Time-of-Flight Detectors


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Overview of this talk:

- Part 1 will cover the basic concepts of a time-of-flight detector
- Part 2 will cover a few specific examples of time-of-flight detectors used at current collider experiments
- Part 3 will cover some examples of time-of-flight detectors for use in upcoming upgrades to experiments

Part 1 – The Basics

Let’s keep this simple

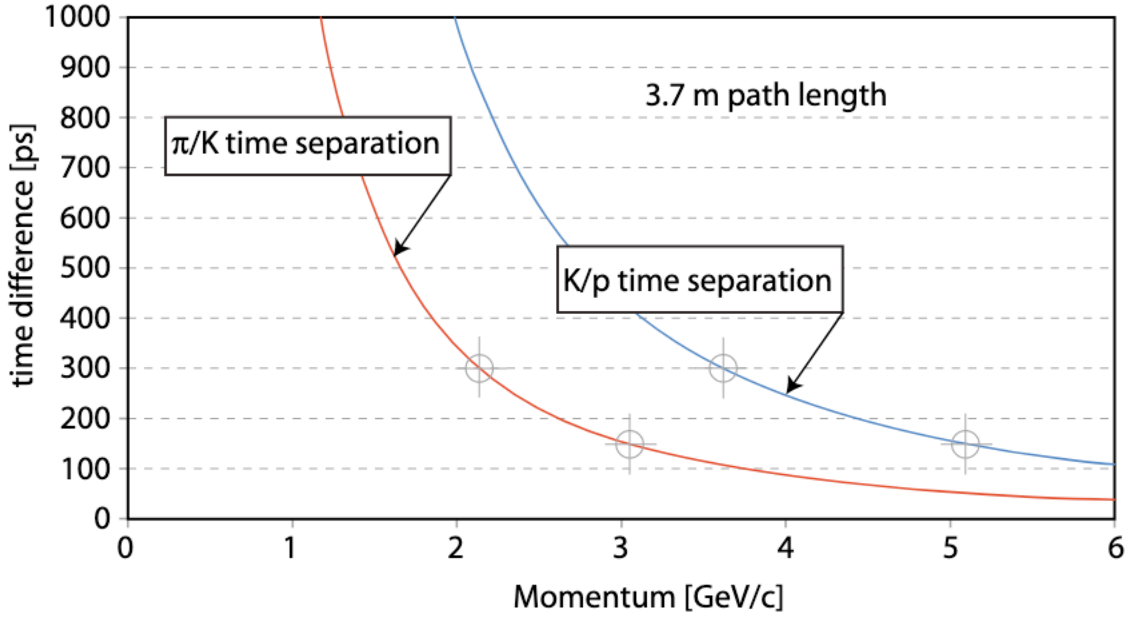
$$\beta\gamma = \frac{p}{mc}$$ or $$\beta = \frac{\frac{p}{mc}}{\sqrt{\left(1+\left(\frac{p}{mc}\right)^2\right)}}$$

- What is a time-of-flight (TOF) detector?
  - A TOF detector measures the **time** it takes for a particle to **fly** from an interaction point or between two detector units

- Why use a TOF detector?
  - Particle identification (PID):
    - Lighter and heavier particles that have the same momentum travel at different speeds
    - We can use a tracker to measure momentum, but that doesn’t give a mass measurement
  - Pile-up suppression:
    - If multiple interactions produce particles at roughly the same point in space but at different times, the particles can be matched to interactions by their temporal separation

Let’s keep this simple

[J. Phys. G: Nucl. Part. Phys. **39** 123001]



- What do we need?
  - Excellent time resolution
- CONTEXT:
  - $c = 299{,}792{,}458$ m/s
  - It takes a photon 3.34 ns to travel 1m
  - It takes a p = 1 GeV charged pion 3.37 ns to travel 1m (v = .99c)
  - It takes a p = 1 GeV proton 4.58 ns to track 1m (v = .729c)
- If flight distances are on the order of 1m, we’re going to want timing resolution that’s in the 10-100 ps range

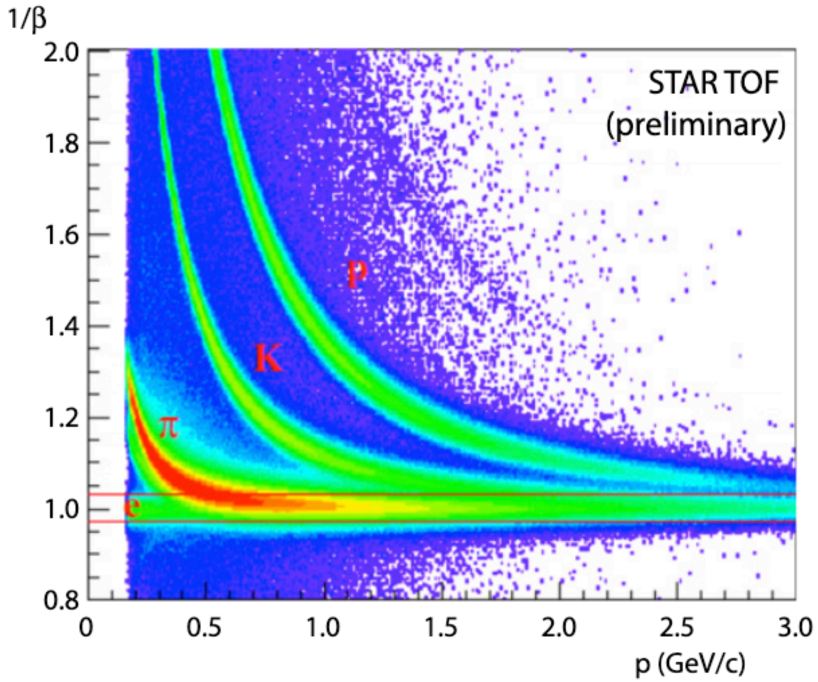
A popular formula

[J. Phys. G: Nucl. Part. Phys. **39** 123001](#)

- If two particles with the same momenta but different masses travel the same distance, L, then the TOF difference will be:

$$\Delta T = T_1 - T_2 = \frac{L}{c}\left(\sqrt{1+\frac{m_1^2}{p^2}} - \sqrt{1+\frac{m_2^2}{p^2}}\right) \approx (m_1^2 - m_2^2)\frac{L}{2cp^2}$$

- It is somewhat typical to compare a particle's ToF to that expected for a pion



Here, β is measured using TOF.
For those in the know, this probably resembles a track dE/dx plot, which a related PID method

The need for good timing resolution

- A mass measurement is performed by measuring the momentum and the TOF
- The error on the TOF-based mass measurement due to momentum, timing, and track length resolution is:

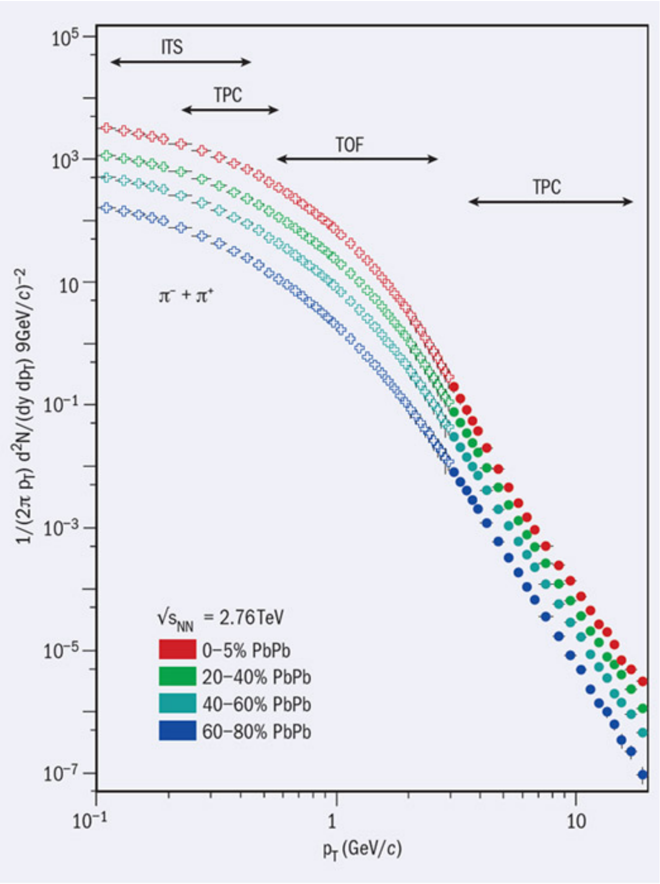
$$\frac{\partial m}{m} = \frac{\partial p}{p} \qquad \frac{\partial m}{m} = \left(\frac{E}{m}\right)^2 \frac{\partial T}{T} \qquad \frac{\partial m}{m} = \left(\frac{E}{m}\right)^2 \frac{\partial L}{L}$$

  - For context, the ALICE TOF detector has a timing resolution of about 100 ps. A 1 GeV pion at ALICE takes 12.5 ns to travel the 3.7m to their TOF detector, so the mass measurement resolution is about 41%
    - For such a particle, $\frac{\partial p}{p}$ is normally about 1-5%
    - An uncertainty on L of 1 cm would correspond to a timing resolution of about 30 ps

The need for good timing resolution

https://cerncourier.com/a/particle-identification-in-alice-boosts-qgp-studies/

- From the $\frac{\partial m}{m} = \left(\frac{E}{m}\right)^2 \frac{\partial T}{T}$ formula, we can see that resolution is poor for high energy particles
- PID is often performed by combining multiple detecting elements and techniques. E.g.:
  - A time projection chamber can give dE/dx (which depends on velocity)
  - A Cherenkov detector's cone angle depends on velocity
  - Transition radiation depends on particle type, so a transition radiation detector can also help with PID



Pion multiplicity observed by ALICE. PID is performed using the techniques indicated as a function of momentum

Part 2 – TOF Detectors Today

Looking backwards

- Many of the TOF detectors in use today in major experiments were designed ~20 years ago at this point
  - Design was limited to the technology available at the time

