Simulation and Performance Study of a Forward RICH at CEPC

Changru Li[1,2], Shengsen Sun[2], Haojie Dong[2], Jian Wang[2], Zhonghua Qin[2], Yifang Wang[2]

[1]University of Chinese Academy of Sciences (UCAS), Beijing 100049, China | [2]Institute of High Energy Physics (IHEP), CAS, Beijing 100049, China

1. Physics Motivation & Forward PID Challenge

- **CEPC Flavor Physics Goal:** Demands exceptional Particle Identification (PID) with **3σ K/π separation for momentum up to 20 GeV/c**.
- **Forward Region Bottleneck:** Baseline PID (dE/dx or dN/dx + ToF) suffers a severe Kaon ID efficiency drop at p > 3 GeV/c in the forward endcap ($|\cos\theta|$ > 0.88).
- **Forward RICH Placement Options:** Option 1 (0.88 < $|\cos\theta|$ < 0.99, between 3rd & 4th ITK endcap) vs. Option 2 (0.94 < $|\cos\theta|$ < 0.99, outside 4th ITK endcap).

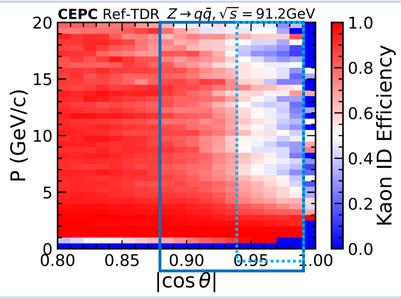


Fig. 1: Baseline Kaon ID efficiency drop in forward region (CEPC Ref-TDR $Z \to q\bar{q}$, $\sqrt{s}$ = 91.2 GeV).

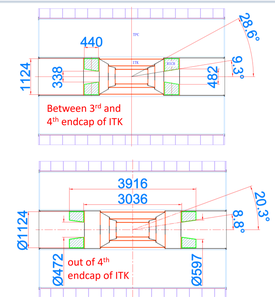


Fig. 2: Candidate locations of Forward RICH inside CEPC tracker volume.

2. CEPCSW Simulation Chain, Geometry & Material Budget

Full Simulation Chain in CEPCSW (Key4hep Stack): DD4hep (detector geometry, materials & optical surfaces) → Geant4 (Cherenkov transport, boundary processes, absorption, Rayleigh scattering) → SiPM Digitization (PDE + Dark Noise) → PID Benchmark.

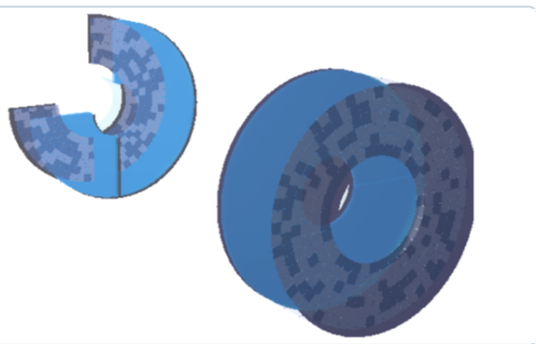


Fig. 3: DD4hep 3D model.

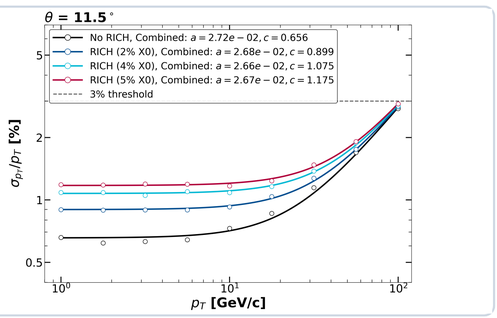


Fig. 4: Impact of RICH material on p_T resolution, still satisfying < 3% requirement.

Component	Material & Thickness	X_0	Budget
Radiator	SiO_2 Aerogel (6 cm)	> 700 cm	< 1% X_0
Photon Det.	SiPM+PCB (1+1 mm)	9.4/19.4cm	1.57% X_0
Shell/Mech.	CF (0.4 mm)+Cu/Ti	40.0 cm	1–3% X_0

Config (θ = 11.5°)	Spatial a	MCS c
No RICH Baseline	2.72e-2	0.656
RICH (2% X_0)	2.68e-2	0.899
RICH (4% X_0)	2.66e-2	1.075
RICH (5% X_0)	2.67e-2	1.175

