CALICE T3B - The time structure of hadronic showers in Tungsten and Steel

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Calorimeter for ILC

Excellence Cluster
Universe

Outline

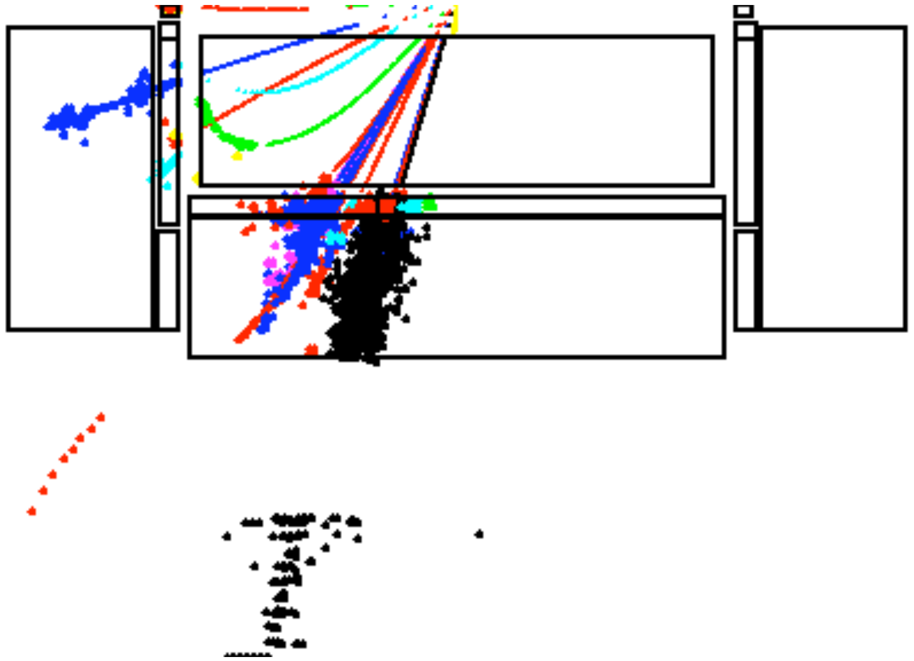
- Hadron Calorimetry at CLIC: Competing Requirements
- CALICE T3B - A Setup for Timing Measurements
  - T3B in Tungsten & Steel
  - Data Analysis
- Timing Results & Comparison to Simulations
- A 4th Dimension: Longitudinal Information
  - The Life of a Pion on a Tungsten Calorimeter
- Summary & Outlook

Original Motivation: Hadron Calorimetry at CLIC

- CLIC: A 3 TeV e^+e^- linear collider

  The key CLIC feature: High Energy!

  - 3 TeV energy means in principle up to 1.5 TeV jets



Shower containment and leakage is a crucial issue

➩ A (very) deep hadron calorimeter is needed

➩ Use compact absorbers to limit the detector radius: Tungsten a natural choice

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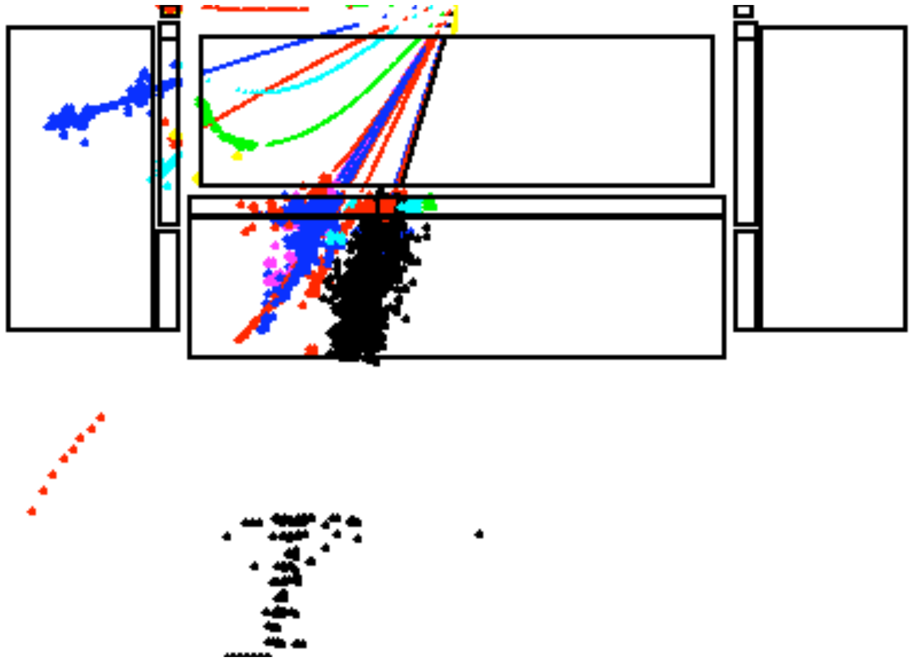

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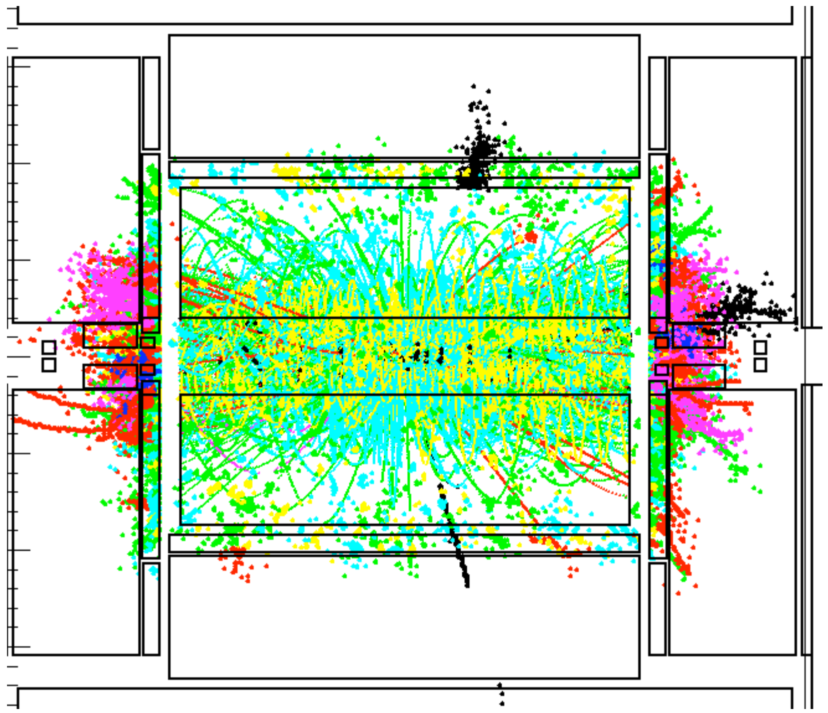
- Key challenge (linked to high energy and machine-specific issues): Background

  - $\gamma\gamma \rightarrow$ hadrons substantial:

    ~ 12 hadrons/bunch crossing in the barrel region

    (4 GeV / bunch crossing) [up to 50 hadrons /

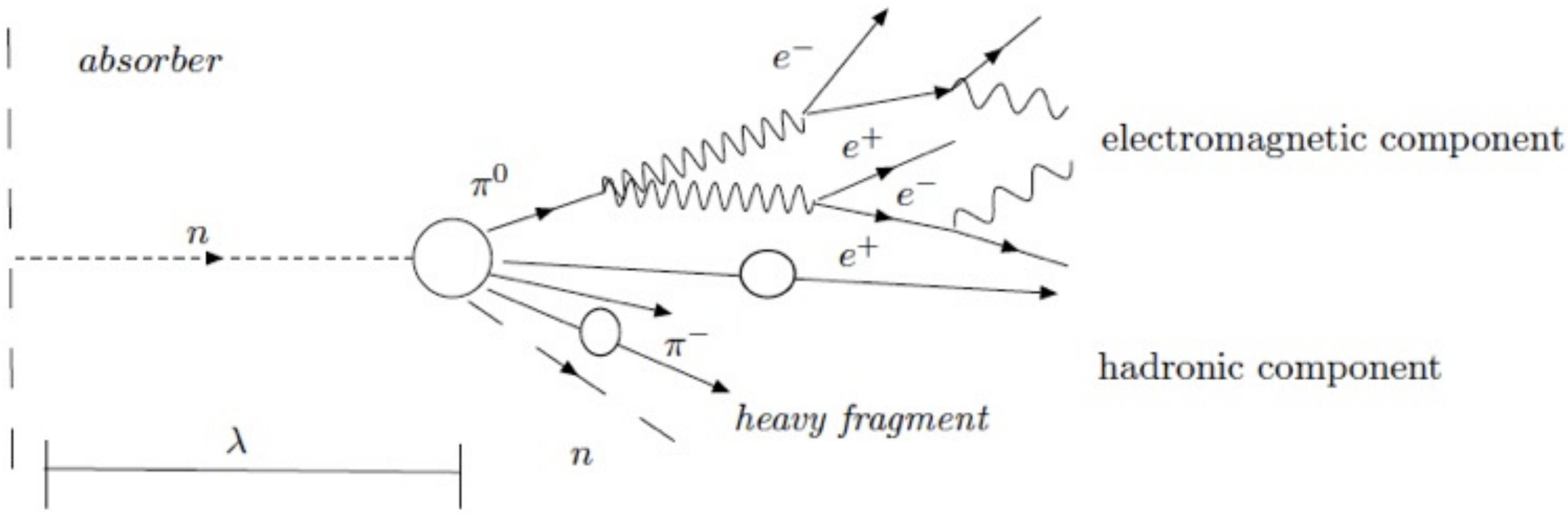
    50 - 60 GeV barrel + endcap + plug calorimeters]

  - extreme bunch crossing rate: every 0.5 ns

➩ Very good time resolution in all detectors important to limit impact of background!

Hadronic Showers: Complex (Time) Structure

- Hadronic showers have a rich substructure:



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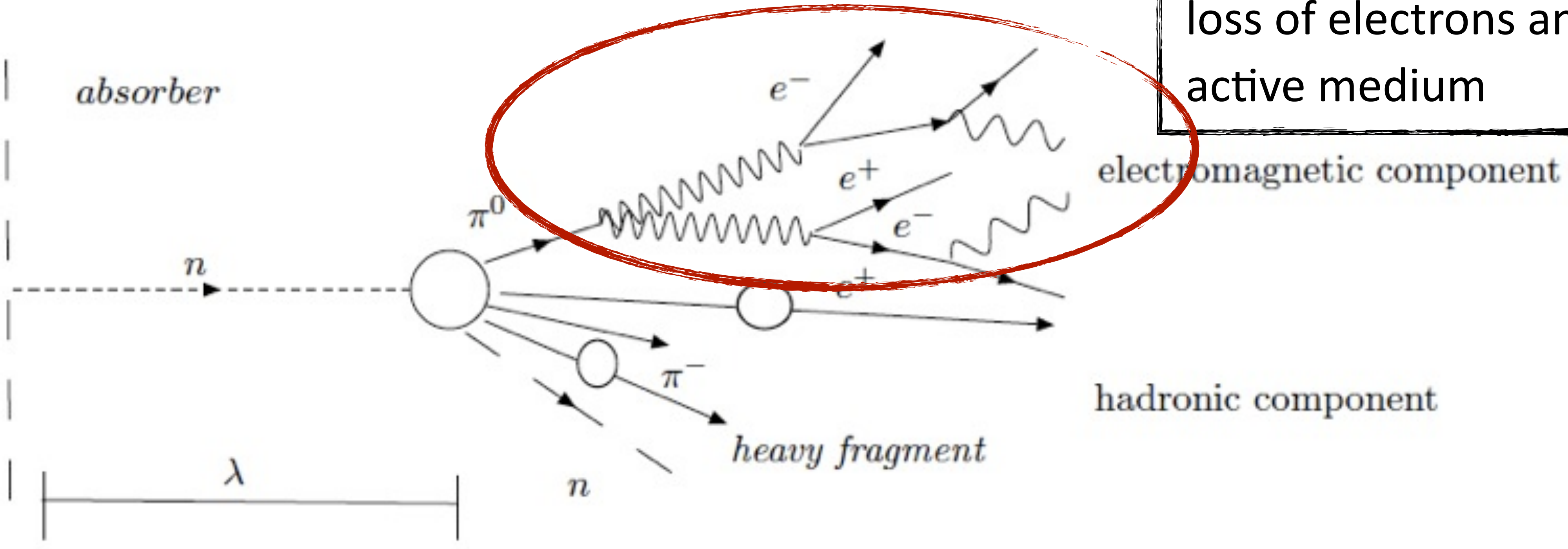

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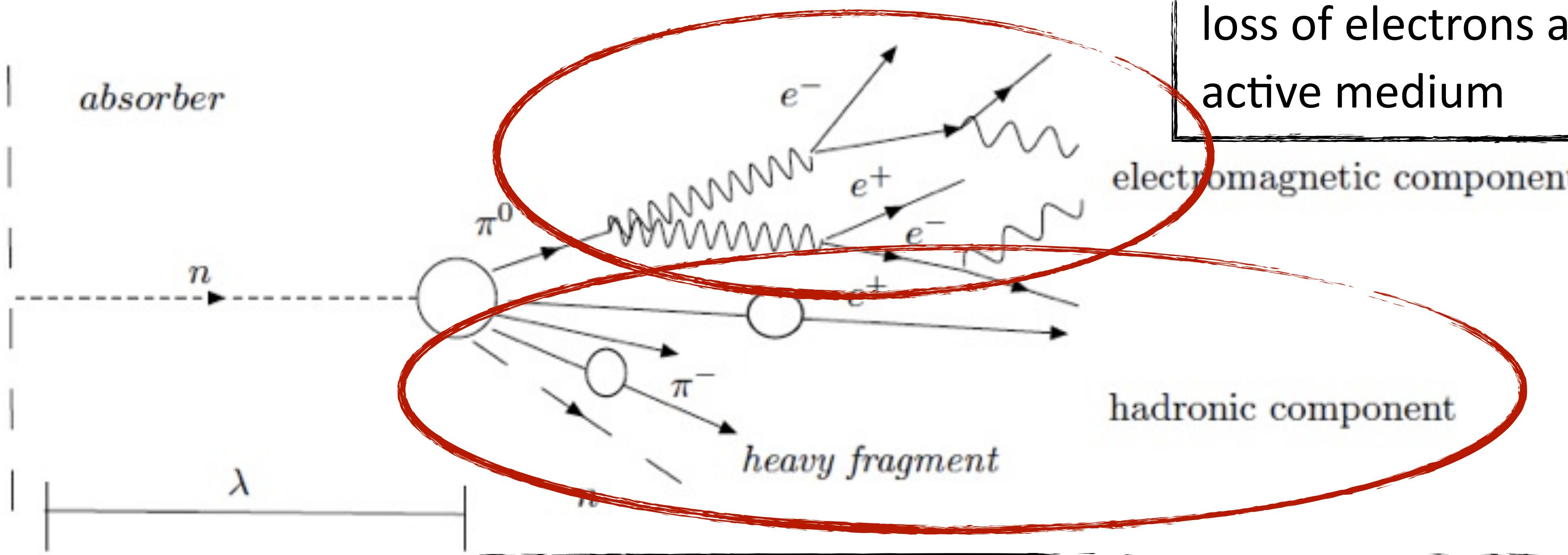

- instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium
- delayed component: photons, neutrons, protons from nuclear de-excitation following neutron capture, detected via e^+e^-, momentum transfer to protons in hydrogenous active medium, energy loss, contributions from time of flight of low energy particles

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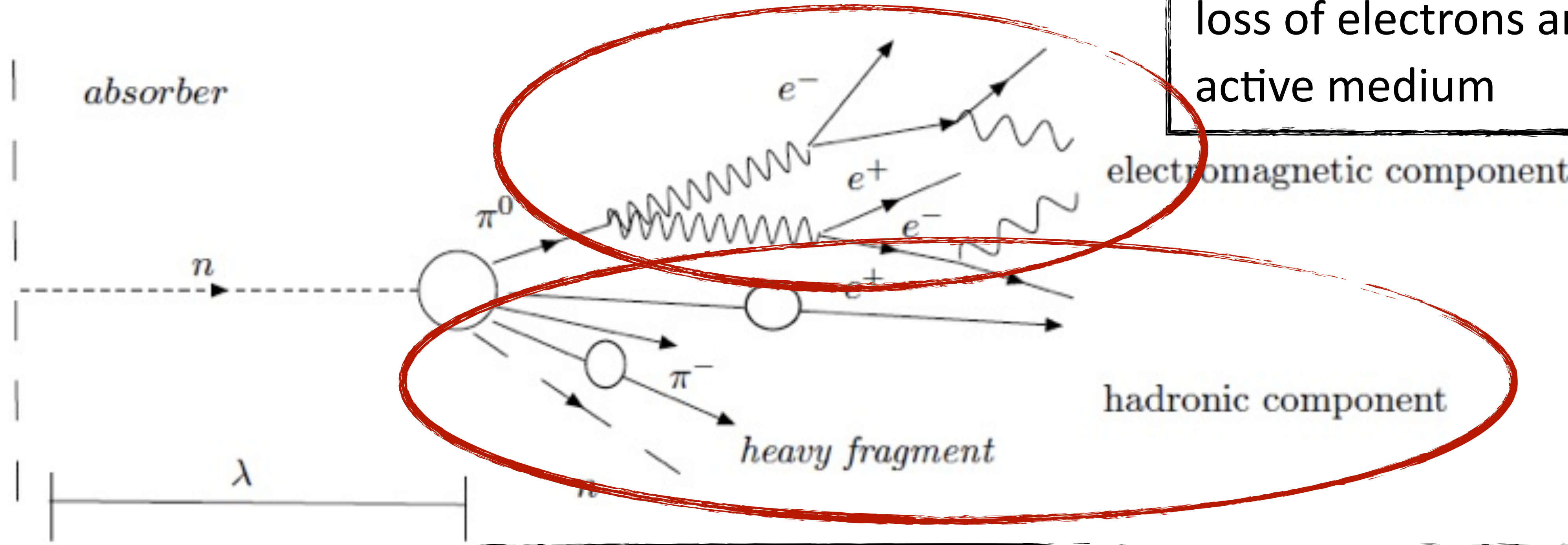

