# Linear Collider Detectors & Physics

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**Munich, Germany**

***MPP Project Review, December 2012***

# The Group

## The Core Group

- *Post-Doc*
  Katja Seidel (04/2012 - 10/2012)
- *PhD Students*
  Veronika Chobanova (still working on Belle analysis) Katja Seidel (until 03/2012), Christian Soldner, Michal Tesar, Lars Weuste
- *Diploma/Master Student*
  Marco Szalay
- *Scientist*
  Ron Settles
- *Group Leader*
  Frank Simon

funded by Excellence Cluster

- Close collaboration with:
  - Belle / Belle-II
    Jeremy Dalseno, Andreas Moll, Kolja Prothmann; Student supervision: Christian Kiesling
  - HLL & Minerva Group
    Jelena Ninkovic, Christian Jendrysek, Laci Andricek, Hans-Günther Moser
  - And the technical departments!

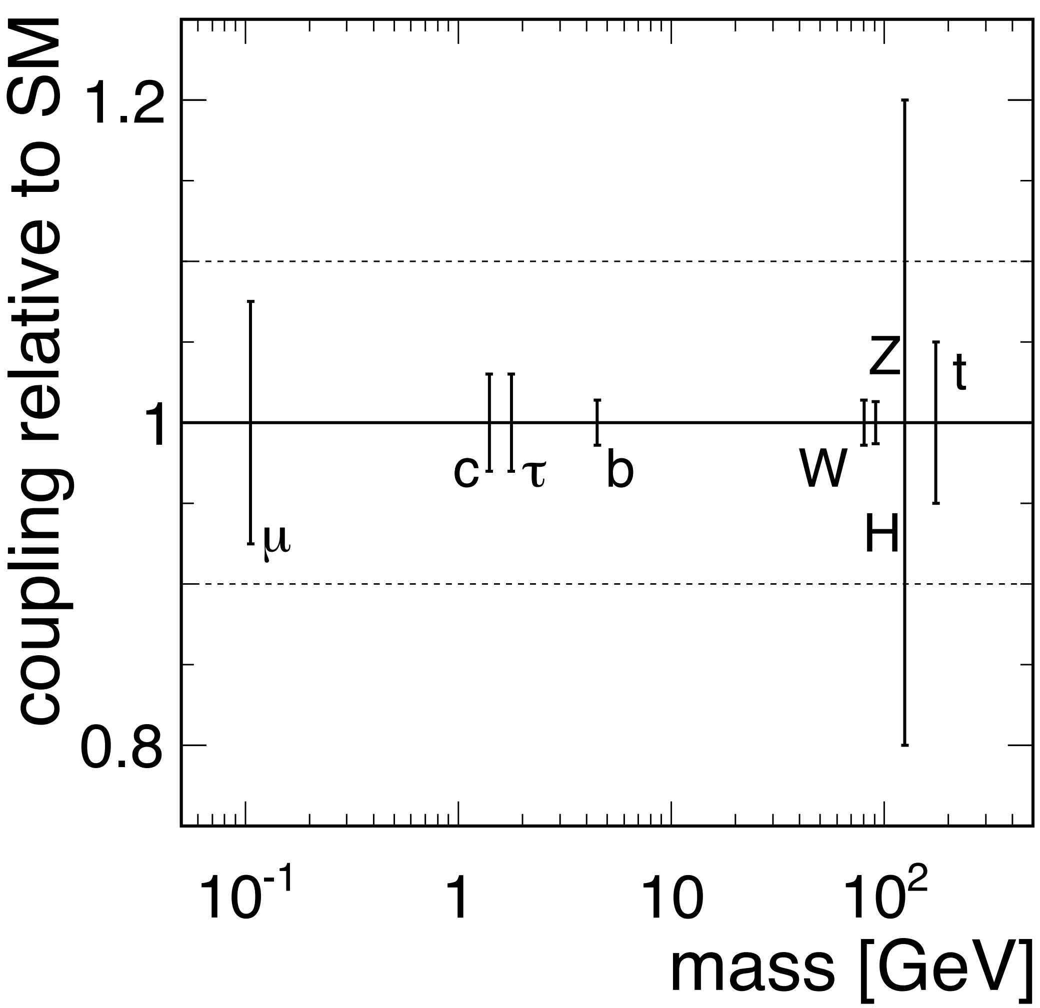
# The Context: A Linear $e^+e^-$ Collider

- The Physics Menu:
  - Full exploration of the Higgs sector (aka the "New Boson" discovered at LHC)
  - Precision measurements within the Standard Model:
    - Top physics
    - Gauge bosons - for example WW production, scattering
    - Potentially precision measurements at the Z pole ("Giga-Z")
  - Search for and spectroscopy of New Physics
    - Particular strength in the weak sector
    - Indirect sensitivity to very high scales in the 10 TeV region and above

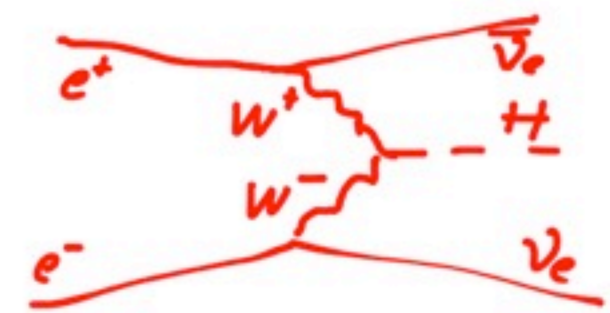
- Highly complementary to the LHC
  - Increased precision due to well-defined initial state
  - Improved access to weak sector due to substantially more favorable background conditions

# One Example: Higgs Physics at a Linear Collider

- A full Higgs program spans a wide energy range
  - 250 GeV - 350 GeV: Model-independent measurement of couplings
  - 500+ GeV: Total width, top-H coupling
  - 500+ GeV; 1+ TeV: Higgs self-coupling
  - 1+ TeV: Access to very small BRs with high statistics

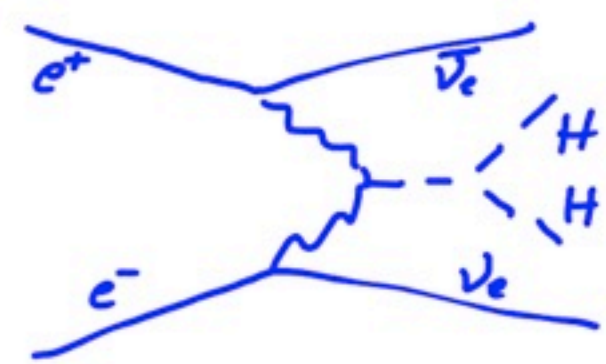








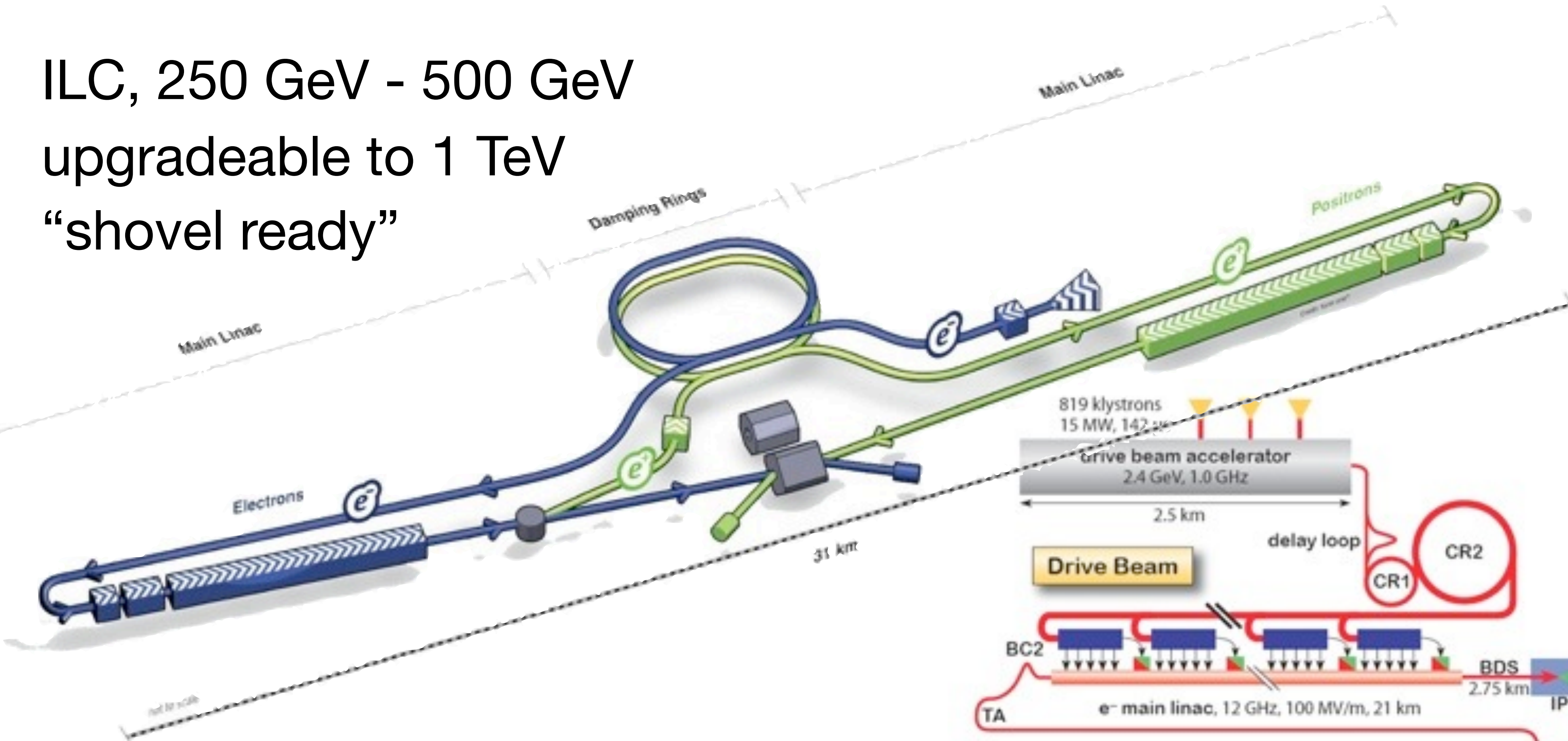

expected accuracy for couplings for a full LC program



# Two Accelerator Concepts

- Large dynamic range in energy through staged construction
- Two technologies - many common issues, collaboration on many aspects
  - In particular also common work on physics & detectors

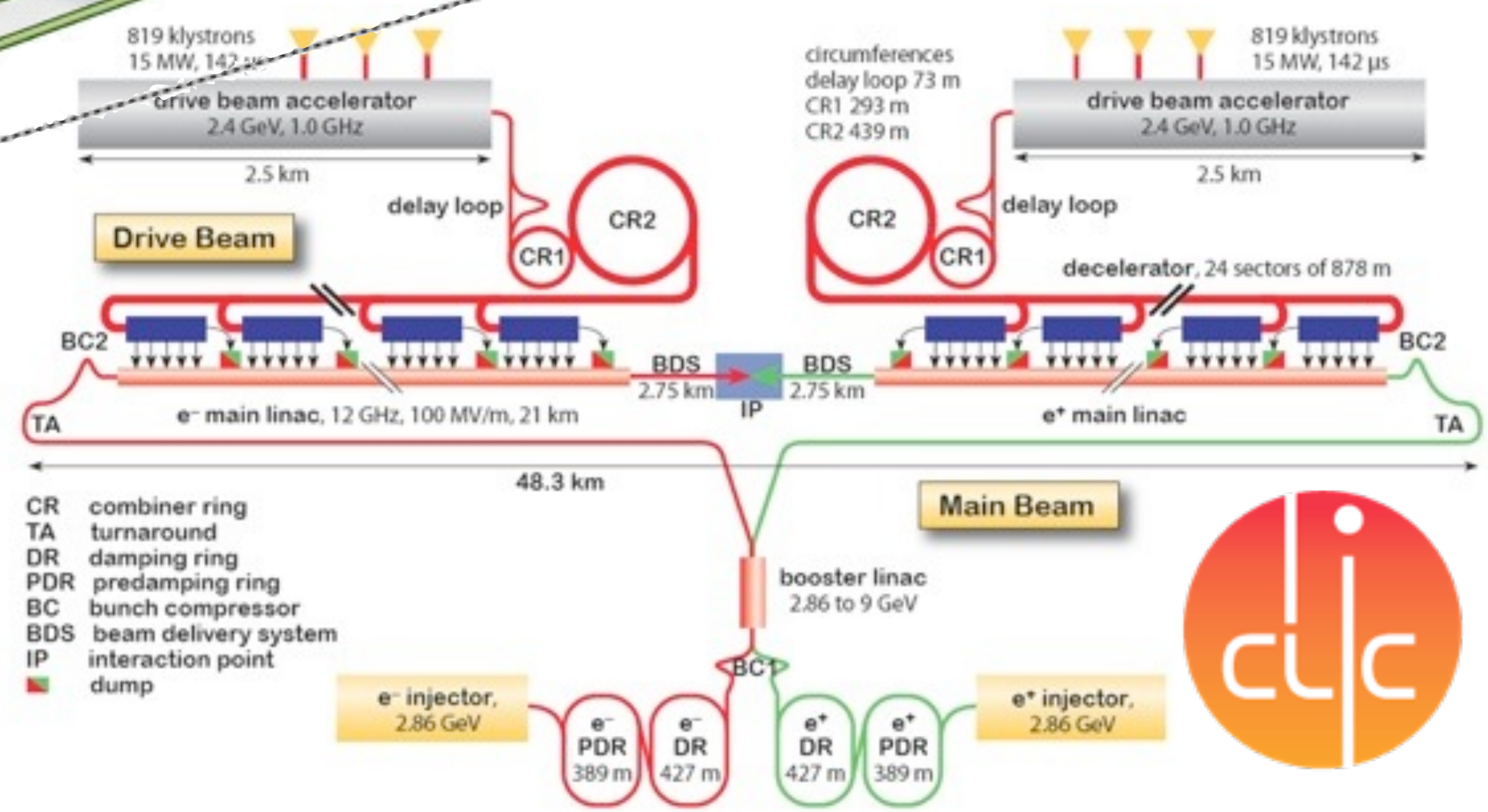
ILC, 250 GeV - 500 GeV
upgradeable to 1 TeV
"shovel ready"




TDR in 2013

CLIC, 350 (250) GeV - 3 TeV, ongoing R&D

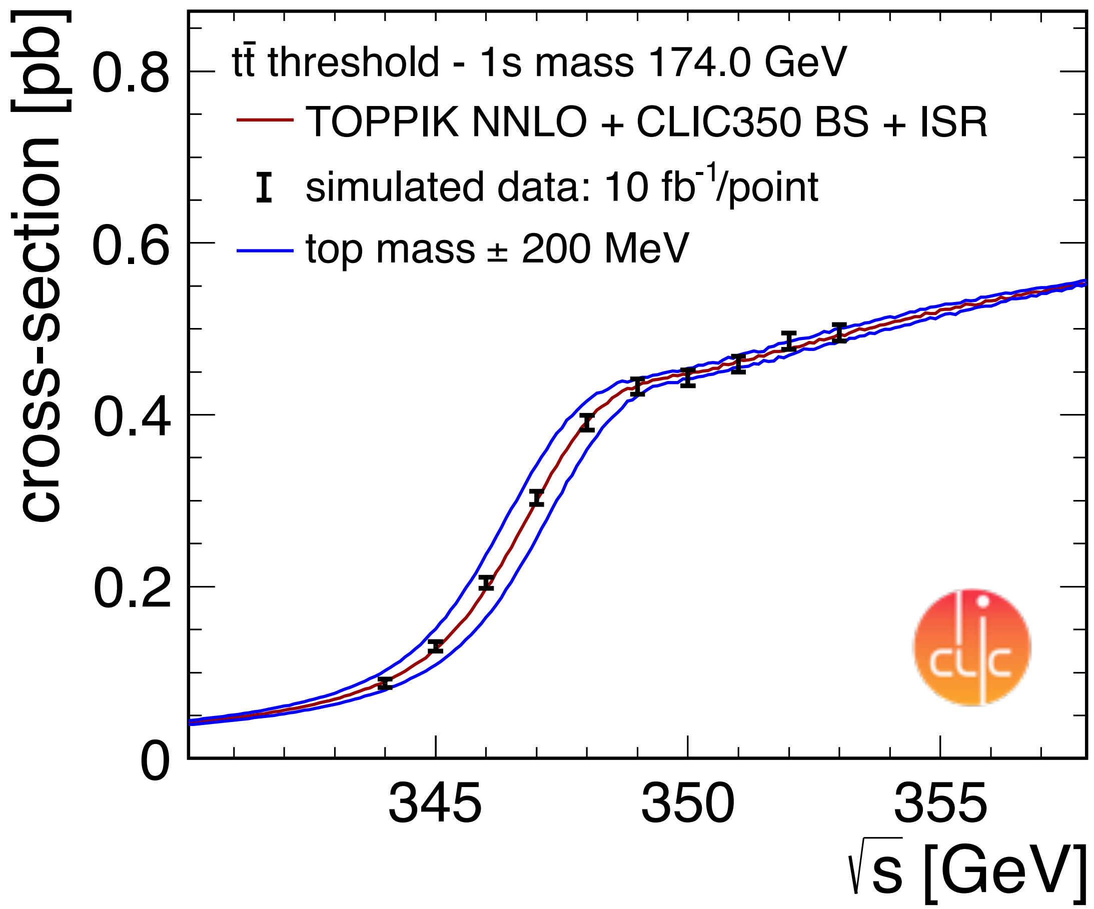
CDR in 2012

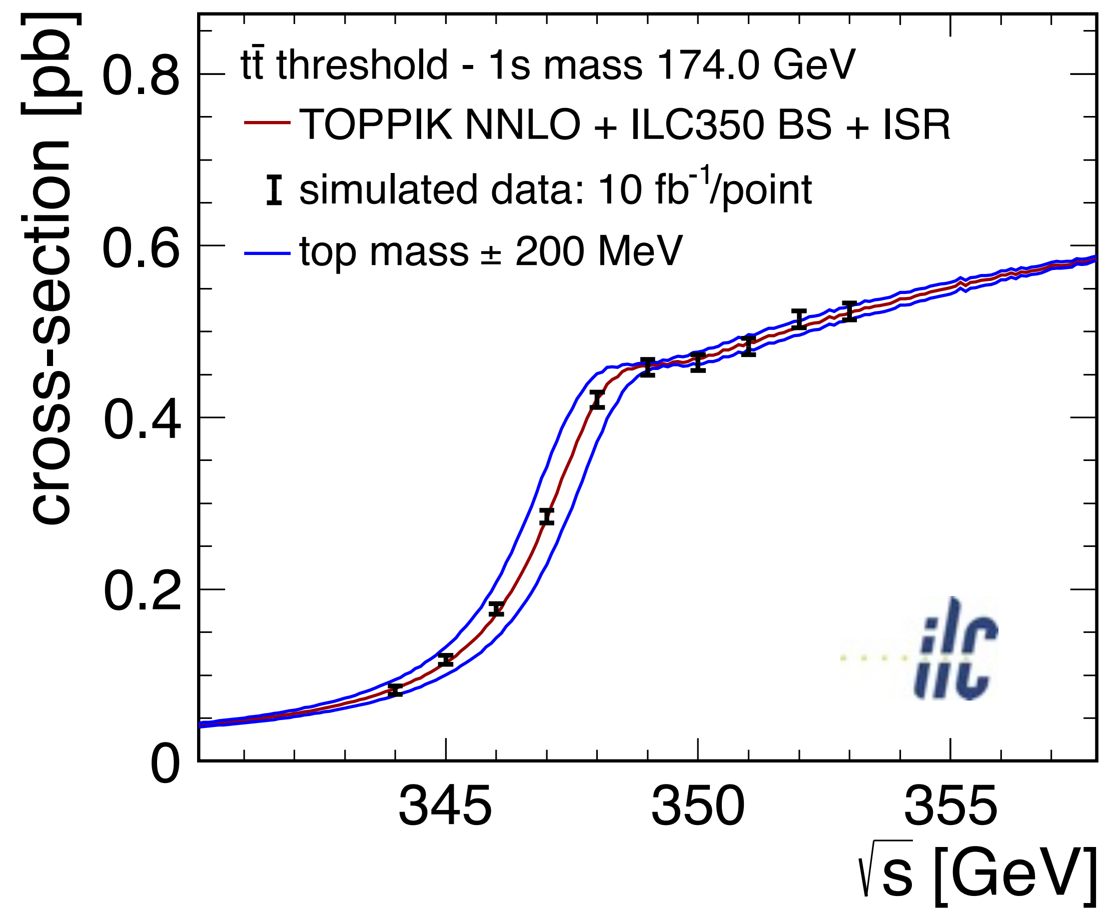


# Physics Studies

- For CLIC CDR and ILC TDR / ILD DBD: Full simulation studies
  - Last year: Top invariant mass & TeV-scale squarks at CLIC
  - This year: Top threshold scan at CLIC & ILC, top invariant mass for ILC in progress

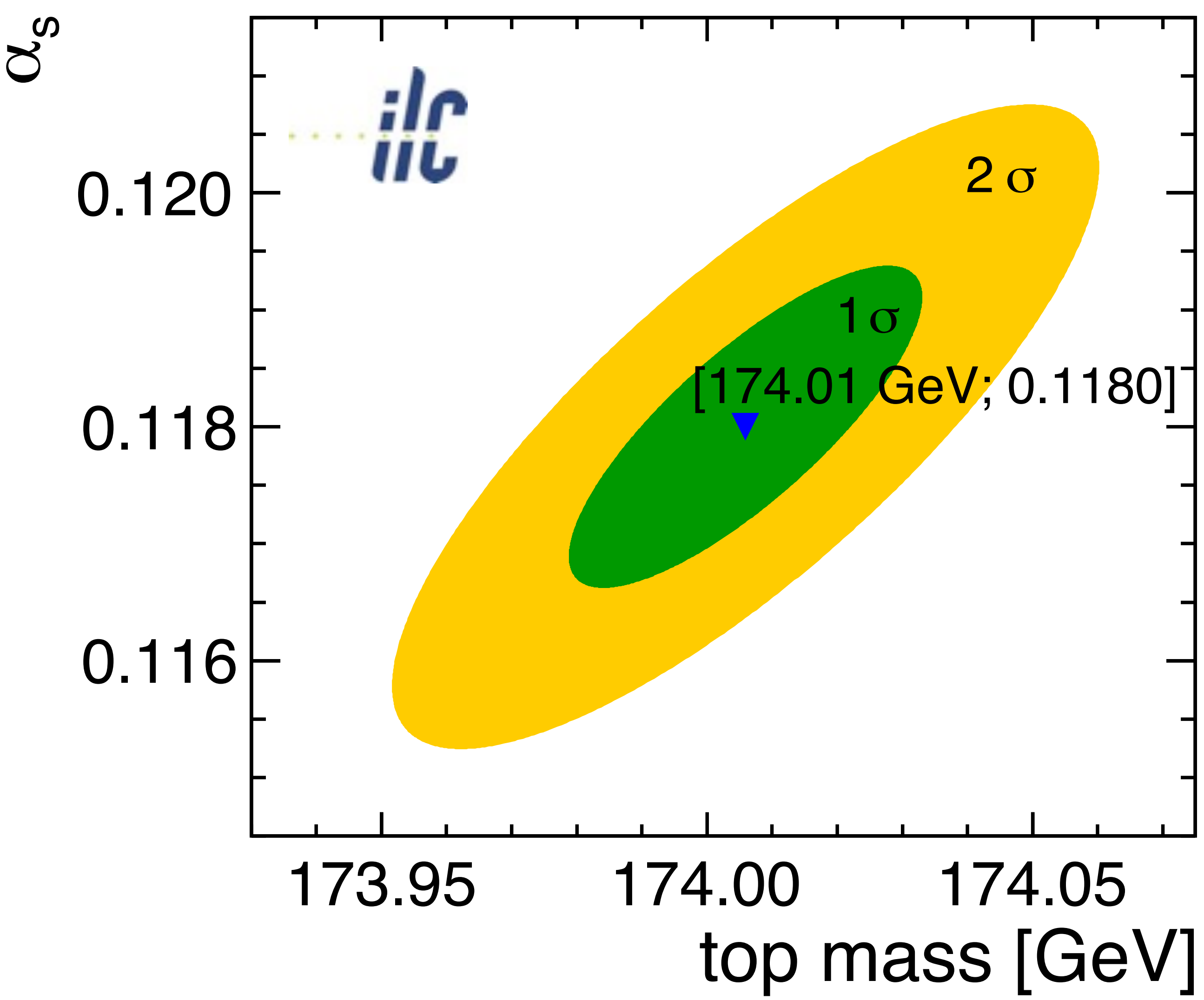
- Top threshold scan: A cross section measurement - Provides sensitivity to the top mass and strong coupling in a theoretically well-defined way
  - The ultimate in precision for the top mass!



