Electron, Muon and Charged Hadron PID systems for detectors of the 2030s and 2040s

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ECFA-UK Meeting on UK studies for the European Strategy for Particle Physics Update
23-26 September 2024, IPPP Durham

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CERN

Electron, Muon and Charged Hadron PID systems

- Focus on UK contributions (current and opportunities) to detector R&D for
  - Particle Identification (DRD4)
  - Calorimetry (DRD6)
  - Gaseous detectors (DRD1)

Liquid detectors (DRD2) → see Roxanne's talk
Solid state detectors (DRD3) → see Eva's talk
Quantum technology (DRD5) → see Ed's talk
Electronics (DRD7) → see Connor's talk

- R&D in line with Task Forces established by ECFA detector R&D roadmap
- Milestones supported by international DRD collaborations
- In the context of major projects foreseen for 2030s and 2040s
  - LHCb Upgrade II, ALICE III, EpIC, FCCee, Super Tau-Charm Facility (STCF), …

…. not exhaustive list of projects !

The different priorities of the physics projects is not topic for this talk → the relative importance of proposed detector R&D activities to these projects is the main aspect that will be discussed

Main Drivers for PID detectors of 2030s/40s

From ECFA DRD Roadmap 2020

- Wide range of **primary drivers for PID detectors** in future PP experiments
- **Flavour physics experiments** (LHCb, Belle II, NA62 and future kaon experiments, FCC-ee..) rely on PID to fulfil their physics goals
- **New PID techniques** important for hadronic and heavy-ion experiments (ALICE, EIC, PANDA..)
- Development of **RICH (Ring Imaging CHerenkov)** and **DIRC (Detectors for Internally Reflected Cherenkov light)** technology is essential for experiments where PID is paramount
- **Time of flight (TOF)** is also important and usually provides low-momentum coverage complementary to RICH information.
- **Picosecond timing** is an important theme running throughout all future PP applications,

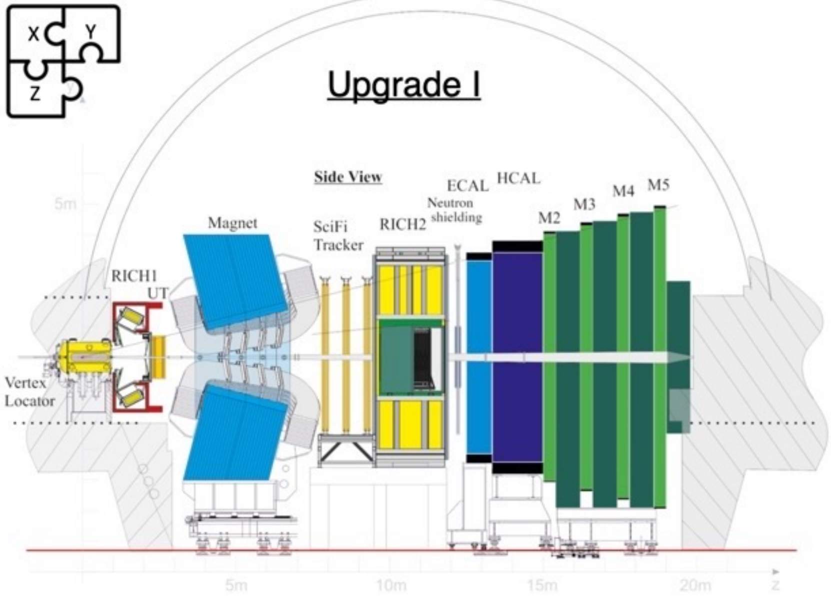
UK leadership and track record in PID detectors (e.g. LHCb RICH, NA62 KTAG)
UK leading contributions to exciting R&D on PID for future experiments
(including but not limited to LHCb U2, FCC-ee, ..)

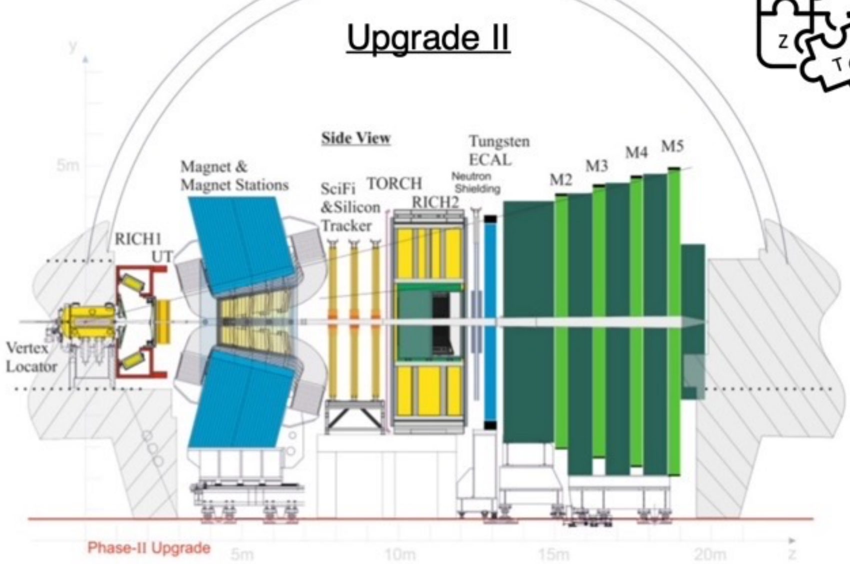
The LHCb Upgrade 2

Upgrade I:

Major detector upgrade to LHCb now in operation

Full software trigger



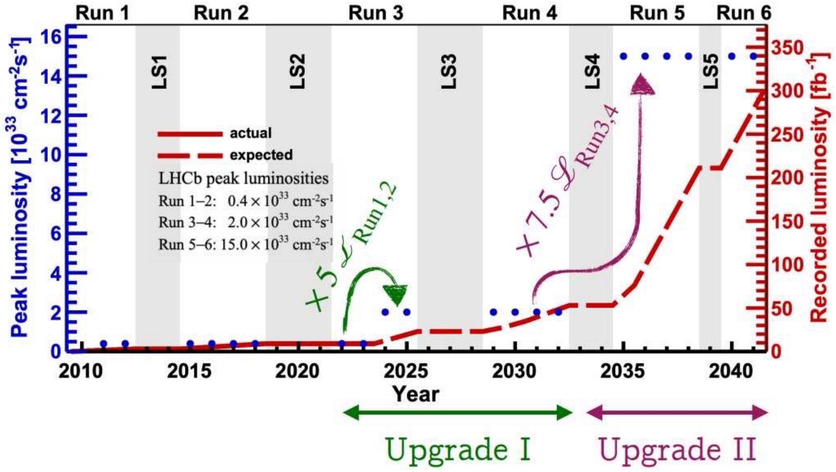


Upgrade 2 Global changes:

Fast timing

Radiation hardness

Remove HCAL, Add TORCH and magnet stations



[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]
[CERN-LHCC-2021-012]

LHCb Upgrade 2 foreseen from 2034
→ ≥ LHC Run 5

Full exploitation of High-luminosity LHC
→ aim to collect ~300 fb^{-1}

Luminosity 1.5 x 10^{34} cm^{-2} s^{-1}
→ x7.5 intensity of Run 3-4

European Strategy Update 2020:
"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"

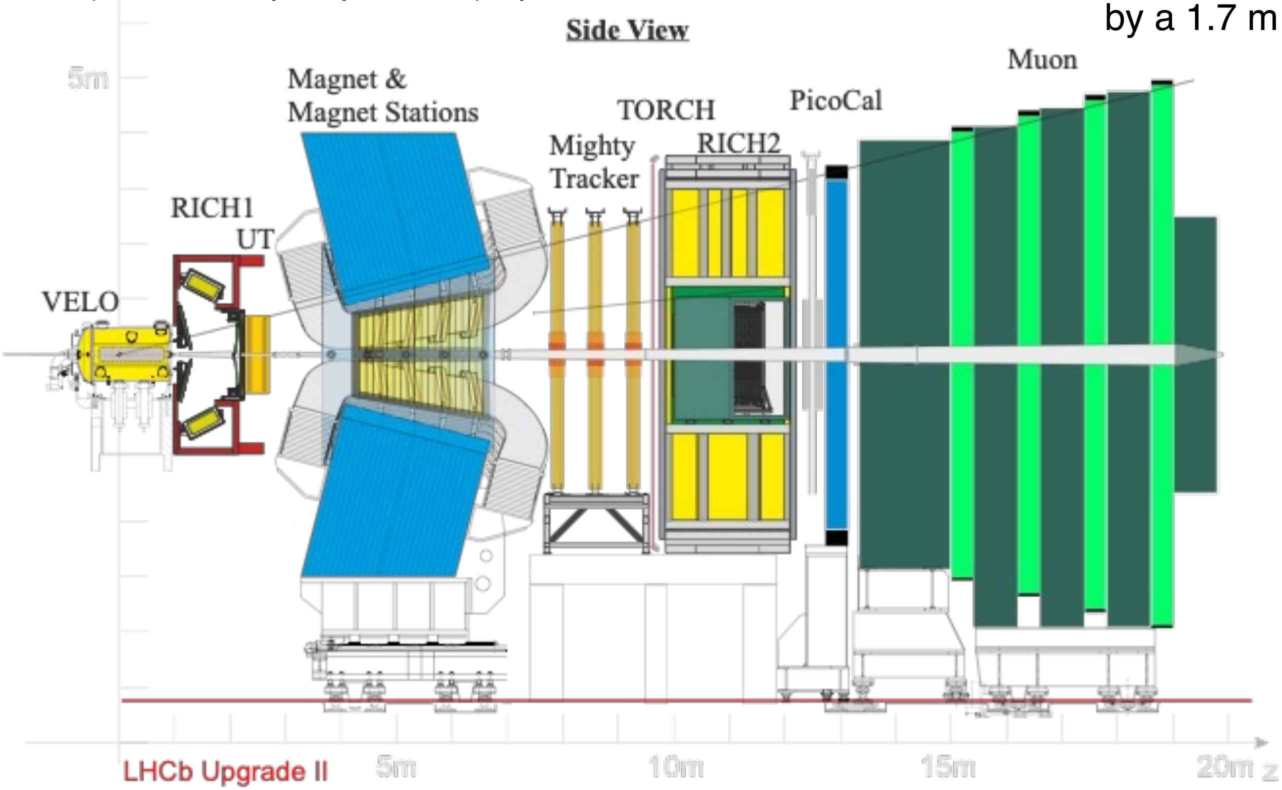
LHCb Upgrade 2 – PID Systems

Ring-Imaging Cherenkov detectors (RICHs) for charged hadron ID (K/π and K/p separation) up to 100 GeV/c

EM calorimeter (PicoCal) for photon, electron and π^0 ID - separated from muon detectors by a 1.7 m thick iron shield

→ H. Cliff PPAP Community Meeting 25-06-2024

UK contributions to PID (RICH and TORCH) and tracking (VELO, Mighty Tracker)

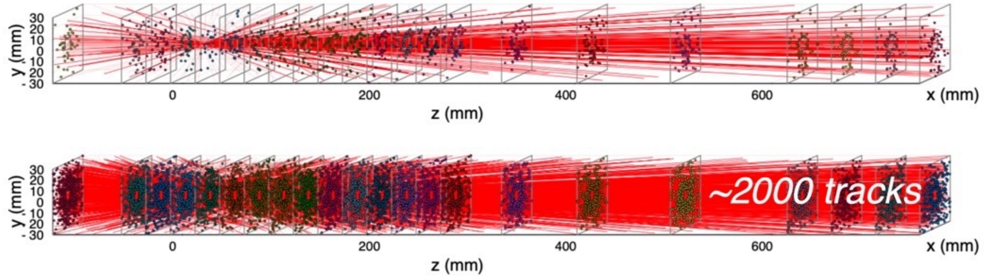


New TORCH (Time of internally reflected Cherenkov light) for charged hadron ID in low momentum range from 2-10 GeV/c

Design challenges posed by the high luminosity:
- Higher granularity, need for non-uniform detectors to cope with busier events
- Radiation-hard detectors to survive intense conditions
- Fast timing to separate overlapping pp interactions

Run 3:
pile- up ~6

Upgrade II:
pile-up ~42

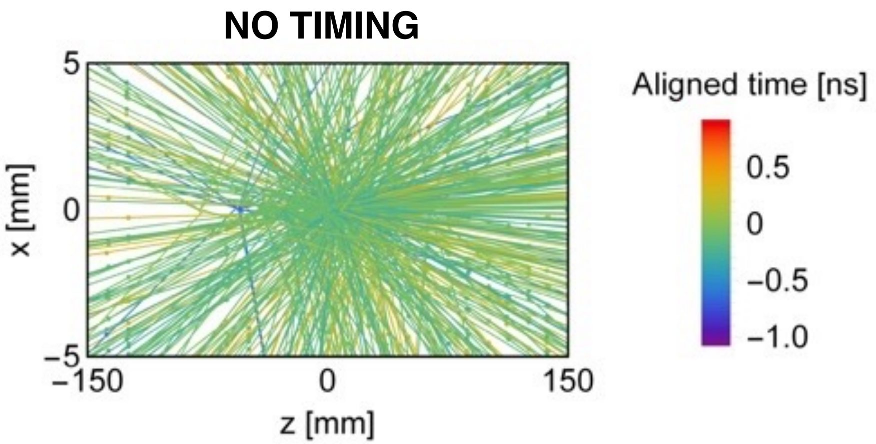


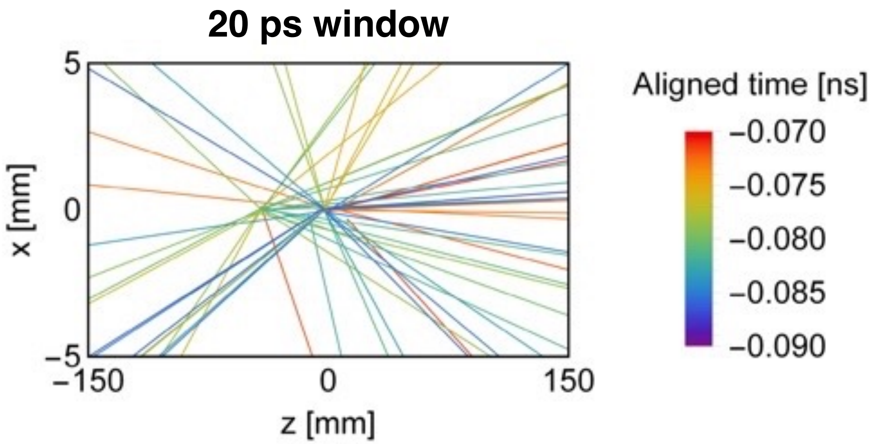
Electron, muon, and charged hadron identification essential to target a broad Flavour Physics programme

LHCb Upgrade 2 – Timing

4D measurement (time and space coordinates) well established technique in current fixed-target kaon experiment at CERN → NA62 beam tracker, PID systems and calo provide ~100ps time resolution across the detector

Fast timing crucial to reduce backgrounds in HL-LHC environment
O(10 ps) time resolution per particle allows charged tracks and photons to be associated to the correct PV





Design challenges posed by high luminosity are shared amongst all HL-LHC experiments

LHC bunches are long (50mm) and pp interactions occur over 0.2 ns
VELO tracker, RICH, TORCH and eCAL (picoCal) will be fast timing detectors:

- Add new dimension to information exchanged between sub-detectors
- Create potential for data suppression in front-end hardware and software trigger
- Set challenging R&D requirements, particularly for sensors and front-end ASICs

The LHCb RICH

RICH system in Run1 & Run2

- RICH 1 (C_4F_{10}): upstream, 2 GeV/c - 40 GeV/c over 25 mrad - 300 mrad
- RICH 2 (CF_4): downstream, 15 GeV/c - 100 GeV/c over 15 mrad - 120 mrad

Upgrades:

- Upgrade I operating from Run 3
- Enhancement foreseen in LS3 for Run 4
- Upgrade 2 expected in LS4 for HL-LHC (≥ Run5)

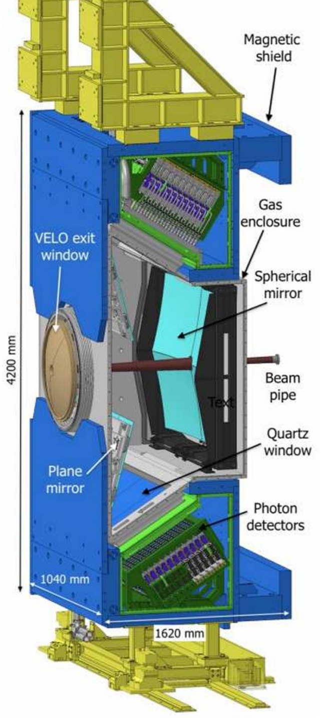
The challenge for Upgrade 2:

- Maintain same excellent PID performance of Run3 in fierce environment of high-luminosity operation

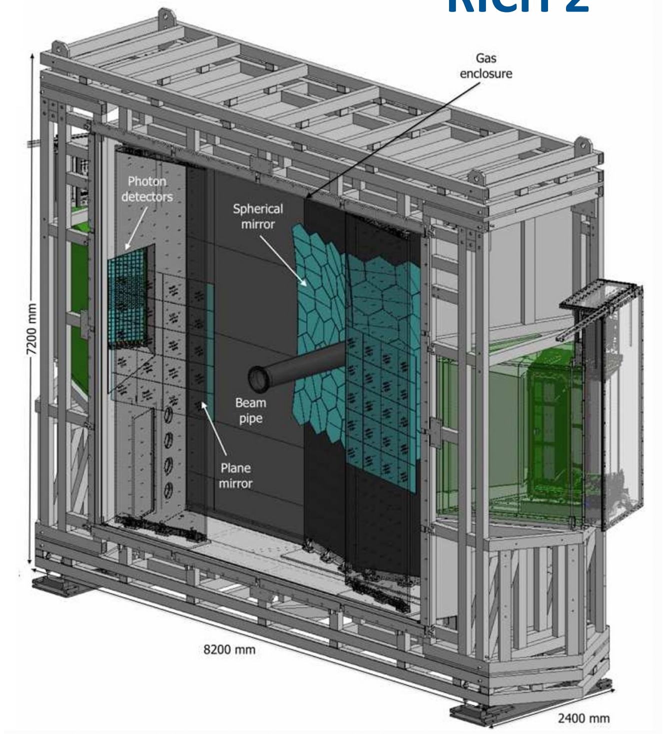
Key specifications for Upgrade 2:

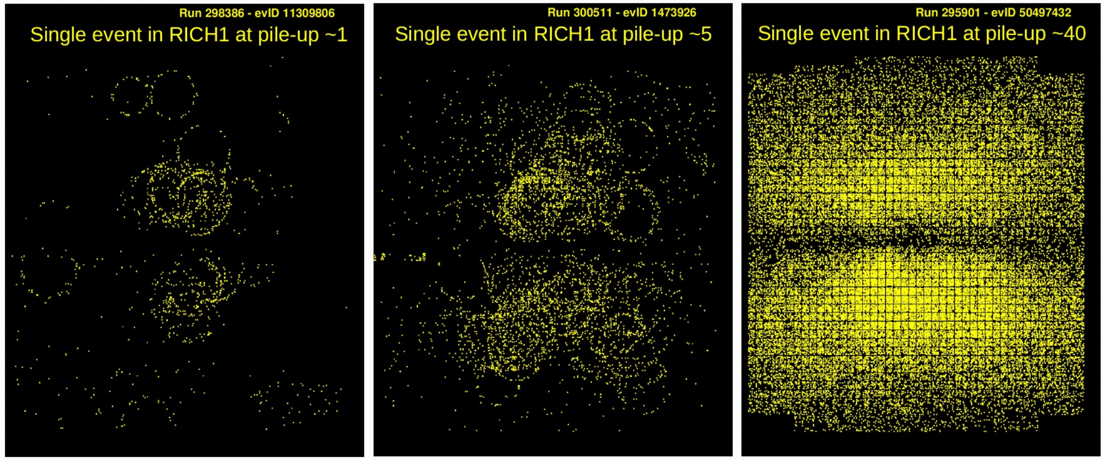
- Improve Cherenkov angle resolution (<0.5mrad) and keep peak occupancy under ~ 30%

RICH 1



RICH 2

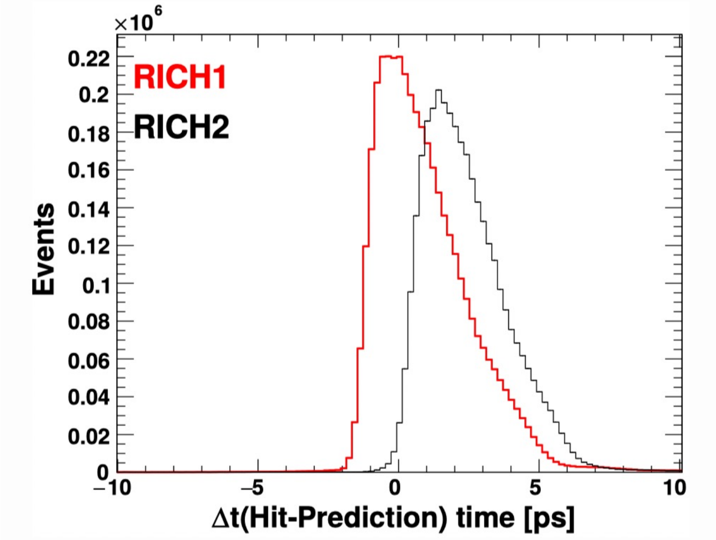


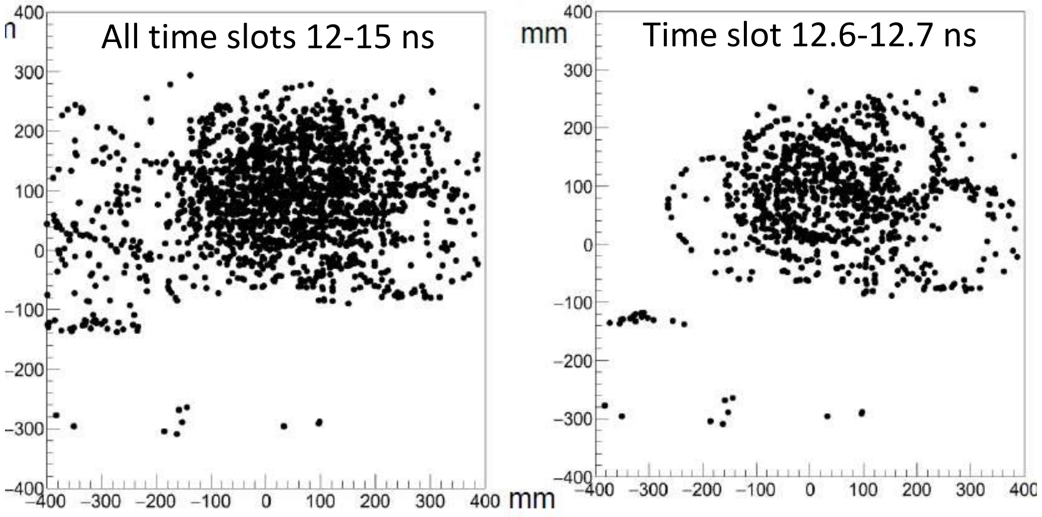


Single event in RICH1 at different pile-up levels

LHCb Upgrade 2 - RICH - Timing

Reconstructed parameters in RICH algorithms and PV t_0, can predict the detector hit times to within 10 ps





