+\pi^-$ BR $\approx$ 99%

$0.5 < M_{\pi\pi}/(\text{GeV}/c^2) < 1.1$

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- $1 < Q^2/(\text{GeV}/c)^2 < 10$ $\Leftarrow$ pQCD & minimisation of SIDIS
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Instead:

$|E_{miss}| = \frac{|M_X^2 - M_p^2|}{2M_p} < 2.5$ (GeV) & subtract SIDIS background

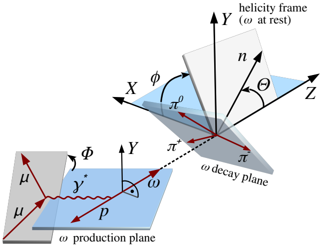
$\Rightarrow$ Final sample: 52,260 events

Experimental access to SDMEs

Through angular dependence of production cross section:

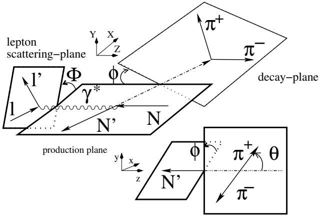
$$\frac{d\sigma}{d\Phi d\phi d\theta} \propto W^{U+L}(\Phi,\phi,\theta) = W^{U}(\Phi,\phi,\theta) + P_{\mu} W^{L}(\Phi,\phi,\theta)$$

23 SDMEs in total, 15 "unpolarised" and 8 "polarised" for different angular/kinematic dependence



Extraction from Unbinned Maximum Likelihood fit of experimental data with:

- Isotropic MC HEPGEN exclusive process
- LEPTO MC for SIDIS
- Background $\sim$ 20%



Spin density elements of ρ

COMPASS arXiv:2210.16932, acc EPJC

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

$$r^1_{1-1} + \mathrm{Im}(r^2_{1-1}) = 0 = 0.000 \pm 0.005 \pm 0.003$$
$$\mathrm{Re}(r^5_{10}) + \mathrm{Im}(r^6_{10}) = 0 = 0.011 \pm 0.002 \pm 0.002$$
$$\mathrm{Im}(r^7_{10}) - \mathrm{Re}(r^8_{10}) = 0 = 0.009 \pm 0.014 \pm 0.028$$

All other elements of C, D, E should be 0

Clear deviation for $\gamma^*_T \to \rho_L$ elements

Interpretation with trans. GPDs:

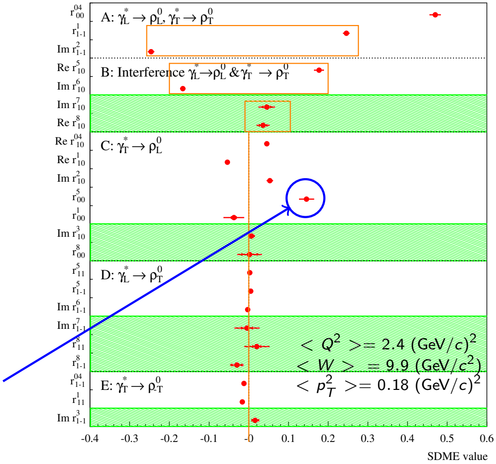
Goloskokov, Kroll, EPJC 74 (2014) 2725

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

ρ: Dominance of first term $\to$ probing $\bar{E}_T$

$$F_\rho = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u + \frac{1}{3}F^d\right)$$

with same sign between u & d GPDs for H and $\bar{E}_T$,
while opposite for H_T and E



In absence of σ_L,σ_T separation $\to$ Schilling and Wolf definition of SDME (Nucl. Phys B 61 (1973) 381)

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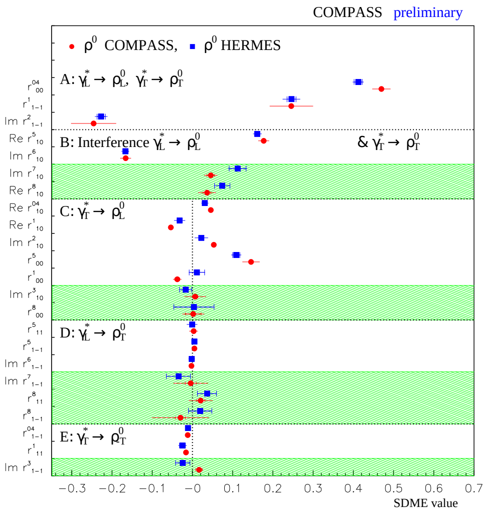
Comparison with HERMES results:

- Similar Q^2 and t but $W_{\mathrm{HERMES}} < W_{\mathrm{COMPASS}}$
- Similar trend despite differences
- Restricted to similar W range: observables are compatible

