UK meeting on detector R&D towards a future e^+e^- collider

5 July 2022

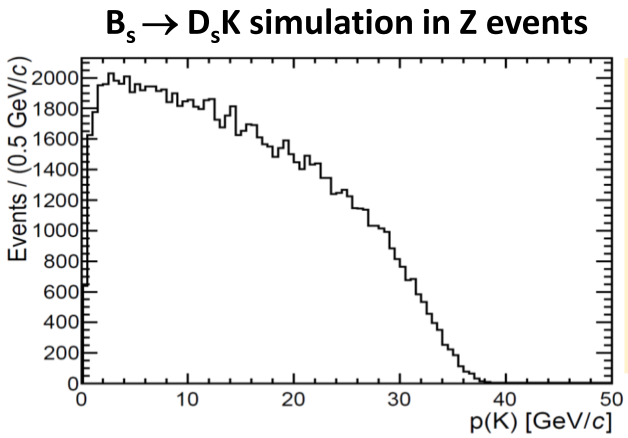
Opportunities in Particle ID

Roger Forty (CERN)

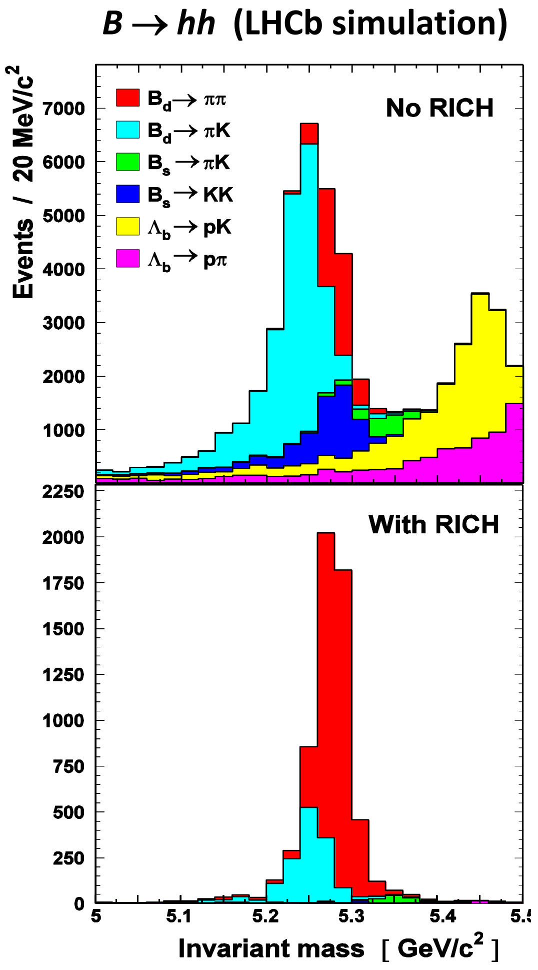
1. Brief review of the various options discussed for particle ID at e^+e^- colliders
2. More detailed discussion of a specific detector concept for a compact RICH

1. Options for Particle ID

- Dedicated detectors for particle ID—in particular charged hadron (π, K, p) separation—have not traditionally featured strongly in design of experiments for an e^+e^- Higgs Factory: focus has been more on precision tracking + particle-flow calorimetry
- Emphasis is changing with the study of circular machines like FCC-ee due to enormous statistics of Z decays foreseen (few x 10^{12})
  Opens the possibility of a world-class **flavour** physics programme, where PID will be essential, e.g. to separate the different signal processes:
- At the Z, momentum range to be covered for b-hadron decay products: 1– 35 GeV
- Studying charm and tau decays, separating H $\to b\bar{b}, c\bar{c}, s\bar{s}$, reinforcing the e-π separation of calo, provide additional physics cases

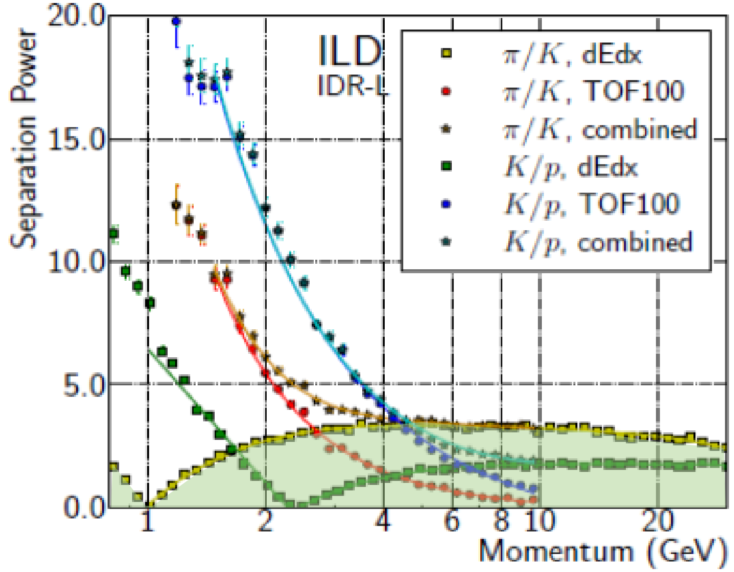


[IAS-HEP, 15/1/2021]



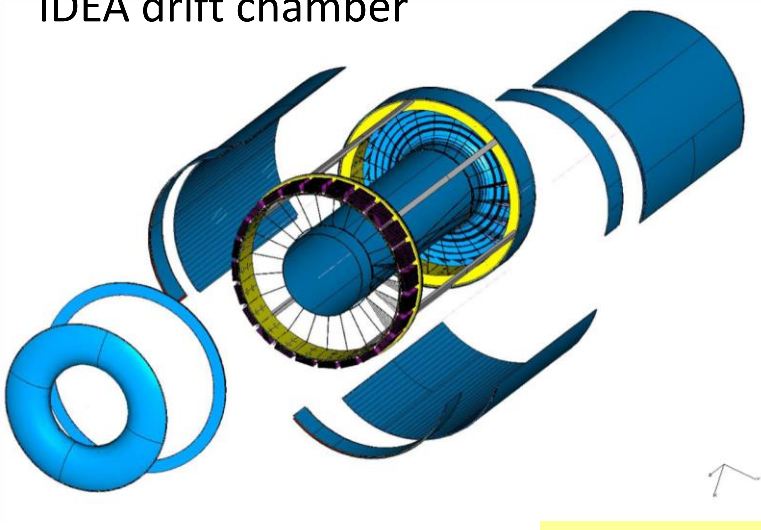
Ionization in tracker

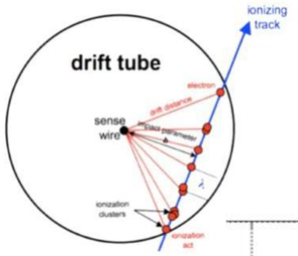
- Comes "for free" from measuring particle energy loss in tracker—but requires careful attention to design/calibration of readout electronics
- Traditional approach using *dE/dx:* limited separation at high momentum
- Cluster counting (*dN/dx*) gives improved resolution: e.g. IDEA concept for extremely transparent drift chamber (He drift gas, no endplates…)
- Needs alternative technique to cover overlap region, e.g. time-of-flight (TOF) with modest resolution ~100 ps

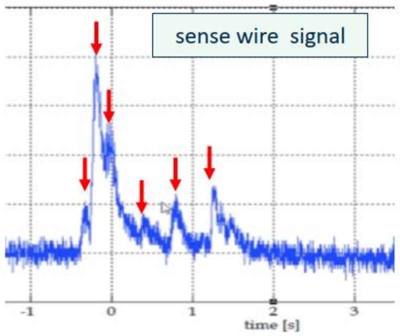


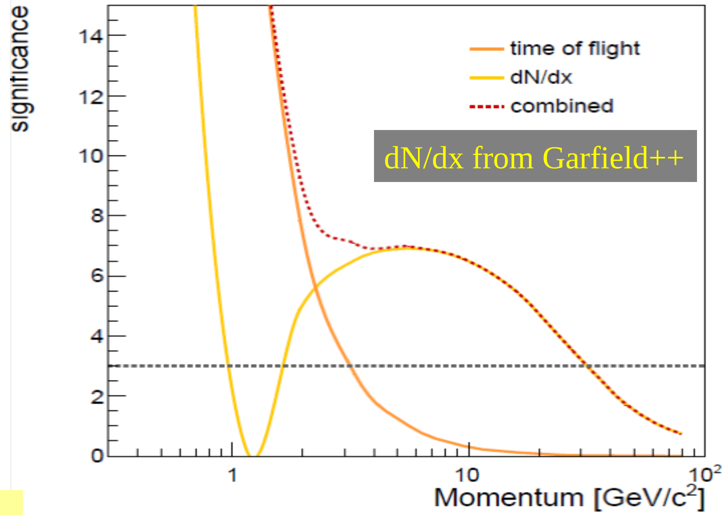
ILD Interim Design Report 2020

IDEA drift chamber





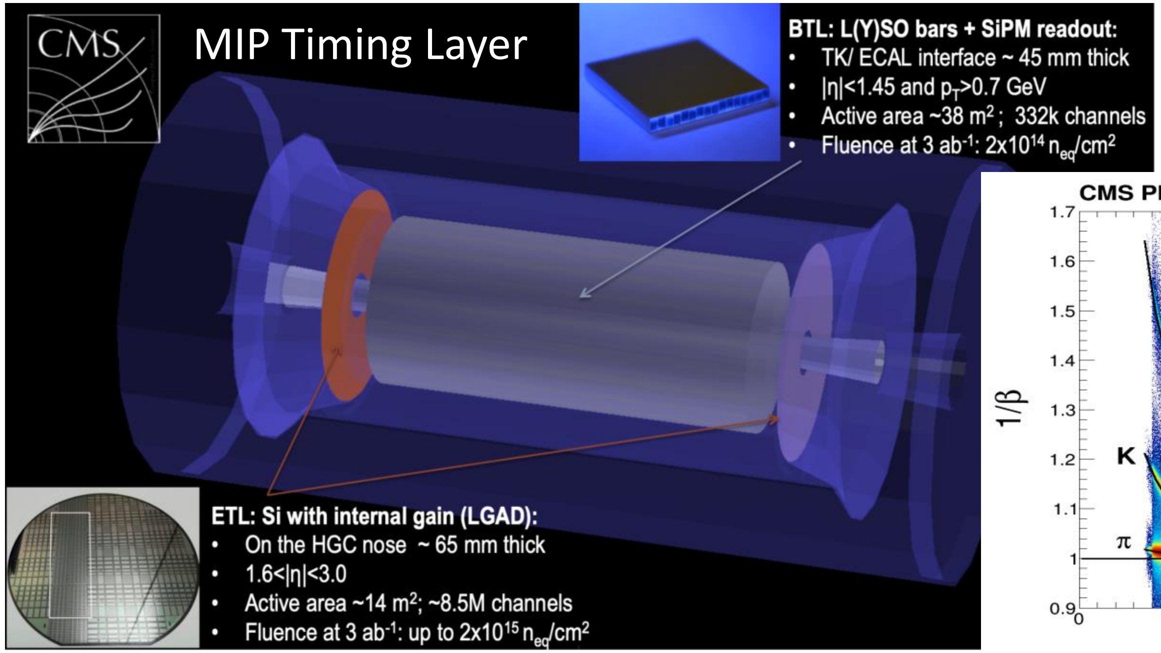




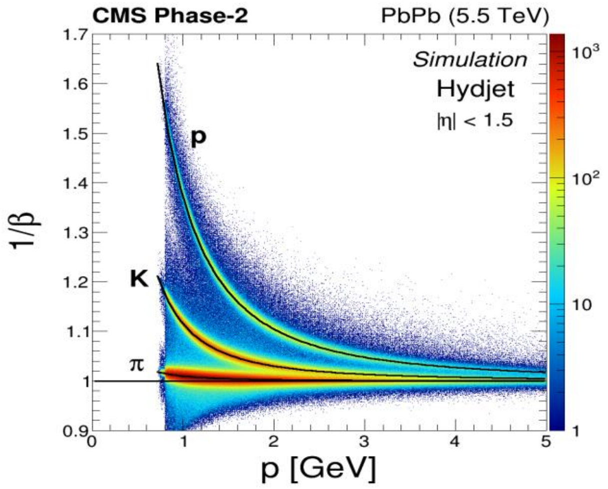
Paolo Giacomelli, kick-off meeting on detector optimisation, 22 June 2022

