ϕ-meson Reconstruction in the STAR TPC

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Abstract

The measurement of ϕ-meson production in heavy ion collisions is interesting, not only because the ϕ contains hidden strangeness, but also because it could be a probe to the restoration of chiral symmetry in matter produced in heavy ion collisions. We investigate the feasibility of reconstructing the ϕ through its K^+K^- decay channel in the STAR TPC. Using the TPC fast simulator and the track reconstruction program, we demonstrate that the ϕ can be reconstructed from charged kaons identified by dE/dx in the TPC. Total 683 central Au+Au events at $\sqrt{s} = 200$ GeV generated by RQMD are used. Of 5.8 ϕ's per event that decay into charged kaons (B.R.=49.1%) within rapidity $-1.5 < y_K < 1.5$ and momentum $p_K < 1$ GeV/c, 1.3 ϕ's are reconstructed from K^+K^- pairs. The signal-to-noise ratio at the ϕ peak in the K^+K^- invariant-mass spectrum is 1/12. The ϕ mass resolution due to kaon momentum resolution is 2.7 MeV/c^2.

1 Introduction

The ϕ-meson is the lowest mass bound state of strange and anti-strange quarks (s and $\bar{s}$), with hidden strangeness. Its production is suppressed in nucleon-nucleon interaction by the OZI rule [1, 2, 3, 4]. An enhanced production of ϕ's in heavy ion collisions could be one of the signatures for the formation of quark-gluon-plasma [5], where $s\bar{s}$ pairs can be copiously produced through gluon fusion ($gg \to s\bar{s}$) [6]. On the other hand, H. Sorge *et al.* argued, using the Relativistic Quantum Molecular Dynamics (RQMD) model, that implementing a novel string fusion mechanism – overlapping strings do not fragment independently but form "ropes" – could enhance the production of ϕ's but not kaon's [7]. Therefore, studies of the production ratios of ϕ to pion and ϕ to kaon are interesting. In particular, the ratio of ϕ to K^- serves as a much cleaner probe than the K^+ to π^+ ratio because very few resonances decay into kaons compared to pions. Fig. 1 shows the ϕ/K^- and $2\phi/(\pi^+ + \pi^-)$ ratios measured at the AGS [8] and the SPS [9], and calculated by the RQMD model (version 2.4) at RHIC energy, compared to the p+p values [10, 11, 12, 13] at the corresponding energies.

Chiral symmetry restoration might be expected under extreme conditions of high energy and/or high baryon density. The restoration of chiral symmetry in a dense medium could lead to modifications of the hadron properties [14]. The small decay energy of $\phi \to K^+K^-$ and the narrow total width (4.41 MeV) make this decay mode very sensitive to such modifications, which could result in changes in the shape of the invariant-mass spectrum of K^+K^- pairs. The degree of change may vary with the ϕ transverse momentum $p_\perp$ and the collision centrality. However, in-medium modification of the ϕ mass may be small, on the order of 10 MeV/c^2 [15], and the ϕ mass width may broaden through rescattering to $\sim$10 MeV/c^2 [16, 17], and only a small fraction of the K^+K^- pairs from ϕ decays in the fireball escape without interacting with the medium. Hence, in-medium modifications may be difficult to detect experimentally through the $\phi \to K^+K^-$ decay channel. Nevertheless, the experimental study of the invariant-mass spectrum of $\phi \to K^+K^-$ is important in the scope of the physics of the chiral symmetry restoration.

Two commonly used heavy ion collision models, RQMD and Venus, predict the ϕ production rate at mid-rapidity differently by almost an order of magnitude: the ϕ yield from Venus is 6 times that from RQMD, as shown in Fig. 2. A large difference is also seen in their predictions of the kaon production rate: the kaon yield from Venus is 3.5 times that from RQMD. The very first measurements of kaon and ϕ production at RHIC should be able to disprove one or both models.

A mass dependence of the inverse slopes of the particle transverse mass $m_\perp$ spectra – the inverse slope increases linearly with the particle mass – has been observed at the AGS and the SPS. The systematics are consistent with transverse radial flow, by which particles flow at a common collective velocity. The observed mass dependence at the AGS and the SPS can be described satisfactorily by the RQMD model (version 2.3) [18]. Therefore, it is of interest to examine the RQMD prediction of the mass systematics of the inverse slopes at the RHIC energy. The inverse slopes calculated by RQMD (version 2.4) are plotted in Fig. 3 as function of particle mass for various particle species. Interestingly enough, all particles follow the same trend – except the ϕ, which displays a similar inverse slope as the kaon's. This is also observed in a UrQMD calculation [19]. A calculation using the Venus model is also shown in Fig. 3.

The feasibility of reconstructing ϕ's in the STAR detector have been investigated by N. Feiman and W. J. Llope. N. Feiman [20] showed, using the Venus model (version 4.12), that the observation of ϕ's was likely in the STAR SVT and TPC, assuming perfect PID and tracking. W. J. Llope [21] studied, using the HIJING event generator and a standalone reconstruction program, the reconstruction of ϕ's from both the $\phi \to K^+K^-$ and $\phi \to e^+e^-$ decay channels. In this note, we investigate the feasibility of reconstructing the ϕ through its K^+K^- decay channel in the STAR TPC, using the full STAR software chain.

