The CALICE highly granular scintillator calorimeters

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Frank Simon
Max-Planck-Institute for Physics

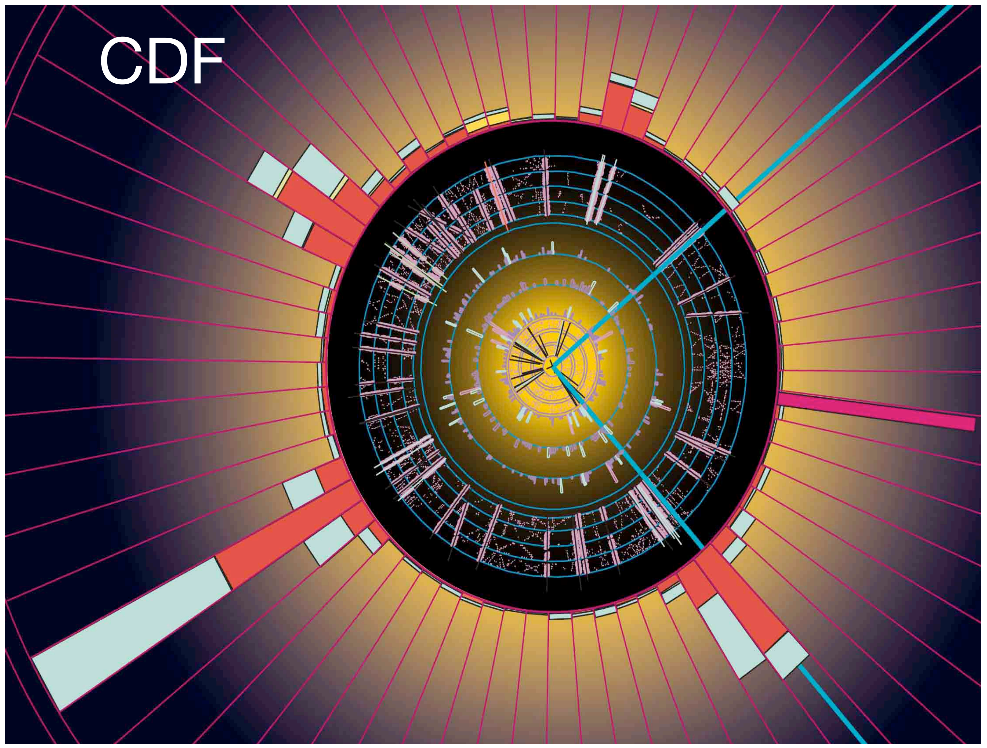
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

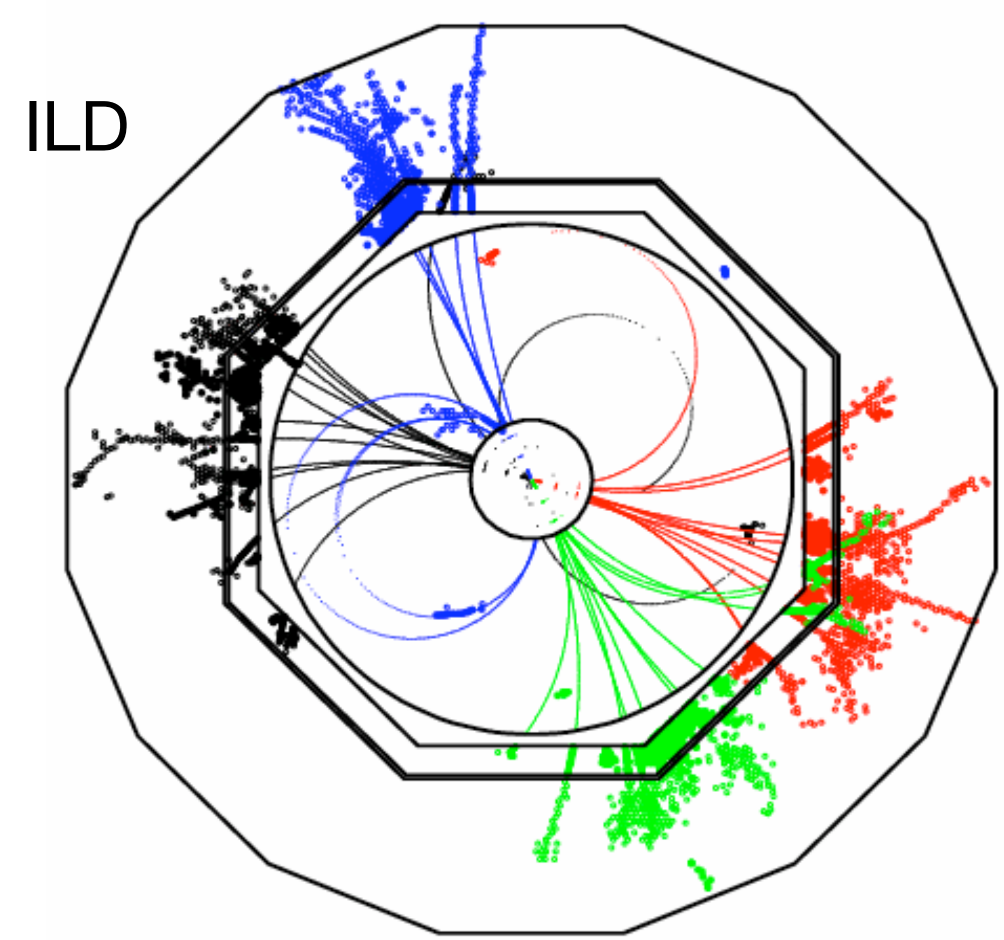
Outline

- Introduction: The CALICE Context
- The CALICE scintillator-based calorimeter prototypes - Overview
- Focus on the analog hadron calorimeter:
    - The technological prototype - hardware details
    - Latest results: QA, timing
    - A few words on simulations
    - Ideas beyond the standard design
- Conclusions

Introduction: Event Reconstruction in HEP

- From towers to particles:





- The ideal event reconstruction in HEP: 4-vectors of individual final-state particles instead of jets formed from calorimeter towers - "*Particle Flow*"

  ➯ Opens up new possibilities in jet reconstruction, background rejection, …

▸ Requires the connection of information from all sub-detectors - and the separation of energy depositions of close-by particles in the calorimeters

  - Best achieved with highly granular detectors

A Few Words on CALICE

- Highly granular calorimeters were initially motivated by the requirements imposed by the physics program of future high-energy linear e^+e^- colliders - but the corresponding calorimeter technology was not available

➯ Dedicated R&D program started to address this issue in 2001 - initially as DESY PRC R&D 01/02 in the context of TESLA

- Completion of the formal founding of the CALICE collaboration in 2005

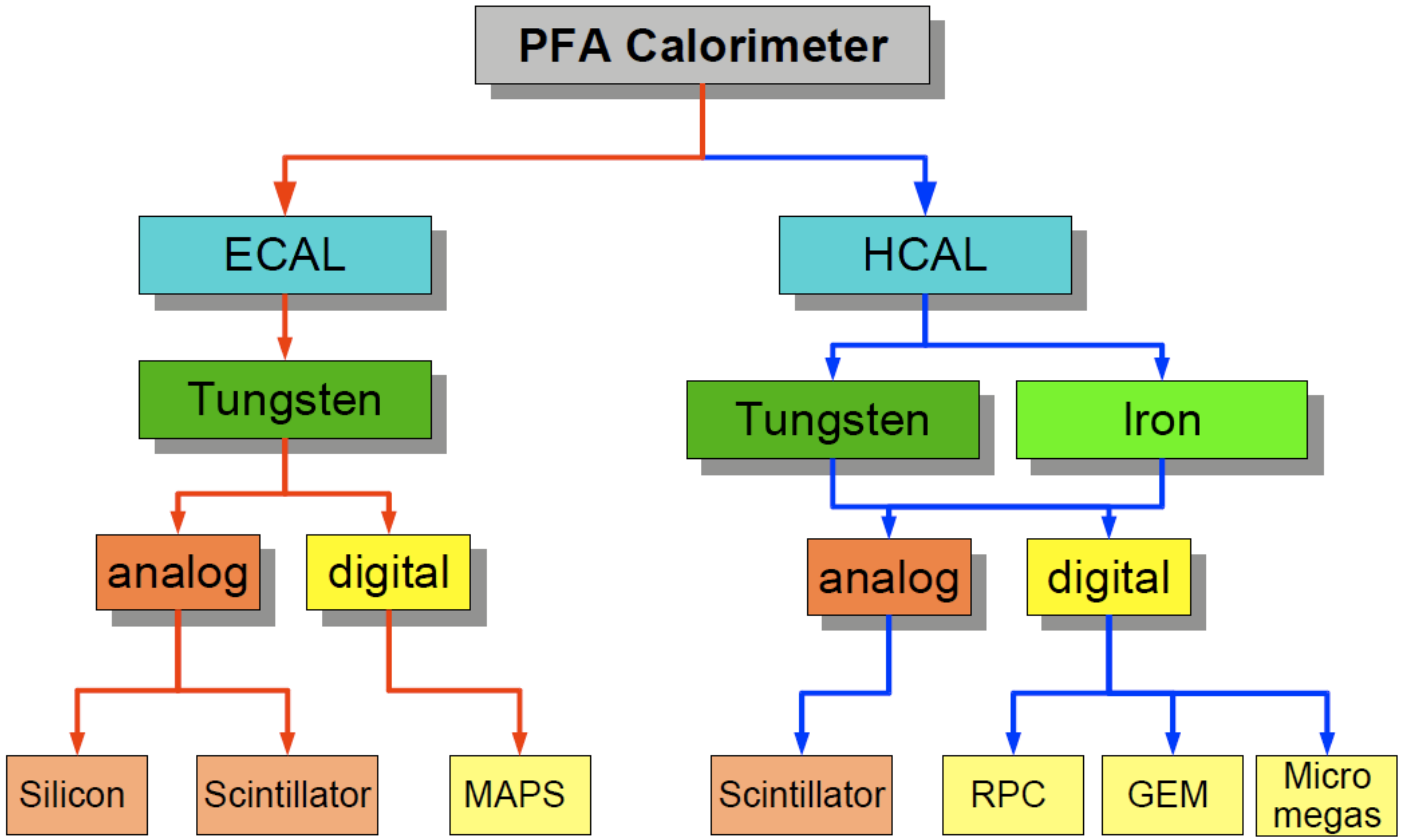
CALICE today:

- 55 institutes in 19 countries (4 continents)
- ~ 350 members

- not exclusive to linear colliders: Also groups from ALICE and with generic calorimetry interest, strong links to LHC Phase 2 Upgrades
  - … and open to new activities.

The CALICE Prototypes

- A rich program exploring the full spectrum of imaging calorimeter technologies



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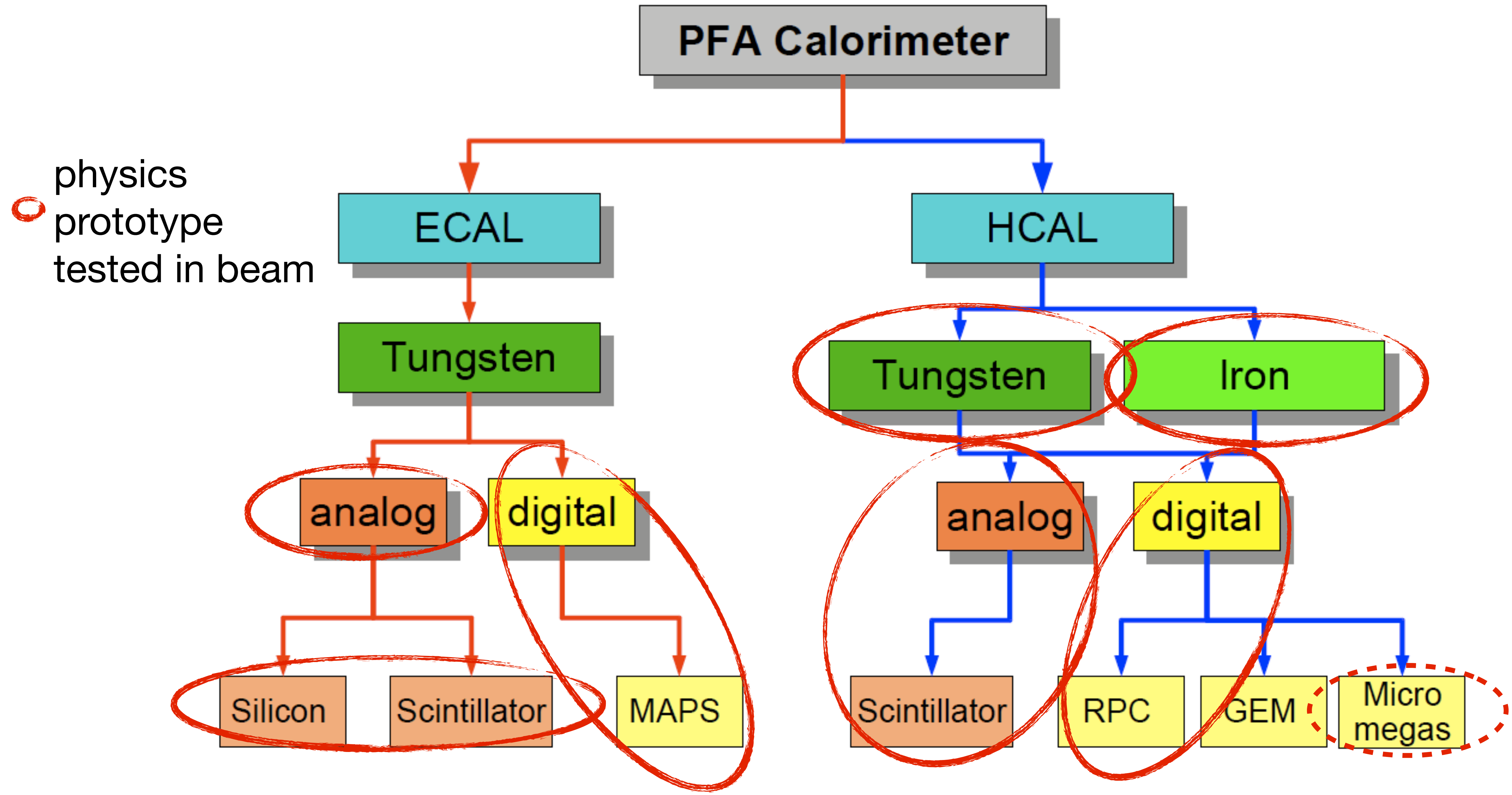
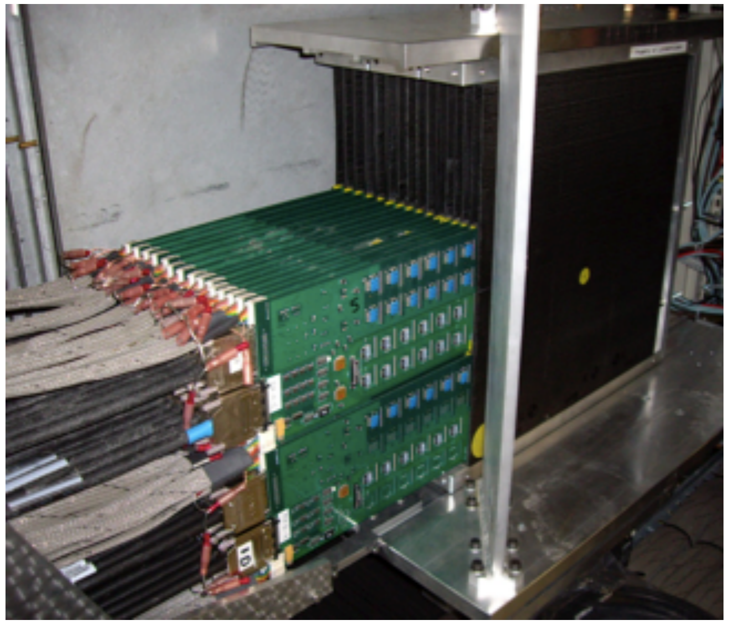
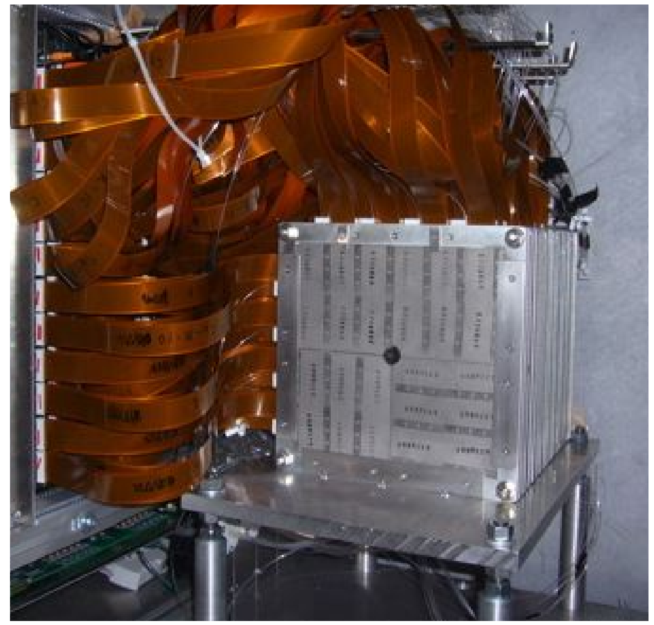


The CALICE Prototypes

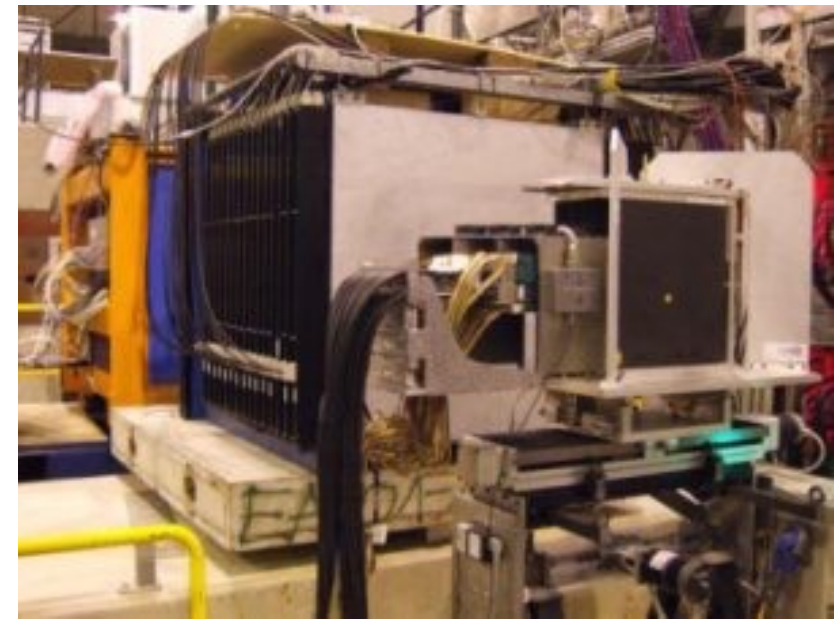
- SiW ECAL



- ScintW ECAL

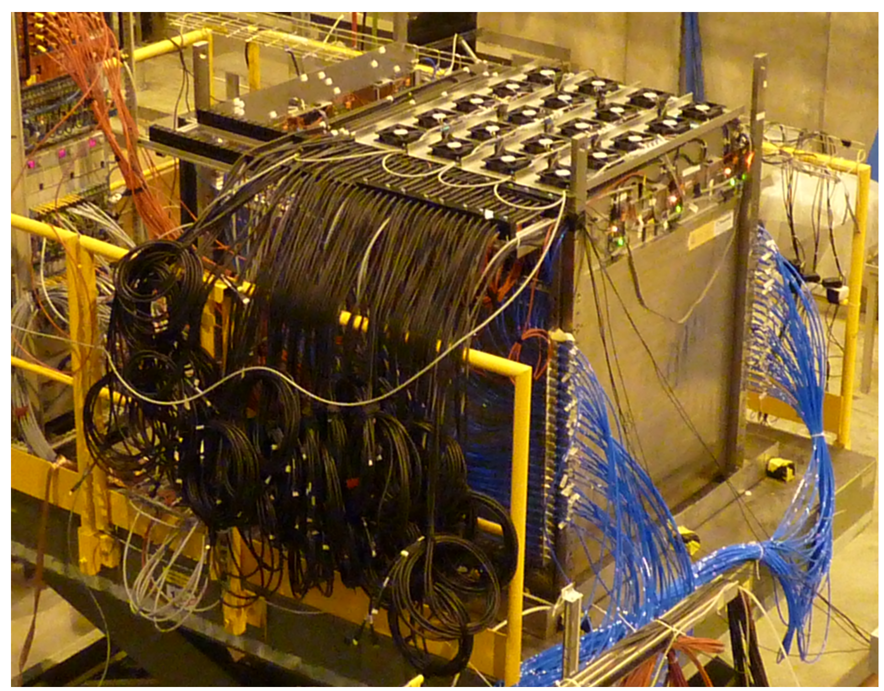


- AHCAL (Fe & W)



- DHCAL (Fe & W)

- SDHCAL



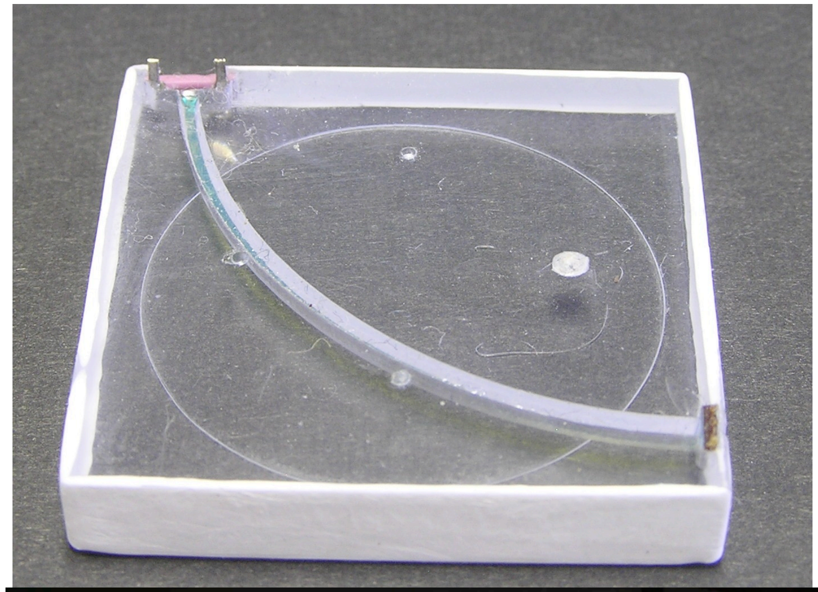
+ a few layers of Micromegas, dedicated experiments to study timing, and a few layers of technological ECAL and HCAL prototypes

