EXTRACT SDMES FOR RHO0

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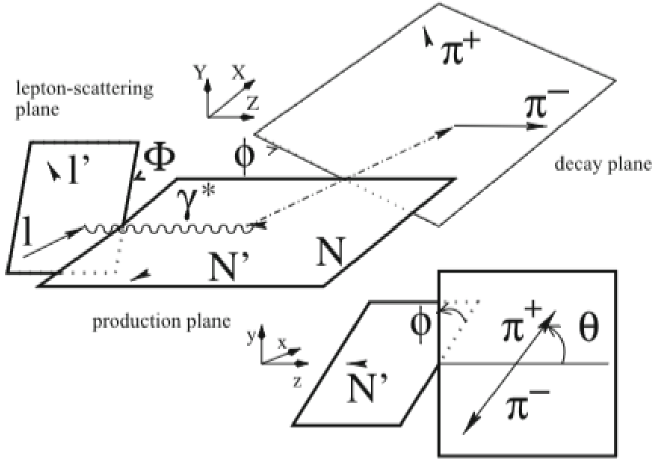
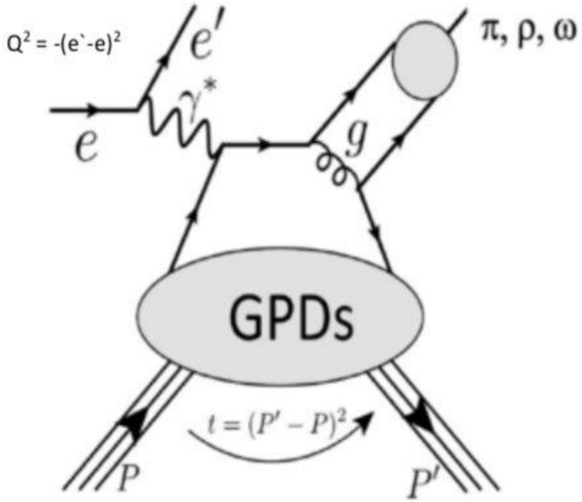
MOTIVATION

- 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
  - o R is the 23 spin density matrix elements
  - o 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:

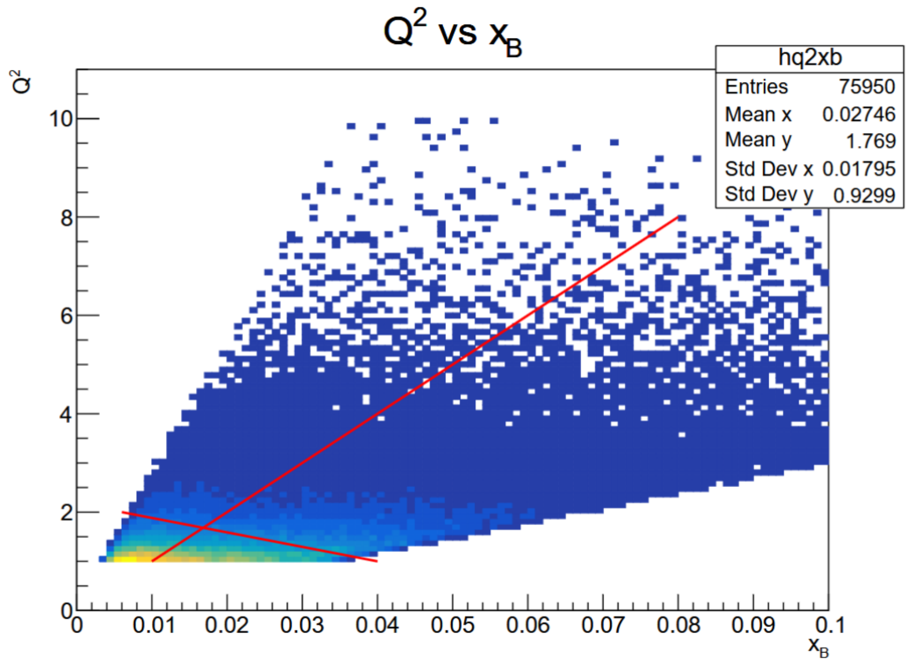
$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln\Big[\frac{(1-f_{bg}) * \mathcal{W}^{U+L}(\mathcal{R};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B})} + \frac{f_{bg} * \mathcal{W}^{U+L}(\mathcal{B};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B})}\Big]$$

