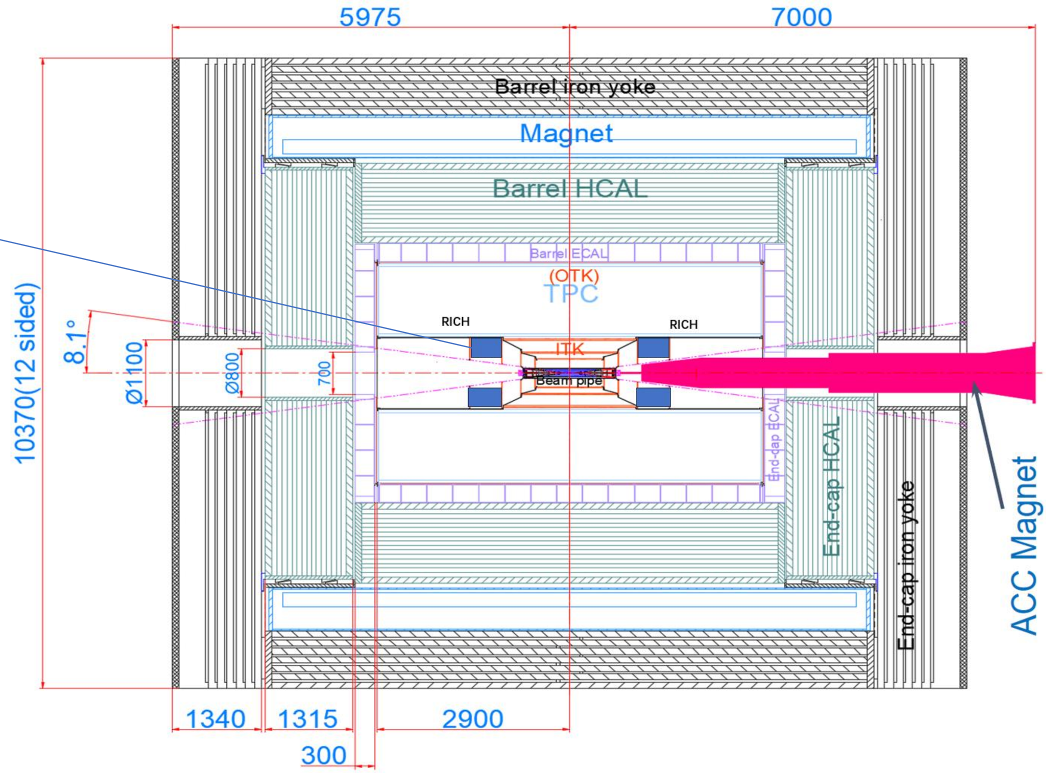
Investigation of an Endcap Cherenkov detector for CEPC

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Cherenkov detector



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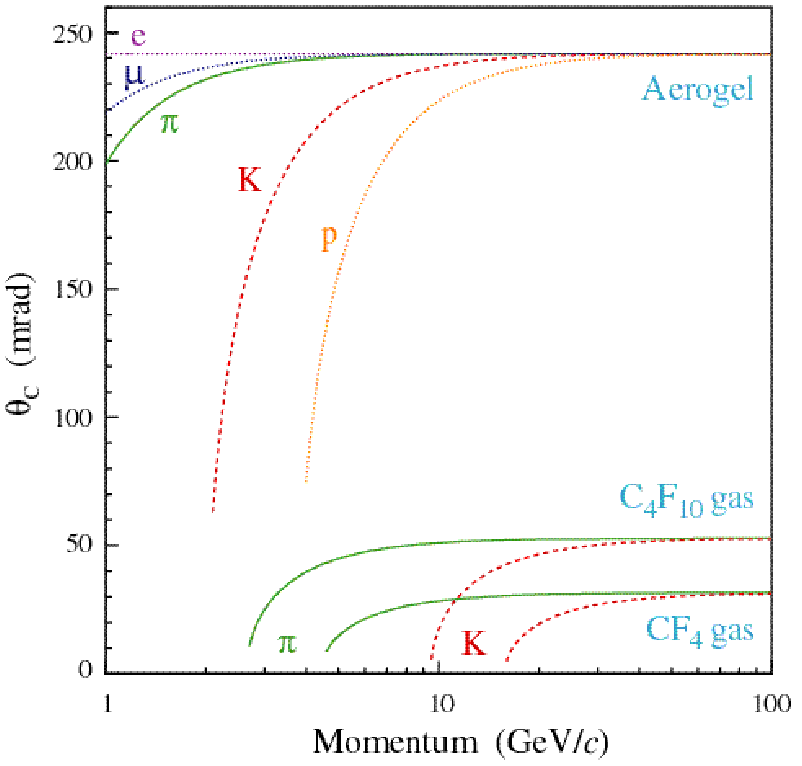
July 15, 2026, Guangzhou

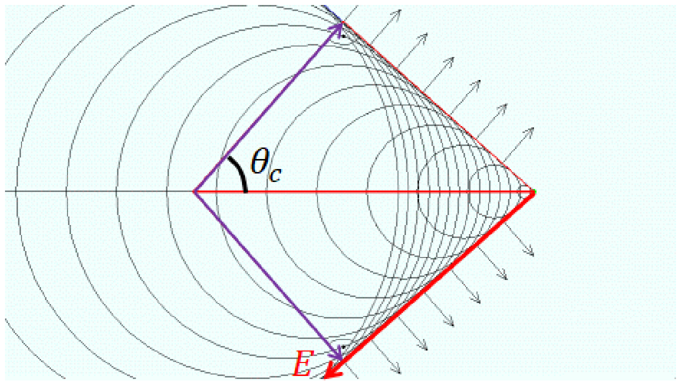
A reminder of the Cherenkov detector

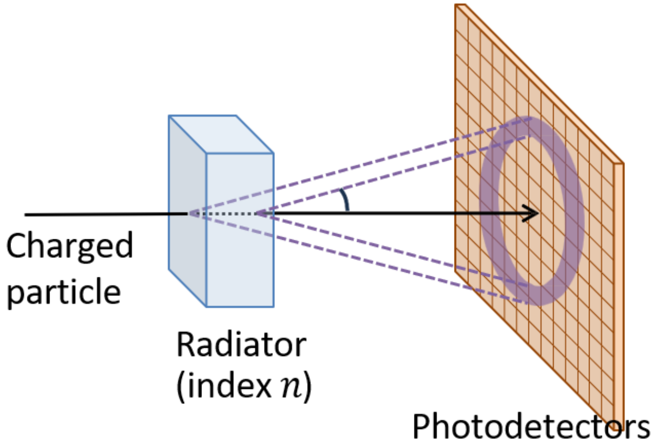
- A powerful detector for particle identification (PID), covering a wide range of momenta from 1-100 GeV/c

LHCb Cherenkov detector as an example:
2-100 GeV/c, different radiators



RICH-1 (Aerogel+C_4F_{10} gas radiator)
RICH-2 (CH_4 gas radiator)





RICH 2025, Kodai Matsuoka

Threshold: $\beta > 1/n$

Cherenkov angle: $\cos\theta_c = \dfrac{1}{n\beta}$

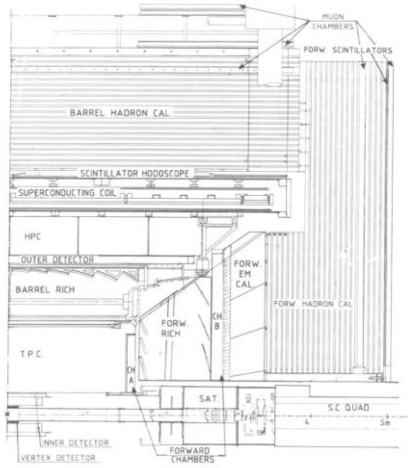
Number of photons: $\dfrac{dN_\gamma}{dE} = \left(\dfrac{\alpha}{\hbar c}\right) Z^2 L \sin^2\theta_C$

Separation power: $N_\sigma \approx \dfrac{|m_1^2 - m_2^2|}{2P^2\sigma[\theta_c(tot)]\sqrt{n^2-1}}$

Cherenkov detectors widely used in multiple experiments

- including particle /nuclear/astro-/neutrino physics experiments around the world

  -DELPHI, CLEOIII, BABAR, BELLE I & BELLE II, LHCb, ALICE, COMPASS, STAR, PANDA, NA62, CLAS12 , AMS02… (neutrino experiments not listed here yet)



DELPHI

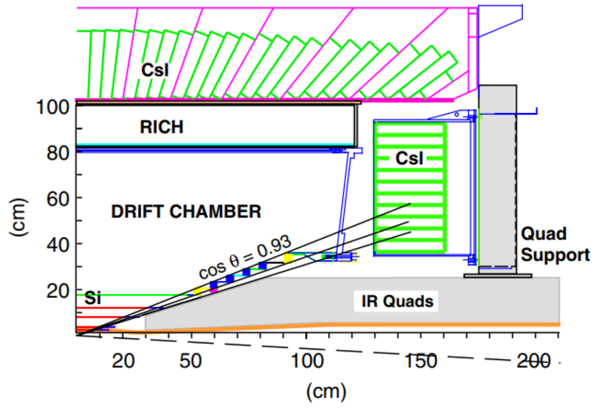
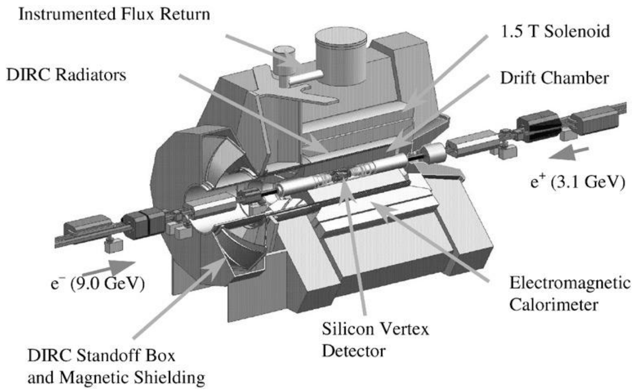
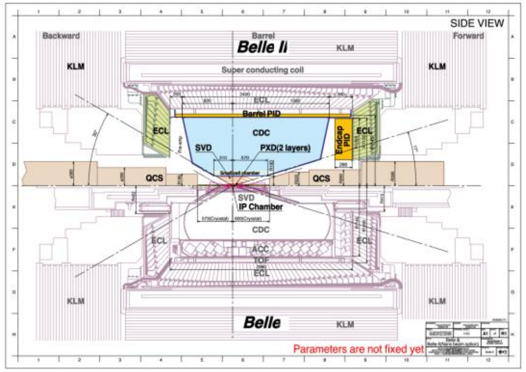


Fig. 3. The CLEO RICH, shown in CLEO-III configuration.

CELOIII



BABAR



BELLE II

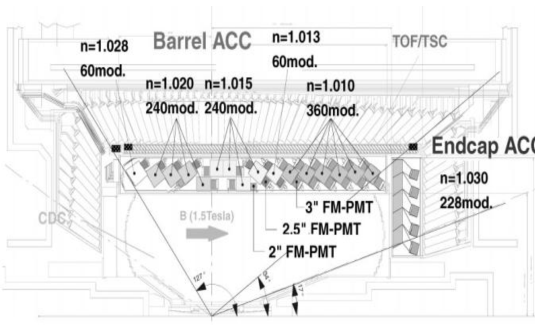


Fig. 1. Schematic drawing of the BELLE-ACC system.

