05 - 09 June FCC WEEK 2023

FCC week in London
8 June 2023

Particle ID and Photon Detector R&D for FCC

Roger Forty (CERN)

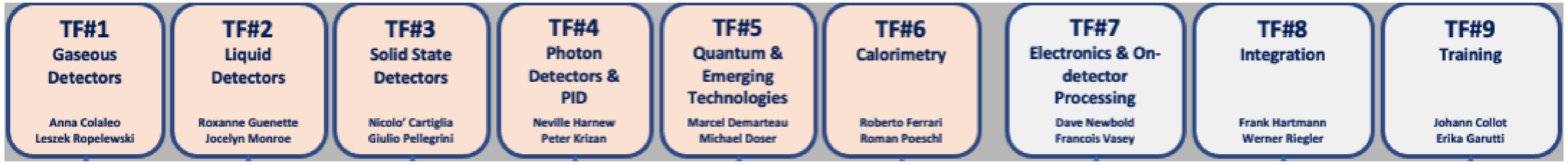
Detector R&D collaborations are being set up to implement the ECFA R&D Roadmap

DRD4 covers *Photon Detectors and Particle Identification*: kick-off meeting was held last month

I will summarize the contributions presented there that may be relevant to the FCC programme (although to be honest they were mostly not “for FCC”)

Birth of DRD4

- The ECFA Roadmap on Detector R&D was published in November 2021; its implementation → **Detector R&D collaborations** set up, to be reviewed at CERN, to focus the effort and coordinate funding
- Topics of each *Task Force* that prepared the Roadmap integrated into corresponding DRD collaborations



- **DRD4** covers *Photon Detectors and Particle Identification*, a (large) field that does not have a pre-existing collaboration structure, unlike solid-state (RD50), gaseous detectors (RD51) or calorimeters (CALICE)
- A survey and community kick-off meeting were organized by Peter Krizan and Christian Joram (replacing Neville Harnew who meanwhile retired) towards preparation of the DRD4 Proposal this summer
  91 people attended meeting on 16-17 May with 24 contributions presented on the following topics:
  - *Photon detector technology:* SiPMs (8), Micro-Channel Plate (MCP) detectors (4), PMTs (1)
  - *Particle identification:* RICH detectors (7), TOF (3), TRD (1)
- Organization of R&D into Working Groups and Joint Projects is now being worked out, ready for proposal

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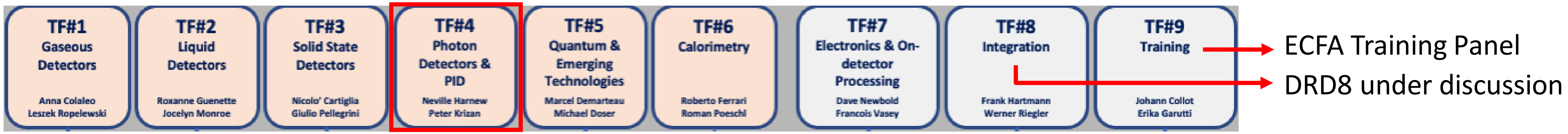

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From the Roadmap

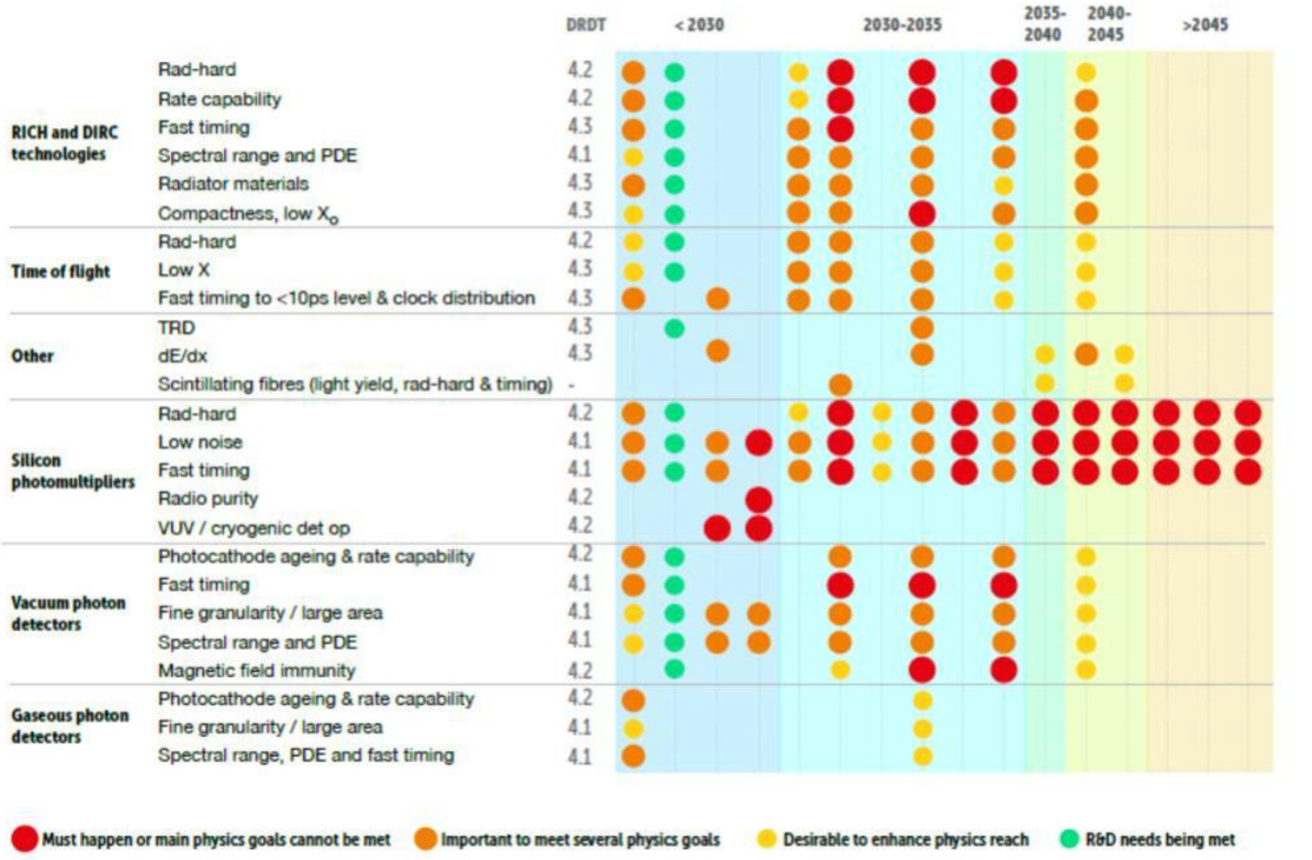
- Critical **Detector R&D Themes** identified:
  1. Fast and efficient photon detectors
  2. Radiation-hard photosensors
  3. RICH/imaging detector development
  4. High performance time-of-flight
- R&D will be pursued in *Joint Projects* (i.e. bringing together groups to work on topics of common interest) organized under those themes

  The first two themes may be combined into a single *Photon detector R&D* theme (since many of the proposals target both fast timing *and* radiation resistance)
- Many aspects of PID and Photon Detector R&D were seen as important for FCC-ee
  Only SiPMs were mentioned for FCC-hh…

R&D themes

R&D needs by facility

PID and Photon		
	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors



[from Figures 4.1 and 11.1]

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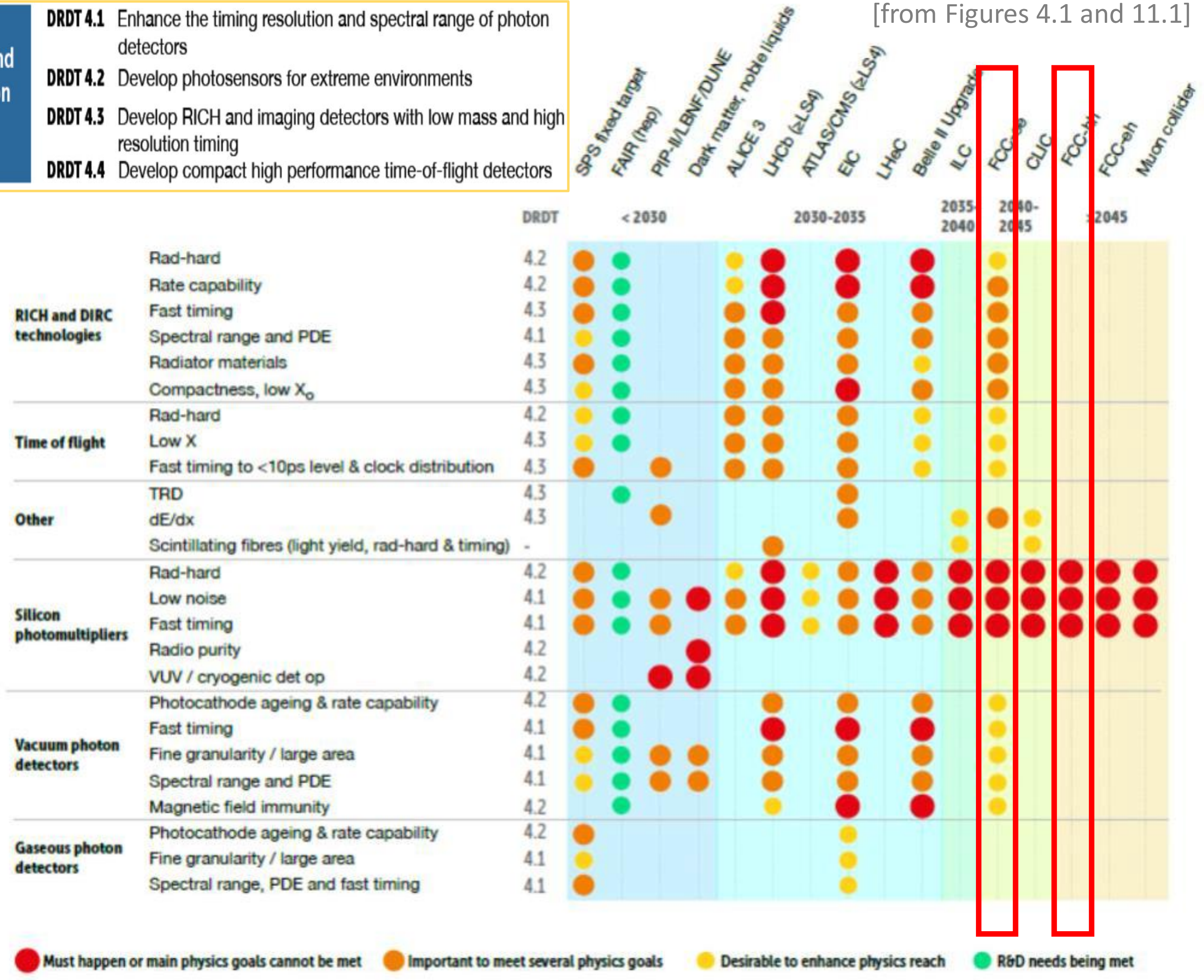
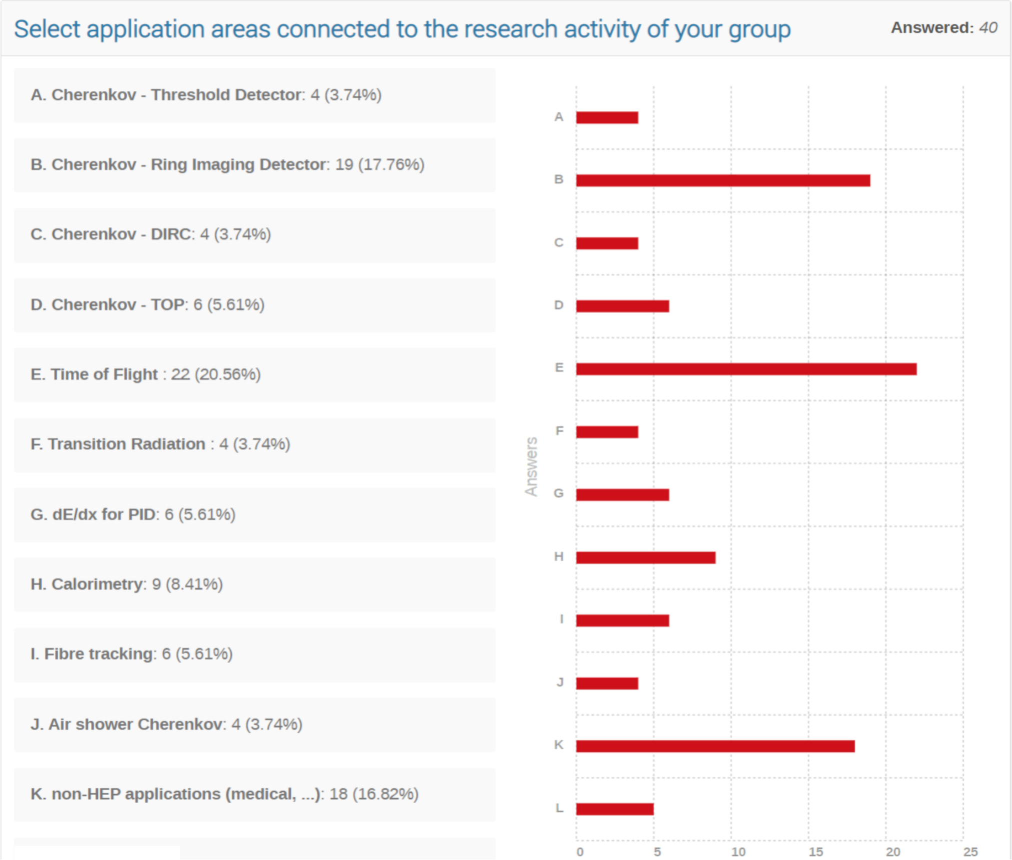
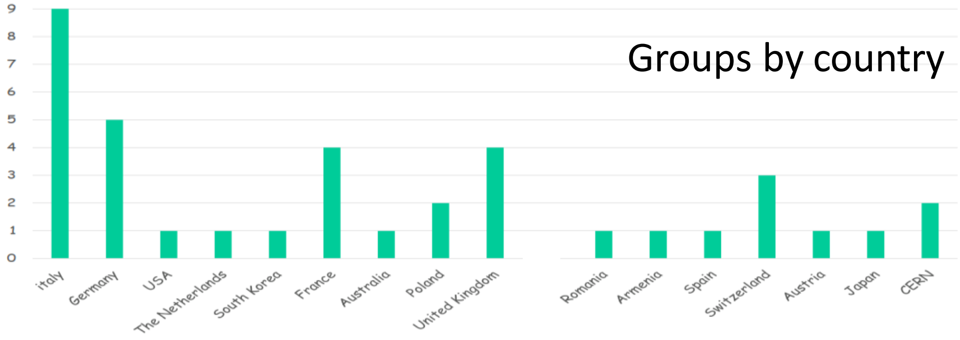


From the Survey

- **47** groups participated in the survey, widely spread
- Note that *all* photon detector R&D is covered by DRD4, not only that needed for particle ID detectors
  → applications in calorimetry and fibre trackers requiring photon detection should also be covered (although main focus is on single-photon sensitivity)
- Boundaries with other DRDs are being clarified:
  - *dE/dx* + *dN/dx* in gaseous detectors → **DRD1**
  - Timing with solid-state detectors such as LGADs → **DRD3** even if used for Time-of-Flight (TOF)
  - Scintillating-fibre tracking is *included* in **DRD4**
  - Transition Radiation detectors too? (in discussion)
- Not much explicit reference made to FCC in the responses apart from the compact RICH proposal (ARC)
  Most ongoing R&D activities have nearer-term targets (LS4 upgrades of LHCb/ALICE, the EIC, etc.)