Fast timing

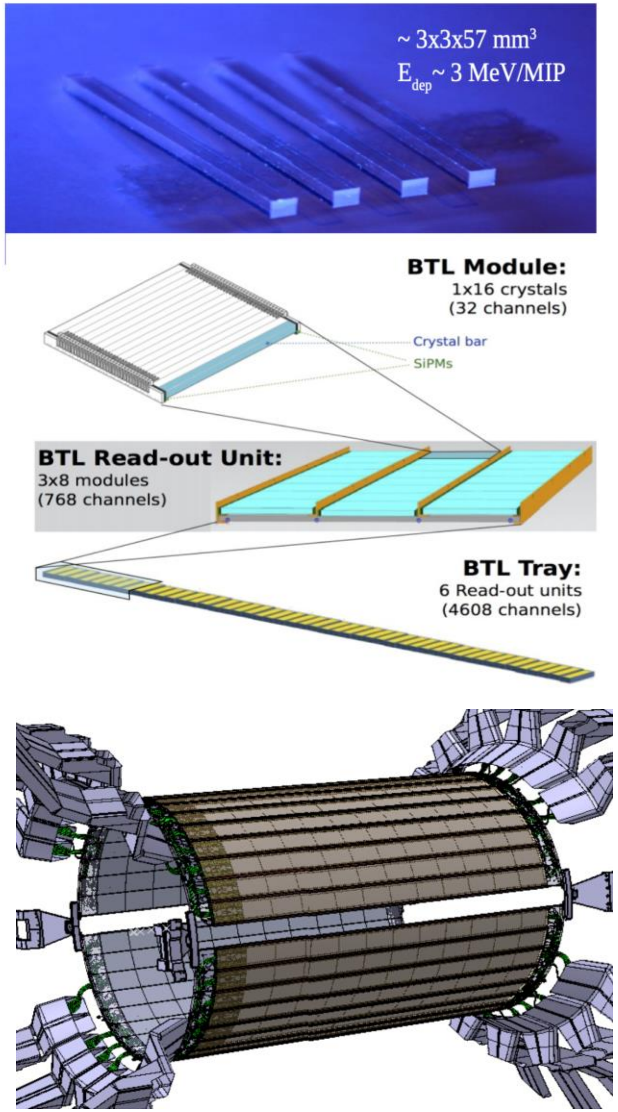
- Widely implemented in the LHC experiments for their Phase II upgrades: 4D tracking, 5D calorimetry (*x,y,z,t,E*)
- However, this is mainly driven by *pileup suppression*, not an issue at e^+e^- Target resolution ~ 50 ps, provides K-π separation by TOF up to few GeV
- Ongoing debate about the appropriate level of timing information for e^+e^- collider environment: trade-off against power/material budget



A. Apresyan, LCWS2021



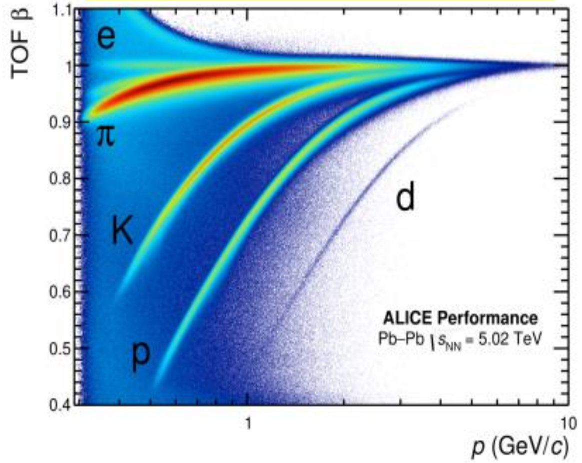
BTL construction



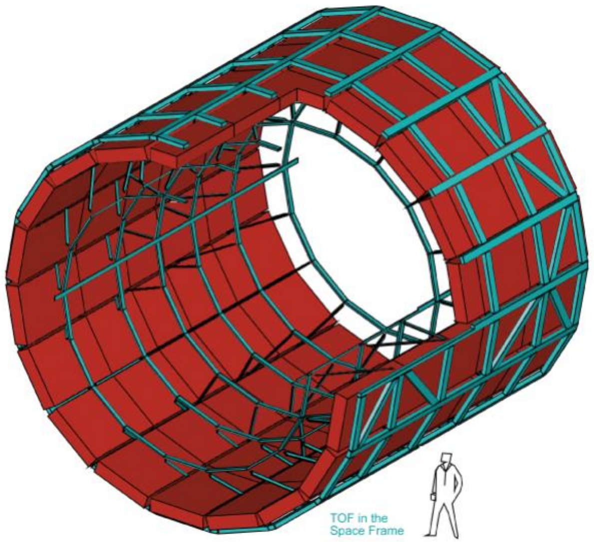
Dedicated TOF detectors

- ALICE TOF detector covers very large area with multi-gap RPC chambers
  Timing resolution 56 ps achieved
- R&D for gaseous detectors targets faster timing, e.g. by increasing number of gaps, or hybrid detection of Cherenkov signal (PICOSEC)
- For future upgrade (ALICE3) propose 20 ps resolution large-area silicon barrel radius 85 cm: fully depleted CMOS sensors, Low-Gain Avalanche Diodes (LGAD) or Single Photon Avalanche Diodes (SPAD)—R&D ongoing

F. Carnesecchi, arXiv:1806.03825

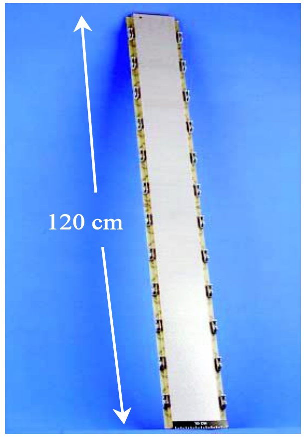


https://cds.cern.ch/record/2803563/files/LHCC-I-038.pdf

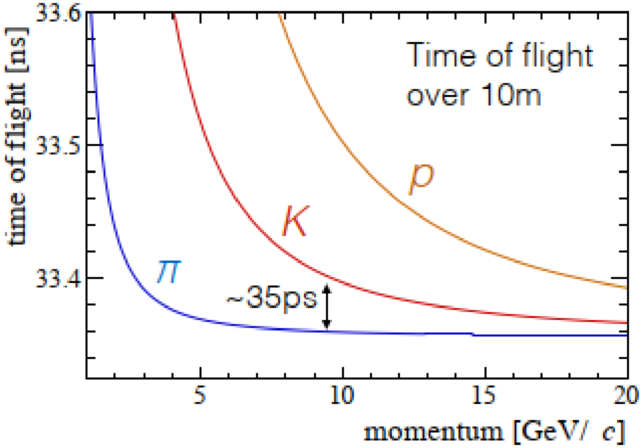


ALICE TOF

3.7 m from IP
150 m^2 total area!
1638 modules

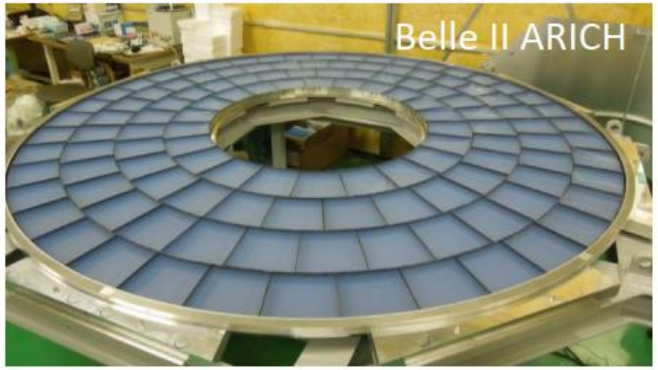


Need O(10 ps) to reach 10 GeV

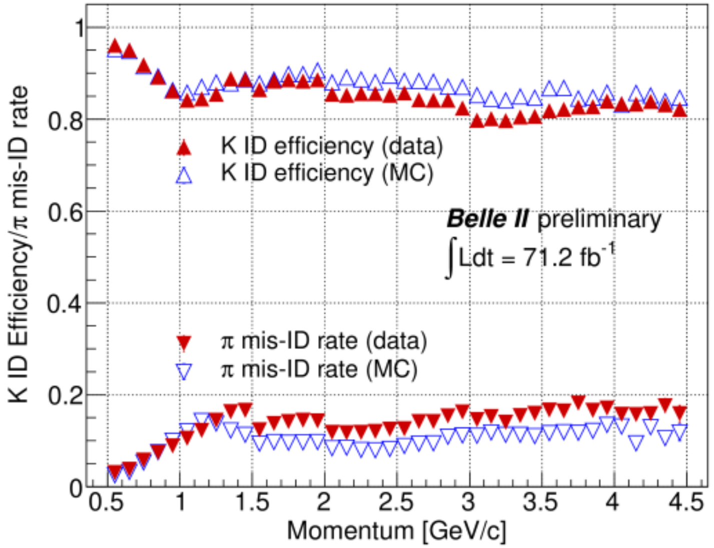


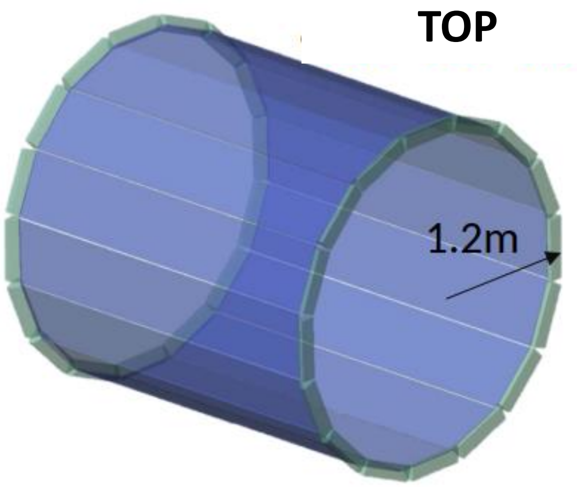
Cherenkov detectors

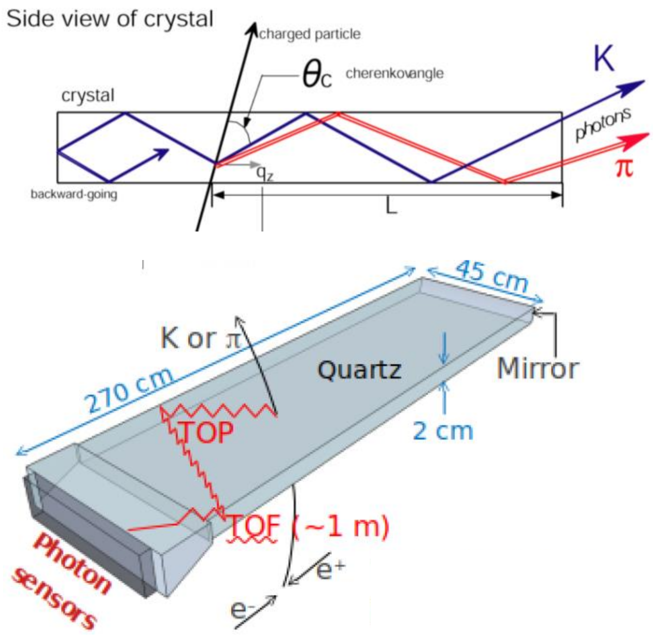
- *Currently operating* e^+e^- collider experiment: **Belle II** at SuperKEKB
  Has strong Particle ID, as expected for a flavour factory
- Uses two solid-radiator Cherenkov detectors: Time Of Propagation (TOP) detector for barrel—development of DIRC with addition of timing—and forward Aerogel RICH (ARICH), proximity focused
- PID performance good, but at low momenta—as required for Υ(4S)



