Hadronic Trigger using electromagnetic calorimeter and particle identification at high-$p_T$ with the STAR Detector

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Abstract

We derive a new method to improve the statistics of identified particles at high transverse momentum ($p_T$) using online-triggered events by the STAR Barrel Electromagnetic-Calorimeter (BEMC) detector. The BEMC is used to select charged hadrons ($\pi^\pm$, $K^\pm$ and $p(\bar{p})$) via hadronic shower energy deposited in the BEMC. With this trigger, the statistics of the high $p_T$ particles are significantly enhanced (by a factor of up to $\sim$100 for STAR) with trigger efficiency up to 20%. In addition, resonant states ($\rho^0$, $K^*$) and weak-decay V0s ($K^0_S$ and $\Lambda(\bar{\Lambda})$) can be constructed by selecting the BEMC-trigger hadron as one of the decay daughters. We also show that the trigger efficiency can be obtained reliably in simulation and data-driven approaches.

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1 Introduction

One of the main physics goals of the Relativistic Heavy Ion Collider (RHIC) with the experiment of the Solenoidal Tracker at RHIC (STAR) [1] in recent (and future) years is to study the properties of the Quark-Gluon-Plasma (QGP) created in the heavy ion collisions [2]. An important probe is to use the identified high-$p_T$ hadrons to study the color charge effect of parton energy loss in heavy ion collisions [3,4,5,6,7,8]. At RHIC, the luminosity is usually much higher than the detector and data acquisition capability. RHIC delivers $p+p$ collision rates of several $MHz$ while the STAR Time Projection Chamber (TPC) readout is around one $kHz$. Trigger detectors are used to implement an online selection of events of interest to the program. An example of such a detector is the electromagnetic calorimeter (EMC) used to select events with high energy deposit from an electromagnetic shower in the detector. This can enhance the event sample with high energy neutral pions or energetic jets with significant electromagnetic components ($\pi^0$ or $\gamma$). However, STAR has no hadronic calorimeter to select the final state charged hadrons although those hadrons do leave ionization tracks behind in the TPC or other tracking detectors. To date, charged hadron spectra in $p+p$ and $A+A$ collisions at RHIC have only been obtained using a minimum-bias trigger and their upper reach in $p_T$ is severely limited by rapidly falling statistics at high-$p_T$ from such an all-inclusive trigger. For example, the charged pion spectra are so far only measured at RHIC to $p_T \simeq 10$ GeV/$c$ in $p+p$ collisions, while the $\pi^0$ spectra reach $p_T \simeq 20$ GeV/$c$. On the other hand, the STAR EMC contains about one hadronic interaction length of material and can perform online trigger selection of events based on energy deposition in finely segmented towers. Charged hadrons do interact and produce showers with a significant amount of energy in the EMC at a lower efficiency.

In this paper, we present a study of hadronic trigger efficiency from the STAR Barrel EMC (BEMC) [9]. Different BEMC energy thresholds and BEMC patch sizes are used in this study. The inclusive charged hadron spectra are selected from the away-side opposite the struck calorimeter tower (or jet patch). PYTHIA simulations are performed to correct for the trigger effect. In addition to the enhancement of single hadron yields at high momentum, these triggers also allow us to construct resonances and weak-decay particles from their charged hadron daughters by requiring that one of the daughters produce a BEMC signal above the trigger threshold. The trigger effect on resonance and V0 reconstructions is corrected using the experimental data. This approach avoids a demanding simulation of the details of the detector and trigger performances on the struck EMC tower. These not only extend the measurements of identified hadron spectra to much higher momentum, but also provide crucial consistency checks among different measurements over the same momentum range: $\pi^0$ vs $\pi^\pm$, $K^0_S$ vs $K^\pm$. The current manuscript provides the technical
details of the triggers, analyses, correction and systematics while the scientific results have been discussed in Ref. [10].

