ECFA H(ss) focus group
16 May 2024

Detector design

(for particle ID at a Higgs Factory)

Roger Forty (CERN)

Valentina asked me to summarize ongoing work towards designing a detector for particle ID at a Higgs Factory, relevant to the H $\rightarrow$ ss studies

This is in the context of the new R&D collaborations set up to implement the ECFA Roadmap on Detector R&D, in particular DRD4 for “Particle ID and Photon Detectors”

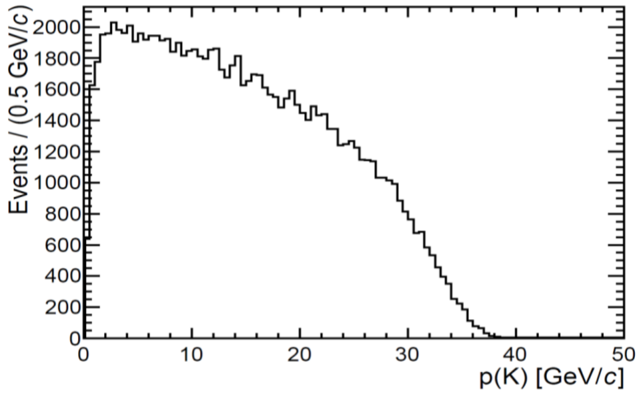
My own focus is on a compact lightweight RICH concept named ARC, intended for inclusion in one of the Higgs Factory experiments — previous talks raided for slides

Motivation

From my original presentation of ARC at an FCC week (July 2021)

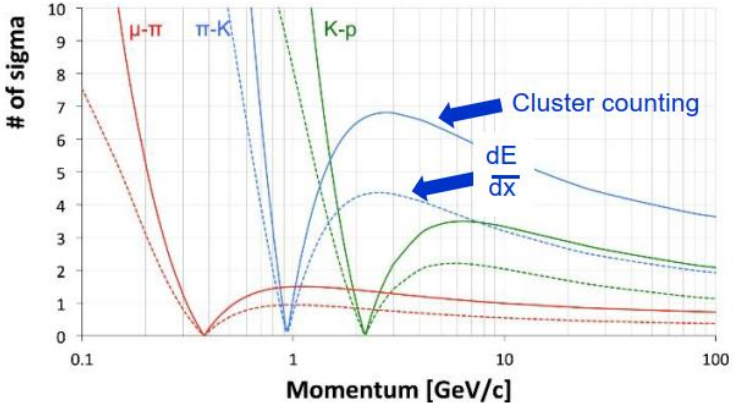
- FCC-ee will make available enormous statistics at the Z opening possibility of a world-class flavour physics programme, in addition to the Higgs and EW physics
- Flavour physics requires excellent **hadron particle identification** (separation of π, K, p) to resolve combinatorics + separate modes
  Will also be important for separating Higgs decays to bb, cc, ss
- Physics motivation and possible detector technologies recently reviewed by Guy Wilkinson [IAS-HEP, 15/1/2021 → figures shown on this slide]
- Two-body Z decays give daughters with 46 GeV momentum
  Range for low multiplicity B decay products: 1–40 GeV
- Designs for e^+e^- collider experiments traditionally do not have dedicated particle ID detectors, focusing instead on leptons, jets, and particle flow
- Time-of-flight may help fill the *dE/dx* hole at low momentum
  Cluster counting *dN/dx* holds promise of improved separation
  [see previous talk, *Attilio Andreazza* on the IDEA tracking system]

$B_s \to D_sK$ simulation in Z events



Guy: Long-standing efforts to demonstrate benefits of cluster counting – hard work!
Word of warning – not from a full simulation!
Based on analytic calc. assuming 80% efficiency

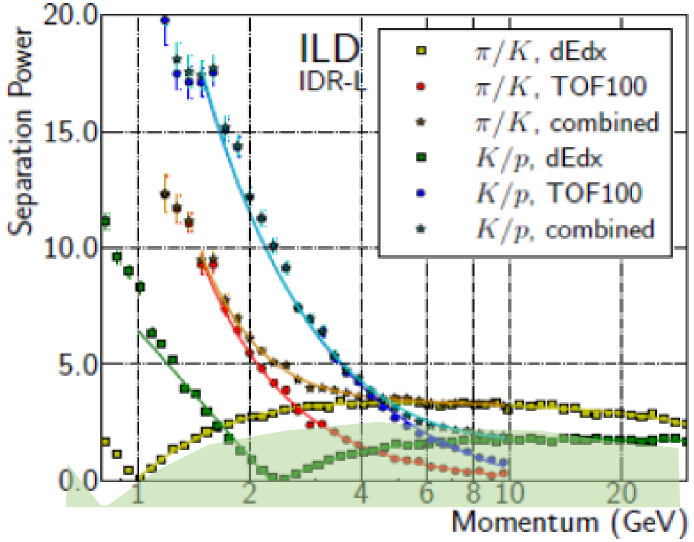
Particle Separation (dE/dx vs dN/dx)



Ionization in tracker

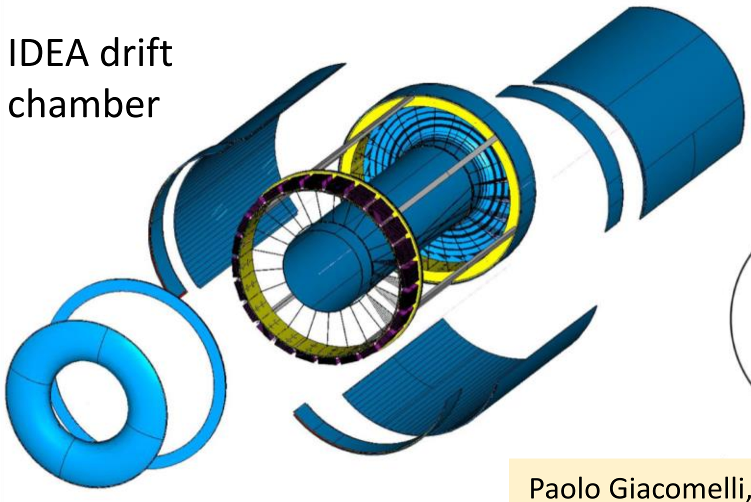
This will be a topic of DRD1 (Gaseous detectors)

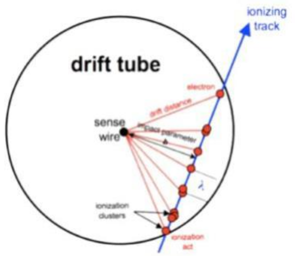
- Comes "for free" from measuring particle energy loss in tracker requires careful attention to design/calibration of readout electronics
- Traditional approach using *dE/dx:* limited separation at high *p*
- Cluster counting (*dN/dx*) can give improved resolution:
  e.g. the IDEA concept for an extremely transparent drift chamber
  (He drift gas, no endplates…)
- Needs alternative technique to cover overlap region, e.g. time-of-flight (TOF) with modest resolution 50 – 100 ps