# Top Threshold at Linear Colliders

- Simultaneous fit of top mass (1S scheme) and $\alpha_s$
  template fit of background-subtracted cross section with different mass and coupling hypotheses

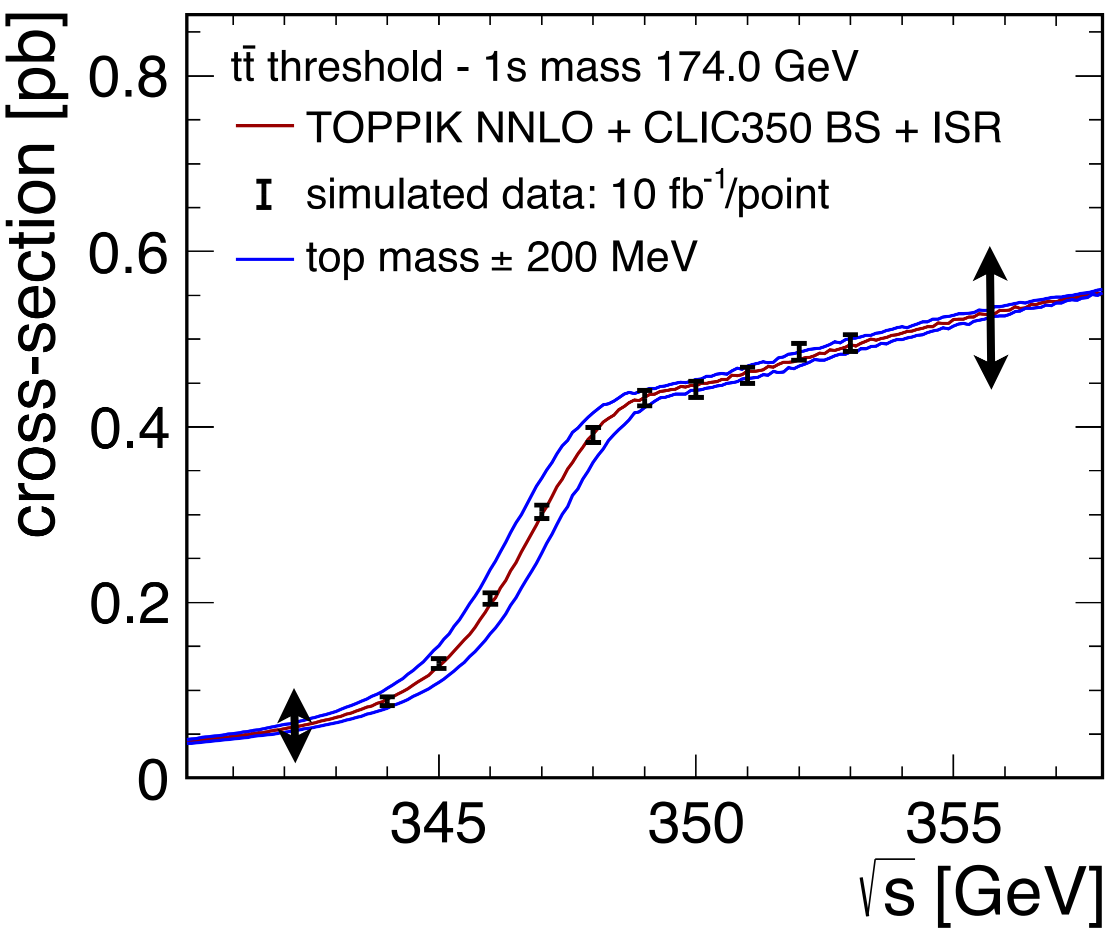



with 100 $fb^{-1}$ (10 $fb^{-1}$ per point):
**27 MeV** stat. error on **mass**,
**0.0008** stat. error on $\boldsymbol{\alpha_s}$
($m_t$ alone: 18 MeV stat error, 17 MeV syst. uncertainty from current WA $\alpha_s$)

With CLIC luminosity spectrum:
~25% larger uncertainty on mass,
~15% larger uncertainty on $\alpha_s$

# Top Threshold - Systematic Uncertainties

- Several systematic effects have been studied:




- Theory uncertainty: Overall cross-section normalization (1% & 3% uncertainty)
  5 MeV / 8 MeV on mass
  0.0008 / 0.0022 on $\alpha_s$
  (also sets the scale for efficiency uncertainties)

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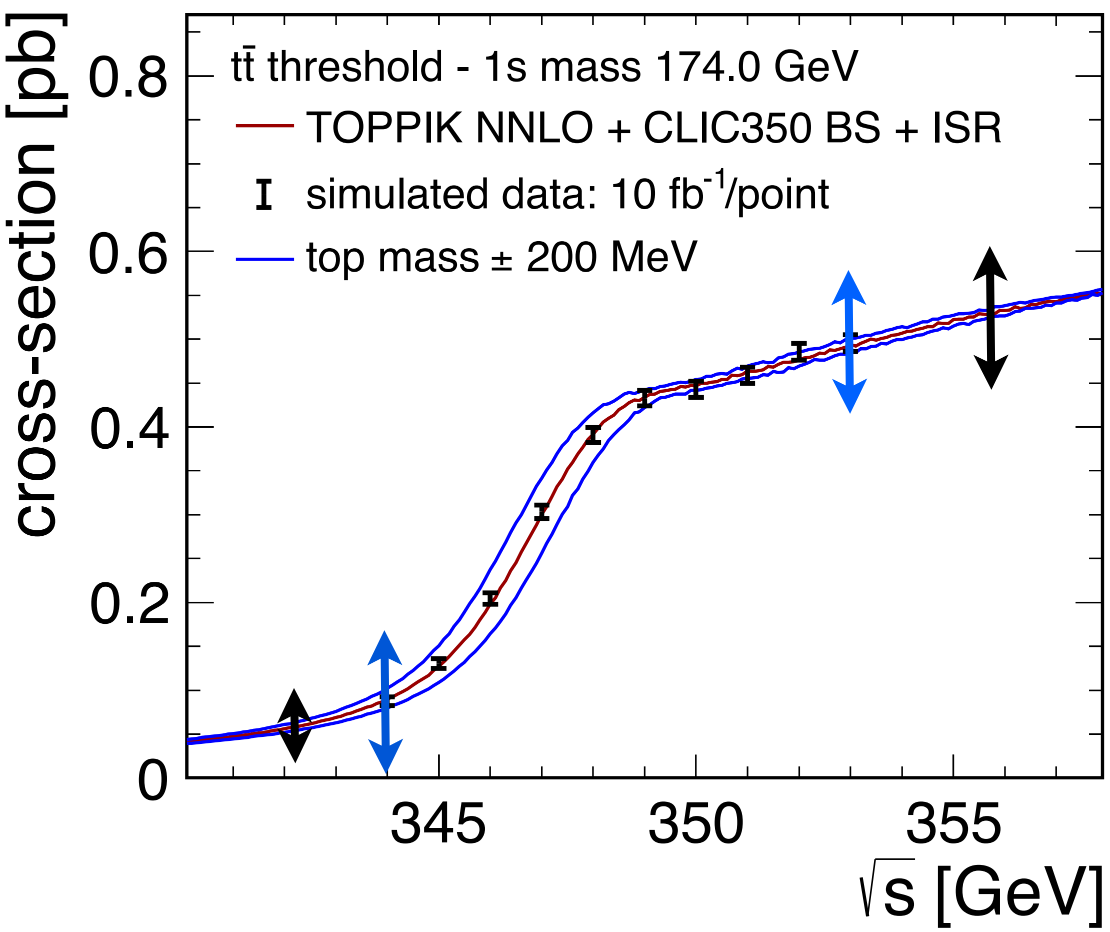


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  18 MeV on mass
  0.0007 on $\alpha_s$

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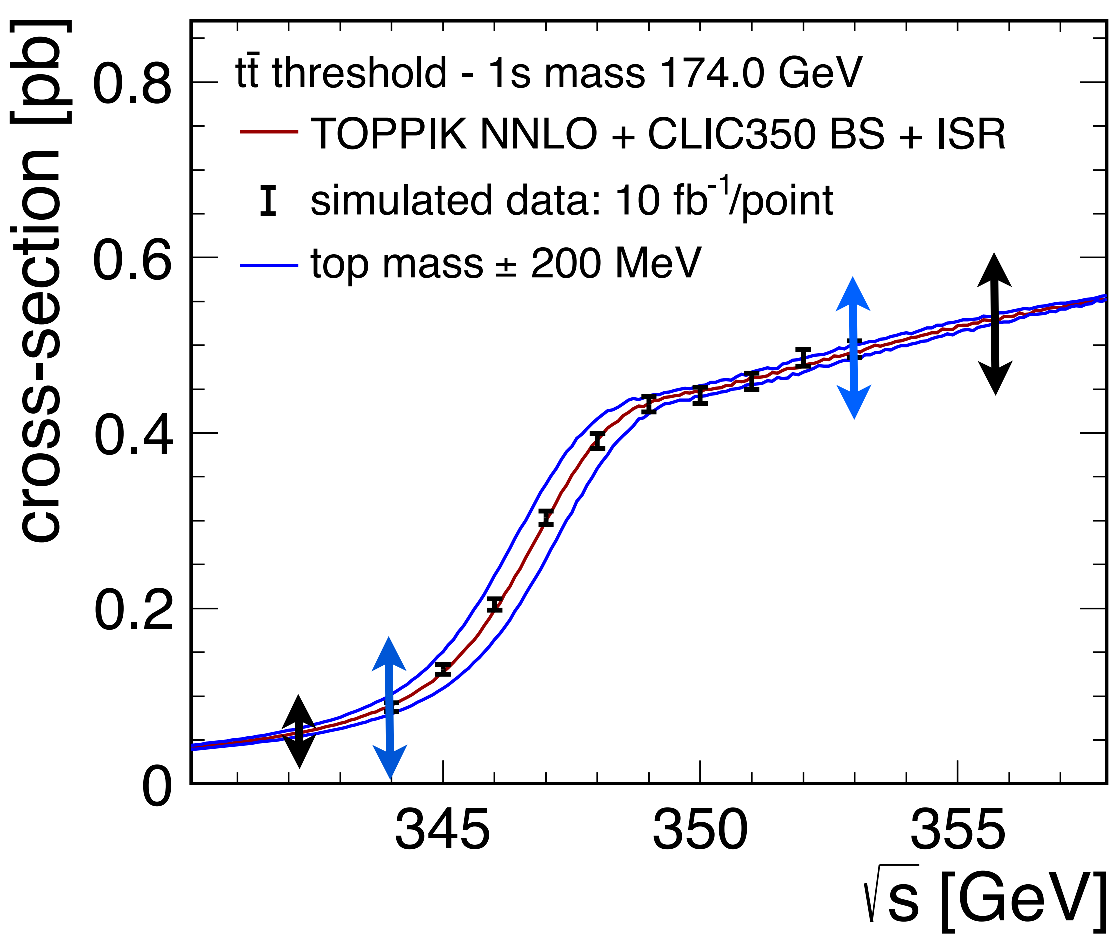


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- In addition: Machine center-of-mass energy, expected to be known at the $10^{-4}$ level from LEP experience and ILC studies: *O* 20 MeV on mass
- Precision of luminosity spectrum -> width of main peak matters most!
  - Precision of measurement currently unknown, 20% uncertainty on RMS results in 75 MeV uncertainty of $m_t$

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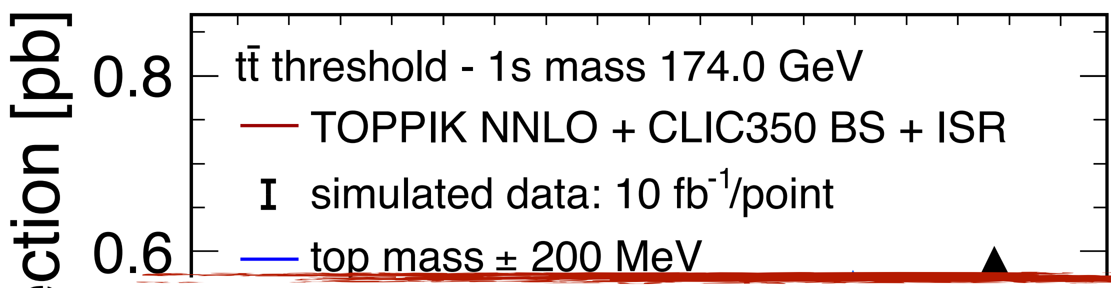


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  5 MeV / 8 MeV on mass

Overall:
Total error of top mass in a theoretically well-defined mass definition below **100 MeV** achievable, independent of accelerator concept.

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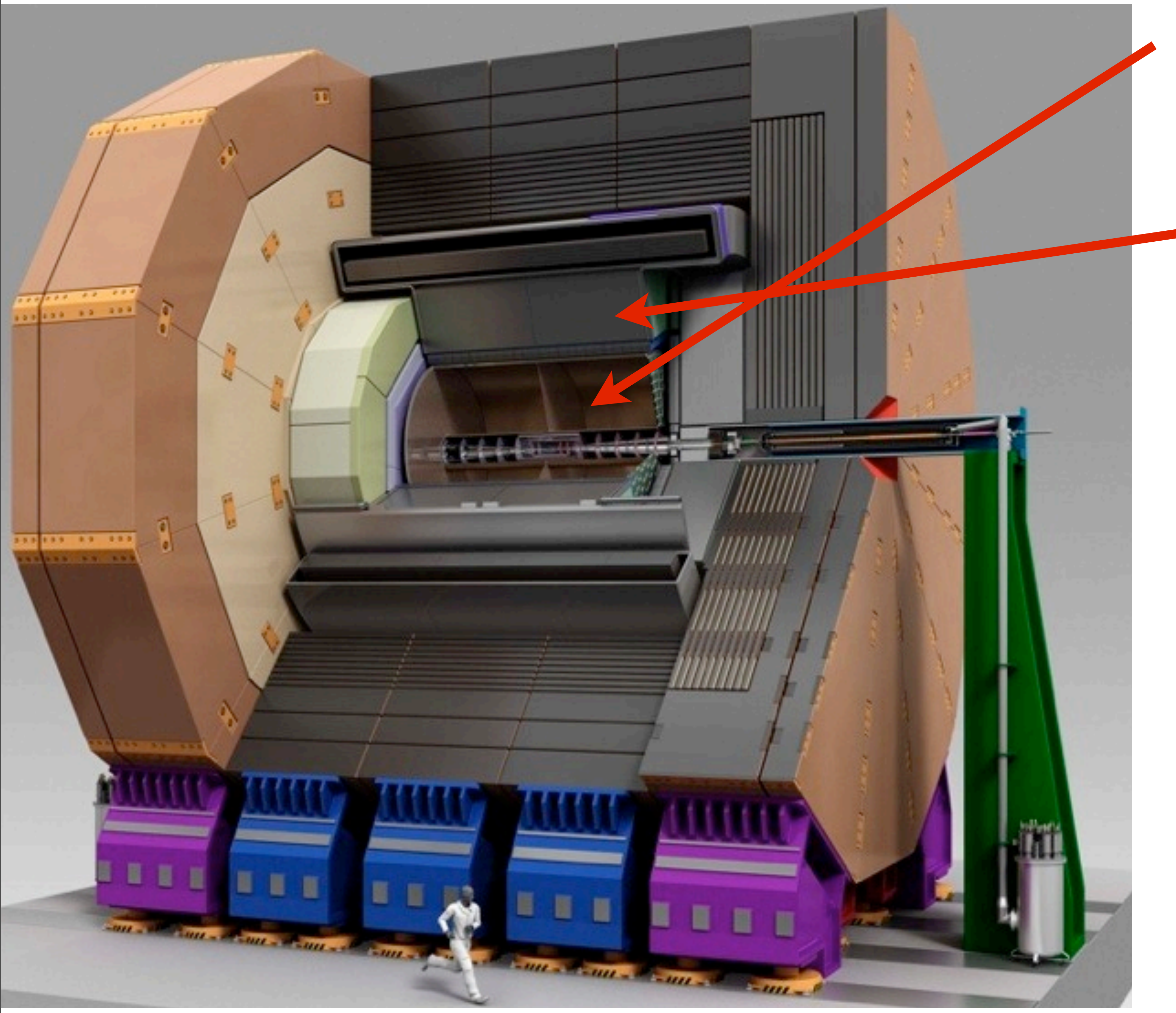
# Precision Physics needs Precise Detectors

- Detectors based on particle flow event reconstruction



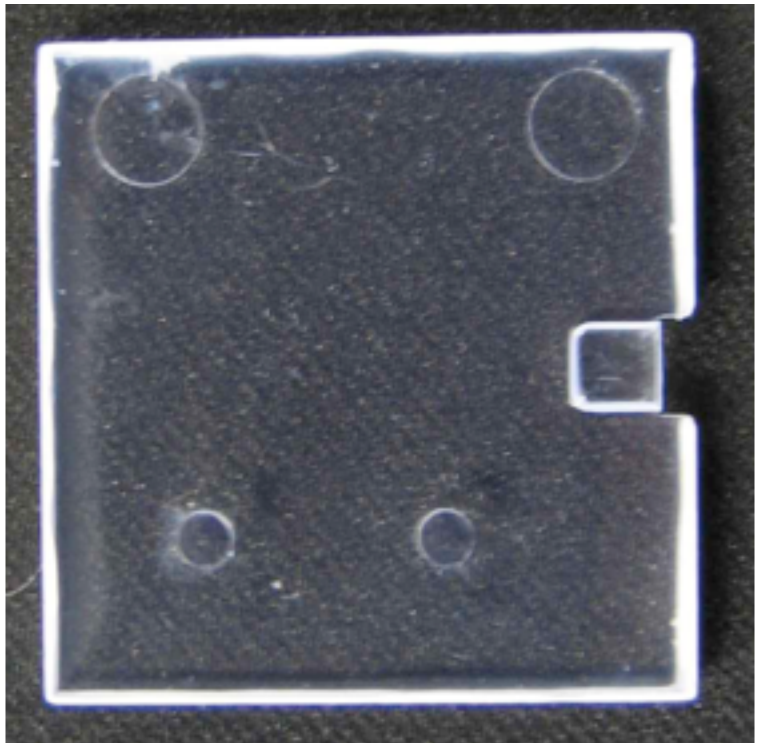
- Precision tracking
- Highly granular calorimeters (electromagnetic & hadronic) to separate particle showers in jets - 10s of Millions of Channels!

