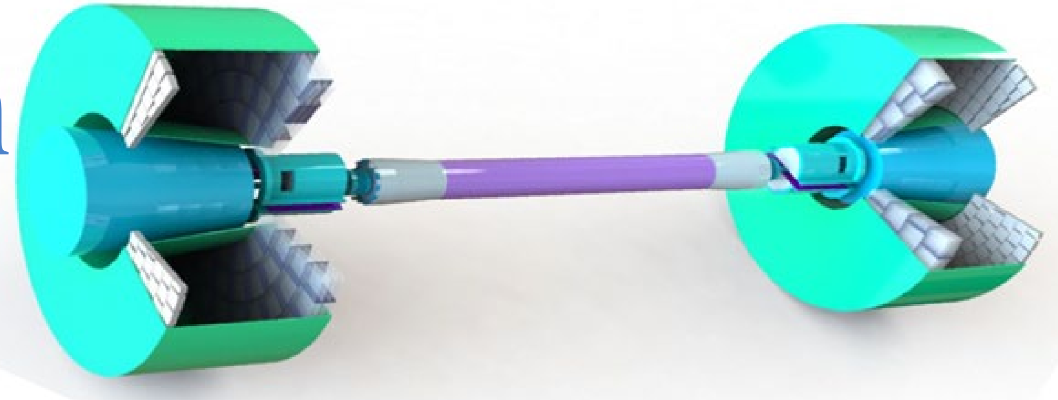
Status of Simulation of Endcap RICH at CEPC



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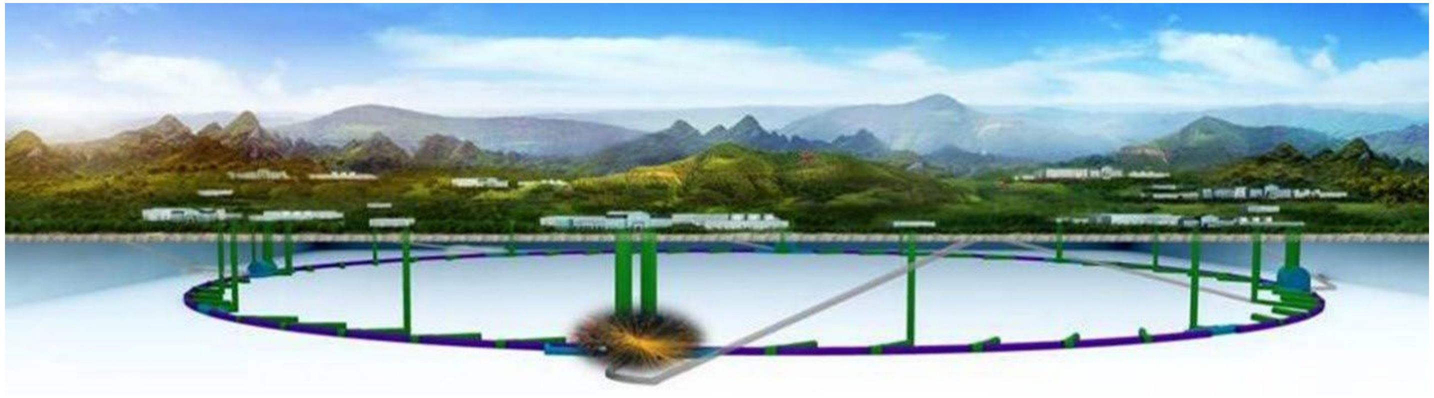
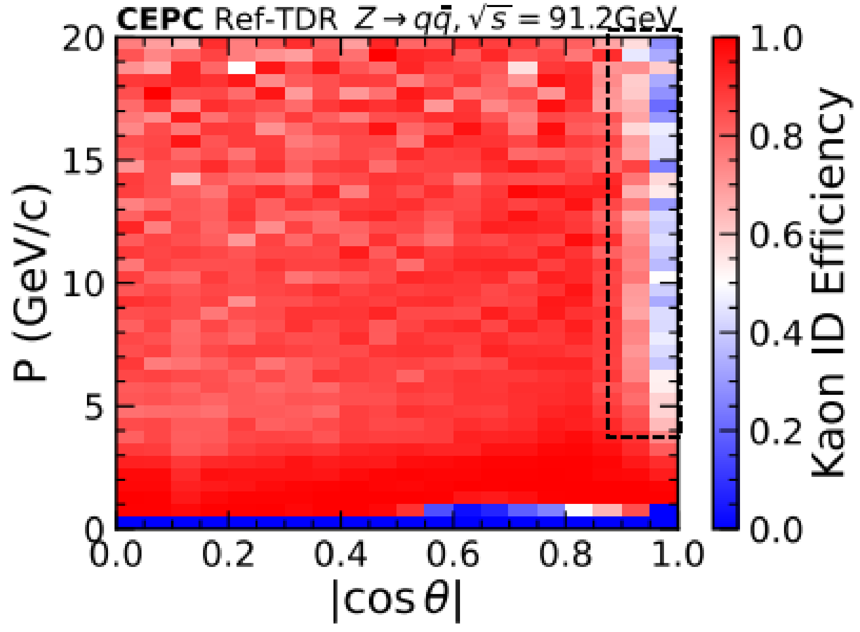
Contents

