Calorimetry

IMPRS Block Course on Detectors

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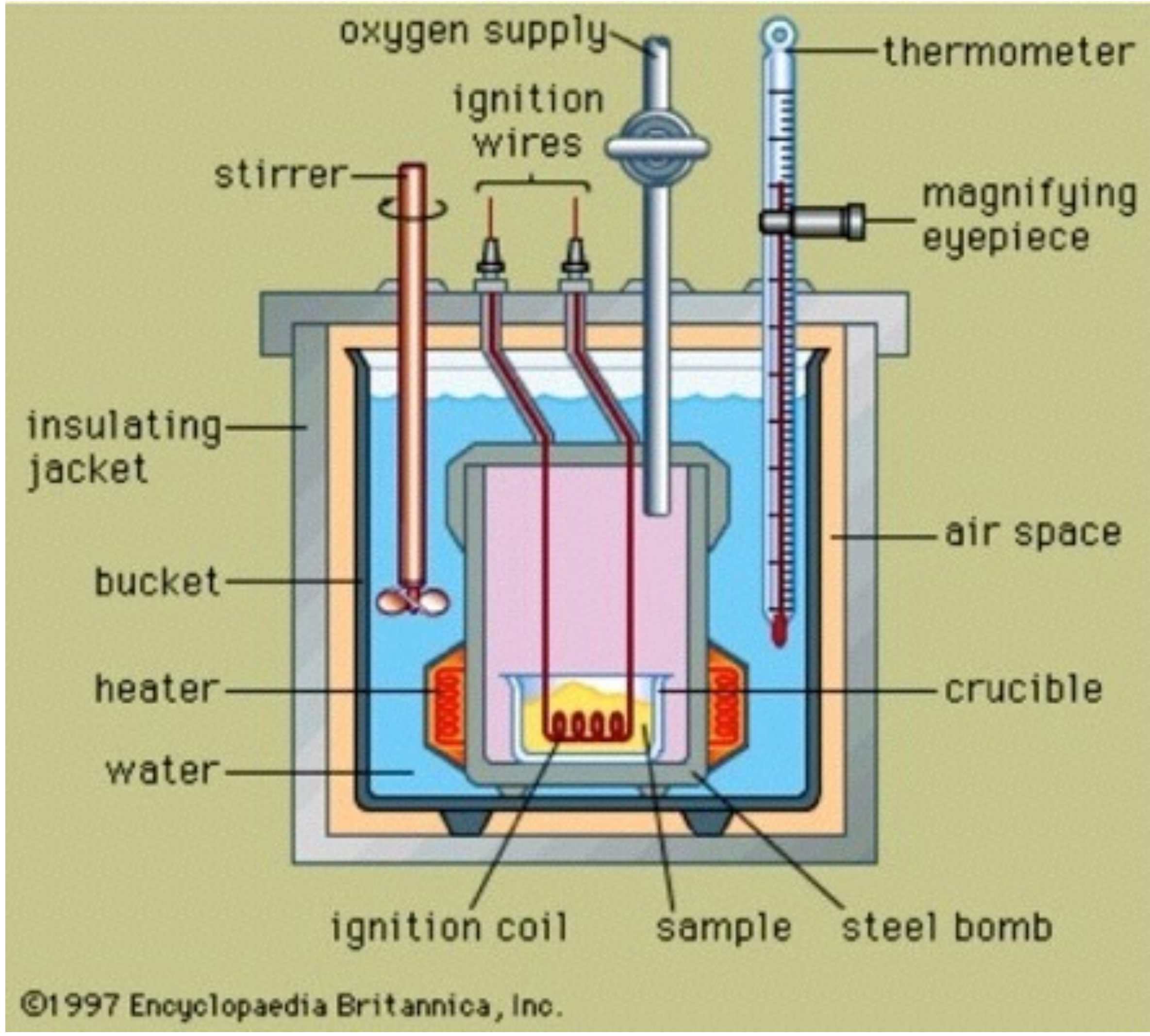
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Calorimetry: The Concept

- Originally from chemistry: Measurement of the released heat by a chemical reaction: Here increase of temperature of a well-known amount of water

- For elementary particles:
  Measurement of the energy of a particle by **total absorption**
  - 1 cal = 10^7 TeV: Very small energies, no temperature increase!
    - Somewhat more sophisticated strategy for energy measurement needed



Course Overview

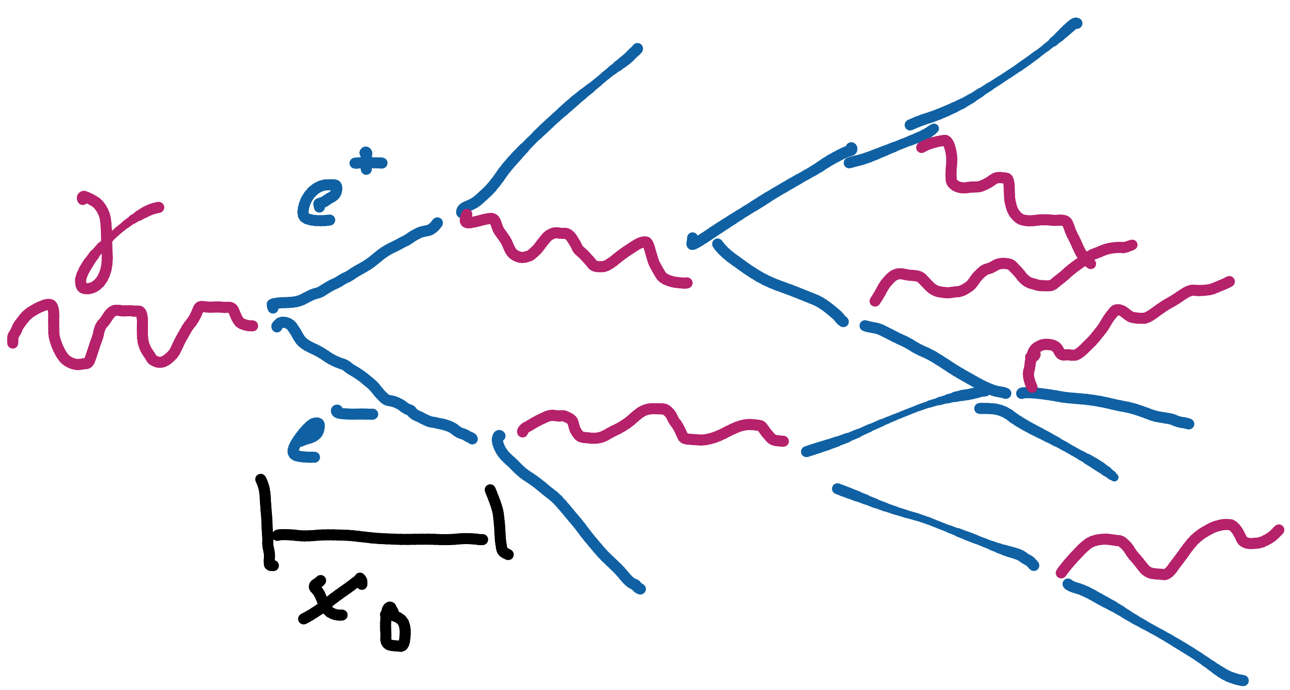
- **Part I - *today***
  - The Basics: Shower Physics
  - Calorimeter Basics
    - Calorimeter Types
    - Drivers of Energy Resolution
  - Readout Technologies & Materials

- **Part II - *tomorrow***
  - Calorimeters in HEP and Medical Imaging
    - The Basics of Calorimeters in Medical Imaging
    - The Basics of HEP Calorimeters
  - New Technologies

The Basics: Shower Physics

Electromagnetic Showers I

- Interaction of high-energy e±, γ in material results in an electromagnetic cascade, triggered by:
  - Bremsstrahlung by interaction of electrons and positrons in the electric field of matter nuclei
  - Production of electron-positron pairs via pair production reaction in the electric field of matter nuclei



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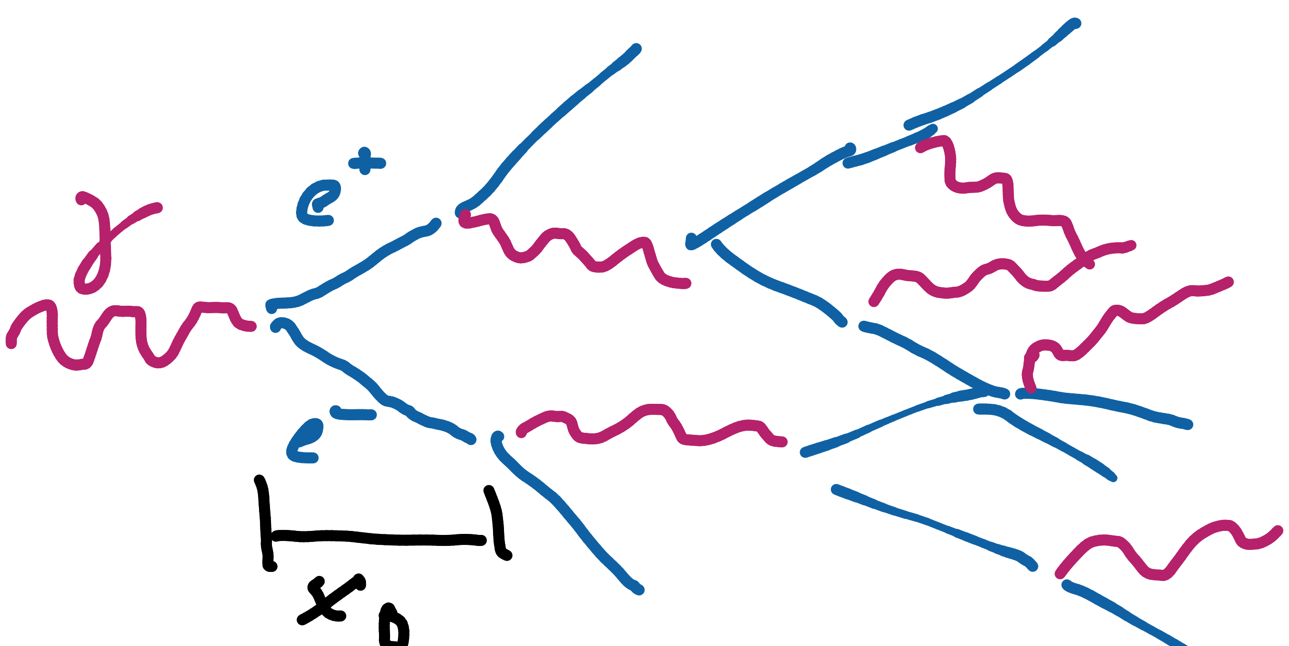
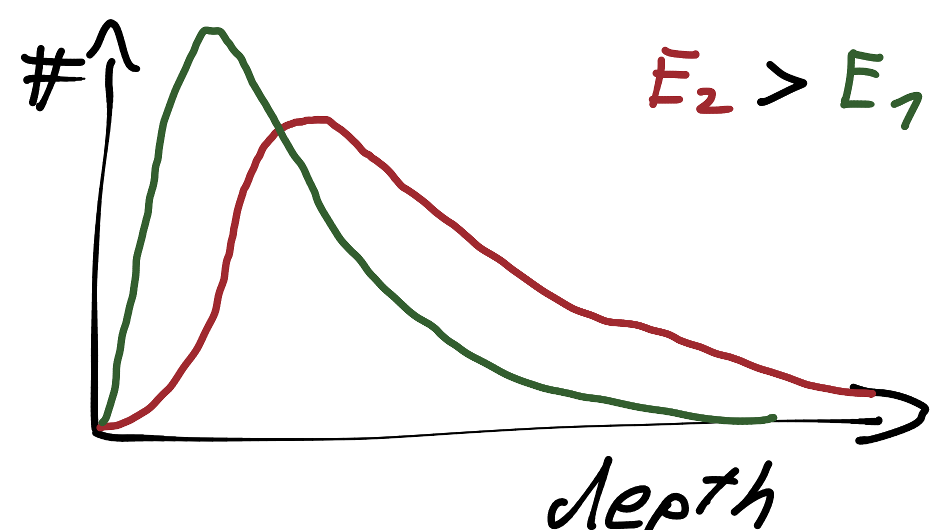


Number of particles is growing with shower depth as long as the energy of secondaries is sufficient to create new particles: Formation of a “shower max”



Electromagnetic Showers II

- A shower is more than bremsstrahlung and pair production:
  - electrons and positrons also loose energy by ionization: Crucial for the generation of detectable signal (and the primary energy loss mechanism once the energy is below a few MeV)
  - photons do other things as well - dominating below a few MeV

Compton scattering

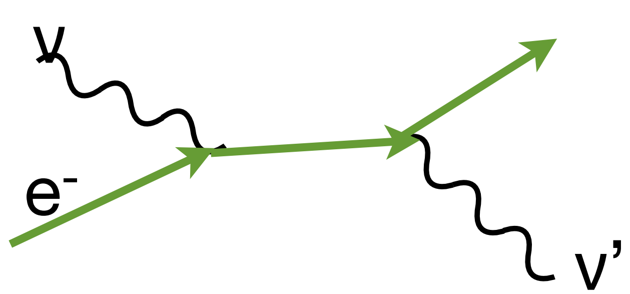
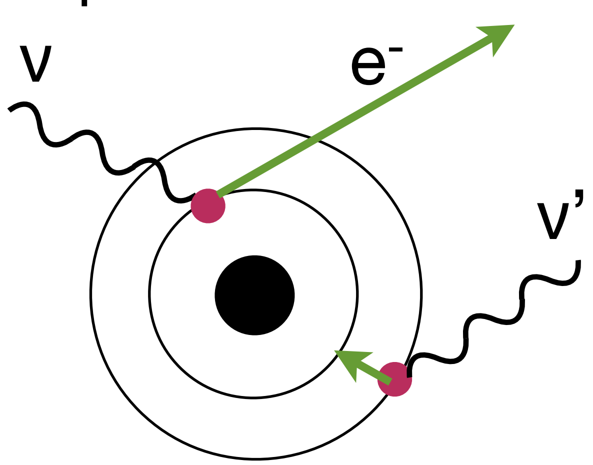


photo effect



Result in low-energy electrons, final energy deposited by ionization

The majority (50+%) of energy in an em shower is deposited by low-energy (< ~ MeV) electrons!

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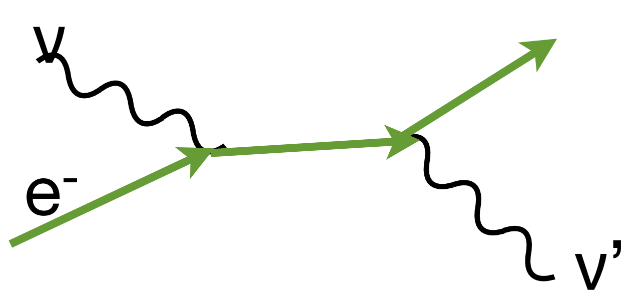

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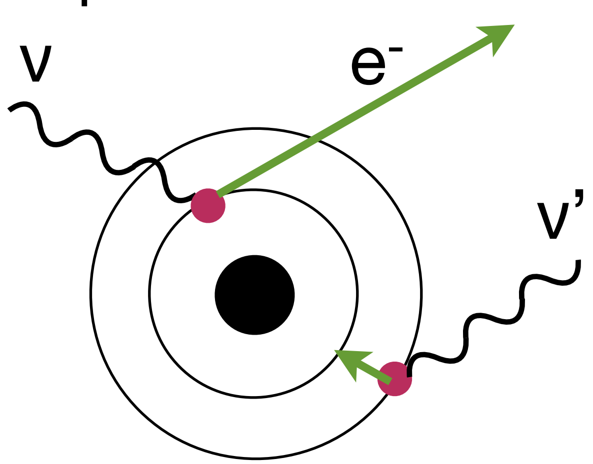

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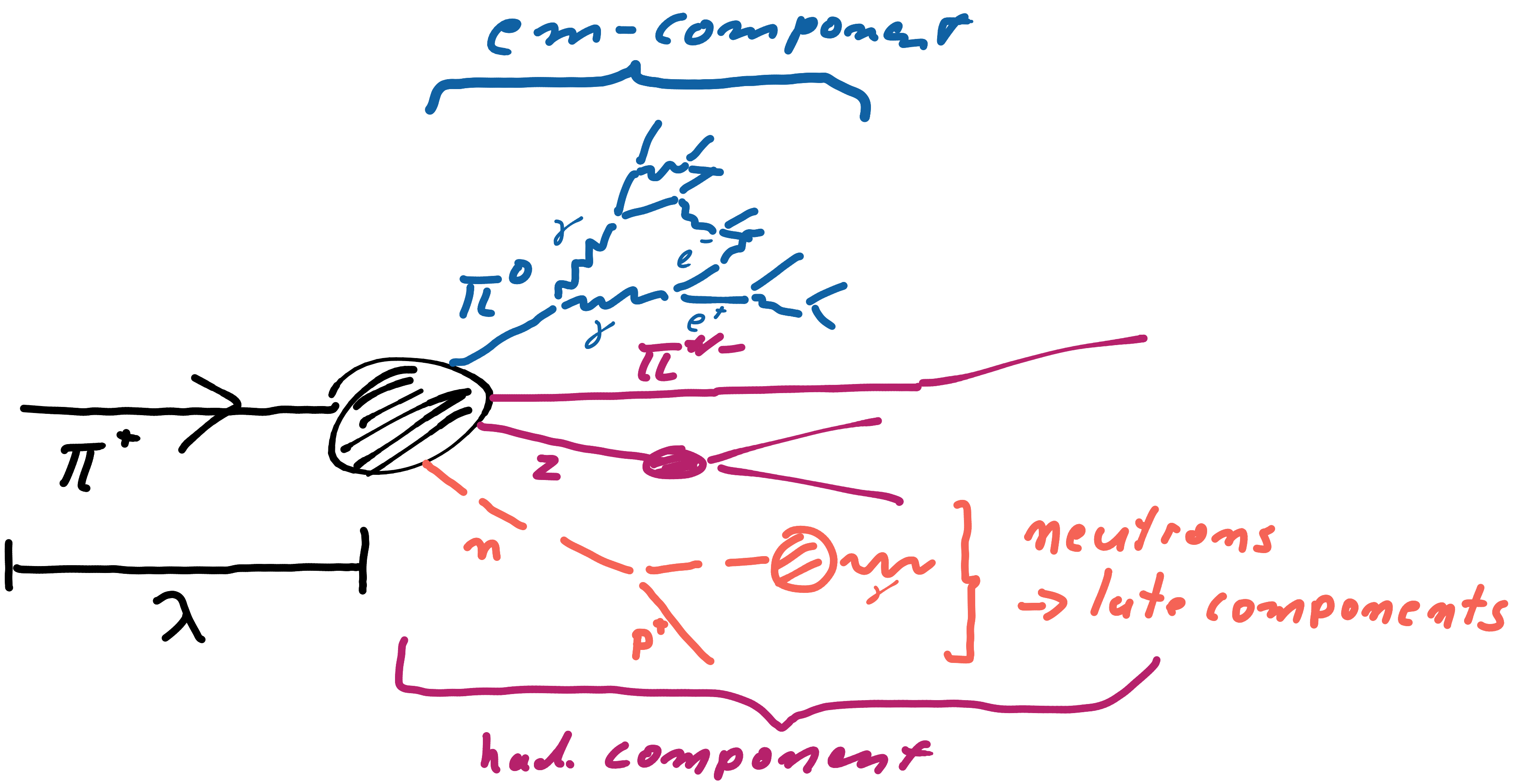
The majority (50+%) of energy in an em shower is deposited by low-energy (< ~ MeV) electrons!

NB: the energy of the transition from bremsstrahlung / pair production to other mechanisms is strongly material dependent - lower energy for higher Z
➯ Showers in high-Z materials are “longer”!

Hadronic Showers I

- Hadronic showers are more complex than electromagnetic showers: larger variety of possible interactions



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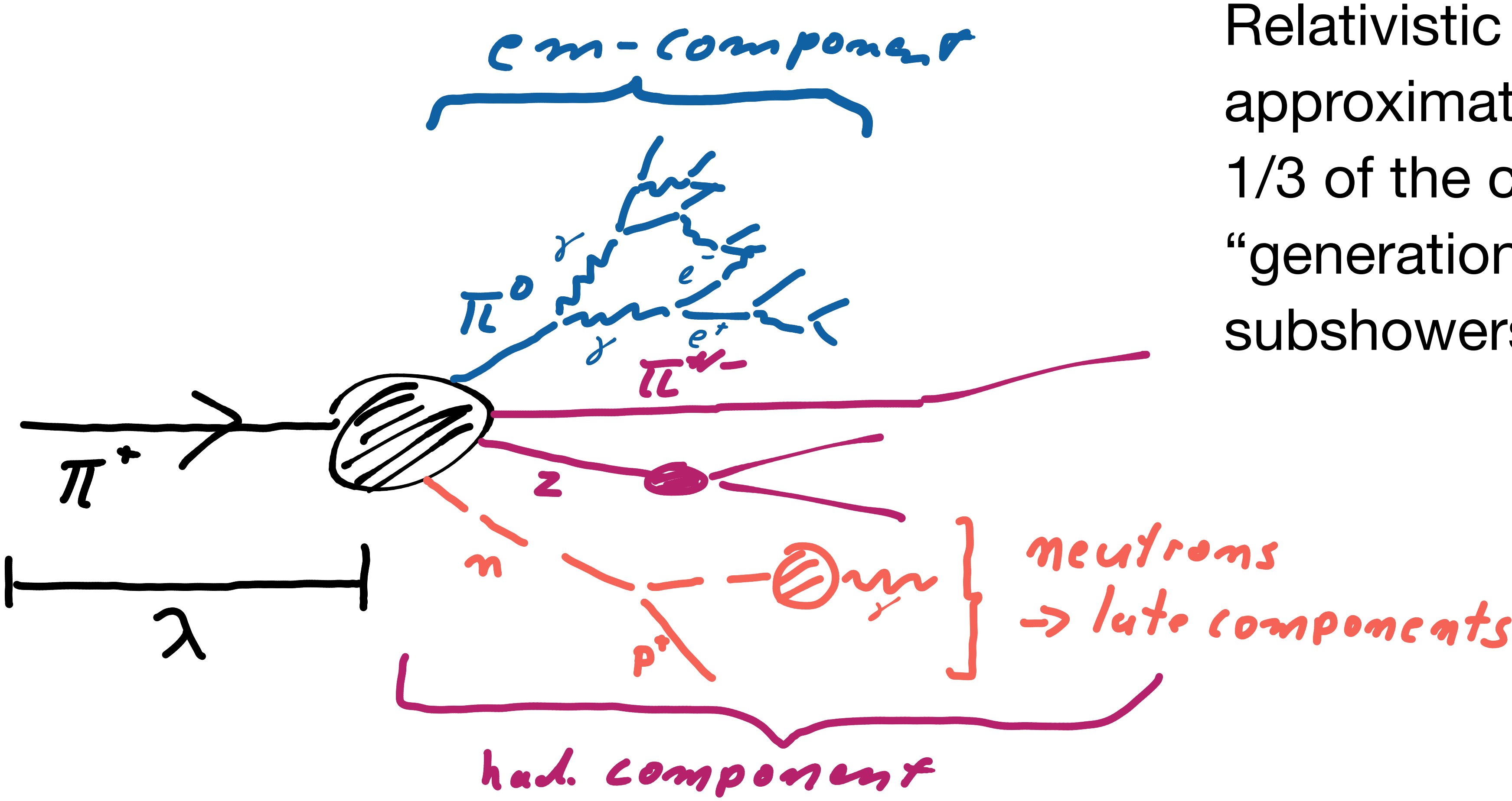

Relativistic component to first approximation consisting of pions: 1/3 of the created pions in each "generation" are π^0: electromagnetic subshowers!

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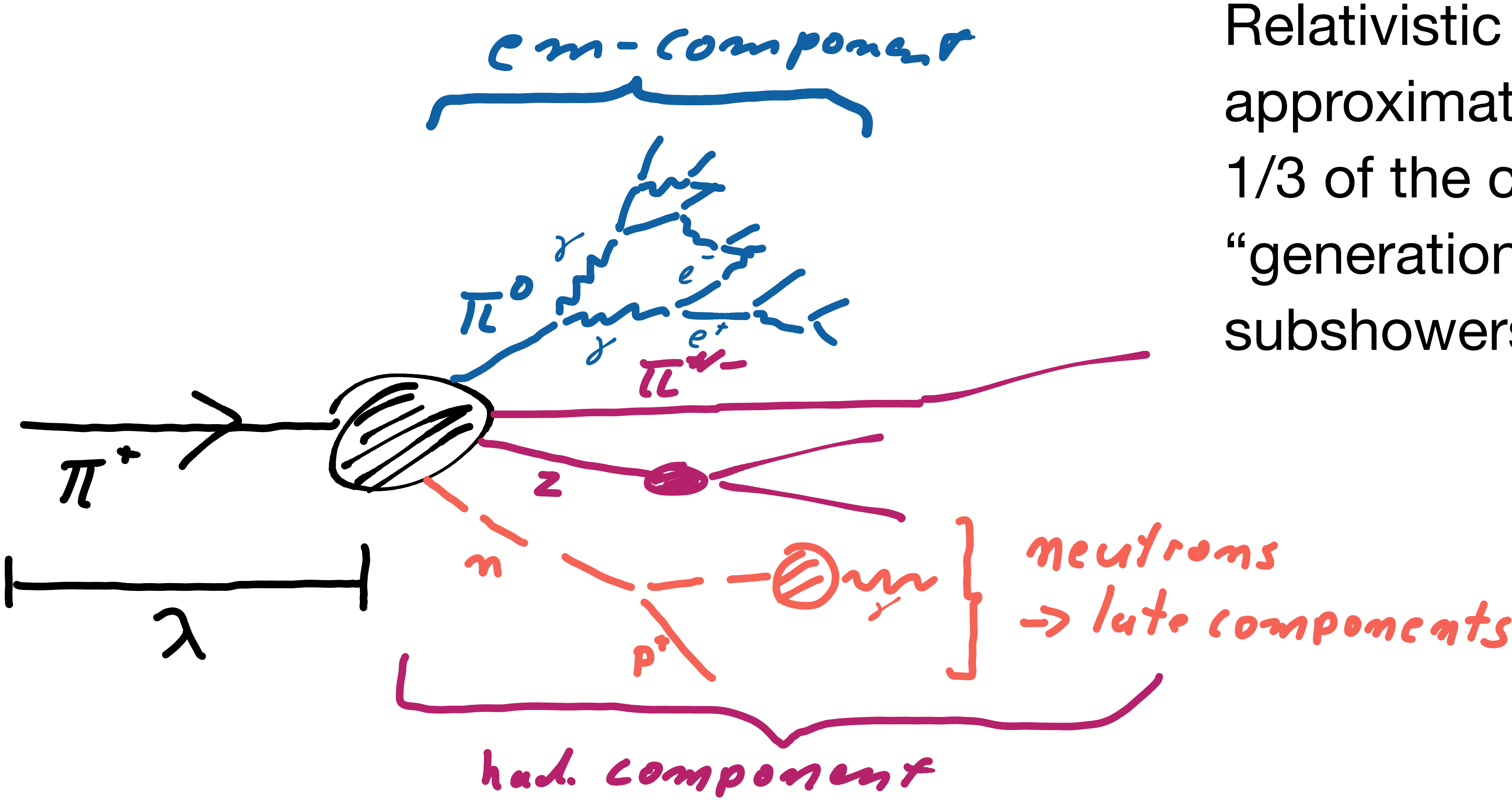

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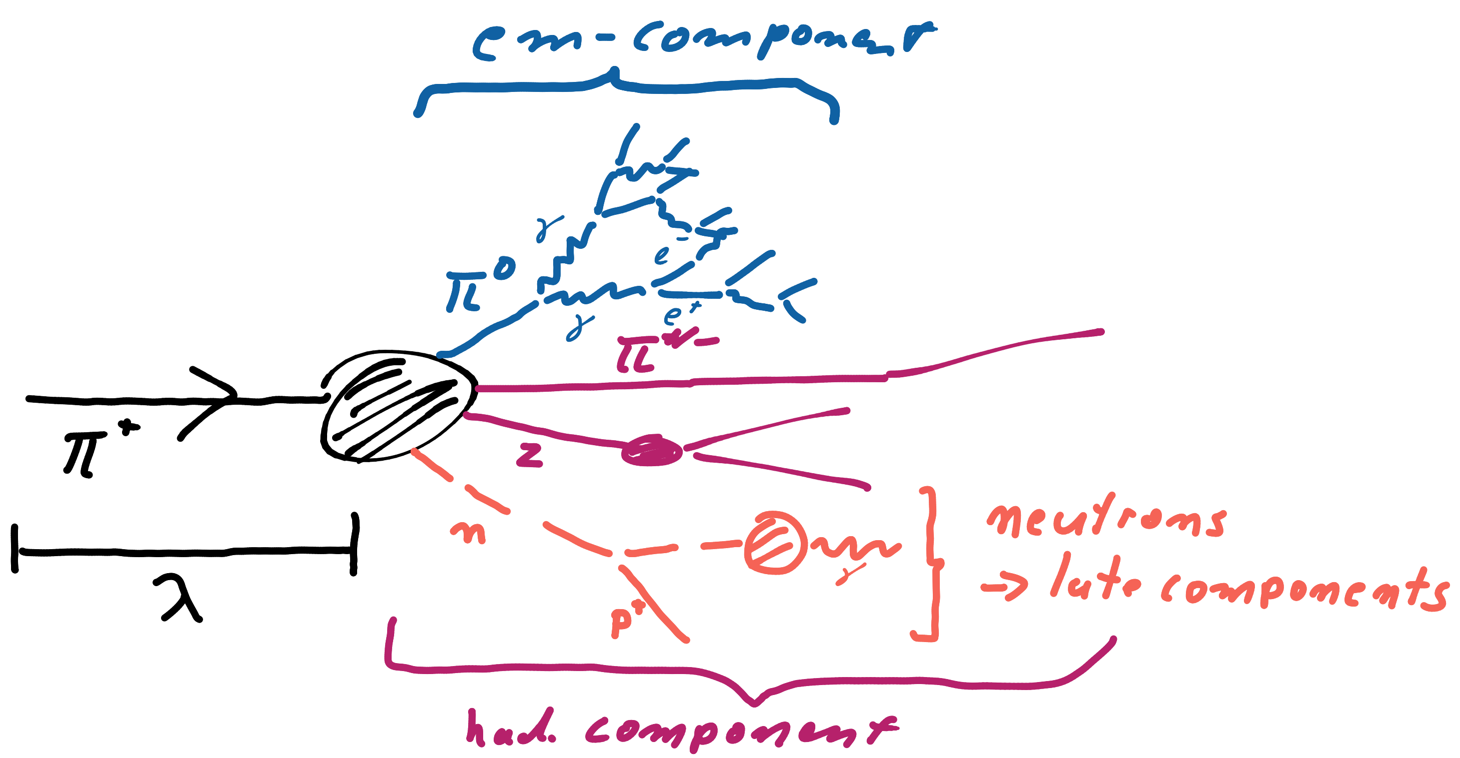
Nuclear interaction length λ ~ 10 - 30 x X_0 in heavy material: hadronic showers more extended, on a shower-by-shower basis "less smooth"

Hadronic Showers II

- Spallation reactions play a substantial role:
  - Energy loss due to binding energy (can be turned into a gain when using U absorbers)
  - Energy transfer to fragments with very small range: Direct absorption in absorber material, no signal in detector



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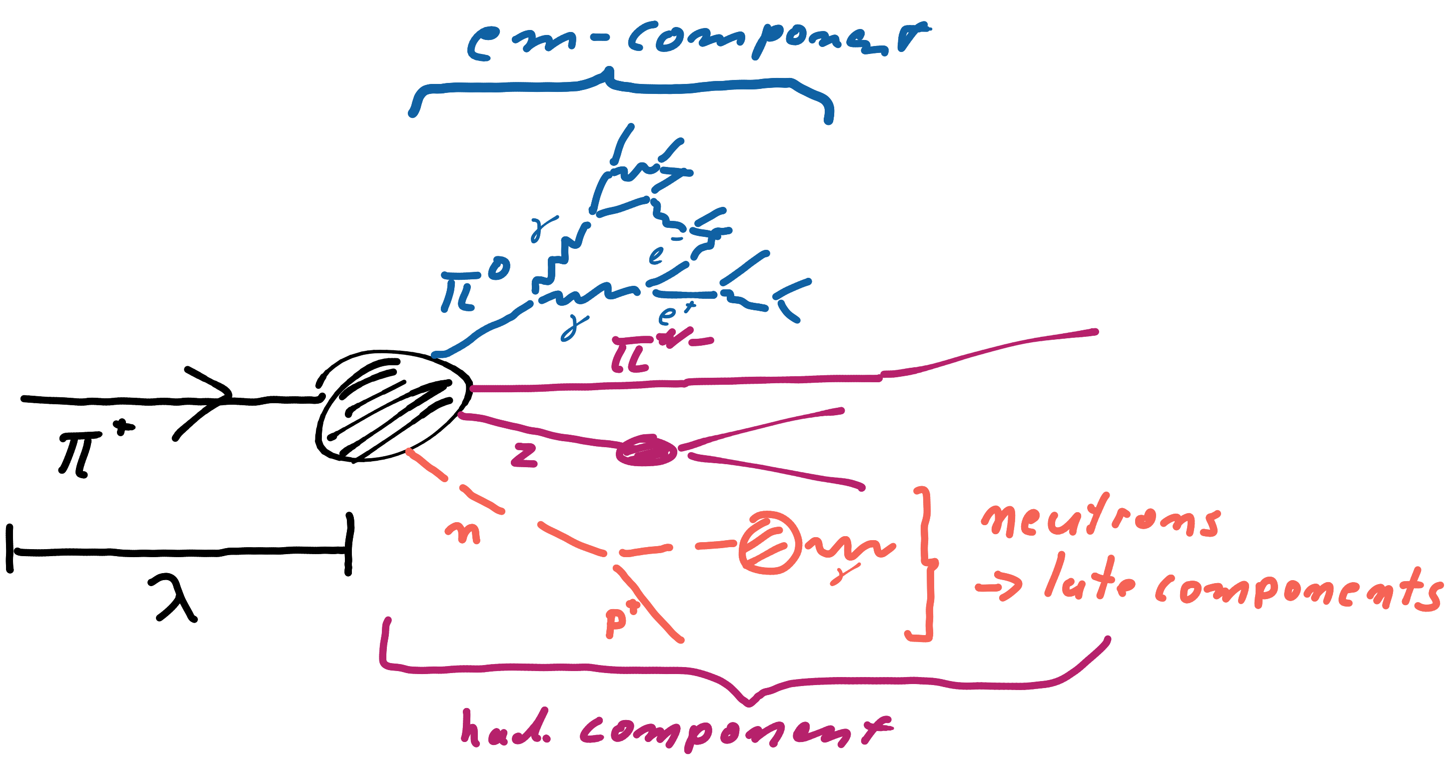
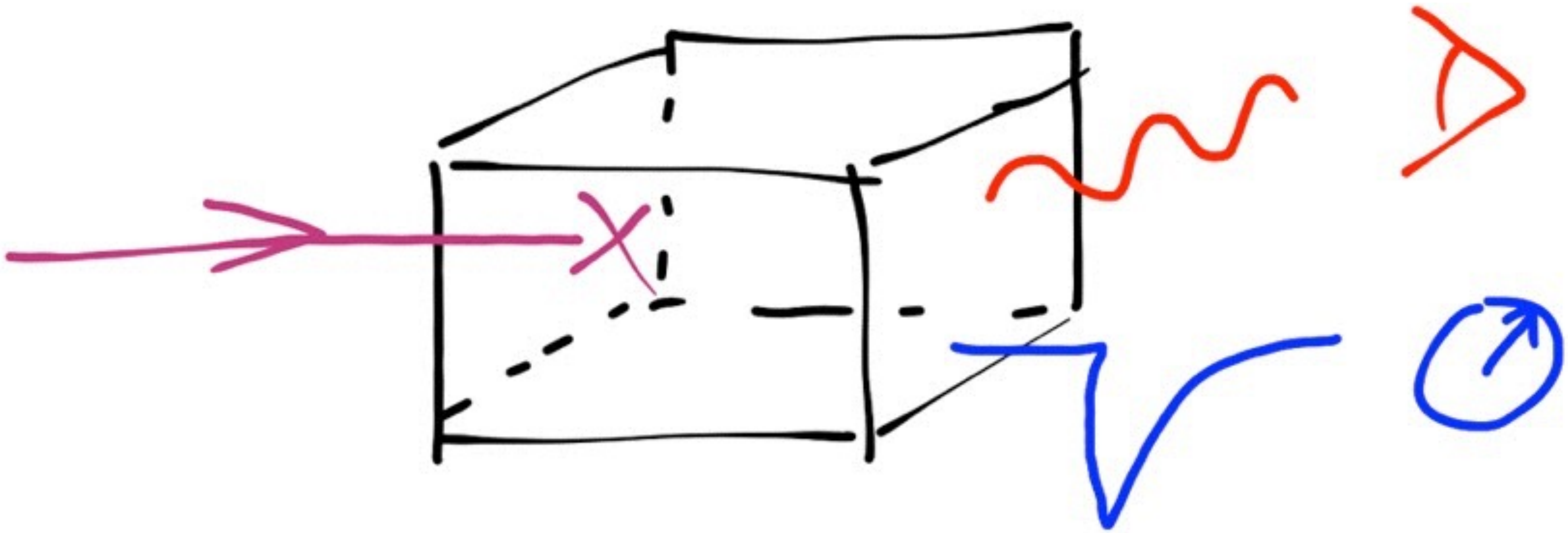


- "Invisible" energy in the shower: Reduced response of detector compared to electromagnetic showers: **e/π > 1**
  - Energy dependent: electromagnetic fraction increases with shower energy
  - Material and geometry dependent: Sensitivity to neutrons, sampling of fragments, …

Calorimetry Basics

Measuring Energy with a Calorimeter

- Convert the energy of the incident particle to a detector response
- Choose something that is easily detectable also for “small” energies
  - Electric charge
  - Photons (in or close to visible range)



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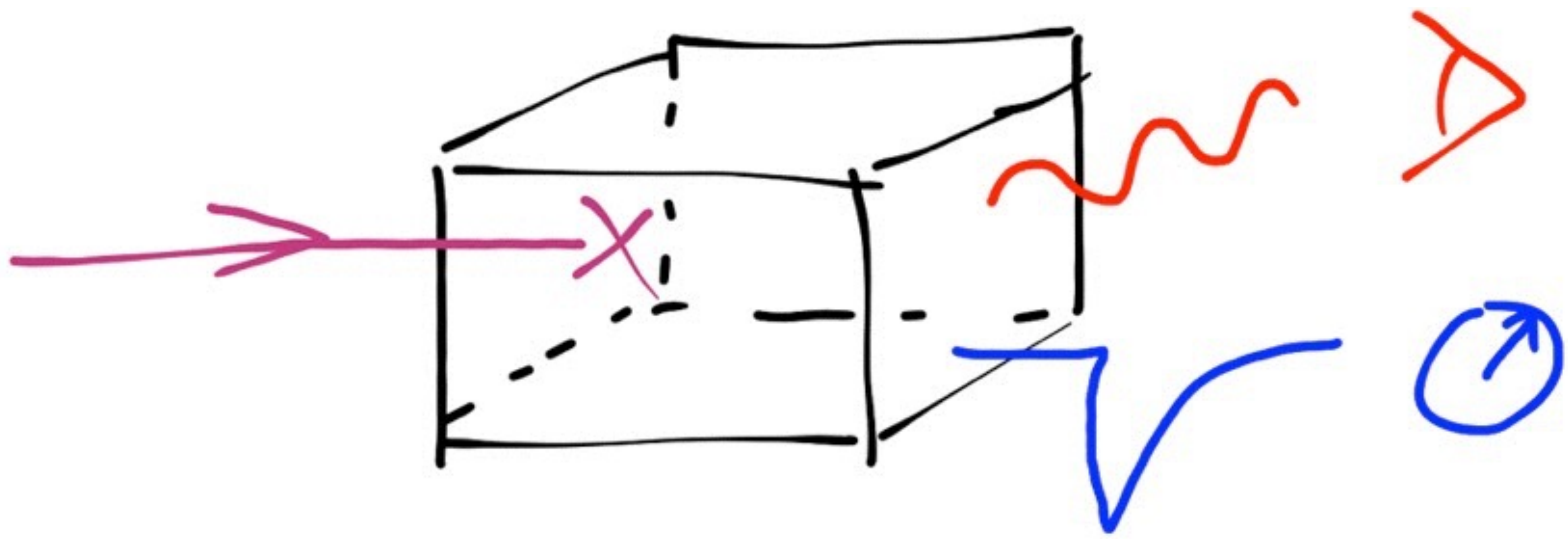
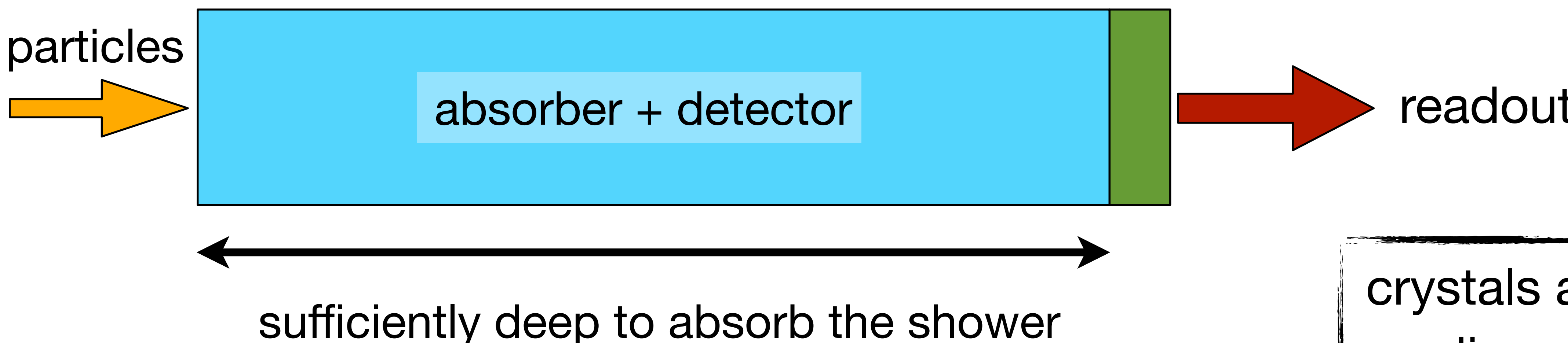


N.B.: Also other channels are used - thermal for example in cryogenic DM-search experiments, acoustic measurements, ... Not covered here!