**Group activities:**

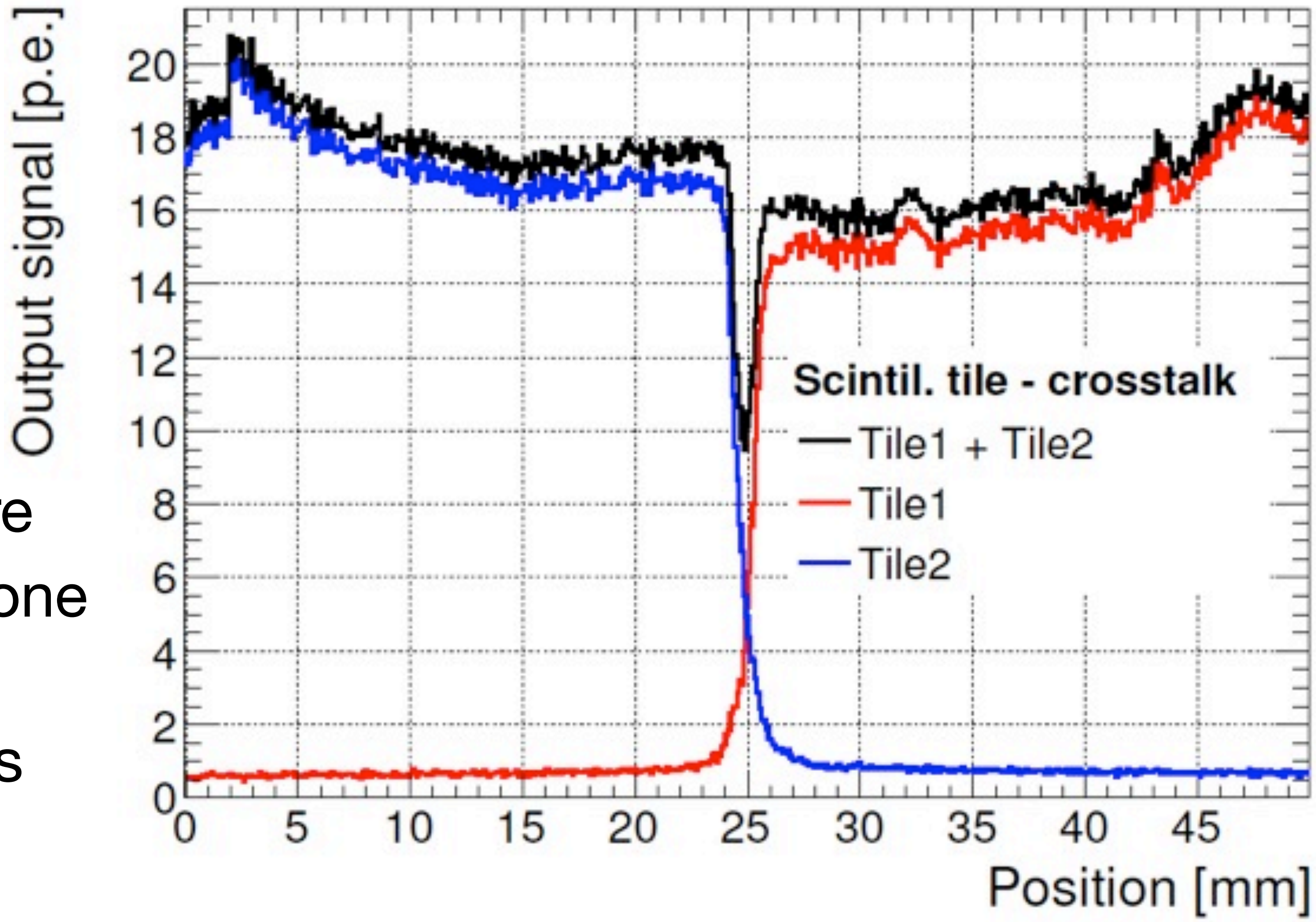
- Development of highly granular hadronic calorimeters (CALICE collaboration)
- Contributions to TPC development (LCTPC collaboration)

# Readout Technology for Hadron Calorimeters

- Scintillator with SiPM readout (without wavelength-shifting fibers)
  - Precise characterization of SiPMs (fill-factor, uniformity, ...)
  - Investigation of mass-produced scintillator tiles



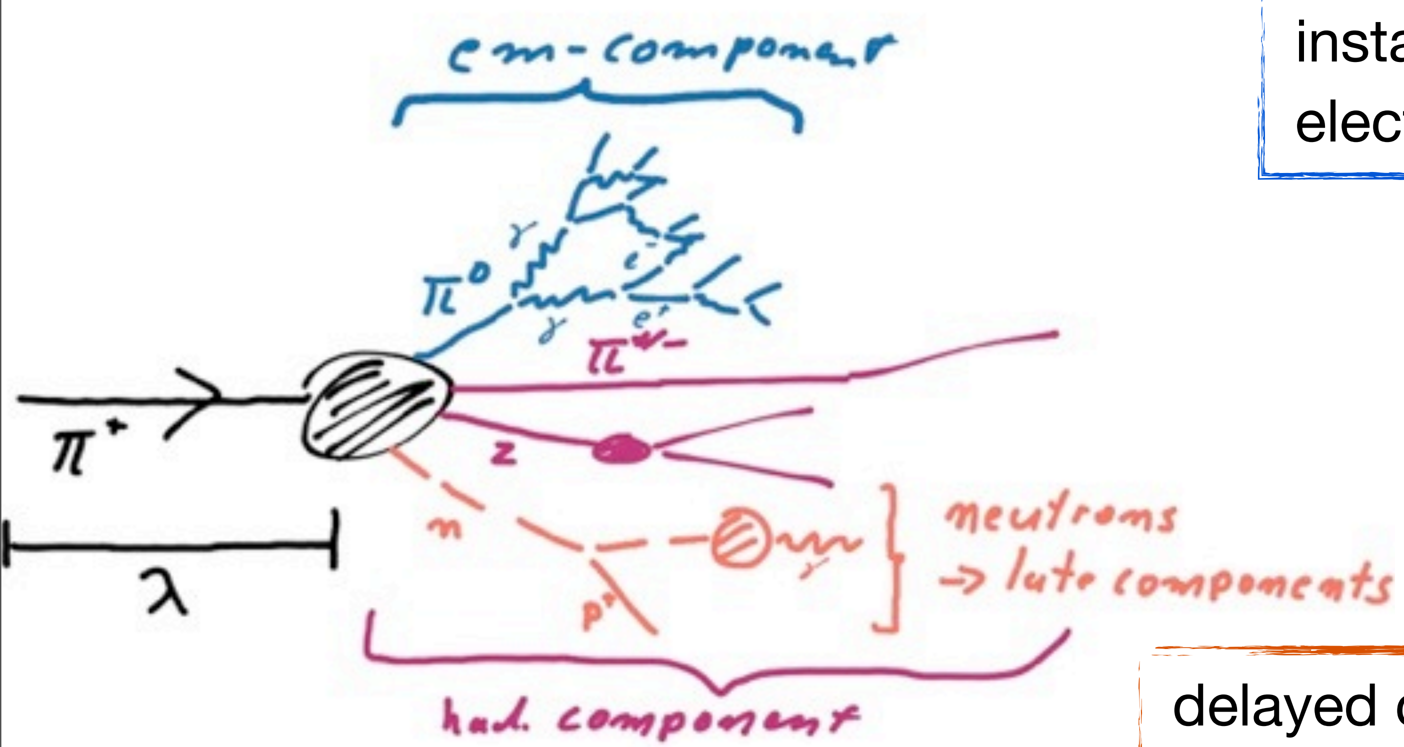
First prototypes of injection-molded tiles based on MPP design, fabricated at ITEP, are available




Detailed scans with $^{90}Sr$ to measure inter-tile gap: 165 μm thick dead zone due to chemical matting, in total ~400 μm inactive gap between tiles
=> Meets expectations

# Exploring Hadronic Showers

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




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

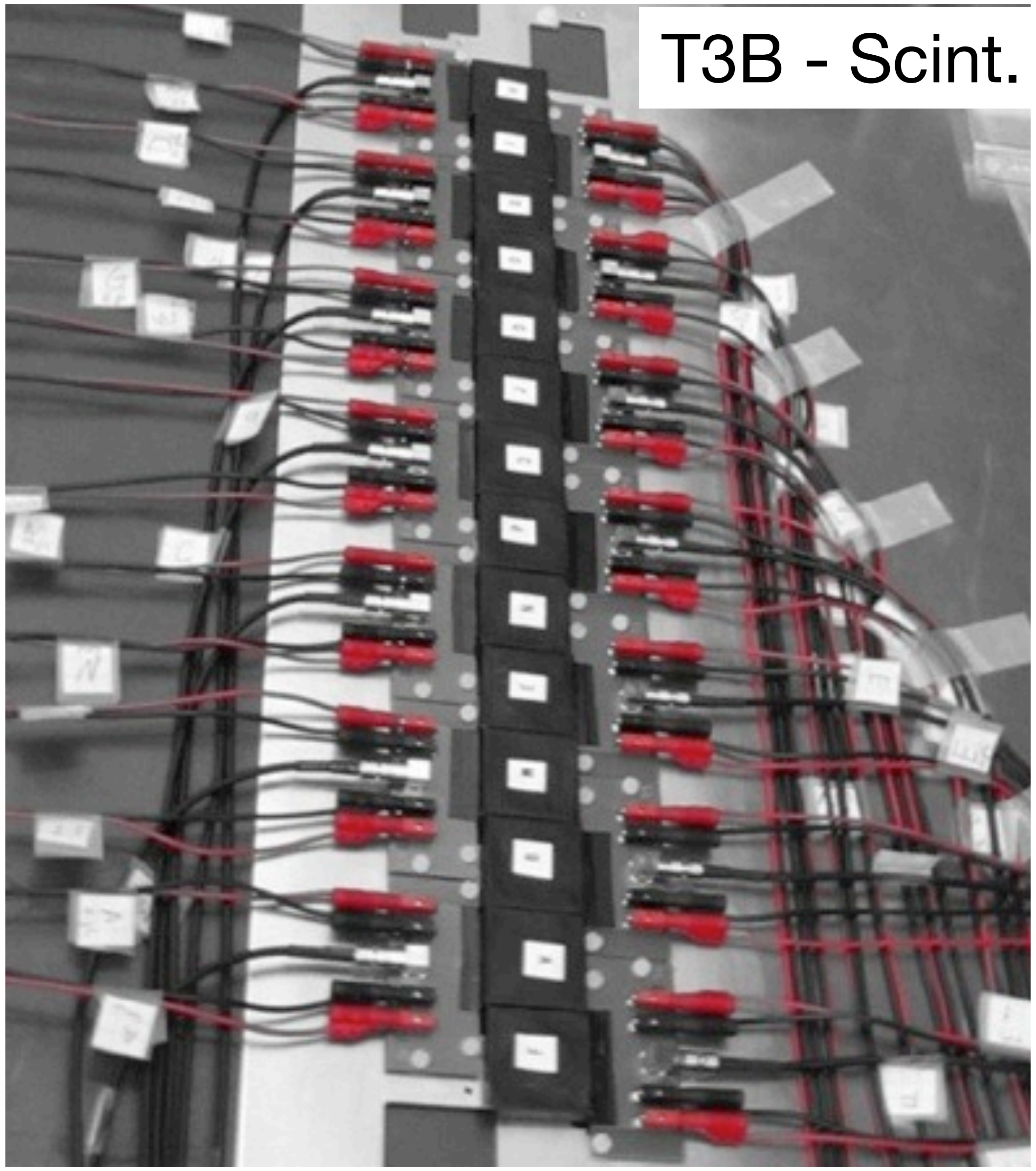
instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium

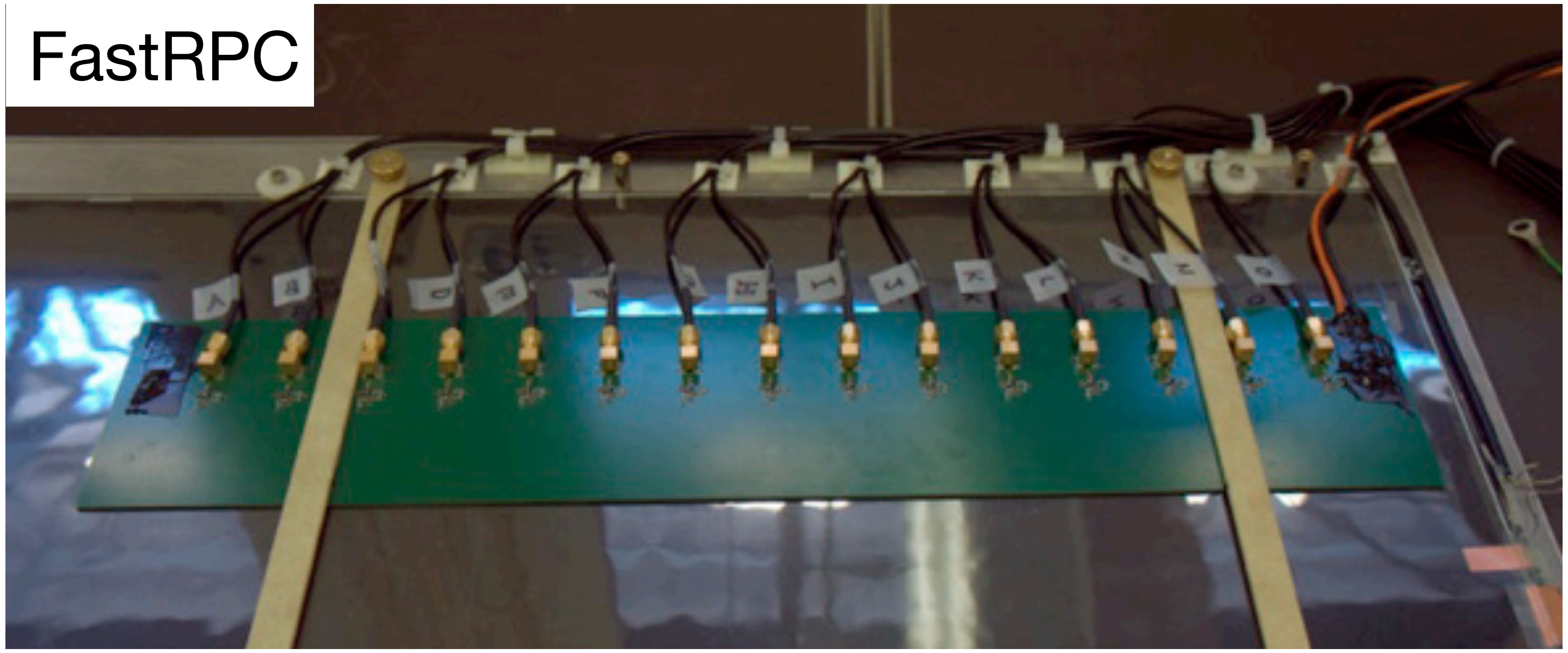
delayed component: photons, neutrons, protons from nuclear de-excitation following neutron capture, momentum transfer to protons in hydrogenous active medium from slow neutrons

- 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

# T3B and FastRPC - Timing in Imaging HCALs

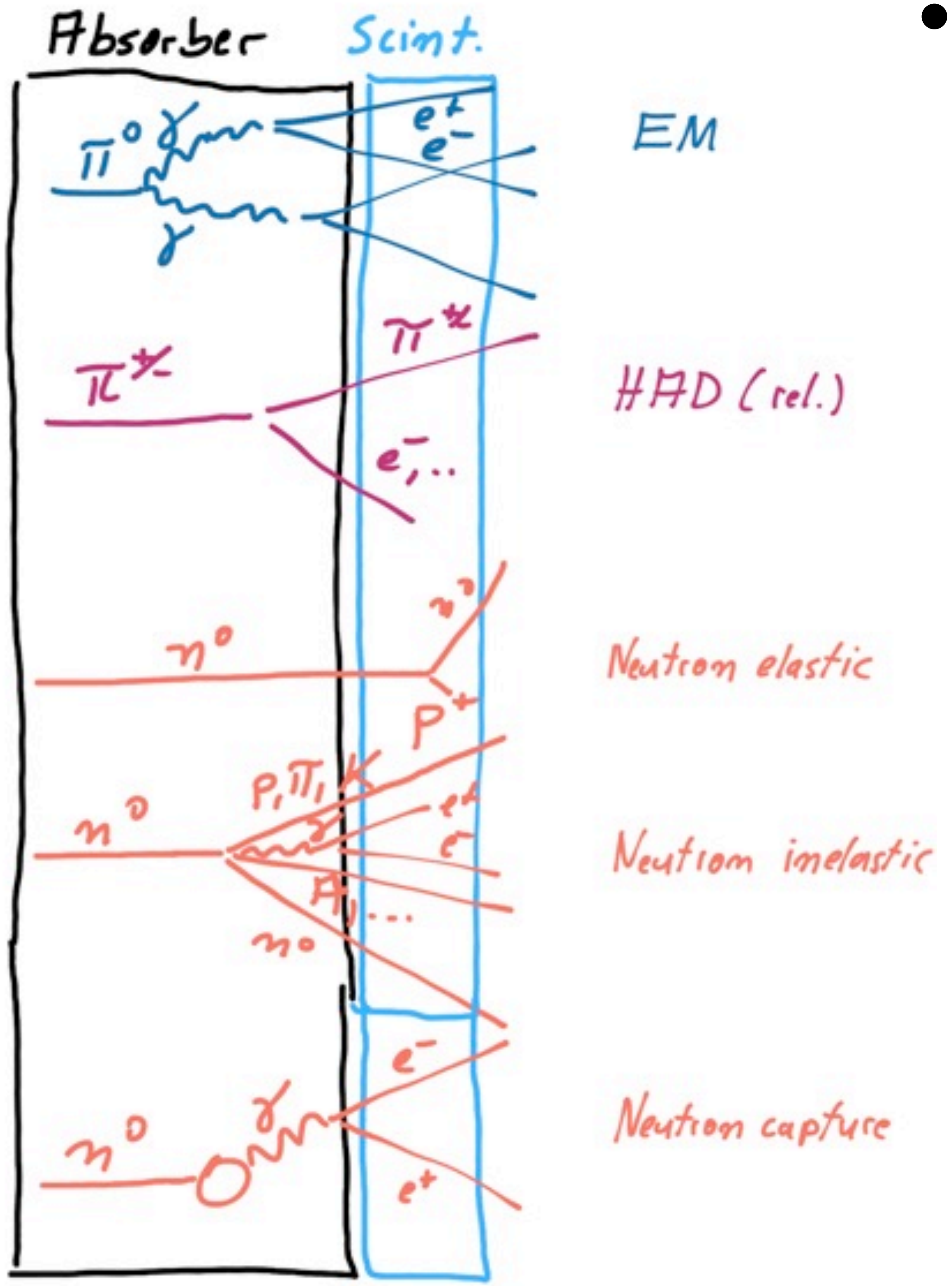
- 15 cells (3 x 3 $cm^2$ each) with sub-ns sampling, 2.4 μs acquisition window
  - Scintillator tiles - analog HCAL - measurements in tungsten and steel
  - RPCs - digital HCAL - measurements in tungsten



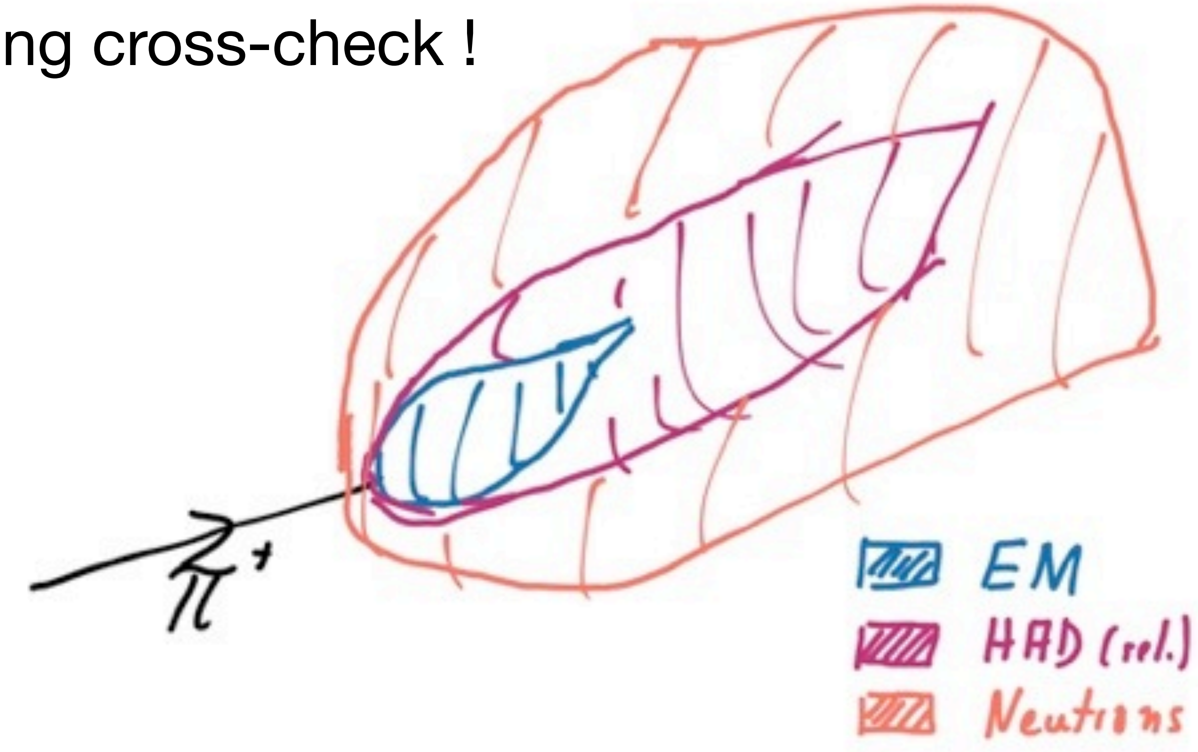




- T3B took data with CALICE WAHCAL in 2010 at PS and 2011 at SPS, with CALICE steel SDHCAL in 2011 at SPS
- FastRPC took data with CALICE WDHCAL in 2012 at SPS

