Reconstruction of neutral mesons using photon conversions

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Abstract[1]

ALICE is a dedicated heavy ion experiment equipped with various particle identification detectors. One of the main goals of this experiment is to measure the properties of the early stages of the fireball created in Pb-Pb collisions. Direct photons can be used to access these early stages, as photons are not subject of the strong interaction. Thus the radiation emitted by the hot Quark Gluon Plasma will not be modified by later stages of the evolution of the plasma and will give access to the temperatures of the early stages.

In ALICE, photons can be reconstructed using two different techniques: either reconstructing the photon from its energy deposit in the two calorimeters (EMCAL and PHOS) or tracking the electrons from photon conversions in the tracking system (TPC, ITS) and identifying them using the ITS, TPC, TRD and TOF. The latter is called photon conversion method (PCM) and allows the measurement of photons down to very low momentum (p_T about 0.2 GeV/c) with a very high purity, while the calorimeters have larger statistics and better resolution at larger momenta ($p_T > 3$-4 GeV/c). The bulk of the thermal photons can be found at low momentum ($p_T < 3$ GeV/c). In order to separate these direct photons from the decay photons a good knowledge of the spectra of π^0, η, $\omega(782)$[2], η' and heavier mass mesons is needed. Photons from these mesons are merely background for the direct photon measurement, but they dominate the inclusive photon invariant yield and thus need to be measured as precisely as possible.

The main subject of this project were feasibility studies for the reconstruction of η and ω mesons in p-Pb collisions, employing the different techniques used in ALICE, focusing on the detection channels in which the PCM method can improve the extraction of the mesons. However, studies combining PCM photons with photons detected in the calorimeters were also performed as well as studies where both photons were detected in the calorimeters. Outputs of this project are corrected yields for η and ω mesons for various p_T.

Dataset: pPb, 5.023 TeV, LHC13bc, Min-Bias

Monte Carlo: pPb, 5.023 TeV, LHC13b2_efix_p[1-4], DPMJET, Min-Bias

AliROOT task: PWGGA/GammaConv/AliAnalysisTaskNeutralMesonToPiPlPiMiPiZero.cxx

[1]Written according to [6].
[2]Throughout this report, ω will always mean $\omega(782)$.

Contents

1 Introduction

1.1 Relevant ALICE detectors

Let us firstly give basic information about various ALICE detectors relevant for this project. This subsection uses information obtained from [2], [3], [4] and [5]:

Tracking detectors

ITS (Inner Tracking System) [2], [4] is the innermost tracking system in the ALICE experiment, consisting of six cylindrical layers of silicon detectors. From inside out, the first two of these layers form the silicon pixel detector (SPD), the next two layers are silicon drift detector (SDD) and the remaining two layers form silicon double-sided micro strip (SSD). Each of these detectors uses different silicon-based techniques for particle tracking. The main purposes of the ITS are:

- to localize the primary interaction vertex and to distinguish it from secondary vertices originating from decays of short lived particles,
- particle identification and tracking of low-momentum particles,
- improvement of momentum and angle measurement of the TPC.

Because of very high track density close to the beam pipe, sufficiently high resolution and efficiency in track reconstruction are needed. These were obtained by optimizing the number of channels, positions of the layers as well as the layer segmentation. In order to provide particle identification via $\mathrm{d}E/\mathrm{d}x$ for low-p_T particles, four outermost layers on the ITS have analog readout. The range in φ and maximum of $|\eta|$, as well as resolutions in $r\varphi$ and z are given in table 1.1.

TPC (Time Projection Chamber) [2], [3] is the main tracking detector in the central barrel. It consists of two main components: the field cage and the read-out chambers located at the end-plates. The cylindrical field cage provides a uniform electrostatic field in the gas volume. The gas is a mixture of neon, nitrogen[3] and carbon dioxide. The voltage between the central electrode at $z = 0$ and the end-plates is 100 kV, leading to an electron drift time of about 90 μs. To reconstruct the actual 3D position of the track points, the value of the drift time (for position in z) as well as output from cathode pads located on the end-plates (for position in xy plane) are used. These reconstructed track points provide information for the reconstruction of the particle path through the TPC. In addition to track reconstruction, the TPC also allows particle identification (PID) via $\mathrm{d}E/\mathrm{d}x$ measurement.

