

Measurement of the muon flux for the SHiP experiment in intermediate field settings

W.F. Leung¹

Abstract

We report the results of the measurement of the muon flux emanating from the SHiP target at the CERN SPS. A replica of the SHiP target followed by a 2.4 m iron hadron absorber was installed in the H4 400 GeV/c proton beamline. To measure the momentum spectrum, a spectrometer consisting of drift tubes and resistive plate chambers (RPCs) was placed around the Goliath magnet. The amount of accumulated data allows us to make a validation of the results from our Pythia and Geant4 based Monte Carlo (FairShip). This analysis is a follow up of the full field inclusive muon flux analysis [1]. It contains the analysis of the data taken with intermediate magnetic field, corresponding to 1.950×10^{10} protons on target (POT).

¹*European Organization for Nuclear Research (CERN), Geneva, Switzerland*

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1 Introduction

This report is a follow up of the muon flux analysis which analyses the experimental data obtained in the intermediate field settings and compares it to the Monte Carlo simulations. For the details of the experimental setup, calibration and reconstruction procedures, these can be found in the muon flux analysis note. [1] The goal is to compare the momentum distributions of the muons emanating from the target obtained from the experiment and the Monte Carlo simulations to see whether the simulations accurately describes what is observed in the experiment. The validity of the Monte Carlo simulation was also checked by comparing the acceptance ratios between the distributions in the nominal and intermediate field settings.

2 Experimental data

1365 spills were recorded corresponding to 1.90×10^{10} not normalised, raw SC01 counts. The relevant runs were 2383, 2388, 2392, 2395 and 2396. This set of data was taken with the intermediate field settings of the Goliath magnet, where GOLIATH and DAVID currents are 2400 A and 1166 A respectively. This setting has a maximum field of around 1.15 T, compared with that of the nominal field setting, 1.5 T. The field maps were measured by the CERN EN-EA and EP-DT groups. [2]

The number of POT for the experiment was calculated from the number of POT/ μ -event with at least one muon reconstructed, which was found to be 625 ± 15 for events with the intermediate field. [3] The number of events with at least a reconstructed track is counted to be 31205773, which gives a POT of 1.950×10^{10} .

3 Monte Carlo data

A large sample of muons was generated with the same procedures carried out in the analysis of the data with the nominal field settings, [1] where Pythia6, Pythia8 and GEANT4 were involved in the simulation under FairShip. An energy cut of 1 GeV on the kinetic energies of the emerging particles is used in the simulation. The full distribution was obtained by first removing charm contributions from the mbias data set, then combining it with the charm data set generated by Pythia6 with appropriate weights. Contributions from beauty flavour production is neglected as they are very small when compared to the rest of the data sets. The number of POT for each data set is summarised in Table 1.

Table 1: The numbers of POT for each Monte Carlo distribution.

Type of data	POT
mbias	1.806×10^9
charm	1.021×10^{10}

4 Results

The reconstructed momentum distributions p and p_T of the experimental and Monte Carlo data were compared. In the Monte Carlo simulation, the muons are produced from a combination of physical processes, including decays of pions, kaons and charmed particles, low mass resonances decaying into two muons, and other rare processes. There are also muons from these physical processes produced when particles pass through the materials. There is no attempt in disentangling these effects from the experimental data.

Similar to the analysis in the nominal field settings, the main purpose is to validate the Monte Carlo simulations for the muon background estimation or the SHiP experiment. The comparison is restricted to the same limit used in the analysis in the nominal field settings, $5 \text{ GeV}/c < p < 300 \text{ GeV}/c$ and $p_T < 4 \text{ GeV}/c$. Only tracks matched to RPC with $\chi^2 < 0.9$ are considered.

Figures 1 and 2 show the p and p_T distributions of tracks tagged by the RPCs. The distributions are normalised to their respective number of POT. For the Monte Carlo data, contributions from individual processes are also shown.

Figure 3 shows the p_T distributions in slices of p . Table 2 shows a numerical comparison of the number of tracks in the different momentum bins for both nominal and intermediate fields. RPC matching was not required for the $5 - 10 \text{ GeV}/c$ momentum bin to enable correct comparison with the nominal field data.

Figure 4 shows the ratio of number of tracks from the experiment to that of the Monte Carlo.

Figure 5 shows the muon phase space distribution in the experimental data.

4.1 Acceptance Ratio

Another way to test whether the Monte Carlo simulations are reliable is to compare the acceptance ratios obtained from the experiment and from Monte Carlo, defined by $N_{\text{nominal}}/N_{\text{inter}}$. The results are shown in Figure 6. The means of the acceptance ratios from the experiment and the simulation were found to be $(97.66 \pm 0.07)\%$ and $(100.02 \pm 0.32\%)$ respectively in the range $5 \text{ GeV}/c < p < 120 \text{ GeV}/c$.

