EXTRACT SDMES FOR RHO0

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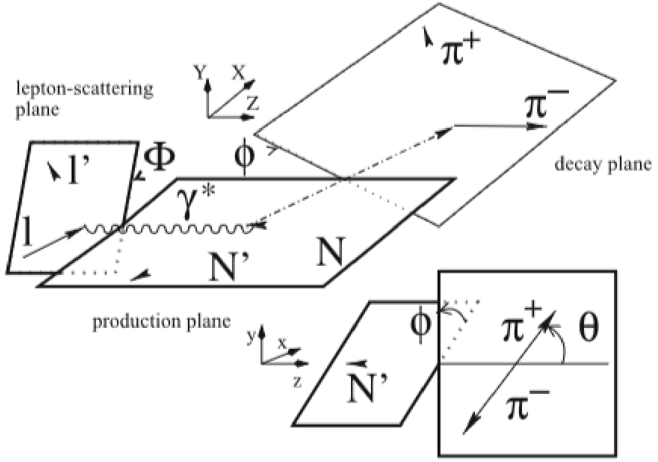
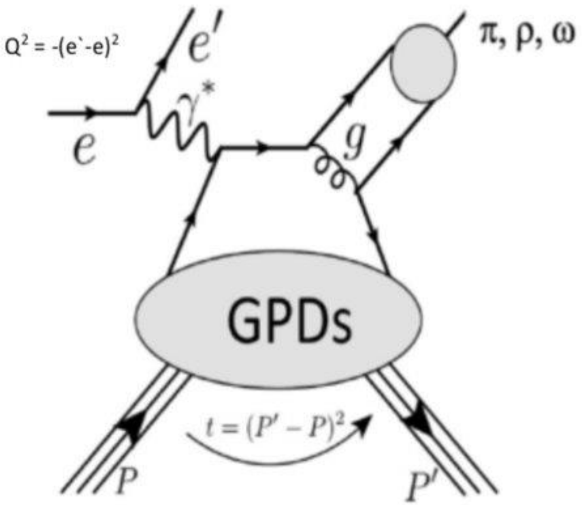
MOTIVATION

- Generalized Parton Distrubutions (GPDs) give insight into the 3D structure of hadrons
- Accessing GPDs can be done using deeply virtual vector meson production (DVMP)
  - DVMP is sensitive to higher order twist terms and chiral odd GPDs
- In the Goloskokov-Kroll (GK) model, SDMEs are relate to GPDs
  - This allows for constrictions on the theoretical calculation of GPDs

$$\frac{2\pi}{\Gamma(Q^2, x_B, E)} \frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi + P_b\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$



W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive ρ0 meson production using the 2012 COMPASS data,internal note, 2021.



MOTIVATION

- The 3D angular distribution can be shown from experimental results of the pion decay
  - Schilling-Wolf showed that Spin Density Matrix Elements (SDMEs) are parameters of the angular distributions
- The SDMEs can be express through helicity amplitudes
  - These helicity amplitudes depend on Q2, W and –t
- The spin density matrix can be expressed in terms of the matrices that depend on the photon polarization and R
  - Where R is the longitudinal-to-transverse virtual-photon differential cross-section ratio
- For the photon polarization:
  - α = [0,3] transversely
  - α = [4] longitudinal
  - α = [5,8] interference

$$
\begin{aligned}
\mathcal{W}^U(\Phi,\phi,\cos\Theta) \;=\; & \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta \\
& - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi - \epsilon\cos 2\Phi\Big(r^1_{11}\sin^2\Theta \\
& + r^1_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^1_{10}\}\sin 2\Theta\cos\phi - r^1_{1-1}\sin^2\Theta\cos 2\phi\Big) \\
& - \epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^2_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^2_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^5_{10}\}\sin 2\Theta\cos\phi \\
& - r^5_{1-1}\sin^2\Theta\cos 2\phi\Big) + \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^6_{10}\}\sin 2\Theta\sin\phi \\
& + \mathrm{Im}\{r^6_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg], \qquad (2.19)
\end{aligned}
$$

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$$
\begin{aligned}
\mathcal{W}^L(\Phi,\phi,\cos\Theta) \;=\; & \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
& + \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi \\
& - r^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Bigg]. \qquad (2.20)
\end{aligned}
$$