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

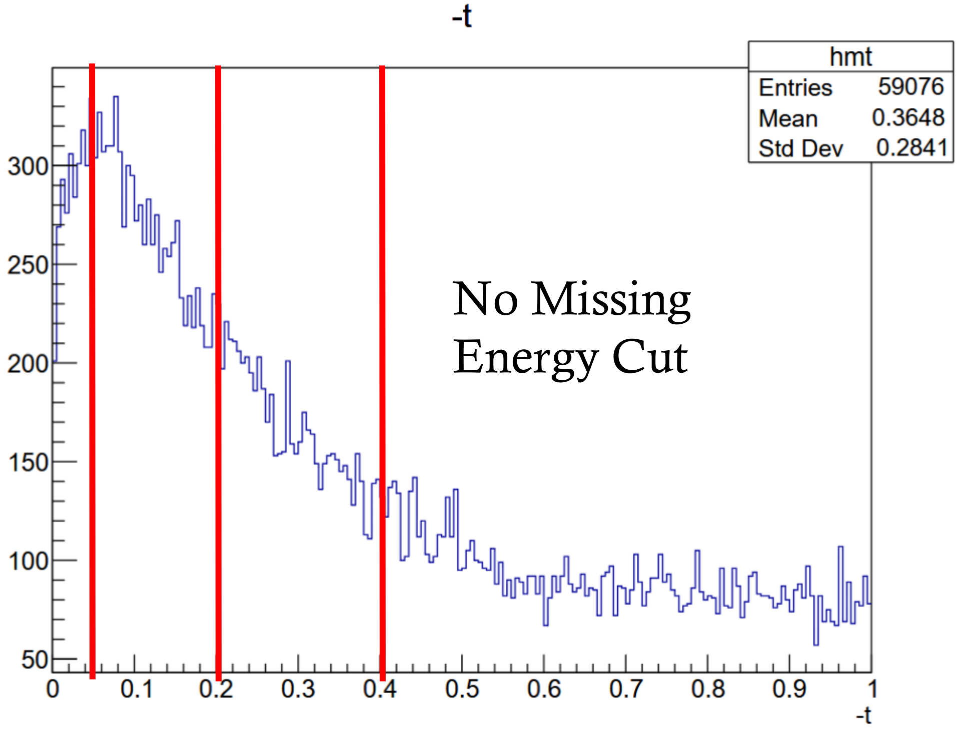
- Here R is the 23 SDME for the signal, and B is the 23 SDME for the background. MLM has to fit 46 parameters
- Fbkg is the fractional background