3. Focusing Aerogel Radiator with Gradient Refractive Index

Increasing radiator thickness l boosts photoelectron yield ($N_{\text{p.e.}} \propto \sin^2\theta_c \cdot l \cdot \Delta E \cdot \epsilon$), but worsens single-photon emission point uncertainty σ_{emission}. Adopting a **3-layer gradient refractive index** (2 cm per layer: **n_1 = 1.007, n_2 = 1.008, n_3 = 1.009**) focuses Cherenkov rings onto the SiPM plane:

$$\sigma_{\theta_c}^{(\text{tot})} = \frac{\sigma_{\theta_c}^{(1\text{pe})}}{\sqrt{N_{\text{p.e.}}}} \quad , \quad (\sigma_{\theta_c}^{(1\text{pe})})^2 = \sigma_{\text{SiPM}}^2 + \sigma_{\text{emission}}^2 + \sigma_{\text{track}}^2 + \sigma_{\text{chromatic}}^2 + \sigma_{\text{rec}}^2$$

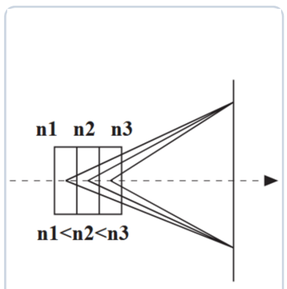


Fig. 5: Focusing principle.

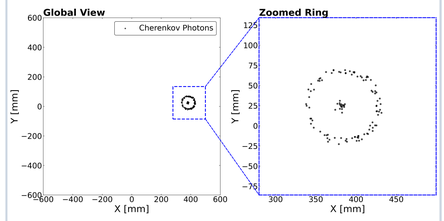


Fig. 6: Unfocused ring (π^-, 10 GeV, θ = 15°).

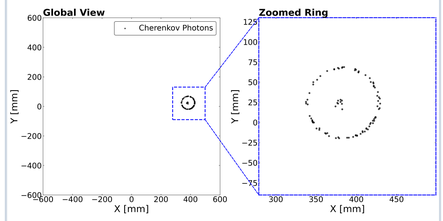


Fig. 7: Focused ring (π^-, 10 GeV, θ = 15°).

4. Optical Processes (Rayleigh, Reflection) & SiPM Digitization

- **Rayleigh Scattering & Mirror Reflection:** $P = 1 - e^{-\Delta s/L_{\text{sc}}}$ with $L_{\text{sc}} = (\lambda/400\text{ nm})^4 \times 4.6$ cm; outer reflection film reflects high-θ photons, forming folded crescent rings.
- **SiPM Granularity & Hamamatsu MPPC Response:** Requires $\sigma_{\theta_c}^{(\text{tot})} < 0.7$ mrad ⇒ pixel pitch ≤ 1 mm ($\sigma_{\text{SiPM}} = \Delta_{\text{channel}} / (L\sqrt{12})$). Modeled with λ_p = 450 nm, peak PDE = 50% (101 → 22 hits), DCR = 100 kHz/mm^2, time window = 5 ns (A = 0.808 m^2).

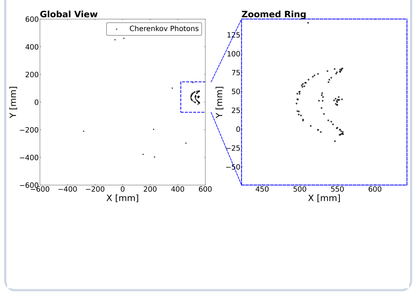


Fig. 8: Ring with Rayleigh & Reflection (π^-, 10 GeV, θ = 22°).

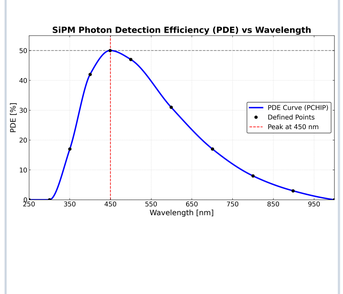


Fig. 9: PDE curve.

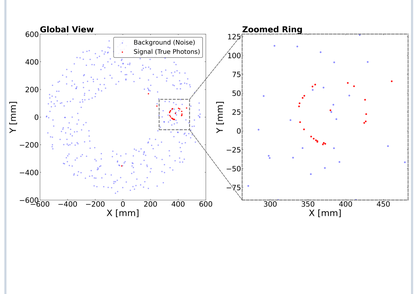


Fig. 10: Ring with PDE + DCR.

