Technology for fast Timing: Calorimetry

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Max-Planck-Institute for Physics

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Disclaimer

- Primarily based on Tuesday’s discussion in IF06 session
- No attempt at completeness, meant as a “panorama”:
  on purpose no hard facts / technological details

- All choices, mistakes, biases my own…

Main input for the talk: White Paper Precision timing for collider-experiment-based calorimetry

Editors: Sergei Chekanov (ANL), Frank Simon (MPP)

- Applications of Timing
- System Options
- Technologies

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Precision timing for collider-experiment-based calorimetry

Editors: S. V. Chekanov[1], F. Simon[2]

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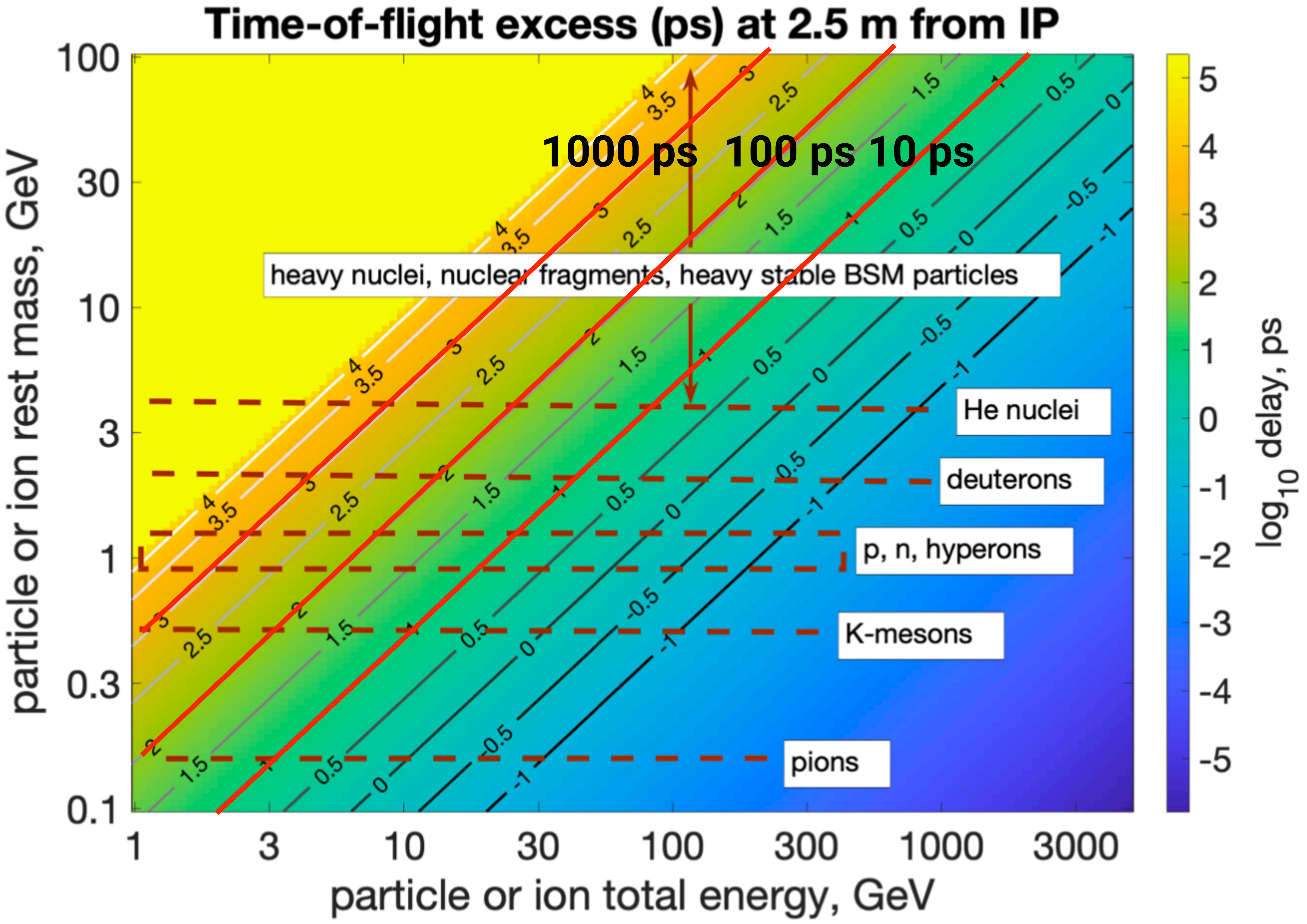
arXiv:2203.07286

Applications of Timing in Calorimetry

Object and Event Reconstruction

- Particle identification - combining energy and time (and momentum for charged particles):



- With a few 10 ps time resolution, particle ID above the pion mass becomes possible
- Particular potential for heavy hypothetical particles: Larger time offsets
  - Standalone in the calorimeter with at least two precise timing layers, for particles without known production vertex