BELLE I

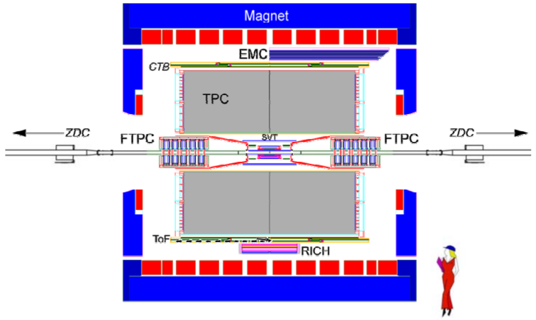
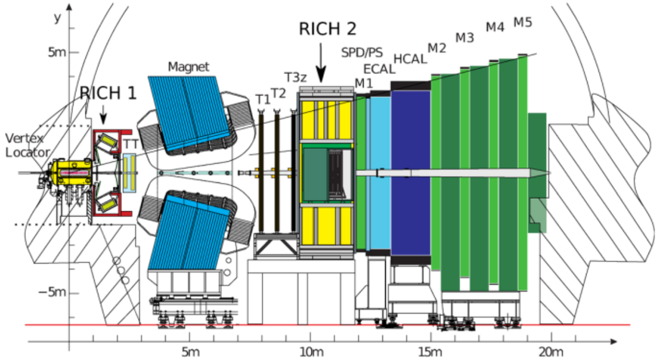
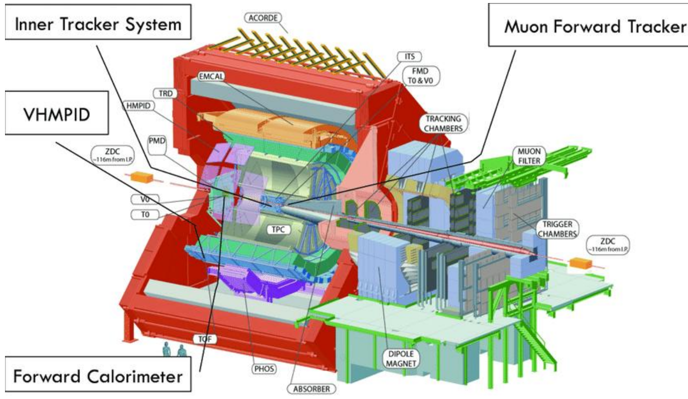


Fig. 2. Cutaway side view of the STAR detector as configured in 2001.

STAR



LHCb



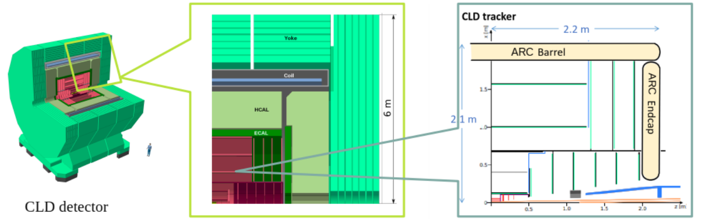
ALICE

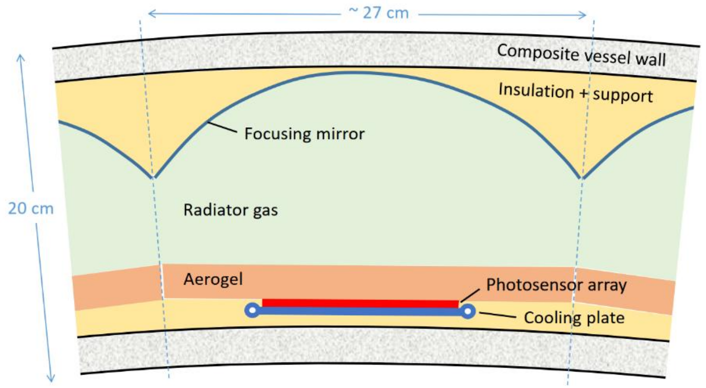
Proposed also by the future experiments

- Such as FCC-ee, EIC, STCF …

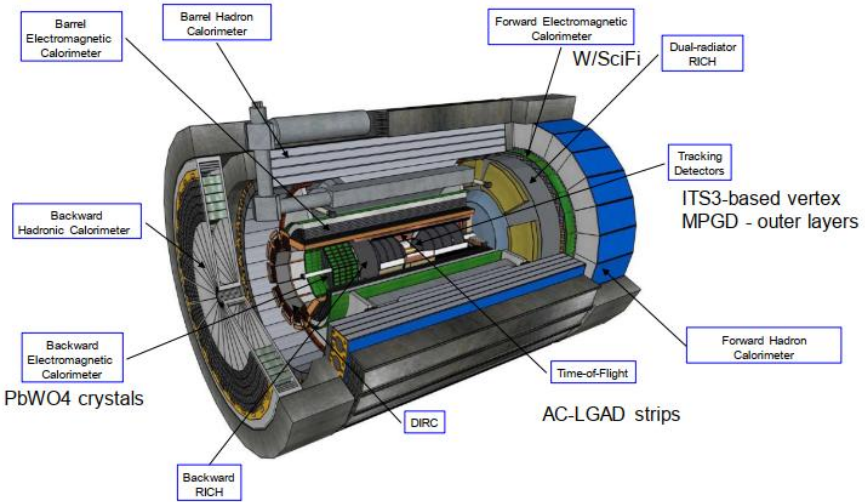
Design of Array of RICH Cells (ARC)

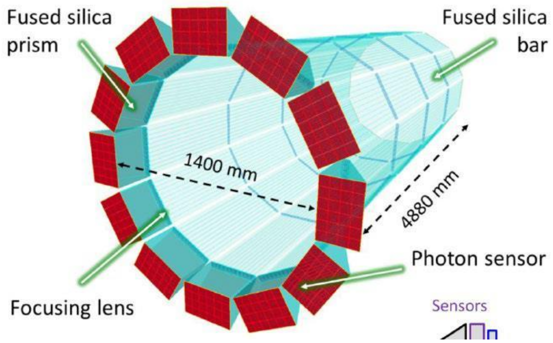
- The ARC was designed to be integrated with the CLD detector, between the tracker and the ECAL
- The ARC thickness is 20 cm, the barrel length is 4.4 m and the endcaps are placed as the bases of the barrel

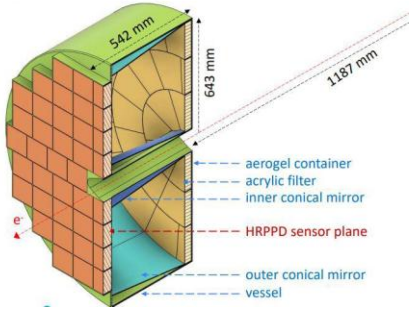




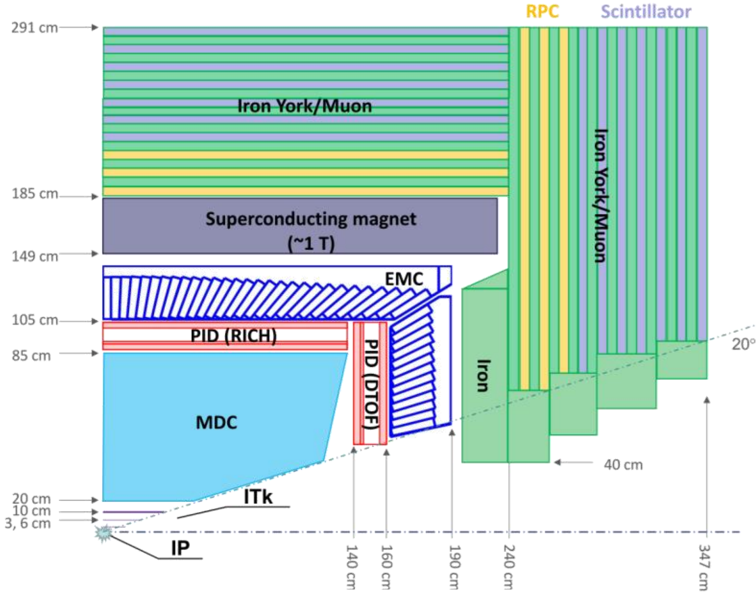
FCC-ee (CLD detector concept)

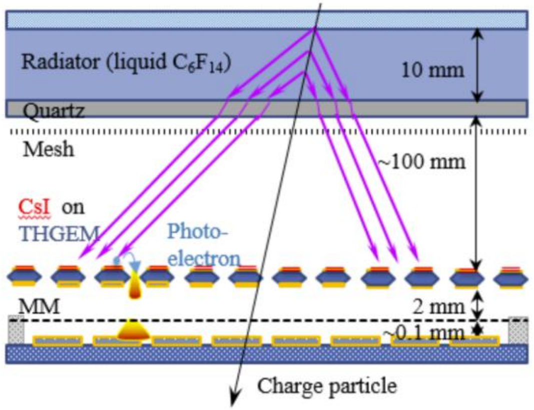






ePIC detector at EIC





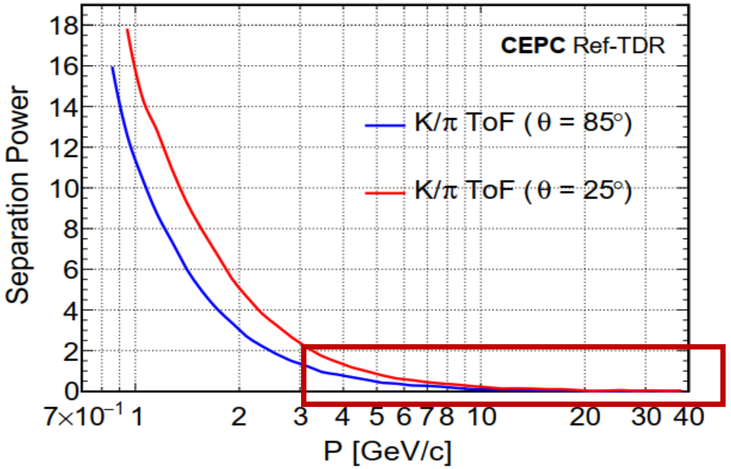
THGEM + MM

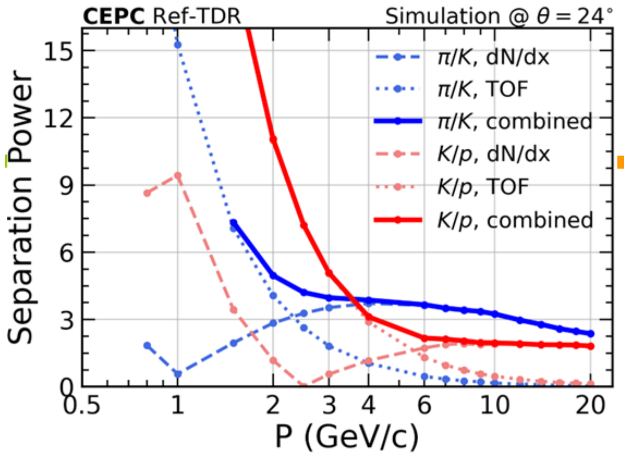
STCF

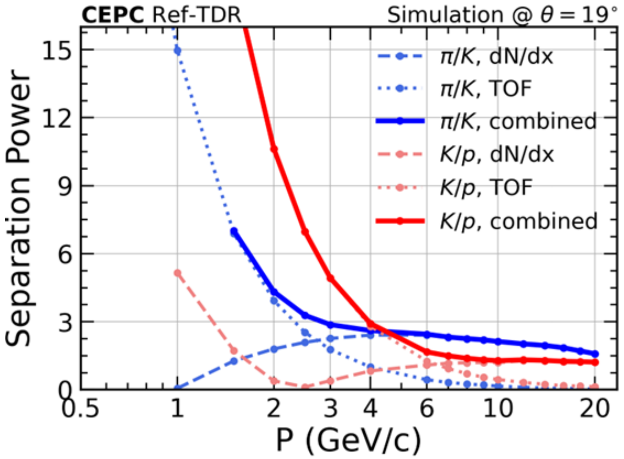
Motivation of the Cherenkov detector for CEPC

- Improve PID performance for:
  - High-momentum range (3-20 GeV/c), in which TOF-based PID performance is degraded
  - Small-angle endcap region (8°–20°), TOF&TPC combined PID performance is worsening

