Status of the Cherenkov detector for CEPC at IHEP

Zhonghua Qin, April 27, 2026

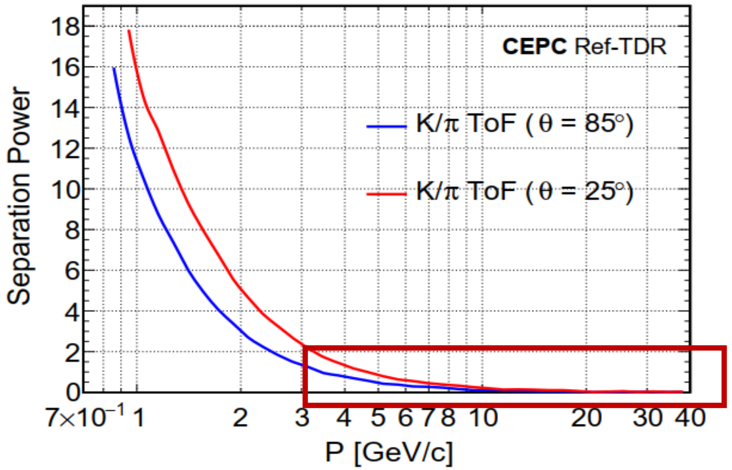
Motivation of the Cherenkov detector for CEPC

- Improve PID performance for:

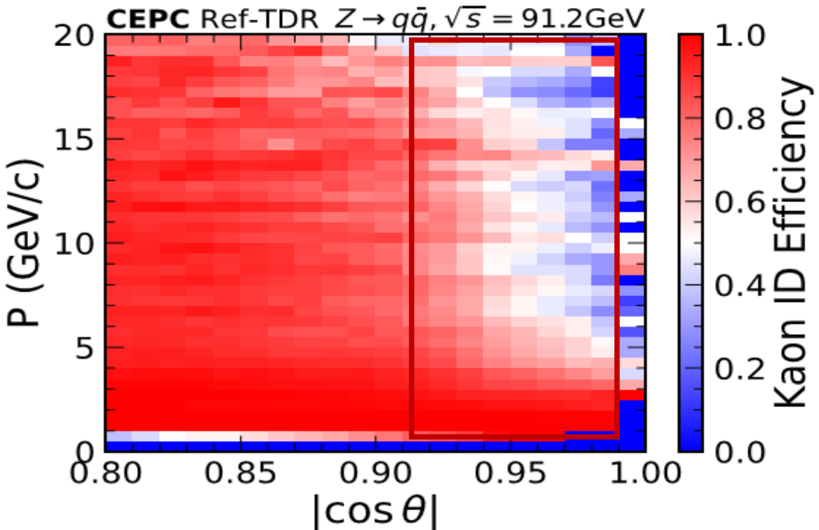
  - High-momentum range (3-20 GeV/c), where TOF PID capability is degraded

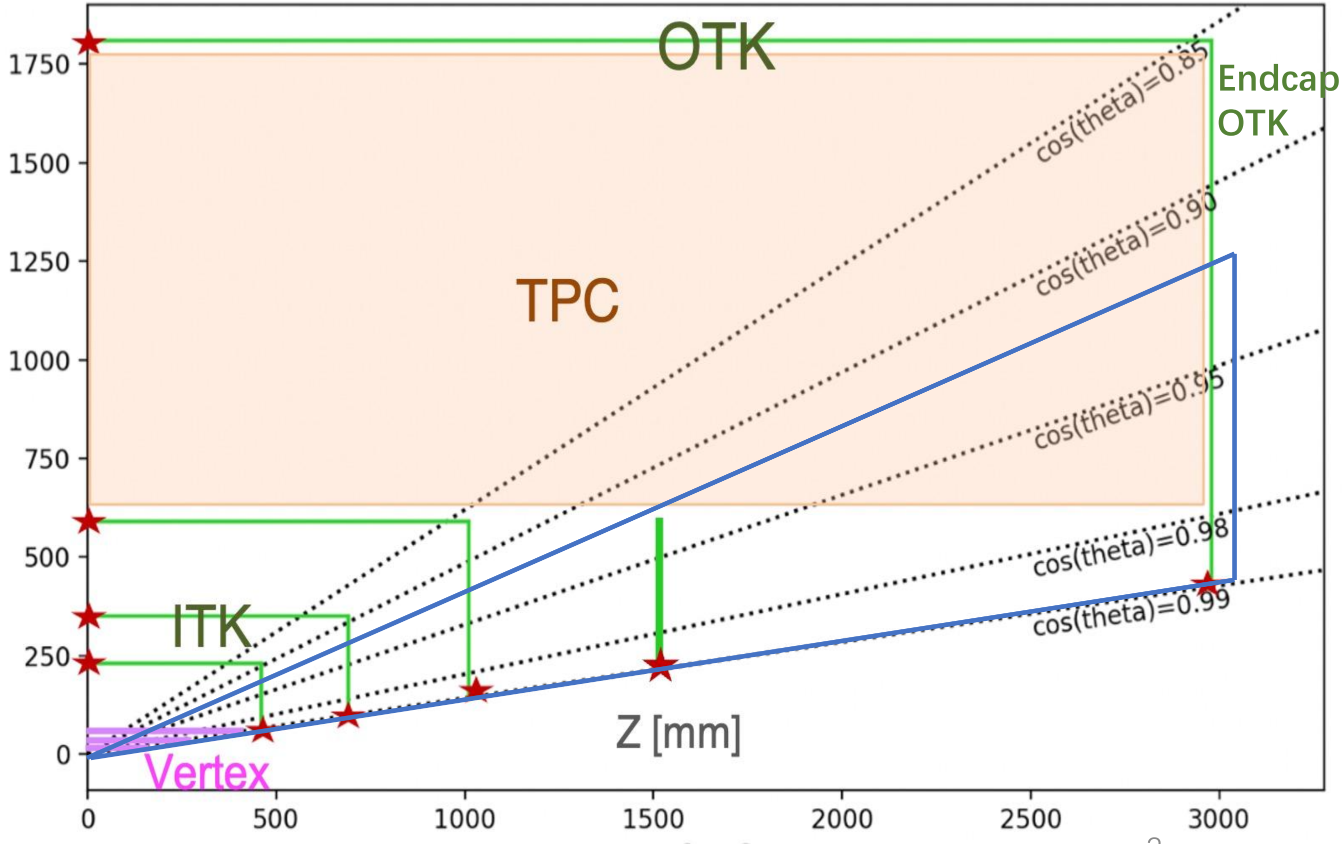
  - Small-angle endcap region (8°–20°, 0.93<cosθ<0.99), where TPC provides short or no tracks

TOF standalon (Ref-TDR)



Kaon ID efficiency (Ref-TDR)

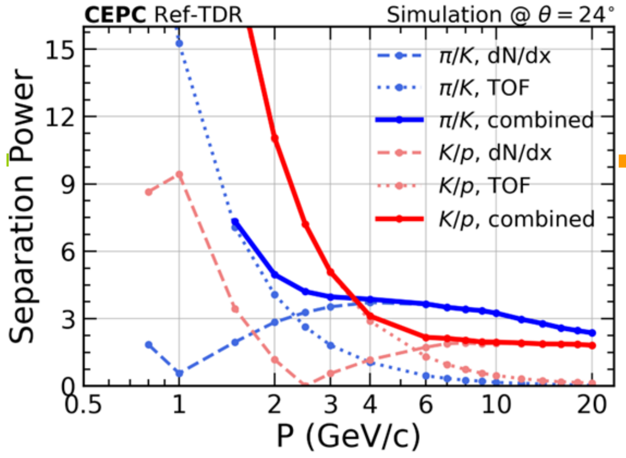


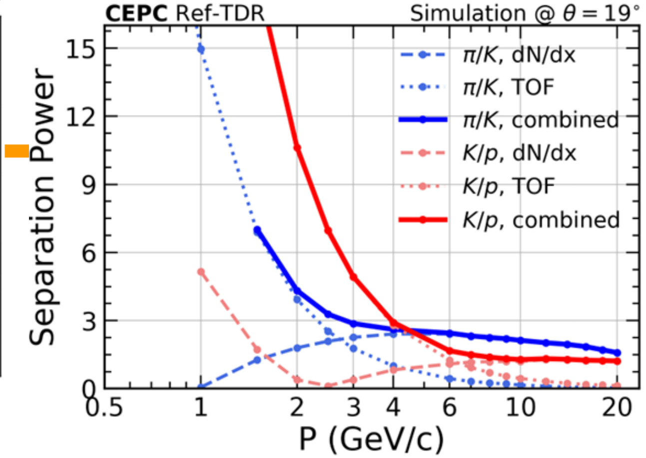


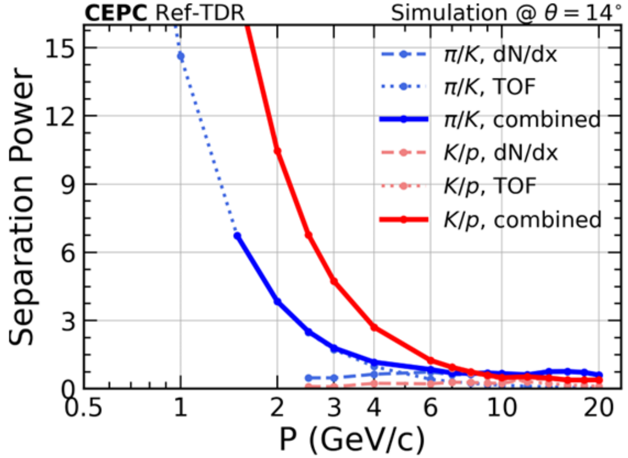
A further check of the PID with current CEPC detector

