T3B Update

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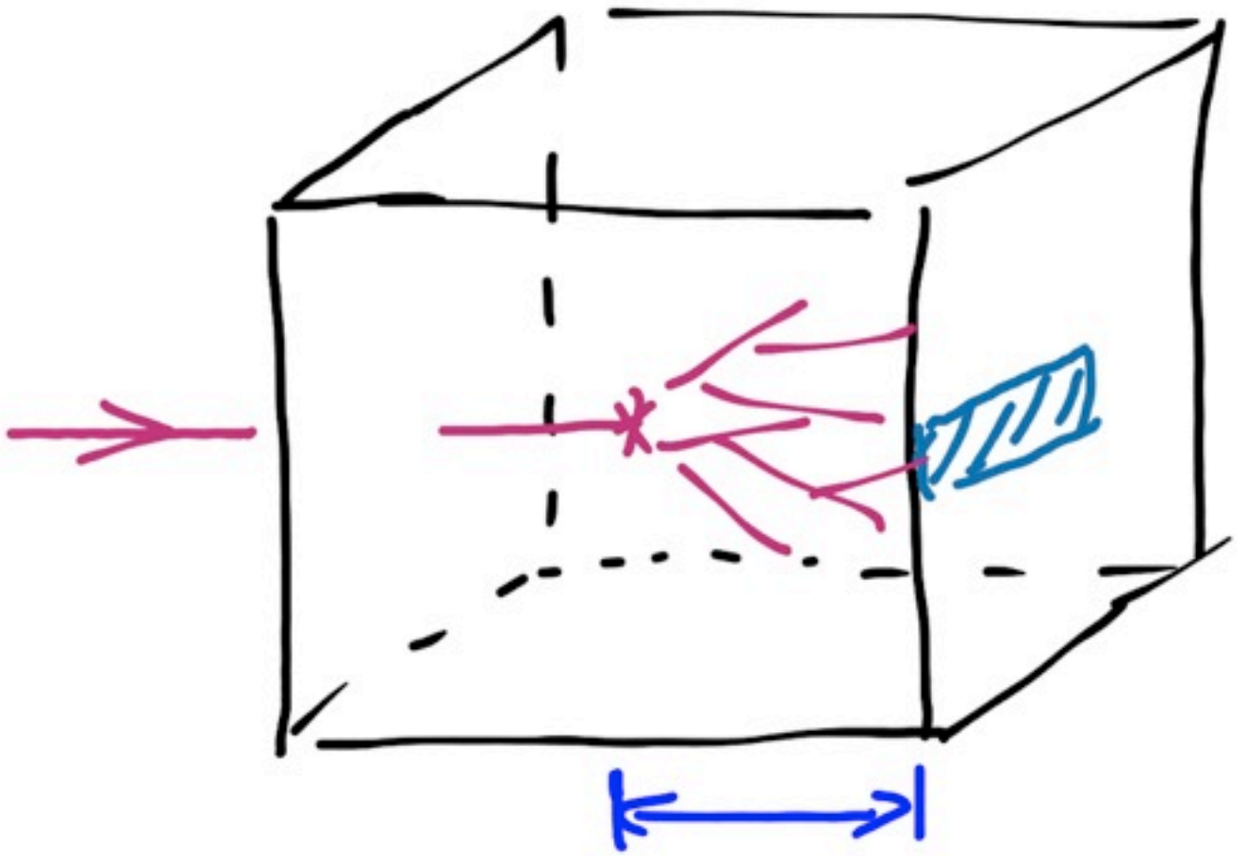
Outline

- Shower Profiles as a Function of Time
- Beyond the Time of First Hit
- Proton / Pion differences

Adding a 4th Dimension: Depth

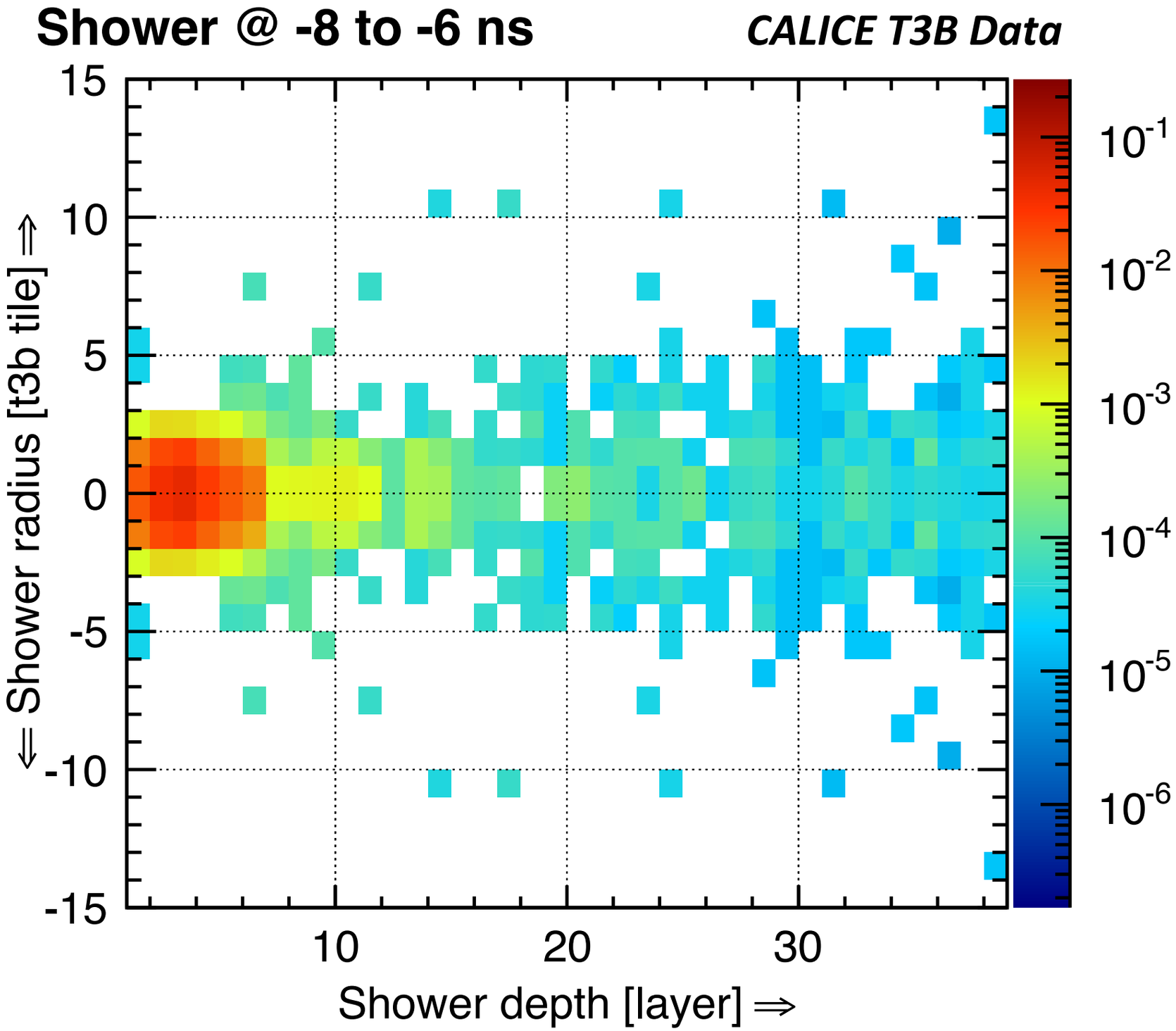
- Correlation of T3B and WAHCAL events provides a powerful addition:



- Event-by-event measurement of the depth of T3B relative to the shower start
- By combining large data samples, the average time structure of hadronic showers can be measured over a depth of 5 λ_I

- 4D shower images with unprecedented granularity

Visually the most spectacular Result: The Movie



T = 0: Activity maximum in layer 39
(rear of calorimeter)

Shown: First hits in each cell only

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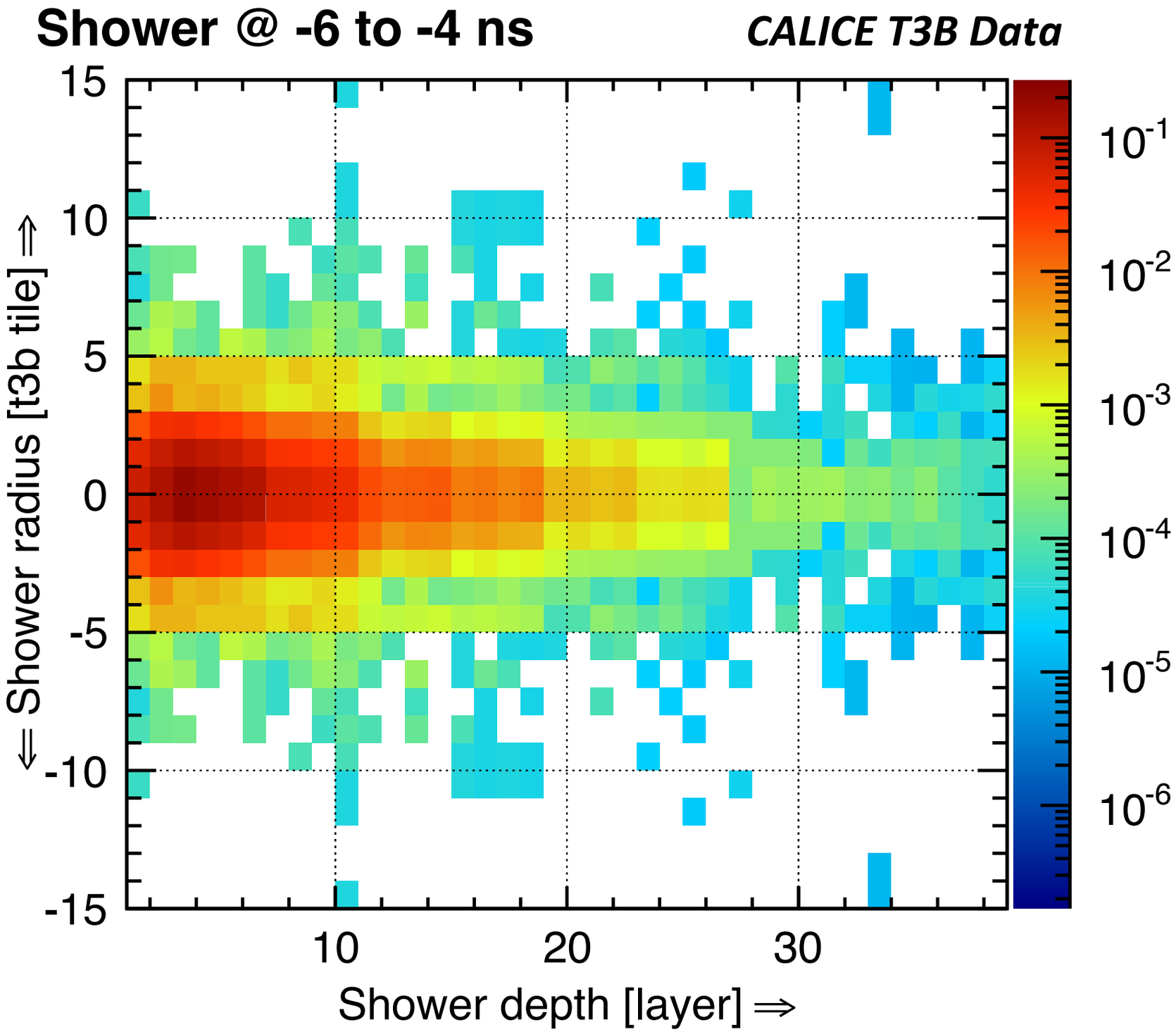

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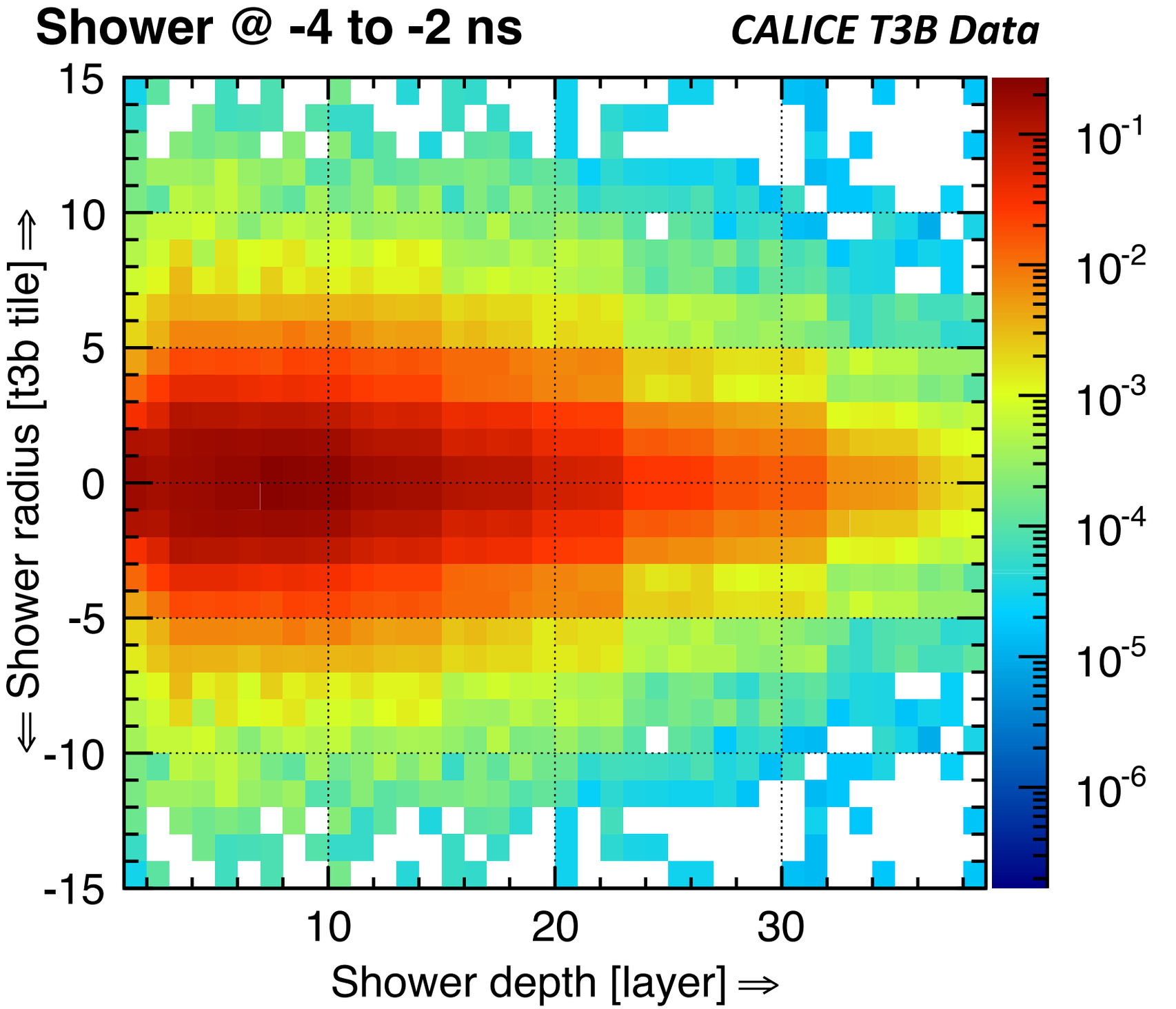

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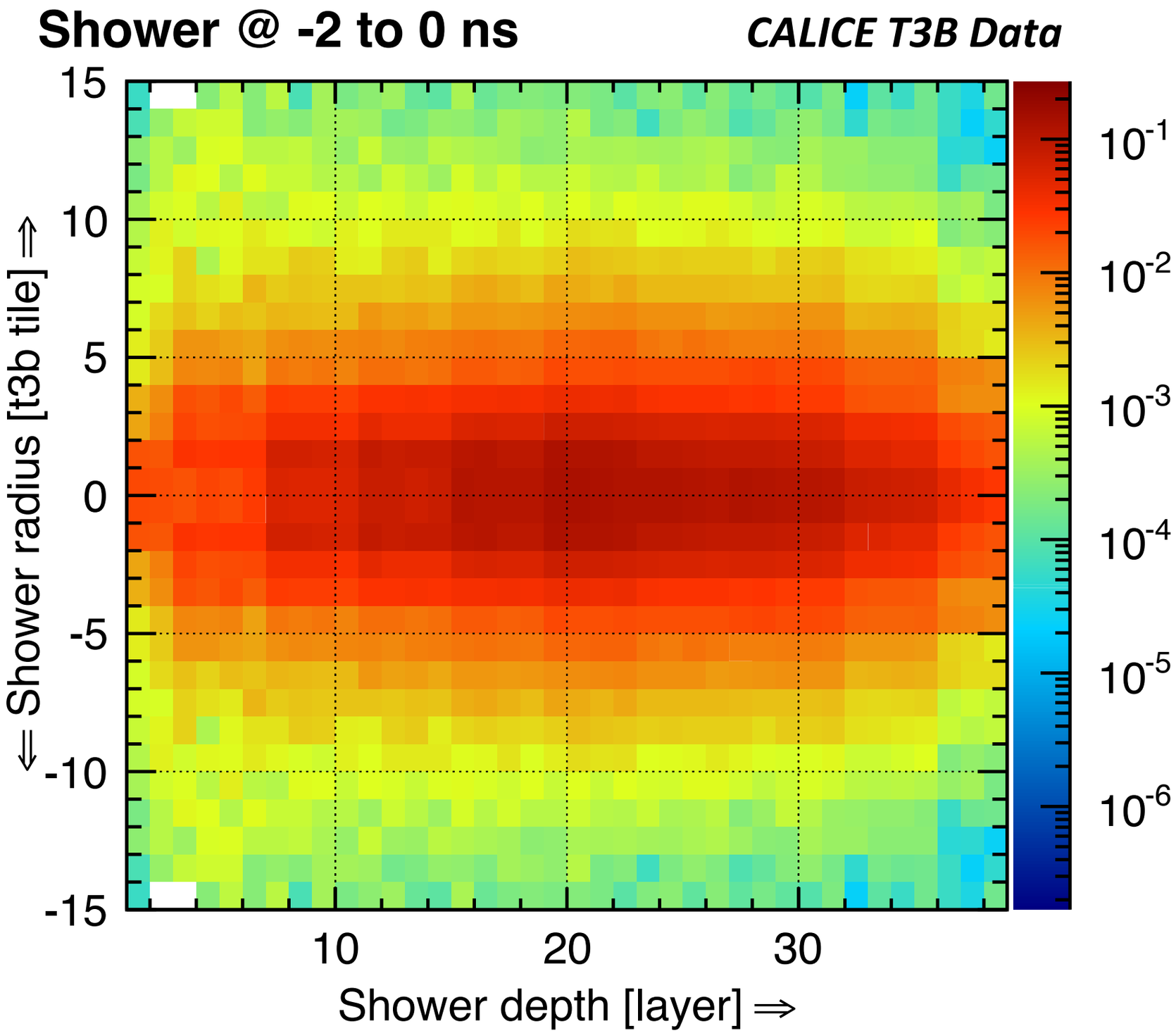

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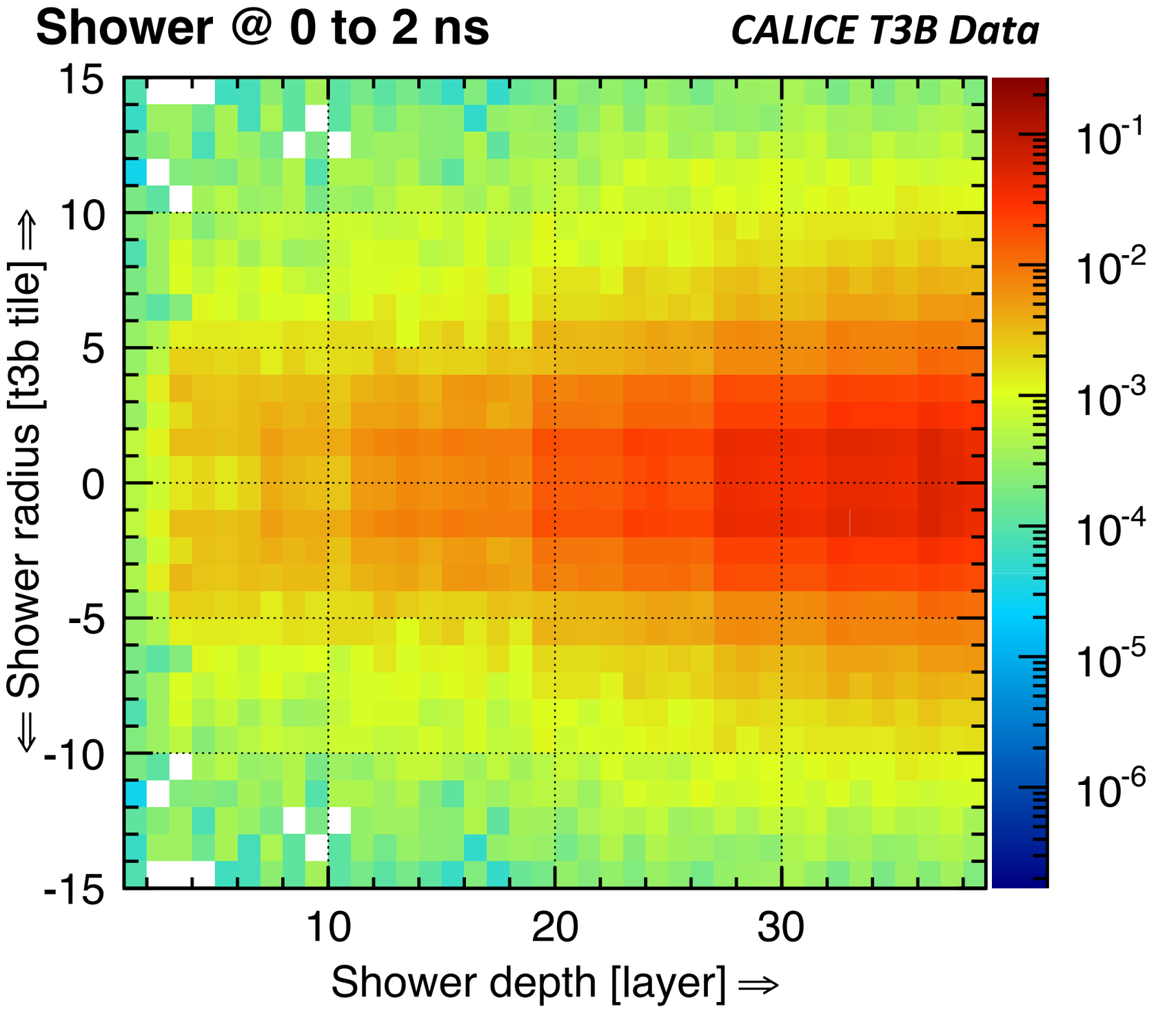

