

# Final Report of the $\bar{\text{P}}$ ANDA PID TAG

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G. Schepers, GSI Darmstadt, et al.

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# 1 Introduction

The  $\bar{\text{PANDA}}$  ([1]) PID TAG (Particle Identification Technical Assessment Group) was installed to give to the collaboration a complete set of parameters for an optimal set of particle detectors. The task given to this TAG is described in more detail:

## Subject

- Requirements from physics
- Evaluate potential of each subsystem
- Matching of systems

## Deliverables

- Definition of global PID scheme
- Optimized set of detectors and parameters

This list reflects roughly the structure of the PID TAG work and of this report. In an additional subsection the tools available for the PID TAG work are presented and explained (see also [2]) . The PID TAG evaluated the necessity of mapping the "Separation Power" in dependence of the momentum and the polar angle of the reaction products which is described in section ?? . Since a "full simulation" was not available to calculate the performance of all the sub detectors, the TAG gathered parameterizations of the single sub detectors which went into a "Fast Simulation" explained in section 4.3. For single physics channels a "Full Simulation" was used.

Amongst others some important questions to solve were:

- PID with and with out the information of a Time Projection Chamber (TPC)
- PID with and with out an Forward Endcap Cherenkov, and with different forms (Focusing Disc DIRC, Time of Propagation Disc DIRC and Proximity RICH)
- PID with and with out a Forward RICH

The PID TAG had about 10 presence meetings and over 15 on line meetings. First PID subsystems were defined. Each subsystem has its responsible representative. Each representative had a replacement of his own group to guarantee always the same level of knowledge in all subsystems. For special subjects experts were asked to present informations in the meeting or to give answers to questions which arose.

The members of the TAG and their special responsibilities are listed at the end of the document (section 9).



## 2 Physics Requirements

The HESR (High Energy Storage Ring) of the new FAIR (Facility for Antiproton and Ion Research) project provides an Antiproton beam of high resolution (down to  $\Delta p = 1 \times 10^{-5}$ ) and intensity from 1.5 GeV/c to 15 GeV/c momentum.

This offers the unique possibility of investigating a broad field of physics. The vast variety of reaction types from meson-production over Charmonium decays to Hyper nuclear reactions demands a complete and compact detector system.

The physics requirements to the detectors are:

- to cover the full angular range of the physics products
- to detect all momenta of the reaction products
- to separate particle types with a defined level of separation over the full range of momenta of the reaction products.

The full solid angle can only be covered by the full set of detectors. Sometimes the momentum coverage has to be fulfilled by a combination of two or even three sub detectors.

For the single subsystems benchmark-channels had to be identified (Table 1) and simulated.

Channel	Final state	Related to detector
$\bar{p}p \rightarrow (n)\pi^+\pi^-$	$(n)\pi^+\pi^-$	EMC
$\bar{p}p \rightarrow \psi(3770) \rightarrow D^+D^-$	$2K\ 4\pi$	DIRCs, ToF
$\bar{p}p \rightarrow \eta_c \rightarrow \phi\phi$	$4K$	DIRCs
$\bar{p}p \rightarrow D_S D_{S0}^*(2317)$	$\pi^\pm K^+ K^-$	DIRCs
		muon
		Forward RICH

Table 1: Benchmark channels to evaluate the performance of the different PID detectors.

At PANDA  $2 \times 10^7$  reactions per second with up to 10 charged particles per reaction have to be digested by the detectors.

### 3 PID Subsystems

The different behavior of charged particles traversing active and passive detector material can be used to identify (on a probabilistic level) the nature of a charged particle. The PID detectors used in PANDA take advantage of the following effects:

- **Specific Energy Loss.** The mean energy loss of charged particles per unit length, usually referred to as  $dE/dx$ , is described by the Bethe-Bloch equation which depends on the velocity rather than momentum of the charged particle.
- **Cherenkov Effect.** Charged particles in a medium with refractive index  $n$  propagating with velocity  $\beta > 1/n$  emit radiation at an angle  $\Theta_C = \arccos(1/n\beta)$ . Thus, the mass of the detected particle can be determined by combining the velocity information determined from  $\Theta_C$  with momentum information from the tracking detectors.
- **Time-of-flight.** Particles with the same momentum, but different masses travel with different velocities, thus reaching a time-of-flight counter at different times relative to a common start.
- **Absorption.** A thick layer of passive material absorb most particles due to electromagnetic ( $e^+e^-$ ,  $\gamma$ ) or hadronic interactions (all charged and neutral hadrons). After a certain amount of material only muons and neutrinos survive. The muons can then be detected easily with any kind of charged particle detector, depending on the desired speed and resolution.

The group of subsystems building the particle identification system of PANDA are listed with growing distance to the Target point:

- Time Projection Chamber
- Time of Flight
- Barrel DIRC
- Barrel Calorimeter
- Forward Cherenkov
- Forward Calorimeter
- Muon Counter

115 **3.1 Central Tracker**

### 3.1.1 Time Projection Chamber (TPC)

The working principle of a GEM-based TPC and the geometrical design of the PANDA TPC [1] are sketched in Figs. 1 and 2. Charged particles traversing the detector volume ionize the counting gas and an electric field separates positive ions from electrons. The cylinder axis of the TPC coincides with the direction of the electrical field lines and also the direction of the solenoid magnetic field of the target spectrometer. The primary electrons are guided towards an amplification stage, which consists of a triple-GEM stack. No gating grid is foreseen for the PANDA TPC to allow a continuous operation at the HESR antiproton storage ring. In order to keep the build-up of space charge inside the drift volume at a minimum, the back flow of slow ions from the amplification stage has to be suppressed as much as possible. GEM foils [3] offer an intrinsic ion suppression if the settings of the whole stack are optimized accordingly. A continuous readout including online tracklet reconstruction is envisaged for the TPC.

In order to accommodate the target pipe, the TPC is split into two half-cylinders of a length of 150 cm. The inner and outer radius is 15 cm and 42 cm, respectively. 65 000 to 100 000 pads of an area of 4-6 mm<sup>2</sup> are planned. A Ne/CO<sub>2</sub> gas mixture (90/10), possibly with a small admixture of CH<sub>4</sub>, and a gain of the order of 1 000 are furthermore foreseen. The drift field is 400 V/cm. Under these conditions  $\approx 50$ -100 energy loss measurements per track are feasible. This allows, in combination with a truncated mean algorithm, the identification of charged particles via their mean energy loss per track length  $dE/dx$  (Bethe-Bloch-formula, see equation 13). The TPC therefore contributes significantly to the overall PID performance of PANDA, in particular in the momentum regime below 1 GeV/ $c^2$ . In Fig. 3 the energy loss distributions for different particle types are shown up to 1.5 GeV/ $c^2$ . The plot has been obtained from the “Fast Simulation” described in section 4.3 assuming a  $dE/dx$  resolution of 8% for the TPC (cf. table 6).

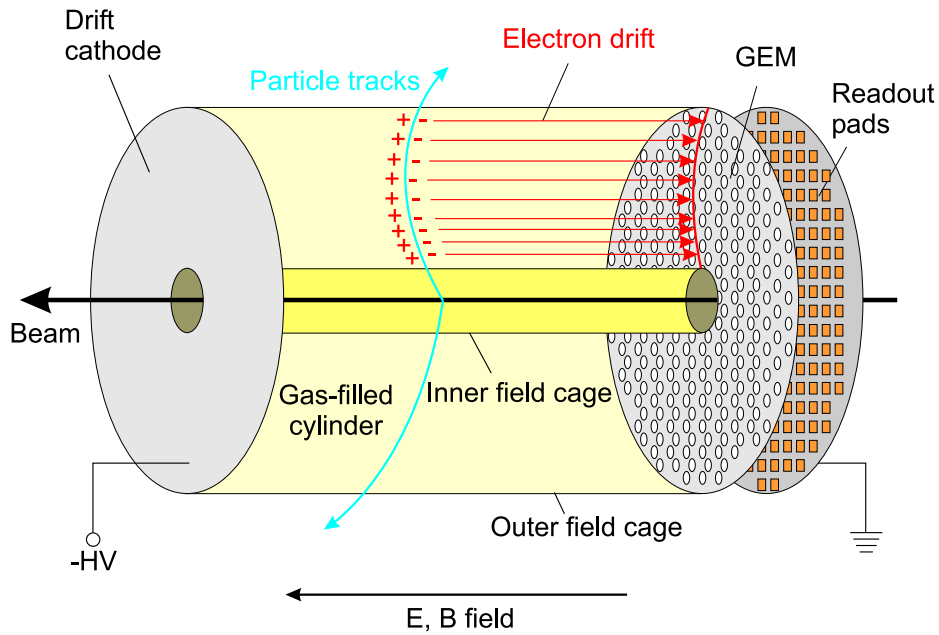


Figure 1: Working principle of a GEM-TPC (see text).

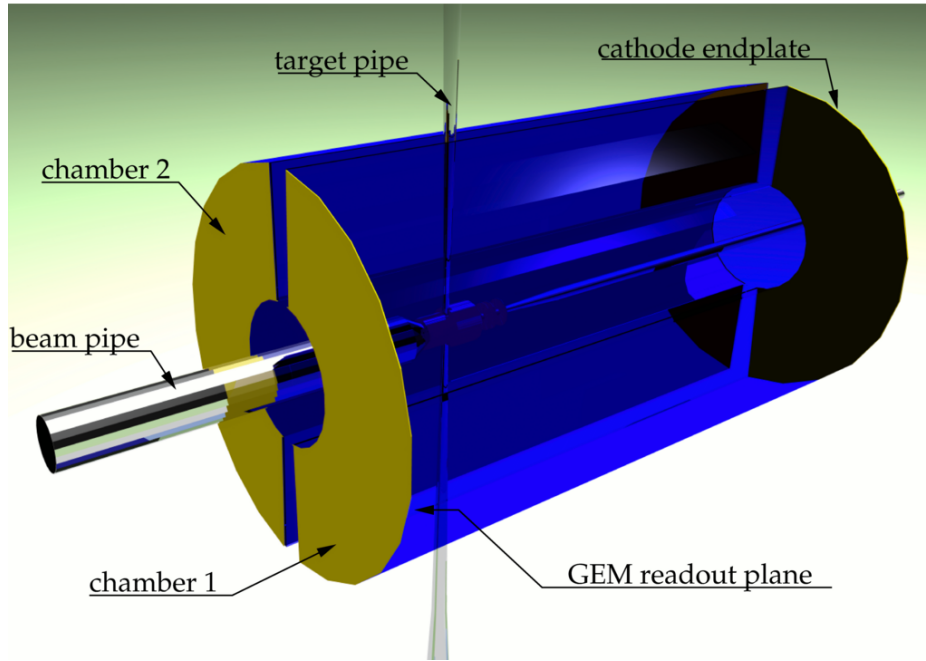


Figure 2: Geometry of the PANDA TPC; for further details see text and [1].

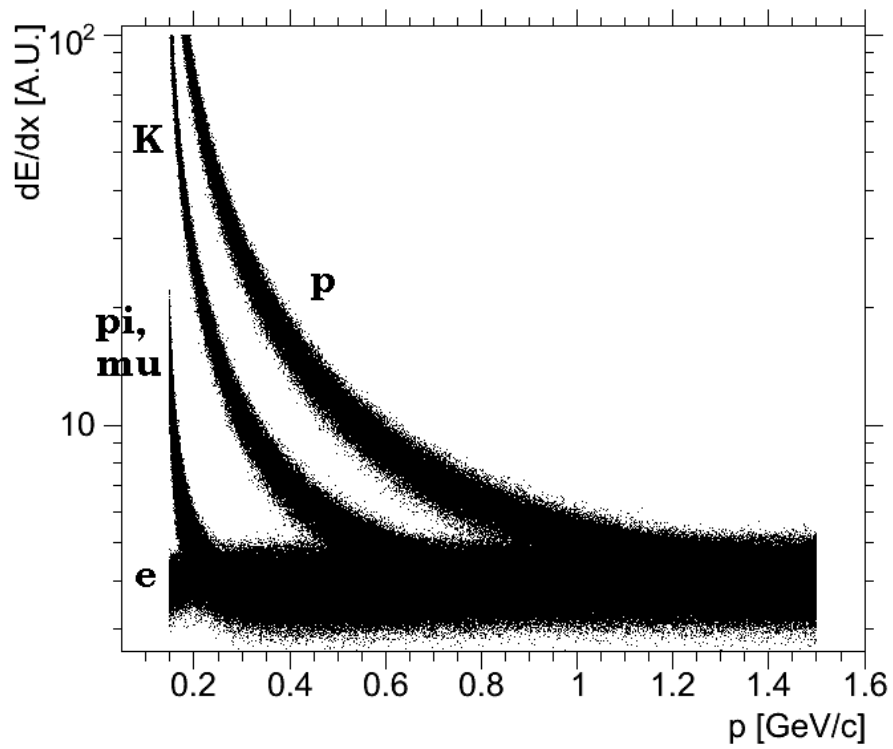


Figure 3: Energy loss in the TPC vs. particle momentum up to  $1.5 \text{ GeV}/c^2$ .

139 **3.1.2 Straw Tube Tracker (STT)**

## 3.2 Time of Flight (ToF)

### Barrel Time-Of-Flight

Barrel Time-of-Light detector (TOF) has to be placed inside solenoidal magnet and provide identification for soft particles at large polar angles from 22 to 140 degrees. The recently developed timing Resistive Plate Chambers (RPC) represent currently the optimal choice for Barrel TOF detector that in principle offers the required resolution of better than 70 ps. The RPC-TOF system was designed to identify particles with momentum of several hundred  $MeV/c$  at short particle flight distance ( $\sim 0.45 m$ ). The identification of pions, kaons and protons is possible up to few  $GeV/c$ . The RPC-TOF is arranged in array around TPC (or STT), and contains 11 modules. A 3D-view of the detector obtained in the frame of PandaRoot is given in Fig. 4. The neighbour modules are overlapped on value of 10 mm. Each module has 64 rows (strips) with multi-gap Resistive Plate Chambers, and with 2 read-out channels in a strip. These lead to a timing resolution of not worse than 75 ps.

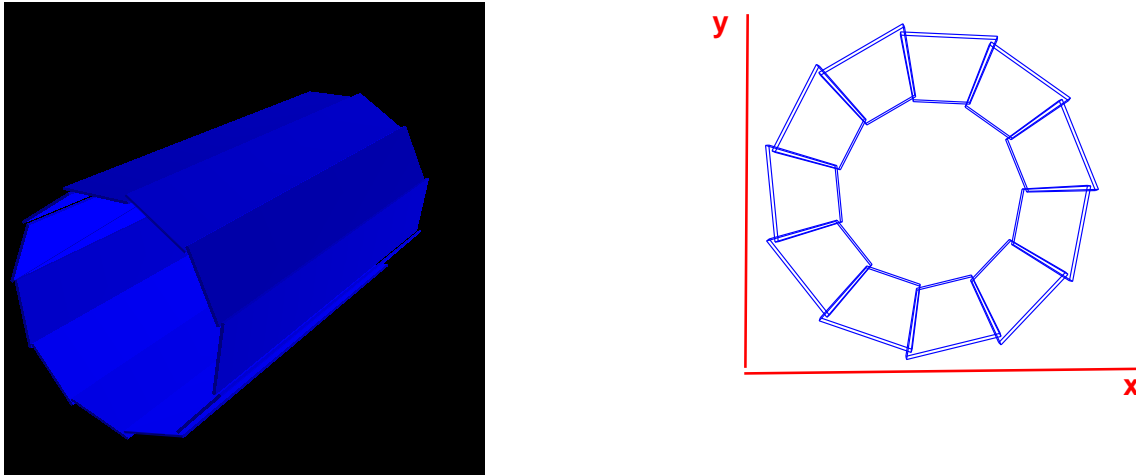


Figure 4: 3D-view and front projection of the RPC-TOF.

#### Geometry:

Inner radius of TOF is 47.5 cm, out radius is 49.5 cm, length is 190 cm. The barrel RPC-TOF covers the solid angle between 22 and 140 degrees. Number of the modules is 11, the module thickness is 10 mm, The module width is 29.8 cm. The common number of multi-gap RPCs is 704. The RPC length is proposed  $\sim 3$  cm, and width is 29.8 cm.

Because of only 2 cm slot was available for the TOF detector, four-gap glass RPC was chosen. Cross-section of 4-gap RPC is shown in fig.5. The RPCs can be made from a "standard" float glass with thickness of 0.7 mm and with bulk resistivity of  $\sim 10^{13} \Omega cm$ . The gaps between glass plates are kept with spacers made of fishing line. RPC contains two identical sets of three glass plates and two 0.3 mm gas gaps. High voltage is applied to the outer glass plates through graphite coating. The read-out strips are made with 15  $\mu m$  Cu on 75  $\mu m$  Kapton. The strips have dimension 2.9 cm  $\times$  29.8 cm. All "reference" strips placed on both outer plates of glass stack have to be connected to ground. Glass RPC are housed in an aluminium case having a bottom part and a cover plate (see fig.6a). Length of a case is  $\sim 200$  cm, its thickness is 10 mm only. Bottom part

of a case is made with 1 mm thick aluminium plate, two longitudinal bars and two end profiles. A case is covered with 1 mm cover plate. O-ring provides gas tightness.

A chamber for the detector contains boards with electronics going along both long sides to get read-out for strips.

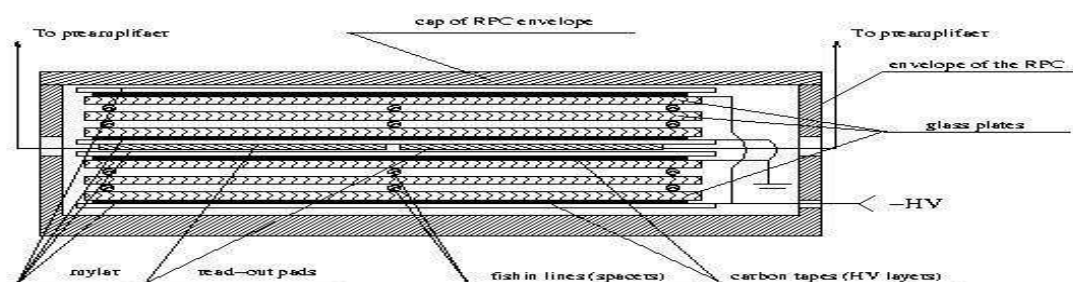


Figure 5: Four-gap RPC. Cross-section through its short side.

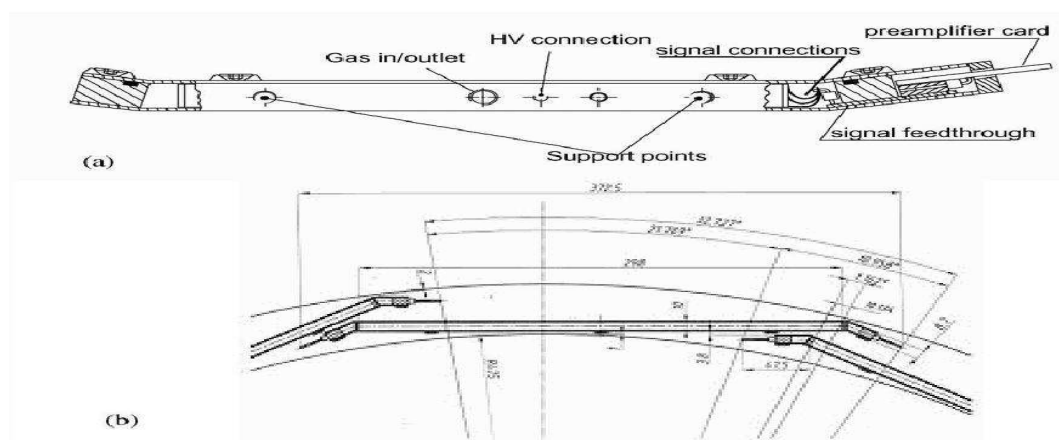


Figure 6: a) Cross-section through a module, b)- arrangement of barrel RPCs.

Set of eleventh TOF modules having total gas volume of  $\sim 60$  liters is operating with a non-flammable gas mixture containing 90%*R134A*, 5% isobutane and 5%*SF<sub>6</sub>*. The flows of three gas components are metered with "electronic mass flow meters". At total flow rate of about  $200\text{ cm}^3/\text{min}$ , a gas exchange of one volume will be every  $\sim 5$  hours. The TOF modules are supplied with gas in groups, say, of four. Each group has its own control and protection systems.

Material budget:

Radiation length for a module containing 4-gap glass RPC is given in Table 2. It was assumed that RPC is made of 0.6 *mm* thick glass. Radiation length  $X/X_0$ , calculated in the Table is only given for a particle which crosses a TOF module perpendicular to its plane.