Electromagnetic calorimeters

ALICE contains two calorimeters in the central barrel: PHOS and EMCal. Their purpose is to observe the thermal and dynamical properties of the initial phase of a heavy-ion collision by measuring low-p_T direct photons and the jet quenching via the measurement of jets, high-p_T π^0 and γ-jet correlations.

PHOS (Photon Spectrometer) [2] is a high-resolution electromagnetic spectrometer covering limited ranges in φ and η (see table 1.1). Measuring low-p_T thermal photons requires fast response as well as good position and energy resolution. The required timing resolution is achieved by using fast scintillators and preamplifiers. This leads to timing resolution of about 2 ns. To achieve the required resolution in position and energy, the material budget in front of the detector has been kept as small as possible. Table 1.1 provides additional information about PHOS, mainly its energy and position resolution and covering ranges.

EMCal (Electromagnetic Calorimeter) [2] is used for full jet reconstruction in ALICE. It is a large Pb-scintillator (Shashlik) sampling calorimeter located about 4.5 m from the interaction point. EMCal provides

[3] Nitrogen was present in the mixture until 2010, when it was removed.

Detector	$|\eta| <$	φ	$\sigma_{r\varphi}$ [μm]	σ_z [μm]	Specific resolution
ITS					
SPD 1(2)	2 (1.4)	full	12	100	
SDD	0.9	full	35	25	
SSD	0.97	full	20	830	$\sigma_{\mathrm{d}E/\mathrm{d}x} = 2.0\%$ at low p_T
TPC					
$r \simeq 1.4$ m	1.5	full	1100	1250	
$r \simeq 2.8$ m	0.9	full	800	1100	
PHOS	0.12	$220^\circ < \varphi < 320^\circ$			$\sigma_E = 1.12\% \oplus \frac{3.6\%}{\sqrt{E}}$
					$\sigma_{x,y}[\mathrm{mm}] = \sqrt{\left(\frac{3.26}{\sqrt{E[\mathrm{GeV}]}}\right)^2 + 0.44^2}$
EMCal	0.7	$80^\circ < \varphi < 187^\circ$			$\sigma_E = 1.5\% \oplus \frac{7\%}{\sqrt{E}}$

Table 1: Covering ranges in φ and η, resolutions in $r\varphi$ and z and specific resolutions for relevant ALICE subdetectors.

fast and efficient trigger for hard jets, photons and electrons. Table 1.1 contains informations about ranges in both φ and η covered by EMCal as well as its energy resolution.

1.2 AliROOT task description

In order to successfully reconstruct η and ω mesons, which are not directly detected, optimal decay channel has to be chosen beforehand. For the purposes of this project, the following decay channel was chosen:

$$\eta/\omega \to \pi^+\pi^-\pi^0 \ (\mathrm{BR}_\eta \approx 22.7\%, \ \mathrm{BR}_\omega \approx 89.2\%)^4,$$

where we assume the π^0 subsequently decays into 2 photons (BR $\approx 98.8\%$), which either

- both undergo photon conversion – production of particle-antiparticle pair[5] (in our case e^+ e^-), or
- only one photons converts and the other one is detected in PHOS or EMCal, or
- both photons are detected either in PHOS or EMCal.

This gives five different cases to study:

PCM–PCM, PCM–PHOS, PCM–EMCal, PHOS–PHOS and EMCal–EMCal.

In all of the cases, charged pions were reconstructed using information obtained from the tracking detectors (ITS and TPC). In order to guarantee a good track quality, a minimum cut on the number of TPC clusters was chosen to be 80. Apart from reconstructing tracks in ITS and TPC, energy loss measured in the TPC as well as in the four outer layers of ITS were taken into account when distinguishing charged pions from other charged particles passing through TPC and ITS. $\mathrm{d}E/\mathrm{d}x$ cuts were taken as follows: for TPC $\pm 3\sigma$ and for ITS $\pm 5\sigma$. Figure 1 shows energy loss of charged pions when passing through the gas of the TPC. Furthermore, the minimum cut of charged pion p_T is chosen to be 100 MeV/c. After reconstruction of charged pions, the next step is to combine them into π^+ π^- pairs originating from the same vertex.

