Status of Simulation of Endcap RICH at CEPC

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CEPC Physics and Detector Plenary Meeting

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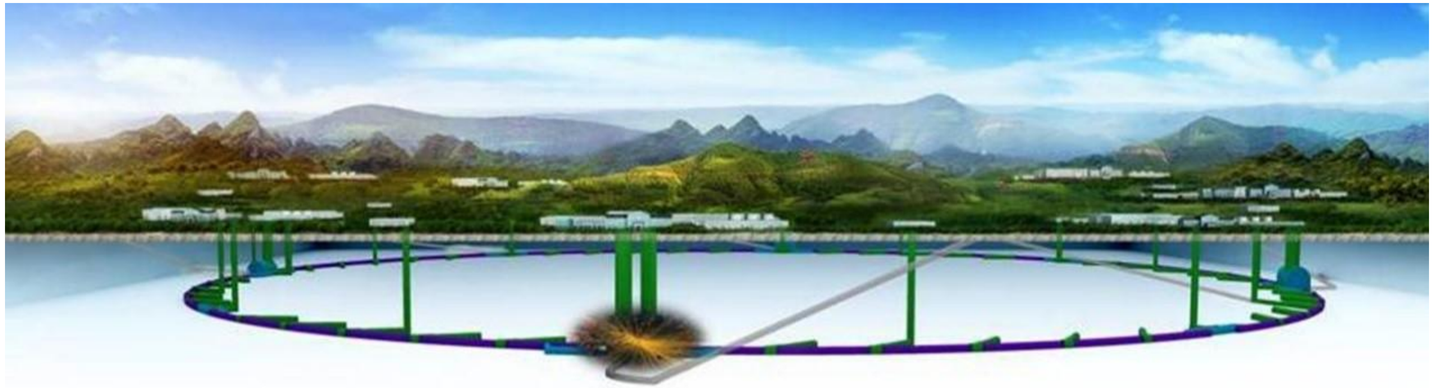
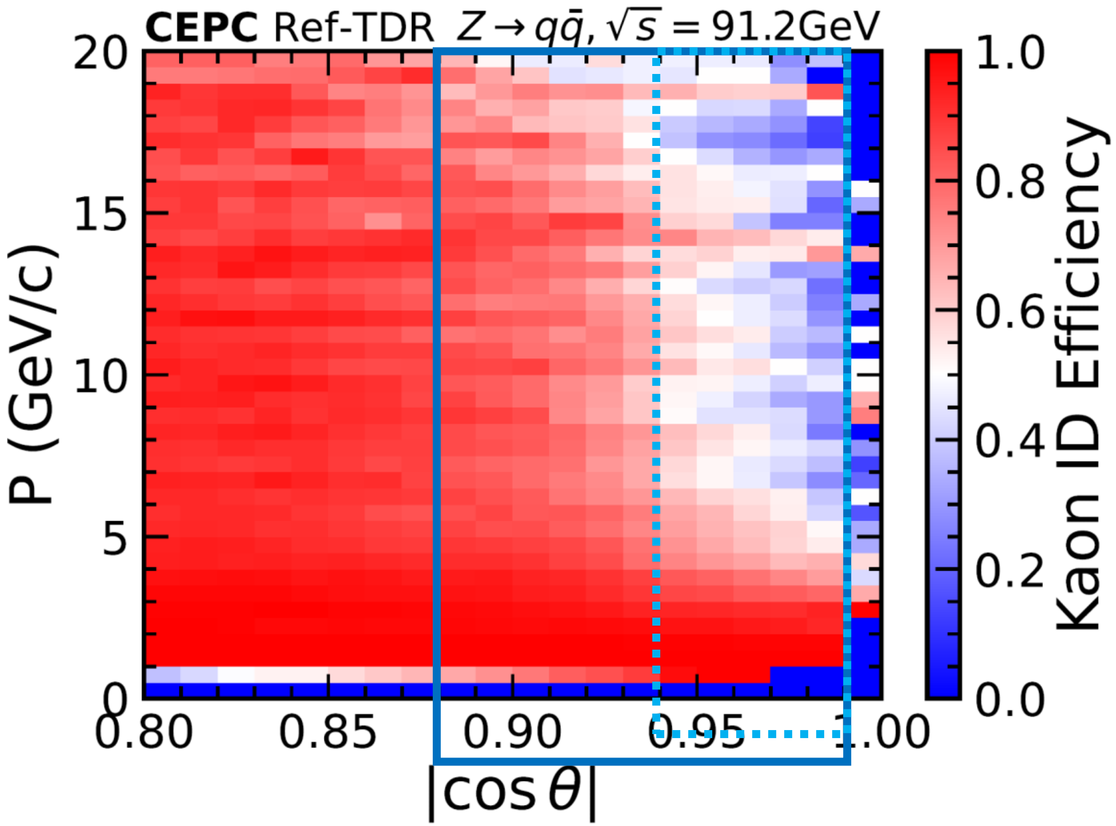
Introduction



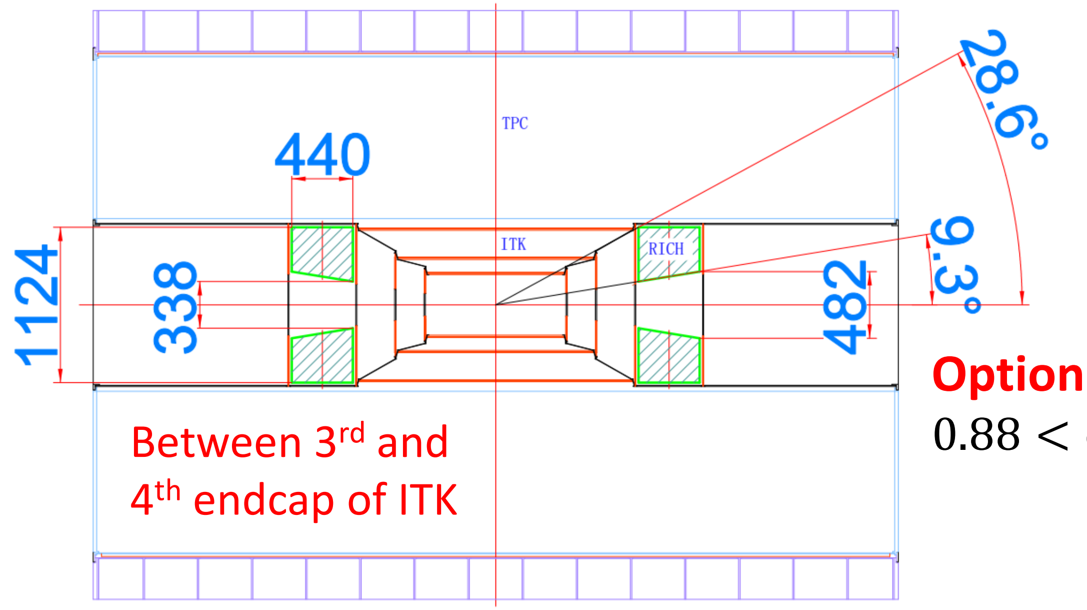
- **The CEPC Project:**
  - A proposed Circular Electron Positron Collider acting as a Higgs factory.
  - Provides an extremely clean environment for precision measurements.
- **Core Physics Objectives:**
  - Unprecedented precision in Higgs, Electroweak, and Top quark properties.
  - Searching for signals of New Physics (Beyond Standard Model).
- **Requirements for Flavor Physics:**
  - Demands exceptional Particle Identification (PID) capabilities.
  - Achieve **3σ K/π separation for momentum up to 20 GeV**.