2 Experimental Setup and Data Analysis

2.1 Detectors and Datasets

The data used for this study were collected with the STAR Experiment in the year 2005 requiring the minimum-bias trigger condition plus energy deposition in the BEMC detector for \( p + p \) collisions. For this data, the total BEMC coverage is \( 0 < \eta < 1 \) and \( 0 < \phi \leq 2\pi \ rad \). Each calorimeter tower covers \( \Delta \eta \times \Delta \phi = 0.05 \times 0.05 \ rad \) in pseudo-rapidity \( (\eta) \), and azimuthal angle \( (\phi) \). The online energy deposition triggers utilize either a single BEMC tower (high-tower trigger, HT) or a contiguous \( \Delta \eta \times \Delta \phi = 1 \times 1 \ rad \) region (jet patch trigger, JP) of the BEMC [11]. A total of 5.6 million JP events with transverse energy \( E_T > 6.4 \ GeV \) are used for \( \pi^\pm, K^\pm \), and \( p(\bar{p}) \) analyses. To reduce trigger biases and to avoid the demandingly precise simulation of hadronic showers and the detector trigger response, only away-side particles (at azimuthal angles \( 90^\circ - 270^\circ \) from the JP trigger) are used in the analyses of the inclusive single charged hadron spectra. The high-tower trigger condition requires the energy of a single calorimeter tower to be at least \( 2.6 \ GeV \) (HT1) or \( 3.5 \ GeV \) (HT2) [12,13]. In total, 5.1 million HT1 and 3.4 million HT2 events were collected from 0.65 \( pb^{-1} \) and 2.83 \( pb^{-1} \) integrated sampled luminosity of proton beams. These datasets are used for \( K^0_S \to \pi^+ + \pi^- \), \( \Lambda \to \bar{p} + \pi^+ \) and \( \rho^0 \to \pi^+ + \pi^- \) reconstruction by requiring that one of the daughter pions or antiproton triggered the high tower.

The TPC covers \( 0 < \phi \leq 2\pi \ rad \) and \( |\eta| \leq 1.3 \) with up to 45 reconstructed hit points to serve as STAR’s main tracking detector. It measures ionization energy loss \( (dE/dx) \) and momentum (via curvature) of tracks in a 0.5 \( T \) solenoidal magnetic field, which together can provide particle identification, including along the relativistic rise at high momentum [14]. Topology of the daughter tracks from high-\( p_T \) \( K^0_S, \Lambda(\bar{\Lambda}) \), \( \rho^0 \), \( K^* \), \( D^0 \) and other resonances can be reconstructed through their hadronic decay into at least one high-\( p_T \) charged hadron. In all of the analyses discussed here, the collision vertex is required to be within 100 cm of the TPC center. More details of hadron identification at high-\( p_T \) [15,16,17] and topological V0 reconstruction of weak-decay particles [8] can be found in the references.
In addition to the required azimuthal angle between the track and the JP trigger center to be $|\Delta \phi| \geq \pi/2 \text{ rad}$ in the analyses of charged hadron spectra of $\pi^\pm$, $K^\pm$ and $p(\bar{p})$, the TPC tracks are selected based on: $|\eta| < 0.5$, distance of closest approach of the track helix projection to the collision vertex to be within $1.0 \text{ cm}$, number of TPC hits to be at least 25 and at least 52% of the maximum possible hits, and the TPC hits involved in the $dE/dx$ calculation after truncation to be at least 15. In each $p_T$ bin, the normalized $dE/dx$, $n\sigma_i$ [15,16,17,18] distributions of positively and negatively charged particles are histogrammed. The detailed method of calibration and extraction of raw counts of the individual identified hadrons from the same data sample has been previously published [15].

