

Perspectives for the measurement of D_s^+ mesons via the $D_s^+ \rightarrow K^+ K^- \pi^+$ channel in the ALICE experiment

S. Senyukov^a
for the ALICE Collaboration

Università and INFN di Torino, via P. Giuria 1, 10125, Torino, Italy

Received: 20 October 2008 / Revised: 2 February 2009 / Published online: 19 February 2009
© Springer-Verlag / Società Italiana di Fisica 2009

Abstract Heavy quarks, such as charm, are produced in hard scatterings in the early stages of high energy nucleus-nucleus collisions and are expected to be a powerful tool to investigate the properties of the quark gluon plasma (QGP). The tracking detectors of the ALICE apparatus will allow to track and identify particles in central rapidity range down to low P_T . Among D mesons it would be particularly interesting to measure D_s yield via an exclusive hadronic decay channel because it could help to disentangle different hadronization mechanisms. The possibility of reconstructing the D_s meson through its $D_s^+ \rightarrow K^+ K^- \pi^+$ decay channel in the central barrel was studied. The problem considered is characterized by the comparatively low yield of the D_s mesons against the huge amount of combinatorial background. Different kinematic and topological cuts have been studied in order to increase the signal-to-background ratio and the statistical significance. In addition, D_s mesons preferentially decay through intermediate resonant states and this fact can improve the separation of signal from background. Results of cut parameters tuning and values of significance for an analysis performed on simulated data are presented.

1 Introduction

ALICE (A Large Ion Collider Experiment) is one of the four main experiments at the Large Hadron Collider (LHC). The main objective of ALICE is the study of nuclear matter under extreme conditions of temperature and energy density. This will be done by analyzing the particles produced in nucleus-nucleus collisions at a center-of-mass energy (for Pb^{208} nuclei) of 5.5 TeV per nucleon pair as well as in proton-proton and proton-nucleus collisions. According

to lattice QCD predictions the accumulation of such large amount of energy into a tiny space will lead to the formation of a new state of matter called Quark Gluon Plasma (QGP). In this state matter no longer consists of separate hadrons, but it is made of their fundamental constituents: quarks and gluons [1].

Detection of charmed mesons created in the nucleus-nucleus collision is of particular interest, since such particles provide a powerful tool to probe the QGP medium. On the other hand charmed quarks are rare observables and one should find special methods to extract the signal from the large amount of background.

The main goal of this work is to assess the feasibility of the detection of D_s mesons through their three-body decay channel $D_s^+ \rightarrow K^+ K^- \pi^+$ in Pb–Pb collisions at the LHC.

2 Physics motivation

Charmed quarks as well as beauty quarks are produced in hard parton-parton scatterings that take place in the early stages of high energy nucleus-nucleus collisions. Charmed quarks have a lifetime longer than the expected lifetime of the Quark Gluon Plasma and provide a useful instrument to investigate nuclear effects on parton production, propagation and hadronization in the QGP medium.

2.1 Primary production of charm

Production of charm quarks in nucleus-nucleus and proton-proton collisions occurs with similar mechanisms. This is the reason why it is better to consider first the pp case and then derive an extrapolation to Pb–Pb.

Heavy-quark production in pp collisions is thought to originate in partonic hard scatterings. Since heavy quarks have a large mass ($m_Q > \Lambda_{\text{QCD}}$), their production can be described by perturbative QCD. The single-inclusive cross

^a e-mail: senyukov@to.infn.it

section for the production of a heavy-flavoured hadron H_Q can be expressed using the factorization theorem as follows [2]:

$$\begin{aligned} & \frac{d\sigma^{NN \rightarrow H_Q X}}{dp_T}(\sqrt{s_{NN}}, m_Q, \mu_F^2, \mu_R^2) \\ &= \sum_{i,j=q,\bar{q},g} f_i(x_1, \mu_F^2) \otimes f_j(x_2, \mu_F^2) \\ & \quad \otimes \frac{d\hat{\sigma}^{ij \rightarrow Q(\bar{Q})\{k\}}}{d\hat{p}_t}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2, m_Q, x_1 x_2 s_{NN}, \hat{p}_T) \\ & \quad \otimes D_Q^{H_Q}(z, \mu_F^2) \end{aligned}$$

This expression is a convolution of different parts. The first two components (f_i and f_j) are parton distribution functions (PDF) of two colliding nucleons. The third term is the partonic cross-section ($\frac{d\hat{\sigma}}{d\hat{p}_t}$). It can be calculated in pQCD. The last term is the fragmentation function $D_Q^{H_Q}$ that represents the probability for the scattered quark to become a hadron with a given fraction of the momentum of the parent quark and it is determined experimentally. μ_F is the factorization scale and μ_R is a renormalization scale of QCD.