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

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

$$
r^{\alpha}_{\lambda_V\lambda'_V} = \begin{cases} \rho^{\alpha}_{\lambda_V\lambda'_V}(1+\epsilon R)^{-1}, & \alpha = 1,2,3, \\ \sqrt{R}\rho^{\alpha}_{\lambda_V\lambda'_V}(1+\epsilon R)^{-1}, & \alpha = 5,6,7,8. \end{cases}
$$

MAXIMUM LIKELIHOOD METHOD

UNBINNED MAXIMUM LIKELIHOOD METHOD

- The Maximum Likelihood Method (MLM) is used to find the best fit of parameters without needing kinematic binning
- The process involves find the Probability Density Function (PDF) which is given by angular distributions and efficiencies:

$$w(\mathcal{R}, \Phi, \phi, \cos\Theta) = \frac{\mathcal{W}^{U+L}(\mathcal{R}; \Phi, \phi, \cos\Theta)\mathcal{E}(\Phi, \phi, \cos\Theta)}{\int \mathcal{W}^{U+L}(\mathcal{R}; \Phi, \phi, \cos\Theta)\mathcal{E}(\Phi, \phi, \cos\Theta)d\Omega}$$

- The likelihood function, L(R), is then calculated and the parameters are determined by minimizing the negative log of the likelihood function

$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}^{U+L}(\mathcal{R}; \Phi_i, \phi_i, \cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R})}$$

EXTRACTING SDME

- 23 SDME elements are extract using the MLM:

$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}^{U+L}(\mathcal{R};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R})}$$

- W is the angular distribution which is part of the unnormalized Probability Density Function
  - R is the 23 spin density matrix elements
  - Both phis and theta are the decay angles from the reaction:
    - $\mu p \longrightarrow \mu' \rho^0 P \longrightarrow \mu' \pi^+ \pi^- P$
- Tilde N is the normalization and can be found using a Monte Carlo:

$$\widetilde{\mathcal{N}} = \int \mathcal{W}^{U+L}(\mathcal{R};\Phi,\phi,\cos\Theta)\mathcal{E}(\Phi,\phi,\cos\Theta)d\Omega \approx \sum_{j=1}^{N_{MC}} \mathcal{W}^{U+L}(\mathcal{R};\Phi_j,\phi_j,\cos\Theta_j)$$

BACKGROUND SUBTRACTION STEPS

BACKGROUND SUBTRACTION USING MISSING ENERGY

- Missing Energy should be centered around zero so background events should be subtracted

- The largest component of the background is SIDIS events. This can be estimated by comparing the same charged hadron events for data and lepto (SCHAD)

- The opposite charged pion lepto events can be weighted to match data using SCHAD events

$$w(E_{\text{miss}}) = \frac{N_{rd}^{sc}(E_{\text{miss}})}{N_{MC}^{sc}(E_{\text{miss}})}.$$

  - Here N is the number of events with same charged pions found in the data (numerator) and the Monte Carlo (denominator)
- The fractional background, fbkg, can be calculated in our signal region [-2.5,2.5] during subtraction

  - This is used to remove the background events for SDME extraction

EXTRACTING SDME WITHOUT BACKGROUND

- Introduce 23 more SDME for just the background events:

$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln\Big[\frac{(1-f_{bg}) * \mathcal{W}^{U+L}(\mathcal{R};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B})} + \frac{f_{bg} * \mathcal{W}^{U+L}(\mathcal{B};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B})}\Big]$$