The analogous HARP RPCs were tested in the T10 test beam. The performance for physics analysis of the full HARP system of the RPCs is described in Ref.[1]. The resolution of  $\sim 175$   $ps$



Table 2: Thickness of the TOF detector.

material	$X_0(mm)$	thickness(mm)	$X/X_0$
glass	127	3.6	2.83%
aluminium	89	2	2.22%
copper	14.4	0.1	0.69%
mylar	287	0.6	0.21%
kapton	286	0.25	$\sim 0.10\%$
Sum			$\approx 6.0\%$

at efficiency of better than 97% has been reached. Typical noise rate was  $\leq 1 kHz/m^2$ .

A stable operation of the such RPCs was observed in extensive tests during many years in various experiments. The RPCs were found to be fully efficient and low-noise chambers. One of useful feature of the RPC is its immunity to magnetic field.

The detector design is based on the HARP TOF [1], but for the PANDA experiment further improvements of the performance are under development. An attempt to replace 4-gap RPC with 6-gap one should be done during *R&D* work. The development of the read-out system has to be a major task during *R&D* study for the PANDA RPC.

Very important question is the **rate capability**. Since the bulk resistivity of glass is  $\sim 10^{13} \Omega \cdot cm$ , the rate capability of a glass RPC could bring a potential problem due to the time needed to neutralize the charge deposited on the resistive plates after discharge inside gas gaps.

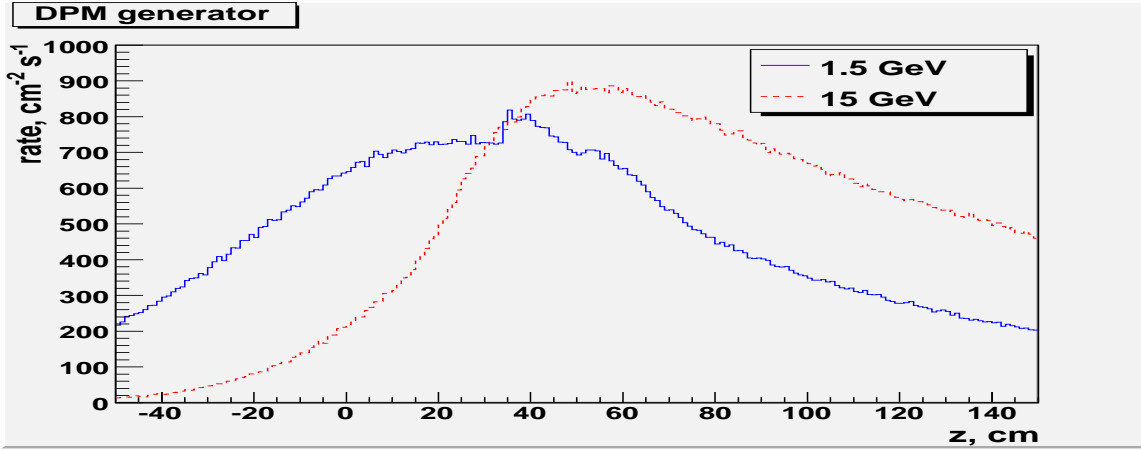


Figure 7: Expected values of particle fluxes computed for two values of incident particle momentum:  $1.5 GeV/c$  and  $15 GeV/c$ .

Because of low multiplicity there were no particular requirements on the RPC rate capability in the HARP experiment. However, one small four-gap RPC was tested against particle rate in the T10 beam area at CERN. It was found that the RPC works well at  $500 Hz/cm^2$ . More precise measurements have been done in the GIF test area for the ALICE TOF detector. It was observed that there was no deterioration of the efficiency and the resolution for the ALICE MRPCs up to  $1 kHz/cm^2$ . This result found for 10-gap glass RPC should be well for 4-gap chamber too. Expected particle flux in the PANDA barrel is shown in fig.7 for two values of the incident anti-proton momentum:  $1.5 GeV/c$  and  $15 GeV/c$ . In both cases a maximal particle rate is less than

201 1 kHz/cm<sup>2</sup>. The estimation was done using Dual Parton Model generator for minimal bias events.

### Particle Identification:

The Barrel RPC-TOF provides a particle identification using a measurement of a particle arrival time and a momentum and length of a track information from the tracking detectors (TPC or STT). A mass of a particle,  $m$ , can be determined from the particle momentum,  $P$ , the particle track-length,  $L$  and a measured time-of-flight,  $t$ , as

$$m = \frac{P}{c} \cdot \sqrt{\frac{c^2 t^2}{L^2} - 1},$$

202 where  $L$  and  $P$  are measured with a tracking system. A possibility to discriminate between a  
 203 lighter and a heavier particle of same momentum depends on time resolution,  $\sigma_t$ , of the TOF  
 204 detector.

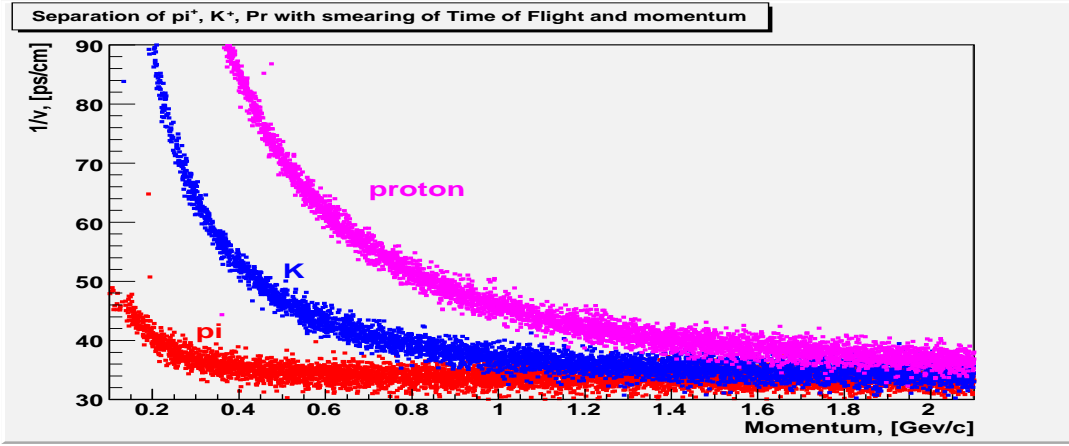


Figure 8: Inverse velocity of particles reconstructed with RPC-TOF vs. momentum.

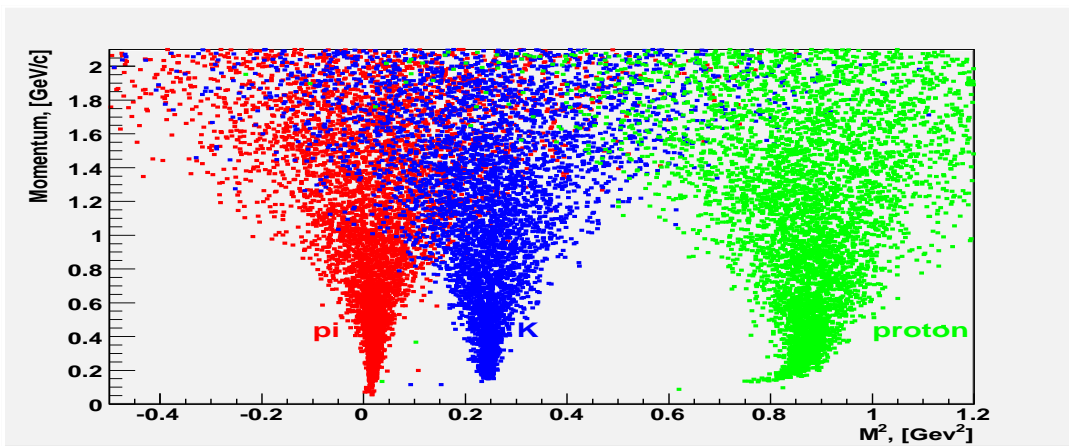


Figure 9: Momentum of particles vs. squared mass reconstructed with RPC-TOF.

At simulations of the RPC-TOF performed in PandaRoot framework, signals are produced when a track of a charged particle penetrates the sensitive cell. One signal is going to the one end, the other signal - to the other end of the cell. A velocity of the propagation is equal 19.05 cm/ns. Times  $t_1$  and  $t_2$  when the signals will reach the ends are given as

$$t_1 = t + (l/2 - x)/v, \quad t_2 = t + (l/2 + x)/v,$$

where  $l$  is the width of the cell ( 29.8 cm),  $x$  is the x-coordinate of the track in the local system of the cell. We obtain from  $t_1, t_2$  a time  $t$ , when the particle penetrates the cell. Each of the times ( $t_1, t_2$ ) is distorted with dispersion about 100 ps. This leads to the time resolution  $\sigma_t$  about 70 ps.

In the PandaRoot framework, we generated events of K, Pi, proton production isotropically through the RPC-TOF with momenta from 0.1 to 2.1 GeV/c. We simulated and reconstructed the events using RPC-TOF, and calculated velocity and squared mass of the particles by formulas:  $1/v = t/l$  and  $M^2 = P^2(1/v^2 - 1)$ . Figs. 8, 9 give results of a particle identification using  $1/v$  and  $M^2$  information from the RPC-TOF.

### Separation power:

Fig.10 shows calculation of a separation power. Difference between time of flight of two different particles divided by the TOF resolution,  $(t_1 - t_2)/\sigma_t$  ("separation power"), is presented in this figure for different pairs of particles for the most hard case - for polar angle  $\Theta = 90^\circ$ , and for polar angle  $\Theta = 30^\circ$ . The computation was done for two values of  $\sigma_t$ : 70 ps and 100 ps.

The calculations of the separation power for angle  $\Theta = 30^\circ$  demonstrate that the barrel TOF with resolution of  $\sim 70$  ps will be able identify hadrons with momentum up to few GeV/c. The RPC-TOF providing the particle identification at low momentum, especially at angle  $\Theta$  close to  $90^\circ$  is supplementary to the TPC/STT and DIRC detectors.

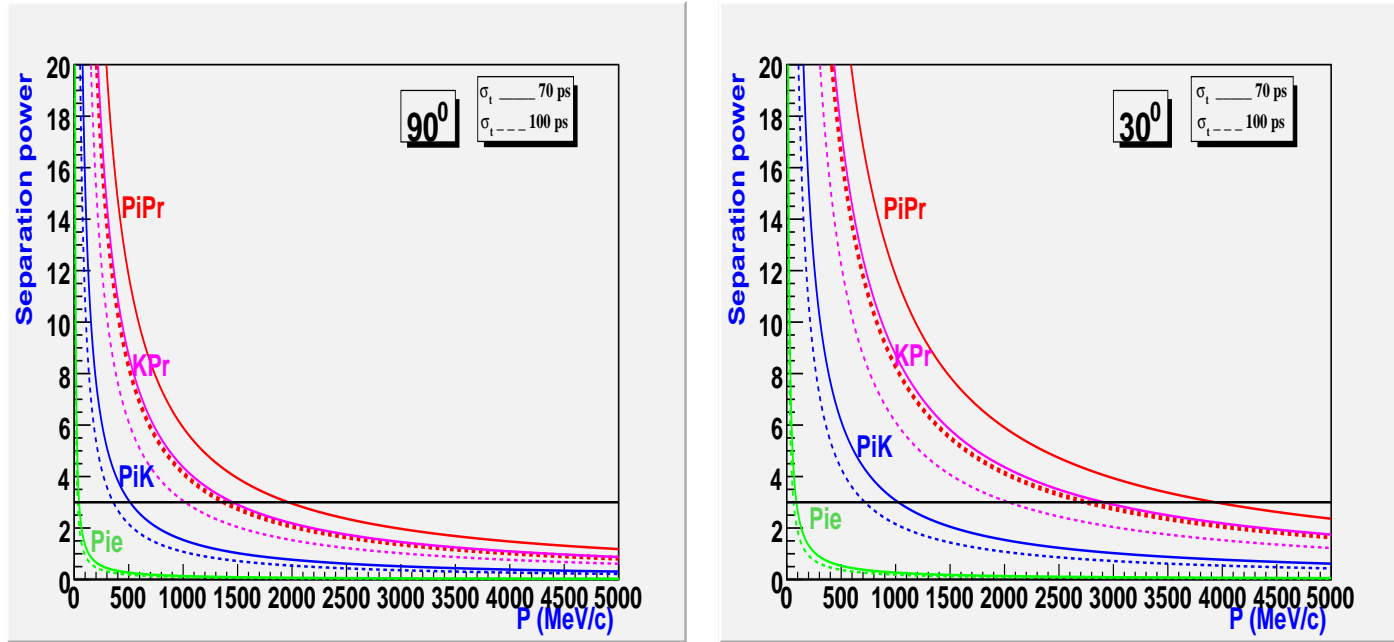


Figure 10: Separation as a function of momentum for polar angles  $\Theta = 90^\circ$  and  $\Theta = 30^\circ$ .

The start reference time is a problem because the stored anti-proton beam in the HESR has no suitable time structure to be used as an external time start.

## References

- [1] "The HARP resistive plate chambers: Characteristics and physics performance", V.Ammosov et al., NIM **A578** (2007) 119-138

### 3.3 Barrel DIRC

The purpose of the Barrel DIRC (Detection of Internal Reflected Cherenkov photons) is to provide a particle identification. The mass of the particle can be achieved by combining the velocity information of the DIRC with momentum information from the tracking detectors. In addition the distinction between gammas and relativistic charged particles entering the EMC behind the DIRC is possible.

Basis for the calculations and simulations are the bar dimensions taken from the BaBar DIRC [4]. With the length adapted to the PANDA setup there are quartz bars of  $17 \times 35 \times 2300 \text{ mm}^3$  and a distance of 480 mm to the target point. Thus the barrel DIRC covers the solid angle between 22 and 140 degrees. The lower momentum threshold for kaons which produce Cherenkov light is for an envisaged refractive index of  $n=1.47$  as low as 460 MeV/c for single photon production. For larger photon numbers the threshold increases.

With 17mm (of thickness) of fused silica the DIRC bars present approximately 14% of a radiation length to normal incident particles. The support structure will add 3%.

This design is initially based on the BaBar DIRC [4] but at PANDA further improvements of the performance are under development. The combination of the spatial image of the photons with their time of arrival gives access not only to their velocity but also to the wavelength of the photons. Thus dispersion correction at the lower and upper detection threshold becomes possible. Further on the reduction of the photon readout in size and number of photon detectors is envisaged. A lens or a set of lenses at the exit of the quartz bar focus the photons to a focal plane behind a readout volume of about 30 cm length. When this volume is filled with a medium with the same refractive index as the radiator material ( $n_{\text{medium}}=n_{\text{radiator}}=1.5$ ) additional dispersion effects and other image distortions are avoided.

A major issue is the maintenance of the barrel DIRC. While in the Babar DIRC a removal of the radiator barrel and the photon detector was not foreseen, the PANDA barrel DIRC is planned removable. The removal is not planned as default operation during maintenance breaks. Rather the access to other detector parts and the replacement of broken DIRC items need a removal procedure. For that purpose a photon detector smaller in size is favorable. The segmentation of the radiator barrel and the optical joints between radiator and photon detector need also careful design. As shown below the design of the photon detector and its link to the radiator define the geometric dimensions of the latter.

258 **3.4 Barrel Calorimeter**

### 3.5 Forward Cherenkov

Two DIRC design options exist for the endcap part of the target spectrometer section. These differ in the photon readout design but both use an amorphous fused silica radiator disc. The endcap detector position covers forward angles of up to  $\vartheta = 22^\circ$  excluding an inner rectangular (**is it now elliptical??**) area of  $\vartheta_x = 10^\circ$  horizontal and  $\vartheta_y = 5^\circ$  vertical half-angles. Simulations using the DPM generator [5] give  $1.0 \pm 0.8$  (at 2 GeV/c) to  $2.3 \pm 1.8$  (at 15 GeV/c) charged particle multiplicity per  $\bar{p}p$  interaction emitted from the target vertex into this acceptance.

In such a one-dimensional<sup>1</sup> DIRC type, a photon is transported to the edge of a circular disc while preserving the angle information. Avoiding too much light scattering loss at the surface reflections requires locally (in the order of millimeters) a surface roughness not exceeding several nanometers RMS.

The lower velocity threshold, which is common to both designs, depends on the onset of total internal reflection for a part of the photons emitted in the Cherenkov cone.

There are several boundary conditions for the disc thickness. Radiation length considerations as the detector is upstream of the endcap EMC call for a thin disc. The focussing design is workable with a 10mm thickness ( $X_0=126\text{mm}$ ). Regarding the mechanical stability and handling during polishing, current company feedback recommends 20mm minimum thickness. The resulting thickness of the radiator disc has to be a compromise.

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<sup>1</sup>Light is only reflected on surfaces of one spatial orientation, here the two disc surfaces both normal to the z axis.

### 3.5.1 Focussing Disc DIRC

In the Focussing Light guide Dispersion-Correcting design (Figures 11 and 12), when a photon arrives at the edge of the circular or polygonal disc, it enters into one of about hundred optical elements on the rim. Here the two-fold angular ambiguity (up-down) is lifted, the chromatic dispersion corrected and the photon focused onto a readout plane. While the optical element entered determines the  $\phi$  coordinate, measuring the position in the dispersive direction on the focal plane of the focussing light guide yields the  $\theta$  coordinate.

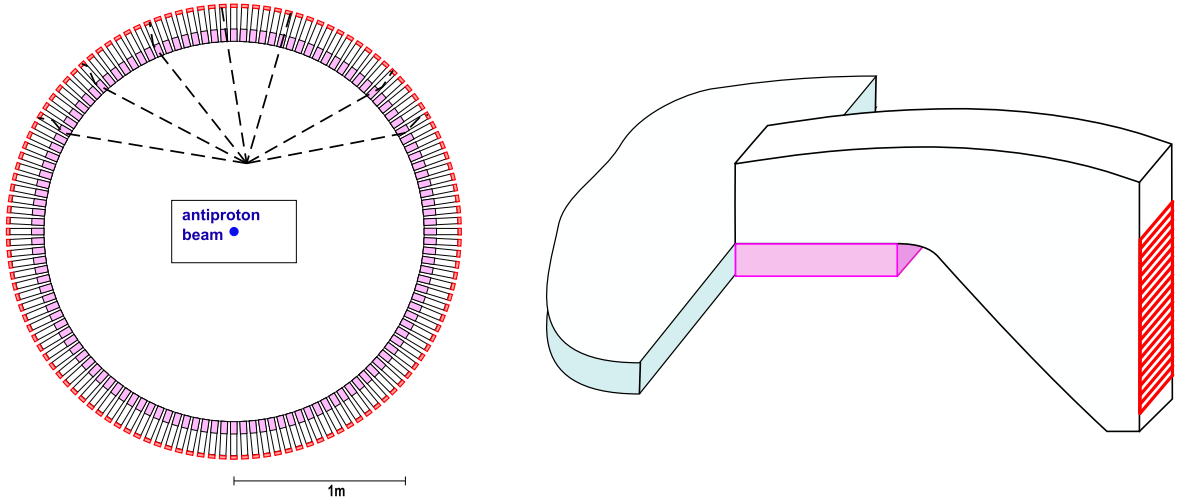


Figure 11: Polygonal disc with focussing light guides attached to the rim used as optical readout components.

Lithium fluoride (LiF) is UV transparent and has particularly low dispersion. Proton beam irradiation of a test sample shows that radiation-produced color centers are confined to sufficiently small wavelength ranges, and are only partially absorbing at the expected PANDA lifetime dose. Hence we believe we can use LiF as a prism element (see Fig. 12) to correct the Cherenkov

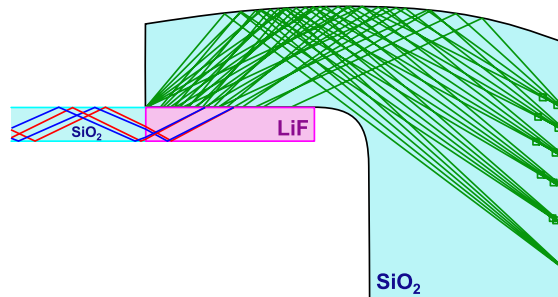


Figure 12: Light guide side view shown with a set of rays used for optimising the light guide curvature. Reflections at the parallel front and back surfaces keep the light inside but do not affect the focussing properties.

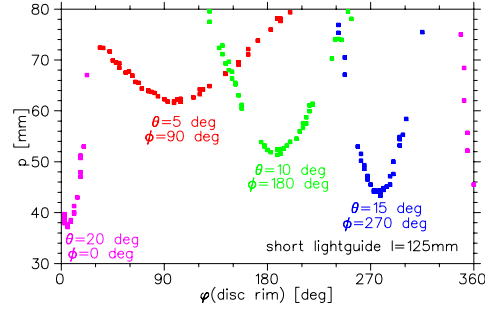


Figure 13: Simulated photon hit pattern for four particles emitted at different angles  $\theta$  and  $\phi$  from the target vertex.