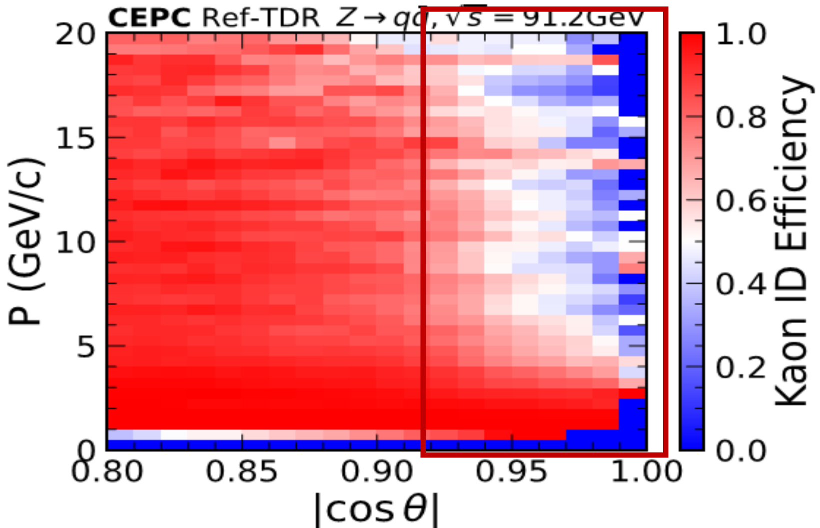
TOF standalone (Ref-TDR)

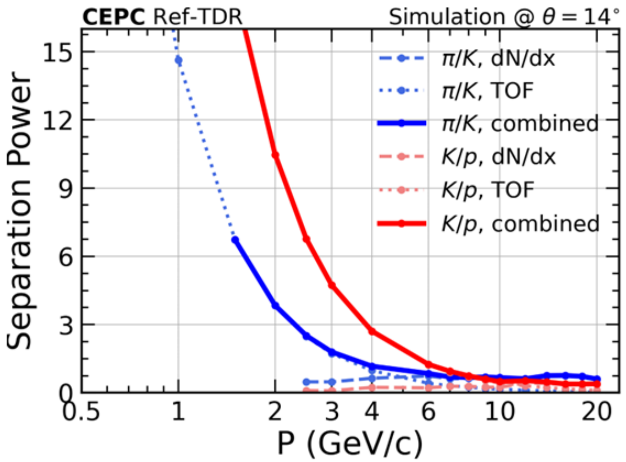


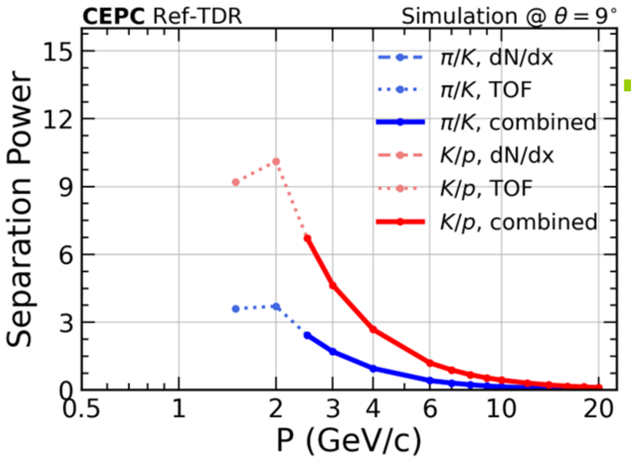




Kaon ID efficiency (Ref-TDR)



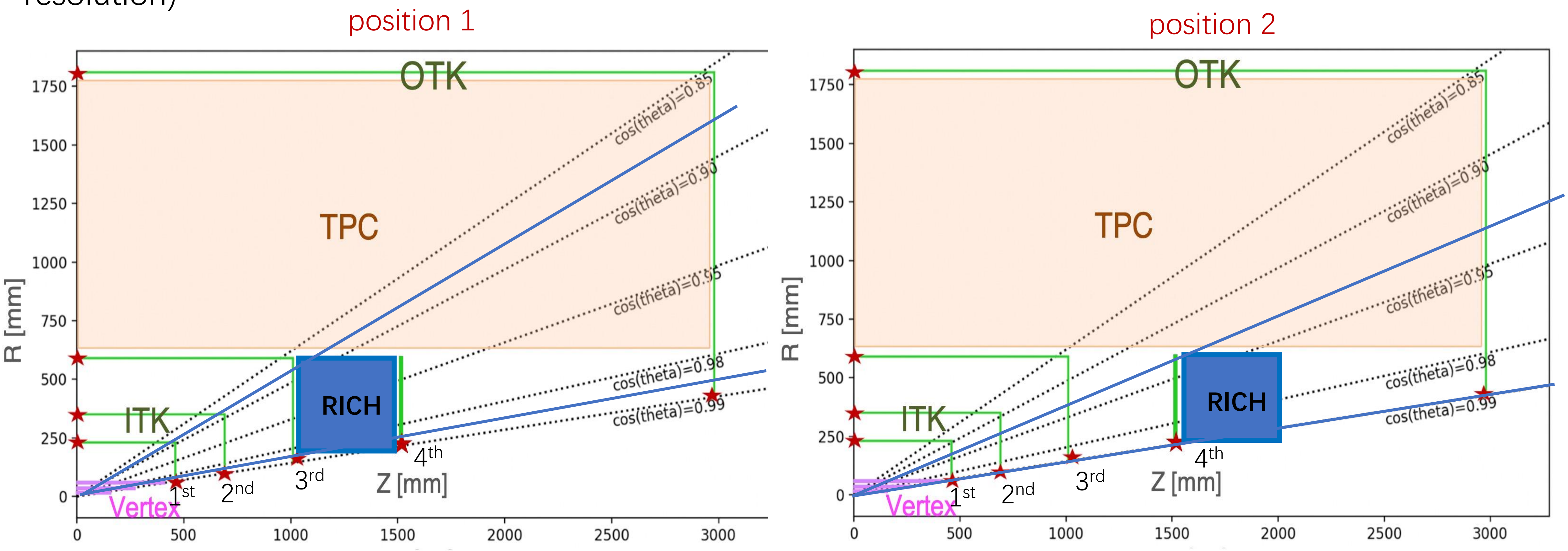




Possible locations of the Cherenkov detector

- 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)



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

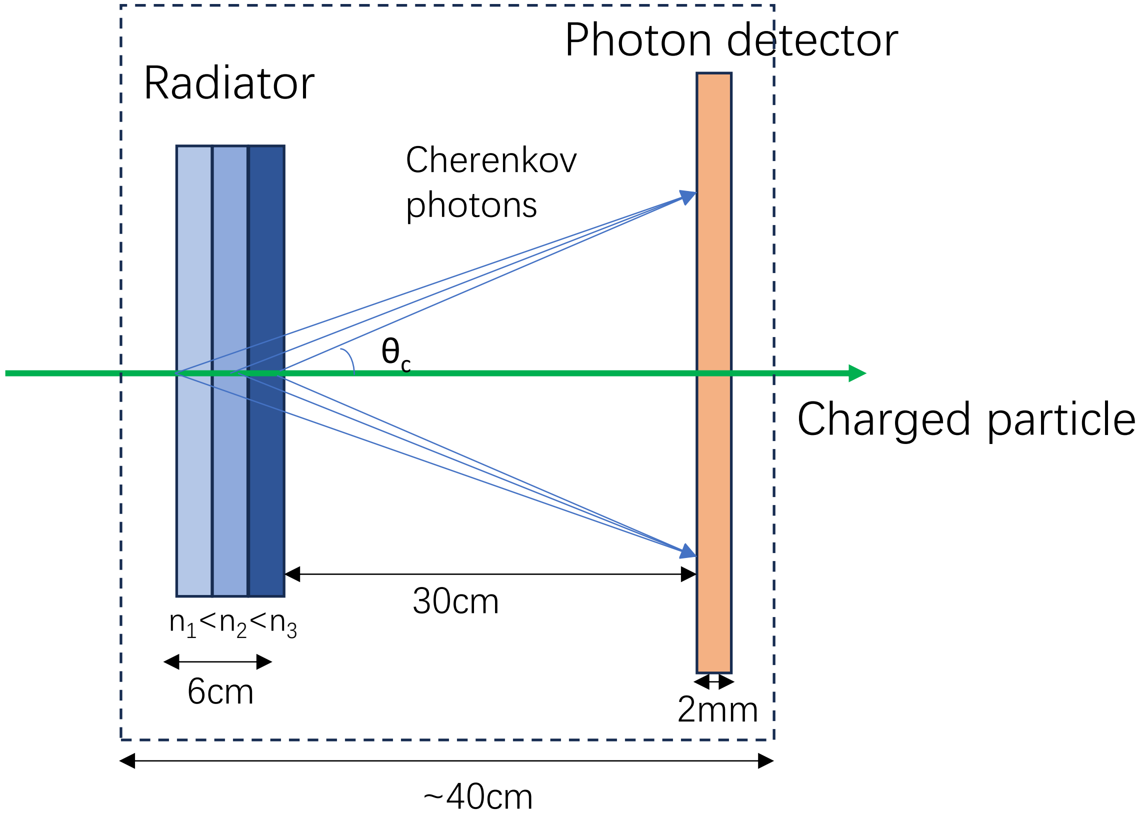
Coverage: 8.8° <θ < 20.3°
or 0.94<cos θ< 0.99

Conceptual design of the Cherenkov detector

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

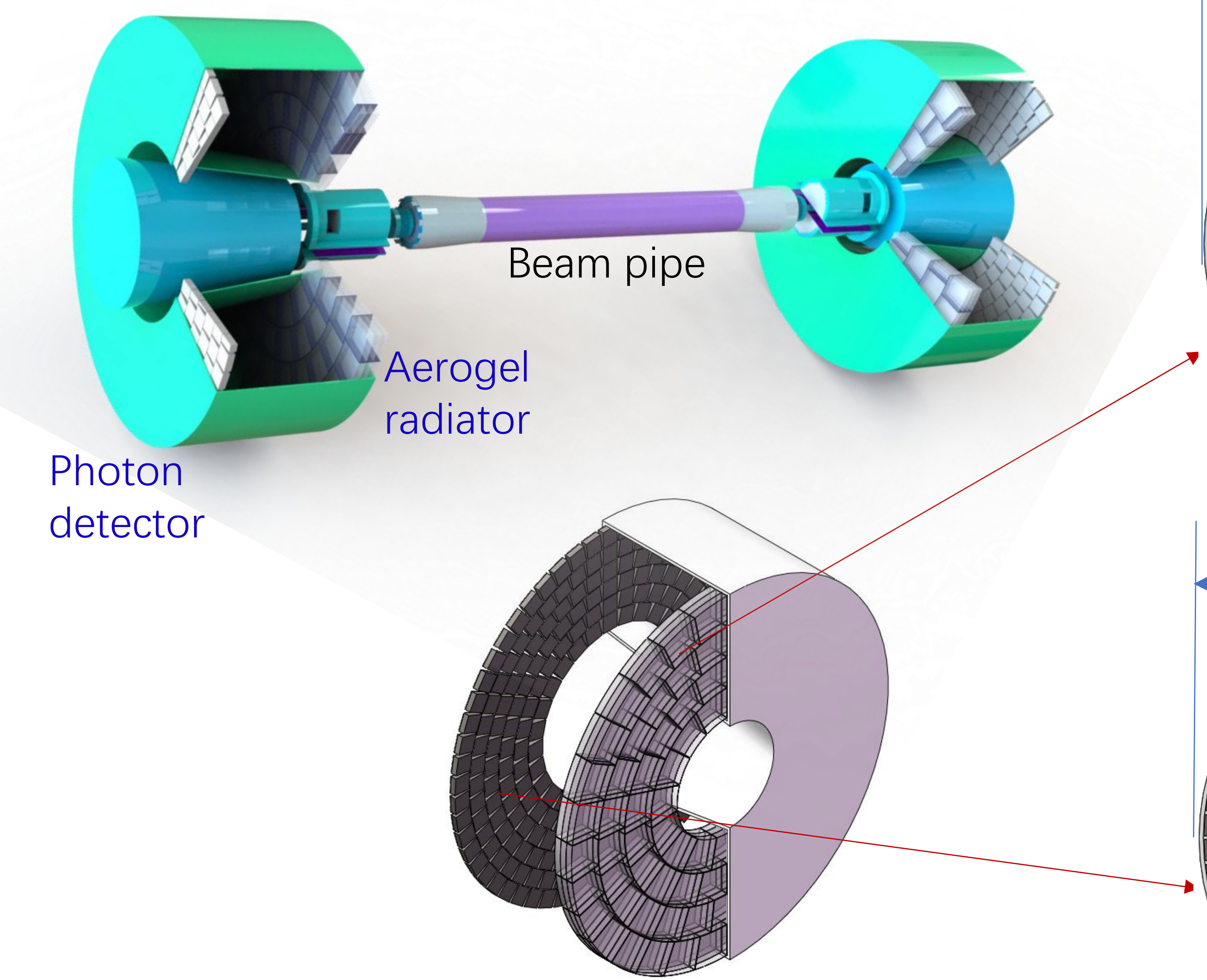
- Multiple layers of aerogel radiators with varying refractive index (n);
- A photon detector used for Cherenkov light detection;
- An expansion gap with a length (L) of around 30 cm;