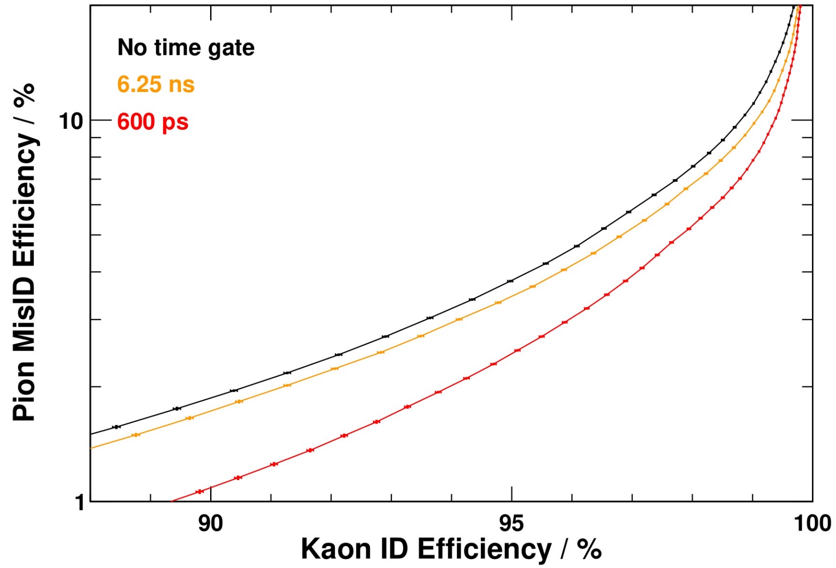
Time gate around the predicted time significantly reduces combinatorial background (and peak occupancy) and helps to recover the same PID performance as in Run 3

Time gate width depends on photon detector resolution → aim for a resolution $\sigma_t(\gamma) < 100$ ps

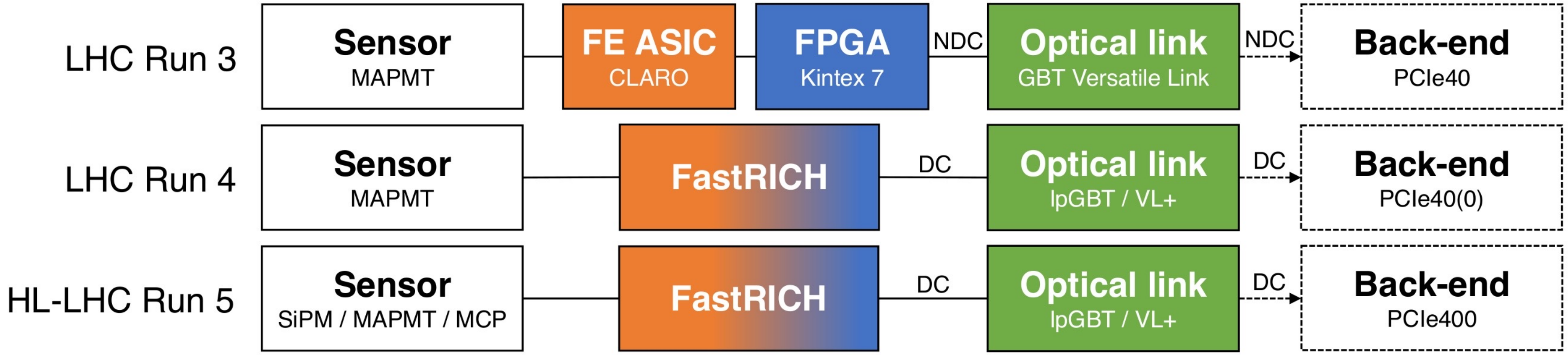
Huge R&D campaigns on fast Photon Detectors (SiPMs, MCP based, next gen MaPMTs) and fast Electronics (fastIC, picoTDC, fastRICH ASIC)

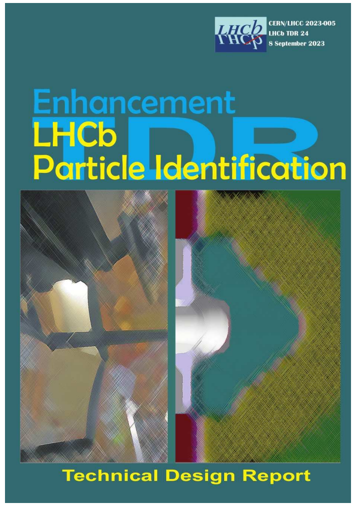
R&D for LHCb RICH Enhancement in LS3

- timing concept new to LHCb but common amongst many systems for LHCb upgrade II
- anticipate ASIC development to LS3: introduce time stamp of photons
- FastRICH ASIC fast enough to be used in upgrade II
  $\Rightarrow$ timing in Run4 limited by photon detectors
- improvement in PID performance expected already in Run4
- LS3 PID TDR [CERN-LHCC-2023-005] approved in March 2024



FastRICH designed in UK
Shared interest and close collaboration with DRD4





R&Ds for RICH in LHCb Upgrade 2

Road to optimization of the Cherenkov angle resolution → goal is <0.5 mrad

Explore modifications to RICH optics and mechanics:
→ Reduce tilt of spherical mirrors, add flat mirrors in LHCb acceptance, reduce emission point error
→ R&D on carbon fibre flat mirrors, light-weight supports and with good resistance to radiation

Studies of low refractive index radiators (fluorocarbon gases) for relatively low chromatic dispersion
→ the chromatic error depends on the convolution between the dispersion and the photon detector QE
→ R&D on new gas mixtures, eco-friendly alternatives, and innovative metamaterials
→ R&D investigating photocathodes (SiPMs) shifted towards the green to reduce single-photon chromatic error

Operating conditions for the LHCb Upgrade II will result in unprecedented conditions for a RICH detector concerning high track and hit densities and radiation environment

R&D ongoing on optics, radiators, photon detectors, fast electronics, mechanics to achieve the ultimate performance of a RICH detector in a high-luminosity environment

Very challenging programme with plenty of room for synergies with other R&D campaigns
Close collaboration with international DRD4 programme in all areas

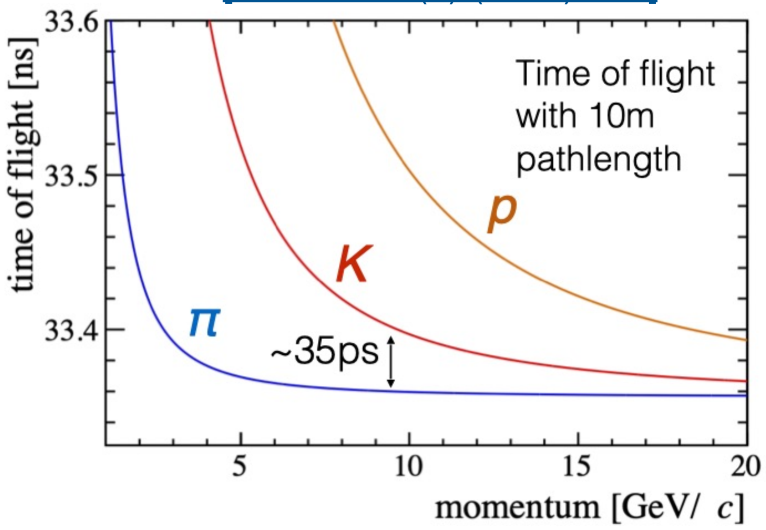
The LHCb Time Of Flight - TORCH

TORCH (Time Of internally Reflected CHerenkov light):

- Large area DIRC-type TOF detector designed to provide PID in the 2–15 GeV/c momentum range.
- Supplement PID performance in momentum region where K/π are below threshold in LHCb RICH detectors.
- Aiming for installation as part of LHCb Upgrade 2 [CERN-LHCC-2017-003]

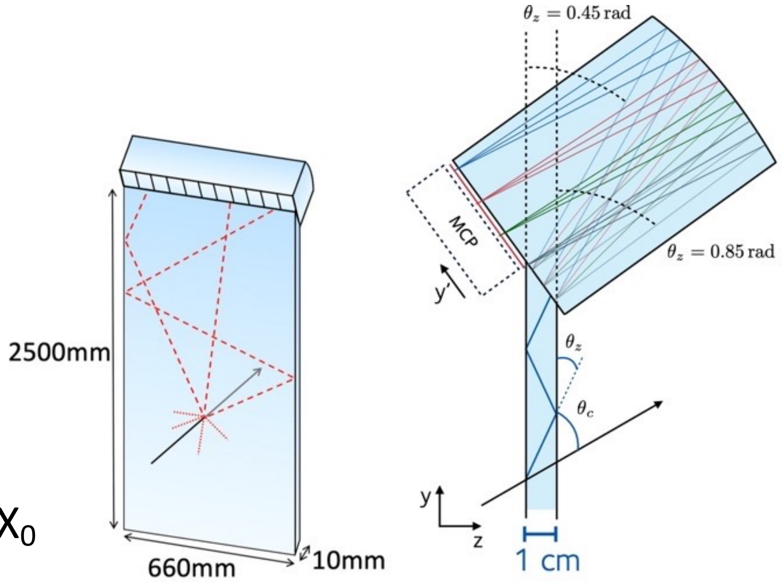
- Highly-polished 1 cm thick quartz plate used as radiator
- Photons internally reflected and focussed onto photon detectors.
- Similar DIRC concept of Belle 2 TOP detector
- Chromatic dispersion corrected and arrival time of photons measured precisely

[NIM A 639 (1) (2011) 173]



Requirements:

- ✓ At 10 metres from collision point, per track resolution of 15 ps for 3σ K/π separation (per photon resolution of 70 ps)
- ✓ Large area detector to cover the full LHCb acceptance (5x6 m^2).
- ✓ High-quality surface on front and rear faces (flatness variation ≤ 3μm and surface roughness 5Å.
- ✓ Light-weight carbon fibre support structure inside detector acceptance to minimise X_0

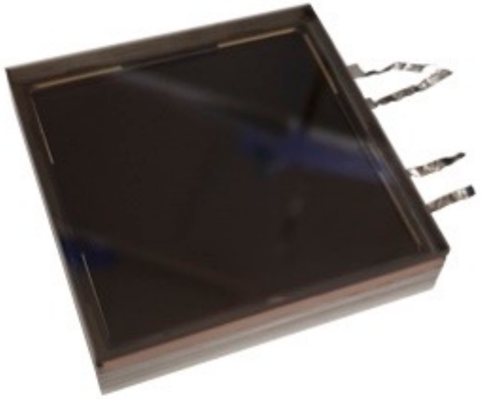


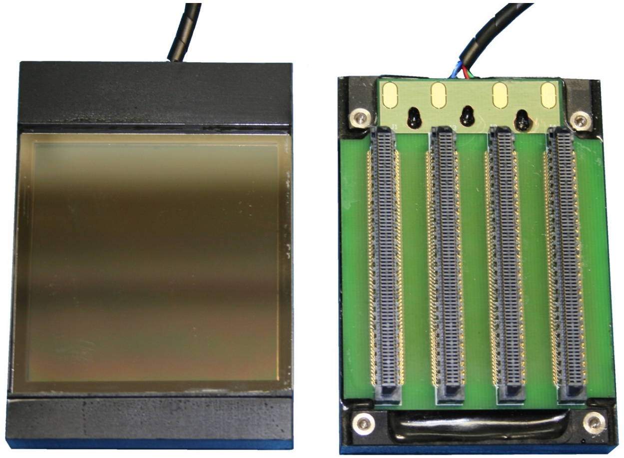
TORCH Photon Detectors

Current TORCH prototype uses custom 53x53mm^2 MCP-PMTs with 64x64 pads [JINST 10 (2015) C05003]

- ❖ Excellent intrinsic time resolution (< 30 ps).
- ❖ MCP is ALD coated for a lifetime > 5C/cm^2
- ❖ Pads modified to form 8x64 pixel arrangement

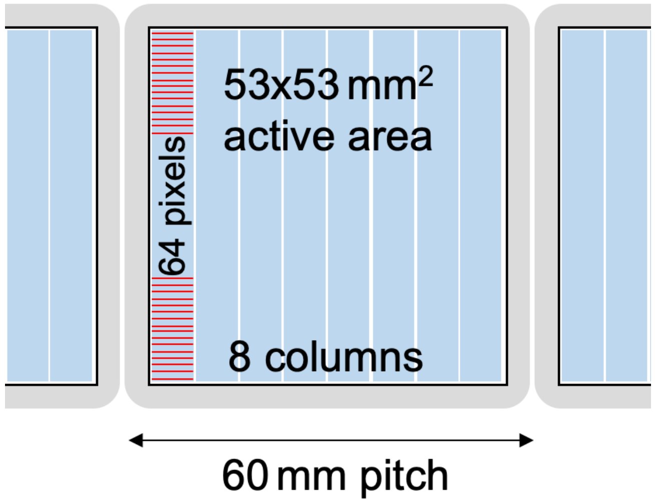
PHOTEK
ENVISAGE THE FUTURE





Ongoing R&D within DRD4 to improve rate capability and lifetime (ideally well beyond 10C/cm^2)
Strong synergies between LHCb RICH, TORCH, Belle 2, future kaon experiments and PID detectors @ ePIC and FCC-ee

Production of customized MCP-PMTs through collaboration with UK industrial partner Photek Ltd



<ins>Opportunity for UK to lead the MCP-PMT developments by exploiting the consolidated connection with Photek</ins>

For electronics plan to use FastRICH ASIC. Common development possible for LHCb TORCH and RICH applications

T. Blake @ Pisa Meeting in Elba 2024

R&Ds for TORCH in LHCb Upgrade 2

- Production of customized MCP-PMTs through collaboration with industrial partner Photek Ltd
- Prototype tests of half-sized TORCH module equipped with Photek customized MCP-PMTs indicate that desired time resolution can be achieved ($\sigma_t(\gamma)$ ~70 ps).
- Aim to assemble a full-scale prototype with light-weight support to be tested at the CERN PS in 2025.

Near-future R&D: construct a full-sized TORCH module, fully equipped with 11 Photek customized MCP-PMTs and light-weight support. The module could be installed in LHCb experiment during LS3.

Future R&D: next-generation high-granularity MCP-PMTs will be developed with Photek and equipped with new-generation of fast electronics

R&D ongoing within DRD4 to develop: MCP-PMTs with increased lifetime; lightweight mechanics; systems to qualify the surface finish of the large area fused-silica radiators.

Shared interests and close collaboration with international DRD4

ALICE 3 (2035+)

Compact and lightweight all-silicon tracker

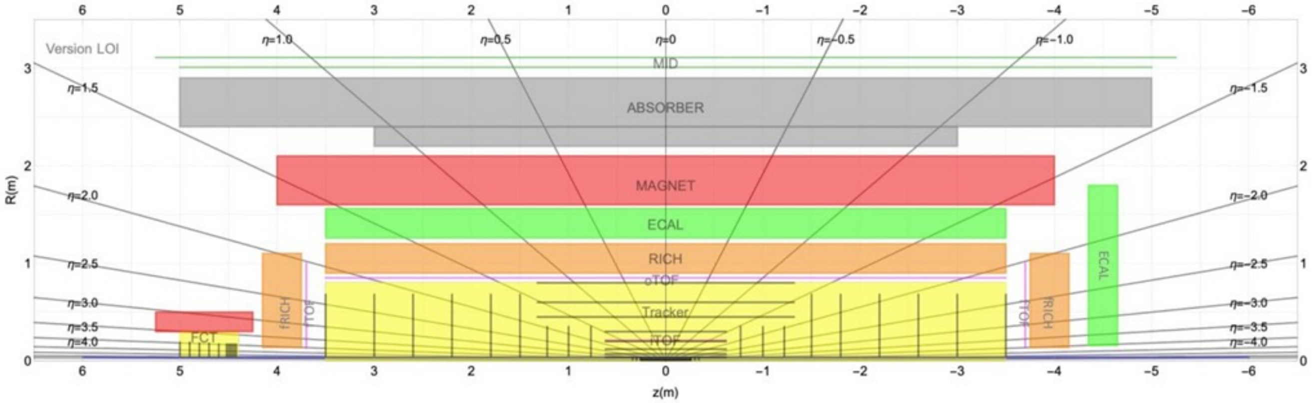
Retractable vertex detector

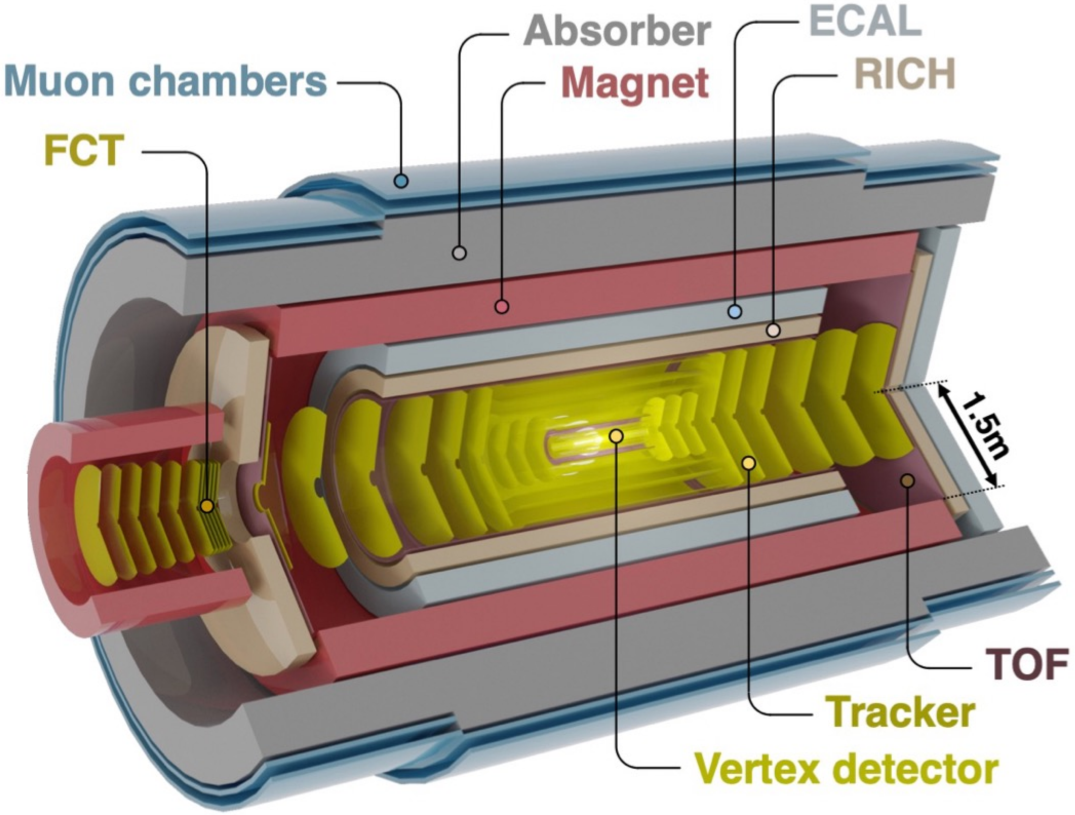
Extensive particle identification capability

Larger pseudorapidity acceptance

Superconducting magnet system

Continuous readout and online processing





P. Jones @ PPAP Community Meeting June 2024

ALICE 3 PID system:

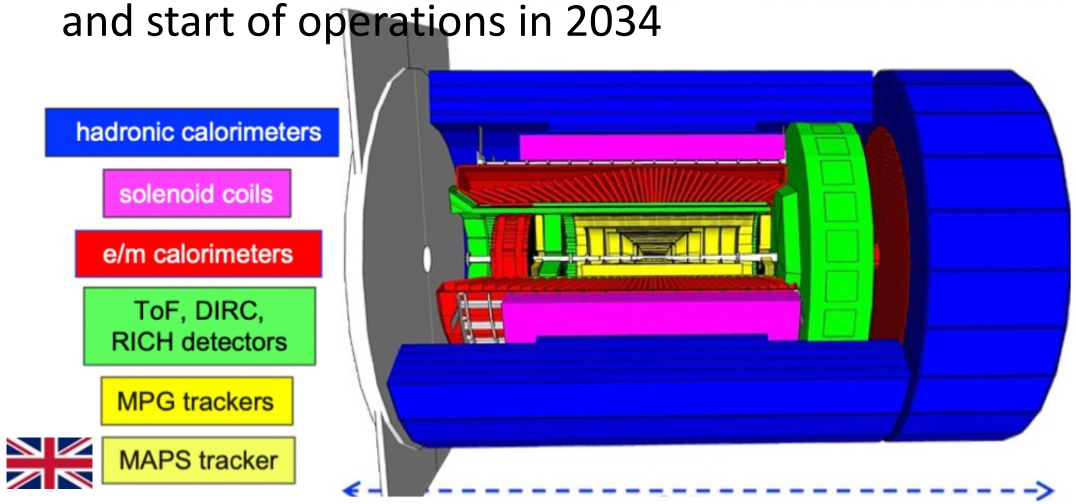
Time-Of-Flight: InnerTOF, OuterTOF, Forward TOF disks
Ring-Imaging Cherenkov: Barrel RICH, Forward RICH
EM Calorimeter: Barrel + Forward ECAL
Muon Identifier Detector: Barrel Muon Identification Detector

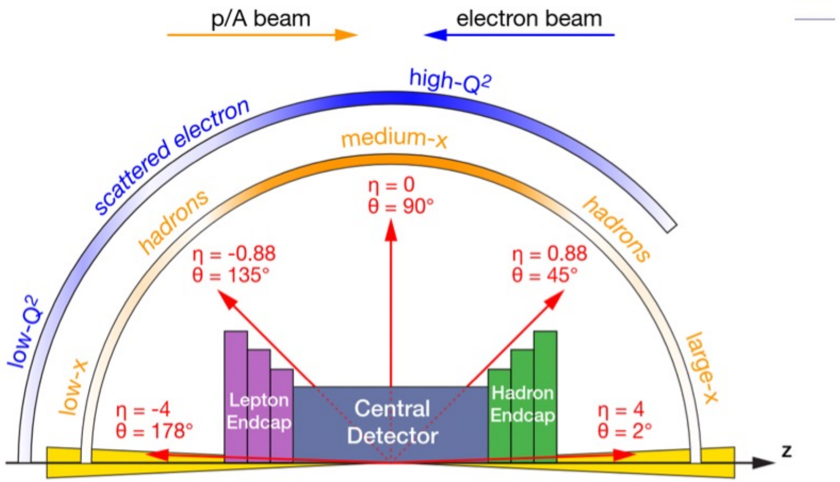
ALICE 2: UK leadership in trigger and track record in Silicon detector design & construction

ALICE 3: Proposed UK involvement in outer tracking and triggering

The ePIC Detector @ EIC

Expect construction approval in 2025 and start of operations in 2034





UK involvement funded through the UKRI Infrastructure Fund

- Magnet and Tracking → **UK contribution to tracking systems**
  - 1.7 T solenoid
  - Micro-Rwell and Micro-Megas
  - Si-MAPS
- Calorimetry
  - Barrel Imaging Calorimeter
  - e-Cap: PbWO4 EMCal
  - Forward: finely segmented EMCal and hCal

PID

Backward
Proximity focusing RICH (aerogel RICH + peripheral conical mirrors + HRPPD)

Central
Time Of Flight (AC LGAD), DIRC (fused silica bar with novel lensing and MCP-PMT based readout)

Forward
Time Of Flight (AC LGAD) and Dual radiator RICH (aerogel + C2F6 gas + spherical mirrors + SiPM sensors)

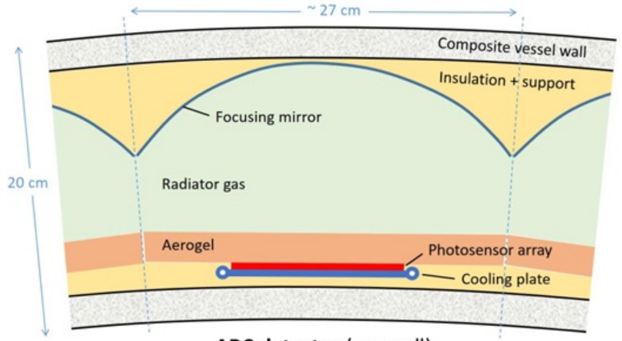
UK (Glasgow) is also part of eRD110: a photosensor R&D program for EIC funded by JLab

eRD110: Characterisation of Photek MCP-PMT (for DIRC) and Incom HRPPD (high-rate large area MCP for pfRICH)

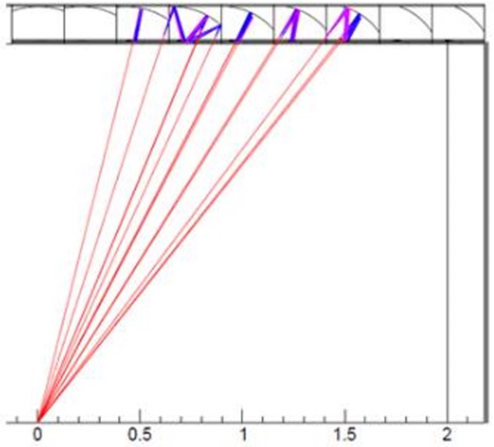
Common goals and synergies with UK R&D on PID systems and photon detectors

Array of RICH Cells @ FCC-ee

- **A**rray of **R**ICH **C**ells (ARC): A novel RICH detector concept
  - First presented by R. Forty at FCC week 2021
  - Compact, low-mass solution for particle ID for FCC-ee
  - Concept inspired by the compound eyes of an insect
- Adapted to fit into the CLD experiment concept, taking 10% from the tracker volume
  - Radial depth of 20 cm, radius of 2.1 m and a length of 4.4 m
  - Aim to keep material budget below $0.1X_0$
- Aerogel and gas radiators with a spherical mirror
  - Aerogel also acts as thermal insulation between gas and detector



ARC detector (one cell)



SiPMs current baseline photon detector technology considered

Future Project (2040+)

Challenge: achieve excellent hadron PID with compact, lightweight layout in a 4π detector at e^+e^- collider (FCC-ee).