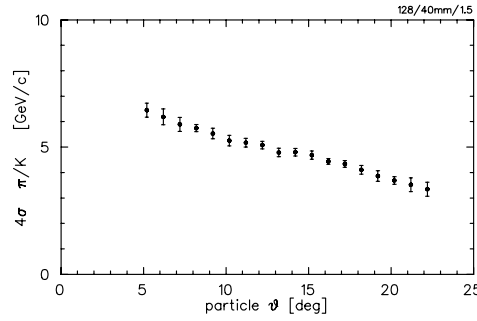


Figure 14: Simulation-derived pion-kaon separation power for a focussing lightguide design with a 15 mm thick amorphous fused silica disc and 0.4 eV photon detection efficiency. Calculation February 2008.

288 radiation dispersion. The two boundary surfaces, with the radiator disc and the subsequent light  
289 guide, make the chromatic dispersion correction angle-independent to first order.

290 As with the radiator, the light impinging on the inside of the light guide's curved surface undergoes  
291 total internal reflection, hence no mirror coating is needed. This reflection makes the focussing  
292 also independent of the wavelength.

293 With the light staying within the dense optical material of the light guide, most of the incoming  
294 light phase space from the disc is mapped onto the focal plane with its one-coordinate readout.  
295 The focussing surface with cylindrical shape of varying curvature has been optimised to give an  
296 overall minimum for the focus spot sizes of the different angles on the focal plane, individual  
297 standard deviations being well below 1 mm for the instrumented area.

298 For an Endcap DIRC detector with 128 lightguides and 4096 detector pixels that fits inside the  
299 target spectrometer return yoke, Figure 14 shows the angle-dependent upper momentum limit  
300 being about 4–6 GeV/c for  $4\sigma$  pion-kaon separation within the acceptance  $\vartheta=5^\circ\text{--}22^\circ$ .

301 Typically all of the 40 detected photons per particle arrive within a 4 ns time window.

302 Each lightguide can individually be assigned its own 0.4 ns acceptance window. For the pixel size  
303 used in this simulation they are contained inside a 40 pixel·ns volume, which at 4K detector pixels  
304 amounts to 10 ps detector occupancy time per particle signature.



305 The detected photon rate (source: presentation KF 2007-03-27 Genova, 2E7 interactions; scaled  
306 to 4K pixels) is  $3\text{E}7\text{ s}^{-1}$  per PMT and  $1\text{E}6\text{ s}^{-1}$  per detector pixel.

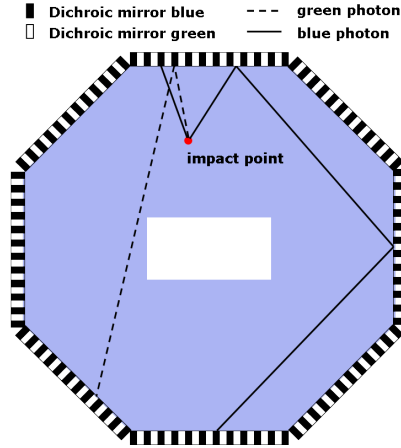


Figure 15: Sketch of the flightpath in the ToP Disc

### 3.5.2 Time of Propagation Disc DIRC

In the Multi-Chromatic Time-of-Propagation design ([6]) small detectors measure the arrival time of photons on the disc rim, requiring  $\sigma_t=30\text{--}50\text{ ps}$  single photon time resolution. For any given wavelength, the disc edge is effectively covered alternately with mirrors and detectors. Only due to the resulting different light path-lengths one can determine accurately enough the start reference time, i.e. the time when the initial charged particle enters the radiator, as the stored anti proton beam in the HESR has no suitable time structure to be used as an external time start.

As some of the light is reflected several times before hitting a detector, the longer path lengths allow a better relative time resolution.

The use of dichroic mirrors as color filters allows the use of multiple wavelength bands within the same radiator (the current design suggesting two bands) resulting in higher photon statistics. The narrow wavelength bands minimise the dispersion effects, and the quantum efficiency curve of the photo cathode material could be optimised for each wavelength band individually.

### 3.5.3 Proximity RICH

As alternative approaches Proximity Imaging Solutions were considered.

- Liquid radiator proximity RICH using CsI GEMs: Proximity focusing RICH detectors use the most simplest imaging geometry. Their resolution depends on the optical quality and crucially on the ratio of radiator thickness to stand-off distance, the distance between the creation and detection of the photon. Using liquid or solid radiators yielding enough Cherenkov photons, the radiator can be kept rather slim, which in turn only require moderate stand-off distances on the order of 100 mm. The ALICE HMPID detector is build in this fashion using a C6F14 liquid radiator and CsI-photon cathodes in an MWPC. This requires a UV optic. It is proposed to use the same radiator technique and combine the third tracking station with a CsI coated GEM photon detector. The detector will be thicker along the beam direction than the DIRC detector previously described, but can be essentially moved to any position along the beam axis. The estimated performance and the ALICE/STAR test results show a significant decrease in performance compared to the DIRC solutions.
- Solid radiator proximity RICH using CsI GEMs: One of the main drawbacks of using the ALICE design is the use of C6F14. This radiator is rather sensitive to impurities and radiation damage requiring a purification system. Using a fused silica disc with a properly machined surface as radiator circumvents the problem while keeping the geometrical advantages of the design. Initial studies show a further reduction of performance mainly due to strong dispersive effects in the UV region.
- Aerogel proximity RICH using PMTs: The Belle endcap Cherenkov threshold counter will be replaced by a proximity imaging RICH counter using an Aerogel radiator and conventional BiAlkali based multi-pixel PMTs as photon detectors. Using a so-called focusing radiator scheme, prototypes show excellent performances. The main technological challenge for this detector is to realise a photon detection matrix in a strong magnetic field. Recent developments in the field of proximity focusing HAPDs seem to make such a detector realistic. The large number of pixels required should the detector be placed behind the EMC, but inside the cryostat merit a detailed look at the costs of such a design.

348 **3.5.4 Forward RICH**

349 **3.6 Forward Calorimeter**

### 3.7 Muon Counter

The main purpose of the PANDA muon system is to achieve the highest efficiency in identification of muons in the medium-high energy range. Muons are present in the final state of many annihilation channels. Among them the physics program is mostly concentrated on dimuon production from Drell Yan at the maximum HESR momentum of 14.5 GeV/c or  $J/\psi$  formation and decay in nuclear matter at 4.1 GeV/c momentum. In addition the study of rare decay of charmed particles could require a single muon identification. The most severe PID requirements to the muon system are set by the DY dimuon production, that has been selected as benchmark channel. Looser identification requirements are set by the  $J/\psi$  production channels, because of the strong kinematics constraint on the dimuon mass.

In general the interesting processes having muons in the final state have small cross section compared with the background, e.g. the DY channel features a very low cross section ( $\approx 1nb$ ) and the unfavourable signal-to-noise ratio ( $\approx 10^{-6}$ ). As a consequence the muon system must provide the maximum acceptance and efficiency. In the dimuon channels the simultaneous identification of a slow and of a fast muon is needed, with a strong correlation angle-momentum.

Muon counters are foreseen both in the Target barrel part and endcap. In the Forward spectrometer the muon counters and filters will act as hadronic calorimeter. The azimuthal angle covered by the muon system ranges from  $0^\circ$  to  $120^\circ$  with a  $2\pi$  polar angle coverage. With respect to the Letter of Intent the muon system has retained the original idea to use the solenoid yoke as muon filter. However the concept design has changed following the results of a preliminary acceptance study and the iron segmentation has been considered for the system optimization.

The momentum range of the DY muons reaching the barrel extends up to few GeV/c. The lower end of the range is fixed by the energy losses and the magnetic bending in the inner detectors (500 MeV/c).

The DY muons crossing the forward endcap show an energy range going from 1 to 3 GeV, with an average energy loss of 250 MeV before to enter the muon counters. The energy of the muons travelling through the Forward spectrometer can be greater than 10 GeV. *here relevant plots*

As a consequence slow muons, mainly produced in transverse direction cannot reach the muon system and must be identified by the inner detector. Medium and high energy muons are identified by the muon system only if they are positively detected by the muon detectors and properly match a charged primary track detected by the central tracker. The muon detector output that can be considered for identification purposes is the hit multiplicity in a selected region and, for isolated tracks, a direction and, where possible, a momentum measurement. Range measurement was also suggested as an effective tool for  $\mu/\pi$  separation and the arrangement presently under simulation is conceived for this purpose, see fig. 16 and fig. 17.

The following plots show the behaviour of some parameters useful for the muon identification.

The background coming from primary hadrons (mostly pions) could be rejected by the evaluation of the number of planes in the muon system crossed by the charged particle (see fig. for muon and pion of equal energy).

The contamination coming from secondary muons produced by the pion decay could be reduced by considering the angular correlation between the track extrapolated from the vertex and the track segment measured by the muon detectors. In this case (see fig. 18) the measurement of the track momentum by the muon detectors could help.

*here( relevant plots*

## REFERENCES

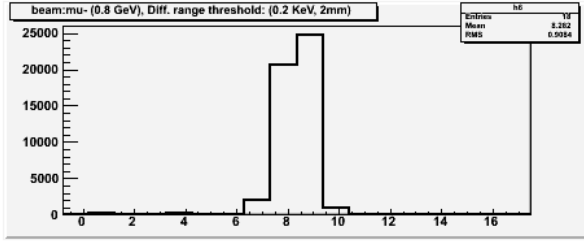


Figure 16: *Range measured as number of crossed planes for a muon with 0.8 GeV energy.*

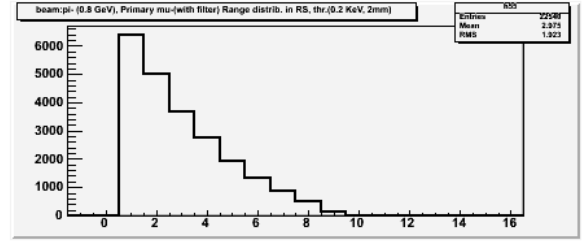


Figure 17: *Range measured as number of crossed planes for a pion with 0.8 GeV energy.*

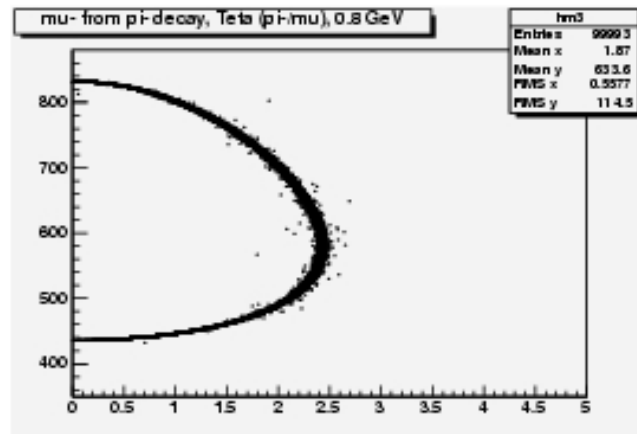


Figure 18: *Muon from decaying pion with 0.8 GeV energy: energy vs decay angle in the Lab system.*

### 3.7.1 Muon system overview

The parameters considered in the choice of the muon detectors are the spatial and time resolution, to allow independent reconstruction of the track segment direction, the simplicity and flexibility of the design, since the area to be covered is large and divided in different shapes, the robustness the reliability, also in terms of ageing and finally the cost. the MDT have been proven to be a mature and widely used technique that join a very high detection efficiency ( $\approx 95\%$ ) to a great simplicity of production, construction and operation. Following the proposal of thye JINR-Dubna group an eight-cell module of MDT is constituted by a metallic cathode extruded with a comb-like profile and covered by a stainless steel cover. The signal wires pitch is 10 mm, the thickness of the profile is  $\geq 0.45$  mm and gives the main contribution to the inefficiency of the counter. here the MDT cross section and the table of the performances

The MDT are one-coordinate detectors and minimum two layers must be installed to get a track space point. An R&D project is going on at JINR Laboratories aiming to use MDT as two-coordinate detector. For this purpose the stainless steel cover should be removed and substituted by a plastic support for strips or pads. In this case the second coordinate is obtained by reading out the induced signal.

The MDT are operated in proportional mode. Both the Yes/No readout or the wires and drift

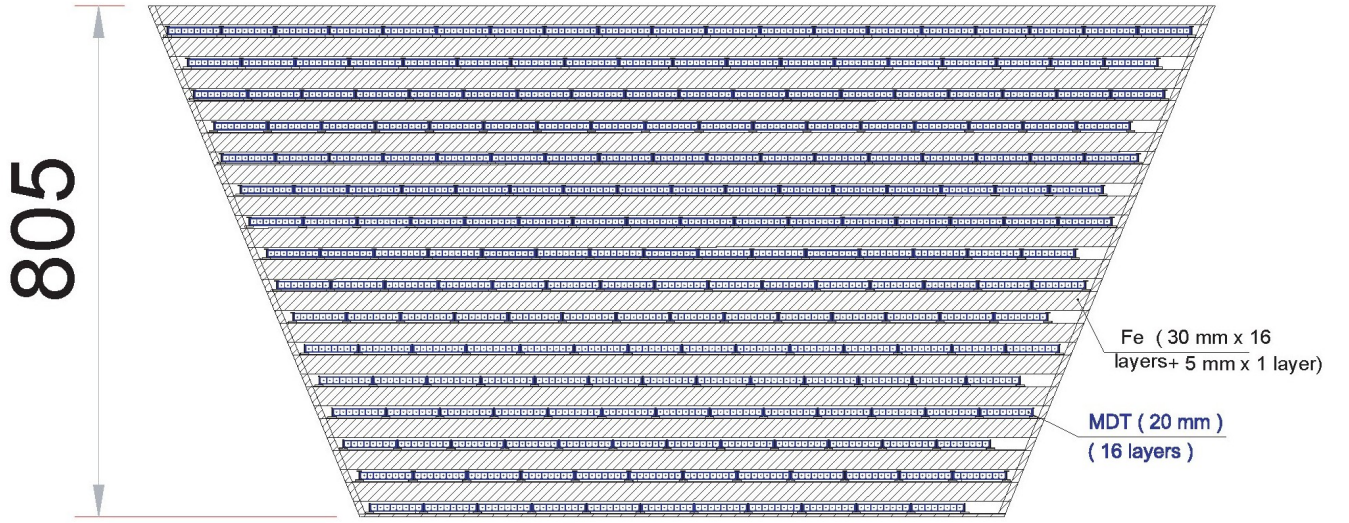


Figure 19: *Cross section of the Muon range system in the Target Spectrometer.*

time measurement are considered for the PANDA operation. The best spatial resolution is obtained in drift mode operation, corresponding to 0.5-0.8 mm r.m.s.

The detector coverage presently considered corresponds to a full coverage of the Target Spectrometer in the trasverse direction with respect to the beam axis (Barrel) and in the forward direction (Forward Endcap), using the yoke of the solenoid as a muon filter. One of the eight parts of the barrel will be only partially covered by muon counters to allow the insertion and the operation of the target and its services. In the Forward Spectrometer (angular coverage from  $5^\circ - 10^\circ$  to  $0^\circ$ ) the hadronic calorimeter could be equipped with muon counters.



## 4 Tools

In this section the TAG work is described. To evaluate the performance of the detectors the PID TAG defined the "Separation Power" as the right tool (see section ??). With the help "Phase Space Plots" (section 4.2) the angular coverage and the corresponding particle momenta could be determined. The "Fast Simulation" (section 4.3) was used to map the separation power over the full angular and momentum range. In a second step important reactions and their relevant background channels were simulated. Thus the regions where a good separation power is needed could be identified and checked whether the detector performance is sufficient there.

## 4.1 Separation Power

This document completely deals with the quality of the particle identification of the projected PANDA detector. Thus the major issue upon which decisions can be made is a proper definition of classification quality or performance.

The according concept chosen for that purpose called 'Separation Power' bases on the assumption that the particular observables of objects of different classes exhibit more or less gaussian distributions.

Consider the situation illustrated in fig. 20.

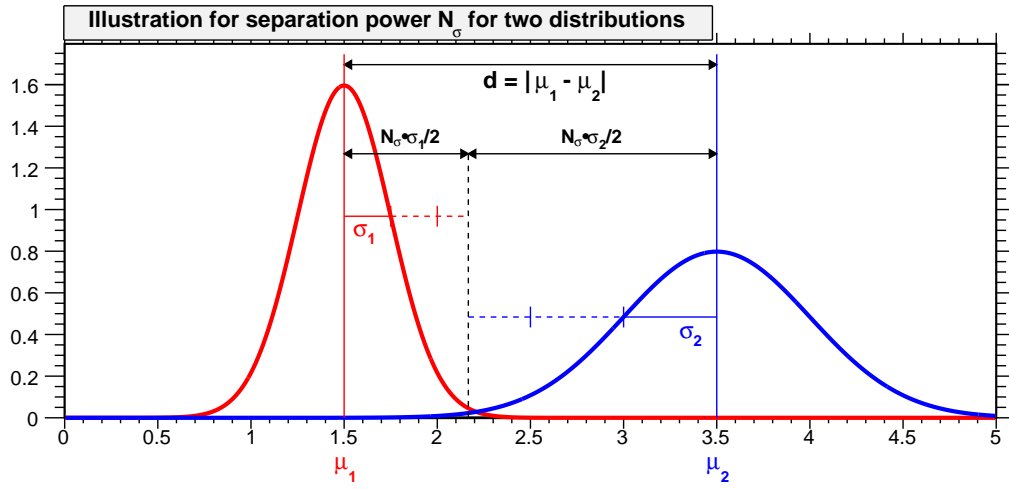


Figure 20: Illustration for the definition of separation power.

There are plotted two gaussian distributions  $G_1(x) \equiv G(x; \mu_1, \sigma_1)$  and  $G_2(x) \equiv G(x; \mu_2, \sigma_2)$  with mean values  $\mu_1 = 1.5$  and  $\mu_2 = 3.5$  and standard deviations  $\sigma_1 = 0.25$  and  $\sigma_2 = 0.5$ . This could be e. g. the probability density distributions of the  $dE/dx$  measurements for two particle species in a small momentum range. Obviously the distributions are separable quite reasonable, but what is the measure for the separation potential?

A proper definition would be to define a particular classifier, e.g. every particle with property  $x_0 < 2$  is considered as member of class 1 (red). Then one can determine two quantities which are of relevance for the quality of classification. The first one is the efficiency, which is part of the distribution 1 (or a random sample of measurements following this distribution) which is identified correctly analytically corresponding to the integral

$$\epsilon = \int_{-\infty}^{x_0} G_1(x) dx \quad (1)$$

for a normalized Gaussian. The second quantity is the misidentification level given by the integral

$$\text{mis-id} = \int_{-\infty}^{x_0} G_2(x) dx \quad (2)$$

which is part of the distribution 2 in the same region thus identified incorrectly as being of class

1. These two values would define clearly the performance of the classifier<sup>2</sup>. But this solution cannot be applied in case when one does not want to define a particular selector. It rather has to be defined a measure for the prospective performance of a possible selector.

Exactly this is the aim of the separation power  $N_\sigma$  which relates the distance of the mean values  $d = |\mu_1 - \mu_2|$  of the two distributions to their standard deviations  $\sigma_1$  and  $\sigma_2$ . The usual unit of  $N_\sigma$  is 'number of gaussian sigmas of the separation potential', which is supposed to relate the number with gaussian integral values.

There are actually a lot of different definitions for that quantity on the market but it has been found an agreement within the PID TAG on the following definition:

$$N_\sigma = \frac{|m_1 - m_2|}{\sigma_\beta} = \frac{|m_1 - m_2|}{(\sigma_1/2 + \sigma_2/2)} \quad (3)$$

This relationship is illustrated in fig. 20. The black dashed line marks the position  $x_0$  between the two distributions, for which the differences to each mean value  $|m_1 - x_0| = N_\sigma \cdot \sigma_1/2$  and  $|m_2 - x_0| = N_\sigma \cdot \sigma_2/2$  are the same in terms of  $\sigma$ 's.

This means a separation of e. g.  $N_\sigma = 4\sigma$  corresponds to a gaussian integral

$$I = \int_{-\infty}^{\mu+4\sigma/2} G(x; \mu, \sigma) dx = 0.9772 \quad (4)$$

which shall express an efficiency around  $\epsilon \approx 97.7\%$  or a mis-ID level around  $\text{mis} = 100\% - 97.7\% \approx 2.3\%$  or both. This integration up to half the number of sigmas  $N_\sigma/2$  seems a bit contra intuitive but is common notion and therefore has kept for the considerations in this document. Another feature of this definition is that it is symmetric for both classes or distributions, even with different  $\sigma$ 's. Furthermore for the particular case of normalized gaussian distributions and a selector requiring  $x < x_0$  for classifying class 1 objects in the upper example, the efficiency  $\epsilon$  and purity  $\pi$  for this selection have the same value, since

$$\epsilon = \frac{\int_{-\infty}^{x_0} G_1(x) dx}{\int_{-\infty}^{+\infty} G_1(x) dx} = \frac{\int_{-\infty}^{x_0} G_1(x) dx}{1} = \frac{\int_{-\infty}^{x_0} G_1(x) dx}{\int_{-\infty}^{x_0} G_1(x) dx + \int_{x_0}^{+\infty} G_1(x) dx} \quad (5)$$

$$= \frac{\int_{-\infty}^{x_0} G_1(x) dx}{\int_{-\infty}^{x_0} G_1(x) dx + \int_{-\infty}^{x_0} G_2(x) dx} = \frac{\int_{-\infty}^{x_0} G_1(x) dx}{\int_{-\infty}^{x_0} G_1(x) + G_2(x) dx} = \pi \quad (6)$$

Tab. 3 lists on the left hand side the mis-id levels  $1 - \int G(x) dx$  with 1-sided and 2-sided gaussian integrals for different values of  $N_\sigma$ , on the right hand side the corresponding values of the separation power for given levels of mis-id according to the upper definition. It shall be emphasized again that for given values  $N_\sigma$  the integration is only performed up to  $N_\sigma/2$ , therefore the mis-id levels might seem surprisingly high for given number of  $\sigma$ 's separation.

