Fast Timing for Collider Detectors

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CERN Academic Training Lectures (1/3)

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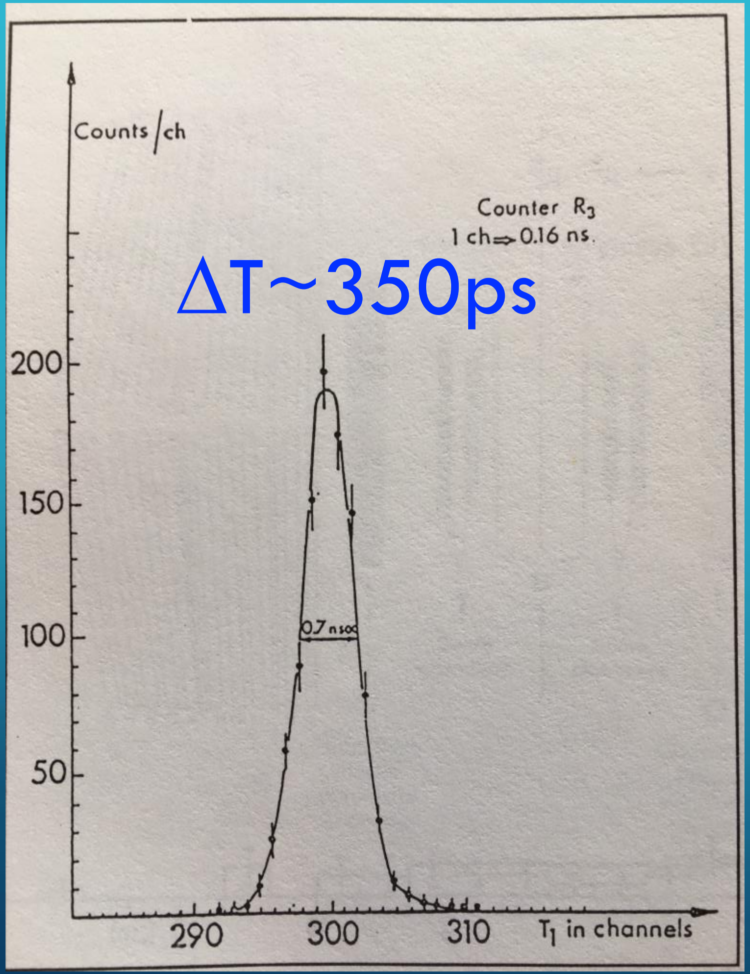
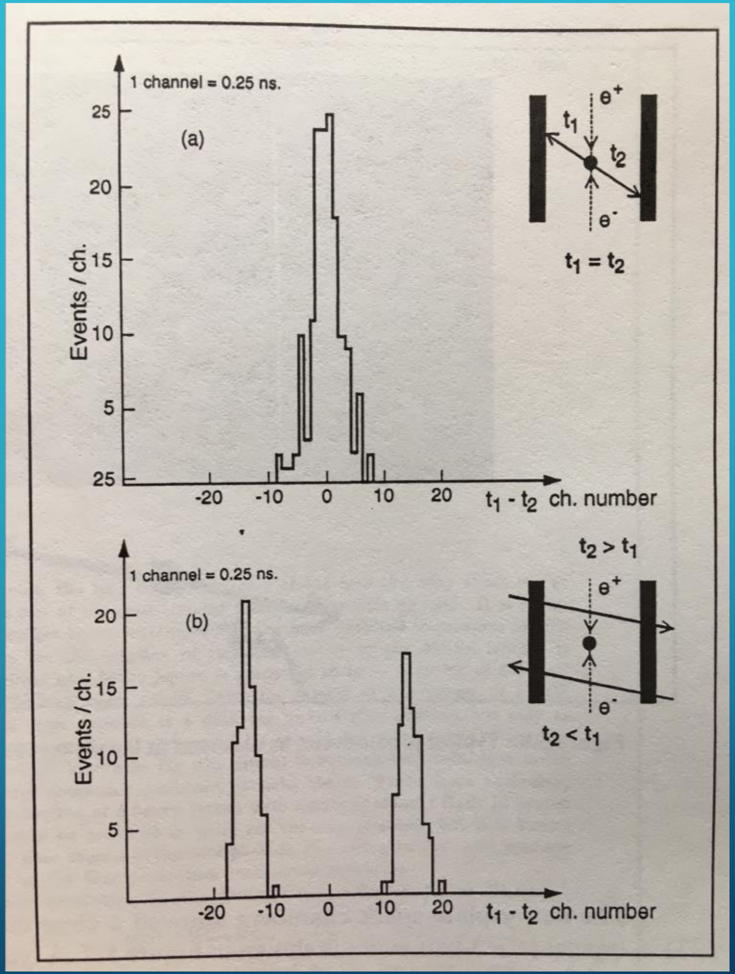
Outline

- Conventional event “snapshots” at the LHC
- Timescales and collision densities at the HL-LHC
- Time-aware event vertexing and particle flow

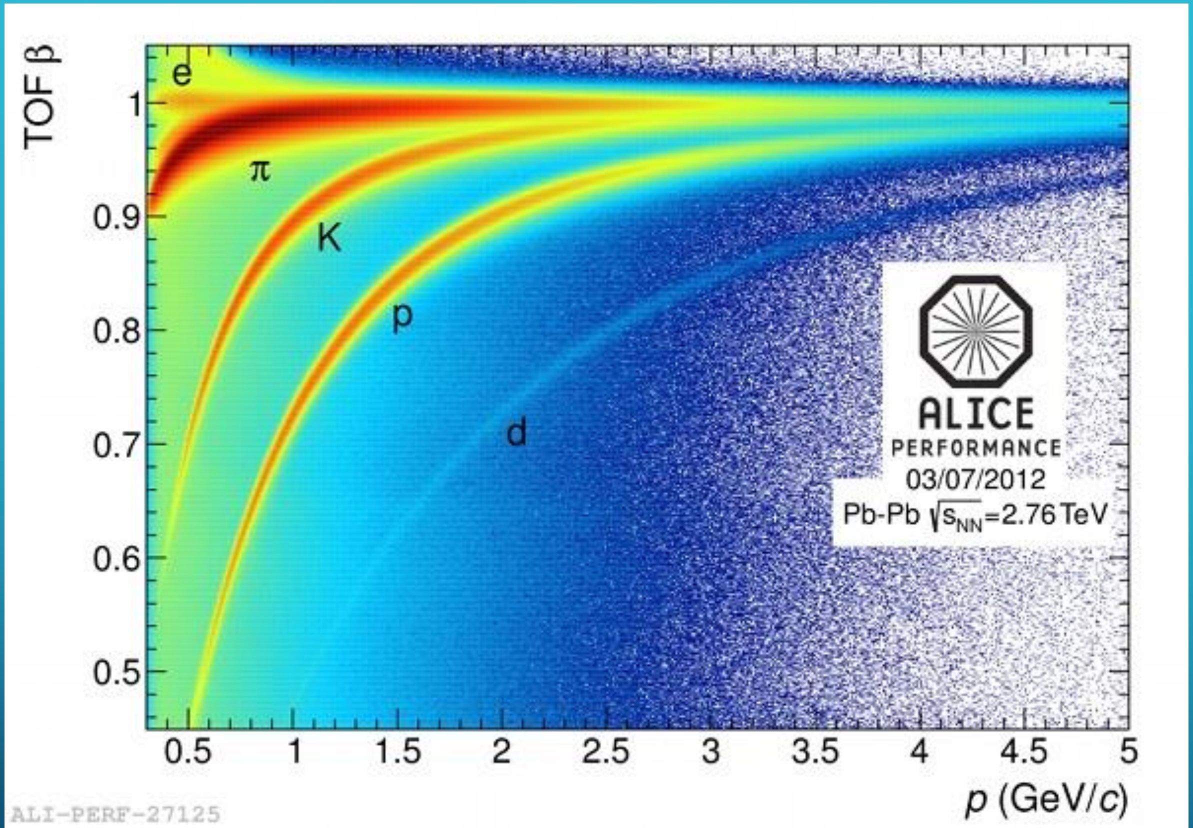
Historical Trends in Timing Resolution at Colliders

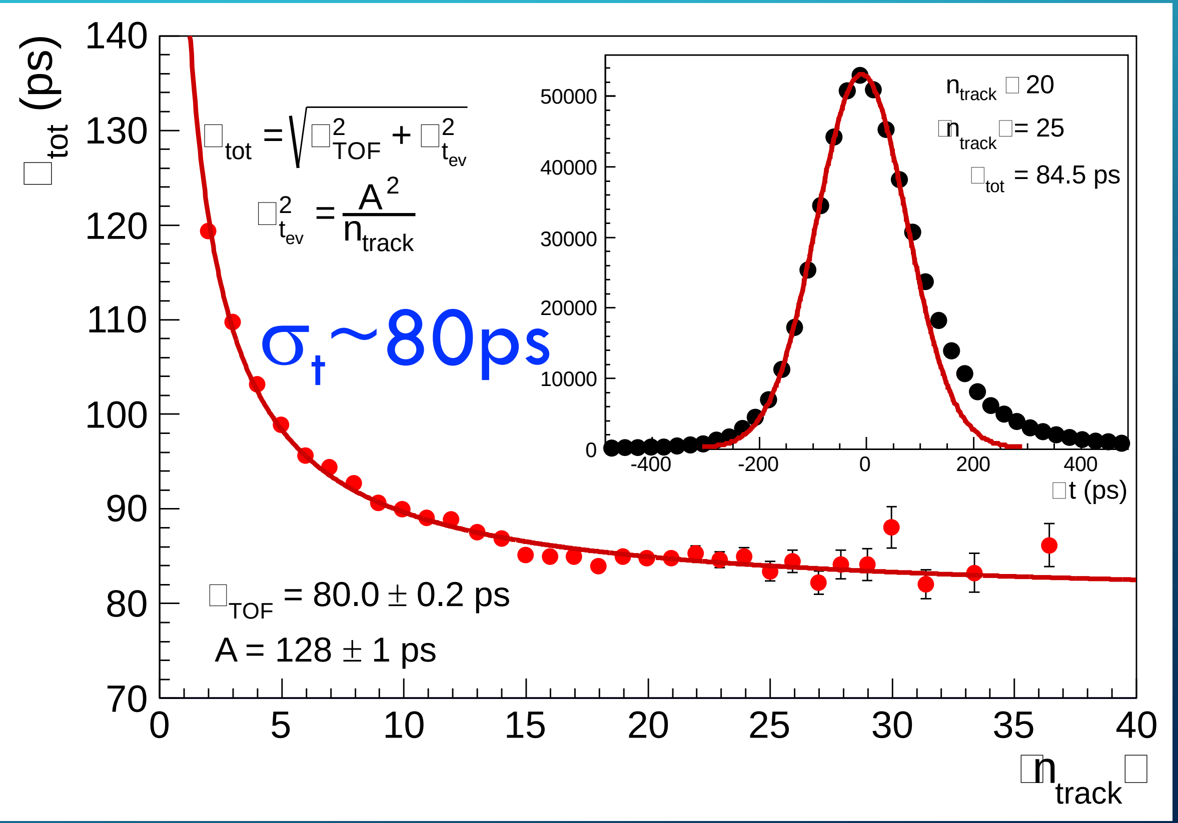




- ADONE (1969)
- Collisions distinguished from cosmic rays with ΔT~350ps timing resolution