S. Sandilya, TIPP 2021



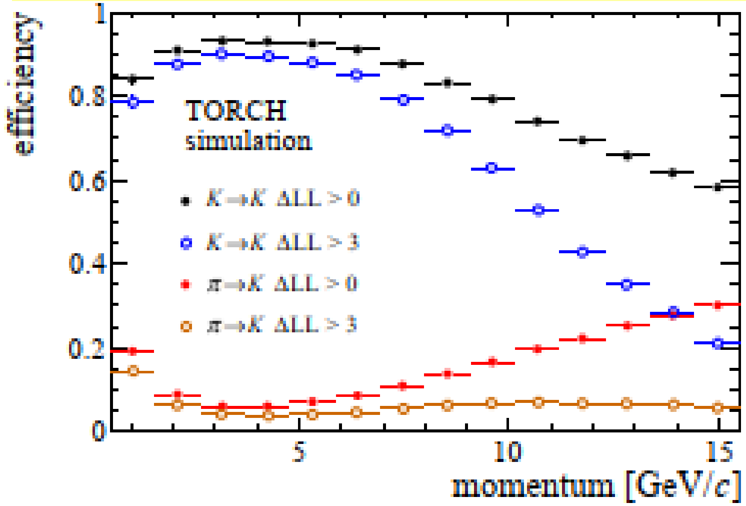


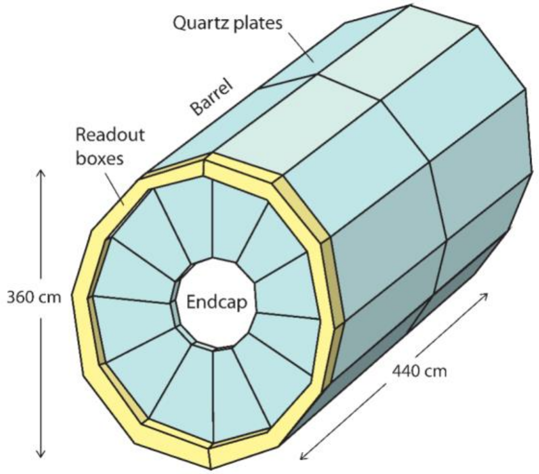


TORCH

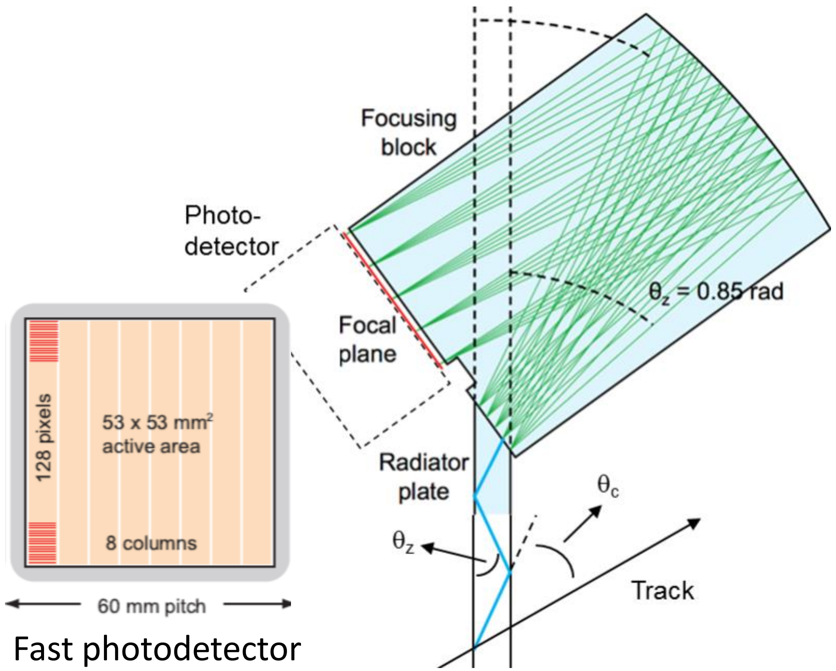
- Evolution of DIRC/TOP concepts, developed for future LHCb upgrade to complement the RICH detectors (on LS4 timescale)—R&D ongoing
- Uses the measured Cherenkov angle to correct for dispersion in the quartz, to push for the highest possible TOF resolution: target of 10-15 ps per track (from combination of ~30 photons)
- Considered possible application at e^+e^- collider, but the limited flight length (*cf* 10 m in LHCb) → challenging to achieve resolution

https://cds.cern.ch/record/2776420/files/LHCB-TDR-023.pdf

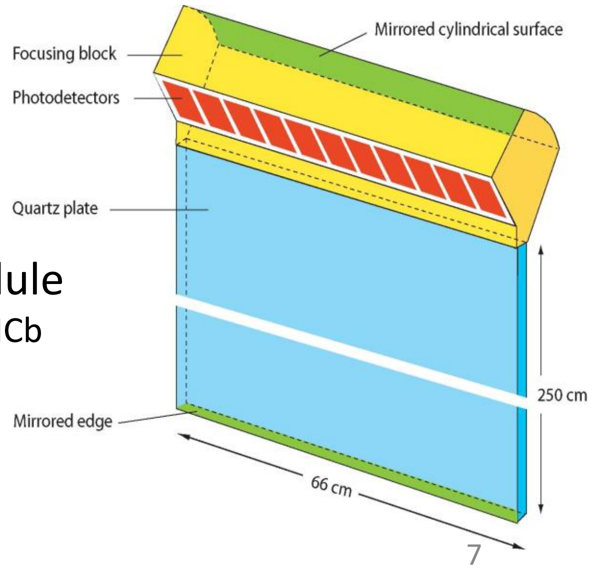




Conceptual layout for an e^+e^- experiment



Fast photodetector
MCP-PMT

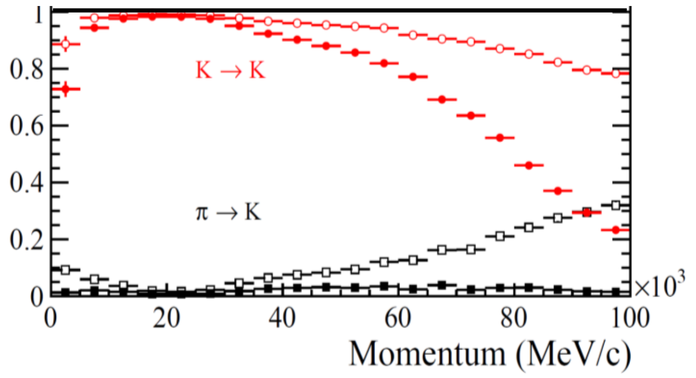


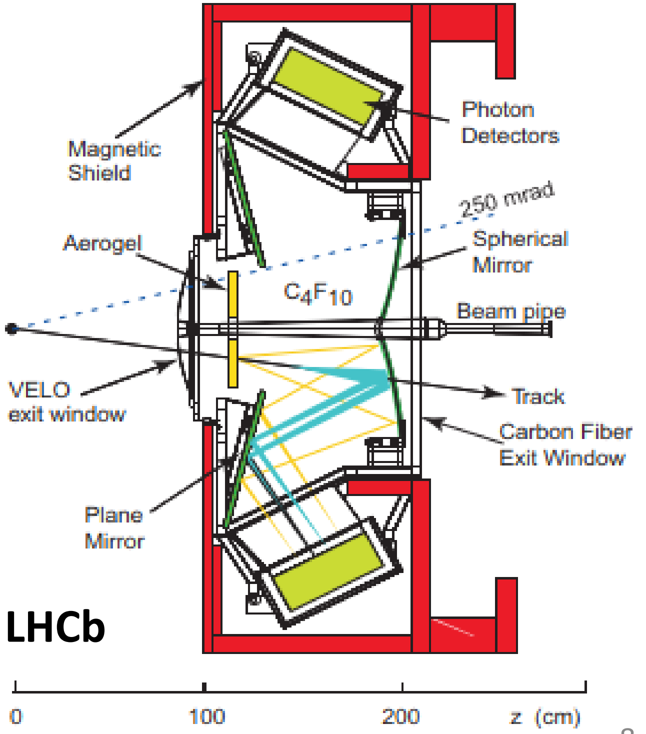
Module
for LHCb

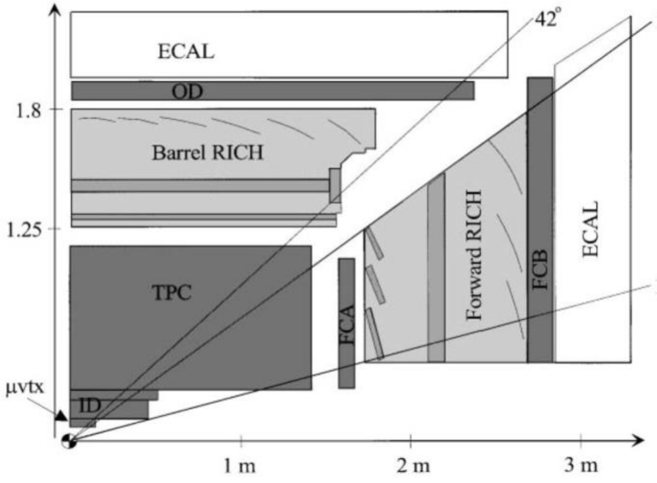
Gaseous RICH detectors

- To push particle ID performance to higher momentum, detector of choice is a RICH with gaseous radiator
- LHCb RICH1 had dual radiator in original design: aerogel + C_4F_{10} gas
  Aerogel photons focused by same mirror as those from gas onto same sensor plane → concentric rings if track above both thresholds
  Aerogel later removed, due to high track density at the LHC
- The rest of this presentation explores the adaptation of such a detector to the geometry of an experiment at an e^+e^- collider
- Previous examples at DELPHI and the CRID of SLD: highly challenging, delicate systems; significant issue was the space they occupied
- However, sensor technology has meanwhile evolved

LHCb RICH performance



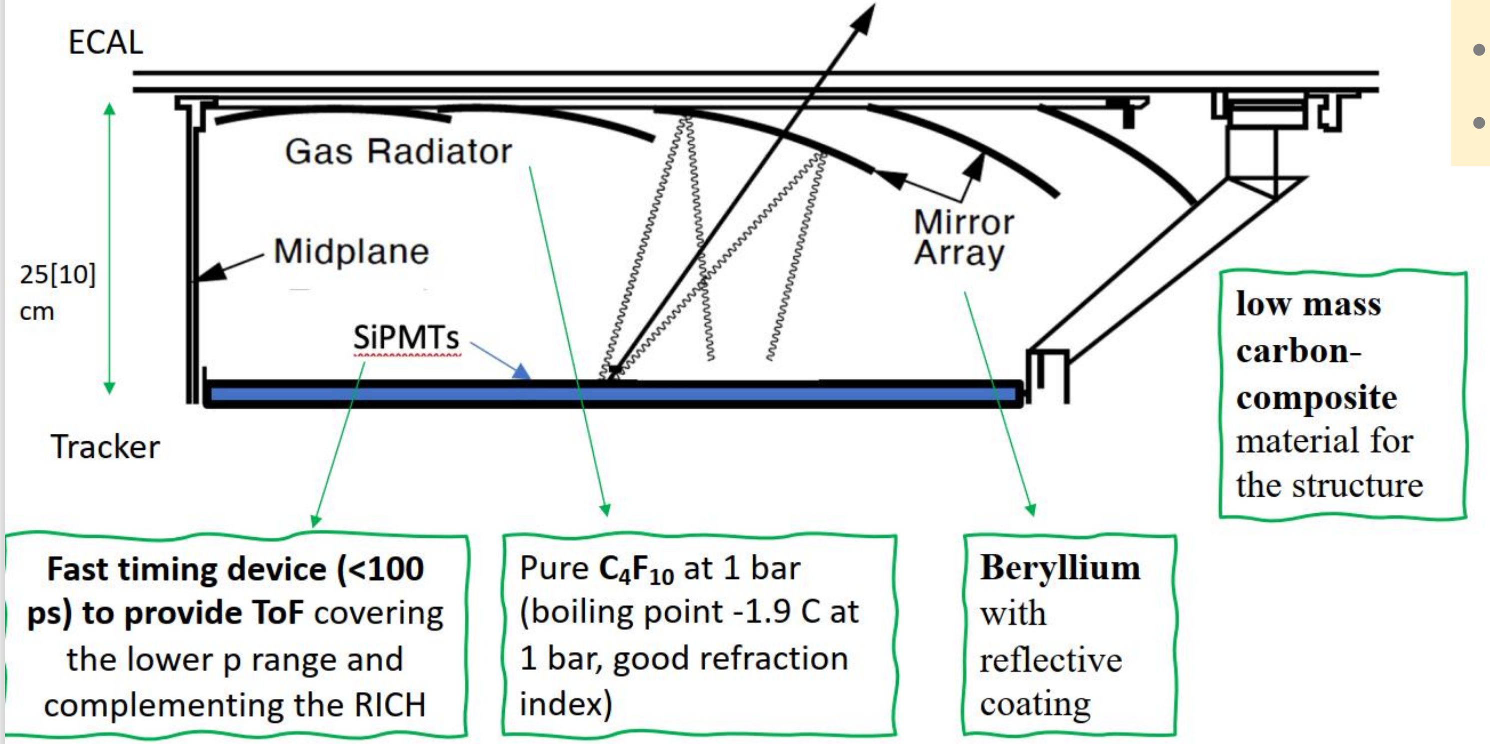




DELPHI

Compact Gaseous RICH with SiPMTs

- **Past** → **Future**:
  - Much **smaller RICH** radial length (CRID ~ 1m), **SiPMTs** rather than TPCs for photon detection
- **Many parameters to look into!**

