Imaging Analog Hadron Calorimetry with Scintillators and SiPMs

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Max-Planck-Institut für Physik
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Why do we care?

- Hadronic calorimeters are mainly used to measure jets: The final product of quarks and gluons created in elementary particle reactions

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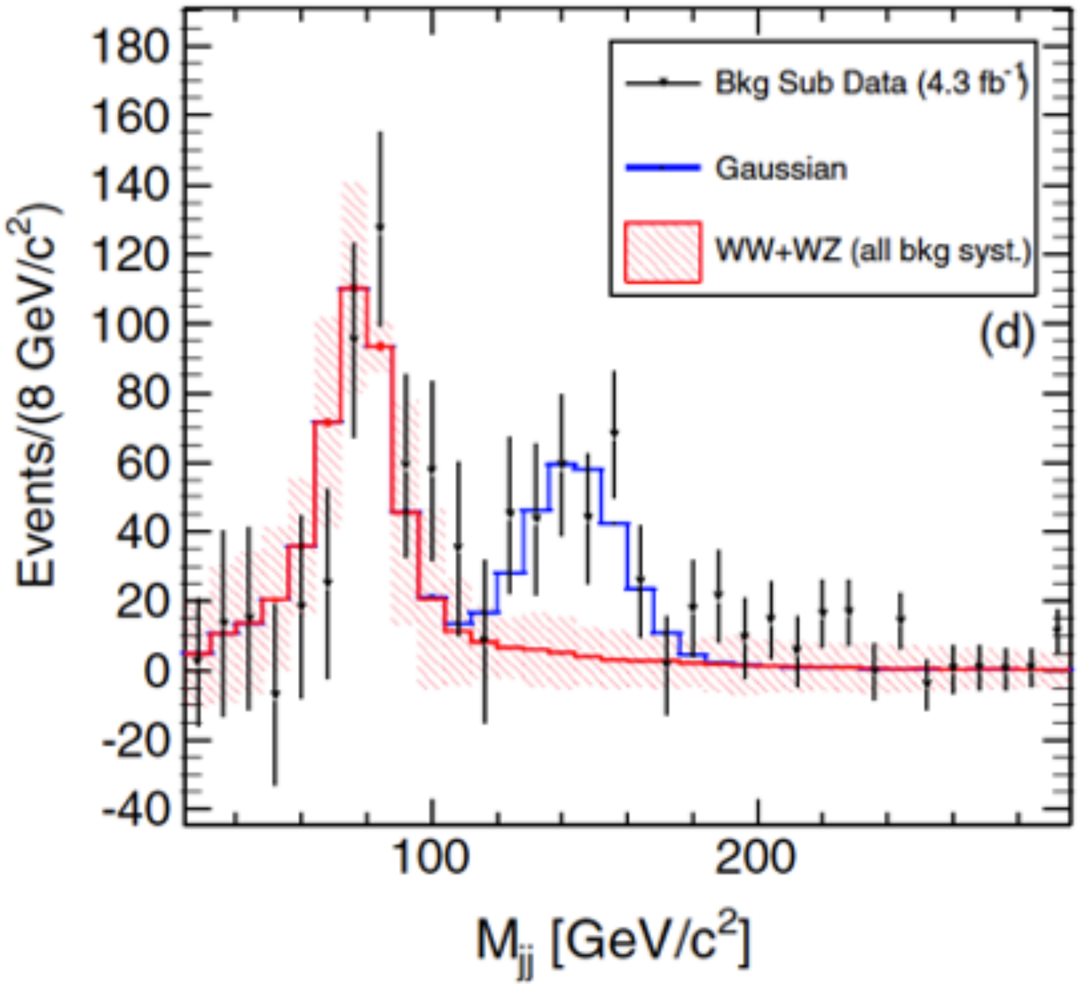

CDF, Phys. Rev. Lett. 106, 171801 (2011)

“Forscher rätseln über neue Naturkraft”

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http://www.spiegel.de/wissenschaft/natur/0,1518,755597,00.html

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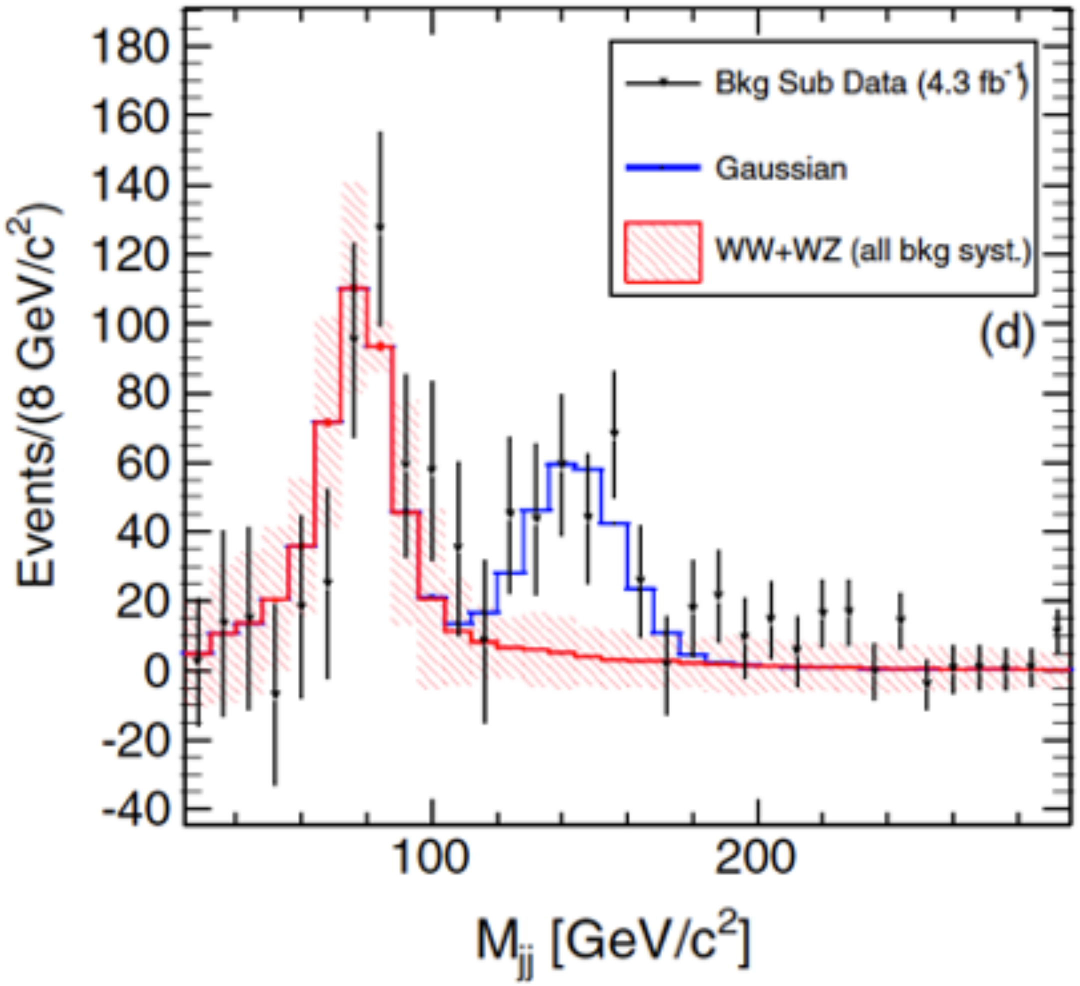

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... imagine you had a factor 2 to 3 better resolution: could make the difference between puzzling observations and hard answers!

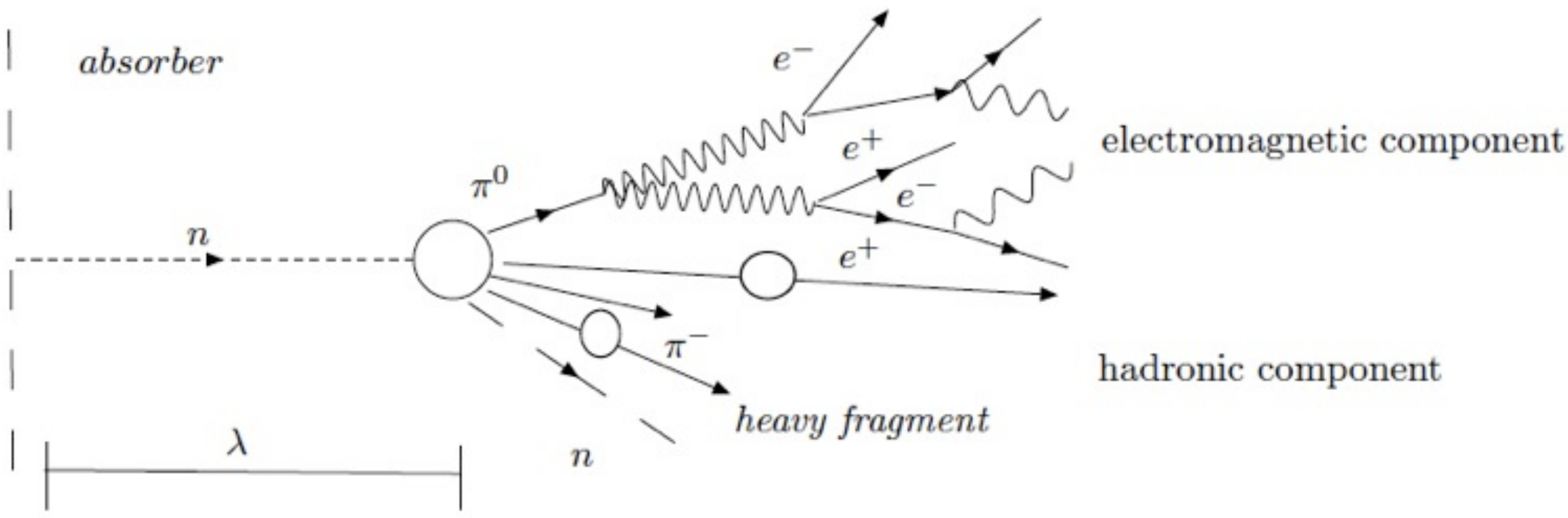
Hadronic Calorimetry in Particle Physics

- Calorimeters measure the energy of particles by total absorption

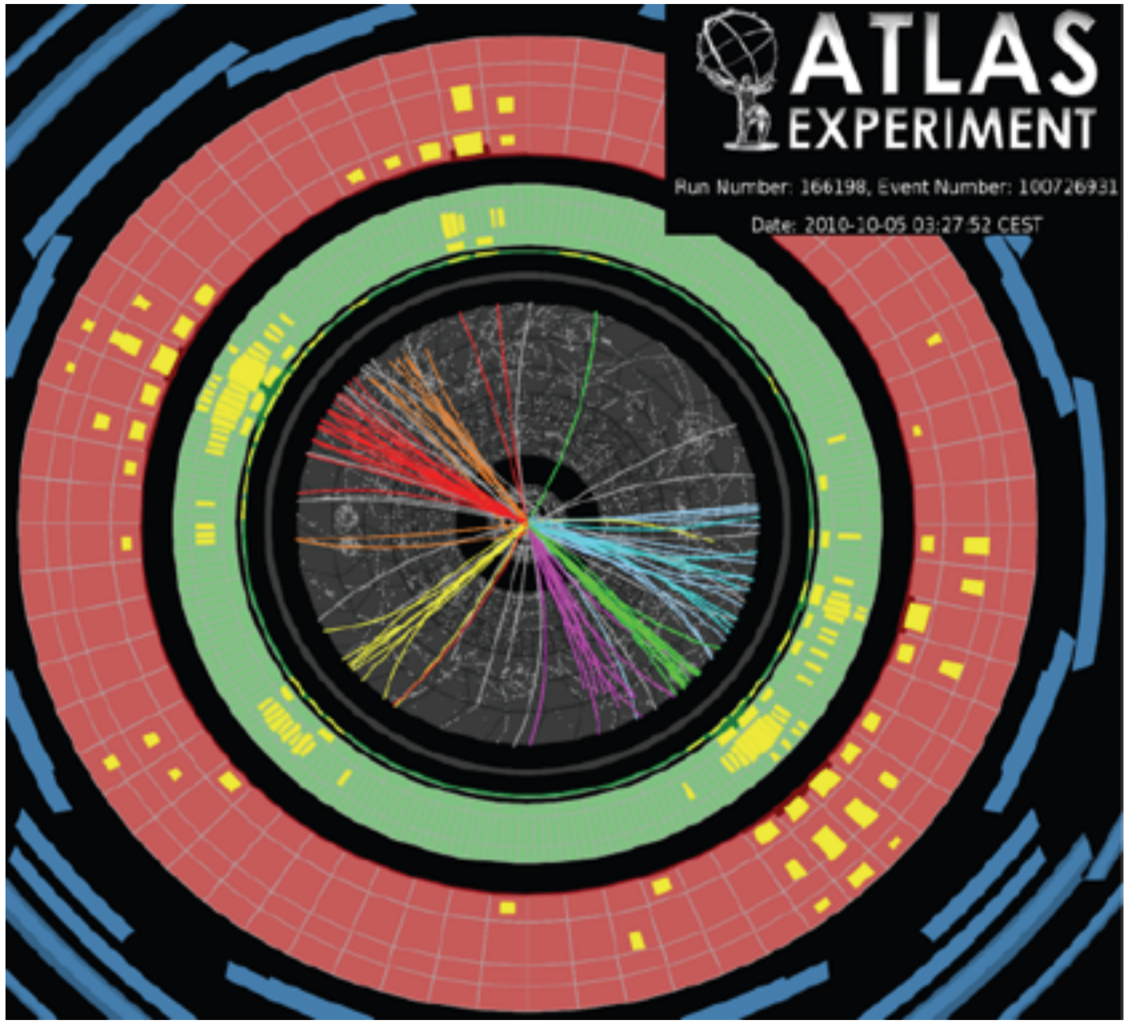
- Hadrons are challenging: Large volumes & dense materials needed
  - Characteristic length scale given by interaction length: typically ~ 100 g/cm^2:

‣ Hadron calorimeters are always sampling calorimeters:
Alternating layers of dense absorbers and active elements

- Hadronic showers have a rich structure: Needs a versatile detection medium



Present Hadron Calorimeters ... And Dreams



- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT)
  O(10k) channels for full detectors

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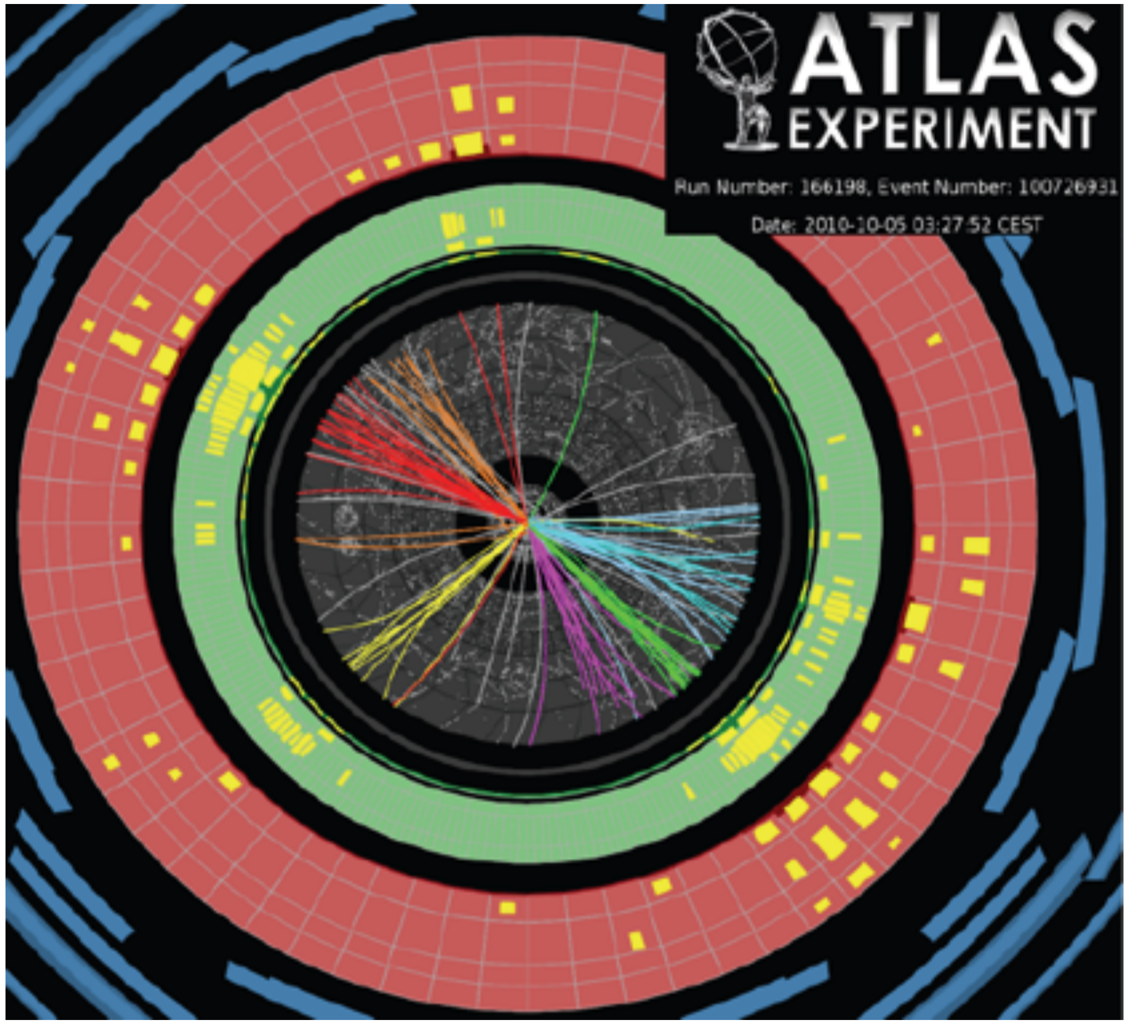

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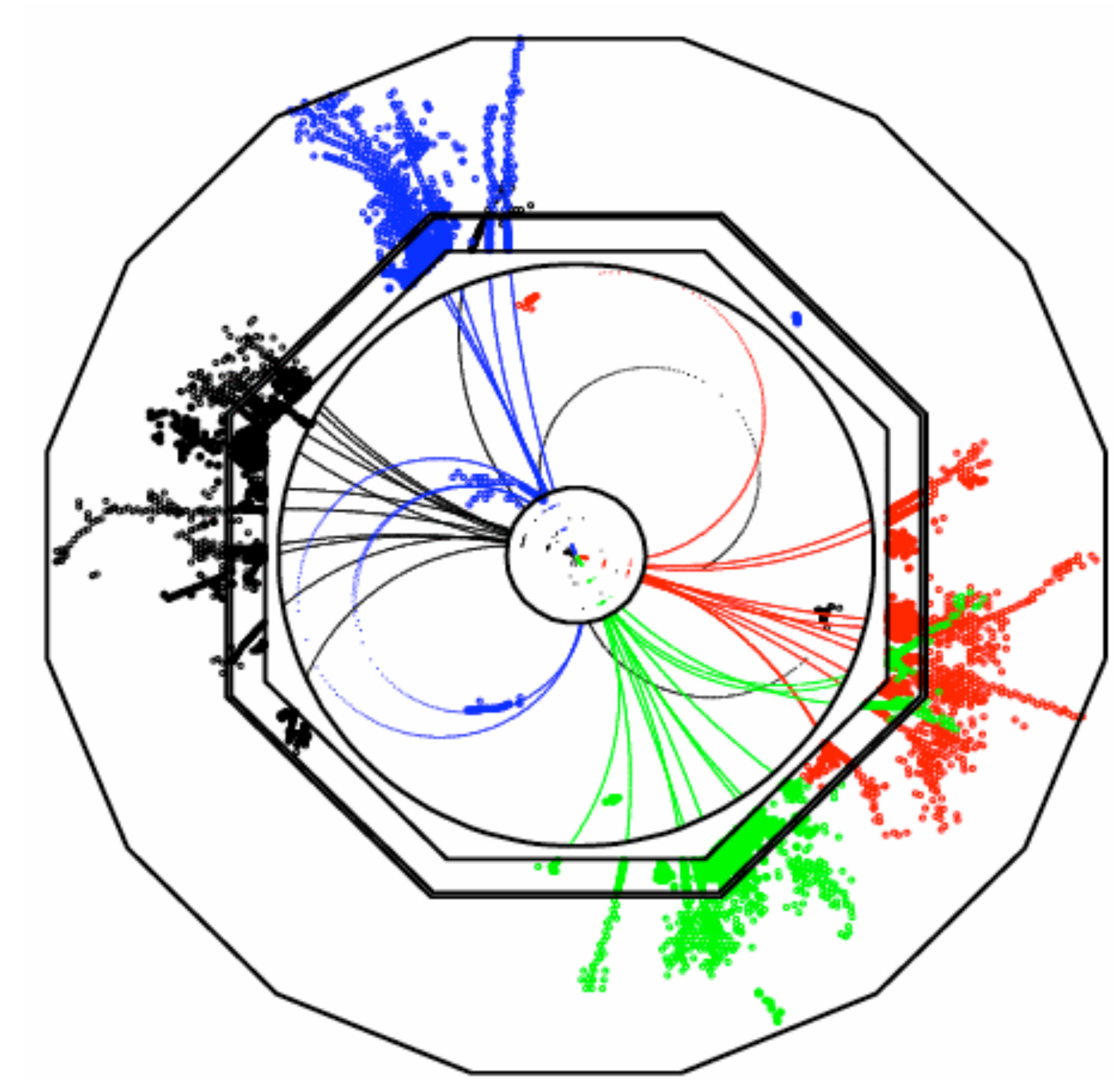

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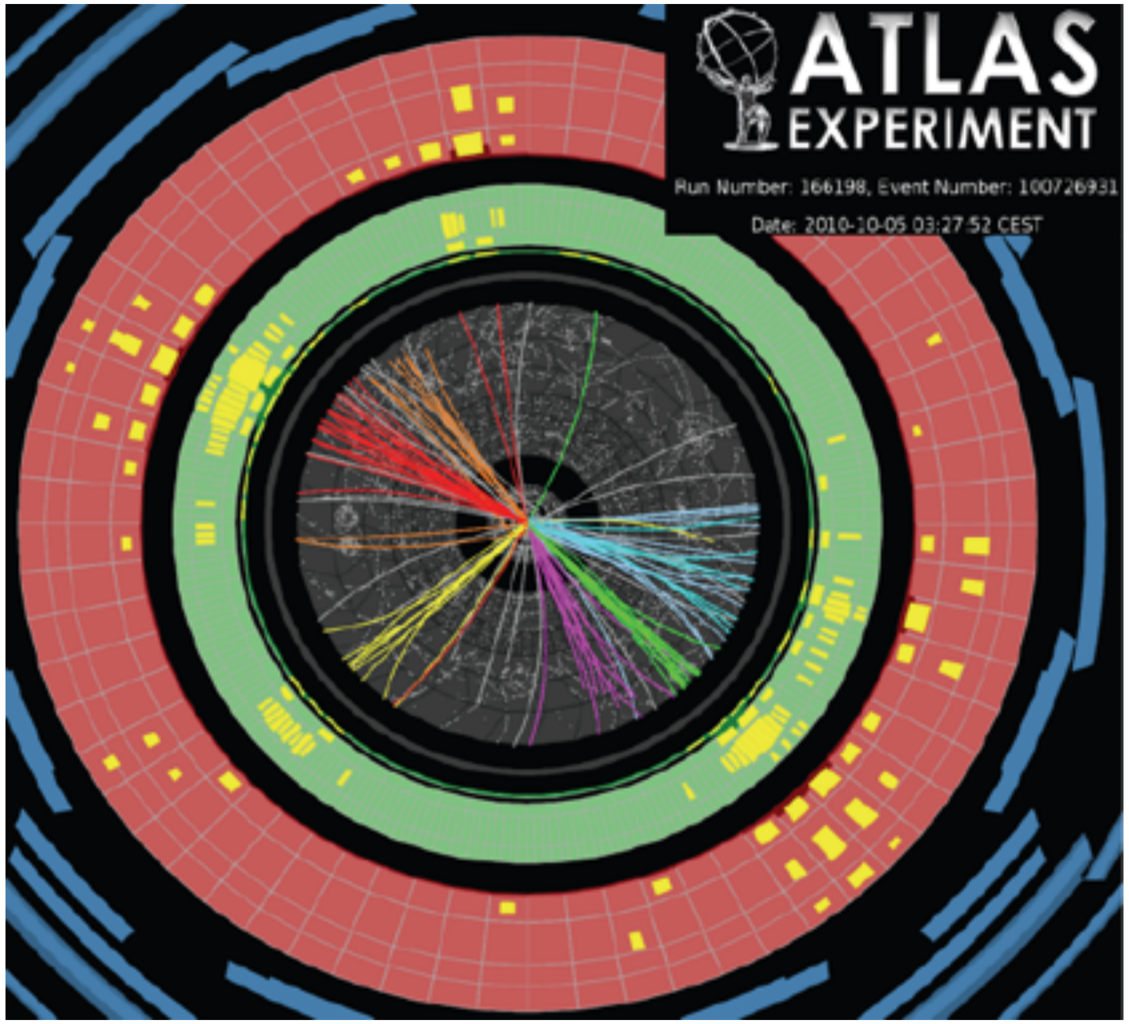

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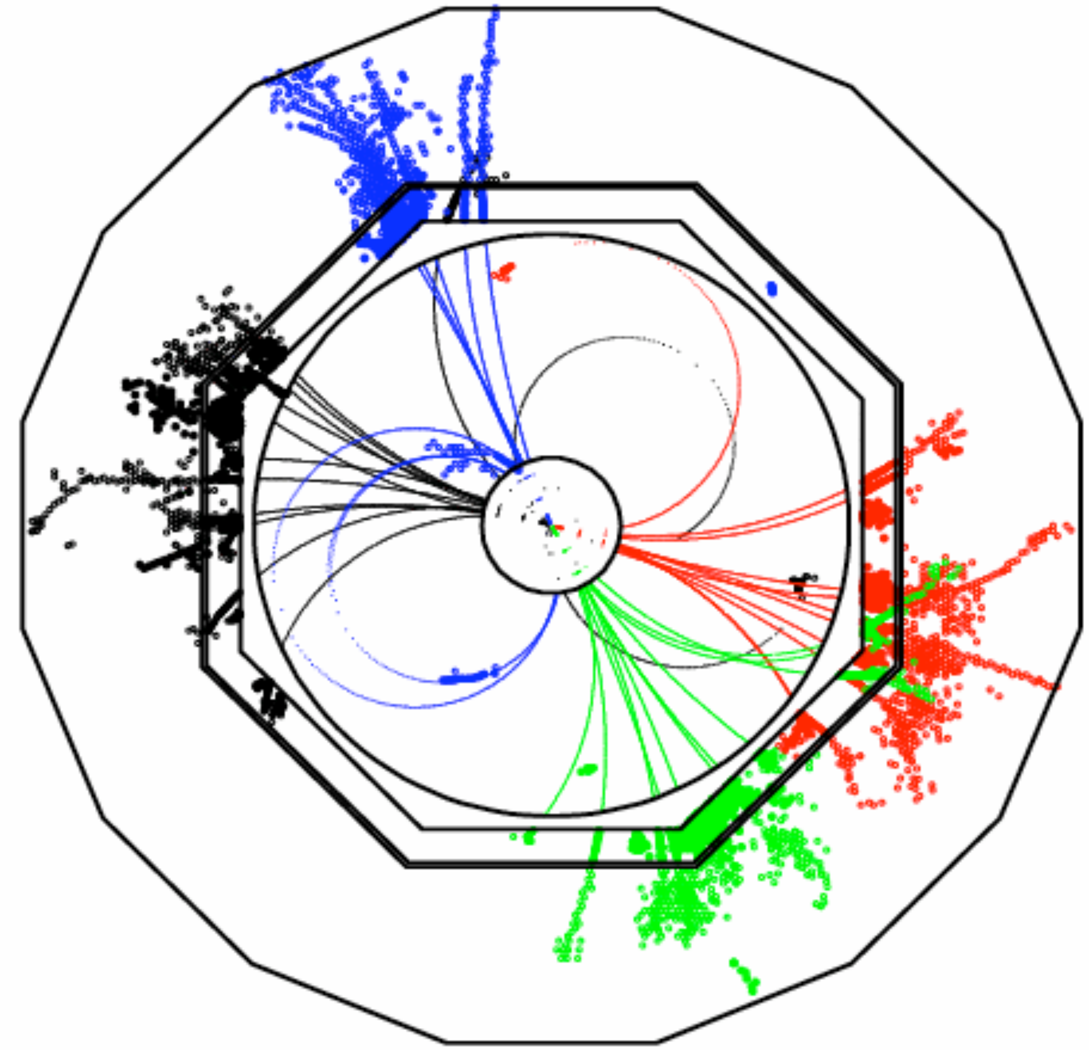

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With PFA, this provides the factor 2 to 3 improvement we are looking for!

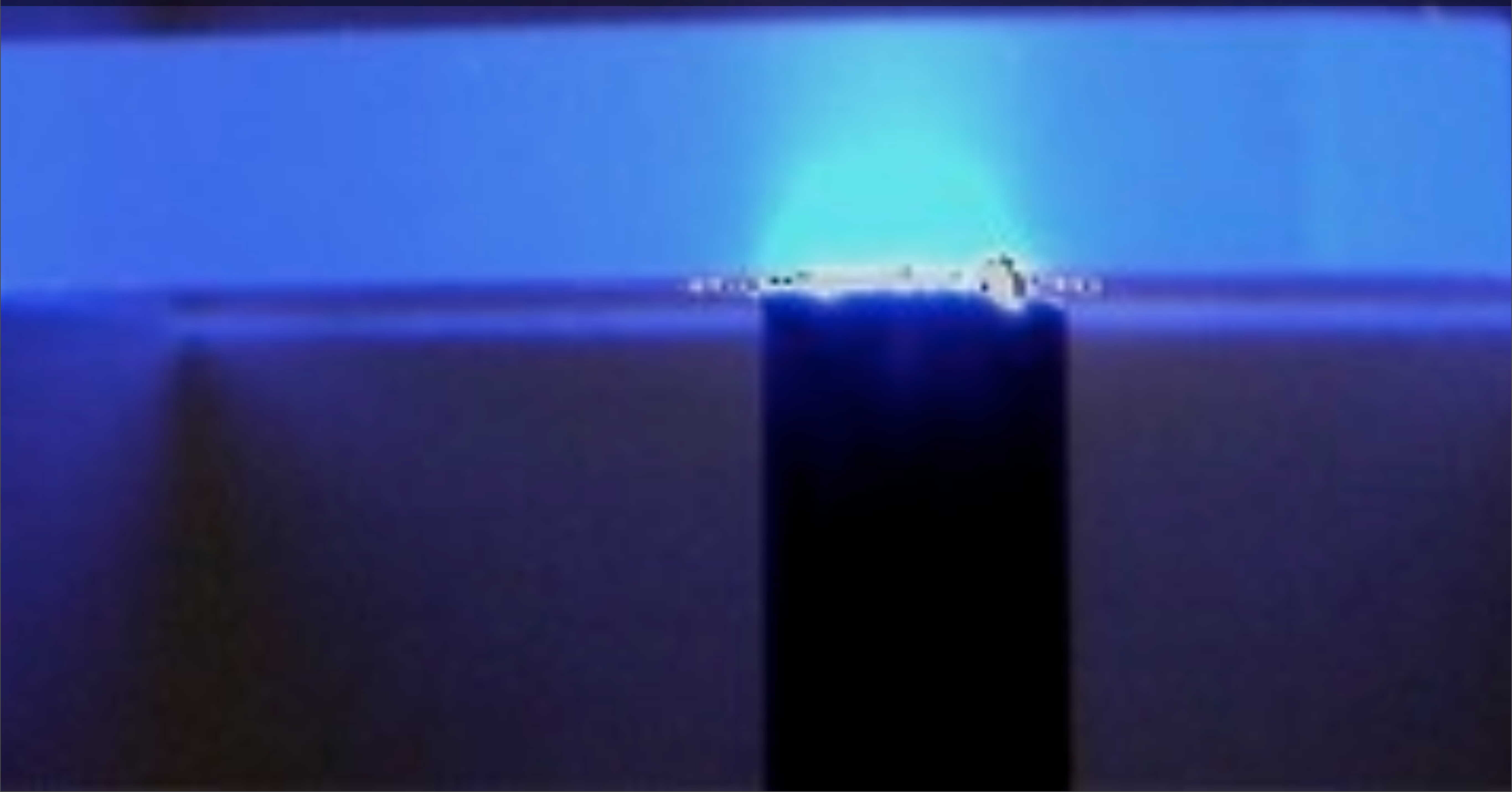
Overview

- The first Imaging Calorimeter: The CALICE analog HCAL
  - Making it possible: Scintillator cells with SiPM readout
  - Performance & Results

- Under the Hood
  - Calibration techniques
  - New ideas for scintillator tiles with SiPMs

- Pushing further: The 4th Dimension
  - The T3B Experiment: First glimpse at the time structure of showers

The First Imaging Calorimeter



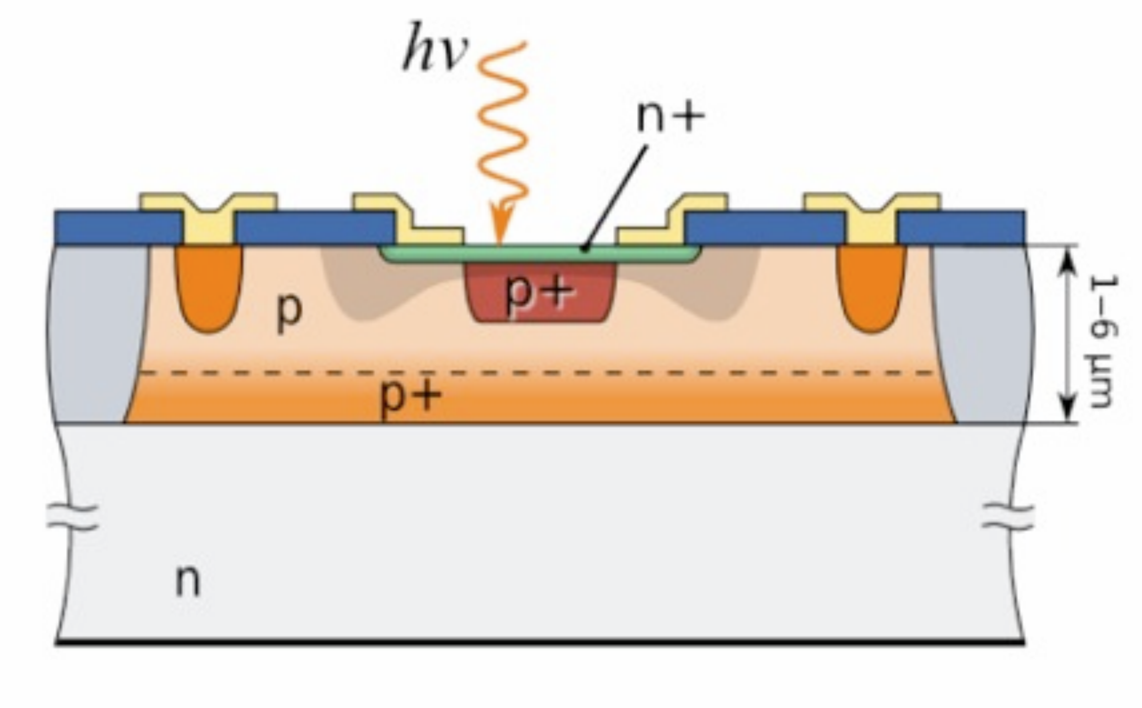
Photodetectors for Imaging Calorimeters

- Bringing the light from many small cells out of the detector is prohibitive: Fibers use up way too much space!

▸ Need a light detector directly on the scintillator cell

- Compact device with low power consumption
- Insensitive to magnetic fields (the calorimeter usually sits inside a multi-T field!)

The tool of choice: Silicon Photomultipliers



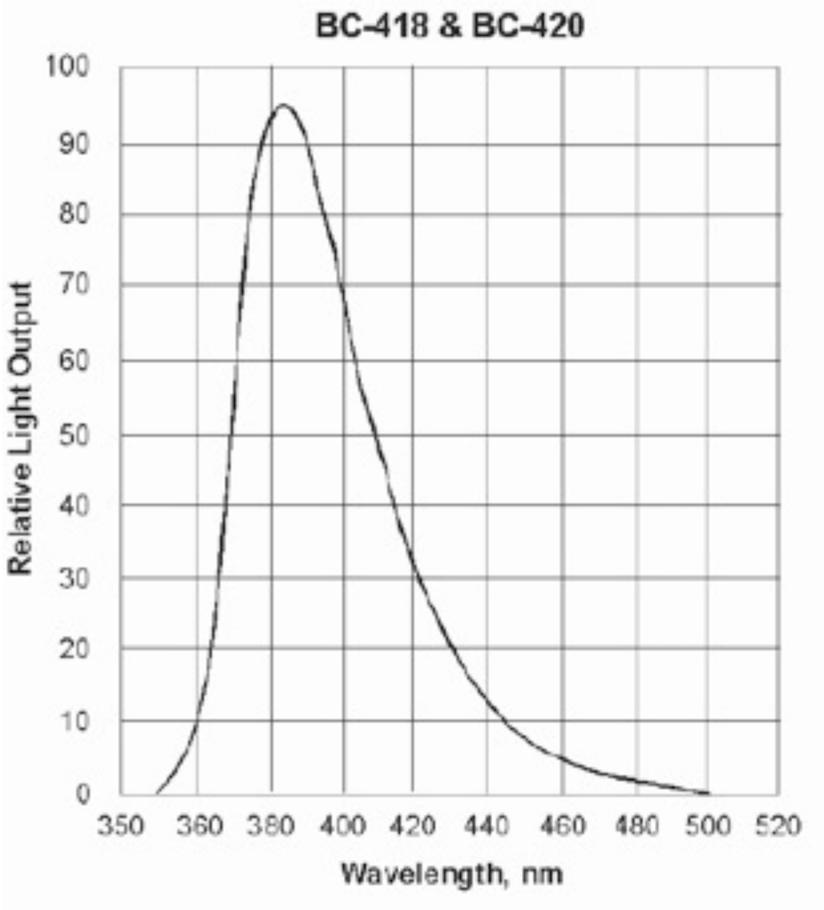
Array of small APDs operated in Geiger mode: Gain 10^5 - 10^6

All pixels combined into one signal line: Output proportional to number of fired pixels

Single photon detector capability

Combining SiPMs with Plastic

- Active medium of choice: Plastic scintillator
  - Cheap, easy to machine, sensitive to charged particles and neutrons, ...