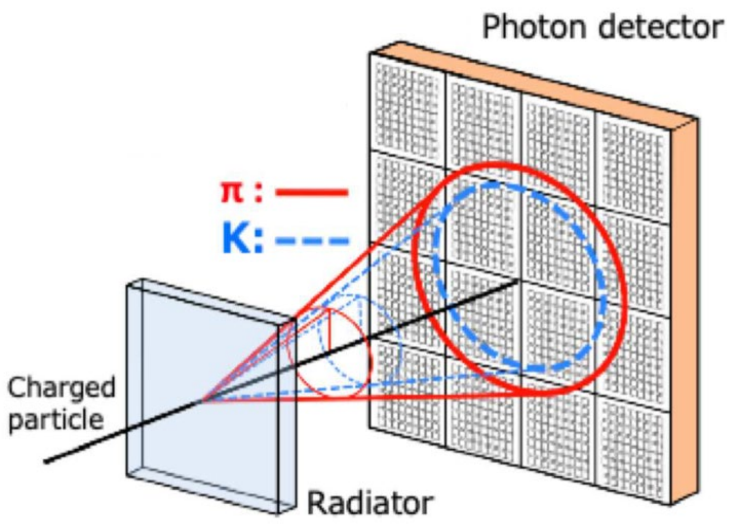
Introduction



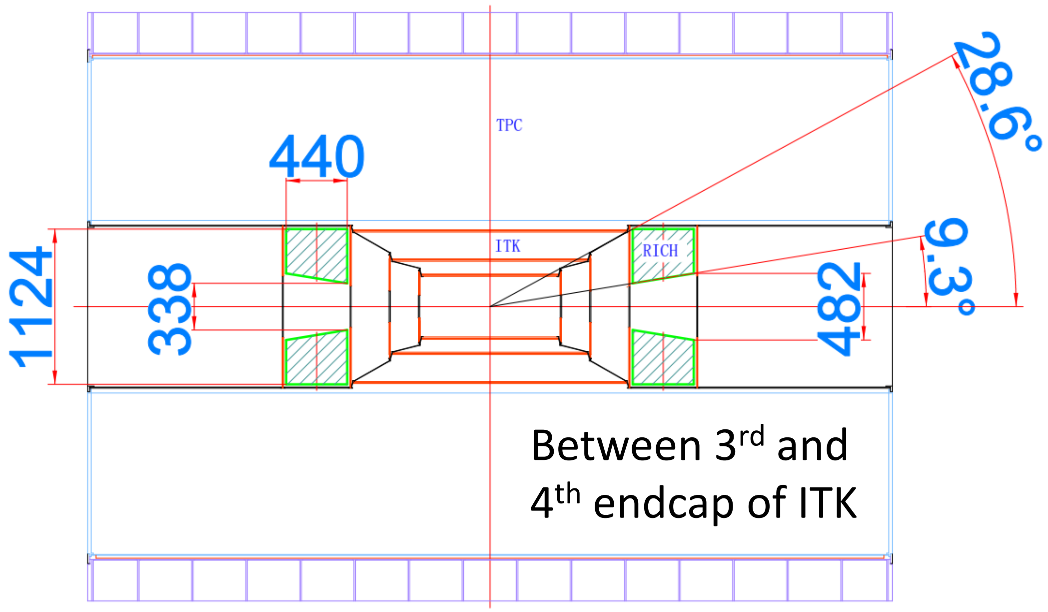
- **The CEPC Project:**
  - A proposed Circular Electron Positron Collider acting as a Higgs factory.
  - Provides an extremely clean environment for precision measurements.
- **Core Physics Objectives:**
  - Unprecedented precision in Higgs, Electroweak, and Top quark properties.
  - Searching for signals 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**.



- Baseline PID: dE/dx + ToF.
- Significant efficiency drop in the forward region ($|\cos\theta| > 0.9$) for Kaons with momentum over 3 GeV.
- Advantages of Cherenkov detector:
  - High efficiency for identifying charged particles.
  - Fill the performance gap left by dE/dx and ToF to meet Flavor Physics requirement.



Conceptual diagram



↑ Proposed RICH, location1

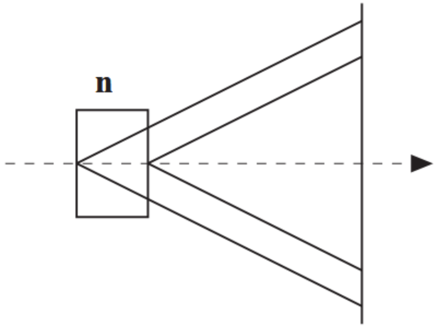
Optimization of K/π Separation Power

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

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

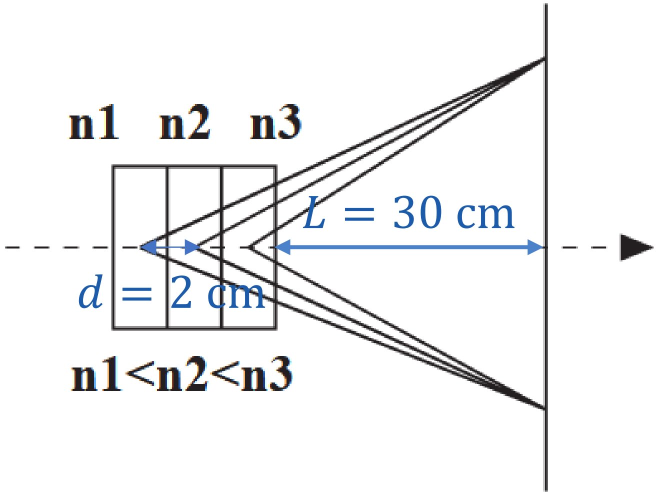
Some strategies for improvement:

- Lower refractive index n.
  - Target $n \approx 1.008$
  - **Aerogel** as radiator
- Increase photon yield.
  - $N_{p.e.} \propto \sin^2\theta_c \cdot l \cdot \Delta E$
  - Requires **thicker radiator**
- Minimize single-photon error.
  - $\sigma^2[\theta_c(1pe)] = \sigma^2_{spatial} + \sigma^2_{thick} + \sigma^2_{track} + \sigma^2_{chromatic}$
  - Emission point error $\sigma_{thick} \propto d$
  - Requires **thinner radiator**



Emission point error

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



Reduce emission point error with **gradient refractive index**

Under approximation:

$$n_{i+1} - n_i = \frac{d}{n_i L}\left[n_i^2 - 1 - \frac{m^2}{p^2}\right]$$

Let $n_2 = 1.008$, then we get:

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

which will be used in simulation.

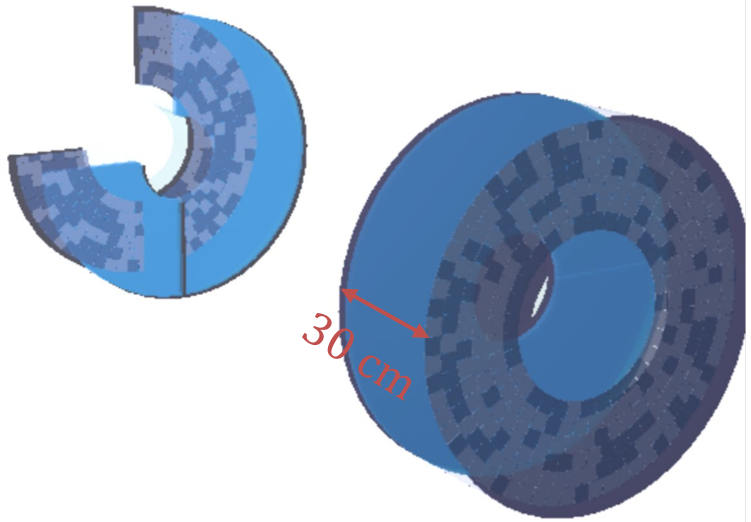
Geometry & Materials

Detector geometry implemented via dd4hep in CEPCSW.
The RICH detector consists of the following components:

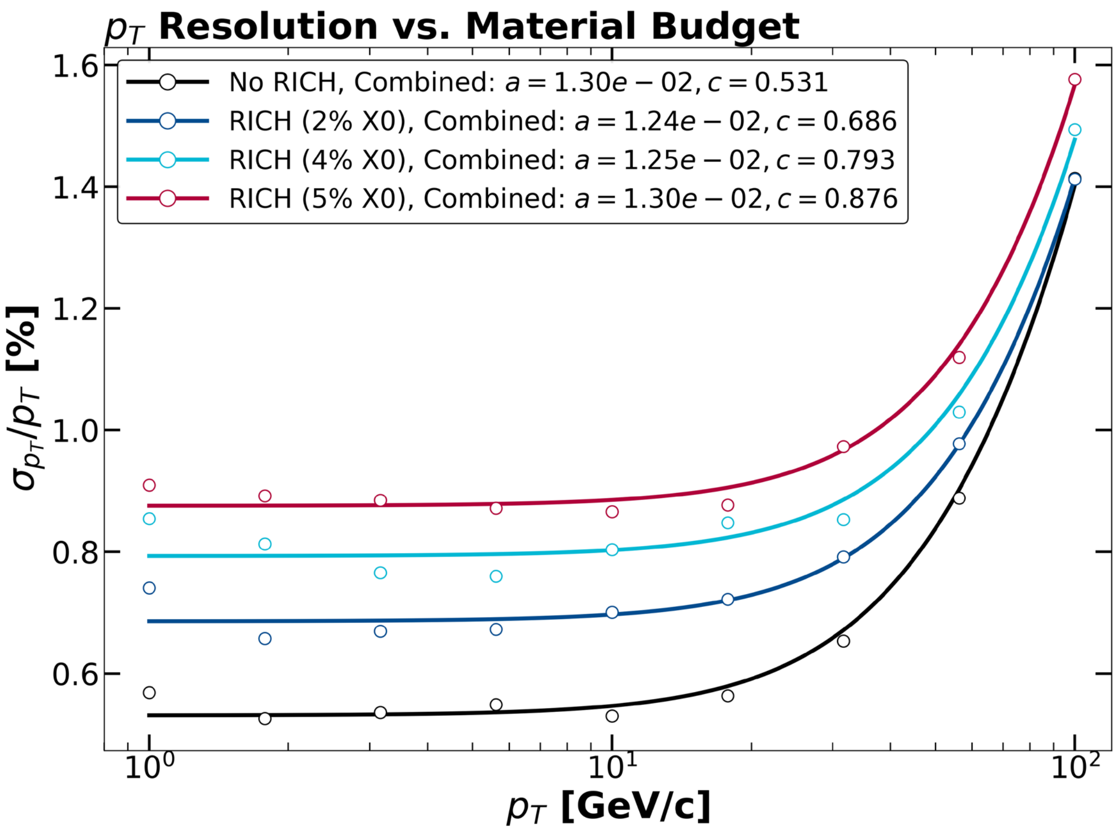
1. Aerogel: 3 layers of SiO_2 $(\rho \approx \rho_{air}, n \approx 1.008)$
$r = 16.9\sim56.2$ cm, $z = 106.6$ cm~112.6 cm

