ECFA
European Committee for Future Accelerators

ECFA R&D Roadmap symposium, 6 May 2021
TF4 *Particle Identification and Photon Detectors*

Time-of-flight technologies

Roger Forty (CERN)

Introduction
1. Scintillator
2. Gaseous
3. Silicon
4. Cherenkov

General considerations

Introduction

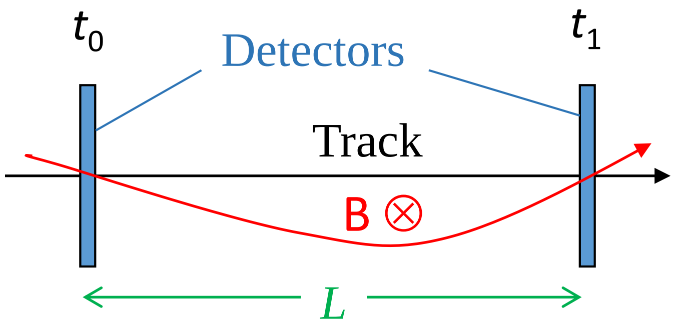
- Time-of-flight principle is *conceptually simple*: measure difference in arrival time of particle at two planes $t = t_1 - t_0$ then velocity: $\beta = L / ct$
- Combine with a measurement of its momentum: $p = \beta\gamma mc$
  Mass of particle can then be calculated:

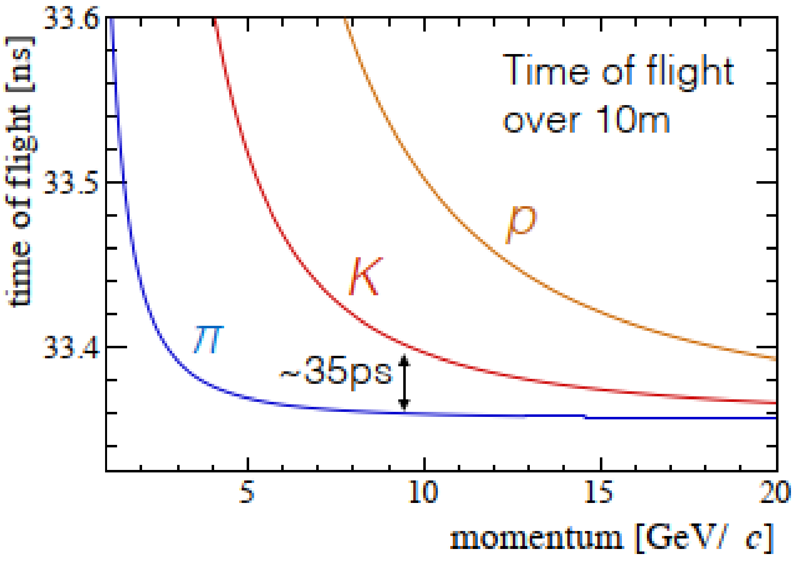
$$m^2 = \frac{p^2}{c^2}\left(\frac{c^2t^2}{L^2} - 1\right)$$

$$\left(\frac{\delta m}{m}\right)_p = \frac{\delta p}{p},$$

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

- 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: $N_\sigma \approx \dfrac{|m_1^2 - m_2^2|\, L}{2\, p^2\, \sigma_t\, c}$

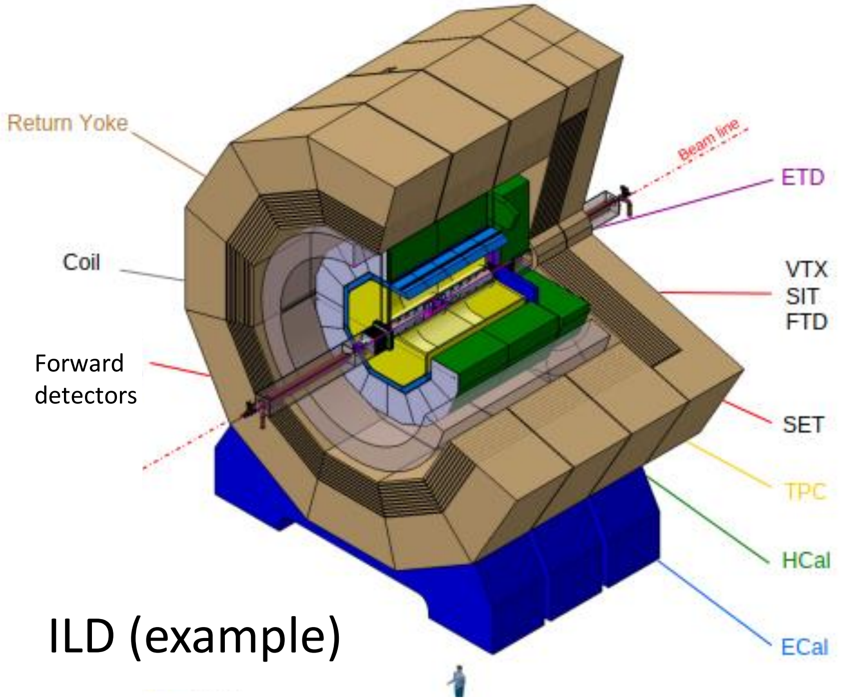




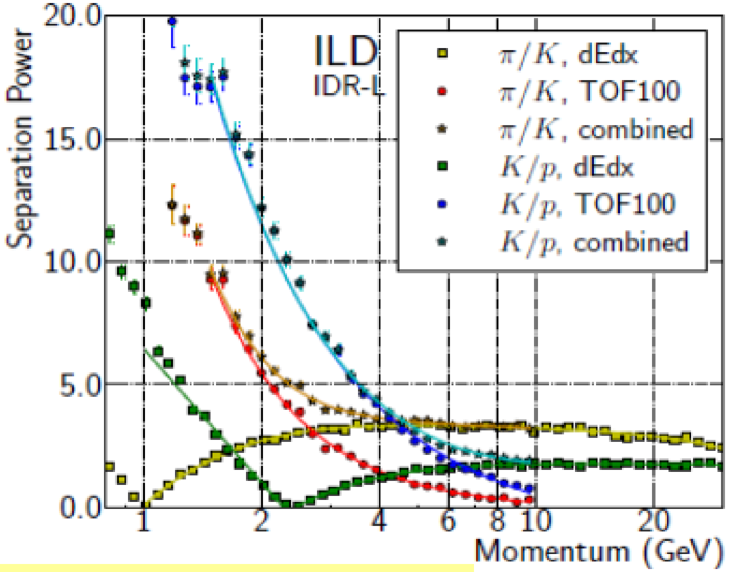
Motivation (1)

- European Strategy for Particle Physics: the next future collider should be an **e^+e^- Higgs factory** → expect this to be a focus for the R&D Roadmap
- Dedicated particle identification detectors have been absent from the designs of experiments, until recently — main focus has been on Particle Flow calorimetry and lepton ID, rather than hadron ID
- However, they do all feature excellent *dE*/*dx* from tracker (or even more performant cluster counting *dN*/*dx*)

  Drawback for particle ID is region where *dE*/*dx* curves cross at around 1-2 GeV for p-K-π separation
- Combination of a modest TOF detector can cover this hole, provides PID up to a few GeV, complemented with *dE*/*dx* at higher momenta
- Here assumed 100 ps/hit, over 10 layers of calorimeter



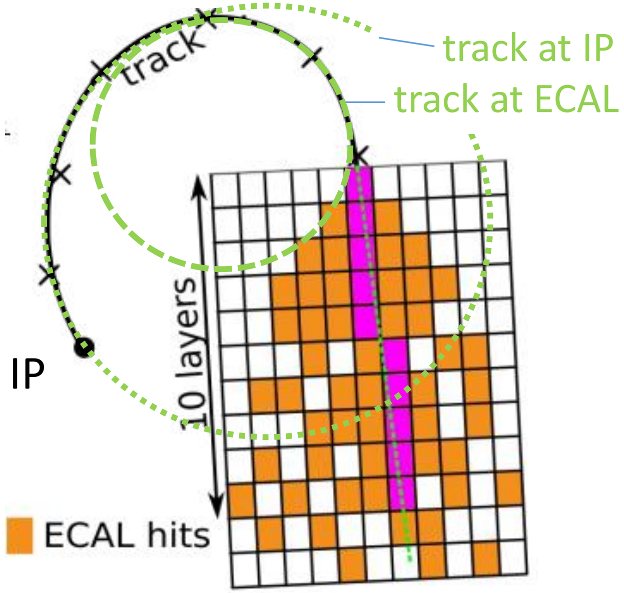
ILD (example)

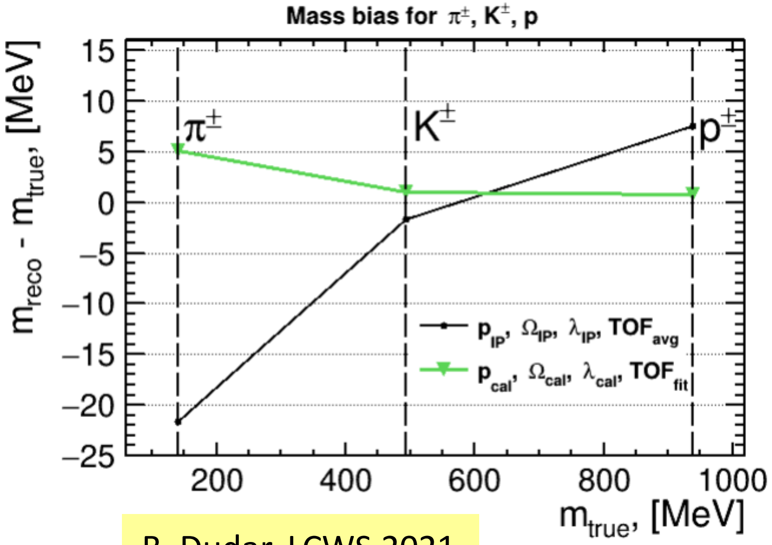


ILD Interim Design Report 2020

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

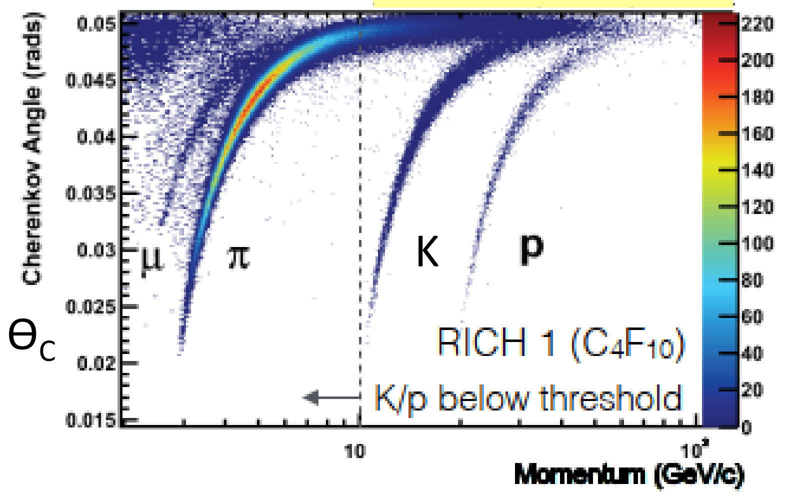
Motivation (2)

- Highest priority of ESPP is of course the full exploitation of the LHC
  Upgrades of **ATLAS** & **CMS** for HL-LHC: R&D now ≈ complete
  However, future upgrades still planned: for **LHCb** & **ALICE** at least
- Excellent hadron ID is essential for **flavour** physics, and there is an broad future programme planned—likely to increase in priority if recent evidence of Lepton Flavour non-Universality persists
- **RICH** detectors are the technology of choice at high momentum
  But limited coverage <10 GeV with gas radiators (unless pressurized)
  Silica **aerogel** as radiator might cover the low-momentum end, but (due to its low density) gives few photons, difficult reconstruction in the busy environment of the LHC → abandoned by LHCb
- Pushing TOF to *10 ps per track* over 10 m path would cover region up to 10 GeV for K-π separation → target for LHCb future upgrade
- One can dream of pushing further towards the *picosecond* level
  → cover the full range of particle ID required, with a single system

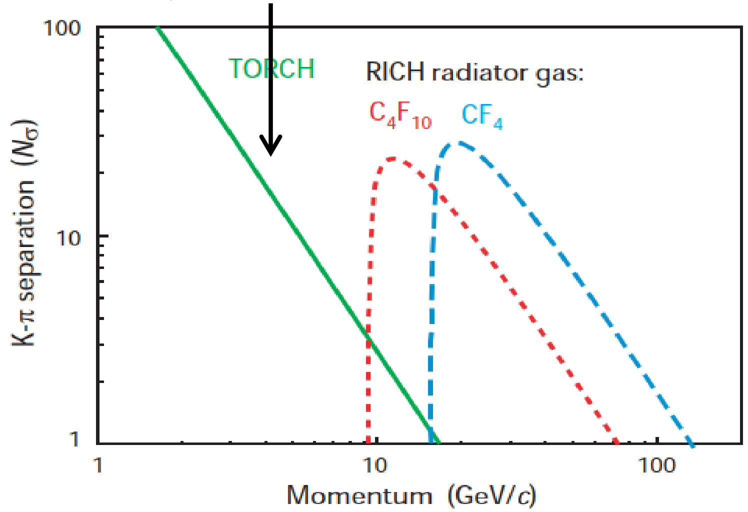
(but bear in mind, 1 ps = 300 μm at the speed of light)

LHCb RICH

EPJC 73 (2013) 2431

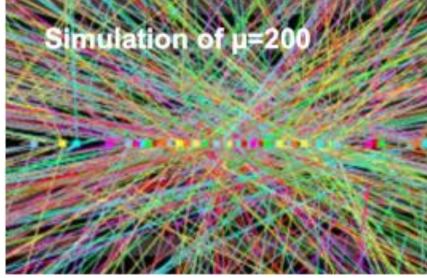


10 ps TOF over 10 m

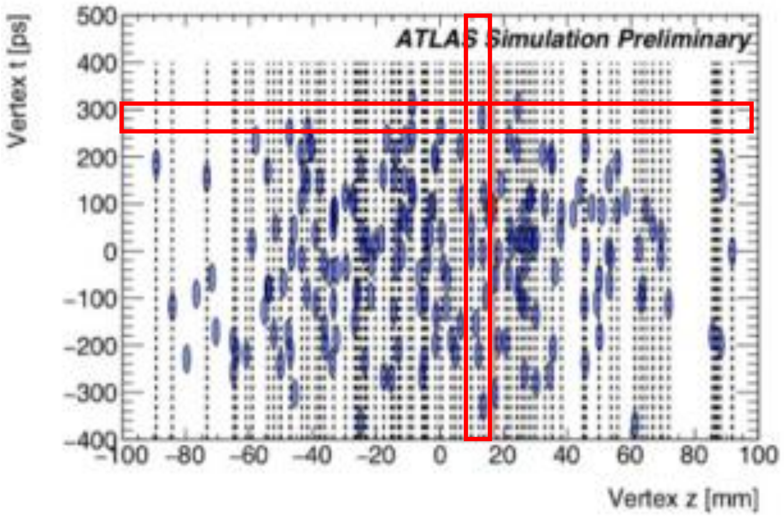


Fast timing

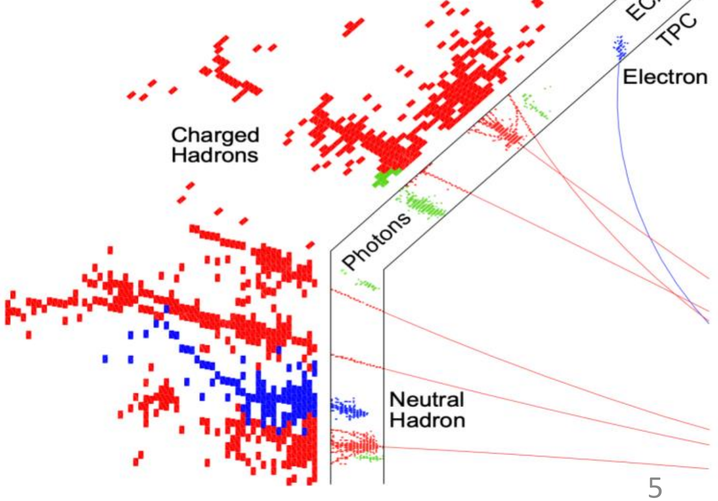
- Fast timing has *many* other applications beyond TOF particle ID
- A fast timing revolution is underway, as detectors that traditionally have been spatially segmented now add time as an extra dimension: typical target is 30–50 ps resolution/MIP
- This has been driven by **pile-up** suppression in hadron colliders —in particular the unprecedented challenges of the HL-LHC: signal events will have up to 200 min-bias collisions superposed
  Can be separated by binning in *time* as well as *space*
- **4D tracking** (*x,y,z,t*), and **5D calorimetry** (*x,y,z,t,E*):
  Contribution to tracking pattern recognition, shower analysis—imagine going from a static image of showers, to a movie where neutral hadrons arrive later than the photons, etc.
- Timing can also extend physics reach, e.g. for long-lived particle (**LLP**) reconstruction—a booming field of dark sector searches
- This extends well beyond the TOF application (e.g. see ≈ all of the other task forces) → should drive synergy in the R&D roadmap