Applications of Timing in Calorimetry

Object and Event Reconstruction

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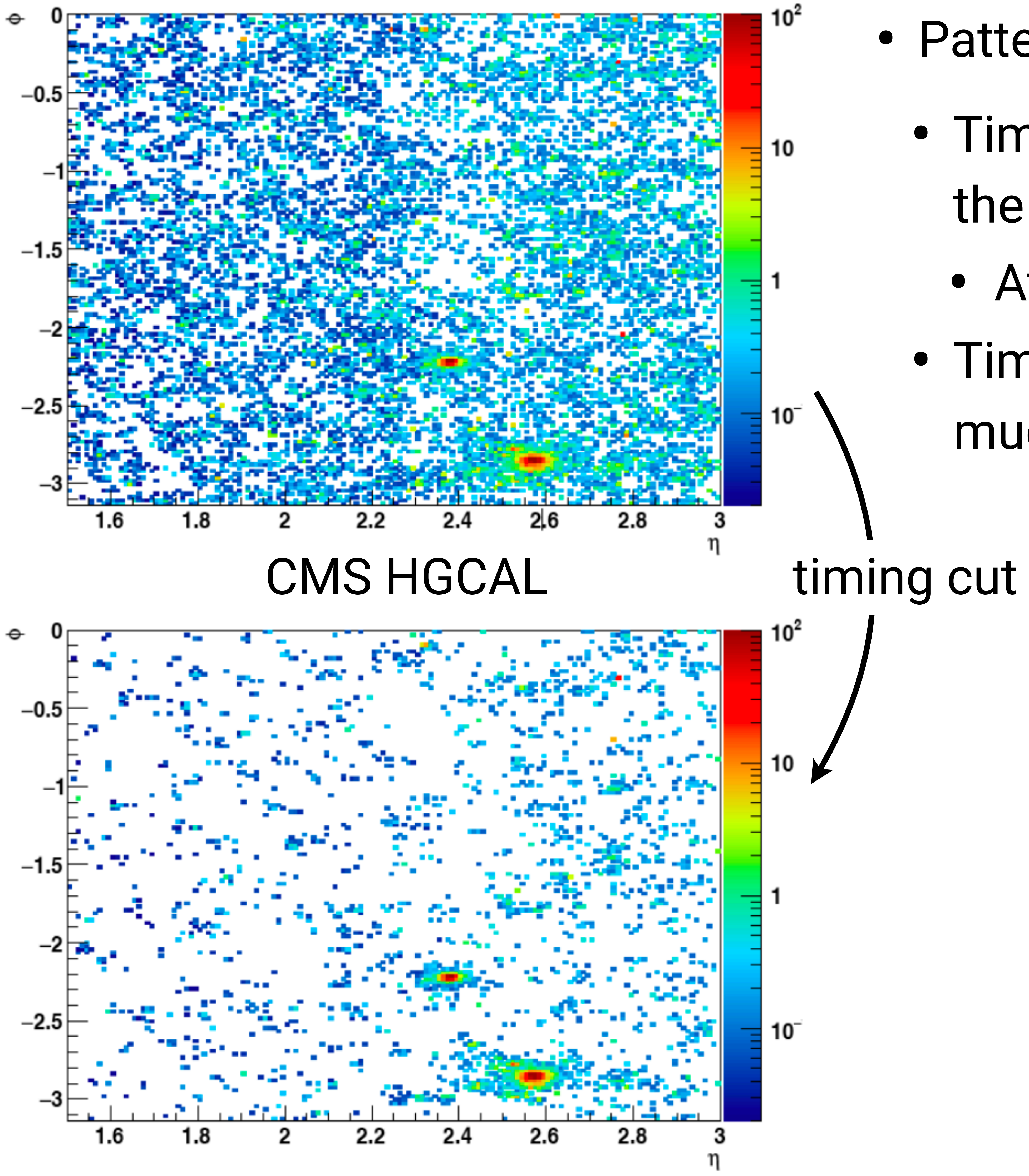
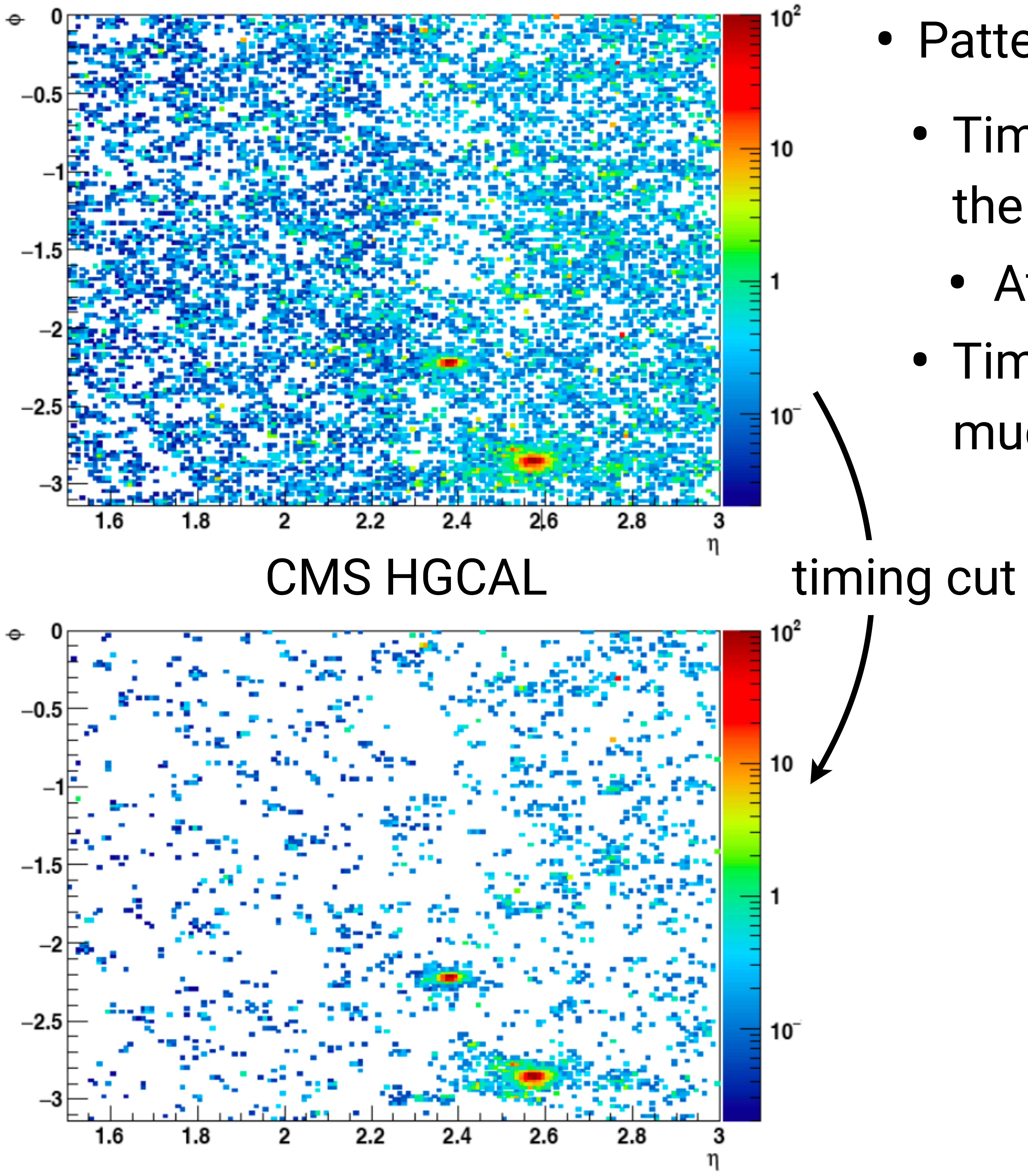


- Pattern reconstruction and pileup rejection
  - Timing on the few 10 ps level enables to reject pileup (particles from the same BX, but slightly out of time / position wrt interesting collision)
    - At FCC-hh: 5 - 10 ps required to reach HL-LHC-like conditions
  - Timing also cleans up hadronic activity: Narrow core of em subshower, much wider hadronic activity, neutron halo