[4] Analysis of the most common decay of the η meson into 2 photons (BR $\approx 71.9\%$) has already been done.

[5] Photon Conversion Method (PCM) is a method of reconstructing high-energy photons by combining tracks of particle-antiparticle pair (in our case electron-positron). This pair originated from interaction of the high-energy photon with a nucleus of the medium the photon was passing through and is reconstructed using mainly information from TPC (clusters and energy loss). The probability of a photon with $p_T > 1$ GeV/c converting into e^+ e^- pair is about 8.5% and falls to zero for lower p_T.

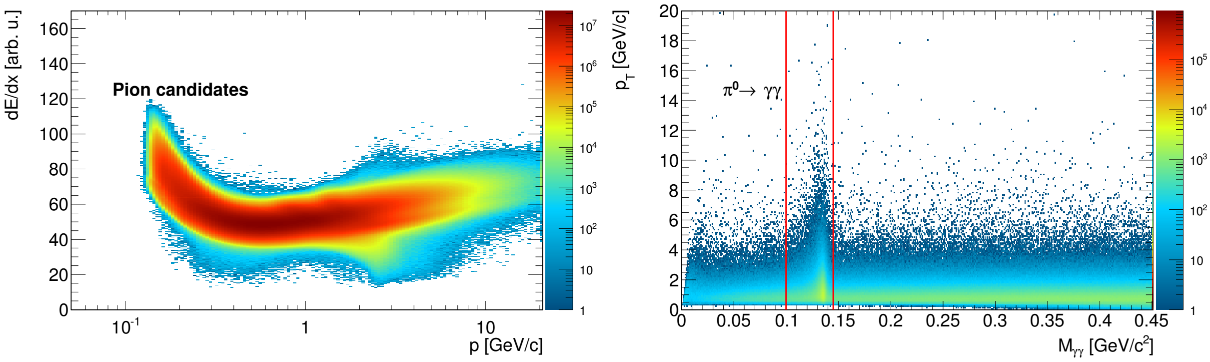

Figure 1: Energy loss of charged pions in TPC (left). $\gamma\gamma$ invariant mass versus p_T, together with a sharp cut in photon pair invariant mass: $M_{\gamma\gamma} \in [0.1, 0.145]$ (right).

Neutral pions are reconstructed by first reconstructing photons (PCM or Calo) from their most probable decay $\pi^0 \to 2\gamma$. These photons, as already mentioned, can be reconstructed with two different techniques: photon conversion method (PCM) and their energy deposit in one of the two electromagnetic calorimeters – PHOS and EMCal. The advantage of the PCM is that it can be used for the reconstruction of photons with very low p_T (about 0.2 GeV/c) with very high purity. On the other hand, only 8.5% conversion probability, which quite drastically drops for p_T smaller than 1 GeV/c (see [2]), can be considered a disadvantage. The calorimeters offer much higher statistics and better resolution at high momenta ($p_T >$ 3-4 GeV/c) however most of the thermal photons from the QGP have p_T smaller than 3 GeV/c and thus only very few photons from it can be reconstructed using the calorimeters. Figure 1 shows $\gamma\gamma$ invariant mass versus p_T together with the sharp cuts used for π^0 selection. The peak corresponding to neutral pions is clearly visible.

Having reconstructed charged pion pairs and neutral mesons, these are now combined together imposing a condition that all three particles originate from the same vertex.

2 Analysis

2.1 Raw yield extraction

Having combined π^+, π^- and π^0 that originate from the same vertex, it is possible to calculate their invariant mass spectrum. Since the shape of this distribution is p_T dependent, it is preferable to create a 2D histogram of invariant mass versus combined p_T of all three pions.

The next step is to generate multiple 1D invariant mass histograms as p_T slices of the 2D one. In order to extract raw yields of η and ω mesons, the combinatorial and correlated BG needs to be subtracted from these distributions. This can be done in several ways:

- By fitting the spectrum outside the peak with a predefined function (in our case fourth degree polynomial) and then extending the domain of the fit into the peak region. This new function should describe the background outside as well as under the peak.
- By using Event Mixing method, which by combining particles from different events (but from the same multiplicity and primary vertex Z position bin) destroys the correlations between them and thus also the peaks. This is the commonly used method and it often describes the underlying background with

very good precision[6]. However, we found that in our case, combining neutral pion from the current event and charged pion pair from other events did not describe the background properly. It could well be that combining them in other ways could lead to the desired background shape, but it was not yet tested.