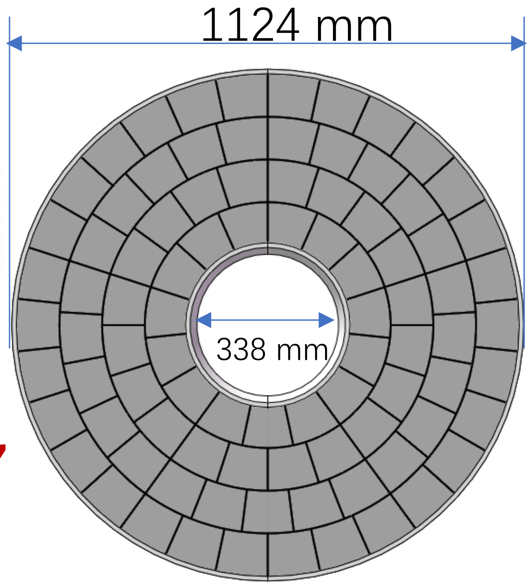
Reference: T.Iijima, NIM A548 (2005) 383; A.Yu.Barnyakov, NIM A553 (2005) 70; D. Sharma, NIM A1061 (2024) 169080



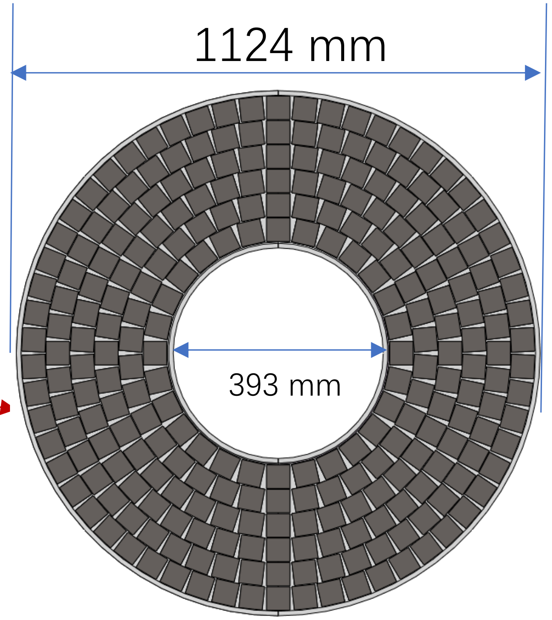
A schematic diagram of the conceptual design

A conceptual drawing of the Cherenkov detector





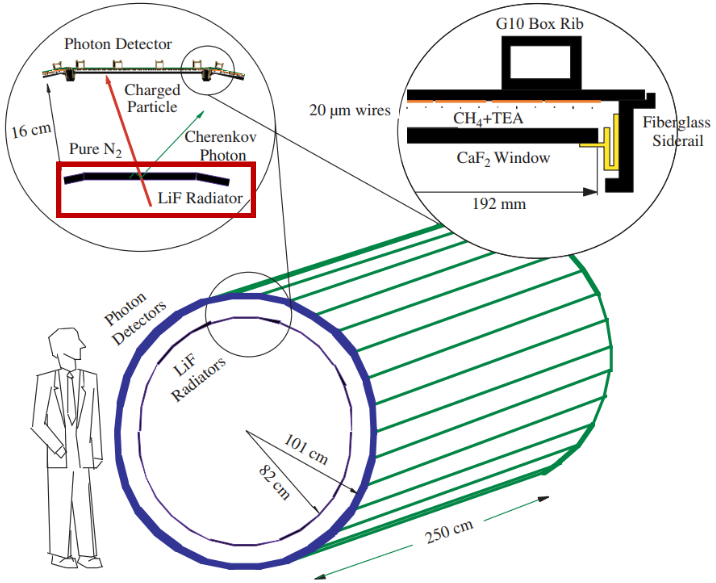
Radiator : ~0.9 m^2
-90 aerogel tiles in 4 layers
-each tile of ~10 cm x 10 cm in size



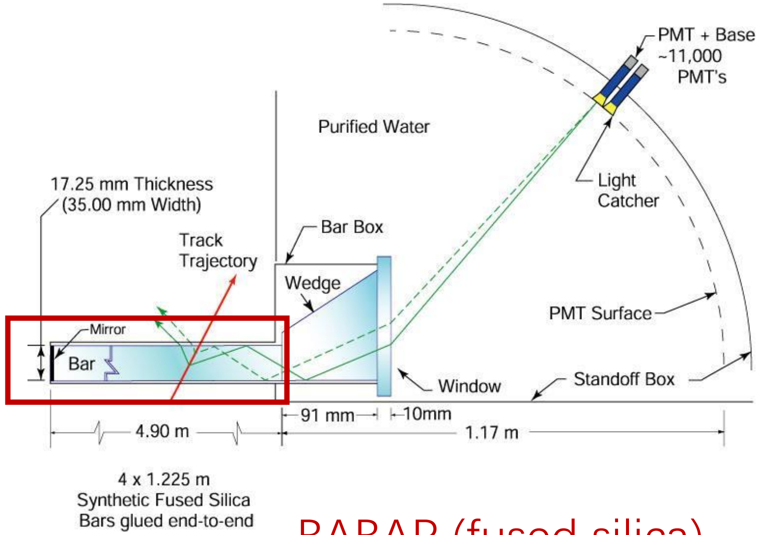
Photon detector: **~0.8 m^2**
-258 photosensor module in 6 layers
-each module of ~5 cm x 5 cm in size

Investigation of the radiator of Cherenkov detector

- Different radiators used:
  - Solid-state or liquid: LiF, NaF, fused Silica, C_6F_{14}(liquid)
  - Gaseous: CF_4, C_4F_{10}, C_5F_{12}
  - Aerogel (silica aerogel)
  - Hybrid: aerogel + gas

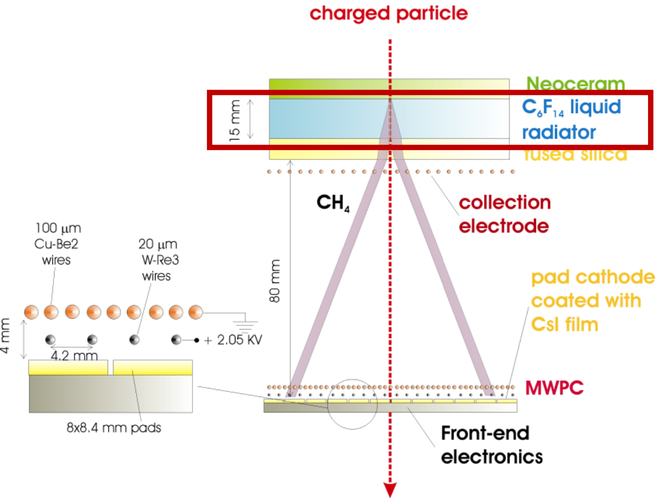


CLEOIII (LiF crystal)

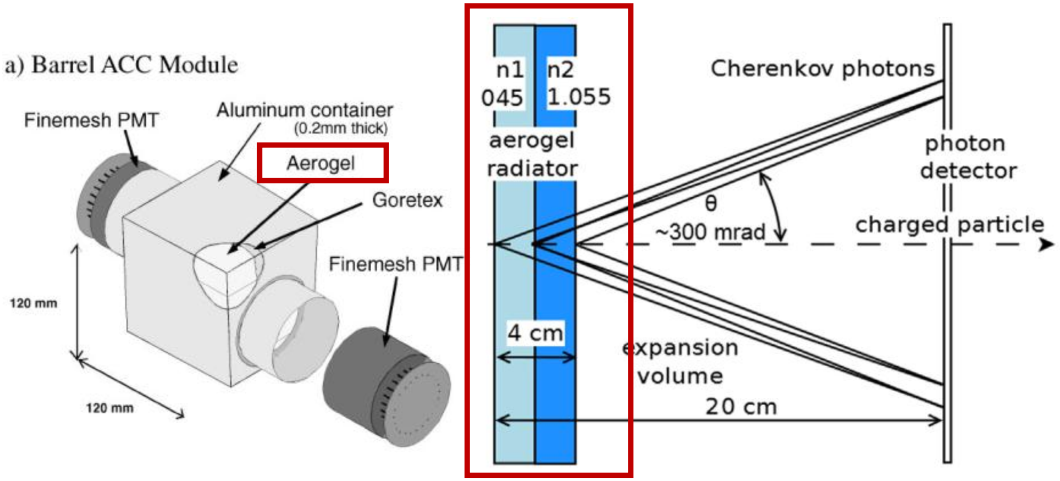


BABAR (fused silica)

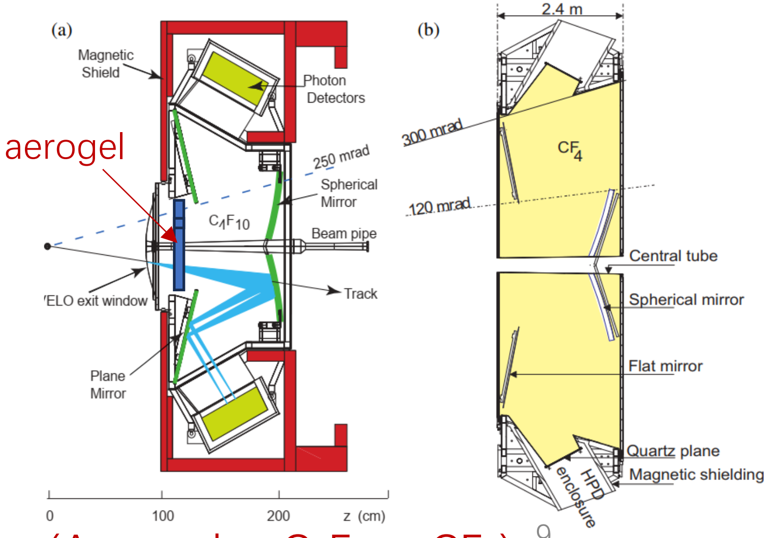
NIM A 554 (2005) 147–194



ALICE (liquid C_6F_{14})



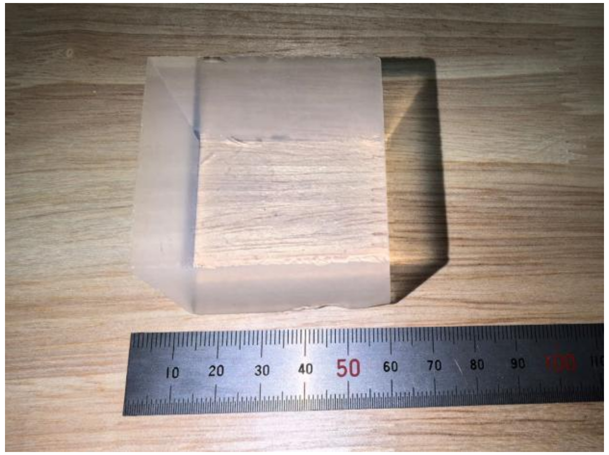
Belle I & Belle II (silica aerogel)