The JP triggers enhance the statistics greatly, but also require additional corrections with normalization and momentum-dependent efficiency. Figure 1 shows raw charged pion spectra in the BEMC-trigger events compared to the published results (squares) in minimum-bias events [4]. This demonstrates that charged pions in the BEMC-trigger data sample are enriched by an order of magnitude at low $p_T$ ($\simeq 3 \text{ GeV/c}$) and by three orders of magnitude at high $p_T$ ($\gtrsim 10 \text{ GeV/c}$). To correct for this trigger effect, PYTHIA events are embedded into the STAR detector geometry in GEANT, which can simulate the realistic response of the STAR detector. The Monte Carlo simulation is based on PYTHIA version 6.205 [19] with CDF Tune A settings [20]. The same simulation setup has been used in other jet related analyses [11]. In order to fully cover the falling power-law spectrum in $p_T$ of reconstructed particles with sufficient statistics, the data samples are generated according to the initial parton $p_T$ (in units of $\text{GeV/c}$) intervals $(0,2)$, $(2,3)$, $(3,4)$, $(4,5)$, $(5,7)$, $(7,9)$, $(9,11)$, $(11,15)$, $(15,25)$, $(25,35)$ and $(>35)$. The spectra are weighted by the cross-sections in each parton $p_T$ range. Table 1 shows the absolute cross-sections ($\sigma_i$) for $p + p$ collisions which generate the partons at each given $p_T$ interval and the number of events ($N_i$) going through the full simulation chain. The obtained hadron spectra have to be weighted with the factor (proportional to $\sigma_i/N_i$) according to their originating partons.

The simulation includes detector response to the signal, electronic readout, and detector and background noise when particles propagate through the detector. The BEMC-trigger configuration and thresholds are then applied in the same way as in the real events from experiment. The resulting charged pion spectra from these simulations are shown on the left panel in Figure 1 for the minimum-bias-trigger and the BEMC-trigger events. The enhancement of charged pions can be calculated by dividing the BEMC-trigger spectra by the minimum-bias-trigger spectra from these PYTHIA simulations. The right panel in Figure 1 shows the enhancement factor as a function of transverse
Fig. 1. The left panel shows pion spectra in minimum-bias and BEMC-trigger events from both measurements and the PYTHIA+GEANT simulation. Triggered enhancement from the simulations versus $p_T$ distribution is shown on the right panel.

Fig. 2. Trigger enhancement factor distribution for kaon and proton are shown on the left and right panels respectively.

momentum. Similarly, the trigger enhancement factors for kaon and proton are calculated and presented in the left and right panels in Figure 2. These factors are then applied to the raw spectra to obtain the inclusive invariant differential cross-section of the charged hadrons in $p+p$ collisions as presented in Ref. [10].

Since the correction for the JP trigger relies entirely on the PYTHIA event generator through the STAR detector simulation chain, concerns were raised whether the PYTHIA event generator simulates the jets and underlying event structure correctly and whether the detector simulation reproduces the JP trigger truthfully. To quantify this, several triggers with different jet-patch and high-tower energy thresholds have been used to study the systematic differences among the spectra after all the corrections have been applied, providing an estimate of the systematic uncertainty due to these effects. These are the largest contributions to the overall systematic uncertainties, especially at intermediate $p_T$ [7,10].

Studies have shown that the underlying event structure [21] and the jet spec-
Table 1
Parton $p_T$ interval, the corresponding absolute cross-section and the number of events generated in PYTHIA through the STAR simulation and reconstruction chain.

| parton $p_T$ (GeV/c) | Cross-section (mb) | Number of events |
|----------------------|-------------------|-----------------|
| (0.2)                | 18.2              | 339083          |
| (2.3)                | 8.11              | 507996          |
| (3.4)                | 1.30              | 400629          |
| (4.5)                | 0.314             | 600980          |
| (5.7)                | 1.36e-1           | 431000          |
| (7.9)                | 2.31e-2           | 412000          |
| (9.11)               | 5.51e-3           | 416000          |
| (11,15)              | 2.22e-3           | 416000          |
| (15,25)              | 3.89e-4           | 408000          |
| (25,35)              | 1.02e-5           | 380000          |
| ( > 35)              | 5.30e-7           | 100000          |