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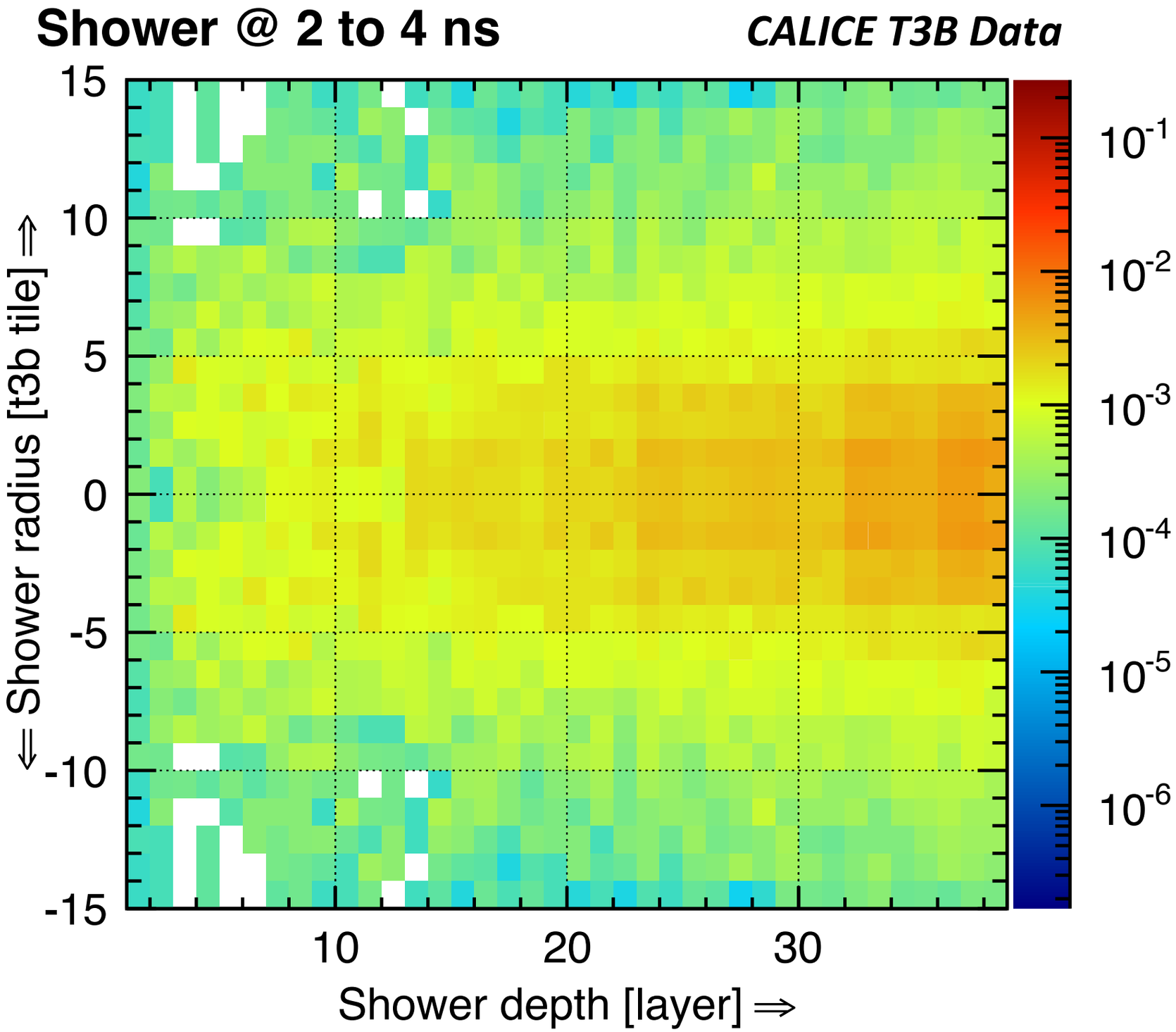

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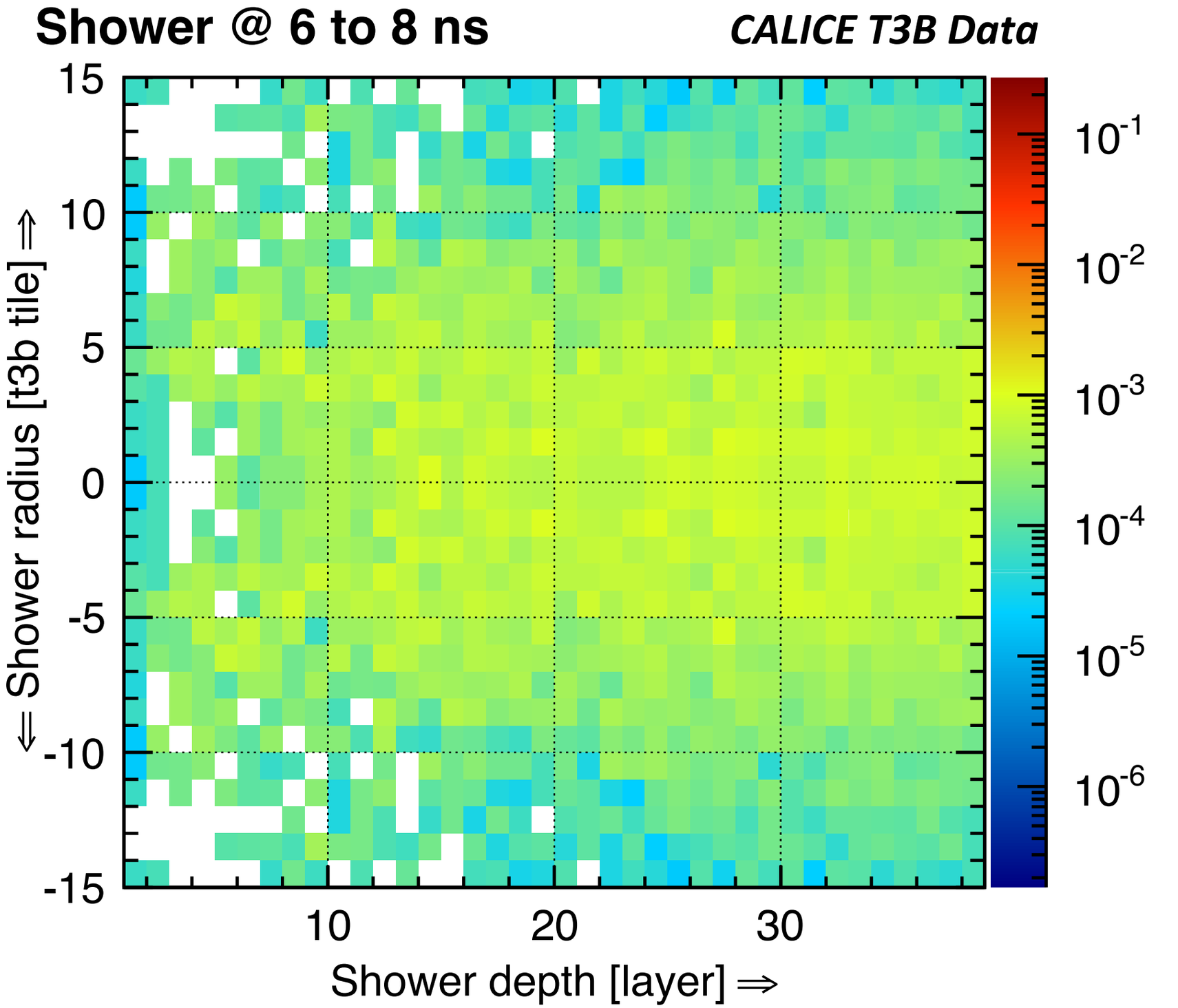

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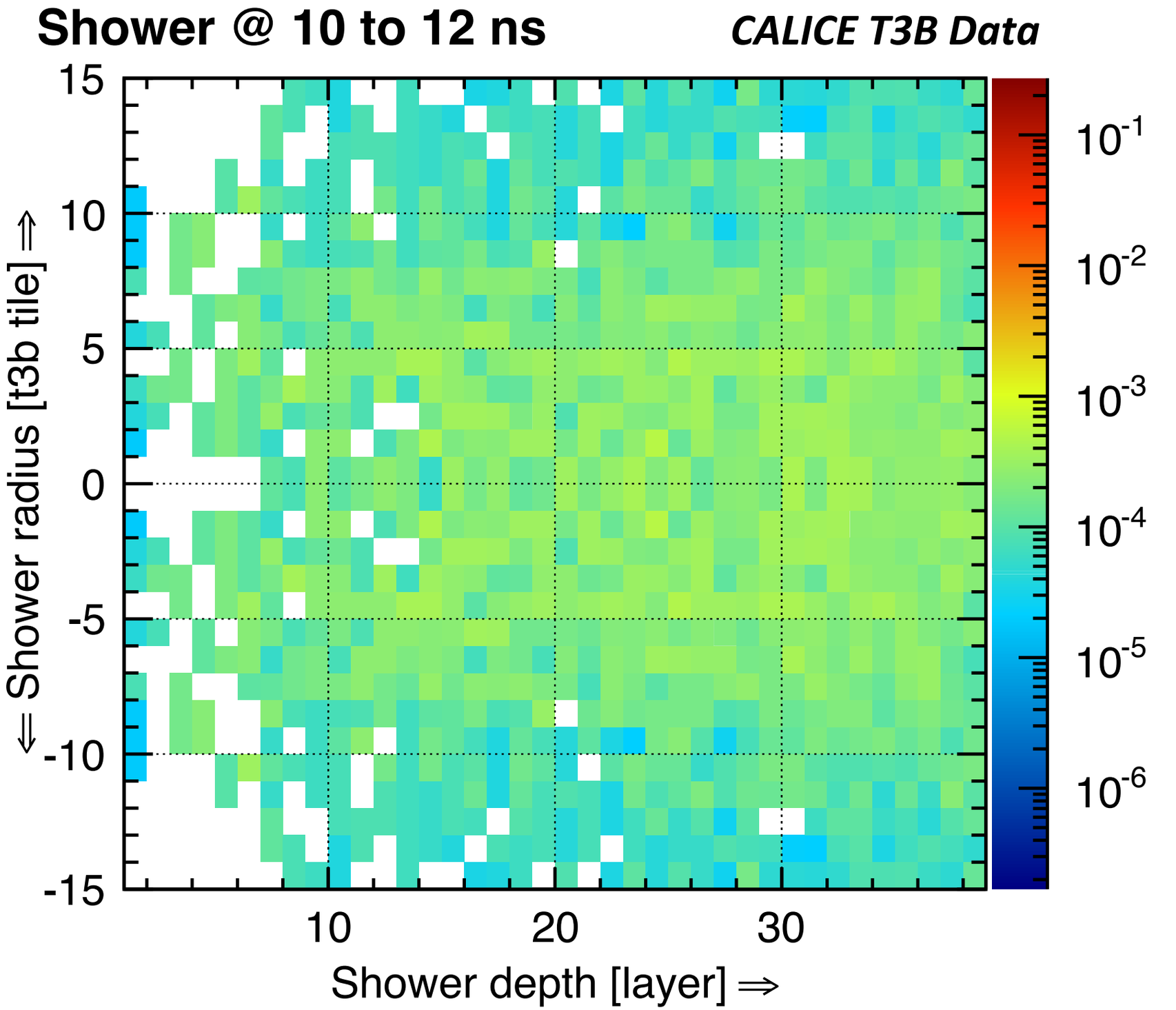

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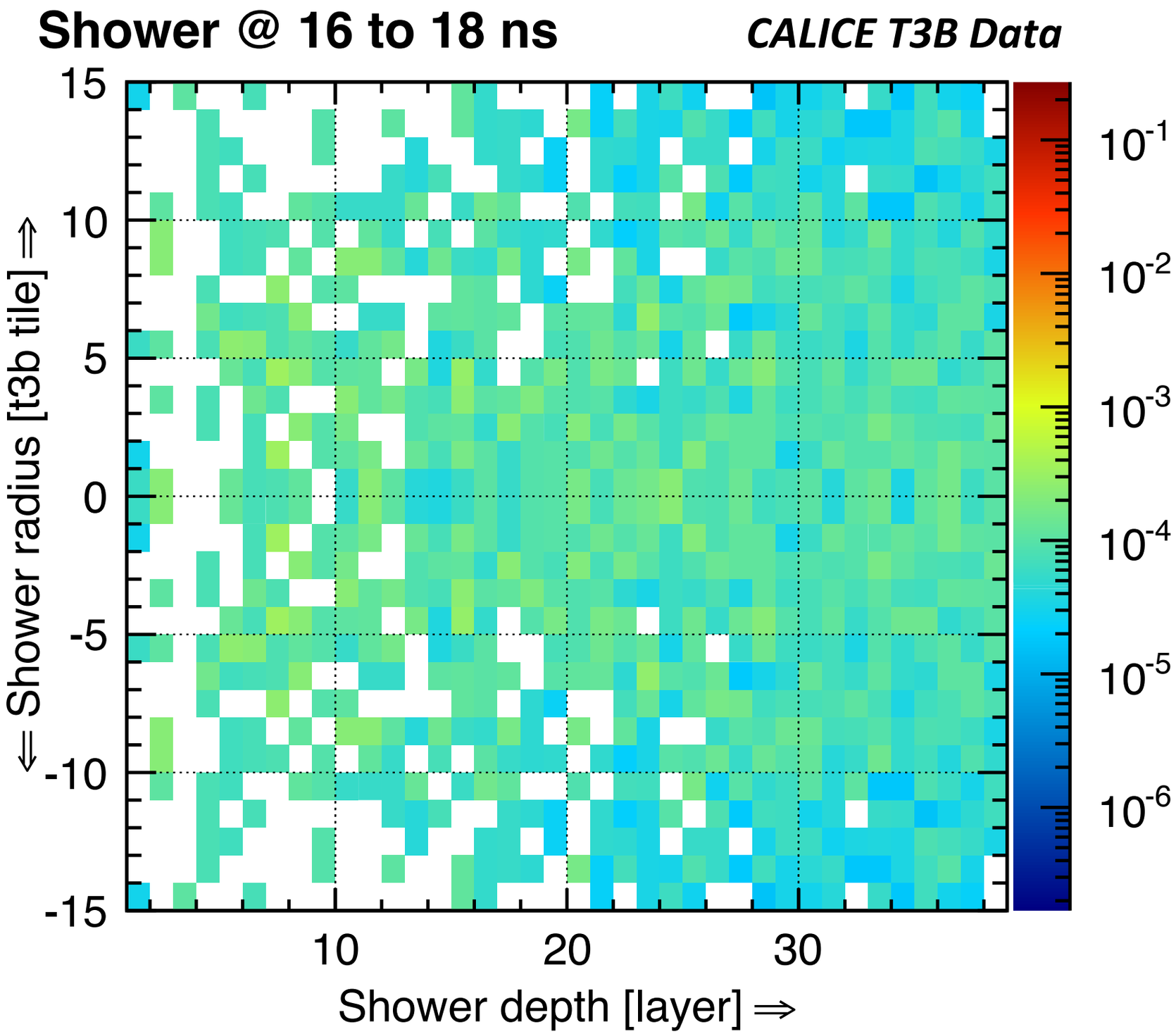

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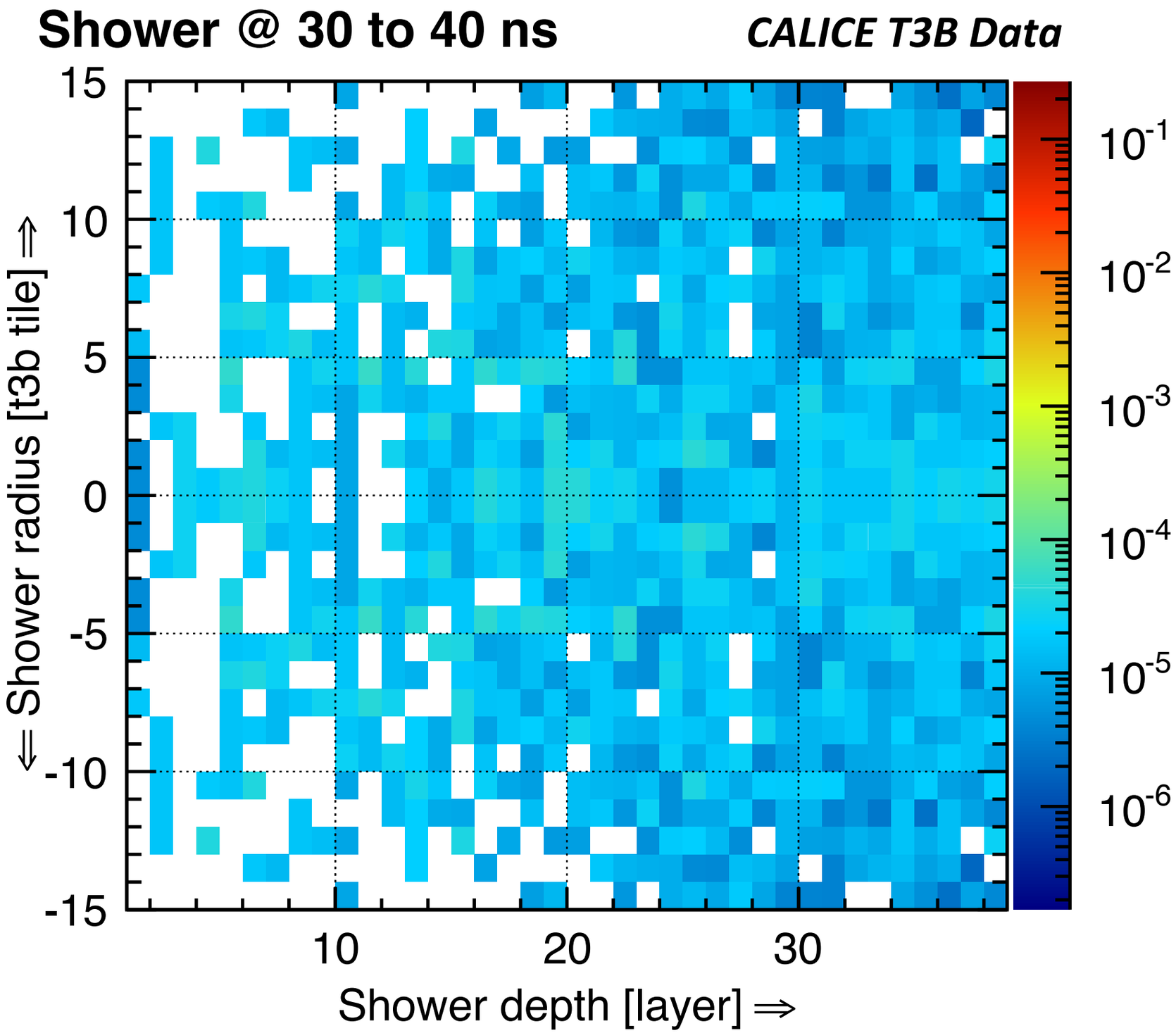

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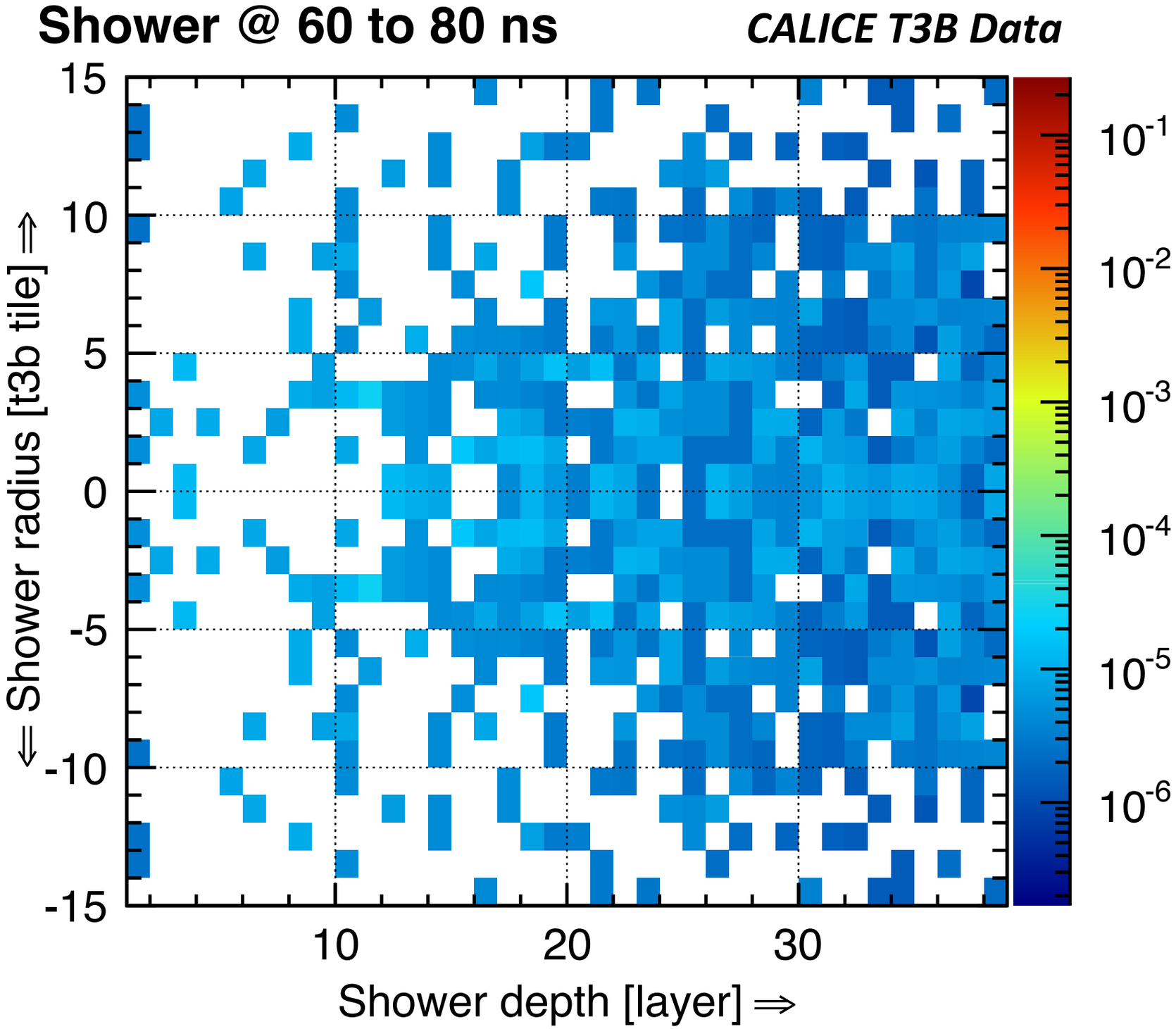