5. Cherenkov Ring Reconstruction & K/π Separation Benchmark

3-Step Simplified Reconstruction:

1. **Pre-selection via Circle Fit:** Reject outliers & background hits.
2. **Single-Photon θ_c Calculation:** Geometric ray-tracing from SiPM hit to emission vertex.
3. **Event-Level Aggregation:** Combine clean photoelectrons to evaluate event θ_c and separation power:

$$N_\sigma \approx \frac{|m_K^2 - m_\pi^2|}{2p^2\,\sigma_{\theta_c}^{(\text{tot})}\sqrt{n^2-1}} \quad \Rightarrow N_\sigma = 3.21 > 3 \text{ @ 20 GeV/}c$$

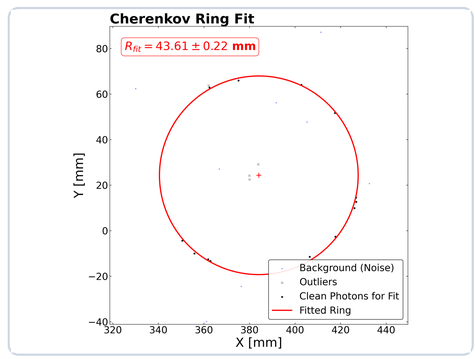


Fig. 11: Circle fit & outlier rejection.

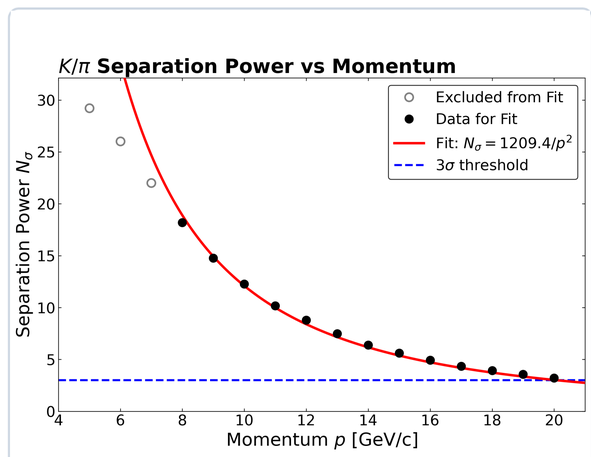


Fig. 12: K/π separation vs. momentum (4–20 GeV/c, θ = 15°).

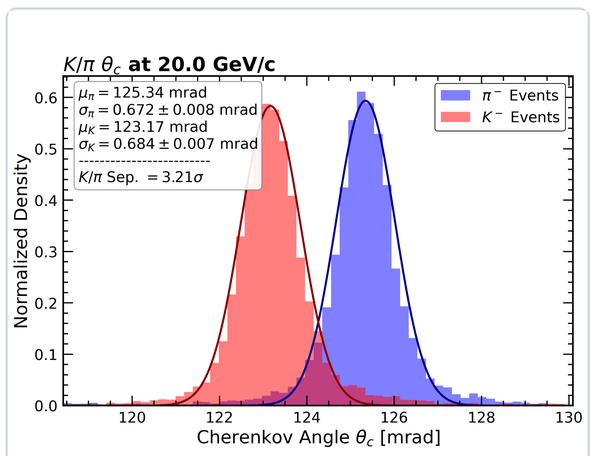


Fig. 13: Reconstructed θ_c at 20 GeV/c (θ = 15°, 3.21σ).

6. Reflection Reconstruction & Cylindrical Mirror Resolution Study

- **Geometric Unfolding ($E \to S \to M \to D$):** Solve virtual refraction point (x_S, y_S) from (x_E, y_E) and reflected hit (x_D, y_D) via geometric optics to reconstruct θ_c.
- **Degradation at θ = 25°:** Mean θ_c is unchanged (μ_π = 125.58 mrad), while σ_{θ_c} broadens from 0.67 to 0.80 mrad, reducing K/π separation from **3.21σ (θ = 15°)** to **2.65σ (θ = 25°)**.
- **Root Cause & Mitigation:** Cylindrical mirror (R = 56.3 cm) stretches a 1 × 1 mm^2 SiPM pixel into ~1.00 × 1.28 mm^2 tangentially (r/B = 1.28). **Planar mirrors** are proposed.

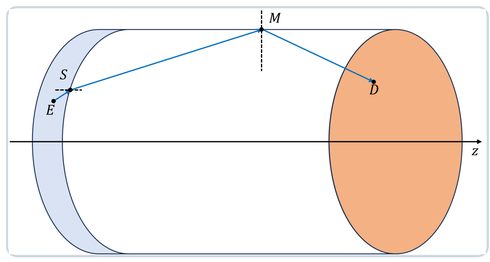


Fig. 14: Reflection unfolding geometry.