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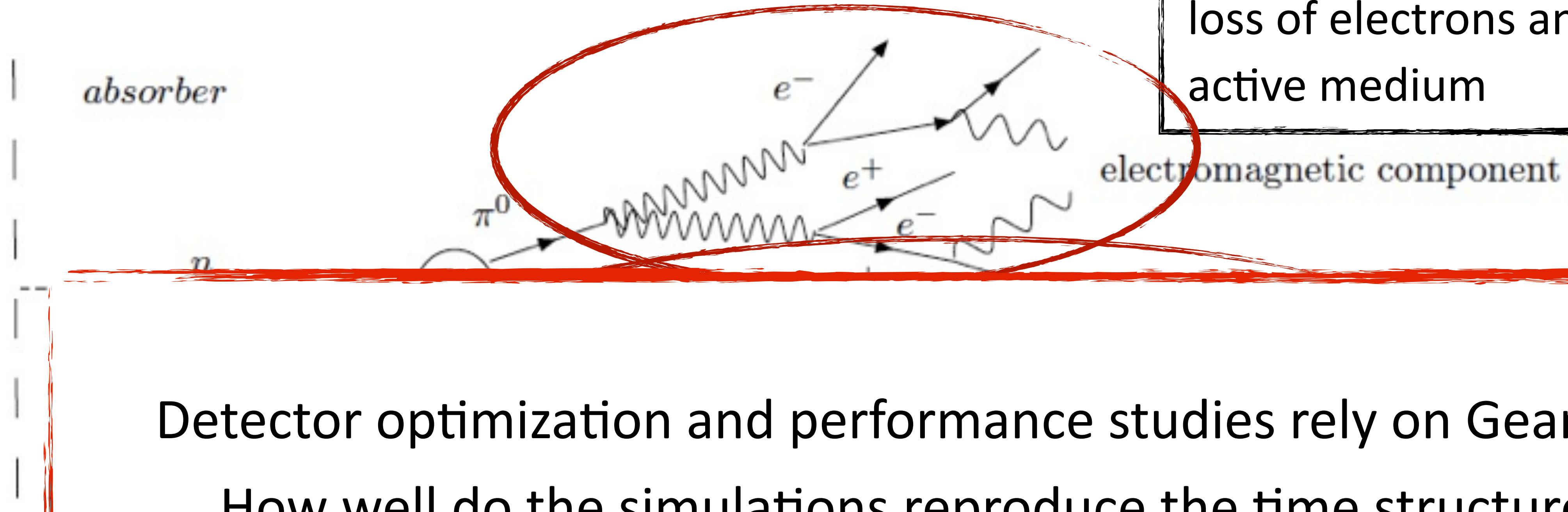

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Detector optimization and performance studies rely on Geant4:
How well do the simulations reproduce the time structure
of the response in the highly granular calorimeters?

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➩ Importance of delayed component strongly depends on target nucleus

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T3B: An Experiment for the Study of the Time Structure

- The CALICE Scintillator-Tungsten HCAL - A CLIC physics prototype
  - 30 layers with 10 mm Tungsten (93% W, 5% Ni, 2% Cu, density 17.6 g/cm^3) absorber
  - Active elements from CALICE AHCAL: 5 mm thick scintillator tiles, read out by SiPMs (no time information available)

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- T3B (Tungsten Timing Test Beam)
  - Goal: Measure the time structure of the signal within hadronic showers in a Tungsten calorimeter with scintillator readout
  - Use a (very) small number of scintillator cells, read those out with high time resolution
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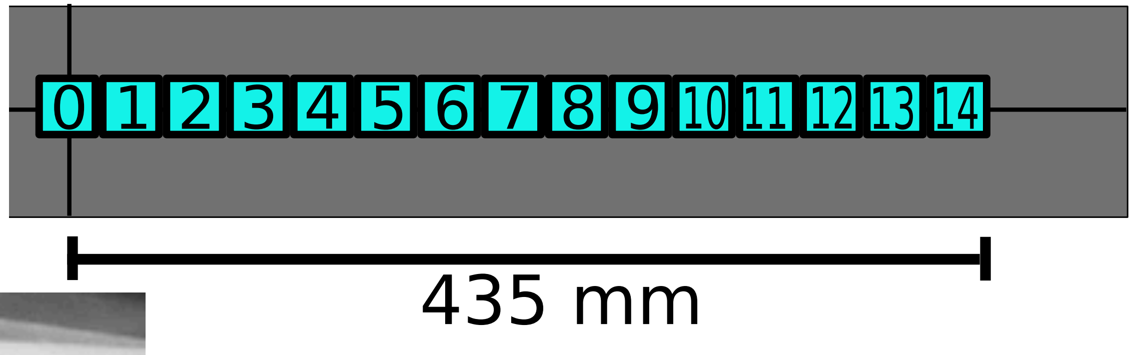
➩ First information on time structure, possibility for comparisons to Geant4, but: no complete "4D" shower reconstruction!

The T3B Setup - Tungsten

- 15 3 x 3 cm^2 scintillator cells, sampling the radial extent of the shower

beam axis
through cell 0



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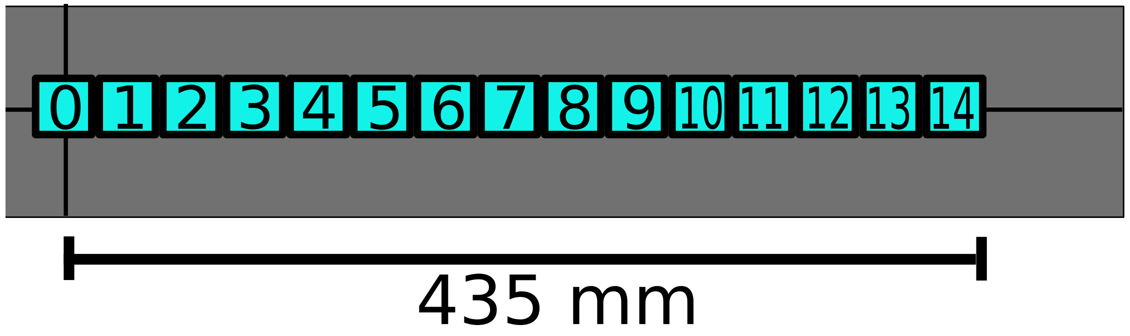


Stand-alone system:

- Installed downstream of CALICE WHCAL, depth ~ 5 λ
- Each cell read out with 1.25 GS oscilloscope, 2.4 µs sampling time per event
- Calibration triggers on dark noise between spills

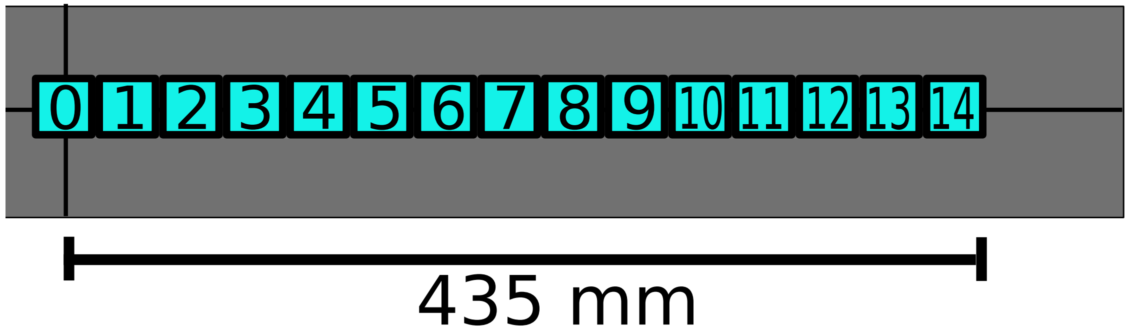
Synchronization with CALICE

- Triggered by CALICE trigger - common analysis possible

The T3B Setup - Steel

- 15 3 x 3 cm^2 scintillator cells, sampling the radial extent of the shower

beam axis
through cell 0



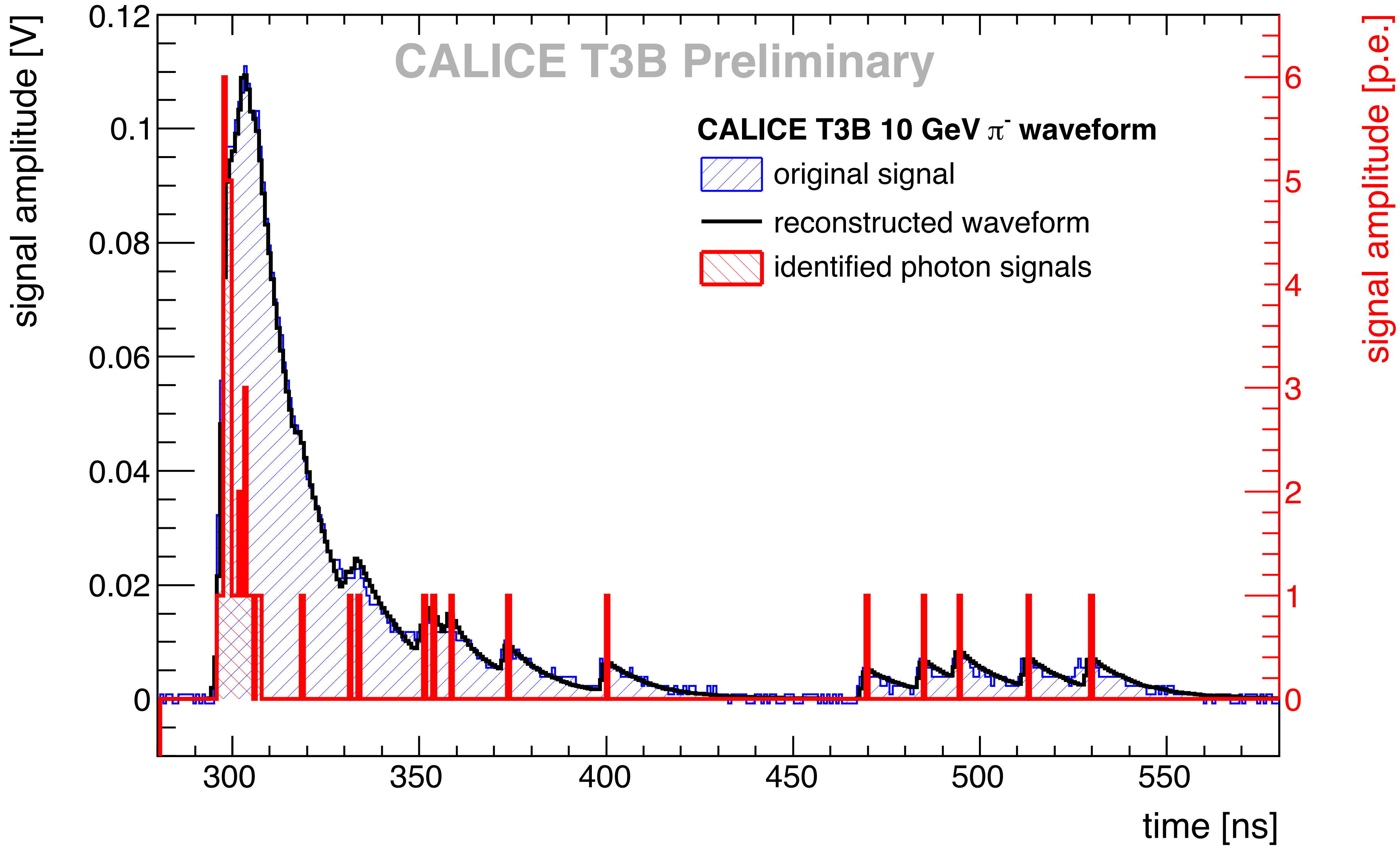
Stand-alone system only:

- Installed downstream of CALICE SDHCAL (Glass RPCs between steel absorbers), depth ~ 6 λ
- Identical readout for T3B
- No correlation of T3B and SDHCAL data streams
  - Different DAQ version
  - Data taken during SDHCAL commissioning: Low data rate, insufficient for timing measurements
  - ▸ Standalone trigger for T3B

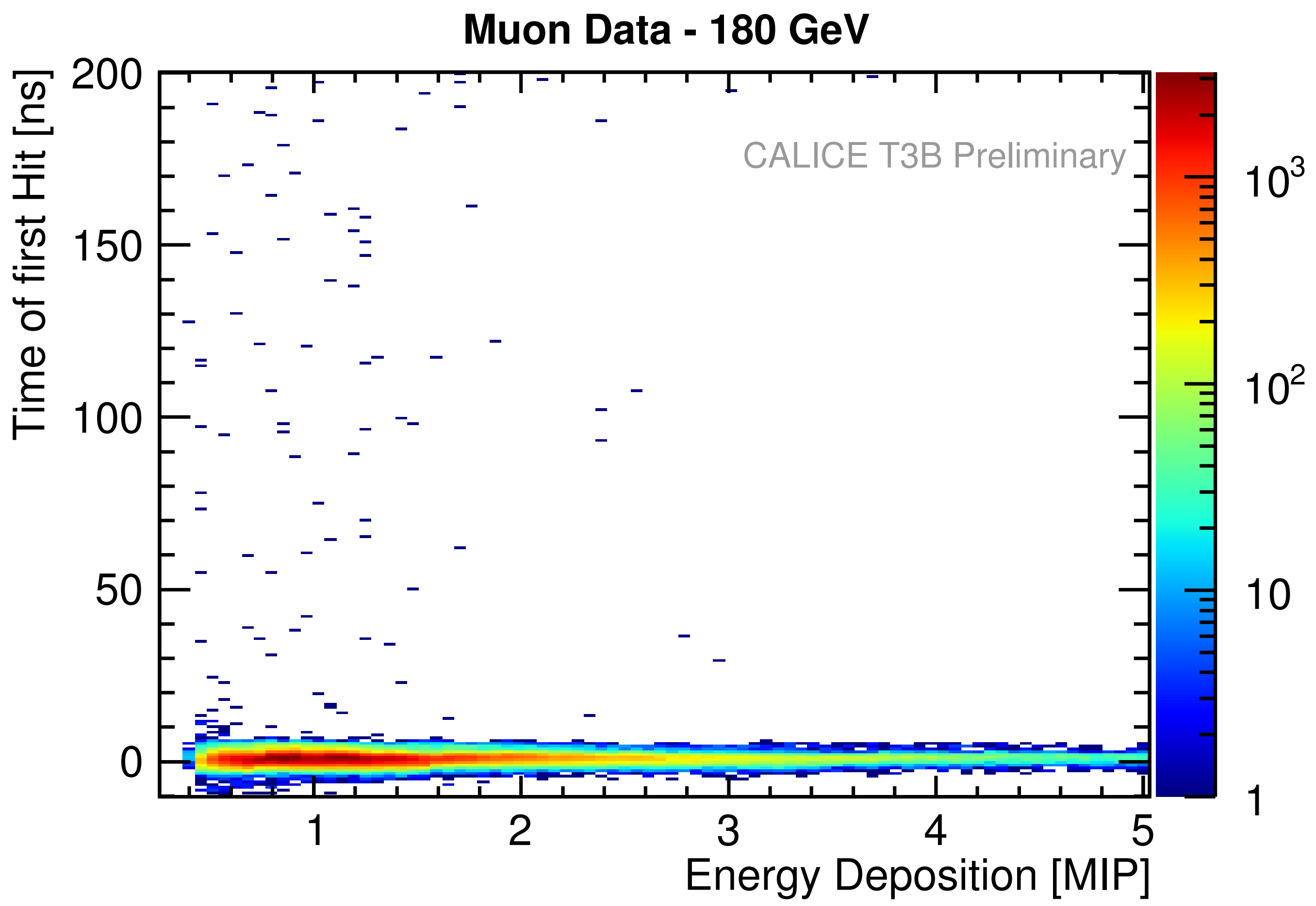
Data Analysis - Technique

- For each channel, a complete waveform with 3000 samples (800 ps /sample) is saved
- Waveform decomposed into individual photon signals, using averaged 1 p.e. signals
  - Average 1 p.e. signal taken from calibration runs between spills, refreshed every 5 minutes: Continuous automatic gain calibration

- Reconstruction of the time of each photo-electron
- In addition: Constantly adjusted MIP calibration based on temperature and voltage



Data Analysis - Results in Steel & Tungsten



- The "universal" T3B observable: Time of First Hit
  - Multiple hits per tile in one event are rare: < 3% at 30% amplitude of primary hit