Some muons would have been swept out of the detector volume when they passed through the magnet. As the Larmor radius is given by $r = p_{\perp}/qB$, the muons are deflected more in stronger fields and therefore have a higher chance of being deflected out of the detector volume. This is best illustrated in the low momentum region of the distributions shown in Figure 7, where there are less number of mouns recorded in the nominal field setting. Also, there should not be a difference between the momentum distributions in the high momentum region, as the muons are much less likely to be deflected away. Therefore it is expected that the acceptance ratio to be 1 in the high momentum region, and this is agreed in the Monte Carlo simulation. The acceptance ratio from the experiment is within the normalisation error of 3.2% which is caused by the error in the number of POT estimated.

By scaling both distributions such that they both have a mean of 1 in the high

Table 2: Number of reconstructed tracks in different momentum bins per 10^9 POT per GeV/c for the experiment and the MC in both field settings. For the experiment, the uncertainties are mostly dominated by the POT normalization, which are 2.1% and 2.4% for nominal and intermediate fields respectively. For the MC, the main uncertainty is due to a different reconstruction efficiency in the MC compared to the experiment, 3.3%.

Nominal field			
Interval	experiment	MC	ratio
5 – 10 GeV/c	$(1.13 \pm 0.02) \times 10^5$	$(1.12 \pm 0.03) \times 10^5$	1.01 ± 0.04
10 – 25 GeV/c	$(2.40 \pm 0.05) \times 10^4$	$(1.85 \pm 0.06) \times 10^4$	1.29 ± 0.05
25 – 50 GeV/c	$(4.80 \pm 0.10) \times 10^3$	$(3.76 \pm 0.11) \times 10^3$	1.28 ± 0.05
50 – 75 GeV/c	$(9.83 \pm 0.2) \times 10^2$	$(8.0 \pm 0.2) \times 10^2$	1.23 ± 0.05
75 – 100 GeV/c	$(2.95 \pm 0.06) \times 10^2$	$(2.5 \pm 0.08) \times 10^2$	1.20 ± 0.05
100 – 125 GeV/c	$(1.1 \pm 0.02) \times 10^2$	$(0.9 \pm 0.03) \times 10^2$	1.14 ± 0.05
125 – 150 GeV/c	21.0 ± 0.4	20.1 ± 7.5	1.04 ± 0.04
150 – 200 GeV/c	6.4 ± 0.1	6.6 ± 0.3	0.96 ± 0.04
200 – 250 GeV/c	0.76 ± 0.02	0.88 ± 0.06	0.86 ± 0.06
250 – 300 GeV/c	0.26 ± 0.01	0.26 ± 0.03	0.97 ± 0.11
Intermediate field			
Interval	experiment	MC	ratio
5 – 10 GeV/c	$(1.12 \pm 0.03) \times 10^5$	$(6.81 \pm 0.22) \times 10^4$	1.65 ± 0.07
10 – 25 GeV/c	$(2.53 \pm 0.06) \times 10^4$	$(1.74 \pm 0.06) \times 10^4$	1.46 ± 0.06
25 – 50 GeV/c	$(4.85 \pm 0.12) \times 10^3$	$(3.62 \pm 0.12) \times 10^3$	1.34 ± 0.06
50 – 75 GeV/c	$(9.90 \pm 0.24) \times 10^2$	$(7.91 \pm 0.26) \times 10^2$	1.25 ± 0.05
75 – 100 GeV/c	$(2.98 \pm 0.07) \times 10^2$	$(2.44 \pm 0.08) \times 10^2$	1.22 ± 0.05
100 – 125 GeV/c	$(1.07 \pm 0.03) \times 10^2$	91.1 ± 3.3	1.17 ± 0.05
125 – 150 GeV/c	42.8 ± 1.07	40.2 ± 1.6	1.07 ± 0.05
150 – 200 GeV/c	14.0 ± 0.36	13.3 ± 0.6	1.06 ± 0.05
200 – 250 GeV/c	4.05 ± 0.12	3.71 ± 0.23	1.09 ± 0.08
250 – 300 GeV/c	1.71 ± 0.06	1.14 ± 0.12	1.49 ± 0.16

momentum region, the acceptance ratios can be compared. This comparison is shown in Figure 8 before and after the correction. In fact, it can be seen that the acceptance ratios obtained from the experiment and the Monte Carlo simulations are very similar after the correction.

5 Conclusions

The momentum distribution of the muon flux emerging from the replica of the SHiP target has been measured with the intermediate field settings of Goliath magnet. The Monte Carlo simulation has once again been validated. In particular, the Monte Carlo simulation correctly describes the drop in the acceptance ratio between the two field

settings in the low momentum regime. The data collected in the intermediate field settings has some 20% – 50% difference observed between the experimental measurements and the simulations.

References

- [1] C. Ahdida et al., *Measurement of the muon flux for the SHiP experiment*, CERN-SHiP-NOTE-2019-003, June 2020.
- [2] M. Rosenthal et al., *Magnetic Field Measurements of the GOLIATH Magnet in EHN1*, CERN-ACC-NOTE-2018-0028, March 2018.
- [3] H. Dijkstra, *Normalization of proton flux during muon flux beam test*, CERN-SHiP-INT-2019-001, April 2019.