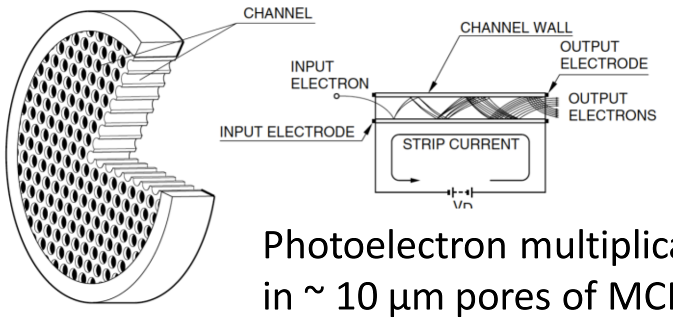
Group interests



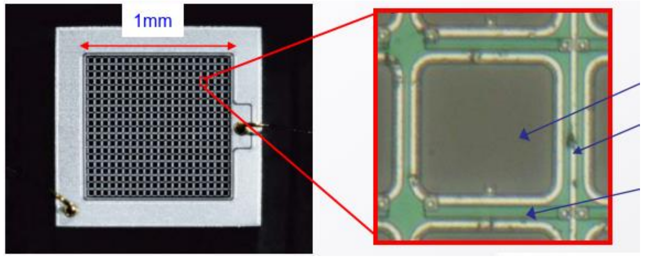


Photon detector R&D

- Only a single contribution on PMTs
- Vibrant R&D on MCPs and SiPM, in close connection with industry
- Small feature sizes → intrinsically fast

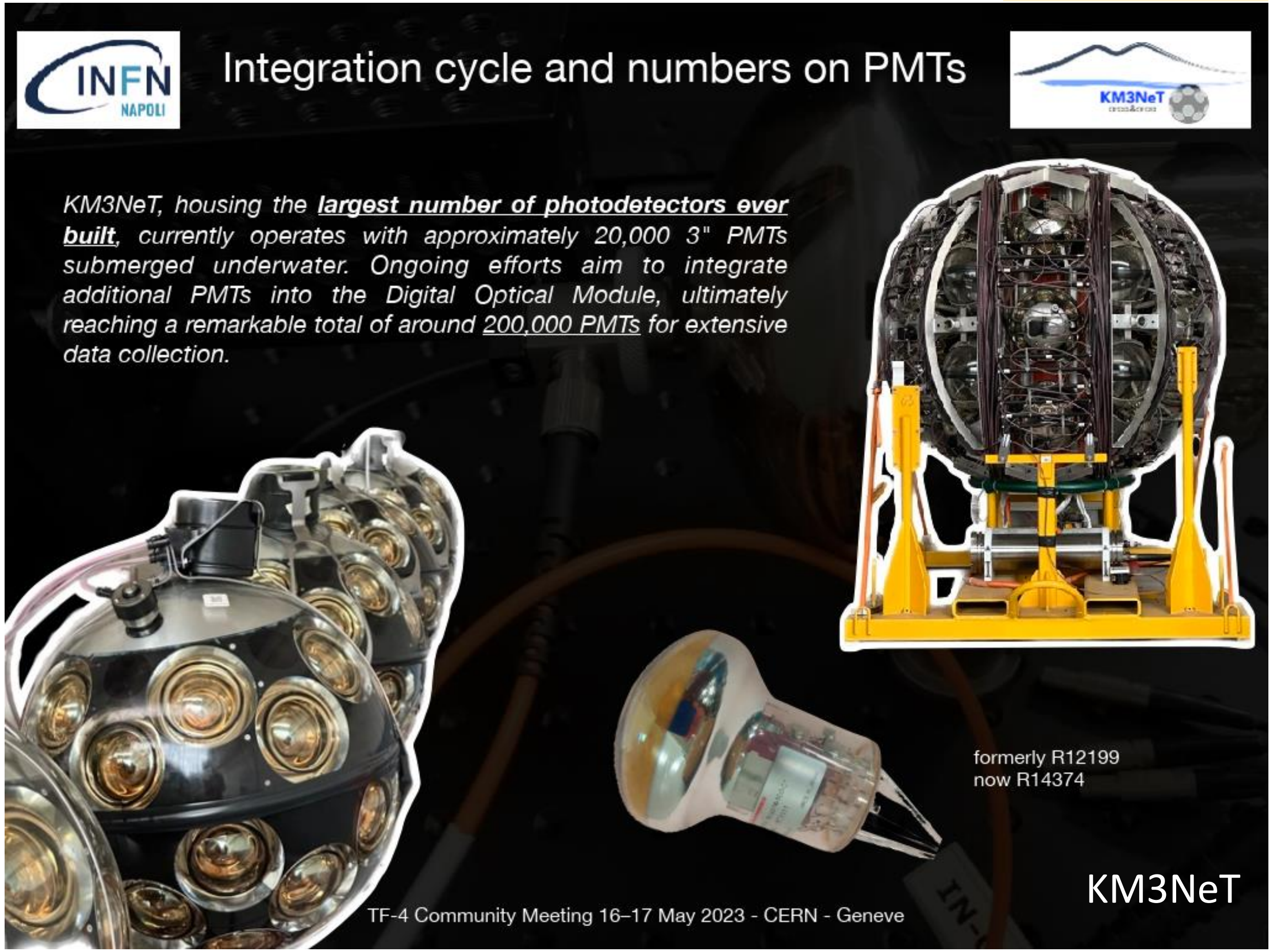


Photoelectron multiplication in ~ 10 µm pores of MCP



SIPM "sub-pixels" (SPADs)
Single Photon Avalanche Diodes

Andreino Simonelli



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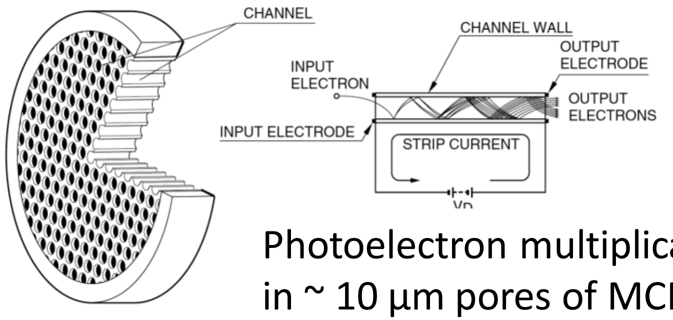

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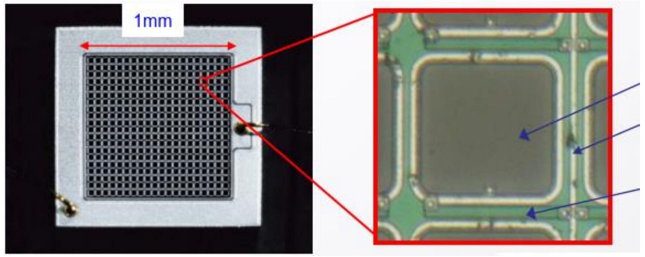

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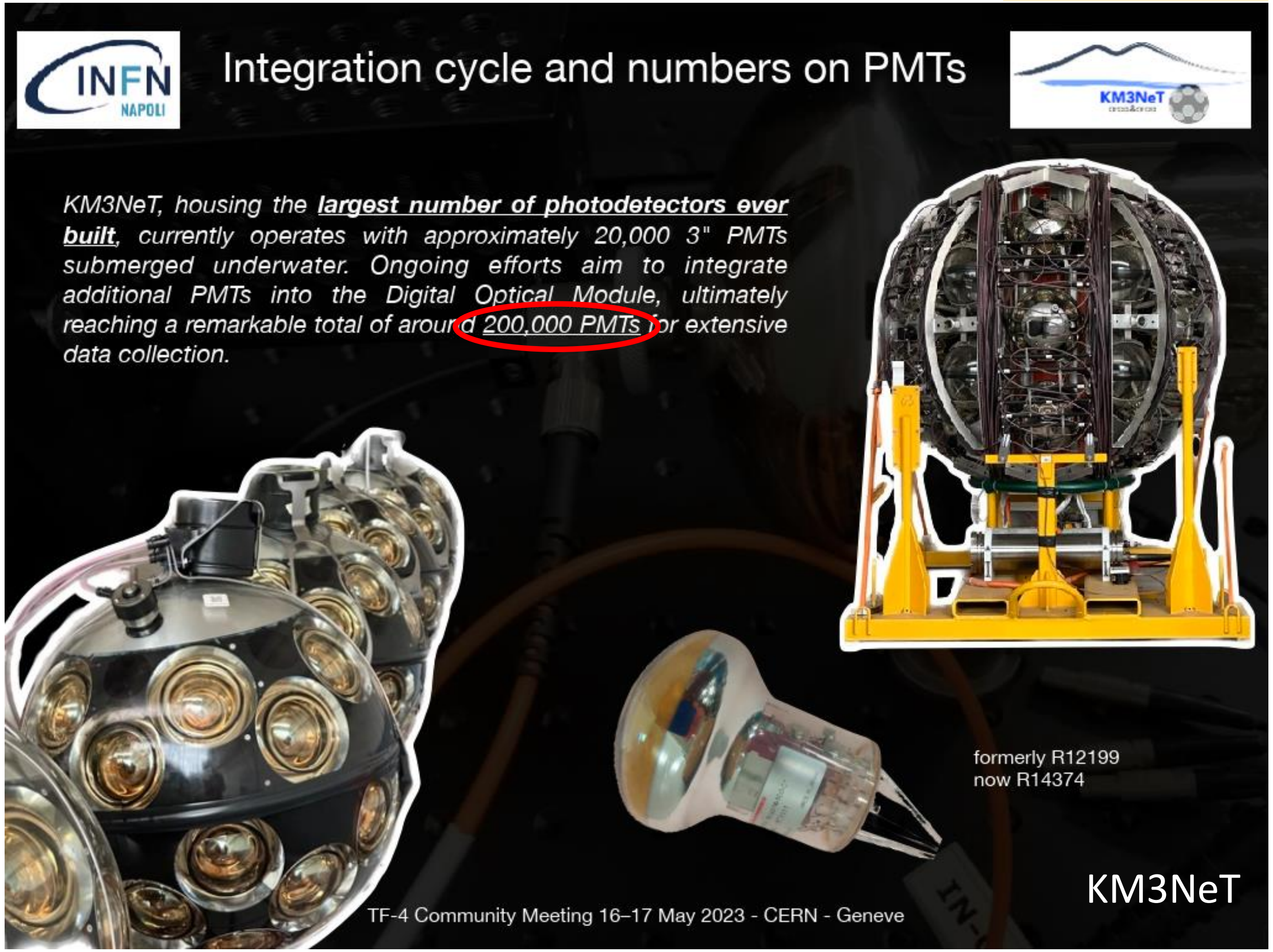
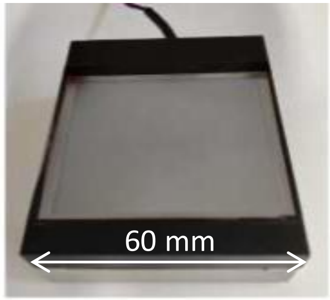
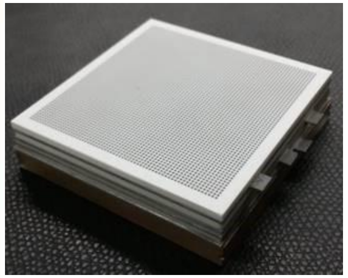


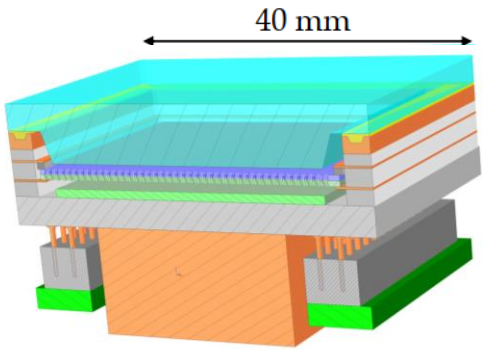
MCP-PMTs

- Under evaluation for LHCb RICH, TORCH, PANDA, HIKE, etc.

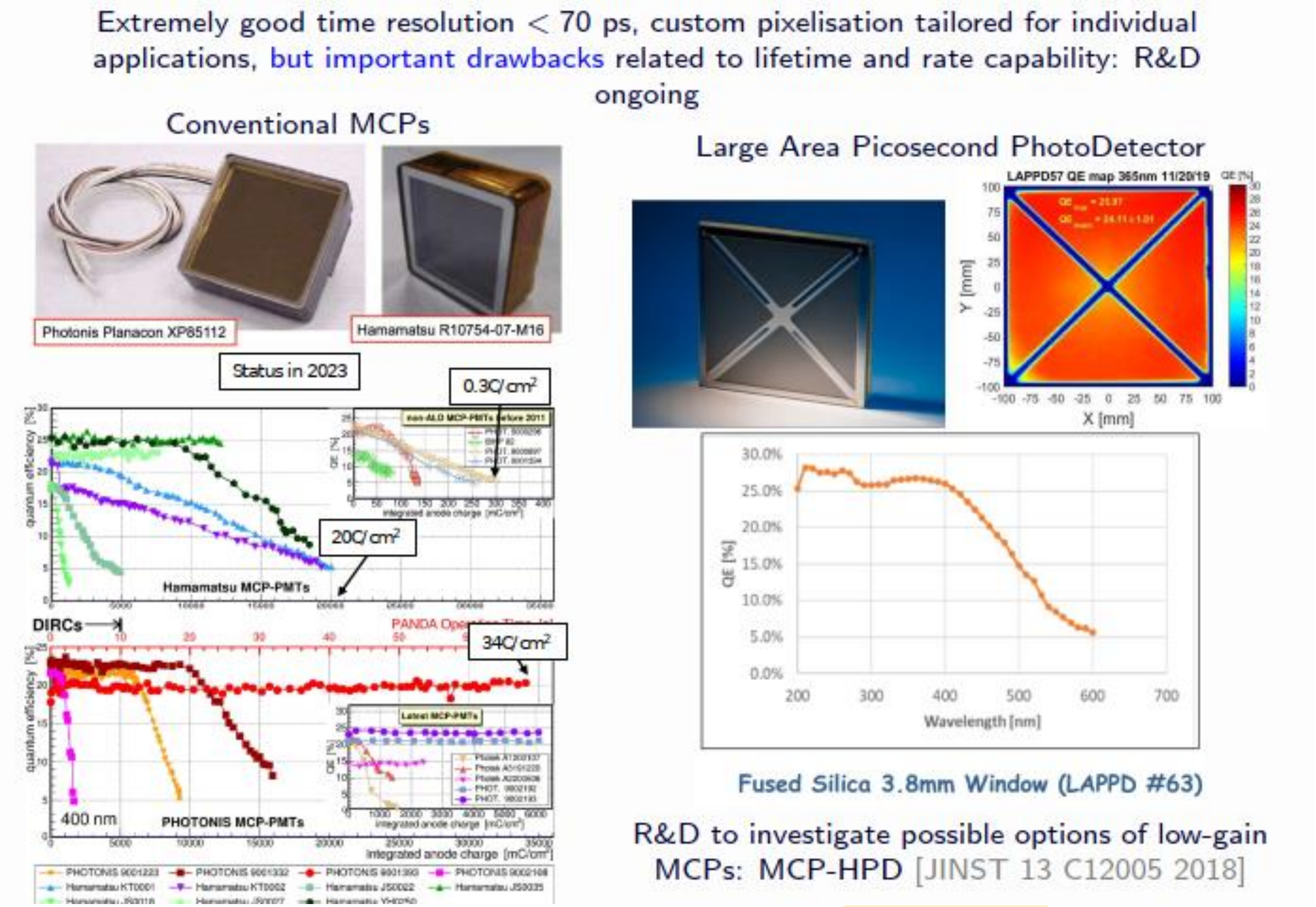




MCP with 64 x 64 anode pads (Photek)