# Shower Physics - Expectations

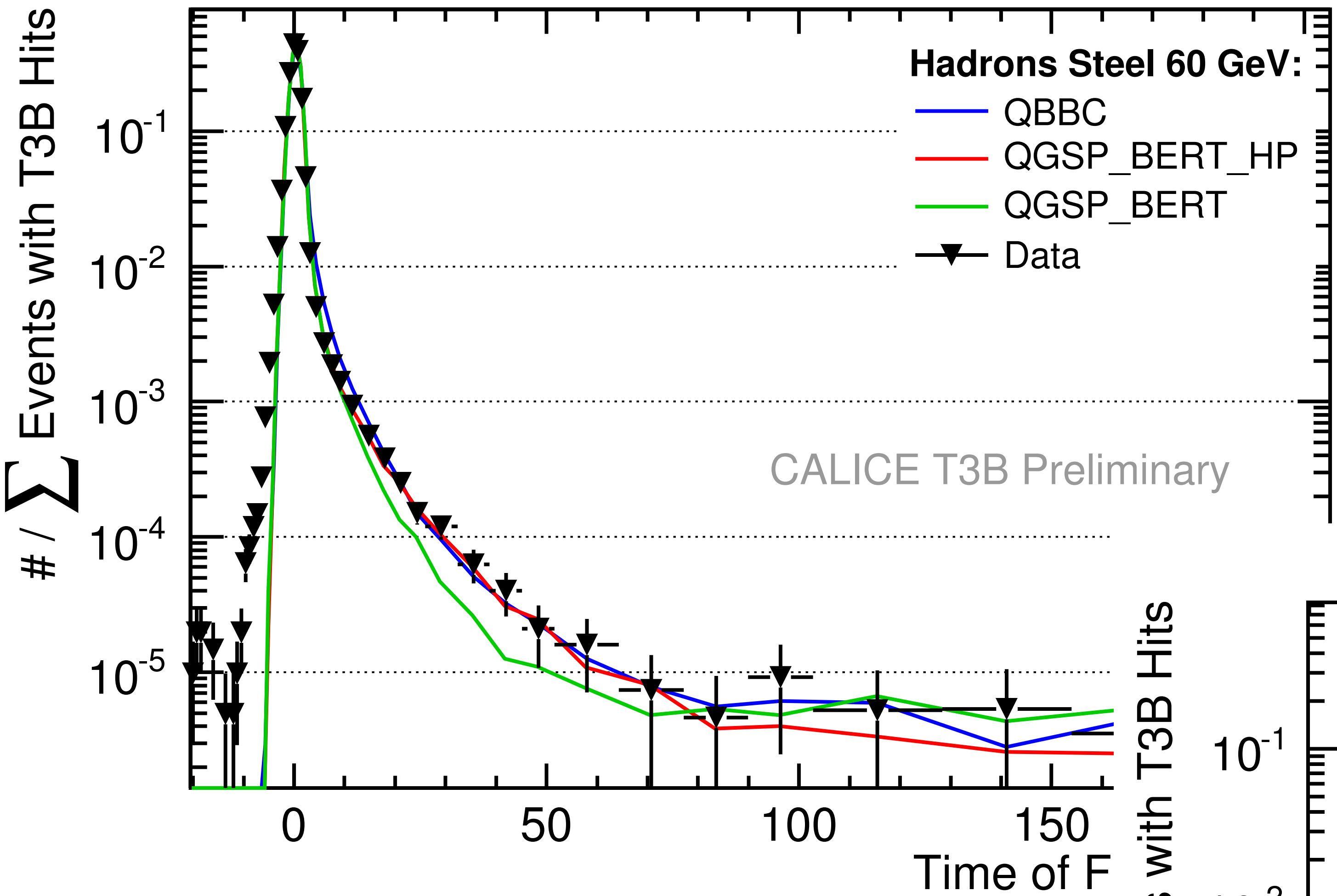



- Sensitivity to a wide range of particles within hadronic shower
  - RPCs blind to n elastic -> interesting cross-check !

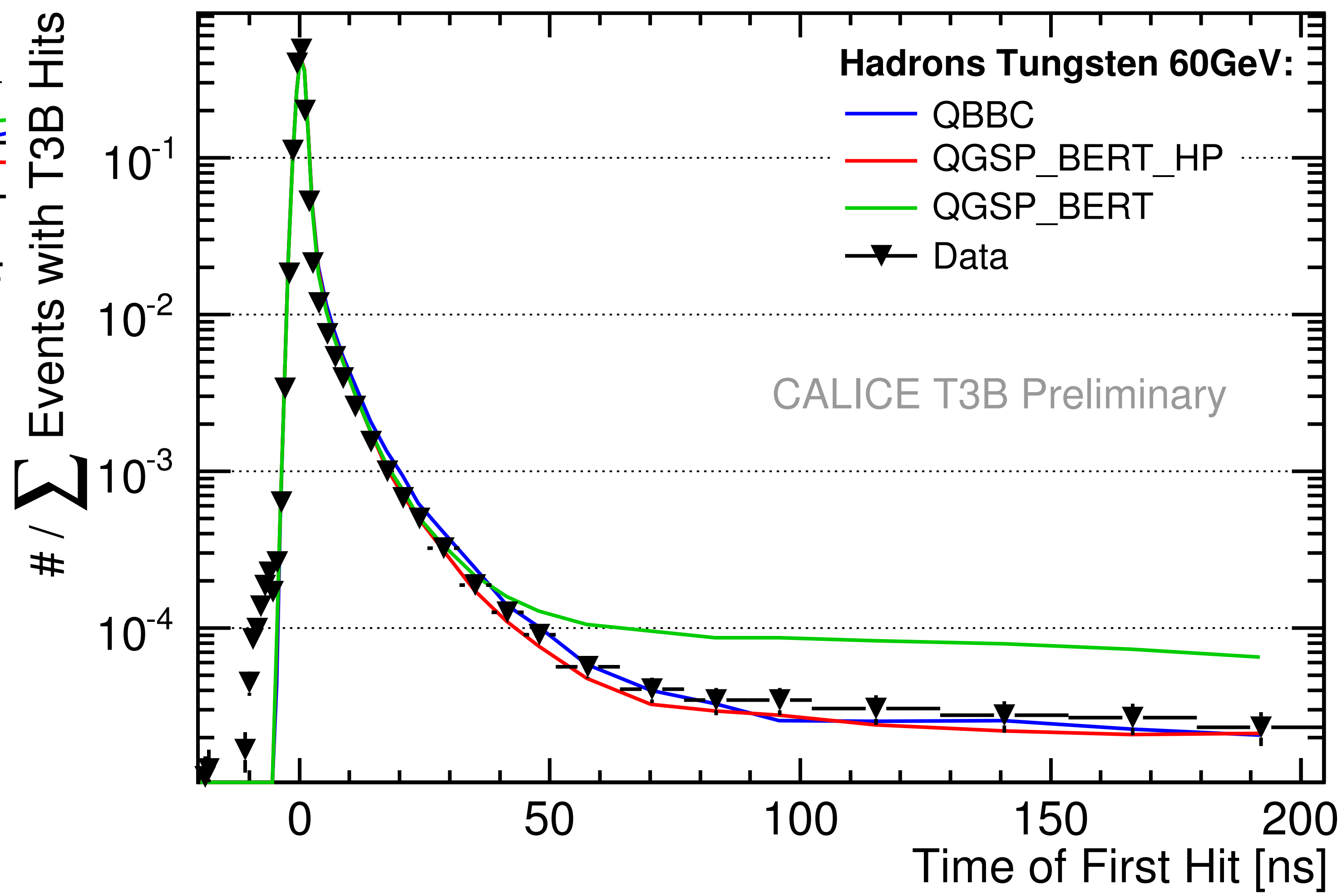



- Late components predominantly related to neutrons, in particular n-capture
- Expect wide spatial distribution: Shower halo most sensitive to time structure, core dominated by prompt relativistic particles

# Results with Scintillators - Global

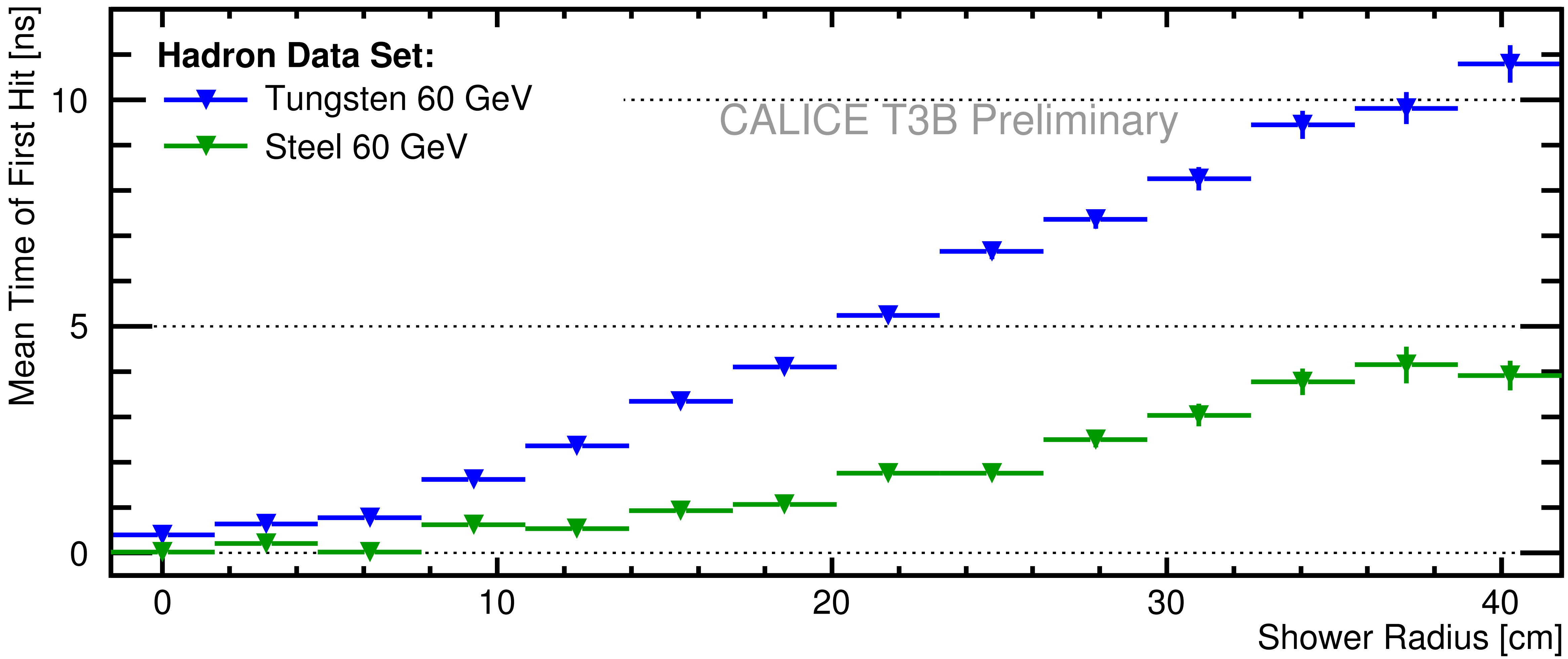



- Time distributions characterized by a sharp peak by prompt particles and a long tail




- In tungsten 5 x more hits than in steel 50 ns after particle impact
  - More complex time structure due to heavier nucleus and higher neutron activity

# Results with Scintillators - Radial Time Profile




- 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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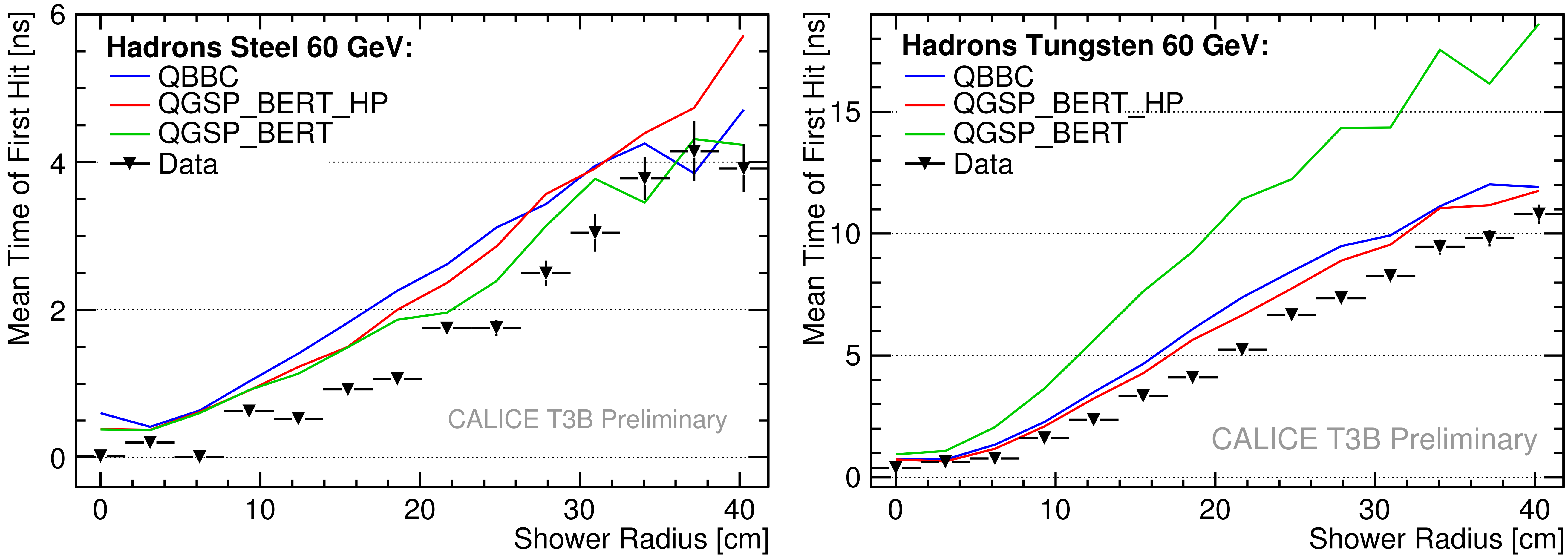
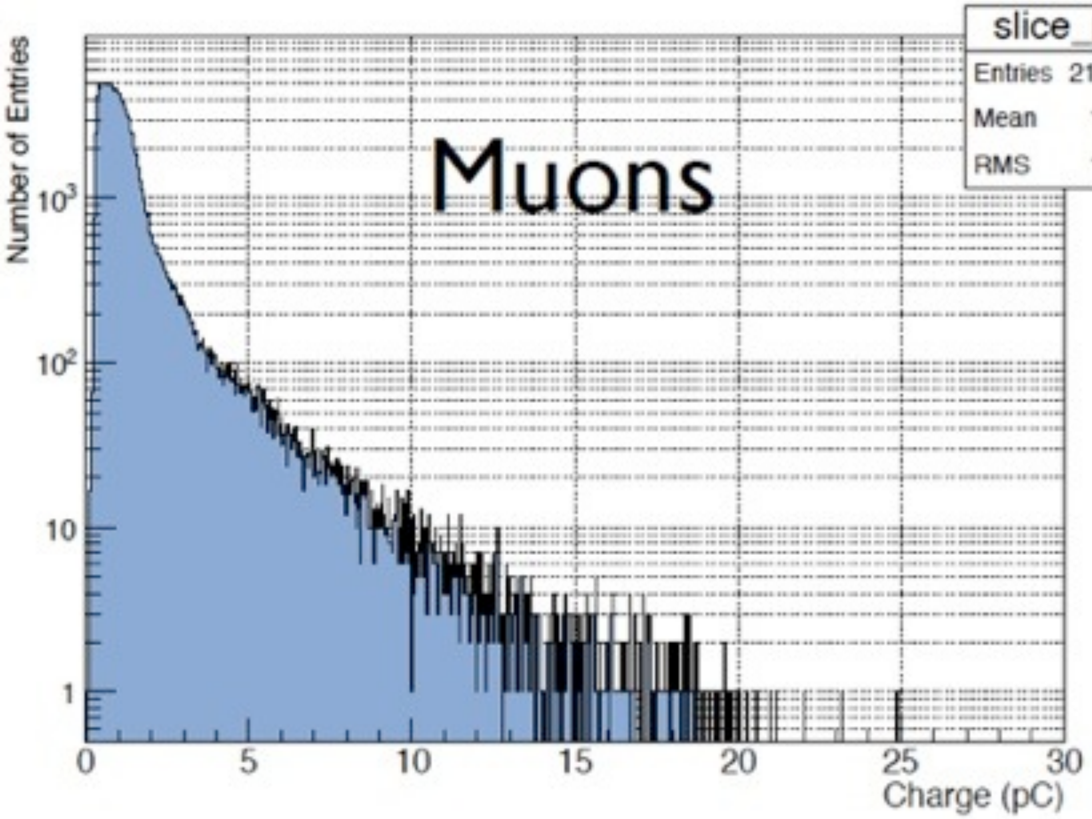
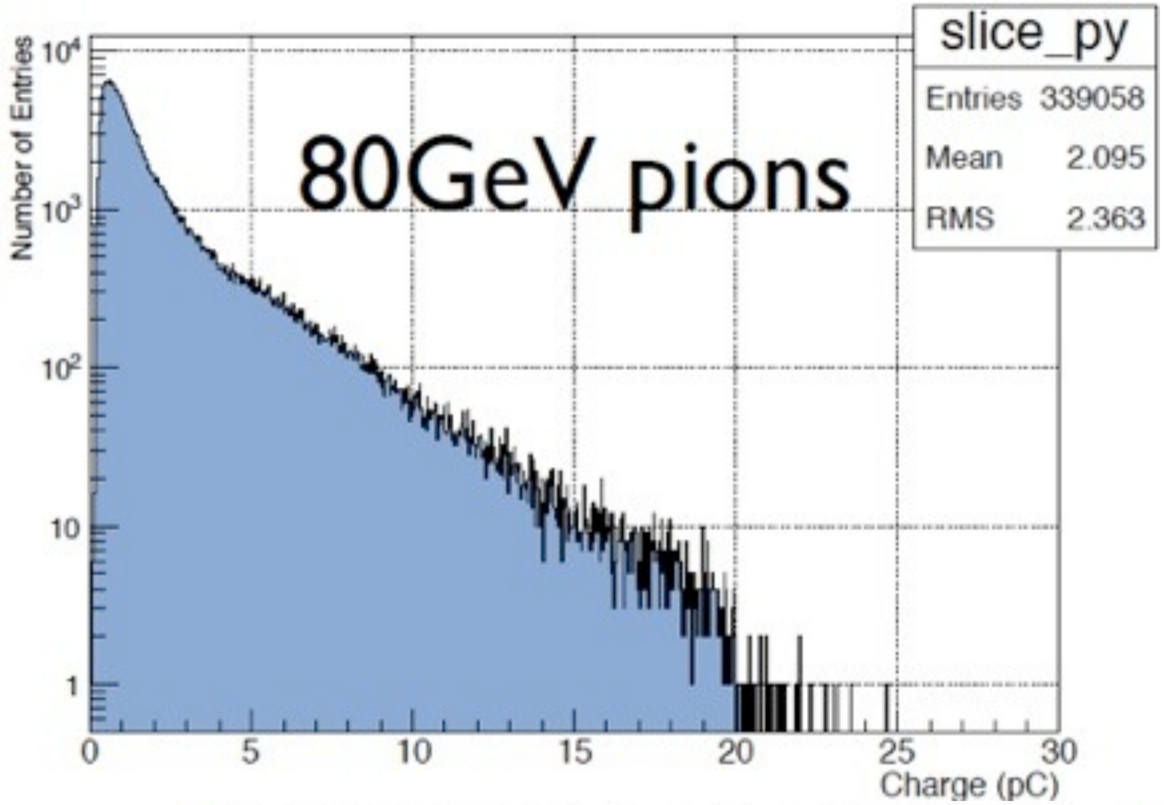


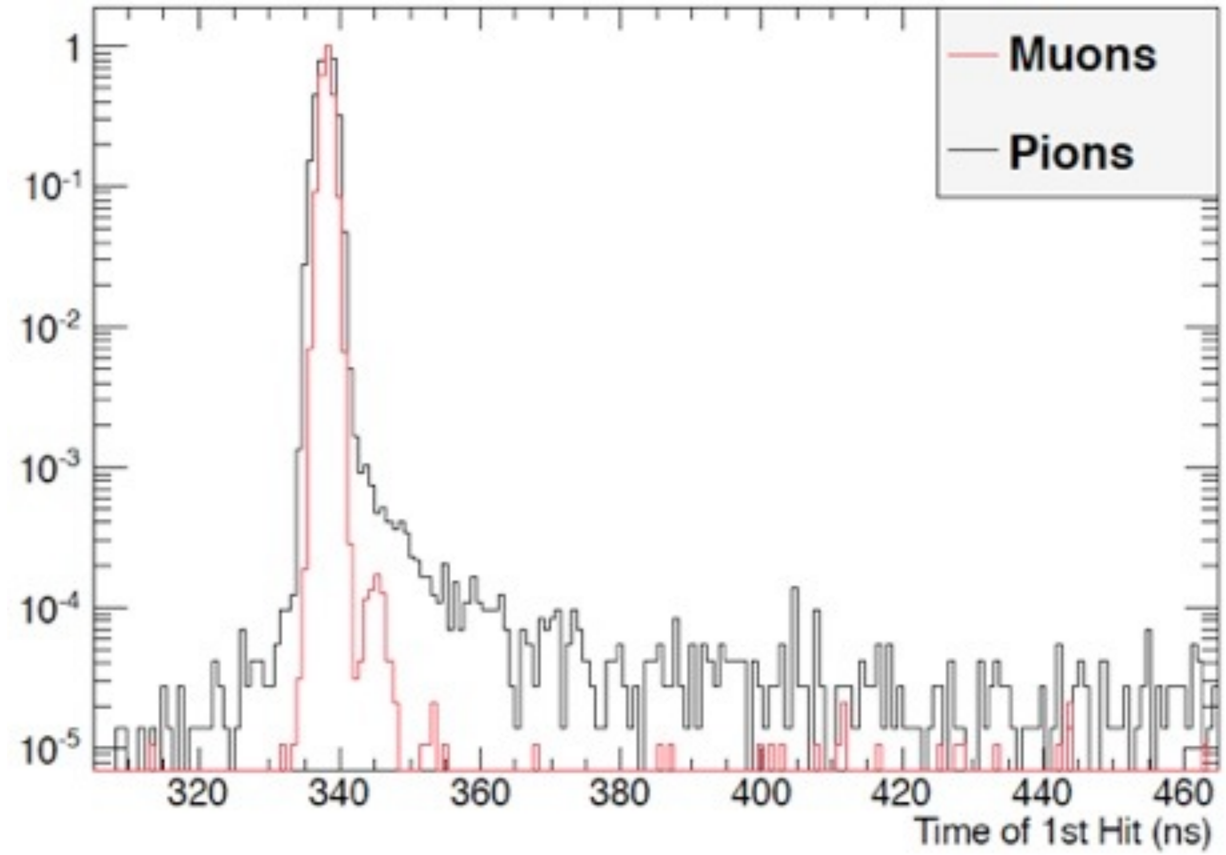

- Late energy deposits are more important in the outer regions of a shower
  - More pronounced effect in tungsten than in steel
- In steel: Good description by Geant4 (on the level of a few 100 ps)
- In tungsten: Neutrons are of key importance - only QGSP_BERT_HP and QBBC Geant4 models provide a good prediction

