Pentaquark searches with ALICE

Summer Student Report

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Project Description

In this report we present the results of the data analysis for searching for possible invariant mass signals from pentaquarks in the ALICE data. Analysis was based on filtered data from real p-Pb events at $\sqrt{s_{NN}}$=5.02 TeV collected in 2013. The motivation for this project was the recent discovery of pentaquark states by the LHCb collaboration (c$\bar{c}$uud resonance P_c^+) [1]. The search for similar not yet observed pentaquarks is an interesting research topic [2]. In this analysis we searched for a s$\bar{s}$uud pentaquark resonance P_s^+ and its possible decay channel to ϕ meson and proton. The ALICE detector is well suited for the search of certain candidates thanks to its low material budget and strong PID capabilities. Additionally we might expect the production of such particles in ALICE as in heavy-ion and proton-ion collisions the thermal models describes well the particle yields and ratios [3]. Therefore it is reasonable to expect other species of hadrons, including also possible pentaquarks, to be produced with a rate predictable through the thermal model. To achieve the main goal of this project we firstly had to complete the intermediate objectives. After the precise check of the quality of the filtered data used we reconstructed the invariant mass for the ϕ mesons through their decay to two charged kaons K^+ and K^- (branching ratio 48.9%). To determine the combinatorial background of uncorrelated pairs we studied three different methods, namely the like-sign method, the event-mixing technique and the multiple-rotations option. After that we reconstructed an invariant mass distribution for proton and ϕ meson and we compared it with the reconstructed invariant mass for proton and side bands of the ϕ meson peak. At the end we outlined the next steps for this analysis, which should be achieved in the near future.

1 Data Selection

The data used in this analysis are obtained from a sample of the data collected during the LHC p-Pb run at $\sqrt{s_{NN}}$=5.02 TeV in 2013. In total, 25 good runs were selected for this analysis.

2 Track Selection

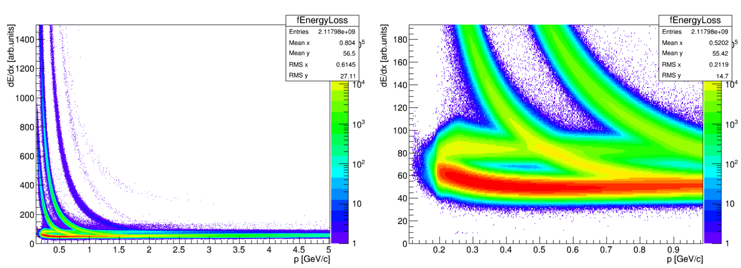
For the track selection we used the ITS and TPC recommended cut set for this data taking period. The applied cuts were:

$0.2 < p_T < 10.0$ GeV/c
pseudorapidity $|\eta| < 0.8$
$|\chi^2/ndf| < 4$
Number of TPC clusters > 70
Number of ITS clusters > 1
Rejection of kink daughters
$DCA_Z < 2$ cm
$DCA_{XY} < (0.0105 + 0.0350/p_T^{1.1})$ cm

We also required both ITS and TPC refit to improve the quality of the tracks. The refitting ensures a good estimation of the track parameters and better invariant mass resolution.

3 Data Quality Check

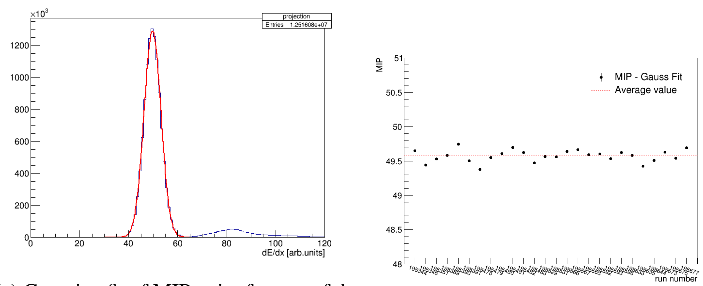
As was described in section 1, we analysed 25 runs in total. As we used filtered trees, we firstly checked if the filtering works reliably.



(a) (b)

Figure 1: Specific energy loss of charged particles in the TPC vs. particle momentum

For the TPC we looked at the energy loss distribution of the charged particles as they were detected in TPC depending on their momentum (fig.1(a)). We examined the minimum ionisation particle (MIP) position, which is calibrated to 50 for the TPC. Fig.1(b) shows the detail of TPC energy losses where the MIP occur. We determined the MIP position for single runs by fitting it with Gauss fit (fig. 2(a)). Fig. 2(b) shows the results of the MIP for the single run numbers. The dashed red line represents value averaged over all the runs. We can observe a small deviation from the calibration value but in the limits of very good performance, so that we concluded that all runs are of acceptable quality.

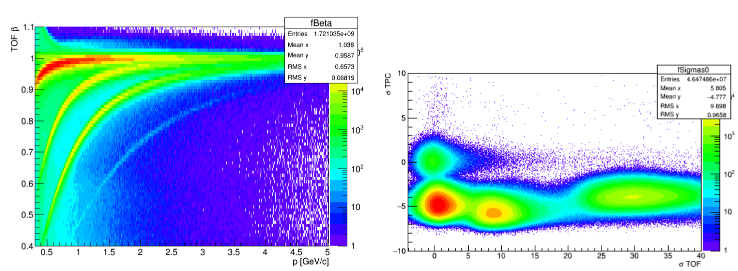


(a) Gaussian fit of MIP point for one of the runs

(b) MIP for the single runs

Figure 2

For the TOF detector we checked the measured β function (β = v/c.) as a function of particles momentum (fig. 3(a)). We also looked at the number of sigma in TPC versus number of sigma in TOF in the selected p_T region ($1.4 < p_T < 1.6$ GeV/c). Fig. 3(b) illustrates this dependence for the electrons. We can clearly see separated electrons (around the origin [0,0]) with pions below and kaons and protons more on the right. Observed results are according to the expectations so we can conclude that our filtered trees are of good quality.