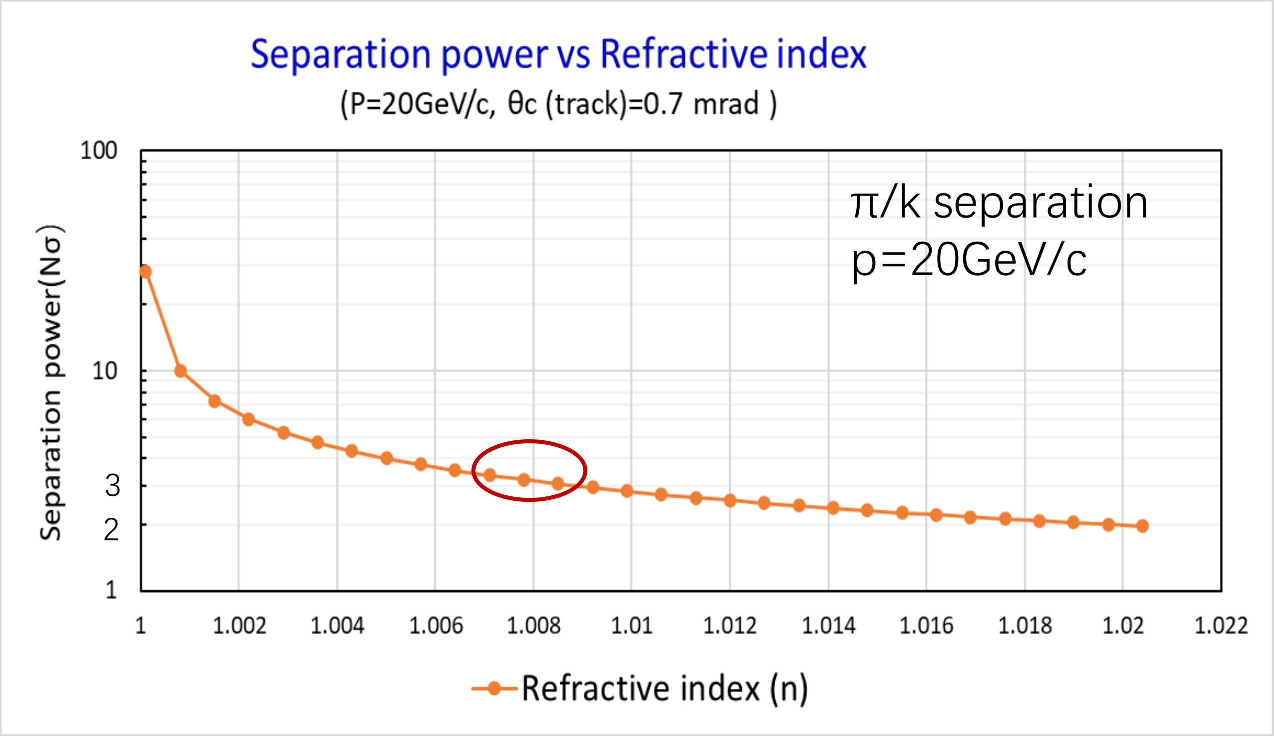
LHCb (Aerogel + C_4F_{10}+ CF_4)

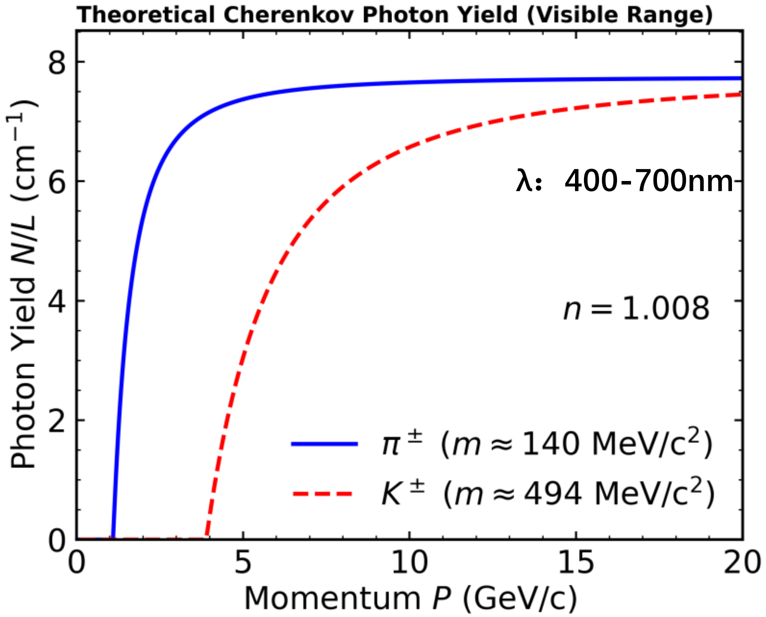
Silica aerogel as a radiator

- 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





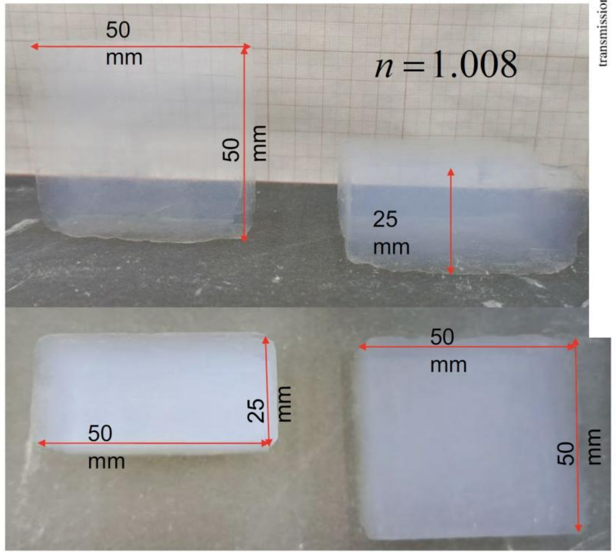
Aerogel radiator R&D

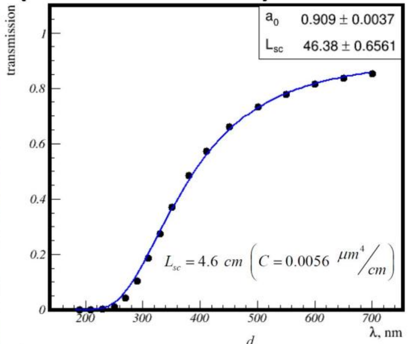
- Working with BINP group,Russia

From Alexander Barnyakov, BINP

Results from BINP

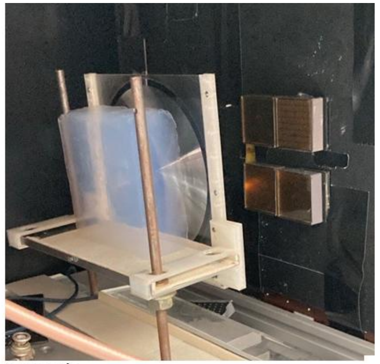
Aerogel with n=1.008 (Novosibirsk)





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

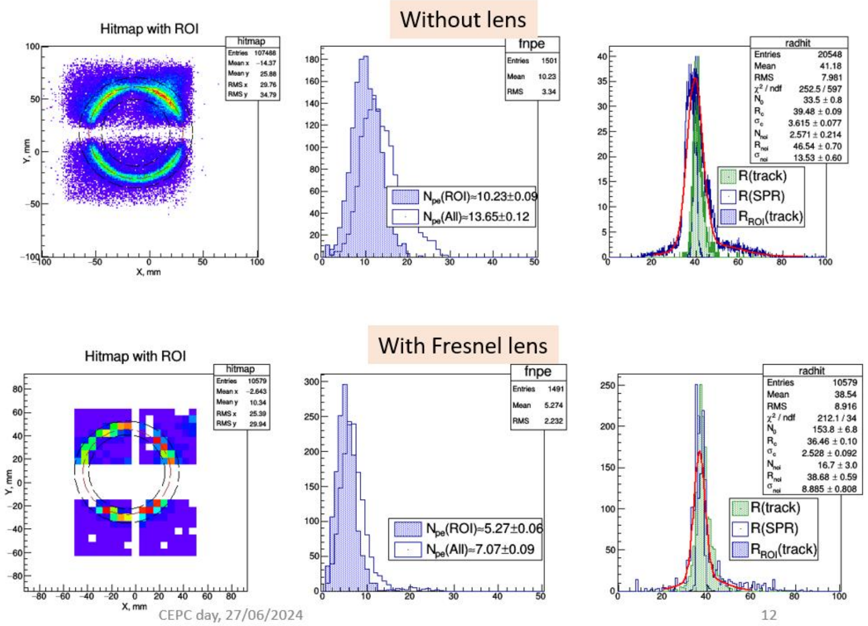
d – thickness of a sample,
λ – wavelength in nanometers,
Lsc – scattering length at 400 nm,
a_0 – surface scattering coefficient,
C – clarity coefficient



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

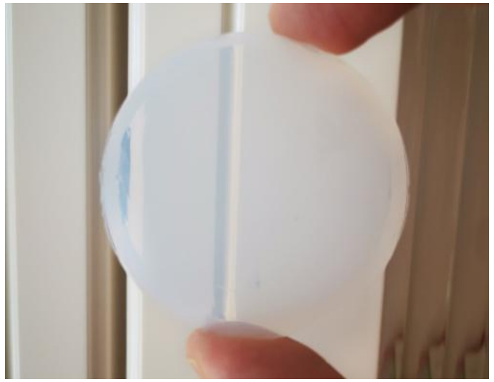
Fresnel lens:
- Acrilic (PMMA)
- L_f=6''
- Manufacturer: Edmund

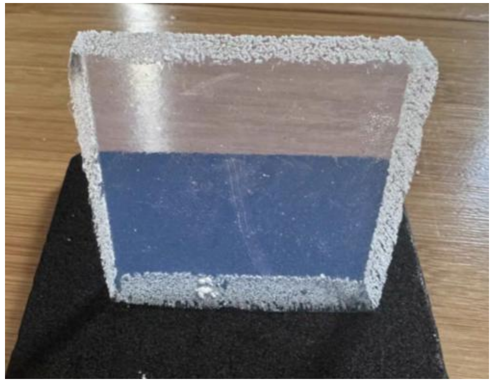
PMT:
- 4 Hamamatsu H12700
- pixel 6x6 mm



- Some commercial aerogels were bought at IHEP

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





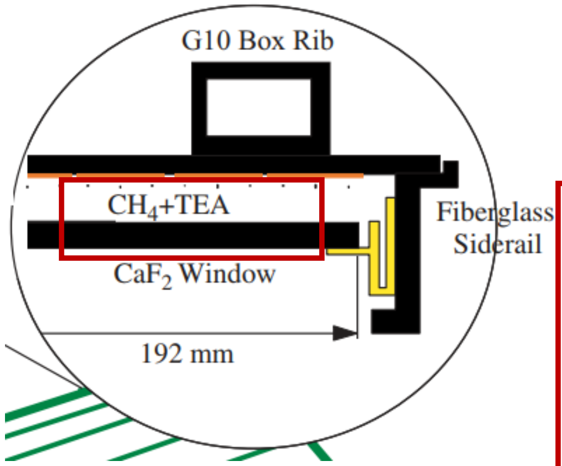
Investigation of the photon detector

- Photon detectors used in past or current Cherenkov detectors in others experiments