COMPASS arXiv:2210.16932, acc EPJC, HERMES, EPJC 62 (2009) 659



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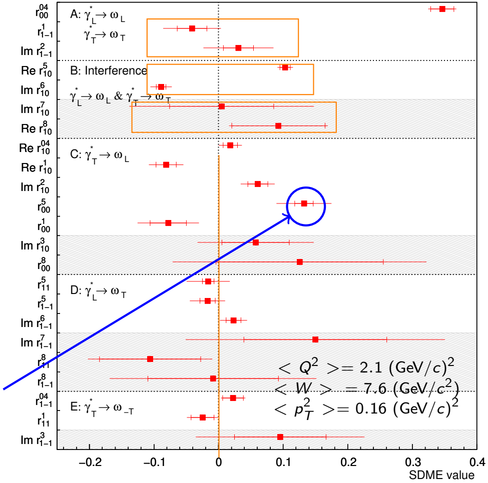
ω: 2 terms contribute $\to$ probing $\bar{E}_T \& H_T$

$$F_\omega = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u - \frac{1}{3}F^d\right)$$

with same sign between u & d GPDs for H and $\bar{E}_T$,
while opposite for H_T and E

COMPASS EPJC 81 (2021) 126



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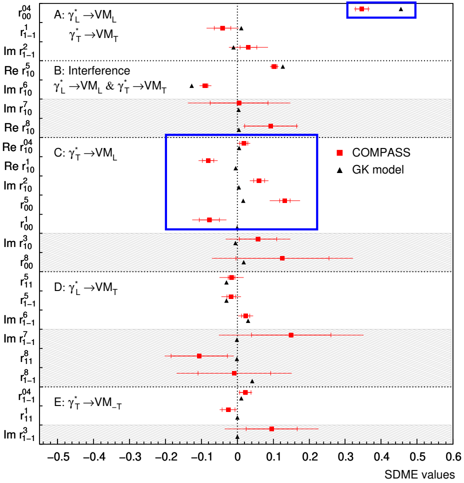
Spin density elements of ω

COMPASS EPJC 81 (2021) 126, GK model EPJA 50 (2014) 146



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Clear deviation for $\gamma^*_T \to \rho_L$ elements

Compared to GK model:

$\to$ r^{04}_{00} is significantly larger than measured

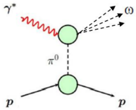
$\to$ SCHC almost compatible with 0

In absence of σ_L,σ_T separation $\to$ Schilling and Wolf definition of SDME (Nucl. Phys B 61 (1973) 381)

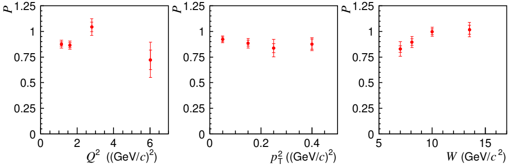
Quantification of NPE/UPE asymmetry for $\gamma^*_T \to V_T$:

$$\frac{d\sigma_T^{NPE} - d\sigma_T^{UPE}}{d\sigma_T^{NPE} + d\sigma_T^{UPE}} \approx \frac{2r^1_{1-1}}{1 - r^{04}_{00} - r^{04}_{1-1}} = P$$

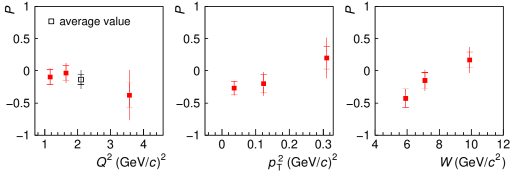
- ρ production
  - Dominance of NPE
  - Sensitivity to GPDs E, H
- ω production
  - UPE dominance at small W and p_T^2
  - NPE$\sim$UPE on average
  - Sensitivity also to GPDs $\tilde{E}$, $\tilde{H}$ and pion pole



ρ COMPASS arXiv:2210.16932, acc EPJC



ω , COMPASS EPJC 81 (2021) 126



Longitudinal-to-transverse cross-section ratio

L-L Chau Wang Phys. Rev 142 (1966) 1187

$R' = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$ can be interpreted as

$R = \frac{\sigma_L(\gamma^*_L \to V)}{\sigma_T(\gamma^*_T \to V)}$ in case of SCHC $\Rightarrow$

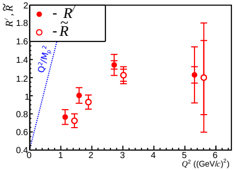
A. Airapetian et al., EPJC 62 (2009) 659

$\tilde{R} \sim R'$ taking into account:

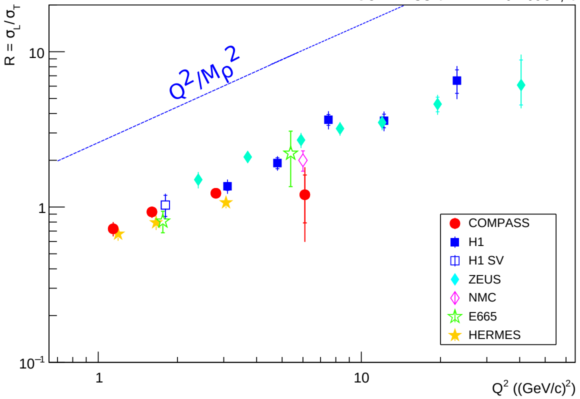
$\to$ SCHC violation

$\to$ only NPE

COMPASS arXiv:2210.16932, acc EPJC



COMPASS arXiv:2210.16932, acc EPJC



All experiments with $Q^2 > 1$ (GeV^2) for ρ production

Deviation from pQCD LO prediction, $R = Q^2/M^2_\rho$

Transverse size effects of the meson smaller for σ_L than σ_T

Conclusion

⇒ SDME in DVMP of ρ and ω from 2012 pilot run were shown

arXiv:2210.16932, acc EPJC

EPJC 81 (2021) 126

⇒ Violation of s-channel helicity conservation for transition $\gamma^*_T \to V_L$ is observed in GPD framework it implies contribution from chiral-odd GPDs