# Early Results with RPCs



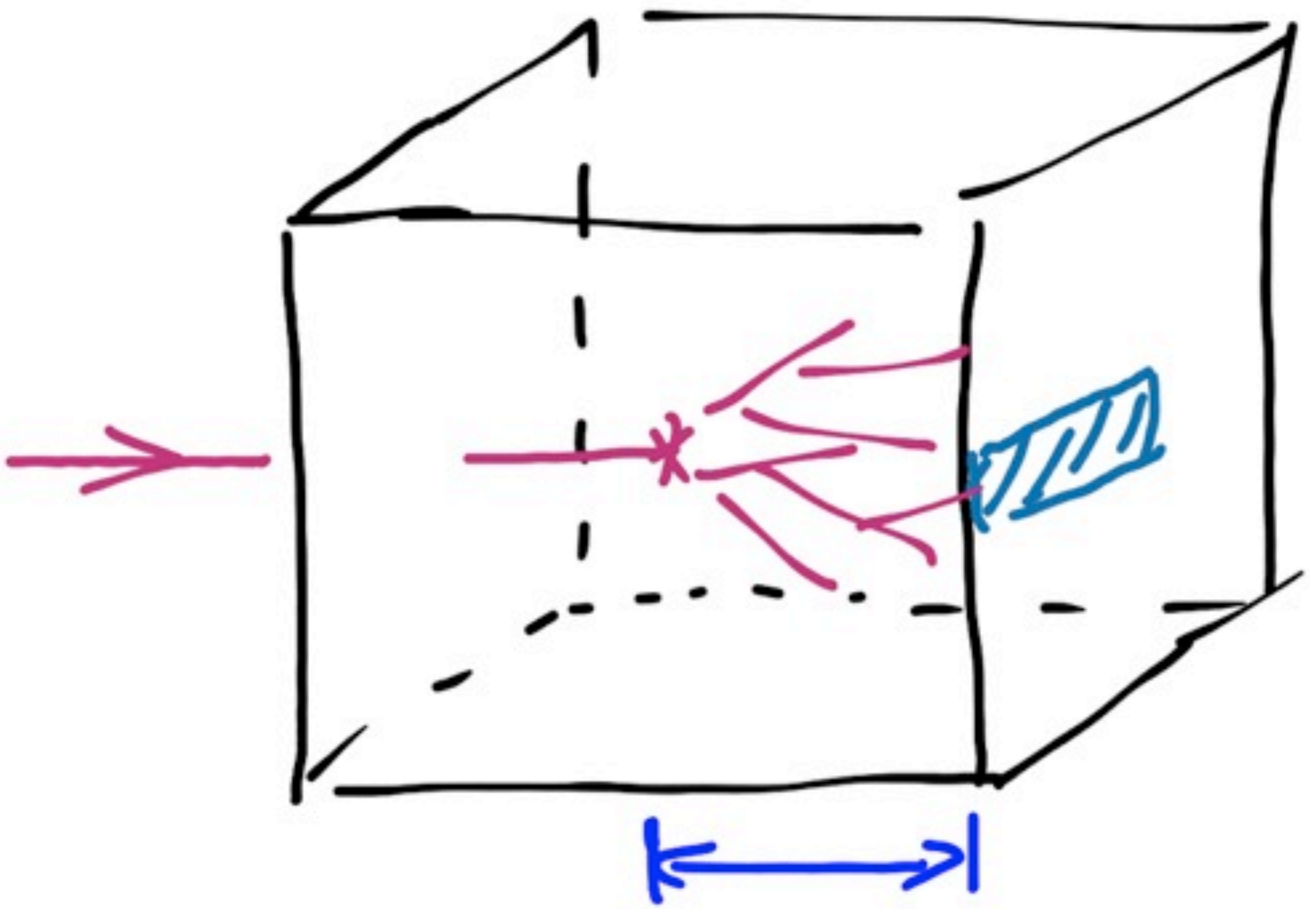




- Identification of hits in RPC: Amplitude differences in muons and hadrons point to high-density em showers
- Late energy deposits visible in pions compared to muons: The T3B principle also works for RPCs!



# Adding a 4th Dimension: Depth

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

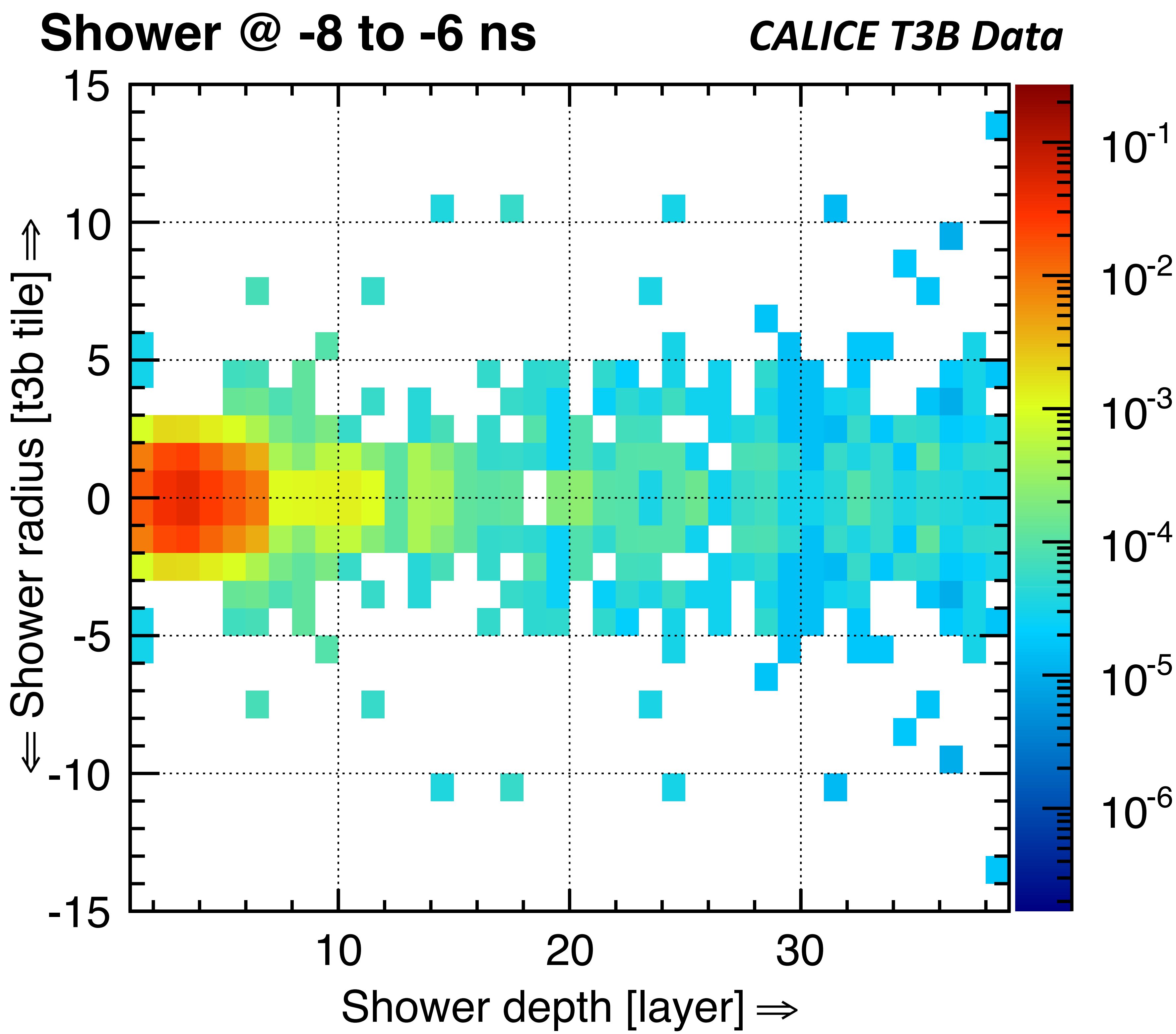


depth of T3B in shower

- 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 $\lambda_I$

- 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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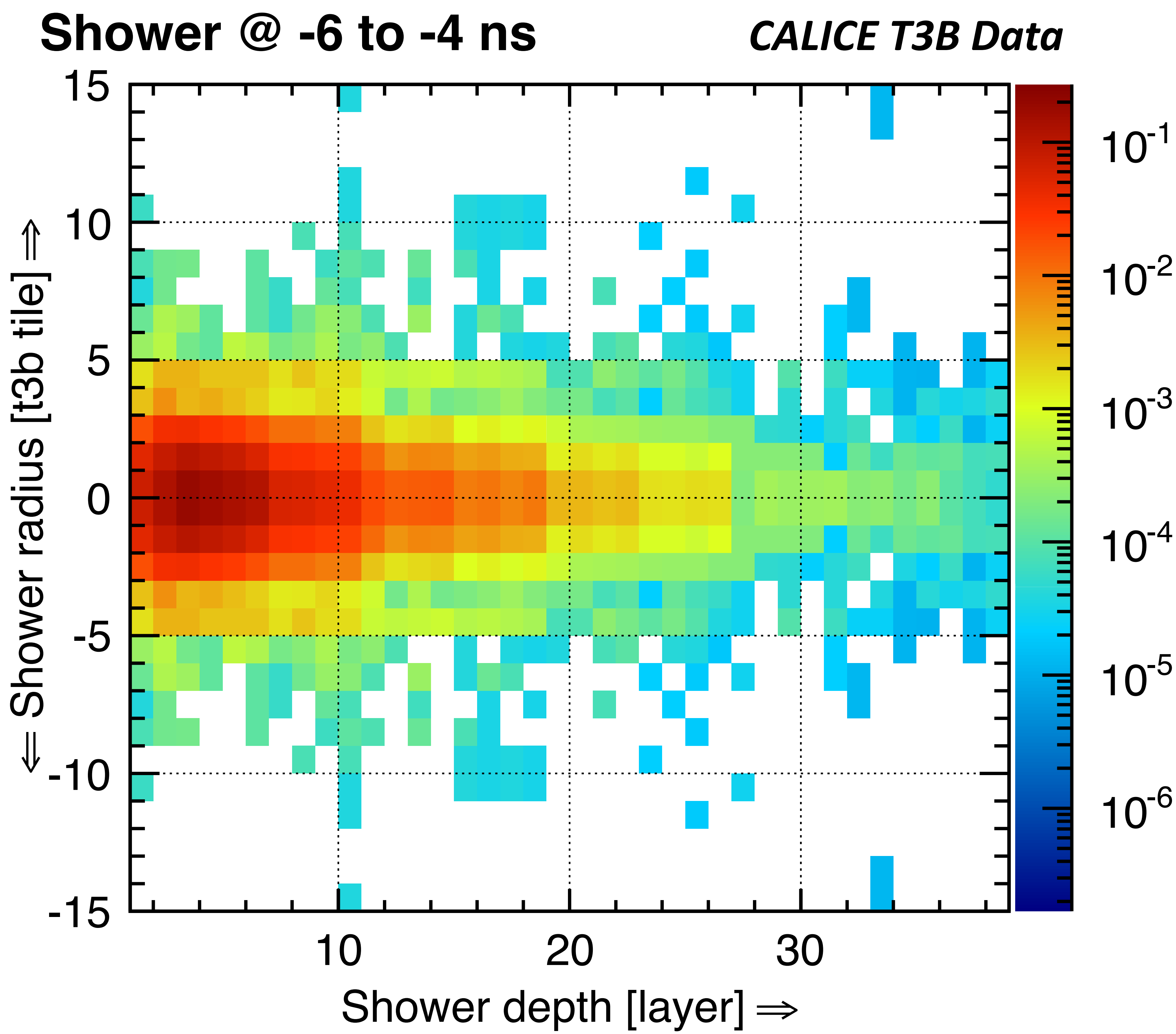


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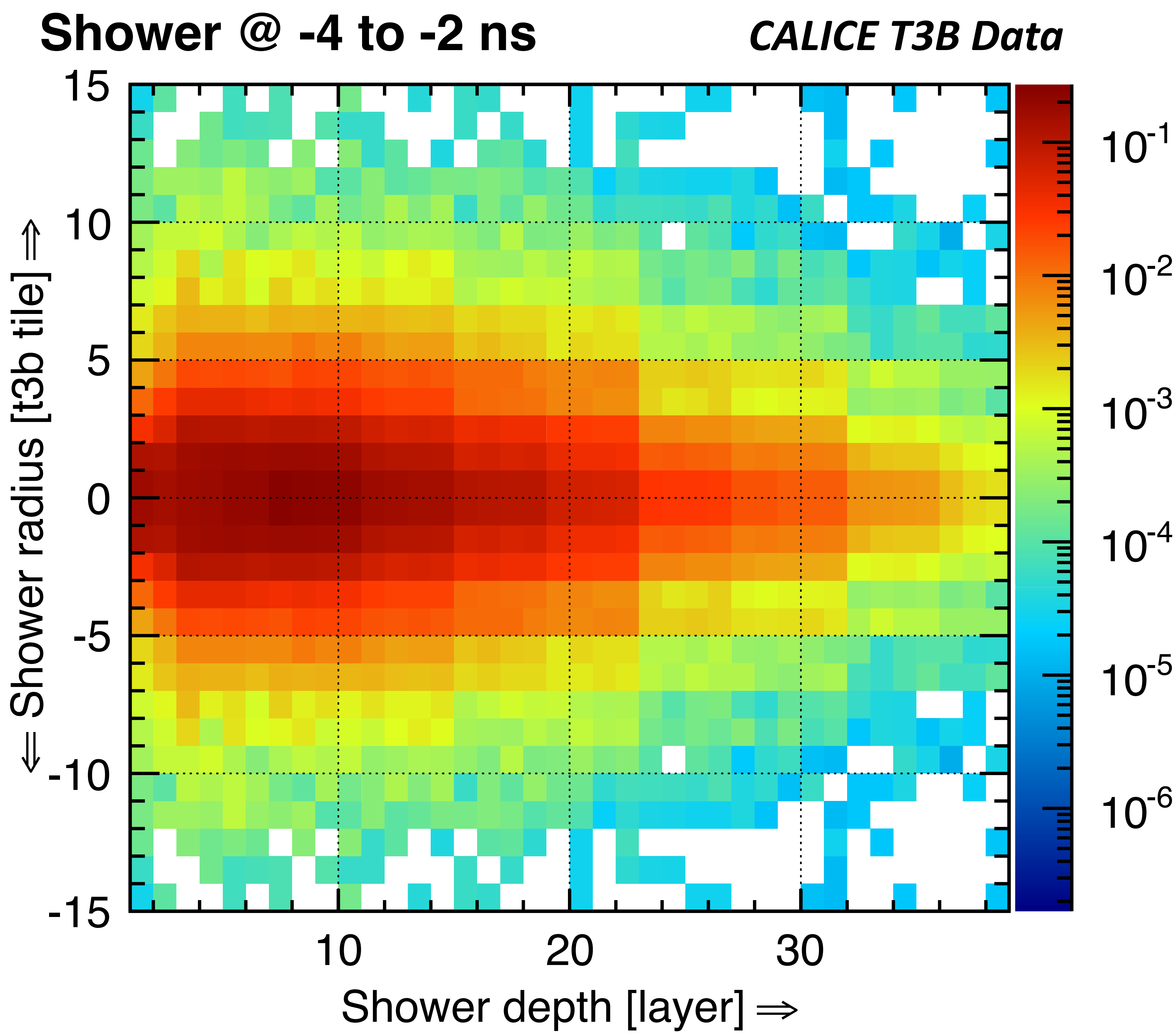


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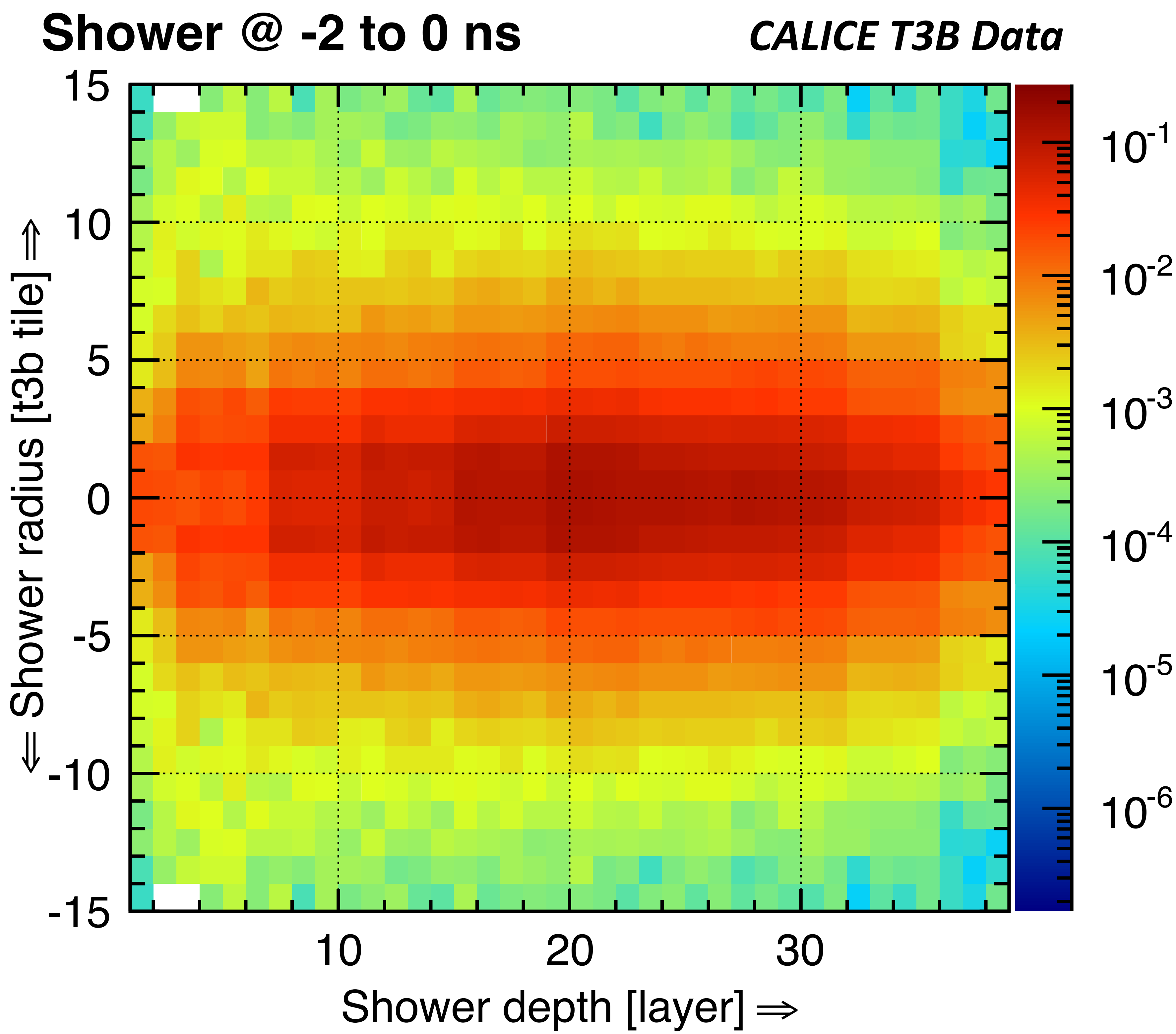