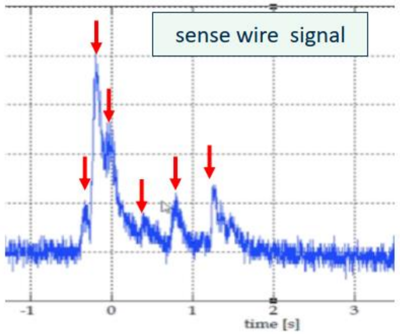


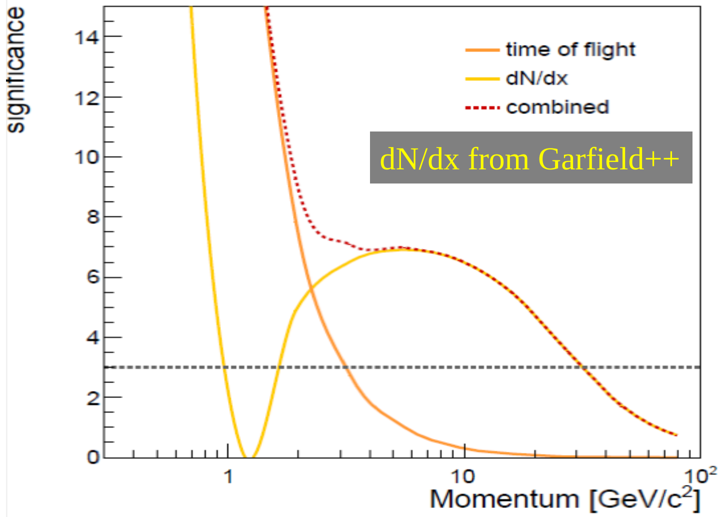
ILD Interim Design Report 2020

IDEA drift chamber









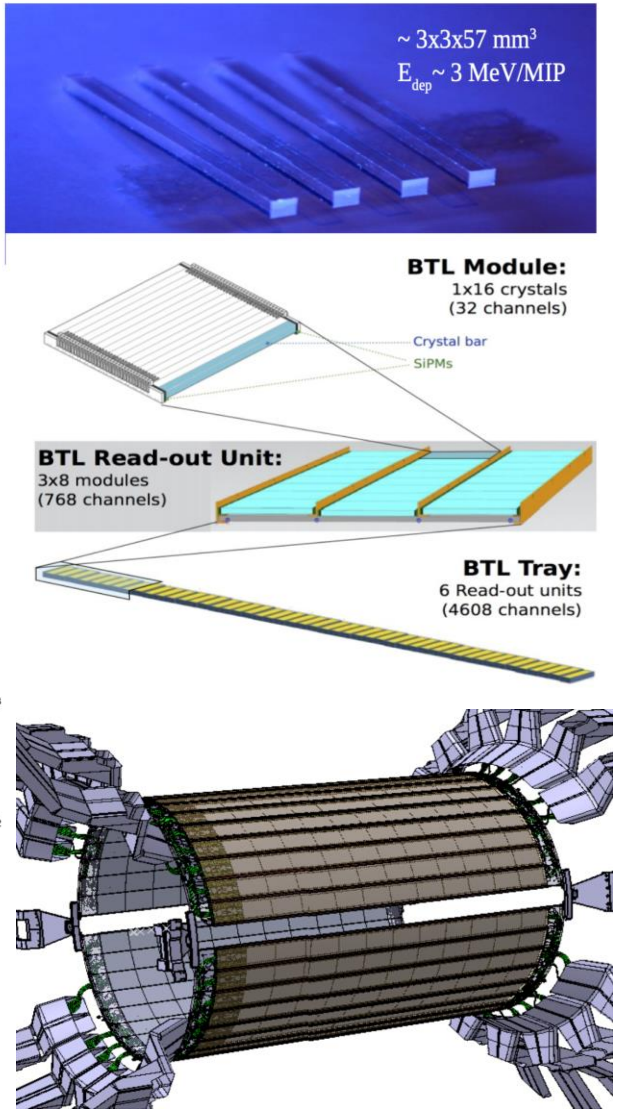
Paolo Giacomelli, kick-off meeting on detector optimisation, 22 June 2022

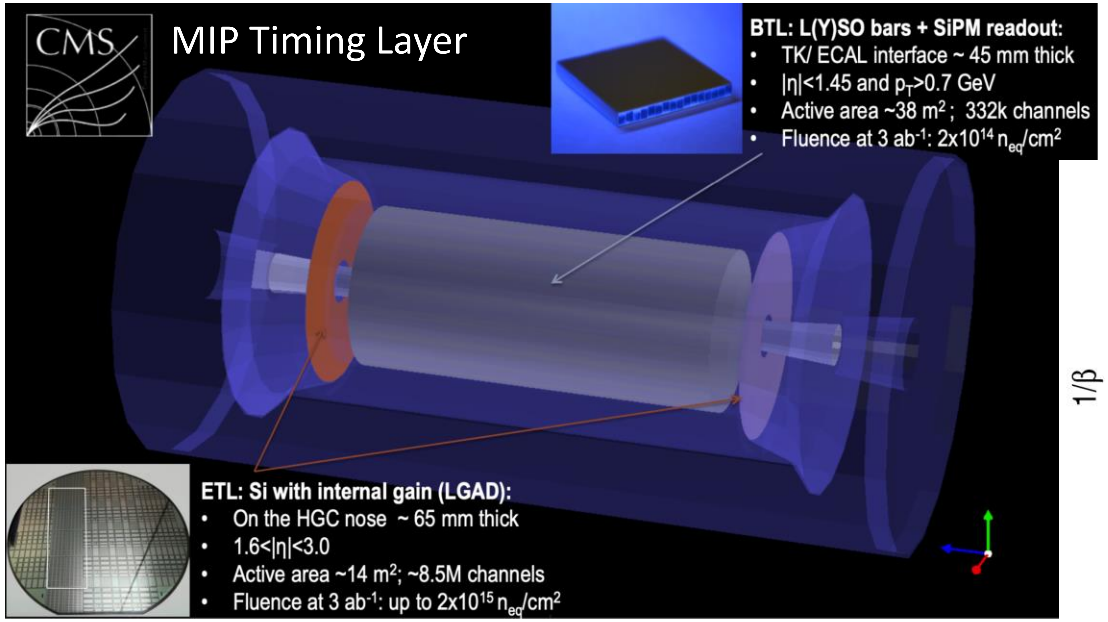
Fast timing

LGAD R&D belongs in DRD3 (Solid-state detectors)

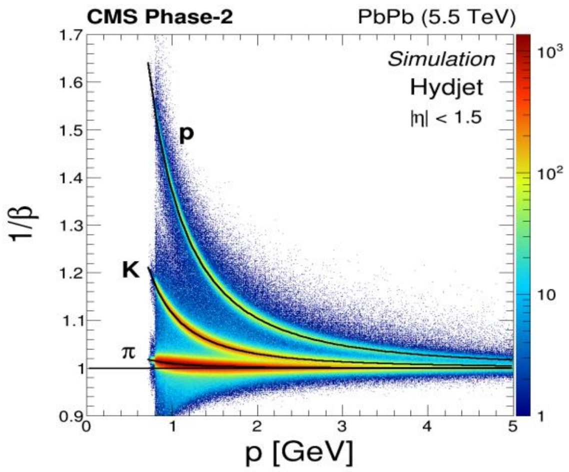
- Widely implemented in the LHC experiments for their Phase II upgrades: 4D tracking, 5D calorimetry (*x,y,z,t,E*)
- However, this is mainly driven by *pileup suppression*, not an issue at e^+e^- Target resolution ~ 50 ps, provides K-π separation by TOF up to few GeV
- Ongoing debate about the appropriate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