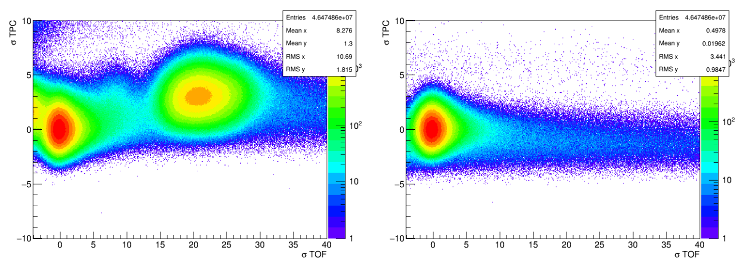
(a) β_{TOF} vs. particle momentum

(b) # σ_{TOF} vs. # σ_{TPC} for electrons

Figure 3

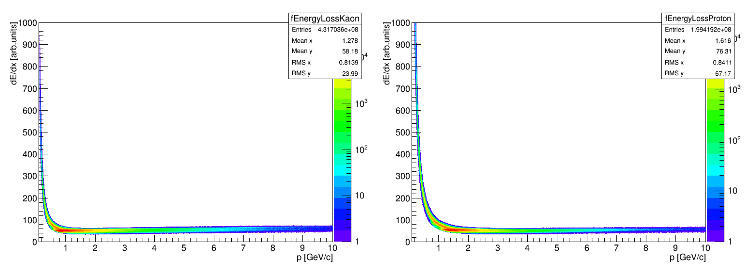
4 PID Selection

To reconstruct the ϕ meson invariant mass through the decay to K^+ and K^- and following reconstruction of ϕp invariant mass distribution we identified the kaons and protons using the number of sigma method. We used both TOF and TPC 3 sigma cut to select the kaons and protons used in the reconstruction. The PID method thus requires that the measured energy loss is consistent with the expected energy loss within three standard deviations. Fig. 4 shows the number of σ_{TPC} vs. number of σ_{TOF} for the kaons, respectively protons. After this cut we had relatively clean PID sample, especially for the particles from the low momentum region. Fig. 5 shows the energy losses for the kaons, respectively protons, after the number of sigma cut was applied.



(a) # σ_{TOF} vs. # σ_{TPC} for kaons (b) # σ_{TOF} vs. # σ_{TPC} for protons

Figure 4



(a) Specific energy loss for selected kaons (b) Specific energy loss for selected protons

Figure 5

5 ϕ Meson Reconstruction

We constructed the invariant mass distribution of the ϕ meson using all positively charged identified kaons combined with all negatively charged identified kaons. The fitted invariant mass distribution for different p_T bins is shown in Appendix in fig.A.1.

Invariant mass distribution was fitted by combining Breit-Wigner function for signal and 2nd order polynomial for the background.

After the examination of the reconstructed distribution we could see a small peak at the beginning of the spectrum, but only in the low p_T regions ($0.6 < p_T < 1.0$ GeV/c). This is due to the contamination of electrons and positrons in our sample, mainly from photon conversions. Since the dip angle between the converted electrons,

$$\delta_{\text{dip}-\text{angle}} = cos^{-1}[\frac{p_{T1}p_{T2} + p_{z1}p_{z2}}{p_1 p_2}] \tag{1}$$

is small, we could apply a cut in the low p_T regions where the small peak was observed. We required to have $\delta_{\text{dip}-\text{angle}}$ larger then 0.04 rad.

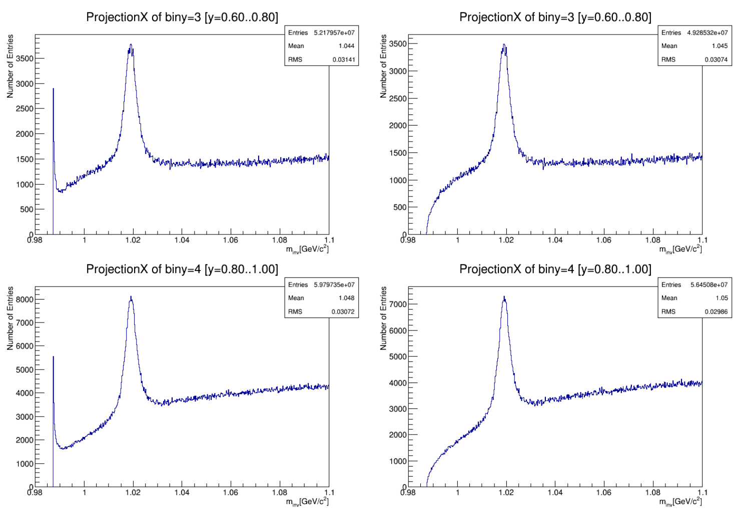


Figure 6: Invariant mass distribution of ϕ meson before (left) and after (right) δ-dip-angle cut was applied

As we can see ϕ meson signal sits above a combinatorial background which is due to the uncorrelated kaons pairs since not all charged kaons in each event originate from the phi meson decays. To determine the combinatorial background we studied three different methods which are described in the following section.

5.1 Backgroud Estimation

In this section like-sign method, event-mixing technique and multiple-rotations method for the background estimation are described. The results obtained after the combinatorial background subtraction by these methods are presented and compared. To subtract the background distribution from the signal distribution it is firstly necessary to scale it. To normalize it we scaled background distribution by the ratio of the integral of the signal and the background distribution in a mass region away from the ϕ meson peak ($1.06 < m_{inv} < 1.09 GeV/c^2$).

5.1.1 Like-Sign Method

Since for the ϕ meson signal only unlike-sign kaons are relevant, we can construct a combinatorial background distribution by combining all positively (negatively) charged kaons with all the others positively (negatively) charged kaons in the same event. In this distribution we cannot observe any signal since we combine only like-sign kaons in it. The advantage of this method is that it does not change event topology - it takes the tracks as they were detected in the detector. On the other hand we have a limited number of like sign kaons in the same event resulting in poor statistics available.

Results

Fig. 7 shows the results for the ϕ meson invariant mass distributions (blue) and scaled invariant mass distributions of like-sign kaons in same events (red) for three different p$_T$ bins (results for more p$_T$ bins can be found in Appendix, fig.A.2).

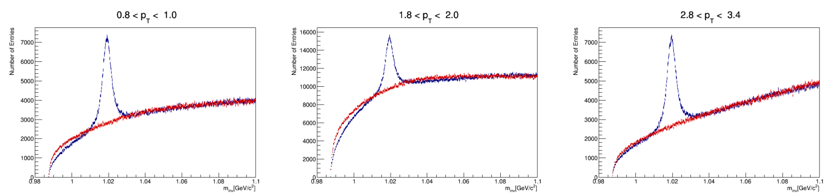


Figure 7: Comparison between signal and like-sign background distributions

This method does not reproduce the shape of the combinatorial background perfectly. That is why other methods for background estimation need to be studied and the like-sign method can be used as a cross check and comparison with the other methods.

Fig. 8 shows the fitted ϕ meson invariant mass distributions after the subtraction of like-sign background (results for more p$_T$ bins can be found in Appendix, fig.A.3).

