New high performance timing detectors

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- **Outline**
  - Introduction
  - Timing devices by examples
    - Time measurement and signal processing
    - Sensors and system aspects
  - Potential future applications

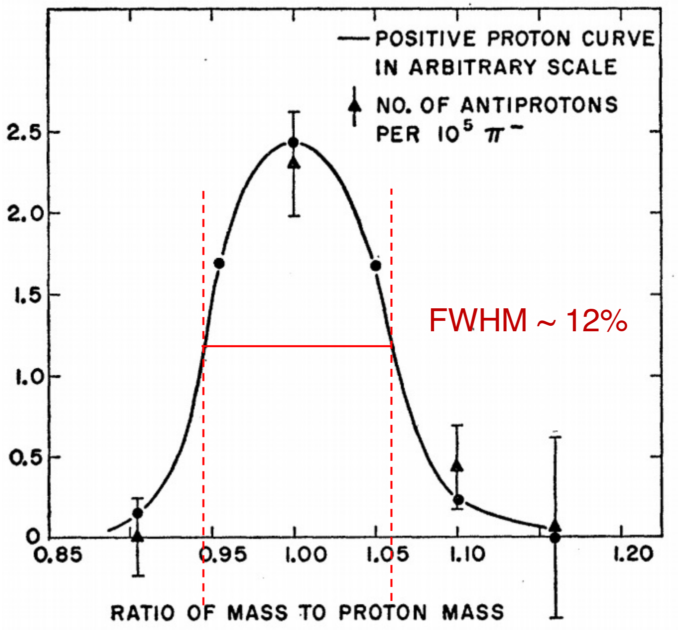
Introduction

[and indication of a few key parameters]

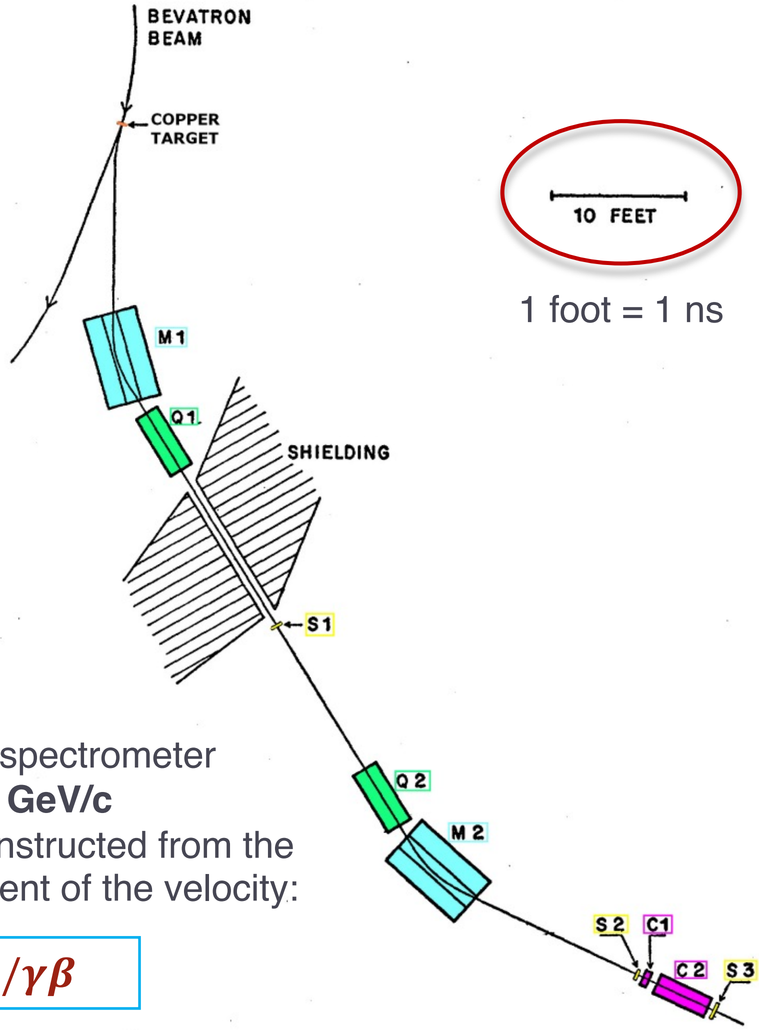
- **Historical trends**
  - Partcile identification with time-of-flight (TOF) measurements
  - Background reduction (rejection of non-beam events)
  - *[Trigger – not discussed]*
- **Applications in other fields include**
  - Background reduction in TOF-PET imaging
  - *[Mass analysis with TOF spectrometry – not discussed]*
- **New paradigm for event reconstruction at colliders (HL-LHC)**
  - “4D event” reconstruction to reduce background from concurrent collisions per beam crossing
  - **Target time resolution ~30 ps on large are systems (several 10 m^2)**
    - Time and space resolution are not comparable but time measurements will help

Observation of the antiproton – 1955

- **Time-of-flight measurement**
  - S1 and S2 plastic scintillators: **ΔL = 40 ft** (~12.2 m)
  - Pion: **β~0.99 → Δt = 40 ns**
  - (Anti)proton **β~0.78 → Δt = 51 ns**
  - Cherenkov counters to suppress pion background from accidental coincidences



FWHM ~ 12%



1 foot = 1 ns

Small-bite spectrometer

- **p = 1.19 GeV/c**

Mass reconstructed from the measurement of the velocity:

$$\boxed{m = p/\gamma\beta}$$

[O. Chamberlain, E. Segrè, C. Wiegand, T. Ypsilantis, https://doi.org/10.1103/PhysRev.100.947]

Observation of the antiproton (II)

- **Time-of-flight measurement**
  - S1 and S2 plastic scintillators: **ΔL = 40 ft** (~12.2 m)
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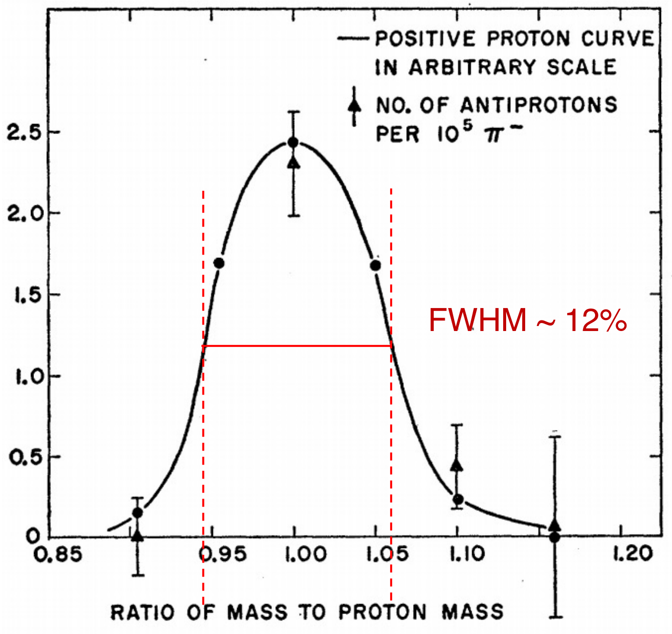


- **Exercise:**
  - Estimate the time resolution of the scintillator counters from the anti-proton mass distribution
  - **[R. σ_t = 0.6 ns per counter]**

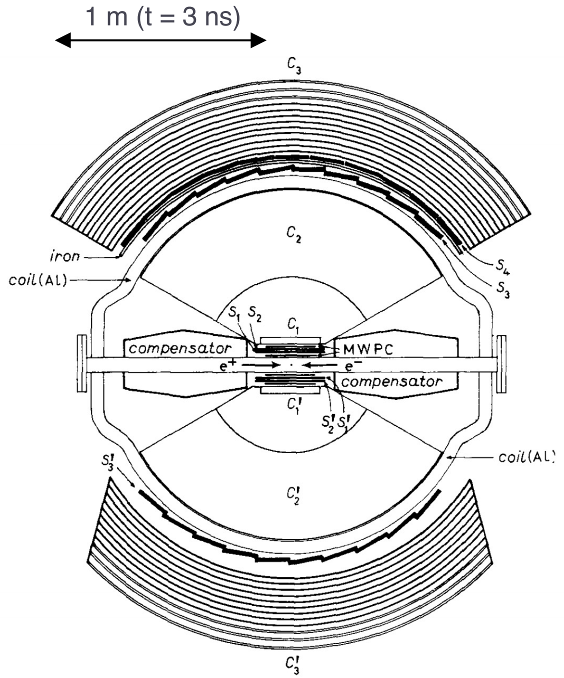
- ***Hints:***
  - *Assume no momentum loss along the beamline and the same time resolution in both counters*
  - *Show that, for negligible uncertainty on **p** and **ΔL**,*

$$\frac{\sigma_m}{m} = p\gamma^2 \left(\frac{\sigma_{\Delta t}}{\Delta t}\right) \qquad (1)$$

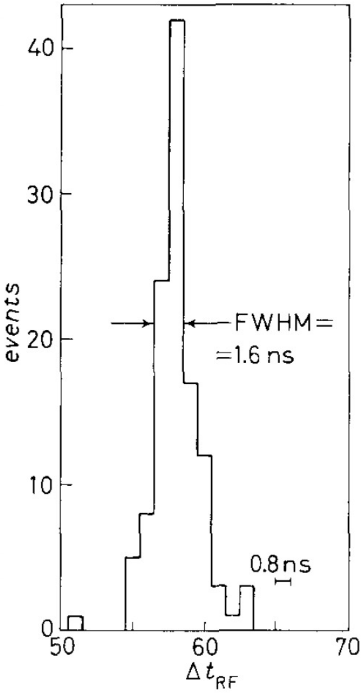
- ***Comment***
  - *In a spectrometer, **ΔL** can be (arbitrarily) large and adapted to the momentum*
  - *The quest for time resolution is limited: **Δt = ΔL/cβ***

Background suppression at colliders - 1969

- **ADONE e^+e^- collider**
  - Collision distinguished from cosmic rays by means of scintillator counters, **by requiring a suitable phase relative to the accelerator radiofrequency**
    - [W.W. Ash et al., LNF 74/69(P)]

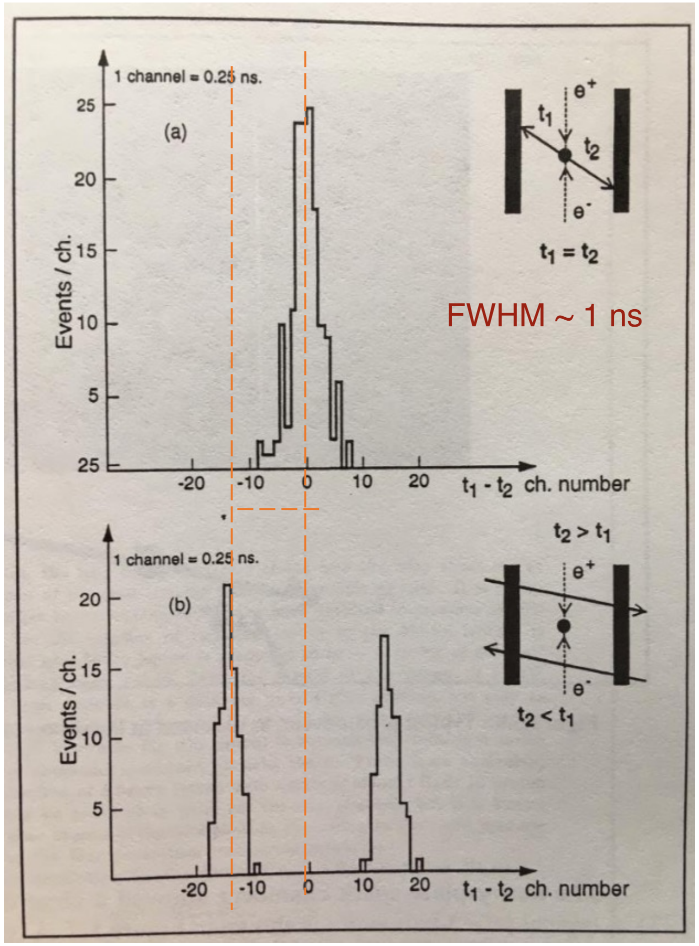


MAE experimental apparatus
[W.W Ash et al., LNF 69/2]
S1,S2, S3, S4 scintillators



