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Fast timing requirements for hadron and e^+e^- colliders

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- **Outline**
  - Introduction
  - Use cases
  - Integration
  - Some remarks

  - More than a structured talk, the sharing a few years of experience to try and integrate the MTD timing detector within the CMS experiment

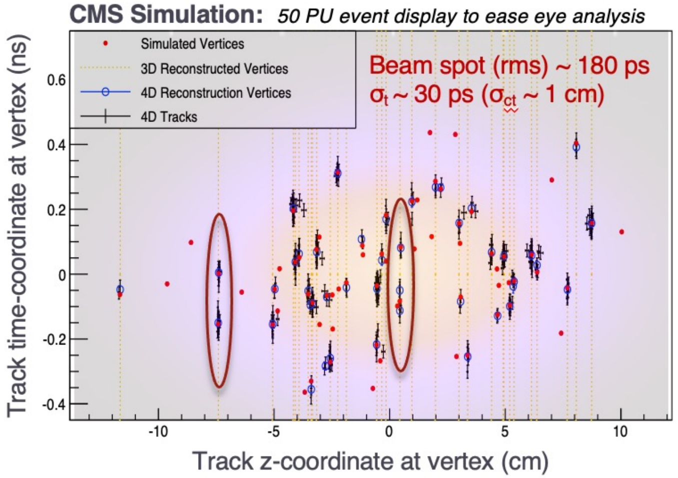
Introduction

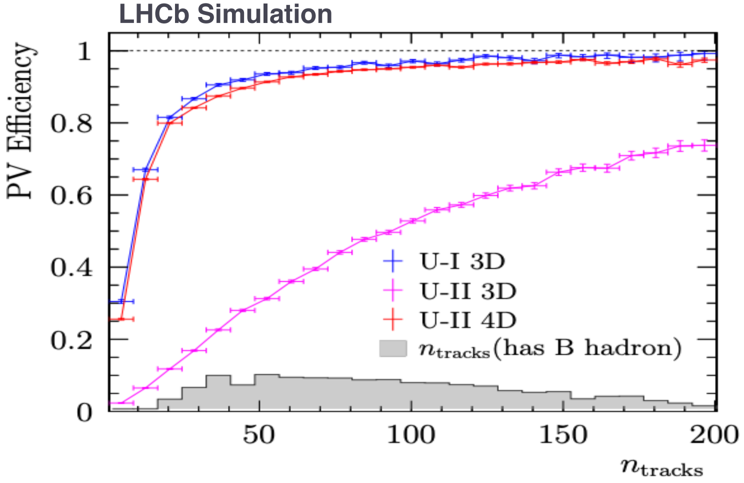
- **Requirements for particle or shower timing follow from:**
  - **The use cases** [scientific goals]
  - **The beam structure** [time and position profile of the beam spot]
  - **The environmental contraints** [radiation levels, safey issues, etc.]
  - **The integration constraints** [impact on performance of other subsystems, material budget within the tracker and in front of ECAL, dead zones/passive material for routing services for readout, power, and cooling needs]

- **R&D programs are often focused on achieving the required time resolution and longevity at the sensor level**
  - The radiation hardness may be the main challenge for future hadron colliders
- **The performance/cost optimization of a timing detector depends also on a careful analysis of the last item**
  - In general (with perhaps one notable exception) the available technologies are adequate to match the needs for detectors at future e+e– collider and the integration aspects might deserve more attention than the sensors themselves

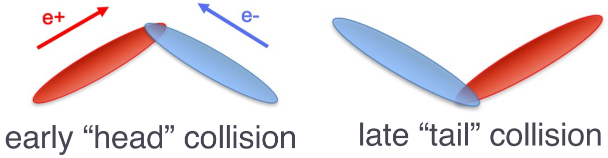
Use case 1: vertex timing (from track timing)