2 Software Chain

In out study, we used 683 Au+Au central events generated by RQMD (version 2.4) at an impact parameter $b < 4$ fm and center-of-mass energy $\sqrt{s} = 200$ GeV. The ϕ's were not decayed in the model. The events were fed into a GEANT simulation of the STAR detector (`gstar`), and the ϕ's were decayed by GEANT using the ϕ lifetime and decay branching ratios from the particle data book [22]. In the GEANT simulation, all year-2 detectors were included:

```
mode cave geom 1
```

```
mode pipe geom 1
mode svtt geom 1 simu 2     | year 2
mode tpce geom 1 simu 2
mode ftpc geom 1 simu 2
mode vpdd geom 1            | year 2
mode btof geom 1
mode calb geom 1            | year 2
mode ecal geom 1            | year 2
mode magp geom 1
mode mfld geom 1
mode g2tm geom 1
mode trac simu 1
detp trac dcay 210 210 0.1 0.01
detp svtt svtg.nlayer = 6
```

and all the relavent physics processes were turned on:

```
DCAY 1
ANNI 1
BREM 1
COMP 1
HADR 1
MUNU 1
PAIR 1
PHOT 1
RAYL 0
LOSS 1
DRAY 1
MULS 1
STRA 0
CUTS .001 .001 .001 .001 .001 .001 .001 .001 .001 .001 50.e-6
```

Using the GEANT output, hits were simulated by the TPC fast simulator (`tfs`) to include the detector response. Tracks were reconstructed from the hits by the TPC track reconstruction program (`tpt`). Specific ionization energies deposited by charged particles in the TPC gas (dE/dx) were calculated by the TPC particle identification package (`tid`). The version used for `tfs, tpt` and `tid` is `98d`.

3 ϕ Acceptance

We used a toy model to study the ϕ acceptance in the STAR TPC. The toy model generated 10^5 ϕ's with a Gaussian dN/dy distribution of $\sigma = 2$, and exponential $m_\perp$ distribution of inverse slope $T = 250$ MeV. The scatter plot of K^+ versus K^- momentum is shown in

Fig. 4 (upper panel). With the particular phase-space distribution used here, the decay kaon momenta peak at ∼500 MeV/c. The decay opening angle versus the momentum of either kaon is shown in Fig. 4 (lower panel). In Fig. 5, we show, as functions of $(y, p_\perp)$ for the ϕ, the percentage of ϕ's decaying into kaons with rapidity $-1.5 < y_K < 1.5$ and momentum $0.23 < p_K < 1$ GeV/c, representing roughly the TPC acceptance. The low-momentum cut of 0.23 GeV/c is dictated by the energy loss of kaons before entering the TPC, including that in the SVT. For year-1 detector configuration, where SVT is not included, the low momentum cut is a conservative estimate. We used an upper momentum cut of 1 GeV/c, although kaons with momentum above 0.6 GeV/c cannot be satisfactorily separated from other particles by dE/dx measurements in the TPC. However, we shall demonstrate in Sect. 4 that strict kaon particle identification (PID) is not required to reconstruct the ϕ's from K^+K^- pairs. From Fig. 5, we conclude that the acceptance of the STAR TPC for K^+K^- pairs from ϕ decays is good. By using the toy model and the simple y and $p_\perp$ cut, we do not intend to study the ϕ acceptance for serious analyses, but rather to convince ourselves that we can pursue the $\phi \to K^+K^-$ physics with the STAR TPC.

4 Invariant-Mass Spectra

In this section, we present the invariant-mass spectra of K^+K^- pairs for three cases.

(I) First, we use the direct output from RQMD. The ϕ's were decayed 100% into K^+K^- pairs by hand; the intrinsic width of the ϕ mass was not included. The decay kaons were mixed together with directly produced kaons. Using those kaons within $|y_K| < 1.5$ and $p_K < 1$ GeV/c, the invariant-mass spectrum of the K^+K^- pairs was reconstructed, and is shown in Fig. 6. A total of 380 Au+Au central events were used in this study. The kaon momentum was smeared using a constant 1.5% resolution, resulting in a mass resolution of 1.1 MeV/c^2. The number of ϕ's per event reconstructed under the mass peak (bottom plot in Fig. 6) is 11.8. This means that about 5.8 ϕ's can be reconstructed, taking into account the $\phi \to K^+K^-$ branching ratio of 49.1%. Note that the low momentum kaons ($p_K < 0.23$ GeV/c) included in the analysis do not contribute significantly to the number of reconstructed ϕ's. (See Fig. 4).

(II) Next, we use the reconstructed momenta and GEANT PID information for the kaons to calculate the invariant-mass spectrum of K^+K^- pairs. Only tracks with more than 5 hits in the TPC were used. About 50 K^+'s and K^-'s each were reconstructed with $p_K < 1$ GeV/c. The invariant-mass spectrum is shown in Fig. 7. All 683 central events were used in this analysis. The mass resolution is 2.5 MeV/c^2. Note that the intrinsic ϕ mass resolution was not included in the ϕ decays inside GEANT, so the reconstructed mass resolution represents the net effect of multiple scattering, energy loss and reconstruction accuracy. The resolution might be improved after the energy loss of kaons in the detector is properly corrected. The number of ϕ's per event reconstructed under the peak (bottom plot of Fig. 7) is 1.4.

(III) Then, we turn to the realistic situation, where only the reconstructed information is used. We use dE/dx to identify kaons. In Fig. 8, the particle dE/dx is plotted as function of particle momentum. We have studied two PID cuts: tight PID is shown in Fig. 8 as the area between the two solid curves with momenta below the dashed curves, and loose PID is shown in Fig. 8 as the area between the two solid curves up to a momentum of 1 GeV/c. For the tight PID, about 30 K^+'s and K^-'s each were identified; for the loose PID, about 60 K^+'s and K^-'s each were identified. The invariant-mass spectra are shown in Fig. 9 and 10 for the tight and loose PID, respectively. All 683 central events were used in both cases. The mass resolution is 2.7 MeV/c^2 for both PID cuts. The signal-to-noise ratios are 1/13 and 1/12, respectively for the tight and loose PID. Numbers of ϕ's per event reconstructed under the peaks (bottom plots of Fig. 9 and 10) are 0.8 and 1.3 for the tight and loose PID, respectively. We emphasize that the mass resolution from both PID cuts is the same, and the signal-to-noise ratio does not worsen (even increases) from the tight PID to the loose PID, with significant gain in the number of reconstructed ϕ's. We also emphasize that the mass resolutions from the dE/dx PID cuts are not much worse than (II), and the reconstructed number of ϕ's drops by less than 10% from (II) to the loose PID studied here.