- In this Part, I'm going to talk about TOF detectors used by
  - STAR
  - ALICE
  - ATLAS Forward Proton Detector

Main technologies as of 2000

1. Plastic scintillator + Photomultiplier readout
   - Pros:
     - A standard method
     - Using a long scintillating bar with a photomultplier gives timing resolution of ~100 ps
   - Cons:
     - It can be difficult to get photomultipliers to work in a magnetic field
     - Photomultipliers are also expensive; a large TOF detector with 100,000 channels could cost $100,000,000

Main technologies as of 2000

2. Pestof Counter

- What is it?
  - Parallel plate detector with high voltage cathode and grounded pestof glass anode around a narrow gas gap (~100 microns)
  - Charged particle causes electron avalanche
  - The glass has high resistance, so avalanche detection can be localized
- Pros:
  - Good timing resolution (~35 ps)
  - Low noise rate
- Cons:
  - Gas must be pressurized to achieve good detection efficiency; requires a unique pressure vessel
  - Difficult to acquire pestof glass and preferred gas

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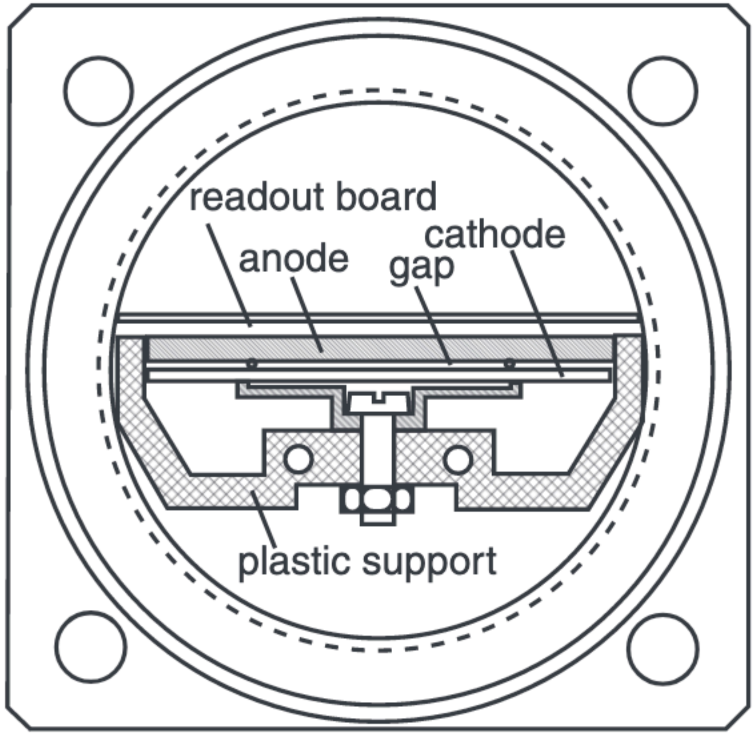

Had they used pestof counters, ALICE had the idea of using 50mm diameter aluminum tubes as their pressure vessels

Main technologies as of 2000

3. Parallel Plate Chamber (PPC)
   - What is it?
     - Two metal plates are kept parallel at a distance of ~500 microns with a high voltage difference between them
     - Electron avalanche caused by ionization can be detected
   - Pros:
     - Relatively cheap
   - Cons:
     - Gas gain must be kept low to avoid a spark between the plates, leading to lower efficiency
     - Relatively poor timing resolution (~250 ps for a setup with 90% efficiency)

MRPCs were introduced in 1996: https://doi.org/10.1016/0168-9002(96)00158-1

Main technologies as of 2000

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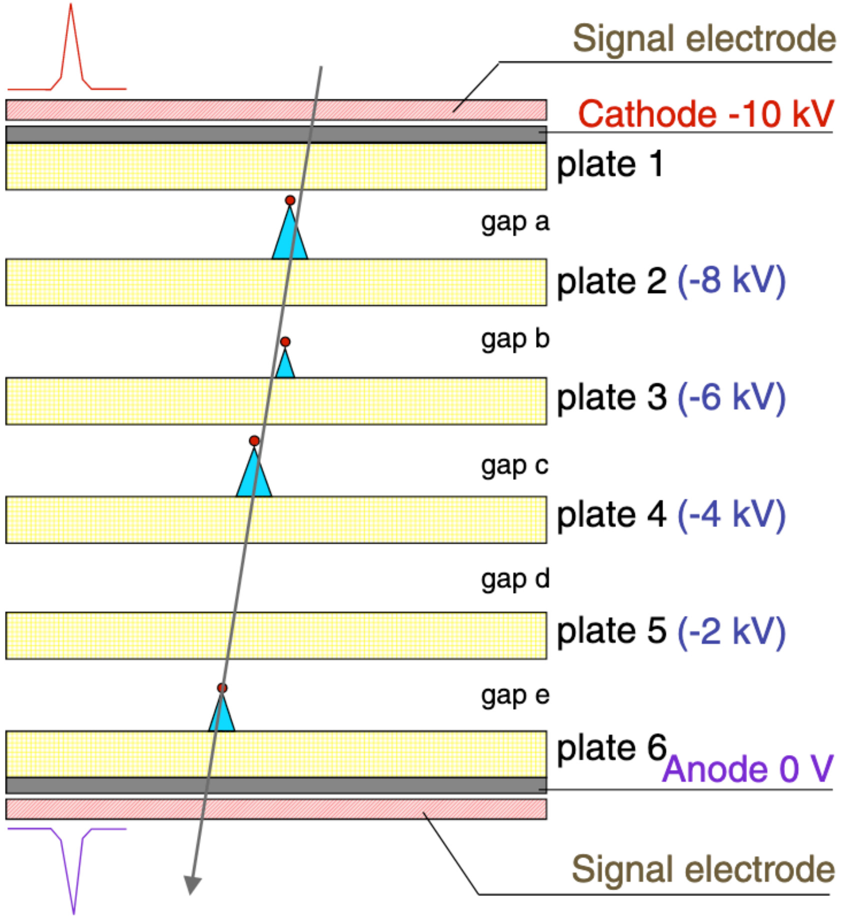
4. Multigap Resistive Plate Chamber (MRPC)

- What is it?
  - Similar to a PPC, but with resistive plates spaced out in the gas gap
  - Resistive plates and their gaps can be something simple like glass separated by fishing line
- Pros:
  - Good resolution
  - Good efficiency
  - Easy to build
- Cons:
  - Somewhat limited rate capabilities
  - Large material budget

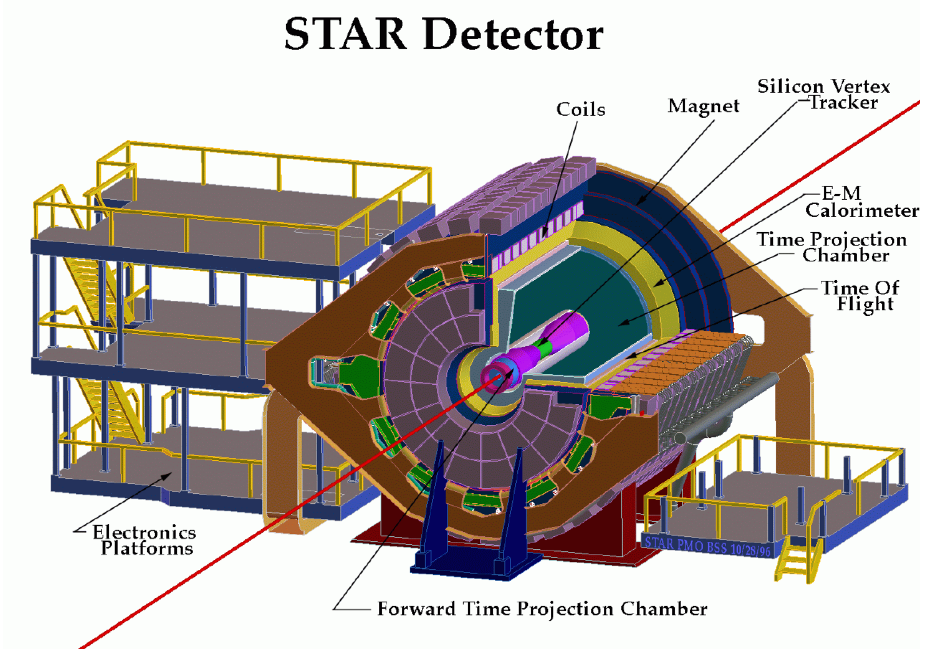


The intermediate plates are not set at the listed voltages; those values result from electrostatics

Example 1: STAR

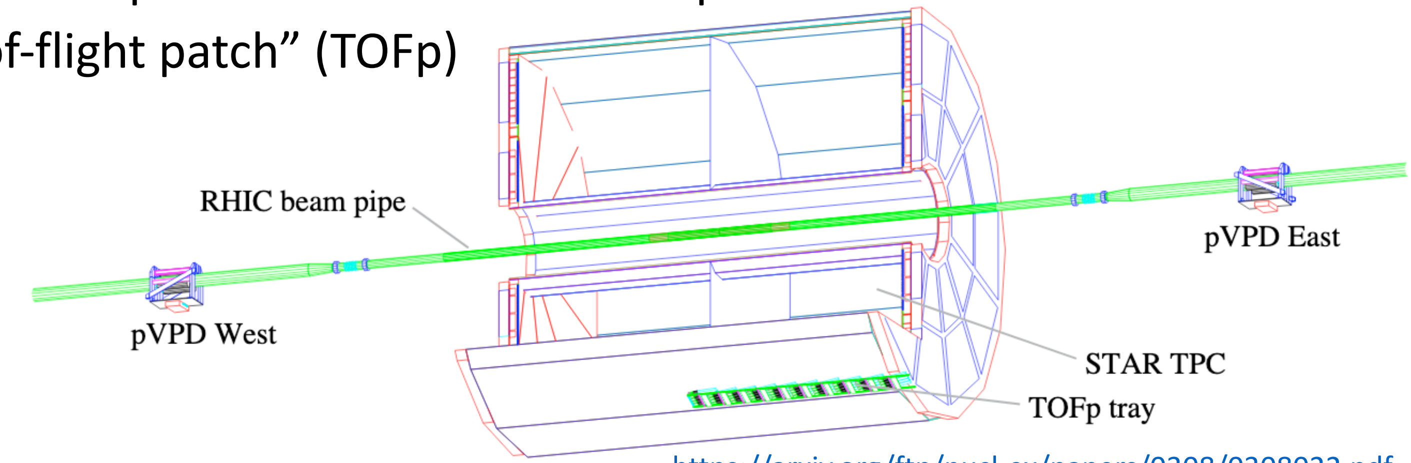
- "STAR" = Solenoidal Tracker at the Relativistic Heavy-Ion Collider
  - High-energy gold collisions mostly result in pions, kaons, and protons; we want to be able to tell these apart!
  - Can do PID with dE/dx for kaons with $0.1<p<0.7$ GeV and protons with $0.1<p<1.0$ GeV
  - Can do PID using a ring imaging Cherenkov detector for kaons with $1.0<p<3.0$ GeV and protons with $1.5<p<5.0$ GeV
  - TOF detector is used for mid-momentum range (around 0.5-2 GeV)