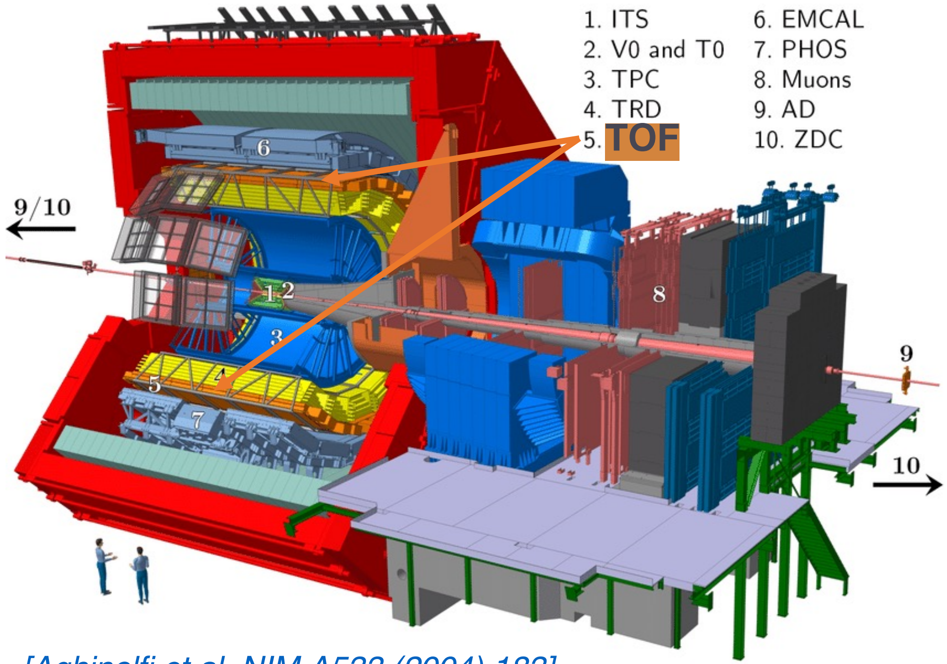
Beam events

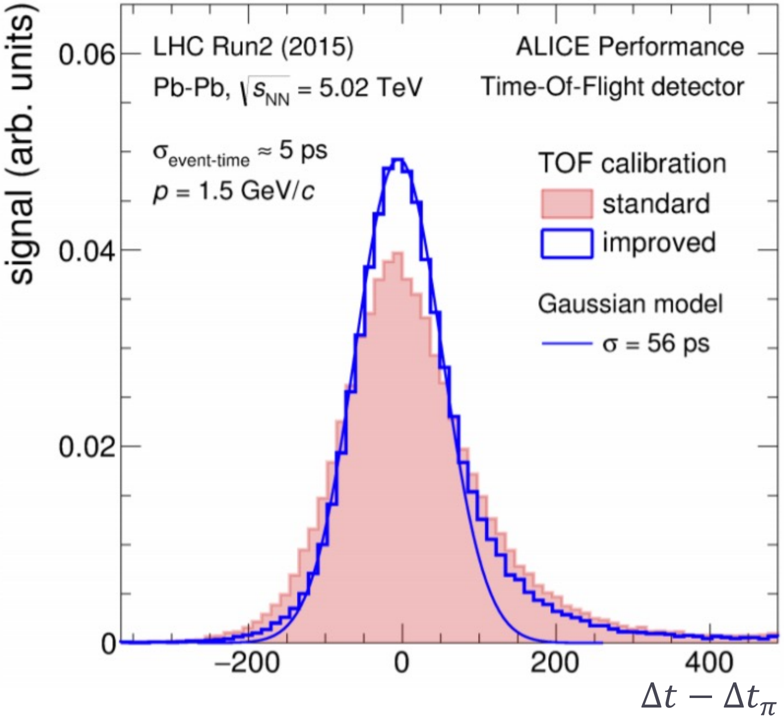
- Collisions distinguished from cosmic rays by means of a TOF measurement with **σ_t ~ 350 ps** timing resolution per counter



State-of-the-art time-of-flight – in operation

- **ALICE TOF at Large Hadron Collider (heavy Ion collision physics)**
  - Particle identification with **140 m²** of Multigap RPCs at **3.7 m** from the interaction point (IP)
  - TOF relative to the IP time (event time) defined using a high multiplicity of tracks: $\Delta t = t_{TOF} - t_{IP}$
- **In-situ single-particle resolution $\sigma_{TOF} \sim 60$ ps**
  - 40 ps with a single channel at test beam
  - (+) 40 ps of **system effects from 10^5 channels**
    - *Channel pulse uniformity, cross-calibration, clock distribution, event time*

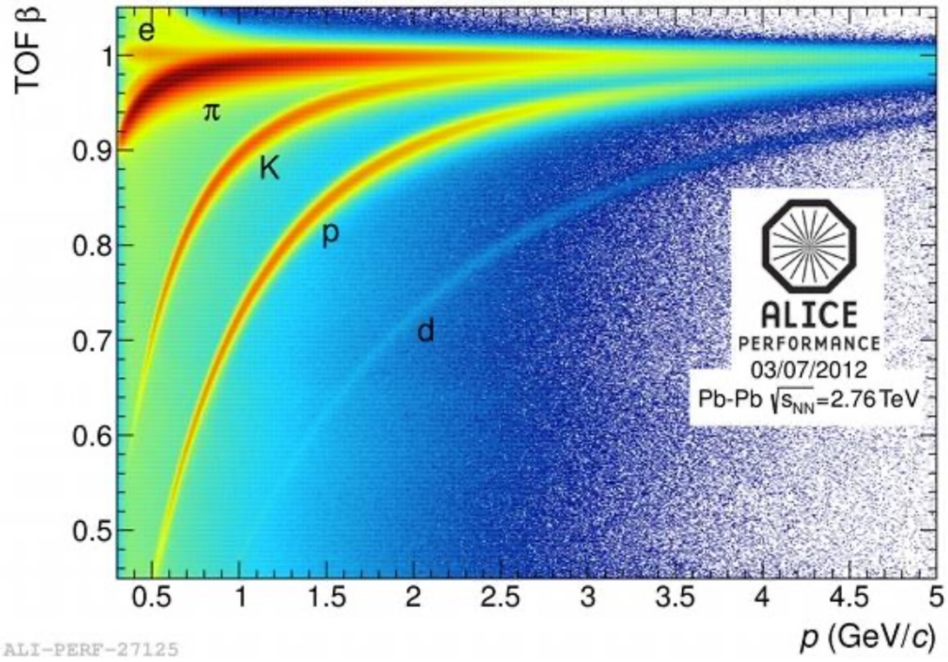




[Aghinolfi et al. NIM A533 (2004) 183]
[Jacazio, ALICE Coll., PoS (LHCP2018, 232]

State-of-the-art time-of-flight (II)

- **Collider vs spectrometer TO systems**
  - Large area detectors → system effects
  - Wide momentum spectrum at “fixed” **ΔL** → the mass separation decreases with increasing momentum



- **Exercise:**
  - Show that the mass separation scales as **$1/p^2$** in the ultrarelativistic limit

- **Exercise:**
  - Show that the mass resolution is

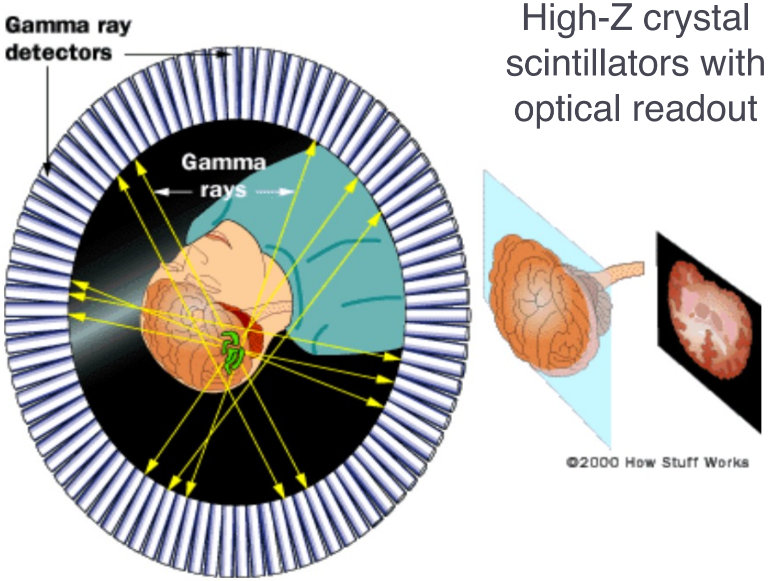
$$\frac{\sigma_m}{m} = \frac{\sigma_p}{p} + p\gamma^2 \left(\frac{\sigma_\beta}{\beta}\right) \qquad (2)$$

  - The second term – amplified by the Lorentz factor – dominates the resolution for typical tracking systems
  - The path-length uncertainty from the track fit is usually small, and the second term reduces to Eq.(1)
    - **The measurement of time is key**

Time-of-flight in medical imaging

- **Positron Emission Tomography (PET)**
  - Functional imagning that exploits the **annihilation of β^+** emitted by a radiotracer **with an electron in the tissue**
    - **β^+ range ~1 mm** (one limit on image resolution)
  - The image is reconstructed from **intersection of lines of responses (LORs)**, formed by two **511 keV γ-rays** detected in coincidence
    - **Signal**: back-to-back γ-rays
    - **Background**: Fake LORs from scattered γ-rays, or accidental coincidences, reduce the image quality

High-Z crystal scintillators with optical readout



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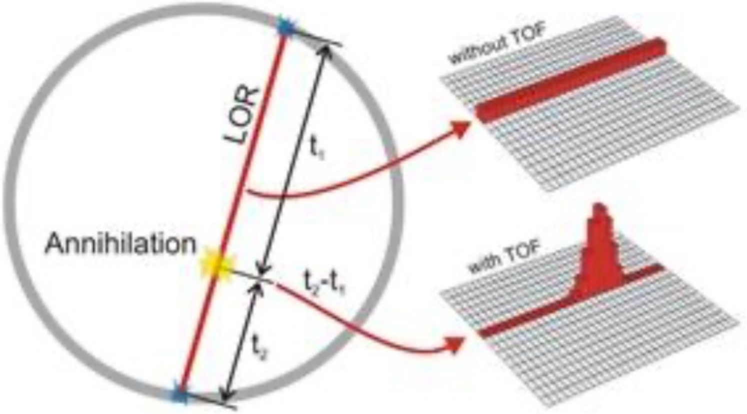
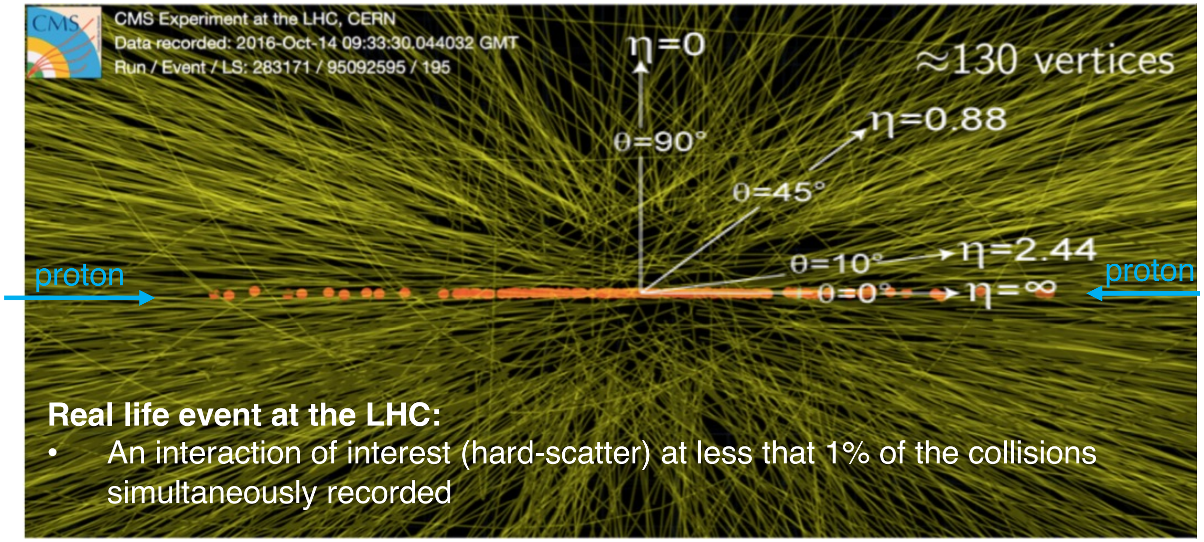
- **TOF-PET help reduce background restricting the search region to a few centimeters of the LOR**
  - State-of-the-art TOF-PET scanners achieve FWHM coincidence time resolutions of O(100) ps
- **Exercise:**
  - Which resolution would be needed to locate the β^+ emission point with a resolution of 1 mm, comparable to the typical β^+ range in tissues?
  - [**R. 3 ps**]

