Detector Requirements Analysis on the Pion-Kaon Separation

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Overview

Introduction

Objective:

- To reconstruct long-lived C-hadrons with the fully charged final states $D^0 \to K\pi$, $\Lambda_c^+ \to pK\pi$, etc.
- To maximize the reconstruction efficiency and purity, distinguish the real signal and the combinatory background
- To scan the detector performance and give preferred working points.

For objects with pion, kaon and/or proton in its decay product:
Performance depends on

- Momentum (fully charged final state)
- Hadron separation, especially π, K separation
- VTX reconstruction. (for heavy flavor hadrons)

Introduction-Software and Sample

Software: The software for **simulation** is **MOKKA** and **reconstruction** is **MARLIN**. Both of them are **Geant** based. MARLIN is a modular C++ reconstruction framework that takes in **LCIO data** and runs multiple processors with either default or user defined parameters, each deals with a specific part of reconstruction.
And the **main categories** are: hit reconstruction, track reconstruction and particle reconstruction.
Sample: A simulated sample of $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ inclusive events at $\sqrt{s} = 91.2\,GeV$.
Method: Use full Simulation validated fast simulation to quantify the dependence between the objective particle reconstruction performance (Max. Efficiency×Purity) and the intrinsic detector performance (VTX - impact parameter resolution, mass or momentum resolution, PID - separation power)

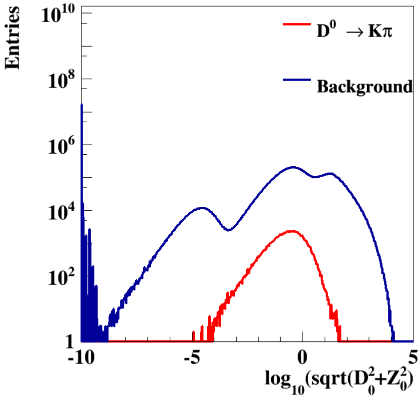
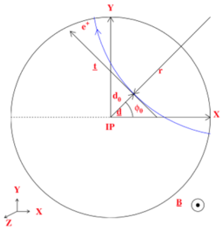


Figure: $Z \to q\bar{q}$ events, background: finally charged undecayed particles, signal: π, K from D^0, impact parameter equal to 0 is set to 1e-10.

Theorem (Impact parameter)

$$\sqrt{D_0^2 + Z_0^2} \qquad (1)$$

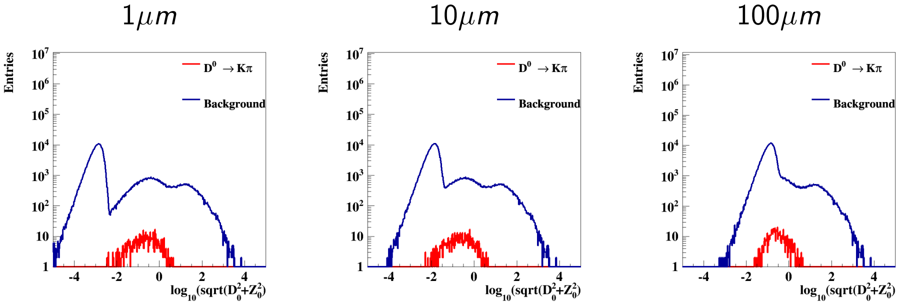
where D_0 is the distance between the nearest point (X_0, Y_0, Z_0) of the track on the $r\phi$ plane and the reference point IP.



Impact parameter and PID for reconstruction

Selection Process for $D^0 \to K\pi$

Step 1: Calculate the nearest distance (D_0, Z_0) of the track and use Gaussian random number generator to mimic (D_0, Z_0) resolution. Set a primary cut to select the signal.

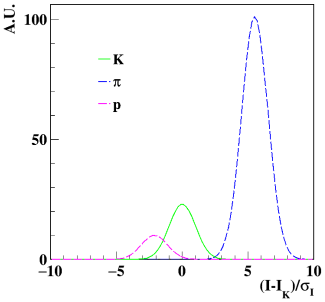


Impact parameter and PID for reconstruction

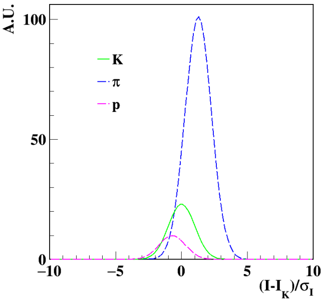
Selection Process for $D^0 \to K\pi$

Step 2: If PID is hadron, use Gaussian distribution to generate random number for good PID resolution and Uniform distribution for bad.