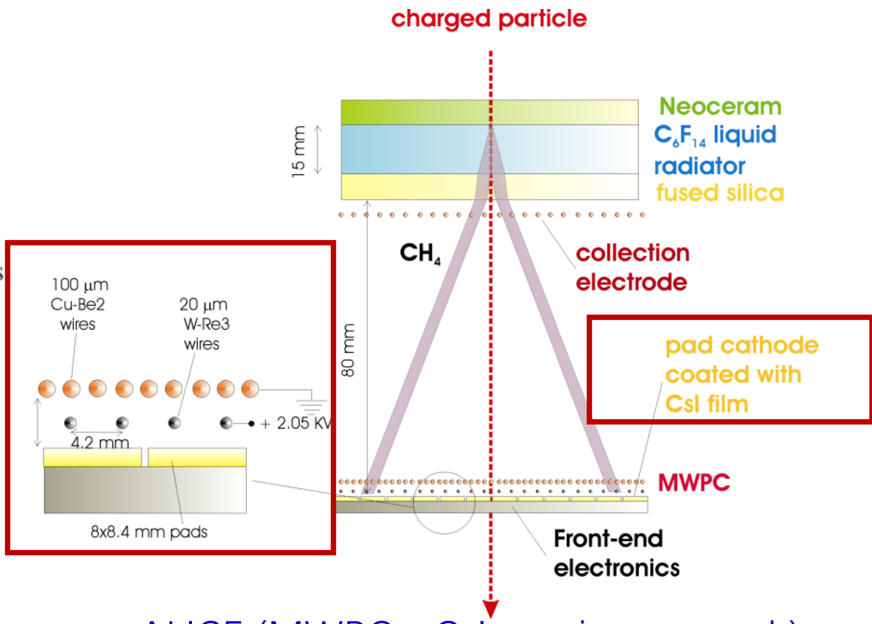
  - Gaseous chambers: TPC-like / MWPC filled with photoionizing gas (TEA, TAME) or coated with photocathode layer (CsI)

  - PMTs: dynode-PMT (fine-mesh, metal channel), MCP-PMT, Multi-anode PMTs

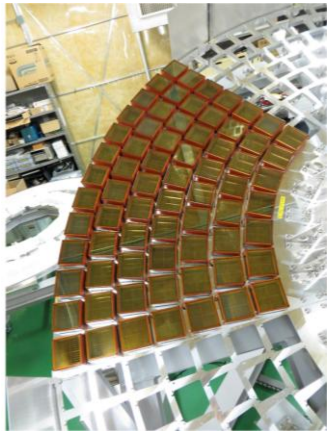
  - Hybrid detectors: HPD or HAPD (hybrid photon detector/ hybrid avalanche photon detector



CLEO III (MWPC with CH_4 +TEA(triethylamine)

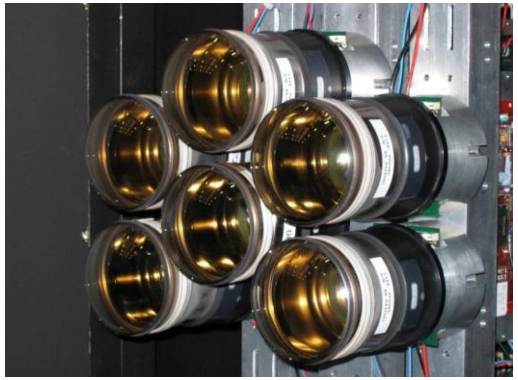


ALICE (MWPC +CsI coating on pad)



Multi-anode HAPD (Belle II endcap)

MCP PMT (Hamamatsu R10754-07-M16),   Belle II barrel(iTOP)



HPD (LHCb RUN1&2)

Multi-anode metal-channel dynode PMT (LHCb RUN3)

Consideration of SiPM as the photon detector

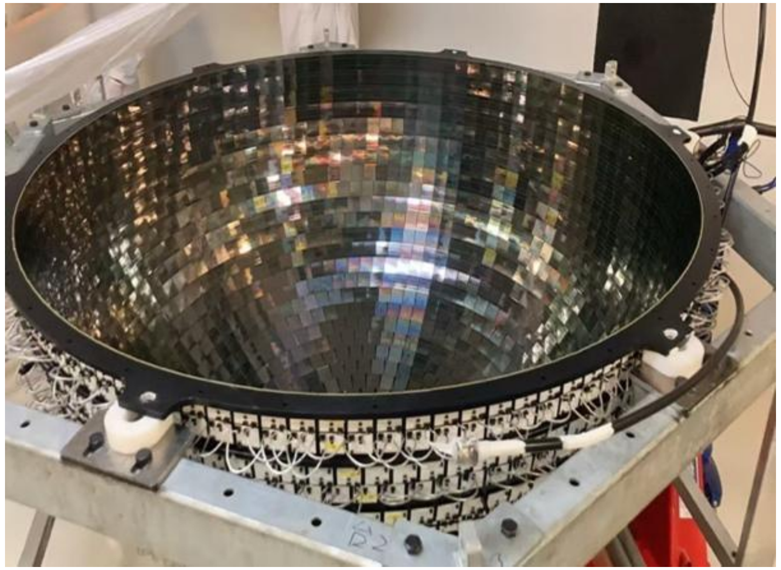
- SiPM is under extensive R&D by a variety of experiments, and shows promise for the future Cherenkov detector applications

➢ 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

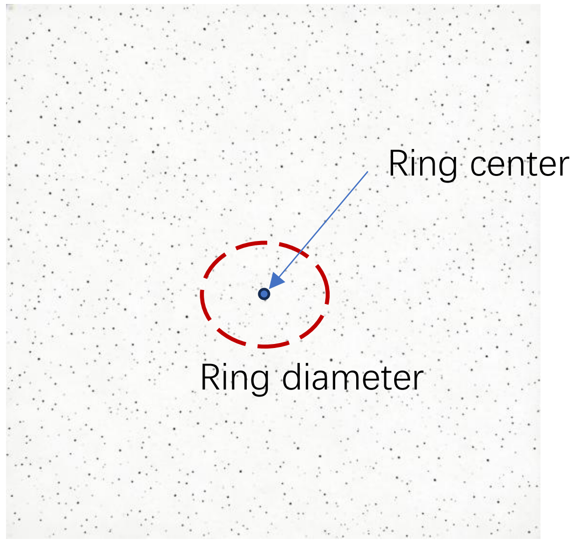
- Dark noise generated hits in the whole photodetector plane: N ≈ 10,000, by applying
  - a typical dark noise rate : 200 kHz/mm^2
  - readout time window: 69 ns(same as VTX, ITK, OTK, Ecal, Muon)
  - photon detector area: 0.8 m^2

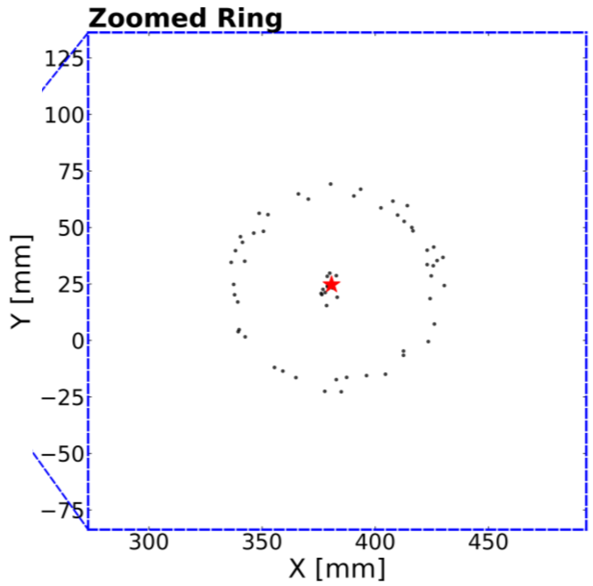
- After associated the event with trackers: N ≈100 in the interesting region
  - Ring diameter (max. ~ 8 cm) limitation, and intersection point (ring center) extrapolation
  - dark noise hits reduced by a factor of ~100

- 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.

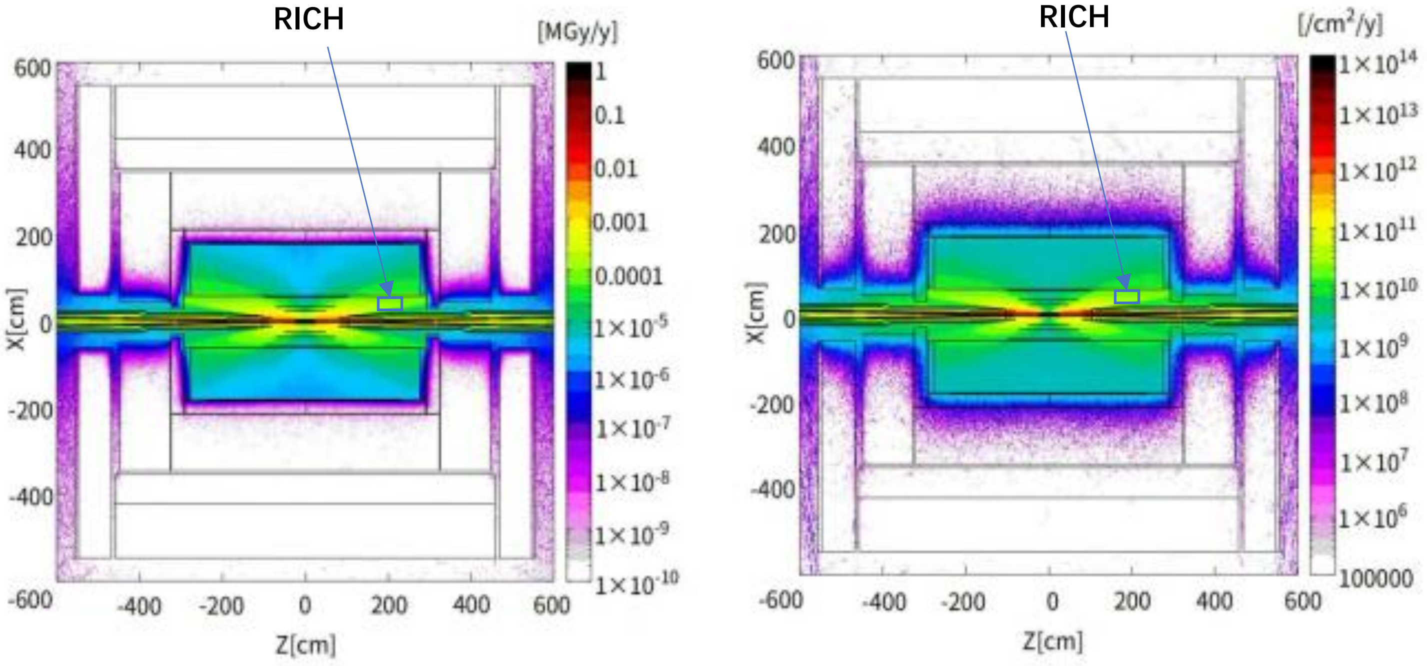




Consideration of the SiPM radiation tolerance

- 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.



(a) (b)

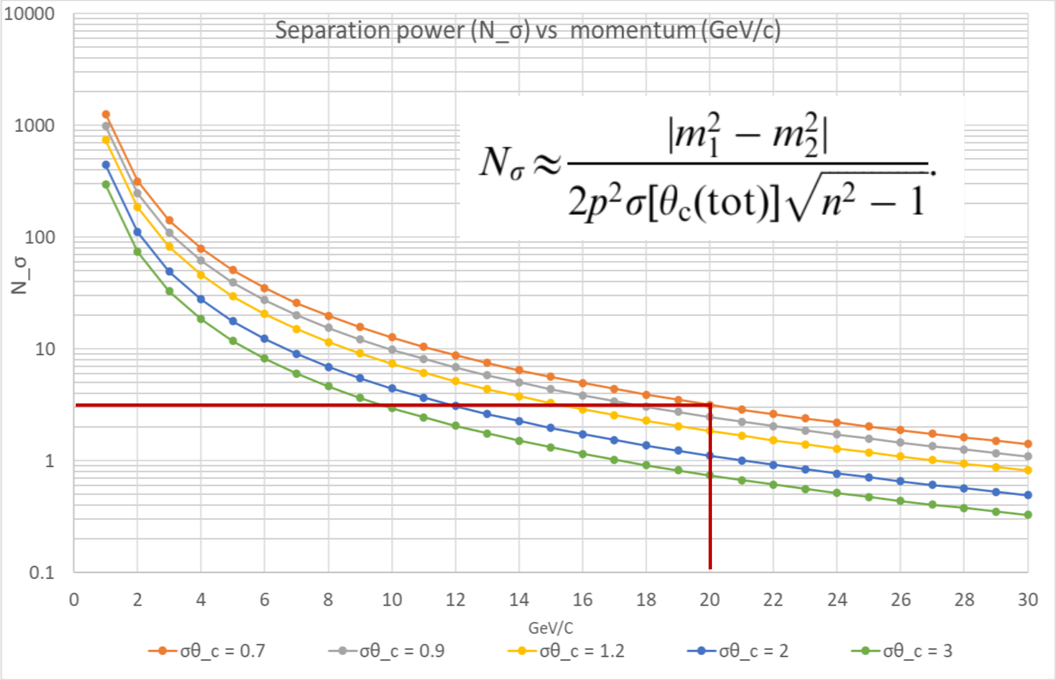
Figure 3.12: The TID and NIEL distributions at Higgs mode on the CEPC detector. The highest TID is lower than 1 MGy per year as shown in a.), while the highest level of NIEL is in the order of $10^{13}(1\ MeVn_{eq})cm^{-2}$ per year as shown in b.).