Typical emission spectrum of plastic scintillator:

Maximum in the violet / blue spectral region 400 nm - 450 nm

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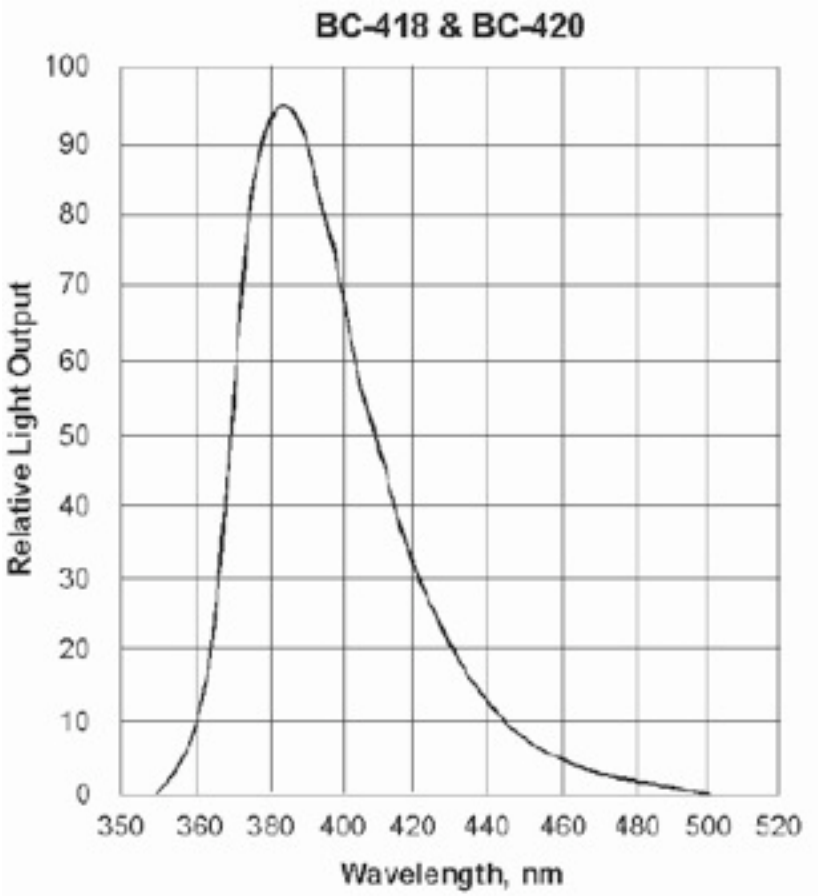

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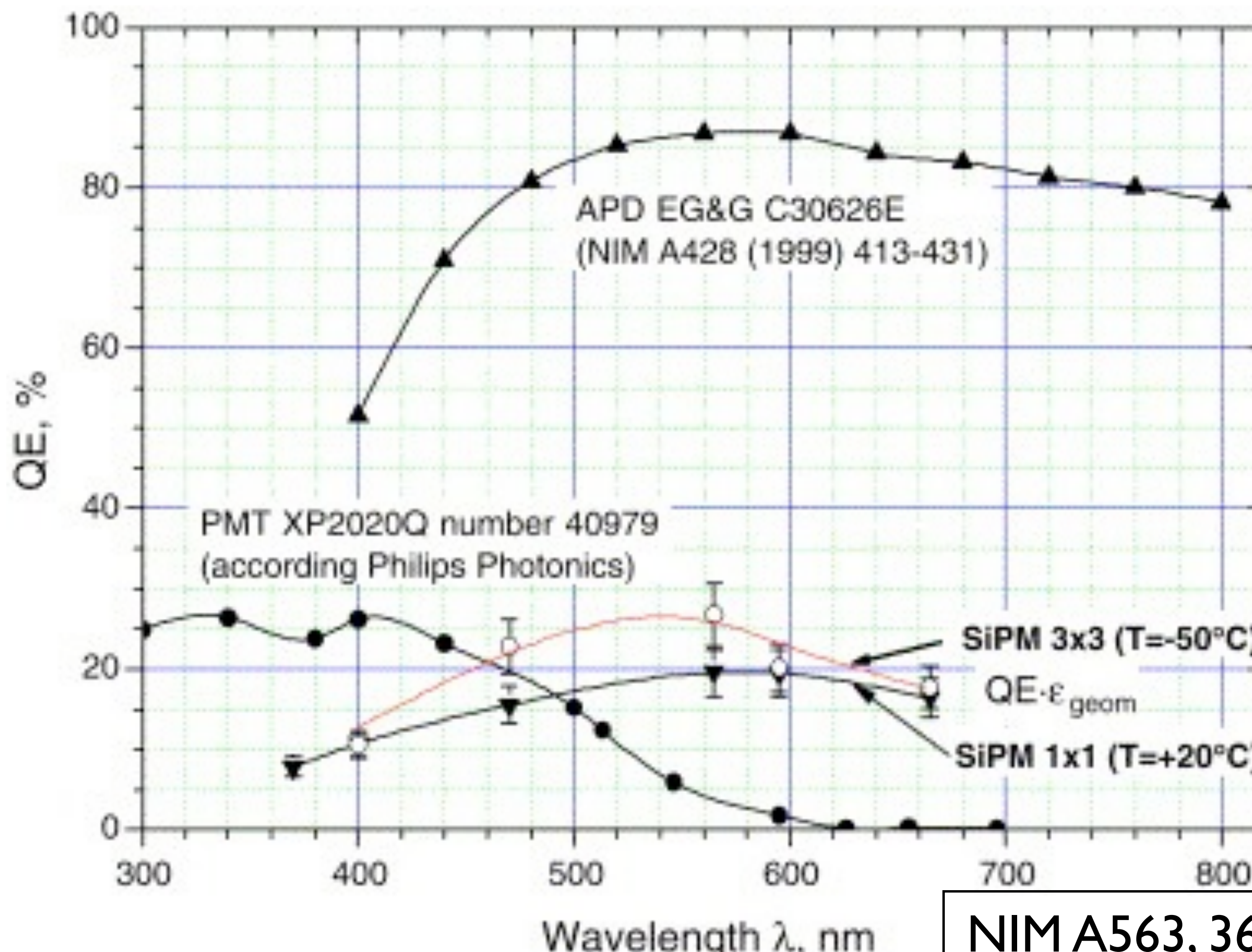
First generation SiPMs:
Sensitivity maximum
~ 550 nm (green)



NIM A563, 368 (2006)

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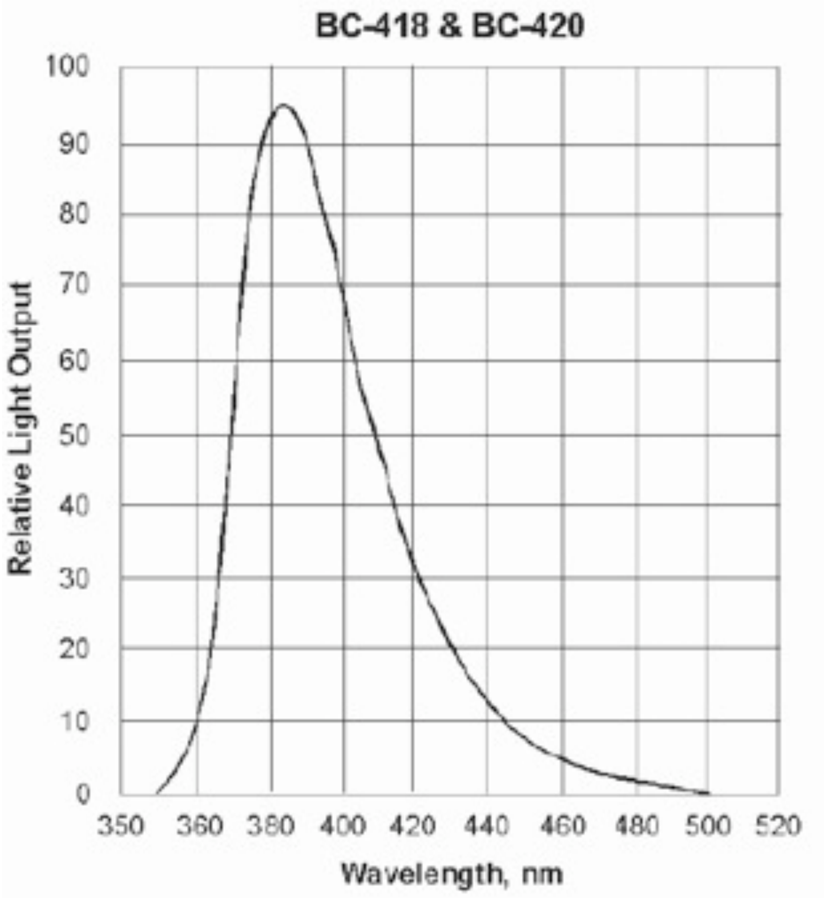

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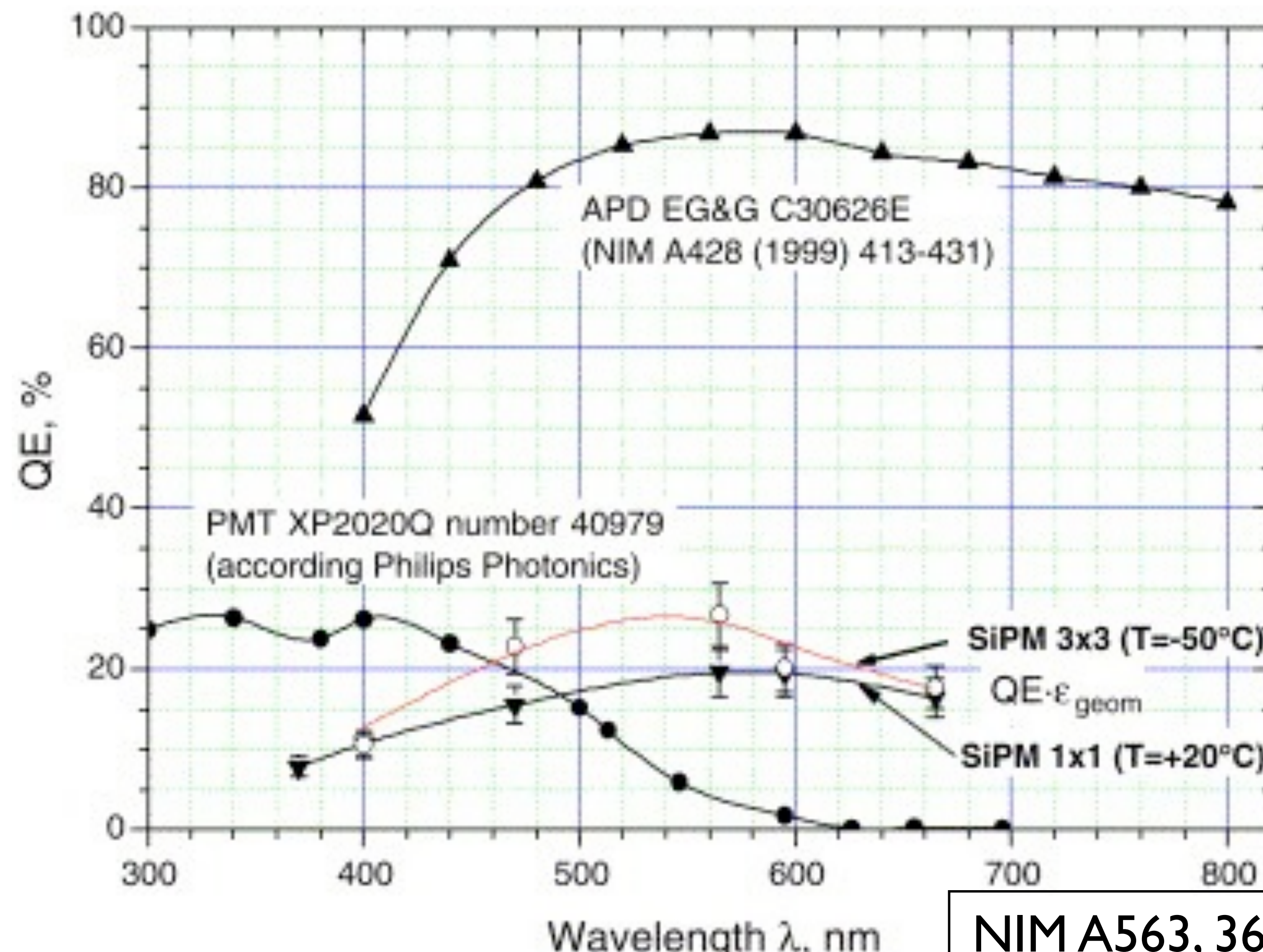

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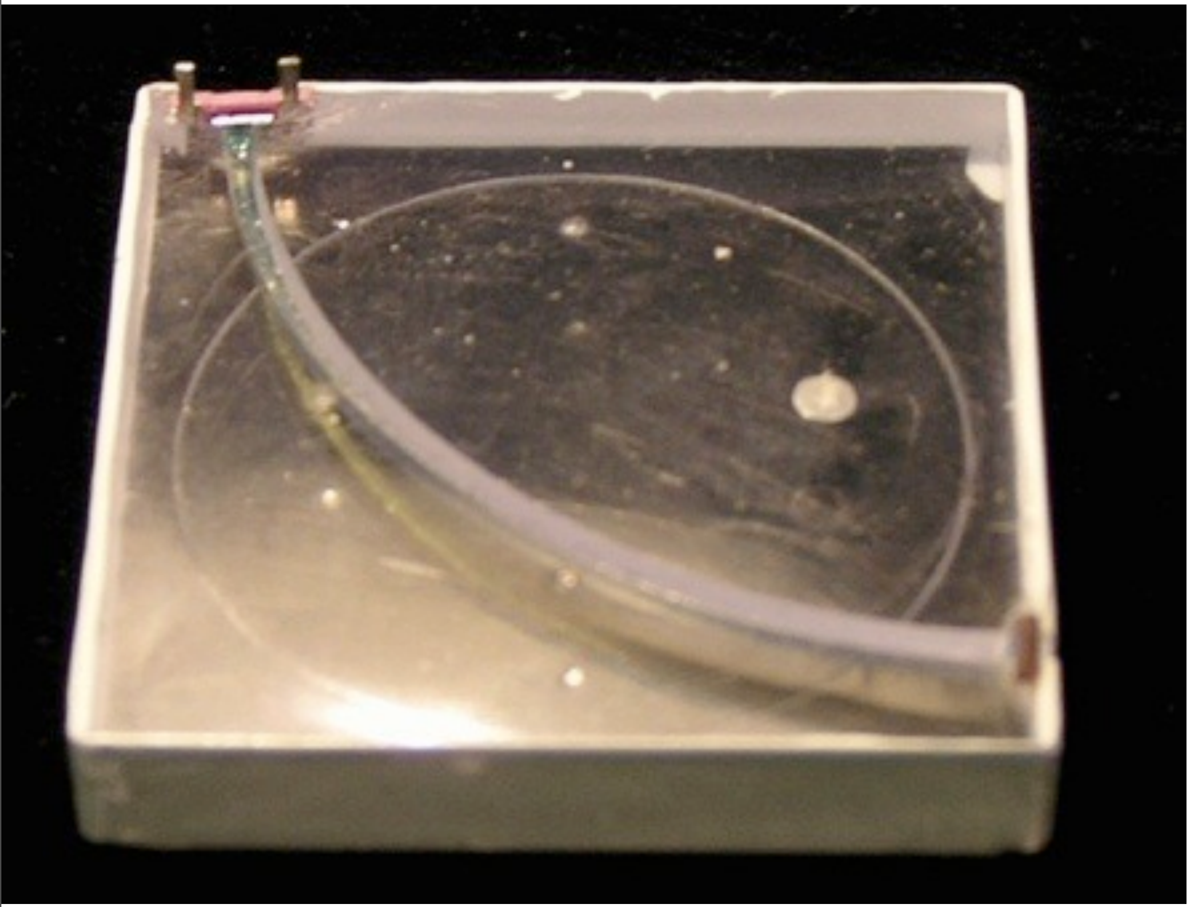
➩ Wavelength-shifter needed!

Adding Scintillators



- Plastic scintillator tile, with a wavelength shifting fiber in a machined grove
  5 mm thick, 3 x 3 cm^2
- Photon detector (Silicon Photomultiplier) coupled to the WLS fiber

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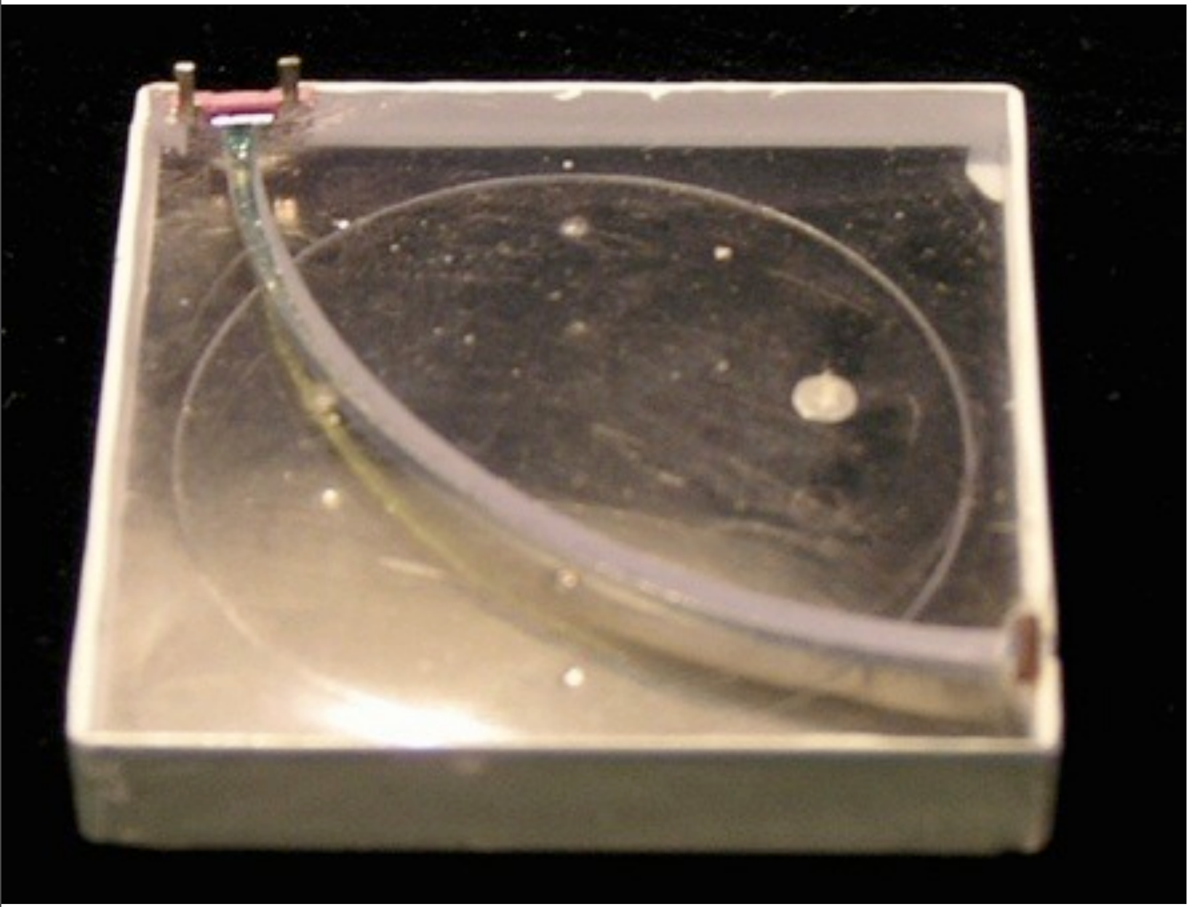

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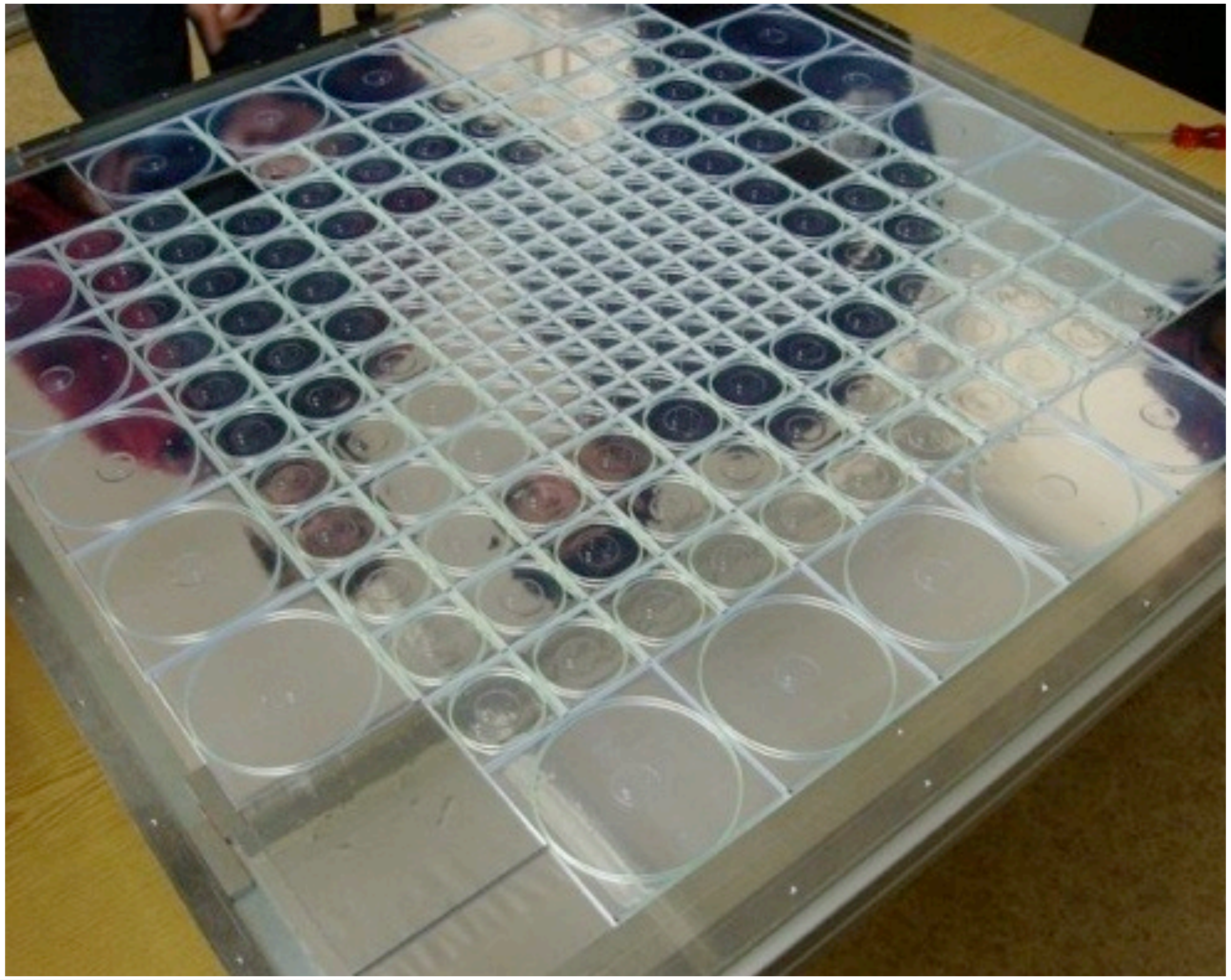
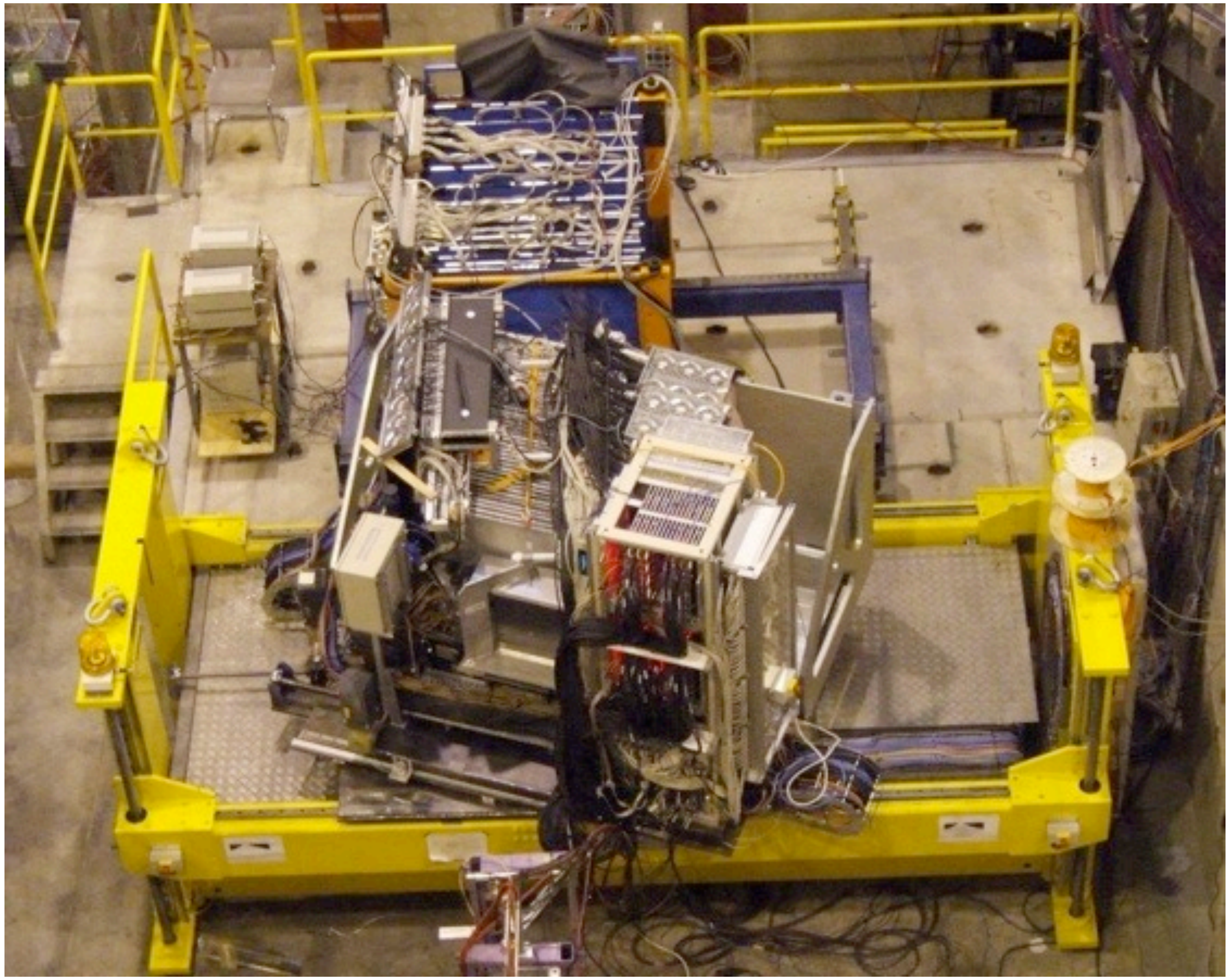


- ~ 200 cells (larger size on the outside for cost reason) make up one 1 m^2 layer

Turning it into a Calorimeter

- Put active elements between passive absorbers
  ~ 20 mm steel in total per layer
  38 layers total: 7602 channels
- Add readout electronics, data acquisition, calibration system ...



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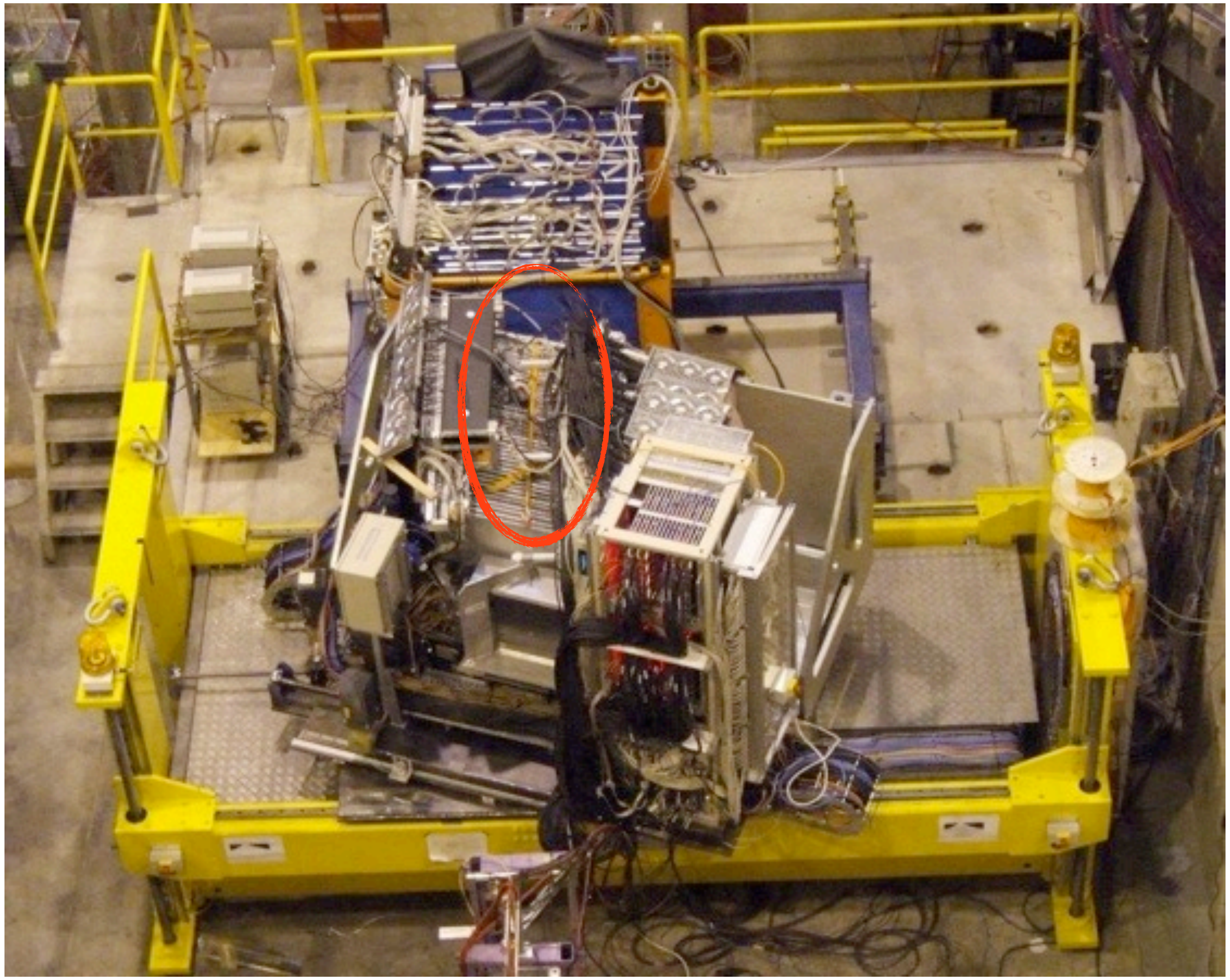

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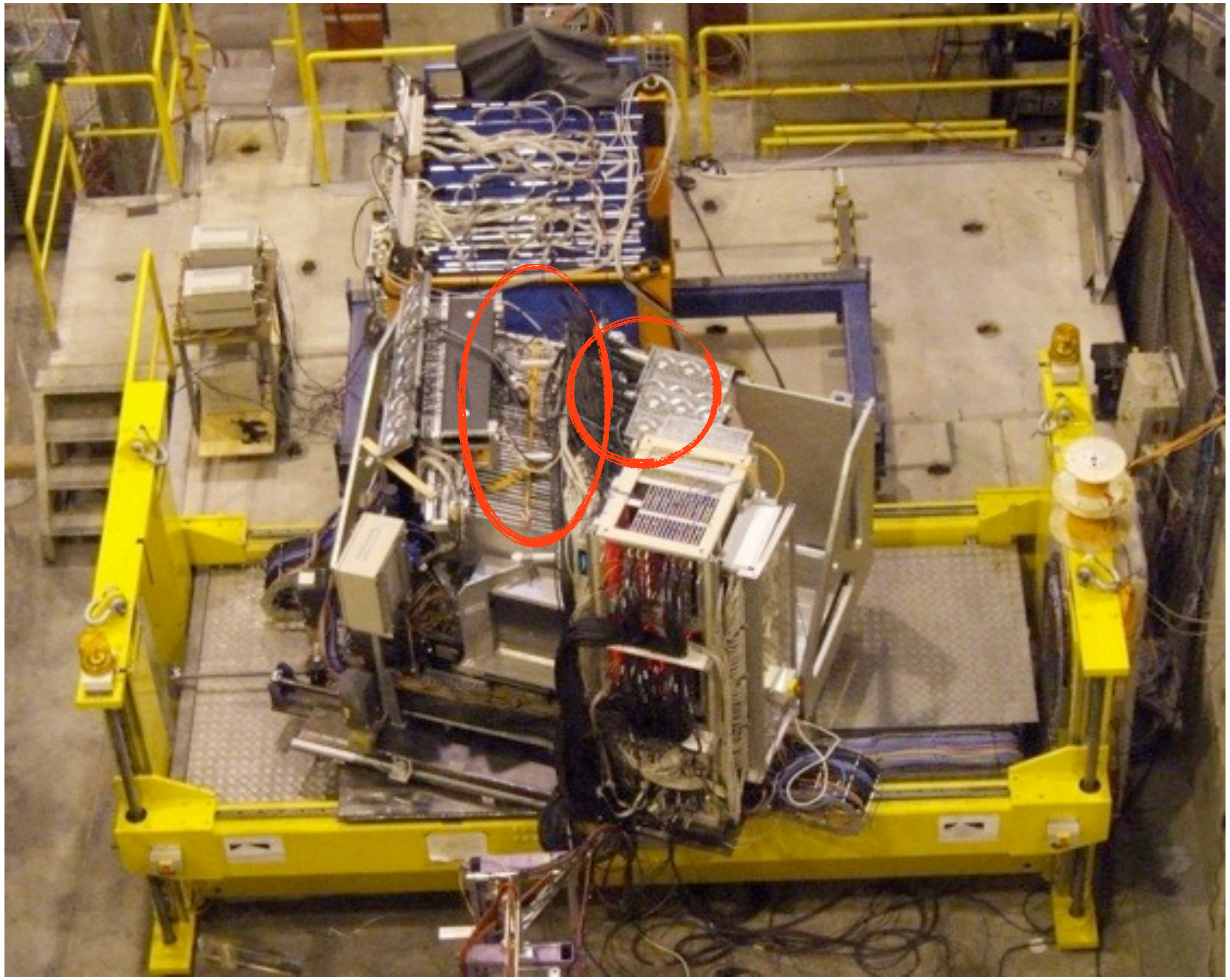

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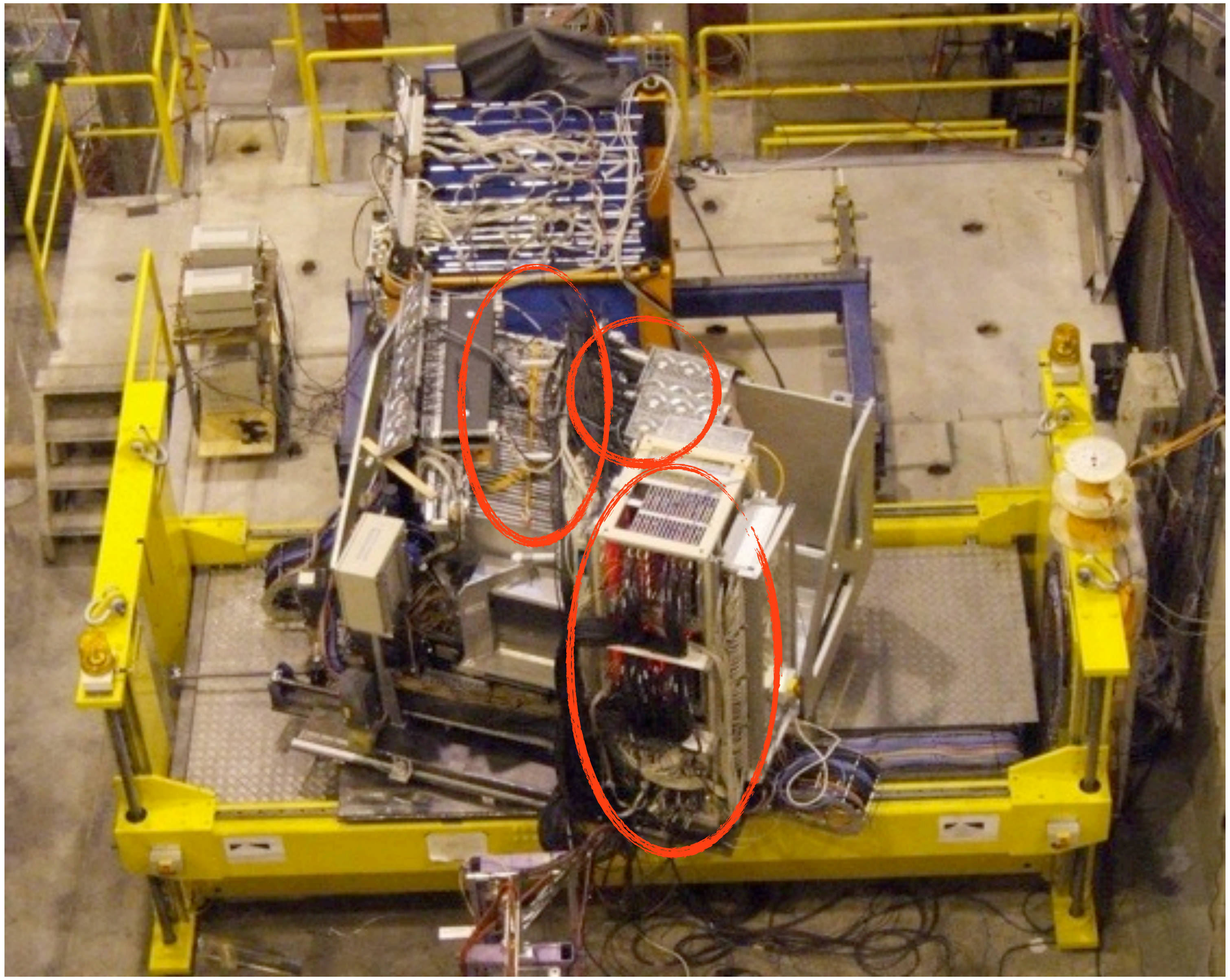

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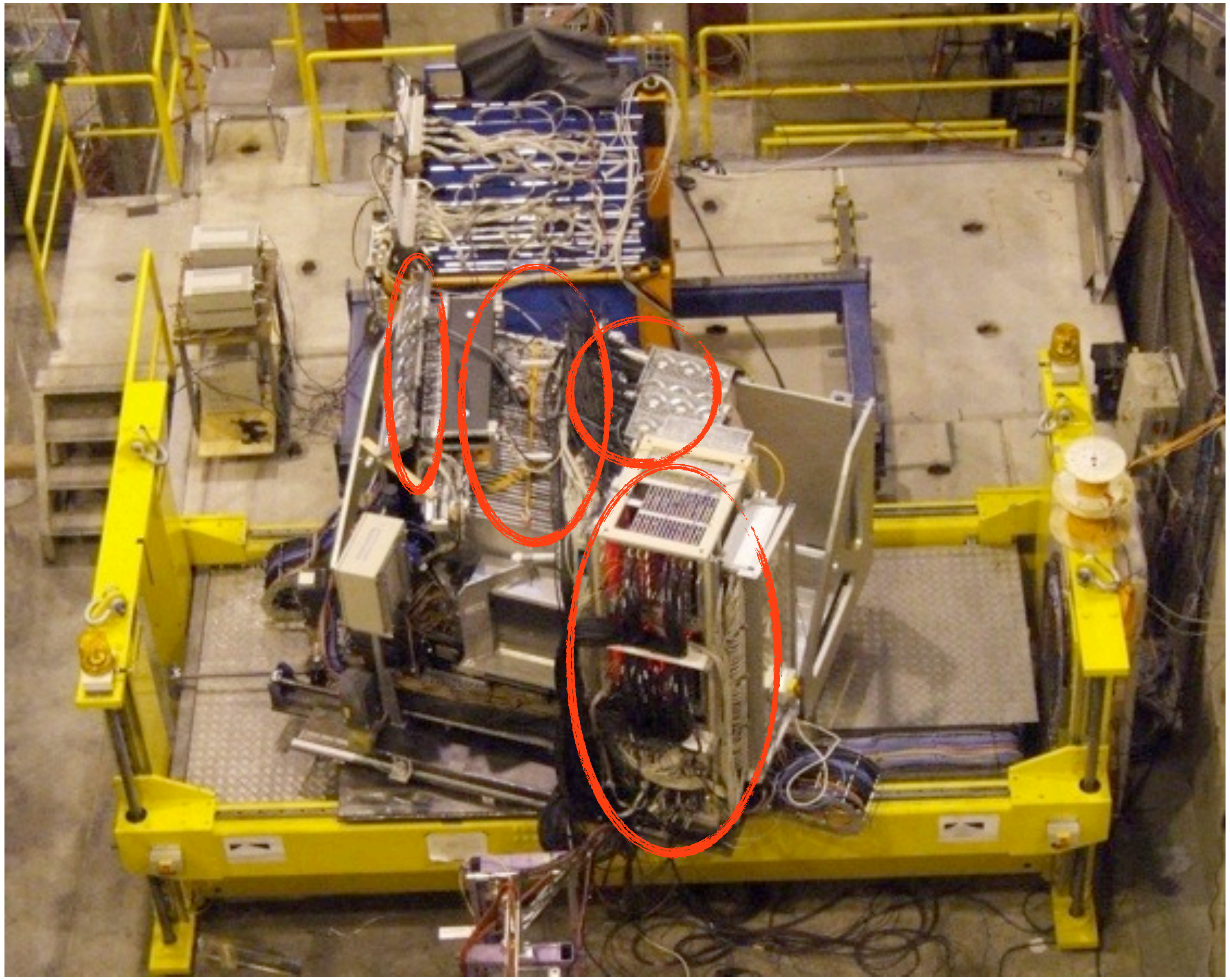

absorbers with active layers

front-end electronics

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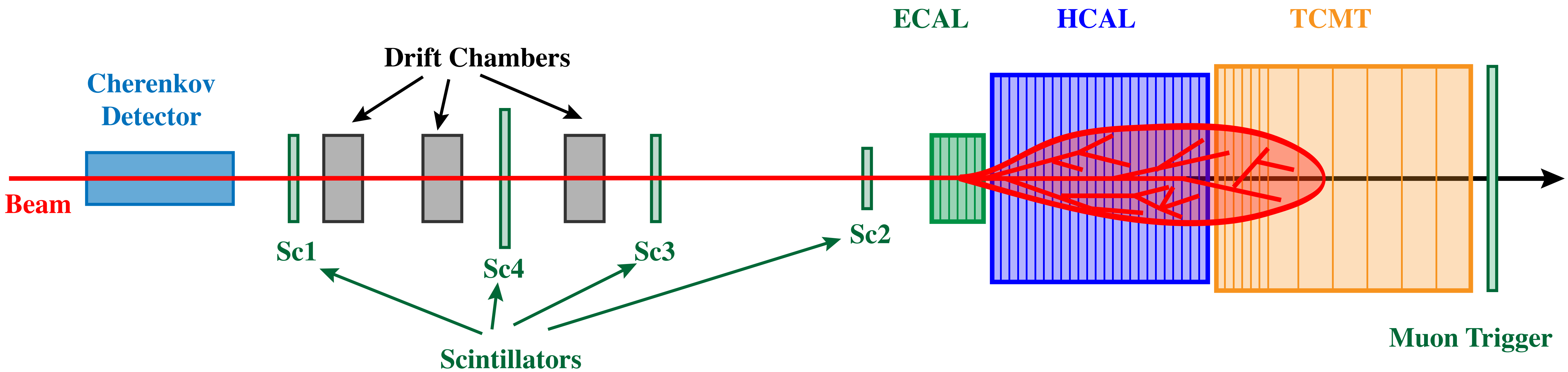
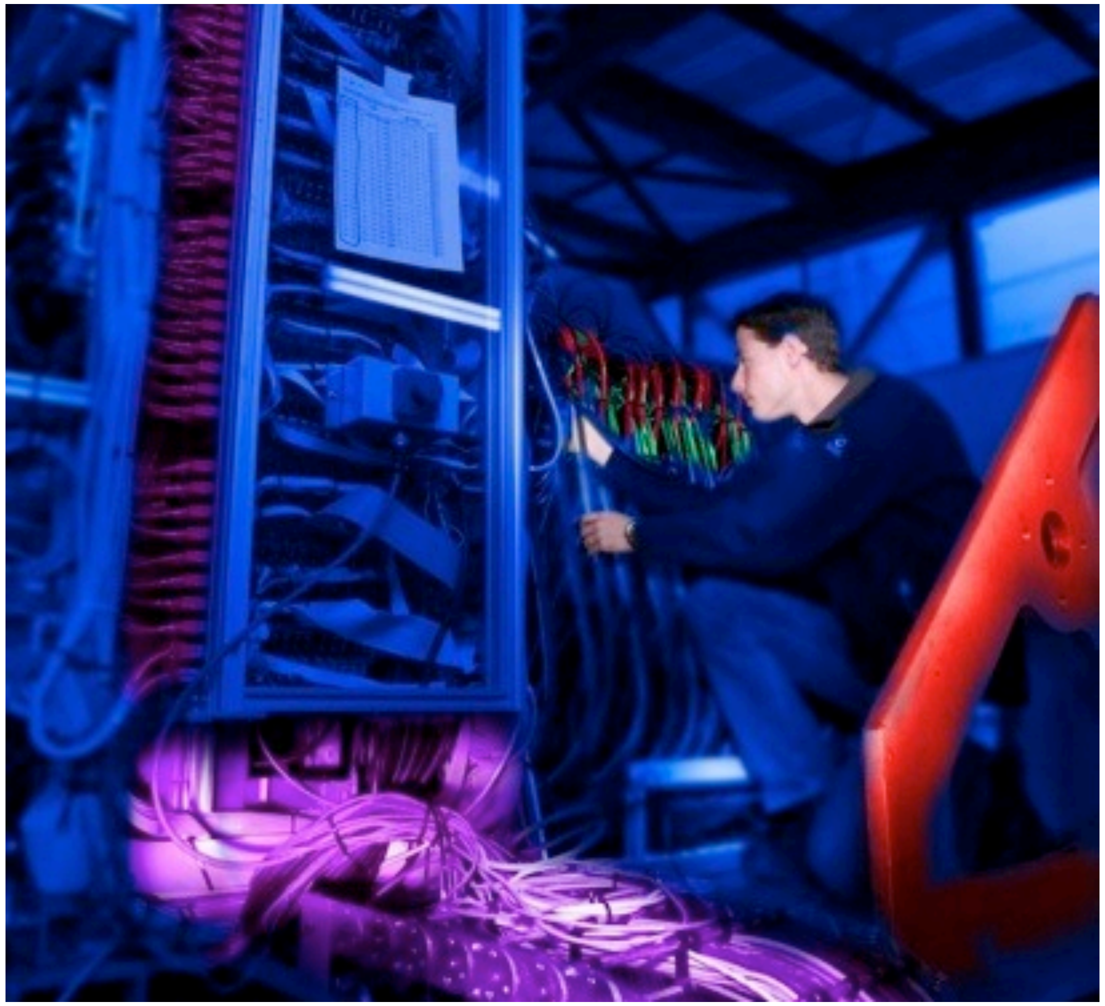
calibration system

... and putting it into Beam!