The Scintillator-based Physics Prototypes

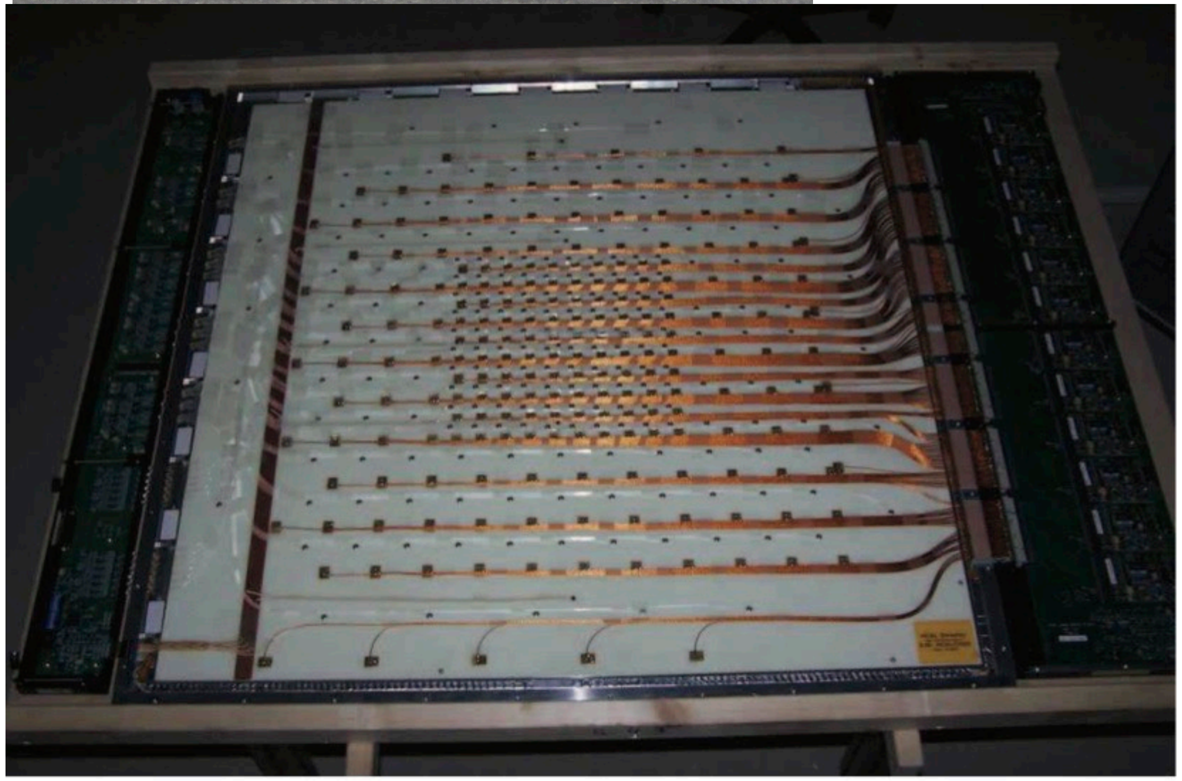
The CALICE AHCAL

- The first large scale use of SiPMs in HEP: A 8000 channel detector, first operated in beam in 2006, used in various configurations until 2011 at DESY, CERN and FNAL

JINST 5 P05004 (2010)



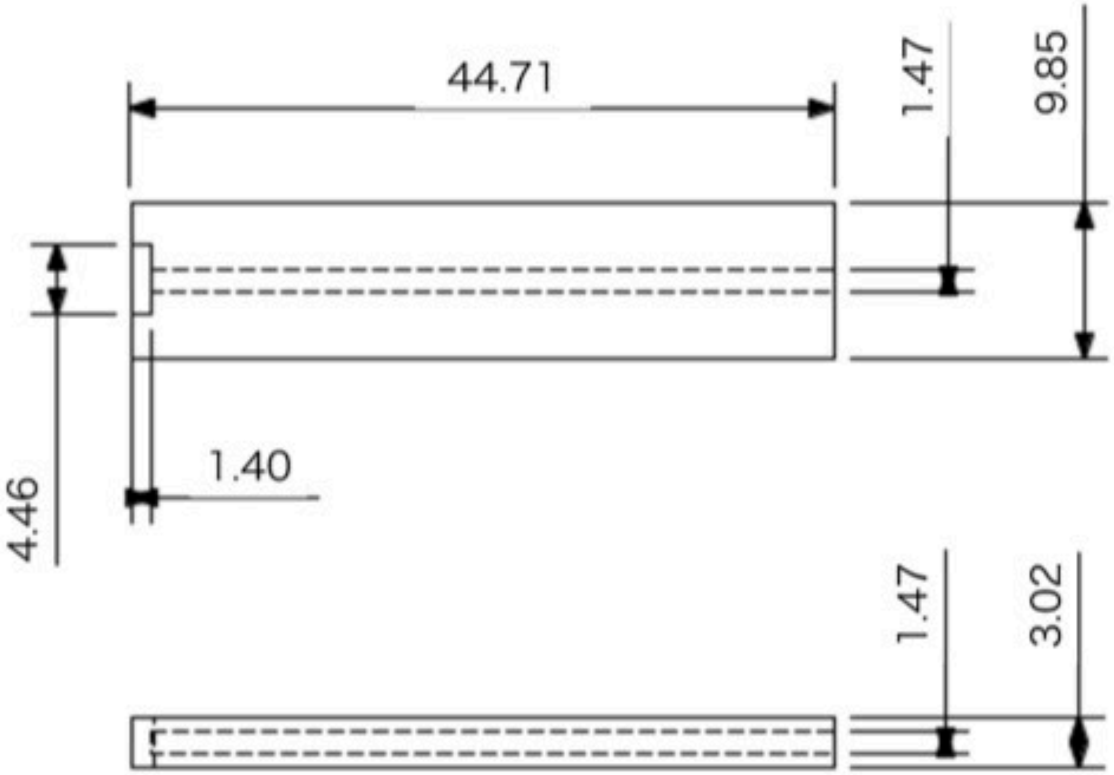
- Based on 3 x 3 x 0.5 cm^3 polystyrene scintillator tiles with WLS fiber in a machined groove (also using 6 x 6 and 12 x 12 cm^2 in outer / rear region)
- MEPhI/PULSAR SiPM, 1.1 x 1.1 mm^2, 1152 pixels (32 x 32 μm^2)



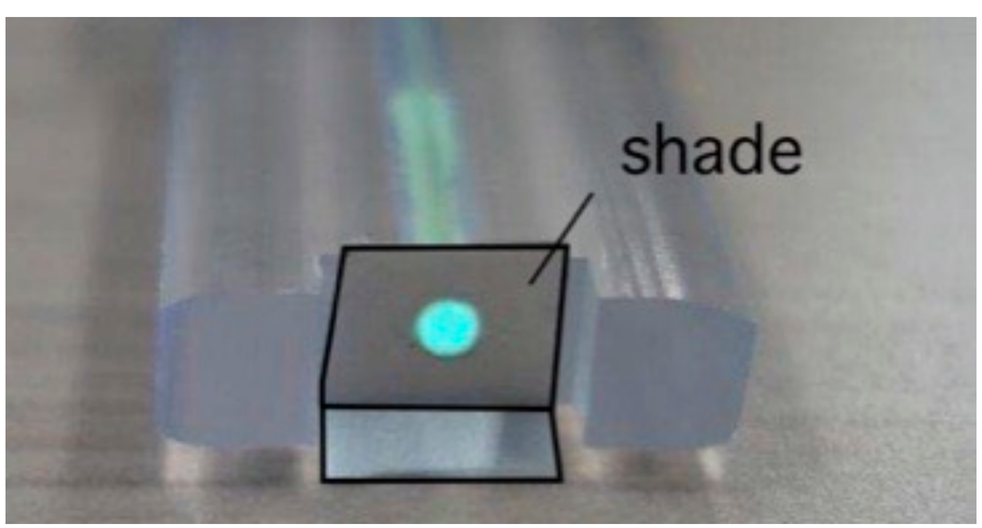
- Signals digitized with custom electronics outside of detector, connected via micro-coax cables up to 1 m long
- LED-based calibration system, UV light delivered to each tile via optical fibers from calibration board outside of detector
- 21.7 mm steel absorber per layer (~ 1 X_0)

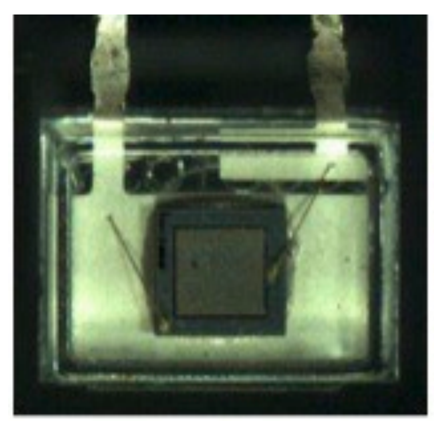
The CALICE Scintillator ECAL

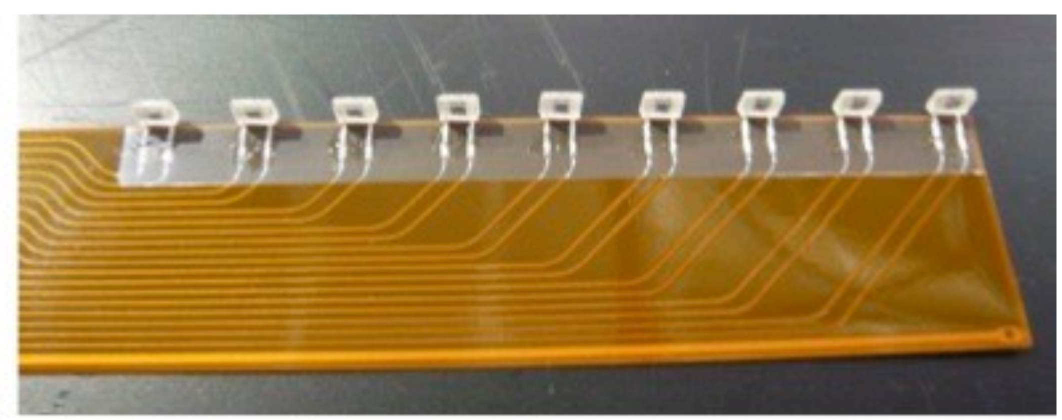
- Scintillator-Strip ECAL - with 3.5 mm thick Tungsten Carbide absorber plates (~ 0.7 X_0)
- Operated at Fermilab in 2009, together with CALICE AHCAL



- Extruded PS scintillator strips with embedded WLS fiber
- Hamamatsu MPPC, equivalent of S10362-11-25P
- crossed strip orientation in adjacent layers, effective 1 x 1 cm^2 granularity

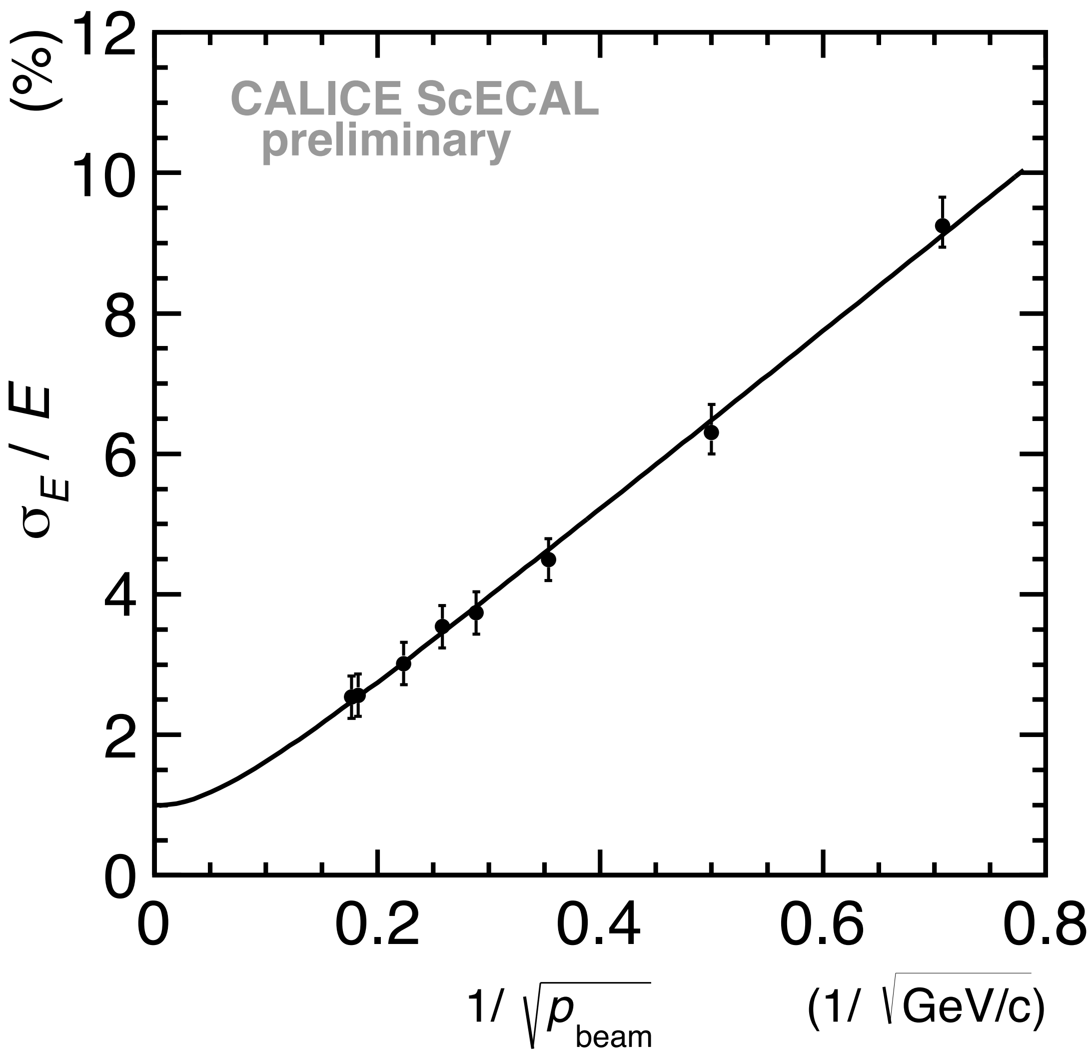






A rich Harvest - Performance and Shower Physics

- Energy resolution (electromagnetic)
  - NB: Optimized on granularity / shower separation rather than single particle resolution



- Linear within ~ 1.5 %
- Energy resolution $12.8\%/\sqrt{E} \oplus 1.0\%$

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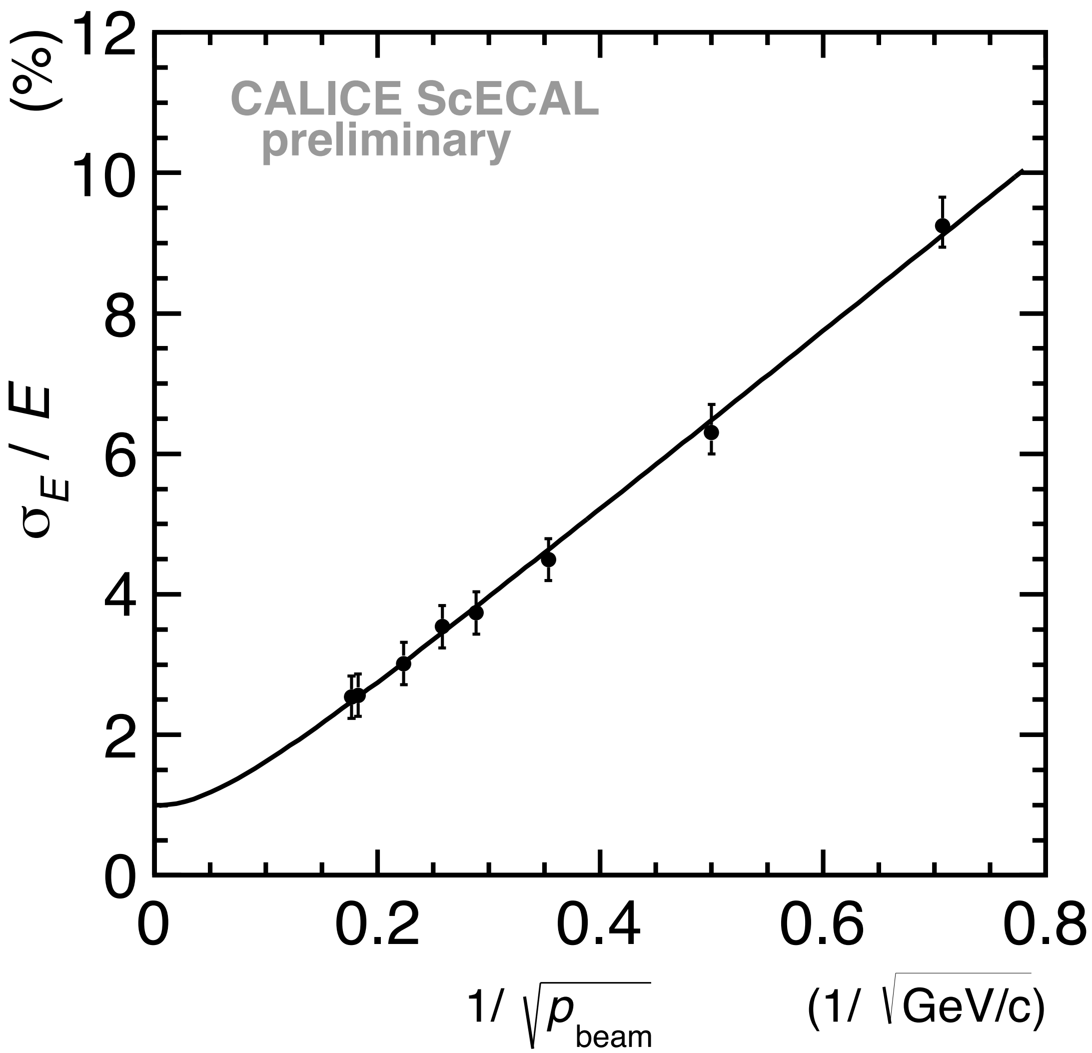
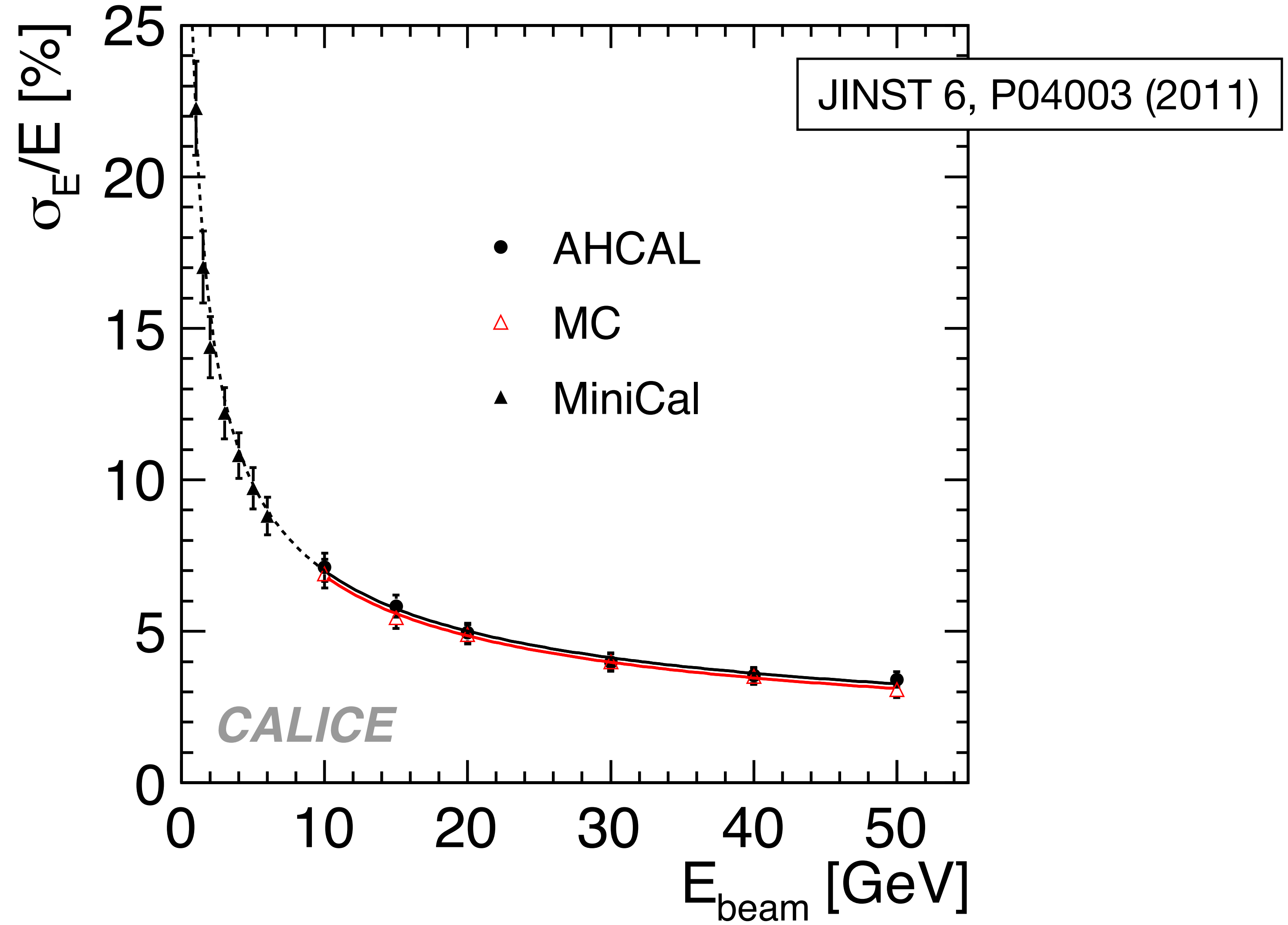