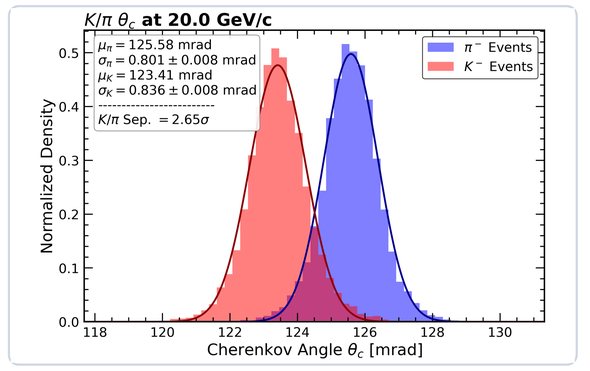


Fig. 15: Reflected ring θ_c (θ = 25°, 2.65σ).

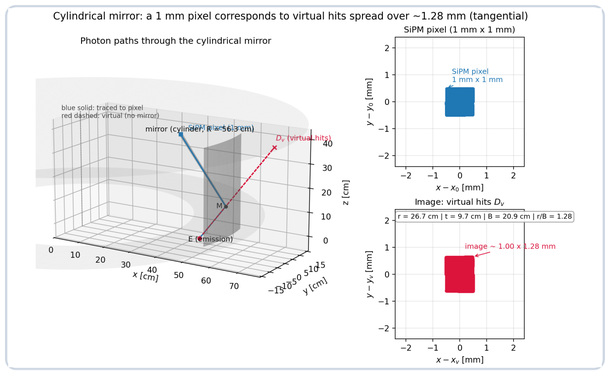


Fig. 16: Tangential virtual pixel stretch.

7. Dual-Radiator Upgrade Concept for 40 GeV/c K/π Separation

- **100 cm Dual-Radiator Architecture:** To extend **K/π separation up to 40 GeV/c**, an extended module (0.95 < $|\cos\theta|$ < 0.99, z ≈ 1500–2500 mm) combining a 6 cm 3-layer aerogel (n ≈ 1.03) and an L = 90 cm gas radiator is explored, forming concentric outer (aerogel) and inner (gas) Cherenkov rings.
- **Focusing Optimization:** Continuous photon emission along the 90 cm gas path introduces large σ_{emission}; optical focusing via mirrors/lenses to redirect photons onto the 2.5 mm detector plane is under active study.

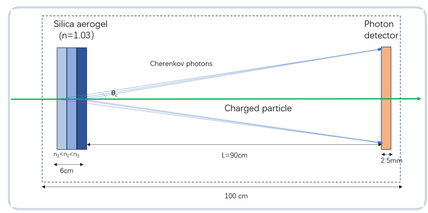


Fig. 17: Dual-radiator concept.

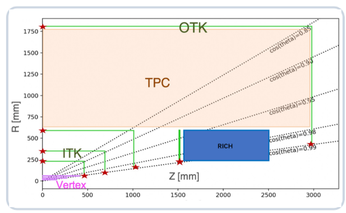


Fig. 18: Extended RICH location.

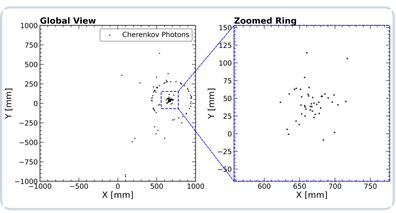


Fig. 19: Dual-radiator photon hit map.

8. Summary & Next Steps

Key Achievements:

- **Simulation Chain Established:** Full DD4hep + Geant4 optical transport & SiPM digitization in CEPCSW.
- **Focusing Aerogel Validated:** 3-layer gradient n suppresses σ_{emission}.
- **Benchmark Met:** 1 mm SiPM achieves **3.21σ K/π separation at 20 GeV/c** (θ = 15°).

Outlook & Next Steps:

- **01. Dark-Noise Impact:** Quantify PID degradation vs. dark count rate.
- **02. Advanced Reconstruction:** Maximum Likelihood + Hough Transform for noisy & reflected rings.
- **03. Full-Chain PID Evaluation:** Performance with realistic response & planar mirrors.

Presenter: Changru Li (UCAS / IHEP, CAS) | **Contact Email:** licr@ihep.ac.cn