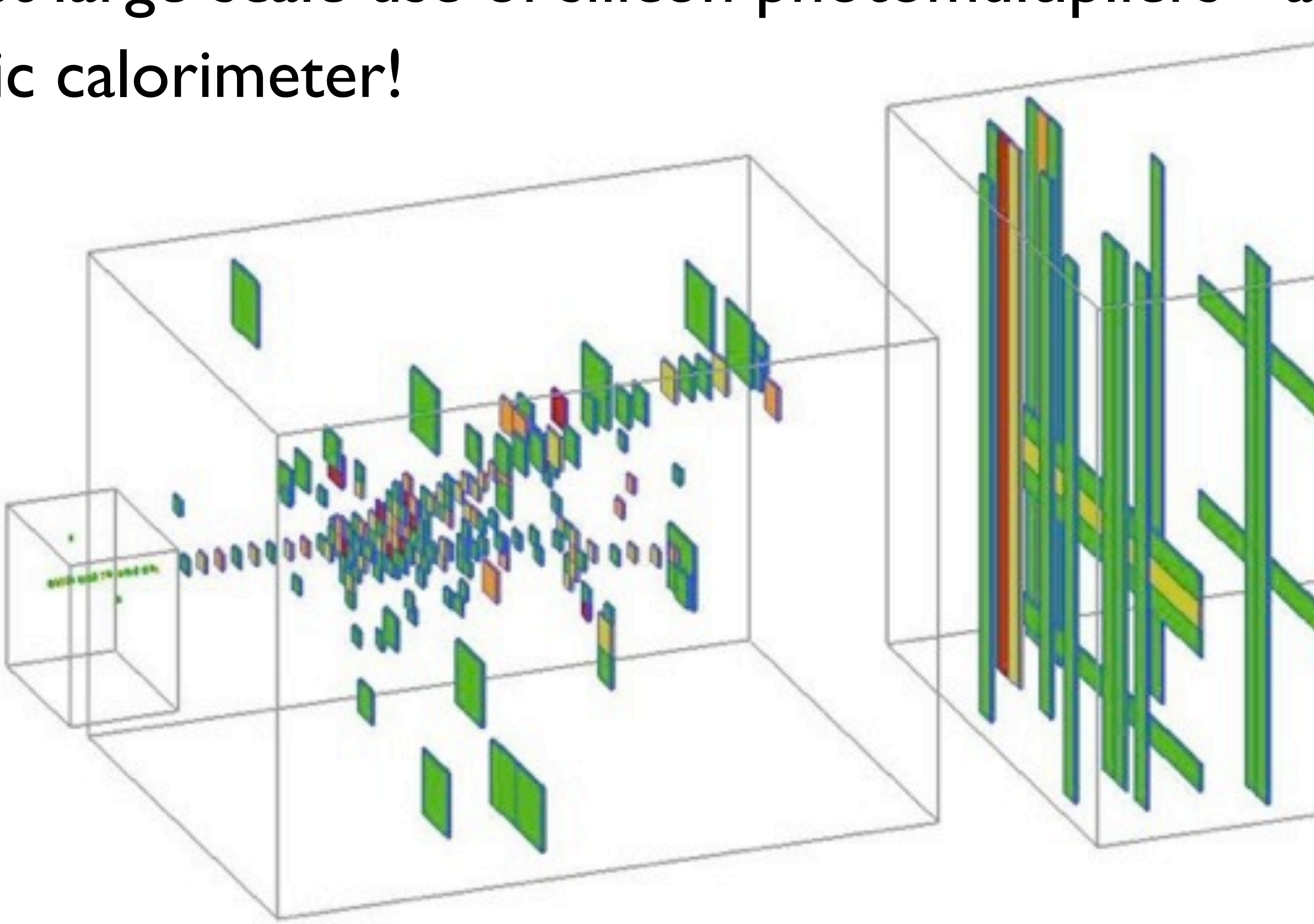




- CALICE AHCAL constructed in 2005/2006, beam tests in various configurations at DESY, CERN and Fermilab every year since then

CALICE Analog HCAL: Beautiful Performance

- The first large-scale use of silicon photomultipliers - and the first imaging hadronic calorimeter!



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Unprecedented possibilities!

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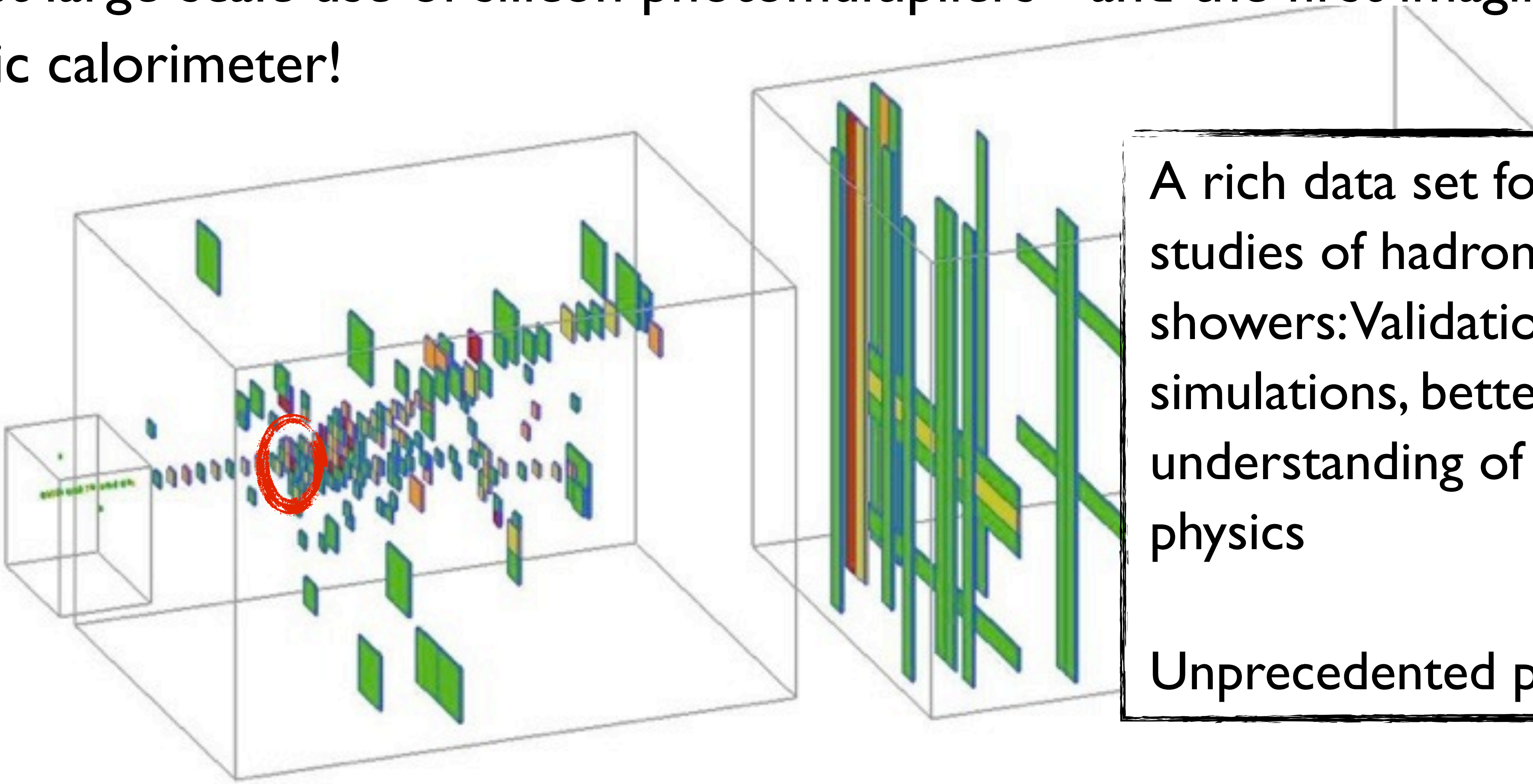

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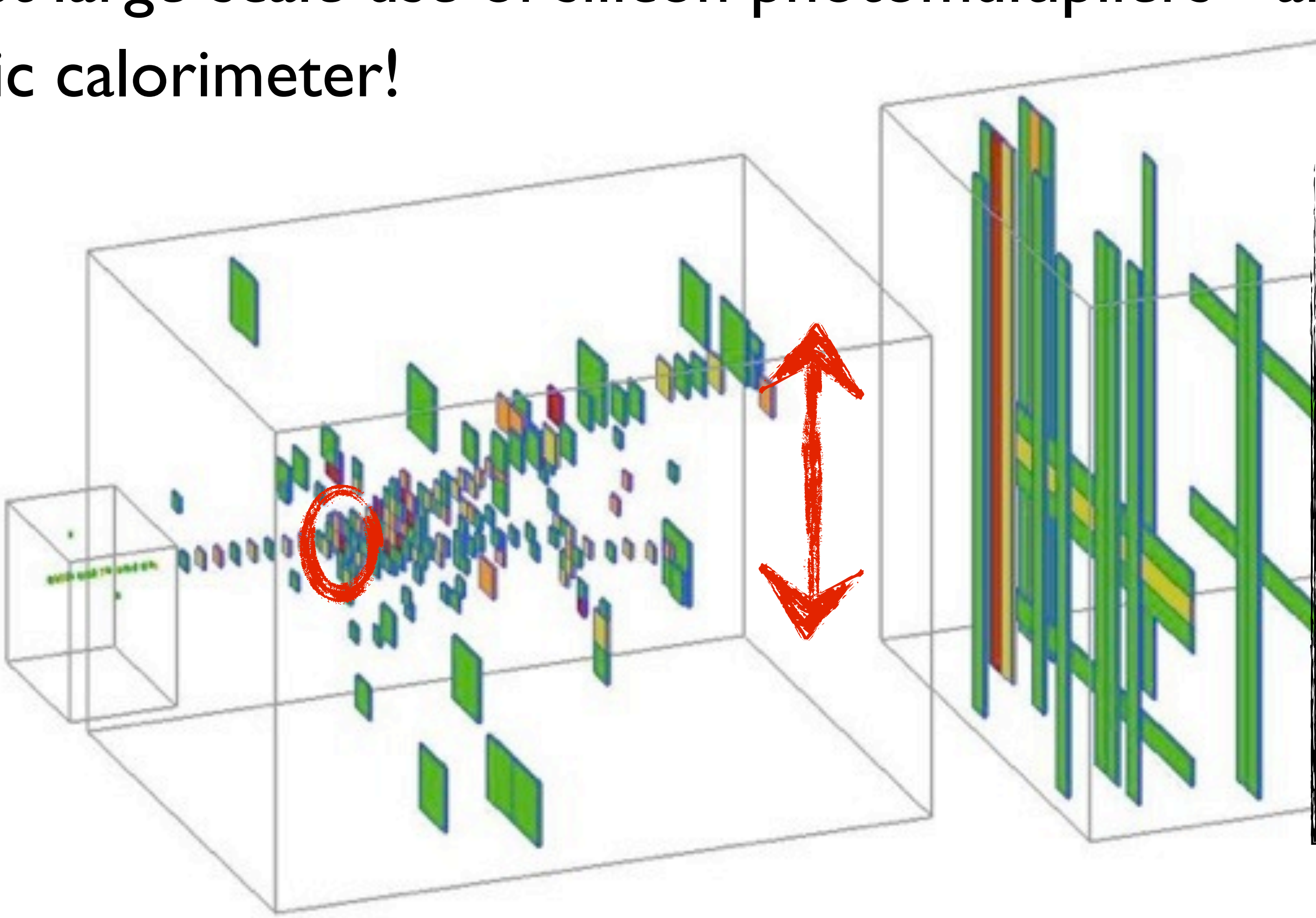

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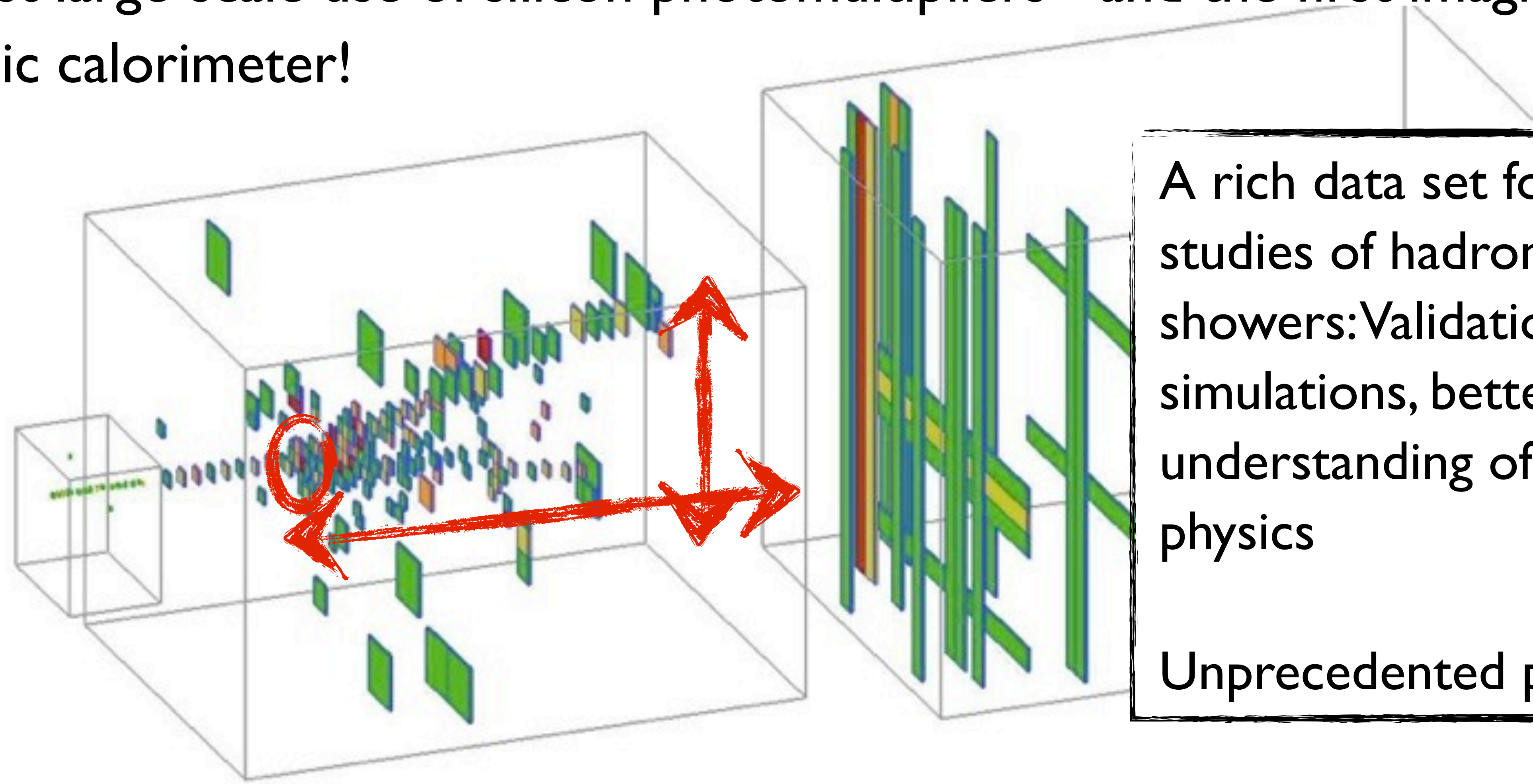

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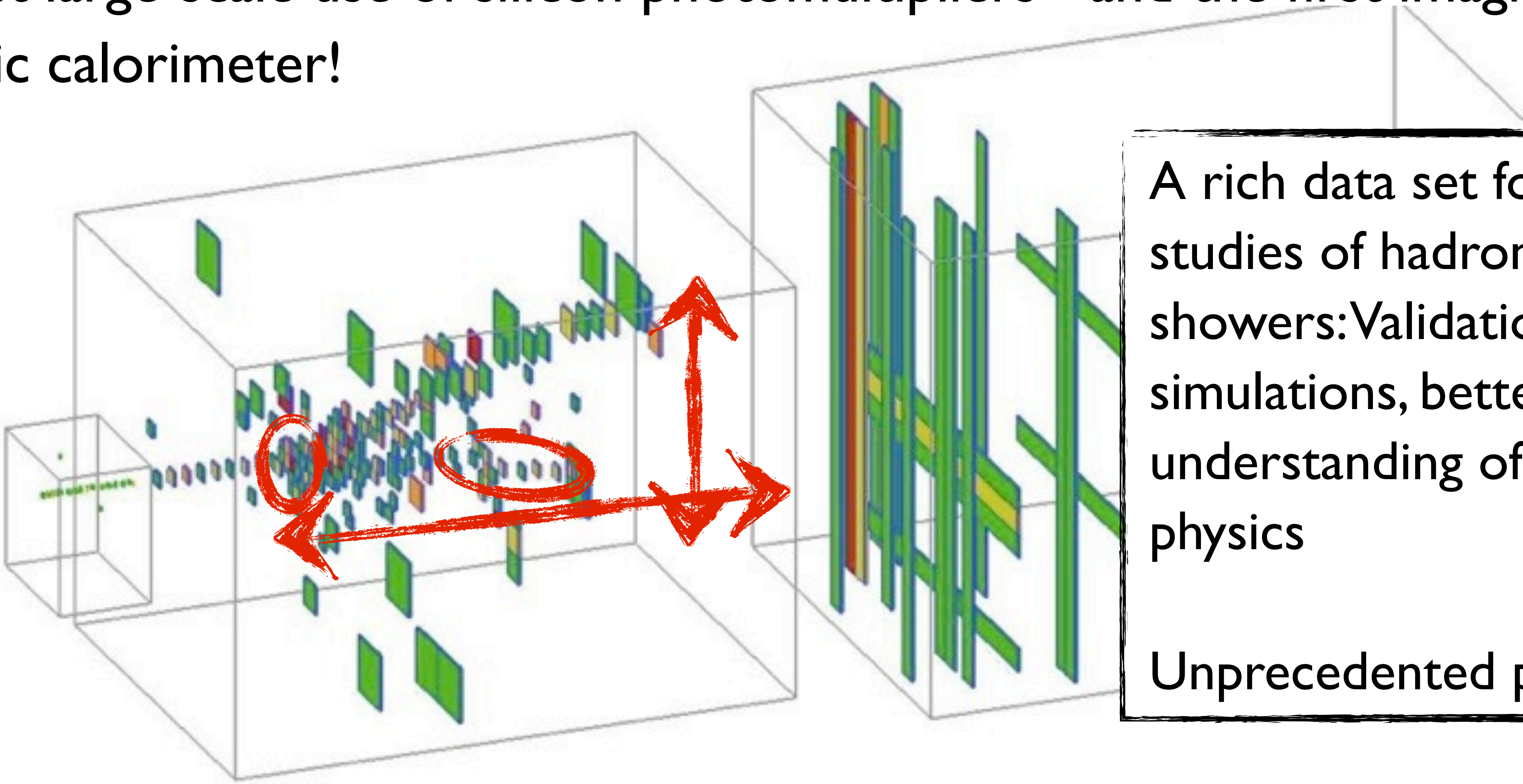

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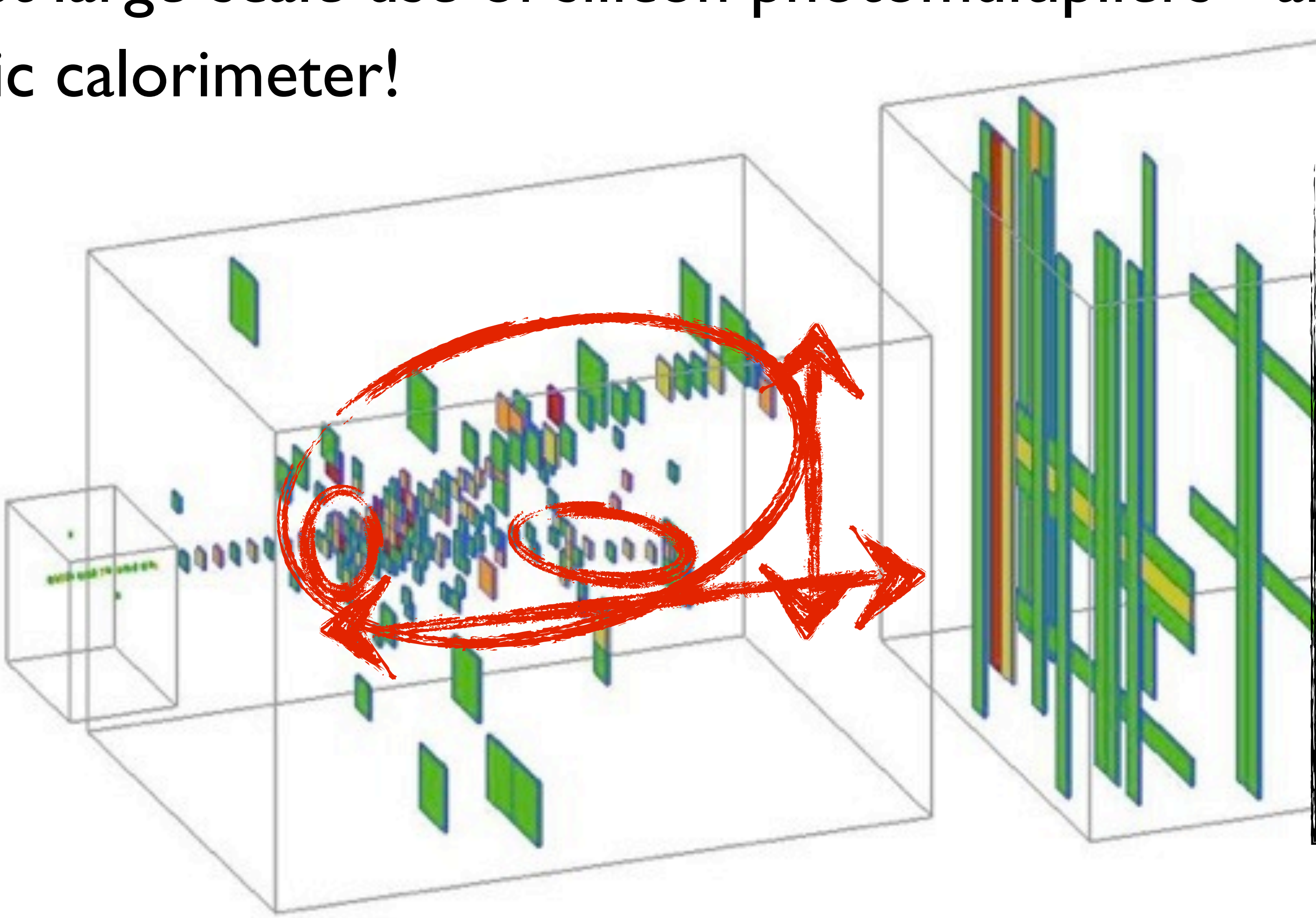

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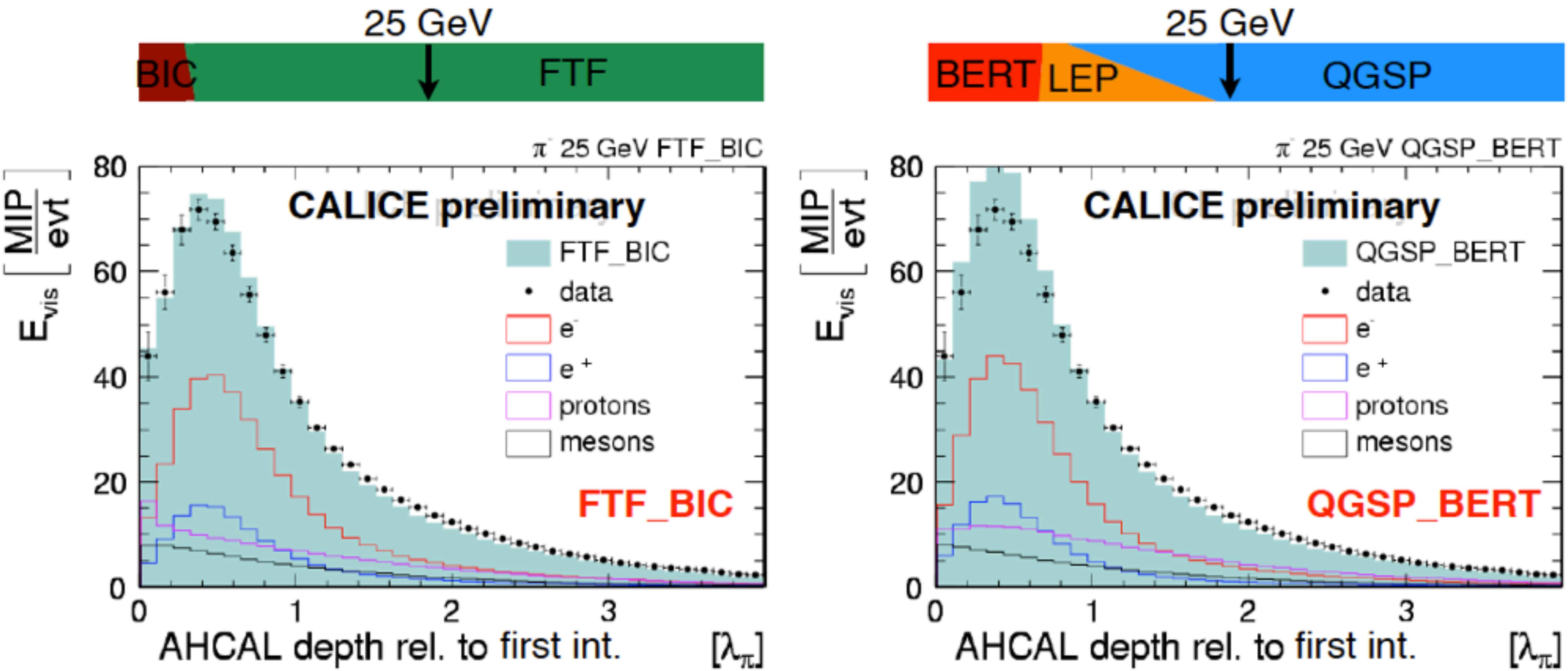
➾ Shower substructure: Detailed information about hadronic interactions
➾ Energy and energy density: Improved resolution with software compensation

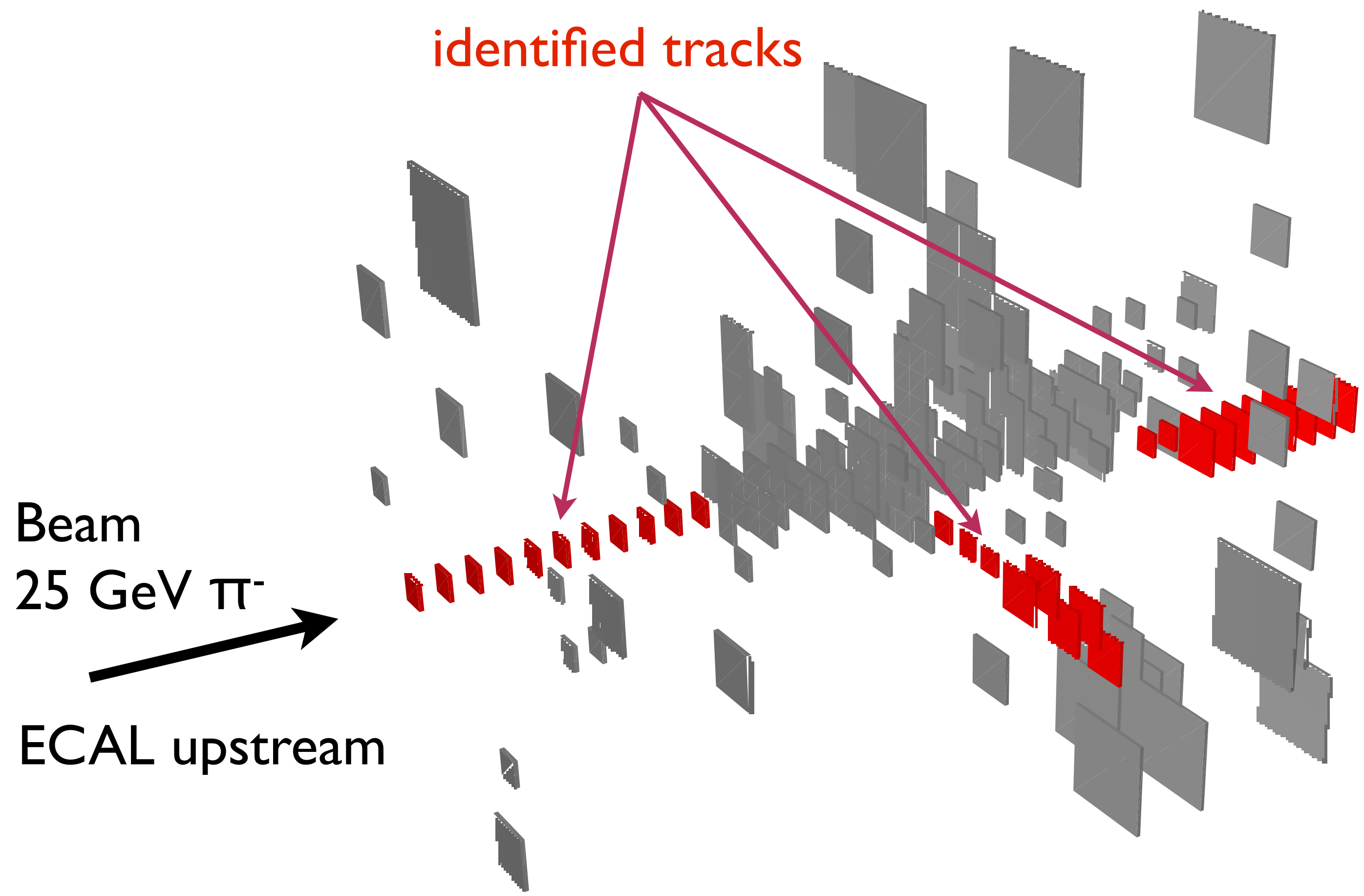
The Things you can do... Comparisons to MC

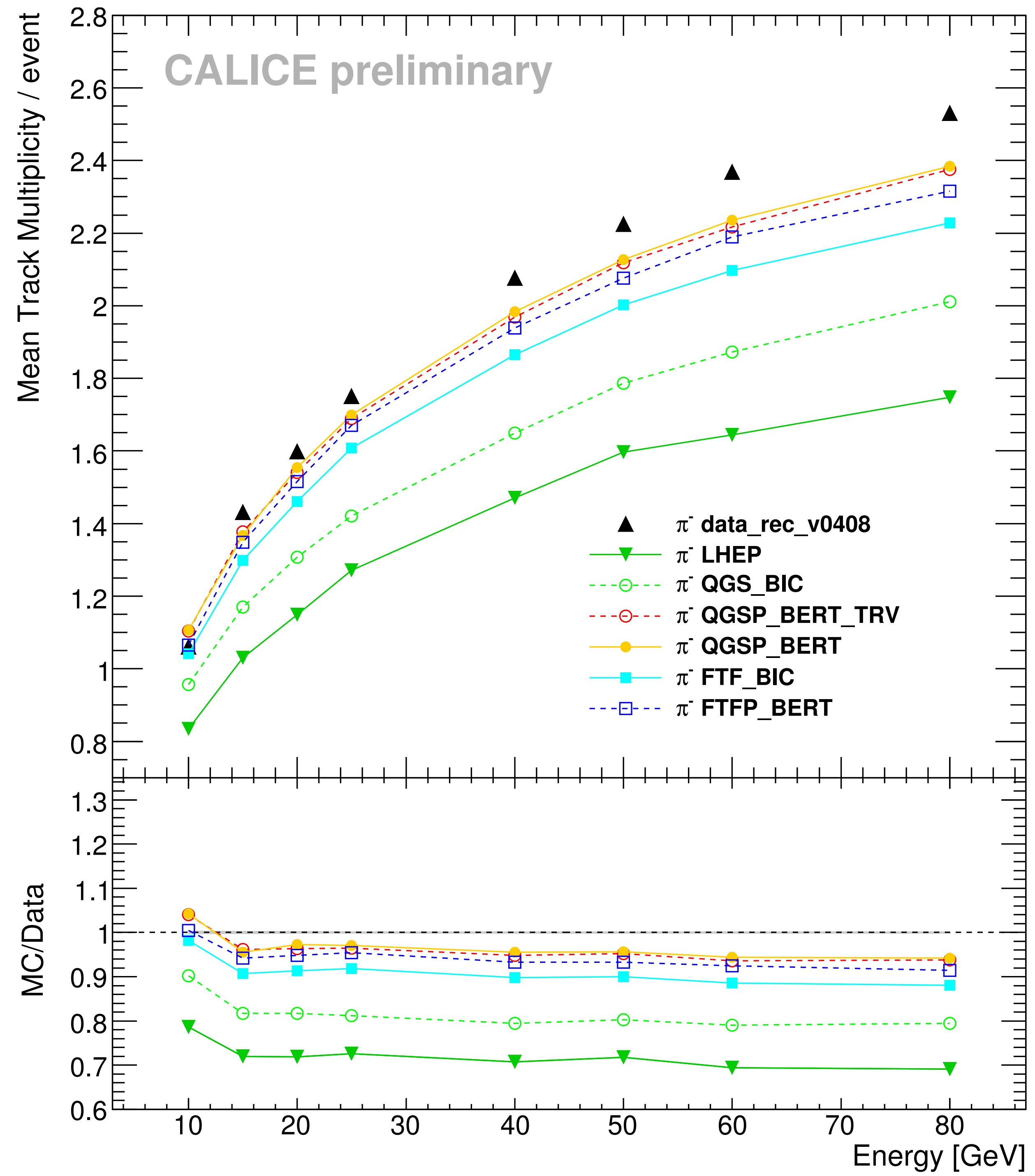
- Comparisons to MC: Understanding shower components



- Provides insight into inner workings of simulations: Which parts work well, which need improvement?

The Things you can do: Shower Substructure

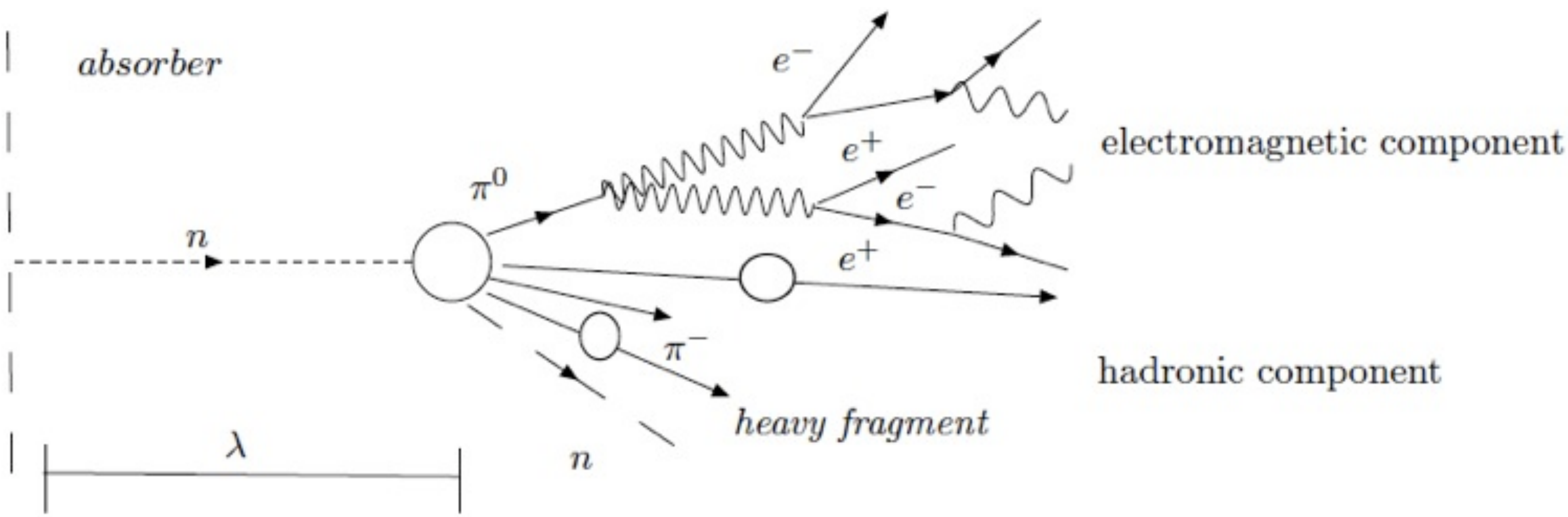




- Unprecedented resolution provides a look deep into the substructure of hadronic showers:
  Resolution of individual MIP-like particles
- Newer simulation codes can reproduce the observations: Builds trust in the Geant4 approach... and in PFA performance studies!

