CERN Summer Student Project Report

Measurement of Neutral Pions in pp Collisions at $\sqrt{s}$=2.76 TeV with the ALICE PHOS

Author: Malte Hecker

Supervisors: Dr. Constantin Loizides, Dr. Jason Kamin

July 8th 2013 - September 28th 2013

1 Introduction

This document describes the analysis of data taken with the ALICE detector at the LHC measuring the production spectrum of neutral pions using the Photon Spectrometer (PHOS).
The PHOS is a high granularity electromagnetic calorimeter capable of measuring the energy and position of electromagnetic particles. Covering $220° < \phi < 280°$ in the azimuth and a pesudorapidity range of $|\eta| < 0.13$, it is divided into three modules each holding 3584 individual cells. A cell consists of a lead tungstate ($PbWO_4$) crystal with a cross section of 22 by 22 mm^2 and a length of 180 mm, which acts as both the absorber and as the scintillator. A PIN photo-diode is used to measure the scintillation light. [Aam08, Del99]

Photons that hit the PHOS produce electromagnetic showers in the crystals, typically depositing their energy across multiple cells. The reconstruction algorithm applied to the data finds clusters of adjacent cells above a certain energy threshold. The total energy of the cluster is the sum of the energies of all contributing cells. The position of the cluster is found at the barycenter of the energy deposition across the contributing cells. The cluster energy, position, number of cells and other information is stored for all clusters in each event. This analysis is based on reconstructed data from the 2011 $p+p$ run at $\sqrt{s} = 2.76$ TeV in 2011.

2 Event Selection and Cuts on PHOS Clusters

The data was taken using minimum bias triggers V0A, V0C and SPD. Only events that contain a reconstructed primary vertex and that are not identified as pile up events through the reconstruction of multiple vertices by the SPD are selected. In total 28.3 million events pass this selection criteria and are analysed.
For the π^0 reconstruction a set of cuts is applied to the clusters to identify photon candidates. Only those clusters are selected that contain two cells or more. Furthermore, a minimum energy threshold for the cluster energy of 300 MeV is applied. To reject clusters that are influenced by bad cells a Bad-Module-Map is used. Bad cells can either be dead cells that are non-functional or hot cells that are constantly firing to due to faulty electronics.

3 π^0-Reconstruction and Raw Yield Extraction

Neutral pions decay into photon pairs with a probability of 98.823% [Nak10]. Due to the short lifetime of the π^0 of $c\tau = 25.5$ nm, they approximately decay right at the vertex of the $p+p$ collision. Therefore, the momentum of the decay photons can be determined

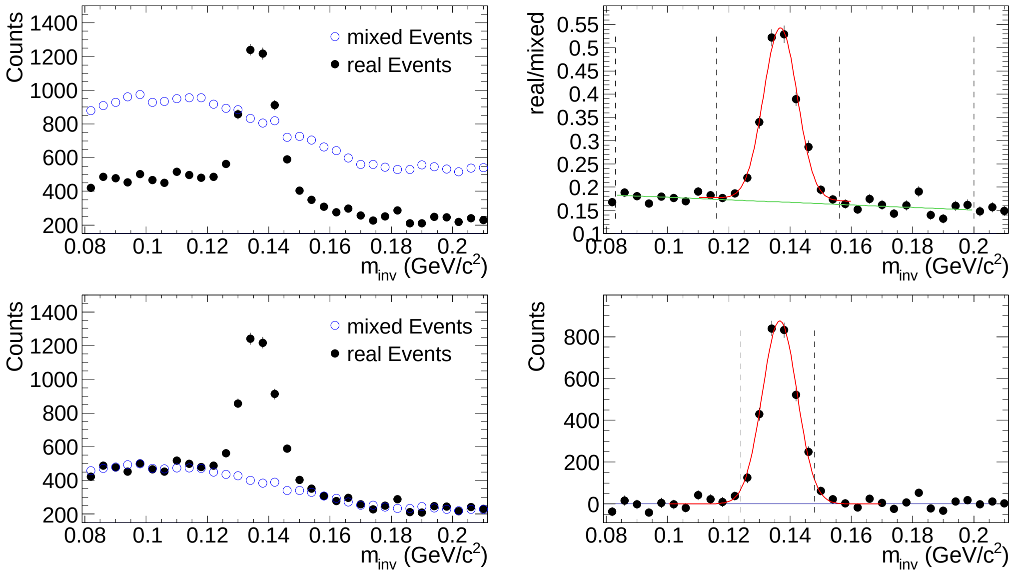

Figure 1: The steps of the background subtraction and peak extraction algorithm for $1.2 < p_T < 1.4$ GeV/c