tra [11] match well between data and PYTHIA. The results also show that the averaged $\pi^{\pm}$ spectrum obtained from this method are consistent with the $\pi^0$ spectra from both STAR [13] and PHENIX [22] to within 10%. The $\pi^0$ spectra were obtained with a completely different trigger scheme: one of the photons from $\pi^0$ decay has to be reconstructed from the BEMC high-tower, which triggers the event. Therefore, the $\pi^0$ trigger is not affected by the event structure but depends on the simulation of the photon response and trigger efficiency. In the following sections, we describe a similar method to reconstruct resonances and V0 decays by using a BEMC high-tower as a hadronic trigger on one of the charged hadronic daughters. The trigger efficiency of the daughter hadrons is obtained directly from dividing the raw observed spectra of $\pi^{\pm}$ and $p(\bar{p})$ by their respective invariant spectra. Powerful consistency checks on trigger bias and $K^{\pm} dE/dx$ uncertainty are possible by comparing the $K^{\pm}$ spectra from jet away-side triggers and published minimum-bias-trigger results [8] with the invariant spectra of $K_S^0 \rightarrow \pi^+ + \pi^-$ from our hadronic trigger.

### 2.3 Trigger enhancement and efficiency for showering hadrons

In this section, we provide the detailed procedure of obtaining the $\pi^{\pm}$ and $p(\bar{p})$ trigger efficiencies when either is associated with the high-tower that passes the online trigger threshold, where these are daughters from resonance...
Fig. 3. The $\Delta \phi$ and $\Delta \eta$ between tracks and BEMC triggered towers. We note that the splitting into two peaks in $\Delta \phi$ (i.e. in the bending plane) is due to the fact that the TPC track helices are projected to the BEMC surface while in reality the hadronic showers are on average deep within the BEMC.

($\rho^0 \rightarrow \pi^+ + \pi^-$) or V0 ($K_S^0 \rightarrow \pi^+ + \pi^-$, $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(+)$) decays. In offline analysis, a track reconstructed in the TPC is projected to the surface of the BEMC and associated with a shower reconstructed from the BEMC tower energies. The distances between the center of the triggered tower and the track projections are shown in Figure 3. We require $|\Delta \phi| < 0.075$ rad and $|\Delta \eta| < 0.075$ for matched tracks. Projecting the backgrounds under the peaks, we find that these cuts include $\sim 3\%$ of accidental coincidences, most of which will be further reduced by additional cuts.

Although hadronic interactions in an electromagnetic calorimeter develop showers for which much of the energy escapes the detector, a significant fraction of hadrons leave a sizable captured energy deposition. Figure 3 shows the correlation between energy deposited in the triggered tower and momentum of the matched track. The particles are selected between two cuts (shown in the figure) on $E \leq 2 \times p$, to remove accidental coincidences with electromagnetic showers, and $E > 2$ GeV, to reject minimum ionizing particles and other low energy background coincidences. This provides a dataset with a wide momentum range for further particle identification.

The normalized $dE/dx$, $n\sigma_\pi$ [15,16,17,18] distributions at $3.25 < p_T < 3.50$ GeV/c, offset by $+6$ for positive particles and $-6$ for negative particles, are shown in Figure 4. The peaks of triggered electrons and positrons are clearly separated from charged hadrons. Statistics of charged pions and anti-protons are significantly enhanced in comparison to the distributions for minimum-bias-trigger data [15]. The yield of triggered anti-protons is much larger than that of protons because they annihilate with the material in the BEMC and deposit an additional $\sim 2$ GeV extra energy.
Fig. 4. Energy of triggered towers versus momentum of matched tracks. Only tracks with $p_T > 3 \text{ GeV/c}$ are used in the analyses.

