Single-Photon Detectors for Particle Identification in High-Energy Physics Experiments

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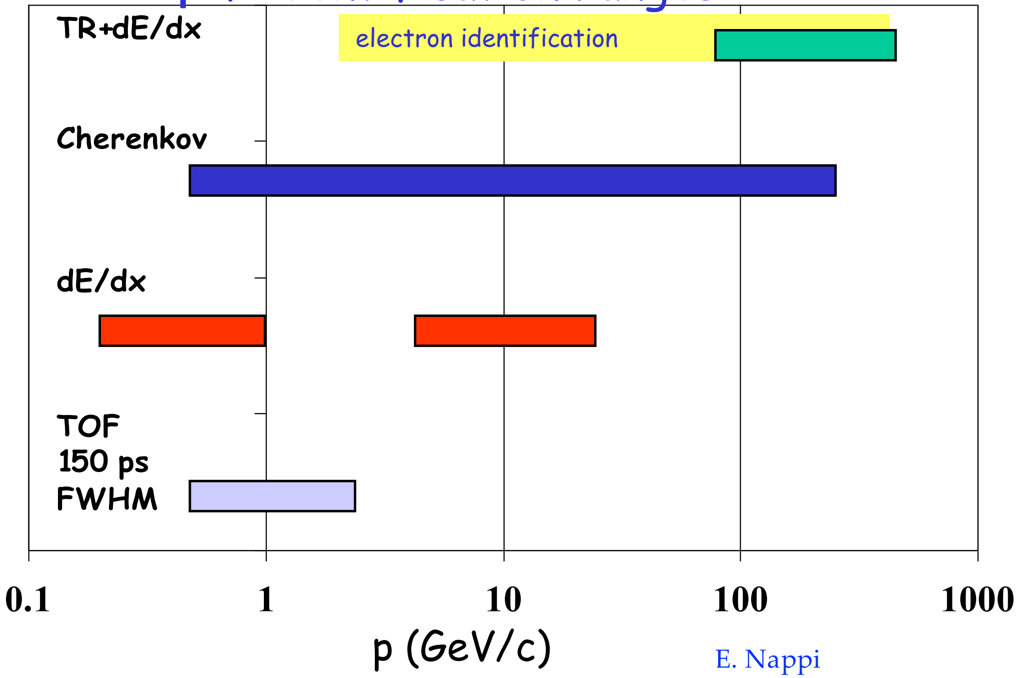
Particle Identification (PID) in HEP

- PID in HEP experiments is of great importance
  - PID techniques based particles detection via their interaction with matter: ionization and excitation (Cherenkov & Transition Radiation)
  - In addition to momentum measurement (magnetic spectrometer), we need other information (e.g. velocity, etc.) to determine PID
- Applicable methods strongly depend on particle momentum (velocity)

p-K identification ranges



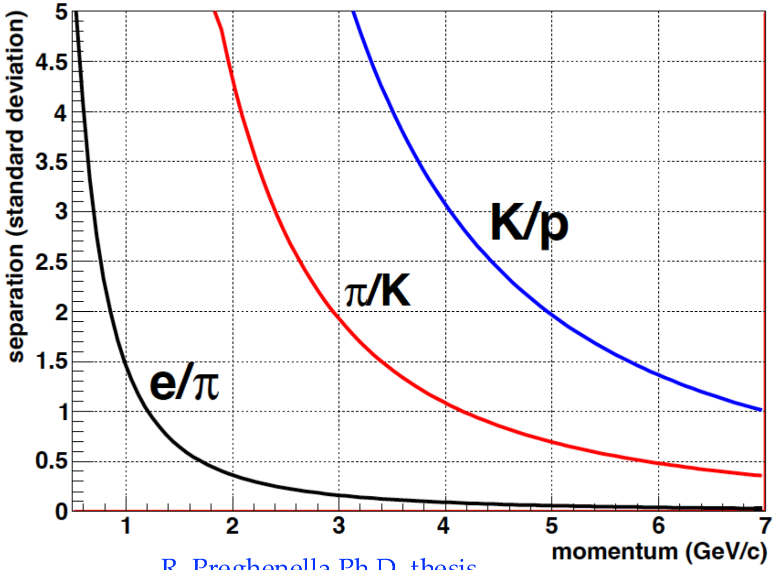
E. Nappi

Time-of-Flight (ToF) detectors

- Extract the velocity from time difference Δt for two particles of known momentum p between the signals of two (usually scintillation or gas) counters at a known distance L

$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left[\sqrt{1+\frac{m_1^2c^2}{p^2}} - \sqrt{1+\frac{m_2^2c^2}{p^2}}\right]$$

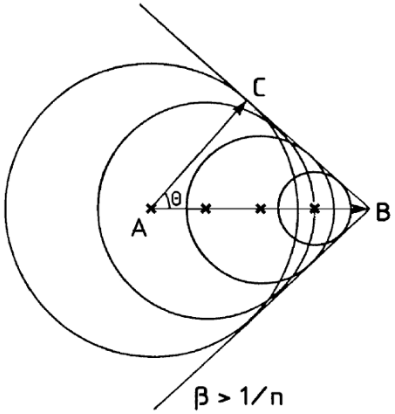
  - With ~100 ps resolution and $L \approx 10$ m, K/π separation up to few GeV/c
  - High particle rates/multiplicities create ambiguities
- Examples: ALICE (MRPC), TORCH project (Cherenkov)



R. Preghenella Ph.D. thesis

Cherenkov radiation

- Generated by charged particle traversing dielectric medium with speed greater than the local phase speed of light
  - Above threshold, a coherent wavefront formed with conical shaped at well-defined angle that depends on index of refraction *n* and particle speed *β*

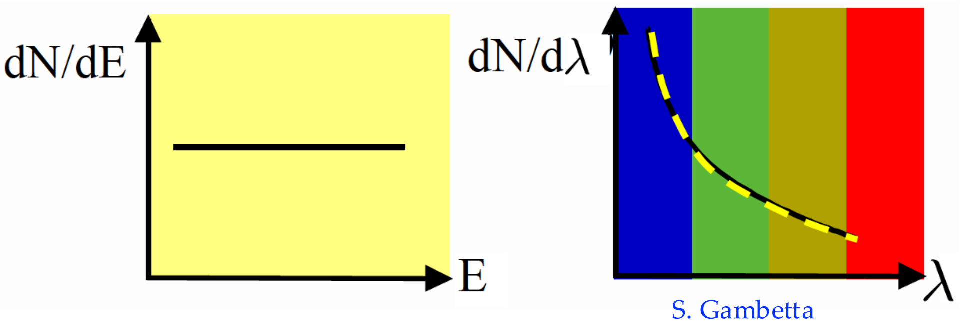


$$\cos\theta_c = (1/n\beta)$$

- Number of photons produced per unit path length per unit energy/wavelength interval of the photon

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$
$$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV^{-1}cm^{-1}} \qquad (z = 1)$$

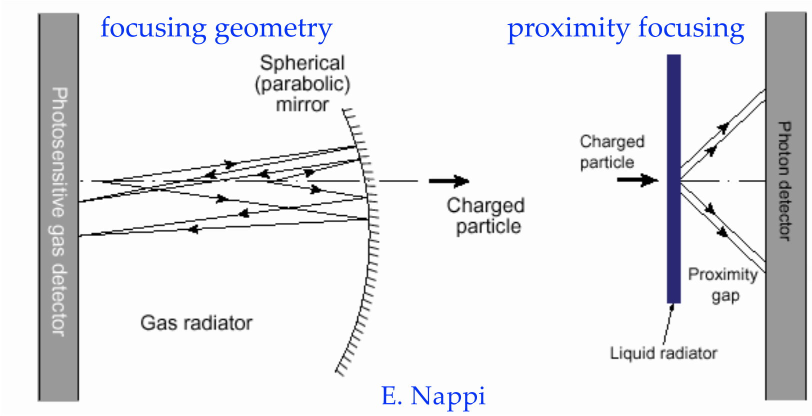
$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$



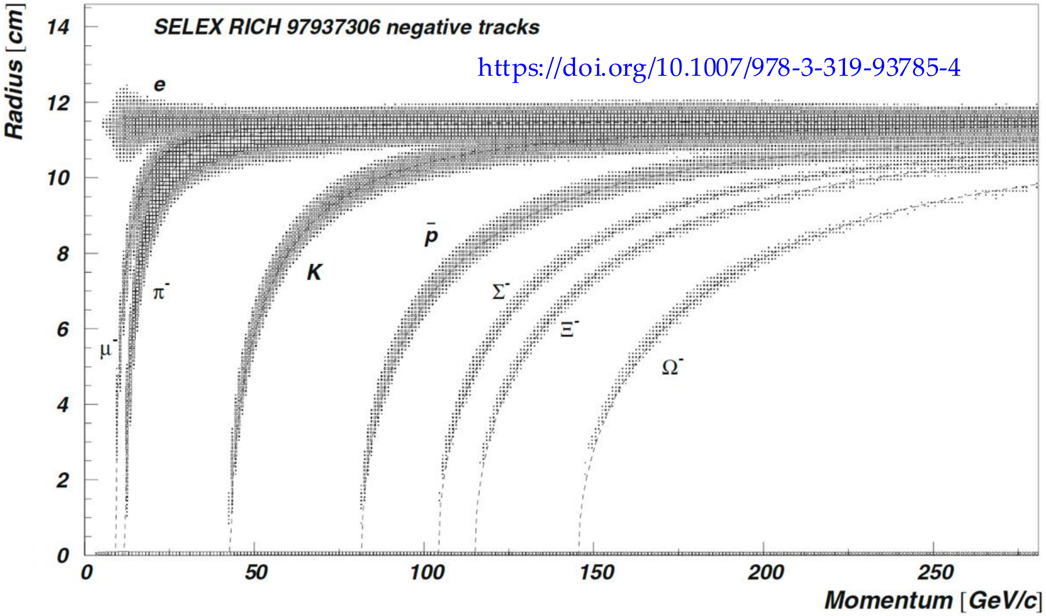
S. Gambetta

Detecting Cherenkov radiation

- Threshold or Ring Imaging Cherenkov (RICH) detectors
  - RICH: measure Cherenkov angle (extract speed β knowing n), combine with momentum p to determine particle mass (PID)
- Very small number of generated Cherenkov photons
  - Example: energy loss of a β~1 electron in 1 cm of water (n=1.33) as visible photons (λ: 400-700 nm) is ~500 eV (~200 photons)
    - Compare with ~2 MeV ionization loss
  - Need to detect maximum number of photons with best possible angular resolution