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

Consideration of the SiPM spatial resolution

- To achieve 3σ K/π separation at 20 GeV/c, a good Cherenkov angle resolution ($\sigma(\theta c(tot))$) of 0.7-1.0 mrad is needed, i.e. the single photon angular resolution requires about 3-4 mrad;

- Resolved the spatial resolution from the angle resolution, requires $\sigma_{spatial} \approx$ 300 μm;



$$\sigma(\theta c(tot)) = \frac{\sigma(\theta c(1pe))}{\sqrt{Npe}}$$
$$= \frac{1}{\sqrt{Npe}} \left(\sqrt{\sigma_{spatial}^2 + \sigma_{thick}^2 + \sigma_{track}^2 + \sigma_{chromatic}^2}\right)$$
$$= \frac{1}{\sqrt{Npe}} \left(\sqrt{\left(\frac{\Delta_{size}}{L\sqrt{12}}\right)^2 + \left(\frac{t \sin\theta_C}{L\sqrt{12}}\right)^2 + \sigma_{track}^2 + \left(\frac{\Delta_n}{n \tan\theta_C}\right)^2}\right.$$

Assuming: $\Delta size = 1mm$, $t = 20mm$, $\sigma_{track} = 0.5mm$, $\Delta_n = 0.0001 (n = 1.008)$, $Npe = 15$,
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 (one readout for each SiPM); or 3x3mm^2 or 6x6mm^2 (with charge sharing readout)	position sensitive SiPM (for 3x3 or 6x6 mm^2) is an option
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..

Some investigation on PS-SiPM

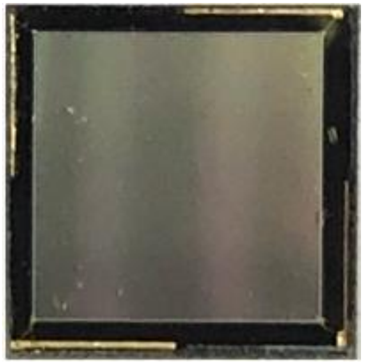
From Fudan University, Xiaolong Wang, etc.

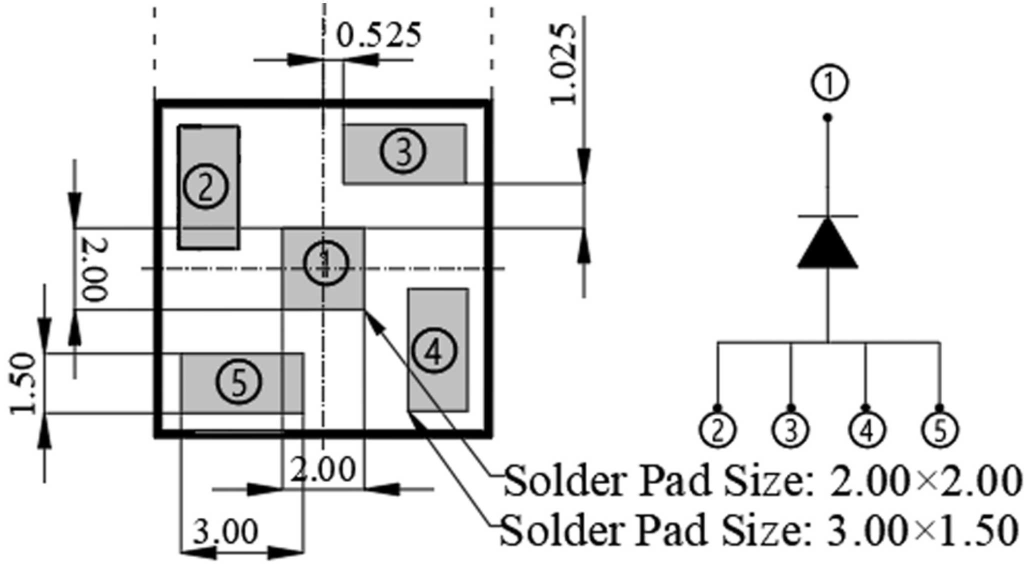
- **Parameters from NDL PS-SiPM series**

Type	PSS 11-3030-S	PSS 11-6060-S
Effective Pitch	10 μm	20 μm
Active Area	3.0×3.0 mm^2	6.24×6.24 mm^2
Micro-cell Number	10000 /mm^2	2500 /mm^2
Typical Breakdown Voltage (V_B)	26.5 V	27.5 V
Peak PDE @420nm	32 %	40 %
Recommended Operation Voltage	V_B + 5 V	V_B + 5 V
Gain	2.0×10^5	8.0×10^5
Dark Count Rate (DCR)	650 kHz / mm^2	150 kHz / mm^2
Configuration of Anodes	Tetra-Lateral Anodes	Square-Bordered Anodes

Above parameters are measured at their recommended operation voltage and 20 °C.

PSS 11-6060-S





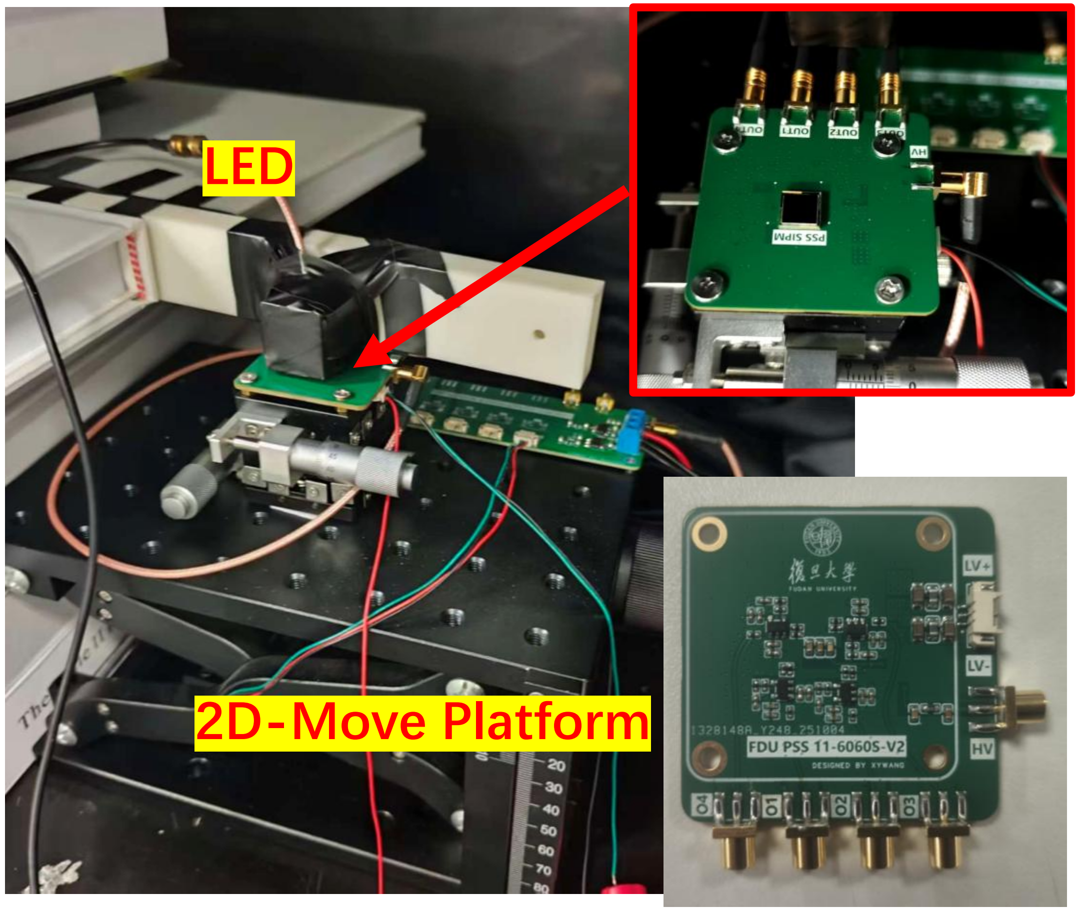
- **Position Algorithm**

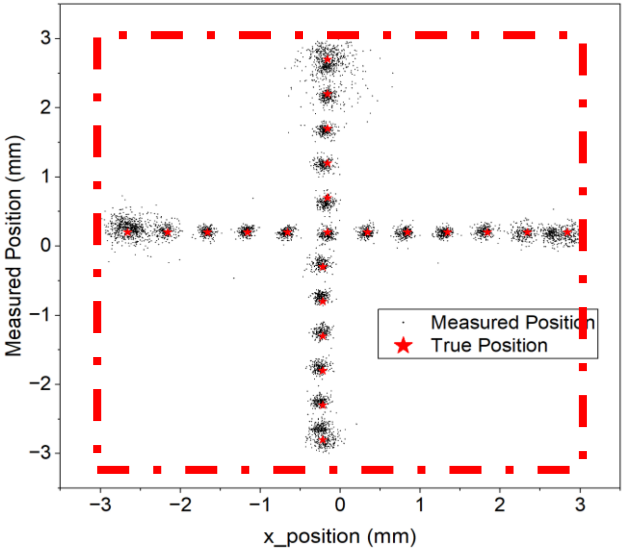
$$x_c = \frac{L}{2} \cdot k \cdot \frac{(Q_2 + Q_3) - (Q_1 + Q_4)}{(Q_1 + Q_2 + Q_3 + Q_4)}$$

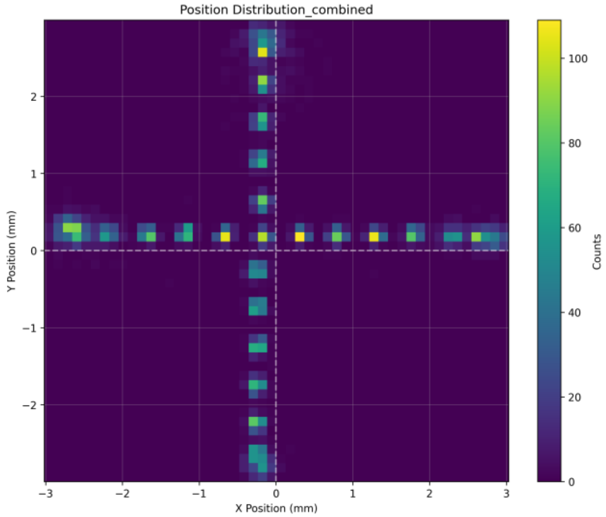
$$y_c = \frac{L}{2} \cdot k \cdot \frac{(Q_3 + Q_4) - (Q_1 + Q_2)}{(Q_1 + Q_2 + Q_3 + Q_4)}$$

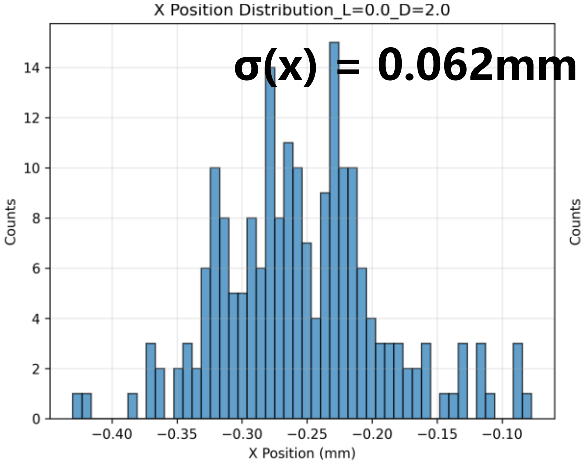
Preliminary test results of PS-SiPM

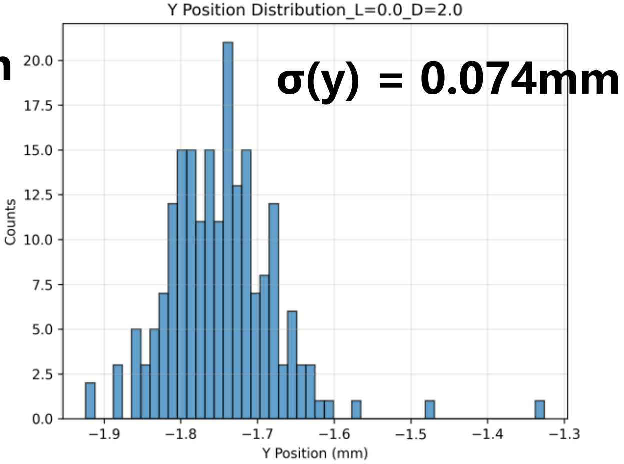
From Fudan University, Xiaolong Wang, etc.











