Improved Event-mixing for Resonance Measurements

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Abstract

This report first analyzed the reason for the deviation of the event-mixing method in background estimation for resonance research, and one possible explanation is that the event-mixing method cannot reproduce the specific angular distribution of produced particles caused by jet-effects. This assumption was checked by Monte-Carlo simulations with PYTHIA, and a certain method of correction called reweighing was proposed to improve the event-mixing method. The improved event-mixing method was then applied for simulation as well as resonance analysis for experimental data from the ALICE experiment, and the results proved that this reweighing method can improve the performance on resonance signal extraction by reducing the residual background.
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1. Introduction

The journey of understanding our world of matter, why it exists, how it works, was once dominated by a series of searching for new particles. Before the Standard Model was set up, our knowledge was limited at the level of protons, neutrons, electrons, and perhaps muons and pions from cosmic rays in some occasions. We already had the evidence of new particles’ existence at that time, although the mechanism of their formations and their interactions were still in deep fog. We could learn some properties from their decays into more stable forms that we already knew, or in analogy to the oscillators, we regarded the decay products as they had been through a specific interaction — a resonance. With the analysis to the resonance processes of these relatively stable particles, many new particle forms of existence were discovered, from the lightest leptonic resonance for photons, to the heaviest top quark resonance. Even with the most delicate detector in modern science research, we still rely on the resonance researches for particles studies, and our efforts for improving this way of research never stops.

Resonance studies need as much information about the decay products as we can obtain. This research is based on a physics quantity called “invariant mass”. As its name describes, this quantity stays invariant no matter in which reference frame we make the observation, which means the invariant masses for the unstable particle of our interest and its decay products are equal if the conservation law holds. Due to the uncertainty principle, this invariant mass will fluctuate within a narrow range, and the possibility density of invariant mass follows the same Cauchy distribution as the intensity of a driven resonant. And we can extract the information about the resonance — the mother particle of decay, from the shape and the location of resonance peak. However, our invariant mass method may introduce certain background along with the resonance, and in order to extract our resonance, we first need to figure out some methods to deal with the background with precision.

In general, these backgrounds can be reconstructed in two ways — mathematical fitting and track mixing. With mathematical fitting, we only need to think out a function that has the similar shape within the range that contains the resonance peak, and do the fitting. But it was suggested that pure mathematical methods could lead to the missing of hidden physics information[1]. The other one is the track mixing, by which we can reconstruct the background by mixing specific tracks that have the same properties as the backgrounds, for example the event-mixing method, that mixes produced particles in the different collisions. We shall deep investigate this event-mixing method and make improvements. In this thesis, some of the flaws of event-mixing were analyzed, and a certain improvement called “reweighing” was proposed to solve these problems that the normal event-mixing encountered. And finally, we shall apply the improved event-mixing method for resonance research on the data from the ALICE experiment at CERN.
2. Theory

2.1 Mechanism

2.1.1 The Quantum Chromodynamics

Quantum Chromodynamics (QCD) is a branch of quantum field theory which mainly describes the strong interactions between nucleus and its constituents. As the Standard Model unified the electromagnetic interactions and the weak interactions with so-called the gauge theory, the electro-weak interactions were introduced with U(1) and SU(2) gauge invariance. Meanwhile, the strong interactions were attributed to the result of SU(3) gauge invariance. Namely, the Lagrangian involving in QCD is:

\[ \mathcal{L}_{QCD} = \bar{\phi}(i\gamma^\mu D_\mu - m)\phi - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} \]  

where \( D_\mu = \partial_\mu - ig_3 \lambda^a G^a_\mu \) is the covariant derivative. By replacing \( D_\mu \) in the normal Lagrangian with \( D_\mu \), the Lagrangian become invariant under SU(3) transformations, which is a basic assumption in the Standard Model. Notice that \( D_\mu \) introduced a spin 1 vector field \( G^a_\mu \) as the gauge boson for SU(3). \( \lambda^a \) as the generator of SU(3), where \( a = 1 \sim 8 \). The relating fermion is therefore have the corresponding charge \( \phi = (\phi_r, \phi_g, \phi_b)^T \).

One characteristic feature for QCD is that the gauge boson named gluon(a linear combination of \( G^a_\mu \)) carries charge itself which not only allows the interaction between quarks, but also gluons themselves. This leads to different features from EM processes. For high energy processes, a certain phenomenon called asymptotic freedom happens, that was due to the virtual gluon loops in quantum field theory, causing the strength of interaction to drop for decreasing distances.

The other feature is the strong confinement when energy drops. This explains why we cannot find any individual quark in experiment. Any fragment of QCD matter will soon turn into a confined state such as meson or baryon, which provides us a good chance for creation of new particles.

2.1.2 Jet

When two hadrons with extremely high energy collide, a certain process called hard scattering might take place, where the quarks and gluons of two hadrons bumps into each other. Then the constituents, such as quarks and gluons, fly away and carry away energy. The fragments soon begin to cool down and start to hadronize into a bunch of particles, or jet, as it was named. The momenta of these products concentrate in small cones that depend on the initial state of jet when it was produced and the interaction with QCD matter. It is a characteristic feature for hard scatterings that the tracks of produced particles are distributed jet-like.
Fig 2.1 Illustration of a collision that creates a dijet event. The momenta of produced particles are mostly concentrated in small cones.

Fig 2.1 is a sketch for dijet event. As it illustrates, two major fragments with high momentum evolve into jets. In relativistic heavy ion physics, jets are important because the originating hard scattering involves many QCD processes.

While the hard scattering breaks up two colliding particles into many fragments, the soft scattering only involves few processes. With a tiny portion of momentum transferred during the scattering, the effective collision energy is limited, and the possibilities for breaking up two colliding particles is heavily reduced as well, where the elastic scattering and inelastic scattering dominate. The productions of soft scattering are much fewer than hard scattering, as well as their angular distribution.

![Elastic scattering and Single Diffraction](image)

Fig 2.2 Two of feature processes of soft scattering

In reality, the soft and hard scatterings happen simultaneously, where the fraction for soft scattering drops when the effective collision energy rises. In order to break the confinement of QCD matter in heavy nuclei, the colliding particles need to be accelerated at high energy, where the hard scattering becomes significant and the production of many heavy particles will be possible. Therefore further studies for hard scattering are worthwhile as they enhance our understanding towards the way the QCD matter interact.

2.1.3 Resonances

So far no evidence has been found to support the existence of stable mesons. But comparatively, the mean life-time of mesons still varies from $10^{-24}$ seconds to $10^{-8}$ seconds (for instance a η meson has a lifetime of $(5.02 \pm 0.19) \times 10^{-19}$s, while a $\pi^\pm$ has $(2.6033 \pm 0.0005) \times 10^{-8}$s [3]). When it comes to the LHC's energy scale (e.g. $\sqrt{s} \sim 10$ TeV), with the help of delicate and sensitive detectors with fast response and large physical size up to ten meters, it is possible to measure long-lived mesons. The difference in the mean life-time decides which of them decays inside or outside
the detector. For the relatively stable mesons such as $\pi^\pm$ and $K^\pm$, they travel through the inner detectors and we can identify them directly by certain method of particle identification. However, for those mesons with comparatively shorter mean lifetime, their existences could only be inferred from their potential decay products.