Vertexing at HL-LHC



Particle flow calorimetry



Resolution

~40 ps = 25 ⊕ 25 ⊕ 15 ps

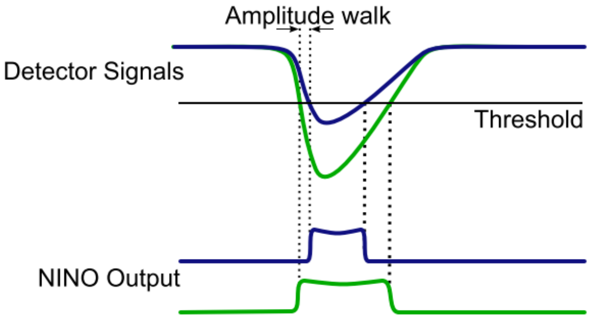
[target resolution for timing layer, ATLAS-TDR-031]

- Contributions to timing resolution: $\sigma^2_{\text{total}} = \sigma^2_{\text{det}} + \sigma^2_{\text{elec}} + \sigma^2_{\text{clock}}$
  - Example of LHC end-cap timing layers: the **detector** contribution σ_{det} comes from Landau fluctuations in the silicon sensors
  - The **electronics** contribution σ_{elec} has following components:

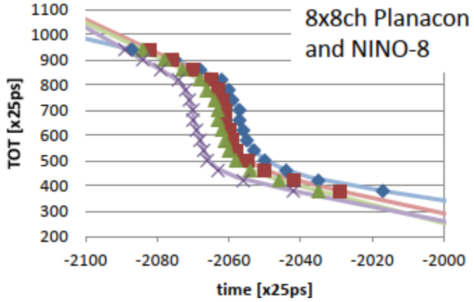
$$\sigma^2_{elec} = \underbrace{\left(\frac{t_{rise}}{S/N}\right)^2}_{\text{Jitter}} + \underbrace{\left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2}_{\text{Time walk}} + \underbrace{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2}_{\text{TDC binning}}$$

  - Need fast signal and excellent *S*/*N*
    LGAD gain: increase signal *S*, but keep noise *N* under control
    Contribution from the TDC bin width, must also correct for integral non-linearity (INL, from uneven bin sizes)
  - The **clock** contribution (needed to synchronize detector) σ_{clock}
- *Other contributions:* transit-time spread (TTS) in photodetectors, pixel size, emission point of photon in radiator, start-time t_0, chromatic effects, cross-talk, etc. → Careful calibration is essential

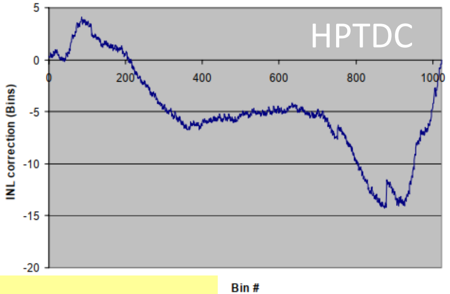
Amplitude → time-over-threshold



Time-walk *vs* TOT



INL: periodic over 1024 bins = 25 ns



J. Schambach, nucl-ex/0305035

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

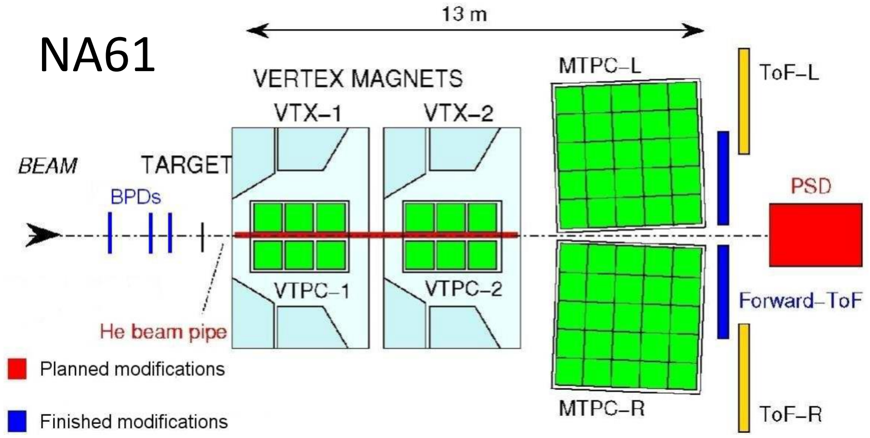
1. **Scintillators:** classic solution, now developed for timing layers (TF5+6, SiPM)
2. **Gaseous detectors:** multigap RPCs, new ideas to push timing resolution with MPGDs (TF1)
3. **Silicon detectors:** recent development of LGADs for end-cap timing layers (TF3, LGAD)
4. **Cherenkov-based detectors:**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

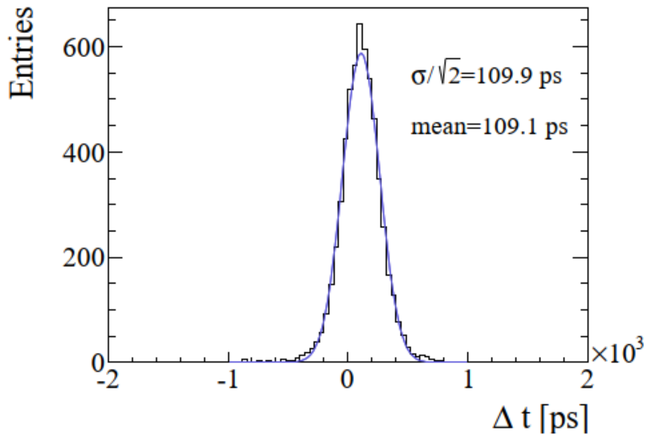
- Cannot cover exhaustively, instead selected a few examples to illustrate detector systems (*existing / in preparation / future development*) for each technology
  + will have to pass quickly over detectors that have been covered elsewhere
- Tried to include detectors mentioned in the questionnaire responses, apologies for any omissions
  + bias toward experiments discussed at CERN—this symposium is opportunity to gather missing input

  Disclaimer: references given to where information collected, rather than original sources
  —thanks to all who have provided material

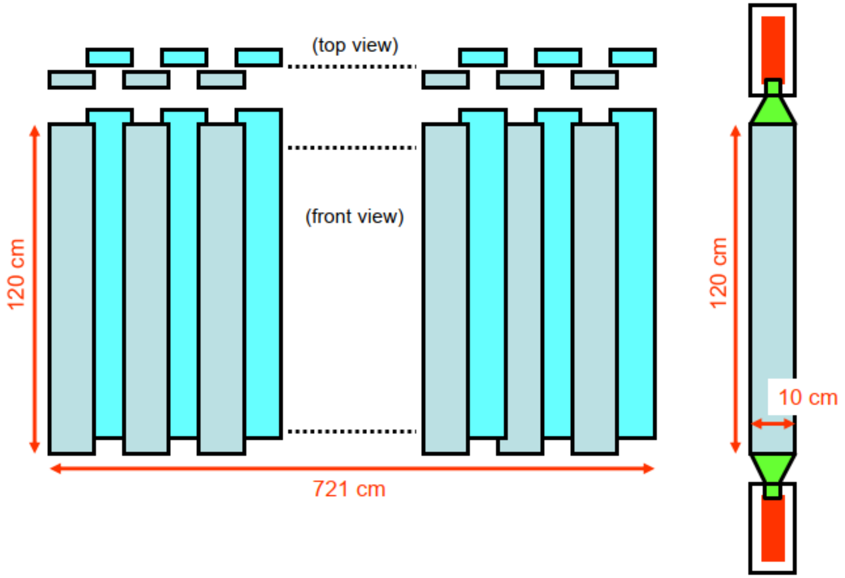
1. Scintillators

- Fixed-target experiments have geometry well adapted to TOF
  Take as example **NA61** (SHINE), flight distance 13 m
- Most recently added scintillator hodoscope: Forward-ToF
  2.5 cm-thick bars of plastic scintillator (Bicron BC-408)
  rise time 0.9 ns, decay time 2.1 ns, attenuation length 210 cm
- Read out at both ends with with fishtail PMMA light-guides to 2″ photomultipliers (Fast-Hamamatsu R1828)
- TOF resolution ~110 ps

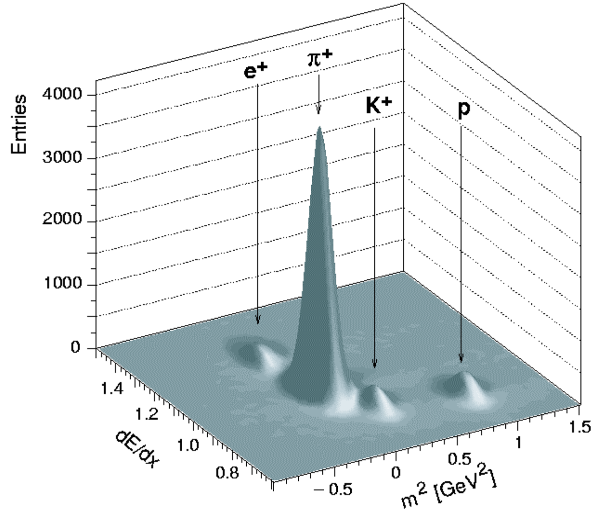




N Abgrall et al 2014 JINST 9 P06005



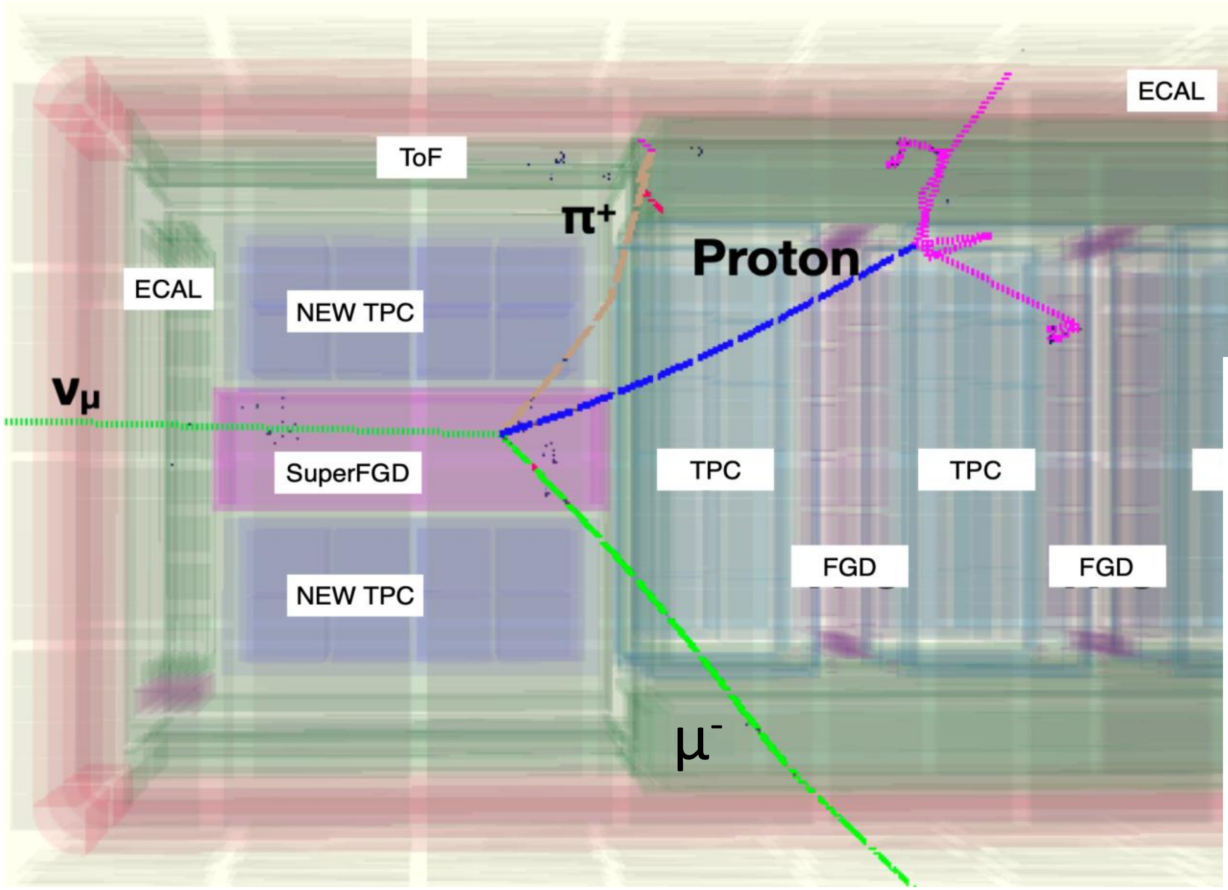
dE/dx + TOF combined (5-6 GeV, NA49 Pb-Pb)



S. Afanasiev et al., CERN-EP/99-001

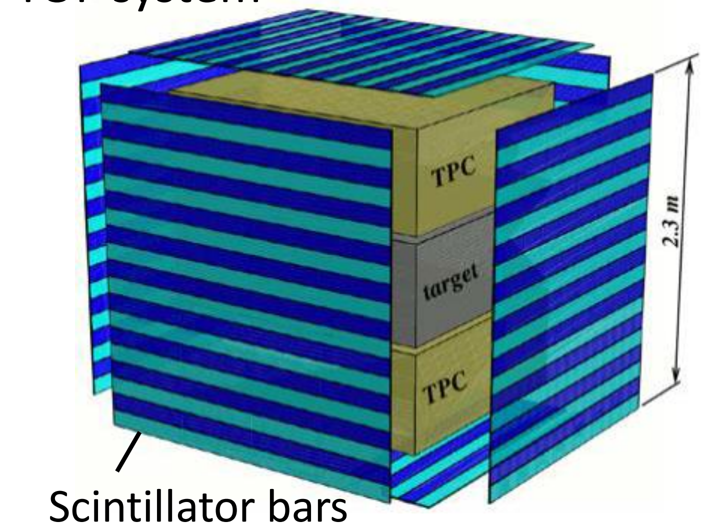
T2K Near Detector upgrade

- The near detector of T2K (long-baseline ν experiment) is being upgraded



Simulated ν interaction in **ND280**

TOF system



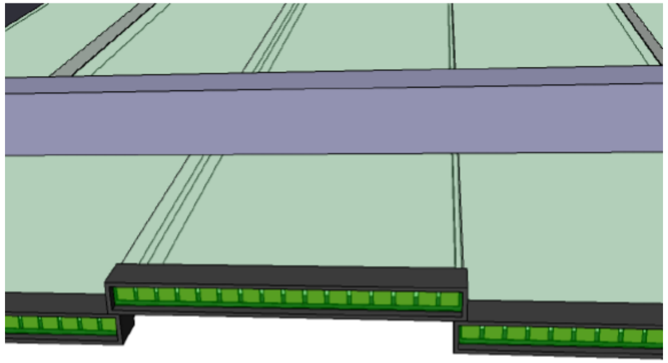
Scintillator bars

T2K Near Detector upgrade

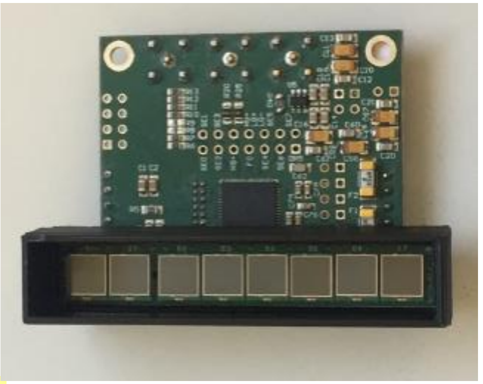
- The near detector of T2K (long-baseline ν experiment) is being upgraded
- TOF system required to give unambiguous determination of the flight direction of charged particles, to ensure tracks come from ν interaction
- I cm-thick cast plastic scintillator bars (EJ-200) read out by array of large area SiPM (6 × 6 mm^2 Hamamatsu S13360-6050PE MPPC)
- **SiPM:** compact, robust, insensitive to B field, operate at low voltage, low power consumption, photodetection efficiency up to 40%; *Drawbacks:* high dark count rate (DCR), radiation sensitivity → cooling

Similar solution explored for PANDA TOF, with smaller scintillator tiles/rods

Overlapping scintillator bars



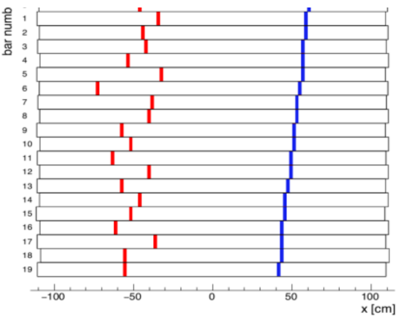
SiPM array (MUSIC readout)