Calorimeter Types

- The dream: Contain the full energy of one particle, convert all energy into a measurable signal which is linear to the deposited energy
  - Reality is often different, in particular when measuring hadrons

Two types: ***homogeneous calorimeters*** and *sampling calorimeters*



crystals as active medium

- The shower develops in the sensitive medium
  - Potentially optimal energy resolution: Complete energy deposit is measured
  - Challenging readout: No passive readout structures in detector volume

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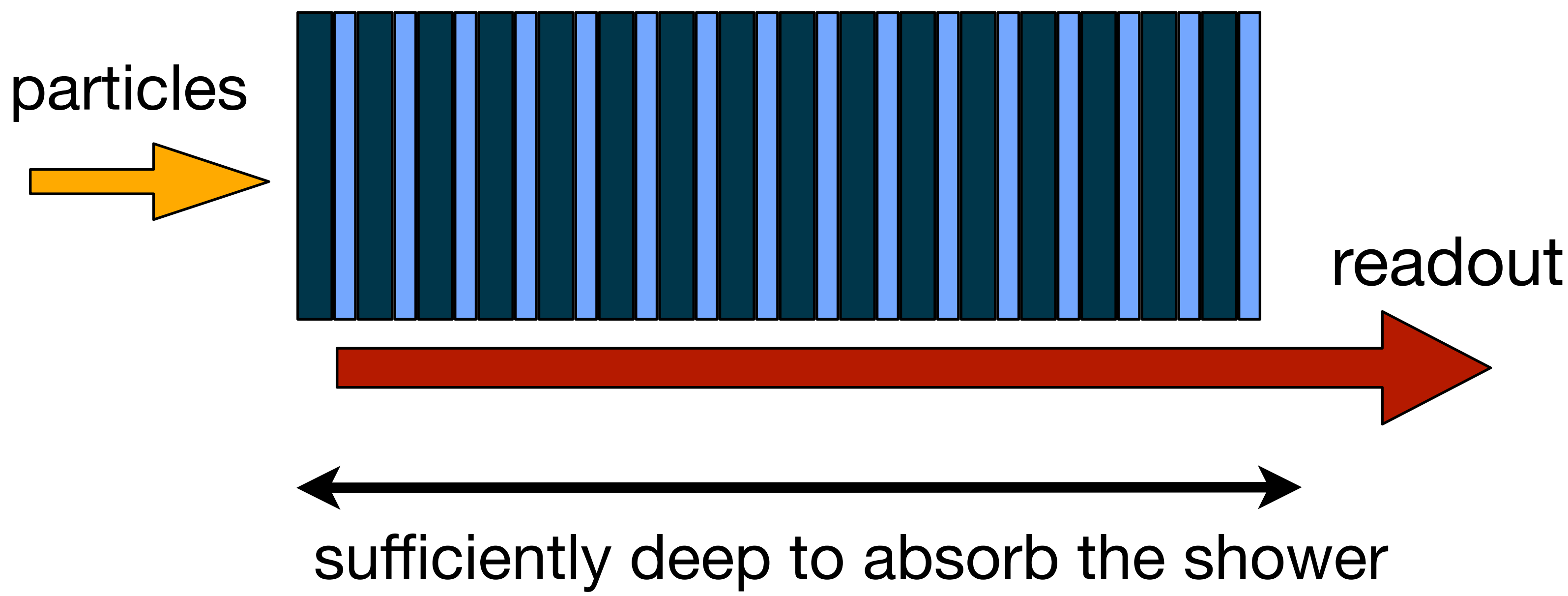


highly flexible in choice of absorbers and active medium

- The shower develops (mostly) in dense absorber medium, particles are detected in interleaved active structures
- Potentially reduced energy resolution: Only a fraction of the deposited energy is detected (expressed by the ***sampling fraction***)

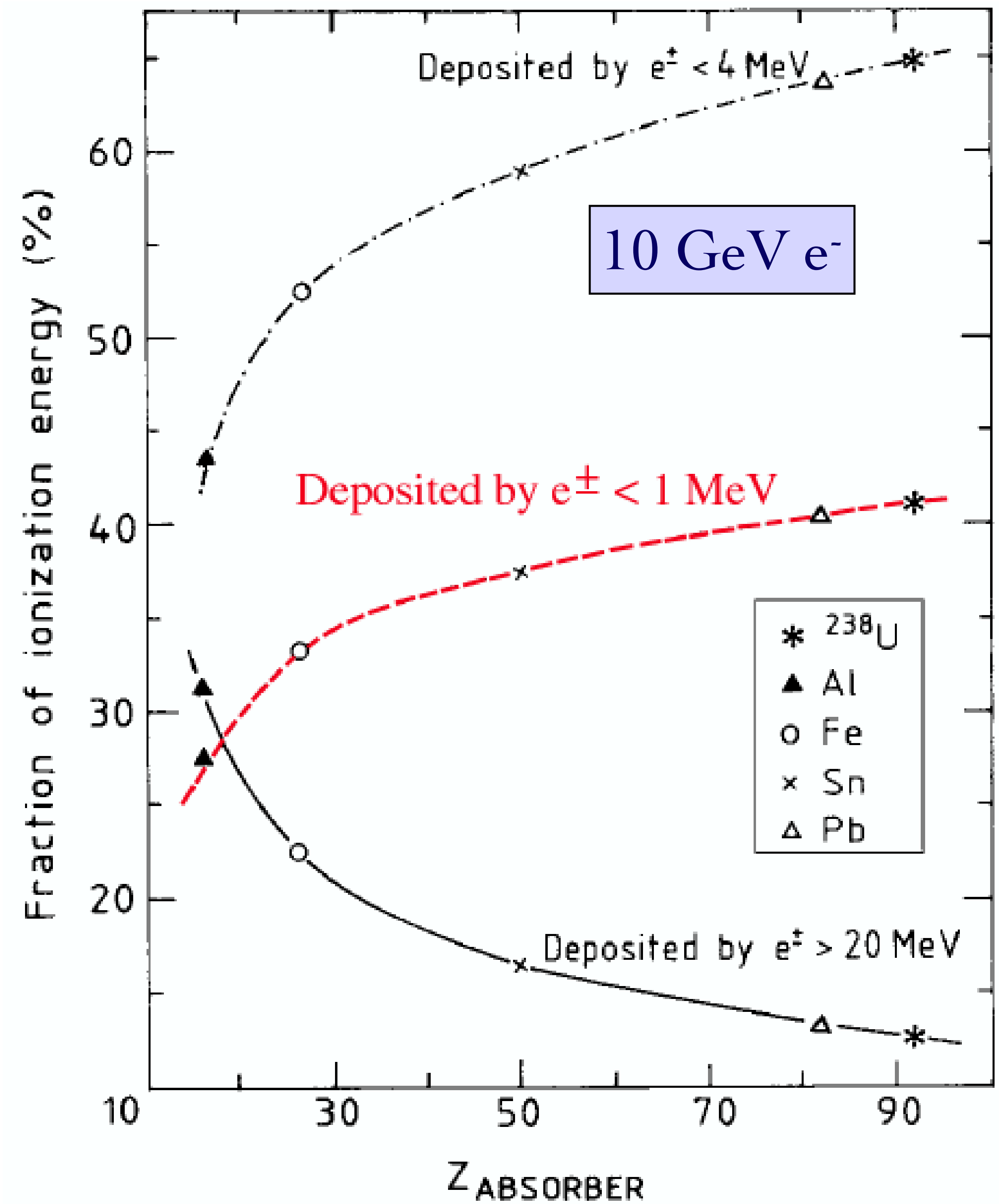
Sampling Calorimeters - Geometry

- A general prejudice:
  sampling layers should be orthogonal to particle incidence

- Remember: Most energy is deposited by low-energy particles - their direction is not correlated with the direction of the incident particle

➯ orientation of sampling layers not critical - different approaches used in practice (orthogonal, parallel, accordion, ...)

simulations



Measuring Energy with a Calorimeter

- Calorimetric processes are stochastic - Naive view:
  - Counting of photons / created charge carriers
  - Number of secondary particles in showers induced by high-energy particles

    (NB: Reality is slightly more complicated - particle type dependencies, …)

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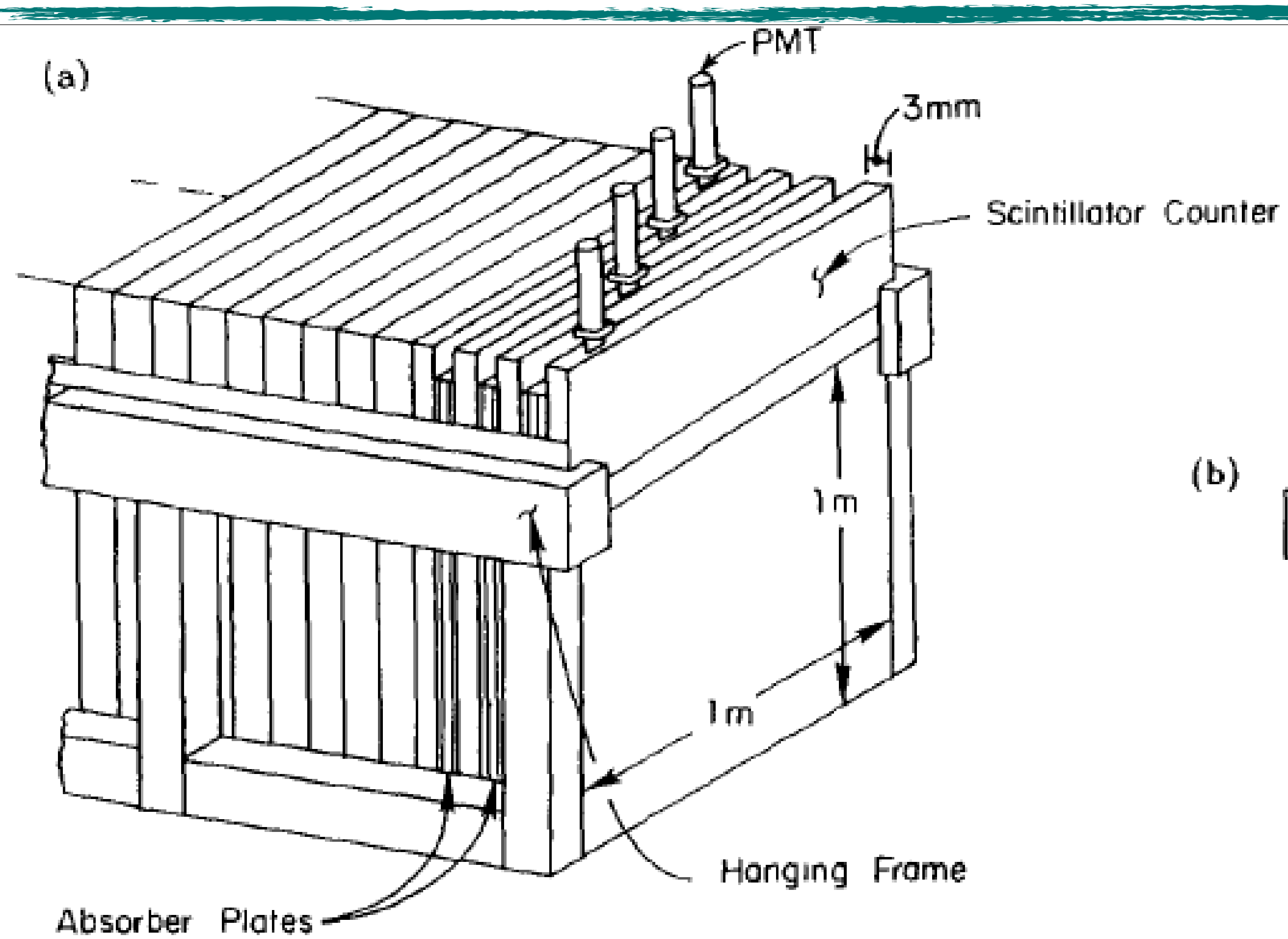
The resolution depends on **fluctuations**:

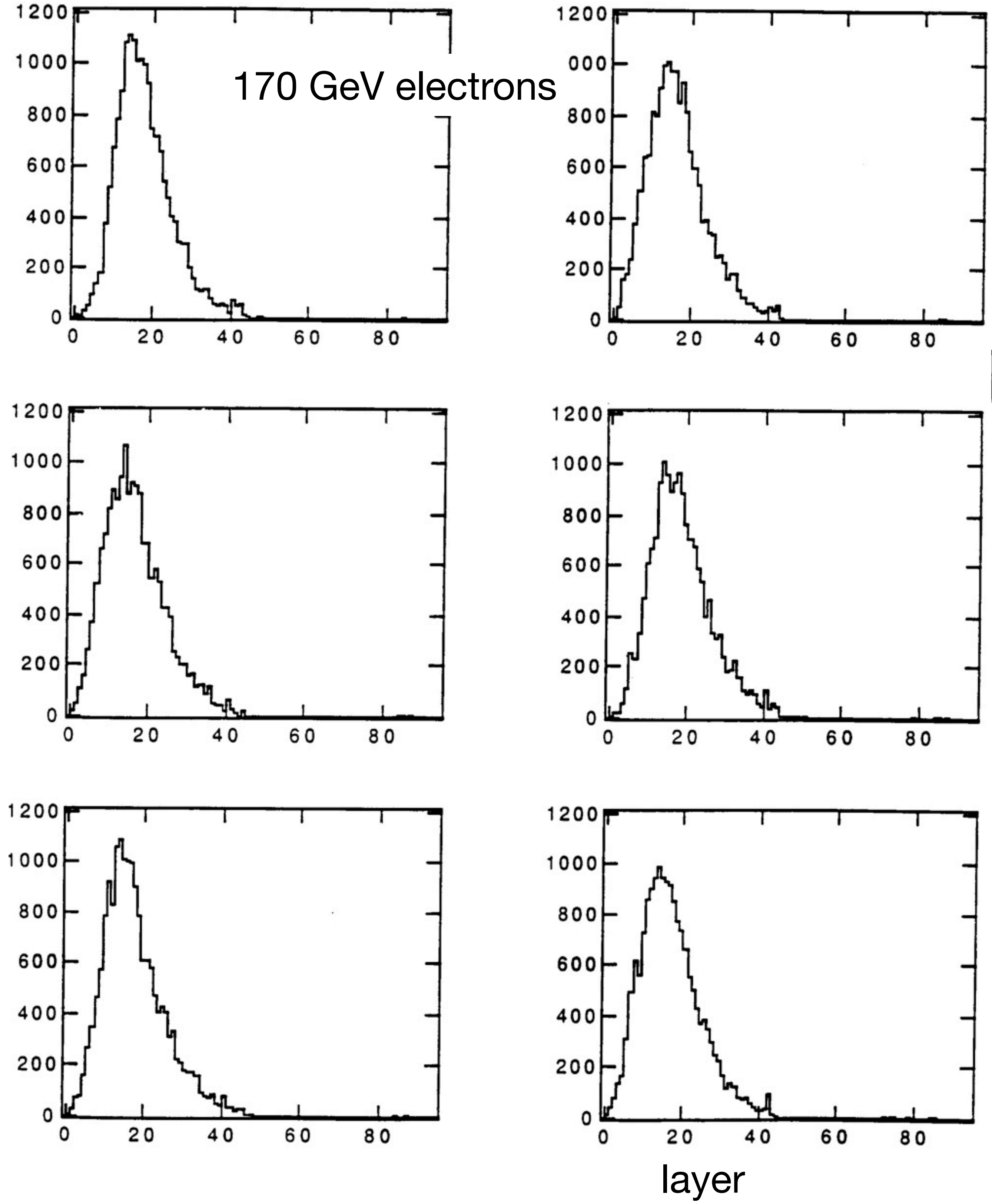
- Unavoidable fluctuations from the physics processes involved in shower formation
- Fluctuations in observed signal introduced by geometry and technology

Fluctuations: Electrons vs Hadrons



- Classic measurements with a sampling calorimeter - “Hanging File Calorimeter”

Fluctuations: Electrons vs Hadrons



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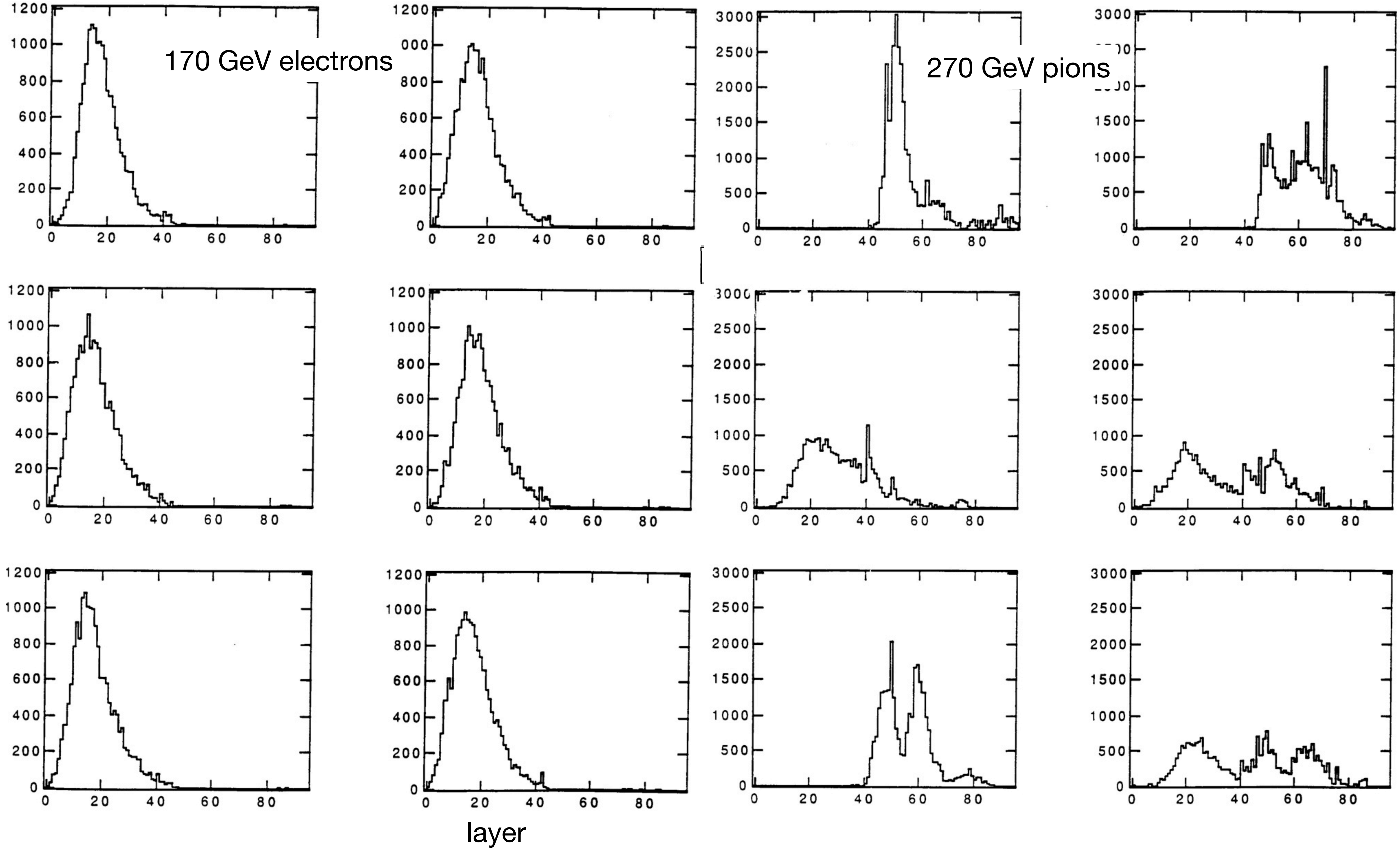
Fluctuations: Electrons vs Hadrons



Measuring Energy with a Calorimeter

Energy resolution often well-described by $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Three components:
  - *a*: The **stochastic** term: The counting aspect of the measurement: Simple statistical error: scales with the square root of the number of particles
    ➩ Resolution term scales with $1/\sqrt{E}$
  - *b*: The **noise** term: Constant, energy-independent noise contribution to the signal -
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  - *c*: The **constant** term: Contributions that scale with energy: Influence of inhomogeneities in the detector material, un-instrumented or dead regions, ...
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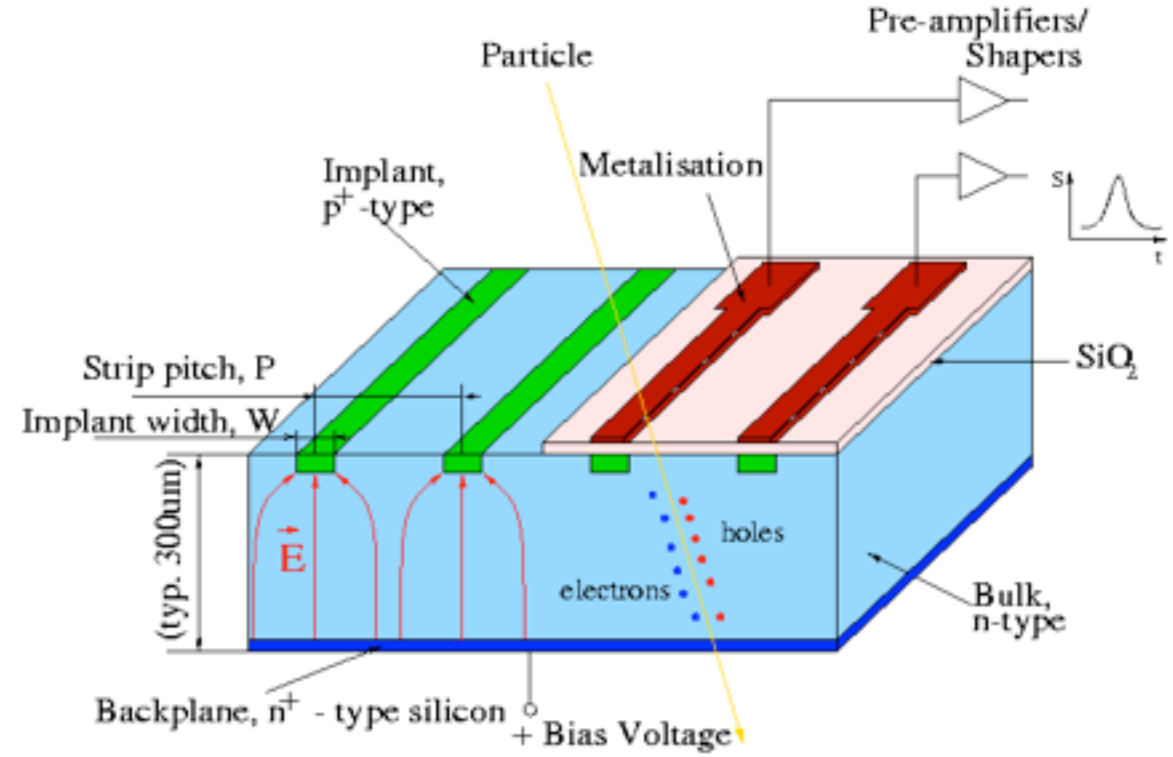
Consequences: At low energies the stochastic term (or, in extreme cases the noise term) dominates the resolution, at very high energies the constant term is most relevant

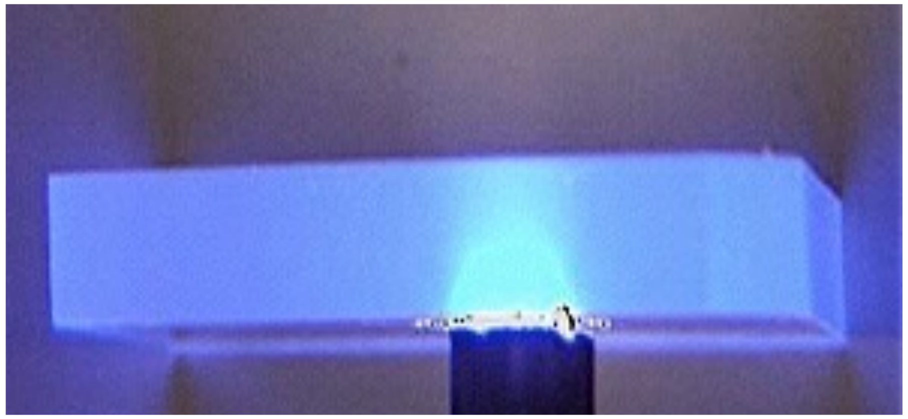
Active Media for Calorimeters

Active Media - Possibilities

- Mostly: Detection of ionization energy loss:
- Direct detection of created charge: Wide range of applications in HEP
  - Semiconductor detectors - Silicon
  - Classical gaseous detectors
    Avalanche amplification
  - Charge collection in nobel liquids
    without charge multiplication



- Detection of energy deposits through the production of scintillation light: Energy partially transformed into light
- Also: Detection of high-energy charged particles through Cherenkov emission



Scintillators

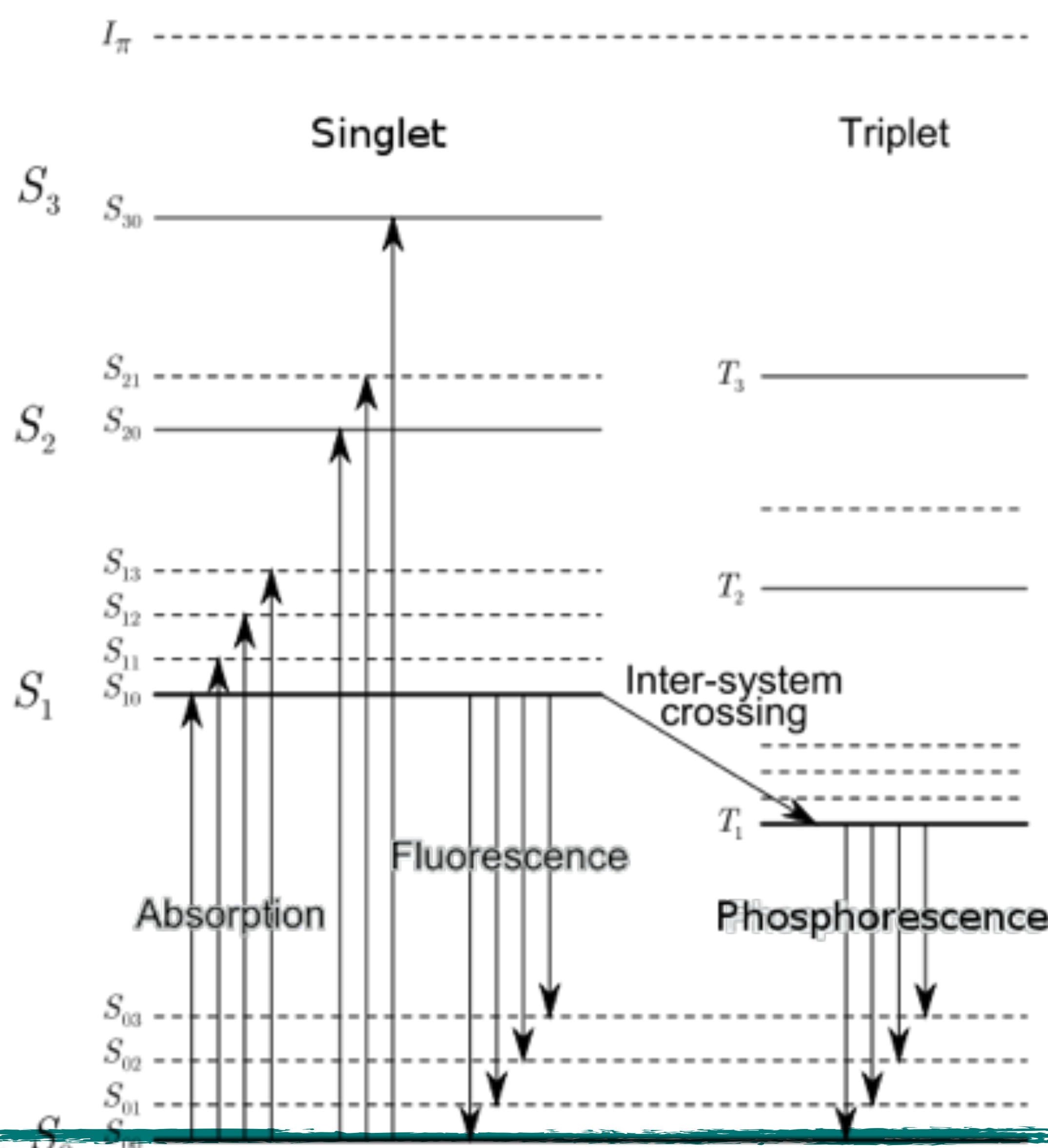
- Scintillators emit light when excited by ionizing radiation - Luminescence
- Two types of scintillators:
  - Inorganic scintillators - Crystalline solids or glasses, often doped with fluorescent ions
  - Organic scintillators - Hydrocarbon compounds, solid, liquid, crystalline (the latter is not used in high-energy physics) - Most common in HEP: Plastic scintillators

➩ Inorganic scintillators have high density and often high light output, but typically a slow response: Used for homogeneous calorimeters

➩ Organic scintillators can be made in arbitrary shapes, are cheap to produce and typically have a very fast response: Used in sampling calorimeters

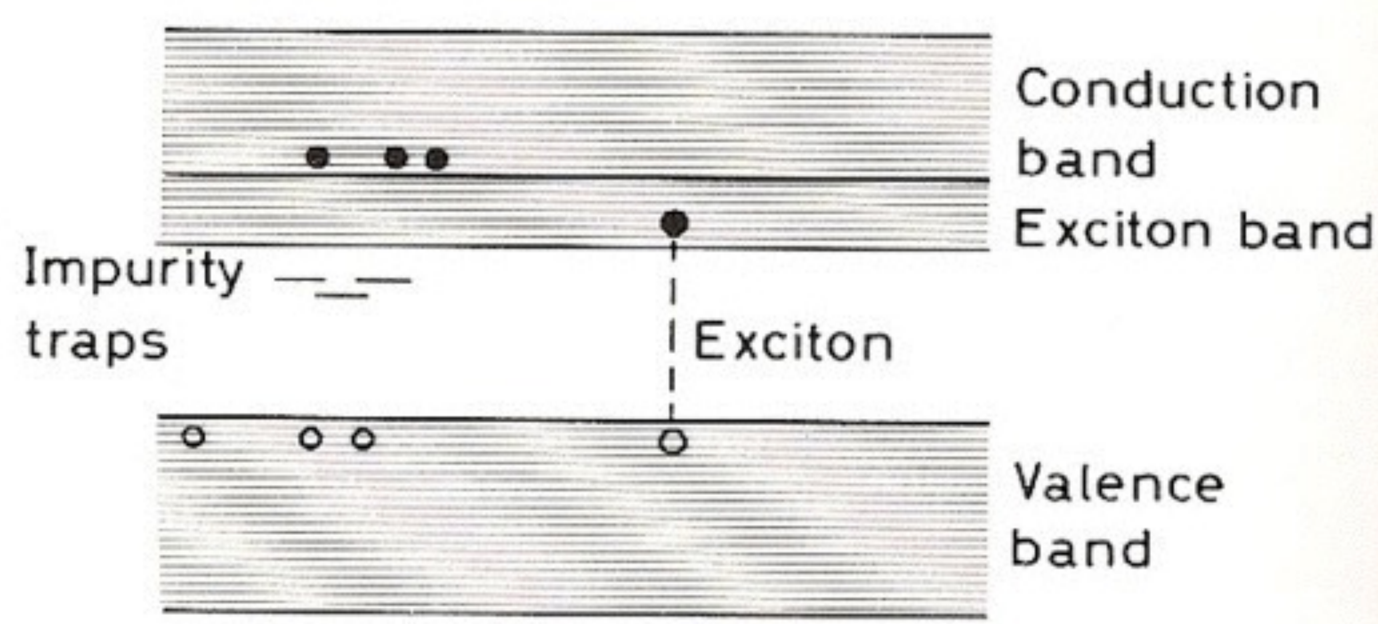
Scintillators

- We distinguish two types of light emission
  - Fluorescence: Prompt light emission - Timescale ns up to µs
  - Phosphorescence: Delayed light emission µs to ms, even hours



Schematic of organic scintillation

Schematic of inorganic scintillation



Scintillator Properties

- Key property: Light output - efficiency of transferring ionization energy loss into scintillation photons
  - Inorganic scintillators: high conversion efficiency, 1 photon for 25 eV
  - Organic scintillators: typically 1 photon for 100 eV

- Important in practical applications: Time constants
  - Depending on detailed structure of levels and trapping centers, several characteristic time scales can exist:
    "Fast" and "Slow" component, very common in inorganic scintillators

- Key to making it work: Transparency for own scintillation light
  - Stokes shift in organic materials: Absorption at higher energies than emission
  - Fluorescent centers in inorganic crystals

Crystals for Homogeneous Calorimeters

- Wish list:
  - high density, short radiation length, small Moliere radius: Compact detectors
  - high light output: high energy resolution
  - in some applications: Fast response - Allow operation in high occupancy environment

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A classic: NaI(Tl): Used in many spectroscopic experiments
High light yield, 40 photons / keV, density 3.7 g/cm^3, decay time 230 ns

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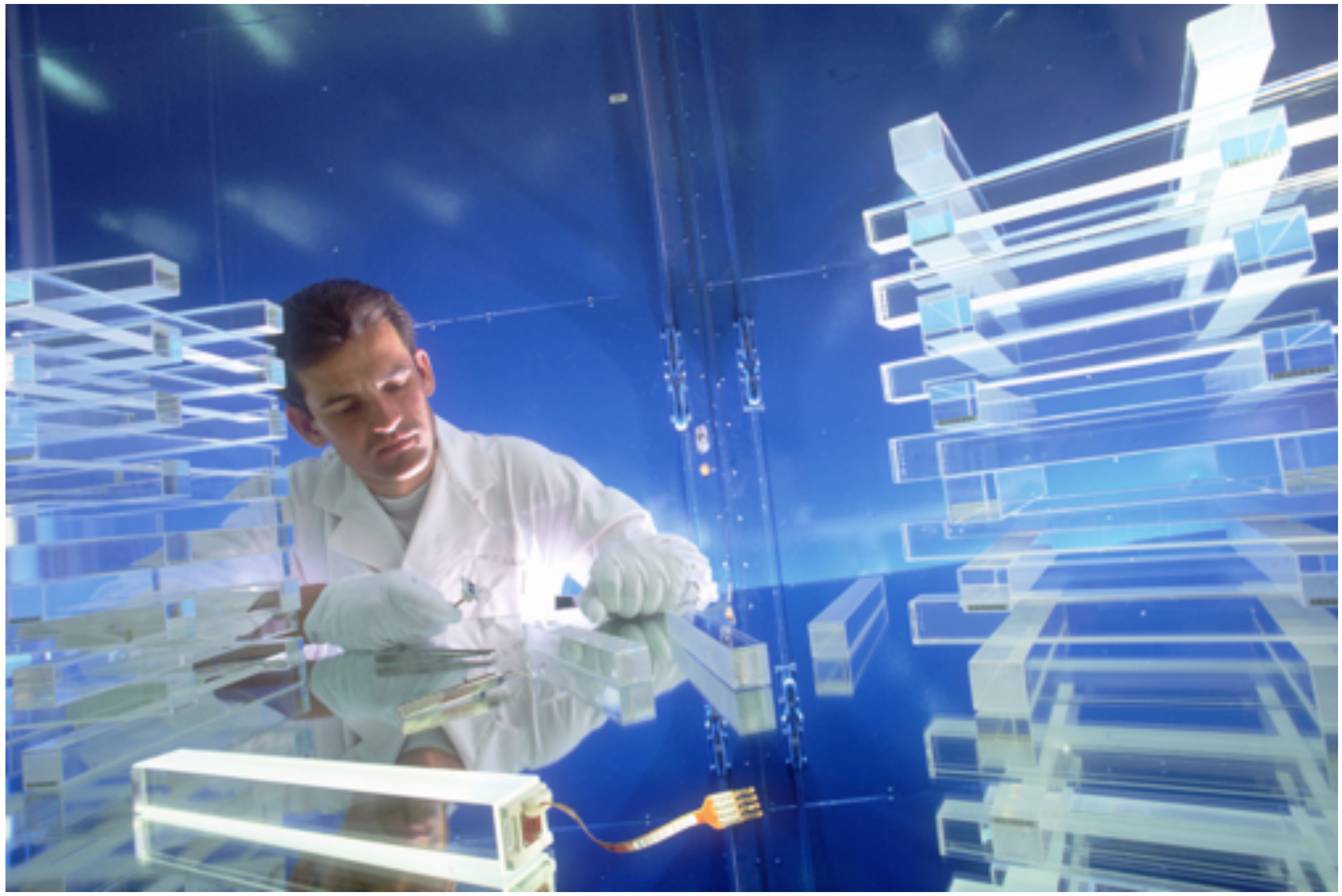
The biggest crystal calorimeter: CMS @ LHC
$PbWO_4$ - High density: 8.3 g/cm^3
decay time 10 ns (fast component)
light yield: 0.12 photons / keV



Crystals for Calorimeters - Overview

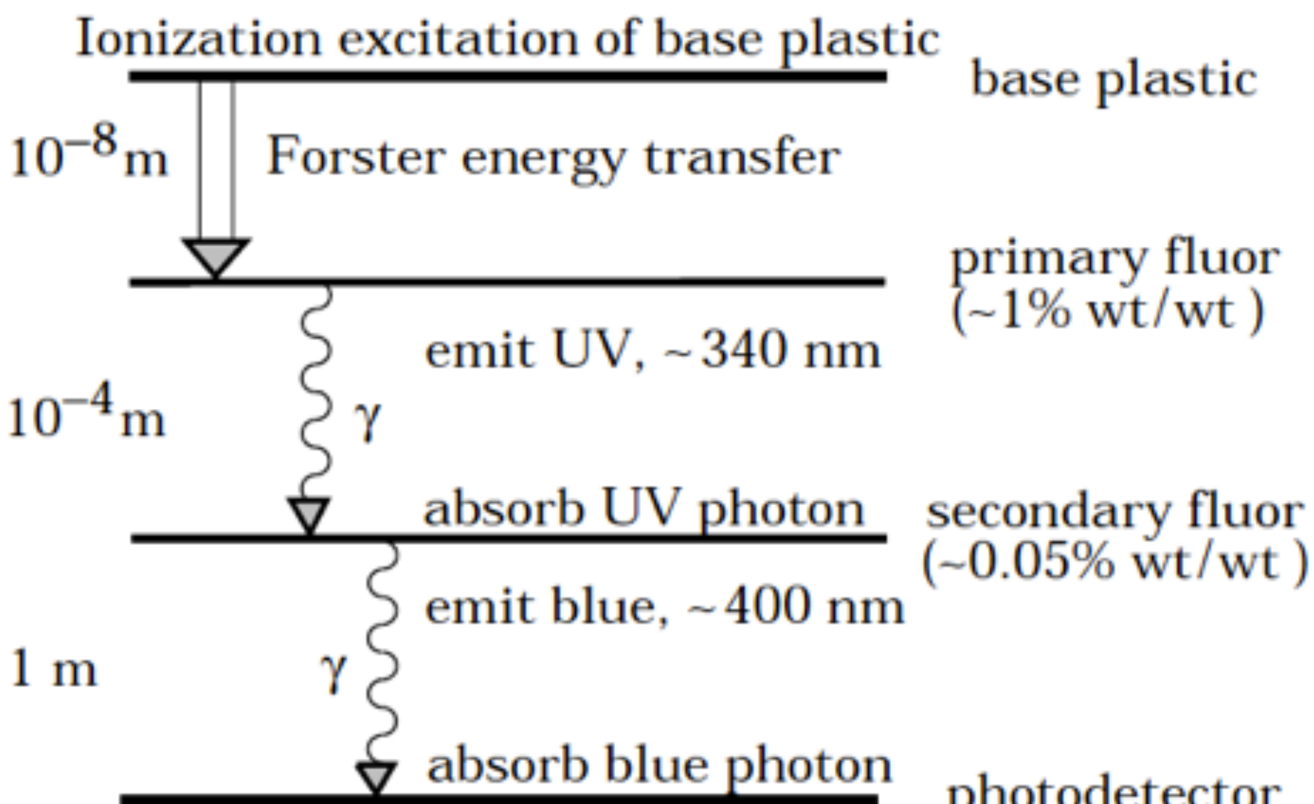
Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro- scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim 0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	83	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

taken from PDG Review of Particle Physics

- Note: The melting point is a key cost driver: High melting point crystals are expensive to produce

Plastic Scintillators for Calorimetry

- Typical plastic scintillators consist of base material plus additional fluors



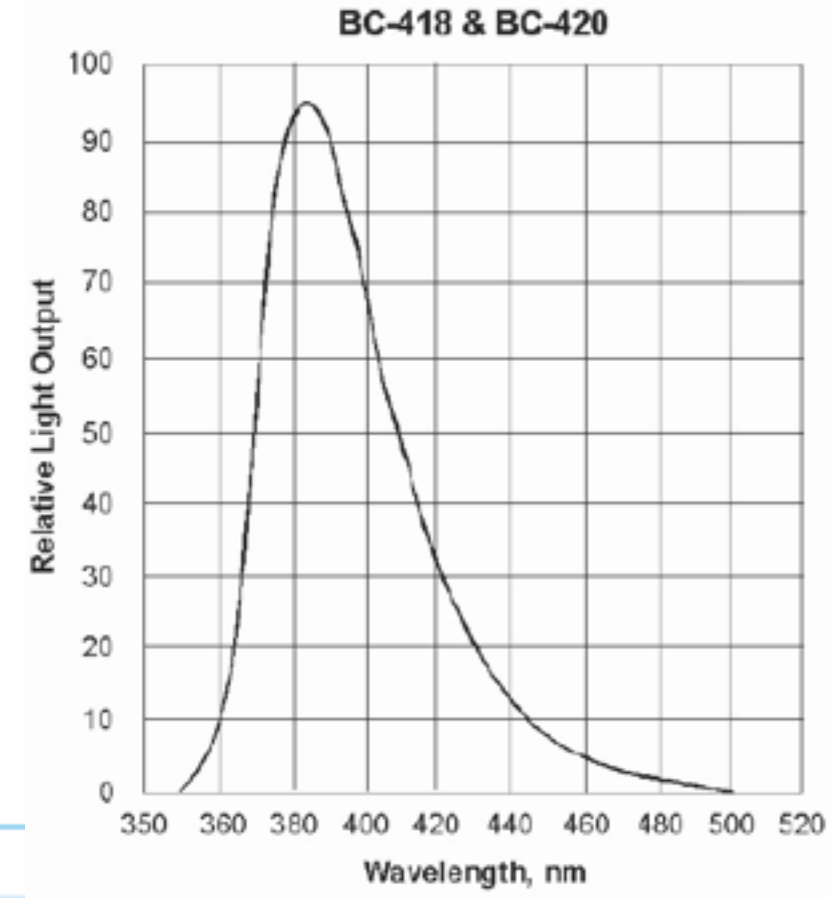
- Typical base material: Polysterene Excitation of higher states Energy transfer to fluor by dipole-dipole interaction (range ~ 10 nm)
- Fast de-excitation of fluor, typically UV emission
- Absorption and re-emission by secondary fluor (wavelength-shifter) if desired

The choice of additives (fluors) defines time constants and wavelengths: High flexibility!

... But: Low density, typically 1.0 - 1.2 g/cm3, not suited for homogeneous calorimeters

Plastic Scintillators - Typical Properties

- Typical decay constants in the ns time range
- Light emission in blue / near UV (other wavelengths are also possible with additional flours)



Physical Constants of SGC Plastic Scintillators

= ~45% of NaI(Tl)

Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, Main Component, ns	Bulk Light Attenuation Length, cm	Refractive Index	H:C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.032	70
BC-404	68	408	1.8	160	1.58	1.107		1.032	70
BC-408	64	425	2.1	380	1.58	1.104		1.032	70
BC-412	60	434	3.3	400	1.58	1.104		1.032	70
BC-414	68	392	1.8	100	1.58	1.110		1.032	70
BC-416	38	434	4.0	400	1.58	1.110		1.032	70
BC-418	67	391	1.4	100	1.58	1.100		1.032	70
BC-420	64	391	1.5	110	1.58	1.102		1.032	70
BC-422	55	370	1.6	8	1.58	1.102		1.032	70

Plastic Scintillators for Calorimetry

- Plastic scintillators can be made in arbitrary geometries, but the light has to be collected and brought to a photon sensor - Sometimes also the wavelength has to be matched to the efficiency of the photon sensor
  The technique: An embedded wavelength-shifting fiber
  - Collects light, shifts it to a lower wavelength, transports it via total internal reflection

- Uniform re-emission of light from wavelength shifter: typically 6% “capture fraction” - transported via total reflection
  - Capture fracture can be increased to 10% by double-cladded fibers

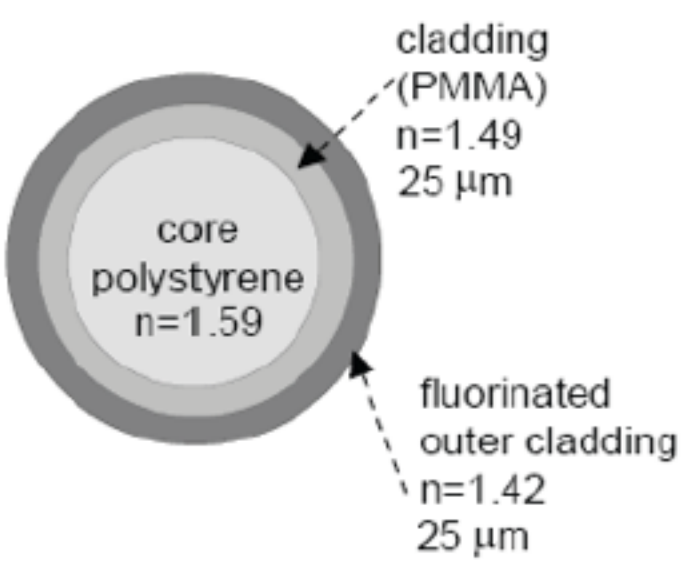
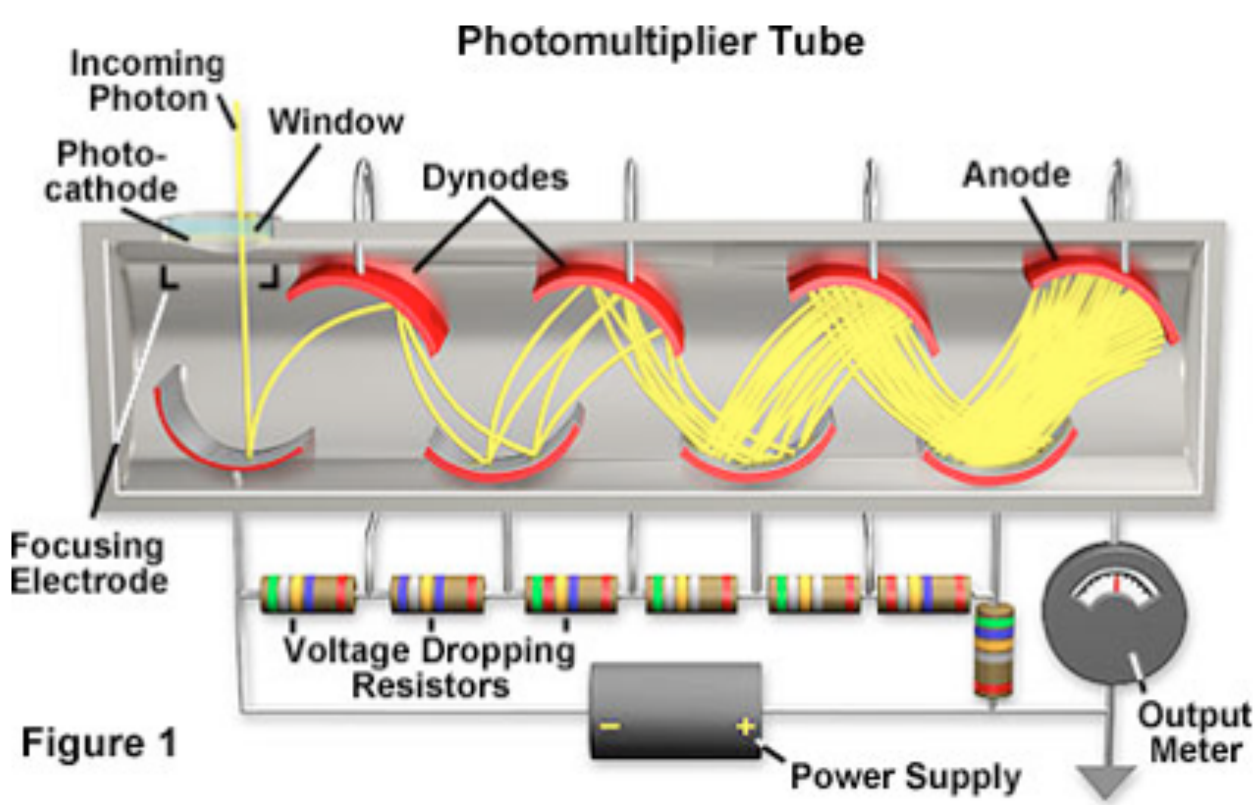


image: CERN

Detecting the Light

- The classic solution: Photomultiplier



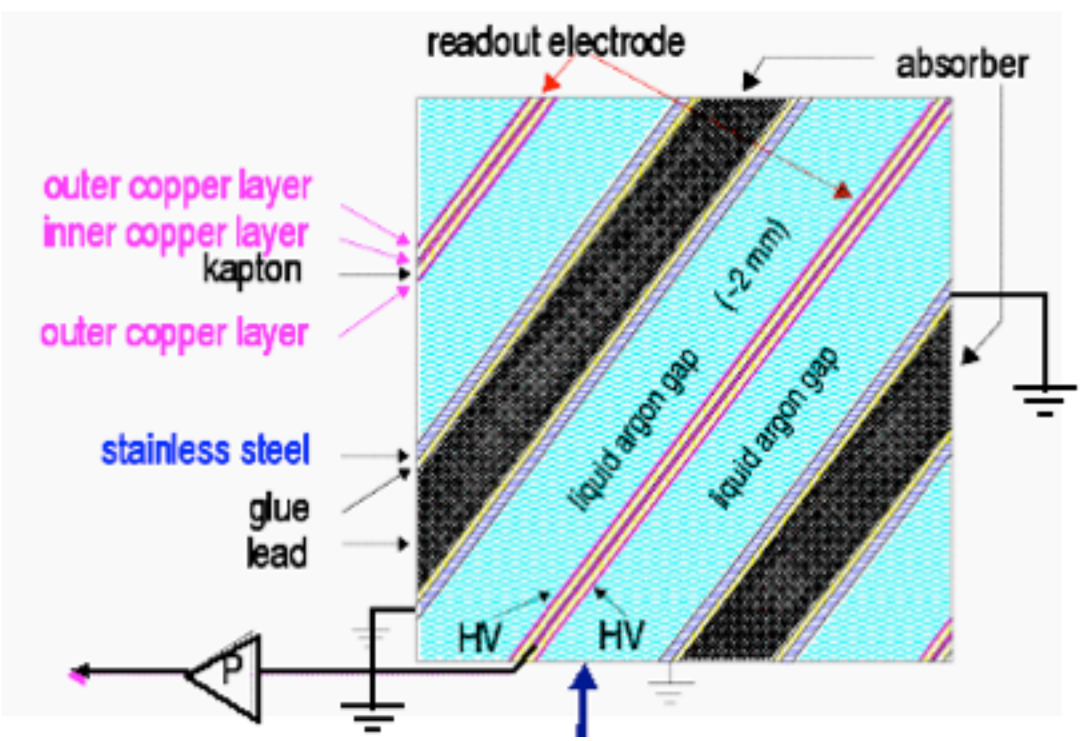
sensitive to magnetic fields
requires HV

image: Hamamatsu

- Nowadays: More and more alternatives
  - Avalanche photo diodes
  - Silicon Photomultipliers
  - ...

Liquid Nobel Gasses

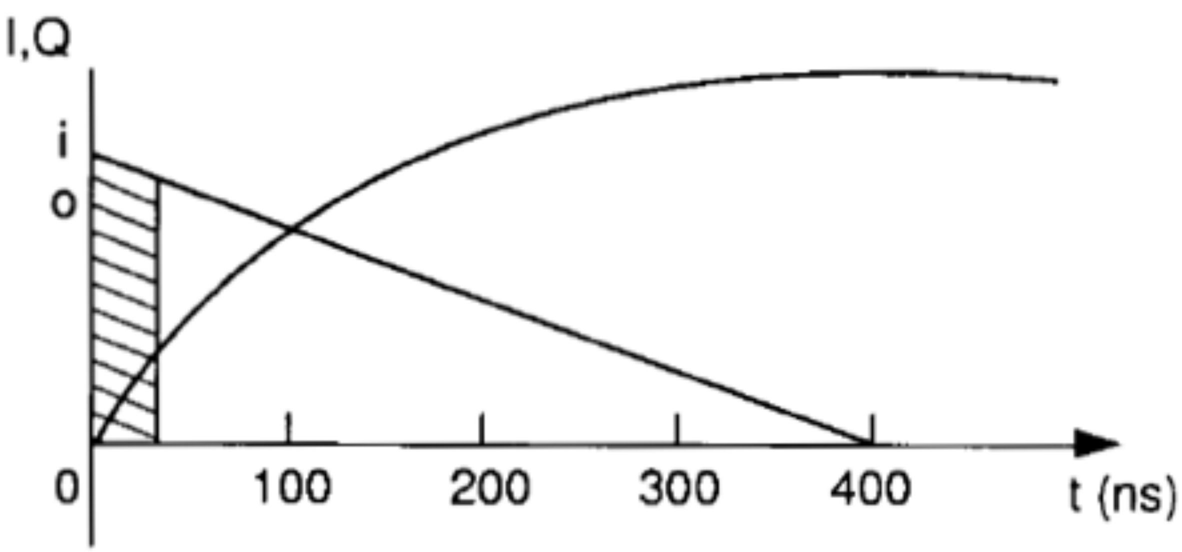
- Direct charge collection, combined with (relatively) high density medium: Large signal even without charge multiplication
- Constant change of active medium: Extremely high radiation hardness
- Most common choice: Liquid argon
  - density 1.4 g/cm3
  - Operating temperature: ~ 85 K: Cryogenic systems needed!