Finally, we briefly discuss the statistics needed for a decent ϕ analysis, and the corresponding running time. We aim for 1,000 ϕ's (the same statistics as shown in Fig. 10) in $1.5 < p_\perp < 2.0$ GeV/c and in rapidity range $-0.15 < y < 0.15$ – so that we have 10 bins in the dN/dy distribution between $-1.5 < y < 1.5$. Using the toy model described in Sect. 3, we arrive at 20,000 ϕ's of rapidity $-0.15 < y < 0.15$ integrated over $p_\perp$, or a total of 200,000 ϕ's of $|y| < 1.5$, assuming a flat rapidity didstribution of the ϕ's. Assuming that, on average, one ϕ is reconstructed per central event, 200,000 central events are required. Suppose we do the study with the 5% most central collisions, and we run minimum-bias trigger only, this corresponds to 4×10^6 minimum-bias events. With a data taking rate of ~ 1 Hz (minimum-bias running is not luminosity limited), and with an arbitrary machine penalty factor of two, only three months of running are required. We note that, the data will give a nice centrality scan, having value beyond that of the 5% central events.

5 Conclusion

We have investigated the feasibility of reconstructing the ϕ through its K^+K^- decay channel in the STAR TPC. Using the RQMD event generator and the full STAR software chain with the TPC fast simulater, we demonstrated that the ϕ can be reconstructed from charged kaons tracked and identified by dE/dx in the TPC. We conclude that the ϕ mass resolutions reconstructed using dE/dx PID and perfect GEANT PID are essentially the same. We also conclude that allowing contamination in kaons at high momenta from other particles does not penalize the signal-to-noise ratio, while increasing the number of reconstructed ϕ's significantly. Of 5.8 ϕ's per event that are generated by RQMD and decay into charged kaons within rapidity $-1.5 < y_K < 1.5$ and momentum $p_K < 1$ GeV/c, 1.3 ϕ's are reconstructed from K^+K^- pairs using the loose dE/dx PID. The signal-to-noise ratio of the ϕ peak in the K^+K^- invariant-mass spectrum is 1/12. The ϕ mass resolution due to kaon momentum resolution is 2.7 MeV/c^2.

Further work is needed to increase the statistics to obtain the ϕ acceptance in the STAR TPC and the reconstruction efficienty, in order to reconstruct the $p_\perp$ spectra and compare to the input. Work is also needed to include the SVT in the track reconstruction and dE/dx particle identification. Technically, the next step is to incoporate the analysis code into the ROOT framework.

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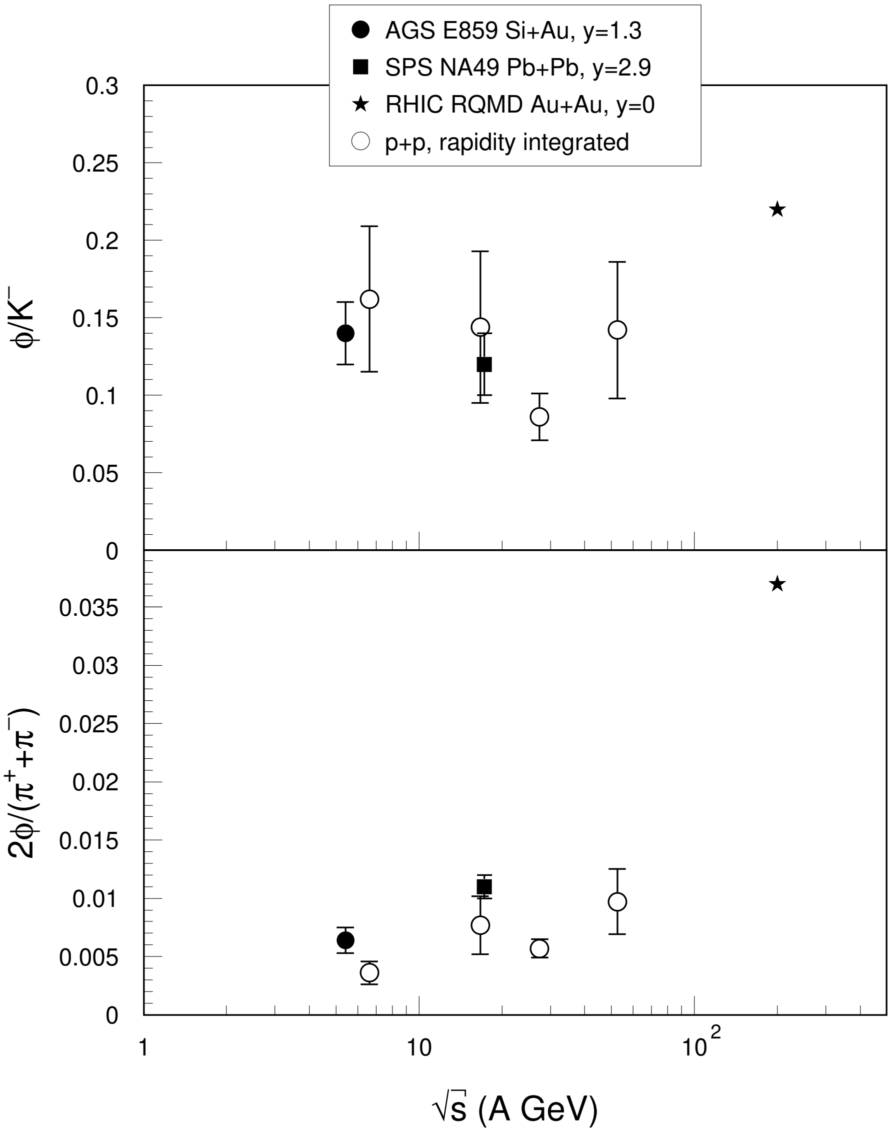

Figure 1: ϕ/K^- and $2\phi/(\pi^+ + \pi^-)$ ratios as a function of bombarding energy.

