The Time Structure of Hadronic Showers in Imaging Calorimeters with Scintillator and RPC Readout

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on behalf of the CALICE Collaboration

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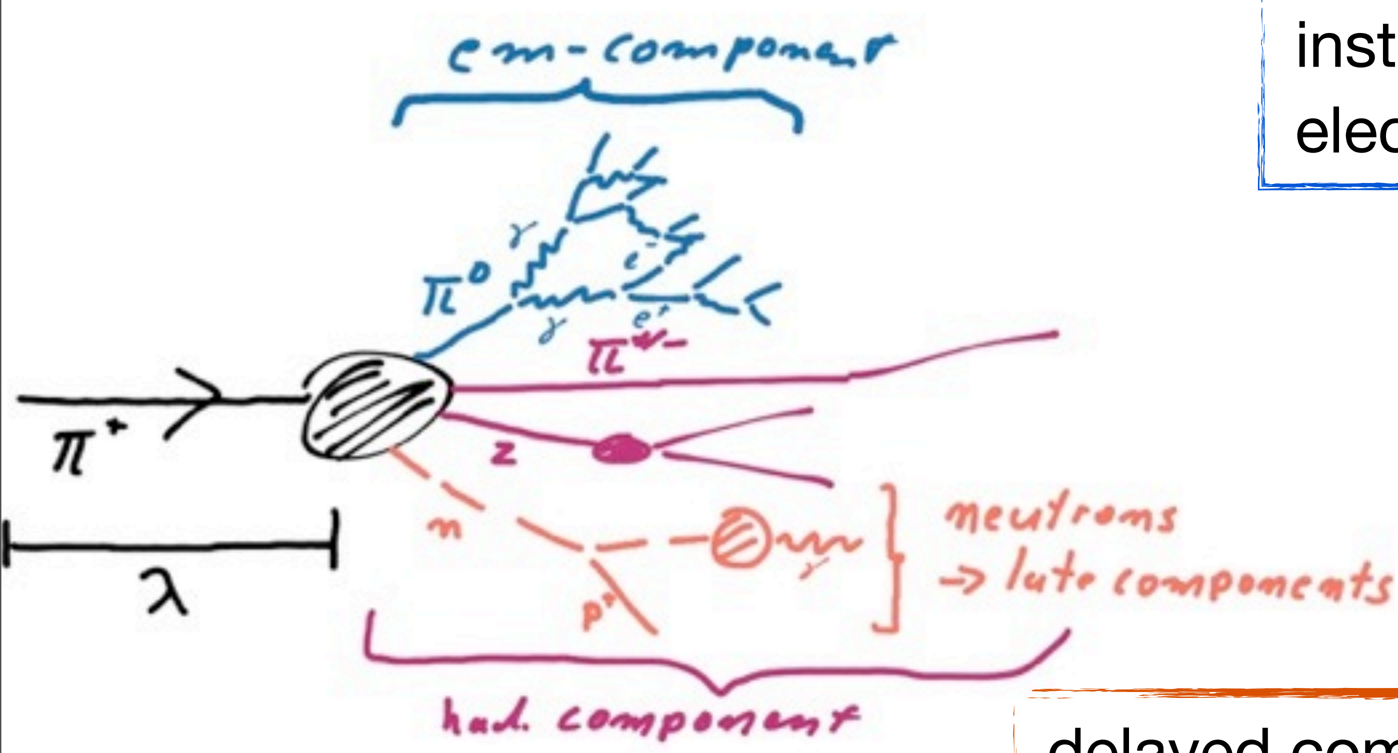
Outline

- Time Structure in Hadronic Showers
- CALICE T3B - A Setup for Timing Measurements
- Timing Results & Comparison to Simulations
- Comparing Scintillator and RPC Readout: FastRPC
- A 4th Dimension: Longitudinal Information
  - The Life of a Pion in a Tungsten Calorimeter
- Summary & Outlook

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

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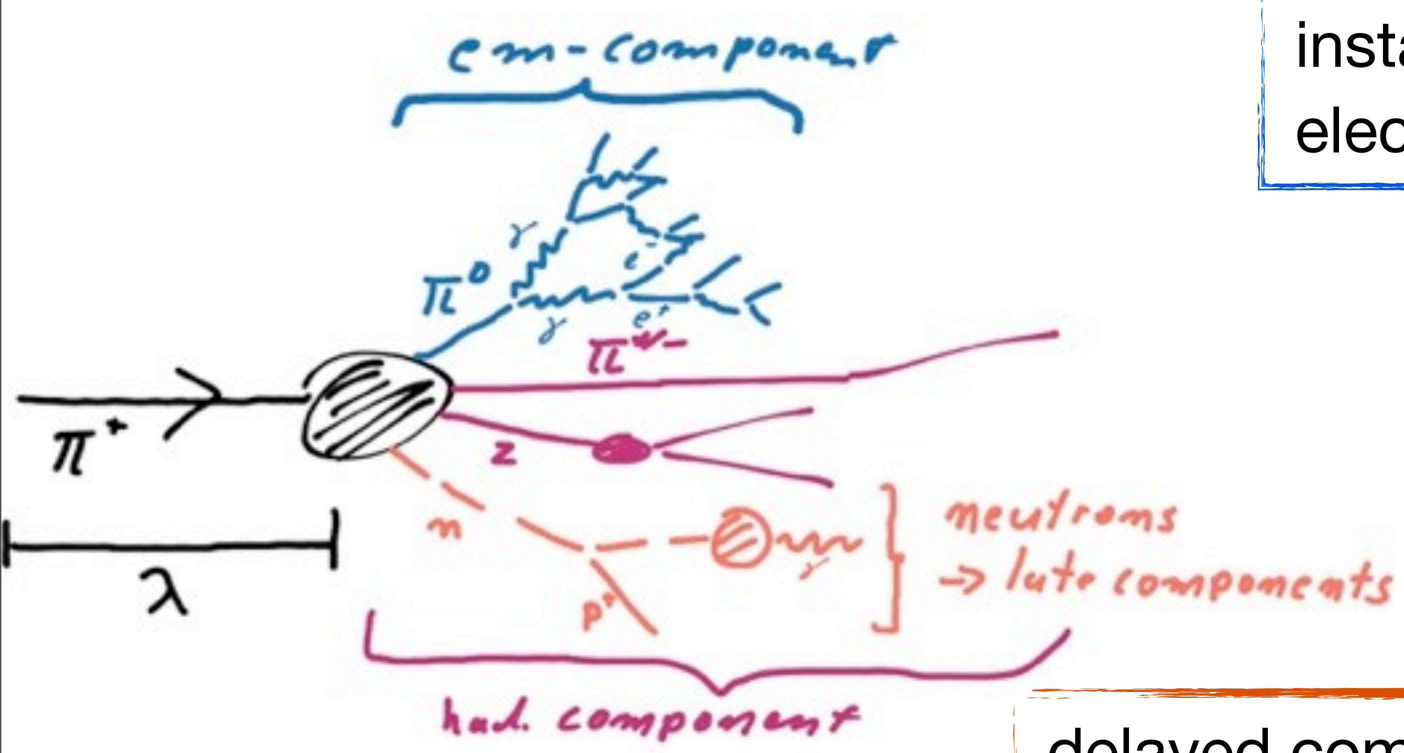

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- neutrons from evaporation and spallation
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➪ Importance of delayed component strongly depends on target nucleus

➪ Sensitivity to time structure depends on the choice of active medium

T3B: The Study of the Time Structure

- The CALICE Scintillator-Tungsten HCAL - A CLIC physics prototype
  - 38 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
  - Record signal over long time window: ~ 2 μs to sample the full shower development

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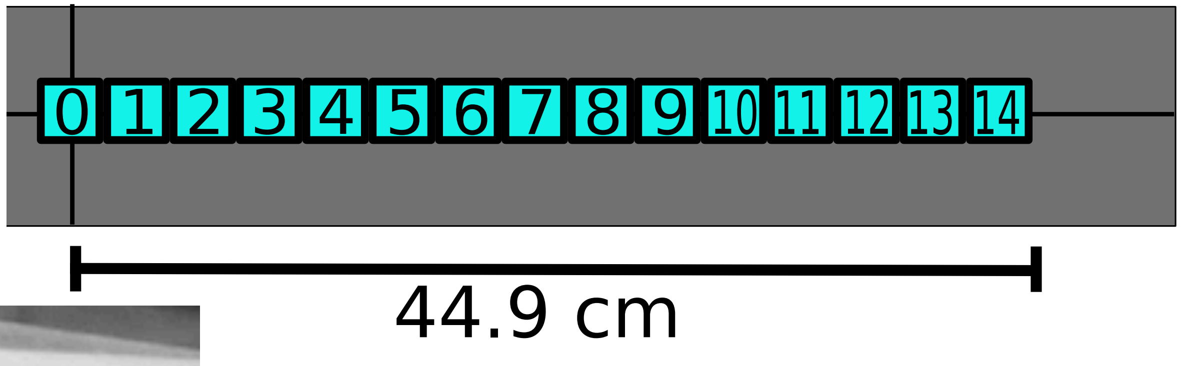
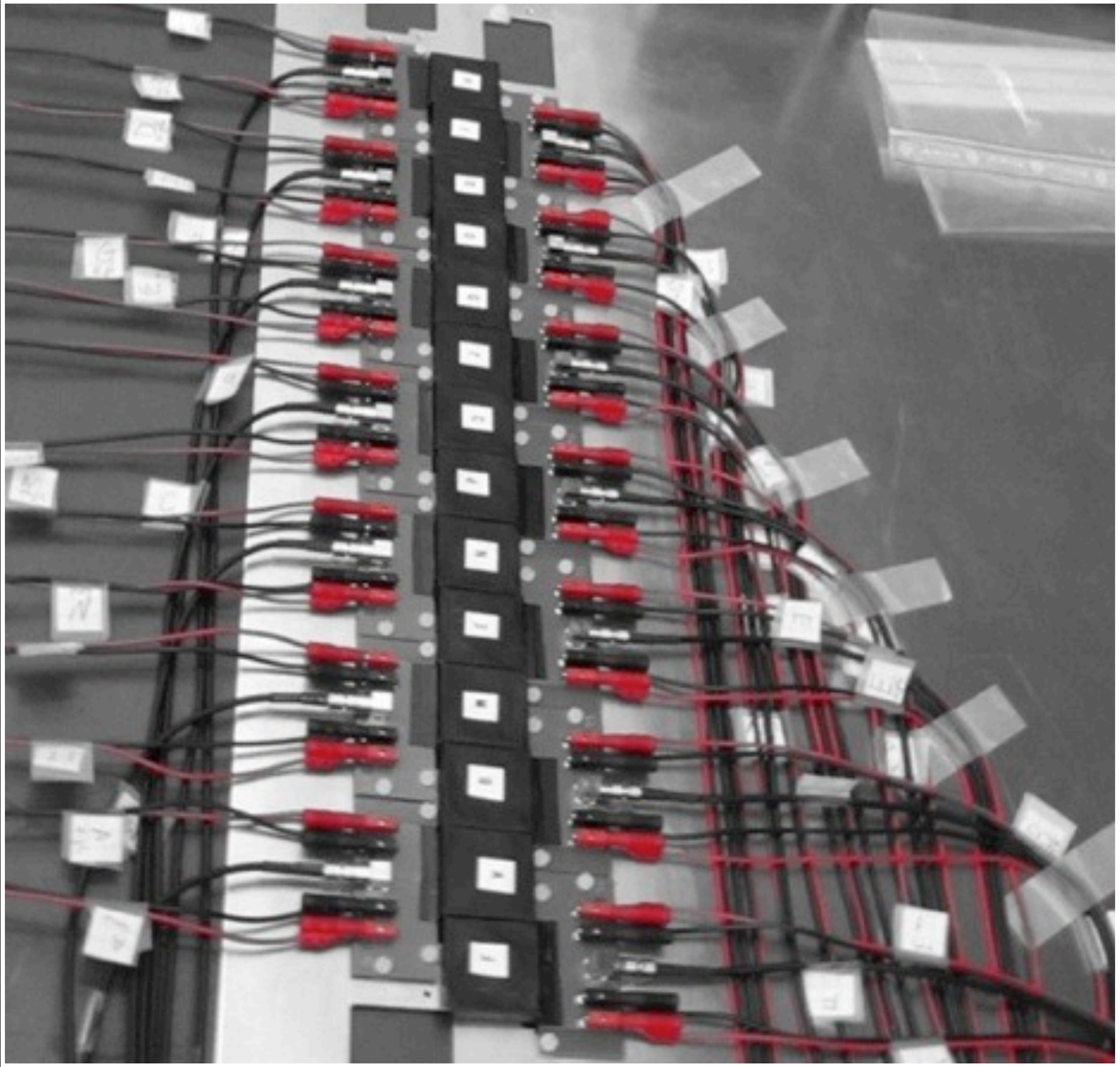
➾ First information on time structure, possibility for comparisons to Geant4, but: no complete “4D” shower reconstruction!

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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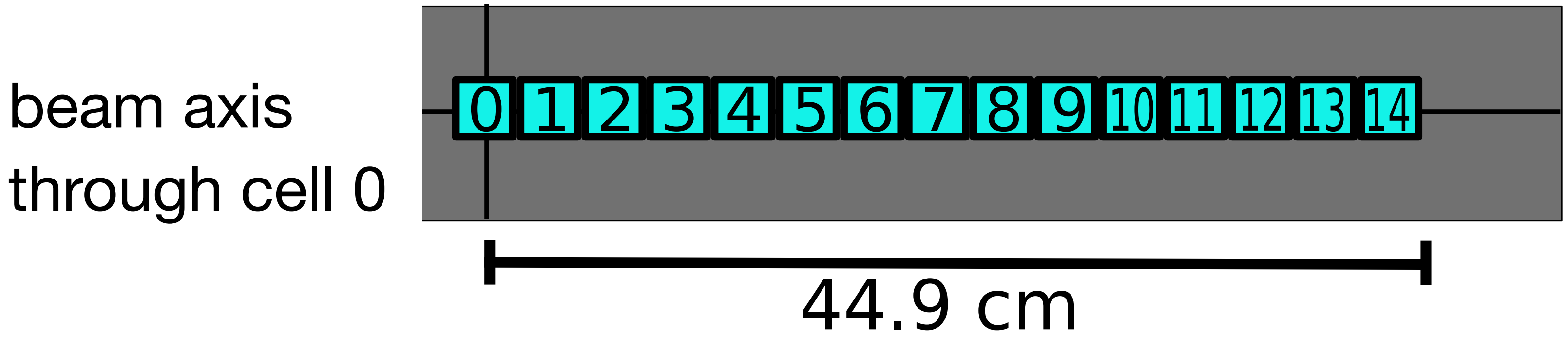


Stand-alone system:

- 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

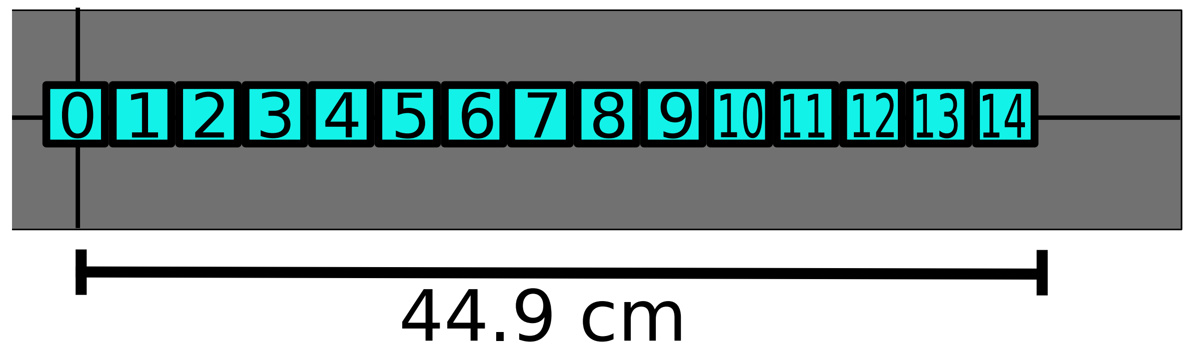
Synchronization with CALICE

- 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

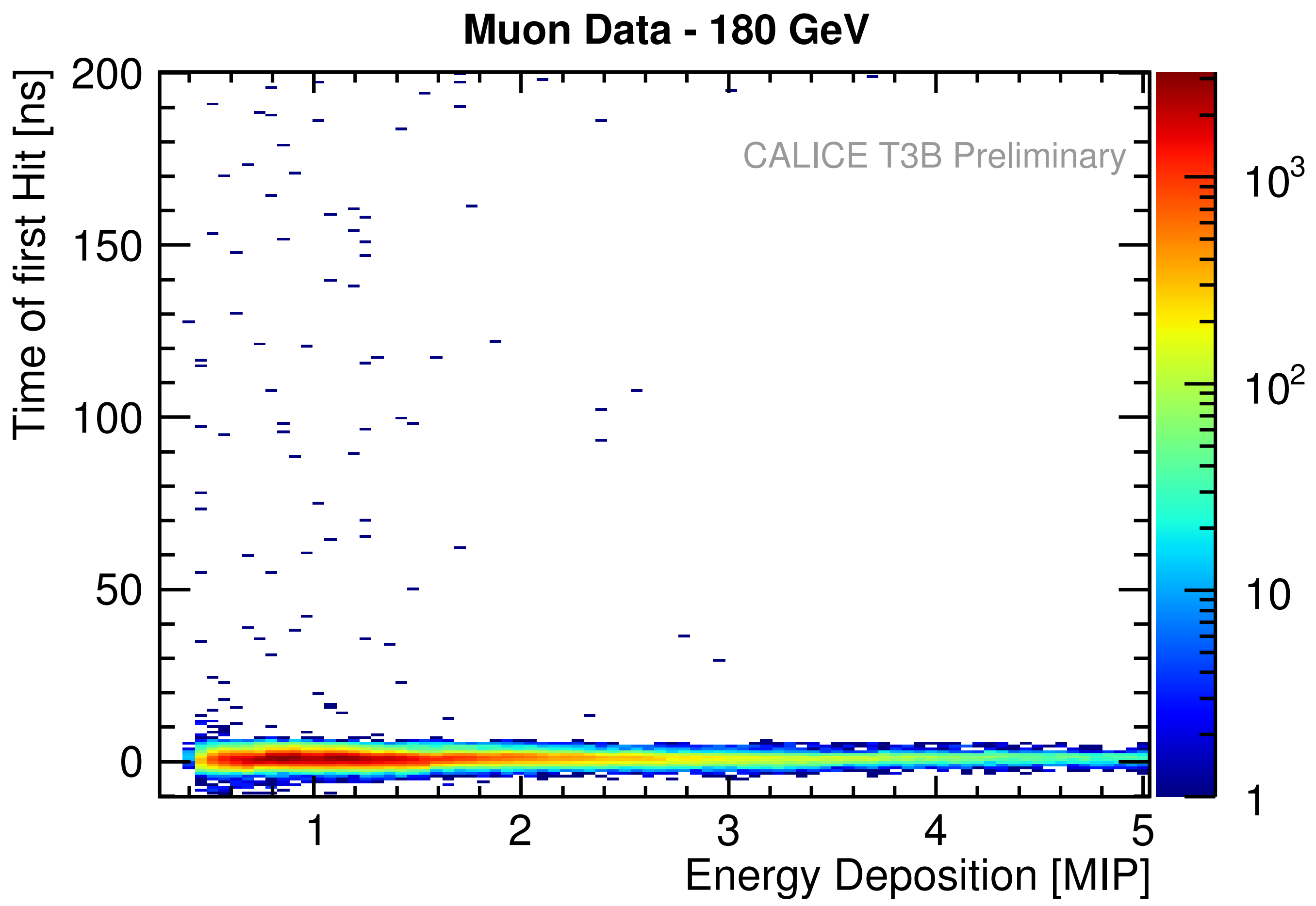
beam axis
through cell 0



Stand-alone system only:

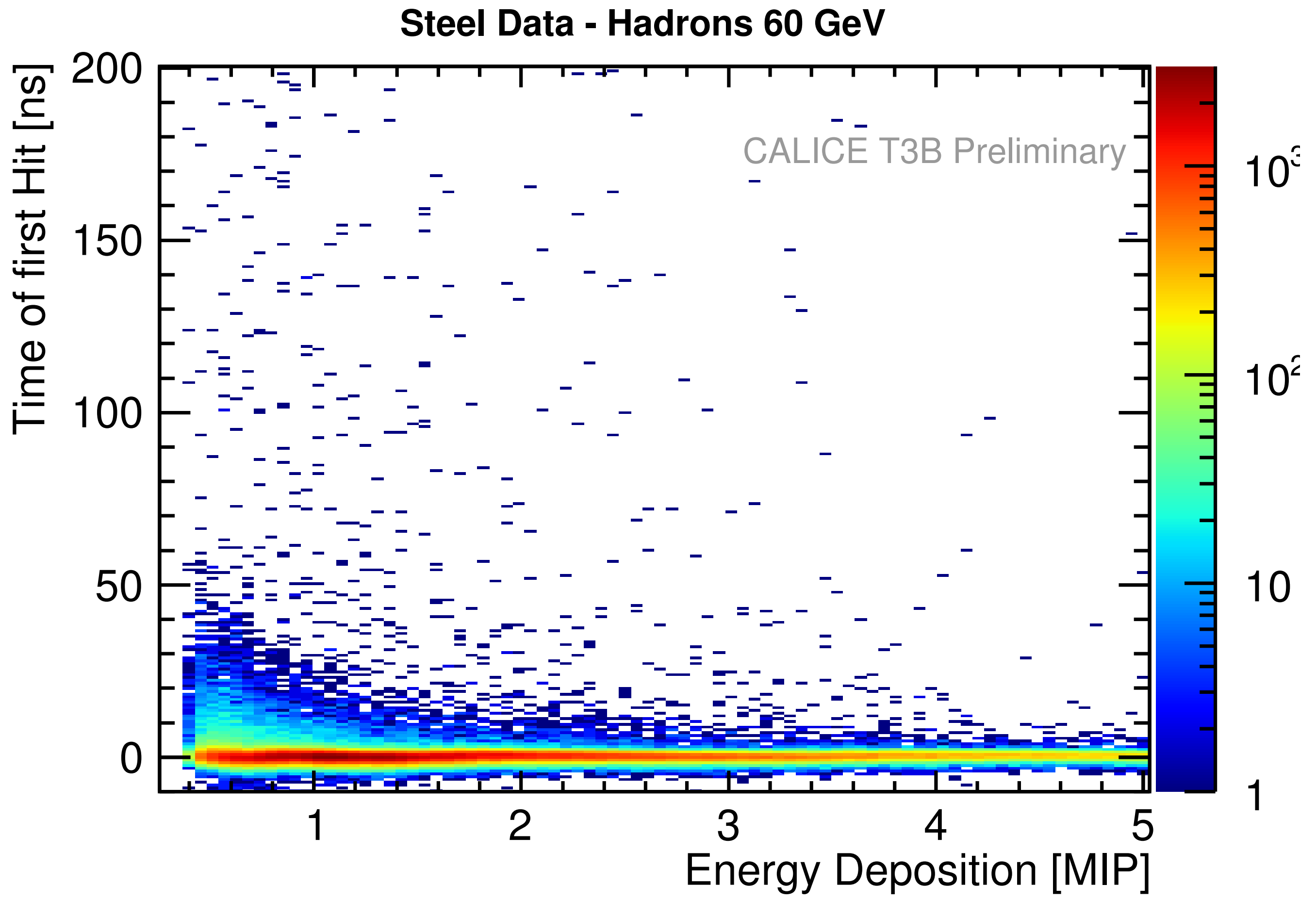
- Installed downstream of CALICE SDHCAL (Glass RPCs between steel absorbers), depth ~ 6 λ
- Identical readout for T3B
- No correlation of T3B and SDHCAL data streams
    - Different DAQ version
    - Data taken during SDHCAL commissioning: Low data rate, insufficient for timing measurements
    - ▸ Standalone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

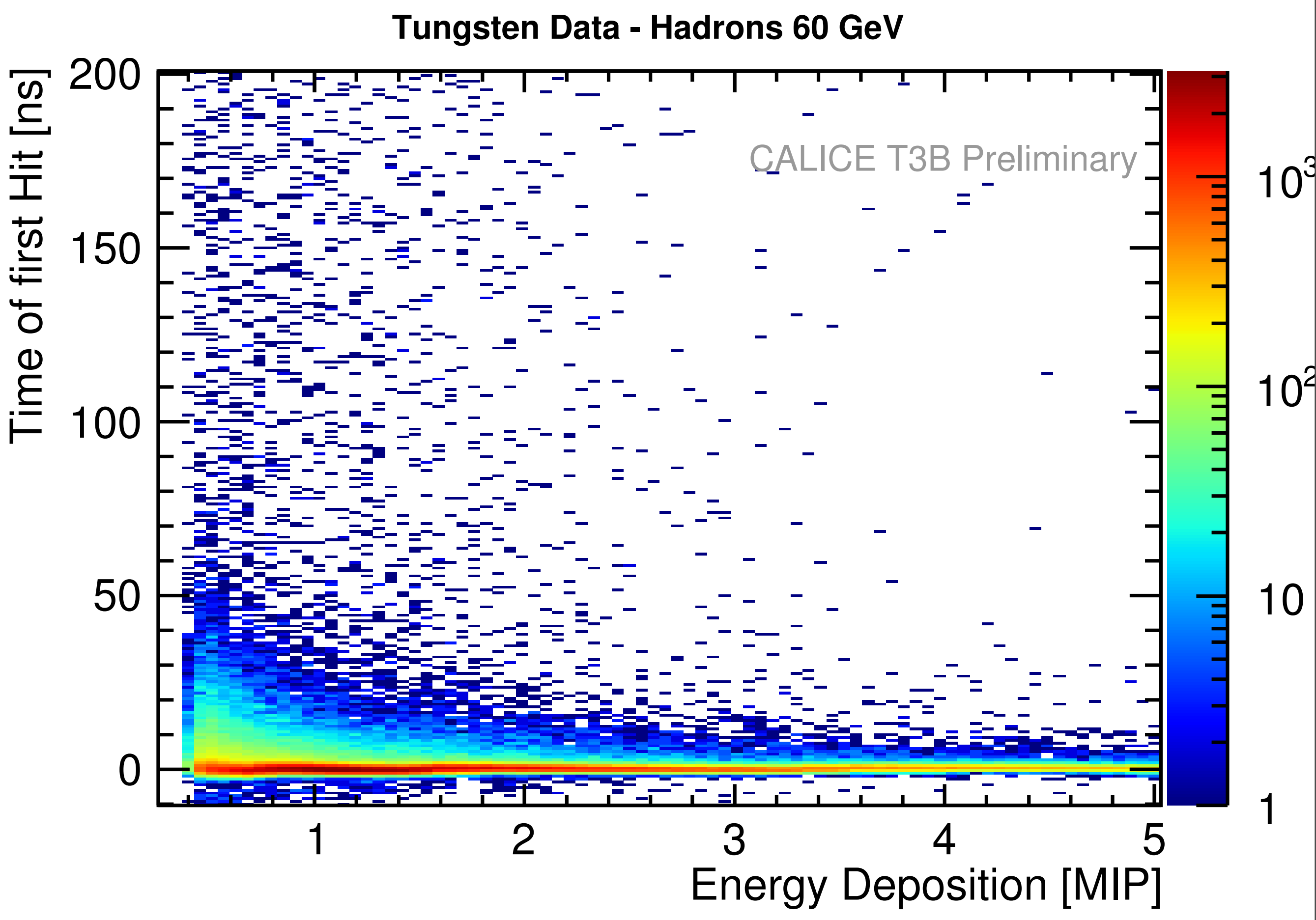
Data Analysis - Results in Steel & Tungsten



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

Data Analysis - Results in Steel & Tungsten

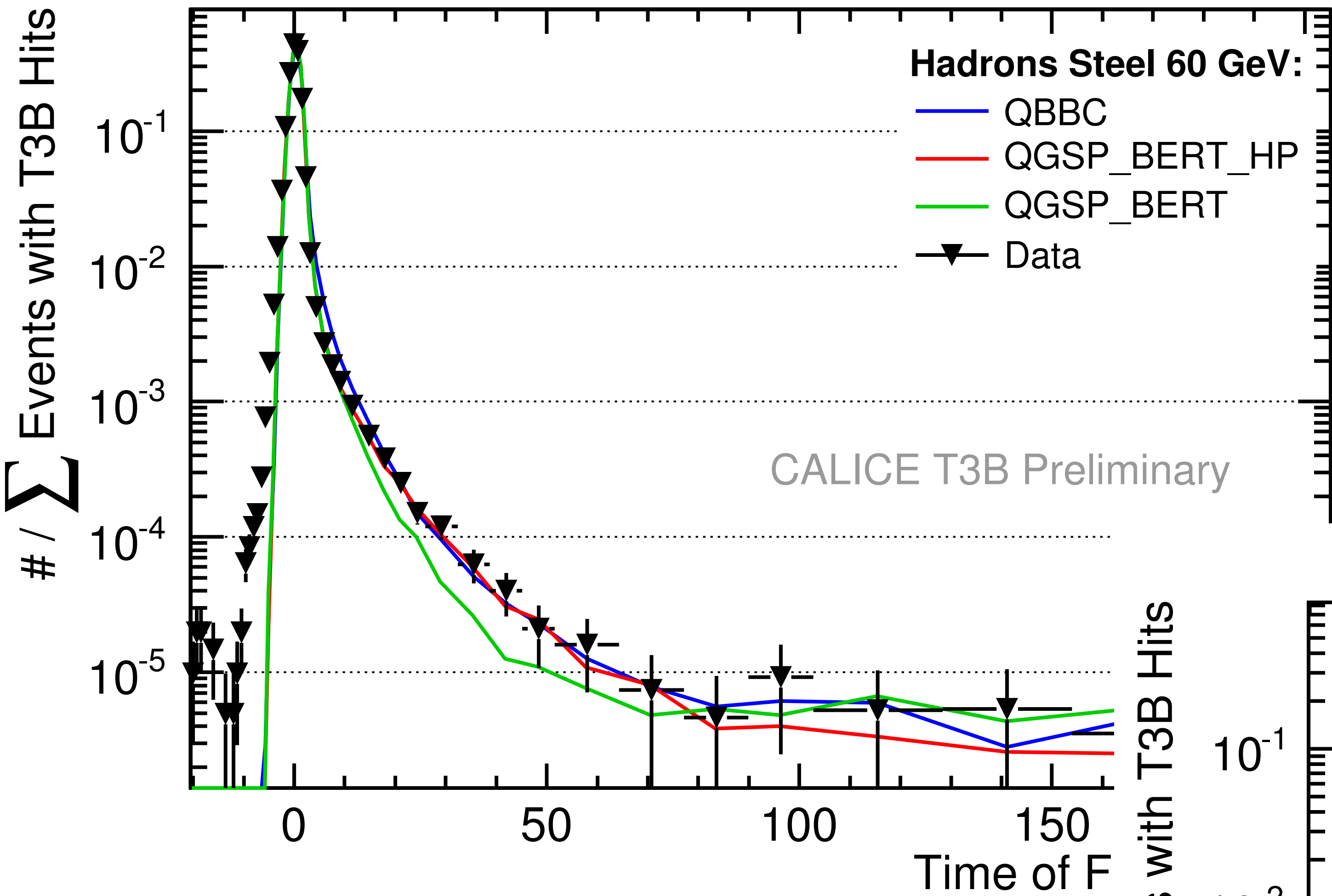




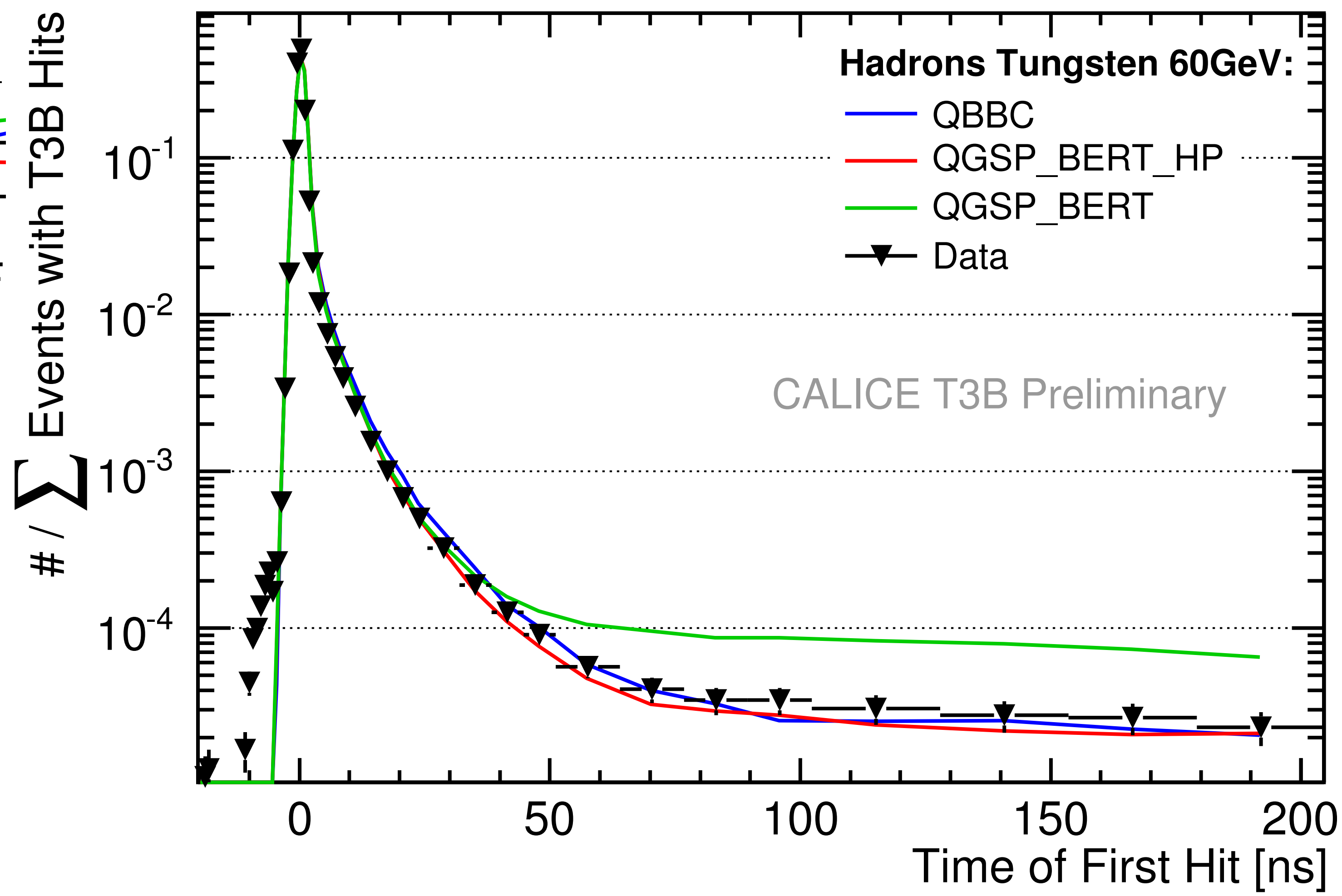
- The “universal” T3B observable: Time of First Hit
    - Multiple hits per tile in one event are rare: < 3% at 30% amplitude of primary hit

- Substantial difference between showers in steel and tungsten: More pronounced late activity in W