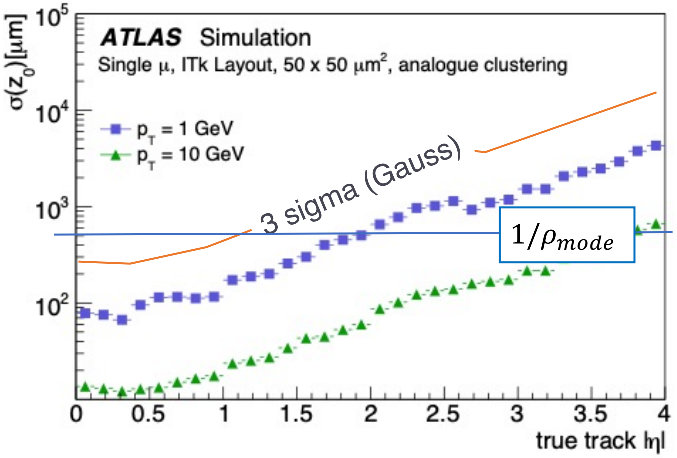


The HL-LHC challenge



Real life event at the LHC:

- An interaction of interest (hard-scatter) at less that 1% of the collisions simultaneously recorded



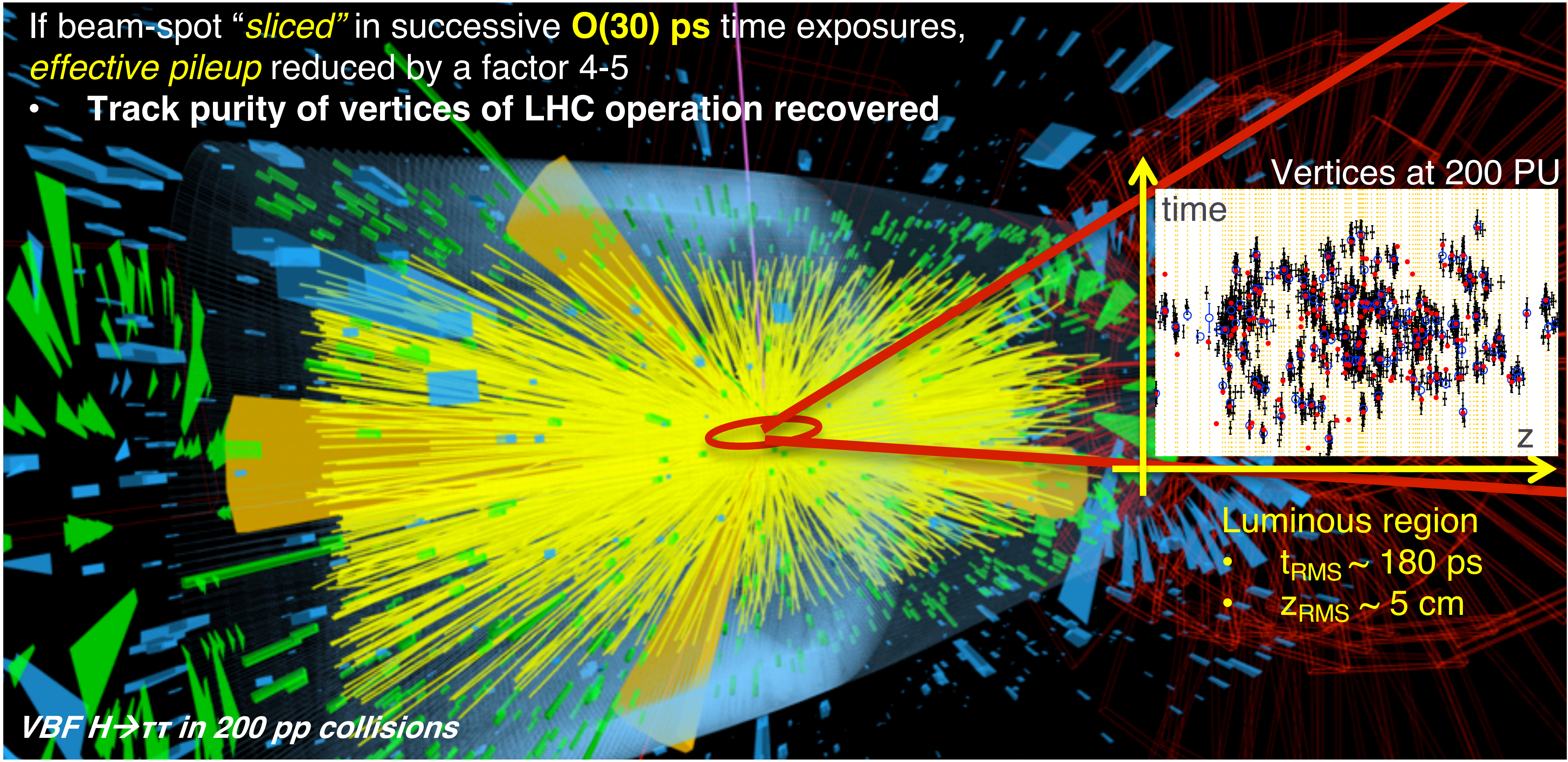
- **HL-LHC (start 2027): upgrade of the optics and injectors to increase the beam intensity**
  - Up to **~200 pileup collisions** (concurrent collisions per beam crossing) from ~50 at current LHC
  - Beam profile unchanged: **z_{RMS} ~ 5 cm** → **mode vertex density $\rho \sim 1.8\ mm^{-1}$**

- **Reconstruction quality depends on *track-vertex assignments,* which become ambiguous when track resolution is comparable to vertex separation**
  - Vertex merging, fake association of "pileup" tracks with vertices, final state kinematics distorted, jet, lepton, photon (final state "objects") classification affected

Pileup mitigation with time information

If beam-spot "*sliced*" in successive **O(30) ps** time exposures, *effective pileup* reduced by a factor 4-5

- **Track purity of vertices of LHC operation recovered**



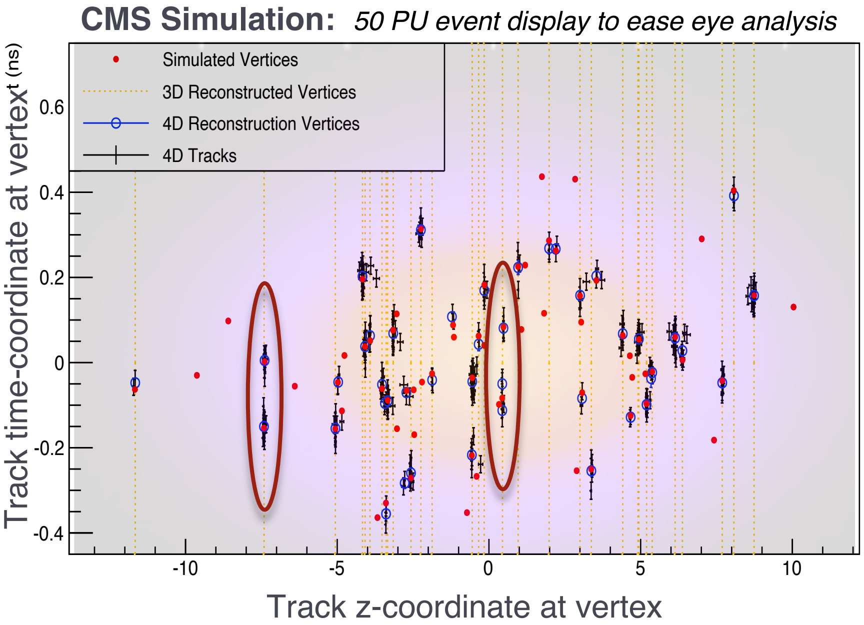
Luminous region

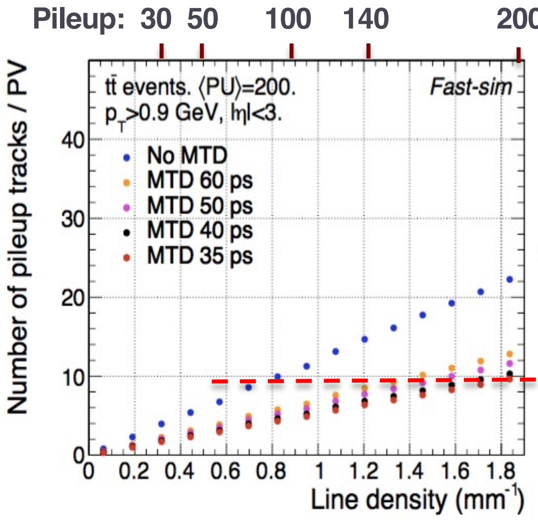
- t_{RMS} ~ 180 ps
- z_{RMS} ~ 5 cm

VBF H→ττ in 200 pp collisions

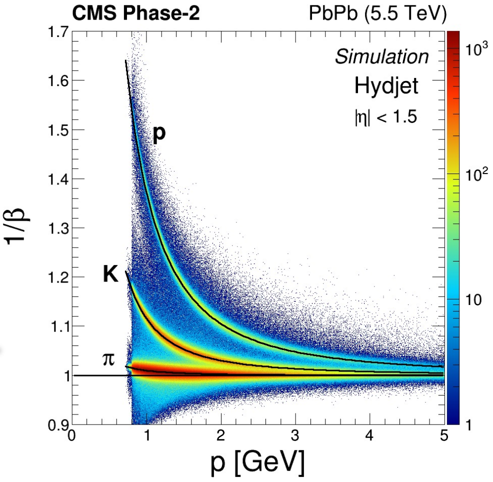
- **Exercise:**
  - Estimate the length of the proton bunches from the spread of the collisions alongs the beam axis (z_{RMS})
  - Estimate the spread in time of of the collisions from the proton bunch velocity (β=1)
    - Note: The exact time spread depends on the crossing-angle and optics details

3D vs 4D event reconstruction





Pileup reduction



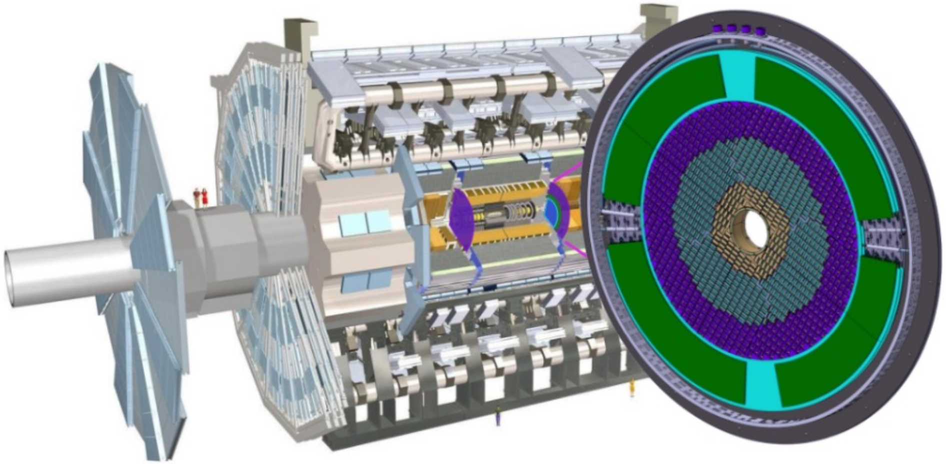
PID: flavour physics

- **Spatially overlapping vertices resolved in the time dimension**
  - Timing reduces the “effective” vertex line density
  - In addition, TOF resolution provides some particle ID capabilities (ΔL not optimized for that)
- **Significant object-level improvements and sensitivity gains across physics program**
  - Equivalent gain in “effective luminosity” ~+25% and additional discovery potential (long-lived particles)
  - See, e.g., C. Ohm, LHCP2021, June 7-12, 2021 for a summary of the ATLAS and CMS studies

The detectors

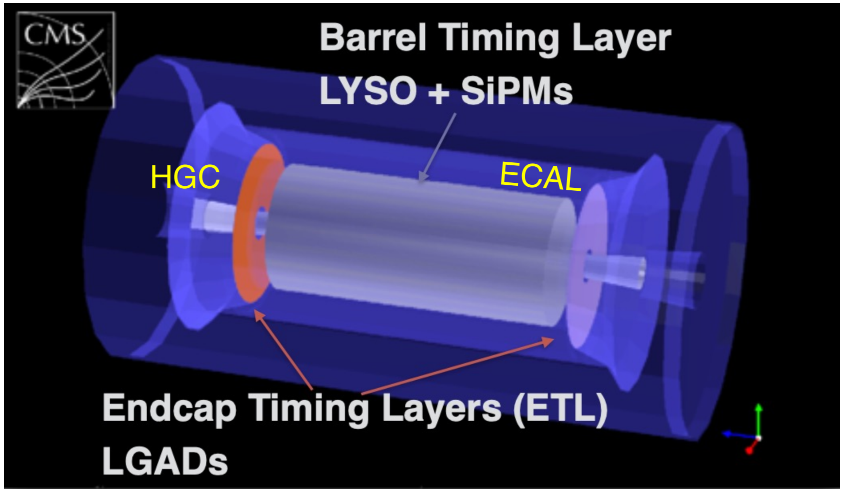
CMS MTD TDR: [CERN-LHCC-2019-003]
ATLAS HGTD TDR: [CERN-LHCC-2020-007]