The simplest way to proceed when extrapolating to heavy-ion collisions is to consider such collisions as a superposition of independent nucleon-nucleon interactions. The charm differential yield can be obtained from the yield in nucleon-nucleon collisions with an appropriate scaling factor N_{coll} :

$$\frac{d^2 N_{AA}^{H_Q}}{dP_t dy} = N_{coll} \times \frac{d^2 N_{NN}^{H_Q}}{dP_t dy}$$

N_{coll} represents the number of binary (i.e. nucleon-nucleon) collisions occurring in a heavy-ion reaction and can be estimated with the Glauber model [3].

Several effects caused by the nuclear medium can break the binary scaling of the formula above.

2.2 Initial state effects

Initial state effects are due to the fact that a nucleon inside the nucleus may behave differently than a free nucleon. Mainly two different mechanisms are responsible for this:

- Cronin effect—can be described as due to an increase of the initial transverse momentum of the parton before the hard collision [4]. This is believed to be induced by elastic collisions prior to the inelastic one. Cronin effect is expected to result in a larger yield of charmed mesons at intermediate P_t .
- Modification of PDFs of the nucleon in the nucleus. At LHC energy the region of low x will be probed where gluon saturation is expected to play an important role [5, 6].

2.3 Final state effects

Final state effects are caused by the interactions of the initially produced partons with the medium created in the collision. A parton flying across the medium can lose its energy by means of induced gluon radiation and by elastic collisions with other partons [7]. This energy loss has two main effects on final particles.

- The momentum of the parton at the moment of hadronization is expected to be lower than it would be in the absence of medium. Also the momentum spectrum will be affected. One can expect a suppression of high- P_t mesons.
- If the energy loss is high enough it could happen that partons become slow enough to undergo recombination inside the medium. At this point two different processes: string fragmentation and recombination may contribute to hadronization. In the intermediate P_t region recombination is expected to dominate and this could affect the yield of different types of charmed mesons.

The magnitude of energy loss inside the QGP medium is expected to be strongly connected with the energy density of the medium.

2.4 Expected charm production at the LHC

In order to evaluate the physics performance of the ALICE experiment we need to have some estimate for the charm yield at the energies that will become available at the LHC. According to the results of calculations performed with the NVQMNR program [8] and interpolation to Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV with the impact parameter $b < 2$ fm, the charm total cross section will be about 16 mb and the total yield will be about 125 $c\bar{c}$ pairs per event.

The total yield and the rapidity density dN/dy in the central region for hadrons with open charm in Pb–Pb at 5.5 TeV at 5% σ^{inel} centrality are presented in Table 2.1. The possible uncertainty on these values is of a factor 2.

2.5 Special motivations for D_s study

Several studies of charmed mesons reconstruction were already performed in ALICE (see [9] for D^0 reconstruction

Table 2.1 Total yield, average rapidity density and relative abundance for hadrons with open charm in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. For the yields PYTHIA approximations were used

Particle	Yield	$dN/dy(y < 1)$	Rel. abundance
$D^0 + \bar{D}^0$	140.8	13.7	61%
$D^+ + D^-$	44.6	4.12	19%
$D_s^+ + D_s^-$	26.8	2.52	12%
$\Lambda_c^+ + \bar{\Lambda}_c^-$	17.9	2.03	8%

and [10] for D^+ reconstruction). In both cases promising results were obtained. The D_s channel is of particular interest:

- In order to have precise evaluation of the total charmed meson yield one should measure as many hadronization channels as possible. The D_s meson is expected to be the third most abundant channel after D^0 and D^+ .
- Measuring the ratio between yields of D^+ and D_s mesons can help to resolve the puzzle of hadronization mechanisms. Presently two ways of hadronization are considered. The first is string fragmentation in the vacuum. In this case the ratio $N(D_s)/N(D^+) \sim 0.64$ (according to PYTHIA [11] and results from Tevatron [12]). This can be explained by the higher probability to create a light d quark than a heavier s quark and by the branching ratios of excited states into D^+ and D_s mesons. On the other hand D mesons could also be created by recombination of c quarks inside the QGP medium. In this case, especially at LHC energies, the probabilities to catch different quarks are almost equal. In the presence of strange enhancement, this fact could manifest itself in an increase of the $N(D_s)/N(D^+)$ ratio.