R&D to develop an MCP with integrated Timepix4 chip (55 x 55 μm^2 pixels)



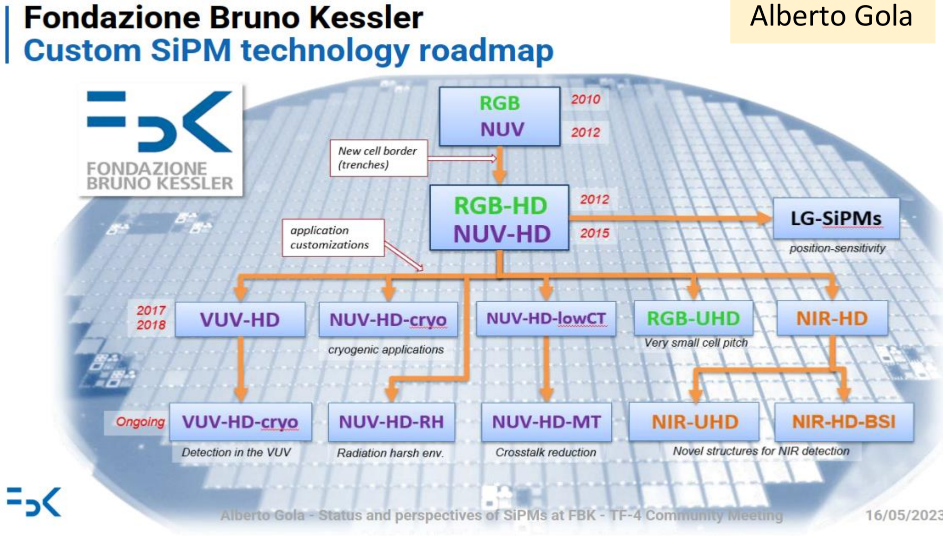
Massimiliano Fiorini

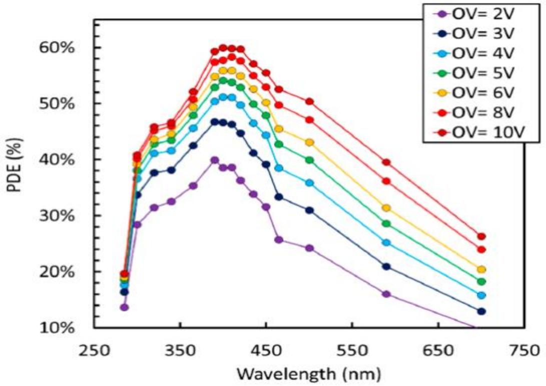
Silvia Gambetta

SiPM developments

- + High detection efficiency, low cost
- – High noise (DCR), neutron damage
- Many lines being followed towards more integrated sensor + electronics
- Detailed presentation made by FBK

Alberto Gola





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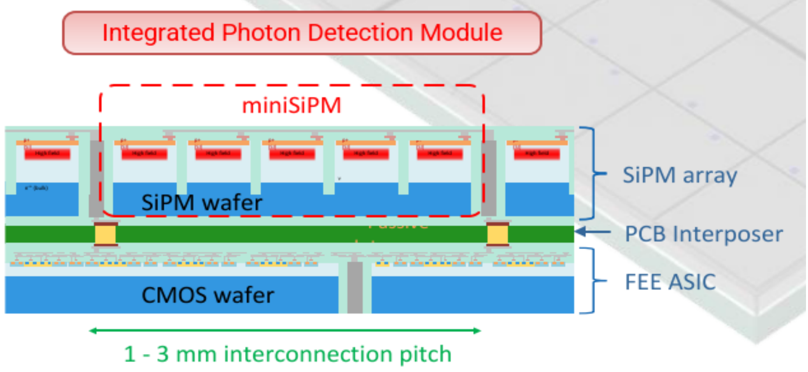


Hybrid SiPM module being developed for ultimate timing performance in ToF-PET

2.5D and 3D Integration

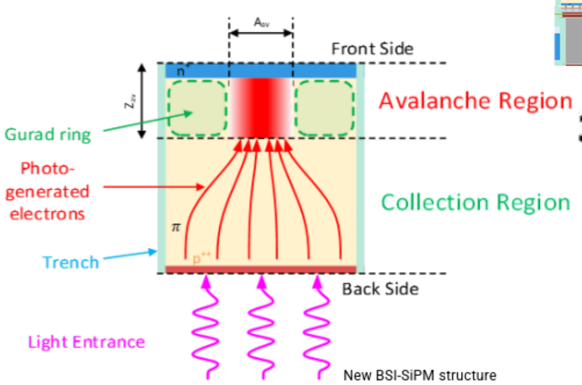
Next-generation development: Backside Illuminated SiPMs

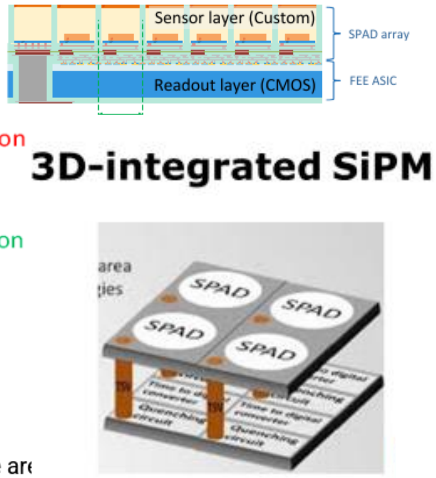
The next-generation of developments, currently being investigated at FBK, is building a *backside-illuminated, NUV-sensitive SiPM*. Several technological challenges should be overcome.

Clear *separation between charge collection and multiplication regions*.

Potential Advantages:

- Up to 100% FF even with small cell pitch
- Ultimate Interconnection density: < 15 um
- High speed and dynamic range
- Low gain and external crosstalk
- (Uniform) entrance window on the backside, ideal for enhanced optical stack (VUV sensitivity, nanophotonics)
- Local electronics: ultra fast and possibly low-power.





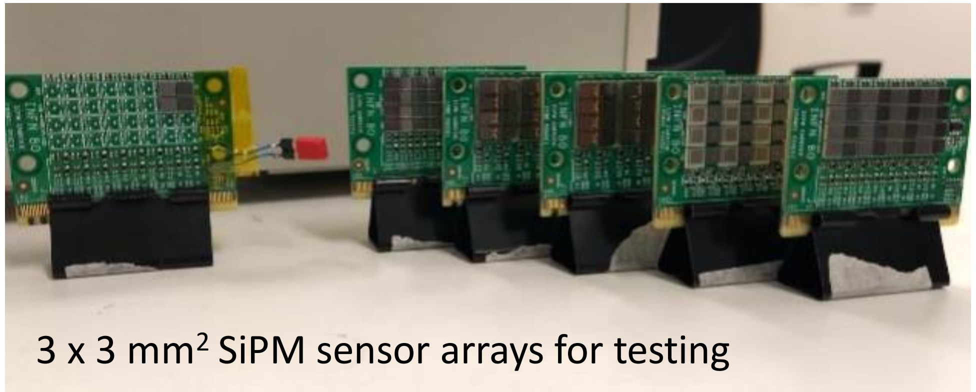
Radiation hardness:

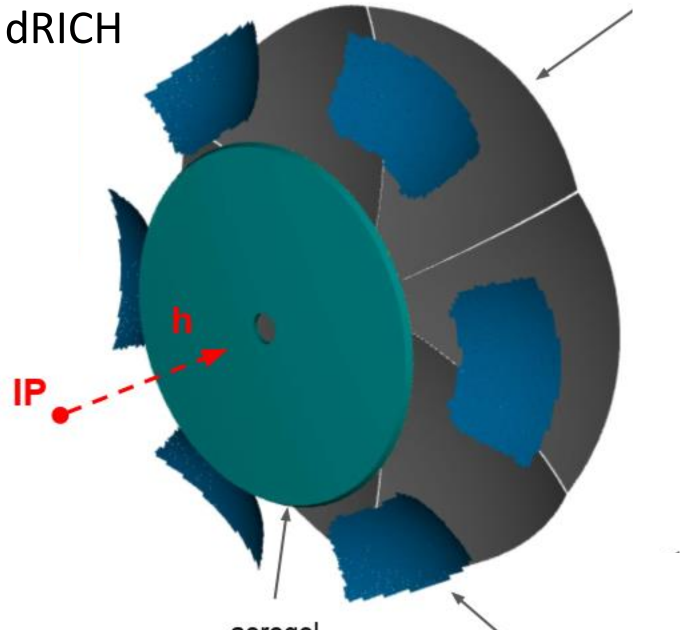
- The SiPM area sensitive to radiation damage, is much smaller than the light sensitive are
- **Assumption**: the main source of DCR is field-enhanced generation (or tunneling).

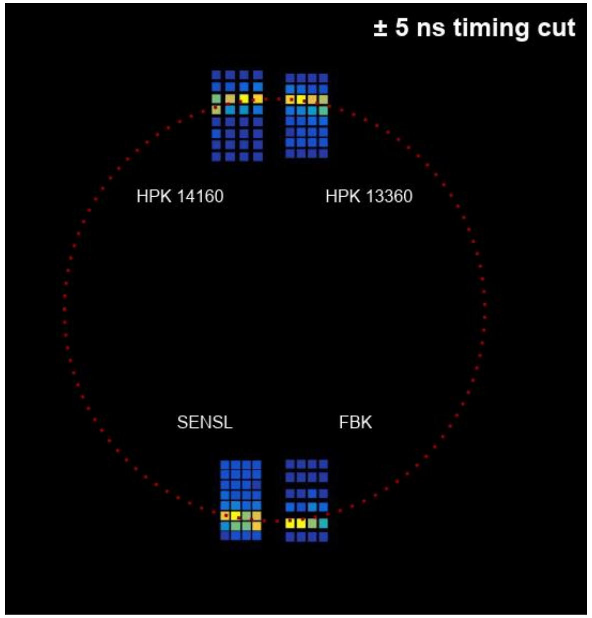
SiPM studies for EIC

Roberto Preghenella

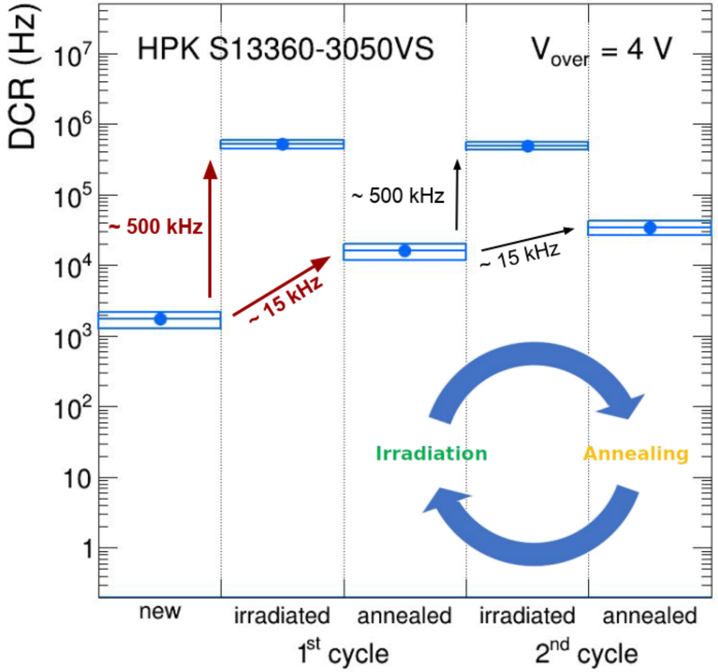
- A dual-radiator RICH is being studied for the EIC
  SiPM arrays from various vendors under test
- Substantial increase in the dark count rate with irradiation (10^9 n_{eq}), largely recovered by annealing (150 hours at 150 °C)







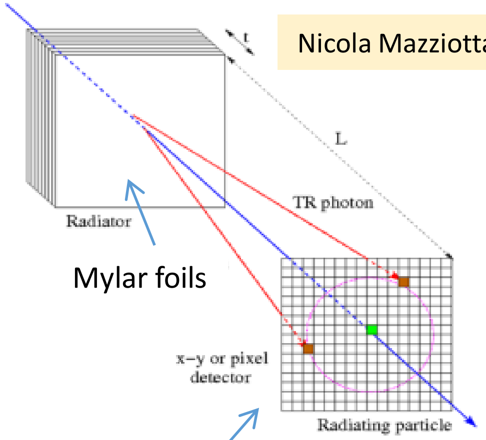
8 GeV negative beam (aerogel rings)



Particle ID R&D contributions

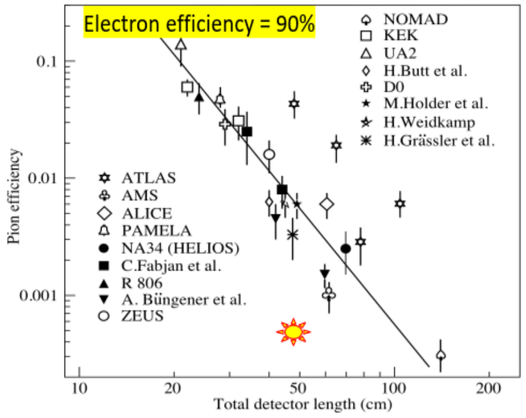
- **RICH** detectors
  - Proximity focusing aerogel development
  - Possible combination with TOF measurement
  - Environmentally friendly RICH radiator gases (replacement for fluorocarbons)
  - Compact RICH with dual aerogel + gas radiators
- **TOF** detectors
  - SiPMs detecting Cherenkov light from their entrance window
  - DIRC-style: TORCH, and the upgrade of the Belle-II TOP detector
- **TR** detectors
  - Solid-state detection of Transition Radiation