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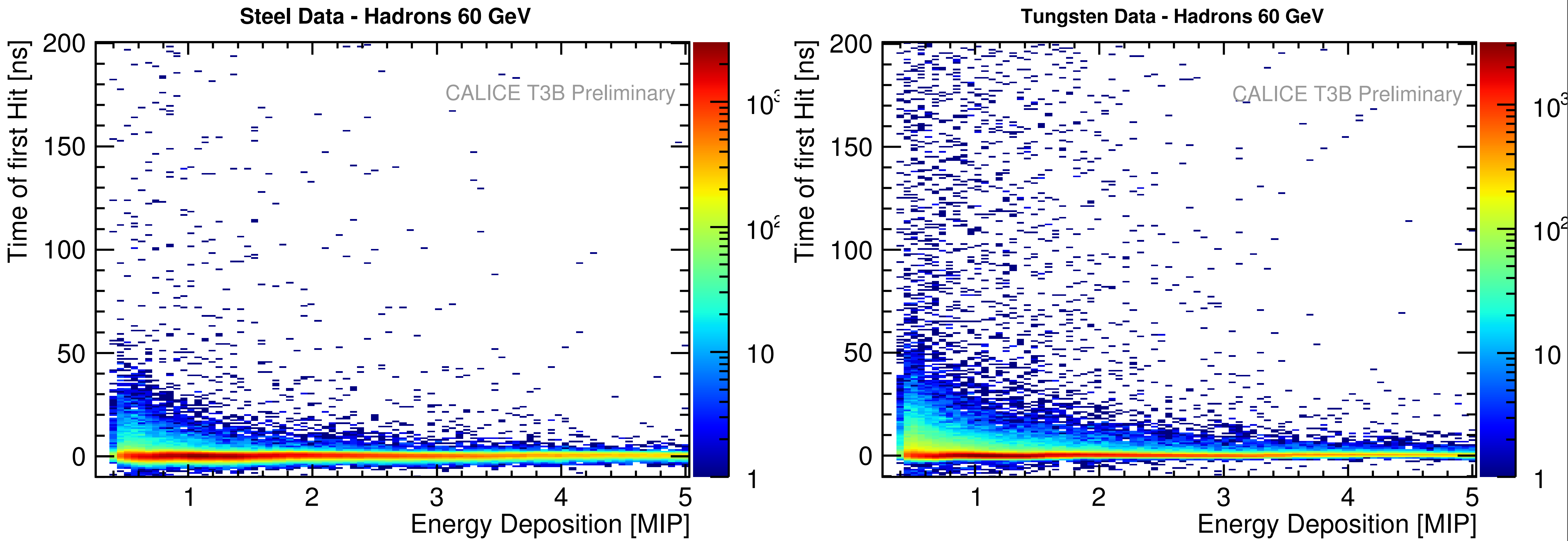
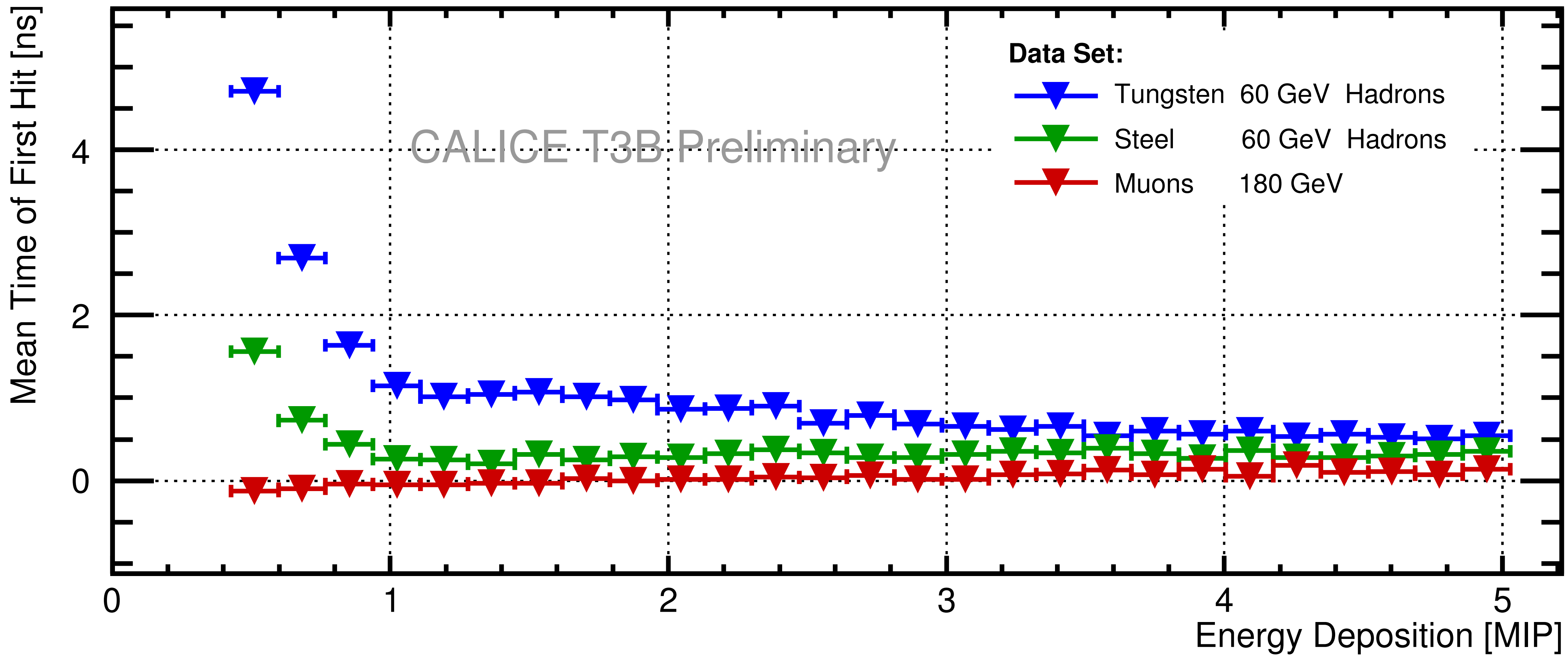


- The “universal” T3B observable: Time of First Hit
  - Multiple hits per tile in one event are rare: < 3% at 30% amplitude of primary hit
- Substantial difference between showers in steel and tungsten: More pronounced late activity in W

Timing as a Function of Hit Energy



- In steel late energy deposits are mostly of low energy, in tungsten also higher-energy late contributions are seen

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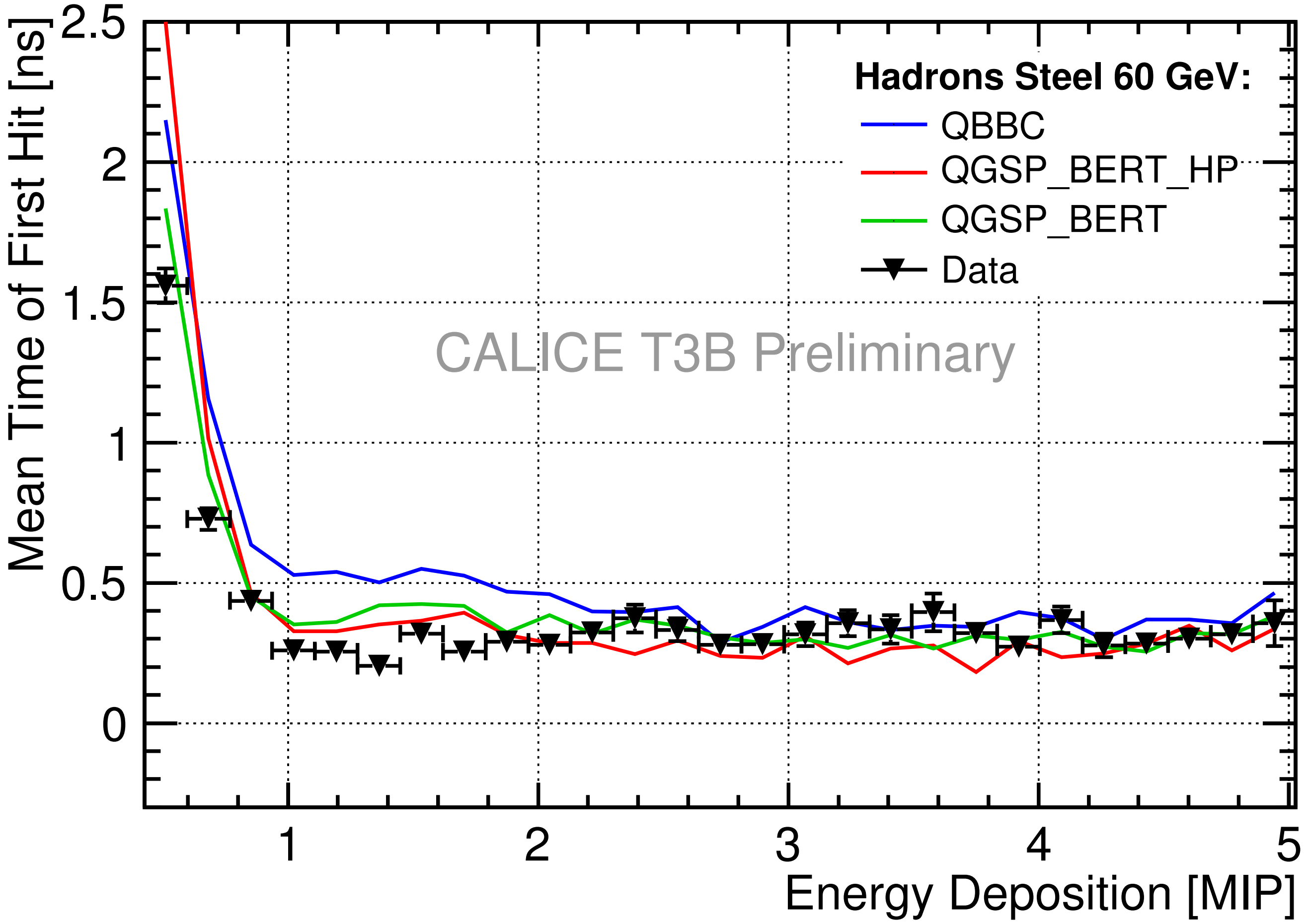
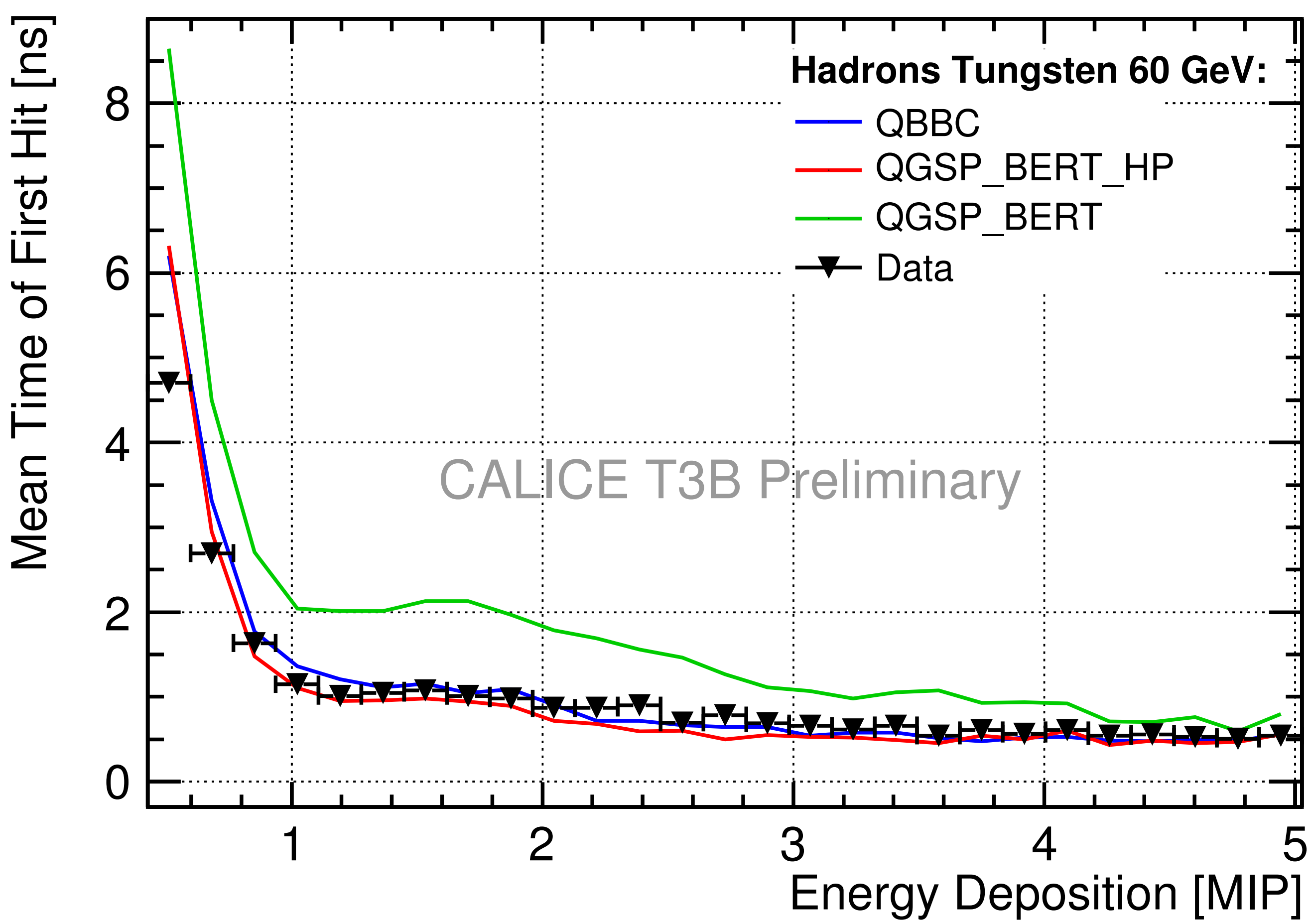
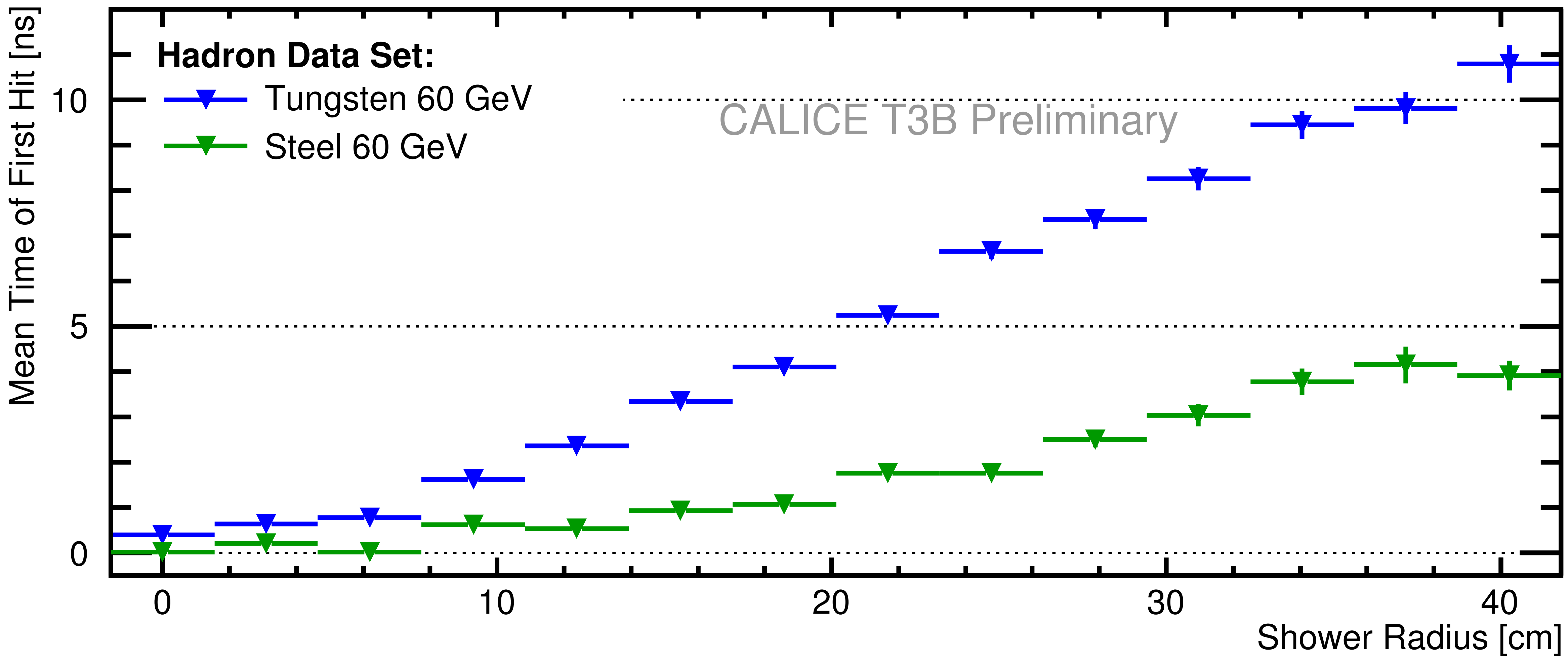




- In steel late energy deposits are mostly of low energy, in tungsten also higher-energy late contributions are seen
- All studied physics lists reproduce behavior in steel satisfactorily
- Neutron treatment important in Tungsten - QGSP_BERT_HP and QBBC only

Timing as a Function of Radius



- Late energy deposits are more important in the outer regions of a shower
  - More pronounced effect in tungsten than in steel