The Things you can do: Energy Resolution

- The primary performance criterion for a calorimeter: Energy resolution
- For hadrons, it is a tough business:



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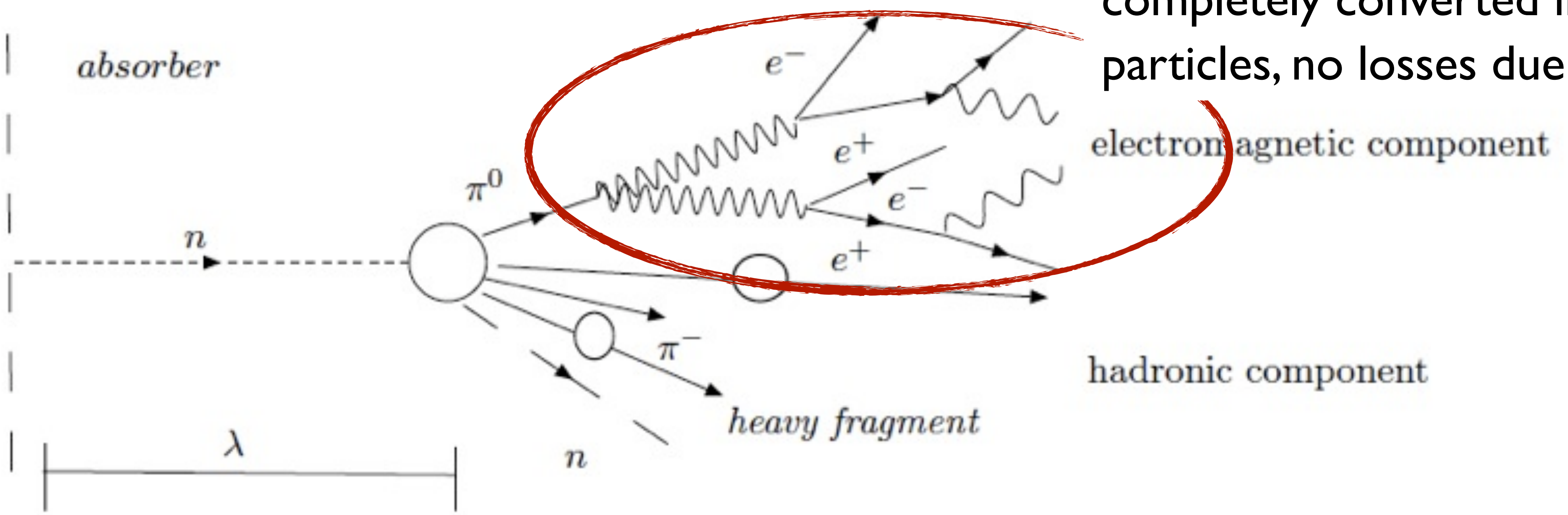

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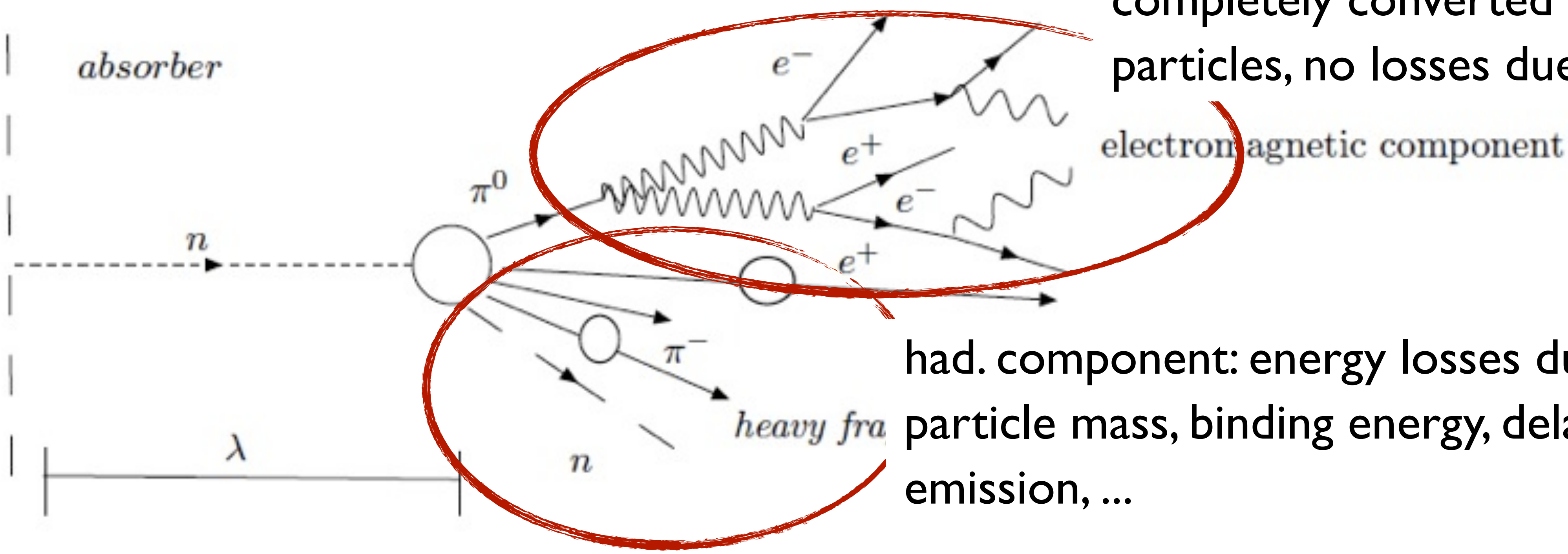

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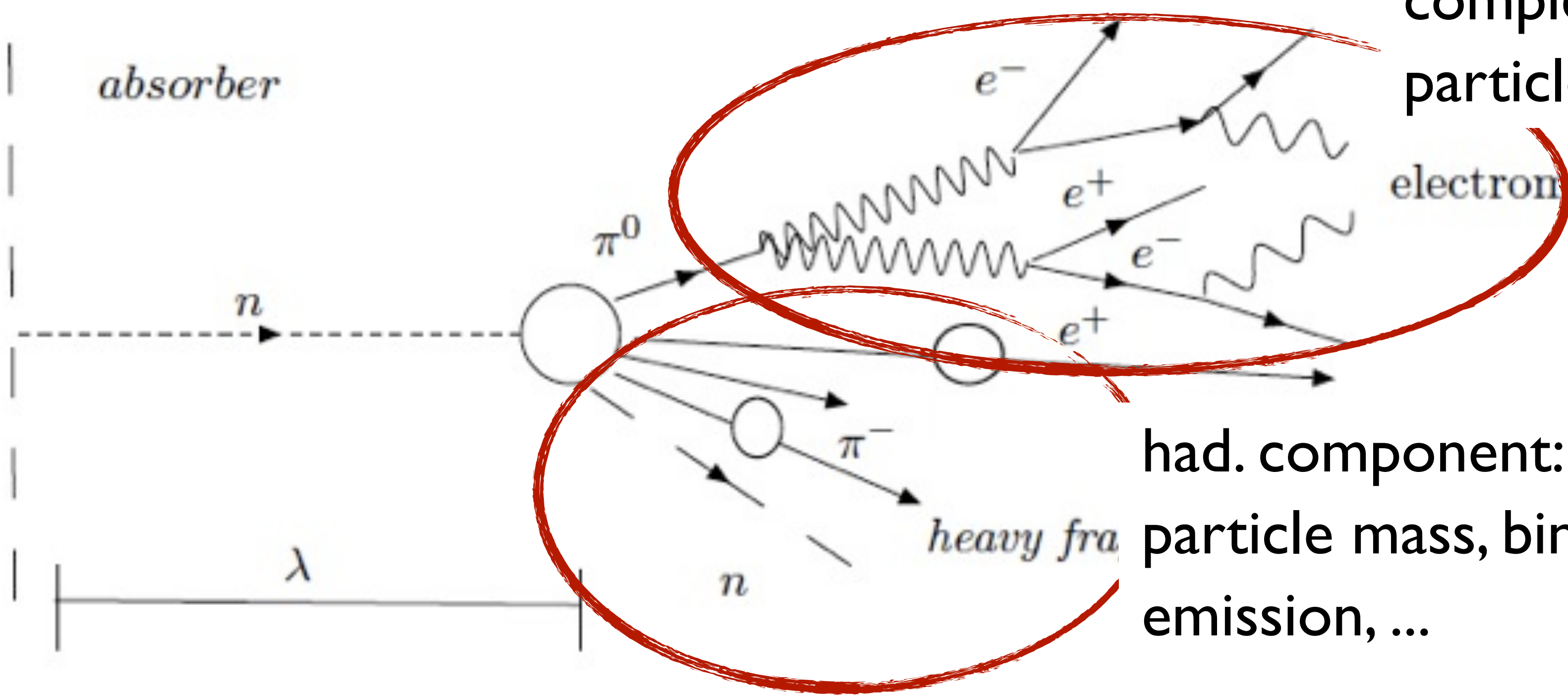

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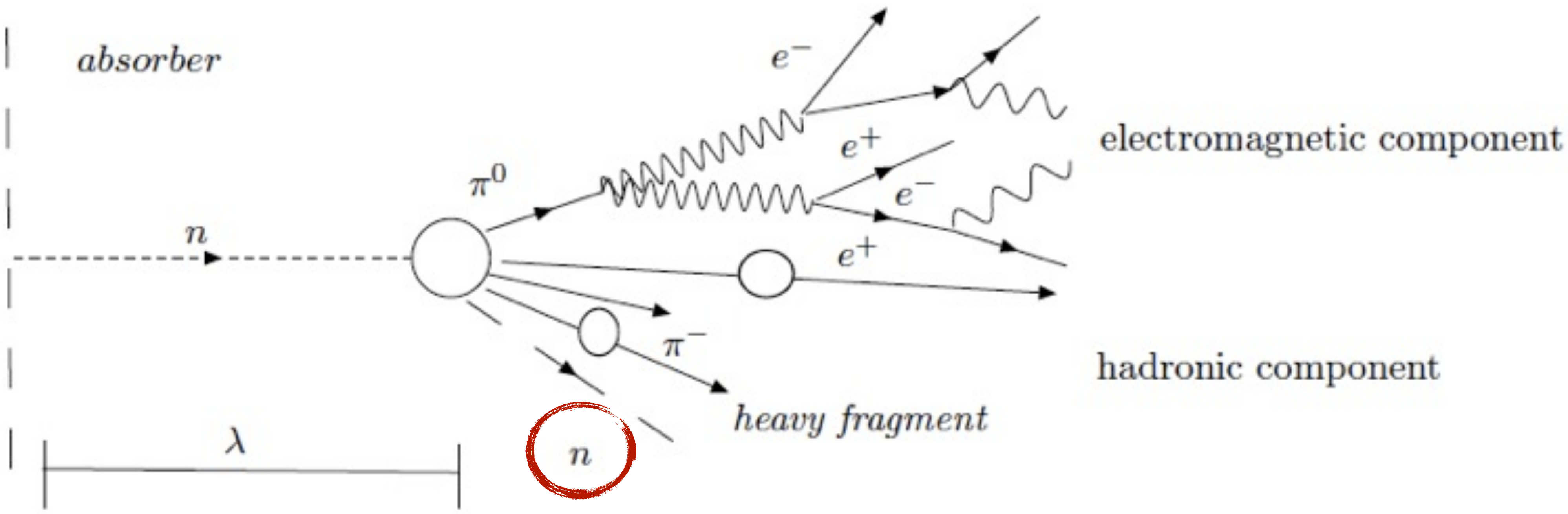
- The challenge:
  - Typically, the response to the em component is larger than to the hadronic component (missing energy in hadronic case), "non-compensation"
  - Large event to event fluctuations between the components

➫ Limited energy resolution of hadronic calorimeters!

The Things you can do: Energy Resolution

- Ways to improve the resolution:



- Increase response to hadronic component:
  Sensitivity to neutrons provided by hydrogenous detection medium
  but: strict requirements on absorber to active medium ratios, longitudinal uniformity,...

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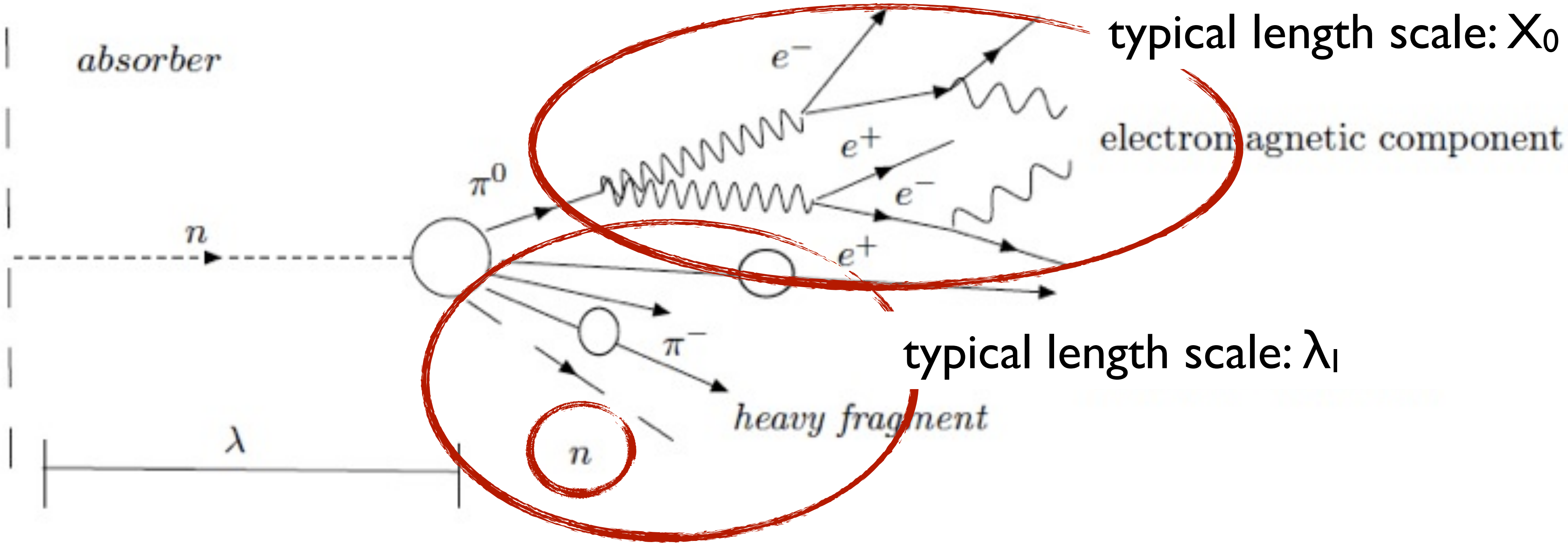
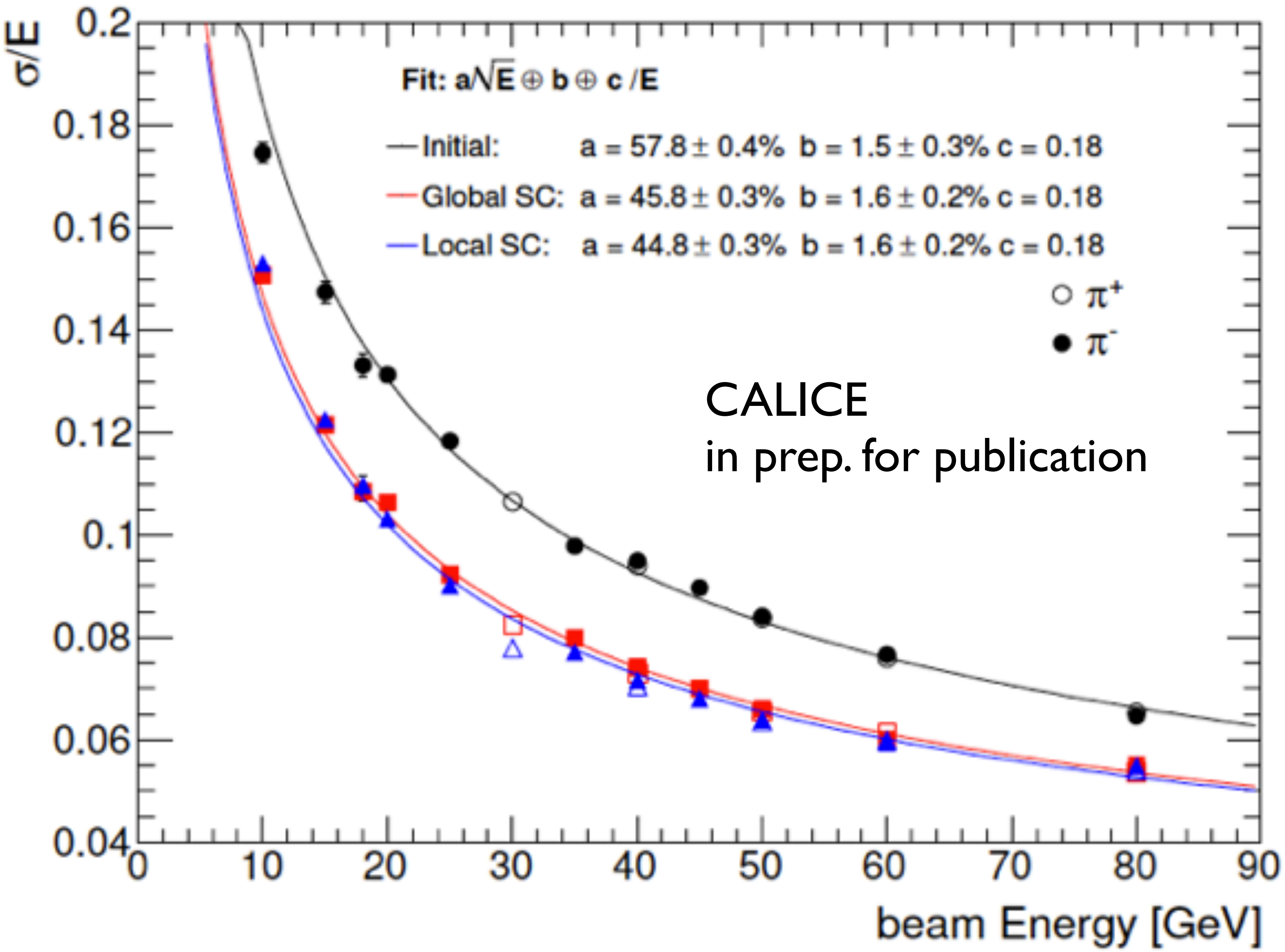


- Increase response to hadronic component:
  Sensitivity to neutrons provided by hydrogenous detection medium
  but: strict requirements on absorber to active medium ratios, longitudinal uniformity,...
- Software compensation:
  Exploit detector granularity to detect topological differences between components
  Weight energy deposits according to local energy density or overall shower density

Energy Reconstruction & Software Compensation

- Software compensation in the CALICE analog HCAL: Two techniques
  - Local: use energy content of each cell
  - Global: use shower properties - number of cells above and below thresholds



Resolution of 45%/$\sqrt{E}$ with small constant term for pions ***in data***

Linear energy reconstruction within 1.5% over the full energy range from 10 GeV to 80 GeV

20% improvement of resolution with software compensation

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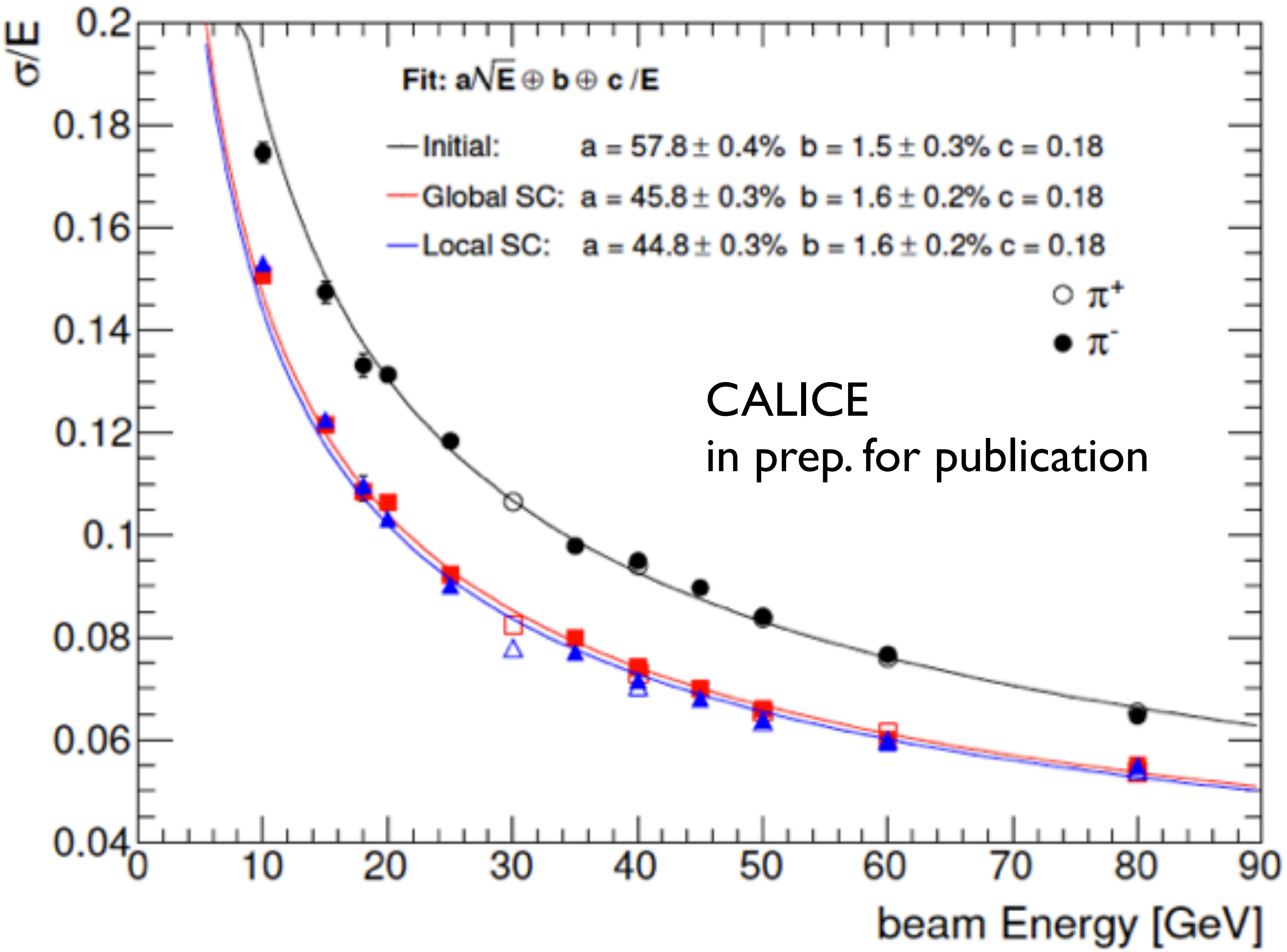

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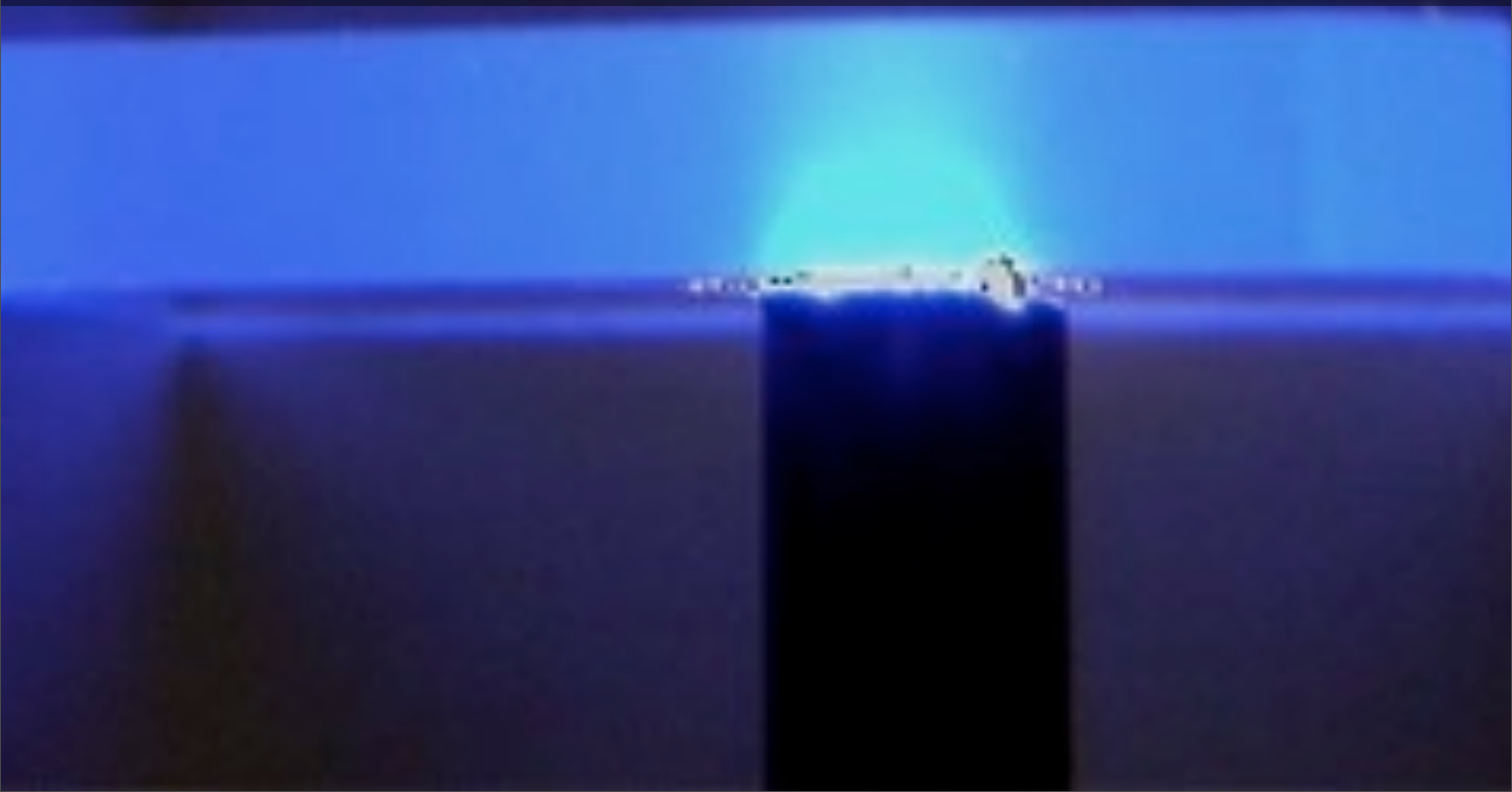
PFA calorimeters can also be pretty good hadronic calorimeters!

Under the Hood:
Calibration, Scintillator Tiles & New Ideas



From Signals to Results

- Several calibration levels applied
  - Pushing far beyond the needs of a hadronic calorimeter to fully understand imaging calorimeters with SiPM readout

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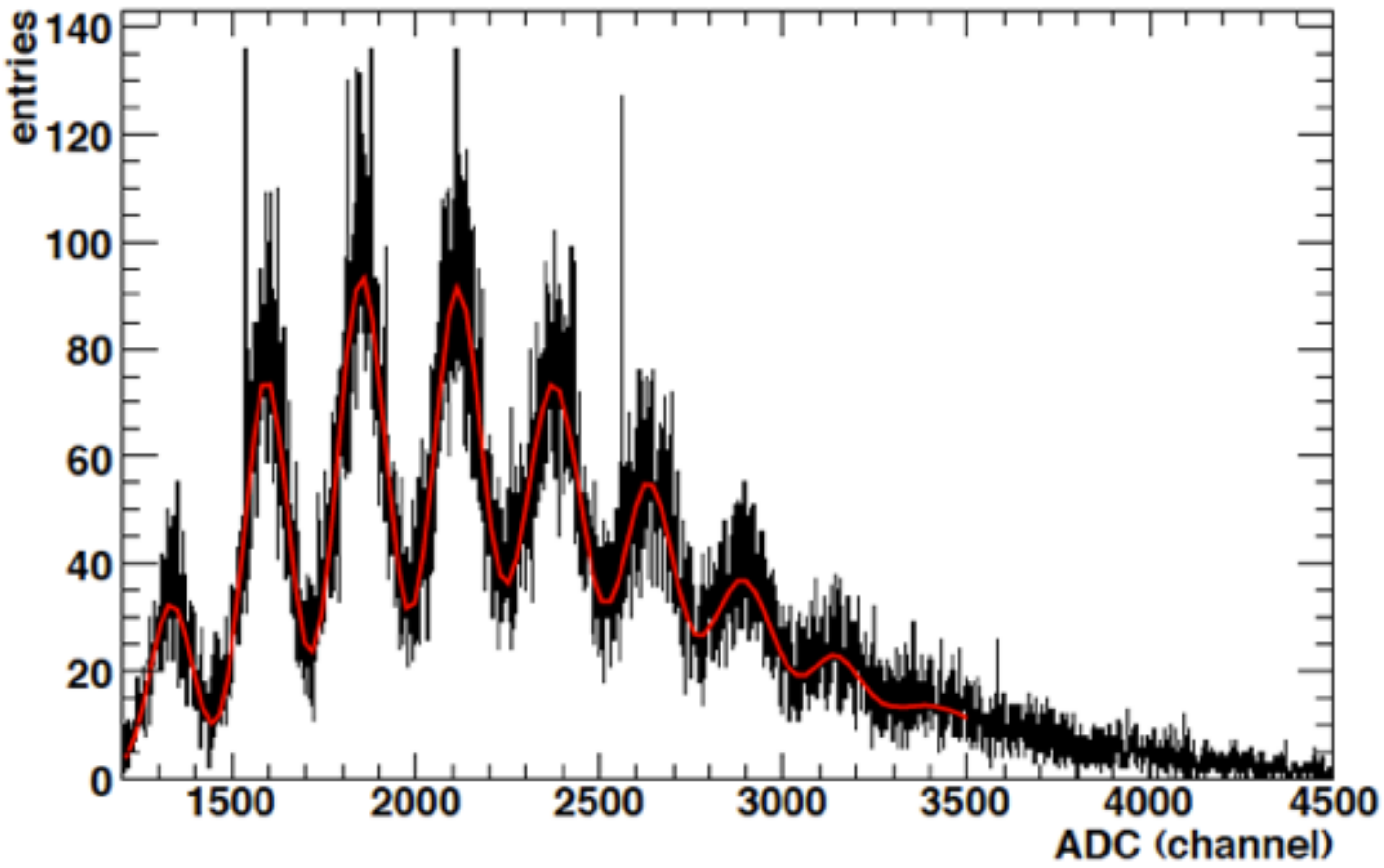
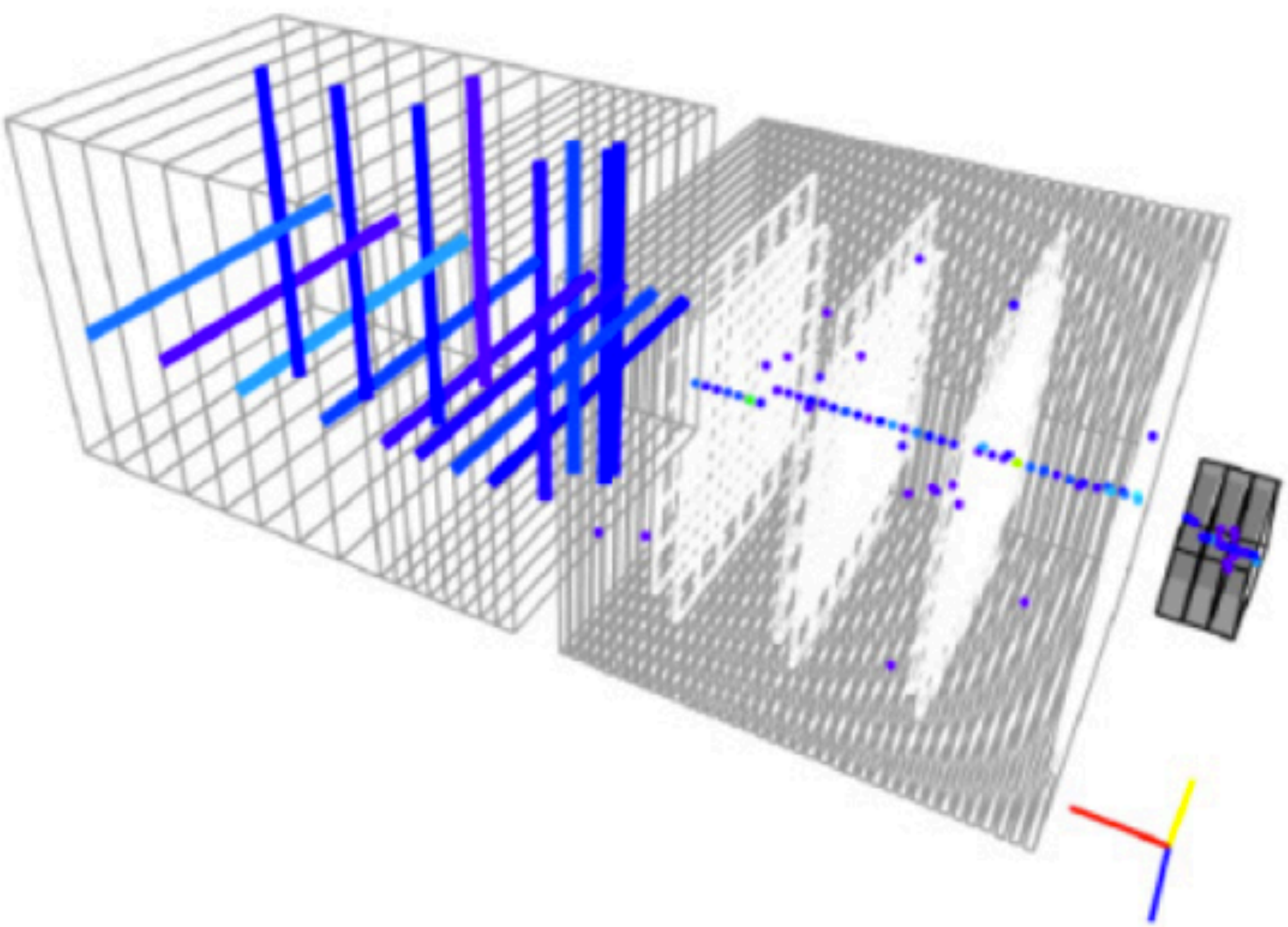


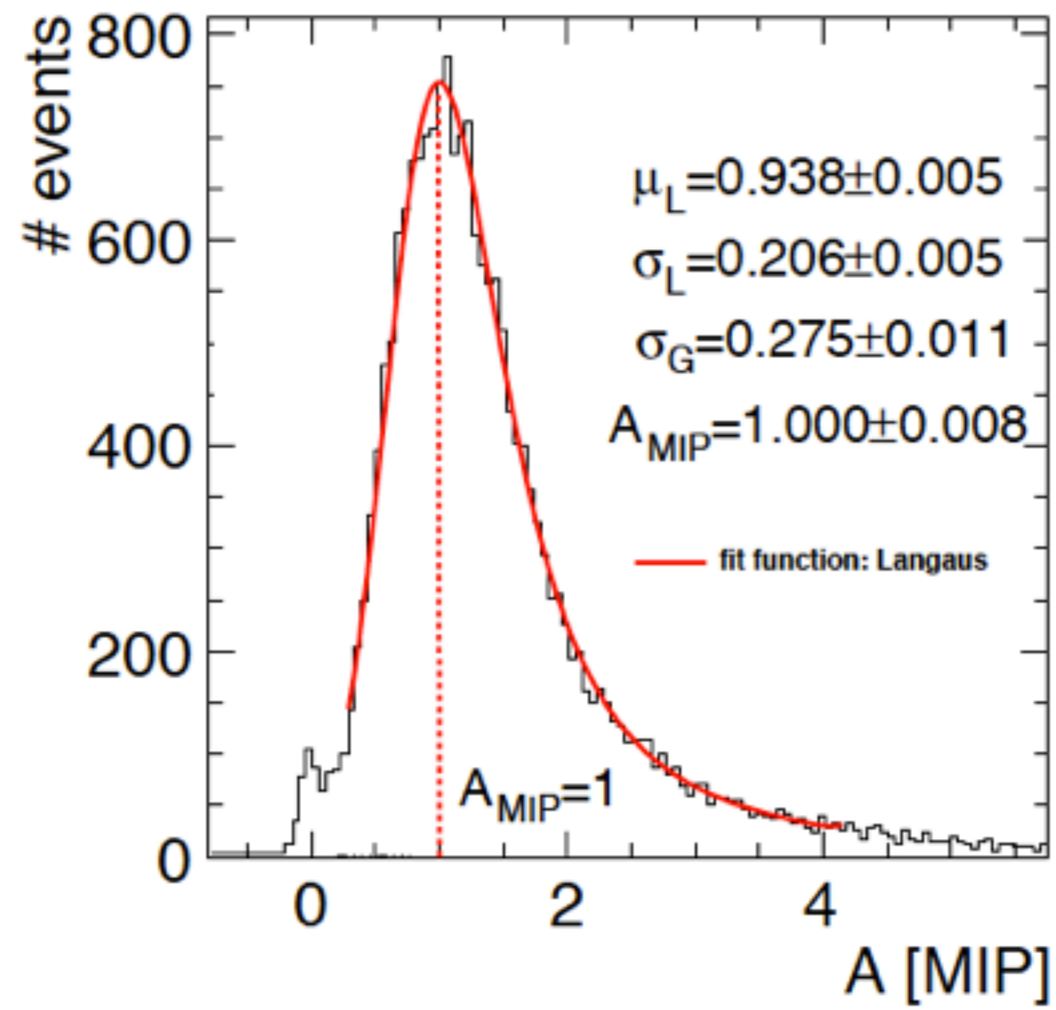
- Auto-calibration feature of SiPMs: Response to individual photons can be clearly identified: Simple gain determination possible
  - In CALICE: Low-intensity LED light coupled to every cell, high gain of front-end electronics

Knowing the gain allows to convert an observed signal into a number of photons: Crucial for saturation corrections

From Signal to Results

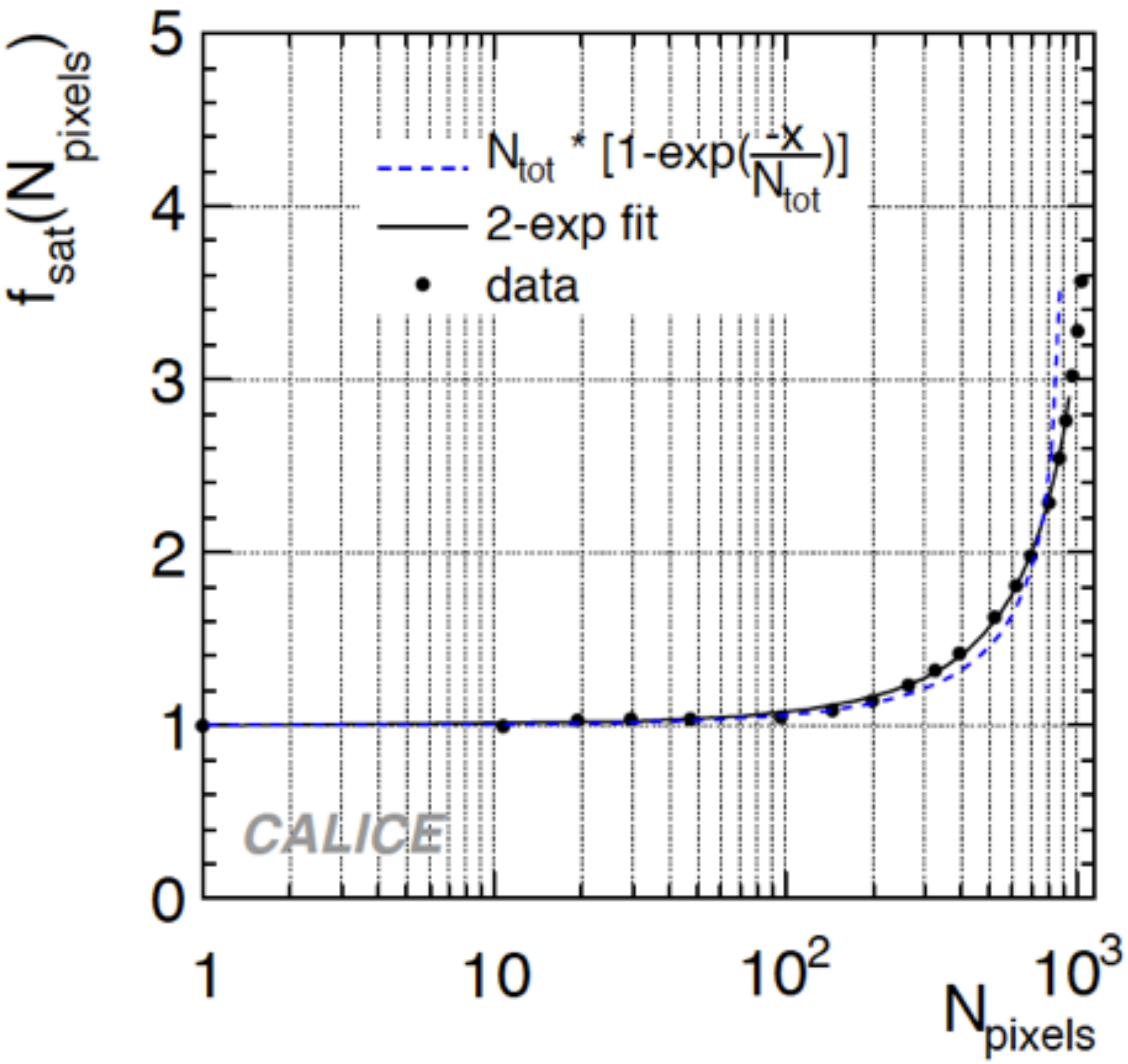
- Calibrating the response of each cell to particles:
  - Setting the overall calibration scale
  - Cell-to-cell intercalibration