Motivation

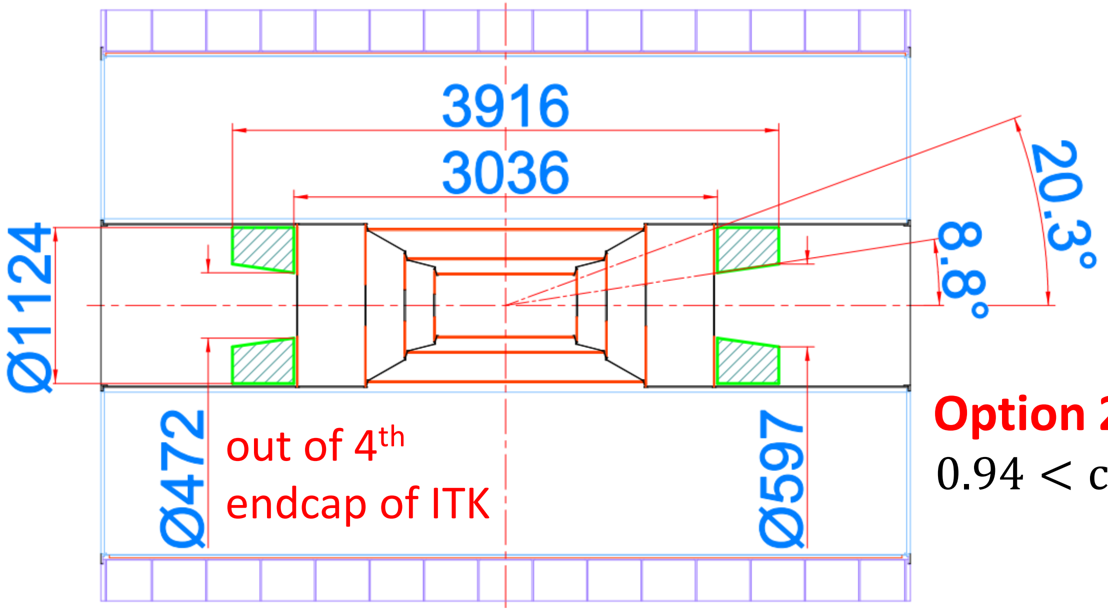


By Ma Xiaotian

Baseline PID: dE (dN) /dx + ToF.
Significant efficiency drop in the forward region for Kaons with momentum over 3 GeV.



Option 1:
$0.88 < \cos\theta < 0.99$



Option 2:
$0.94 < \cos\theta < 0.99$

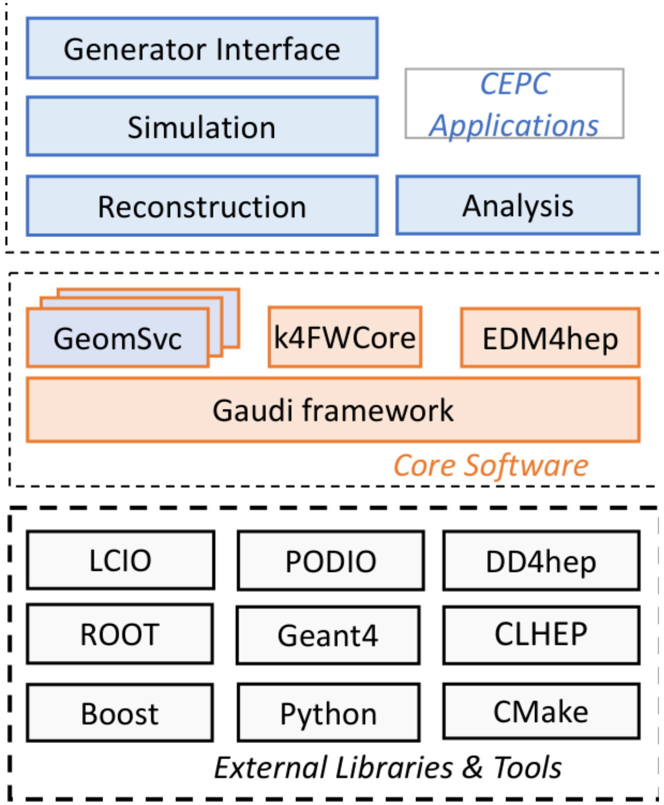
By Wang Jian

Software

CEPCSW

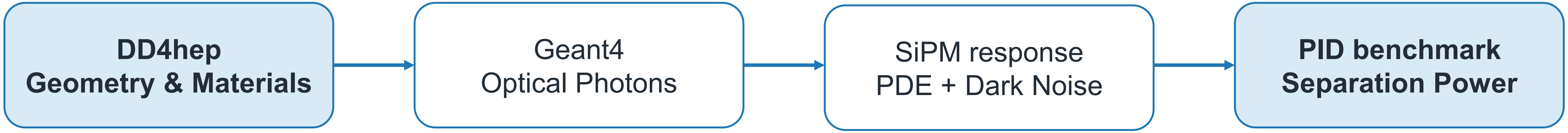
A CEPC offline software prototype based on the Key4hep common software stack.

DD4hep detector geometry, materials and optical surfaces
Geant4 tracking and optical photon transport
EDM4hep common event data model for the full chain

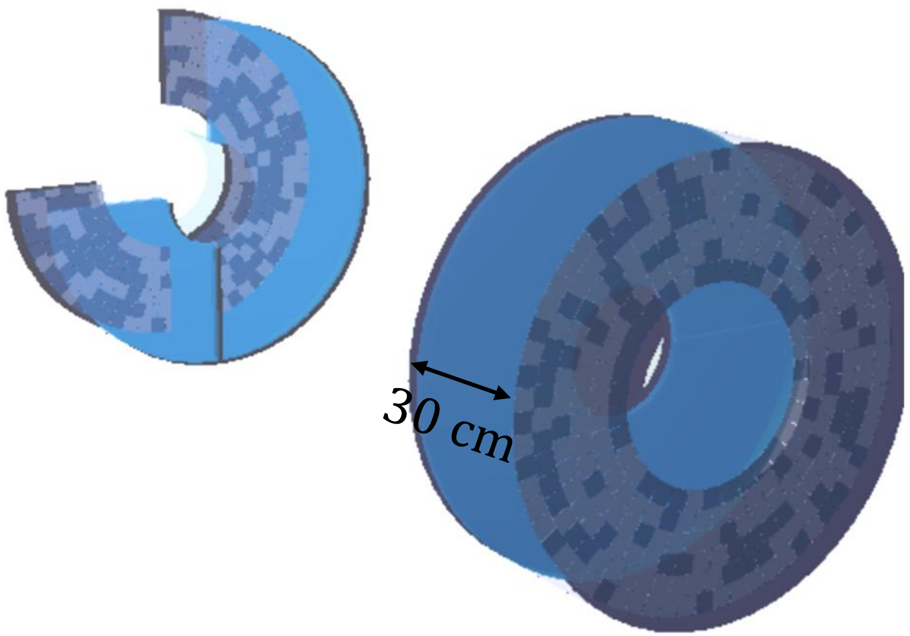


Optical process

Produced by the **Cherenkov**
Transported with wavelength, time and polarization
Affected by **absorption**, **boundary** processes and **Rayleigh** scattering
Scintillation, WLS/WLS2 and Mie scattering are disabled



Overall Geometry & Materials



RICH components:

1. Aerogel: 3 layers of SiO_2 ($\rho \approx \rho_{air}, n \approx 1.008$)

$r = 16.9\sim56.2$ cm

$z = 106.6$ cm~112.6 cm

2. Photon Detector (SiPM & PCB + electronics)

SiPM: G4_Si, PCB + electronics: Pb, Cu, C, O…

$r = 24.1\sim56.2$ cm

3. Carbon Fiber Shell $t = 0.2$ mm

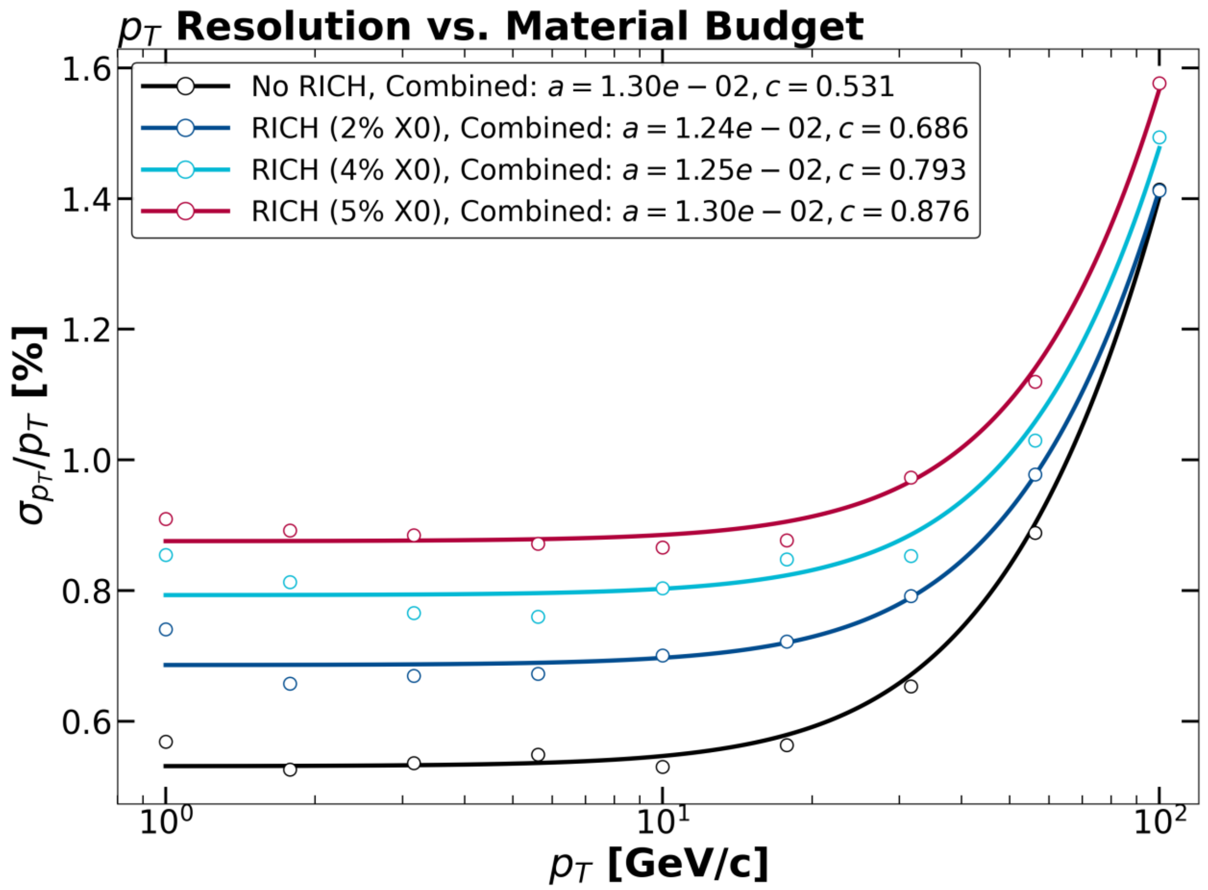
4. Reflector film $t = 0.08$ mm

5. Mechanical Support

6. Cooling

	Material	Thickness	Radiation Length	Material Budget
Radiator	Aerogel (SiO_2)	6 cm	> 700 cm	< 1% X0
SiPM	Si	1 mm	9.36 cm	1.06% X0
PCB	PCB	1 mm	19.4 cm	0.51% X0
Shell	Carbon Fiber	0.4 mm	40.0 cm	0.10% X0
Others	Cu, Ti, …	/	/	1~3% X0

Impact on p_T resolution



Incident angle $\theta = 15°, \mu^-$

$$\frac{\sigma_{p_T}}{p_T} = a p_T \oplus \frac{b}{\beta\sqrt{\sin\theta}} \approx a p_T \oplus c$$

- a: Spatial resolution term
- b / c: Multiple Coulomb scattering term

Material Budget	Spatial resolution term a	Multiple Coulomb scattering term c
No RICH	1.30e-2	0.531
2% X0	1.24e-2	0.686
3% X0	1.25e-2	0.793
5% X0	1.30e-2	0.876

Layout of Aerogel

$$N_\sigma \approx \frac{|m_1^2 - m_2^2|}{2p^2\sigma[\theta_c(tot)]\sqrt{n^2-1}}$$

$$\sigma[\theta_c(tot)] = \frac{\sigma[\theta_c(1pe)]}{\sqrt{N_{p.e.}}}$$

Aerogel with $n \approx 1.008$ as radiator

$$\sigma^2[\theta_c(1pe)] = \sigma^2_{SiPM} + \sigma^2_{emission} + \sigma^2_{track} + \sigma^2_{chromatic} + \sigma^2_{rec}$$

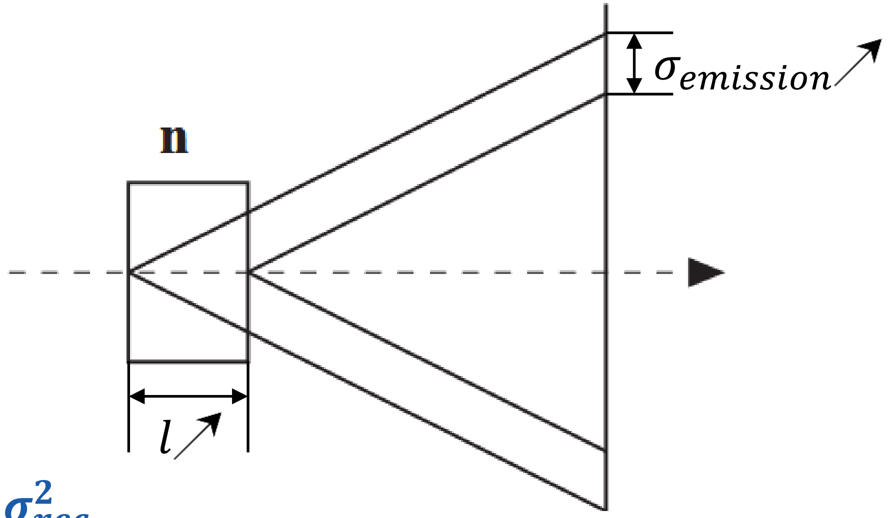
$$N_{p.e.} \propto \sin^2\theta_c \cdot l \cdot \Delta E \cdot \varepsilon$$

$$N_\sigma \nearrow \leftarrow N_{p.e.} \nearrow \leftarrow l \nearrow \rightarrow \sigma_{emission} \nearrow \rightarrow N_\sigma \searrow$$

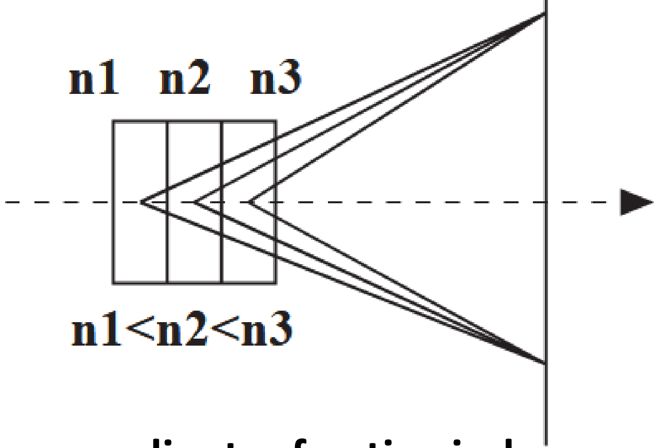
2cm per layer to achieve best $\sigma[\theta_c(tot)]$ for aerogel at Belle II