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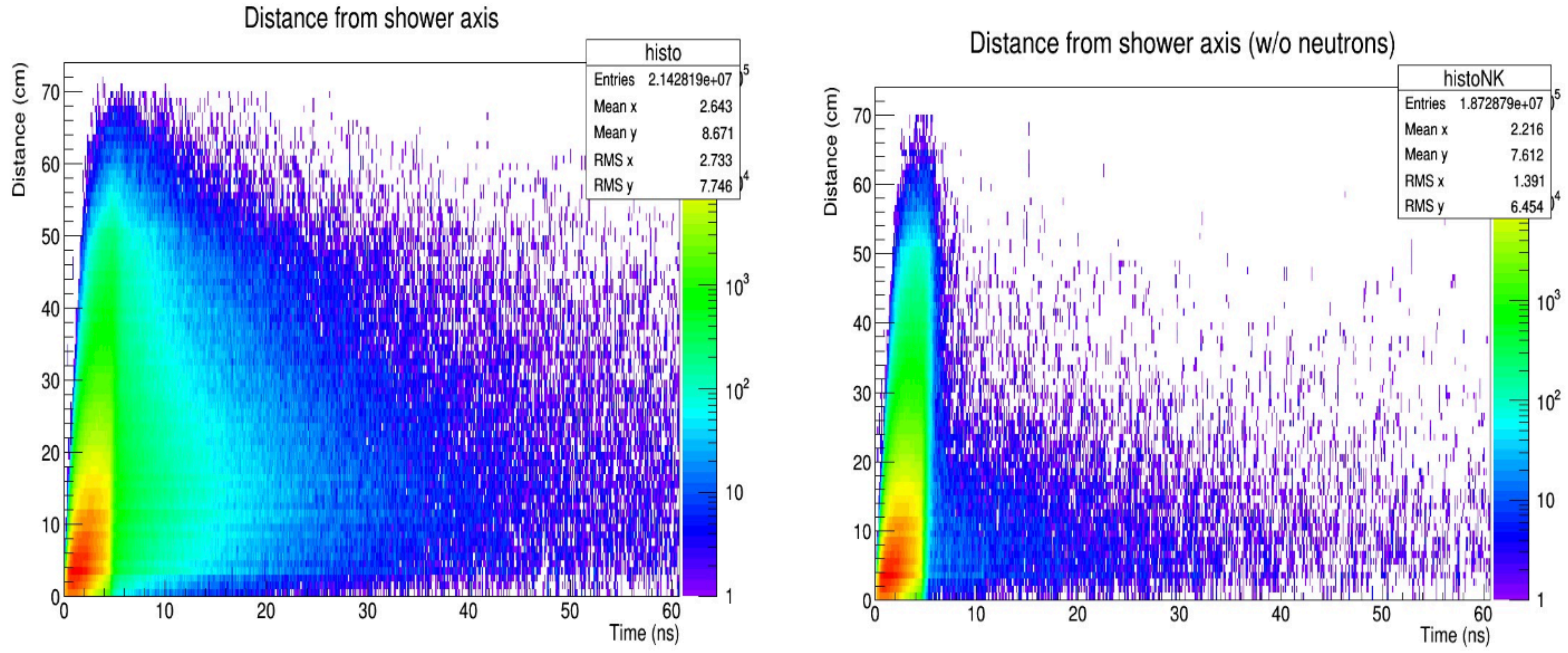
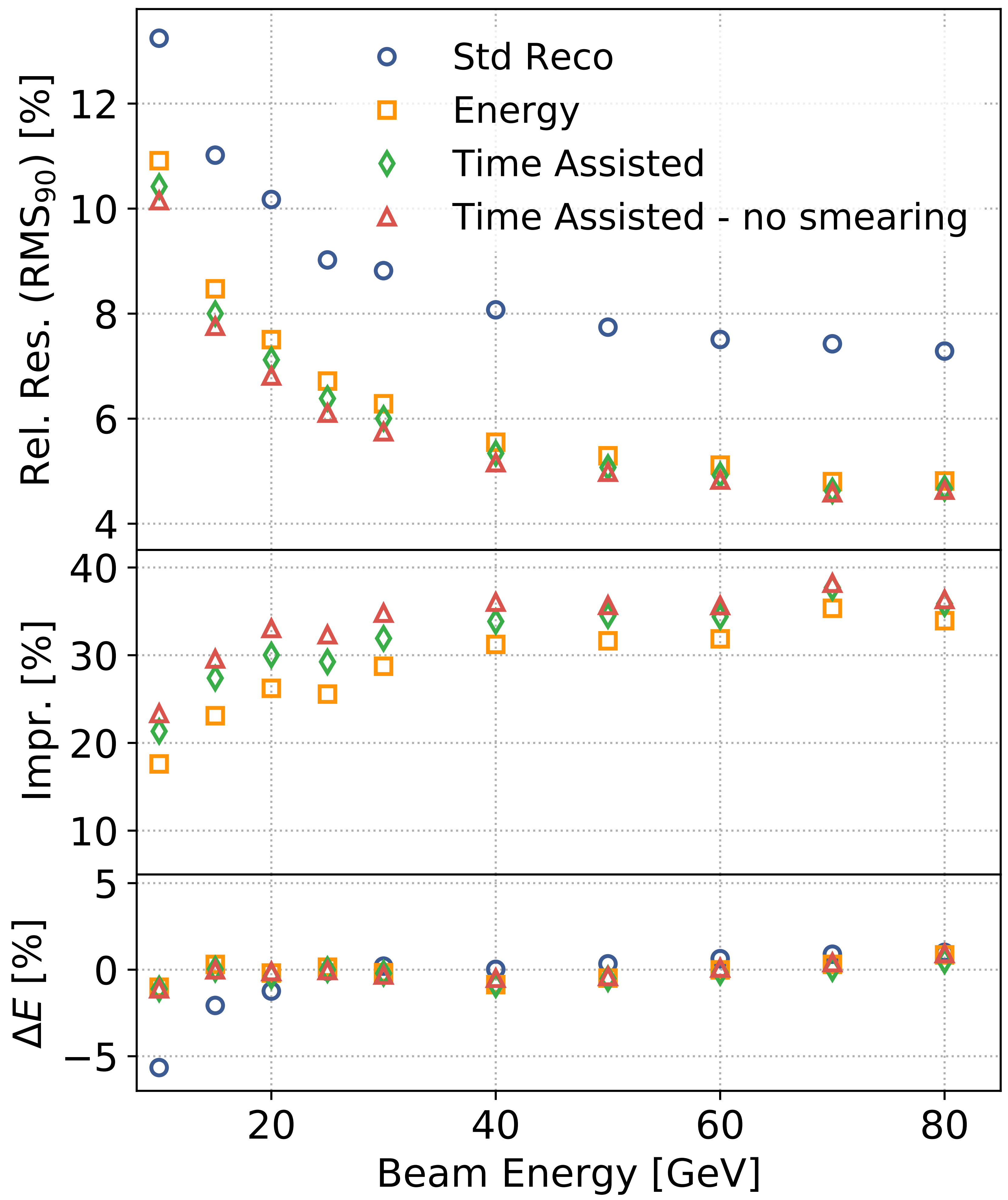
Illustrated for gaseous HCAL (CALICE SDHCAL):



Applications of Timing in Calorimetry

Hadronic Energy Reconstruction

- Hadronic energy reconstruction in non-compensating calorimeters



- Using time in software compensation: Exploiting delayed nature of neutron signals, which track hadronic activity.
  1 ns resolution helps, slight further potential when reaching the ~ 100 ps level (on cell-by-cell basis)