BTL construction





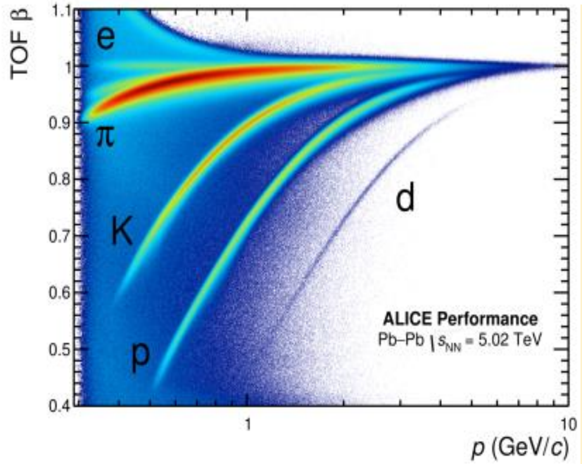
A. Apresyan, LCWS2021



Dedicated TOF detectors

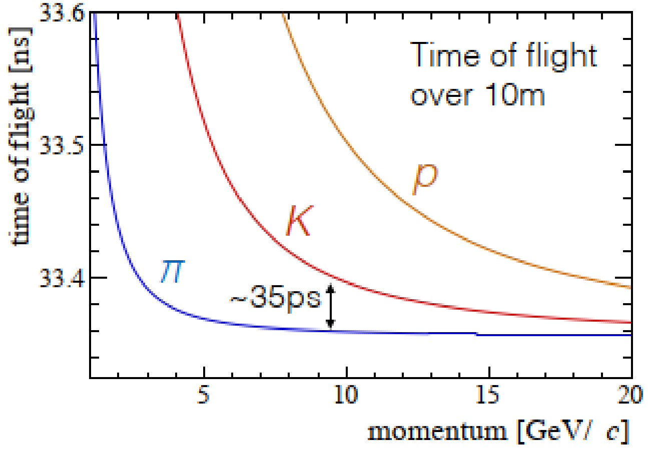
TOF is covered in DRD4

- 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

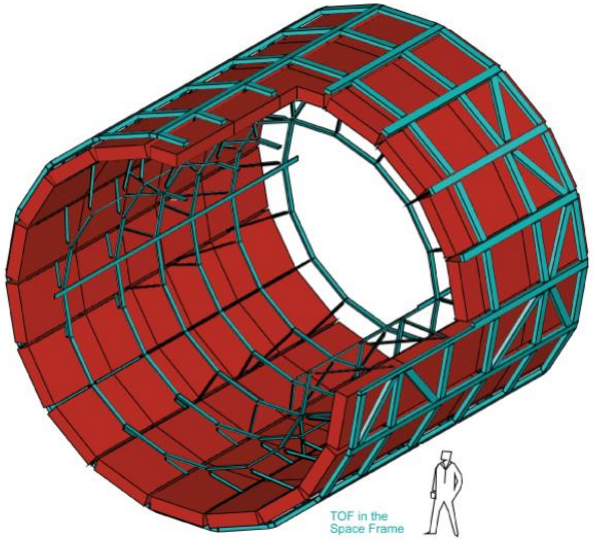


F. Carnesecchi, arXiv:1806.03825

Need O(10 ps) to reach 10 GeV

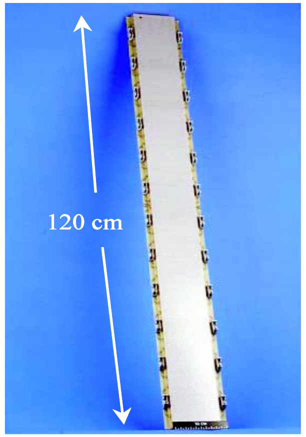


https://cds.cern.ch/record/2803563/files/LHCC-I-038.pdf



ALICE TOF

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

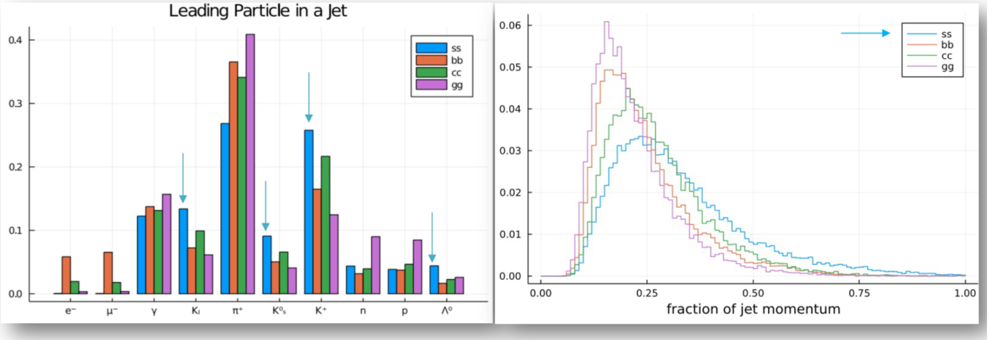


This is the target of the TORCH detector developed for LHCb Upgrade II (see backup)

The Strange Quark as a probe for new Physics in the Higgs Sector

Matt Basso (U. of Toronto)
Valentina Maria Martina Cairo (CERN)
Chris Damerell (RAL)
Markus Elsing (CERN)
Ariel Schwartzman (SLAC)
Su Dong (SLAC)
Jerry Va'vra (SLAC)

J. Strube's studies



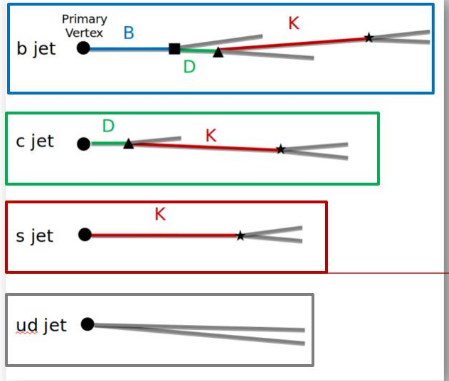
Need **K/π discrimination** over a momentum range of approximately (0.2-0.7) x 0.5 x 125 ≅ **12 to 50 GeV**

M.J. Basso *et al.*, "A gaseous RICH detector for SiD or ILD", NIMA 1059 (2024) 168992 https://arxiv.org/pdf/2307.01929

From Valentina's presentation at an FCC week (Feb 2022)

Experimental Handles for Flavour Tagging

T. Tanabe's presentation

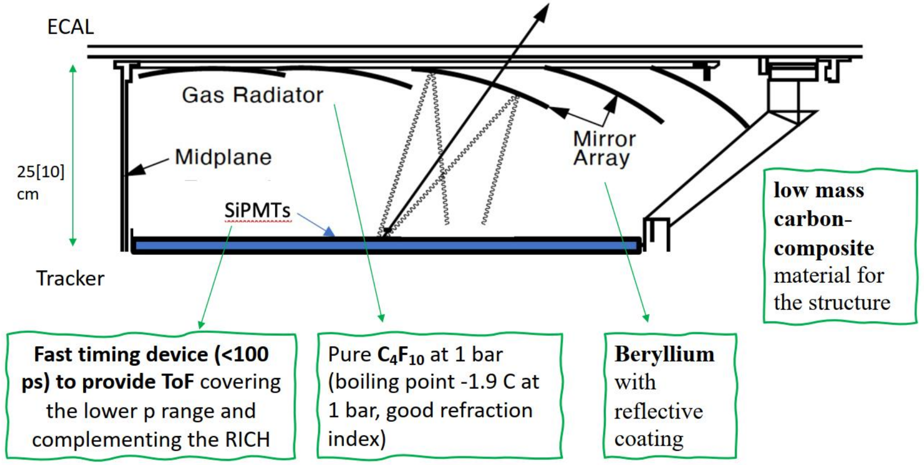


	# of secondary vertices (excluding V^0)	# of strange hadrons ($K^{\pm}$, K_L^0, K_S^0, Λ^0)
b	2	≥1
c	1	≥1
s	0	≥1
ud	0	0

Strange Hadron reconstruction
- $K^{\pm}$ [PID]
- $K_S^0 \rightarrow \pi^+\pi^-$ [Vertex] (BF ~69.2%)
- $\Lambda^0 \rightarrow p\pi^-$ [Vertex] (BF ~64%)
- K_L^0 [Particle Flow]