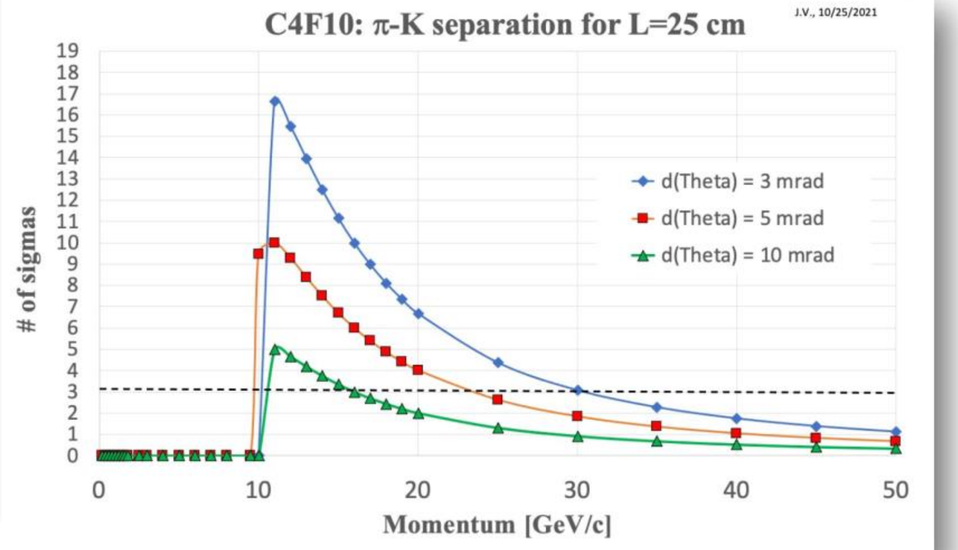


February 8th 2022 V. M. M. Cairo 15

- One approach that is being pursued: update the CRID design to be more compact

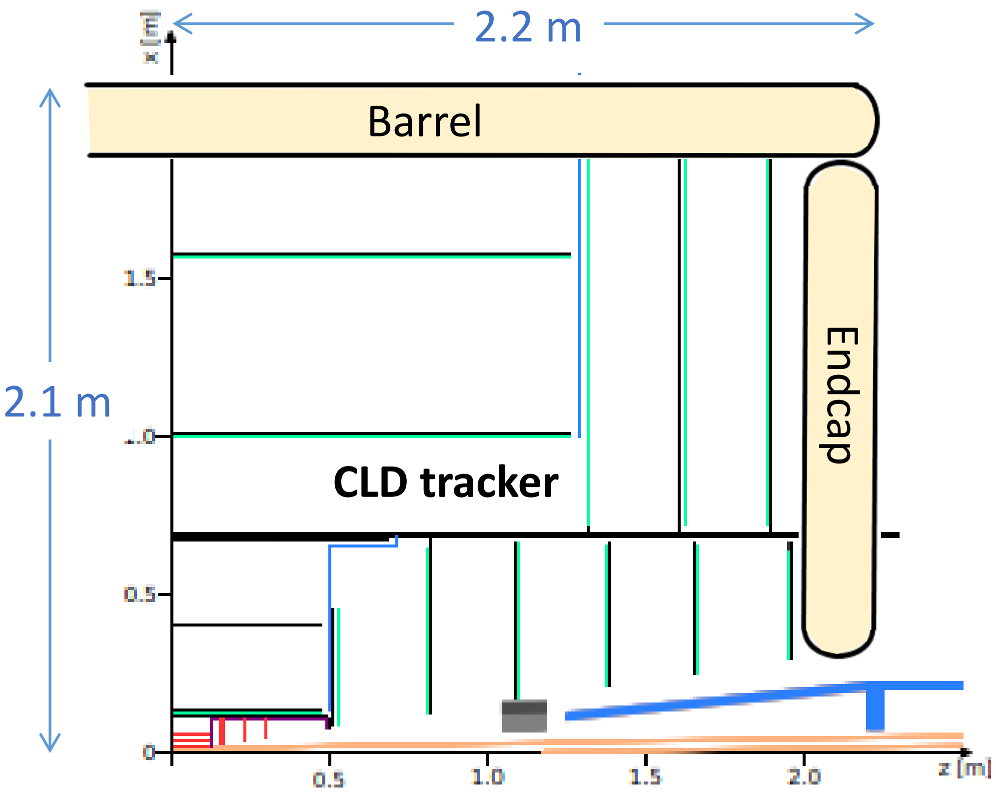
Valentina Cairo, FCC physics workshop, 8 Feb 2022
work done with Chris Damerell, Jerry Va'vra *et. al*

- Particular interest in $H \to s\bar{s}$ tagging
- Angular resolution is critical for performance



2. Compact RICH concept

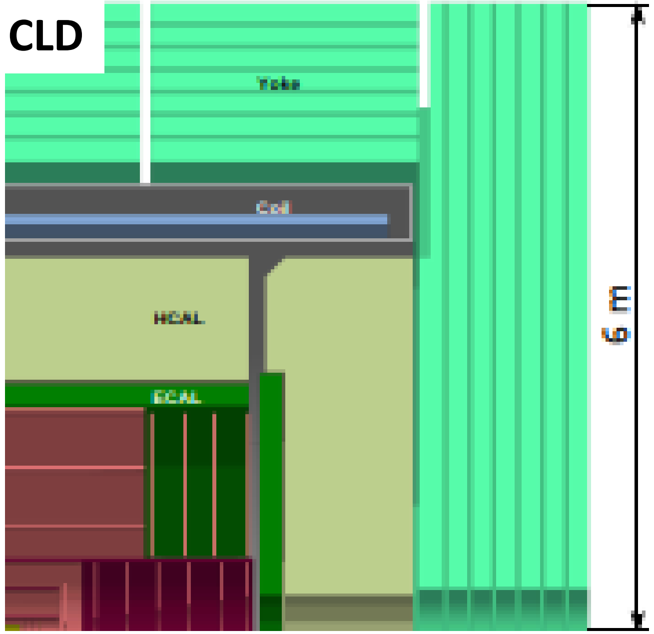
- Alternative geometry investigated for a compact RICH concept
  To be concrete, based around the design of the current CLD experiment proposed for FCC-ee N. Bacchetta et al., arXiv:1911.12230
- Target a radial depth of 20 cm and material budget of < 10% X_0

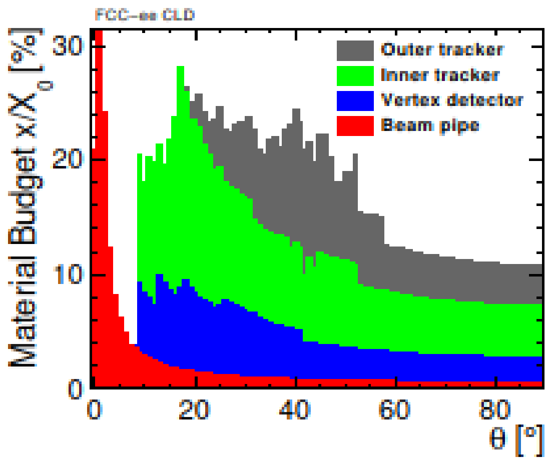


RICH vessel
(barrel + endcaps)
= solids of revolution around the beam axis

Tracker would need to be re-optimized using 10% less radial space

(already studied in Appendix B of CLD note: intended to make calorimeter smaller and save money…)

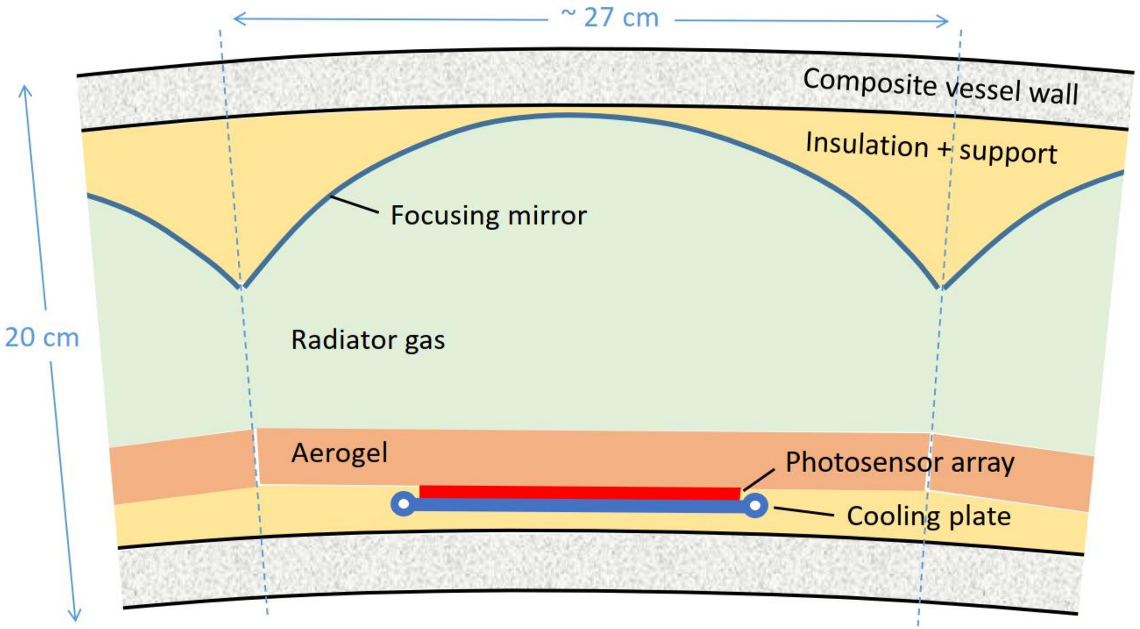




Detector cell

- Challenge to arrange optical elements so that Cherenkov light focused onto a single sensor plane, as the detector radial thickness is reduced
- Concept inspired by the compound-eye of an insect: tile the plane with many separate cells, each with its own mirror and sensor array
- Use spherical focusing mirrors: focal length = radius-of-curvature/2
  → select radius-of-curvature $R \approx 30$ cm for radiator thickness of 15 cm