https://drupal.star.bnl.gov/STAR/public/img



Example 1: STAR

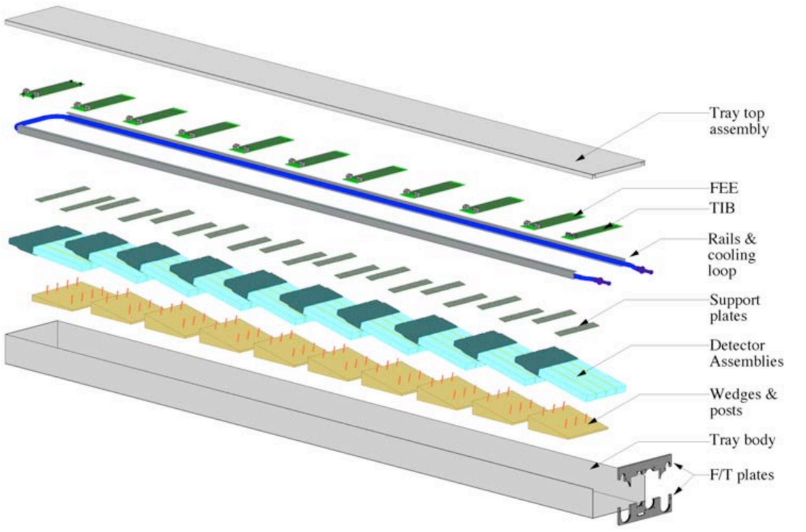
- STAR elected for the scintillator+photomultiplier TOF detector
- The STAR TOF detector system has two components
  1. Forward elements on both sides of the detector are used to detect very forward photons. Located about 5m from the interaction point
     - Called “pseudo vertex position detector” (pVPD)
     - There are 3 sensitive elements on either side, and averaging the time value of the 6 tubes gives a start time for the collision
  2. A central element covers 1 unit of pseudorapidity and 1/60th of the azimuthal angle around the beampipe (41 channels in total)
     - This is used to give a stop time for the hadrons in question
     - Called the “time-of-flight patch” (TOFp)



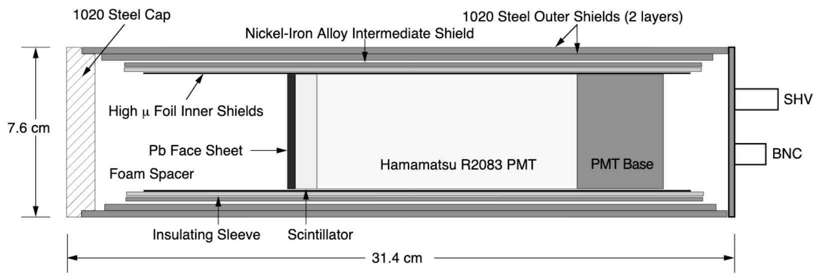
https://arxiv.org/ftp/nucl-ex/papers/0308/0308022.pdf https://arxiv.org/ftp/nucl-ex/papers/0308/0308022.pdf

Example 1: STAR

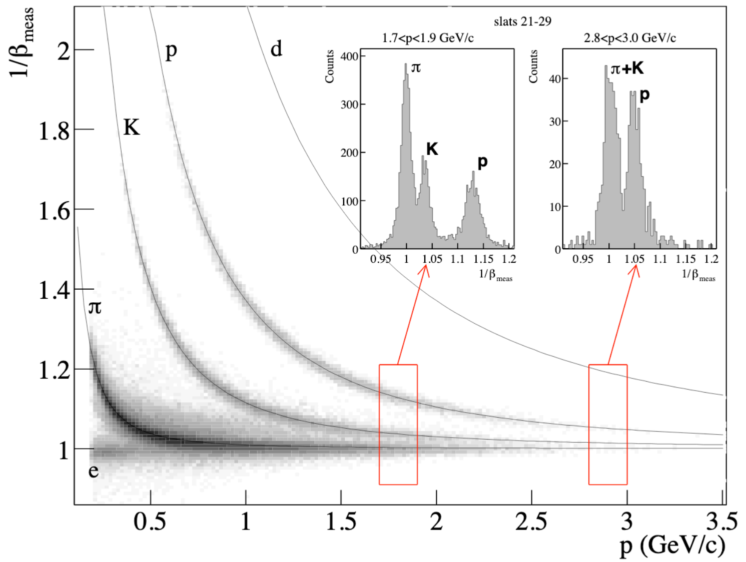
- Start time resolution from pVPD is about 24 ps
- The total time resolution is about 87 ps on average when accounting for both start and stop time resolution



Layout of the TOFp



Layout of the pVPD



Example 2: ALICE

- The ATLICE TOF detector is a cylinder of radius 3.7 m, covering the pseudorapidity region [-0.9, 0.9] (~141 m^2 of area)
- ALICE uses a MRPC for its TOF detector; there are 1593 MRPC strips in total, each divided into 2 rows of 48 pickup pads
  - 152928 total channels
- Gas gap between glass layers is 250 microns

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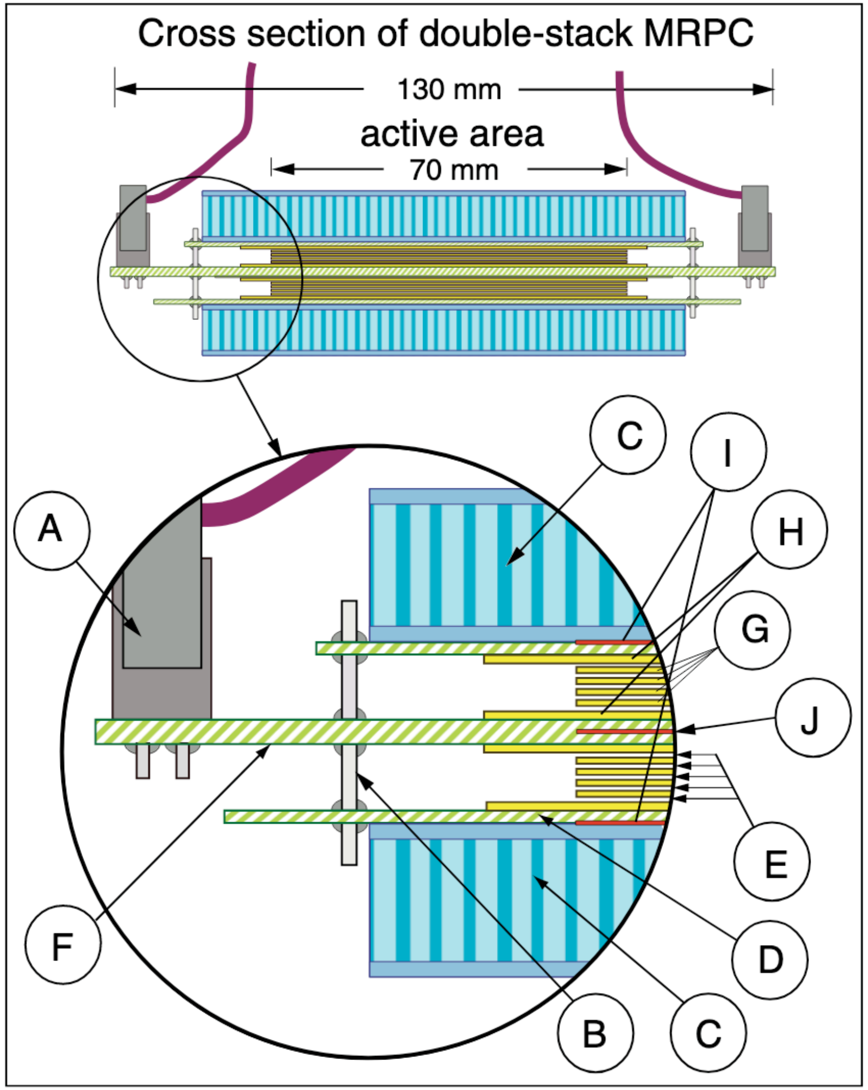
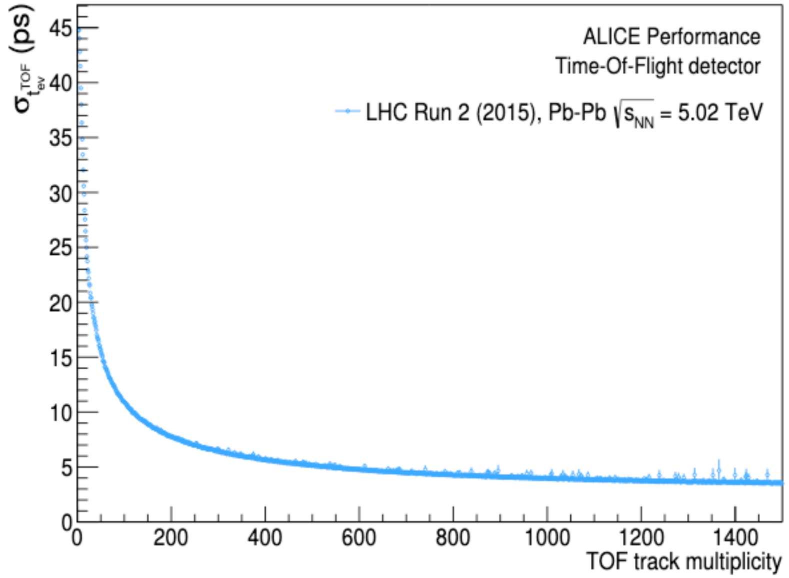


