Opzioni per un timing layer dedicato con scintillatori e SiPM a FCC

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RD_FCC WP Silicon Mini-Workshop

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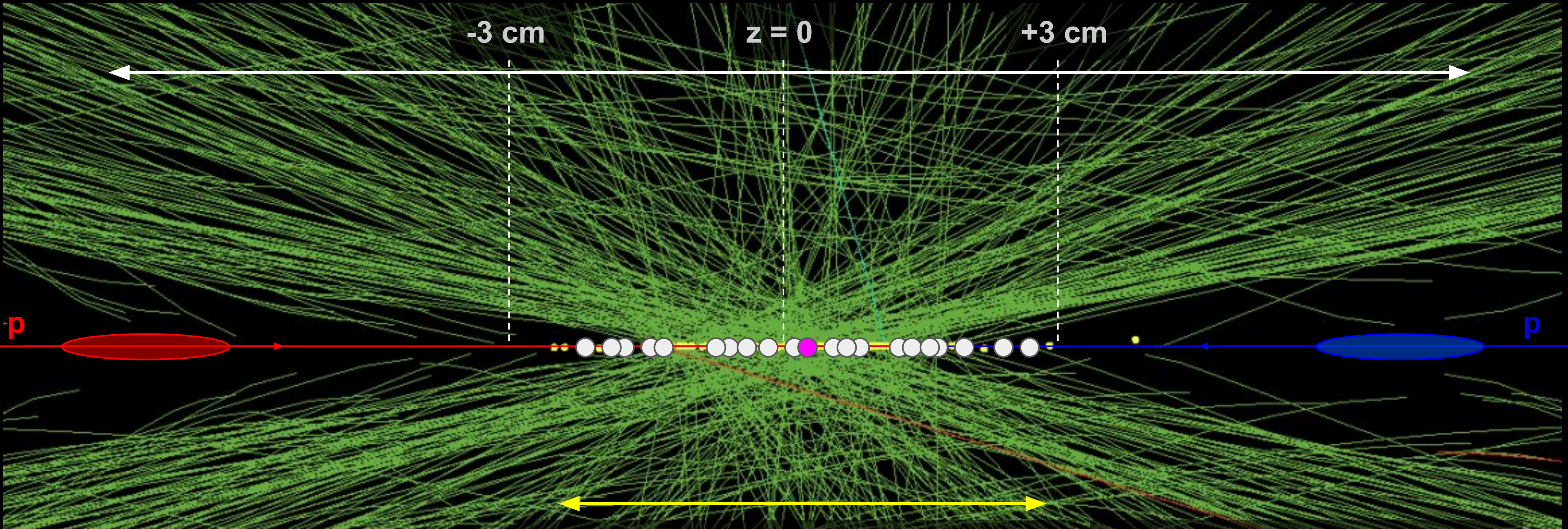
Why and what timing at FCC colliders?

- Three use-case categories for precision timing in collider detectors:
  (see T.Tabarelli's talk at Snowmass 2022 for a sharp overview of the topic)
  - Vertex timing (from track timing)
  - Time-of-flight
  - Calorimetry (timing of neutrals and temporal structure of showers)

- Use-cases and detector requirements for e^+e^- and hh are different, focus on:
  - MIP timing *before* the calorimeter
  - *e+e- collider environment* (closest time horizon)
  - *Scintillator based* timing detectors capitalizing the past ten year efforts to design and integrate the Mip Timing Detector in the CMS experiment [CMS-MTD-TDR]

Vertex timing for pileup mitigation at hadron colliders



Up to **200 vertices** every 25 ns spread over **4.5 cm** in space
Vertices start to spatially overlap and become difficult to distinguish at HL-LHC with usual tracking algorithms

At HL-LHC, efficiencies and background back to LHC level with σ_t ~30 ps
Most likely **required also at FCC-hh but not FCC-ee**

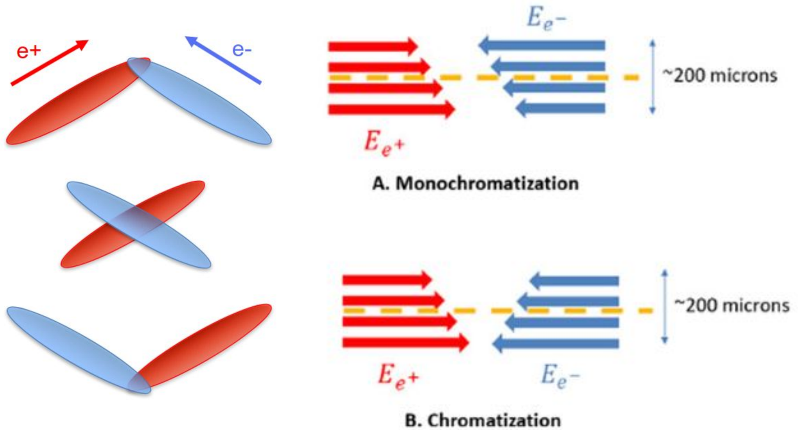
Snapshot of a bunch crossing at HL-LHC

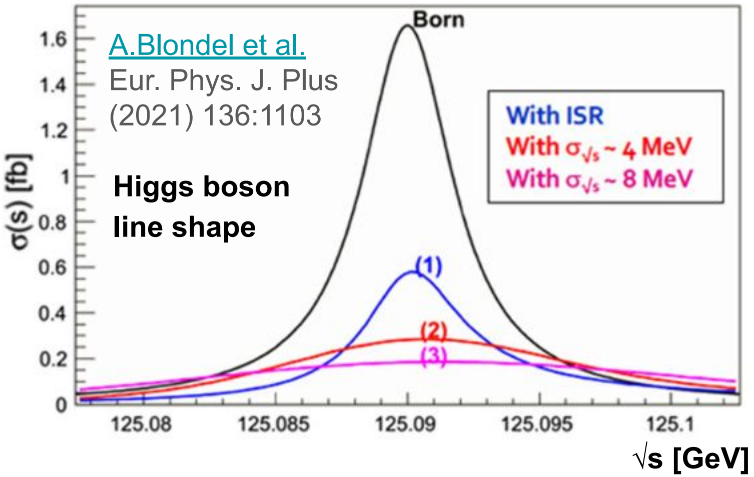
Vertex timing at e^+e^- colliders

- For beam optics "chromatization" schemes, the **particle energy correlates with the longitudinal particle position in the bunch**, and thus to the collision time

- Vertex timing with **O(5 ps)** precision offers a **√s scan at fixed centre-of-mass energy** (e.g. scan of the Higgs resonance for a run at the Higgs pole) [Azzi and Perez, FCC-ee, 2020]

- Vertex time resolution ($\sigma_{VTX} \sim \sigma_{TRK} / \sqrt{N_{tracks}}$) and clock synchronization << 5 ps