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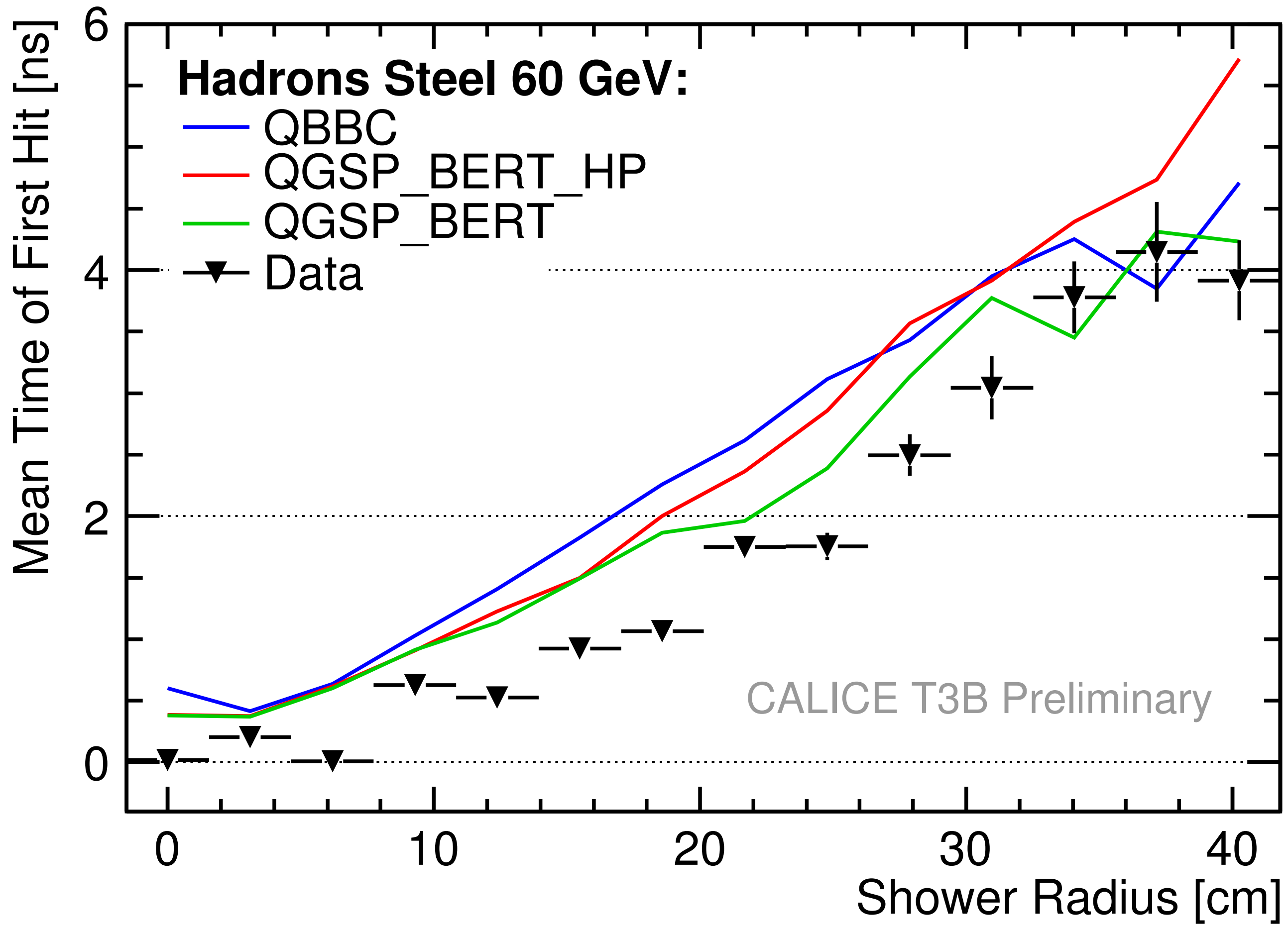
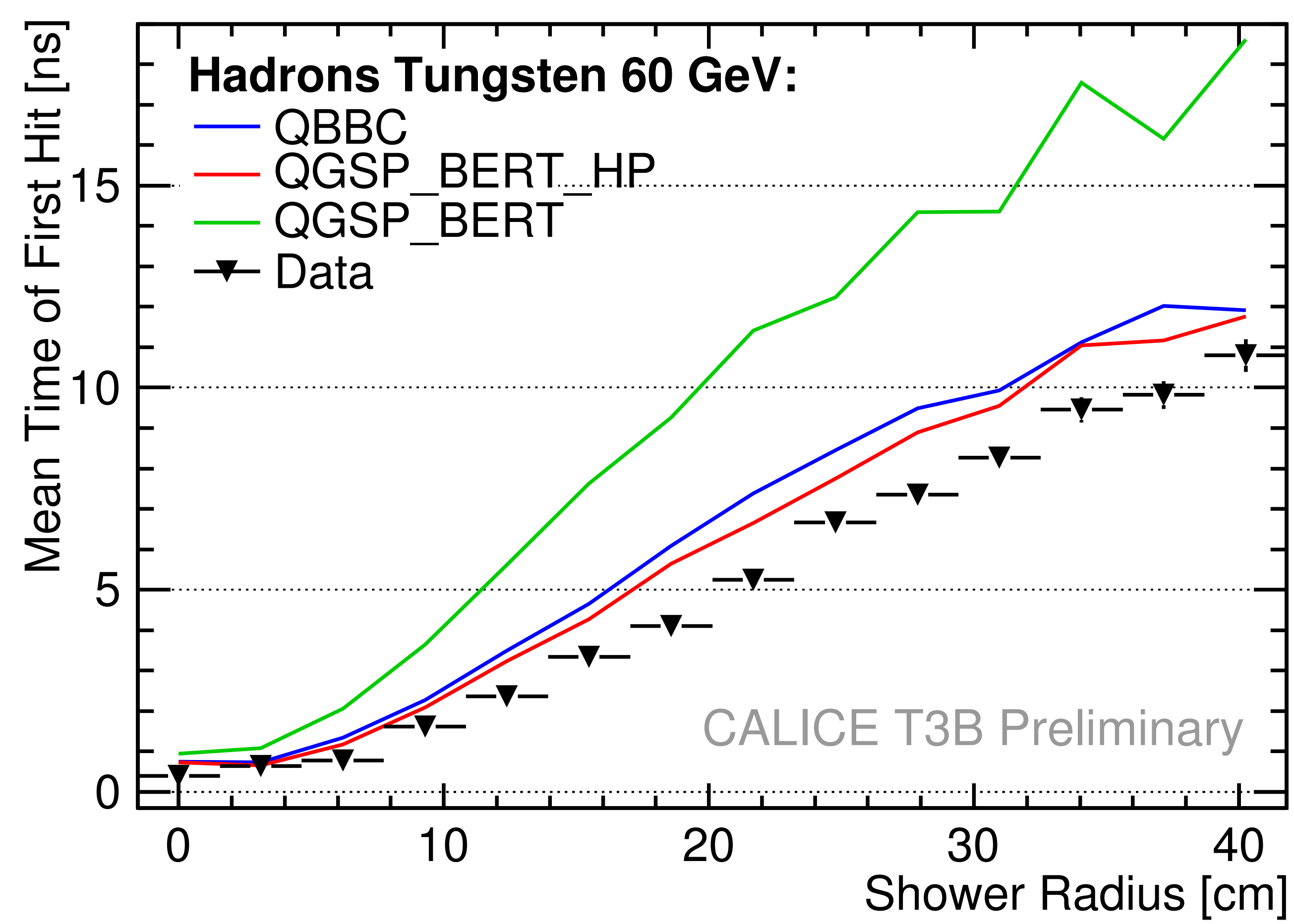
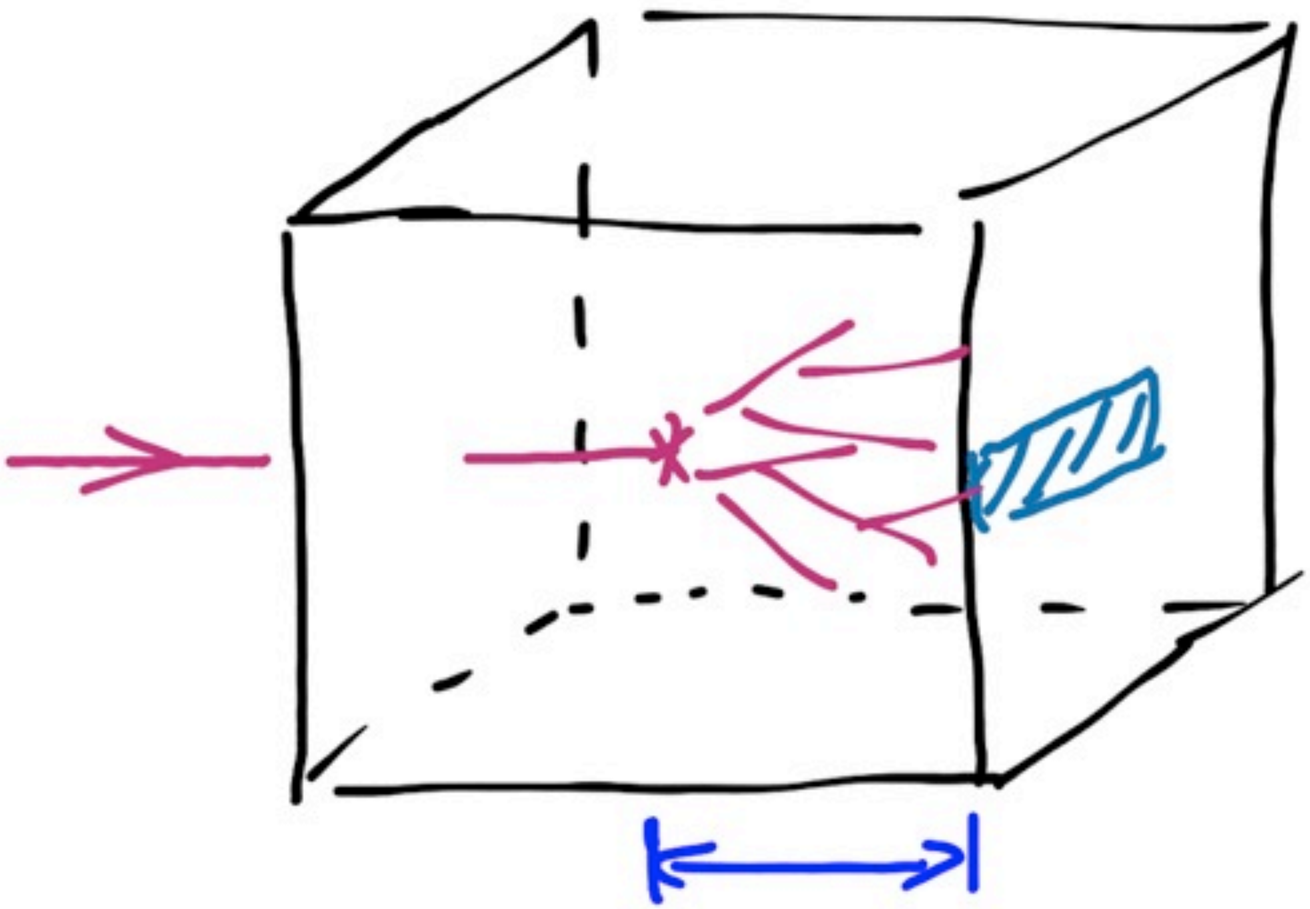




- Late energy deposits are more important in the outer regions of a shower
  - More pronounced effect in tungsten than in steel
- In steel: Good description by all physics lists (on the level of a few 100 ps)
- In tungsten: Neutrons are of key importance - only QGSP_BERT_HP and QBBC provide a good prediction

Adding a 4th Dimension: Depth

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



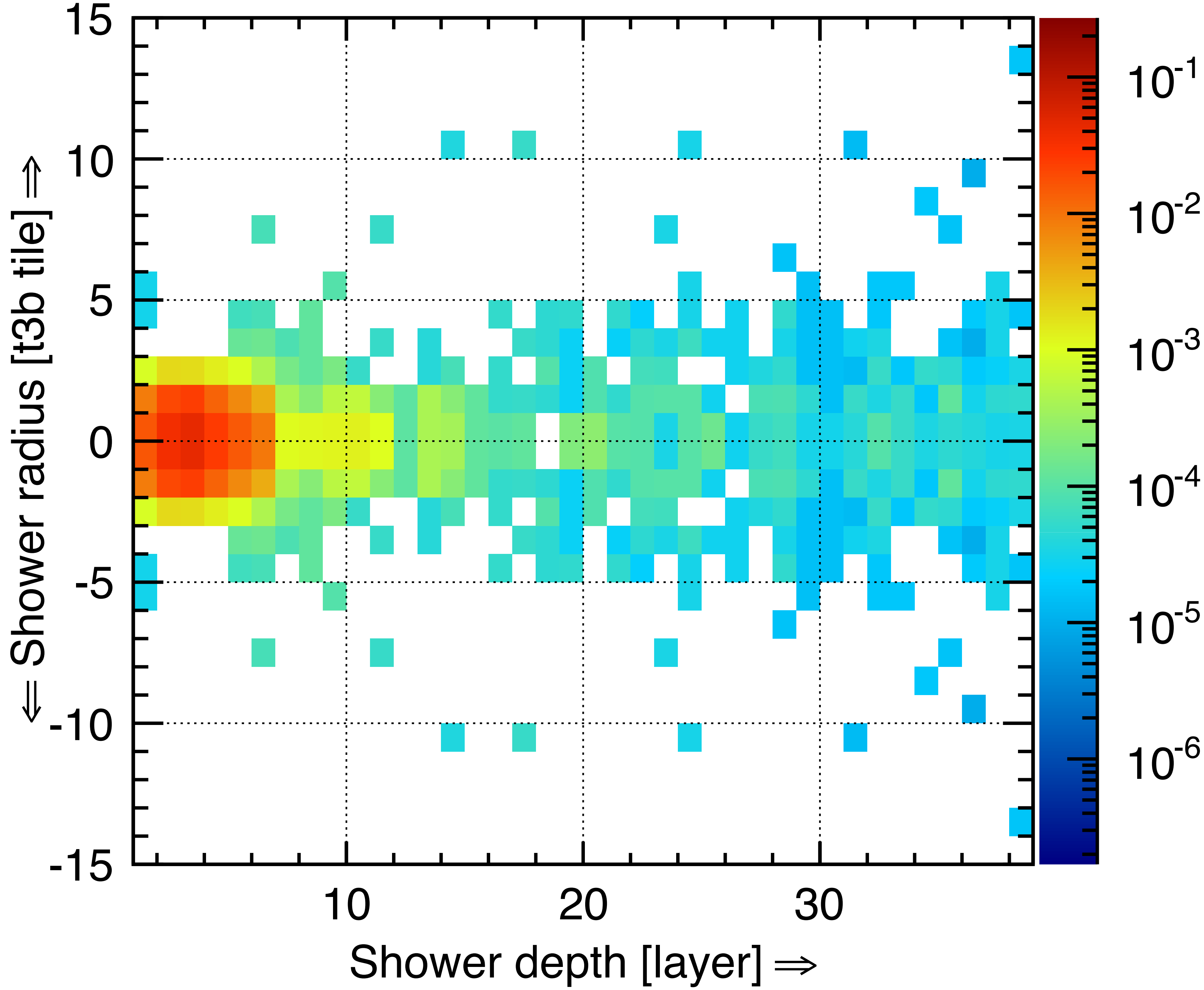
depth of T3B in shower

- 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

The Life of a Pion in the WAHCAL

Shower @ -8 to -6 ns



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

Shown: First hits in each cell only

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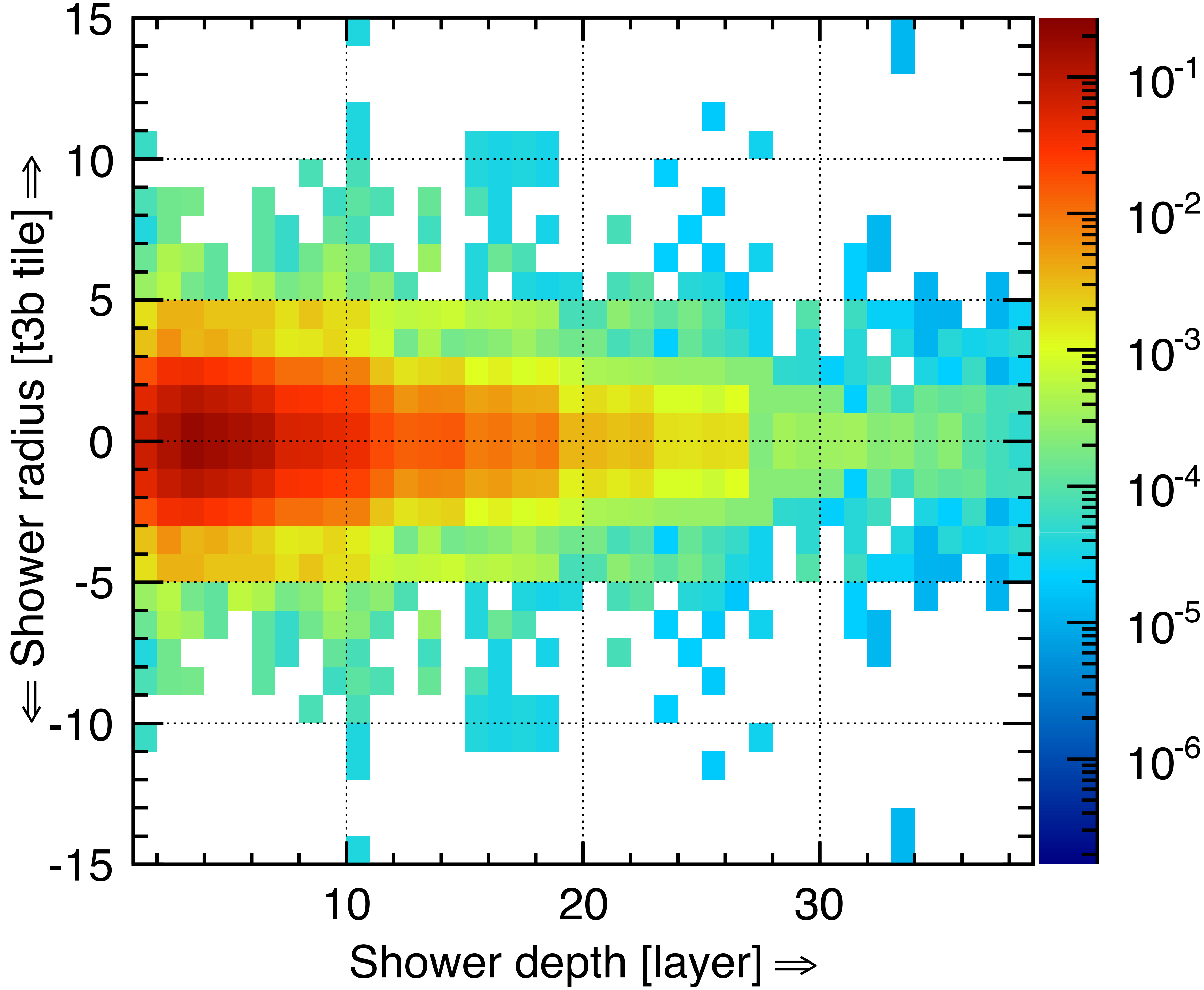
Shower @ -6 to -4 ns