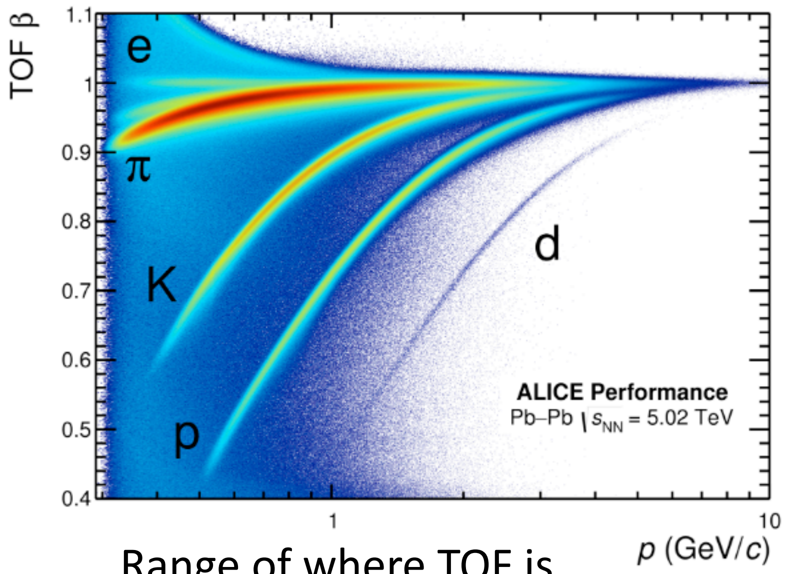
https://arxiv.org/pdf/1806.03825.pdf

Example 2: ALICE

- PID is performed by calculating the value:
  - $t_{TOF} - t_{event} - t_{trk,i}$
  - Here, t_{TOF} is the time measured at the MRPC, t_{event} is the start time of the event, and $t_{trk,i}$ is the expected arrival time for different mass hypotheses (pion, kaon, protons)
- t_{event} is calculated using either the dedicated T0 detector (limited coverage) or a weighted averaging based on all of the tracks observed in the MRPCs



Resolution of t_{event} in LHC Run 2

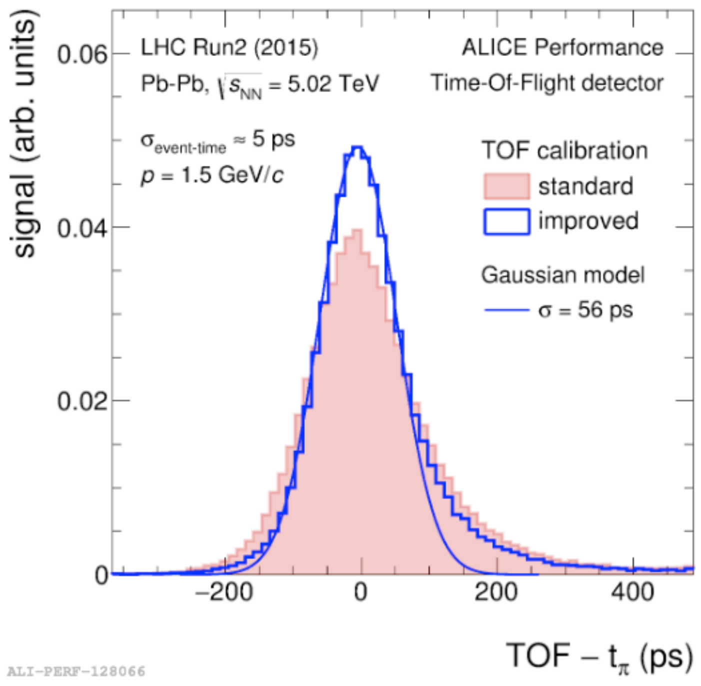


Range of where TOF is applicable for PID

Example 2: ALICE

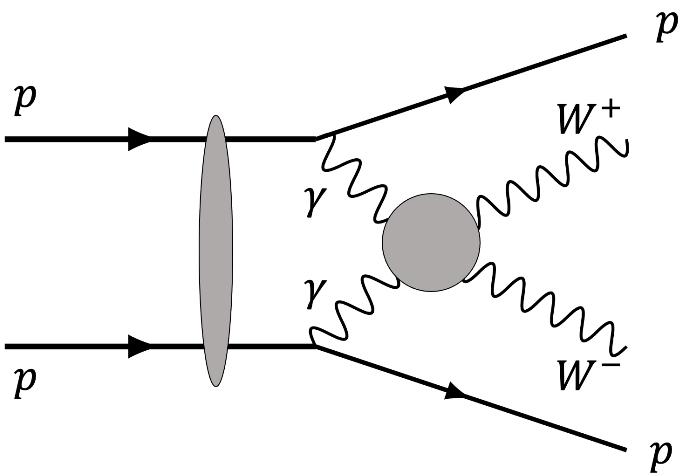
- Resolution for time measurements (total resolution is sum in quadrature of the following):
  - 12 ps intrinsic resolution for 10 gap MRPCs (if you know where the particle hits the MRPC)
  - 20 ps from front end readout
  - 30 ps for time to digital conversion
- Combined that's about ~40ps
- However, uncertainty on t_{event}, $t_{trk,i}$, and calibration raised this to ~56ps (at the end of Run 2) [1806.03825]
  - Previously quoted as ~84ps (calibration improved since then)

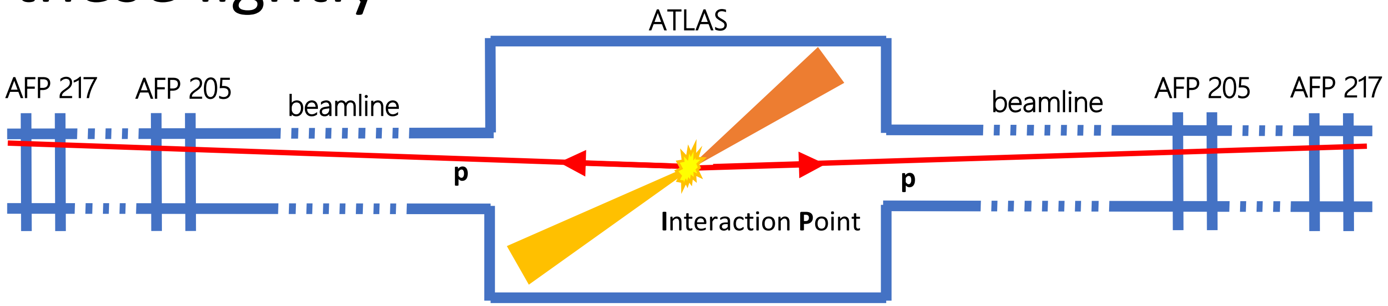
https://arxiv.org/pdf/1806.03825.pdf



Example 3: ATLAS Forward Proton Detector (AFP)

- In proton-proton (or heavy ion) collisions, the ions can radiate color-neutral particles that interact, leaving the initial ions intact
  - Often called “exclusive” production
- The intact ions lose a bit of energy and get deflected a little, but still continue down the beampipe
- The AFP is designed to detect these lightly scattered protons

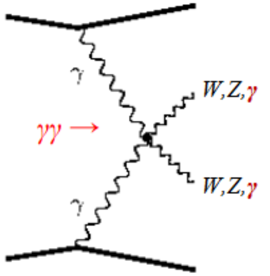




Roman Pots at ~ 205 & 217 m; at both sides of the IP

Example 3: AFP

- What does this have to do with TOF?
  - Pretty much everything going through this detector should be protons, so PID isn't really needed…
  - This is the other use of timing that I mentioned at the beginning: pileup rejection
- Using the central part of ATLAS, you roughly know where the interaction occurred (using central tracking), and using the AFP, you know how much energy the protons lost
  - Using that info, you should know how long takes for the deflected protons to reach the AFP
- However, other protons will be deflected and pass through the AFP (called "pileup" in this context)
  - Using TOF, you can tell which protons are from the interaction of interest and which are just random protons



ToF is **not** absolutely needed, but is good as additional cross check

CEPjj

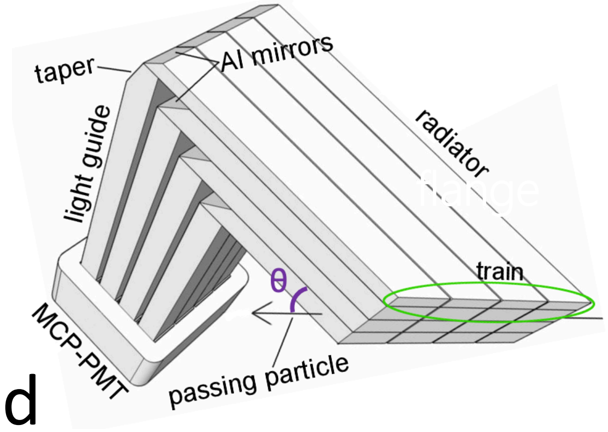
ToF is **crucial** for background rejection and purity

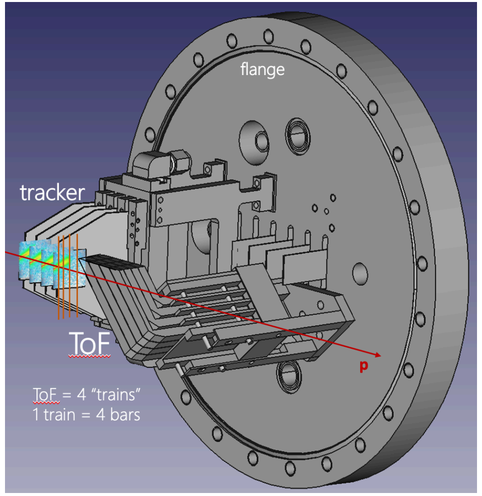
Exclusive production of EW objects is pretty distinct. It's hard to tell when an event is exclusive production of QCD objects.