- **Background suppression**
  - Event cleaning at hadron colliders with O(30 ps) timing
    - Spatial overlaps of concurrent collision vertices are resolved in time by “slicing” the beam spot in successive time exposures
      - At HL-LHC, *efficiencies and background* back to LHC level with
        - σ_t ~ 30 ps per track (σ_{ct} ~ σ_z for very forward tracks)
      - Hermetic [CMS MTD 2019] or forward coverage [ATLAS HGTD 2020, LHCb U-II 2021]
    - Likely needed at the FCC-hh, with requirements depending on beam properties and on the spatial resolution of the tracking system
  - Cosmic ray rejection at e+e– colliders with O(1 ns) timing
    - Historical example the ADONE e+e– ring at LNF in the ‘60 [ADONE, 1969]
    - Superseded by improved tracking systems and vertex spatial resolution



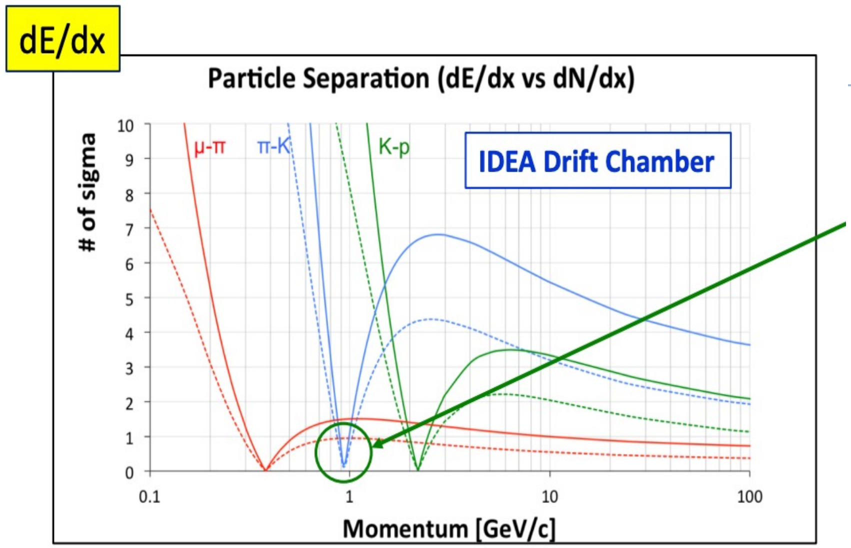


- **Energy vs time correlation in e+e- colliders**
  - For some beam optics (“chromatization” scheme), the particle energy correlates with the longitudinal particle position in the bunch, and thus to the collision time
  - Vertex timing with O(5 ps) precision offers a √s scan at fixed centre-of-mass energy (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