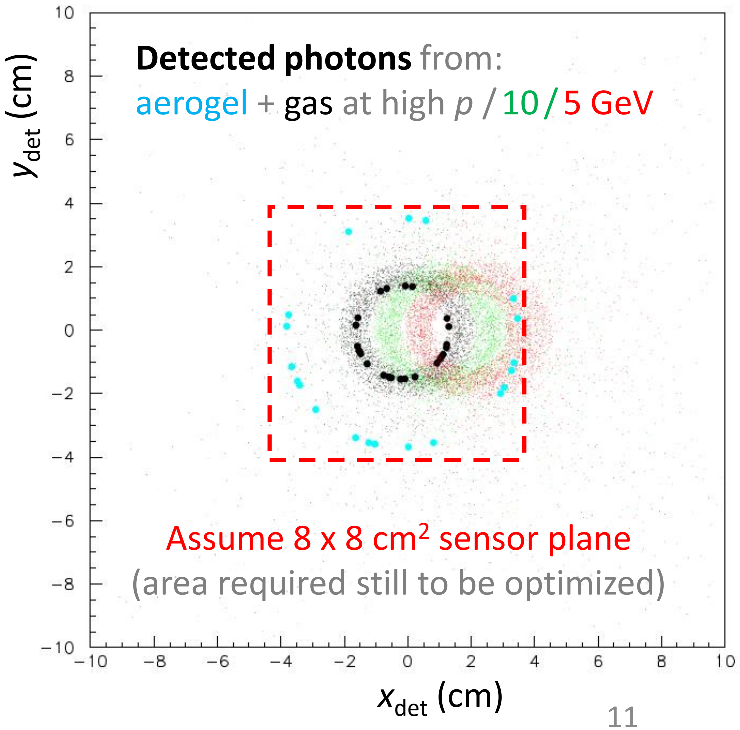
https://www.findlight.net/blog/2019/01/23/artificial-compound-eyes/



Array of RICH Cells (ARC)

Simulate tracks from IP crossing detector uniformly over acceptance and ray trace Cherenkov photons to sensor plane: (here for $\theta \approx 90°$)

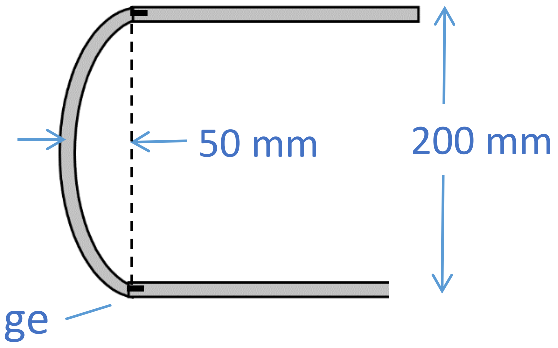
Ring radii = $R \cdot \theta_C / 2$ = 1.1 cm (3.6 cm) for gas (aerogel)



Detector vessel

- Lightweight vessels for cryostats currently under intensive R&D, strong synergy with aerospace (e.g. for composite fuel tanks)
- Working group in CERN-EP strategic detector R&D programme led by Corrado Gargiulo
  He made a first design for this application: can sustain pressure up to 4 bar
- Carbon-fibre composite sandwich, foam core
  12-fold symmetry → **sectors**

Side-view at end:
removable
semi-elliptical caps

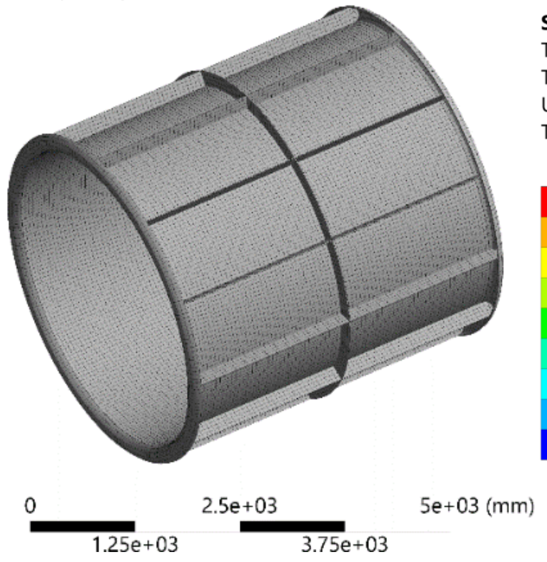


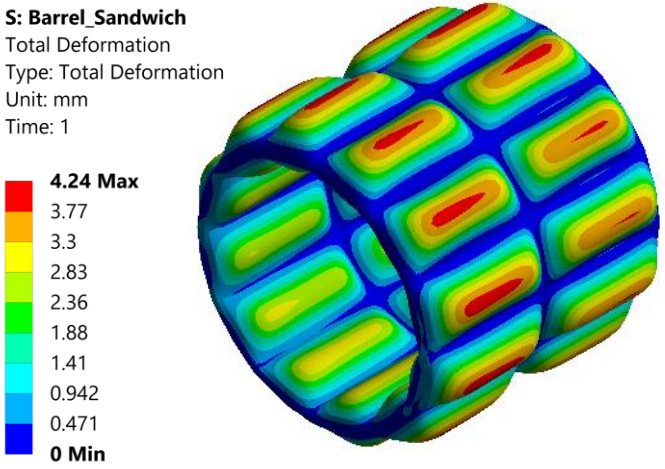
- R&D required to develop such a light-weight vessel

External wall hidden
to show reinforcing ribs

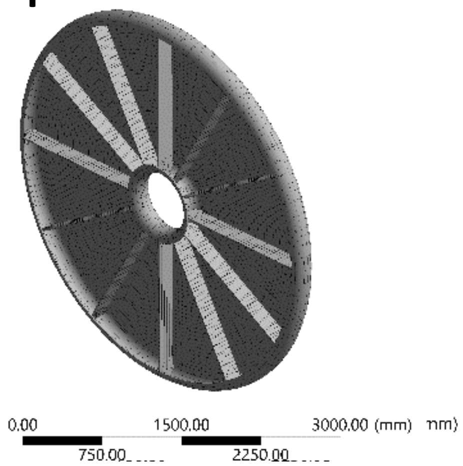
CAD study: deformation at 4 bar
(safety factor 2)

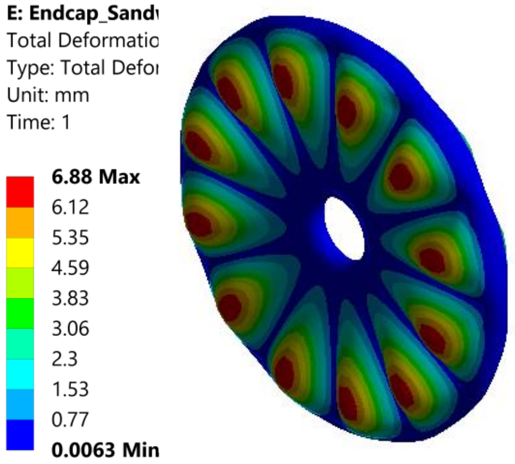
Barrel





Endcap

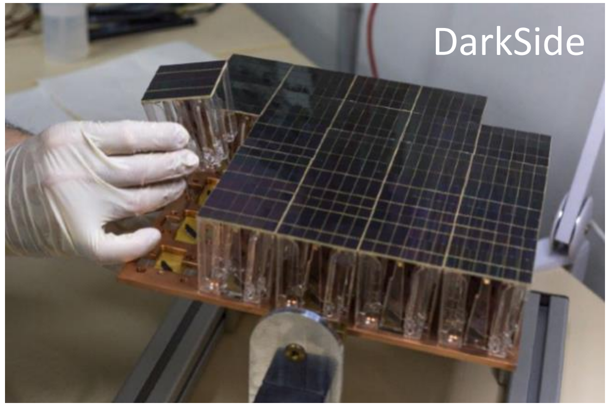


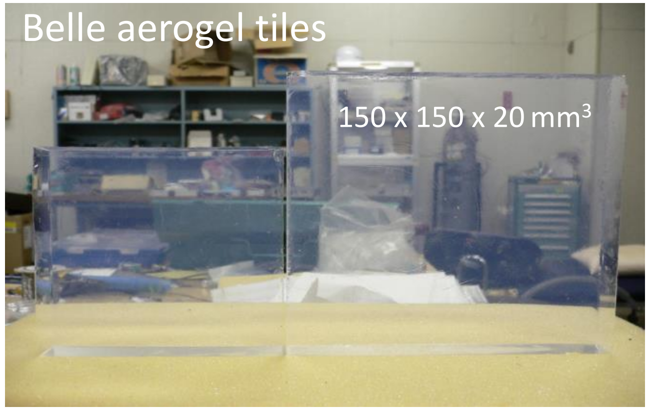


Photosensors + aerogel

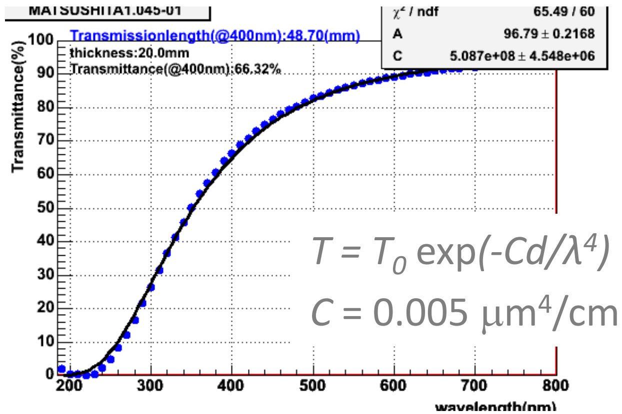
- **Silicon PMs** have come of age: widely adopted e.g. in MEG, DarkSide (30 m^2 area!), LHCb SciFi, CMS Barrel Timing Layer
- Excellent photon detection efficiency > 50% possible, mostly in visible
  Extremely compact, assume can fit the photosensor (and its readout electronics) in a few mm-thick layer: very active R&D
- Excellent granularity (sub-mm possible, e.g. 250 μm for SciFi)
  and fast timing resolution; cooling helps to limit noise
- High clarity, large area **aerogel** tiles developed for ARICH of Belle
  assume 1 cm thick tiles, n = 1.03 → $\theta_C \approx$ 240 mrad
  Excellent thermal insulator