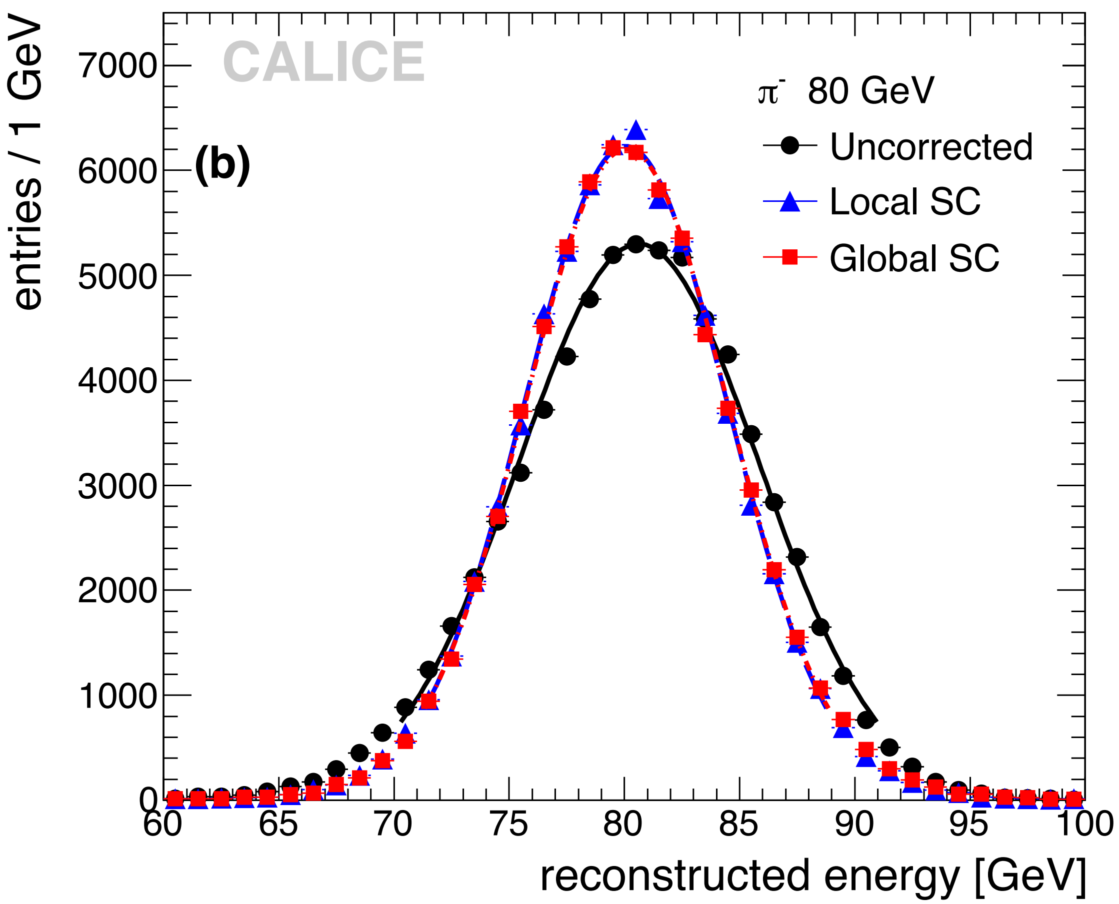


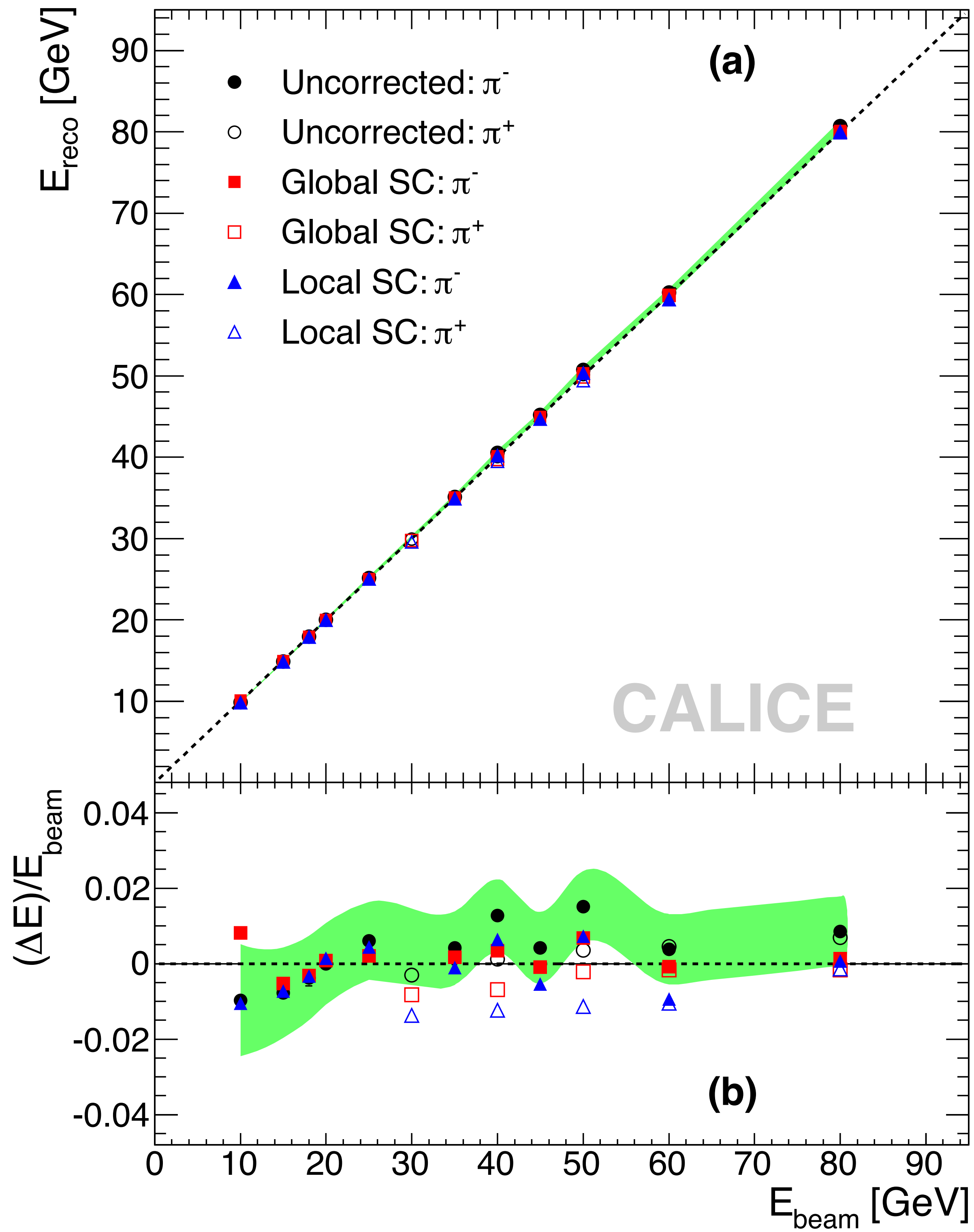
- Linear within ~ 1.5 %
- Energy resolution 12.8%/√E ⊕ 1.0%

- Linear within ~ 1 % up to 30 GeV
- Energy resolution 21.9%/√E ⊕ 1.0%

Hadronic Energy Reconstruction

- Linear energy response of AHCAL + TCMT: within ± 1.5%
- High granularity allows software compensation: Use shower density to correct for different response to em and purely hadronic showers





JINST 7, P09017 (2012)

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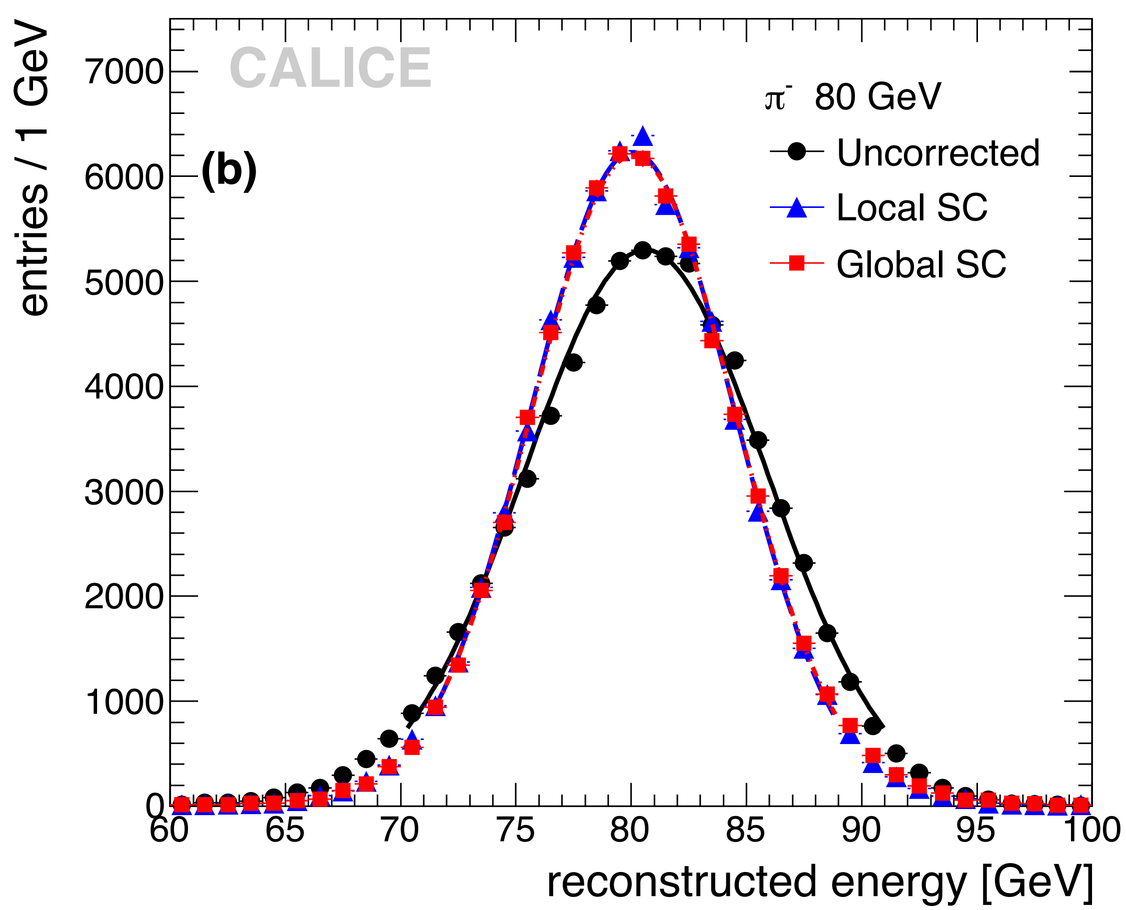

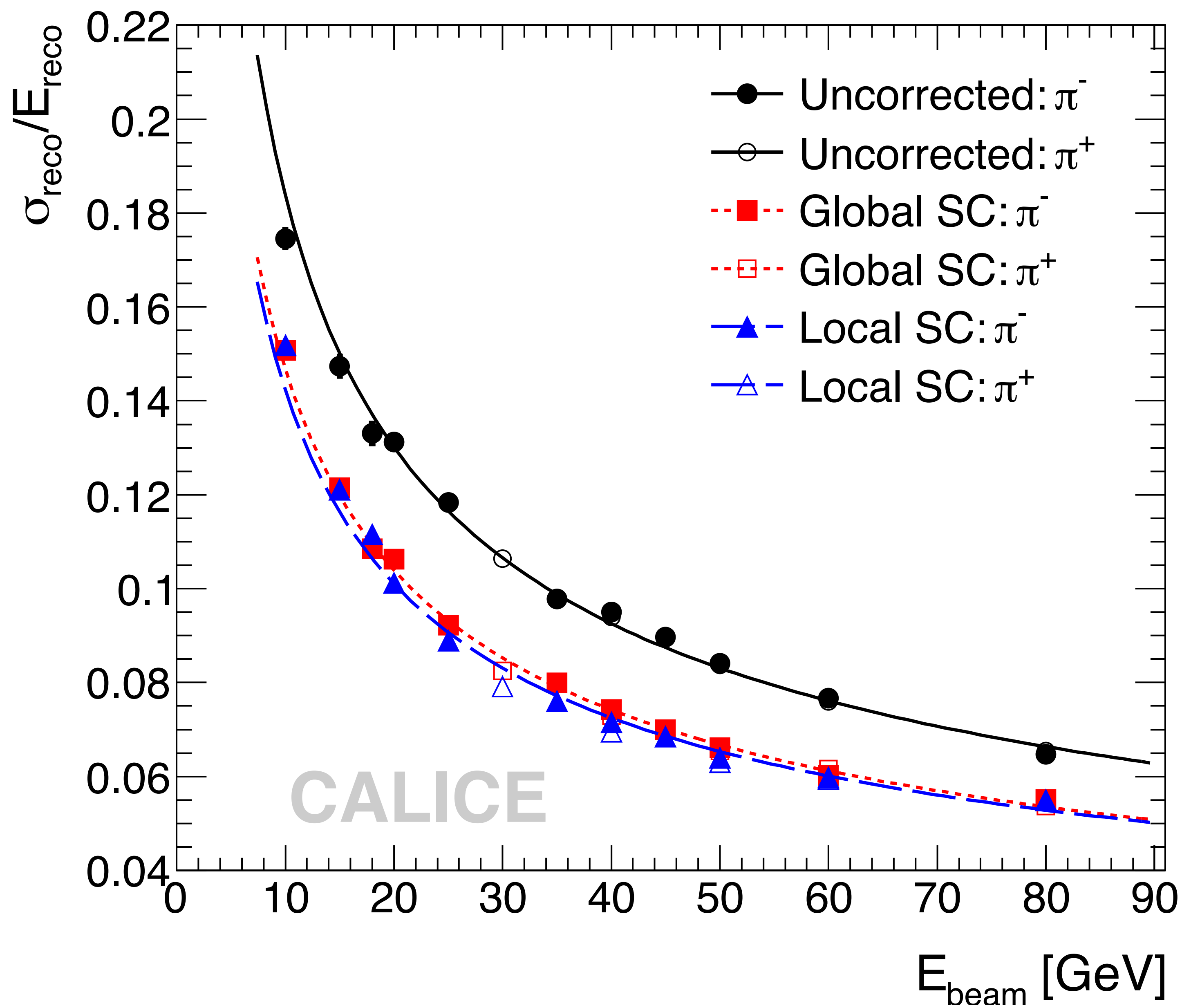

Excellent energy resolution:
$45\%/\sqrt{E} \oplus 1.8\%$

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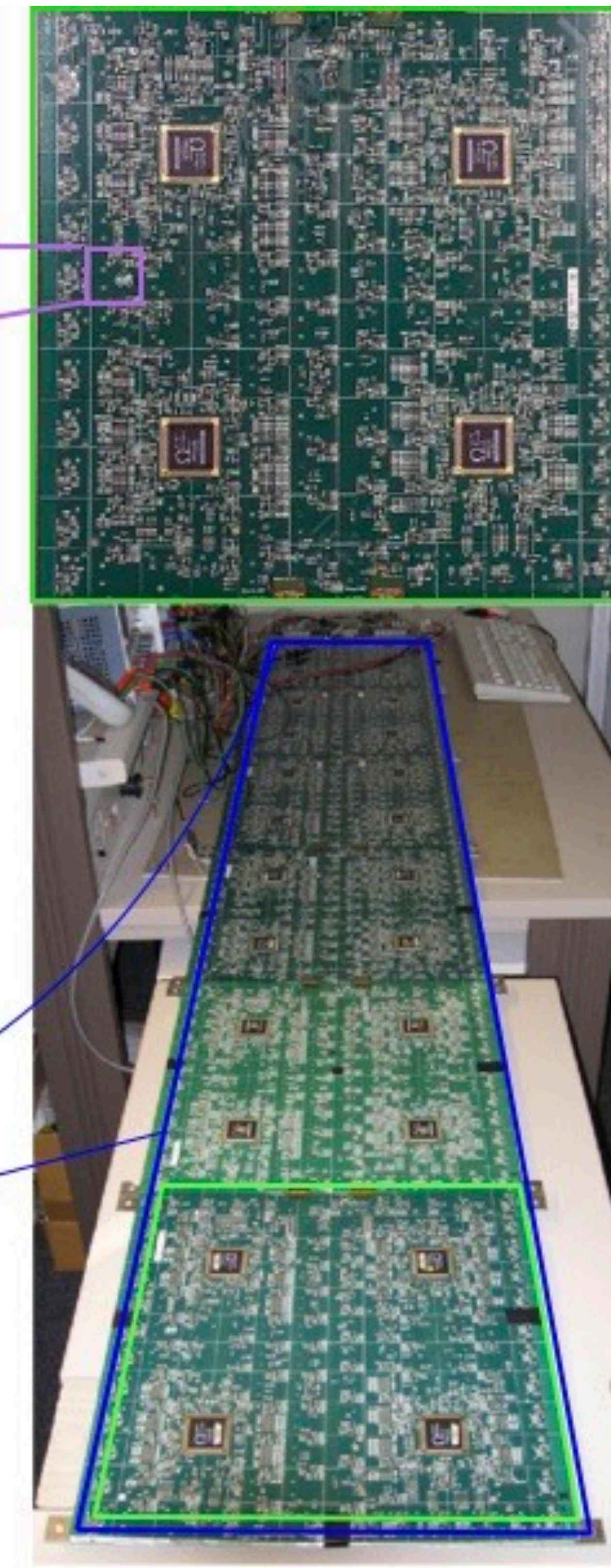
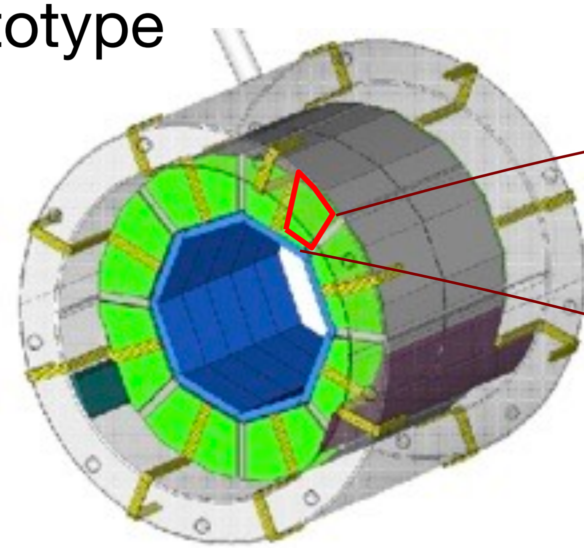
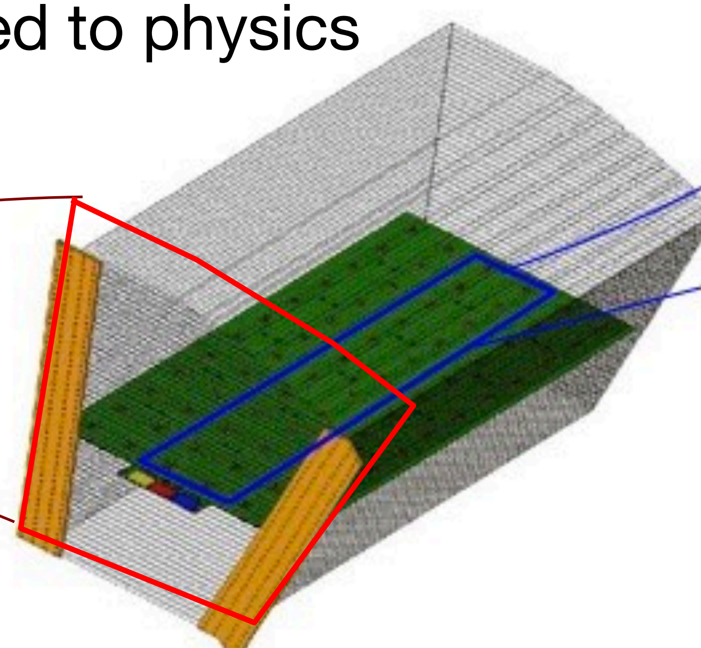
The AHCAL Technical Prototype - A Closer Look

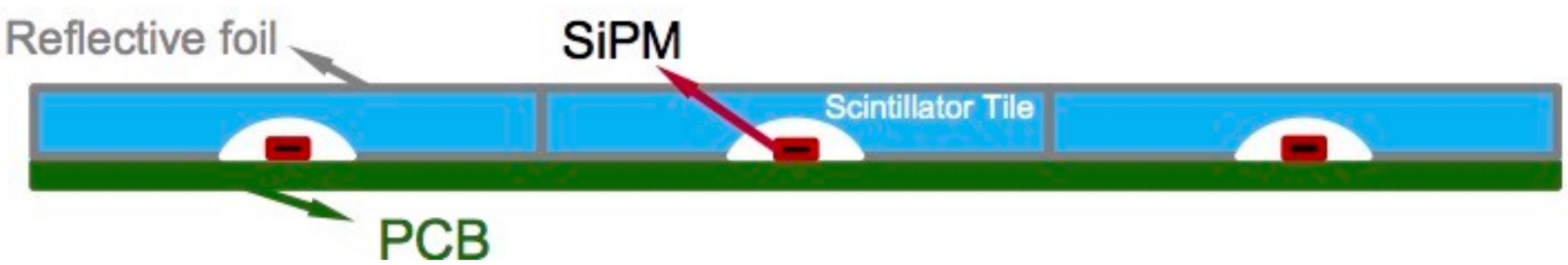
- CERN
- DESY
- University Hamburg
- University Heidelberg
- University Mainz
- MPP Munich
- Lebedev Moscow
- Omega Palaiseau
- Prague
- University Wuppertal

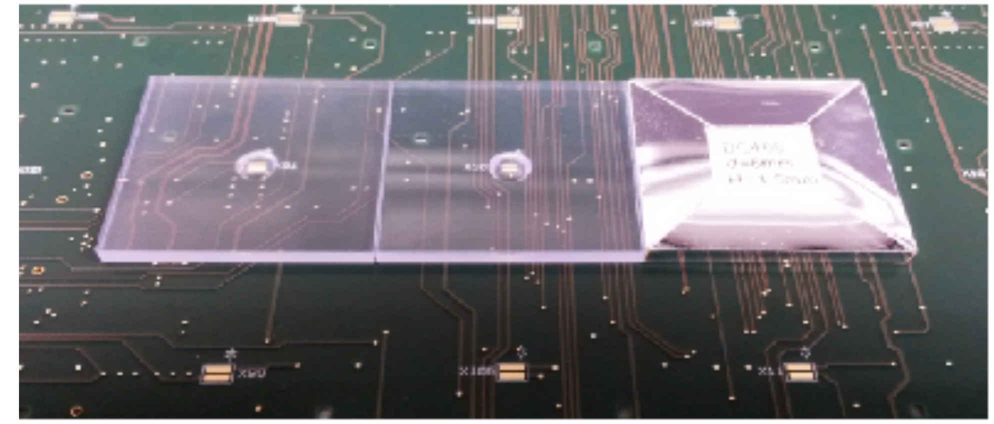
Overall Detector Concept

- Sandwich calorimeter based on scintillator tiles (3x3cm^2) readout using Silicon Photomultipliers (SiPM)
- Fully integrated electronics
- HCAL Base Unit (HBU): 36x36cm^2,
    - 144 channels readout by 4 ASIC chips
- In total 8M channels (full collider detector), challenge for data concentration
- Technological prototype: demonstrate scalability to full detector
- Improvement in all aspects compared to physics prototype