E. Nappi



https://doi.org/10.1007/978-3-319-93785-4

Photodetector requirements for PID

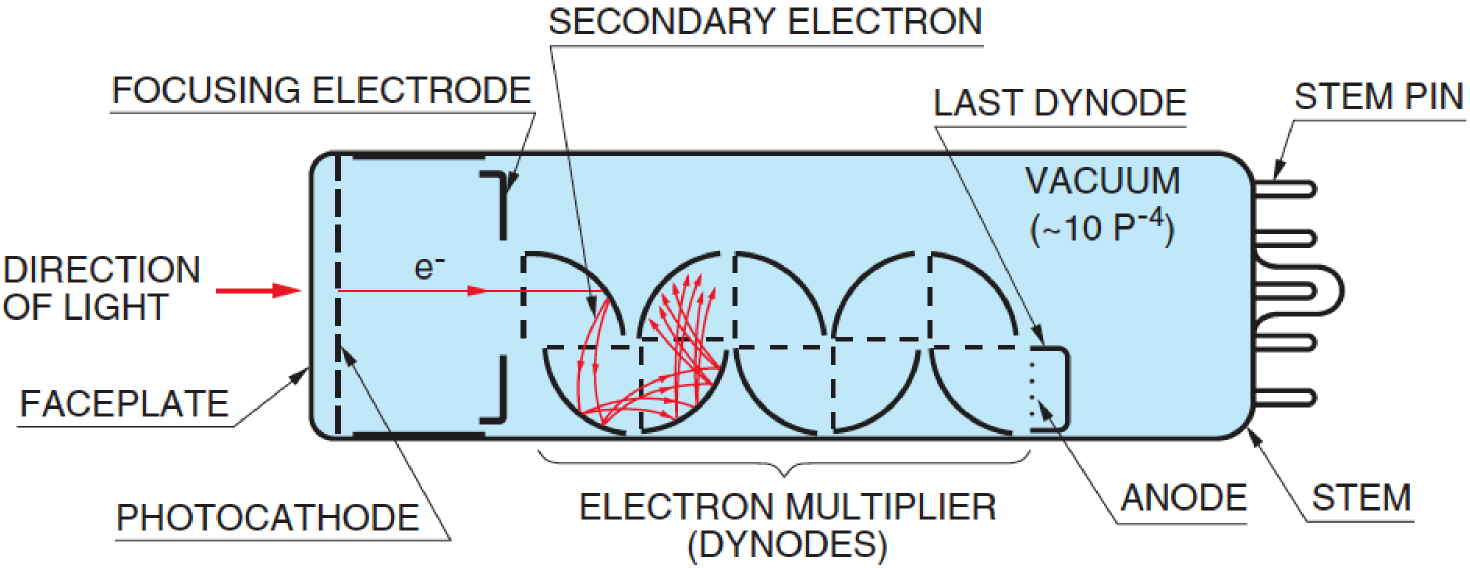
- Main requirements for PID detection system
  - Single photon sensitivity
  - High photon detection efficiency (PDE)
    - Quantum efficiency: probability that incident photon generates a photoelectron
    - Collection efficiency: probability that photoelectron starts electron multiplication
  - Low dark count rate or dark current
  - Large area coverage, with high active-area fraction
  - High granularity
  - High-rate capability
  - Timing resolution
  - Reliability and long-term ageing resistance (including radiation hardness)
  - “Affordable” procurement and operating costs
- Detection of photons proceeds in three steps:
  - Incident photons generates primary photoelectron or electron-hole (e-h) pair via the photoelectric/photoconductive effect
  - Number of electrons increased to a detectable level by charge multiplication
  - Secondary electrons produce electric signal

Vacuum-based photon detectors

- Photocathode and electron multiplication stage are in vacuum
  - Typ. enclosed in vessel made of glass, ceramics, metal
- Essentially three types of detectors:
  - Photomultiplier tubes (PMTs)
  - Microchannel plate photomultiplier tubes (MCP-PMTs)
  - Hybrid photodetectors (HPDs)
- Vacuum-based photon detectors are still the primary choice of technology for many applications even 90 years after their invention
  - Their relatively high gain, large area and excellent intrinsic time resolution make PMT, MCP-PMT and HPD the most suitable detectors to equip most Cherenkov-based and ToF detectors used in PID

PhotoMultiplier Tubes (PMTs)

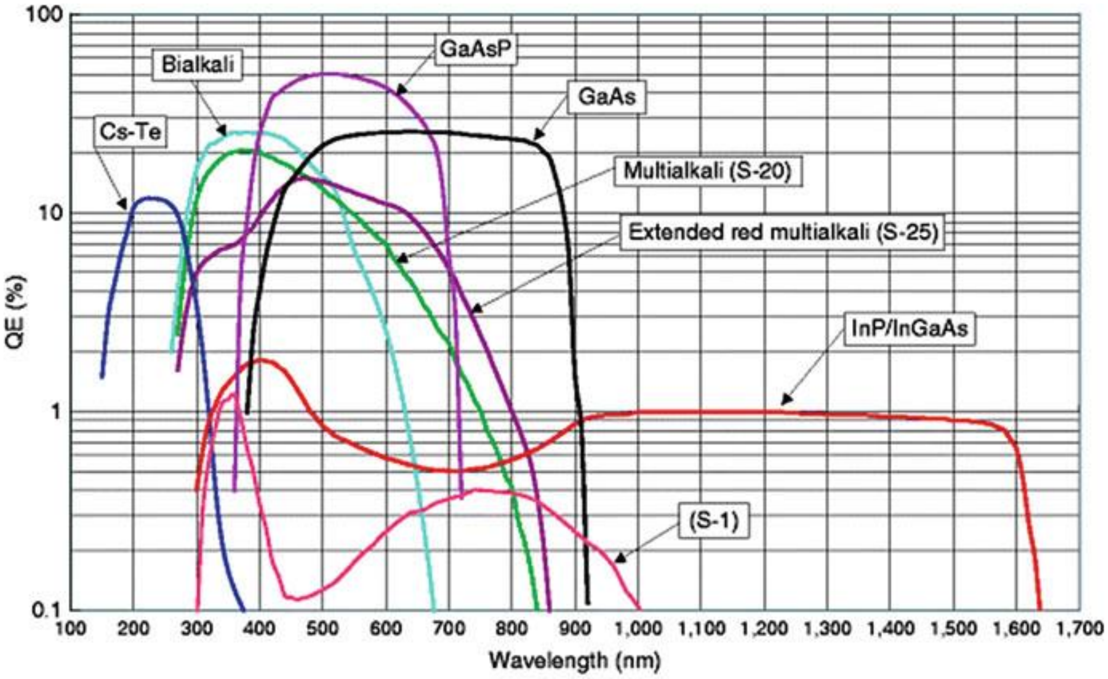
- PMTs have been the most common photodetector in HEP experiments and medical imaging up to recent years
  - Large sensitive area
  - Fast response and timing performance
  - High gain and low noise
- High magnetic fields affect electron trajectories



Hamamatsu Handbook

Wavelength sensitivity

- Sensitive wavelength range determined by photocathode material
  - Usually Cs- and Sb-based compounds such as CsI, CsTe, bialkali (SbRbCs, SbKCs), multialkali (SbNa2KCs), as well as GaAs(Cs), GaAsP, etc.
- Low-wavelength cutoff determined by window material
  - Usually, borosilicate glass for IR to near-UV; fused quartz and sapphire (Al2O3) for UV; MgF2 or LiF for XUV