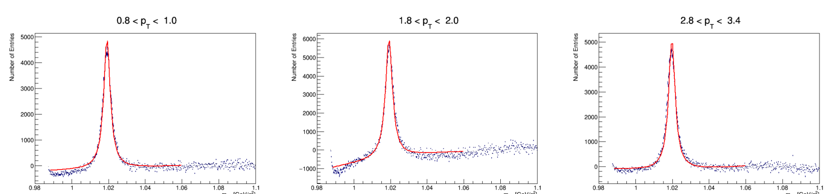


Figure 8: Fitted ϕ meson signal after the like-sign background subtraction

5.1.2 Mixed Event Technique

Another method studied for the background estimation was the mixed-event technique. In this method the correlation arising from misidentified resonances can be broken by combining tracks from different events. In this method an invariant mass distribution is constructed using all positively (negatively) charged kaons from one event with all the negatively (positively) charged kaons from another n events. In our case n=10, but in principle it can be different, but it should only be reasonably high to minimize the effect from the statistical fluctuations. Effects from the multiplicity fluctuation are minimized by dividing the events into 4 multiplicity classes. In addition to minimize the fluctuations due to the acceptance effects, within each multiplicity class the events are sub-devided into 10 bins according to z-vertex position ($|z| < 10$cm). Because the mixed events should have a similar topology, the mixing is done only for the events within the same sub-class.

Results

Fig. 9 shows the results for the ϕ meson invariant mass distributions (blue) and scaled invariant mass distributions of kaons in mixed events (red) for three different p$_T$ bins (results for more p$_T$ bins can be found in Appendix, fig.A.4).

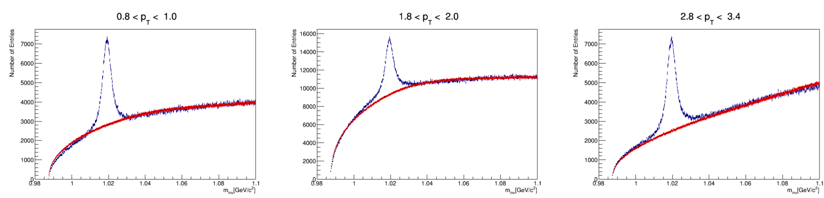


Figure 9: Comparison between signal and mixed-event background distributions

We can see that this method reproduces the shape of the combinatorial background very precisely. Mixing different events breaks the correlations arising from misidentified resonances. This method has a big advantage in that in principle we can mix an arbitrary number of events to minimize effects from statistical fluctuations in the background.

Fig. 10 shows the fitted ϕ meson invariant mass distributions after the subtraction of mixed-event background (results for more p$_T$ bins can be found in Appendix, fig.A.5).

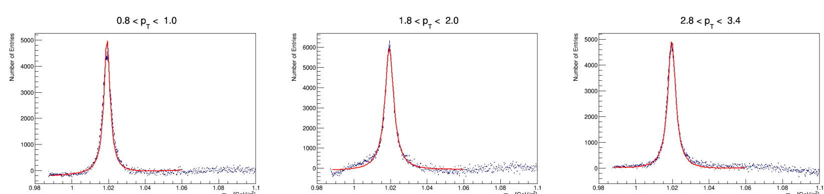


Figure 10: Fitted ϕ meson signal after the mixed-event background subtraction

5.1.3 Multiple-Rotations Method

The combinatorial background distribution can be estimated by rotating negative (positive) tracks in the detector's plane transverse to the beam direction and combining it with non rotated positive (negative) ones. This breaks the correlation between existing pairs and produces a distribution devoid of any signal. By rotating the tracks over several angles we can easily increase the statistics and have a better control over the fluctuations. The number of rotations and the actual values of the rotation angles should be chosen carefully. In this analysis we rotated tracks over 90°, 144°, 180° and also a random angle to examine the effects and behaviour of this method. For smaller rotation angles we could notice a peak from the resonance since the smaller angles do not break the correlation sufficiently. This method is not very commonly used so we tried to compare it with like-sign and mixed-event methods which are widely used for the estimation of the background.

Results

Fig. 11 shows the results for the ϕ meson invariant mass distributions (blue) and scaled invariant mass distributions of kaons where one of the two tracks is rotated (red) for three different p$_T$ bins (results for more p$_T$ bins can be found in Appendix, fig.A.6).

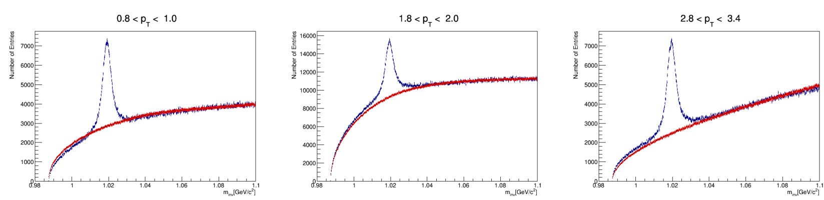


Figure 11: Comparison between signal and rotational background distributions

We can observe that results from multiple-rotations method are very similar to those from the mixed-event technique. This means that rotating one of the tracks breaks any correlations between tracks very effectively. This method can be used to significantly increase the statistics by rotating the tracks several times over different angles. Another advantage for this method in comparison with the mixed-event is that it is very simple and does not require the recalculation of the selection cut parameters. As we can see, according to the results, this method could be used at least as a cross-check for other analyses, and also for possible background estimation of the ϕp invariant mass distribution.

Fig. 12 shows fitted ϕ meson invariant mass distributions after the subtraction of rotational background (results for more p$_T$ bins can be found in Appendix, fig.A.7).

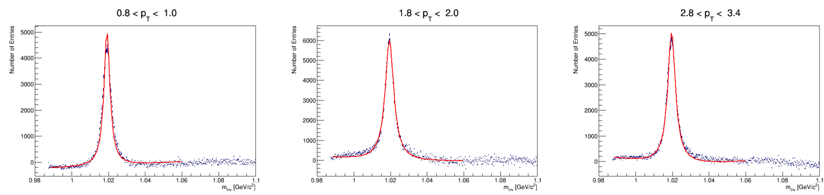


Figure 12: Fitted ϕ meson signal after the rotational background subtraction

5.1.4 Comparison of the Background Methods

All the methods we studied are comparable and give parameters for mass and widths which are compatible with the PDG values within systematics. Interesting is that also results from not very commonly used multiple-rotation method are promising and could be more studied in the future.

6 ϕp Invariant Mass Reconstruction

The main object of this project was reconstruct the invariant mass for ϕ and proton which could be a possible decay channel of potential pentaquark states $s\bar{s}uud$. At the beginning of this project we studied the ϕ meson invariant mass distribution and different background estimation methods mainly for the educational purpose and also to practise determination of the background for the future application for the ϕ and proton invariant mass distribution. After this study we combined all identified protons and ϕ mesons (in 3 sigma region around the mean of the peak) and reconstructed invariant mass distribution for possible pentaquark state $s\bar{s}uud$. After the first reconstruction we could see a significant peak near the kinematic limit, but after further examination it was only a bug in a code where we accidentally combined the same tracks together. After the fixing the bug, we obtained the spectrum shown in fig. 13.