Goal Performance: 3σ K-π separation in the range 2-50 GeV/c

Importance of proposed detector:
- enable a rich Flavour Physics programme at FCCee
- enhance the capabilities in Higgs, WW and top physics (e.g. H decays to strange quarks)

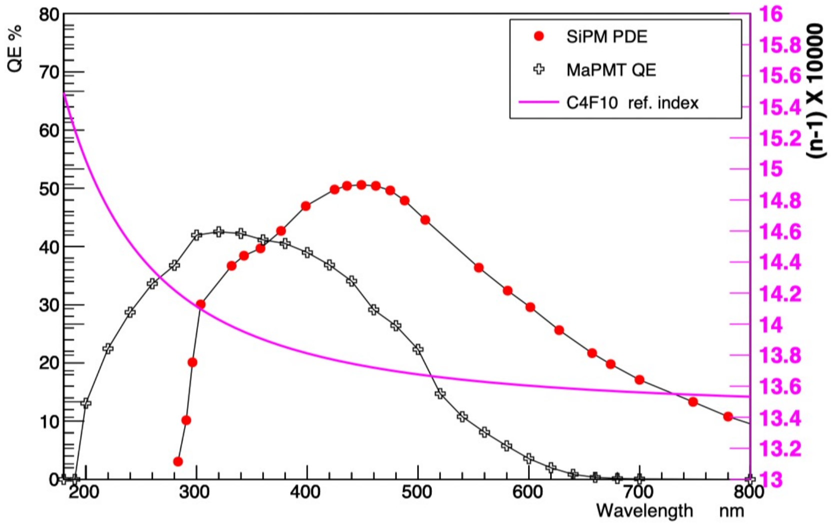
R&D for ARC concept is a recognized goal of international DRD4 with deliverable: evaluation of a prototype ARC cell

UK interested groups: Bristol, Cambridge, Oxford, RAL and Warwick

Silicon PhotoMultipliers (SiPMs)

SiPMs have several advantages:

- extremely fine granularity
- resilience to magnetic fields
- high photon detection efficiency
- good time resolution (~ 100 ps)



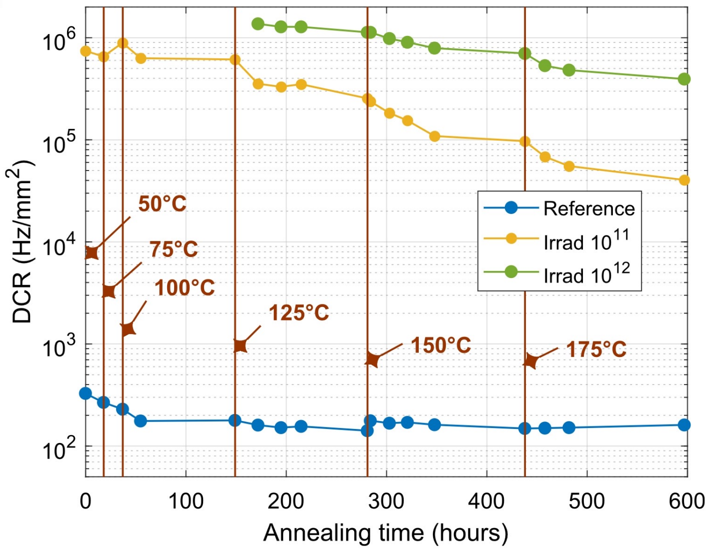
But important drawbacks:

- dark count rates after irradiation

⇒ R&D on cryogenic operations

⇒ R&D on local cooling of SiPM with design of dedicated housing

⇒ R&D on implementing annealing to compensate for irradiation effects



[NIM A 922, 243-249 (2019)]

SiPMs are possible candidates for LHCb RICH Upgrade 2:

- used in green wavelength region to reduce single-photon chromatic correction
- improved granularity to 1.0 x 1.0 mm^2 pixels to reduce peak photon occupancy << 100%

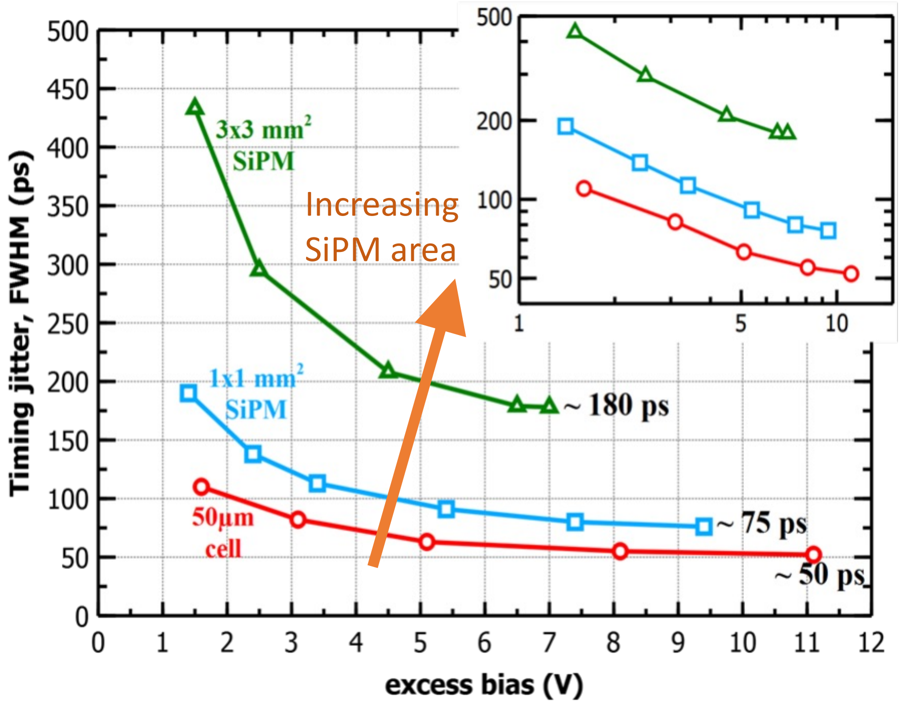
SiPM application across all future PP experiments → radiation hardness, lower noise and fast timing are important drivers

Shared interests and close collaboration with international DRD4

R&D on SiPMs

SiPM application across all future PP experiments → radiation hardness, lower noise and fast timing are important drivers

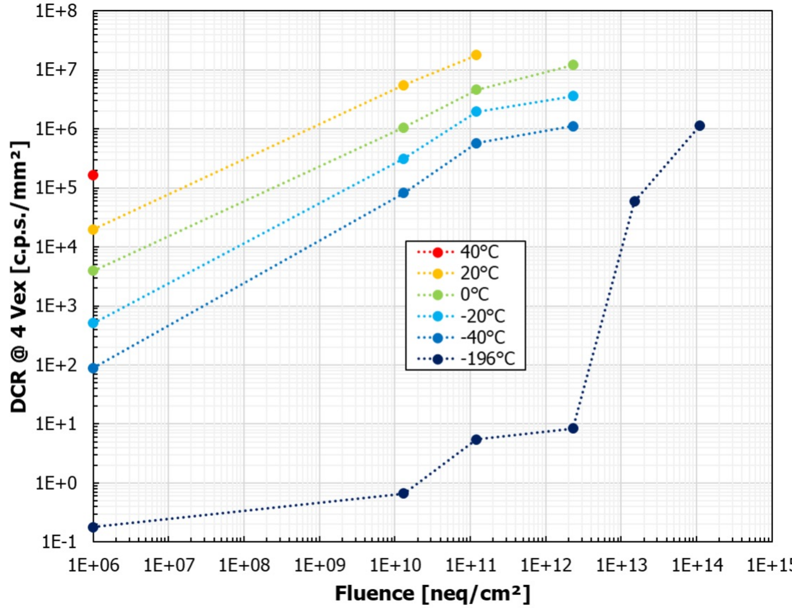
- SiPM single photon time resolution is dependent on sensor area
- Segmentation of active area into small pixels is a solution
- Each pixel instrumented with its own readout channel
- Signals can then be summed, or timing information combined



Acerbi, Fabio, et al. "Characterization of single-photon time resolution: from single SPAD to silicon photomultiplier." IEEE Transactions on Nuclear Science 61.5 (2014): 2678-2686.

- Major effect of radiation
  - Increase of dark count rate (DCR)
  - DCR strongly mitigated by lower temperature operation
  - Cooling is very effective in reducing DCR after irradiation up to ~$1 \cdot 10^{12}$ n_{eq}/cm^2
  - Benefits of cooling seem to disappear at high fluences
- Annealing can produce partial recovery

Main sensor developments from FBK and INFN Italy



S. Merzi – Study of Radiation Damage on FBK SiPMs, CERN Workshop 2022

R&D on SiPMs for TOF Detectors

Develop a SiPM array for single-photon detection, with mm-scale pixelation, suitable for use in TOF prototypes

- ❖ R&D on SiPM detectors and electronics to provide:
  - **mm-scale position sensitivity and fast timing**
  - at very high rates expected with HL-LHC and future colliders
- ❖ Focus on the system aspects of combining:
  - **SiPM arrays with radiation hardness, mm-scale pixelation, and cooling**
  - The major effect of high irradiation levels will be elevated dark noise
  - **Integrated with multichannel readout electronics** such as the FastIC ASIC family
- ❖ SiPMs with segmentation providing several pixels per device
  - Event timing to ~10-20 ps will require close integration of the sensor and electronics
  - Power dissipation in the sensor at the very high rates anticipated will be large
  - Active cooling required for stable device gain and to reduce elevated dark noise
- ❖ Overall aim – to achieve the best possible time resolution at required pixelation

J. Lapingdton @ DRD4
Collaboration Meeting 2024

TOF plays a pivotal role for experiments such as PANDA and CBM at FAIR and is considered for future upgrades of LHCb, ALICE, ATLAS/CMS, and at EIC and FCC-ee as well as in future kaon experiments and beam dump facilities

Shared interests and close collaboration with international DRD4

MicroChannel Plate (MCP)

Hamamatsu, Photek, Photonis MCP-PMTs
Tests for PANDA DIRC detector

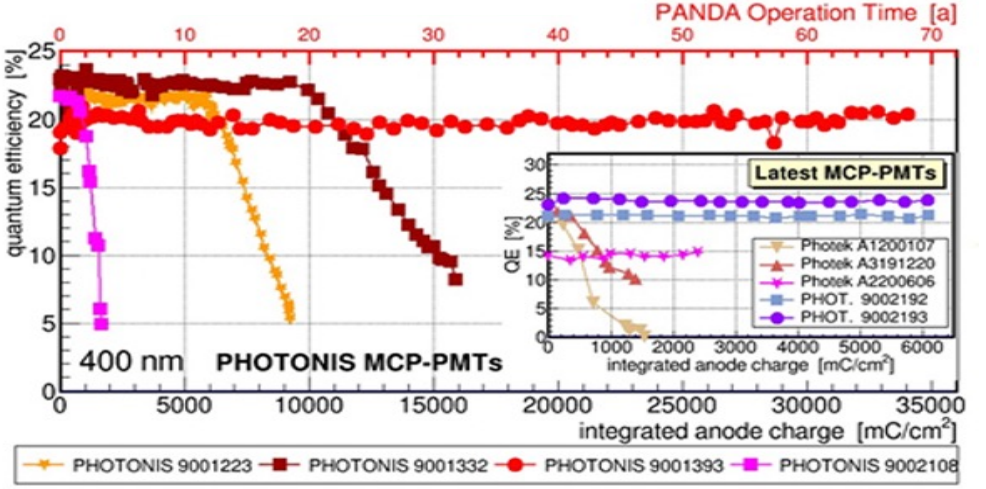
- Extremely good single-photon time resolution < 40 ps,
- Custom pixelisation tailored for individual applications
- Drawbacks related to lifetime and rate capability

Photocathode aging due to ion feedback

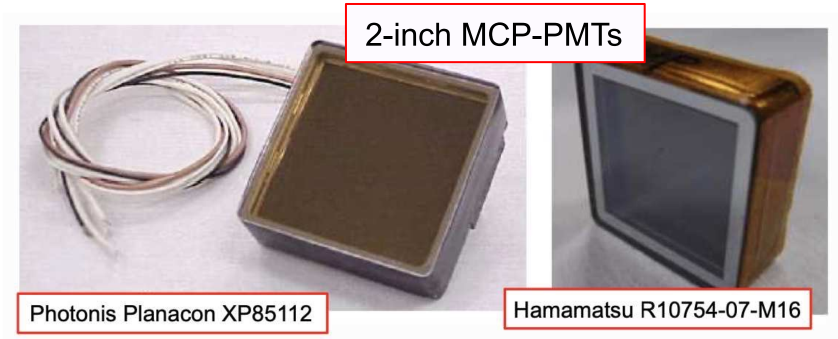
Gain decreases at high photon rates (τ = RC)

- 2-inch Photonis/Photek MCP-PMTs: ~1 MHz/cm² (with 10^6 gain)
- 1-inch Hamamatsu R10754 ≥10 MHz/cm²
- Rate capability also depends on MCP resistance, gain operation

Lifetime measurements

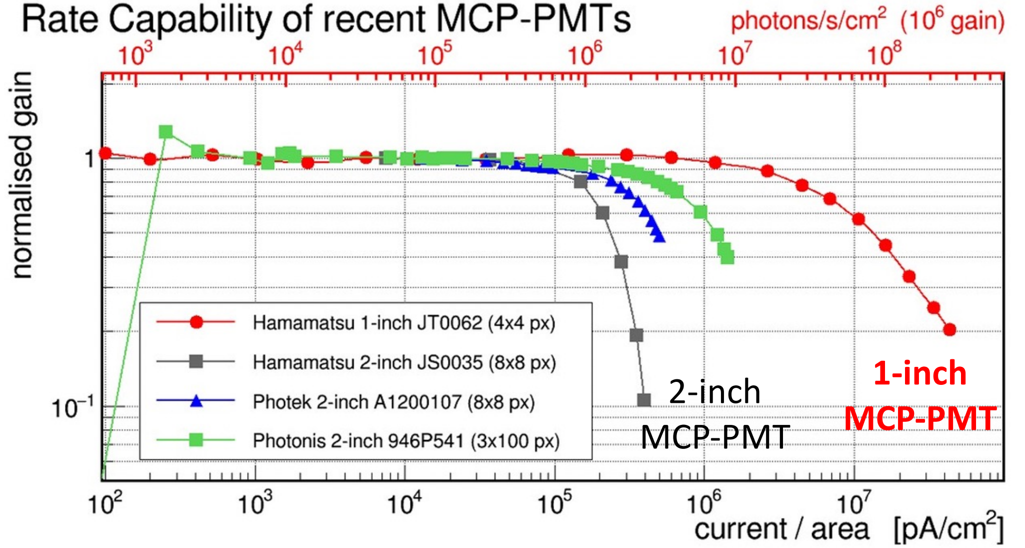


Photonis ALD coated MCP-PMT >30 C/cm²



R&D to investigate options of low-gain MCPs: MCP-HPD [JINST 13 C12005 2018]

Rate Capability of recent MCP-PMTs



UK R&D on MCP based photon detectors includes:

Developments of MCP-PMTs with increased lifetime with Photek Ltd (UK)

Characterisation and tests of Photonis 2-inch MCP-PMT with 2 ALD layers

Studies of Large Area Picosecond Photodetector (LAPPD)

Vacuum photon detectors have an essential future role → rate capabilities and lifetime must be further developed

Shared interests and close collaboration with international DRD4

Large Area Picosecond Photodetector (LAPPD)

Main R&D for future photodetectors will involve the time implementation

Large Area Picosecond Photodetector (LAPPD)

Micro Channel Plate photomultiplier, dimension 20 x 20 cm^2

Supplied by INCOM (US)

Advantages:

- Time resolution lower than 60 ps
- High gain (~ 10^7)
- capable of imaging single photons
- Large tile - benefit for instrumentation, more cost-effective

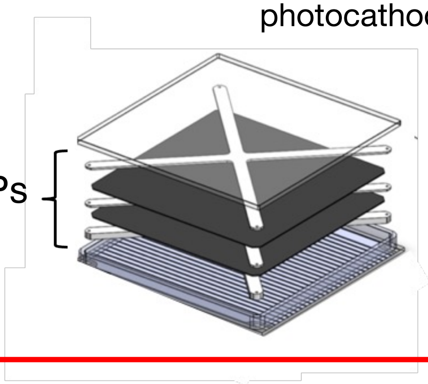
- **Gen II LAPPD 97 @ Edinburgh**
- Gen II LAPPD, pixel readout, **20 μm pores**
- Spectral response 160-650 nm
- 5 taps for independent voltage control of the photocathode and entry/exit of each MCP

LHCb RICH Edinburgh group

LAPPD scheme

Fused silica window with photocathode *on inside surface*

20 cm x 20 cm MCPs



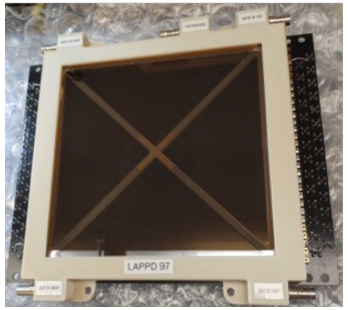
Previous tests in Edinburgh

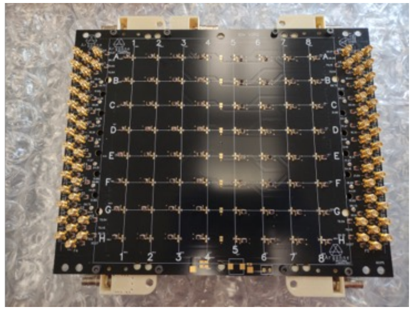
Default INCOM readout board 64 pixels

Pixel size:

25 mm pitch to pitch

(24 x 24 mm^2 active area, 1 mm dead gap)





Edinburgh progress

Custom readout board V0, 512 pixels

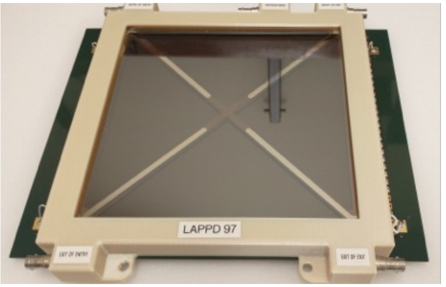
Pixel size:

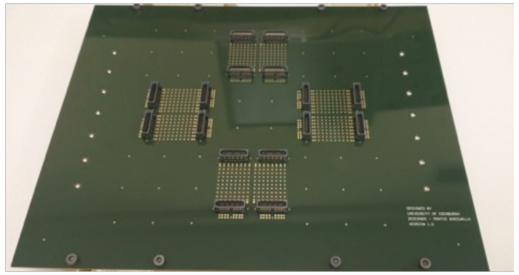
3 mm pitch to pitch

(2.9 x 2.9 mm^2 active area, 0.1 mm dead gap)

✓ Designed in Edinburgh by P.Gheewalla

✓. Assembled to the LAPPD in Edinburgh





The RICH group tested the LAPPD in 2023/2024 at CERN SPS, coupled to a multi-channel fast electronics chain (FastIC+picoTDC based) see poster presented at the Pisa Meeting

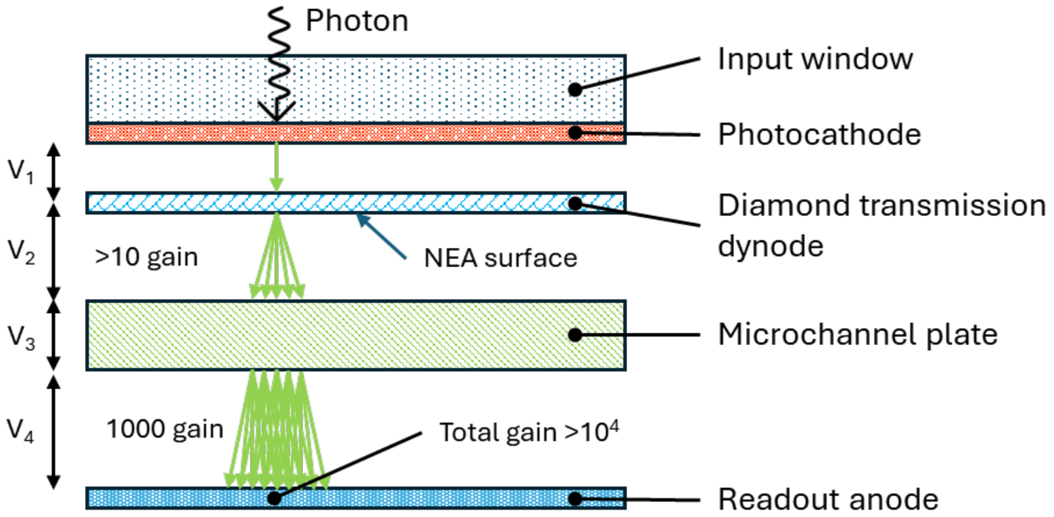
- High Rate Photodetector (HRPPD) supplied by INCOM **soon in Edinburgh**, with **10 μm pores,** and directly coupled pixellated anode → better time resolution and spatial footprint

Shared interests and close collaboration with international DRD4

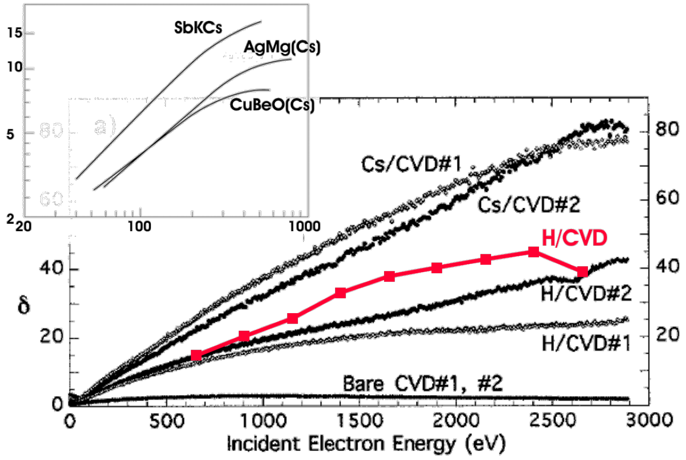
Transmission Dynodes: Enhancing Vacuum Photodetectors

- Ultra-thin transmission diamond dynode between photocathode and MCP
- Provides a barrier for ion backflow
  - → **longer photocathode lifetime**
- Provides electron gain
  - → **Tighter pulse height distribution at lower overall gain**
  - → Higher maximum count rate
- Future – replace MCPs altogether with transmission dynode stack
  - → Excellent single photon spectrum
  - → Improved timing precision ~10 ps

