

# Simulations on the measurement of the $D_s$ meson semileptonic form factor with the PANDA detector

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**Abstract.** We report on software development to evaluate the expected performance of the PANDA detector to measure the semileptonic form factor  $D_s \rightarrow e + \nu + \pi, \eta, \eta'$ . The related decay models in this chain are checked via a Dalitz plot analysis; the present version of EvtGen in PandaRoot has been enhanced by a new model describing the  $D_s \rightarrow KK\pi$  decay. With the help of theoretical predictions of the cross section, the expected count rate is estimated.

## 1. Introduction

The PANDA experiment [1] is one of the major projects of the FAIR facility in Darmstadt and will study the interactions between an intense, phase space cooled beam of antiprotons provided by the High Energy Storage Ring (HESR) and hydrogen or heavier nuclear targets in the momentum range of 1.5-15 GeV/c. In order to serve the wide physics potential with antiprotons, PANDA is designed as a general purpose detector covering nearly the complete solid angle for both neutral and charged particles with good momentum and particle identification (PID) resolution as well as excellent vertex determination. By performing resonance and threshold scans with the high precision anti-proton beams, PANDA will achieve more than an order of magnitude higher mass resolution compared to existing facilities, e.g. the B-factories.

The semileptonic  $D_s$  decays are governed by both the weak and strong forces; extraction of the weak CKM parameters requires knowledge of strong interaction. These can be parameterized by the form factor encapsulating the QCD bound state effects. Techniques such as lattice quantum chromodynamics (LQCD) offer increasingly precise calculations of these form factors, but as the uncertainties in the predictions shrink, experimental validation of the results becomes increasingly important.

Recent data from CLEO on semileptonic  $D \rightarrow \pi, K$  decays [2, 3] have been used for more accurate determinations of the CKM matrix elements  $|V_{cd}|$  and  $|V_{cs}|$  [4], and some of those authors are currently extending that work to the  $\eta$  and  $\eta'$  in the final state. The principal difference is that now gluonic contributions couple to the singlet component of the  $\eta$  and  $\eta'$ , and the mass corrections are more important due to the larger strange quark mass. The theoretical uncertainty to the ratio of the branching ratios  $\mathcal{B}(D_s^+ \rightarrow e + \nu + \eta')/\mathcal{B}(D_s^+ \rightarrow e + \nu + \eta)$  is dominated by uncertainty to the gluonic contribution, thus an improvement of the relative branching ratio can help to pinpoint the gluonic contribution [5].

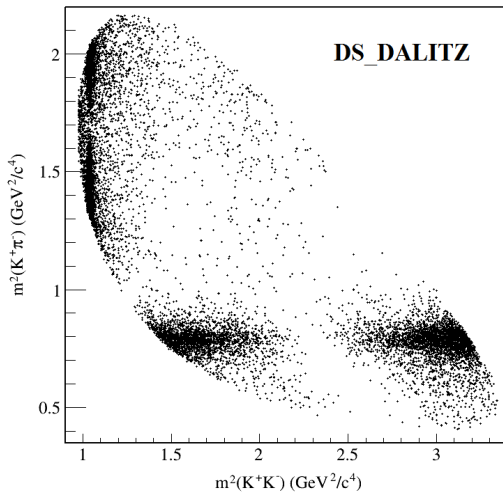
In the semileptonic decay of  $D_s$  meson, there is one neutrino in the event. The achievable performance of the PANDA detector for these types of reactions has not yet been studied in detail; however, this is expected to work very well based upon the design performance and



