Brief Summary on “ECFA Detector R&D Roadmap Symposium of Task Force 4 Photon Detectors and Particle Identification Detectors”

10 September 2021

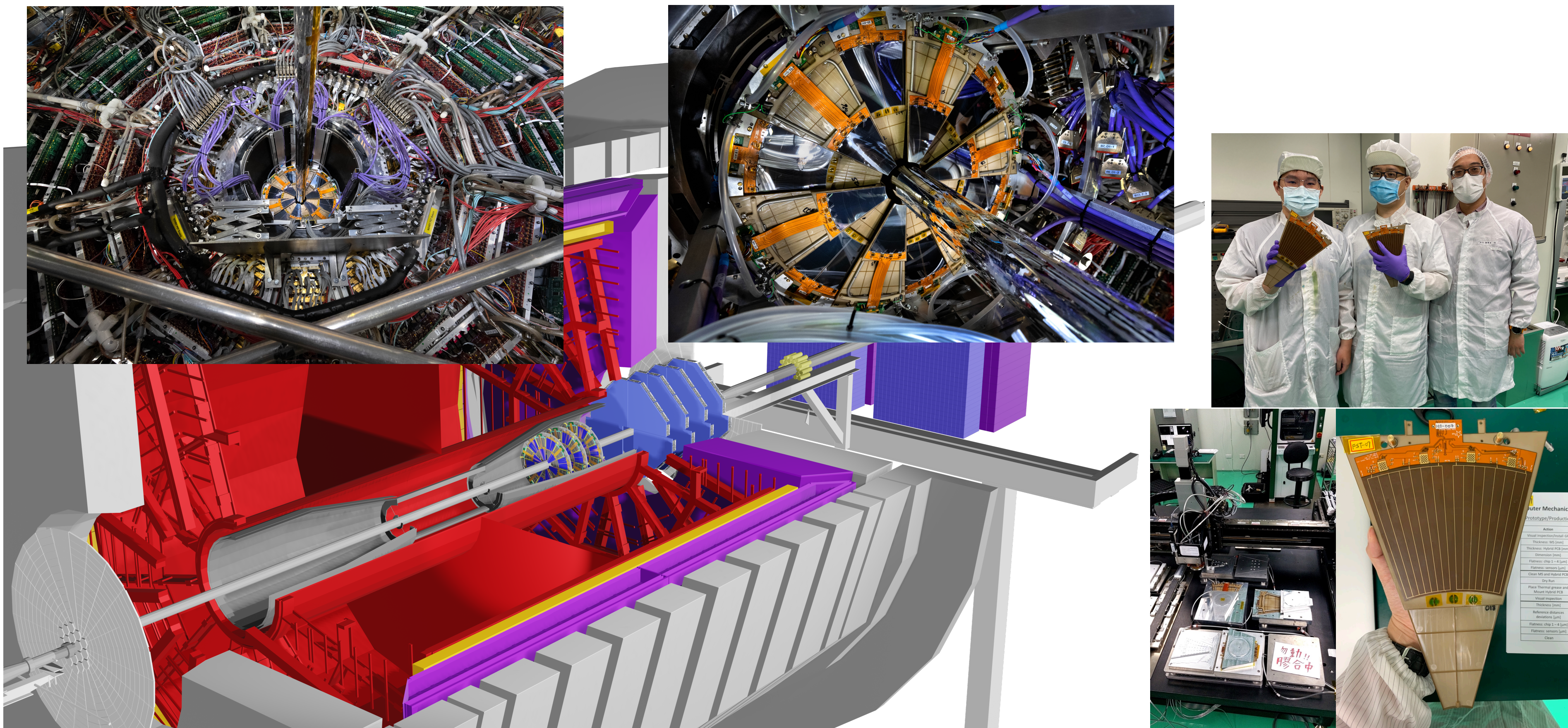
@ TIDC workshop on Future detector R&D for HEP

Yi Yang

National Cheng Kung University

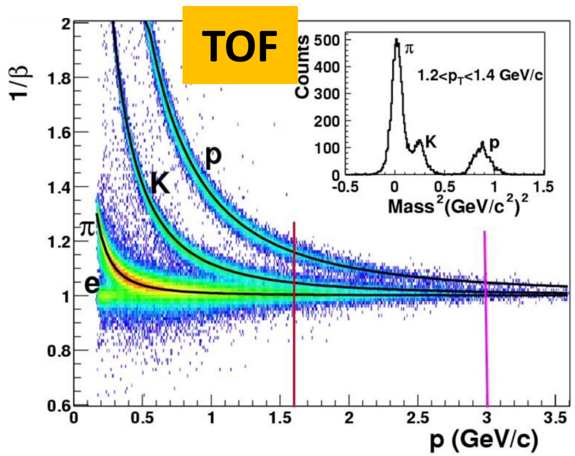
STAR Forward Silicon Tracker Installed

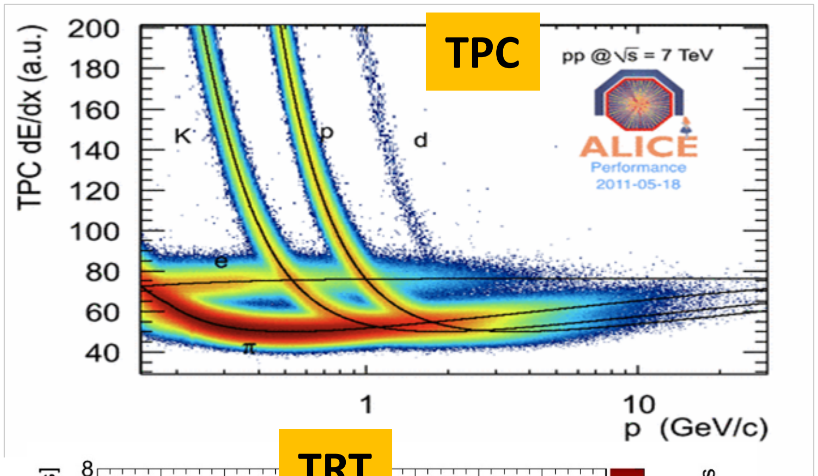
- NCKU designed and manufactured (@TIDC) the mechanical structure for the silicon tracker
- **It was successfully installed in STAR in August**