3 ALICE experimental setup

The ALICE setup consists of a central barrel covering the full azimuthal angle in $|\eta| \leq 0.9$ and several forward systems. The central system is embedded in a magnetic field $B \leq 0.5$ T. The central detectors are, in the order from the interaction vertex to the outside, the Inner Tracking System (ITS) with six layers of silicon detectors, the Time Projection Chamber (TPC) which is the main tracking detector, the Transition Radiation Detector (TRD) for electron identification and the Time Of Flight detector (TOF) which extends the momentum range of particle identification (PID) up to 4 GeV/ c . Two other detectors with reduced η and ϕ acceptance complement the central barrel: the High-Momentum Particle Identification Detector (HMPID) consisting of an array of ring-imaging Cherenkov counters and the Photon Spectrometer (PHOS) which is an electromagnetic calorimeter. The last addition to the ALICE design is the Electromagnetic Calorimeter (EMCal): it will be put in the central barrel and will be dedicated to the physics of jets and high- P_T photons.

The main detectors contributing to the study of charmed meson production by the measurement of hadronic decays are: the Inner Tracking System, the Time Projection Chamber and the Time Of Flight detector.

3.1 Inner tracking system

The Inner Tracking System (ITS) consists of six cylindrical layers of silicon detectors located in the central barrel at

radii, $r \approx 4, 7, 15, 24, 39$ and 44 cm. The two innermost layers are made with Silicon Pixel Detectors (SPD), then follow two layers of Silicon Drift Detectors (SDD) and the two outermost layers consist of Silicon Strip Detectors (SSD). The tasks of the ITS are:

- Primary and secondary vertex reconstruction with the high resolution required for the detection of particles with open charm and open beauty.
- The measurement of the impact parameter of the tracks. The impact parameter is defined as the distance of closest approach of the track to the primary vertex.
- Reconstruction and identification of low momentum tracks with $p < 100\text{--}200$ MeV/ c , which are bent too strongly by the magnetic field to be reconstructed by the TPC.
- Reconstruction and identification of those particles which traverse the dead regions of the TPC.
- Improvement of the momentum resolution for the high momentum particles.

3.2 Time projection chamber

The Time Projection Chamber (TPC) is the main tracking detector in ALICE: it provides charged-particle track reconstruction, identification via dE/dx , momentum measurements. All these requirements have to be full-filled at the Pb–Pb nominal luminosity, corresponding to an interaction rate of 8 kHz, about 10% of which are central collisions with an impact parameter $b < 5$ fm. The TPC has been designed in order to operate with multiplicities as high as $dN/dy = 6000$.

The TPC allows the study of hadronic and leptonic observables with transverse momentum between ~ 0.1 GeV/ c and 100 GeV/ c in the pseudorapidity window $|\eta| < 0.9$.

3.3 Time of flight detector (TOF)

The TOF detector of ALICE covers the central pseudorapidity region ($|\eta| < 0.9$) and plays an important role in the identification of pions, kaons and protons in the intermediate momentum range. Since a large area has to be covered, multi-gap resistive-plate chamber detectors (MRPC) were chosen.

The TOF measures the time of flight, defined as the interval between the production of a particle and its detection in the MRPC. Particles with different masses can be separated once the time of flight and momentum are known.

The time resolution is of the order of 60–80 ps. With a time resolution of 80 ps, the TOF is expected to provide π/K and K/p separation up to momentum $p \approx 2.5$ GeV/ c and $p \approx 4$ GeV/ c respectively.

More technical details on the design of the ALICE detector can be found in [13].