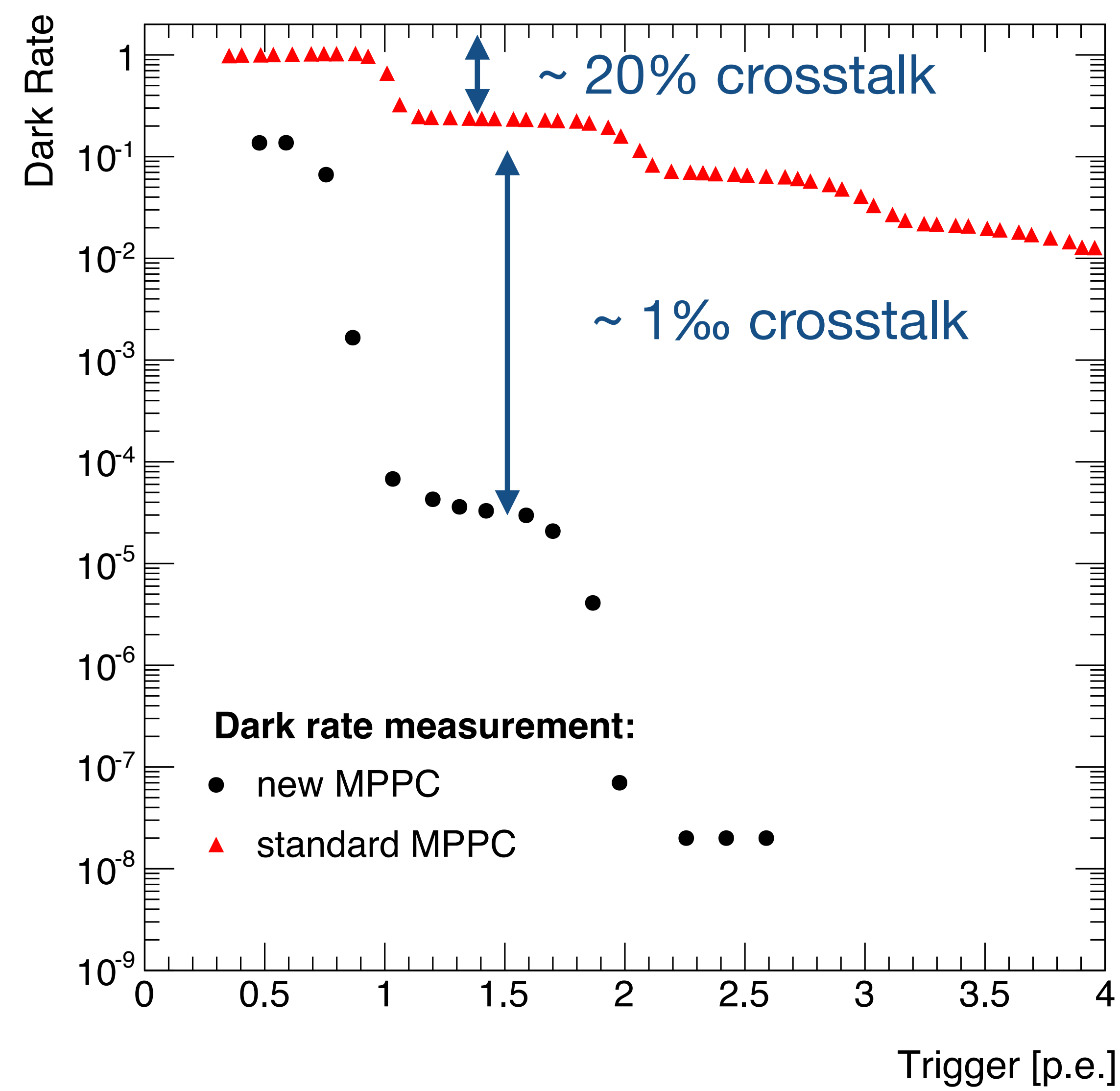





Technological Choices





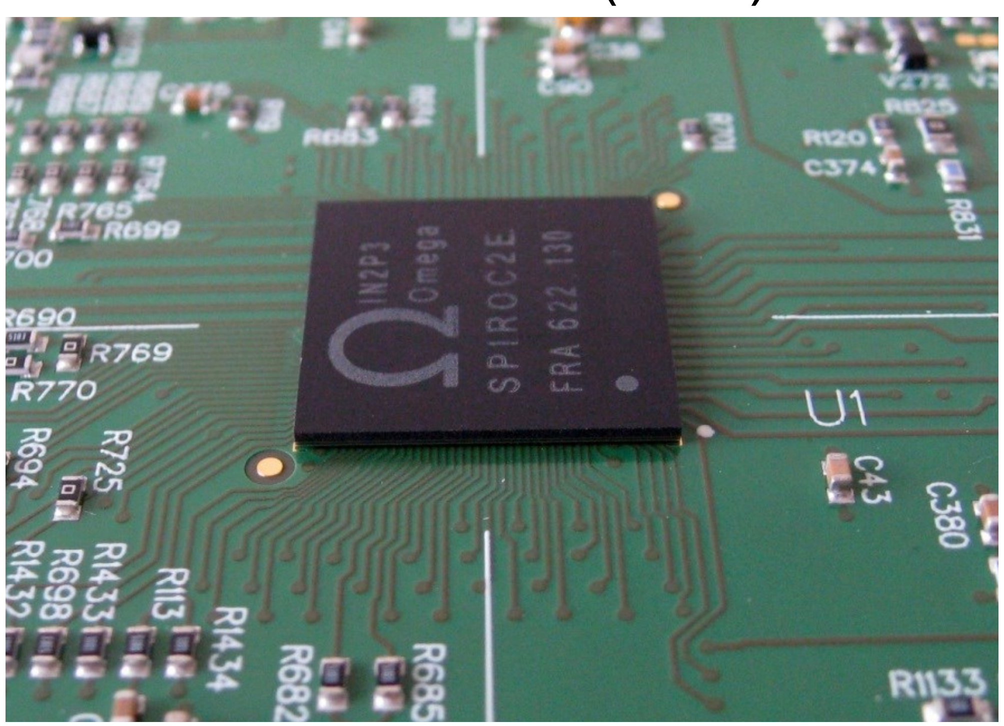
- Current SiPMs are blue-sensitive: No need for WLS fiber (apart from light collection)
- Latest generation available in SMD package: coupling from bottom rather than from the side
- Latest generation of MPPCs has very effective cross-talk suppression: Full auto-triggered system possible for light yields of ~ 15 photons / MIP
  - In technological prototype: MPPC S13360-1325PE
  - Very good device-to-device uniformity: power full modules with one bias voltage setting



Electronics

- Fully integrated electronics for mass production
  - Latest generation read-out ASIC SPIROC2E (OMEGA group, Palaiseau) successfully tested, interesting developments also in Heidelberg (KLauS chip)
  - reduced power consumption and many improvements
- BGA package of ASIC leads to significant PCB cost reduction and easier soldering
- HBU designed for surface mounted SiPMs & suitable for automated tile assembly
- LED driver circuit improved channel uniformity: minimise time for test and calibration runs

HCAL Base Unit (HBU)



The Prototype - Different Configurations

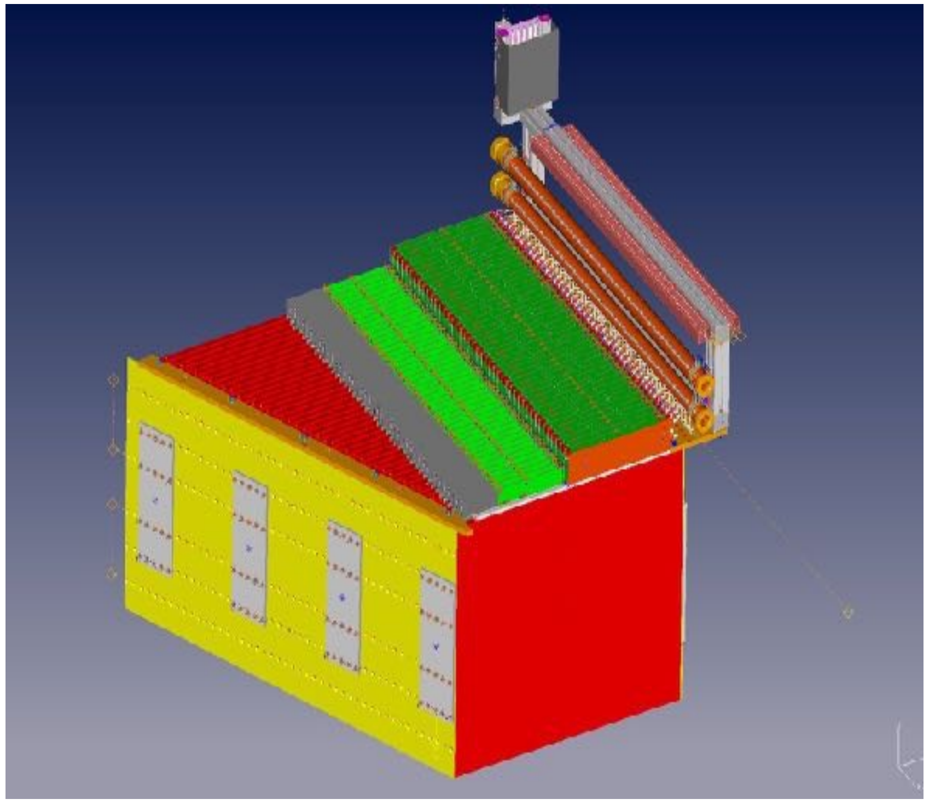
Single HBU - 144 channels

- component tests
- assembly procedures
- magnetic field test
- commissioning

15 layer "em prototype",
1 HBU / layer - 2k channels

- electromagnetic & hadronic showers
- particle showers in magnetic field up to 3 T
- system integration, cooling, power

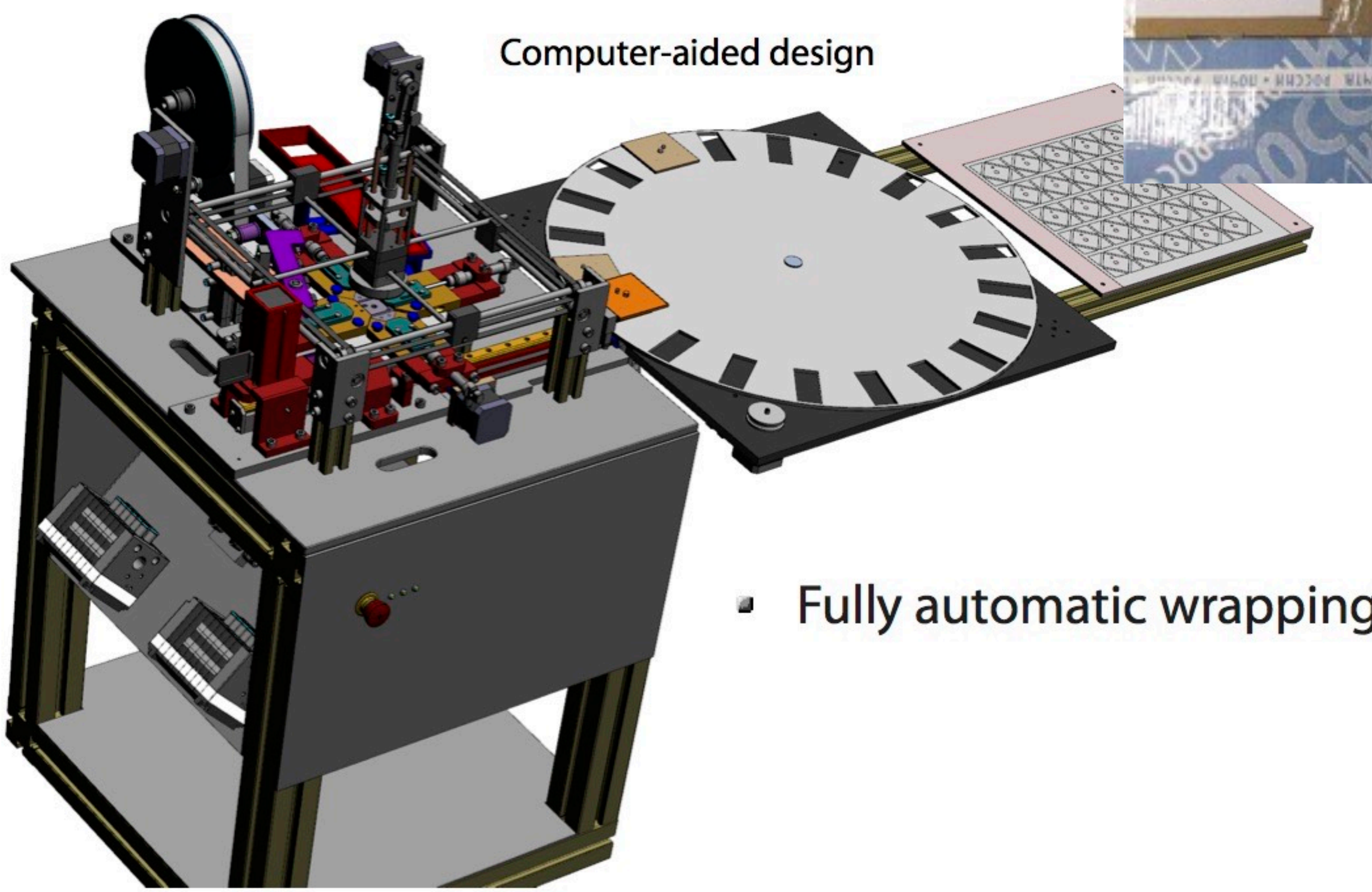
40 - 48 layer "em prototype",
2 x 2 HBUs / layer - 23k - 30k channels



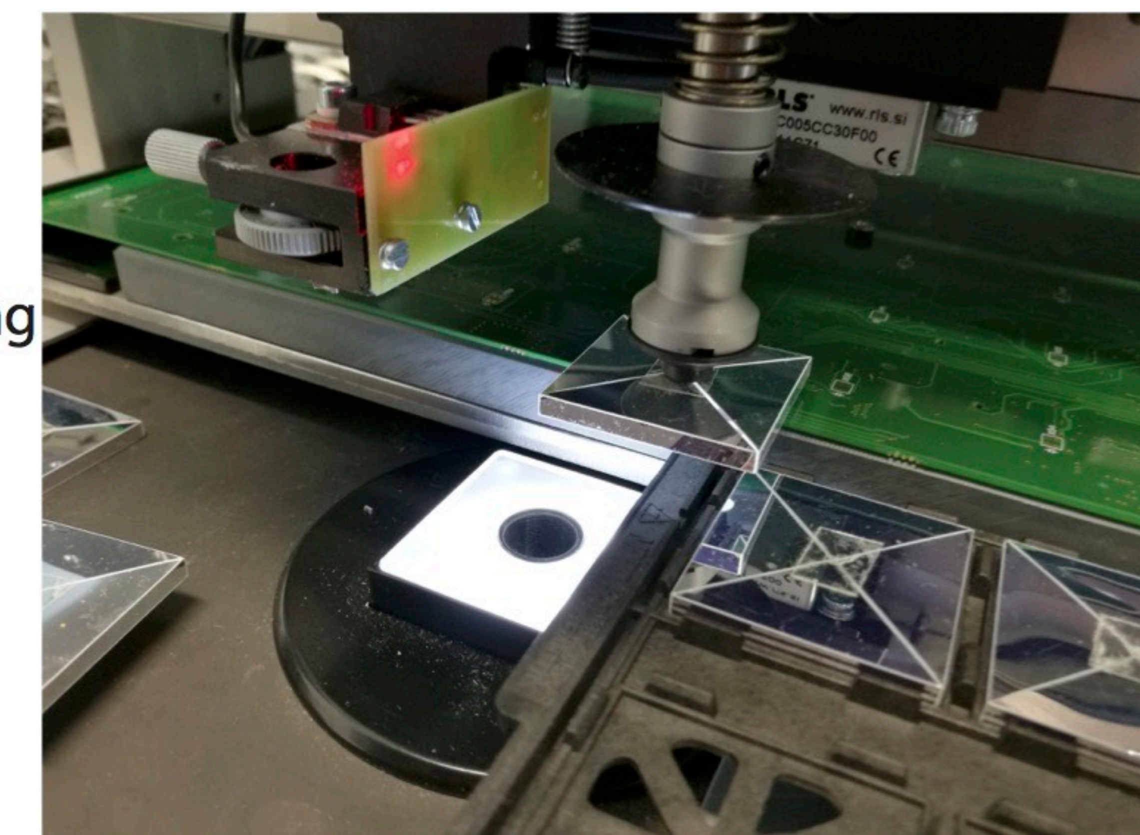
- full containment of hadronic showers
- large-scale production, integration, operation
- scalability to full detector
- rich physics program

Working with large Numbers

- 28 000 scintillator tiles for TP produced in Russia, now delivered to Hamburg
- Automatic wrapping in development



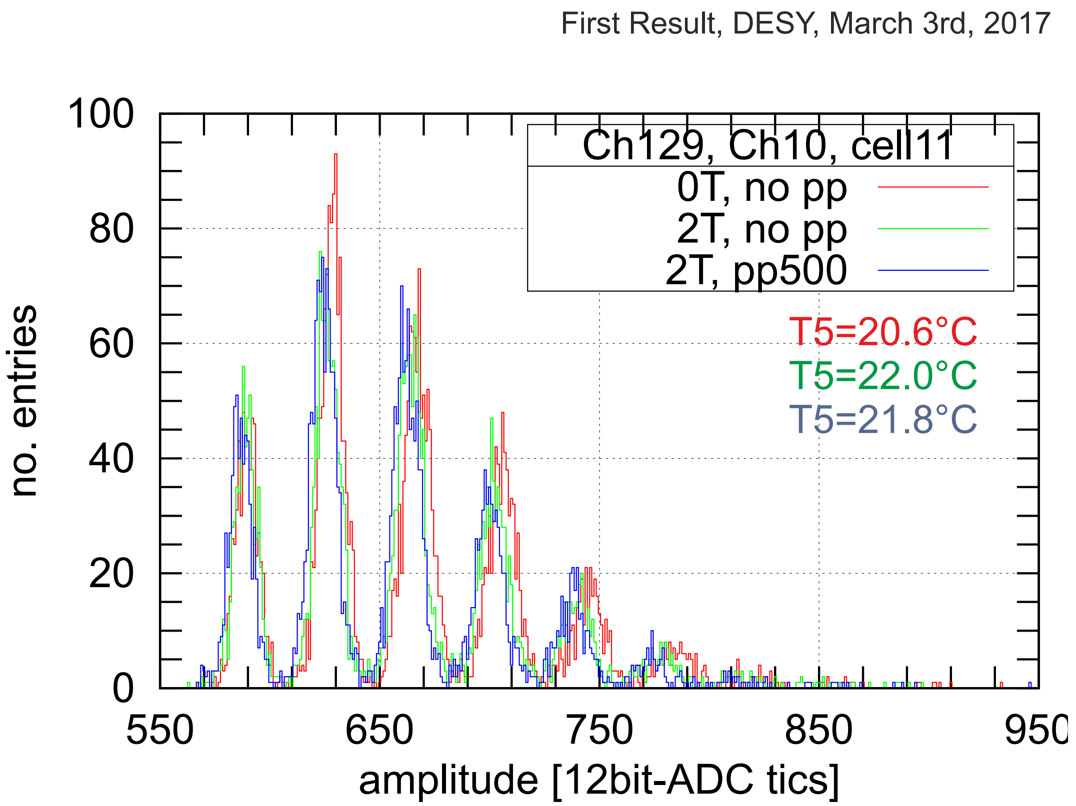
- Placement and gluing of tiles on electronics with pick-and-place machine



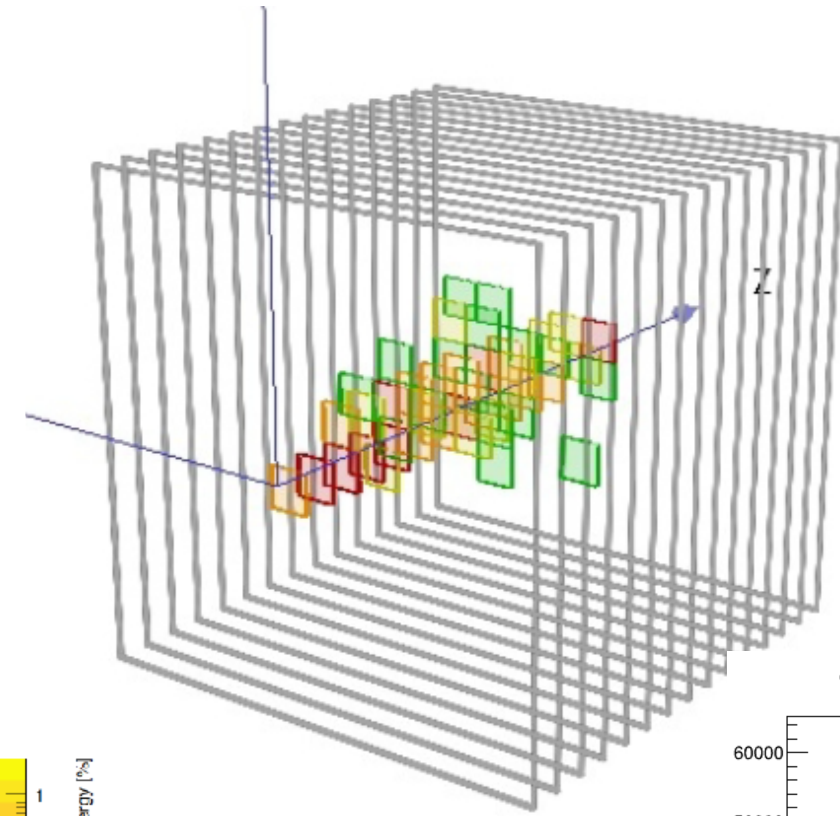
First Results - Beam, Magnetic Field

- Fully equipped HBUs have already been tested in up to 2T - also with power pulsing

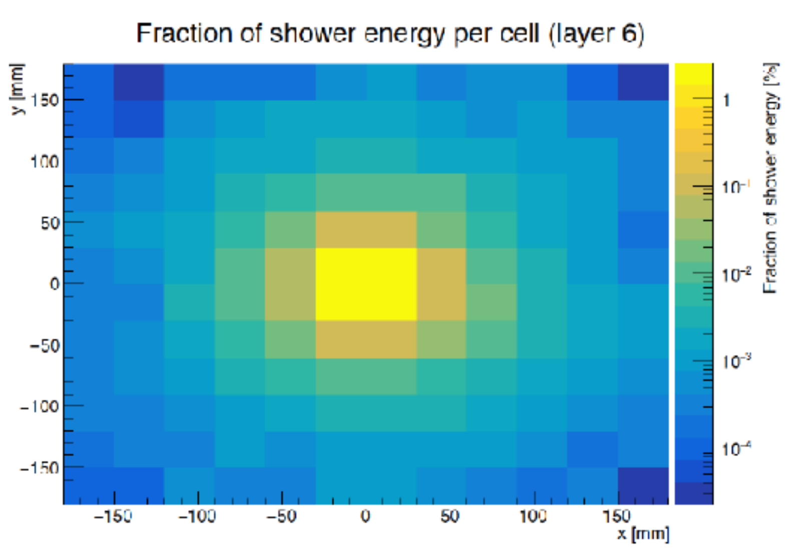
HBU5_BGA test in 2T magnetic field



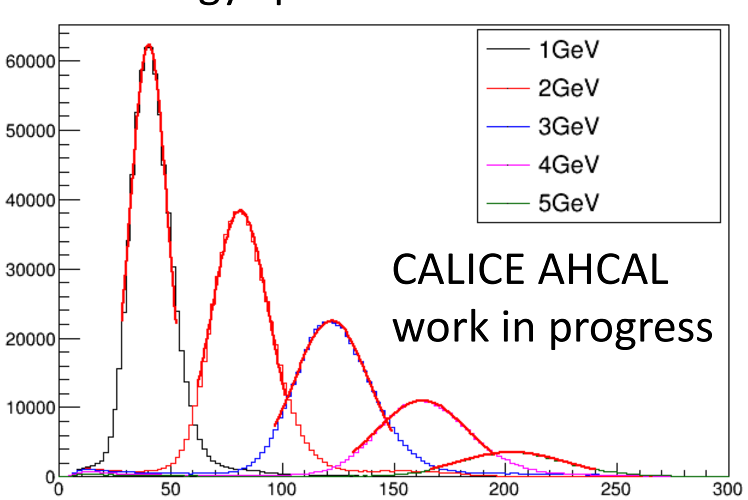
Test w/o beam; beam test with multiple layers in 3T coming up in May at CERN SPS