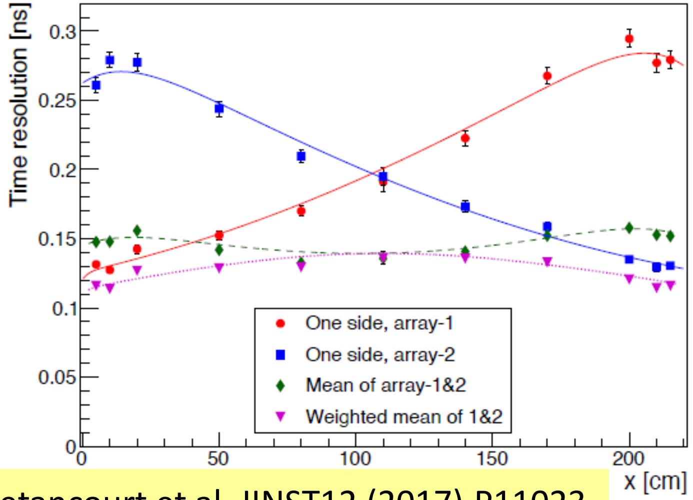
T. Lux, SPSC 13/4/21

Constructed planes

Cosmic events

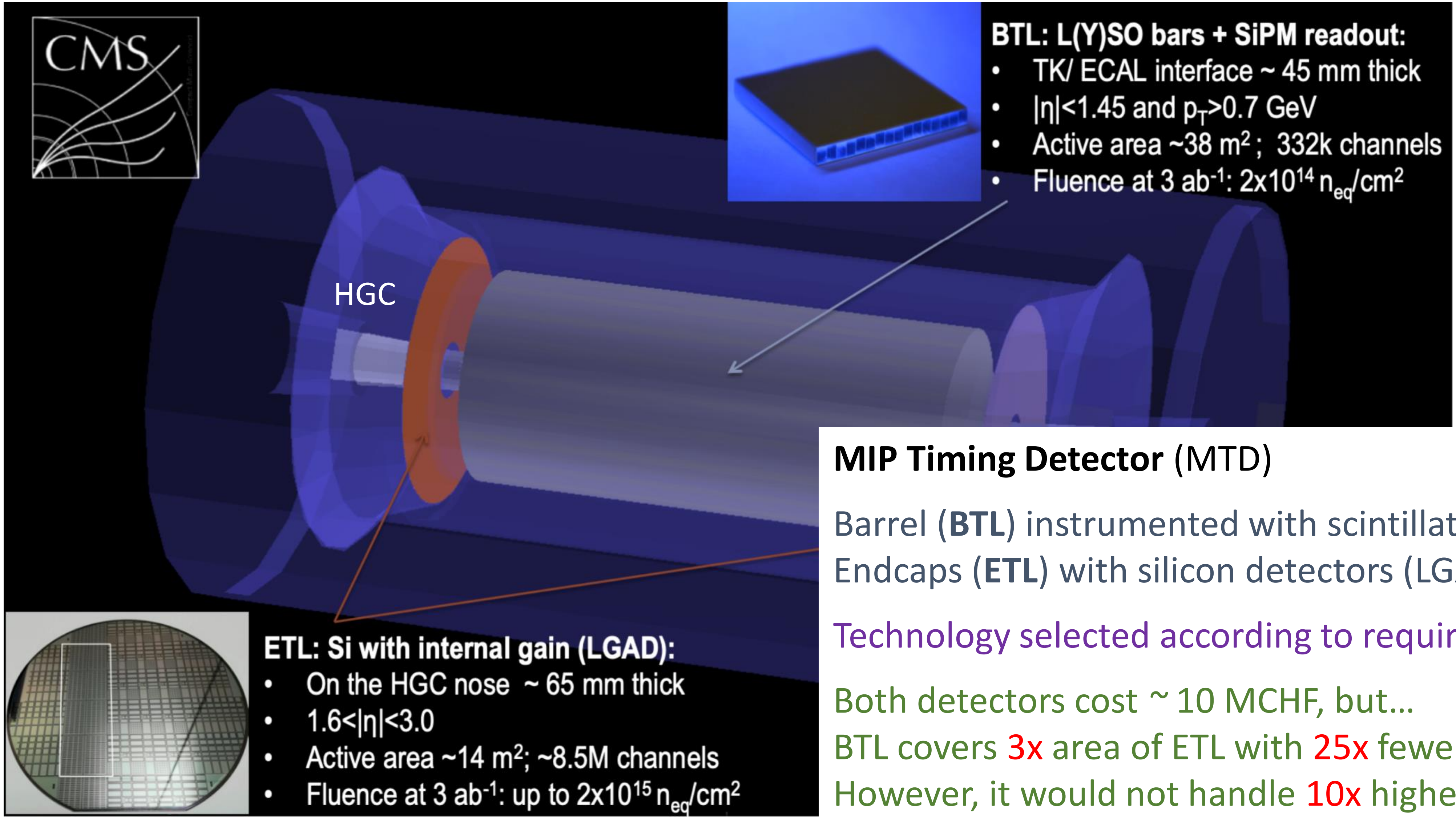


~ 130 ps resolution



C. Betancourt et al, JINST12 (2017) P11023

CMS Timing Layer



BTL: L(Y)SO bars + SiPM readout:
- TK/ ECAL interface ~ 45 mm thick
- $|\eta|<1.45$ and $p_T>0.7$ GeV
- Active area ~38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2

ETL: Si with internal gain (LGAD):
- On the HGC nose ~ 65 mm thick
- $1.6<|\eta|<3.0$
- Active area ~14 m^2; ~8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

MIP Timing Detector (MTD)

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

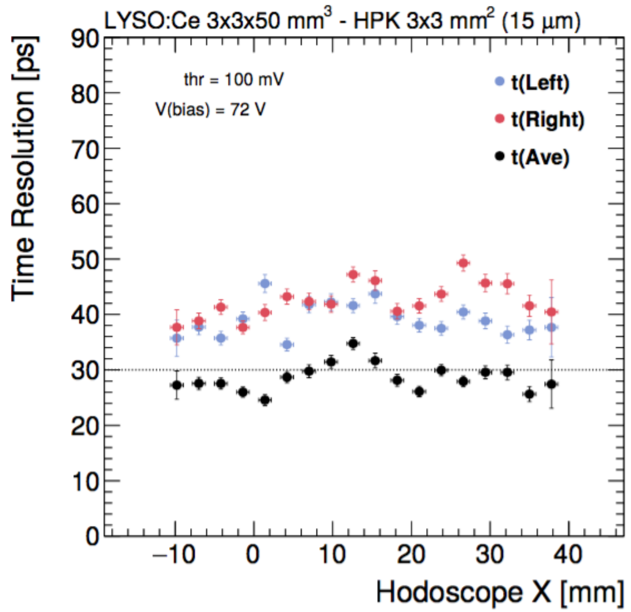
Technology selected according to requirements:

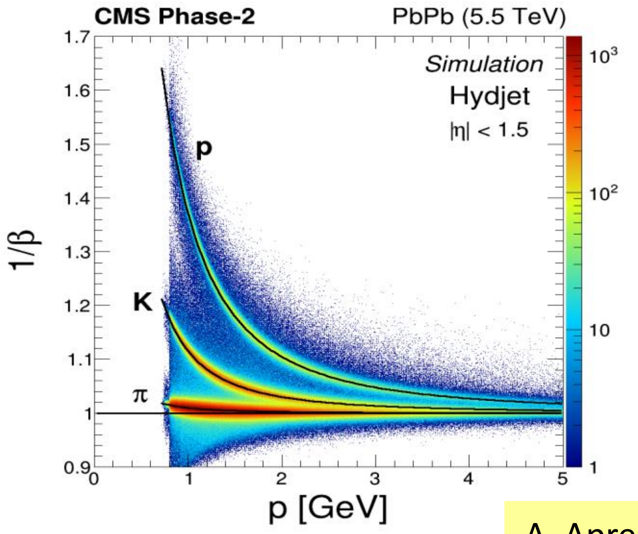
Both detectors cost ~ 10 MCHF, but…
BTL covers 3x area of ETL with 25x fewer channels
However, it would not handle 10x higher radiation

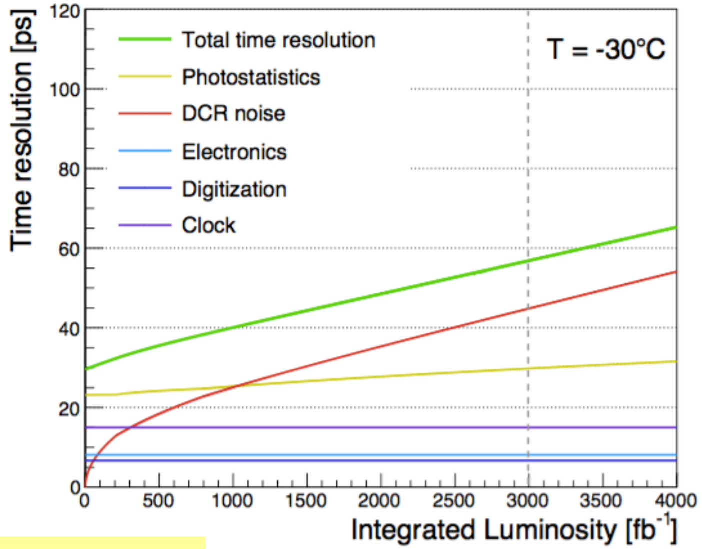
CMS Barrel Timing Layer

- **Faster scintillators:** LYSO:Ce (Lutetium Yttrium Orthosilicate crystals doped with Cerium): excellent radiation tolerance, high light yield (~ 40,000 photons/MeV), fast scintillation rise-time (< 100 ps), relatively short decay-time (~ 40 ns)
- Well-established in **PET** scanners: excellent cross-fertilization! TOF also very relevant there: provides resolution along line-of-flight
- **166k** LYSO crystals readout with SiPMs at each end, attached to the inner wall of Tracker Support Tube (*r* = 1.15 m, length = ±2.6 m) → has to be installed before tracker
- Thermoelectric coolers to improve SiPM radiation tolerance: run at -45°C
- Time resolution: 35 ps at start and 60 ps by the end of HL-LHC

  Time-of-flight particle ID as a "bonus": 2σ K-π separation up to *p* ~ 2 GeV



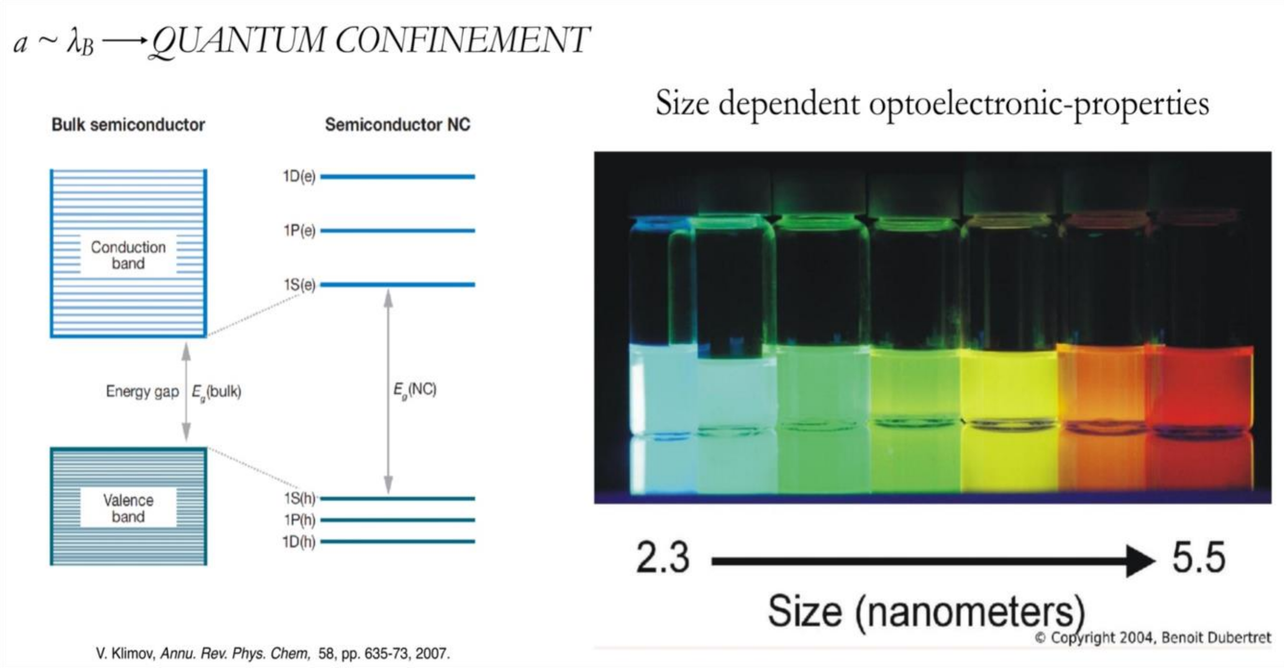




A. Apresyan, LCWS2021

Quantum fast-scintillator R&D [see TF5]

- Colloidal Quantum Dots irradiated with a UV light: different sized nanoscale dots emit different colours of light due to quantum confinement
- Semiconductor scintillator based on InAs Quantum Dots functioning as luminescence centres embedded in a GaAs matrix can have uniquely fast scintillation properties with low self-absorption



V. Klimov, *Annu. Rev. Phys. Chem,* 58, pp. 635-73, 2007.

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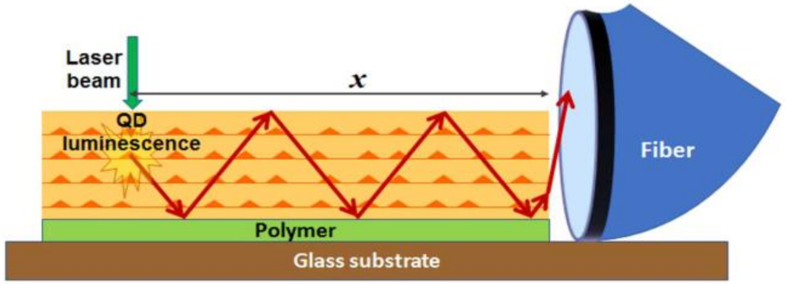
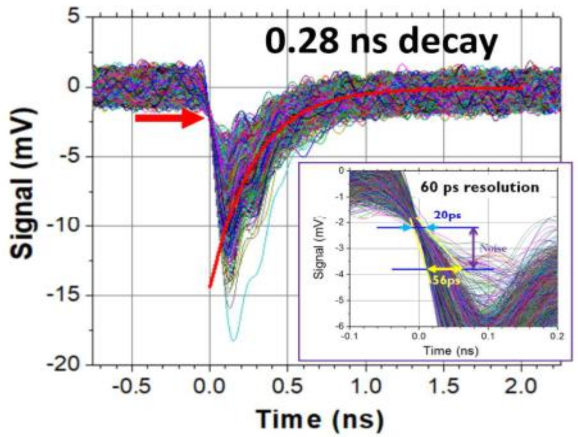
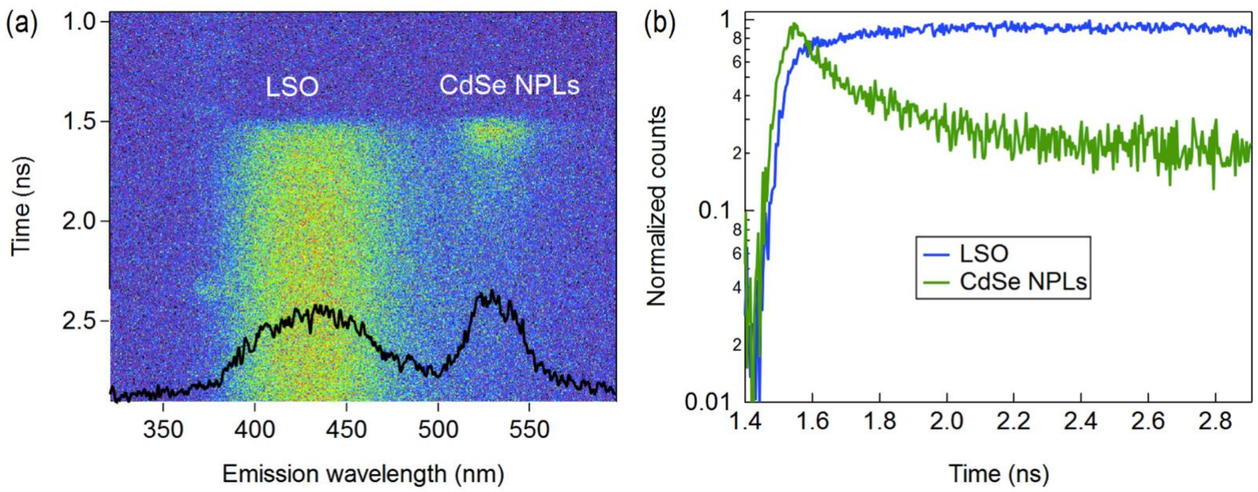