Hybrid MCP detector with input transmission dynode



Traditional dynode materials



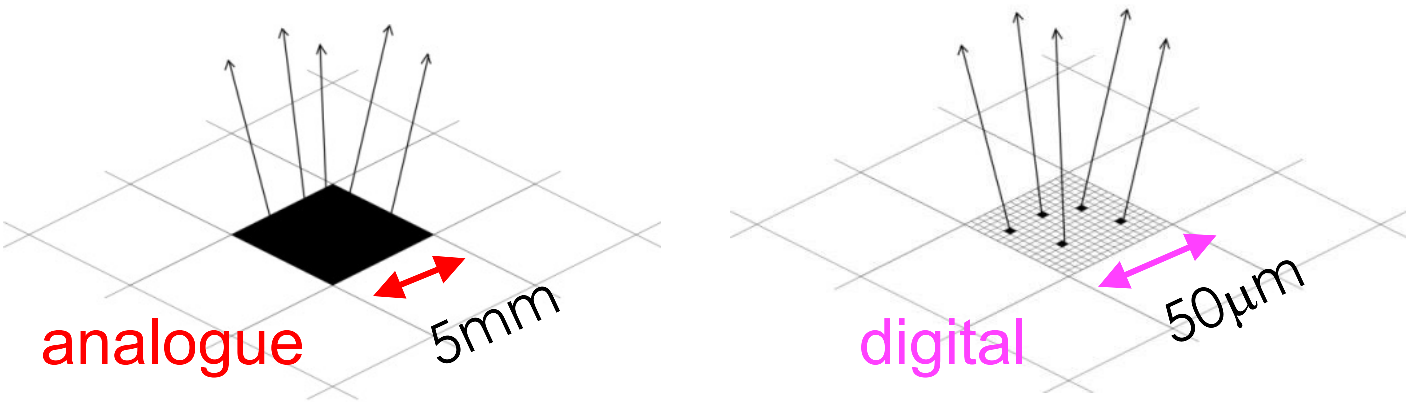
Measured diamond secondary electron yield (reflection)

Accepted for full submission to UKRI Early-Stage R&D scheme 2024
If fundings are granted → aim at the production of MCP-hybrid demonstrator with a single diamond layer
(in collaboration with Photek Ltd)

DRD6: Digital ECAL Concept

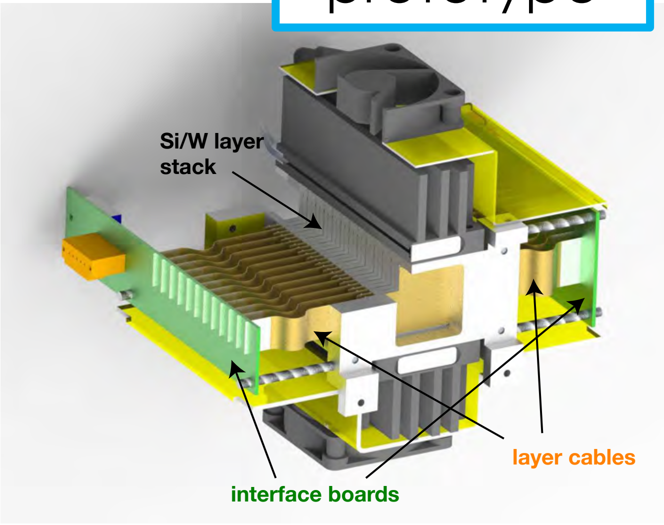
UNIVERSITY OF BIRMINGHAM

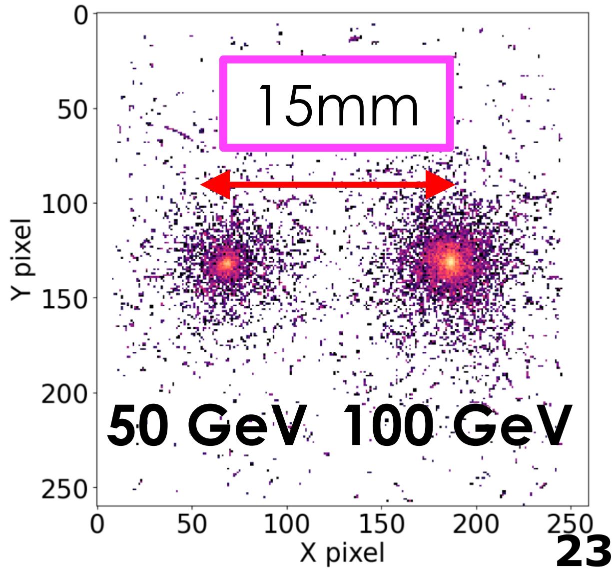
- Calorimeter samples energy between ~30 W absorber layers
- Analogue, e.g. CMS HGCAL (~ex-ILC), **sum energy** in 5x5 mm^2 Si cells
- Digital: **count every individual particle** in EM shower
  - *Need ultra*-small pixels! Ideally 1 particle/pixel → binary approach
  - EM shower core density at 500GeV ~100/mm^2
  - Pixels <100x100μm^2 for no saturation
  - ~10^{12} pixels for ECAL barrel



- Using CMOS MAPS, simpler construction, + expect lower cost
- A `tracking calorimeter', separates boosted decays, e.g. $\tau, \pi^0 \rightarrow \gamma\gamma$ …
- 20 X_0 prototype calorimeter in test beams

EPICAL-2 prototype

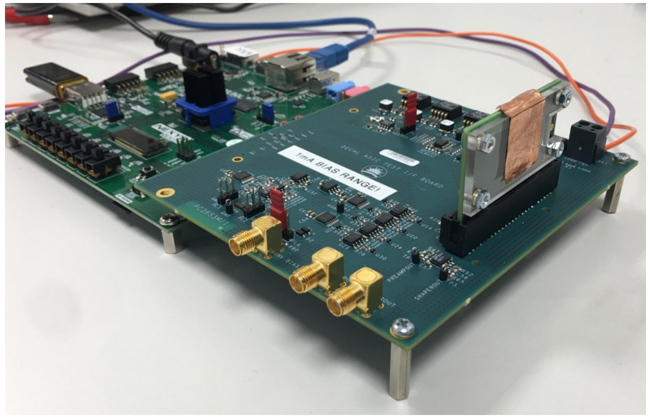


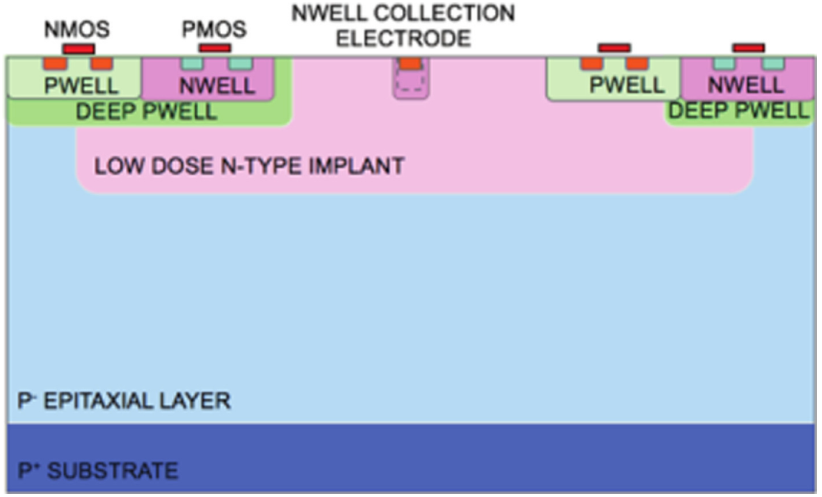


(UK) DECAL Sensor Plans

UNIVERSITY OF BIRMINGHAM

- Original UK idea enabled use of fully efficient MAPS sensors
- Potentially reconfigurable sensor technology: outer tracker/preshower/ECAL
  - I.Kopsalis et al, NIM A1038 (2022) 166955 and P.P.Allport et al, Sensors 2022, 22(18) 6848
- Main R&D goals
  - Reduce ~20-100mW/cm^2 power consumption (collider-specific pulsing or …)
  - Resolve identified issues with current DECAL sensor design
- Other ideas
  - 3d stack + semi-digital approach
  - Multi-threshold pixels
  - Increased configurability
  - Configurability, chip → FPGA
  - Modelling





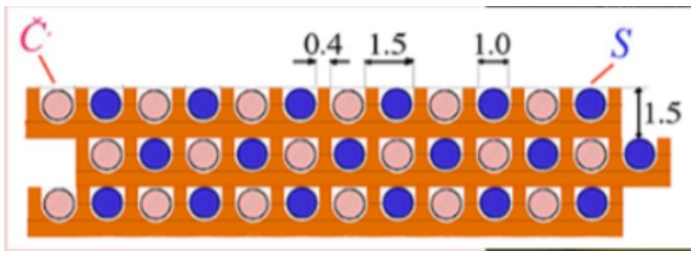
- Collaborate with SLAC/Oregon, review overlaps/division of fundamental R&D goals
- Designer effort critical, cannot rely on effort from outside UK, e.g. Germany
  - If we want to be involved in this activity in future, need access to resources

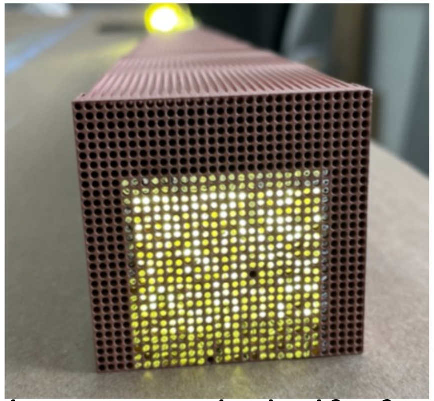
Dual readout Calorimeter - the principle

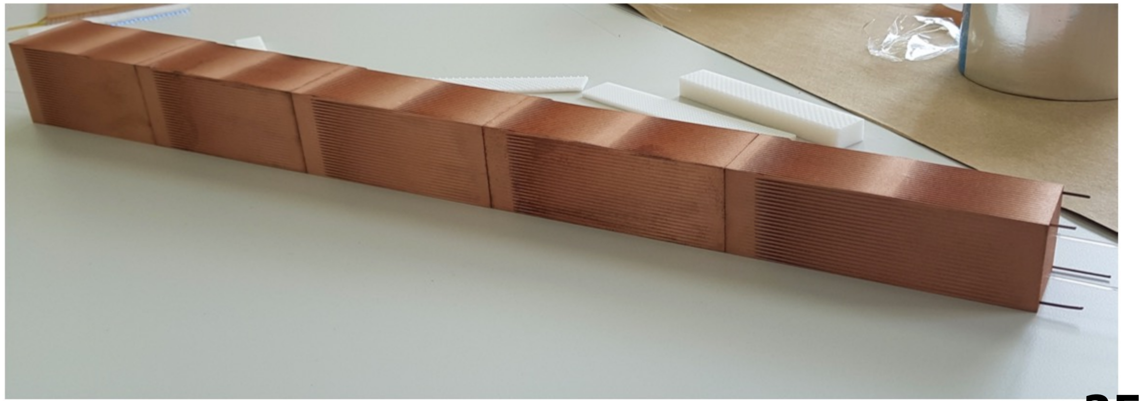
UNIVERSITY OF SUSSEX

- Single device for EM and HAD calorimetry
- Resolution of hadronic energy measurement affected by fluctuations
  - % energy carried by $\pi^0 \rightarrow \gamma\gamma$ (f_{em})
- Two readouts with different EM/hadronic response
  - Determine f_{em} and incident energy E.
- How? e.g. IDEA detector concept (FCC and CEPC CDRs)
- Spaghetti calorimeter, alternating clear (Cherenkov) and doped (Scintillating) fibres.
  - Cu absorber, 1 mm fibres, 1.5 mm pitch, readout by SiPM

UK involved in IDEA collaboration, which has built and tested a dual-readout calorimeter prototype at CERN







Slides provided by Nigel Watson and Fabrizio Salvatore on behalf of UK-DRD6

Technologies for Gas Detectors (DRD1)

Gas detectors (GDs) employed in many system categories (No other technology provides a similar diversity of uses):

- **Muon systems, tracking, calorimetry, PID/TOF, ….**

GD technologies include TPC, Gas Electron Multiplier (GEM), Micromegas, RPC, μ-RWELL, Straw tubes, Drift Chambers, Micro-Pattern Gaseous Detector (MPGD), THGEM …..

All future facilities/detectors of 2030s and 2040s will use one or more GD technology

- HL-LHC, EIC, PANDA/CMB @ FAIR, future kaon experiments, ee colliders, STCF, muon colliders, …

MAIN Drivers for GDs from facilities:

Main challenges at future facilities include **large area coverage with precision timing** info (DRDT 1.1) to ensure correct track-event association, and **ability to cope with large particle fluxes using eco-gas mixture** (DRDT 1.3).

Requirements for central tracking are **high-rate capability and excellent spatial resolution** for precision momentum measurement and PID with **minimal material budget and lightweight mechanical support** structures (DRDT 1.2)

Liverpool Glass THGEMs

Novel Glass THGEMs developed at Liverpool (Patent GB2019563.2)

PI: K.Mavrokoridis@Liverpool.ac.uk

50cm x 50cm glass THGEM
1.1mm thick,
500µm ID holes,
800µm pitch hexagonal array

For more details:
https://www.mdpi.com/2076-3417/11/20/9450

A Novel Manufacturing Process for Glass THGEMs and First Characterisation in an Optical Gaseous Argon TPC

Slide by K. Mavrokoridis

TPCs used in neutrino and dark matter sectors (DUNE, DarkSide-20k, ArDM, LZ….)

Glass THGEM Facility

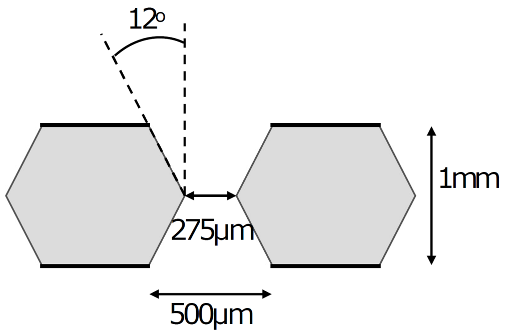
MicroPattern Detector Facility

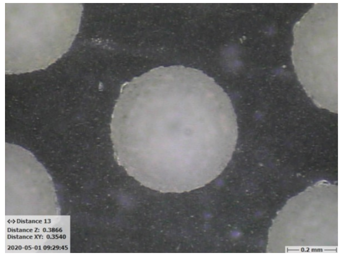
G-THGEM: https://www.mdpi.com/2076-3417/11/20/9450

A new abrasive machining facility in preparation at the University of Liverpool

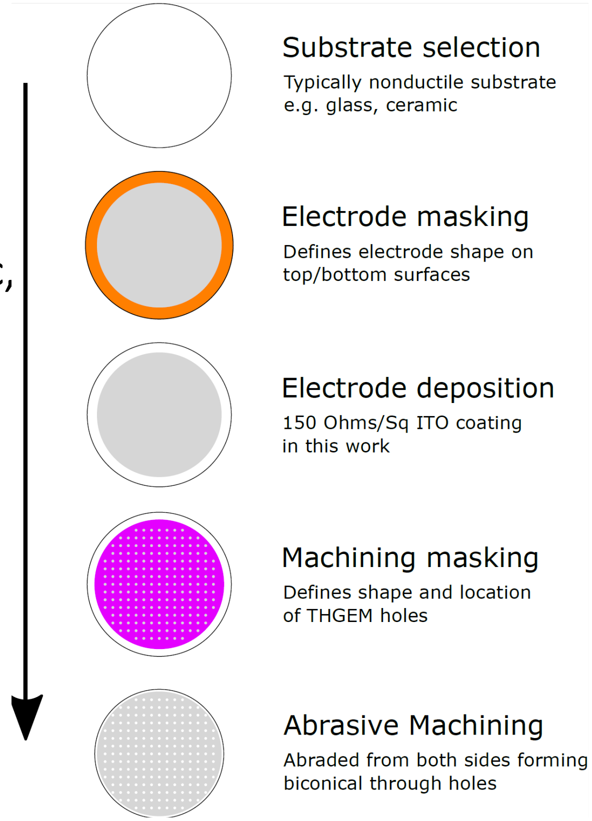
Fully automated
Capable of machining 850mmx850mm active area
Not limited to glass, any brittle material i.e. ceramic, carbon fibre etc.

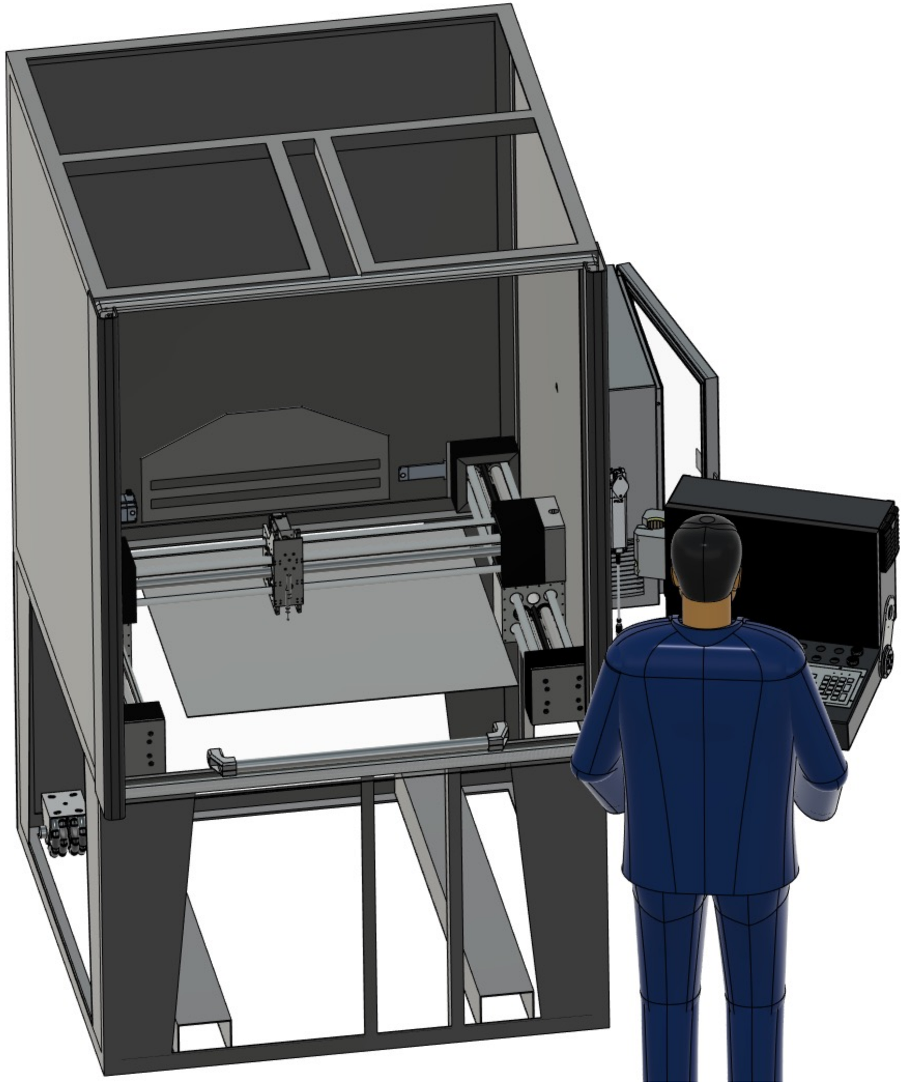
Will lead glass THGEM R&D





G-THGEM with **ITO electrodes** and holes formed by **abrasive machining**.

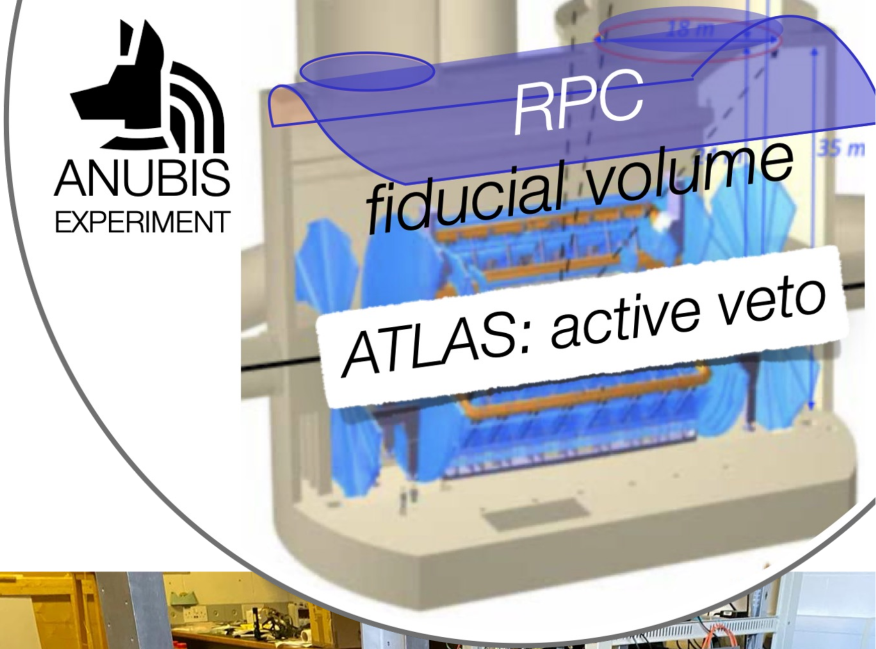




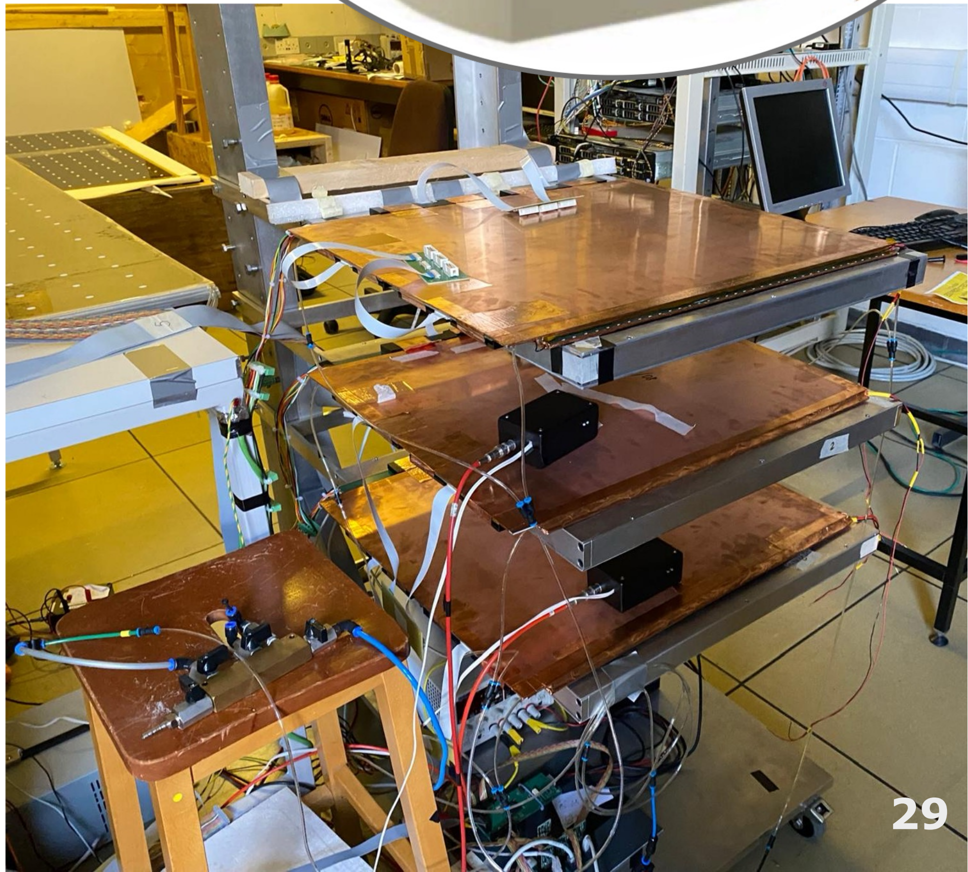
The abrasive machining manufacturing process has big impact on neutrino and dark matter sectors, as well as in medical imaging

Slide by K. Mavrokoridis

ANUBIS: full HL-LHC exploitation



- ANUBIS: Resistive Plate Chambers (RPC) to identify
  - Muons
  - Charged particles from long-lived particle decays
- R&D on RPCs for PID:
  - Eco-gases (intermediate rate & ageing requirements)
    - Essential requirement to realise ANUBIS
    - Current gas mixture (CO_2, $C_2H_2F_4$ i-C_4H_{10}, SF_6): GWP ~ 1400 (!)
  - Optimisation for spatial resolution
  - Dedicated serial readout with data concentrators
    - Benefit from intermediate event rate
    - Substantially simpler infrastructure
  - Sealed RPC detectors (fill and forget)
  - Quality assurance techniques to probe longevity
- ANUBIS is a UK-lead international collaboration



Slides provided by Oleg Brandt and Pawel Majewski on behalf of UK-DRD1

Summary and outlook

- Electron, muon, and charged hadron identification essential to target a broad Flavour Physics programme
- UK has leadership and a track record in PID detectors providing a major contribution to the ESPPU
- UK is leading exciting R&D in line with the main drivers identified by the ECFA Detector R&D roadmap
- UK R&D for HL-LHC is a very challenging programme with plenty of synergies with other R&D campaigns (detectors at EIC and future kaon experiments)
- UK is looking ahead to longer-term future projects (FCC, STCF, …) to exploit R&D synergies and possibilities to expand its contribution to the next ESPP update

Special Thanks for their inputs to:
Tom Blake, Oleg Brandt, David Evans, Jon Lapingdton, Pawel Majewski, Konstas Mavrokoridis, Rachel Montgomery, Paul Newman, Federica Oliva, Fabrizio Salvatore, Nigel Watson, Guy Wilkinson.