- A system was designed to perform the X-Y scan on a single PSS 11-6060-S SiPM

- the positions can be reconstructed with good resolution ~ 100 μm

Simulation of the Cherenkov detector

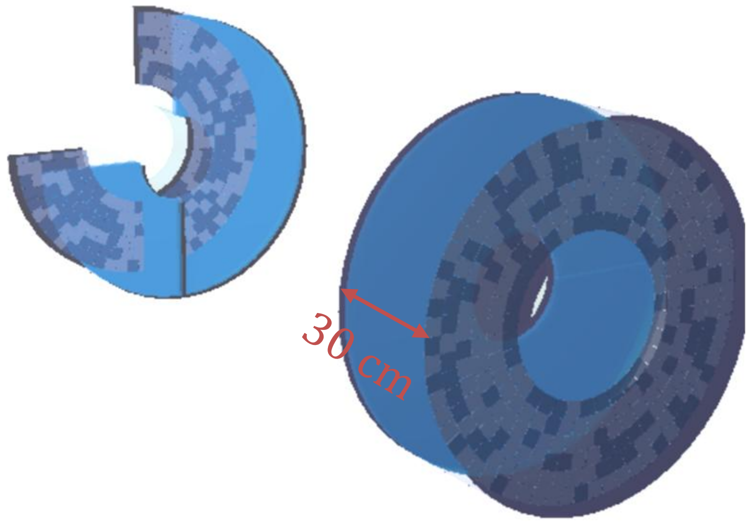
From IHEP Software group
Changru Li, Shensen Sun etc.

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

1. Aerogel: 3 layers of $\mathrm{SiO_2}$ $(\rho \approx \rho_{air}, n \approx 1.008)$
$r = 16.9{\sim}56.2\ \mathrm{cm}, z = 106.6\ \mathrm{cm}{\sim}112.6\ \mathrm{cm}$

2. Photon Detector (SiPM & PCB + electronics)
SiPM: G4_Si, PCB + electronics: Pb, Cu, C, O…
$r = 24.1{\sim}56.2\ \mathrm{cm}$

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

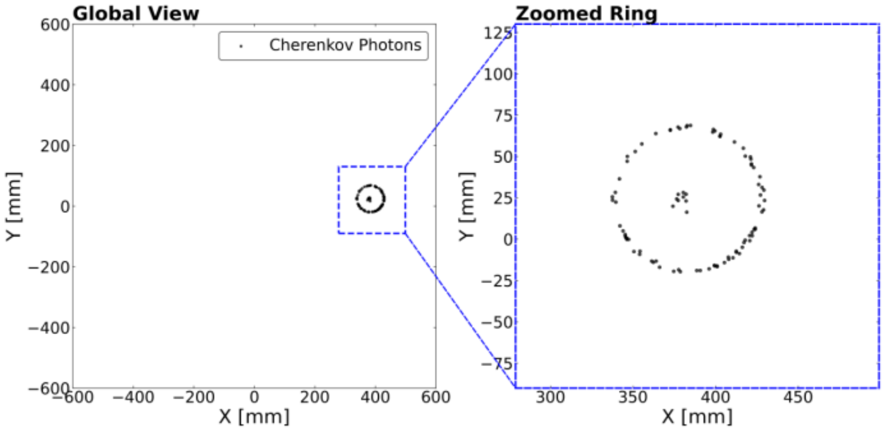


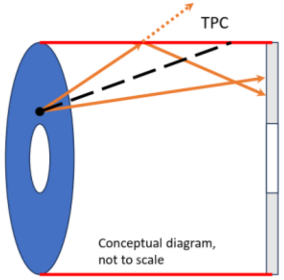
geoDisplay at CEPCSW, box clipped
30 cm from aerogel to SiPM
$5\ \mathrm{cm} \times 5\ \mathrm{cm}$ modules of PD

Preliminary results of simulation

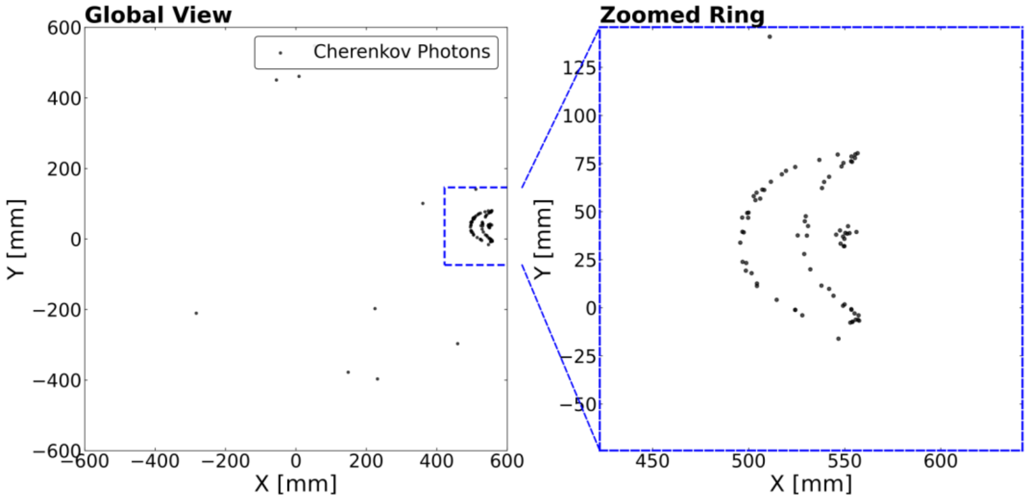
From IHEP Software group
Changru Li, Shensen Sun etc.

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

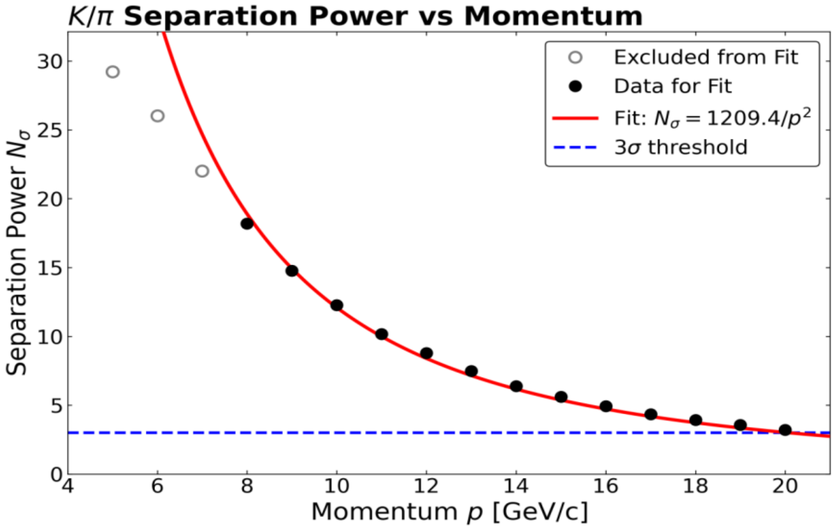


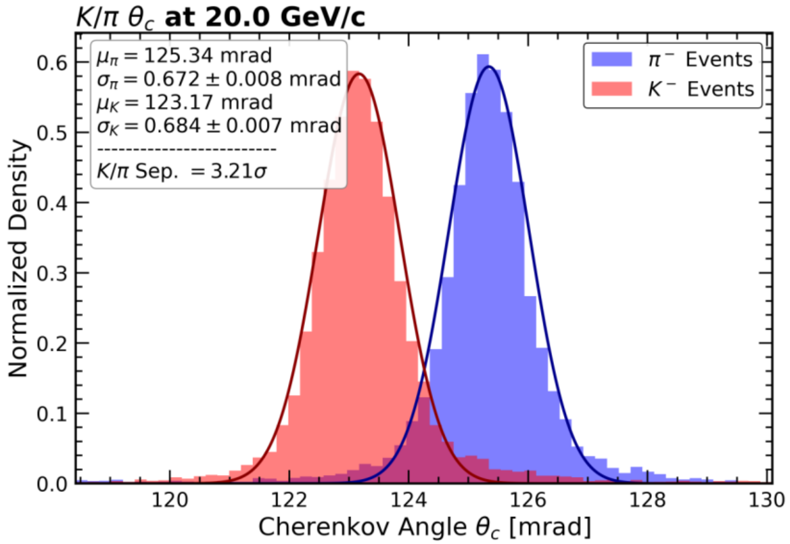


More complex topology after reflection



Preliminary performance: 3σ K/π separation up to 20 GeV/c



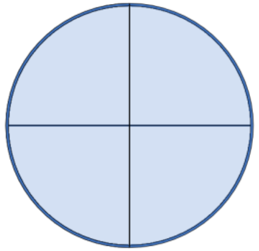


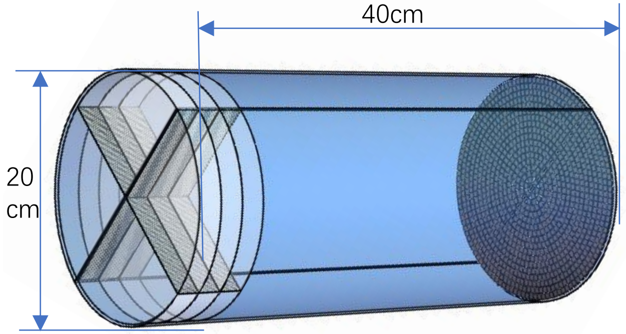
Plans for the further study

- there are a lot of things to do:
  - Overall detector design and specifications determination
  - Aerogel and SiPM investigation and testing
  - SiPM irradiation, cooling and annealing study
  - Reflector/Mirror design, mechanical design
  - Readout electronics consideration and design
  - Detector simulation and reconstruction
  - Build a prototype with aerogel and SiPMs
  - Finish the Cherenkov detector design (CDR&TDR) in 3-4 years
  - Join the CERN DRD4 (Photodetector & PID)

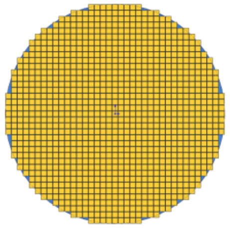
the prototype under consideration:
- diameter: 20cm;
- length: 40cm;

Silica aerogel





SiPM array



Thank you for your attention!
Welcome to join us!