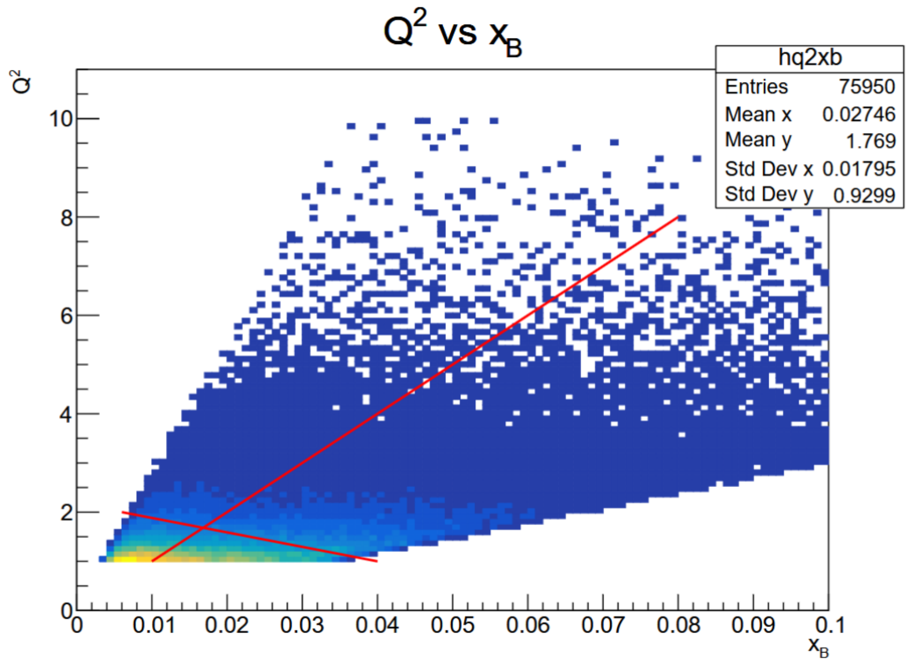
$$\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B}) = \sum_{j=1}^{N_{MC}} [(1-f_{bg}) * \mathcal{W}^{U+L}(\mathcal{R};\Phi_j,\phi_j,\cos\Theta_j) + f_{bg} * \mathcal{W}^{U+L}(\mathcal{B};\Phi_j,\phi_j,\cos\Theta_j)]$$

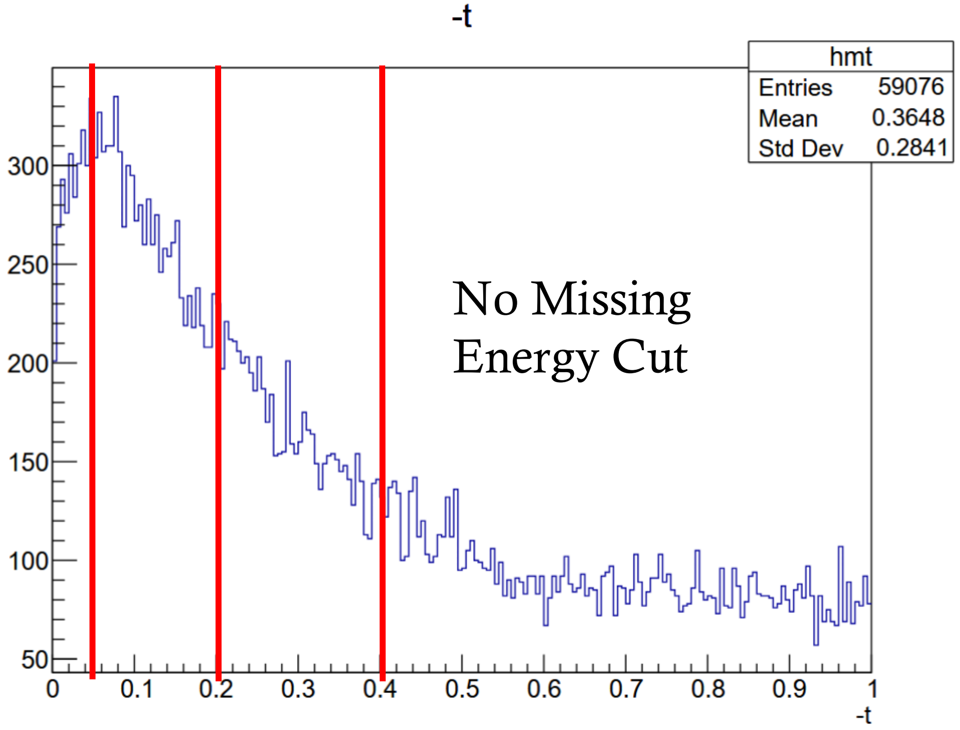
- Here R is the 23 SDME for the signal, and B is the 23 SDME for the background.
- 23 background SDME are calculated using lepto
- Fbkg is the fractional background