- **ATLAS forward region (2.4 < |η| < 4.0)**
  - 3-4 layers of **Low Gain Avalanche Diodes (LGADs)** at z = ± 3.5 m from the IP



  - Typically, 2–3 hits per track: $\sigma_t \sim$ 30–50 ps/track

- **CMS hermetic coverage (|η|<3.0)**
  - BTL: Single layer of **LYSO crystals with dual-end SiPMs** readout at R=1.1 m
  - ETL: Two disks of **LGADs** per end (z = ± 3 m)



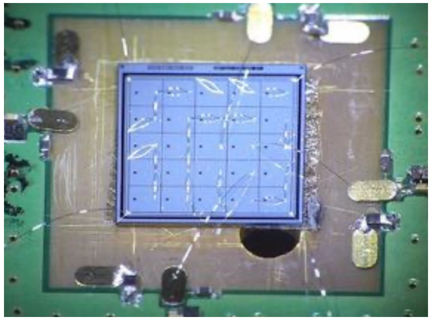
  - $\sigma_t \sim$ 30-40 ps at start up, barrel degrades to 50-60 ps at end of HL-LHC (radiation damage)

- **Cost-effective coverage of large areas**
  - Mechanics, services and schedule compatible with existing upgrades
  - Minimal impact on calorimeter and tracker performance
  - Rate capability and radiation tolerance
    - Radiation ~ 10x LHC: **$2\text{x}10^{14}$** (Barrel), up to **$2\text{x}10^{15}$** (CMS Endcaps) and **$6\text{x}10^{15}$ n_{eq}/cm^2** (ATLAS)

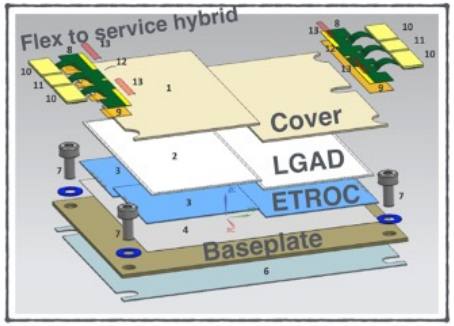
Some parameters

- **LGAD arrays for ATLAS / CMS**
  - **16x16 pads of 1.3x1.3 mm^2 x 50 μm** bump-bonded to dedicated readout ASICs (130 / 65 nm technology)
    - 3.5 / 8 MChannels in ATLAS / CMS
    - Surface 4.6 / 14 m^2 in ATLAS / CMS including multiple layers
  - Low temperature operation (T = –30 ^{0}C) with CO$_2$ dual-phase cooling
  - Power need ~5 kW / m^2

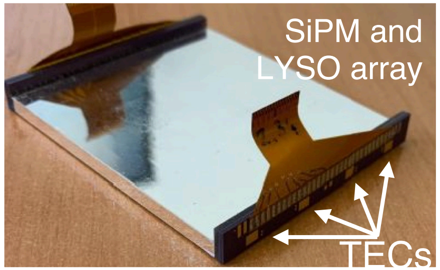
5x5 pads prototype

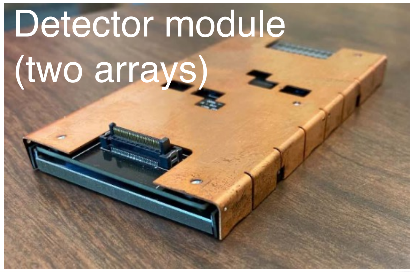


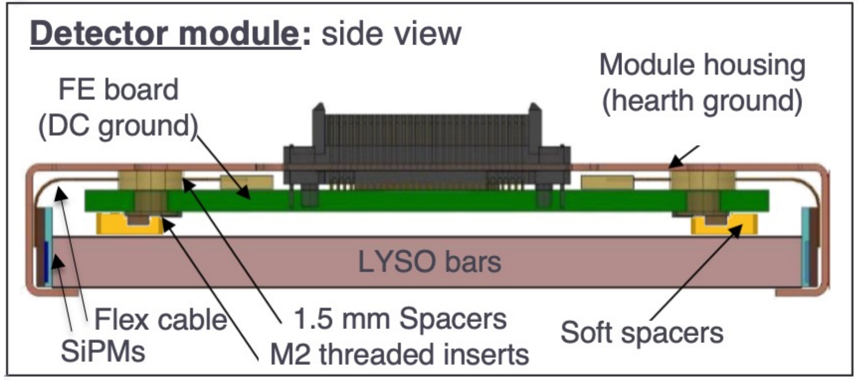
ETL module (exploded)



- **BTL arrays for the CMS barrel**
  - **16 LYSO bars 3x3x57 mm^3**
  - **16 SiPMs arrays** on each side with **thermoelectric coolers** on the back
  - Dedicated readout chip (110 nm tehcnology)
    - 332k Channels
    - Surface ~38 m^2 (SiPM surface ~ 2 m^2)
  - Low temperature operation (T < –40 ^{0}C) with CO$_2$ dual-phase cooling and additional ~10 ^{0}C local cooling from TECs
  - Power need ~ 1 kW/m^2







Timing sensors by exampes

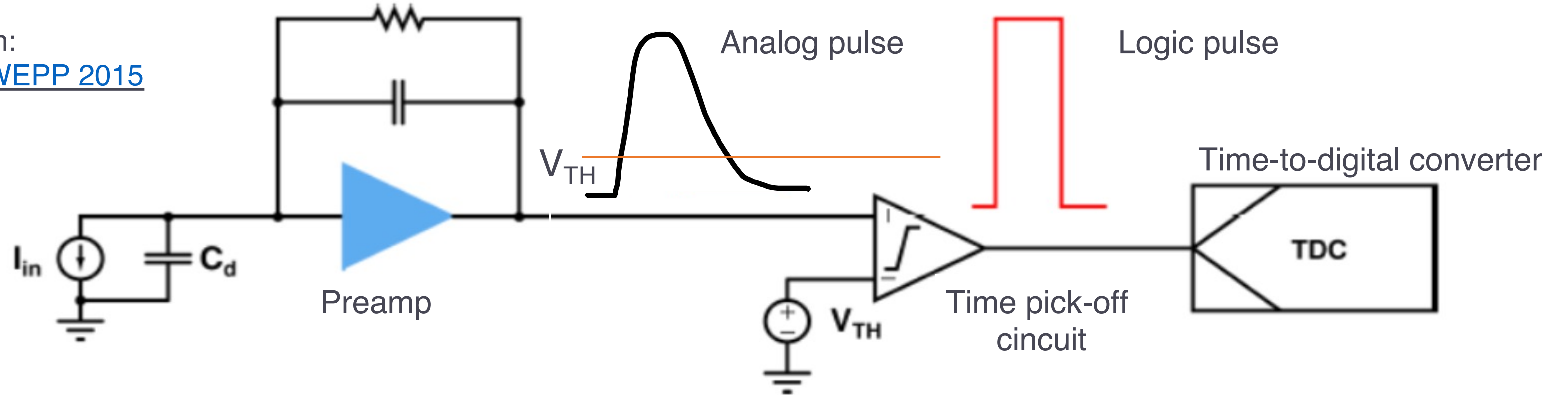
Time measurement and signal processing, sensors, system aspetcs

- **Time measurements key parameters**
  - Rule of thumb: **the spread on a small time is small**
    - Keep the charge generation localized and have fast signals (short time collection)
    - [and comply with integration and environment constraints]

- **Example of time detectors and sensor optimization**
  - Silicon detectors: the Low Gain Avalanche Diodes
  - Light detectors: the CMS barrel timing layer example
  - *[Gas detectors - not discussed*
    - *e.g., ALICE Multigap RPCs, GEMs, Micromegas with Cherenkov radiatior, …*
    - *Radiation tolerance, rate capability, and/or maturity insufficient for this application]*

Time measurement

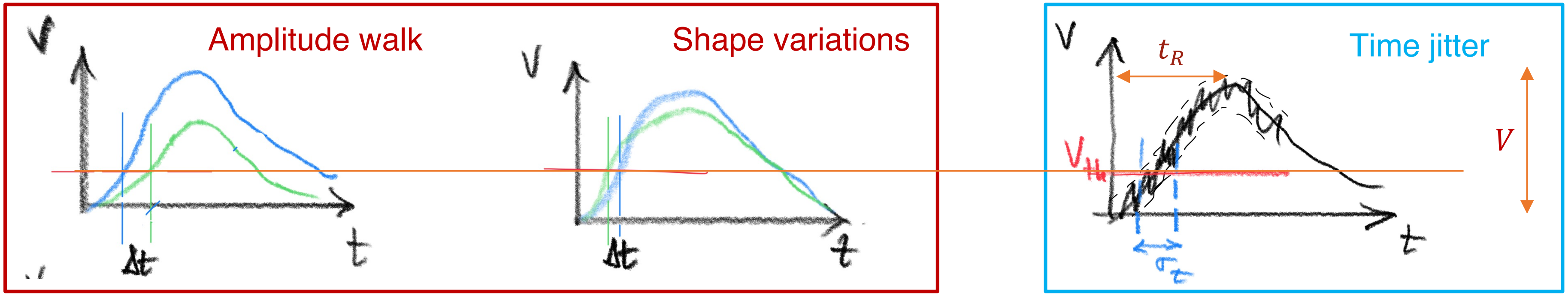
Adapted from:
A. Rivetti, TWEPP 2015



- **Time measurement:**
  - Time pick-off: generation of a **logic pulse** whose leading edge indicates the time of occurrence of an input **analog pulse** (shaped pulse of the current signal from the sensor)
  - The time information is digitized by a time-to-digital converter (TDC)
- **The time resolution depends on:**
  - Pulse properties at the input of the time pick-off device (combination of detector and shaping properties)
  - The time pick-off method
    - Leading edge discrimination with a (settable) threshold comparator most popular in ASICs
  - The digitization step (sub-leading)
- **Strong interplay between sensors and electronics**

Time resolution terms

$$\sigma_t^2 = \sigma_{\mathrm{ioniz.}}^2 + \sigma_{\mathrm{jitter}}^2 + \left[\sigma_{\mathrm{TDC}}^2 + \sigma_{\mathrm{clock}}^2\right]_{\mathrm{subleading}} + \sigma_{\mathrm{system}}^2$$



Leading edge discrimination

- **Time walk (inaccuracy from amplitude or shape variation)**
  - **Fluctuations in signal formation** from ionization process and uniformity of charge collection
    - Sensor and time pick-off method dependent
    - Amplitude walk corrected offline using time and amplitude (proxies) readout *[online methods - not discussed, e.g., CFD]*
- **Time jitter (inaccuracy from noise at constant amplitude)**

⇒ Sensors with **large and fast risetime signals** (fast collection time)

⇒ Wide readout bandwidth (matched to the risetime: $BW \sim 1/t_R$)

$$\boxed{\sigma_t = \sigma_V / \langle dV/dt \rangle \approx \frac{\sigma_V}{V} t_R}$$

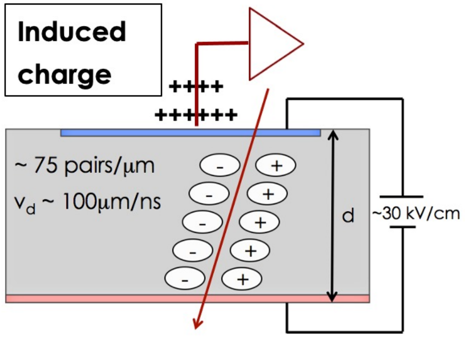
- **Other terms (subleading with proper design)**
  - $\sigma_t = \Delta T_{bin} / \sqrt{12}$ (minimize TDC bin size)
  - $\sigma_{clock} < 15\ ps$ (specification for the HL-LHC systems – See O. Sahin's Laboratory)