Table 4.1 Some properties of D^0 , D^+ and D_s decays

	D^0	D^+	D_s
Combinations (full inv. mass range)	10^6 pairs	10^9 triplets	10^8 triplets
$c\tau$ (μm)	123	312	150
Hadronic BR %	3.8	9.2	4.3
Abundance ^a	30	9	5

^aPb–Pb central events: NLO pQCD + Binary scaling + EKS98, in central acceptance

4 Reconstruction of charmed mesons

Reconstruction of heavy-flavoured mesons is a demanding task: the decay products of the meson should be selected among the large number of particles created in a high-energy Pb–Pb collision. All tracks that are identified as pions and kaons are combined into triplets or pairs with the correct combination of charge signs. Then an invariant mass spectrum for all these candidate combinations is calculated and the signal is obtained by background subtraction. Estimated numbers of such combinations for single event for different D mesons are presented in Table 4.1. The estimate was taken from HIJING generator [14] at $dN/dy = 6000$ in central acceptance in a full invariant mass range.

The only solution is to find some properties of the real triplets that allow distinguishing them from the combinatorial background and applying cuts on these variables. Some important characteristics of D_s decay in comparison with D and D^+ are presented in Table 4.1. From this table one can see that reconstruction of D_s meson is a challenging task because of the comparatively small decay distance, branching ratio and abundance against the huge number of the combinatorial background. Obviously when removing the background some signal also should be sacrificed. The task is to find optimum tuning for cut values. Distance between primary vertex of the collision and decay vertex of the meson is a good example of such variable because detectors of ALICE should be able to measure this distance with a good accuracy separating particles coming directly from primary vertex from those produced in secondary decays of short-lived mesons. Other properties and their use will be discussed later in Sect. 6.

5 Analysis of simulated events

ALICE is now in a start-up phase and no real data are presently available. Thus simulated events were used for this study.

Since heavy-quark observables are rare signals, as discussed in Sect. 2, the simulation of such processes would demand a huge amount of central Pb–Pb events in order to have

enough statistics to study the charmed meson decays. To facilitate the generation of the required statistics a separate production of signal and background events was done. The background events are central Pb–Pb events generated with HIJING [14]: we considered for this study the most central events with impact parameter of the collision $0 < b < 2$ fm. The corresponding multiplicity is $dN/dy = 6000$. As HIJING doesn't reproduce well the amount of charm expected from NLO calculations, charm processes are switched off in HIJING and the expected number of $c\bar{c}$ pairs is added with PYTHIA [11]. The parameters of the PYTHIA generator were tuned to reproduce the P_t spectra of $c\bar{c}$ pairs predicted by the MNR [8] code. Signal events are generated with PYTHIA tuned to agree with MNR predictions. They contain a fixed number of $c\bar{c}$ pairs that are forced to hadronize to D_s mesons which then are forced to decay into $K^\pm K^\mp \pi^\pm$ final state via ϕ or K^{*0} resonant channel. The number of D_s per event was chosen to be 9100 in order to reproduce the HIJING multiplicity of a central Pb–Pb event. This is done in order to have similar reconstruction performance as for the background events. For particle identification (PID) an ideal situation was considered, i.e. particle species are taken from Monte-Carlo generator.

All generated particles were fully transported through the detectors using the GEANT 3.21 package [15] and reconstructed with a proper version of the ALICE software framework called AliRoot.¹

These generated samples are used for the cut tuning procedure. During this procedure different values of a particular cut are applied simultaneously to the signal and background events and the following numbers are calculated:

- S_{kept} , fraction of real D_s mesons remaining after cut;
- B , number of track combinations per event remaining after cuts for the background sample.

These values should be scaled in order to calculate the significance with respect to one year of data taking that corresponds to 10^7 central Pb–Pb events.

¹<http://aliceinfo.cern.ch/Offline/>.

To obtain the yield of selected D_s mesons per event the following formula is used:

$$S = N(D_s) * Br(D_s) * Rec F * Acc F * S_{kept}$$

where $N(D_s)$ —is the number of D_s mesons predicted by NLO in one central Pb–Pb collision (see Table 2.1), $Br(D_s)$ —is the branching ratio of D_s meson to hadronic channel, $Rec F$ —is the reconstruction efficiency factor that takes into account that all three decay products should be reconstructed in the detector, $Acc F$ —is the acceptance factor that takes into account the limited pseudorapidity coverage of the detector and S_{kept} —is the fraction mentioned above.

We can multiply S and B by 10^7 to obtain the number of D_s mesons and background triplets after one year of data taking ($S(10^7)$ and $B(10^7)$). The statistical significance in one year is:

$$Sig = \frac{S(10^7)}{\sqrt{S(10^7) + B(10^7)}}$$

Optimal values of the cuts are found by maximizing the significance.