The information of those products were analyzed. Here the Lorentz-invariant rest mass $m_{inv}$ was used:

$$m_{inv} = \sqrt{(\sum_i E_i)^2 - (\sum_i \vec{p}_i)^2}$$

(2)

The sum indices are over all products in one single decay. It's important to choose one that was invariant under the Lorentz transformation, because we change between detector frame and the CM(center of mass) frame frequently. Besides $\sqrt{s}$ was referred as invariant mass $m_{inv}$ if we use nature units ($c = h = 1$), since it also describes the rest mass of initial particle when certain decay was investigated. With conservation of energy, the invariant mass should remain unchanged after the decay. That means, if we calculate the invariant mass of any potential combination of decay products, the peak should be revealed at the corresponding rest mass of mother particle. This shows similar scheme as a "resonance" of two daughter particles.

The resonance signal is usually described by a continuous probability distribution which comes from the Breit-Wigner function.

$$f(E) = \frac{k}{2\pi} \frac{1}{(E-m_0)^2 + \Gamma^2/4}$$

(3)

There are 3 properties of a resonance peak with Breit-Wigner form: The position of the peak $m_0$ that gives the mass of initial particle, the height of the peak, and the Full Width Half Maximum(FWHM) $\Gamma$ that depends on the lifetime $\tau$ via $\Gamma = 1/\tau$. Besides, the total area of the peak gives the yield of events, i.e. the total number of resonances detected.

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**Fig 2.3 An example of Breit-Wigner Peak**
2.2 Particle Correlations and Background

2.2.1 Invariant mass method

One crucial reason to abandon the analysis in the momentum space is to reduce the cost of storage space. For example, the analysis above are within the momentum space, where the statistics will become enormous when investigating a huge number of events. If we assume an event that gives N tracks, then it will take up at least 4N units of storage space for all 4 components of momentum. The pairing process then almost squares the statistics, by a scaling N-1 factor. If we continue calculating in the momentum space, two individual momentum 4-vectors will take up 4N(N-1) each at least. To reduce the fluctuation, the data per run usually contains 100 millions of events and nearly 100 tracks per event, and the processing could take few days.

Hence all data regarding to individual momentum were replaced by their invariant mass distribution. For each pair only their $m_{inv}$ was recorded, and the storage cost could be reduced to 1/8 approximately as well as the time consumption, which is more acceptable. Moreover, the analysis on the invariant mass of particle pairs is more straight and clear than their own momentum. The correlations of resonance will show as narrow peaks, while the uncorrelated pairs will show as background in the $m_{inv}$ distribution (will be further explained in 2.2.2 and 2.2.3), which is convenient to extract the relating information about the resonance of interest.

For our analysis on the resonance, the decay channel was fixed at a specific type, for example, $K^+K^-$ pair. With this method, we assume the mass of every decay product to be $m_{K^\pm}$, where all tracks except for real $K^\pm$ were mistakenly counted. The invariant mass distribution of the track pairs that involves such mistakenly counted tracks will contribute the background. Usually, a proper particle identification (PID) process could reject those tracks and reduce the background. Namely the mass for each track can be determined with its velocity and momentum:

$$m^2 = \vec{p}^2 (\beta^{-2} - 1)$$  (4)

$\beta$ is the velocity of track in nature unit, which can be determined by the Time-of-Flight (TOF) detector. Unfortunately this type of PID method will not work for low $p_T$ tracks since they will not sustain long enough to reach the TOF. For this reason, the PID data was not used in this thesis. And according to the simulation result, our methods of background reconstruction can actually reproduce the part that involves with these mistakenly calculated tracks, therefore the PID is not necessary here. To further discuss the background in the invariant mass method, we can use simulation data to separate these components since all information regarding to each track is accessible for simulated event.

2.2.2 Correlated pairs

To reconstruct the resonance peak for short-lived mesons, one must acquire information from their decay products, which are relatively stable particles, such as $\pi^\pm$, $K^\pm$, photon, or proton. These particles were recorded by detectors and output as signals independently. In order to obtain the invariant mass at the right “position”, the pair of selected decay products has to come from the same resonance. This is impossible to achieve especially for events with high multiplicities [1, p546], where tens of secondary products are generated per collision but most of them are not related to each other by the resonance of interest.

In this report we only investigate the $A \rightarrow B + C$ decays, and all other decay channels giving 3 or more secondaries are regarded as background. When we pick any two tracks from one event, several possibilities could happen. If these two tracks come from the same resonance, then they are
correlated due to the conservation of momentum. In the CM frame, the momenta of these two particles always have same magnitude but opposite direction, and the width of invariant mass peak is equal to the decay width of resonance particle. When we observe them in the laboratory frame, the momentum vectors of these two decay products become closer. Namely, we denote the resonance distribution by[1]:

$$\Phi(\vec{P}_1, \vec{P}_2) = \int d^3 P_R \, d m_R \, d^3 P \, f_R(m_R, \vec{P}_R) f(\vec{P}) \delta^3(\vec{P}_1 - L(\vec{v}_R, m_1)\vec{P}) \delta^3(\vec{P}_2 - L(\vec{v}_R, m_2)(-\vec{P}))$$  (5)

where $f_R(m_R, \vec{P}_R)$ is the momentum and mass distribution of resonance particle, $f(\vec{P})$ is the production multiplicity of particle 1 from resonance R in its rest frame, and $L(\vec{v}_R, m)$ is the Lorentz transform operator that changes momentum in CM frame of resonance into the laboratory frame. We denote $\Phi(\vec{P}_1, \vec{P}_2)$ as $\Phi_{12}$ for simplicity. The resonance signal is proportional to the total number of resonances created in this event as well. If the initial particle is produced at rest, i.e. $\vec{v}_R = 0$, then the signal $\Phi$ only exists for $\vec{P}_1 = -\vec{P}_2$ as we described for the CM frame. For anywhere $\vec{P}_1 \neq -\vec{P}_2$, the resonance signal gives zero. Other correlations are neglected, such as the global momentum conservation and the momentum conservation in the jet evolution, due to the high production multiplicity in heavy ion collisions[1, p546]. Normally, $\vec{v}_R \neq 0$ and therefore $\vec{P}_1$ is not necessarily equal to $-\vec{P}_2$. Although the invariant mass remains unchanged, the width of a moving resonance peak is much wider than a stationary decay width.