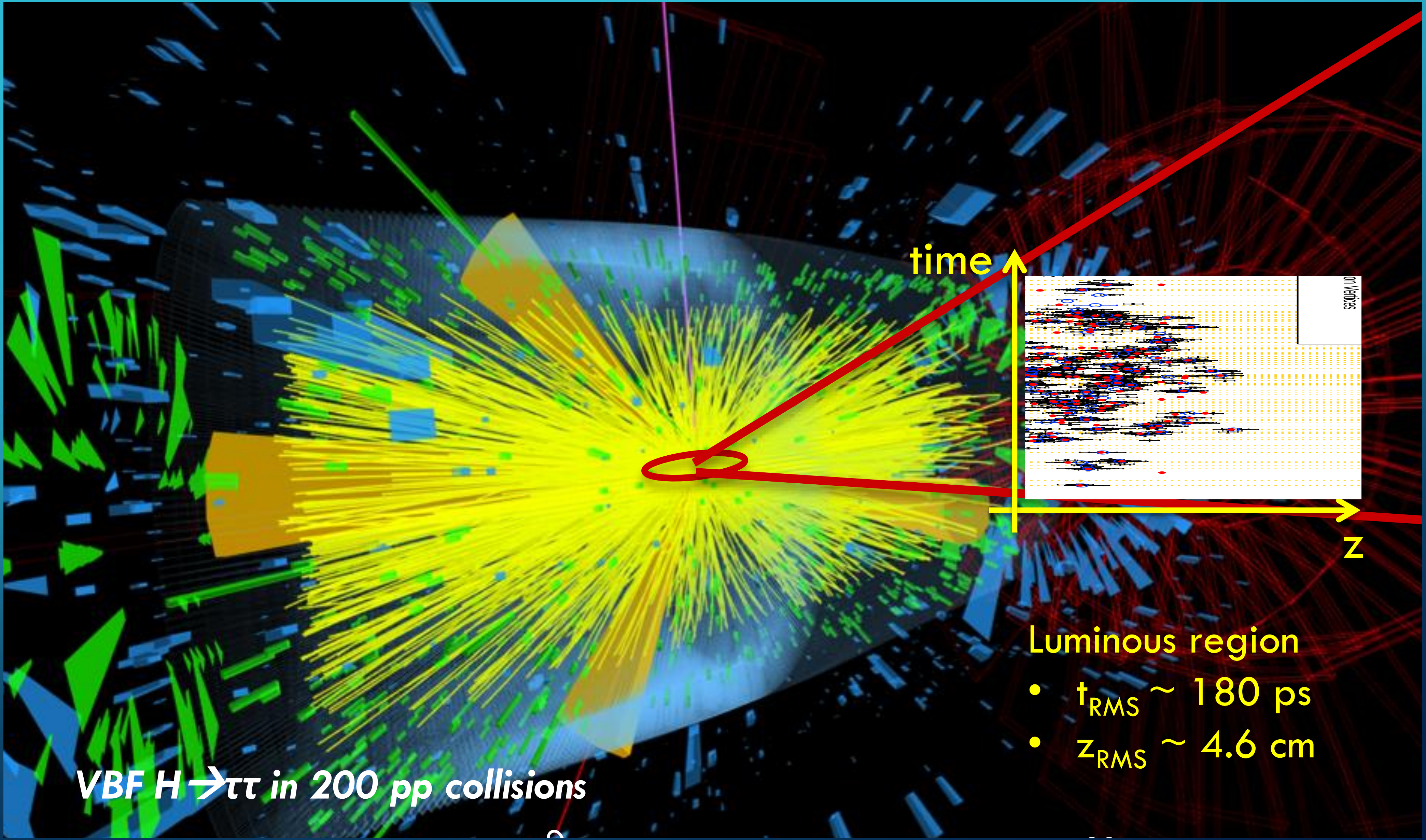
State-of-the-Art Time-of-Flight



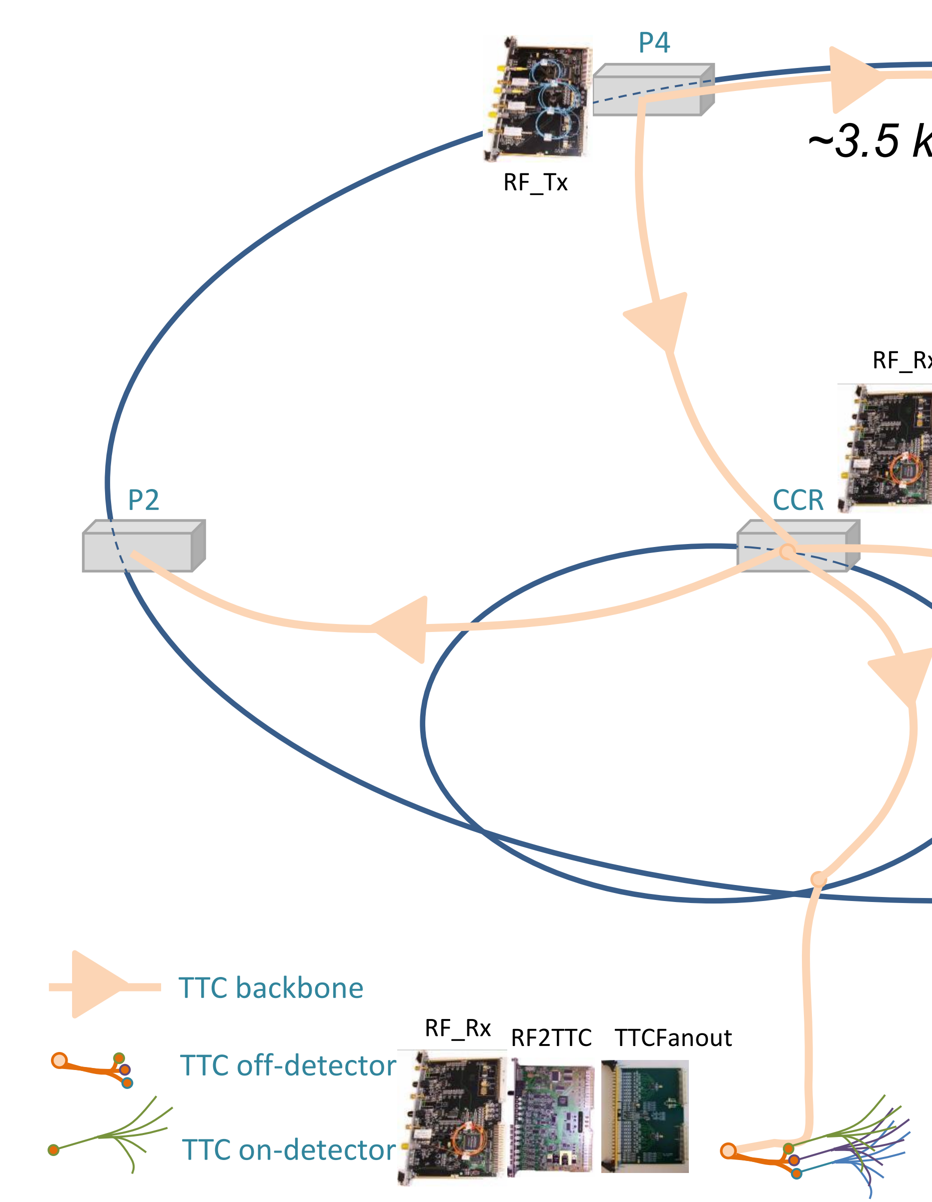


- Time-of-flight σ_t~80ps Particle Identification System (semi-relativitistic particles) with a time reference (t0) forward detector that uses a high multiplicity of tracks

High-Luminosity LHC



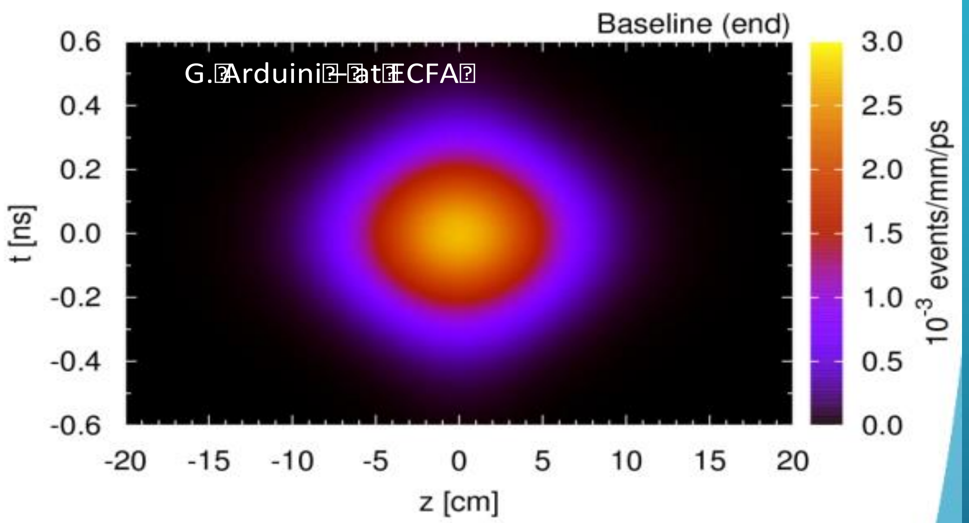
Timing from the Machine

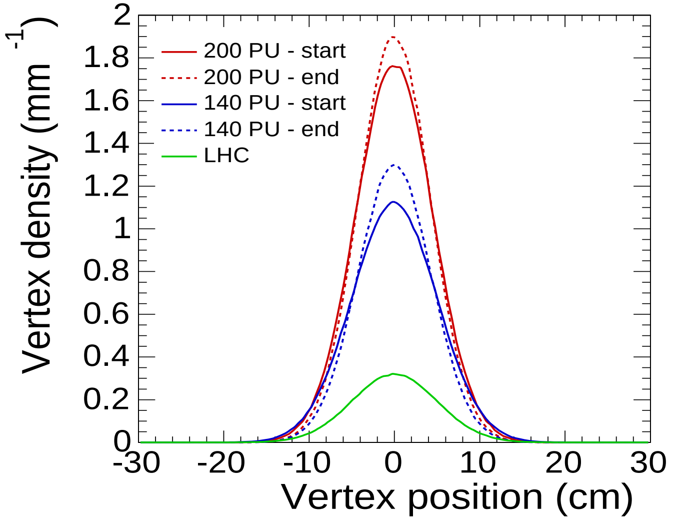


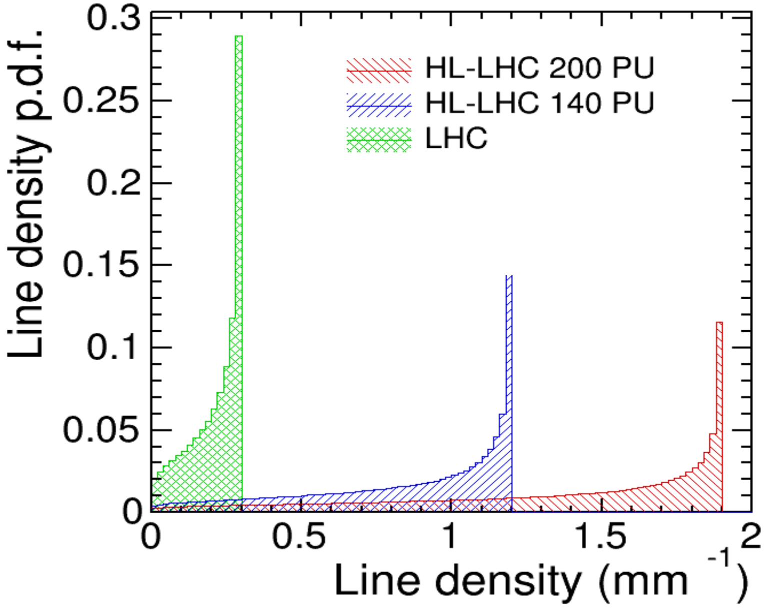
- Signals received per beam:
  - F_{rev} a.k.a. "Orbit": 11 kHz
  - Bunch clock: 40.079 MHz

Luminal Region at the LHC and HL-LHC

- **Baseline at ECFA 2016:**
  - **z_{RMS} ~ 4.8 cm start of the fill**
    ~ 4.0 cm end of the fill
  - **t_{RMS} ~ 180 ps**