Nicola Mazziotta

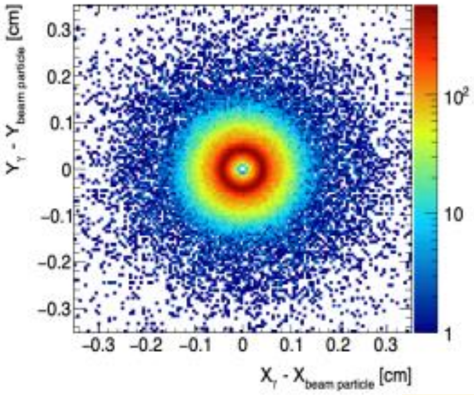


Mylar foils

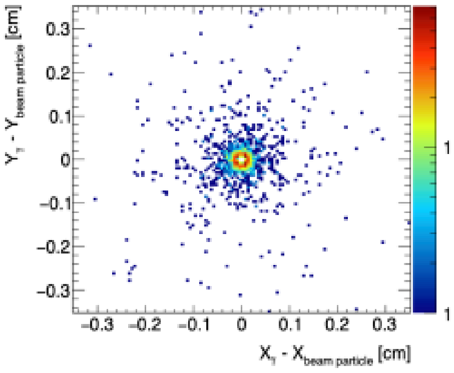
GaAs sensor + Timepix3 readout chip



Electrons



Pions



NIMA 958 (2020) 162037

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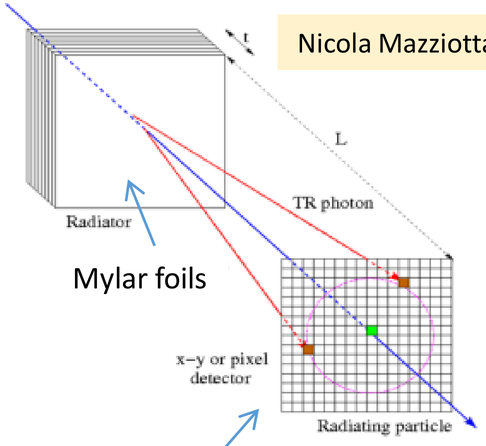

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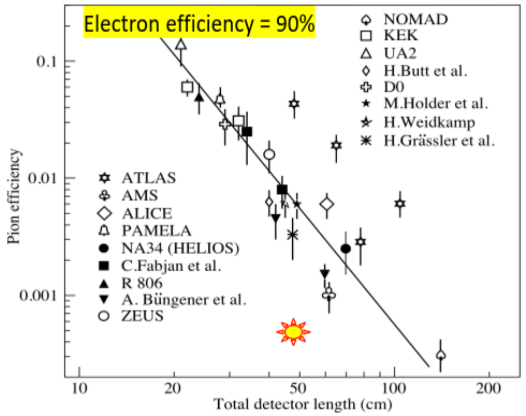

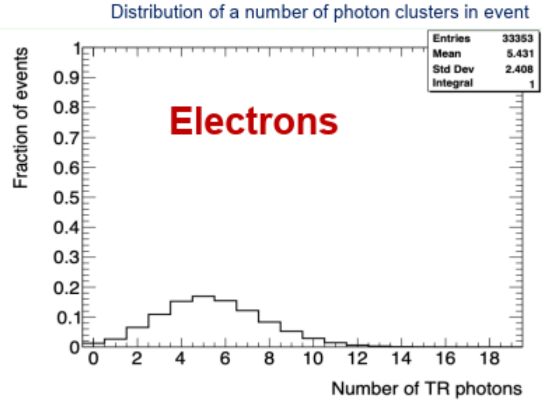

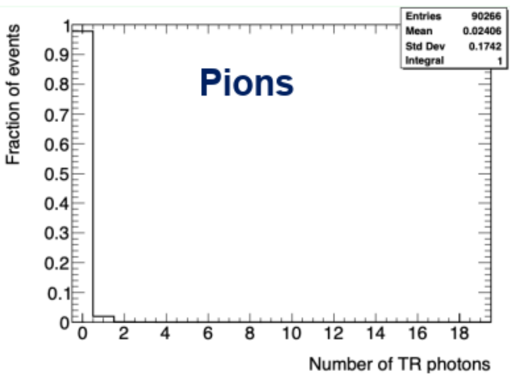

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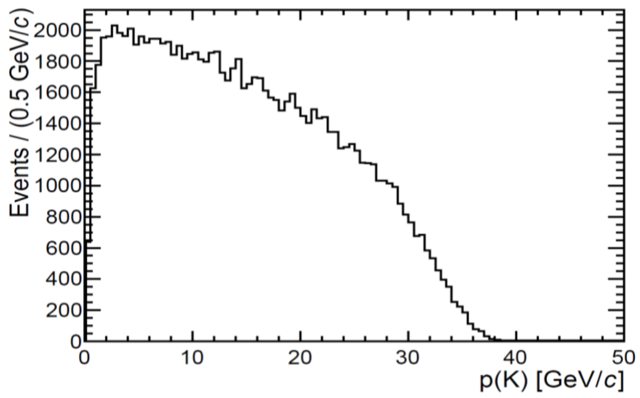
Particle ID for FCC-ee

- Experiments designed for Higgs Factories have traditionally concentrated on precision tracking + particle-flow calorimetry
- Recent increased interest for adding **charged-hadron separation**
  - identify $H \to$ bb, cc, ss and $W \to$ ud, cs decays
  - measure more precisely Z couplings to quarks R_b, R_c, A_{FB} etc.
  - exploit *flavour physics* enabled by the huge statistics at the Z
- Momentum range required = ~ 1– 40 GeV/*c*
- **Cluster counting** in gaseous trackers ($\to$ DRD1)
  Requires (modest) TOF to cover overlap region
- **RICH** technique is also well suited, in particular for those experiments with silicon trackers

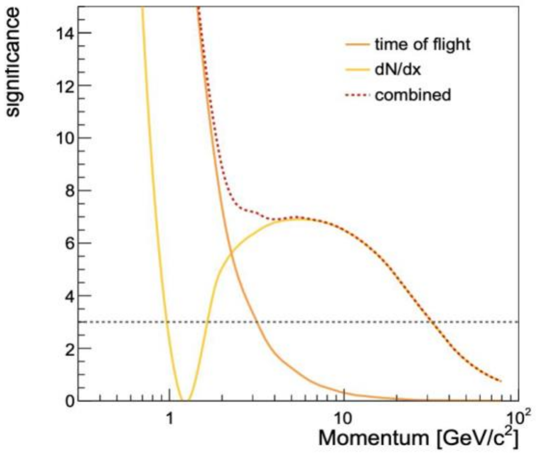
  How to fit a RICH detector in a 4π experiment? $\to$ ARC concept, first presented at FCC week of 2021

  Before that, show briefly the TOF contributions

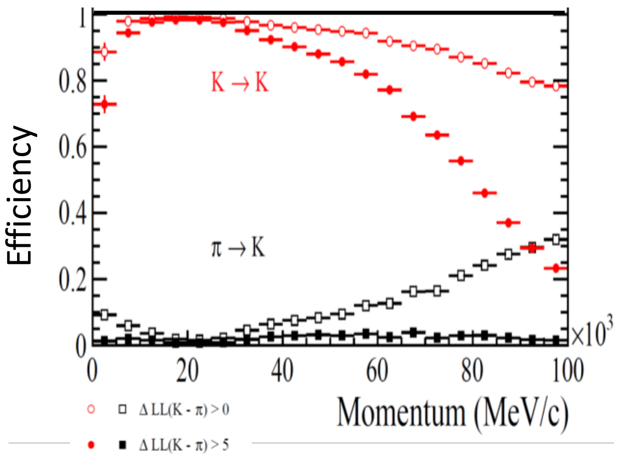
$B_s \to D_sK$ simulation in Z events



dN/dx + TOF (IDEA simulation)



RICH performance (LHCb)

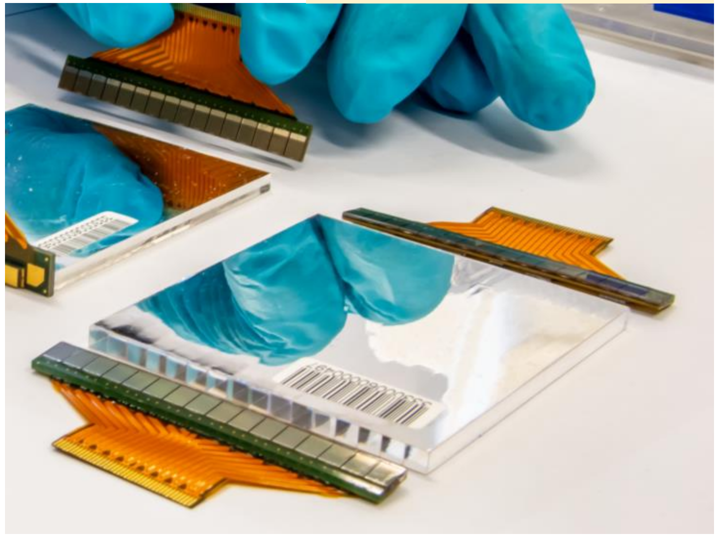


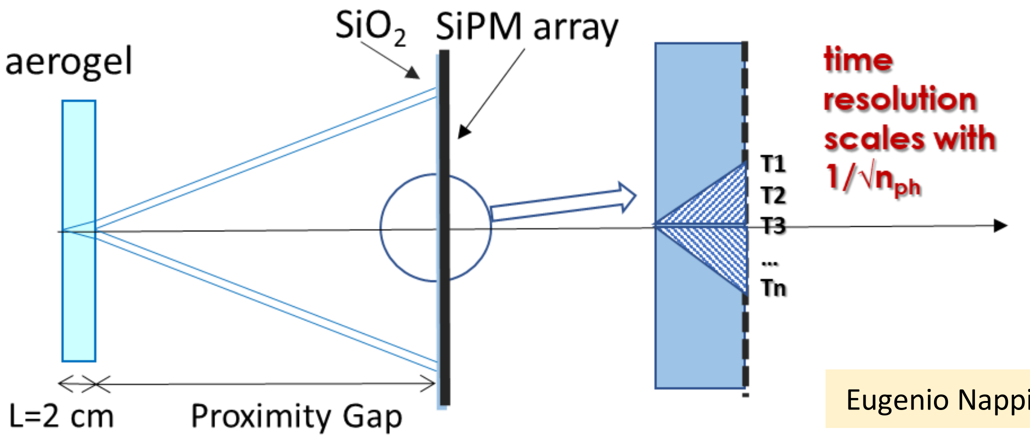
Time-of-Flight R&D

- Fast silicon detectors (LGAD, for the endcaps) and LYSO crystals + SiPM (barrel) used for the *Timing Layers* of the ATLAS/CMS Phase II upgrades
- Targeting 30 ps resolution, may degrade to ~ 60 ps due to radiation damage by the end of HL-LHC: acceptable for the required **pileup rejection**, but of limited use for TOF particle ID
- Can reach improved timing precision by coupling SiPM to a Cherenkov radiator—even the resin used as entrance window Proposed as part of a combined aerogel RICH + TOF system

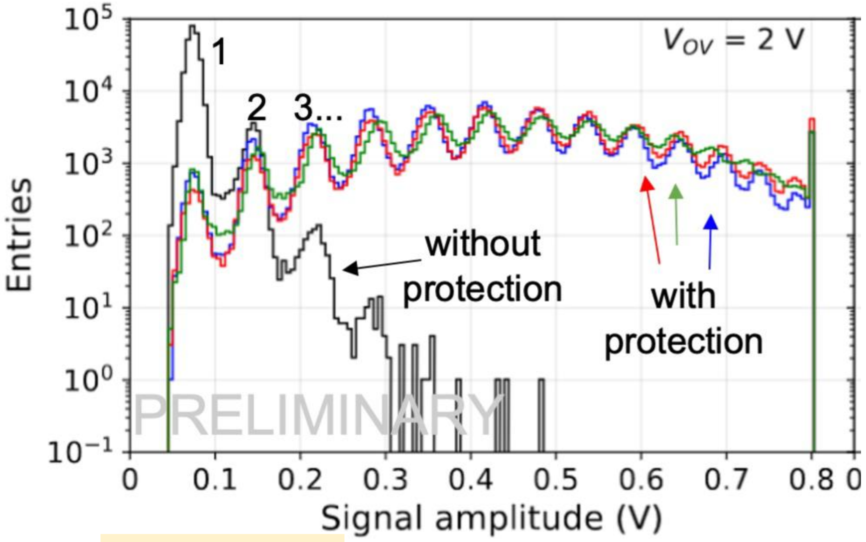
CMS BTL

Federico De Guio, FAST2023





Eugenio Nappi



Pietro Antonioli

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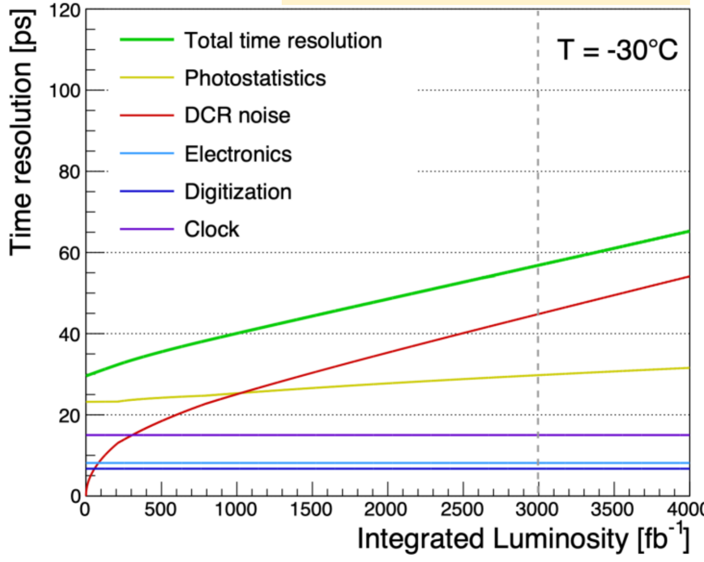

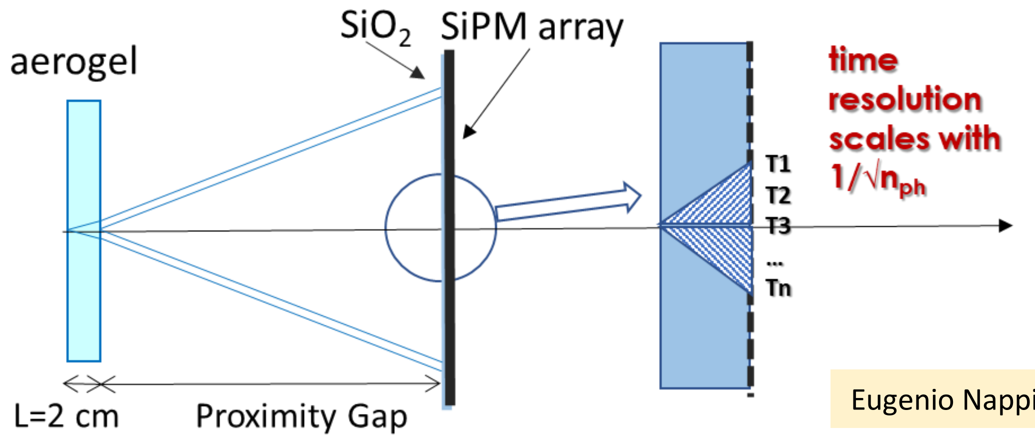

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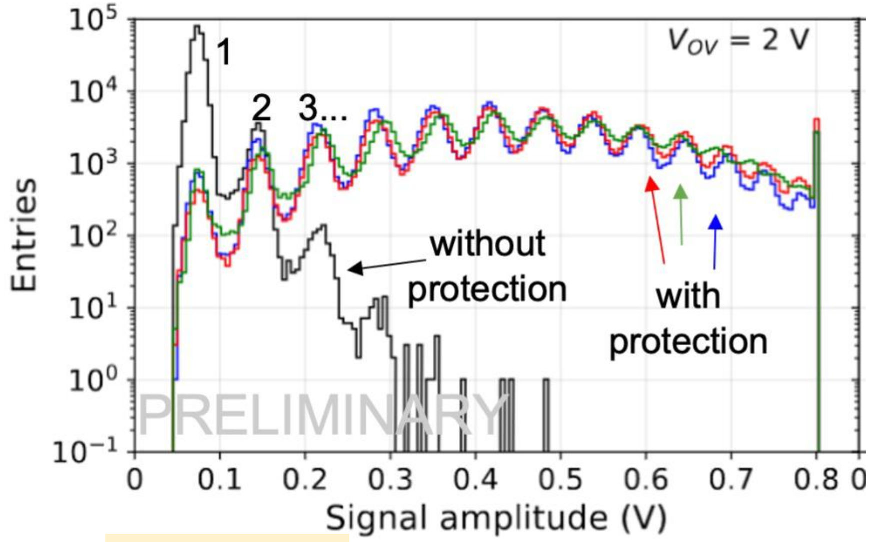