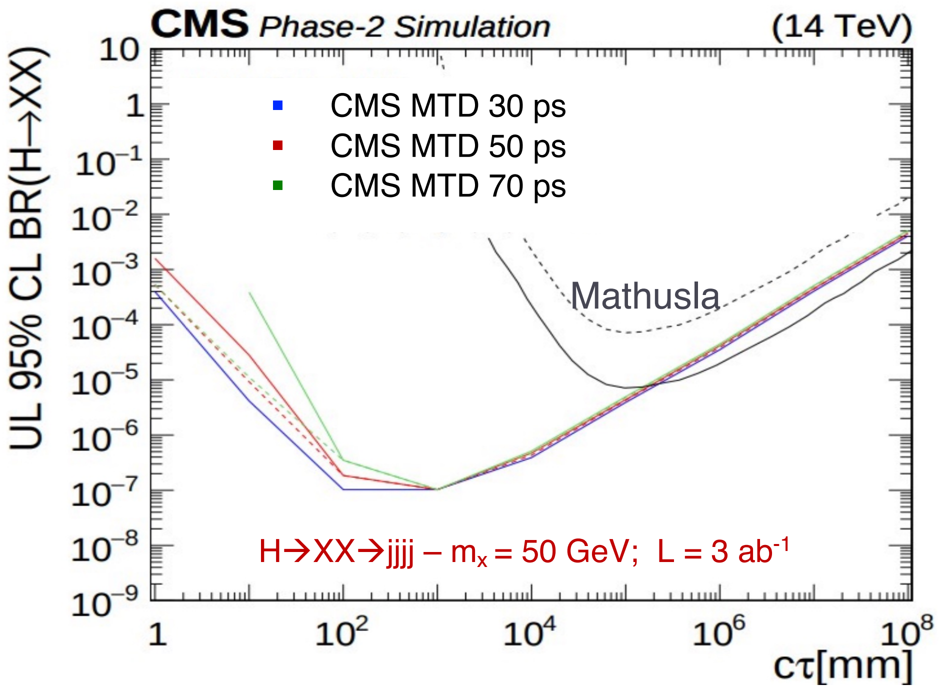


Use case 2: time-of-flight

- **Hadron identification for flavour physics jet flavour tagging**
  - Compelling physics case at e+e- (and potentially at future heavy ion and hadron colliders)
    - [Wilkinson & Monteil, FCC-ee, 2020, Bedeschi *et al*, 2202.03285]
  - Future e+e- detectors largely rely on dE/dx (or dN/dx) and Cherenkov for PID
  - 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.
  - Moreover,
    - TOF could provide redundant π/K separation up to ~5 GeV
    - TOF also provides vertex timing ($\sigma_{Vtx} \sim \sigma_{TOF} / \sqrt{N_{tracks}}$)

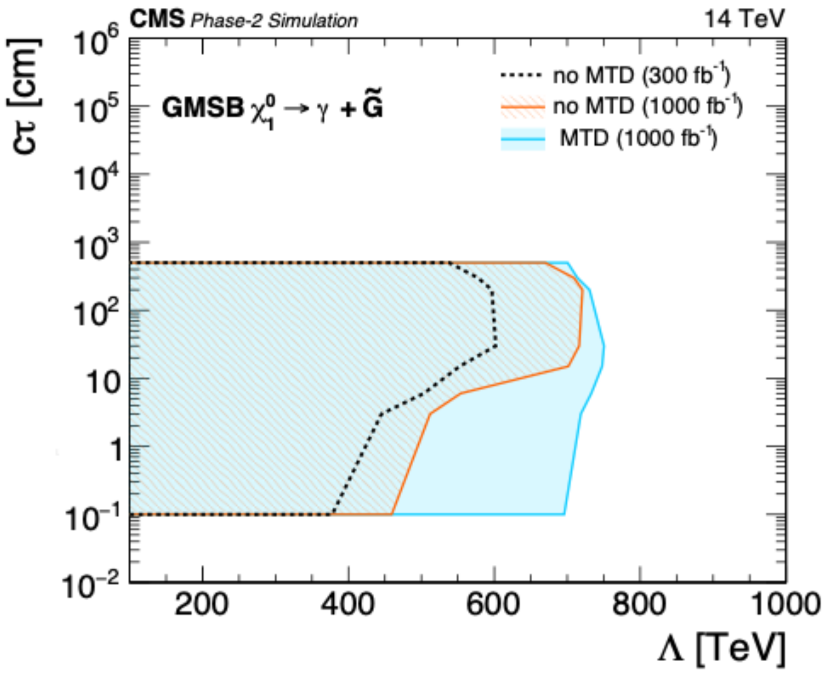


- **Long lived particles**
  - One of the leading concepts for probing the highest mass scales in BSM models
  - Although the sensitivity increases with time resolution, the large multiplicity of final state topologies softens the requirements on time resolution [CMS MTD 2019, CMS MTD 2022]
    - Plot shows the sensitivity to a heavy X scalar decaying to jets using time information from the CMS MTD at 1 m from the vertex
    - No time information from calorimeters is used
  - Which window will remain open after HL-LHC?