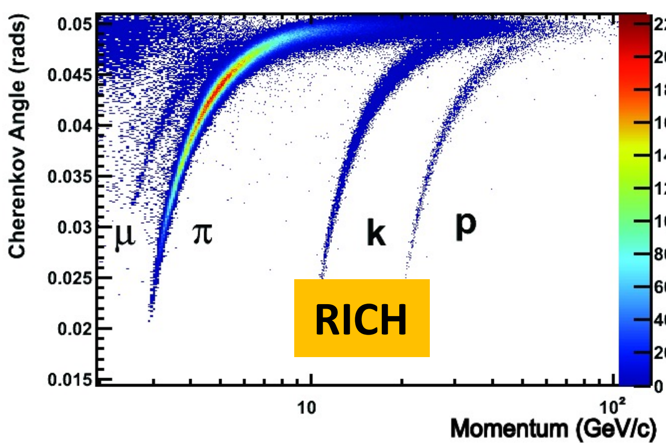


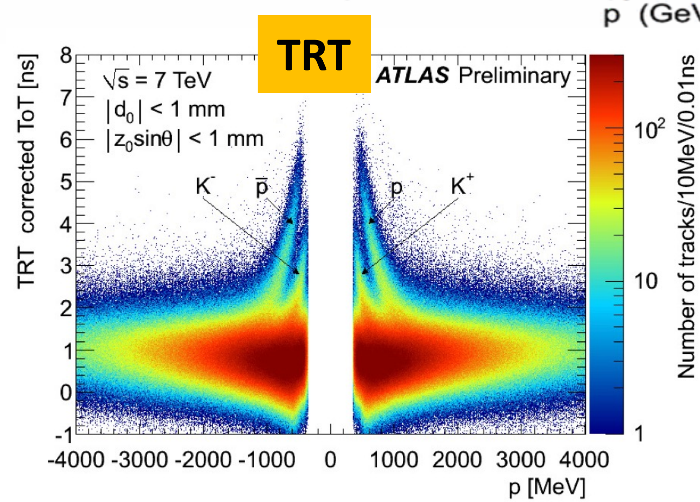
PID & Photon Detectors

- PID plays the crucial role in the high energy experiment



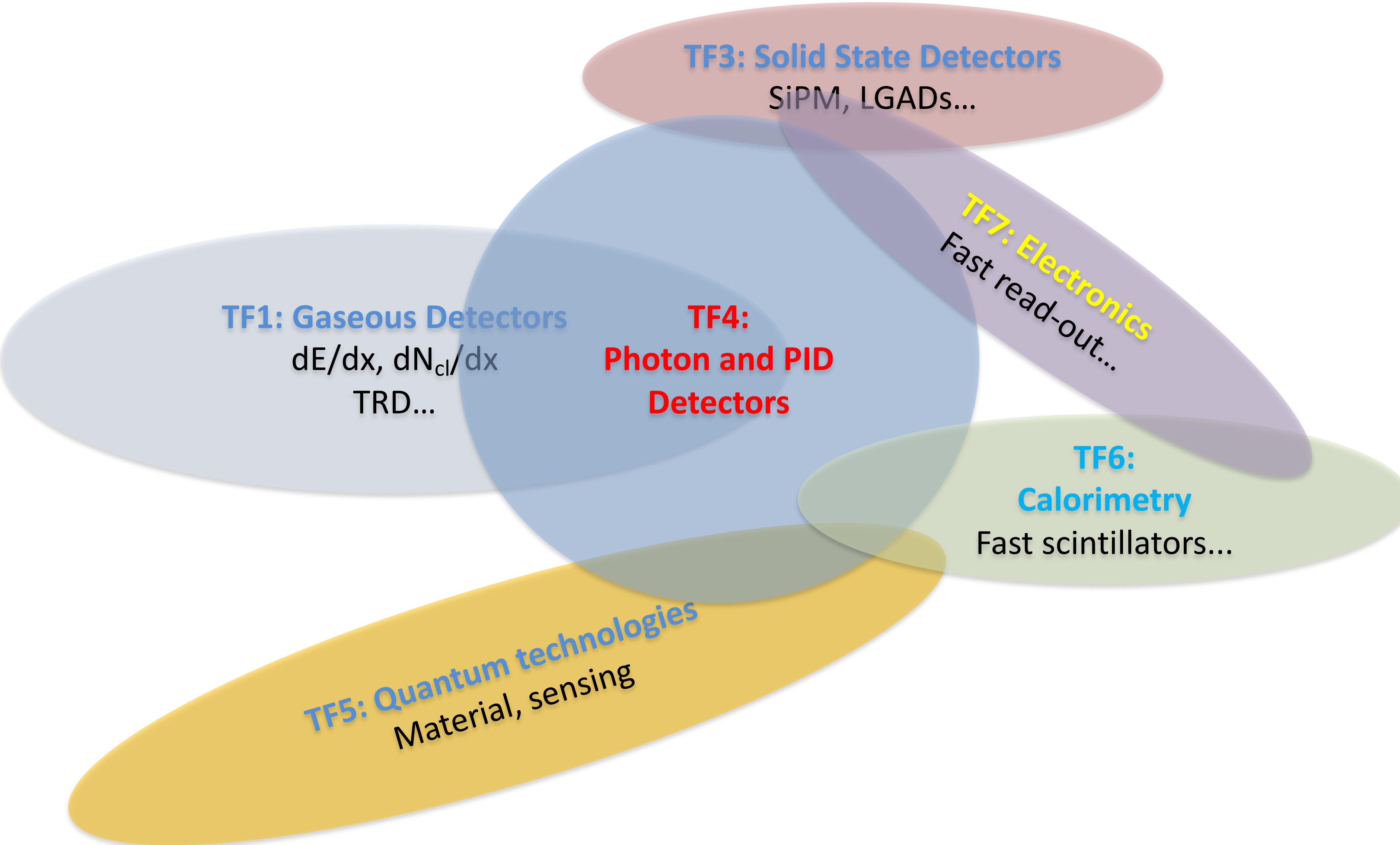






- Photon detector normally is part of PID detector, except for dark matter searching…