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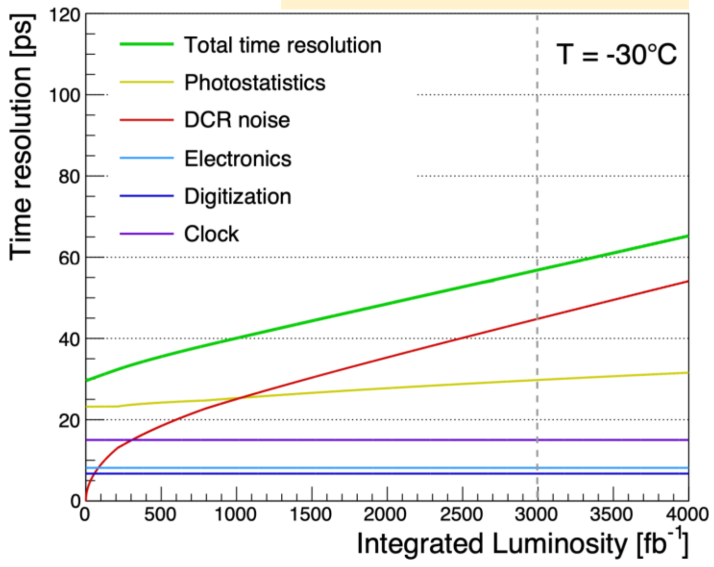

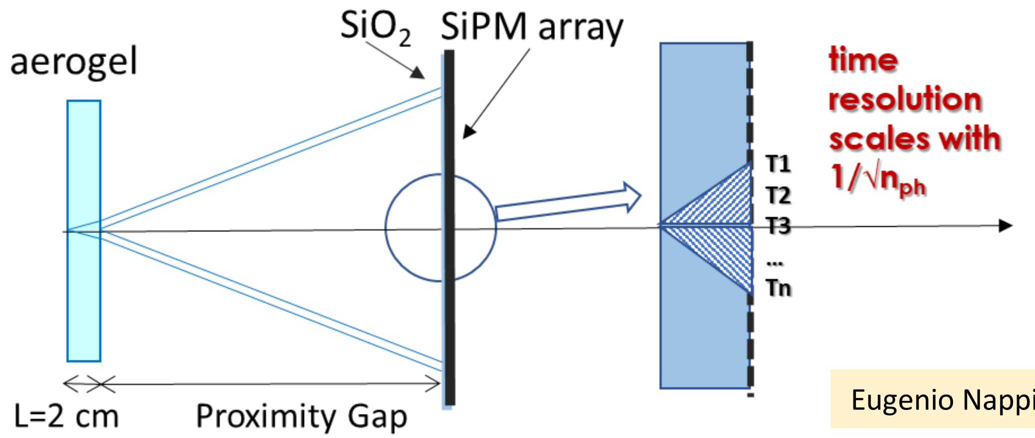

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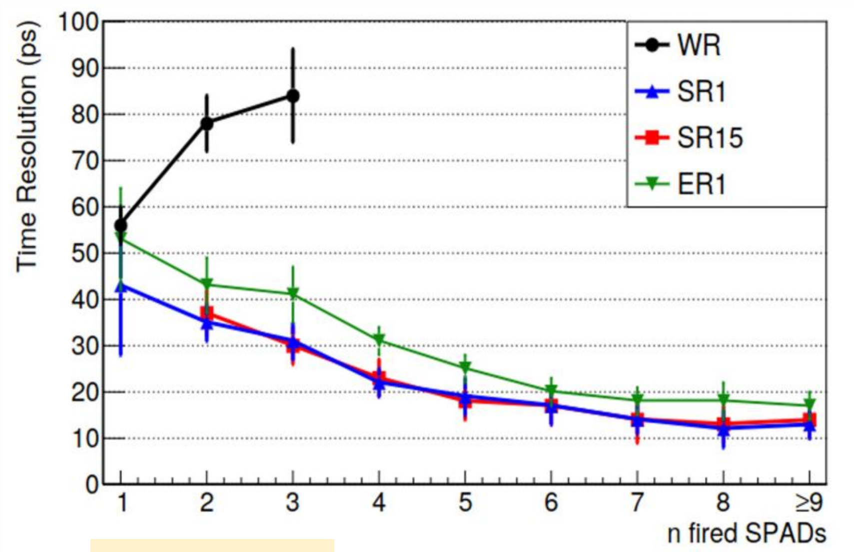

Pietro Antonioli

TORCH

- TORCH uses a DIRC-like solution to push TOF beyond the current state-of-the-art towards 10 ps resolution per track over large areas
- Adopted for the Upgrade II of LHCb, to be installed in LS4 LHCb-TDR-023
- High resolution is achieved by combining the timing of ~ 30 photons per track, with modest timing precision required per photon ~ 70 ps achieved using custom MCP photon detectors NIMA 1050 (2023) 168181
- Prototype has been built and tested in beam last year with > 3000 channels, to validate the concept
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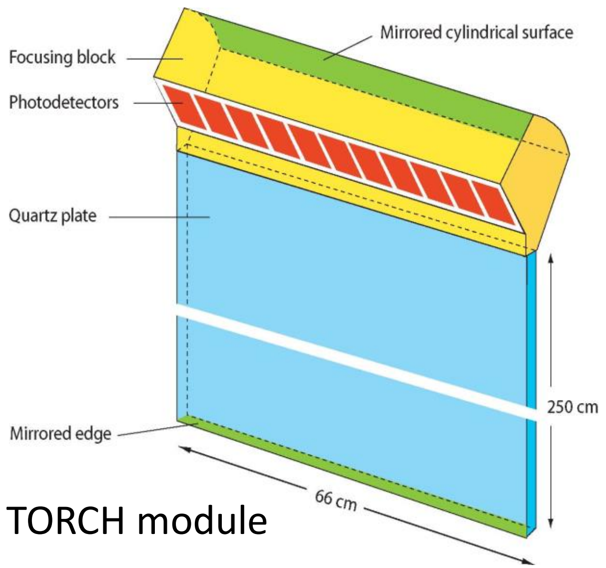
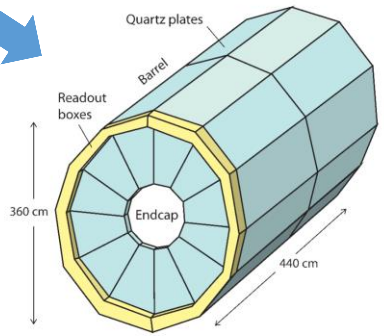
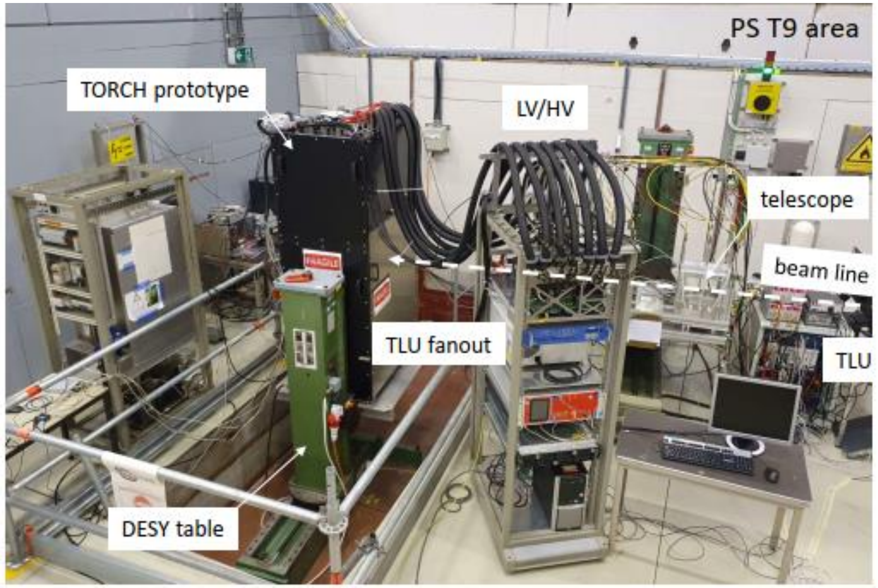


TORCH module





TORCH

- TORCH uses a DIRC-like solution to push TOF beyond the current state-of-the-art towards 10 ps resolution per track over large areas
- Adopted for the Upgrade II of LHCb, to be installed in LS4 [LHCb-TDR-023]
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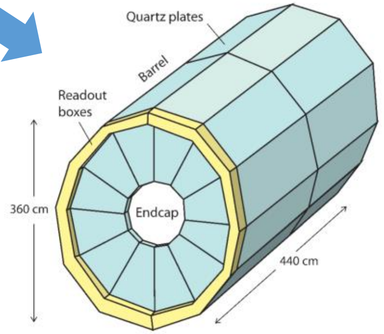
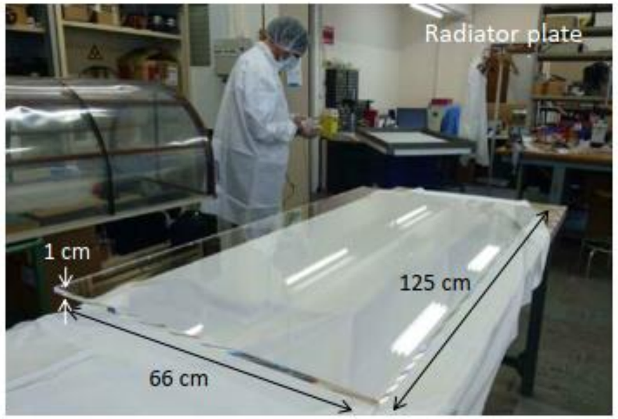
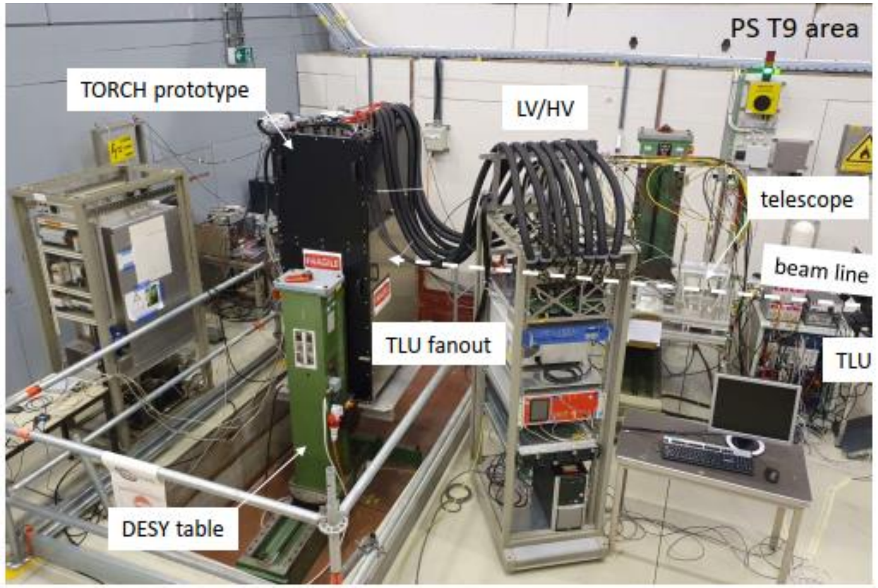


Highly polished quartz radiator (surface roughness < 0.5 nm)





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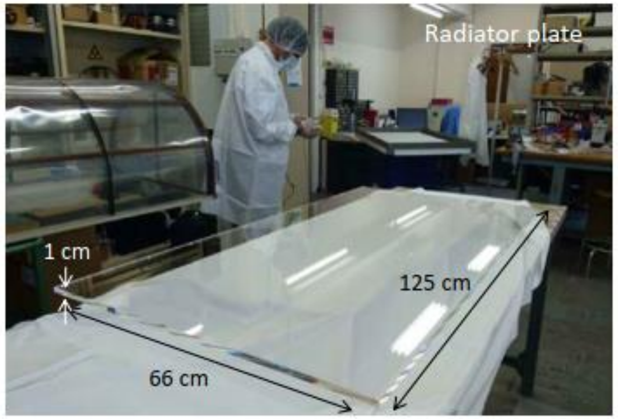
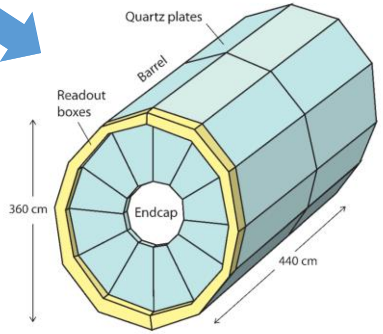
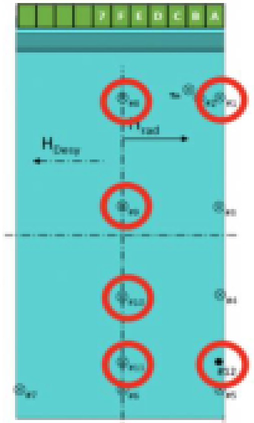
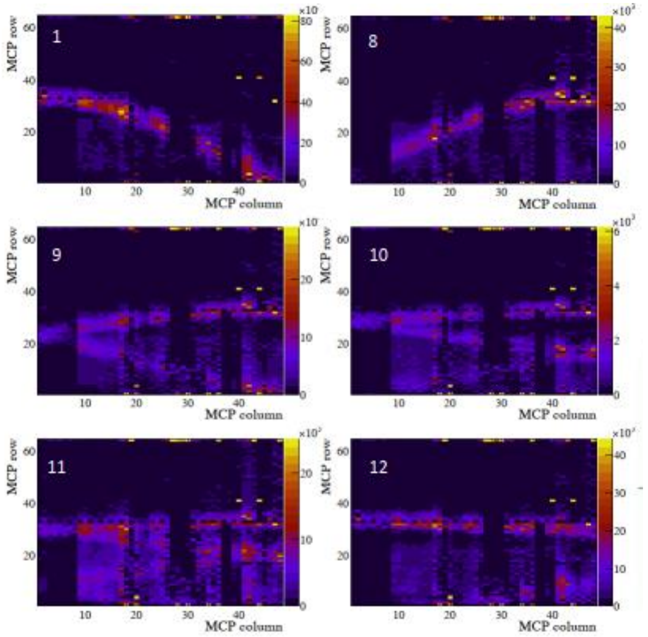