Trade off

Gradient refractive index can reduce emission point uncertainty while increasing thickness



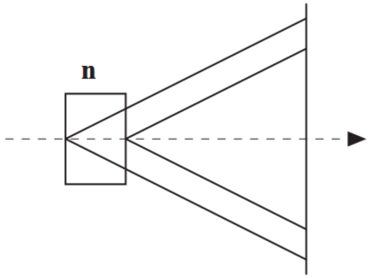
Emission point uncertainty



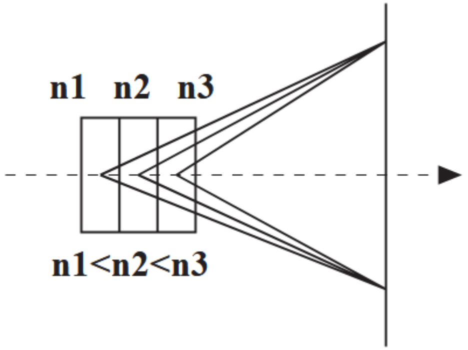
gradient refractive index

$n_1 = 1.007, n_2 = 1.008, n_3 = 1.009$

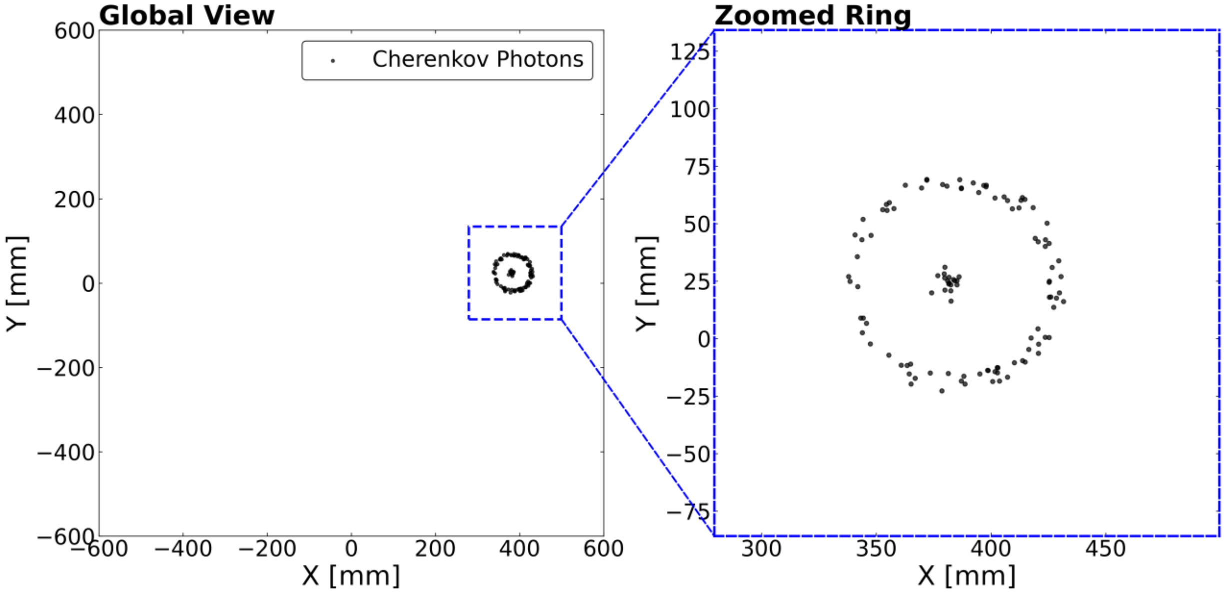
Gradient Refractive Index

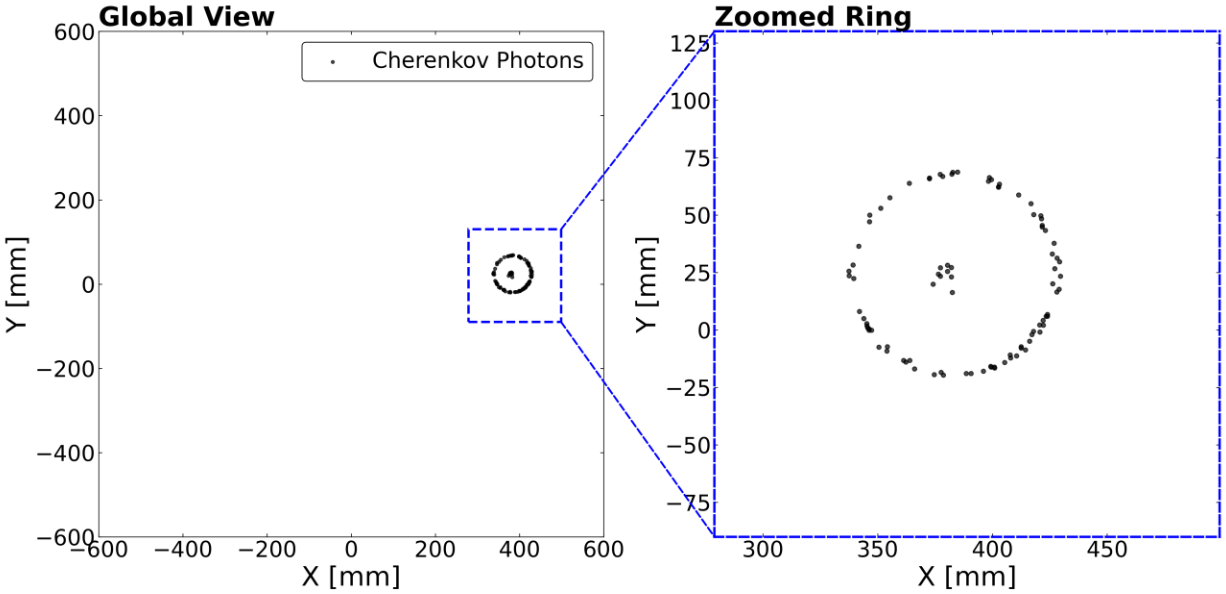


$n = 1.008$



$n = 1.007, 1.008, 1.009$





Cherenkov ring is more "focused" after adopting gradient refractive index

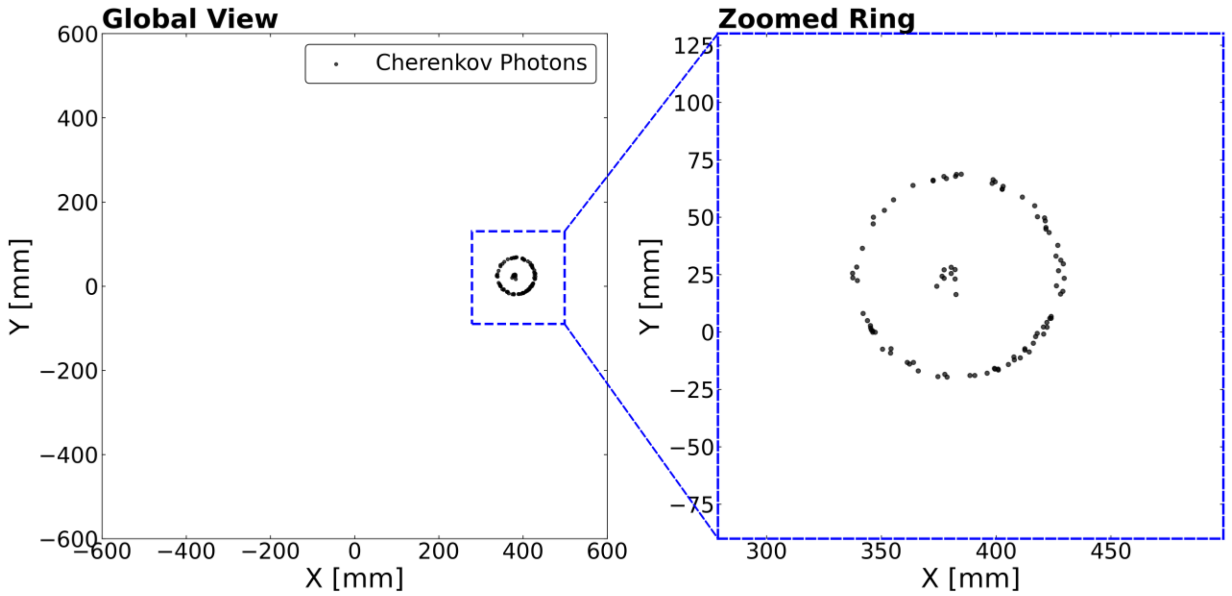
$\pi^-, p = 10\ \text{GeV}, \theta = 15°$ Rayleigh Off
SiPM Efficiency is 100% before digitization