Correcting Saturation

- The number of pixels on the SiPMs is finite: The number of photons that can be detected simultaneously (meaning within a few ns) is limited
  - Leads to saturation for high-amplitude signals



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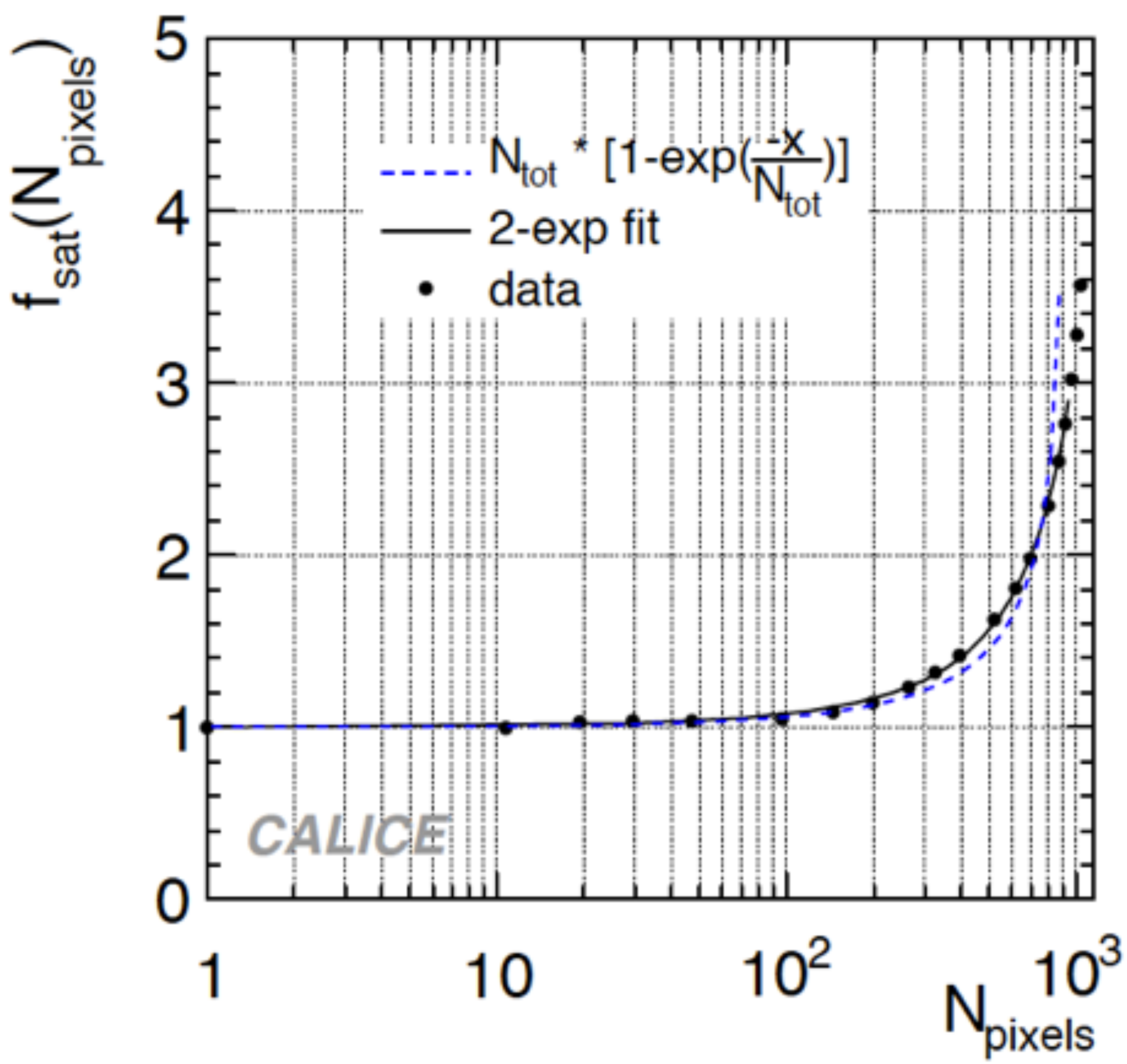

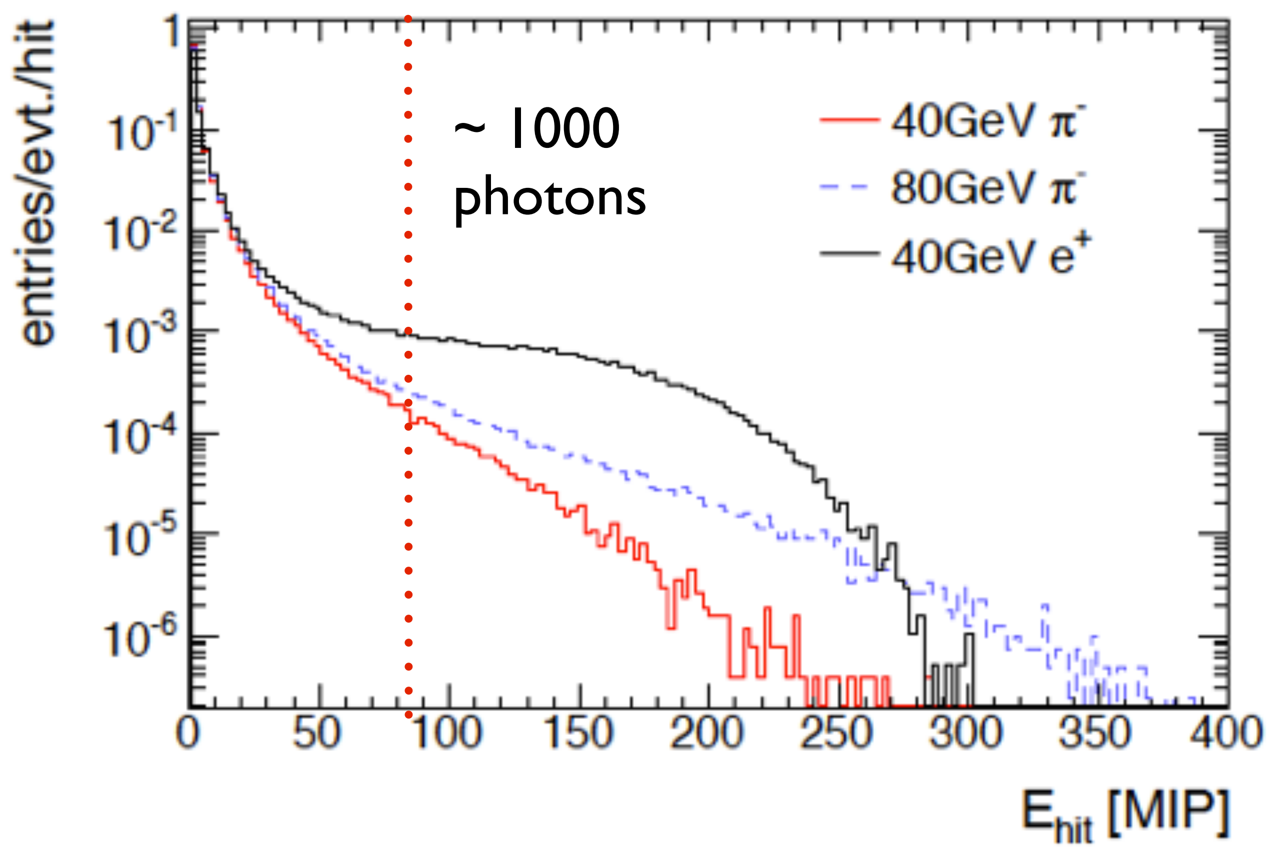

Mostly an issue for electromagnetic showers...

Correcting Saturation

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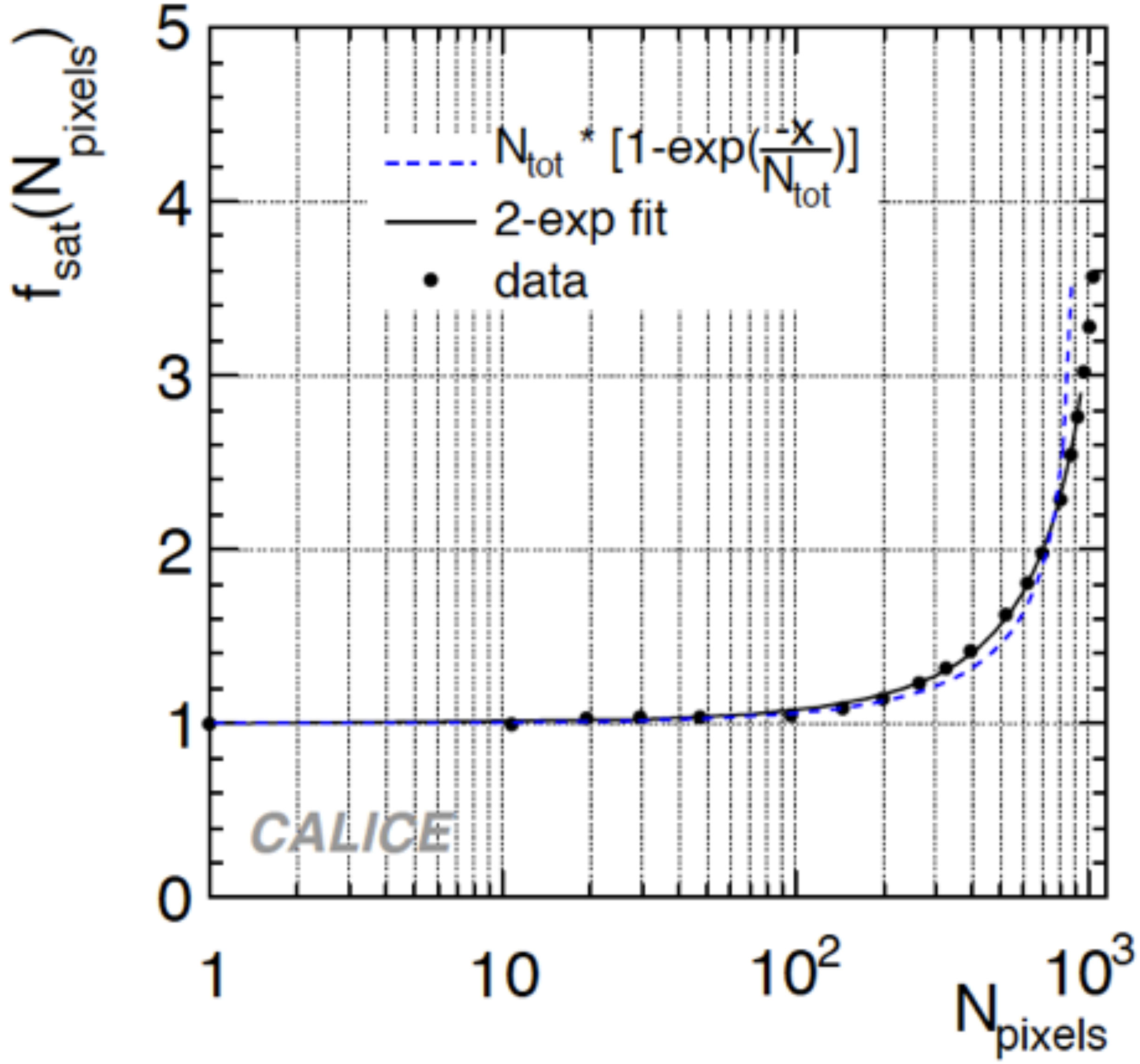
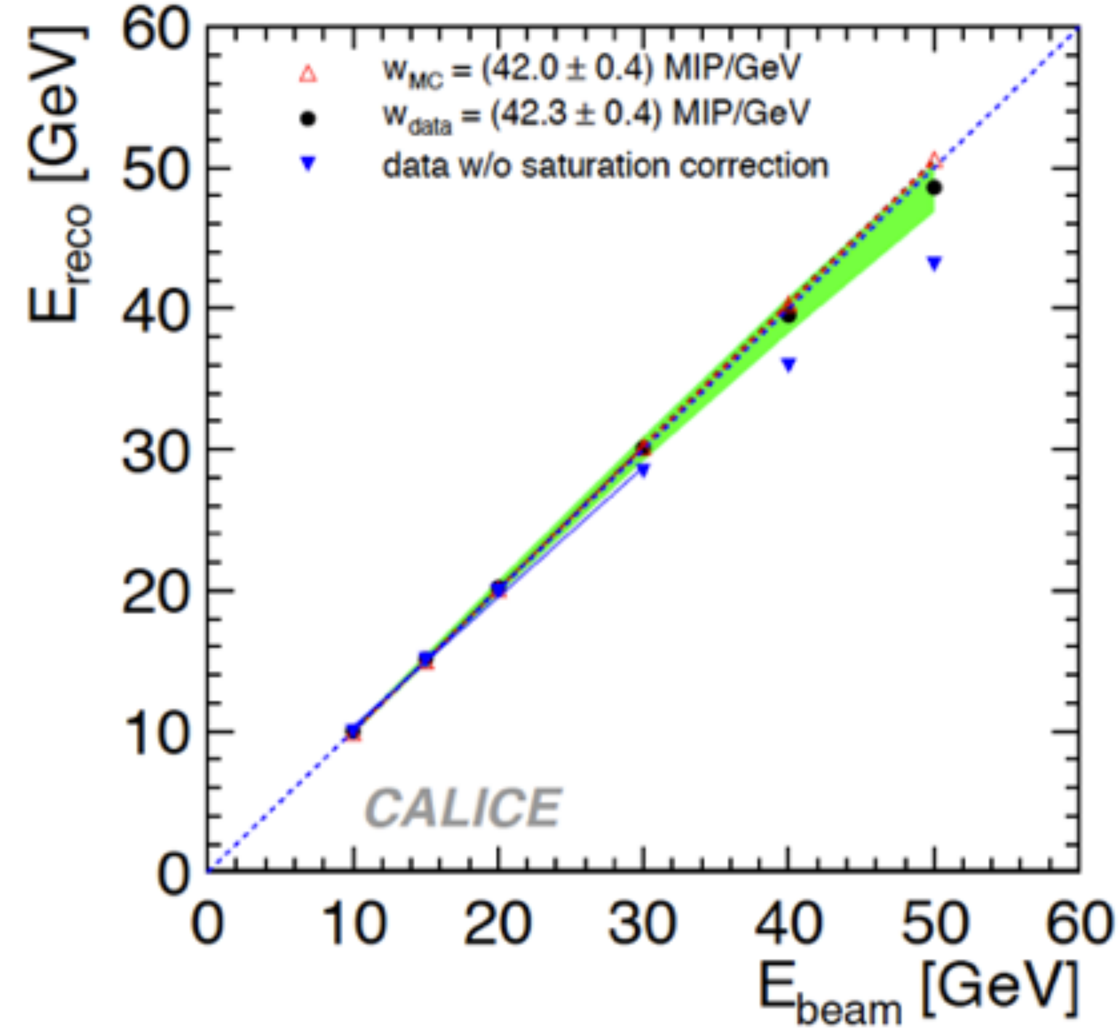
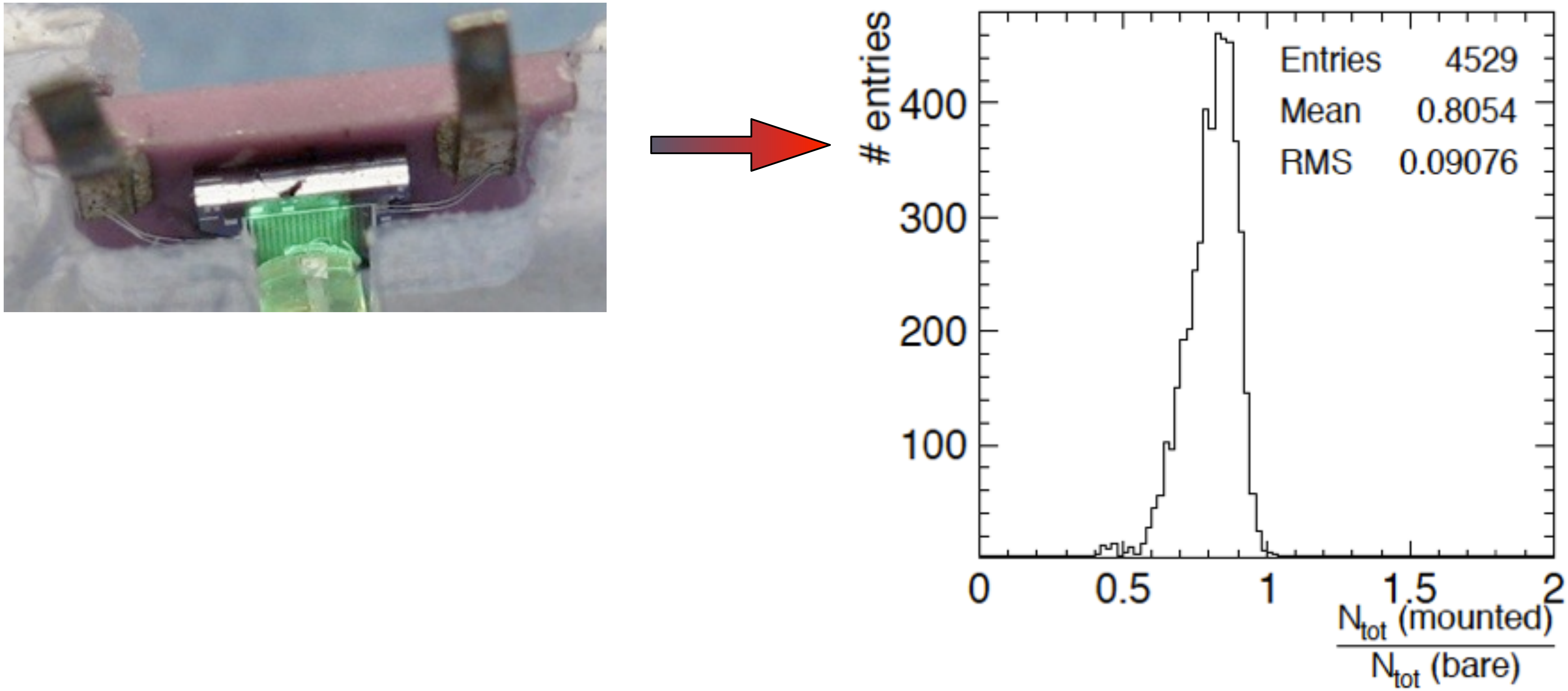




Saturation correction works well for electromagnetic showers:
No performance reduction for hadrons!

Fine Details - Spreads & Variations

- Matching of fiber to SiPM is tricky: Slight misalignments lead to reduced number of effective pixels - Affects saturation correction



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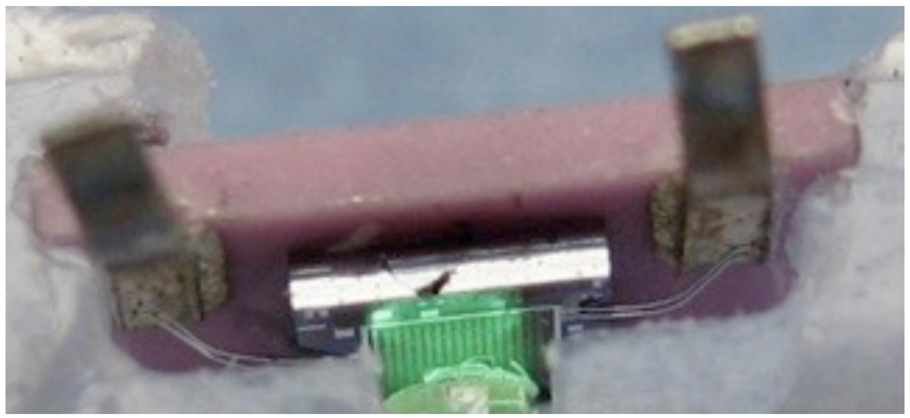
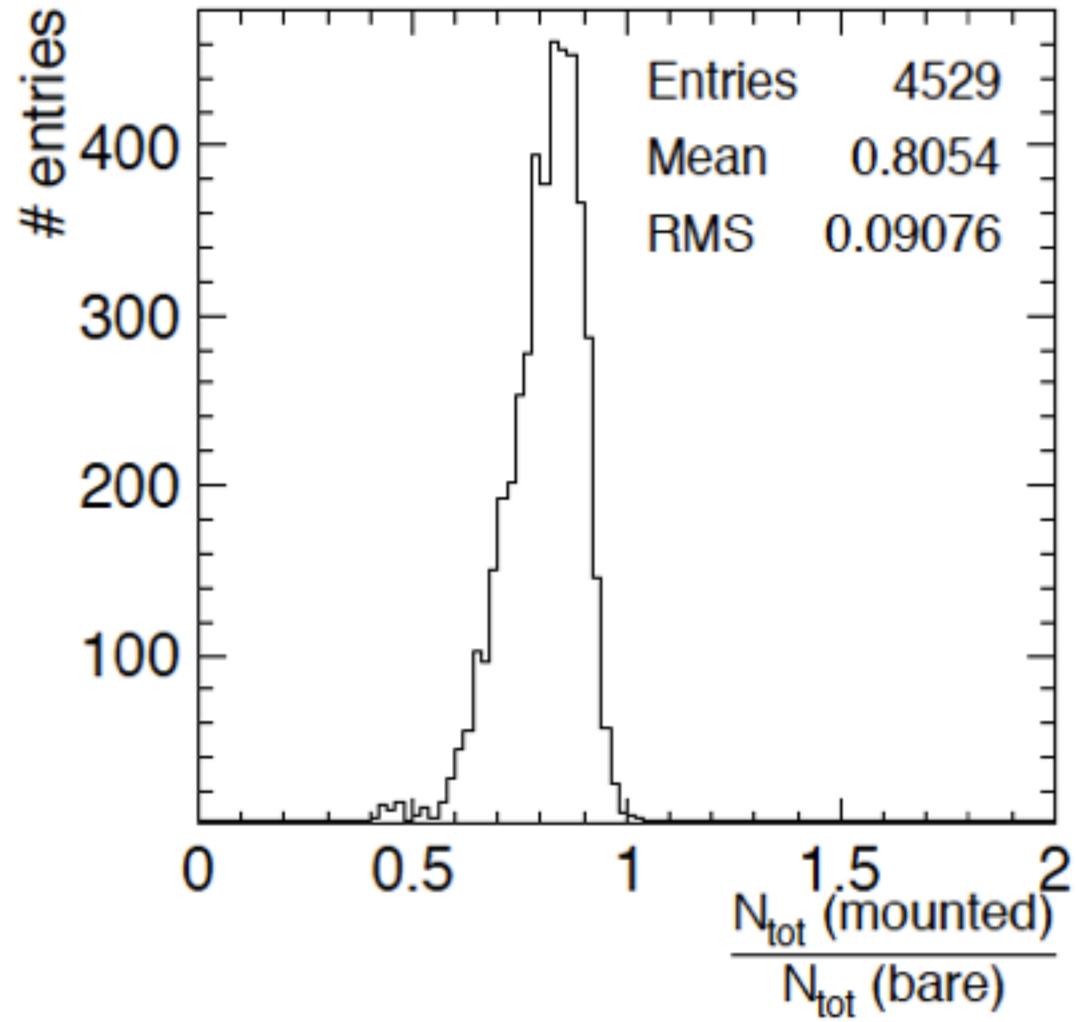
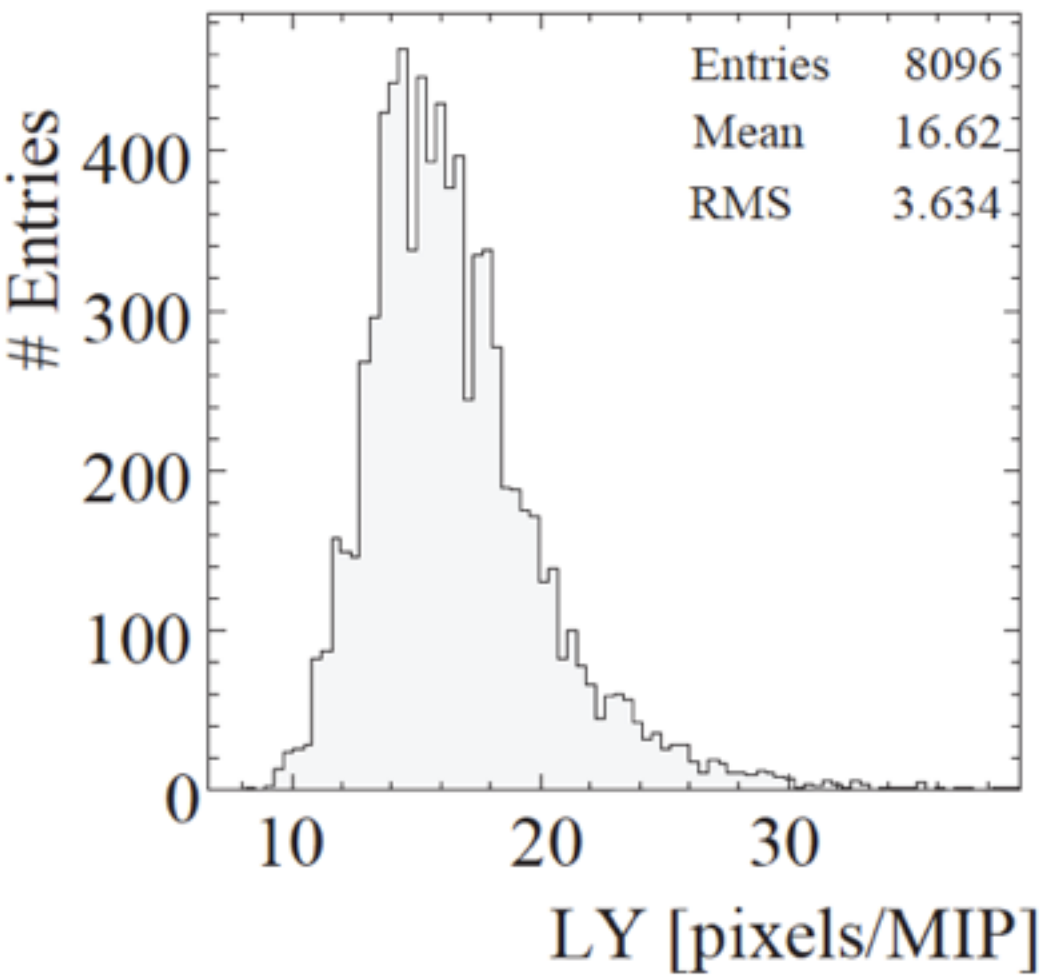




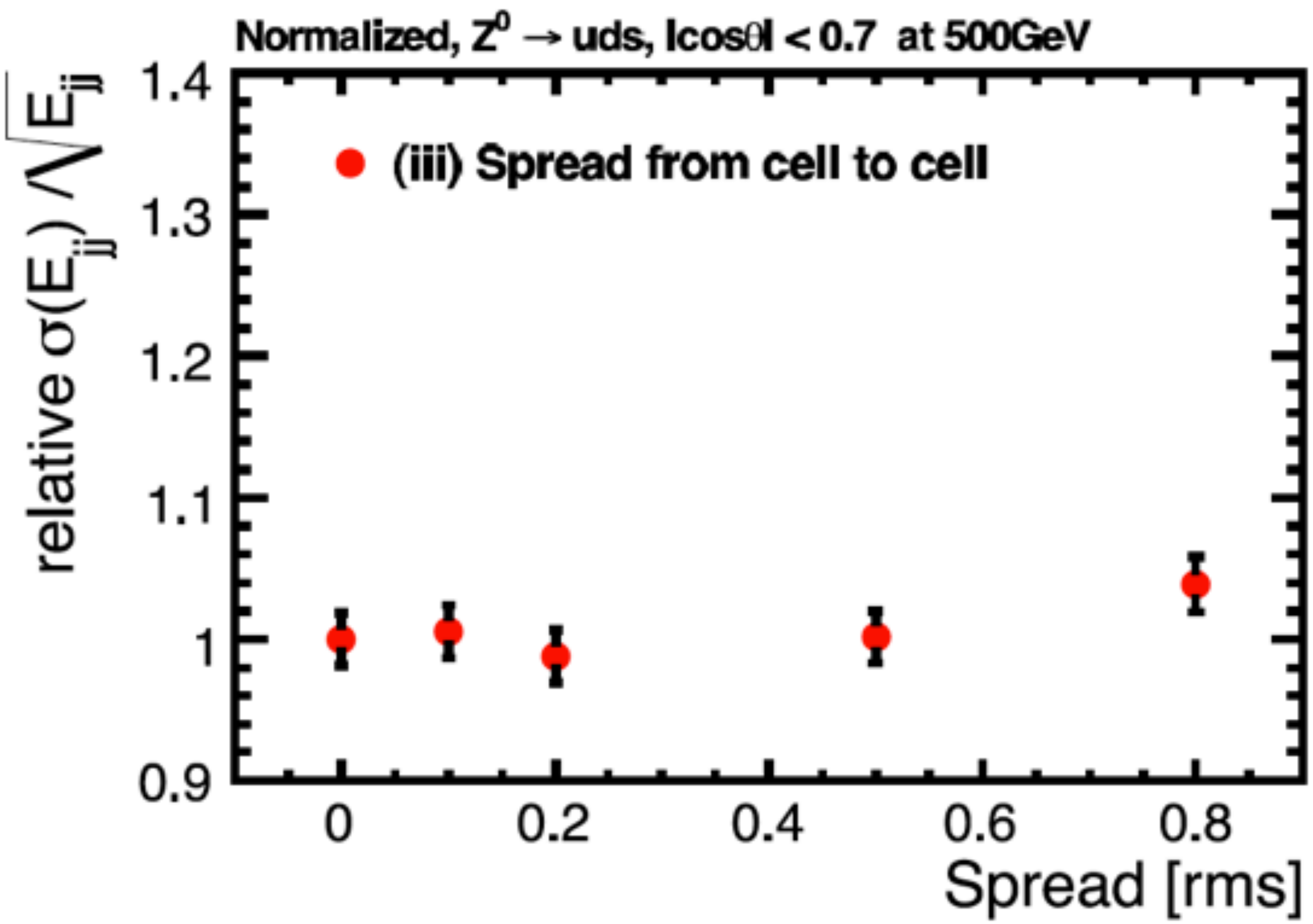


- ~ 30% RMS variation of signal (here for penetrating electrons from ^{90}Sr source): A variety of factors - Taken care of by MIP calibration

Do Cell-to-Cell Spreads Matter?

- High granularity here comes in in our favor: Typically 10 cells / GeV Variations average out

Study in full simulations with PFA event reconstruction:
It takes more than 50% RMS cell-to-cell variations to take a hit in jet energy resolution.
Requirement here is not set by resolution, but by possibility for calibrating in groups
Expected requirement: ~ ± 10%



New Ideas for the Next Generation

- The wavelength-shifting fiber in the scintillator cells comes at a price:
  - increased mechanical complexity: Fiber needs to be inserted into every tile
  - reduced tolerances: Alignment of fiber end to SiPM critical: Decides light yield of cell and saturation level
  - Slower response: Additional time constant from WLS

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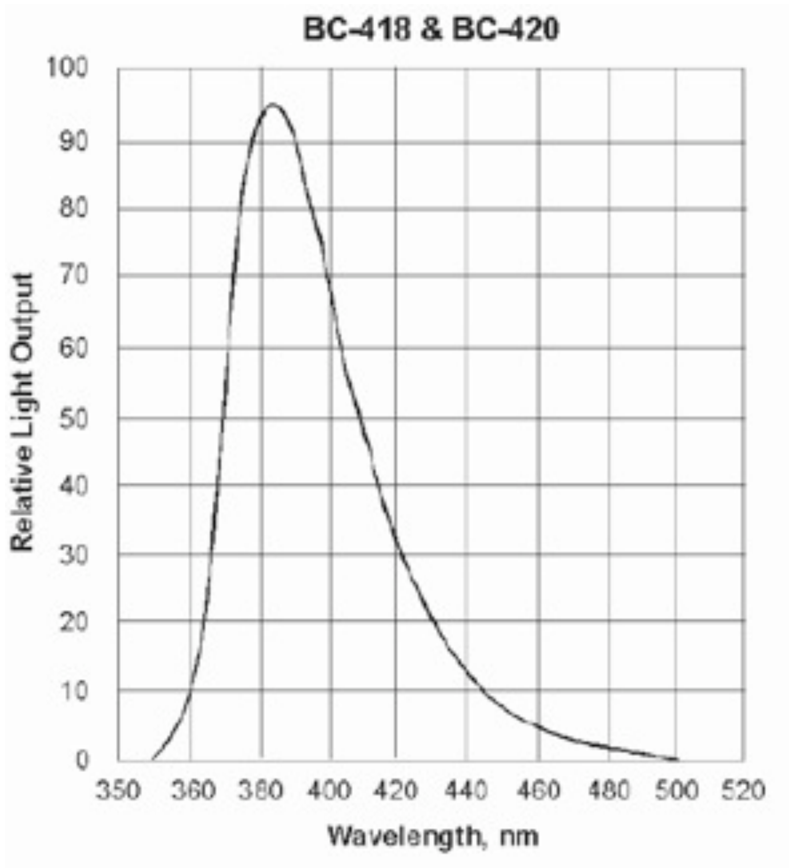
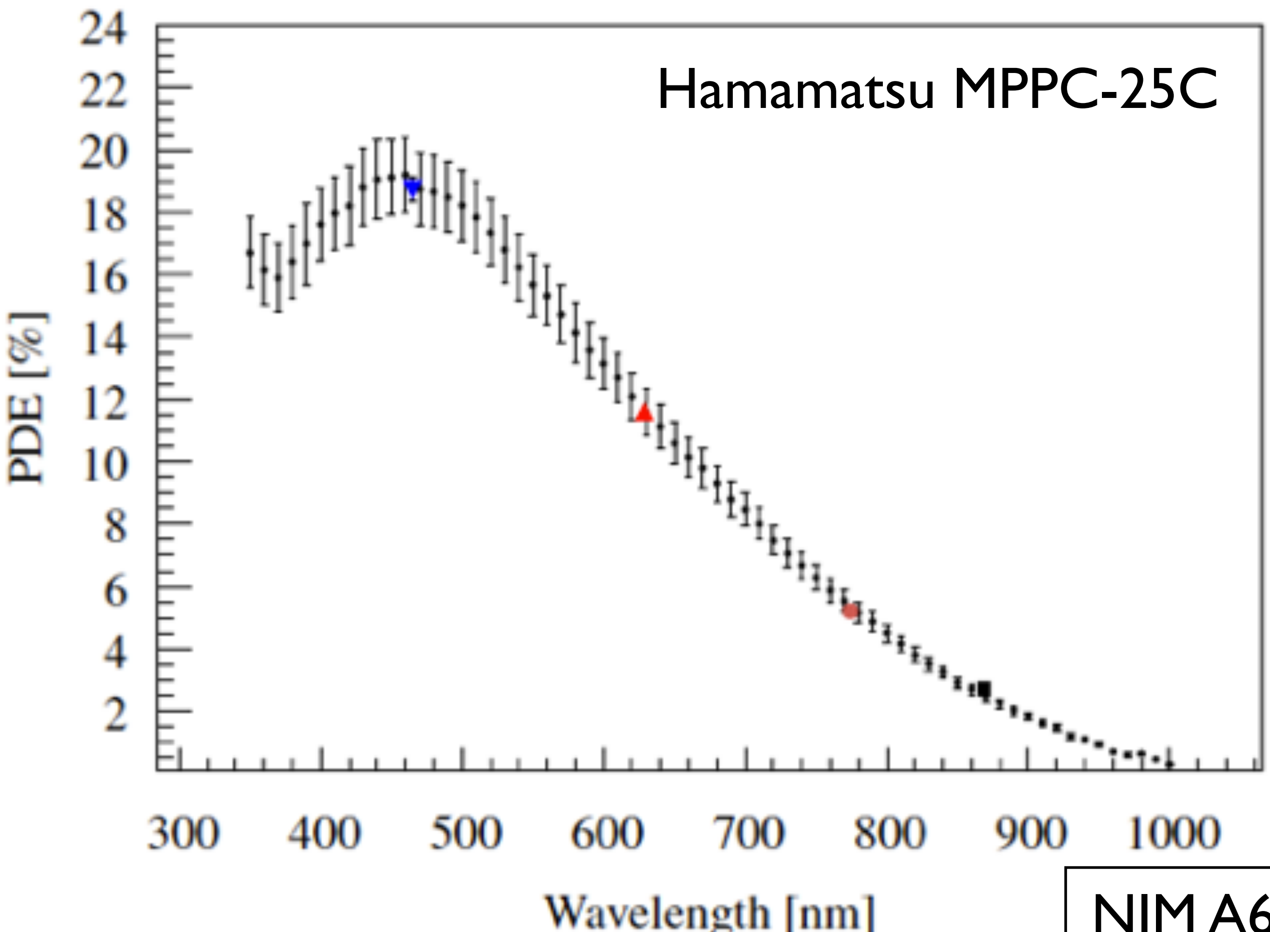
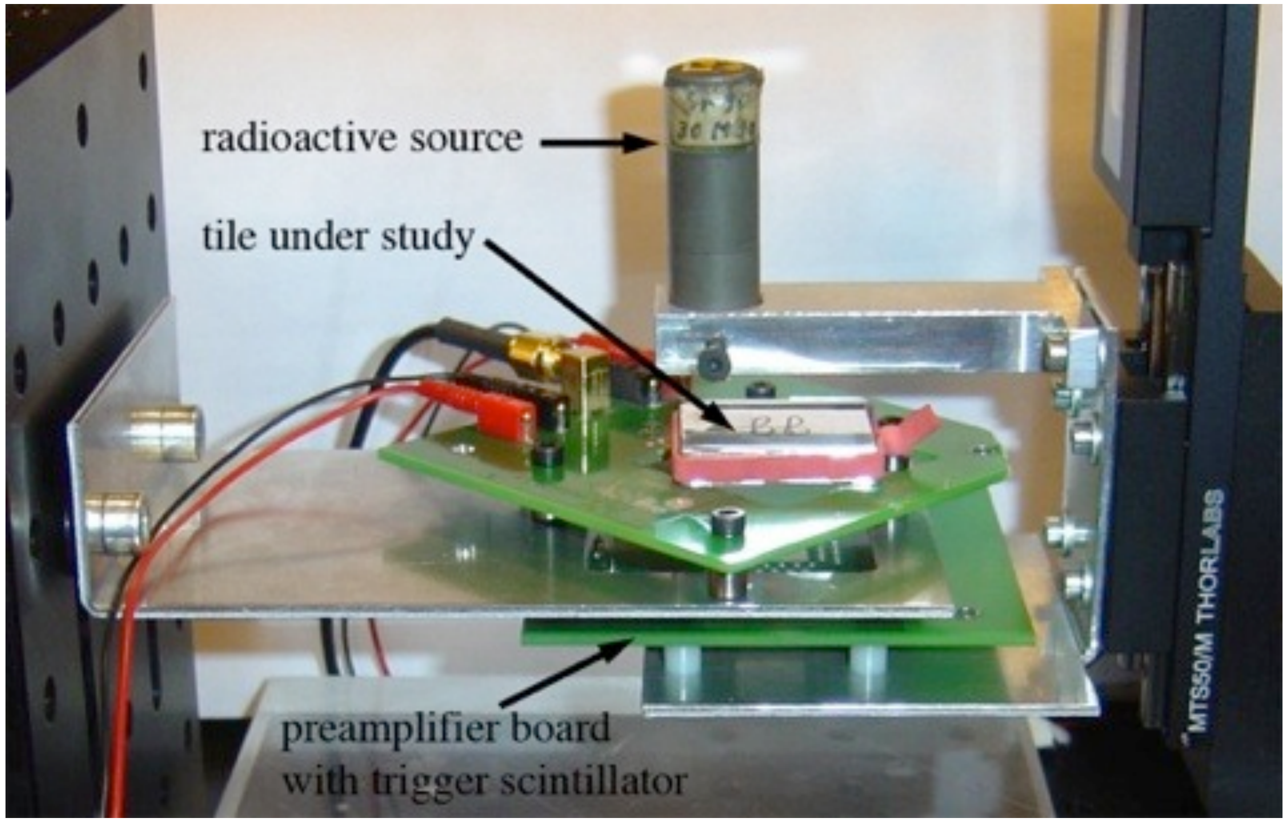
➫ Ideally, we would like to get rid of the fiber - and we can, now that blue / near-UV sensitive SiPMs exist