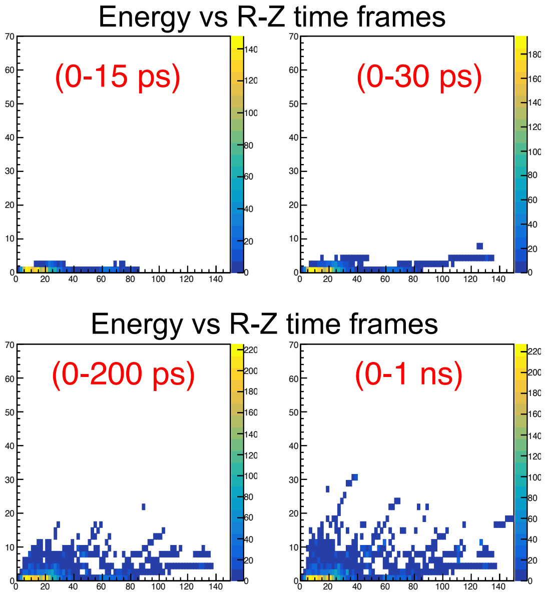


Use case 3: calorimetry

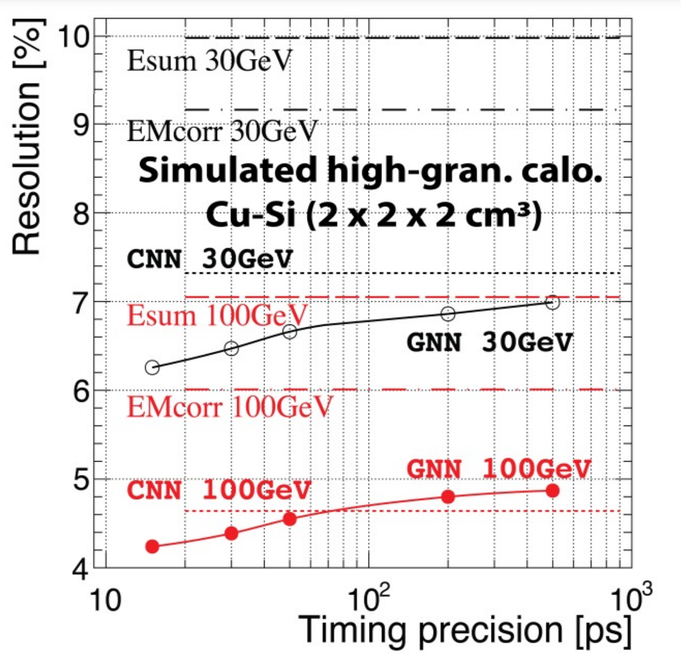
- **Extend LLP searches to neutrals <u>(time-of-flight of showers relative to vertex)</u>**
  - Example: HL-LHC with 30 ps resolution for photons
  - Sensitivity at short cτ limited by timing resolution, with dominant contributions from:
    - Beam spot size w/o vertex timing
    - Shower time resolution w/ vertex timing
  - Which window will remain open after HL-LHC?



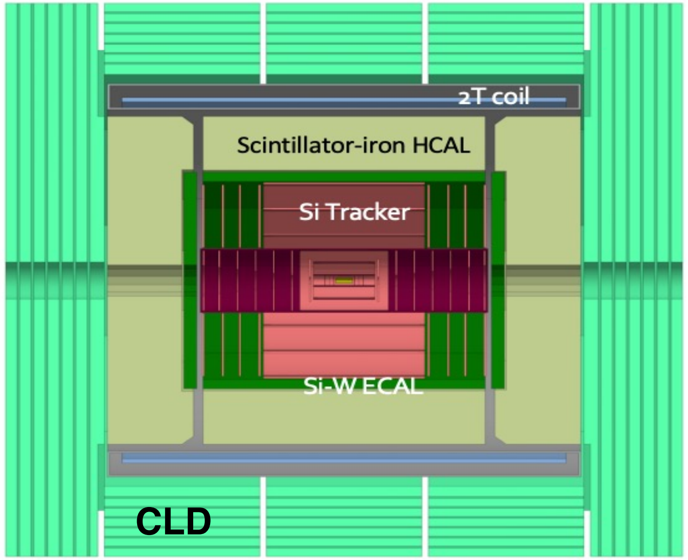
- **Add time information to hadron shower reconstuction <u>(timing within the shower)</u>**
  - Pion energy resolution improves while progressively including shorter time slices in the energy estimates (GNN)
    - O(10 ps) / cell for significant resolution gain over CNN cluster energy sums [N. Akchurin, ECFA Symposium, 2021]
  - Can also improve linearity, particularly important for ultra-high-energy colliders such as FCC-hh