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. Enhanced Specular Reflector (ESR) $t = 0.08$ mm
5. Mechanical Support
6. Cooling



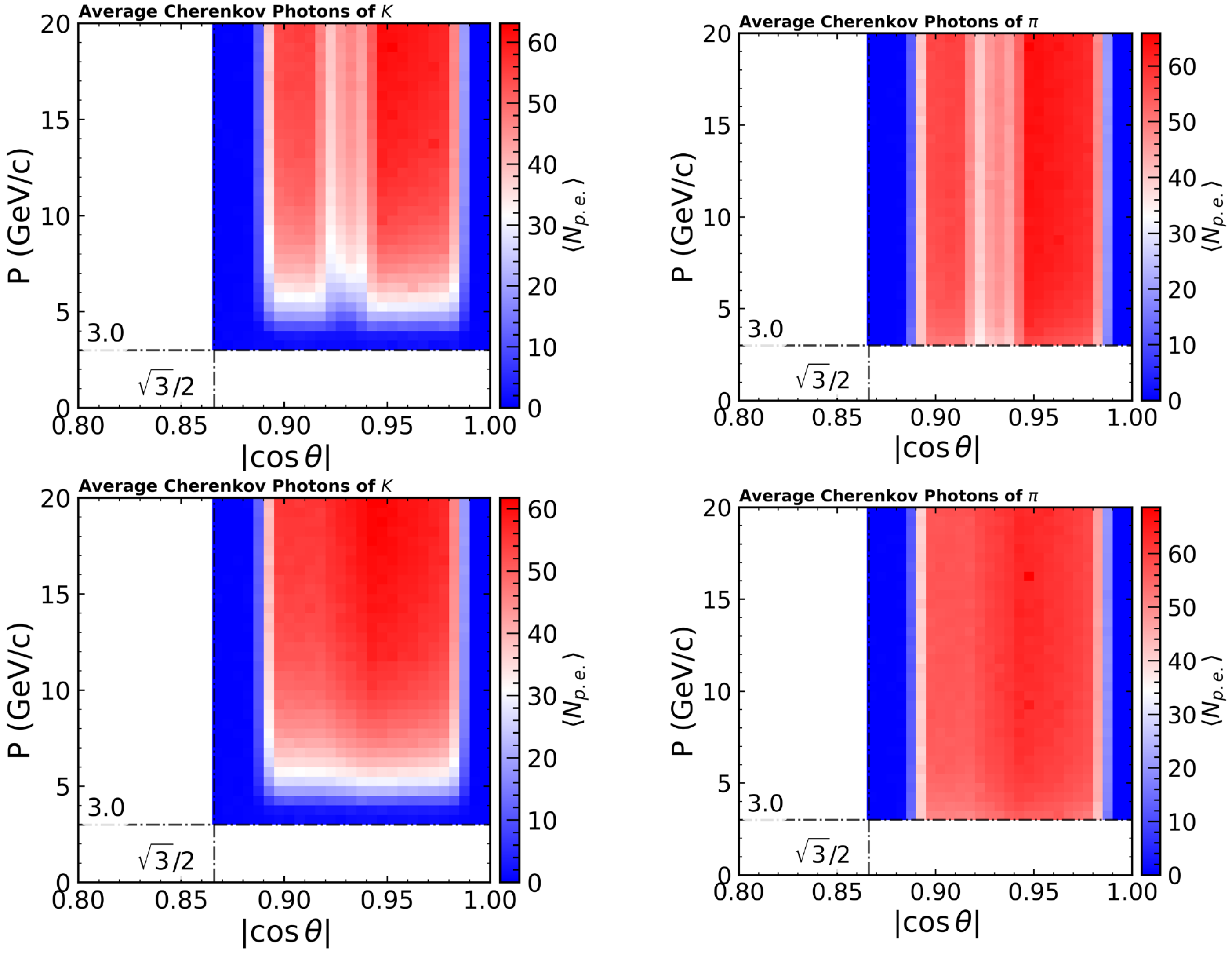
geoDisplay at CEPCSW, box clipped
30 cm from aerogel to SiPM
5 cm × 5 cm modules of PD



- Transverse momentum resolution of tracker
- Incident angle $\theta = 15°$
- $\frac{\sigma_{p_T}}{p_T} = ap_T \oplus \frac{b}{\beta\sqrt{\sin\theta}} \approx ap_T \oplus c$
- a: Spatial resolution term
- b: Multiple Coulomb scattering term