Rayleigh Scattering

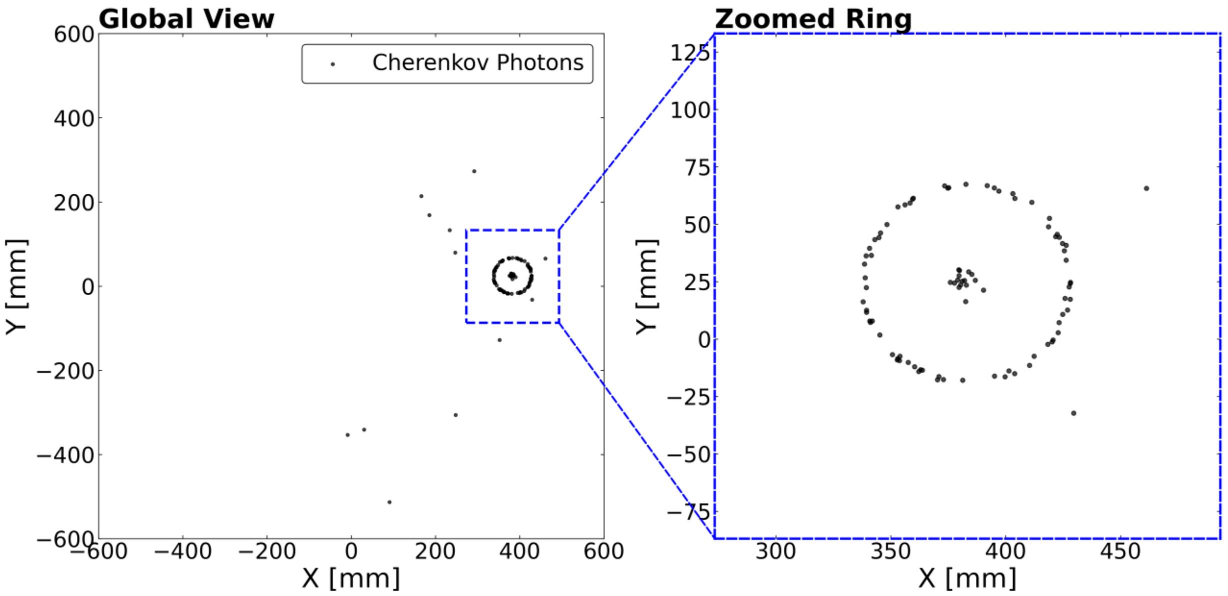
Photons elastically interact with microscopic refractive-index fluctuations, **changing direction while conserving energy**

Scattering probability $P = 1 - e^{-\Delta s/L_{sc}}$,

$$L_{sc} = \left(\frac{\lambda}{400\ \mathrm{nm}}\right)^4 \times 4.6\ \mathrm{cm}$$