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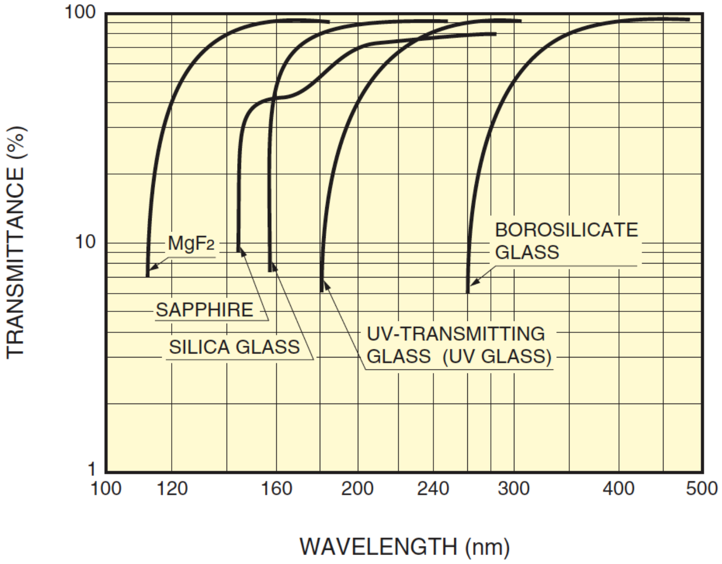
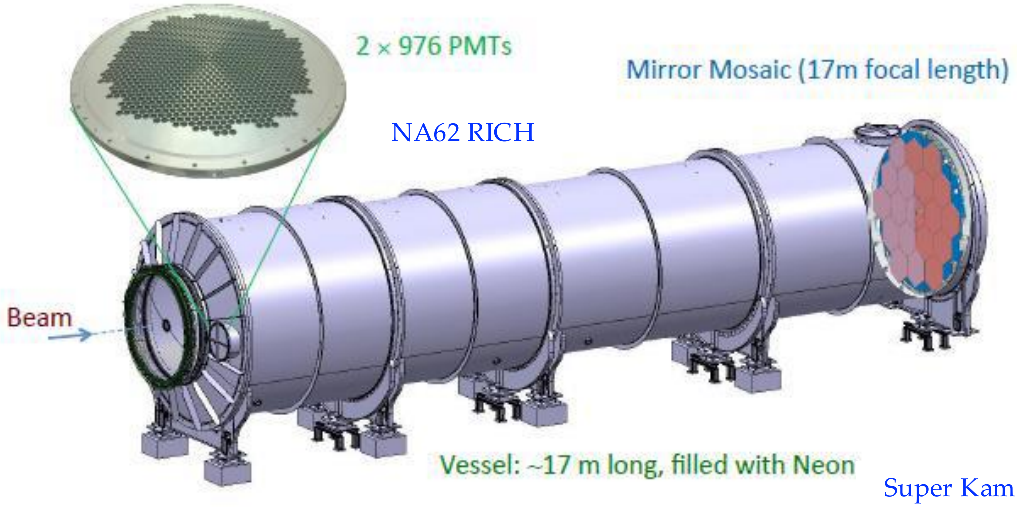


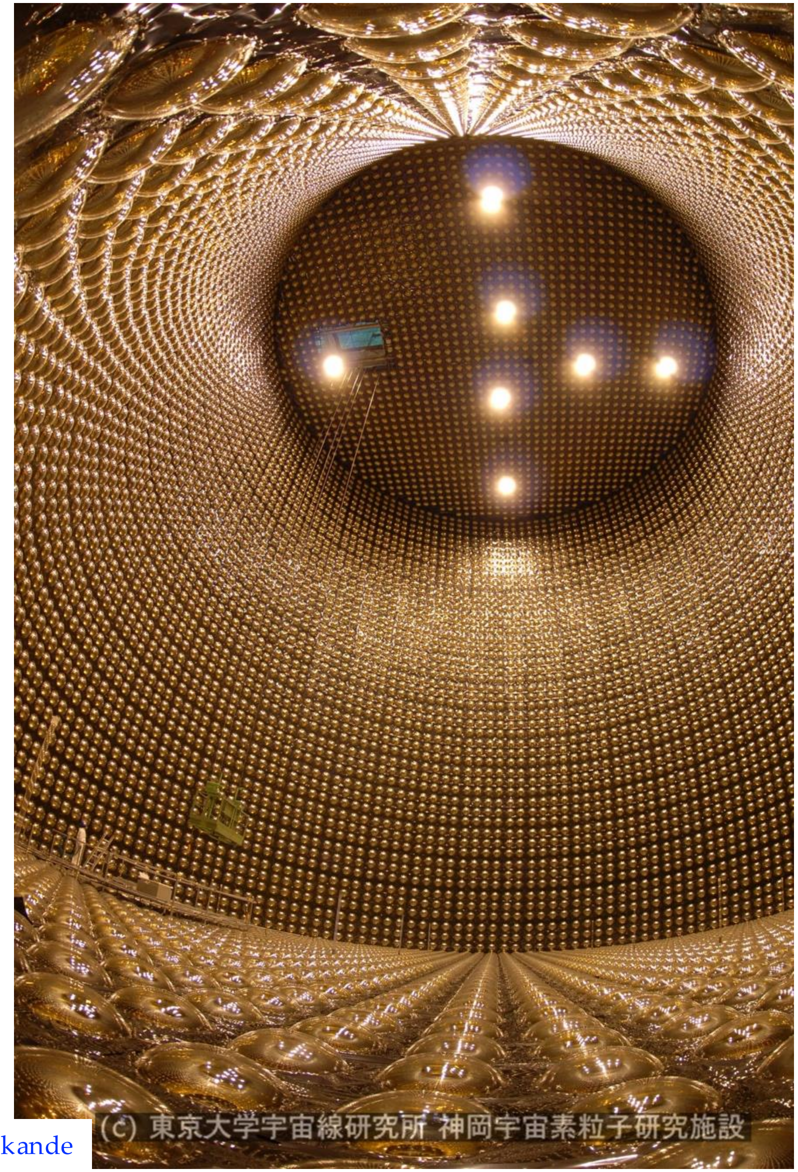
Hamamatsu Handbook

PMTs: large area coverage

- Examples
  - Super Kamiokande
    - 11,146 Hamamatsu R3600 (50 cm diameter), 22kton fiducial mass with 40% photocathode coverage
  - NA62 RICH
    - 1,952 Hamamatsu R7400-U03 PMTs (8 mm effective diameter) arranged in two disks
    - Winston cones for better light collection



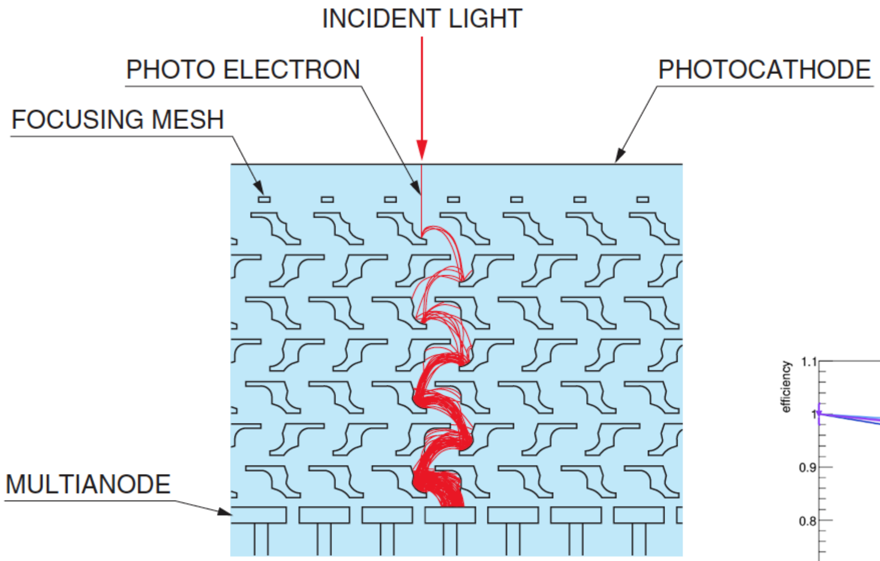
NA62 RICH



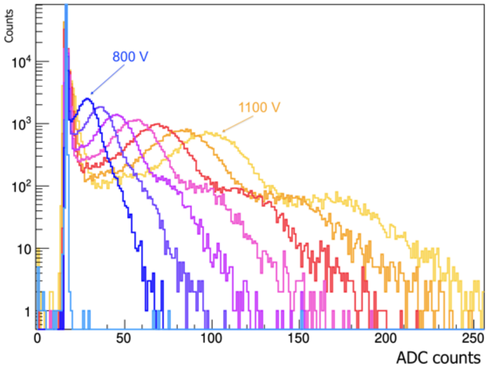
Super Kamiokande

Multi-anode PMTs

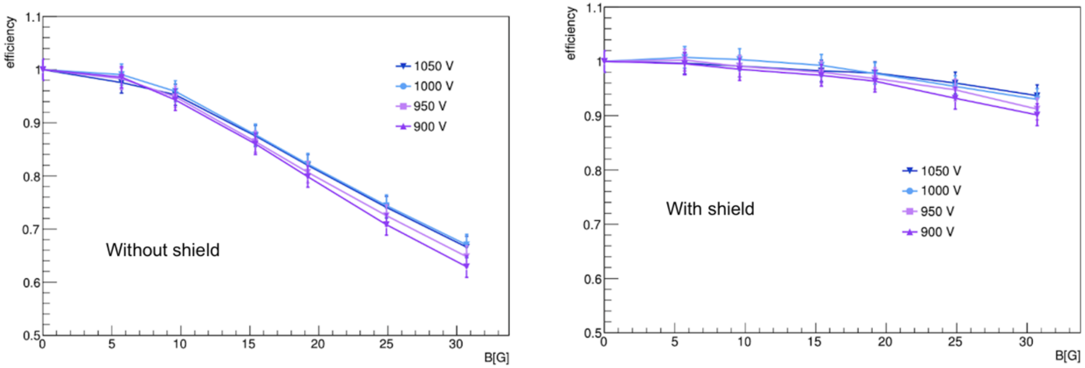
- Position sensitive PMT: metal channel dynode structure (minimum spatial spread of secondary e$^-$) with multiple independent anodes
  - Pioneered for HERA-B, later used in the COMPASS, CLAS12 GlueX and LHCb RICH detectors (planned for CBM)
  - Excellent performance (excellent single photon detection efficiency, very low noise, low cross-talk), best choice for large areas with small B field