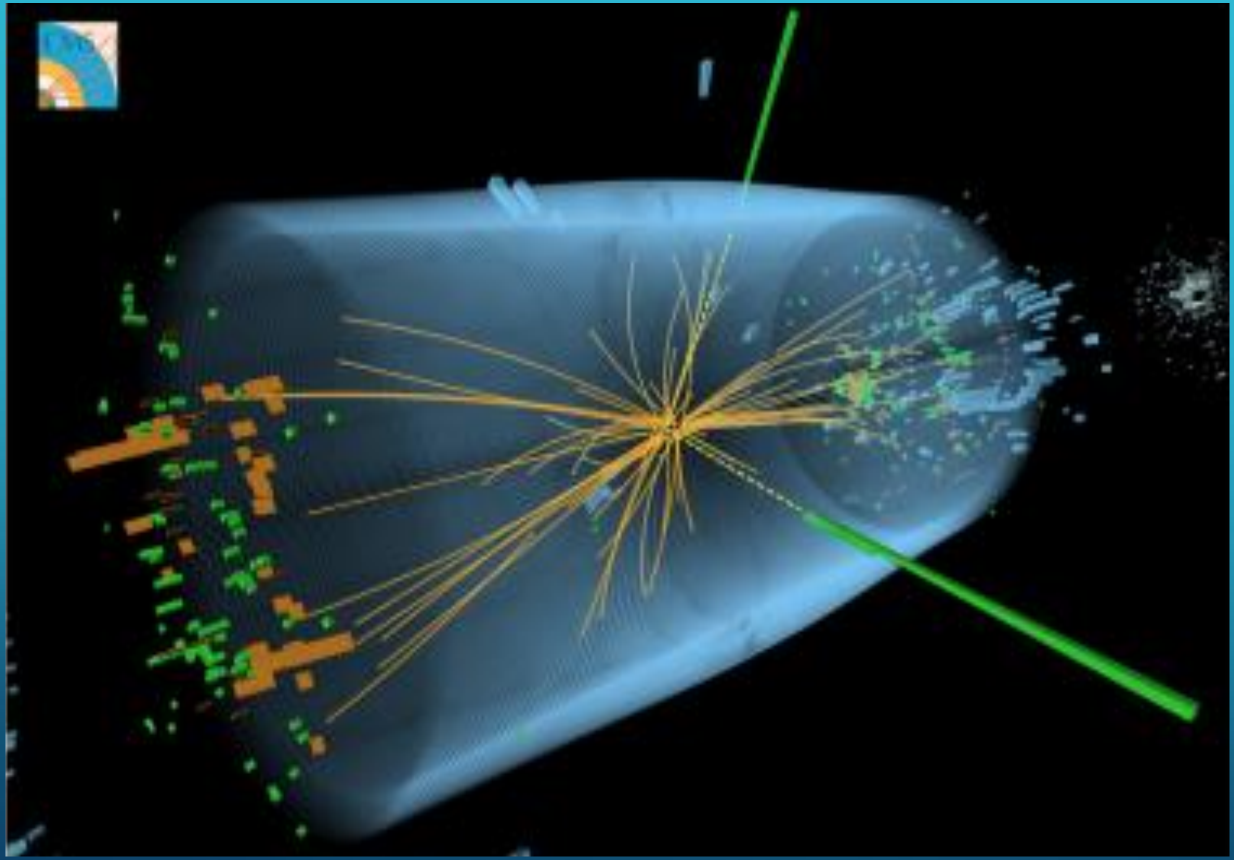




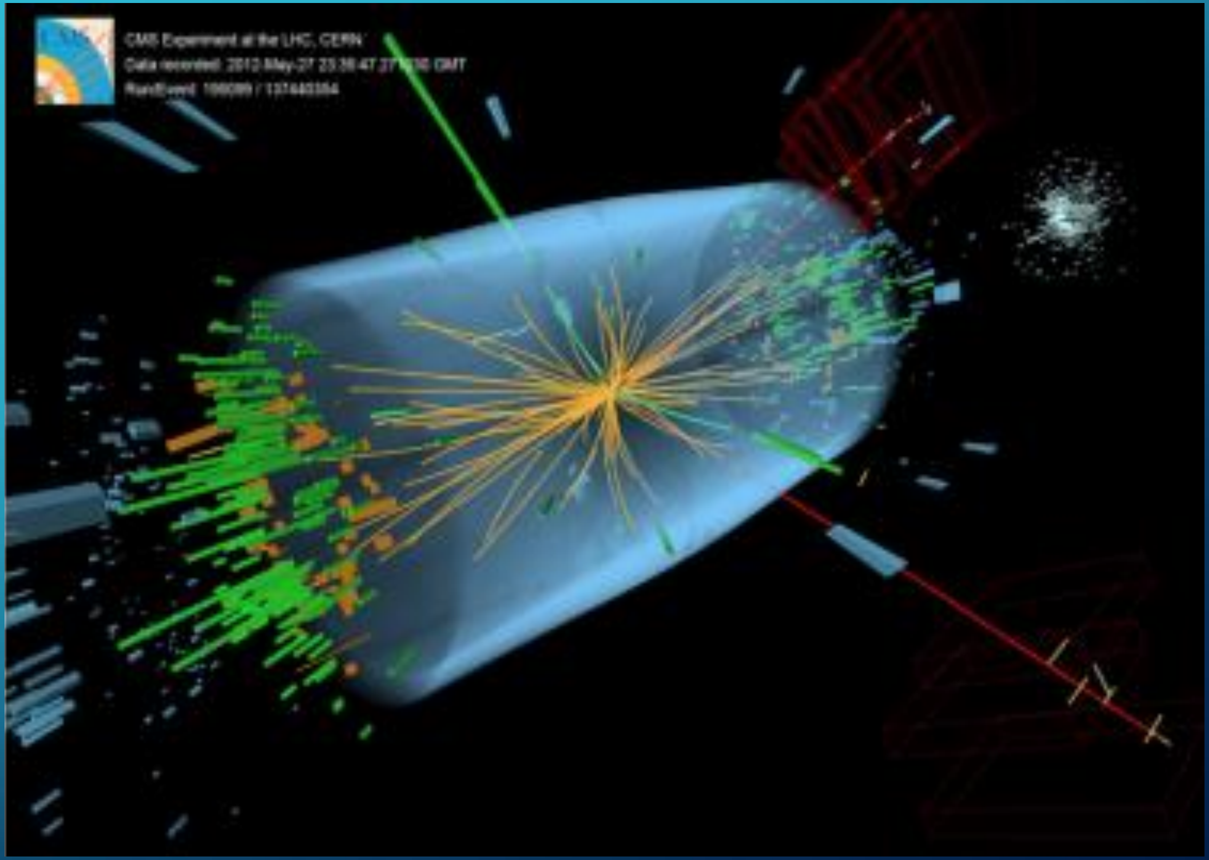


"Snapshots" of Higgs Boson Events at the LHC

$H \rightarrow \gamma\gamma$

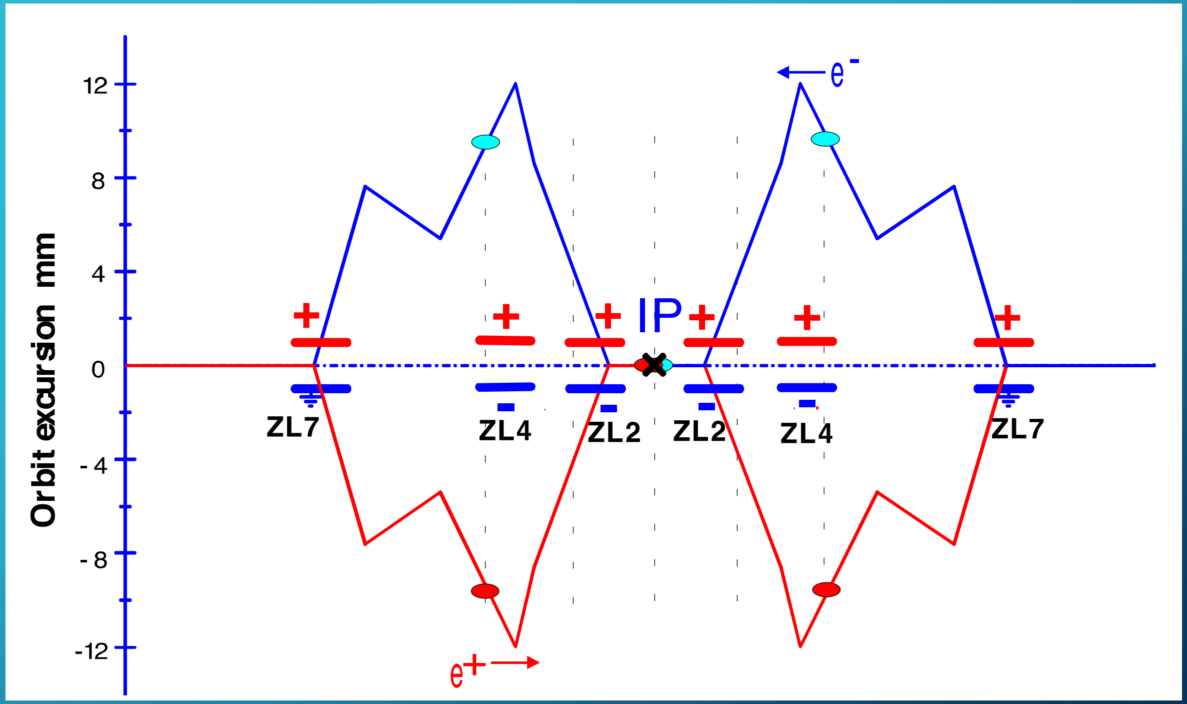


$H \rightarrow ZZ^* \rightarrow ee\mu\mu$



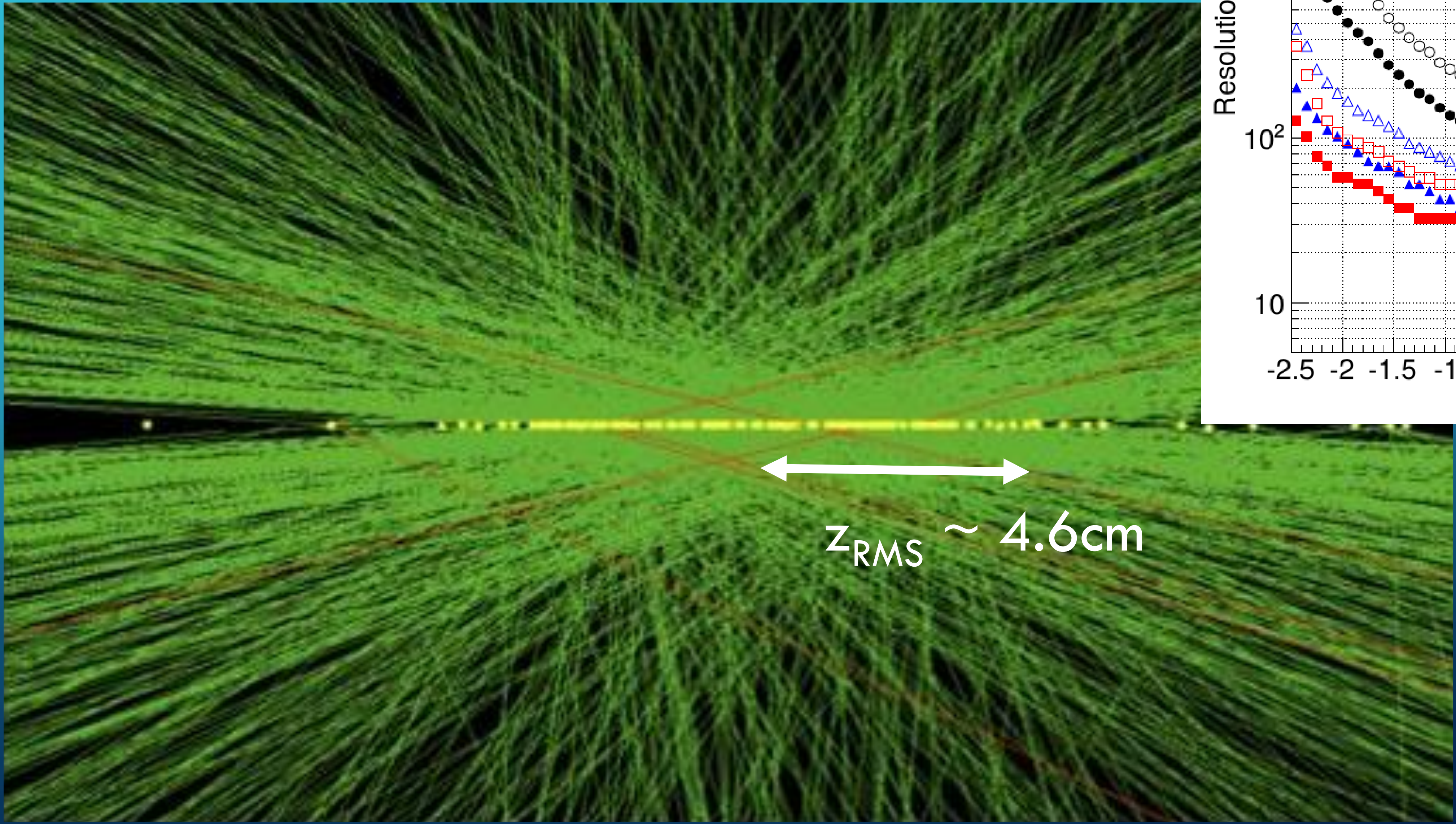
Circular Colliders and Detector Timing Measurements

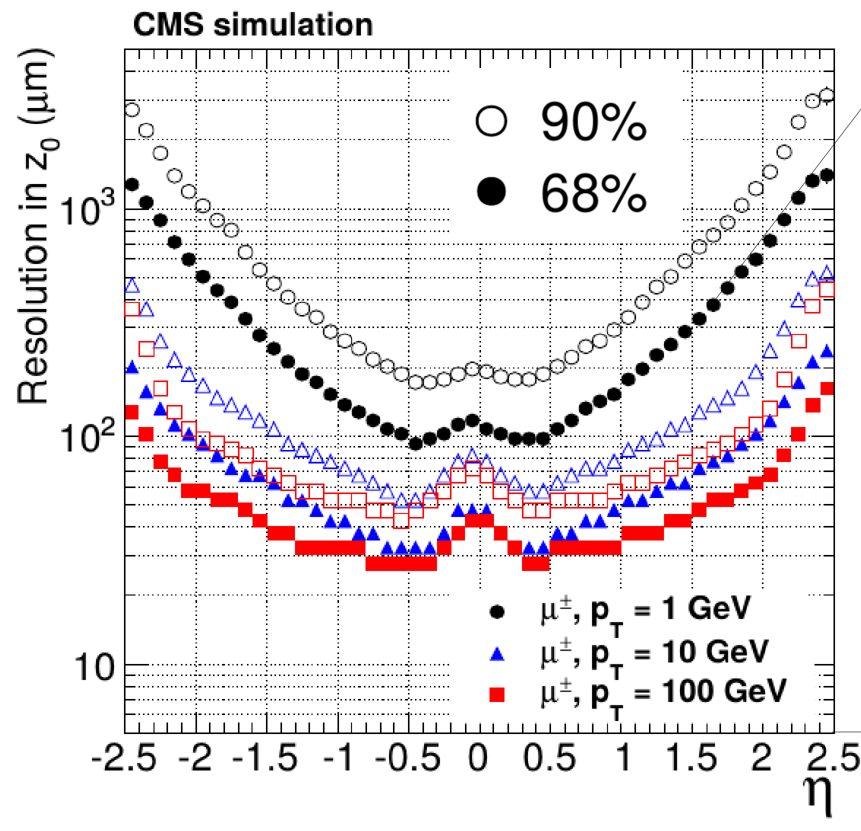
- Bunch Trains at LEP (1995)
  - Four bunch trains of up to 4 bunchlets each (spacing 247.5ns, $87\lambda_{RF}$)
  - Phase lock for synchronous BGO calorimeter readout gate (5µs)
  - Offline analysis tagged which bunchlet within a train the signal event originated from (and corrected for signal integration)
  - e^+e^- is forgiving – less than 1 event per crossing and very loose trigger (triggered on and counted single photons above 1 GeV to cross-check number of neutrino families from ISR)