Efficiencies can be derived by dividing the raw $p_T$ spectra in the BEMC-trigger events by the inclusive invariant spectra obtained previously (shown in Figure 6 and Figure 7 respectively), and these efficiencies for pions and (anti-)protons are shown in Figure 8 and Figure 9. Although the efficiency is not as high as a pure electromagnetic shower, the trigger enhancement is quite high. Taking pion efficiency as an example, at $p_T=5 \text{ GeV/c}$, the triggered pion efficiency in HT1 is $\sim 2\%$, and therefore the 5.1 million HT1 events (from $0.65 \text{ pb}^{-1}$ sampled luminosity) are equivalent to luminosity $(0.65 \text{ pb}^{-1}) \times \sigma_{pp}^{\text{NSD}}(30 \text{ mb}) \times \text{[trigger efficiency]}(2\%)/\text{[tracking efficiency]}(90\%) = \sim 450$ million minimum-bias-trigger (non-single diffractive [NSD]) events. This means a factor of $\sim 100$ times more statistics for charged pions at this $p_T$ in this data sample than in the previously published minimum-bias-trigger sample [3]. At higher $p_T$, the trigger efficiency and the minimum-bias event equivalents are much higher. The details can be found in Tables 2 and 3. Therefore, the BEMC-trigger data samples significantly enhance the available statistics of the particles at high $p_T$. 

Fig. 5. Normalized $dE/dx$ distributions at $3.25 < p_T < 3.50 \text{ GeV/c}$.

Fig. 6. pion $p_T$ spectra from minimum-bias events and BEMC-trigger events.

Fig. 7. Proton $p_T$ spectra from minimum-bias events and BEMC-trigger events.
Fig. 8. Trigger efficiency and tracking efficiency of pion from BEMC-trigger events.

Table 2
The number of equivalent minimum-bias events ($N_{eq}$) for charged pion at given $p_T$ bin from 5.1 million HT1 and 3.4 million HT2 events respectively.

| $p_T$ | $N_{eq}(\pi^+)$ HT1 | $N_{eq}(\pi^-)$ HT1 | $N_{eq}(\pi^+)$ HT2 | $N_{eq}(\pi^-)$ HT2 |
|-------|---------------------|---------------------|---------------------|---------------------|
| 3.125 | 4.66e+07            | 3.61e+07            | 1.53e+07            | 1.16e+07            |
| 3.375 | 7.56e+07            | 6.11e+07            | 2.89e+07            | 2.15e+07            |
| 3.625 | 1.11e+08            | 9.28e+07            | 5.29e+07            | 4.10e+07            |
| 3.875 | 1.53e+08            | 1.32e+08            | 8.81e+07            | 7.08e+07            |
| 4.25  | 2.29e+08            | 2.03e+08            | 1.64e+08            | 1.37e+08            |
| 4.75  | 3.52e+08            | 3.21e+08            | 3.11e+08            | 2.68e+08            |
| 5.25  | 4.97e+08            | 4.64e+08            | 5.15e+08            | 4.54e+08            |
| 5.75  | 6.62e+08            | 6.30e+08            | 7.77e+08            | 6.97e+08            |
| 6.25  | 8.41e+08            | 8.11e+08            | 1.10e+09            | 9.98e+08            |
| 6.75  | 1.03e+09            | 1.00e+09            | 1.47e+09            | 1.35e+09            |
| 7.5   | 1.32e+09            | 1.30e+09            | 2.13e+09            | 1.97e+09            |
| 9     | 1.86e+09            | 1.83e+09            | 3.59e+09            | 3.38e+09            |
| 11    | 2.38e+09            | 2.26e+09            | 5.33e+09            | 5.02e+09            |
| 13.5  | 2.73e+09            | 2.32e+09            | 6.38e+09            | 5.92e+09            |

2.4 Resonance and V0 reconstruction

The BEMC-trigger data sample not only increases the stable hadron yields to tape, but also provides those high-statistic stable hadrons for the resonance and V0 reconstructions. To reconstruct $K_S^0$ or $\Lambda(\bar{\Lambda})$ via their dominant weak decay channels, $K_S^0 \rightarrow \pi^+ + \pi^-$, $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(+)$, we look for at least
Table 3
The number of equivalent minimum-bias events \((N_{eq})\) for proton and anti-proton at given \(p_T\) bin from 5.1 million HT1 and 3.4 million HT2 events respectively.