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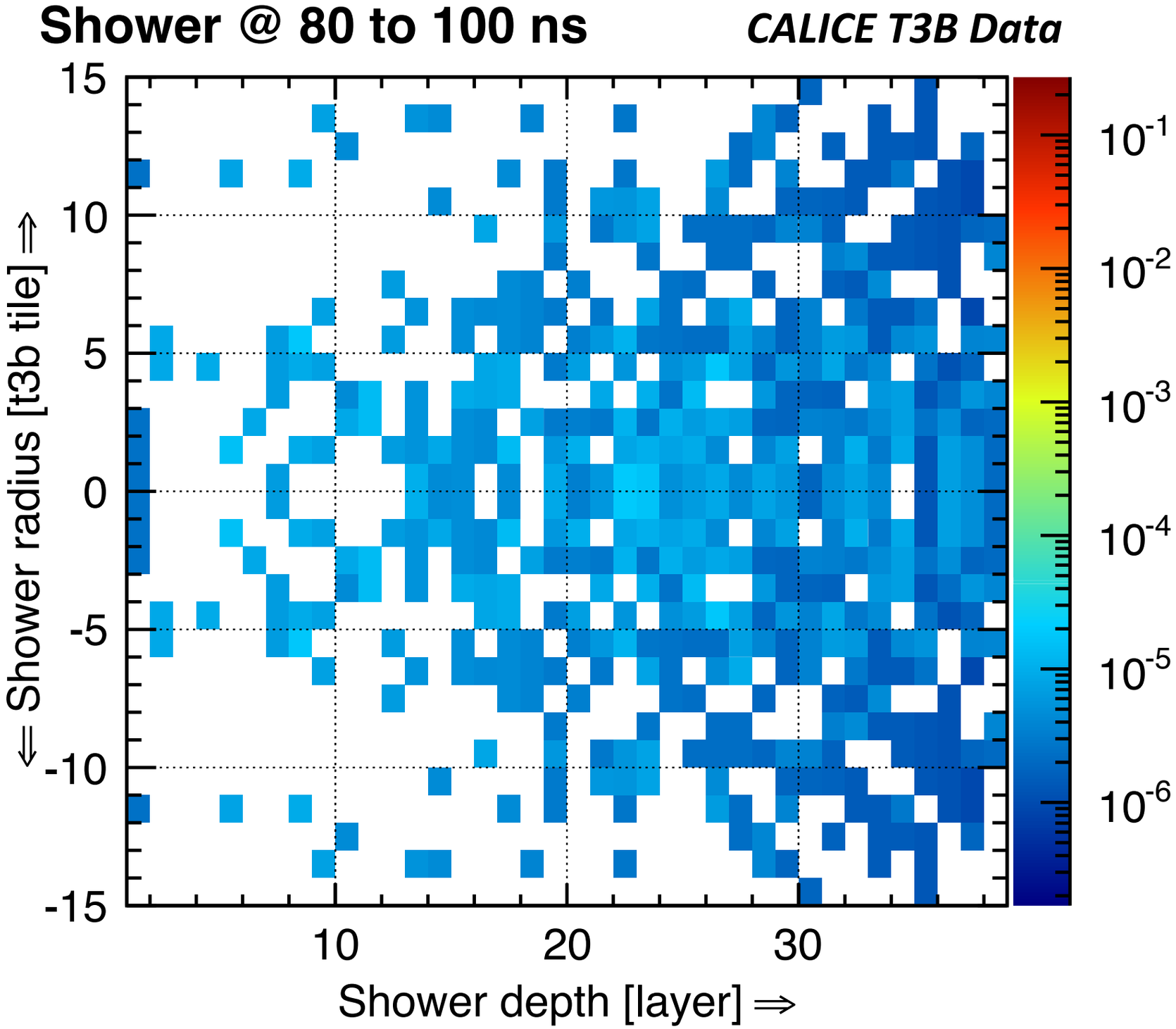

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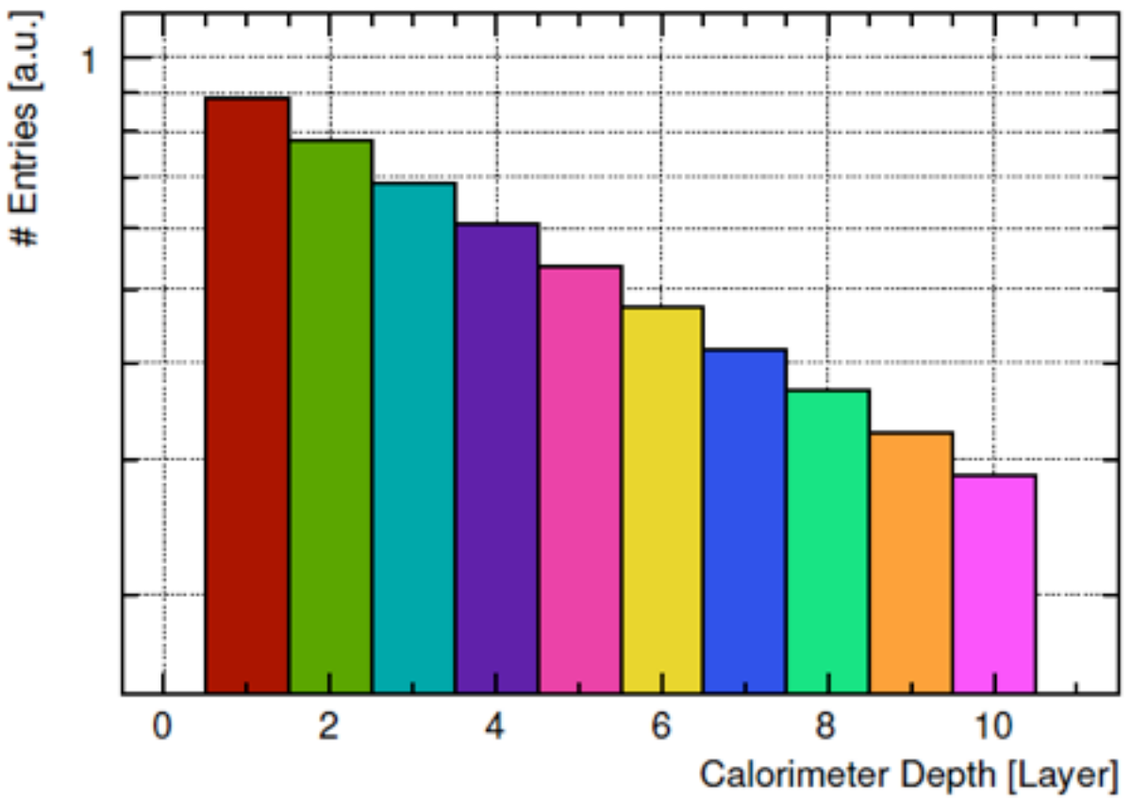
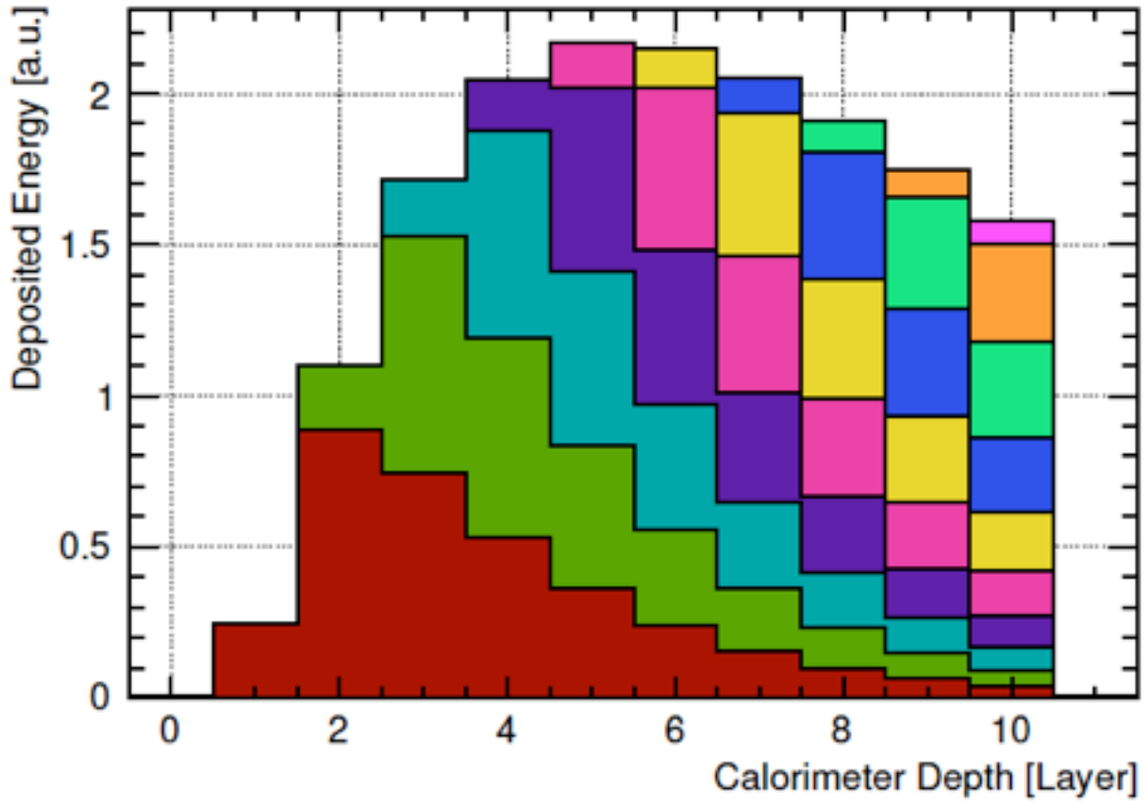
Reconstructing Longitudinal Profiles

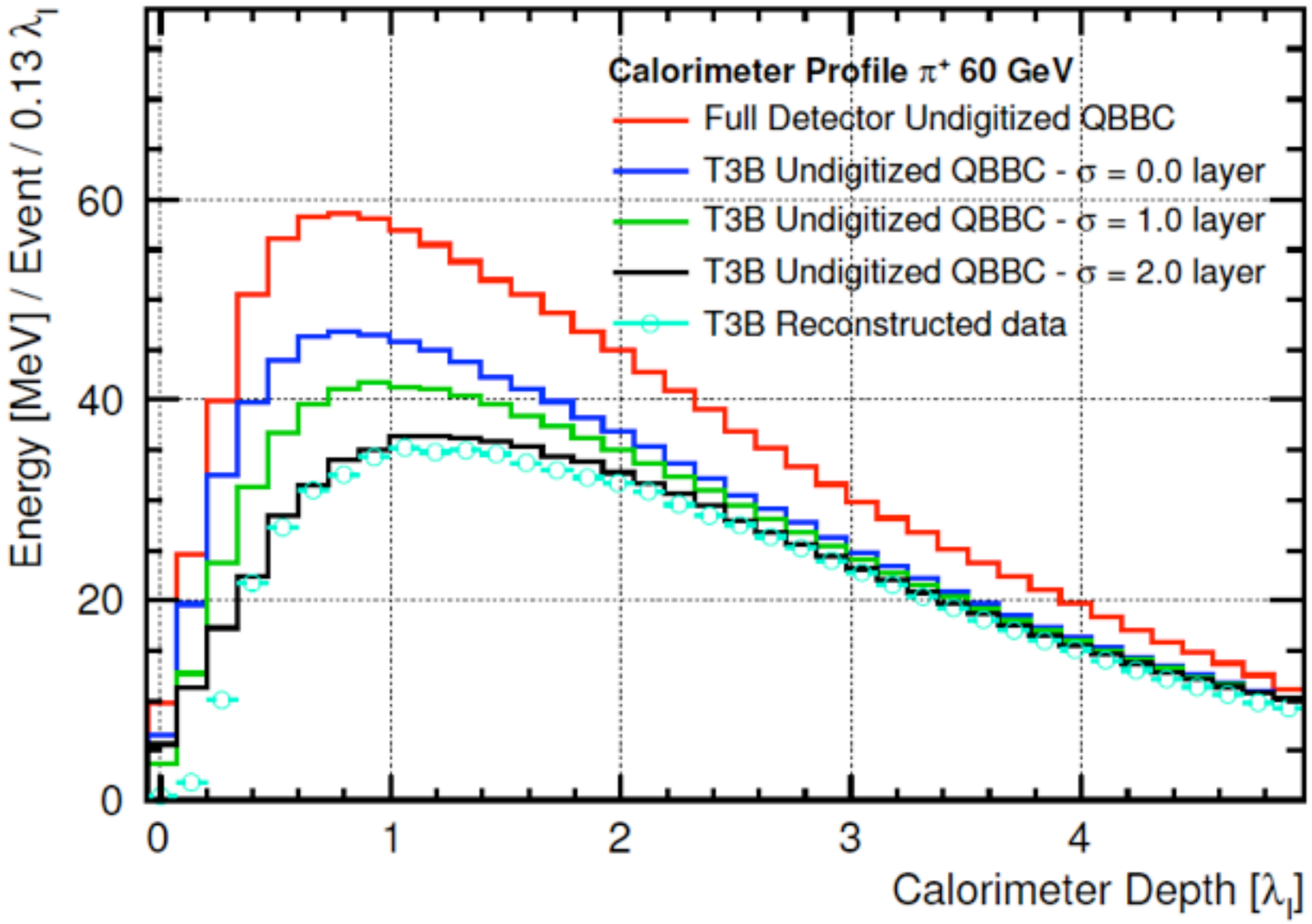
- T3B samples the tail of the shower (early shower start) more often than the front of the shower (late shower start): Has to be corrected when reconstructing longitudinal profiles by weighting reconstructed energy according to number events with a given shower start
- For Calorimeter profiles: Additional weighting with the shower start distribution:





Precision of Profiles

- Shower start reconstruction is not exact, in particular in the WHCAL data: Results in a smearing of the profiles

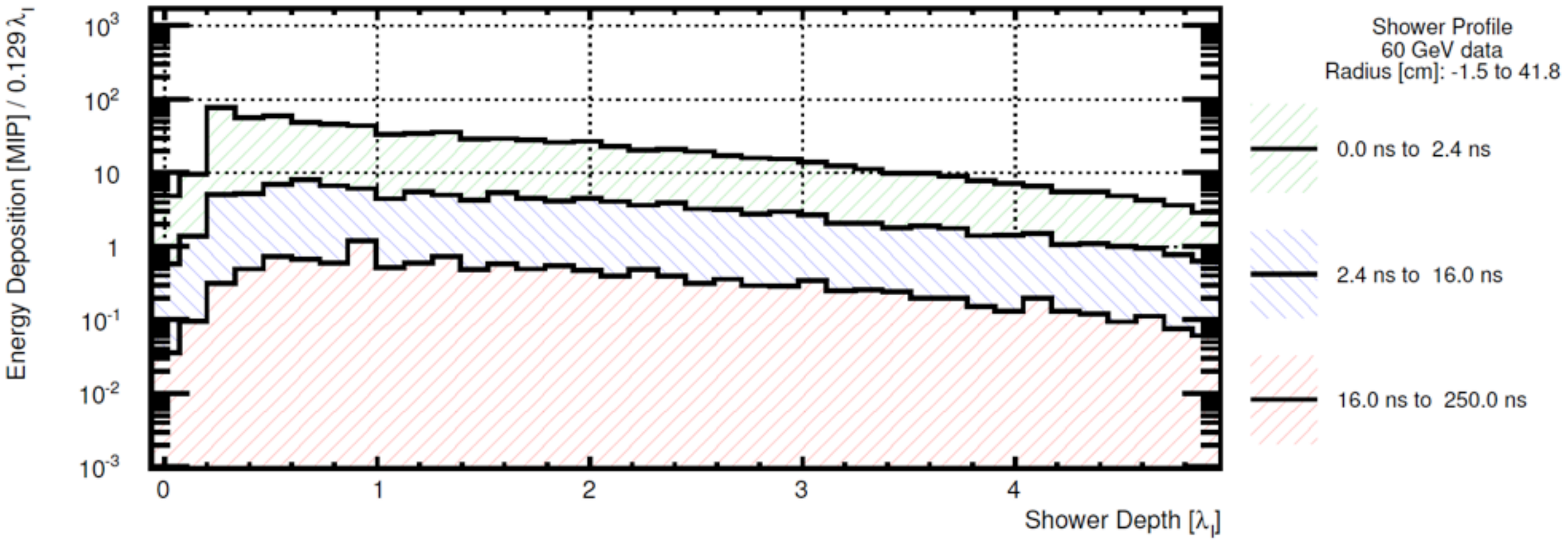


Currently, no corrections for this effect are made

It is also implemented in the simulations

- Uncertainty of 2 layers, combined with a steeply falling shower start distribution results in a lowering and a backward shift of the peak

Longitudinal Profiles in Time

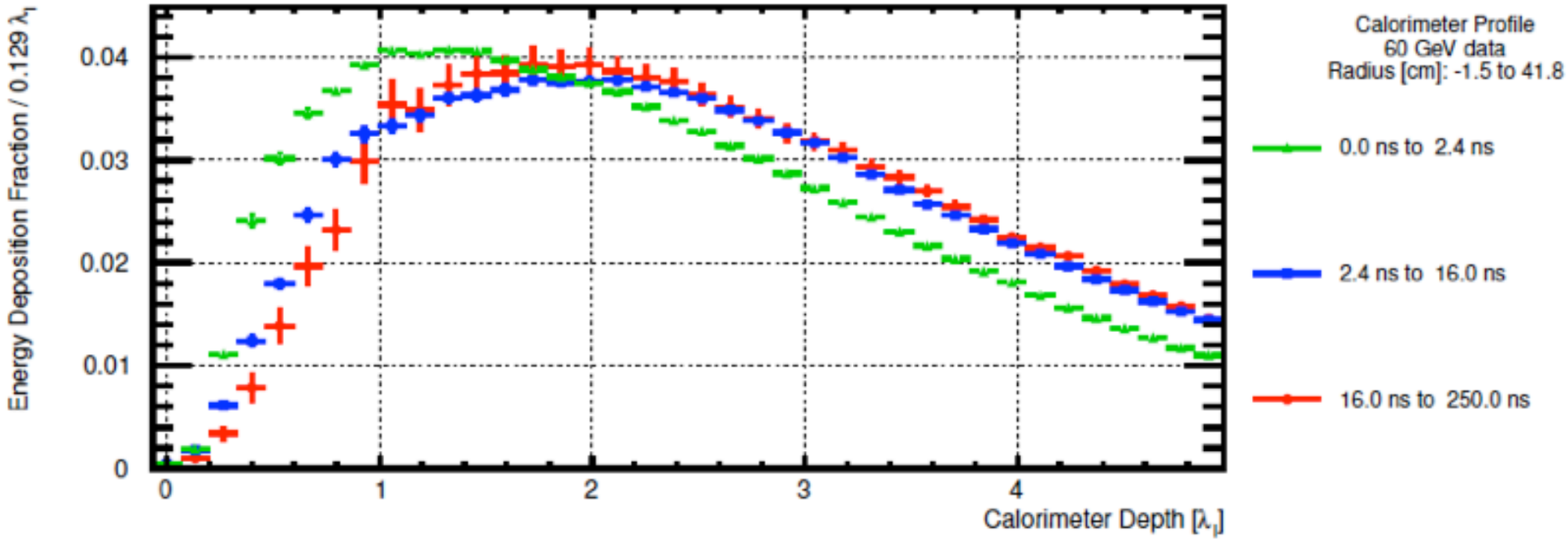


fast component has a peak after 5 - 10 X_0: EM fraction

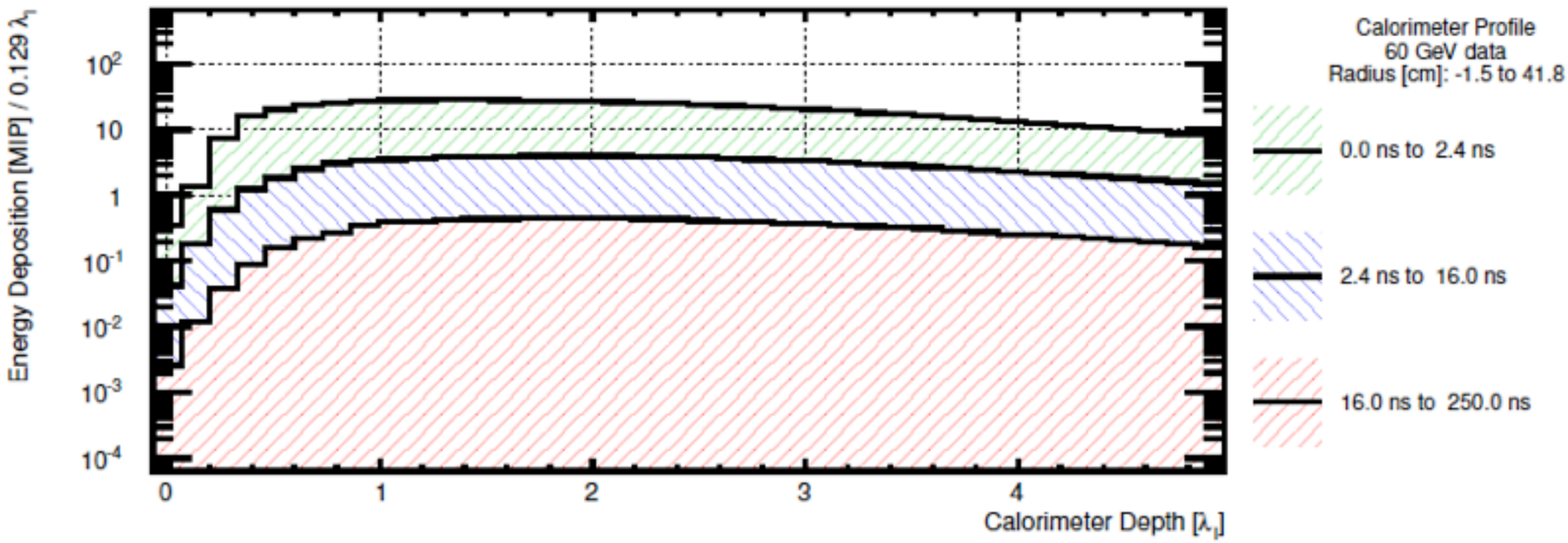
late components peak slower: dominated by hadrons