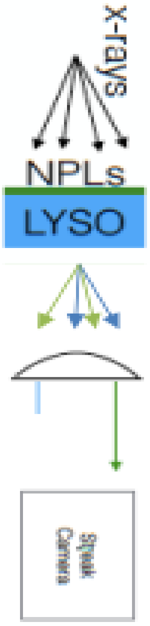


K. Dropiewski et al, NIMA 954 (2020) 161472

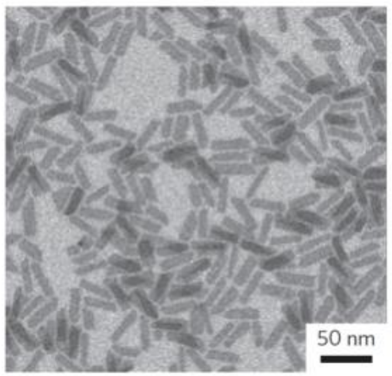
Quantum fast-scintillator R&D [see TF5]

- Colloidal Quantum Dots irradiated with a UV light: different sized nanoscale dots emit different colours of light due to quantum confinement
- Semiconductor scintillator based on InAs Quantum Dots functioning as luminescence centres embedded in a GaAs matrix can have uniquely fast scintillation properties with low self-absorption
- Related R&D pursued by **RD18** (Crystal Clear) [see E. Auffray, TF5]
  CdSe nano-platelets deposited on LYSO substrate → faster response
- Challenge to produce large-scale samples: **3D printing** of scintillator being investigated, to produce arbitrary shapes



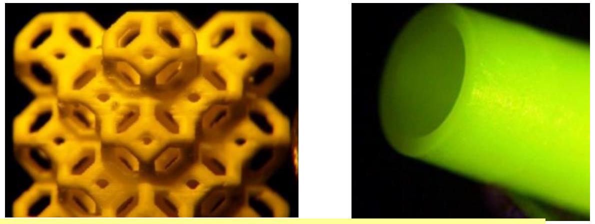


Cadmium selenide nano-platelets



R. Turtos et al., JINST 11 (2016) P10015

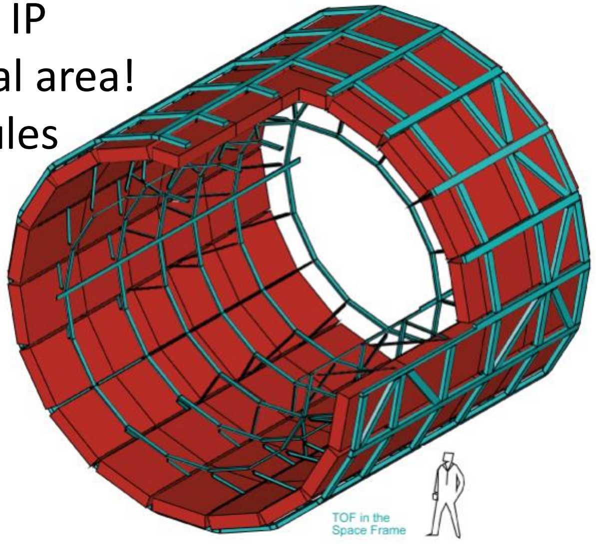
YAG (voxel size ~ 50 x 50 x 10-50 μm)



G. Dossovitky, Kurchatov Institute

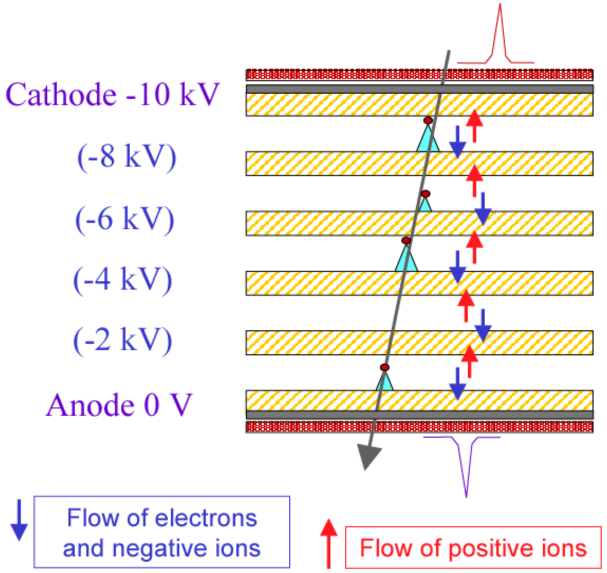
2. Gaseous detectors [see TF1]

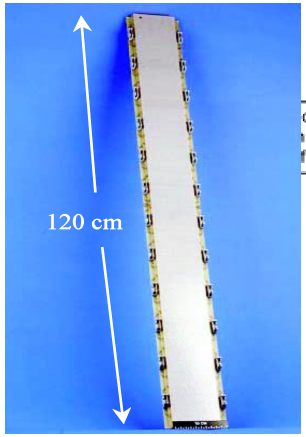
3.7 m from IP
150 m^2 total area!
1638 modules

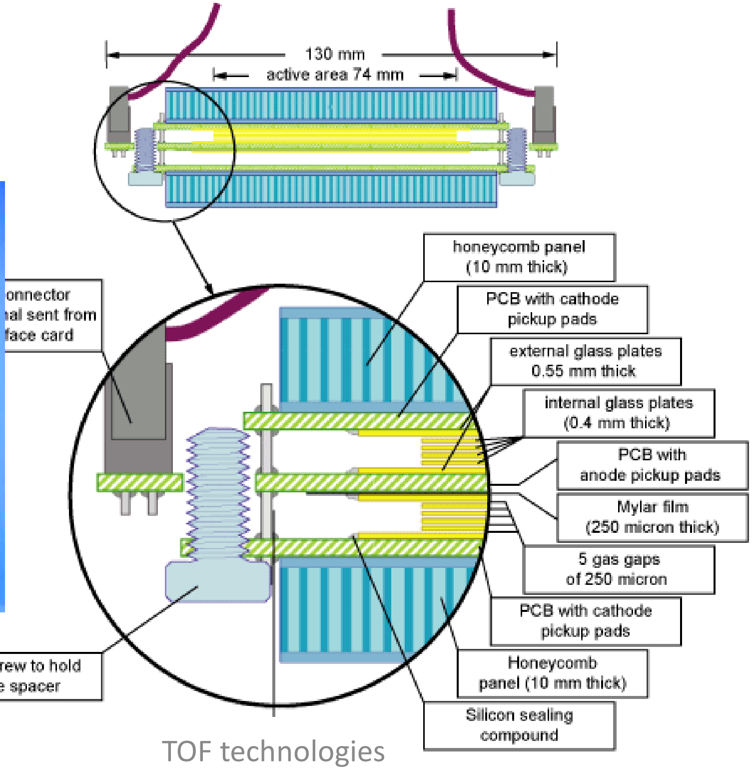


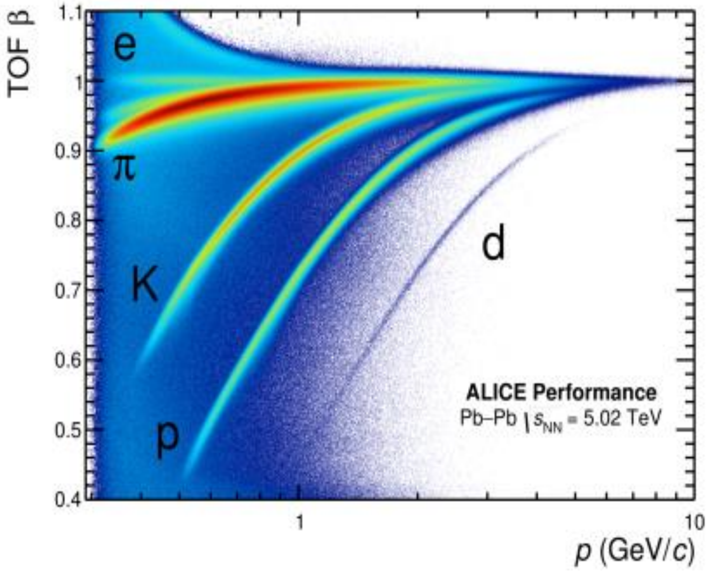
- **Multi-gap RPC** well-established technique, excellent timing, easily segmented, work in strong magnetic field, relatively easy to build e.g. **ALICE TOF**
- Stacks of 1 mm glass plates, total of 10 gas gaps of 250 μm
  High resistivity plates required (> 10^{10} Ωcm) to limit discharge area
- Gas used is $C_2F_4H_2 + SF_6 + C_4H_{10}$
- Timing resolution 56 ps achieved

F. Carnesecchi, arXiv:1806.03825







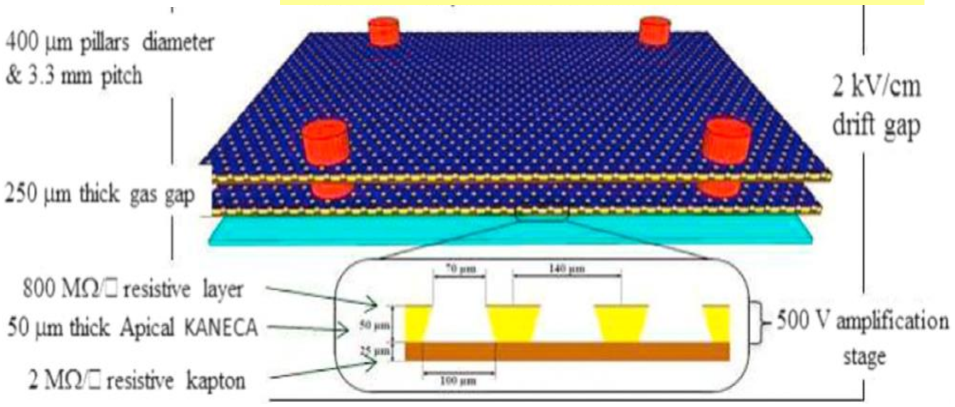


Gaseous-detector R&D

- **MRPC** are in widespread use for TOF systems: upgrade of NA61, proposals SHiP and Water Cherenkov Test Experiment @CERN
  HADES@GSI, EMPHATIC@Fermilab, E50@J-PARC, BGOegg@Spring-8, CBM, STAR…
- Developments towards:
  - faster timing (e.g. increasing number of gaps)
  - Higher rate capability: managing gas flow, glass resistivity
- Fast timing micro-pattern gas detectors also being developed e.g. FTM based on the μ-RWELL structure [see P. Verwilligen, TF1]

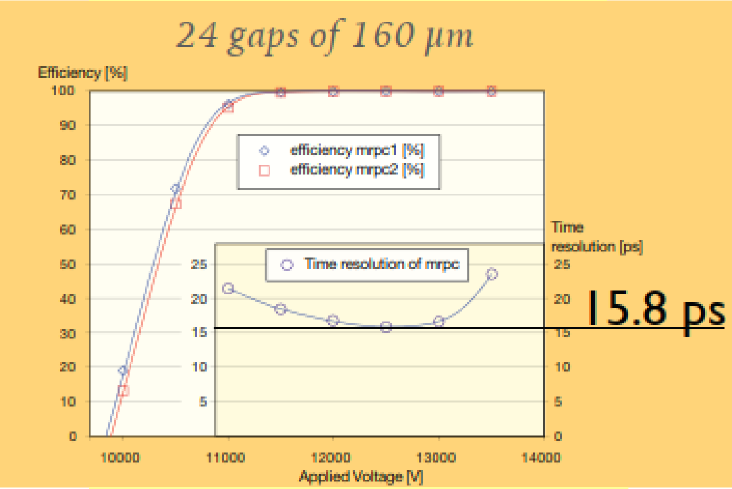
FTM

M. Poli Lener et al, NIMA 824 (2016) 565

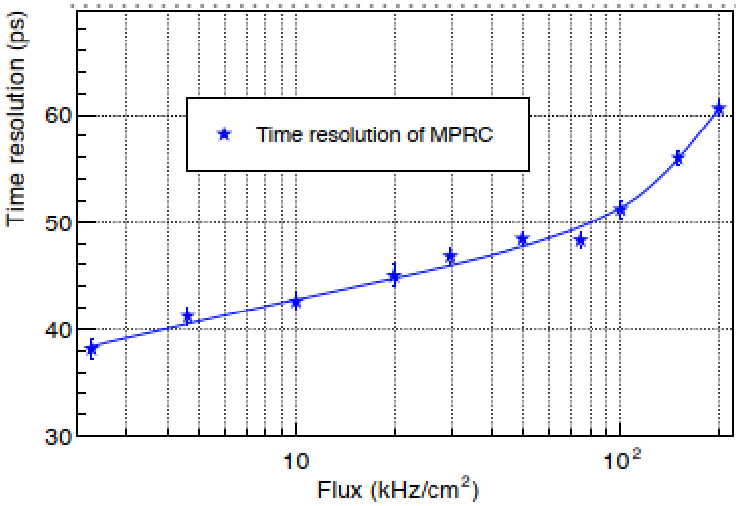


- ~300 ps resolution seen for simulation [Y. Maghrbi et al, NIMA 954 (2020) 161666]
- Alternative approach: couple Cherenkov radiator to MPGD

S. An et al, NIMA 594 (2008) 39



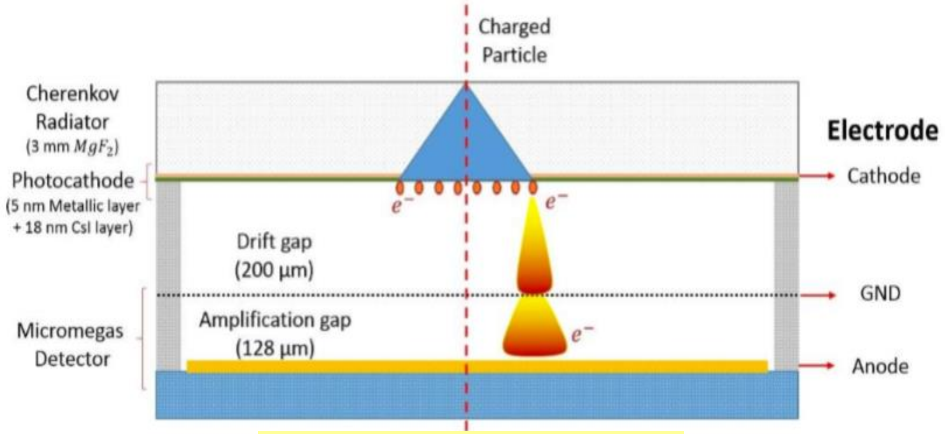
C. Williams, AIDAinnova 14/4/21



PICOSEC development

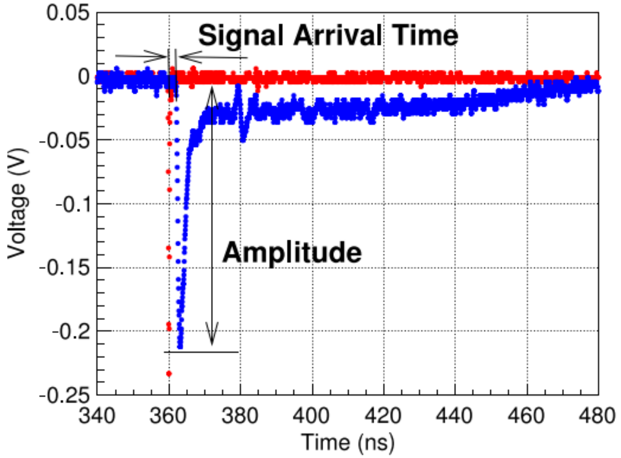
- Hybrid detector: Cherenkov signal (CsI PC) amplified via MPGD
  Developed with **RD51** [see next talk, F. Tessarotto]
- Micromegas: 80% Ne + 10% C_2H_6 + 10% CF_4 (COMPASS gas)
  Signal has two distinct components: fast electron peak (≈ 0.5 ns) slow ion tail (≈ 100 ns)
- Now working on detector stability, photocathode robustness (DLC, nano-diamond), large-area coverage: 10x10 pad module planned

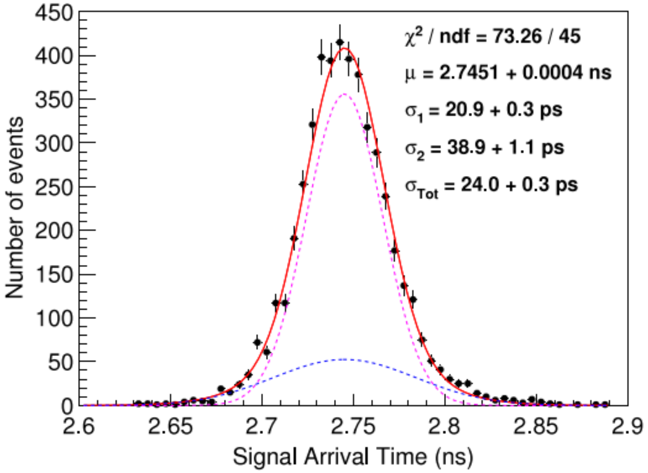
Considered for muon system of ENUBET (R&D for tagged ν beam)