A. Kish, CERN Detector Seminar, 28/5/2021



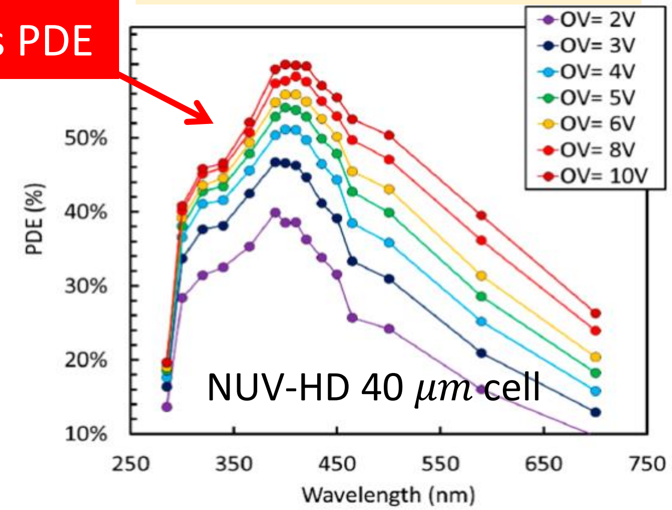


I. Adachi, ECFA TF4, 6/5/2021



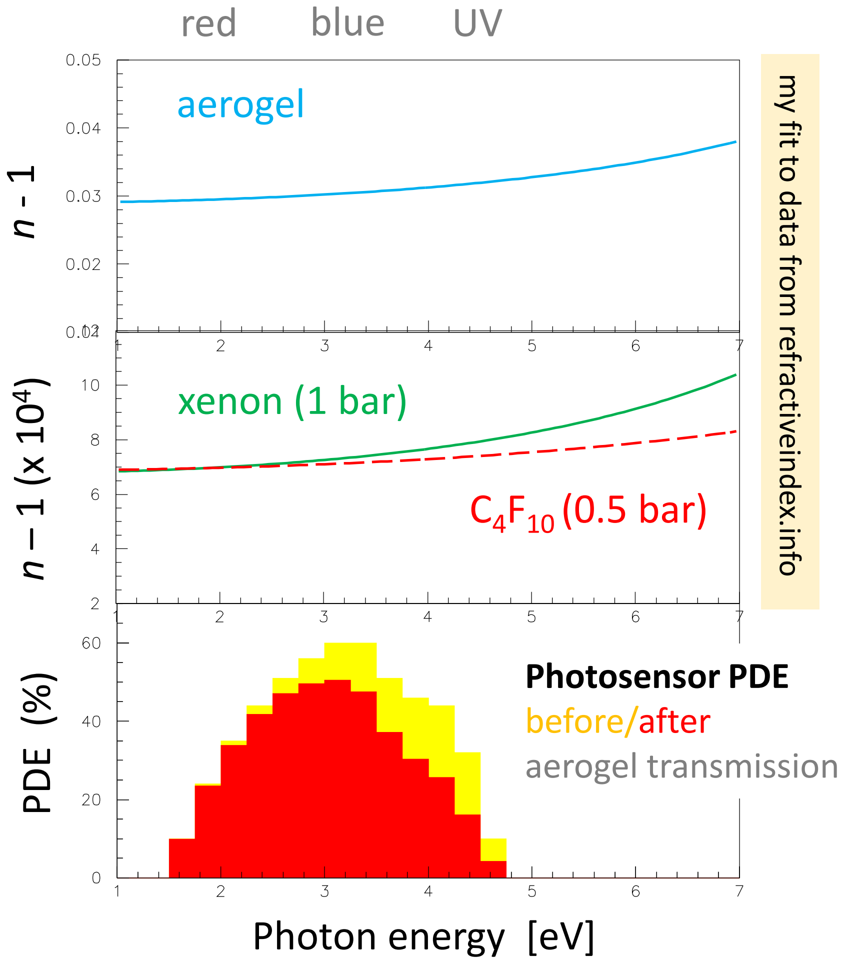
Assume this PDE

A. Gola et al, Sensors 19 (2019) 308



Gaseous radiator

- **C_4F_{10}** is baseline assumption: well-known, used in LHCb RICH1
- Refractive index increases with pressure ($n - 1 \propto$ density)
  n = 1.0014 at room temp, n = 1.0049 at 3.5 bar → $\theta_C \approx$ 100 mrad
  Chromatic dispersion also increases, but still excellent
- *Drawbacks:* fluorocarbons are greenhouse gases (GWP ~ 8000);
  → issues of cost and availability, may eventually be banned;
  at 3.5 bar pressure, boiling point of C_4F_{10} increases to 33 °C
  → would need to maintain gas volume at ~40 °C
- **Xenon** is not a greenhouse gas, and stays in gas phase at room temperature up to over 20 bar
  Lower refractive index n = 1.0007 so would need higher pressure than C_4F_{10}, and somewhat worse dispersion
- For this (or other) new gas choices, R&D would be needed to study their suitability

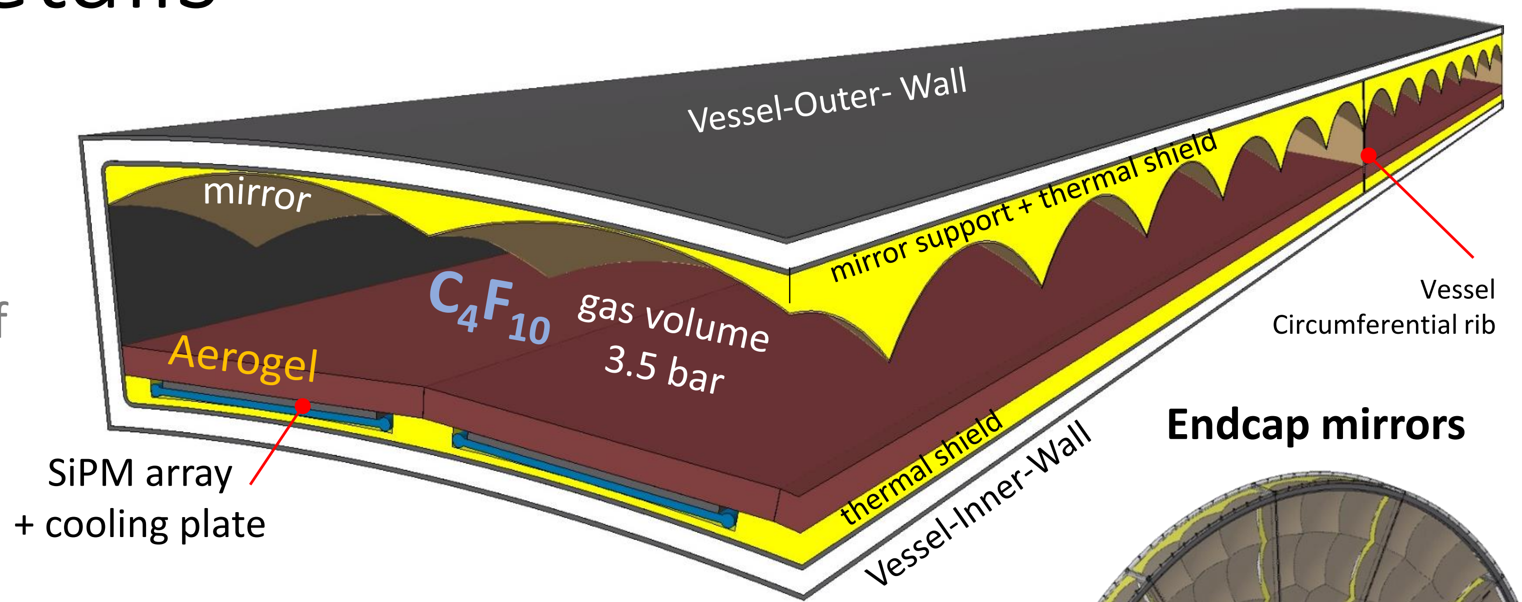


ARC detector details

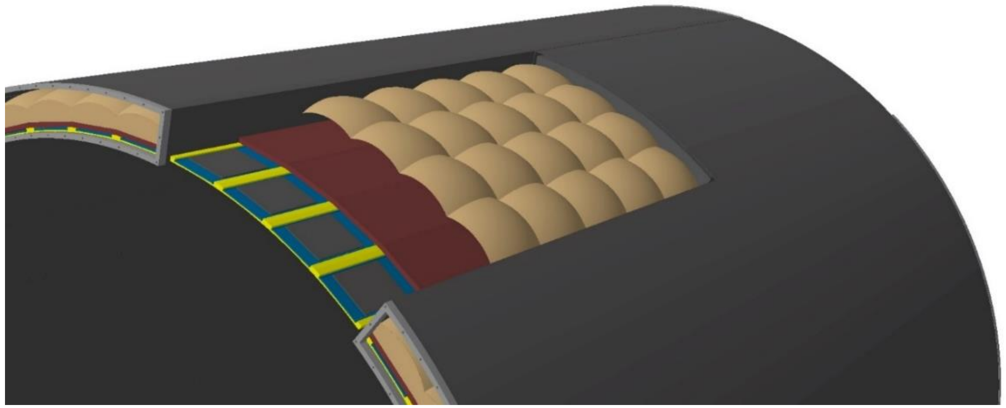
- CAD views from Corrado Gargiulo
- Thermal insulation around the mirror and sensor array would be very low mass (MLI: the shiny stuff that satellites are wrapped in)

Initial material budget estimate
(assuming pressurization here)

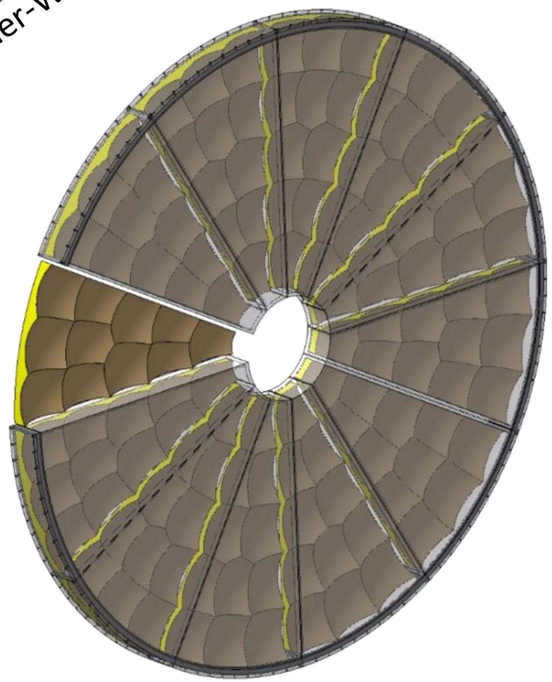
Detector component	X/X_0
2 x vessel wall	5 %
Photosensor array/electronics	1 %
Cooling plate (3 mm CF)	1 %
Aerogel (2 cm, *n* = 1.03)	1 %
C_4F_{10} gas (13 cm @ 3.5 bar)	1 %
Focusing mirror	1 %
Total	10 %