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!**

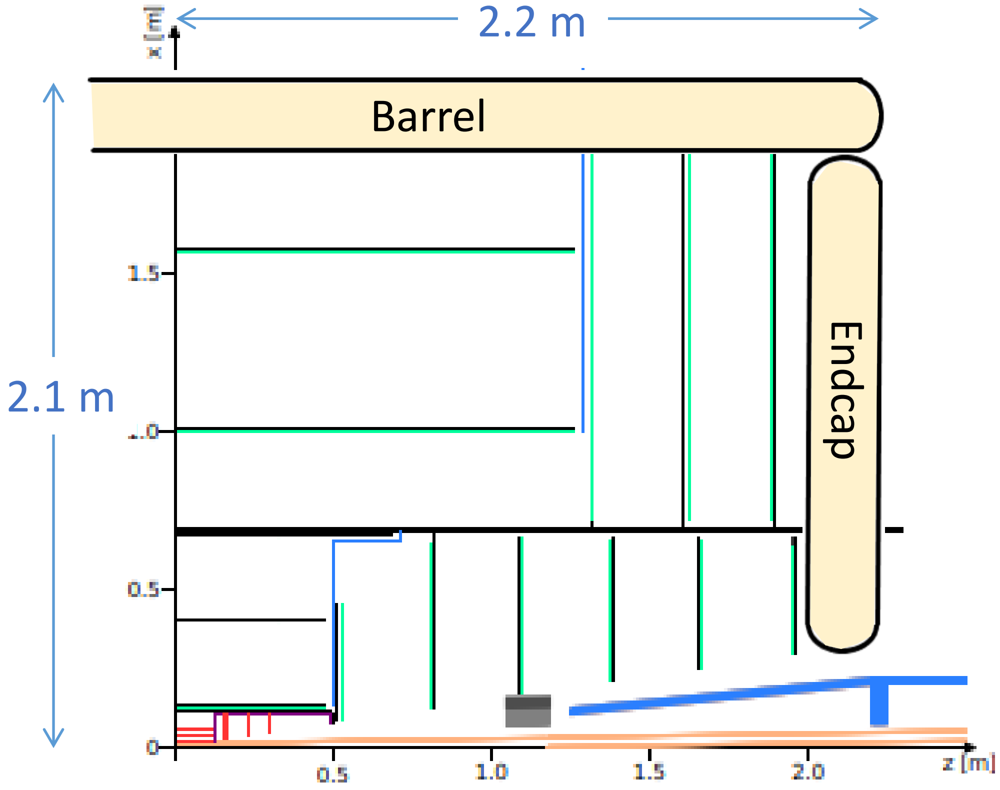


Alternative design for a compact RICH: **ARC** (Array of RICH Cells)

Collider RICH layout

- To be concrete, based the design on the current **CLD** experiment concept for FCC-ee [N. Bacchetta et al., arXiv:1911.12230]
- Target a radial depth of 20 cm, and material budget of < 10% X_0

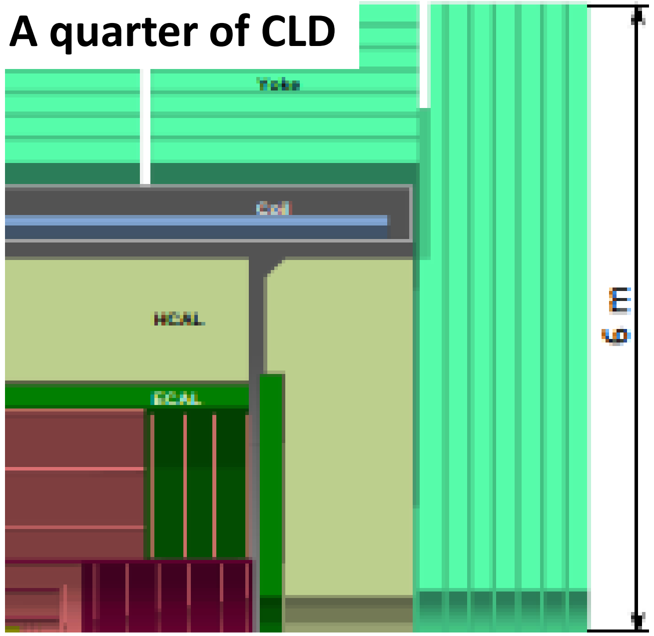
CLD tracker



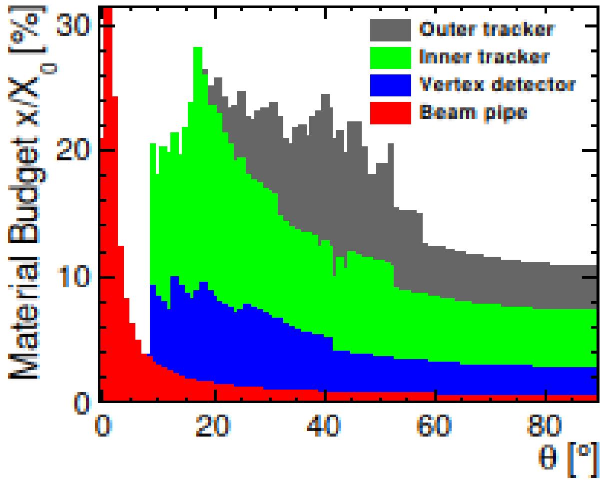
RICH vessel
(Barrel + Endcaps)
= solids of revolution around the beam axis

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…)

A quarter of CLD



CLD x/X_0

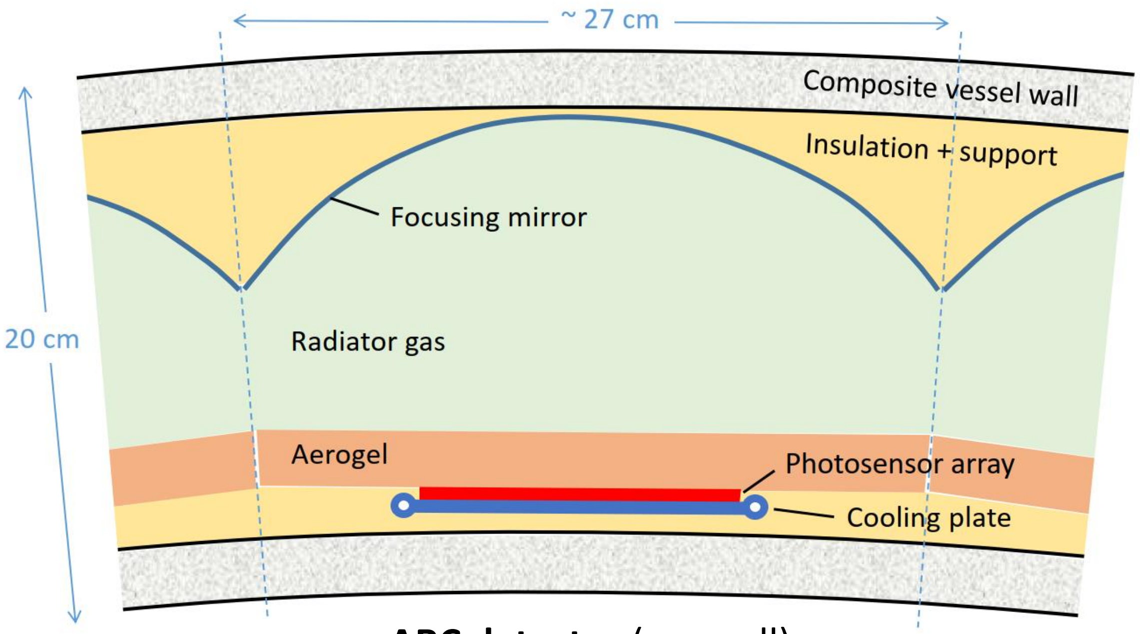


Detector cell

Main differences: individual cells are independent, and aerogel included
Otherwise the designs have converged, e.g. use unpressurized C_4F_{10} gas