Good PID separation



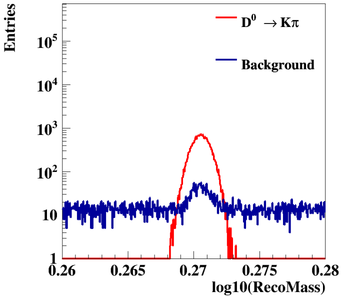
Bad PID separation



Impact parameter and PID for reconstruction

Selection Process for $D^0 \to K\pi$

Step 3: If the two particles after step 2 are K and π respectively, select those which satisfy certain constraints on mass error. 4-momentum is computed using two particles at the production vertex.



Impact parameter and PID for reconstruction

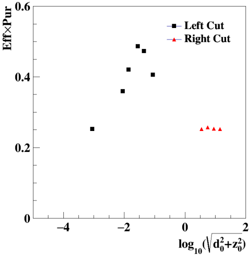
Selection Process for $D^0 \to K\pi$

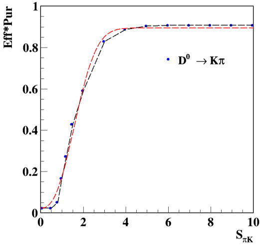
Step 4: Optimization impact parameter's cut for maximizing *Effiency*$(\varepsilon) \times$ *Purity*(p).

Theorem (The parameterization of $\varepsilon \times p$)

$$0.87 \times (1 - e^{-0.19 \times S^{2.49}}) + S_0 \tag{2}$$

$$\varepsilon = \frac{N_{D_0 \to D_0}}{N_{D_0}}$$
$$p = \frac{N_{D_0 \to D_0}}{N_{D_0 \to D_0} + N_{other \to D_0}} \tag{3}$$

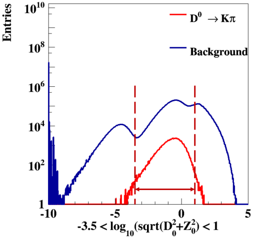


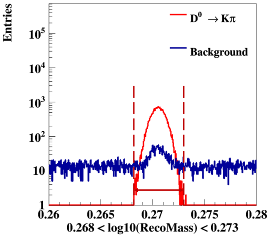


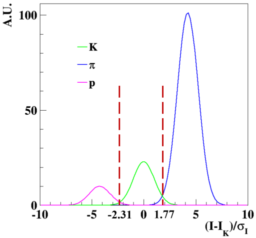
Impact parameter and PID for reconstruction

$\sigma_{mass} = 2\ MeV,\ \sigma_{dEdx} = 5\%,\ \sigma_{TOF} = 100\ ps$

constrain	cut	ε	p	Max($\varepsilon \times p$)
Impact Para.	$10^{-3.5} < \sqrt{D_0^2 + Z_0^2} < 10^{1.0}$	0.917	0.463	0.425
Mass	$1.855 < Recomass < 1.875$	0.912	0.912	0.833
PID 3σ	$K : -2.31 < \frac{I - I_K}{\sigma_I} < 1.77$	0.942	0.915	0.863







Impact parameter and PID for reconstruction

If both the ε and p of the D^0 reconstruction are required to be better than 90%, the requirement for (D_0, Z_0) resolution is $4\,\mu m$ with the pion and kaon separation power equal to 3σ.

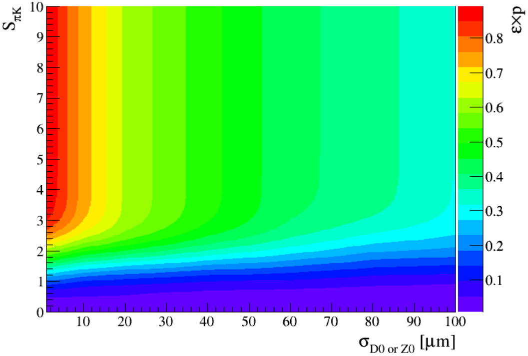


Figure: Surface distribution: $\varepsilon \times p$ as a function of dEdx & TOF resolution for π, K and (D_0, Z_0) resolution.