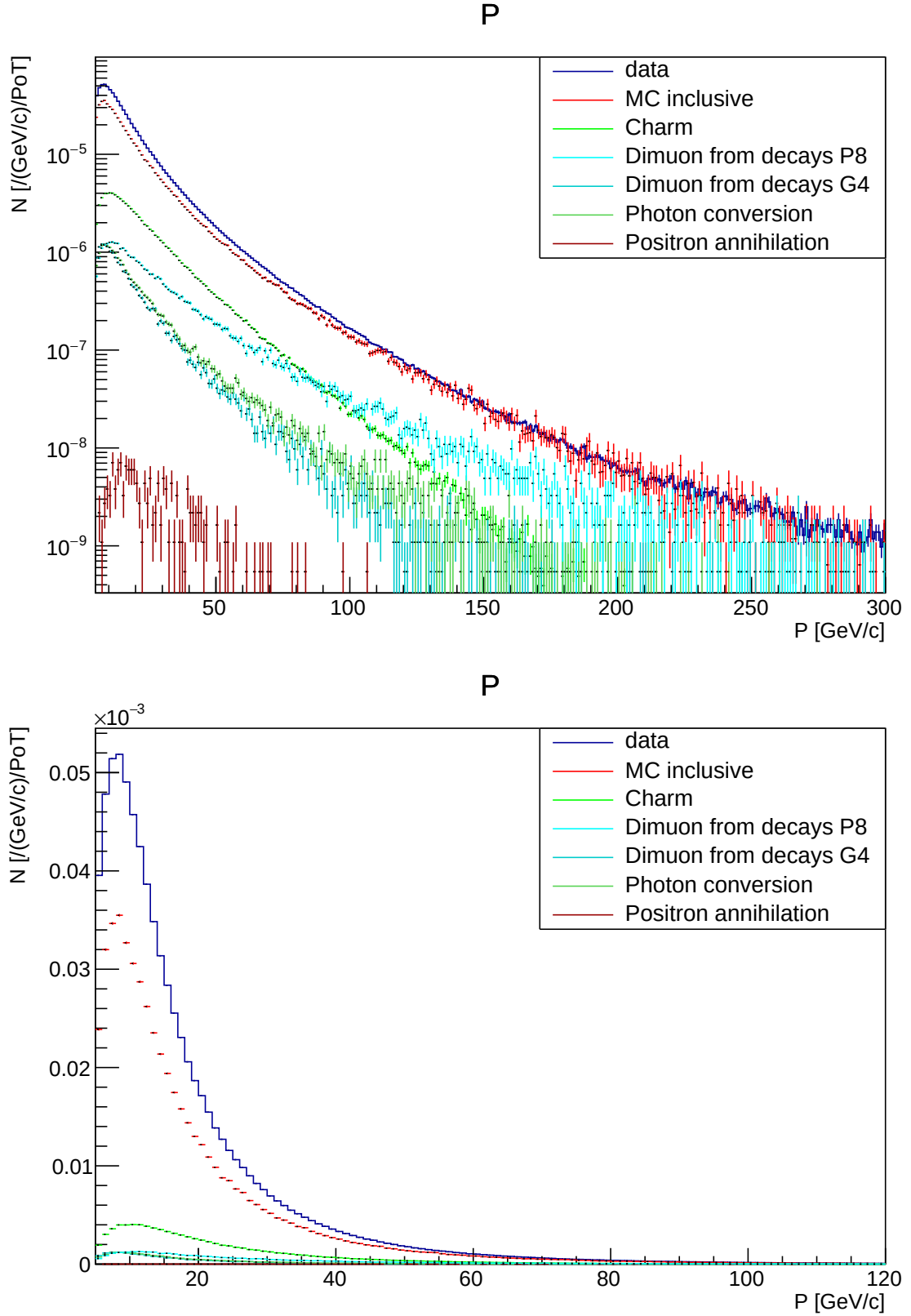


Figure 1: Momentum distributions from data and MC, top full range in log scale, bottom detail of the low momentum range with a linear scale. The distributions are normalized to the number of POT. For MC data, some individual sources are highlighted, muons from charm (green), from dimuon decays of low mass resonances in Pythia8 (cyan), in Geant4 (turquoise), photon conversion (dark green) and positron annihilation (brown).