Main R&D for PID detectors of 2030s/40s

From ECFA DRD Roadmap 2020

1. Enhance timing resolution and spectral range of photon detectors
   - ➢ crucial for fast timing in Cherenkov and TOF detectors
   - ➢ for operation with high particle fluxes and pile-up
   - ➢ to extend the wavelength coverage of scintillation photons from noble gases and Cherenkov photons
2. Develop photosensors for extreme environments
   - ➢ essential for operation in the high-radiation environments at the HL-LHC, Belle II upgrade, EIC and FCC; and similarly for cryogenic operation.
3. Develop RICH and imaging detectors with low mass and high-resolution timing
   - ➢ required for PID at HL-LHC, Belle II upgrade, EIC, and FCC-ee
4. Develop compact high-performance time-of-flight detectors
   - ➢ as complementary approach for PID at HL-LHC, EIC and FCC-ee

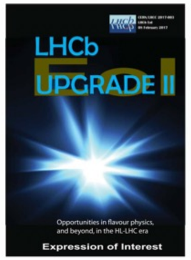
UK contributions to the above R&D lines identified by the ESPPU
→ this talk

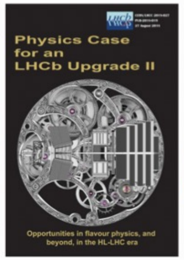
LHCb Timeline

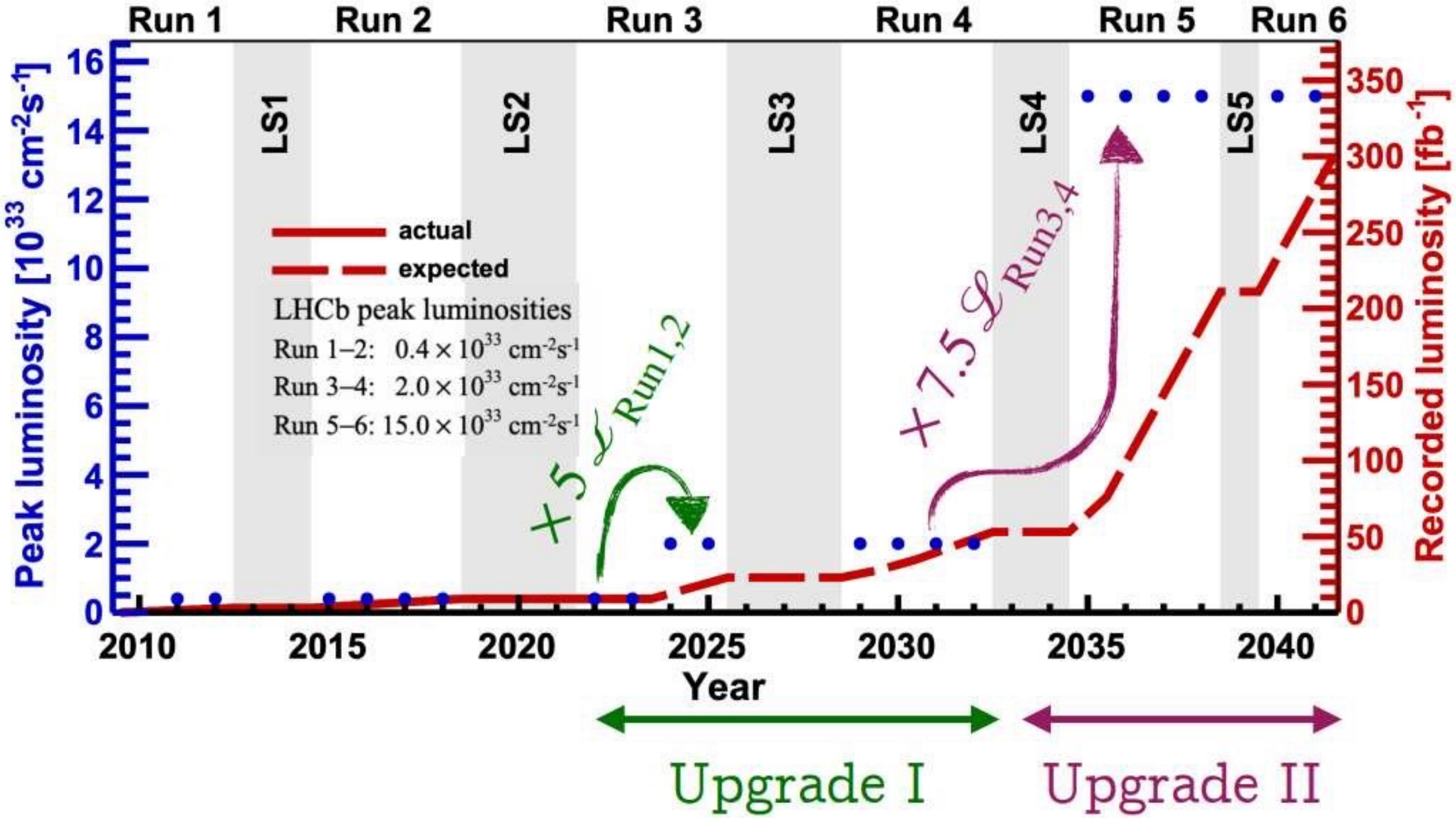
Most physics statistically rather than systematically or theoretically limited → motivates high luminosity experiment.
Upgrade1 aims to record 50fb^{-1} by the end of Run4 Upgrade2 aims to record 300fb^{-1} by end of HL-LHC.

- LHCb experiment[2010-2018] collected 9 fb^{-1} see Yasmine's talk
- LHCb Upgrade I[2022-] expected to collect $\sim$ 50 fb^{-1} see Giulia's talk
- LHCb Upgrade II[2034-] to collect $\sim$ 300 fb^{-1} see Renato's talk

[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]
[CERN-LHCC-2021-012]





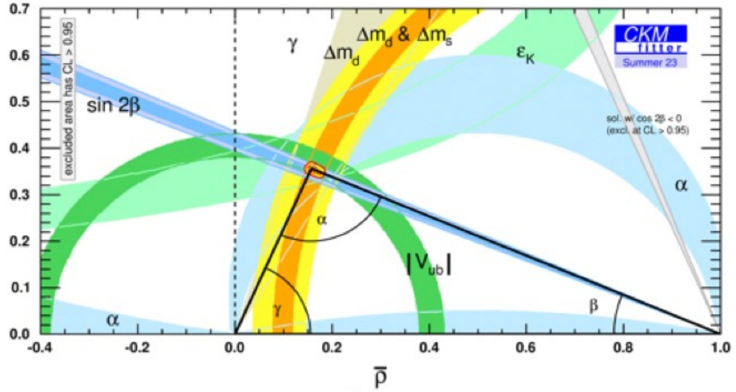


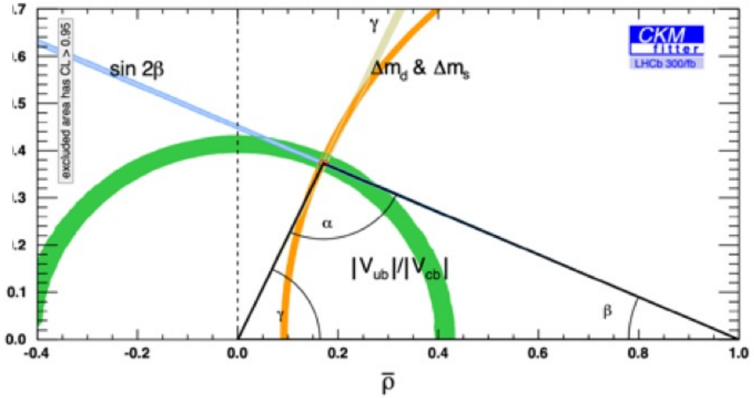
European Strategy Update 2020:
"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"

The LHCb Upgrade 2

Physics programme aiming at huge improvements in precision on key flavour observables

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$ ($B_s^0 \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038



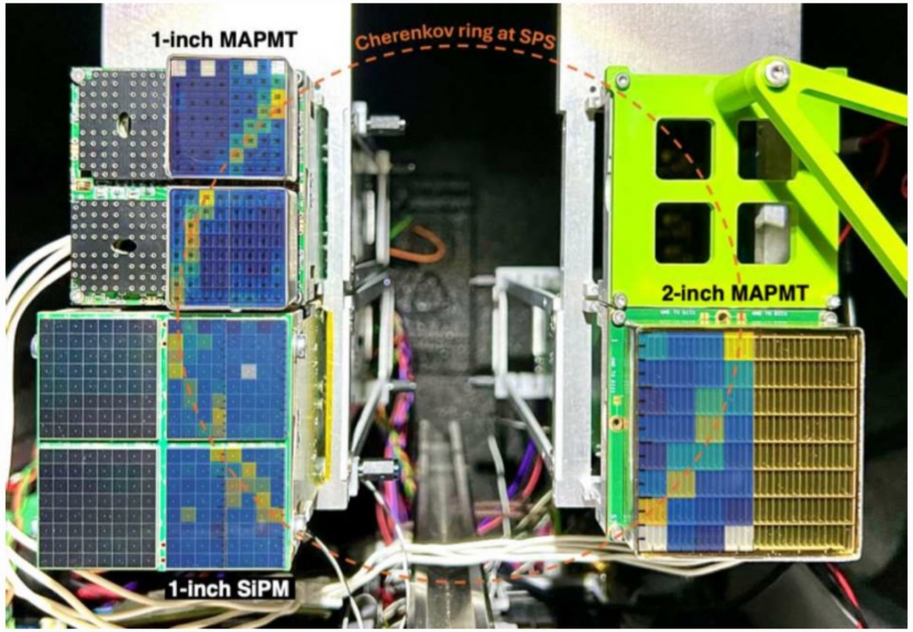


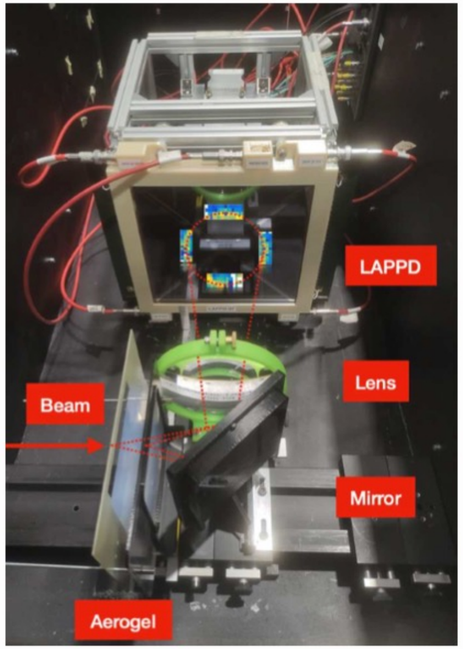
Electron, muon, and charged hadron identification essential to target a broad Flavour Physics programme

European Strategy Update 2020:

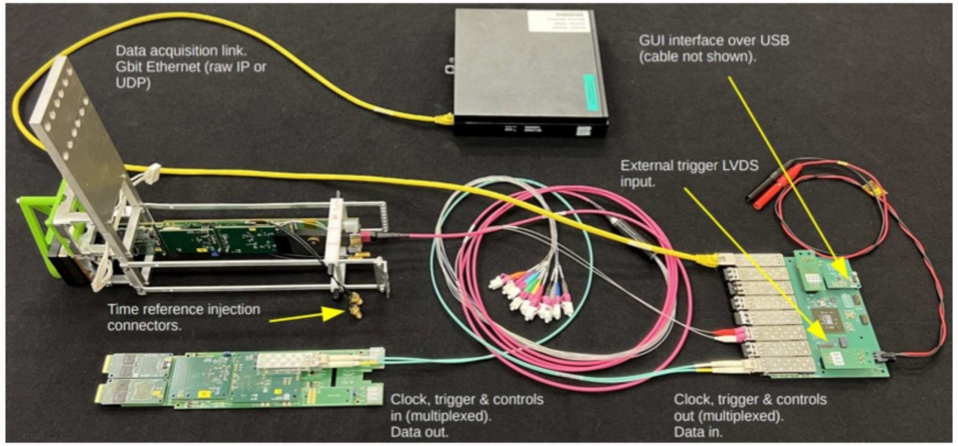
"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"

R&D for LHCb RICH LS3 & Upgrade 2



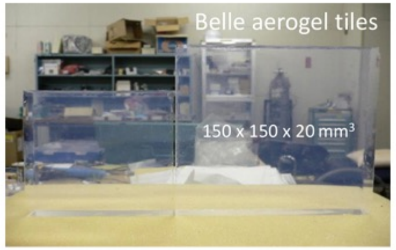


- intense testbeam campaign ongoing
- test prototype electronics for LS3 with MaPMTs currently operated in the RICH Upgrade
- test candidates for photon detection in Upgrade II



ARC @ FCC-ee: Radiators & Ray Tracing

- C_4F_{10}:
  - Baseline assumption, well known from LHCb RICH1
  - $n = 1.0014 \implies \theta_c = 53\,\text{mrad}$, suitable for high momentum particles
  - C_4F_{10} is a greenhouse gas, plan to replace with suitable Novec gas, such as $C_5F_{10}O$
- Aerogel:
  - Well known as a RICH radiator, e.g. from ARICH at Belle II
  - $n = 1.01\text{-}1.10 \implies \theta_c = 141\text{-}430\,\text{mrad}$, suitable at low momentum
  - Very low thermal conductivity
    - Suitable to separate gas from detector, which must be cooled
    - Cherenkov photons come for "free" and are focused by the same mirror
  - Drawback: Some loss of photons from scattering



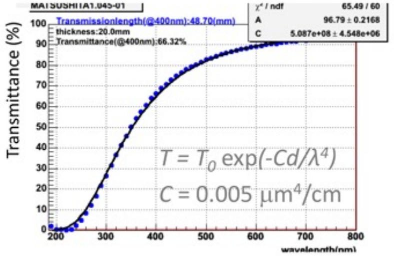
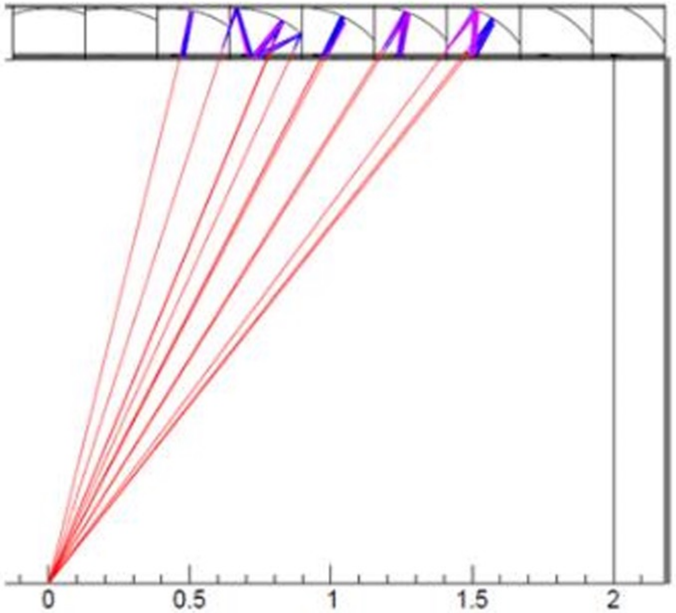


Figure 6: Belle aerogel tiles (left) and aerogel transmission function (right).



Ray-tracing simulation of an ensemble of cells in the barrel region

ARC @ FCC-ee: Performance (Simulation)

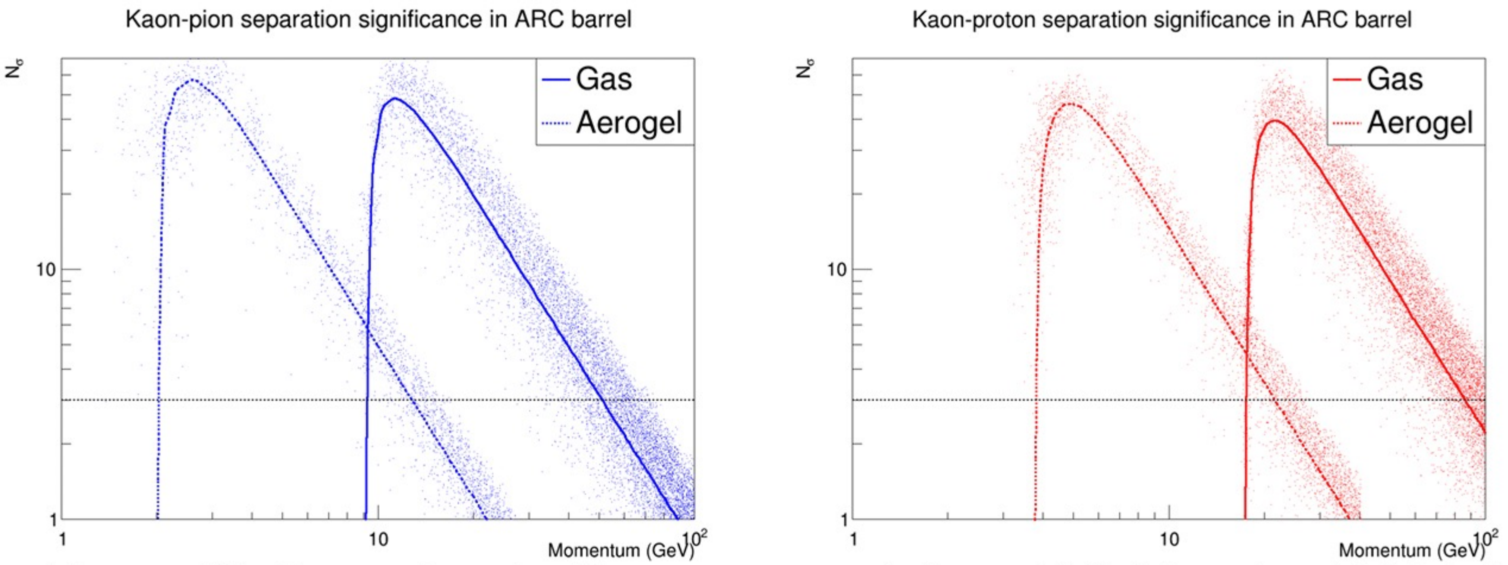


Figure 10: Separation significance per track for π-K (left) and p-K (right)

- Gas (aerogel) provides over 3σ pion-kaon separation in the range 10-50 GeV (2-10 GeV)
  - These plots do not include (small) effects of the magnetic field
- Combined, the aerogel and gas ensure excellent PID performance over the whole range of interest to flavour physics

A single cubic cell with gas, aerogel, cooling plate, vessel walls and mirror has been implemented, and it passed the overlap check!

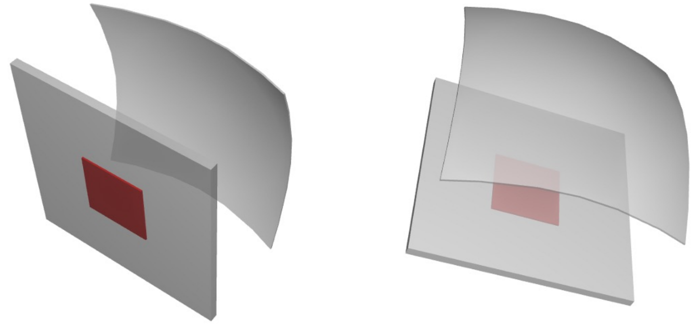


Figure 14: Graphical display of a single cubic ARC cell. Vessel walls and cooling plate have been removed for easier visualisation.