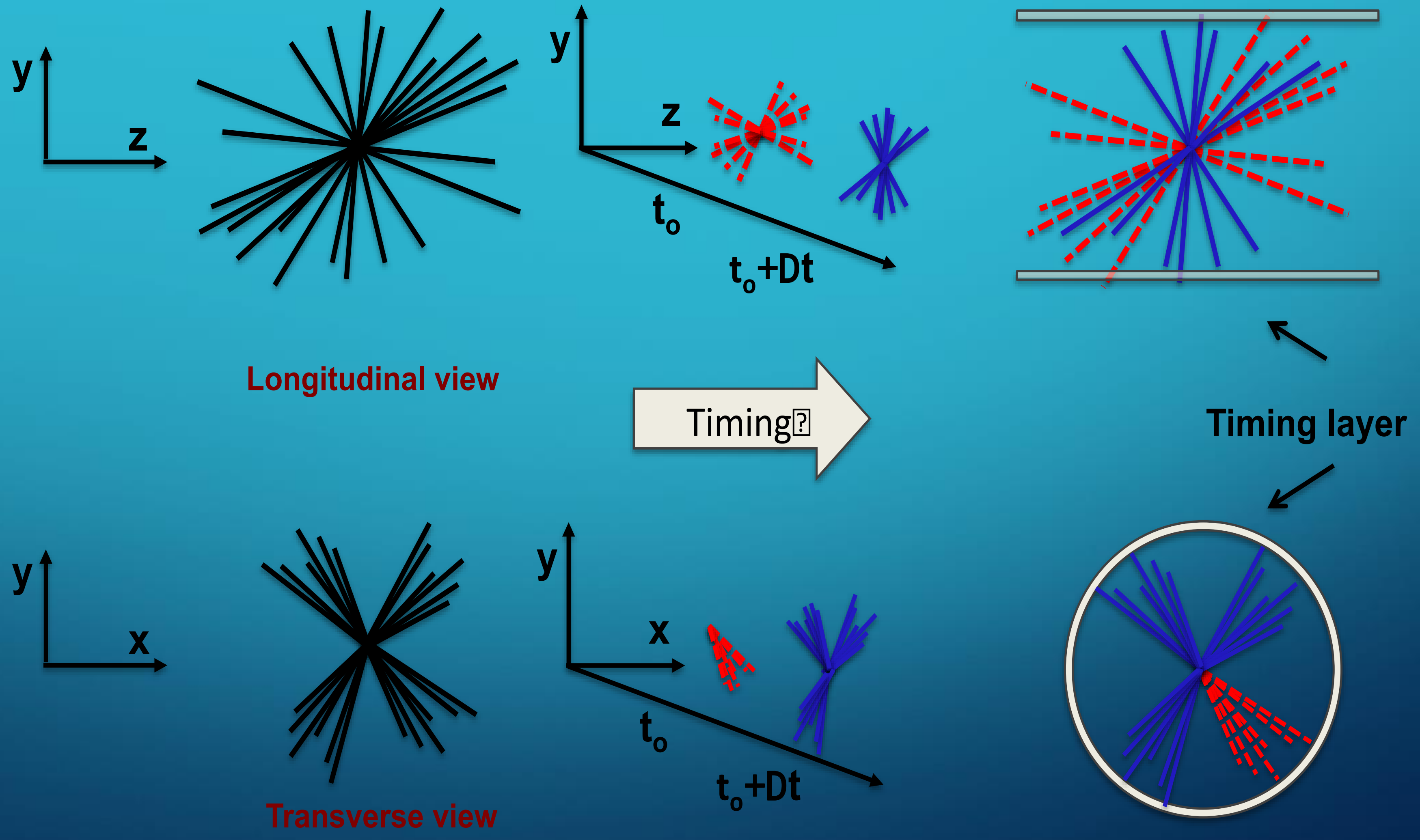
General truism: Experimentalists will do everything they can to accommodate higher luminosity operation of the collider