Rayleigh Off



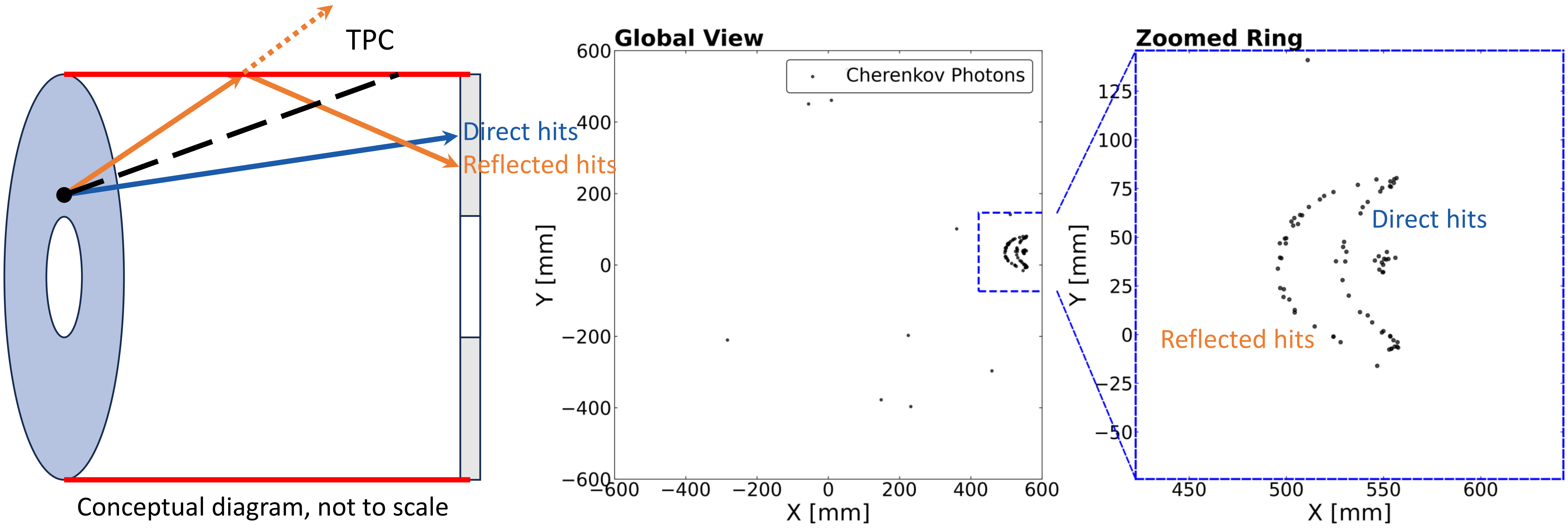
Rayleigh On

Realistic physical response, more background hits

$\pi^-, p = 10\ \mathrm{GeV}, \theta = 15^\circ$ Gradient-n

SiPM Efficiency is 100% before digitization

Reflection



More complex topology after reflected by ESR

$\pi^{-}, p = 10\ \mathrm{GeV}, \theta = 22°$ Gradient-n

SiPM Efficiency is 100% before digitization

SiPM Granularity

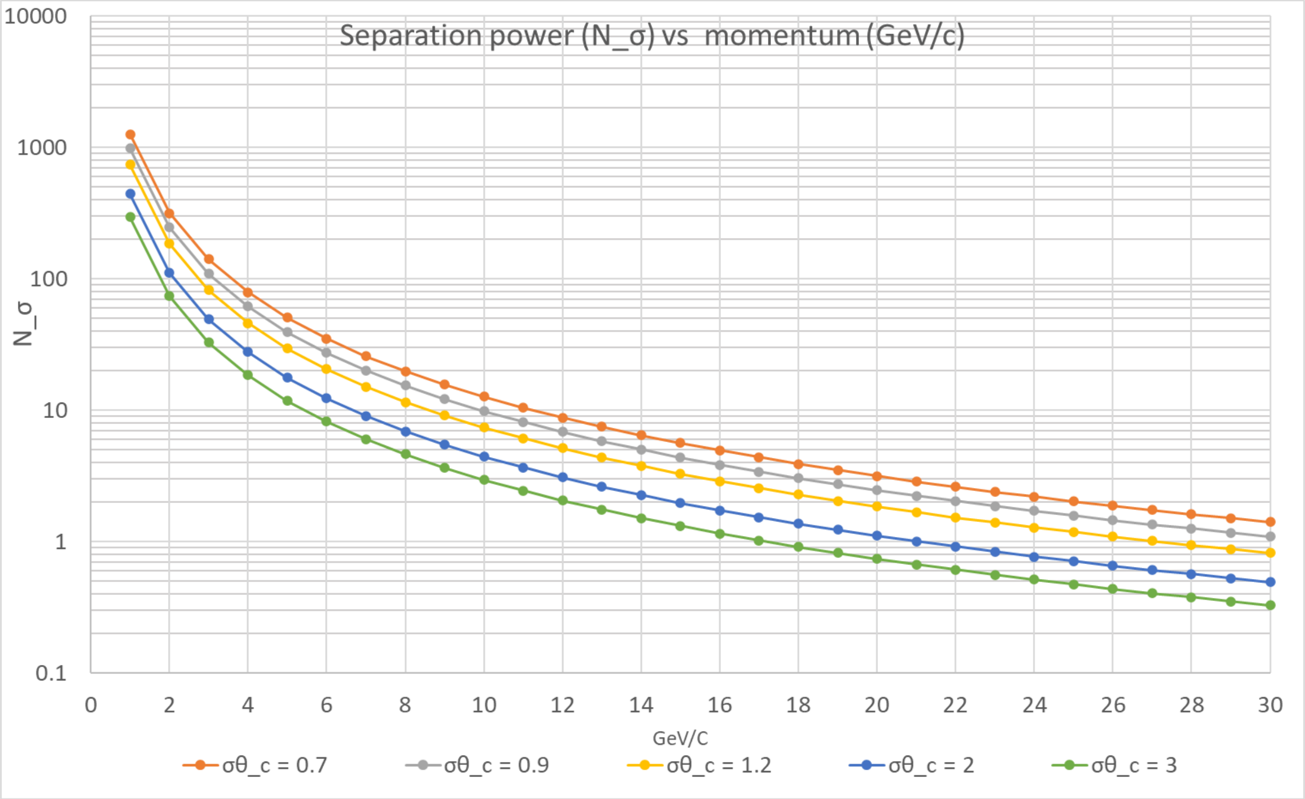
$$N_\sigma \approx \frac{|m_1^2 - m_2^2|}{2p^2\sigma[\theta_c(tot)]\sqrt{n^2-1}}$$

To achieve 3σ K/π separation at 20 GeV, a Cherenkov angle resolution better than **0.7 mrad** is needed

$$\sigma[\theta_c(tot)] = \frac{1}{\sqrt{N_{p.e.}}}\sqrt{\sigma_{SiPM}^2 + \sigma_{emission}^2 + \sigma_{rec}^2}$$