Hit Time Distributions - Compared to Simulations

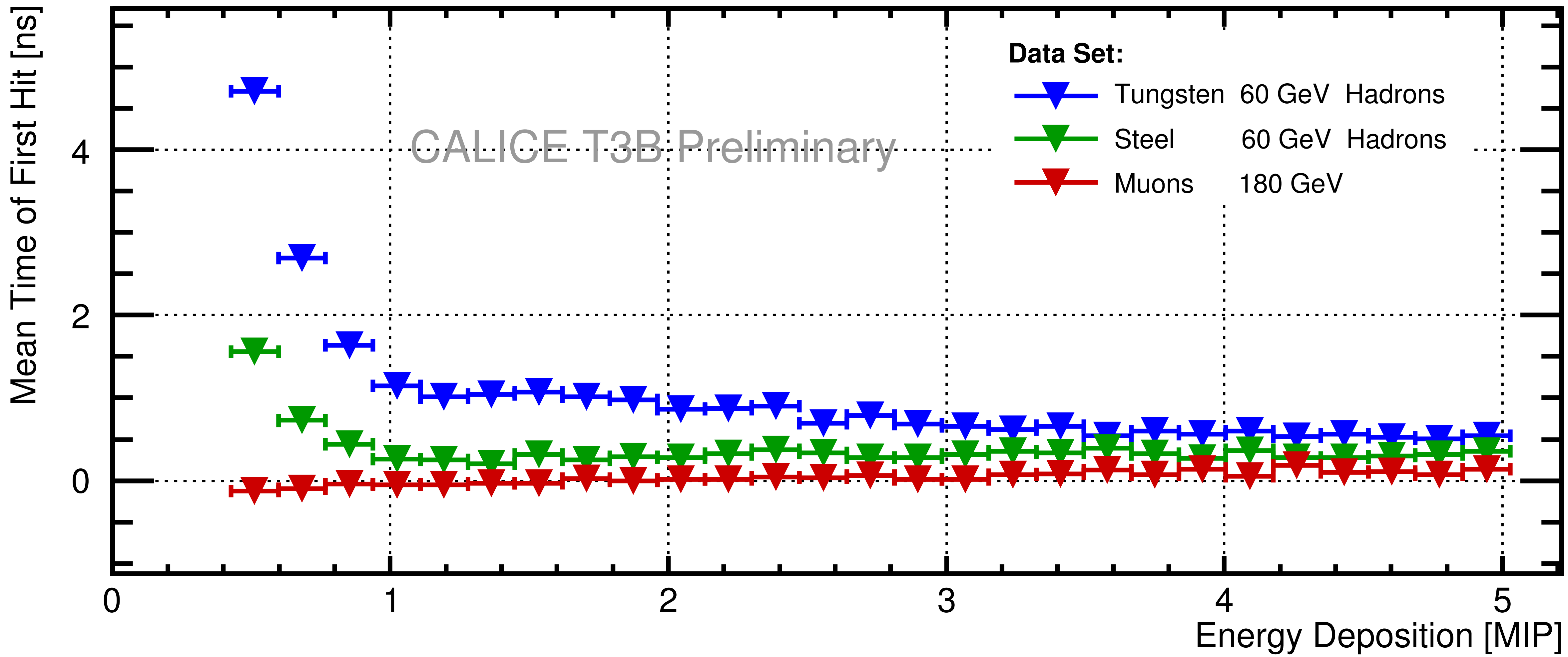


- Sharp fall-off of hit numbers with time: Most of the hits are within the few ns



- Good reproduction of distribution in steel by all models
- In tungsten sophisticated neutron treatment is mandatory: high precision (HP) neutron tracking

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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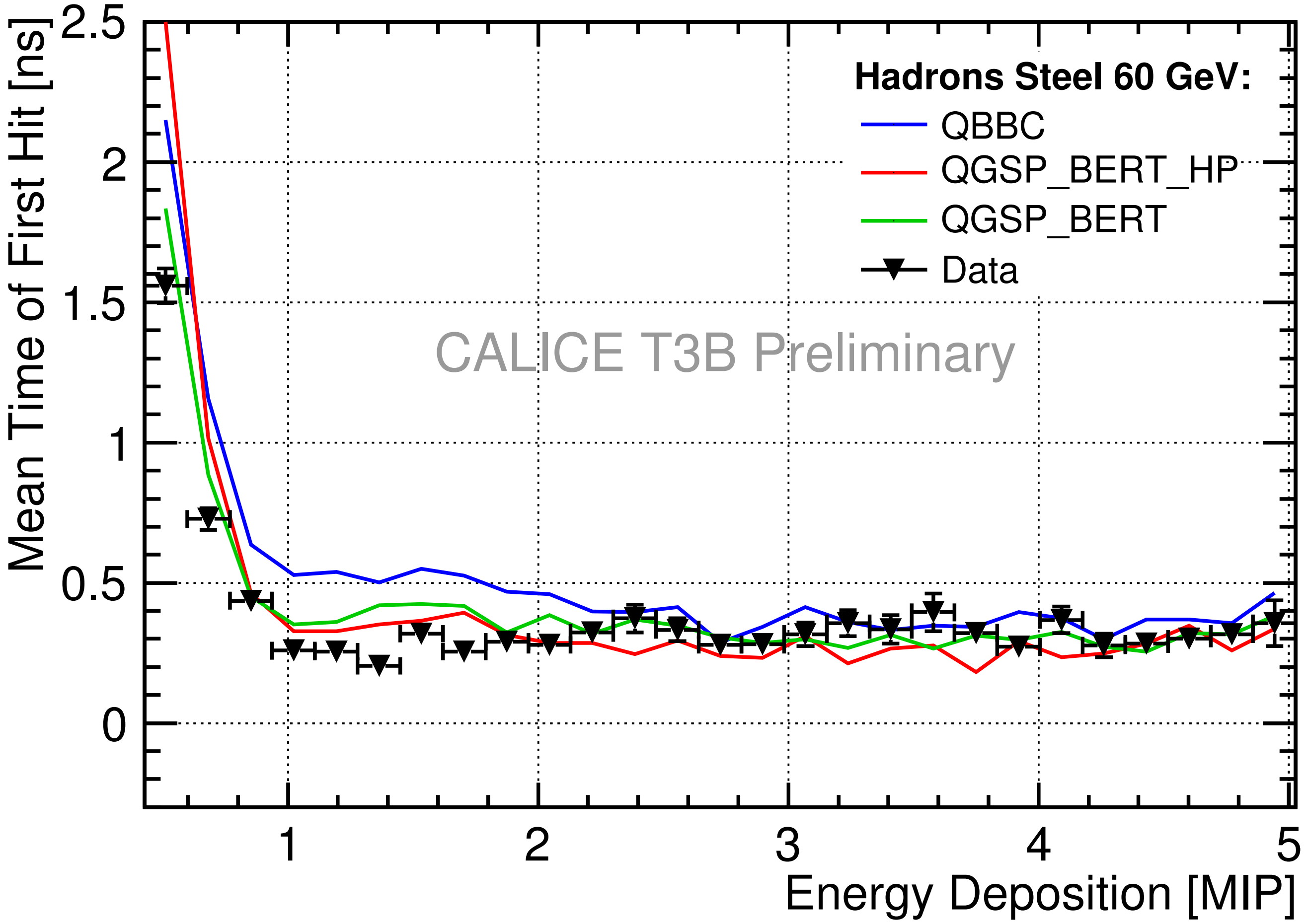
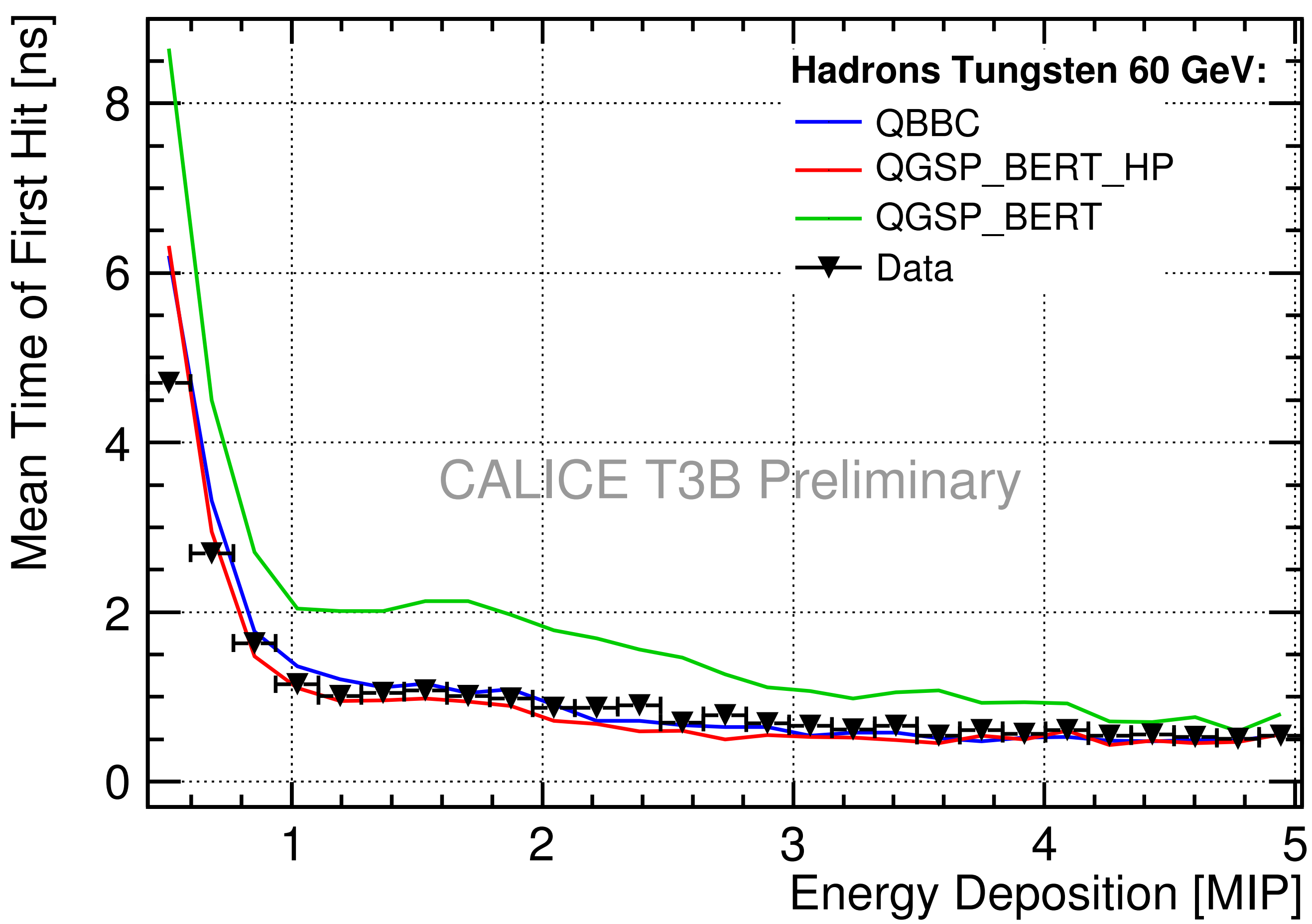
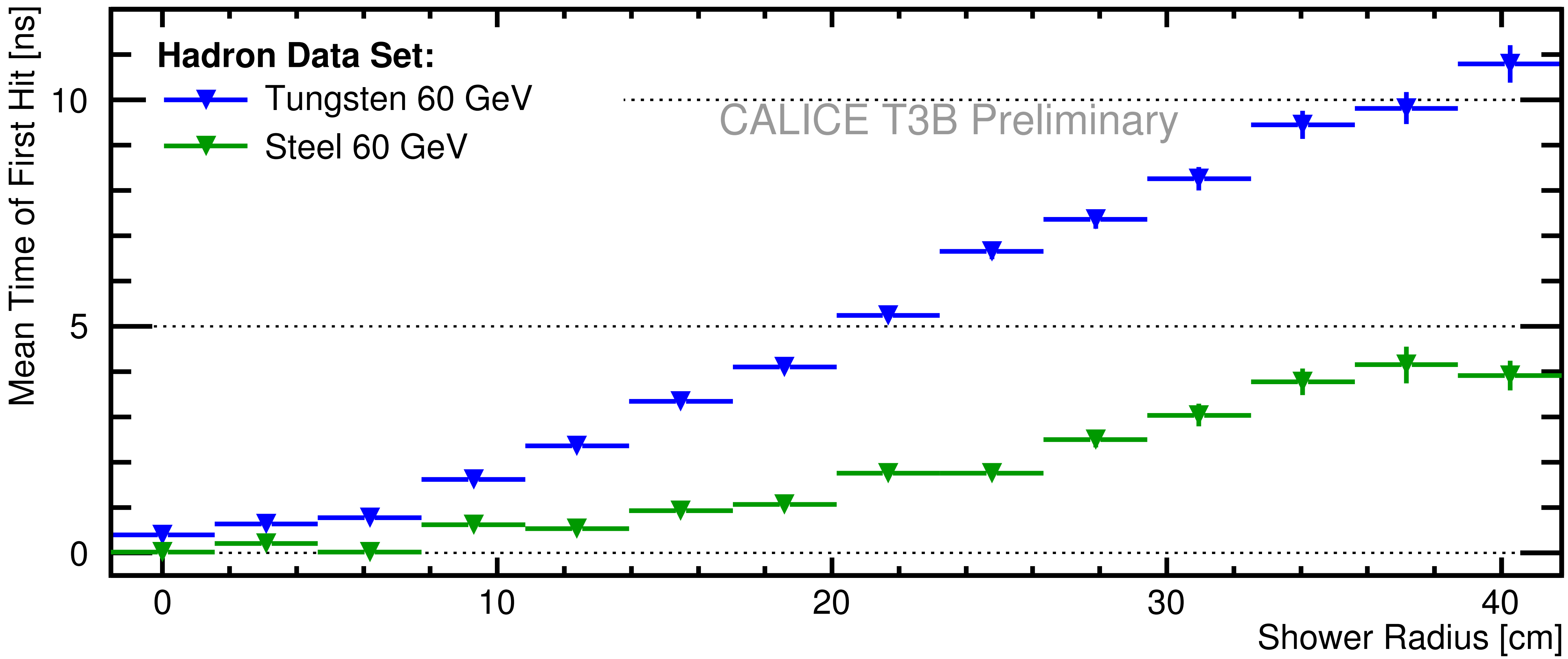




- In steel late energy deposits are mostly of low energy, in tungsten also higher-energy late contributions are seen

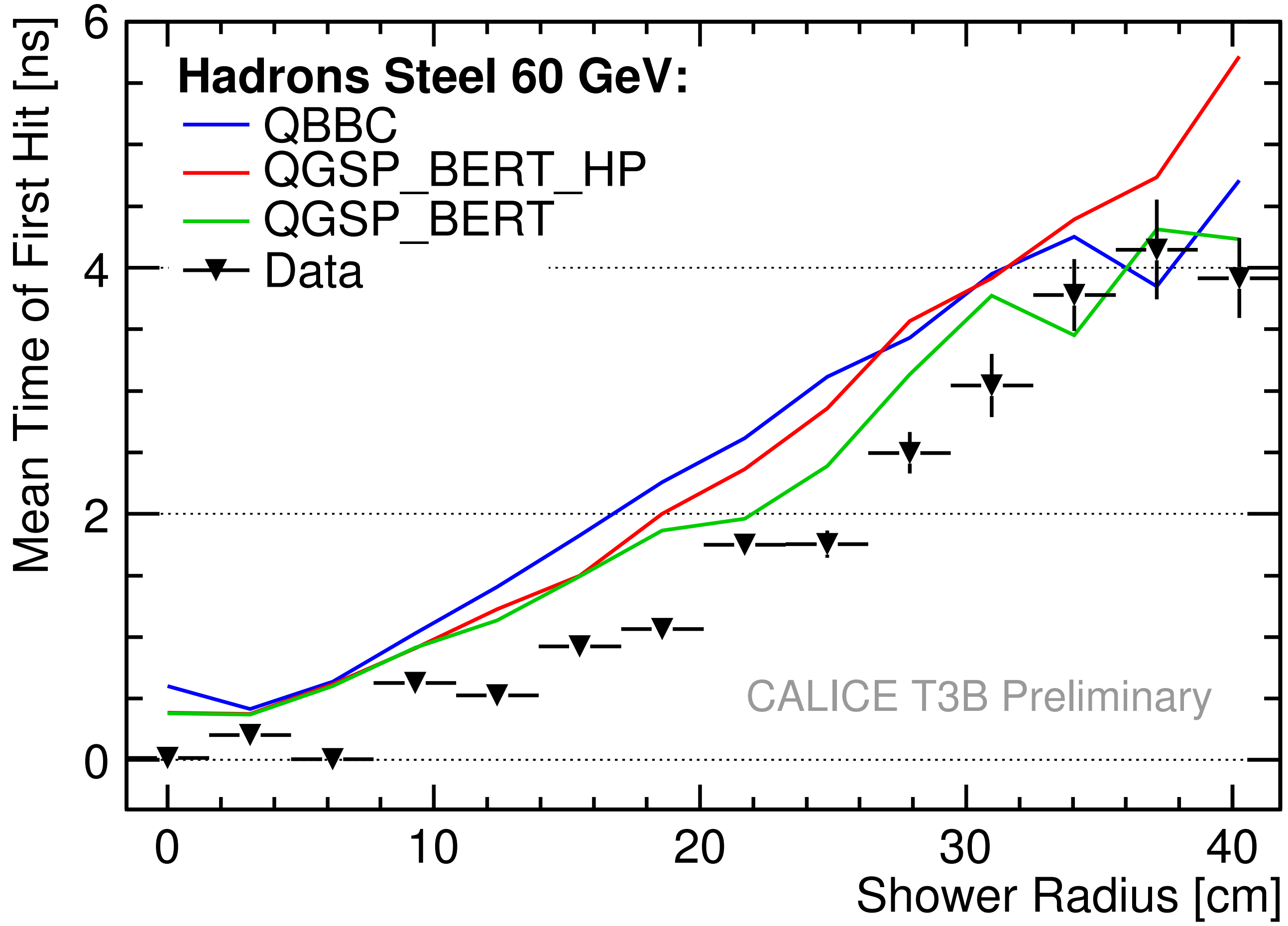
- All studied physics lists reproduce behavior in steel satisfactorily
- Neutron treatment important in Tungsten - QGSP_BERT_HP and QBBC only