Overlapping Topics



Summary of ECFA TF4

- It is impossible to provide detailed information on each detector/component, please find more details in https://indico.cern.ch/event/999817/

PID Detector

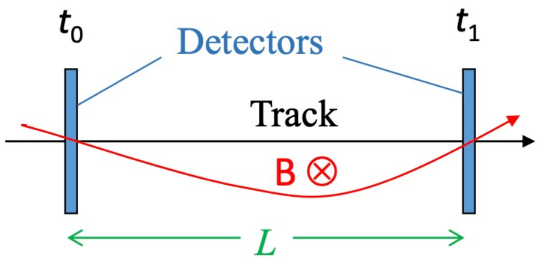
Time-of-Flight (ToF)

From Roger Forty's presentation:
https://indico.cern.ch/event/999817/contributions/4253048/attachments/2240084/3797788/TOF%20technologies.pdf

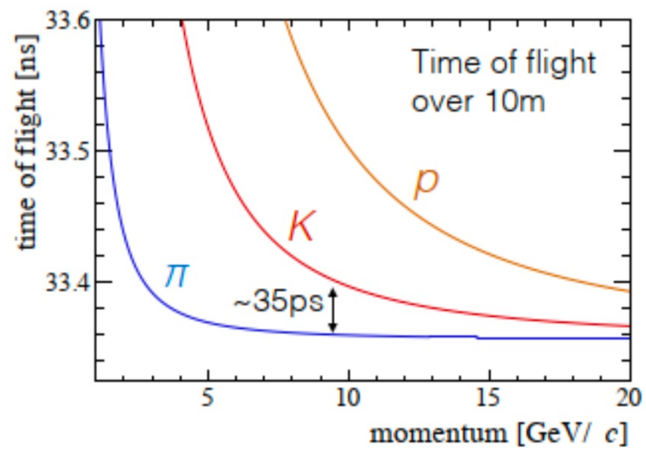
- Time-of-flight principle is *conceptually simple*: measure difference in arrival time of particle at two planes $t = t_1 - t_0$ then velocity: $\beta = L / ct$
- Combine with a measurement of its momentum: $p = \beta\gamma mc$
  Mass of particle can then be calculated:

$$m^2 = \frac{p^2}{c^2}\left(\frac{c^2 t^2}{L^2} - 1\right)$$

$$\left(\frac{\delta m}{m}\right)_p = \frac{\delta p}{p},$$
$$\left(\frac{\delta m}{m}\right)_t = \gamma^2 \frac{\delta t}{t}$$

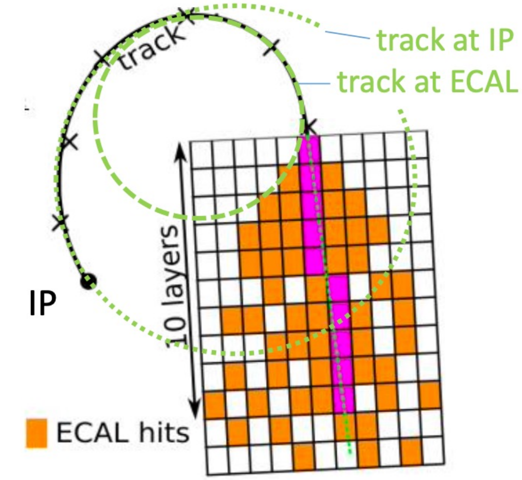


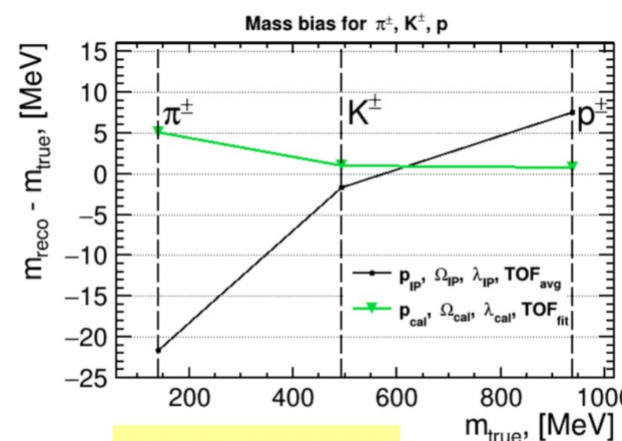
- At high energies particles are relativistic: velocity saturates → *c*, time difference drops fast
- Focused on long-lived charged-particle identification (e, μ, **π, K, p**) in particular charged hadron separation at low momentum
- The time for a kaon to travel 10 m is 33.37 ns at 10 GeV, while for a pion it would be 33.34 ns: the difference is only 35 ps
- The separation in standard deviations: $N_\sigma \approx \frac{|m_1^2 - m_2^2|\, L}{2\, p^2\, \sigma_t\, c}$



Complications

- Energy loss + multiple scattering between the IP and TOF detector
  → track length and momentum measurement biased
  → minimize material before TOF detector
- Combining signals within a layer, and between layers, of the TOF detector requires care (see example illustrated)
- Dedicated TOF detector placed after tracker but before calorimeter
  → its own material budget should be limited
- Increasing the path length improves TOF (linearly), but the area to be covered by the detector increases as the *square*
  → detectors typically need to cover **large areas**, cost-effectively
- **Radiation tolerance** is an issue for application at hadron colliders
- **Start time** (t_0) needed, from dedicated detector or elsewhere
- **Electronics:** balance between time resolution, spatial resolution, data rate and power consumption
- **System issues:** synchronization over a large area challenging