$$\sigma_{SiPM} = \frac{\Delta_{channel}}{L\sqrt{12}}$$

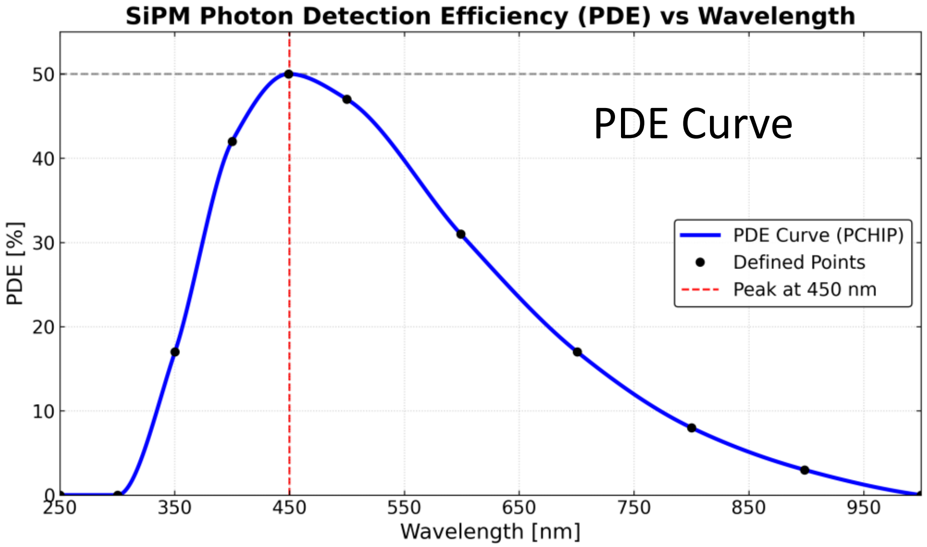
Spatial resolution of SiPM $\leq$ 1 mm



By Qin Zhonghua

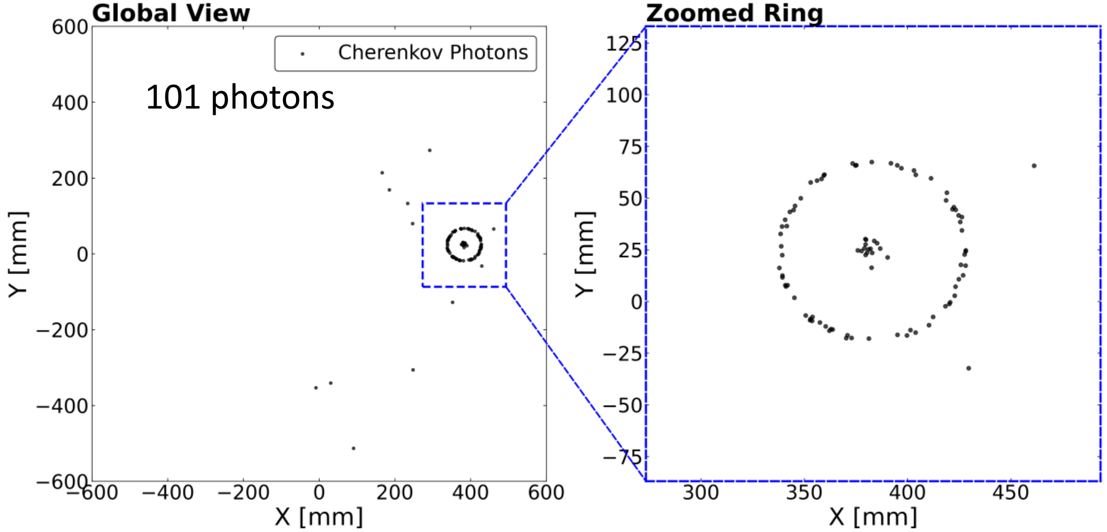
Photon Detection Efficiency

http://share.hamamatsu.com.cn/specialDetail/2018.html

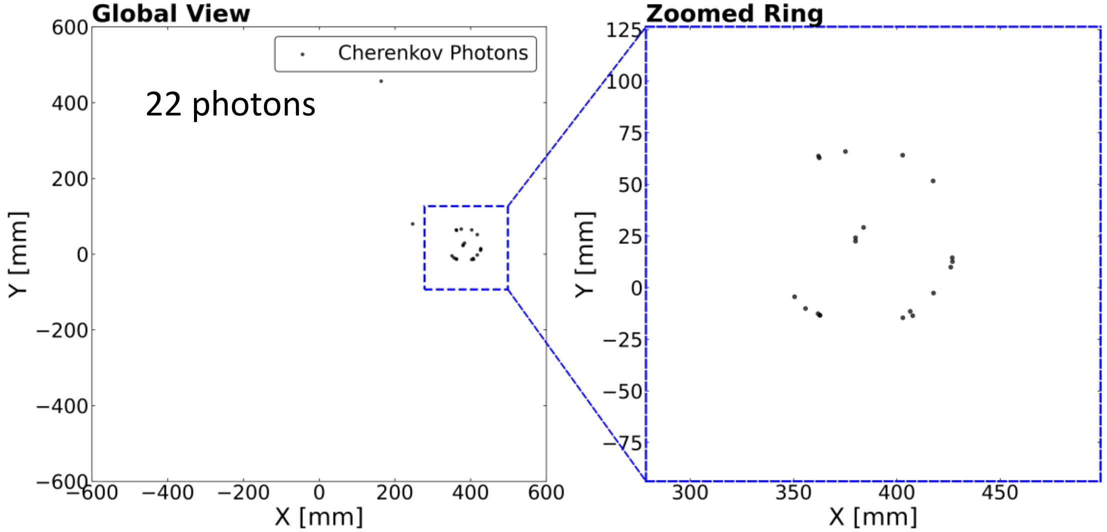


$\pi^-, p = 10$ GeV$, \theta = 15°$ Rayleigh On

Effective PDE Modeling via optical surface Transmittance



PDE



Peak sensitivity wavelength $\lambda_p = 450\ \mathrm{nm}$

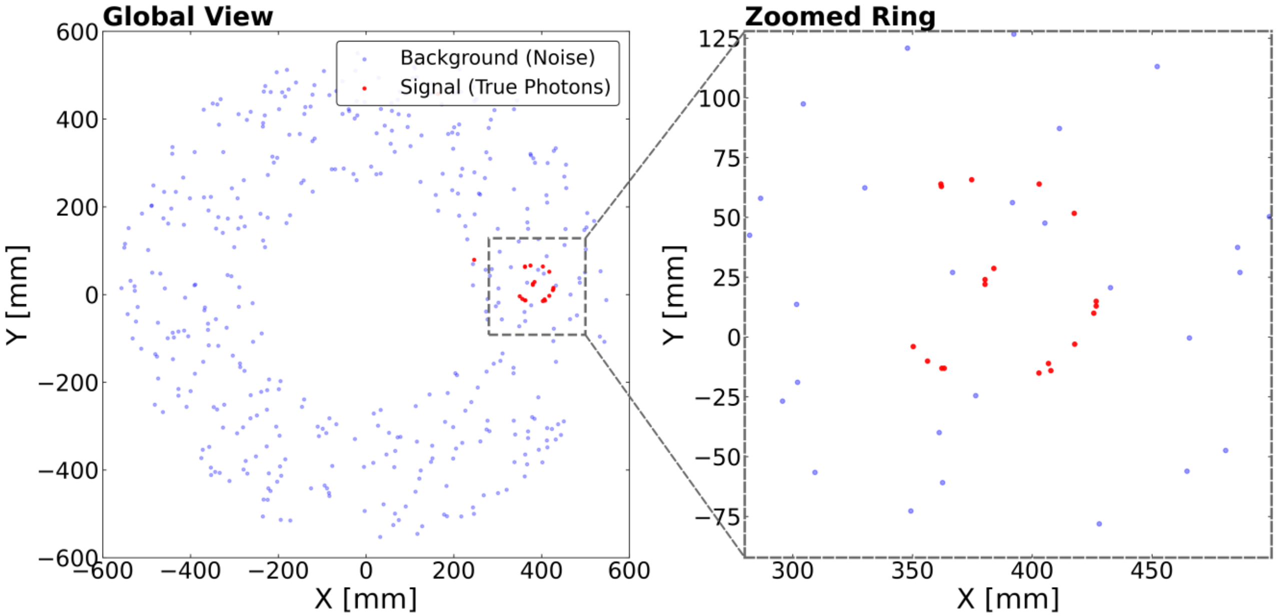
Photon detection efficiency PDE $(\lambda = \lambda_p)$ $\varepsilon_p = 50\%$

Dark Noise

http://share.hamamatsu.com.cn/specialDetail/2018.html

Type no.	Size	Typ. Dark count (kHz / tile)	Typ. Dark count (kHz / mm^2)
S13360-1375	1.3 × 1.3 mm^2	90	53.25
S13360-3075	3.0 × 3.0 mm^2	500	55.56
S13360-6075	6.0 × 6.0 mm^2	2000	55.56

Dark count rate is independent from SiPM size



Area 0.808 m^2

Time Window = 5 ns

Dark Rate = 100 kHz / mm^2

$\pi^-, p = 10\text{ GeV}, \theta = 15°$ Rayleigh On

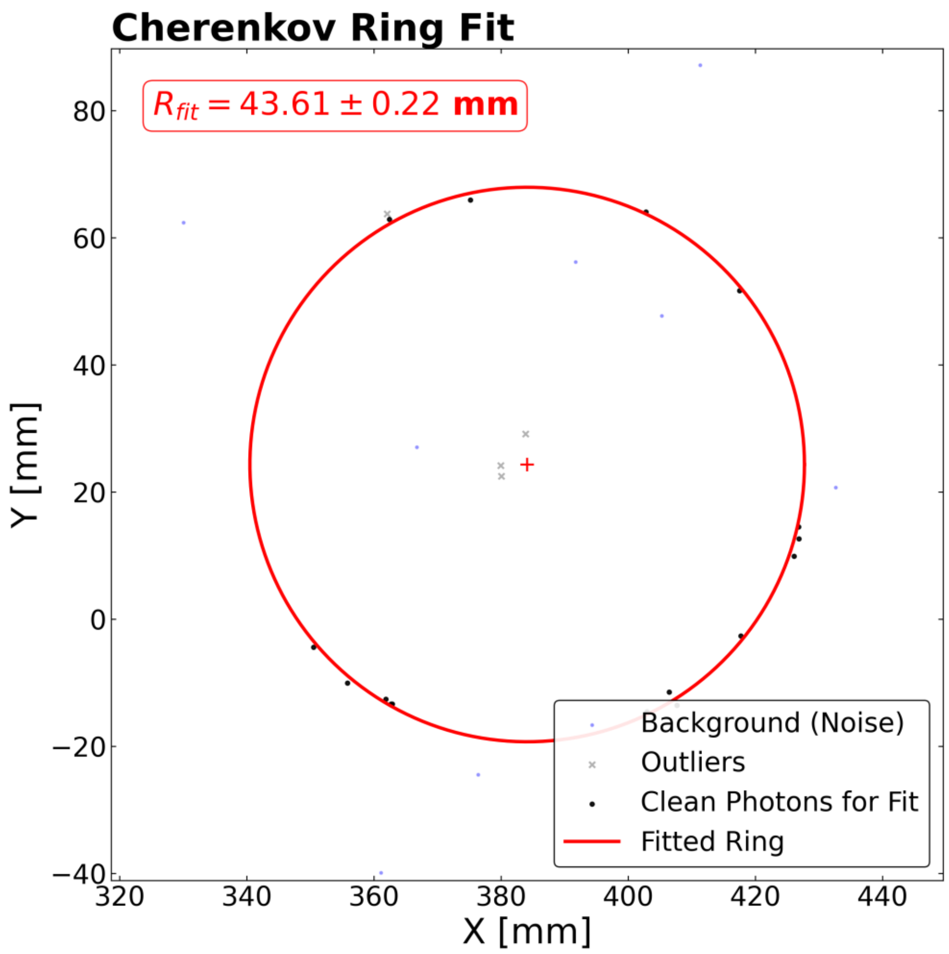
Simplified Reconstruction

Realistic detector response with:

- Focusing aerogel
- Rayleigh scattering
- Absorption
- Boundary (refraction & reflection)
- SiPM PDE
- Dark Noise

Assuming photon hits and dark noise can be separated completely

$$\sigma[\theta_c(tot)] = \frac{1}{\sqrt{N_{p.e.}}}\sqrt{\sigma_{SiPM}^2 + \sigma_{emission}^2 + \sigma_{rec}^2}$$