Hamamatsu Handbook



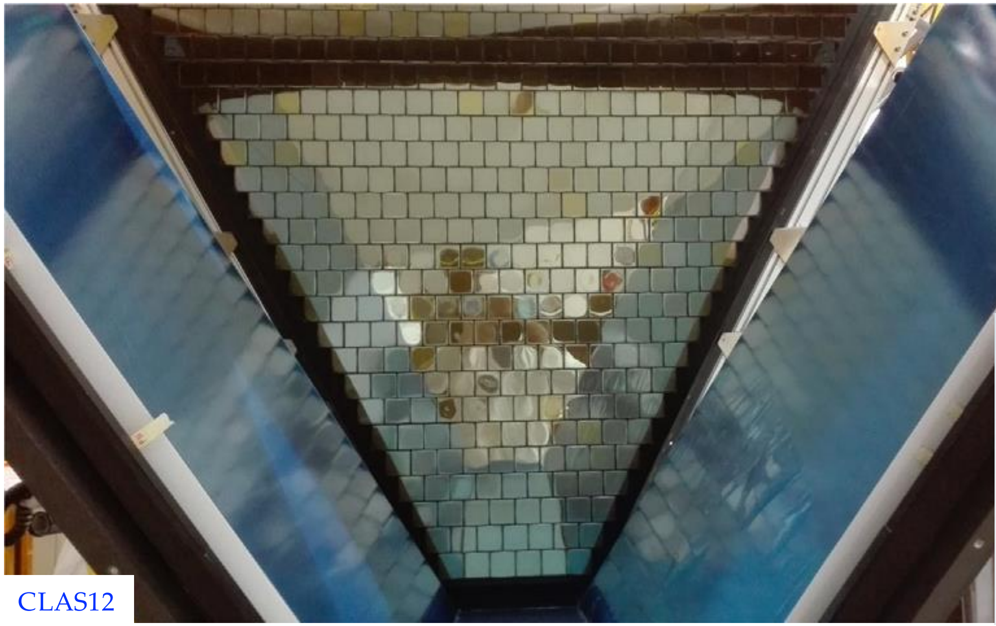
LHCb RICH



Ma-PMTs: large area coverage

- Examples
  - CLAS12 RICH
    - 315 Hamamatsu H12700 (+ 76 H8500), 8 × 8 channels array, 6 × 6 mm^2 pixels
    - ~1 m^2 instrumented area (active area ratio 87%)
  - LHCb RICH
    - 2,272 R11265 (R13742, 2.9 × 2.9 mm^2) + 768 R12699 (R13743, 6 × 6 mm^2), 8 × 8 channels array
    - ~3 m^2 instrumented area (active area ratio 77% - 87%)

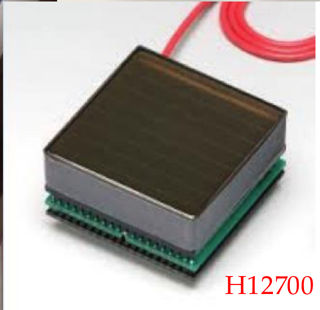
LHCb



CLAS12

R11265 RICH1 and RICH2

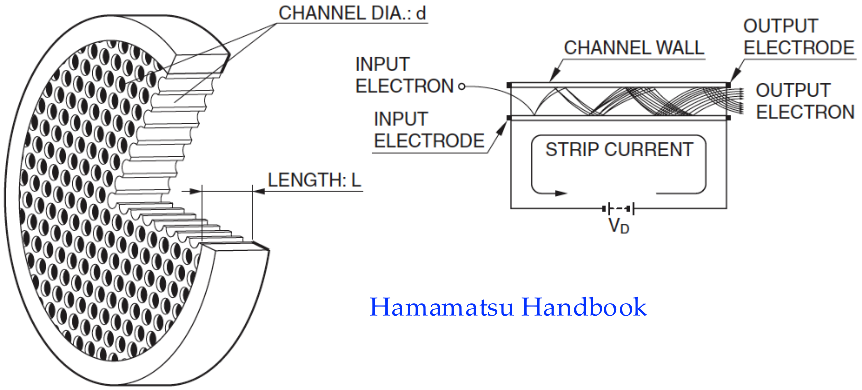
R12699 RICH2 only



H12700

MicroChannel Plate (MCP) PMTs

- Two-dimensional array of glass capillaries (channels with ~5-25 μm diameter) bundled in parallel in a MCP plate
  - Channel act as continuous dynode
  - Gain depends exponentially on channel length to diameter ratio
- MCP-PMTs
  - Excellent timing resolution (~20 ps r.m.s.)
  - Position resolution depends by anode segmentation
  - Can tolerate random magnetic fields up to 0.1 T and axial fields >1 T
  - High gain; collection efficiency ~60%



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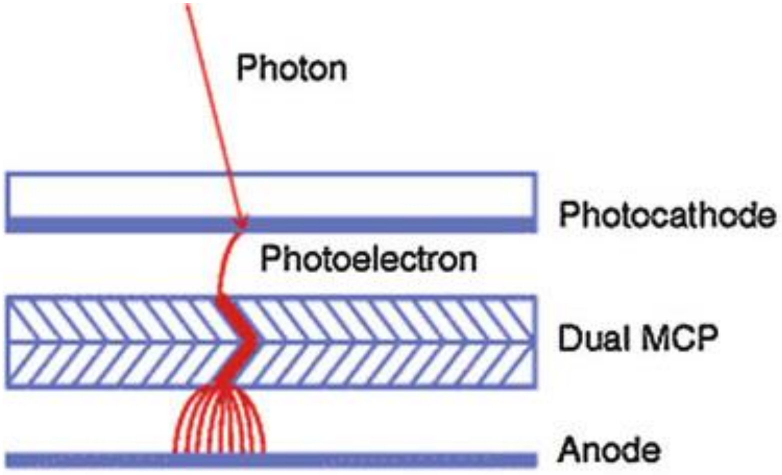

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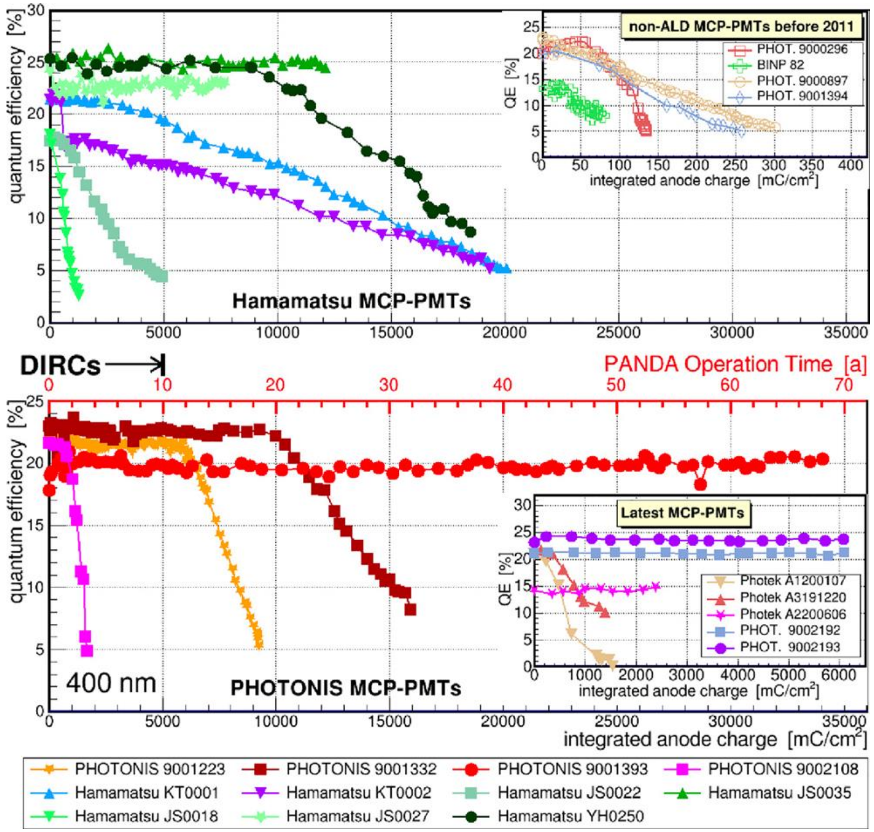
MCP-PMT recovery time and ageing

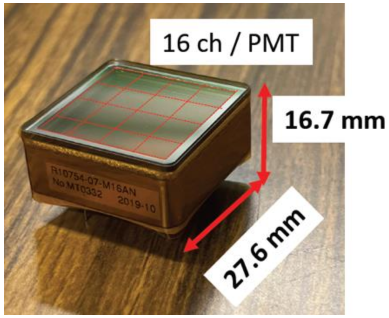
- MCP-PMT limitations
  - Relatively long recovery time per channel
  - Short lifetime: ageing due ion feedback (residual gas in the channels) that hit and degrade photocathode
- MCPs widely employed as image intensifiers: so far not so used in HEP
  - Interest increased by need to perform Cherenkov imaging within magnetic spectrometers combined with excellent timing resolution
  - First use of MCP-PMTs on large scale: Time-of-Propagation (TOP) counter (Belle II experiment), and planned PANDA experiment
- MCP-PMT lifetime limited by the integrated anode charge, which leads to a strong QE reduction
  - From 0.2 C/cm^2 to >35 C/cm^2 in recent years thanks to ALD