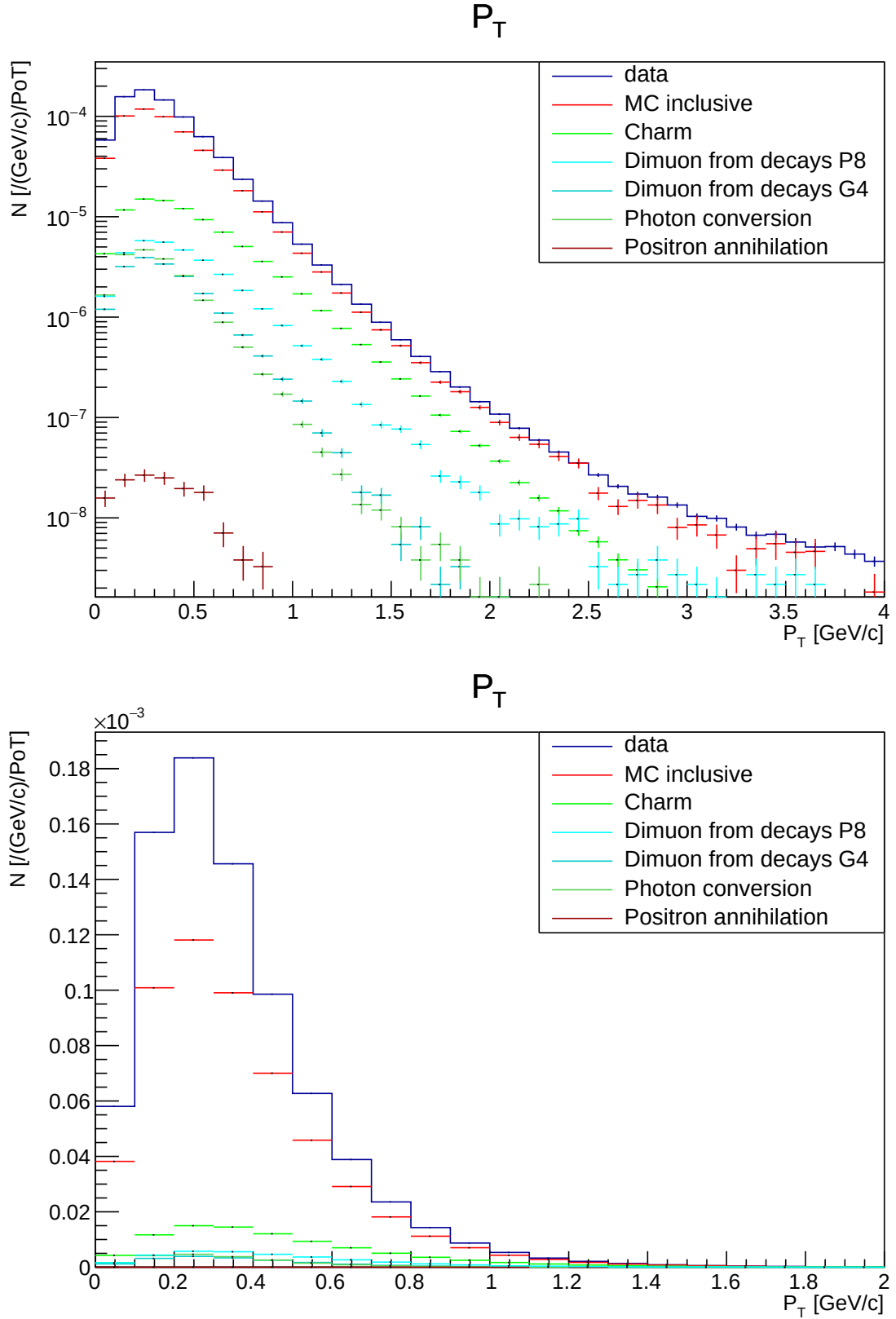
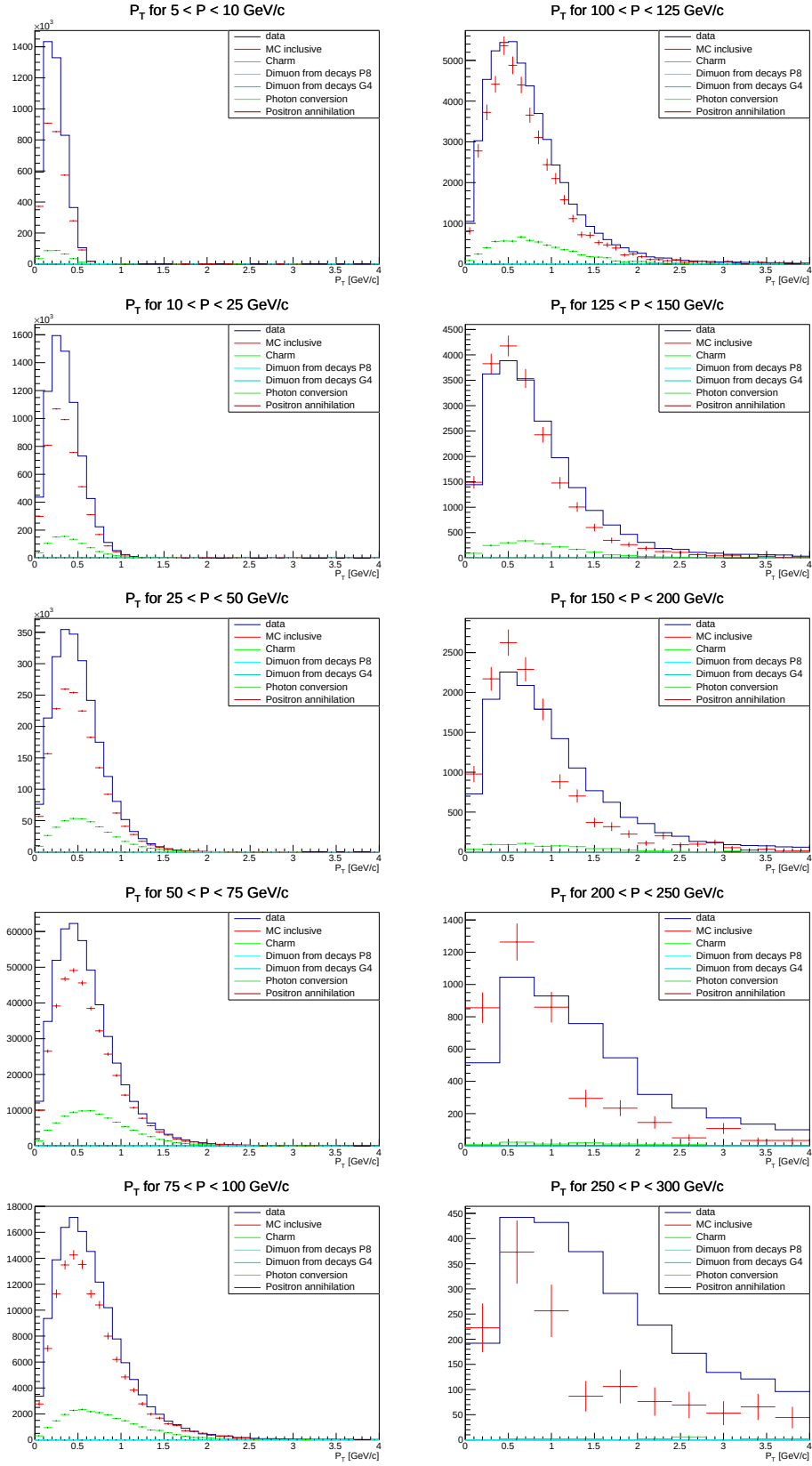