	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	4 mm	40 cm	0.10% X0
Others	Cu, Ti, …	/	/	1~3% X0

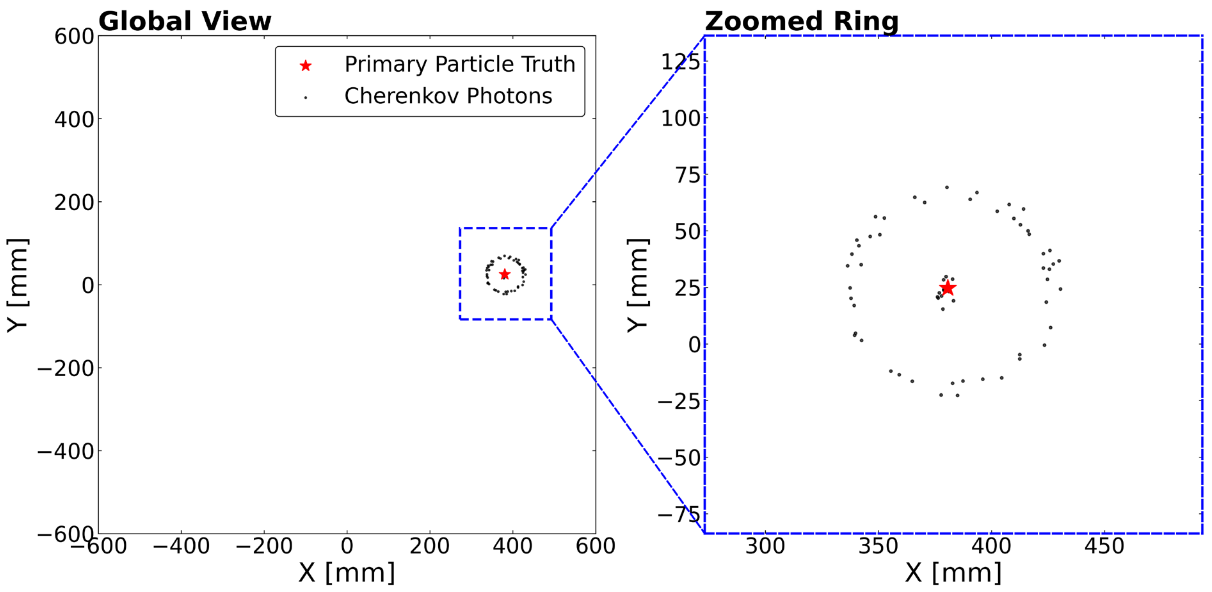
Monte-Carlo Simulation



- Average Cherenkov photons detected by SiPM
- **All MC hits are recorded before digitization**
- Yield drops at specific polar angles due to module gaps

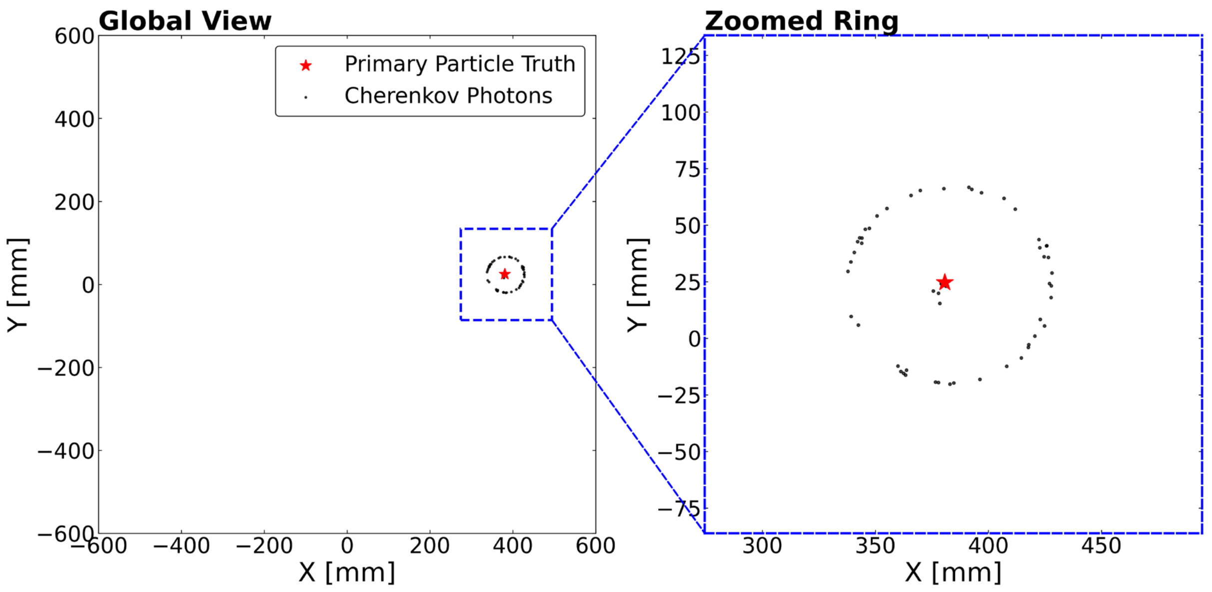
- Module size changed to 1 cm × 1 cm
- Drops eliminated
- Technology & cost