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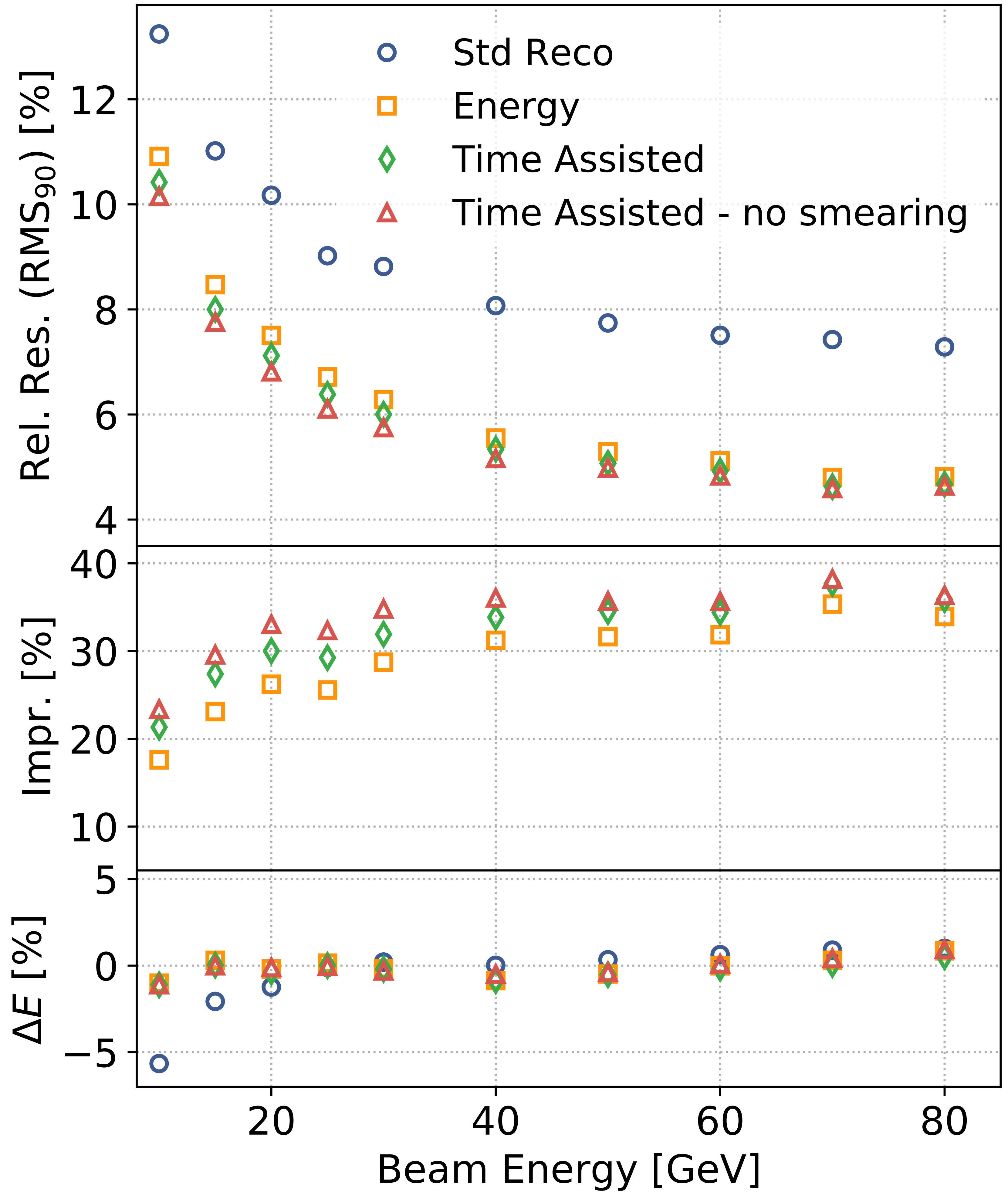