Typical layout:
Liquid argon gap, with HV electrode in the middle
Signal pickup: Induced signal in the center

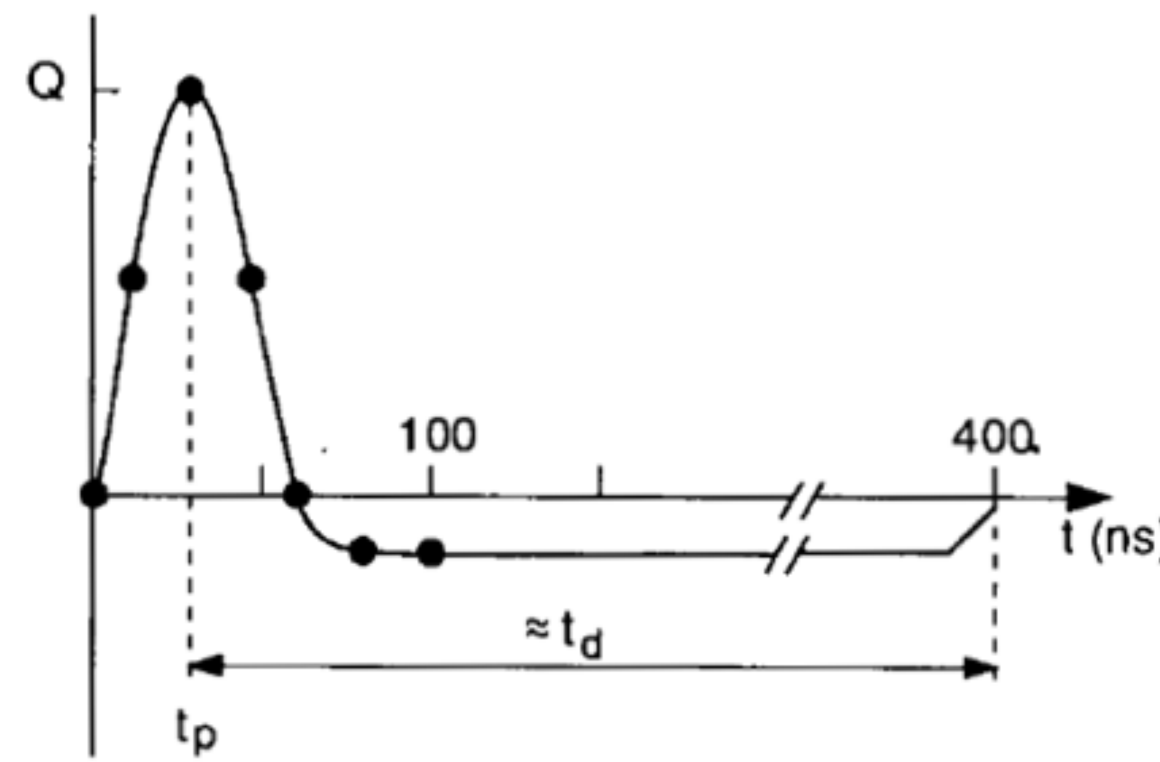
Liquid Nobel Gases

- Drift time defines readout speed:
  at 1 kV/mm ~ 200 ns / mm drift
  - Typical time scale in HEP: 25 ns bunch crossing frequency at LHC



NIM A309, 438 (1991)

Drift current and charge vs time in a LAr calorimeter

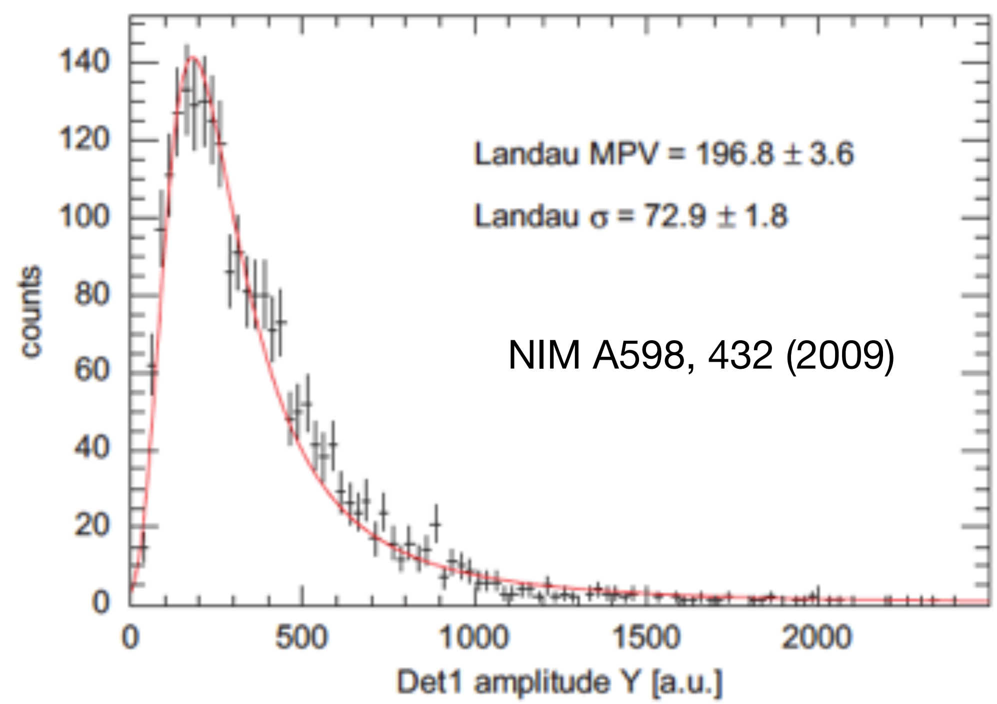


Response of a fast shaping amplifier with a peaking time of 20 ns to LAr pulse: Fast extraction of signals is possible!

Careful: Potential limiting factor is the capacitance of the readout electrodes!

Gaseous Detectors

- Classic detection technique - cheap to produce and operate large areas
  But:
  - Low density medium! A through-going particle produces only ~ 100 electrons / cm (~ 30 primary interactions / cm)
  - ➯ Large fluctuations: The well-known Landau tail
  - ➯ Low sampling fraction: No shower development in the medium
  - ➯ Simple energy sum will result in poor resolution!



NIM A598, 432 (2009)

- The strategy: Use highly segmented detectors, just count hit cells:
  Back to the idea of counting particles, eliminates Landau fluctuations

➯ The concept of the Digital Calorimeter

Semiconductor Detectors

- Silicon commonly used in tracking systems for charged particles
- Can be used as active material in calorimeters (usually in combination with Tungsten absorbers)
  - Density 2.3 g/cm^3 : Reasonable sampling fractions can be achieved (however, silicon detectors are typically less than 500 μm thick)
  - High charge output for a given energy loss: Only ~ 1 eV per electron-hole pair (compare to 25 eV per photon in Na(Tl), 100 eV per photon in plastic scintillators, 26 eV per electron-ion pair in Ar)
  - Very high lateral segmentation possible - Pixel sizes as small as 25 μm no problem nowadays

- Highly pure Germanium crystals are used as calorimeters for low energies: Fantastic energy resolution (see lectures by Iris)

Course Overview

- **Part I - *yesterday***
  - The Basics: Shower Physics
  - Calorimeter Basics
    - Calorimeter Types
    - Drivers of Energy Resolution
  - Readout Technologies & Materials

- **Part II - *today***
  - Calorimeters in HEP and Medical Imaging
    - The Basics of Calorimeters in Medical Imaging
    - The Basics of HEP Calorimeters
  - New Technologies

Calorimeters in Medical Imaging and Particle Physics

Very Different Environments

- In Medical Imaging: Small energies, photons only
  - PET: 2 photons @ 511 keV
  - Commercial systems, large numbers,...
- In High Energy Particle Physics: High energies, jets, electrons, photons
  - At Colliders: Energies up to the TeV region
  - One-of-a-kind systems

Very Different Environments

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... and different goals:

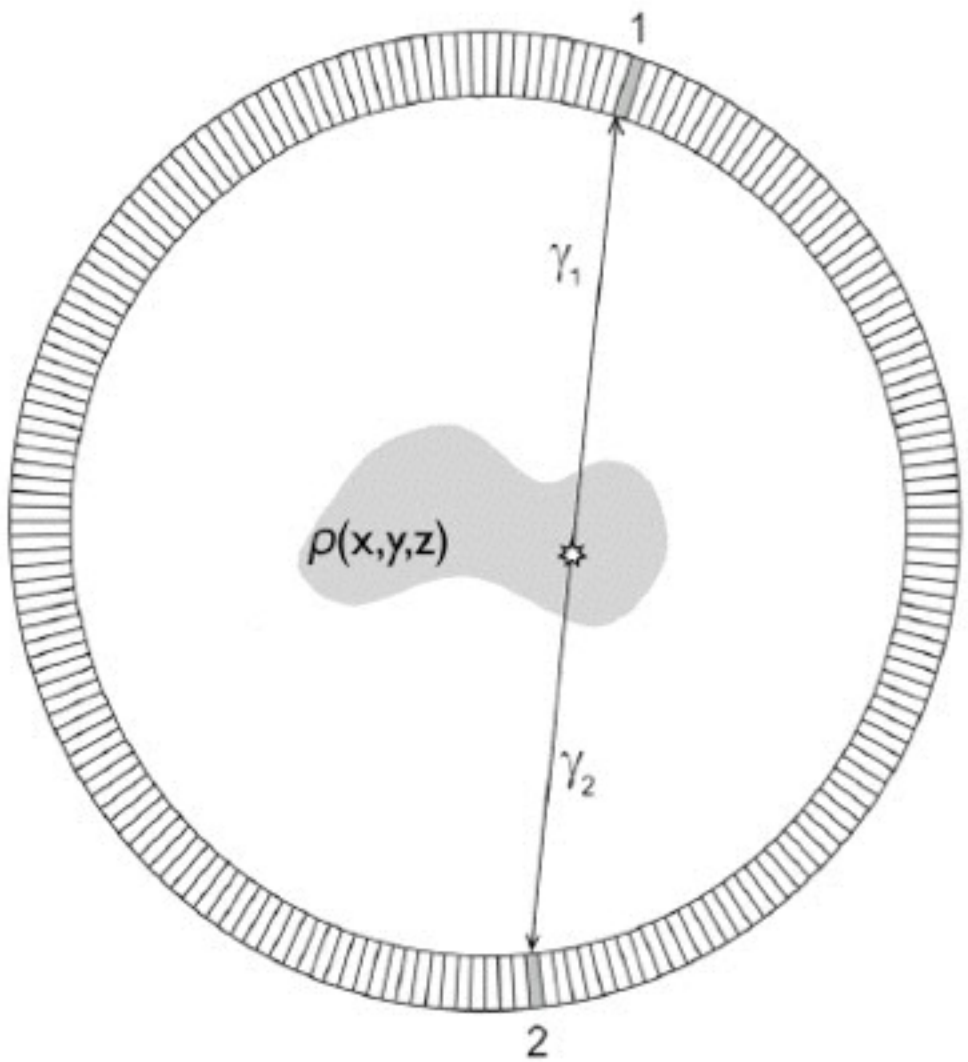
- In medical imaging the main purpose is to measure coordinates (spatial and angular resolution, time) - The energy of the particles is known
- In HEP, the main purpose is to measure energies: Photons, hadronic jets, also electrons

So - What's in Common?

- Common technologies: Developments from nuclear and particle physics find their way into medical diagnostics
- A favorite energy measurement technique: Scintillation
  - Elegantly solves the problem how to get information out of the active medium to some form of readout: visible (or close to visible) light!
  - Requires: Scintillators & Photon Detectors: Synergies between medical imaging and particle physics
    ... in addition data acquisition systems, analysis algorithms, ...

Calorimeters for Medical Imaging - Basics

- The PET Principle:



The goal: Determination of the position of the decay of the radio-nuclide

Requires:

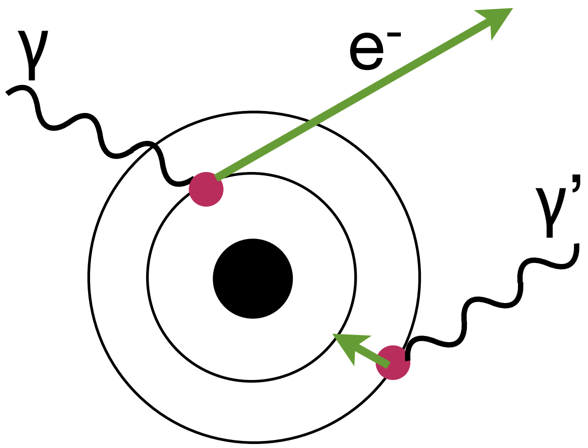
- Good pointing accuracy: Determine line of flight
- Good timing: Limit background / wrongly matched photon pairs

Limitations from physics:

- Positron range before annihilation
- Scattering / absorption of photons

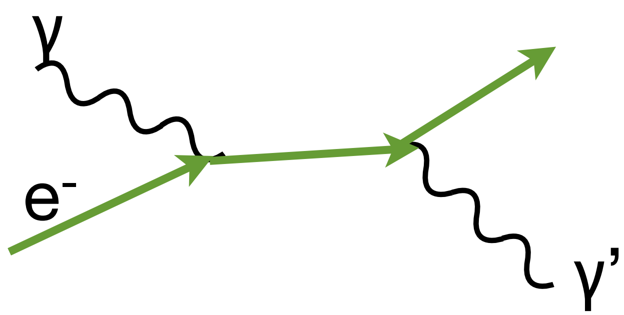
Calorimeters for Medical Imaging - Basics

- Measurement of 511 keV photons:
  - No electromagnetic shower - Interaction with matter:
    - Photo-effect



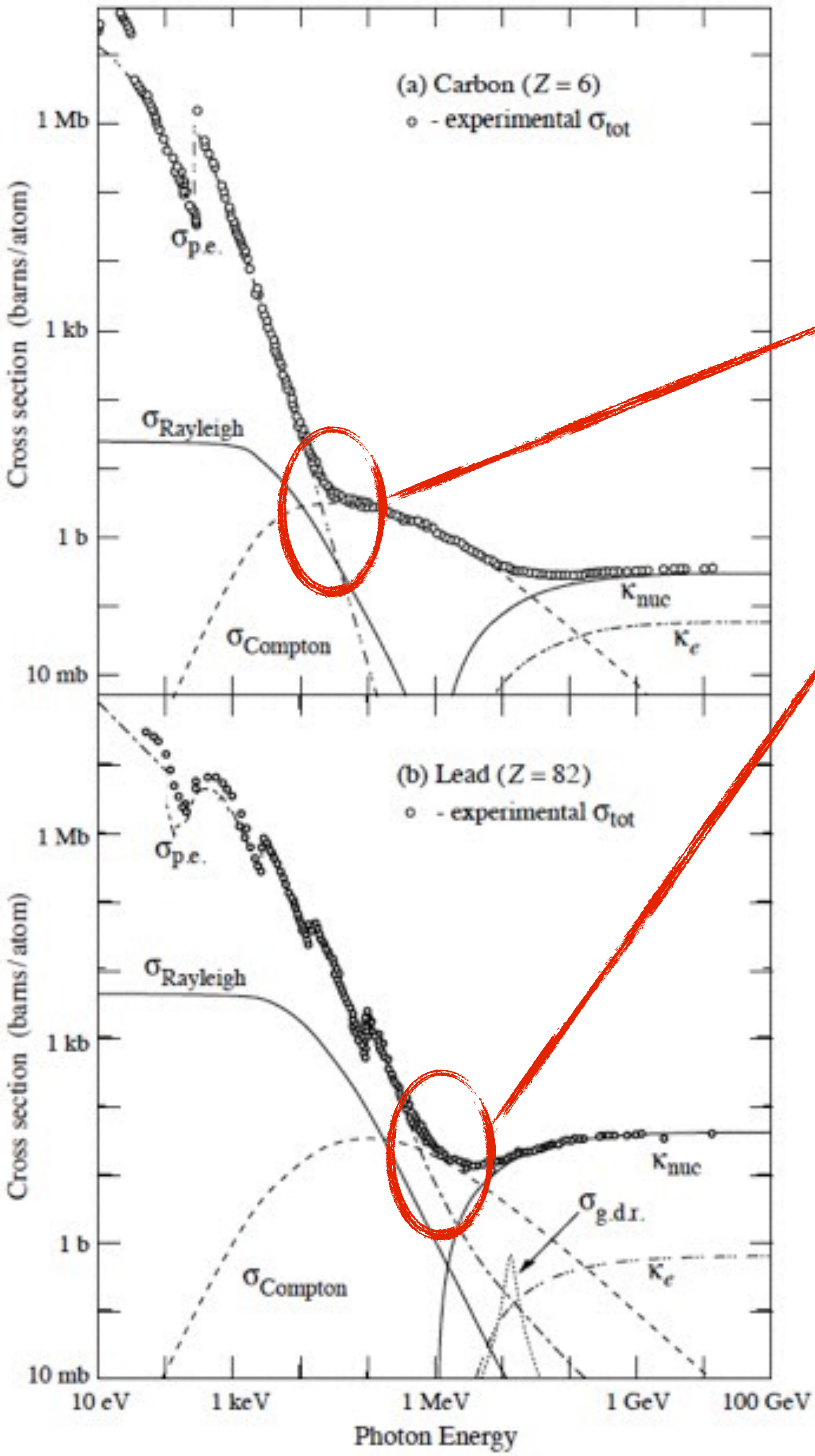
Dominates at low energy, depends on Z

    - Compton scattering



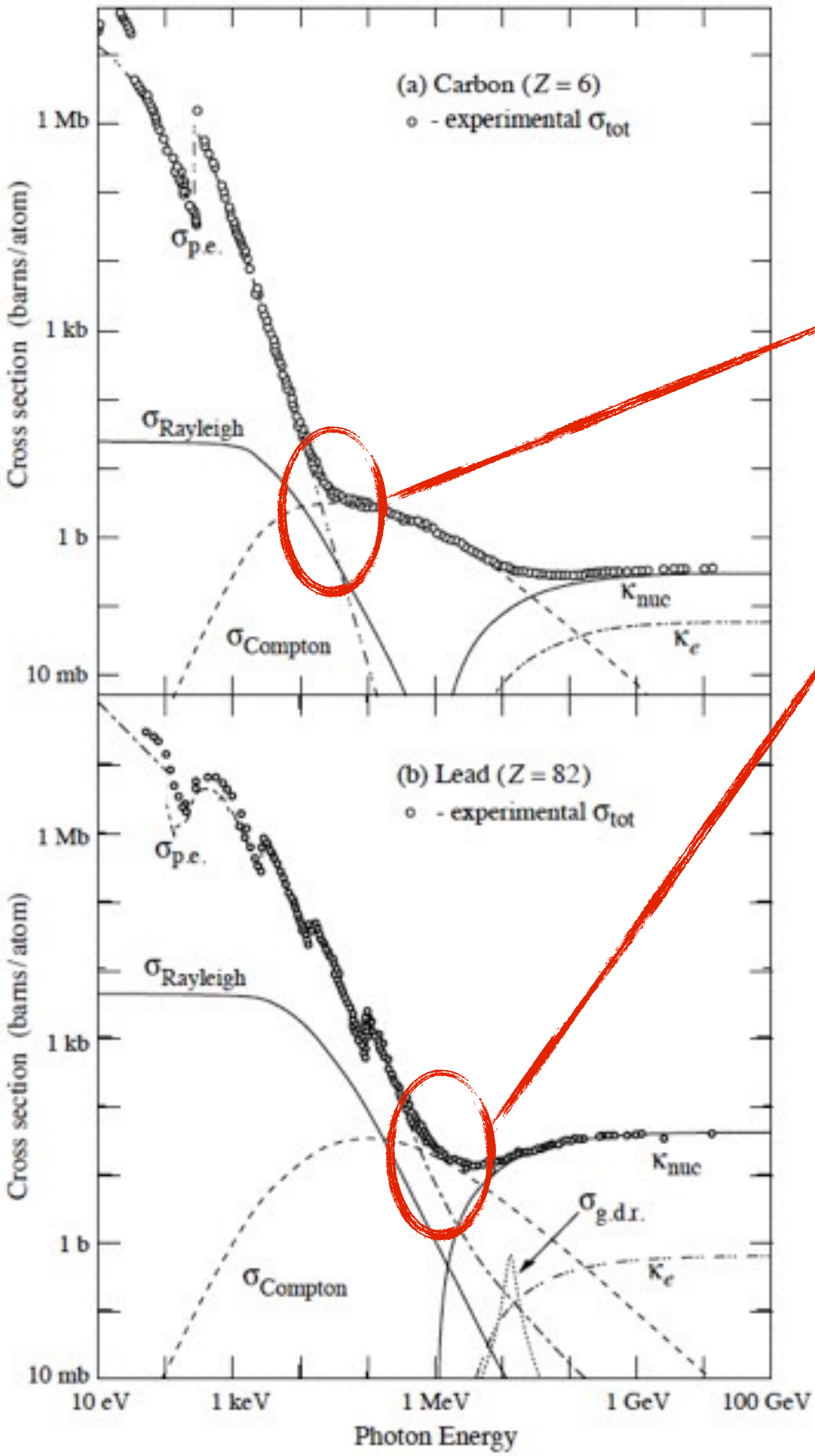
Intermediate energy, before pair creation kicks in at > 1 MeV

Calorimeters for Medical Imaging - Basics



- Relative importance of different processes at a given energy depends strongly on Z
  - Carbon (Z = 6): Compton wins above ~ 10 keV
  - Lead (Z = 82): Compton wins above ~ several 100 MeV

Calorimeters for Medical Imaging - Basics



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  - Carbon (Z = 6): Compton wins above ~ 10 keV
  - Lead (Z = 82): Compton wins above ~ several 100 MeV

Does it matter? Yes!

- Photo-electric effect leads to very localized absorption of all energy: High position accuracy
- Compton scattering spreads the signal out over larger volumes - Traveling distance of scattered photon in particular

▸ High-Z detectors preferred!

Calorimeters for Medical Imaging - Basics

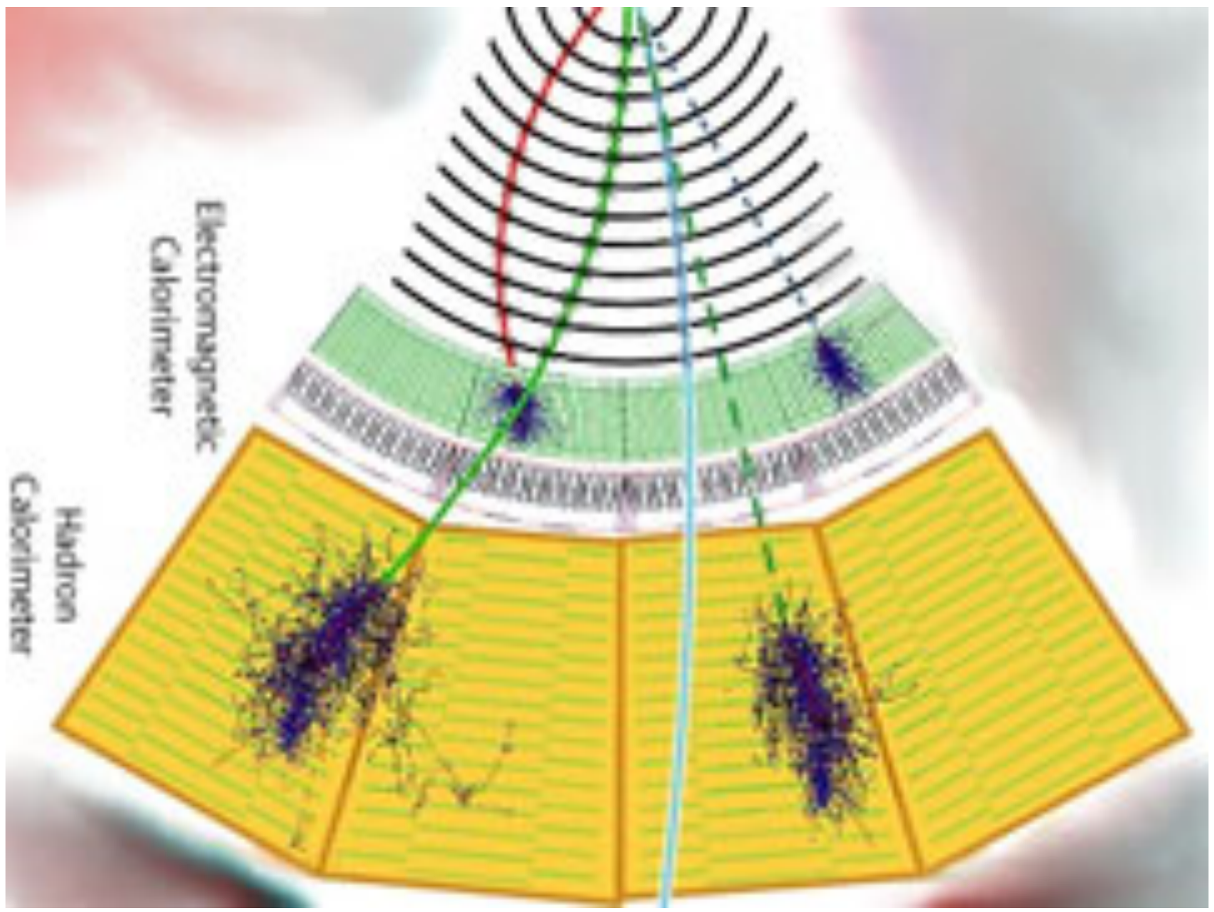
PET - Putting it together:

- A high-Z scintillator: Maximize photo-effect for 511 keV
- A dense scintillator: Short free length for photons, good position resolution
- A fast scintillator: good timing - reduction of pile-up, TOF
- High light yield: Good energy resolution
- LSO / LYSO best currently available (Density 7.3 g/cm^3, <Z> = 65)

- In addition: Highly efficient, fast photon detectors - Reading out matrices of scintillating crystals

Calorimeters for HEP - Basics

- Measurement of the energy of most particles in a HEP event
  - Electromagnetic and hadronic

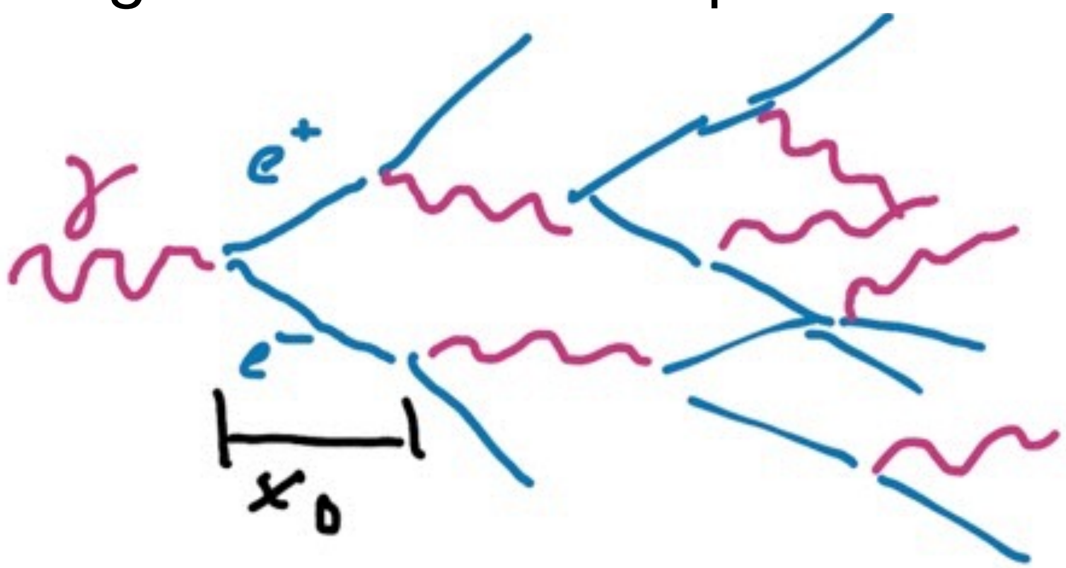


Requirements:

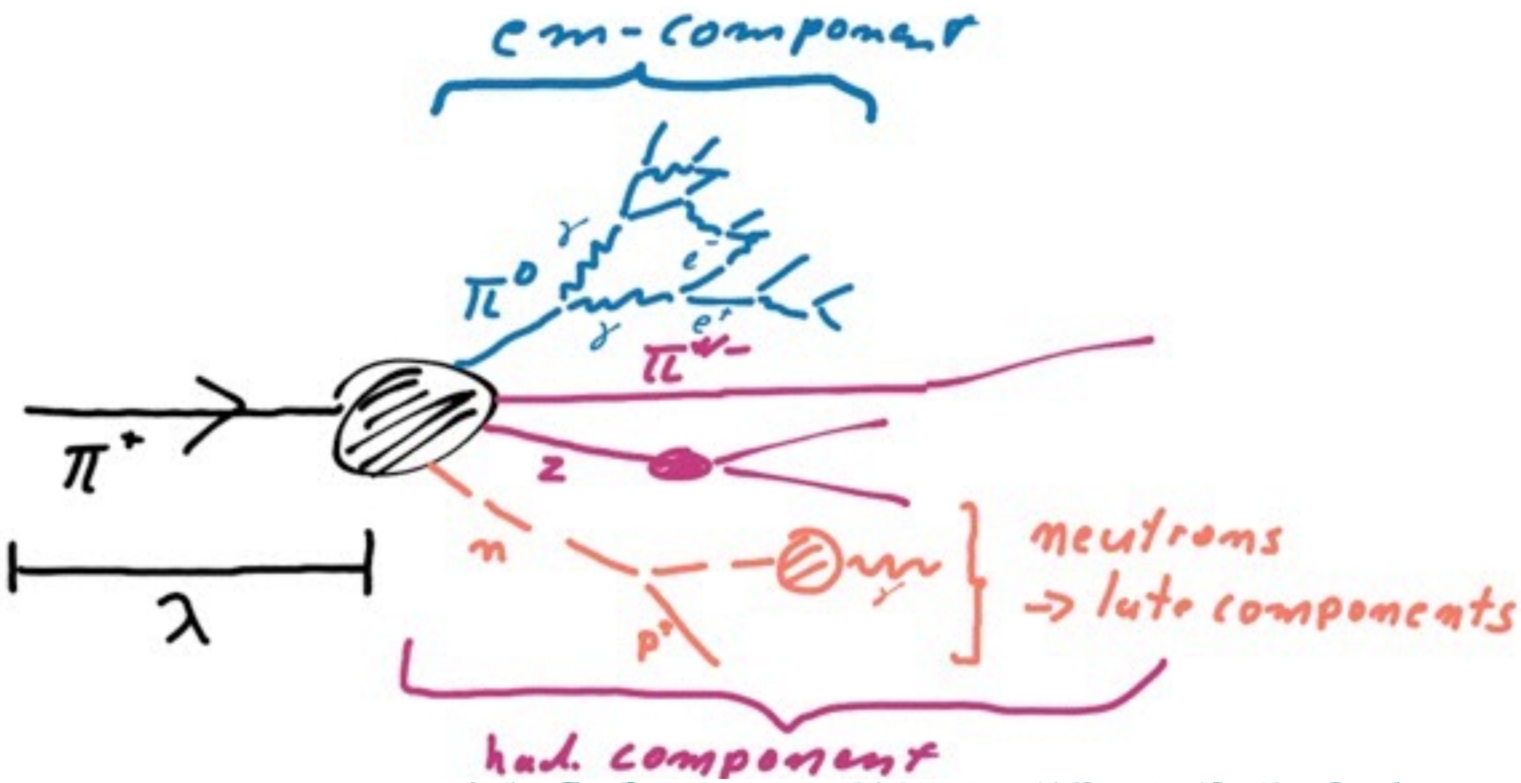
- Good energy resolution for electromagnetic and hadronic particles
- Large depth: absorb high-energetic particles
- Good timing: Reduce pile-up
- Operate inside magnetic fields
- Radiation hardness

Calorimeters for HEP - Basics

- Measurement of highly energetic particles: Showers
  - Electromagnetic: Successive pair creation / Bremsstrahlung



  - Hadronic: Hadronic cascade with hadronic and em content

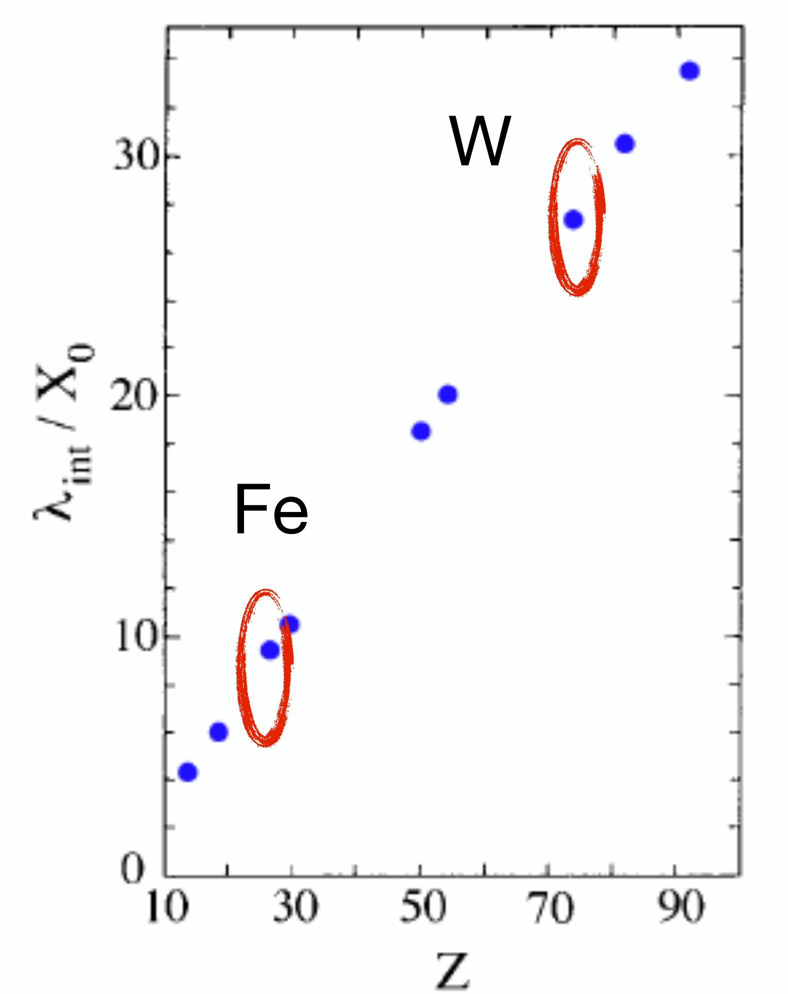


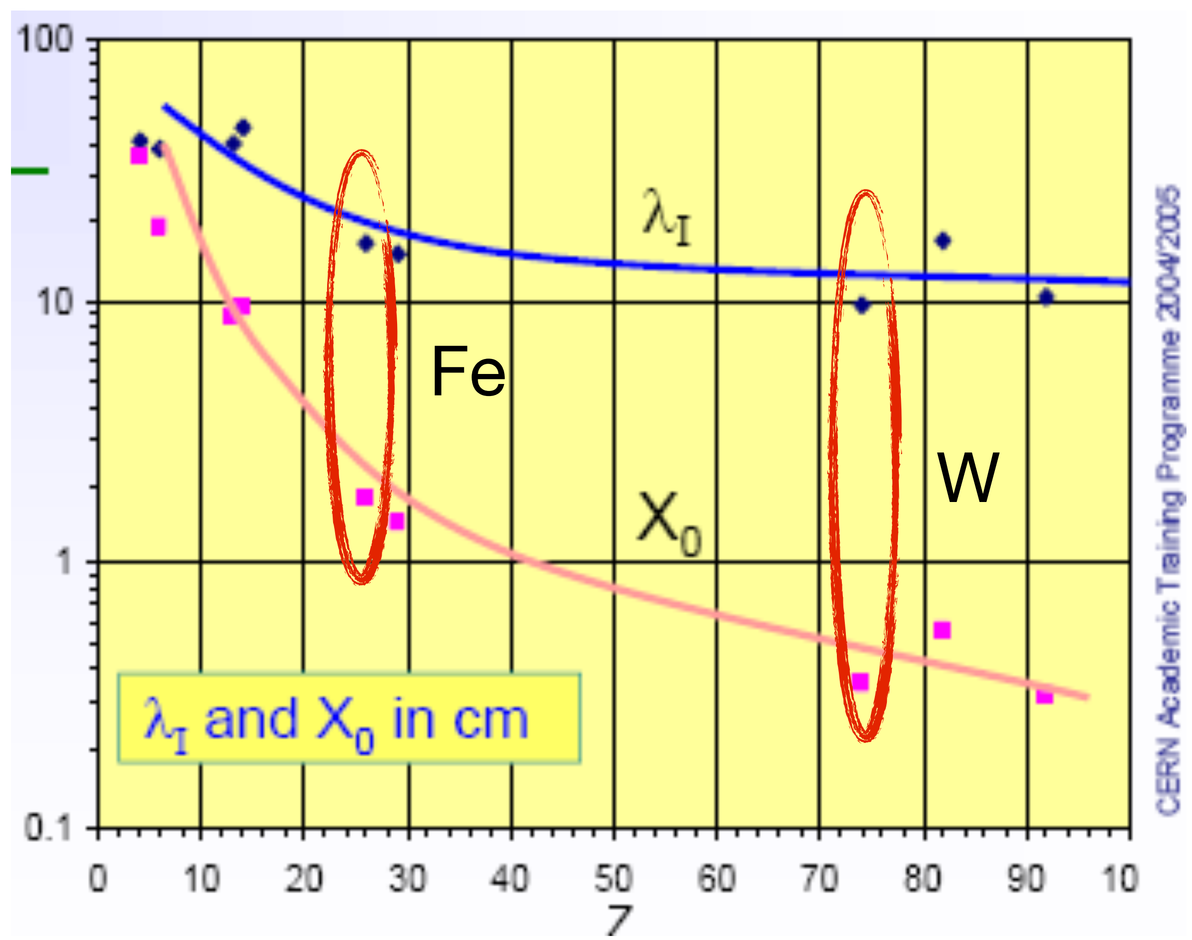
Calorimeters for HEP - Basics

- Electromagnetic and hadronic showers: A challenge
  - Detectors often show a different response to electromagnetic and hadronic showers
    - Hadronic showers have “invisible” energy - binding energy loss etc
    - Complex time structure: Integration time matters
    - Energy loss can be (over-) compensated by sensitivity to neutrons
  - Typically: Higher response to electrons than pions - e/pi > 1
    - Results in non-linearities, calibration challenges when using different em and hadronic calorimeters

Calorimeters for HEP - Basics

- The challenge of wanting it all:
  Hadrons don't care about the separation into em and hadronic calorimetry: 30% - 60% of all hadronic showers start already in the em section of a HEP calorimeter system



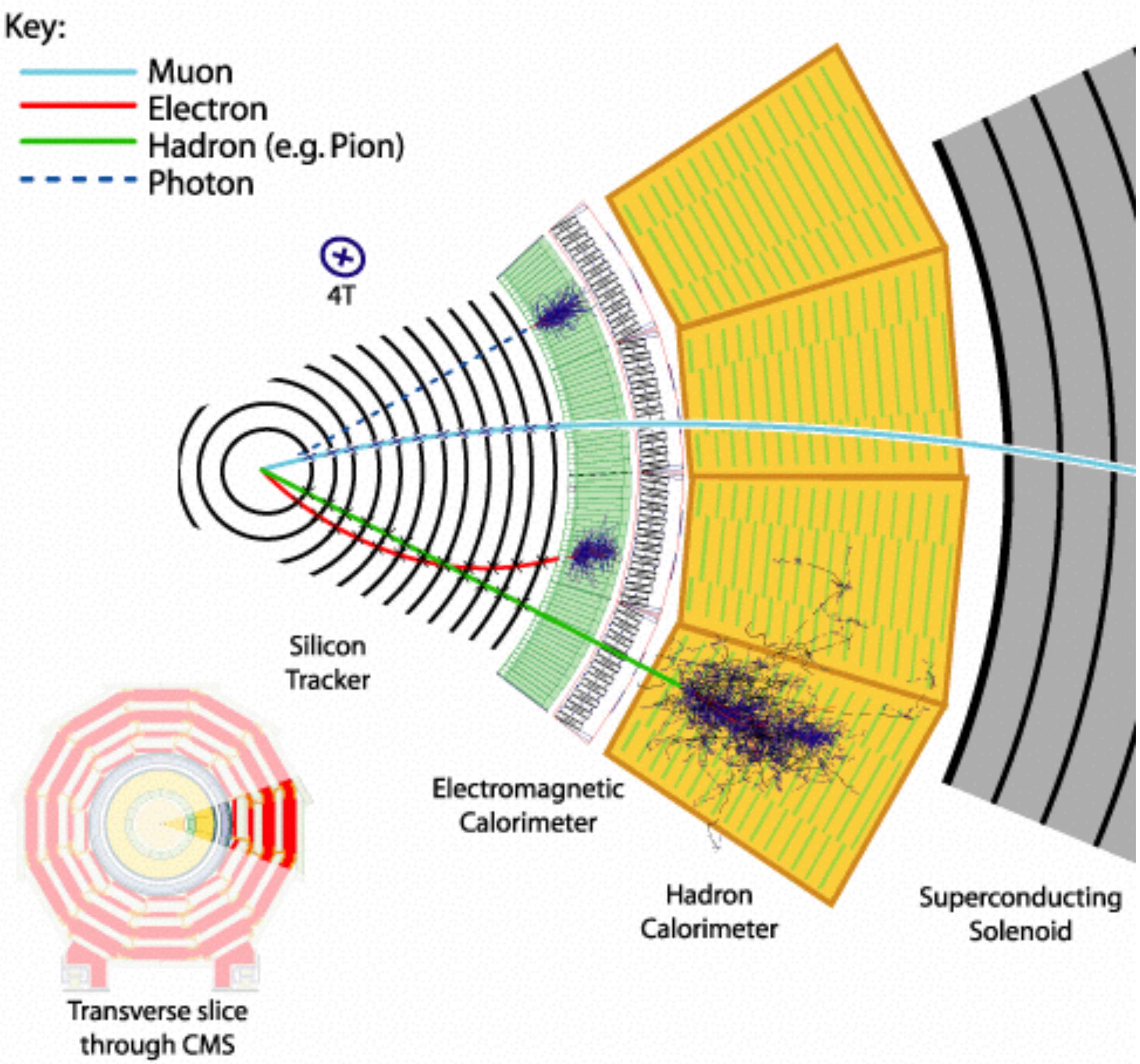


The choice of absorber strongly influences the relative sensitivity to em and hadronic shower components

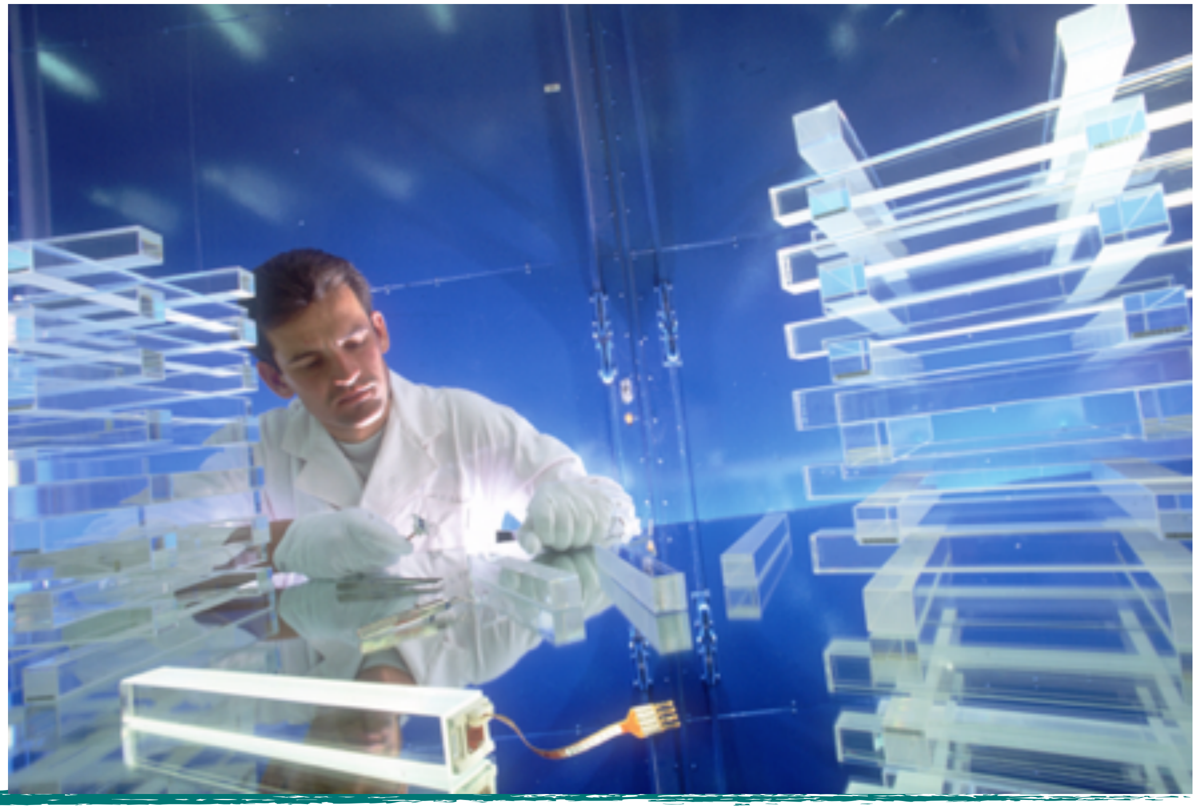
➩ Need to make compromises / set priorities