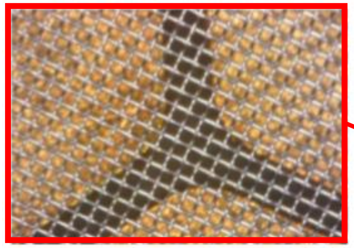
F. Brunbauer, INSTR-2020

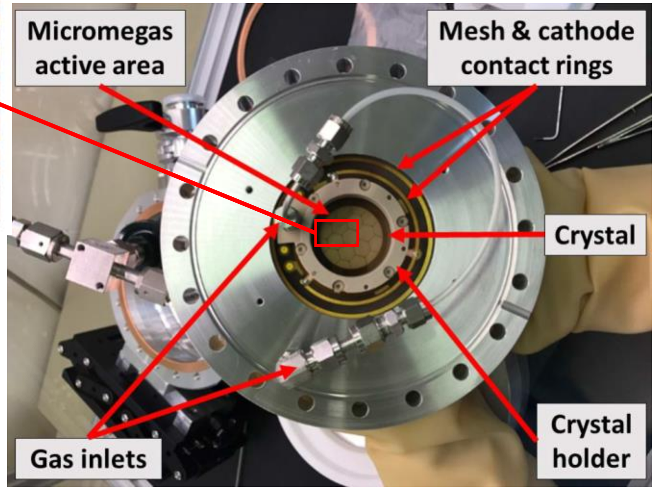
Multipad prototype (each 1 cm)





J. Bortfeldt et al, NIM A 903 (2018) 317





24 ps for muons
(~ 10 p.e./muon)

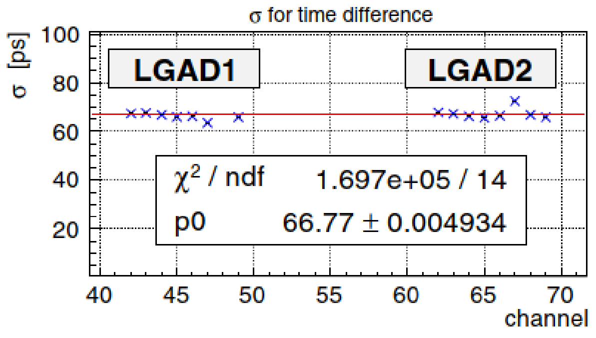
3. Silicon detectors [see TF3]

- Low-gain avalanche diodes (**LGAD**) are currently the silicon detectors of choice for fast timing, adopted by ATLAS/CMS
  Initial idea was for “APD with low gain” to compensate for charge loss after irradiation [P. Fernandez, PhD thesis 2014]

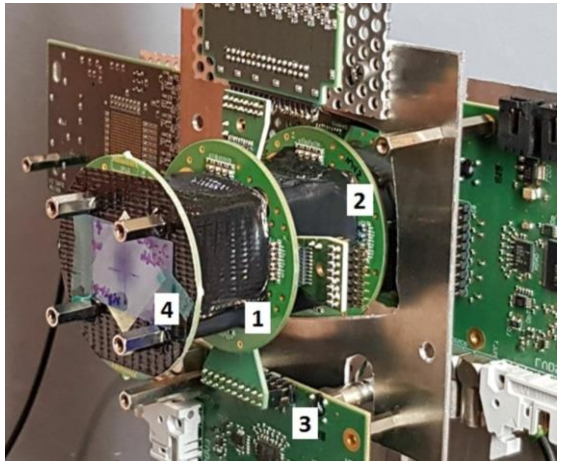
  Multiplication layer adds modest gain x 10–20:
  improves signal slope while keeping noise under control

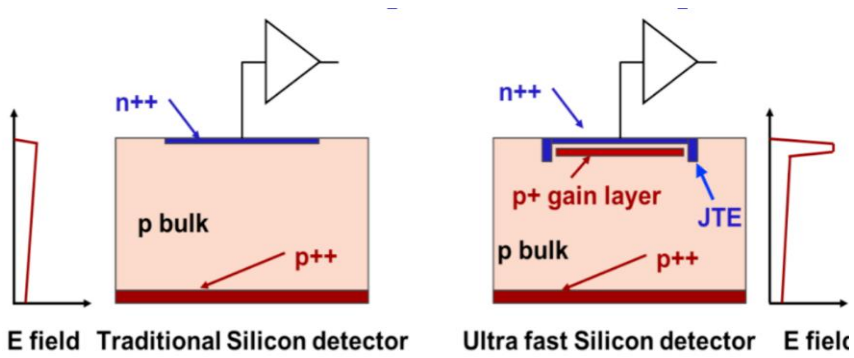
- *Early adopter:* **HADES** prototype beam telescope
  150 µm strips, provides start time t_0 for TOF system

Corresponds to 47 ps/hit



J. Pietraszko et al, Eur. Phys. J. A (2020) 56

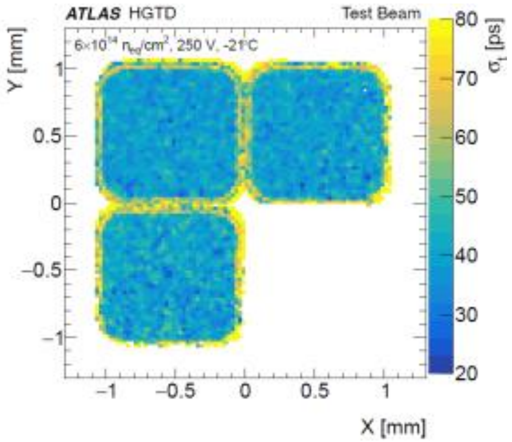




S. Grinstein, IAS-HEP 2021

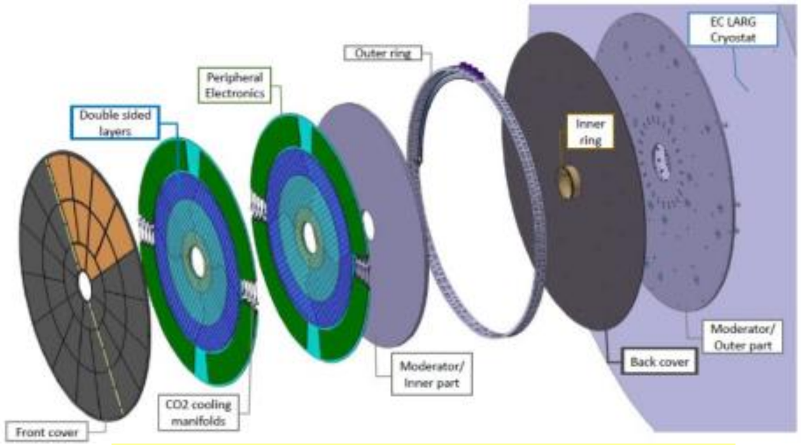
Insensitive area around gain layer
Junction Termination Extension (JTE): 50-100 µm
limits ability to achieve fine pitch

ATLAS/CMS use 1.3 x 1.3 mm^2 pads
Need to scale up from ~cm^2 to ~10 m^2 area



ATLAS Timing Layer

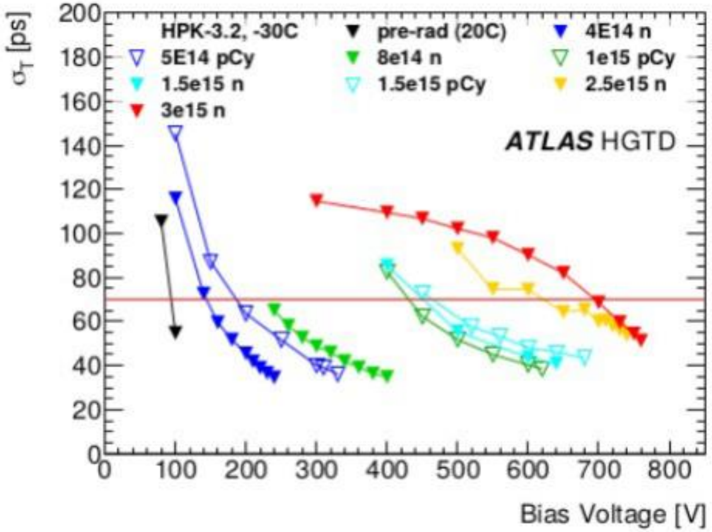
- High Granularity Timing Detector (**HGTD**) for the end-caps (similar design for CMS ETL, some common development)
- Active area: 12 cm < *r* < 64 cm, 2 disks per side, each supporting double 50 µm sensor layers : 15x30 pads of 1.3x1.3 mm^2
- Bump-bonded to readout ASICs, flex tail to outer-radius electronics Cooling plate operates at -30 °C: evaporative CO$_2$, 20 kW/endcap
- Maximum fluence: 2.5x10^{15} MeV n$_{eq}$/cm^2, 2 MGy by end of HL-LHC Inner ring will be *replaced* every 1000 fb^{-1} due to radiation damage Layout optimised for uniform performance *vs* radius

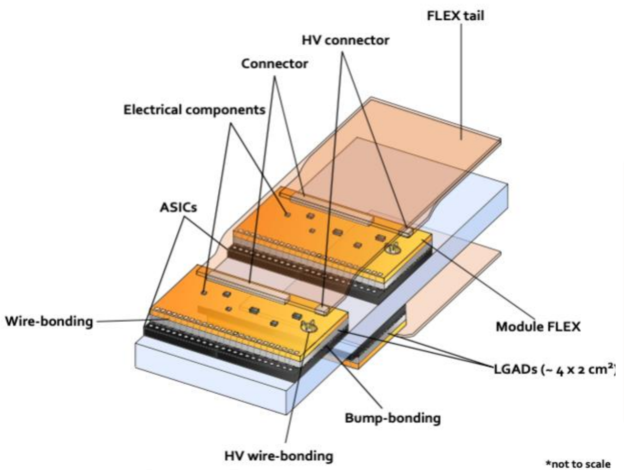


CERN-LHCC-2020-007; ATLAS-TDR-031

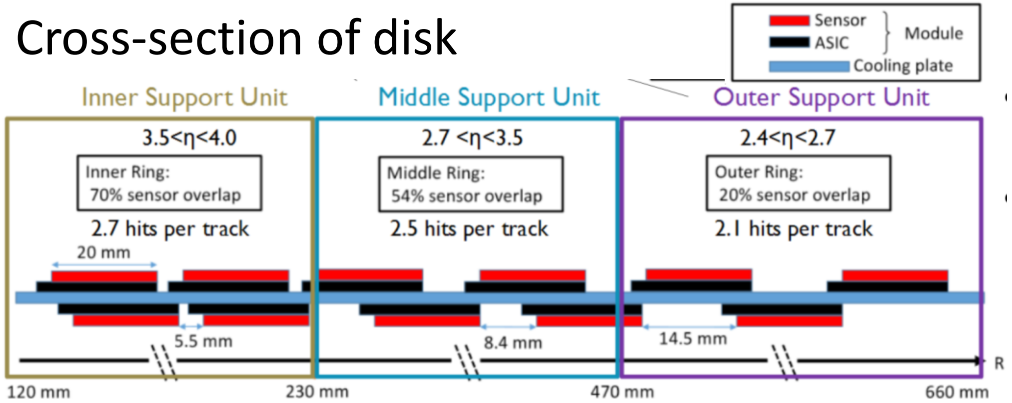
3.6 M channels, 6.4 m^2, 30-40% X$_0$

Effect of irradiation





Cross-section of disk



Fast silicon R&D

- Very active area, in the framework of **RD50** and elsewhere:
LGAD stability after heavy irradiation remains a concern → increase radiation tolerance further + achieve finer granularity + push timing

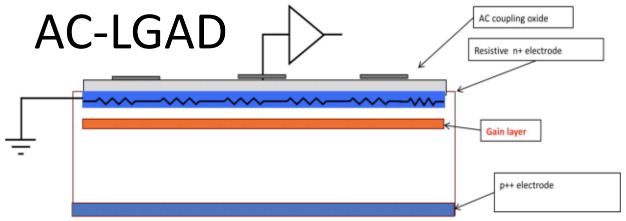
  For single (thin) layers, timing resolution < 20 ps has been achieved
  Would be difficult to achieve for a large system? [discussion at TF3]

- **AC-LGAD**: gain layer charge coupled capacitively to surface through thin (~ 500 nm) oxide layer, segmentation provided simply by surface electrodes
Excellent spatial resolution can be achieved via charge-sharing

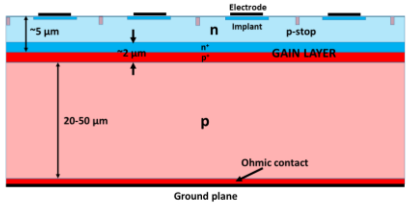
  Also Deep Junction (**DJ-LGAD**), Trench isolated (**TI-LGAD**), Inverse (**iLGAD**)...

- Other approaches to fast timing in silicon may also compete: 3D, Timepix...
Solid-state Electron Multiplier (**SSEM**): amplification layer obtained via a GEM-like metal structure embedded within the silicon bulk

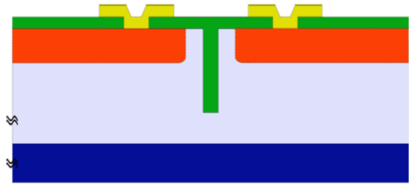
AC-LGAD



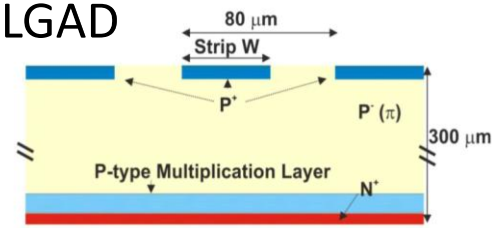
DJ-LGAD



TI-LGAD



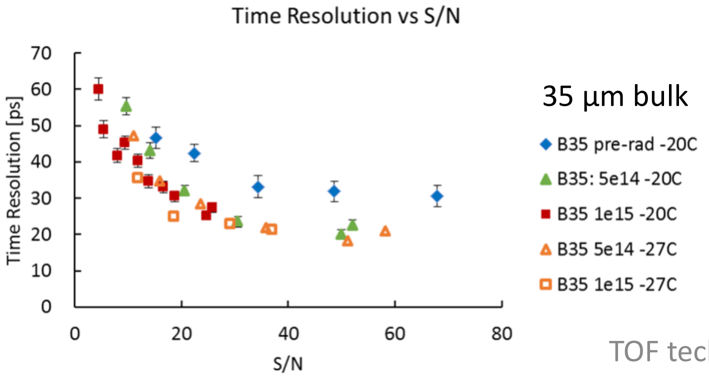
iLGAD

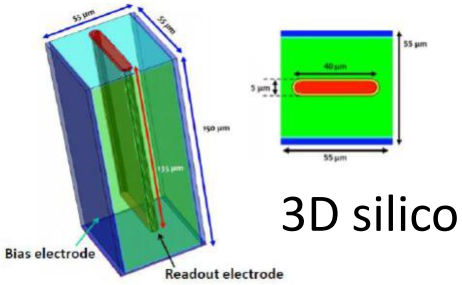


E. Currás, VERTEX 2020
N. Cartiglia, TF3

LGAD timing

Y. Zhao et al,
NIM 924 (2019) 387





3D silicon

Silicon prospects

- **ALICE 3**: new detector based around CMOS MAPS (Monolithic Active Pixel Sensors) under study for the HL-LHC era

  TOF resolution < 20 ps needed at system level, requires advances both on sensors and microelectronics [L. Musa, input symposium 19/2/21]

- **Belle II** detector upgrades planned in ~2026: pile-up suppression not an issue for e^+e^- colliders, but use of timing layer under consideration to cover gaps between radiator bars of TOP detector

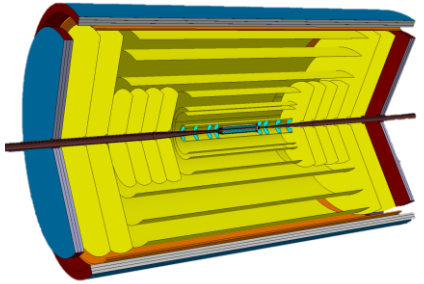
- **EIC**: now an approved project, detector technologies not yet fixed

- **FCC-hh**: pileup 1000, timing requirement to mitigate even more severe: resolution < 10 ps required "or very clever new ideas needed…" [M. Aleksa, input symposium 19/2/21]

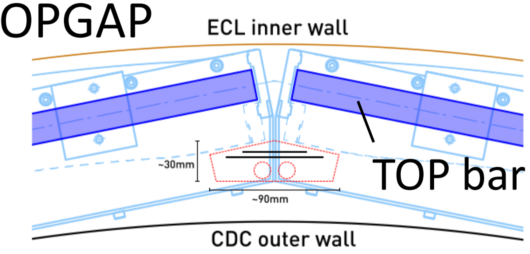
  + radiation dose 10x higher—but there is time for R&D, technical design would only start in *O*(15 years)