- late components suppressed by one / two orders of magnitude

The Calorimeter Profile

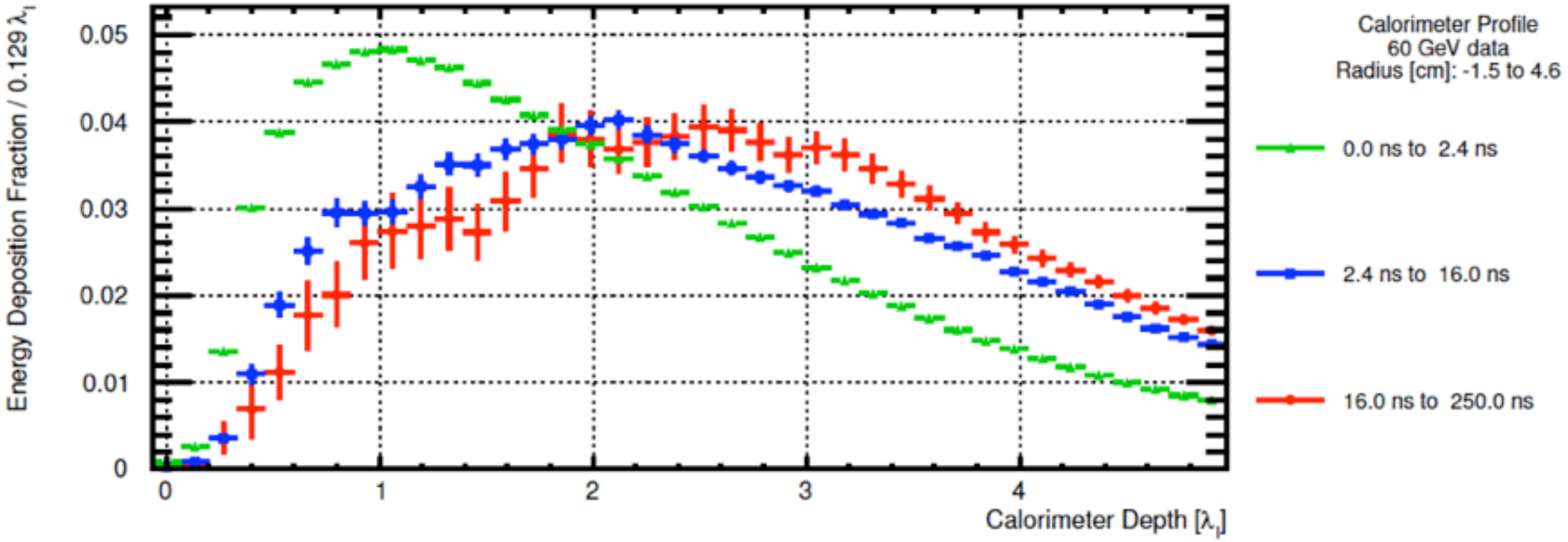


normalized - shape comparison



Adding Radial Information

- Calorimeter Profile - Normalized for shape comparison



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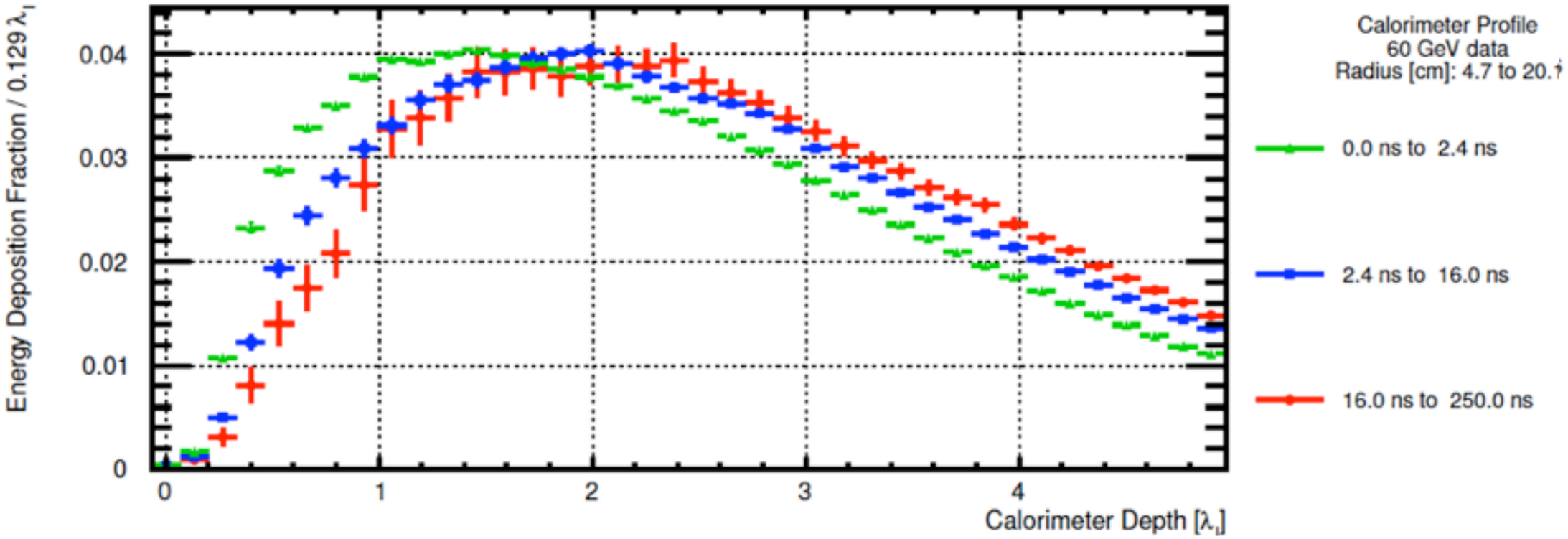

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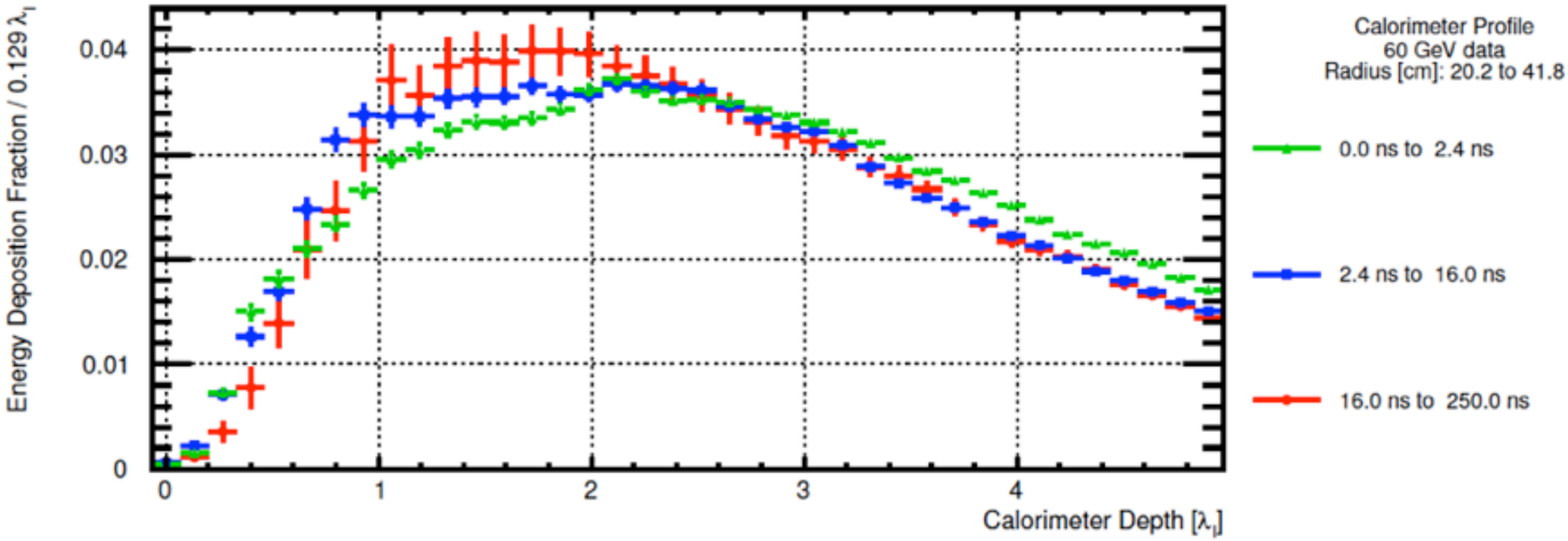
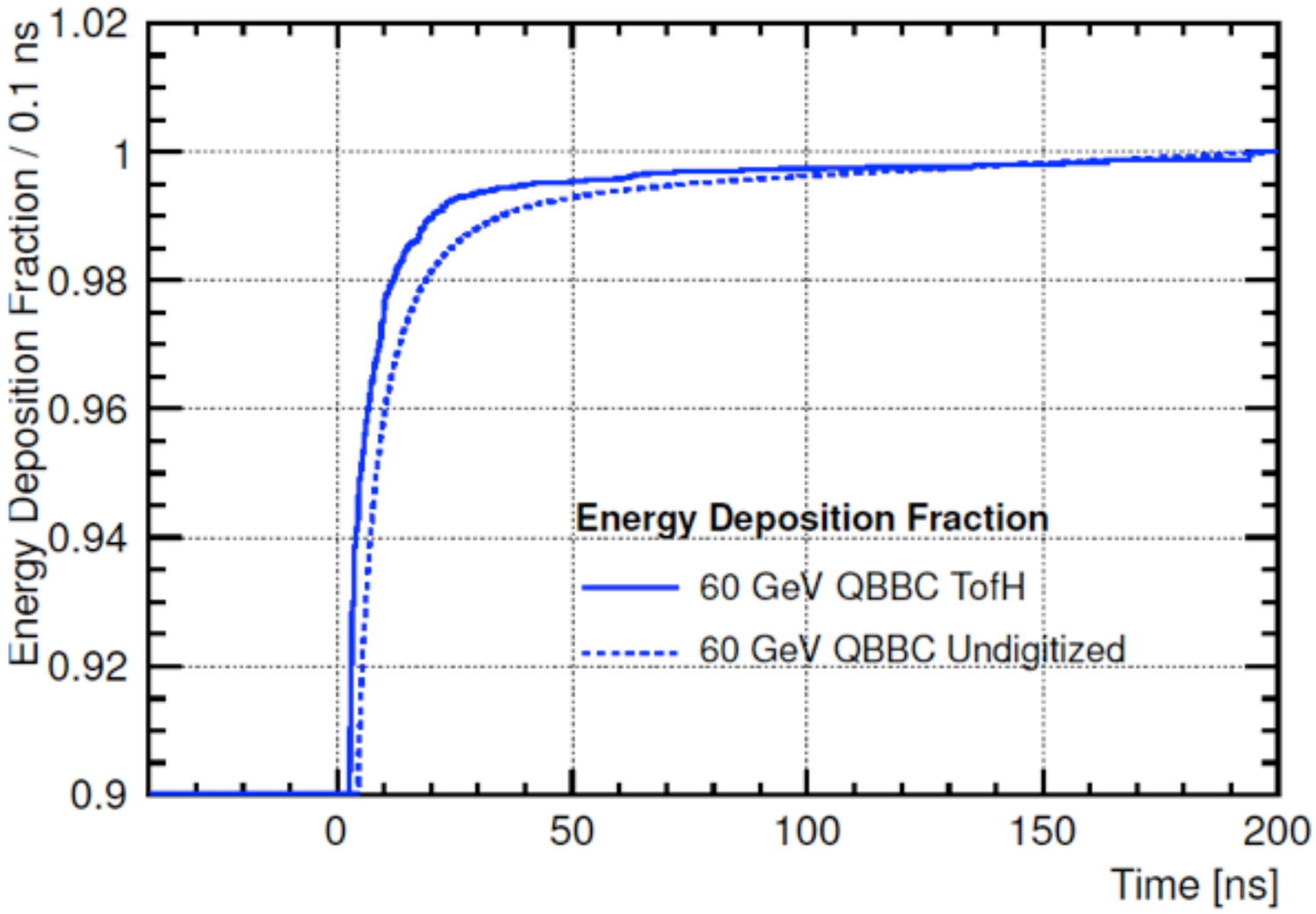


- The central part (dominated by EM - particles) drives the difference in shape - In the outer regions of the calorimeter the shower looks the same at all times...

Shower Integration Time

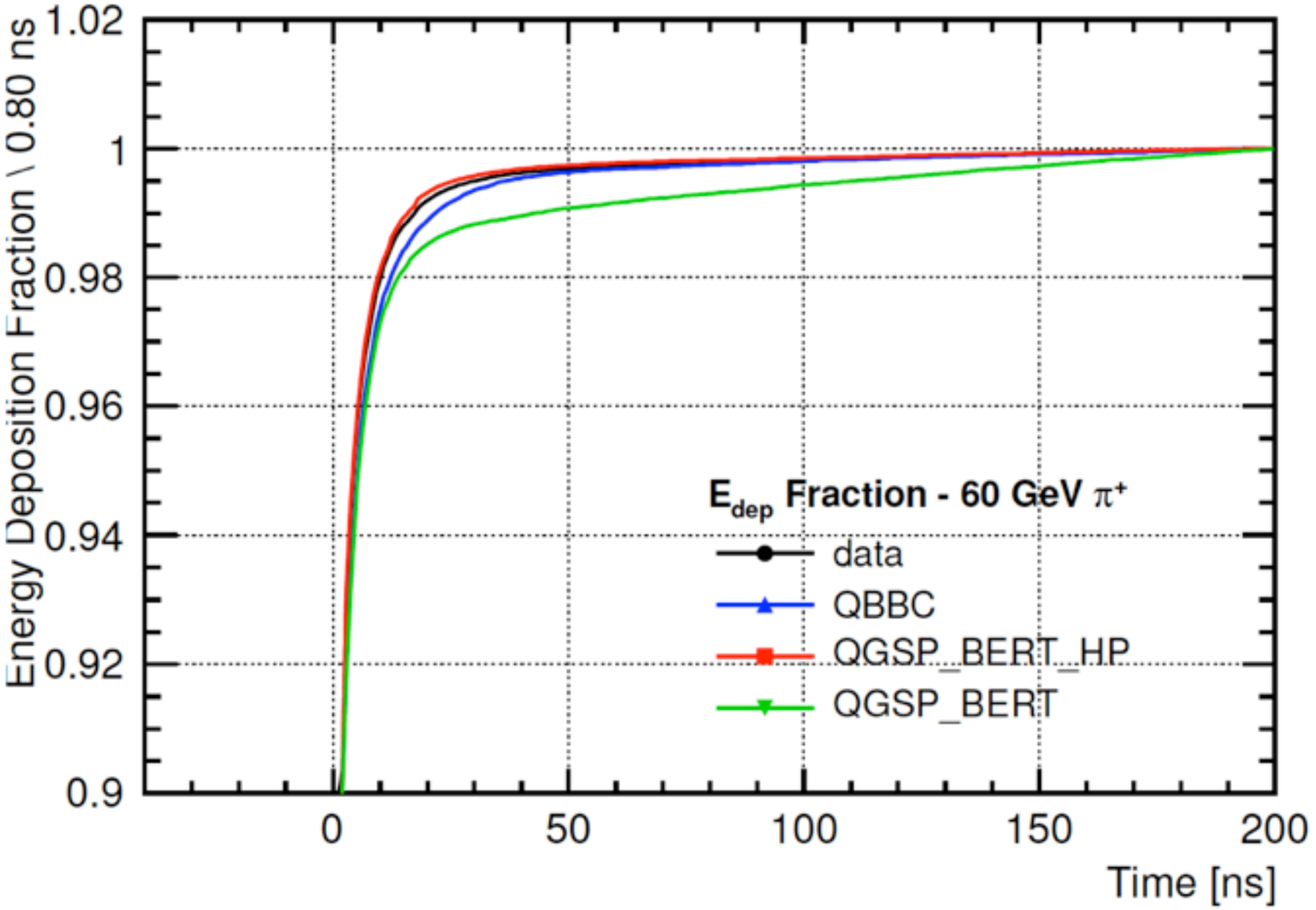
- From the time-dependent shower profile the integration time required to reach a certain energy fraction can be determined (100% here defined as the energy after 200 ns)
- Some corrections due to the use of the time of first hit - Studied with MC



Time of first Hit T3B data is faster than the full calorimeter - but not dramatically

Time of first Hit: Timing of the second photon is used for each hit (energy above threshold starting from the first photon)

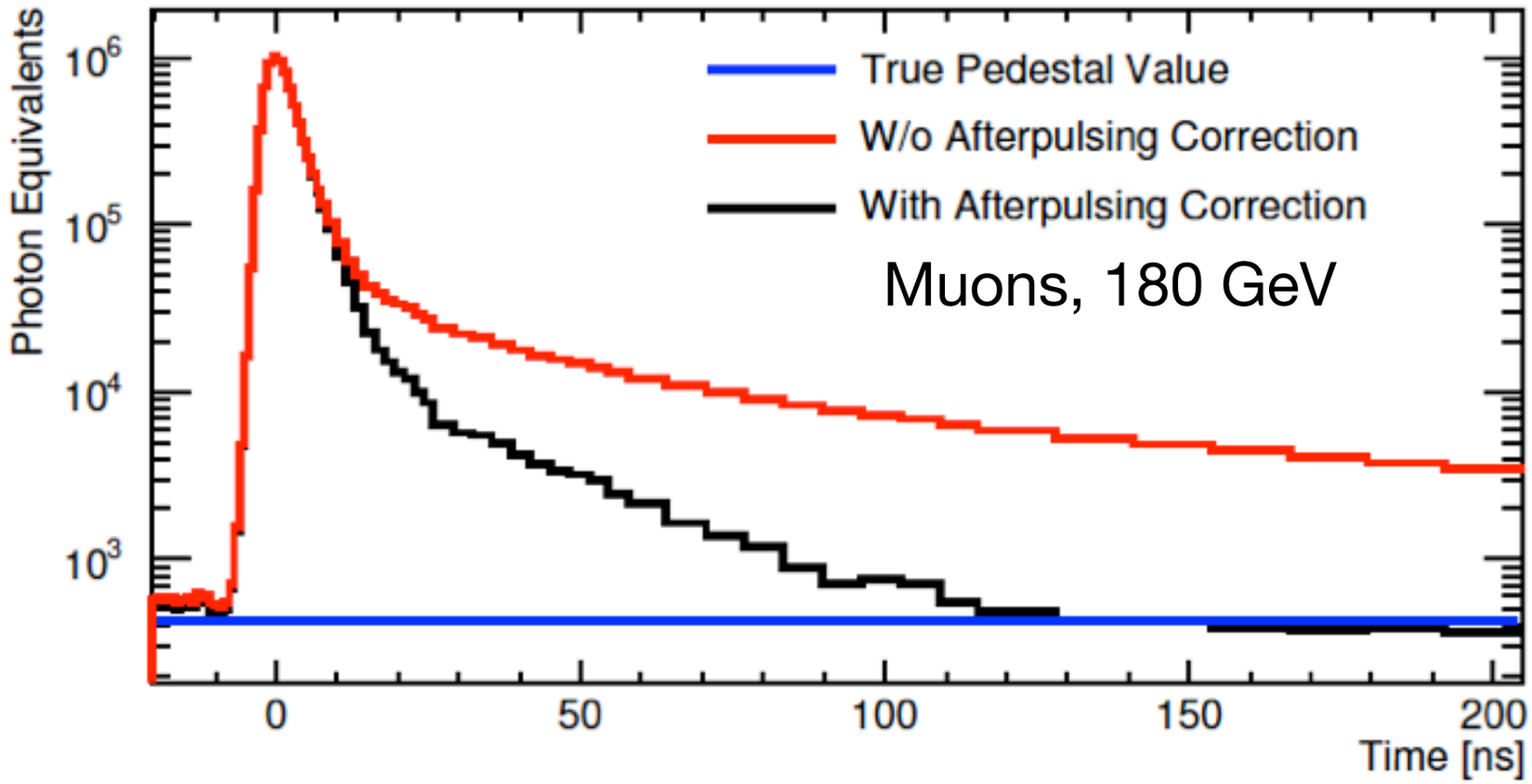
Shower Integration Time



- Very good agreement with QGSP_BERT_HP - 98% after 10 ns (would be reached after 20 ns without the Time of first Hit definition)
  - The data show that very long integration times are not required, even for tungsten

Back to 3D: The Time of Hit

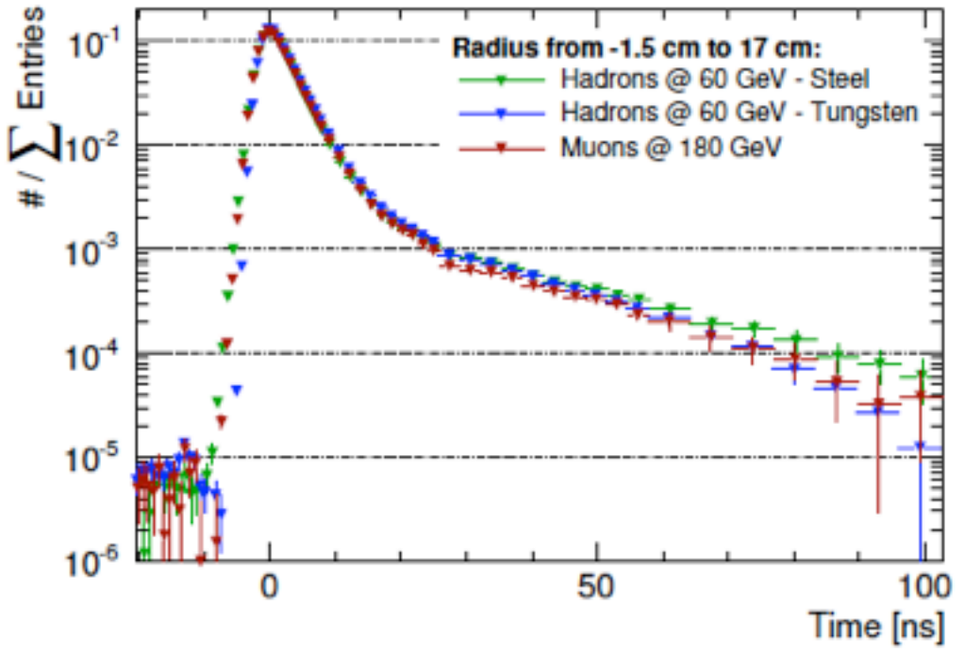
- The goal: Use the time of each photon due to real energy depositions in the analysis, give up “first hit” definition
  - The challenge: Photon sensor afterpulsing - Can only be corrected for statistically, impossible to distinguish event by event - This is photon-sensor specific!