Calorimeters for HEP - Basics

- A state of the art system: CMS

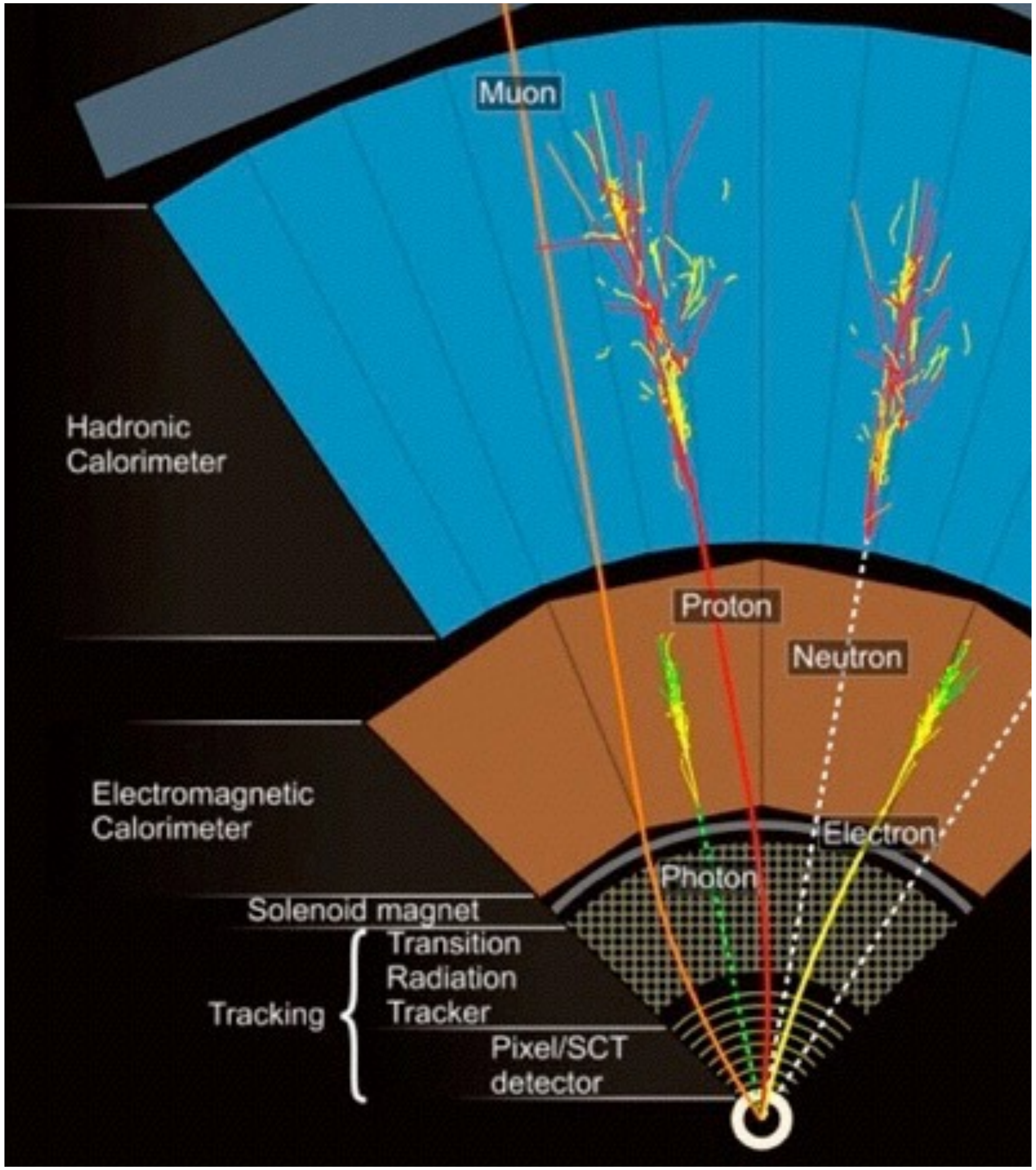


- A fantastic ECAL - $PbWO_4$ crystals with APD readout
- EM energy resolution ~ 2.8%/√E
- The price to pay: Single hadron stochastic term ~93%



Calorimeters for HEP - Basics

- A state of the art system: ATLAS



- LAr ECAL, Scintillator HCAL in Barrel both longitudinally segmented
  - EM resolution ~9%/$\sqrt{E}$
  - Single hadron stochastic term ~42%

New Technologies

New Photo-Sensors

- For decades the tool of choice: The PMT

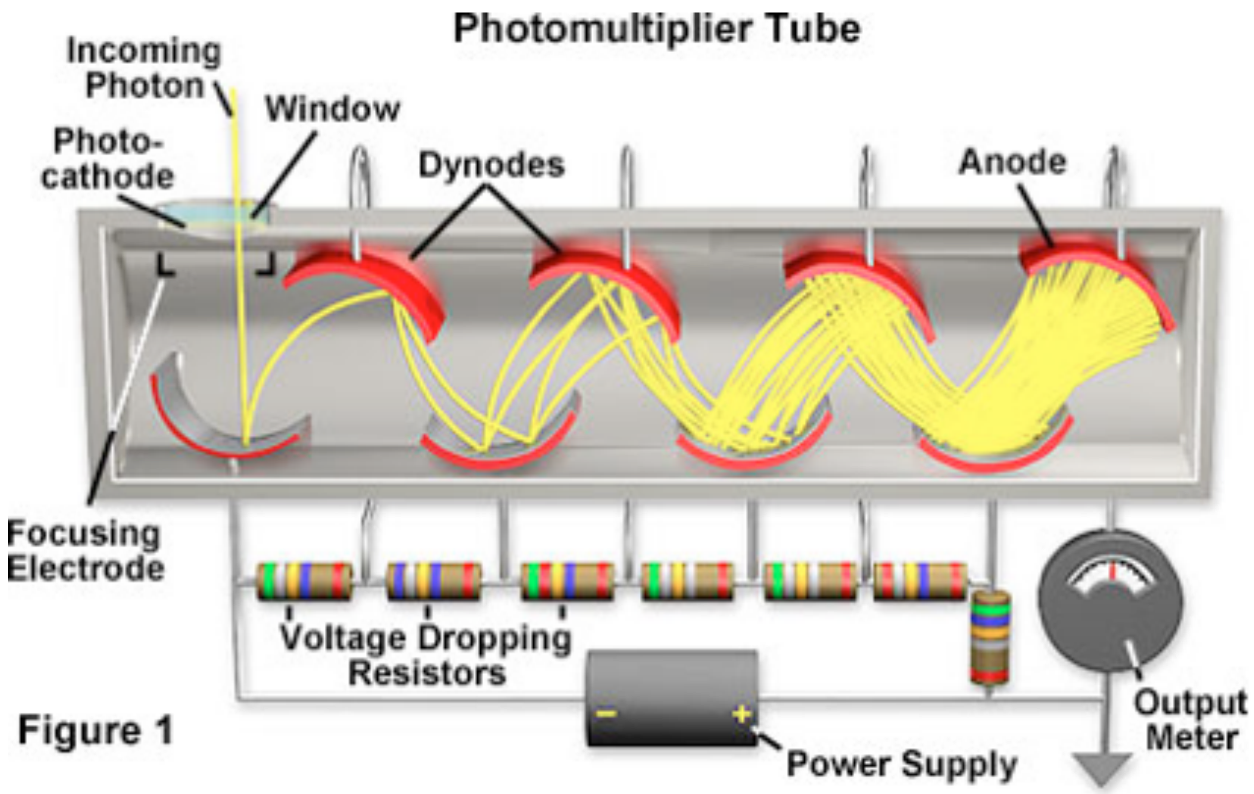
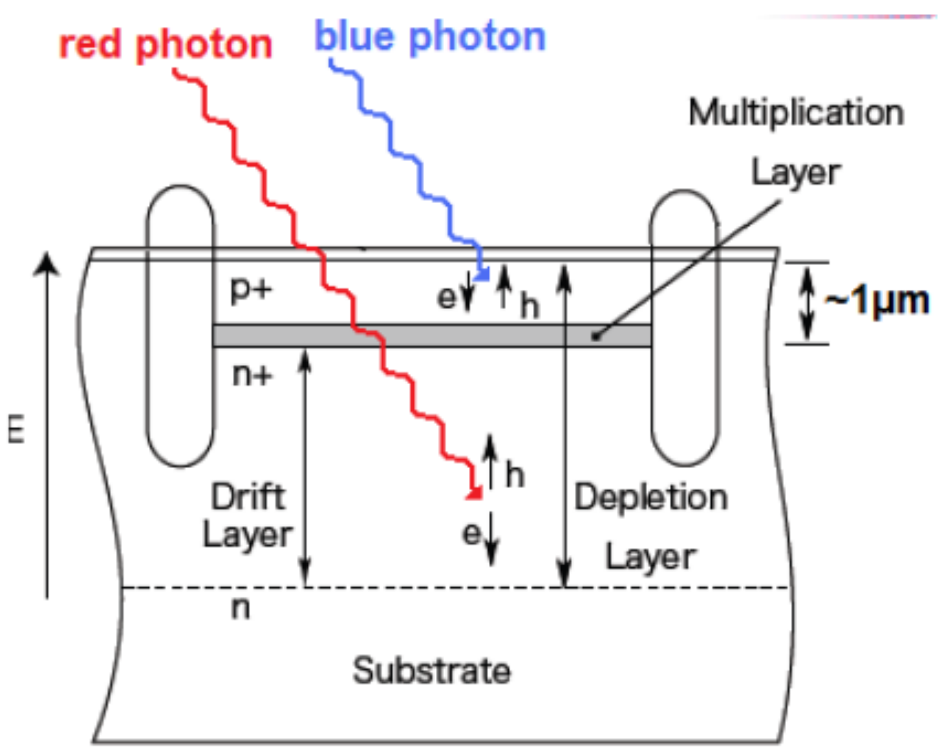


image: Hamamatsu

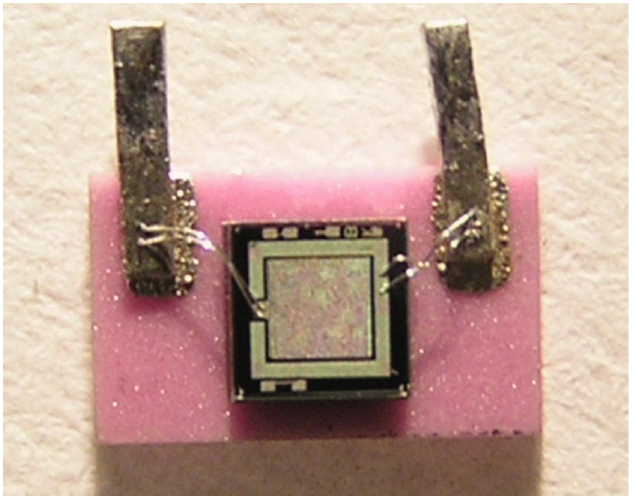
- Main limitations:
  - Size (and cost)
  - In-ability to operate in magnetic fields (a few Gauss are a problem, and for PET + MRI and HEP we have multiple Teslas...)
  - Need for high voltage

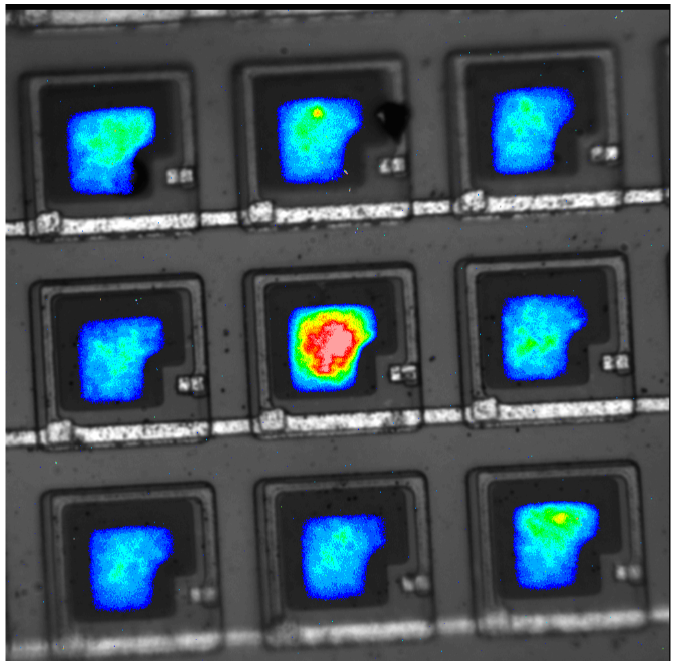
SiPMs - Revolutionizing Calorimetry

- A quantum leap forward:
  - High gain -> Fast electronics no problem
  - Small size, low cost -> High channel counts possible (up to 10s of millions in HEP)
  - Insensitivity to B-Fields: Photon detectors in magnetic field



SiPM from MEPHI / PULSAR

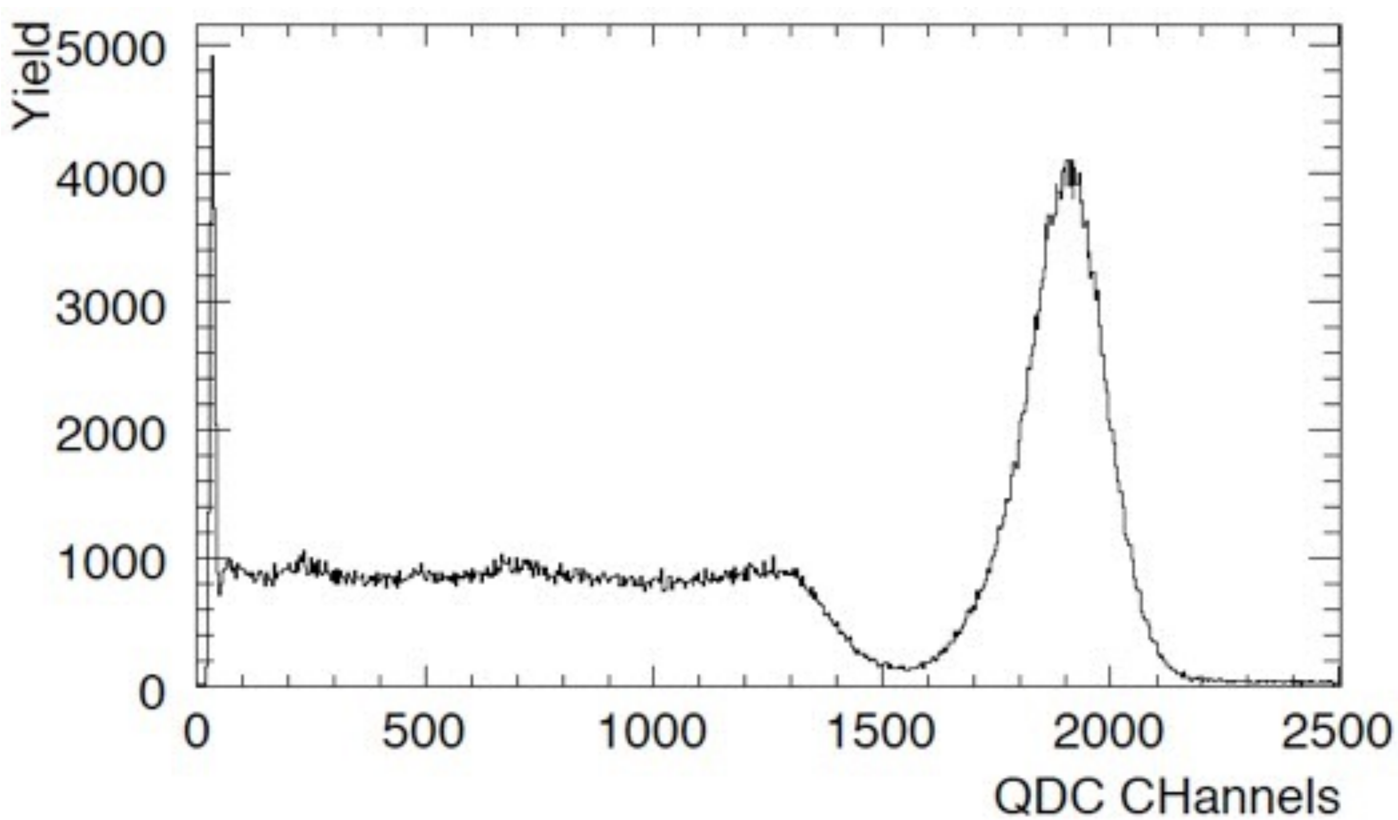




- The first large-scale use of these devices: The CALICE analog HCAL, a physics prototype for Linear Collider detectors -> almost 8k channels (SiPMs)

Possibilities in Medical Imaging

- Compactness of high-density crystals & readout with SiPMs + insensitivity to magnetic fields: PET systems can be installed inside MRIs
  - Combining structural measurements (MRI) with metabolic measurements (PET)
    - Structural information can be used to improve PET resolution
    - (Almost) Endless possibilities!



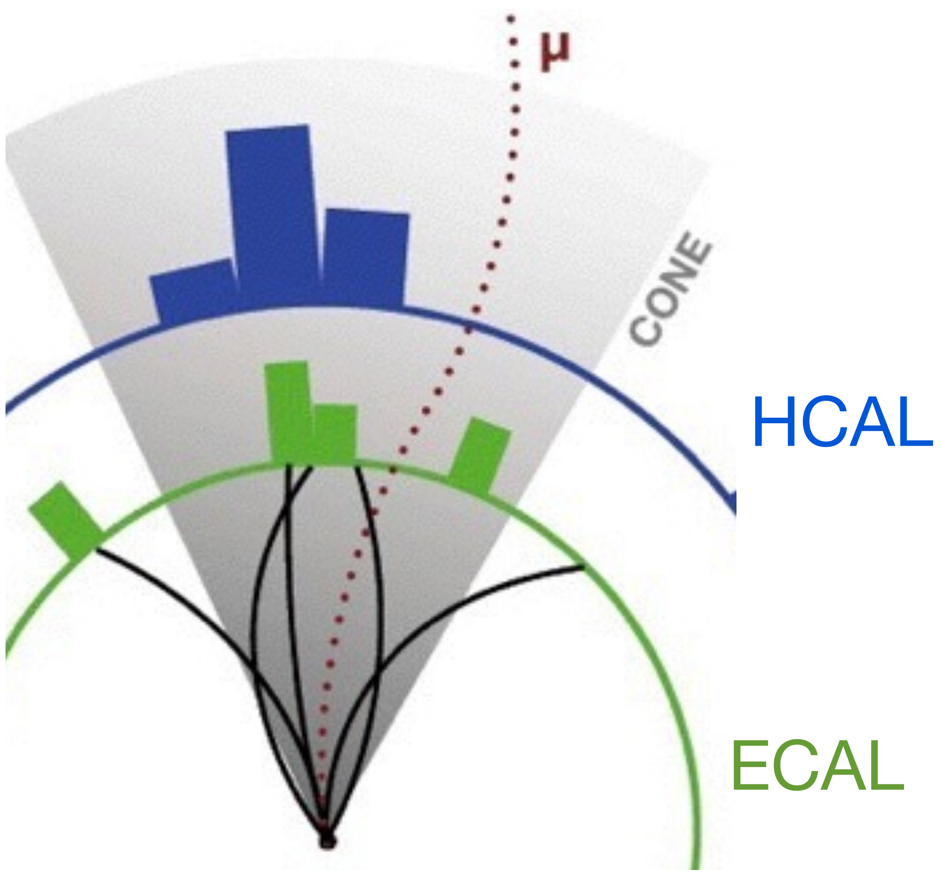
Here: Hamamatsu 3 x 3 mm^3 MPPC (50 x 50 μm^2 micro-cells) on a 3 x 3 x 15 mm^2 LSO crystal

arXiv:0805.0525

Current Frontiers in HEP Calorimetry

- At high energies the measurement of jets is crucial
  - Multi-jet final states (outgoing quarks, gluons)
  - Missing energy reconstruction - Invisible particles

The principle of jet reconstruction: Sum energy in a cone (geometry etc given by jet finding algorithm) to determine energy of original parton



The limitations:
Neutral hadrons, photons from neutral pion decay: Cannot just sum charged tracks - The calorimeter with the worst energy resolution (the HCAL) drives the performance for jets!

Current Frontiers in HEP Calorimetry

- The goal for next-generation experiments: A quantum leap in jet energy resolution: A factor ~2 improvement compared to current state of the art
  - Motivated by the requirement to separate heavy bosons W, Z, H in hadronic decays

- Two approaches:
  - Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons: Dual / Triple readout calorimetry
  - Precise reconstruction of each particle within the jet, reduction of HCAL resolution impact: Particle Flow Algorithms & Imaging Calorimeters

Improving HCAL Resolution

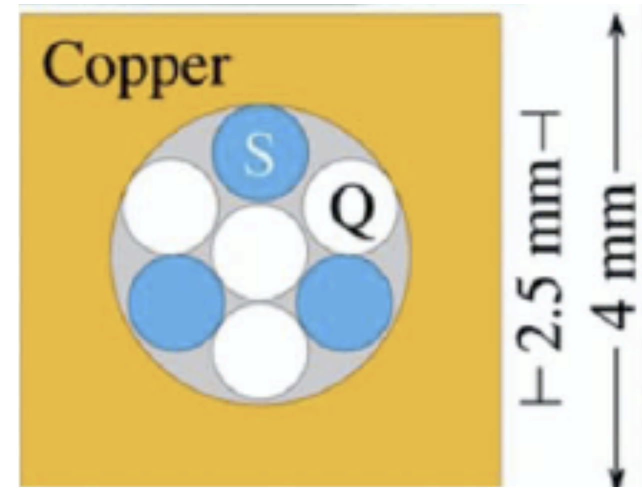
- The key to good energy resolution: Compensation
    - Equal response to electromagnetic and to hadronic showers
    - Eliminates resolution penalties from fluctuations in the em fraction of showers

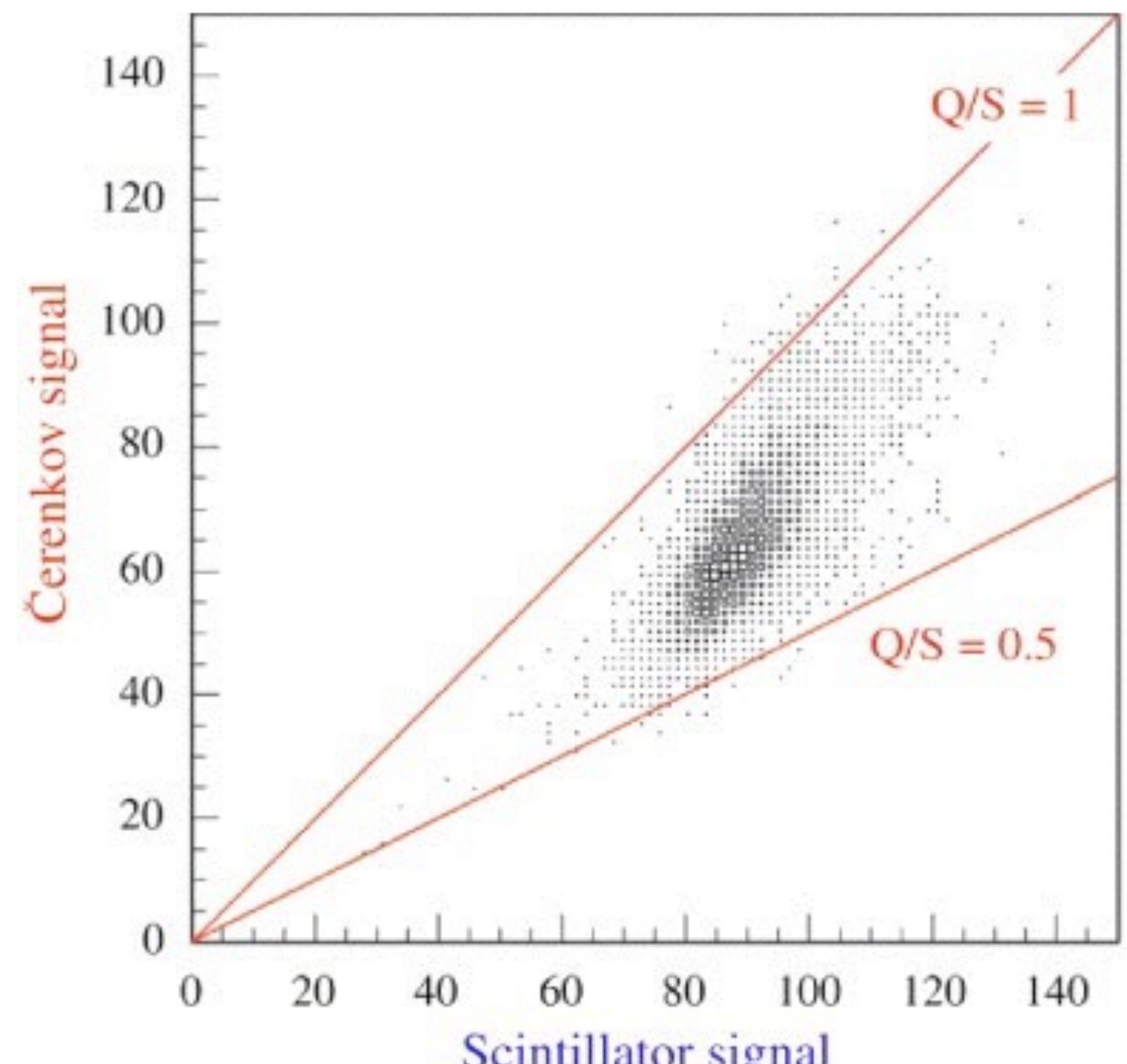
- Not a new concept: Compensating calorimeters have been built - Most prominent example: ZEUS Uranium-Scintillator calorimeter, but: Imposes strict requirements on used materials and geometries, limited resolution due to coarse sampling: ~ 35%/Sqrt(E) for single pions

- Taking this to a new level: Dual / Triple readout - Separate signals from electromagnetic and hadronic components, measure em fraction and compensate response event by event

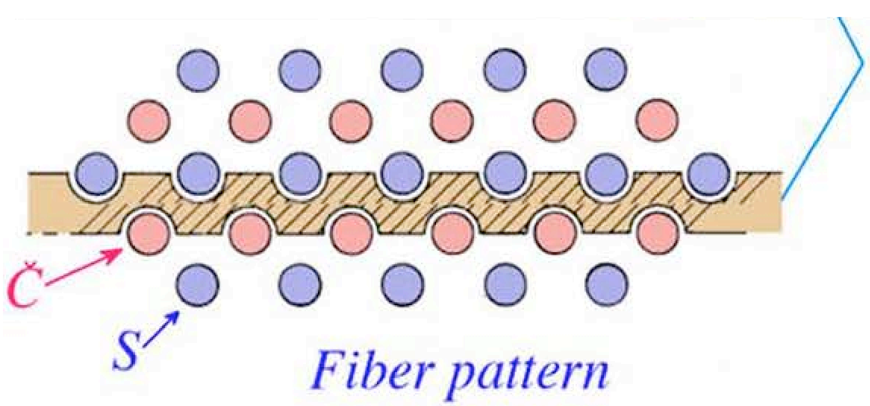
The DREAM Principle

- Dual readout module: Two active media
  - Scintillating fibers: Sensitive to all charged particles in the shower
  - Quartz Cherenkov fibers: Sensitive to relativistic particles: EM only
  - ▸ Very different e/h: S ~ 1.4, Q ~ 5
  - ▸ Energy reconstructed by combining scintillator and Cherenkov signals: event-by-event correction for em-fraction





Now further developed in RD52 Collaboration

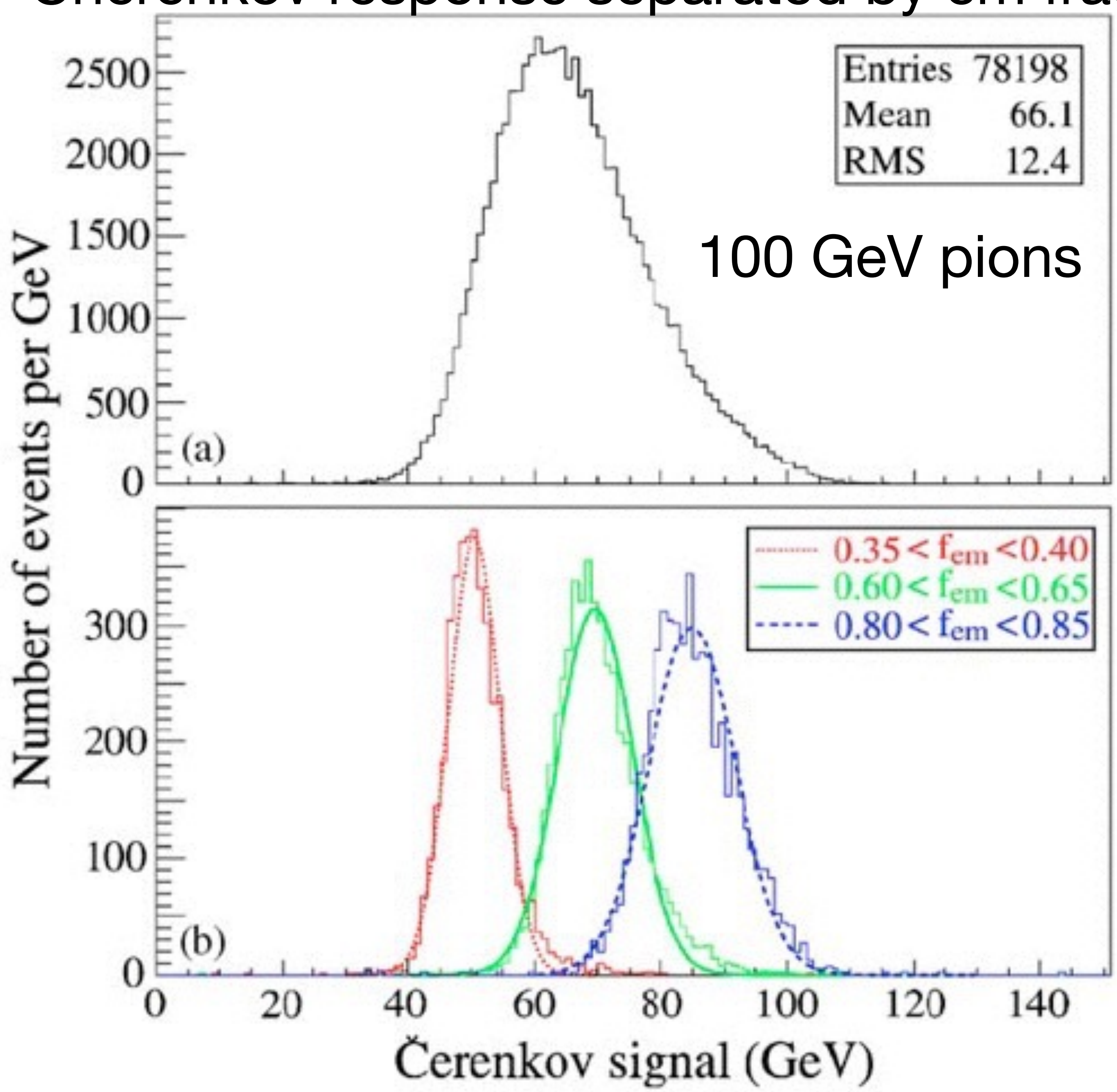


"Super-DREAM"

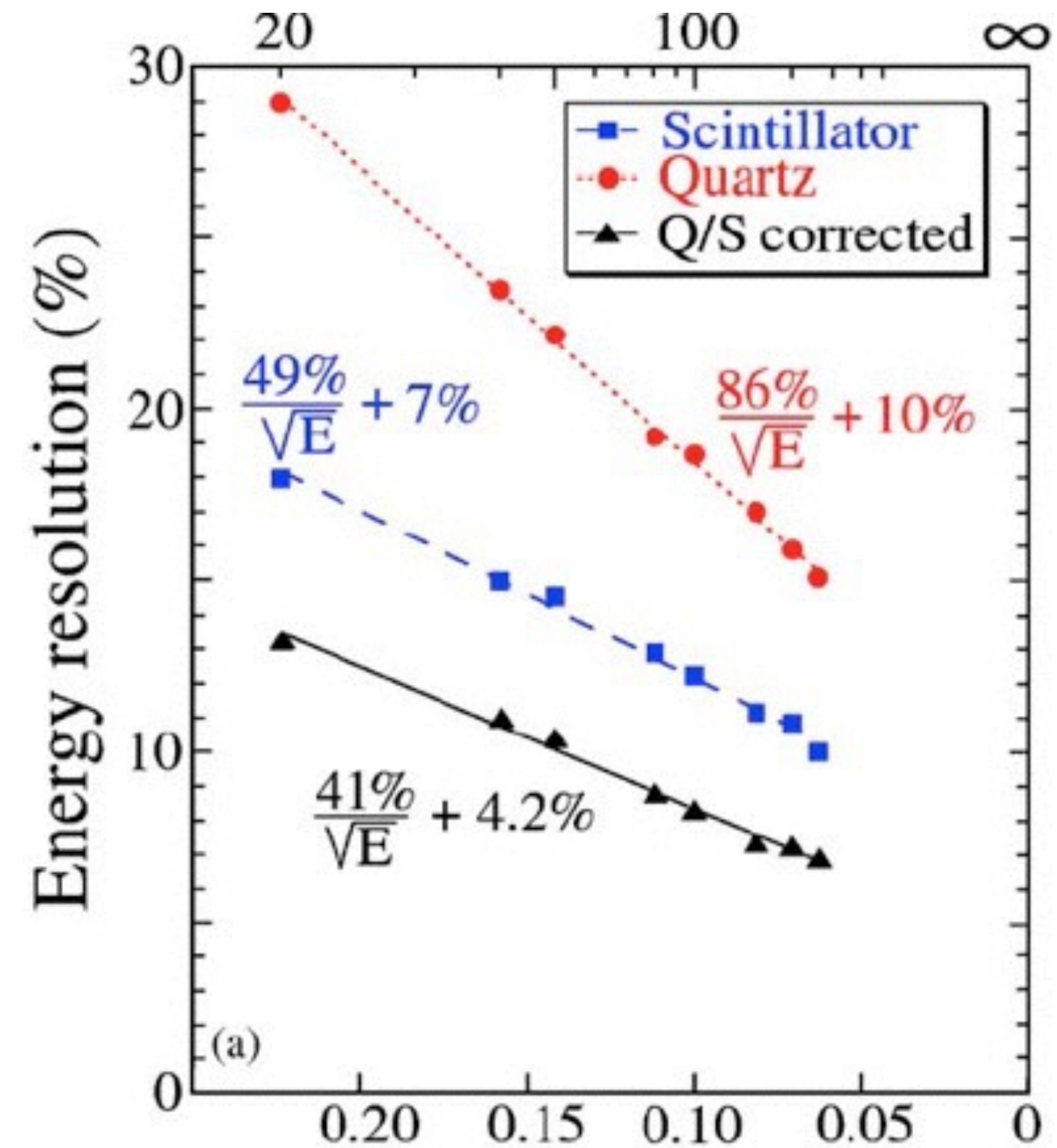
DREAM Results

- Results from a first test module
    - Note: Size insufficient for full shower containment

Cherenkov response separated by em fraction



pion energy [GeV]



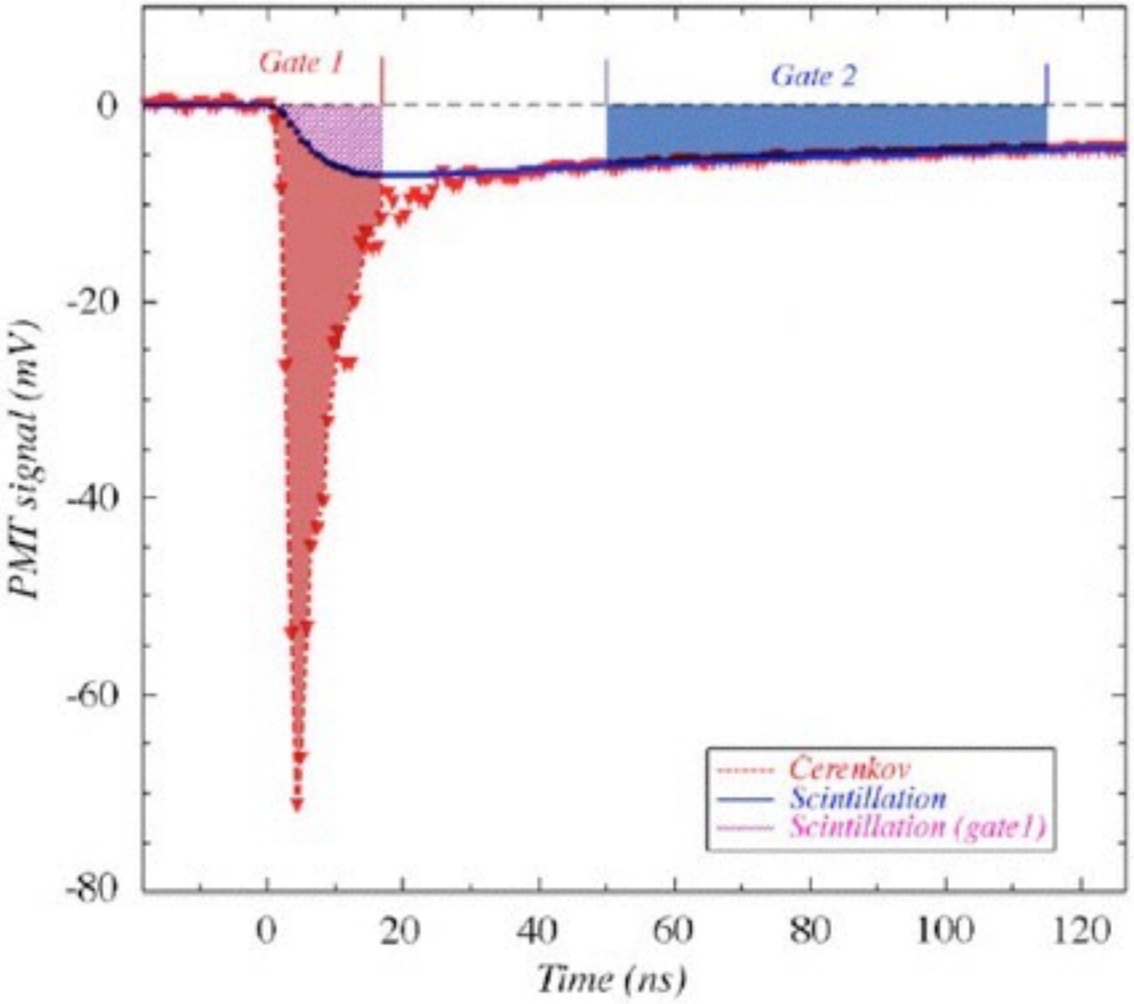
NIM A537, 537 (2005)

$1/\sqrt{E}$

Pushing it further: DR with Crystals

- A way to solve the issue of photon energy resolution: A crystal section with dual readout - separate Cherenkov and scintillation based on time and wavelength

NIM A610, 488 (2009)



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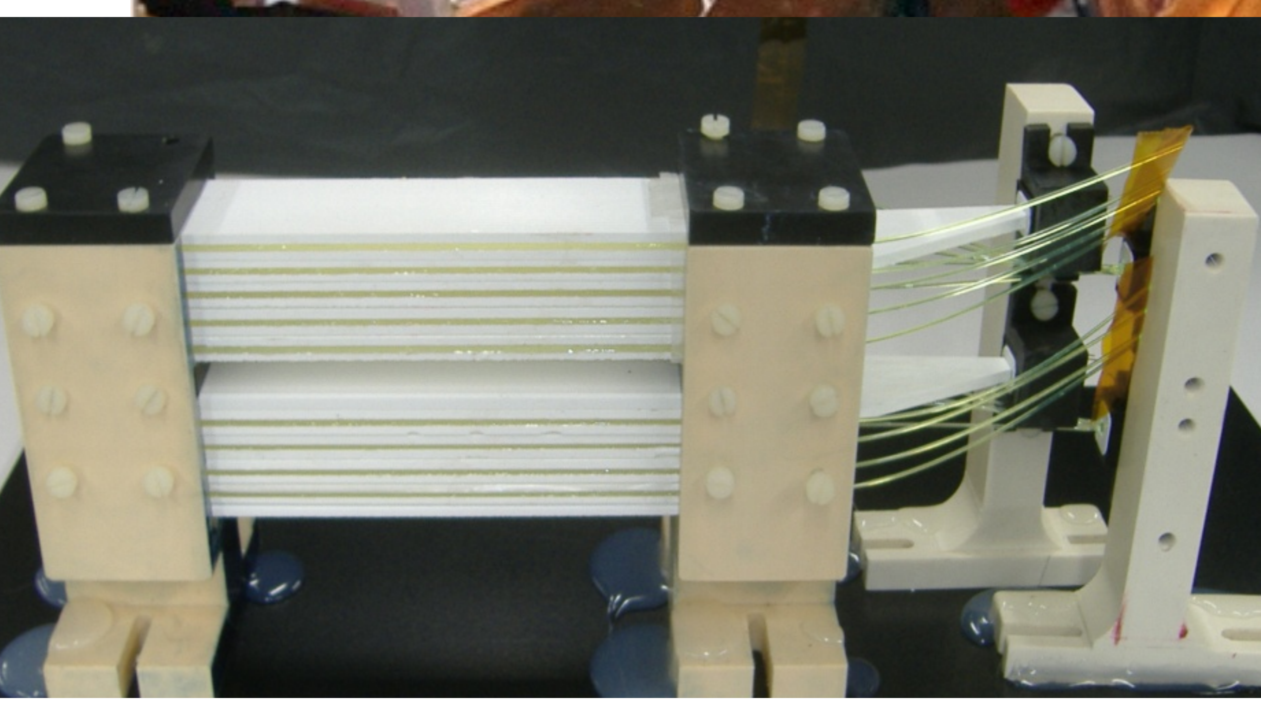
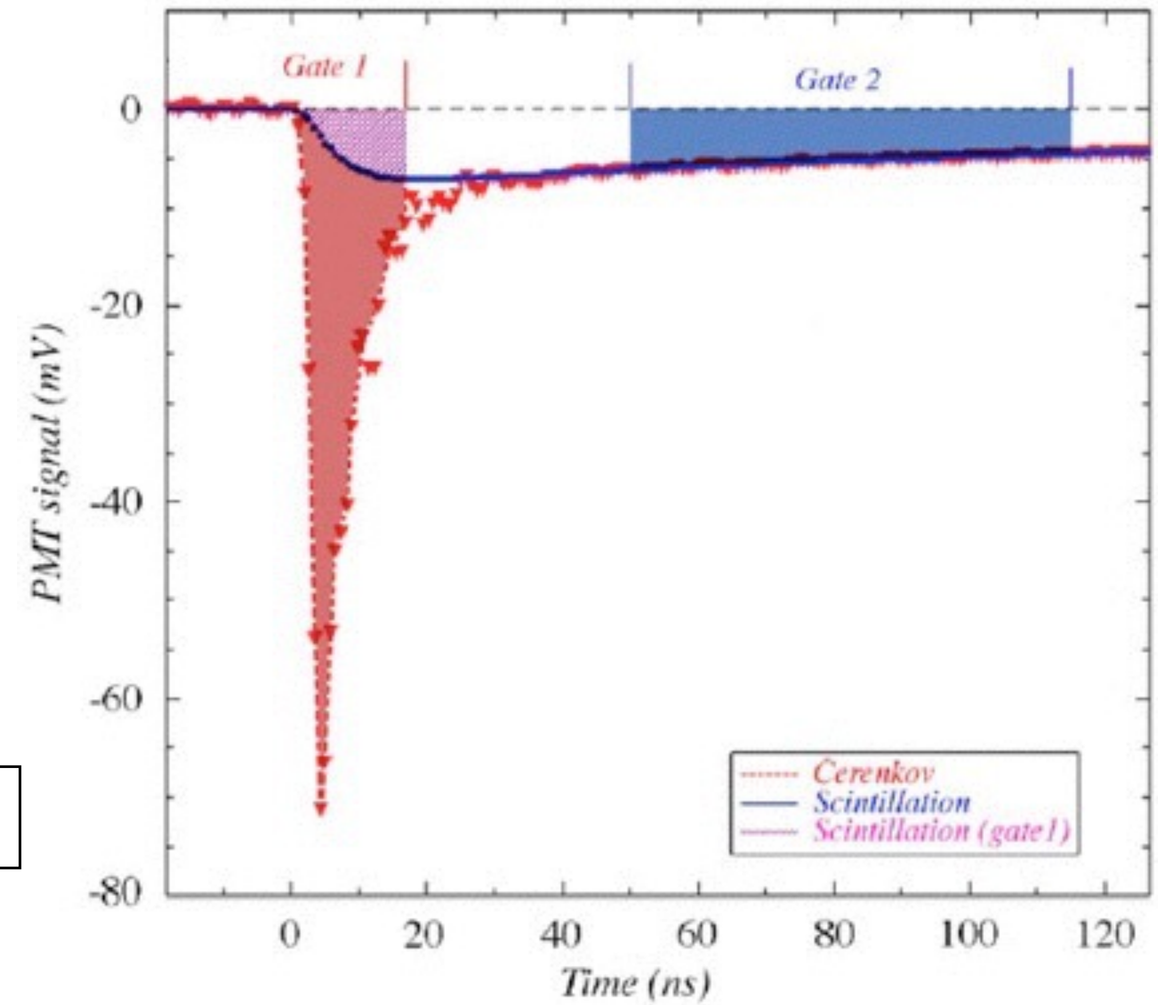


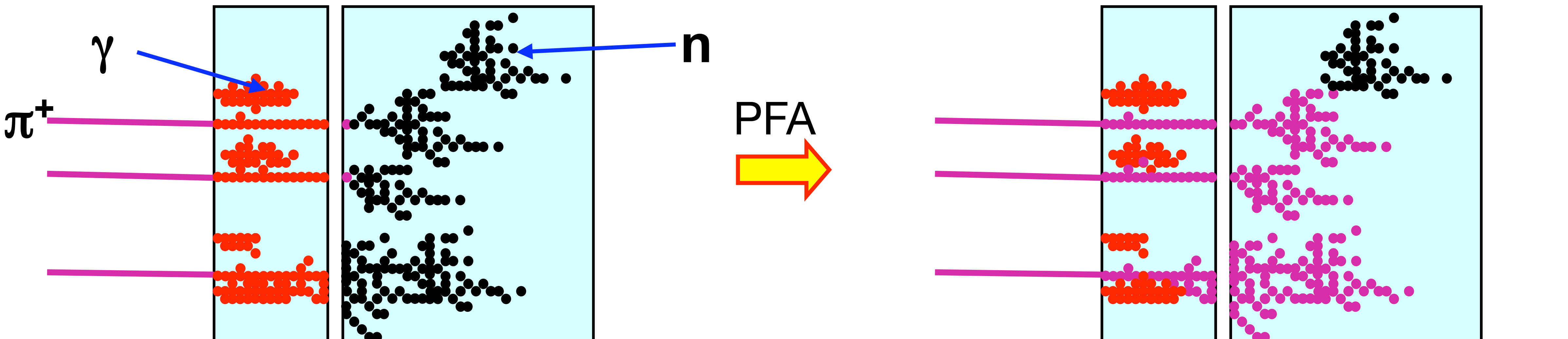
3 (2009)



- Going even further: A “sampling” calorimeter using high-density glass as absorber and Cherenkov radiator and scintillating fibers - ADRIANO

Particle Flow - Jets from Individual Particles

- Improve jet energy reconstruction by measuring each particle in the jet with best possible precision
  - Measure all charged particles in the tracker (remember, 60% charged hadrons!)
    - Significantly reduce the impact of hadron calorimeter performance: Only for neutral hadrons
    - Measure only 10% of the jet energy with the HCAL, the "weakest" detector: significant improvement in resolution

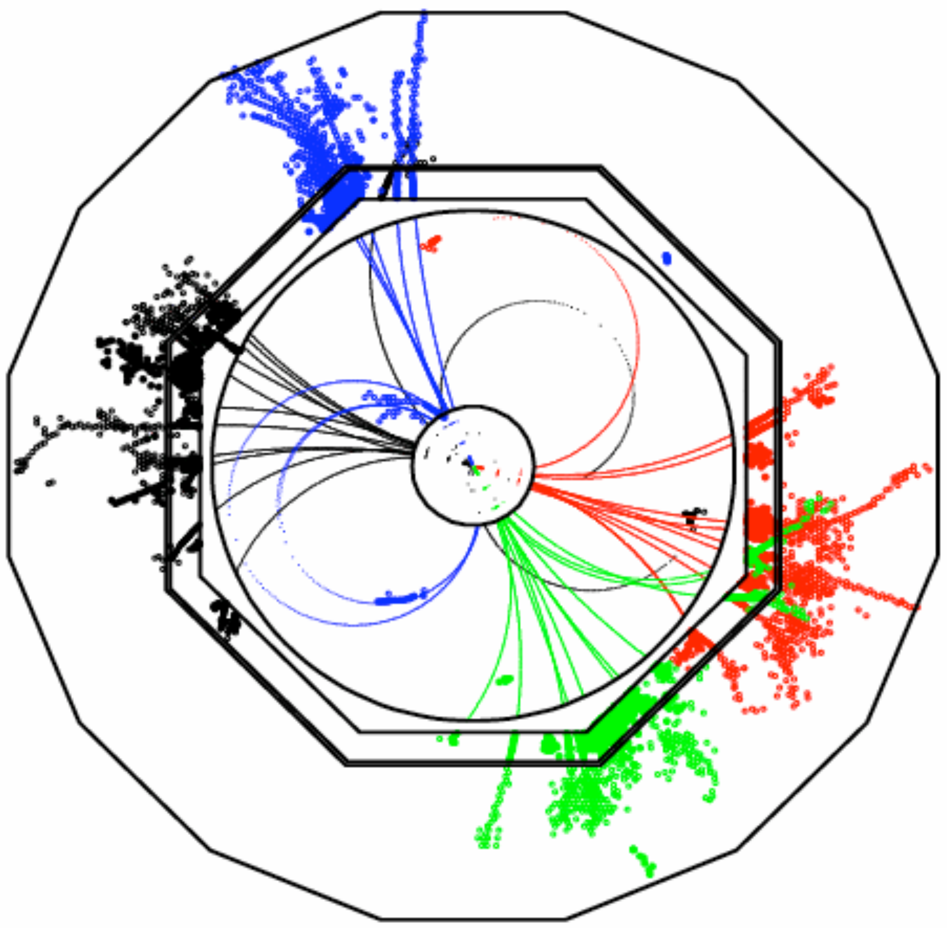


$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Imaging Calorimeters: Making PFA Happen

- For best results: High granularity in 3D - Separation of individual particle showers
  - Granularity more important than energy resolution!
  - Lateral granularity below Moliere radius in ECAL & HCAL
  - In particular in the ECAL: Small Moliere radius to provide good two-shower separation - Tungsten absorbers
    - Highest possible density: Silicon active elements - Thin scintillators also a possibility
  - And: Sophisticated software!