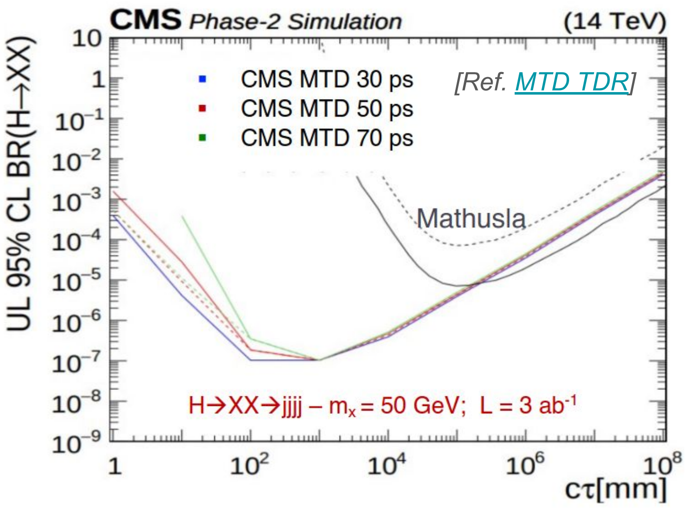


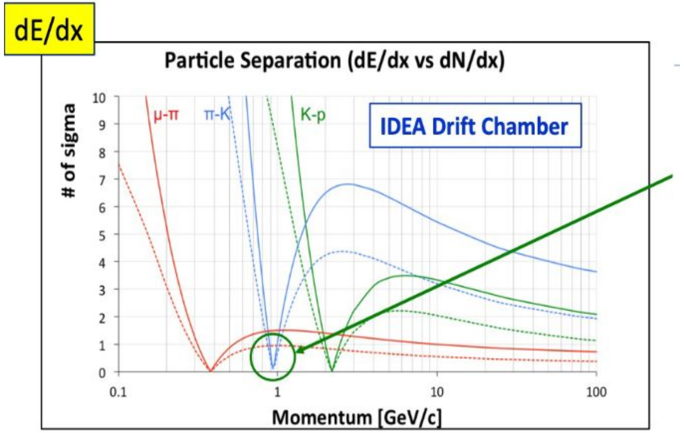


Time-of-flight detector

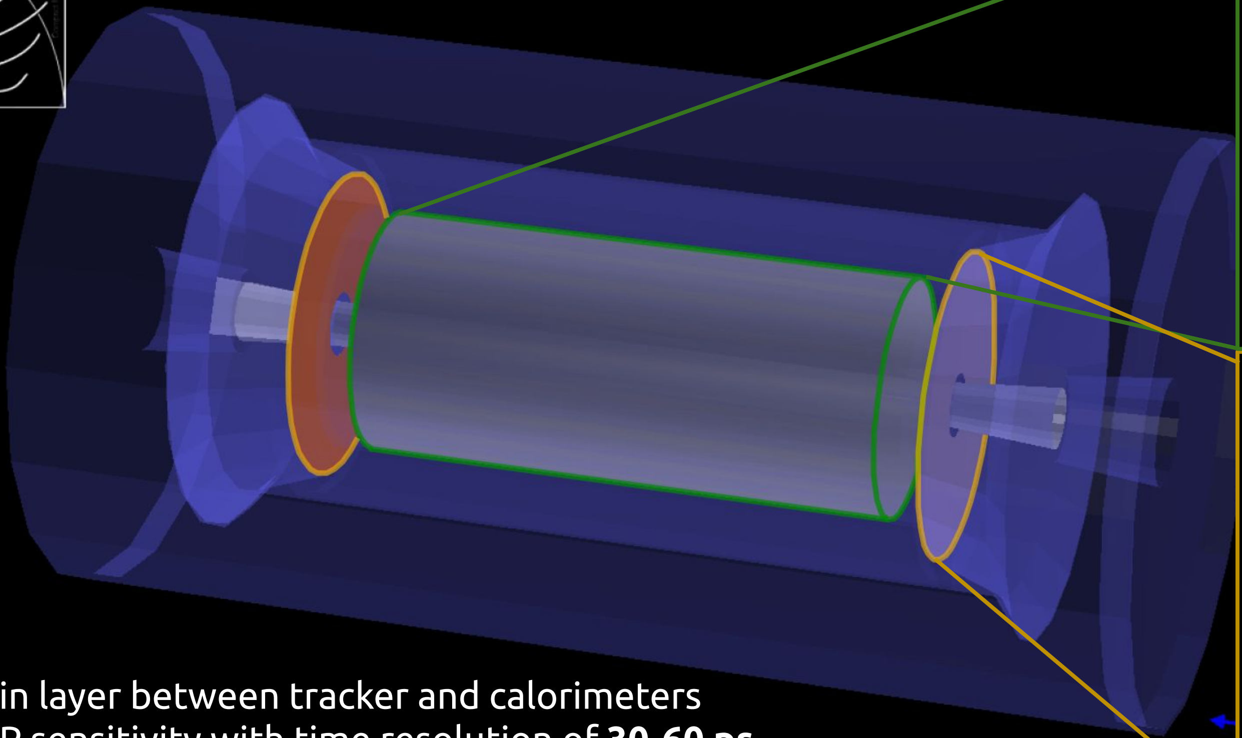
- Potential for **direct measurement of Long Lived Particles** (LLPs) mass by reconstruction of the time of the displaced vertices
  - The large multiplicity of final state topologies softens the requirements on time resolution
  - Will this remain of interest after HL-LHC?

- **Hadron identification for flavour physics and jet flavour tagging**
  - A compelling physics case for e+e- colliders [Bedeschi et al, 2202.03285]
  - A TOF detector providing an "unchallenging" resolution **of O(100 ps) at 2 m** could cover the "π/K cross-over window" at ~ 1 GeV, where dE/dx is blind





The Mip Timing Detector: an example from CMS upgrade



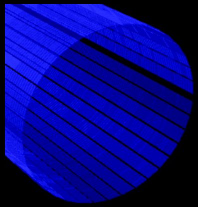
BARREL

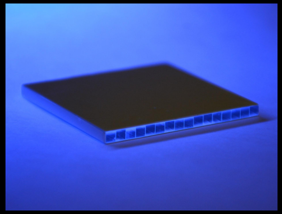
Surface ~ **38 m²**

Number of channels ~ **332k**

Radiation level ~ **2×10^{14} n_{eq}/cm^2**

Sensors: LYSO crystals + SiPMs





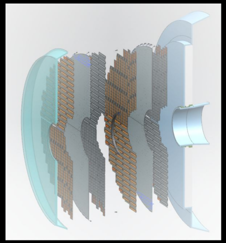
ENDCAPS

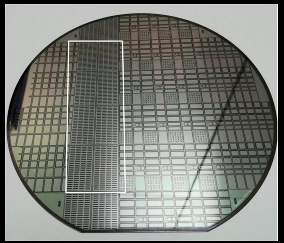
Surface ~ **14 m²**

Number of channels ~ **8500k**

Radiation level ~ **2×10^{15} n_{eq}/cm^2**

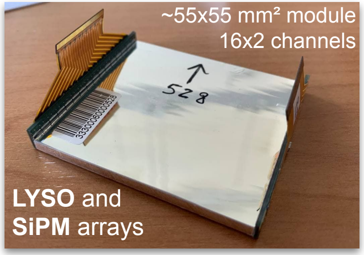
Sensors: Low gain avalanche detectors

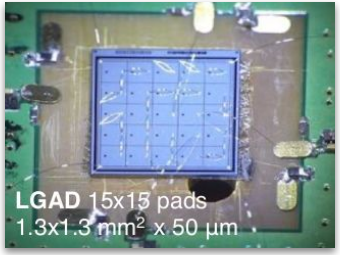




- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of **30-60 ps**
- Hermetic coverage for $|\eta|<3.0$