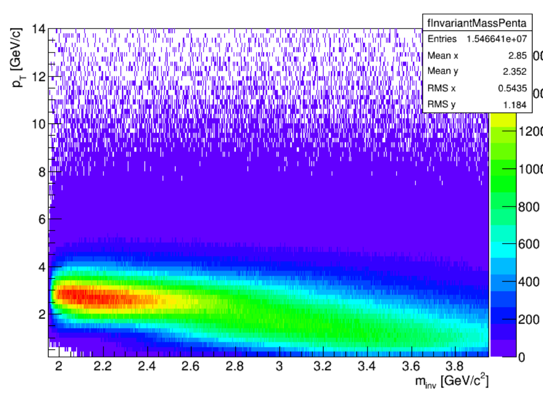


Figure 13: Integrated spectrum of ϕp invariant mass distribution

6.1 ϕp Sideband Background

For the simple and first background estimation we used combination of sidebands around the ϕ peak (3 sigma) and proton. Fig. 14 shows the colored areas in ϕ meson distribution we took to obtain a signal (blue) and the sideband background (red) of the ϕp. We normalized these two distributions by the integral ratio in invariant mass region $3.0 < m_{inv} < 3.6\ GeV/c^2$.

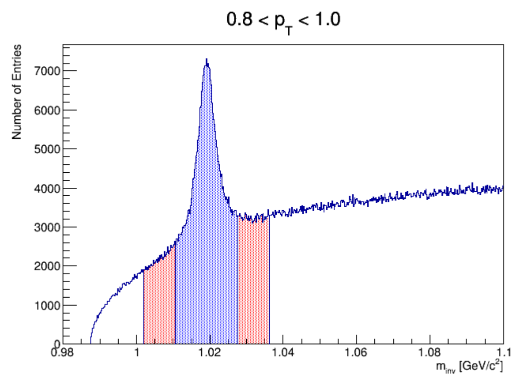


Figure 14: ϕ meson distribution and 3sigma regions to obtain ϕp signal (blue) and ϕp sideband background (red)

We compared these two invariant mass distributions in a different p_T bins, fig. 15 shows the results for 3 bins (the others can be found in Appendix, fig.A.8). Results obtained after the subtraction of the sideband background can be also found in Appendix, fig.A.9. We did not observe any significant deviation from the sideband background. However, we would like to compare obtained ϕp spectrum with the rotation background method and mixed-event technique. This work is still in progress.

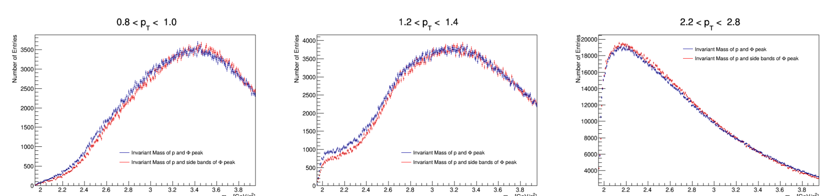


Figure 15: Comparison between ϕp invariant mass distribution (blue) and scaled sideband background distribution (red)

7 Conclusion

In this report we presented the results from the summer student project based on data analysis for searching for invariant mass signals from possible $s\bar{s}uud$ pentaquark resonance P_s^+. Analysis was based on filtered trees from real p-Pb events detected by the ALICE experiment.

7.1 Results Achieved

The work on this project went step by step from the checking of the quality of the filtered data, through the reconstruction and study of the ϕ meson invariant mass distribution to finally reconstruction of the ϕp invariant mass distribution as a possible pentaquark resonant state P_s^+. We did not want to go directly to the main goal of the project but go through this partial goals to understand and learn how data analysis in high energy physics works and to apply acquired knowledge for the further future analysis. After the data quality check described in section 3 we reconstructed the ϕ meson invariant mass distribution through its decay to two oppositely charged kaons. We studied three different method for the background estimation for ϕ meson from which two of them (mixed-event and multiple-rotations methods) could be also used in the future for the background estimation for the ϕp invariant mass distribution. We compared three methods for the background estimation for ϕ meson. Finally we reconstructed the ϕp invariant mass distribution and compared it with sideband background distribution. No significant deviation was observed. However further studies are needed, and also a comparison with MC is necessary to calculate the efficiency. The next steps are described in the following section.

7.2 Future Steps

The next step which should be done in near future is to analyse MC production to calculate the efficiency and acceptance. Then we should be able to determine and upper limit for production cross section. We plan to apply analysis to the recent data sets and also try to study different possible decay channels.

Acknowledgements

I would like to express my thanks of gratitude to my three supervisors, namely Alexander, Maximiliano and Orlando, who were very helpful, taught me a lot of new things and gave me a lot of creative ideas and motivation. Special thanks to Maximiliano for the filtered data set and helping with the code. I am also very thankful to ALICE collaboration that I could have been a part of them during this summer.

References

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Appendix

The ϕ meson invariant mass distribution for the different p_T bins fitted by Breit-Wigner function and 2nd order polynomial.