Beam test at DESY, previous electronics / tile design (side coupling)

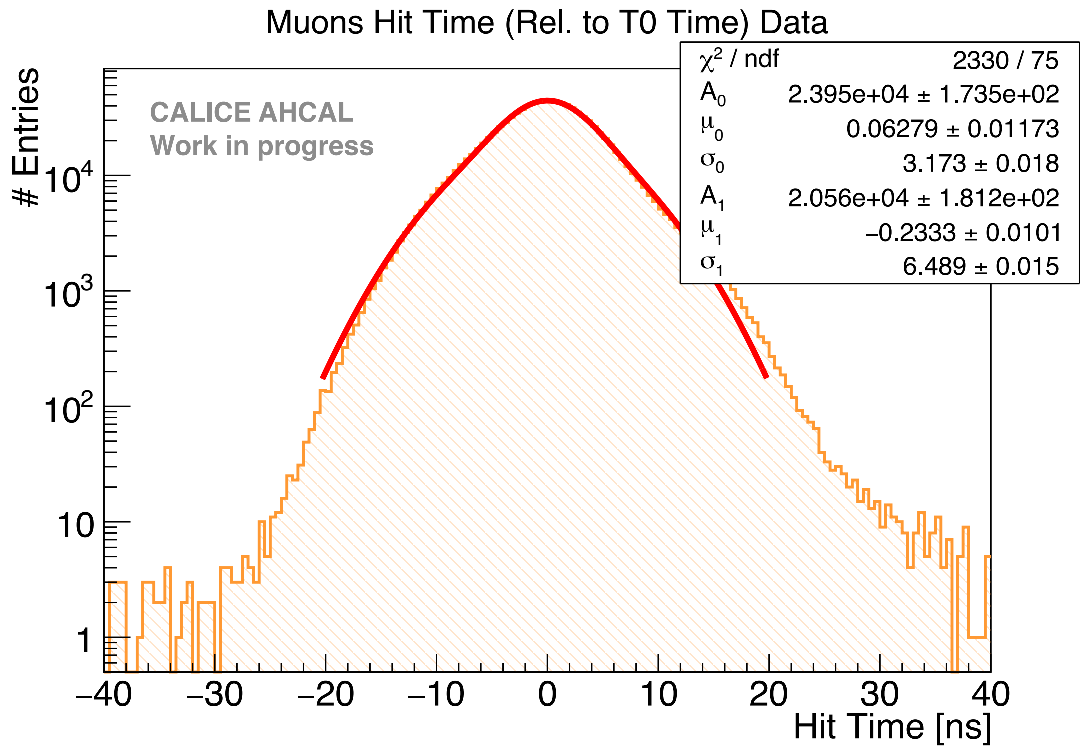


energy spectrum for 1-5 GeV



A Word on Timing

- CALICE AHCAL electronics provide capability for sub-ns timing - in “standard” test beam environment operated with x 20 slower TDC ramp, reduced resolution



- Single cell resolution for MIP-like amplitudes ~ 5.5 ns in test beam mode - obtained at CERN SPS with 80 GeV muons
  - Somewhat worse resolution in showers due to electronics problem - presumably fixed in new generation, will know more in a few months

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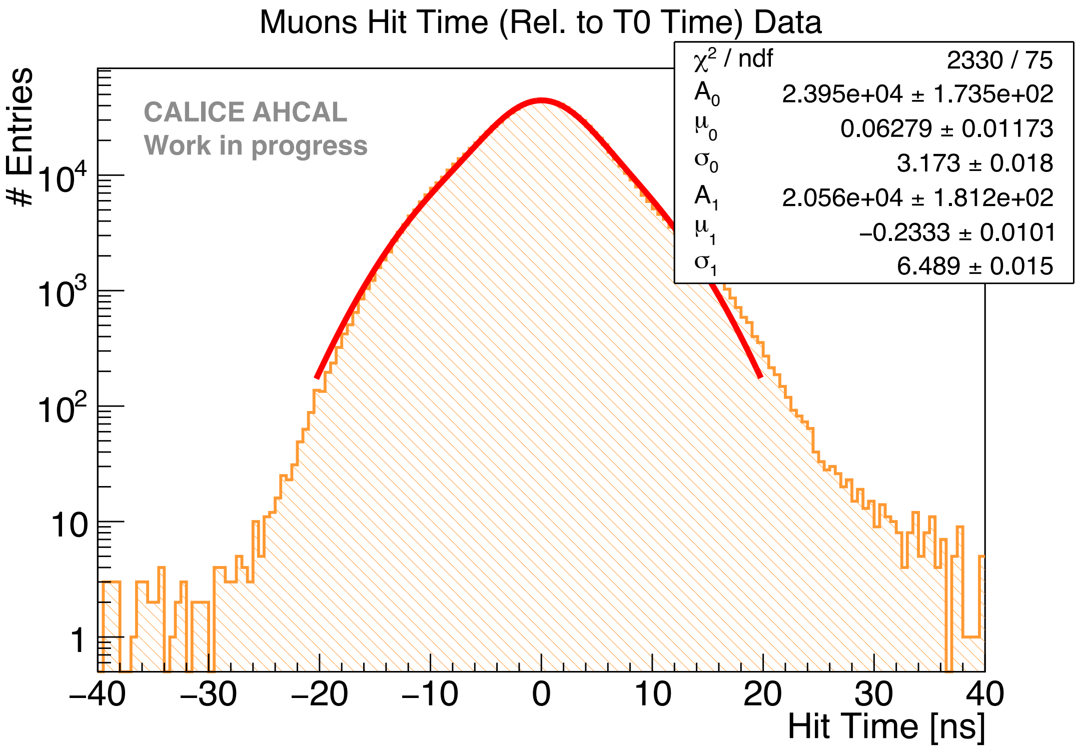

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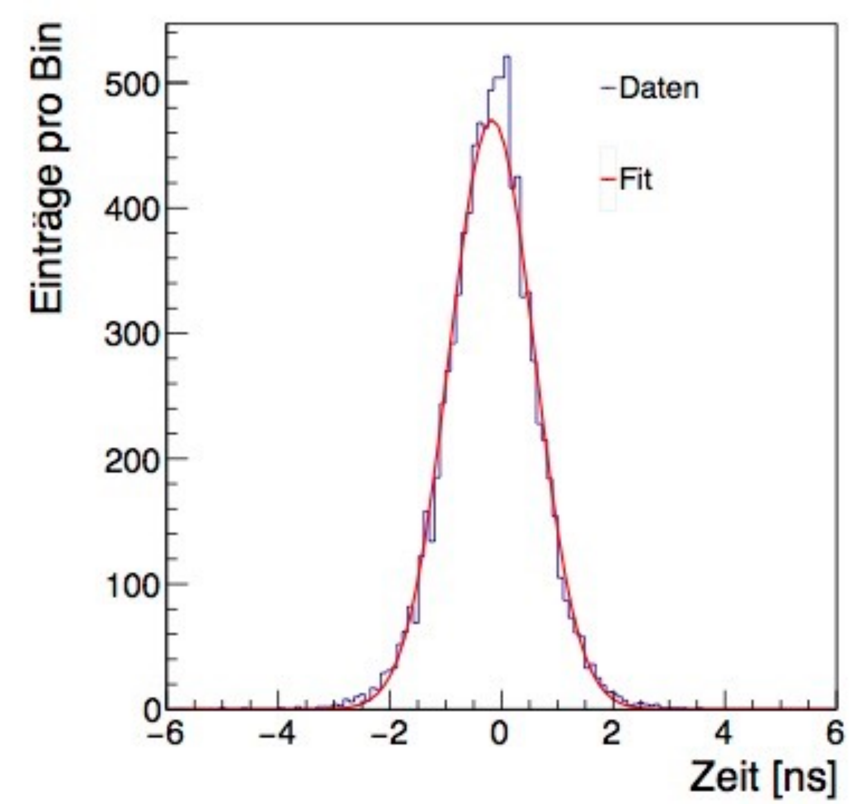
- Tested single scintillator tiles with SMD MPPCs read out with oscilloscope with 0.8 ns sampling (CALICE “spin-off” used in SuperKEKB commissioning)
  - Δt ~ 0.8 ns for two-tile setup: ~ 500 ps single tile resolution for MIPs (including oscilloscope sampling)



Simulating the AHCAL - Focus on Digitization

- Simulation plays a key role in CALICE:
  - Demonstrates understanding of detectors with em showers
  - Enables comparison to / validation & improvement of G4 hadronic physics models
  - Crucial for studies of full detector performance, development of algorithms,…

- Precise modeling of a highly granular SiPM-based calorimeter needs multiple steps:
  - raw calibration: G4 Energy -> MIP
  - timing cuts to model electronics / analysis time windows
  - single cell amplitude thresholds
  - light yield: number of fired pixels / MIP
  - number of pixels per SiPM: saturation effects
  - electronic noise, pixel-to-pixel non-uniformity

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Raw SimHits

+ timing

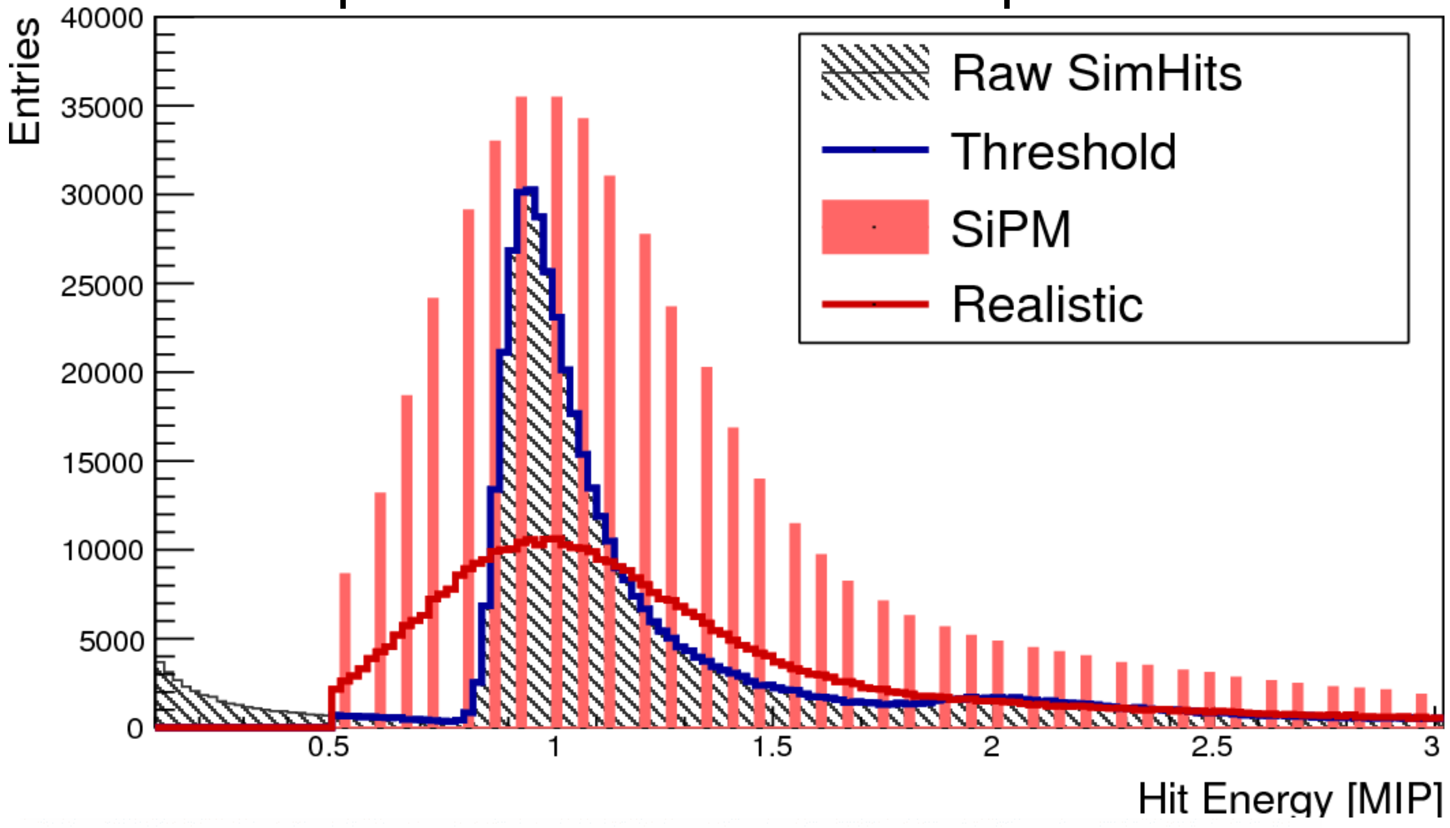
+ threshold

+ SiPM

realistic

Simulating the AHCAL - Focus on Digitization

- The impact of the different steps on the raw signal:



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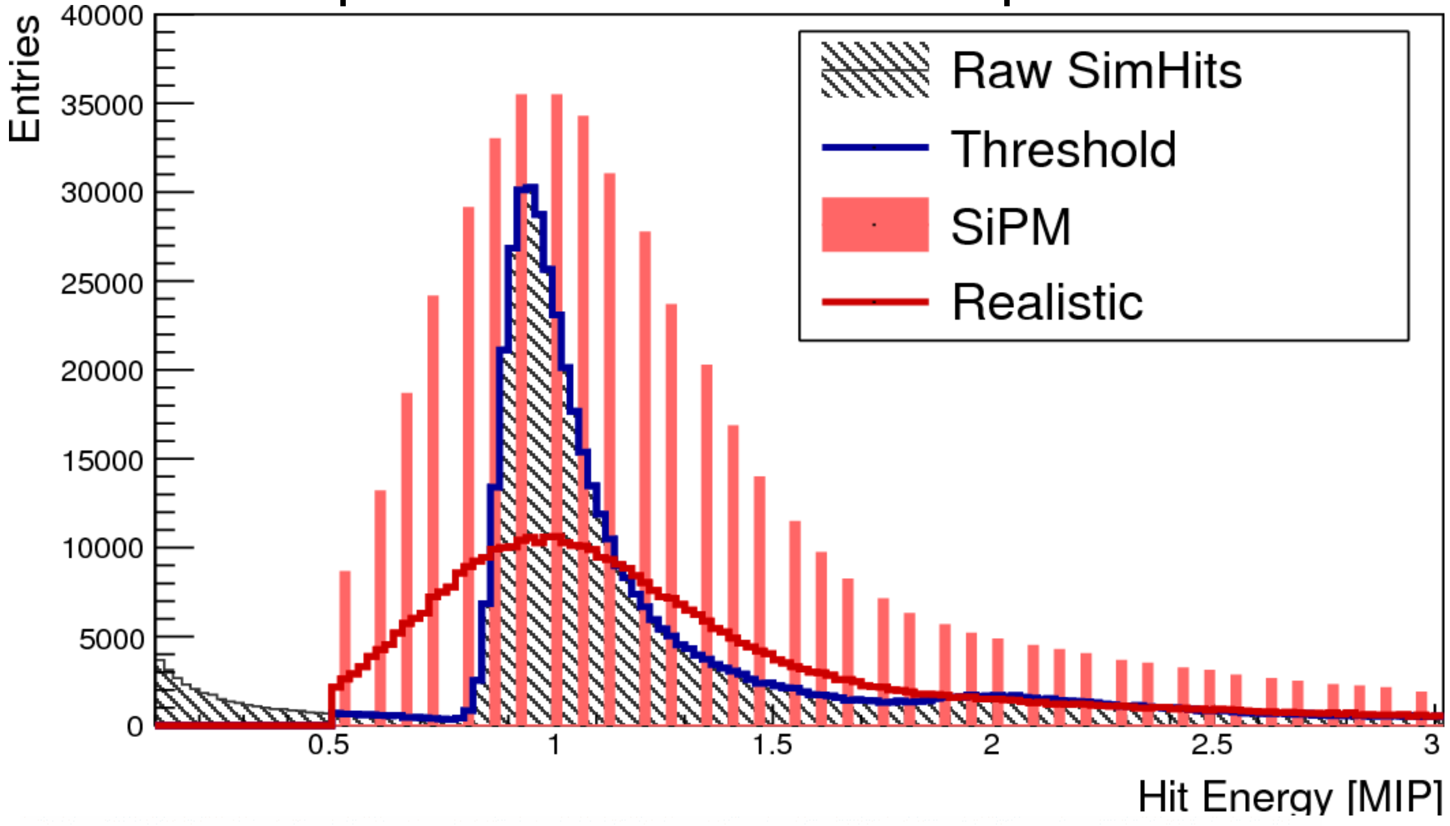

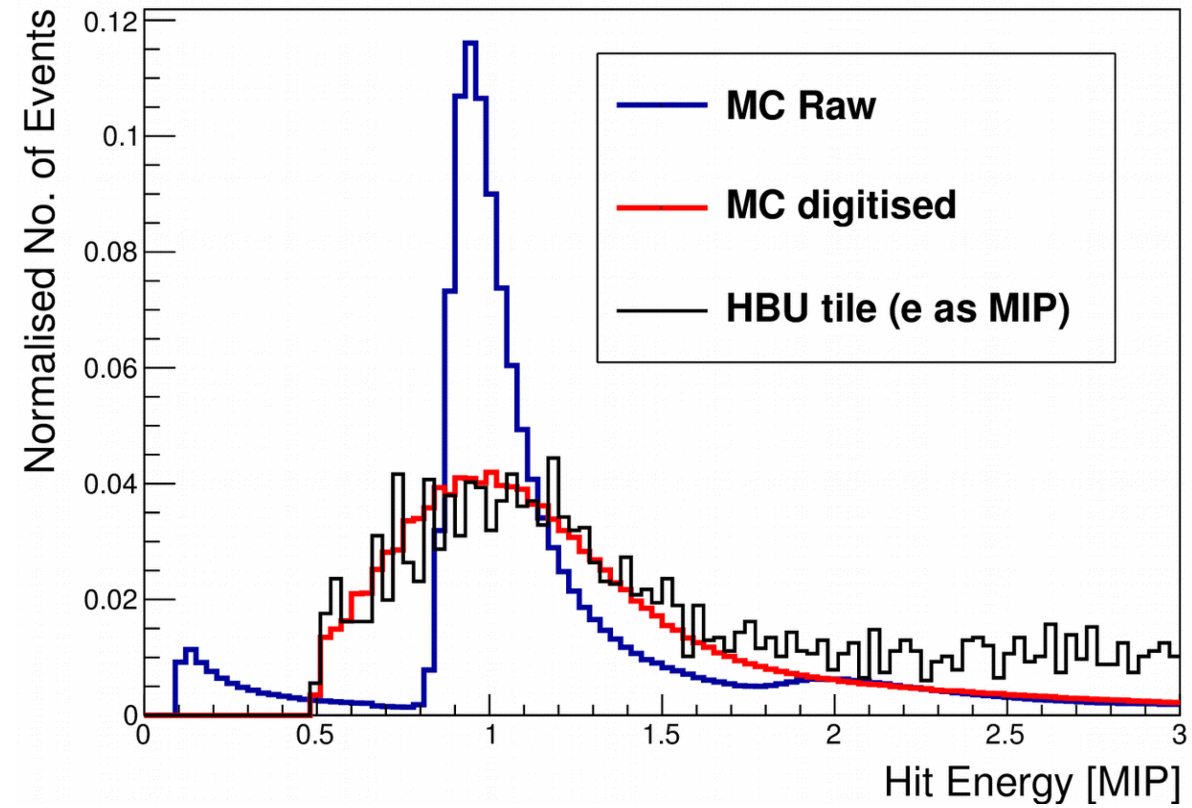

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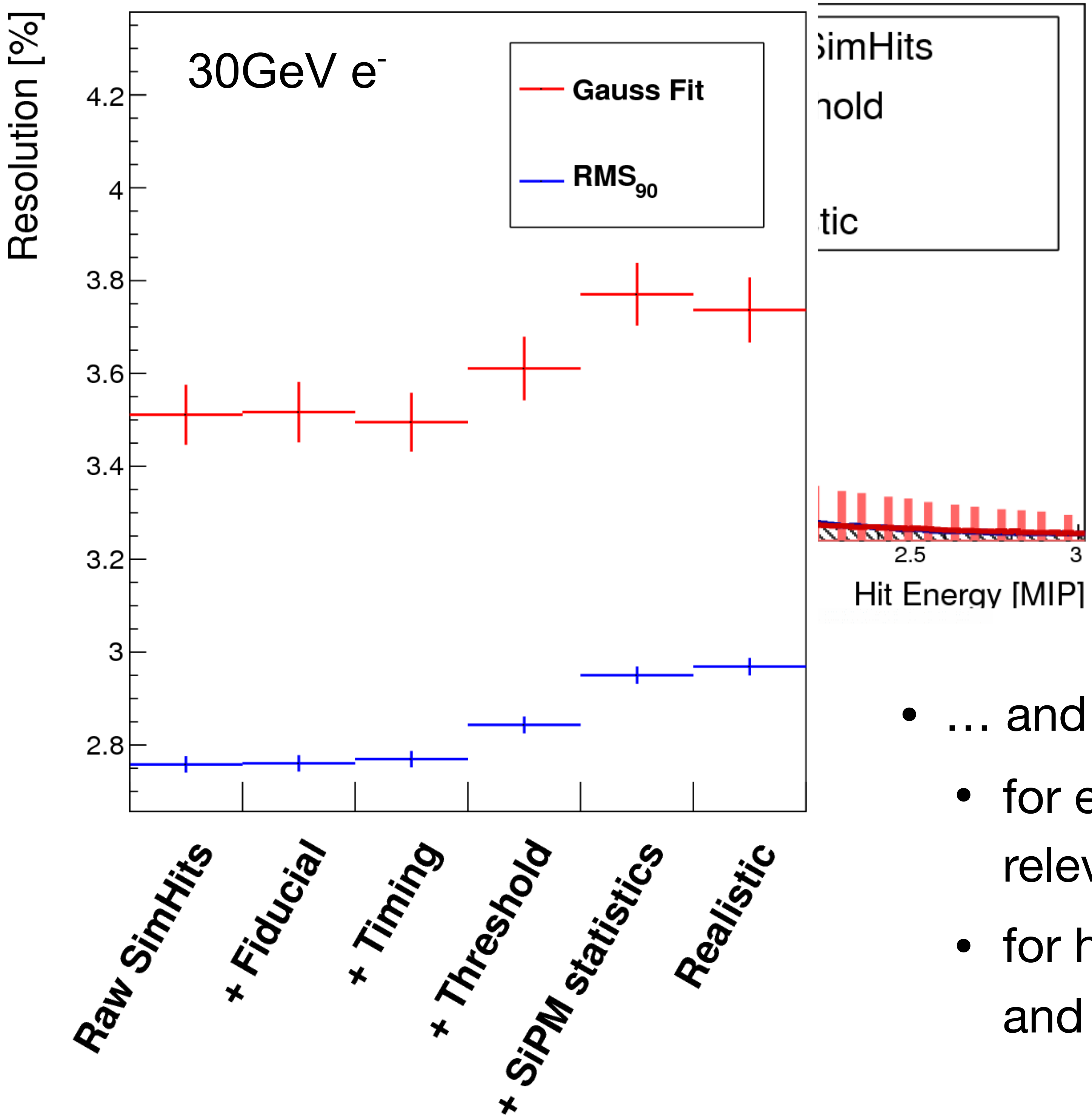