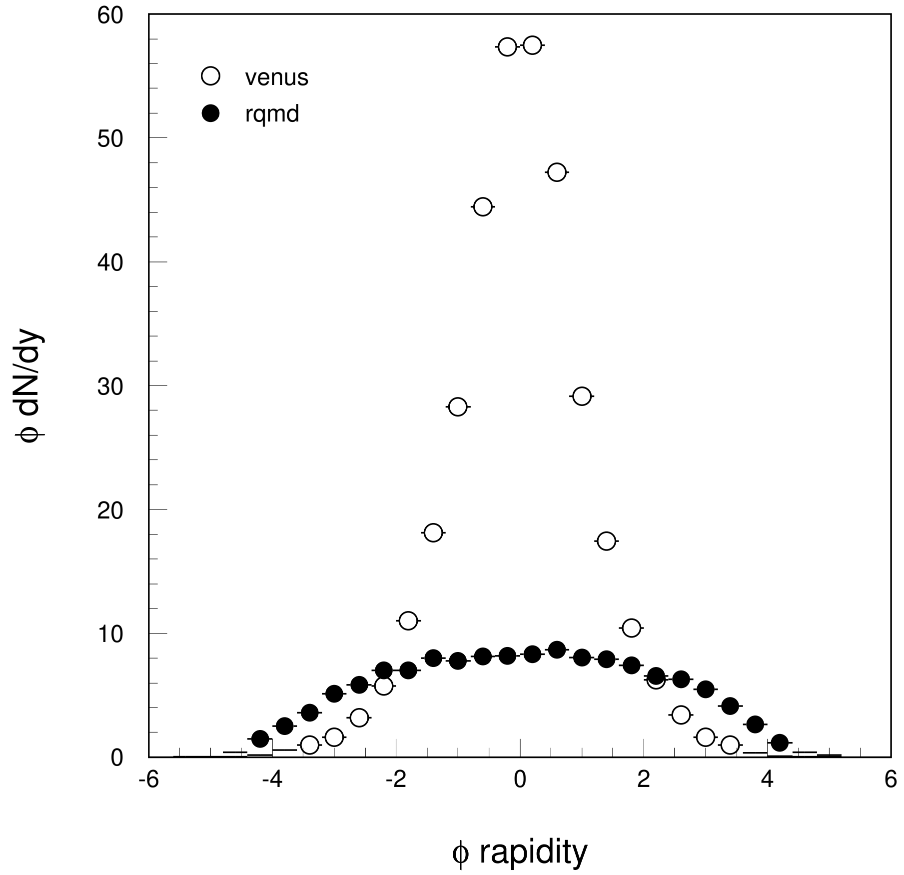

Figure 2: ϕ dN/dy, as predicted by two models: RQMD version 2.4 (filled circles) and Venus version 4.12 (open circles).

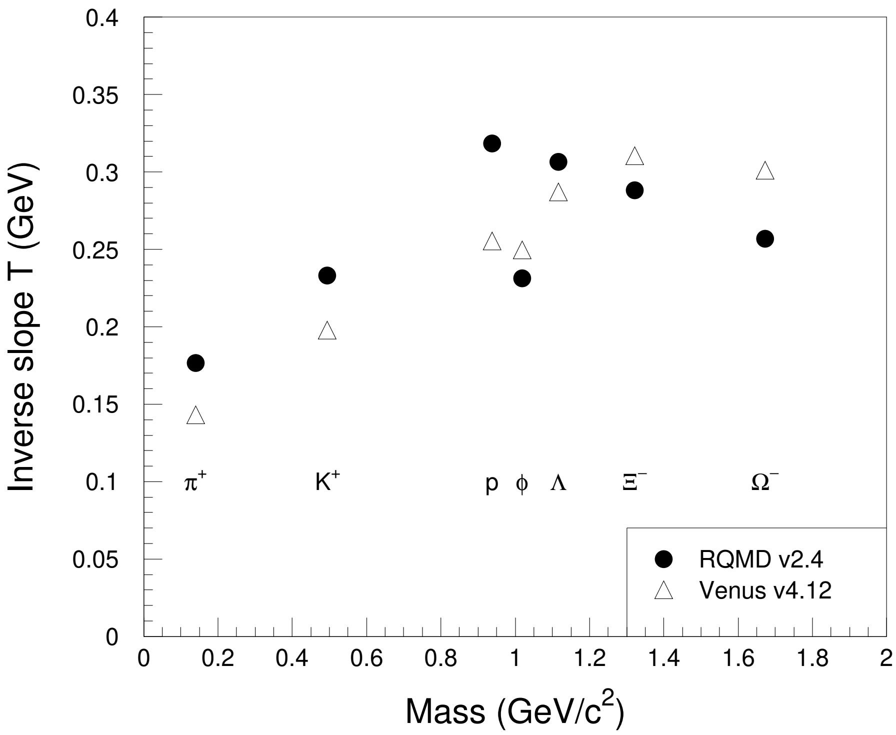

Figure 3: Mass systematics of the inverse slopes of particle $m_\perp$ spectra at mid-rapidity of central Au+Au collisions at RHIC energy, predicted by RQMD version 2.4 (filled points) and Venus version 4.12 (open traingles).