Rough comparison of MTD technologies





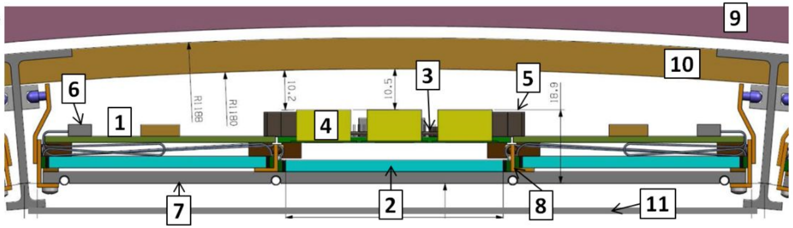
[from MTD TDR]	**Barrel region**	**Endcap region**
Total surface	38 m^2	16 m^2
Sensor technology	LYSO+SiPMs	LGADs
Highest radiation level [1 MeV n.eq./cm^2]	2e14	2e15
Cost / m^2	**~250 k€**	**~700 k€**
Power consumption / m^2	**~1 kW** (50% from radiation damage)	**~5 kW**
Channel count / m^2	**~9k**	**~530k**
Radiation length [X0]	0.3-0.5 (dominated by sensors)	0.15 (dominated by mechanics/services)
Time resolution (before/after irrad.)	30 / 60+ (limited by radiation damage)	40 / 40 (contribution from electronic noise)

- Different technologies are best suited for different environments/constraints
- In the absence of heavy radiation damage LYSO+SiPM offer a viable option for the instrumentation of **large surfaces with contained cost, channel count and power budget**

Detector integration challenges - BTL

- **Space**: sensors, electronics and services had to fit within a **4 cm radial envelope** (detector will be inserted inside the new tracker support tube!)
- CO_2 based system to extract **heat** from SiPMs and electronics and cool down to *-35°C (only required to mitigate radiation damage effects)*
- **Radiation length** in front of ECAL(~0.4 X_0) has no impact on calorimeter performance

1 : TOFHIR board with 6 ASICs
2 : LYSO array with 16 LYSO bars, bars oriented in ϕ
3 : Concentrator card
4 : DCDC converter
5 : CC-to-FE connector
6 : SiPM-to-FE connector
7 : Cooling bar with CO_2 pipes
8 : Cooling fins
9 : TST
10 : Insulation
11 : BTL compartment cover plate



1 : TOFHIR board with 6 ASICs
2 : LYSO array with 16 LYSO bars, bars oriented in ϕ
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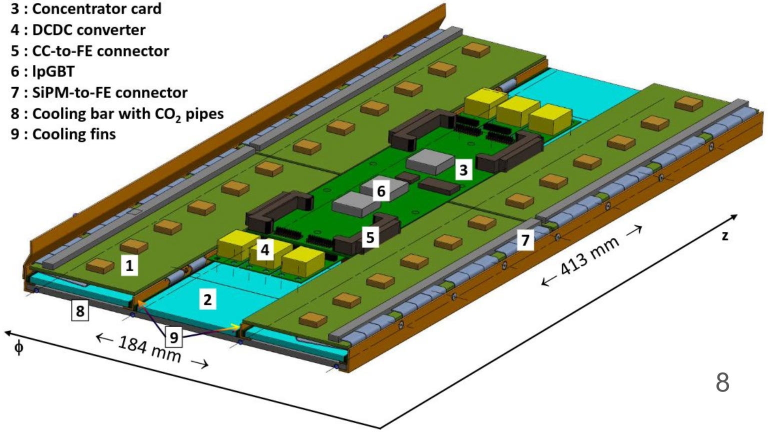


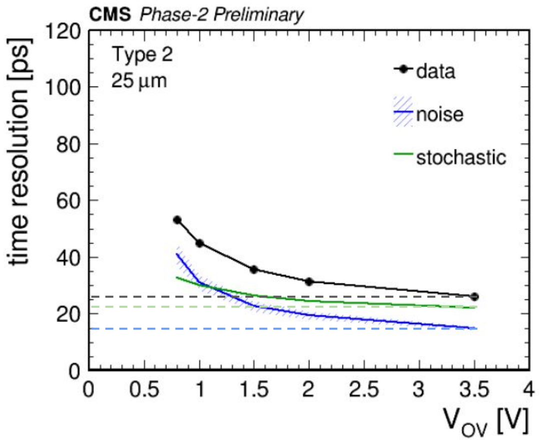
BTL sensors highlights

- **3x3x50 mm^3 LYSO:Ce scintillating crystals** packaged and wrapped in arrays already from manufacturer (10+ vendors worldwide)
- **Custom developed Silicon Photomultiplier arrays** optimized for timing and radiation tolerance (2 vendors tested)
- **Mini thermoelectric coolers** integrated with SiPM package for “smart” temperature control

*A. Bornheim et al 2023 JINST **18** P08020*
https://doi.org/10.1088/1748-0221/18/08/P08020

Resolution drivers in scintillator+SiPM timing detectors

- *Without* radiation damage time resolution in BTL is limited by
  - Electronic noise ~15 ps
  - Photo-statistics (sensors) ~ 22 ps
- There are **handles to customize the detector design**



$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{dep} \cdot LY \cdot LCE \cdot PDE}}$$

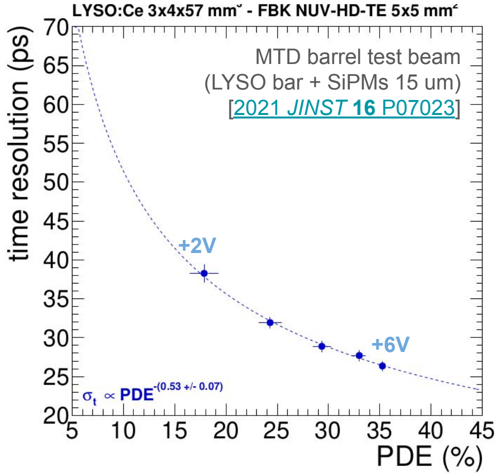
Scintillation rise and decay time constants