2.2.3 Uncorrelated pairs

Although some specific detectors allow us to reconstruct the primary vertex of tracks, the accuracy is not enough for telling the correlation directly. Therefore it's impossible to distinguish the origin of resonances product from initial data. For example, to find a resonance $\Phi(1020)$, we need to use its decay channel into a pair of $K^\pm$(The other two main channels were neglected since we only count in $A \rightarrow (P + C$ decay)). Meanwhile, other processes are also possible to create $K^+$ or $K^-$, giving “the background tracks” regarding to our resonance of interest. Hence we have many possibilities when picking out a $K^+$ and a $K^-$ from the same event. Namely, if we assume collision event that produced N tracks in the end, where only $N_R$($N_R$ is usually much less than N) $\Phi(1020)$ resonances were created during the event, the possibilities of randomly picking out two charged kaons are:

1. Two kaons are from the same resonance $\Phi$
2. Two kaons are from the different resonance $\Phi$
3. One of them is the background track, the other one from the resonance $\Phi$
4. Both of them are the background tracks

2, 3, 4 are therefore uncorrelated pairs. The most straight way to identify any pair of resonance is to apply the exhaustion method, that combines all possible track pairs in same event. By doing so, not only correlated pairs but also uncorrelated pairs were counted in.

![Fig 2.3 Correlated pair and uncorrelated pair in the invariant mass method. The arrows represent the momenta of these tracks in their CM frame.](image)
An example of correlated pairs is sketched in Fig 2.3 left, where the distribution of invariant mass should be confined in a narrow region at the mass of R1 due to their correlation. While in Fig 2.3 right above, we pick two tracks from the same event, where A1 is from resonance R1 and B2 is from R2. They are not correlated since they don’t originate from same decay and we already neglected other correlations except for resonances. Hence the invariant mass of this pair could take any value even if R1 and R2 are the same type of resonance. As a result, the invariant mass of those uncorrelated pairs would follow a much broader distribution than resonance peak. This part of invariant mass distribution was named as “combinatorial background”[2].

To extract the resonance signal from all these correlated and uncorrelated pairs, one must first manage to reconstruct the combinatorial background. For relatively weak background with less or no fluctuation near the resonance peak, the polynomial fitting is useful. However the fitting does not contain any physics information, and its correspondence to the background will not be satisfying especially for comparatively weak resonance signal with strong background in the fitting region. To avoid that, the background reconstruction needs to be processed with the methods that correctly utilize the physics information from experiment, such as the event-mixing method and the like-sign method. In the following sections we will mainly focus on the event-mixing method and its problems while the like-sign method as a comparison, then the improved event-mixing method will be applied to analyze the data from ALICE experiment.

2.3 Background Reconstruction

2.3.1 Like-sign and unlike-sign

For the resonance of two opposite charged particles, the extraction of signal can be done with the like-sign background reconstruction. The major assumption of this method is that the so-called unlike-sign pair distribution must contain the resonance signal, while the like-sign do not contain any resonances. By combining all possible pairs with the same sign of electric charge(like-sign), the correlation of resonance is completely excluded as the assumption. On the other hand, the unlike-sign consist of all correlated pairs as well as those uncorrelated but opposite-charged pairs. When calculating the invariant mass distribution of these two, the unlike-sign method gives the resonance peak of interest that comes from the correlated pairs and the background from those uncorrelated pairs with opposite charge. Correspondingly, the like-sign method only gives the background that comes from uncorrelated pairs with same sign of charge. These two backgrounds are approximately the same and therefore we can use the like-sign distribution to estimate the background and to extract resonance signal from unlike-sign distribution.

One major problem of the like-sign method is that the distribution of like-sign uncorrelated pairs and unlike-sign uncorrelated pairs are not exactly the same. This difference in statistics between positively charged and negatively charged may result from the limited detector acceptance ability, which leads to extra deviations for background reconstruction.

Besides, the like-sign method was limited because it needs that the decay products have opposite electric charge. For those decay channels that give neutral products or only one charged product, we need to find another method.

2.3.2 Event-mixing method

The event-mixing method uses tracks in different events to estimate the uncorrelated pair distribution(the “combinatorial background” as referred) when calculating invariant mass distribution. The discussion in section 2.3.3 has already showed that the combinatorial background
is from track pairs that do not correlate directly. Then we can artificially choose some uncorrelated pairs, for example the pair from different events, to reproduce the background.

For example in Fig 2.4, the event-mixing method combines the track A from the resonance R, and track B from resonance R’, where R’ was produced in any event other than which R comes from. By doing this, A and B’ are definitely uncorrelated, while the types of their resonances are still the same[2]. Therefore the distribution of event-mixing in general start at the same point with combinatorial background.

![event-mixing and same event](image)

**Fig 2.4 Sketch of a event-mixing pair and a same event pair. Both of pairs are uncorrelated and their distributions of invariant mass give background.**

However, the normal event-mixing method missed one characteristic feature in high energy collisions, the jet-effect in hard scattering. As we mentioned in 2.1.1, the fragments created in collision will evolve into jets that centralized the angular distribution of a single event. And the relative direction of A and B’ in Fig 2.4 left will be closer rather than isotropic. On the other hand, the event-mixing method only involves the pairs totally uncorrelated, where the relative direction of A1 and B2 in Fig 2.4 right will be totally isotropic as result. This will certainly deteriorate its correspondence with the background. As we divide all statistics by their total transverse momentum $p_T$, we even expect the event-mixing in high $p_T$ bins fit worse than in low $p_T$ bins since the high $p_T$ bins for same event have more centralized angular distribution.

An another intrinsic drawback for the event-mixing is its low correspondence in reproducing the background for low multiplicity events. In principle, the event-mixing method is efficient for the type 3 and 4 background in 2.3.3, given enough production multiplicity to create approximately same structure for background particles. Yet for low multiplicity events, such as proton-proton collisions, the structure of background particles sometimes are diverse, preventing it from reproducing background type 3 and 4. As we only focus on lead-lead collisions, this problem will not show up in our analysis in this report.
3. Data Resource

3.1 PYTHIA 8.2

In order to develop our understanding of background distributions mentioned in 2.3, we need a tool to simulate the collision events so that we can study the information which experimental data cannot give us, such as the knowledge of the mother particle. Using this information, it is even possible to know whether a pair was correlated or not.

The PYTHIA program[5] is a standard tool that is able to generate events in high-energy collisions of elementary particles. It is based on both QCD and phenomenological models, where parameters were determined from data. The program includes a set of physics models for hard processes, soft processes and parton-related processes that describe the evolution from hard scattering processes to complex multi-particle final states.

Before PYTHIA, there was a former program called JETSET that began development in 1978. The older version of PYTHIA was written in Fortran 77. Since PYTHIA 8100, the whole program was rewritten with C++. The transition from old version to new frame is still in progress to make up any missing features that old version once had, add new functions, and fix any potential bugs. By now the newest released version is 8200, which has reached a good completeness that offers full replacement for most applications in old versions, especially for LHC physics studies. Besides, many new feature should make improved description of data[5].