Signal Vertex Efficiency

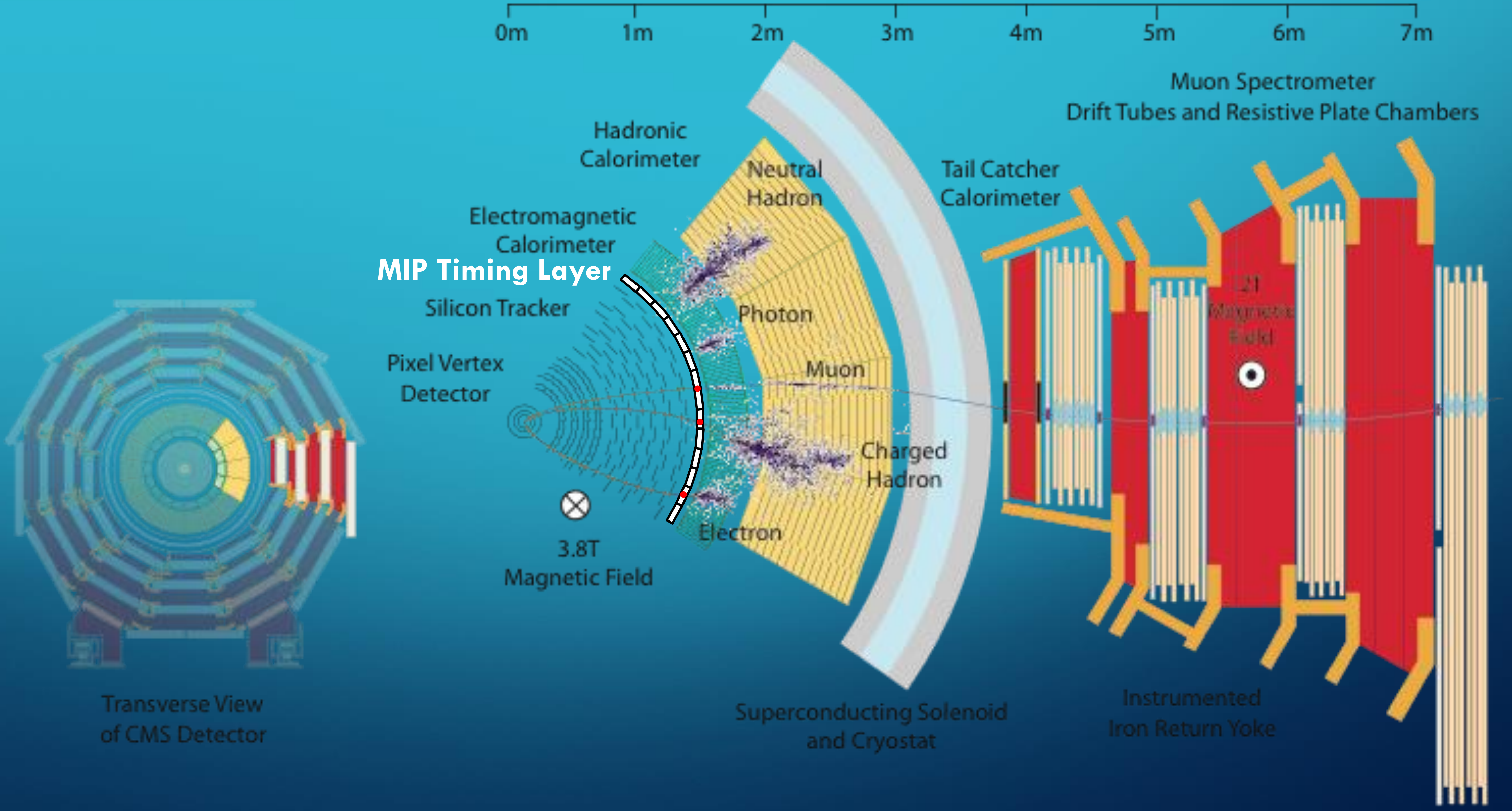




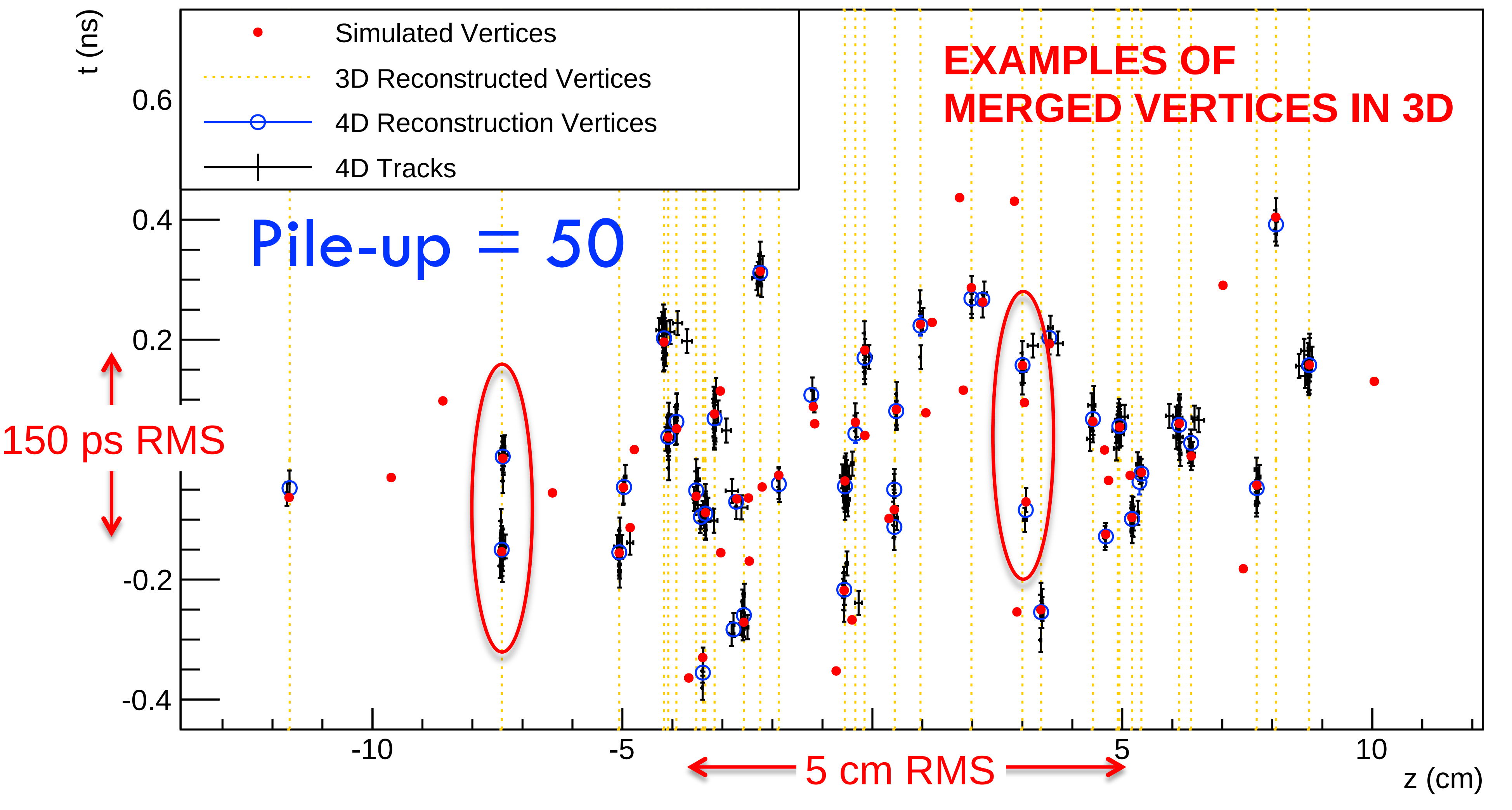
Time-Aware Vertexing



Particle-flow Event Reconstruction

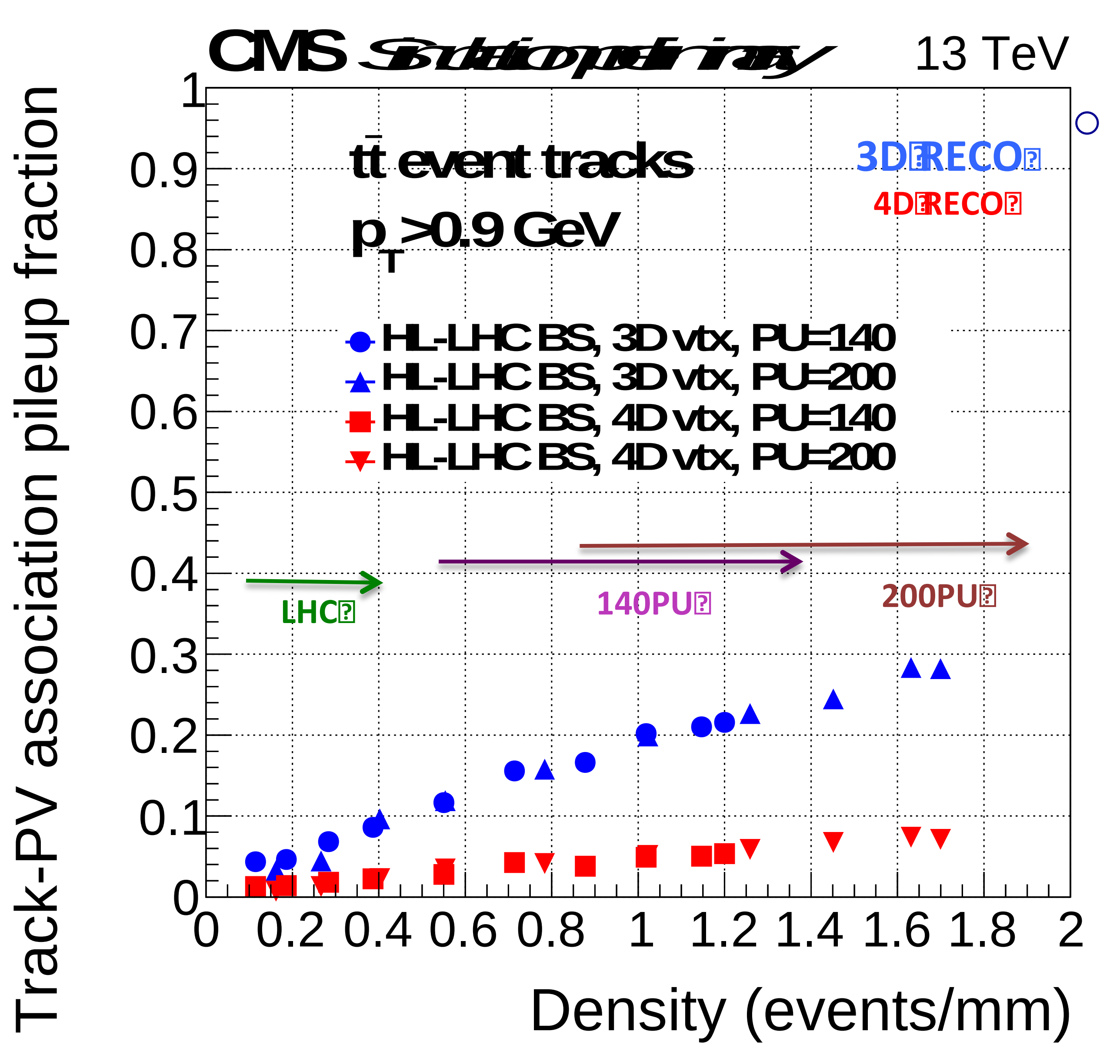


3D vs. 4D Vertex Reconstruction



- 4D reconstruction with track time information at ~25 ps

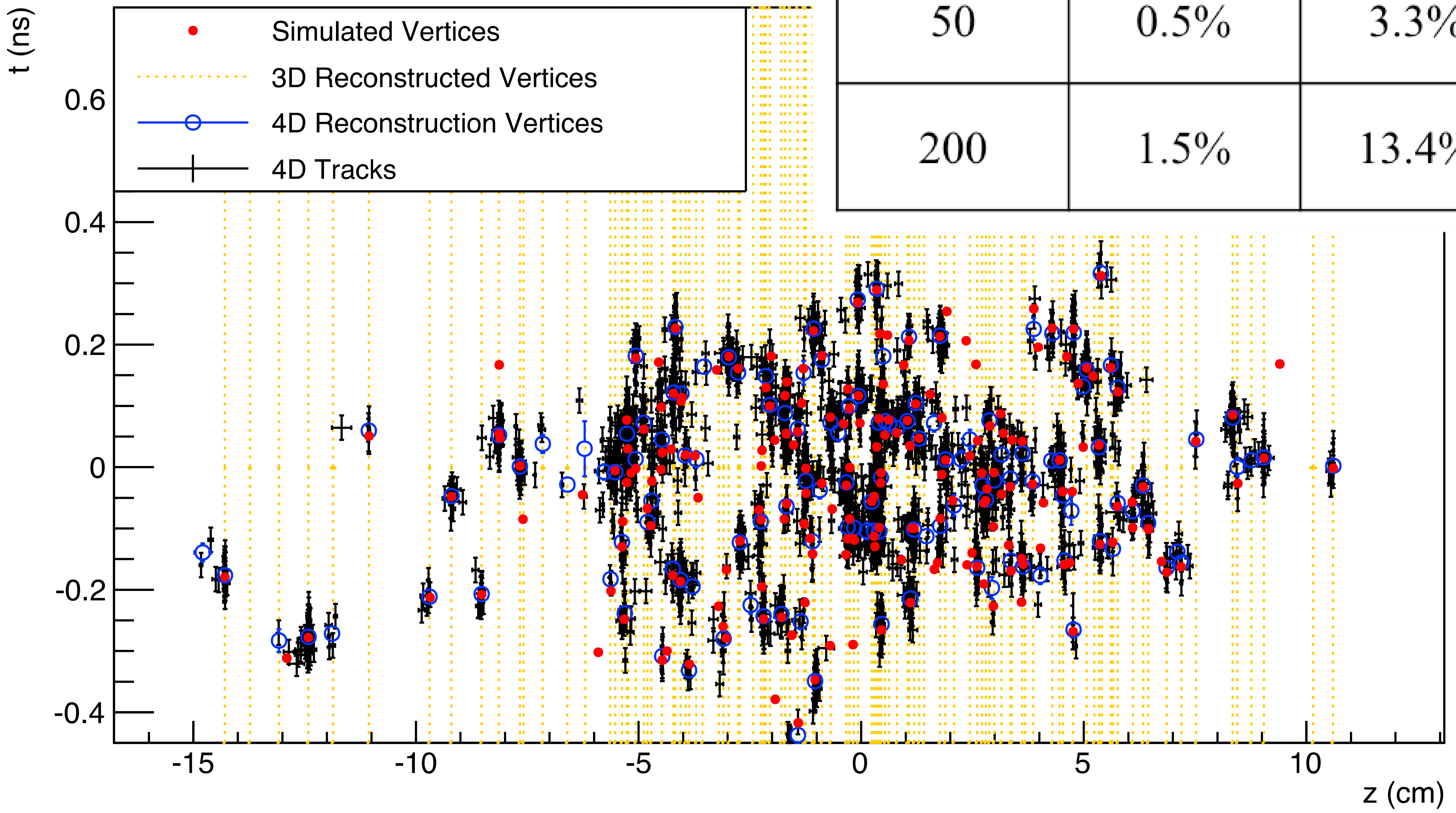
Signal Vertex Track Purity



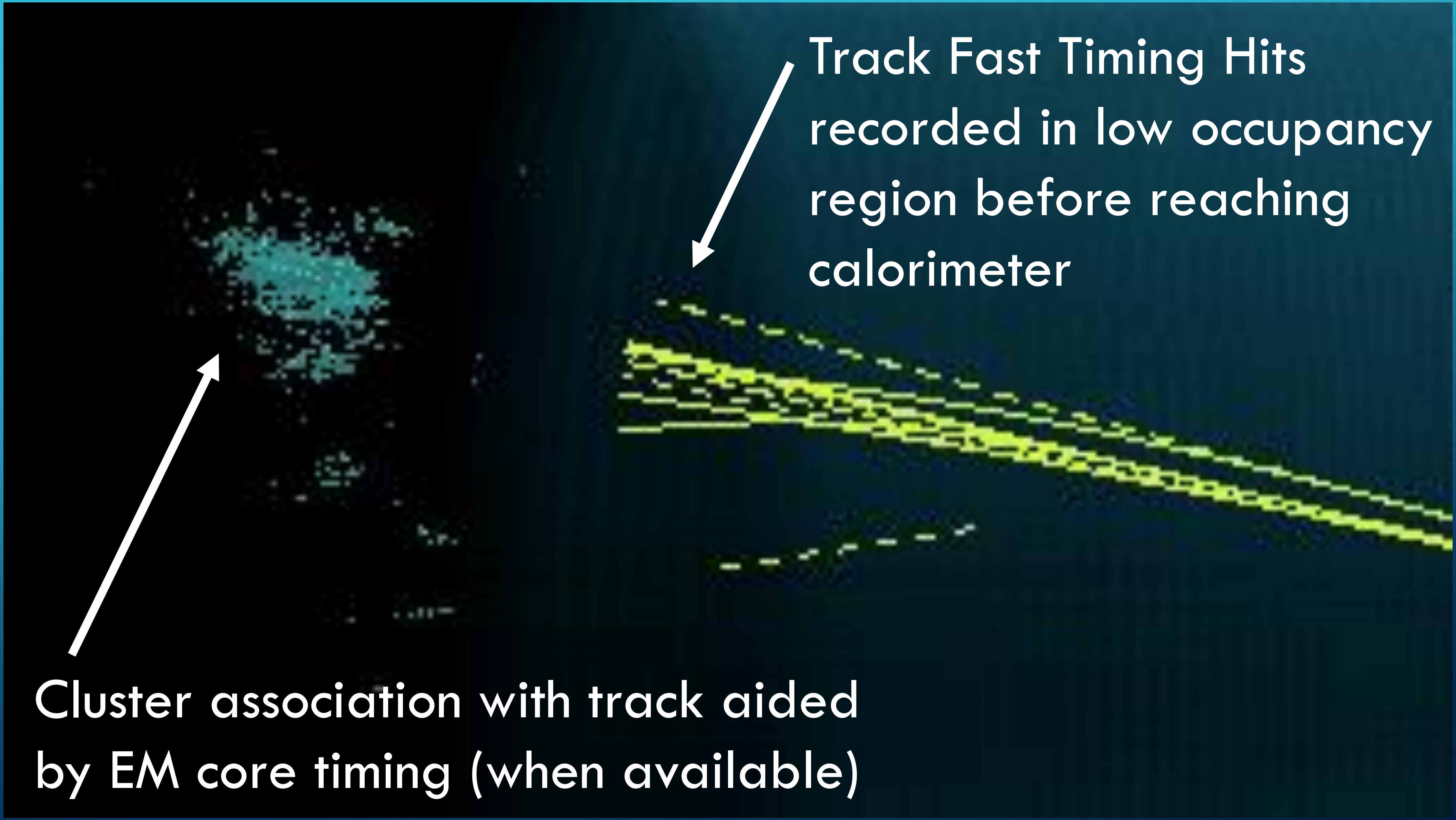
Pile-up = 200

CMS Simulation

<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

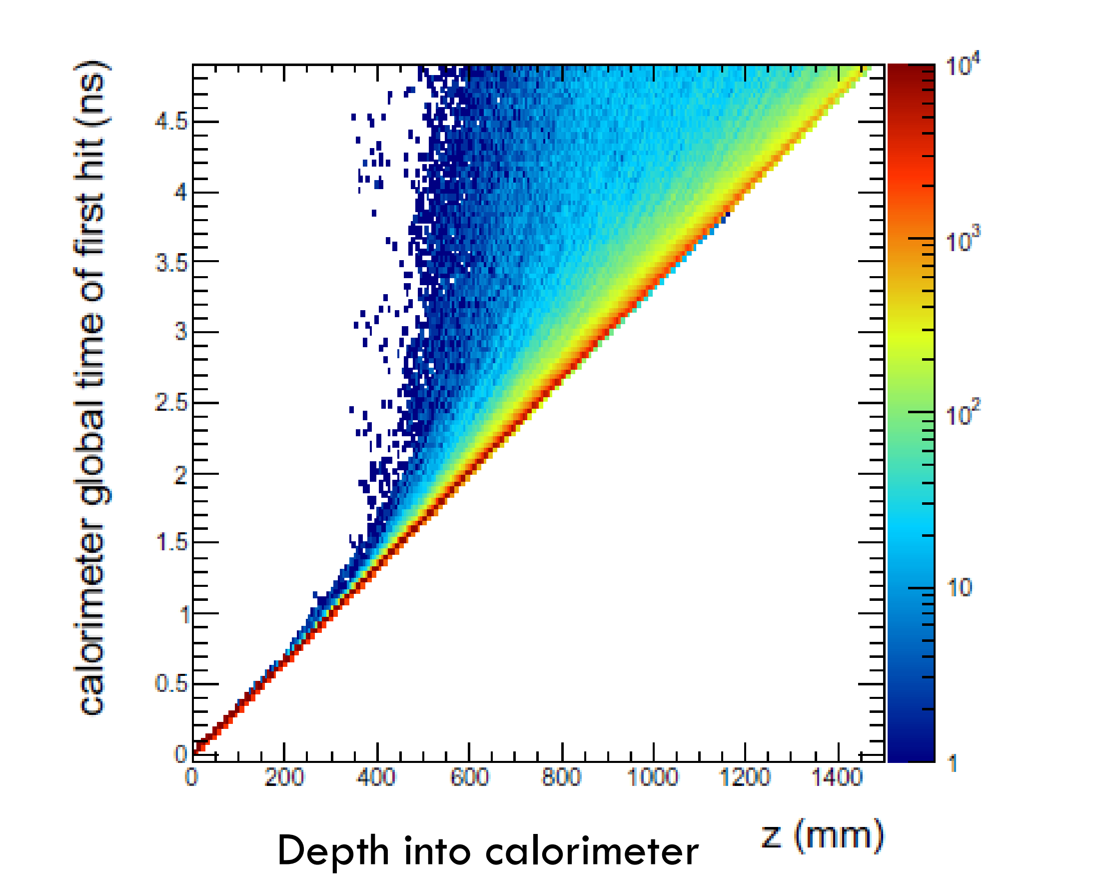


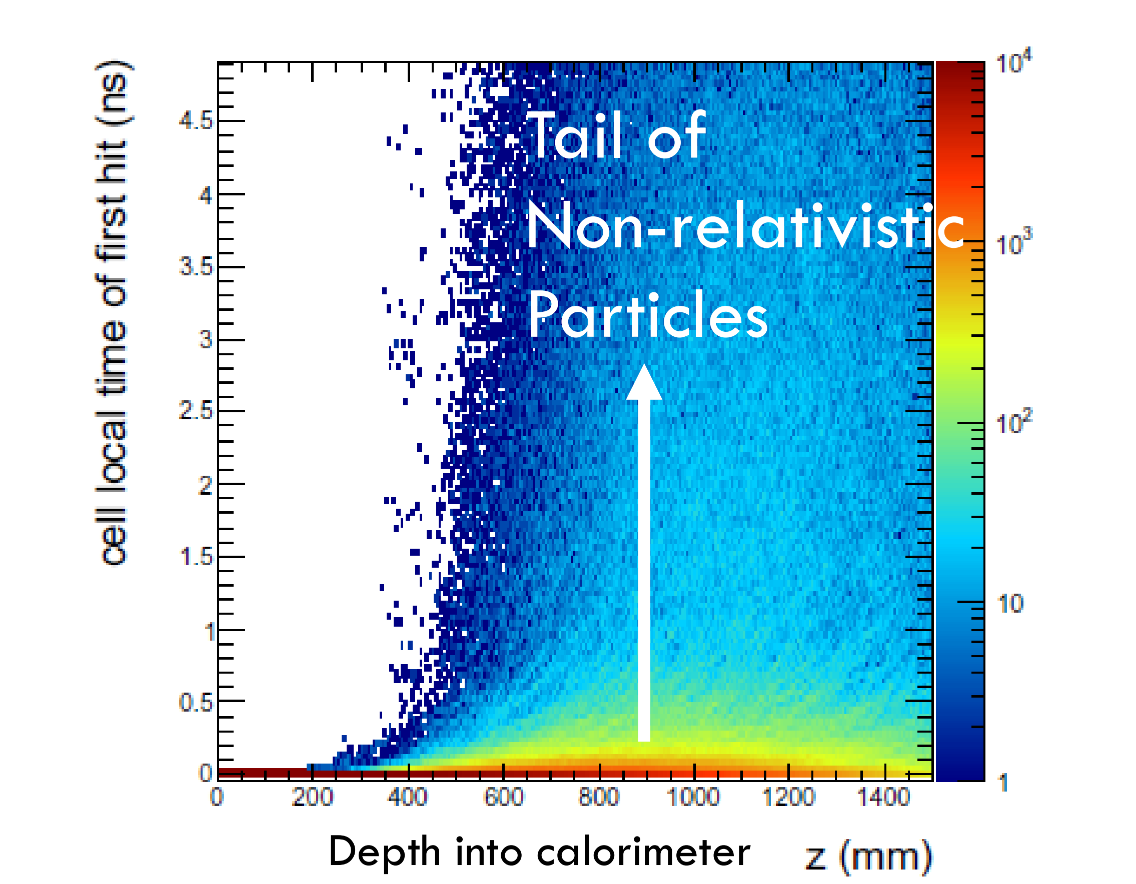
Track-Cluster Association with Timing



Time Development of Energy Deposition in Hadronic Showers

A. Para (CALOR 2016)



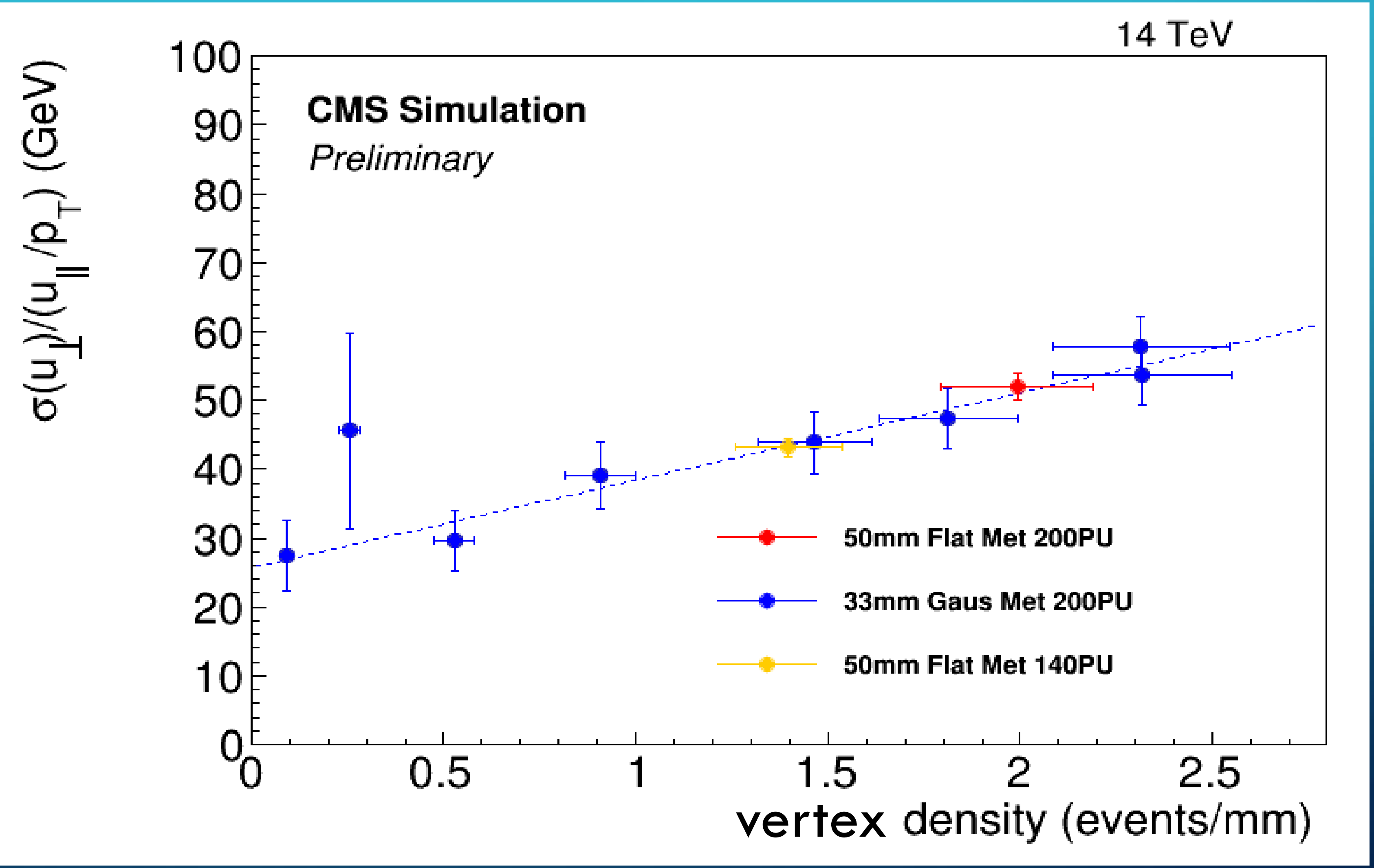


At nsec scale the timing is dominated by geometry (time of flight) even for hadronic showers.

'Local' time = T – z/c

Dual-Gate Calorimeter (TOF within hadronic shower for energy compensation.

Missing Transverse Energy Resolution vs. Vertex Density



Summary – Lecture 1

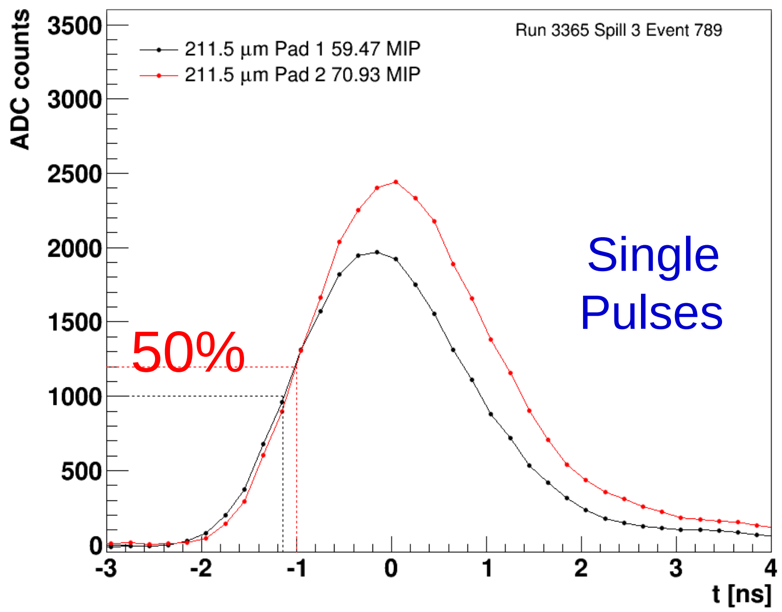