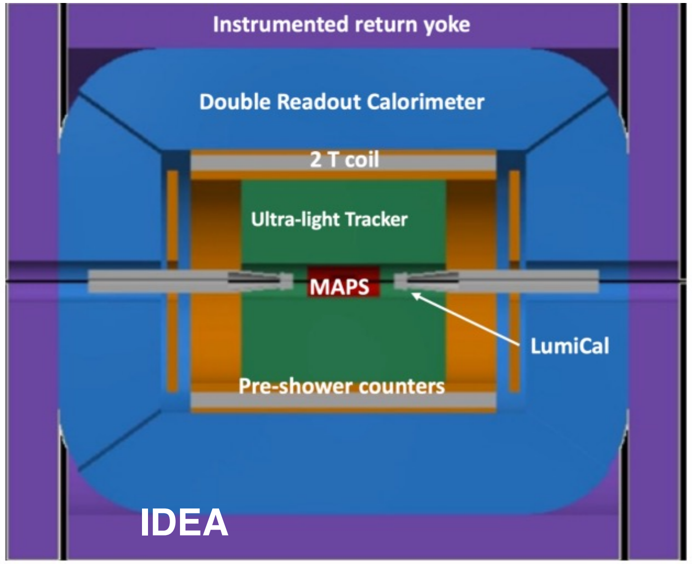


121 GeV pion



Integration: where and which timing detector?





- **Track-time embedded in the (silicon) tracker**
  - Vertex timing

Not compelling for e+e–
Likely needed at FC-hh (crowded environment)

- **Designated TOF detector in front of the calorimeter**
  - Vertex timing + PID from TOF + LLPs sensitivity
- **Calorimeter with front section sensitive to MIPs**
  - Vertex timing + PID from TOF + LLPs sensitivity including neutrals

Clear physics case at e+e–
Required resolution is being achieved in large systems for the HL-LHC upgrades

- **Whole calorimeter**
  - Jet energy reconstruction

As attractive as challenging

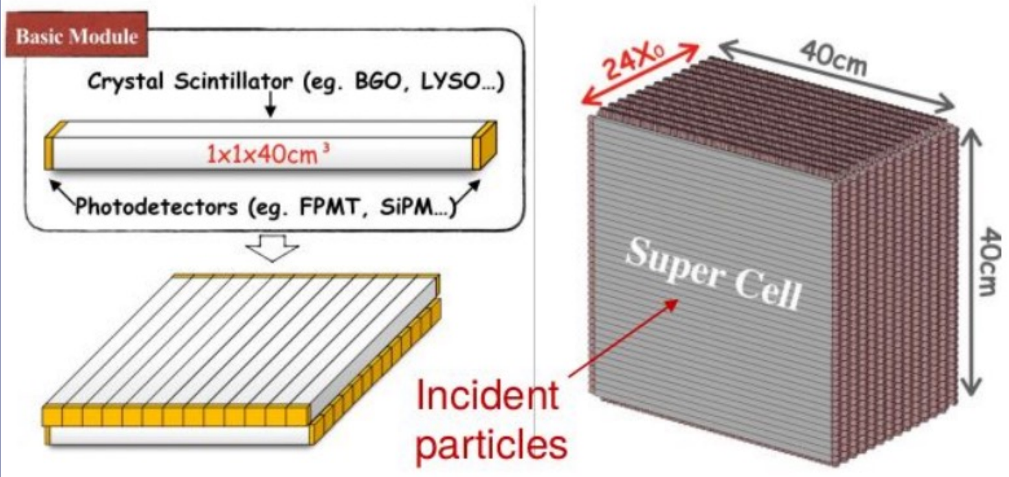
- **Time information at the trigger level – not covered**
  - It might be useful at FC-hh for early background filtering but no compelling evidence from HL-LHC studies