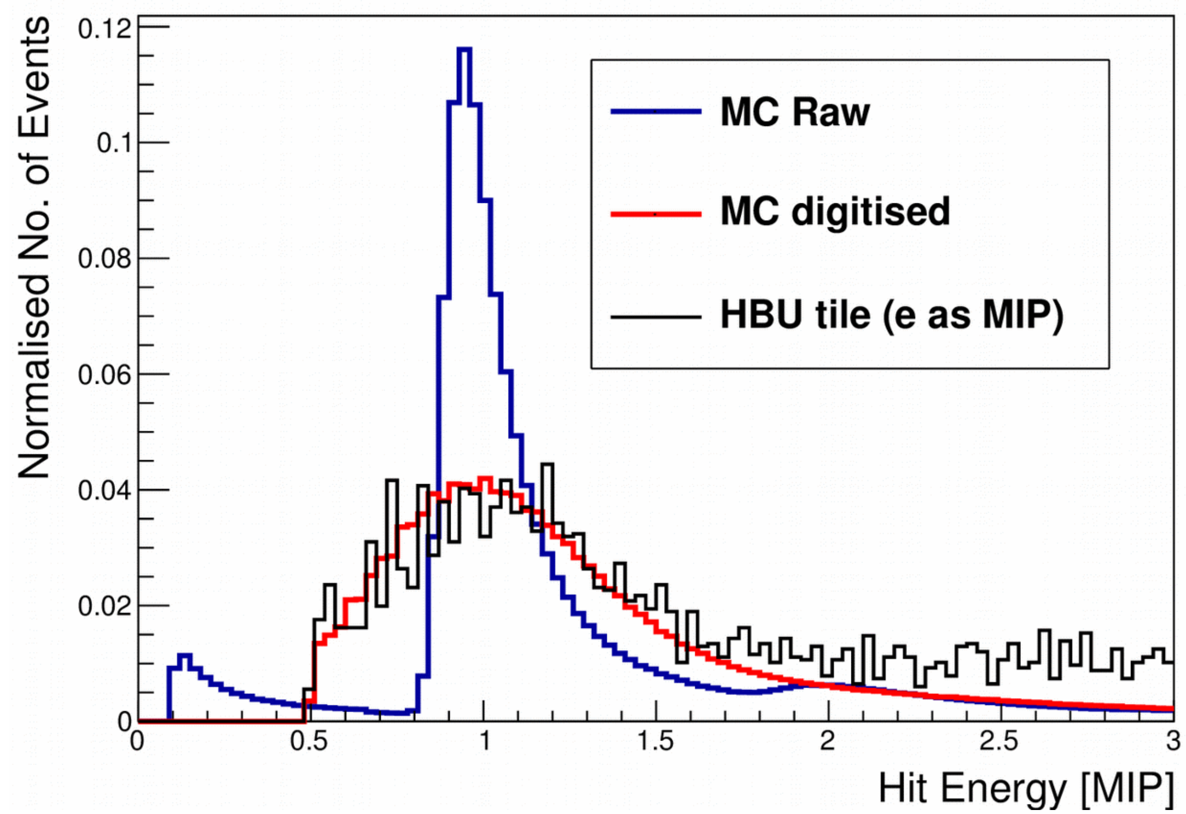

- … and the consequence on resolution
  - for em showers, threshold and SiPM most relevant - effects grow with energy
  - for hadronic showers fiducial volume, timing and thresholds main drivers

Scintillator Readout Schemes beyond Baseline

- Alternatives to individually wrapped tiles are also being explored:
  - megatiles - larger plates optically separated into square tiles

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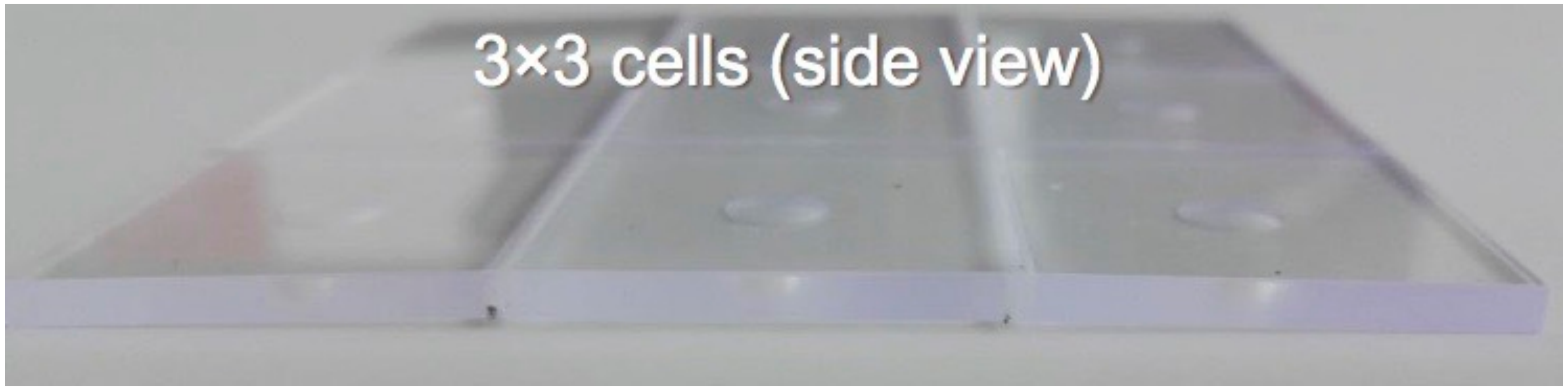
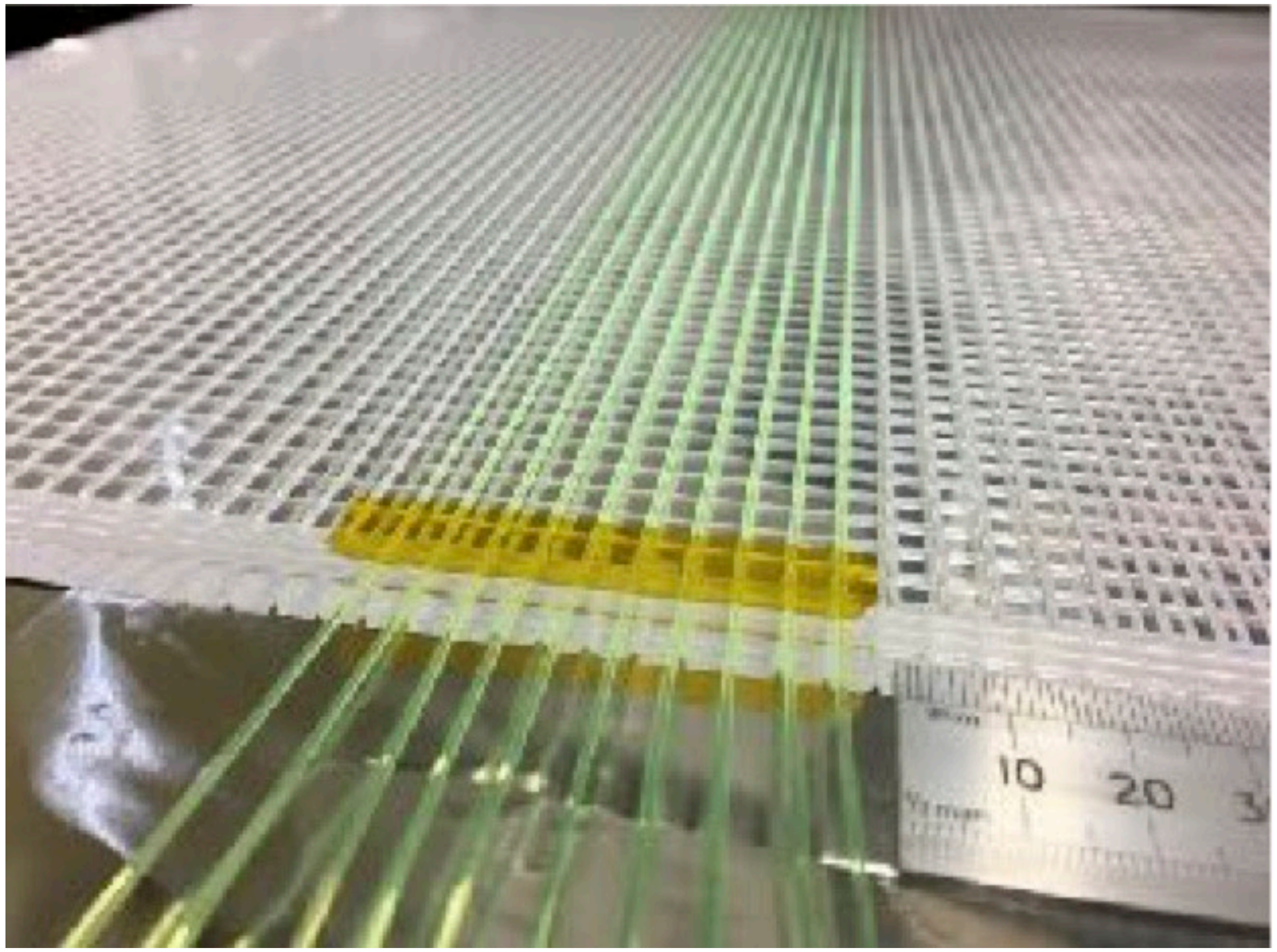


- Larger scintillator plates with orthogonal groves machined into top and bottom - light read out via WLS fibers
  - Position resolution on each coordinate from multiple fiber signals

U Tokyo



Conclusions

How is this relevant for DUNE?

- The CALICE calorimeters are primarily developed for energy-frontier colliders - different location in “optimization space” than detectors for neutrino beams - but:

- The technology is a good match - with obvious modifications
  - thinner absorbers to improve em resolution
  - less granularity required - but potentially maintaining / increasing effective granularity through crossed strips / crossed readout
  - time resolution to reject pileup / enable exotic searches
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Start a first simulation effort at MPP, complemented by some scintillator prototyping

Summary

- CALICE: very extensive experience with highly granular calorimeters for energy-frontier colliders with a wide variety of technologies
- Now being adopted in many different projects: LHC Phase 2 upgrades (approved or under consideration for all four experiments), spin-offs used also at SuperKEKB, …
- Also a key motivation for PandoraPFA

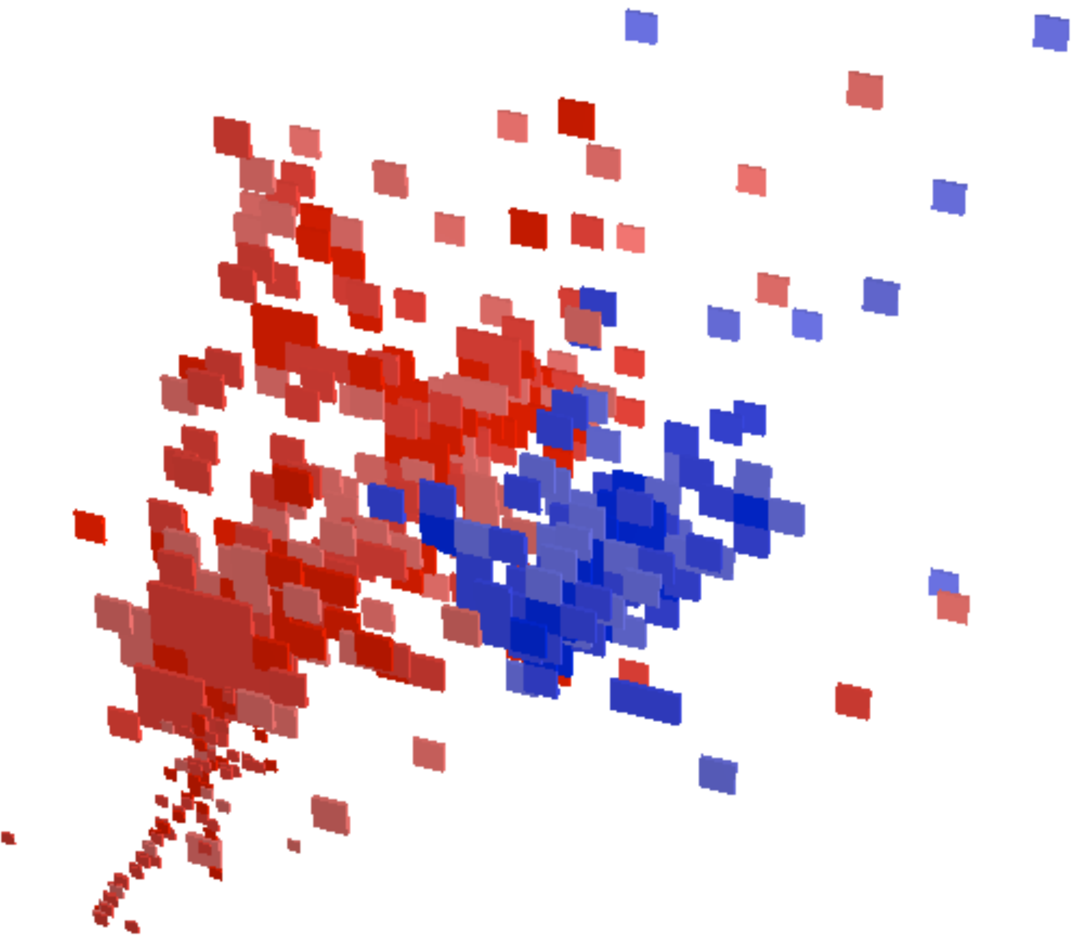
- CALICE analog HCAL technology potentially very relevant for Near Detector ECAL - with suitable modifications
  - Currently gauging interest among contributing groups
  - First studies about to begin at MPP - ideas & suggestions very welcome!

Extras

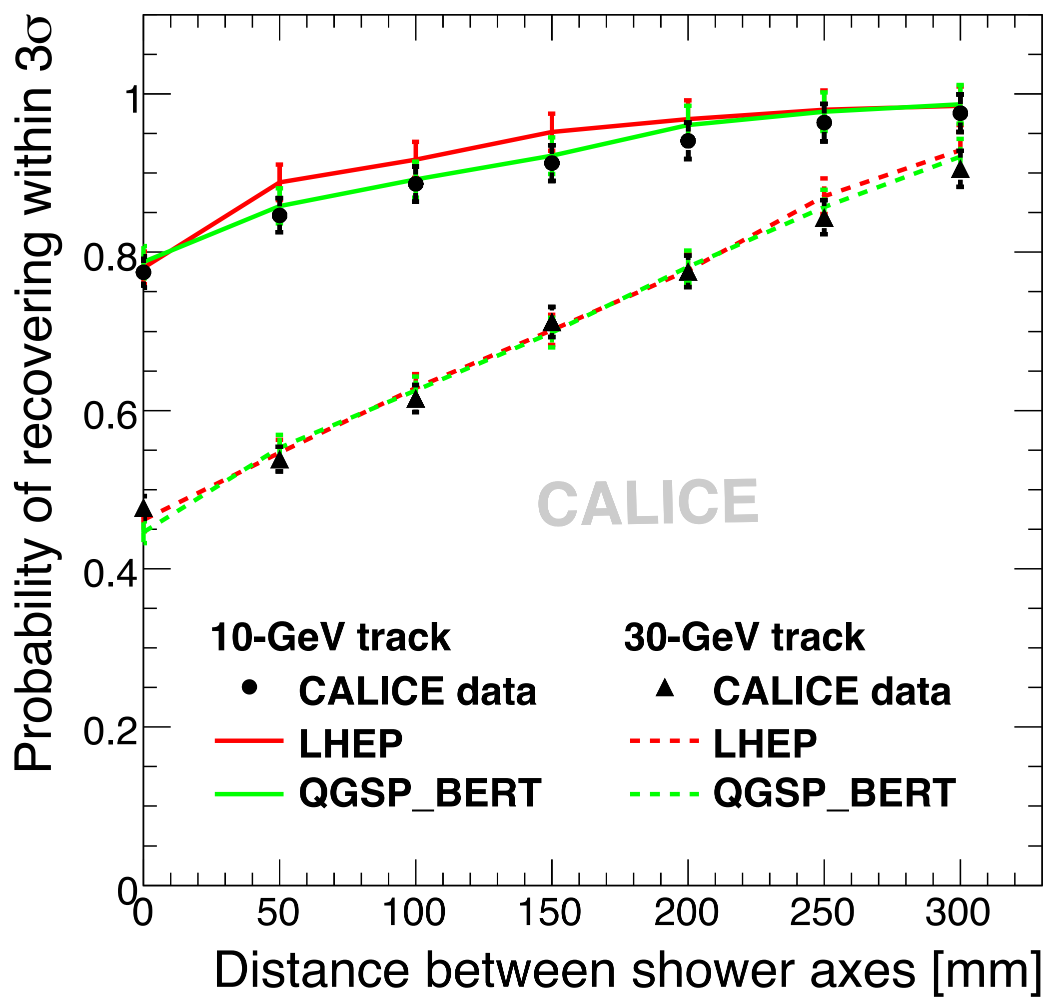
Combined System: PFA Performance

- A key performance criterion: Separation of showers
    - NB: Full PFA performance essentially impossible to validate in test beams: requires magnetic field, tracking, “jets” with realistic particle distribution
- ▸ Use CALICE data projected into full detector geometry, apply PFA (PandoraPFA code) to separate neutral from charged hadrons - validate MC prediction

JINST 6, P07005 (2011)

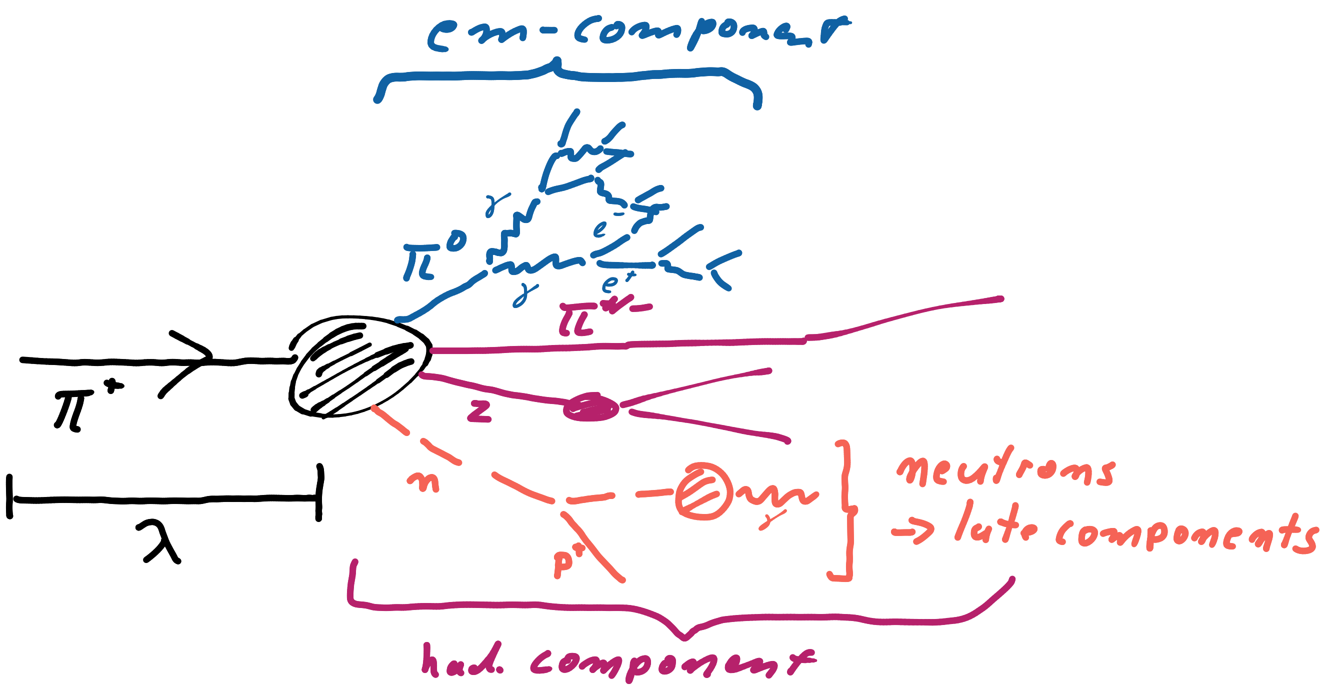


Excellent reproduction of two-particle separation in SiW ECAL + Scint. AHCAL



Studying and Simulating Hadronic Showers

- Hadronic showers exhibit a complex structure



compact - characterizes regions close to inelastic interactions

sparse - results in MIP-like particles connecting regions of higher activity

extended in time:

- few 10 ns from travel time of MeV-scale neutrons
- longer delays up to μs (and more) from thermal neutron capture and subsequent photon emission