SiPM Photon Detection Efficiency (~cell size, operating voltage)

Energy deposited in the scintillator (~thickness, density)

Scintillation Light Yield

Light Collection Efficiency

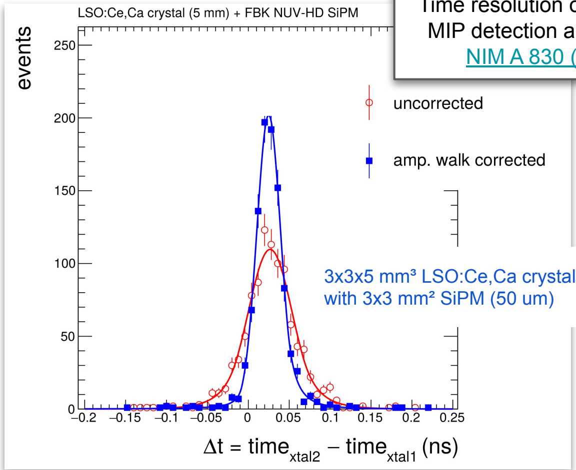


Flexibility and optimization in scintillator+SiPM timing detectors

Keep the material fixed and work on design/photodetector

++ Performance

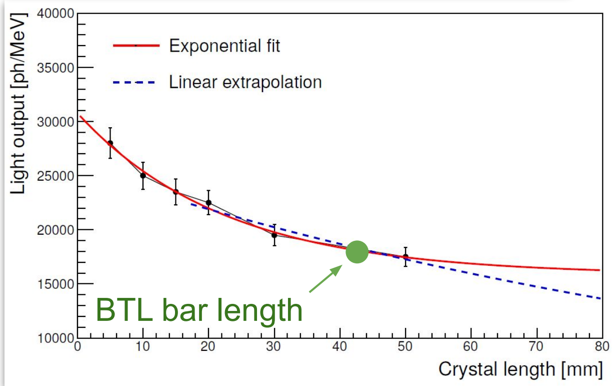
- Operation at larger over-voltage
- Use of SiPMs with larger cell size
- Increase granularity
- Increase crystal thickness



Time resolution of **10 ps** for single MIP detection achieved in 2016!
NIM A 830 (2016) 30-35

++ Integration

- Increasing crystal length exploiting total internal reflection
- Reduce SiPM channel count, cost and power consumption



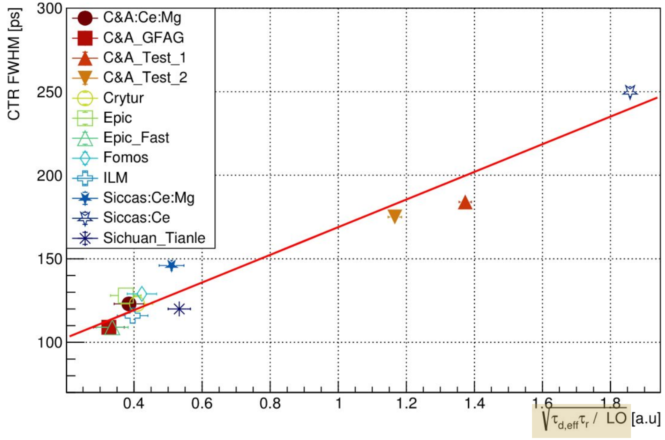
Flexibility and optimization in scintillator+SiPM timing detectors

Keep the detector design fixed and optimize the scintillator

- Key features of LYSO for a timing detector
  - Good radiation tolerance
  - Competitive cost and mass production capability
  - Emission wavelength matching common SiPM technologies
  - Easy to handle (not hygroscopic, not too brittle)
  - Good scintillation properties for timing $\sim\sqrt{(\tau_R \tau_D / LY)}$

- Competing with LYSO: faster, brighter, denser
  - Exploit **bandgap engineering** to push against scintillator limits, e.g. with multicomponent garnet crystals
  - Exploiting **ultra fast-emission processes** (**Cherenkov**, hot intraband luminescence, **cross-luminescence**) →typically more in the UV→challenging photodetection

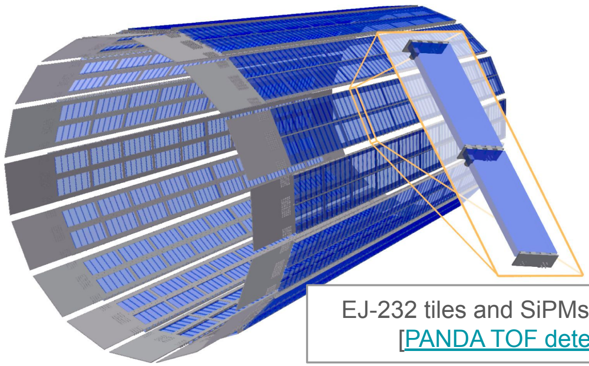
L.Martinazzoli et al., *Scintillation properties and timing performance of state-of-the-art GAGG single crystals*, NIM A 1000 (2021)165231



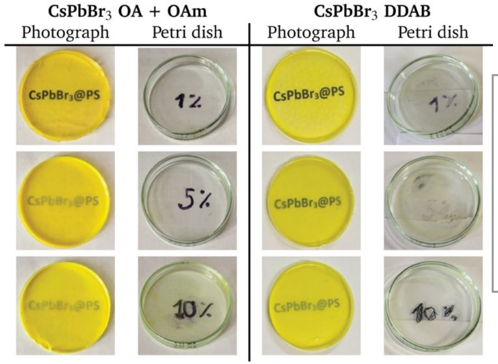
Crystals vs other scintillators

- **Plastic scintillators** with sub-ns decay time **broadly explored and exploited for timing** (and also for sampling calorimeters)
  - **Less radiation tolerant than crystals but perfectly fine for an e+e- collider!**
  - Lower energy deposited by MIPs
  - **Could reduce timing layer cost by ~20% compared to crystals**

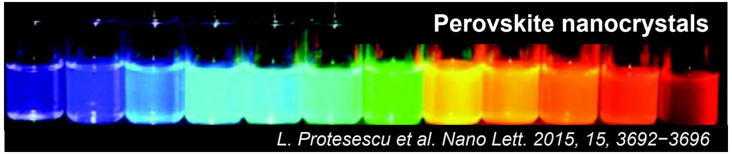
- **Nano scintillators** with sub-ns scintillation may also represent **a further leap towards** precision timing
  - A recent stimulating frontier with open challenges for detector applications (medium opacity, low density, …)



EJ-232 tiles and SiPMs, σ_t~50 ps
[PANDA TOF detector]