- Fast timing resolutions that are a factor 5-10 smaller than the timing spread of the beam collisions open up new capabilities for collider detectors at the HL-LHC
- Time-Aware Vertex Algorithms pull apart collision vertices in the time domain.
- Signal Vertex Track Purity grows to an order one problem without fast timing
- Particle-flow methods at the HL-LHC are directly degraded by track purity loss in the primary vertex – further enhancement of timing in the calorimeters will benefit track-cluster association and provide neutral EM timing

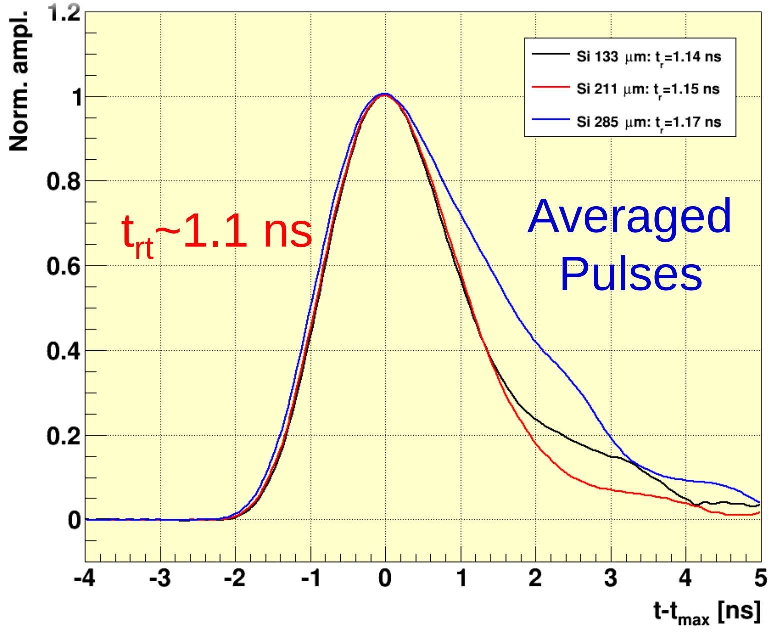
Backup

Event "snapshots" at the LHC

- Timing at the LHC was not an immediate concern for Run 1
  - Triggers identify events that are low probability for pp collisions
    - Include high-pT leptons, photons, jets, MET
  - With increasing instantaneous luminosity, triggers tighten ID/isolation and require multiple trigger objects and bring in additional kinematical or topological requirements
    - If you know what you are looking for, then this tightening is straight-forward and known signals are evaluate for efficiency with Monte Carlo and existing data are evaluated to extrapolate the rates for higher luminosities