Detector Concept

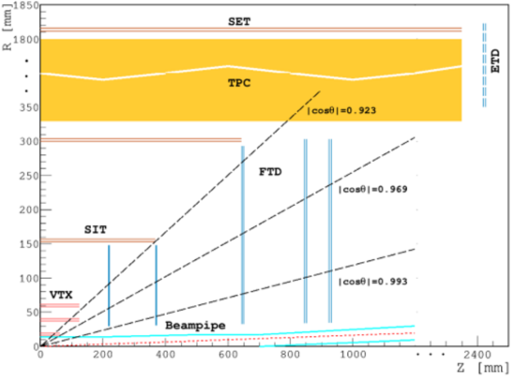


Figure: Preliminary layout of the tracking system of the CEPC baseline detector concept

The outer radius(R_{in} and R_{out}) and drift length of the TPC are chosen as the boundary conditions to record the time of flight for particles π, K, p.

TOF for π, K, p

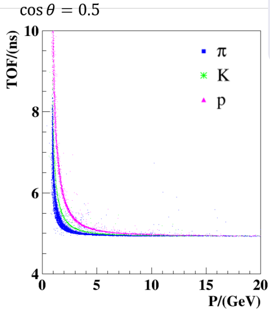


Figure: Time of fight for π, K, p through the TPC chamber

Theorem (TOF in Z-direction Projection)

$$t_z = t_{total} = \frac{\Delta z}{\beta_z \gamma c}, \quad (4)$$

where Δz equals to the difference of z_{in} and z_{out}, which are depended on the inner and outer radius of the TPC(R_{in} and R_{out}).

A circular helix of radius R, slope $R/tan\theta$ and central axis(A_x, A_y, A_z) of the particle VTX is described by the following parametrization:

Theorem (Circular Helix)

$$x = Rcos\phi + A_x, y = Rsin\phi + A_y, z = \frac{R\phi}{tan\theta} + A_z, \quad (5)$$

$p = 2GeV \ \cos\theta = 0.5$

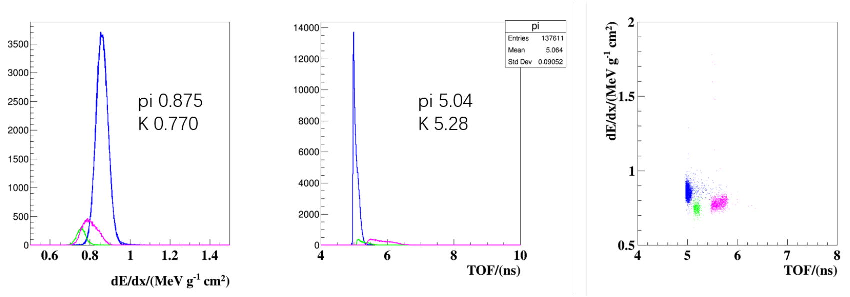


Figure: dEdx and TOF distribution for π, K, p with specific momentum and direction

ΔdEdx & ΔTOF distribution for π, K

The difference of dEdx and TOF between π and K is shown below:

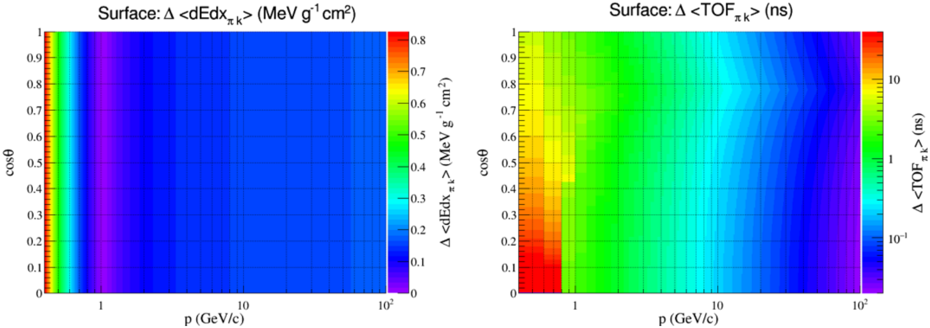


Figure: Surface distribution: ΔdEdx & ΔTOF for π, K in kinematic space

Separation Power for $\pi - K$

$p = 2GeV \ \cos\theta = 0.5$

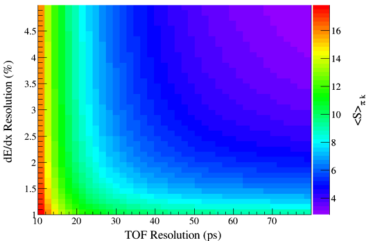


Figure: Surface distribution: Separation Power as a function of dEdx & TOF resolution for π, K

Theorem (Separation Power for $\pi - K$)

$$S_{\pi K} = \sqrt{\frac{(I_\pi - I_K)^2}{\sigma_{I_\pi}^2 + \sigma_{I_K}^2} + \frac{(T_\pi - T_K)^2}{\sigma_{T_\pi}^2 + \sigma_{T_K}^2}} \quad (6)$$

where $I(T)$ and $\sigma_I(\sigma_T)$ are the average $dE/dx(TOF)$ measurement and the corresponding resolution.

In the ideal case assuming no degradation and σ_I and σ_T are in the range of $[1-5\%]$ and $[10-80ps]$ respectively.

$S_{\pi K}$ is estimated at the CEPC as a function of σ_I, σ_T, p and $cos\theta$.

Average Separation Power for $\pi - K$

The average separation power $\langle S \rangle$ versus σ_I and σ_T after integrating over the $cos\theta$ and momentum dimension.

Theorem (The integral form)

$$\langle S_{\pi K}(\sigma_I, \sigma_T) \rangle = \frac{\int_0^1 \int_1^{20} S_{\pi K}(\sigma_I, \sigma_T, p, \cos\theta)\, PDF(p, \cos\theta) dpd\cos\theta}{\int_0^1 \int_1^{20} PDF(p, \cos\theta) dpd\cos\theta} \tag{7}$$

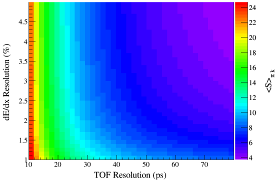
The integral form is rewritten into a summation form:

Theorem (The summation form)

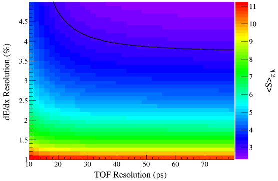
$$\langle S_{\pi K}(\sigma_I, \sigma_T) \rangle = \frac{\sum \sum S_{\pi K}(\sigma_I, \sigma_T, p_i, \cos\theta_j)\, PDF(p_i, \cos\theta_j)\, \Delta p \Delta \cos\theta}{\int_0^1 \int_1^{20} PDF(p, \cos\theta) dpd\cos\theta} \tag{8}$$

Average Separation Power for $\pi - K$

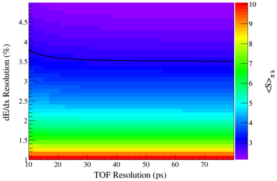
$p = 1 - 5\ GeV$



$p = 5 - 10\ GeV$



$p = 10 - 15\ GeV$



$p = 15 - 20\ GeV$

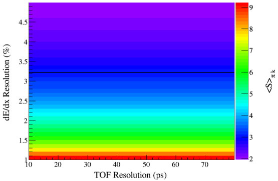


Figure: Surface distribution: Average Separation Power as a function of dEdx & TOF resolution for π, K

Average Separation Power for $\pi - K$

A preferred star point is given as the dEdx and TOF resolution for detectors.