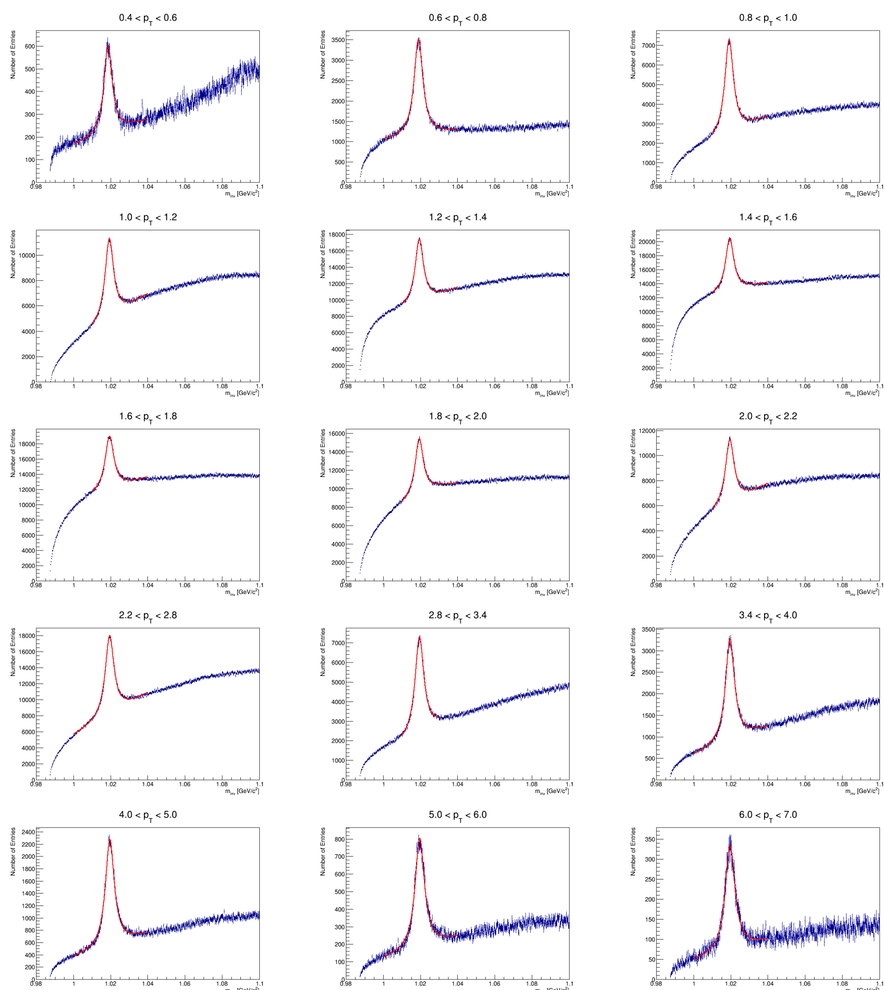

Figure A. 1: ϕ meson invariant mass distributions for the different p_T bins, red line represents the Breit-Wigner fit plus 2nd order polynomial

Results obtained for the ϕ meson invariant mass distribution and scaled like-sign background distribution for the different p_T bins.

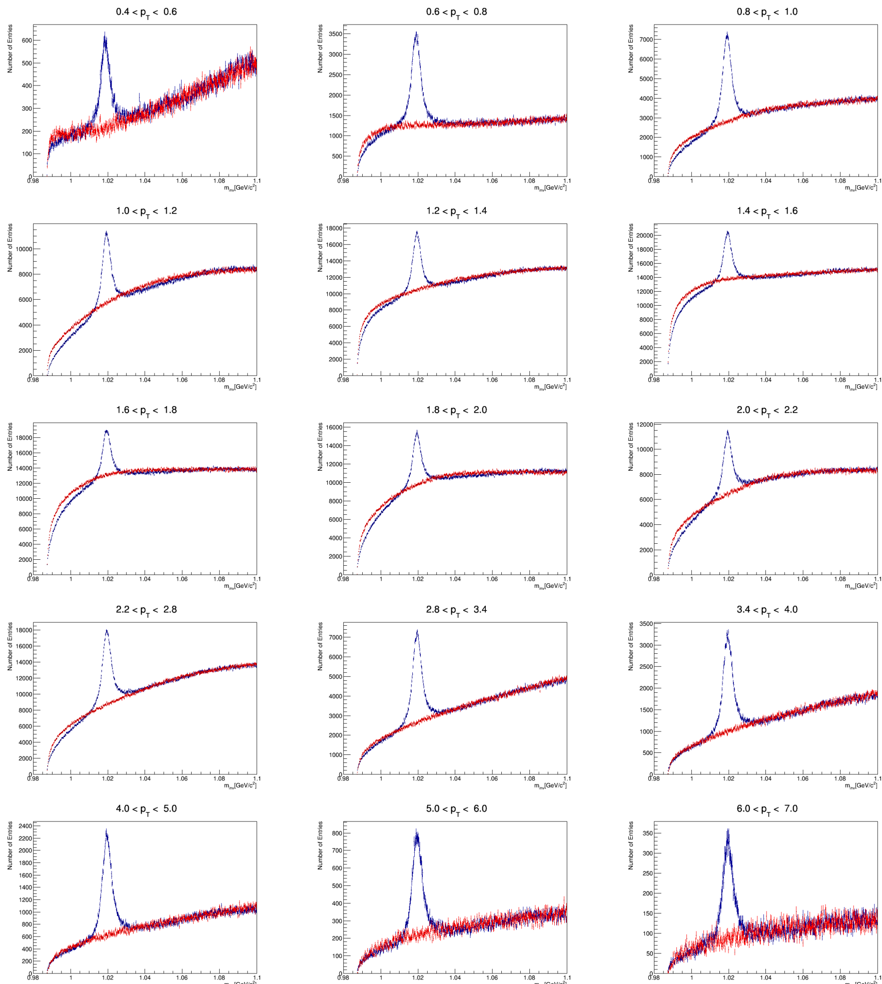

Figure A. 2: Comparison between signal (blue) and like-sign background (red) distributions for the different p_T bins

Results obtained after the subtraction of the like-sign background from the ϕ meson invariant mass distribution for the different p_T bins. The obtained spectrum is fitted by Breit-Wigner function and 2nd order polynomial.