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

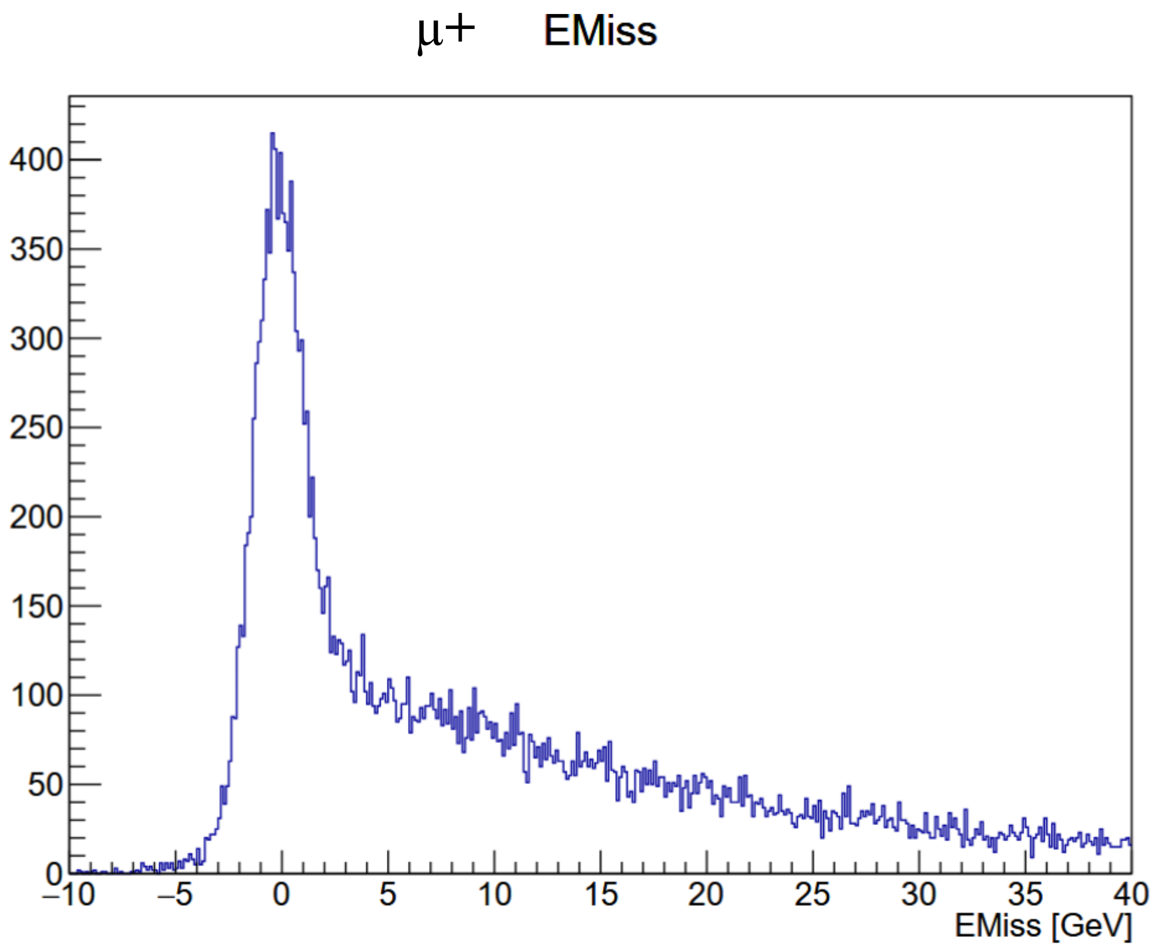


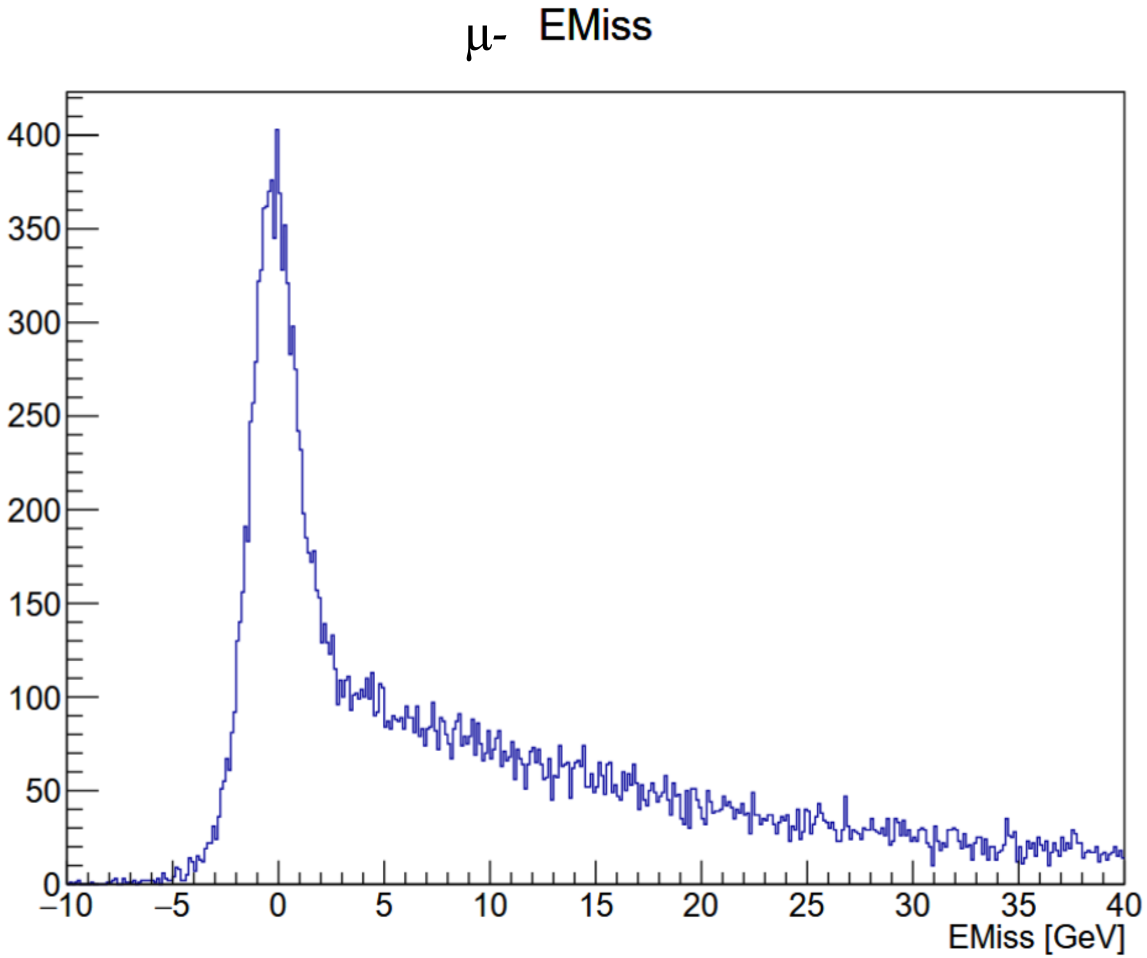
STEP BY STEP PROCESS

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. Use the MLM background subtraction to find SDMEs for the signal (23) and background (23)
4. 3D binning in Q2, W and –t since our SDME depends on them
   - 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
5. Repeat step 4 for bins of Q2, xB and –t and Look at the different muon beams