Figure 2: Transverse momentum distributions from data and MC, top full range in log scale, bottom detail of lower transverse momentum with a linear scale. The distributions are normalized to the number of POT. For MC data, some individual sources are highlighted, muons from charm (green), from dimuon decays of low mass resonances in Pythia8 (cyan), in Geant4 (turquoise), photon conversion (dark green) and positron annihilation (brown).

Figure 3: p_T distributions in slices of p for data and MC.

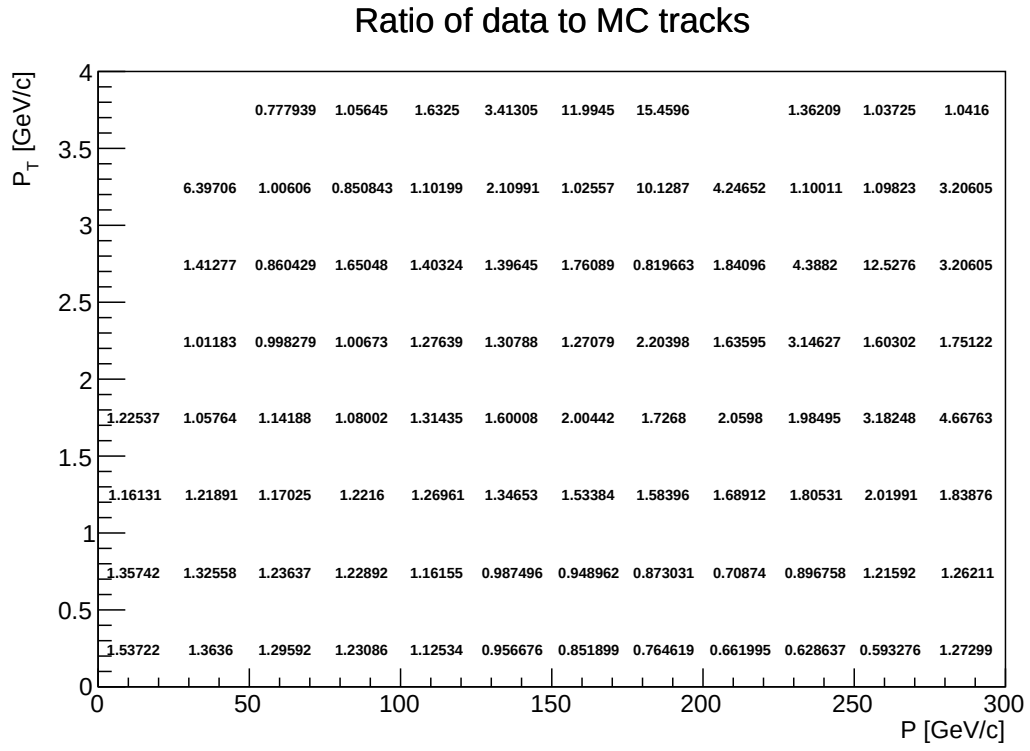


Figure 4: Ratio of data to MC tracks, $R = \frac{N_{data}}{N_{MC}}$ in bins of p and p_T .