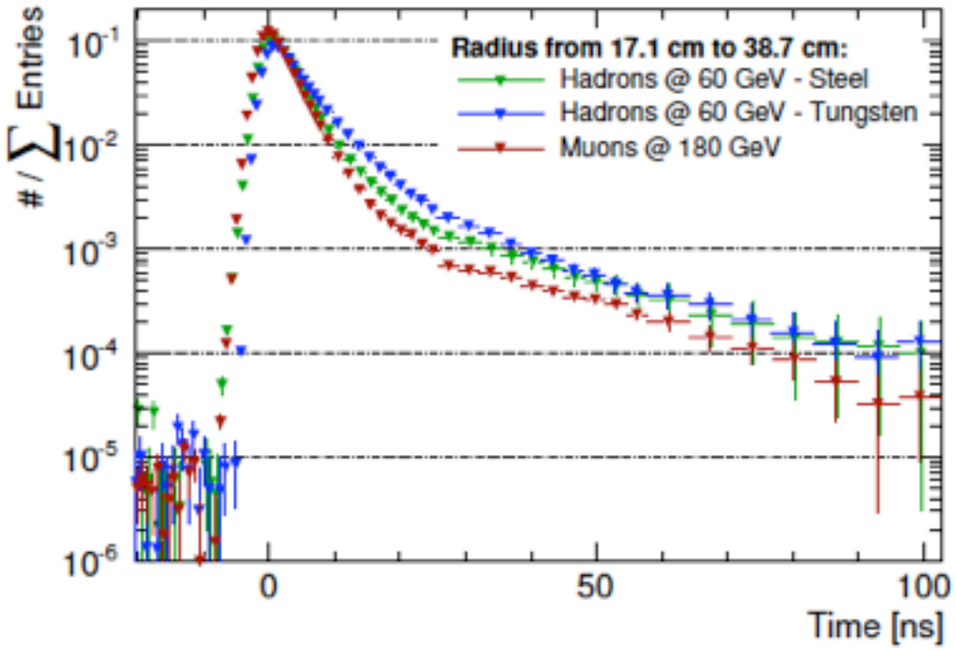


T3B: MPPC50 “old” series

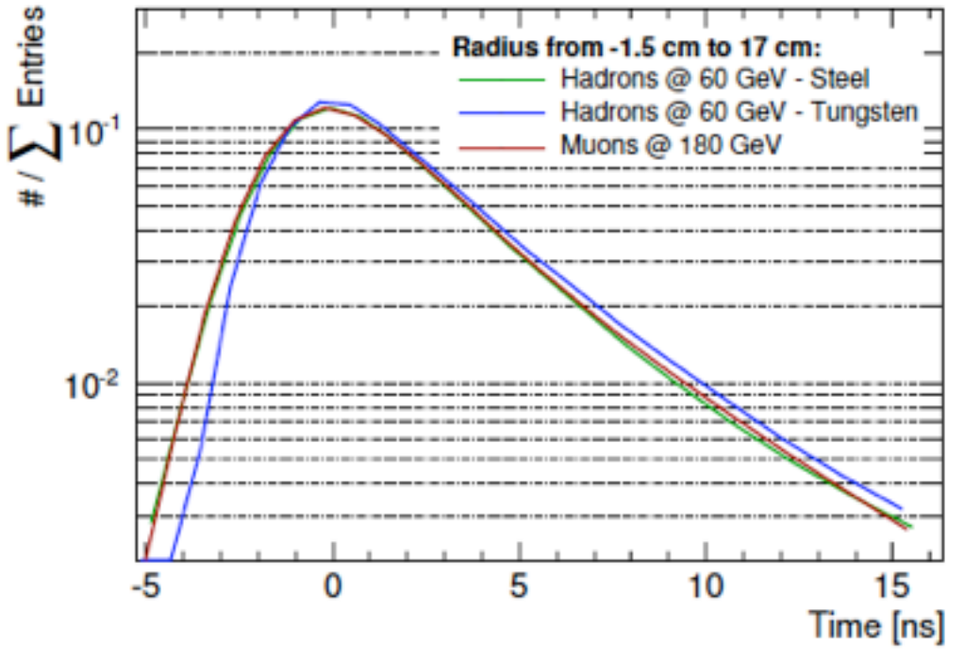
- Indication for a slow signal component beyond that expected from the scintillator and the reconstruction - Scintillaton of reflective foil, potential imperfections of AP correction (on the sub-% level!)

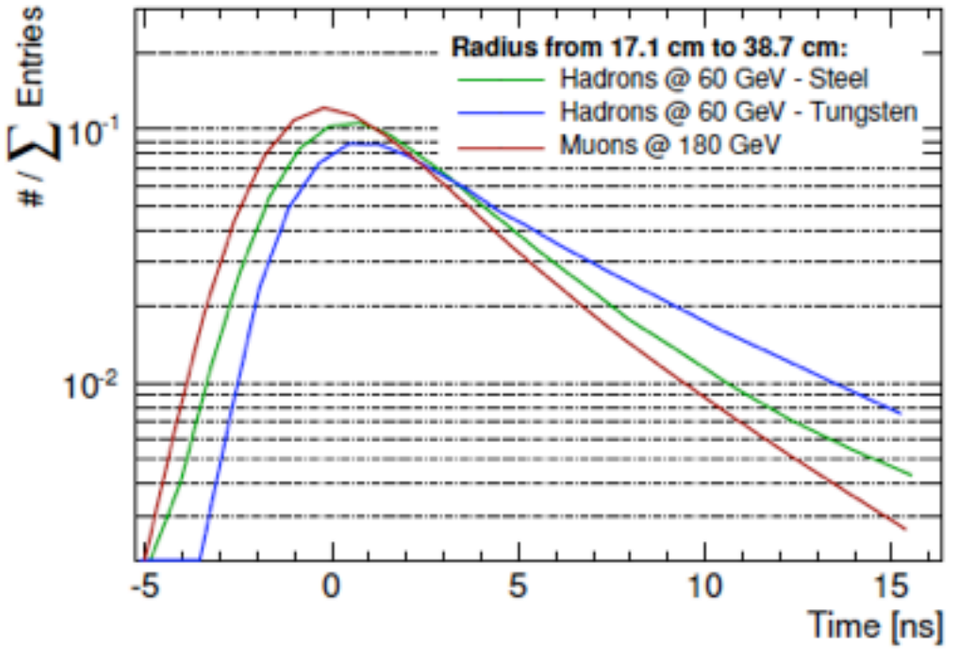
The Time of Hit



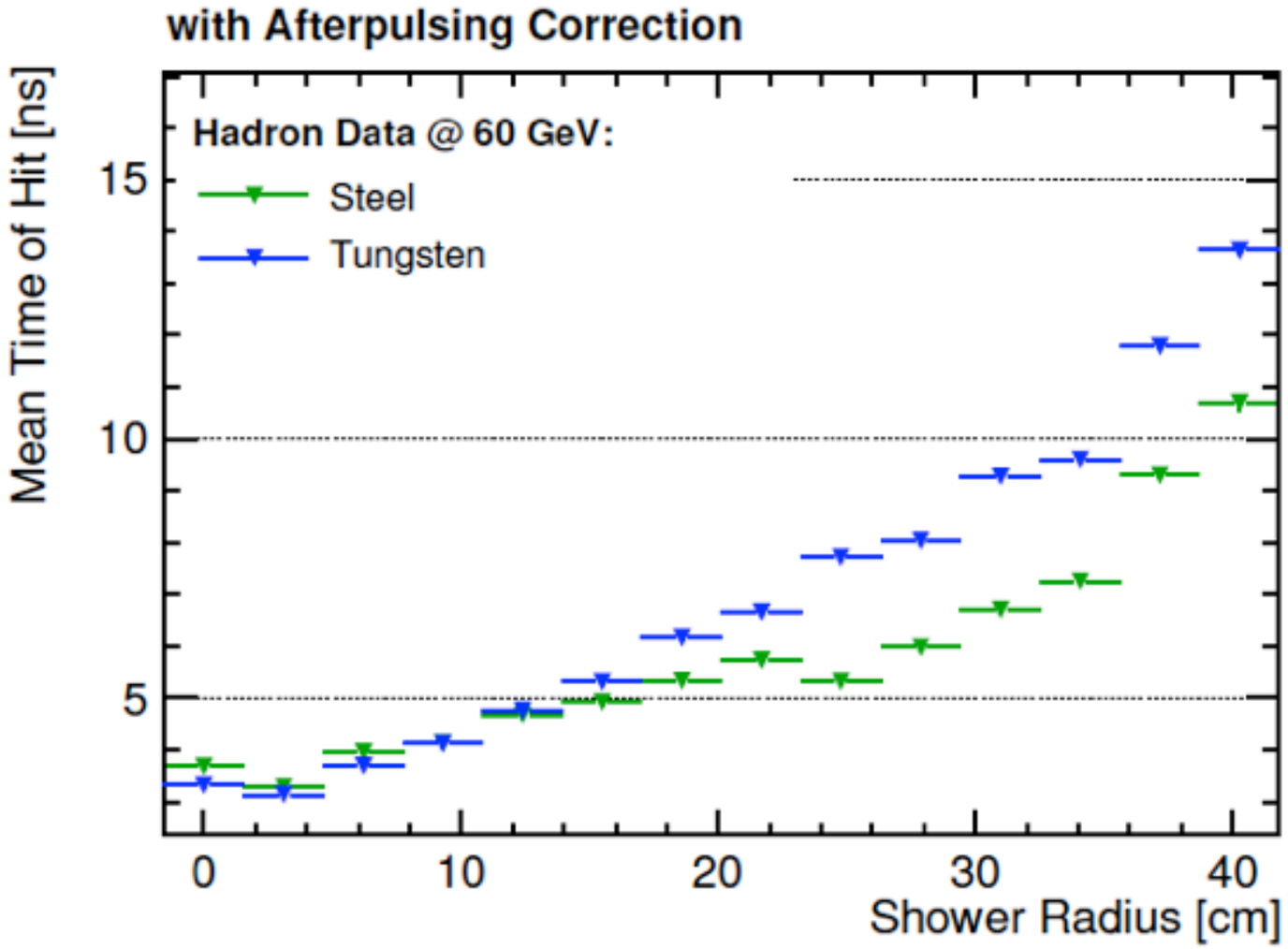


- Differences between absorbers most pronounced at large radius



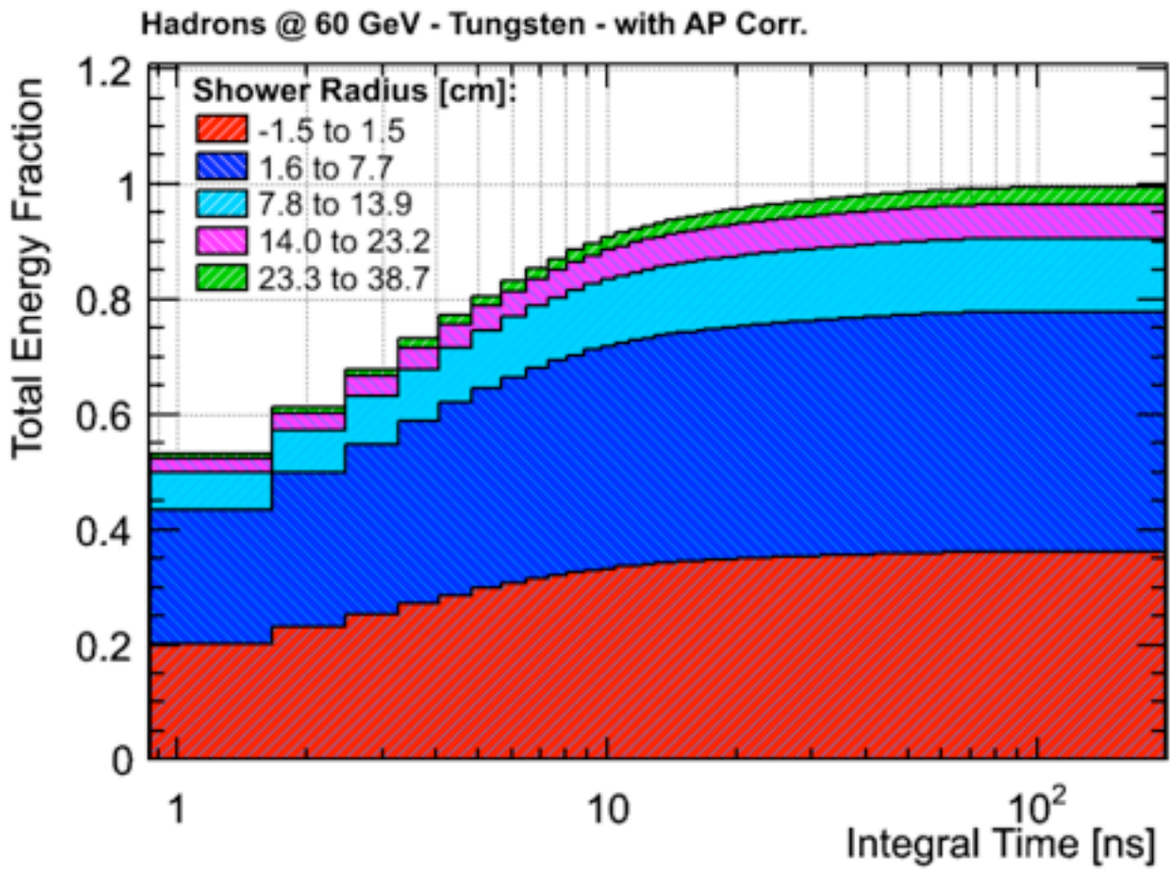


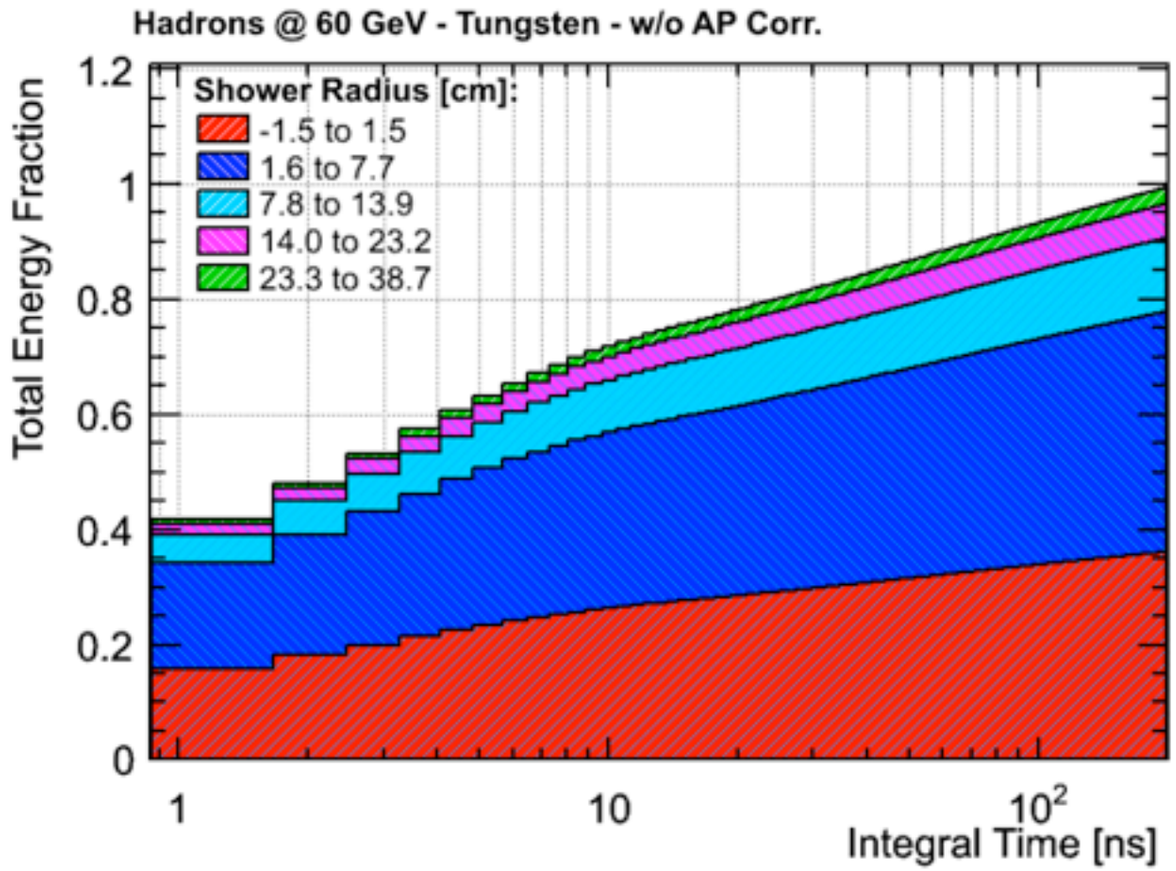
Time of Hit - Radial Dependence



- Good agreement with behavior observed for Time of First Hit - No substantial benefit for shower understanding