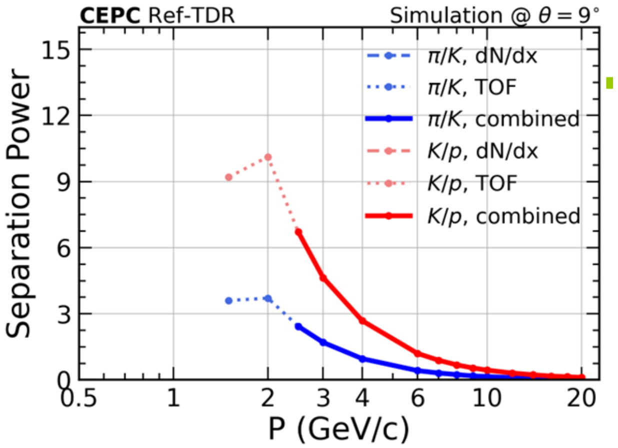
- **Separation power vs momentum, at different θ (24°, 19°, 14°, 9°)**

From physic performance group



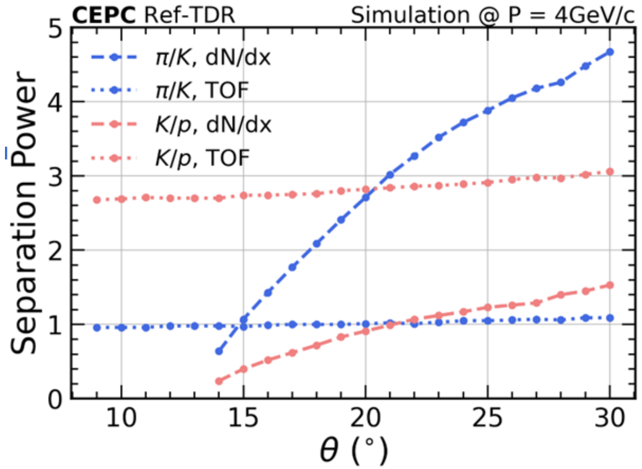


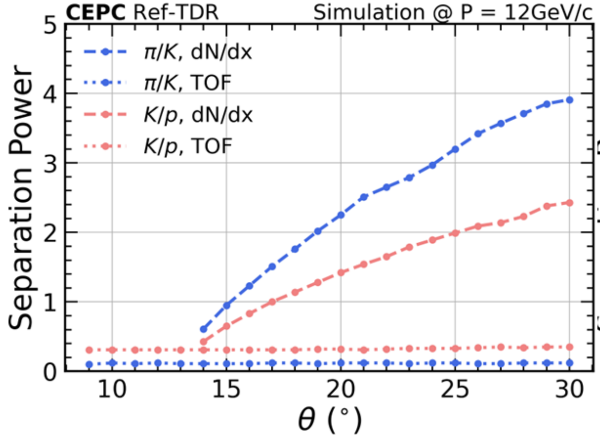


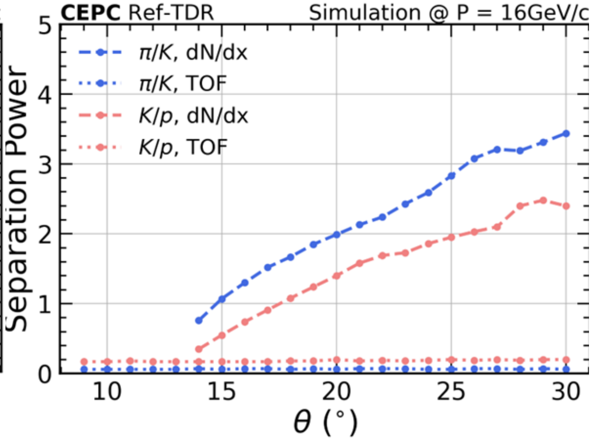


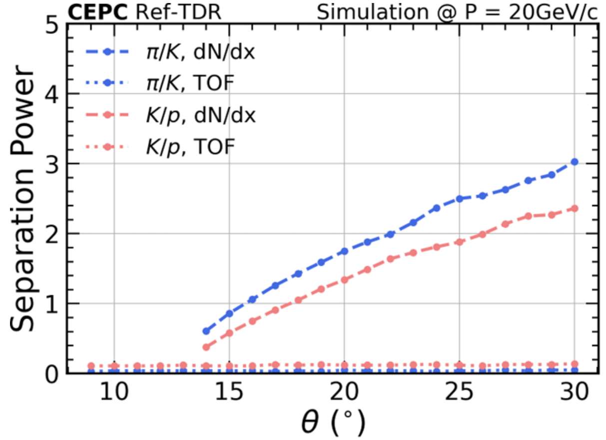
- **Separation power vs θ, at different momentum (4, 12, 16, 20 GeV/c)**

PID performance worsening in small θ and high P regions







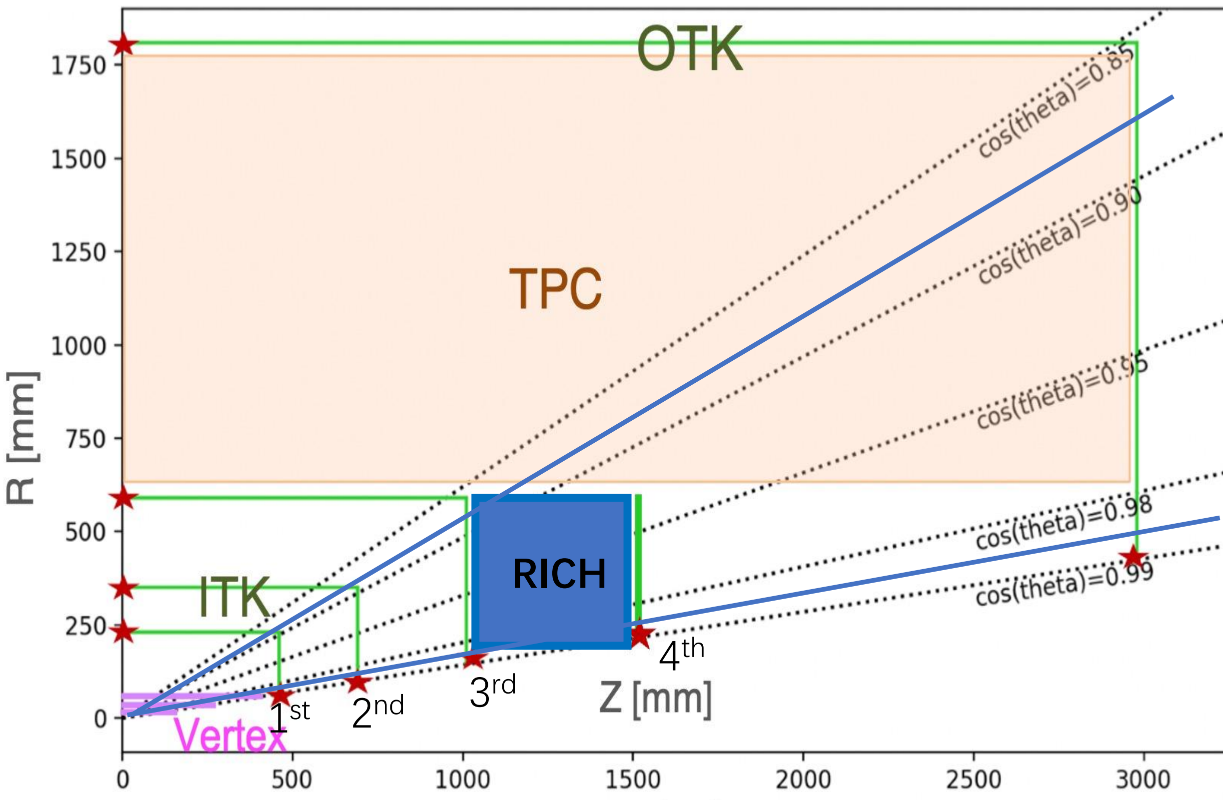


Possible locations of the Cherenkov detector

- Put the detector in empty space, without changing the design of other sub-detectors
- Currently two positions, the better one depends on two factors:

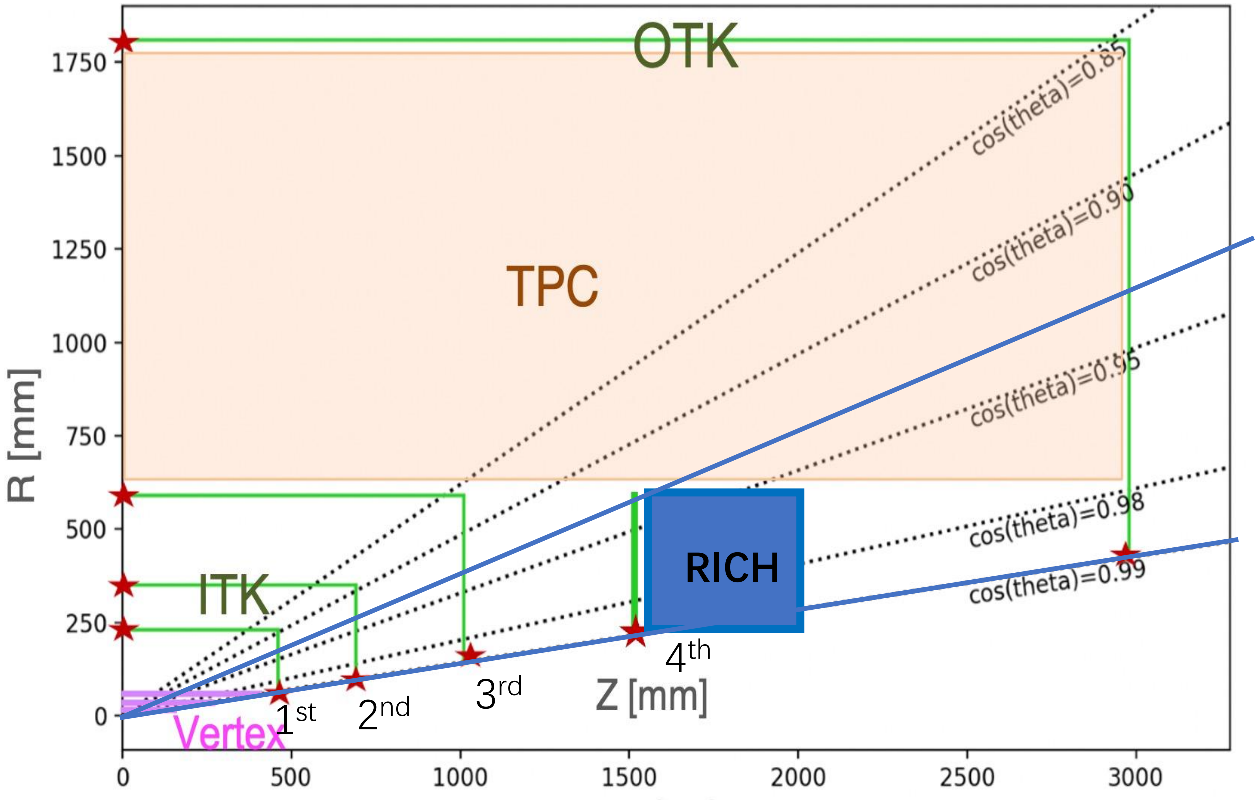
  1) performance of the Cherenkov detector itself; 2) Impact on other sub-detectors (e.g., momentum resolution)

position 1



Coverage: 9.3° <θ <28.8°
or 0.88<cos θ< 0.99

position 2

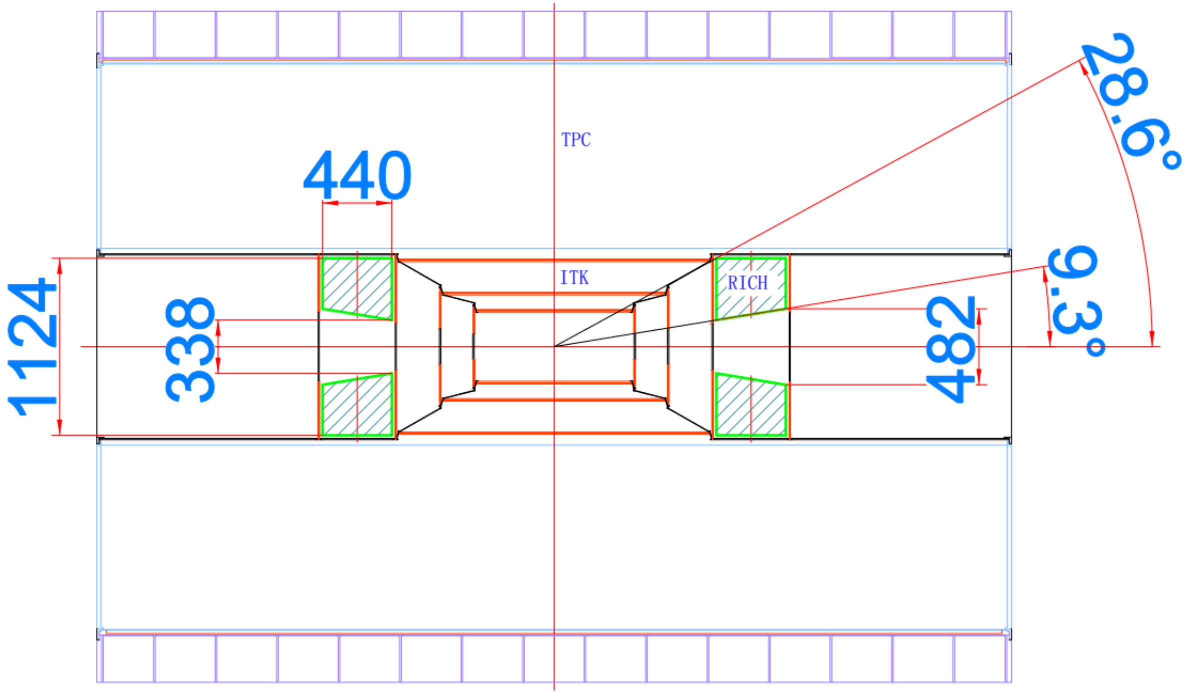


Coverage: 8.8° <θ < 20.3°
or 0.94<cos θ< 0.99

A schematic drawing of the Cherenkov detector

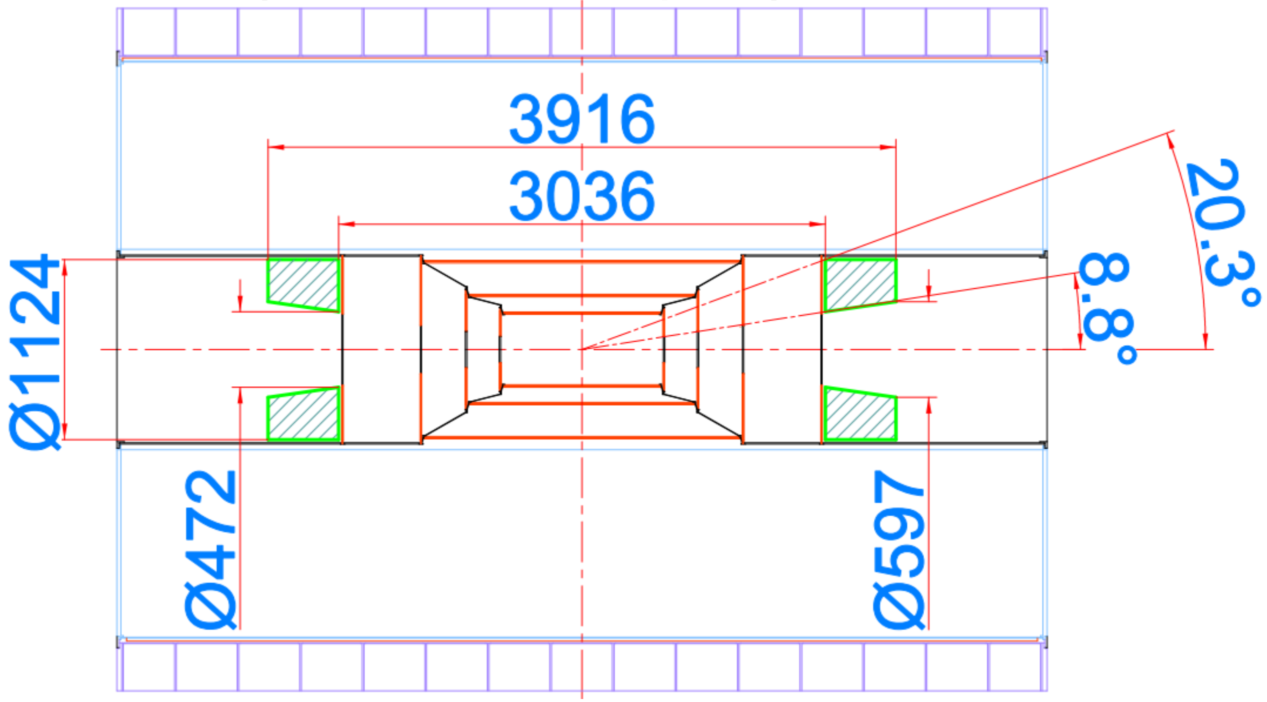
From Jian Wang, mechanics group

Positon 1 (between 3rd and 4th endcap ITK)



	Inner diameter	Outer diameter	Total area (two endcaps)	Length (single endcap)
Radiator	33.8 cm	112.4 cm	1.81 m^2	44cm
Photon detector	48.2 cm	112.4 cm	1.62 m^2	

Position 2 (outer of 4th endcap IKT)