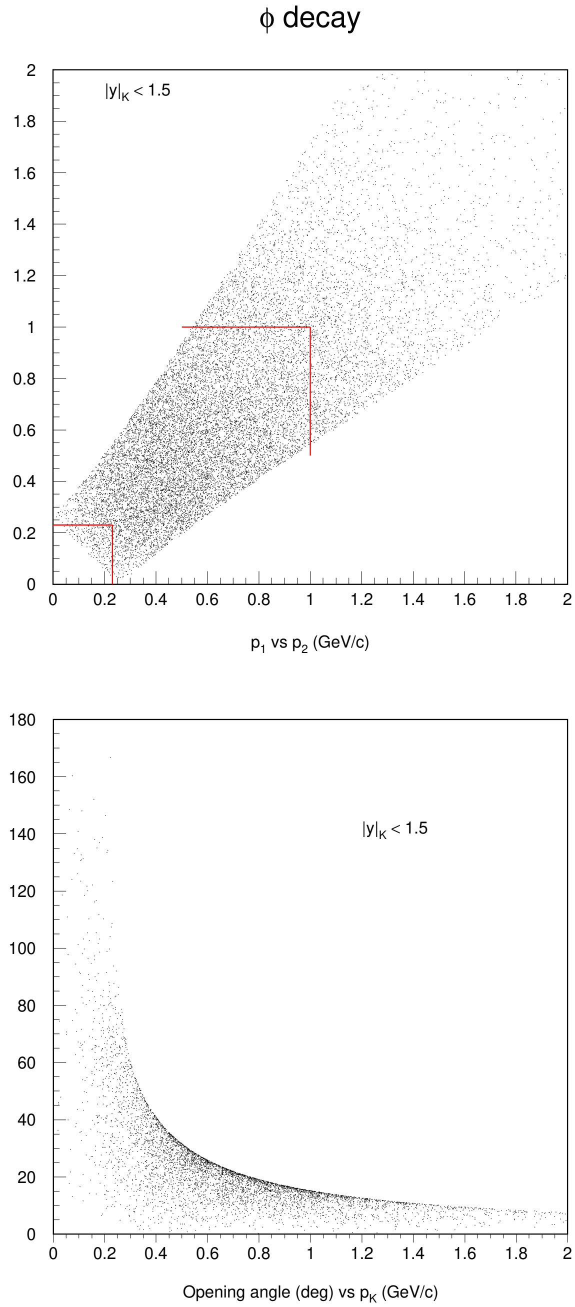

Figure 4: ϕ decay kinematics: (upper) scatter plot of the K^+ versus K^- momentum; (lower) decay opening angle versus the momentum of either kaon. The lines in the upper plot represent the kaon momentum range $0.23 < p_K < 1$ GeV/c.

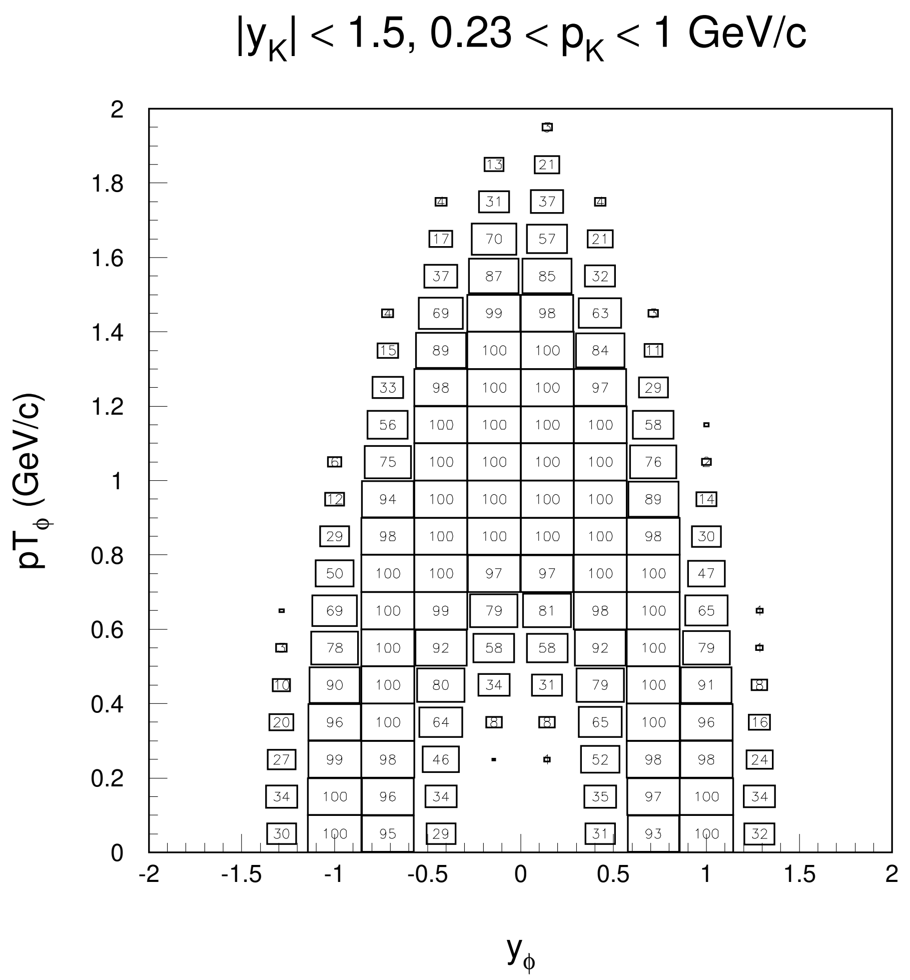

Figure 5: Rough estimate of ϕ acceptance of the STAR TPC in $p_\perp$ versus rapidity.