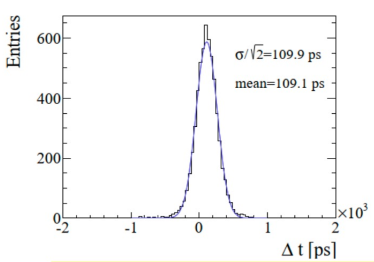
B. Dudar, LCWS 2021

Technologies

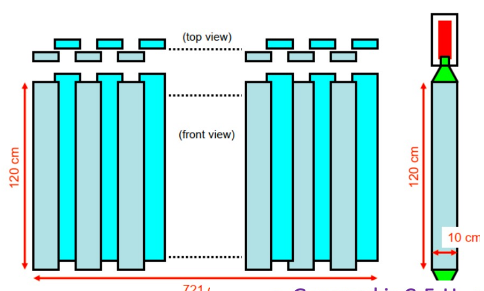
- Many of the technologies used cross over with other disciplines, from tracking to calorimetry, and use the sensors discussed elsewhere in this (and the other) task forces

1. **Scintillators:** classic solution, now developed for timing layers (TF5+6, SiPM)
2. **Gaseous detectors:** multigap RPCs, new ideas to push timing resolution with MPGDs (TF1)
3. **Silicon detectors:** recent development of LGADs for end-cap timing layers (TF3, LGAD)
4. **Cherenkov-based detectors:** pushing for ultimate resolution (MCP)

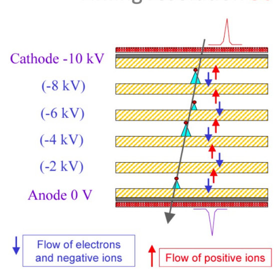
- TOF resolution ~110 ps



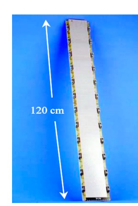
N Abgrall et al 2014 JINST 9 P06005

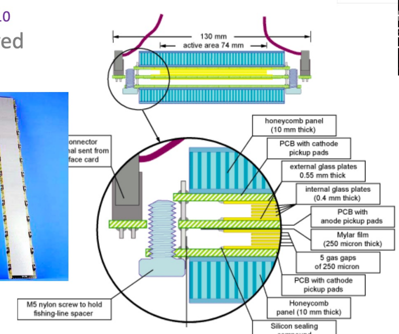


- Gas used is $C_2F_4H_2 + SF_6 + C_4H_{10}$
- Timing resolution 56 ps achieved

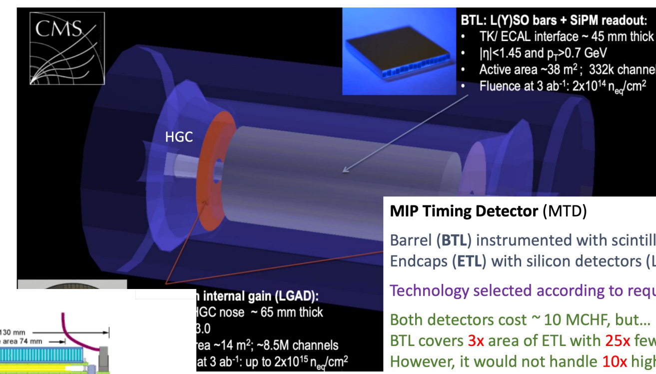


Roger Forty





TOF technologies



MIP Timing Detector (MTD)

Barrel (**BTL**) instrumented with scintillator bars
Endcaps (**ETL**) with silicon detectors (LGAD)

Technology selected according to requirements:

Both detectors cost ~ 10 MCHF, but...
BTL covers 3x area of ETL with 25x fewer channels
However, it would not handle 10x higher radiation

Conclusions

- Development of TOF technologies is currently booming with general interest in **fast timing** Provides a very compact particle ID detector, e.g. suitable for collider experiments
- Well-established technologies: **scintillator** hodoscopes and **MRPCs** with resolution *O*(**100 ps**) good for covering low momenta up to a few GeV, e.g. complementing *dE*/*dx* from trackers
- Fast-timing detectors developed for the LHC upgrades: fast scintillators and **LGAD** silicon aim for **30-50 ps** resolution for pile-up suppression, will also provide TOF particle ID as a bonus
- To achieve momentum coverage up to 10 GeV for K-π separation (to complement RICH coverage) requires pushing beyond current state-of-the-art, towards **10 ps** resolution
  - Cherenkov radiators very suitable: **PICOSEC**, **LAPPD** and other approaches under development
  - **TORCH** achieves this by combining many photons per track, with modest individual resolution
  - Scintillators this fast (e.g. quantum R&D) would be breakthrough for **TOF-PET**: mm-resolution
- Long-term goal to reach **picosecond-level** timing, could satisfy the *full* particle ID needs
  - Requires vigorous R&D on radiators, sensors, electronics
  - System aspects will become increasingly more important

→ Fast timing should feature strongly in the R&D Roadmap + reserve some space for new ideas!

Ring-Imaging Cherenkov detector (RICH)

From Carmelo D'Ambrosio' presentation:
https://indico.cern.ch/event/999817/contributions/4253045/attachments/2239937/3797505/carmelo_2021_05_06.pdf

- RICH detectors have to evolve with time, as the whole experiments do.
- Environments ahead are given by high luminosities and radiation levels, high event rates, by wide momenta and acceptance coverages, by compact central and high rapidity geometries.
- The challenge is to maintain high performance and full efficiencies in such environments.
- Technologies (whether existing or to be developed) will have to assure the compliance of the detector to the needed specifications and resulting performance.
- New optical components and designs, new materials, vessels, radiators, electronics, photosensors: all needs to be re-visited in the light of the future challenges and eventually re-developed. Number of detected photons and space are critical parameters.
- The push for the future will consist in developing RICH detectors with very high angular precision, with unique time properties and … as compact as possible.