Taking into account that quantities in reality never have gaussian shape the values  $\sigma$  in fact are not necessarily gaussian sigmas but calculated as the root-mean-square (which actually is the standard deviation)

$$\sigma_{\text{rms}} = \sqrt{\sum_i (x_i - \mu)^2} \quad (7)$$

---

<sup>2</sup>For Bayes' classification a flux correction would have to be taken into account additionally. This requires of course knowledge about a posteriori probabilities of particle fluxes which not necessarily is available since significantly dependent on the given trigger and reaction type.

what in case of gaussian distribution would be indeed identical with the gaussian  $\sigma$  from above.  
For the given example in fig. 20 the definition (3) computes to

$$N_{\sigma,1} = \frac{2}{0.25/2 + 0.5/2} \sigma = \frac{2}{0.375} \sigma = 5.333 \sigma \quad .$$

Another issue with directly is connected with the upper definition is the question how to define the combined separation  $N_{\sigma,\text{tot}}$  e.g. for values  $N_{\sigma,i}$  achieved by various detector components to express the overall performance. The agreement of the PID-TAG concerning this was to consider the quadratic sum

$$N_{\sigma,\text{tot}} := \left( \sum_i N_{\sigma,i}^2 \right)^{1/2} \quad (8)$$

as a good measure. In order to evaluate the goodness of that expression it first of all is necessary to make aware what meaning the value  $N_\sigma$  has in terms of probability. When considering something similar to equation (4) as a appropriate measure, namely the integral of a Gaussian from  $-N_\sigma/2$  to  $+N_\sigma/2$  the expression for the corresponding probability of mis-identification is given by

$$P_{\text{mis}}(N_\sigma) = 1 - \int_{-N_\sigma/2}^{+N_\sigma/2} G(x; \mu = 0, \sigma = 1) dx \quad (9)$$

which directly defines the mis-identification probability for  $n$  statistically independent separation capabilities as the product

$$P_{\text{mis,tot}} = P_{\text{mis}}(N_{\sigma,1}) \times \cdots \times P_{\text{mis}}(N_{\sigma,n}) \quad (10)$$

in addition. Hence equation (9) implicitly specifies  $N_{\sigma,\text{tot}}$  as that value where the intergral yields exactly  $P_{\text{mis,tot}}$ . This procedure has been pursued for two values  $N_{\sigma,1}$  and  $N_{\sigma,2}$  as presented in fig. 21. In (a) the combined separation power is shown as 2-dimensional function of the two input values, (b) presents the difference

$$\Delta = \left| N_{\sigma,\text{tot}} - \sqrt{N_{\sigma,1}^2 + N_{\sigma,2}^2} \right| \quad (11)$$

of the resulting value and equation (8), which obviously reasonably reproduces the correct value with a maximum deviation of about  $0.5\sigma$  in the range of single values up to  $N_\sigma = 6$ .

#### 4.1.1 Parametrization of the Electromagnetic Calorimeter

Although not implemented in the Fast Simulation, a parametrization of part of the response of the EMC has been persued for the estimation of overall PID quality. It is based on fully simulated data but only information about electron-pion-separation was taken into account up to now. Fig. 22 (a) shows the distributions of the parametrized ratio of the calibrated cluster energy in the electromagnetic calorimeter and the reconstructed track momentum  $E_{\text{clus}}/p$  for simulated electrons (green) and pions (black). The source for modelling the parametrizations can be found in the PANDA Physics Book [?]. It is clearly visible that above momenta of approximately 500 MeV this quantity is a powerful tool to separate electrons from pions, demonstrated in fig.22 (b), where the separation power has been determined dependend of the track momentum  $p$  by the

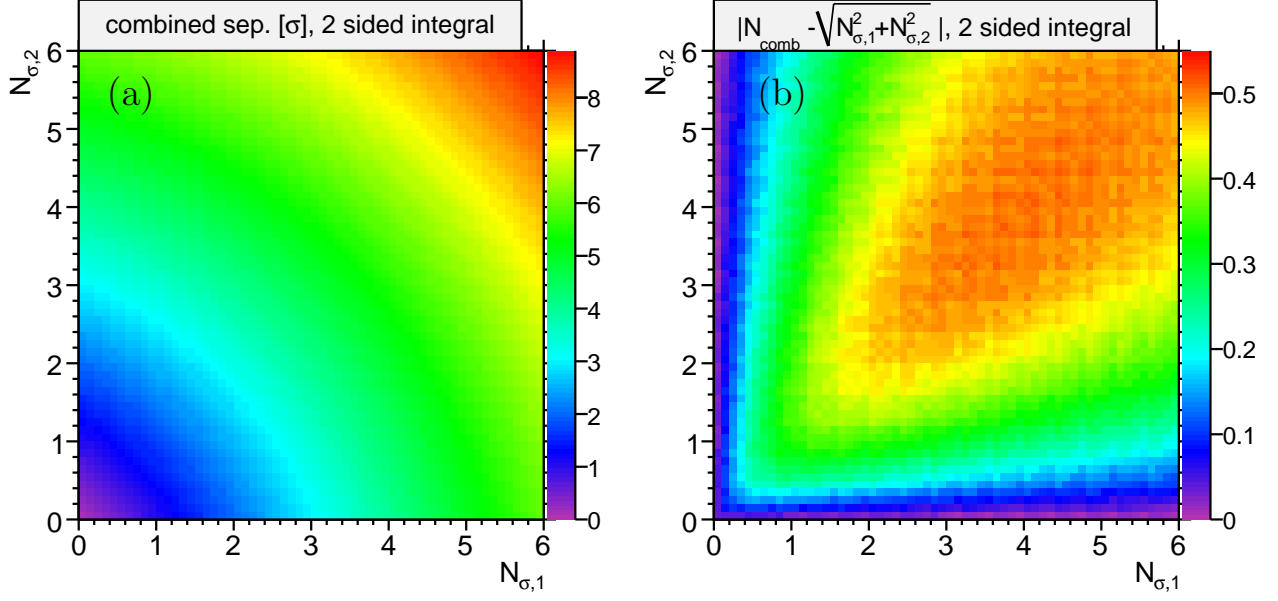


Figure 21: (a) Graphical representation of the combined separation power  $N_{\sigma,\text{tot}}$  of two values  $N_{\sigma,1}$  and  $N_{\sigma,2}$ , (b) the corresponding difference  $\left|N_{\sigma,\text{tot}} - \sqrt{N_{\sigma,1}^2 + N_{\sigma,2}^2}\right|$ .

$N_\sigma$	mis-id (1s) [%]	mis-id (2s) [%]	mis-id [%]	$N_\sigma$ (1s)	$N_\sigma$ (2s)
1.0	30.854	61.708	10.000	2.6	3.3
2.0	15.769	31.538	5.000	3.3	3.9
3.0	6.681	13.361	1.000	4.6	5.1
4.0	2.254	4.507	0.500	5.1	5.6
5.0	0.621	1.242	0.100	6.2	6.6
6.0	0.133	0.266	0.050	6.6	7.0
7.0	0.023	0.047	0.010	7.4	7.8
8.0	0.003	0.006	0.005	7.8	8.1
9.0	0.000	0.001	0.001	8.5	8.8

Table 3: Relation between separation power and mis-id level

504 definitions given above. Since no  $\theta$  dependence was available this separation power is assumed to  
 505 be constant over the complete  $\theta$  range.

506 According to the software chapter of the PANDA Physics Book  $e/\pi$  separation is the most difficult  
 507 one. Therefore this distribution is assumed to also hold for separating electrons from any other  
 508 particle species.

509 As a very naive assumption without a proof the additional separation power provided by the EMC  
 510 for any other particle combination is taken to be  $1\sigma$  over the complete phase space covered by the  
 511 EMC.

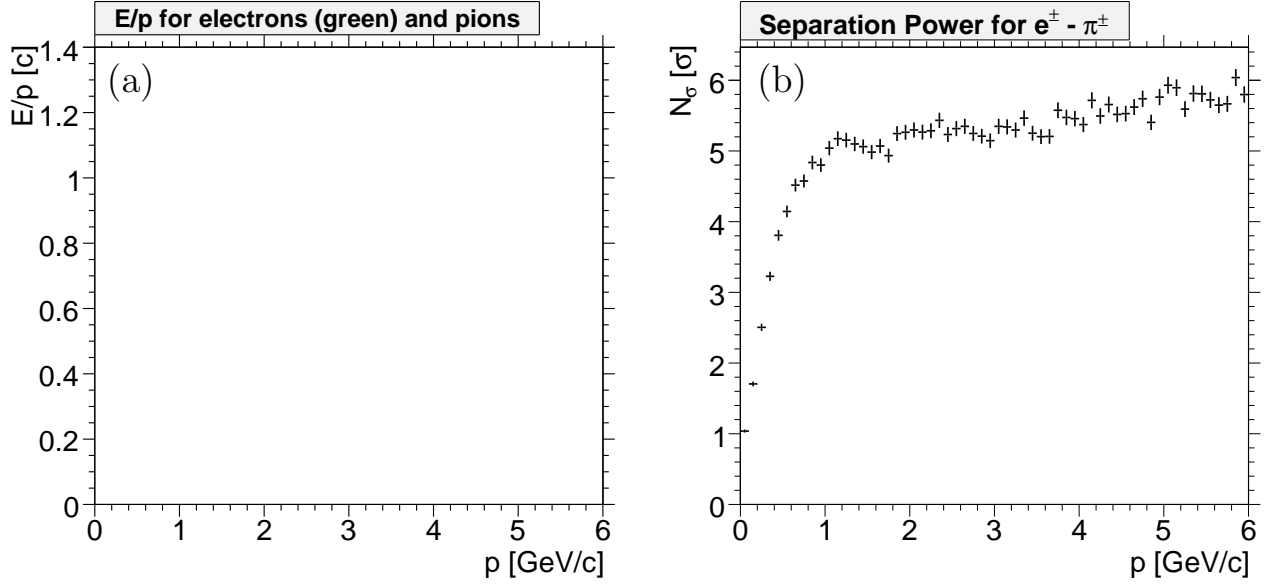


Figure 22: (a) Parameterized distribution of  $E_{clus}/p$  for electrons and pions and (b) the resulting separation power  $N_\sigma$  as function of the track momentum  $p$ .

#### 4.1.2 Mapping Separation Power

For the purpose of illustration the relationship between kinematic distributions of physics channels and the PID quality the separation power defined in (3) has been determined as 2-dimensional histogram in phase space  $(p, \theta)$ . Therefore it was necessary to compute the mean value  $\mu$  and standard deviation  $\sigma$  for every bin  $i$  with  $[p_i \dots p_i + dp; \theta_i \dots \theta_i + d\theta]$  for bin widths  $dp$  and  $d\theta$  for every detector and particle species.

One technical remark: To avoid the computation of  $(x - \mu)$  for every measurement in order to determine  $\sigma$ , which is very time consuming for large datasets, the relationship

$$\sigma = \frac{1}{N} \sqrt{\sum x_i^2 - \left(\sum x_i\right)^2} \quad (12)$$

has been exploited which does not require a previous calculation of the mean value  $\mu = \bar{x}$ .

In order to evaluate the contributions of the various detectors to the overall classification potential, the separation power defined above has been determined for every single detector component and all possible particle combinations, which add up to the following 10 possibilities:

1.  $e^\pm - \mu^\pm, e^\pm - \pi^\pm, e^\pm - K^\pm, e^\pm - p/\bar{p}$ ,
2.  $\mu^\pm - \pi^\pm, \mu^\pm - K^\pm, \mu^\pm - p/\bar{p}$ ,
3.  $\pi^\pm - K^\pm, \pi^\pm - p/\bar{p}$ ,
4.  $K^\pm - p/\bar{p}$ .

The results are determined based upon 5 million isotropic distributed single track events with particle momenta up to 6 GeV/ $c$ .

Figs. 23 and 25 show as examples the  $p$ - $\theta$ -dependent separation power for  $e^\pm - \pi^\pm$ ,  $\pi^\pm - K^\pm$  and  $K^\pm - p/\bar{p}$  for all 8 detector components

- Micro Vertex Detector (MVD)
- Barrel Time of Flight System (TOF)
- Barrel DIRC
- Disc DIRC
- Ring Image Cherenkov Detector (RICH)
- Electro Magnetic Calorimeter (EMC)
- Straw Tube Tracker (STT)
- Time Projection Chamber (TPC)

under investigation. The color codes in these 2 dimensional representations correspond to the numbers of  $\sigma$ 's  $N_\sigma$  of separation with a cutoff  $N_\sigma > 8$ , so in the red regions are possibly values above that limit.

To get an impression of the overall particle identification performance the values  $N_{\sigma,i}$  from the different detectors  $i$  have been combined by quadratic summation according to (8) under the assumption of statistically uncorrelated  $N_{\sigma,i}$ . Since there are two central tacker options (STT and TPC) which cannot contribute to the same total separation, two different scenarios with either the STT or the TPC are considered separately. Fig. 26 shows the combined information for the STT option and fig. 27 for the detector setup with the TPC as central tracker. All maps are based on the requirement of positiv identification of a particle species. This means, that particle type  $A$  is only considered to be dsistinguishable from another particle type  $B$  when both create a signal in the particular detector and the given phase space region.

One should keep in mind that the conclusive power of separations involving electrons and muons is limited for the time being since only limited information from the electromagnetic calorimeters and none for the muon detectors has been incorporated so far, which has significant impact on electron and muon identification respectively.

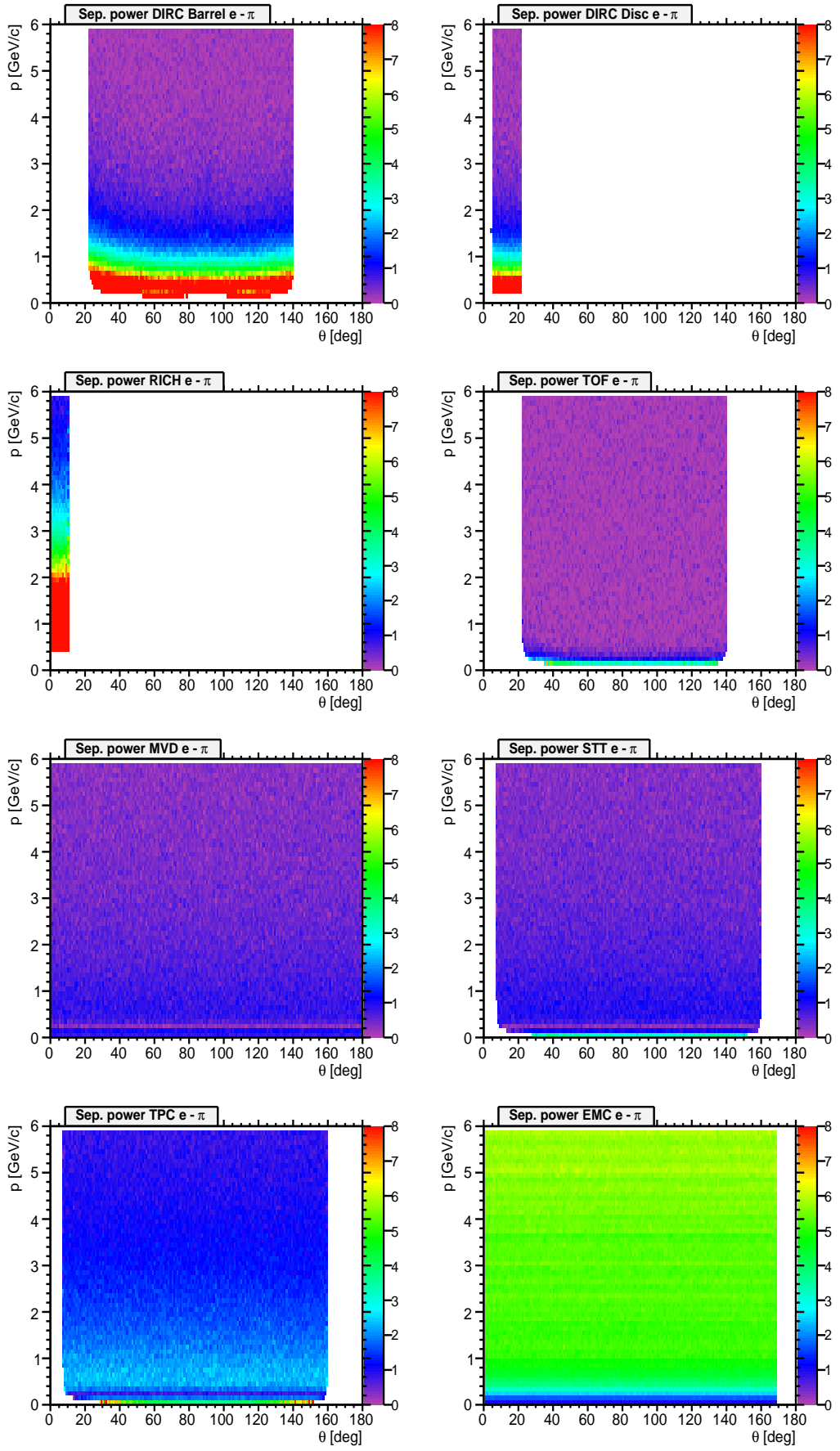


Figure 23: Map of separation power for  $e^\pm\pi^\pm$  separation. Color code corresponds to  $N_\sigma = 0 \dots 8$ .



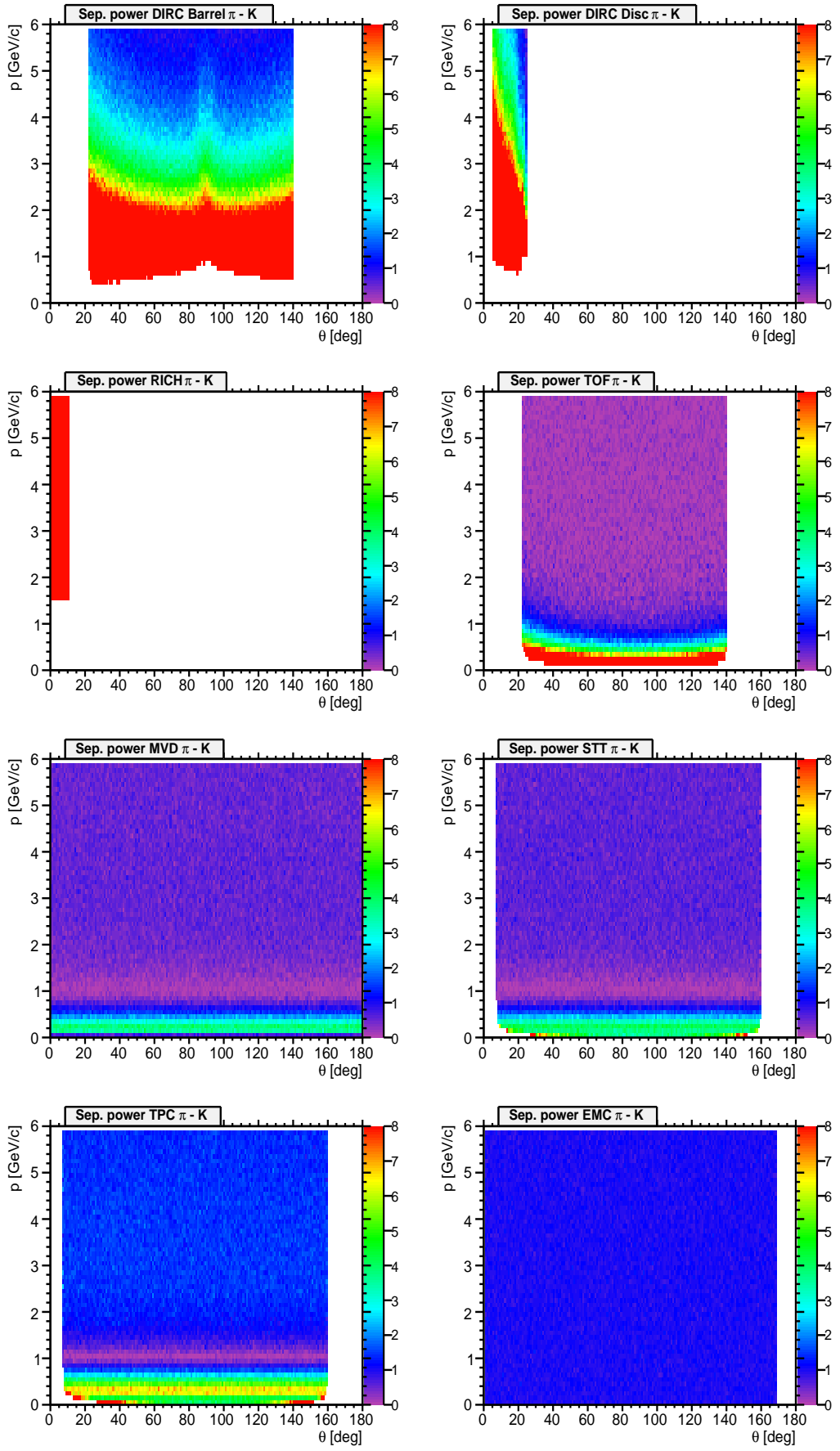


Figure 24: Map of separation power for  $\pi^\pm$ - $K^\pm$  separation. Color code corresponds to  $N_\sigma = 0 \dots 8$ .

