Hadrons in a SiW Electromagnetic Calorimeter for a Future Linear Collider

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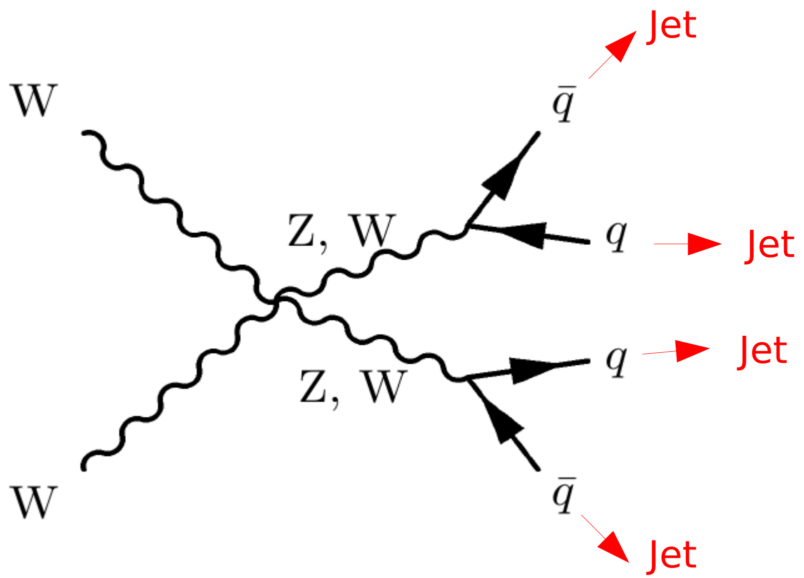
EUDET Annual Meeting DESY Hamburg
September/October 2009

Hadronic Decays of W and Z Bosons

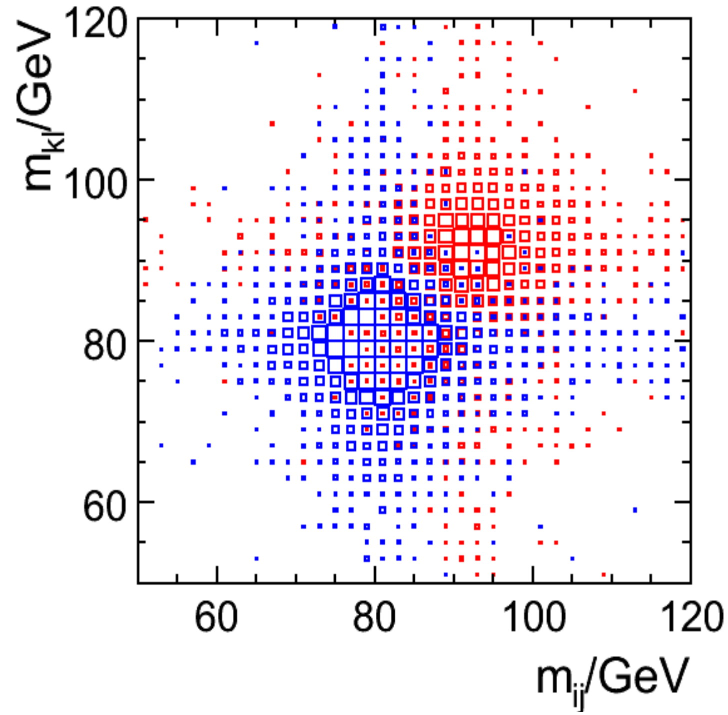
Boson Boson Scattering

What if no Higgs?