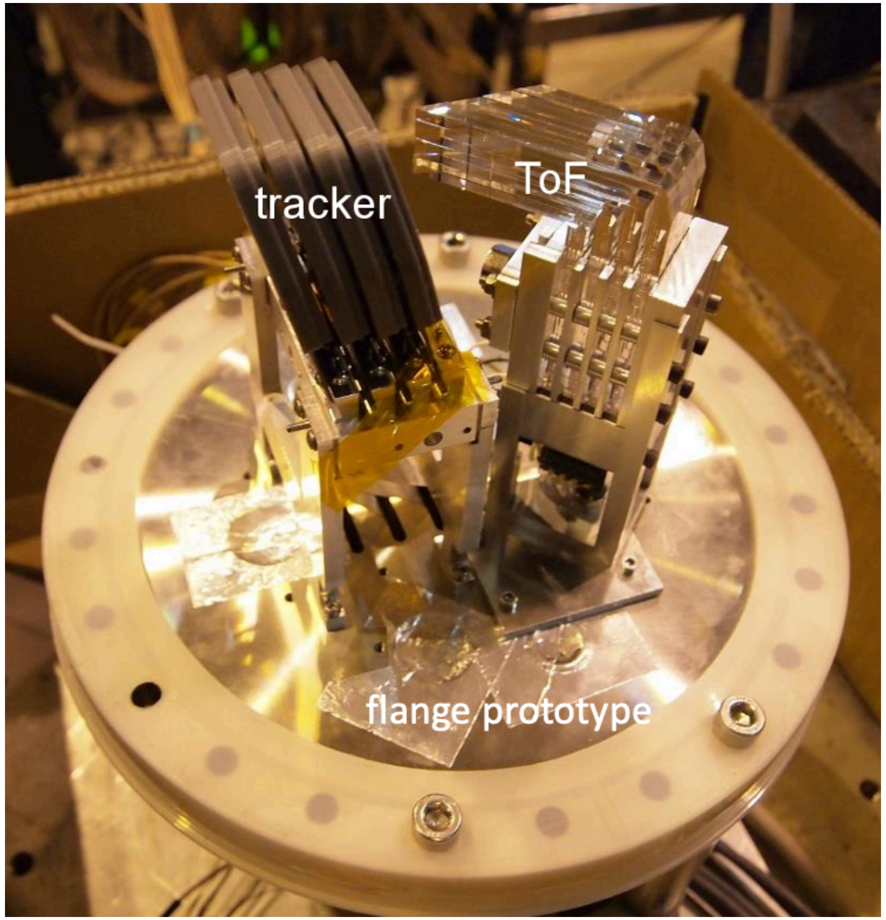
*Summary: energy, interaction location, and timing should all match up

Example 3: AFP

- The AFP timing component is L-shaped quartz bars read out by fast photomultipliers
  - The quartz is angled at the Cherenkov angle (48 deg for LHC protons) for maximum efficiency
  - Protons should pass through 4 bars each
- Current timing resolution is a bit better than 25 ps
  - Corresponds to interaction point resolution of 4-5mm (beamspot size ~40mm typically)



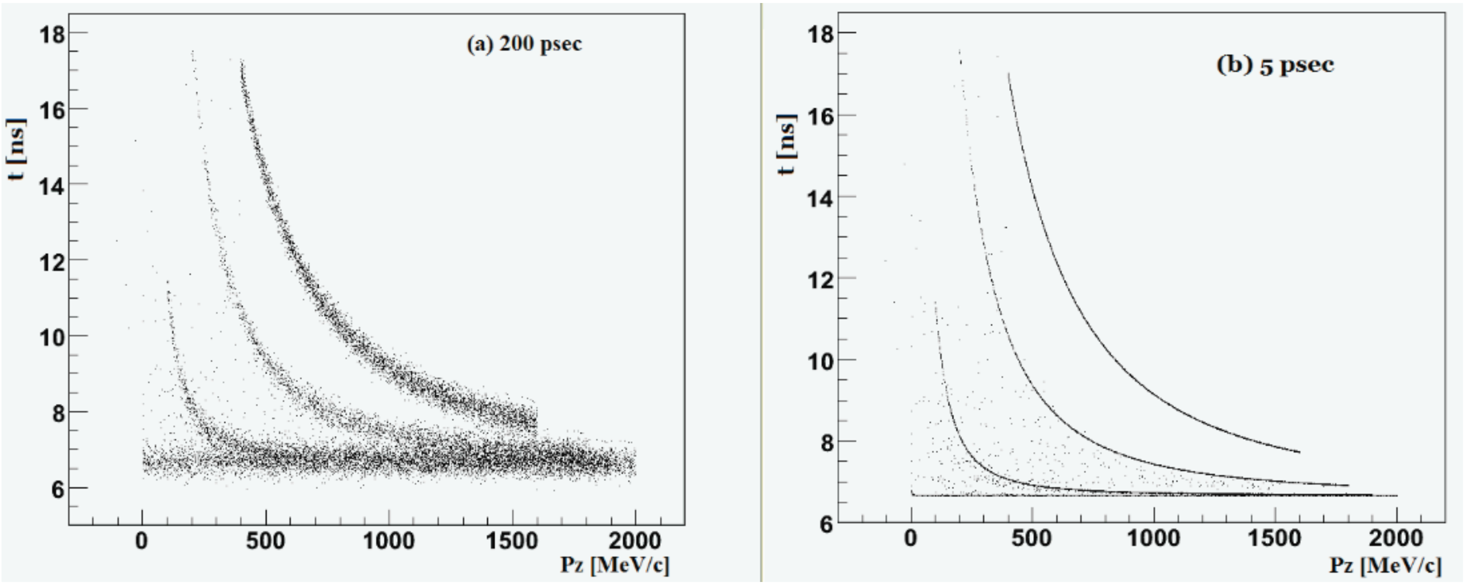




Part 3 – TOF Detectors Tomorrow

The future of TOF

- What do we want in TOF detectors?
  - Better time resolution
  - Better spatial resolution
  - Ability to instrument large areas (within budget)

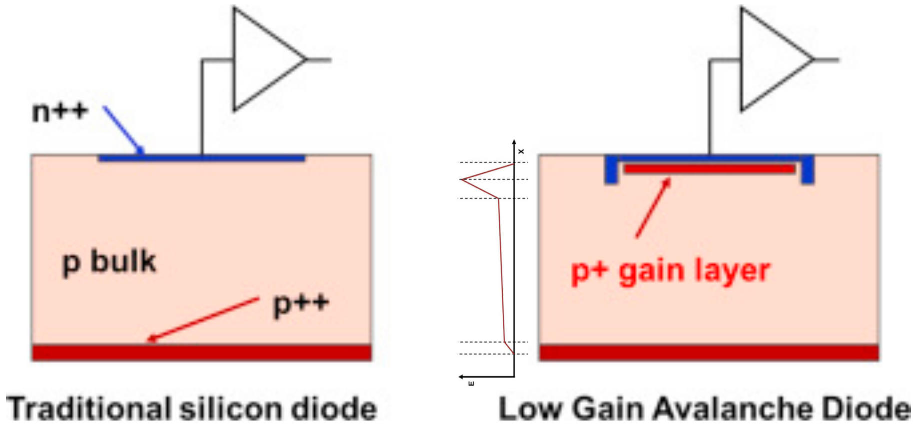


https://www.sciencedirect.com/science/article/pii/S1875389212017464

Technological drivers

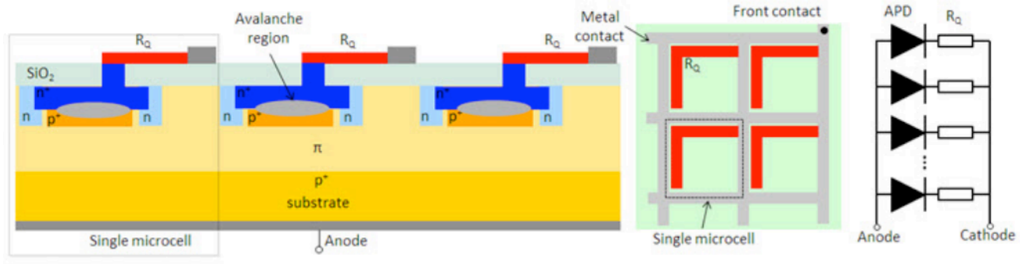
- Silicon technology has improved in the past 20 years
- Two silicon technologies to be highlighted
  - Low Gain Avalanche Detectors (LGAD): gain of 10-50 without breakdown, results in fast, sharp signal. Radiation Hard!
  - Silicon Photomultipliers (SiPM): cheaper than traditional photomultiplier tubes