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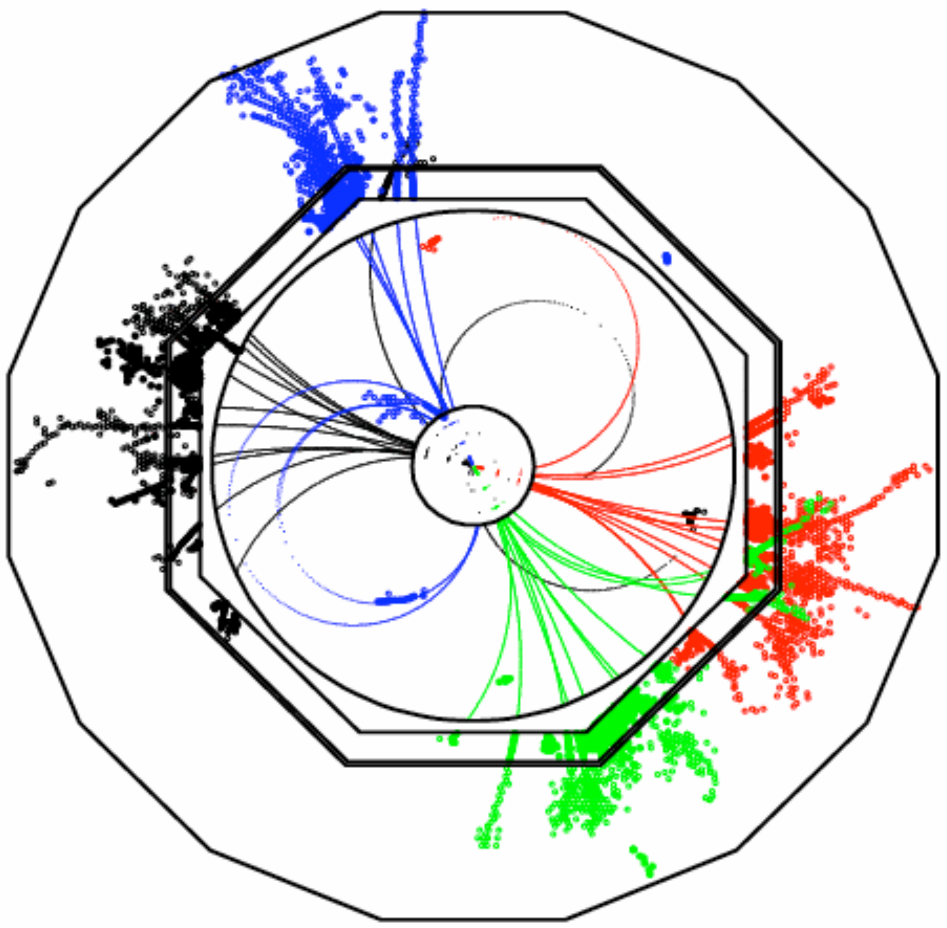
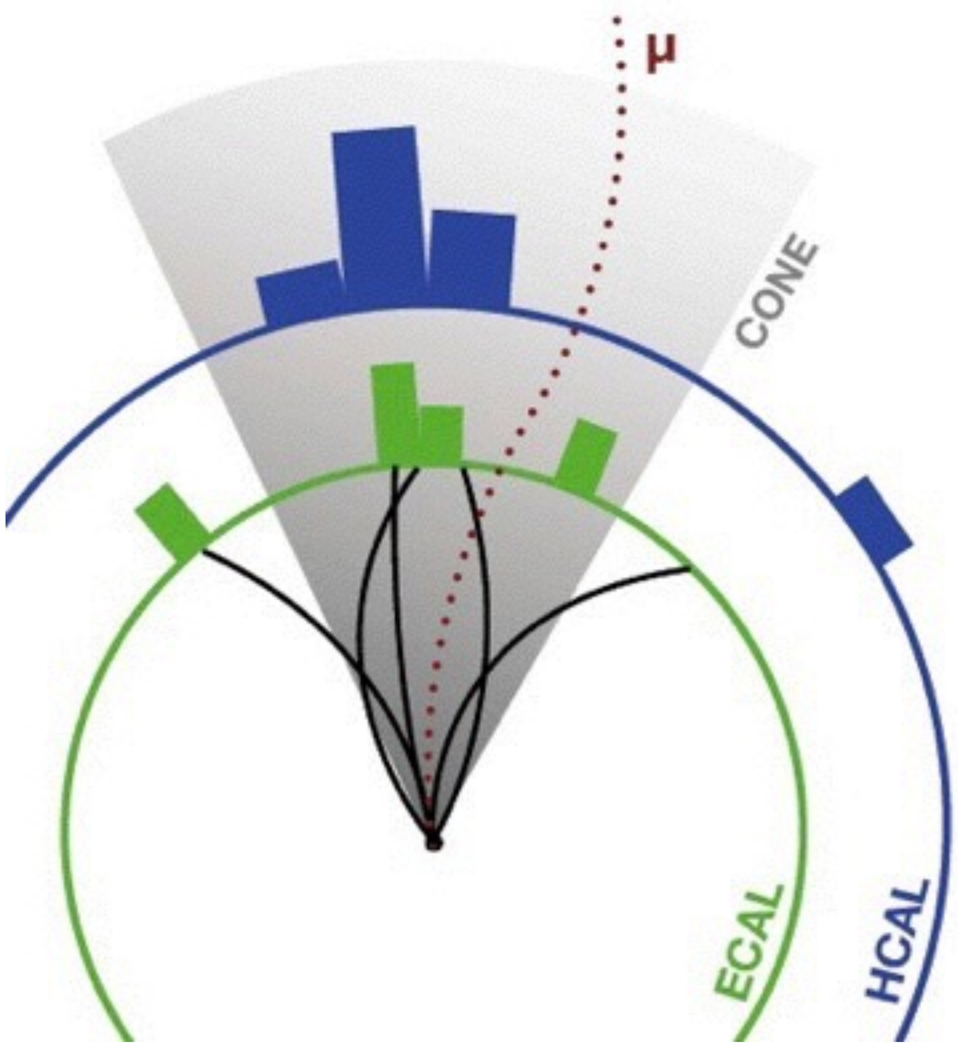
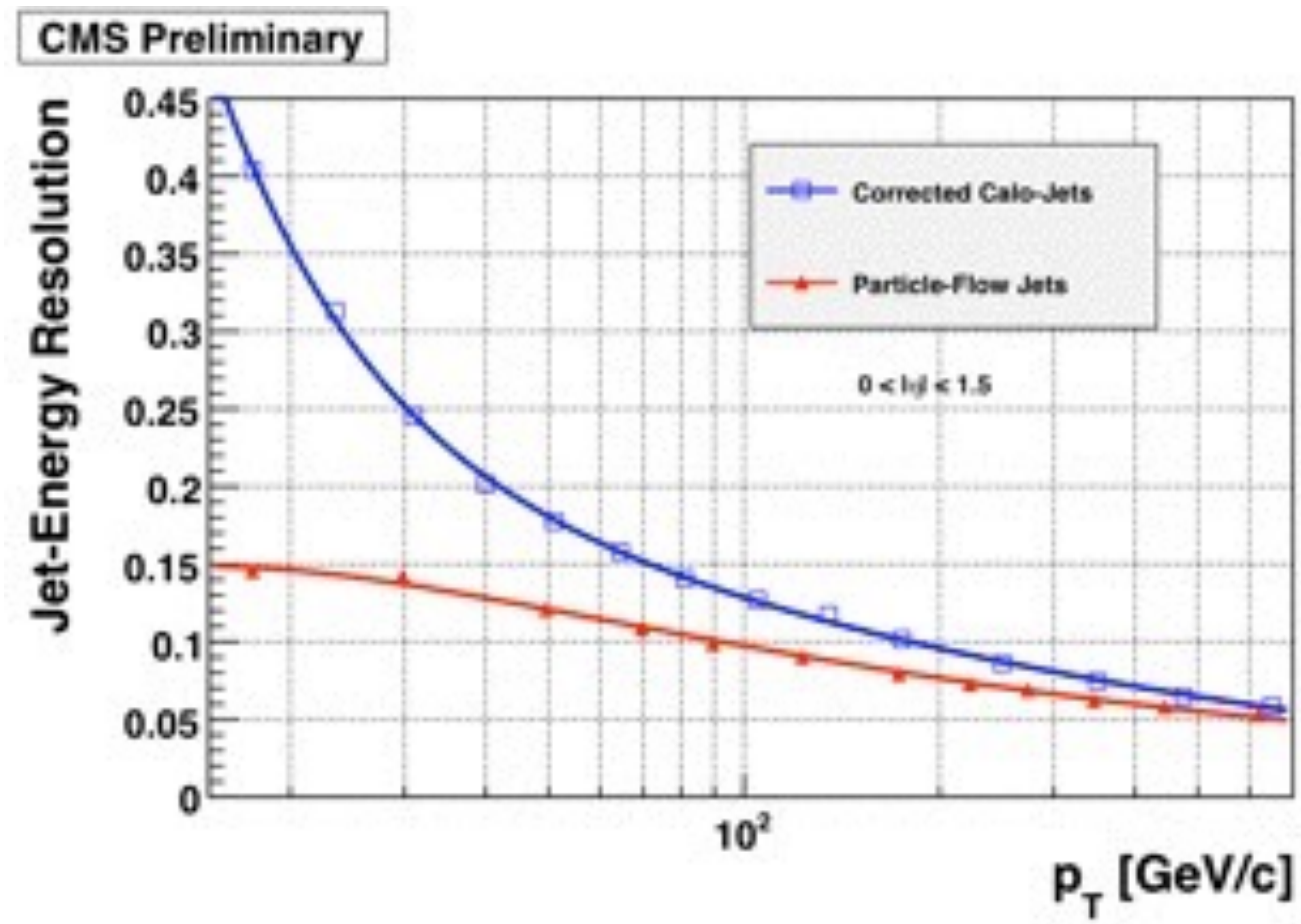


Extensively developed & studied for Linear Collider Detectors: Jet energy resolution goals (3% - 4% or better for energies from 45 GeV to 500 GeV) can be met

PFA - Not Just a Crazy Idea

- Successfully used in CMS - A granular detector (but far less so than linear collider detectors)

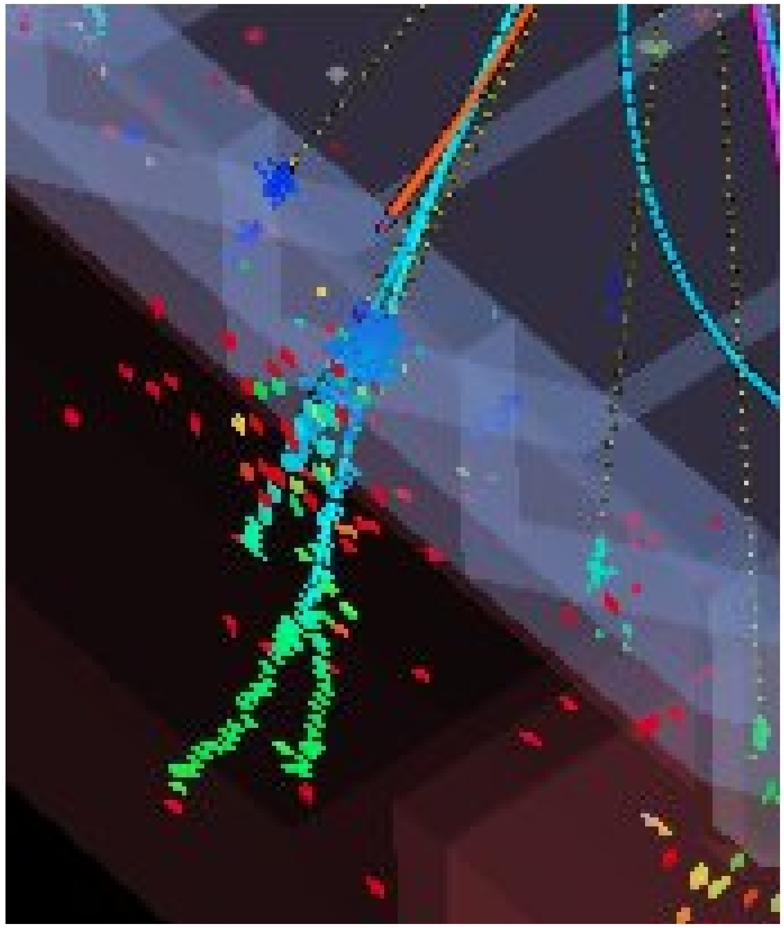




- Resolution improved by up to a factor of 3 at low energy

PFA & Granularity: Additional Benefits

- Rejection of Background: Detailed reconstruction of individual particles and separation of showers enables suppression of background
  - particularly powerful when combined with timing: Used to suppress background at CLIC
  - Pushing timing further: With cluster timing on the level of 10 - 20 ps (requires cell-by-cell timing of *O* 50 ps) pile-up rejection for neutrals at HL-LHC based on reconstruction of the z position of the particle origin
  - Ultimately: Improved energy reconstruction, particle identification, …



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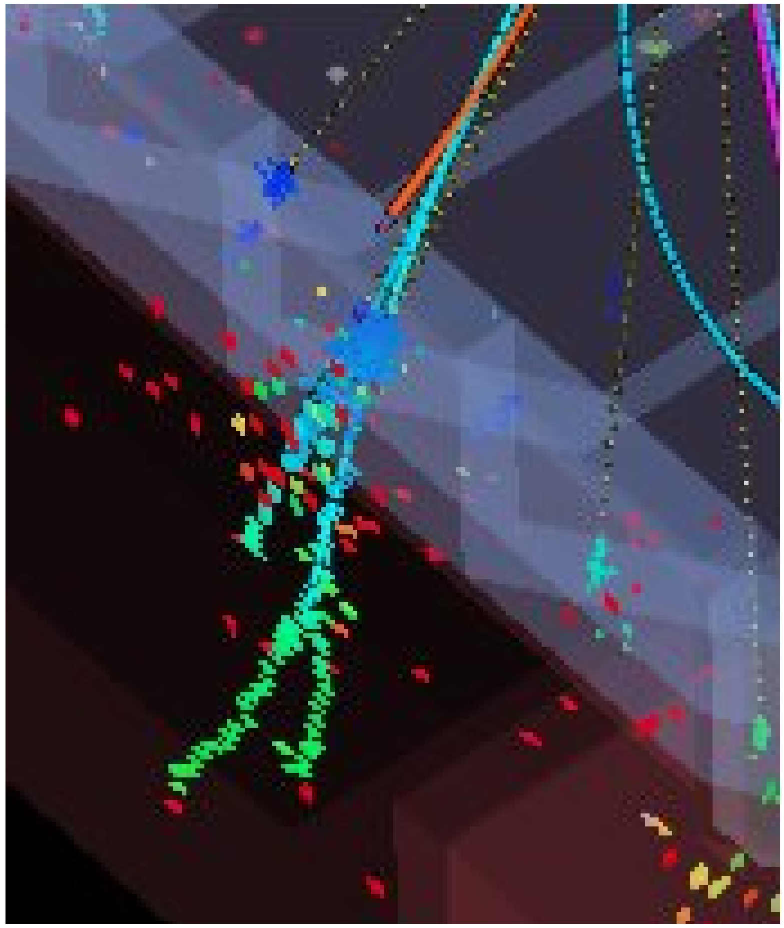

Now the *de-facto* standard in HEP - all collider experiments at center-of-mass energies in the 200+ GeV energy range have upgrade plans involving imaging calorimeters, or are even based completely on the PFA concept

Calorimeters optimised for PFA: Geometry

- The detectors where PFA “happens” - Quite different than calorimeter systems at current experiments in terms of granularity: Segmentation finer than the typical structures in particle showers
  - ECAL: X_0, ρ_M (length scale & width of shower)
  - HCAL: length scale ~ λ_I, but em subshowers impose requirements not too much different than in ECAL

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Depends on material:
- in W: X_0 ~ 3 mm, ρ_M ~ 9 mm
- in Fe: X_0 ~ 20 mm, ρ_M ~ 30 mm

NB: Best separation for narrow showers particularly important in ECAL
➩ Use W in ECAL!

When adding active elements: ~ 0.5 cm^3 segmentation in ECAL, ~ 3 - 25 cm^3 in HCAL

➩ *O* 10^{7-8} cells in HCAL, 10^8 cells in ECAL for typical detector systems!
- ▸ fully integrated electronics needed
- ▸ require active elements that support high granularity and large channel counts

Silicon-Based Calorimeters

- When CMS moved to an all-silicon Tracker (ca. 2000), this was a revolution: A 200 m^2 silicon system - far beyond anything people had dared to imagine up to then
- Today: We are talking about sampling calorimeters with silicon as active material - up to several 1000 m^2 of Si area!

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- Today: We are talking about sampling calorimeters with silicon as active material - up to several 1000 m^2 of Si area!

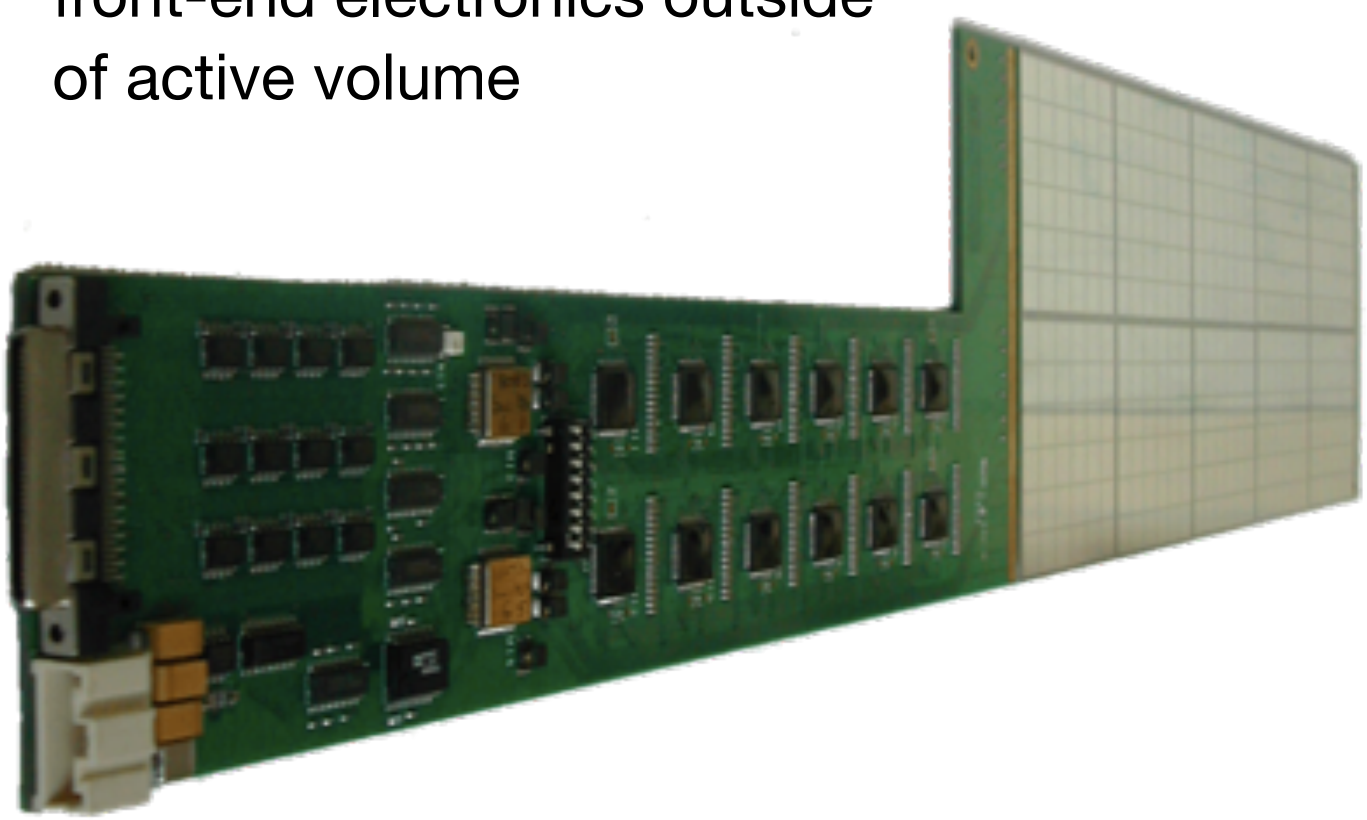
- Silicon-based calorimeters are not entirely new - very small devices were already in use at LEP, for example, but: Large, highly granular systems suitable as main calorimeters for collider detectors fairly recent: Pioneered by the CALICE Collaboration in the last decade

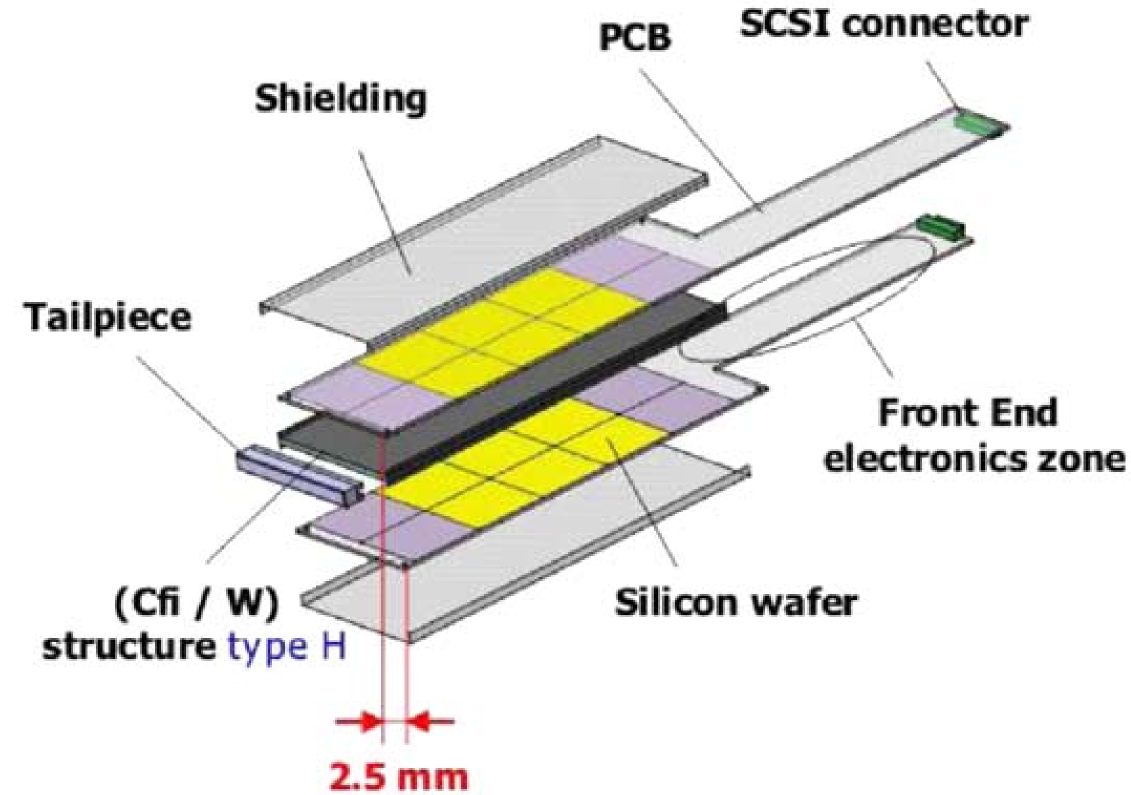
The CALICE Silicon-Tungsten ECAL

- Key features:
  - (relatively) high density, low required energy per e$^-$/hole pair: large sampling fraction also for thin active layers, large signals
  - Easily segmentable, stable against changing environmental parameters

Used in electromagnetic calorimeters

In physics prototype: 6 x 6 cm wafers, front-end electronics outside of active volume





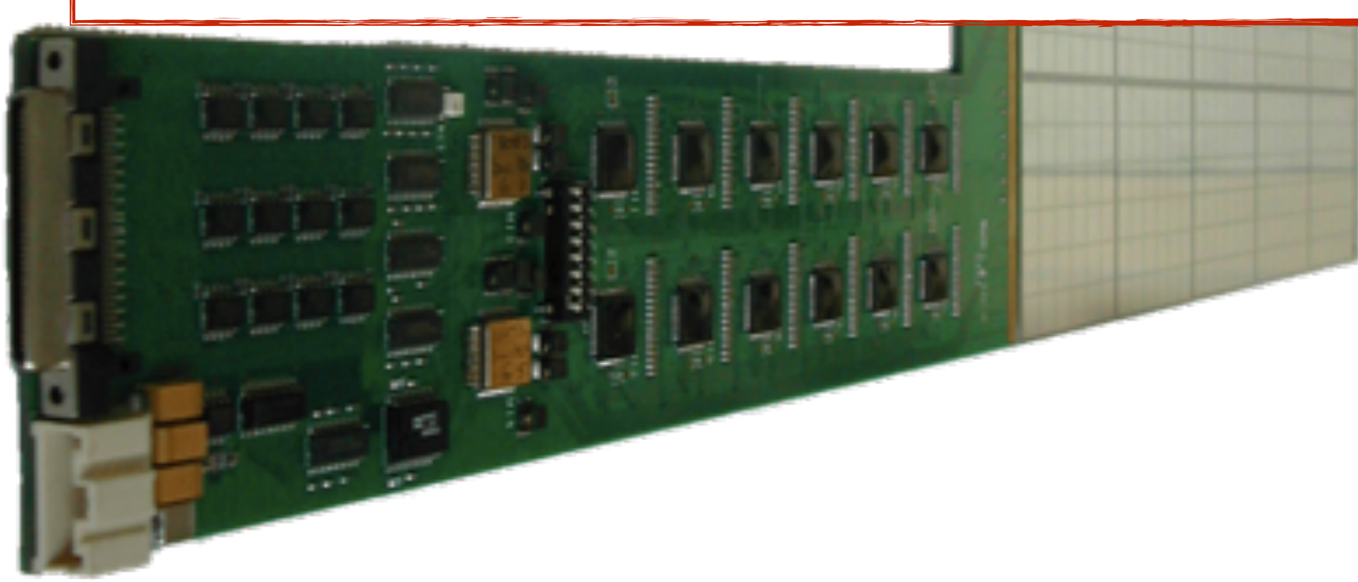
1 x 1 cm^2 cells in physics prototype

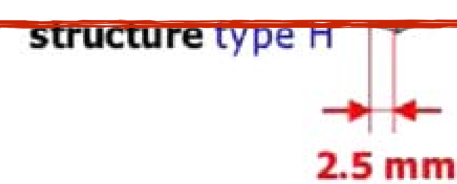
5 x 5 mm^2 cells for technological prototype fully integrated electronics

The CALICE Silicon-Tungsten ECAL

- Key features:
  - (relatively) high density, low required energy per e$^-$/hole pair: large sampling fraction also for thin active layers, large signals
  - Easily segmentable, stable against changing environmental parameters

First full prototype (10 000 Channels) in various test beams since 2006
Proof of principle for large-scale Si calorimeter systems:
The motivation for LHC Phase II upgrades and ECAL systems at future colliders





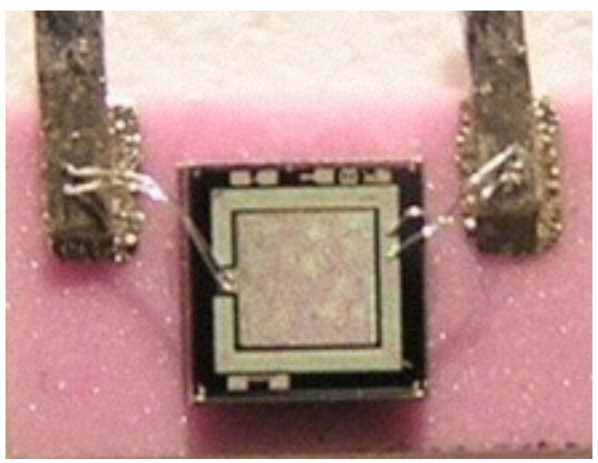
1 x 1 cm^2 cells in physics prototype

5 x 5 mm^2 cells for technological prototype fully integrated electronics

High Granularity with SiPMs

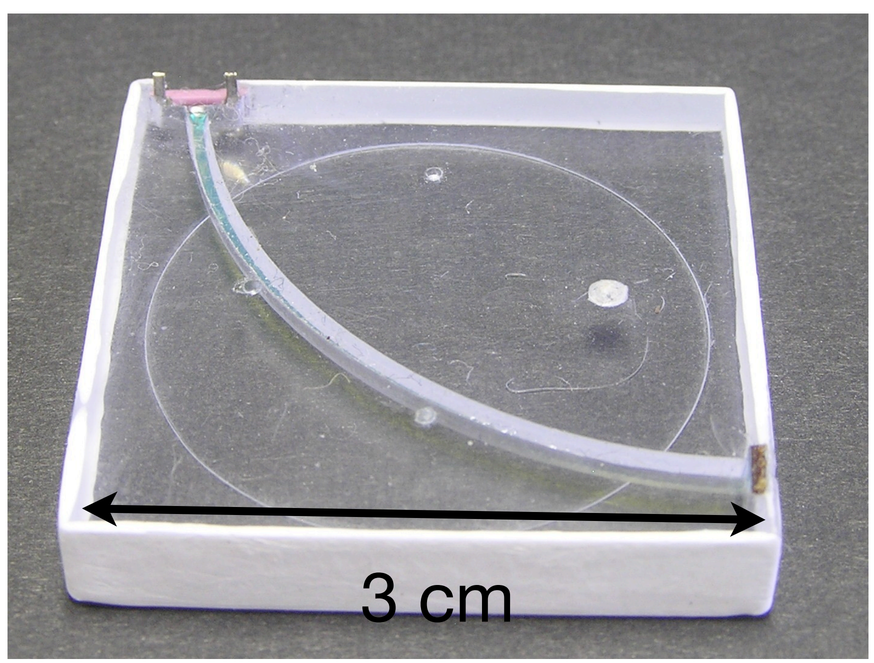
- Highly granular hadronic calorimeters: Silicon prohibitively expensive for full volume: Other technologies in the focus
  - HCALs with Steel and W absorber, Scintillator + SiPM & Gas detector readout (all developed in CALICE)

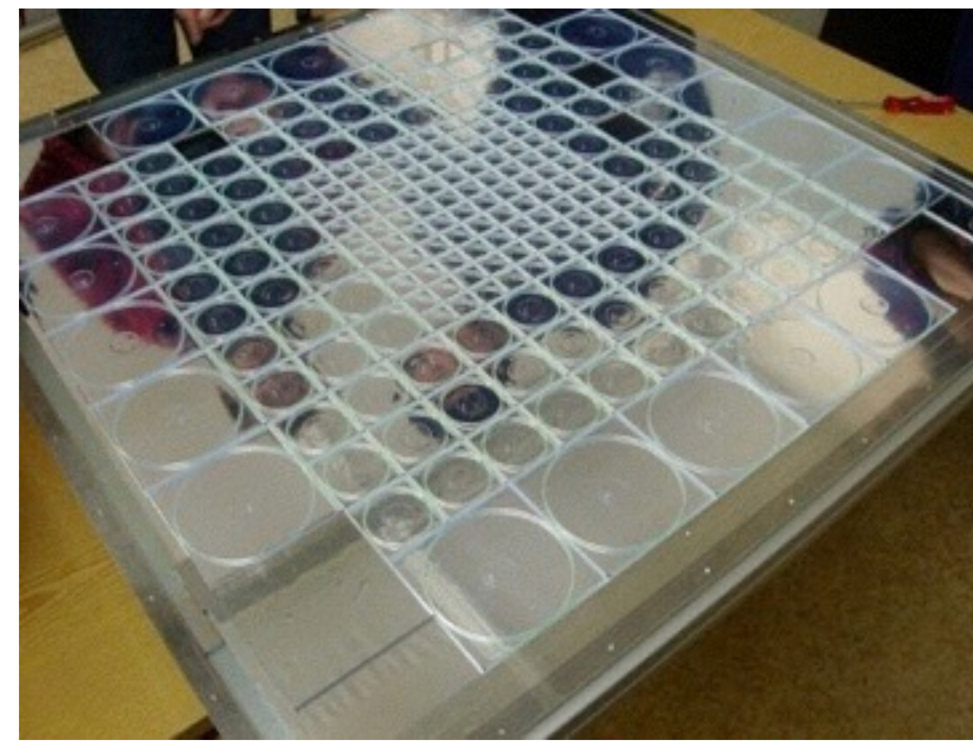
One of the technology highlights: The first large-scale use of SiPMs in the CALICE analog HCAL



SiPM: 1156 pixels, manufactured by MePhI/PULSAR

Plastic scintillator tiles with WLS fiber & SiPM



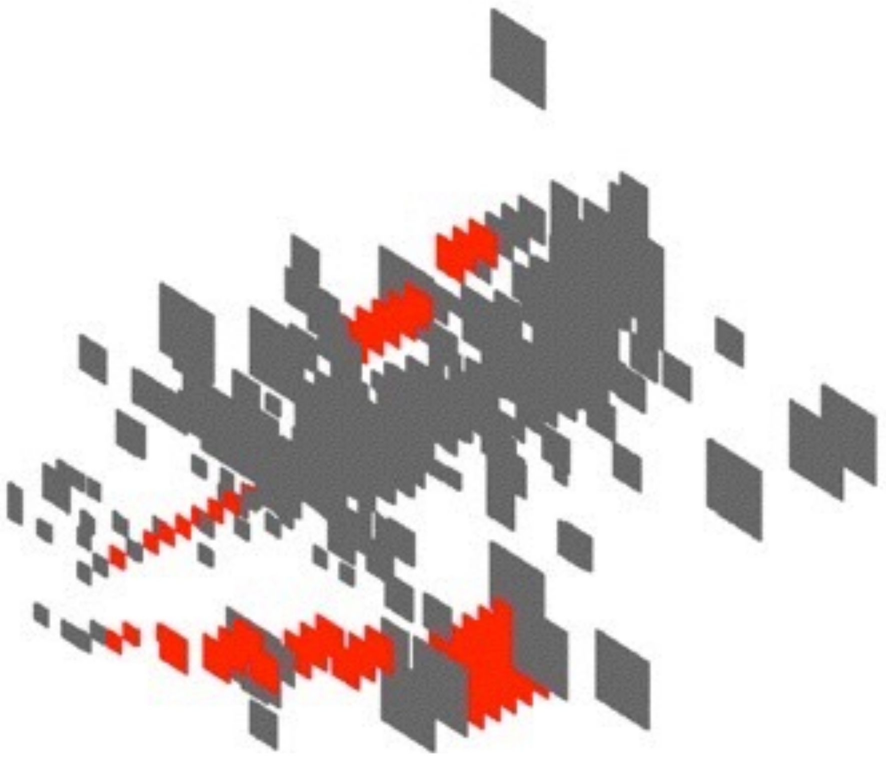


212 scintillator tiles per layer, 38 layers, each channel read out separately

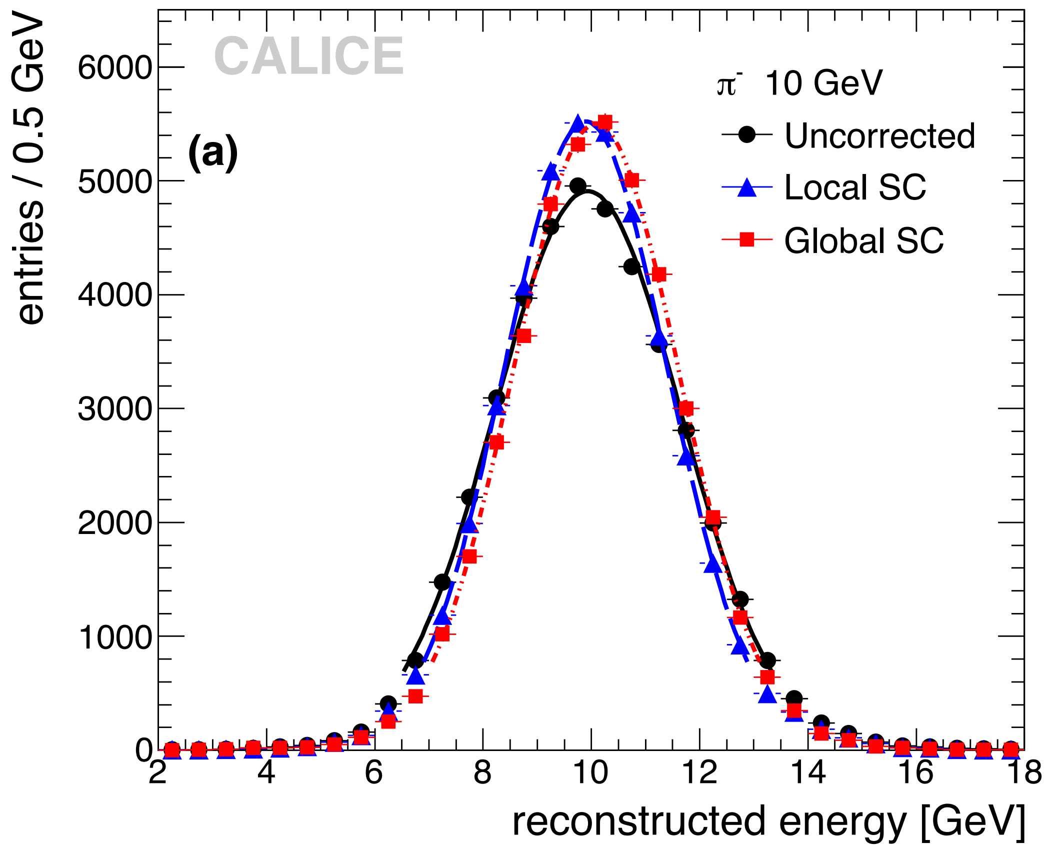
8 000 channels in total

Imaging HCAL with SiPMs - Performance

- Looking deep into showers



- Reconstructing energy



Imaging HCAL with SiPMs - Performance

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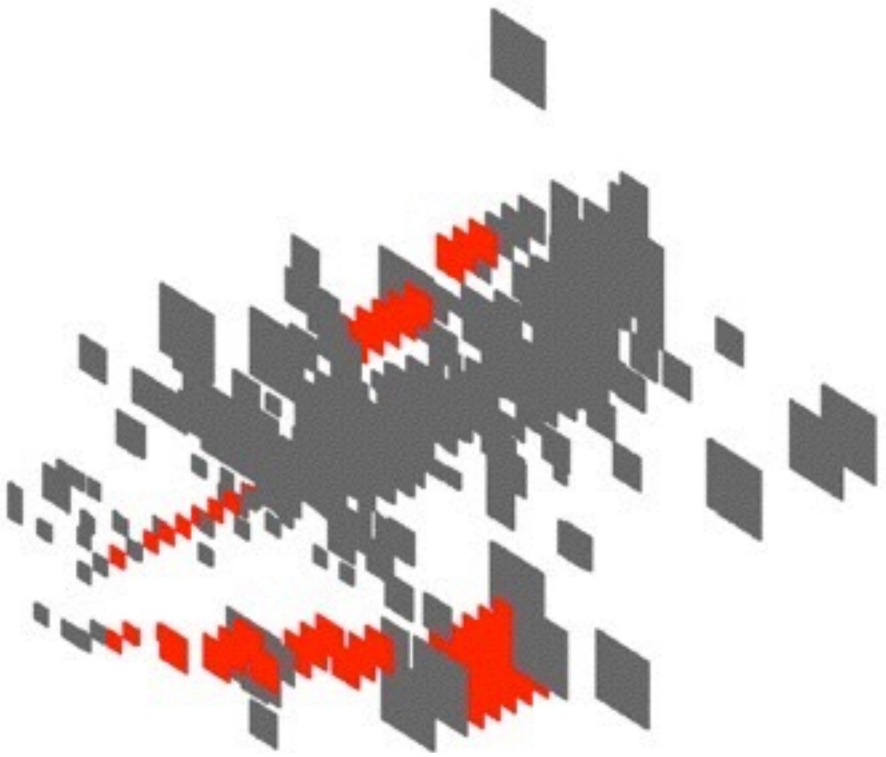
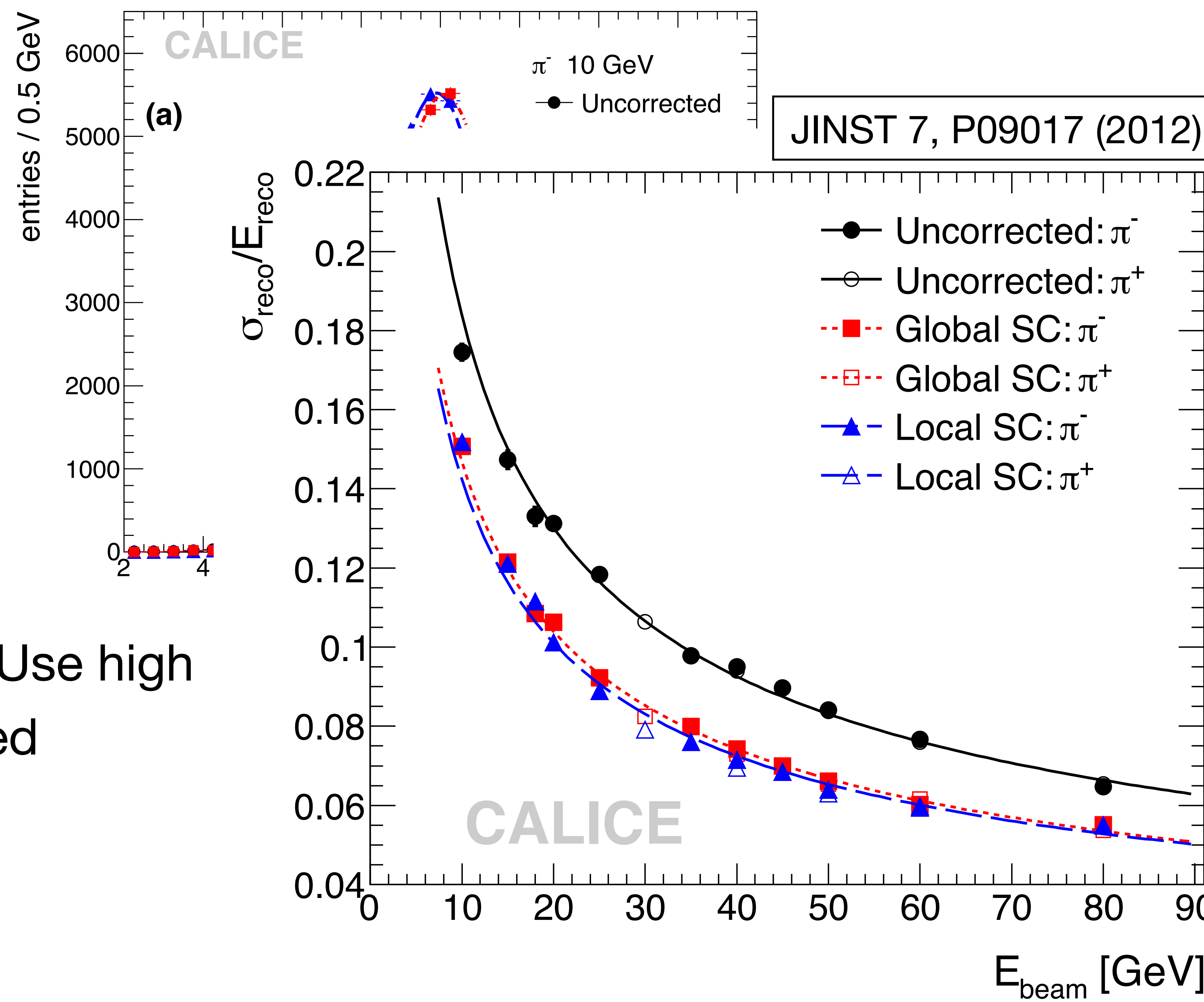