Manifestation of new physics
Strong Electroweak Symmetry Breaking



W, Z separation in the ILD Concept

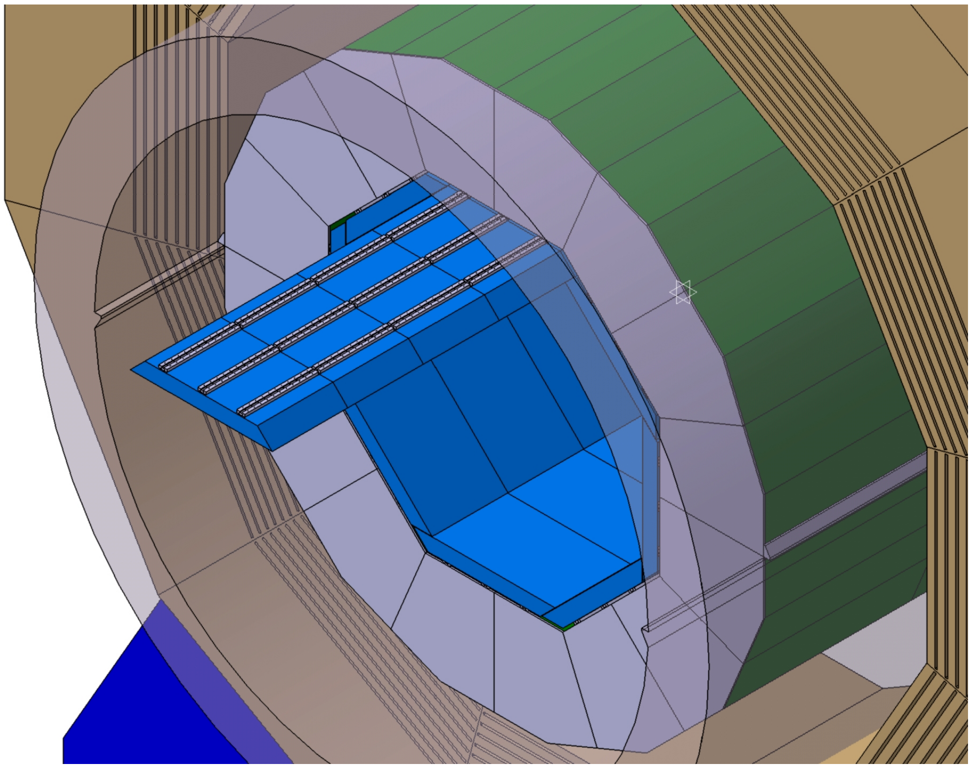


Remember: $M_Z - m_W \approx 10$ GeV

- Need excellent jet energy resolution to separate W and Z bosons in their hadronic decays
  $3\%/E_{jet}$-$4\%/E_{jet}$
- Basic mean: Highly granular Calorimeters

SiW Ecal - Basics

The SiW Ecal in the ILD Detector



Basic Requirements

- Extreme high granularity
- Compact and hermetic

Basic Choices

- Tungsten as absorber material
  - X_0=3.5mm, R_M=9mm, λ_I=96mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisation
  - Large signal/noise ratio

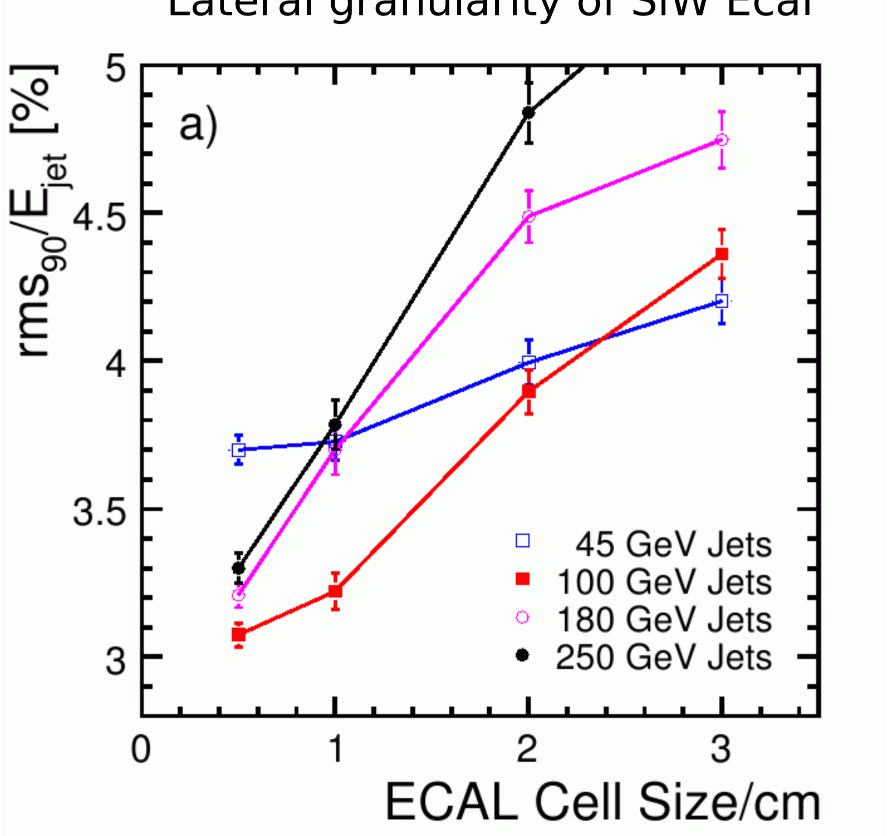
SiW Ecal designed as Particle Flow Calorimeter