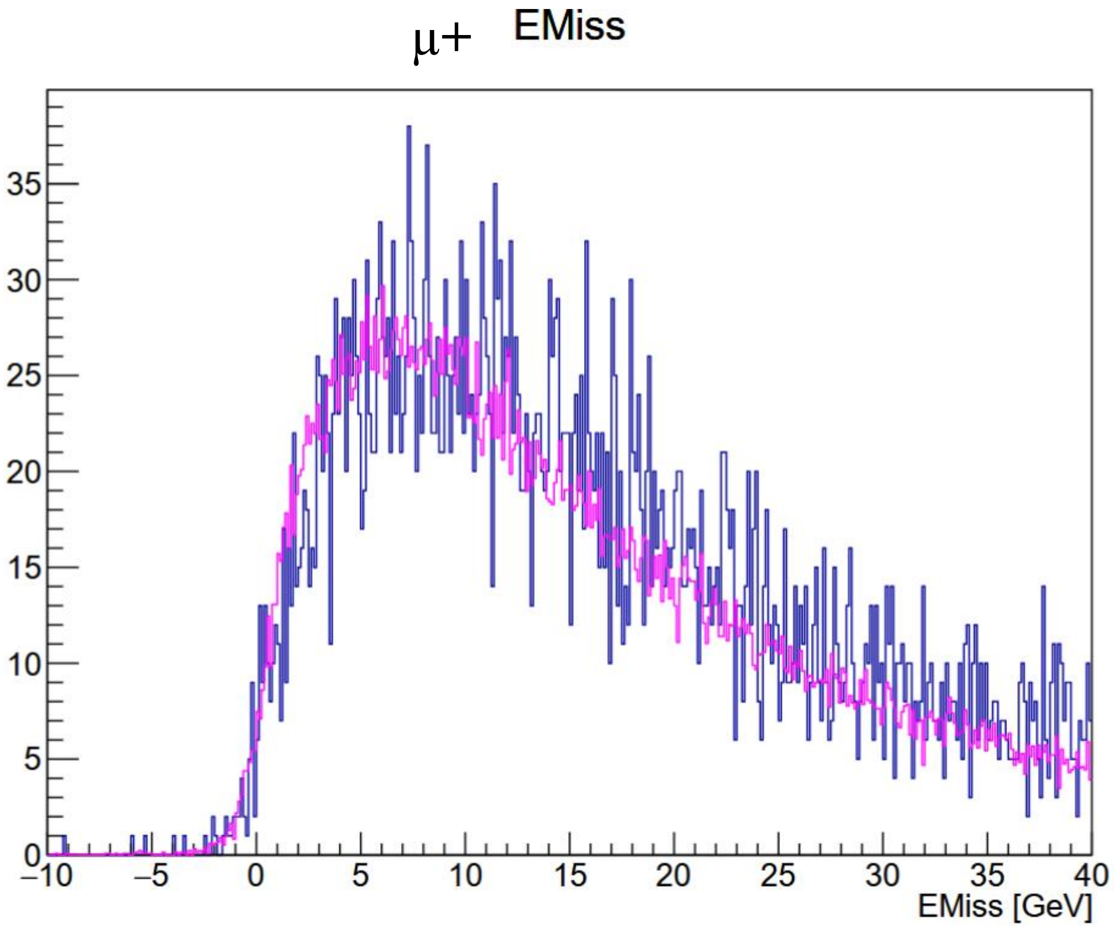
MU+ VS MU- BEAMS

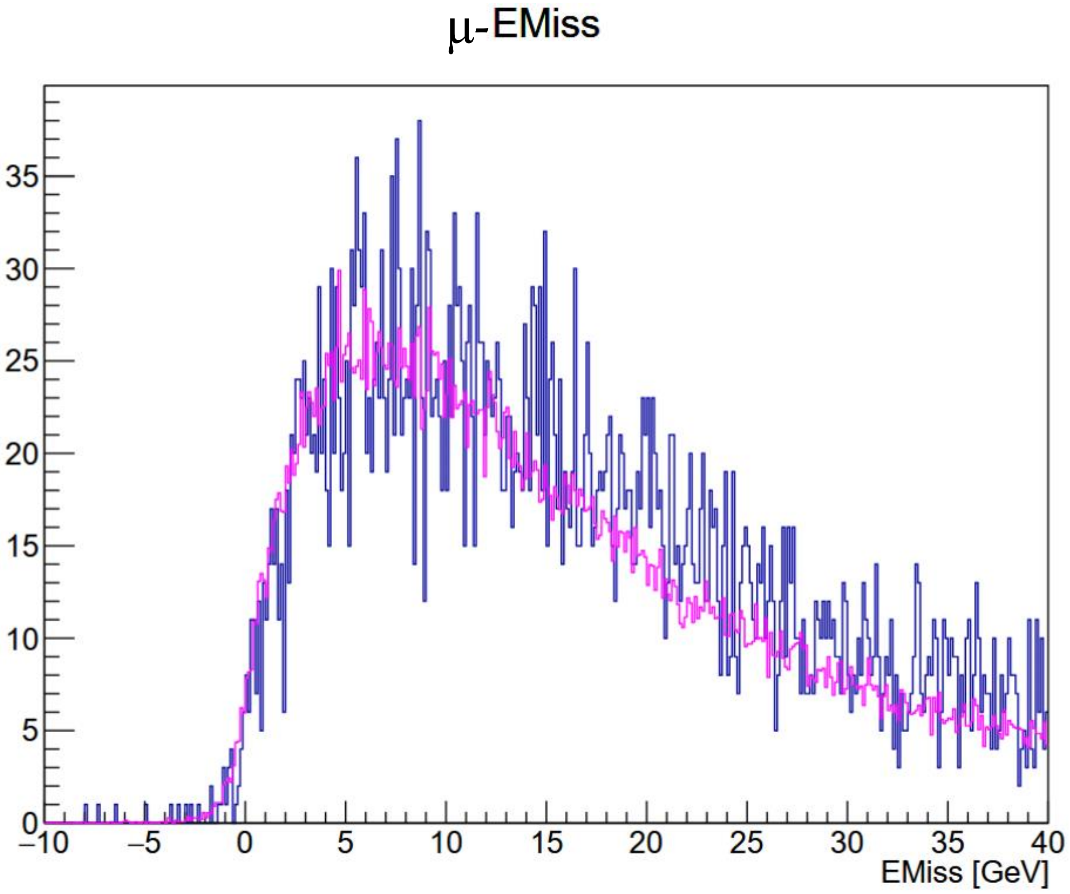
EMiss per Muon beam





EMiss per Muon beam Same Charge Hadron Events



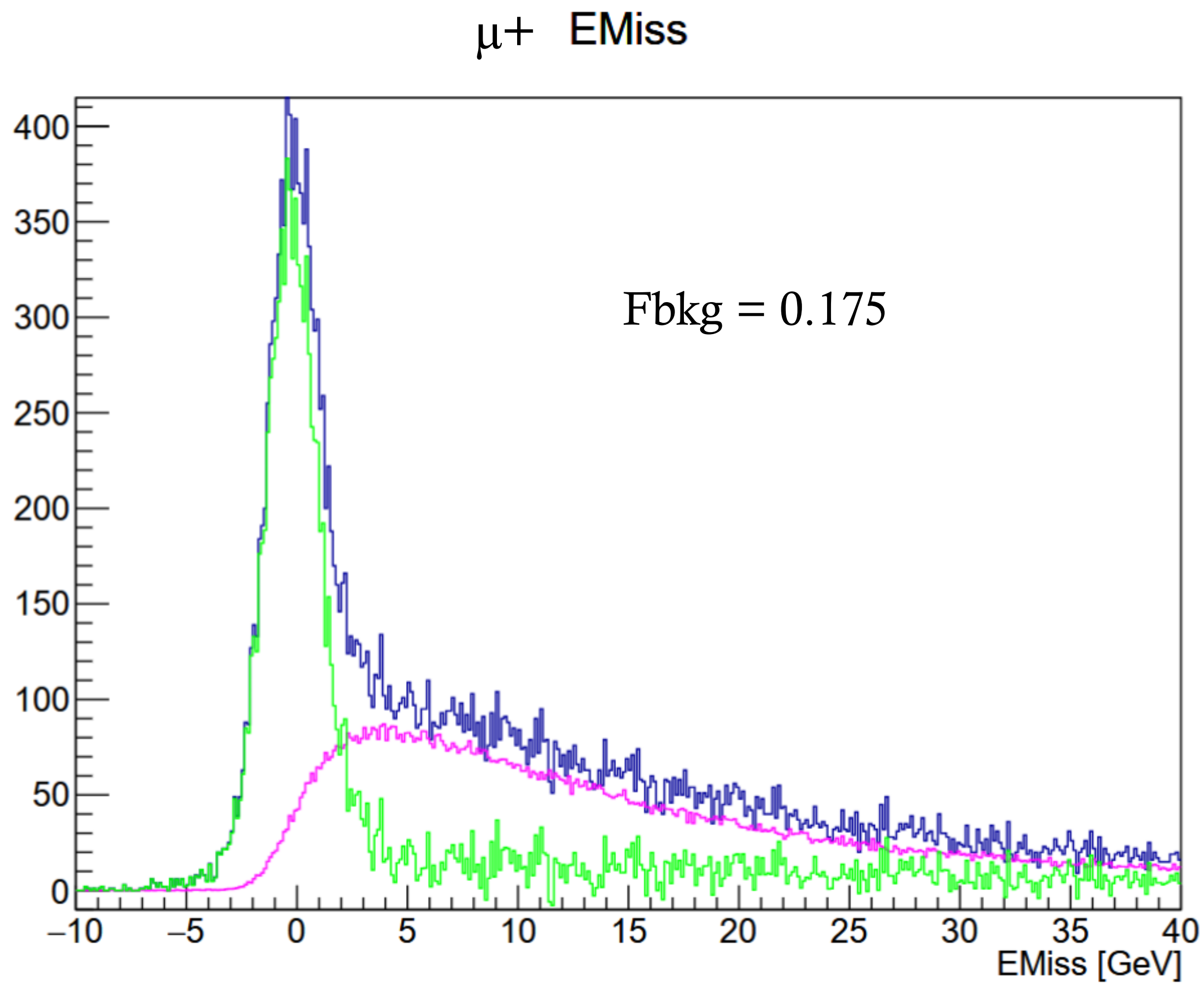


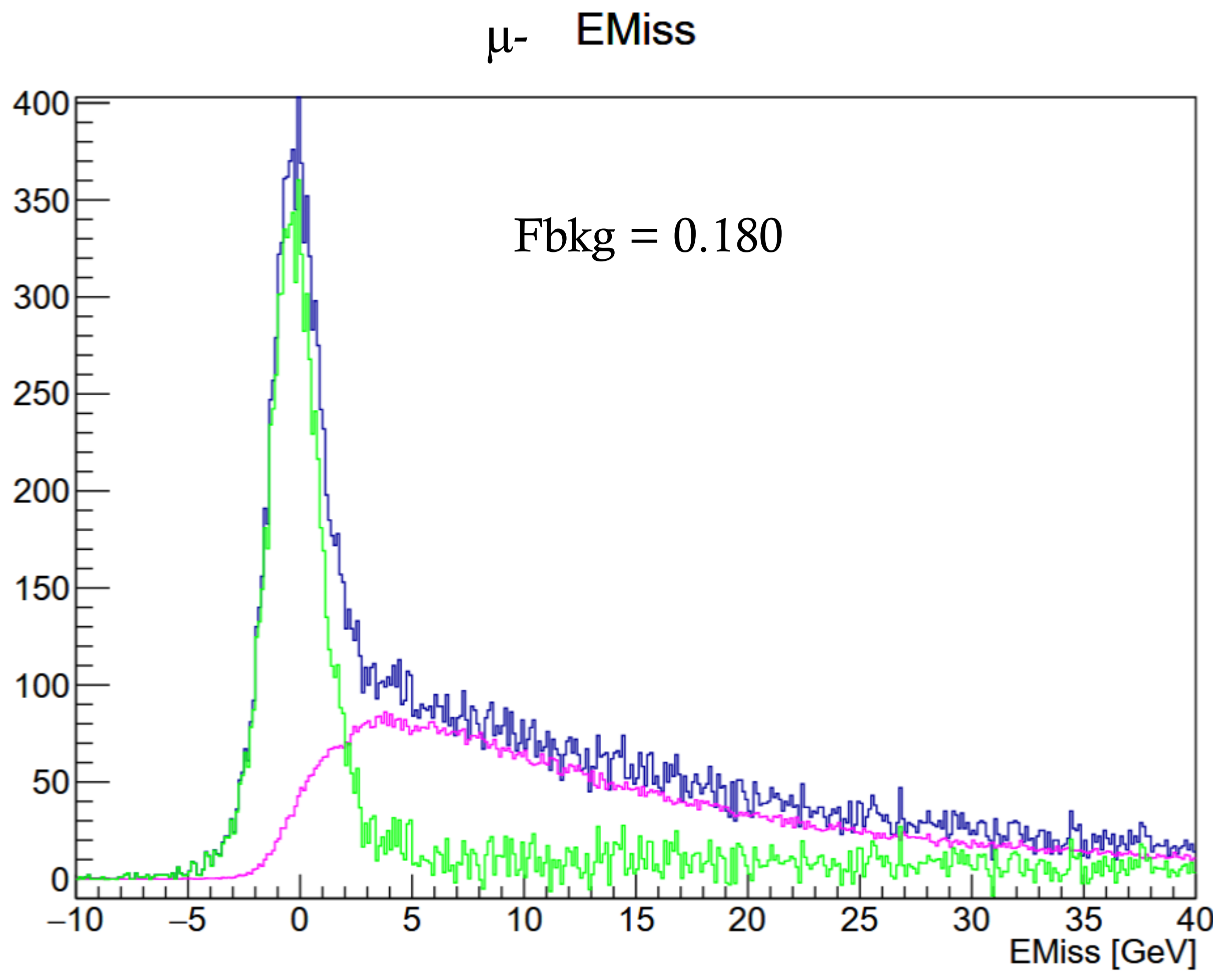
Data

Lepto