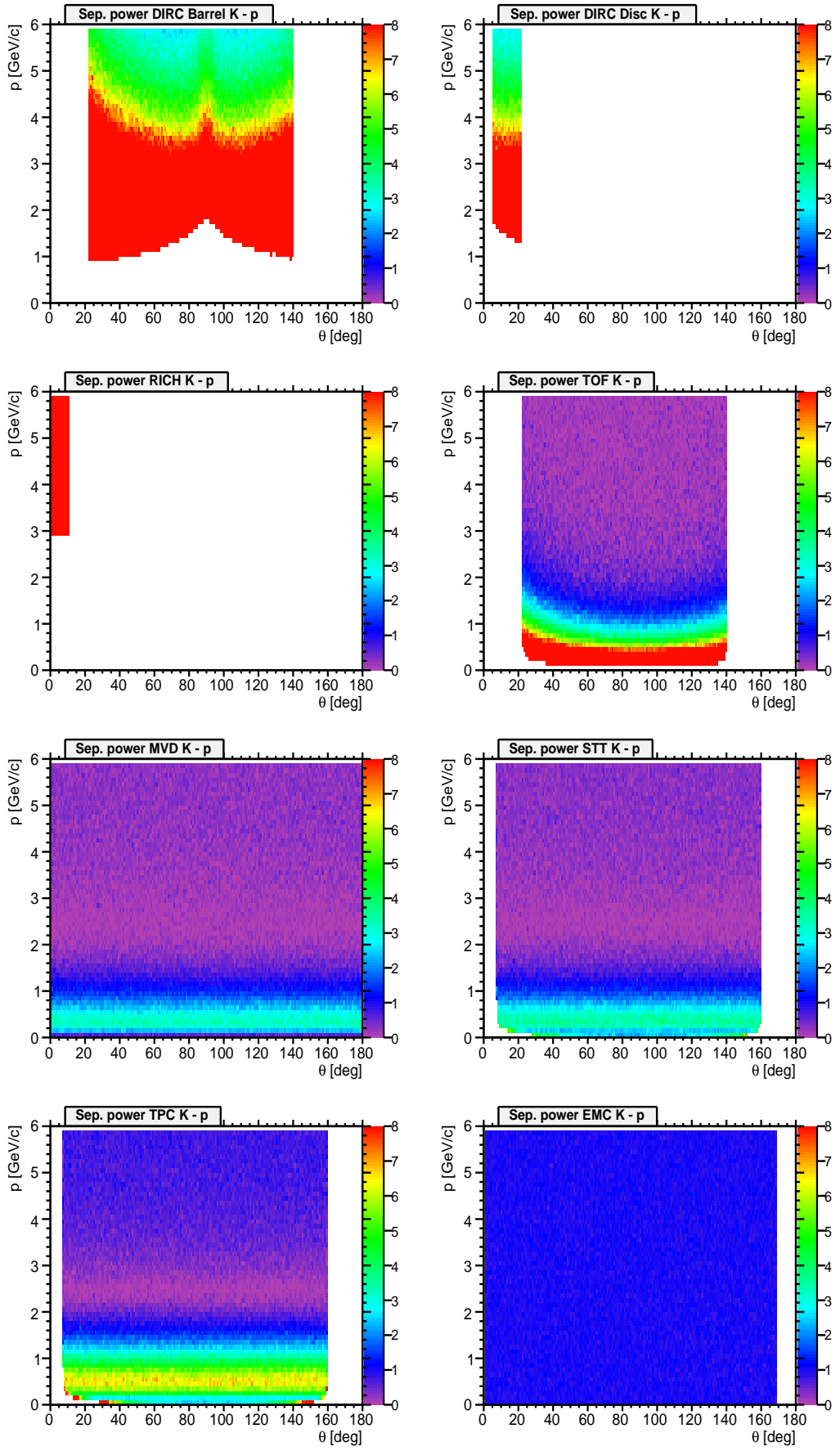


Figure 25: Map of separation power for  $K^\pm p/\bar{p}$  separation. Color code corresponds to  $N_\sigma = 0 \dots 8$ .

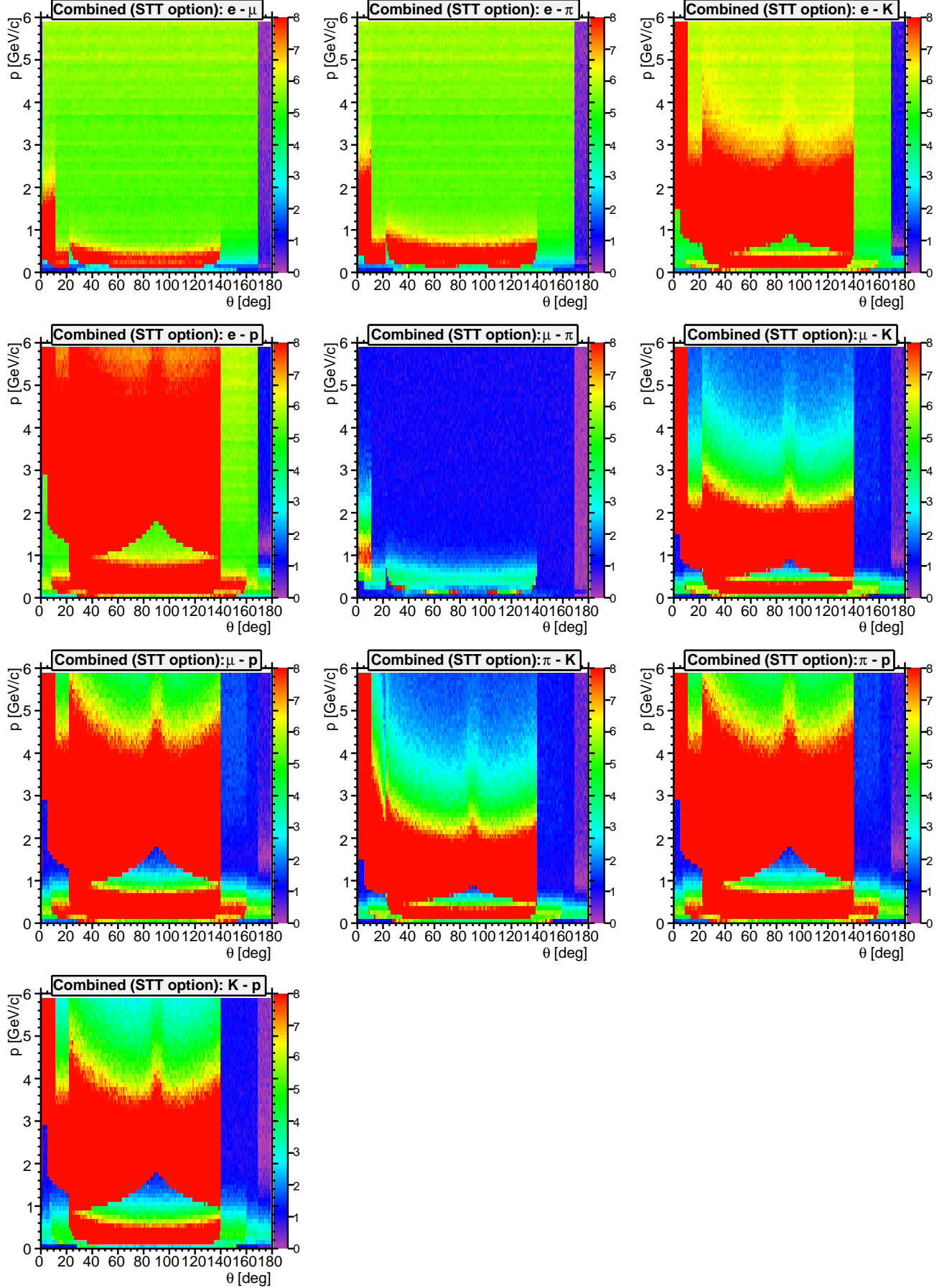


Figure 26: Combined map of Separation Power with STT as central tracker option including the TOF system. Color code corresponds to  $N_\sigma = 0 \dots 8$ .

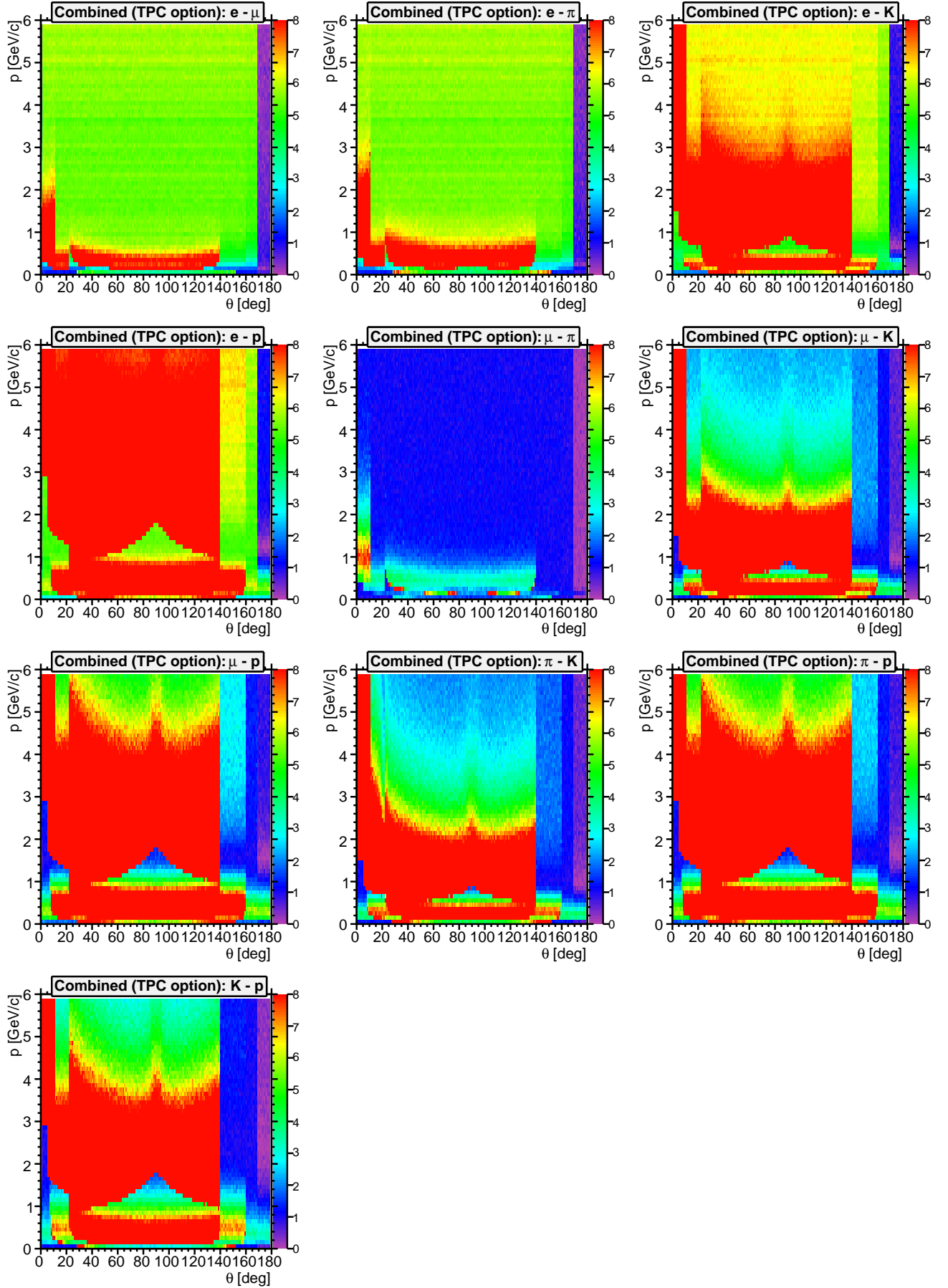


Figure 27: Combined map of Separation Power with TPC as central tracker option including the TOF system. Color code corresponds to  $N_\sigma = 0 \dots 8$ .

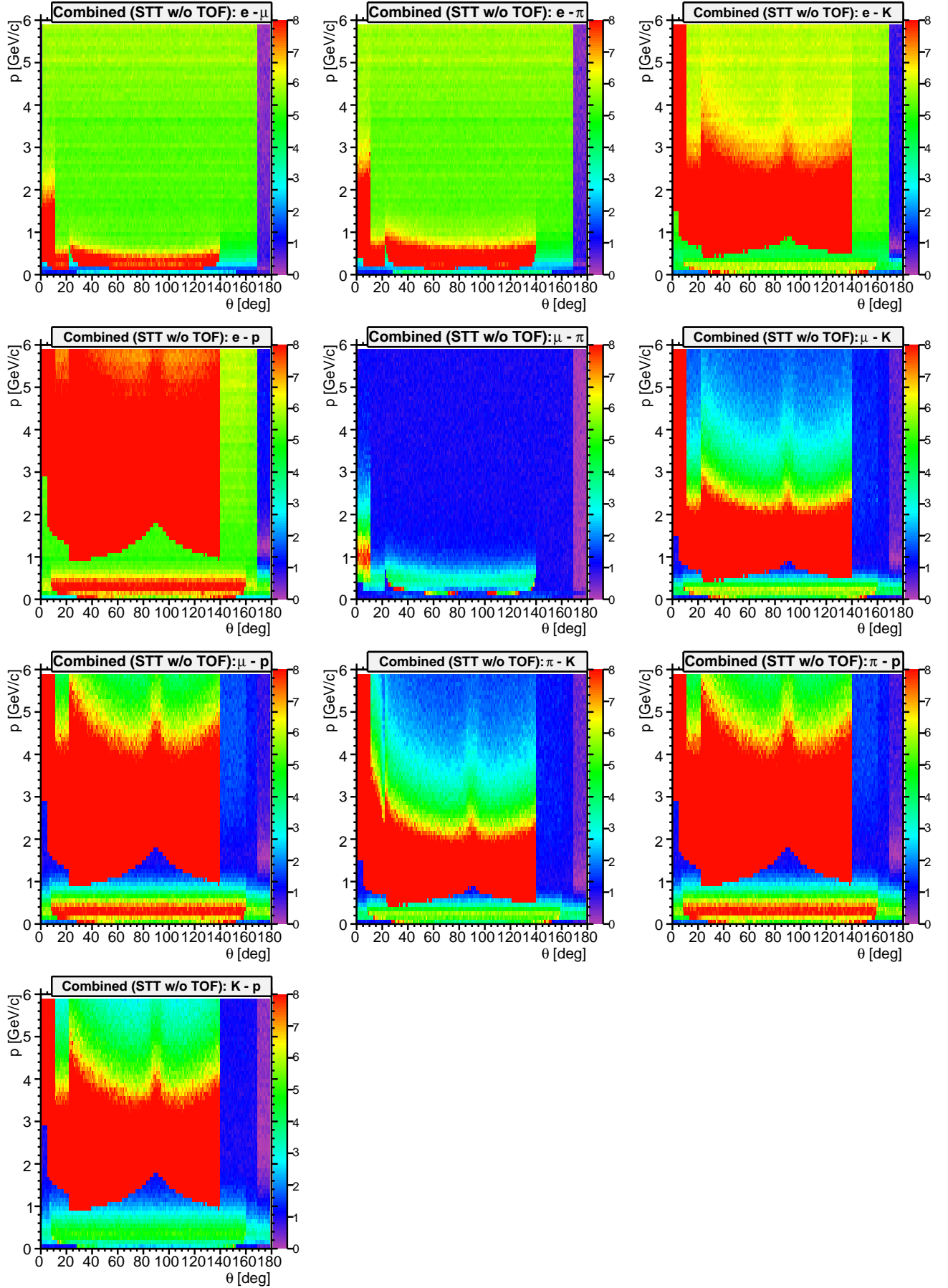


Figure 28: Combined map of Separation Power with STT as central tracker option without the TOF system. Color code corresponds to  $N_\sigma = 0 \dots 8$ .

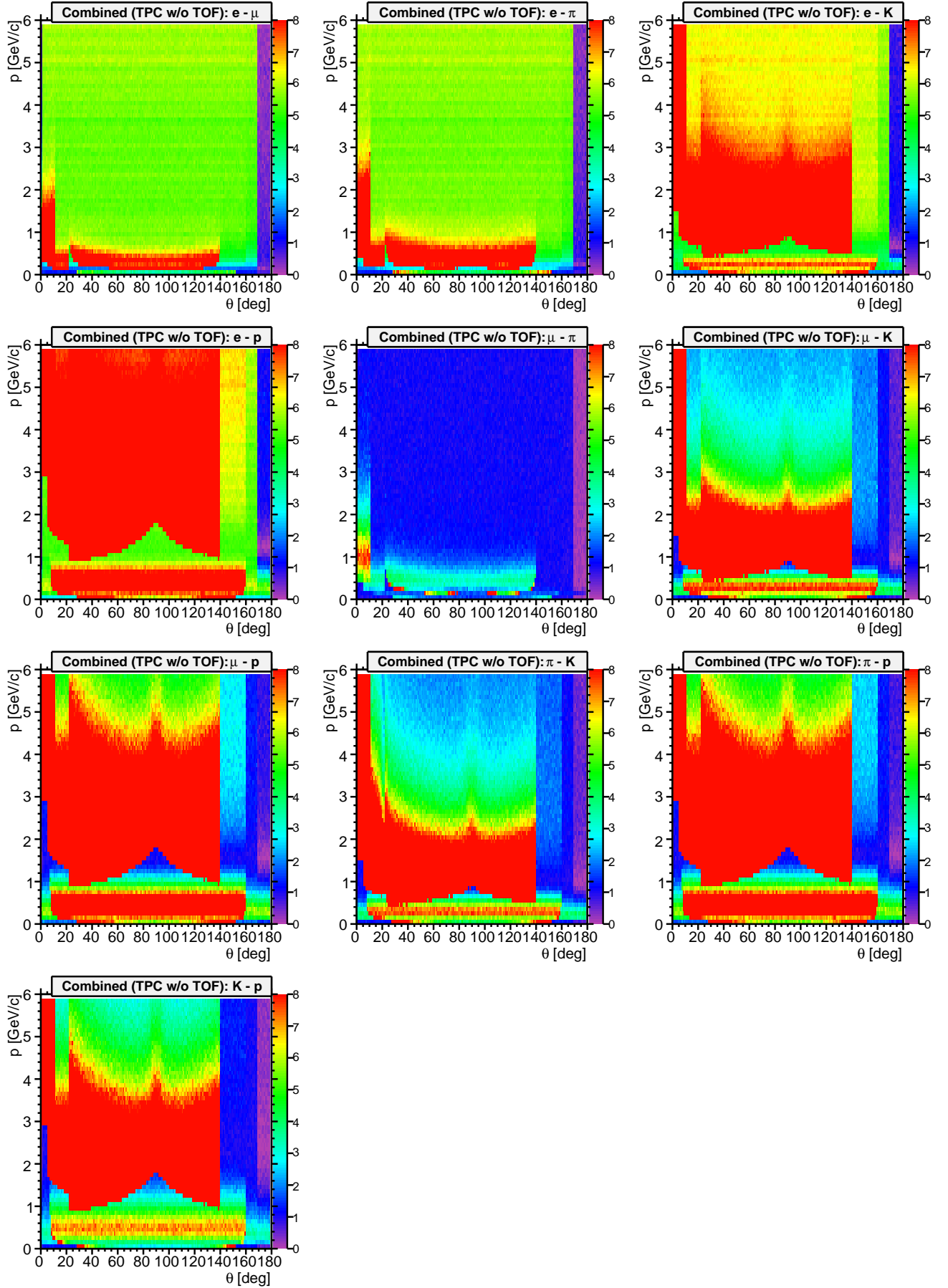


Figure 29: Combined map of Separation Power with TPC as central tracker option without the TOF system. Color code corresponds to  $N_\sigma = 0 \dots 8$ .