⇒ Only NPE for ρ production, unlike large UPE contribution for ω

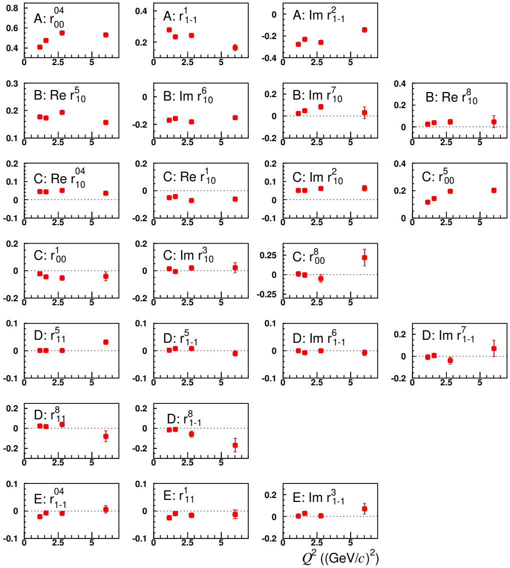
⇒ Measurement of R in agreement with previous experiments

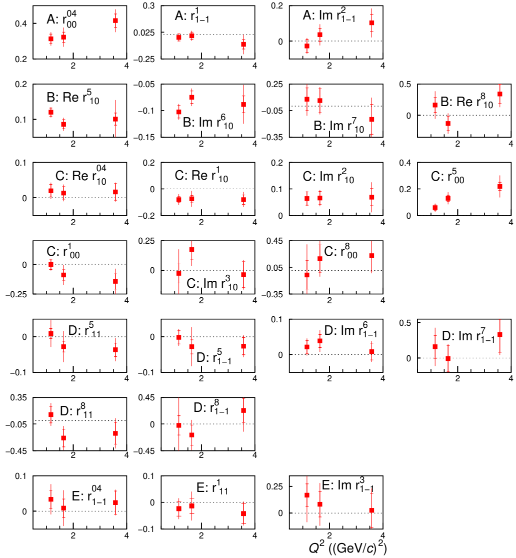
Ongoing analyses of exclusive production of π^0, ϕ, ω and J/ψ with 2016/2017 data
⇒ 10 × larger than from 2012

Stay tuned

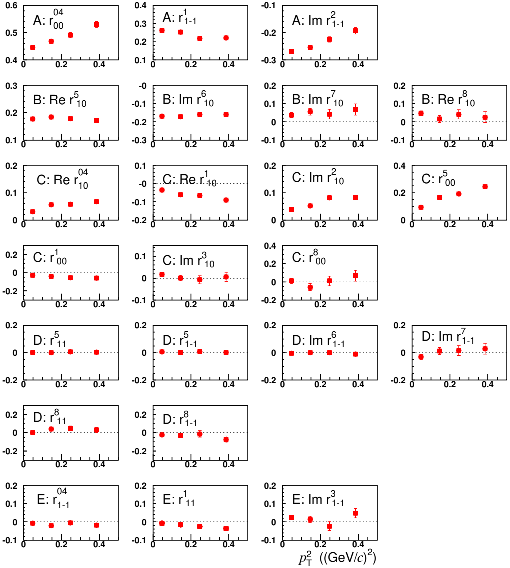
BACKUP

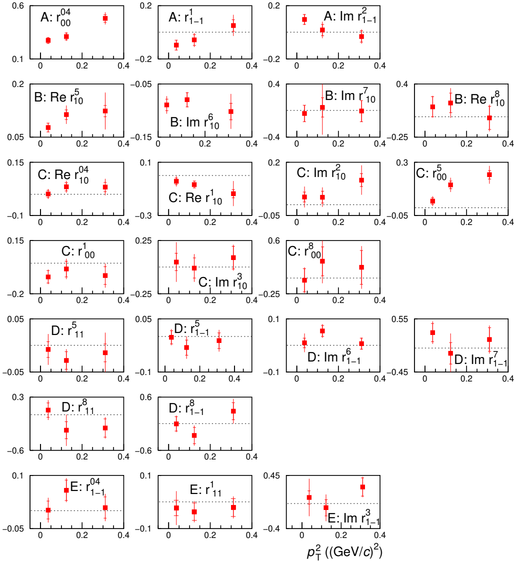
SDME dependence upon Q^2: ρ(left), ω(right)





SDME dependence upon p_T^2: ρ(left), ω(right)





SDME dependence upon W: ρ(left), ω(right)