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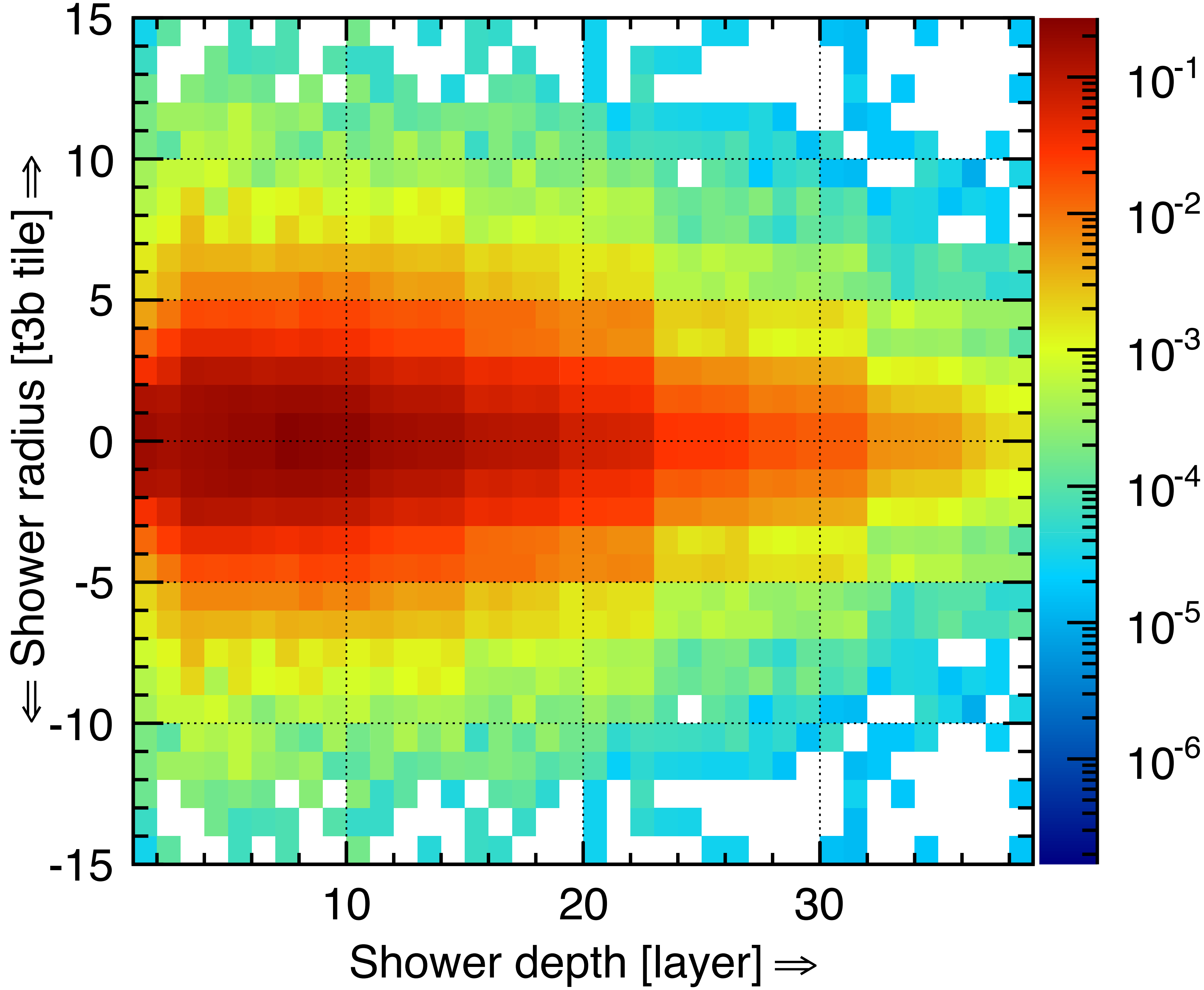
Shower @ -4 to -2 ns



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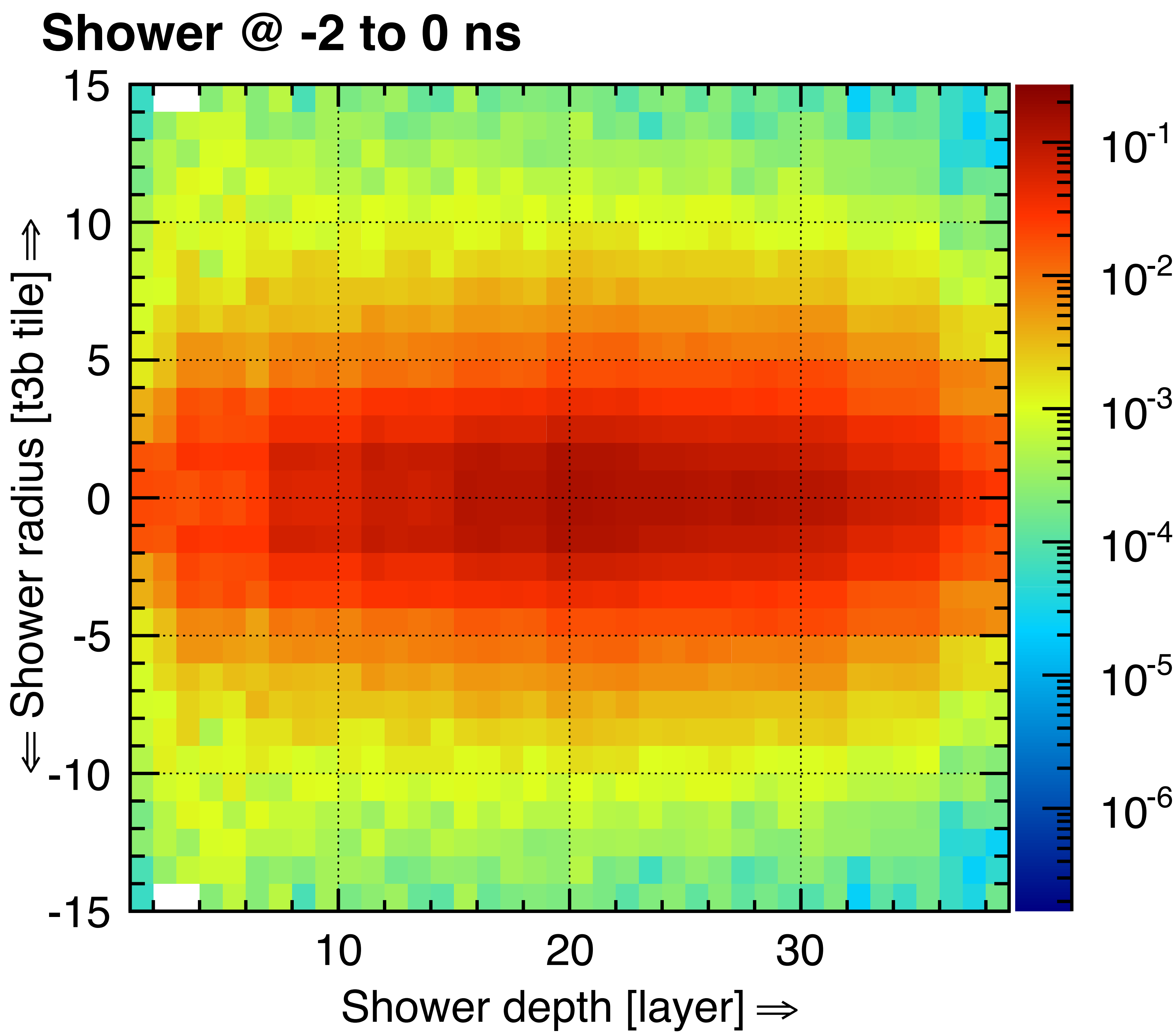

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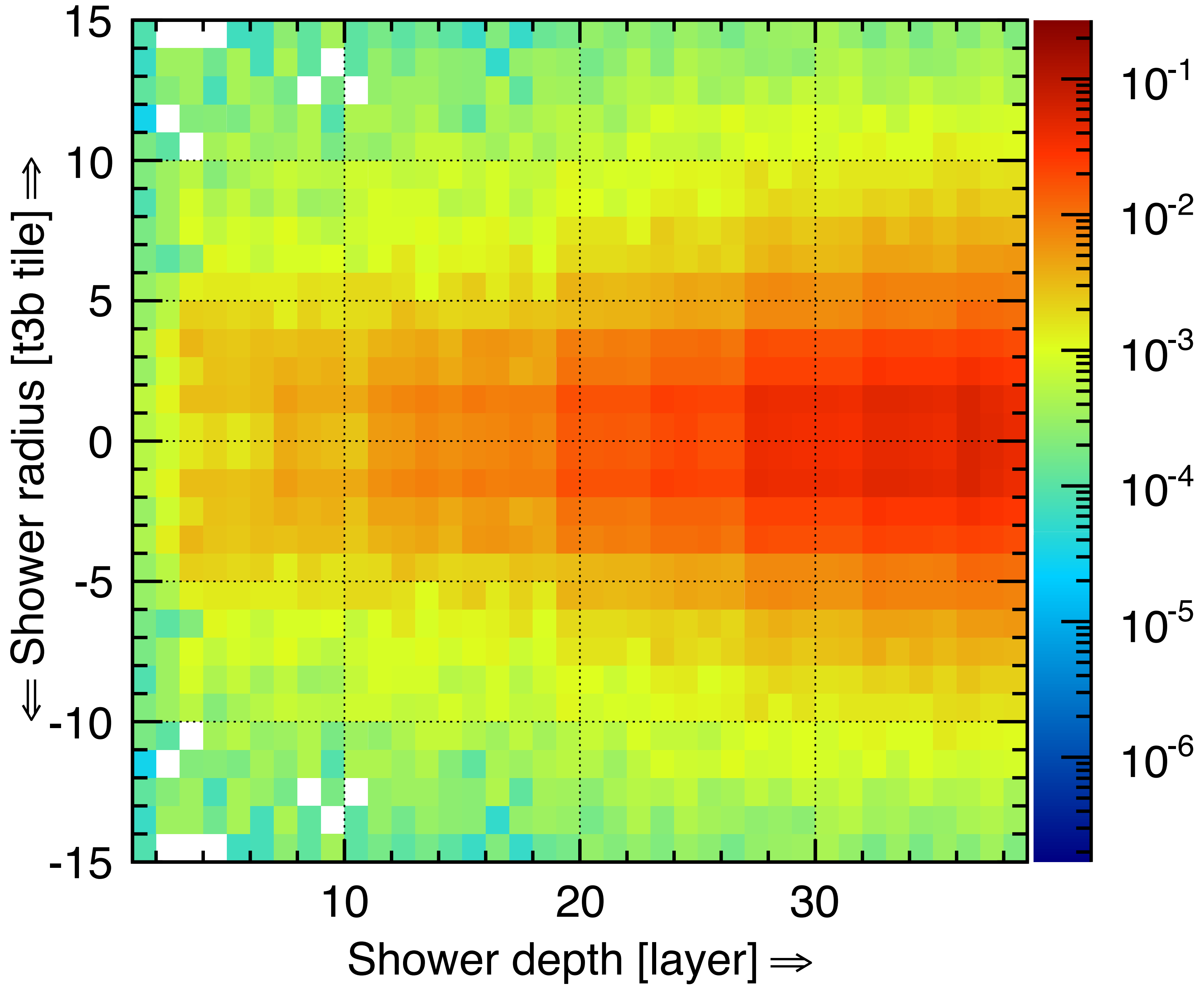
Shower @ 0 to 2 ns



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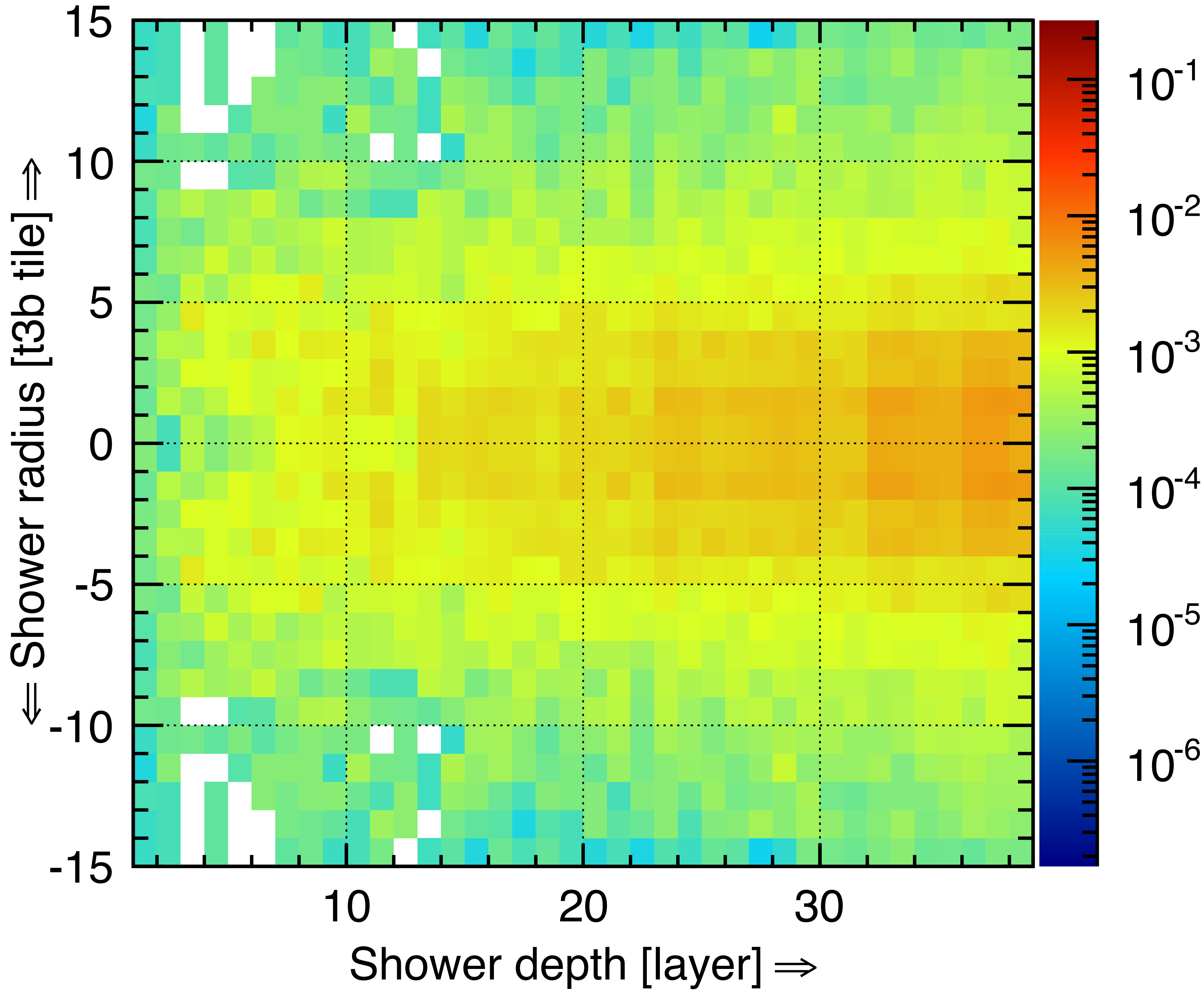
Shower @ 2 to 4 ns



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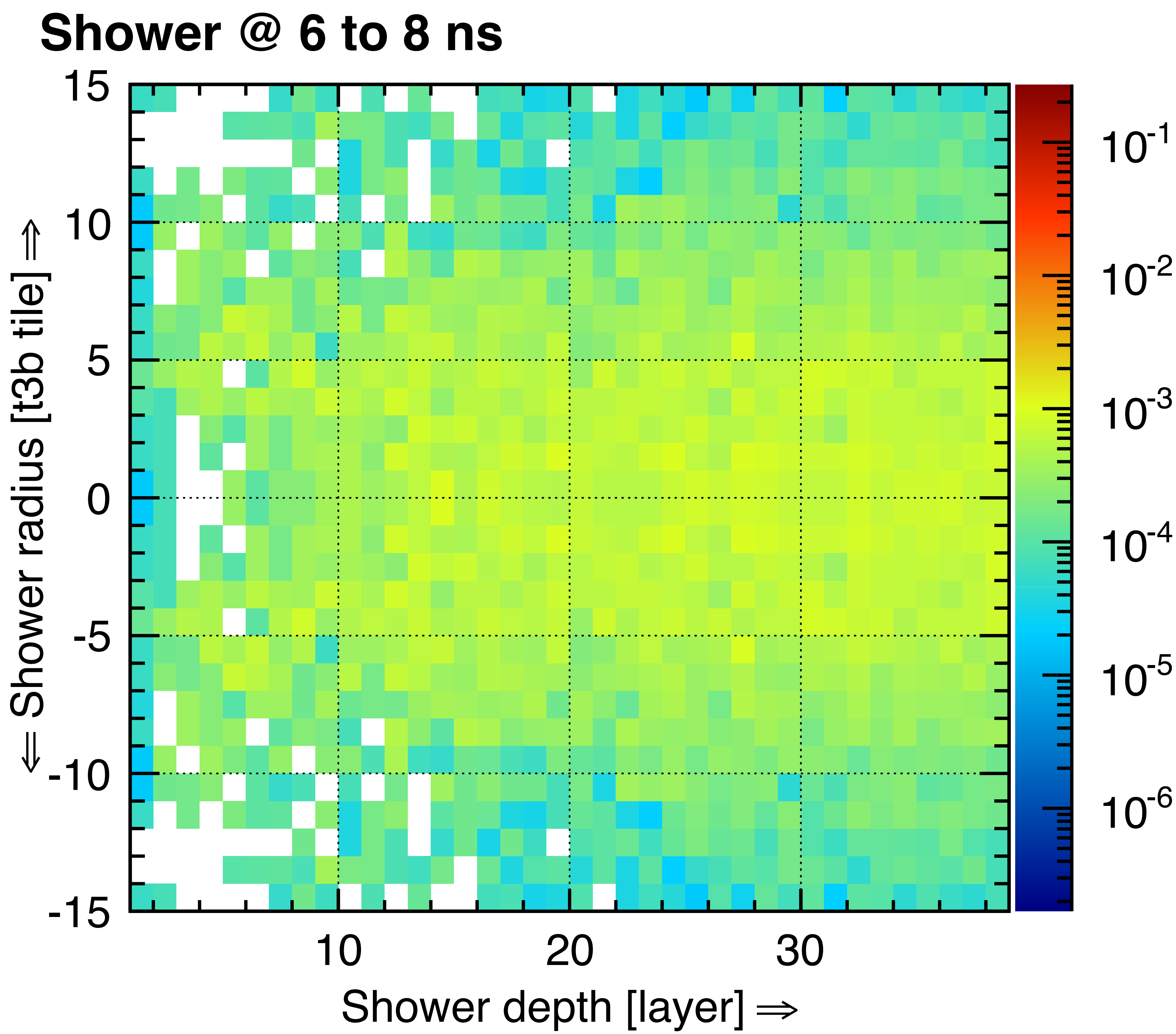