Main quantities affecting system performance

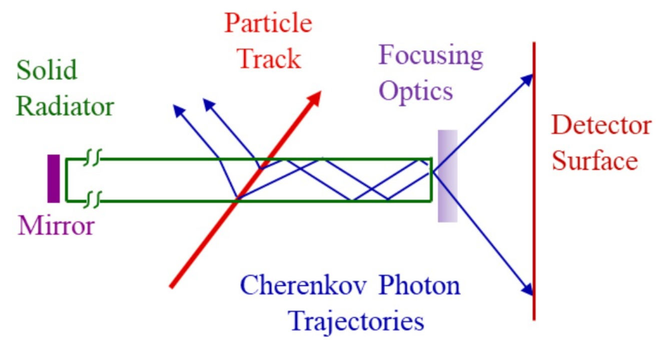
- Number of detected photons
- Occupancy
- Pattern Recognition strategy
- Uncertainties on the Cherenkov angle measurement $\sigma_{space}/\sqrt{N}$:
  - Chromatic;
  - Emission;
  - Pixel;
  - Trackers;
- Uncertainties on the photon time measurement (new) σ_{time} :
  - Sensor + electronics time resolution;
- Uncertainties on the “ring/track” time measurement (new) $\sigma_{time}/\sqrt{N}$:
  - Chromatic;
  - t_0.

Detection of Internally Reflected Cherenkov Light (DIRC)

From Jochen Schwiening's presentation:
https://indico.cern.ch/event/999817/contributions/4253047/attachments/2239796/3797410/20210506-ECFA-TF4-DIRC-schwiening.pdf

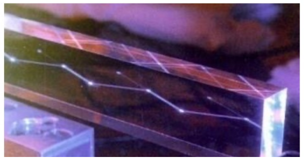
- DIRC: Compact subtype of RICH (Ring Imaging CHerenkov) detector
  utilizing total internal reflection of Cherenkov photons in a solid radiator medium

- Charged particle traversing radiator with refractive index n
  with $\beta = v/c > 1/n$ emits Cherenkov photons on cone
  with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.



- For $n>\sqrt{2}$ some photons are always
  totally internally reflected for $\beta\approx1$ tracks.

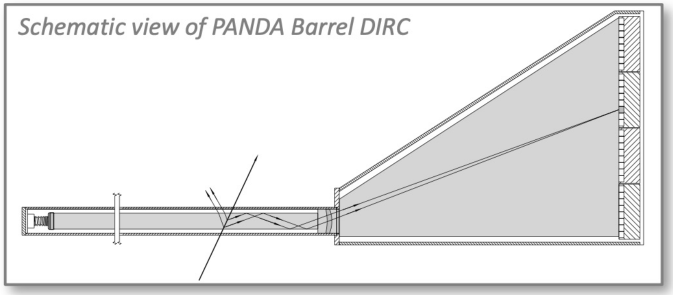
- Radiator and light guide: bar, plate, or disk,
  typically made from Synthetic Fused Silica ("Quartz")



- Magnitude of Cherenkov angle conserved during many internal reflections
  (provided optical surfaces are square, parallel, highly polished)

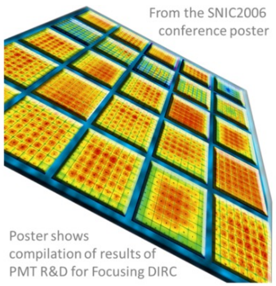
- Mirror attached to one bar end, reflects photon back to readout end.

- Photons exit radiator via optional focusing optics
  into expansion region, detected
  on photon detector array.


Schematic view of PANDA Barrel DIRC

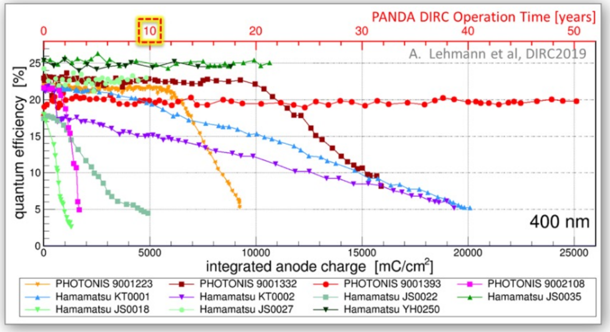
- DIRC is intrinsically a 3-D device,
  measuring: x, y, and time of Cherenkov
  photons, defining θ_c, ϕ_c, $t_{propagation}$.

Sensor development has been crucial to DIRC progress



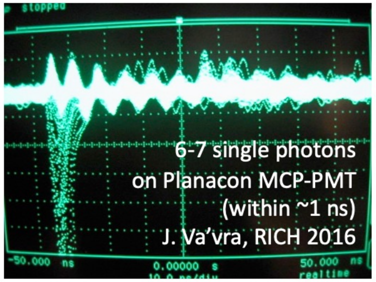
Main development goals: Smaller pixels and faster single photon timing

- reduces sensitivity to backgrounds
- improves Cherenkov angle resolution per photon
- allows chromatic dispersion mitigation
- anode design needs to match required angular resolution (required pitch may be asymmetric – see PANDA EDD)



Main challenge: Maintain fast timing and single photon sensitivity

- in high magnetic fields for compact camera designs (up to 3 Tesla for EIC?)
- after large ionizing radiation doses and neutron fluxes
- during long lifetime (10-20+ C/cm² integrated anode charge)
- during high interaction rates and photon hit rates (MHz/cm²)
- for high hit multiplicities per event (coherent oscillation?)