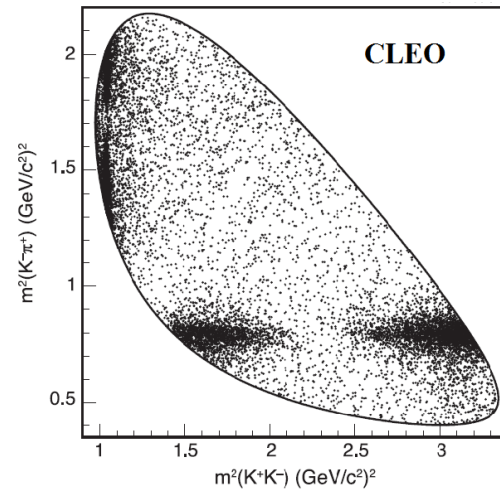
experience with other detector systems due to the kinematic constraints which allow these events to be completely reconstructed despite one particle not being measured. The goal of this study is to evaluate and optimize the physics performance of the PANDA detector to measure the form factor of semileptonic  $D_s$  meson decays. In the following sections, we will introduce the new DS\_DALITZ decay model and the details of the reconstruction procedure. The output histograms are shown with the reconstruction results. Finally, the expected rate to measure the events is estimated by using the reconstruction efficiency presented here and a theoretical estimate of the production cross section.

## 2. Simulation and decay model

Antiproton annihilation on a proton target will be used to generate  $D_s$  pair at PANDA with the beam momentum of 8 GeV/c. One of the  $D_s$  mesons will be used as a "trigger", and can be reconstructed via a decay branch that is relatively common and has a simple final state, e.g. hadronic mode  $D_s \rightarrow KK\pi$ . For a reasonable simulation, we import a new decay model DS\_DALITZ in the PandaRoot [6] software, which is the official framework of the Collaboration for both simulation and analysis, and is mainly based on the object oriented data analysis framework ROOT [7]. DS\_DALITZ includes contributions from the following resonances:  $K^*(892)K^+$ ,  $K_0^*(1430)K^+$ ,  $f_0(980)\pi^+$ ,  $\Phi(1020)\pi^+$ ,  $f_0(1370)\pi^+$  and  $f_0(1710)\pi^+$ . The original code is partly from the EvtGen package developed jointly for the BaBar and CLEO collaboration, where the  $D_s \rightarrow KK\pi$  decay is implemented as a branch of the existing D\_DALITZ model. We tested its performance in Monte Carlo simulation via a Dalitz plot analysis and the result is shown in Figure 1, where the substructure of resonances is clear and comparable with the experimental measurements [8–10]. Figure 2 shows the Dalitz plot obtained by the CLEO experiment with 14,400 events [9]. In the semileptonic channel, we adopt the ISGW2 model to simulate the decay  $D_s^+ \rightarrow e + \nu + \eta'$  and the ETA\_DALITZ model for the  $\eta \rightarrow \pi^+\pi^-\pi^0$  decay.



**Figure 1.** Output of Dalitz plot in MC simulation with DS\_DALITZ model.



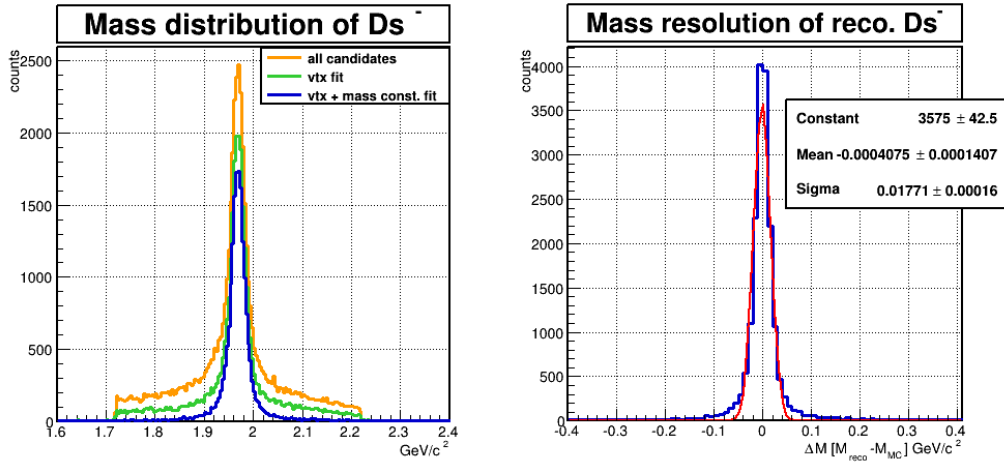
**Figure 2.** Measured Dalitz plot for the decay  $D_s^+ \rightarrow K^+ K^- \pi^+$  [9].