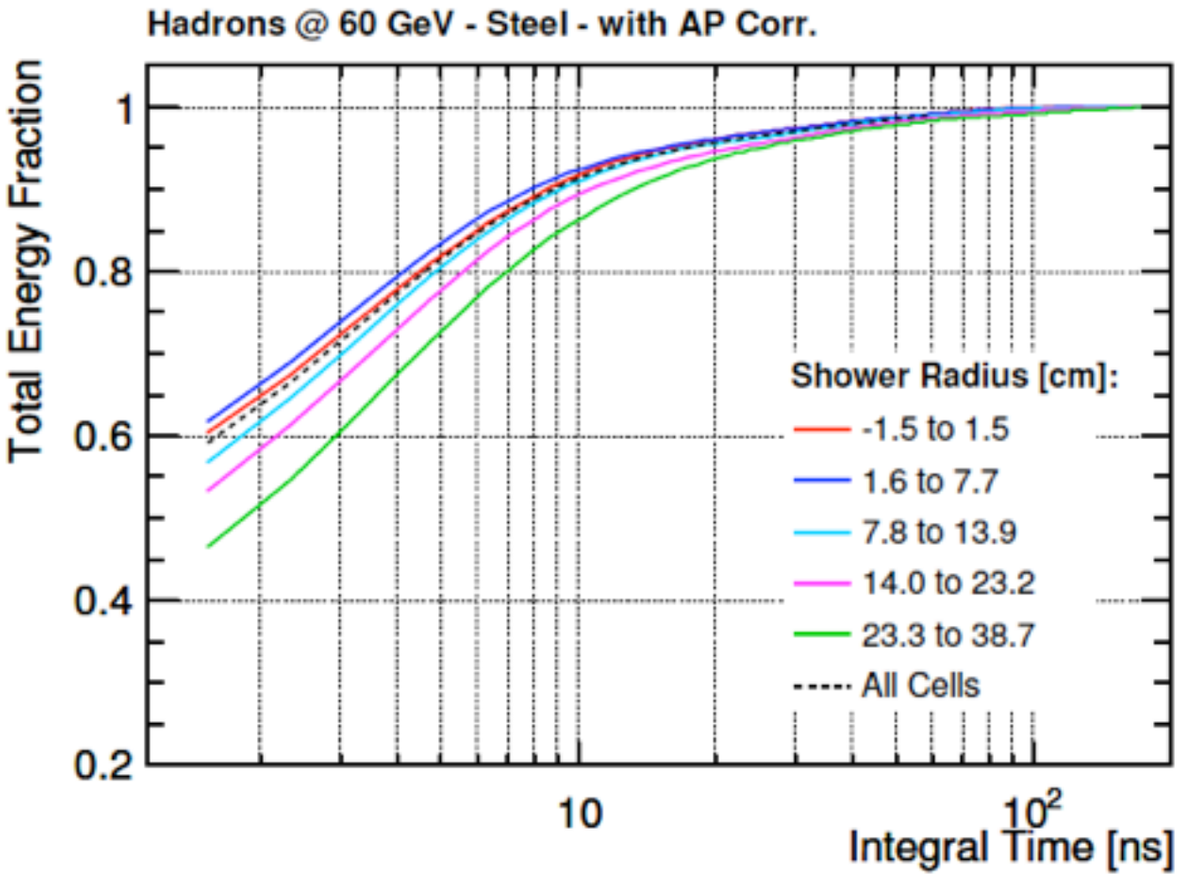
The Effect of Afterpulsing

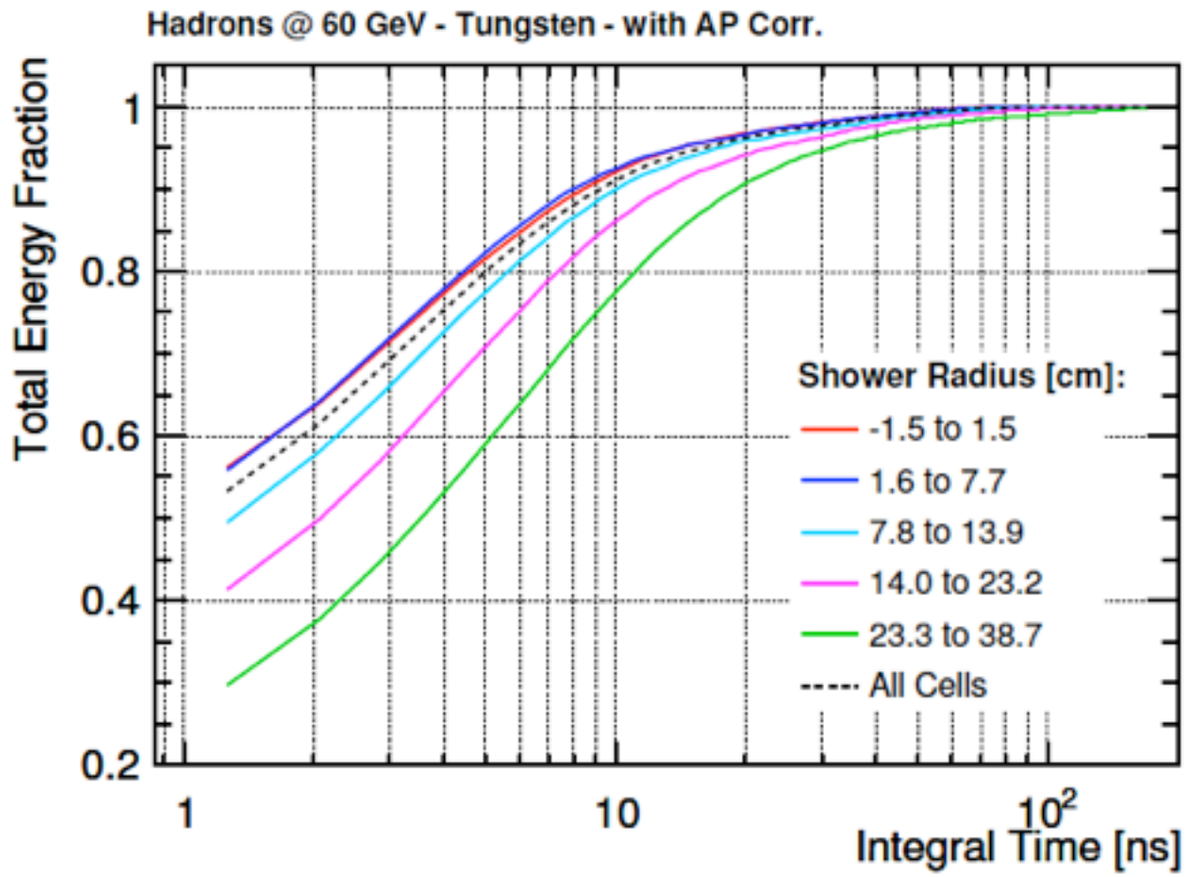




- Fraction of total energy (= 200 ns integration time) in T3B (not weighted to full calorimeter)
- Without reduction of afterpulses, there is no point to integrate longer than ~ 20 ns, after that, almost all is afterpulsing (with the T3B MPPCs)

Integration Time - Comparing Steel and Tungsten

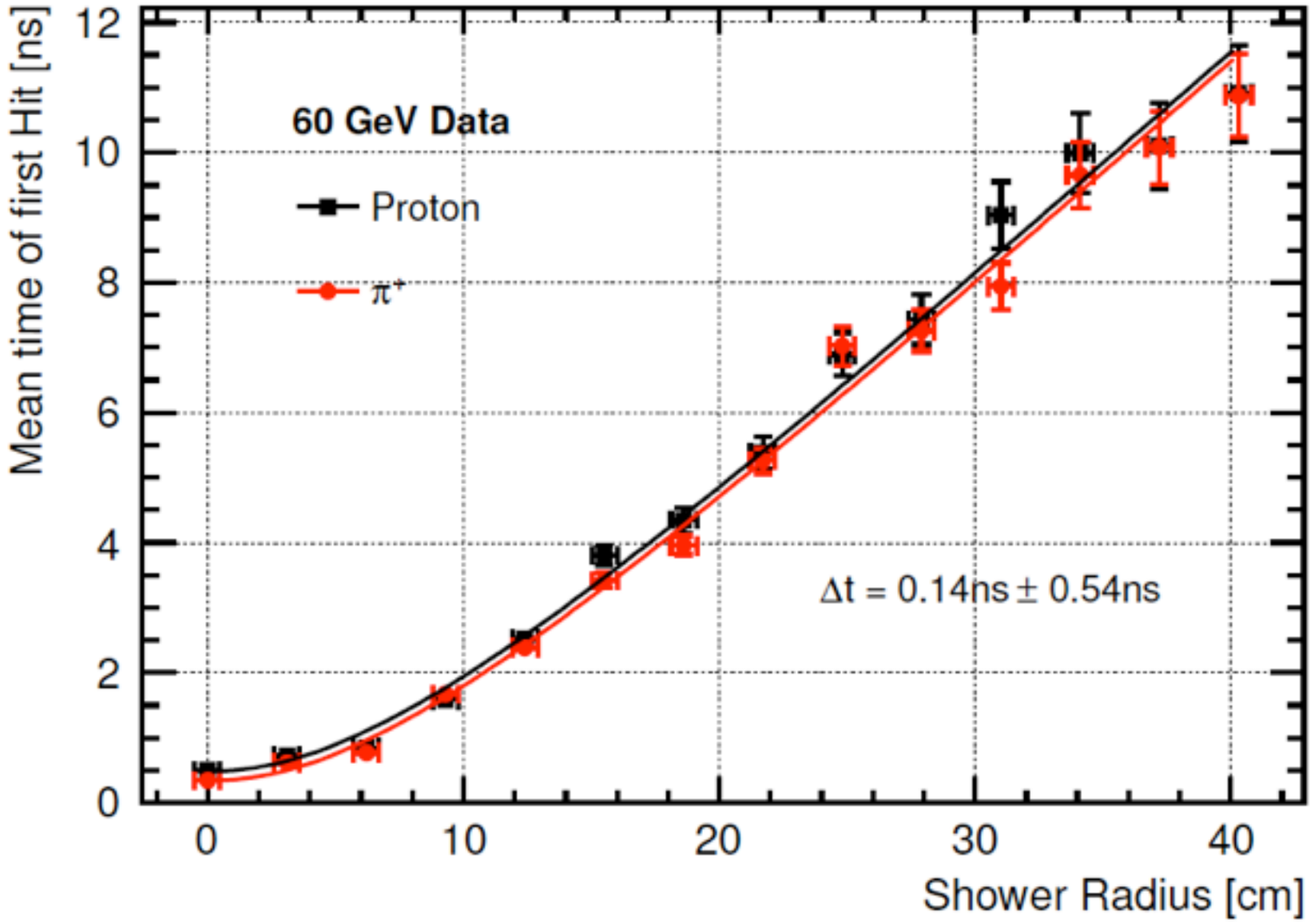




- As expected tungsten somewhat slower than steel (but overall very small difference), most pronounced at large radius

Protons & Pions

- For correlated events with the WAHCAL, the Cherenkov information is available: Provides particle ID



- Compare protons and pions: No significant difference in timing profile seen

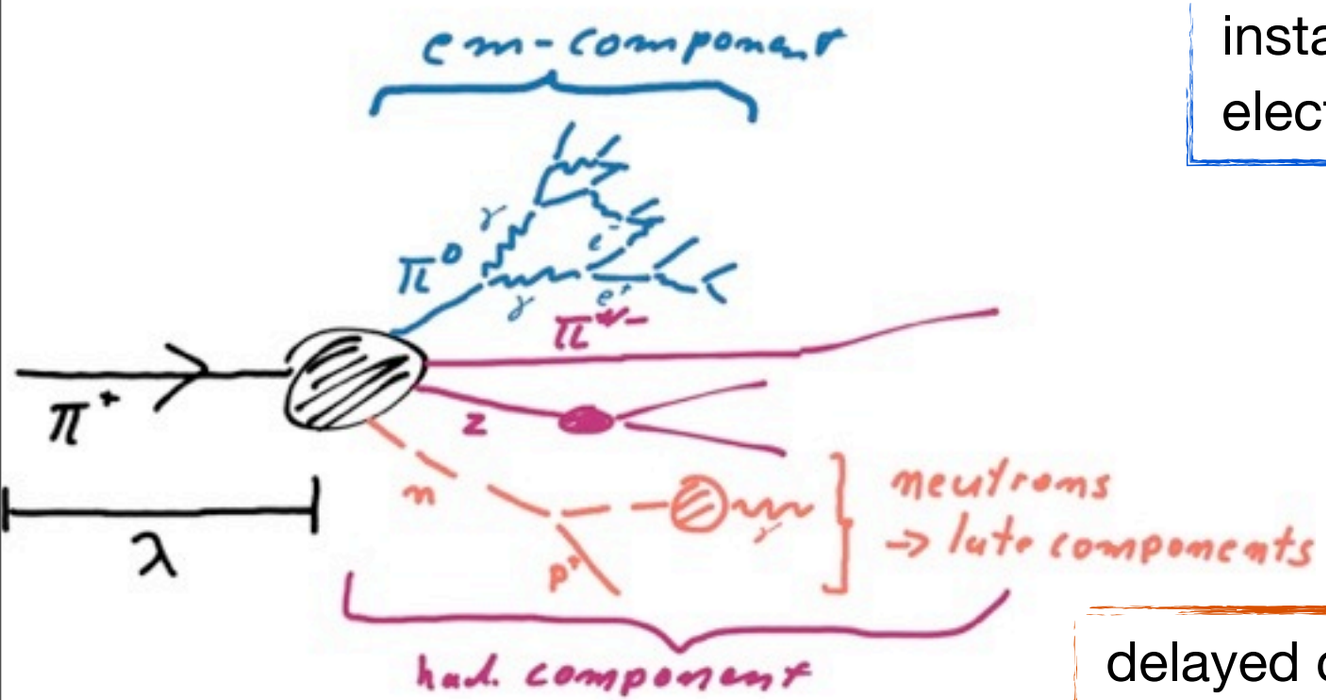
Conclusions

- The current T3B analysis campaign is nearing completion with the competion of the theses of Christian and Lars
- New results this time:
  - Longitudinal profiles split in time - Profiles at early times are characterized by a quick rise due to EM component, at later times they exhibit the slower rise expected from purely hadronic reactions
  - Even in tungsten the overall signal integration can be quite quick: 98% of all energy is seen within 10 - 20 ns (depending on method of reconstruction)
  - We can also look at the time of each photon - requires statistical subtraction of afterpulses: Results are consistent with the already public time of first hit results
  - With the current photo-sensor (MPPC50) there is no point in integrating for more than 20 ns, after that almost everything is afterpulsing
  - Differences in the radial timing profile between proton and pion showers are negligible

Backup

Exploring Hadronic Showers

- Hadronic showers have a complex structure - also in time!



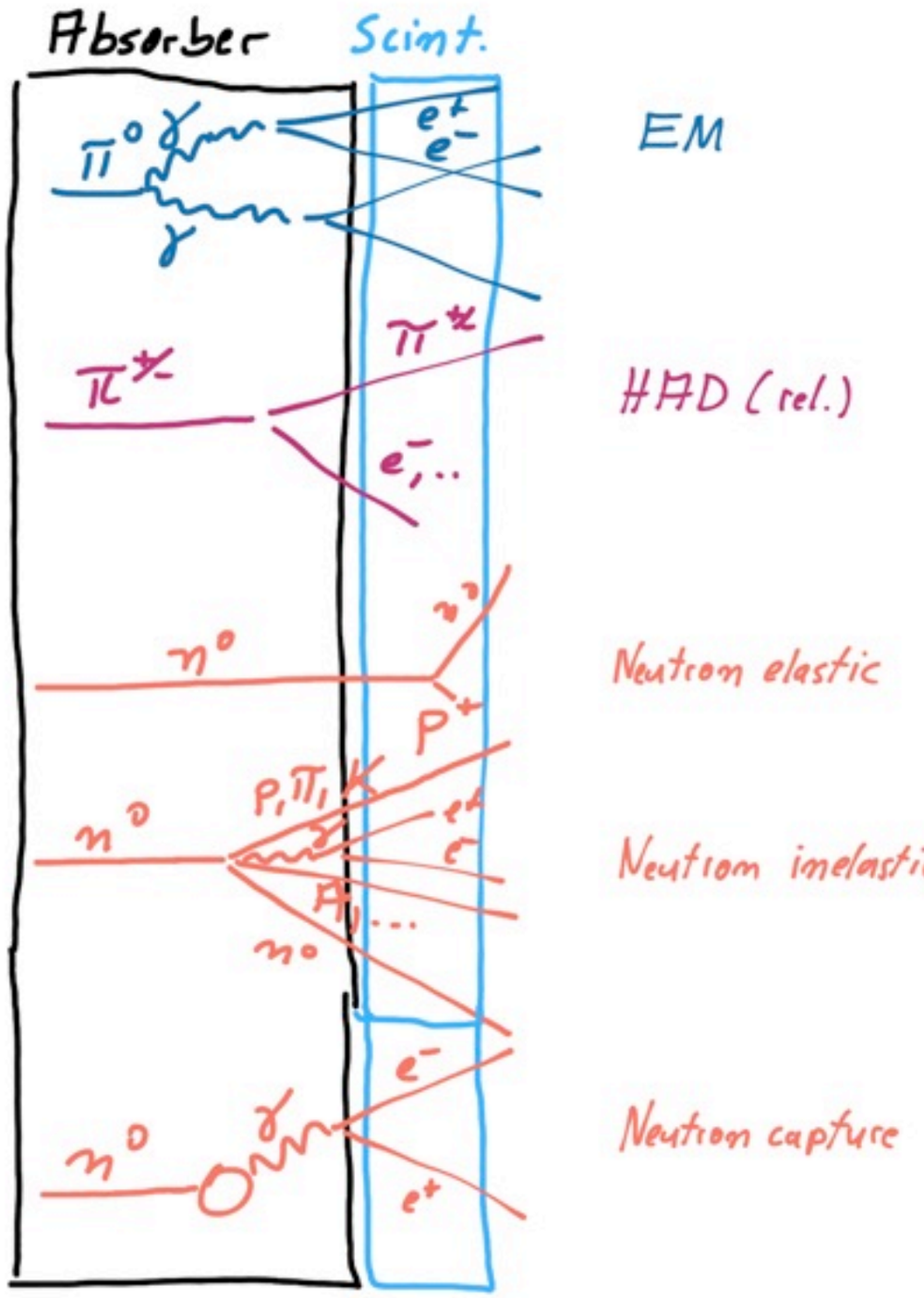
instantaneous, detected via energy loss of electrons and positrons in active medium

instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium

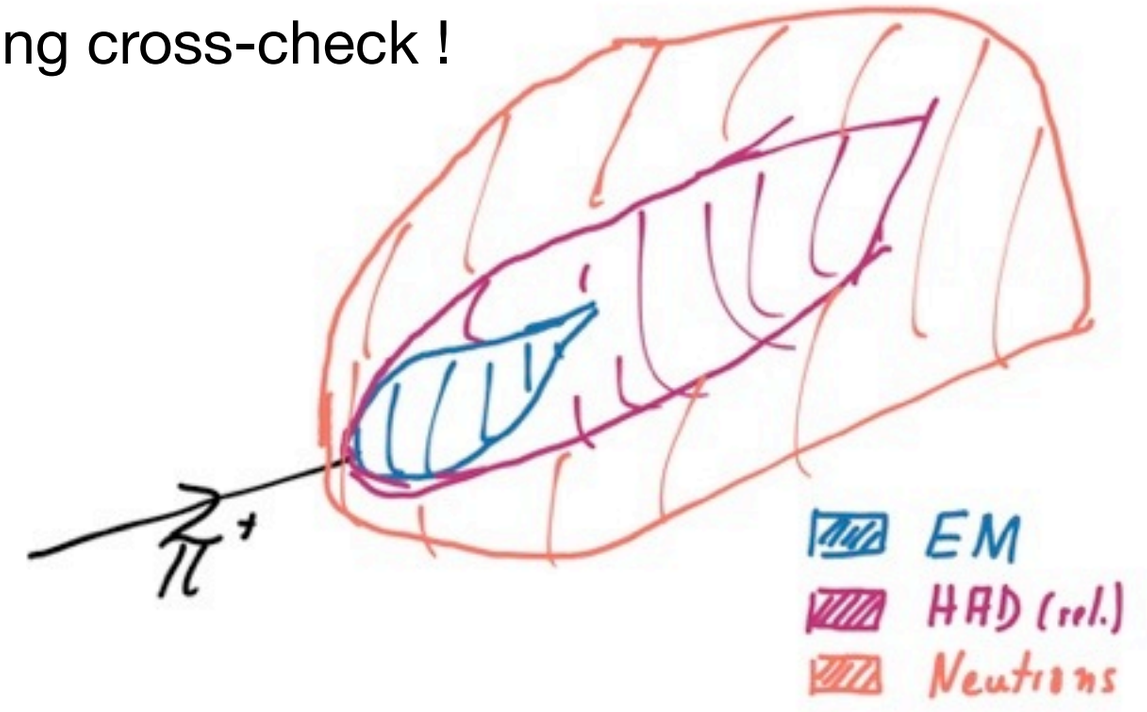
delayed component: photons, neutrons, protons from nuclear de-excitation following neutron capture, momentum transfer to protons in hydrogenous active medium from slow neutrons

- The time structure in granular calorimeters is highly relevant
  - influence on shower separation with PFAs depending on shower timing capability
  - impact on background rejection at CLIC: 0.5 ns between bunch crossings
  - particularly interesting in tungsten: heavy nucleus, so far little data

Shower Physics - Expectations

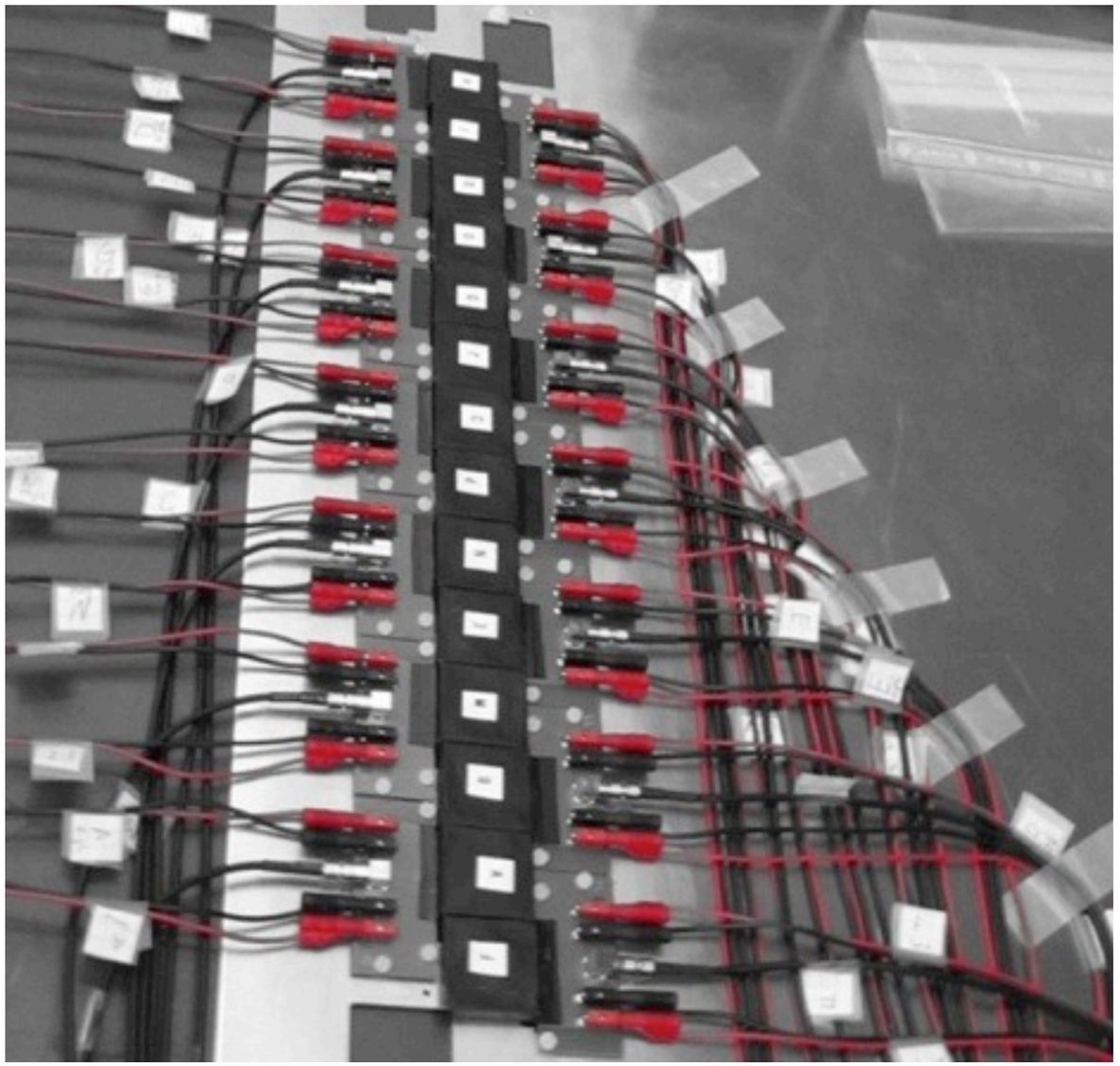


- Sensitivity to a wide range of particles within hadronic shower
  - RPCs blind to n elastic -> interesting cross-check !