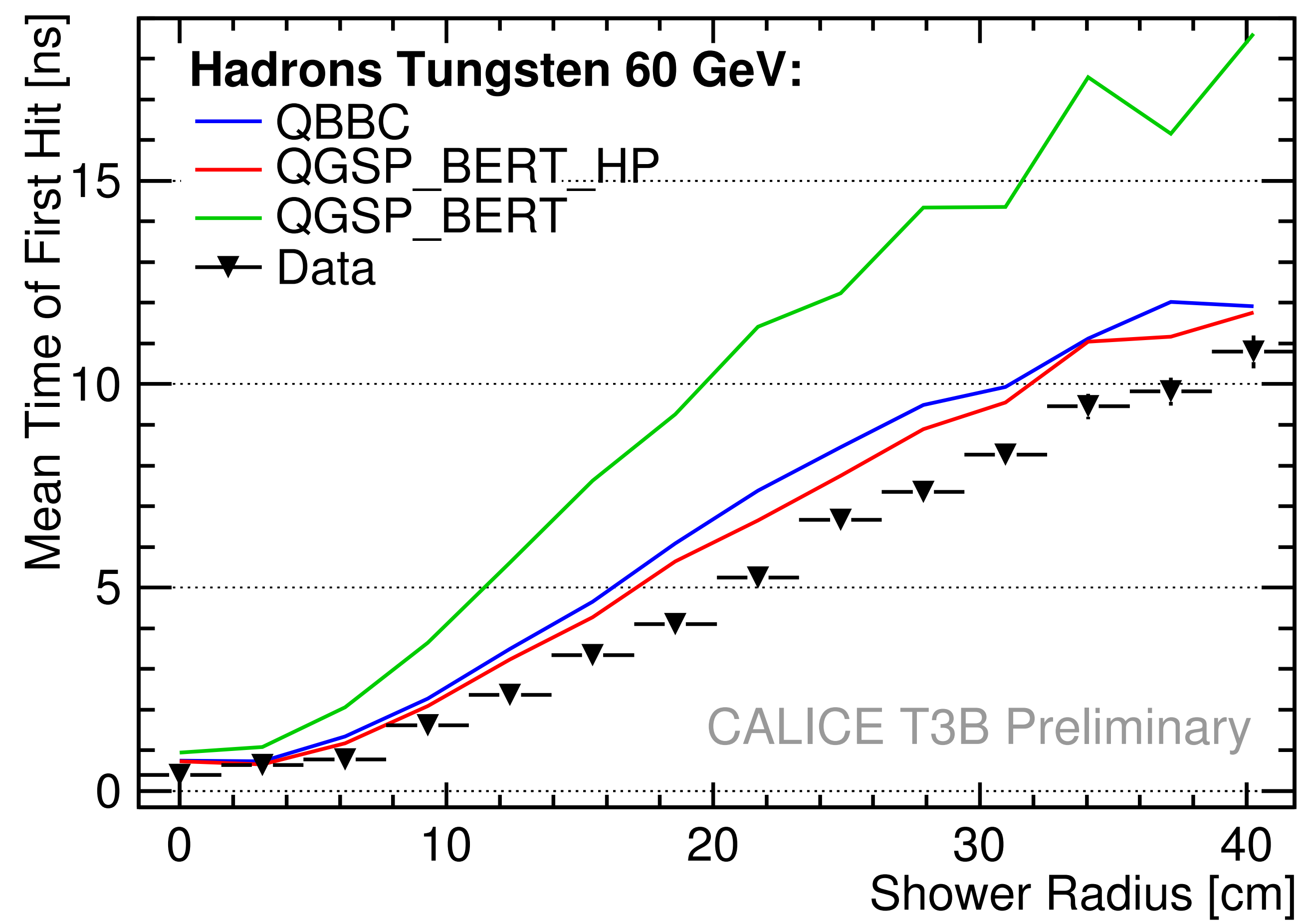
Timing as a Function of Radius



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

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
- 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

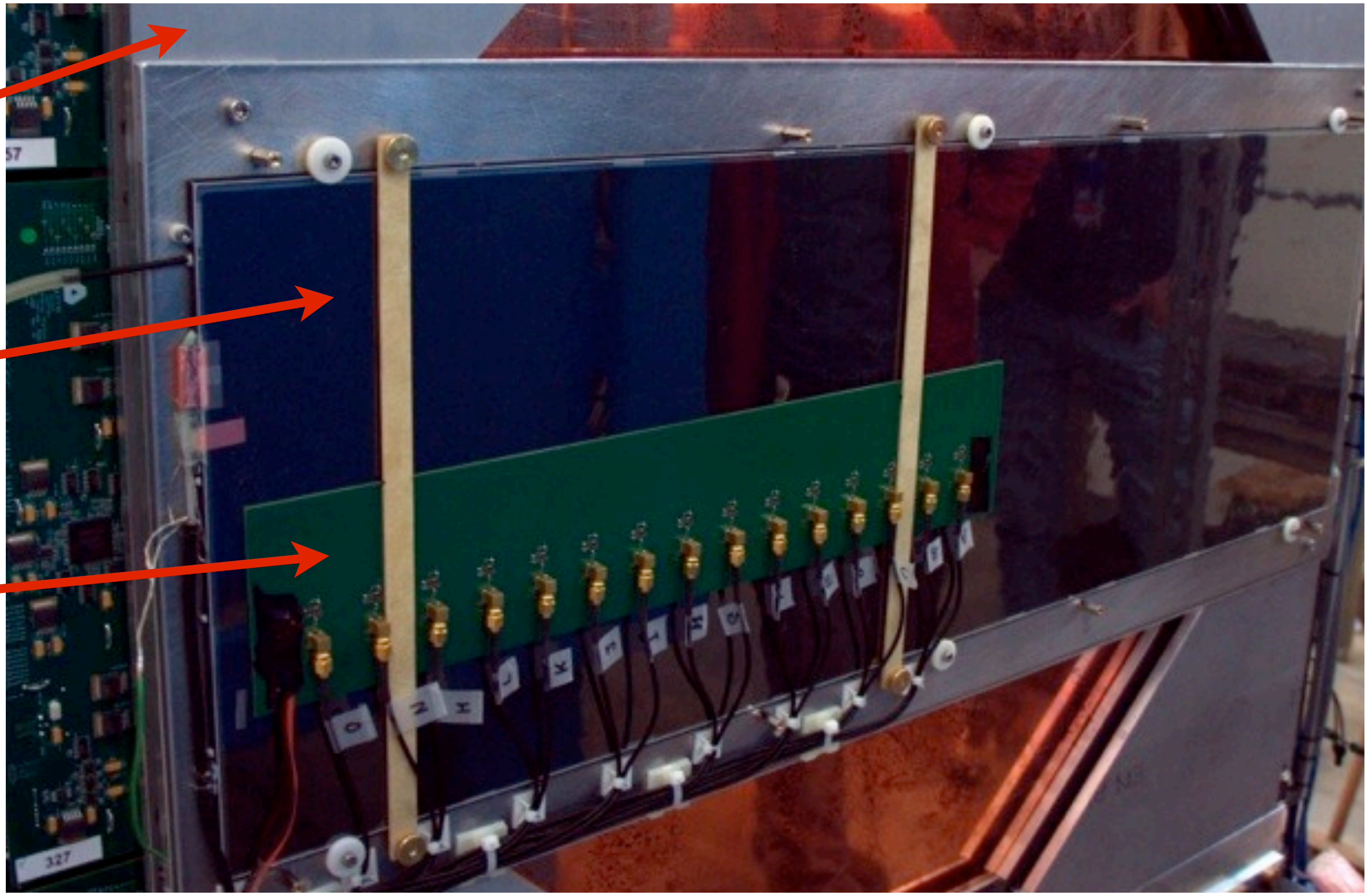
Alternative Readout: Glass RPCs

- Provide a direct comparison of scintillator and gaseous readout:
  FastRPC - A 1 to 1 copy of T3B, but with a glass RPC instead of scintillators
  - identical granularity: 3 x 3 cm^2, one strip behind the CALICE WDHCAL
  - identical data acquisition: 2.4 μs acquisition window with 800 ps readout
  - identical analysis strategy - reconstruction of time of first hit

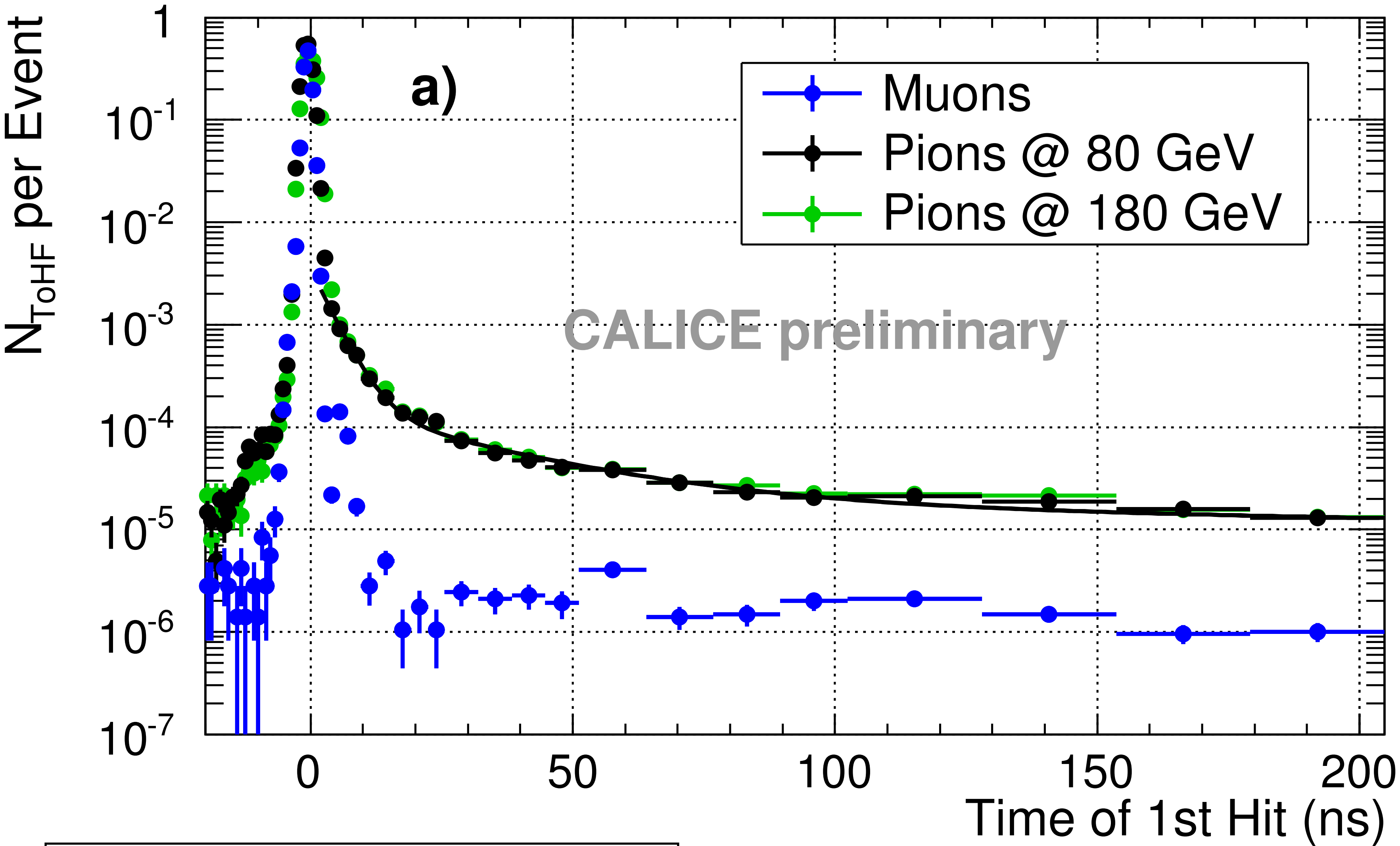
CALICE WDHCAL, ~ 5λ tungsten & RPC active layers

RPC (produced at ANL)

FastRPC readout board, connected to oscilloscopes



Sensitivity to Time Structure - RPCs



normalized to number of events with FastRPC hits

- RPCs are also sensitive to late shower components in tungsten
    - No beam energy dependence of late contributions observed

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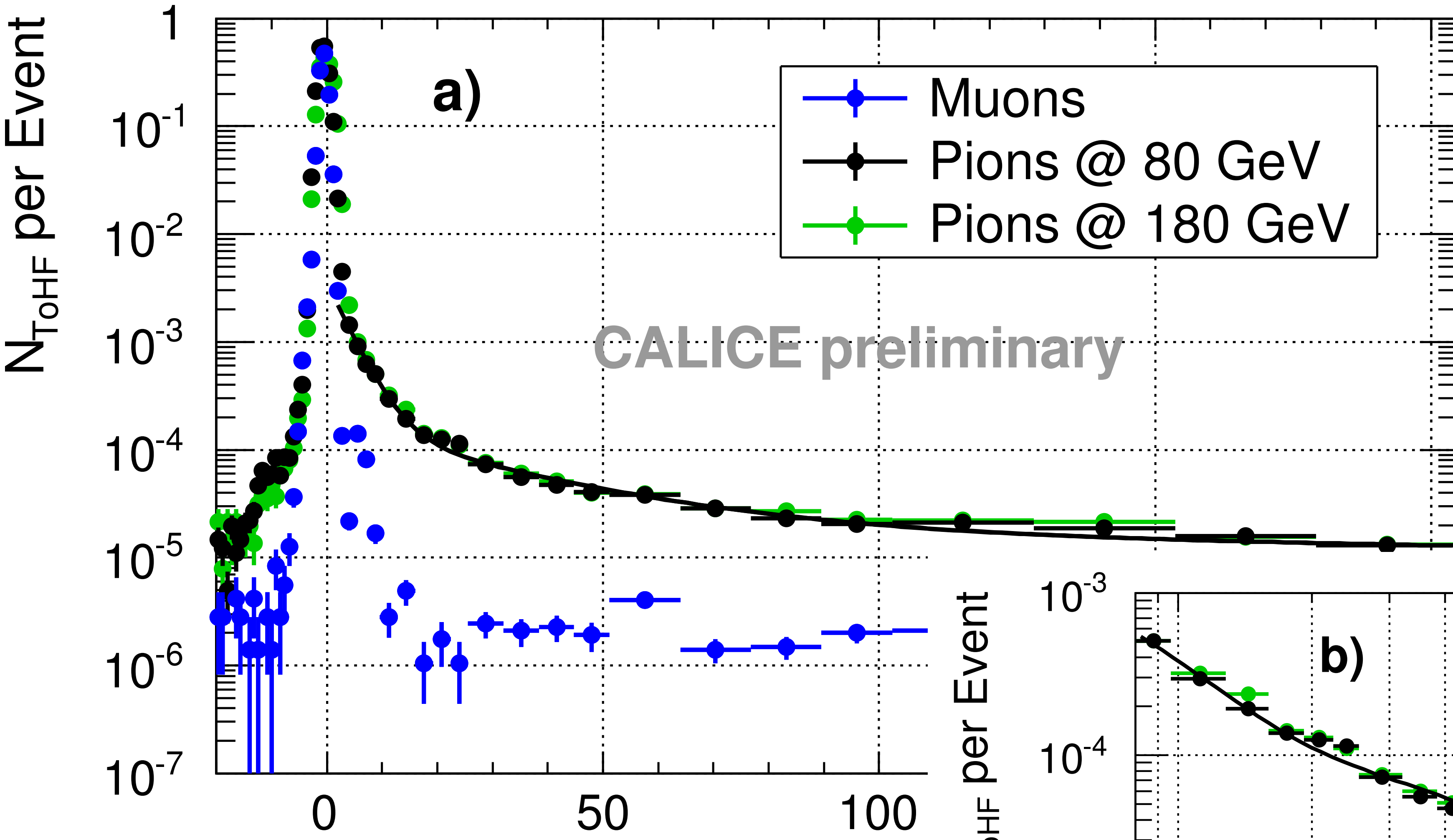

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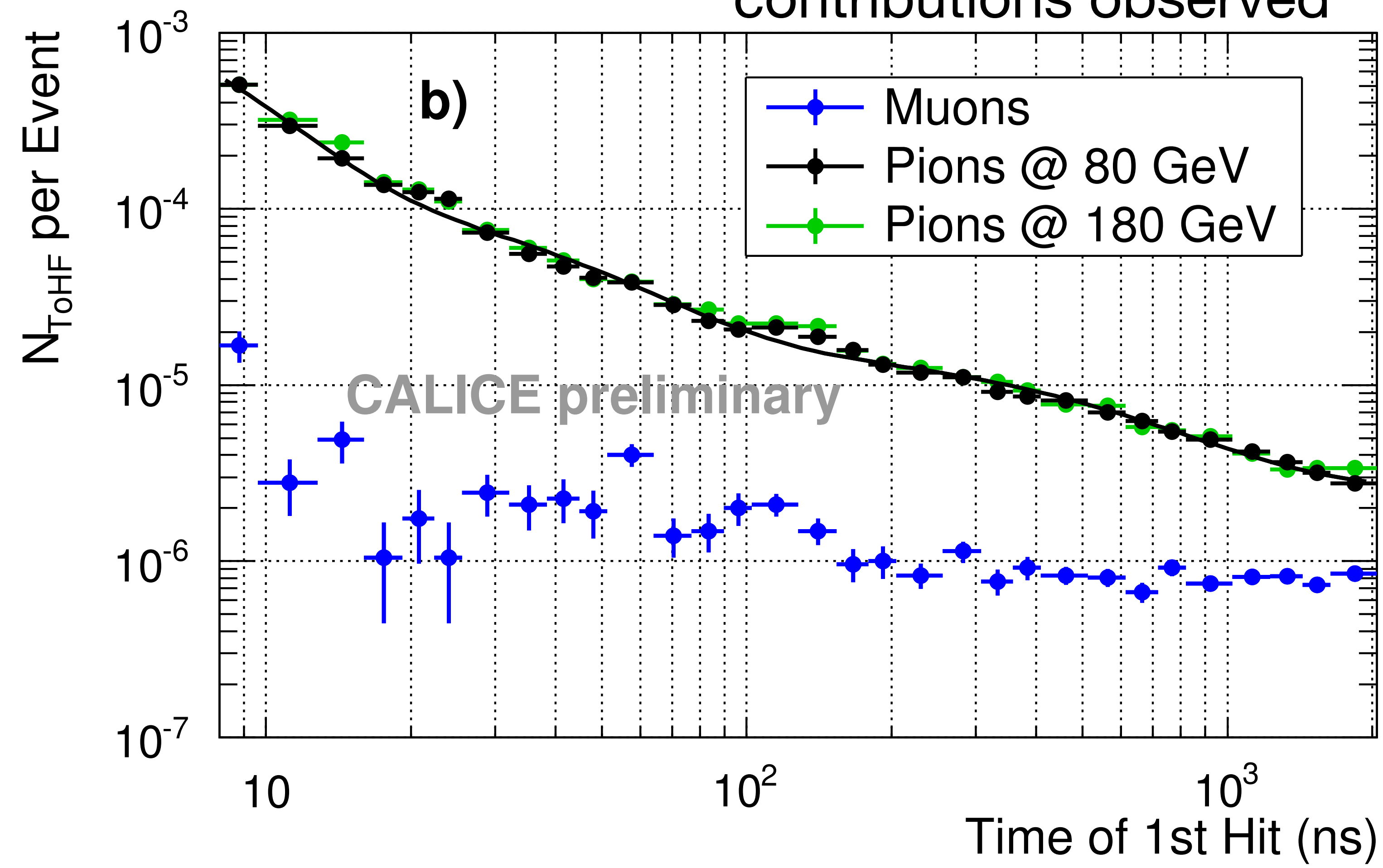