## 3. Reconstruction

In the reconstruction procedure, we focus on developing the software and evaluating the expected precision of these measurements using Monte Carlo simulation of the PANDA detector. In order

to extract the invariant mass squared of the lepton-neutrino system, we have to reconstruct the semileptonic decay product  $\eta$  and the other charged  $D_s$  meson from the initial  $p\bar{p}$  system.

We have reconstructed the hadronic channel  $D_s^- \rightarrow K^+ K^- \pi^-$  with 100,000 events, where the mass window for  $D_s^-$  is  $0.5 \text{ GeV}/c^2$ . Using the present software, we perform the vertex fitting and mass constraint fitting for all candidates. The reconstruction efficiency of  $D_s^-$  is about 18%. As shown in Figure 3, the mass resolution is  $17.7 \text{ MeV}/c^2$ . Figure 4 summarizes the expected momentum and vertex resolutions of the reconstructed  $D_s$  meson.

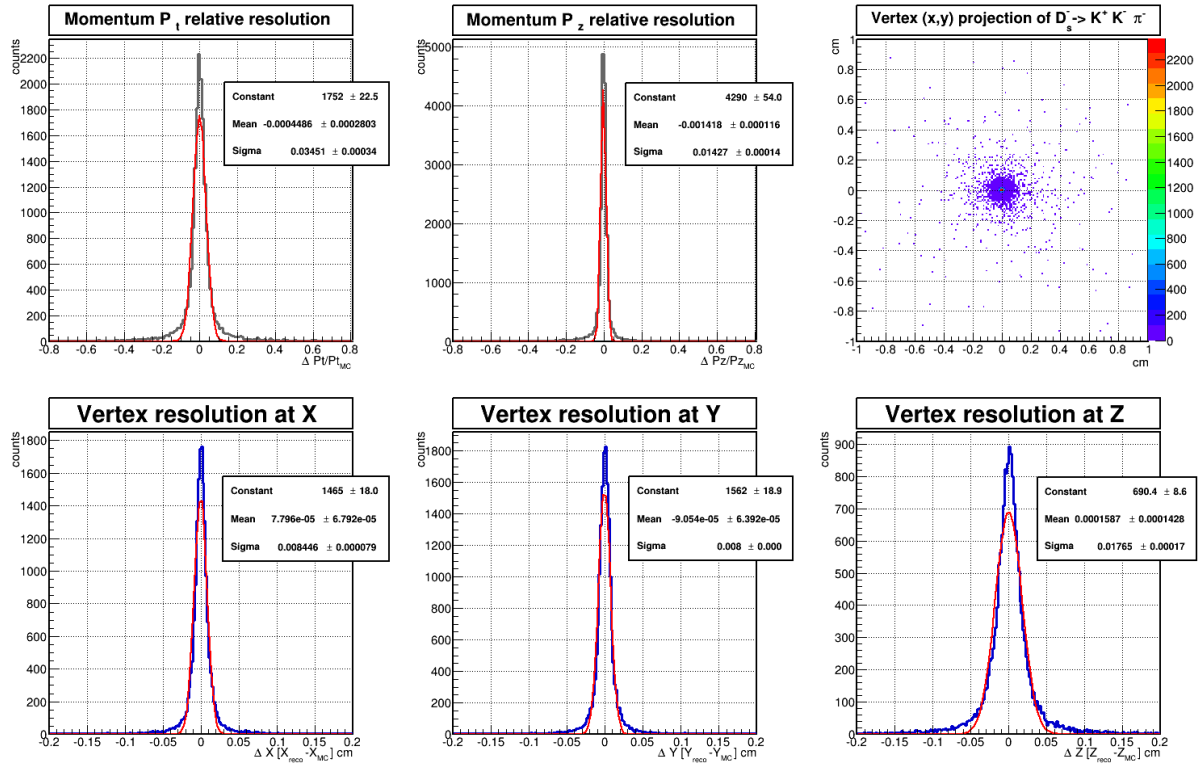


**Figure 3.** Mass distribution and resolution of reconstructed  $D_s^-$ .  $KK\pi$  invariant mass distributions (left) for all candidates (orange), after the vertex fit (green), and after the additional mass constraint fit (blue). Invariant mass distribution of the reconstructed  $D_s^-$  (right) and a Gaussian fit to determine the resolution.