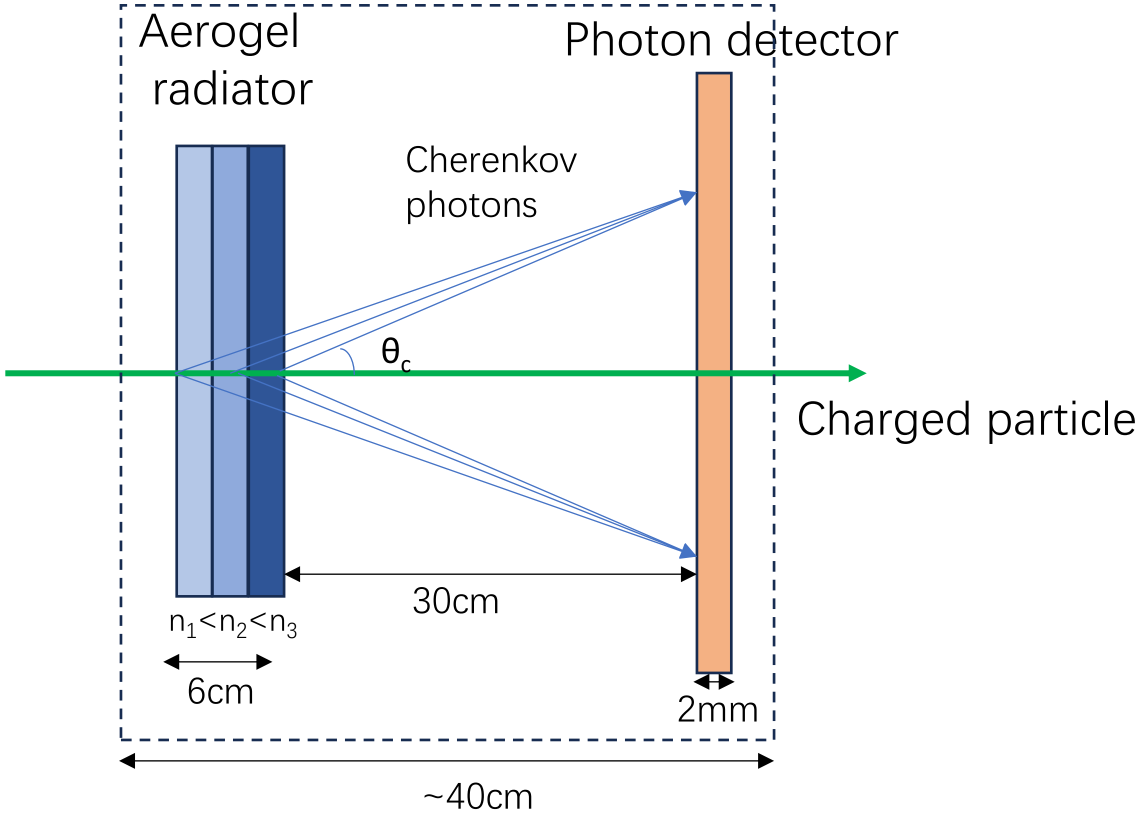
	Inner Diameter	Outer diameter	Total area (two endcaps)	Length (single endcap)
Radiator	47.2 cm	112.4 cm	1.64 m^2	44cm
Photon detector	59.7 cm	112.4 cm	1.43 m^2	

Conceptual design of the Cherenkov detector

- Ring-imaging Cherenkov detector (RICH) based on proximity-focusing method:

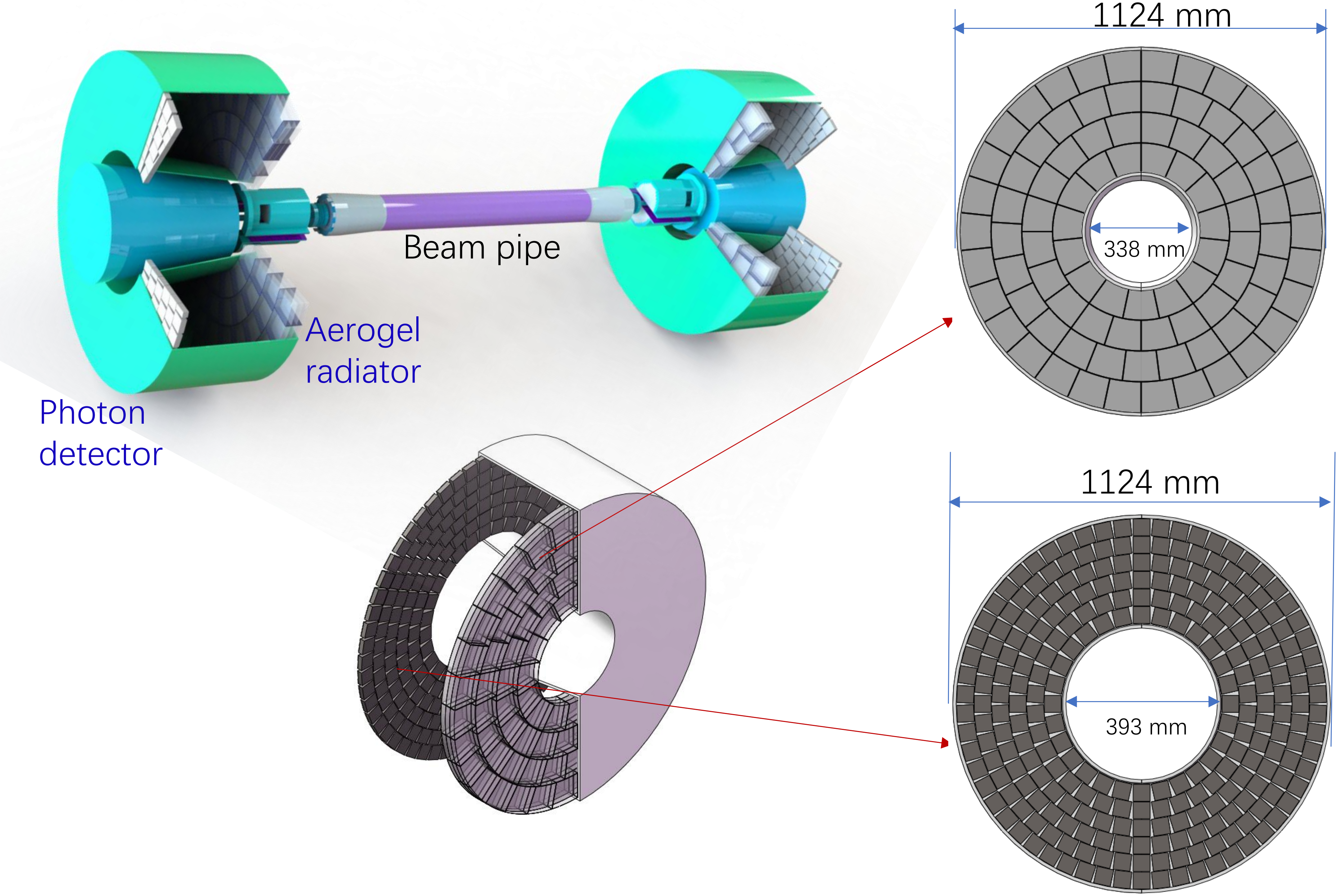
- Multiple layers of aerogel radiators with varying refractive index (n);
- A photon detector used for Cherenkov light detection;
- An expansion gap with a length (L) of around 30 cm;

Reference: T.Iijima, NIM A548 (2005) 383; A.Yu.Barnyakov, NIM A553 (2005) 70; D. Sharma, NIM A1061 (2024) 169080



A schematic diagram of the conceptual design

A conceptual drawing of the Cherenkov detector

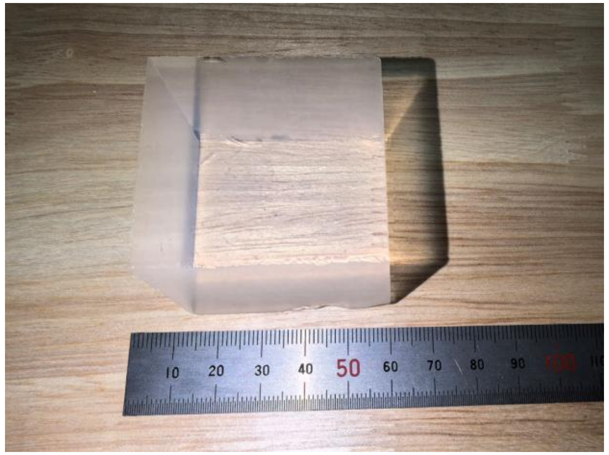


Aerogel radiator : ~0.9 m^2
- -90 aerogel tiles in 4 layers
- -each tile of ~10 cm x 10 cm in size