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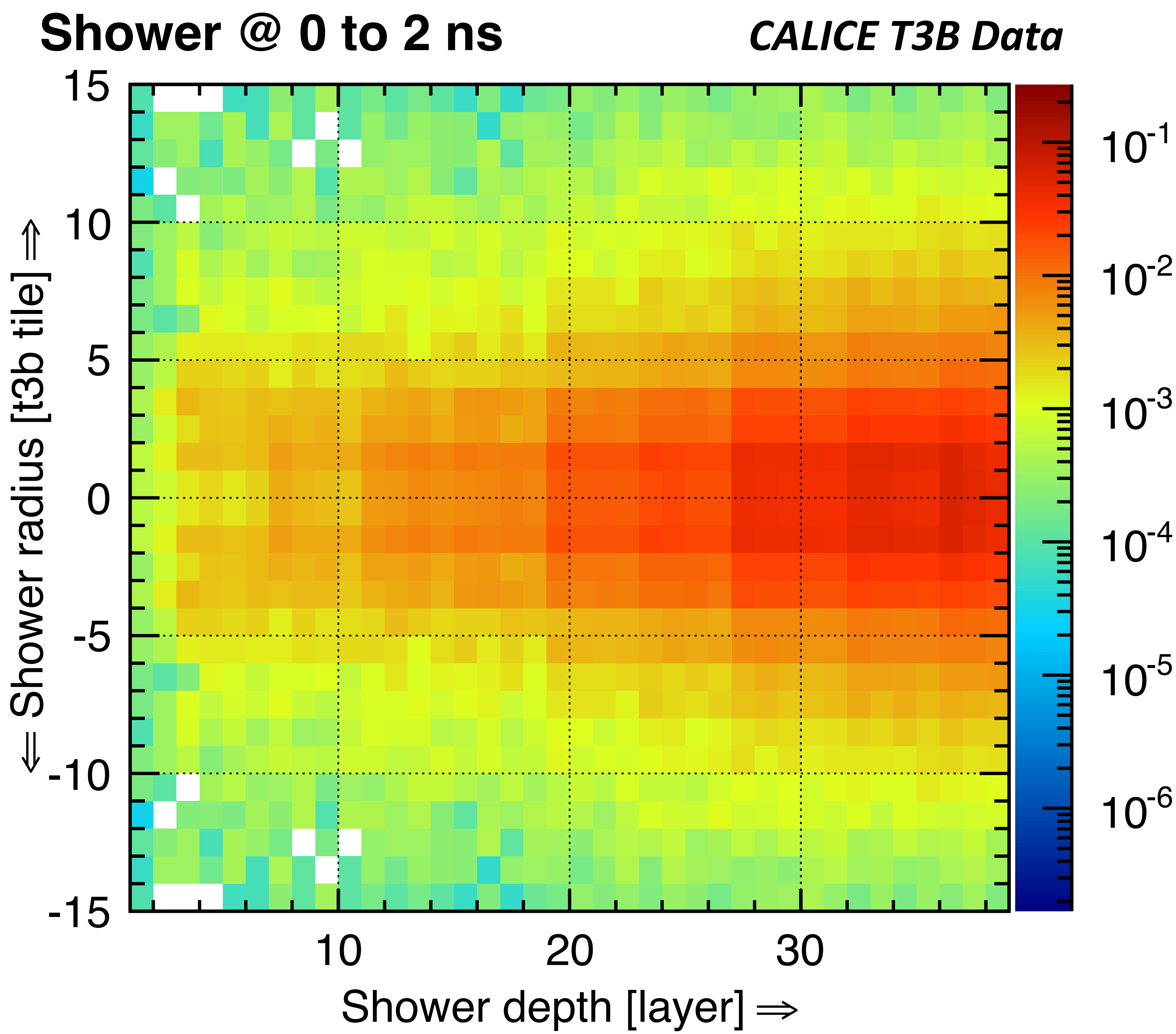


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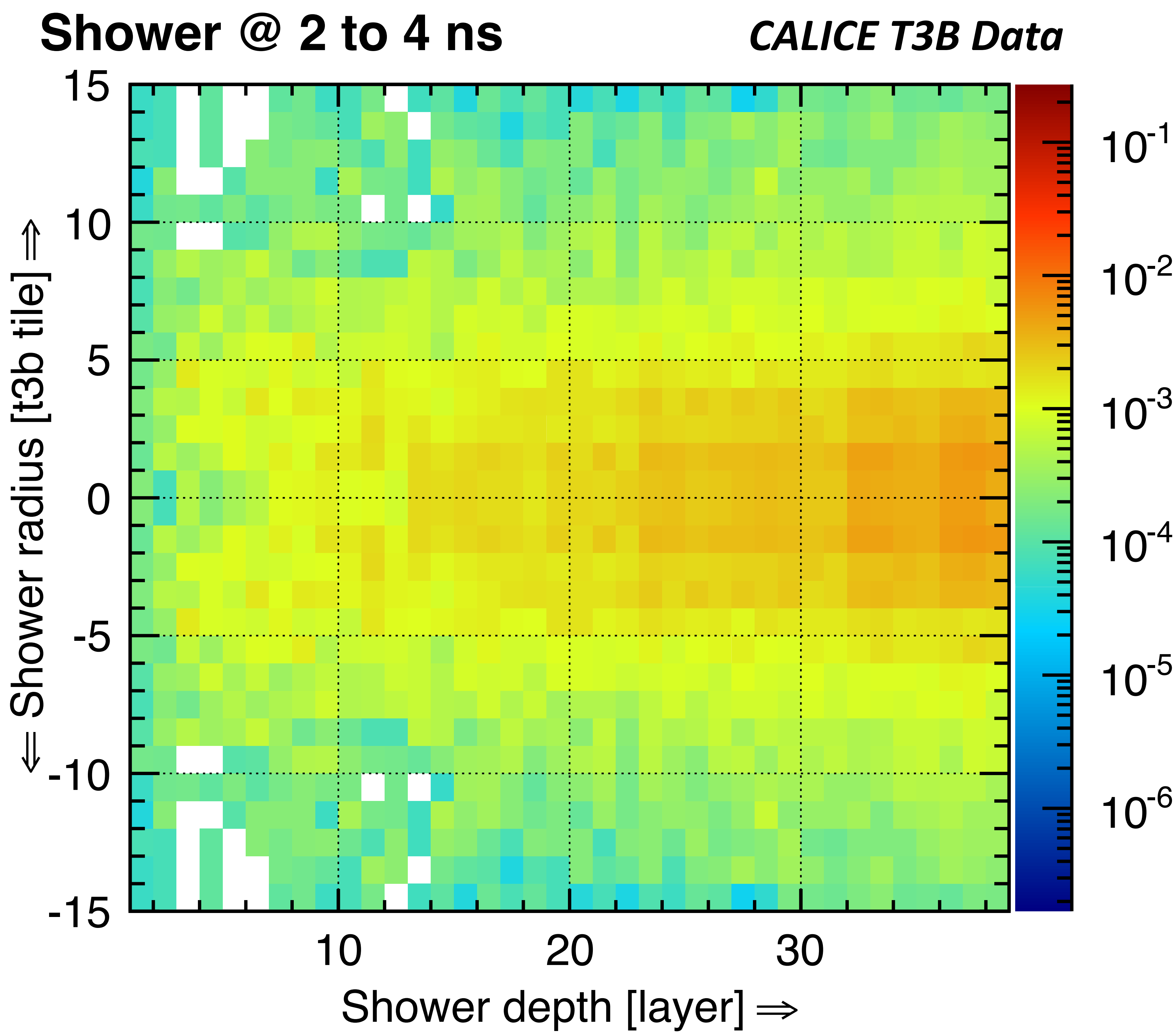


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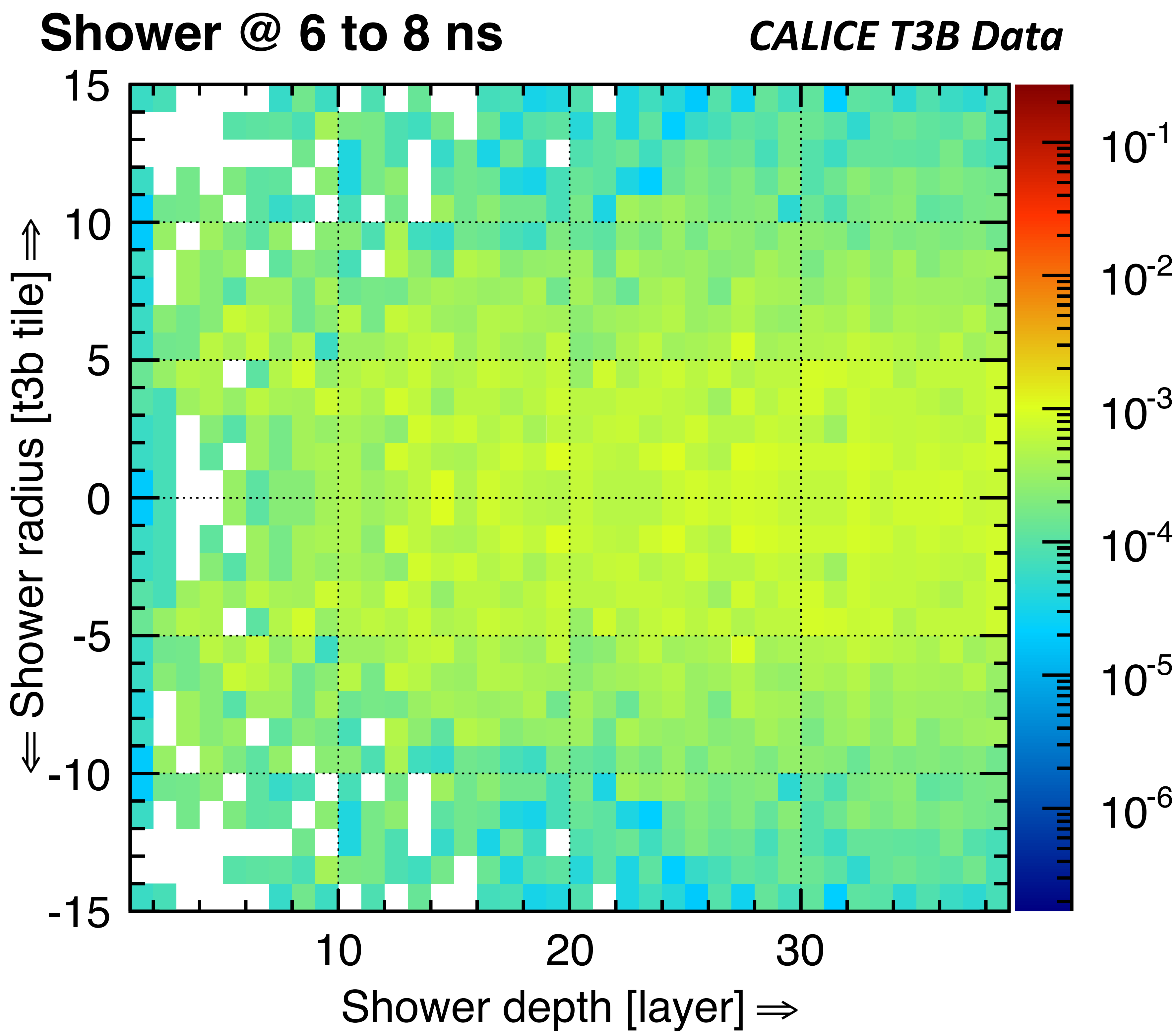


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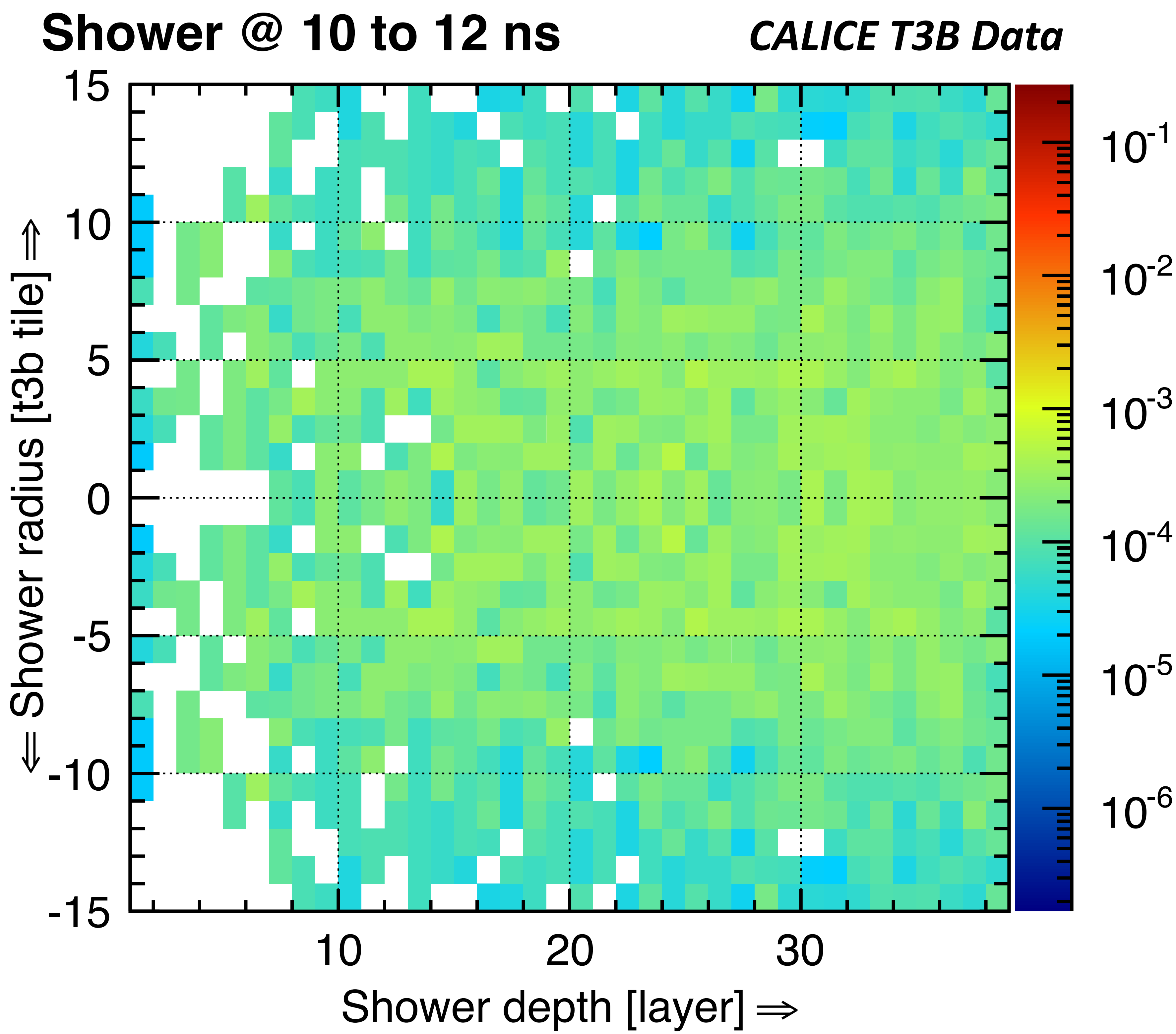


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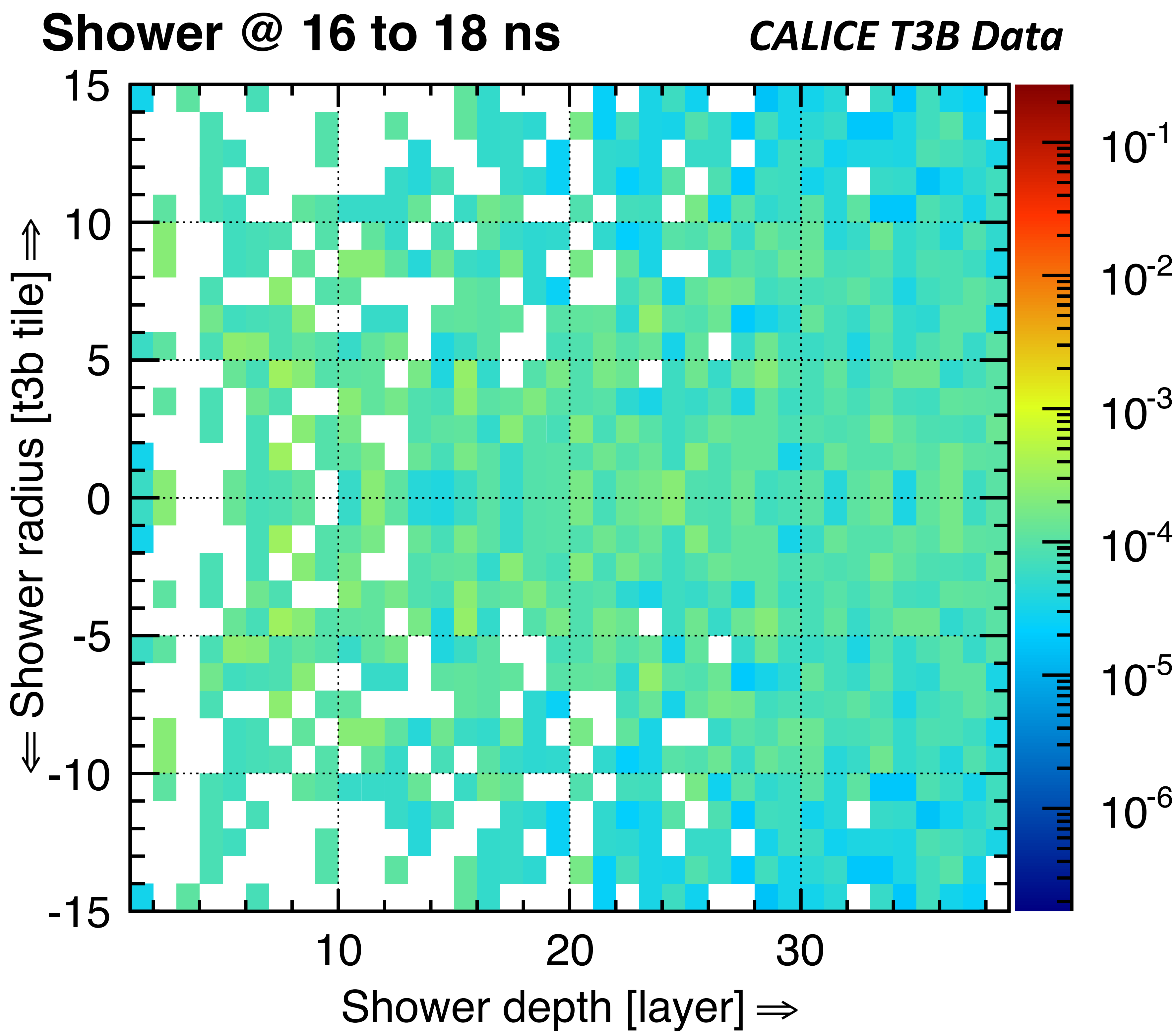


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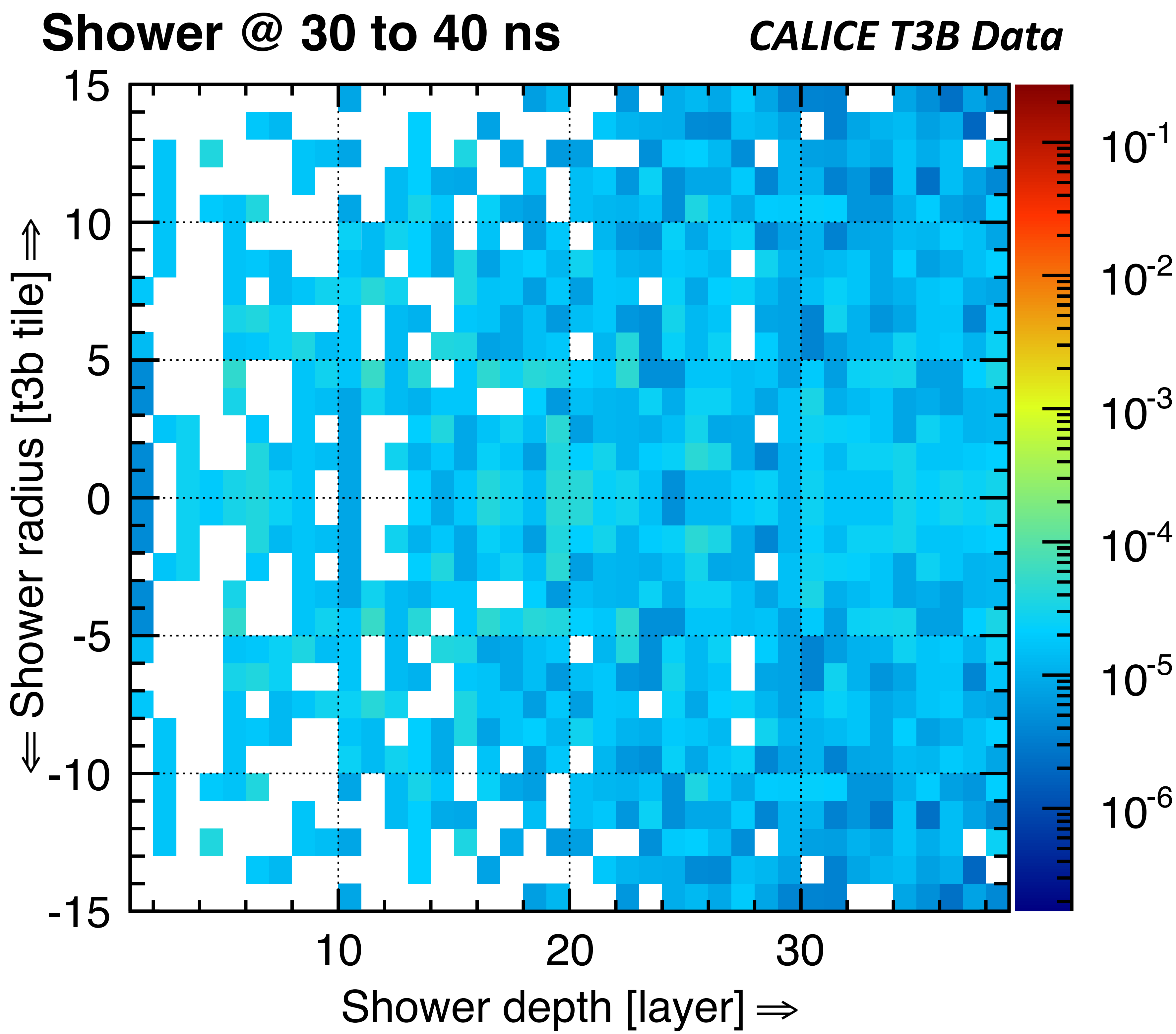