EMiss per Muon Beam Opposite Charge Hadron Events

Fbg is in the region
–2.5 < Emiss < 2.5





Data

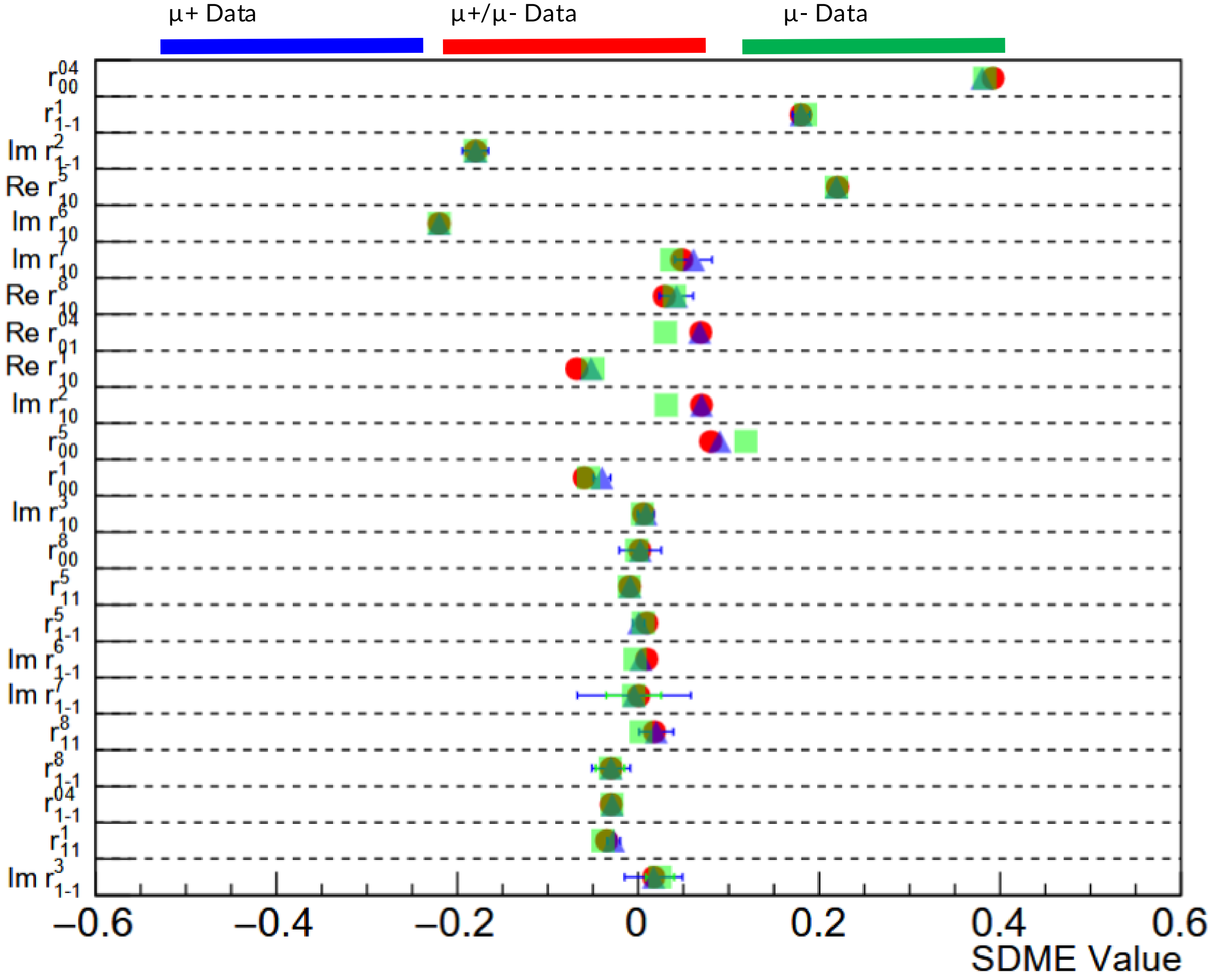
Lepto

Data - Lepto

Fractional Background and SDME for Muon Beam

Fbg is in the region
–2.5 < Emiss < 2.5

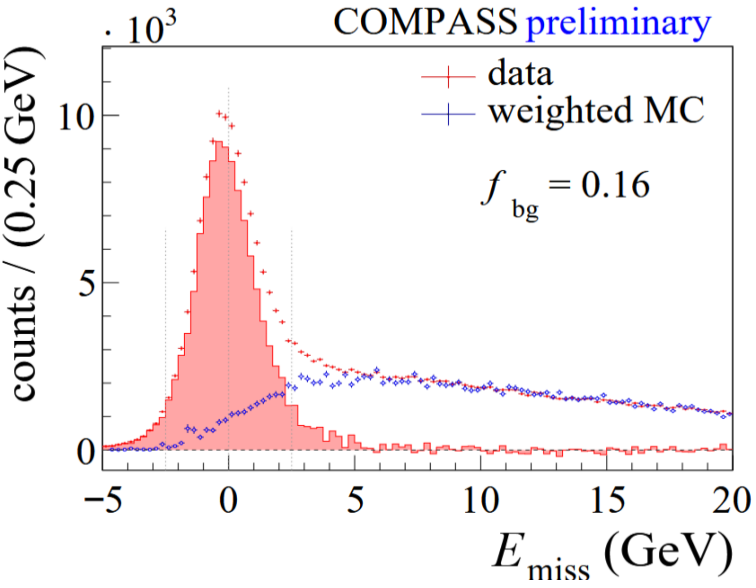