| \(p_T\) | \(N_{eq}(p)\) HT1 | \(N_{eq}(\bar{p})\) HT1 | \(N_{eq}(p)\) HT2 | \(N_{eq}(\bar{p})\) HT2 |
|---|---|---|---|---|
| 3.125 | 7.88e+06 | 9.66e+07 | 3.75e+06 | 4.41e+07 |
| 3.375 | 1.59e+07 | 1.41e+08 | 6.79e+06 | 6.70e+07 |
| 3.625 | 2.53e+07 | 1.94e+08 | 1.17e+07 | 1.04e+08 |
| 3.875 | 3.66e+07 | 2.55e+08 | 1.90e+07 | 1.56e+08 |
| 4.25  | 5.77e+07 | 3.62e+08 | 3.53e+07 | 2.63e+08 |
| 4.75  | 9.61e+07 | 5.32e+08 | 7.01e+07 | 4.63e+08 |
| 5.25  | 1.50e+08 | 7.30e+08 | 1.25e+08 | 7.29e+08 |
| 5.75  | 2.24e+08 | 9.53e+08 | 2.06e+08 | 1.06e+09 |
| 6.25  | 3.19e+08 | 1.19e+09 | 3.18e+08 | 1.45e+09 |
| 6.75  | 4.38e+08 | 1.44e+09 | 4.69e+08 | 1.89e+09 |
| 7.5   | 6.56e+08 | 1.81e+09 | 7.77e+08 | 2.62e+09 |
| 9     | 1.16e+09 | 2.46e+09 | 1.68e+09 | 4.09e+09 |
| 11    | 1.66e+09 | 2.92e+09 | 3.20e+09 | 5.50e+09 |
| 13.5  | 1.86e+09 | 2.85e+09 | 4.53e+09 | 5.86e+09 |

one of the decay daughters to be the particle firing the BEMC trigger. This procedure has also been used in the cross section measurement reported in Ref. [8,23].

The reconstructed event vertex is required to be along the beam axis and within 100 cm of the TPC center to ensure uniform tracking efficiency. A search is made in each event to find a (anti-)proton and pion tracks of the opposite curvature. The tracks are then paired to form a \(K_0^0\) or \(\Lambda(\bar{\Lambda})\) candidate and topological selections are applied to reduce backgrounds. Figures 10 and 11 show invariant mass distributions of the triggered \(K_0^0\) and \(\Lambda(\bar{\Lambda})\) at high \(p_T\) with only 3.4 million HT2 BEMC-trigger events, while 10 million minimum-bias events can only reach 5 GeV/c due to limited statistics [8].

To obtain the invariant spectra, we need to apply the correction factors due to the efficiencies of trigger, tracking and topological cuts. The correction is divided into two factors: kinematic efficiency and topological efficiency. We define the kinematic efficiency to include the effects of the BEMC response and trigger, the TPC tracking efficiency, and the acceptance due to kinematics. The topological efficiency includes the effects due to the topological requirements in V0 reconstruction and is found to be \(p_T\) independent at 92% for \(K_0^0\) (the
Fig. 10. Invariant mass of $K^0_S$ at several high $p_T$ bins.

Fig. 11. Invariant mass of $\Lambda$ at several high $p_T$ bins.

217 topological efficiencies of $\Lambda(\bar{\Lambda})$ are still under study as of this writing) [8].

Figures 12, 13 and 14 are the kinematic efficiencies as a function of $p_T$ for the
reconstruction of parent particles $K^0_S$, $\bar{\Lambda}$ and $\rho^0$, respectively.

220 Resonances ($\rho^0 \rightarrow \pi^+ + \pi^-$, $K^* \rightarrow K^{\pm} + \pi^{\pm}$ etc.) can be reconstructed in
a similar fashion. Since $\rho^0$ decays strongly with a lifetime of about 1 fm/c,
reconstruction from its pion daughter pairs is made without the displaced de-
cay topological constraints used in V0 reconstruction. The invariant masses
of unlike-sign ($\pi^+ + \pi^-$) and like-sign ($\pi^\pm + \pi^\mp$) pion pairs are calculated and
shown in Figure 15. Panel (a) from this figure is for the invariant distribu-

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Fig. 12. Kinematic efficiency of $K_S^0$ vs. $p_T$.