BINNING SCHEME

Binning for Background Subtraction

1. Overall Goal is 3D binning {Q2,xB,-t}
   - Q2 xB bin not final
2. 1D which can be done with P09 data
   - Bins: Q2,xB, and –t
3. Also look at the different muon beams





STEP BY STEP PROCESS

1. Create and match a Monte Carlo for the reaction
   - Using HepGen as the Generator and COMPASS detector simulation
   - Using MLM calculate SDME integrated over all kinematics (WITH BACKGROUND)
2. Use a Monte Carlo to subtract the background
   - Lepto Generator is used
   - Find Fbkg
   - Reweight HepGen to match background subtracted data
3. Find 23 background SDMEs using lepto
4. Use the MLM background subtraction to find SDMEs for the signal (23)
5. 3D binning in Q2, W and –t since our SDME depends on them
   - Do the process for both types of beams
   - Statistics might be lacking for full 3D binning, start with 1D for each
   - Use xB instead of W since our cross-section has this dependence, greater kinematic coverage between jlab and compass
   - COMPASS used pt2 for 2012 data instead of –t: |t| - t0 ~ Pt2
6. Repeat step 4 for bins of Q2, xB and –t

COMPASS

- Data
  - Year 2016, period 09, slot 9
  - Periods 4-11 for all data
- Monte Carlo
  - HepGen, Lepto
- Channel: $\mu p \longrightarrow \mu' \rho^0 X \longrightarrow \mu' \pi^+ \pi^- X$
  - Where X is the proton, and it is identified through the missing mass
  - ρ^0 decays into $\pi^+\pi^-$

Event Selection Muons

Muon Beam:

- Using primary track
- Muon beam exist
- -78.5 < Z vertex < -318.5
- 1 Hit in BMS
- probability of back propagation is bigger than 0.01
- Chi2 fit < 10
- Momentum and Momentum Error

Outgoing Muon:

- Track exist
- HodoHelper – Matches Muons
- Events are measured before and after SM1
- Chi2 fit < 10
- Radiation length > 15

Both:

- Muons have the same charge
- 3 outgoing particles

Event Selection Hadrons

Coming from 2012 Rho analysis (W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive ρ0 meson production using the 2012 COMPASS data,internal note, 2021.)

Both Pions:

- Both have tracks that exist
- Pions first (last) track is before (after) SM1
- Radiation length >10
- Chi2 fits < 10
- Pions have opposite charge

Event Selection MISC

- Wider Missing Energy Cut: -10 GeV to 20 GeV
- Muon beam is 140 to 180 GeV
- In target and Cross Cell (PaAlgo function)
- Scattered Muon energy is less than Muon beam
- total Z
- Triggers
- Bad Spills and time in spills
- Exclusive selection (The same as before)

Coming from 2012 Rho analysis (W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive ρ0 meson production using the 2012 COMPASS data,internal note, 2021.)

KINEMATIC CUTS

- $W > 5.0$ GeV to remove the kinematic region where the cross section for the semi-inclusive reactions changes rapidly due to a resonances production.
- $0.1 < y < 0.9$, lower cut suppresses events with a poorly reconstructed kinematics. The upper cut on y remove events with large radiative corrections.
- $1.0 < Q^2 < 10.0$ $(\mathrm{GeV/c})^2$, lower cut on virtuality Q^2 ensures hard processes regime and the upper one suppresses background due to the hadron production in DIS which hereafter is referred to as "SIDIS background".
- $\nu >$ 16 GeV   0.1 < y ----> 160*0.1 -----> 16 < nu
- squared transverse momentum of ρ^0 with respect to the virtual photon: $0.01 < p_T^2 < 0.5$ $(\mathrm{GeV/c})^2$.
- $0.5 < M_{\pi^+\pi^-} < 1.1$ GeV/c^2 invariant mass of two pions.
- $-2.5 < E_{miss} < 2.5$ GeV . $E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$, with M_p the proton mass and $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$ - the missing mass squared, where p, q, p_{π^+} and p_{π^-} are the four-momenta of target nucleon, virtual photon, and each of the two pions, respectively.
- momentum of ρ^0 $P_{\rho^0} > 15$ GeV/c. To reduce the semi-inclusive background contribution.