Simulated Cherenkov Ring images ($\pi^-, p = 10$ GeV, $\theta = 15°$) OpRayleigh False



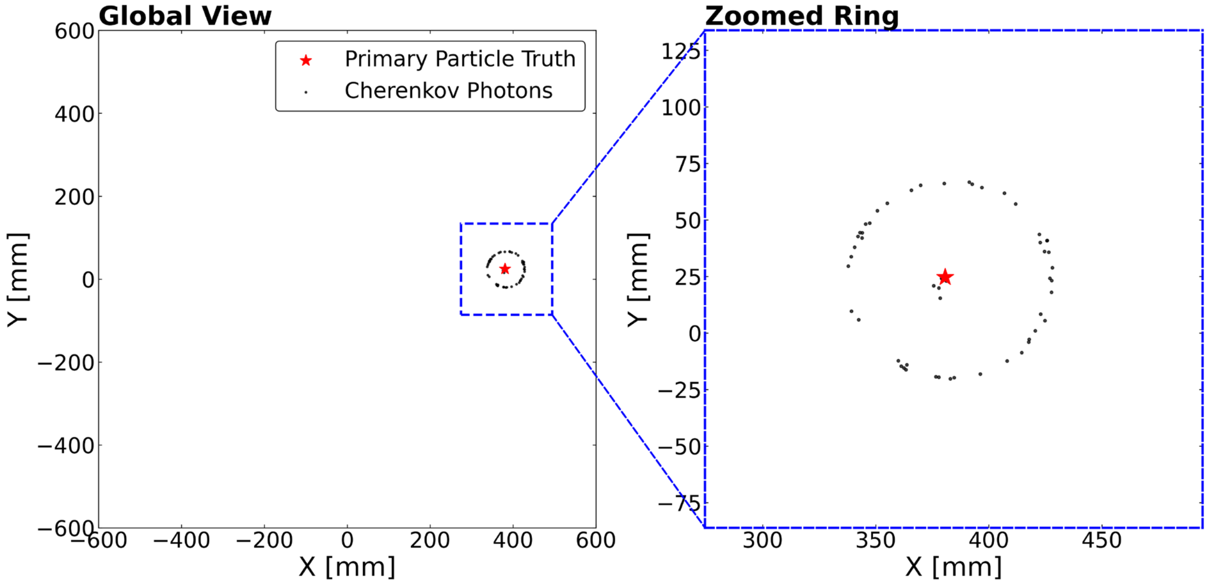
$n = 1.008$

All MC hits are recorded before digitization



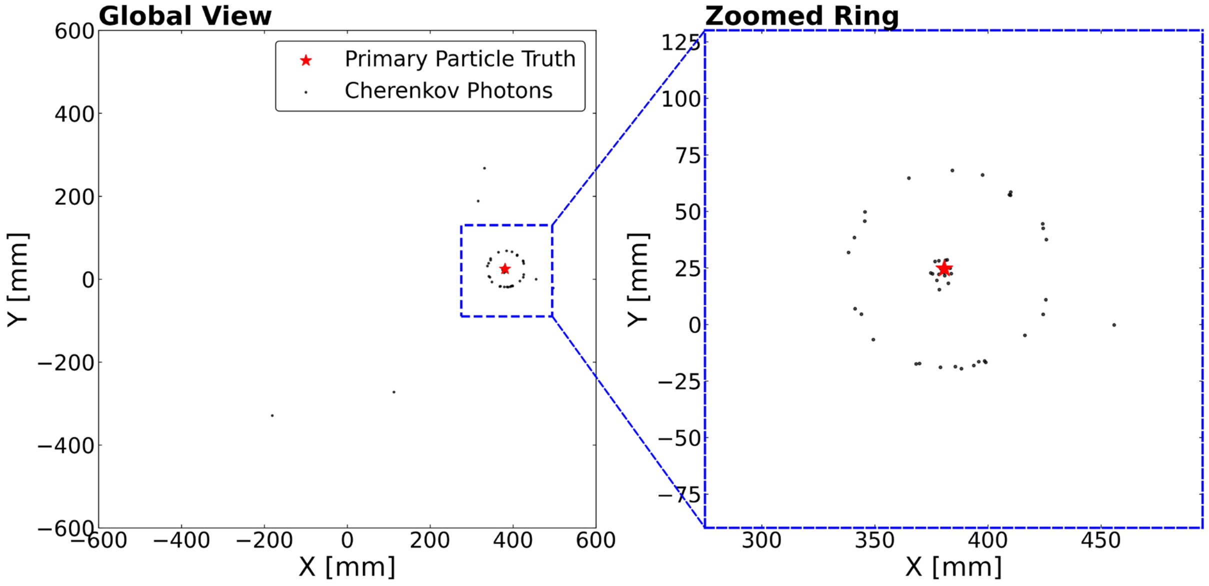
$n = 1.007, 1.008, 1.009$

Simulated Cherenkov Ring images ($\pi^-, p = 10$ GeV, $\theta = 15°$) Gradient n



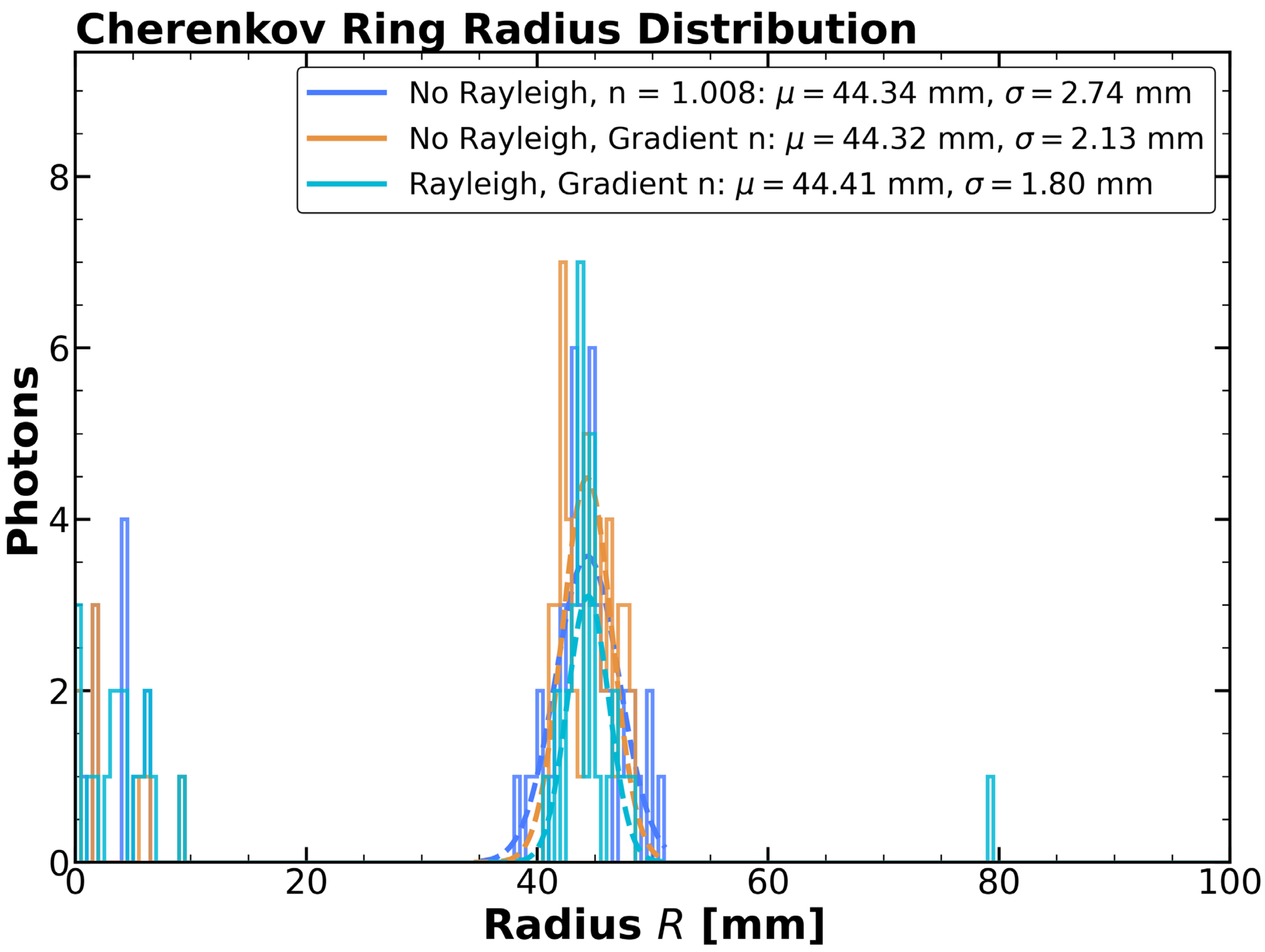
OpRayleigh False

All MC hits are recorded before digitization



OpRayleigh True
$L_{sc} \propto \lambda^4$

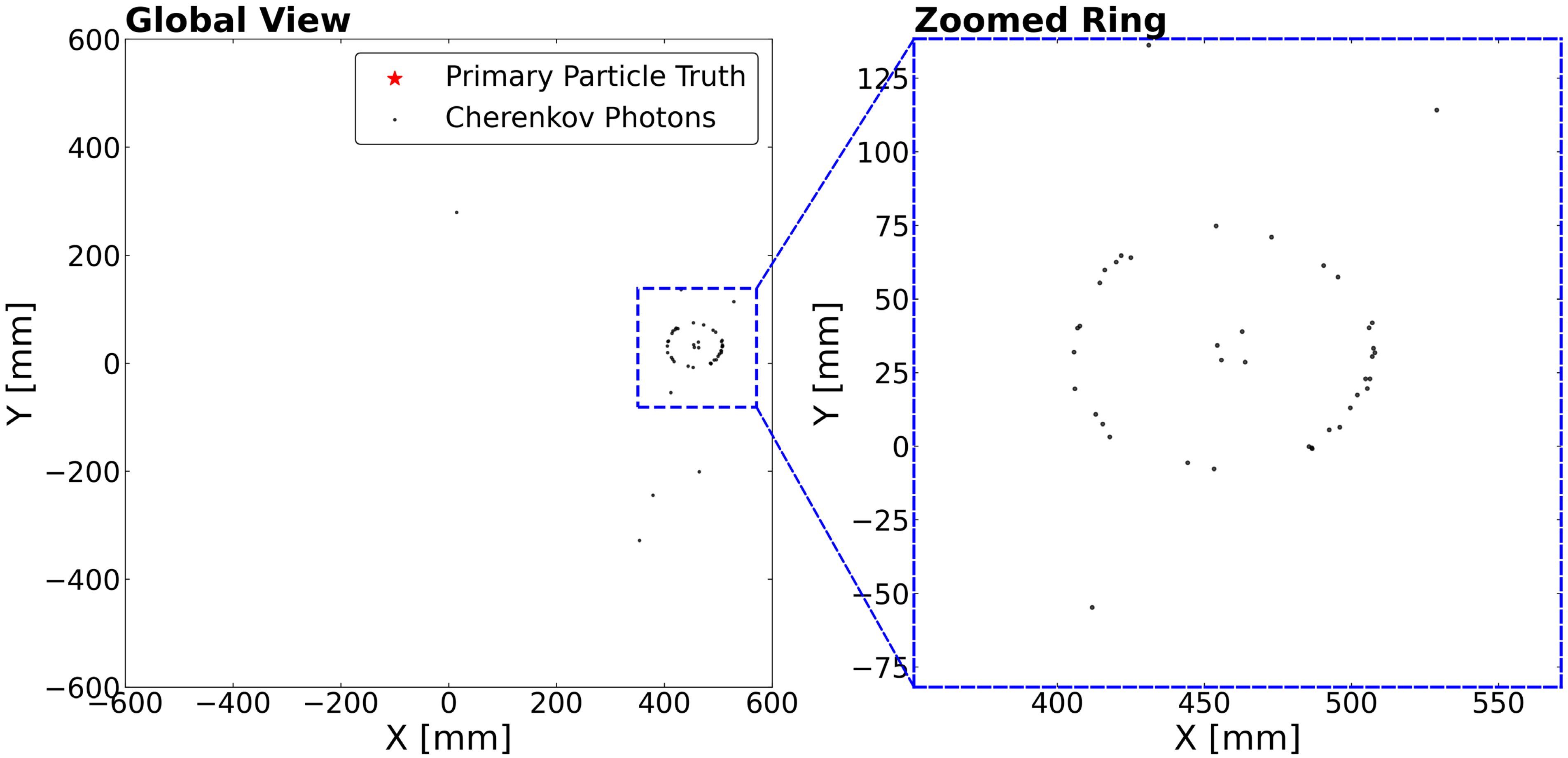
Cherenkov Ring "Radius" Distribution ($\pi^-, p = 10$ GeV$, \theta = 15°$)



- **"Radius":** Distance between optical photon hits and the primary particle hit on the SiPM plane.
- **Outlier Rejection**
  - "Background" hits are excluded from the core Gaussian fit.
  - Cherenkov photons emission in air or Rayleigh scattering.
- Unexpectedly smaller σ with Rayleigh scattering.