- By using Monte Carlo to get the grasp on the shape of the background in the following way. Firstly taking signal+background from the Monte Carlo reconstructed ($h_{\mathrm{SB}}^{\mathrm{MC}}$) and subtracting true MC signal ($h_{\mathrm{True}}^{\mathrm{MC}}$), obtaining distribution we will call true MC background ($h_{\mathrm{TB}}^{\mathrm{MC}}$). Ideally, this could (after normalization) describe the real data background very well. However, we observed that additional multiplication by a correction function is needed. This correction function is obtained by taking ratio $h_{\mathrm{SB}}^{\mathrm{Data}}/h_{\mathrm{TB}}^{\mathrm{MC}}$, fitting it outside of the expected peak region with 4^{th} degree polynomial and then extending the fit function domain into the peak region. This can be written as

$$\text{background for Data} = h_{\mathrm{TB}}^{\mathrm{MC}} * \overline{\left(\frac{h_{\mathrm{SB}}^{\mathrm{Data}}}{h_{\mathrm{TB}}^{\mathrm{MC}}}\right)},$$

where $\overline{(...)}$ means 'fit ... outside the expected peak region and then extend the domain of the fit into the peak region', and $h_{\mathrm{TB}}^{\mathrm{MC}} = h_{\mathrm{SB}}^{\mathrm{MC}} - h_{\mathrm{True}}^{\mathrm{MC}}$. This is the method we eventually used to obtain raw yields of η and ω mesons.

After background subtraction, the remaining histogram is fitted with linear function that tries to account for whatever is left of the background, plus Gaussian function combined with exponential low-energy tail to account for electron bremsstrahlung (see [2]):

$$\text{peak fit function} = A\left(G(M) + \exp\left(\frac{M - M_0}{\lambda}\right)(1 - G(M))\theta(M_0 - M)\right) + B + CM,$$

where

$$G(M) = \exp\left(-\frac{1}{2}\left(\frac{M - M_0}{\sigma_M}\right)^2\right),$$

where M is the invariant mass of π^+, π^- and π^0; A, B, C, M_0, λ and σ_M are fit parameters. Figures 2 and 3 represent the PCM–PCM case, where the peak extraction was the most successful. All subsequent plots in this report will be from the PCM–PCM case, because reconstruction of the π^+, π^- and π^0 invariant mass peak was more difficult in other cases.

After peak fitting, raw yields are obtained by integration of the peak fit function and then subtracting the integral of only its linear part. For the extraction of the raw yields of η and ω mesons, we duplicated and modified already existing macro *ExtractSignalV2.C*[1] into macros *ExtractSignalPiPlPiMiPiZero.C* and *ExtractSignalPiPlPiMiPiZeroTemplate.C*[7], which are currently limited to work only for p-Pb collisions at $\sqrt{s} = 5.023$ TeV.

It is necessary to mention that in some of the p_T slices the fit does not necessarily describe the peak correctly. This is either caused by the fact that the peak is too insignificant and is lost in the rather large error bars, or by the fact that there really is no peak in the current p_T slice and the fit only fits the noise. Therefore, in the current state of analysis, the obtained raw (and also corrected) yields of both η and ω mesons should not be regarded final. Further improvements in BG subtraction and signal purification would be needed in order to trust the results.

[6] Of course, the combinatorial background needs to be properly normalized according to the signal+background histogram. The normalization factor is usually the ratio of integrals of combinatorial background and signal+background to the left or to the right of the peak. The left normalization is usually worse than the right one. In our case, it was so bad we completely skipped it and chose left+right normalization instead, where the integrals for the normalization go over the intervals to the left and right of the peak.

[7] All the histograms in this report are from this macro, which uses the third mentioned method of background subtraction, using also MC information.