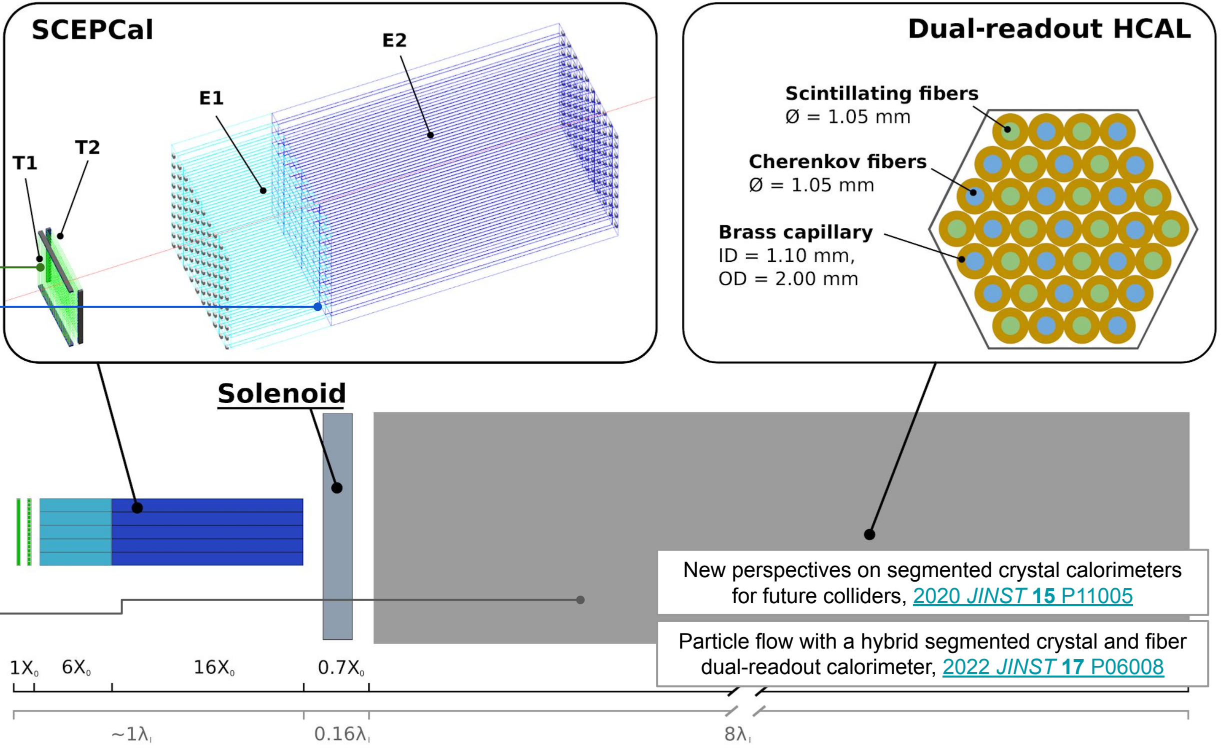
K. Děcká et al.,
Timing performance of lead halide perovskite nanoscintillators embedded in a polystyrene matrix,
J. Mater. Chem. C, 2022



Maximum information crystal calorimeter for IDEA

- **Precision timing** for charged particles and EM showers
- **Higher segmentation** for PID and particle flow algorithms
- **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - $\sim 0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries



New perspectives on segmented crystal calorimeters for future colliders, 2020 *JINST* **15** P11005

Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter, 2022 *JINST* **17** P06008

Summary

- MIP **timing technologies** for vertex tracking and TOF developed for HL-LHC experiments can **already provide a time resolution that satisfies requirements** at e+e- colliders (σ_t ~ 20-100 ps)

- **Optimization** of a scintillator+SiPM based timing detector **for an e+e- collider** (low radiation environment) **can offer further improvement** of time resolution (<20 ps) at lower cost (<20%) compared to applications at HL-LHC

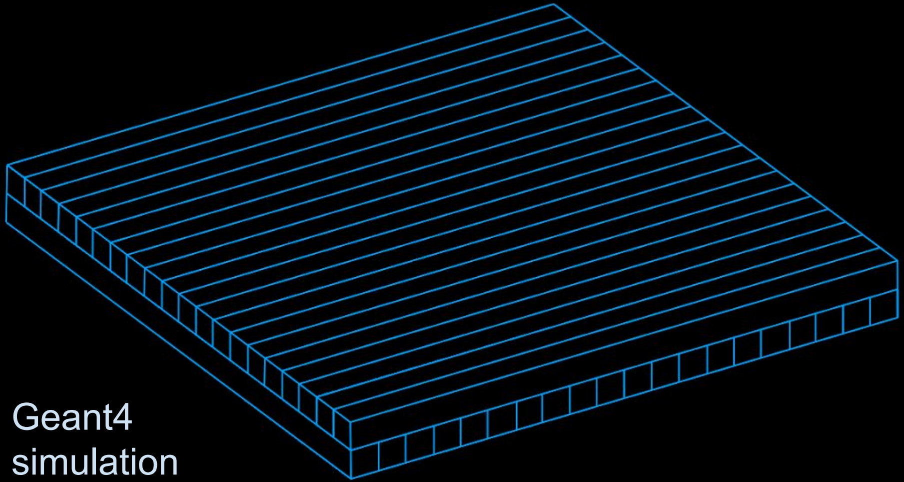
- A scintillator + SiPM timing layer can offer a more **natural integration with a homogeneous optical calorimeter** (it can provide a precise energy measurement and exploits similar technologies)