Fig. 13. Kinematic efficiency of $\Xi$ vs. $p_T$.

Fig. 14. Kinematic efficiency of $\rho^0$ vs. $p_T$.

Fig. 15. Invariant mass distributions of the unlike-sign pairs $\pi^+ + \pi^-$ and like-sign pairs $\pi^+ + \pi^\pm$ around the $\rho^0$ mass. Panels (a) and (b) show the distributions from Au+Au and $p+p$ collisions respectively. The like-sign pairs represent the random combinatoric background and the excess above this background distribution in the unlike-sign is attributable to particle decays ($\rho^0$, $\omega$, $f_0$, and $f_2$). Figure 16 shows the $\pi^+ + \pi^-$ invariant mass distribution after like-sign background subtraction.
Fig. 16. Invariant mass distribution of $\pi^+ + \pi^-$ around the $\rho^0$ mass. The three panels show fits for (a) a four-species cocktail, (b) cocktail with additional $\sigma_0$, and (c) cocktail with an additional interference term.

For the line shape of $\rho^0 \rightarrow \pi^+ + \pi^-$, the procedure and formula from a low-$p_T$ study are used with the $\rho^0$ mass at 775 $MeV/c^2$ and Breit-Wigner width of 155 $MeV/c^2$ [24]. As with that study, a four-species cocktail describes the data quite well except that it under-describes data at invariant mass around 600 $MeV/c^2$. This is clearly visible in Figure 16(a). To investigate the possible missing components of the cocktail and how they impact the extracted $\rho^0$ yields, we perform two additional studies by adding a $\sigma_0$ to the cocktail and by adding an interference term between $\rho^0 \rightarrow \pi^+ + \pi^-$ and direct $\pi^+ + \pi^- \rightarrow \pi^+ + \pi^-$ scattering. Inclusion of the possible $\sigma_0$ particle [25] (mass at $\sim$600 $MeV/c^2$ and Breit-Wigner width scanning from 100 to 500 $MeV/c^2$) results in 20% lower $\rho^0$ yields and improves the $\chi^2$ per degree of freedom ($\chi^2/NDF$) from 120/36 to 38/33, a factor of nearly 3 improvement. This fit is shown in Figure 16(b) and is used to obtain the default $\rho^0$ yields, where the $\sigma_0/\rho^0$ ratio is about 25% independent of $p_T$. An additional systematic check is performed using the modified Soeding parametrization for a possible interference effect on the $\rho^0$ line shape [26]. This parametrization and the relative amplitudes of its two interference terms are determined from clear signals and well-defined processes in ultra-peripheral Au+Au collisions. Both the resulting $\chi^2/NDF$ and the $\rho^0$ yield fall between the other two fits. Figure 16(c) shows that including the interference over-corrects the high-mass tail of the $\rho^0$ spectral distribution and therefore under-predicts the data.

3 Summary

An electromagnetic calorimeter (the STAR BEMC) is leveraged to enhance the event sample containing charged hadrons at high transverse momentum, utilizing the STAR TPC for momentum reconstruction and species identification through $dE/dx$. The away-side hadrons opposite triggered jet patches (high collective energy in a group of BEMC towers) are used to determine inclusive spectra of identified stable charged hadrons at high $p_T$. Events triggered by high energy in a single BEMC tower are used to find hadronic shower
candidates by matching these towers to high $p_T$ TPC tracks. These tracks are then paired with other charged hadrons to reconstruct $K^0_S$ and $\Lambda(\bar{\Lambda})$ through their dominant decay channels: $K^0_S \rightarrow \pi^+ + \pi^-$ and $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^- (+)$. With this method, spectra of the identified charged hadrons, $K^0_S$ and $\Lambda(\bar{\Lambda})$ have been extended to higher $p_T$ ($\sim 12$ GeV/c) under the existing detector and RHIC luminosity capabilities [8]. This method is also used to extend the $p_T$ reach for efficiently reconstructing strongly decaying particles, such as $\rho^0$ and $K^*$. 

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