Barrel sector and integration

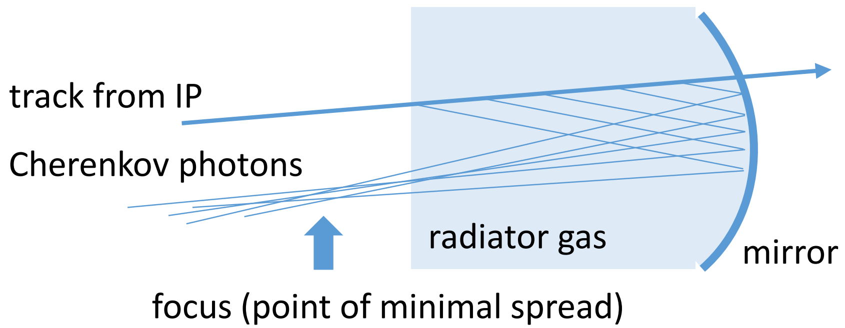


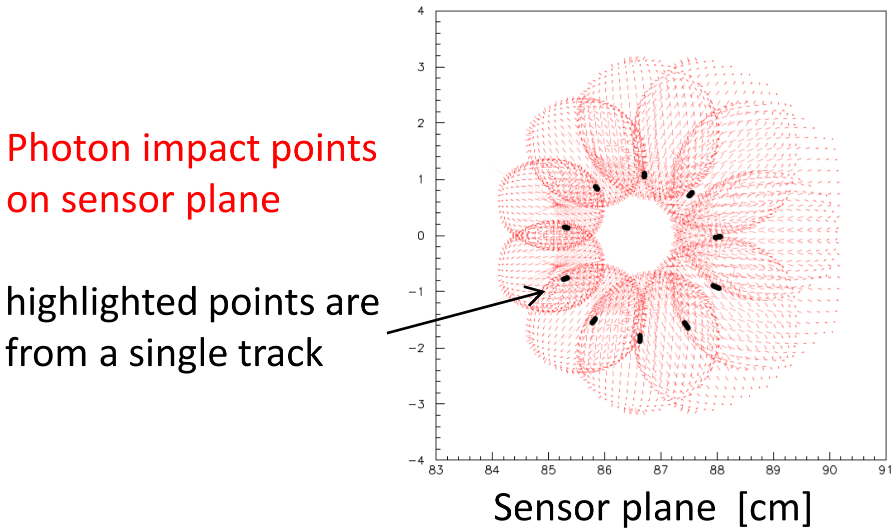
Endcap mirrors



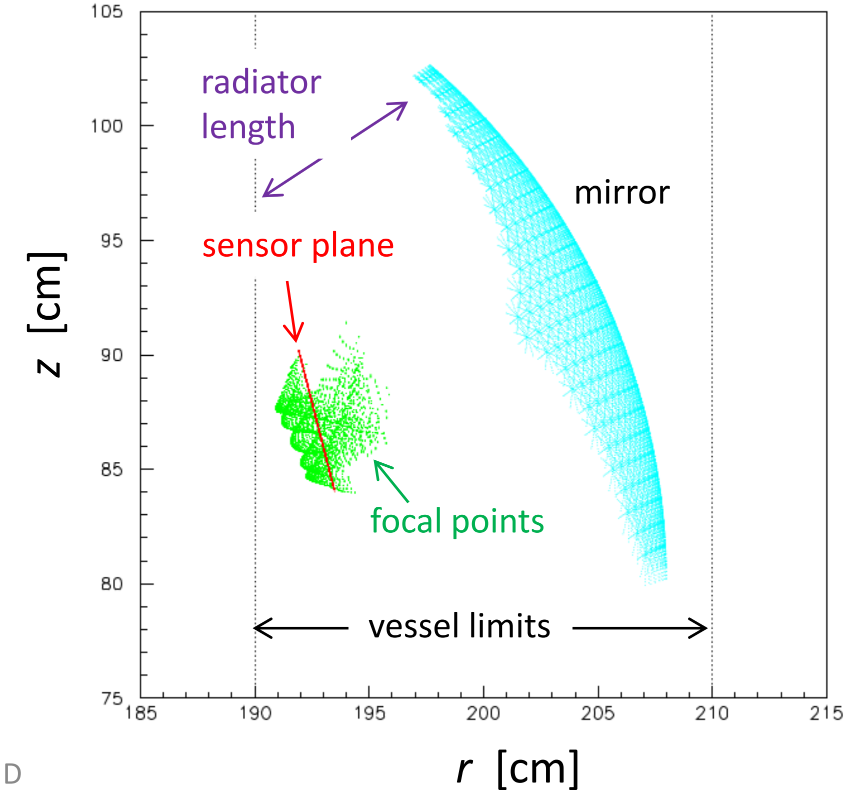
Optimizing the optics

- Scan tracks from the IP across each cell in turn ray-trace photons at constant Cherenkov angle (ϑ,φ) reflect off mirror, find point of minimal spread
- Photon focus points form a cloud, into which the sensor plane is adjusted
- *Parameters:* mirror curvature, offset, tilt, sensor plane offset, tilt; *Constraints:* vessel limits, radiator length
- Image on sensor plane:





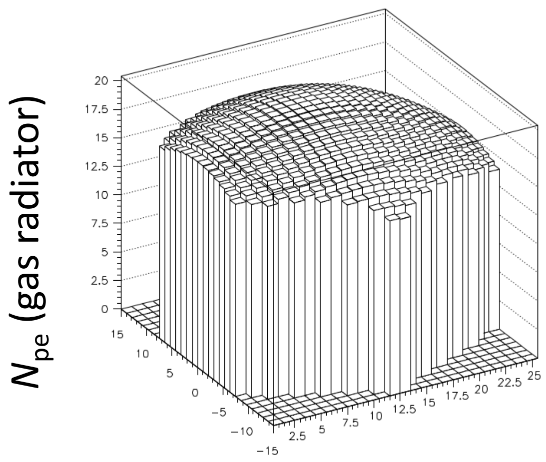
Side view of a cell



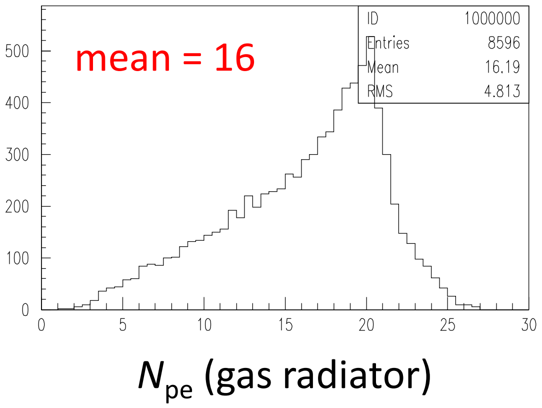
Optimized optical layout

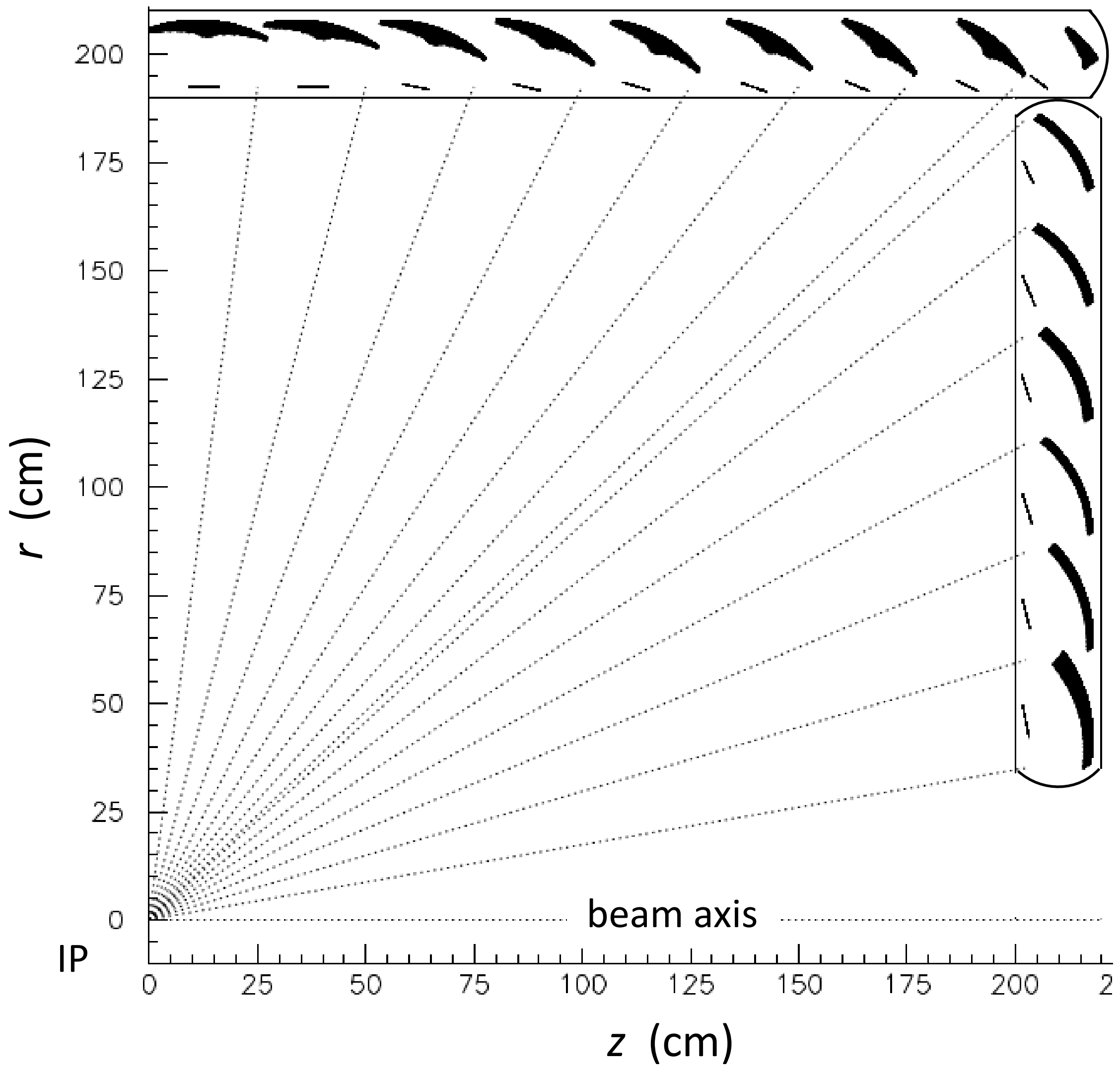
- Use only spherical mirrors (simplicity, cost)
  Best fit radii-of-curvature range: 27–33 cm
- Determine photon yield as a function of track impact point
- Case study made here replacing C_4F_{10} with xenon

One cell



All cells (xenon 3.5 bar)



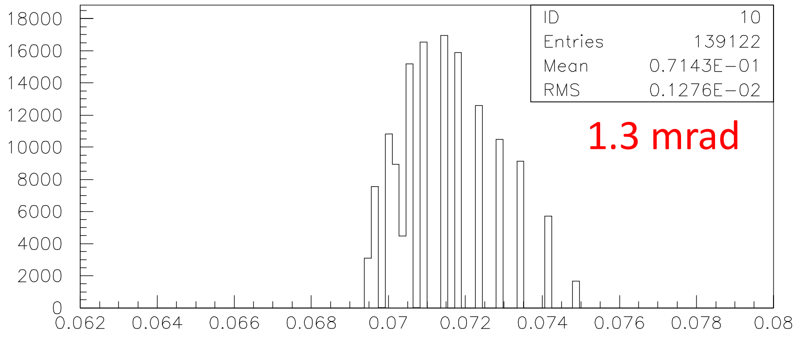


Resolution

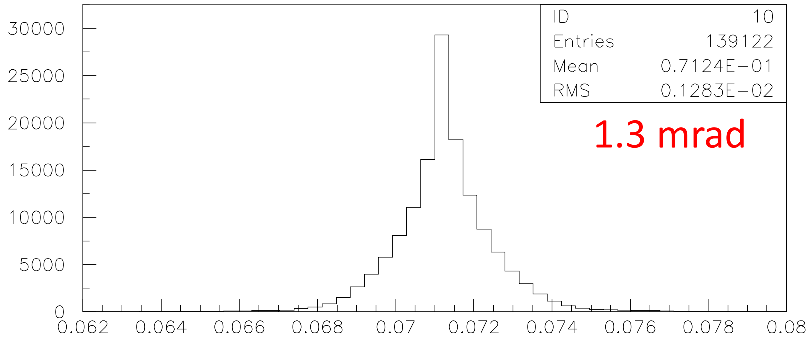
- **Chromatic** dispersion in the radiator is the fundamental limit once the bandwidth of the photosensors has been chosen
  → 1.3 mrad (2.4 mrad) for gas (aerogel), per detected photon
- **Emission-point** uncertainty: reflects quality of the focusing (i.e. how well photons emitted at different points along the track are brought to the same focus on the sensor)
  1.3 mrad achieved for gas image at high momentum
- **Pixel** size chosen to avoid limiting the angular resolution for d = 0.5x0.5 mm^2 (square pixels) → $2d/\sqrt{12}\,R \approx 1$ mrad (factor √12 for the RMS of a top-hat distribution)
  → ~25,000 pixels per SiPM array, total channel count ~35 M*
- **Track** angular resolution error must be good enough not to limit RICH performance: requires $\sigma_{track} << \sigma_{photon} / \sqrt{N_{pe}} \approx 0.5$ mrad (given 4-25 *billion* silicon channels in CLD tracker, should be OK)

* If cost is part of the optimization, probably use 1 mm pixels → reduce to 9 M channels

Chromatic error (xenon, 3.5 bar)



Emission-point error (avg. over full detector)



Reconstructed Cherenkov angle [rad]

Overall resolution per photon:

$\sigma_{photon} = \sigma_{chromatic} \oplus \sigma_{emission} \oplus \sigma_{pixel}$

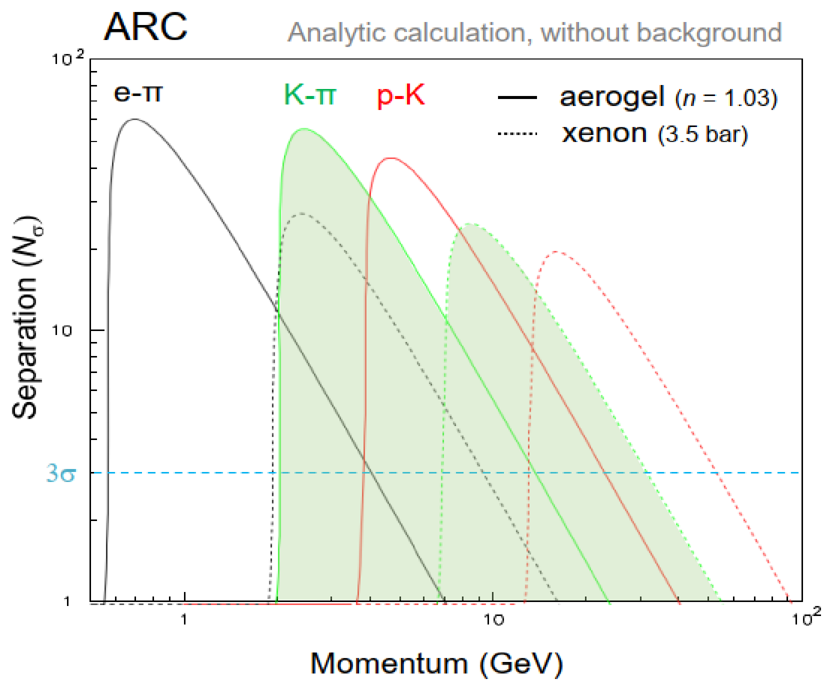
≈ 2.0 mrad (2.7 mrad) for gas (aerogel)