## 4.2 Phase Space Plots

The question which has to be answered concerning particle identification is not only how good the classification works or has to work, but also in which region of the phase space one needs good separation, and in which parts one possibly doesn't need almost any.

Therefore it is a crucial task to visualize the kinematic behaviour of various important physics channels to get a better insight to the above issue. Furthermore not only kinematic distributions of signal events are relevant, since good PID is only useful in cases where kinematic overlap of particles of species  $A$  from signal events and particles of species  $B$  from background events really exists. In scenarios where particles of the same type  $A$  appear in signal as well as background events in the same phase space location the background suppression cannot be improved by means of PID.

Following a request of the PID TAG phase space plots from all the reactions relevant for the physics book were produced. The set of plots shows for each particle species of the reaction the particle momentum versus theta angle.

Tab. 5 lists part of the benchmark channels discussed in the PANDA Physics Booklet and some additional ones to study inclusive open charm analysis together with relevant background channels. In particular channels were investigated which might suffer significantly from insufficient PID capabilities<sup>3</sup>.

The acronym DPM in the table refers to generic background events generated with the **D**ual **P**arton **M**odel generator. In the last column references to the corresponding figures are given. Tab. 4 gives some standard decay channels which apply to cases where nothing different is specified in tab. 5.

In figs. 30 - 34 kinematic distributions (momentum  $p$  vs. dip angle  $\theta$ ) at various beam momenta are shown for some of the signal-background scenarios listed in 5, one particle species per plot. To easier spot signal and background, the latter ones are colored blue.

Particle	Decay channel
$J/\psi$	50% $e^+e^-$ , 50% $\mu^+\mu^-$
$\eta$	$\pi^+\pi^-\pi^0$
$D^0$	$K^-\pi^+$
$D^+$	$K^-\pi^+\pi^+$
$D^{*+}$	50% $D^0\pi^+$ , 50% $D^+\pi^0$
$D^{*0}$	$D^0\pi^0$
$D_s^+$	$\phi\pi^+$
$\phi$	$K^+K^-$
$\Lambda$	$p\pi^-$
$\pi^0$	$\gamma\gamma$

Table 4: Standard decay channels for some particles

<sup>3</sup>Signal channels with background reactions comprising the same final state can only be identified due to different kinematic behaviour, which goes beyond the capabilities of PID

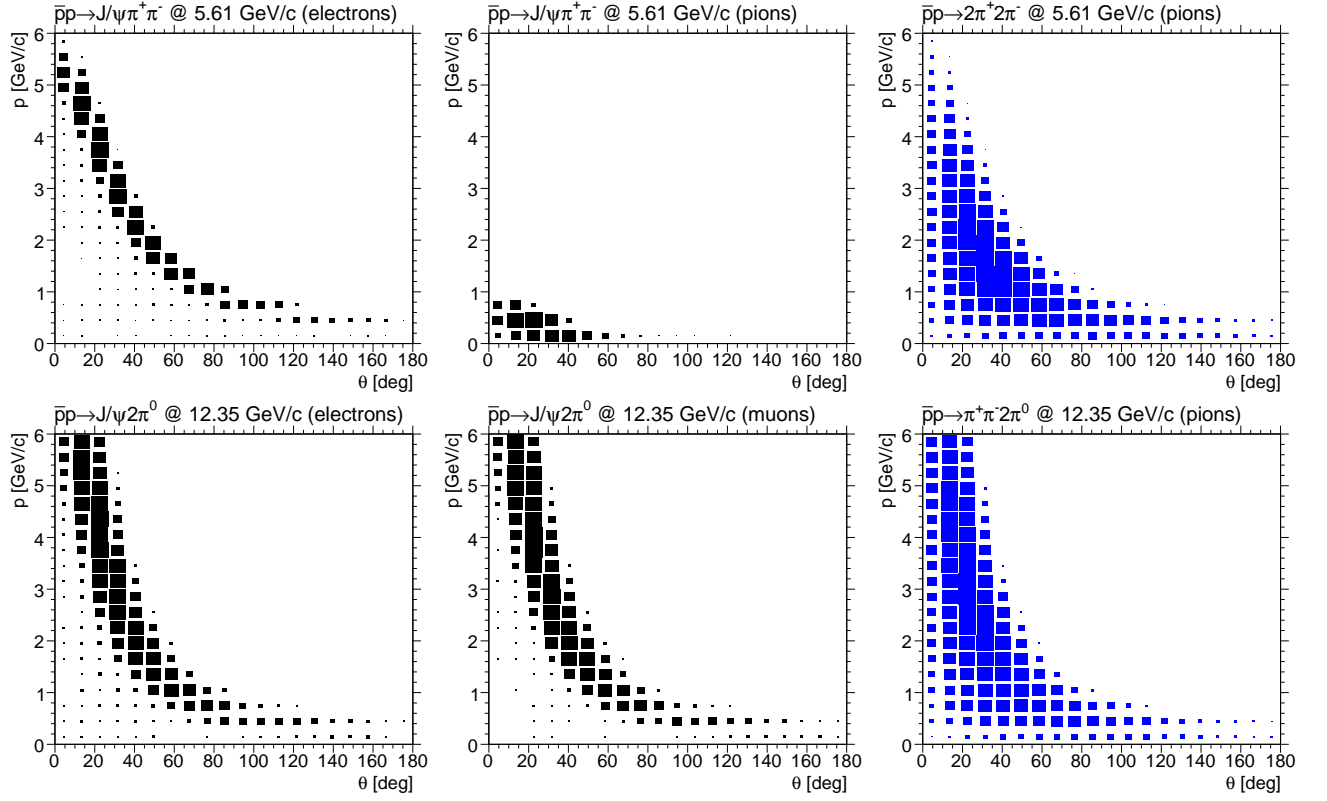


Figure 30:  $\bar{p}p \rightarrow J/\psi \pi^+ \pi^-$  @ 5.609 GeV/c (top),  $\bar{p}p \rightarrow J/\psi 2\pi^0$  @ 12.3485 GeV/c (bottom)

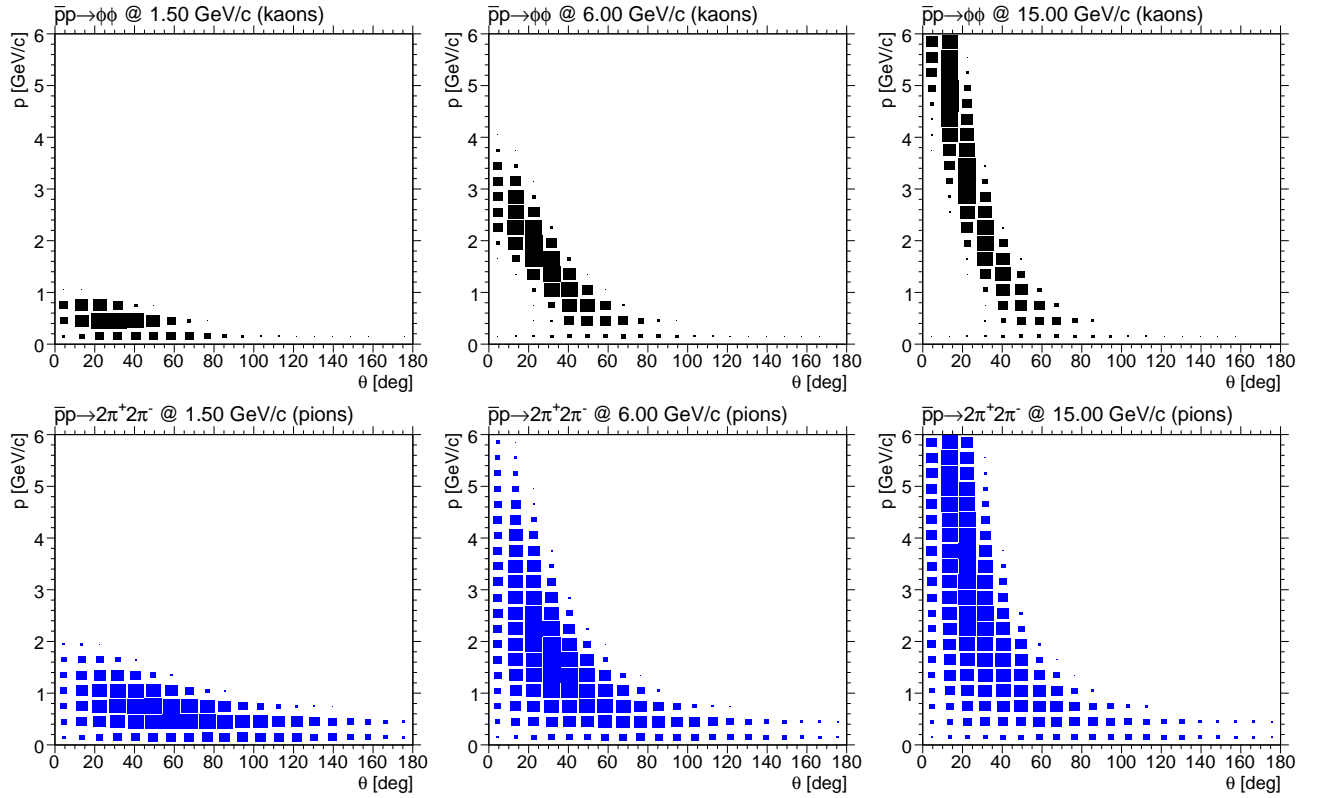
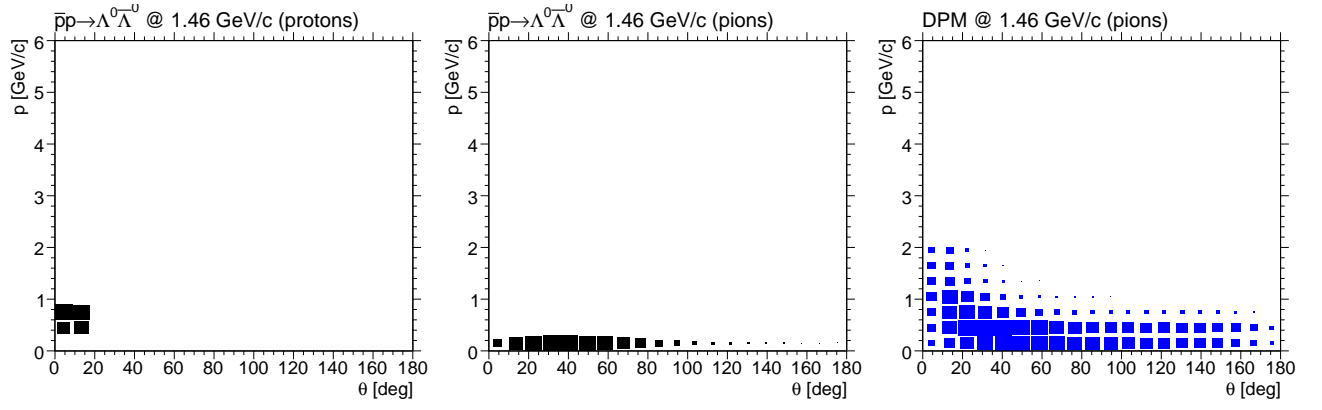
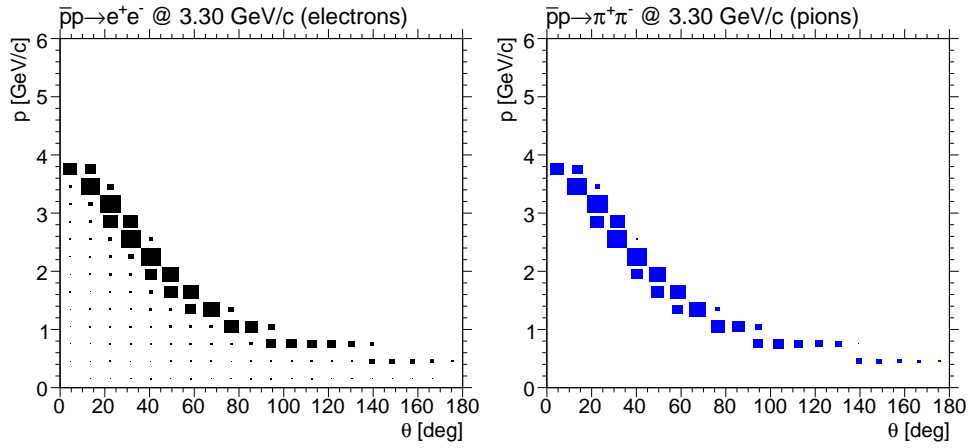
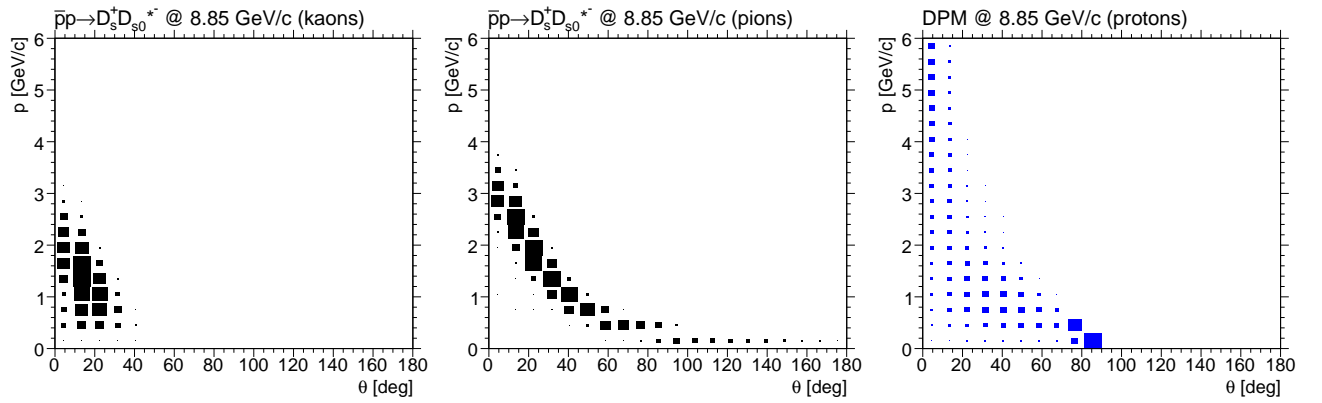


Figure 31:  $\bar{p}p \rightarrow \phi\phi$  @ 1.5, 6.0, 15.0 GeV/c



Figure 32:  $\bar{p}p \rightarrow \Lambda^0 \bar{\Lambda}^0$  @ 1.4601 GeV/cFigure 33:  $\bar{p}p \rightarrow e^+ e^-$  @ 3.30 GeV/cFigure 34:  $\bar{p}p \rightarrow D_s^+ D_{s0}^{*-}(2317)^-$  @ 8.847 GeV/c

Signal	Background	$p_{\bar{p}}$ [GeV/c]	Fig.
$J/\psi 2\pi^0$	$\pi^+\pi^-2\pi^0$	5.609 / 6.232 / 8.682 10.295 / 12.349	30
$J/\psi \pi^+\pi^-$	$2\pi^+2\pi^-$	5.609 / 6.232 / 6.988 8.682 / 10.295 / 12.349	-
$J/\psi \eta$	$2\pi^+2\pi^-\pi^0$	6.990 / 8.7	-
	$2\pi^+2\pi^-$	6.080 / 6.990 / 8.7	-
	$3\pi^+3\pi^-$	6.080 / 6.990 / 8.7	-
$\phi\phi$	$2\pi^+2\pi^-$	1.5 / 6.0 / 12.0 / 15.0	31
	$3\pi^+3\pi^-$	1.5 / 6.0 / 12.0 / 15.0	-
$\Lambda^0\bar{\Lambda}^0$	$\Sigma^0\bar{\Sigma}^0$	1.914 / 3.101 / 6.0	32
	DPM	1.460 / 8.0 / 10.0	-
$e^+e^-$	$\pi^+\pi^-$	1.7 / 3.3 / 7.9 / 10.9 / 15.0	33
$D_s^+ D_{s0}^* (2317)^-$	DPM	8.847	34
	$3\pi^+3\pi^-\pi^0$	8.847	-
$D_s^+ D_s^- \gamma$	$3\pi^+3\pi^-$	8.847	-
	DPM	7.361 / 7.746 / 8.0 / 12.0 / 15.0	-
$D^{*0} \bar{D}^{*0} \gamma$	DPM	7.746 / 8.0 / 12.0 / 15.0	-
$D^{*+} D^{*-} \gamma$	DPM	7.746 / 8.0 / 12.0 / 15.0	-
$D^0 \bar{D}^0 \gamma$	DPM	6.488 / 8.0 / 12.0 / 15.0	-
$D^+ D^- \gamma$	DPM	6.488 / 8.0 / 12.0 / 15.0	-

Table 5: Table of Phase Space Channels

### 4.3 Fast Simulation

In order to get information about phase space (i.e. momentum-polar angle dependence) coverage of the different PID relevant subsystems maps of separation power have been generated based on fast simulations of single track events, i.e. the particles properties are modified with an effective parametrization of detectors responses and PID information is estimated and attached to the resulting particle candidate. Since no microscopic simulation is performed and no exact geometry information is taken into account, the accuracy of this approach is limited, the computation time on the other hand is orders of magnitude shorter offering the possibility to do studies with higher statistics.

### 4.4 General Technique

In contrast to microscopic simulations using software systems like Geant or Fluka the Fast Simulation is based on acceptance filtering and effective parametrization of all observables of the particular subsystems. Underlying assumption is that the detector system will be able to reconstruct the true particles properties like momentum, direction, energy, charge and particle identification (PID) information with uncertainties which are basically uncorrelated and can be described reasonable by parametric models. That could as simple example be gaussian uncertainty for momentum reconstruction with  $\delta p/p = \sigma_p = 2\%$ , which will be used to modify the true (i.e. generated) tracks parameters accordingly. Additionally a simple geometric acceptance requirement will decide whether a track has been detected by a particular detector component or not.

There is a lot of freedom for the implementation of the subsystems, but a minimalistic detector description comprises

- Sensitivity information: Detects charged or neutral particles or both?
- Polar angle coverage:  $\theta_{\min} < \theta < \theta_{\max}$
- Gaussian resolution of observables:  $\sigma_1, \dots, \sigma_n$

In order to apply these simulation scheme for every trackable particle coming from the event generator the following procedure is processed:

1. For all detectors  $D_j$ ,  $1 < j < m$ 
  - In case  $D_j$  detects the particle, collect resolution information for all measurable quantities.
2. When no detector detected the track, skip it.
3. Merge all resolution information; when e. g. the particle has been detected by  $n$  devices capable of measuring momentum  $p$  with resolutions  $\sigma_{p,1}, \dots, \sigma_{p,n}$ , the total resolution is

$$\sigma_p = \left( \sum_{i=1}^n \frac{1}{\sigma_{p,i}^2} \right)^{-\frac{1}{2}}$$

4. Modify the according quantities  $x$  of the original track in the way  $x' = x + \delta x$ , with  $\delta x$  randomly chosen from gaussian distribution  $G(\mu = 0, \sigma_x)$
5. Create PID information according to the particles properties and attach to the particle; add particle to the track list
6. (Optional) Create secondary particles related to particles properties and add to the track list

With the so prepared track list analysis can be performed. The interface for doing that is exactly the same as the one for full simulated events.

Since this document is focussing on PID the relevant features will be describe in more detail in the following chapters. This will be done effect- or observable-wise instead of detector-wise, since the observed quantities

- specific energy loss  $dE/dx$  (MVD, TPC, STT)
- Cherenkov angle  $\theta_C$  (Barrel DIRC, Disc DIRC, RICH)
- reconstructed squared mass  $m^2$  (TOF)
- EMC related measurements like  $E_{\text{cluster}}/p$  or Zernike momenta
- signals from Muon Chambers

govern the PID quality and performance and thus are a better ordering criterion. Unfortunately the latter two informations from e.-m. calorimetry and the muon detectors are not implemented in the Fast Simulation for the time being.

## 4.5 Tracking Detectors

Although not of direct impact to the field of PID the process of tracking delivers vital information for many of the PID relevant systems. Most of these like e.g. the Time-of-flight (TOF) system or Cherenkov devices (DIRCs and RICH) do not allow for performing a stand alone position measurement, thus their information have to be linked to tracks reconstructed by tracking devices. In addition for the purpose of evaluating PID likelihood functions one usually needs to compute expected values for observables like the Cherenkov angle  $\theta_C$  or energy loss  $dE/dx$  which will be computed for the reconstructed momentum value of the track. This certainly will differ from the true momentum value and therefore track reconstruction accuracy has important impact on likelihood based classification methods.

The approach for reconstruction of momenta in the Fast Simulation nevertheless is a very simple one assuming a global momentum resolution  $\delta p/p$  for the track reconstruction, since due to technical reasons the particular detector components cannot exchange information. This implies that the tracking devices are not able to feed their information into the PID systems.