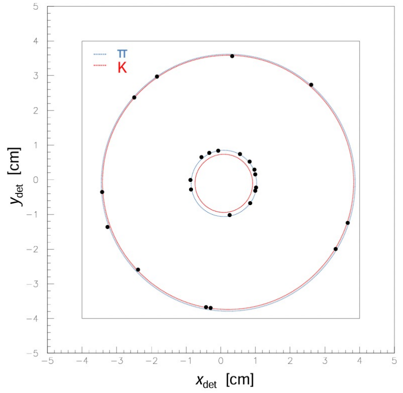
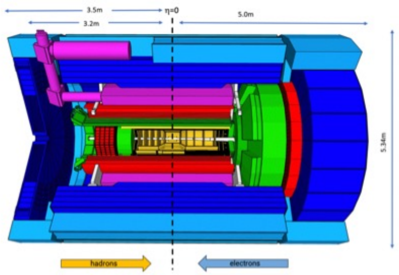


Figure 7: Photon hits on photodetector

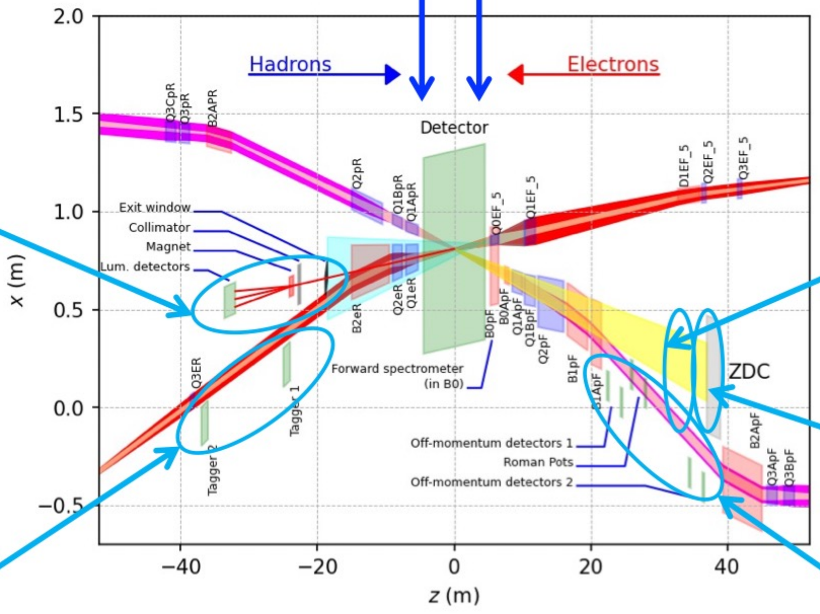
EIC Project Detector



8.5m

Beamline instrumentation is essential to deliver the EIC science programme

In addition, there will be a **UK contribution to the accelerator**: cavity design and cryomodule fabrication for the Energy Recovery Linac that is part of the hadron beam cooler



Luminosity Monitor

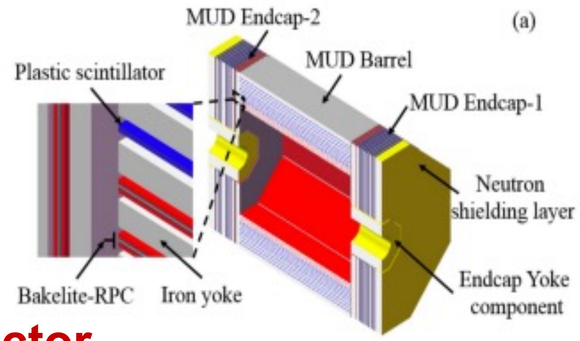
Electron Tagger

Recoil Neutron Polarimeter*
(*potential future upgrade)

Zero Degree Calorimeter

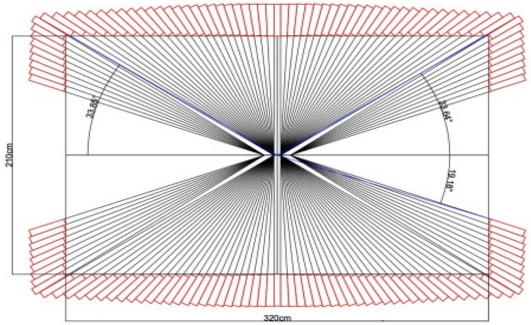
Off-momentum Detectors

Super Tau-Charm Facility (STCF)



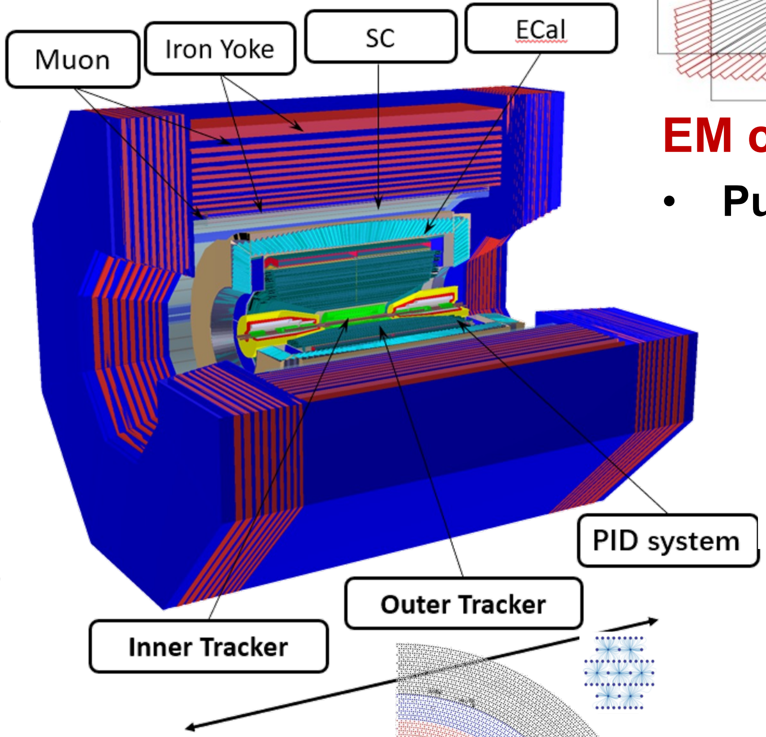
Muon detector

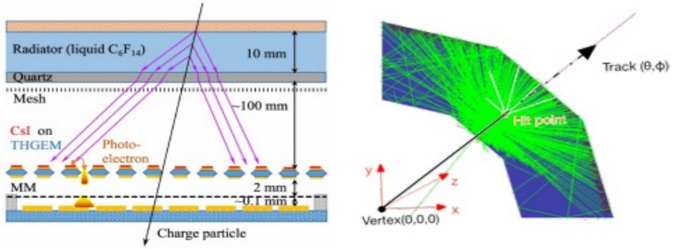
- Bakelite RPC + Scintillator strips



EM calorimeter

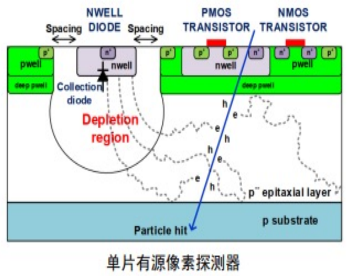
- Pure CsI crystal + APD

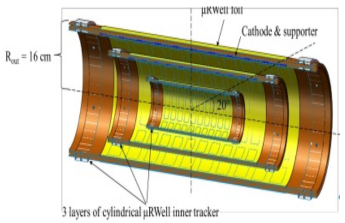




Particle Identification

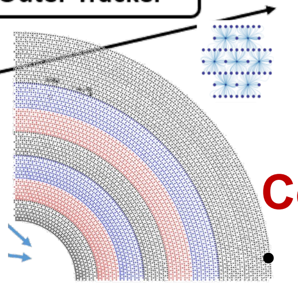
- Barrel : RICH
- EndCap : DIRC-Like TOF





Inner Tracker

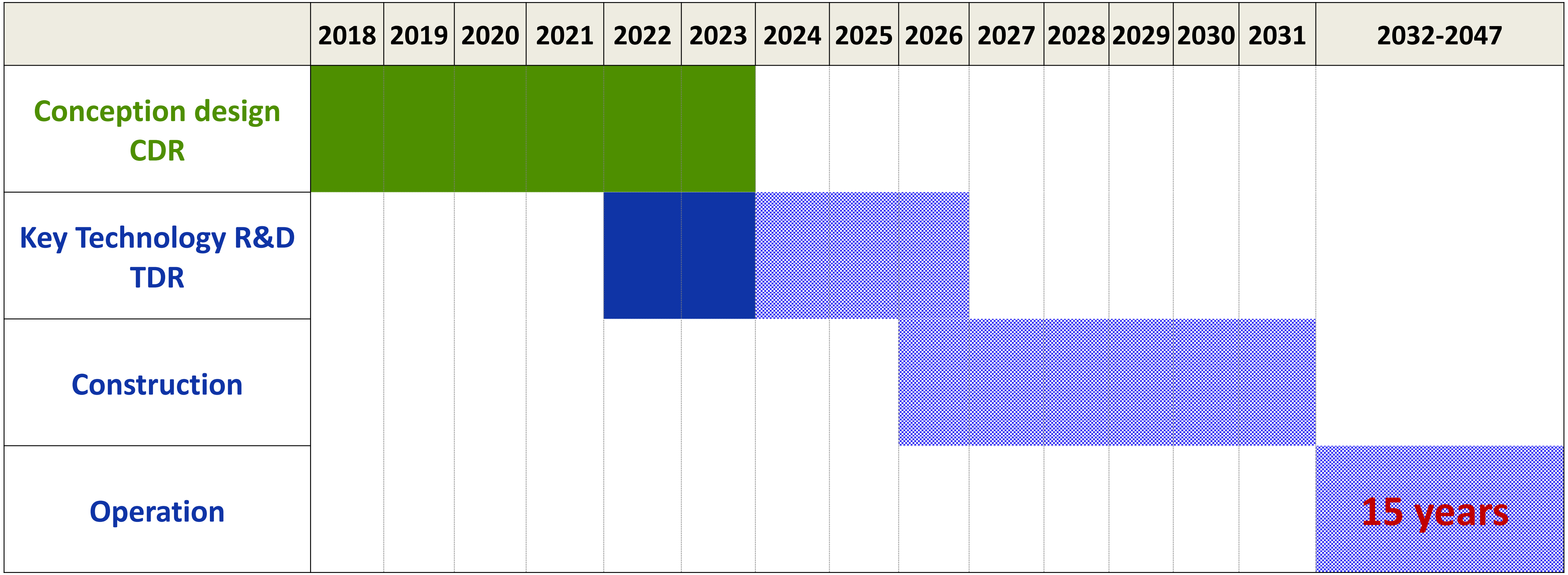
- MPGD: Cylindrical μRWELL
- Silicon : CMOS MAPS



Central Tracker

- Drift Chamber with extreme-low mass and small cell

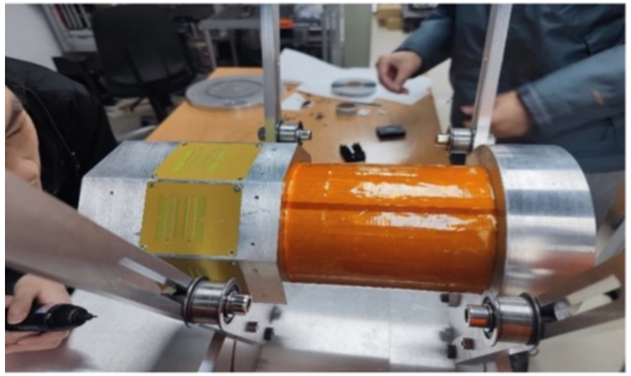
Tentative Implementation Plan of STCF



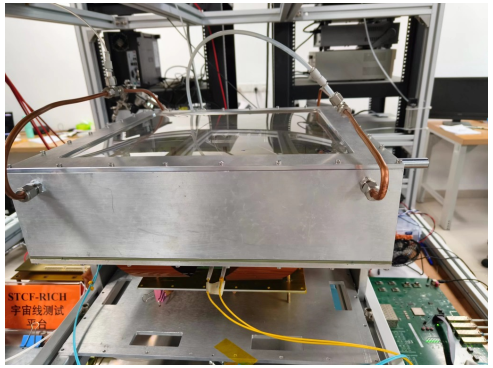
As presented by H.Peng at the STCF workshop held in January 2024

STCF: Progress of Technology R&D

MPDG: μRWELL

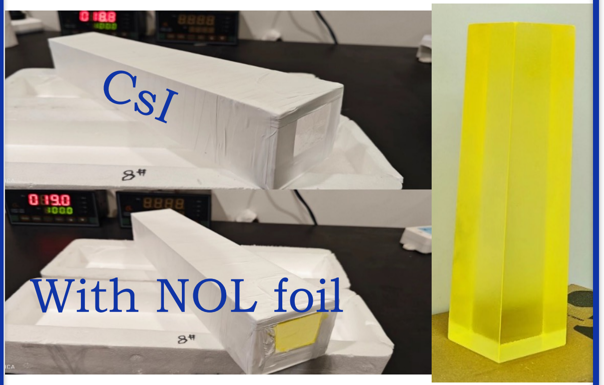


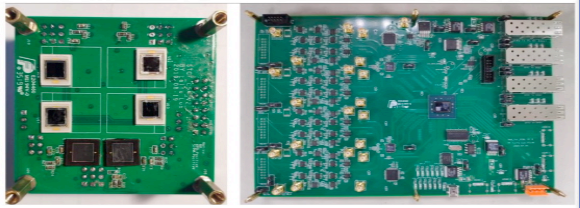
RICH



30*30 cm^2 prototype RICH

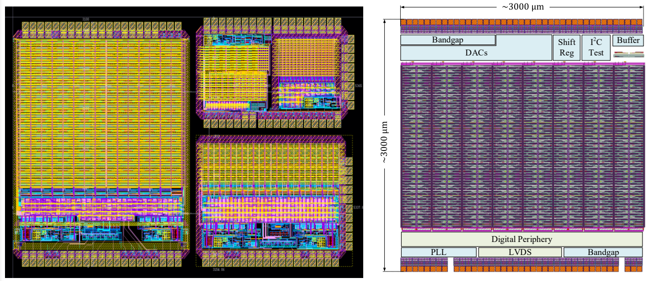
EMCAL





Waveform Digital Electronics
For waveform acquisition and time measurement

Si pixel: time



TowerJazz 180 nm   FCIS 90 nm

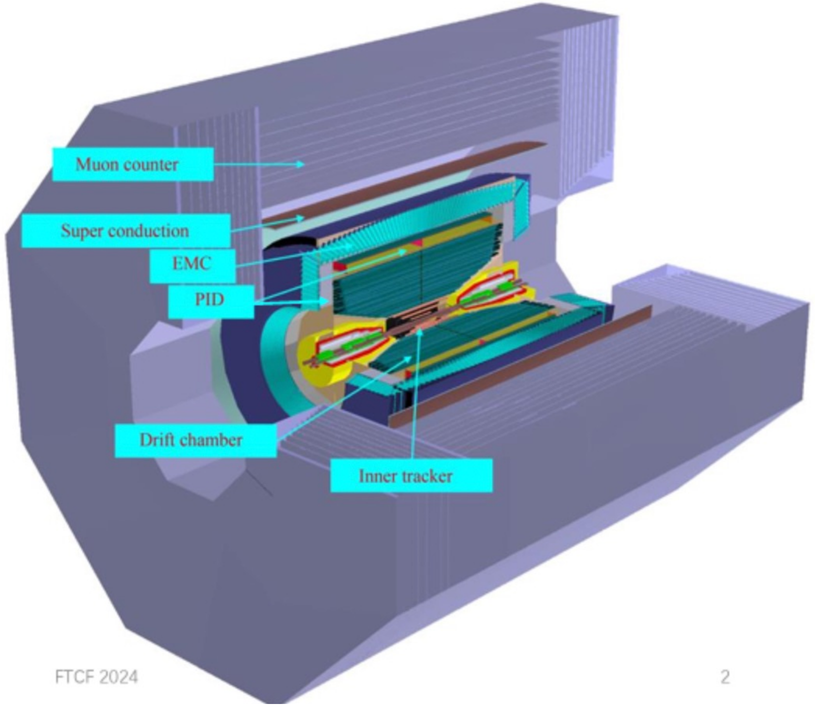
DTOF

Full size prototype DTOF
σ_t< 28 ps (cosmic ray test)

Particle Identification Detectors at STCF

STCF detector

MUD • μ/π suppression power >30 at p < 2 GeV/c
EMC • Energy range: 25 MeV - 3.5 GeV • σ_E/E ~ 2.5% at E = 1 GeV • σ_{pos} ~ 5 mm, σ_T ~ 300 ps at E = 1 GeV
PID • π/K (and K/p) 4σ separation power up to 2 GeV/c
MDC • σ_{pos} = 130 μm • dE/dx ~ 6%, σ_p/p = 0.5% at 1 GeV/c • Efficiency > 99% at p_T > 0.3 GeV/c and >90% at p_T = 0.1 GeV/c
ITK • ~0.25% X_0/layer • σ_{pos} = 100 μm for single hit



Endcap PID detector requirements

- >4σ π/K separation power at p≤2 GeV/c
- Compact structure, thickness<20 cm
- Low material budget (<0.5 X_0)
- High counting rate capability (~150 kHz/cm²)
- High radiation tolerance

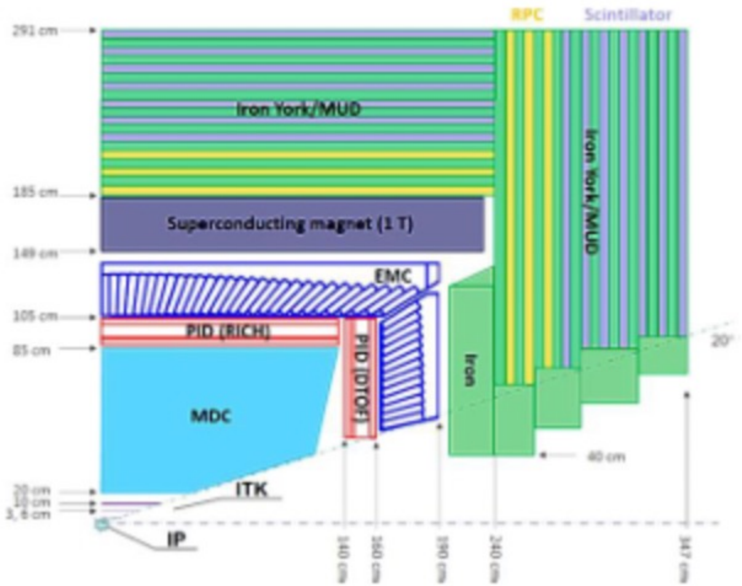
➤ A **TOF detector** based on **detection of internal reflected Cherenkov light** technology (**DIRC-like TOF**) can meet these requirements.

The project plans RICH in the barrel and a **DIRC-like TOF (called the DTOF)** as end-cap PID detector in the forward region. The expected performance of the DTOF detector was simulated, showing its performance met the STCF PID requirements.

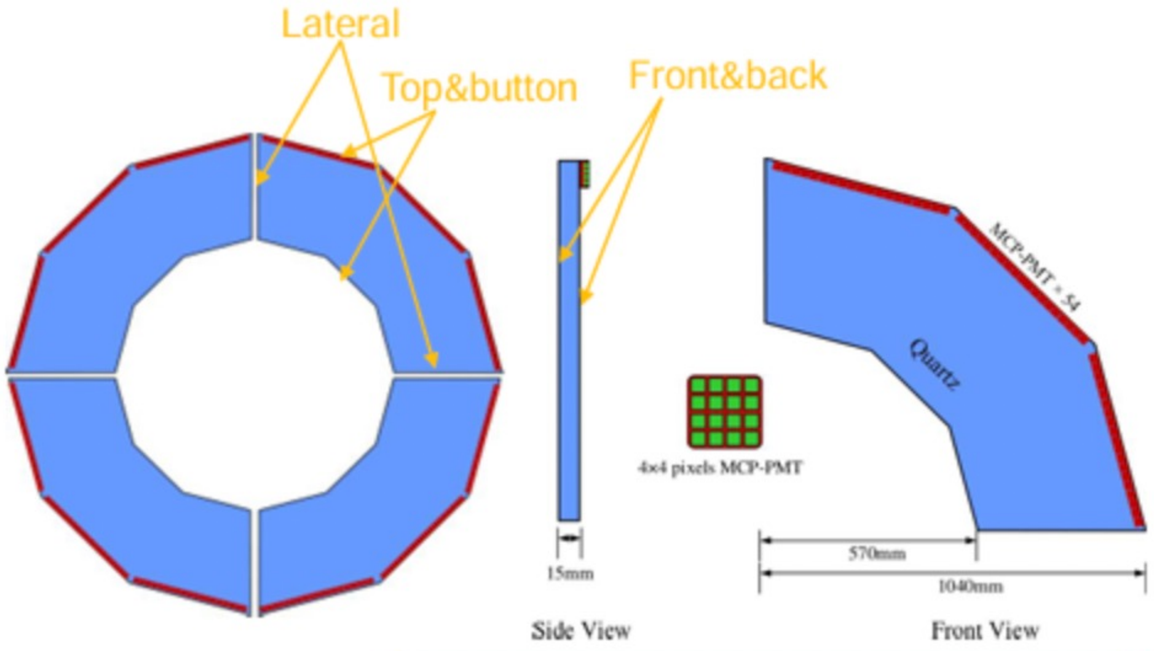
A full-size DTOF prototype was developed and tested using cosmic-ray. **Single track time resolution found to be ~22 ps**

Synergies with UK R&D: ongoing developments including also lifetime extended MCP-PMT, fast ASIC readout, …

DTOF detector



- STCF endcap PID detector
- Polar angle coverage 21°-36°
- Large area fused silica radiator
- Multi-anode MCP-PMT



$$\sigma_{tot}^2 \sim \sigma_{trk}^2 + \sigma_{T_0}^2 + \left(\frac{\sigma_{elec}}{\sqrt{N_{p.e.}}}\right)^2 + \left(\frac{\sigma_{TTS}}{\sqrt{N_{p.e.}}}\right)^2 + \left(\frac{\sigma_{det}}{\sqrt{N_{p.e.}}}\right)^2$$

~40 ps

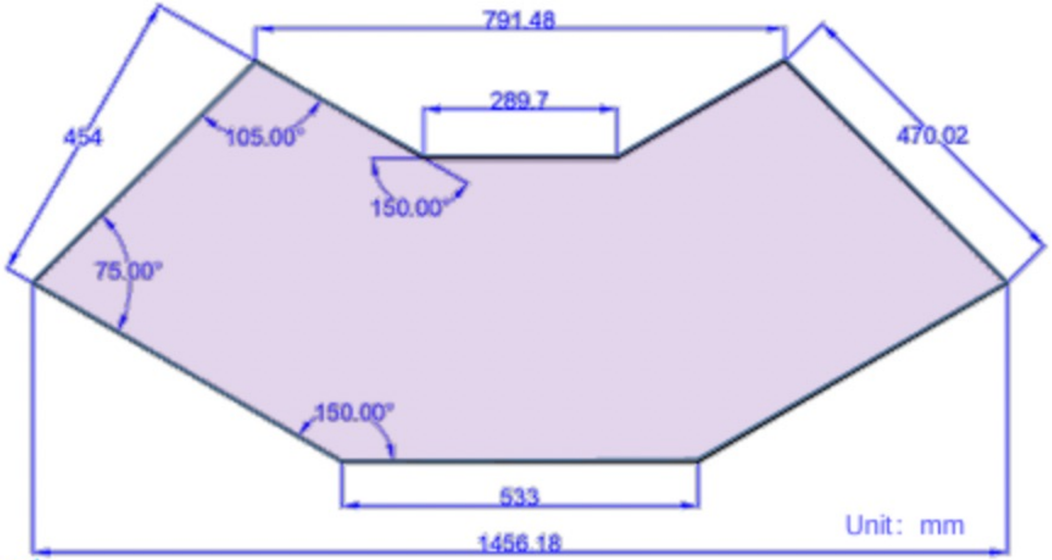
- 4σ π/K separation power at p≤2 GeV/c
  - ➔Total time resolution $\sigma_{tot} < 50$ ps
  - ➔DTOF intrinsic time resolution $\sigma_{DT} < 30$ ps

A full-size DTOF prototype was developed and tested using cosmic-ray. Single track time resolution found to be ~22 ps

Cherenkov radiator

Heraeus Suprasil 312 synthetic fused silica

- High purity, transparency>99%@200 nm
- High radiation tolerance
- Thickness=15 mm, area ≈ 0.56 m^2

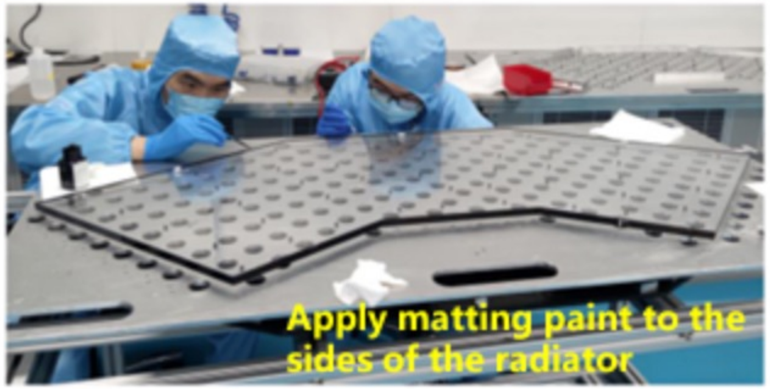


Some requirements

- Front&back surfaces, RMS <1 nm (0.75 nm, ☺)
- Lateral surfaces, RMS <5 nm (not qualified ☹➔absorber)
- Top&button surfaces, absorber
- Thickness=15±0.1 mm, T_{max}-T_{min}<25 μm

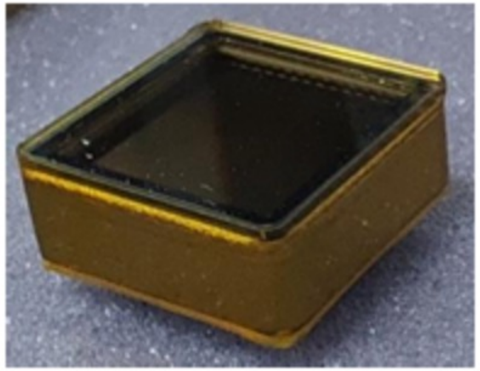
Keep Cerenkov photon direction information