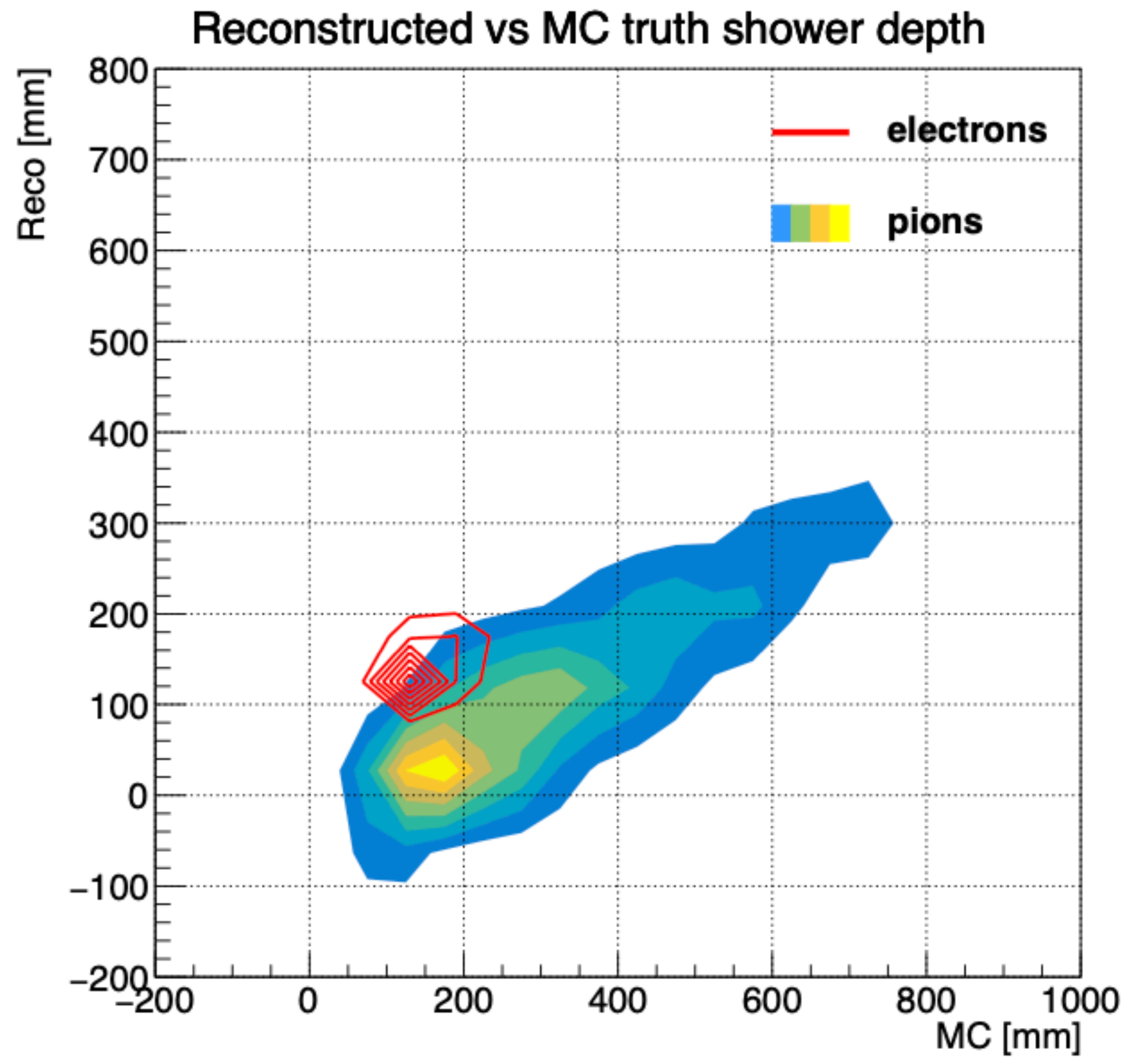
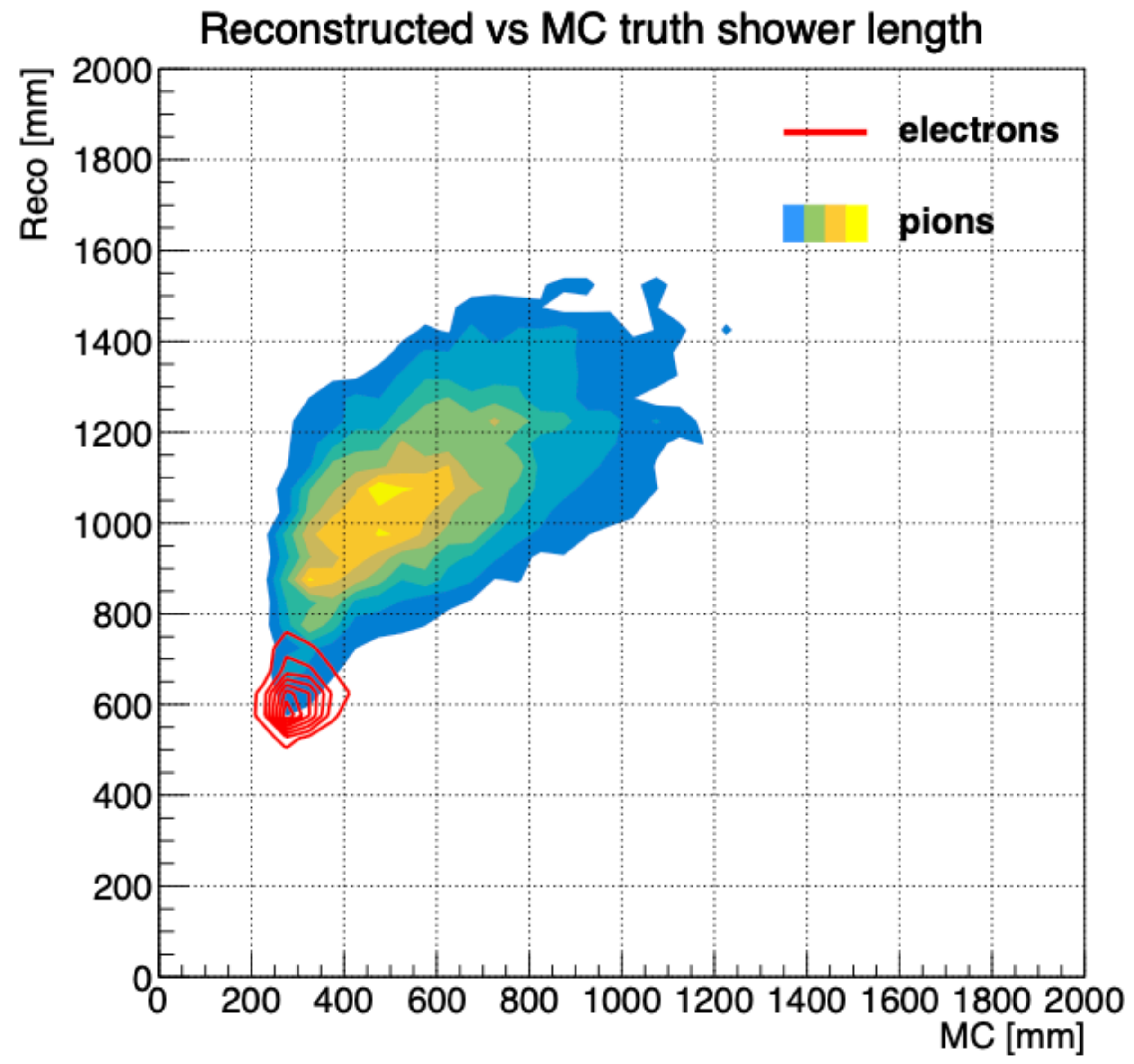