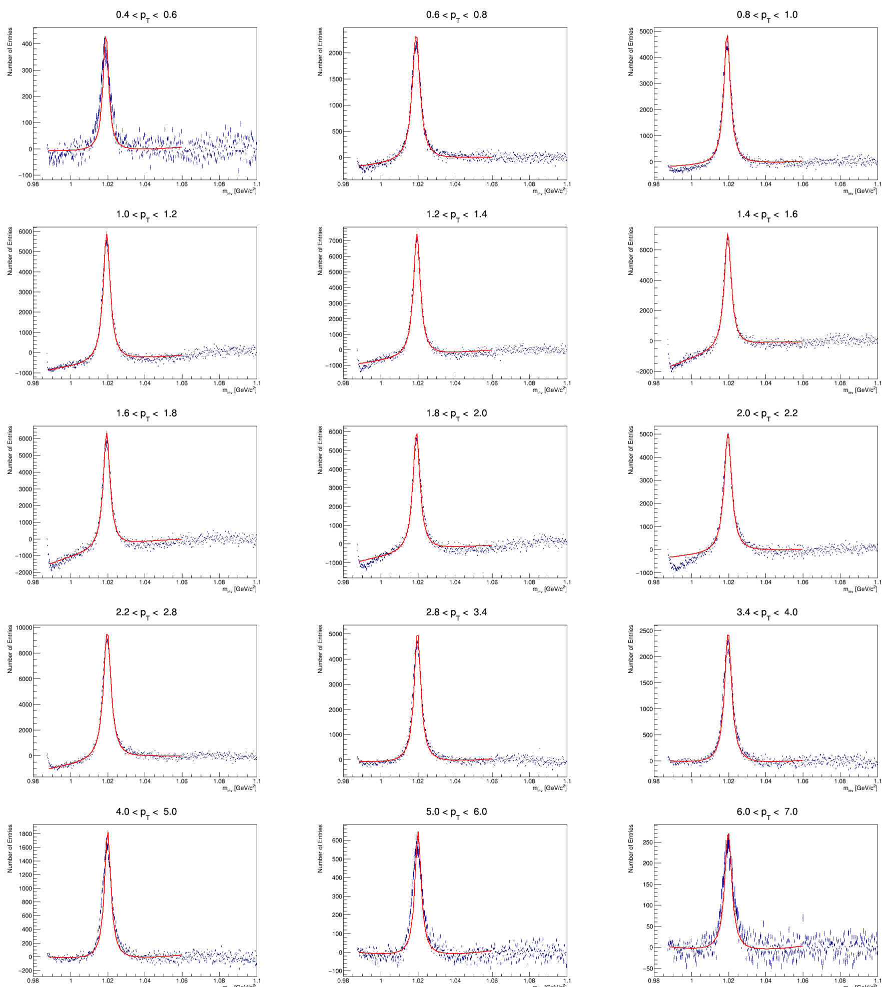

Figure A. 3: ϕ meson invariant mass distributions for the different p_T bins after the like-sign background subtraction, red line represents the Breit-Wigner fit plus 2nd order polynomial

Results obtained for the ϕ meson invariant mass distribution and scaled mixed-event background distribution for the different p_T bins.

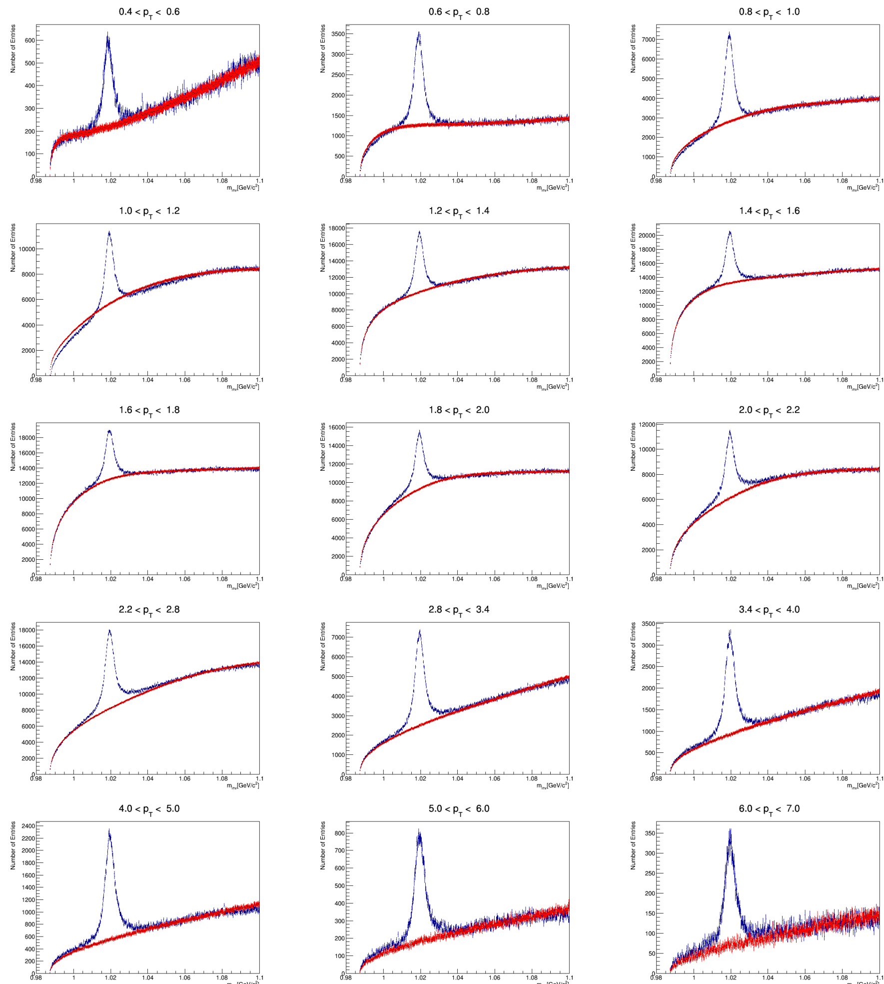

Figure A. 4: Comparison between signal (blue) and mixed-event background (red) distributions for the different p_T bins

Results obtained after the subtraction of the mixed-event background from the ϕ meson invariant mass distribution for the different p_T bins. The obtained spectrum is fitted by Breit-Wigner function and 2nd order polynomial.

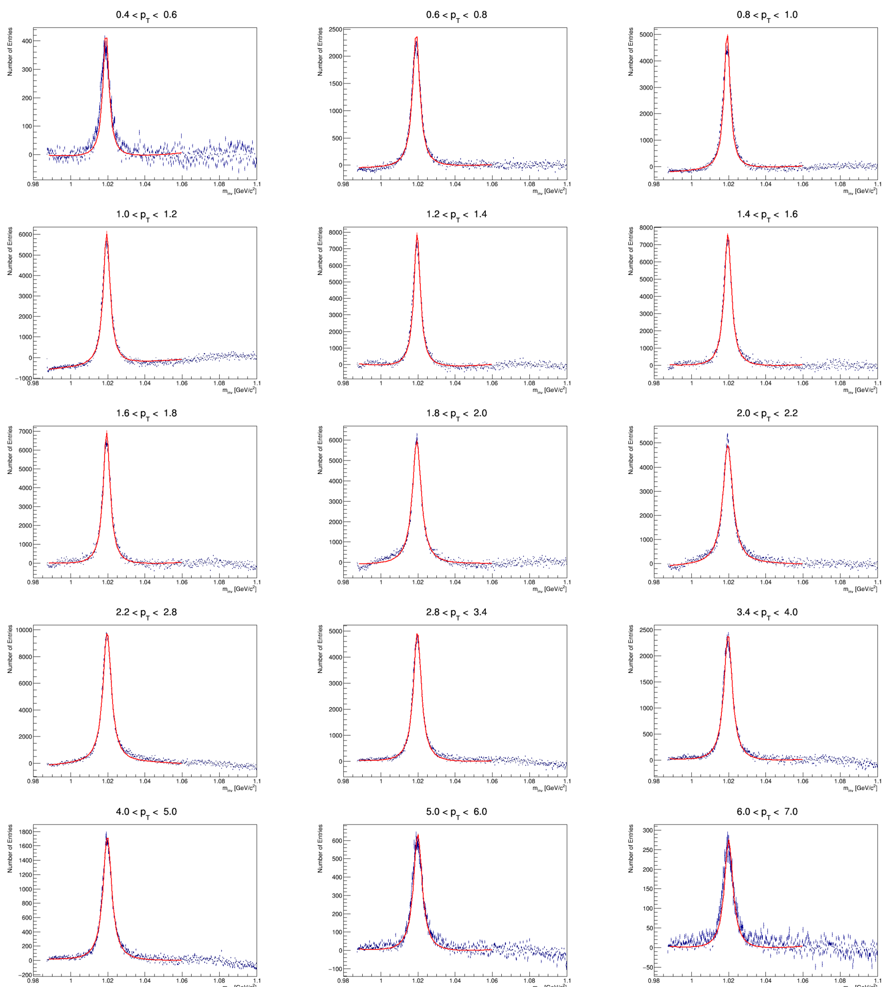

Figure A. 5: ϕ meson invariant mass distributions for the different p_T bins after the mixed-event background subtraction, red line represents the Breit-Wigner fit plus 2nd order polynomial

Results obtained for the ϕ meson invariant mass distribution and scaled multiple-rotations background distribution for the different p_T bins.