μ+	μ-	|Diff(μ+,μ-)|	Combined
0.175	0.180	0.005	0.198

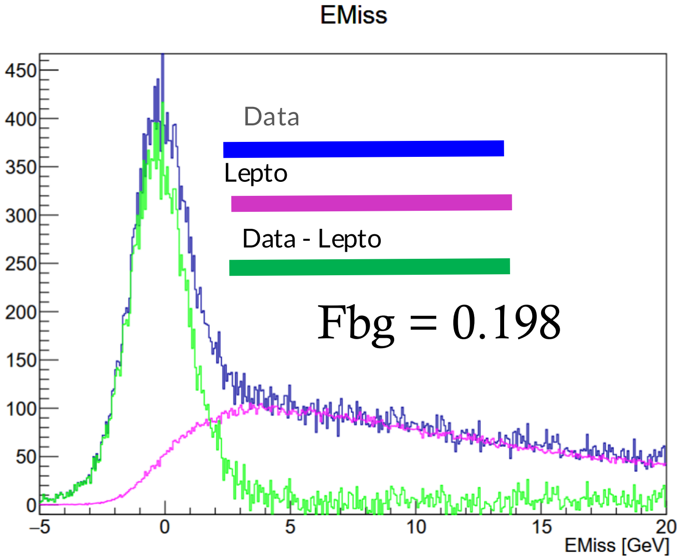


Background is subtracted for all three cases

CROSS CHECK

CROSS CHECK WITH BAKUR





Bakur's Data

```
RD: mu^+- beam, h+- data

bin               N(RD)
Q2 [1.0;1.3]      12444
Q2 [1.3;2.0]      13600
Q2 [2.0;4.0]      10319
Q2 [4.0;10.0]     4341
total: 40704
```

Nick's Data

RD h+-:
Q2 bin 1:16231
Q2bin 2: 18084
Q2bin 3: 14192
Q2 bin4: 6696
total N: 55203
total B: 40704

A large difference between the data, LEPTO and HEPGEN. Further investigation into each cut needed