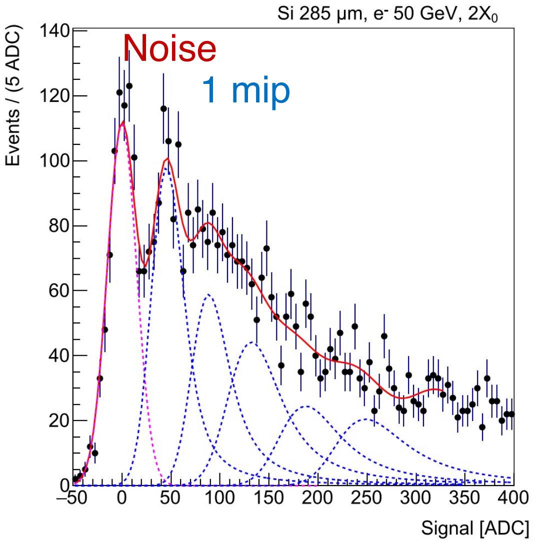
Timing with silicon diodes

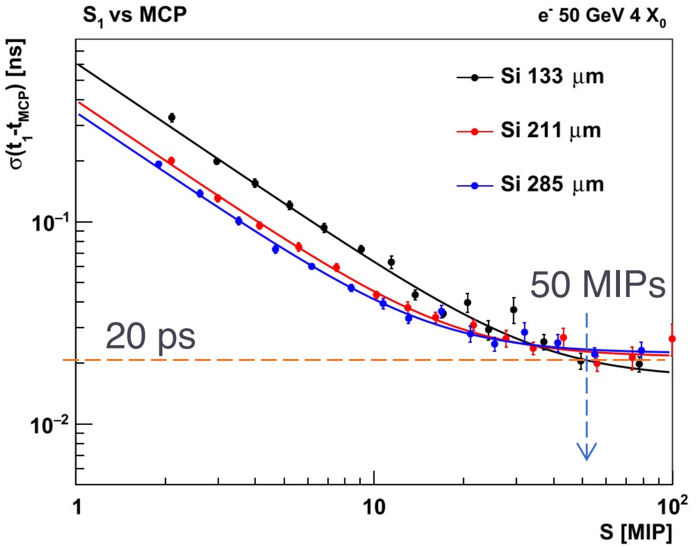
- **Traditional diode (parallel plate) detector with no gain**
  - Small signal-to-noise ratio
  - Good time resolution only at high track multiplicity (CMS High Granularity Calorimeter)
  - S/N ratio only slighly better with thicker sensors (reduction of the series noise with $C_d \propto 1/d$)

Test beam results with large BW preamplifier

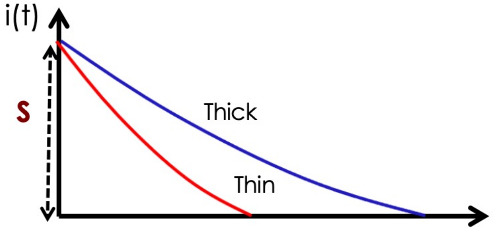
N. Akchurin et al.., NIM A 859 (2017) 31-36





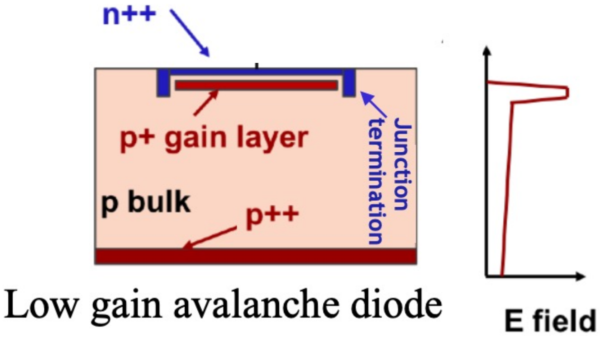


- **Exercise:**
  - Show (via Ramo's theorem or charge induction) that **for uniform ionization in the bulk the max signal is independent of the Si thickness**: $\boldsymbol{i_{max} = Nqv}$
    - $N = 75$ e-h/µm ionization density for MIPs
    - $v = 100$ µm/ns saturated drift velocity (E > 30 kV/cm)
  - The thickness affects the total charge and the signal duration (drift time)



Low gain avalanche diodes (LGADs)

- **Structure**
  - Additional p+ implant to localize signal formation in a thin region
  - Avalanche with gain of O(10) in a thin p+/n++ layer (E > 300 kV/cm)



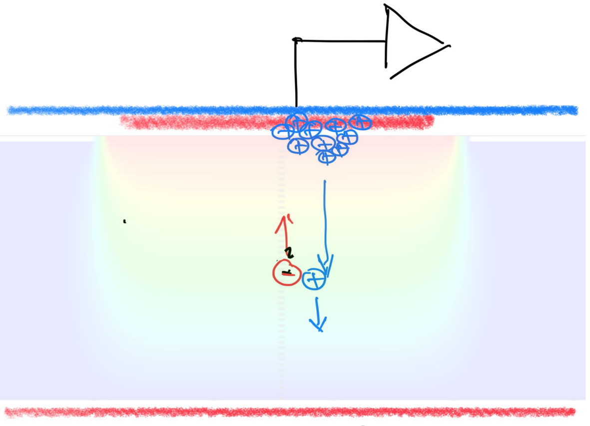
Low gain avalanche diode

- **Exercise: Find the (approximate) signal shape**
  - Sum (convolution) of the currents due to avalanche holes drifting from the anode (gain layer) to the p++ cathode (square pulses) starting when electrons from primary ionization reach the gain layer

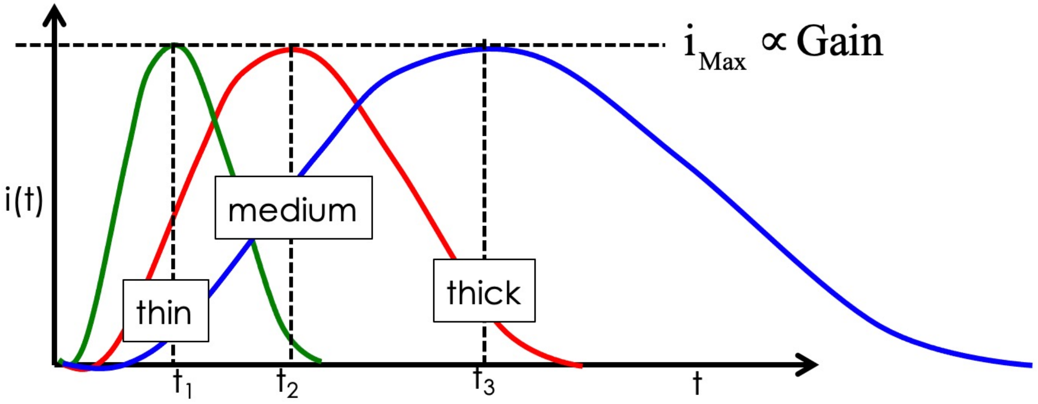
  - Signal amplitude proportional to the gain
  - Signal risetime proportional to max electron drift time

$$\frac{dV}{dt} \propto \frac{G}{d}$$

"Go thin"



one pad



- At d=50 µm, the pulse is ~ 500 ps up (primary-electron drift time) and 500 ps down (holes drift time)
- Uniform field (implant quality) to control pulse shape variations with impact point

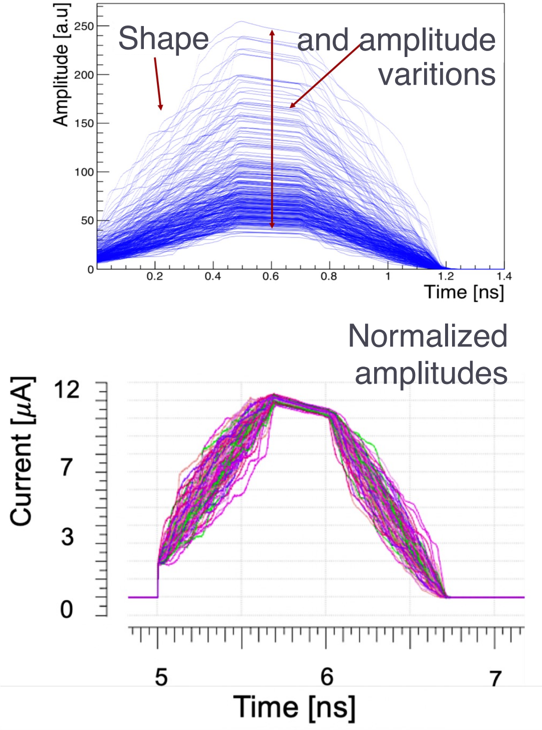
Pulses from: H. F-W Sadrozinski, A. Seiden, and N. Cartiglia: *Rep. Prog. Phys.* **81** 026101 (2018)

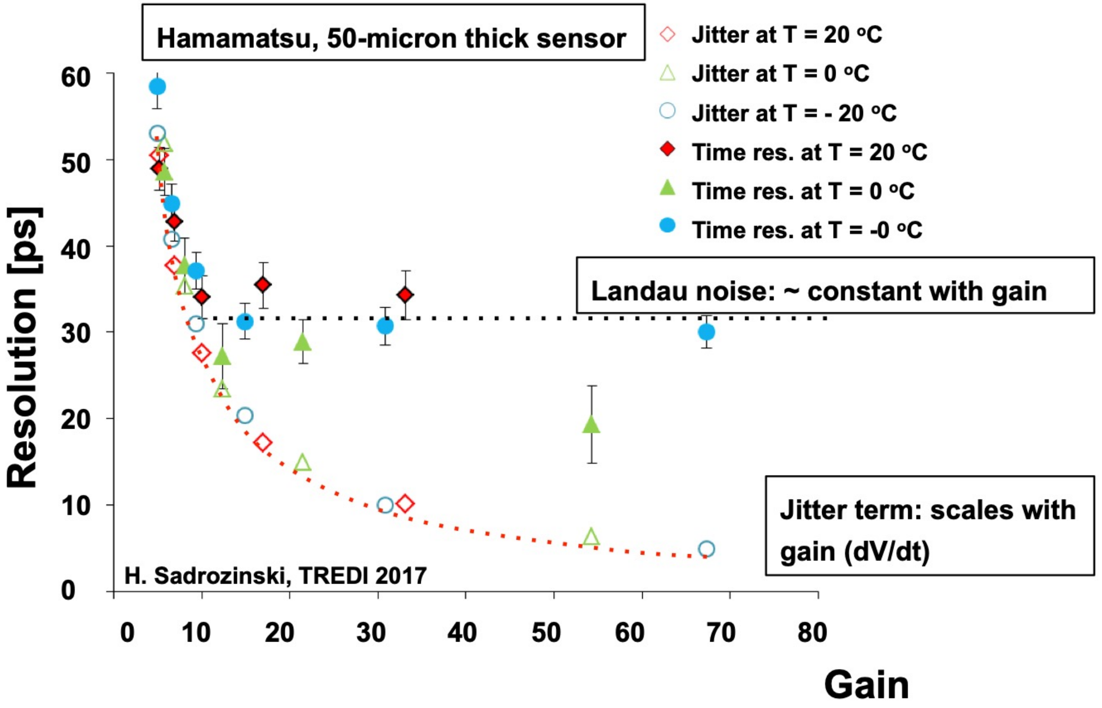
Time resolution optimization

- **The thickness of 50 µm is a trade-off between the jitter and the ionization terms**
  - At low gain, the jitter term dominates: $\sigma_{jitter} \propto \frac{e_n C_{det}}{Q_{in}} \sqrt{t_R}$
  - Al large gain, plateaus at ≈30 ps due to fluctuations in the ionization process
    - Landau fluctuations → the time spread of the primary current ($\sigma_{ioniz,}$) grows with thickness
- **CMS design targets (ATLAS slightly more stringent):**
  - Sensors gain above G~10 (>10 fC)
  - ASIC targets handling small signals (down to ~5 fC).