- 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

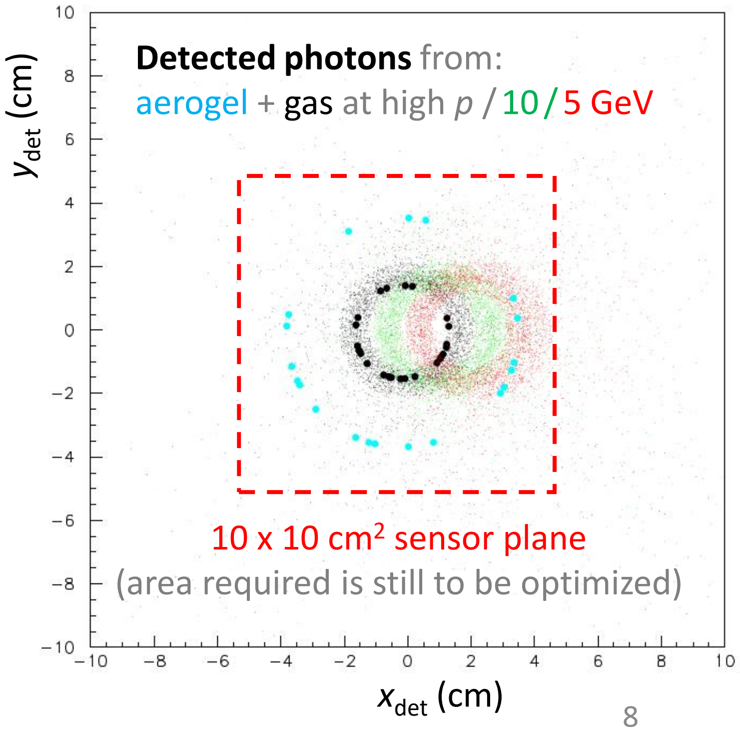
https://www.findlight.net/blog/2019/01/23/artificial-compound-eyes/



ARC detector (one cell)

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

Ring radii = $R \cdot \theta_C / 2$ = 1.5 cm (3.6 cm) for gas (aerogel)



Software implementation of ARC is led by Alvaro as a member of the FCC-ee computing team

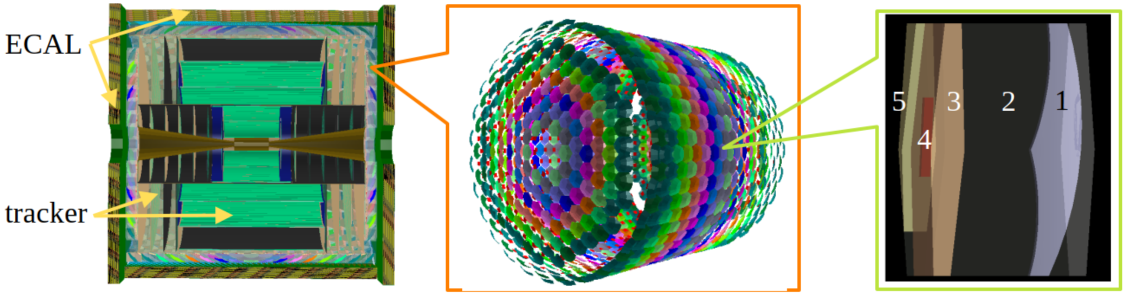
Particle Identification with ARC

Alvaro Tolosa-Delgado (CERN)

FCC physics week 2024, Annecy

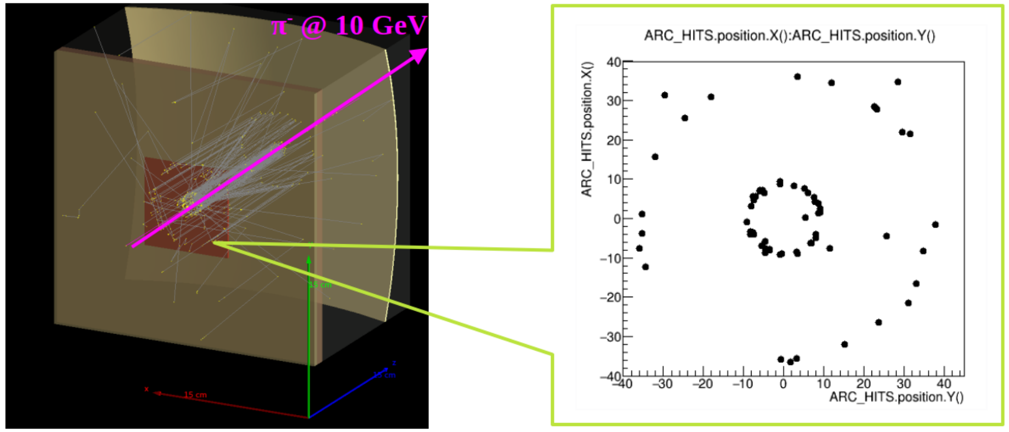
Feb. 1st, 2024

- The detector geometry, material description (including optical properties) and sensor readout is fully implemented in DD4hep framework
- The **ARC** consist on an large array of **RICH cells** placed as in the picture below (only mirrors and sensors are visible for simplicity)
- Each RICH cell consist in an spherical mirror (1) which focus the light produced in the two Cerenkov radiators (2,3) into a light sensor (4)
- **CLD option 3** has a smaller tracker compared to option 2 to leave space for the ARC, which is placed between the tracker and the ECAL



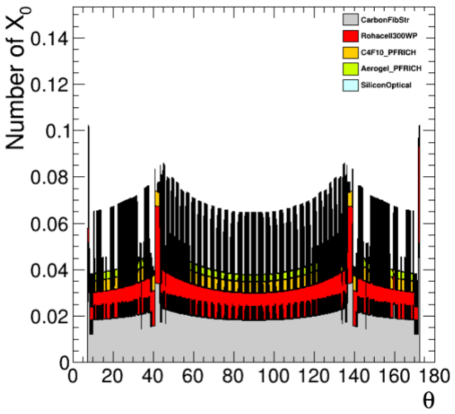
CLD option 3 ARC RICH cell

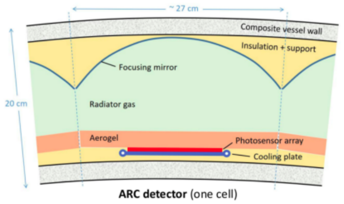
- The hit pattern in the sensor corresponds to two concentric rings
- DD4hep and Geant4 are used to simulate the behavior of the ARC detector