Detection of Internally Reflected Cherenkov Light (DIRC)

Sensor development has been crucial to DIRC progress

Single photon detection

- excellent rms timing precision more important than TTS
- reduce tails in timing distribution

High photon yield (up to 100 photoelectrons per particle)

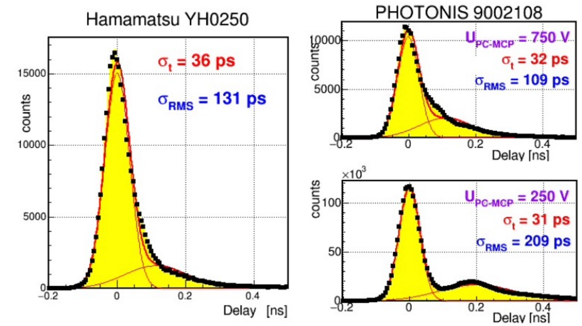
- need pixelated readout to determine position without ambiguities
- need tolerance for high occupancy per sensor

Long photon propagation paths in bar (arrival time often spread over >30ns)

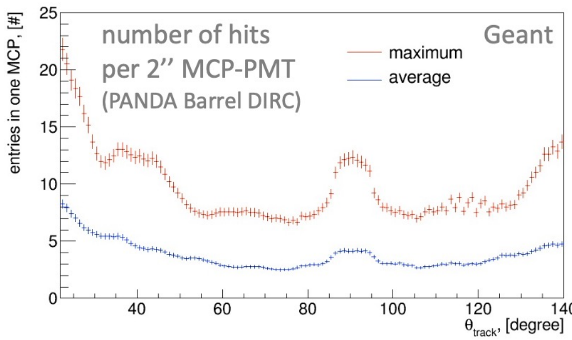
- need low noise rates (coincidence timing very difficult/impossible to use)

Leading candidates: MCP-PMT and SiPM

- see detailed discussion of both sensors types later today



A. Lehmann
RICH2018



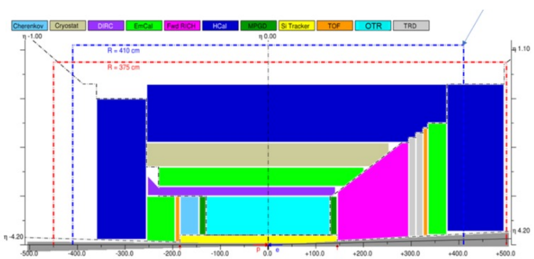
J.S.
ANL MCP-PMT Workshop 2014

Example

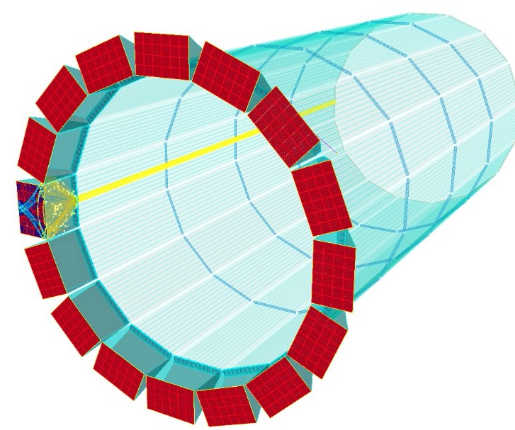
EIC High-Performance DIRC (hpDIRC)

- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation

- being developed by the EIC PID consortium (eRD14), EIC generic detector R&D program;
- push DIRC performance significantly past state-of-the-art, increase π/K range by 50%:
- 3σ π/K separation up to at least 6 GeV/c for rapidity range $-1 \leq \eta \leq +1$ (Cherenkov angle resolution ≤1mrad), add supplemental e/π separation up to 1.2 GeV/c;
- narrow bars for robust performance in high-multiplicity jet events;
- radiation-hard 3-layer spherical lens;
- high-precision tracking, expect 0.5mrad polar angle resolution;
- post-DIRC tracking layer (MPGD) for multiple scattering mitigation;
- selected as baseline hadron PID system for EIC detector barrel (reference detector).

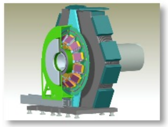


EIC Yellow Report, arXiv:2103.05419



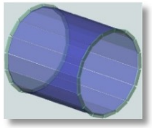
Summary

DIRC counters have become a popular solution for compact hadronic PID.



DIRCs are radially very compact, providing more space for calorimeters or tracking detectors.

BABAR DIRC was the first DIRC, PID for barrel region, very successful, π/K up to ~4 GeV/c (1999-2008).



Prompted DIRC interest by several experiments: Belle II, SuperB, PANDA, GlueX, and others;

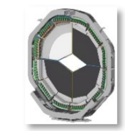
- R&D to make DIRC readout more compact, expand momentum reach, use for endcap.

Very active and complex R&D, applying advances in sensors, electronics, imaging, algorithms.

AI?

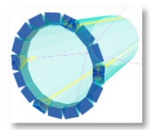
Main R&D directions *(with significant overlap/synergy)*:

- (a) focusing design emphasizing spatial resolution, x&y pixels (fDIRC, GlueX);
- (b) focusing design emphasizing high-precision photon timing (Belle II);
- (c) focusing design with time and space coordinates with similarly high precision (PANDA, EIC).



Exploring mitigation of previously irreducible RICH resolution terms: chromatic dispersion, multiple scattering.

EIC hpDIRC design extends BABAR π/K range by 50%, adds useful e/π separation at low momentum.



Even after 20 years, R&D still very active, pushing the DIRC performance limits further.