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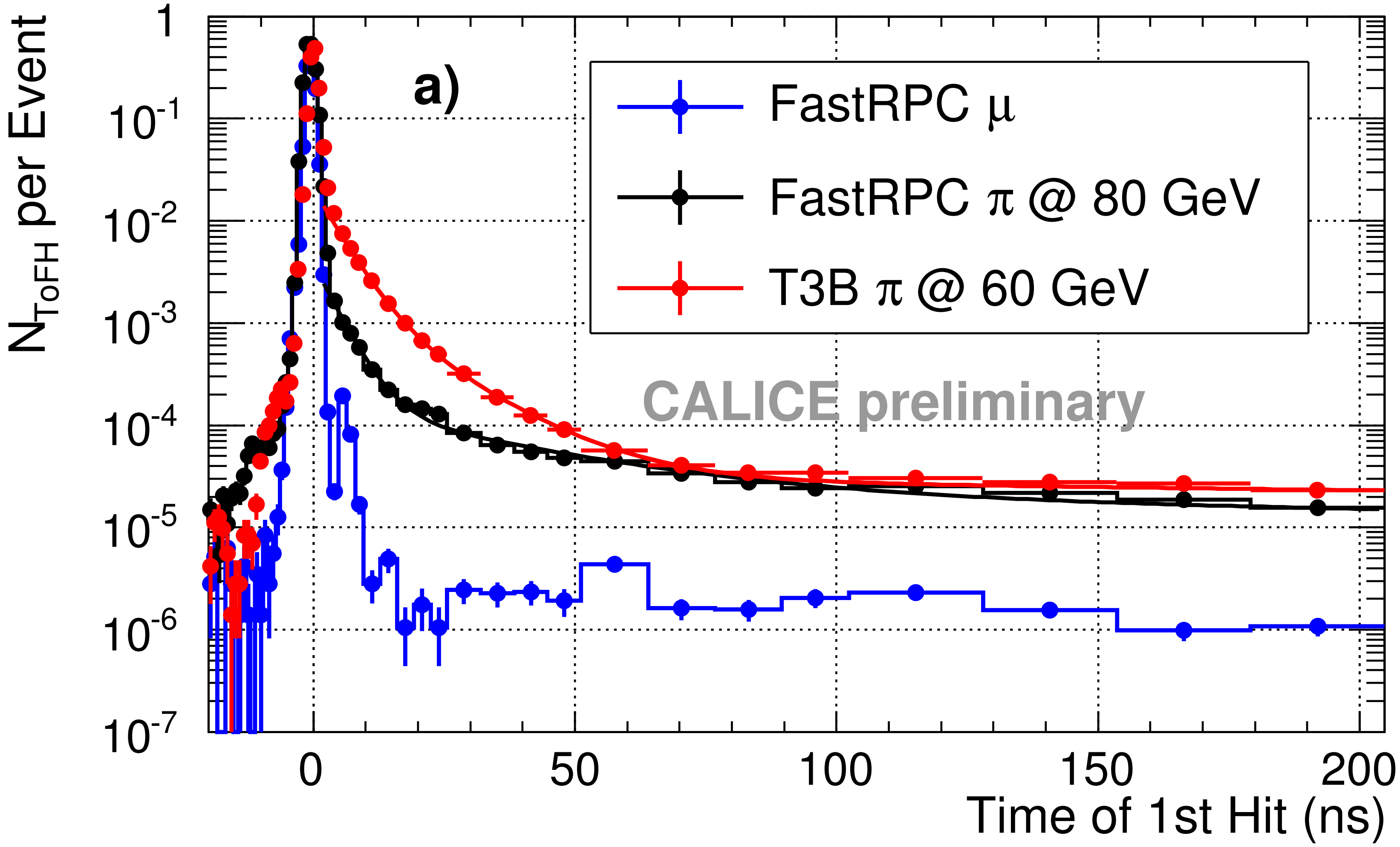
Scintillator vs Gas - Difference in Sensitivity



- Comparable behavior for prompt component
- Striking difference in intermediate range: ~ 8 ns to 50 ns

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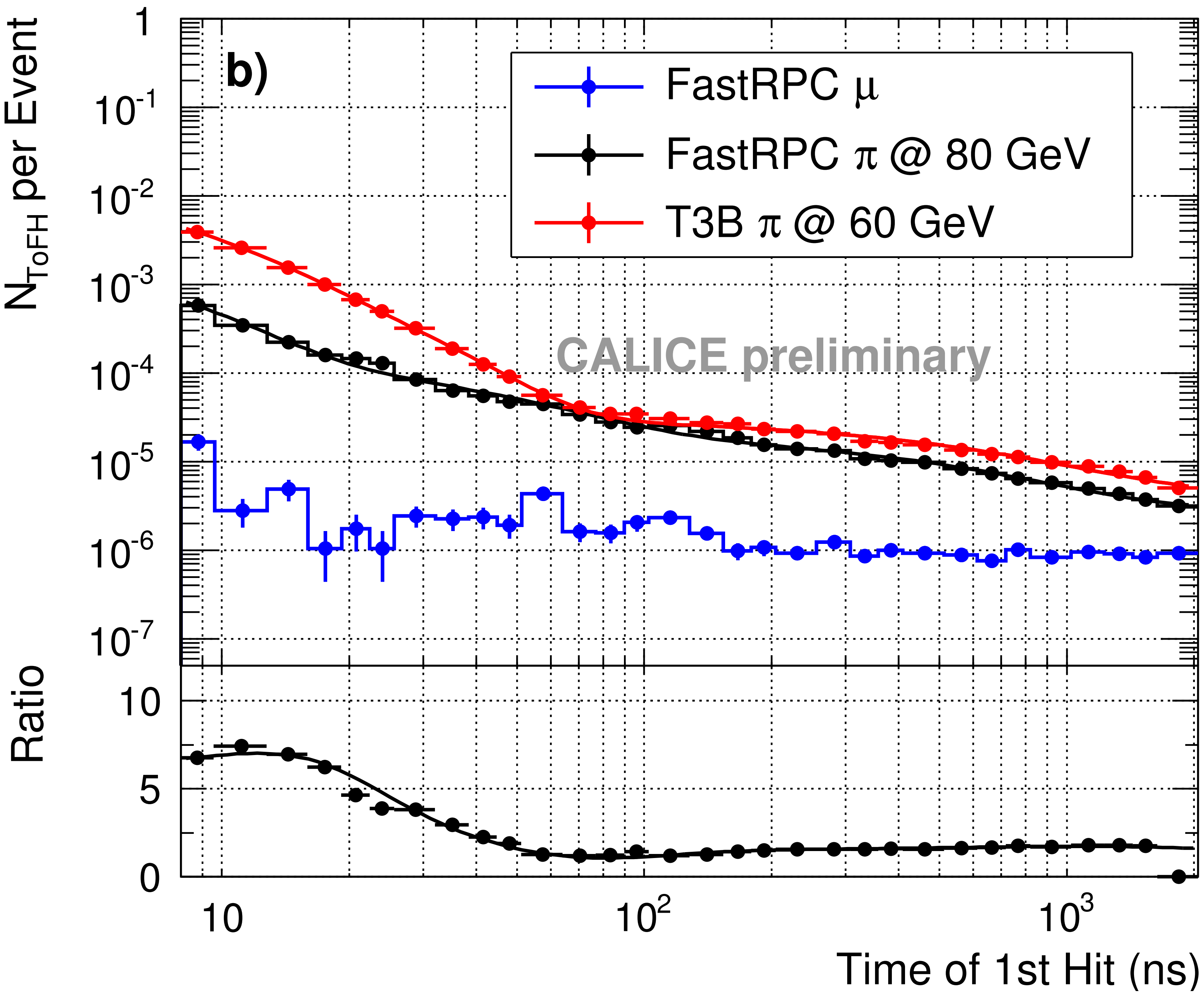


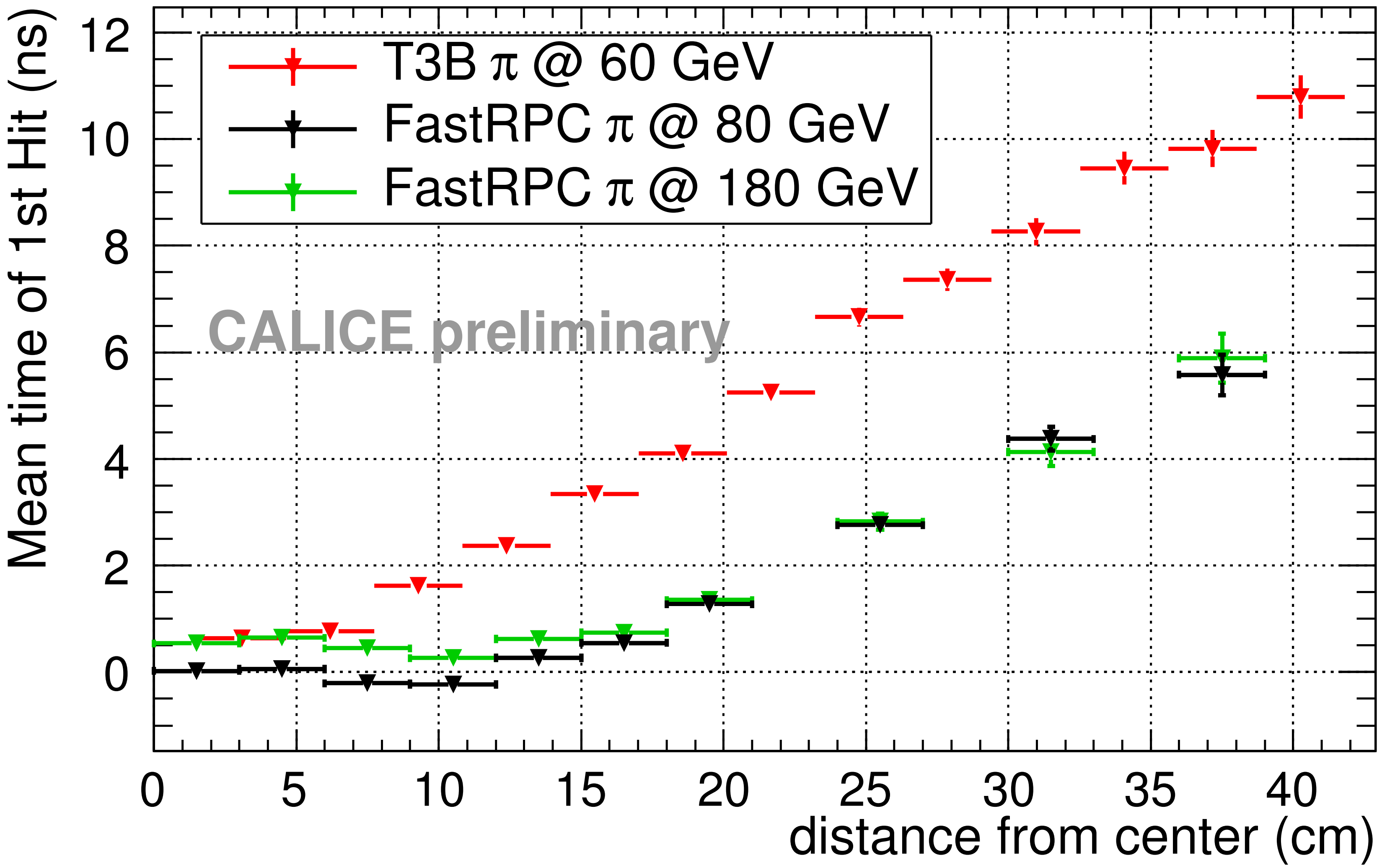
normalized to number of events with FastRPC hits

Comparable behavior for prompt component

Striking difference in intermediate range: ~ 8 ns to 50 ns

- Further quantified: Factor 5 - 8 suppression of intermediate component in gaseous detectors: MeV - scale neutrons: High sensitivity of scintillators through elastic scattering on H

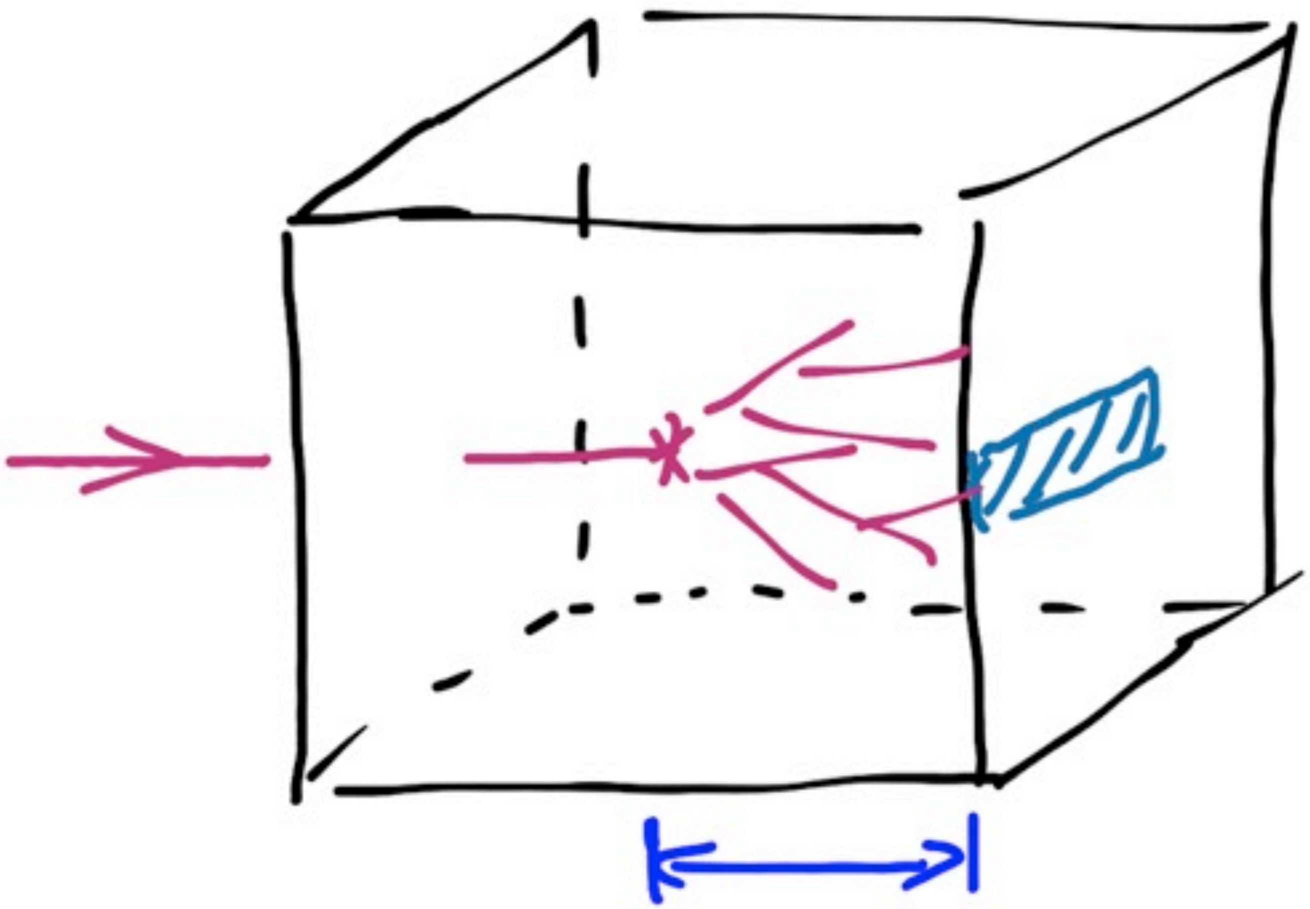
Radial Profile with Gaseous and Scintillator Readout



- Reduced late component with RPC readout: Prompt shower core dominates mean hit timing out to larger radii, overall reduced mean

Adding a 4th Dimension: Depth

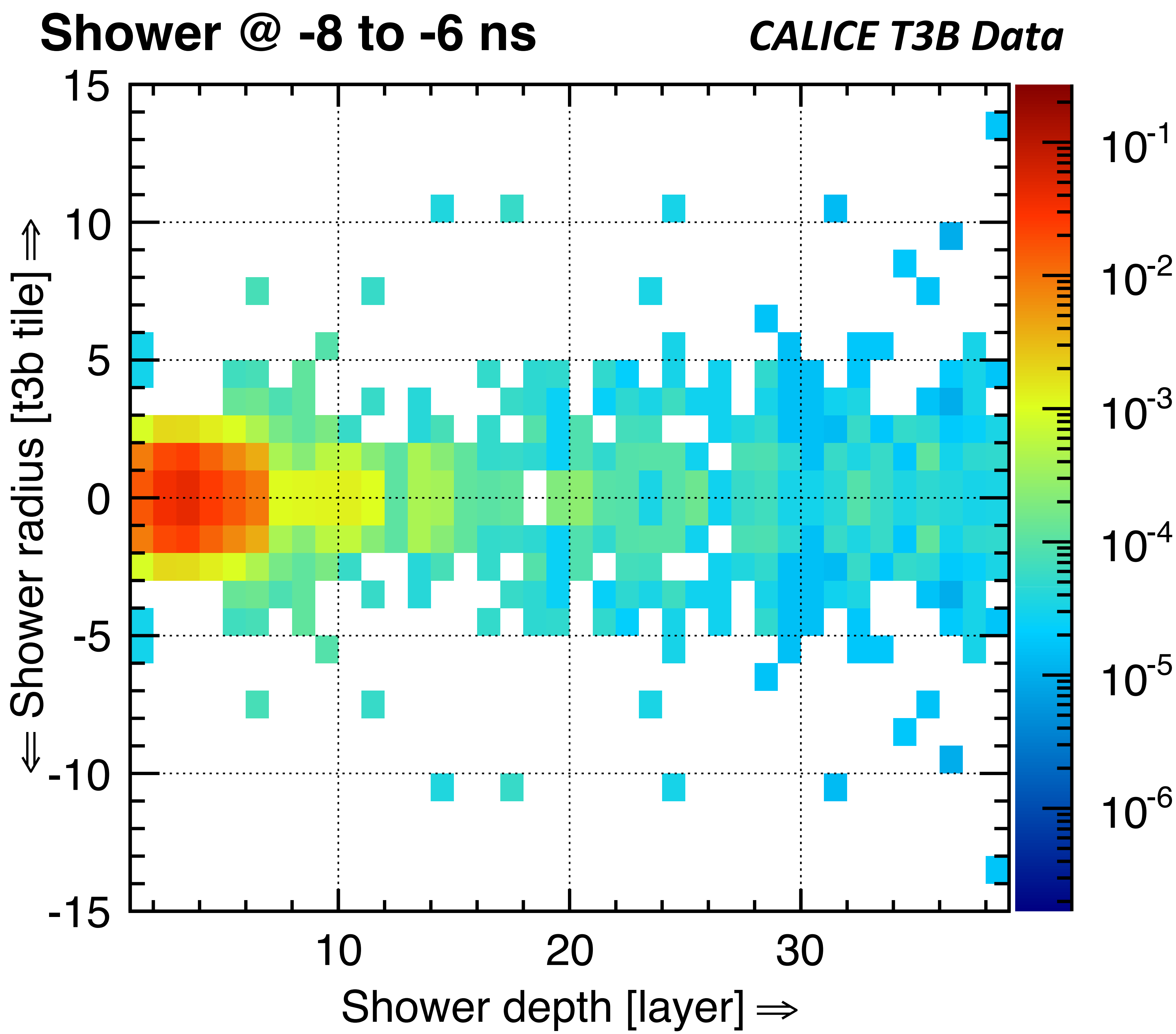
- Correlation of T3B and WAHCAL events provides a powerful addition:



- 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

The Life of a Pion in the WAHCAL



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

Shown: First hits in each cell only

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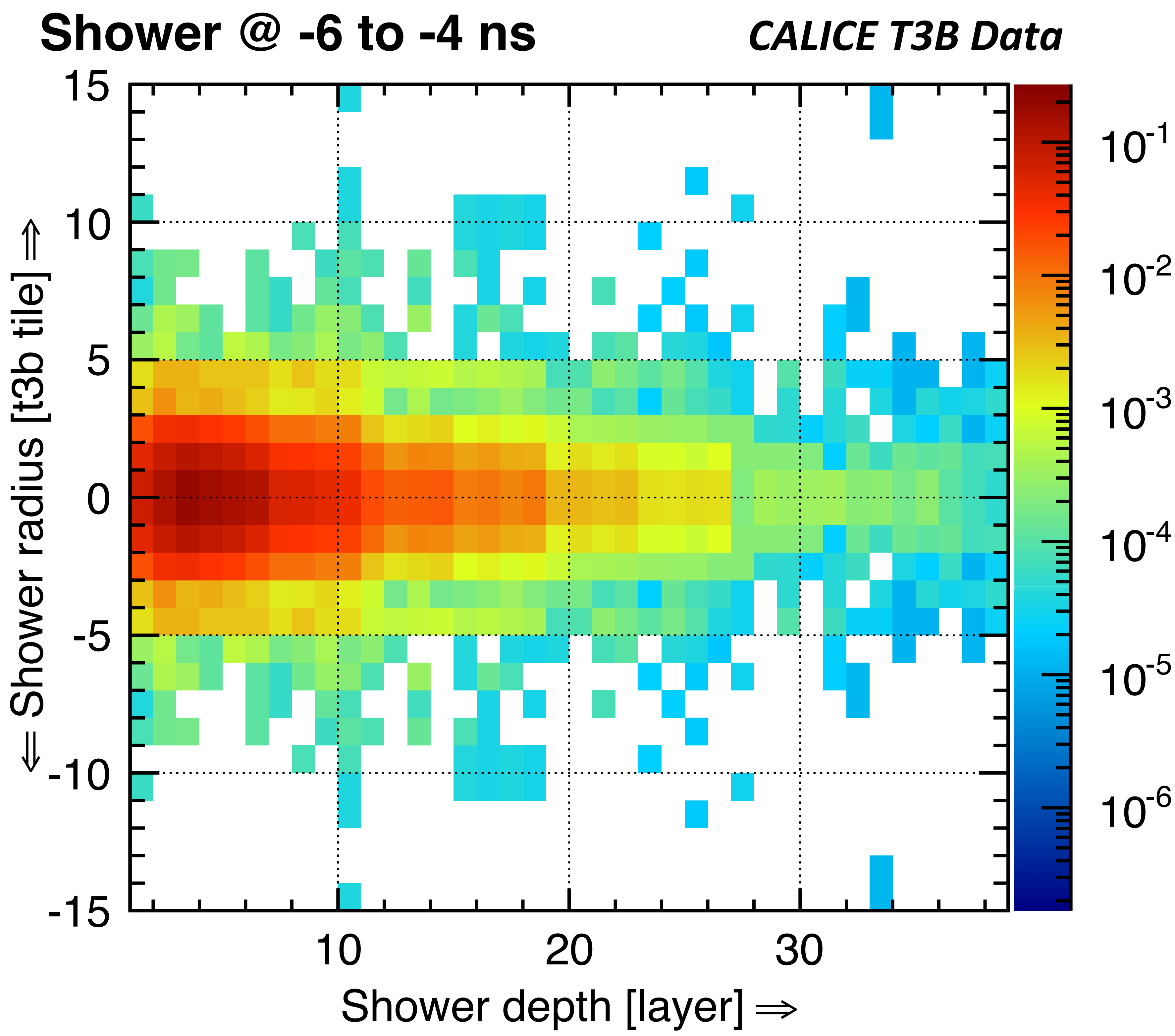

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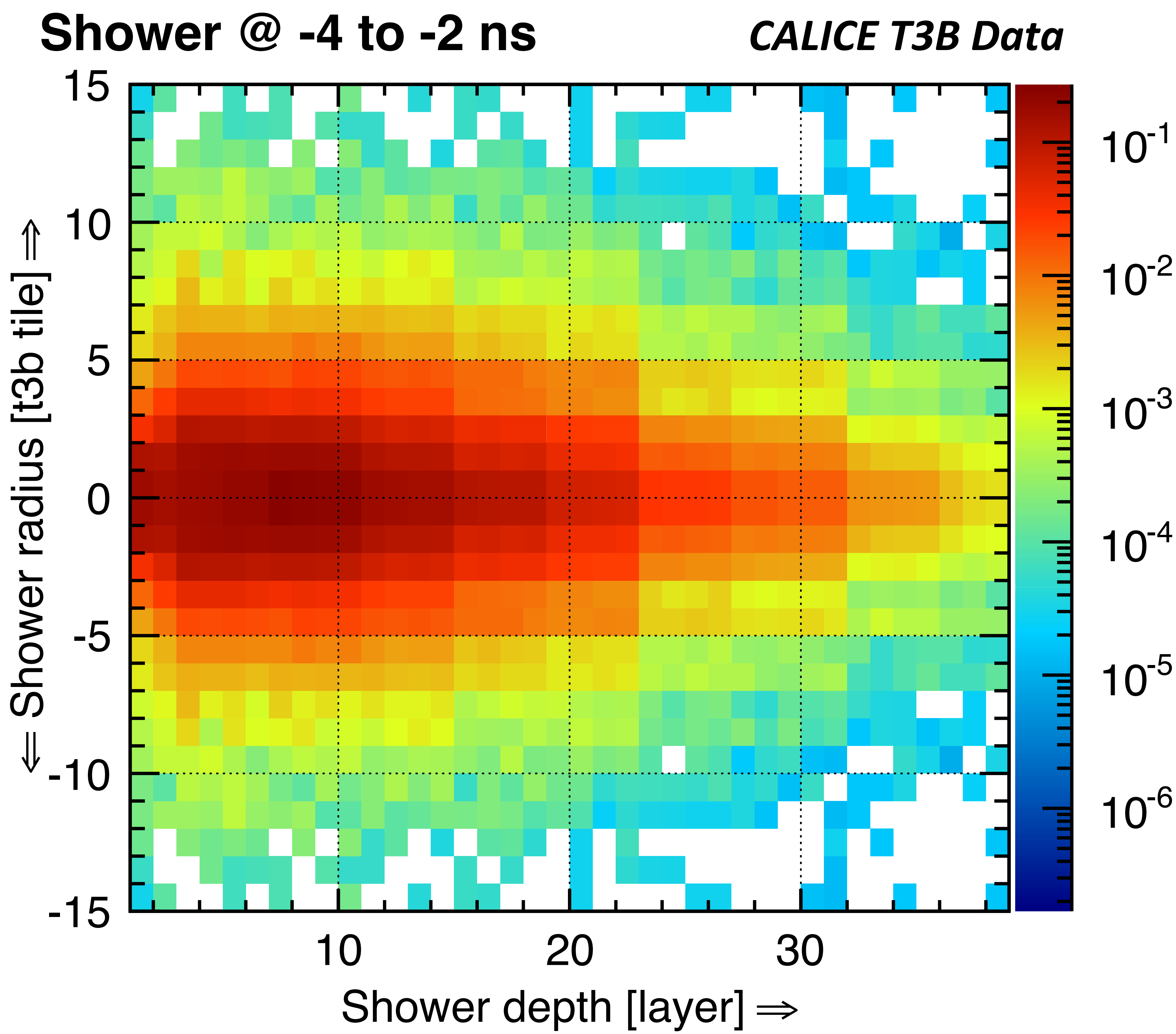

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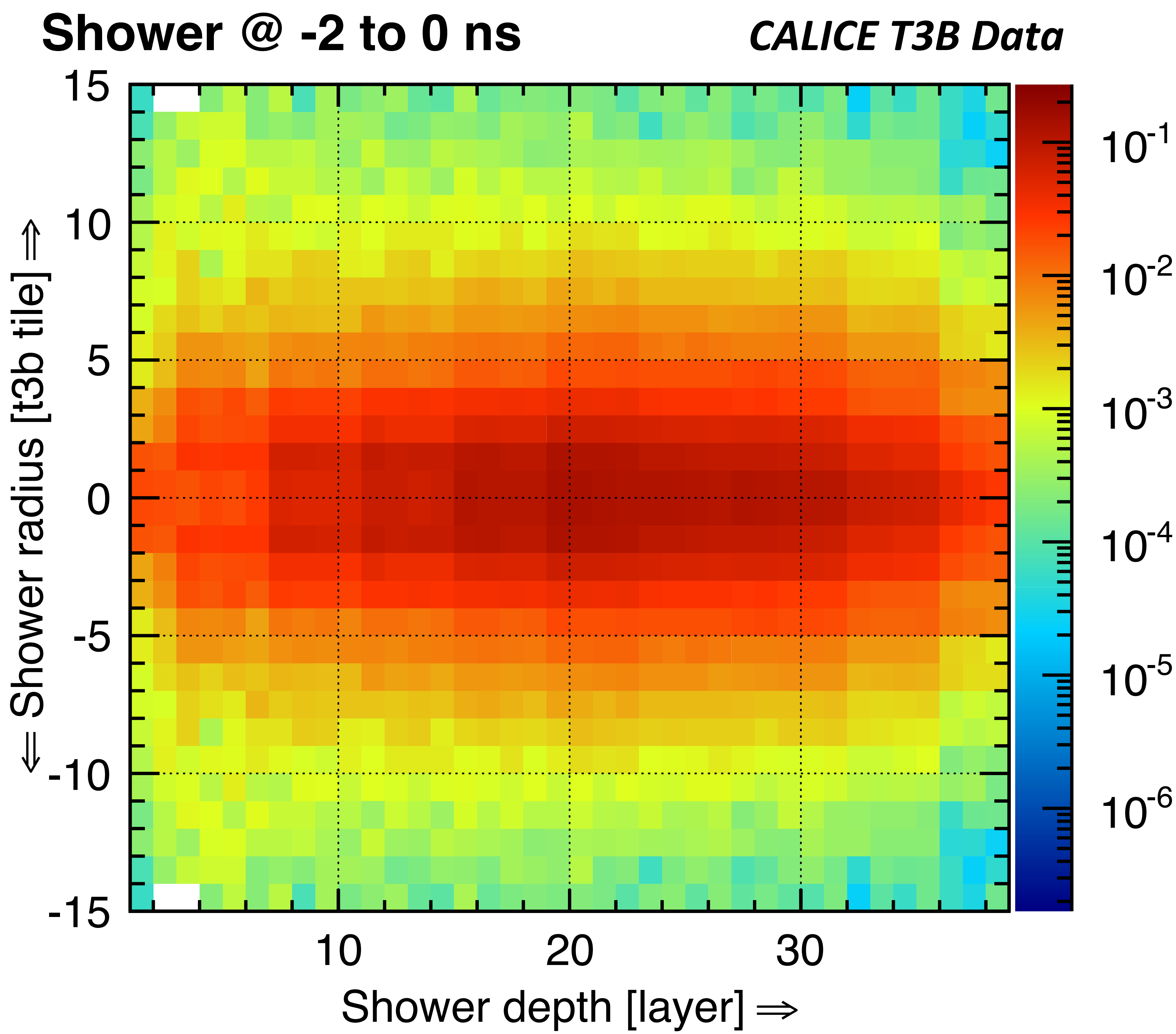

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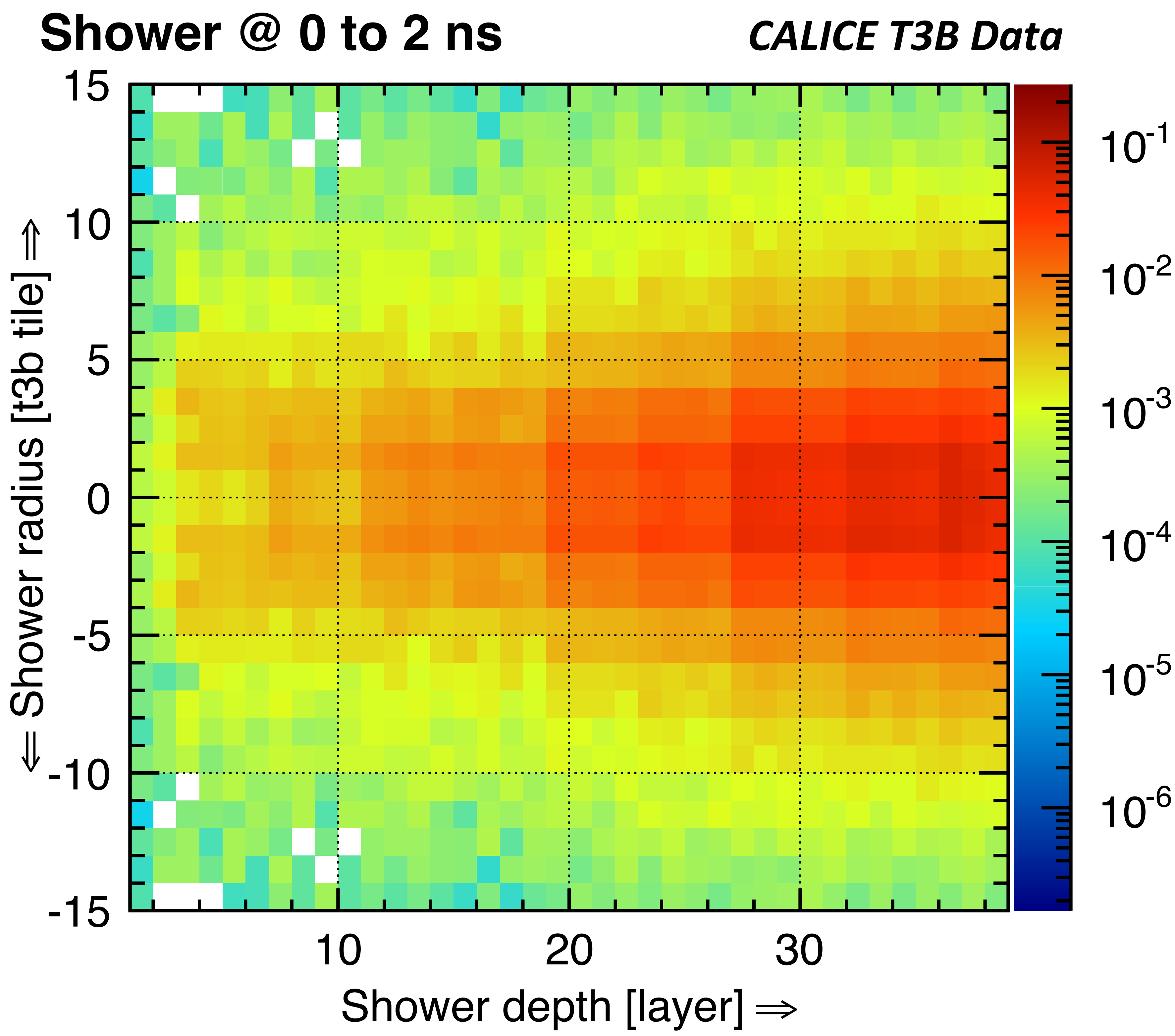

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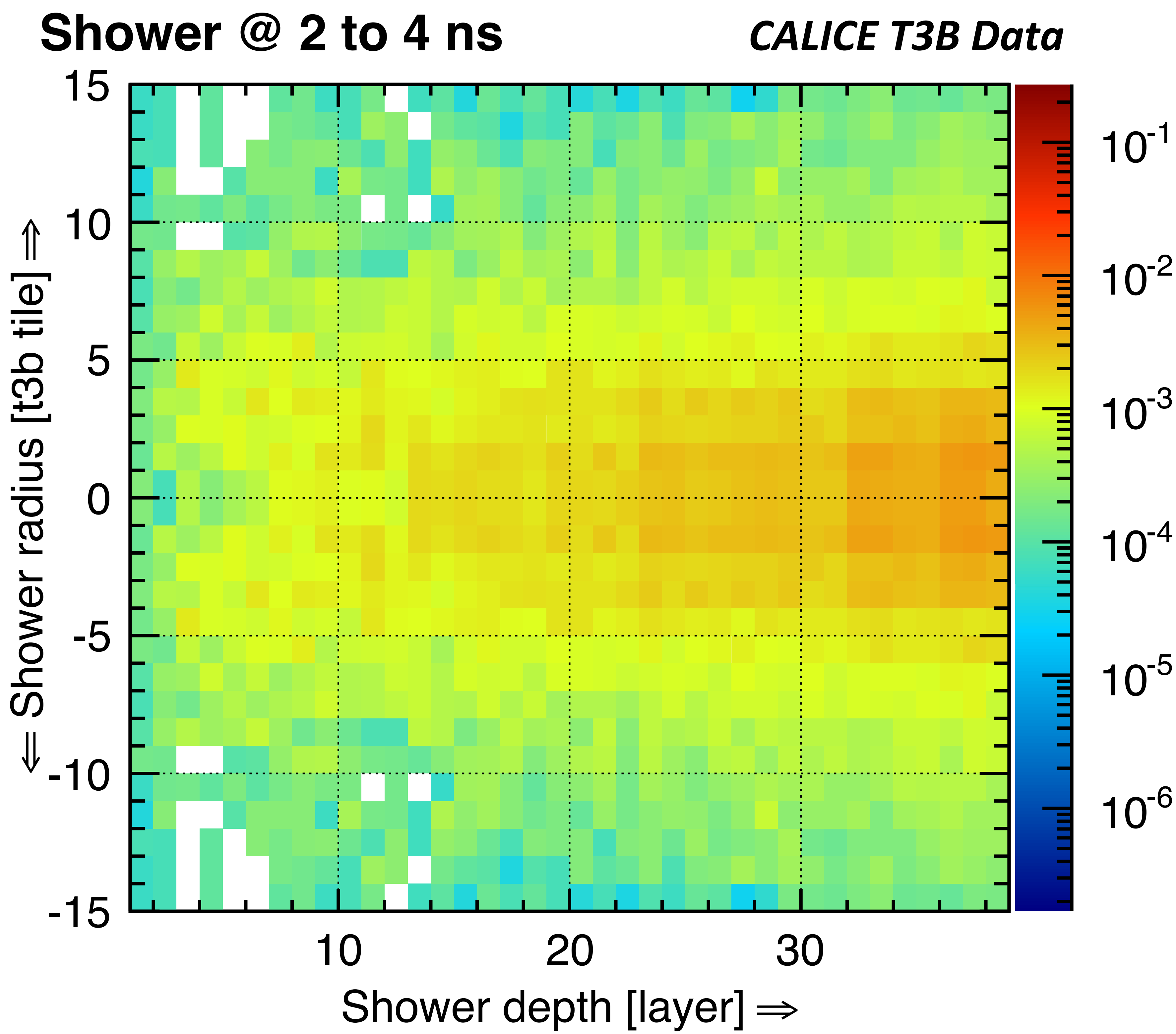