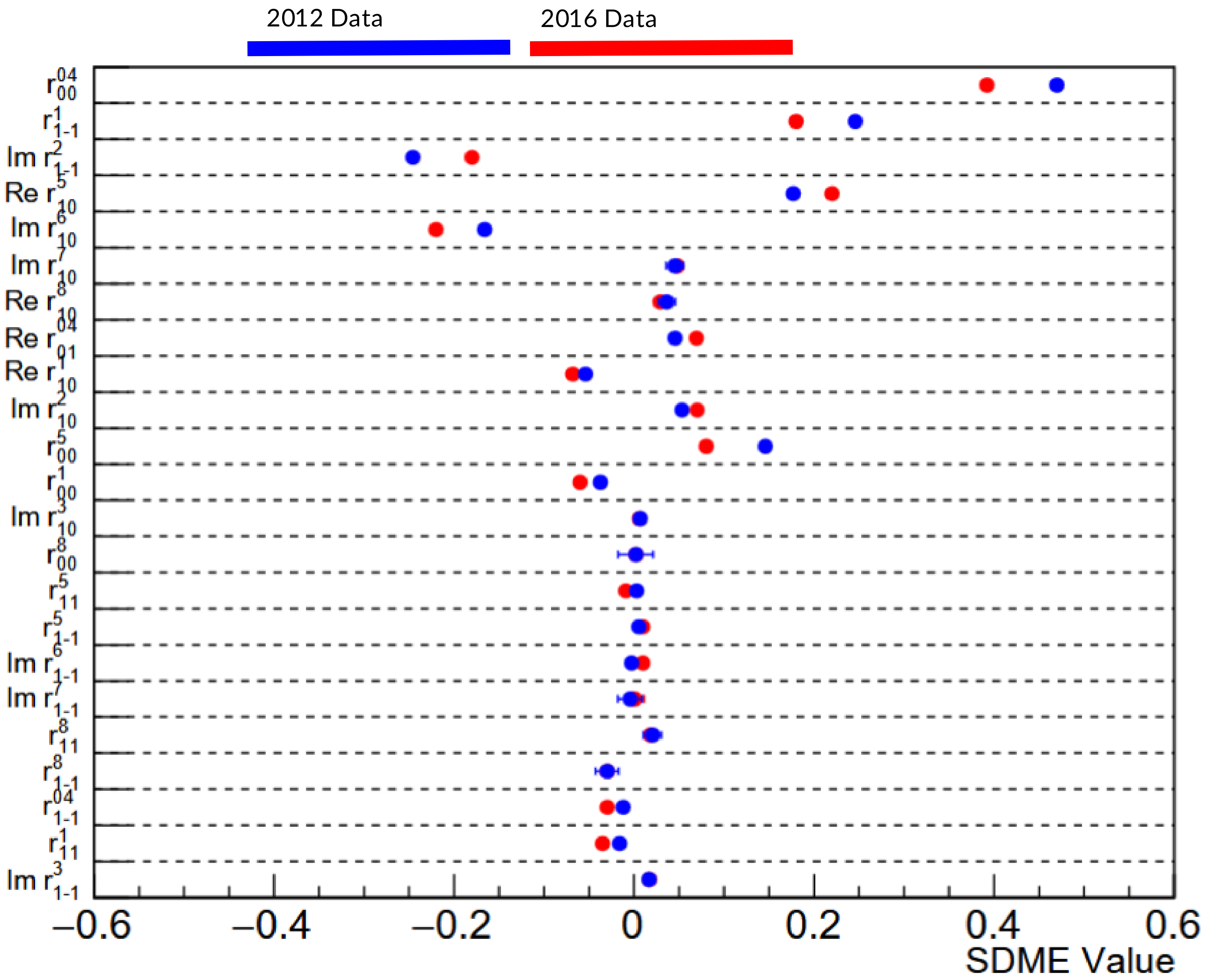
CROSS CHECK WITH BAKUR- RUN275515

- Ran with microDST
    - First few cuts are redundant
- Bakur is away this week still waiting on his values

Cut	Nick's Count	Bakur's Count	Nick/Bakur
Total Events	14331	1	14331
Events with Primary Vertex	14331	1	14331
Beam Measured before Target	14331	1	14331
Beam Momentum	14331	1	14331
Beam Momentum Error	14331	1	14331
Deteceted by BMS	14331	1	14331
Deteceted by SCIFI	14330	1	14330
Detected by SI	14330	1	14330
Beam Crosses Full length of target	12634	1	12634
beam track meantime	6674	1	6674
beam track spills	5890	1	5890
vertex is in target	7655	1	7655
Phyiscs Triggers	5445	1	5445
Scattered Muon Pass Hodoscope	4652	1	4652
Scattered Muon has same charge	4652	1	4652
first and last scattered muon z coord. are measured before and after SM1	4648	1	4648
Tracks have three outgoing particles	618	1	618
Penetration length of Hadron	524	1	524
Hadrons tracks have good quality of fit	510	1	510
The track of the hadron is before the first magnet	508	1	508
Hadrons have opposite charge	364	1	364
W Cut	321	1	321
y Cut	305	1	305
Q2 Cut	238	1	238
nu Cut	236	1	236
pt2 Cut	182	1	182
Mrho0 Cut	92	1	92
Emiss Cut	22	1	22
Mom_rho Cut	22	1	22

SPIN DENSITY MATRIX ELEMENTS

SDME EXTRACTION



COMPASS 2012

SDME	
r^{04}_{00}	$0.4698 \pm 0.0035 \pm 0.0220$
r^{1}_{1-1}	$0.2457 \pm 0.0037 \pm 0.0064$
$\mathrm{Im}\, r^{2}_{1-1}$	$-0.2459 \pm 0.0038 \pm 0.0049$
$\mathrm{Re}\, r^{5}_{10}$	$0.1769 \pm 0.0015 \pm 0.0041$
$\mathrm{Im}\, r^{6}_{10}$	$-0.1662 \pm 0.0014 \pm 0.0040$
$\mathrm{Im}\, r^{7}_{10}$	$0.0453 \pm 0.0096 \pm 0.0156$
$\mathrm{Re}\, r^{8}_{10}$	$0.0362 \pm 0.0095 \pm 0.0121$
$\mathrm{Re}\, r^{04}_{10}$	$0.0454 \pm 0.0021 \pm 0.0058$
$\mathrm{Re}\, r^{1}_{10}$	$-0.0539 \pm 0.0029 \pm 0.0040$
$\mathrm{Im}\, r^{2}_{10}$	$0.0532 \pm 0.0028 \pm 0.0043$
r^{5}_{00}	$0.1456 \pm 0.0033 \pm 0.0129$
r^{1}_{00}	$-0.0376 \pm 0.0062 \pm 0.0114$
$\mathrm{Im}\, r^{3}_{10}$	$0.0067 \pm 0.0067 \pm 0.0045$
r^{8}_{00}	$0.0019 \pm 0.0194 \pm 0.0253$
r^{5}_{11}	$0.0027 \pm 0.0016 \pm 0.0025$
r^{5}_{1-1}	$0.0050 \pm 0.0020 \pm 0.0025$
$\mathrm{Im}\, r^{6}_{1-1}$	$-0.0028 \pm 0.0020 \pm 0.0019$
$\mathrm{Im}\, r^{7}_{1-1}$	$-0.0045 \pm 0.0134 \pm 0.0224$
r^{8}_{11}	$0.0203 \pm 0.0101 \pm 0.0305$
r^{8}_{1-1}	$-0.0300 \pm 0.0128 \pm 0.0091$
r^{04}_{1-1}	$-0.0120 \pm 0.0027 \pm 0.0032$
r^{1}_{11}	$-0.0162 \pm 0.0032 \pm 0.0037$
$\mathrm{Im}\, r^{3}_{1-1}$	$0.0163 \pm 0.0085 \pm 0.0043$