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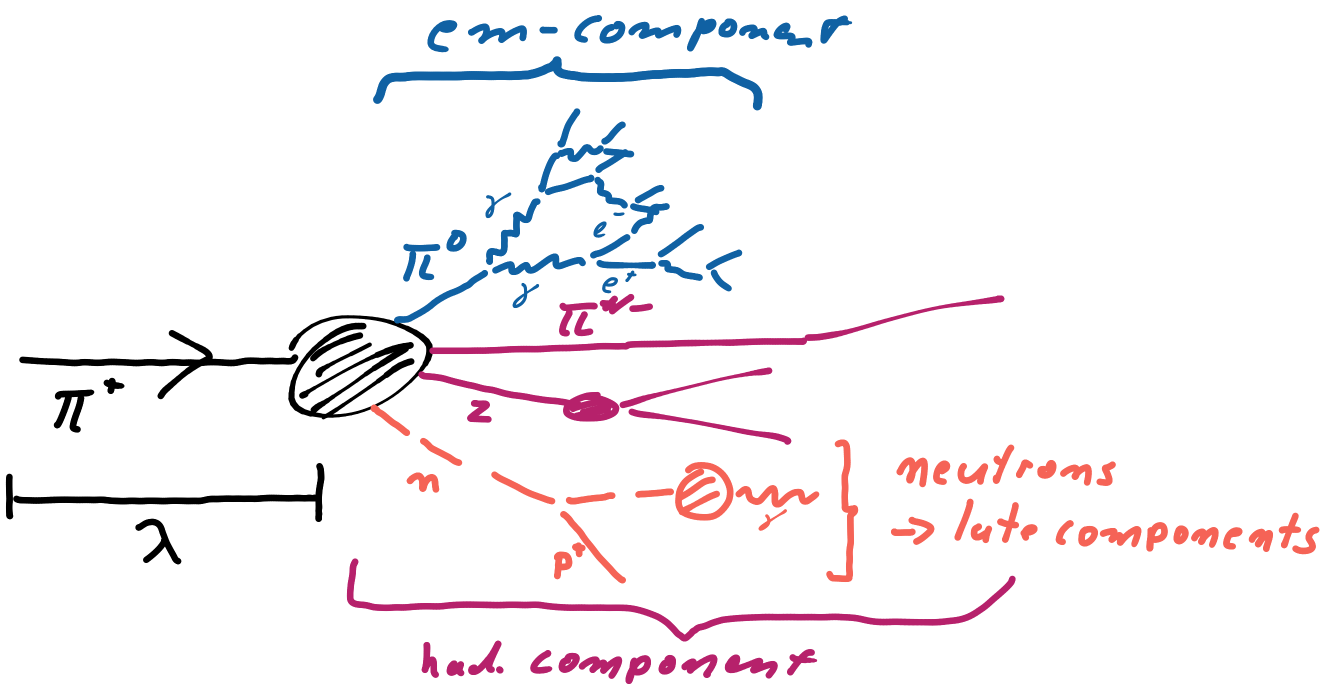

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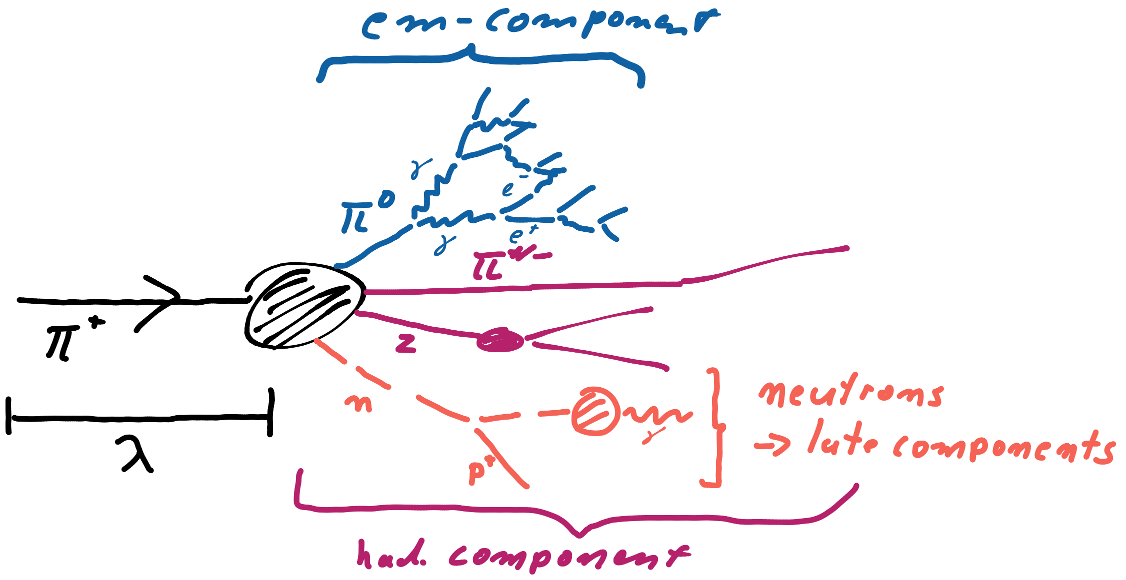
- Simulation is crucial to optimise detectors and to analyse data

▸ CALICE data with unprecedented granularity provides a new level of information to improve modelling of showers in GEANT4

Understanding Hadronic showers



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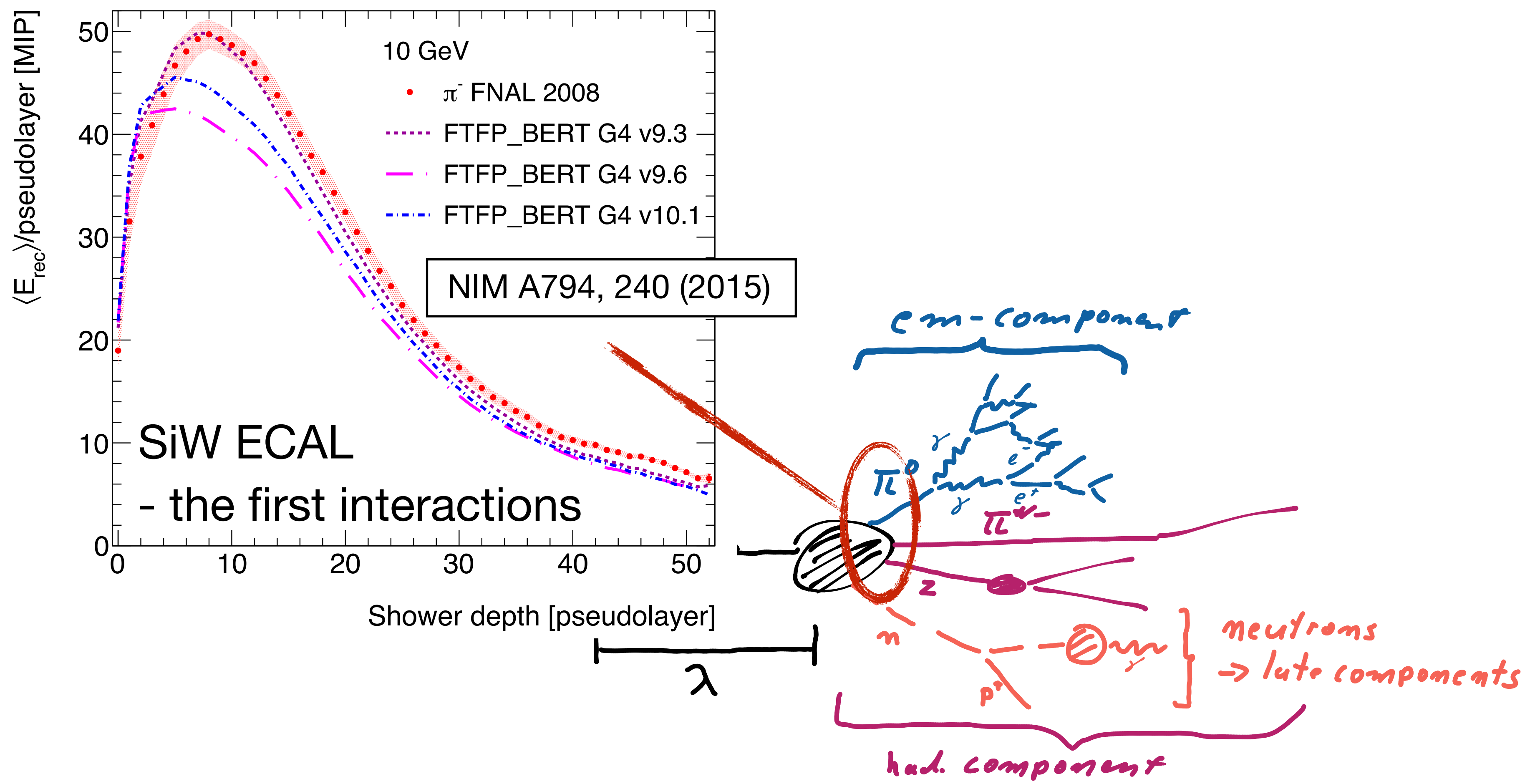

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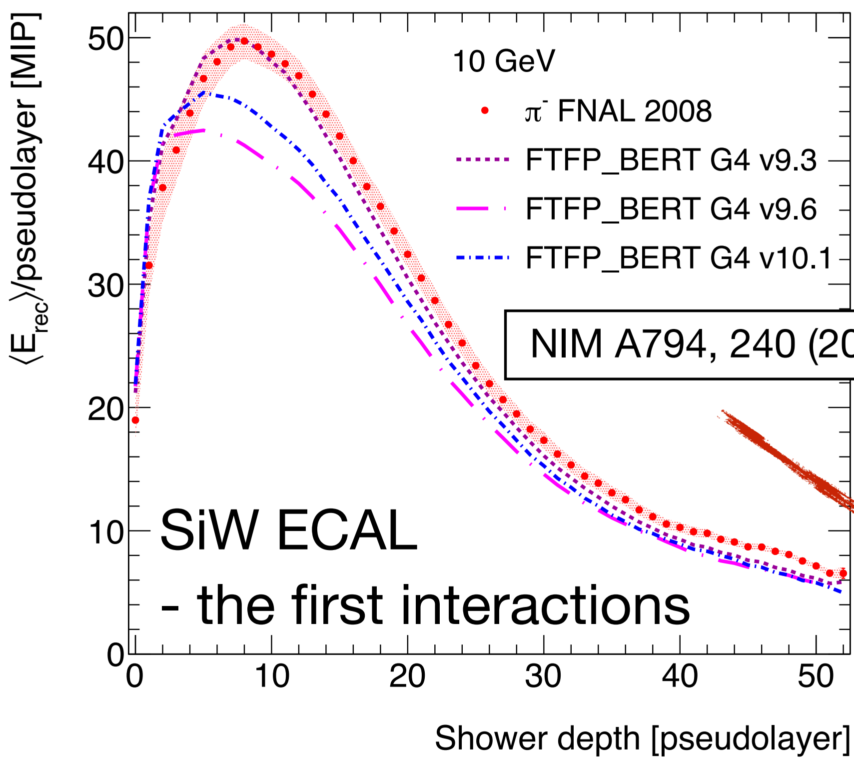
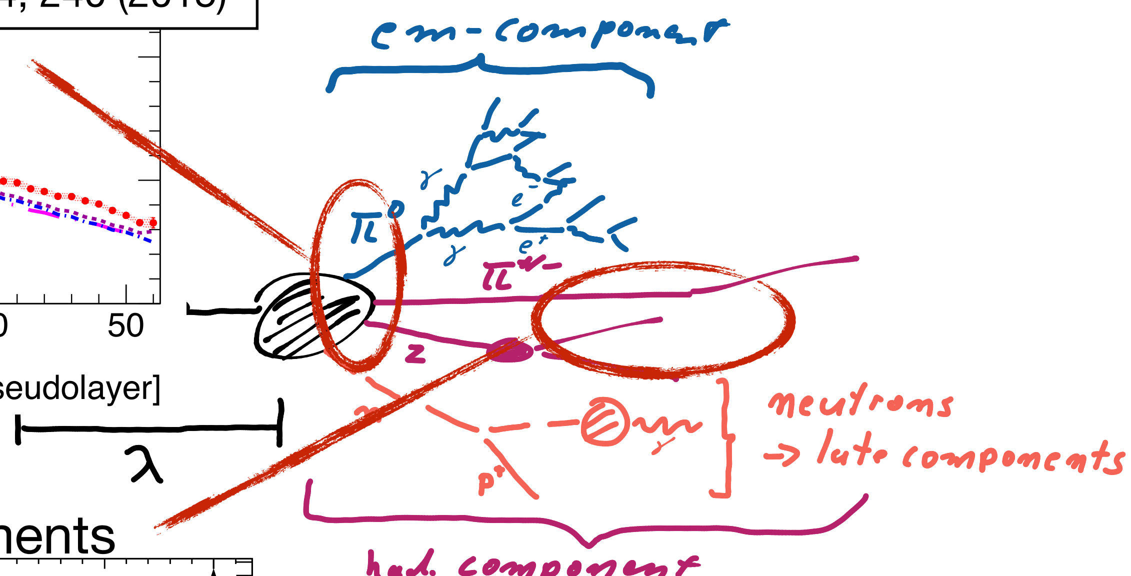
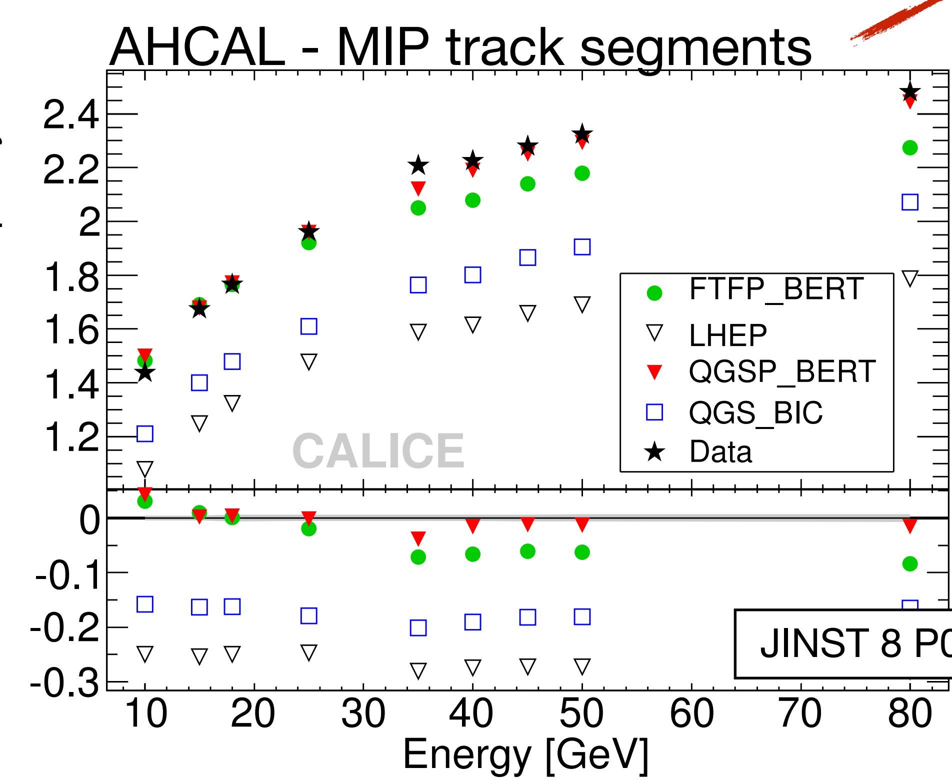


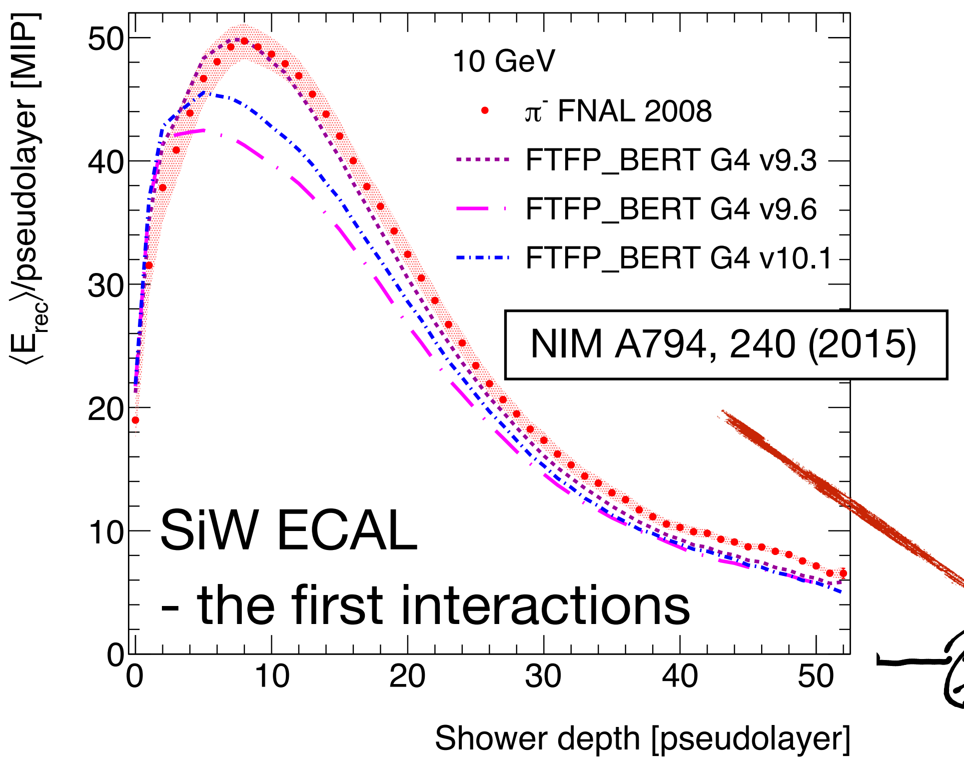
NIM A794, 240 (2015)

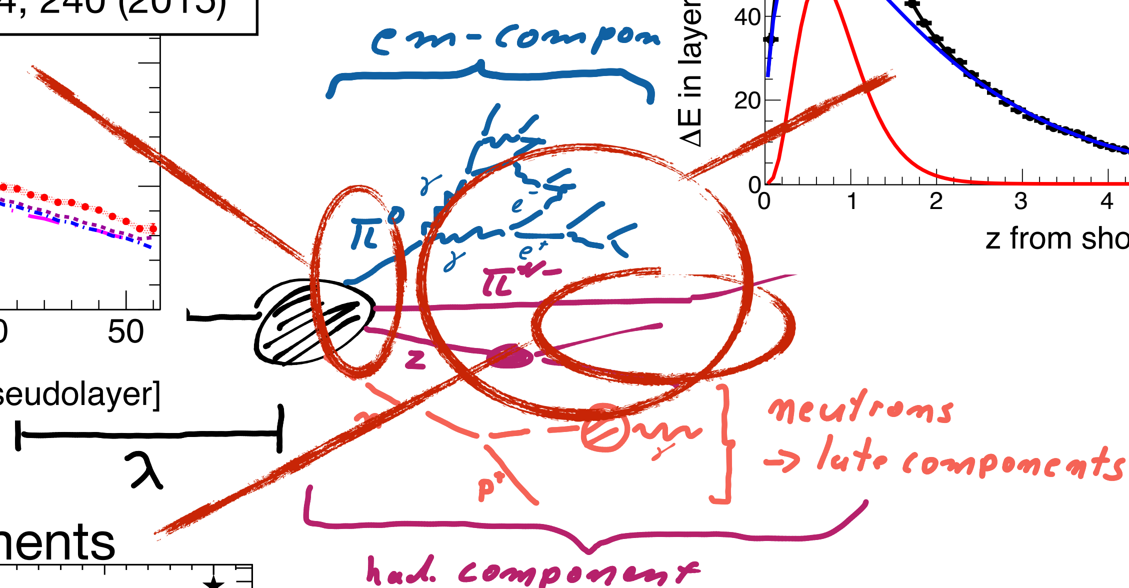


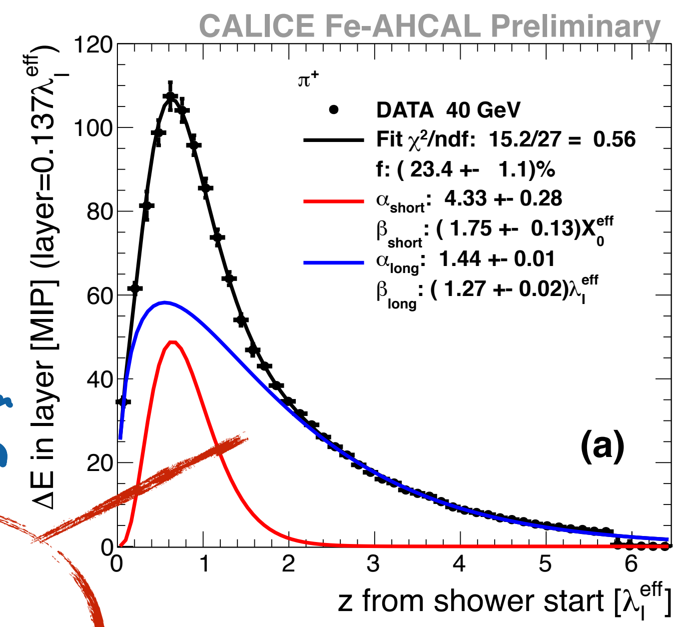


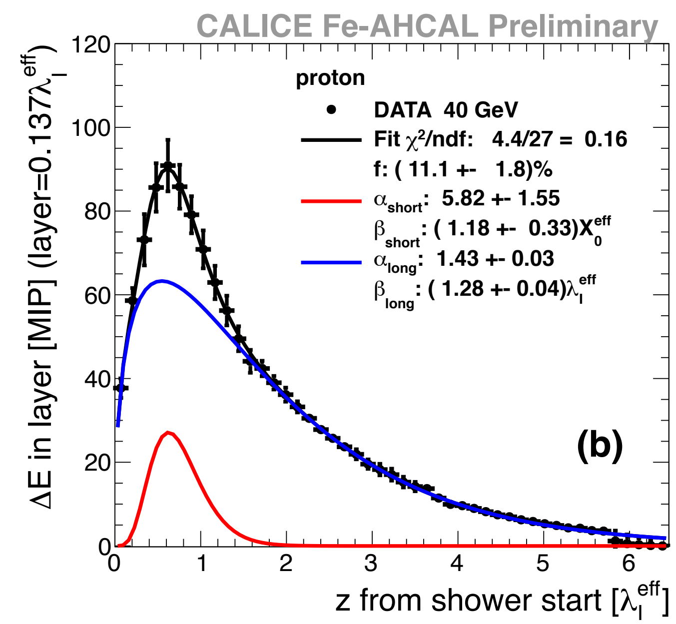
JINST 8 P09001 (2013)