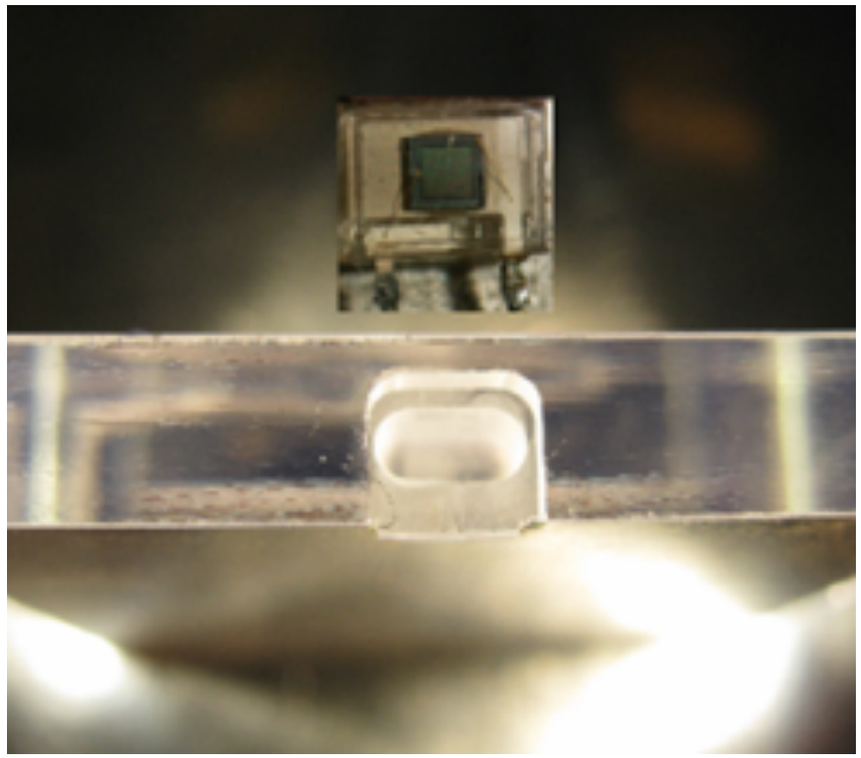


- Late components predominantly related to neutrons, in particular n-capture
- Expect wide spatial distribution: Shower halo most sensitive to time structure, core dominated by prompt relativistic particles

The T3B Setup



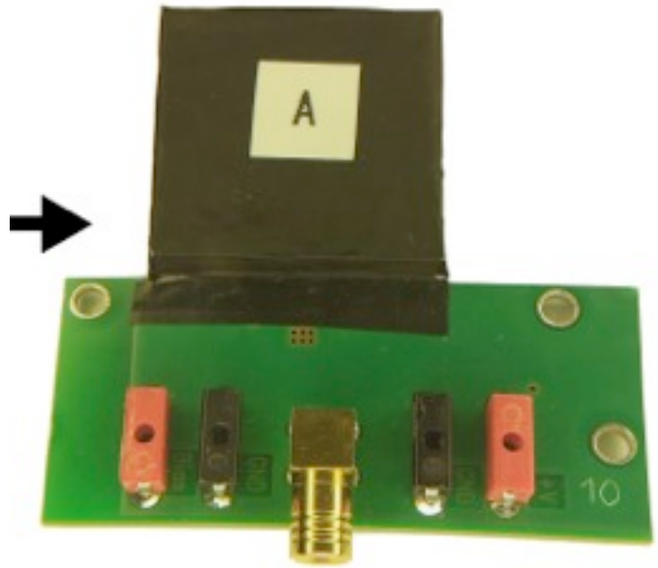
- 15 cells behind the WAHCAL / SDHCAL



- Directly coupled MPPC-50P
- Bicron BC420 scintillator (391 nm peak emission, pulse FWHM 1.3 ns, 0.5 ns rise time)
- Wrapped in 3M reflective foil

T3B Readout

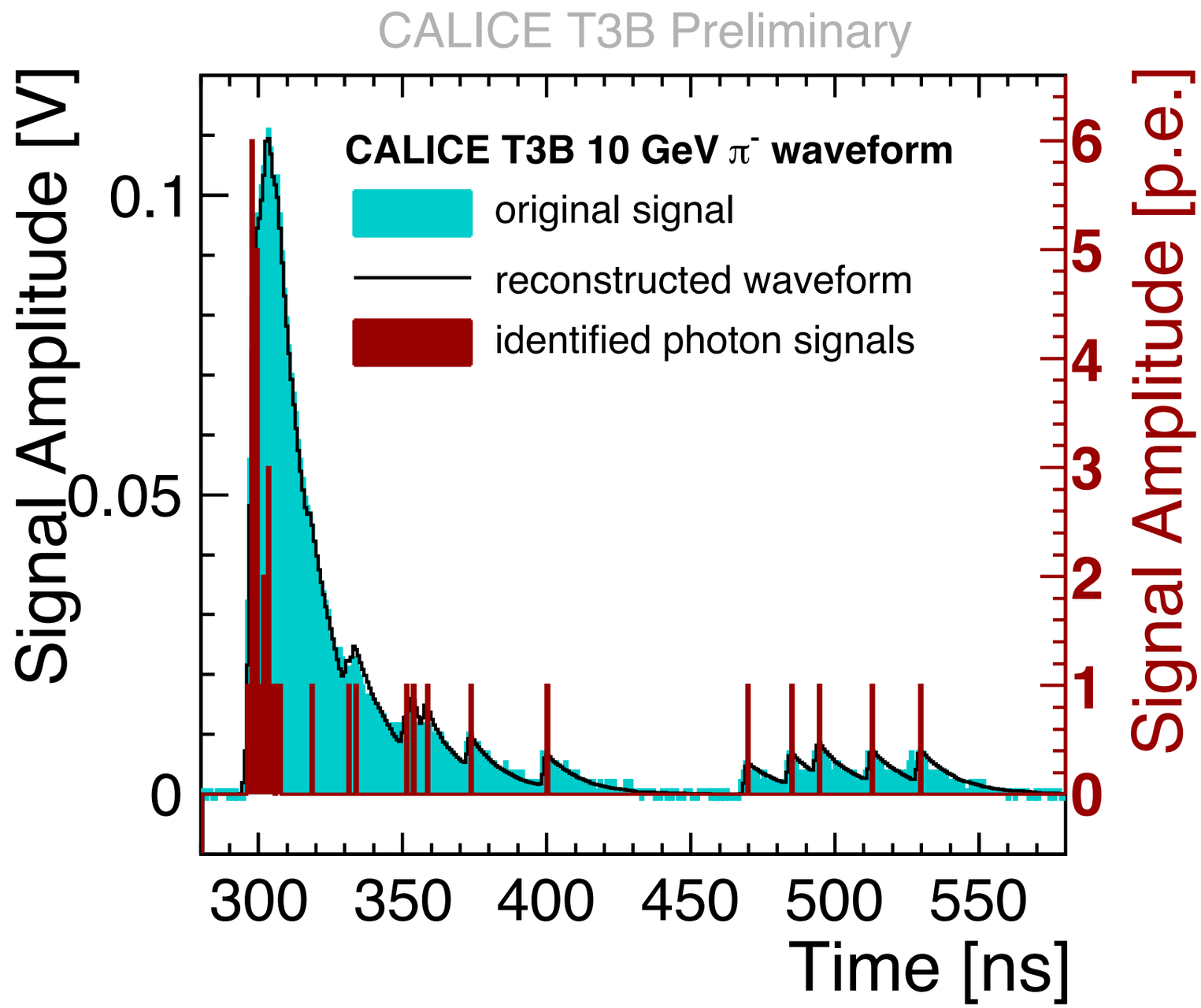
- SiPM mounted to high band-width preamplifier (x8.9 amplification)



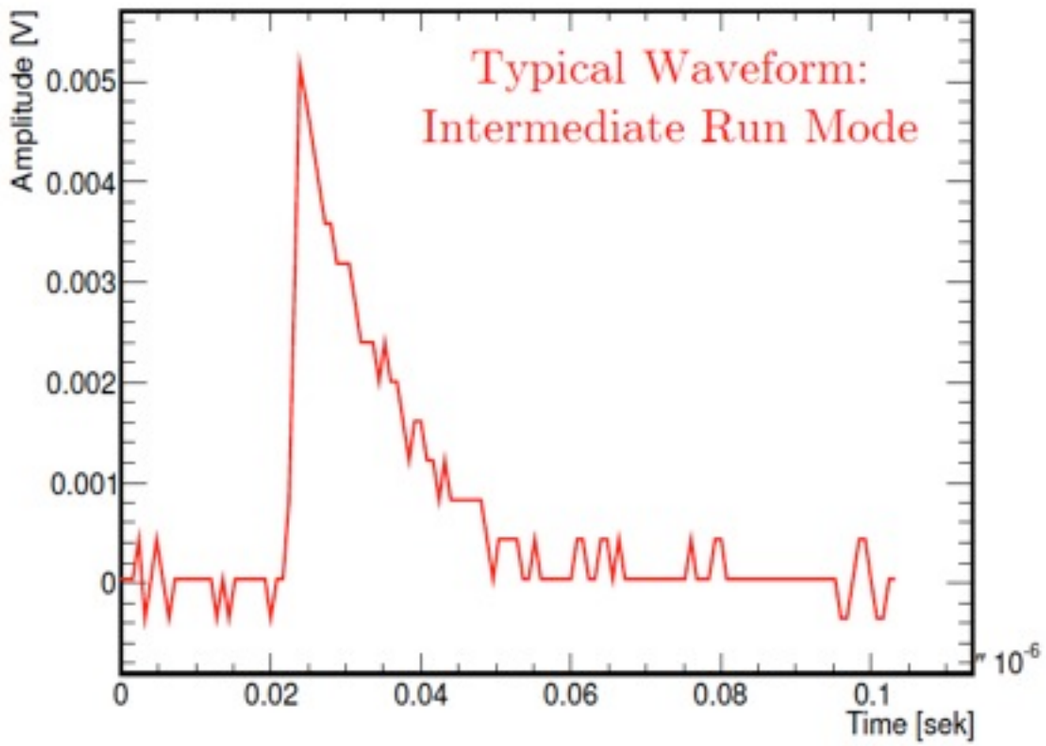
- Each channel read out with PicoScope PS6403
  - 1.25 GS/s
  - 2.4 μs acquisition window
  - max. trigger rate > 100 kHz

Data Reconstruction

- Full waveform recorded for each channel
- Individual photon arrival times (and total amplitude) determined by iteratively subtracting 1 p.e. signals

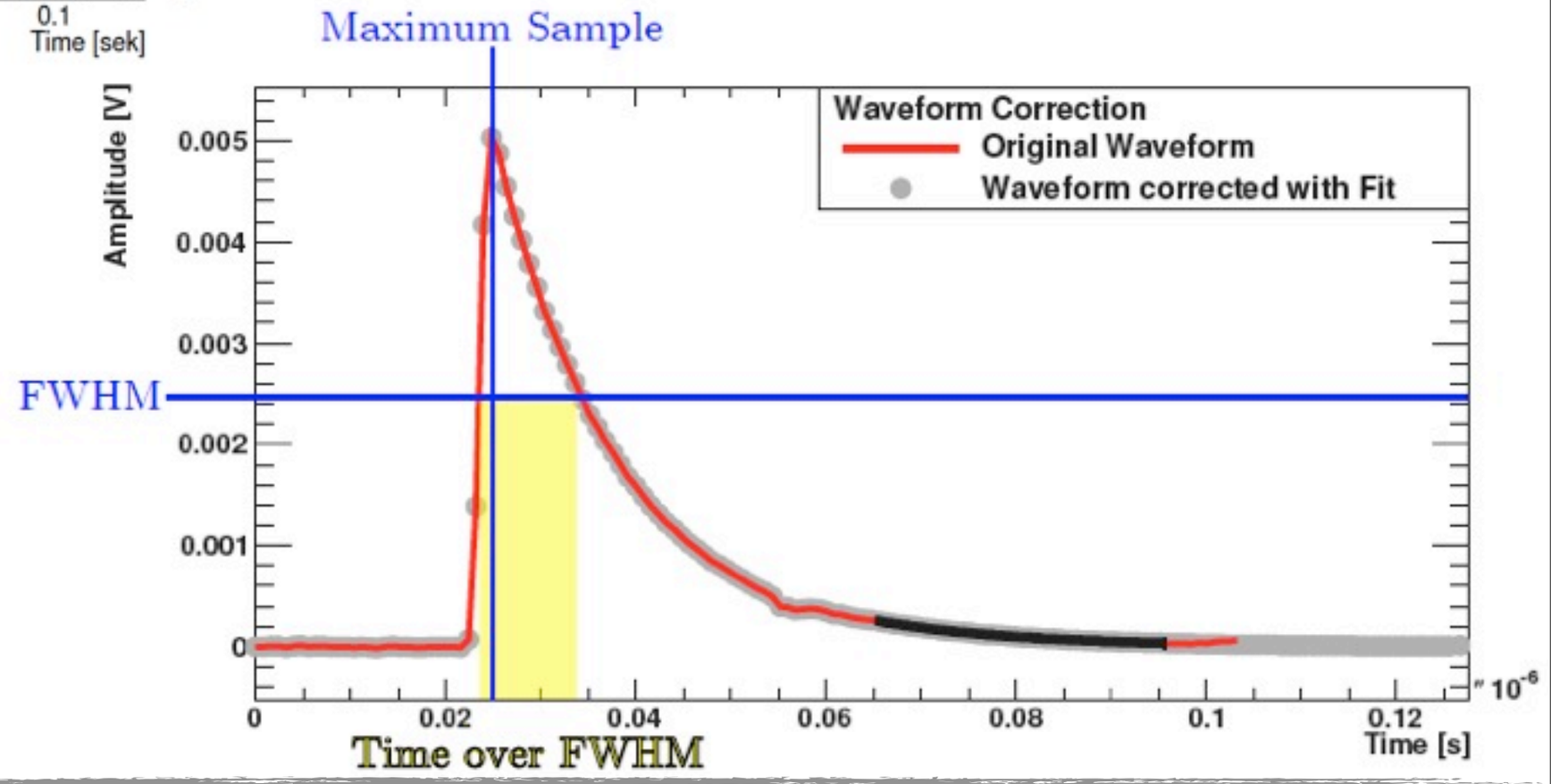


Calibration - Average 1 p.e. signal



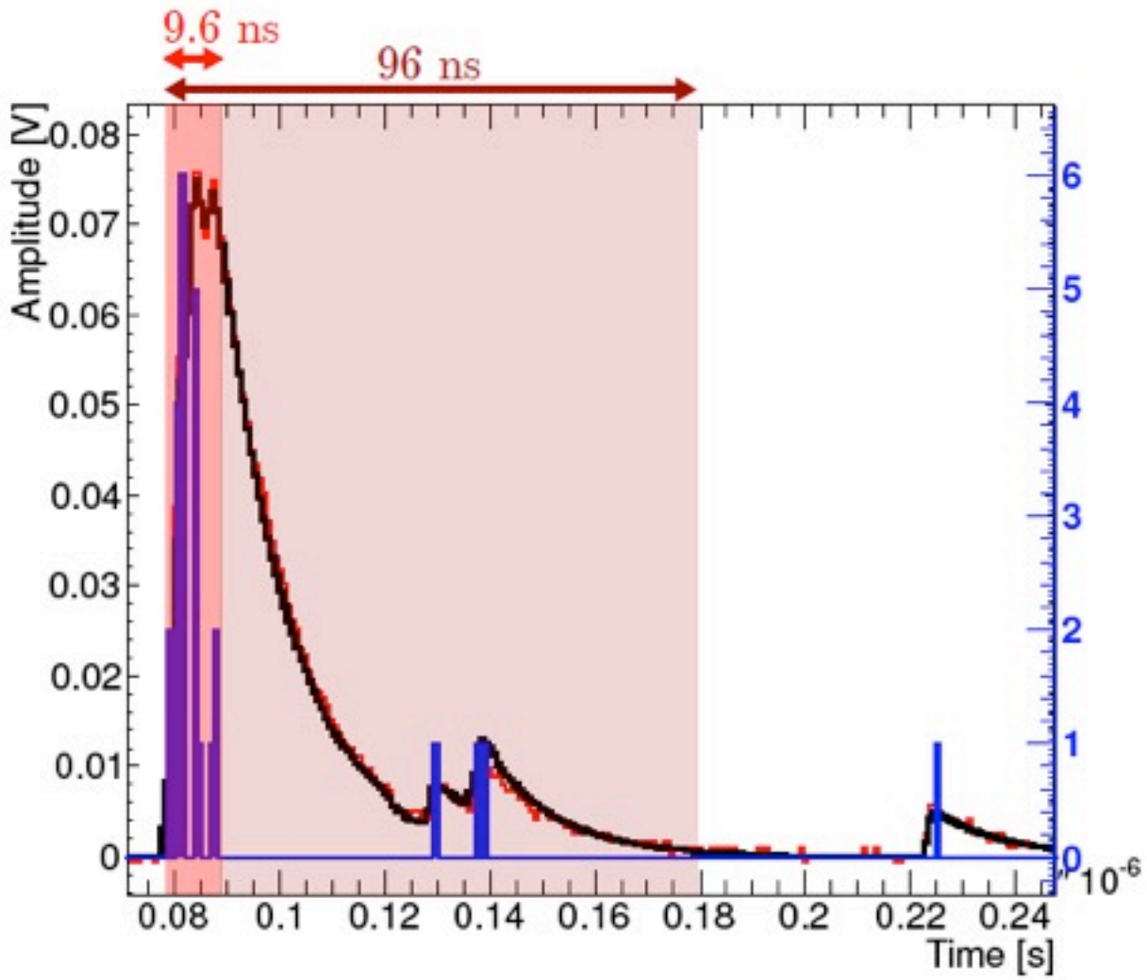
- Dark noise recorded between spills
- Every few minutes a reference 1 p.e. signal for each channel is built from data
- Automatic gain correction!