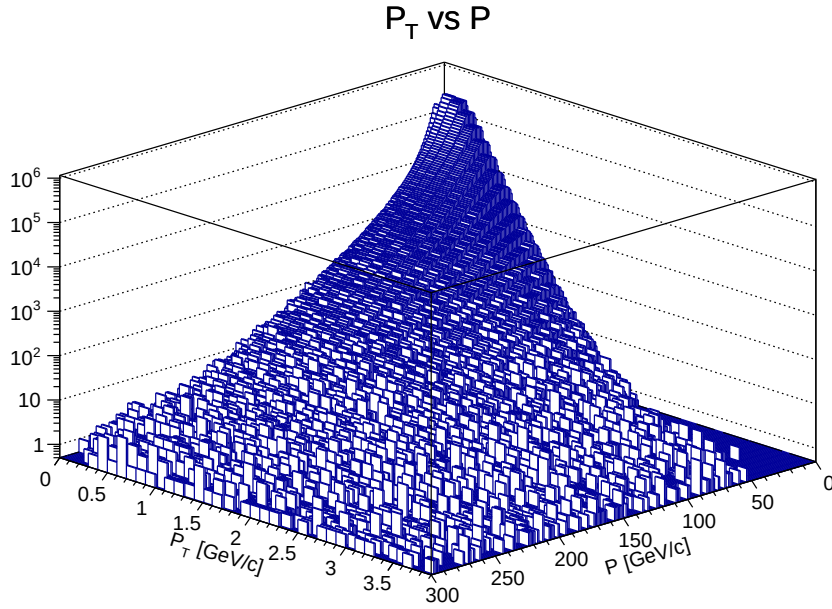


Figure 5: p_T vs p for data.

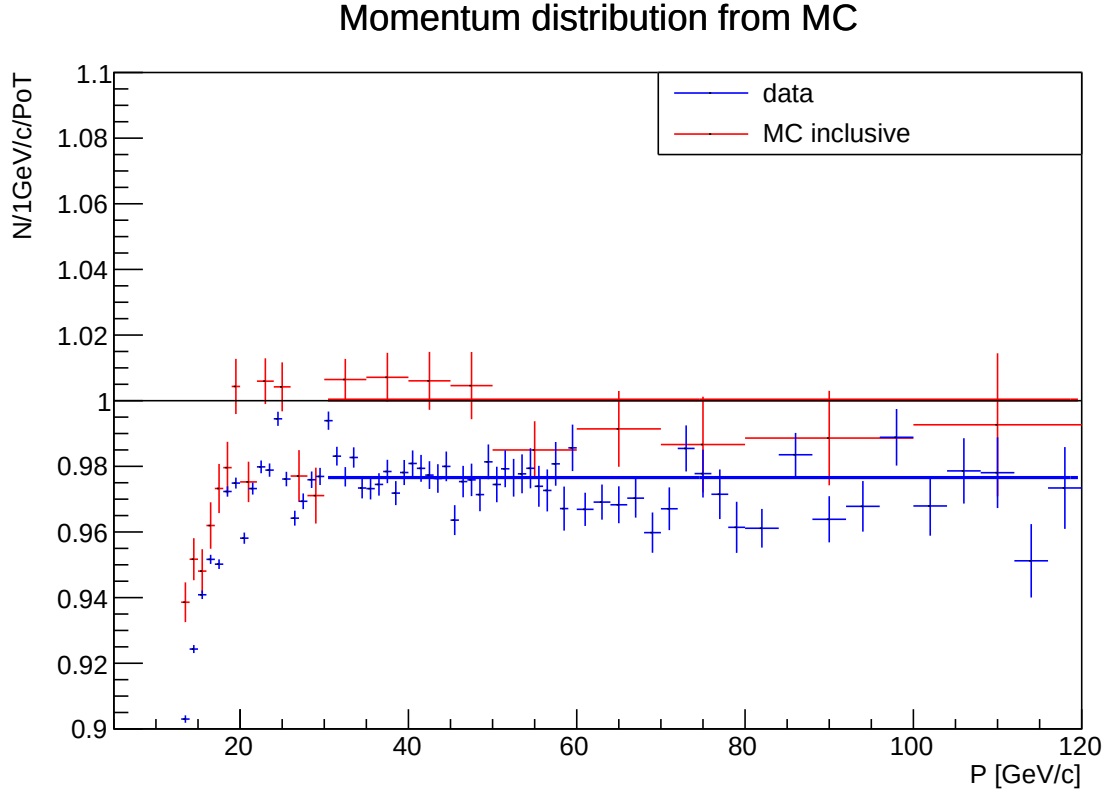


Figure 6: Acceptance ratios between momentum distributions obtained from dividing the number density in the nominal field by the number density in the intermediate field in the range $5 \text{ GeV} < p < 120 \text{ GeV}$. The means of the acceptance for $30 \text{ GeV}/c < p < 120 \text{ GeV}/c$ were $(97.66 \pm 0.07)\%$ and $(100.02 \pm 0.32\%)$ for the experiment and Monte Carlo respectively, drawn as horizontal lines. Ratios from experiments are blue and Monte Carlo are red.