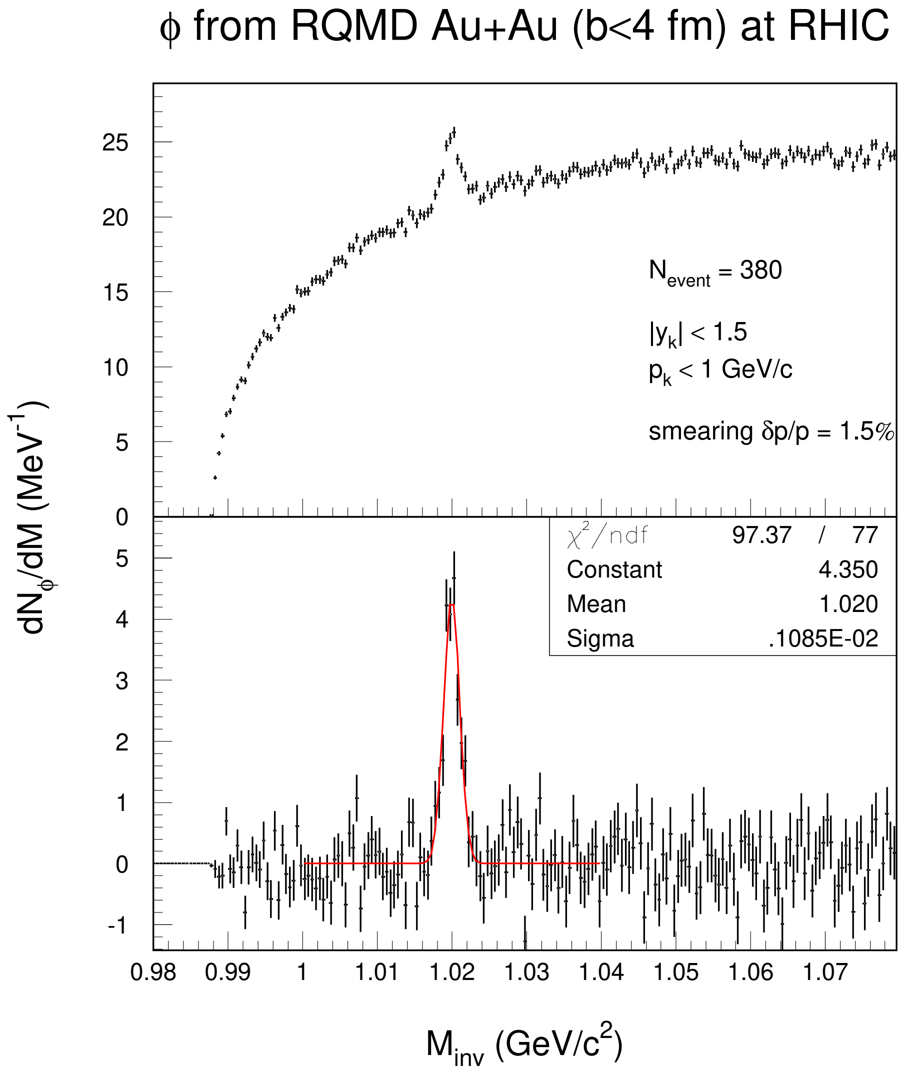

Figure 6: Top: invariant-mass spectrum of K^+K^- pairs using direct RQMD output. ϕ's were decayed 100% into K^+K^- pairs by hand. The ϕ intrinsic mass width was not included in the decays. Only kaons with rapidity $-1.5 < y_K < 1.5$ and momentum $p_K < 1$ GeV/c were used in the invariant-mass spectrum. A total of 380 Au+Au central events were used. Bottom: signal obtained after background subtraction. The background was obtained by pairing oppositely charged kaons from different events and normalized to the invariant-mass spectrum by the total number of entries. The curve is a Gaussian fit to the signal. About 11.8 ϕ's are under the Gaussian peak.

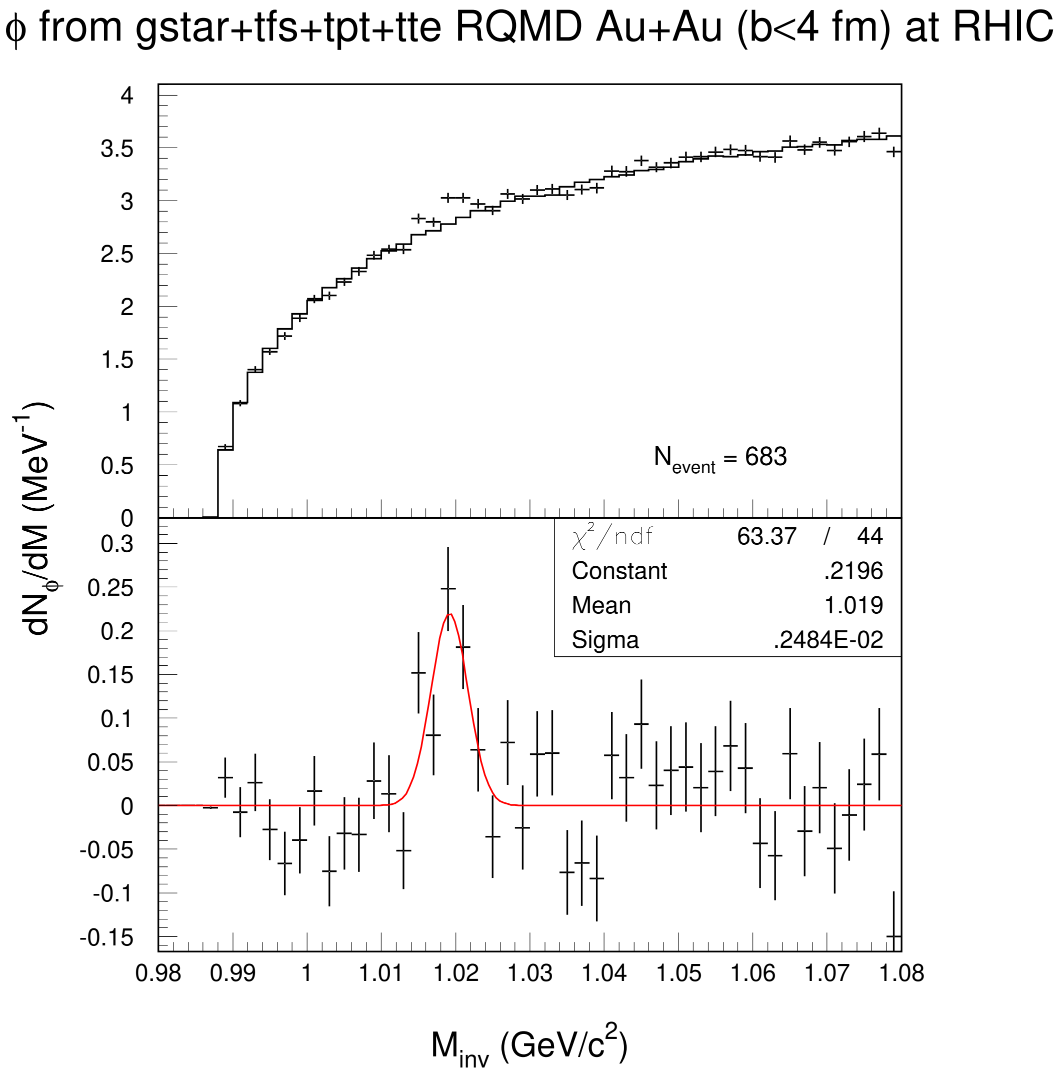

Figure 7: Top: invariant-mass spectrum of K^+K^- pairs calculated from reconstructed kaon momenta, with the kaon PID assumed from GEANT. ϕ's were decayed inside GEANT with the proper lifetime and branching ratios. The ϕ intrinsic mass width was not included in the decays. Only kaons with momentum $p_K < 1$ GeV/c were used in the invariant-mass spectrum. A total of 683 Au+Au central events were used. Bottom: signal obtained after background subtraction. The background (shown as the histogram in the top panel) was obtained by pairing oppositely charged kaons from different events and normalized to the invariant-mass spectrum by the total number of entries. The curve is a Gaussian fit to the signal. About 1.4 ϕ's are under the Gaussian peak.