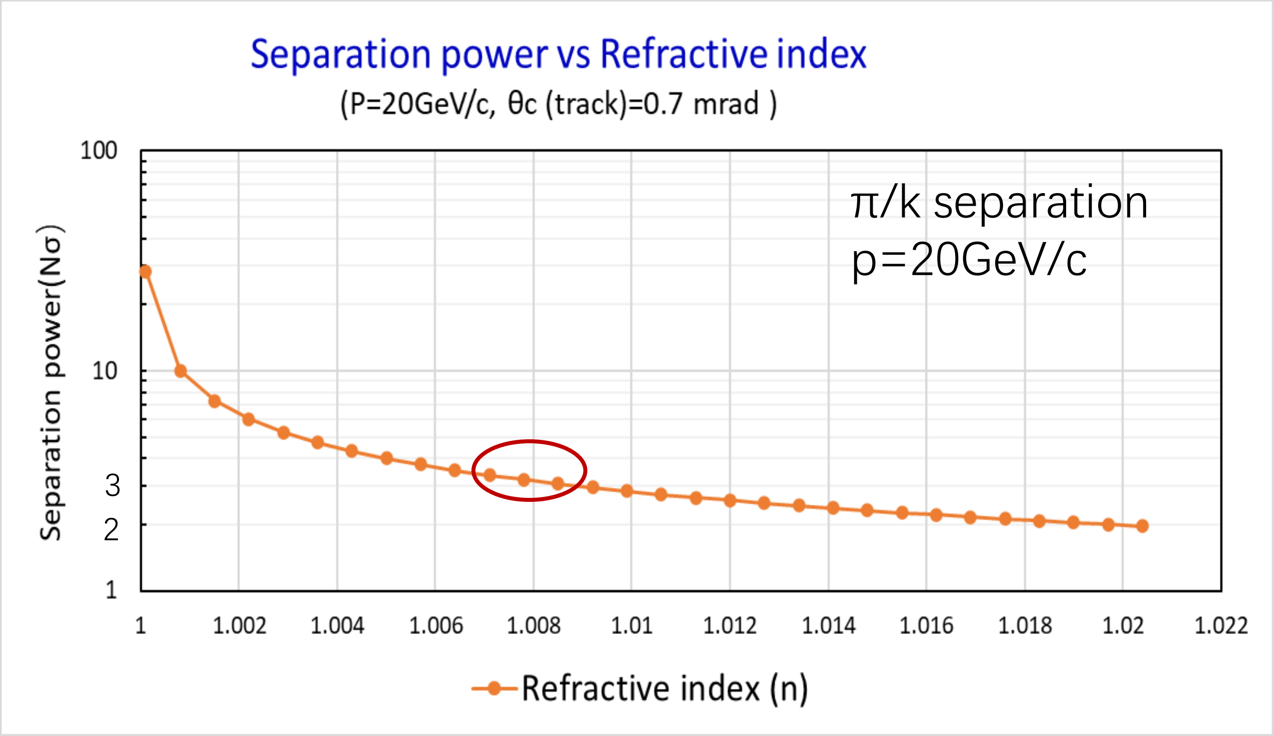
Photon detector: ~0.8 m^2
- -258 photosensor module in 6 layers
- -each module of ~5 cm x 5 cm in size

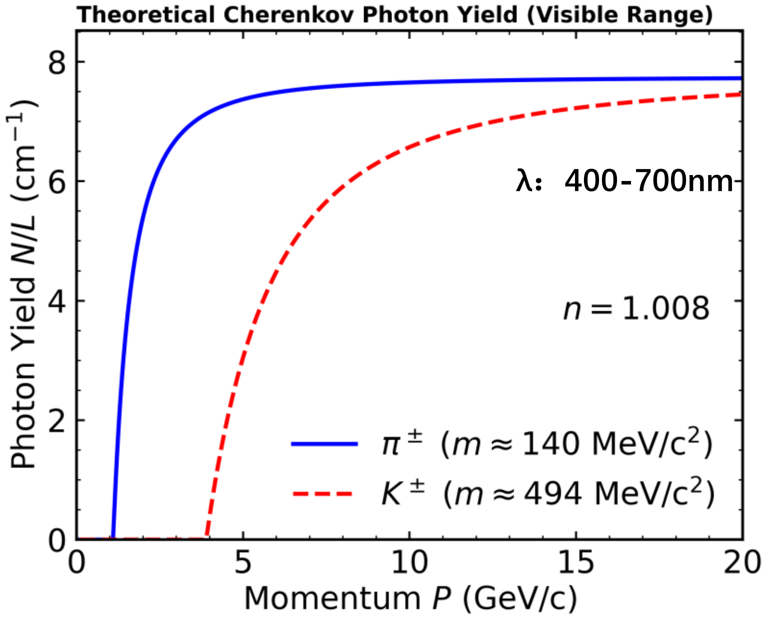
Silica aerogel as a radiator

- To have good PID performance in 3-20 GeV/c range, refractive index (n) should be ~1.008
  - Solid-state/liquid radiators : n >1.2, for PID in low momentum range;
  - Gaseous radiators: n<1.001, for PID in very high momentum;
  - Aerogel with n=1.008, π/k can be separated at 3σ up to 20GeV/c;
  - However, photons emitted from such aerogel are a few: <10 /cm in the visible range (400-700 nm)



Aerogel from BINP

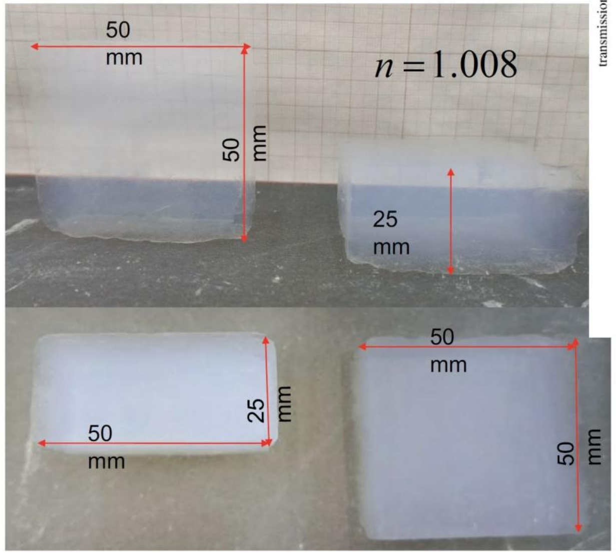


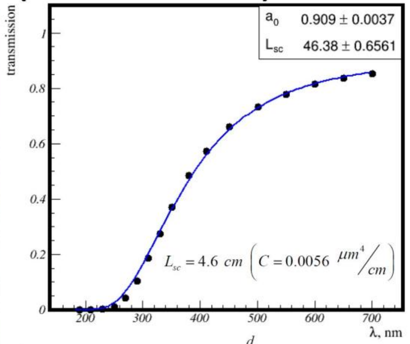


Aerogel radiator R&D

- Working with BINP group

Aerogel with n=1.008 (Novosibirsk)

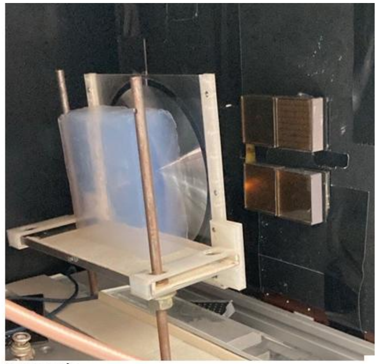




$$T = \frac{I}{I_0} = a_0 \cdot e^{-\frac{d}{L_{sc}\cdot(\lambda/400)^4}} = a_0 \cdot e^{-\frac{C\cdot d}{\lambda^4}}$$

d – thickness of a sample,
λ – wavelength in nanometers,
Lsc – scattering length at 400 nm,
a_0 – surface scattering coefficient,
C – clarity coefficient

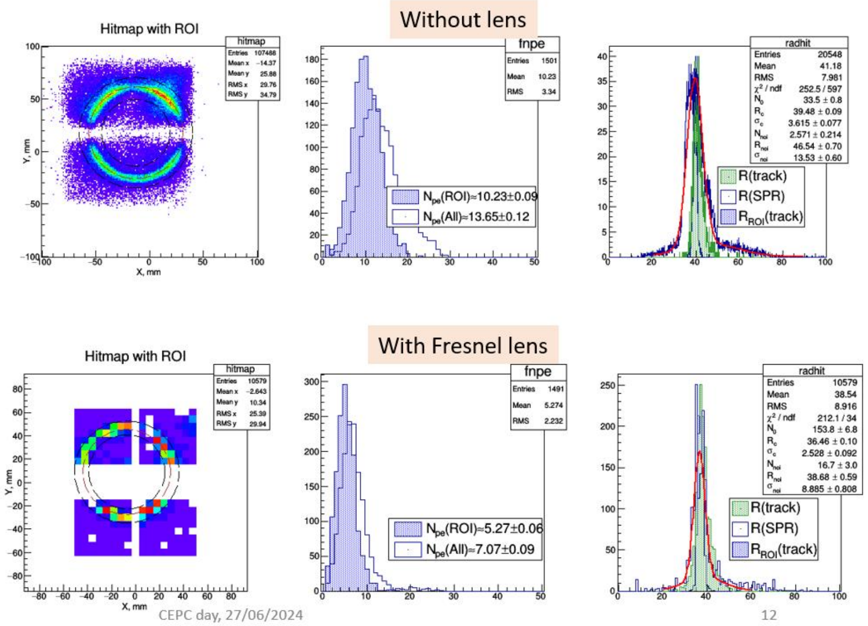
Results from BINP



Aerogel:
- n=1.028
- L_{sc}(400nm)=48.2±0.7 mm
- Thickness=40mm

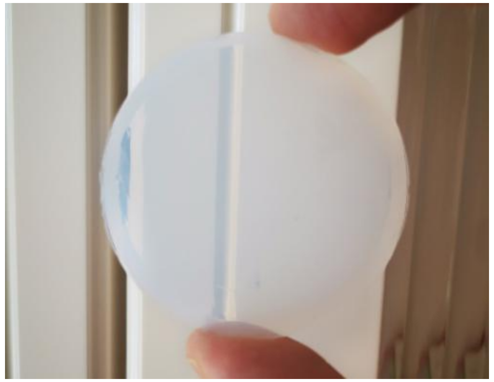
Fresnel lens:
- Acrilic (PMMA)
- L_f=6''
- Manufacturer: Edmund