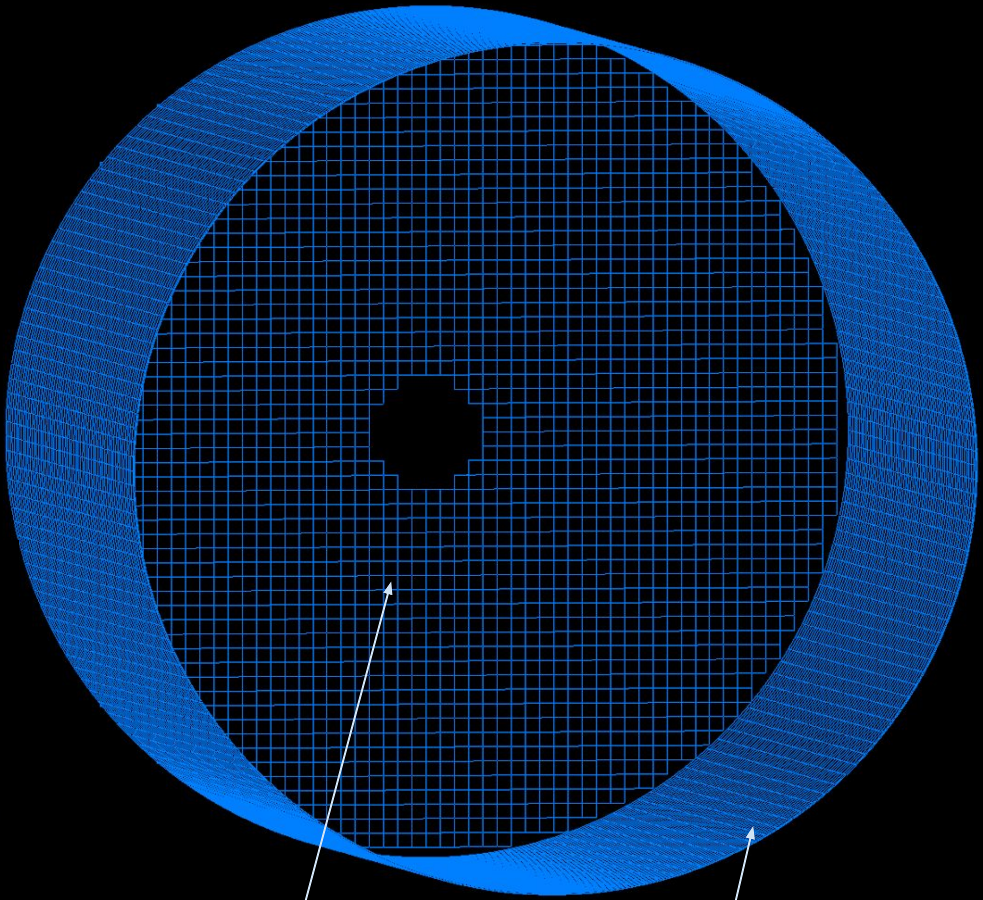
- **Integration challenges, cost and power consumption** are a big challenge and will most likely drive the sensor technology choice (LYSO+SiPMs chosen by MTD as more cost effective and less power hungry than LGADs in the "low" radiation region)

Additional material

Timing layers

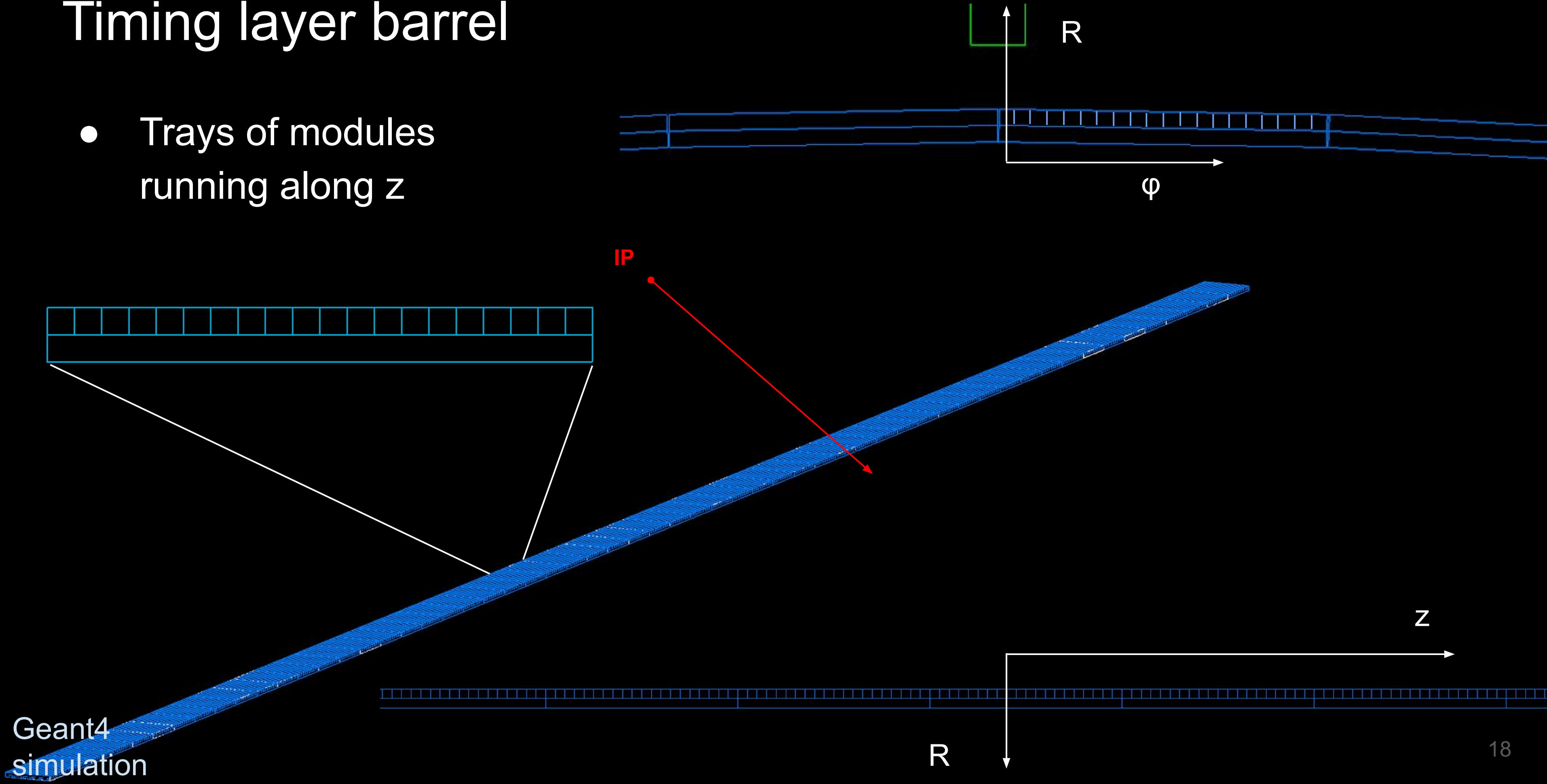
- Inner radius: 1775 mm
- Outer radius: 1795 mm
- Module size: 60x60x6 mm³
- Crystal size: 60x3x3 mm²