6 Selection strategy

6.1 Single track cuts

The first step of the selection is applied at the level of single reconstructed tracks before combining them to triplets. At this stage, the selection is based on transverse momentum of particles P_t and their impact parameter in the bending plane d . Pions and kaons originating from D_s decays are slightly harder than prompt ones. They also have a larger track impact parameter. For these reasons a track is accepted if $P_t > P_{t,cut}$ and $d > d_{0,cut}$. Values of $P_{t,cut}$ were tuned separately for kaons and pions in order to reduce the amount of the background while preserving the possibility of reconstructing D_s mesons with transverse momentum down to 1 GeV/c. The chosen cuts are: $P_{t,cut}(K) = P_{t,cut}(\pi) = 0.5$ GeV/c and $d_{0,cut} = 35 \mu\text{m}$, that allow to keep 20% of initial signal, reducing the background from 10^8 to 10^7 .

6.2 Cuts on track pairs

The tracks that have passed the previous selections are combined into pairs with opposite charge sign. Thereby two types of pairs are obtained: K^+K^- and $K^-\pi^+$ or $K^+\pi^-$ pairs. The vertex of these pairs of tracks is calculated using the standard vertexing algorithm used in ALICE. After that for each vertex two values are derived:

- Distance among the tracks and found vertex:

$$\sigma^2 = \sum_{k=1}^2 [(x_k - x_o)^2 + (y_k - y_o)^2 + (z_k - z_o)^2]$$
—that gives an estimate of the quality of the vertex.

- Distance between primary vertex and found cross-point.

Only pairs with $\sigma < 300 \mu\text{m}$ and $d_{pair} > 300 \mu\text{m}$ are accepted. Values for these two cuts were found by maximizing the significance. 10% of signal and 10^6 of combinatorial combinations remain after this step.

6.3 Cuts on track triplets

For each selected track pair a third track is added to form a triplet with the correct combination of charge signs. Once the triplet is formed, its invariant mass ($m_{triplet}$) can be calculated and from now on only triplets passing the following condition $|m_{triplet} - m(D_s)| < dm_{cut}$ will be used for significance calculation. A value of $dm_{cut} = 12$ MeV/c corresponds to 1σ of the expected invariant mass resolution of the ALICE detector for D_s meson. Then the vertex is reconstructed and a dispersion parameter is calculated by summing the distances among the tracks and the found vertex. A cut on this dispersion is applied at $420 \mu\text{m}$ in order to maximize the significance. Additional fine tuning of this cut will be considered in Sect. 6.5.

6.4 Cuts on the resonance masses

After combining candidate tracks into triplets and after a preliminary rejection based on their invariant mass and on track dispersion around the vertex the following cut is applied. This cut is based on the particular properties of the hadronic decay of the D_s meson that it preferentially decays to kaons and pions via intermediate resonance states. Indeed two decays channels were observed:

- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
- $D_s^+ \rightarrow K^+K^{*0} \rightarrow K^+K^-\pi^+$

Figure 6.1 shows the distribution of invariant masses for the K^+K^- and $K^-\pi^+$ pairs (Dalitz plot) for signal triplets. One can easily see that this distribution has two significantly

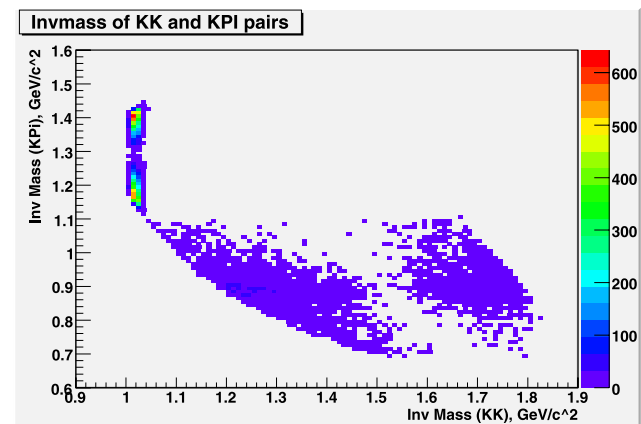


Fig. 6.1 Dalitz plot for signal triplets

more populated regions corresponding to $m_{inv}(KK) = m(\phi) = 1020 \text{ MeV}/c^2$ and to $m_{inv}(K\pi) = m(K^{*0}) = 892 \text{ MeV}/c^2$. In the Fig. 6.2 the same plot for the background events is shown. There the distribution is more flat and homogeneous. Thereby a cut on the values of invariant masses of the pairs can be applied. A candidate triplet is accepted if one of the two conditions is satisfied:

- $|m_{inv}(KK) - m(\phi)| < \Delta m_1 = 4 \text{ MeV}/c^2$
- $|m_{inv}(K\pi) - m(K^{*0})| < \Delta m_2 = 35 \text{ MeV}/c^2$

Values of Δm_1 and Δm_2 were tuned to maximize the significance.

Depending on which of these two conditions is satisfied selected candidate triplets are divided in two classes: ϕ -like triplets and K^{*0} -like triplets. Because of the previously applied cut on the invariant mass of the triplet there are no triplets that can satisfy both conditions simultaneously. Subsequent cuts were tuned separately for these two samples. It can be seen that ϕ -like channel is more promising because it has narrower selection on the invariant mass of the KK -pair.

6.5 Final multi-dimensional cut

Five variables were chosen to perform a final selection of the useful signal. Namely they are:

1. $\text{Cos } \theta_{point}$ where θ_{point} is the pointing angle, i.e. the angle between the direction of the reconstructed D_s (see Fig. 6.3) momentum in the bending plane and the line connecting the primary and secondary vertices. If the

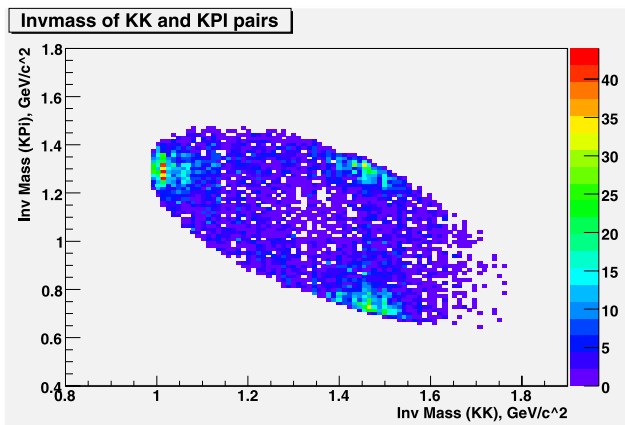
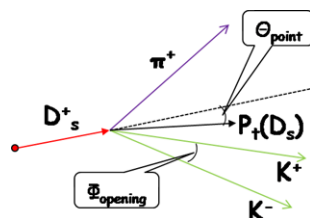


Fig. 6.2 Dalitz plot for background triplets

Fig. 6.3 The scheme of D_s decay



found vertex really corresponds to a D_s decay vertex, then $\theta_{point} \approx 0$ and $\text{Cos } \theta_{point} \approx 1$.

2. $\text{Cos } \Phi_{opening}$, where $\Phi_{opening}$ is the angle between two opposite sign tracks (see Fig. 6.3). In the case of ϕ -like triplets this angle is measured between to K^+ and K^- tracks and in case of K^{*0} -like triplets the opening angle is measured between K^+ and π^- tracks. This angle is smaller for the real triplets.
3. Sum of the squares of the three tracks impact parameters with respect to the primary vertex. This cut is based on the fact the signal tracks are coming from the displaced secondary vertex.
4. Distance between the primary and secondary vertices.
5. Quality of the found secondary vertex based on the dispersion of three tracks around the vertex. Actually this step was added to tune better the value found before.

In order to optimize the cuts a method that simultaneously tunes all the variables has been developed. This method is based on multi-dimensional matrices for both signal and background events. The dimension of the matrix is equal to the chosen number of independent cuts—five in our case. Each cell of the matrix corresponds to some combination of cut variables and contains the number of signal or background triplets passing the cuts. From two matrices for signal and background one matrix for significance is derived. Optimal values of the cuts then correspond to the cell with a maximum value of significance.

All candidate triplets were divided in four classes according to the total transverse momentum: $P_t < 2 \text{ GeV}/c$, $2 < P_t < 3 \text{ GeV}/c$, $3 < P_t < 5 \text{ GeV}/c$ and $P_t > 5 \text{ GeV}/c$. Separate tuning of the cuts for each of these bins was performed.