Particle Identification with ARC alvaro.tolosa.delgado@cern.ch 7

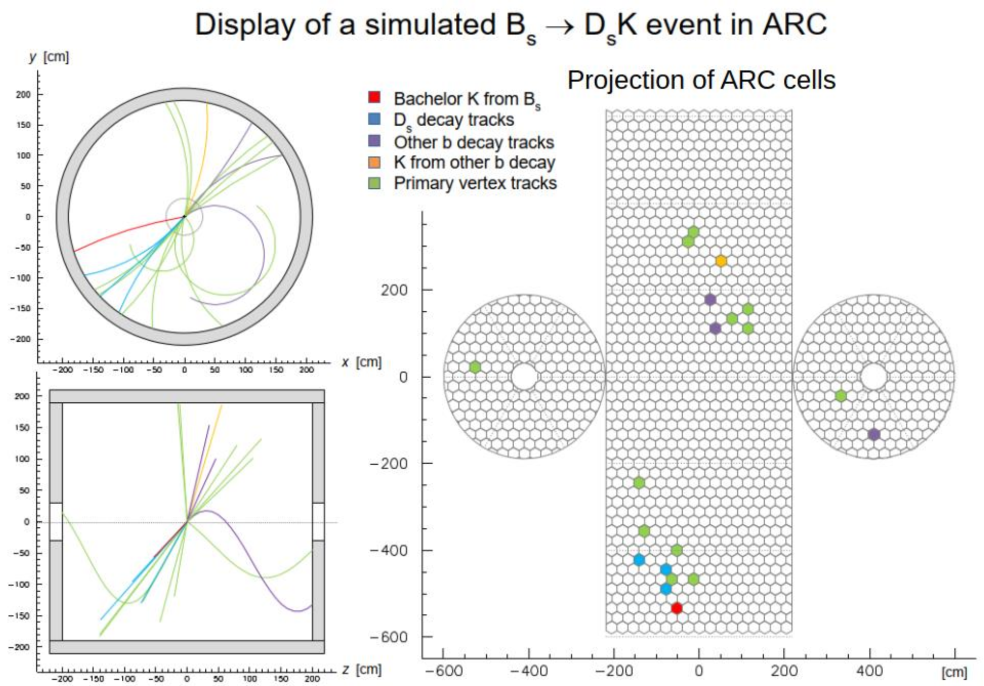
- A critical feature for the ARC design to be accepted in an experiment is to minimize the material budget: the current design checked in simulation is only 5% X_0 (on average)
- To make this a reality, R&D will be needed on the lightweight composite vessel and the photosensor; the baseline gas radiator is unpressurized C_4F_{10}, but alternatives are under study (e.g. Novel gas mixtures, or xenon)
- Development of the ARC concept is one of the work packages in new R&D Collaboration on Photon detectors and Particle ID —see task 4.3.4 in the DRD4 proposal
- DRD4 was set up last month, further participation welcome (Coordinator: Massimiliano Fiorini, CB chair: Guy Wilkinson)



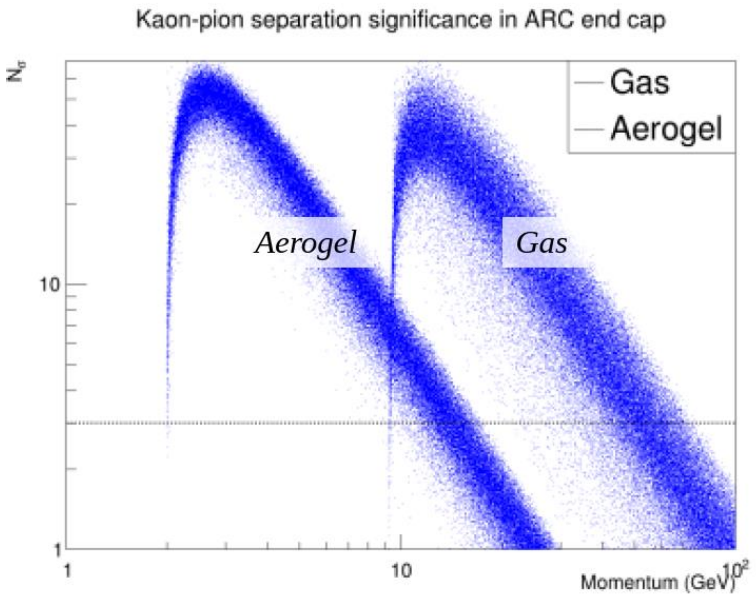


ARC reconstruction for Particle Identification

Preliminary simulations show low track occupancy of ARC in Z decay events



M. Tat, R. Forty



Gas (aerogel) provides over 3σ pion-kaon separation in the range 10-50 GeV (2-10 GeV)

- Full simulation of detector is now available
- Work in progress: implement pattern recognition and assign particle ID to tracks
- Task defined within DRD4 to construct a prototype of a single cell with SiPM sensors over the next few years

Performance studies made so far with analytical expression (appropriate for isolated tracks, low background)
Covers the momentum range 2–50 GeV/*c* required

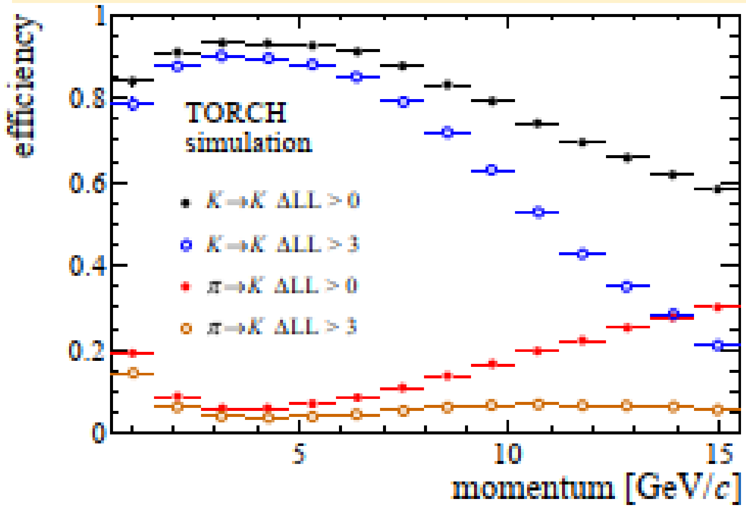
Conclusions

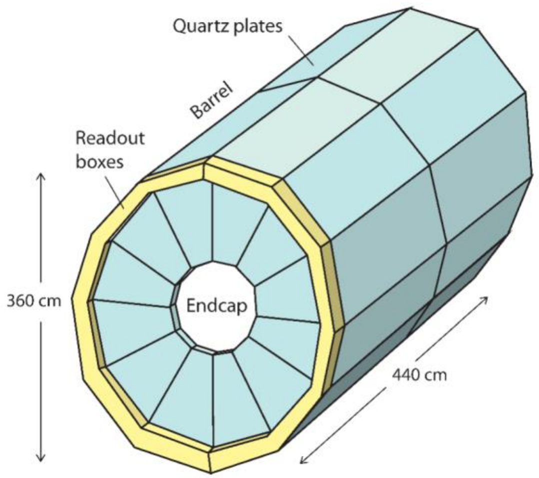
- Particle ID (identifying charged hadrons) enhances the physics of future Higgs Factory experiments both for the selection of H $\rightarrow$ ss decays, as well as flavour physics at the Z, and beyond
- Existing detector concepts include *dE/dx* + TOF, some are developing cluster counting (like IDEA)
  A compact RICH would be a powerful alternative for those without a gaseous tracker (such as CLD)
- ARC is a cellular RICH design proposed to fit the geometry of a 4π collider experiment
  It is the focus of studies at FCC-ee (but could be adapted for other future colliders)
  providing excellent PID while limiting its radial depth (20 cm) and material budget ($< 10\%$ X_0)
- Software studies are well advanced, with a full simulation in an adapted CLD-like experiment
  The next step is to develop the reconstruction, but also to quantify the impact of the material and slightly reduced tracker volume on the overall experimental performance, to facilitate its adoption
- Detector R&D to demonstrate the feasibility of the concept is underway in the context of DRD4
- Anyone interested is very welcome to join the effort!