- Using time in software compensation: Exploiting delayed nature of neutron signals, which track hadronic activity.
  1 ns resolution helps, slight further potential when reaching the ~ 100 ps level (on cell-by-cell basis)
- As a means of reconstructing the shower profile in longitudinally unsegmented DR calorimeters





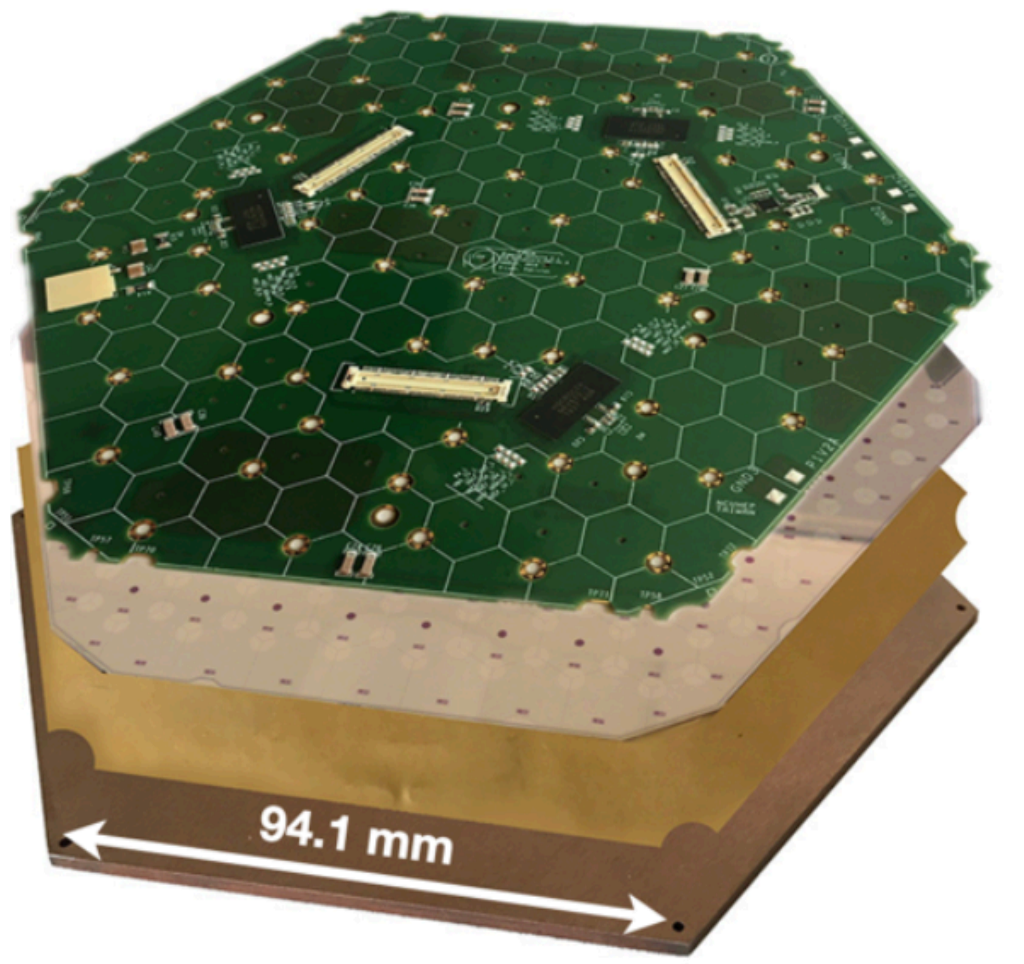
System Options - Volume Timing

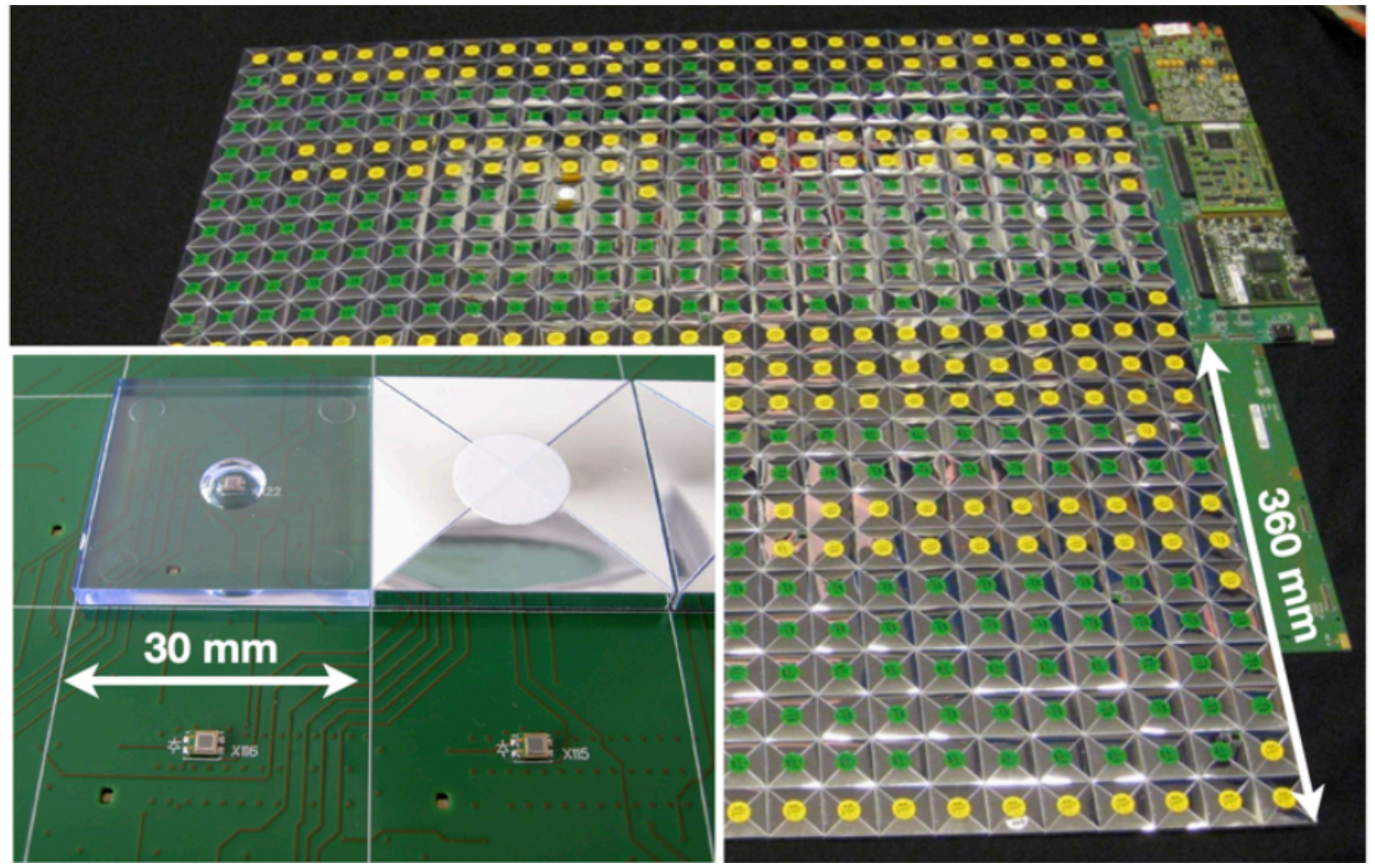
Highly granular calorimeters

- ***Volume timing***: good time resolution on the cell level in highly granular calorimeters
  - requires technologies that can provide this timing; significant implications for electronics
  - potential compromises in timing for objects

Classic examples:

- CMS HGCAL Phase II upgrade,
- CALICE calorimeters for future colliders





For objects:
Profit from large number of contributing cells
(~ 10 cells per GeV in hadronic section typically)

To put some numbers to it:
CMS HGCAL silicon:
equivalent MIP time resolution O(1 ns)
[but in reality below ToA threshold]
=> ~ 30 ps for 2 GeV γ
(20 cells above threshold)

CALICE SiPM-on-Tile: Intrinsic resolution per cell for 1 MIP ~ 500 ps (800 ps with current electronics)