Understanding Hadronic showers

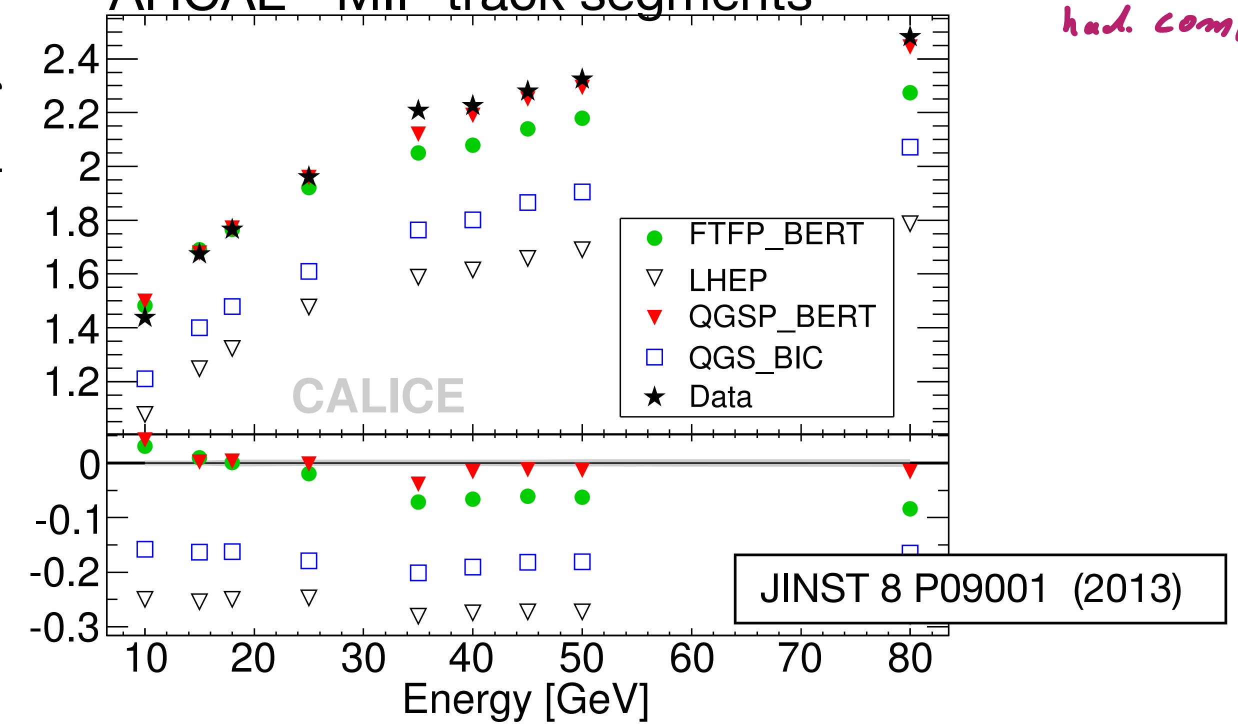








AHCAL - MIP track segments



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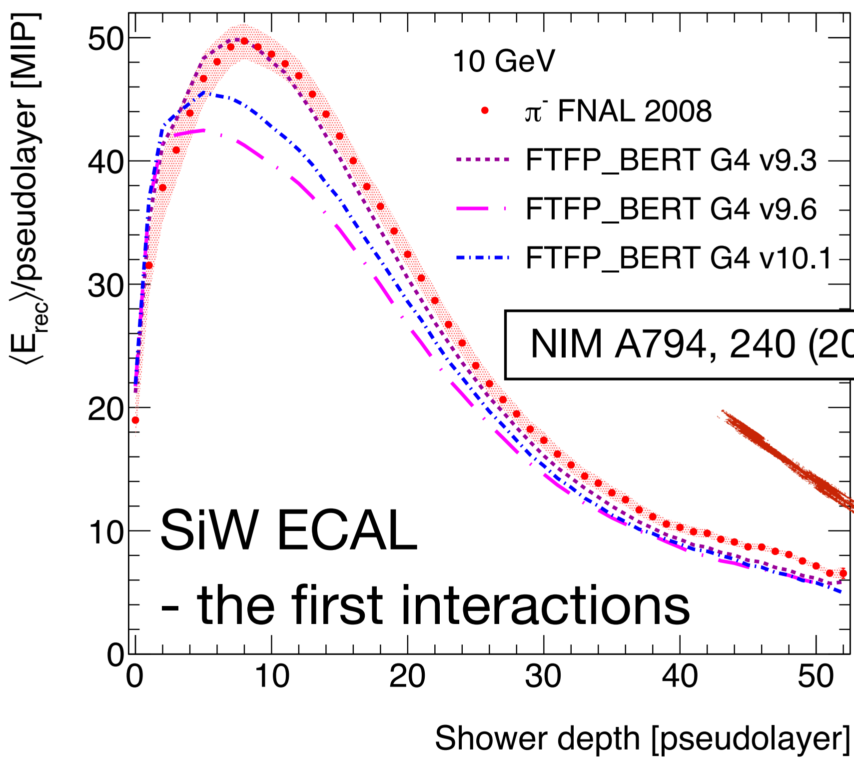

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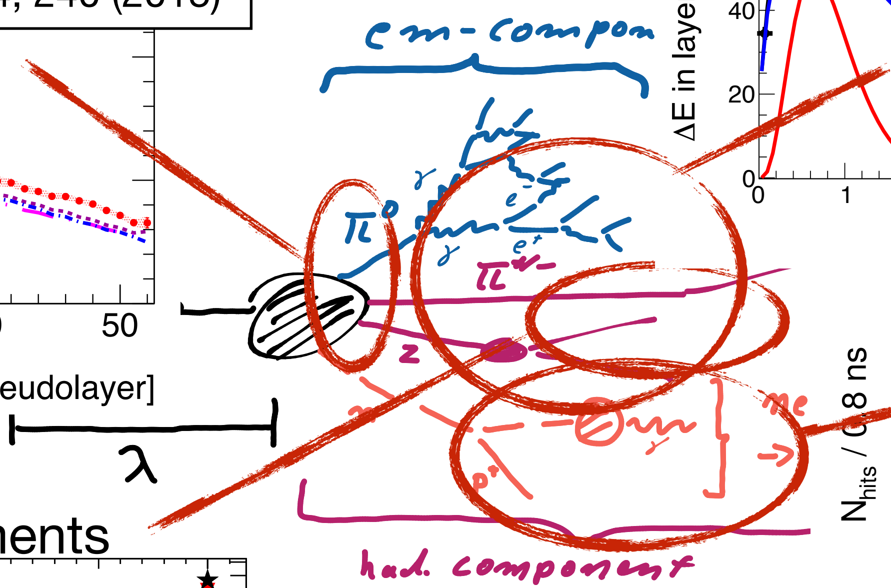
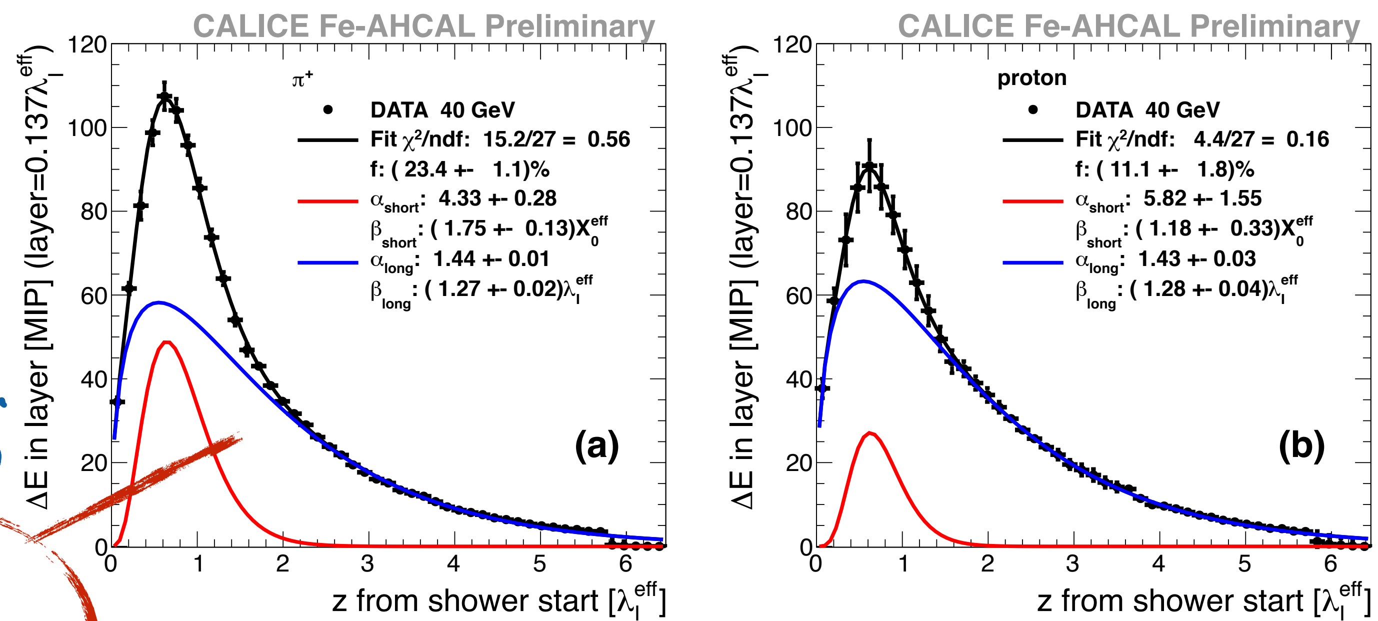
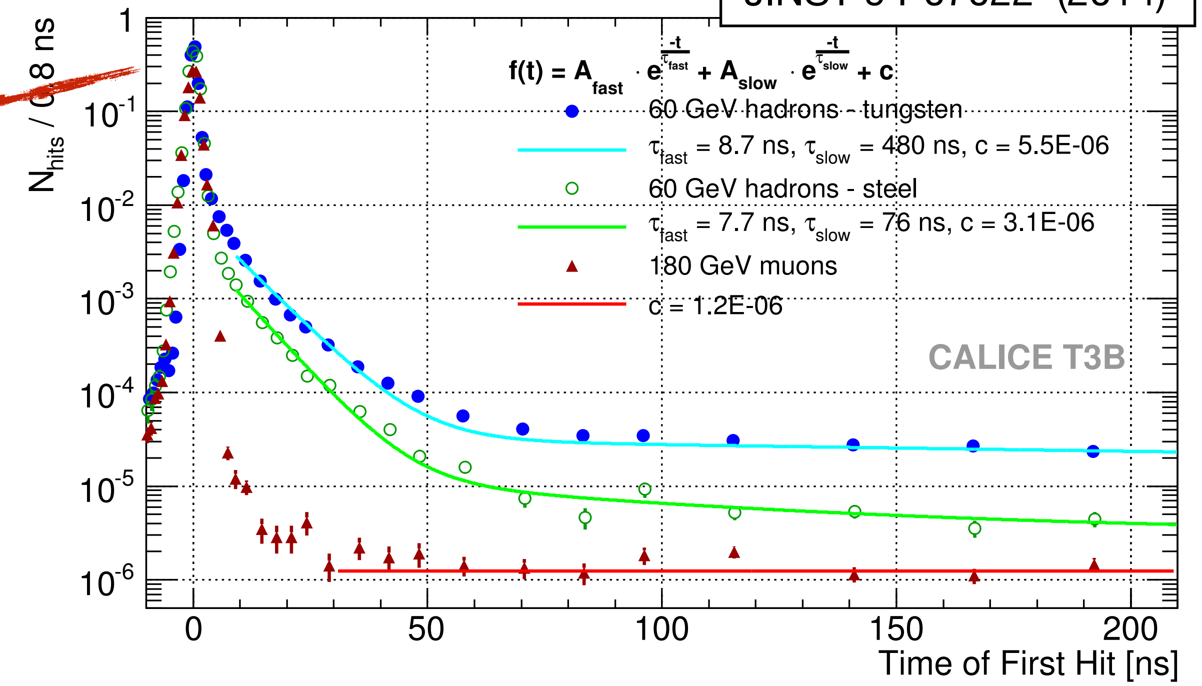




JINST 9 P07022 (2014)



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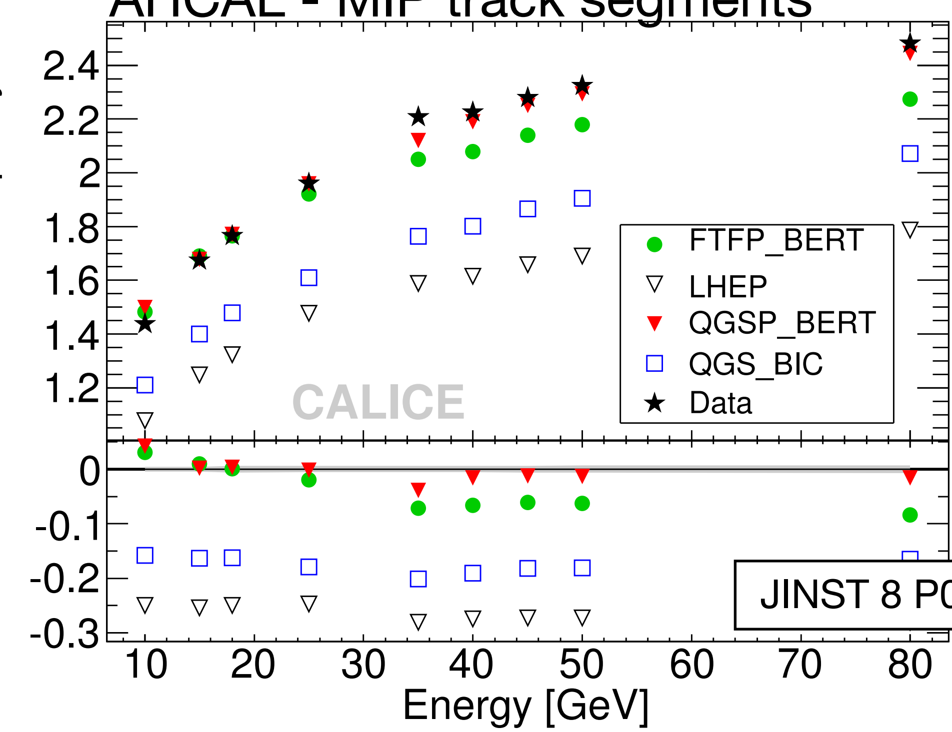
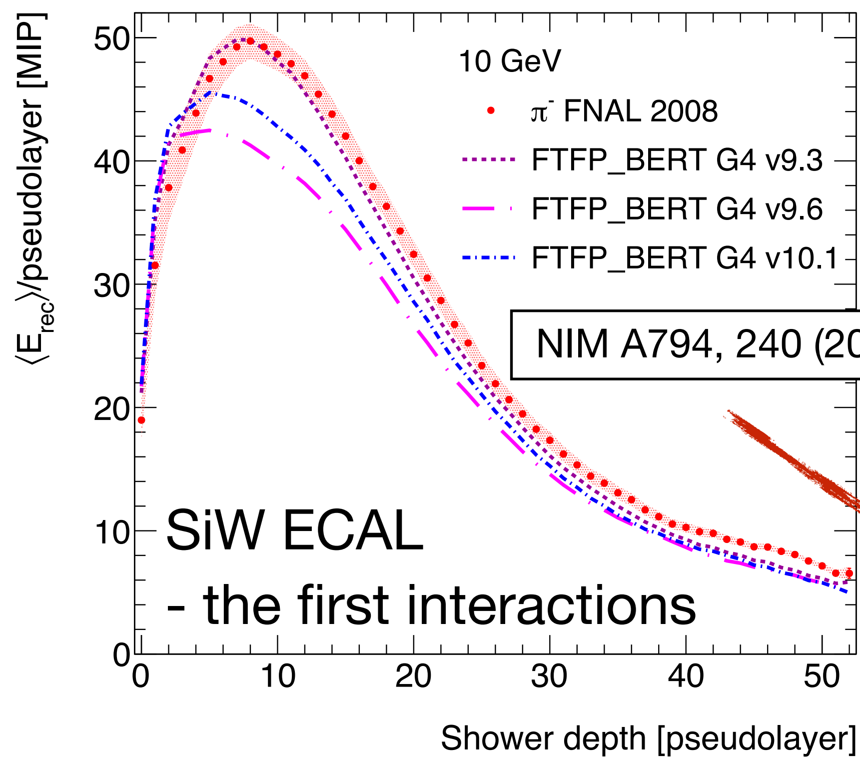


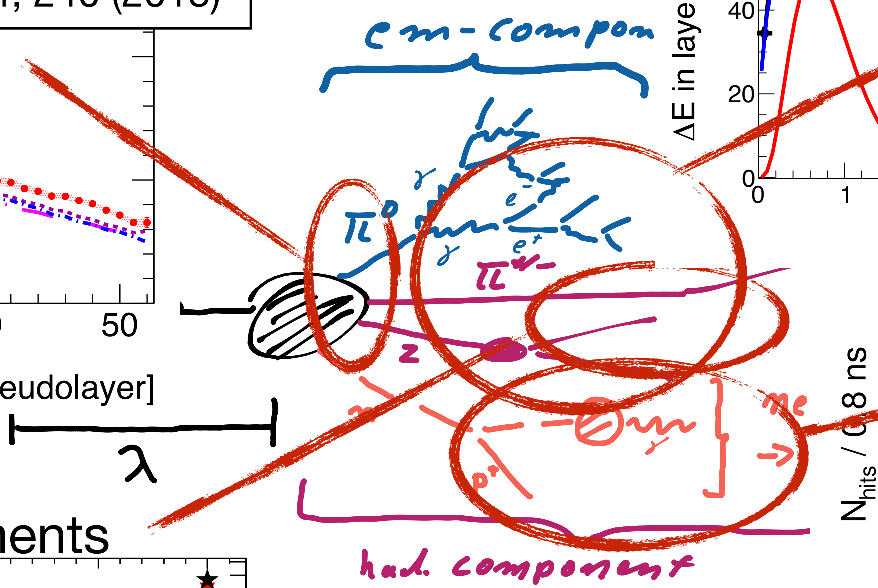
JINST 8 P09001 (2013)

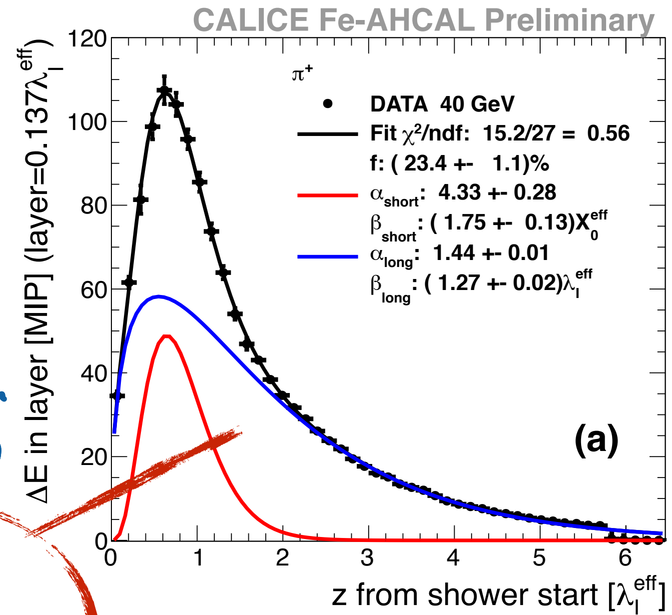
Understanding Hadronic showers

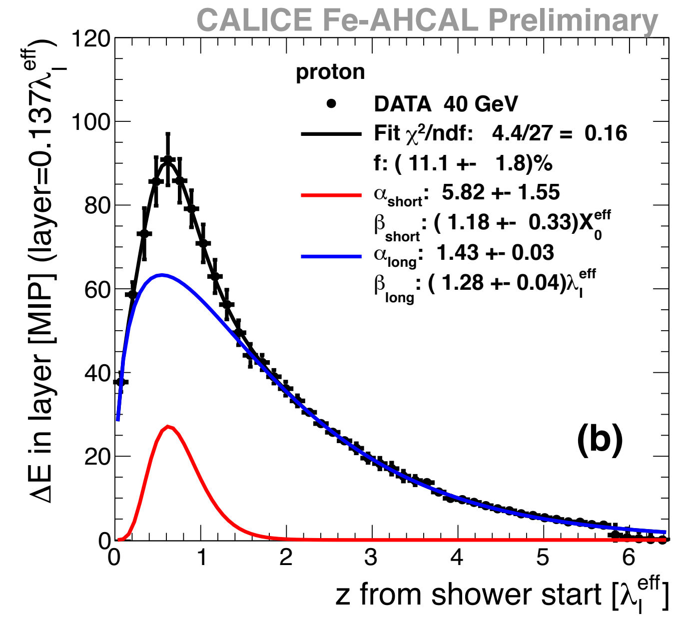


SiW ECAL
- the first interactions

NIM A794, 240 (2015)







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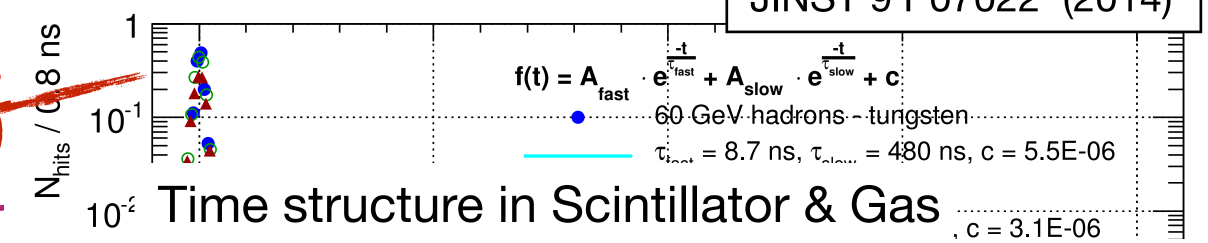

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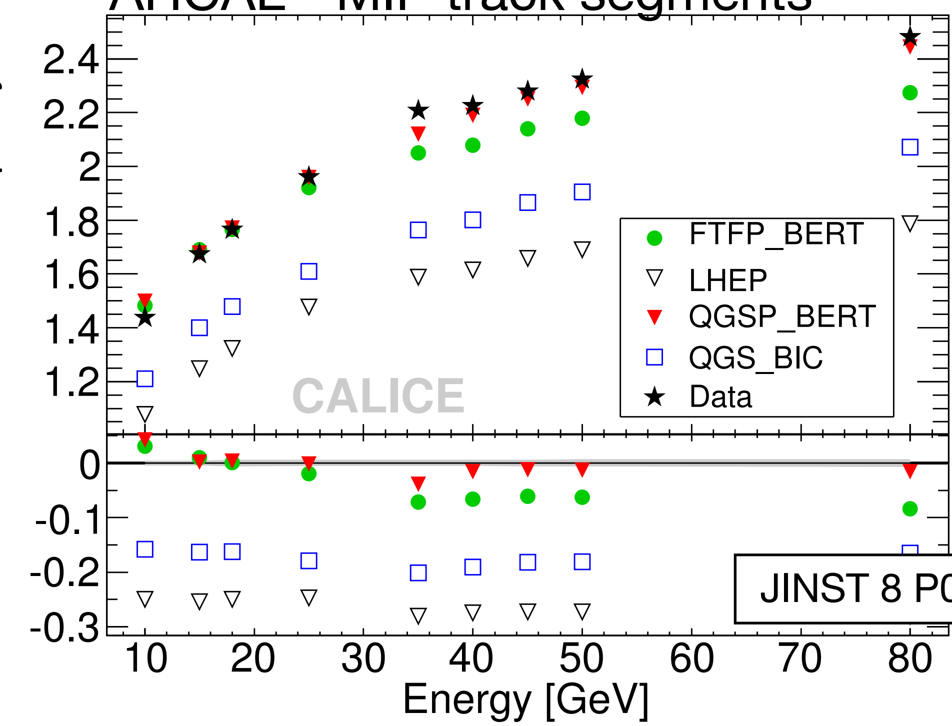

JINST 8 P09001 (2013)

Time structure in Scintillator & Gas