Beam images: photon patterns across the MCP array

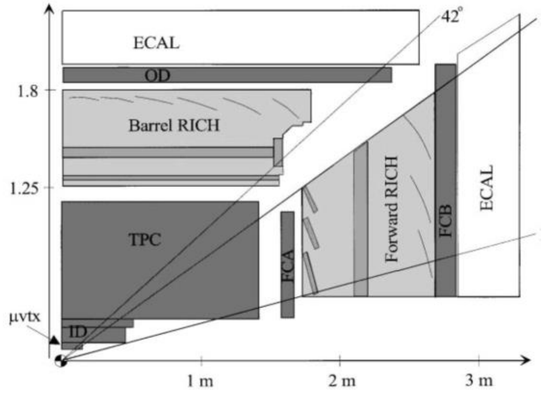




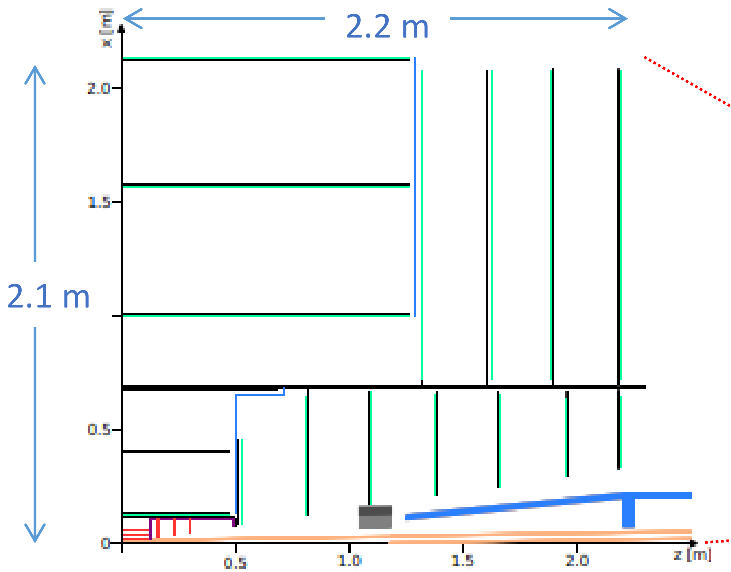
Compact RICH detector for FCC-ee

Recap

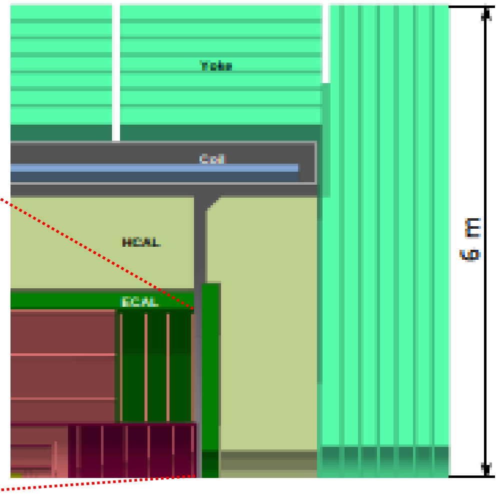
- Earlier examples of RICH detectors at e^+e^- colliders include those of DELPHI and SLD: large radial dimensions, challenging photosensors
- To be concrete, new proposed design is based on the current **CLD** experiment concept for FCC-ee   N. Bacchetta *et al.*, arXiv:1911.12230
- Target a radial depth of 20 cm, and material budget of few % X_0
  Such aggressive parameters necessary for it to be accepted…



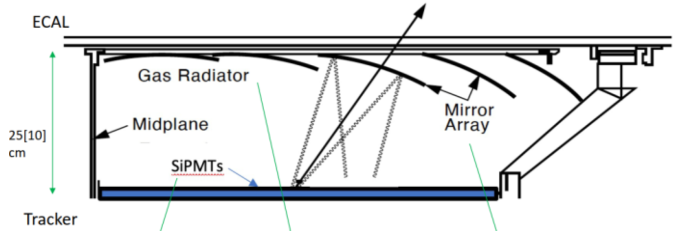
Zoom on tracker



A quarter of **CLD**



Adapted version of SLD CRID   V. Cairo *et al.*



→ Tracker would need to be re-optimized using 10% less radial space
Already studied in Appendix B of note (to reduce cost of calorimeter)

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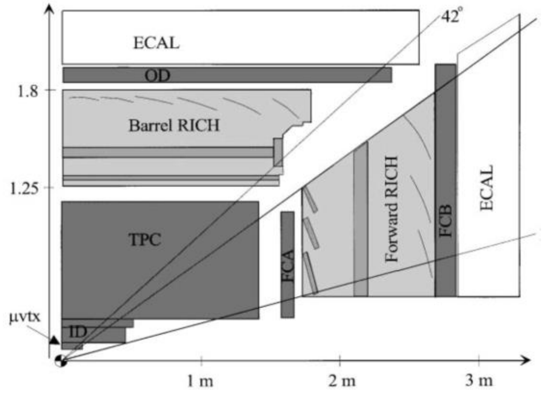

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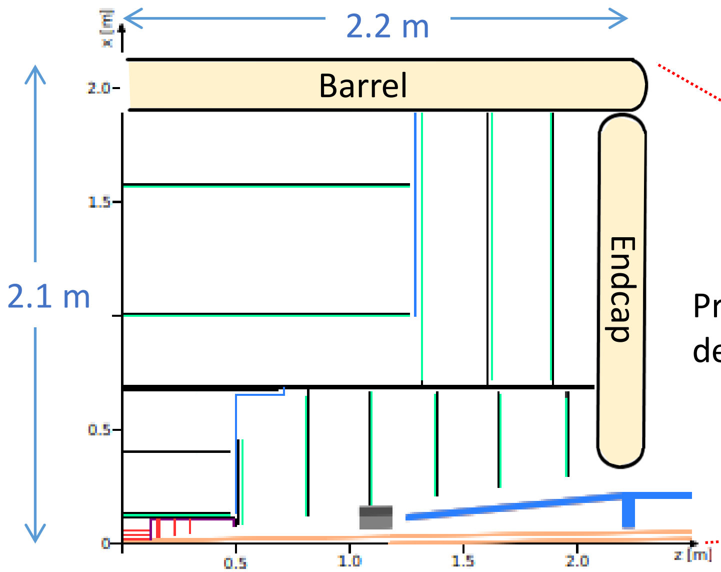
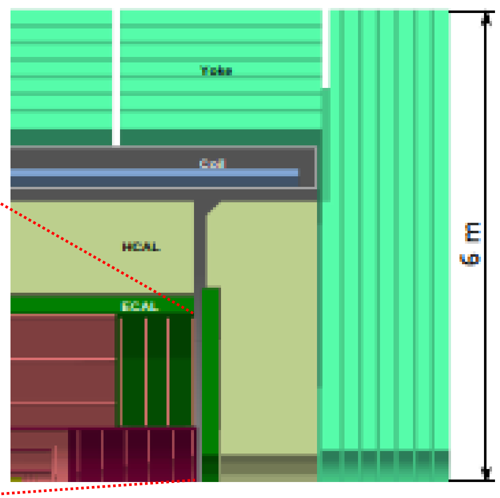


Proposed **ARC** detector

A quarter of **CLD**



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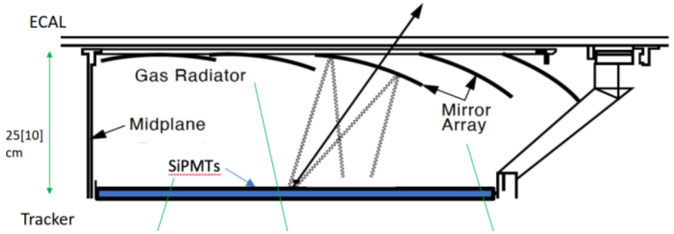


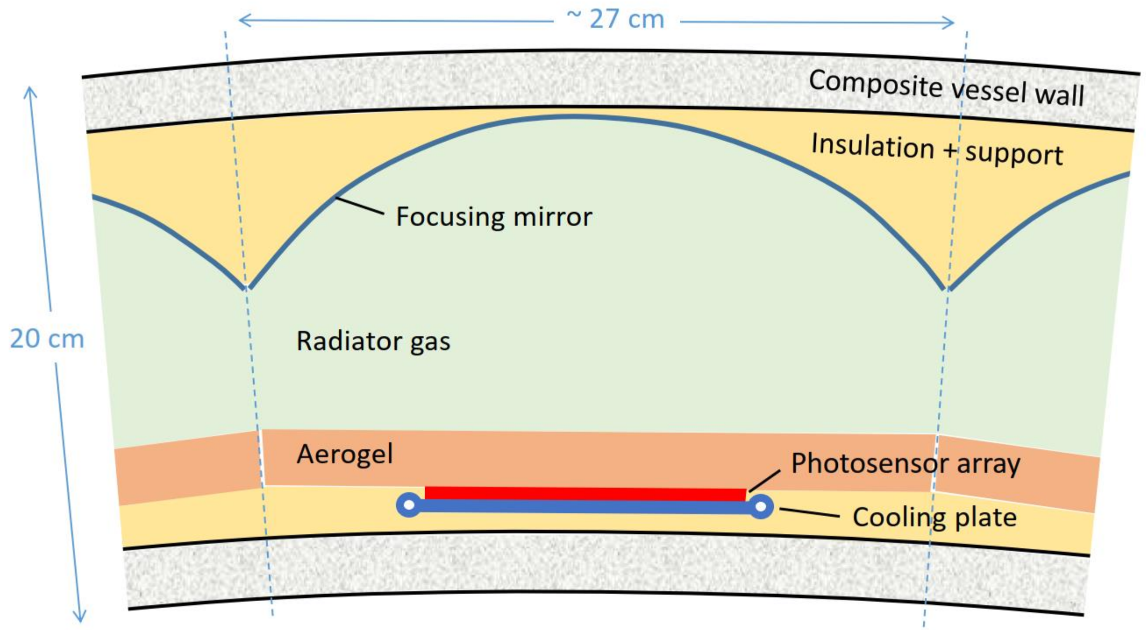
→ Tracker would need to be re-optimized using 10% less radial space
Already studied in Appendix B of note (to reduce cost of calorimeter)

ARC: Array of RICH Cells

Recap

- 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

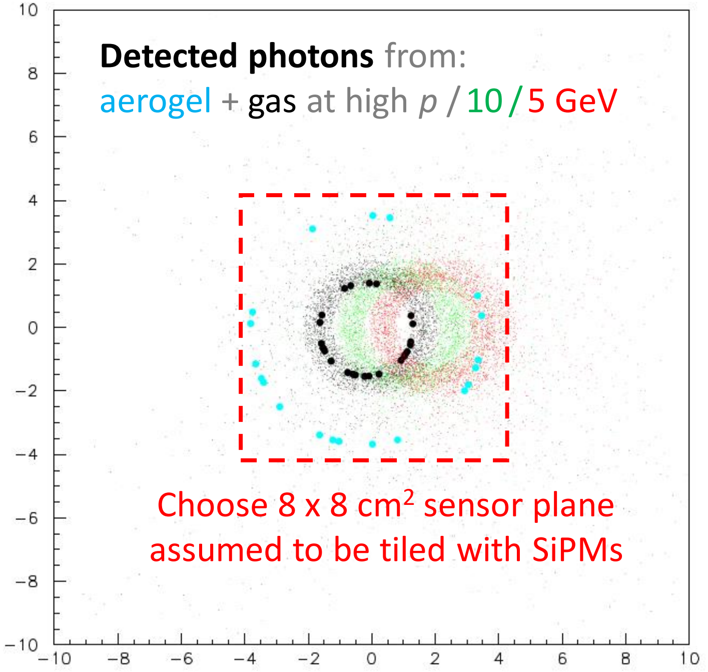
https://www.findlight.net/blog/2019/01/23/artificial-compound-eyes/



ARC detector (one cell)

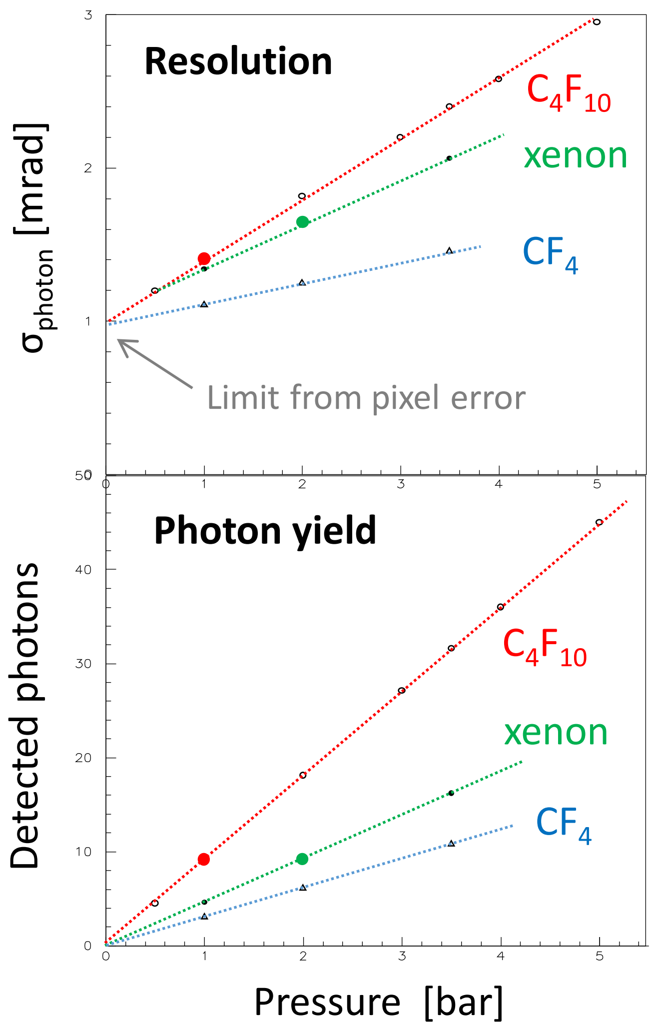
Simulate tracks from IP crossing detector uniformly over acceptance and ray trace Cherenkov photons to sensor plane:

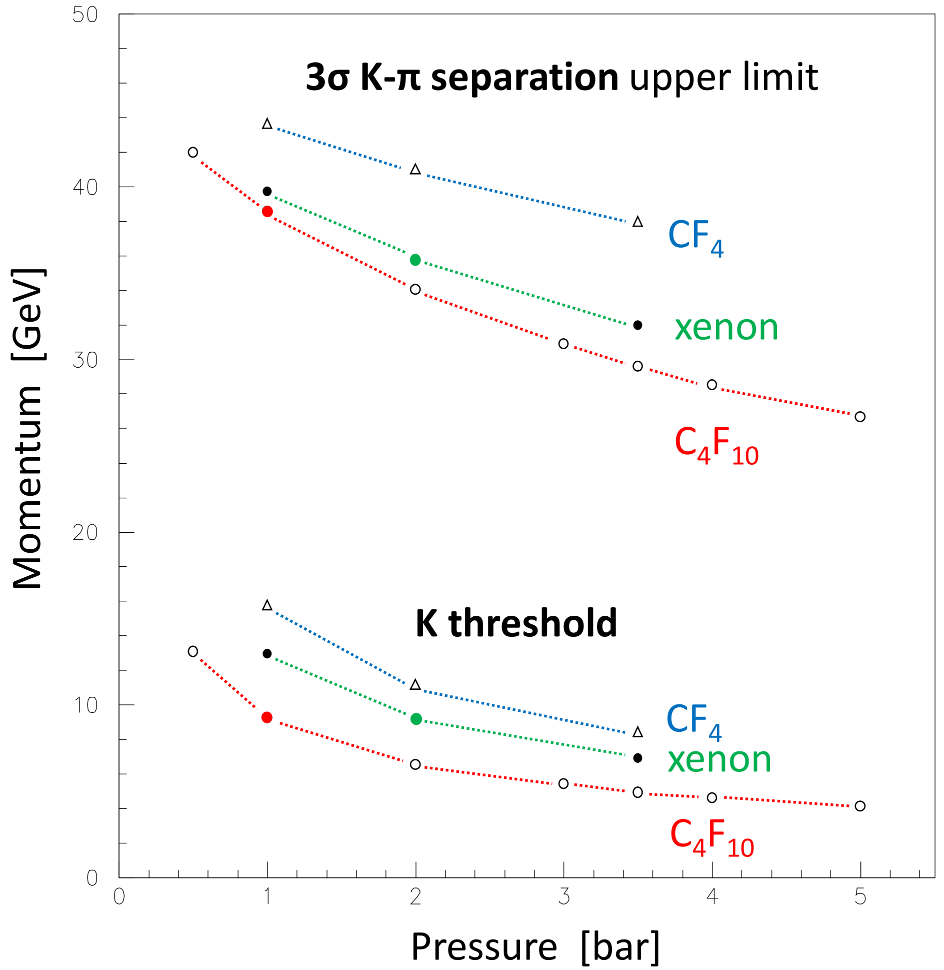
Ring radii = $R \cdot \theta_C / 2$ ≈ 1 cm (3.6 cm) for gas (aerogel)



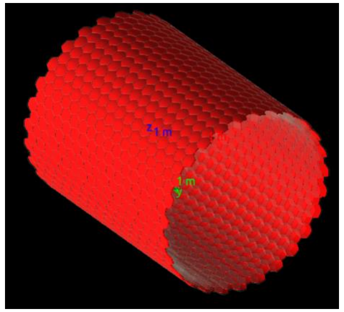
Radiator gas parameter scan

- Original concept was *pressurized*
  Performance studied varying the gas type and pressure
- *Outcome:* new baseline is for **unpressurized C_4F_{10}**, allows material budget to be minimized
- C_4F_{10} at atmospheric pressure gives good momentum range for K-π separation, with acceptable photon yield for the parameters assumed
- **Xenon** at 2 bar may provide similar performance, if fluorocarbons unacceptable
- Optimal point may change in the presence of background



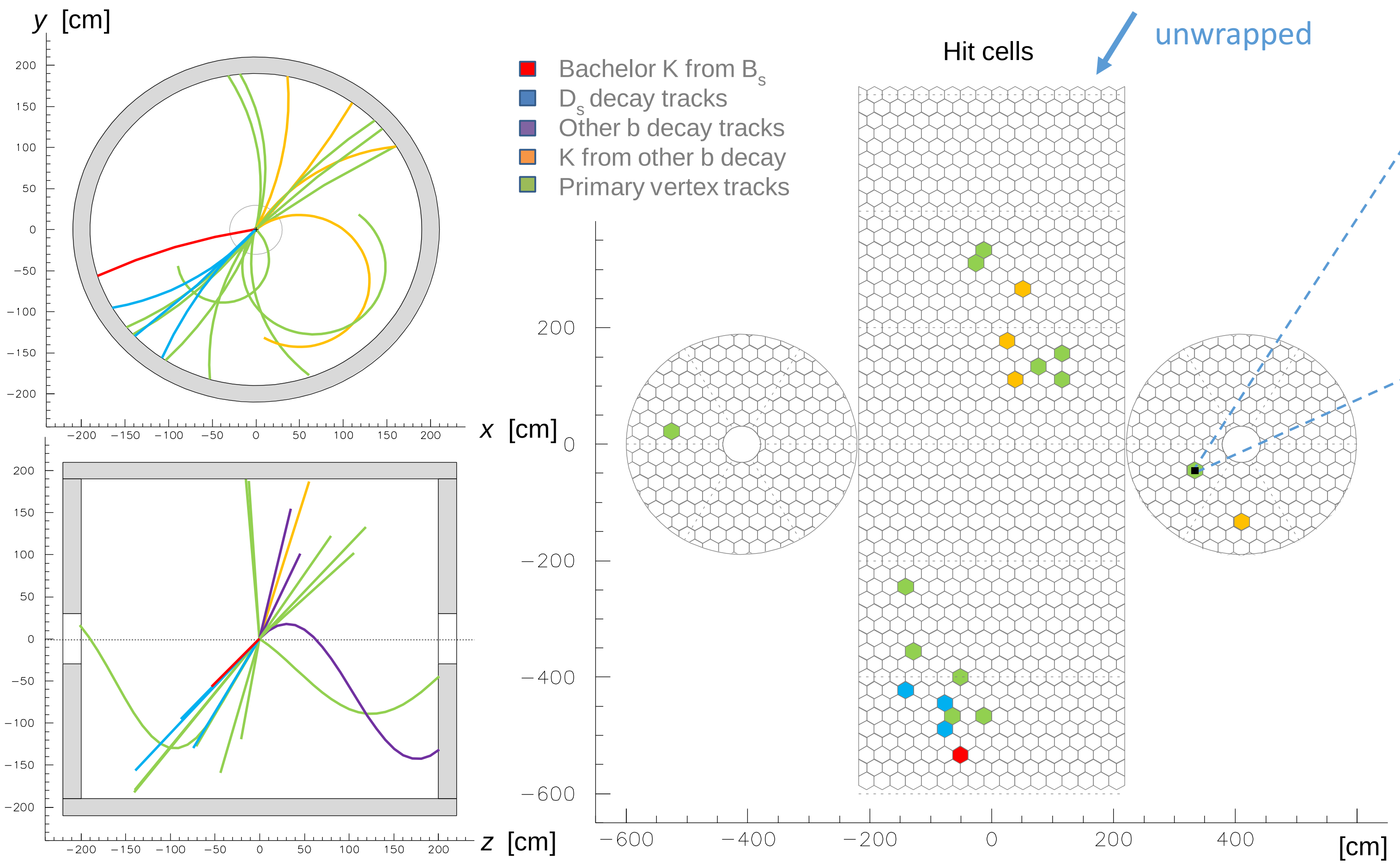


ARC simulation



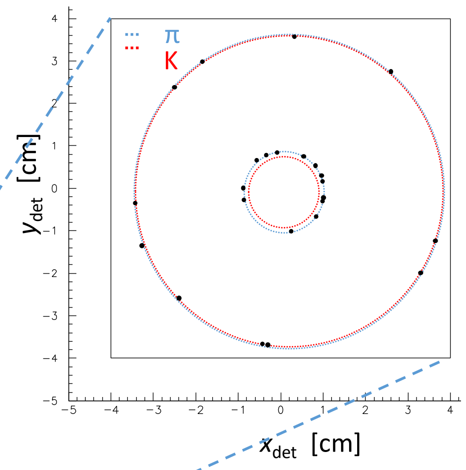
Event display of $B_s \to D_s K$ decay in Z event in ARC

Track density is sparse, typically only single track/cell

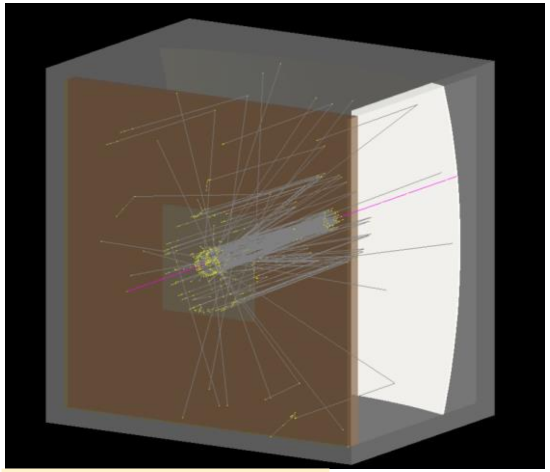


Zoom on hits in sensor of one cell

Concentric rings from the two radiators



ARC cell simulated with Geant4

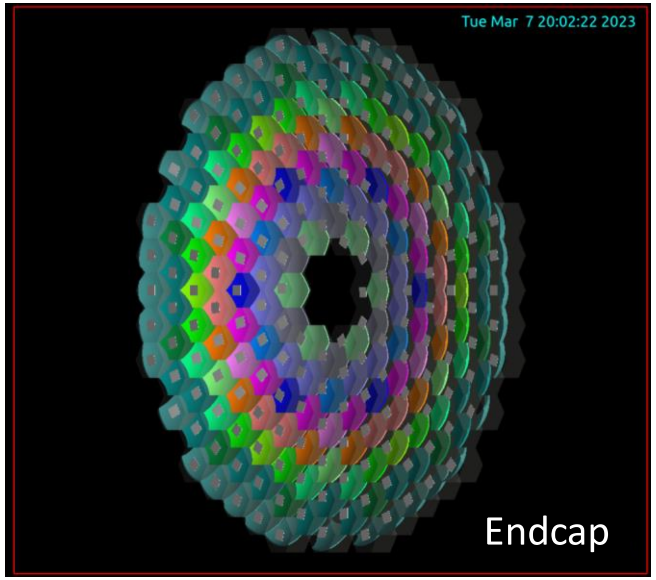


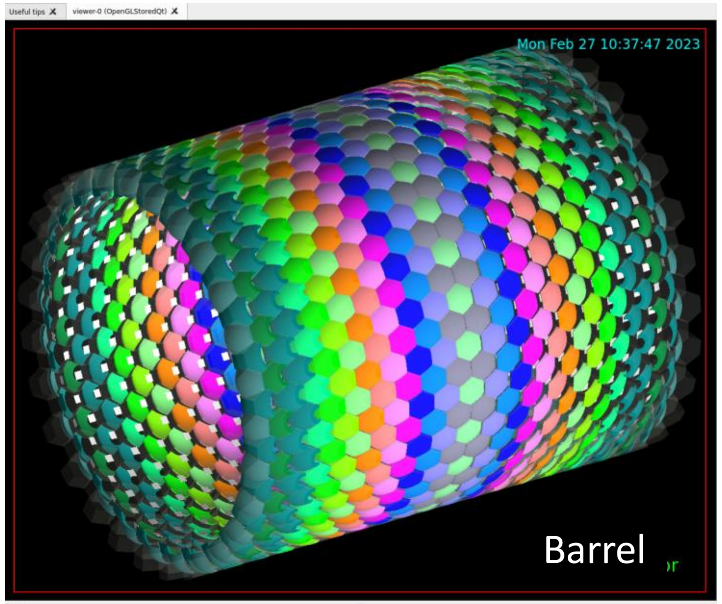
Alvaro Tolosa Delgado

ARC performance

- Resolution optimized, now using ~ 1300 similar *hexagonal* cells
- Optical layout has been optimized via a standalone ray-tracing study: adjusting the position, curvature and tilt of mirrors and sensors for each of the 39 unique cells Martin Tat
- Geometry has been described in Key4hep in collaboration with the FCC software group Gerardo Ganis *et. al*
- Details will be presented by Alvaro Tolosa Delgado in the *PED: Software and Computing* session this afternoon

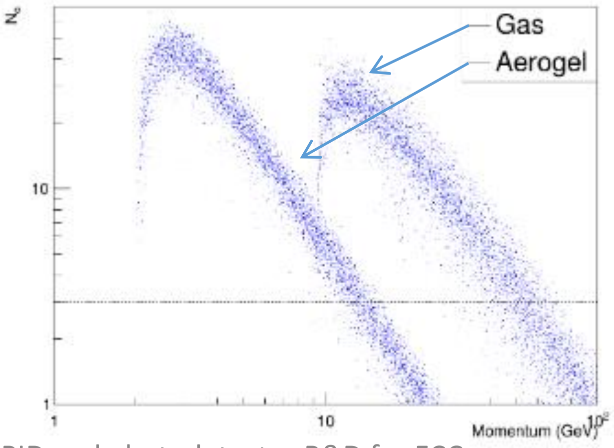
→ Excellent K-π separation predicted over momentum range 2–50 GeV/*c*





Optimized mirror layout Alvaro Tolosa Delgado

K-π separation



From standalone simulation, *including* 2T B-field Martin Tat

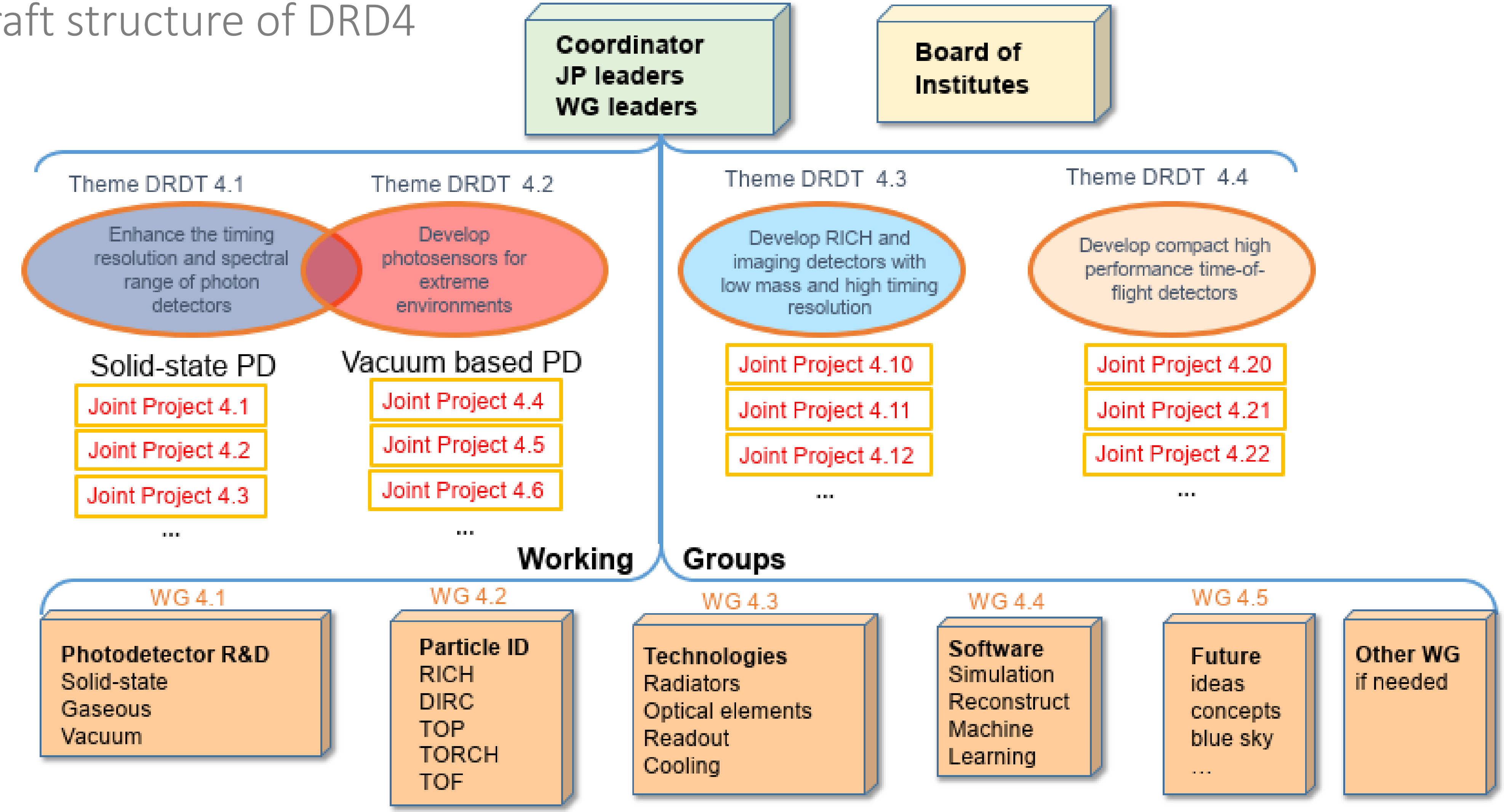
(to be followed up with the full Geant4 simulation)