Reduce the misidentification of photon paths



Synergies with UK R&D: ongoing developments including also lifetime extended MCP-PMT, fast ASIC readout, …

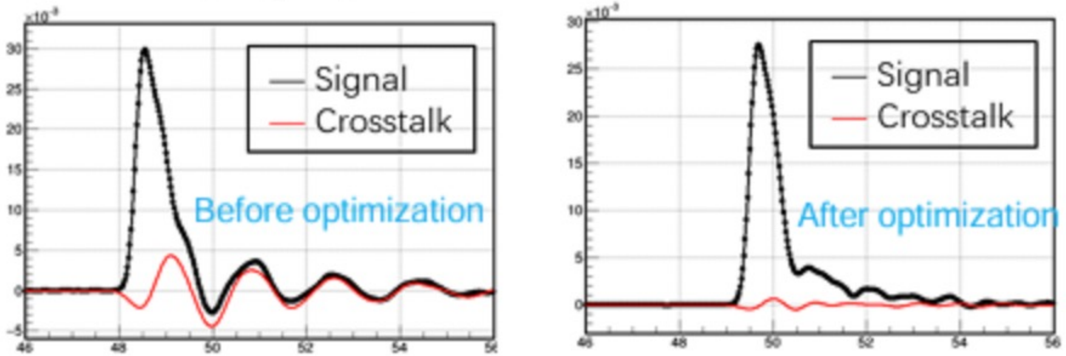
MCP-PMT



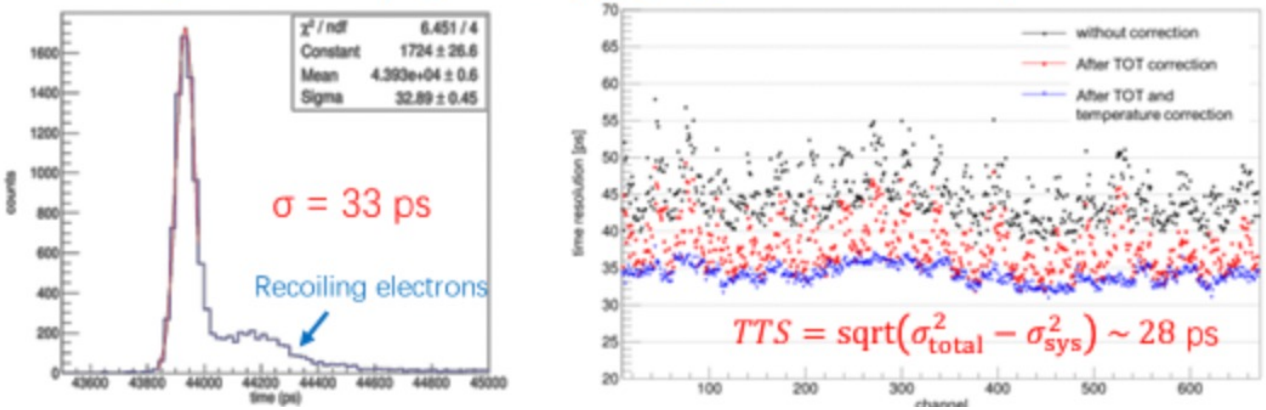
Hamamatsu R10754 MCP-PMT ×42

- Sensitive area, 23×23 mm^2
- Segmentation, 4×4 pixels
- Pixel size, 5.5×5.5 mm^2
- spectral response range, 200-850 nm
- Quantum efficiency, ~25%@λ=400 nm
- Gain: >10^6, uniformity~14% (σ/μ)
- Transit time spread: ~28 ps

➢ **Readout optimization to reduce crosstalk and ringing**
- Optimize PCB routing and ground plane to ensure signal integrity and reduce distributed capacitance
- Separate high-voltage power supply and signal readout
- The decoupling capacitors are distributed around the MCP



➢ **Laser (width=60 ps) test, applying TOT and temperature correction**



Synergies with UK R&D: ongoing developments including lifetime extended MCP-PMT, ASIC readout, …

DRD1 – Main Drivers from the facilities – Muon Systems

Summary of main facilities, the proposed technologies to address the main challenges, and the most stringent conditions expected in muon systems

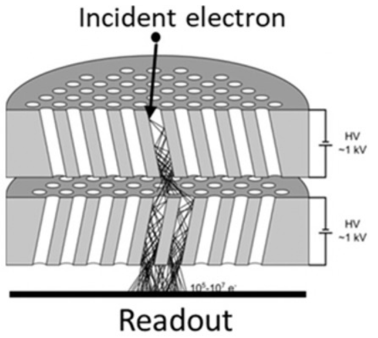
Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm² Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm² (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA):** Max. rate: 10 kHz/cm² Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm²
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm² ($\theta<8^0$) < 2 kHz/cm² (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm²
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR):** Max rate: <500 kHz/cm² Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{13} neq/cm²/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm² Spatial resolution = 50 μm Angular resolution = 70 μrad (η=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

DUNE Phase II

- R&D work ongoing for high pressure gas TPCs for large volume low occupancy neutrino physics scenario
- People actively pursuing readout electronics (generic low occupancy detector readout systems plus benchmarking frontend ASICs for gas detectors), gas mixtures, amplification stages (GEMs, THGEMs etc.)
- We have a UK-led test stand in a beam at Fermilab.

MicroChannel Plate (MCP-PMT)

Operating principle of MCP electron amplifier



DOI: 10.1109/NSS/MIC42677.2020.9507831

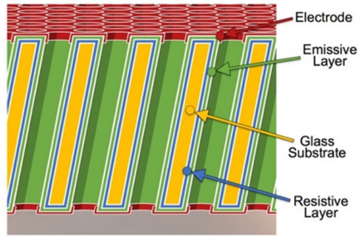
High-speed single photon counting applications (<50ps TTS, <100ps RMS)

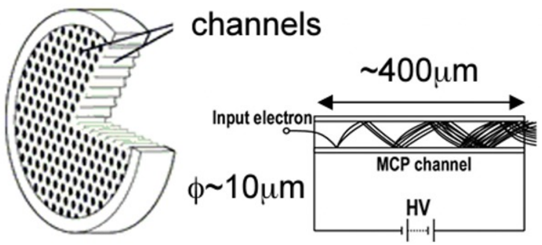
- Similar to PMT → dynode structure replaced by MCP
- MCP is thin glass plate with an array of holes (capillaries) of 3-25μm diameter
- Continuous electron multiplication in thin glass capillaries
- High gain (10^6) even in strong magnetic field (1T)

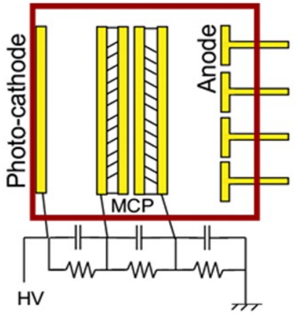
Limitations:

1. Photo Cathode aging (feedback ions)
2. Rate capability (τ=RC)

ALD Coating







Atomic Layer Deposition (ALD) coated MCP

- Ultra-thin films of resistive and emissive layers (MgO, Al_2O_3) applied to glass capillaries
- ALD-coated MCP improved lifetime up to ~10 C/cm² integrated anode charge (IAC)
- Rate capability still marginal (1-10 MHz/cm² depending on PMT size, and MCP resistance)

→ → → PMT sizes range from 1x1/2x2 inch² (Hamamatsu, Photonis, Photek)

Lifetime and Rate Capability

PC aging due to ion feedback is a limitation

- Aging of PC for MCP-PMT → shorter lifetime than dynode PMTs
- Main issue for high intensity experiments is QE degradation
- Lifetime was poor (<200 mC/cm² IAC) until ~12 years ago
- ALD coating of MCP pores → ~100x PC lifetime increase
- **No QE degradation for Photonis MCP-PMT (R2D2) >34 C/cm²**

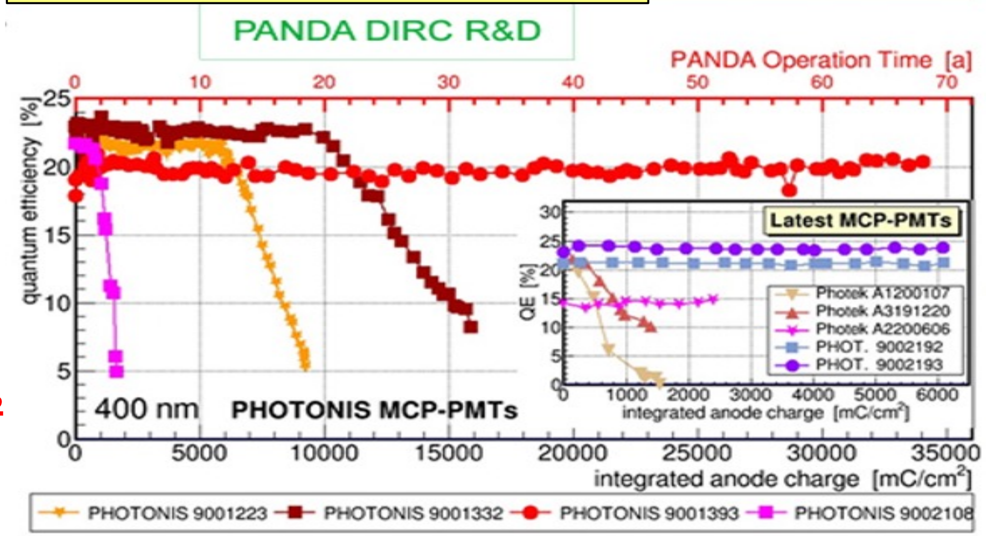
MCP-PMTs Gain decreases at high photon rates (τ = RC)

- 2-inch MCP-PMTs: ~1 MHz/cm² (with 10^6 gain)
- 1-inch Hamamatsu R10754 ≥10 MHz/cm²
- Rate capability depends on MCP resistance
- Up to 20 MHz (for ~25 PE) in low gain operation (NIM A(2022)167330)

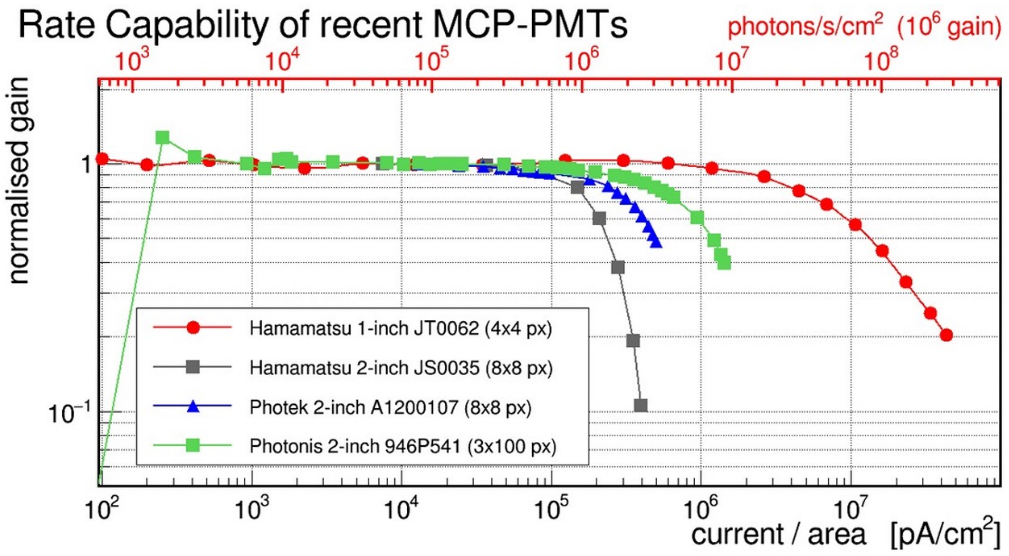
Increasing rate capability in MCP-PMTs

- Lower MCP resistance (ranging at tens of MΩ)
- Lower capacitance
- Low gain operation (for single photon detection)

Photonis & Photek ALD MCP-PMTs



PANDA Tests



Task 4.4.2 - Develop a SiPM array for single-photon detection, with mm-scale pixelation, suitable for use in TOF prototypes

The focus will be on the system aspects of combining

- SiPM arrays with improved radiation hardness and dark count rate, mm-scale pixelation;
- State-of-the-art timing multichannel readout electronics;
- Integrated cooling;

with the overall aim of achieving the best possible time resolution

Deliverables		date*)
D4.4.2	Prototype of array of cooled, mm-scale segmented SiPMs with integrated readout, with report on design and performance	36
Milestones		date*)
M4.4.2	Demonstrate performance for single-photon detection of SiPM arrays with FastIC readout	18

*) date in months after project start

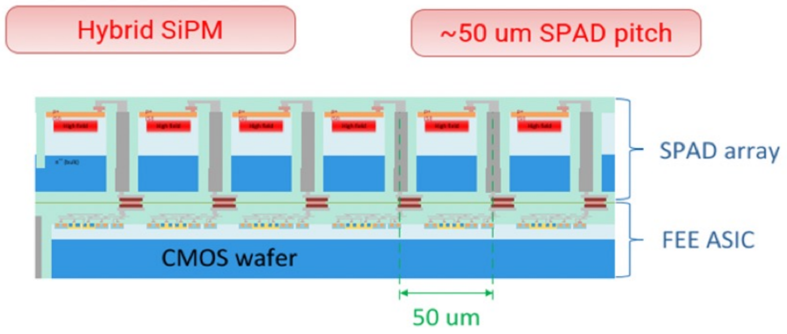
Principal Investigator	Group
Karl Ziemons	Aachen
David Gascon	Barcelona
Eugenio Nappi	Bari
Alberto Gola	FBK
Jon Lapington	Leicester
Christian Morel	Marseille

Task 4.4.2 – R&D Challenges

R/O electronics

Vertical integration to optimize timing resolution by reducing the parasitic inductances and capacitances of the interconnections. Features close to the photosensors (active quenching, single spad control…)

A. Gola (PHOSE23 Workshop): FBK is investigating the potential of microTSVs to achieve single cell connection

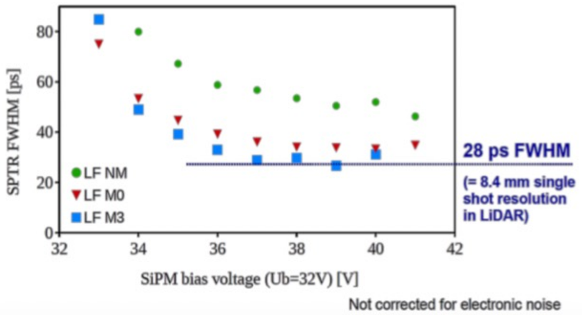


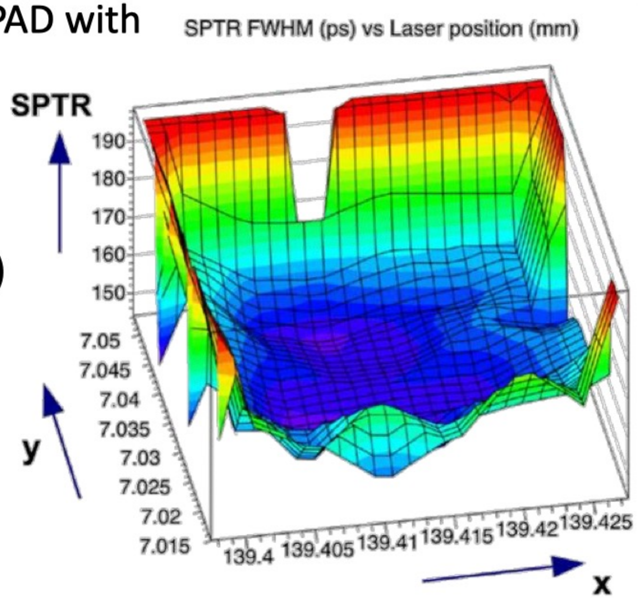
Optimization of SPTR with masking

CHK-HD SiPMs is a variant of the NUV-HD SiPMs built to improve SPTR and detection efficiency

- Masking of outer regions of SPAD: Improve signal peaking and mask areas of SPAD with worse SPTR

A remarkable Single Photon Time Resolution of 28 ps FWHM was measured at Aachen (S. Gundacker)





Microlenses (or metalens-based light concentrators) to enhance radiation hardness

- ❑ Photons are focused on a smaller light-sensitive area within each microcell
- ❑ The silicon area sensitive to radiation damage is reduced
- ❑ The Fill Factor (FF), and thus the PDE of the SiPM microcells, is enhanced

Task 4.4.3 - Develop lightweight mechanical supports for DIRC-type TOF detectors

- Cherenkov radiators typically large, heavy quartz plates.
- Mechanics require high geometrical precision.
- Prototype support developed using lightweight materials.
  - Adjustable and accurate positioning required.
  - Minimize distortion + support quartz, detectors, electronics.
  - Lightweight materials will be investigated.
- Prototype for performance verification.

Deliverables		date*)
D4.4.3	Prototype of a lightweight mechanical support for a DIRC-type TOF detector, with report on design and performance	36
Milestones		date*)
M4.4.3	Report on material choices and mechanical design for a lightweight TOF module	18
	*) date in months after project start	

Principal Investigator	Group
Jochen Schwiening	GSI
Jianbei Liu	Hefei USTC
Guy Wilkinson	Oxford

Task 4.4.3 – R&D Challenges

Mechanical Supports

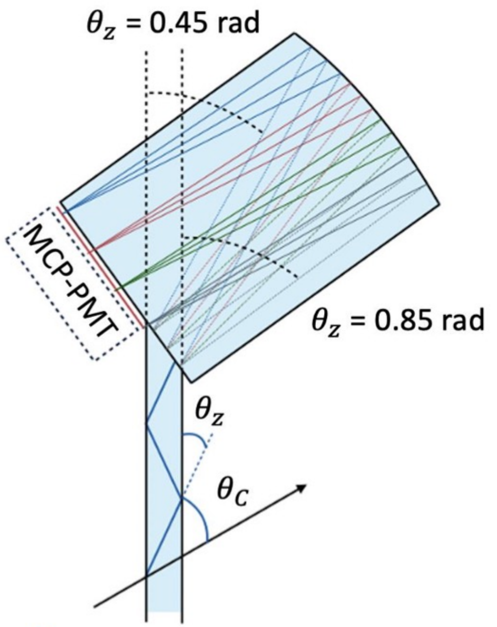
Mechanical supports for large, heavy, fragile Cherenkov radiators

- Typically a set of highly polished quartz plates several tens of square metres in area

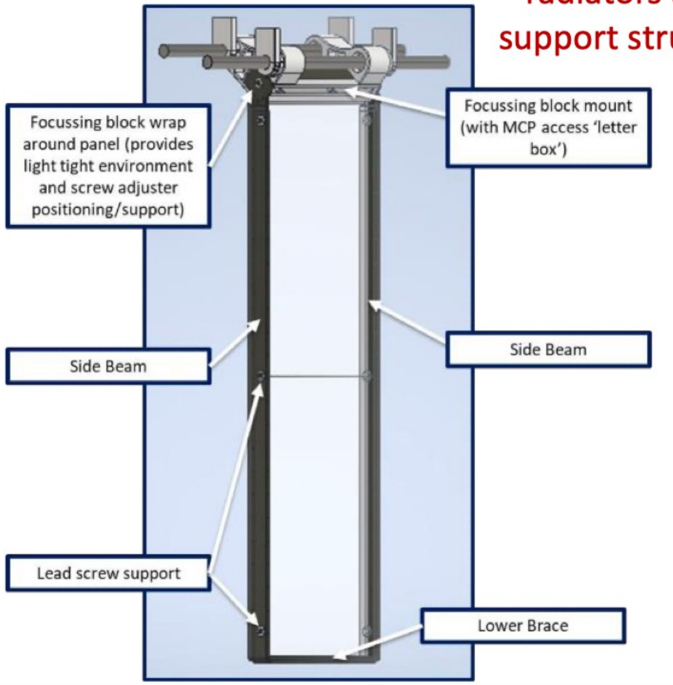
Mechanical supports must be lightweight and minimize

- contact with optical surfaces
- Material in detector acceptance

TORCH prototype optical design



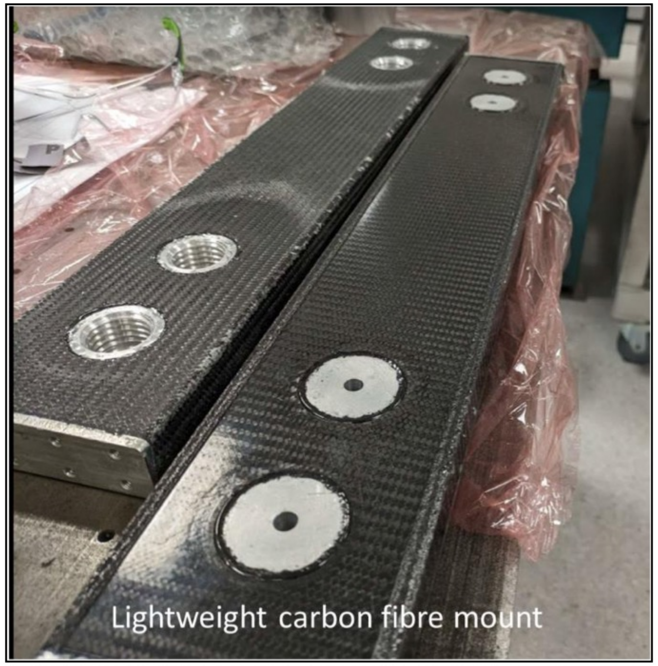
Proposed quartz Cherenkov radiators and lightweight support structure for TORCH



Lightweight materials

Lightweight materials such as carbon-fibre based composites necessary

- Removable handling jigs for installation
- Prototype lightweight mechanical structure developed and verified.



Lightweight carbon fibre mount

Optical Coupling

High precision optical coupling with other optical components to the detectors

- Optical components require adjustable and highly accurate positioning

Supports must keep geometrical distortion to a minimum while supporting:

- Large overall weight of the quartz
- Services such as detectors and electronics

Task 4.4.4 - Develop techniques for measuring the optical properties of optical components for TOF detectors

- Characterization of the quartz Cherenkov radiators.
  - Radiator optical specification is demanding.
  - Challenging to manufacture and difficult to measure.

- Facilities already exist within the project partners.
  - These will be available for task collaborators.

- Precision measurement will be further developed.