Additional slides

- TORCH is an evolution of DIRC/TOP concepts, developed for LHCb Upgrade II to complement the RICH detectors (on timescale of LS4)
- 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

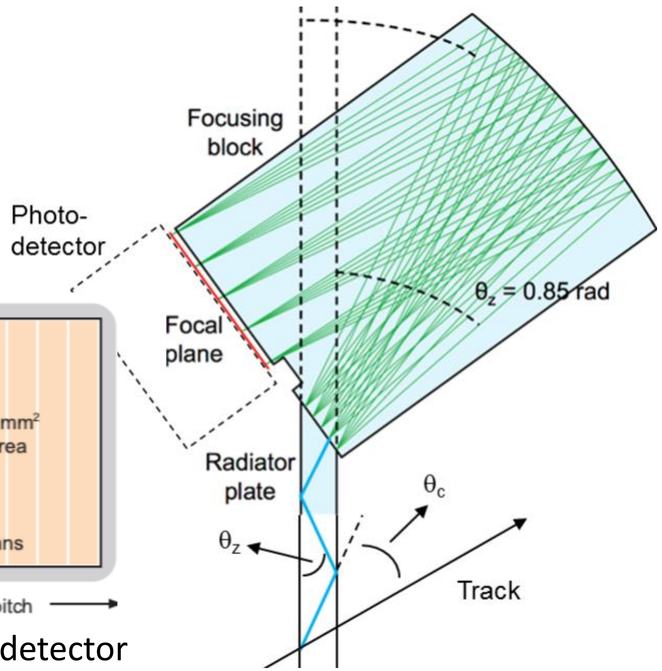
https://cds.cern.ch/record/2776420/files/LHCB-TDR-023.pdf

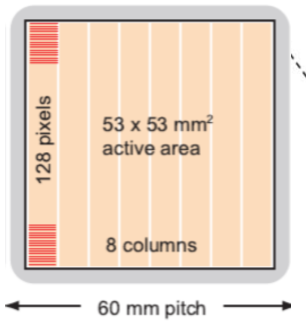




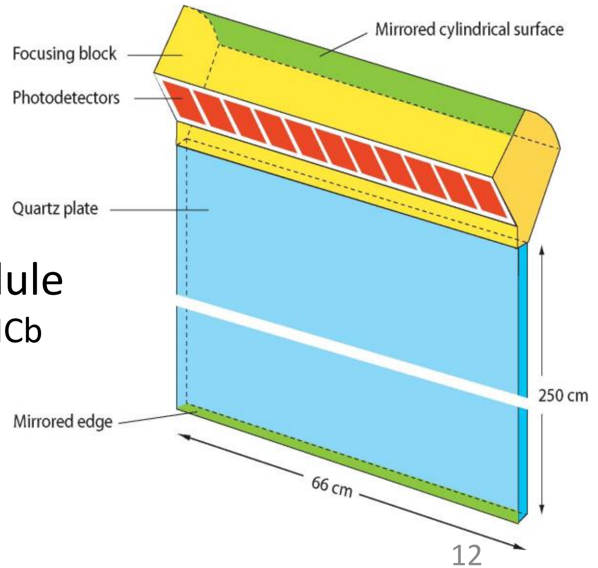
Conceptual layout for an e^+e^- experiment

TORCH focusing block





Fast photodetector MCP-PMT



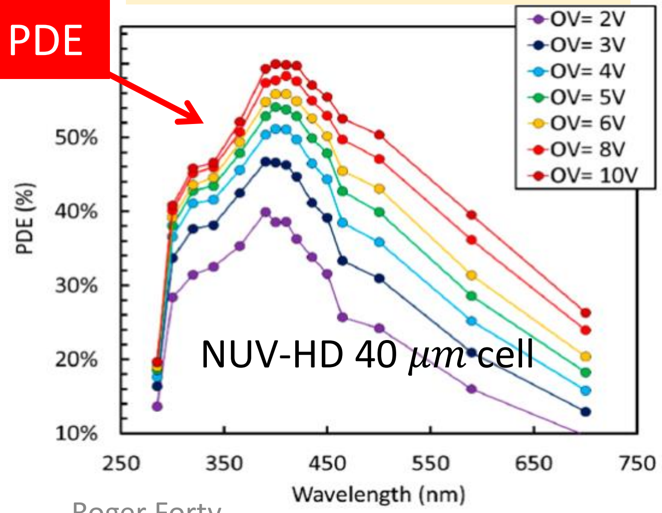
Module for LHCb

Photosensors for ARC

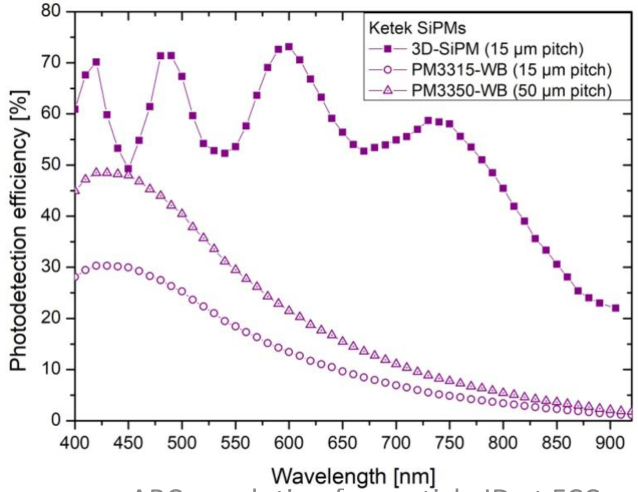
- Silicon PMs have come of age: widely adopted e.g. in MEG, DarkSide (30 m^2 area!), LHCb SciFi, CMS Barrel Timing Layer
- Excellent Photon Detection **Efficiency** > 50% possible, mostly in the visible: rapidly developing, e.g. in automotive industry
- Extremely **compact**, assume can fit the photosensor (and its readout electronics) in a few mm-thick layer
- Excellent **granularity** (sub-mm possible, e.g. 250 µm for SciFi) and fast timing resolution at ~ 10 ps level