From: N. Cartiglia, IEEE, IEEE - 27/10/19

Pulse simulations



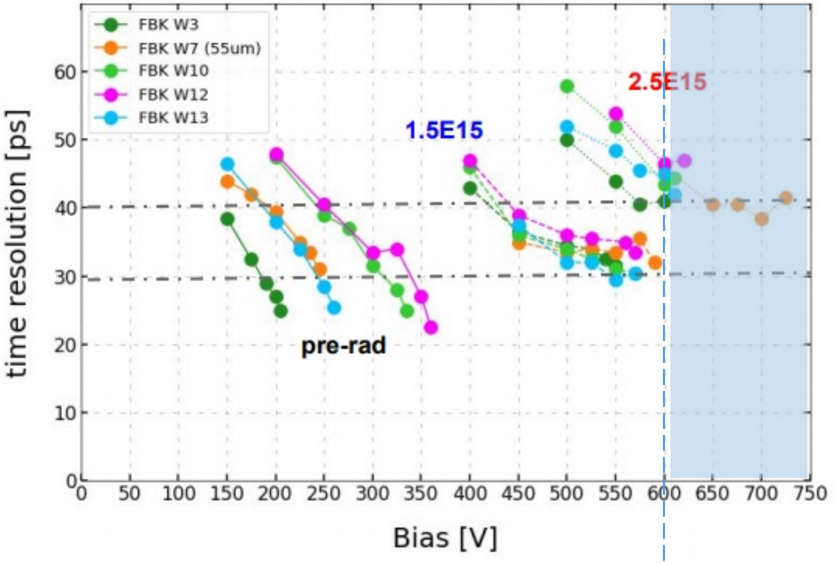


H. Sadrozinski, TREDI 2017

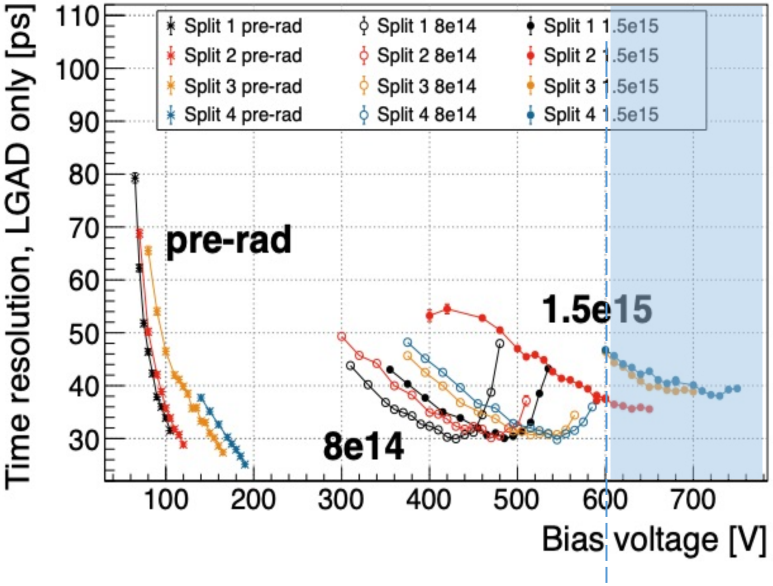
Measurements

LGAD radiation tolerance

- **Irradiation de-activate p-doping removing Boron from the reticle**
  - Addition of Carbon or tuning of the doping profile can mitigate the effect
- **Increase bias voltage to maintain gain after irradiation**
  - The bulk gain becomes more important
    - ⇒ slower risetime increases the jitter term
    - ⇒ bulk current increase additionally contributes to the noise term (mitigated with cooling at –30 ^{0}C)
- **Radiation tolerance in latest prototypes: keep 40 ps resolution to end of (CMS) operation**
  - Test beam studies show sparking damage to sensors above 600 V (120 kV/cm)
  - LGADs compatible with safe operation at HV < 600 V up to full (CMS) fluence



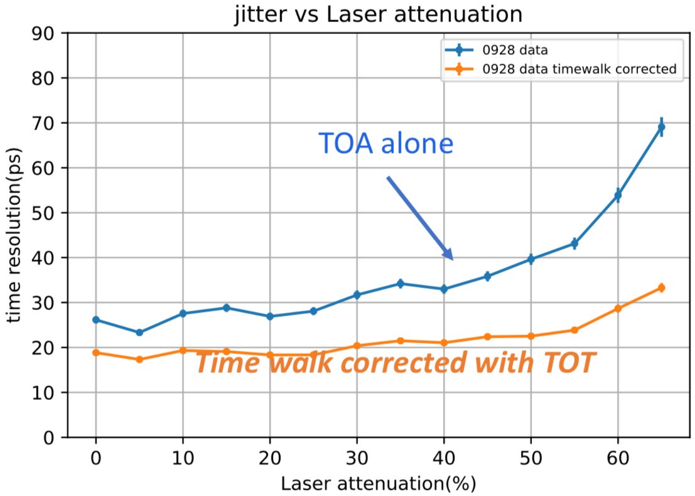
Common ATLAS/CMS R&D with sevral sensor producers

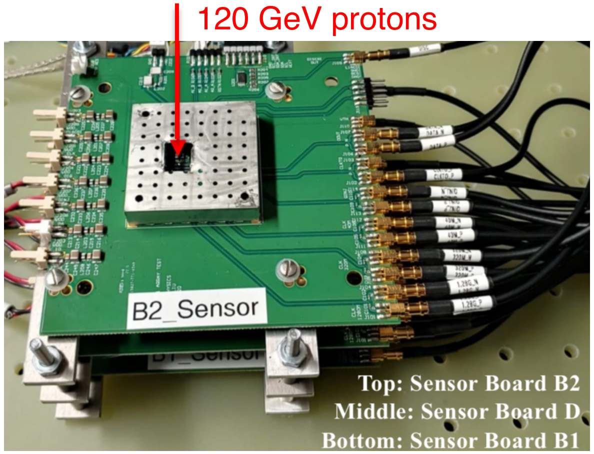


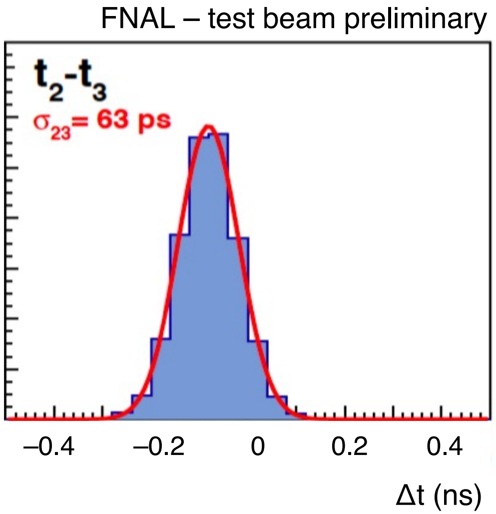
ASICs prototyping

- **Test beam result with LGAD and ETROC prototypes (CMS)**
  - Obtain **45 ps per hit (matches specifications <50 ps/hit and 30 ps/track with two hits/track**)
  - Indicates expected performance from ETROC1's clock distribution, jitter, and time walk correction

  - Time walk correction confirmed with laser pulses (localized charge deposition: no Landau fluctuations)
    - ToA (Time of Arrival) = Leading Edge discrimination w/o time walk correction
    - TOT = Time over threshold (proxy of the pulse amplitude)

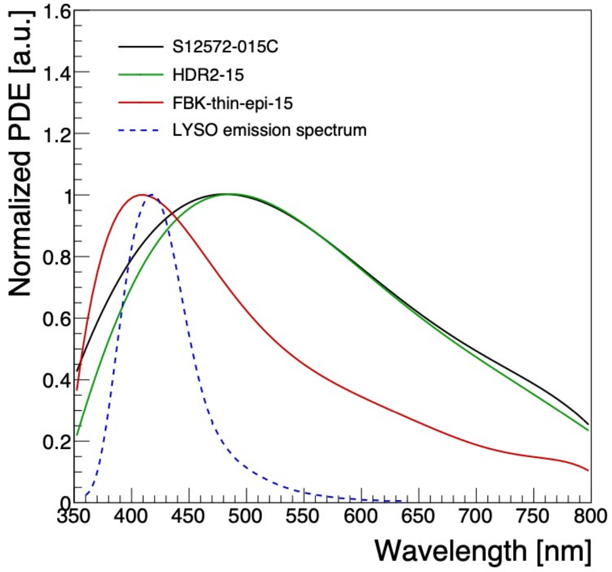

jitter vs Laser attenuation

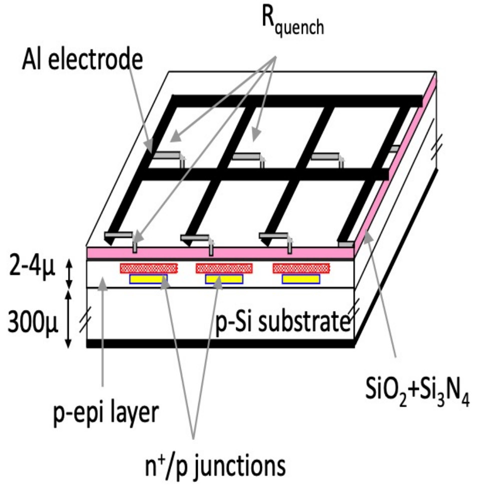


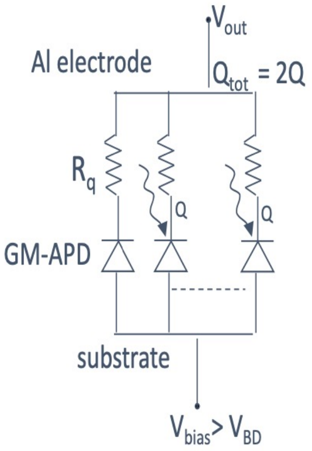

FNAL – test beam preliminary

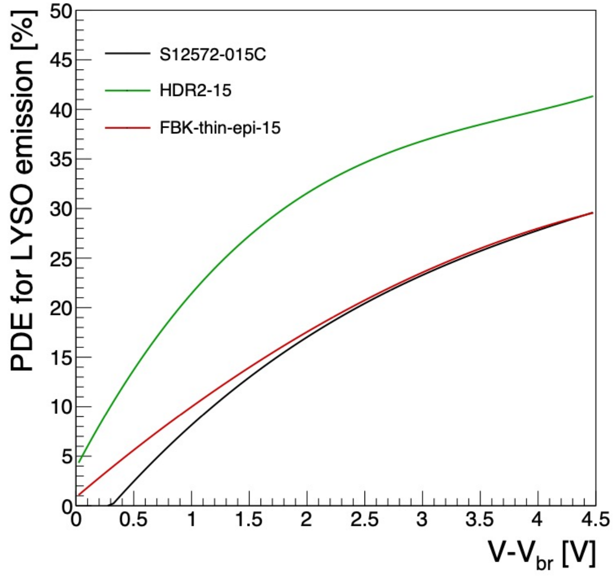
CMS barrel timing layer sensor

- **LYSO:Ce crystals as scintillator**
  - Dense (>7.1 g/cm^2), bright (N = 40000 ph/MeV)
  - Fast rise time (<100 ps) and decay time $\tau_S \sim 40\ ns$
    - Excellent radiation tolerance
- **Silicon photomultiplier (SiPMs) as photon detector**
  - Compact, insensitive to magnetic fields
  - Fast (single photon response time spread σ_{SPTR} ~100 ps)
  - High quantum efficiency matched to LYSO scintillation
    - Affected by radiation