by measuring their energy and position in the PHOS as well as measuring the position of the vertex of the collision. Since the source of any particular photon is unknown, all combinations of photons in an event are considered as π^0 candidates (referred to as "real events"). The invariant mass (m_{inv}) of a photon pair is calculated as:

$$m_{inv}(\pi^0) = \sqrt{2 \cdot E(\gamma_1) \cdot E(\gamma_2) \cdot (1 - cos(\alpha))}. \quad (1)$$

The top left panel of Figure 1 shows the m_{inv} spectrum of all real event photon pairs (black closed circles) for a p_T-range of 1.2 to 1.4 GeV/c. A peak is visible in the region of the π^0 mass sitting on top of a combinatorial background. The photon pairs that are, in fact, decay products of single π^0s contribute to the peak, while the background consists of photon pairs that did not belong together. To subtract the background the "mixed event" method is used. Photons from one event are combined with those from a different event to create a "mixed event" m_{inv} spectrum. This spectrum is also shown in the top left panel of Figure 1 (blue open circles) scaled by 0.35 to display it in one plot with the real event spectrum. Since the paired photons are not from the same events, by construction they are not correlated. The mixed event m_{inv} spectrum has a very similar shape as the combinatorial background of the real events.

The top right panel of Figure 1 shows the ratio of the m_{inv} spectra of real and mixed events. The ratio of the background is fit with a polynomial of first order (green curve) excluding $\pm$ 4 σ around the peak. This σ is determined with a Gaussian fit to the peak (red curve). The fit region is indicated with vertical doted lines in the top right panel in

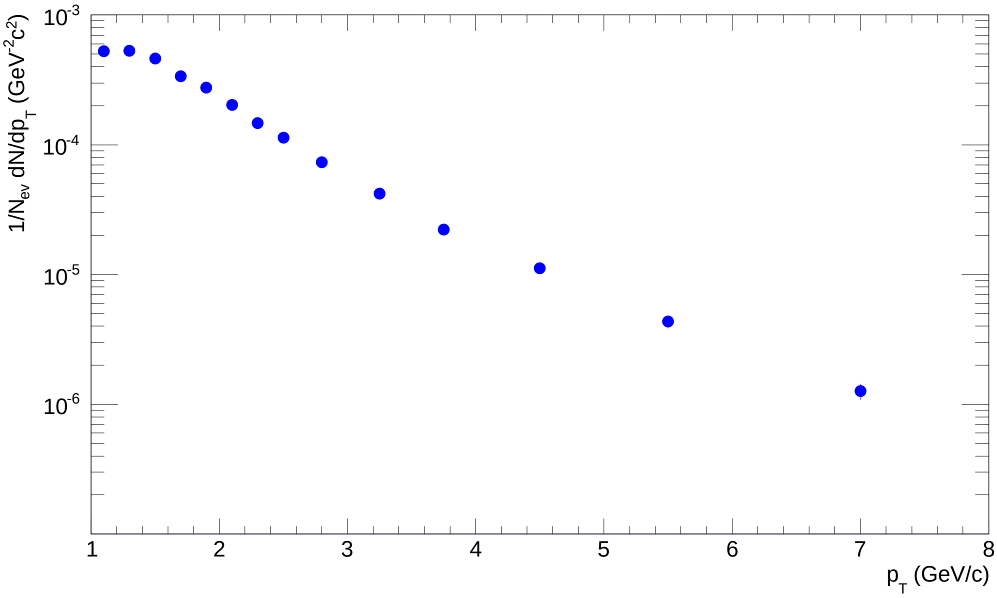

Figure 2: Raw π^0 yield

Figure 1. The first order polynomial is applied to the mixed events as a mass dependent scale factor. This is necessary for the overall normalization as well as to account for slight differences in the slope of the mixed event spectrum compared to the real event spectrum. The bottom left panel of Figure 1 shows the m_{inv} spectra of the real events and the scaled mixed events. The scaled mixed events describe the background outside the π^0 peak very well and so can be used to subtract the background.