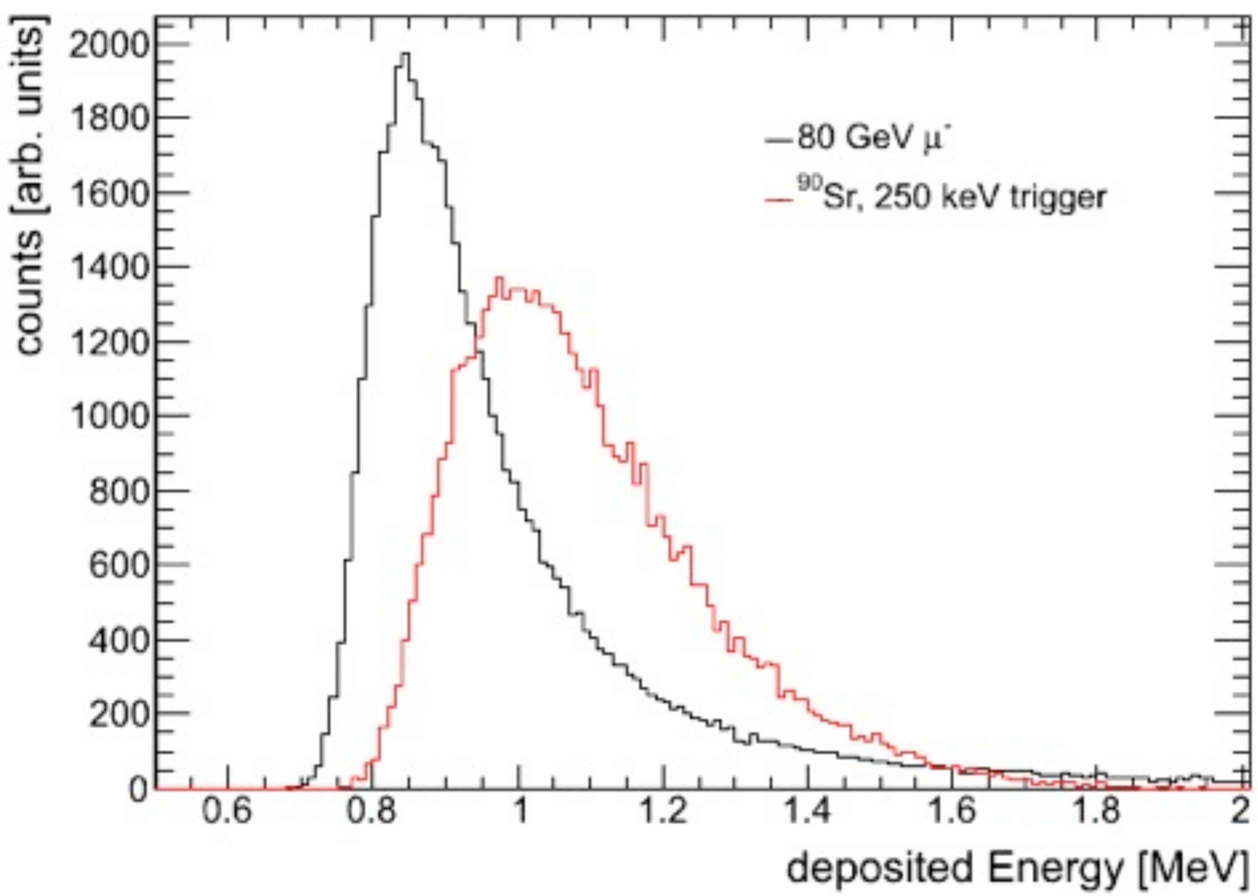
NIM A620, 217(2010)

Testing Scintillator Tiles in the Lab



- Crucial: Capability to test performance of scintillator cells with SiPMs on the bench
- Setup with ^{90}Sr source, allows scanning over the active tile area

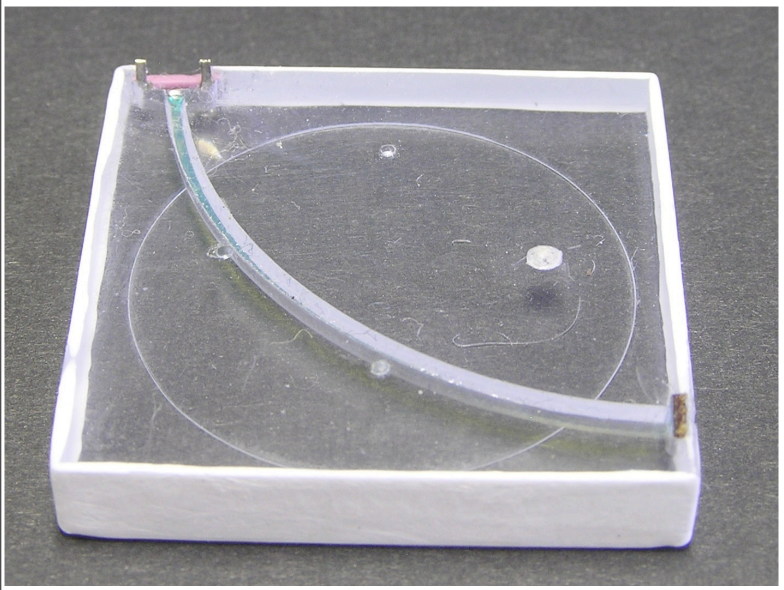
GEANT4 simulations, 5 mm scintillator



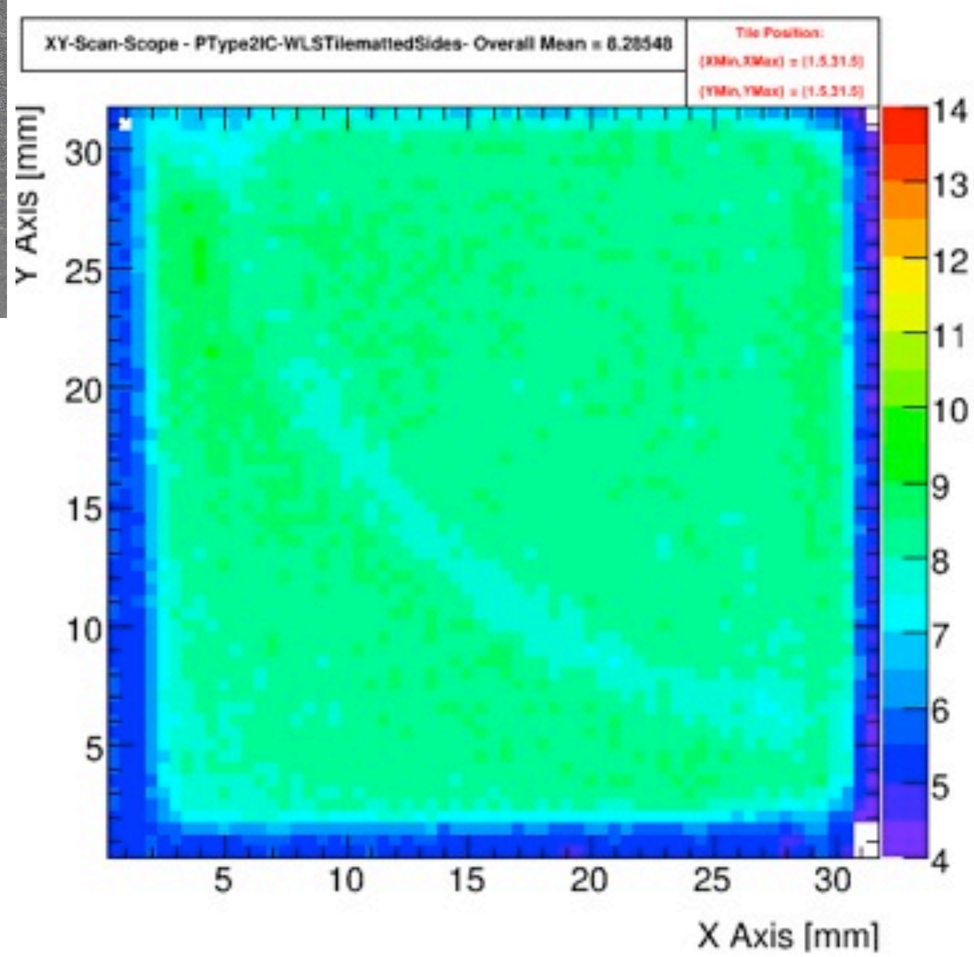
- Performance criteria:
  - Overall signal amplitude ("light yield")
  - Uniformity of response over active area
- Key requirement: Select only penetrating electrons (close approximation of MIPs)
  - Trigger scintillator below tile under study

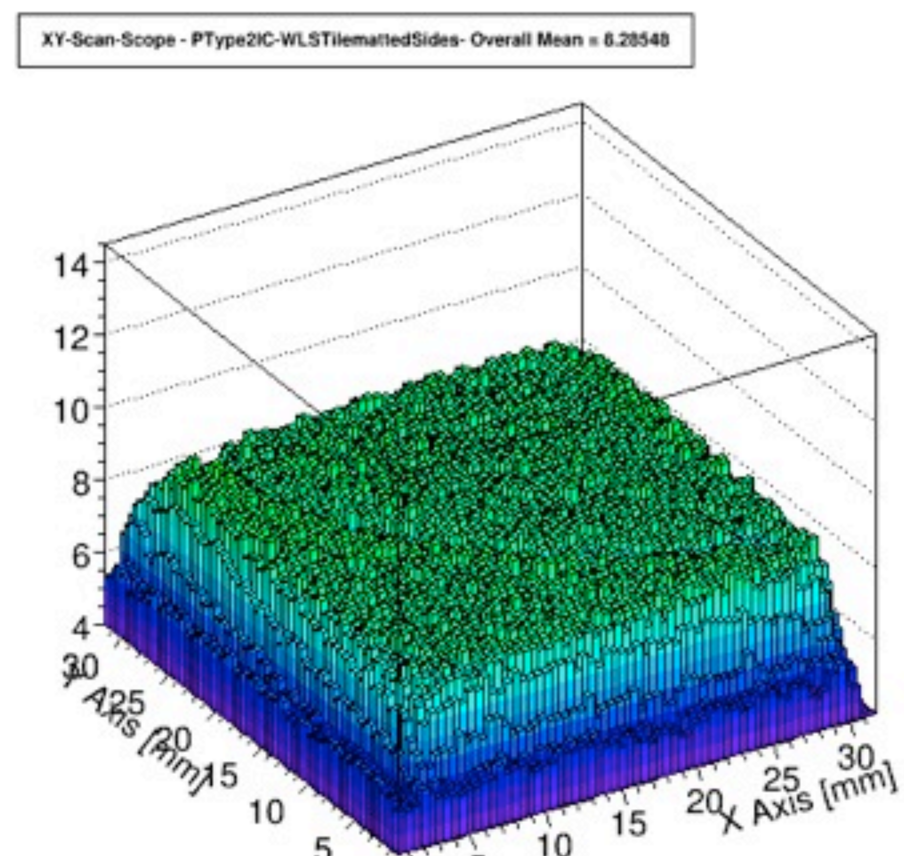
Fiber Benefits: Uniformity

- The fiber does not only shift the wavelength - it also collects light and guides it to the SiPM by total internal refection:
  Provides uniform response over the tile surface



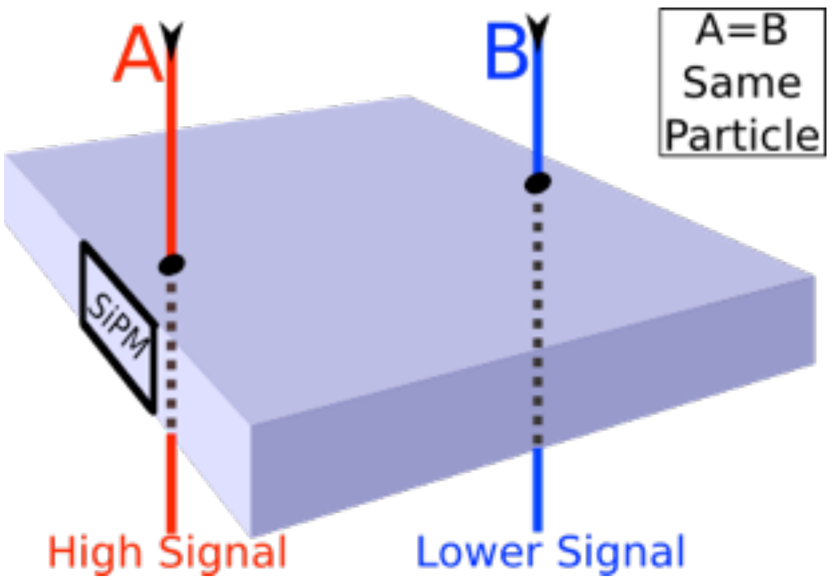
For this test: tile read out with MPPC - sensitivity not well matched to fiber emission

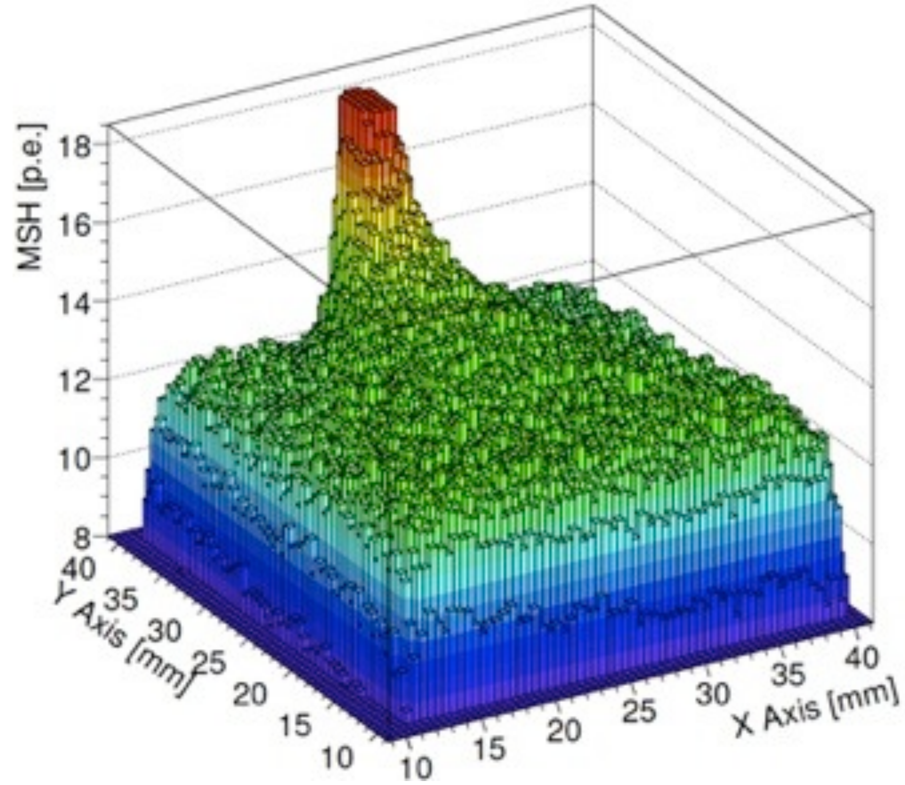




Going Fiberless: A Challenge

- Just putting a SiPM to a piece of scintillator does not work:





- Strategy for improvement:
  - Reduce amount of scintillating material close to photon sensor
  - Diffuse light to reduce spatial dependence
  - Optimize light yield

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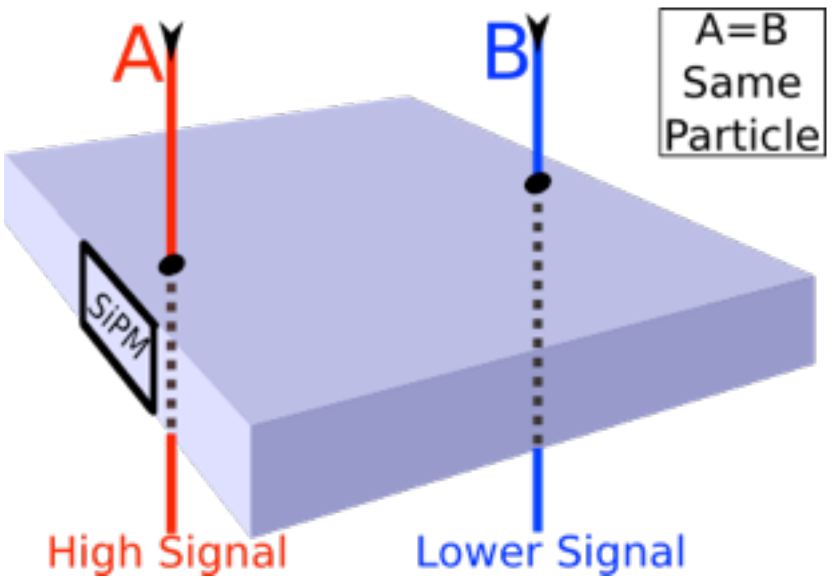

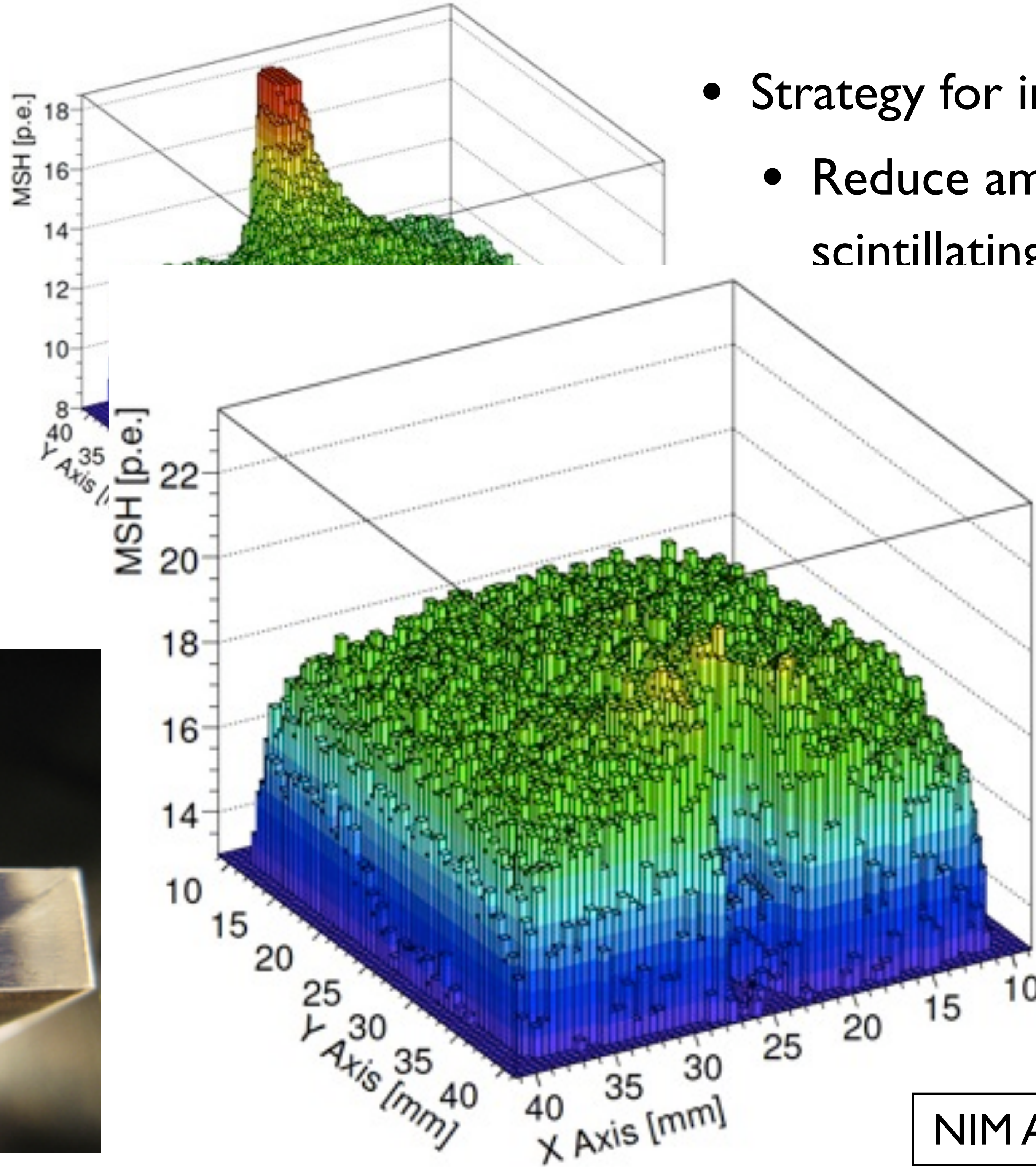

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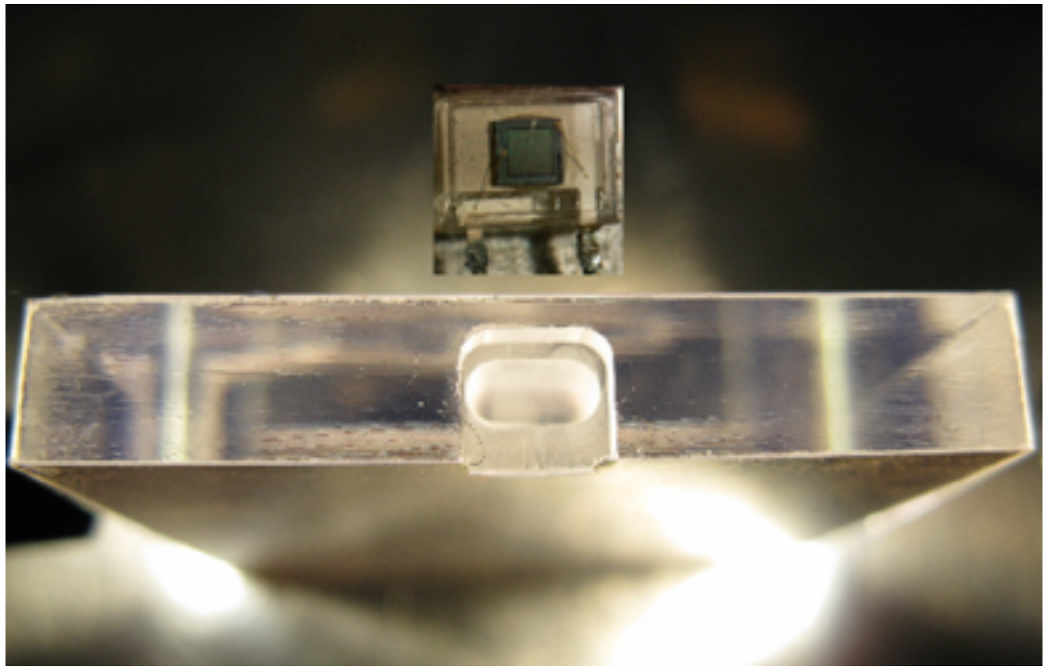
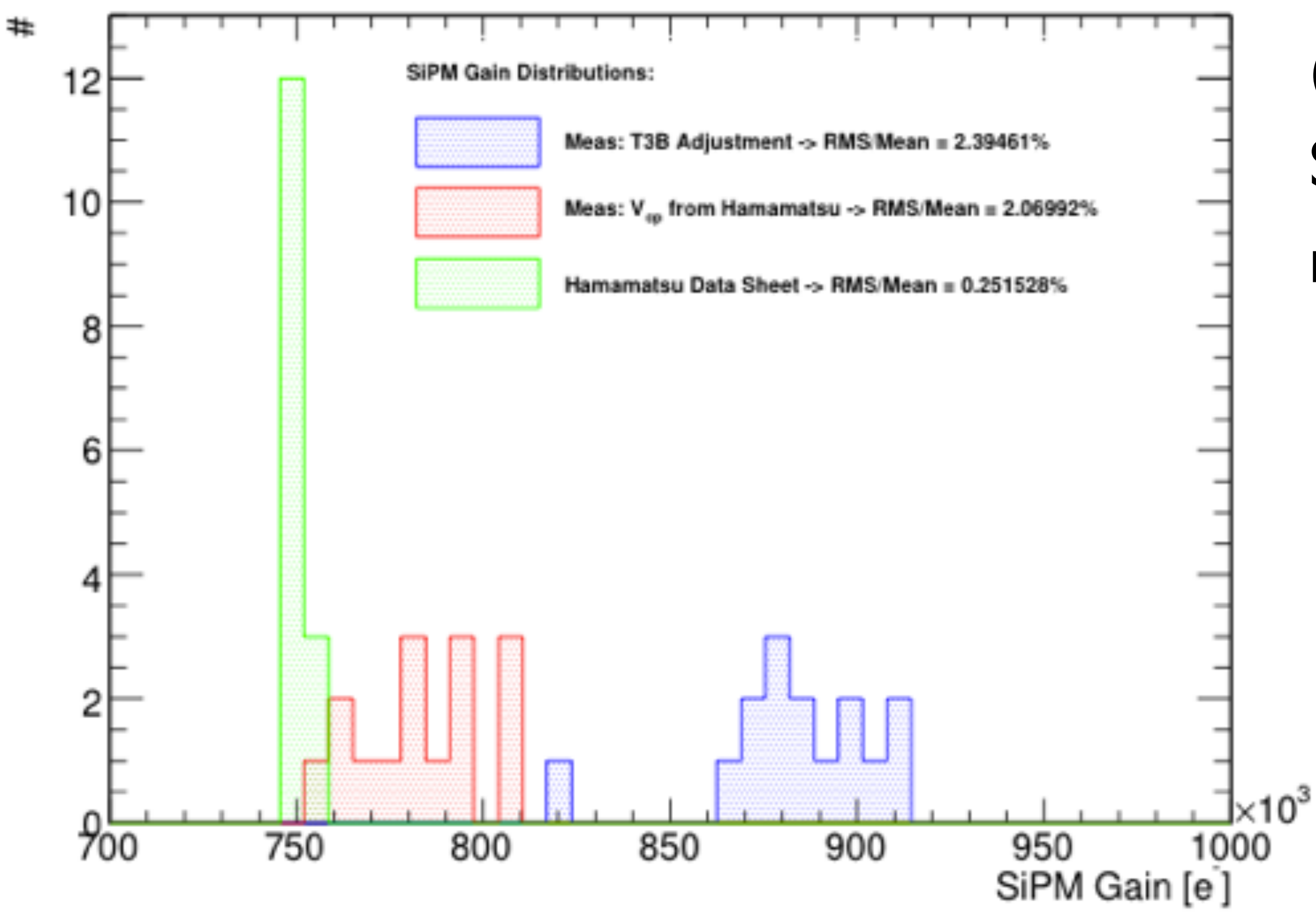
After many iterations:



NIM A620, 196 (2010)

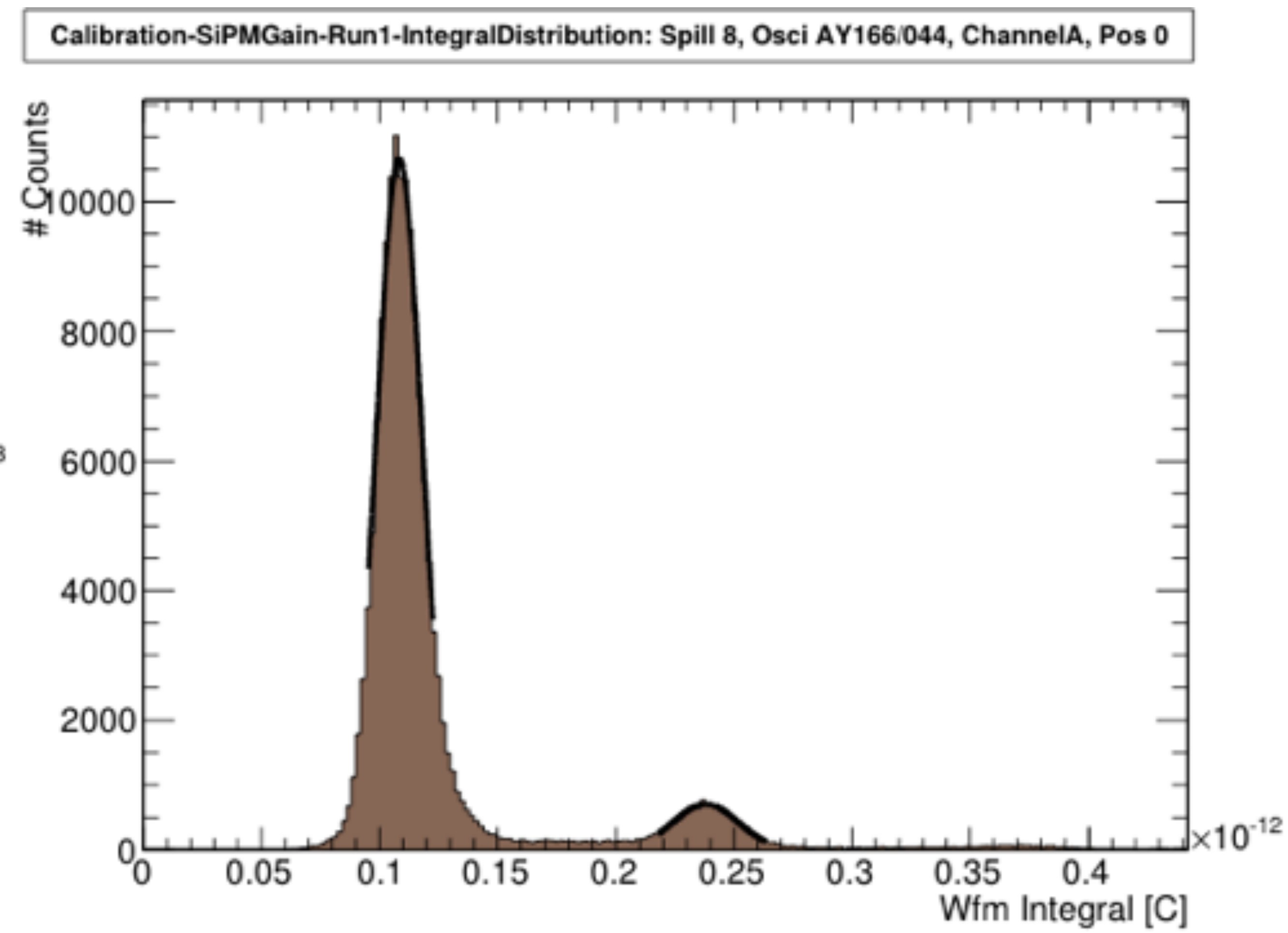
Fiberless Coupling: Reproducibility

- Comparing performance of a small sample of tiles (16 tiles)
  - Each tile read out with a MPPC-50C (thanks Erika!)



All photon sensors adjusted to the same gain (slightly higher than specs)

Spread likely due to (automated) measurement procedure



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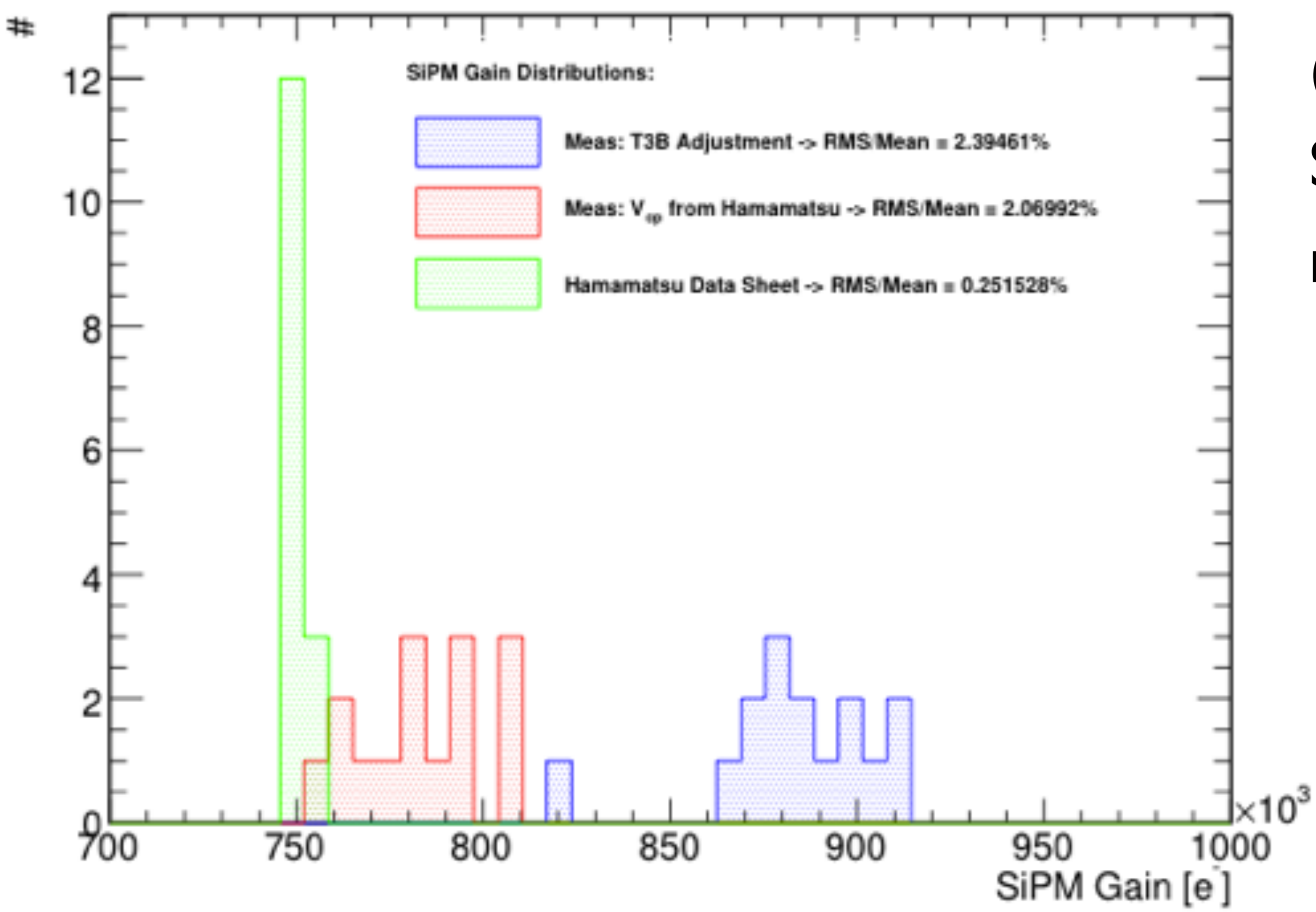

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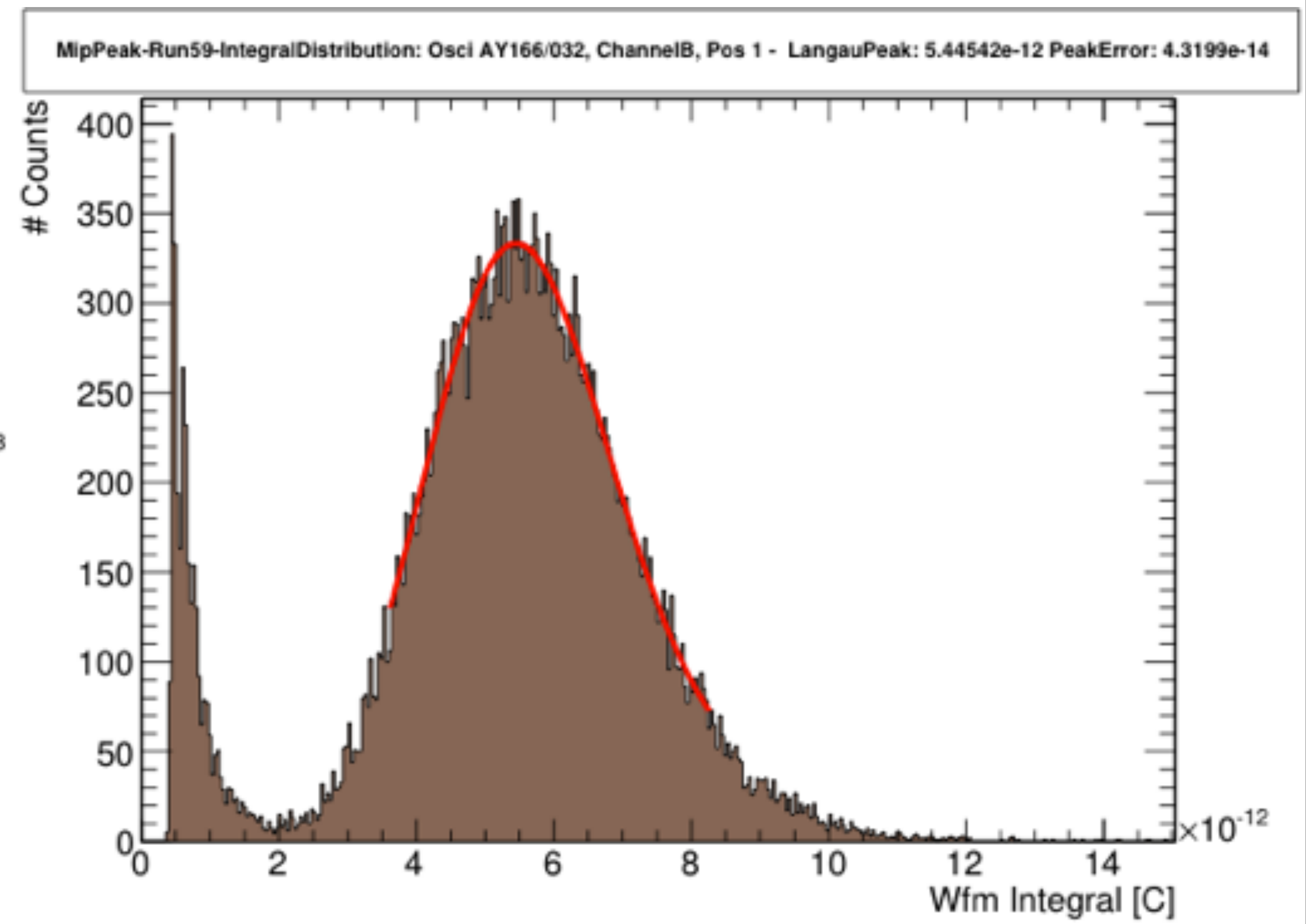
Tile response measured with ^{90}Sr source, extracted with Landau + Gauss fit



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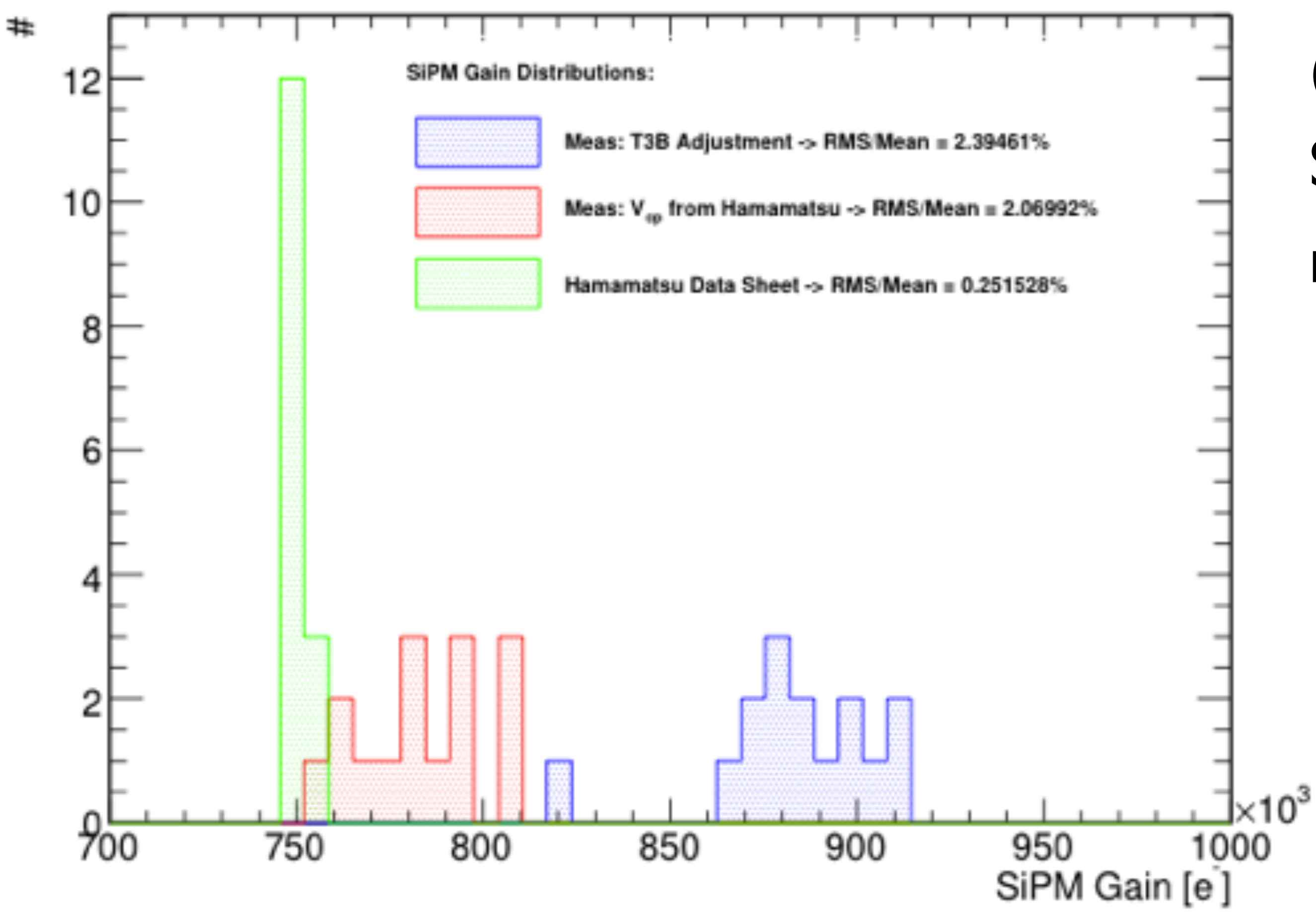