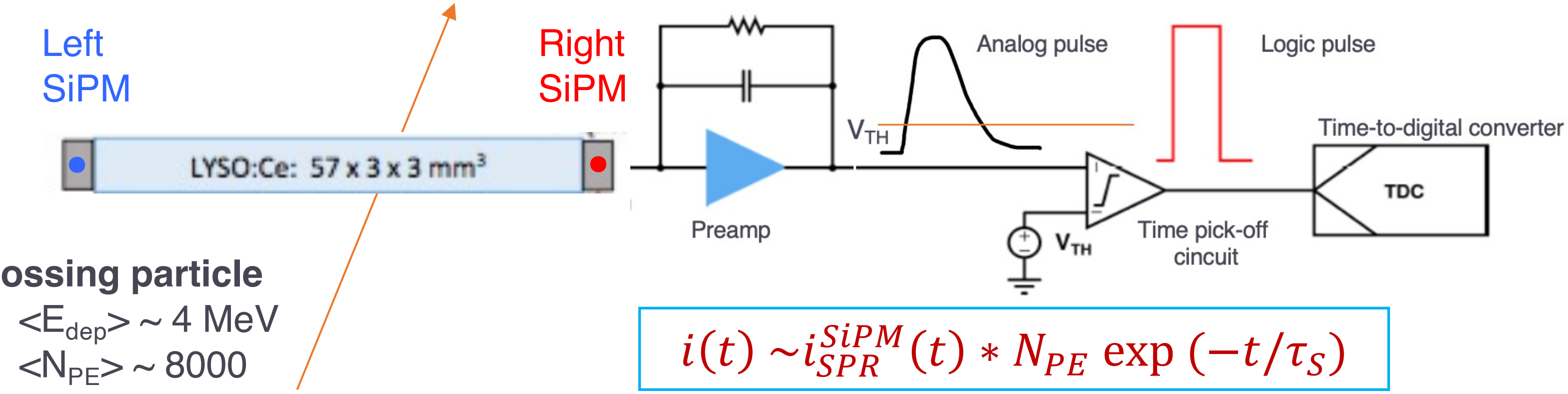






SiPMs: Arrays of SPADs in Geiger-mode operation

The LYSO + SiPM detector chain



Crossing particle

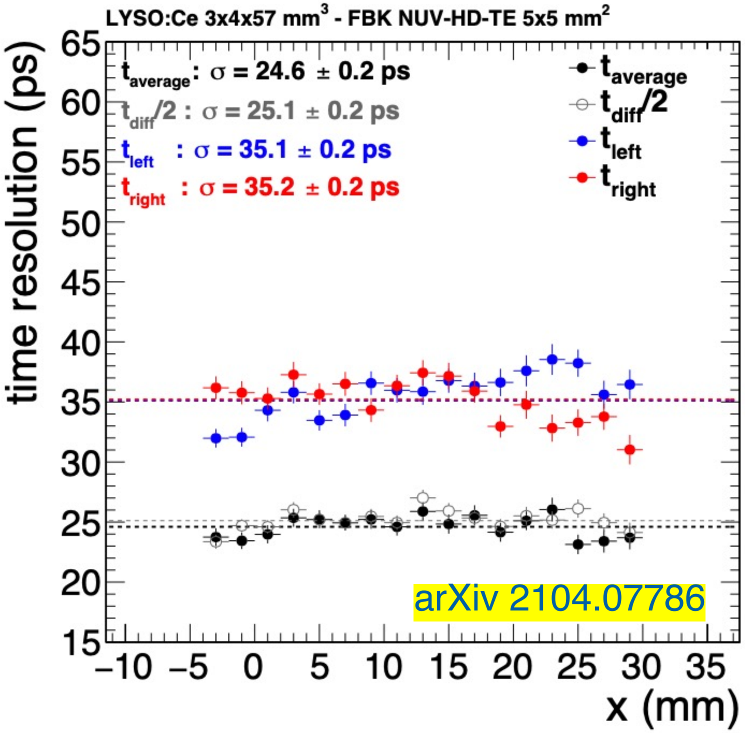
- $<E_{dep}> \sim 4$ MeV
- $<N_{PE}> \sim 8000$

$$i(t) \sim i_{SPR}^{SiPM}(t) * N_{PE}\exp\left(-t/\tau_S\right)$$

- **Ionization processes (affecting the leading-edge pulse shape variations)**
  - Δt - “ionization depth” → Reduced by dual-end readout
    $t_{transit}$ - variation in the optical paths → Minimized by geometry (and no diffusive wrapping)
    t_{SPTR} - photon detector response time spread → Sub-leading for thresholds > 10 p.e. ($\sigma_{SPTR}/\sqrt{N_{thr}}$)
    t_{Npe} - scintillation and photon detection process → Dominant: $\sigma_{stoch.}\,\alpha\,\tau_S/\sqrt{N_{PE}}$
- **Detector noise (jitter contribution)**
  - SiPM single photon dark-count rate (DCR) from thermal noise → $\sigma_{DCR} \propto \sqrt{DCR}$
- **Exercise:**
  - Estimate the time needed to pass a 100 photoelectons (PE) threshold for $\tau_S = 40\,ns$ and $N_{PE} = 8000$
  - [R. $\tau_{100} \sim 500\,ps$] - **Yes, 99% of the scintillation is wasted but the spread on a small time is small**

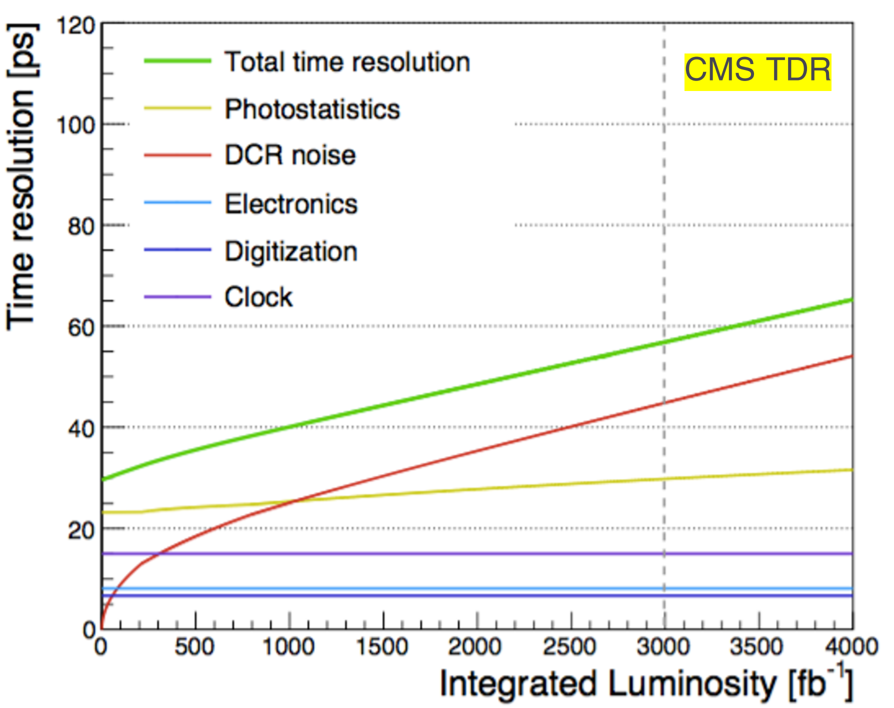
Timing performance

- **Dominant contributions**
  - Photostatistics dominates resolution before irradiation
  - SiPM dark rate becomes significant after irradiation (14 GHz / mm^2 at the end of operation)
- **Key innovations to fight SiPM DCR**
  - Noise cancellation in ASIC (TOFHIR)
  - Clever thermal management (low temperature operation and in-situ annealing)


LYSO:Ce 3x4x57 mm^3 - FBK NUV-HD-TE 5x5 mm^2

arXiv 2104.07786

Test beam results - before irradiation



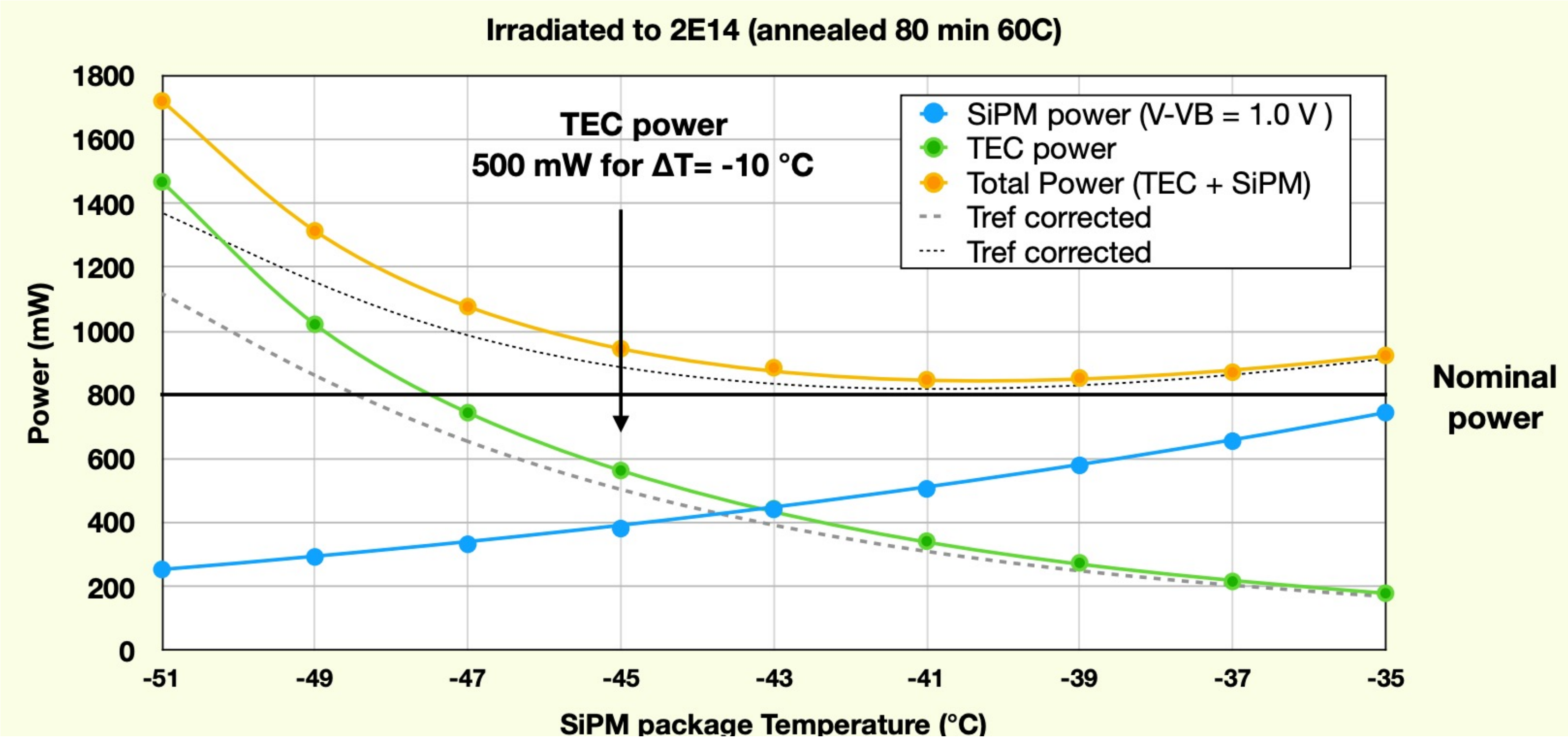
CMS TDR

Performace projecton – with irradiation

Thermal management

- **Total power consumption for full (16 SiPM) array**

[A. Heering, CPAD21]



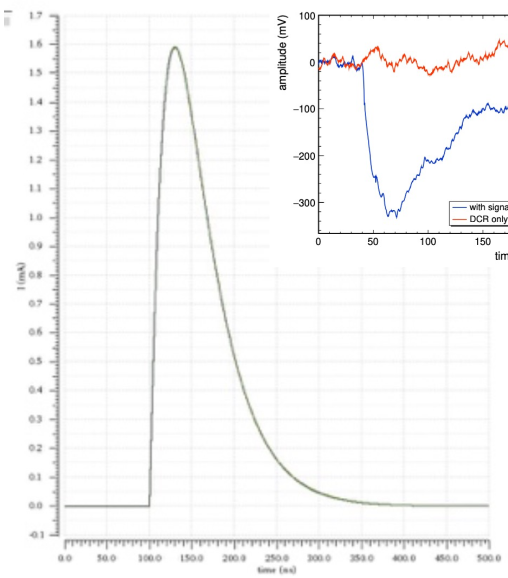
- **Cooling and annealing studies**
  - Information used in performance projections

1. **SiPM dark current (and dark counts) reduced by factor ~2 for ΔT = –10 ⁰C**
2. **Periodic annealing at +40 ⁰C will decrease the SiPM dark current by a factor >2.5**

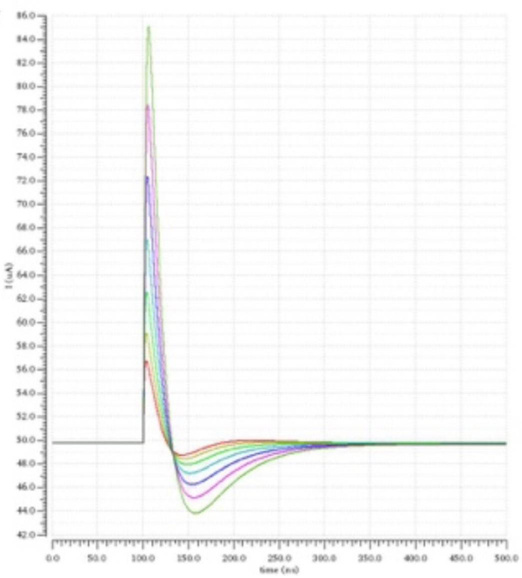
DCR suppression in the ASIC

- **Differential leading-edge discrimination (DLED) in the TOFHIR2 ASIC**
  - Inverted and delayed pulse is added to the original pulse
  - Delay line is approximated by a RC net in the ASIC
    - The DCR noise is reduced (auto-correlated noise on the time scale of the single p.e. pulse)
    - The leading edge of the signal (“early photoelectrons”) is preserved