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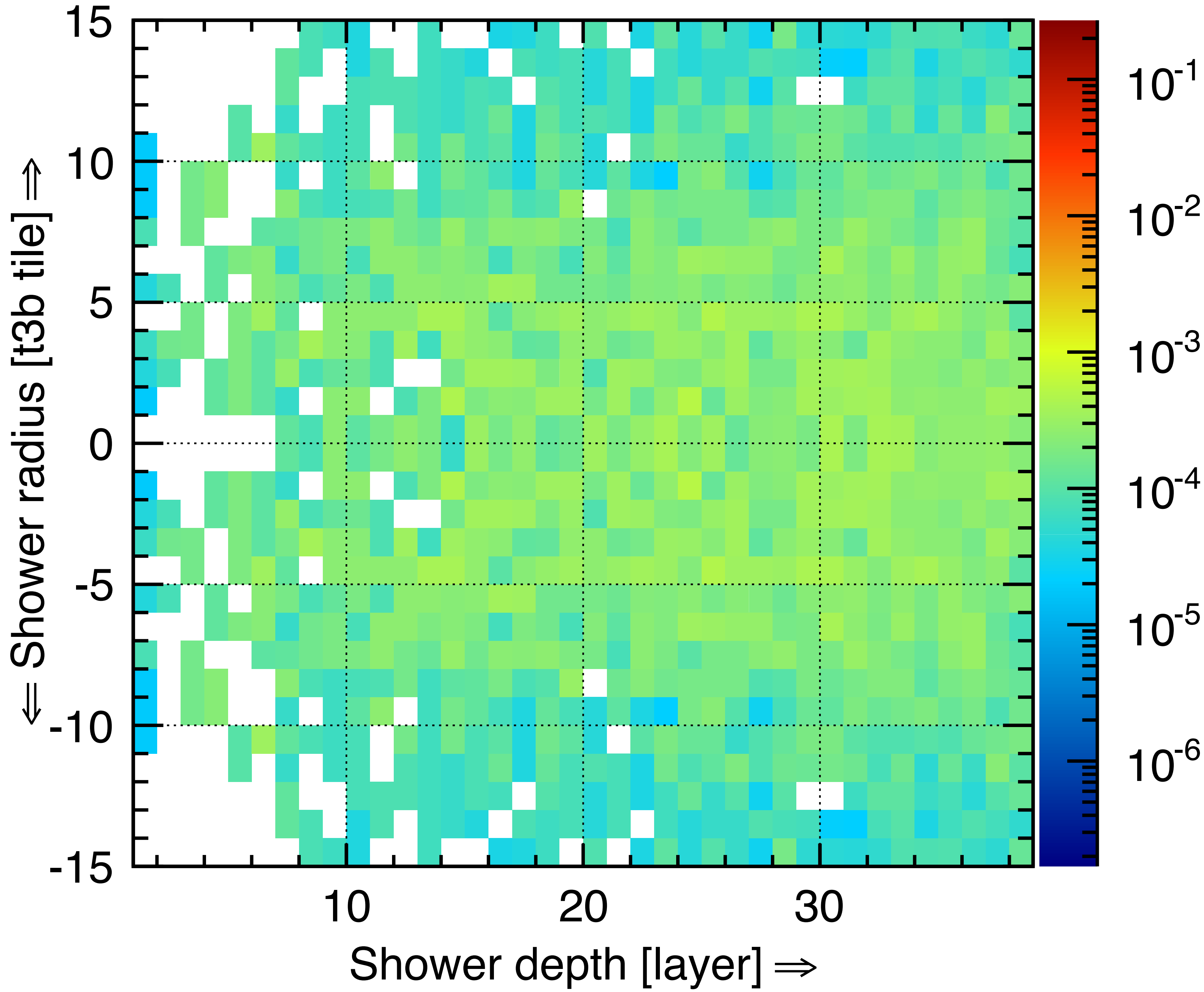
The Life of a Pion in the WAHCAL

Shower @ 10 to 12 ns



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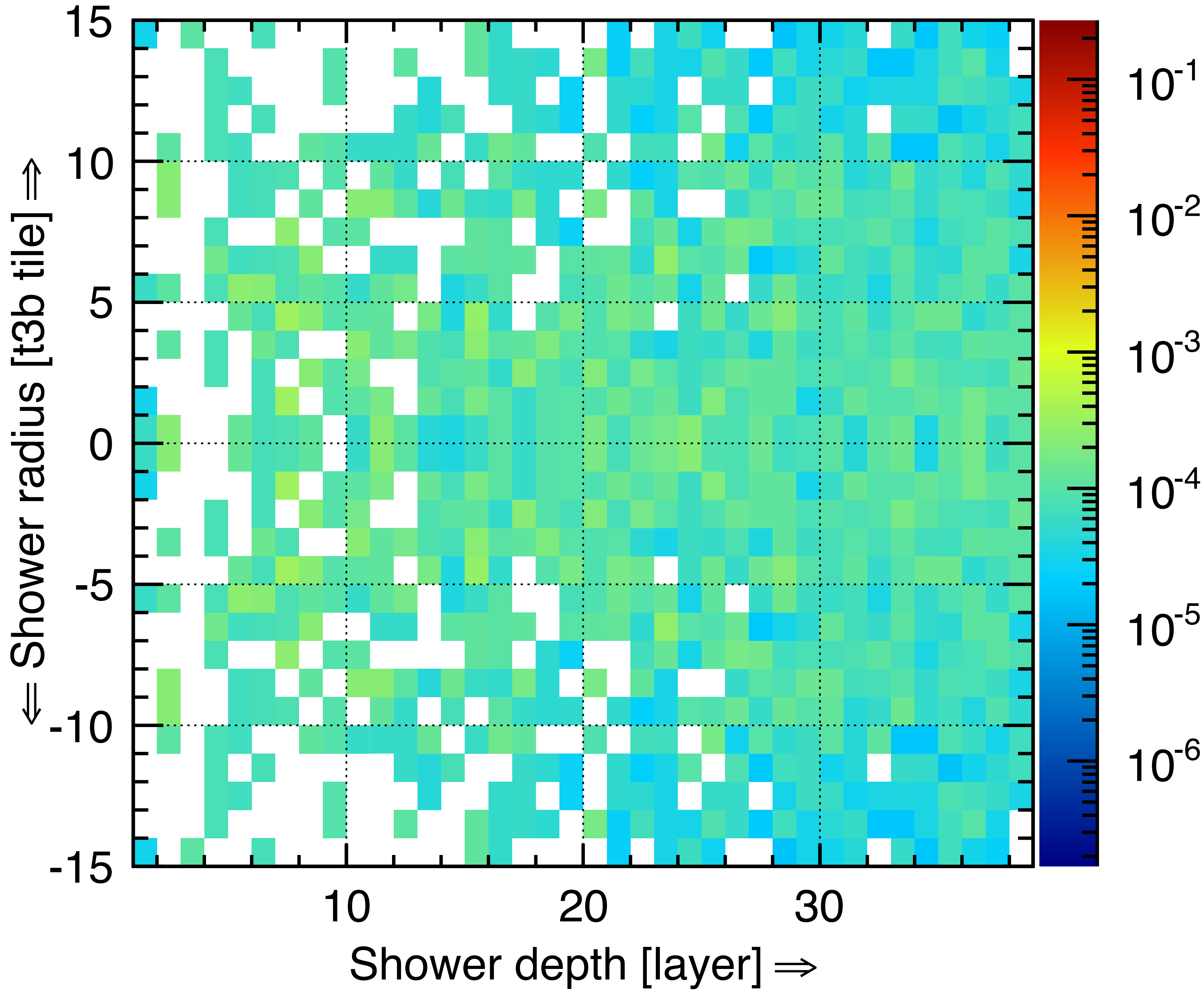
The Life of a Pion in the WAHCAL

Shower @ 16 to 18 ns



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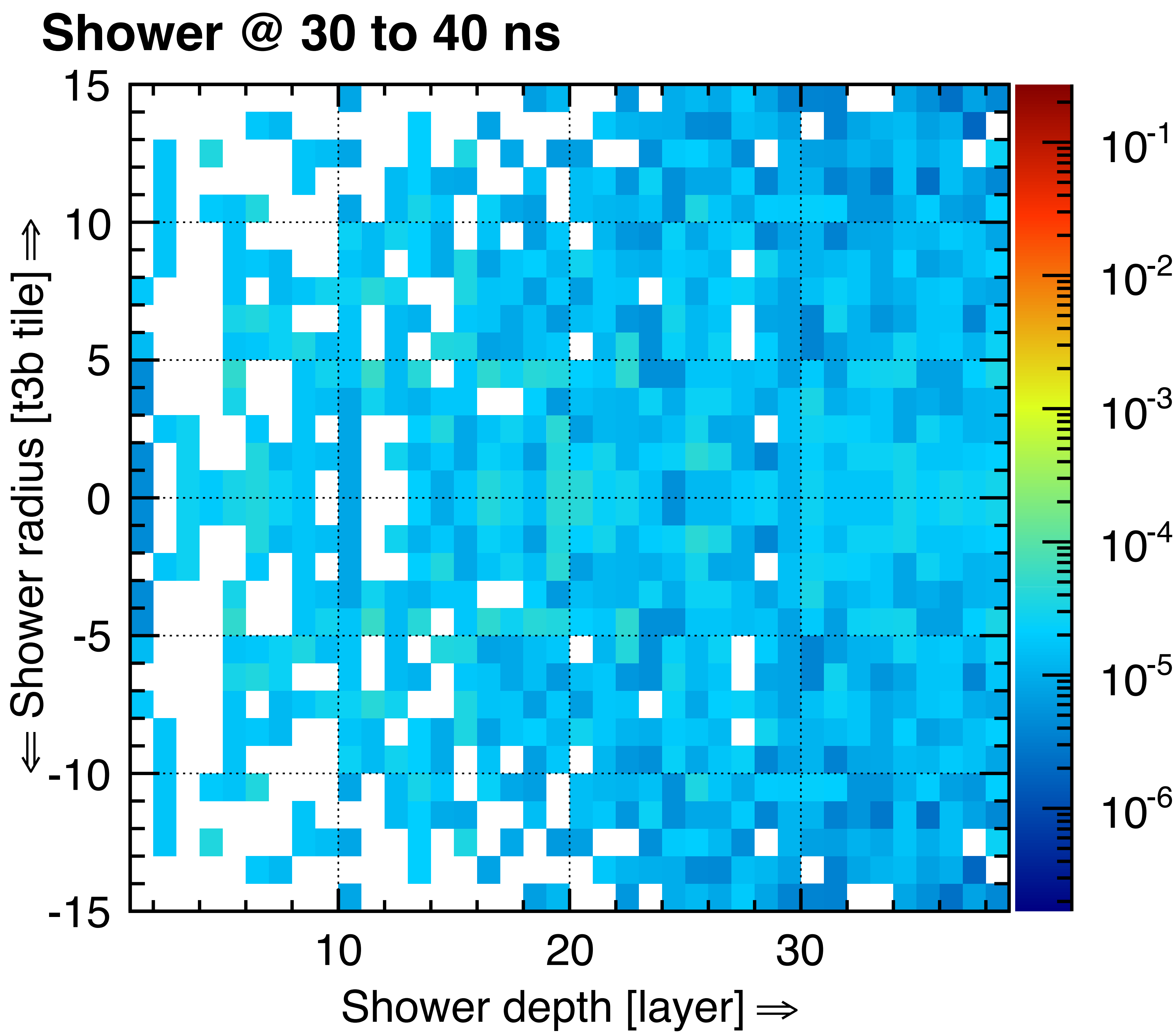

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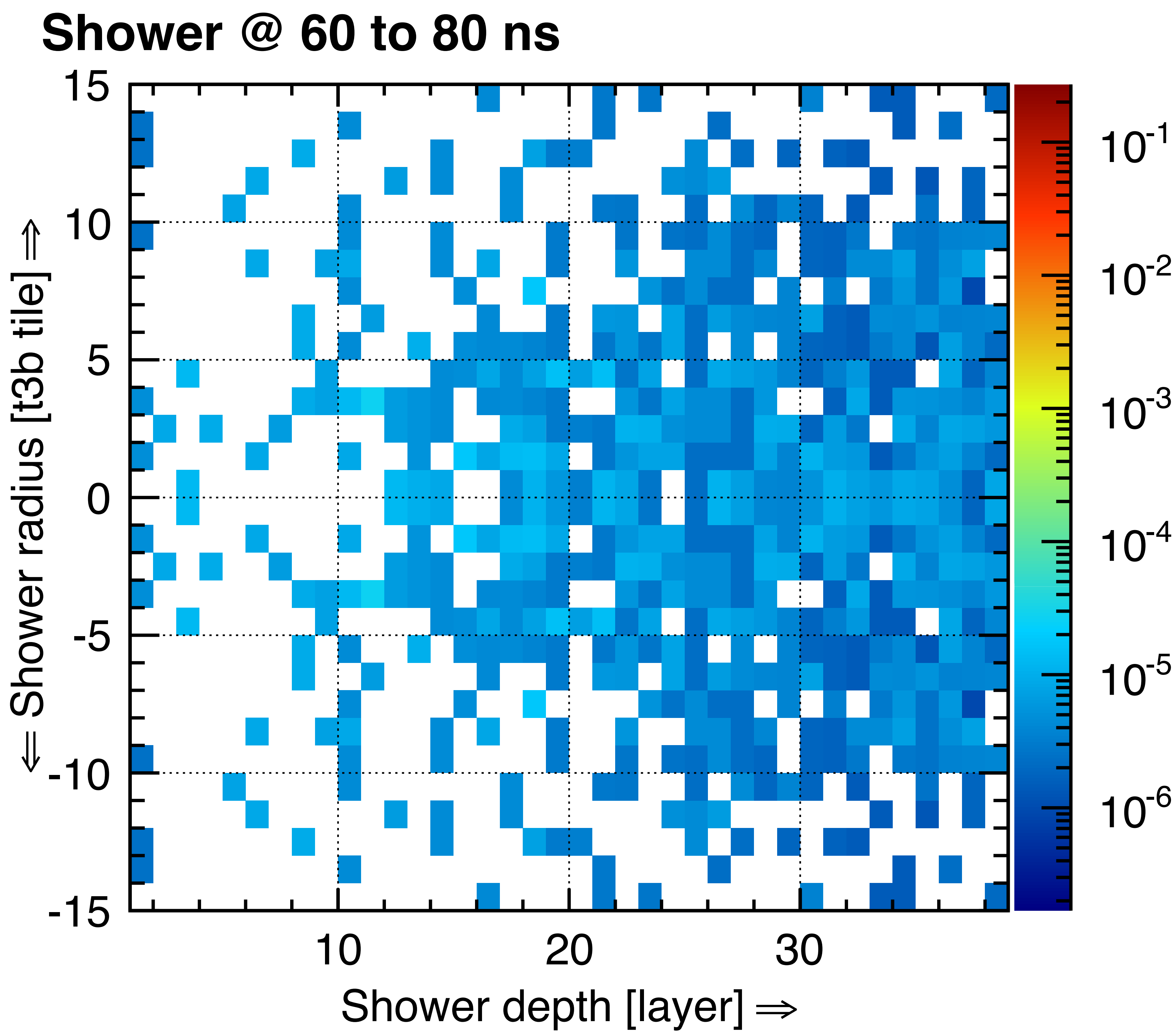

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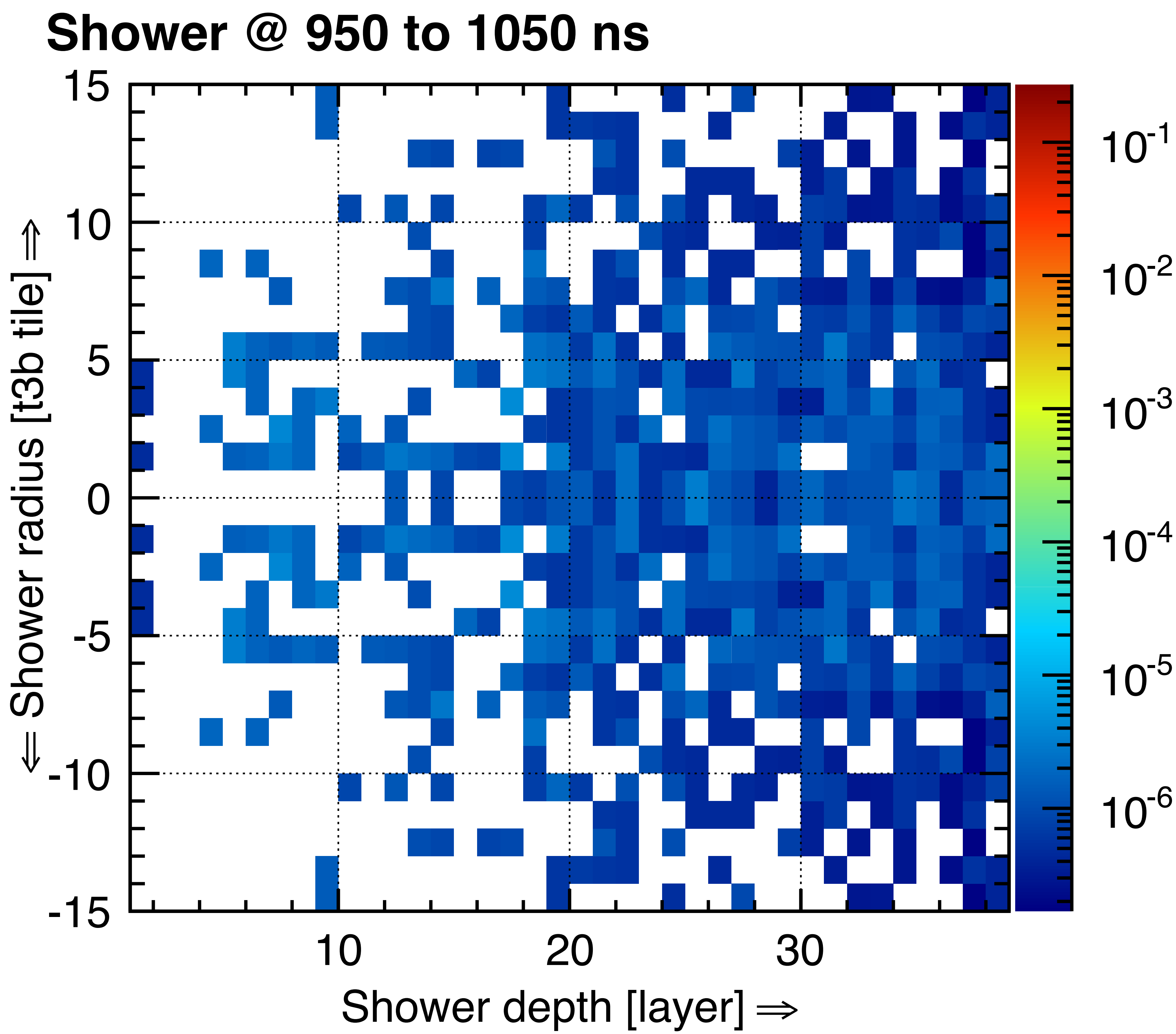