Photon Detectors

Gaseous detectors with photocathodes

From Fulvio Tessarotto's presentation:
https://indico.cern.ch/event/999817/contributions/4253049/attachments/2239980/3797597/tessarotto_ECFA_TF4_Gaseous_Photon_Detectors.pdf

General characteristics:

Not commercially available

Most cost-effective solution for covering large area

Minimal material budget

Compatible with magnetic field

3 main technologies for large area:

MWPCs with CsI pad photocathodes (RD-26), CH_4 and fused silica windows

Triple GEMs with CsI coating (HBD), CF_4 windowless

Micromegas and Double THGEMs with CsI coating (COMPASS), CH_4 and fused silica windows

Active field of R&D:

New basic detector architectures

New hybrid combination of technologies

New ideas for specific applications

New materials and procedures

New photoconverters

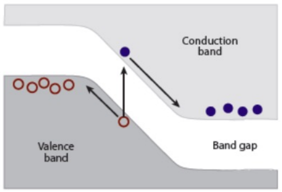
Silicon PhotoMultipliers (SiPM)

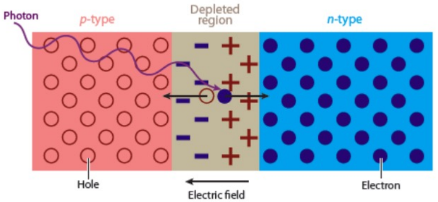
From Samo Korpar' presentation:
https://indico.cern.ch/event/999817/contributions/4253051/attachments/2240249/3798094/TF4-Korpar.pdf

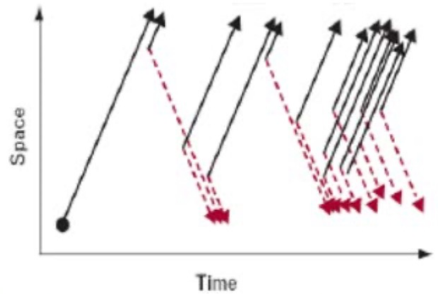
SiPM

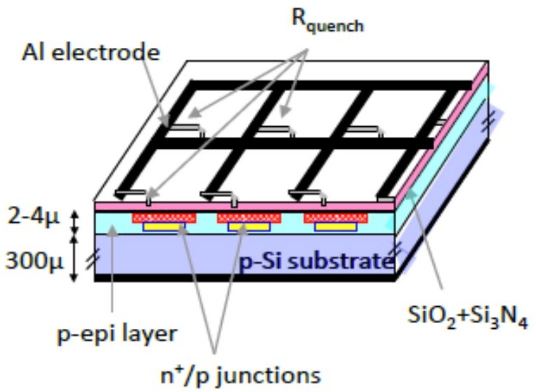
An array of APDs operated in Geiger mode – above APD breakdown voltage (microcells or SPADs – single photon avalanche diodes)

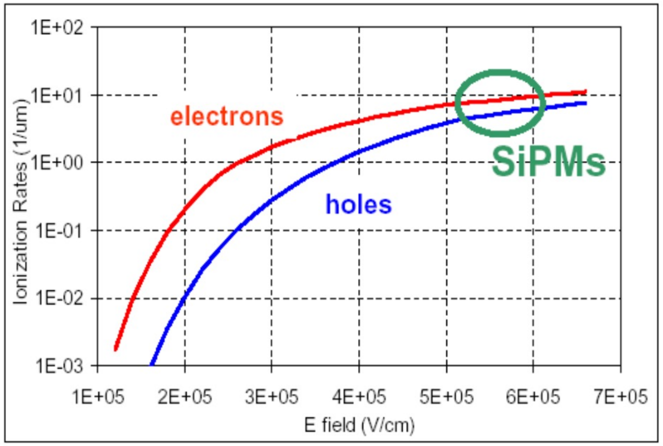
Detection of photons:
- absorbed photon generates electron-hole pair (QE,ϵ)
- avalanche is triggered by the carrier in the high field region (P_{trig}) $\rightarrow$ signal
- voltage drops below breakdown and avalanche is quenched (passive or active quenching)
- each triggered microcell contributes same amount of charge to the signal

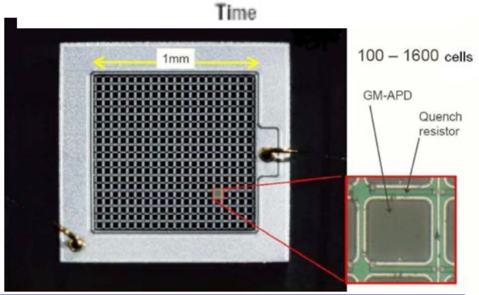












Silicon PhotoMultipliers (SiPM)

Summary and outlook

- SiPMs have some very nice properties: low operation voltage, high PDE, high gain, excellent timing, insensitive to magnetic field, easy to operate, not damaged by operation at ambient light ...,
- and some drawbacks : high dark count rate, gain variation with temperature, sensitive to neutron irradiation ...

- Intrinsic timing resolution $< 20\,ps$ FWHM can be achieved for single SPAD timing resolution of SiPM is affected by large device capacitance and optical cross-talk effects.
- Further improvement of timing with electronics integration at SPAD level.

- Light concentrators can be used to improve S/N and timing at the device level and micro-cell level $\longrightarrow$ optimisation of light concentrators

- More compact detector design using high resolution of SiPMs to improve S/N

- Main problem for HEP applications is increase of dark count rate with neutron irradiation! $\longrightarrow$
  - optimisation for high radiation environment
  - search for new material with reduced DCR

MCP-PMT

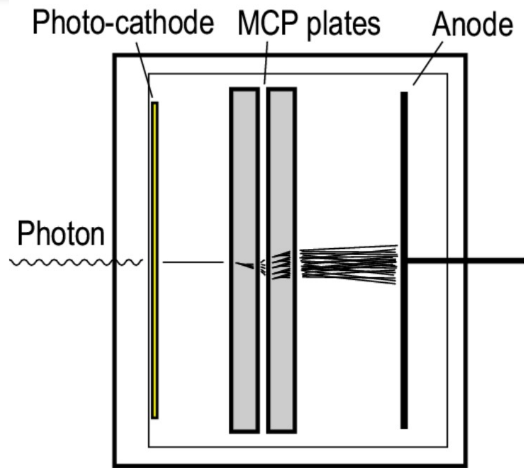
From Kenji Inami’s presentation:
https://indico.cern.ch/event/999817/contributions/4253050/attachments/2240234/3798061/20210506MCP_inami_s.pdf