- **Muon collider** experiments: fast timing at 10 ps level needed to reject beam-induced background [N. Pastrone, input symposium 19/2/21]

ALICE 3

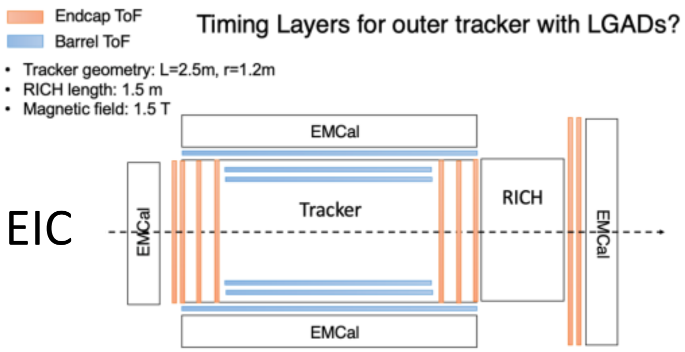


STOPGAP



O. Hartbrich et al, LOI Snowmass 2021

EIC

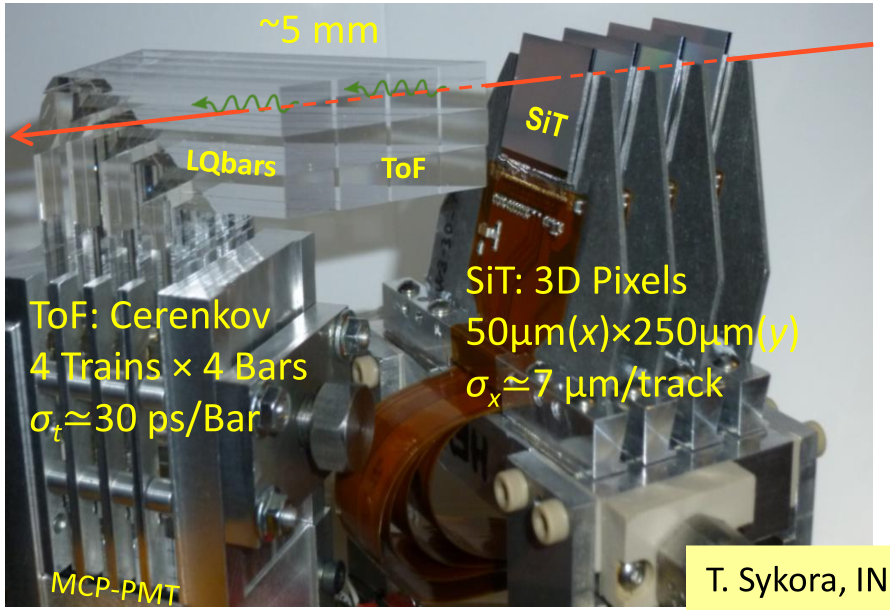


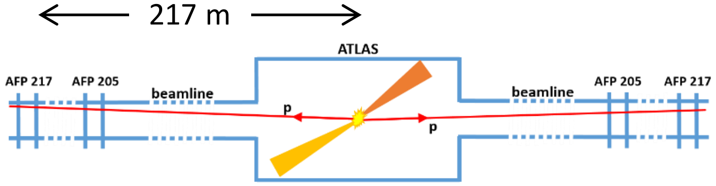
T. Hemmick, IAS-HEP 14/1/2021

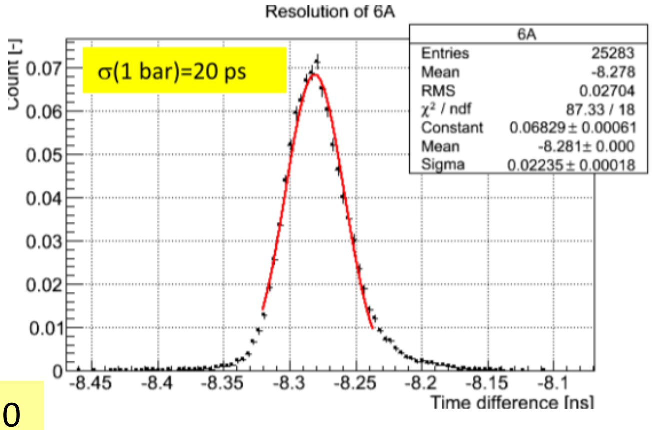
4. Cherenkov-based detectors

- Cherenkov radiation is *prompt*, ideal for ultimate timing: detect photons rather than charge
- Adding timing to RICH detectors: only available for particles which are *above* threshold
  → main use is for background suppression there, at least for gaseous radiators
  Room for clever ideas with aerogel? but few photons → use solid **quartz** (synthetic fused silica)

ATLAS Forward TOF: L-shaped bars

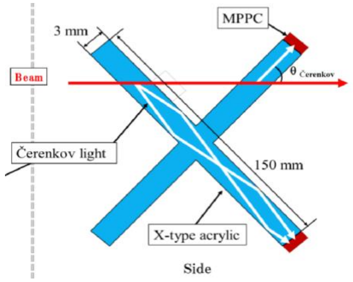


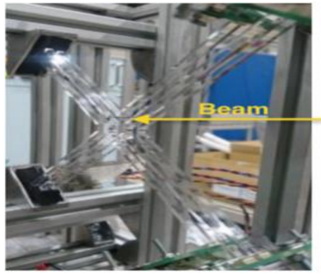




T. Sykora, INSTR2020

Another example:
EMPHATIC t_0 counter

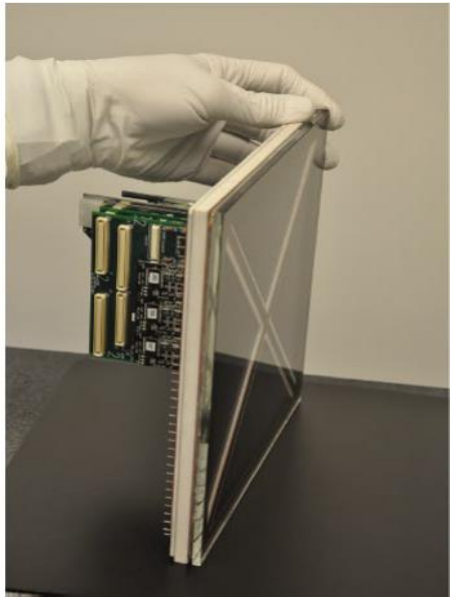




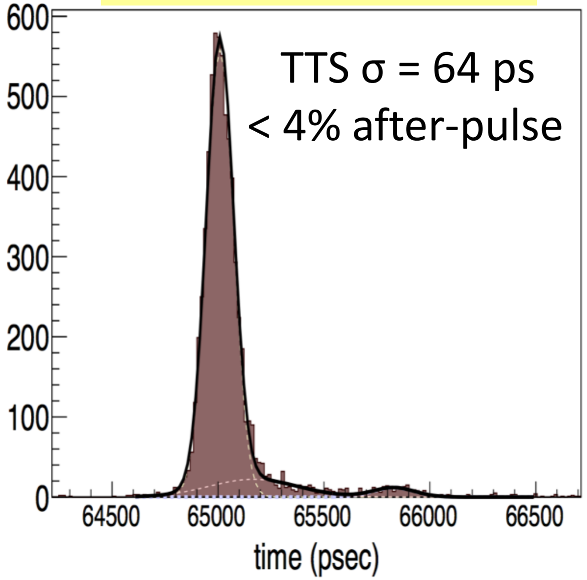
- Excellent performance ~ 20 ps, but for a small system—how can this be achieved over large areas?

LAPPD development

- One approach is to develop *large-area* picosecond-level photodetectors and use to time Cherenkov light produced in their entrance window
- **LAPPD**^{TM} development: use cheaper MCP-PMT components to limit cost e.g. borosilicate float glass + ALD treatment, strip-line readout
  Now commercialized by Incom Inc.
- Adopted by **ANNIE** (**A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment): water-Cherenkov neutrino experiment at Fermilab with 30 tons of Gadolinium-loaded water, to help in their muon reconstruction
- Also explored as a timing layer at shower-max in the LHCb calorimeter upgrade: 18.6 ps timing resolution achieved for 5.8 GeV e^- test beam
- Second generation under development with capacitive-coupled anode to allow pad readout more suitable for high-rate environments
  Lifetime and B-field sensitivity? [see talk of K. Inami]
- **Issue**: although cheaper than traditional MCPs, they are not *that* cheap
  Tiling a large area is currently still prohibitive, $O(1\ \mathrm{MCHF/m^2})$



V. Fischer, Lake Louise 2019

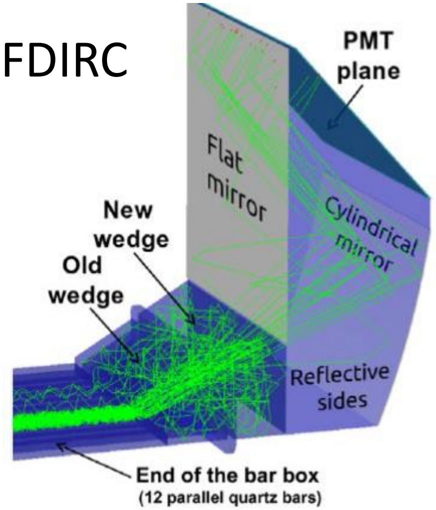


DIRC evolution

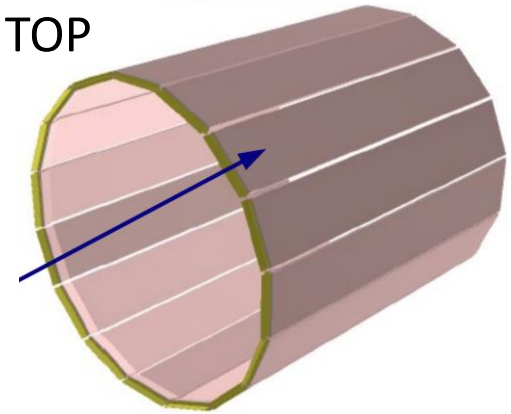
- To avoid tiling the full area, propagate the photons to photodetectors located at the *edge* using total-internal reflection in highly-polished quartz radiator [see previous talk, J. Schwiening]
- Issue to be handled: *chromatic dispersion* of the material—trade-off between photon bandwidth to increase yield, *vs* resolution

  From $E_\gamma = 2–4\,\text{eV}$, refractive index changes $\Delta n = 7\%$
  Over 1 m propagation → time difference = 300 ps
- **FDIRC**: demonstrated use of photon timing to improve the Θ_C resolution, adapting BaBar DIRC
- **TOP**: time-of-propagation detector of Belle II timing *vs* position enhances K-π separation
- **Disc DIRC** (PANDA): move from bars to planar geometry
- These elements all brought together for **TORCH** concept

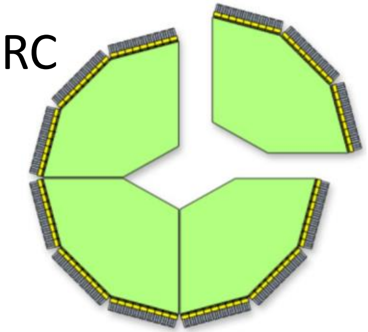
FDIRC



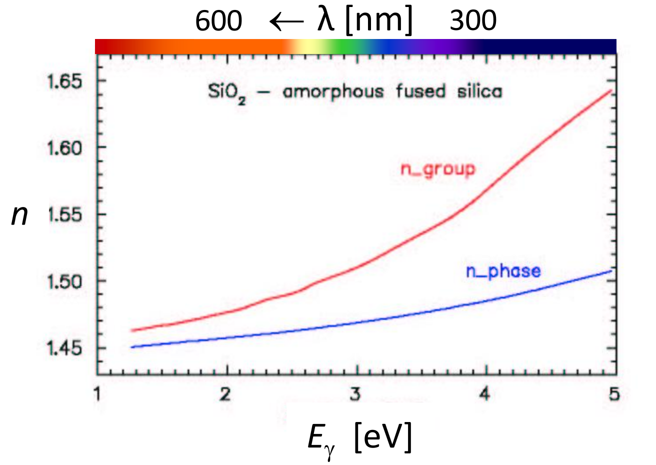
TOP

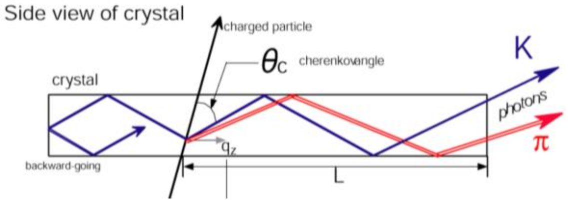


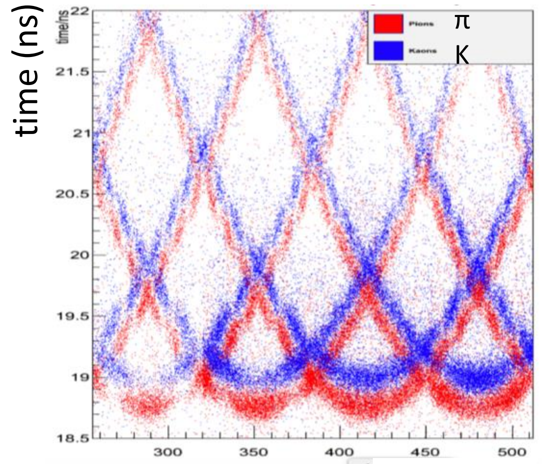
Disc DIRC



Quartz refractive index n *vs* E_γ





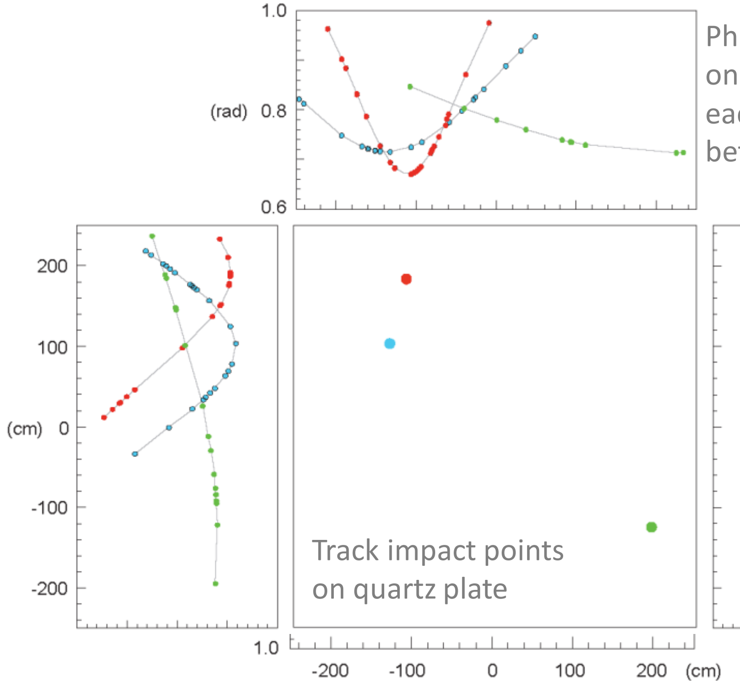


J. Fast, RICH 2016

TORCH concept

- **TORCH** (**T**iming **O**f internally **R**eflected **CH**erenkov light) uses polished 1-cm thick quartz plate as radiator (~ 10% X_0) Measure precisely arrival time and position of individual photons, and combine to measure track arrival time
- Requires ~ 1 mrad precision on angle of photon, so that path length in radiator can be reconstructed: focused with a cylindrical lens onto fine-granularity pixellised detector
- *Key innovation:* measured Cherenkov angle used to correct dispersion: $n = 1/\beta \cos\Theta_C$ → effectively determine *wavelength* for each photon i.e. Cherenkov angle is used to correct timing (*cf* DIRC, where timing is used to correct the Cherenkov angle)
- Resolution on photon arrival time has contributions from pixel size and photodetector (intrinsic + electronics)—target to keep each ~ 50 ps, giving overall resolution 70 ps per photon

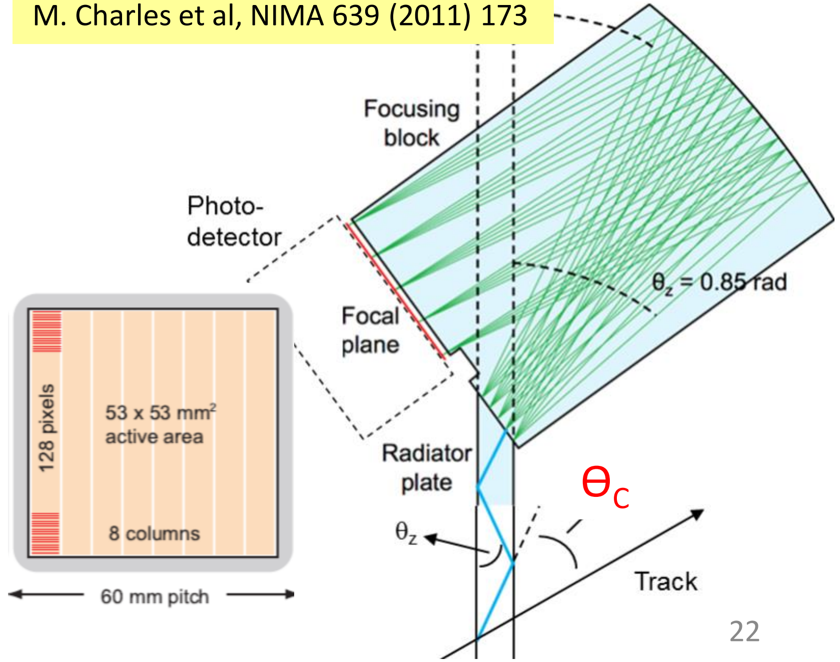
  On average 30 photons detect per track through radiator → per-track resolution of 10-15 ps — *if independent* some uncertainties (e.g. from track) common between p.e.