## 4.6 Energy Loss Parametrization

The computation of the specific energy loss is based on the Bethe-Bloch formula

$$-\frac{dE}{dx} = \kappa \cdot \frac{Z}{A} \cdot \frac{e^2}{\beta^2} \cdot \left[ \ln \left( \frac{2m_e \beta^2 \gamma^2 T_{\max}}{I^2} \right) - 2\beta^2 - \delta \right] \quad \left[ \frac{\text{MeV} \cdot \text{cm}}{\text{g}} \right] \quad (13)$$

which very precisely takes into account the processes of charged particles interacting with matter. The formula and detailed information about parameter meanings in this term can be found in [7].

The expression looks quite complicated but can be evaluated straight forward with momentum  $p$  and mass  $m$  given as input. Additionally one has to substitute a lot of other, material related constants. Since we are not interested in the absolute energy loss but only in relative losses for different particle species it is not crucial to have very precise knowledge about the fixed parameters.

In order to generate a simulated detector response for detectors capable of measuring  $dE/dx$  a gaussian resolution  $\sigma_{dE/dx}$  has been set for each of them. The simulated measured  $(dE/dx)_{\text{sim}}$  value thus has been simply computed with formula (13) to

$$\left( \frac{dE}{dx} \right)_{\text{sim}} = \left( \frac{dE}{dx} \right) + \delta \left( \frac{dE}{dx} \right) \quad (14)$$

with randomly chosen value  $\delta(dE/dx)$  from a gaussian distribution  $G(\mu = 0, \sigma_{dE/dx})$ .

## 4.7 Cherenkov Angle Parametrization

Basic theoretical information about the origin of Cherenkov radiation can be found elsewhere and will not be discussed here. The Cherenkov angle defined as the opening angle of the cone of radiation relativ to the direction of the incident charged particles momenta in medium with refractive index  $n$  is given by the expression

$$\theta_C = \arccos \left( \frac{1}{\beta \cdot n} \right) \quad (15)$$

with  $\beta = p \cdot c/E$  being the velocity of the particle. Obviously computation of the expected Cherenkov angle for any given particle detected by the specific detector is straight forward. Key ingredient of the parametrization of the detector response is the resolution estimation. In case of DIRC detectors experience from the working device in the BaBar experiment tells us that the overall reconstruction resolution of the Cherenkov angle can be based on a single photon resolution  $\sigma_{\text{s.phot.}} \approx 10 \text{ mrad}$ . Responsible for the overall resolution then exclusively is the number of detected Cherenkov photons  $N$  through

$$\sigma_{\text{tot}} = \frac{\sigma_{\text{s.phot.}}}{\sqrt{N}},$$

which is simple count statistics. This number  $N$  has to be estimated and depends on

- the number of generated photons

$$N_0 = 2\pi \cdot \alpha \cdot L \left( \frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}} \right) \cdot \sin^2 \theta_C = 2\pi \cdot \alpha \cdot L \left( \frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}} \right) \cdot \left( 1 - \frac{m^2 + p^2}{p^2 \cdot n^2} \right) \quad (16)$$

with parameters

- fine structure constant  $\alpha$
- trajectory length  $L$  in the radiator material
- mass and momentum  $m$  and  $p$  of the incident track
- wave length region  $\lambda_{\min}$  and  $\lambda_{\max}$  where the photon detector is sensitive and
- refraction index  $n$
- the trapping fraction  $r_{\text{trap}}$  which is the fraction of the photons kept in the radiator/lightguide due to total reflection and
- the detection efficiency  $\epsilon$  of the photon detector, e.g. a photo multiplier tube (PMT)

In order to derive the path length  $L$  in the material one has to distinguish between the different Cherenkov devices.

In case of the **Barrel DIRC** one first of all has to compute the curvature due to the motion of a charged particle in a magnetic solinoidal field  $B = B_z$ . The radius  $r$  of the circular shape in  $(x, y)$  projection is given by

$$r = \frac{p_t}{q \cdot B} = \frac{3.3356 \cdot p_t [\text{GeV}/c]}{B [\text{T}]} \quad (17)$$

for a particle with charge  $q = \pm e$  and transverse momentum  $p_t = p \cdot \sin \theta$ . Based on this one can calculate the entering angle  $\psi$  in  $\phi$  direction to

$$\psi = \arccos \frac{r_B}{2 \cdot r} \quad (18)$$

with  $r_B$  being the radius of the DIRC Barrel i.e. the distance between the bars and the beam line. Here it is obvious that particles with  $2 \cdot r < r_B$  will not hit the detector at all defining a minimum transverse momentum  $p_{t,\min}$ . The path length after some geometrical considerations then computes to

$$L \approx d_{\text{bar}} \cdot \sqrt{\frac{1}{\sin^2 \theta} + \frac{1}{\tan^2 \psi}} \quad (19)$$

where  $d_{\text{bar}}$  is the thickness of the radiator bars and  $\theta$  the dip angle of the helix of the track. The expression is an approximation because curvature within the bar has been neglected. This leads to significant wrong values for particles with  $2 \cdot r \approx r_B$ .

For the **Disc DIRC** and the **RICH** computing the radiator path length is much simpler. Here  $L$  only depends on the dip angle and the radiator thickness  $d_{\text{rad}}$  resulting in

$$L = \frac{d_{\text{rad}}}{\cos \theta} \quad (20)$$

Also here no curvature within the radiators has been taken into account. This anyway would lead to more complicated estimates since angular changes along the radiator path results in systematic worsening of the Cherenkov angle which is neglected completely.

Finally we still need the trapping fraction  $r_{\text{trap}}$  to determine the number of detected photons. There is no known analytic expression to compute this, thus 2 dimensional lookup tables  $r_{\text{trap}}(\theta, p)$  for every particle species have been prepared. Figure 35 shows as an example the trapping fraction in the Barrel DIRC bars for muons and protons as a function of momentum  $p$  and dip angle  $\theta$ .

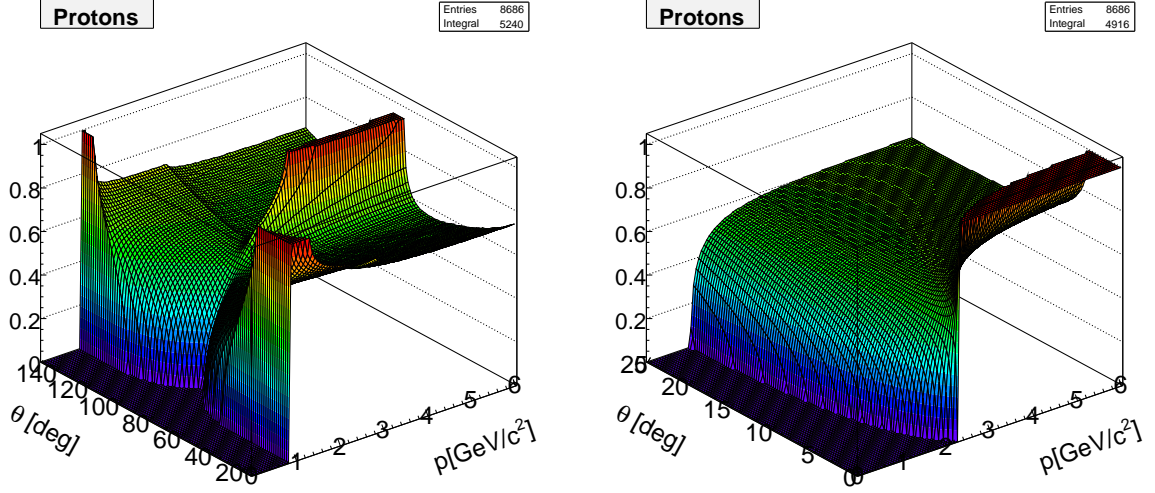


Figure 35: 2-dimensional picture of the trapping fraction for protons in the Barrel DIRC (left) and the Disc DIRC as a function of momentum  $p$  and dip angle  $\theta$ .

With the path length  $L$  one can evaluate expression (16) so that the detected number of photons can be estimated to

$$N = N'_0 \cdot \epsilon \cdot r_{\text{trap}} \quad (21)$$

where the  $N'_0$  is randomly generated from Poisson distribution with input value  $\lambda = N_0$ . This directly leads to the expected resolution  $\sigma_{\text{tot}}$  which is taken as the absolute uncertainty of the measurement of the Cherenkov angle. The simulated measured Cherenkov angle thus has been computed with formula (15) to

$$\theta_{C,\text{sim}} = \theta_C + \delta\theta_C \quad (22)$$

with randomly chosen value  $\delta\theta_C$  from a gaussian distribution  $G(\mu = 0, \sigma_{\text{tot}})$ .

## 4.8 Time Of Flight Parametrization

From the geometrical point of view the calculation of the expected time of flight of a particle has similarities to the considerations done in 4.7 for the Barrel DIRC, since the TOF detector has also cylindrical shape. This requires also the particles with curvatures given by equation (17) to have a minimum transverse momentum  $p_t$  to reach the detector and produce a signal.

In order to compute the time of flight  $t_{\text{TOF}} = s/v$  one in principal only needs the traveled distance  $s$  and the velocity  $v$  of the particle. While the latter one is simple to get by via the particles  $\beta = p \cdot c/E$ , the distance is not so easy to calculated due to the tracks curvature in the magnetic field. Nevertheless the calculation can be simplified exploiting the fact that the particles motion in  $z$  direction is independent of that one in the  $(x, y)$  plane. Therefore  $t$  can also be calculated via the ratio of the travelled angle  $\Phi$  and the angular velocity  $\omega$

$$t_{\text{TOF}} = \frac{\Phi}{\omega} = \frac{1}{\omega} \cdot 2 \arcsin \frac{r_B}{2r} \quad (23)$$

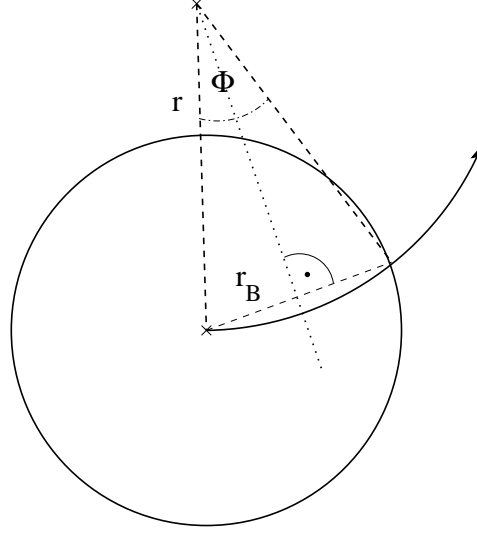


Figure 36: Projection of particle trajectory to  $(x, y)$  plane in order to determine  $\Phi$ .

with the determination of  $\Phi$  illustrated in fig. 36. The angular velocity in the projected plane is given by

$$\omega = \frac{B}{3.3356 \cdot E} \quad (24)$$

for a magnetic field  $B$  [T] and  $E$  [GeV]. With these expressions one can derive the true expected time of flight. What now has to be simulated is the expected accuracy of the measurement achieved by the detector. This depends on the time resolution assumed to be  $\sigma_t \approx 100$  ps on one hand and on the resolution connected to track reconstruction on the other hand since the transverse momentum  $p_t = p \cdot \sin(\theta)$  is needed to compute the flight length. Only a relative uncertainty  $\sigma_p = \delta p/p \approx 2\%$  for the reconstructed absolute value of the momentum has been taken into account with respect to this, neglecting errors in polar angle measurement.

This results in measured values

$$t'_{\text{TOF}} = t_{\text{TOF}} + \delta t \quad (25)$$

$$p' = p \cdot (1 + \delta p) \quad (26)$$

with gaussian distributed deviations  $\delta t$  and  $\delta p$  according to  $G(\mu = 0, \sigma_t)$  and  $G(\mu = 0, \sigma_p)$ . The primes denote from now the 'measured' or 'simulated' quantities. Now one basically has to reverse the process from above to get the simulated reconstructed value for the energy  $E$  needed to compute the squared mass

$$m'^2 = E'^2 - p'^2 \quad (27)$$

which acts as the observable of the TOF detector. Starting point is eq. (24) which forms to  $E' = B/(3.3356 \cdot \omega')$  etc. The resulting term depending only on the quantities  $t'_{\text{TOF}}$ ,  $p'$  and  $\theta$  looks like

$$m'^2 = \left( \frac{B \cdot t'_{\text{TOF}}}{2 \cdot 3.3356 \cdot \arcsin\left(\frac{r_B}{2 \cdot 3.3356 \cdot p' \sin(\theta)}\right)} \right)^2 - p'^2 \quad (28)$$



## 4.9 Parameter Settings

Tab. 6 presents the complete set of relevant parameters which were used in the Fast Simulation to extract most of the results presented in this note, in particular in section 5.3.

Meaning	Quantifier	Value
<b>Global</b>		
Magnetic Field Strength	$B = B_z$	2 T
Relative Momentum Resolution	$\sigma_p/p$	1 %
<b>Micro Vertex Detector (MVD)</b>		
Angular Acceptance	$[\theta_{\min}; \theta_{\max}]$	$[0.0^\circ; 180.0^\circ]$
Relative $dE/dx$ Resolution	$\sigma_{dE/dx}$	22 %
<b>Straw Tube Tracker (STT)</b>		
Angular Acceptance	$[\theta_{\min}; \theta_{\max}]$	$[7.765^\circ; 159.44^\circ]$
Relative $dE/dx$ Resolution	$\sigma_{dE/dx}$	20 %
Inner Radius	$R_I$	15 cm
<b>Time Projection Chamber (TPC)</b>		
Angular Acceptance	$[\theta_{\min}; \theta_{\max}]$	$[7.765^\circ; 159.44^\circ]$
Relative $dE/dx$ Resolution	$\sigma_{dE/dx}$	8 %
Inner Radius	$R_I$	15 cm
<b>Barrel DIRC</b>		
Angular Acceptance	$[\theta_{\min}; \theta_{\max}]$	$[22.0^\circ; 140.0^\circ]$
Inner Radius	$R_I$	48 cm
Single Photon Resolution	$\sigma_{ph}$	10 mrad
Thickness of Slab	$d_S$	1.7 cm
Refractive Index of Quarz	$n_Q$	1.472
Total Photon Detector Efficiency	$\epsilon_{PD}$	7.5 %
<b>Disc DIRC</b>		
Angular Acceptance	$[\theta_{\min}; \theta_{\max}]$	$[5.0^\circ; 22.0^\circ]$
Single Photon Resolution	$\sigma_{ph}$	10 mrad
Thickness of Disc	$d_D$	1.7 cm
Refractive Index of Quarz	$n_Q$	1.472
Total Photon Detector Efficiency	$\epsilon_{PD}$	7.5 %
<b>Ring Image Cherenkov Detector (RICH)</b>		
Angular Acceptance	$\theta_{\min}$	$0.0^\circ$
	$\alpha_{\max} \text{ (vert.)}$	$5.0^\circ$
	$\alpha_{\max} \text{ (hor.)}$	$10.0^\circ$
Single Photon Resolution	$\sigma_{ph}$	10 mrad
Thickness of Radiator	$d_D$	1 m
Refractive Index of Radiator	$n_R$	1.05
Total Photon Detector Efficiency	$\epsilon_{PD}$	7.5 %
<b>Time of Flight system (TOF)</b>		
Angular Acceptance	$[\theta_{\min}; \theta_{\max}]$	$[22.0^\circ; 140.0^\circ]$
Inner Radius	$R_I$	38 cm
Total Time Resolution	$\sigma_t$	141 ps

Table 6: Parameter Settings used for the Fast Simulation

## 5 Evaluation

### 5.1 Potential of the Subsystems

### 5.2 Matching of the Subsystems

### 5.3 Maps of Separation

In order to evaluate the PID performance applied to specific physics channels the information about

1. kinematic distribution of signal channel
2. kinematic distribution of possible background
3. separation power in phase space

have been combined in the way, that signals distributions for every particle species have been projected on the according map of separation power with either STT or TPC option. Since the implementation of the TOF detector is still under investigation at the time of writing, the studies for both options also have been performed without the information of the TOF system.

Background has been taken into account by punching the according separation map with its distribution leaving only regions colored where in fact background particles appear.

For instance to determine the PID quality for kaons from  $\bar{p}p \rightarrow D^+D^-\gamma$  reactions at a particular energy against pions from DPM background, the phase space histogram of kaons from the signal channel has been projected on the  $\pi^\pm - K^\pm$  separation map which has been punched with the distribution of pions from DPM events at the same total energy.

This procedure gives access to the information how good a particle type for a specific signal channel can be identified. In particular it offers the possibility to identify regions with insufficient PID quality. As a quantitative measure for the goodness or badness of a certain projection two quantities have been determined:

1. the fraction of the signal  $f$  where separation power is  $N_\sigma < 8$
2. the average  $\sigma_{\text{avg}}$  for that region

As an arbitrary criterion all projections fulfilling

$$f > 0.2 \quad \&\& \quad \sigma_{\text{avg}} < 5\sigma \quad \text{or} \quad f > 0.5$$

have been listed as problematic cases. Tab. 7 contains all channels with  $\bar{p}$  momentum below 8.7 GeV/c, tab. 8 shows channels with  $p_{\bar{p}} > 8.7$  GeV/c. In order to assign additional structure to this vast amount of information the numbers have been colored according to the severeness of PID deficiency. Since intuitively higher values  $f$  and smaller values  $\sigma_{\text{avg}}$  can be considered as bad

and vice versa smaller fractions  $f$  and larger  $\sigma_{\text{avg}}$  are considered as good, the coloring scheme was chosen as:

$$\begin{aligned}
 f &= 0 \dots 30 \quad \dots 40 \quad \dots 50 \quad \dots 60 \quad \dots 70 \quad \dots 80 \quad \dots 90 \quad \dots 100 \% \\
 \sigma_{\text{avg}} &= 0 \dots 1.5 \quad \dots 2.0 \quad \dots 2.5 \quad \dots 3.0 \quad \dots 3.5 \quad \dots 4.0 \quad \dots 4.5 \quad \dots 5.0 \sigma
 \end{aligned}$$

with values marked red being worse than values marked green or yellow. The four different combinations  $(f, \sigma)$  correspond to the combinations

1. TPC option including TOF
2. STT option including TOF
3. TPC option w/o TOF
4. STT option w/o TOF

i. e. to contrast TPC and STT PID performance compare either  $(f_1, \sigma_1)$  and  $(f_2, \sigma_2)$  with TOF or  $(f_3, \sigma_3)$  and  $(f_4, \sigma_4)$  without TOF. The PID hypothesis column has always been colored with the 'worst' color in the row in order to easier spot separation problems between particular hypothesis.

Figs. 37 – 39 present the corresponding plots for some selected channels. Each column shows the results for one particular channel and the four different detector setups in the same order from top to bottom as given in the list. In tabs. 7 and 8 those channels are marked with a bullet ( $\bullet$ ) in the PID column.

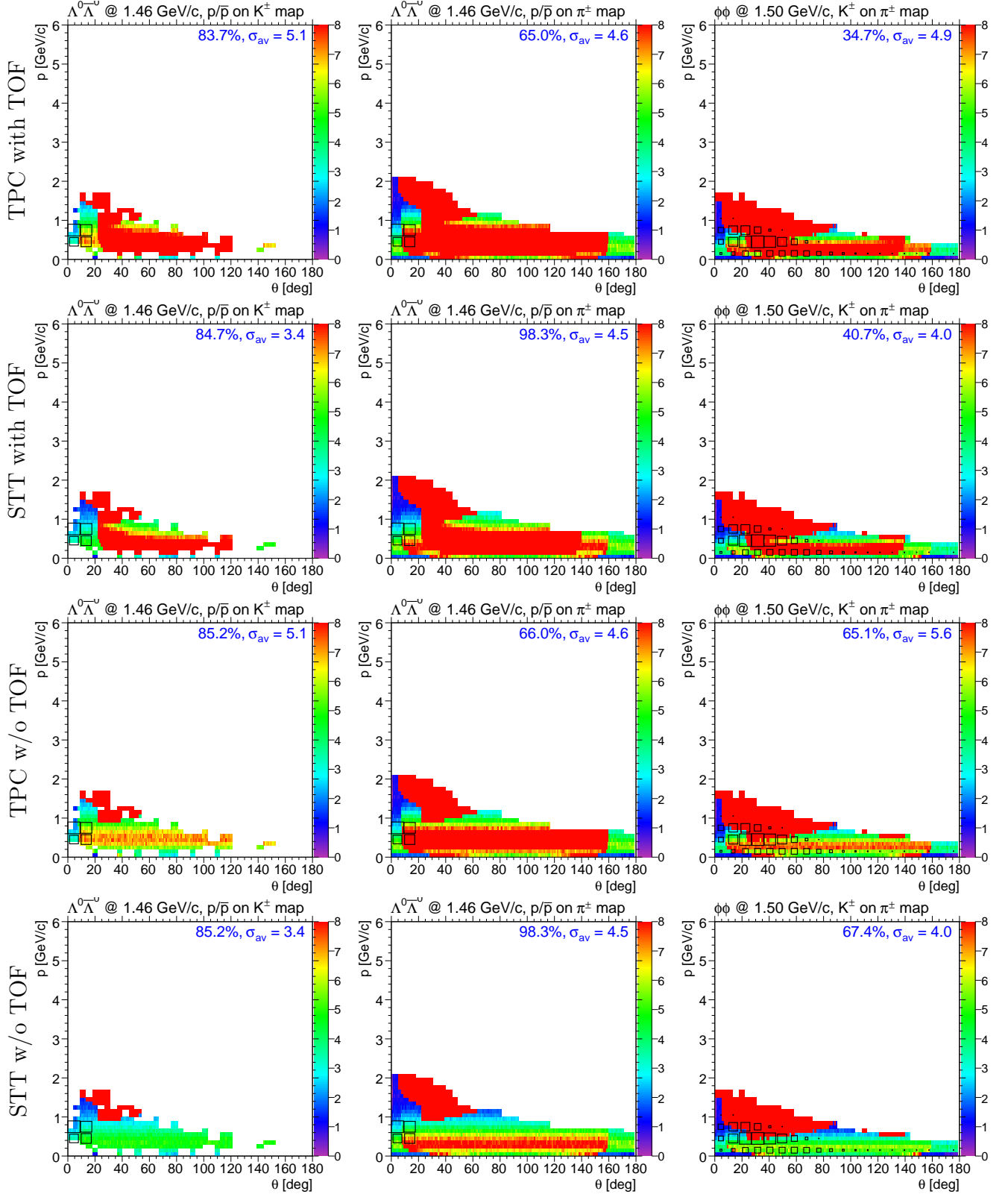


Figure 37: Projection of kinematic distributions on separation maps (1).