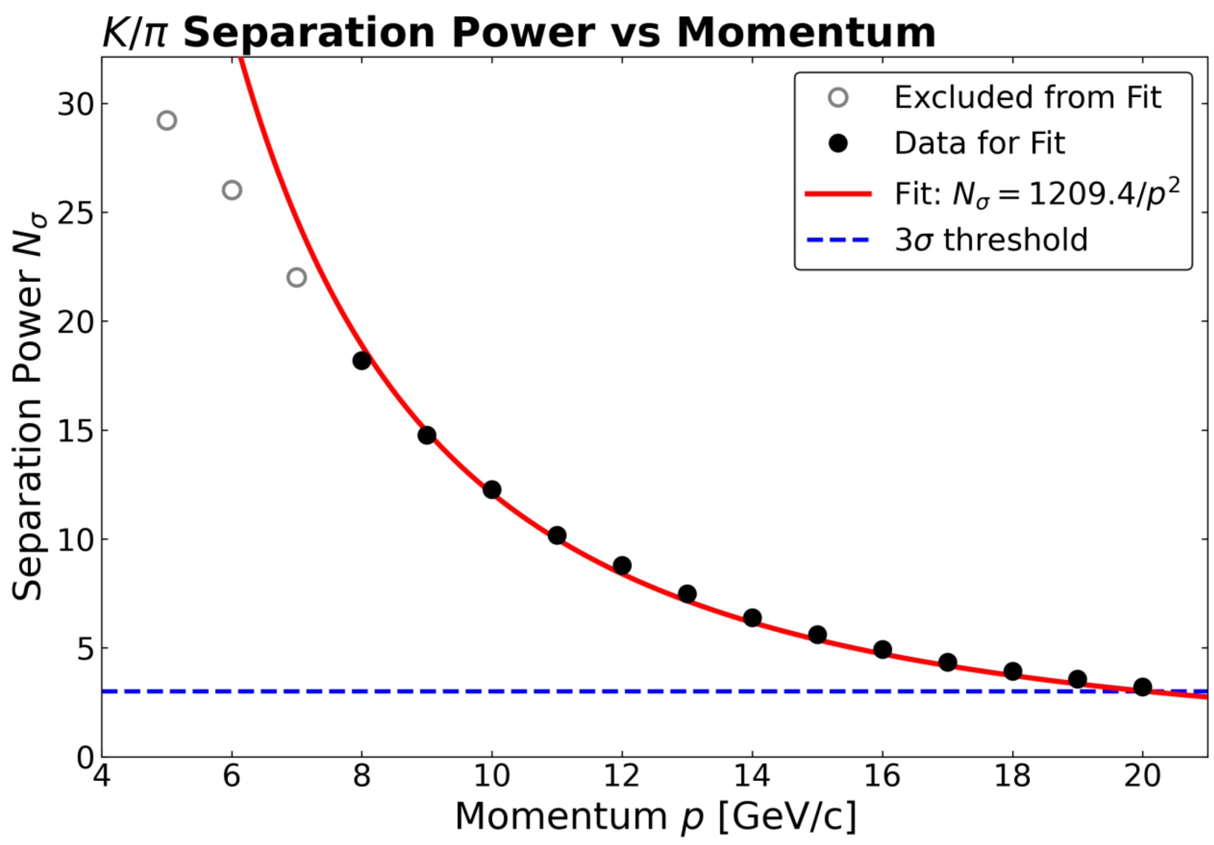


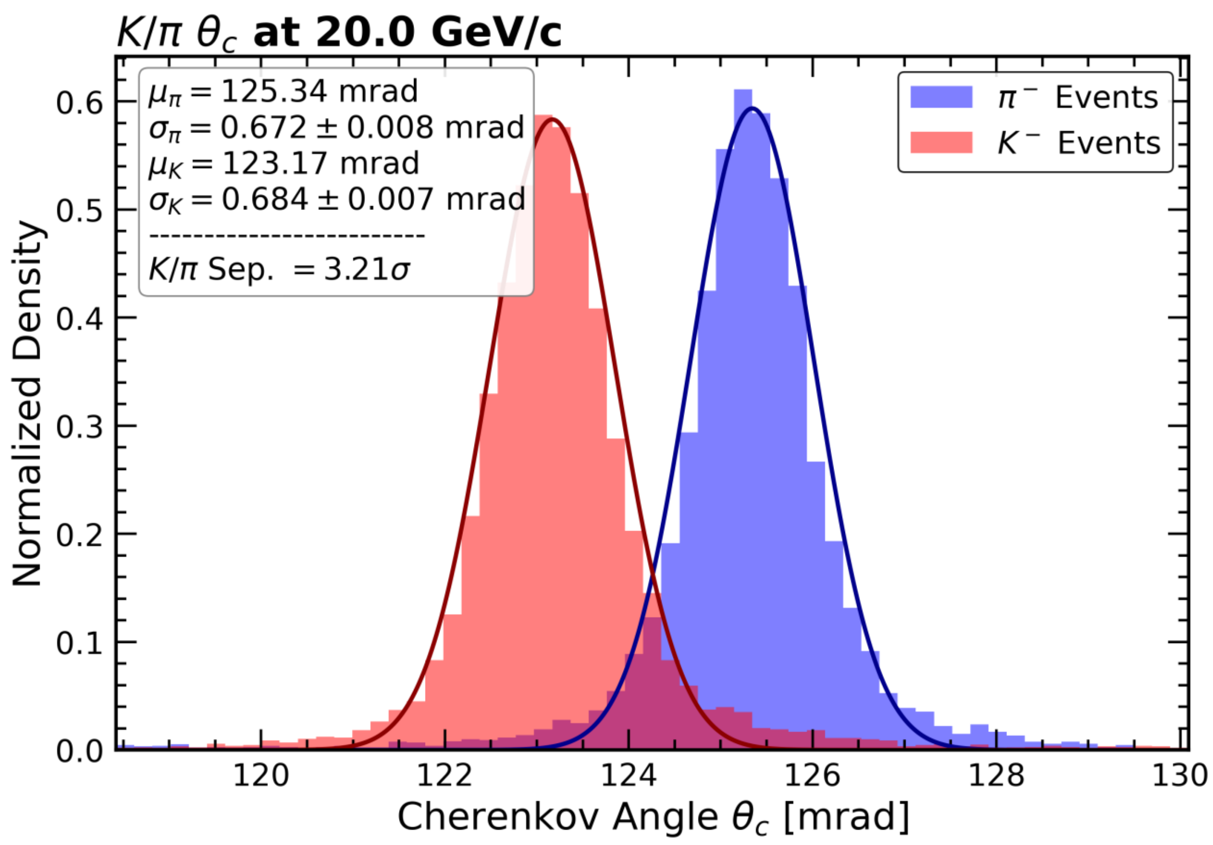
Step 1: Pre-selection via Circle Fit

Step 2: Single-Photon θ_C Calculation

Step 3: Event-Level Aggregation

Performance Evaluation





$$N_\sigma = 3.21 > 3 \text{ @ } 20 \text{ GeV}$$

$\pi^- \,\&\, K^-, p = 10 \text{ GeV}, \theta = 15°$

θ is fixed for full ring without reflection

Summary

Progress: simulation chain established

Geometry & material | Optical response | SiPM digitization | PID potential

Outlook:

- Focusing aerogel: thicker radiator increases photon yield; gradient n suppresses emission-point uncertainty
- Optical processes: Cherenkov, boundary (refraction / reflection), absorption and Rayleigh scattering included
- 1 mm spatial resolution SiPM, parameters from Hamamatsu (PDE, DCR and time window), results acceptable
- K/π separation ~3.2σ @ 20 GeV achieved, Detector configuration proven feasible

Next step: evaluation + reconstruction

01 **Dark-noise impact assessment** — quantify PID degradation versus dark counts

02 **Reconstruction algorithm development** — Maximum Likelihood + Hough Transform for noisy and reflected rings

03 **Full-chain PID evaluation** — performance after realistic response and reconstruction

Thank you!