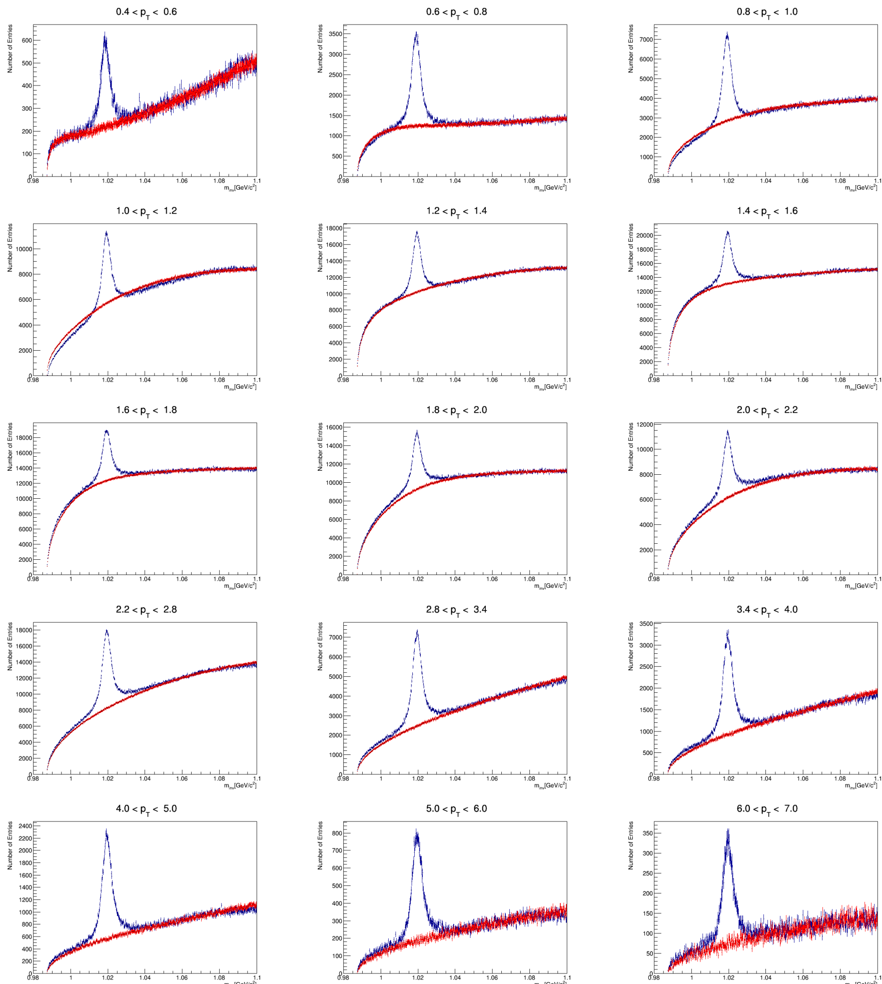

Figure A. 6: Comparison between signal (blue) and multiple-rotations background (red) distributions for the different p_T bins

Results obtained after the subtraction of the multiple-rotations background from the ϕ meson invariant mass distribution for the different p_T bins. The obtained spectrum is fitted by Breit-Wigner function and 2nd order polynomial.

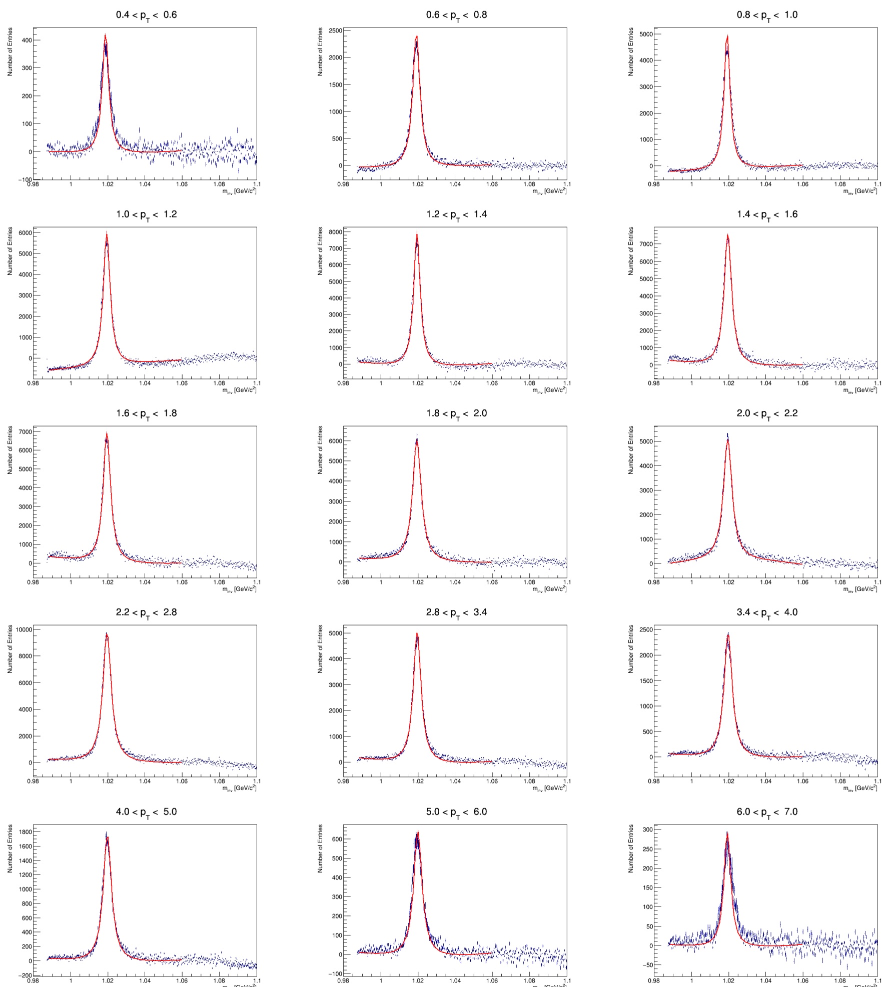

Figure A. 7: ϕ meson invariant mass distributions for the different p_T bins after the multiple-rotations background subtraction, red line represents the Breit-Wigner fit plus 2nd order polynomial

Results obtained for the ϕp invariant mass distribution and scaled sideband background distribution for the different p_T bins.