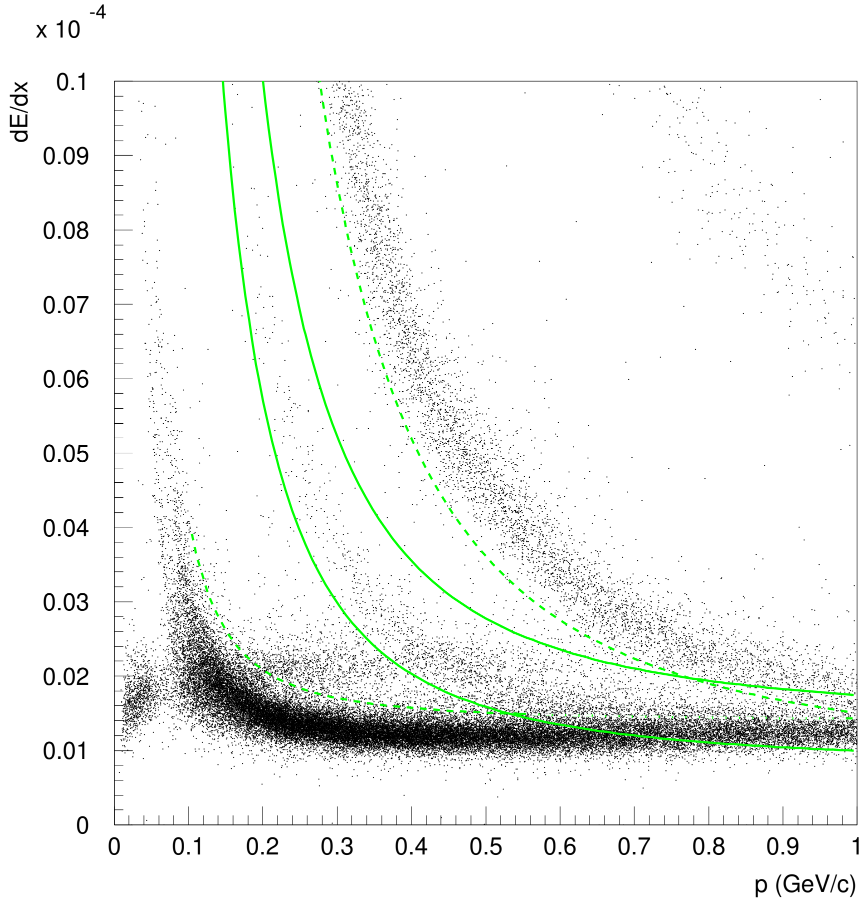

Figure 8: Kaon identification by dE/dx. Loose kaon PID cut: area between the two solid curves up to 1 GeV/c momentum. Tight kaon PID cut: area between the two solid curves with momenta below the two dashed curves.