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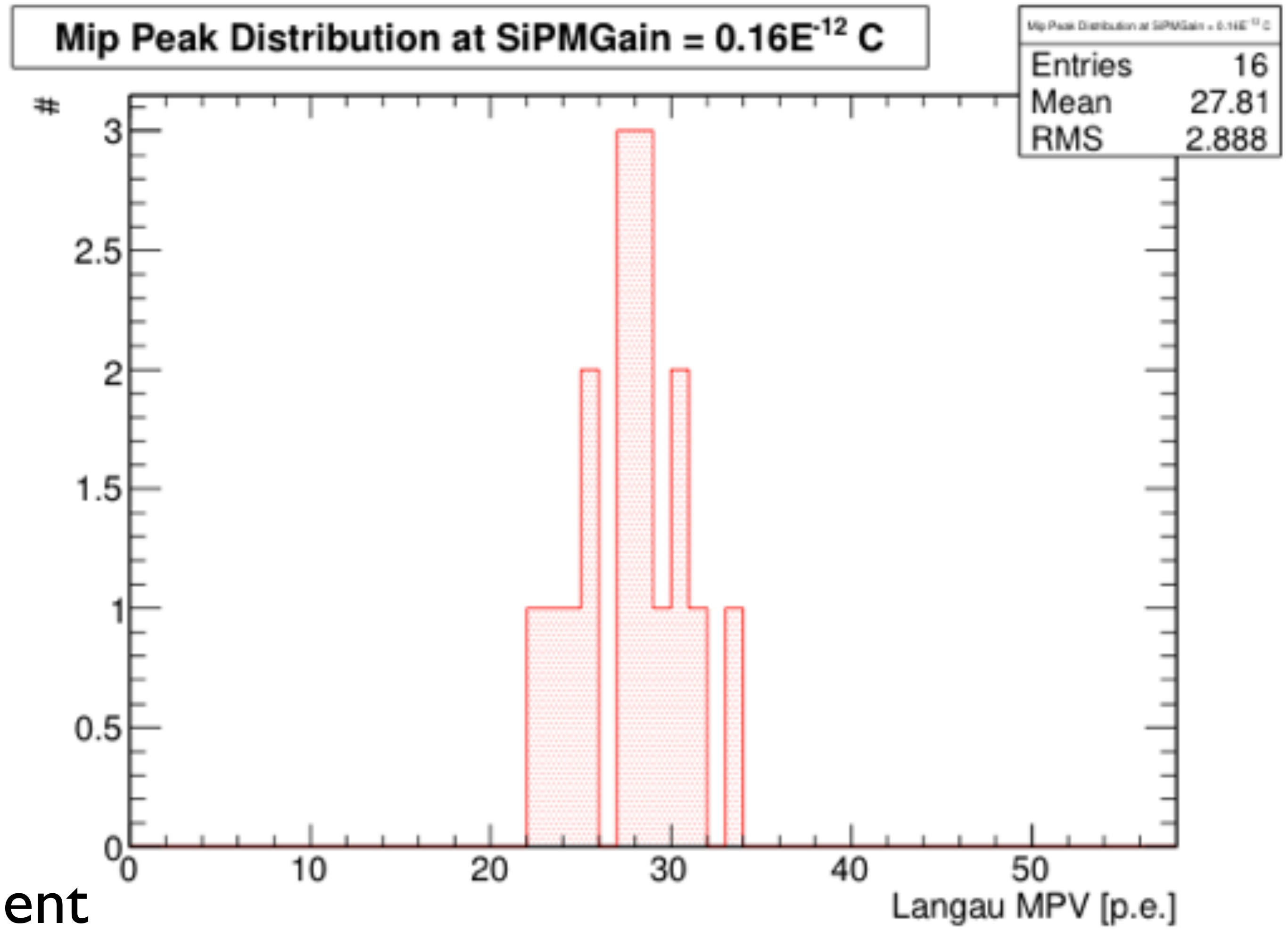
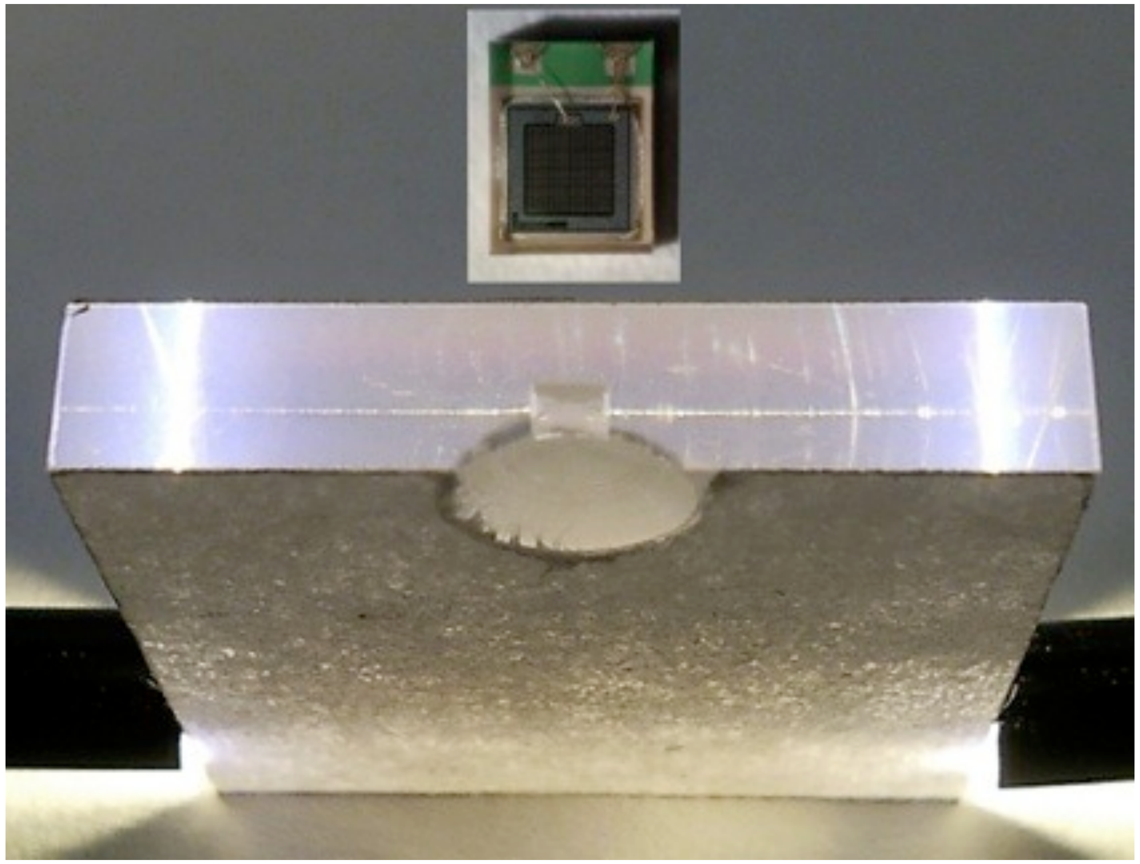


Tile response measured with ^{90}Sr source, extracted with Landau + Gauss fit

10% RMS spread observed for sample: corresponds to expected precision requirement

Fiberless Coupling: Scalability?

- An open question: How can we produce millions of cells needed for a complete collider detector?
  - Clear advantage for fiberless design: Should be easier to fabricate



- Designs suited for molding show good uniformity and satisfactory signal amplitudes
- Next steps: Try it out!
  Need the right material, and a company who can do it... Ideas?

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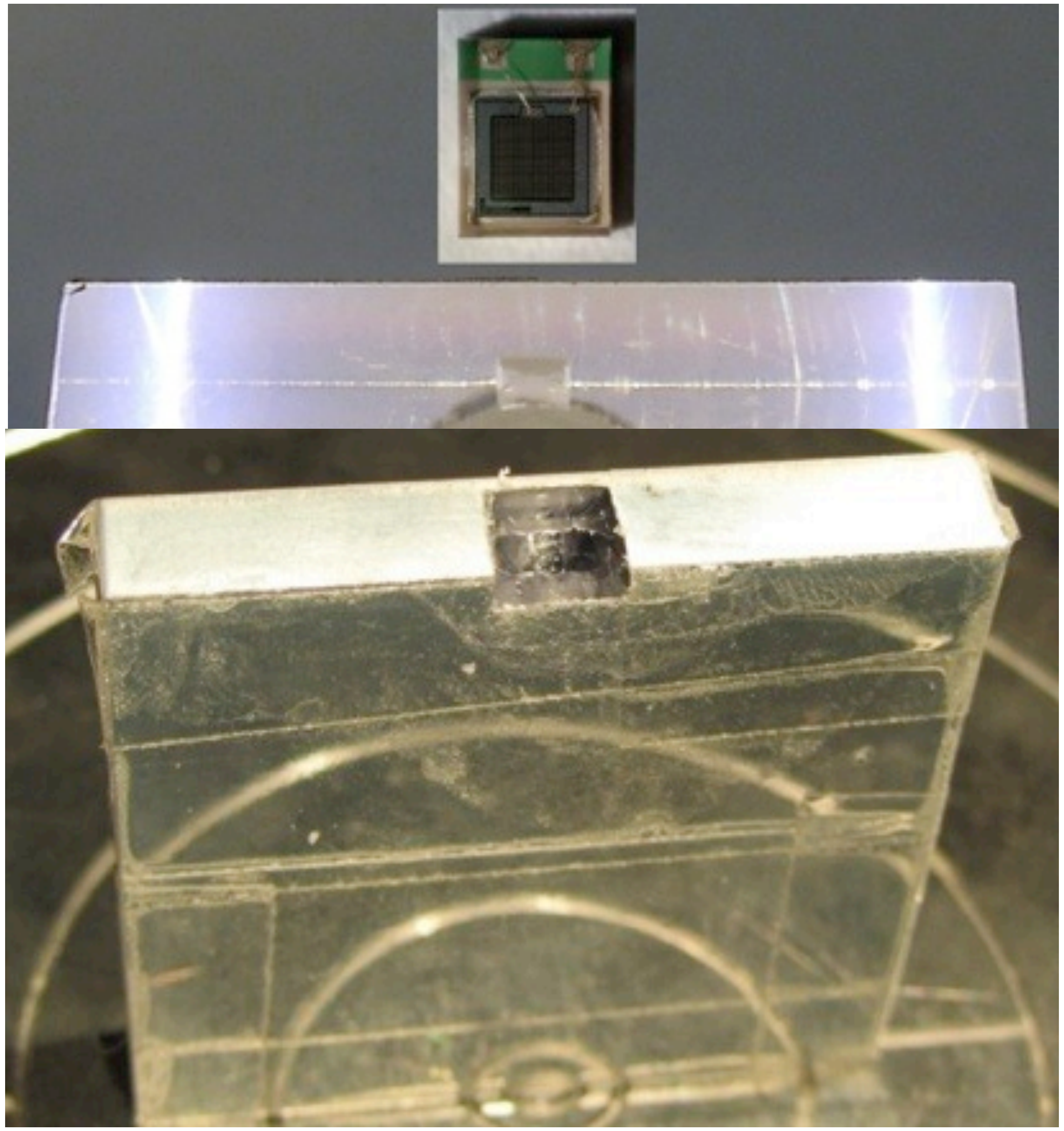
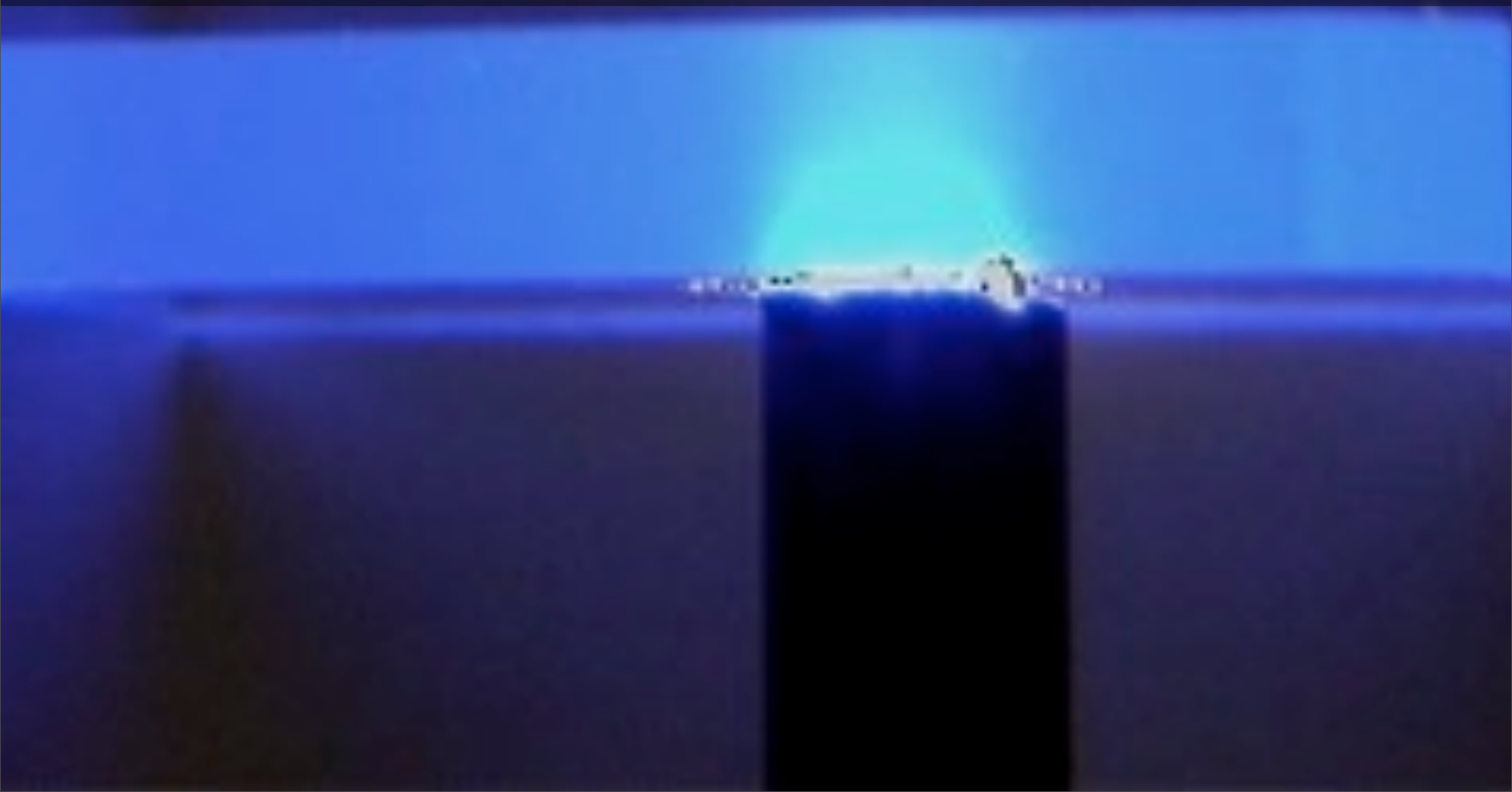


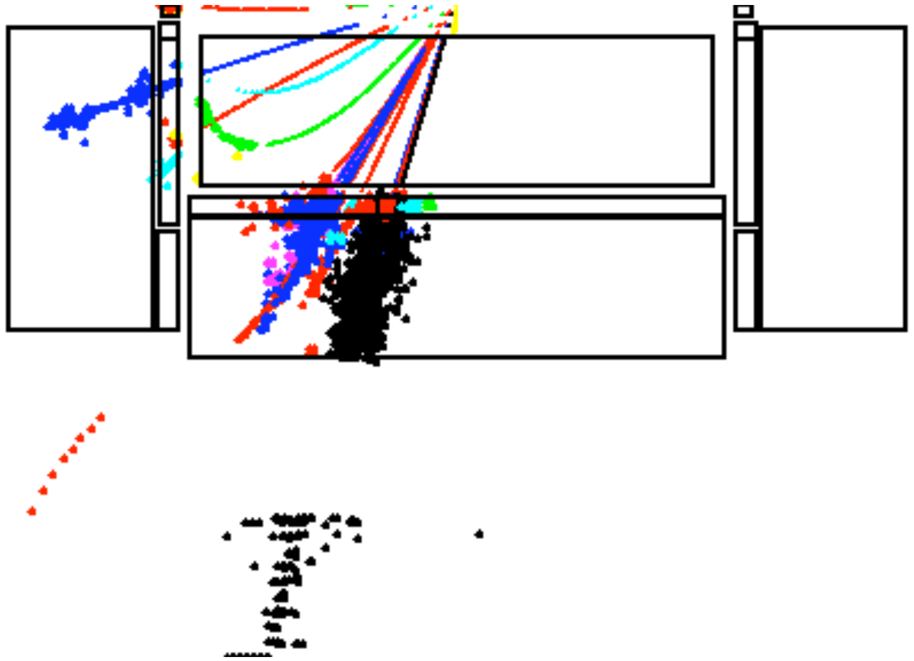
- Designs suited for molding show good uniformity and satisfactory signal amplitudes
- Next steps: Try it out!
  Need the right material, and a company who can do it... Ideas?

- Additional issues: Coating of tiles
  - Possible solution: Al sputtering
    First tests revealed problems with oxidation due to discharged: needs further investigation

Pushing Further: The 4th Dimension



Setting the Stage: 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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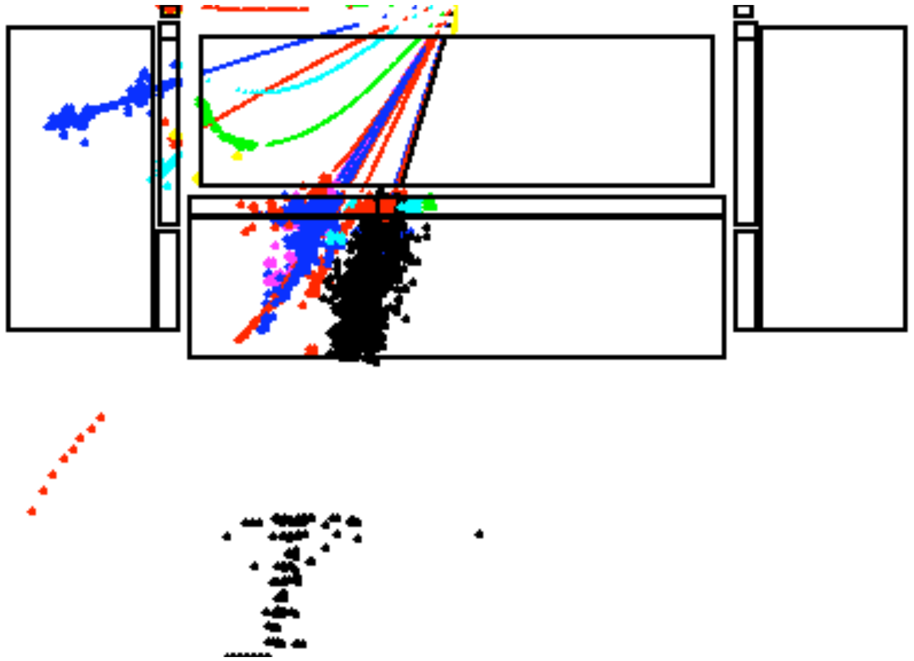
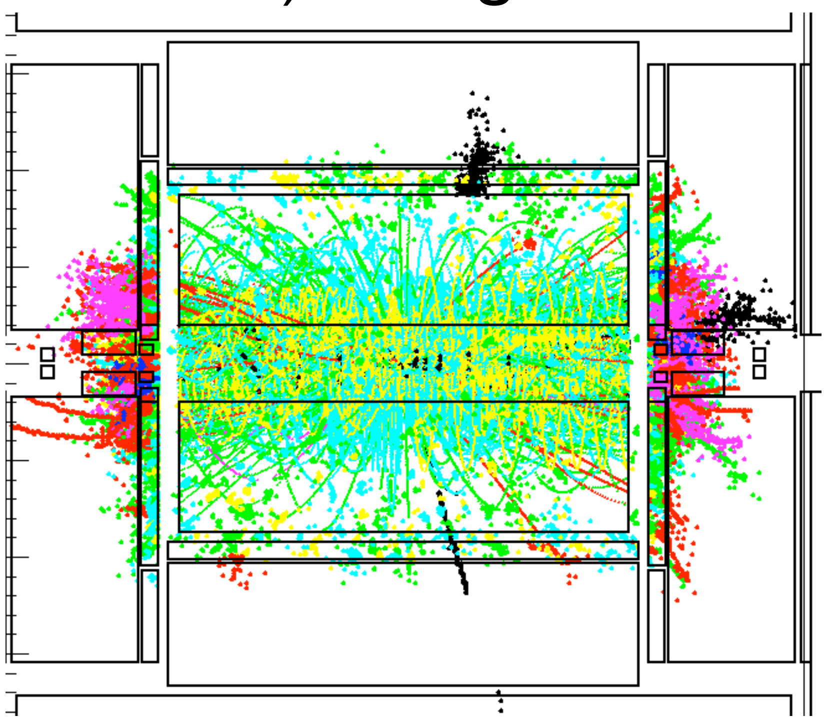


Shower containment and leakage is a crucial issue

➩ A (very) deep hadron calorimeter is needed

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

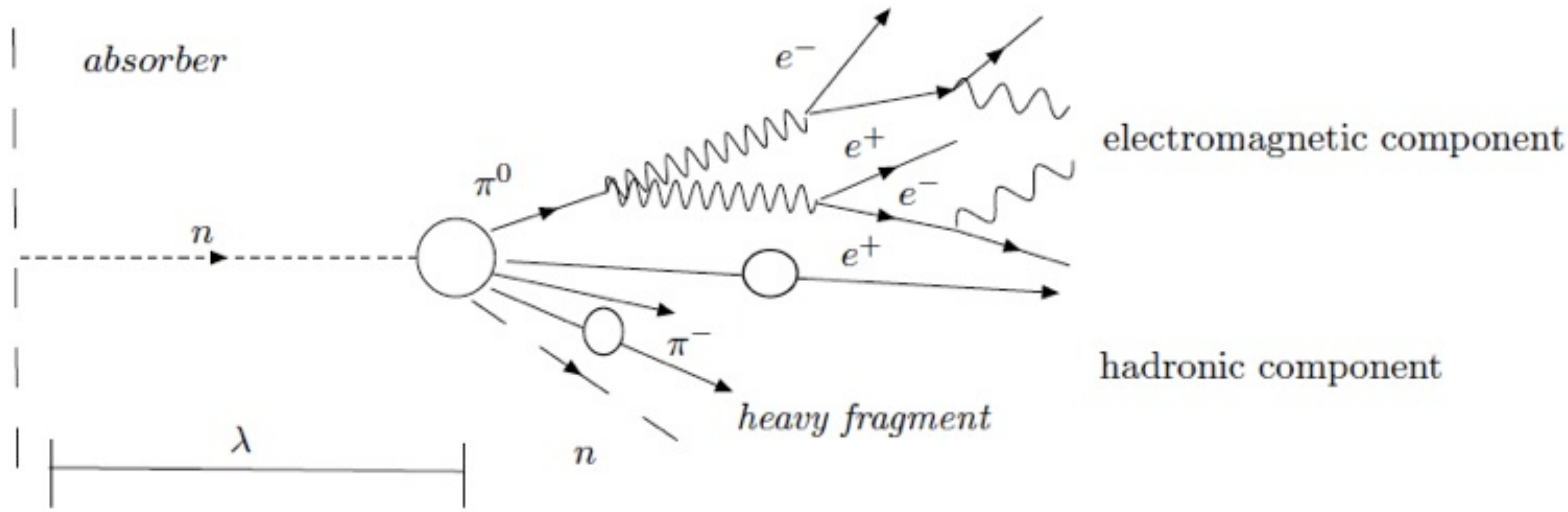
- Key challenge (linked to high energy and machine-specific issues): Background
  - $\gamma\gamma \rightarrow$ hadrons substantial:
    ~ 12 hadrons/bunch crossing in the barrel region (4 GeV / bunch crossing) [up to 50 hadrons / 50 - 60 GeV barrel + endcap + plug calorimeters]
  - extreme bunch crossing 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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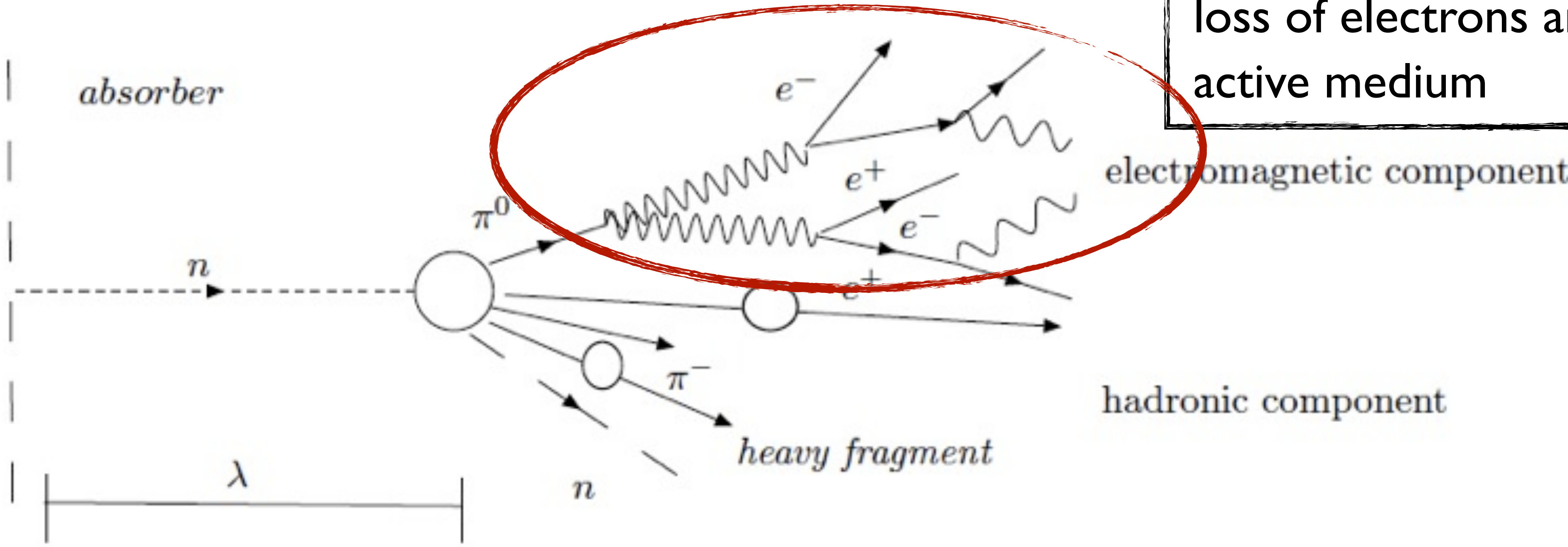

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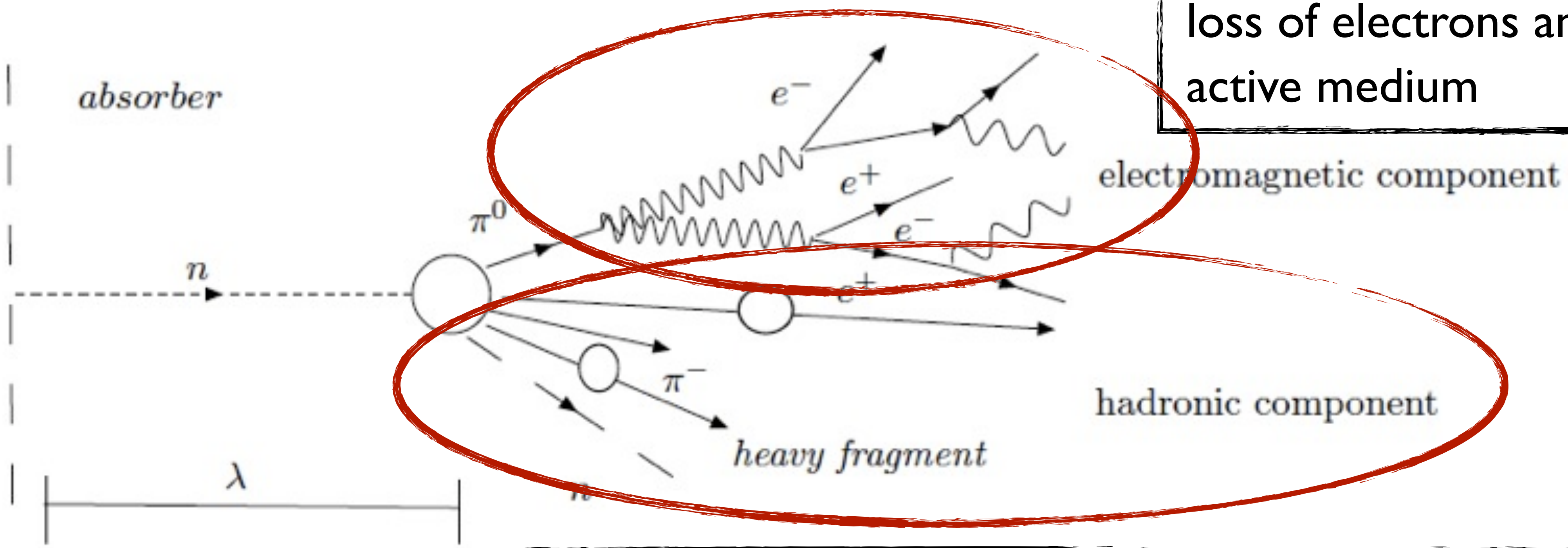

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- instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium
- delayed component: photons, neutrons, protons from nuclear de-excitation, detected via e^+e^-, momentum transfer to protons in hydrogenous active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

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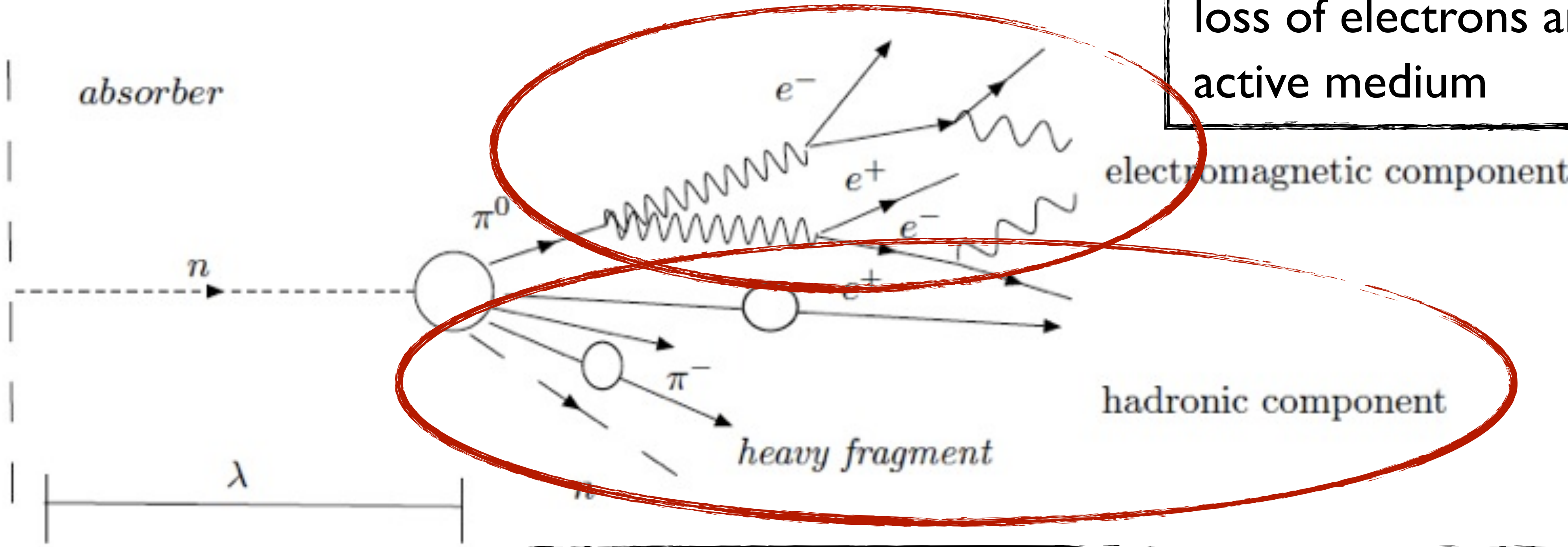

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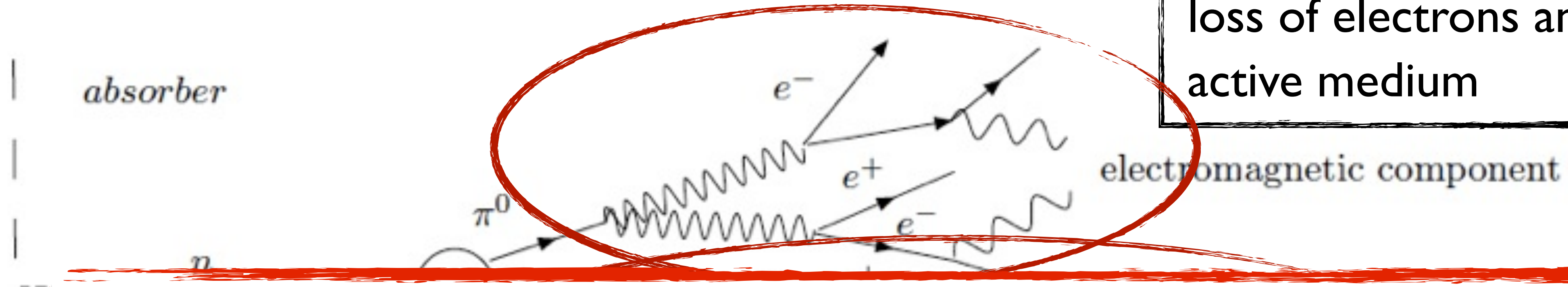

Detector optimization and performance studies rely on Geant4:
How well do the simulations reproduce the time structure
of the response in the CLIC HCAL?

nergy

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T3B: An Experiment for a First 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 (steel of AHCAL prototype replaced by Tungsten)
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  - Goal: Measure the time structure of the signal within hadronic showers in a Tungsten calorimeter with scintillator readout
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  - First test beam campaign: November 2010, CERN PS
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➩ First information on time structure, possibility for comparisons to Geant4, but: no complete "4D" shower reconstruction!