Assume this PDE

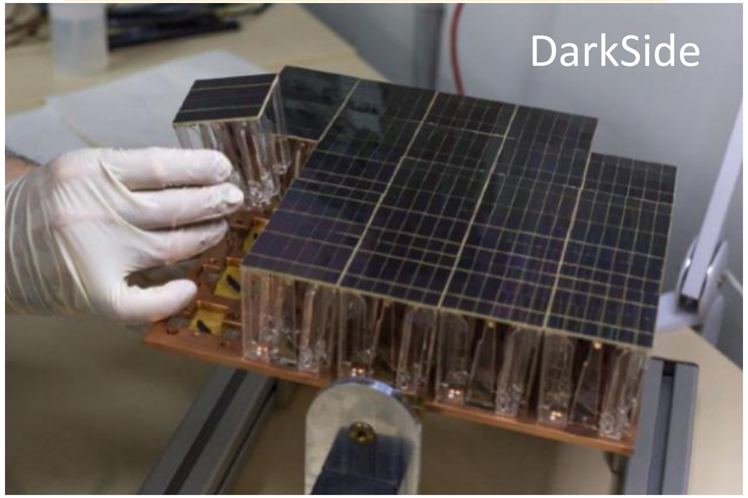
A. Gola et al, Sensors 19 (2019) 308

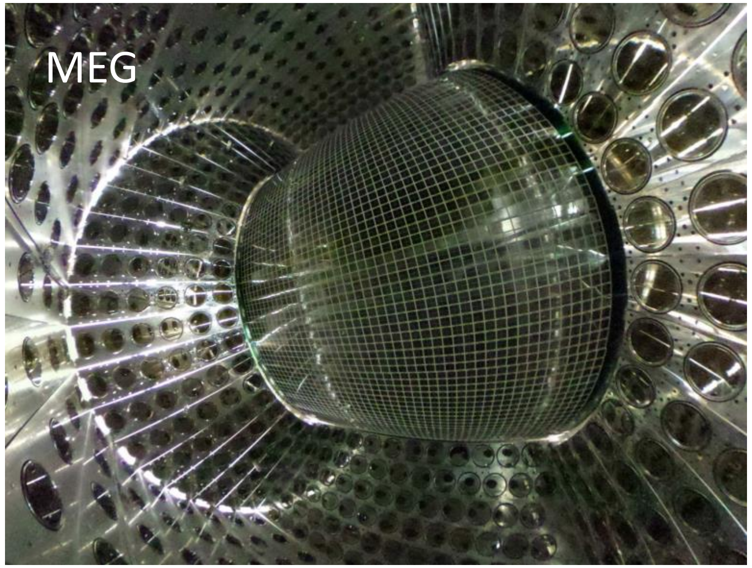


arXiv:2010.10183, K. Krüger, ECFA TF6



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



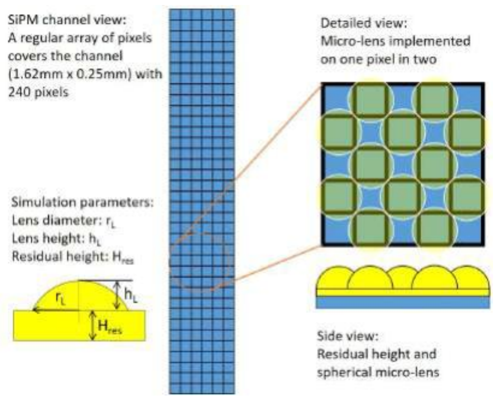


SiPM challenges

Alternative concept uses timing rather than cooling to suppress DCR

- The active area fraction of sensors can be limited, various approaches investigated to improve (e.g. microlenses)
- Their main issue is Dark Count Rate (**DCR**): high at room temperature but falls fast as temperature is reduced
- No problem for cryogenic detectors like DarkSide or MEG; CMS BTL will use CO_2 (-30°C) or add thermoelectric (-45°C)
- Major concern at LHC is increase of DCR with irradiation: *not an issue* at FCC-ee (ILC vertex detector: ~10^{11} n_{eq}/cm^2)
- Ring-imaging detectors are robust against random noise, and timing cuts can suppress it → acceptable level of DCR (and hence target temperature) needs to be established
- Nevertheless, assume cooling will be required → SiPMs + electronics mounted on cooling plate with CO_2 circulation
- Need to insulate from gas volume, while allowing Cherenkov light through: **aerogel** is an excellent thermal insulator!

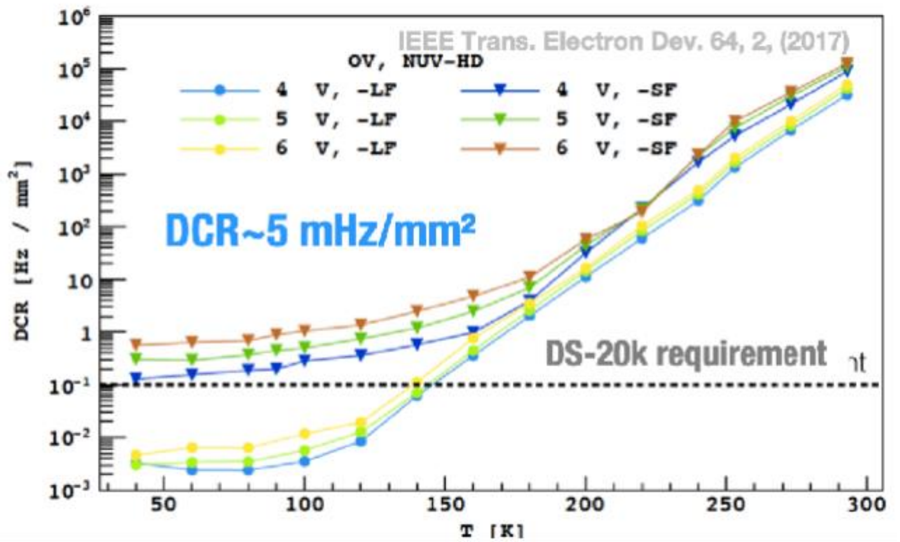
SciFi microlens concept



250 µm ↔

A Kuonen, EPFL thesis 8842 (2018)

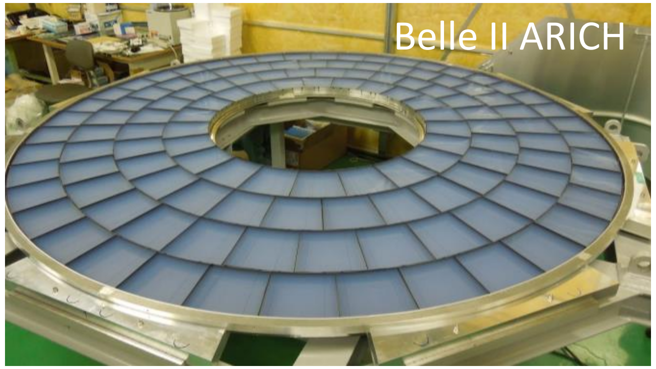
Wikipedia

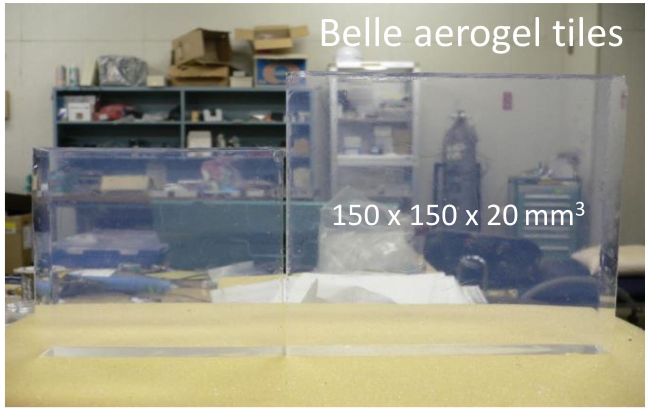


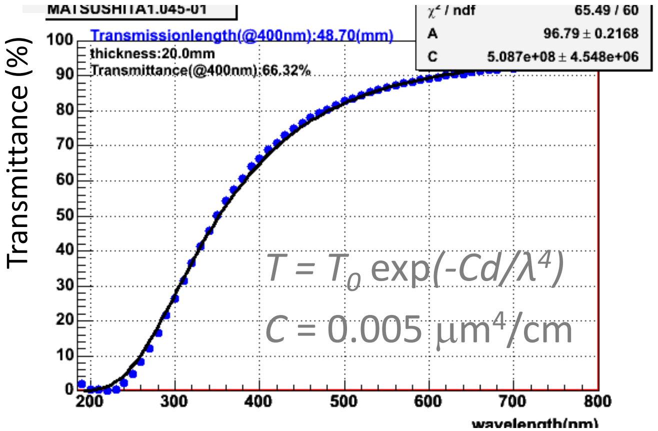
Aerogel radiator

- Silica aerogel is amazing stuff: the lightest solid, withstands pressure > 4000 bar [M. Gorgol et al, Acta Phys Polonica A 132 (2017) 1531], tunable refractive index n = 1.01–1.10, **thermal conductivity** is tiny: ~ 0.015 W/m·K
- For 2 cm thickness, assuming ΔT = 70 K, heat transmitted through a 20 x 20 cm^2 tile is only a few watts << heat that will anyway need to be extracted from the electronics
- Propose to use both as a secondary Cherenkov radiator (suitable for the low momentum tracks) *and* as thermal insulation around sensors
- *Drawback:* the photons from the gas radiator have to pass through aerogel → some loss from scattering, but also shifts towards visible
- High clarity, large area aerogel tiles developed by Belle for ARICH [I. Adachi, ECFA TF4, 6/5/2021] (other recipes also available): assume 2 cm thick tiles of clarity C = 0.005 μm^4/cm, n = 1.03 → $\theta_C \approx$ 240 mrad
- Aerogel photons focused by same mirror as those from gas onto same sensor plane → concentric rings if track above both thresholds

Efficient use of same sensors for both radiators







ARC gas radiator parameter scan

- For optimized detector layout, study systematically dependence on gas type and pressure
- A working point using pressurized xenon shown (if fluorocarbons banned)
- 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