https://www.sciencedirect.com/science/article/pii/S0168900218317741



Additional gain layer creates high E field

https://hub.hamamatsu.com/jp/en/technical-note/how-sipm-works/index.html



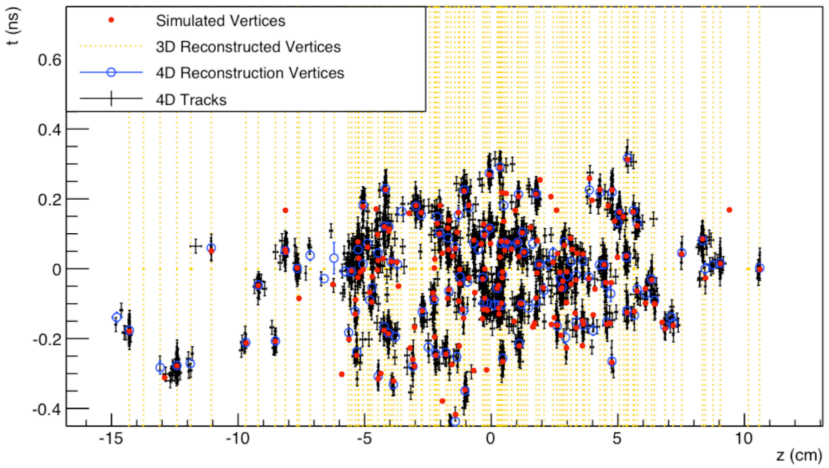
Hammamatsu SiPM layout

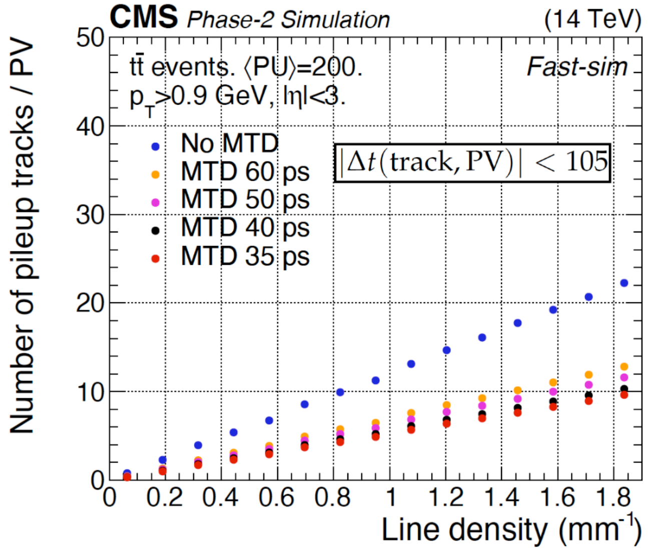
*MTD = MIP Timing Detector

Future Example 1: CMS MIP Timing Detector

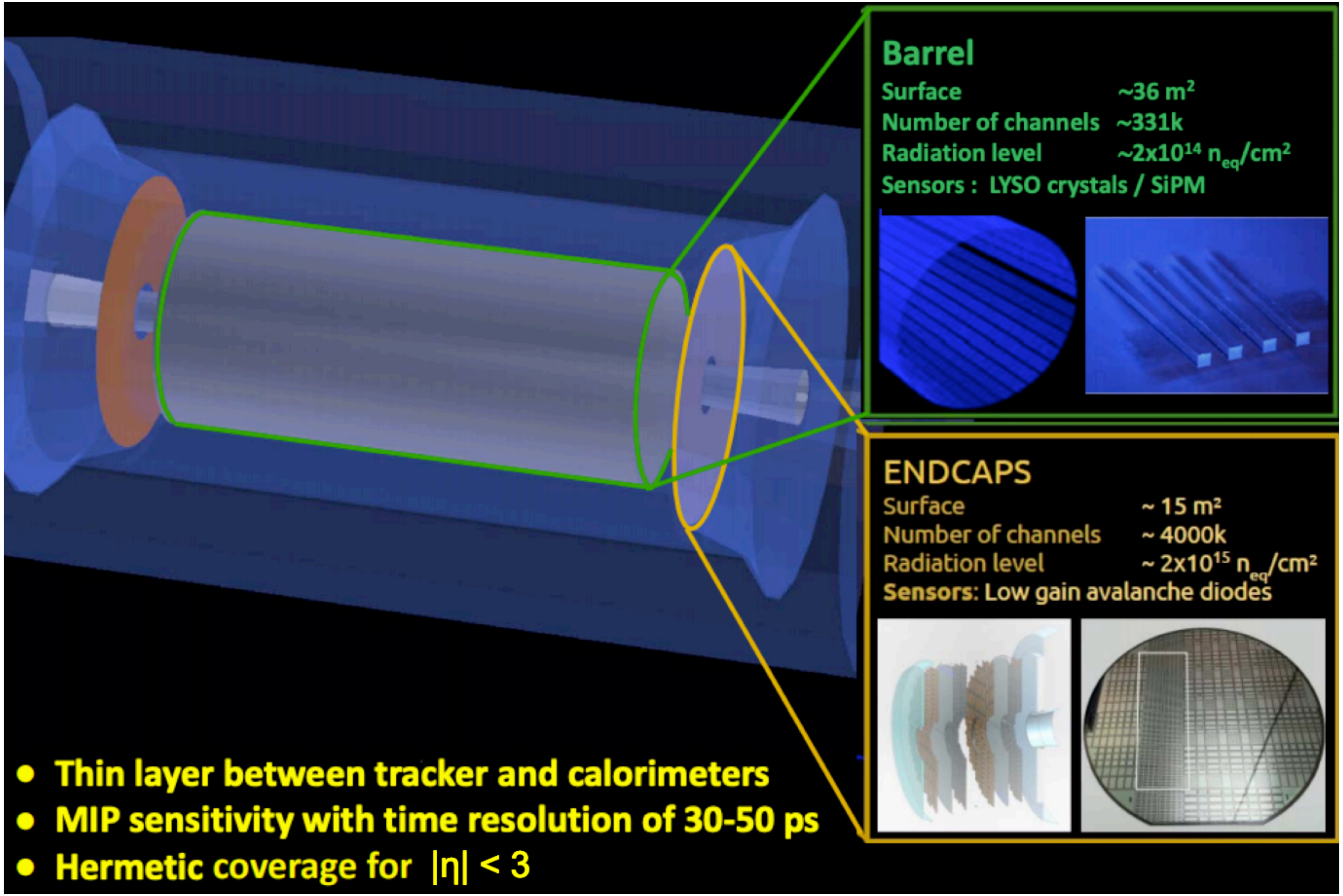
https://indico.cern.ch/event/868940/contributions/3813829/attachments/2080780/3498057/ICHEP2020_CMS_BTL_NanLu.pdf

- “MIP” = Minimum Ionizing particle
- MTD is to be installed before HL-LHC running
- Goal of MTD is to provide a time measurement for (most) tracks
  - Tracks are the reconstructed trajectories of charged particles
- **Important for pileup mitigation**
  - PP interactions are distributed in time as well as space, so you can use timing information to avoid associating tracks to the wrong interaction
- Also, with time info, CMS can do PID like ALICE





Future Ex. 1: CMS MTD



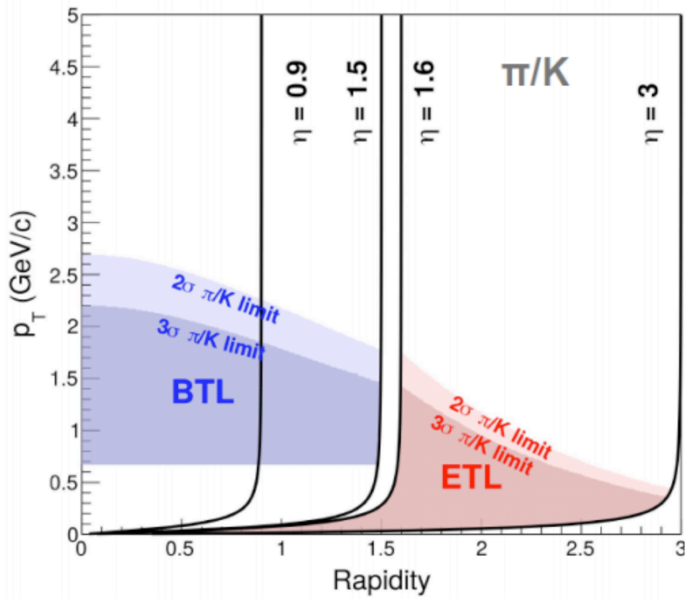
https://indico.cern.ch/event/782953/contributions/3468378/attachments/1887594/3112511/20190729_DPFMeeting_MTDPhysics.pdf

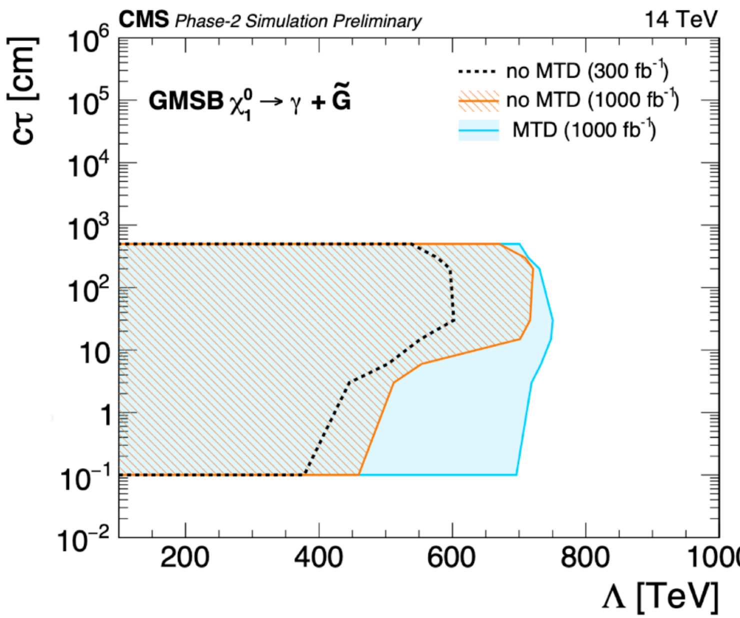
Application of SiPM in barrel region, with Cerium doped Lutetium based scintillation crystal

Application of LGAD in endcap, where rad hardness is more important https://indico.cern.ch/event/782953/contributions/3468378/attachments/1887594/3112511/20190729_DPFMeeting_MTDPhysics.pdf