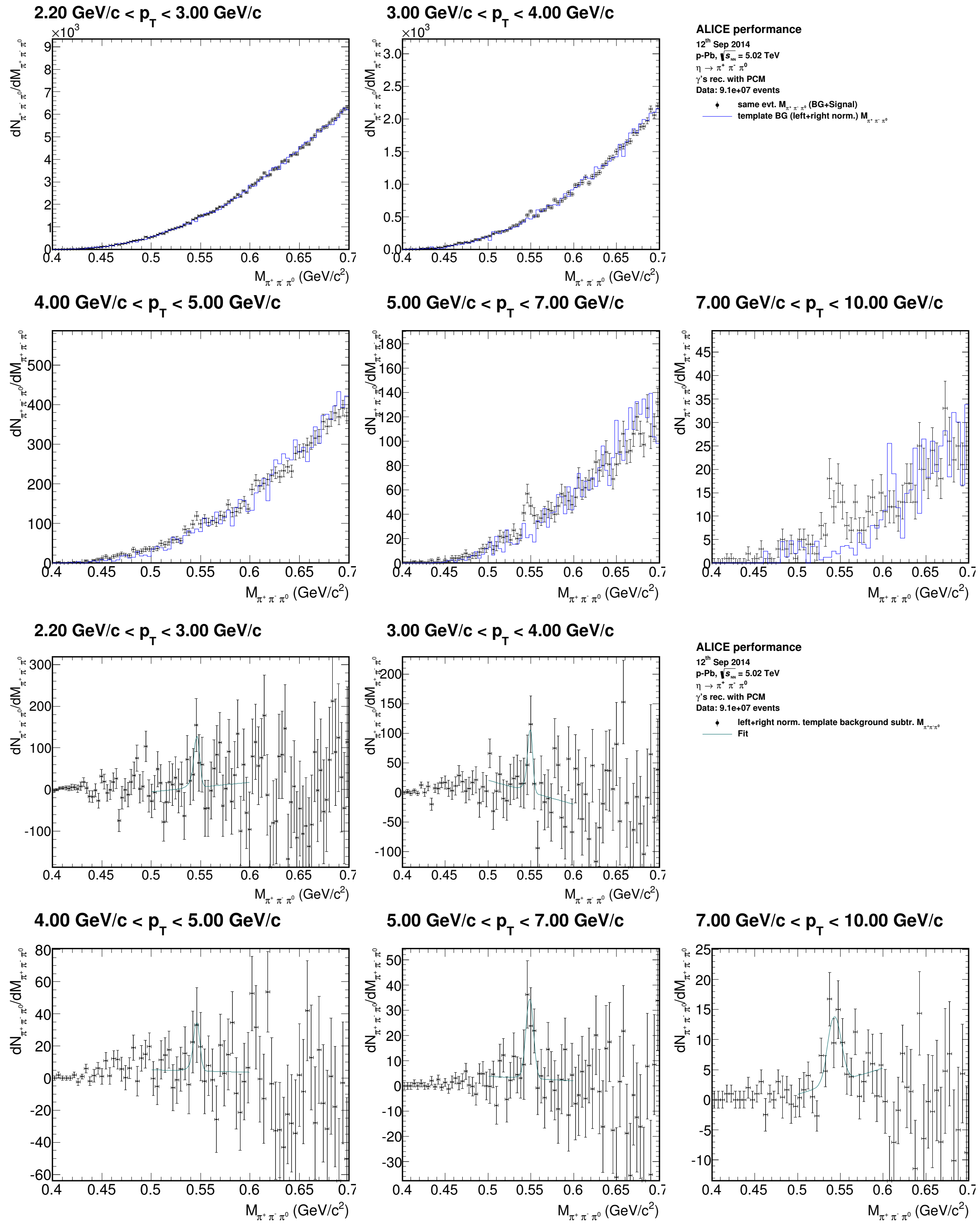

Figure 2: π^+, π^- and π^0 invariant mass in multiple p_T slices together with template background (up) and subtracted template background (down). Invariant mass range chosen to contain η peak.