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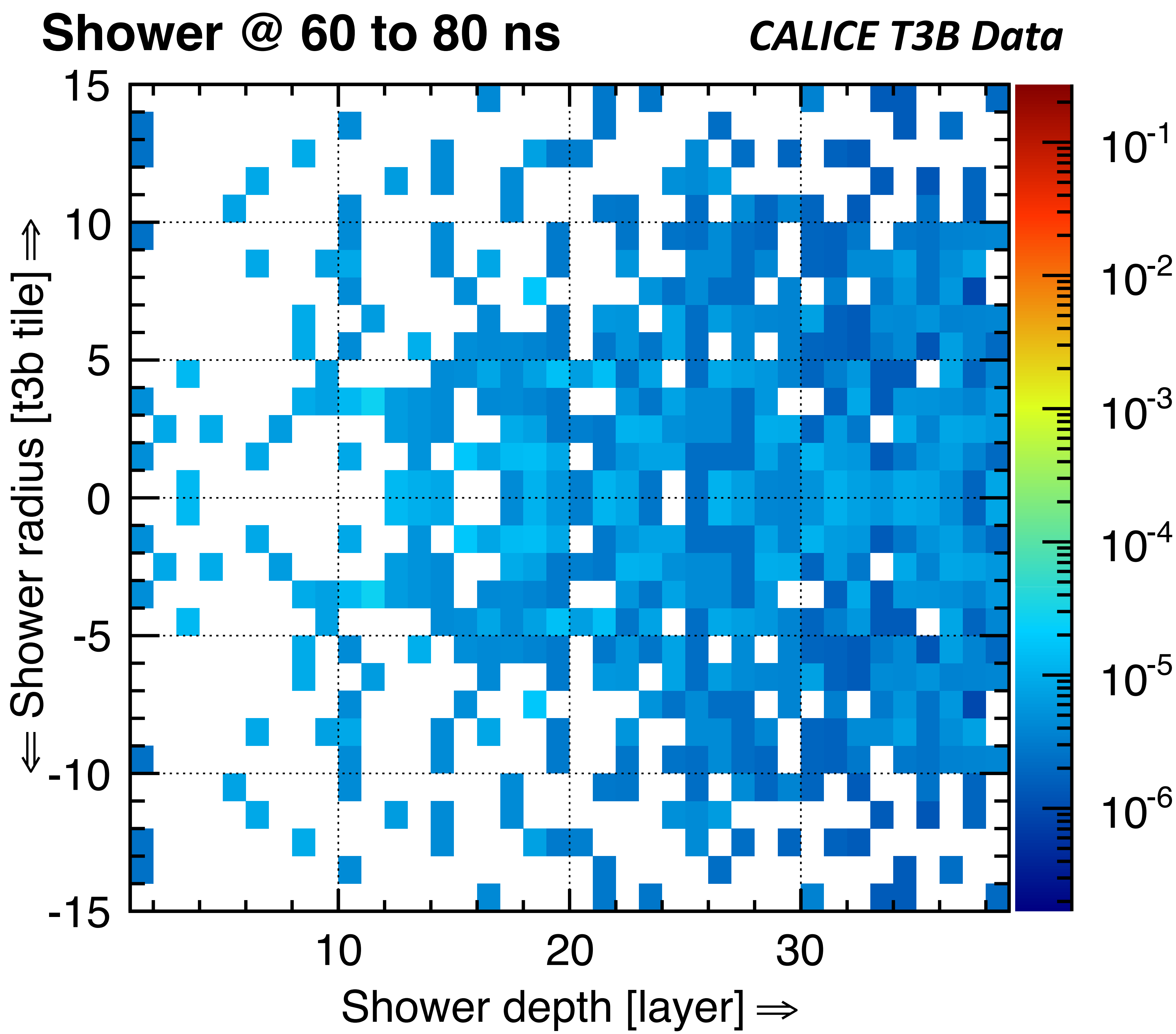


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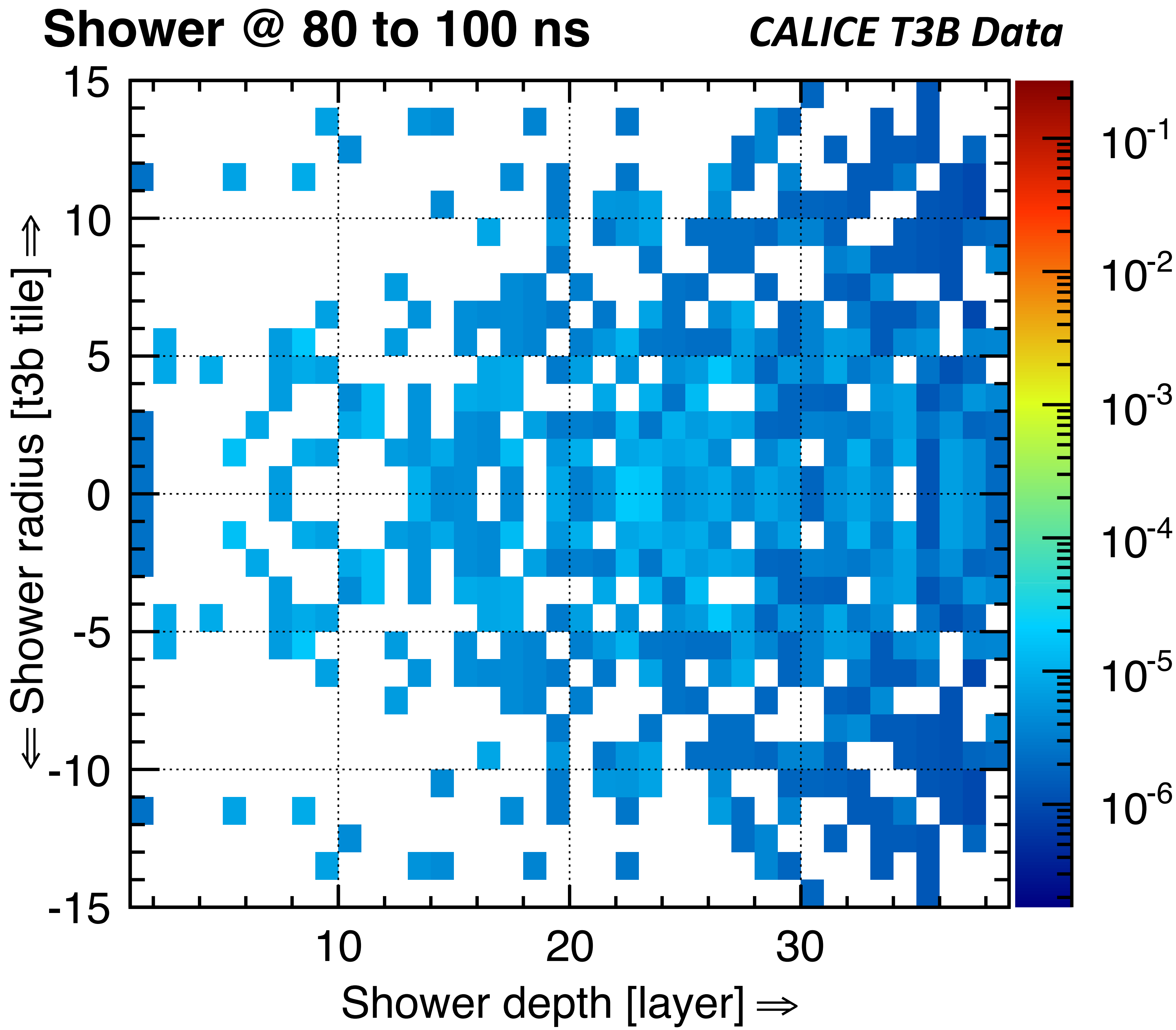


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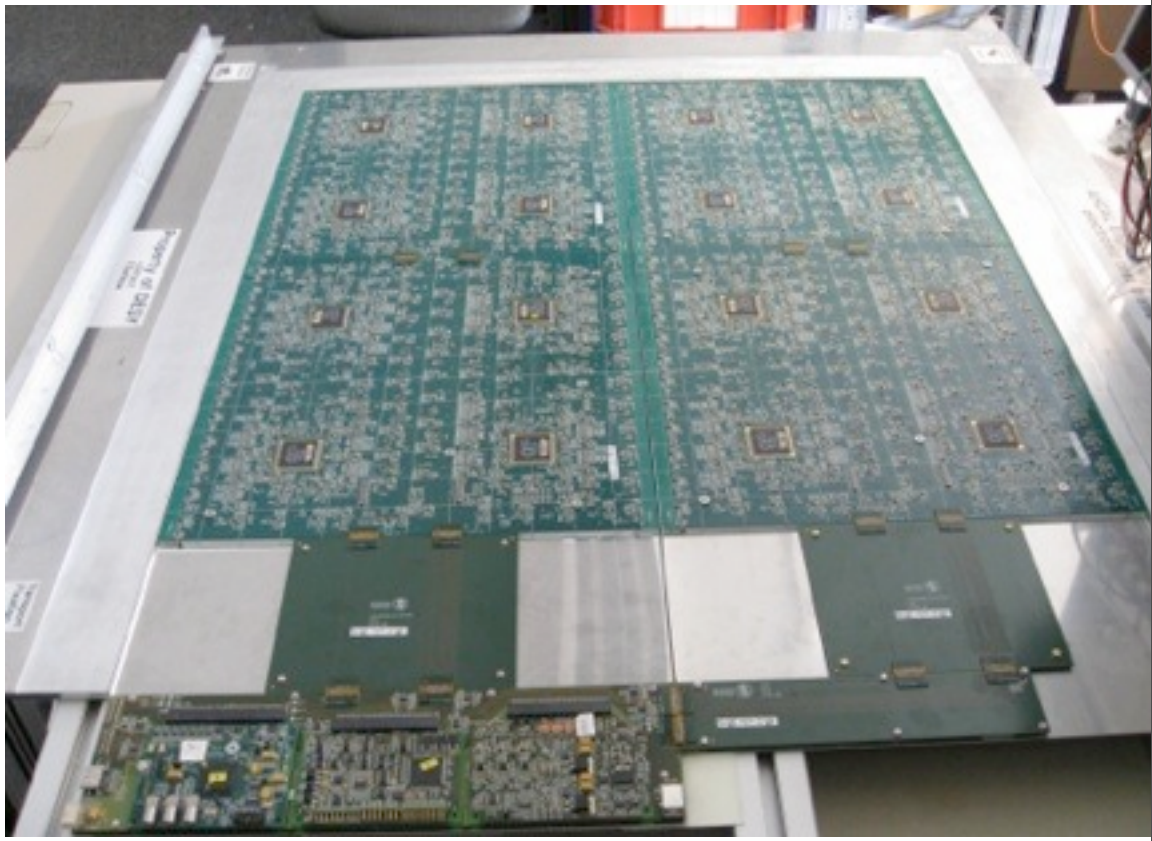
# Conclusions

- The discovery of the Higgs (like) particle at the LHC has further intensified the interest in a Linear Collider

- The MPP plays a very visible role in this effort
  - Editor and main editor roles for the CLIC CDR
  - Editor roles for the ILD DBD (part of ILC TDR)
  - Major contributions to physics studies for ILC & CLIC
  - Detector development for LC Experiments
    - Imaging calorimetry: Development of scintillator & SiPM readout options, advanced energy reconstruction algorithms, study of substructure of hadronic showers - space and time
    - Time projection chamber - Contributions to prototype R&D
    - Pixel detectors: DEPFET for Belle-II also promotes technology for a Linear Collider

# What's ahead



- The R&D will continue:
  - Next-generation prototype of CALICE AHCAL, with fully embedded electronics to demonstrate the full technology chain on the system level
    - Will include scintillator cells based on design developed at MPP
  - Investigate use of scintillator technology for a (more) cost-effective ECAL, potentially finer-segmented HCAL
  - Participate in comprehensive study of physics potential for Higgs sector

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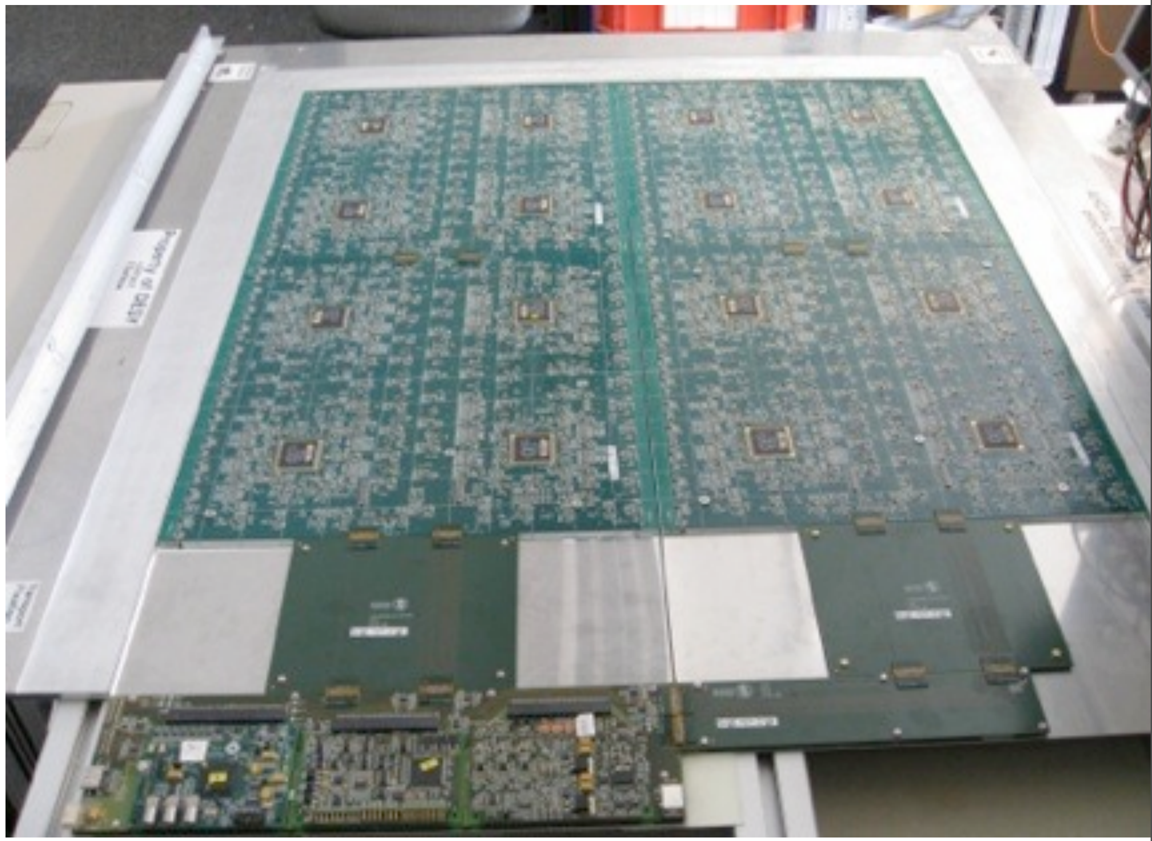
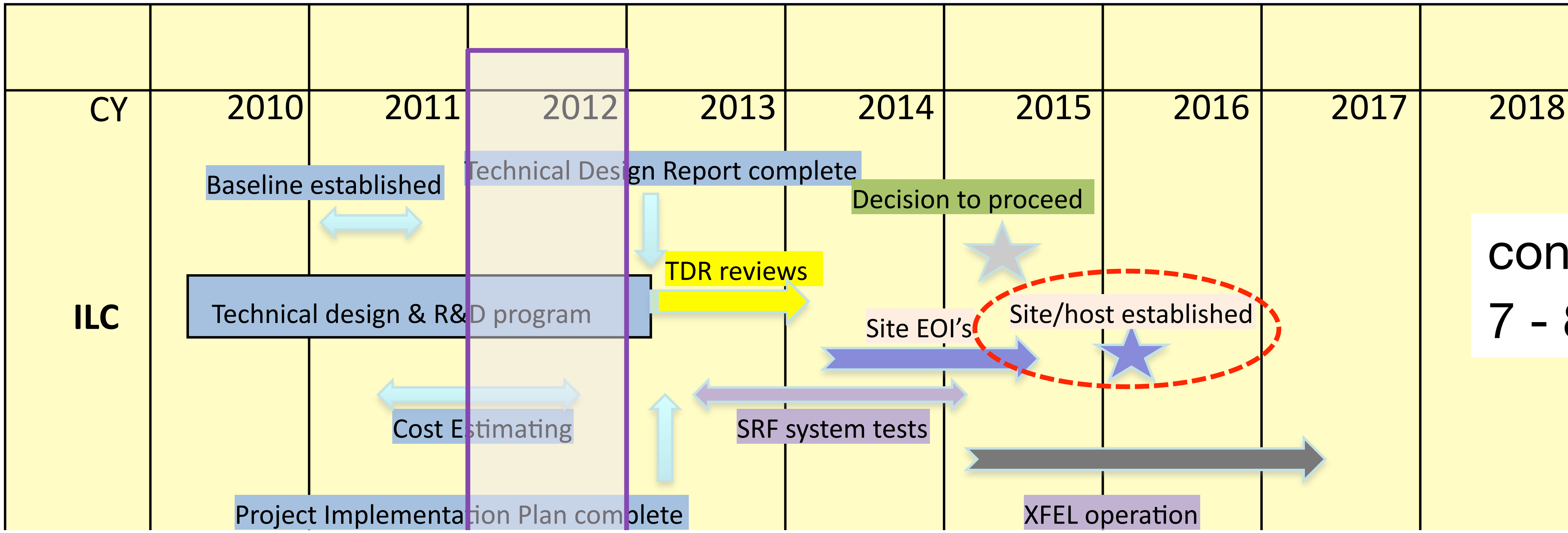


  - Investigate use of scintillator technology for a (more) cost-effective ECAL, potentially finer-segmented HCAL
  - Participate in comprehensive study of physics potential for Higgs sector

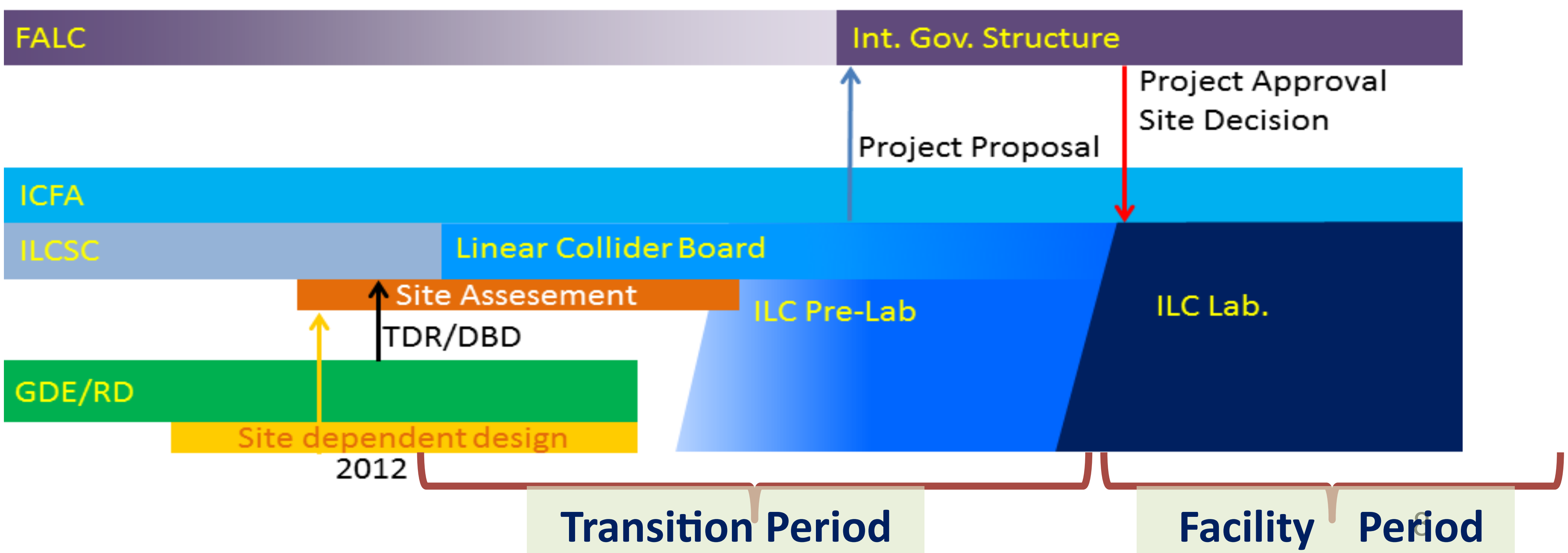
- The prospects for the realization of a Linear Collider:
  - No firm decision yet - Strategy update processes ongoing in Europe and US
  - Strong expression of interest by Japanese community

# Backup

# Possible ILC Timeline



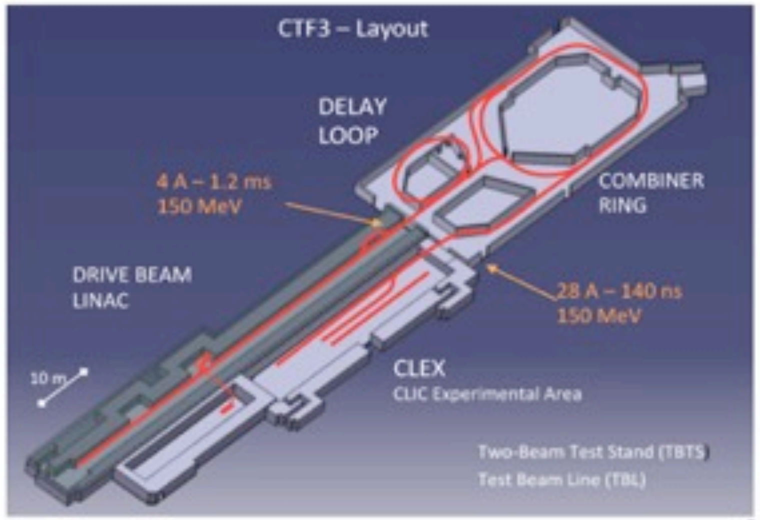

construction time
7 - 8 years



# Towards a Realization of CLIC

## 2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



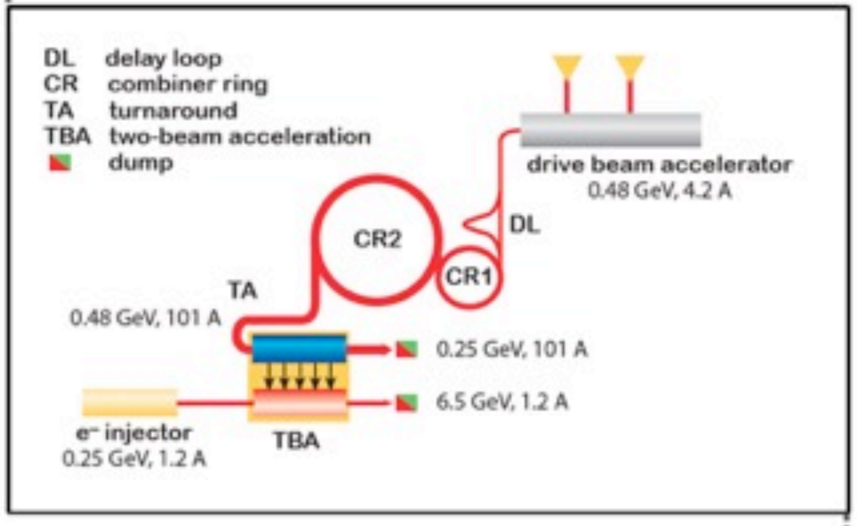

## 2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

## 2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



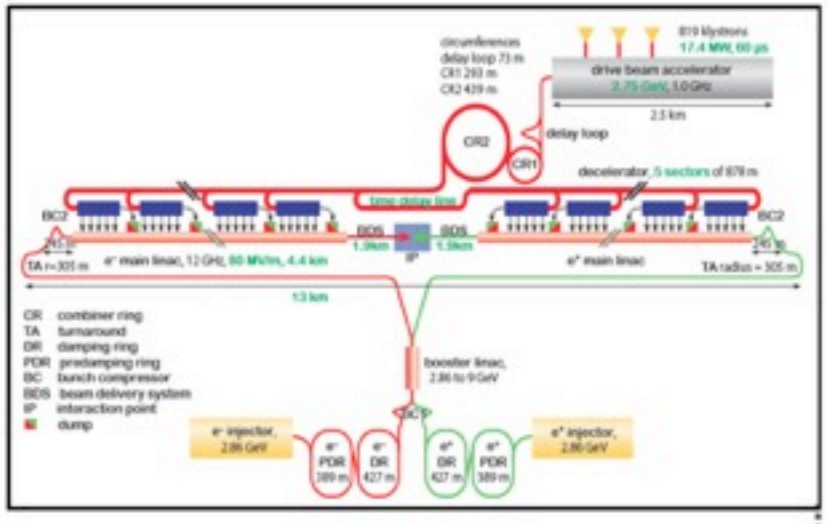

## 2022-23 Construction Start

Ready for full construction and main tunnel excavation.