There are few places of approximate calculation in PYTHIA frame, for instance the hadron-hadron cross section calculation, the string-fragmentation model. When the CM energy drop below 10GeV(corresponding to proton beam energy of 50GeV on fixed proton target), the approximation start to fail, hence the result from PYTHIA is no longer reliable. The opposite extreme case is at high CM energy. The PYTHIA model is reported mismatching with experimental data when it comes to the extrapolation at 7TeV[5]. Therefore we should keep it in mind to utilize PYTHIA at proper energy scale.

![Fig 3.1 Sample final state data of pseudo-rapidity and mass distribution, generated by PYTHIA with proton-proton collision at $\sqrt{s} = 13$TeV](image-url)
3.2 The ALICE Experiment at the LHC

A Large Ion Collider Experiment (ALICE) is a heavy-ion detector designed for strong-interaction studies of the Standard Model (QCD processes). The experiment is located at the CERN Large Hadron Collider in Geneva, which is one of the largest particle physics experimental facilities in the world.

In comparison with other experiments at the LHC, the ALICE detector was optimized for heavy-ion collisions, such as Pb-Pb collisions. The goal for the design was to investigate the strong interacting matter at extreme temperature and energy densities in nucleus-nucleus collision, and the phase of matter called quark-gluon plasma. It allows a comprehensive study of hadrons, electrons, muons, and photons, since the heavy nuclei collisions produce these in very high multiplicities[4].

![Fig 3.2 The schematic layout of ALICE detector](image)

The ALICE detector is made of multiple sub-detectors and each one of them has its covering aspect. Here we only present 3 major sub-detectors involved with the example data related to this report, the Inner Tracking System (ITS), the Time Projection Chamber (TPC), and the Time-of-Flight detector (TOF).

3.2.1 The Inner Tracking System

The Inner Tracking System is installed surrounding the beam pipe with label ○ in Fig 3.1. The main tasks for the ITS are to locate the vertex of tracks with a resolution better than 100 μm, to cover the dead region for the Time Projection Chamber or tracks with insufficient momentum (less than 0.2 GeV) to reach the TPC, and to enhance the resolution of the momentum vector reconstructed.
The ITS consists of six cylindrical, coaxial layers that are mounted around the beam pipe. The innermost two layers are Silicon Pixel Detectors (SPD), which have supreme spatial resolution to handle the most extensive impacts inside. The outer two layers are double-sided Silicon micro-Strip Detectors (SSD), which provide the dE/dx information of each track. For non-relativistic measurement, this could be used as particle identification. The two layer between SPD and SSD are Silicon Drift Detectors that supplement SPD and SSD to form 3-D reconstruction of incoming tracks. There are also thermal layers between SPD and SDD, SDD and SSD to keep them working under proper temperature.

### 3.2.2 The Time Projection Chamber

The Time Projection Chamber (TPC) is the main tracking device of ALICE. It is optimized for charged particle momentum measurements. Besides, it also measures dE/dx for PID.

The TPC is based on the mechanism of gas chambers, as a combination of drift chamber and multi-wire chamber. As Fig 3.4 shows, the basic shape of TPC is a hollow cylinder, and the beam pipe is installed along the z-axis in the hole with the ITS. The drifting volume is filled with the gas mixture (Ne/CO₂/N₂), and the central HV electrode create a strong electric field nearly parallel to the z-axis. When the charged particles travel through the drift chamber, they soon trigger ionization along the track. The electrons liberated are then accelerated by electric field and drift towards the readout wire chambers at the end of TPC. The readout wire chambers measure the electrons information, such as the time of flight, and the total electric charge, as digital signal for further analysis. Technically, a TPC can fully reconstruct the track of any incoming charged particle as well as its energy loss per unit length, and the precision of detection can be improved in coordination with other detectors such as the ITS.
The TPC installed at ALICE covers full tracks with pseudo-rapidity $-0.8 < \eta < 0.8$, where the pseudo-rapidity is defined as:

$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$$

where $\theta$ is the polar angle. It also enables $2\pi$ azimuthal angle detection coverage for charged particles. The resolution for tracks in the x-y plane depends on the capability of the readout wire chambers. The readout chambers are actually multi-wire proportional chambers. Due to the radial dependency of the track density, the readout chamber is segmented into two different regions. For the inner part, the active radial region is from 84.8cm to 132cm, and for outer chambers, the active radial region is from 134.6cm to 246.6cm[6]. This design optimizes the spatial resolution and separation for different active areas, but will create an acceptance gap between two instrumental sectors, as illustrated in Fig 3.4.

### 3.2.3 The Time-of-Flight Detector

Outside the TPC, a cylindrical surface shaped detector was installed for the purpose of PID in the intermediate momentum range(<2.5GeV for kaons and pions, <4GeV for protons). Coupling with the ITS and TPC for track and vertex reconstruction and for dE/dx measurements in the low momentum range(<1GeV)[4], the time-of-flight detector will provide a detailed PID information of large samples, which can help reducing a considerable fraction of background in the invariant mass studies.

![Fig 3.5 Schematic cross section of a 10-gap double-stacked MRPC strip](image)

The main frame of Time-of-Flight detector consists of 18 sectors azimuthal and 5 segments in z direction covering $-0.9 < \eta < 0.9$, where each one mounted a module made of a group of 10-gap double-stacked multi-gap resistive plate chambers(MRPC) strips. The strips are placed inside gas-sealed modules which act as Faraday cages, and the gaps are filled with gas where high voltage is applied. The particle traversing the gap will trigger a ionization cascade along with its track, and the signal is then picked up by electrodes outside the gaps. After proper discriminating and amplifying, the signal from the MRPC then forms the information of movement about the traversing particle. By comparing with the interaction time with other detectors, we can deduce the time of flight[4].
4. Analysis Method

4.1 Simulation Result

The PYTHIA program provides the possibility to recover all information regarding to the tracks in simulated events. Thus we can preview the performance of our methods on the background reconstruction before applying them to real data. By doing so we can also discover the problem with event-mixing in first place.

The simulation was run with the PYTHIA 8200, for proton-proton collision at $13\text{TeV} E_{\text{CM}}$, and 300000 events were produced totally. In order to simulate the TPC acceptance limitation in the ALICE experiment, an artificial limit of pseudo-rapidity was applied to PYTHIA output data that $|\eta| < 0.8$.

![PYTHIA Result: Same Event](image)

**Fig 4.1** A simulated invariant mass distribution $m_{\text{inv}} = 0\sim 1.4\text{GeV}$, all tracks calculated with their real mass

The plot above is the result from PYTHIA with invariant mass method applied, where the real mass of every track has been applied to calculate the invariant mass. By doing so, all resonance peaks are revealed at once, which needs full PID information if we try to achieve this for real data. The black solid line is the invariant mass distribution of all pairs. Then the distribution was separated into red and blue by whether two tracks in the pair share the same mother particle or not. The red line is for pairs that two tracks don’t share the same mother particle(s) so they can’t come from the same resonance at all. This represents the combinatorial background without the elastic scattering part. The blue line is for pairs have the same mother particles. It consists of peaks and continuous part, where the peaks are the resonance signal that we want, and the continuous part is due to elastic scattering processes.
Fig 4.2 The same simulating result of invariant mass in different decay channels (γγ, ππ, and KK)

For real data, we apply the invariant mass method for only one decay channel once, and therefore only the corresponding resonances show in the right frame. Fig 4.2 illustrates the invariant mass distribution of a same set of data from PYTHIA simulation in 3 different decay channels. The backgrounds always start at the total mass of two investigated decay products i.e. for γγ it starts at 0GeV, for ππ it starts at $2m_{π^±} \approx 0.279$GeV, and for KK it starts at $2m_{K^±} \approx 0.987$GeV, meanwhile the resonances only show given the right frame.