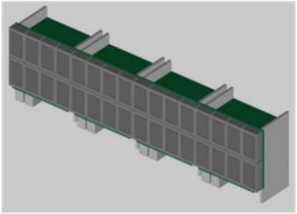


D. Miehling, A. Lehmann et al., NIM A 1049 (2023) 168047

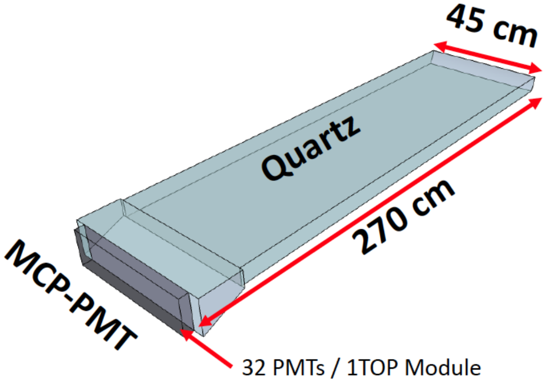
MCP-PMT: large area coverage

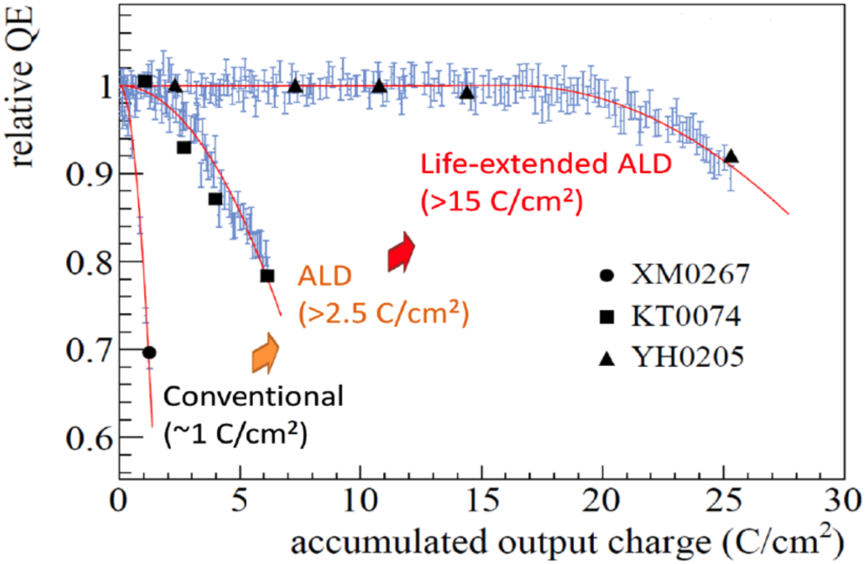
- Belle II TOP counter (barrel PID detector)
  - 512 Hamamatsu R10754 MCP-PMTs (QE ~30%, time res. ~30 ps r.m.s.)
  - QE degradation at few C/cm² lead to replacement with Life-extended ALD





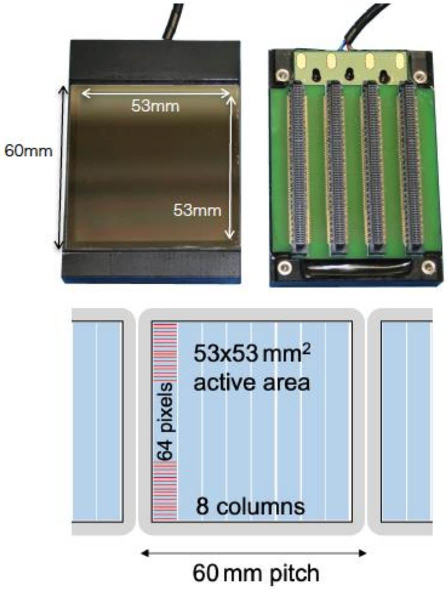
16 PMTs x 2 rows
per module



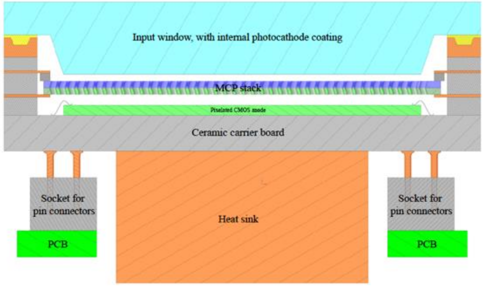


Recent MCP-PMT developments

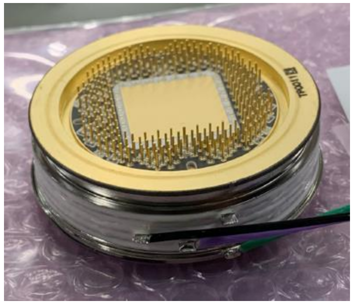
- TORCH detector by Photek (LHCb Upgrade)
  - $53 \times 53 \text{mm}^2$ prototype with 64×64 pads; time resolution <30 ps
  - MCP is ALD coated for lifetime > 5 C/cm^2
- LAPPD (Incom)
  - 20 cm square with internal stripline; capacitively-coupled (CC) with anodes (5mm thick glass or 2mm thick ceramic)
  - HRPPD: 10 cm square with no support structures in window; directly coupled through ceramic anodes (~3mm pixels); capacitively-coupled with 2mm anode
- MCP-PMT with embedded Timepix4 ASIC as anode
  - Complete integration of sensor and electronics (55 μm pixel pitch, 195 ps TDC bin, data driven read-out up to 160 Gbps)
  - On-detector signal processing, digitization and data transmission with large number of active channels (~230 k pixels)

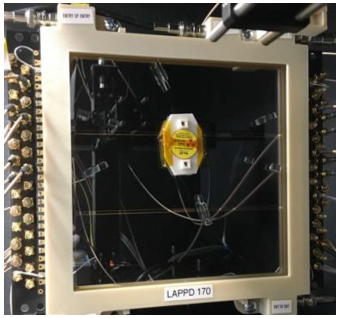


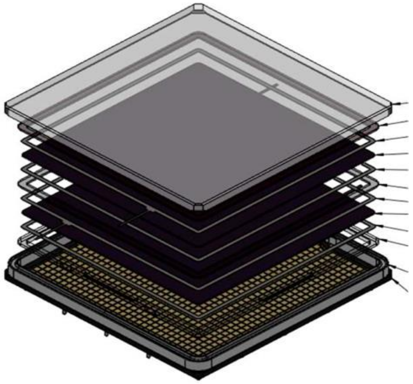
T. Blake Pisa Meeting 2024



M. Fiorini Pisa Meeting 2024



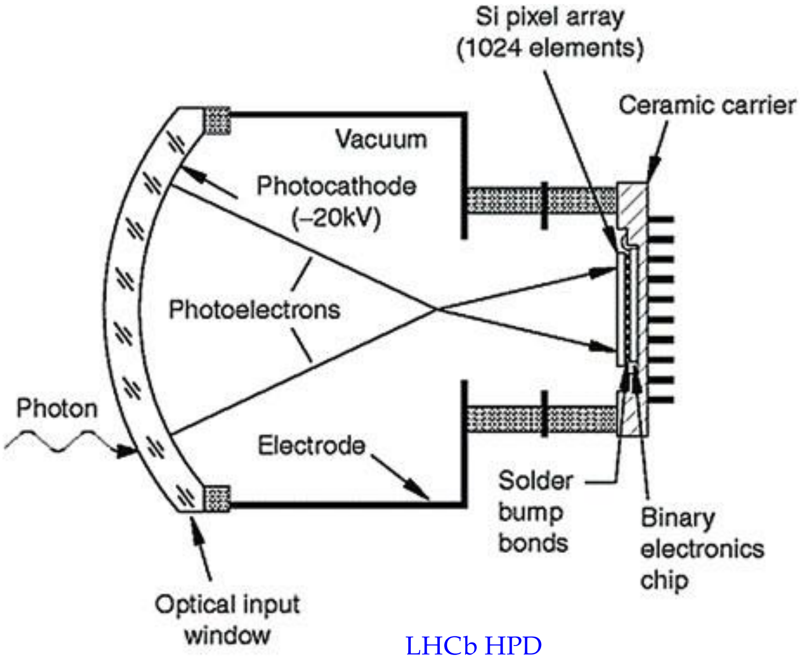




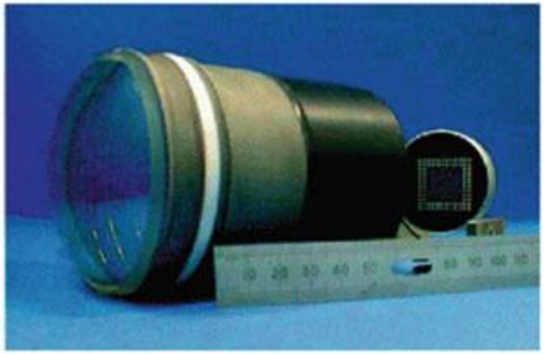
M. Popecki (Incom)

Hybrid Photon Detectors

- HPDs combine the sensitivity of a vacuum PMT with excellent resolutions of a Si sensor
  - Photoelectron accelerated by a potential difference of ~10-20 kV
  - Proximity focusing or focusing (Si sensor smaller than window, high active area ratio)
  - Very high segmentation possible
- Photoelectron detected using:
  - Segmented PIN diode (HPD)
  - Avalanche photodiode (HAPD)
  - Silicon photomultiplier (VSiPMT)
- Employed on a large scale:
  - HPD: RICH1+RICH2 of LHCb (Run 1+2), CMS HCAL
  - HAPD: Aerogel RICH detector of Belle II