## 2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

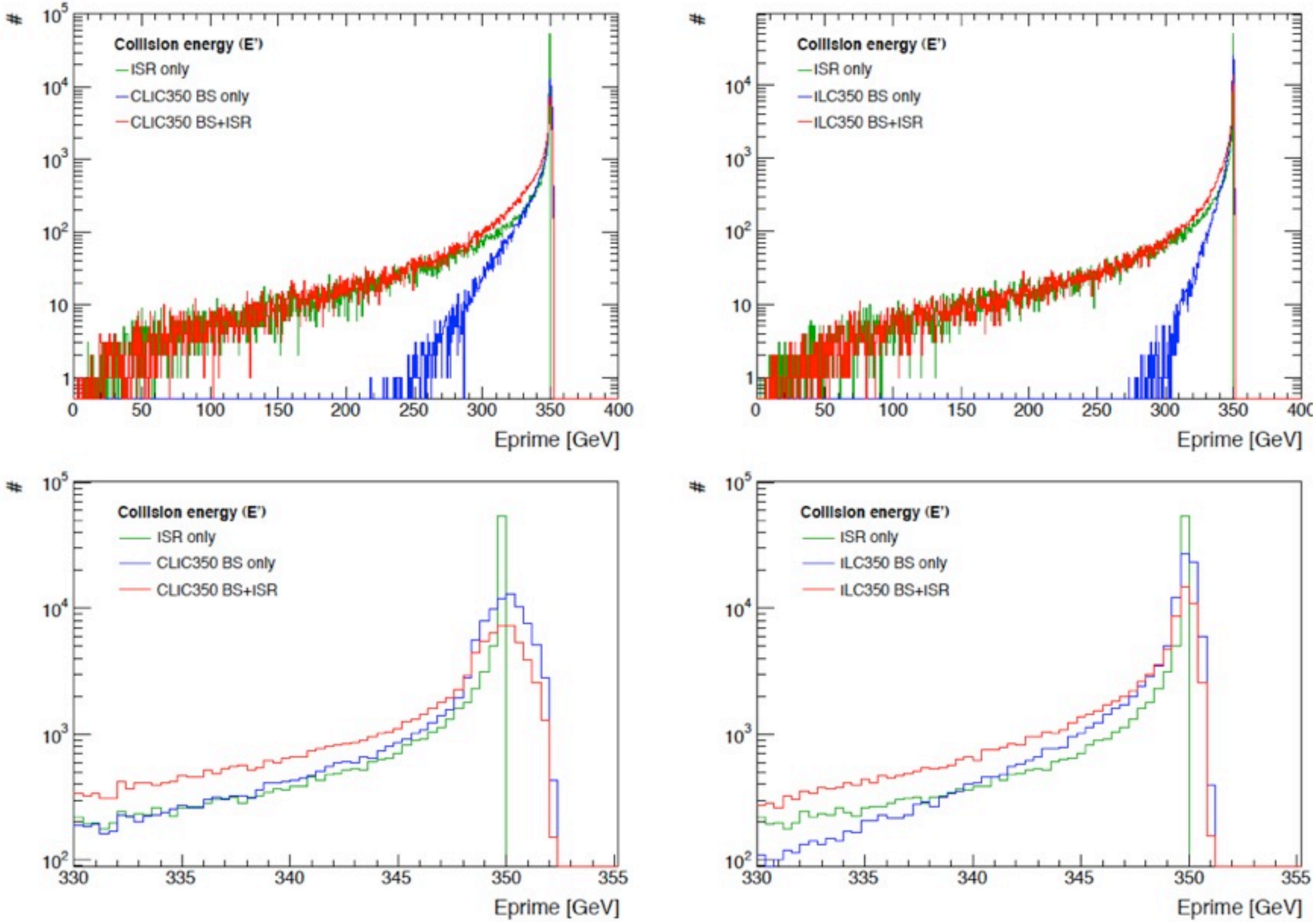
Preparation for implementation of further stages.



## 2030 Commissioning

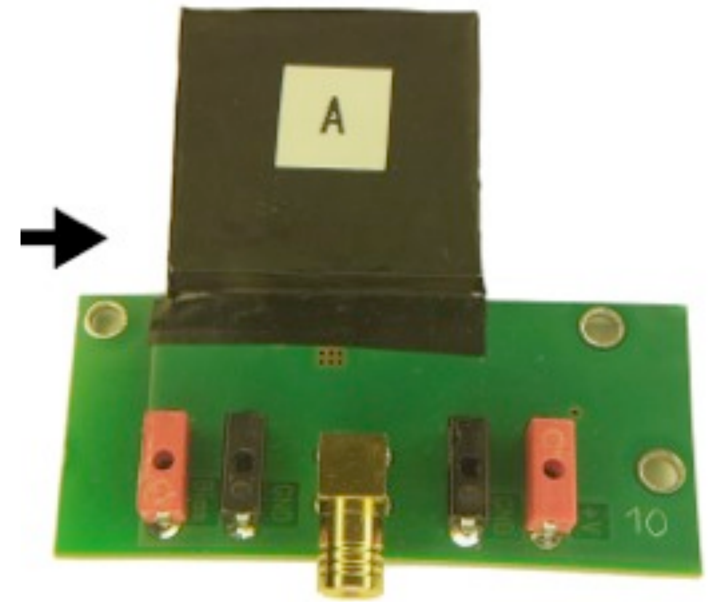
From 2030, becoming ready for data-taking as the LHC programme reaches completion.

# Luminosity Spectrum



# T3B Readout

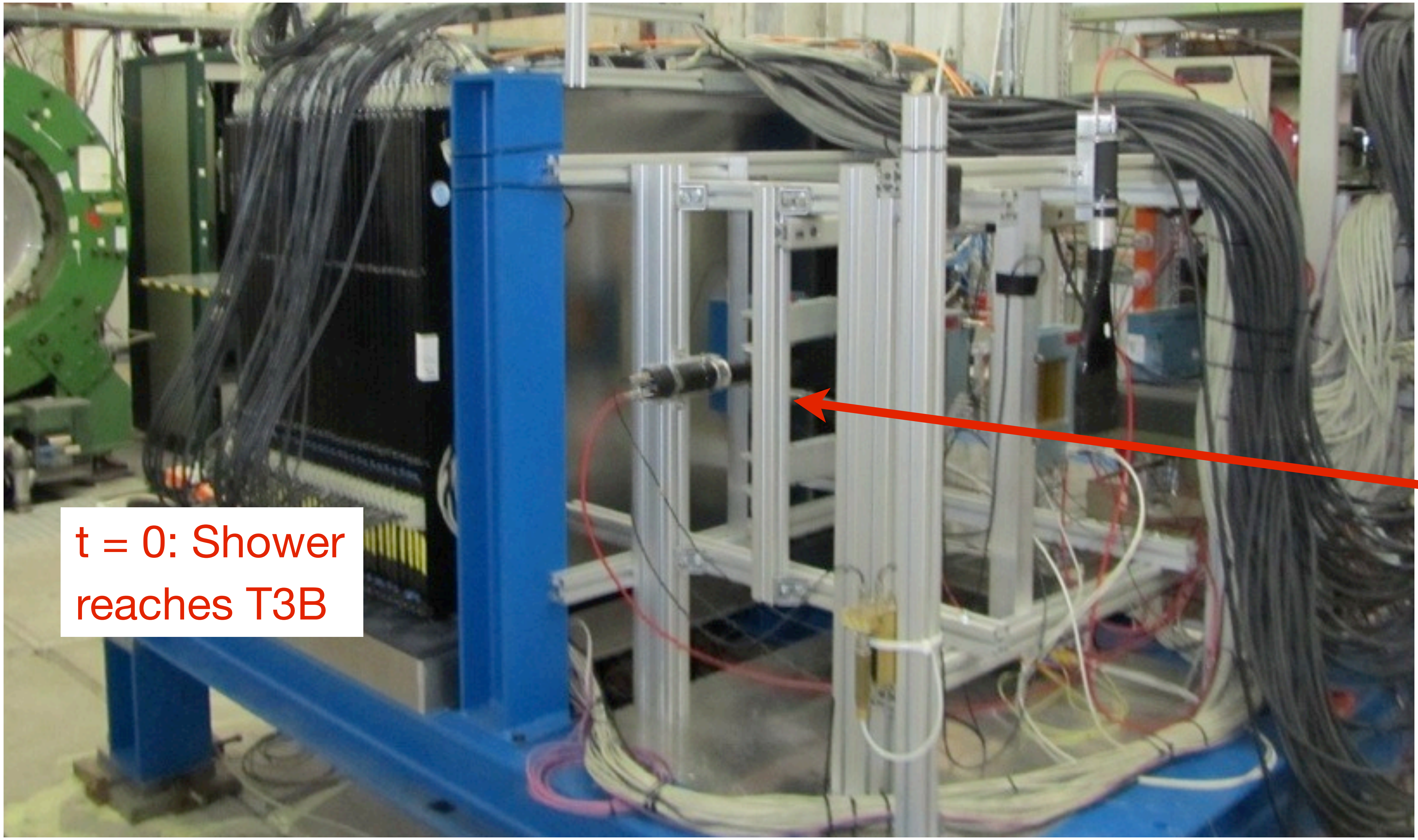
- SiPM mounted to high band-width preamplifier (x8.9 amplification)





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

# The Life of a Pion in the WAHCAL

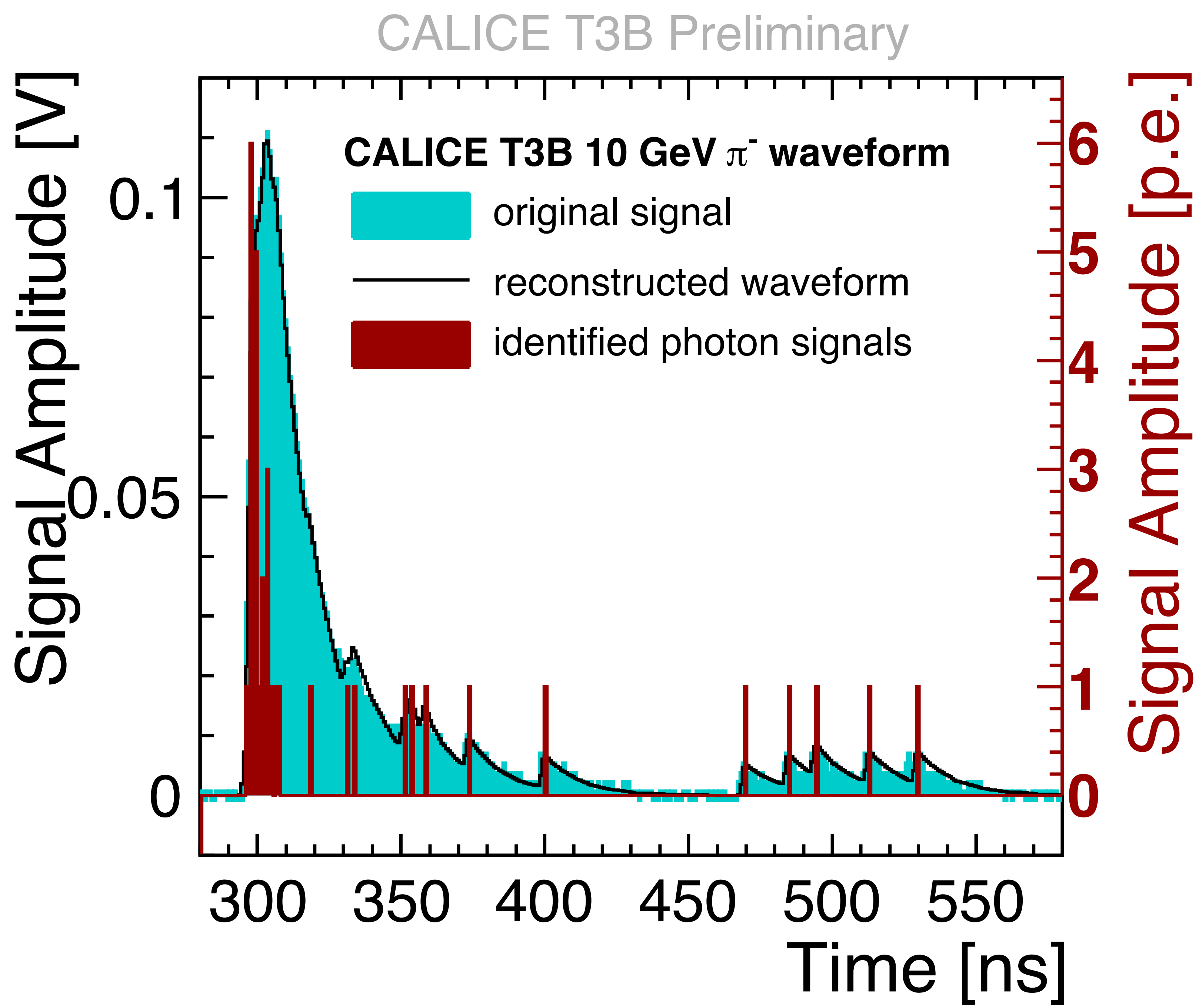



60 GeV pion

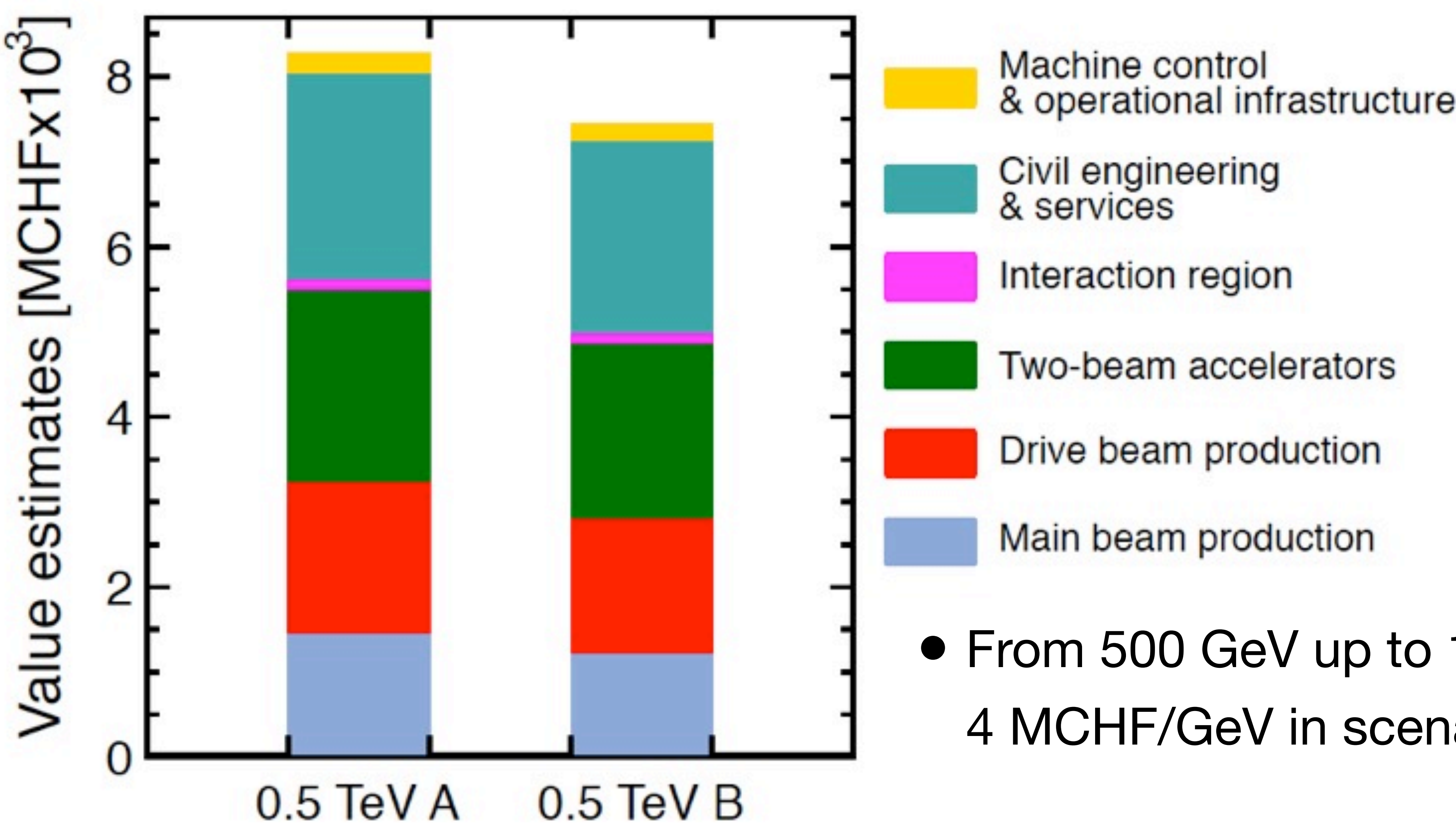
• `

# Data Reconstruction

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



# Cost




- From 500 GeV up to 1.5 TeV: 4 MCHF/GeV in scenario B

- NB: Substantial initial cost for components used at all energies, from the start planned for up to 3 TeV final energy

# Power

Table 5.1: Nominal power and efficiency for staging scenarios A and B, where $W_{main\ beam}$ is for the two main beams.

| Staging scenario | $\sqrt{s}$ (TeV) | $\mathscr{L}_{1\%}$ ($cm^{-2}s^{-1}$) | $W_{main\ beam}$ (MW) | $P_{electric}$ (MW) | Efficiency (%) |
|---|---|---|---|---|---|
| A | 0.5 | $1.4 \cdot 10^{34}$ | 9.6 | 272 | 3.6 |
| | 1.4 | $1.3 \cdot 10^{34}$ | 12.9 | 364 | 3.6 |
| | 3.0 | $2.0 \cdot 10^{34}$ | 27.7 | 589 | 4.7 |
| B | 0.5 | $7.0 \cdot 10^{33}$ | 4.6 | 235 | 2.0 |
| | 1.5 | $1.4 \cdot 10^{34}$ | 13.9 | 364 | 3.8 |
| | 3.0 | $2.0 \cdot 10^{34}$ | 27.7 | 589 | 4.7 |

Table 5.2: Residual power without beams for staging scenarios A and B.

| Staging scenario | $\sqrt{s}$ (TeV) | $P_{waiting\ for\ beam}$ (MW) | $P_{shutdown}$ (MW) |
|---|---|---|---|
| A | 0.5 | 168 | 37 |
| | 1.4 | 190 | 42 |
| | 3.0 | 268 | 58 |
| B | 0.5 | 167 | 35 |
| | 1.5 | 190 | 42 |
| | 3.0 | 268 | 58 |