T3B Technology

- Scintillators and photon sensors:
  - Fast response - Use fiberless scintillator tiles
  - High light yield to provide sensitivity to small energy deposits
    - Use photon sensors with high PDE, limited dynamic range: MPPC-50C (400 pixels)

- Data acquisition:
  - Fast sampling to allow for single photon resolution: 1 GHz or more
  - Long acquisition window to provide sensitivity to late shower components: 2+ μs
  - High trigger rate: faster than CALICE AHCAL trigger, > few kHz

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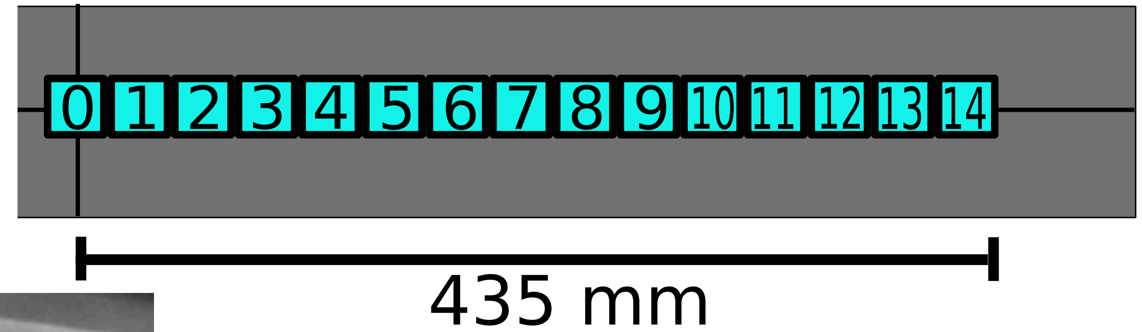
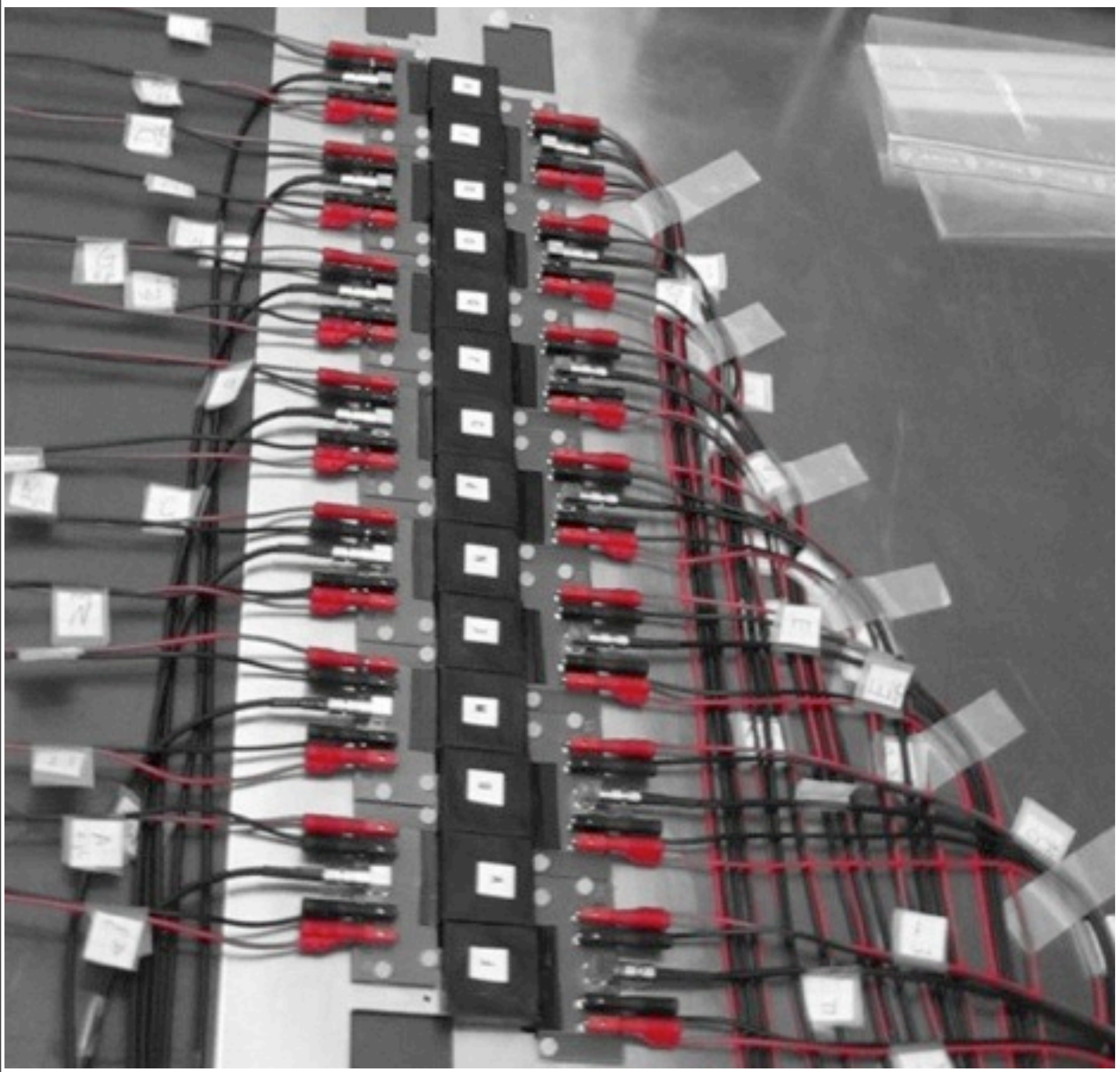
- Adopted solution for T3B: PicoScope 6403 (USB controlled oscilloscope)
  - 1.25 GHz sampling for 4 channels per unit
  - 1 GB buffer memory (shared between channels)
  - Burst trigger mode: Maximum rate determined by window length:
    ~ 500 kHz for 2μs acquisition window

The T3B Setup: Test Beams at CERN PS & SPS

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

beam axis
through cell 0





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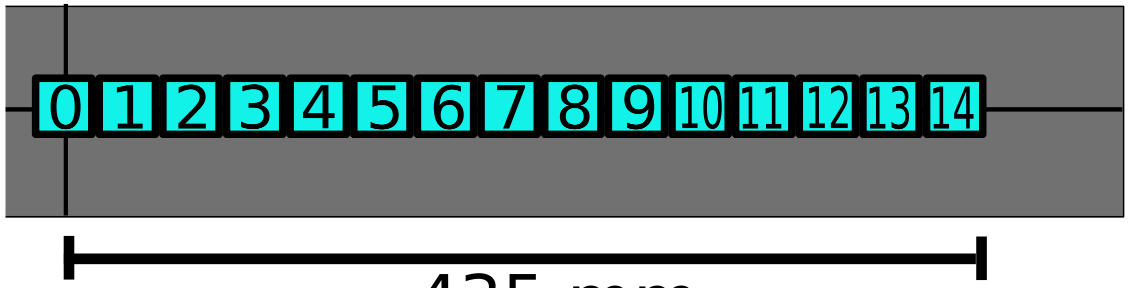


Stand-alone system:

- Installed downstream of CALICE WHCAL, depth ~ 4 λ
- Calibration triggers on dark noise between spills

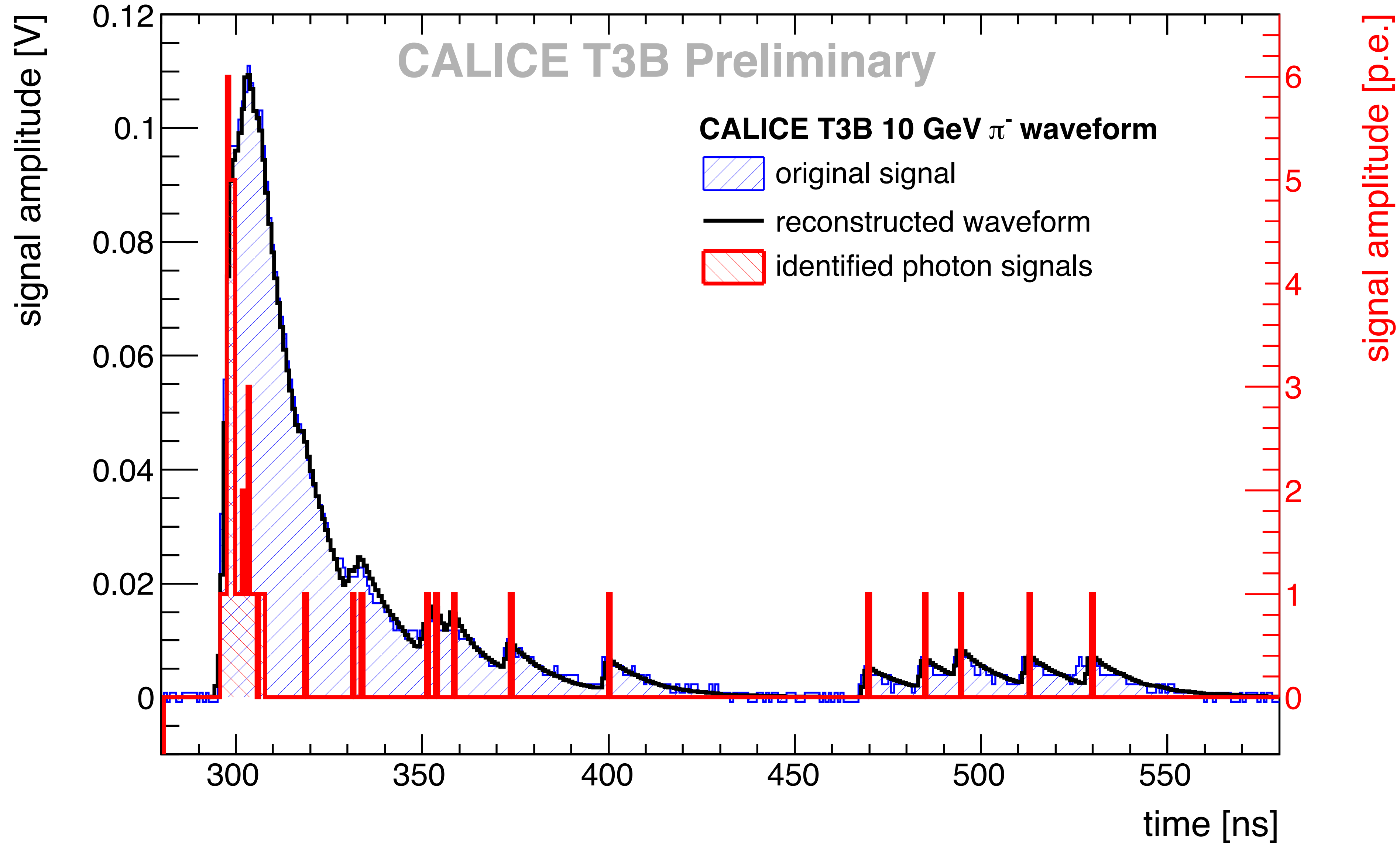
Synchronization with CALICE

- Triggered by CALICE trigger - common analysis possible in the future

Data Analysis - Technique

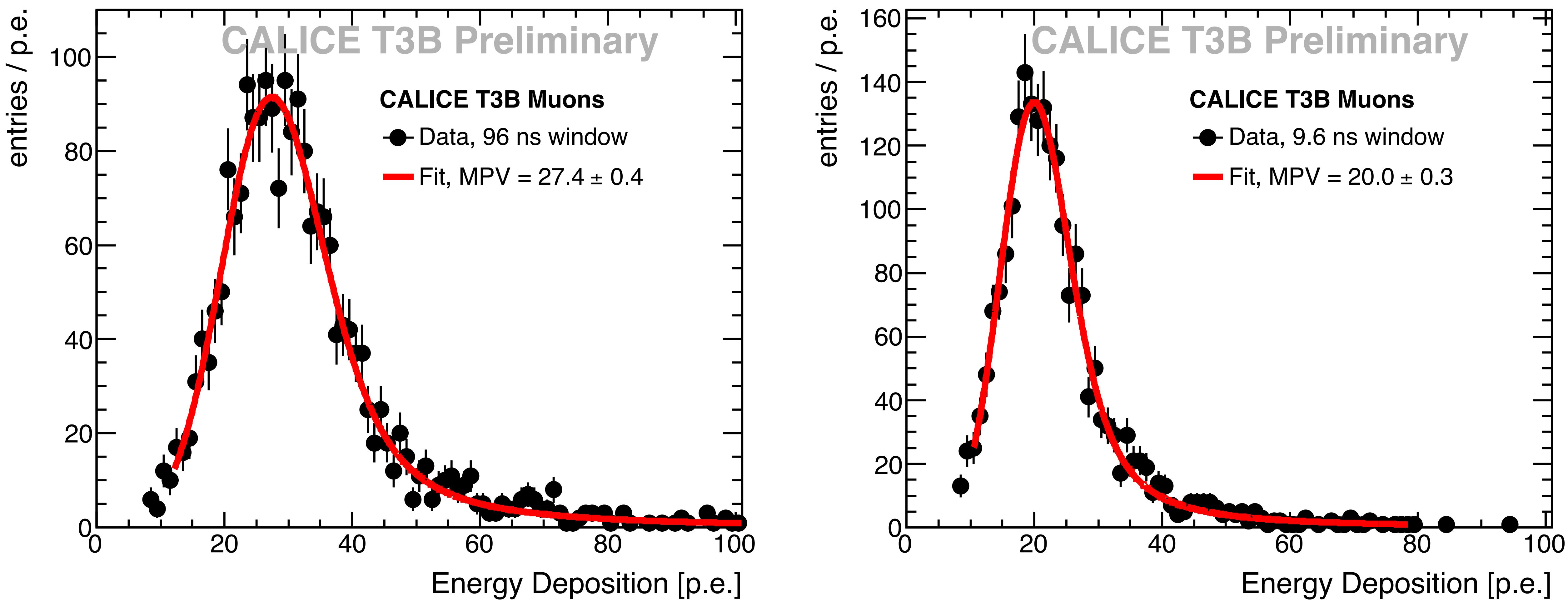
- For each channel, a complete waveform with 3000 samples (800 ps /sample) is saved
- Waveform decomposed into individual photon signals, using averaged 1 p.e. signals
  - Average 1 p.e. signal taken from calibration runs between spills, refreshed every 5 minutes: Continuous automatic gain calibration

- Reconstruction of the time of each photo-electron: Allows various different analyses



First Results - Muons

- Energy of muons reconstructed in the central T3B tile
  - Full reconstruction with waveform decomposition
  - Response variations from cell to cell: 10% (from bench measurements)



- Two integration times: Short time window rejects a significant fraction of SiPM afterpulses (detailed investigations of other contributions ongoing)

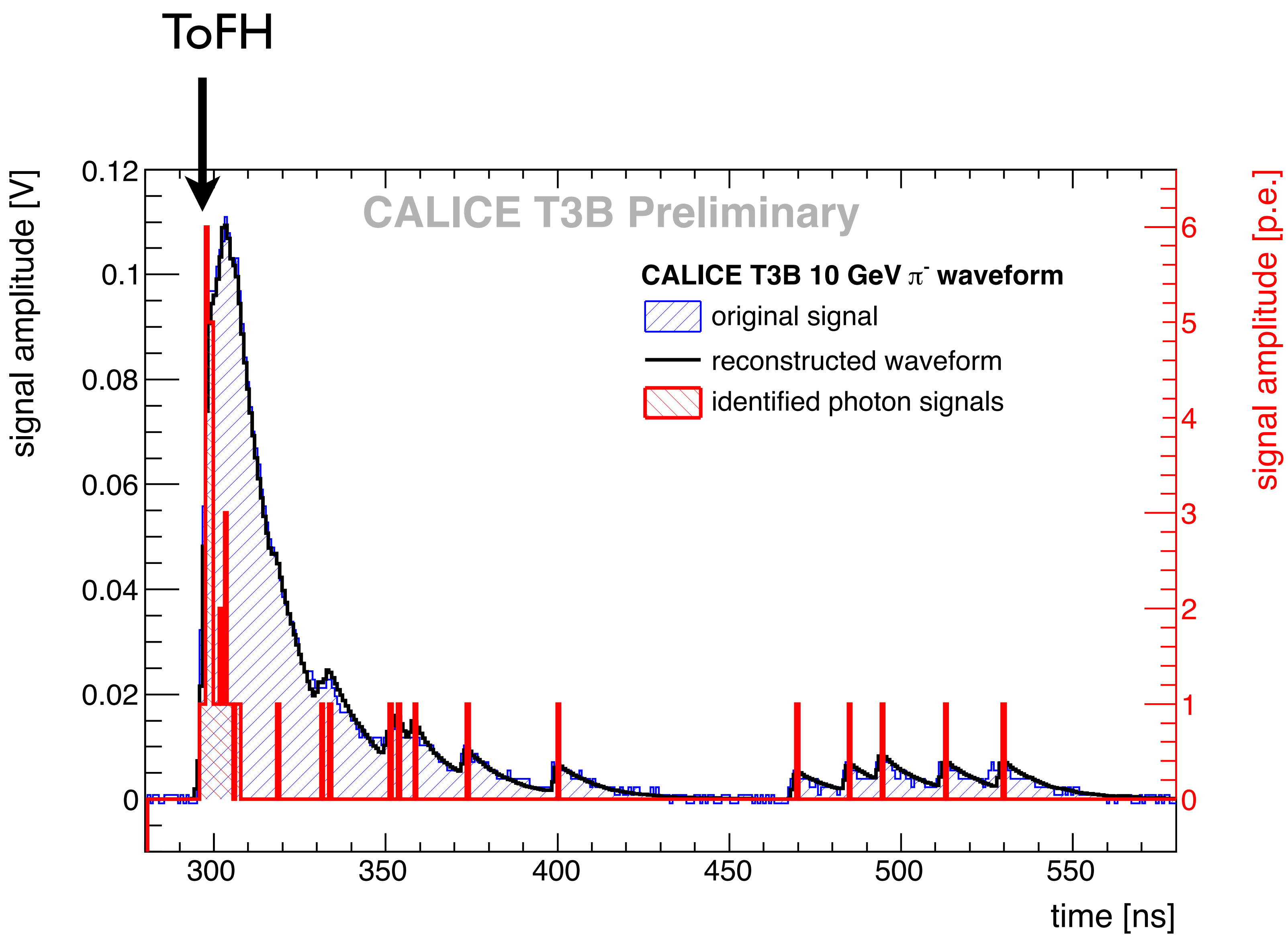
First Results - Muon Timing

- Present analysis: determining the Time of First Hit
  - minimum of 8 p.e. (~ 0.4 MIP) within 9.6 ns

Time of First Hit for Muons:

- Response to instantaneous energy deposit

Muons from PS:
Energy a few GeV



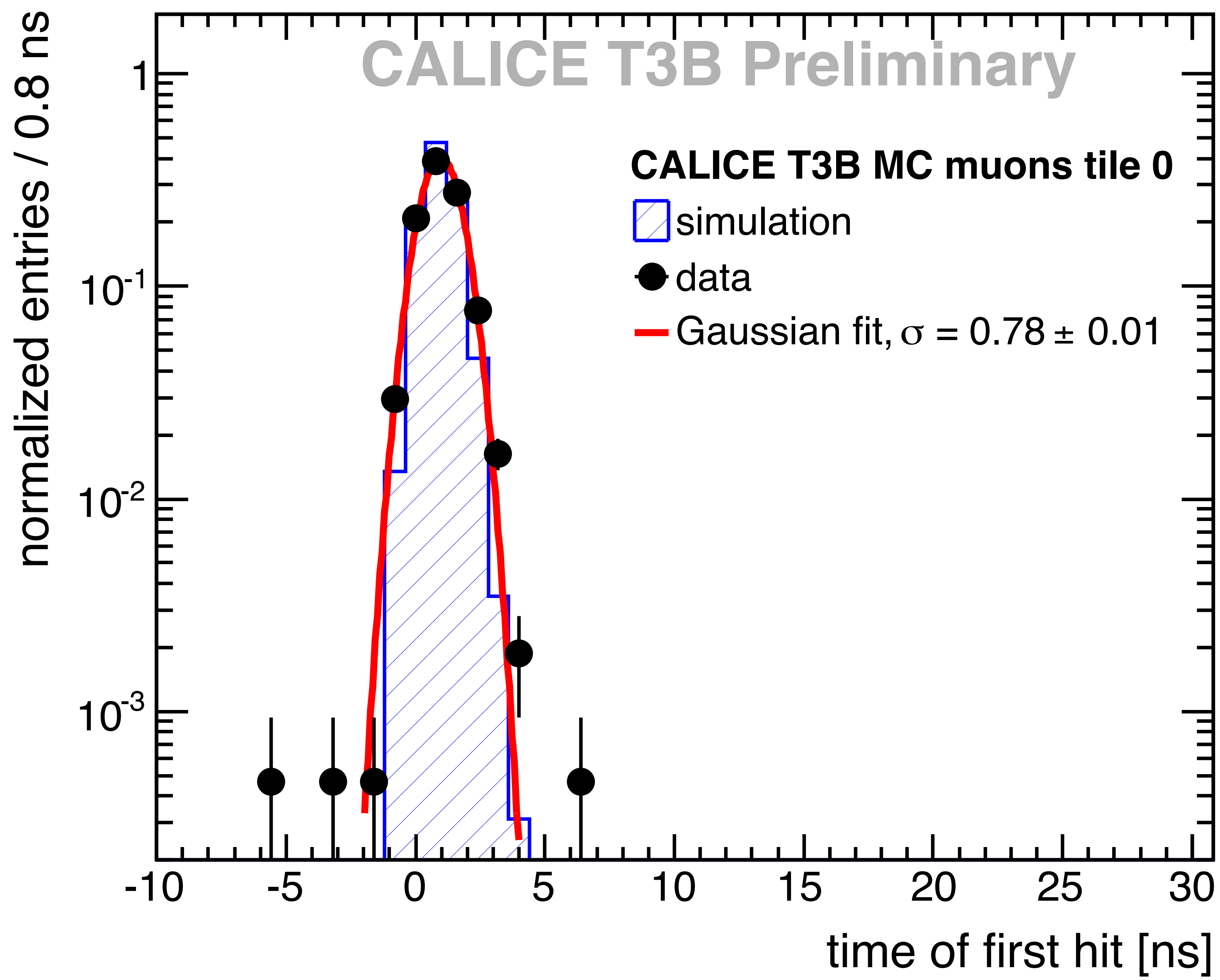
First Results - Muon Timing

- Present analysis: determining the Time of First Hit
  - minimum of 8 p.e. (~ 0.4 MIP) within 9.6 ns

Time of First Hit for Muons:

- Response to instantaneous energy deposit
- Time resolution (including trigger): ~ 800 ps
- Consistent with simulations including time smearing

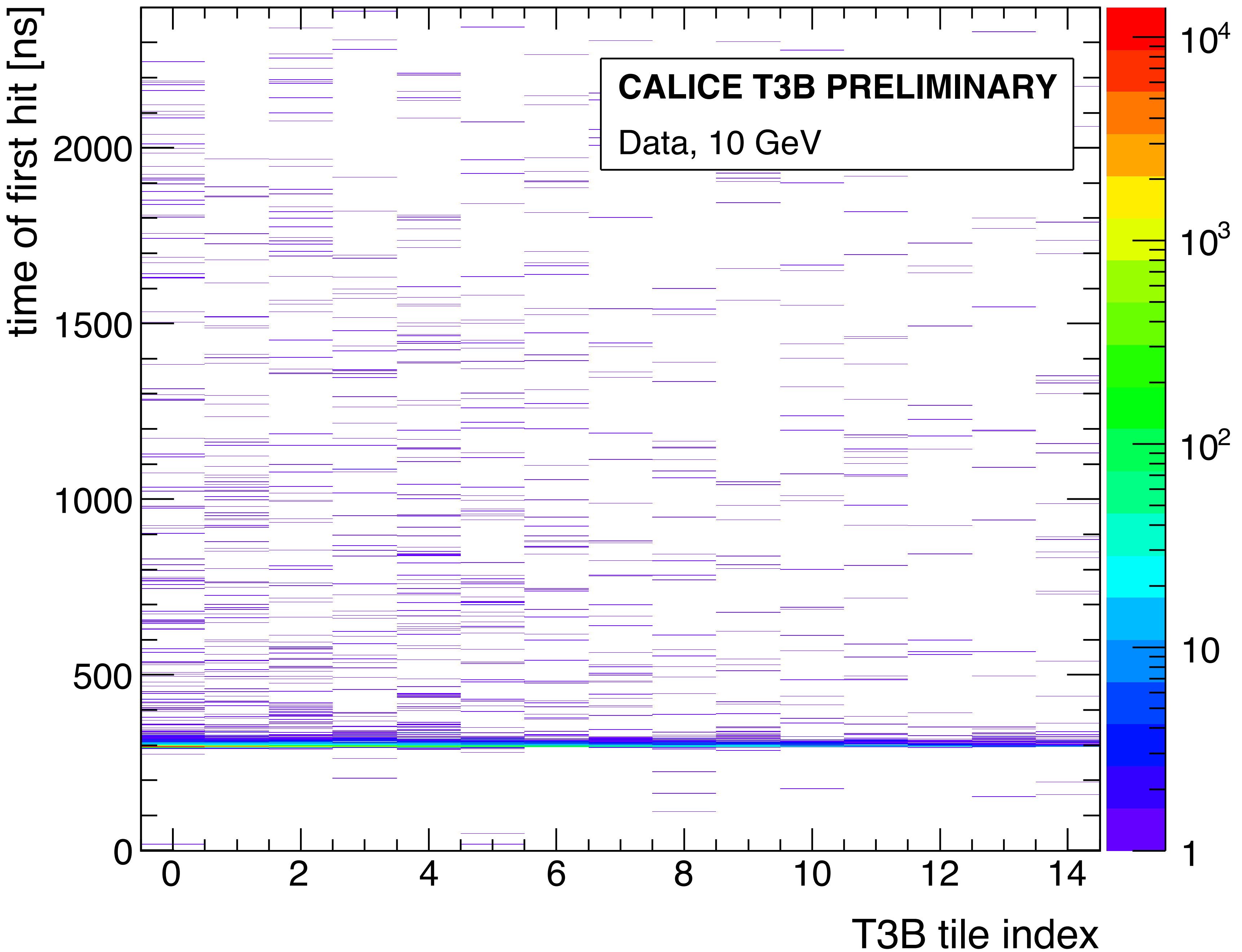
Muons from PS:
Energy a few GeV



First Results - Pion Data

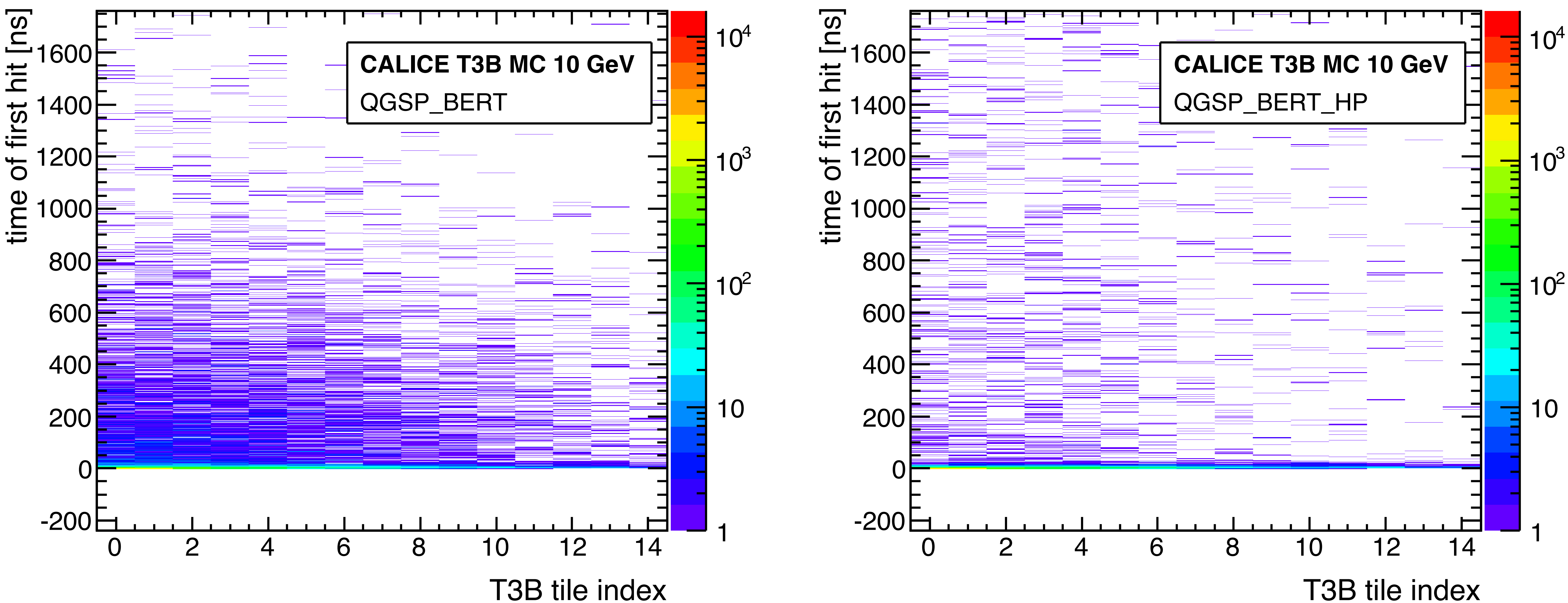
- Data taken in CALICE WHCAL Testbeam at CERN PS
  - Current analysis: Highest energy taken at PS - 10 GeV π^-
  - Time of First Hit

Time of first hit:
Easy to define in data and MC without detailed treatment of
- afterpulsing
- time distribution of scintillator response
- photon travel
- ...

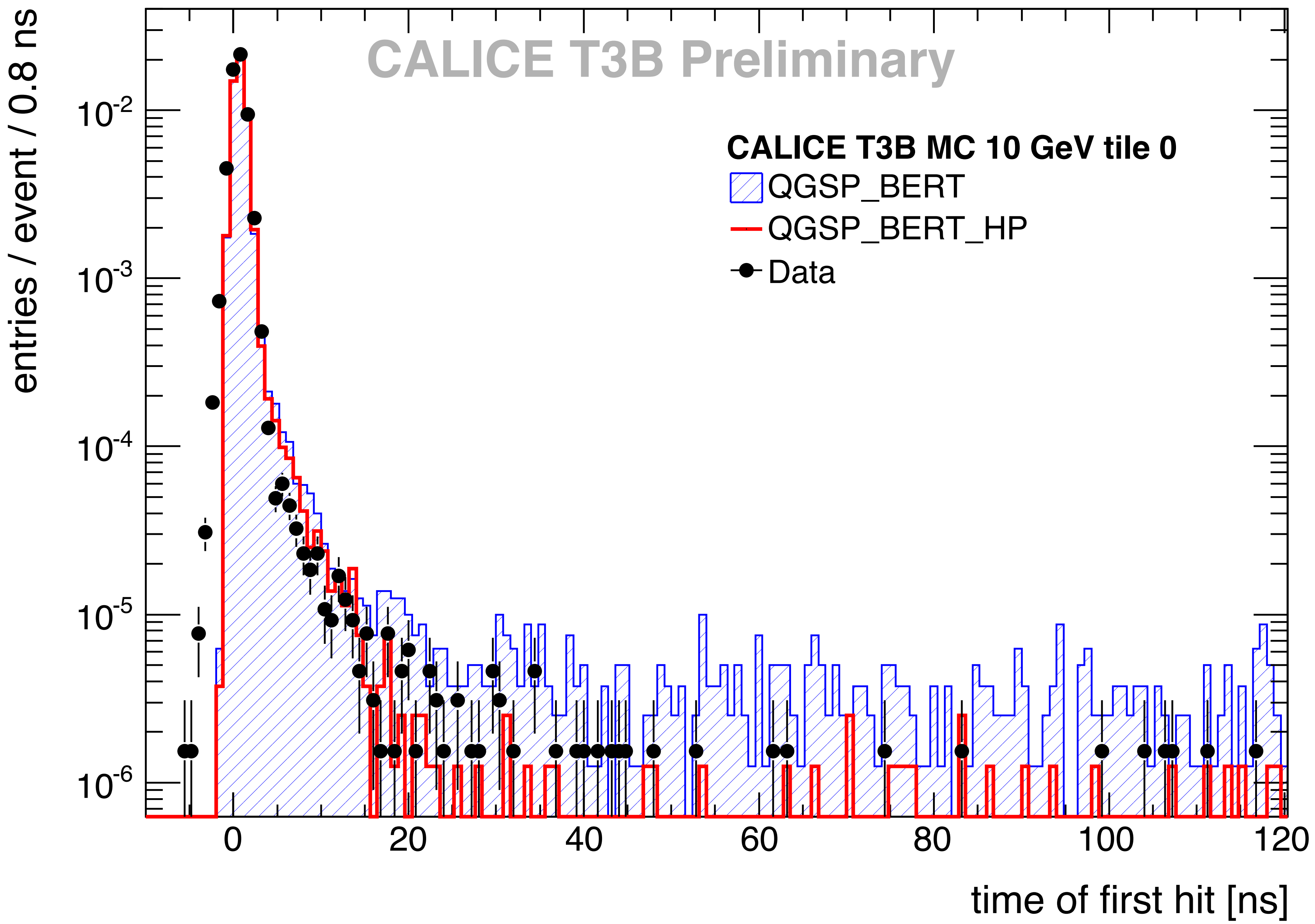


Time of First Hit in Simulations

- Simulations using smeared photon distributions
- Same analysis procedure as real data
- Two physics lists:
  - QGSP_BERT: LHC standard, used for CLIC detector studies
  - QGSP_BERT_HP: Variant with high precision neutron tracking



Data & Simulations - First Results

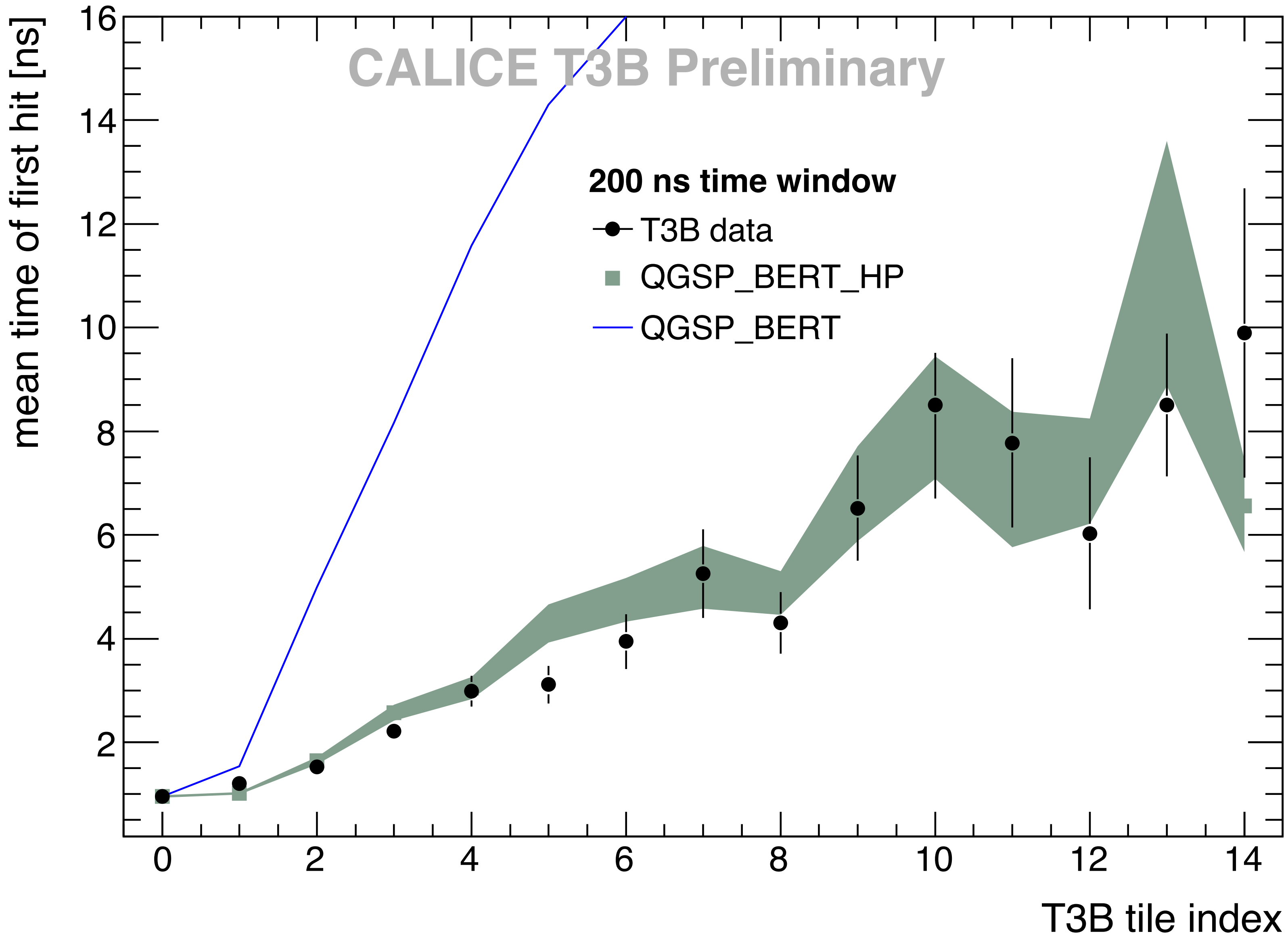


Central T3B cell:

Distribution of the Time of First Hit

- QGSP_BERT shows a pronounced tail of late energy depositions
- Data agrees better with QGSP_BERT_HP - Reduced activity beyond 20 ns

Data & Simulations - First Results



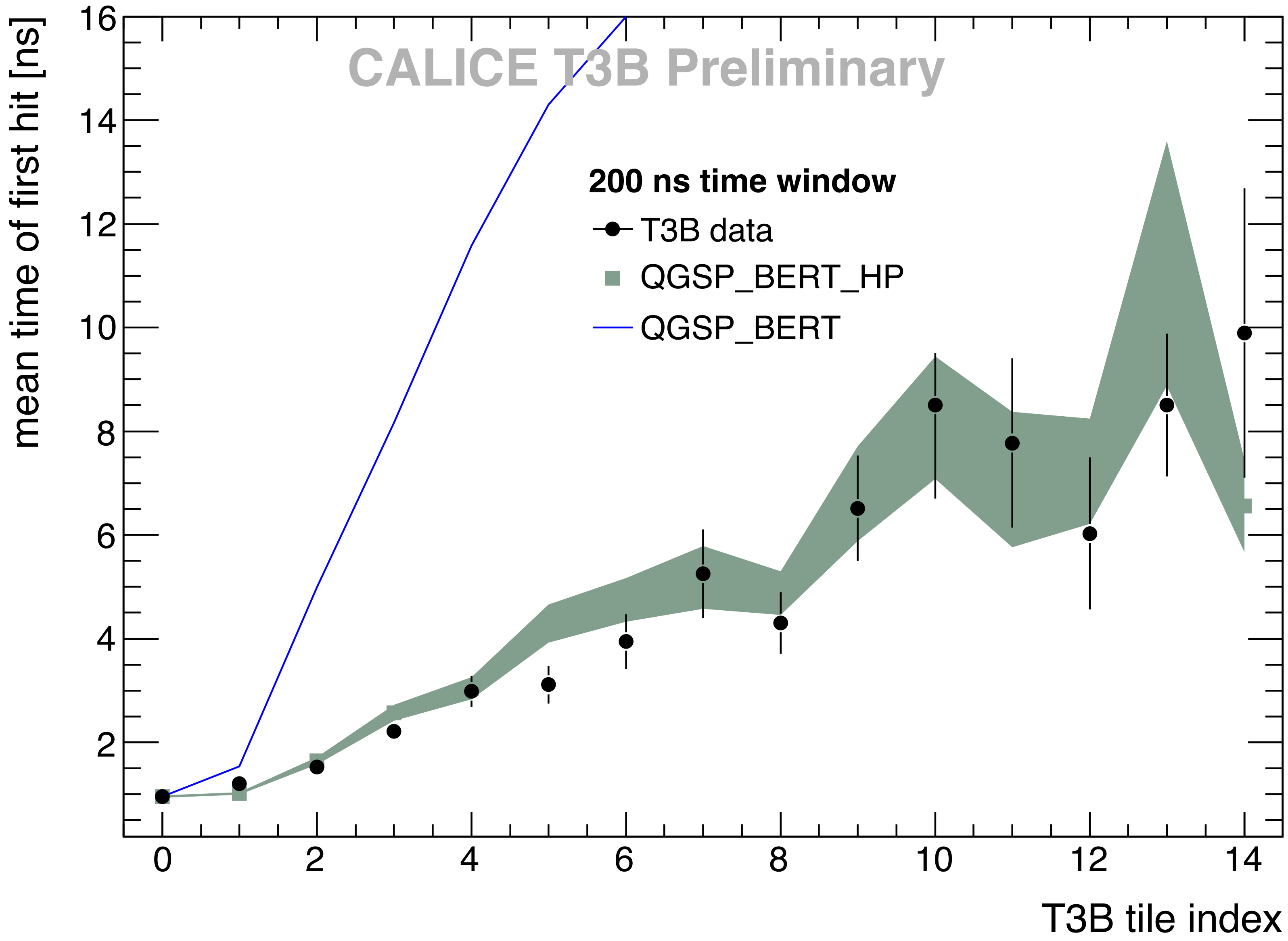
Compact Comparison:

Mean Time of First Hit

- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)

- Data consistently described by QGSP_BERT_HP
    - QGSP_BERT deviates strongly

Data & Simulations - First Results



Compact Comparison:

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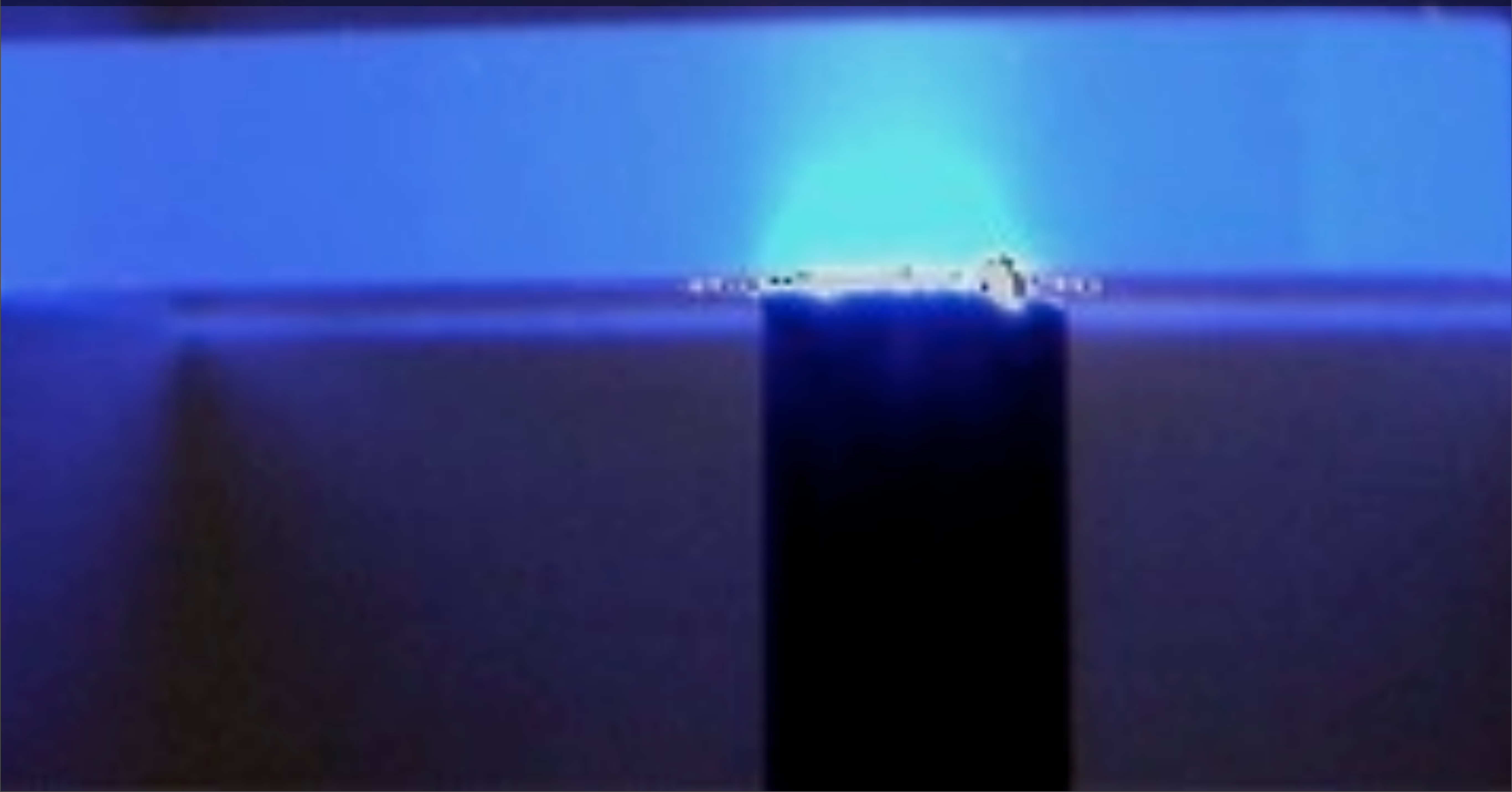
➯ High precision neutron tracking or other means to suppress excessive late energy depositions necessary to describe observed time structure in T3B

Conclusion & Outlook



Summary I

- For a new generation of colliders, we want a new generation of detectors: High granularity, paired with sophisticated algorithms promises unprecedented resolution

- Compact silicon-based photon sensors enable highly granular calorimeters with scintillators as active medium

- CALICE has 5 years of operational experience with a physics prototype
  - First large-scale use of SiPMs - Successful proof of concept
  - Good performance: A PFA calorimeter can be a very good HCAL as well!
  - Fantastic opportunities to study the details of hadronic showers: Unprecedented possibilities for the validation and improvement of simulation models

Summary II

- Detailed understanding of the characteristics of a SiPM calorimeter - often beyond what is needed to obtain good hadronic performance
  - Calibrations with muons & LEDs
  - Correction for saturation of photon sensors
  - Large sample studies of scintillator tiles and SiPMs

- Ideas for the next generation of detectors
  - Not discussed here: Technical prototype of CALICE: Compact, fully integrated readout electronics
  - Fiberless scintillator tiles: Fast response, good uniformity & reproducibility Need ideas for mass production!

Summary III / Outlook

- A versatile technology: With the right readout, the time structure of hadronic showers is accessible
  - First proof of concept measurements - Already a physics conclusion:
    The current default physics list in HEP, QGSP_BERT, has too much late energy deposit: Overestimation of needed integration time.
    High precision neutron tracking provides improved performance

- Upcoming opportunities:
  - Next generation electronics for the CALICE AHCAL:
    Time stamping for every channel - Potentially a full "4D-Calorimeter"
  - Currently taking data with Tungsten absorbers: A whole new game of shower model validations & detector studies

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... and who knows what other exciting ideas and projects come next!