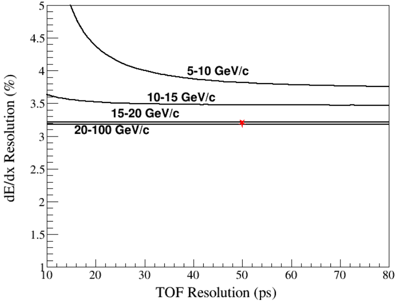


Figure: All 3σ lines for different momentum integral range

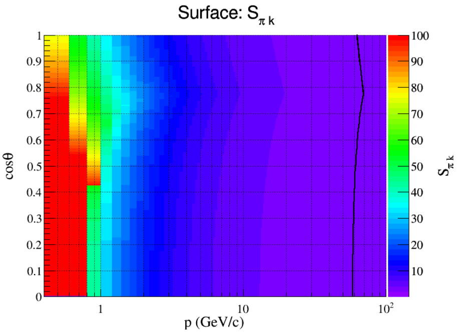


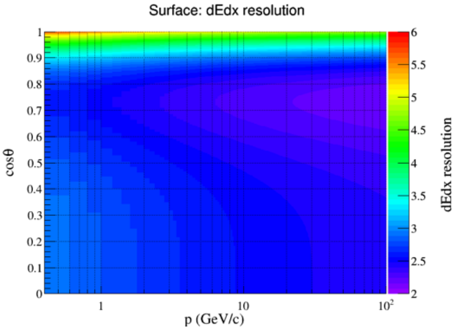
Figure: Separation power with preferred detector working point in Kinematic Space

dEdx resolution for $\pi - K$

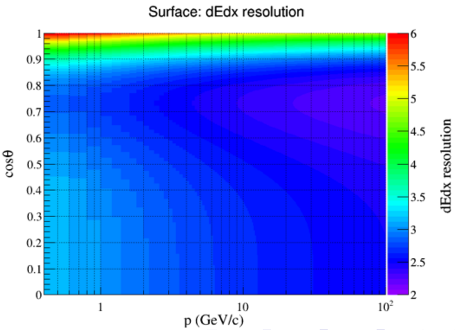
Theorem (The parameterization of σ_I)

$$\frac{\sigma_I}{I} = \frac{13.5}{n^{0.5} \cdot (h\rho)^{0.3}} \left[2.05 + 0.8(\beta\gamma)^{-0.3}\right] \times \left[2.5 - 1.5(\cos\theta)^4 + 3.9(\cos\theta)^{10}\right] \tag{9}$$

π

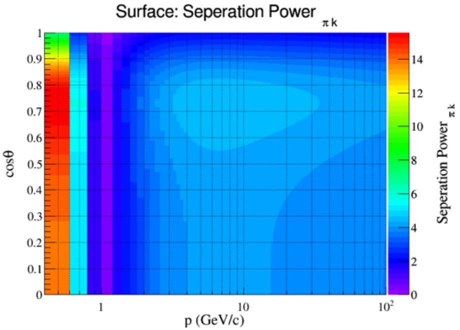


K



Seperation Power in Kinematic Space

Use *dEdx* without *TOF*



Use *dEdx* with *TOF*

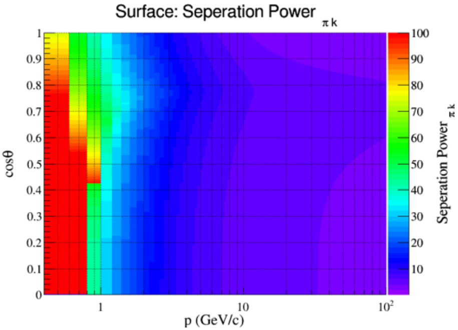


Figure: Separation Power in kinematic space for π, K wi/wo TOF

Summary

To identify charged Kaon(hadrons) up to 20 GeV

VTX: reconstructed parent mass or momentum and impact parameter
PID: dEdx and TOF

Preliminary Conclusion:

If both the ε and p of the D^0 reconstruction are required to be better than 90%, the requirement for (D_0, Z_0) resolution is 4 μm with the pion and kaon separation power equal to 3σ.
Preferred Working Point: 3σ separation of $\pi - K$, corresponding to 3.2 % for dE/dx resolution and 50 ps for TOF resolution, is appreciated.
Detector Separation Power: The parameterization of resolution need be proved.

Next:

Optimize the reconstruction process.

Thanks for your attention!

Backup

CEPC Detector Requirement from CDR

- **Vertex detector**: the intrinsic resolution σ_{D_0} in the absence of multiple scattering is $5\,\mu m$.
- **Tracker**: the intrinsic momentum resolution σ_{1/p_T} of the tracker is $2 \times 10^{-5}\ GeV^{-1}$.
- **PID**: An expected pion/kaon separation better than three standard deviations.