The aim of event-mixing method and like-sign method is to reconstruct the background, i.e. the continuous part in blue plus the red one above, then extract the pure resonance within the signal. In fact, we can not completely wipe out all backgrounds because of lacking enough understanding the nature of those resonances and the uncertainties in production. After the background subtraction, the resonance along with the residual of background left, which enables us to looking into the resonances with higher precision. With less background left, we can achieve a higher precision and more clear physics picture in our analysis. In other words, the performance of resonance extracting depends on the scale of remnant background after the background subtraction.

4.1.1 Normal Event-mixing

The distribution of event-mixing pairs was rescaled by a factor approximately $1/N_{\text{mix}}$, where $N_{\text{mix}}$ is the number of events used for mixing, to make the estimated background with event-mixing closer to the real background where no resonance exists.
Fig 4.3 Event-mixing in different decay channels. It works for all these 3 decay channels, but the residual backgrounds still exist

4.2 Problems in Normal Event-mixing

In general, the event-mixing method reproduces the combinatorial background with good matching overall, including the elastic scattering part as well. But it is not hard to find that the shape of event-mixing background did not match the real background perfectly. One possible reason, as we mentioned in 2.3.5, is the missing jet-effect in event-mixing. To prove this assumption, we can start from a simplified version that only considers the jet-effect on the transverse direction.
Fig 4.4 The transverse projection of momentum for high $p_T$ bins(left) and for low $p_T$ bins(right). The relative $\Delta \phi$ distribution for high $p_T$ bins will be more asymmetric than low $p_T$.

First, we divide all statistics by their total transverse momentum $p_T$. In high $p_T$ bins, the transverse momentum accounts for a larger fraction in its total momentum, as well as the asymmetric property caused by jet-effect as illustrated in Fig 4.4. When it comes to the low $p_T$ region, less asymmetry on the transversal surface will show up. This feature can be observed by looking at the $\Delta \phi$ distribution.

Fig 4.5 The $\Delta \phi$ distribution for same event signal and for event-mixing. The jet-effect in signal leads to a centralized distribution, meanwhile it is totally isotropic for event-mixing.

The overall $\Delta \phi$ distribution for same event is jet-like as blue crosses illustrate in Fig 4.5, centered near $\Delta \phi = 0$. Meanwhile, the distribution for event-mixing in red is isotropic which accords with our understanding. Then we divide the $\Delta \phi$ by $p_T$ into 3 regions: low $p_T$ from 0-2GeV, intermediate $p_T$ from 2-5GeV, and high $p_T$ from 5-10GeV.
Fig 4.6 The $\Delta\phi$ distribution for 3 different $p_T$ regions. The asymmetry due to jet-effect can be inferred from the same event to event-mixing ratio.

Notice that $\Delta\phi$ distribution for event-mixing is not completely isotropic for any fixed $p_T$ bins. Actually when the investigated $p_T$ region is fixed, the choice for $\Delta\phi$ are affected as since they are not independent to each other:

$$p_T = \sqrt{(p_{x1} + p_{x2})^2 + (p_{y1} + p_{y2})^2} = \sqrt{p_{T1}^2 + p_{T2}^2 + 2p_{T1}p_{T2}\cos (\Delta\phi)}$$  \hspace{1cm} (7)

Where $p_{T1} = \sqrt{p_{x1}^2 + p_{y1}^2}$ and $p_{T2} = \sqrt{p_{x2}^2 + p_{y2}^2}$. The same event to event-mixing ratio of $\Delta\phi$ in Fig 4.6 could be used as a comparison between jet-like signal and isotropic event-mixing. Namely, the $\Delta\phi$ distribution in high $p_T$ region is more centralized at 0 than low $p_T$. Comparing to the isotropic event-mixing, the signal contains twice the track pairs that have same azimuthal angle($\Delta\phi = 0$) due to the jet effect. Meanwhile, in low $p_T$ region, this ratio only slightly fluctuates, representing a similar $\Delta\phi$ distribution as random mixed, i.e. low asymmetry comparing to the situation for high $p_T$.

Since the invariant mass was related to $\Delta\phi$ by:

$$m_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} = \sqrt{m_1^2 + m_2^2 + 2E_1E_2 - 2p_{T1}p_{T2}\cos (\Delta\phi) - 2p_{x1}p_{x2}}$$  \hspace{1cm} (8)

We can do the same dividing with $p_T$ for the invariant mass distribution. In Fig 4.7, the event-mixing is overestimated on the left and underestimated on the right for low $p_T$ bins. And this
relation interchanged for high \( p_T \) bins. Even after a proper rescaling of the estimating background, this problem does exist, especially for high transverse momentum pairs.

Fig 4.7 The simulation result of invariant mass from PYTHIA, statistics are divided by their total transverse momentum \( p_T \)

From above we notice that the remnant background shows different pattern for low \( p_T \) and high \( p_T \) bins. For low \( p_T \) bins, the fractional residual background varies from around -0.04 to 0.04, which means the event-mixing can reconstruct about 90\% of background in low \( p_T \) region. This fraction significantly drops when we reproduce background in intermediate \( p_T \) and high \( p_T \) region. For 2-5GeV bins, the fractional residual background varies from -0.06 to about 0.2, and in high \( p_T \) region it even increased. This phenomenon proved our assumption about the event-mixing, that the major problem for event-mixing is the missing jet-effect. If we manage to reproduce the jet-like \( \Delta\phi \) distribution in event-mixing, it would be possible to improve the performance of event-mixing.