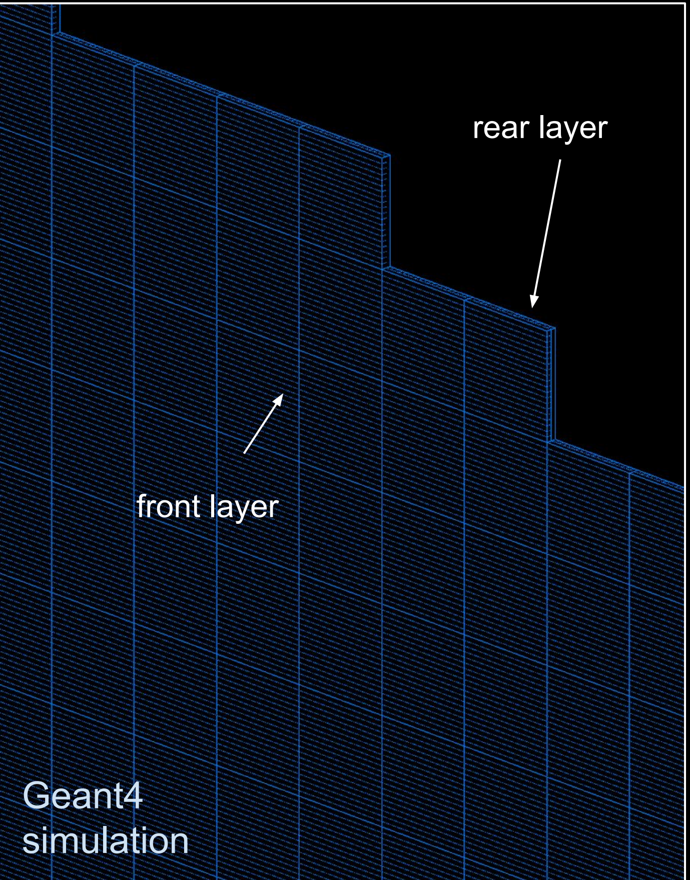


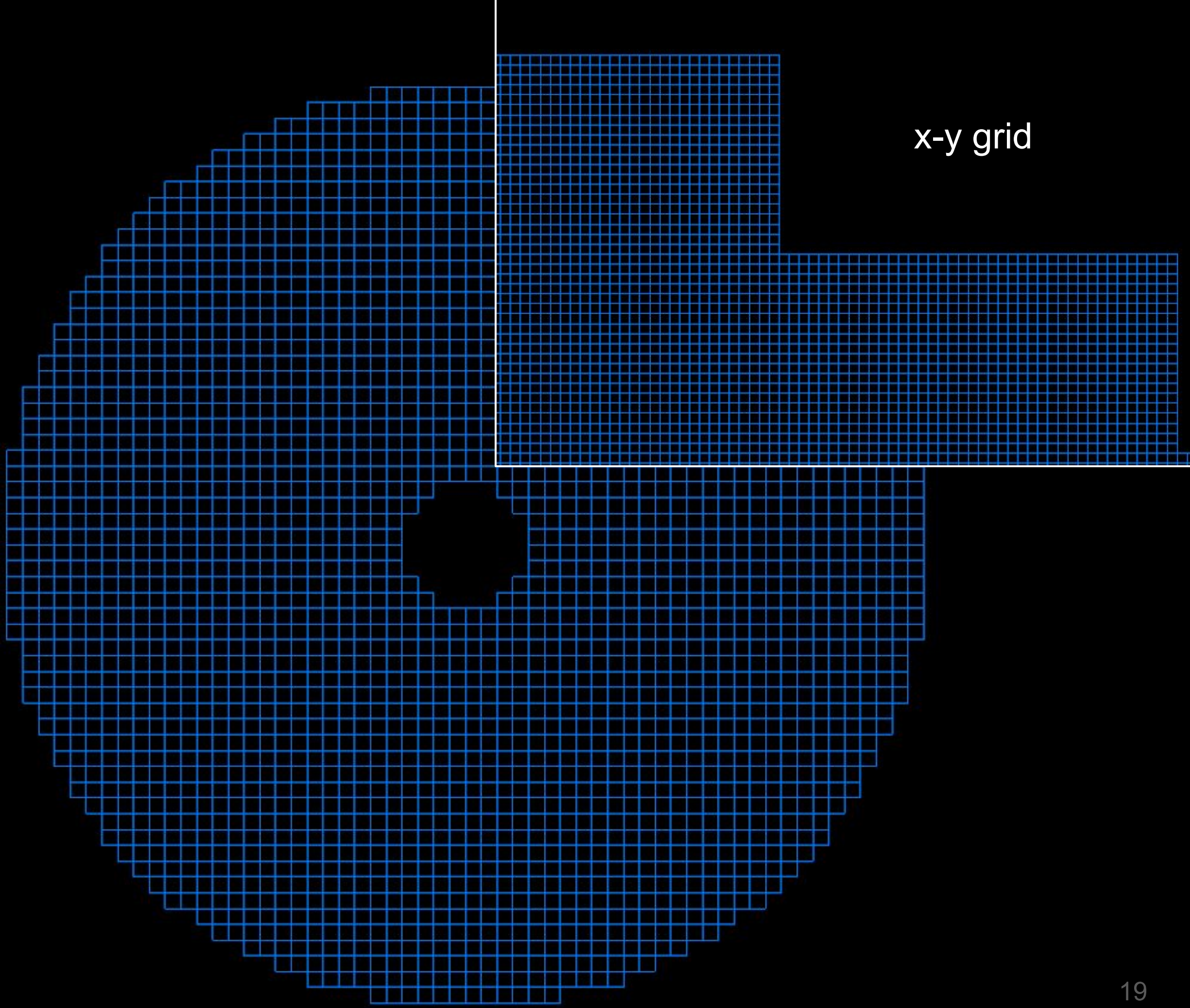
Timing layer barrel

- Trays of modules running along z



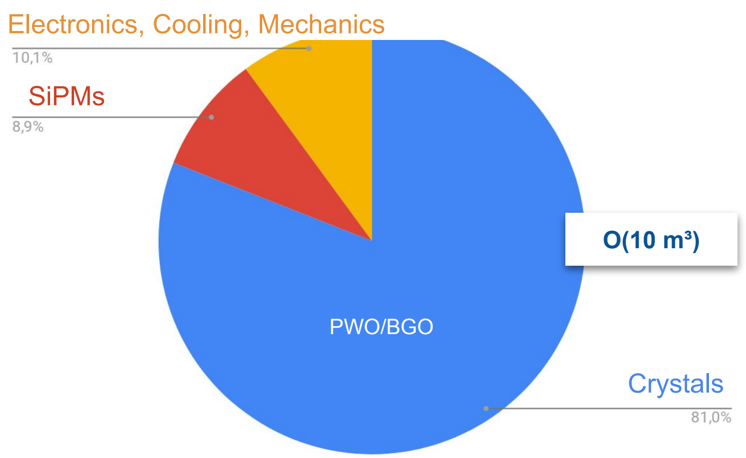
Timing layer endcap



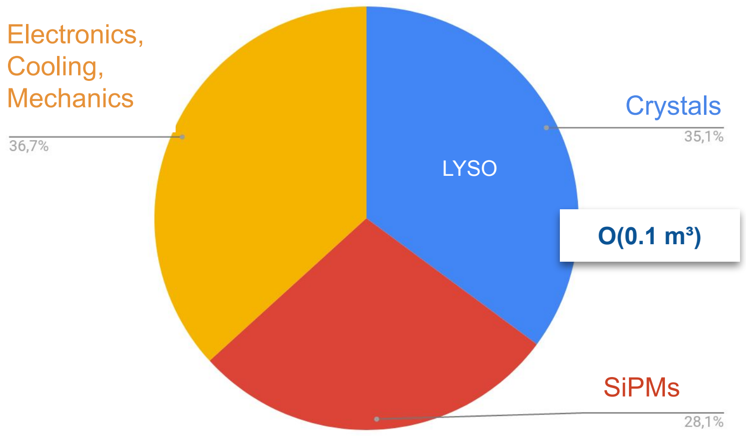


The **cost** issue

Costing exercise for an **hermetic EM homogeneous calorimeter**
(R=1.8 m, 1 cm² transverse granularity,
2 longitudinal layers, 22X_0, ~600k channels / layer)