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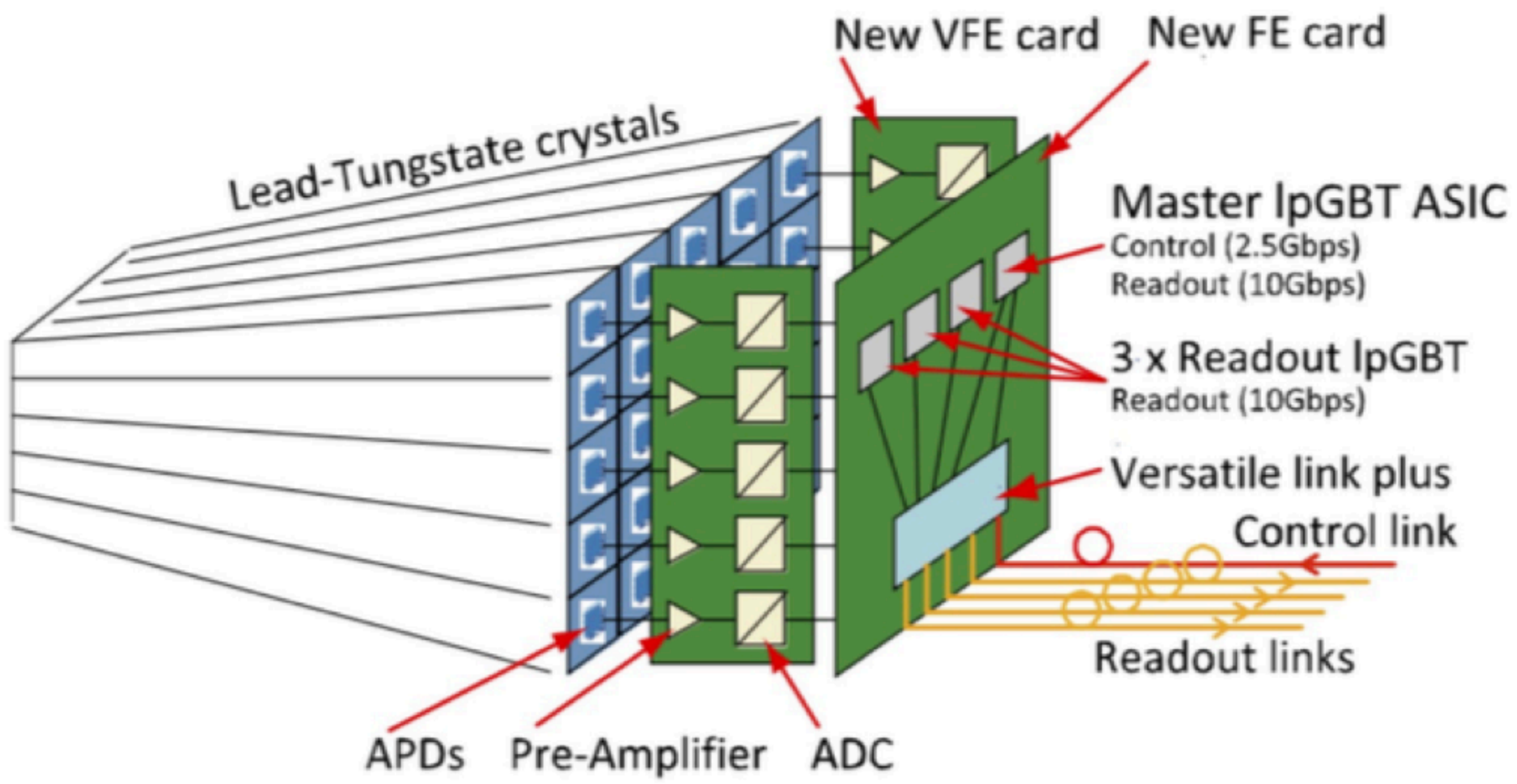
System Options - Unsegmented / Poorly Segmented

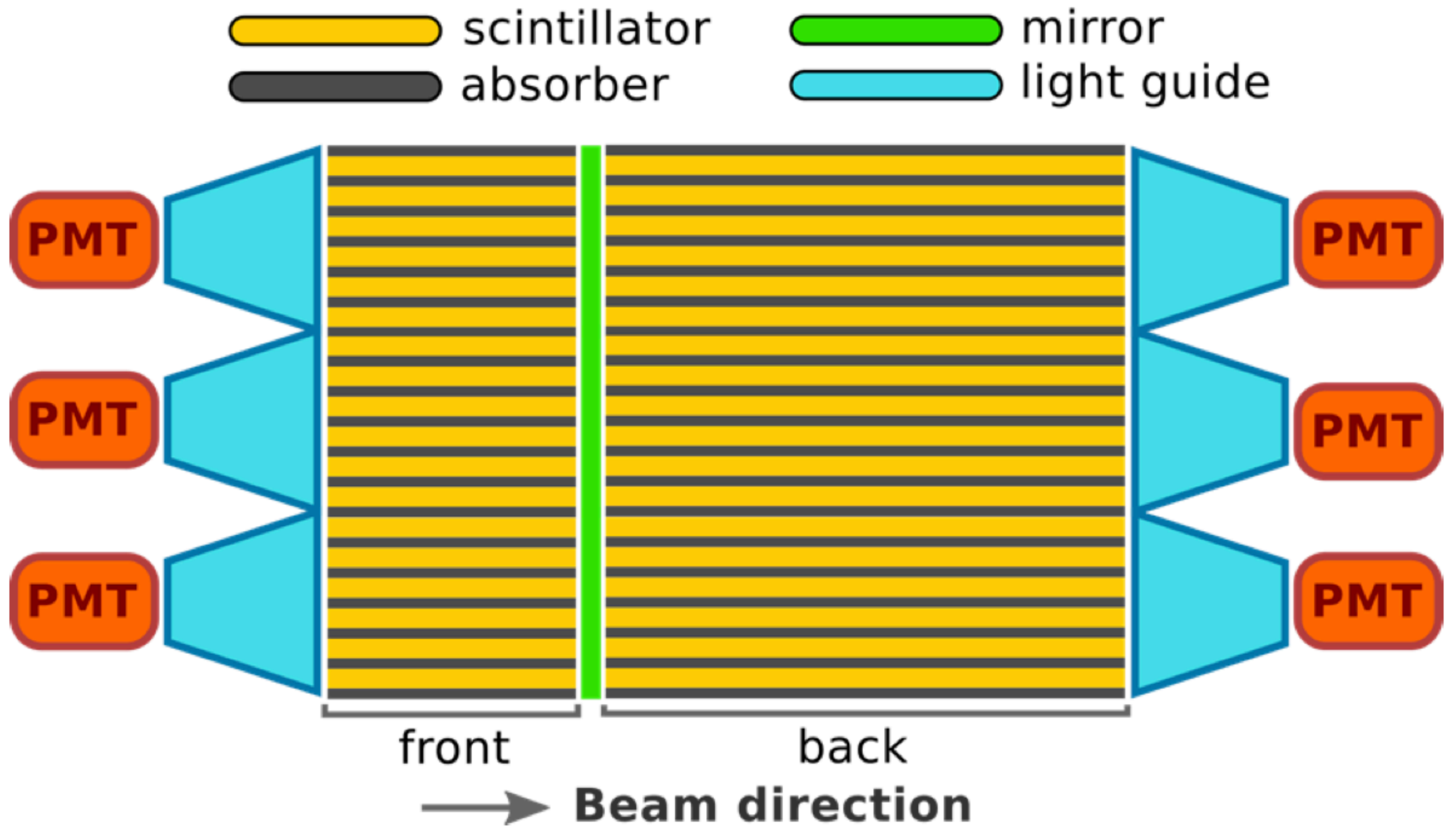
Classic calorimeters - with timing

- The classic example: CMS ECAL: $PbWO_4$ crystals with APD readout, with Phase II upgraded electronics