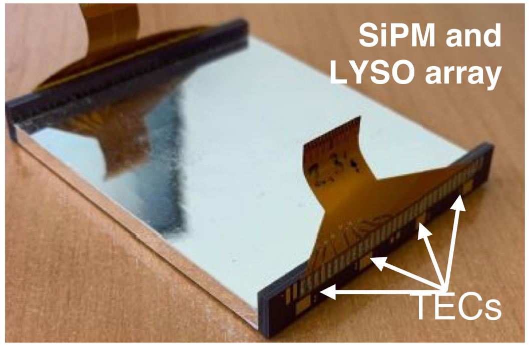
Integration: where and which timing detector?

- **Calorimetry: "all-in-one" option for e+e- colider detectors**
  - Timing of showers + TOF in the front layers of the calorimeters
    - E.g., crystals for high-resolution EM calorimetry
      - **~25 ps/MIP** in LYSO-SiPM before radiation(*) [CMS MTD 2104.07786]
    - Or silicon pads in a Si-W calorimeter:
      - < 30 ps/shower [CMS HGCal 2018]
      - **~200 ps/MIP** with Si diode w/o internal gain(*) [N.Akchurin *et al.*, 2017]
      - **~30 ps/MIP** with Si diode w/ internal gain (LGADs)(*) [CMS MTD 2019]
  - May add timing everywhere for improved jet energy reconstruction
    - Very attractive concept but challenging timing resolution and integration (power and service hungry detector) for significant gain in resolution

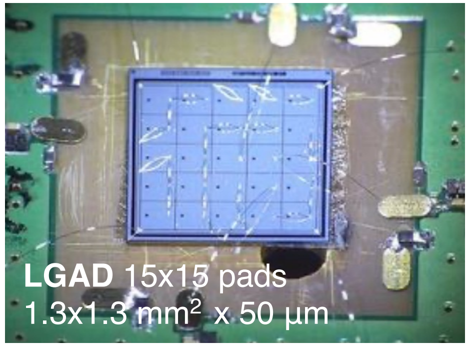
- **Supplemental vertex timing capabilities from tracker may be needed in high occupancy events (FCC-hh)**
  - Time measurement embedded in the tracker or vertex detector
  - "light / thin technologies" on small surface (cost and power effective)
    - E.g., 3D silicon pixels as proposed for the LHCb upgrade [LHCb U-II 2021]

Concept for an e+e- EM calorimeter [Y.Liu @IAS2021]





CMS MTD Barrel module
- ~ 1 kW/m² (~50% from SiPM radiation damage)



CMS MTD Endacap / ATLAS HGTD sensors
- ~ 5 kW / m²

(*) One layer

Final remarks

- **Timing requirements for e+e- detectors are, in general, relatively loose and can be matched by existing technologies**
  - Current HL-LHC upgrades provide viable solutions for the integration of a TOF detector in the (front layers) of a calorimeter
  - Integration aspects and the interplay with other subsystems (e.g., Cherenkov systems at and of tracker) need dedicated effort
- **The measurement of the time evolution of showers can potentially improve the hadron energy measurement**
  - Very attractive concept requiring precision timing over large area with challenging integration requirements (power and services)
  - Need scientific, conceptual, and technical progress for ultimate performance with O(10 ps) timing of the shower development
- **Requirements on timing resolution for background suppression at future hadron colliders are likely similar or tighter than at HL-LHC**
  - Resilience to radiation damage at unprecedented levels needs to be studied
  - Some (current) technologies are already hitting their limits at the HL-LHC