Costing exercise for an **hermetic timing layer**
(design à la MTD BTL)

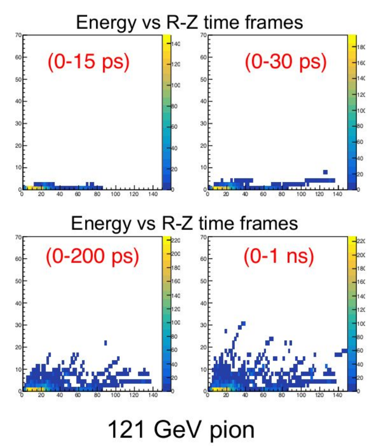


Timing *inside* calorimeters

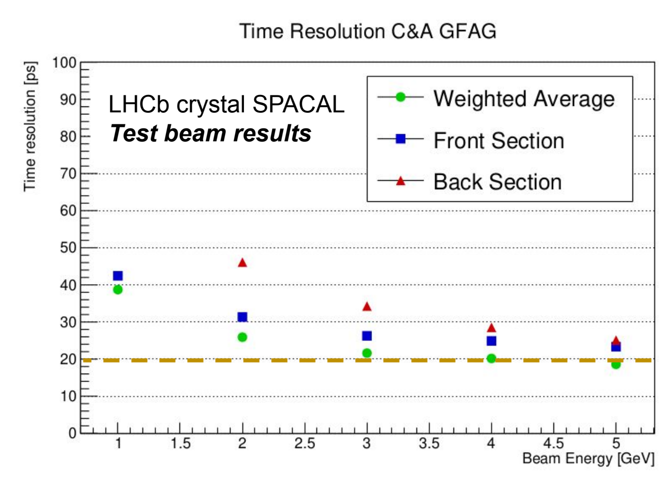
- **Benefits**: timing for neutral particles and information on the time development of EM and HAD showers

- Typically implies dealing with 'large' energy deposits (many MIPs per active element)

- **State-of-the-art** examples (EM showers)
  - Time resolution of ~**30 ps** for E>30 GeV with the **CMS ECAL in Phase 2 Upgrade**
    - PWO+APDs
  - **Sub-20 ps** time resolution for E>5 GeV with the crystal **SPACAL for the LHCb upgrade**
    - GFAG+PMTs

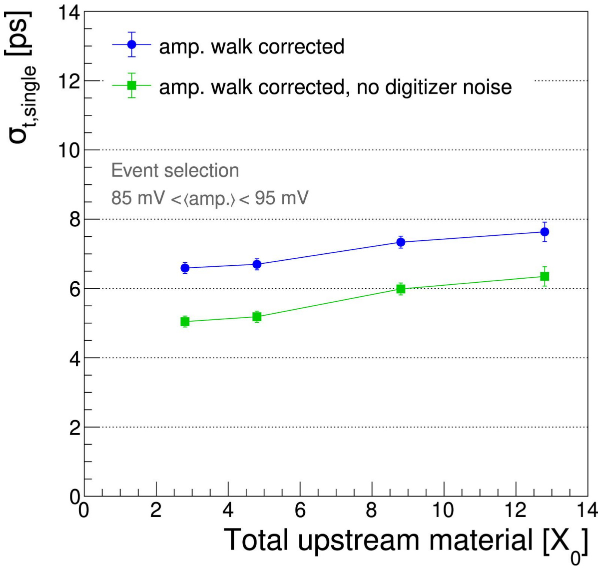


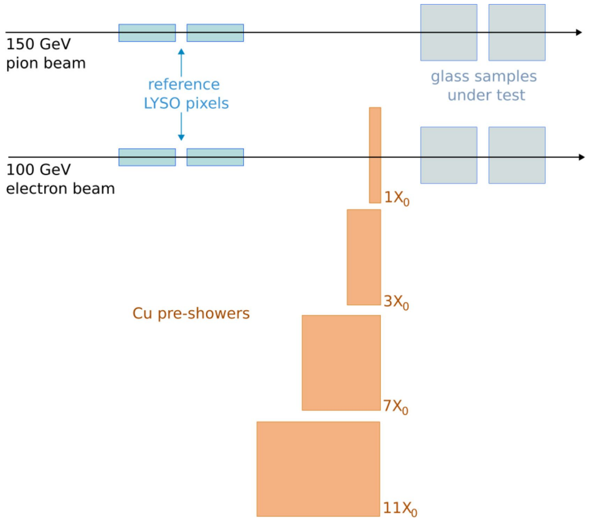
Timing to improve HAD shower reconstruction (simulation)
See N.Ackurin @ECFA Symposium 2021



Resolution to electromagnetic showers

- Time resolution of O(5 ps) for EM showers within reach (glasses+SiPMs) at single sensor level →most likely a challenge to scale it up (clock, electronics, etc.)





Sub-10 ps time tagging of electromagnetic showers with scintillating glasses and SiPMs

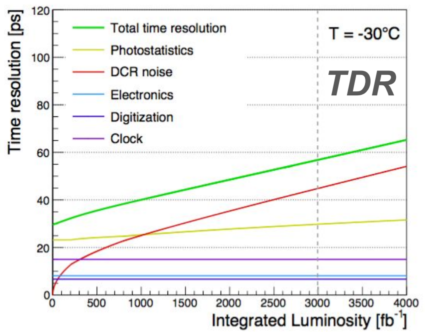
Nuclear Inst. and Methods in Physics Research, A 1051 (2023) 168214

Time resolution drivers in BTL [updated]

dominant contributions

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$

$$\begin{cases} \sigma_t^{phot} \propto \frac{1}{\sqrt{S}} \\ \sigma_t^{DCR} \propto \frac{N}{S} \\ \sigma_t^{ele} \propto \frac{\sigma_{noise,ele}}{dI/dt} \end{cases}$$



Time resolution driven by photon signal (**S**), radiation induced dark counts (**N**) and electronic signal rising slope (**dI/dt**):

crystals | crystals + SiPM | SiPM

$$S = E_{dep} LY \cdot LCE \cdot PDE$$

SiPM

$$N = \sqrt{DCR}$$

SiPM | TOFHIR

$$dI/dt \propto S \cdot Gain \cdot f(R_q, C_g) \cdot \xi(ASIC)$$

E_{dep}: energy deposit by MIP
LY: crystal light yield
LCE: light collection efficiency
PDE: photon detection efficiency
DCR: rate of dark counts
R_q: quenching resistor
C_g: grid capacitance