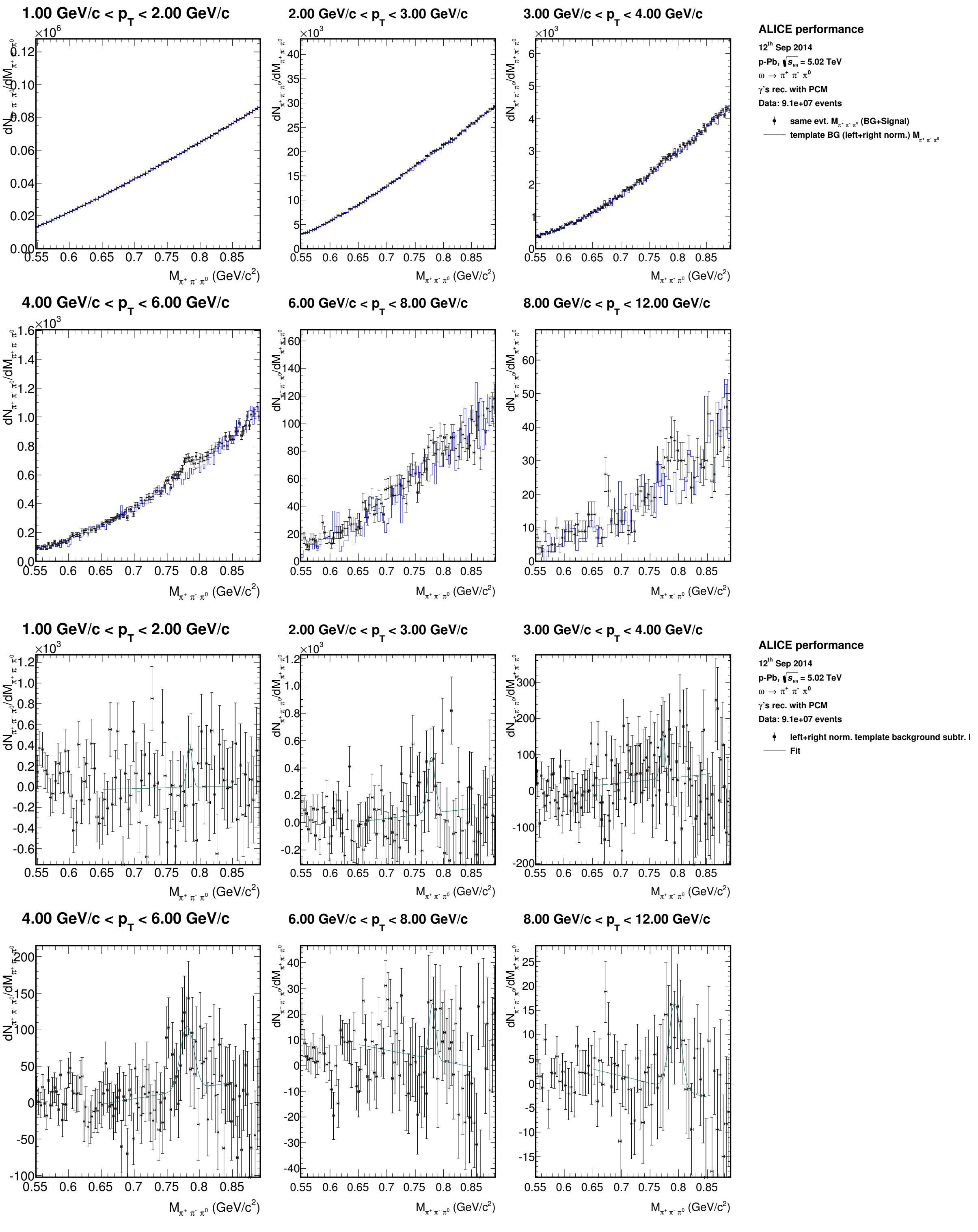

Figure 3: π^+, π^- and π^0 invariant mass in multiple p_T slices together with template background (up) and subtracted template background (down). Invariant mass range chosen to contain ω peak.