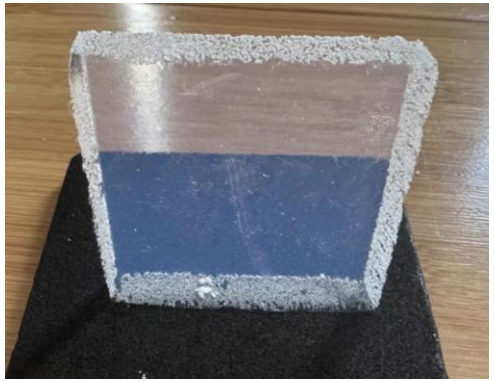
PMT:
- 4 Hamamatsu H12700
- pixel 6x6 mm



- Some commercial aerogels were bought at IHEP

  -quality is not good, just for mechanical test purpose, i.e, mounting, machining etc..





Consideration of SiPM as the photon detector

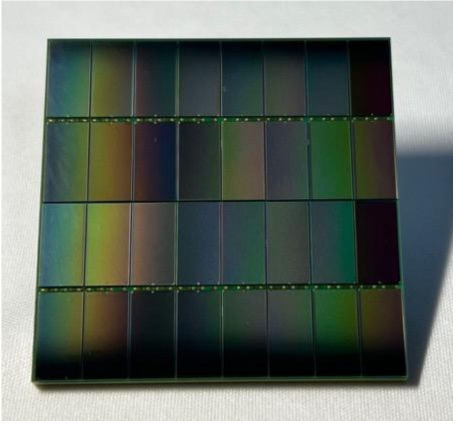
- PMTs/HPD/HAPD have large material budget (usually > 10% X0), which will significantly impact on the momentum resolution of the trackers in CEPC
- Gaseous detectors are generally complicated and not very compact
- SiPM is under extensive R&D by a variety of experiments, and shows promise for the future Cherenkov detector applications

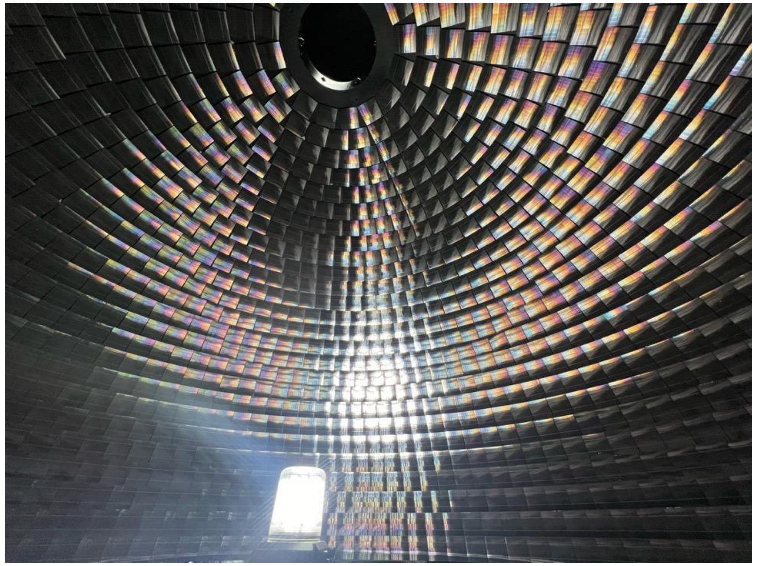
➢ many advantages from SiPM (with respect to other photodetectors)

- high photon detection efficiency (40%-50%)
- insensitive to magnetic field
- good time resolution (100-200 ps)
- good spatial resolution (sub mm level)
- highly compact and easy to integrate
- low material budget (a few percent)
- relatively cheap for large area

➢ major disadvantages:

- large dark noise rate (> 100 kHz/mm^2)
- not radiation tolerant (< 10^{10} n_eq/cm^2 ?)





JUNO-TAO SiPMs (~10m^2)

Consideration of the SiPM dark noise

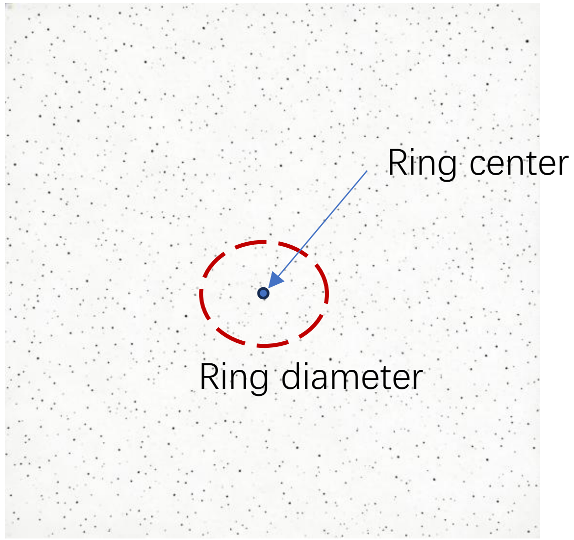
- Dark noise generated hits in the whole photodetector plane: N ≈ 10,000, by applying
  - a typical dark noise rate : 200 kHz/mm^2
  - readout time window: 69 ns(same as VTX, ITK, OTK, Ecal, Muon)
  - photon detector area: 0.8 m^2

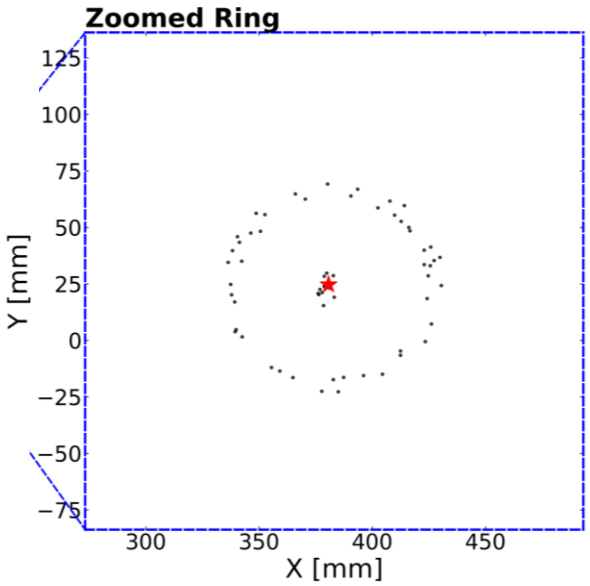
- After associated the event with trackers: N ≈100 in the interesting region
  - Ring diameter (max. ~ 8 cm) limitation, and intersection point (ring center) extrapolation
  - dark noise hits reduced by a factor of ~100

- After applying a shorter readout time widow (~5ns): N ≈10
  - 5 ns vs. 69 ns, further a factor of 10 can be reduced

So, the uncorrelated hit number is acceptable, if the SiPM dark noise rate remains constant at several hundred kHz level.

However, SiPM will become much noisy after heavy irradiation.





Consideration of the SiPM radiation tolerance

- From CEPC Ref-TDR, for where the Cherenkov detector will be located:
  TID: ~1 kGy/year;
  NIEL: ~1 x 10^{11} Neq. /cm^2 /year

- This requires a radiation tolerant SiPM:
  1x10^{12} Neq./cm^2 , for 10 years running;
  or 1x10^{13} Neq./cm^2 in case an under estimation of radiation from the simulation.