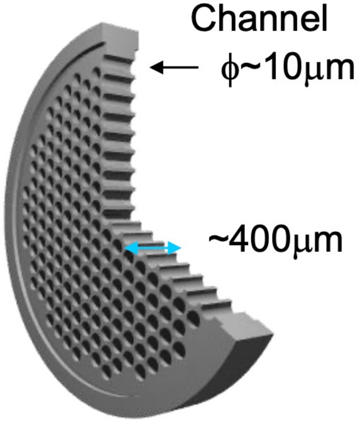
- Micro-Channel-Plate
  - Tiny electron multipliers
    - Hole diameter 6~25μm, length ~400μm
  - High gain
    - ~10^6 for two-stage type

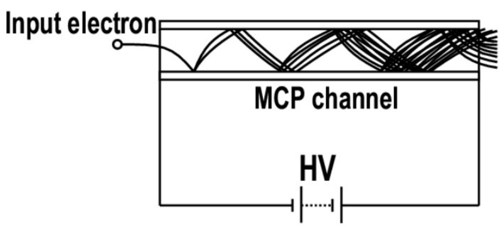
  → Fast time response

  Pulse rise time <400ps

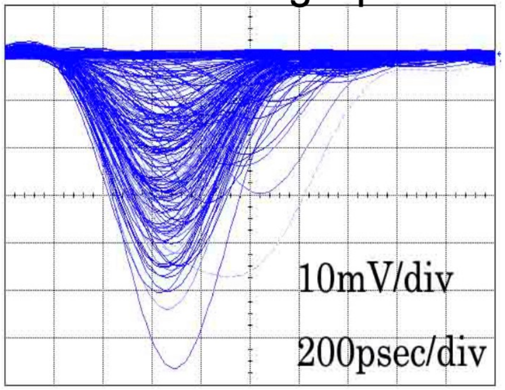
  Timing resolution < 50ps for single photon
  - can operate under high magnetic field (~1T)
  - Atomic-Layer-Deposition technique for current production







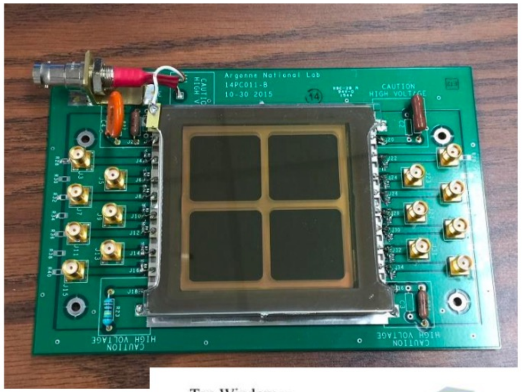
Single photon

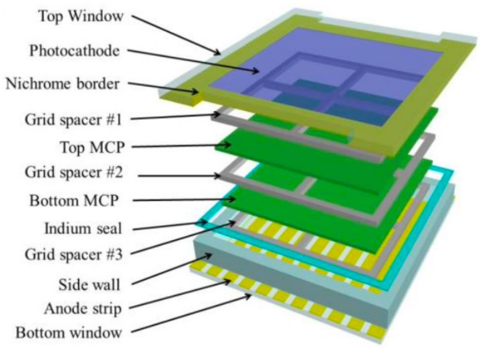


MCP-PMT

Nucl . Instr. Meth. A 936 (2019) 527 531

- LAPPD project aims to achieve low cost, large area (20 cm x 20 cm) with picosecond timing.
- Applications: picosecond timing, mm spatial resolution on large area
  - Particle physics: optical TPC, TOF, RICH
  - Medical imaging: PET scanner, X ray imaging devices
  - National security: Detection of neutron and radioactive materials
- Small LAPPD (6 cm MCP-PMT) was produced at Argonne for R&D. Knowledge's, Design and Experiences were transferred to Incom to support commercialization of 20 cm LAPPD™.
- Production for several experiments started.
  - 20μm pore size, strip line readout
- Gen II; Capacitive-coupled readout (pixel readout)





MCP-PMT

- MCP-PMT shows very fast timing response for single photon.
  - Gain~10^6, TTS<40ps for single photon detection
  - Useful for RICH/TOF detectors
- Large square-shape MCP-PMT is being developed.
  - Hamamatsu 1-inch; Mass production for Belle-II TOP
  - Photonis, Photek; 2-inch PMTs in commercial
  - Incom started 20cm LAPPD production for several experiments.
- ALD technique improves photocathode lifetime.
  - Now standard.
  - Lifetime is achieving >15 C/cm^2

    → Applicable for coming high intensity experiments

    - Need continuous improvement for future

Superconducting Devices

From Sae Woo Nam's presentation:
https://indico.cern.ch/event/999817/contributions/4253054/attachments/2240354/3798324/TF4_Nam.pdf

Conventional Single-Photon Detectors

	Wavelength Range	QE (%, max)	DCR (cps)	Jitter	Max Count Rate (cps)
PMT (visible)	400-900 nm	40	100	300 ps	10×10^6
PMT (IR)	1000-1600 nm	2	200K	300 ps	10×10^6
Silicon (thick)	400-1050 nm	65	25	400 ps	10×10^6
Silicon (thin)	400-1000 nm	49	25	35 ps	10×10^6
InGaAs APD	950-1600 nm	20	75K	350 ps	10×10^3

- Commercially available
- Relatively inexpensive

Superconductors

	Wavelength Range	QE (%, max)	DCR (cps)	Jitter	Max Count Rate (cps)
W-TES (NIST)	UV-2 um	>98%	$<<10^{-5}$	10-100 ns	100×10^3
SNSPD: NbN	UV-5 um	>90%	100-1000	~3 ps	100×10^6
SNSPD: WSi	UV-5 um	~98%	$<<10^{-5}$	~5 ps	10×10^6
MKID	UV-2 um	~30%	low	~1 us	100×10^3

Useful for dark matter search!

- No afterpulsing problems
- Excellent prospects for longer wavelengths

Summary and Outlook

- It is impossible to provide detailed information on each detector/component, please find more details in https://indico.cern.ch/event/999817/
- There are many interesting and open areas for photon and PID detectors
- Personally, I think that developing advanced SiPM and quantum sensing are two good directions in Taiwan