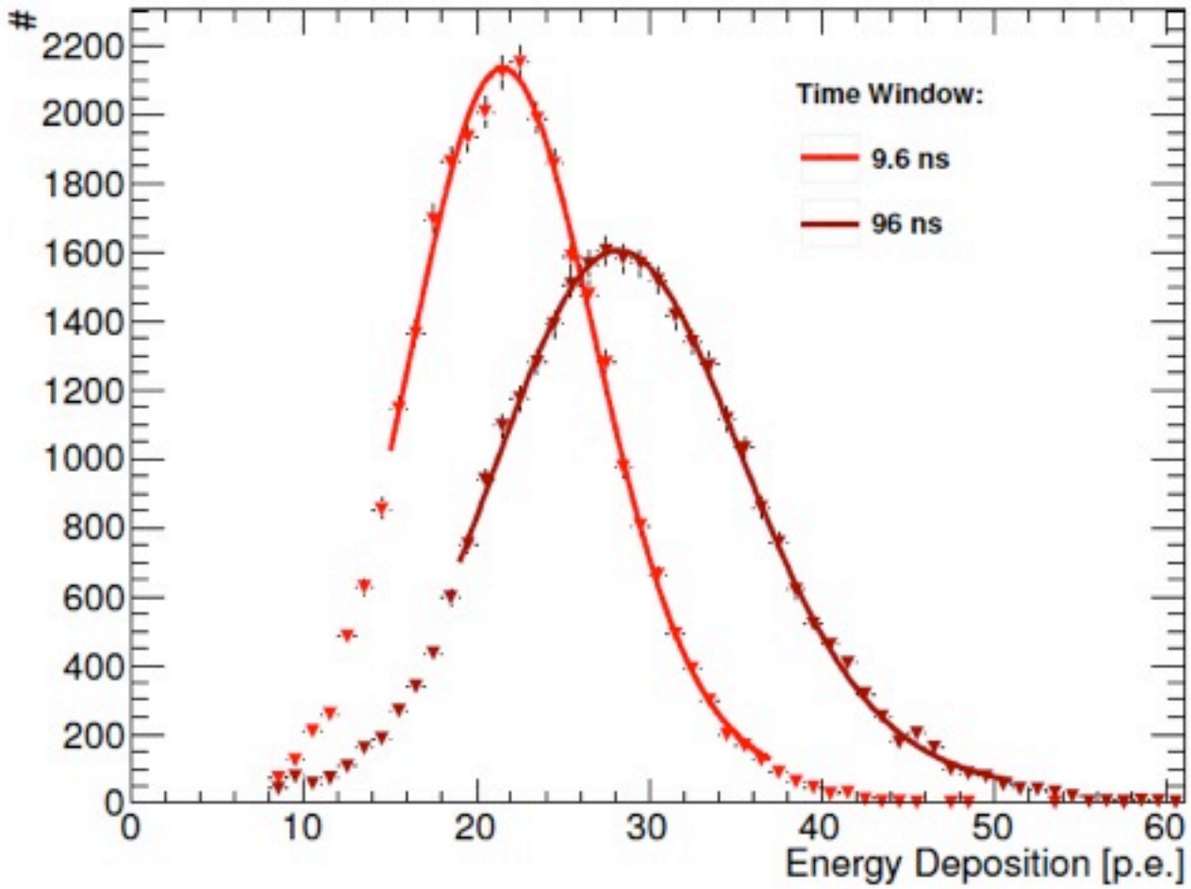
- Reference waveform determined by fit, including smooth extrapolation to avoid artifacts from end of acquisition window



Calibration - Energy

- Calibration of the time energy scale in the lab with a ^{90}Sr source
  - Additional correction factor to MIP scale: 0.82 (deposited 805 keV for MIPs compared to ~1 MeV for ^{90}Sr electrons

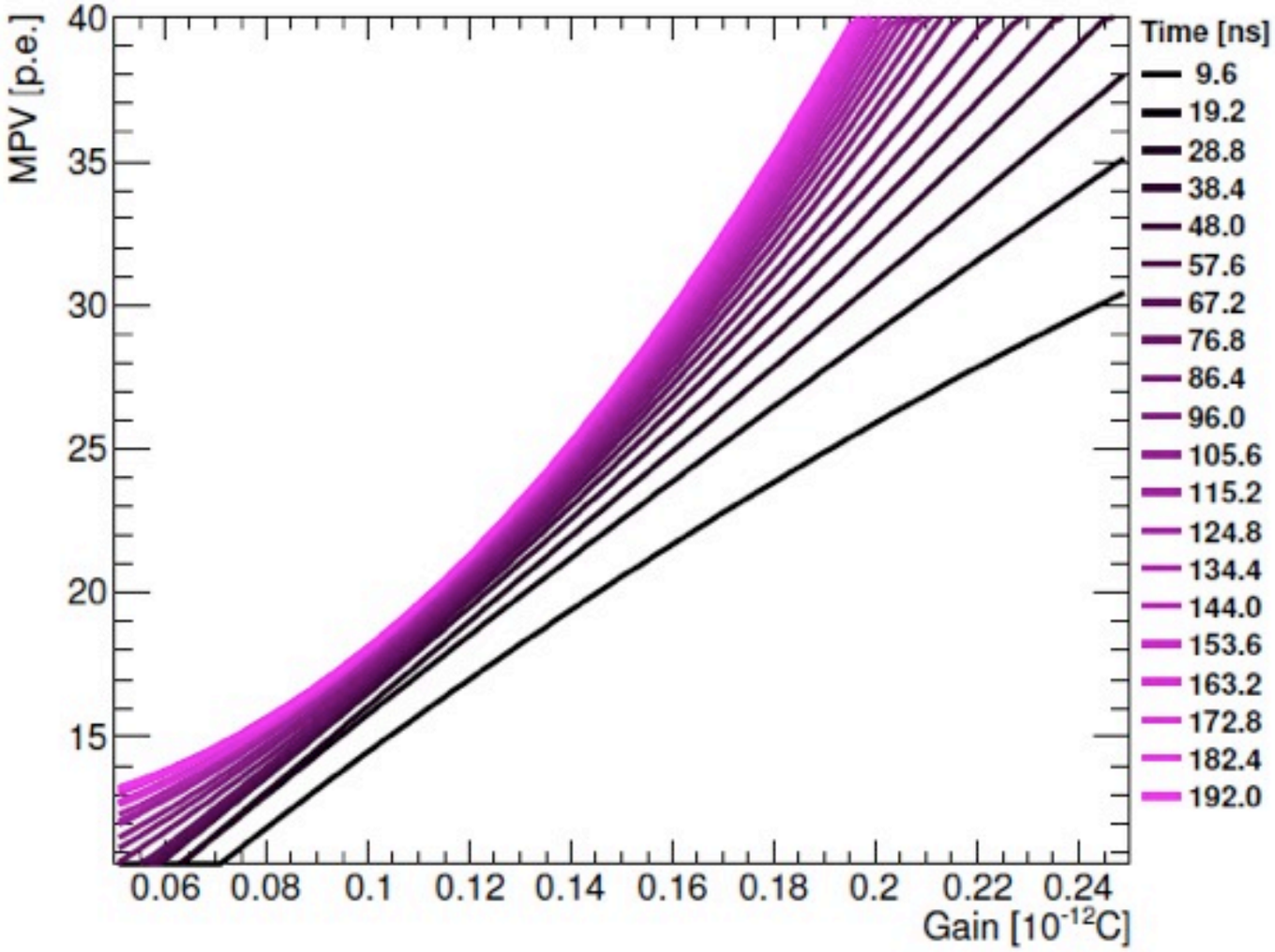




- MIP amplitude in p.e. depends strongly on integration time: Afterpulses of the photon sensor!

Calibration - Energy

- Temperature matters: Direct effect on the gain (since we keep the operating voltage constant)
- But beware: Afterpulses also change with temperature and voltage!
- **Temperature correction is integration-time dependent!**



For short integration times
(< recovery time of MPPC micro-cells):
Linear dependence of MIP on gain

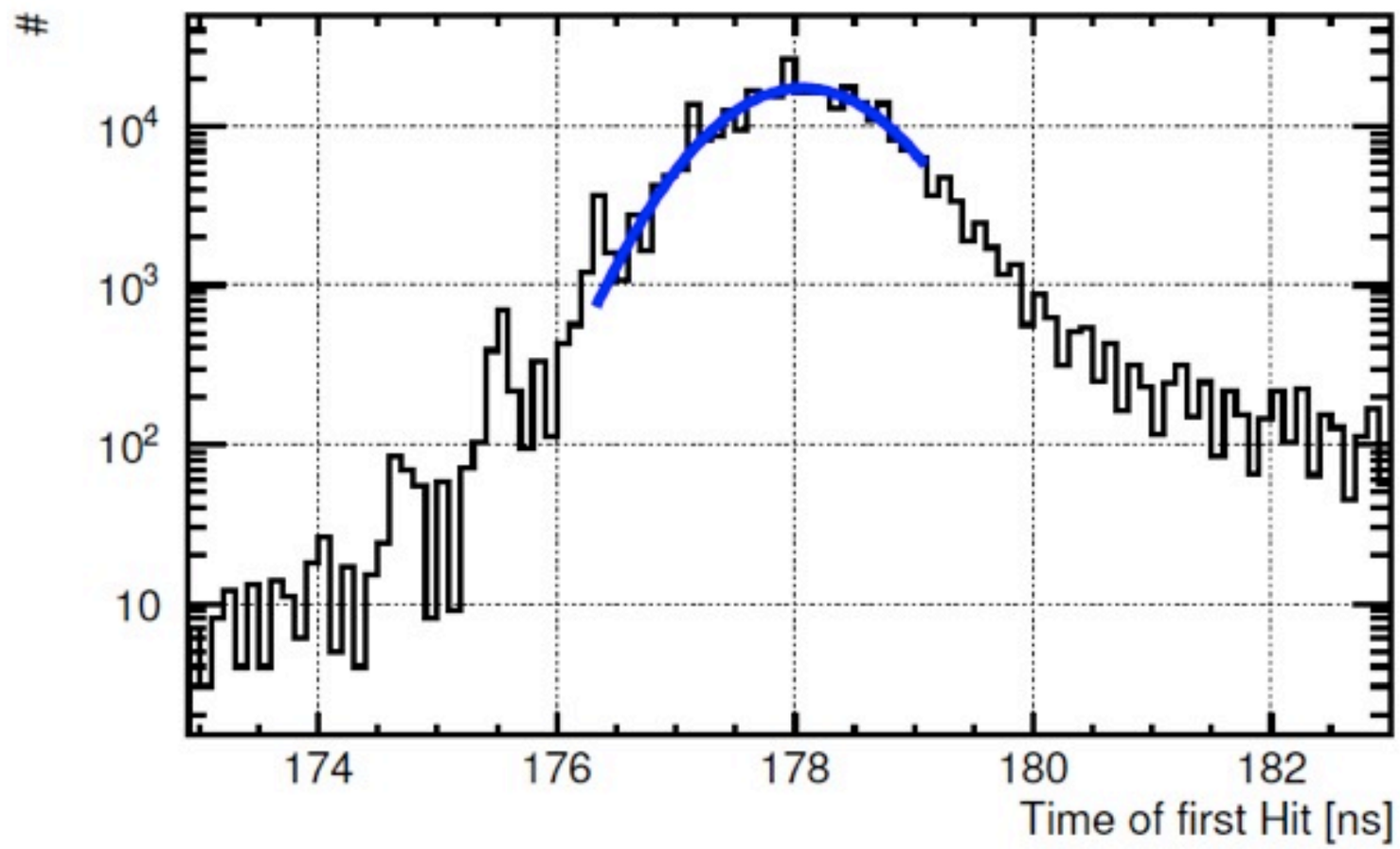
For long integration times
(>> recovery time of MPPC micro-cells):
Quadratic dependence of MIP on gain

Calibration - Time

- T3B is not capable of measuring absolute time: No careful study of signal running times from trigger system to T3B
  - Triggers taken from CALICE DAQ backplane with WAHCAL, directly from scintillator coincidence with SDHCAL
- But: Took great care that all oscilloscopes trigger at the same time: uniform cable lengths to Picoscope external trigger, uniform cable lengths for T3B tiles (on the 1 - 2 cm (50 - 100 ps) level)

- To measure time relative to primary particle impact, a measurement of the latency of the whole system is required
  - Since channel-to-channel timing is fixed, this can be done with a single cell

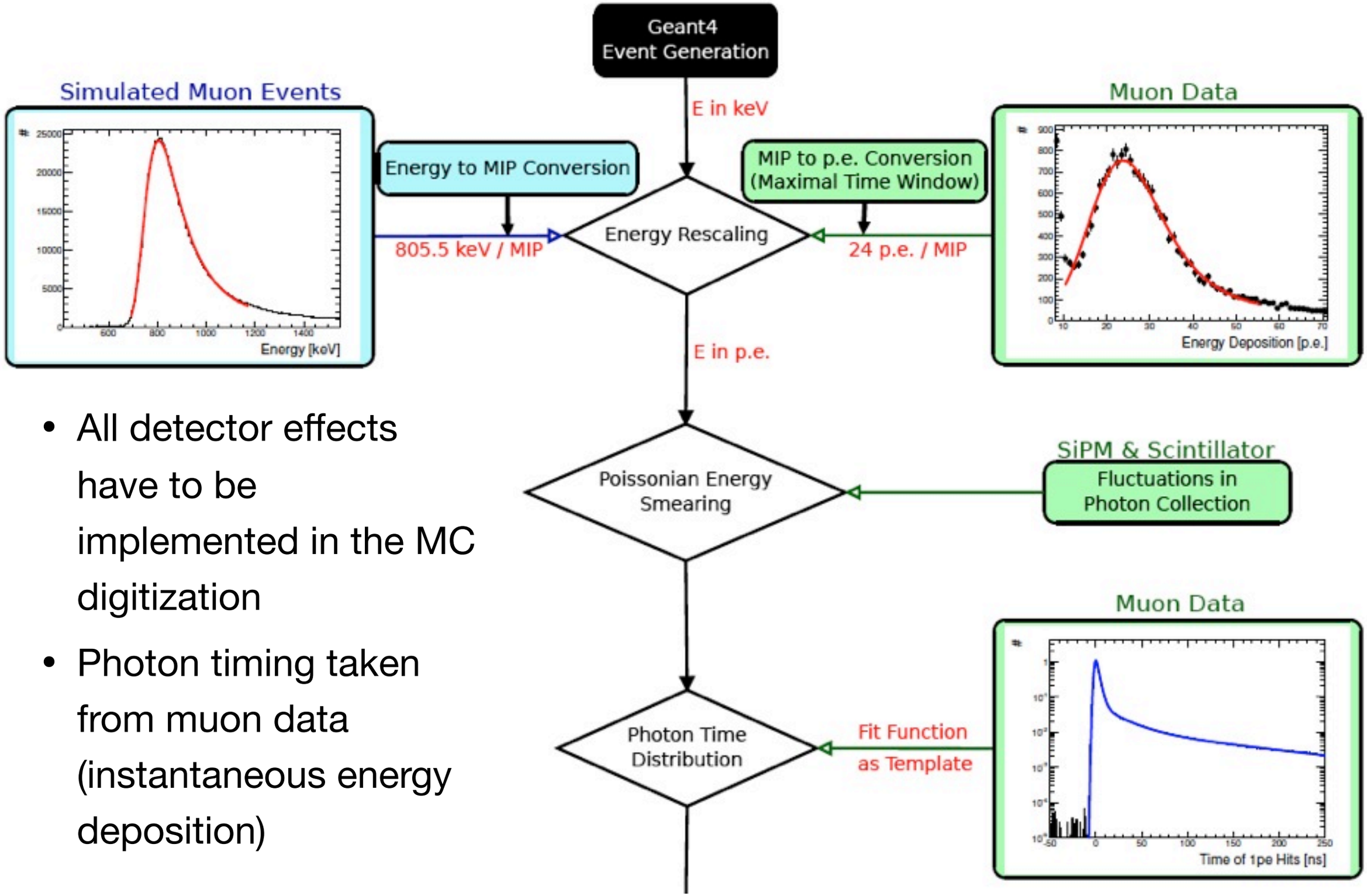
Calibration - Time



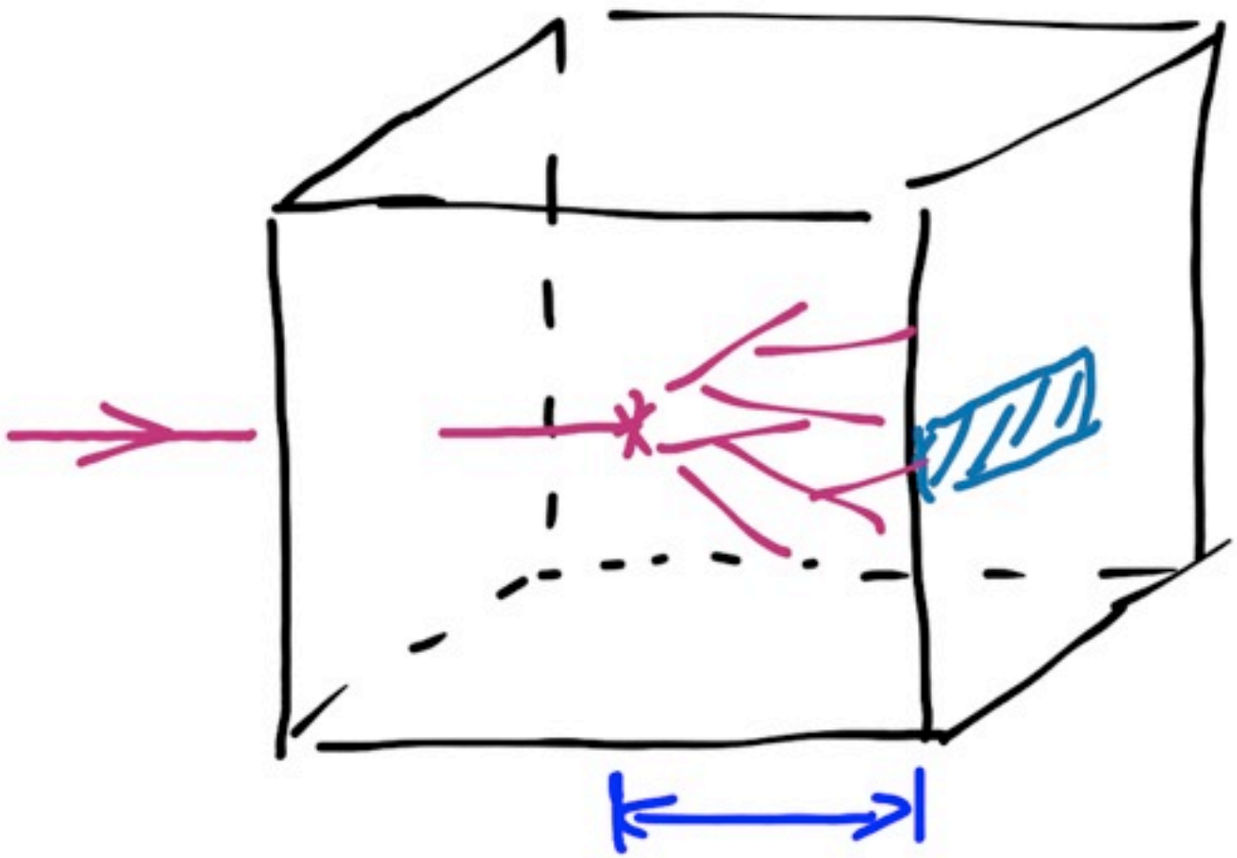
- Fix the global timing: Penetrating particles in the central tile of T3B
  - Done on time of first hit distribution: The main peak corresponds to instantaneous (relativistic) particles - Peak determined with a Gaussian, set to t = 0 in analysis

Simulations

- All detector effects have to be implemented in the MC digitization
- Photon timing taken from muon data (instantaneous energy deposition)

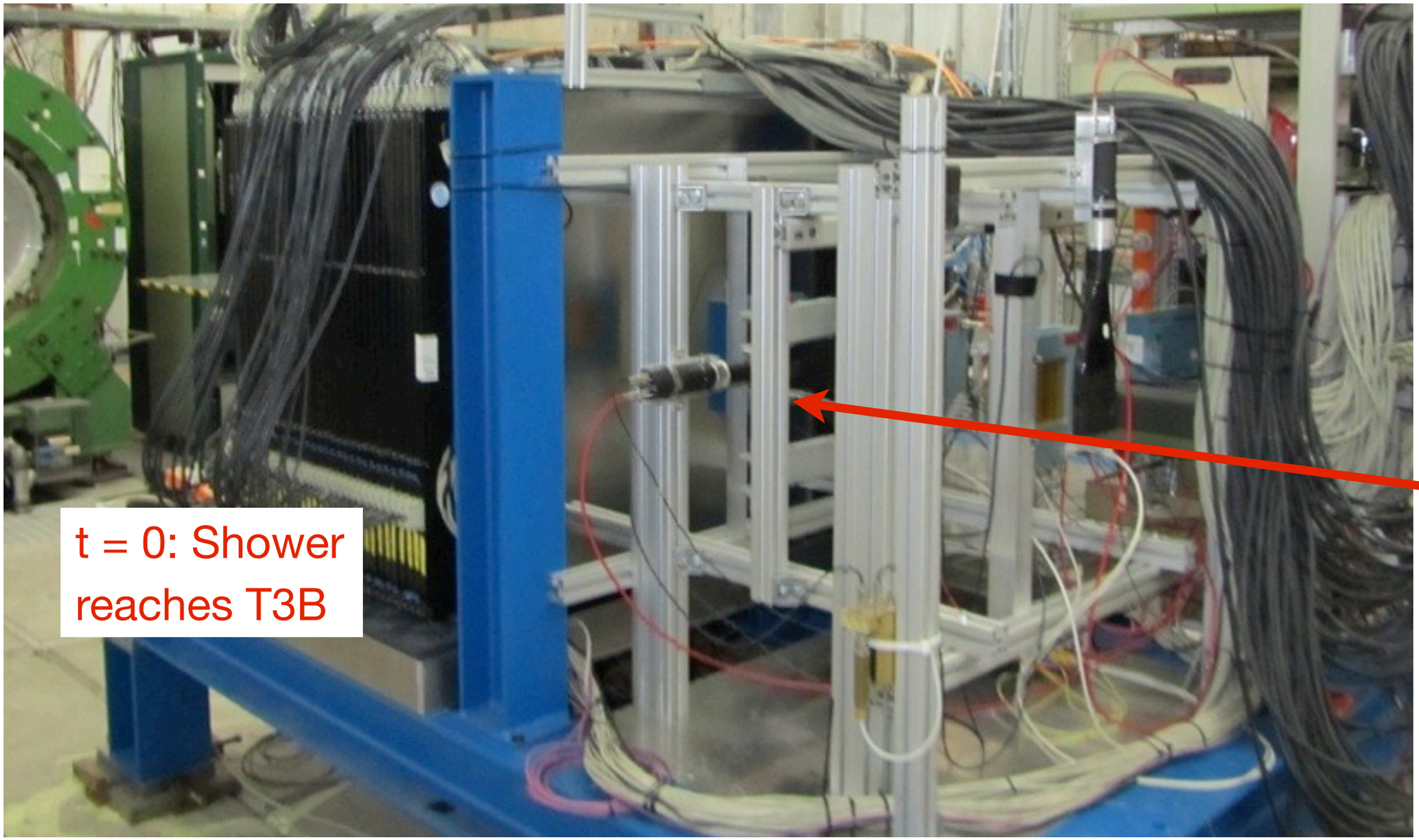


The Making Of: The Movie



- Correlate T3B and WAHCAL events: Event-wise shower start information
- Split data set (identified first hits) into 3D - histogram:
  - radial position: T3B cell id
  - longitudinal depth in shower: distance of shower start and T3B (the number of events in the shower start bins is used as normalization basis: gets longitudinal profile right!)
- time: measured time of first hit, corrected for speed of light propagation from shower start to T3B

The Making Of: The Movie



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