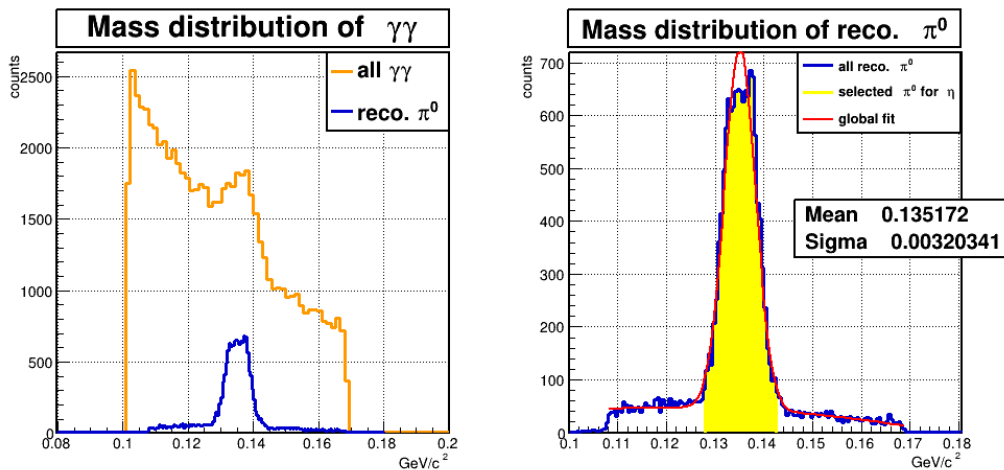
The reconstruction strategy for this semileptonic decay chain has several steps:  $D_s^+ \rightarrow \nu_e e^+ \eta$ ;  $\eta \rightarrow \pi^+ \pi^- \pi^0$ , and  $\pi^0 \rightarrow \gamma\gamma$ . We started from the combination of two photons which can be detected by the electromagnetic calorimeter (EMC) equipped in the PANDA target spectrometer. The pre-selection has been applied for the reconstruction according to the subdetector specific properties of the EMC [11], e.g. the minimal laboratory angle between two photons should be larger than the EMC spatial resolutions  $\sigma_\theta$ : on the backward end-cap  $\sigma_\theta = 0.5^\circ$ , on the barrel  $\sigma_\theta = 0.3^\circ$  and on the forward end-cap  $\sigma_\theta = 0.1^\circ$ . The mass constraint fitting is performed on the  $\gamma\gamma$  system to select the "best" fitted  $\pi^0$  for reconstructing the mother particle  $\eta$  (see Figure 5). The charged tracks  $\pi^+$  and  $\pi^-$  determine the vertex reconstruction of  $\eta \rightarrow \pi^+ \pi^- \pi^0$ , and in this step the performance of the fitter plays an essential role on the total efficiency of the reconstructed  $\eta$ , since the neutral daughter  $\pi^0$  has achieved a high efficiency with the mass resolution of  $3.2 \text{ MeV}/c^2$ . After applying these fit procedures, 26% of the events have been reconstructed (see Figure 6). The preliminary results of reconstruction efficiency  $\epsilon$  and resolutions  $\sigma$  of the  $D_s$  and  $\eta$  are listed in Table 1.