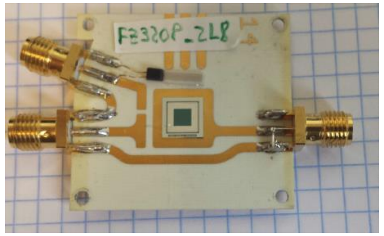
Silicon Devices with no gain

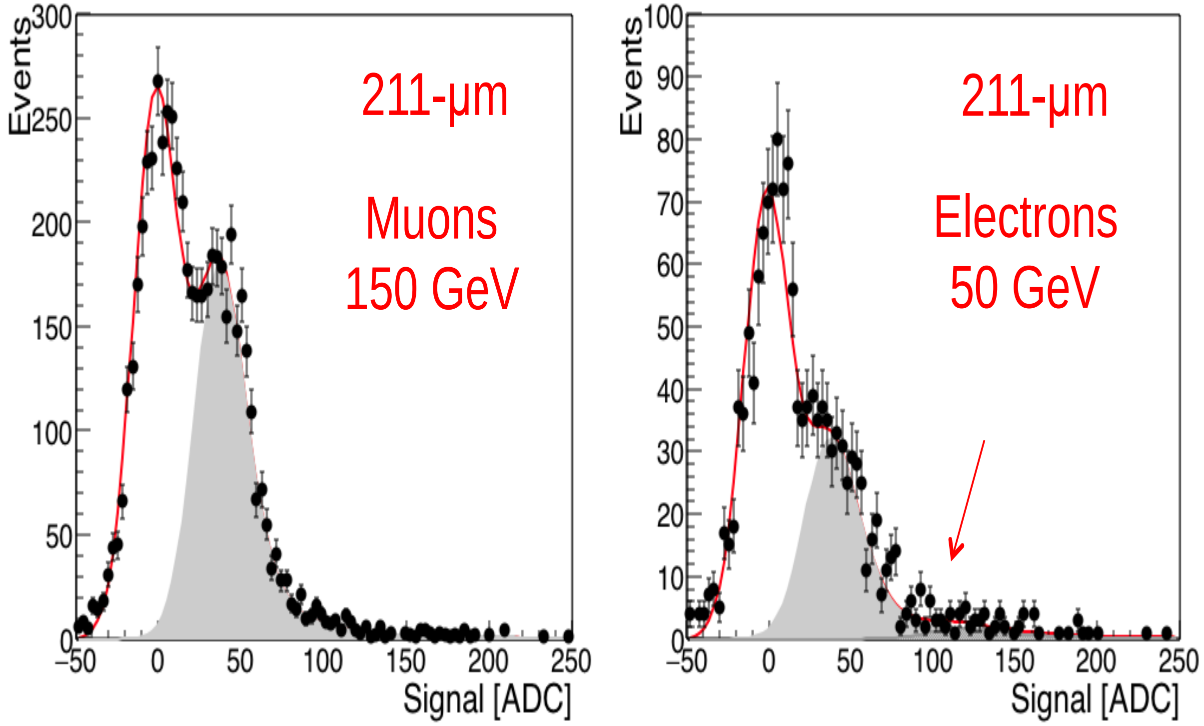




Two sensors of the same type tested at the same time:

- 133, 211 and 285 µm depletion thickness (capacitance 22.5, 13.6, and 9.9 pf)
- *n*-on-*p* FZ-dd sensors with 5×5 mm^2 sensitive area from Hamamatsu
- 400, 600, and 700 V (nominally at 600 V) fully depleted bias
- Cividec broadband amplif er (2 GHz, 40 dB)
- 1 ADC count = 0.25 mV
- Noise level ~ 2 mV



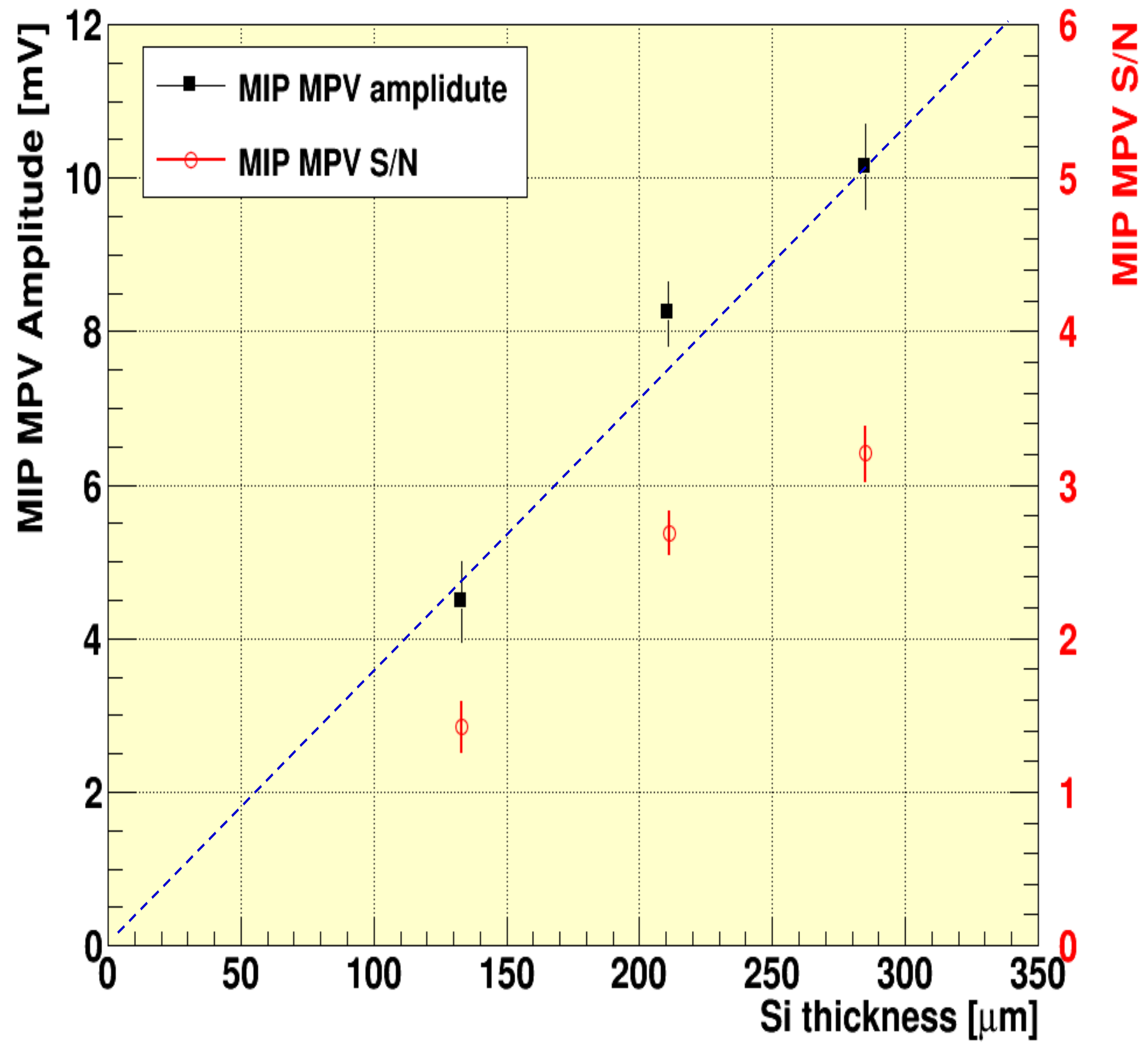


Noise was modeled by a Gaussian centered at zero

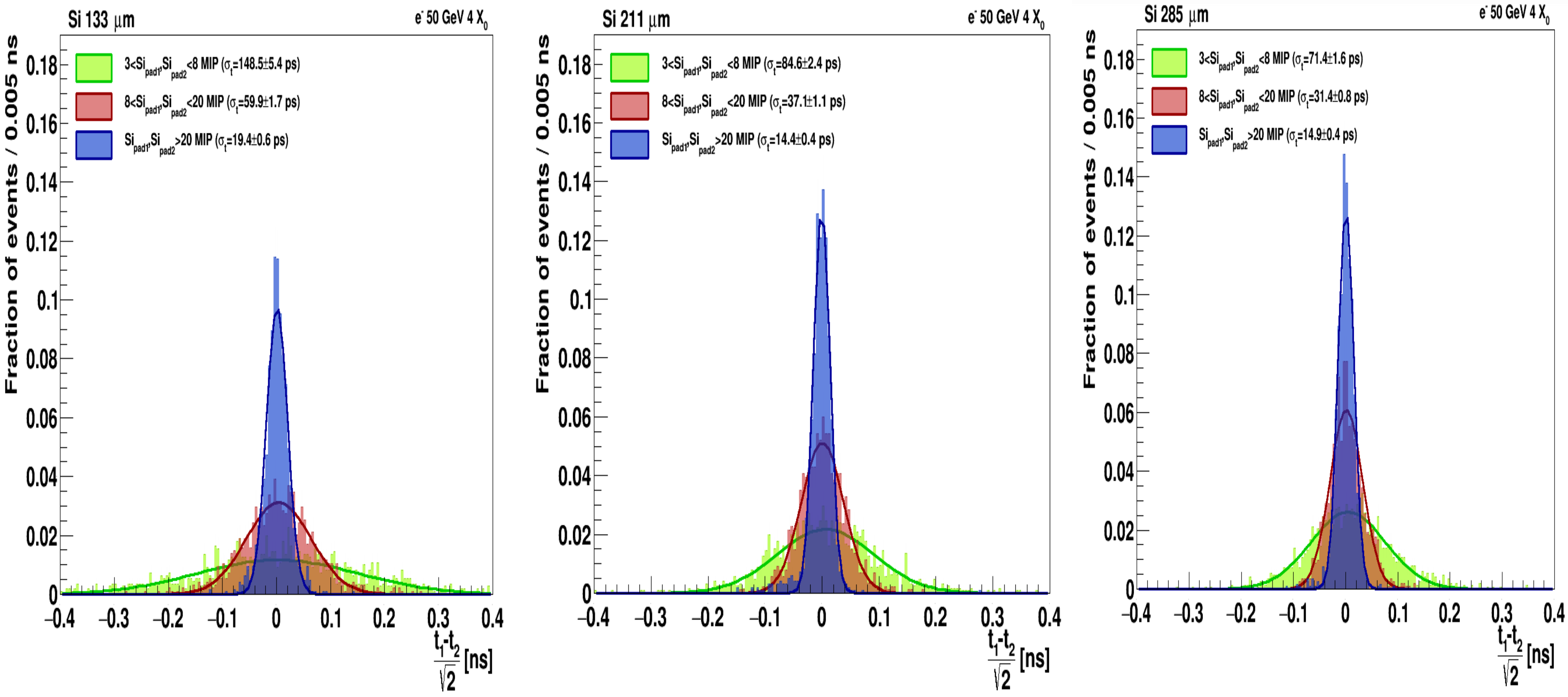
Events selection required signals from MCP and the back sensor