- Reconstructing energy

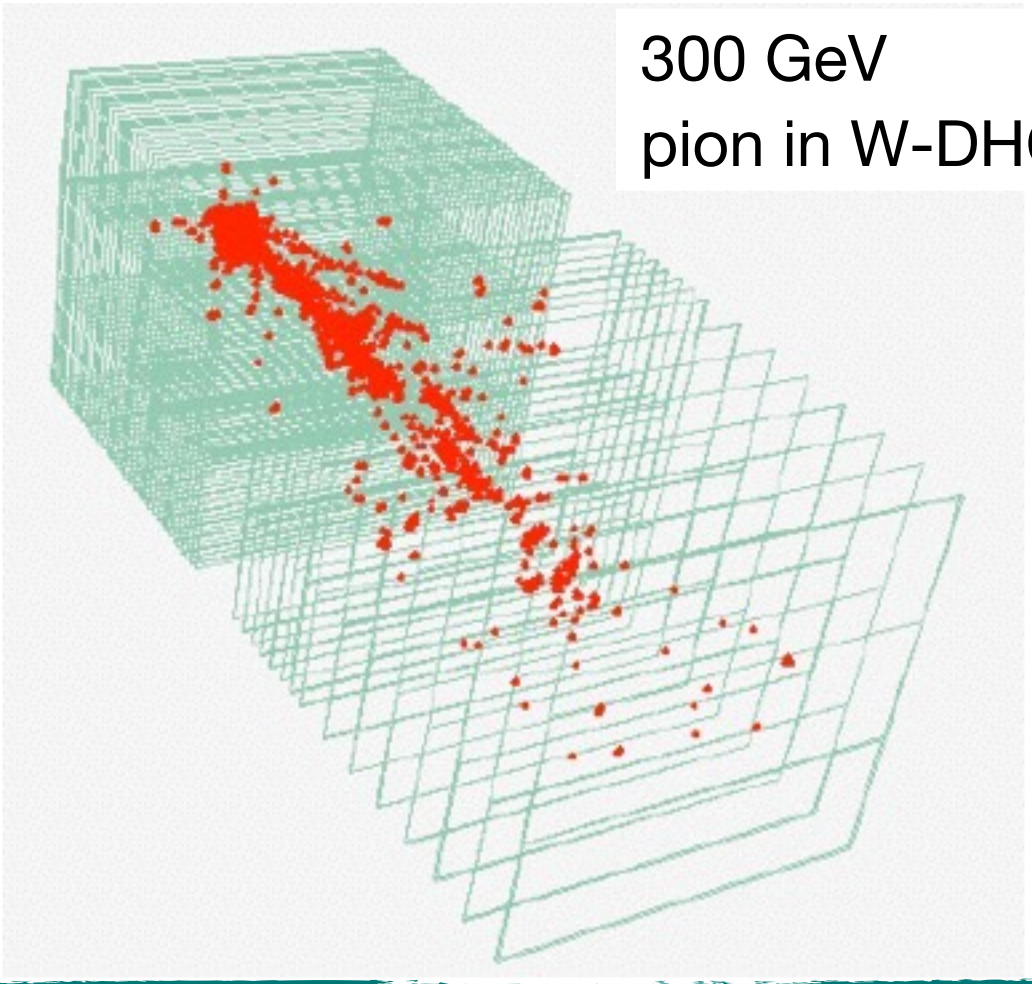


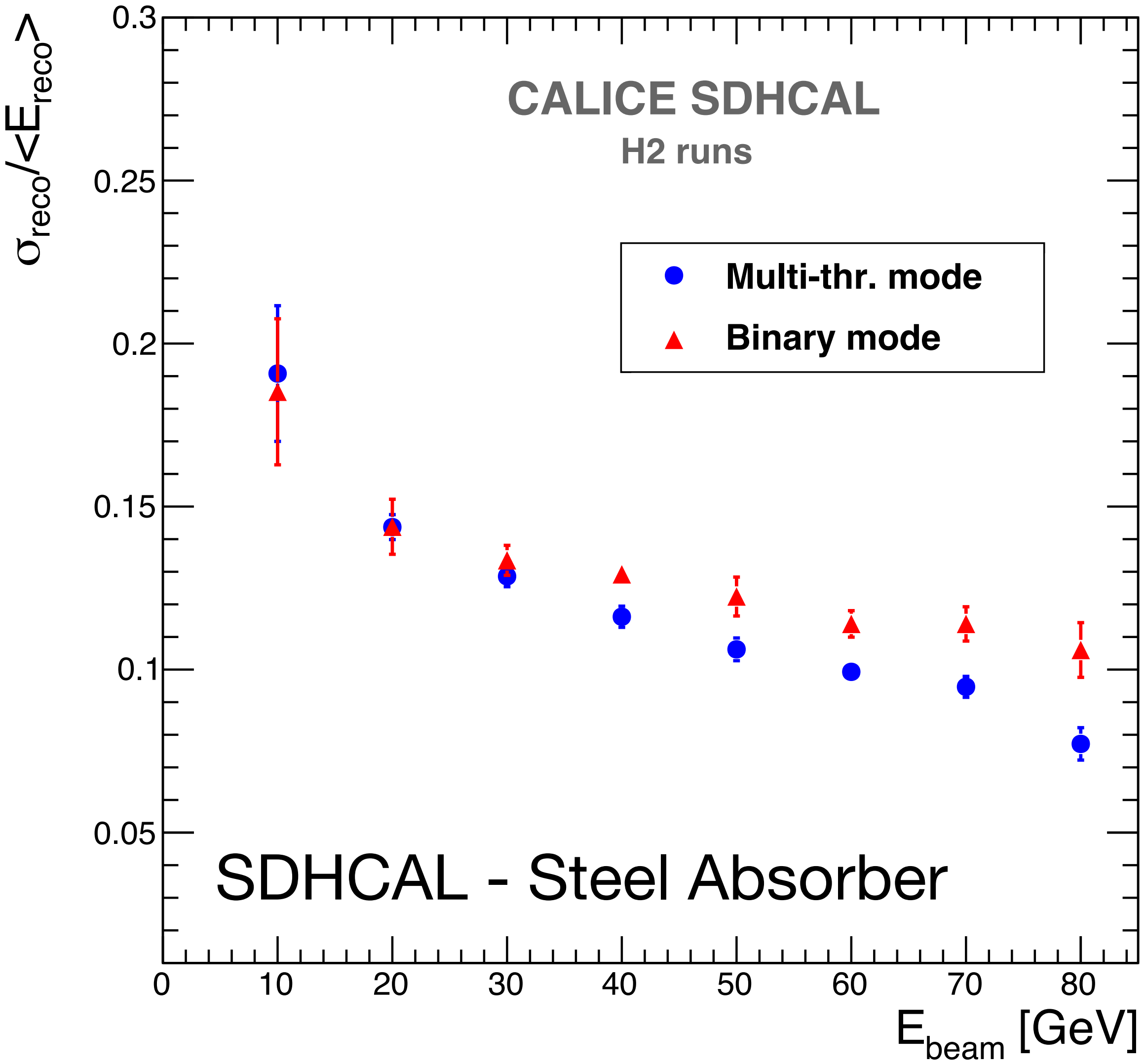
JINST 7, P09017 (2012)

- Excellent energy resolution: Use high granularity for software-based compensation methods: $45\%/\sqrt{E} \oplus 1.8\%$

Digital Calorimeters: Granularity Redefined

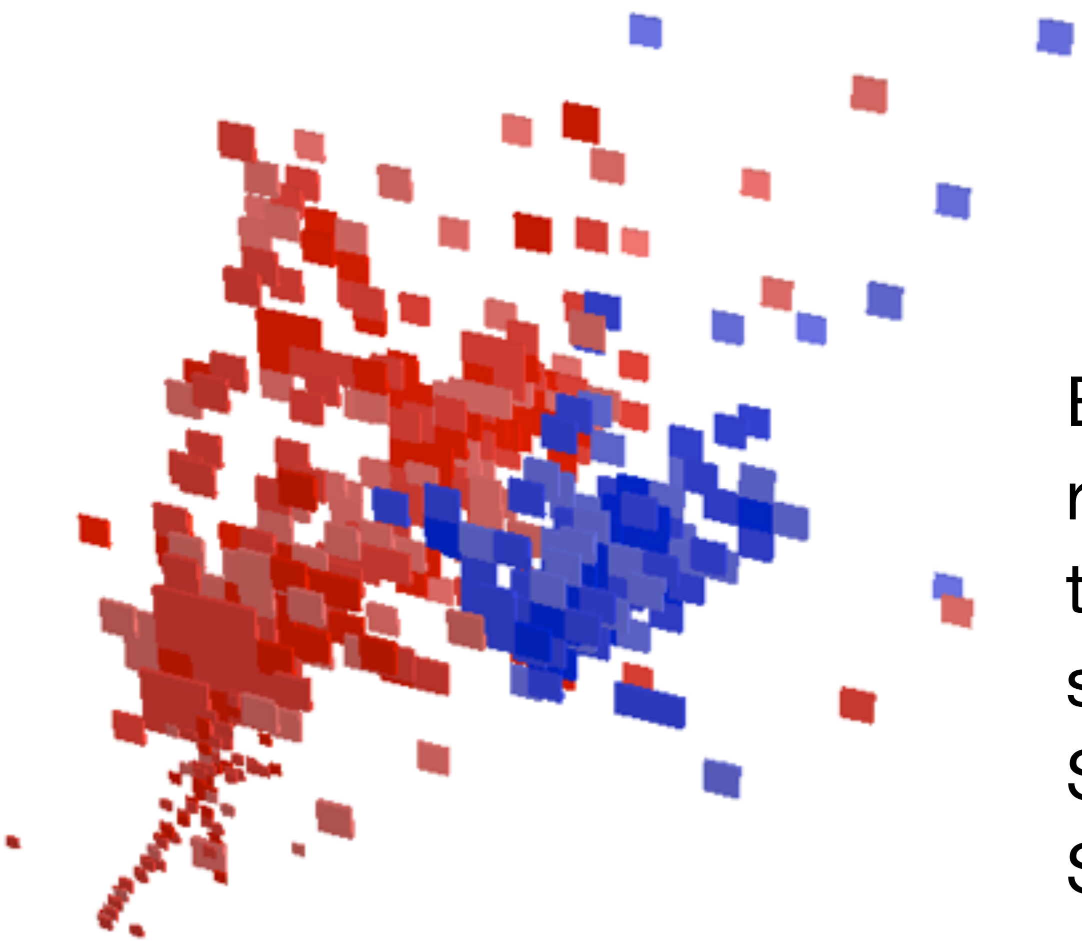
- Pushing granularity further: Need simpler detectors and simpler readout- Gas detectors with one or two bit readout per cell
  - RPCs a natural choice for large area detectors
  - 1 cm^2 cell size, 1 and 2 bit readout tested in CALICE
  - World-record channel counts for calorimeter systems: > 500k channels - and these are just 1 m^3 prototypes!





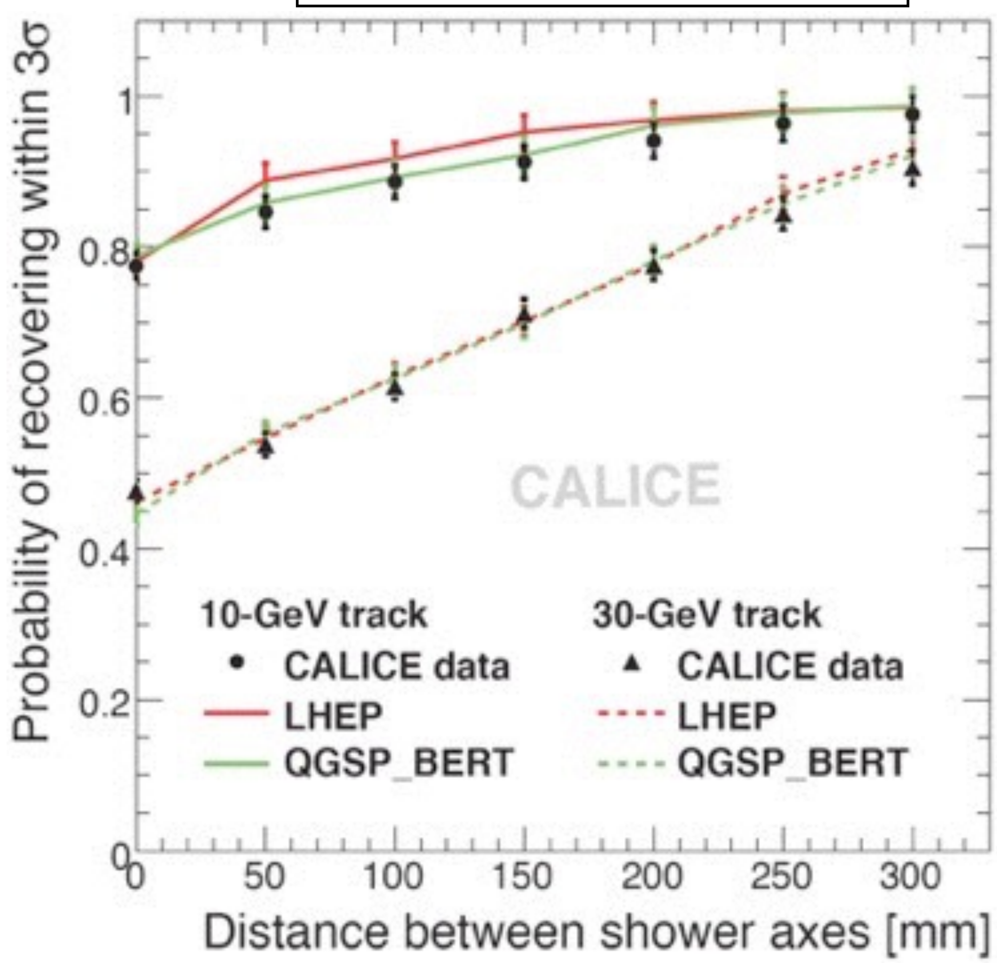
Simulating & Understanding Showers

- Simulations are key for developing experiments:
  - Optimize detector designs, compare performance of technology options
  - Develop event reconstruction techniques, assess physics performance
- Reliably simulating hadronic showers in GEANT4 on the level of granularity of modern calorimeters is crucial!

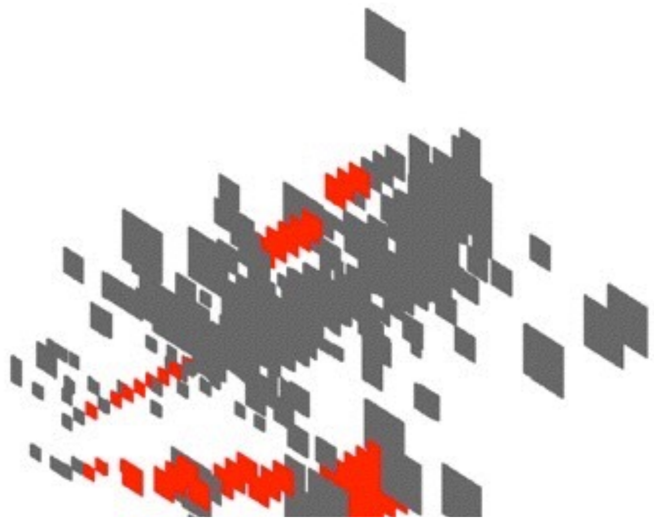


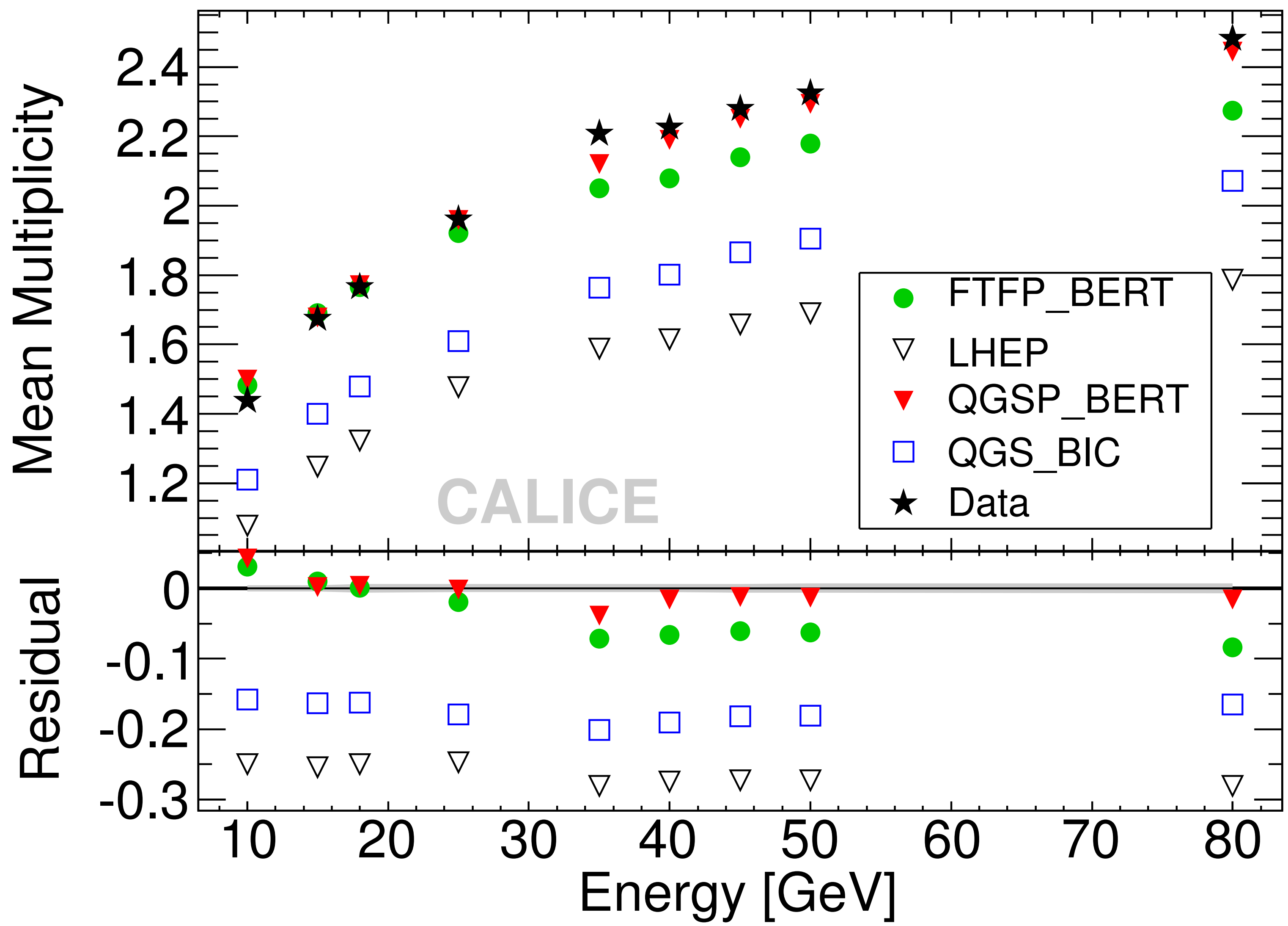
Excellent reproduction of two-particle separation in SiW ECAL + Scint. AHCAL

JINST 6, P07005 (2011)



Simulating & Understanding Showers





Identification of MIP-like track segments in the AHCAL:

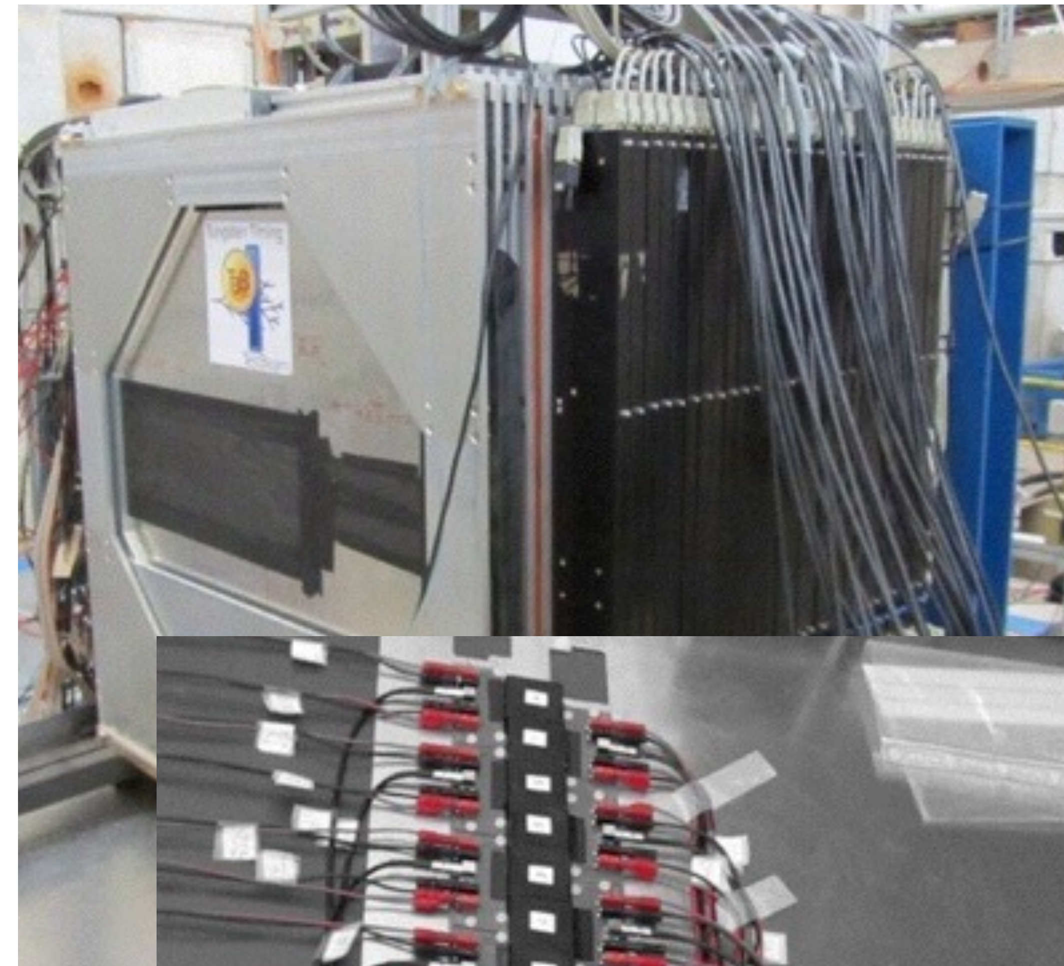
Hadronic showers are **not** amorphous blobs of energy in the detector, but tree-like structures with MIP-like hadrons connecting regions of denser activity

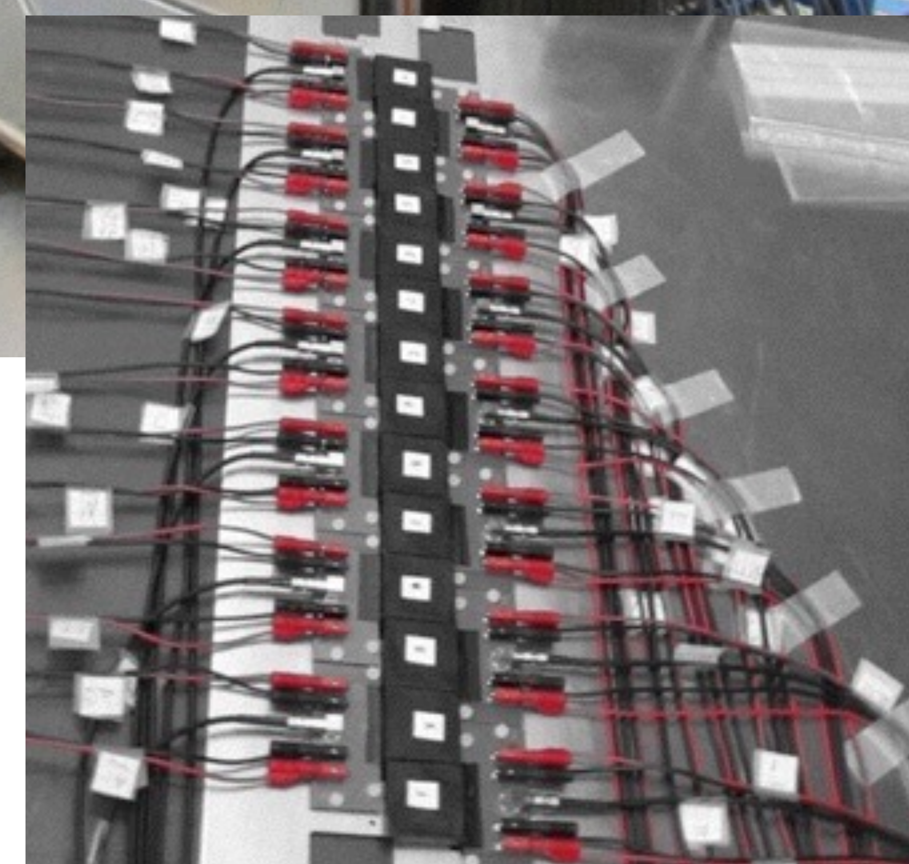
... and modern simulation models in GEANT4 predict / reproduce this structure already with good accuracy!

JINST 8 P09001 (2013)

Timing

- Timing plays a crucial role - in particular in environments with high background levels (at CLIC, LHC)

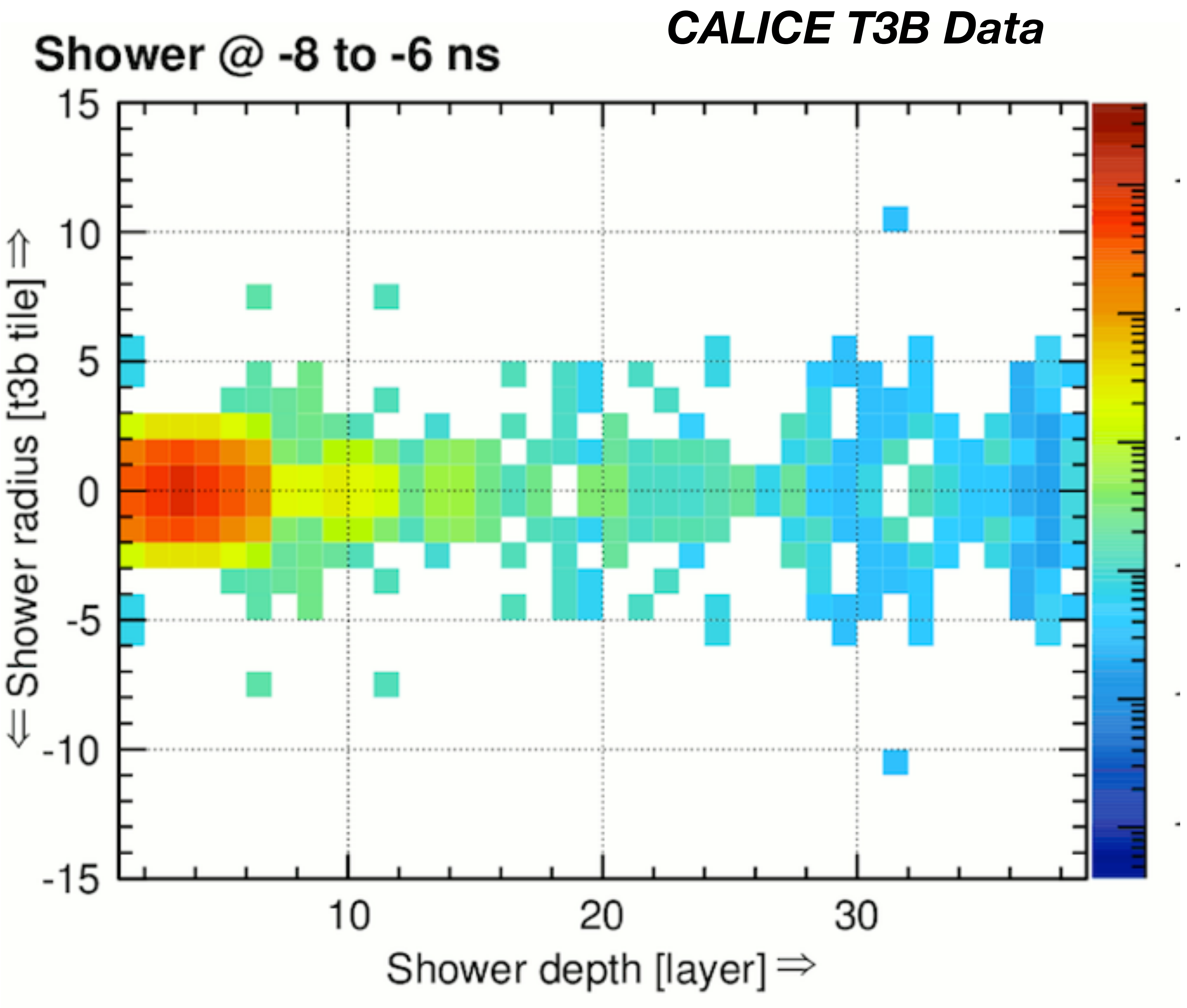




For PFA calorimeters, the time structure of hadronic showers can impact pattern recognition, particle separation, ... in the presence of background

Studied in a Tungsten scintillator HCAL with 15 scintillator cells read out with SiPMs and 800 ps digitizers - Coupled with shower information from the full calorimeter to provide 4D shower profiles

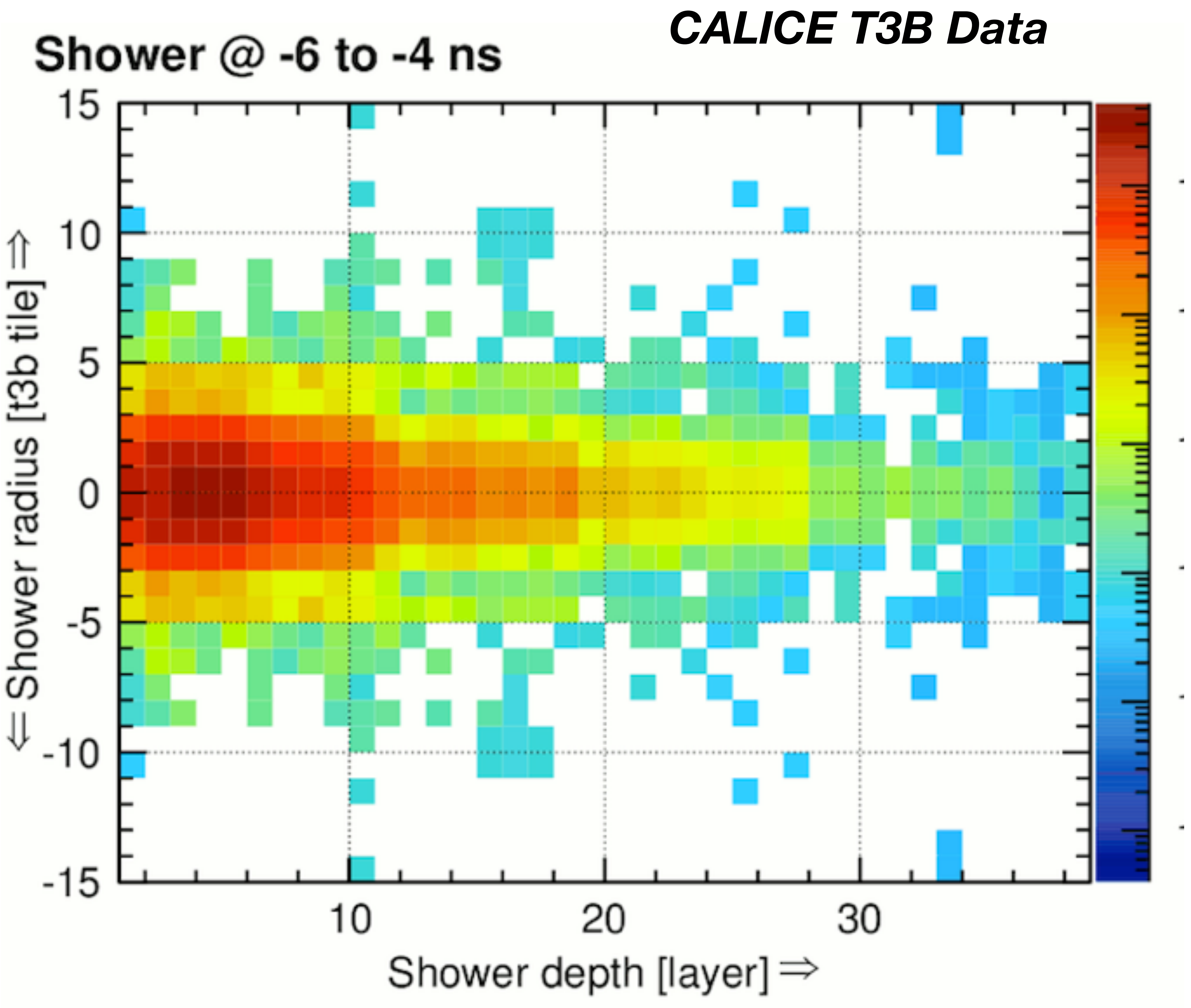
Timing: The Life of a Pion in the WAHCAL



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

Shown: First hits in each cell only

Timing: The Life of a Pion in the WAHCAL



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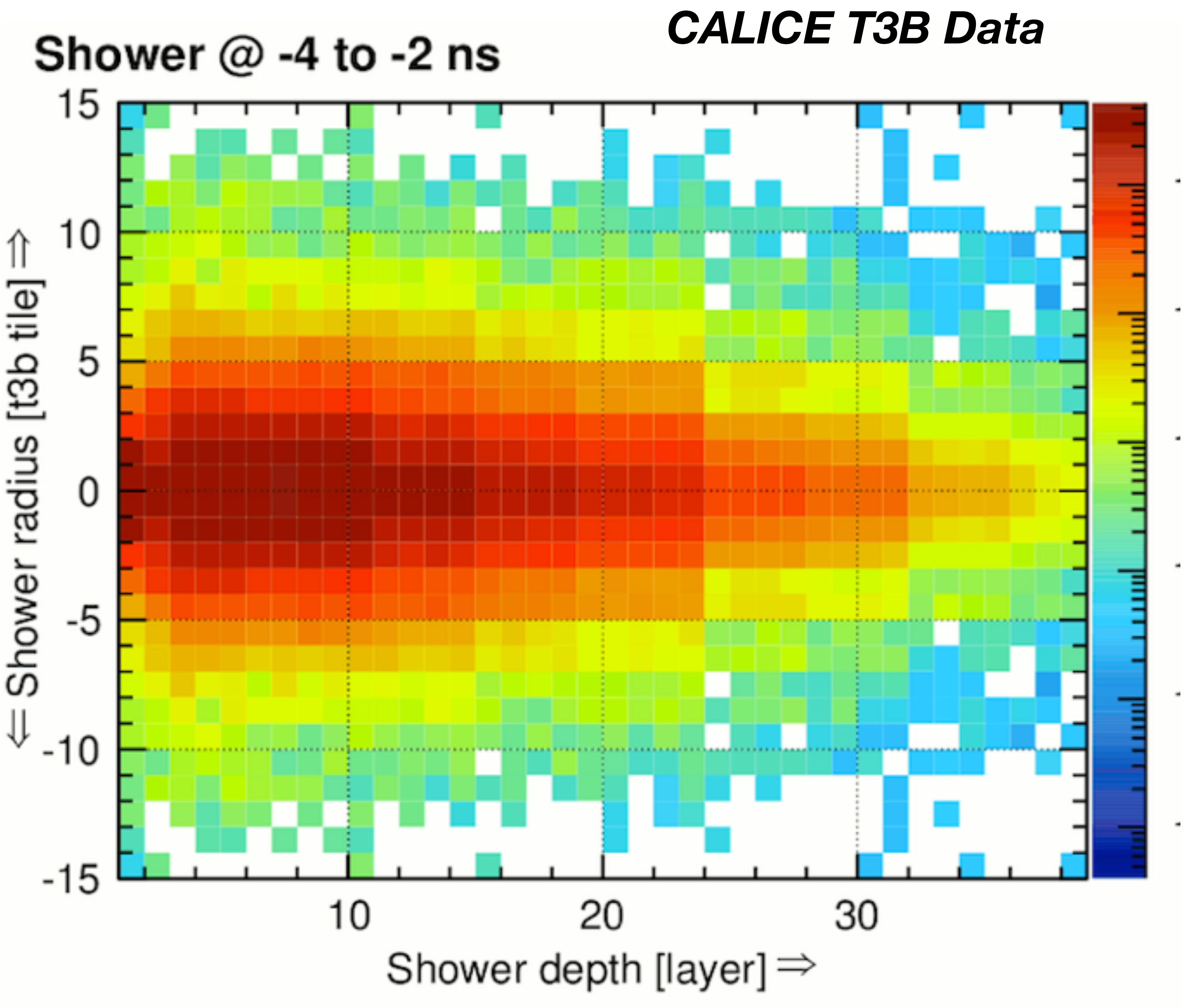

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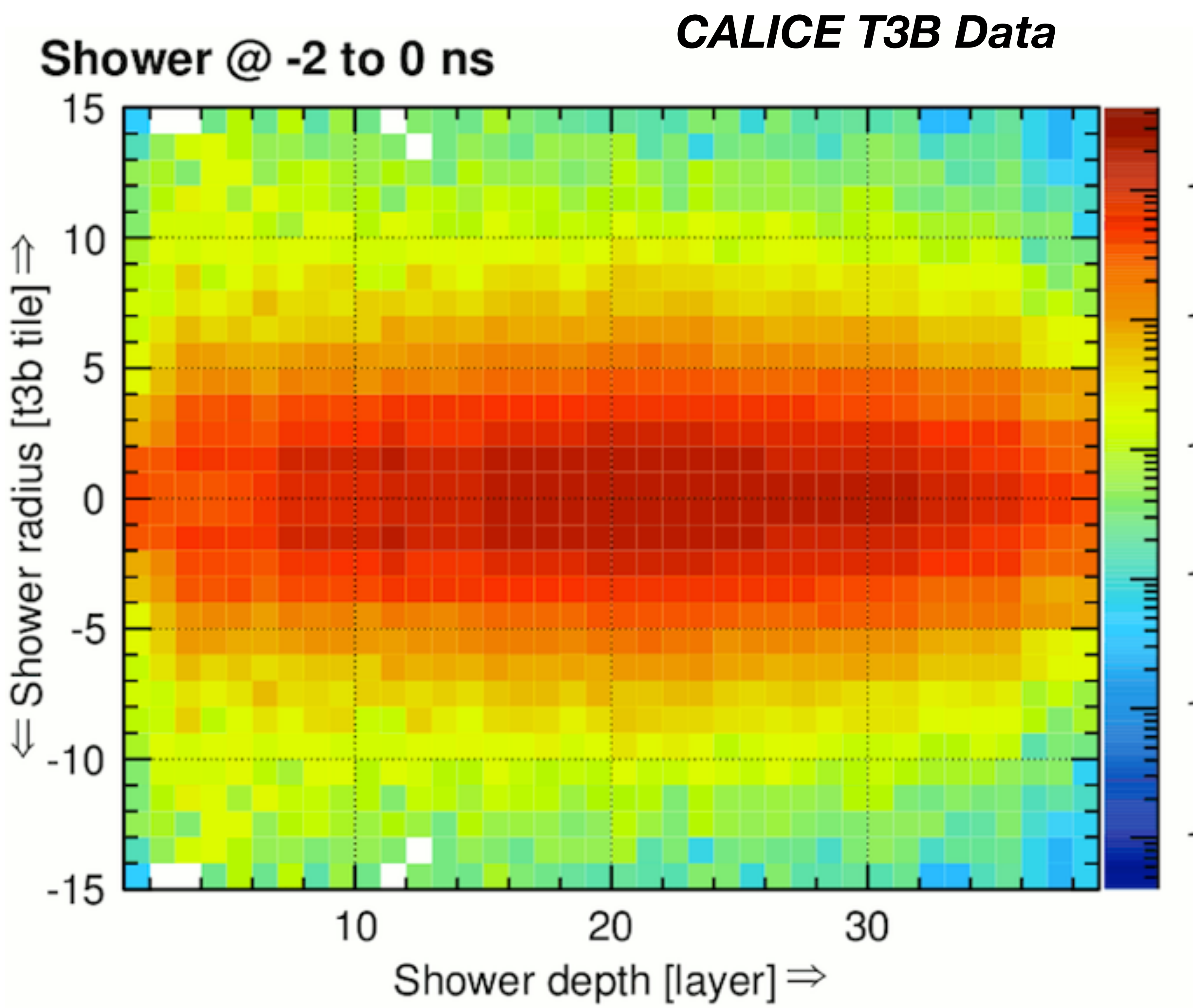

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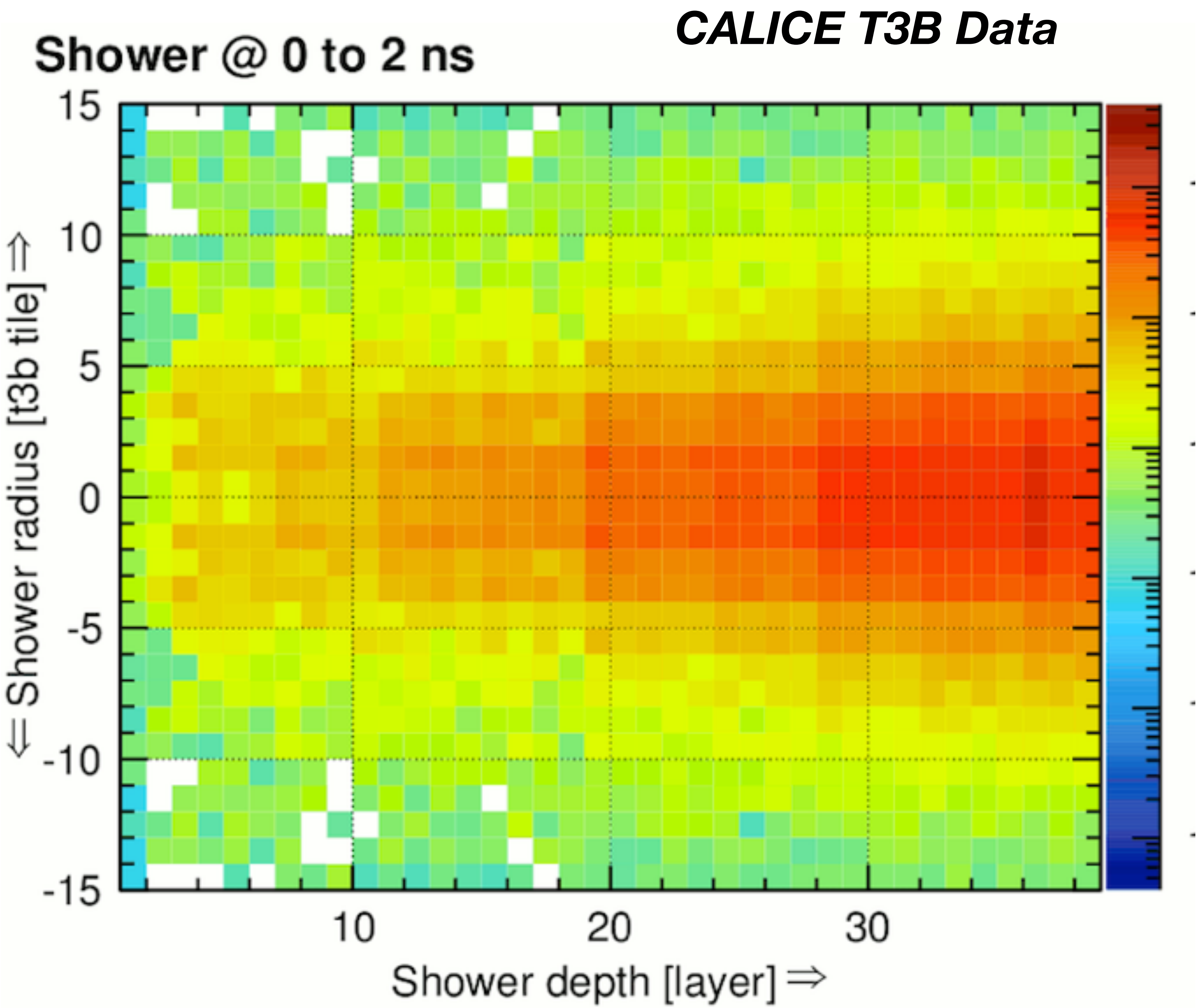

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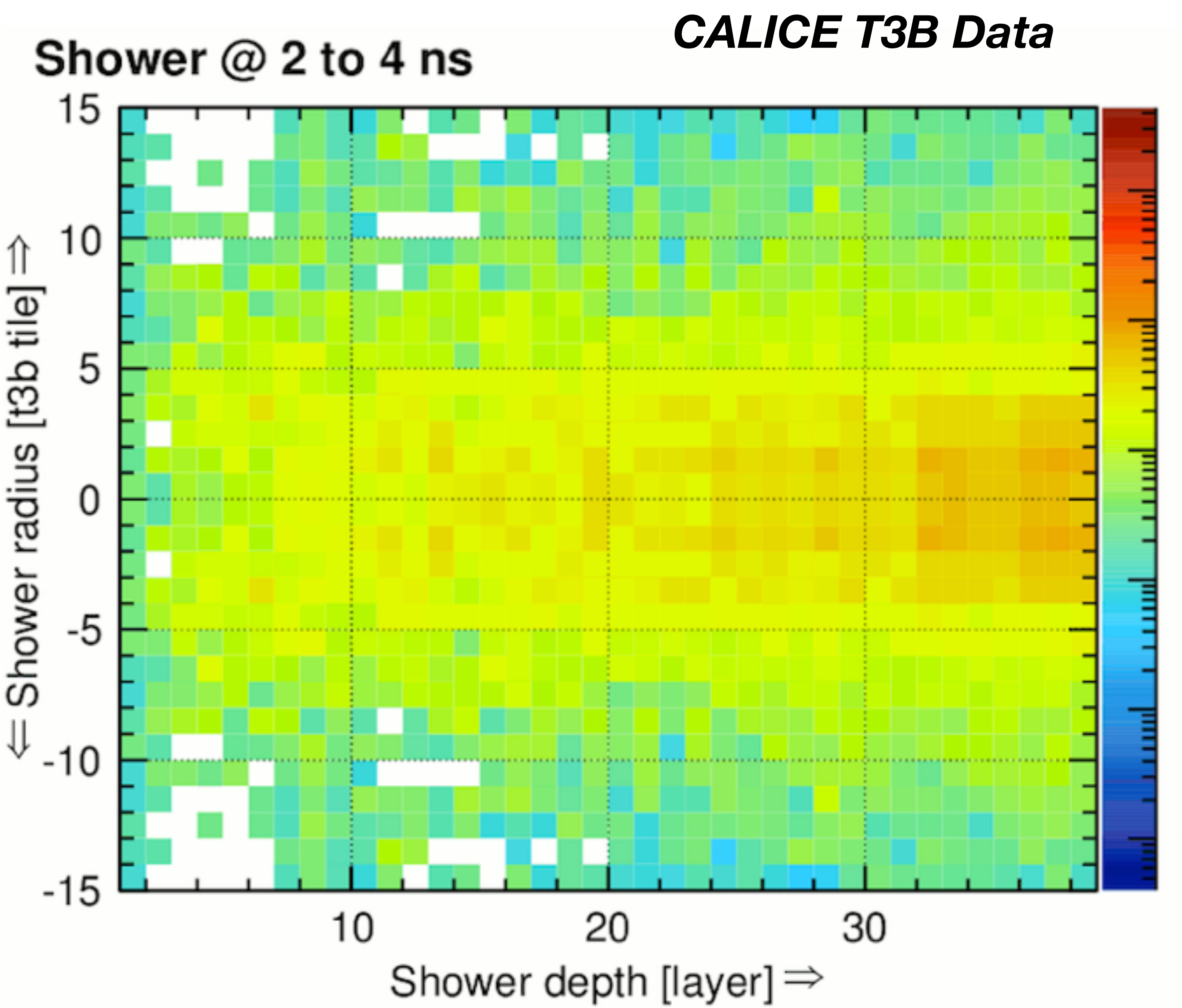

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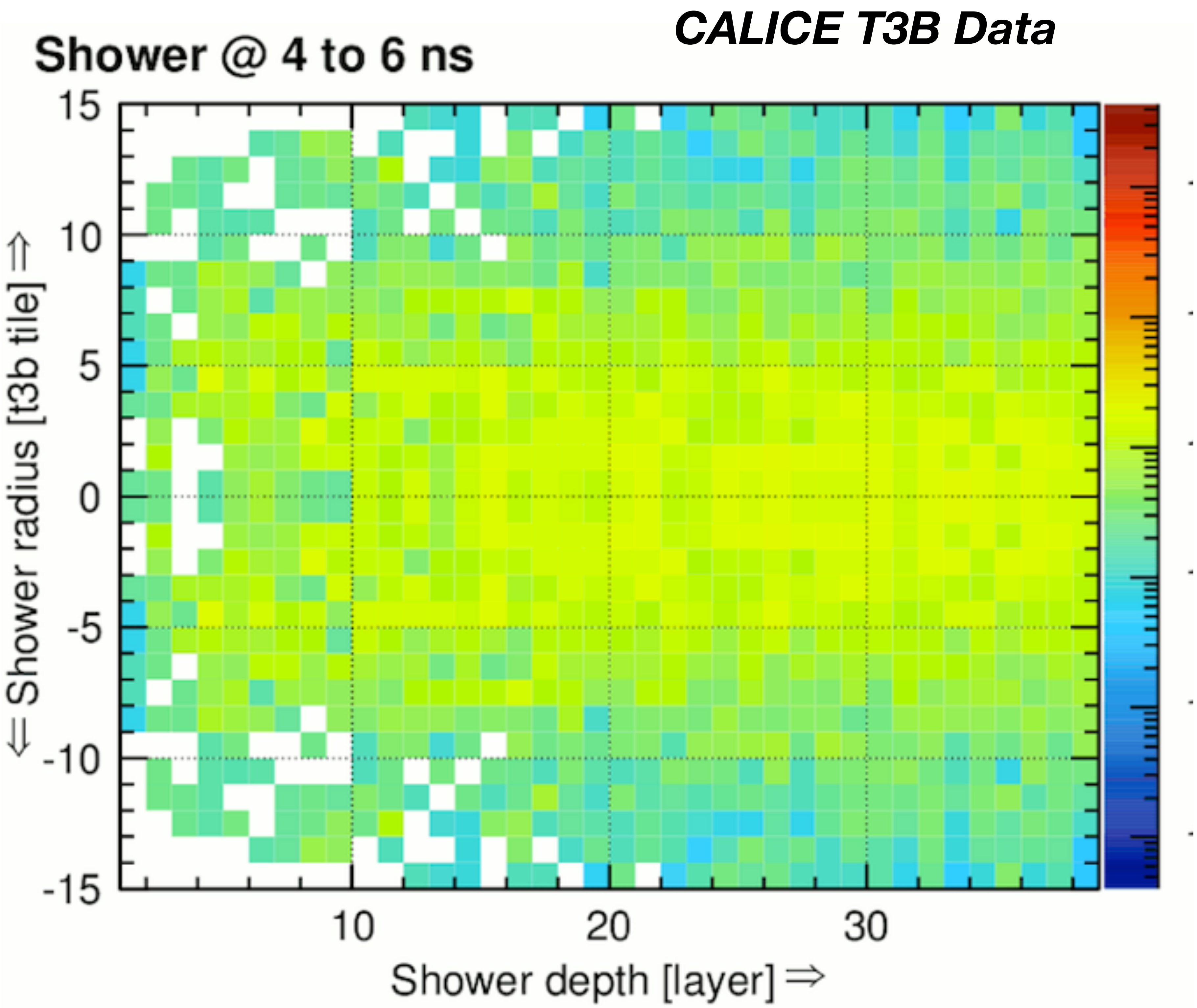