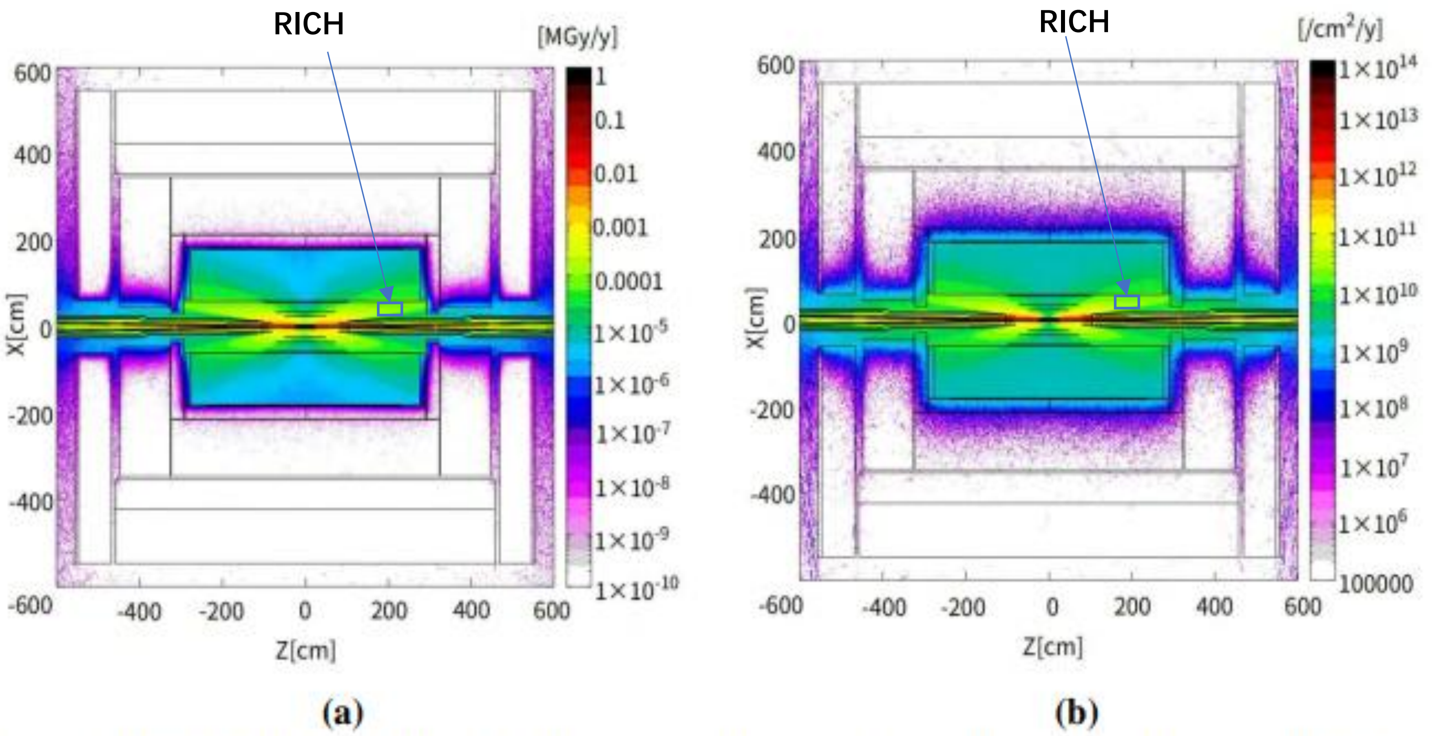


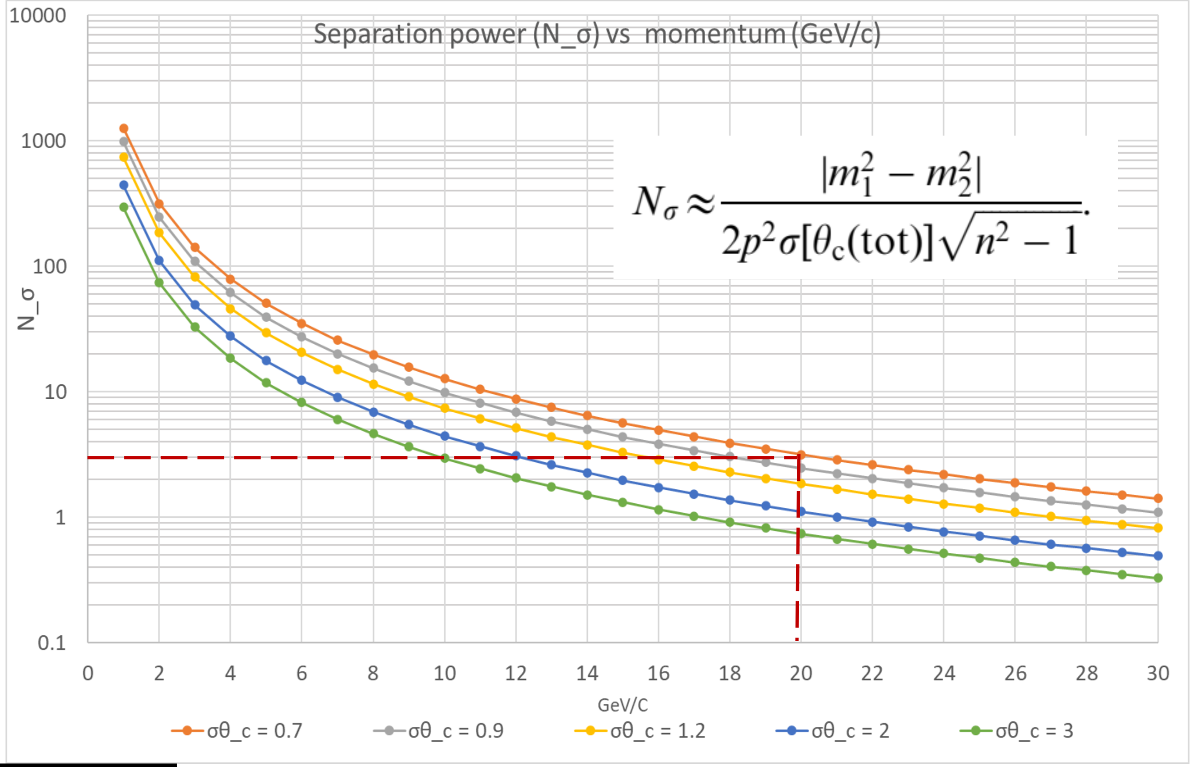
Figure 3.12: The TID and NIEL distributions at Higgs mode on the CEPC detector. The highest TID is lower than 1 MGy per year as shown in a.), while the highest level of NIEL is in the order of $10^{13}(1\ MeVn_{eq})cm^{-2}$ per year as shown in b.).

Under this radiation level, probably cooling and annealing are necessary for SiPM?
or advanced design of SiPM?

Consideration of SiPM spatial resolution

- To achieve 3σ K/π separation at 20 GeV/c, a good Cherenkov angle resolution ($\sigma(\theta c(tot))$) of 0.7 mrad is needed;

- Resolve the spatial resolution from the Cherenkov angle resolution formula:



$$\sigma(\theta c(tot)) = \frac{\sigma(\theta c(1pe))}{\sqrt{Npe}}$$

$$= \frac{1}{\sqrt{Npe}} \left(\sqrt{\sigma_{spatial}^2 + \sigma_{thick}^2 + \sigma_{track}^2 + \sigma_{chromatic}^2}\right)$$

$$= \frac{1}{\sqrt{Npe}} \left(\sqrt{\left(\frac{\Delta_{size}}{L\sqrt{12}}\right)^2 + \left(\frac{t \sin\theta_C}{L\sqrt{12}}\right)^2 + \sigma_{track}^2 + \left(\frac{\Delta_n}{n\tan\theta_C}\right)^2}\right)$$

A SiPM with a pitch of 1mm x 1mm, corresponding to $\sigma_{spatial} = (1mm/\sqrt{12}) \approx 300$ μm

Assume: $\Delta size(pitch) = 1mm$, $t = 20mm$, $\sigma_{track} = 0.5mm$, $\Delta_n = 0.0001 (n = 1.008)$, $Npe = 15$, Then: $\sigma(\theta c(tot)) \approx$ **0.7 mrad**

Preliminary specifications of SiPM

Parameters	Values	Comments
Spectral response range	>300 nm	to get more photoelectrons
Photon detection efficiency	Peak value ~50%	
Spatial resolution	~300 μm	better angular resolution then better PID performance
Single SiPM size	1x1mm^2 (traditional readout); or 3x3mm^2 or 6x6mm^2 (with charge sharing readout)	position sensitive SiPM (PSS)
Time resolution	100-200 ps	to have short readout time window
Dark noise rate	100 – 200 kHz @ room temperature	acceptable if keep unchanged
Radiation tolerance	10^{12} - 10^{13} $N_{eq.}$ /cm^2	to be further studied
Working conditions	cool down to -20℃ ? regular annealing needed?	to be further studied
Crosstalk	a few percent (1-5%) ?	Keep it low for compact arrange and large size
Total area	~1.6 m^2	an initial calculation

Still many other parameters not included, such as Gain, V_{bias}, Fill factor, etc..