Photon impacts on detectors along each edge (θ_z vs. x) before dispersion

Track impact points on quartz plate

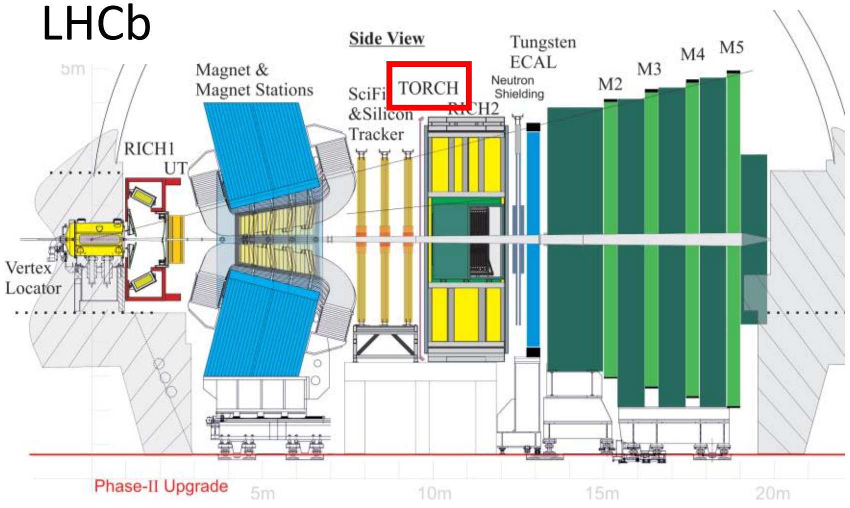
M. Charles et al, NIMA 639 (2011) 173



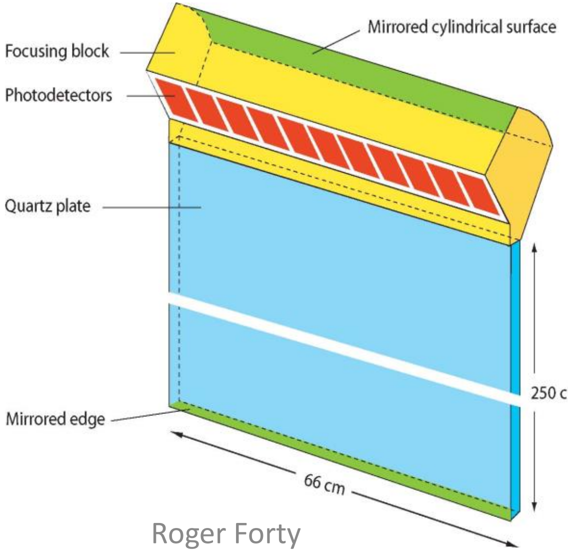
TORCH in LHCb

- Proposed for upgrade of LHCb in ~2027 for HL-LHC (Upgrade 2) → needs to handle luminosity ~ 10^{34} $cm^{-2}s^{-1}$
- Location after tracker, before RICH2 which will be upgraded at same time [see talk of C. D'Ambrosio] → flight path 10 m, area 30 m^2
- *Practicalities:* subdivide into identical modules, reflection off sides to reach photodetectors at top/bottom edge
- Performance (full simulation): clean K-π separation up to 10 GeV as required

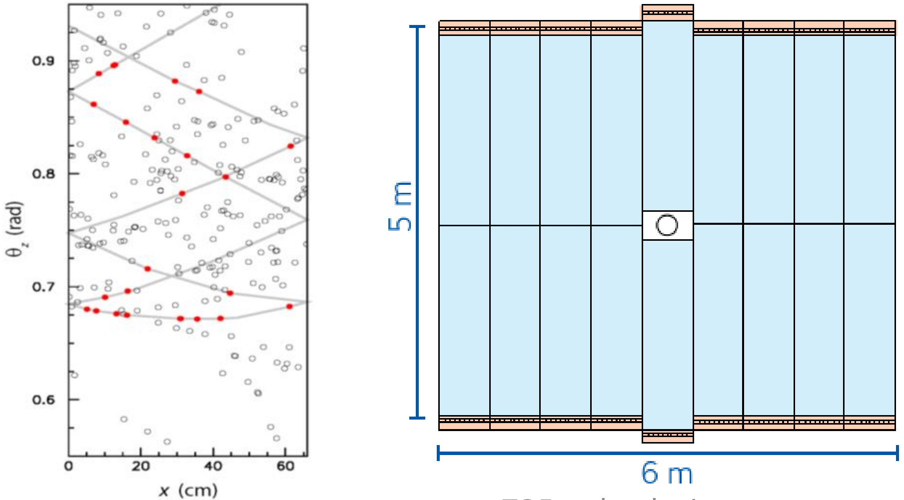
LHCb



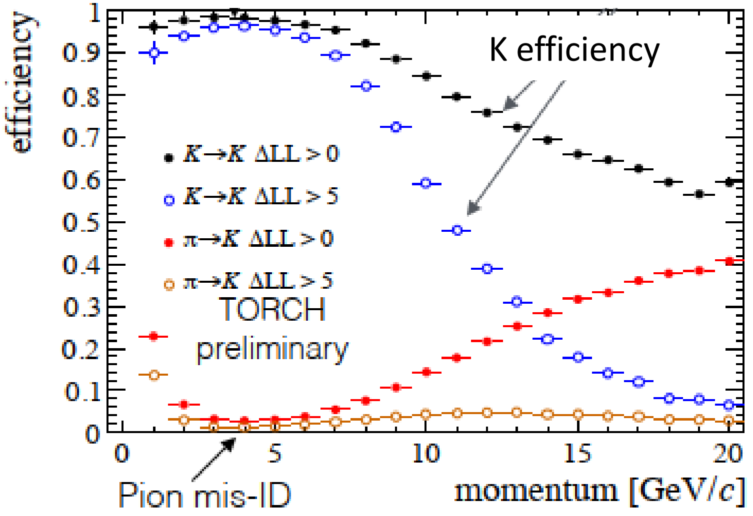
Module



Effect of modules: signal folded



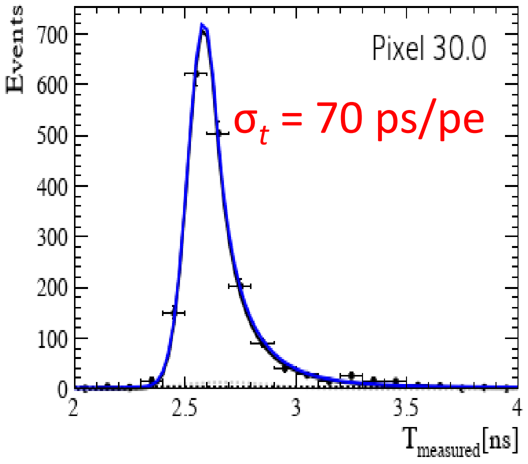
Full LHCb simulation (GEANT4-based)



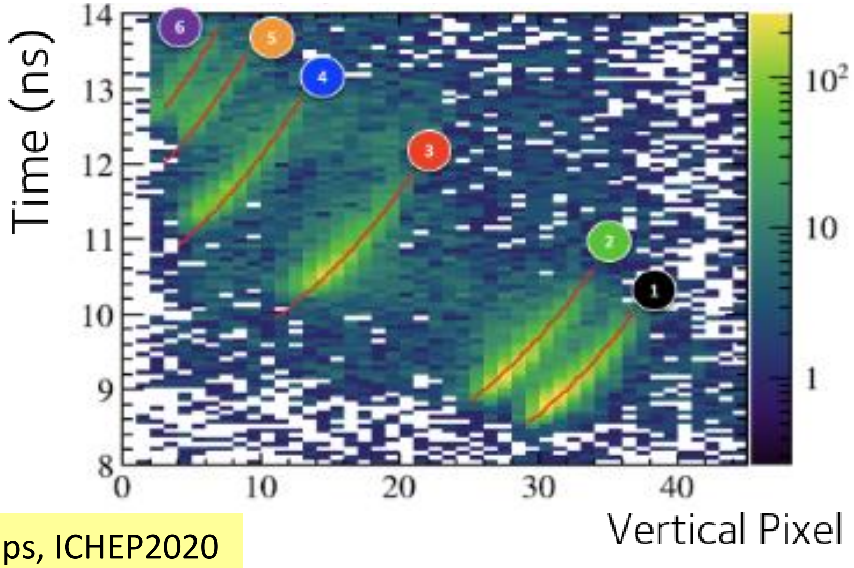
TORCH development

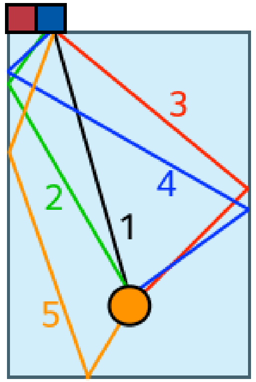
- TORCH concept has been tested using ≈ full-size prototype
- Instrumented with two 512-channel MCP-PMT photodetectors
  Campaign of measurements with low-momentum π/p beam from SPS
  → Target of 70 ps timing resolution per detected photon achieved
- *Next step:* confirm that combination gives expected $\sqrt{N_{pe}}$ behaviour
  → prototype will be fully instrumented with MCP-PMTs for further tests

Project along time axis



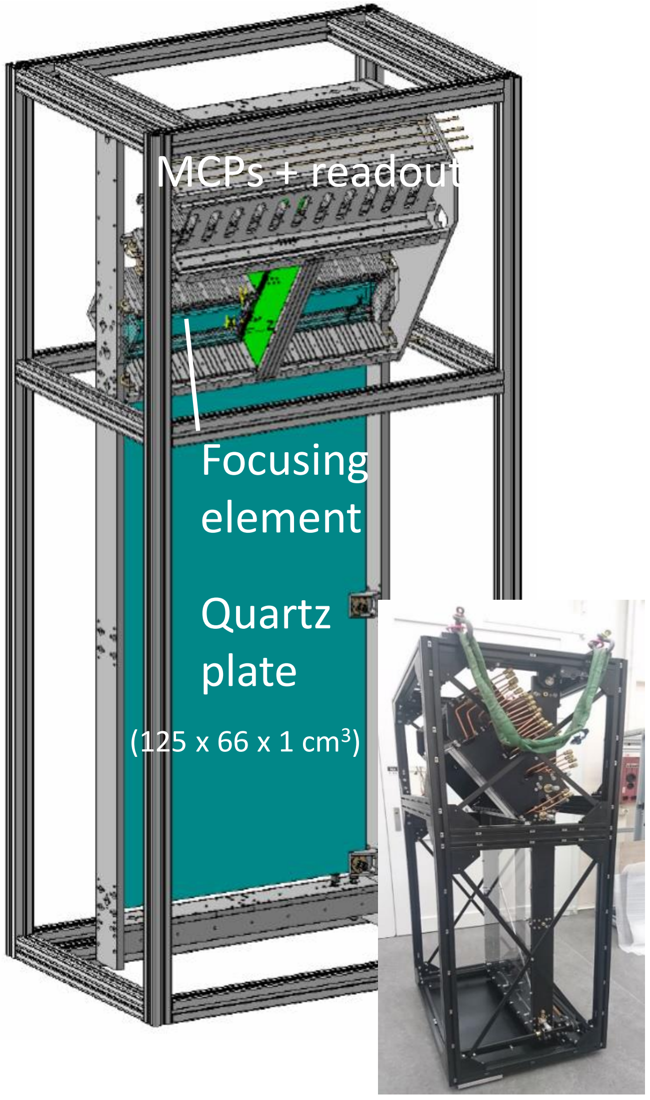
Time vs position (for one MCP column)





M. Kreps, ICHEP2020

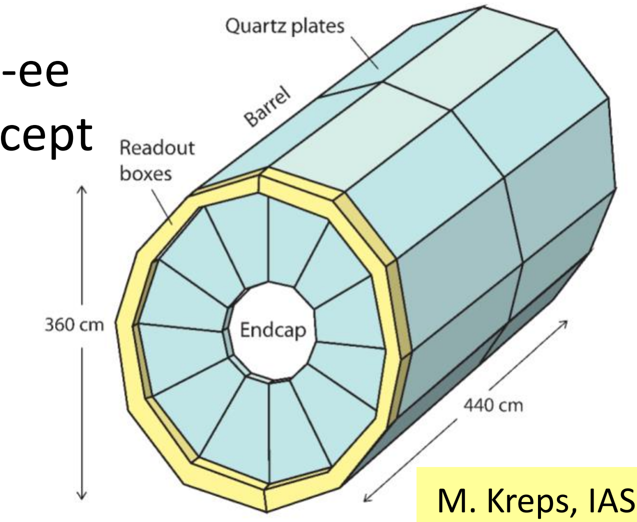
TORCH prototype



Cherenkov-based TOF prospects

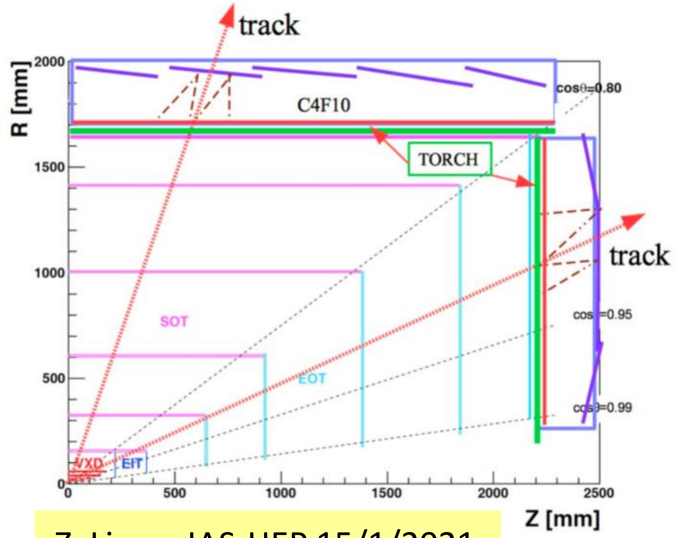
- **Forward TOF** of ATLAS is being upgraded for the next run
- **TORCH** features in Framework-TDR for LHCb upgrade [→ LHCC, 9/2021]
- Interest for e^+e^- Higgs factory designs—the circular ones at least perhaps due to their phenomenal $Z \to b\bar{b}$ statistics
  Conceptual layout for use of TORCH in an **FCC-ee** experiment:
  Flight distance < LHCb → TOF lower, but TOP increases (they add)
- Also for future fixed-target/beam-dump experiment proposals:
  e.g. **TauFV**: search for LFV $\tau \to \mu\mu\mu$ in beam dump at the SPS
- *Related concept:* **DTOF** at Super Tau Charm facility [B. Qi et al, arXiv:2104.05297]
  similar to FTOF detector proposed for SuperB [N. Arnaud et al, NIMA 718 (2013) 557]