The bottom right panel shows the m_{inv} spectrum of the real events after background subtraction. The red line is a Gaussian fit to the peak. The raw number of π^0s is extracted from the peak by integrating the counts within 2σ around the mean (μ) of the Gaussian fit. This 2σ range is indicated with vertical doted lines in the bottom right panel of Figure 1. This is done for a number of p_T ranges from 1 to 8 GeV to extract the the raw π^0 yield as a function of p_T. The π^0 p_T spectrum is shown in Figure 2.

Above 8 GeV the statistics are very low. Only a few π^0s are counted in the ~30 million events and, therefore, the Gaussian fits become unstable making this method unreliable. Below 1 GeV the signal-to-background ratio is very low, and therefore the simple mixed events approach is not precise enough to ensure a reliable signal extraction. The π^0 yield drops with increasing p_T, however the yield at 1.1 GeV is slightly lower than at 1.3 GeV. This is due to the limited acceptance of PHOS. The lower the p_T of the π^0, the higher the opening angle of the decay-photons. Thus it is more likely to loose the π^0 because the probability that both photons hit the detector is lower.

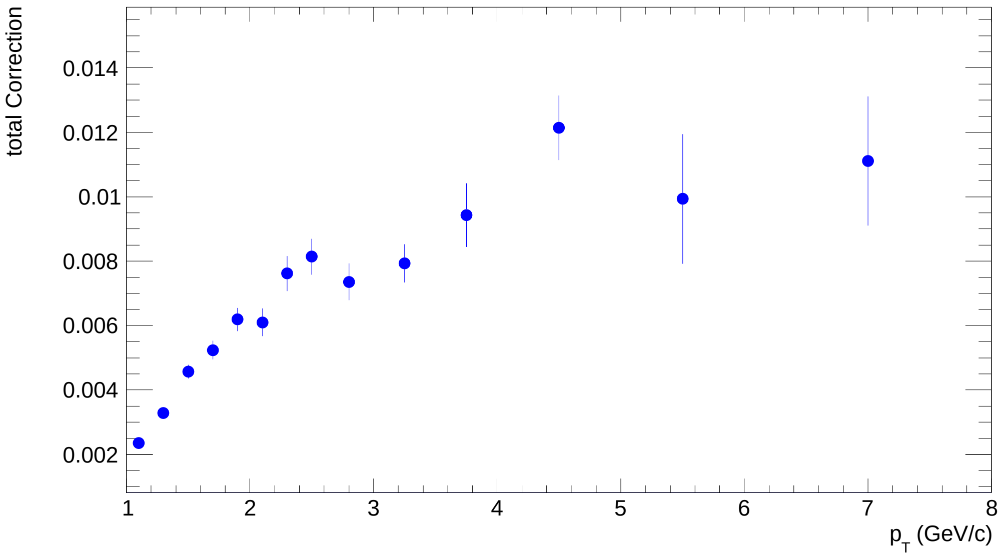

Figure 3: Ratio of reconstructed over produced π^0

4 Acceptance and Efficiency Correction

The π^0 p_T spectrum shown in Figure 3 is the raw yield of π^0s reconstructed in the PHOS. However, this is not yet a meaningful physical quantity. To obtain the overall yield of all π^0s produced in a $p+p$ collision in a certain ϕ and rapidity (y) range, it is necessary to correct for π^0 loss due to the limited acceptance and reconstruction efficiency of the PHOS. The limited acceptance is due to the small coverage of the PHOS of approximately 4% of the solid angle. The limited reconstruction efficiency comes from the limited spatial and energy resolution of the PHOS as well as loss of π^0s during the peak extraction.
The corrections are determined using a full Monte Carlo Simulation of pp collisions at $\sqrt{s}$=2.76 TeV. Roughly 30 million events were generated using Pythia 6 as an event generator. The entire ALICE detector with all material and electronics was simulated by GEANT 3. The simulation was run in 2012 and produced data in the same format as the data from the real detector, with the additional information of the true generated particle spectra.