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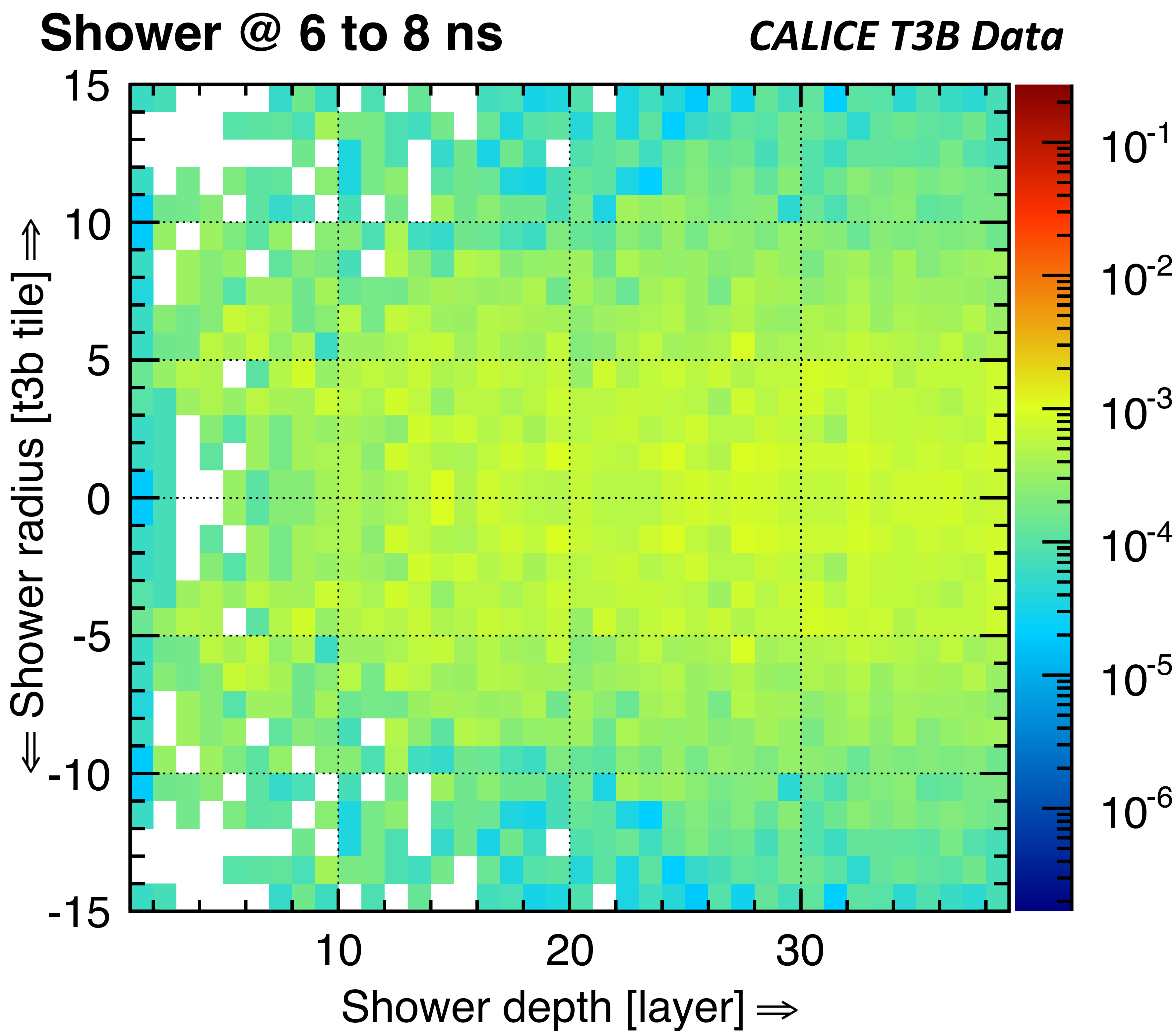

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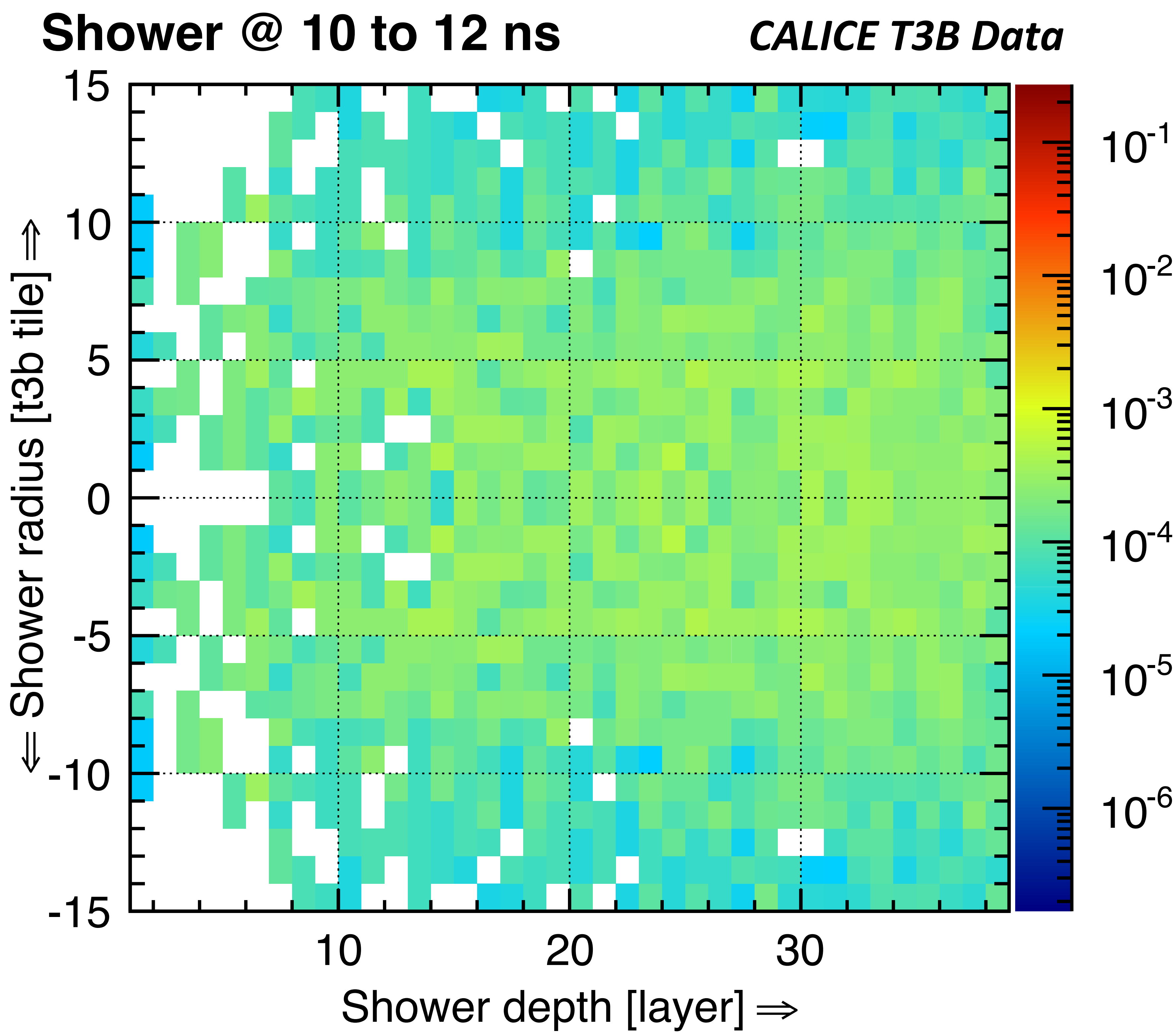

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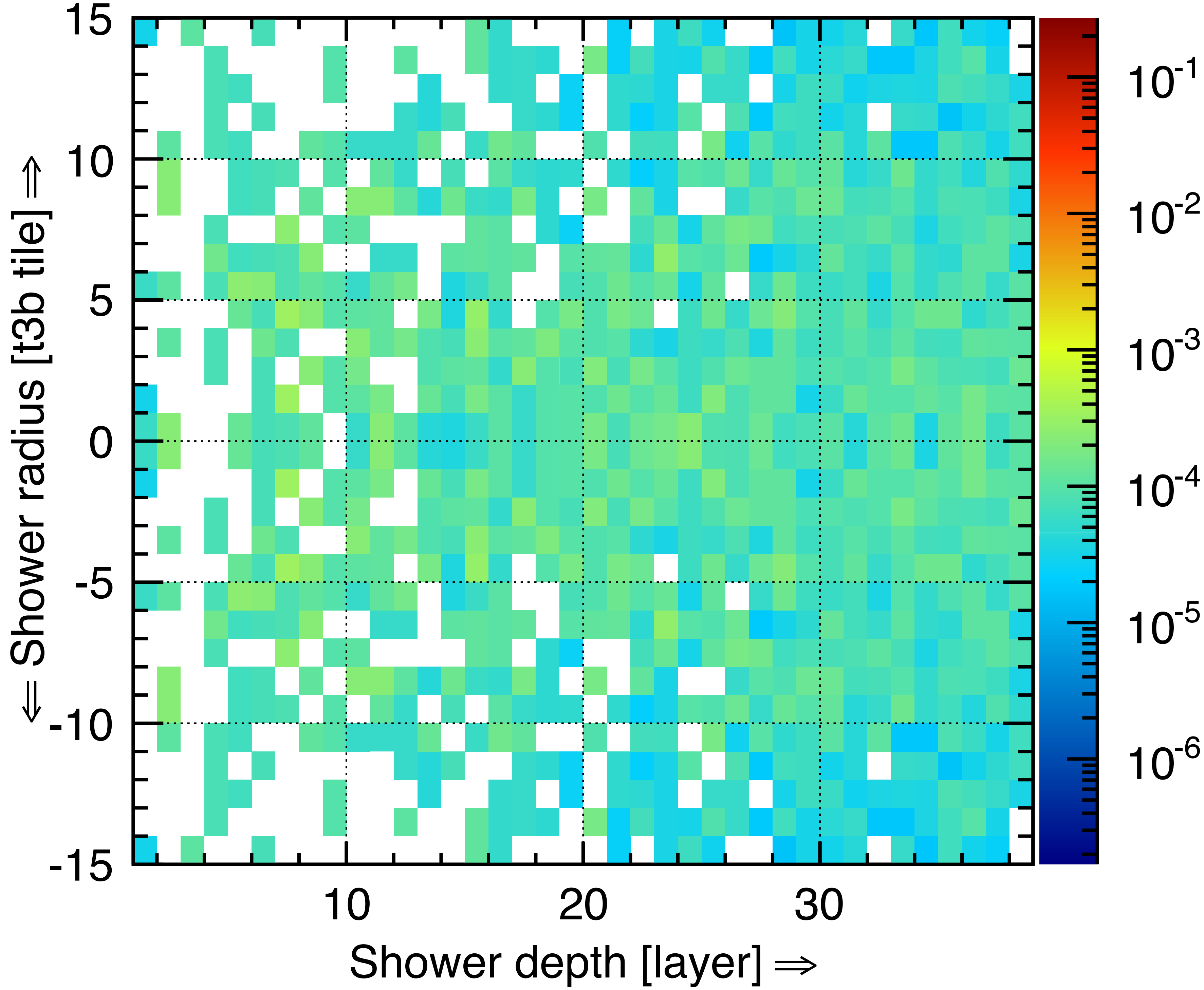
The Life of a Pion in the WAHCAL

Shower @ 16 to 18 ns *CALICE T3B Data*



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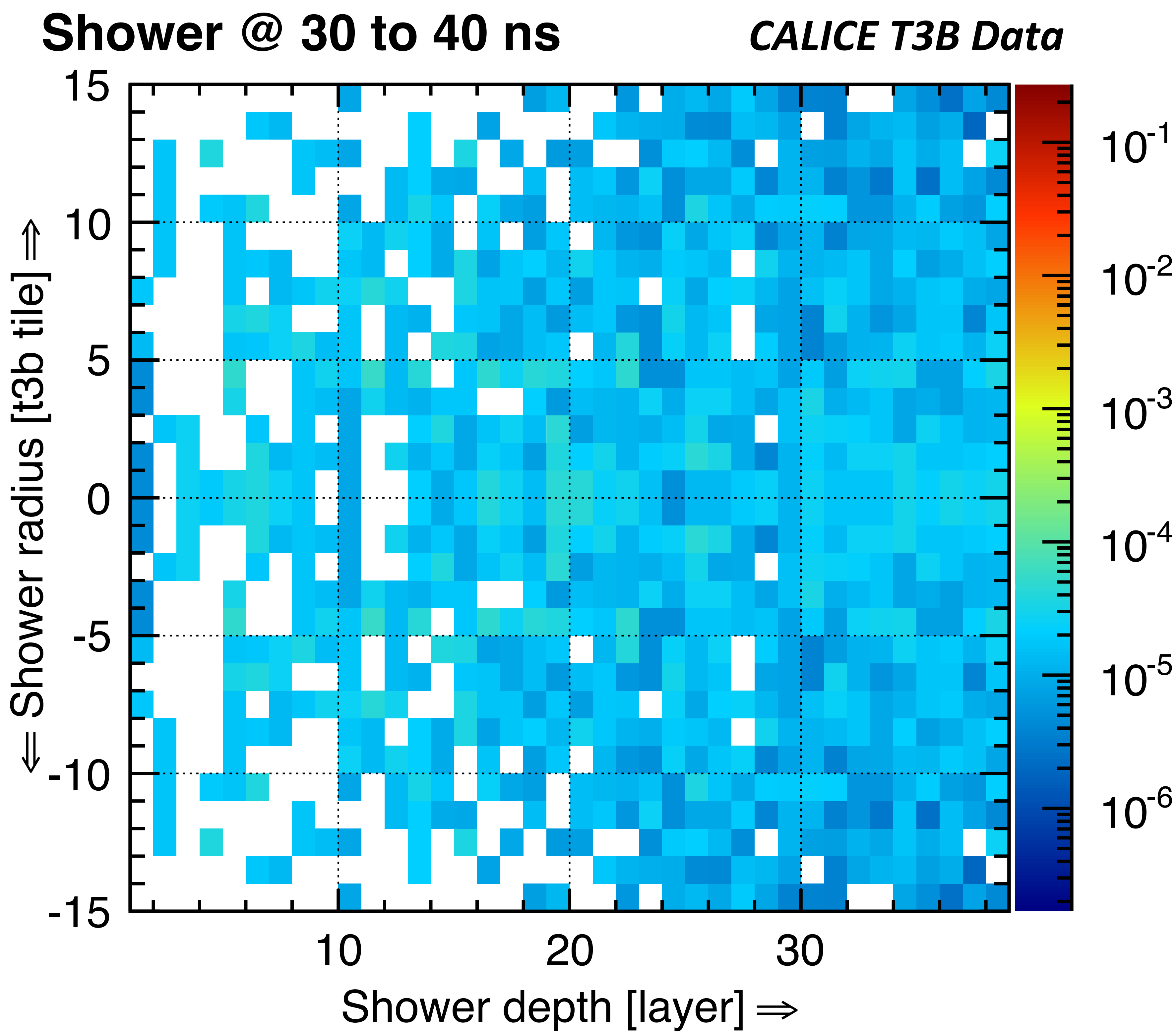

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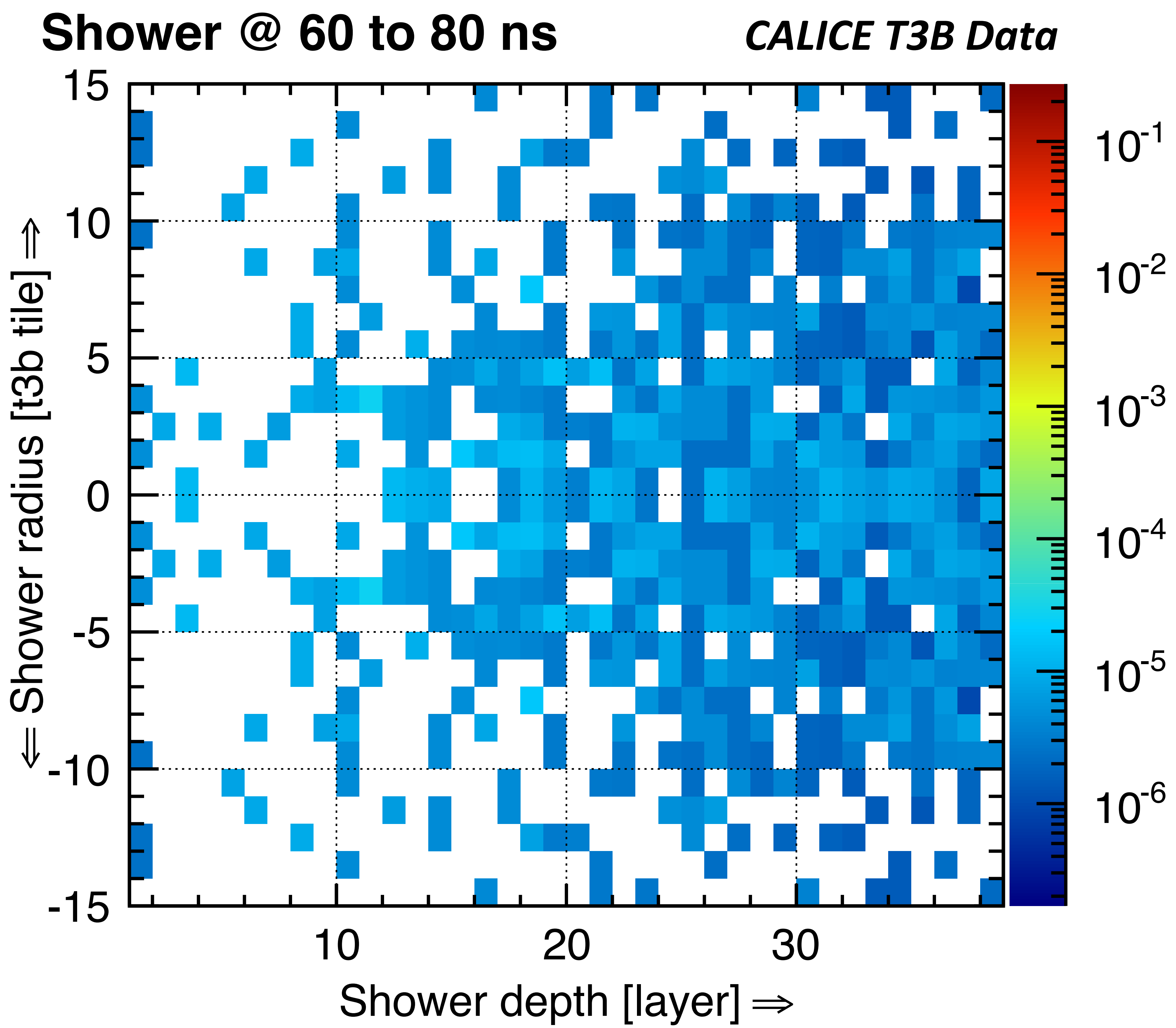