- Caused by limited single-event statistics and strict outlier cuts.

Simulated Cherenkov Ring images ($\pi^-, p = 10\ \mathrm{GeV}, \theta = 25°$)

All MC hits are recorded before digitization



"Stretched Ring" after reflected by ESR

Reconstruction

1. **Ring Recognition**
    - Traditional geometric fitting approach
    - Currently used by LHCb for assistive analysis
2. **Maximum Likelihood**
    - Current mainstream algorithm
    - Evaluates global hit patterns via Probability Density Functions (PDFs)
    - Primary method adopted by Belle II and LHCb
3. **Machine Learning**
    - Emerging data-driven technique
    - Optimized for high-speed, real-time processing

Maximum Likelihood Method of ARICH on Belle II

- Six particle hypotheses: electron, muon, pion, kaon, proton, and deuteron (no deuteron on LHCb)
- Likelihood function for **a particle hypothesis**:

$$\mathcal{L}_h = \prod_{\text{pixels}} p_{h,i}(n_{h,i})\,; \qquad p_{h,i}(n_{h,i}) = \frac{e^{-\mu_{h,i}}\mu_{h,i}^{\,n_{h,i}}}{n_{h,i}!}$$

- Assuming binary readout, $p_{h,i}(\text{no hit}) = e^{-\mu_{h,i}}$, $p_{h,i}(\text{hit}) = 1 - e^{-\mu_{h,i}}$, then

$$\ln \mathcal{L}_h = -N_h + \sum_{\text{hits}} \left[\mu_{h,i} + \ln(1 - e^{-\mu_{h,i}})\right]$$

- Likelihood ratios $R_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$
- $\mu_i = S_i + B_i$, sum of signal and background

- Need further research

Summary

- **Current Progress:**
  - Detector geometry implemented via dd4hep in CEPCSW.
  - Monte-Carlo simulation pipeline successfully established.
  - Impact of material budget on momentum resolution evaluated.
- **Future Work:**
  - Digitization:
    - Implement SiPM Quantum Efficiency (QE).
    - Integrate electronics effects: dark noise & time window cuts.
  - Reconstruction:
    - Construct Maximum Likelihood-based reconstruction framework.
    - Evaluate global K/π separation power with full statistics.

Thanks for listening