Performance

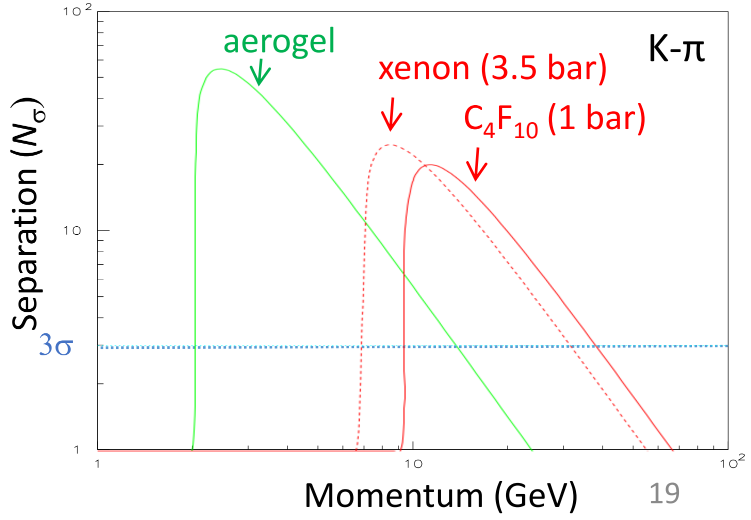
- Number of detected photons $N_{pe} = A\, L \int \varepsilon \sin^2 \theta_C\, dE$
  where L is radiator length, $A = \alpha^2 / r_e m_e c^2 = 370\ \mathrm{cm^{-1}\,eV^{-1}}$
  Efficiency ε = PDE · active area · mirror reflectivity · aerogel transmission, as a function of photon energy E
- Assume SiPM active area = 0.8, mirror reflectivity = 0.9
  → $\langle N_{pe} \rangle$ = 16 (12) for gas (aerogel)
- Angular resolution per track from combining photons:
  $\sigma_\theta = \sigma_{photon} / \sqrt{N_{pe}} \oplus \sigma_{track} \approx$ 0.5 (0.8) mrad for gas (aerogel)
- Significance of K-π separation: $N_\sigma = \dfrac{|m_K^2 - m_\pi^2|}{2\, p^2\, \sigma_\theta \sqrt{n^2-1}}$
- Threshold for K, p to give light: 7, 13 (2, 4) GeV for gas (aerogel)
  Dual radiator in ARC → performance is combination of both

→ Excellent PID performance over the full momentum range required

- *Bonus:* provides **e-π** separation in the region of a few GeV, where it may be difficult for the calorimeter [Felix Sefkow]

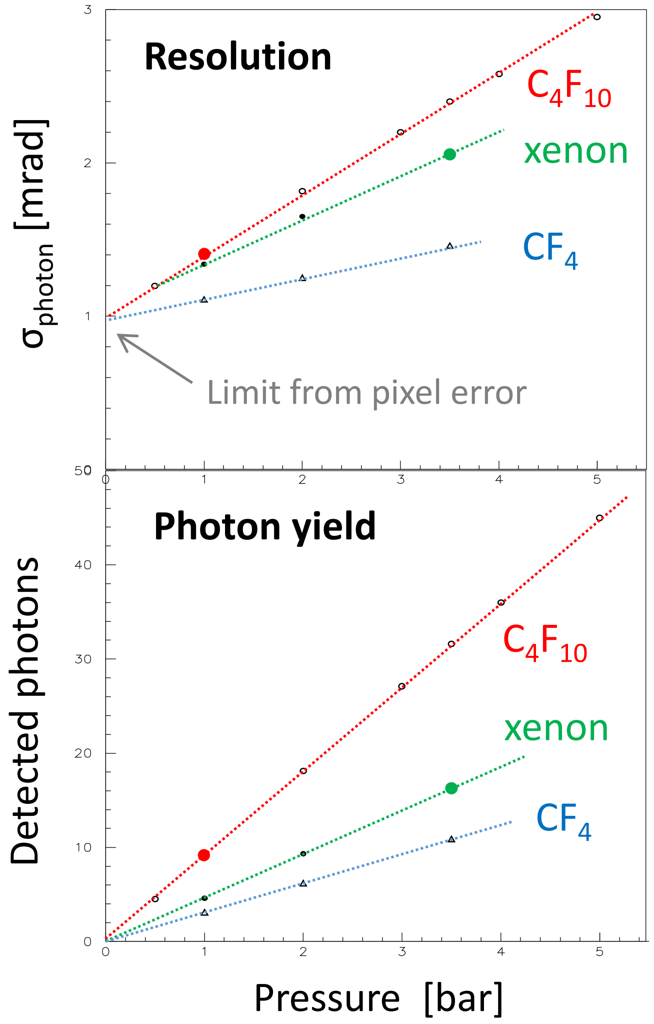


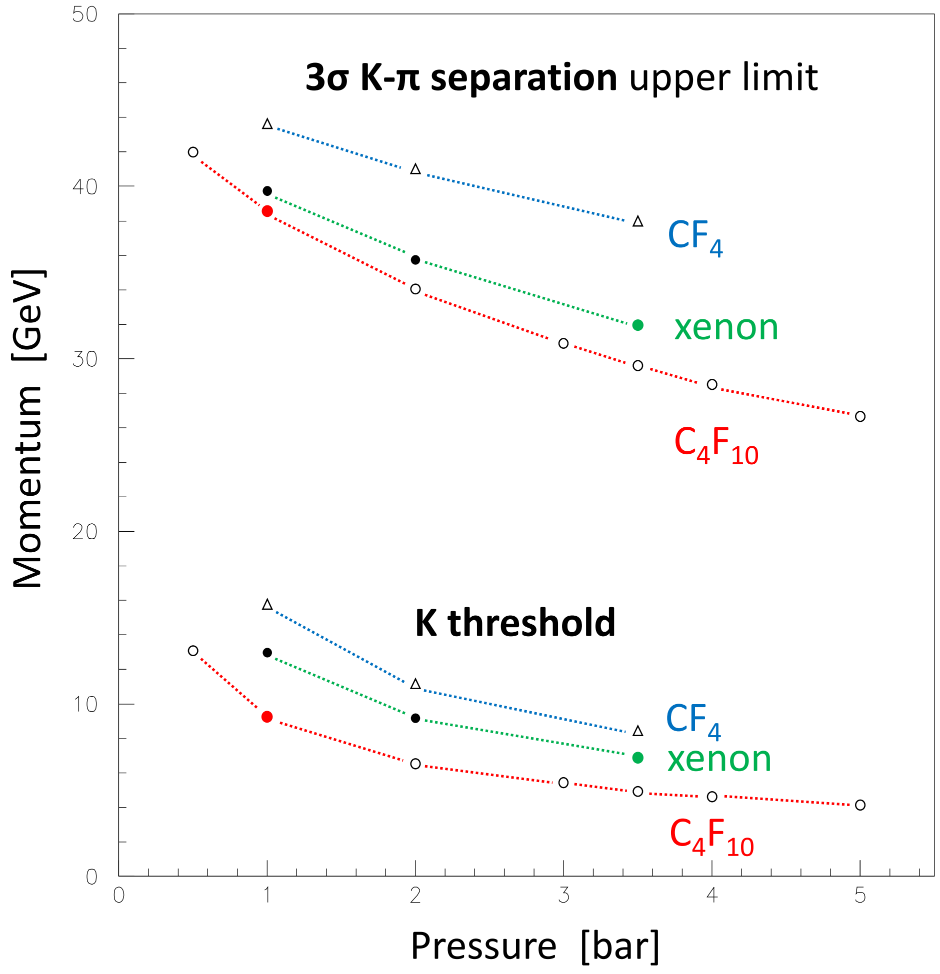
Pushing to higher momentum:



Parameter scan

- For optimized detector layout, study systematically dependence on gas type and pressure
- Two working points for performance shown on previous slide indicated
- C_4F_{10} at atmospheric pressure gives better upper limit to K-π separation, at cost of higher threshold and lower photon yield
- Optimal point may be expected to change in the presence of background



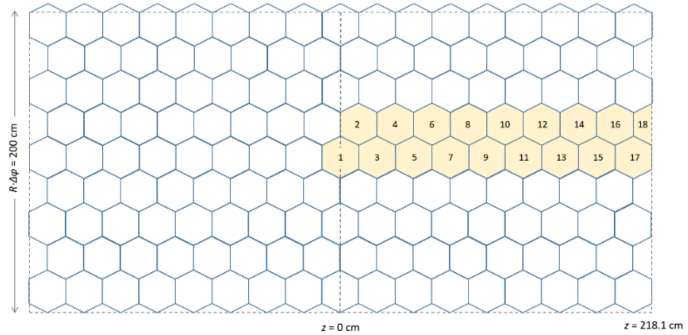


Further development

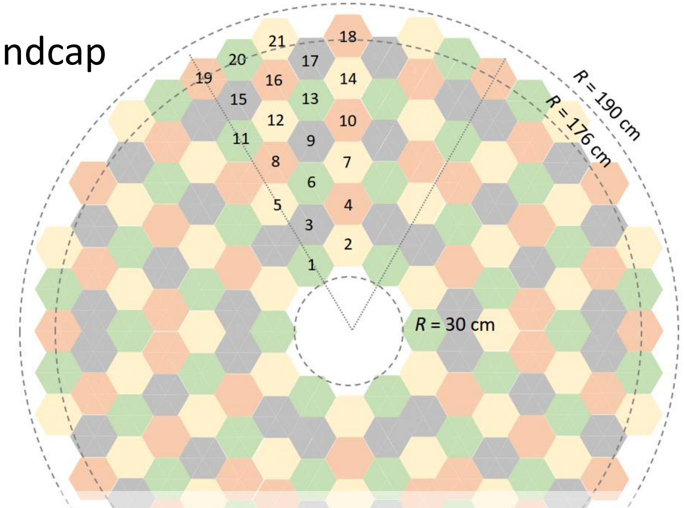
- Converging on unpressurized C_4F_{10} as the optimal radiator, *if* photon yield can be kept high enough and background low
  → can cross-fertilize with the alternative CRID-based concept
- Avoiding need for pressurization will lead to further gains in material budget, can conceive of a detector of only a few % X_0
- *Next steps:* move to uniform hexagonal cells covering barrel and endcaps, thinner walls, and study in full Geant4 simulation
  Discussed with Guy Wilkinson, Martin Tat (Oxford), Valentina Cairo + collaborators

  See if this will be adopted as part of one of the detector concepts for a future e^+e^- collider (whether linear or circular)
- *Many compelling related R&D topics:* **SiPM** as photosensors (in the single-photon regime) crucial, to define realistic target for PDE and active area coverage, acceptable noise level → operating temperature, use of timing etc.; light-weight composite **vessel**, alternative **gas** radiator choices, **aerogel** compatibility…
- Interest in the development of such a detector is very welcome
  UK groups have led much of the development of RICH detectors at the LHC

ARC hexagonal cell layout (60° barrel sector)



Endcap



945 cells in barrel, 204 in each endcap
→ 1353 cells in total
If each has 8 x 8 cm^2 sensor array
→ ~ 9 m^2 total area to instrument