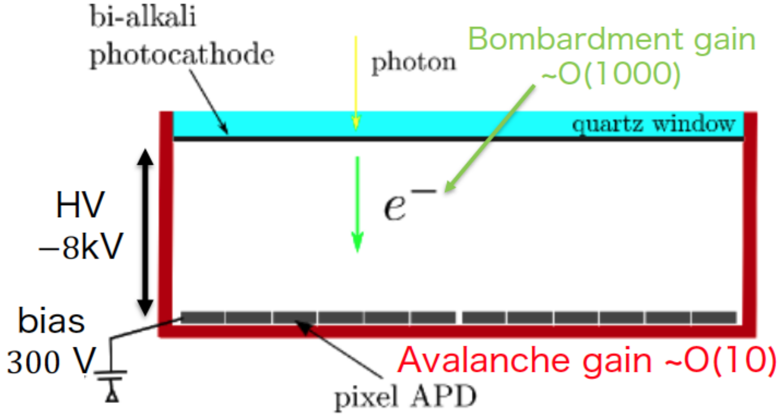


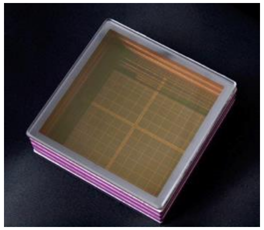
LHCb HPD



HPD/HAPD: large area coverage

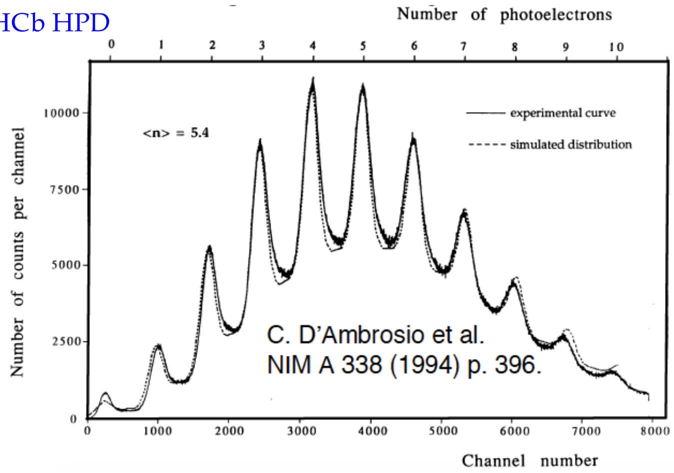
- Hybrid Avalanche Photo-Detector (HAPD), Belle II Aerogel RICH
    - 420 HAPDs; 73 × 73 mm^2, 144 pixels 4.9 × 4.9 mm^2, Hamamatsu
    - Gain 7×10^4; works in 1.5 T magnetic field
- LHCb RICH (Run 1 and 2)
    - 484 HPDs for a total area of 3.3 m^2
    - Low noise 145 e$^-$ (signal 5000 e$^-$ typ.)
    - Collaboration with Photonis-DEP



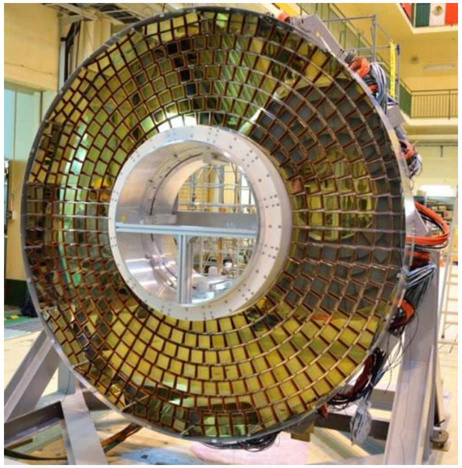


Belle II HAPD

LHCb HPD

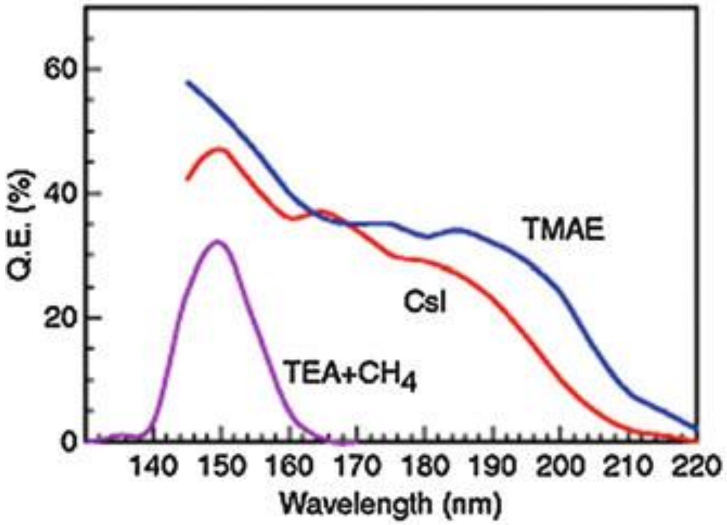


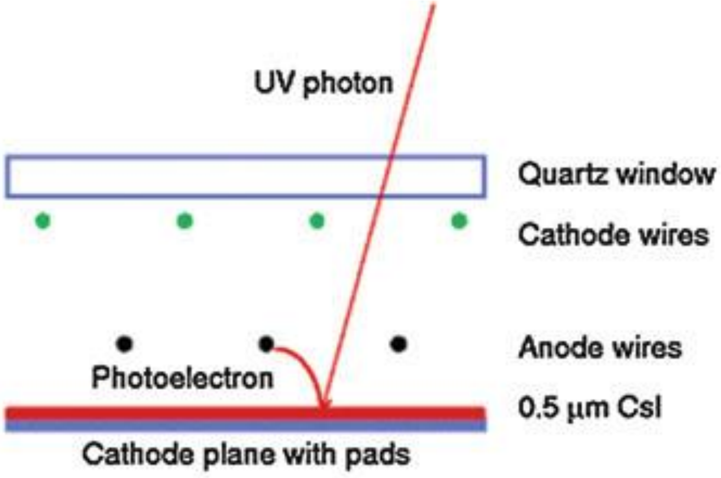
C. D'Ambrosio et al.
NIM A 338 (1994) p. 396.



Gaseous Photodetectors

- Electron multiplication happens in an avalanche in the high-field region of a gaseous detector (as for gaseous tracking detectors)
  - Photoelectrons generated either on a photosensitive component of the gas mixture or on a solid photocathode material
  - Cathodes can be structured in pads of few mm size → position-sensitive
  - Can cover large areas (several m^2), operate in high magnetic fields, and are relatively inexpensive
  - Drawback: sensitive only in the UV
- Examples: ALICE, COMPASS, Hades, JLAB-Hall A

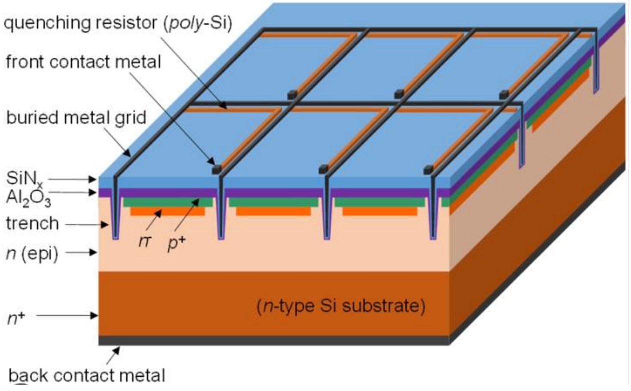


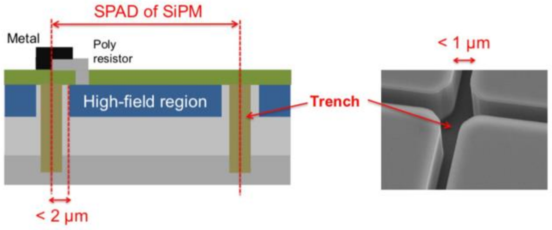


https://doi.org/10.1007/978-3-319-93785-4

Solid State Photon Detectors

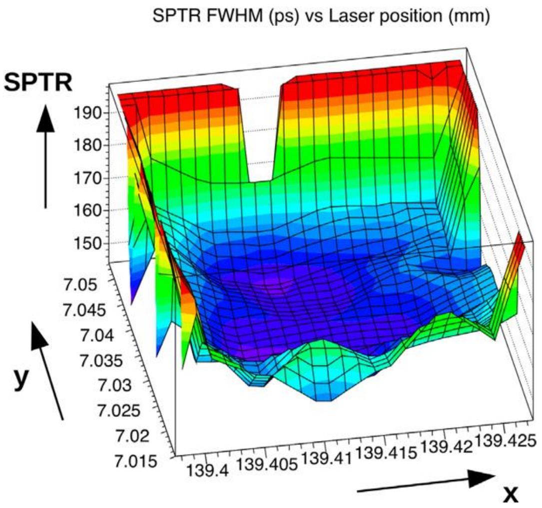
- Production and detection of photoelectrons in the same thin material
- Very low levels of light detection (single photon) possible with Avalanche Photo Diode (APD) operated in Geiger mode
  - Silicon Photomultiplier (SiPM)
- Many interesting features:
  - High gain (~10^6)
  - Excellent single photon separation
  - Good granularity
  - Could use micro-lenses to increase active area
  - Excellent time resolution
  - Insensitive to magnetic fields
  - Low voltage operation
- Drawbacks:
  - High dark count rate (DCR), typ. ~100 kHz/mm^2
  - Very sensitive to neutrons and ionizing particles