Single MIP (Landau MPV) ~ 34.4 ADC counts

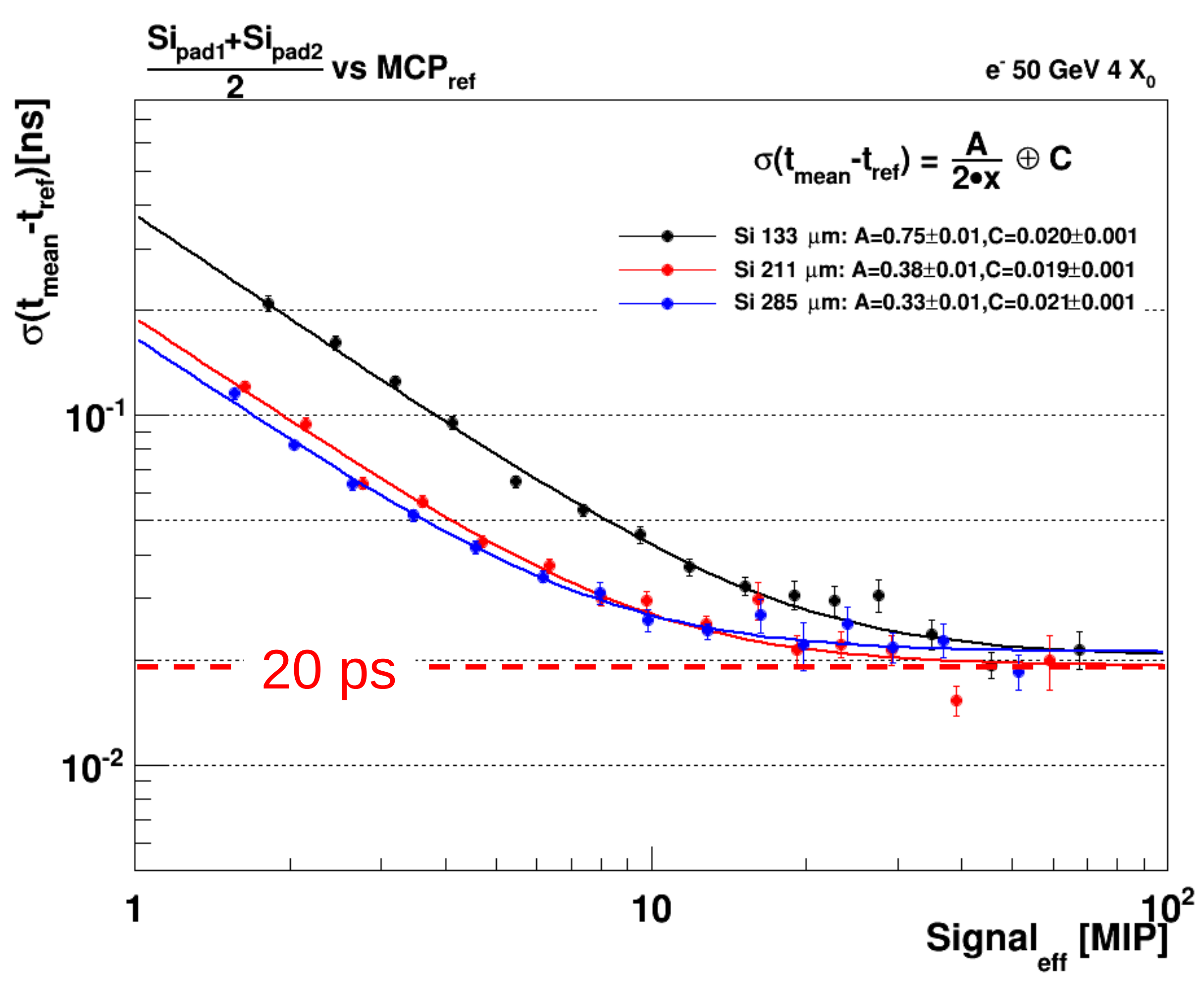
3-MIP events visible in electron sample

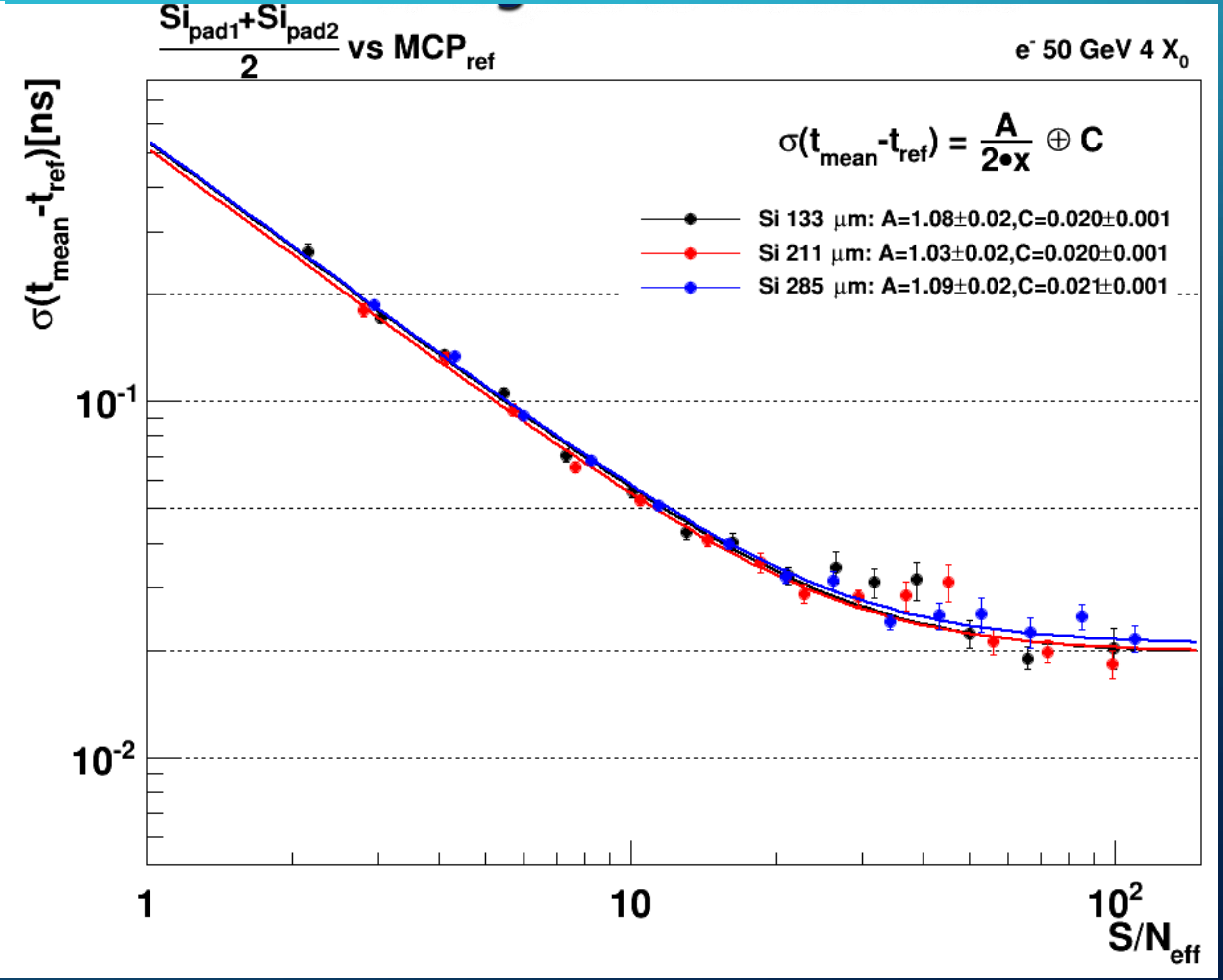


Timing Resolution depends on amplitude of signal

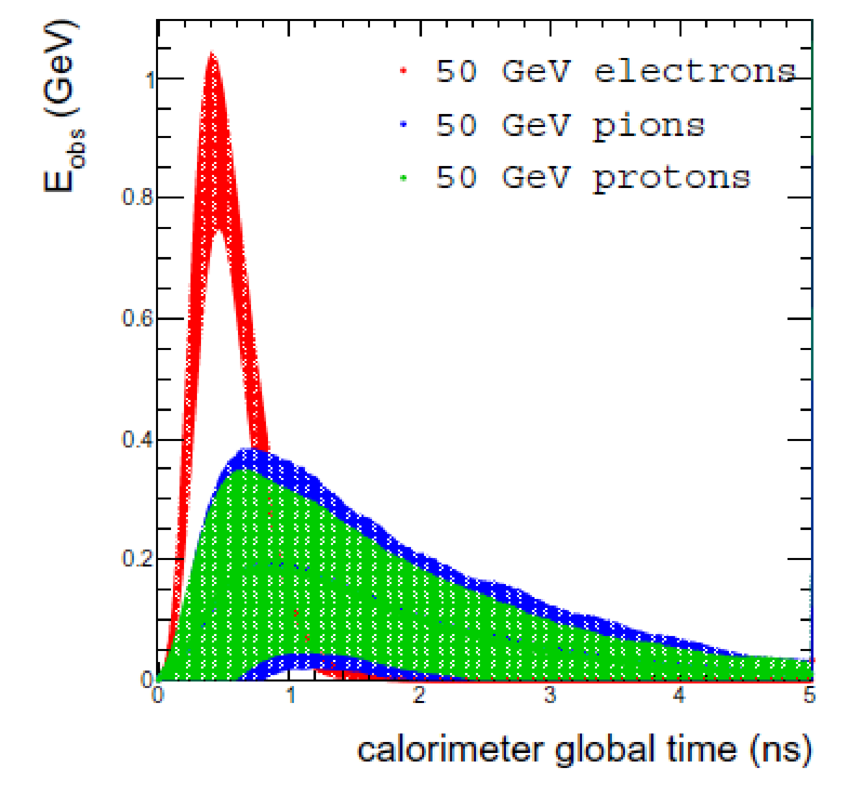


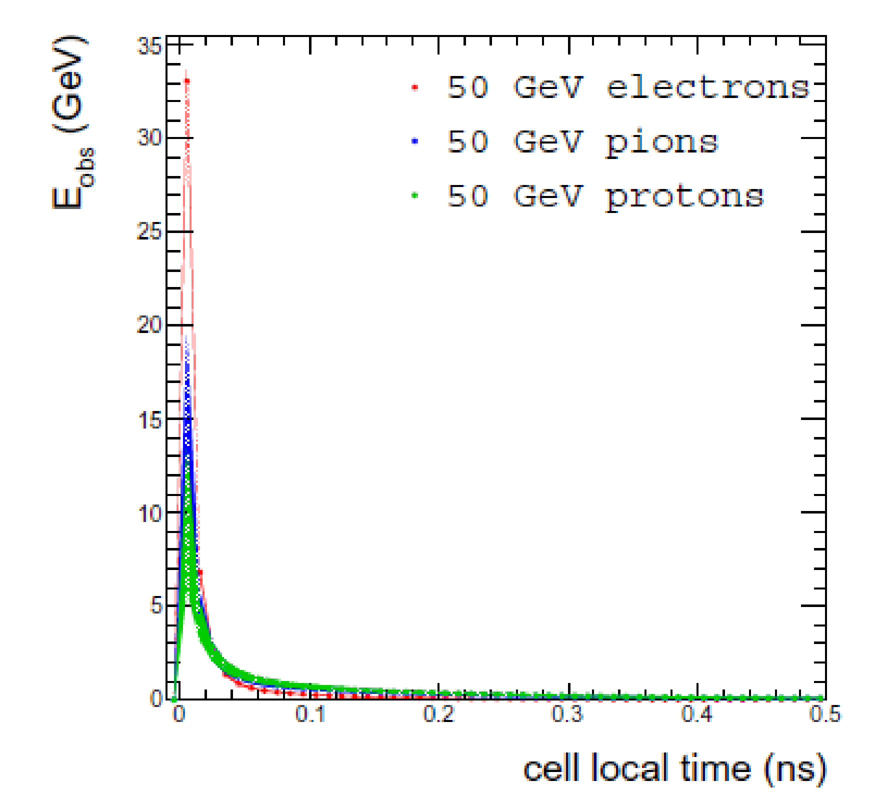
Silicon device timing





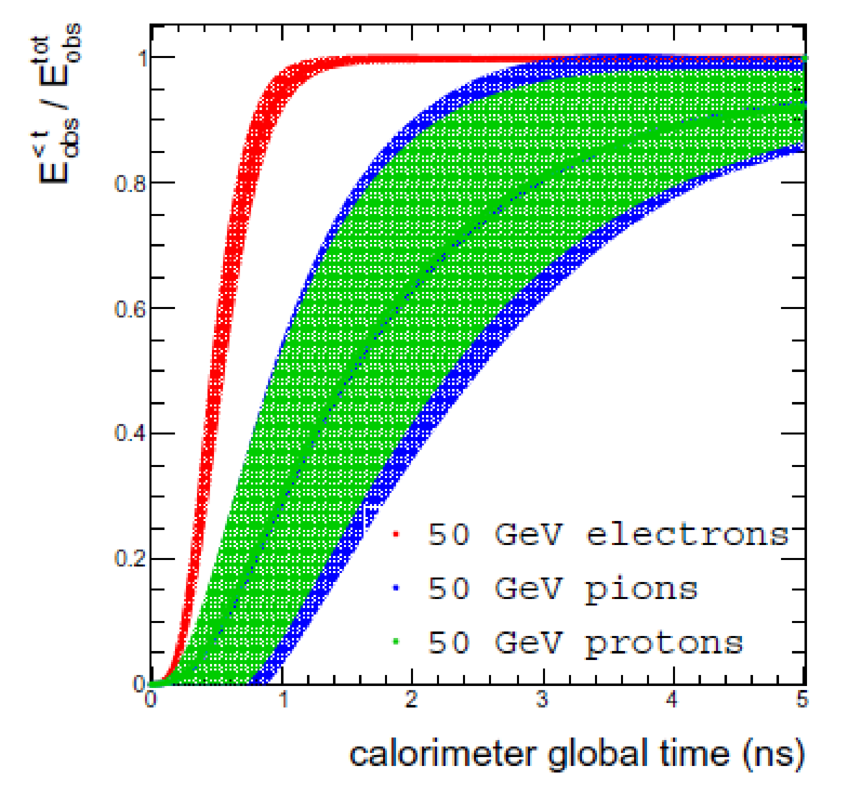
Fast Component of Showers

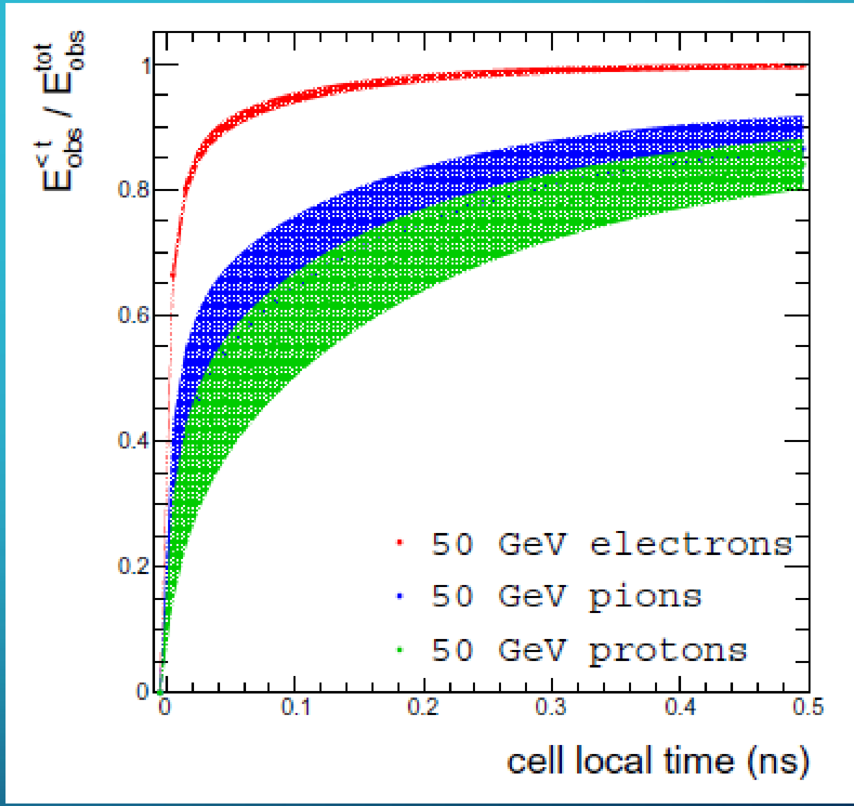




After the time-of-flight correction the core of the shower develops at the time scales of tens of picoseconds. Even for hadronic showers.

Fast Component of Showers





About 80% (on average) of the energy of hadronic showers is deposited within 0.5 ns)