4.3 Reweighing

One possible method to reproduce the jet effect in event-mixing method is to apply an weighing ratio for each pair in event-mixing. The reweighing ratio \( W \) is defined as:
\[
W(p_T, \Delta \phi) = \frac{\int dm f(m_{\text{inv}}, p_T, \Delta \phi) - \sum_i \int_{M_i - n\Gamma_i/2}^{M_i + n\Gamma_i/2} dm f(m_{\text{inv}}, p_T, \Delta \phi)}{\int dm f_{\text{em}}(m_{\text{inv}}, p_T, \Delta \phi) - \sum_i \int_{M_i - n\Gamma_i/2}^{M_i + n\Gamma_i/2} dm f_{\text{em}}(m_{\text{inv}}, p_T, \Delta \phi)}
\]

(9)

where \( f \) is the same event pair distribution, and \( f_{\text{em}} \) is the event-mixing distribution. The integral limit is from \( M_i - n\Gamma_i/2 \) to \( M_i + n\Gamma_i/2 \), where \( M_i \) is the approximate position of the \( i \)-th resonance peak, and \( \Gamma_i \) is the corresponding width. In general, the reweighing ratio is the quotient of two marginal distributions, while the region \( m_{\text{inv}} \sim (M_i - n\Gamma_i, M_i + n\Gamma_i) \) that contains the resonance peak excluded. The reason for rejection is to make less correlated pairs involved in reweighing. For any Breit-Wigner resonance peak, \( n = 1 \) rejects 50.32\% of resonance yield, and \( n = 5 \) rejects 87.99\%. But notice that the reweighing also need enough uncorrelated pairs to reproduce the asymmetry in our signal due to the jet effect. For large width resonances, we need to reduce \( n \) to 0~3 for a better jet-effect reproduction. But for narrow width high production resonances, we can increase the width of rejection region by raising \( n \) to 3~20 to exclude more resonance pairs for a better background reconstruction.

As the reweighing of \( \Delta \phi \) may reproduce the jet-effect in the transverse direction, we can also reproduce it in \( z \) direction. The alternative for \( \Delta \phi \) is \( \Delta \eta \), the difference of pseudo-rapidity as defined in 3.2.2. While \( \Delta \phi \) describes the relative transverse direction of two tracks, \( \Delta \eta \) actually describes the relative polar angle. Owing to the acceptance limit of the TPC, \( \eta \) was limited within -0.8~0.8.

The combination of \( \Delta \phi \) and \( \Delta \eta \), \( \Delta R = \sqrt{\Delta \phi^2 + (\Delta \eta)^2} \), which integrated two angular parameters, describes these two at once, and it obviously provides more information than \( \Delta \phi \) since it also describe the angular relation in the \( z \)-axis.

![Image](image.png)

**Fig 4.8 The \( \Delta R \) distribution for different \( p_T \) regions**

By applying this reweighing ratio to normal event-mixing method, in principle, it compensates the difference for event-mixing and same event pair background in \( p_T \) and \( \Delta \phi \) distribution. And we may also compare the performance of different reweighing ratios. Here is the comparison:
According to the result of PYTHIA, the reweighed event-mixing method obviously had a better performance than normal event-mixing at least for light resonances. The residual background to background ratio was reduced to $(-0.039, 0.028)$, while the ratio for normal event-mixing was $(-0.046, 0.065)$. The narrower this region is, the less percent of residual background would be.

4.4 Analyzed Data

The data analyzed was from the ALICE experiment, run no. 195531 in 2013 second pass, in proton-lead collision at 13TeV. The raw data directly from the ALICE was made available in a simple
format by the particle physics division of Lund University. Some parts of information about tracks, events were reduced to save the storage space and to increase the processing efficiency.

The reweighed event-mixing method was put to test in processing this set of data. Besides, the normal event-mixing and the like-sign method were also applied as a comparison. We mainly focus on extracting the resonance peak of $\phi(1020) \rightarrow K^{+}K^{-}$. The products expected were a pair of unlike-sign charged particles, therefore the like-sign method could be applied as well. As the simulation result shows, the reweighed method only improves the correspondence of background, but a certain residual background was still left. The remnant background after the background subtraction is then fitted with a 4th order polynomial.

Since the mathematical fitting is not always satisfying especially when the shape of the residual background has complicated shapes, it will be of much help if it proves that the reweighed event-mixing method reduces the magnitude of residual background in actual data analysis. To be noticed, we may reconstruct any shape of residual background with polynomial given enough orders theoretically. In practice, we only apply a limited-order polynomial when doing the fitting for approximation. Therefore, the residual background needs to be constrained in relatively small scale comparing to the resonance peak for better fitting qualities. We will use this as criteria for the reweighing method.

To do that, we could use the signal to residual background ratio (STBR), which is defined as:

$$R = \frac{\text{Resonance peak height}}{\text{Residual BG average} - \text{Residual BG minimum}}$$

In this way, if the reweighing method narrows down the fluctuation region of remnant background, the SRBR could increase dramatically, since the resonance signal would not vary much for reweighing. In our analysis, the SRBR was done for different transverse momentum bins to further investigate other potential improvements.
5. Results

The results were separately displayed in this section for different $p_T$ regions, where $p_T$ is the total transverse momentum of the track pair. As we mentioned in 2., the events with more asymmetric distribution on the transverse direction should have more useful energy transferred into products, and therefore have higher possibility to create more resonances of interest. The data was divided into groups by their $p_T$, i.e. “low $p_T$” with $p_T$ 0-2GeV, “high $p_T$” with $p_T$ 5-10GeV.

We compare the performance of the event-mixing method and the one with reweighing. Besides, the result from unlike-sign and like-sign pair method was presented as comparison.

5.1 Performance for $\phi(1020)$ resonance

First we shall look for the invariant mass from 1 to 1.05GeV, where the $\phi(1020)$ resonance is located. All event-mixing methods were rescaled to match the background in the region of our interest. After the background subtraction, the remnant background and resonance peaks were left. All three methods could reveal the resonance peak at least, but their performance varies.

For $p_T$ 0-1GeV bins, the resonance was too weak to be extracted from the original invariant mass distribution. Actually, for very low $p_T$ bins, the main processes are soft scatterings, such as elastic and inelastic scatterings. The resonance production is rare, therefore we can exclude these bins to reduce the background.

Then we change the low $p_T$ region to 1-2GeV. The overall results of signal extracting, which equals to the difference of invariant mass distributions and the mixing backgrounds, were illustrated in Fig 5.2. And the black horizontal zero line represents zero difference between combinatorics of same event and event-mixing distribution. The normal event-mixing have left a part of background, with a decline shape in this range. The fitting for residual background was done with the Breit-Wigner formula plus a 4th order polynomial. After the reweighing, the remnant background was reduced significantly. Since the yield of resonance peak barely changed, we expect an increased relative size of peak to the residual background.
The overall invariant mass distributions for the normal event-mixing, the reweighed event-mixing and the like-sign method.

The last one was for unlike-sign method. Since we assume the mass of both tracks to be $K^\pm$ mass, the background would become out of shape if their real mass are different from $K^\pm$ as we simulated in last section. This enlarged the difference of reconstructed background and real background, especially near the low cap of invariant mass. As it shows in Fig 5.2, the remnant background for like-sign method was ascending in contrast.
Fig 5.3 Extracted signal from 3 different transverse momentum region

Then the remnant background and the resonance peaks. In Fig 5.4, the resonance peaks were on the top of background, while the signal to background ratios for low and medium $p_T$ were much lower than high $p_T$. For low $p_T$ bins, the normal event-mixing background has a significant difference with real background, hence the extracted signal was not in good shape. The fitting result was
showed with red solid line in Fig 5.4, while the polynomial fitting part (remnant background) was in blue. As we can see, the remnant background for normal event-mixing and the like-sign method in this region (1.00-1.05GeV) has too strong fluctuation to fit with a 3rd polynomial. The fitting was only applied to a narrower region than the determined one. At mean time, the reweighed method reduced the remnant background to make a better signal to background ratio, but the fitting quality in this region is still not good enough. In the first plot in Fig 5.2, it is not hard to find that the original background was too strong comparing to the resonance signal in this region. But the reweighing already made it better than the normal event-mixing and the like-sign method.