Future Ex. 1: CMS MTD

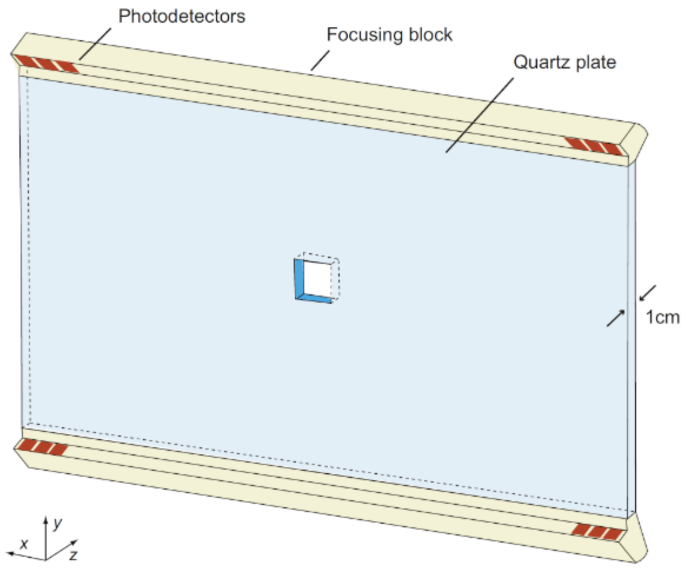
- In addition to PID and pileup suppression, can improve:
    - Lepton isolation identification
    - Jet b-tagging
    - Photon vertexing (there is timing information from the EM calorimeter)
- Physics examples:
    - Can increase effective luminosity of $H \to bb\gamma\gamma$ by 22% and $H \to \gamma\gamma$ by 30% in HL-LHC
    - Extended reach for long-lived particles searches

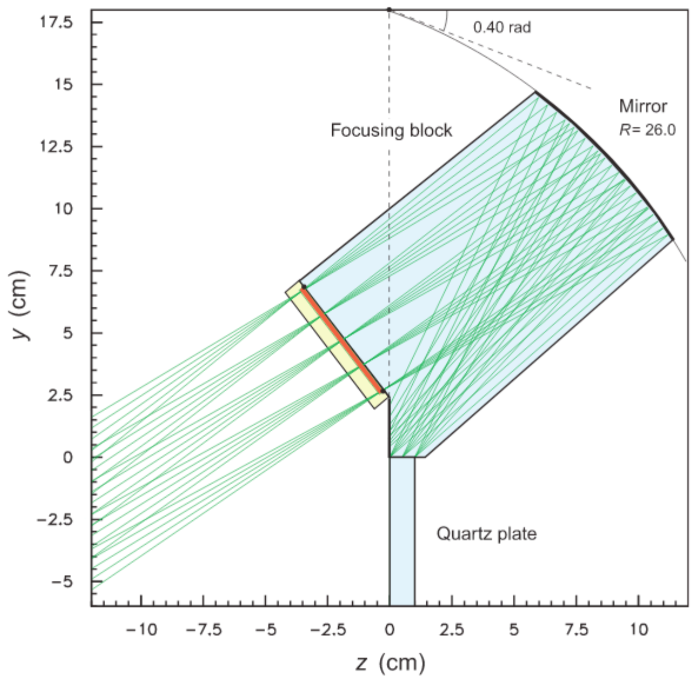




Future Example 2: LHCb's TORCH

- TORCH seeks to provide PID for particles with momentum between 2-10 GeV
- Here, a charged particle creates Cherenkov light when it traverses a 10mm thick quartz plate
- Cherenkov photons are captured by micro-channel plate photomultiplier (MCP-PMT)
  - Relatively new tech and techniques have been developed to improve rad hardness



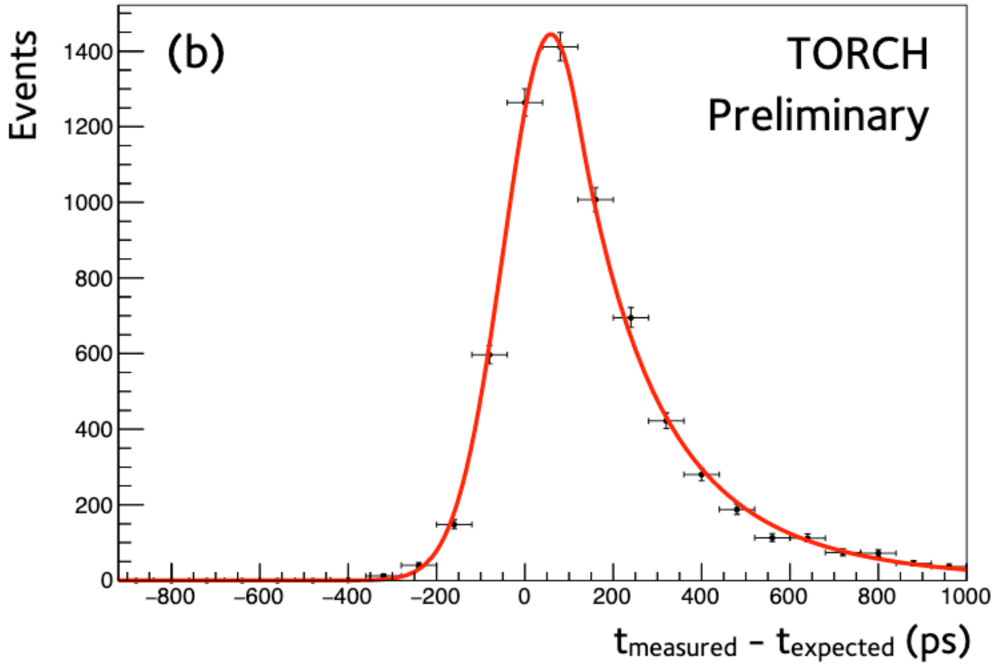


https://ora.ox.ac.uk/objects/uuid:aef79505-c7f2-418c-81c0-28265352a4c9

Future Example 2: LHCb's TORCH

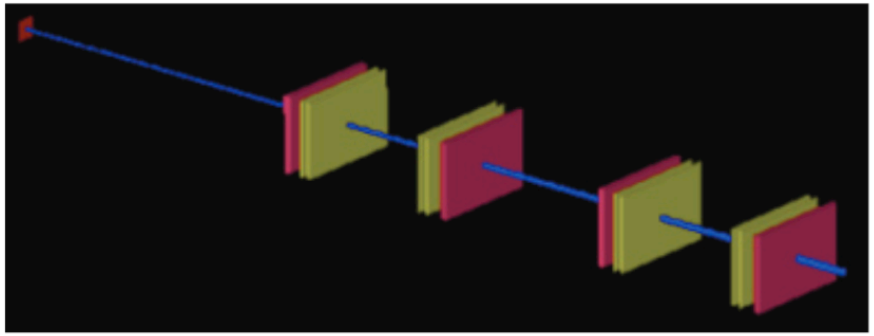
- Single photon timing resolution of about 70 ps
- With ~30 photons expected per particle, achieves a total time resolution of about 13 ps

https://arxiv.org/pdf/1810.06658.pdf

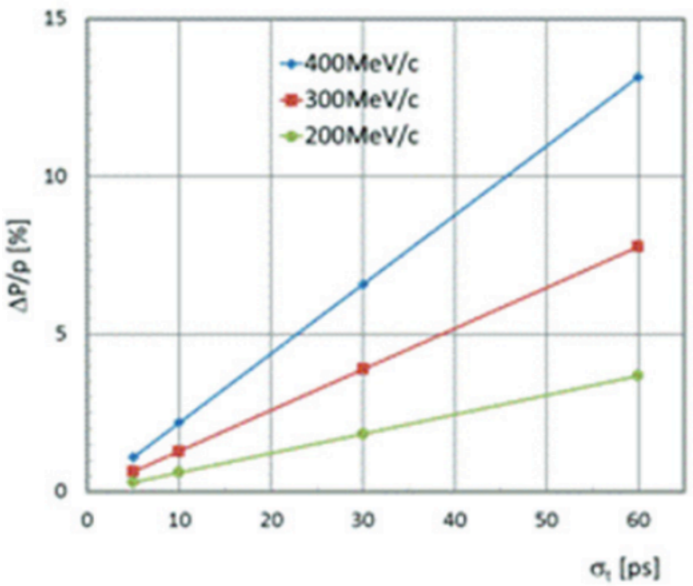


Future Example 3: MICE

https://www.sciencedirect.com/science/article/pii/S1875389212017464



- "MICE" = Muon Ionization Cooling Experiment
  - Ionization cooling is used to slow down particles in a beam, to reduce the beam emittance (transverse spread)
    - This effectively focusses the beam
  - End goal here is potentially enabling a muon collider
- The application of TOF here is to measure muon momenta without the use of a magnet:
  - In this experiment, they care about muons with momenta of ~200 MeV
  - You can use TOF to measure a particle's velocity (just distance/time), giving relativistic β and γ
  - Need timing resolution of ~10 ps to make good momentum measurements though
- Idea here is to Large Area Picosecond Photo Detectors
  - Free-standing particle timing detectors
  - Use MCP-PMTs and scintillator
  - Can achieve single-photon timing resolution of ~50ps



Summary

- TOF detectors can be built in many ways
  - Scintillator + PMT (which can be set up in many different ways)
  - MRPC
  - LGAD silicon detectors
- Main uses:
  - Particle ID
  - Pileup suppression
  - Momentum measurement (potentially)
- They find applications in most major particle experiments
  - Examples above for the 4 major LHC experiments, STAR, and standalone experiments