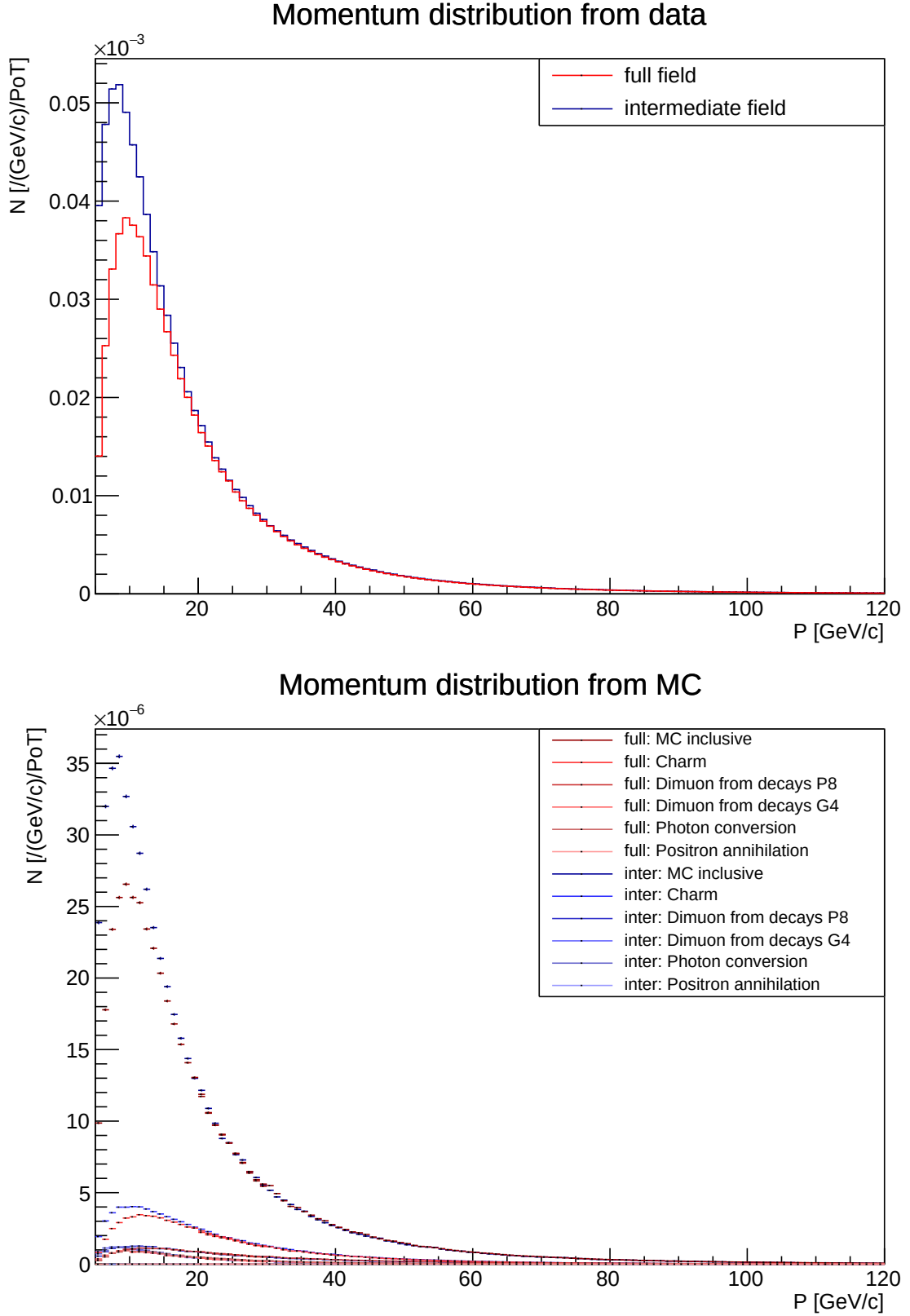


Figure 7: Comparison of momentum distributions from the nominal (red) and intermediate (blue) field settings. The top figure shows the distributions obtained from experiments and the bottom figure shows the distributions obtained from Monte Carlo simulations and its contributions. They are normalised with their respective POTs.