Simulation of the Cherenkov detector

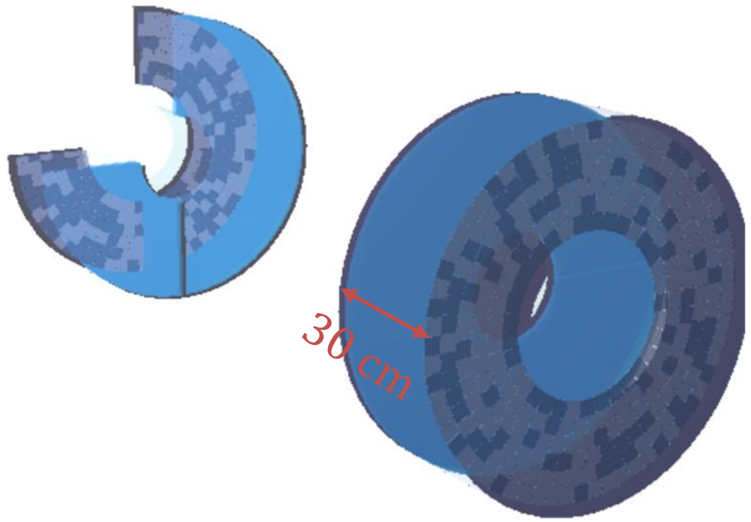
From IHEP Software group
Changru Li, Shengsen Sun

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

1. Aerogel: 3 layers of $\mathrm{SiO_2}$ $(\rho \approx \rho_{air}, n \approx 1.008)$
$r = 16.9\sim56.2\ \mathrm{cm}, z = 106.6\ \mathrm{cm}\sim112.6\ \mathrm{cm}$

2. Photon Detector (SiPM & PCB + electronics)
SiPM: G4_Si, PCB + electronics: Pb, Cu, C, O…
$r = 24.1\sim56.2\ \mathrm{cm}$

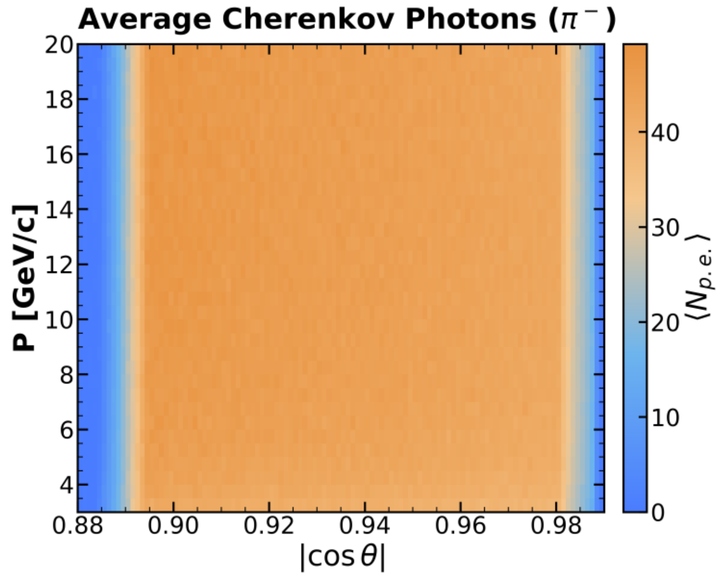
3. Carbon Fiber Shell $t = 0.2\ \mathrm{mm}$
4. Enhanced Specular Reflector (ESR) $t = 0.08\ \mathrm{mm}$
5. Mechanical Support
6. Cooling



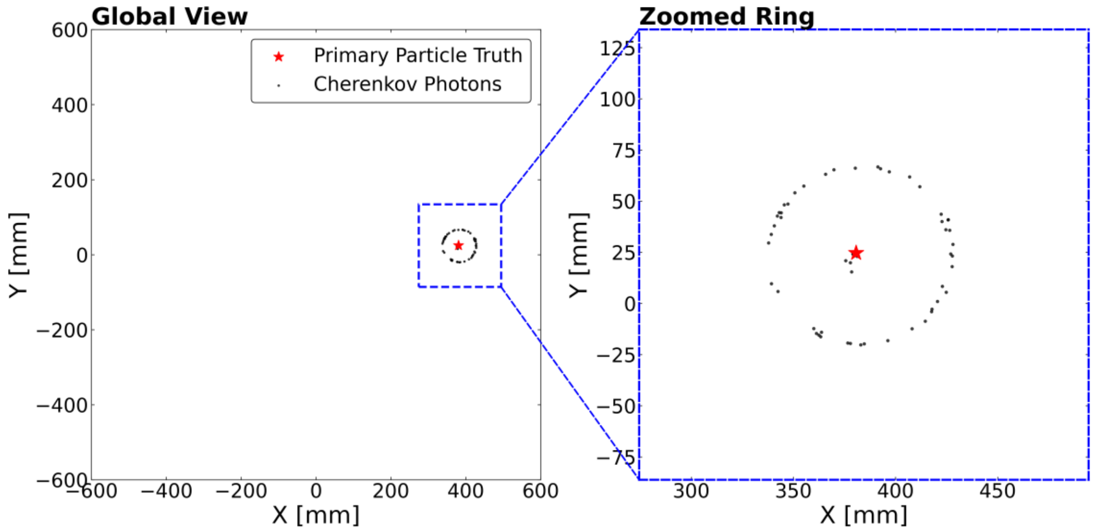
geoDisplay at CEPCSW, box clipped
30 cm from aerogel to SiPM
5 cm × 5 cm modules of PD

Preliminary results of simulation

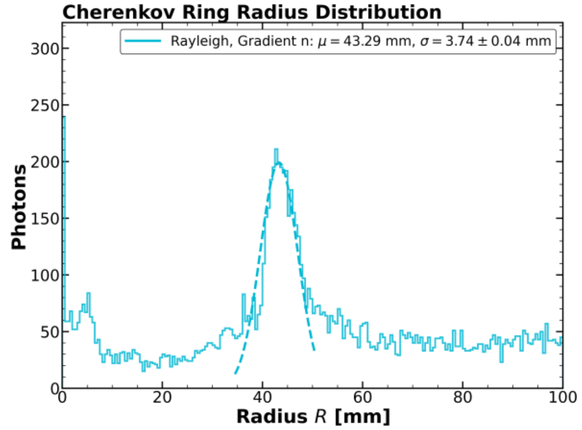
Average photons detected by photosensors

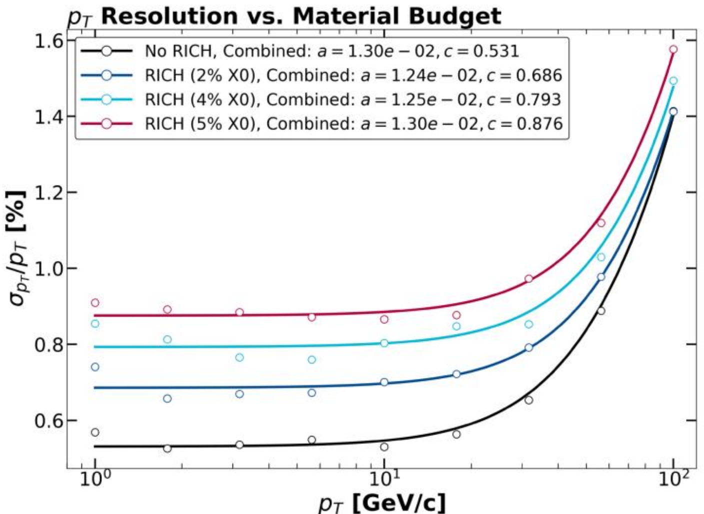


Simulated Cherenkov Ring images ($\pi^-, p = 10$ GeV, $\theta = 15°$) Gradient n



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





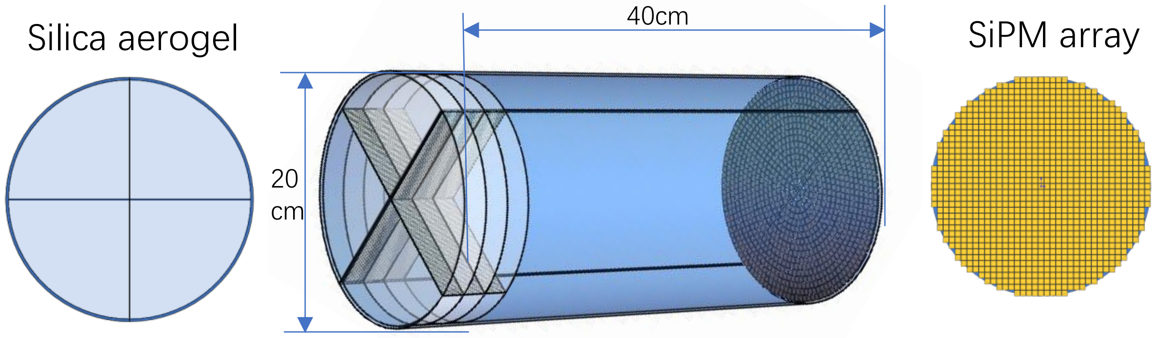
Impacting on Momentum resolution from material budget

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

Plans for the further study

- there are a lot of things to do:
  - Overall detector design and specifications determination
  - Aerogel and SiPM investigation and testing
  - SiPM radiation hardness, cooling and annealing study
  - Readout electronics consideration and design
  - Detector simulation and reconstruction
  - build a small-scale prototype with aerogel and SiPMs
  - Finish the Cherenkov detector CDR in 2-3 years

the prototype under consideration:
- diameter: 20cm;
- length: 40cm;



About the funding for Cherenkov detector

- Approved:

  IHEP innovation fund: ~800,000 RMB in 3 years (we can ask for more if needed)

- Under application (proposal submitted)

  NSFC general: ~650,000 RMB in 4 years

  RSF-NSFC joint: ~3M RMB (1.5 M from each side) in 3 years

- Possible some other funding later