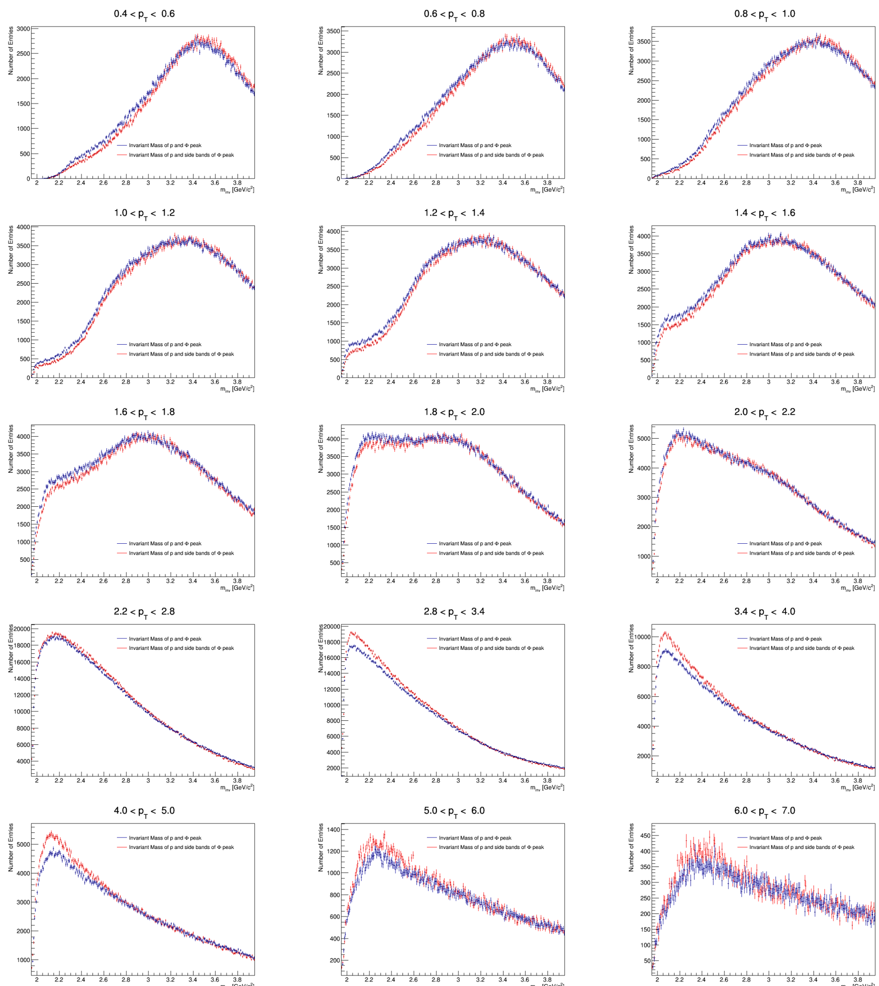

Figure A. 8: Comparison between ϕp invariant mass distribution (blue) and scaled sideband background distribution (red) for the different p_T bins

Results obtained after the subtraction of the sideband background from the ϕp invariant mass distribution for the different p_T bins.

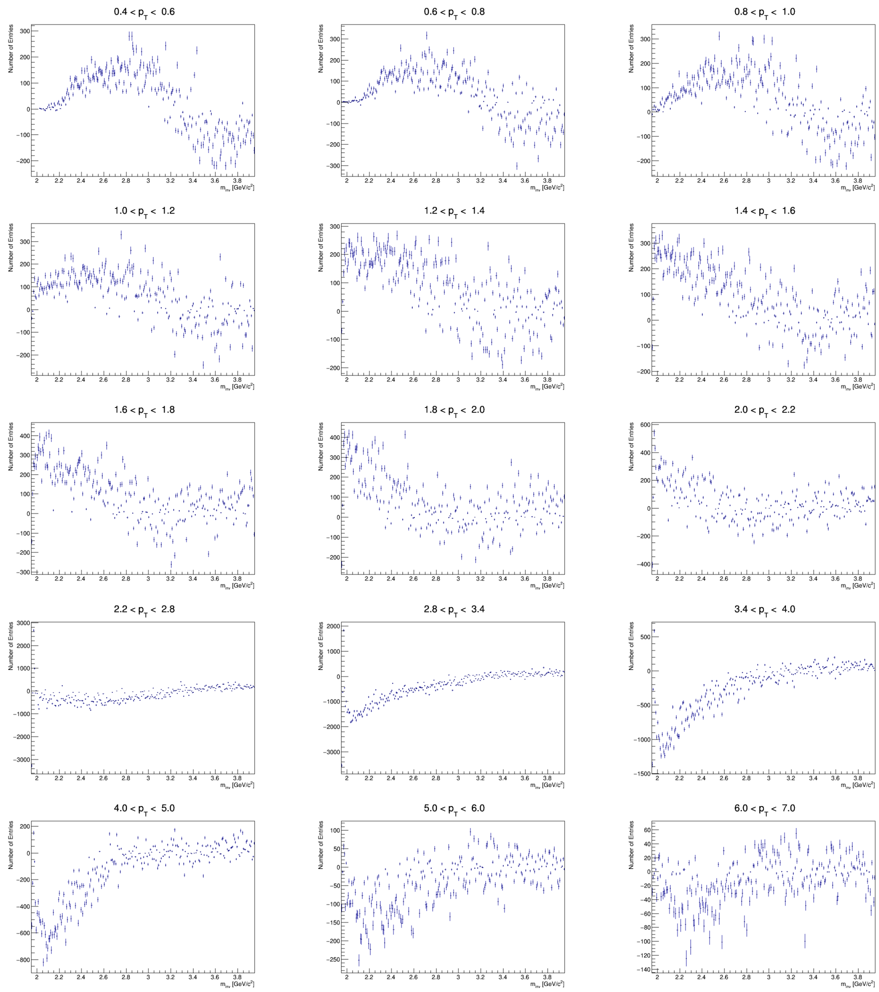

Figure A. 9: ϕp invariant mass distributions for the different p_T bins after the sideband background subtraction