FCC-ee concept



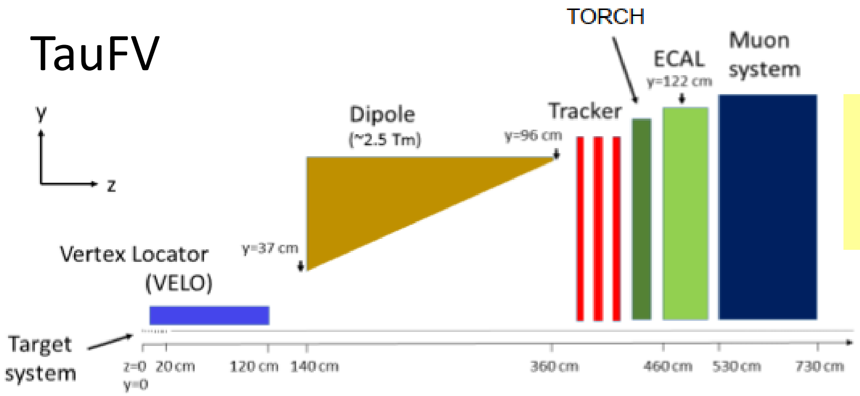
M. Kreps, IAS-HEP

Study of PID detectors for CEPC



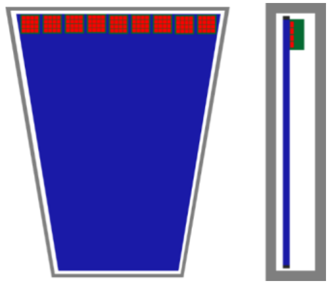
Z. Liang, IAS-HEP 15/1/2021

TauFV



G. Wilkinson,
PBC workshop
1/3/2021

DTOF



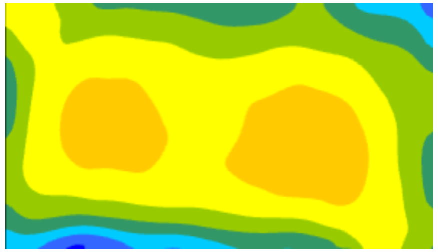
General considerations

- End with discussion of some more general aspects relevant to different technologies, where R&D is in progress/needed

Focus on issues relevant to *this* task force, illustrated with examples from work on TORCH that I know best

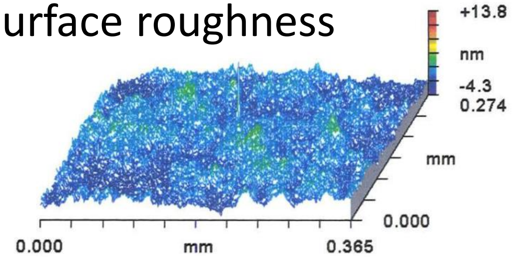
Radiator/detector material [see talks of I. Idachi, J. Schwiening]

- *Quartz:* needs high clarity, radiation tolerance, surface quality, polishing to sub-nm surface roughness—currently a cost driver



Surface flatness over TORCH plate (1 µm contours)

Surface roughness



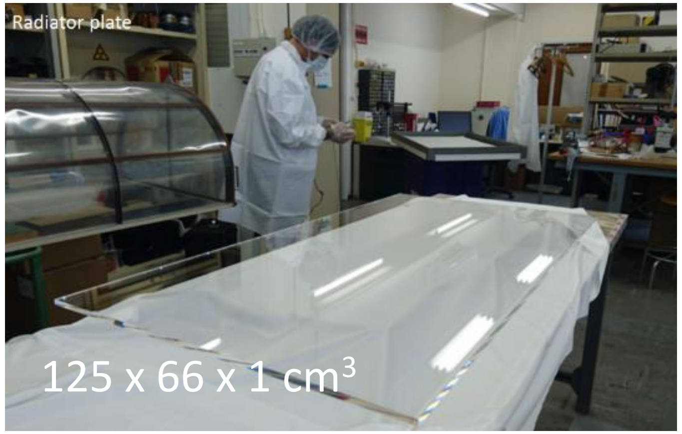
- Larger area plates: would allow module size to be adapted to track occupancy in LHCb
- *RPC gas systems:* [see TF1] target leak free + gases with reduced environmental impact:

B. Mandelli, TF1

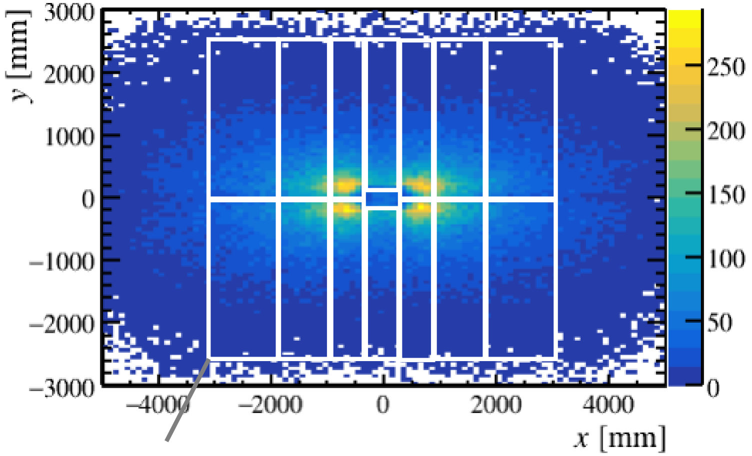
R134a
($C_2H_2F_4$)
GWP 1430

HFO-1234ze
($C_3H_2F_4$)
GWP 6

Radiator plate of TORCH prototype



Track distribution at TORCH in LHCb

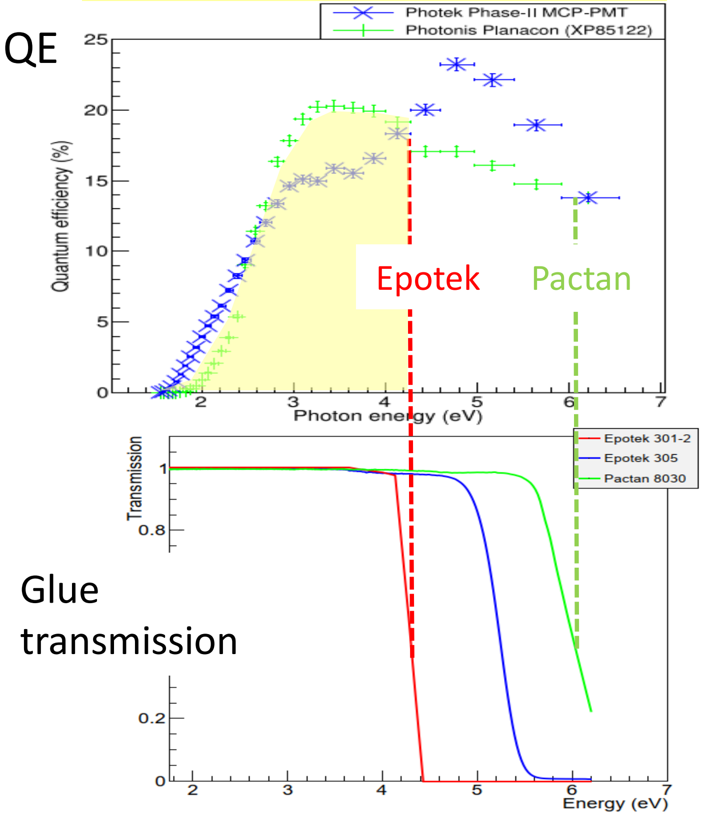


Possible adapted module layout

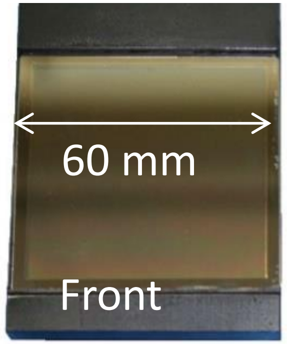
Sensors

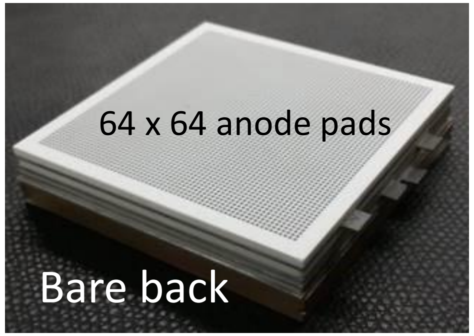
- For silicon see TF3, for scintillator see TF5+6; fast **photodetectors**: MCP-PMT and SiPM [see talks of K. Inami, S. Korpar, Y. Musienko]
- For **MCP**: push towards finer granularity, lifetime, rate capability, etc. Connectivity: e.g. using anisotropic conductive foil (ACF)
  Fast + longer lifetime MCPs relevant for future high-intensity kaon experiments
- For **SiPM**: naturally fine granularity, but developments to improve active-area, radiation tolerance, noise, adjust spectral sensitivity
- Increasing quantum efficiency increases photon yield (+ occupancy)
  Cherenkov spectrum ~ flat with photon energy → extending toward UV can increase yield, but requires control of full optical system

M. van Dijk, CERN-THESIS-2016-039

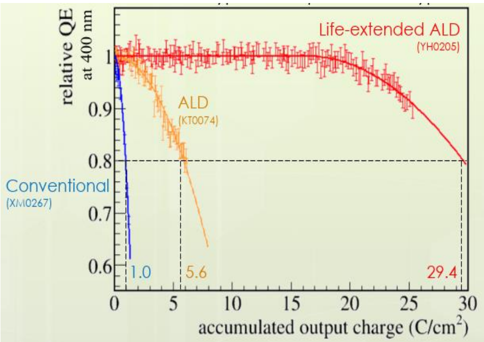


TORCH MCP-PMT (developed with Photek)

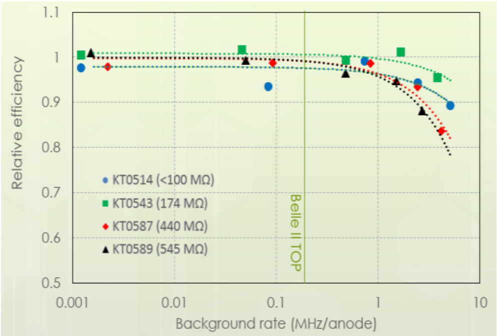




Lifetime (Belle II MCPs)



Rate capability



K. Matsuoka, RICH2016

Readout electronics [see TF7]

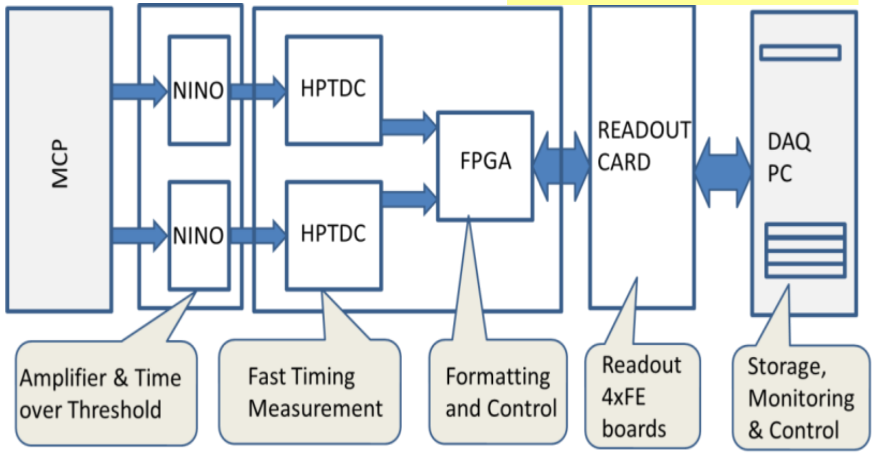
- **NINO** + **HPTDC** chipset developed in 2004 (0.25 μm CMOS) for ALICE TOF, and now widely used—also for single p.e. although intended for the larger charge of MRPC signals
  TDC: 32 channels for 100 ps bins, or 8 ch for 25 ps bins
- **FastIC** + **PicoTDC** successors recently developed (65 nm)
  [R. Ballabriga, J. Christiansen et al, Users meeting] —many potential clients

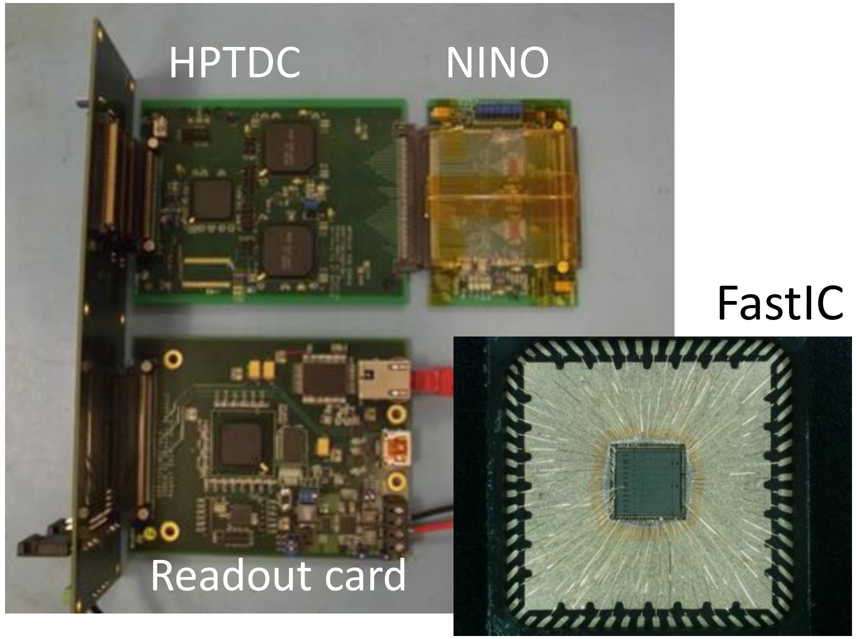
  FastIC addresses NINO limitations (non-linearity of energy measurement, power consumption) suitable to operate with SiPM, PMT, MCP, i.e. a wide range of detector capacitances
  PicoTDC has increased channels (64 ch), finer binning (12/3ps)
- ASICs for LHC timing layers (130 nm): HGTD front-end **ALTIROC**
  MTD-BTL uses **TOFHIR** ASIC developed from TOFPET
  MTD-ETL uses **ETROC**; baseline for distributing the clock is to use DAQ links (**lpGBT**, 65 nm)

  CMS developing a backup distribution system: pure clock link
  Requires development of a rad-hard fan-out ASIC and board and deployment of ~ 2000 additional fibres

TORCH readout

R. Gao, TWEPP 2016





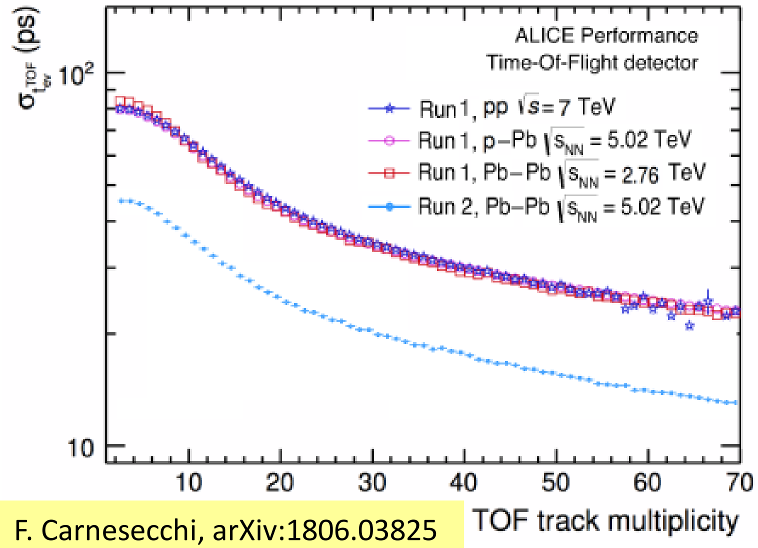
Start time

- To determine the time-of-flight a start time (t_0) is required
- This may be achieved using timing information from the accelerator, but if bunches are long (~ 20 cm at the LHC)
  → have to correct for vertex position
- Can use a dedicated detector, e.g. the **T0** detector of ALICE and those shown earlier from HADES and EMPHATIC
  or e.g. a vertex detector (if equipped for fast timing)
- Alternatively use other tracks in the event, from the primary vertex—as also done by ALICE, due to limited T0 acceptance
- Most PV tracks are pions, so for TORCH the reconstruction logic can be reversed, and the start time determined from average of tracks from primary vertex *assuming* they are π

  Outliers from other particle types removed, iteratively

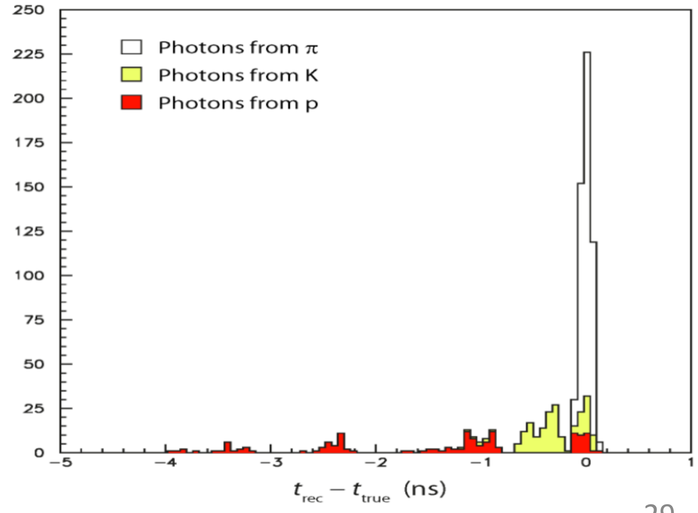
  → Should be able to achieve few-picosecond resolution on t_0 from the detector itself, using the *other* tracks in the event

Resolution on t_0 (ALICE TOF)



F. Carnesecchi, arXiv:1806.03825

Photons in TORCH from PV (single event)



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 **MRPC**s 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!