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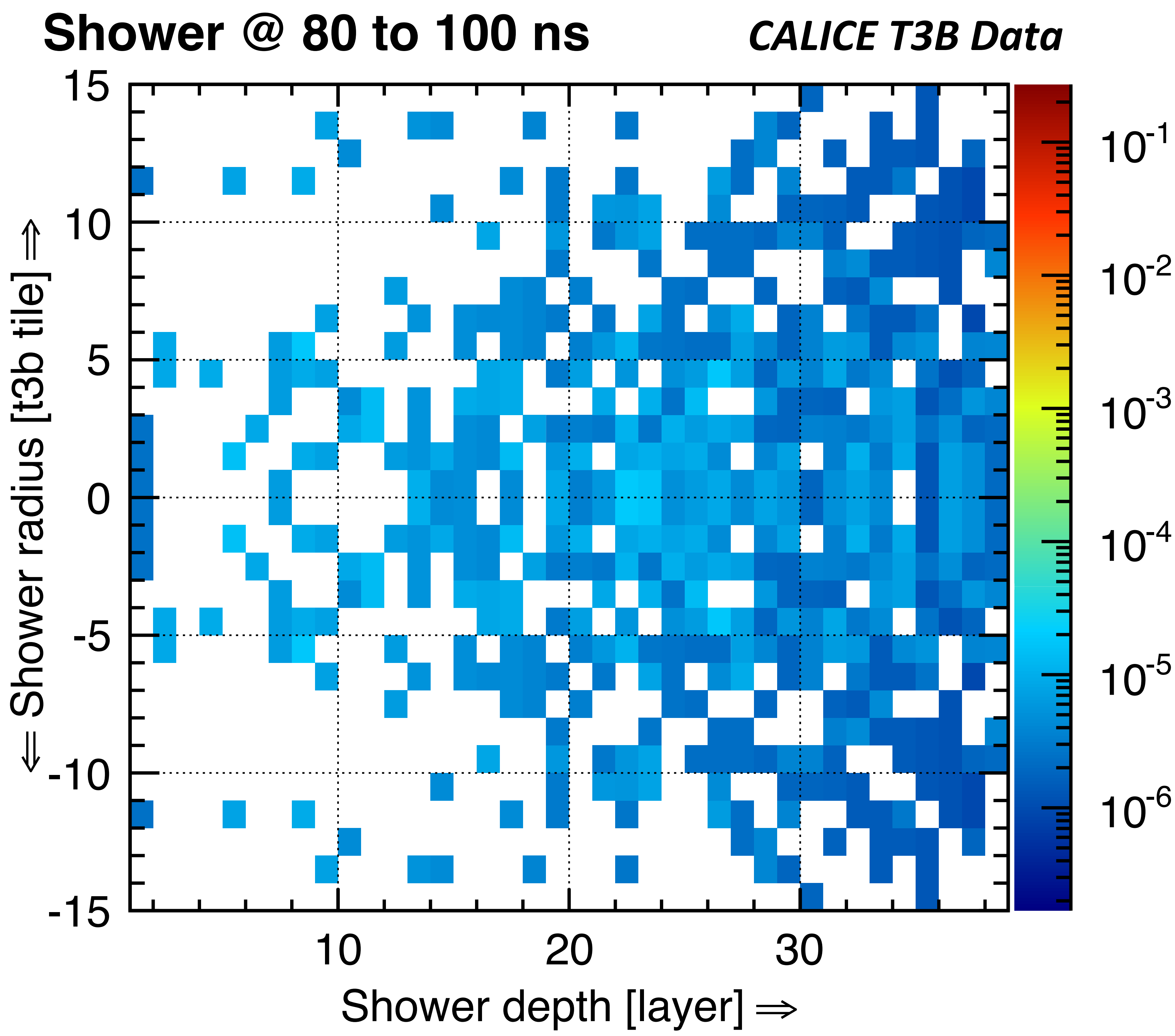

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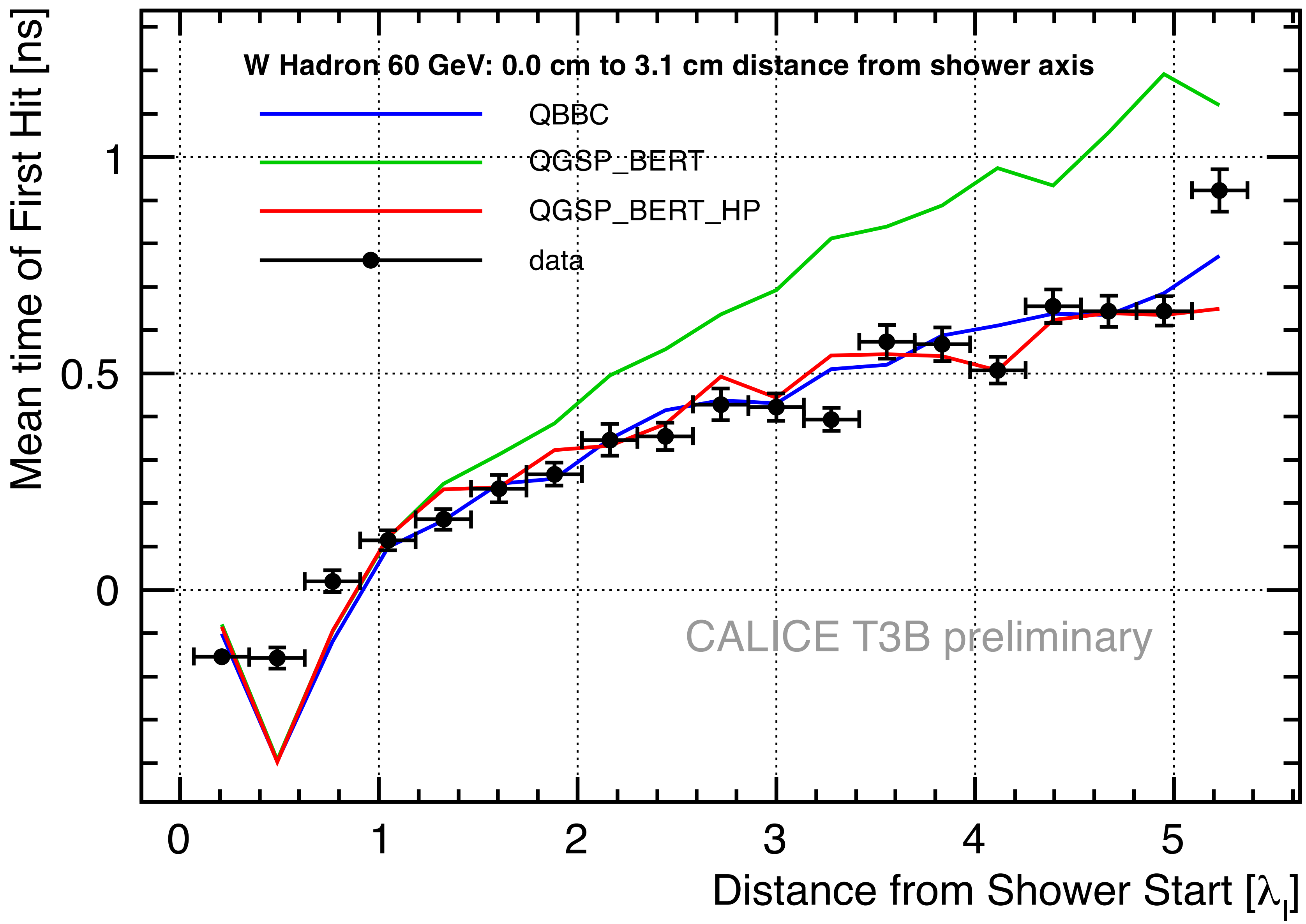
Longitudinal Dependence - Comparison to MC



- Increased importance of late shower contributions towards the rear of the shower

- Well reproduced by physics lists with precise neutron treatment
  - QGSP_BERT shows significant deviations from the data - overestimation of late components towards shower rear

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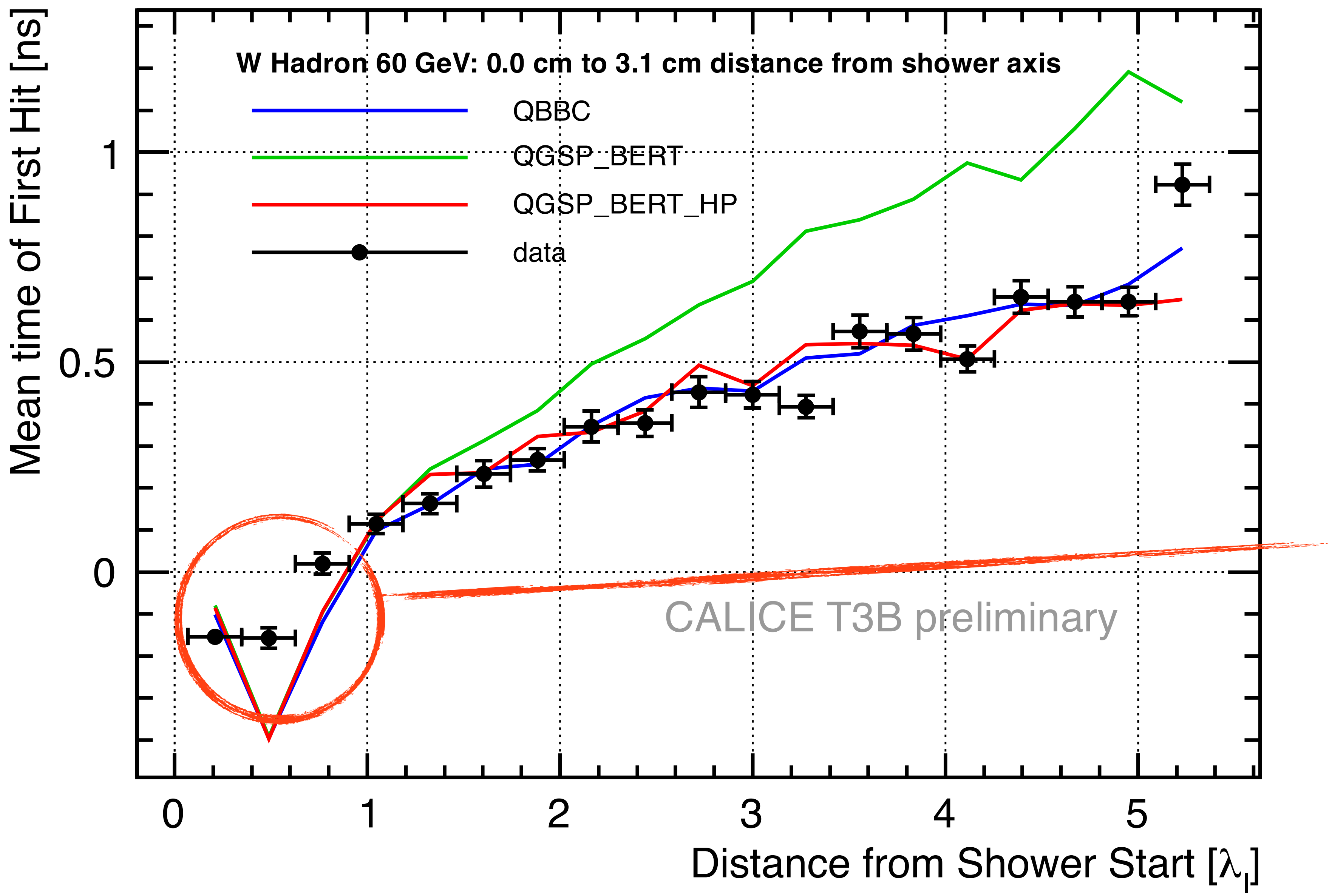


- Increased importance of late shower contributions towards the rear of the shower
- Region most dominated by electromagnetic sub-showers: Large dominance of prompt hits

- Well reproduced by physics lists with precise neutron treatment
  - QGSP_BERT shows significant deviations from the data - overestimation of late components towards shower rear

Summary

- Time structure of hadronic showers highly relevant for calorimetry at future colliders
  - Within CALICE dedicated experiments have been carried out to study it in tungsten and steel with scintillators (T3B) and gaseous detectors (FastRPC)

- 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

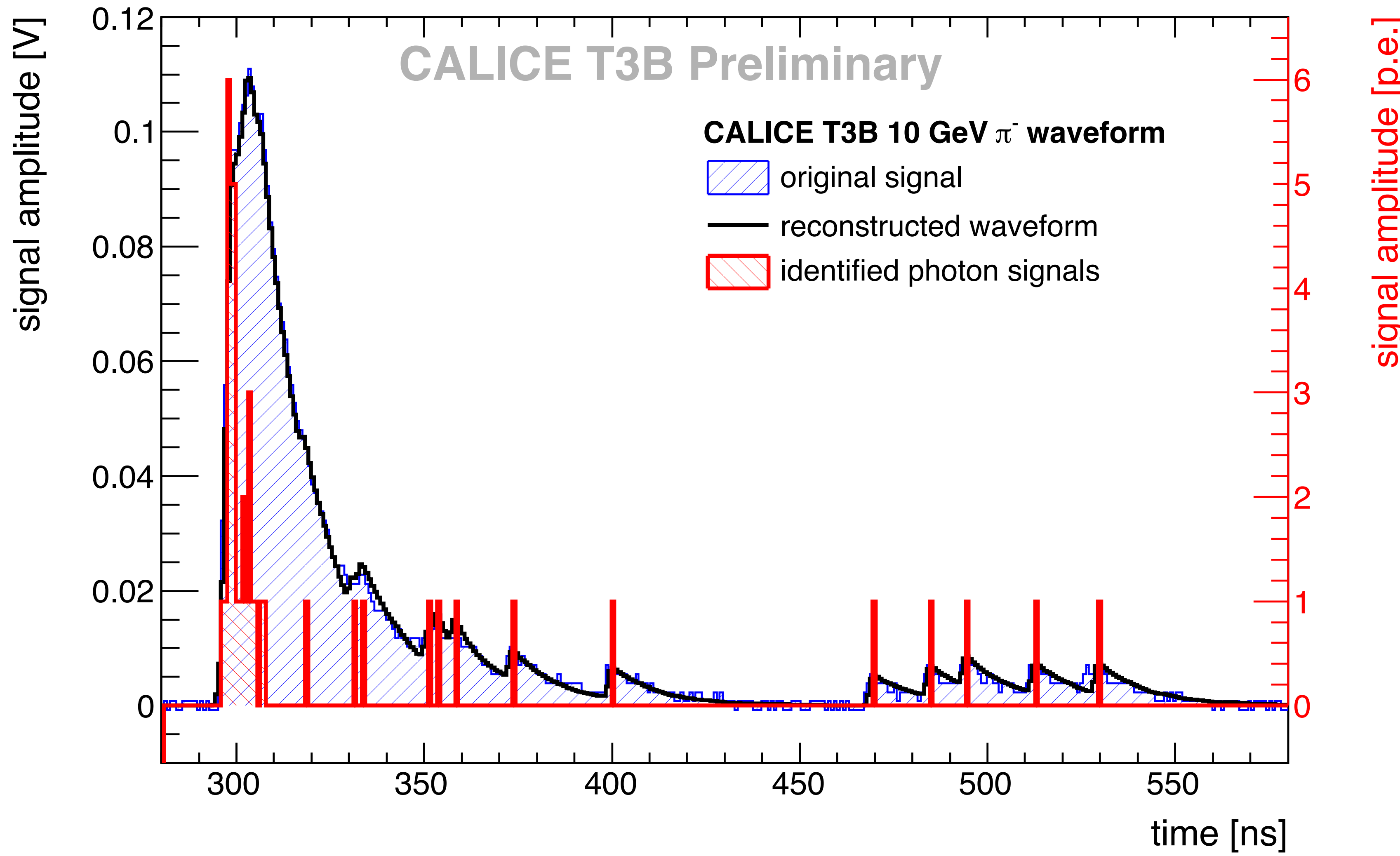
- In gaseous detectors, the sensitivity to late components is reduced, in particular to MeV-scale neutrons from spallation and evaporation in the few to a few 10 ns time frame

Backup

Data Analysis - Technique

- For each channel, a complete waveform with 3000 samples 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



Triple Exponential Fit - Results

A_0	τ_0 (ns)	A_1	τ_1 (ns)
$3.75\times10^{-3}\pm1.50\times10^{-4}$	4.09 ± 0.13	$1.44\times10^{-4}\pm1.4\times10^{-5}$	33.0 ± 2.6

A_2	τ_2 (ns)	c
$1.82\times10^{-5}\pm8.2\times10^{-7}$	480 ± 28	$2.93\times10^{-6}\pm1.38\times10^{-7}$

Table 1: Fit parameters for the 80 GeV π^+ FastRPC data, using the fit function in equation 4.1.

A_0	τ_0 (ns)	A_1	τ_1 (ns)
$1.89\times10^{-2}\pm1.3\times10^{-3}$	4.58 ± 0.22	$2.01\times10^{-3}\pm2.8\times10^{-4}$	13.7 ± 10.6

A_2	τ_2 (ns)	c
$2.66\times10^{-5}\pm6.2\times10^{-7}$	566 ± 26	$4.46\times10^{-6}\pm2.22\times10^{-7}$

Table 2: Fit parameters for the 60 GeV π^+ T3B data, using the fit function in equation 4.1.

$$\frac{N_{ToFH}}{\sum Events\ with\ FastRPC\ Hits} = A_0 \cdot e^{\left(-\frac{t}{\tau_0}\right)} + A_1 \cdot e^{\left(-\frac{t}{\tau_1}\right)} + A_2 \cdot e^{\left(-\frac{t}{\tau_2}\right)} + c, \tag{4.1}$$