Deliverables		date*)
D4.4.4	Completion of commissioning of an optical laboratory for characterizing the performance of a DIRC-style quartz radiator plate	36
Milestones		date*)
M4.4.4	Report on progress in setting up optical laboratory for characterizing TOF radiator	18
*) date in months after project start		

Principal Investigator	Group
Jianbei Liu	Hefei USTC
Jochen Schwiening	GSI
Suat Ozkorucuklu	Istanbul
Guy Wilkinson	Oxford
Mauro Piccini	Perugia INFN
Amur Margaryan	Yerevan

Task 4.4.4 – R&D Challenges

Characterization of Cherenkov radiators

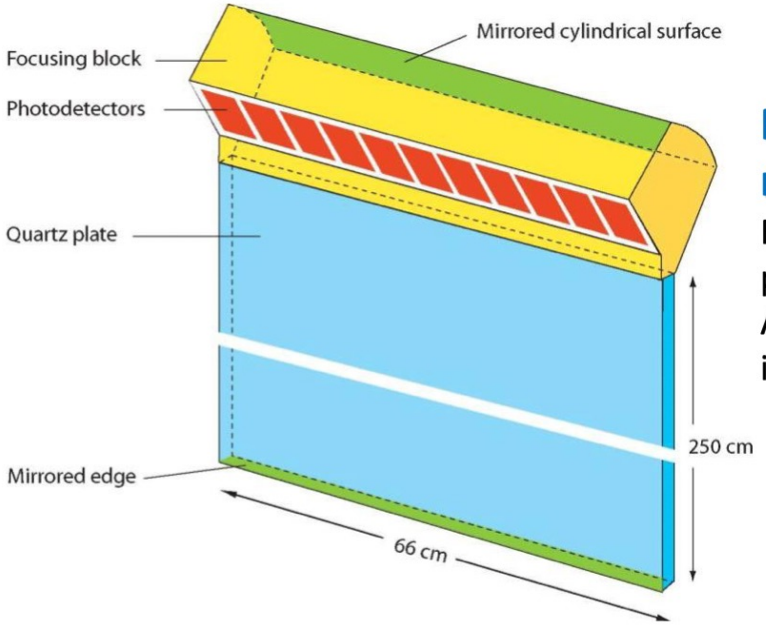
Techniques for characterization of the quartz Cherenkov radiators

Techniques for coupling of optical components

Radiator requirements include:

- Very high level of polish → very low surface roughness
- High degree planarity
- Difficult to achieve and to accurately measure with the required precision

TORCH prototype optical design

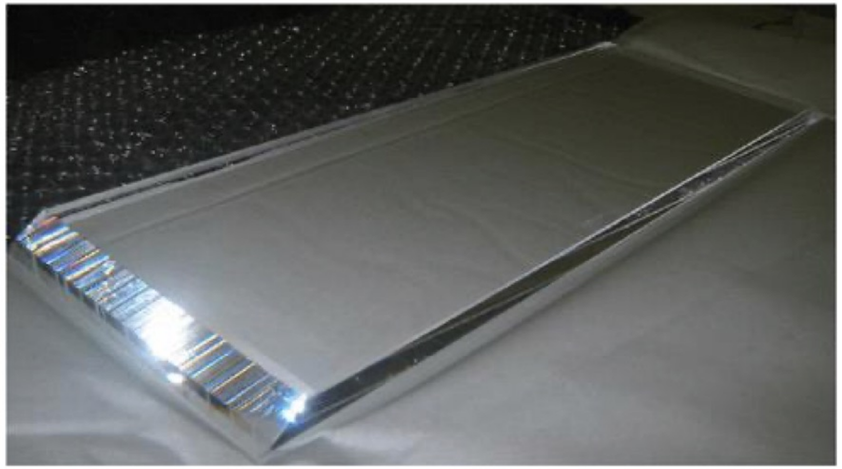


Further precision measurements

Further develop techniques for higher precision.

Additional measured parameters will include:

- Planarity, optical transmission, scattering, defect size and density, radiation darkening



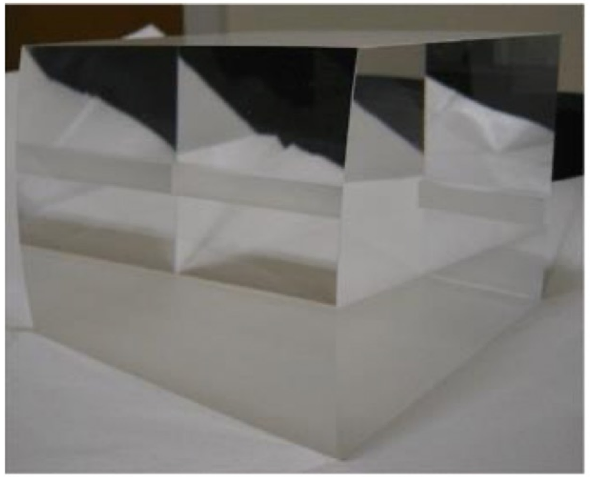
Bevelled quartz radiator plate

Existing Facilities

Facilities already exist within the project partners

- Existing temperature-stabilized optical lab
- Polarized laser beams with six different wavelengths
- → coefficient of total internal reflection, bulk attenuation of TOF/DIRC bars or plates

Available on request to collaborators within Task 4.4.4



Quartz focusing block

Granularity and segmentation

- FBK proposing segmented large area SiPMs as next stage
  - Strip SiPMs

"SPTR and CRT performance is degraded when reading out SiPMs with large areas.

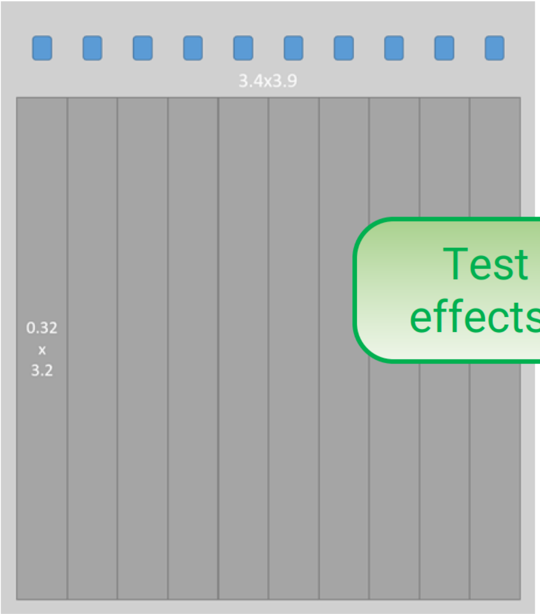
A possible solution can be the segmentation of the active area into small pixels"

"The goal for FBK is upgrading … by developing TSVs, micro-TSV and Backside Illuminated SiPMs"

"This will allow high-density interconnections to the front-end and high-segmentation"

Strip SiPMs

10 strips
0.32 x 3.2 mm²
each, no dead border between strips



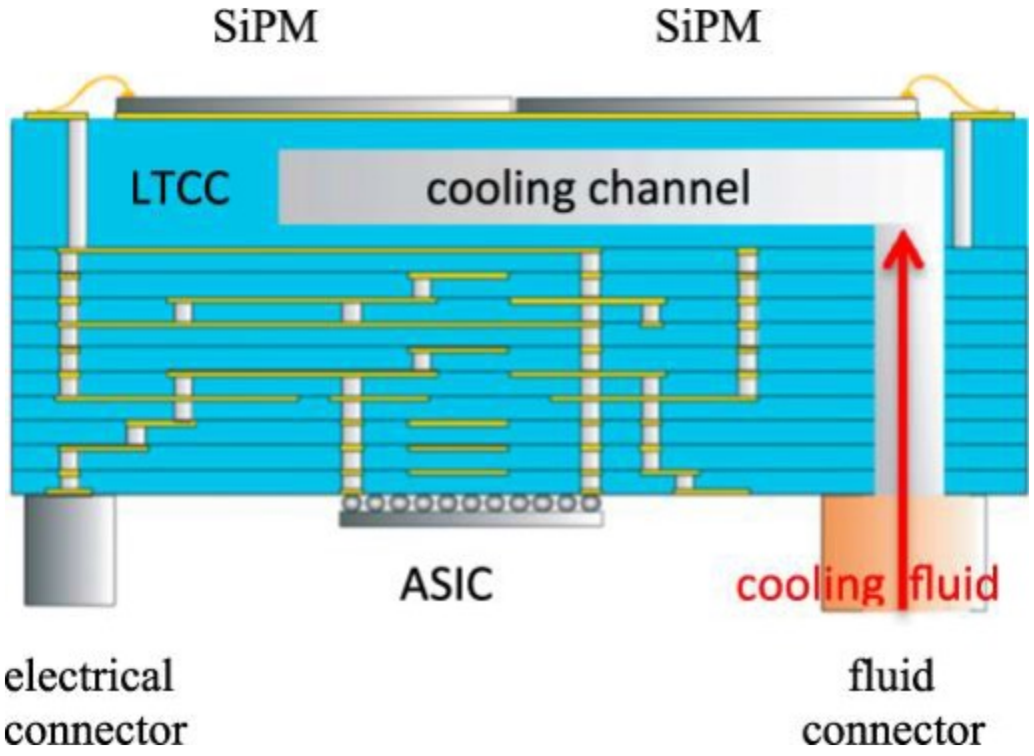
Test vehicle to study effects of segmentation

Example of segmented SiPM layout: a 3x3 mm2 active area is divided in 10 0.3x3 mm2 strip-SiPMs.

Alberto Gola - Status and perspectives of SiPMs at FBK – CERN 2023

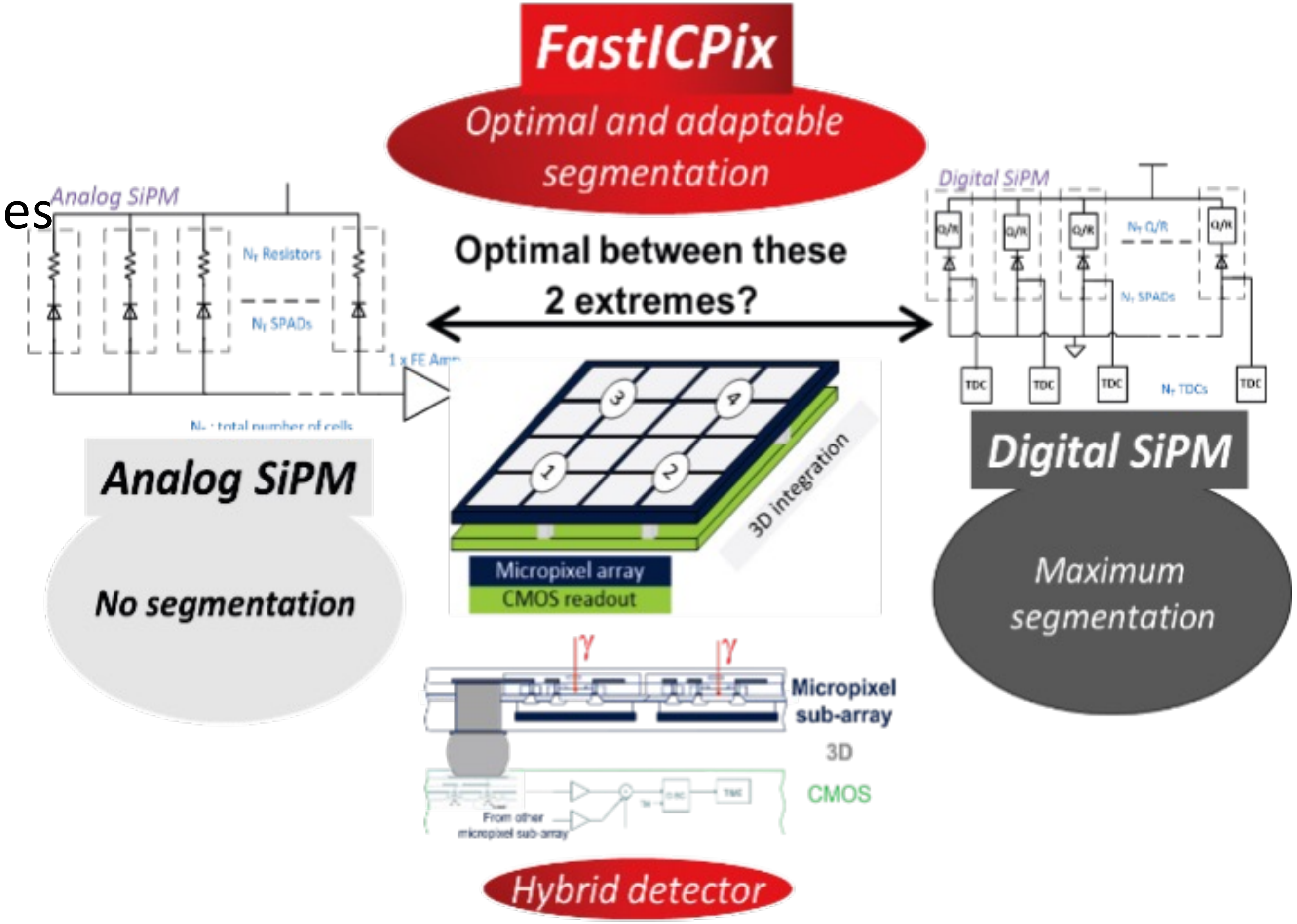
Power dissipation and cooling

- Rate or lifetime not an issue for SiPM
  - Power dissipation and cooling likely required
  - Energy dissipated per event = $\frac{C_{cell}}{2}\left(V_{op}^2 - V_{ov}^2\right)$
  - 600 Mevent/s ≈ 21 mW/cm^2
- FBK have made interesting developments in cooling technology
  - 2.5D integration allows micro cooling channels integrated inside a passive interposer



Electronics compatibility

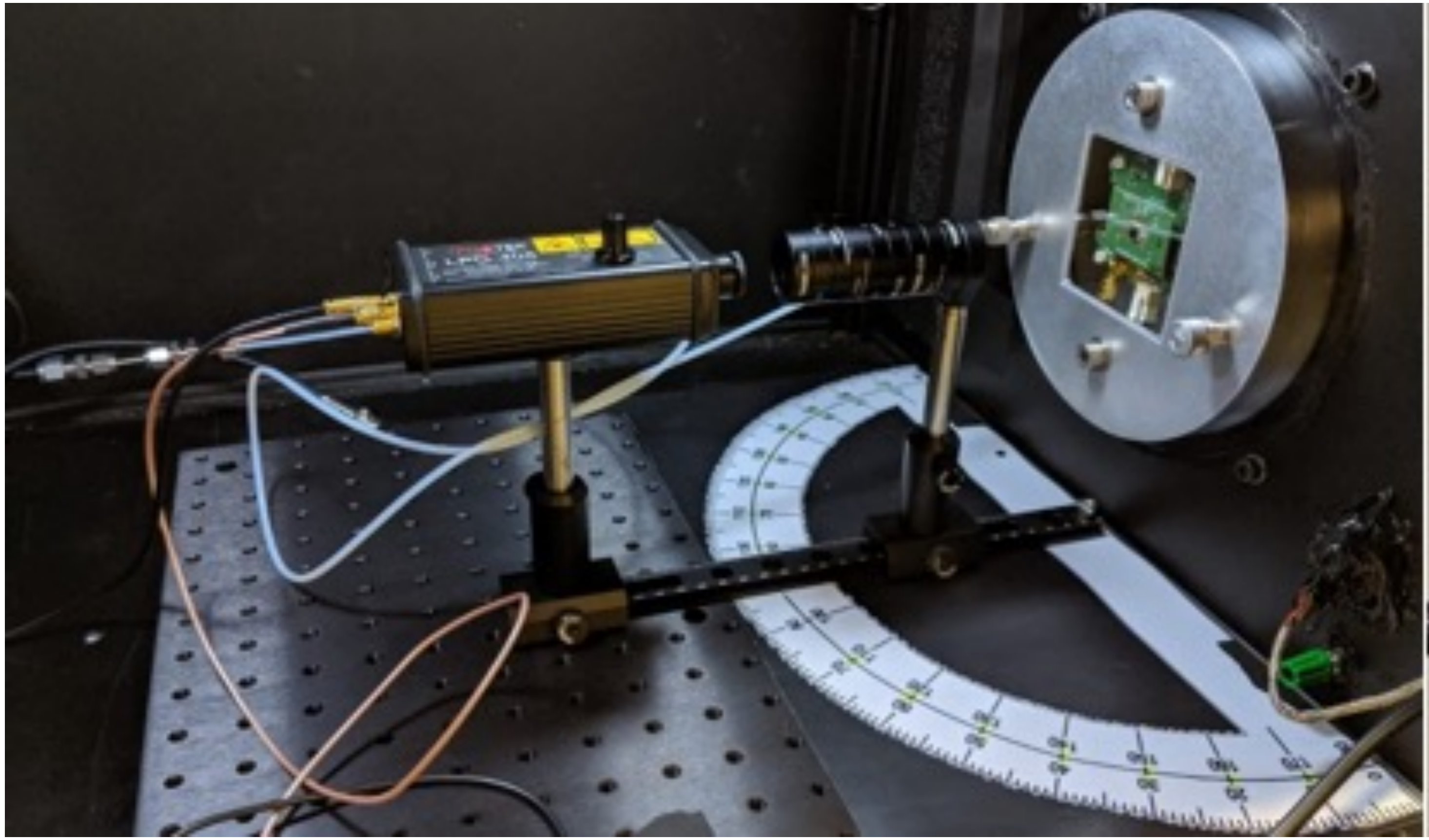
- FastIC family of electronics designed for SiPMs
- FastIC developments from the have already superseded previous technologies e.g. NINO
- Future FastIC developments include FastICpix:
    - Aim to exploit optimal segmentation of SiPM
    - Optimization for a given power budget
    - Investigation of new circuit topologies
    - 3D integration
- FastICpix aim:
    - Optimal and adaptable segmentation
    - Using a hybrid detector



David Gascon, ICCUB, Barcelona

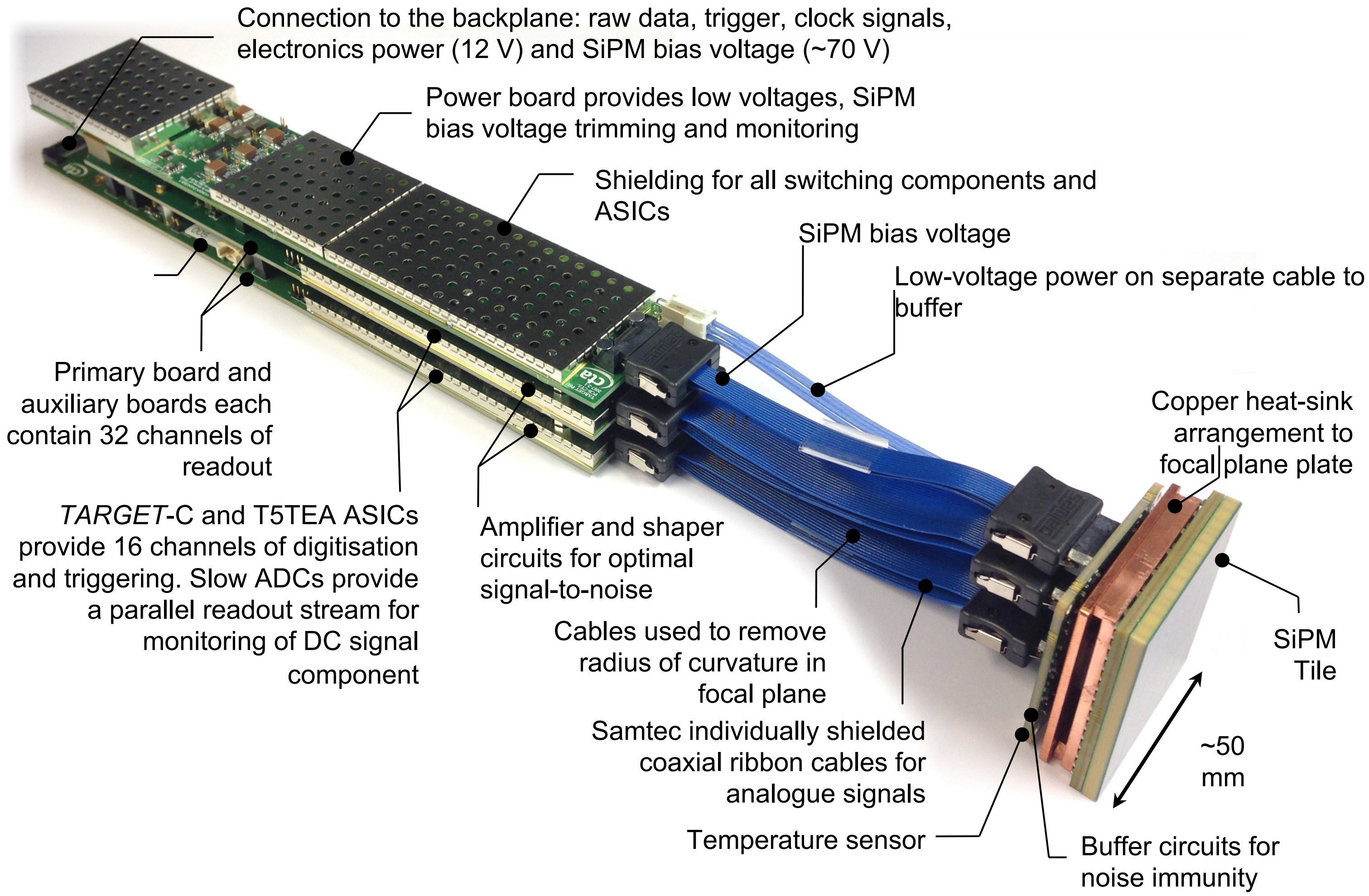
Temperature controlled dark box

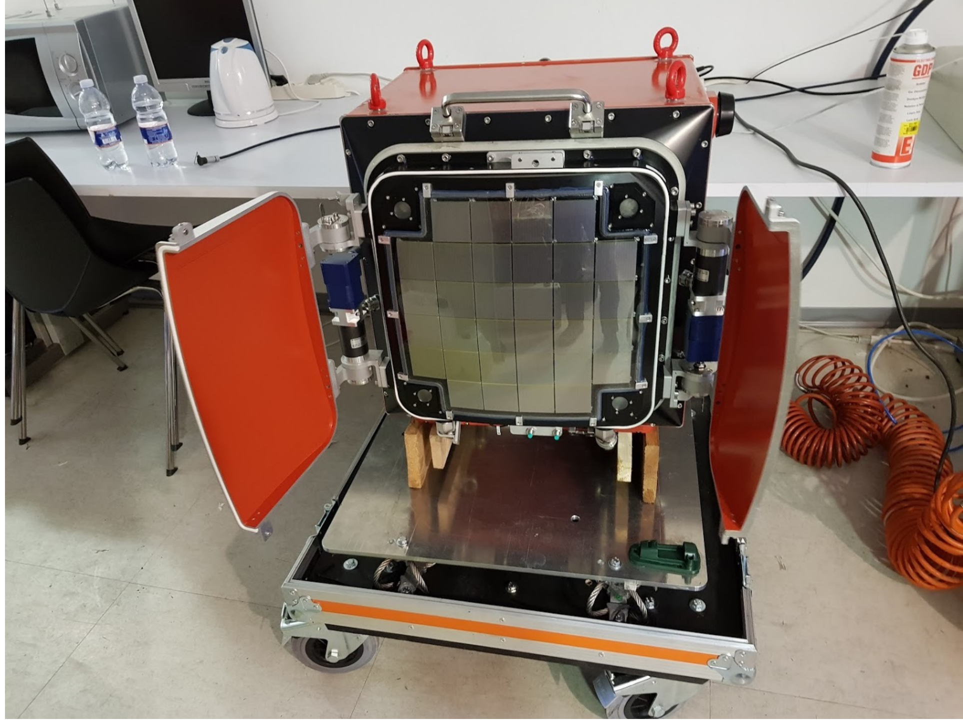
SiPM testing from -20 °C to +40 °C

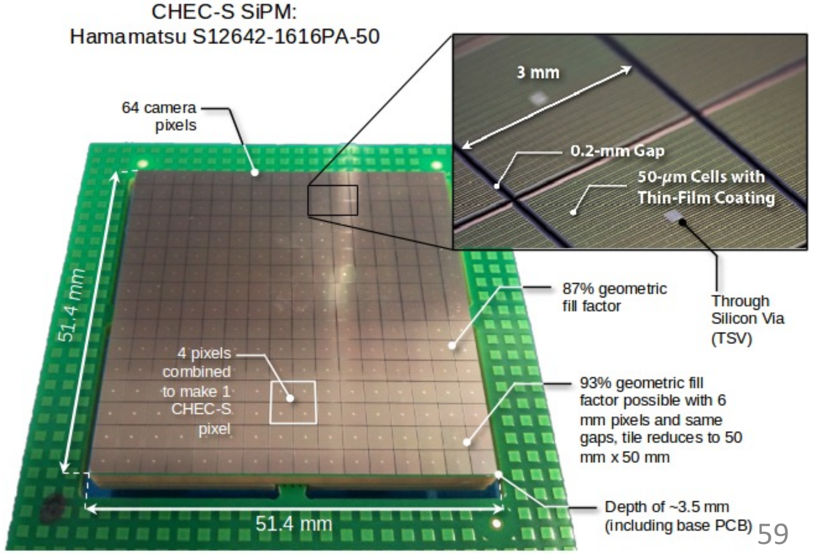


SiPMs for CTA SST Camera

Pixellated SiPM tile - TARGET ASIC waveform capture







ASIC FEE experience – NINO32 design

Pixellated MCP detector using NINO + HPTDC – forerunner to TORCH prototype