7 Preliminary results and conclusion

Results for the significance with respect to 10^7 central Pb–Pb events are presented in Figs. 7.1 and 7.2. Figure 7.1 cor-

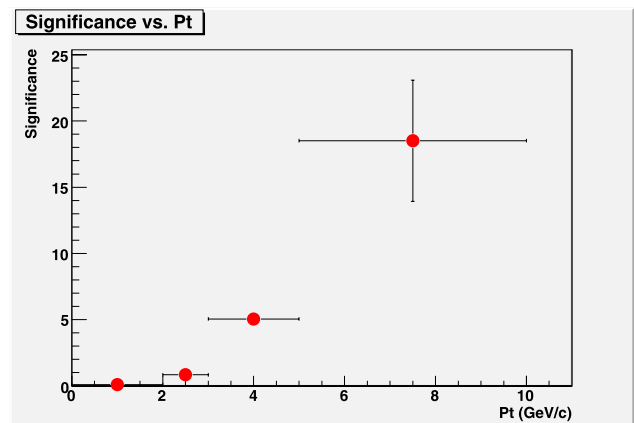


Fig. 7.1 Significance with respect to total transverse momentum for ϕ -like triplets

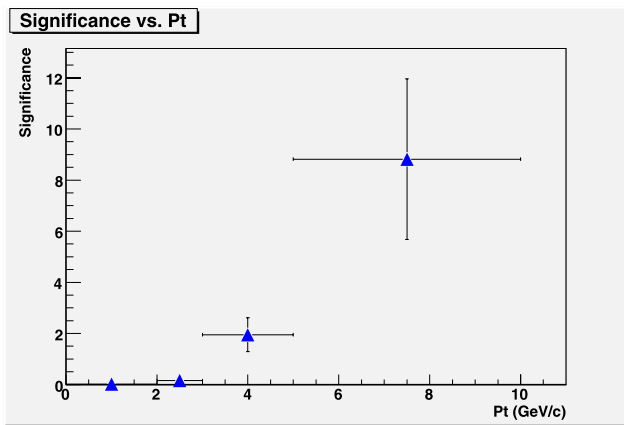


Fig. 7.2 Significance with respect to total transverse momentum for K^{*0} -like triplets

responds to the ϕ -like events and Fig. 7.2 corresponds to K^{*0} -like events (see Sect. 6.4 for more details).

One can see that reconstruction of the D_s meson is likely to be feasible for transverse momenta down to 3–4 GeV/c and as it was supposed before, decay channel via ϕ meson is easier to reconstruct. The fraction of the signal remaining after applying all cuts is about 1% in the whole p_T range.

The results presented here were obtained assuming ideal particle identification and thus give an upper limit for the achievable significance. In order to take the effects of the expected inefficiencies of the PID-methods into account, the same study will be repeated using a more realistic approach to PID.

References

1. E.W. Shuryak, Phys. Rep. **61**, 71 (1980)
2. G. Sterman, J.C. Collins, D.E. Soper, Nucl. Phys. B. **263**, 37 (1986)
3. R.J. Glauber, G. Matthiae, Nucl. Phys. B. **21**, 135 (1970)
4. D. Antresyan et al., Phys. Rev. D **19**, 764 (1979)
5. M. Arneodo, Phys. Rep. **240**, 301 (1994)
6. D. Kharzeev, K. Tuchin, Nucl. Phys. A **735**, 248 (2004)
7. A. Dainese, N. Armesto, M. Cacciari, C.A. Salgado, U.A. Wiedemann, Heavy-quark energy loss at RHIC and LHC, in *AIP Conf. Proc.*, vol. 842, pp. 74–76 (2006)
8. M.L. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B **373**, 295 (1992)
9. A. Dainese, PhD thesis, Universita degli Studi di Padova, 2003
10. E. Bruna, PhD thesis, Universita degli Studi di Torino, 2007
11. T. Sjostrand et al., PYTHIA 6.301 Manual
12. D. Acosta et al. (CDF II Collaboration), Phys. Rev. Lett., **91** (2003)
13. K. Aamodt et al. (The ALICE Collaboration), The ALICE experiment at the CERN LHC. J. Instrum. **3** (2008)
14. X.N. Wang, M. Gyulassy, Phys. Rev. D **44** (1992)
15. GEANT, Detector Description and Simulation Tool