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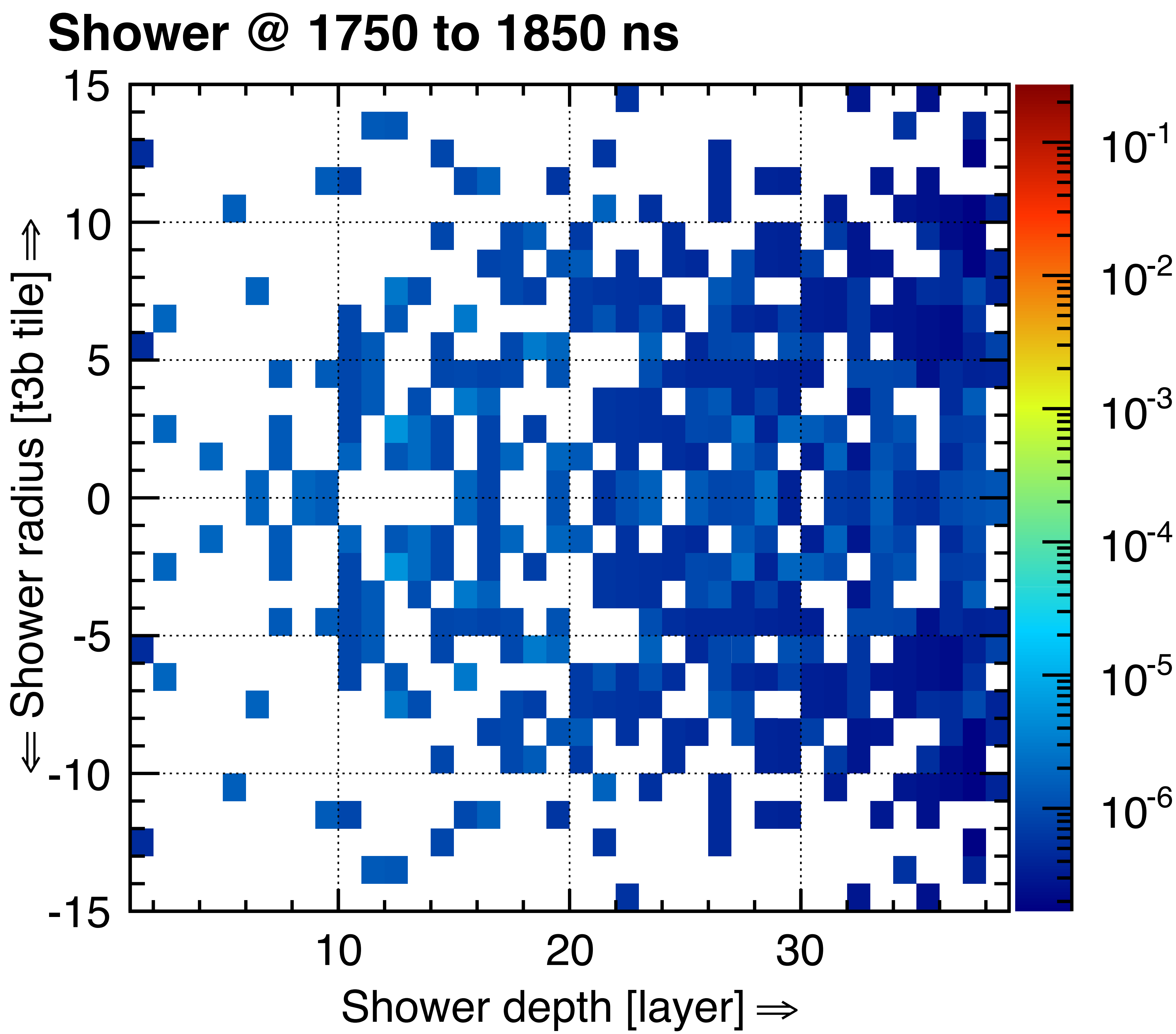

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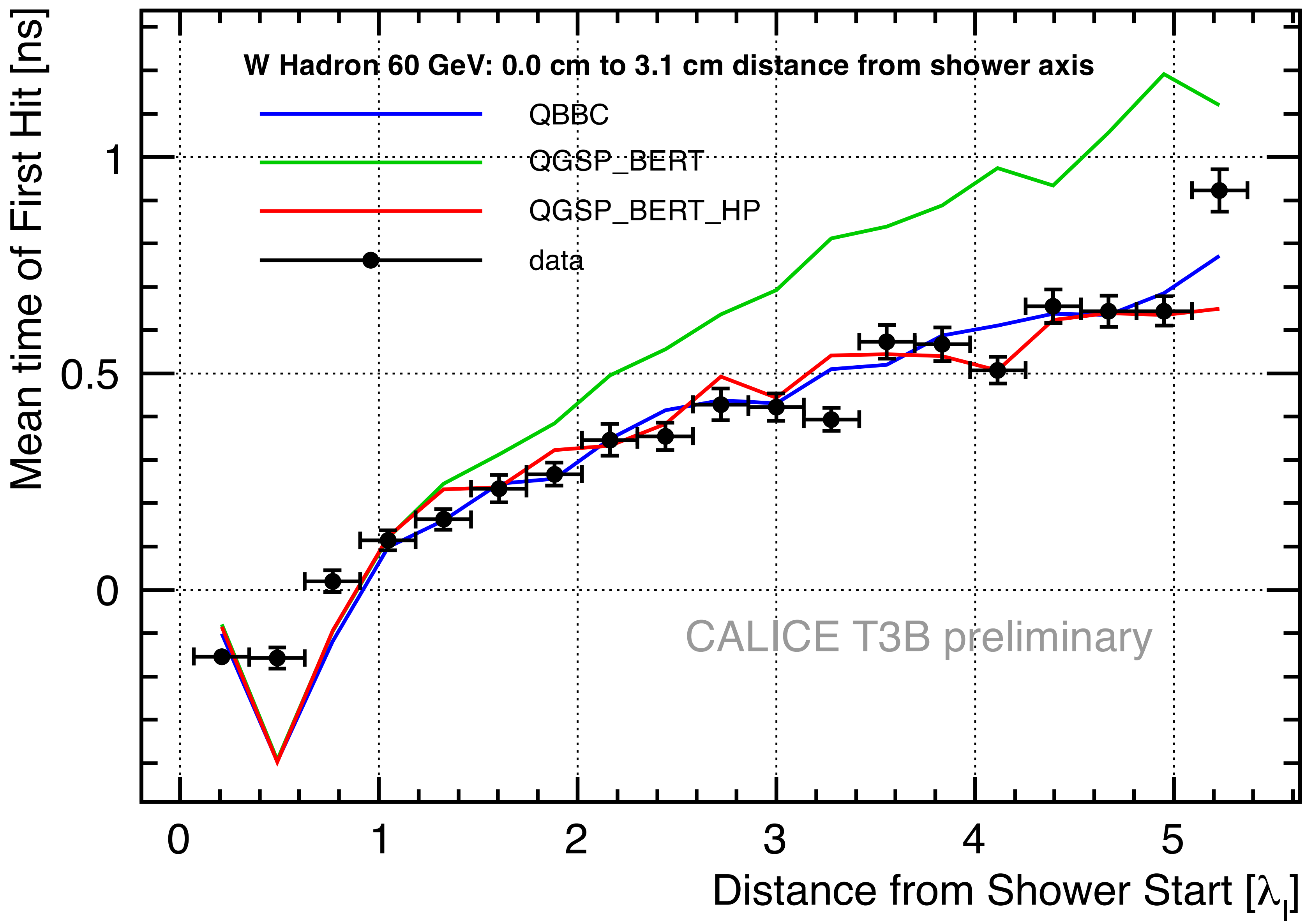
Longitudinal Dependence - Comparison to Simulations



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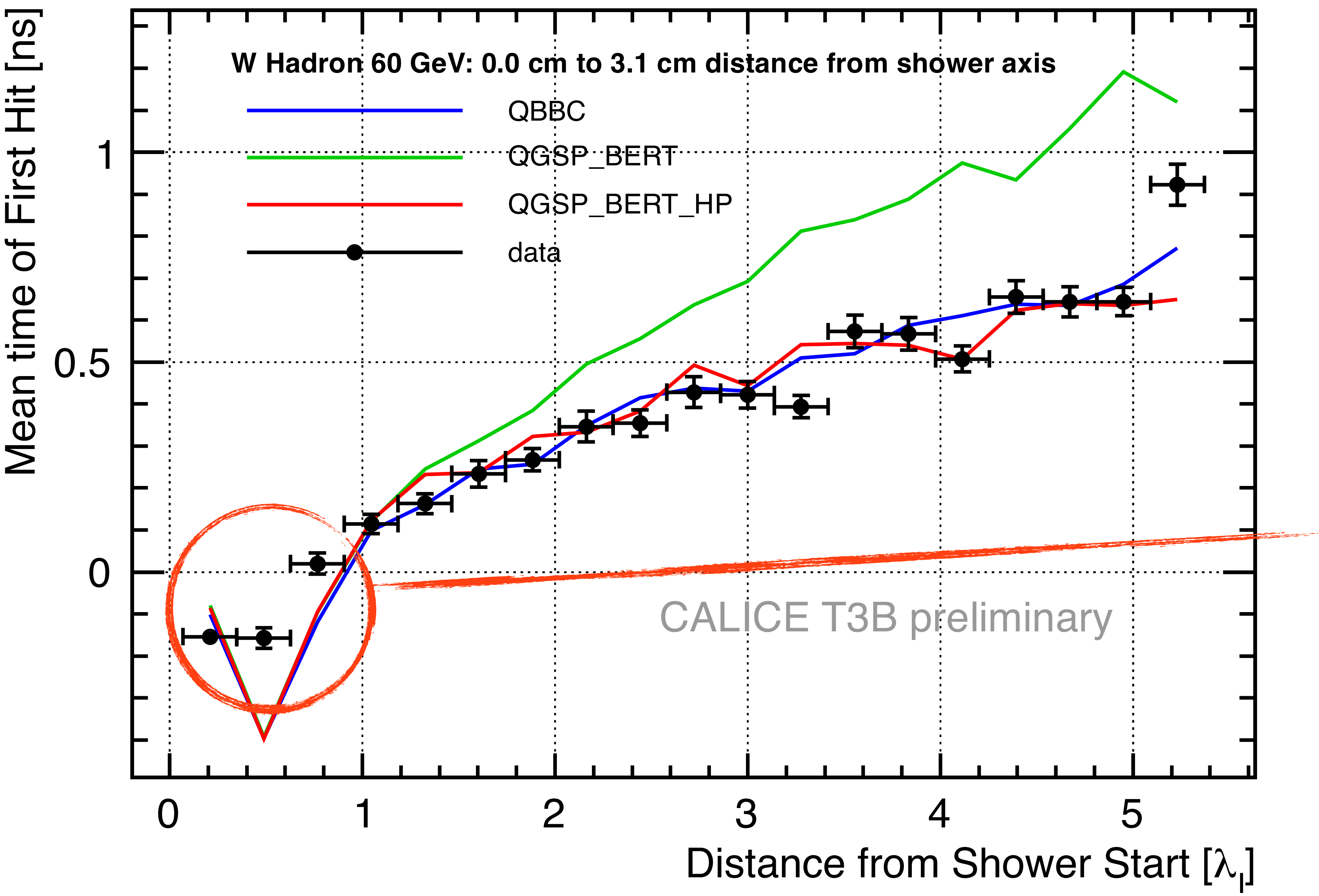

- Increased importance of late shower contributions towards the rear of the shower
- Region most dominated by electromagnetic sub-showers: Large dominance of prompt hits

- Well reproduced by physics lists with precise neutron treatment
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Summary & Outlook

- Time resolution is important in PFA calorimeters, in particular at CLIC
- Hadronic showers are not instantaneous: Limits to the time resolution of the hadronic calorimeters

- CALICE T3B is a dedicated experiment to provide measurements of the time structure with scintillators & SiPM readout in steel and tungsten

- Results demonstrate that good treatment of neutrons, provided by the GEANT4 QGSP_BERT_HP and QBBC physics lists, is crucial for tungsten
- Time structure in steel in general well described by all investigated models

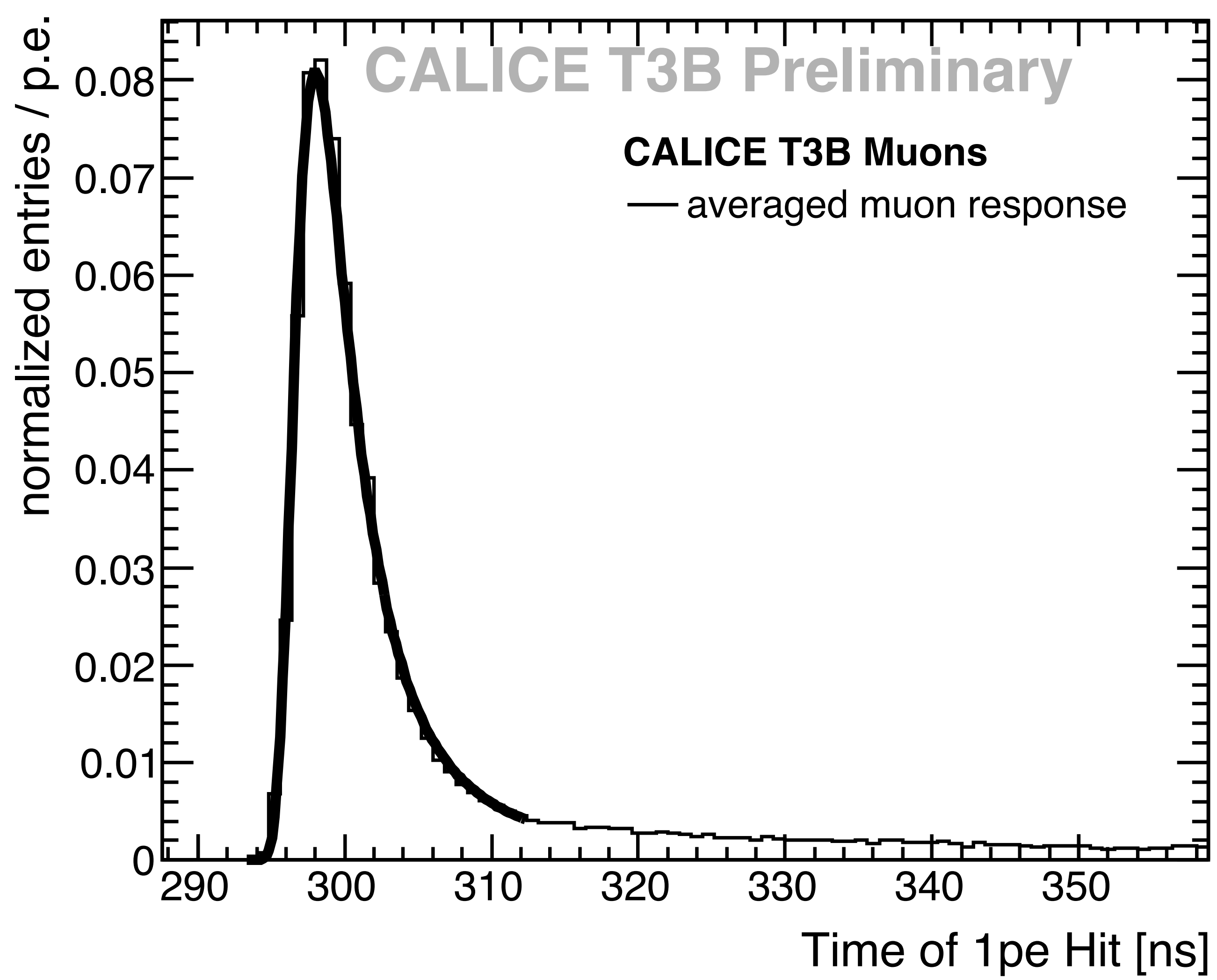
- Together with the CALICE WAHCAL longitudinally resolved time measurements are possible: Increased importance of late components in shower rear

- Coming up: Results of timing measurements with RPCs in Tungsten - Data being analyzed!