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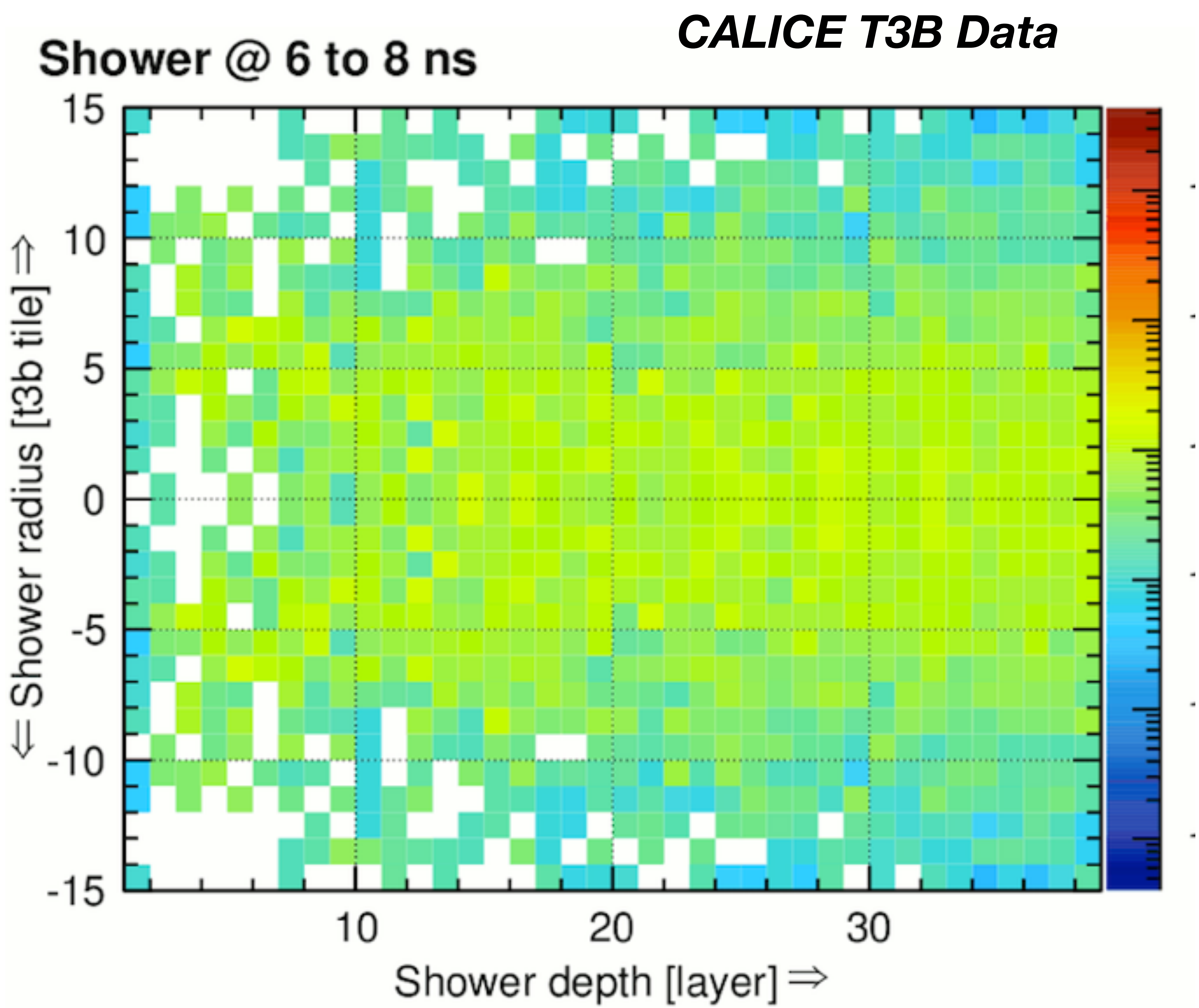

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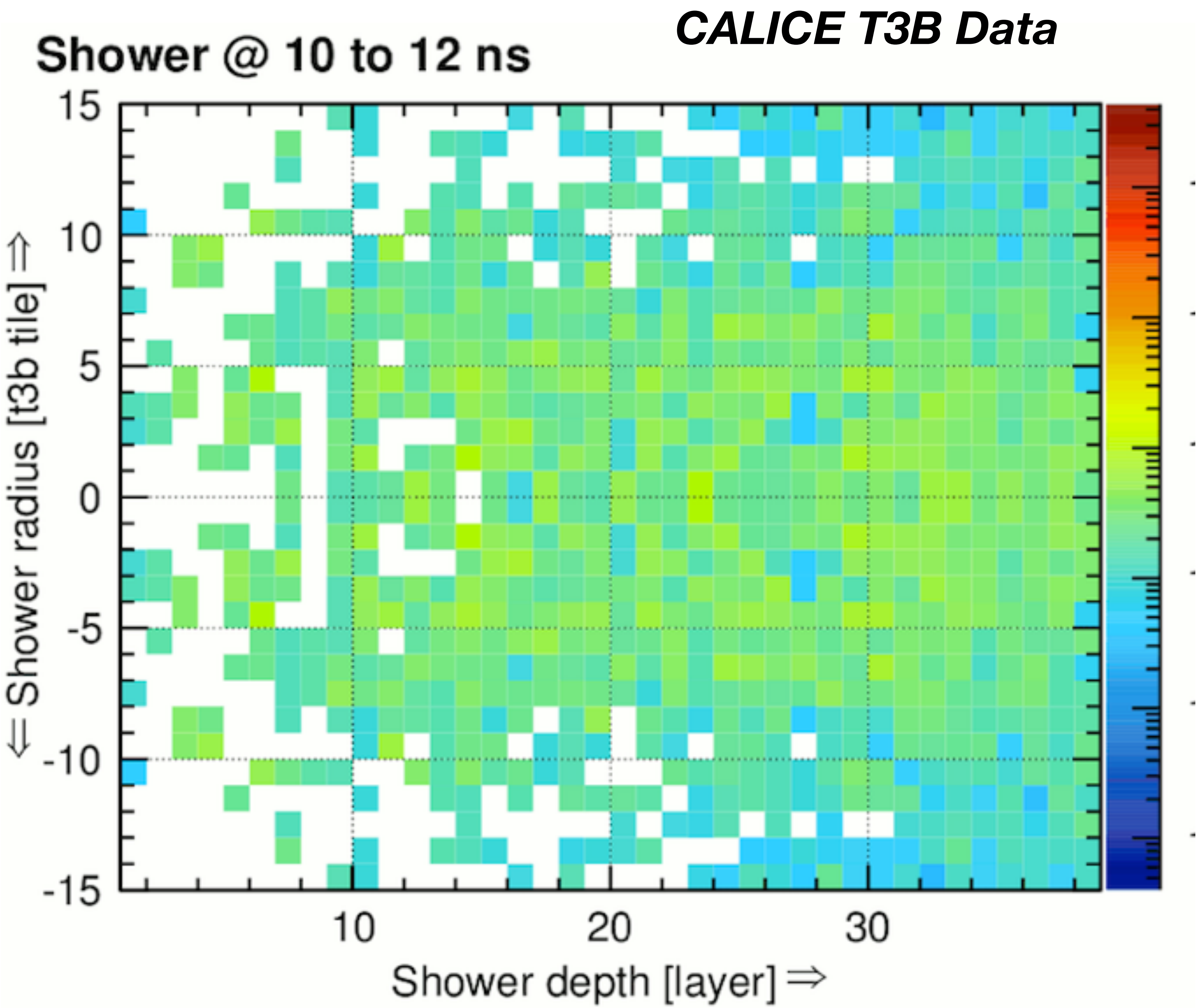

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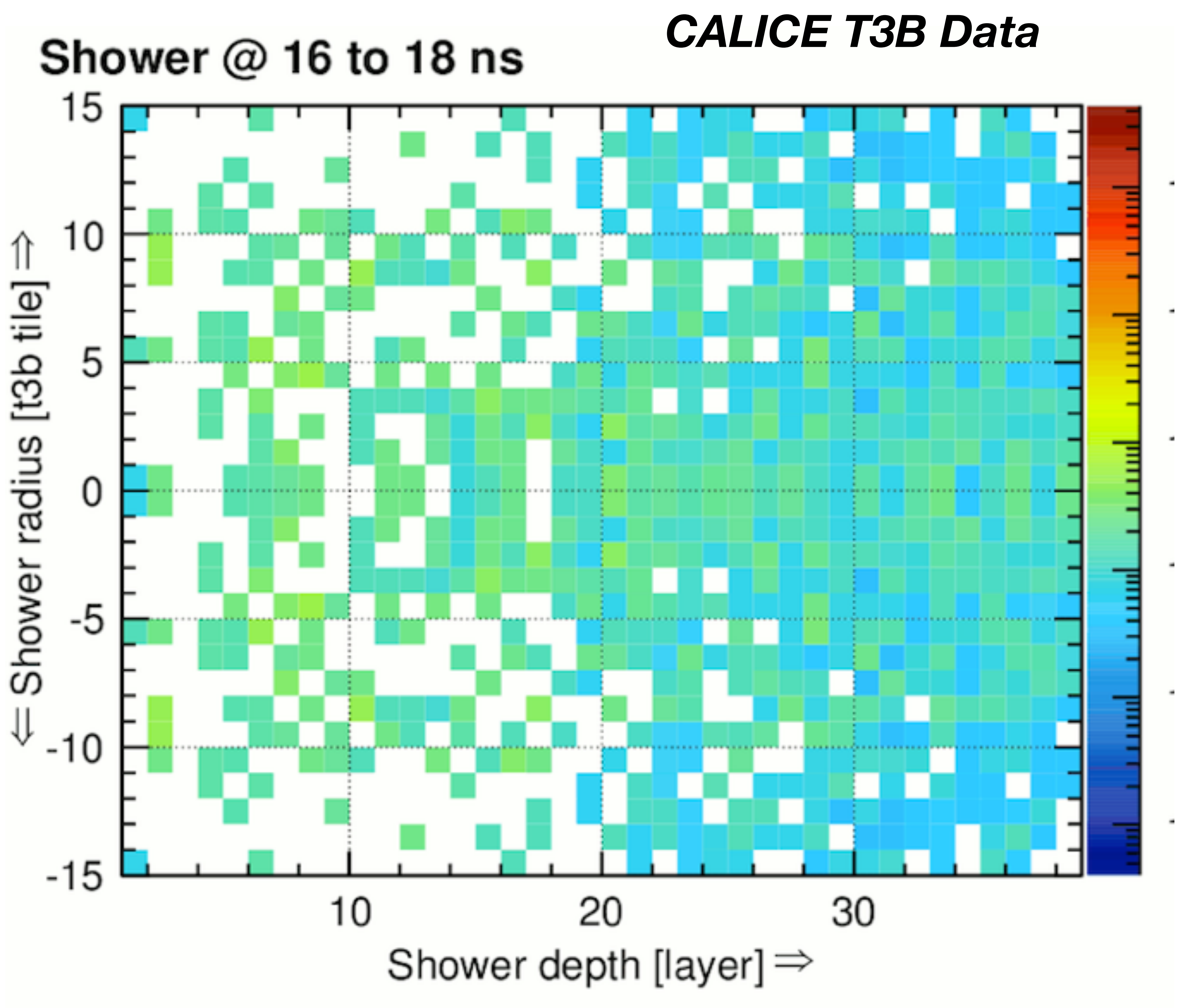

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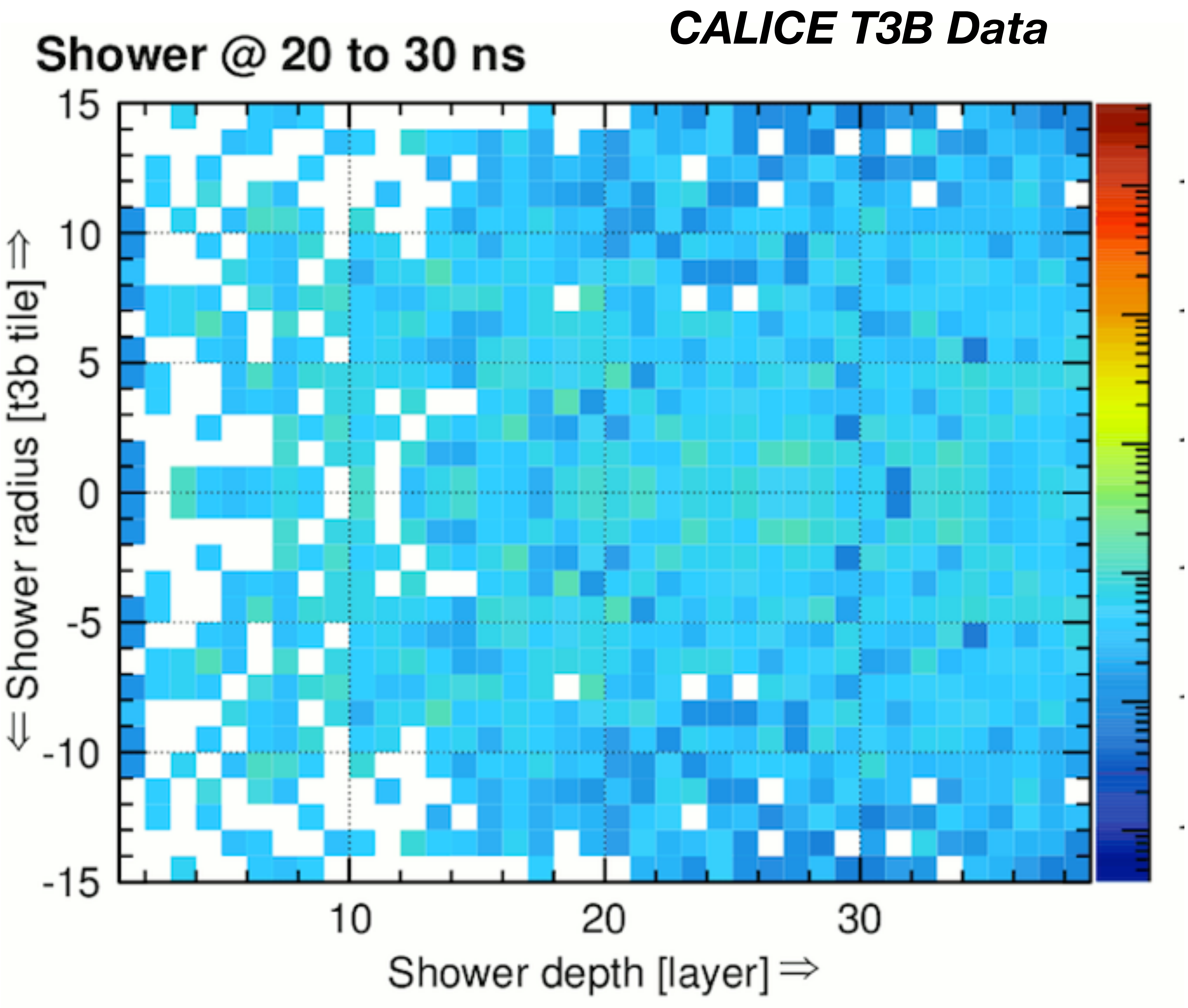

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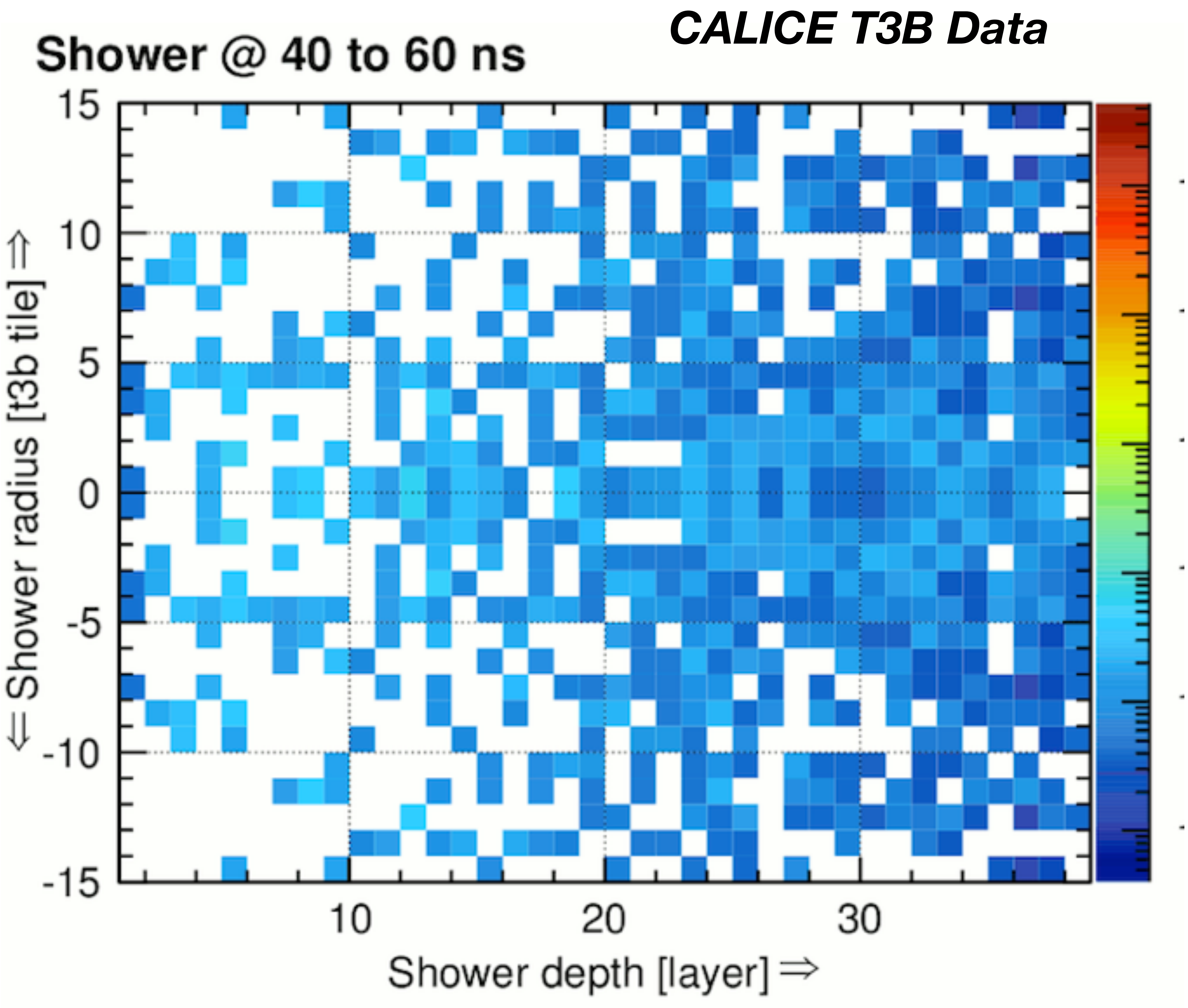

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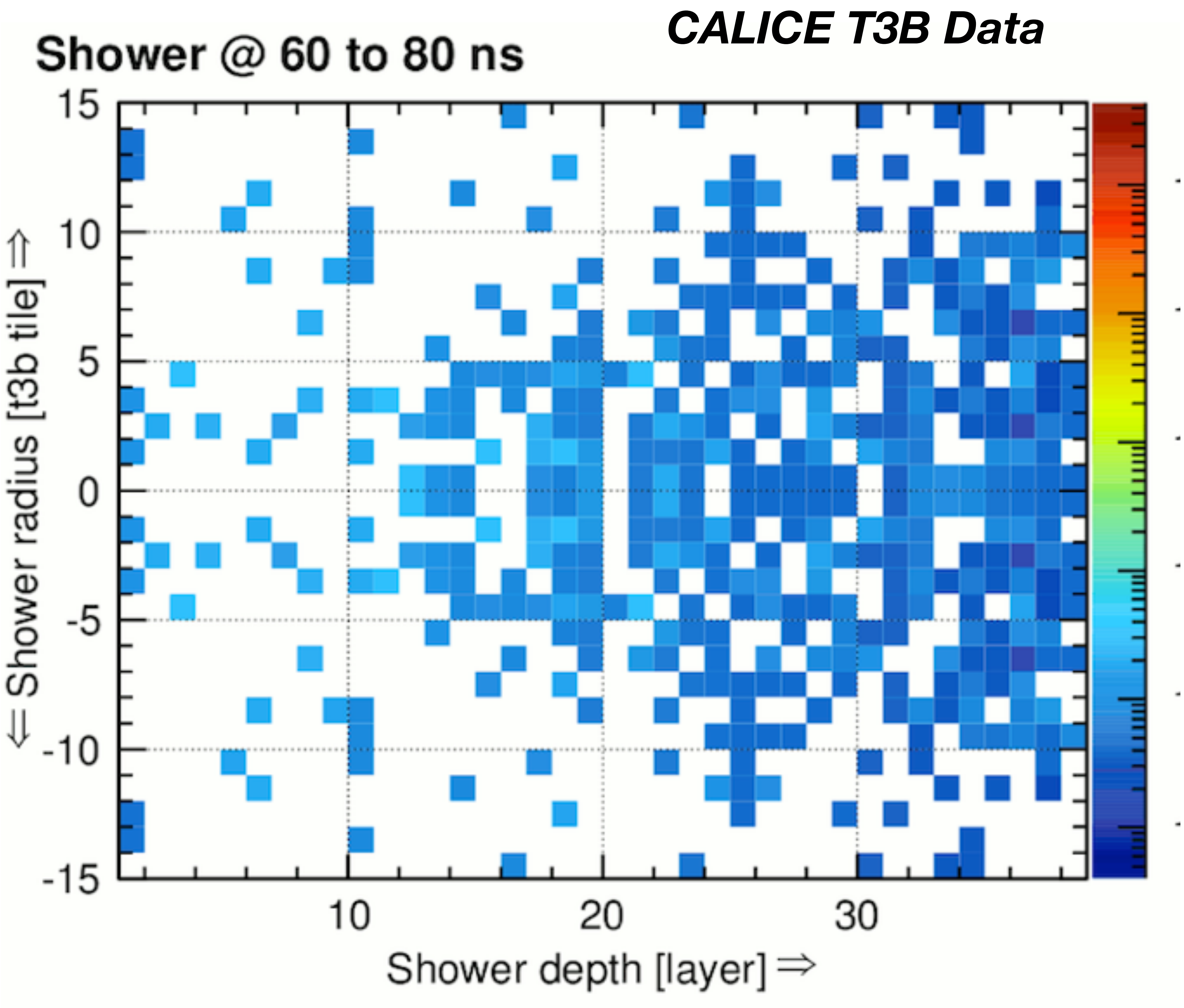

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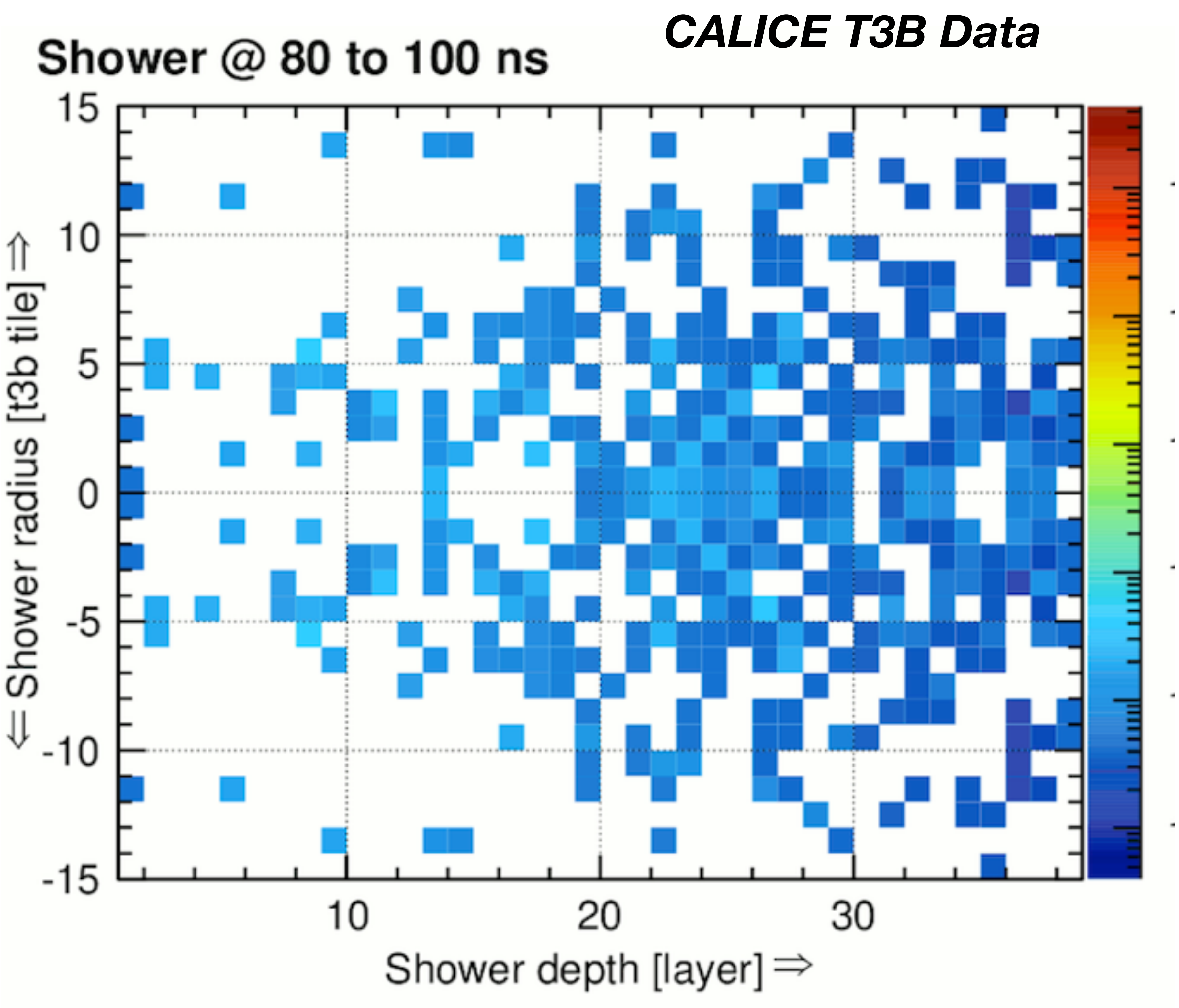

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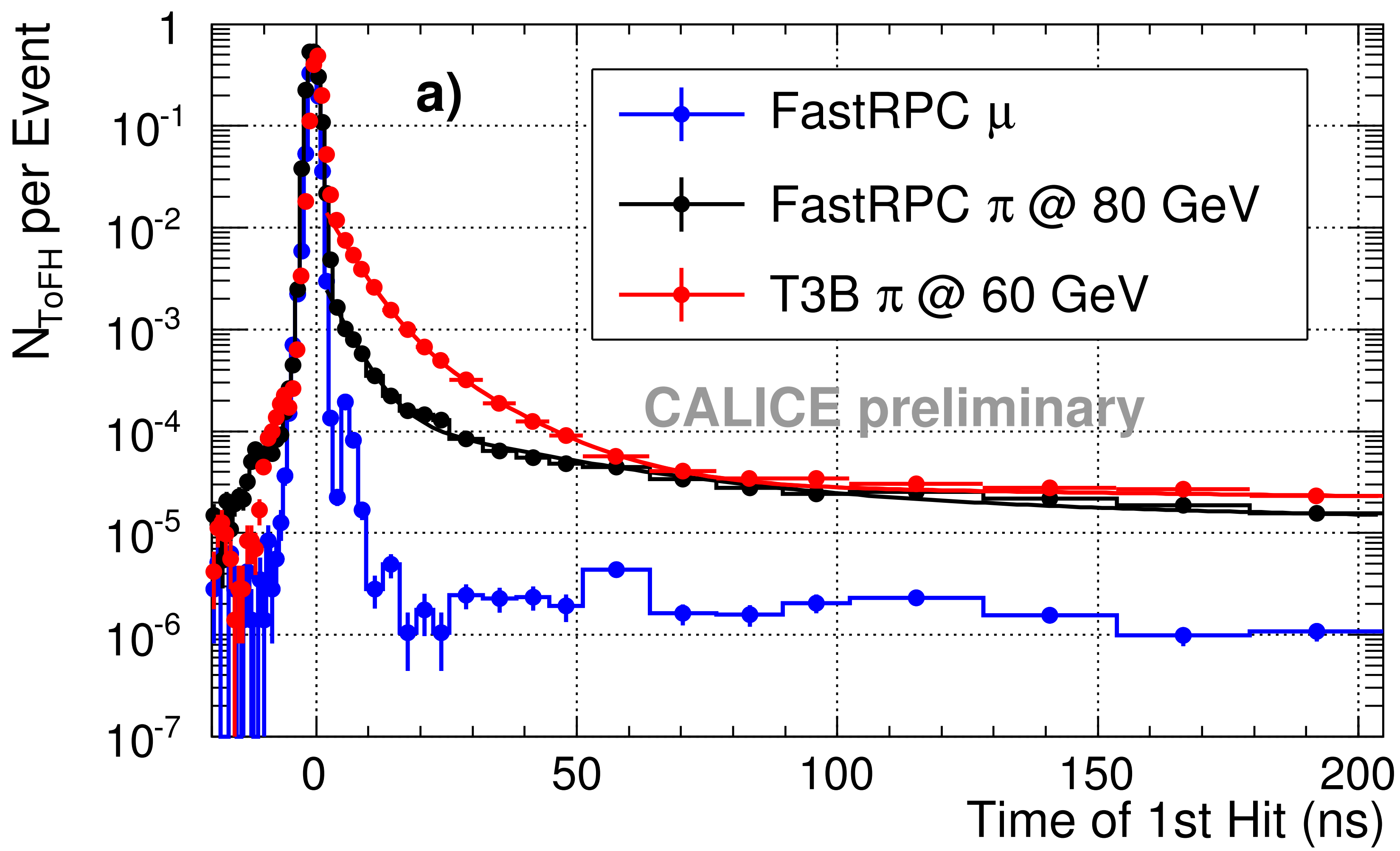
Hadronic Showers: Understanding the Details

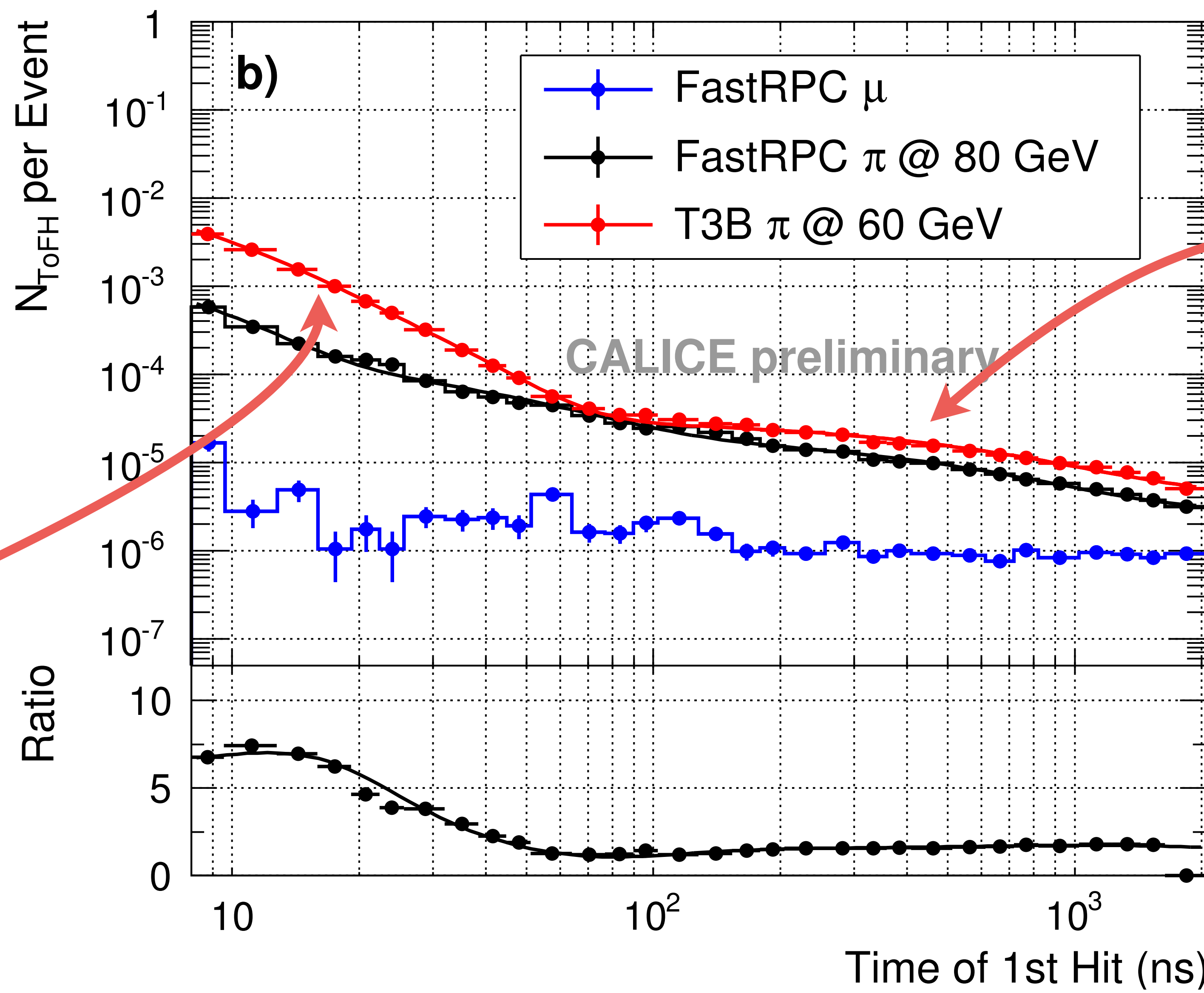
- Combining detailed results with sophisticated detector simulations - one example: Timing studies in CALICE

Comparison of the time structure observed with scintillator and with RPC readout - detector geometry otherwise identical



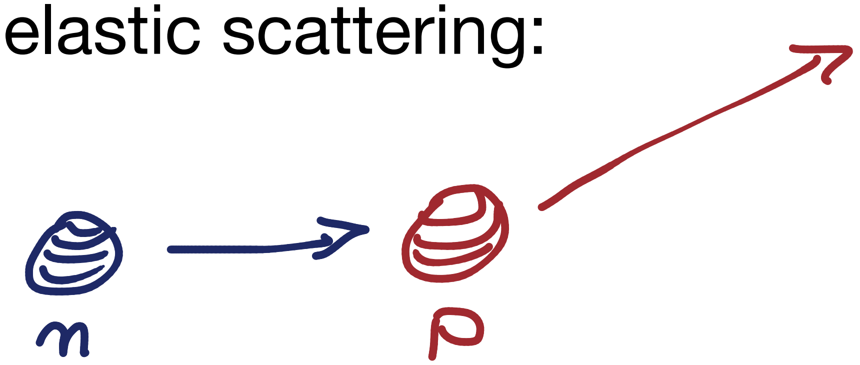
Hadronic Showers: Understanding the Details

suppression in gas detectors by a factor 8: no hydrogen in gas detector!

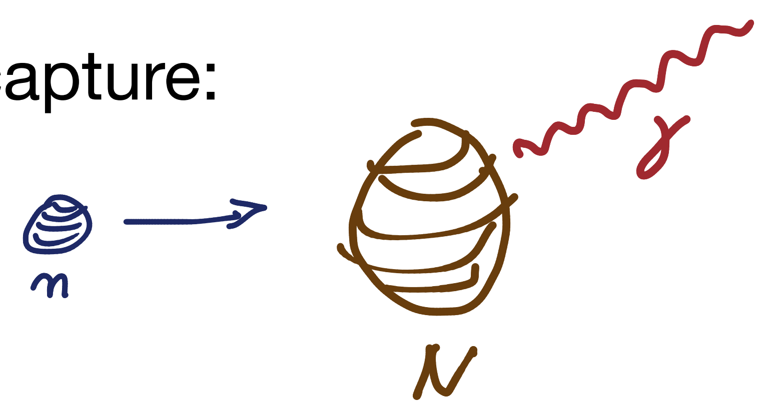


light suppression in gas detectors by a factor 1.5 - 2: neutron capture in absorber, sensitivity to de-excitation in both technologies

elastic scattering:

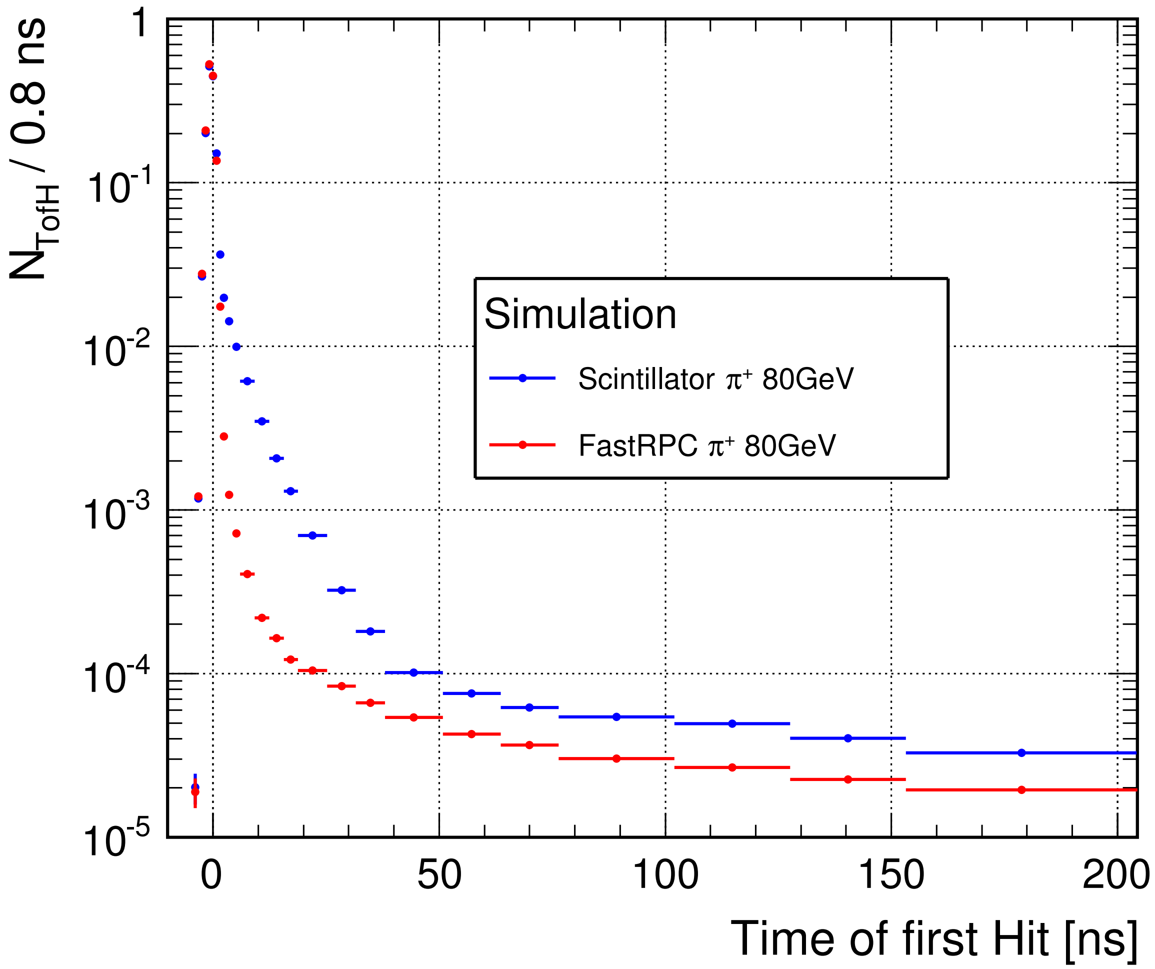


neutron capture:



Hadronic Showers: Confirming with Simulations

- GEANT4 simulations with detailed tracking of shower particles and processes (MSc thesis Philipp Goecke)



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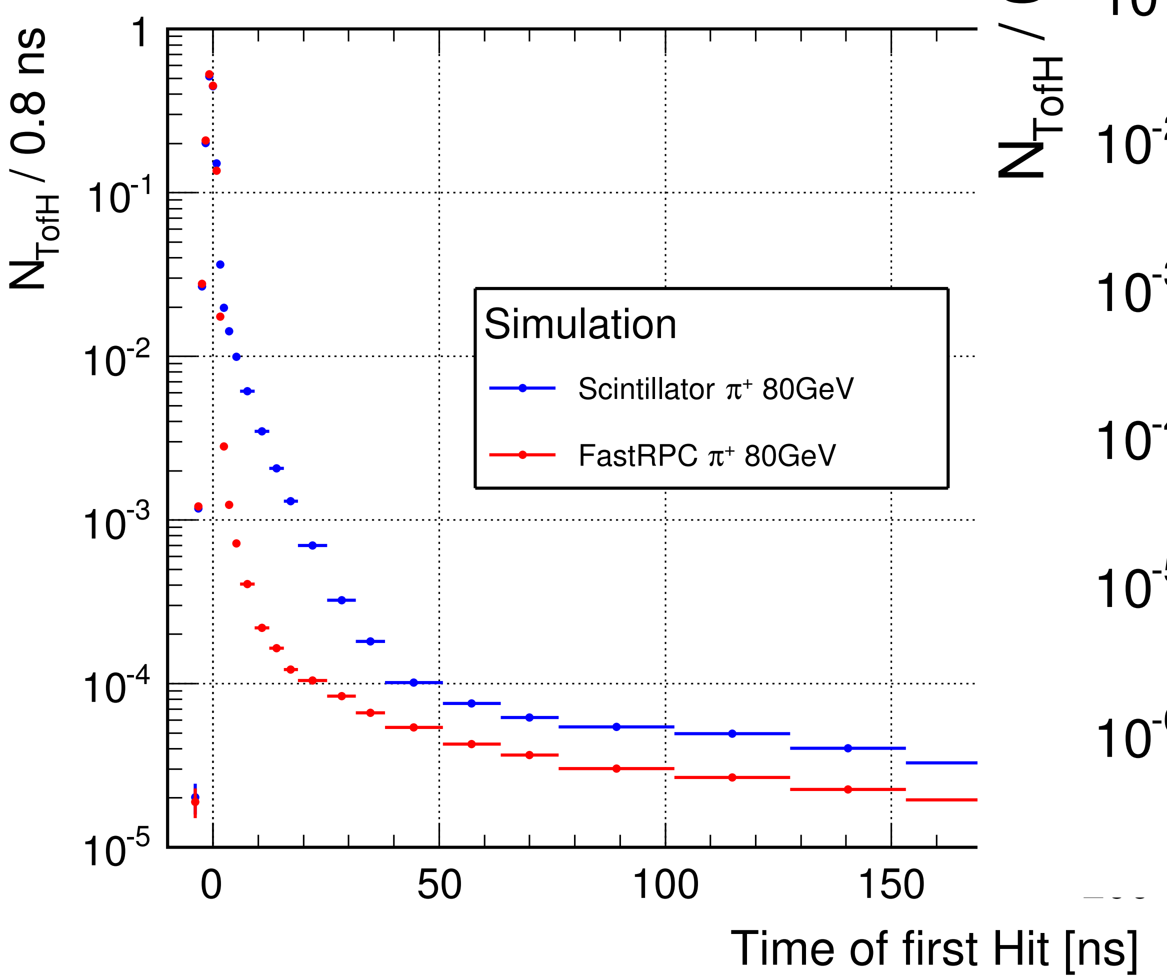