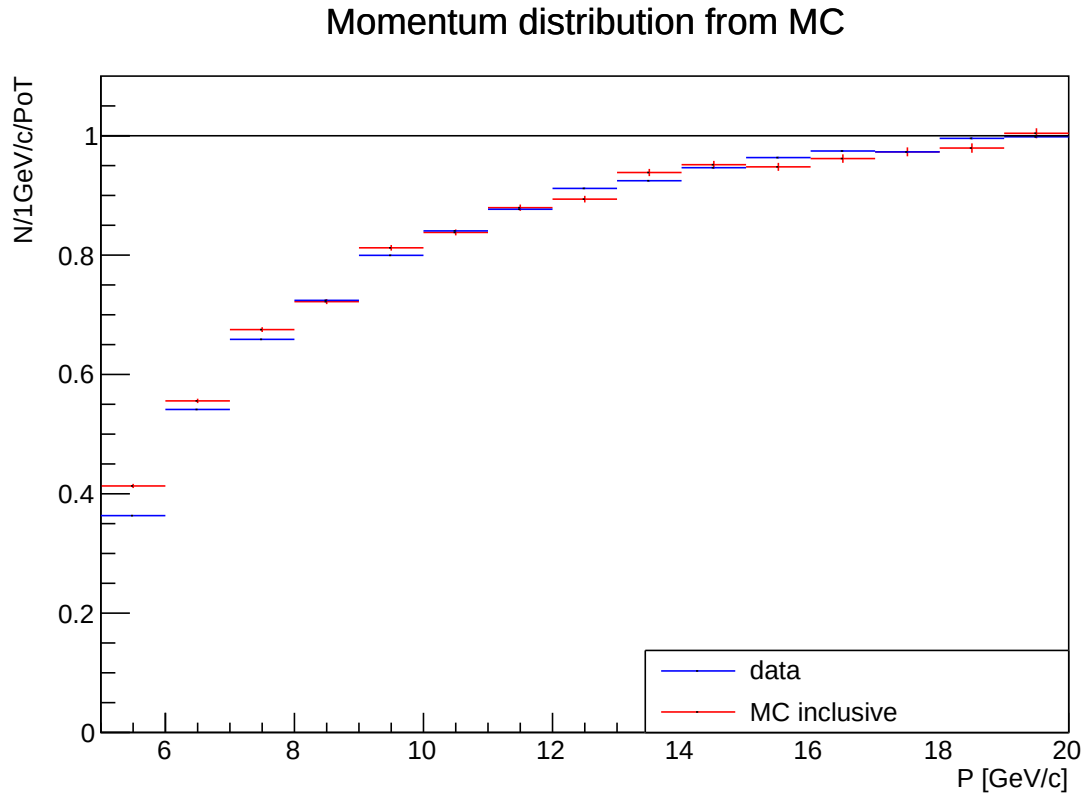
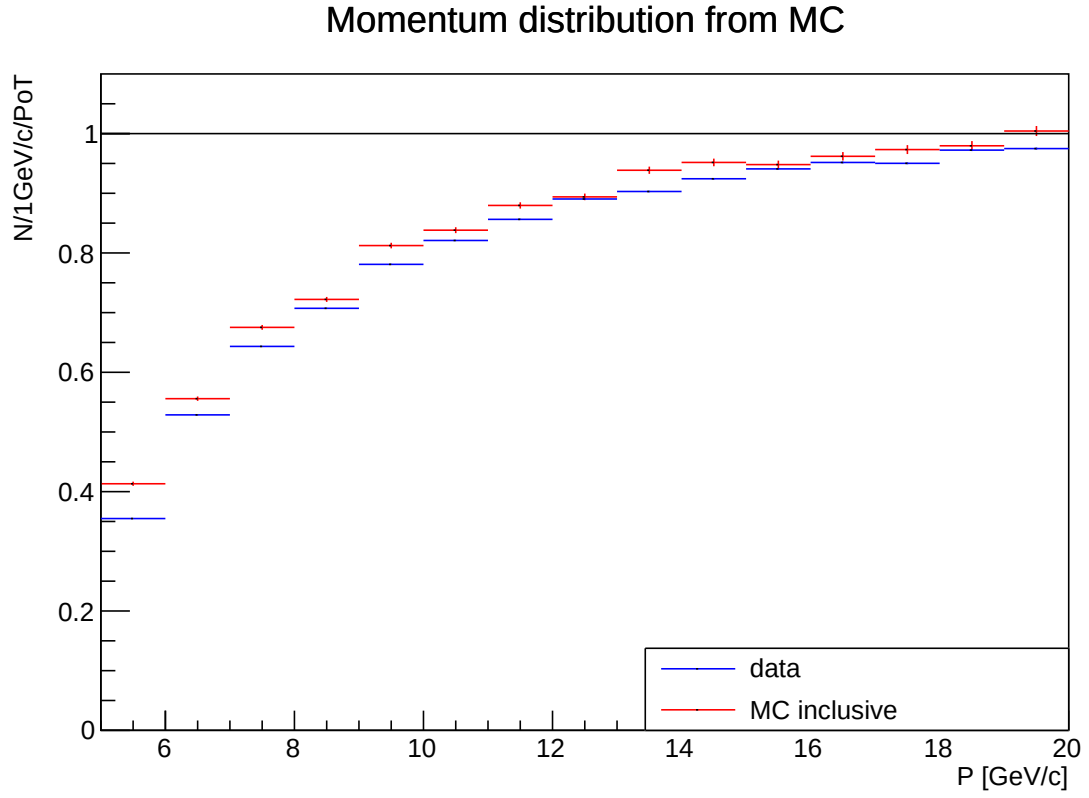


Figure 8: The plots show the acceptance ratios for $5 \text{ GeV}/c < p < 20 \text{ GeV}/c$, where the top plot is uncorrected and the bottom plot has both distributions scaled such that their means are 1 in the high momentum region. Ratios from experiments are blue and Monte Carlo are red.