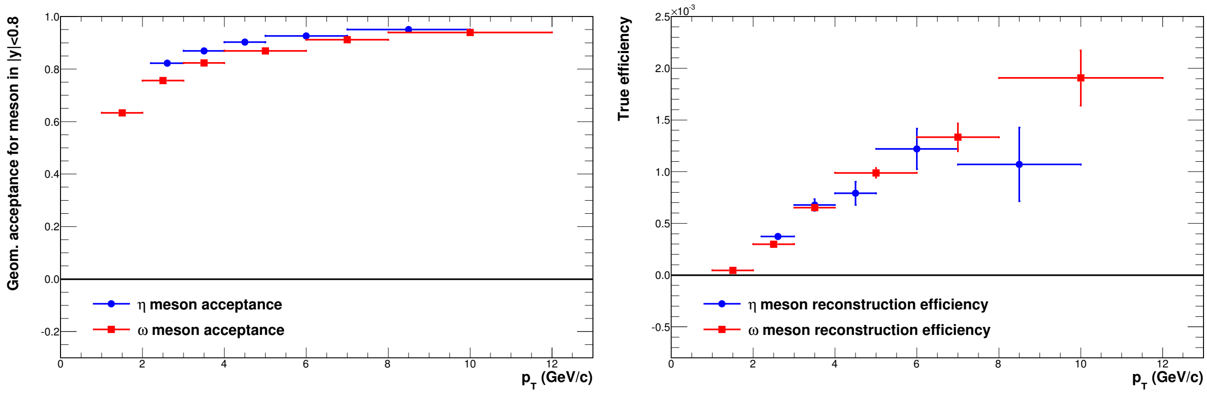

Figure 4: Geometrical acceptance (left) and reconstruction efficiency (right) for η and ω mesons in PCM–PCM case.

2.2 Obtaining corrected yield

In order to obtain corrected yields from the raw ones, corrections for geometrical acceptance and reconstruction efficiency have to be made. For this purpose, Monte Carlo simulations listed in abstract were used and already existing macro *CorrectSignalV2.C* was duplicated and modified to fit our purposes[8]. The new macro is called *CorrectSignalPiPlPiMiPiZero.C*.

Geometrical acceptance $A_{\eta(\omega)}$ is defined as follows:

$$A_{\eta(\omega)} = \frac{N_{\eta(\omega),|y|<0.8} \text{ with the daughter particles within } |\eta_{\pi^0}| < 0.9, |\eta_{\pi^\pm}| < 1.4}{N_{\eta(\omega),|y|<0.8}}.$$

Reconstruction efficiency $\epsilon_{\eta(\omega),\text{reco}}$ is obtained by reconstructing Monte Carlo data as if it were real data and then determining how much the reconstructed MC differs from the true one. Acceptance and efficiency plots for PCM–PCM method of photon reconstruction for η and ω mesons are shown in figure 4. In figure 5, we show reconstructed and true η and ω masses versus p_T as well as FWHM/2.35.

Knowing acceptance and efficiency, we may finally proceed to the calculation of the corrected yields in the following way:

$$\text{corrected yield} = \frac{1}{2\pi N_{\text{evt.}}} \frac{1}{p_T} \frac{1}{A_{\eta(\omega)} * \epsilon_{\eta(\omega),\text{reco}}} \frac{N_{\eta(\omega)}}{\Delta y \Delta p_T},$$

where $N_{\text{evt.}}$ is the number of events for normalization and $N_{\eta(\omega)}$ is the reconstructed raw yield for η or ω meson within rapidity interval $[-0.8, 0.8]$ and transverse momentum bin Δp_T. The corrected yields of η and ω mesons for the PCM–PCM method of photon reconstruction are shown in figure 6.

[8]This mainly involved changing histogram names the macro expects to find in the data and Monte Carlo root files as well as modifying legends and axis labels for exported histograms.