< 30 ps for E > 50 GeV, from waveform

- LHCb Upgrade II ECAL: Scintillator/absorber Shashlik configuration, PMT readout

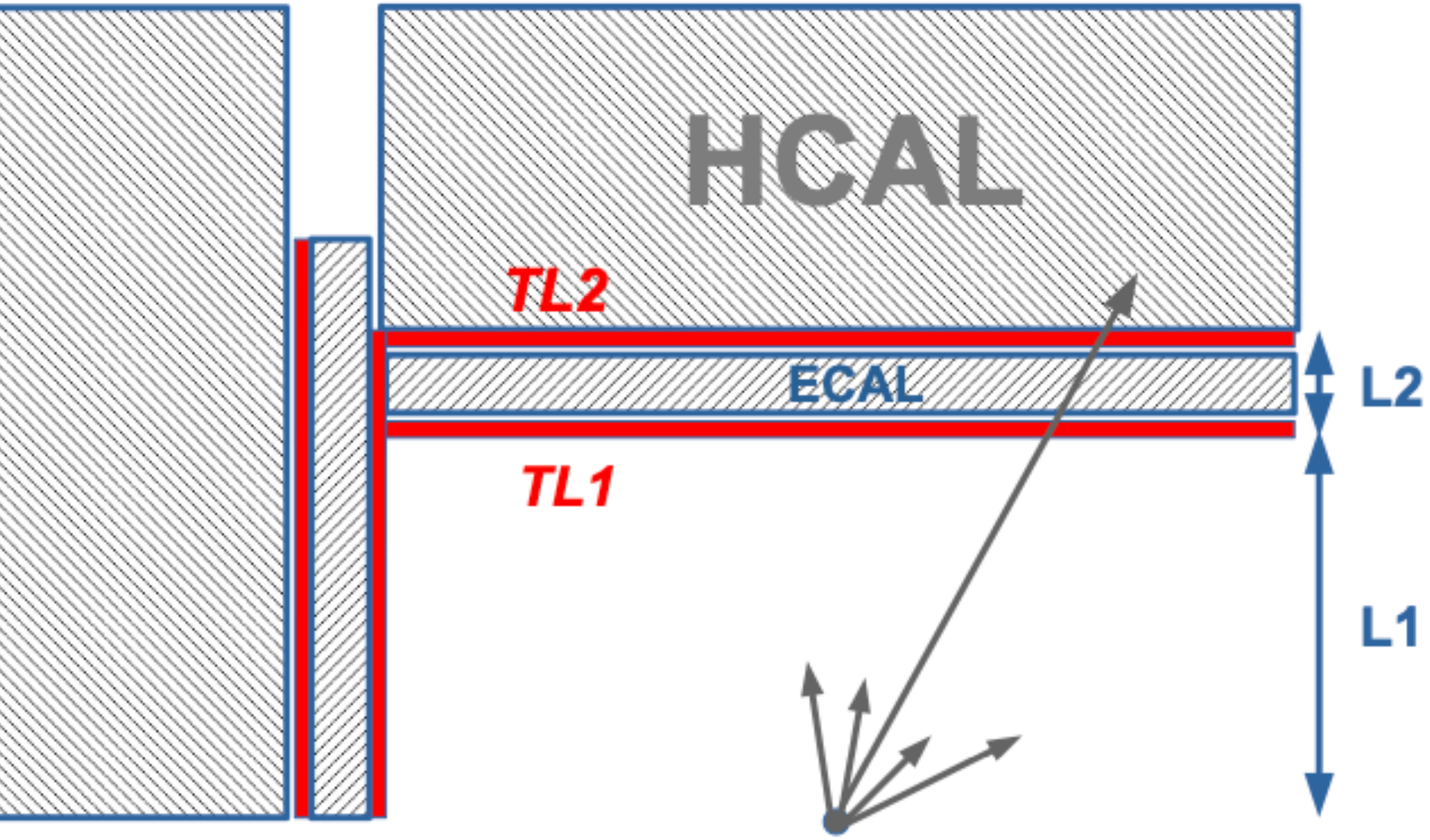


< 20 ps for E > 40 GeV, demonstrated in test beams

- Timing on the object level, not within showers

System Options - Timing Layers

Bringing timing to calorimeters regardless of



- ***Timing layers***: extreme timing in a few selected layers inside of the calorimeter system
  - can be combined with a wide range of technologies, also those not capable of fast timing themselves
  - excludes applications that require timing in the full shower volume, rather than on object level
- Performance is that of timing detectors - ~30 ps for MIPs, better for larger signals

Technologies

A (non-exhaustive) list, by

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- Timing layers - 30 ps or less (for MIPs)
  - LGADs
  - CMOS timing sensors
  - MCPs
  - Fast gas detectors
  - Very fast crystals + SiPMs (LYSO, …)
  - Microwave Cherenkov detectors
  - Ultra-fast Si detectors

"the ps frontier"

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"the ps frontier"

- Volume timing - a few 100 ps or less (for MIPs)
  - Silicon sensors in various forms
  - SiPM-on-Tile
  - RPCs, in particular MRPCs
  - Highly segmented crystal calorimeters
  - Digital SiPMs coupled to scintillators

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  - Digital SiPMs coupled to scintillators
- Unsegmented / poorly segmented elements - a few 10 ps for showers
  - (reasonably) fast crystals
  - Shashlik elements; conventional or DR

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R&D Needs & Main Directions

A few thoughts

- ***Sensors & active elements:***
  - Improved performance: time resolution - faster sensors, very fast, bright scintillator materials
  - Reduction of cost - most critical for volume applications (1000(s) of m^2)
  - Improved radiation hardness - in the long(er) term - FCC-hh, μCol
  - Connect to new technologies developed in industry beyond our current "workhorses"
- ***Electronics:***
  - Need to match sensor capabilities in terms of resolution, rad hardness etc.
  - Reduction of power, while maintaining or improving resolution - particularly critical for volume applications
  - Efficient handling of systems with 10s or 100s of million of electronics channels
- ***System aspects:***
  - Time synchronisation over the full volume - also in the context of what it means in a shower
  - Mechanical and thermal integration - particular challenge for timing layers; services (power, data, cooling)
- ***Reconstruction and Readout:***
  - Advanced ML algorithms efficiently handling 5D calorimeter data (space, energy time)
  - Data reduction, reconstruction in front- or backends fully exploiting timing information

Summary

Wrapping up

- Timing plays an increasingly important role in calorimetry
  - Timing of physics objects (showers, particle flow objects, …) on the few 10 ps level
  - Using time information within showers in highly granular “5D” calorimeters to improve energy reconstruction, pattern recognition etc.

- A wide range of technologies is used - typically not unique to calorimetry, or to HEP

- Key challenges particular to calorimetry:
  - Hardware: Very large areas, channel counts, integration
  - Reconstruction: Efficiently handling and exploiting 5D data sets

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Many opportunities for exciting R&D!