For the analysis described in this report the Monte Carlo dataset is analysed with the same algorithm as the real data. Using the additional information, the π^0 p_T spectrum produced by the event generator within $0<\phi<2\pi$ and $|y|<0.5$ is extracted. Figure 3 shows the ratio of the reconstructed MC p_T spectrum to the p_T spectrum produced by Pythia 6. This quantifies all the losses of π^0s in the detector including those from the reconstruction and peak extraction algorithms and can be used to correct for these effects in the real data.

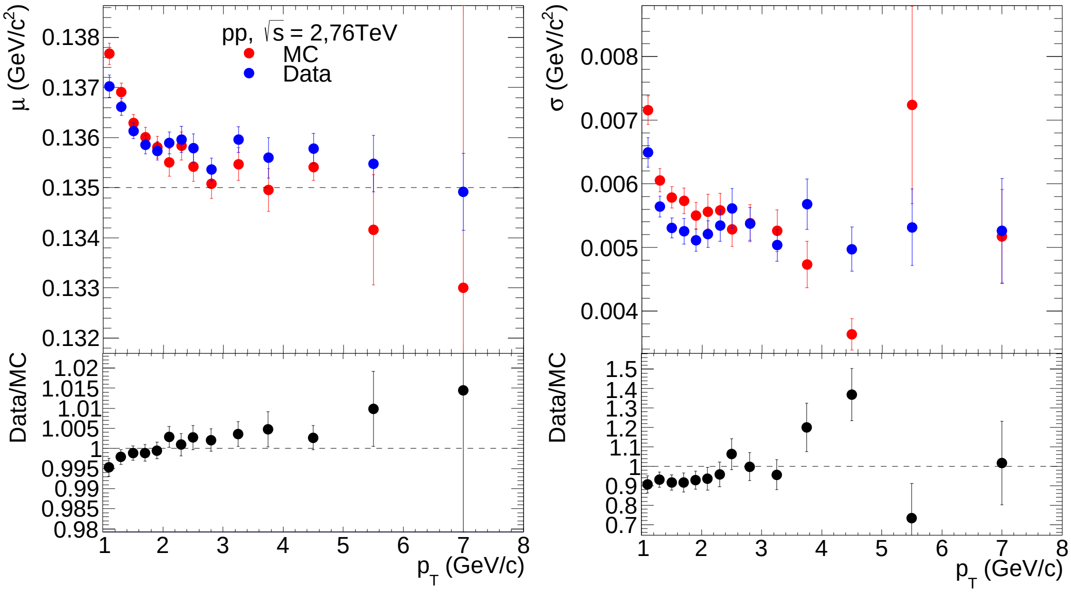

Figure 4: Comparison of μ and σ in real data and Monte Carlo.

The rising shape of the ratio shows that π^0s with lower p_T are more likely to be lost than those with higher p_T.

The main reason lies in the larger opening angle of photon pairs from decays of π^0s with lower p_T. Since the successful reconstruction of a π^0 relies on *both* its decay photons to hit the detector, it is generally more likely for a high p_T π^0 to be reconstructed than a low p_T one. Also, the energy and position resolution of the PHOS is energy dependent and improves slightly for higher energies.

Figure 4 shows the comparison of the μ (left panel) and σ (right panel) of the Gaussian fit to the π^0 peak in both real and simulated data. The μ represents the average value of the reconstructed mass of the π^0 and consequently is an indication of the overall photon energy scale calibration of the detector. The standard deviation σ indicates the mass resolution, which is a convolution of the energy and spatial resolution of the detector. The ratio of data to Monte Carlo in the left panel of Figure 3 shows that the reconstructed π^0 mass in data and Monte Carlo agree within 1 to 2 %. However, there is a rising shape to this ratio. The ratio in the right panel shows, that the agreement in the mass resolution of data and Monte Carlo is within 10% for p_T<4 GeV and within 30% above 4 GeV. This ratio also rises with increasing momentum. The disagreement of data and Monte Carlo in both μ and σ shows that further tuning of the Monte Carlo is necessary to ensure that the calibration of the real and the simulated detector are the same and all effects for π^0 loss are fully taken into accounted.