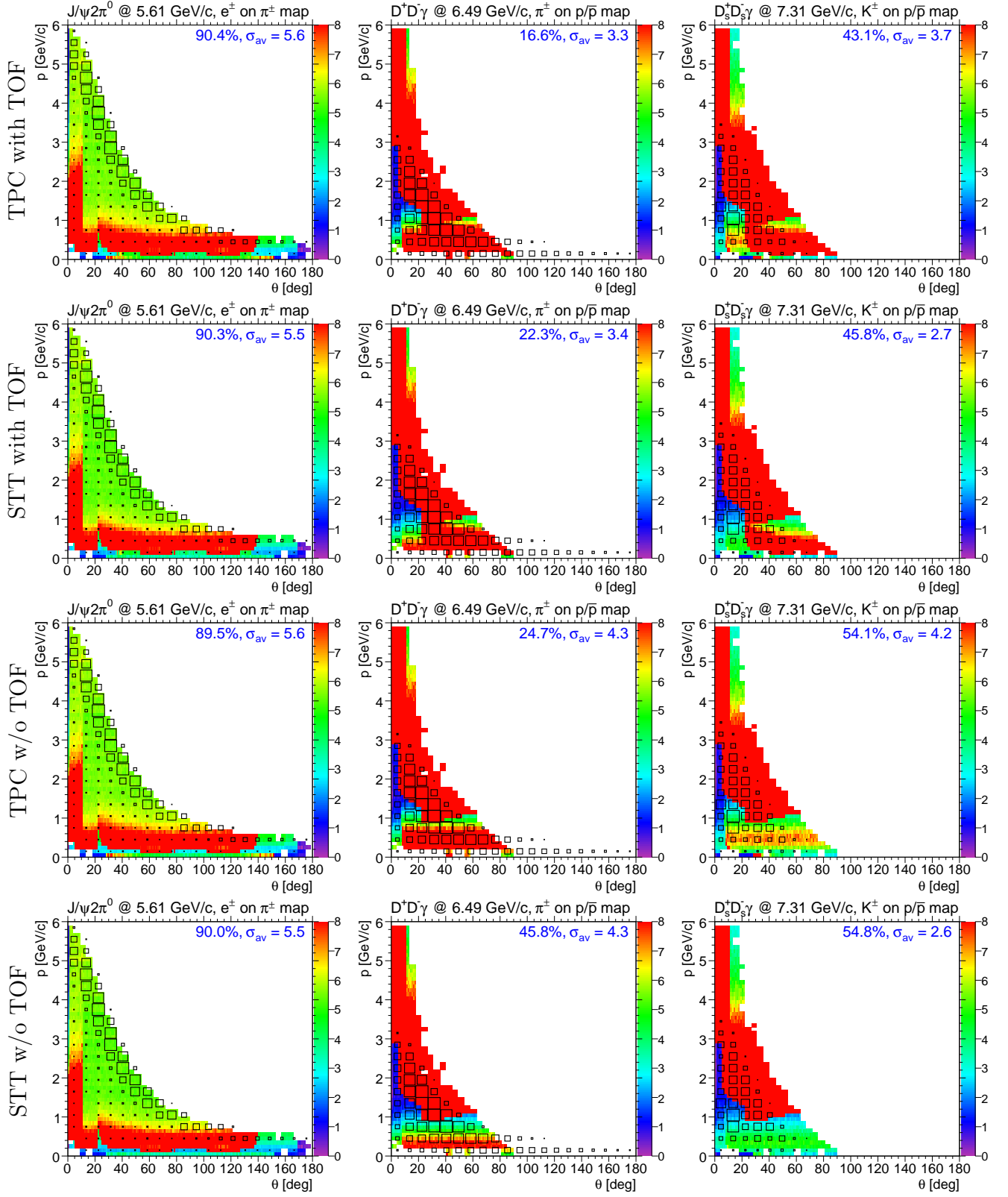


Figure 38: Projection of kinematic distributions on separation maps (2).

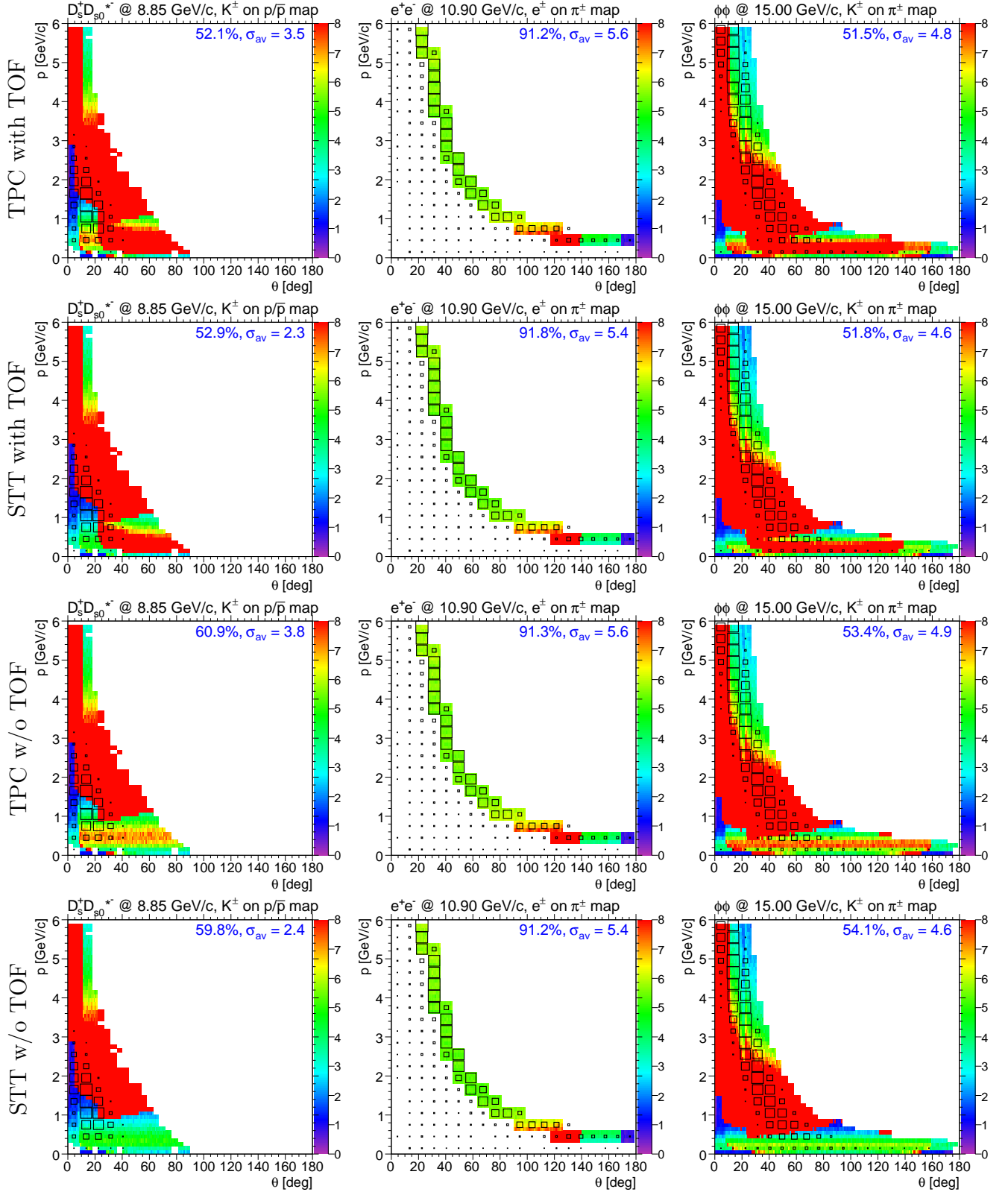


Figure 39: Projection of kinematic distributions on separation maps (3).

$p_{\bar{p}}$ [GeV/c]	Signal	PID	$f_1$ [%]	$\sigma_1$	$f_2$ [%]	$\sigma_2$	$f_3$ [%]	$\sigma_3$	$f_4$ [%]	$\sigma_4$
1.460	$\Lambda^0 \bar{\Lambda}^0$	$\pi - e$	64	4.0	64	3.3	64	3.7	66	2.9
		$\pi - \mu$	30	2.6	30	2.5	31	2.5	30	2.3
		$p - e$	49	5.3	72	5.6	50	5.3	72	5.6
		$p - \pi$ ●	63	4.6	98	4.5	65	4.6	98	4.5
		$p - K$ ●	85	5.1	85	3.4	84	5.0	84	3.4
1.500	$\phi\phi$	$K - \pi$ ●	34	4.9	41	4.0	65	5.6	65	4.0
1.700	$e^+e^-$	$e - \pi$	91	5.9	92	5.6	91	5.9	92	5.6
3.300	$e^+e^-$	$e - \pi$	93	5.7	93	5.5	94	5.7	93	5.5
5.609	$J/\psi 2\pi^0$	$e - \pi$ ●	90	5.7	89	5.5	90	5.6	90	5.5
		$\mu - \pi$	92	1.3	92	1.2	92	1.2	92	1.2
	$J/\psi \pi^+ \pi^-$	$e - \pi$	88	5.7	88	5.5	88	5.6	89	5.5
		$\mu - \pi$	92	1.3	91	1.2	92	1.3	92	1.2
6.080	$J/\psi \eta$	$e - \pi$	65	5.6	64	5.5	65	5.6	65	5.5
6.232	$J/\psi 2\pi^0$	$e - \pi$	90	5.6	89	5.5	89	5.6	89	5.5
		$\mu - \pi$	93	1.3	92	1.2	92	1.2	92	1.2
	$J/\psi \pi^+ \pi^-$	$e - \pi$	90	5.6	91	5.5	91	5.6	91	5.5
		$\mu - \pi$	93	1.3	94	1.2	94	1.2	94	1.2
6.488	$D^+ D^- \gamma$	$\pi - p$ ●	16	3.4	21	3.5	25	4.5	45	4.3
		$K - p$	23	4.0	27	3.4	38	4.9	38	3.0
6.988	$J/\psi \pi^+ \pi^-$	$e - \pi$	92	5.6	93	5.5	93	5.6	93	5.5
		$\mu - \pi$	96	1.2	96	1.2	96	1.2	96	1.2
6.990	$J/\psi \eta$	$e - \pi$	77	5.6	77	5.5	77	5.6	77	5.5
7.314	$D_s^+ D_s^- \gamma$	$\pi - p$	13	4.1	23	4.6	21	4.9	43	4.8
		$K - p$ ●	42	3.7	44	2.7	54	4.2	54	2.6
7.746	$D^{*+} D^{*-} \gamma$	$\pi - K$	17	4.2	18	3.9	20	4.5	21	3.7
		$\pi - p$	24	4.8	27	4.8	28	4.9	38	4.8
		$K - p$	14	5.0	17	4.7	24	5.4	25	3.4
	$D_s^+ D_s^- \gamma$	$\pi - p$	13	4.0	23	4.4	19	4.8	40	4.8
		$K - p$	41	3.6	43	2.7	51	4.1	51	2.6
7.900	$e^+e^-$	$e - \pi$	91	5.6	91	5.5	91	5.6	91	5.5
8.000	$\Lambda^0 \bar{\Lambda}^0$	$\pi - K$	22	4.2	24	3.2	35	5.2	36	3.5
		$\pi - p$	35	3.8	49	3.8	45	4.4	80	4.6
	$D^{*0} \bar{D}^{*0} \gamma$	$K - p$	10	6.5	13	5.9	19	6.1	20	4.2
	$D^+ D^- \gamma$	$\pi - p$	17	3.4	22	3.5	25	4.4	44	4.3
		$K - p$	23	4.0	26	3.3	36	4.6	35	3.0
	$D^0 \bar{D}^0 \gamma$	$K - p$	13	6.1	17	5.6	23	5.9	22	4.4
	$D_s^+ D_s^- \gamma$	$\pi - K$	12	4.9	14	3.7	20	5.4	20	3.6
		$\pi - p$	13	4.1	23	4.5	22	4.8	41	4.8
	$D^{*+} D^{*-} \gamma$	$K - p$	40	3.6	43	2.6	50	4.0	51	2.6
		$\pi - K$	22	4.0	23	3.5	25	4.4	26	3.3
		$\pi - p$	26	4.3	31	4.6	29	4.5	40	4.6
		$K - p$	13	5.1	17	4.5	25	5.4	24	3.6
8.682	$J/\psi \pi^+ \pi^-$	$e - \pi$	91	5.6	93	5.5	92	5.6	93	5.5
		$\mu - \pi$	96	1.3	96	1.2	96	1.3	96	1.2
	$J/\psi 2\pi^0$	$e - \pi$	92	5.6	92	5.5	92	5.6	92	5.5
		$\mu - \pi$	96	1.3	96	1.2	96	1.3	96	1.2

Table 7: Table of projection results (1). Marked channels (●) appear in figs. 37 – 39.

$p_{\bar{p}}$ [GeV/c]	Signal	PID	$f_1$ [%]	$\sigma_1$	$f_2$ [%]	$\sigma_2$	$f_3$ [%]	$\sigma_3$	$f_4$ [%]	$\sigma_4$
8.700	$J/\psi\eta$	$e - \pi$	90	5.6	91	5.5	90	5.6	90	5.5
8.847	$D_s^+ D_{s0}^{*-}$	$\pi - p$	5	4.4	9	5.0	11	5.2	20	4.5
		$K - p$ •	53	3.4	53	2.3	59	3.8	61	2.4
10.000	$\Lambda^0 \bar{\Lambda}^0$	$\pi - K$	17	4.0	20	3.1	28	5.0	28	3.4
		$\pi - p$	32	3.5	43	3.4	41	4.3	71	4.3
		$p - \pi$	17	5.6	19	5.4	19	5.5	23	5.0
10.295	$J/\psi 2\pi^0$	$e - \pi$	93	5.6	93	5.5	92	5.6	93	5.5
		$\mu - \pi$	97	1.3	97	1.2	97	1.3	97	1.2
	$J/\psi \pi^+ \pi^-$	$e - \pi$	93	5.6	93	5.5	93	5.6	93	5.5
		$\mu - \pi$	98	1.3	98	1.2	98	1.3	98	1.2
10.900	$e^+ e^-$	$e - \pi$ •	90	5.6	91	5.5	91	5.6	91	5.4
12.000	$D^{*0} \bar{D}^{*0} \gamma$	$\pi - p$	10	5.8	12	5.6	13	5.9	20	5.0
		$K - p$	20	5.4	22	5.2	27	5.5	28	4.4
	$D_s^+ D_s^- \gamma$	$\pi - p$	16	4.1	23	4.0	22	4.6	38	4.5
		$K - p$	33	3.4	34	2.7	39	3.8	40	2.6
	$\phi\phi$	$K - \pi$	41	5.3	41	5.1	44	5.3	44	5.0
	$D^+ D^- \gamma$	$\pi - p$	17	3.6	22	3.5	24	4.3	38	4.2
		$K - p$	26	4.1	27	3.5	33	4.5	34	3.3
	$D^0 \bar{D}^0 \gamma$	$\pi - p$	11	5.6	14	5.5	15	5.6	22	4.8
		$K - p$	22	5.1	24	5.0	29	5.3	29	4.3
	$D^{*+} D^{*-} \gamma$	$\pi - K$	31	4.4	32	3.4	34	4.5	33	3.4
		$\pi - p$	24	4.4	37	5.1	27	4.8	45	5.1
		$K - p$	22	4.9	24	4.6	30	5.2	30	4.0
	$\phi\phi$	$K - \pi$	41	5.3	42	5.1	44	5.3	44	5.0
12.349	$J/\psi 2\pi^0$	$e - \pi$	93	5.6	93	5.5	93	5.6	93	5.5
		$\mu - \pi$	98	1.3	98	1.2	98	1.3	98	1.2
	$J/\psi \pi^+ \pi^-$	$e - \pi$	93	5.6	93	5.5	93	5.6	93	5.5
		$\mu - \pi$	98	1.3	98	1.2	98	1.3	98	1.2
15.000	$D^+ D^- \gamma$	$\pi - \mu$	22	3.3	22	3.2	22	3.2	23	3.3
		$\pi - p$	17	3.5	20	3.4	22	4.3	35	4.1
		$K - p$	24	4.1	26	3.5	30	4.3	31	3.2
	$e^+ e^-$ $D^{*+} D^{*-} \gamma$	$e - \pi$	90	5.6	89	5.4	89	5.6	90	5.5
		$\pi - \mu$	30	3.6	30	3.6	31	3.6	30	3.7
		$\pi - K$	25	3.9	26	3.0	27	4.1	28	2.9
		$\pi - p$	21	4.1	36	4.8	25	4.4	43	4.8
		$K - \pi$	22	5.3	22	5.1	24	5.4	24	5.0
		$K - p$	21	4.6	23	4.3	27	4.9	27	3.9
		$K - p$	19	5.1	20	4.8	25	5.3	25	4.2
	$D^{*0} \bar{D}^{*0} \gamma$	$K - \pi$ •	51	4.8	52	4.7	54	4.9	53	4.6
	$D_s^+ D_s^- \gamma$	$\pi - \mu$	23	3.4	22	3.3	22	3.4	23	3.4
		$\pi - p$	17	3.9	22	3.8	22	4.4	36	4.3
		$K - p$	30	3.3	30	2.8	34	3.7	34	2.7
	$\phi\phi$ $D^0 \bar{D}^0 \gamma$	$K - \pi$	51	4.8	52	4.6	53	4.9	53	4.5
		$K - \pi$	24	5.4	24	5.1	25	5.4	26	5.0
		$K - p$	18	5.0	20	4.6	24	5.2	24	4.1

Table 8: Table of projection results (2). Marked channels (•) appear in figs. 37 – 39.



## 6 Global PID Scheme

The PANDA spectrometer will feature a complete set of innovative detectors for particle identification. The detection of neutral particles will be performed by a highly granular electromagnetic calorimeter. Charged particles will be identified in the low momentum region by their energy deposit and ToF, in all other momentum regions by innovative DIRC detectors. The target spectrometer will be complemented by a forward spectrometer to detect high momentum particles and surrounding muon detectors. Each detector systems performance is optimised in itself. Studies have begun to combine the responses of various detectors in a common framework based on a likelihood scheme or a carefully trained neural network. These combined likelihood schemes are successfully employed at various detector systems like HERMEs, Belle and BaBar. They rely on a reliable parametrisation of the detector component response from simulation and test-beams. This has to be taken into account in testing PANDA's individual components. The combined performance of the system will be significantly better than the individual separation powers.

801 **7 Conclusion**

## 8 Acknowledgments

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## 9 Appendix

### Members of the PID TAG

- G. Schepers, C. Schwarz - Barrel Dirc (Chairs)
- B. Kopf, R. Novotny - Barrel Calorimeter
- B. Seitz - Cherenkov Counter (Global PID)
- O. Denisov / M. P. Bussa - Muon Counter
- K. Föhl / P. Vlasov - Forward Cherenkov
- J. Smyrski / O. Wronska - Forward Calorimeter
- Q. Weitzel / S. Neubert - Time Projection Chamber
- C. Schwarz, A. Galoyan - Time of Flight
- K. Götzen - Fast Simulation
- K. Peters - Physics