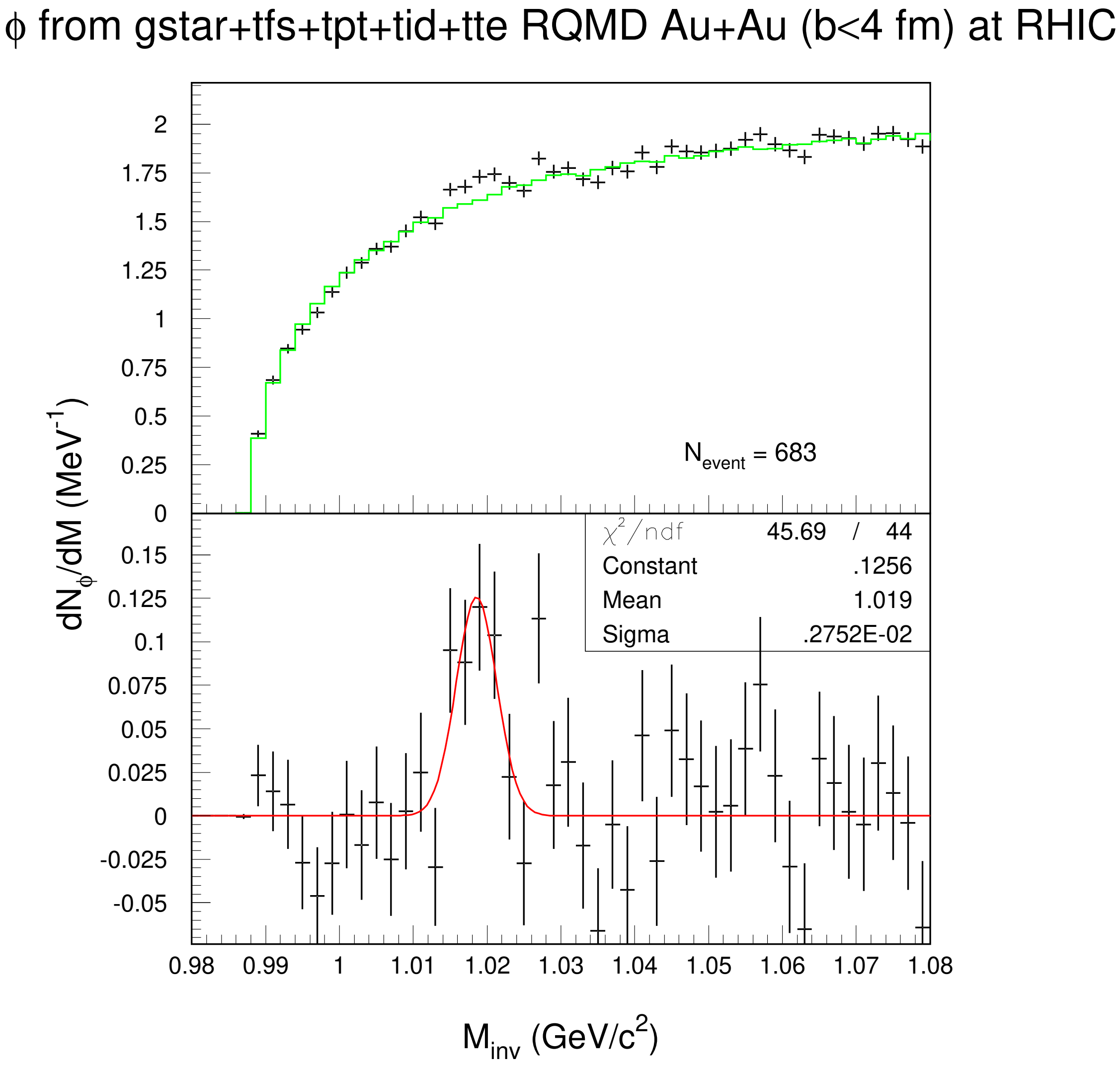

Figure 9: Top: invariant-mass spectrum of K^+K^- pairs calculated from reconstructed kaon momenta, with kaons identified by the tight PID. ϕ's were decayed inside GEANT with the proper lifetime and branching ratios. The ϕ intrinsic mass width was not included in the decays. A total of 683 Au+Au central events were used. Bottom: signal obtained after background subtraction. The background (shown as the histogram in the top panel) was obtained by pairing oppositely charged kaons from different events and normalized to the invariant-mass spectrum by the total number of entries. The curve is a Gaussian fit to the signal. About 0.8 ϕ's per event are under the Gaussian peak.

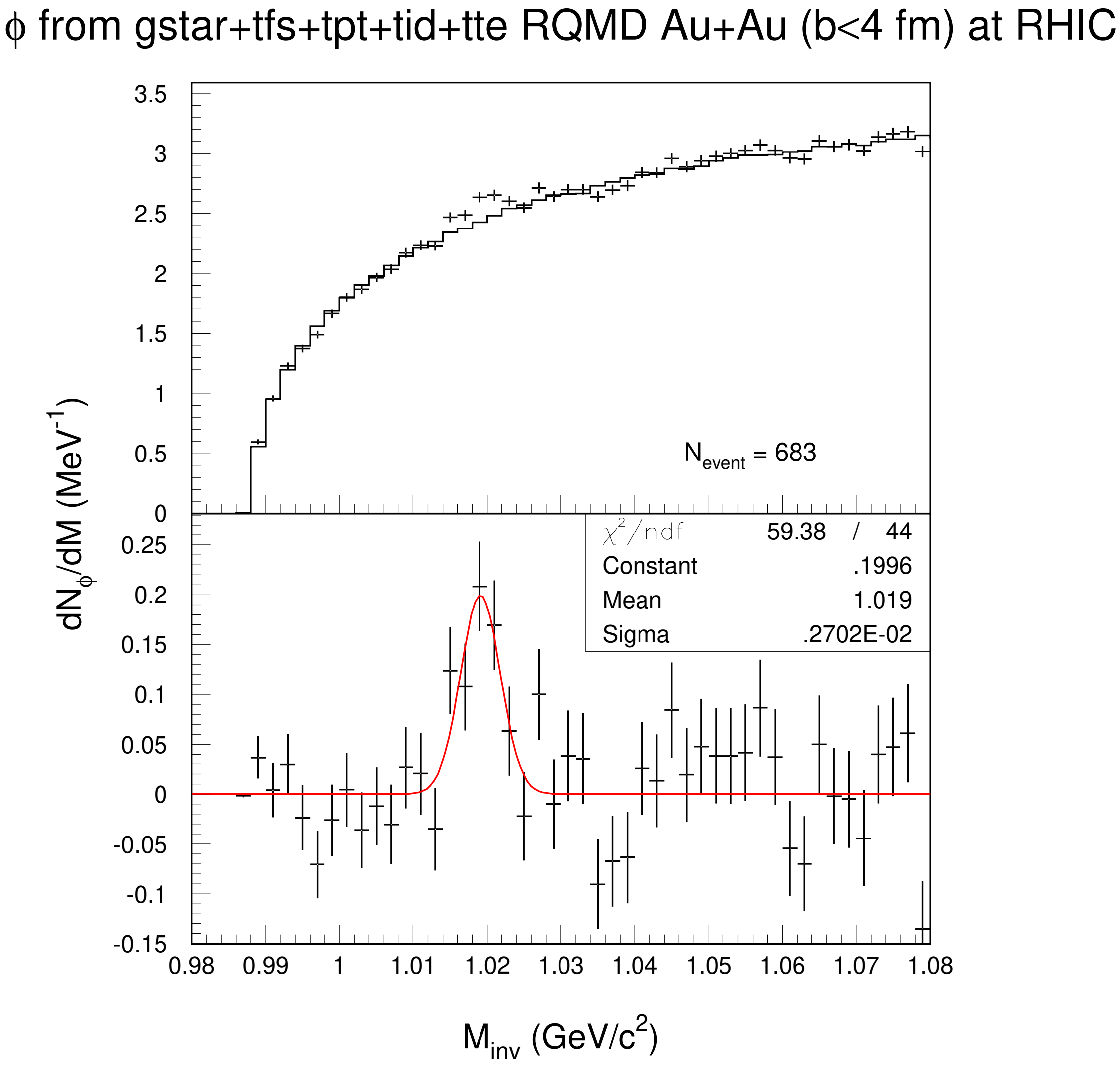

Figure 10: Top: invariant-mass spectrum of K^+K^- pairs calculated from reconstructed kaon momenta, with kaons identified by the loose PID. ϕ's were decayed inside GEANT with the proper lifetime and branching ratios. The ϕ intrinsic mass width was not included in the decays. A total of 683 Au+Au central events were used. Bottom: signal obtained after background subtraction. The background (shown as the histogram in the top panel) was obtained by pairing oppositely charged kaons from different events and normalized to the invariant-mass spectrum by the total number of entries. The curve is a Gaussian fit to the signal. About 1.3 ϕ's per event are under the Gaussian peak.