It also might be necessary to apply a misalignment correction for the module positions,

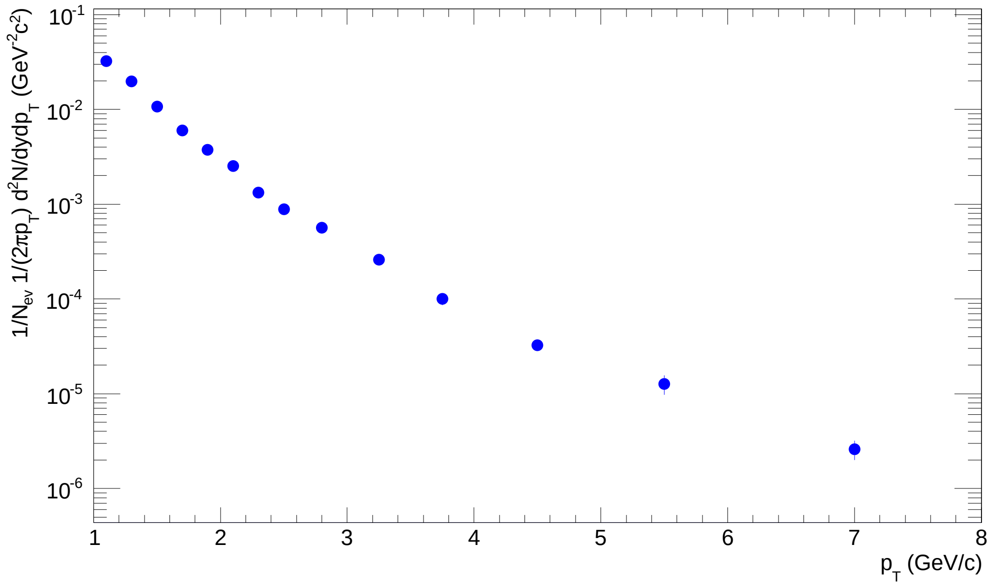

Figure 5: Fully corrected π^0 production spectrum

as has been reportedly applied in other PHOS analyses. This would mainly affect the invariant mass of low p_T Pions because it is more likely that their decay photons hit different modules. This could account for the falling shape of the mass vs p_T for p_T<1.5 GeV for both data and Monte Carlo.

5 Corrected Production Spectrum

To obtain the fully corrected p_T spectrum of all π^0s produced in the $p+p$ collisions within $0<\phi<2\pi$ and $|y|<0.5$ the raw yield shown in Figure 2 is divided by the total correction shown in Figure 3. The proper Jacobian $1/p_T$ normalized result is shown in Figure 5.

The current systematic uncertainties are large primarily due to the differences in the mass position shown in Figure 4. A 1% difference in the energy calibration makes a difference of ~4% in the extracted yield, so the current disagreement of up to 2% of data and Monte Carlo indicates that the yield is potentially shifted to the level of 8%.

Further studies will include adding a timing cut on the clusters as an additional pile up rejection from different bunch crossings, misalignment and energy recalibration studies, better background subtraction methods including a fast Monte Carlo to estimate the contribution of correlated background under the π^0-peak and tuning of the full Monte Carlo results to match the position and the resolution of the reconstructed m_{inv} of the π^0.

The analysis presented is to be seen as a first order baseline analysis. The successful proof of principal analysis has been shown and establishes the efficacy of a full Monte Carlo based efficiency correction. It is the first of its kind with the PHOS detector and provides a foundation for future PHOS analyses at ALICE.

References

[Aam08] K. Aamodt, *et al.* [ALICE Collaboration], *The ALICE experiment at the CERN LHC* , JINST 3 S08002, 2008.

[Del99] G. Dellacasa, *et al.* [ALICE Collaboration], *Technical Design Report of the Photon Spectrometer (PHOS)*, CERN-LHCC-99-04, 1999.

[Nak10] K. Nakamura, *et al.*, *Review of particle physics*, J.Phys., **G 37**:075021, 2010.