**Fig 5.4** $p_T$ from 1 to 2GeV
In medium $p_T$ region, the normal event-mixing start to work properly, as the scale of background falls. As we can see, the fitting remnant background in blue with 3$^{rd}$ polynomial was almost flat. We can evaluate the performance of these methods by comparing the difference between maximum and minimum of residual background as we did in section 4.3. The residual background for normal event-mixing was within $(-4040, 4170)$, while the reweighing make this drop to $(-1100, 785)$. The fluctuation of residual BG was reduced by nearly 3/4. And as comparison, the like-sign method left a remnant within $(-3050, 392)$. Under the circumstance that the scale of resonance peak for 3 different methods are nearly the same, less residual background makes the fitting with Breit-Wigner form work better.

![Graphs showing comparison of residual background for different methods.](image)

**Fig 5.5** $p_T$ from 2 to 5GeV
Fig 5.5 shows the result for high $p_T$ bins. For these pairs with high total transverse momentum, the original backgrounds were already low enough to be fitted with polynomial already as it showed in Fig 5.2c. However, the invariant mass method could still improve the STBG though. Here in Fig 5.5a, the residual background for normal event-mixing varies within $(-121.50, 79.96)$, while the reweighing improved it to $(-62.66, -10.00)$, also reduced by nearly 3/4. And the like-sign method leaves residual background within $(-89.00, 18.73)$. 

Fig 5.6 $p_T$ from 5 to 10 GeV
5.2 Fitting results

5.2.1 Signal to Remnant Background Ratio

The performance of signal extraction methods depends on the STBR as we analyzed in section 4.4. And here is an example of calculating the STBR with the fitting result.

The signal of pairs was processed firstly by subtraction with any method of background reconstruction. And the leftover are resonance peaks and residual background, which were going to be applied with polynomial fitting next. The numerical fitting can separate the resonance signal and the residual background given that the STBR is sufficient. Then we would be able to draw resonance signal and the residual background independently. We use the difference between the average of residual background and its minimum as reference level of residual background in this region, since the absolute level of background also depends on the scaling factor of event-mixing background.

Moreover, one should always keep in mind that the polynomial fitting work for small scale residual background for approximation. Therefore an improved event-mixing method should provide a higher STBR than normal one in order to make it easier for resonance signal extraction.
Fig 5.8 STBR for normal event-mixing, reweighed event-mixing and like-sign method at different $p_T$ bins. Higher implies a better signal extraction.

Fig 5.8 has plot the STBR for normal event-mixing method and reweighed one. It’s not hard to find that the reweighed method has improved the STBR significantly. The general trend is that the STBR increases with $p_T$ because the scale of background is much lower for high $p_T$ bins than low $p_T$ bins. The other feature is that the STBR stops rising when it comes to high $p_T$ region, for reweighed method STBR even drops to around 17 where the like-sign method achieved almost the same. The related resonance signal and remnant background was shown in Fig 5.6, that the remnant background was suppressed due to the excellent conformity of background reconstruction by reweighing. According to our analysis in 4.2, the asymmetry for jet-effect should be more significant for high $p_T$ pairs, and consequently the reweighing method improves the background rebuilding especially in high $p_T$ region. However, when it comes to the high $p_T$ bins, the number of samples is much smaller than low and medium $p_T$ regions. The yield of resonance was limited by the sampling scale in high $p_T$ bins, hence the STBR in this region was constrained as well.

Except for the performance of reproducing background, we also care about the mass and the width of the resonance. Two black dotted lines indicate the corresponding caps of average data from particle data group(PDG).

5.2.2 Resonance mass

The mass of resonance extracted from like-sign method has good conformity with PDG, where the resonance mass for different $p_T$ bins averagely located near or within the given boundaries. Besides, the mass from fitting exhibits a minor increasing trend with $p_T$.

For event-mixing methods(normal and reweighed), the average resonance mass is slightly higher than the boundaries. It’s hard to determine whether reweighing method improved the precision of resonance mass or not.

![Resonance Mass](image1)

![Resonance Width](image2)

Fig 5.9 The mass and the width of the resonance $\phi(1020)$ extracted by 3 different methods. The two dotted lines indicate the average boundaries from PDG

5.2.3 Width

About the resonance width, on the other hand, the extracted width for these three methods has a deviation from the determined average decay width. Since the decay width is not Lorentz invariant, we may find the width different especially for particles with their velocity close to c.
5.3 Alternative reweighing ratio

We can also compare the performances for different reweighing ratio $W$. Fig 5.10 plots the overall invariant mass distribution after the background subtraction.

![Graph 1](image1.png)

![Graph 2](image2.png)

![Graph 3](image3.png)

**Fig 5.10** The comparison between $W(p_T, \Delta \phi)$ reweighing and $W(p_T, \Delta R)$ reweighing for different $p_T$ bins

The reweighed method with $W(p_T, \Delta R)$ has even better performance than $W(p_T, \Delta \phi)$. Under the proper rescaling, it almost gave the pure resonance signal near 1.02GeV. After all the reweighing with $\Delta R$ should compensate the difference between isotropic event-mixing and jet-like in same event. This also proves that the jet-like property of same event pairs not only applied to the transverse direction, but also to the projection on z-axis.

5.4 X(1070) Resonance

Besides the $\phi(1020)$ peak, there is another resonance within 1.066-1.079GeV that has not been further investigated. The Particle Data group(PDG) recorded this as X(1070) resonance with two
Since the difference in mass for $K_S^0$ and $K^\pm$ is little ($K^\pm$ at 493.7MeV and $K_S^0$ at 497.6MeV). At low $p_T$ region the $X(1070)$ resonance was even stronger than $\phi(1020)$.

Although our analysis was in $K^\pm$ channel, we still observed a peak with long tail in this given region. In Fig 5.11, the fitting consists of two Breit-Wigner branches and a 4\textsuperscript{th}-ordered polynomial as residual background.

![Fig 5.11 The fittings plots for extracted signal between 1.05-1.10GeV in different transverse momentum regions. The fitting formula contains a dual BW peak and a 4\textsuperscript{th}-ordered polynomial background.](image)

As it shows, the solution for long tail peak fitting in this research is a dual peak fitting, where the fitting quality may suffer a severe drop when they are located too close. For $p_T$-0-1GeV bins, the peak was very significant since the reweighing method already removed the background with high conformity. Therefore the extracted signal can be split into two peaks where peak1 located at 1.0700GeV and peak2 at 1.0732GeV. For $p_T$-1-2GeV, the yield of both peaks drop quickly, while
peak2 drops slower than peak1. The peak1 is located at 1.0700 GeV and peak is located at 1.0732 GeV. For \( p_T: 2-5 GeV \), the STBR drops to approximately 2 and the residual background almost has the same strength as the peaks. The corresponding mass for peak1 and peak2 shifted to 1.0712 GeV and 1.0780 GeV separately. This shifting could be lead by the fitting precision dropping.
6. Discussion and Conclusion

6.1 Summary

From the comparison with the event-mixing and the like-sign method, it’s not hard to find that event-mixing method has the versatility on the background reconstruction for resonances while the like-sign method only applies to charged decay channels. However the traditional event-mixing cannot reproduce the jet-effect which is crucial in high-energy particle collisions. This shortage leads to a deviated background estimation especially for high transverse momentum regions.