References

- “Particle identification using time of flight”: *J. Phys. G: Nucl. Part. Phys.* **39** 123001
- “Performance of the ALICE Time-Of-Flight detector at the LHC”: https://arxiv.org/pdf/1806.03825.pdf
  - Also “Performance of the ALICE Time-Of-Flight detector at the LHC”: https://link.springer.com/article/10.1140/epjp/i2013-13044-x
- “Particle identification in ALICE boosts QGP studies”: https://cerncourier.com/a/particle-identification-in-alice-boosts-qgp-studies/
- “The TOFp/pVPD Time-Of-Flight System for STAR”: https://arxiv.org/ftp/nucl-ex/papers/0308/0308022.pdf
- “ATLAS Forward Proton Phase-I Upgrade: Technical Design Report”: https://cds.cern.ch/record/2017378/files/ATLAS-TDR-024.pdf
- “Prospects and results from the AFP detector in ATLAS”: https://cds.cern.ch/record/2673239/files/ATL-FWD-SLIDE-2019-165.pdf
- “Applications of Fast Time-of-Flight System”: https://www.sciencedirect.com/science/article/pii/S1875389212017464
- “What is an SiPM and how does it work?”: https://hub.hamamatsu.com/jp/en/technical-note/how-sipm-works/index.html
- “The Physics of Precision Timing in CMS using the MIP Timing Detector”: https://indico.cern.ch/event/782953/contributions/3468378/attachments/1887594/3112511/20190729_DPFMeeting_MTDPhysics.pdf
- “Precision Timing with the CMS MTD Barrel Timing Layer for HL-LHC”: https://indico.cern.ch/event/868940/contributions/3813829/attachments/2080780/3498057/ICHEP2020_CMS_BTL_NanLu.pdf
- “A MIP Timing Detector for the CMS Phase-2 Upgrade: Technical Design Report”: https://cds.cern.ch/record/2667167/files/CMS-TDR-020.pdf
- “TORCH: a large area time-of-flight detector for particle identification”: https://arxiv.org/pdf/1810.06658.pdf
- “The TORCH PMT: a close packing, multi-anode, long life MCP-PMT for Cherenkov applications”: https://ora.ox.ac.uk/objects/uuid:aef79505-c7f2-418c-81c0-28265352a4c9
- “Applications of fast Time-of-Flight system”: https://www.sciencedirect.com/science/article/pii/S1875389212017464
- “Pilot Production of Large Area Picosecond Photodetector”: https://indico.cern.ch/event/432527/contributions/1071935/attachments/1319657/1979729/Pilot_Production_of_LAPPD_-_Aug_5_2016_FINAL_V5.0_08-03-2016.pdf

Backup

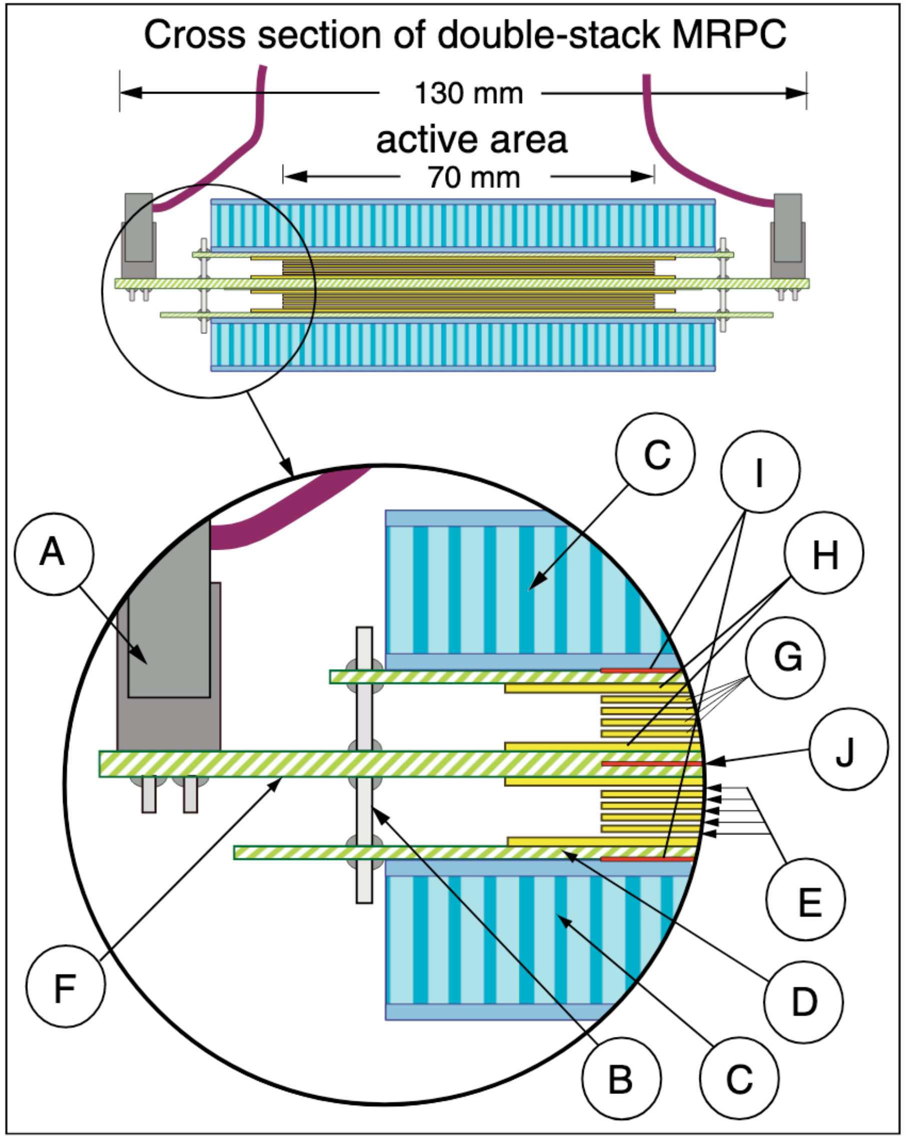
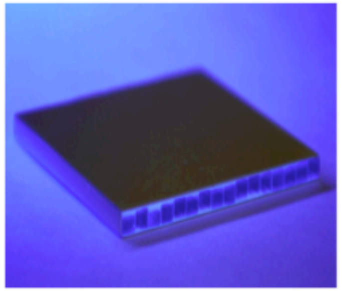


Figure 11. Cross section of the double-stack MRPC used for the ALICE time-of-flight. (A) Flat cable connector that take a differential signal from the MRPC to the front-end electronics; (B) pins used to bring signal from the cathode pick-up pads to the central pcb; (C) honeycomb panel (1 cm thick); (D) pcb with cathode pickup pads; (E) gas gaps (250 μm width); (F) central pcb containing anode pick-up pads; (G) intermediate glass plates (400 μm thick); (H) outer glass plates (550 μm thick) with outer surface painted with resistive paint; (I) cathode pick-up pad; (J) anode pick-up pad.

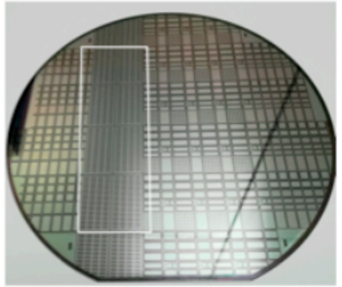
BTL: LYSO bars + SiPM readout:

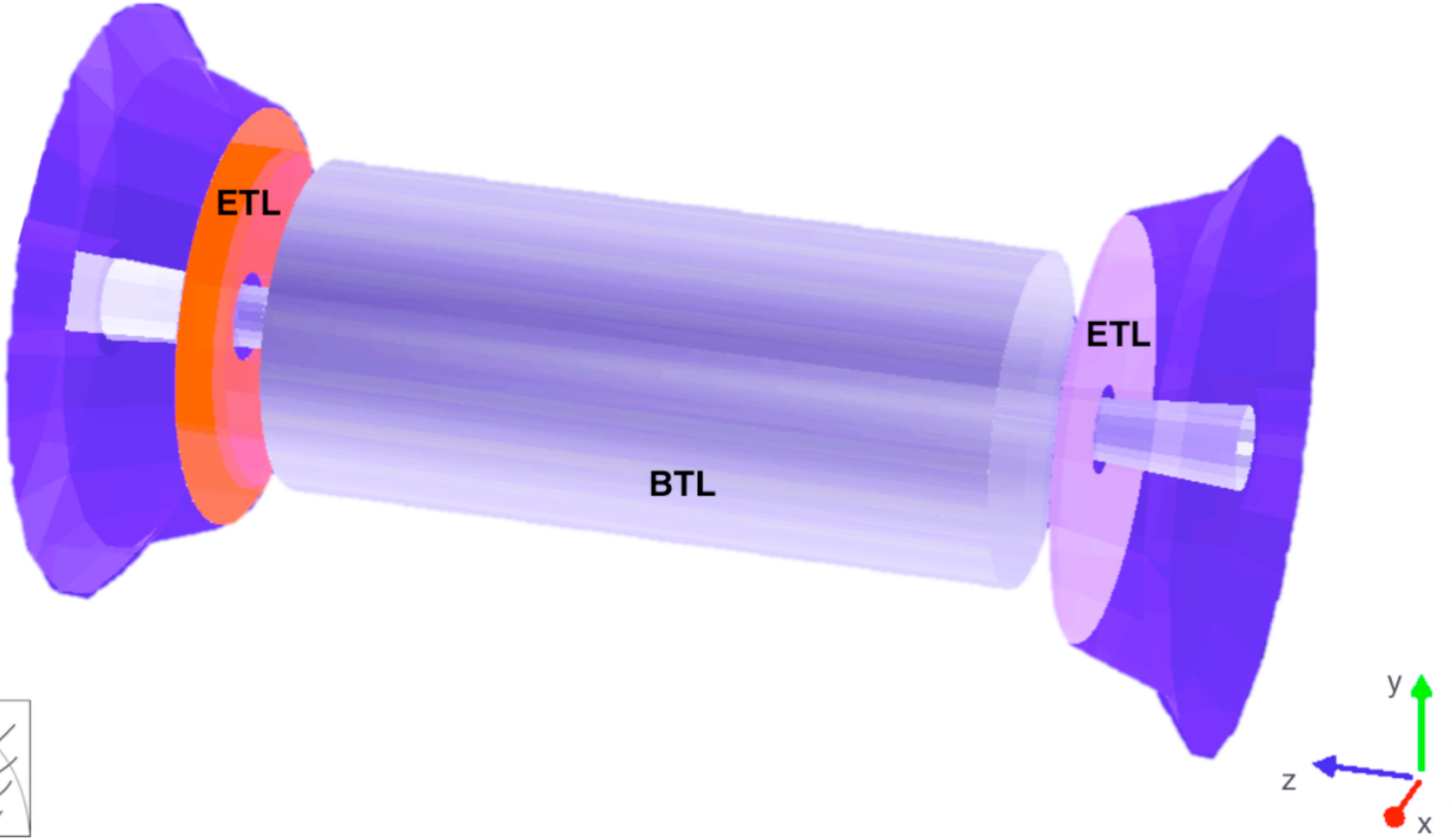
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2





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