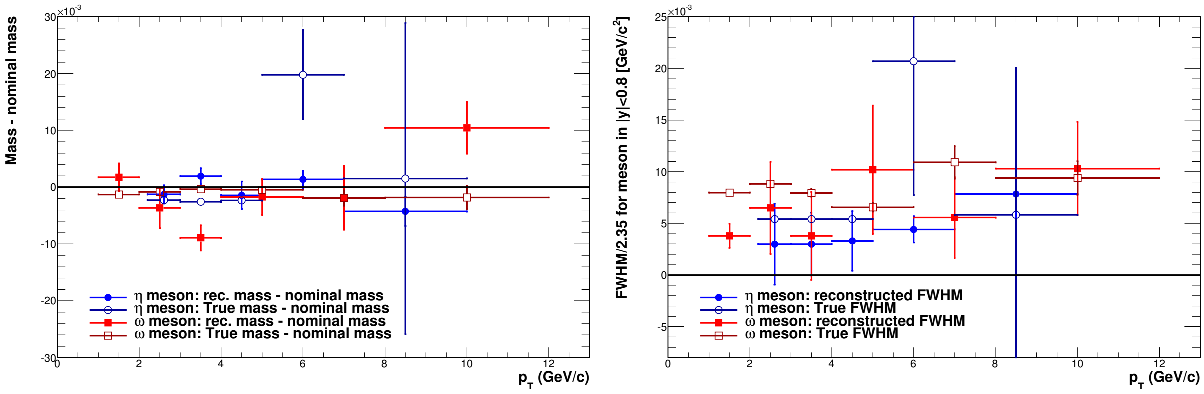

Figure 5: Deviation from nominal meson mass (left) and FWHM/2.35 (right) for η and ω mesons in PCM–PCM case.

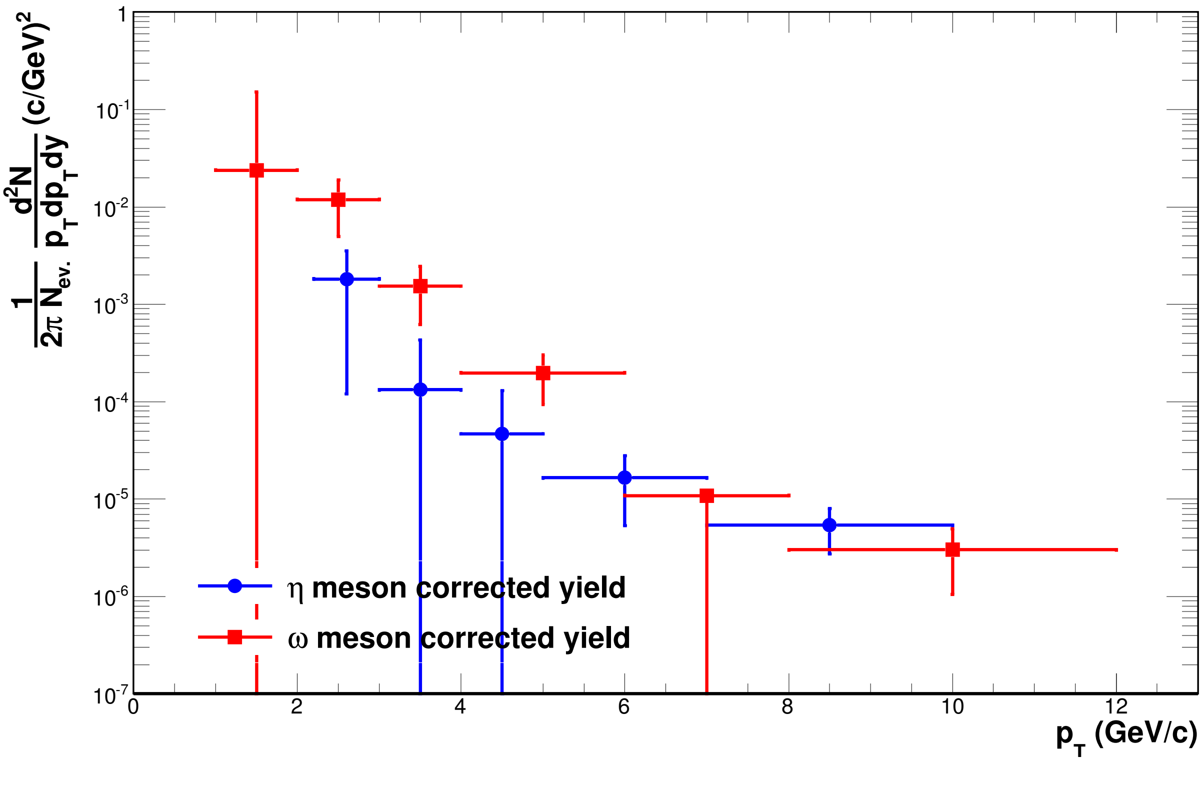

Figure 6: Corrected yields of η and ω mesons in PCM–PCM case.

References

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