Conclusions

- R&D on Particle ID and Photodetectors is very active, and will hopefully be further nurtured within the new **Detector R&D Collaboration** (DRD4) that is being set up to implement the ECFA Roadmap
- *Photon detector* developments concentrate on solid-state (SiPM) and vacuum-based detectors (MCP) with excellent timing resolution, which are likely to have applications in FCC experiments
  - **SiPM**: reducing the dark count rate with cooling and/or annealing, making them more radiation resistant (important for FCC-hh), and developing possible digital SiPM with integrated electronics
  - **MCP**: improving the lifetime and rate capability, increasing efficiency, reducing the cost
- *Particle ID* detector R&D is currently focused on nearer-term applications, for RICH/DIRC/TOF
  - **Time-of-flight** important for FCC-ee, to complement *dE/dx* or cluster counting in gaseous trackers: various lines under development, using LGADs, fast crystals, SiPM + radiator, TORCH
  - **RICH** detectors are ideal for hadron separation at high momenta, R&D underway for applications in LHCb/ALICE upgrades and EIC, dedicated design for an FCC-ee experiment (ARC) is progressing
- Support from the FCC community is important for the long-term strength of the R&D collaboration

Additional slides

Draft structure of DRD4



Z-Factories are great Flavour Factories

See S. Monteil, FCC CDR overview '19

Working point	Lumi. / IP $[10^{34}\ cm^{-2}.s^{-1}]$	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	1000	500

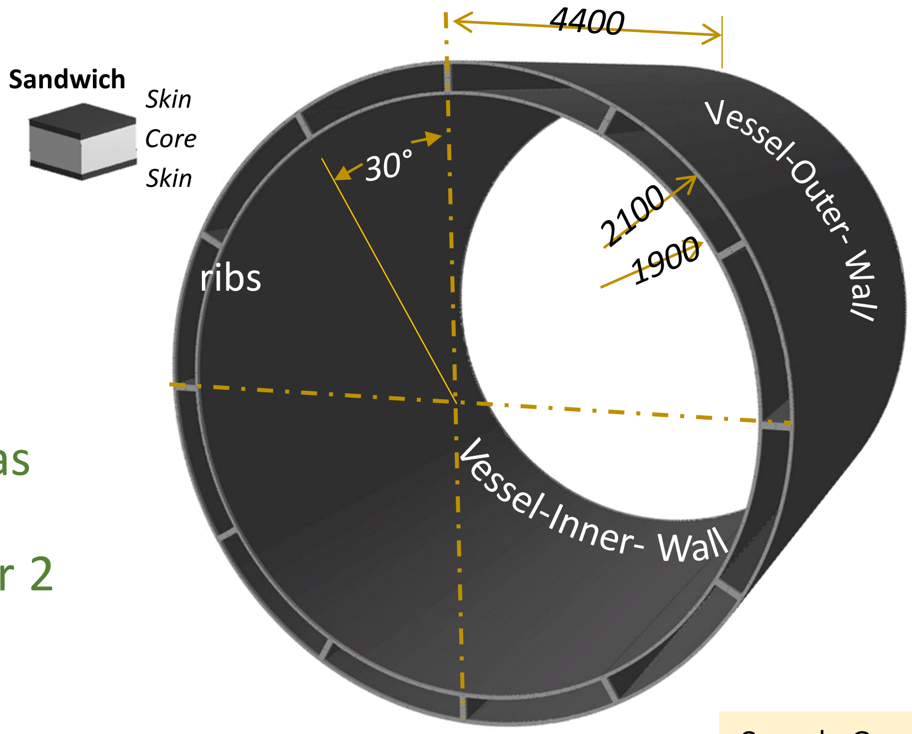
Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^{\pm}K^{\mp}$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

out of reach at LHCb/Belle

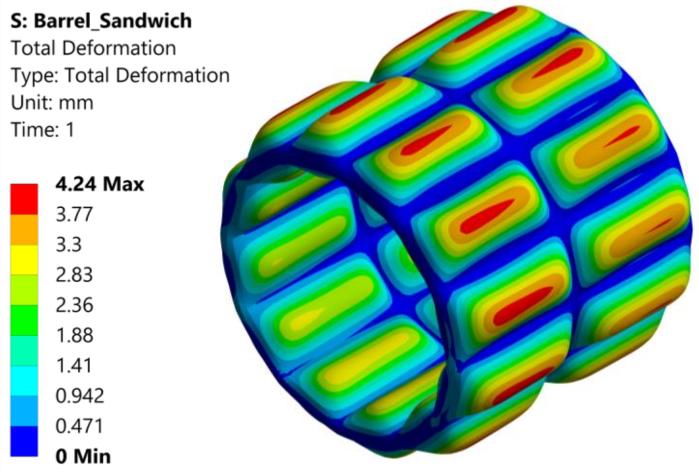
boosted b's/τ's at FCC-ee

ARC vessel

- Should be as lightweight as possible: propose to use carbon-fibre composite sandwich with foam core
- Initial concept was for pressurized radiator gas up to 4 bar
  Related R&D already underway for lightweight cryostats
- Finite-element analysis made for 4 bar pressure, over the gas volume of ~ 10 m^3 → maximum deflection of walls under pressure: 4 mm (barrel), 7 mm (endcap) with a safety factor 2
- Achieved with 20 mm-thick walls, for a remarkably low material budget: 2.7% X_0 (per wall)
- Subsequent studies indicated that an *unpressurized* radiator may be sufficient (depending on the sensor PDE) → material can be further reduced, currently assume 10 mm-thick walls
- **R&D** needed to ensure leak tightness of CF walls (liner-less), out-of-autoclave curing to avoid need of large autoclave, etc.
  Also to develop suitable lightweight spherical mirrors

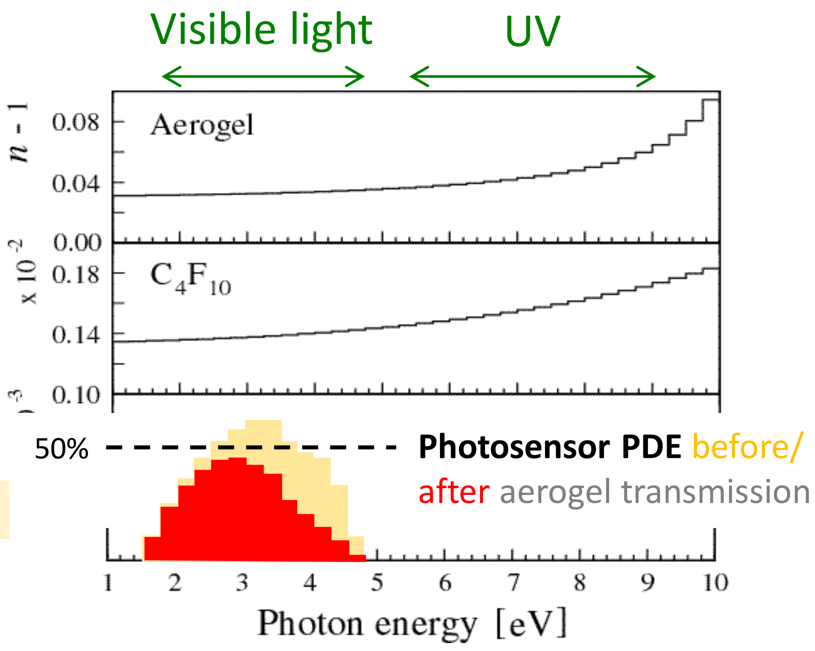


Corrado Gargiulo



Radiator gas R&D

- Baseline choice is **C_4F_{10}** due to its excellent chromatic properties → optimizes resolution (~ 1 mrad is the target)
- However, fluorocarbons have high global warming potential (GWP ~ 9000 for C_4F_{10}) and even though one would aim for a leak-less system, it may be prudent to investigate alternatives
- Replacing the gas radiators with a mixture of $C_5F_{10}0$ and N_2 may allow refractive index to be tuned to that of C_4F_{10}
  Greg Hallewell, RICH2022
  $C_5F_{10}0$ is one of the Novec family of gases (#5510), GWP < 1
  However, long term Novec supply is also in question…
- **Xenon** is not a greenhouse gas, and stays in gas phase at room temperature up to over 20 bar
  However, lower refractive index (n = 1.0007) so would need higher pressure than C_4F_{10}, and somewhat worse dispersion
  Pressurized **argon** is also discussed as an option
- For such new gas choices, **R&D** needed to ensure suitability e.g. level of scintillation, compatibility with materials, etc.



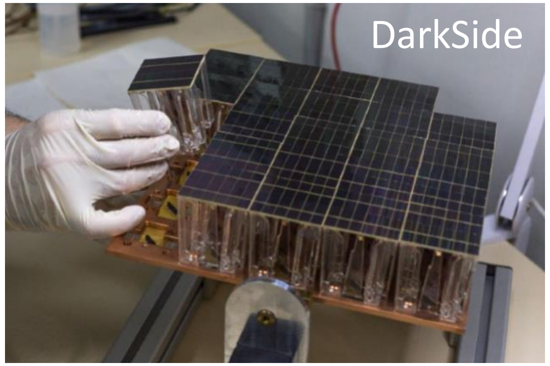
Dispersion is also reduced if photosensor is sensitive to lower (visible) wavelengths

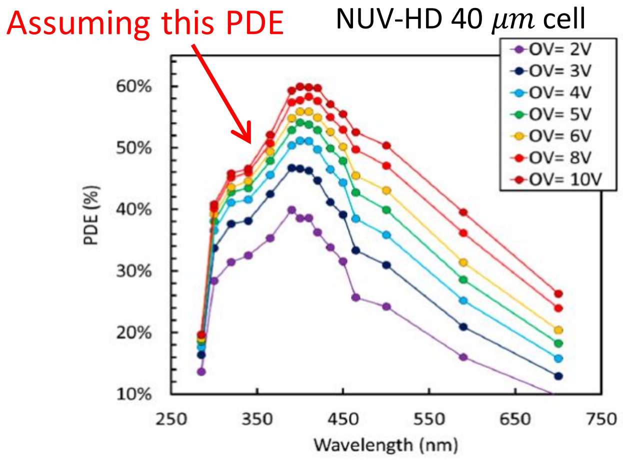
Use of aerogel as a "filter" in front of the photosensor works in this direction

ARC photosensor R&D

- Photosensor performance is crucial for this concept: needs to be compact, low material budget, high efficiency, mm-scale pixellization, cheap (~ 8m^2 active area, 8M pixels)
- **SiPM**s look like the ideal candidate, but not yet well established in RICH detector instrumentation (single-photon detection)
- Level of acceptable dark-count rate should be established, will probably require cooling → potential issue with liquefying radiator gas

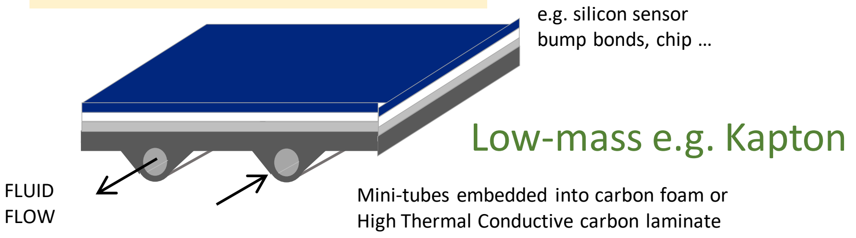
  Note that radiation dose expected is low at FCC-ee so major concern at LHC of increase of DCR with irradiation should not be an issue
- Nevertheless, assume cooling will be required → sensor + electronics mounted on cooling plate with CO_2 circulation
- Need to insulate from gas volume, while allowing Cherenkov light through: use **aerogel** as an excellent thermal insulator





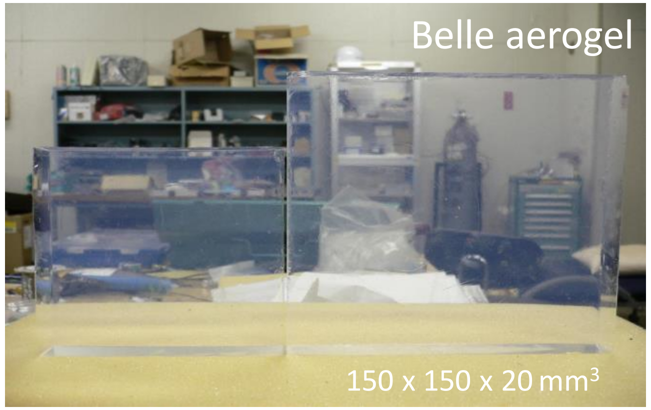
A. Gola et al, Sensors 19 (2019) 308

D. Hellenschmidt, CERN-EP R&D

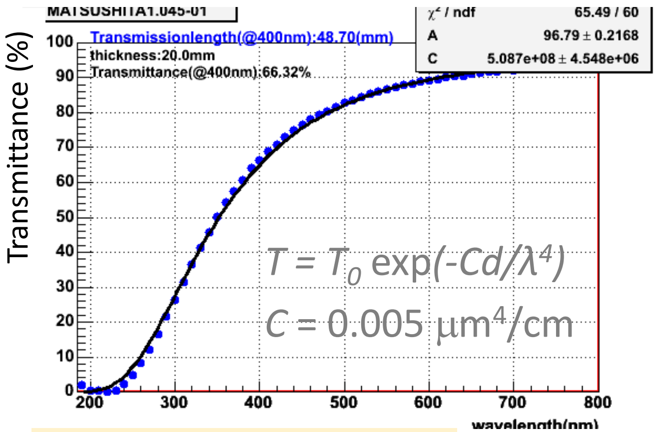


Aerogel R&D

- Silica aerogel can withstand high pressure, tunable refractive index n = 1.01–1.10, v. low **thermal conductivity**: ~ 0.015 W/m·K
- For 1 cm thickness, assuming ΔT = 70 K, heat transmitted through a 25 x 25 cm^2 tile is only a few watts < heat from the electronics
- Propose use both as a secondary Cherenkov radiator (suitable for low momentum tracks) *and* as thermal insulation around sensors 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 (other recipes also available): assume 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
- **R&D** issues: developing larger, thinner tiles, testing use as thermal insulator (suitable mounting, joints, etc.), compatibility with gas, etc.



Transmittance *vs* wavelength



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