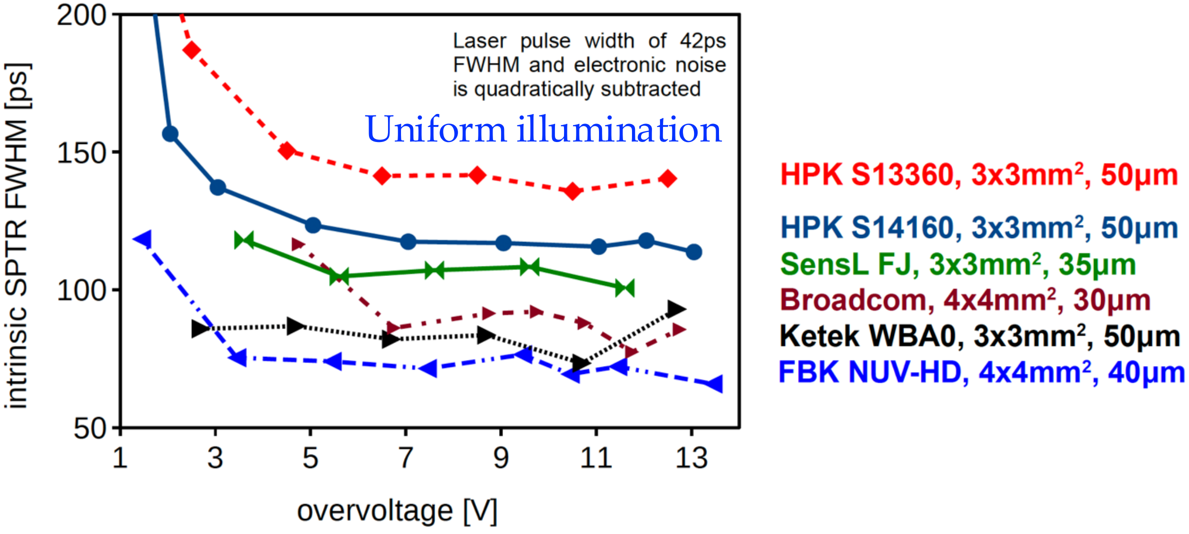


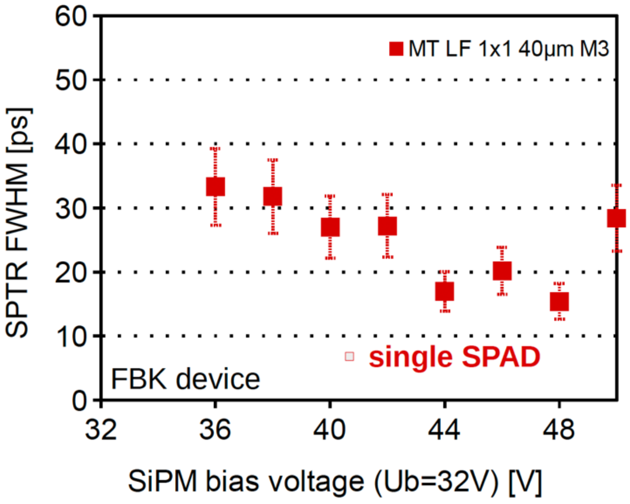
SiPM timing resolution

- Single Photon Timing Resolution (SPTR)
  - Extract "intrinsic" SiPM contribution
- SPTR is position-dependent
  - Worse at the edges due to low electric field
  - Possible solutions: masking/microlensing
- Worse SPTR for larger cells
- Analog single SPAD SPTR below 20 ps (FWHM)
  - 40 μm^2 cell if masked (~30 ps not masked)



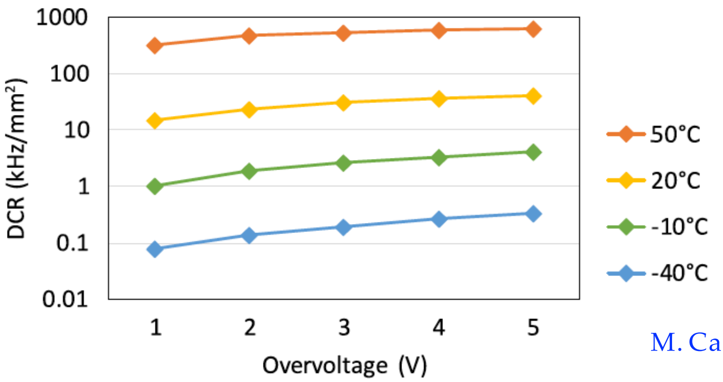
S. Gundacker et al.



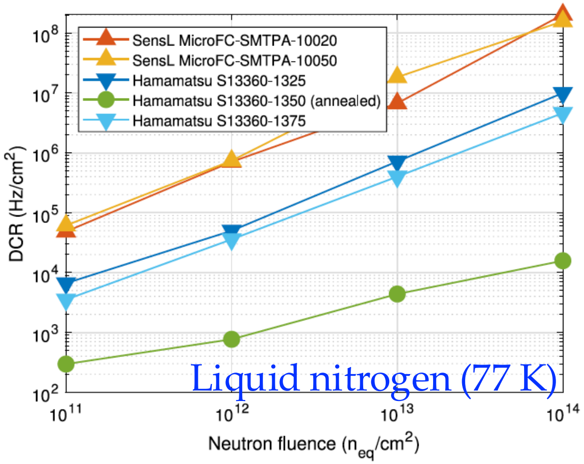


SiPM radiation hardness

- DCR highly depends on temperature and irradiation
- Can be mitigated by cooling (and annealing)



M. Calvi NIM A 952 (2020) 161788



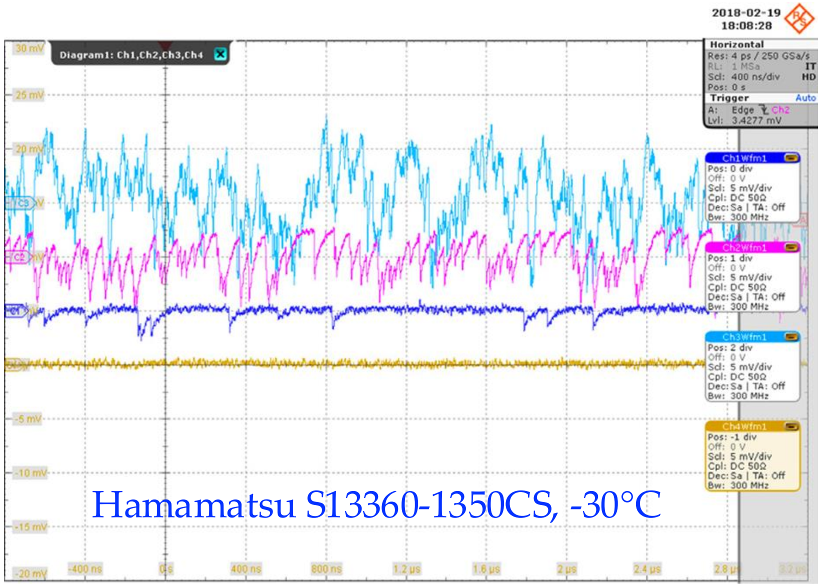
Liquid nitrogen (77 K)

10^{13} n_{eq}/cm^2

10^{12} n_{eq}/cm^2

10^{11} n_{eq}/cm^2

non irradiated



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18:08:28
Horizontal
Res: 4 ps / 250 GSa/s
RL:  1 MSa            IT
Scl: 400 ns/div       HD
Pos: 0 s
Trigger             Auto
A:   Edge ⌊ Ch2
Lvl: 3.4277 mV

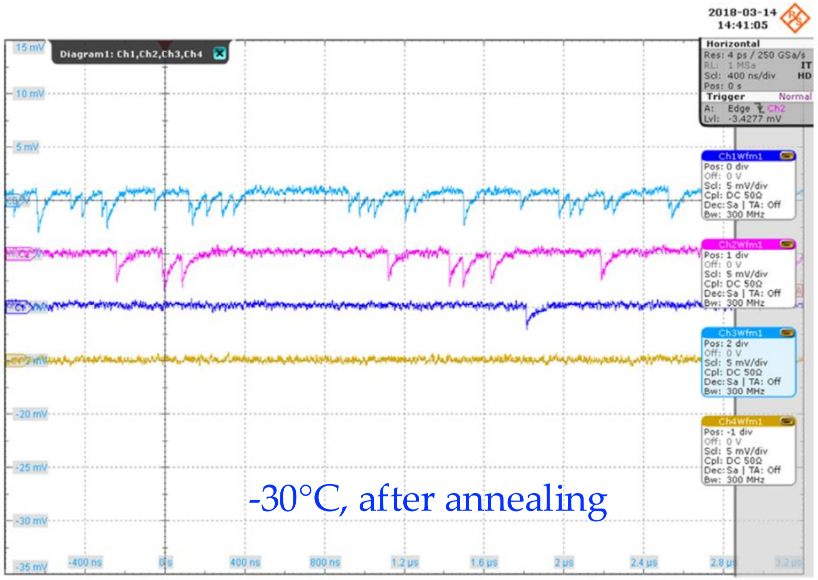
Ch1Wfm1
Pos: 0 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz

Ch2Wfm1
Pos: 1 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz

Ch3Wfm1
Pos: 2 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz

Ch4Wfm1
Pos: -1 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz
```

Hamamatsu S13360-1350CS, -30°C



```
2018-03-14
14:41:05
Horizontal
Res: 4 ps / 250 GSa/s
RL:  1 MSa            IT
Scl: 400 ns/div       HD
Pos: 0 s
Trigger           Normal
A:   Edge ⌊ Ch2
Lvl: -3.4277 mV