Backup

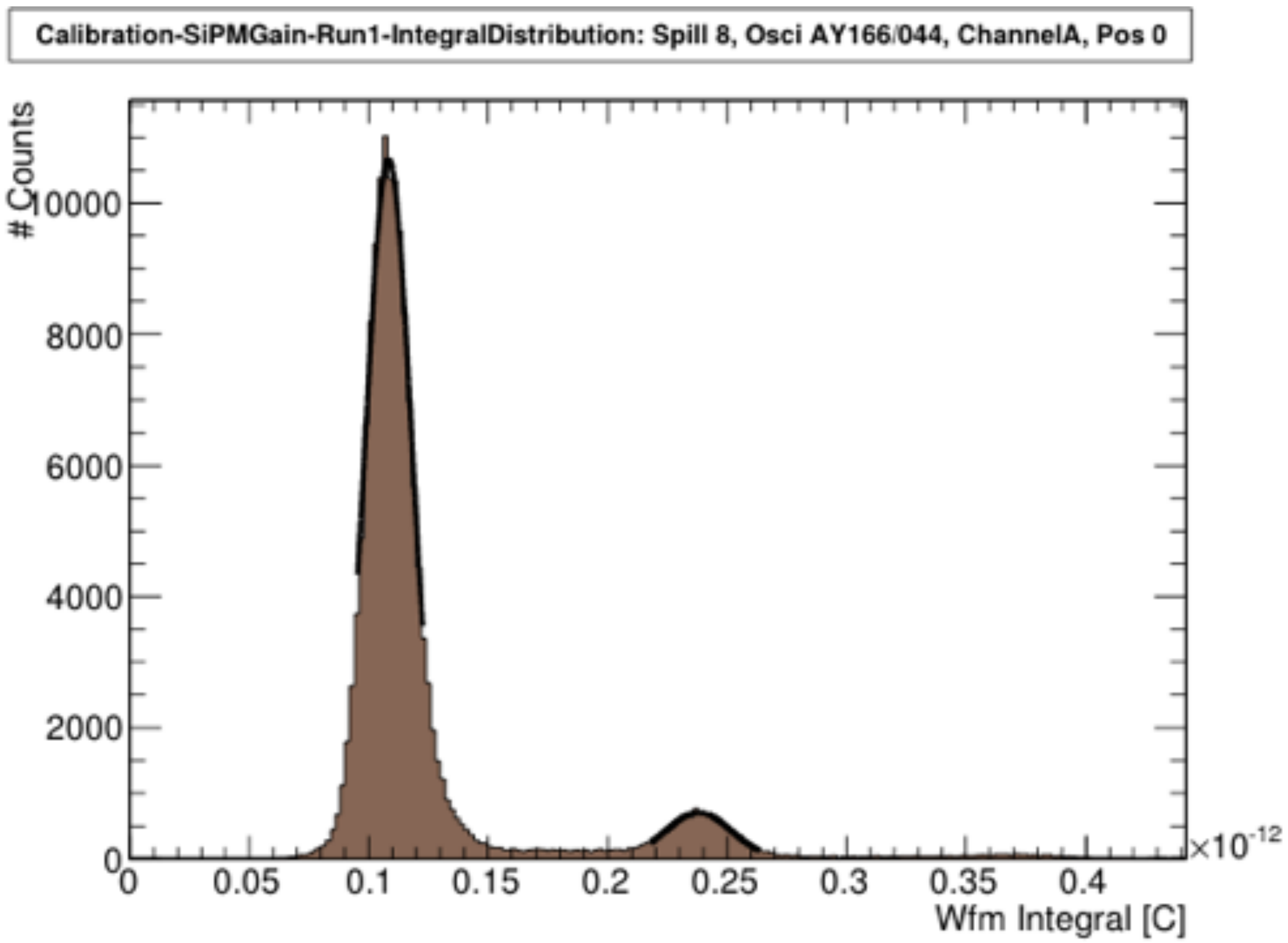
Simulations

- Geant 4.9.3.p01, Simplified simulation setup:
  - 31 layer HCAL, with 1 cm W + 1 mm Steel absorber
  - CALICE AHCAL cassette (2 x 2 mm Steel, 5 mm scintillator + PCB, cables, air)
    - Use T3B as the last layer of the setup
- Simulation of the time structure:
  - record the time and energy deposit of each Geant4 step in the T3B scintillator volume
  - bin in 800 ps time bins, convert to number of photons according to the energy in the bin
  - smear the time distribution of the photons according to observed time distribution of muon signals
    - ad-hoc fit with a Landau: σ ~ 1.3 ns



T3B Scintillator Tiles - Performance Studies

- Gain calibration of photon sensors: dark noise



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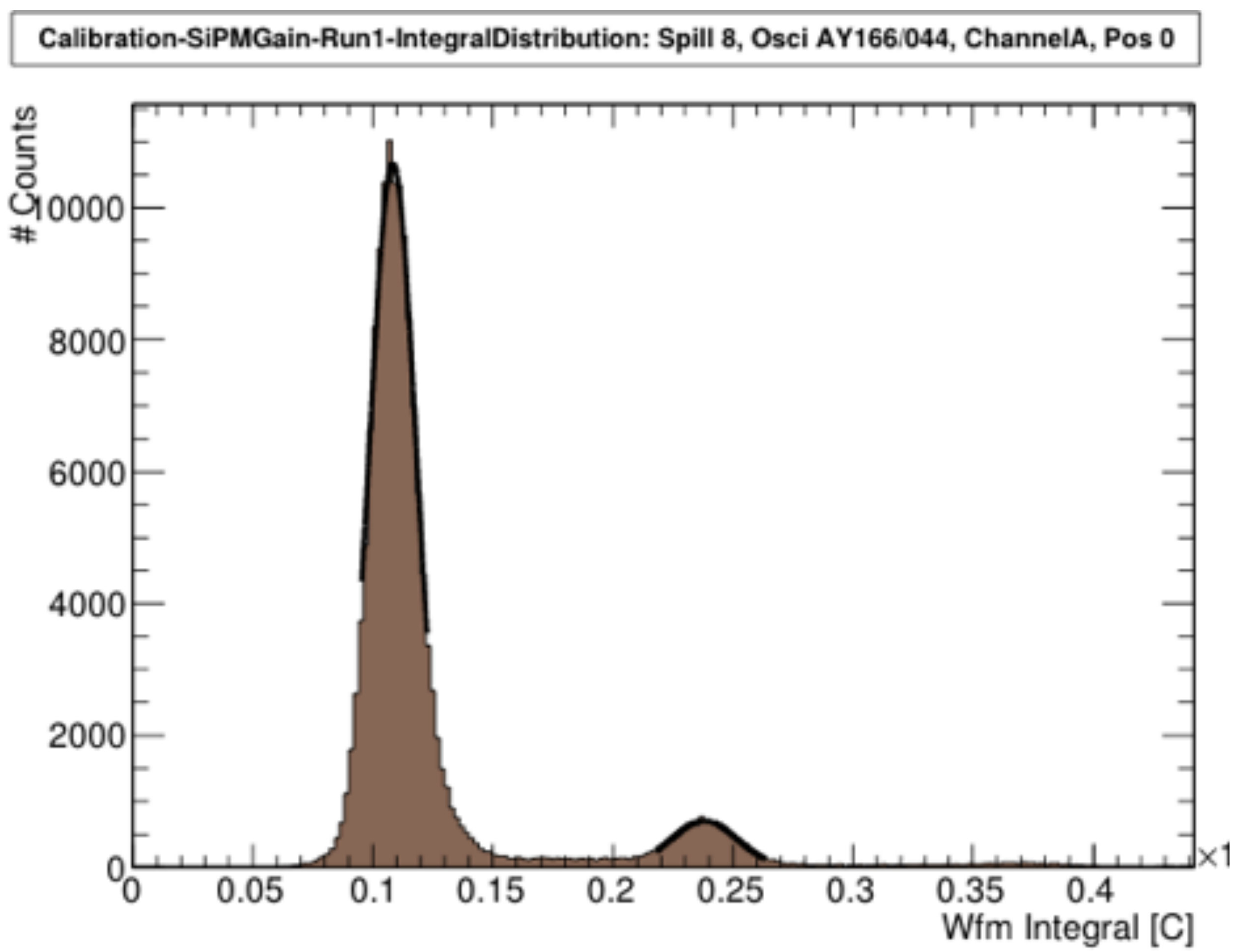

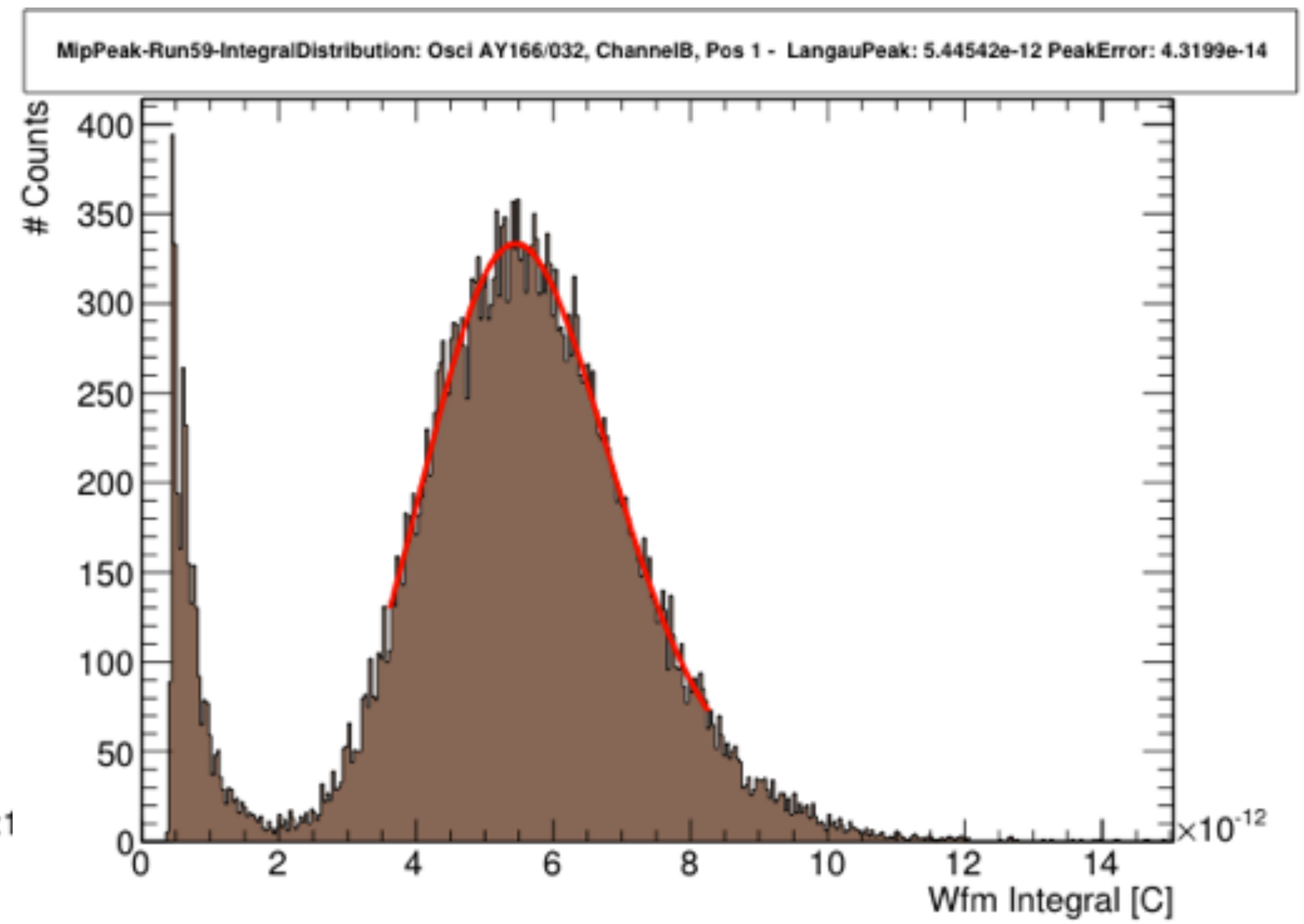

- Calibration of tile response to charged particles: Penetrating electrons from ^{90}Sr
  Calibration factor (most probable value) extracted from Landau conv. with Gaussian fit

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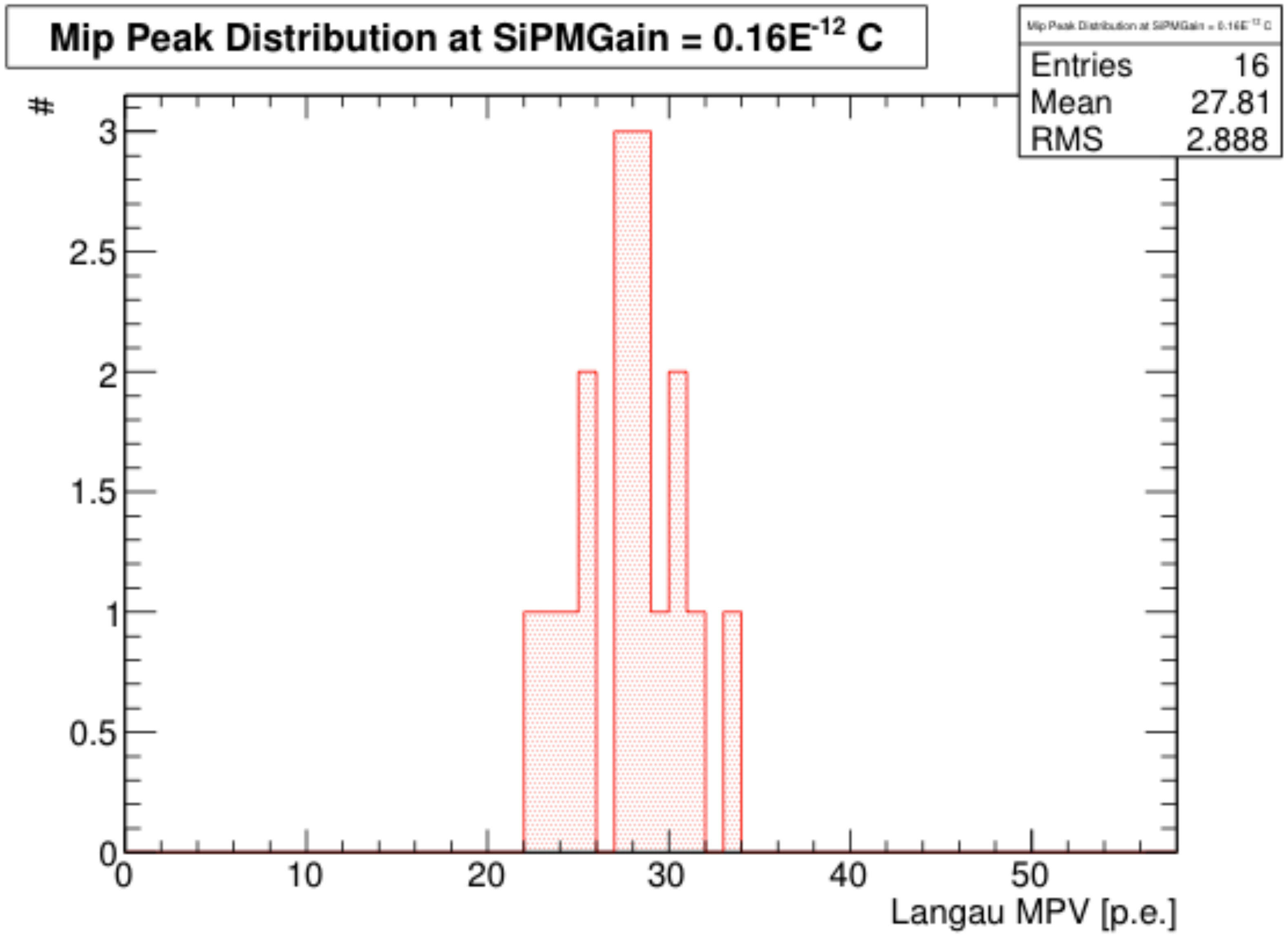

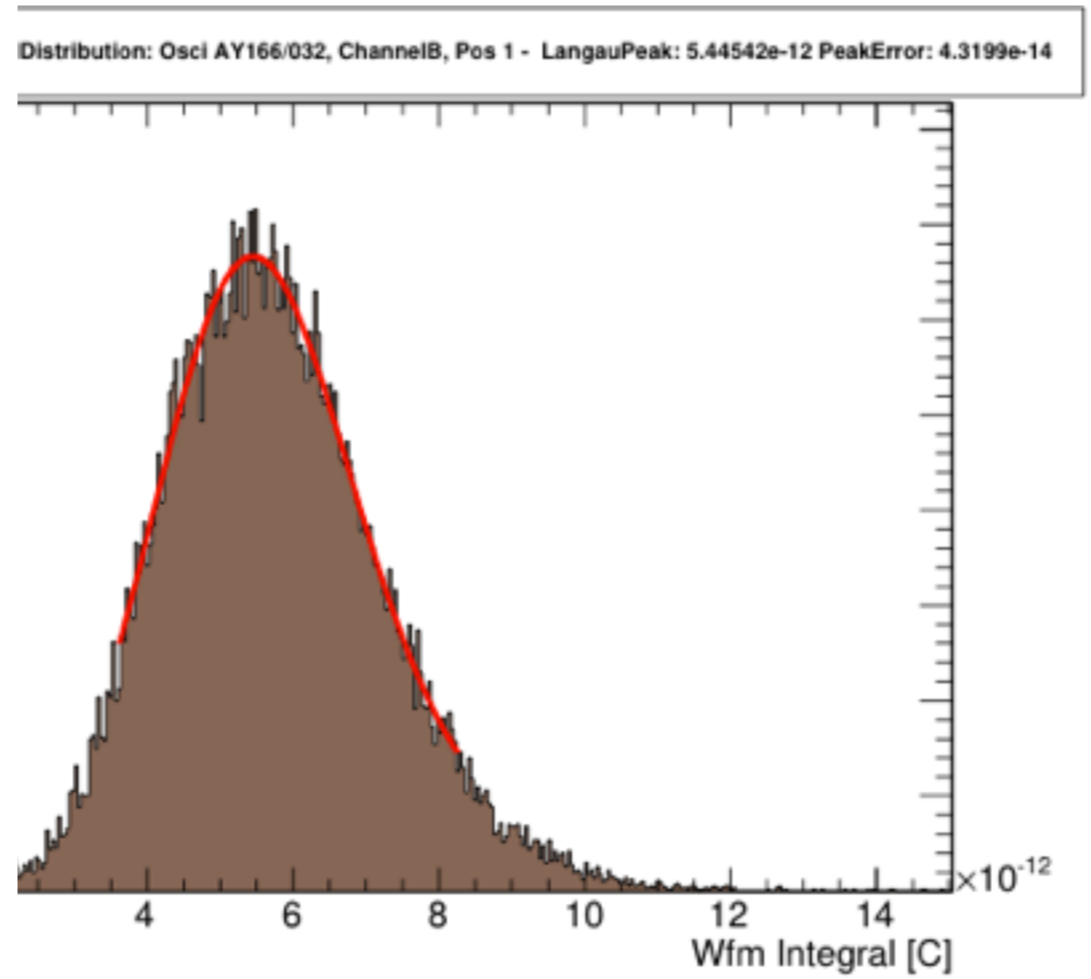

Penetrating electrons from ^{90}Sr

Calibration factor (most probable value) extracted from Landau conv. with Gaussian fit

- Distribution of response over sample of T3B tiles: 10% RMS variation