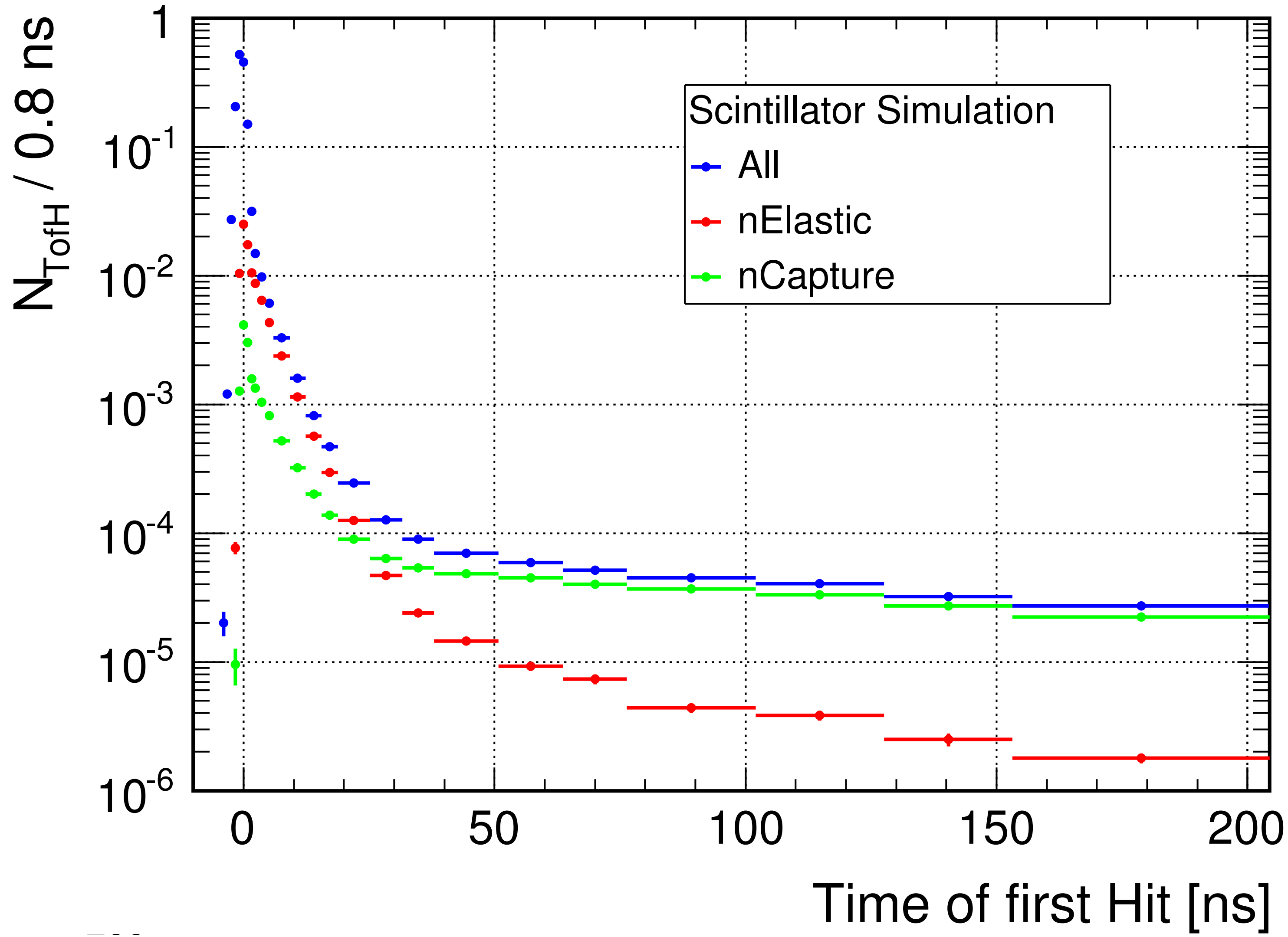

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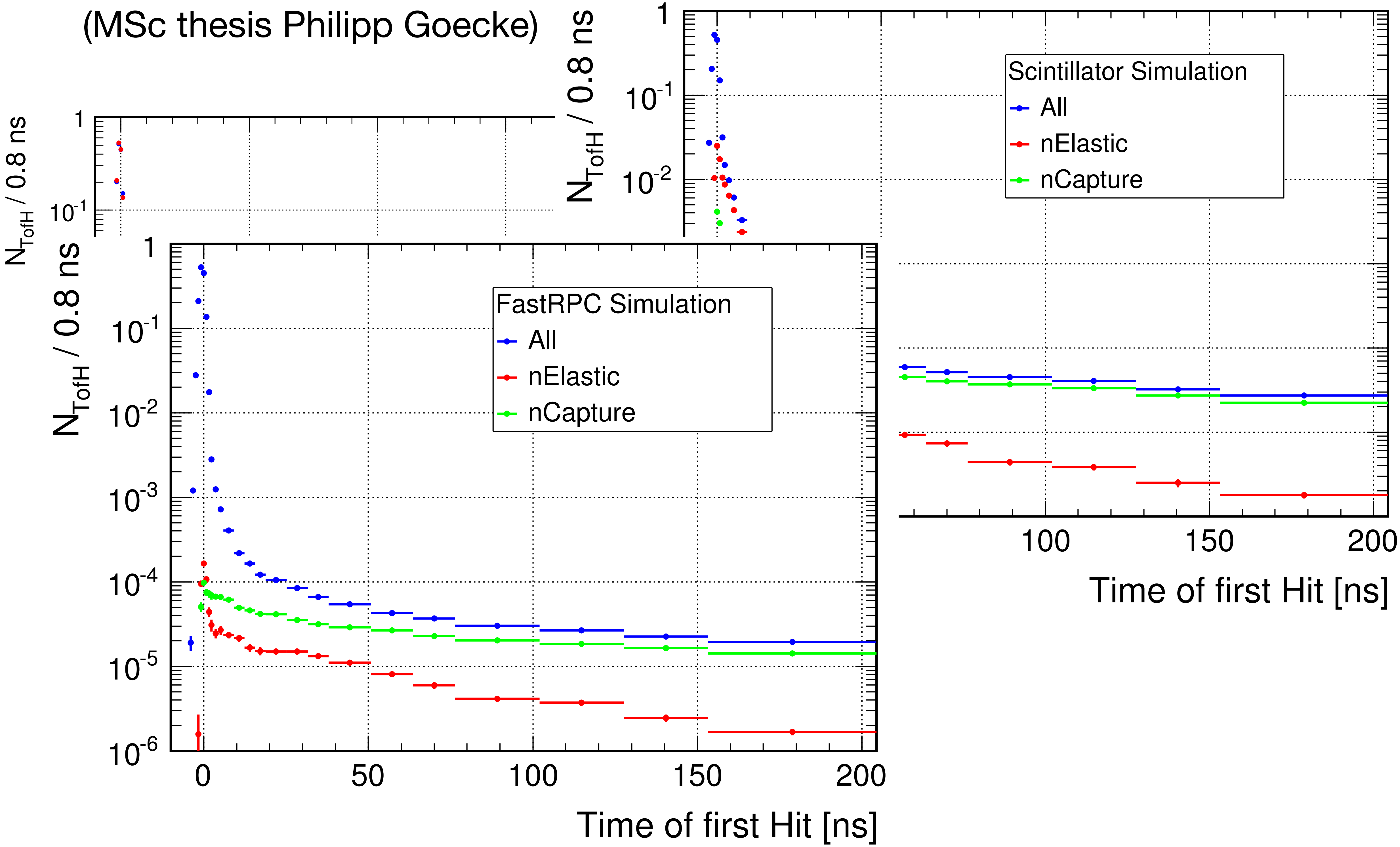
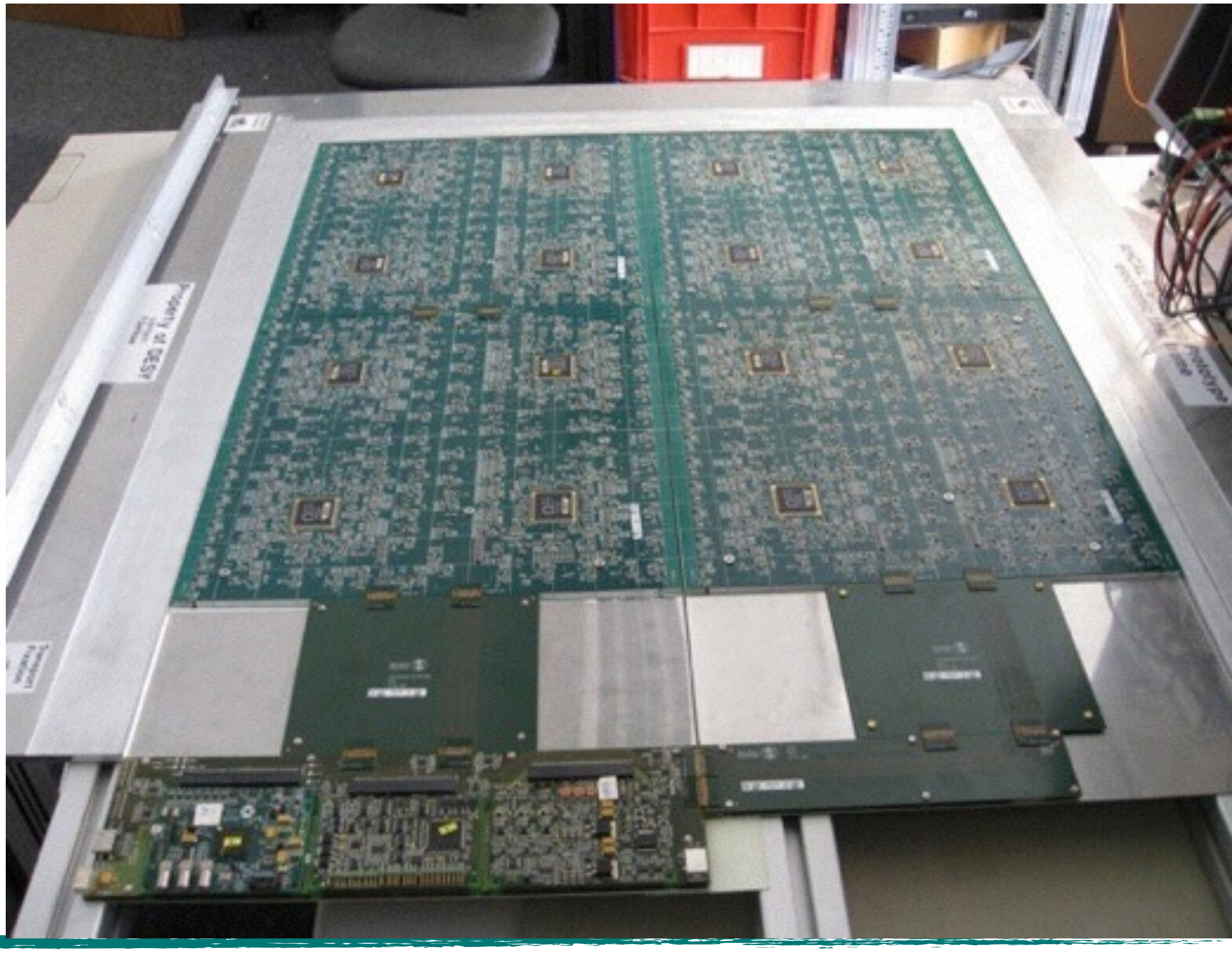


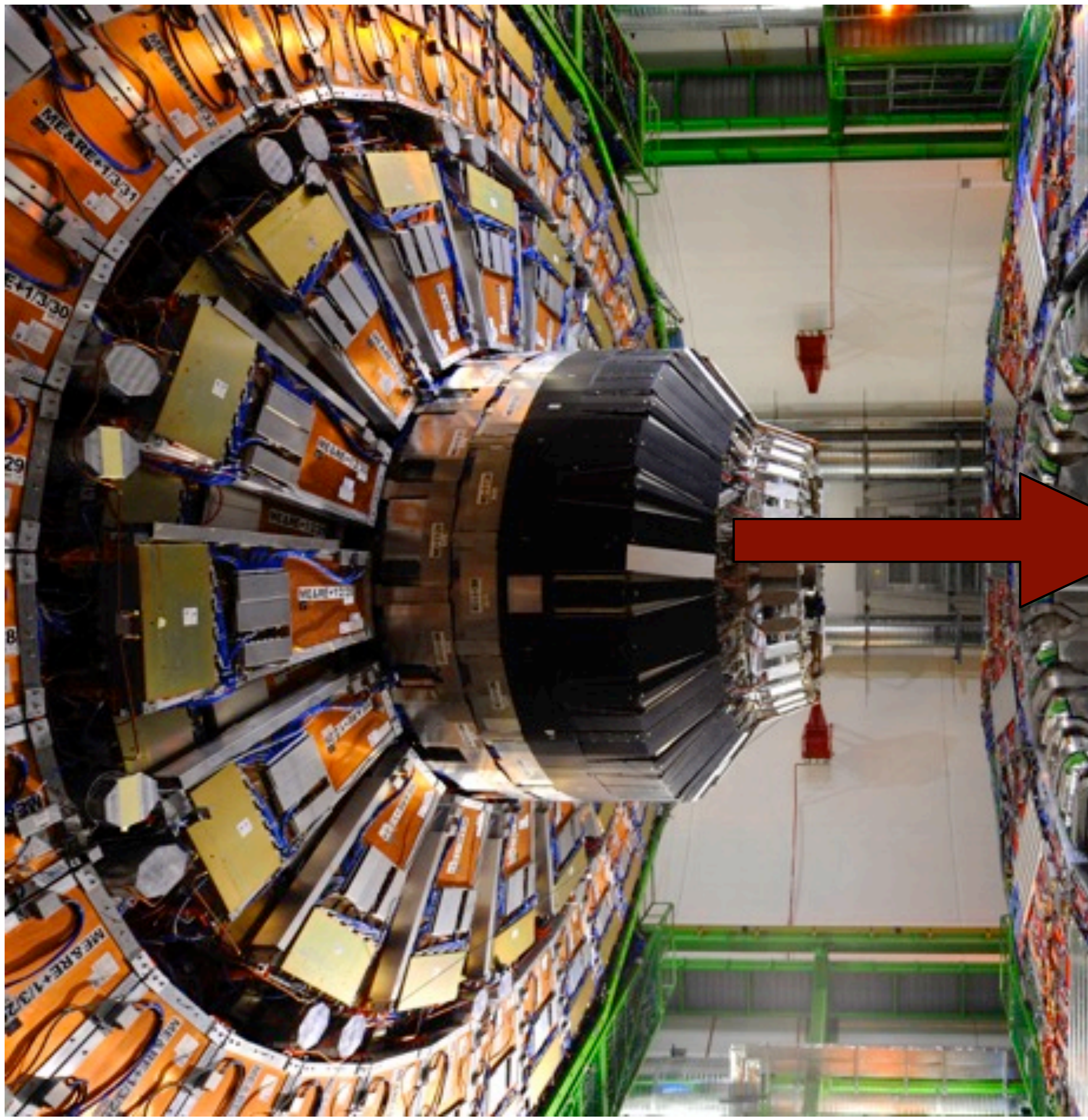
Challenges for Full Calorimeter Systems

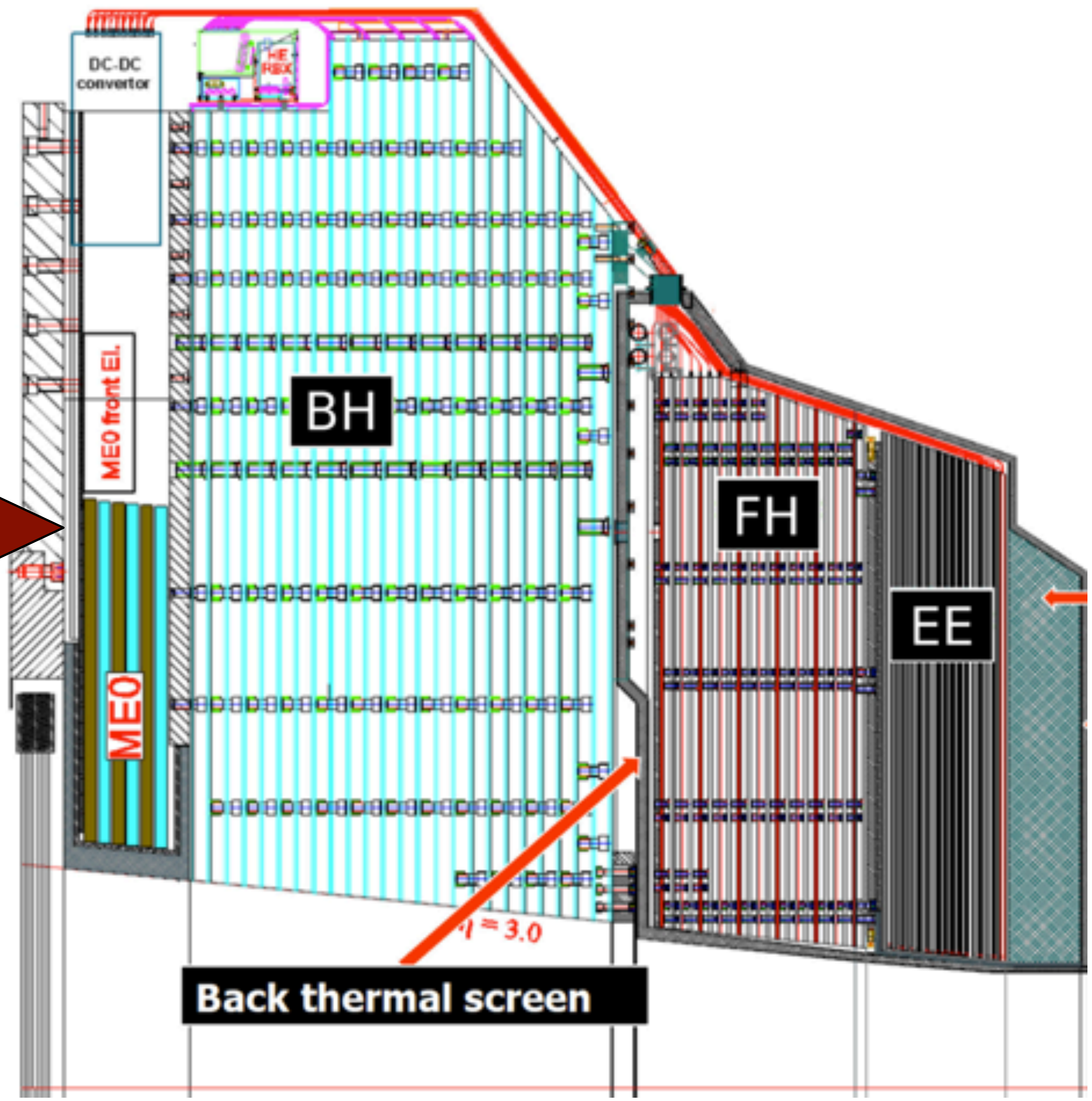
- Good jet energy resolution requires minimal material in front of Calorimeter: ECAL + HCAL inside of solenoid
  - Compact design
- PFA Calorimeters: 10s to 100s of Millions of channels (CMS ECAL: 76k, ATLAS HCAL 10k)
  - Fully integrated electronics, power pulsing, ...
  - Triggerless operation, background rejection: Cell-by-cell auto-trigger, time stamping, ...



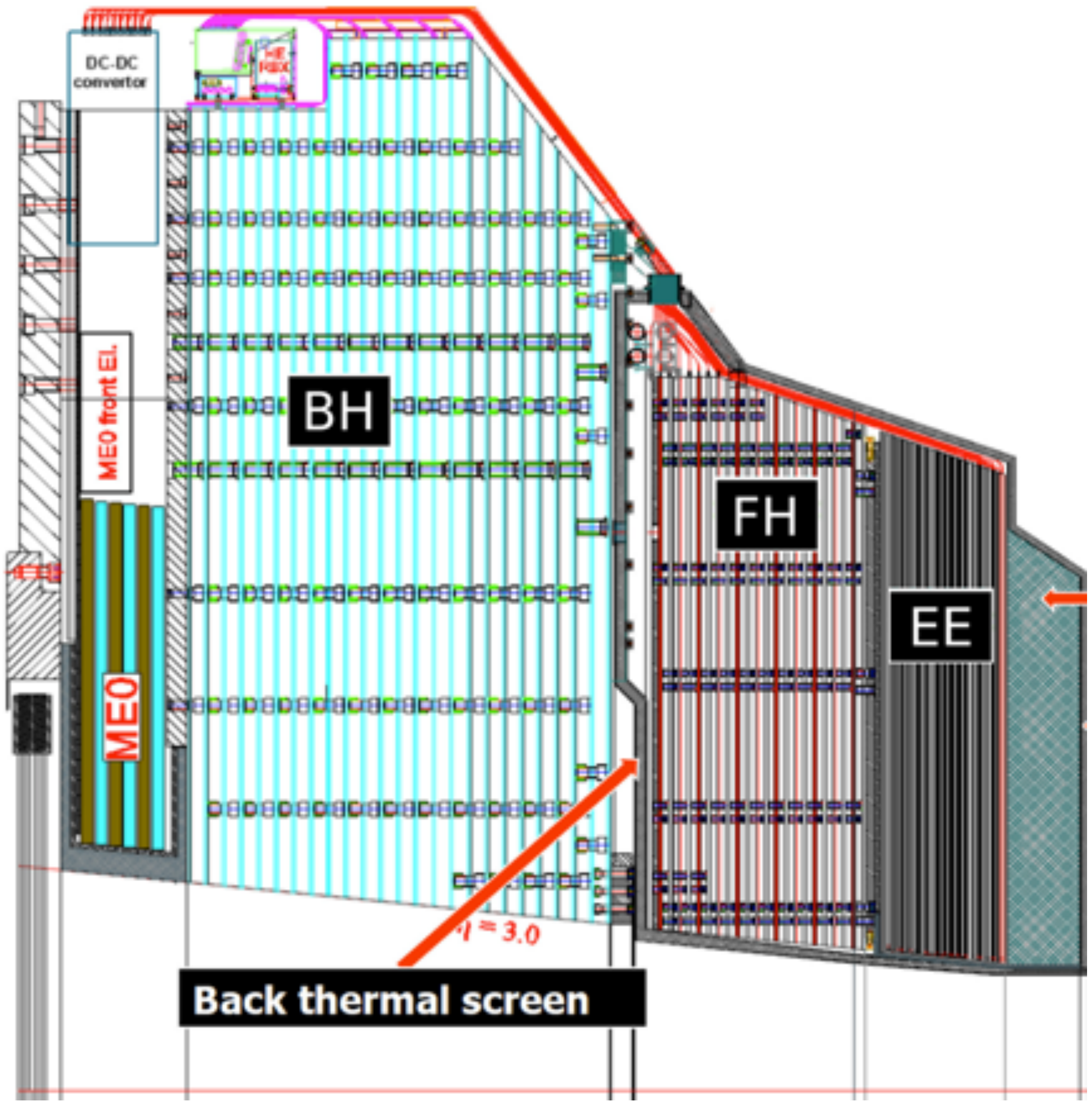
A Reality Check: CMS Phase II Upgrade

- CMS Phase 2 upgrade of endcap calorimeters: The HGCAL (High Granularity Calorimeter)





The CMS HGCAL



Construction:
- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes inserted into absorber structures at integration site (CERN)*

Key parameters:
- *593 m² of silicon*
- *6M ch, 0.5 or 1 cm² cell-size*
- *21,660 modules (8" or 2x6" sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 120 kW.*

System Divided into three separate parts:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_0 + ~1.3 λ

FH – Silicon with brass absorber – 12 sampling layers – 3.5 λ

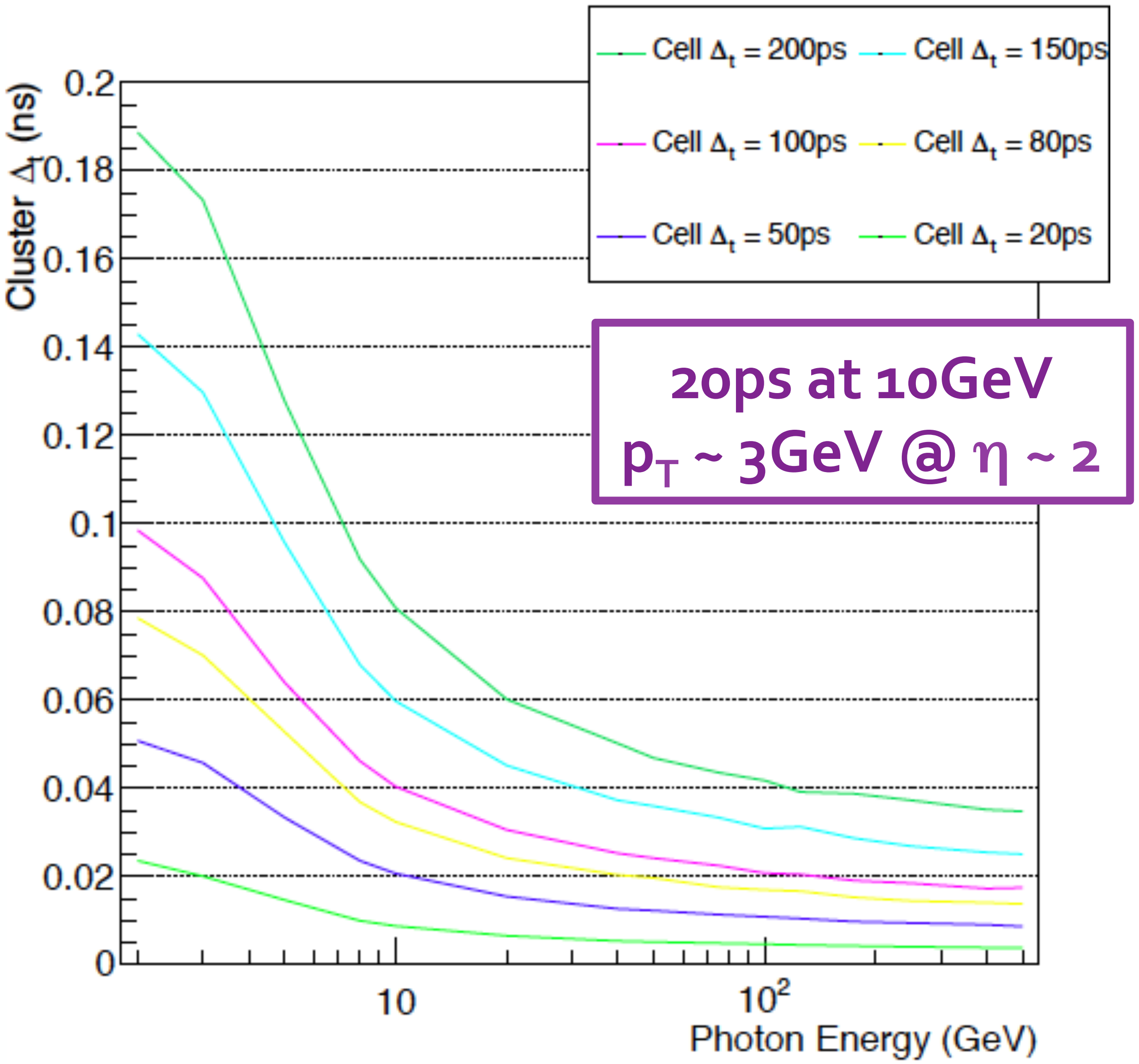
BH – Scintillator with brass absorber – 11 layers – 5.5 λ

EE and FH are maintained at – 30°C. BH is at room temperature.

The CMS HGCAL: Intense R&D Phase

- One goal: timing!

simulated performance for photons



Δ_t is 68% effective RMS
20ps * c = 6mm

- One goal: timing!

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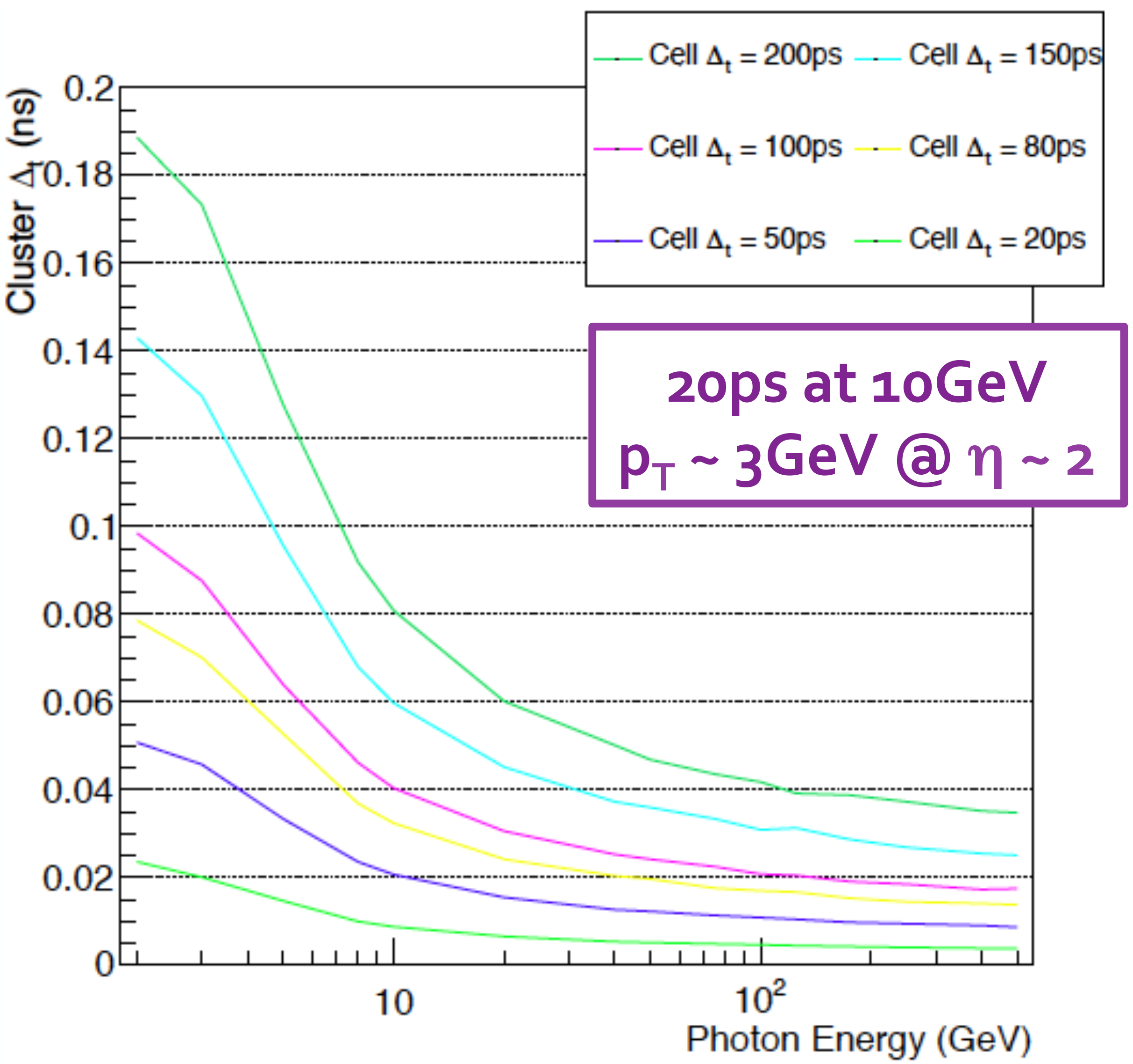
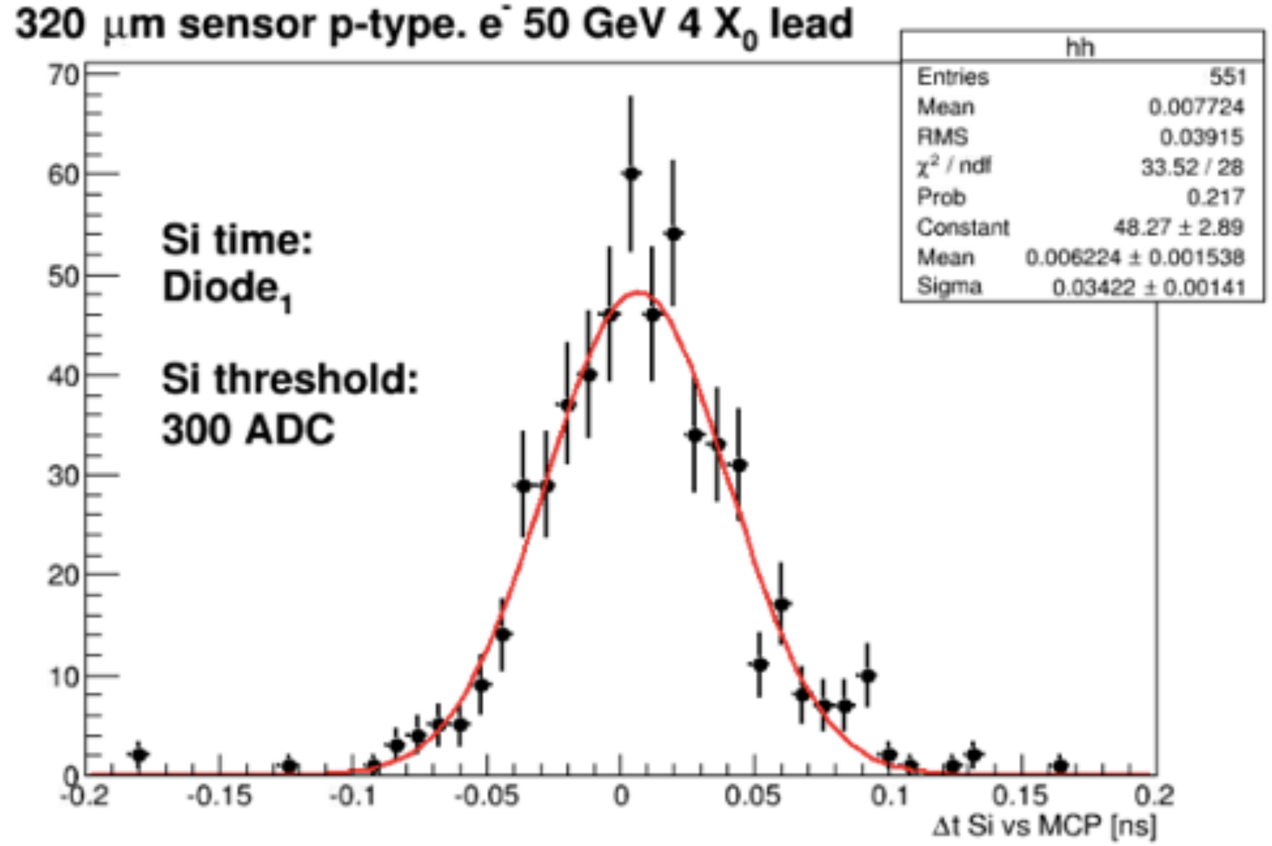


Δ_t is 68% effective RMS
20ps * c = 6mm

… combined with test beam performance of a sensor prototype



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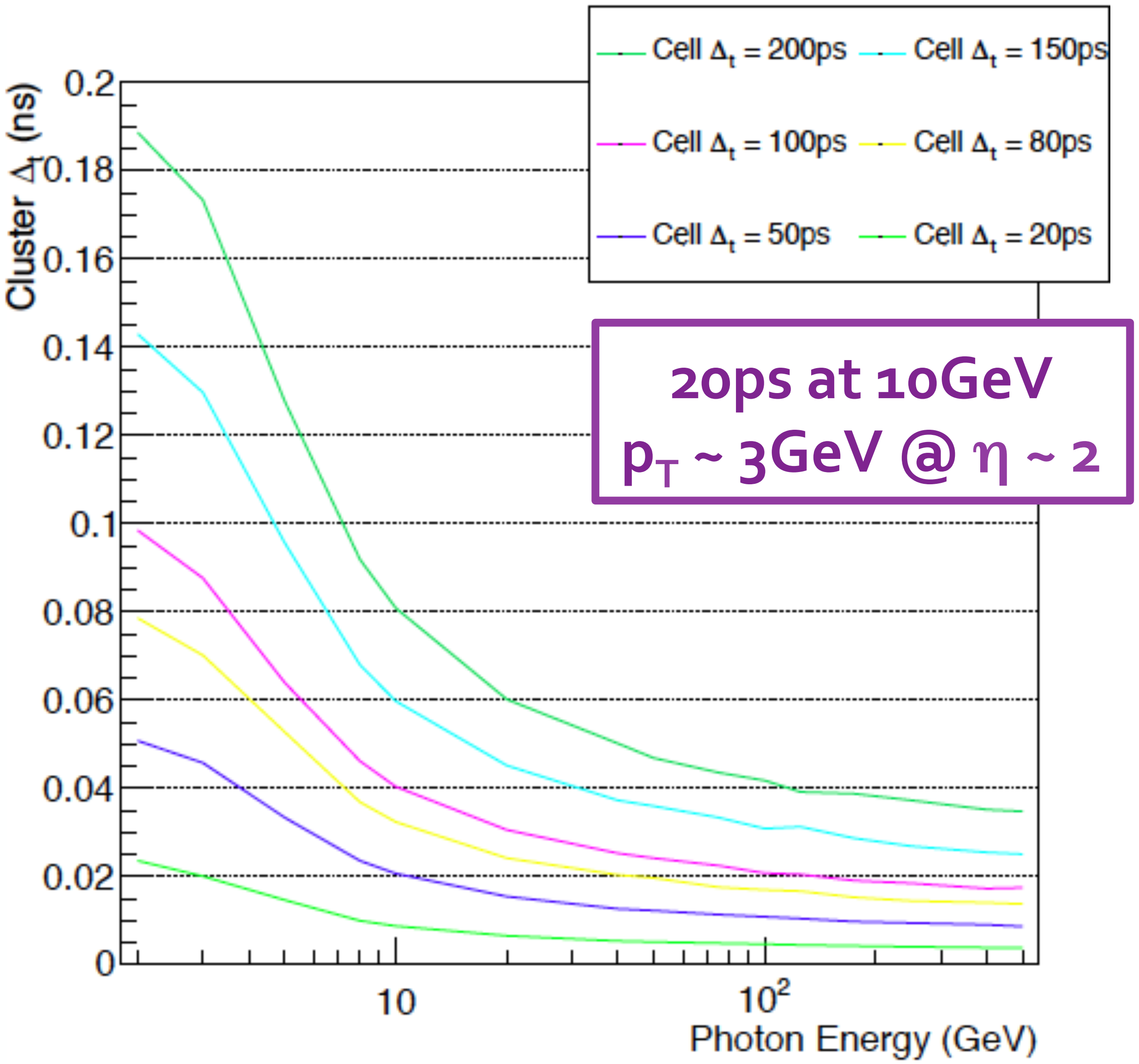

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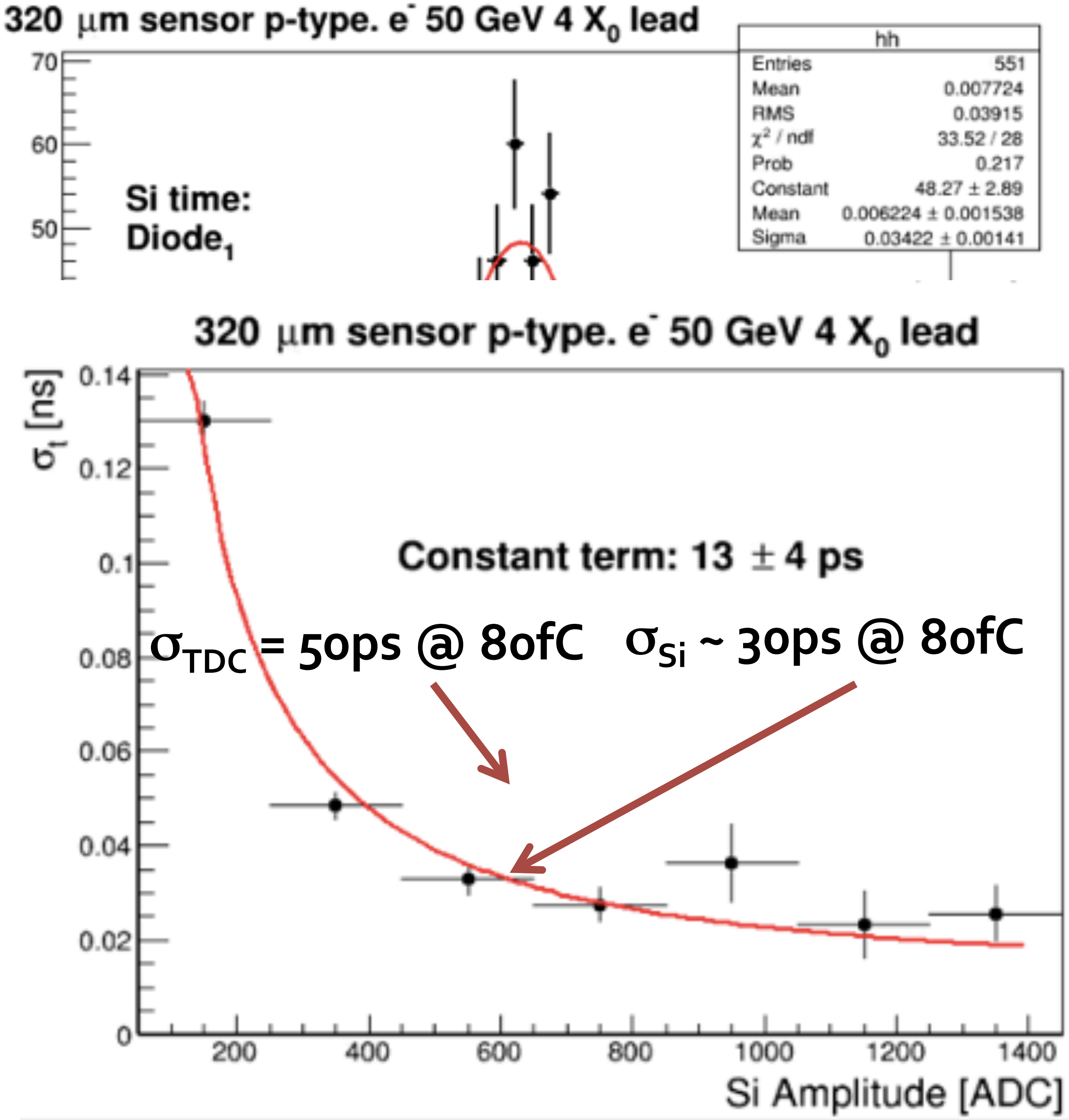
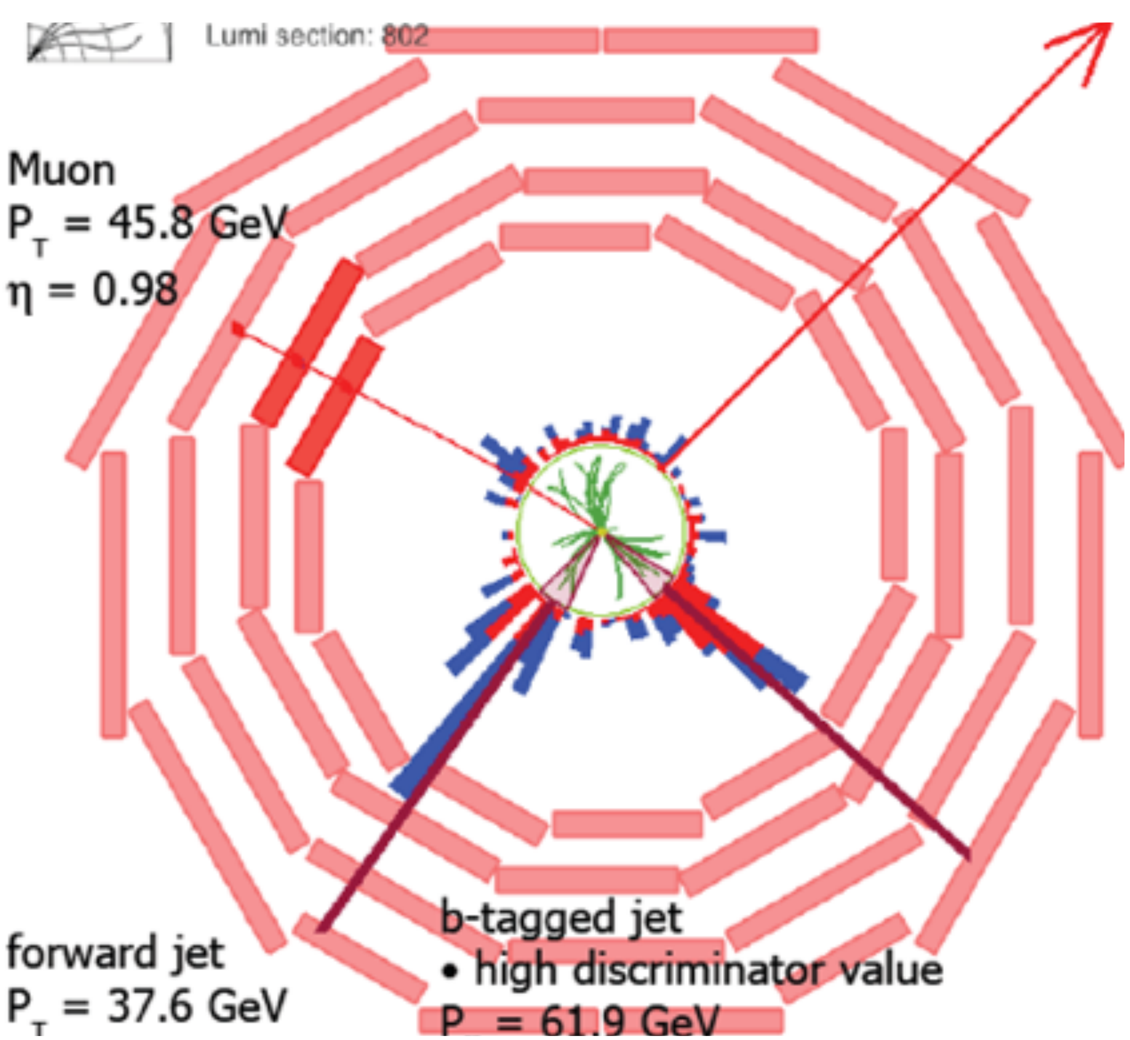


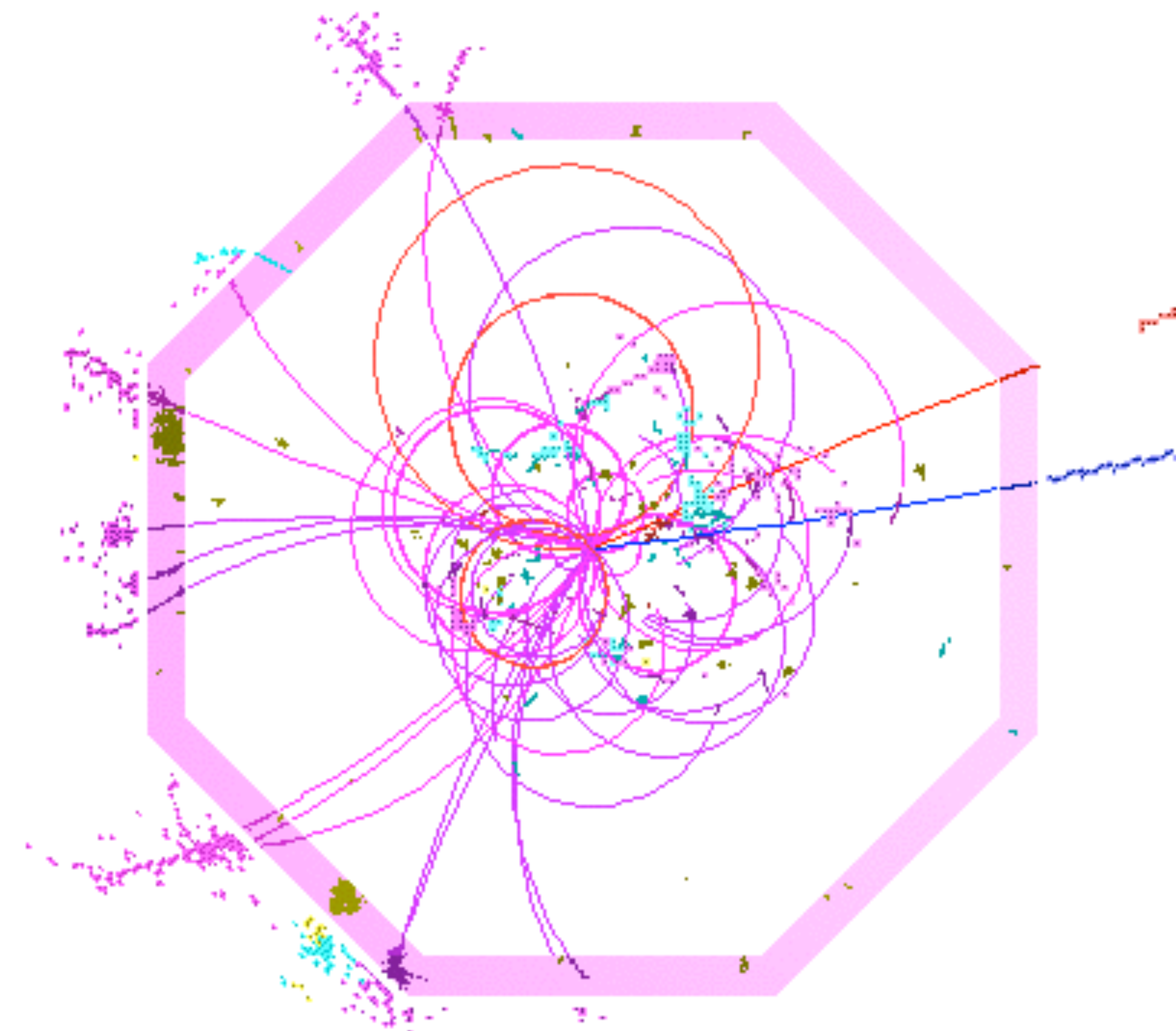
Summary & Outlook

- Calorimetry is an active, rapidly changing field at present - with applications in HEP and medical imaging
- New technologies provide new opportunities
  - High density crystals for PET and HEP
  - New silicon-based photon sensors: Compact, low power, magnetic field insensitive, fast timing for enormous channel counts
- New ideas change the way we measure energies
  - Multi-mode measurements to improve energy resolution for hadrons
  - Truly imaging detectors for Particle Flow: An integrated approach to HEP detectors, combining the strengths of all subsystems

Summary & Outlook

- Calorimeters today are not the heavy, bulky detectors from earlier experiments...





... but 4D precision instruments which are opening access to new frontiers in high energy physics and medical imaging.

Backup

Crystals for Calorimeters - Overview

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim 0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	83	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

taken from PDG Review of Particle Physics

- Note: The melting point is a key cost driver: High melting point crystals are expensive to produce