#### 4. Summary

The hadronic decay  $D_s \rightarrow KK\pi$  and the decay  $\eta \rightarrow \pi^+ \pi^- \pi^0$  emanating from the semileptonic decay  $D_s^+ \rightarrow \nu_e e^+ \eta$  have been investigated within the PandaRoot software in order to estimate the resolution and efficiency to measure these channels. Table 1 summarizes the obtained efficiency and resolutions of the reconstructed  $D_s$  and  $\eta$ . The next step will be to expand the kinematic fit to include the unmeasured neutrino in the semileptonic decay branch.

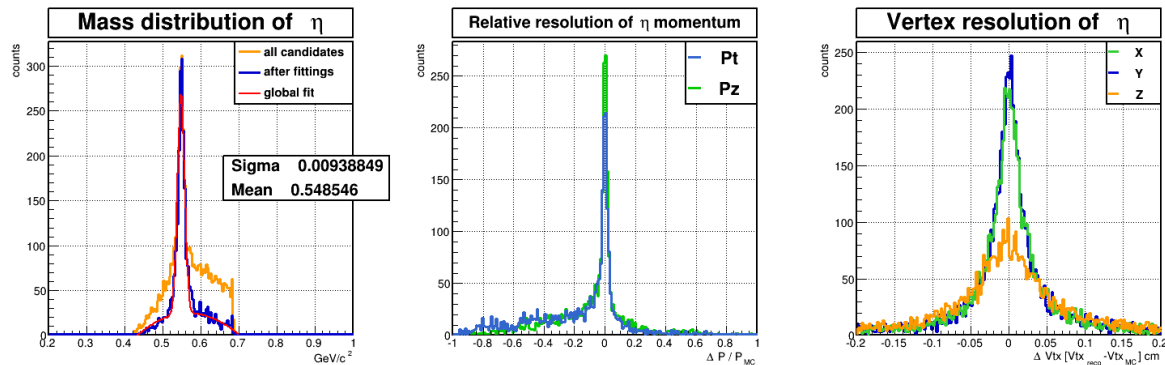


**Figure 4.** Resolutions of kinematic properties of reconstructed  $D_s^-$ . The top left and center frames indicate the relative resolution for the transverse and longitudinal momentum, respectively. The top right frame indicates the reconstructed vertex distribution for the  $D_s^-$  decay branch, and the lower line indicates the vertex resolution in the X,Y,Z projections.



**Figure 5.** Invariant mass distribution of  $\gamma\gamma$  (left) and the reconstructed  $\pi^0$  (right).

The efficiency of the  $\nu_e e^+$  system should be the product of the efficiencies of  $D_s^-$  and  $\eta$  (listed in Table 1). At this moment, the value we obtained is about 4.7%. The cross section of  $D_s$



**Figure 6.** Resolution of mass and kinematic properties of reconstructed  $\eta$ . Three pion invariant mass distribution from eta decays (left), transverse (blue) and longitudinal (green) momentum resolution of the reconstructed  $\eta$ , and the vertex resolution in all three Cartesian projections.

pair at PANDA is roughly estimated to be 10 nb with the beam momentum of 8 GeV/c [12]. With the average branching ratios  $\mathcal{B}(D_s^+ \rightarrow \eta e^+ \nu_e) = 2.67\%$  and  $\mathcal{B}(D_s^- \rightarrow K^+ K^- \pi^-) = 5.49\%$ , the production rate is estimated to be approximately 200 events per month with the luminosity of  $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ . This result is not the final estimate, since the present PandaRoot software is under development. The reconstruction efficiency including the resolutions can be improved in the near future. On the other hand, an explicit prediction of cross section from the theory is urgently needed. This issue will be also interesting for the theorists working on the different models.

**Table 1.** Reconstruction results of  $D_s^-$  and  $\eta$ .

Particle	eff. [%]	Mass reso. [MeV/c <sup>2</sup> ]	Vertex reso. [ $\mu\text{m}$ ]			Momentum reso. [%]	
			$x$	$y$	$z$	$p_t$	$p_z$
$D_s^-$	18	17	78	80	177	3.5	1.4
$\eta$	26	9	318	287	675	3.8	4.3

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