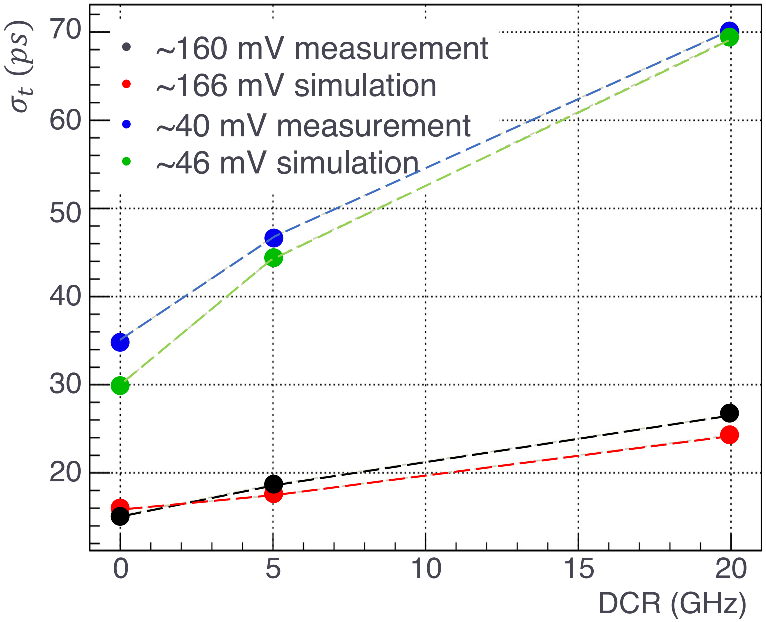
[J. Varela, IEEE—NSSMIC-2020]



Pulse at the TOFHIR2 input
Inset: An inverted pulse and baseline with 100 GHz DCR



Output of the DCR filter for 200 to 500 ps delays



Time resolution before and after the filter as a function of DCR (test with laser pulses)

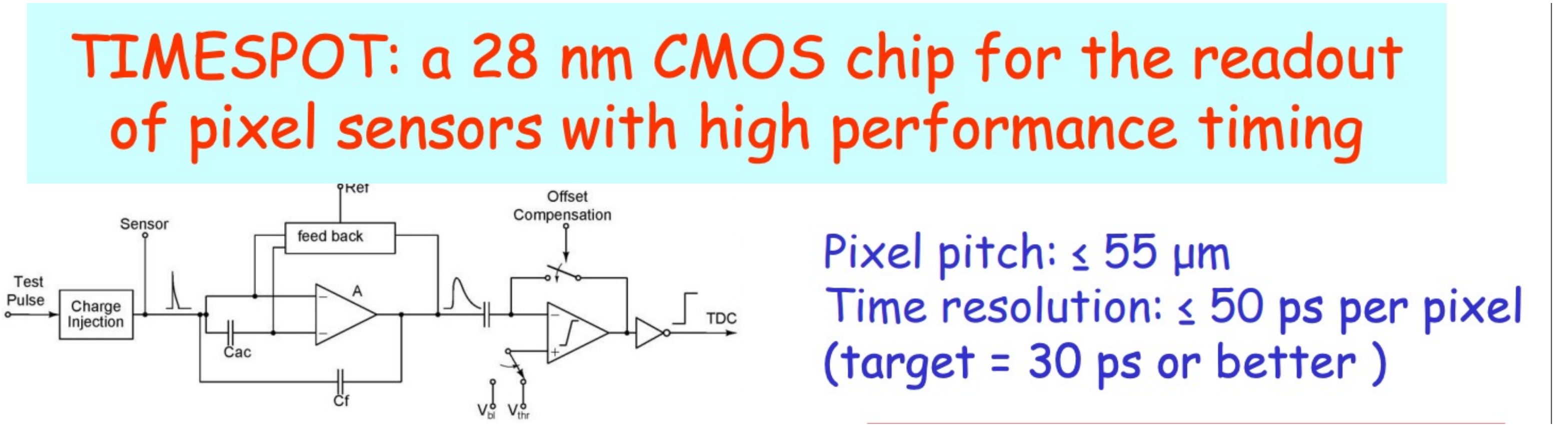
Future applications

ATLAS and CMS detectors are still to be built and operated

- **Tracking**
- **Calorimetry**

Tracking

- **The barrel timming layer cannot be integrated into a tracker (thick absorber)**
- **LGADs are a good candidate for integration in a 4D-tracking system**
  - However, for TOF measurement ΔL should be large (current designs)
  - For vertex timing, one may go close to the vertex, and alternative options exist



TIMESPOT: a 28 nm CMOS chip for the readout of pixel sensors with high performance timing

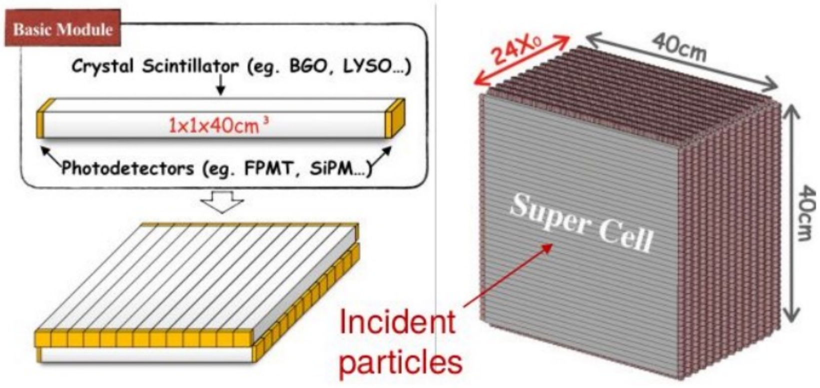
Pixel pitch: ≤ 55 μm
Time resolution: ≤ 50 ps per pixel
(target = 30 ps or better)

- See, V. Re – INFIERI – Slide 20
- R&D targeting the LHCb upgrade (next talk)

- The timespot project is not just the chip, but include 3D Si pixels:
  A. Lai et al., https://web.infn.it/timespot/index.php

Calorimetry

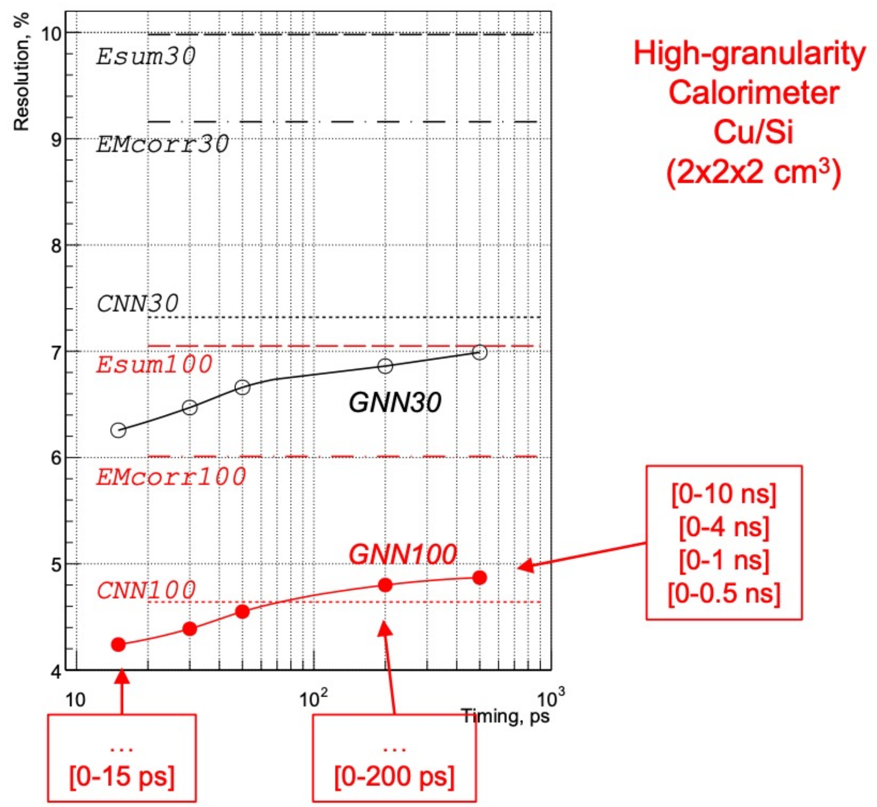
- **Combine particle flow energy reconstruction for jets (high granularity), with high energy resolution for photons, and electrons**



"A stack of BTL layers"

- [Y.Liu, Detector concept with crystal calorimeter @IAS Conference 2021]
- [M. Lucchini, Crystal calorimetry, ECFA TF6 Symposium, May 2021]

- **Adding time information in hadron shower reconstuction**
  - Active compensation of the EM and hadron components



High-granularity Calorimeter Cu/Si (2x2x2 cm³)

[0-10 ns]
[0-4 ns]
[0-1 ns]
[0-0.5 ns]

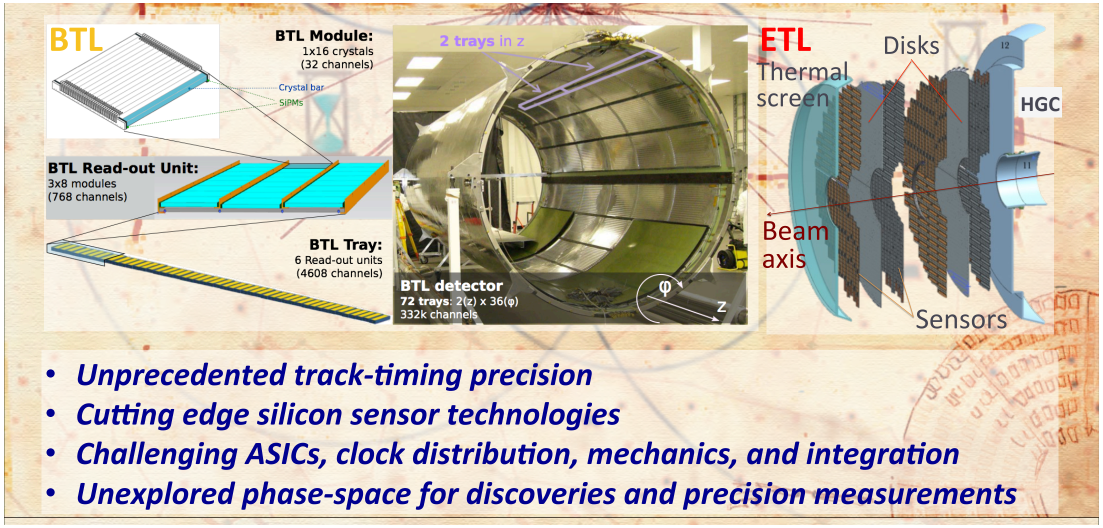
...
[0-15 ps]

...
[0-200 ps]

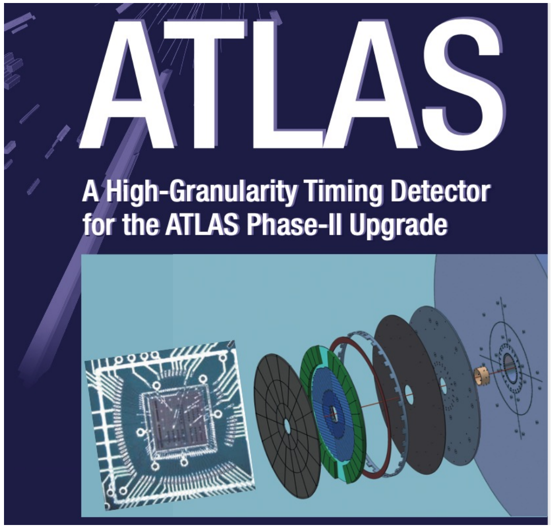
- [N. Akchurin, Precision Timing and Its Application in Calorimetry, ECFA TF6 Symposium, May 2021]

Instead of a summary

- **Join the ATLAS HGTD or CMS MTD timing project!**
  - Strong interplay between sensor and electronics
  - ‘Prototyping phase progressing, detectors still to be built and operated



- *Unprecedented track-timing precision*
- *Cutting edge silicon sensor technologies*
- *Challenging ASICs, clock distribution, mechanics, and integration*
- *Unexplored phase-space for discoveries and precision measurements*



ATLAS

A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade

- **Posters at INFIERI on this topic *[all posters are worth a visit]***
  - **J. Villlegas**, Low Gain Avalanche Detector (LGAD) for ATLAS and CMS experiments
  - **S. Cholak**, Evaluation of the PETSys TOFPET2 ASIC SiPM readout system in the scintillating fiber tracker
  - **V. Gautam**, Development of SPADs for NIR light detection
- **Credits:**
  - Inspired by lectures on LGADs given by **N. Cartiglia** (INFN Torino) at IEEE 2019 and on Timing given by **C. Tully** (Princeton) for CERN Academic Training in 2017