Ch1Wfm1
Pos: 0 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz

Ch2Wfm1
Pos: 1 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz

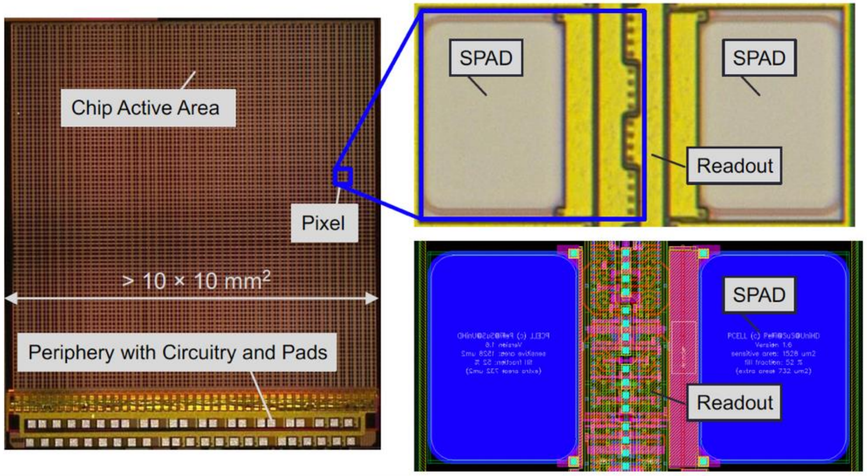
Ch3Wfm1
Pos: 2 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz

Ch4Wfm1
Pos: -1 div
Off: 0 V
Scl: 5 mV/div
Cpl: DC 50Ω
Dec:Sa | TA: Off
Bw:  300 MHz
```

-30°C, after annealing

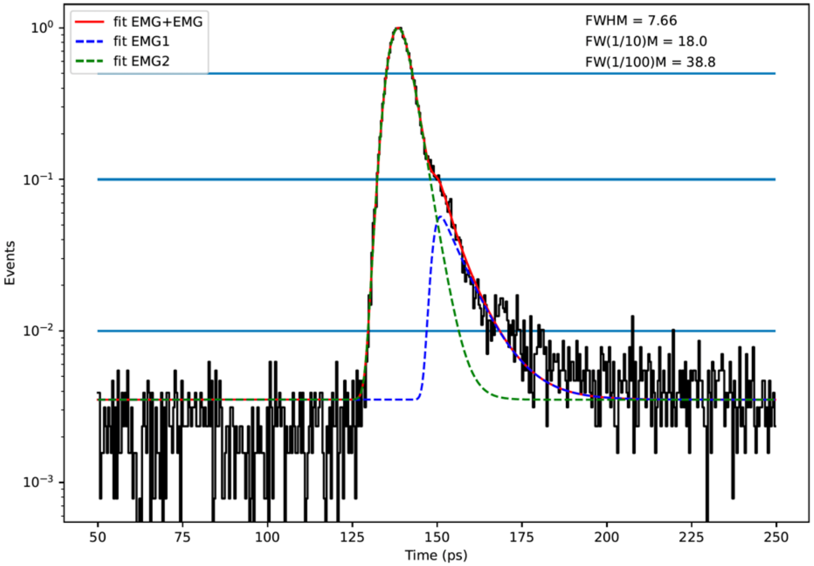
Digital SiPM

- Digital SiPM (or “CMOS SPAD”) chips combines SPAD and transistors on the same chip
- Advantages
  - Can switch off individual noisy cells
  - Integrated read-out
  - Large signal from single SPAD (low power readout)
  - <100 μm spatial resolution easy to achieve
  - Excellent timing performance (<10 ps FWHM)
  - CMOS mass production technology



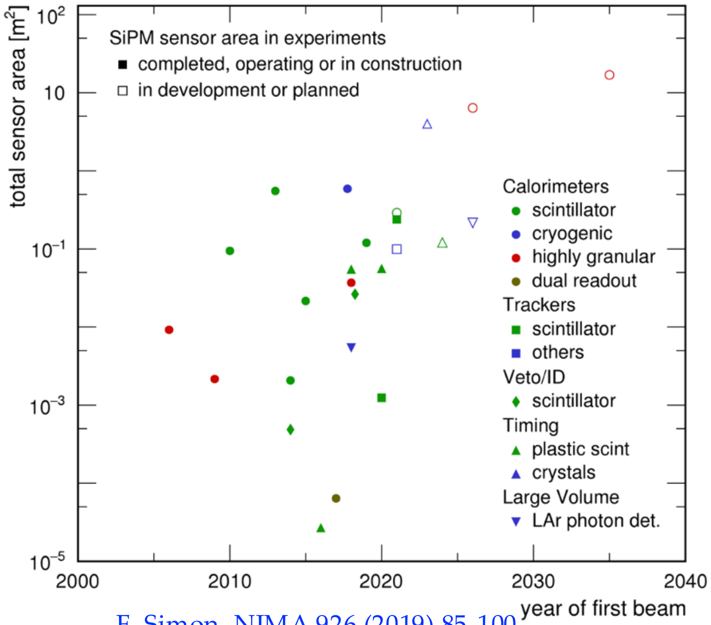
P. Fischer

Nolet, Pratte et al. (Sherbrooke)

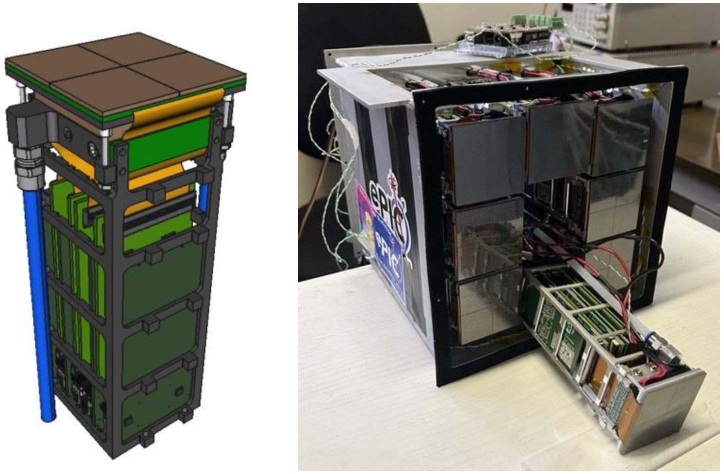


SiPM: large area coverage

- SiPM are widespread in HEP and neutrino physics experiments
  - Most common application to detect scintillation light (calorimeters, SciFi)
- RICH detector based on SiPM (in a running experiment) not realized so far
  - Pioneering work during Belle II Upgrade studies (S. Korpar, P. Krizan)
- Many potential users:
  - Belle II; LHCb RICH Upgrade 2; RICH for SuperCharm-Tau factory; ALICE3; EIC RICH; etc.
- Dual RICH (dRICH) detector for ePIC
  - 4 × SiPMs matrix Hamamatsu 8 × 8 S13361
  - Read-out board with front-end chip and FPGA, and cooling
  - Advanced design and prototype tests



F. Simon, NIMA 926 (2019) 85-100



P. Antonioli, R. Preghenella, L. Rignanese

Conclusions

- The next generation of particle physics experiments requires single-photon detectors with ever increasing performance
  - Excellent timing resolution
  - Increased granularity and number of channels
  - Wider spectral range
  - Improved radiation hardness

- Many exciting developments underway, in particular on SiPMs and MCP-PMTs
  - Not all of them could be covered in this talk

- A detector R&D collaboration (DRD4) has been recently formed to facilitate collaboration in this area of research
  - See next slides

The DRD4 Collaboration: R&D on photon detectors and PID techniques

INFN
Istituto Nazionale di Fisica Nucleare

Massimiliano Fiorini
(INFN and University of Ferrara)

University of Ferrara

6th International Workshop on New Photon-Detectors (PD24)
Vancouver, 19-22 November 2024

DRD4 organization

- DRD4: international Collaboration with CERN as host laboratory
  - Approved by the CERN Research Board in December 2023
- Main goal: bundle and boost R&D activities in **photodetector technology** and **Particle Identification (PID) techniques** for future HEP experiments and facilities
- To be more specific, DRD4 covers the following topics:
  - Single-photon sensitive photodetectors (vacuum, solid state, hybrid)
  - PID techniques (Cherenkov based, Time of Flight)
  - Scintillating Fiber (SciFi) tracking
  - Transition Radiation (TR) using solid state X-ray detectors
- DRD4 structure initially defined in the Proposal document
  - 6 Working Groups (WGs) reflecting the main areas of R&D
    - Scientific forums for discussion: no agreed tasks, no committed resources
    - Facilitate exchange of information, know-how, samples, infrastructure, etc.
  - 5 Work Packages (WPs) reflecting the main ECFA roadmap themes and goals
    - Run like projects: divided in tasks, with agreed goals, milestones, deliverables, and are jointly funded by the resources of the participants

DRD4 activities

- 74 institutes joined DRD4 at the time of Proposal
  - Additional institutes joined later (2 in January, 1 in June, 4 in October)
  - 20 nationalities
  - Many small groups, many with no prior experience in large R&D collaborations
  - Large effort to constitute a collaborative effort amongst a research community that has not traditionally worked together in the recent past
  - Industrial partners (very important asset)
- DRD4 scientific activities ramped up since the beginning of 2024: many scientific and technological discussions
  - See Indico pages for more details
  - These meetings allow building our community, enabling discussion of activities and the spread of information
- Future Collaboration meetings at CERN
  - 7-11 April 2025; 13-17 October 2025

DRD4 collaboration

- New groups are welcome to join DRD4
  - For more information: https://drd4.web.cern.ch
  - Many PD24 participants are already part of the DRD4 community
  - If interested, please contact us (or simply subscribe to the "drd4-interested" list to be informed about ongoing activities)

Group photo at the DRD4 Constitutional meeting (CERN, January 2024)

Social dinner (DRD4 Collaboration meeting at CERN, October 2024)