To supplement jet effect to event-mixing, the reweighing method was introduced in this report for normal event-mixing. Then the reweighed event-mixing method was applied on $\phi(1020) \rightarrow K^+K^-$ resonance along with other two methods for their performance testing.

**Signal to Residual Background Ratio**

Since the like-sign method has better conformity with real background than normal event-mixing method as we analyzed, we expect less residual background for like-sign, therefore the STBR for like-sign should be higher than normal event-mixing, and we indeed observed it for $\phi$ resonance. After the reweighing to event-mixing, we reproduce the jet effect for randomly mixed pairs, hence the performance improved. The STBR for reweighed event-mixing is much higher than other two methods.

The $p_T$ bins we choose also have effect on the improvement of reweighing. The general trend is that the STBR rises when we look into higher $p_T$ bins because the background itself drops. But when it comes to $p_T$:5-10GeV bins, the STBR for reweighing EM descend to the same level as like-sign method due to the resonance yield dropping dramatically in this region, while there lies another factors having influences on the background reconstruction.

**Resonance Mass and Width**

The resonance masses and widths were obtained from the fitting of extracted signal and compared to the average data from the PDG.

The resonance masses extracted have a rising trend with $p_T$, but their average is located near the mass that PDG gives. For like-sign method, the masses for different $p_T$ bins averagely distributed at two sides of the given boundaries considering the statistic errors. For normal and reweighed event-mixing, the average of extracted masses is slightly above the given $1.01945 \pm 0.00002$GeV. This is partly because the resonance of $\phi$ was already deeply investigated since it was found, the mass and the width are fairly precise with massive research. However, the reweighing did not improve the extracted mass according to our research.

As for the width extracted, all three methods give overestimated value than the PDG gives($4.26 \pm 0.04$MeV). For event-mixing methods, their widths are broader for higher $p_T$ bins, while the like-sign method extracted a less fluctuating one.
6.2 Discussion

6.2.1 Reweighing

From the comparison with the un-reweighed event-mixing method and the like-sign method, we found that the reweighing method improved the performance of background reconstruction by reducing the residual background after the background subtraction. Even we didn’t utilize the PID information for low p_T regions either, the reweighing still increase the signal to residual-background ratio by multiple times. The suppression of residual background for reweighed method was even better than the like-sign method that should have excellent conformity for charged decay channels.

However our reweighing with $W(p_T,\Delta R)$ was not a perfect choice due to the need of reducing statistics. Although for invariant mass researches, we only record all data that concerns track pairs, such as total transverse momentum $p_T$, the relative azimuthal angle $\Delta \phi$, or the relative pseudo-rapidity $\Delta \eta$, we can always try to reproduce the jet-effect by increasing the dimension of our statistics. For example, we know that the invariant mass $m_{inv}$ is:

$$m_{inv} = \sqrt{m_1^2 + m_2^2 + 2E_1E_2 - 2p_{T1}p_{T2}\cos(\Delta \phi) - 2p_{z1}p_{z2}}$$

where the jet-effect can influence the invariant mass via $\Delta \phi$ distribution and $\Delta \eta$ distribution (where $p_{z1}$ and $p_{z2}$ are involved), rather than via $\Delta R$ directly. Therefore a reweighing ratio with more dimensions such as $W(p_T,\Delta \phi,\Delta \eta)$ might have even better performance than $W(p_T,\Delta R)$.

One should also notice that the choice of normalization region could possibly change the shape of resonance. As we scale the estimated background with different ratios, the shape of extracted peak will be changed depending on the shape of background and the located of peak. The tail of peak can be enlarged if its center locates at somewhere the background has dramatically fluctuation. This could lead to a overestimation of the resonance width, as well as the mass deviation.

Although the $\beta - P$ PID was not accessible for high $p_T$, we can apply an alternative $dE/dx - P$ PID according to the Bethe-Bloch function. The background particles from the soft-scattering and other due to our assumed decay channel into $K^+K^-$ were actually not all charged kaons, and they contributed to the combinatorial background as well. With PID we can obtain a better statistics for better resonance research, since a large fraction of background particles will be rejected, while it was not applied in this report since the purpose is to enhance our understanding of event-mixing method and the improvement of it.

6.2.2 X(1070)

As we mentioned in the result section, a certain peak was revealed near 1.07GeV, where the dual-peak fitting indicated that the first peak is at 1.0700GeV and the second one is at 1.0732GeV. The Particle Data Group only recorded two pieces of relative file which suggested that it should be a resonance of $K_SK_S$, where the resonance mass is $1072.4 \pm 0.8$MeV and the width is $3.5^{+1.5}_{-1.0}$MeV, created in $\pi^-p$ fixed target experiment[3].

Since our invariant mass method was for $K^+K^-$ channels only, the research should be brought to $K_SK_S$ channel as well as the mass of charged kaon and k-short are nearly the same(4MeV difference only). One feature to be noticed is that this suspicious “resonance” only exist for low $p_T$ bins, that in 5.4 we showed a decreasing yield for X(1070), and the comparison between $p_T$:0-2GeV bins and $p_T$:2-5GeV bins indicated this.
6.3 Conclusion

The main purpose of this thesis was to enhance our understanding of the mixing background methods, and to improve the event-mixing method for further studies. The core of the improvement was the reweighing method, that reproduces the jet-effect for an event-mixing background, whereas the normal one usually can not do that. From the analysis part, we have proved that the jet-effect does have impact on the final performance of background reconstruction, and this effect would be crucial since it is common in high-energy collisions. The reweighing method was proven in the simulation of PYTHIA, and then put to a test for real statistics from the ALICE experiment at CERN. In comparison to the normal event-mixing and the like-sign method, it turned out that the reweighing method improved the performance by reducing the residual background, which was fitted with 4th-order polynomials.

Event-mixing methods are versatile and can be used in various situations. Unlike mathematical fitting, they utilize all information from the events to estimate the background, and they are certainly more reliable than pure mathematical fittings. Although the traditional event-mixing ignored the special angular distributions in real events, the reweighing method introduced in this thesis should be able to compensate for this drawback, and increase the precision of signal extraction. Moreover, the reweighing ratio defined in this report is not the only choice for improvement. With more research and further understanding of the mechanism of jet evolution, the reweighing would be more efficient and more reliable.
References