SiW Ecal Optimisation

LOI for 2009 ILC Detectors
Optimisation using Jet Events and Pandora Particle Flow Algorithm

(see talk by M. Thomson)

Lateral granularity of SiW Ecal



Jet Energy resolution strongly sensitive on cell dimensions

- Better separation power

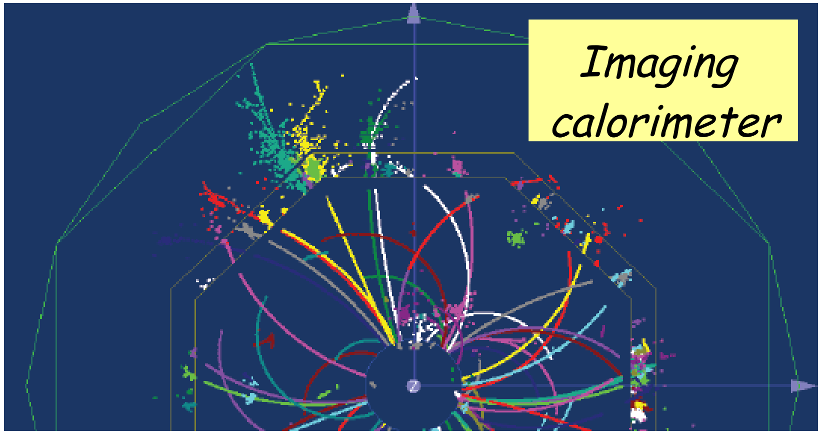
- Importance grows towards higher energies

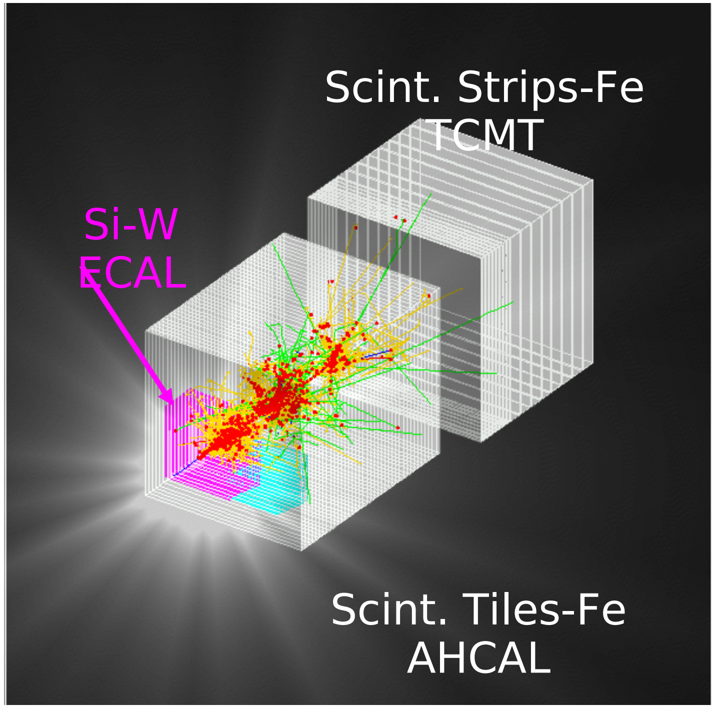
High granularity of Ecal is crucial for precision measurements

The Calice Mission

Final goal:

A highly granular calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider

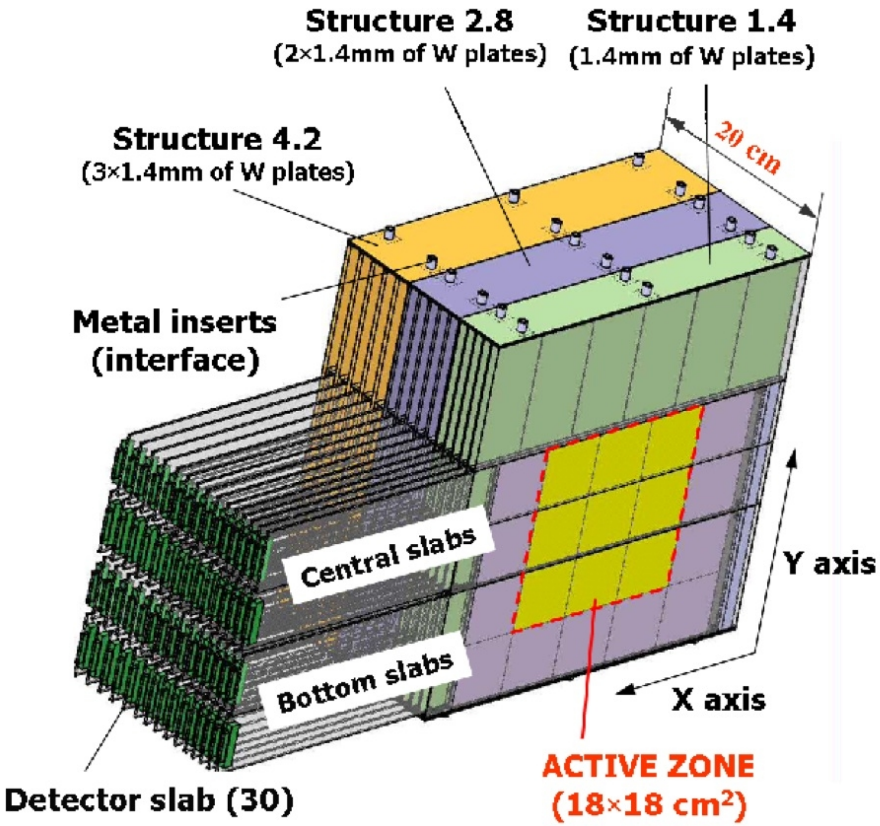


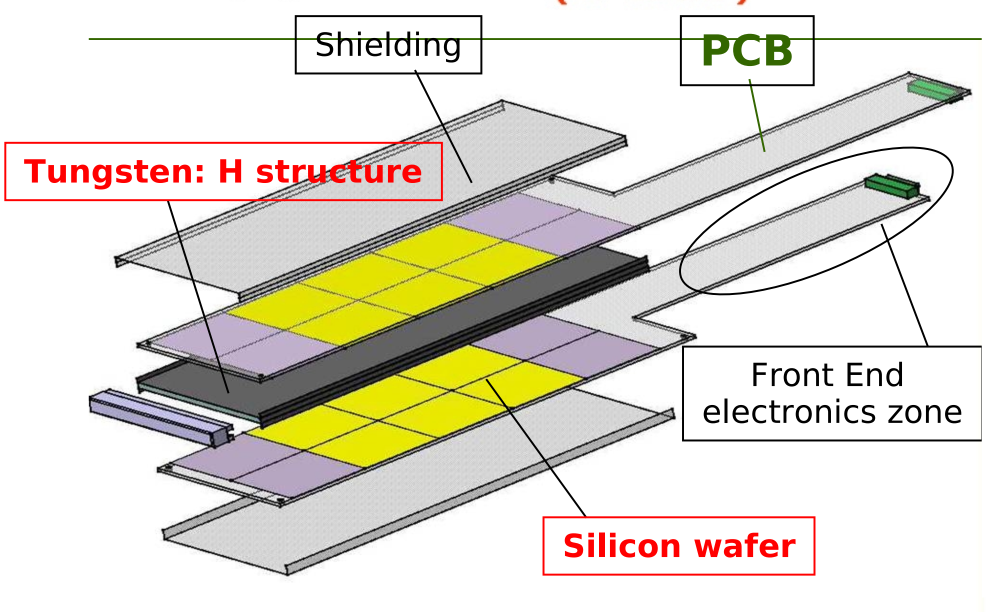


Intermediate task:

Build prototype calorimeters to
• Establish the technology
• Collect hadronic showers data with unprecedented granularity to
  - tune clustering algorithms
  - validate existing MC models

SiW Ecal Physics Prototype





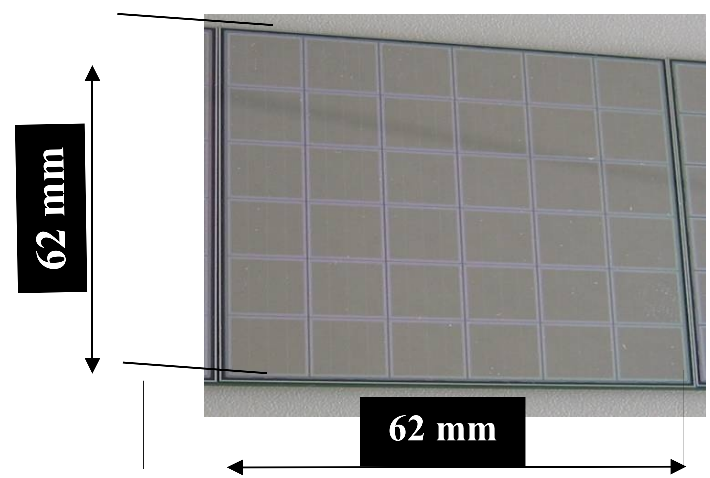
30 layers of Tungsten:

- 10 x 1.4 mm (0.4 X_0)
- 10 x 2.8 mm (0.8 X_0)
- 10 x 4.2 mm (1.2 X_0)
- 24 X_0 total, 1 λ_I

½ integrated in detector housing
⇒ Compact and self-supporting detector design

6x6 PIN Diode Matrix

Resistivity: 5kΩcm - 80 (e/hole pairs)/µm



Thickness:
525µm

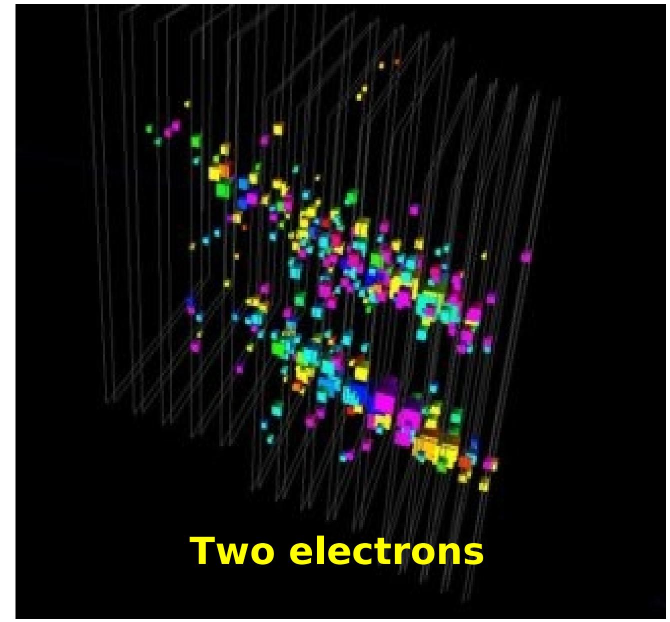
Total: 9720 Pixels/Channels

Large Scale Beam Tests

Experimental Setup

Zoom into Ecal

Particle Distance~ 5 cm
→ No Confusion !!!



- 2006, Ecal 2 / 3 equipped
  Low energy electrons (1-6 GeV at DESY), high energy electrons (6-50 GeV at CERN)

- 2007, Ecal nearly completely equipped
  High energy pions (6-120 GeV CERN), Tests of embedded electronics

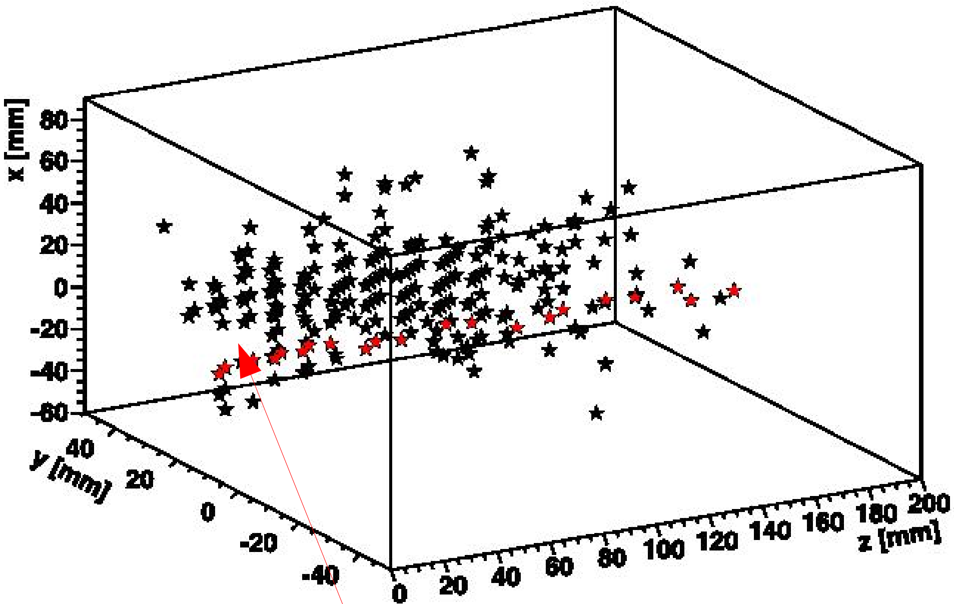
- 2008 FNAL, Ecal completely equipped
  Pions at low energy,
  Data taking with Digital Hcal (>2010?)

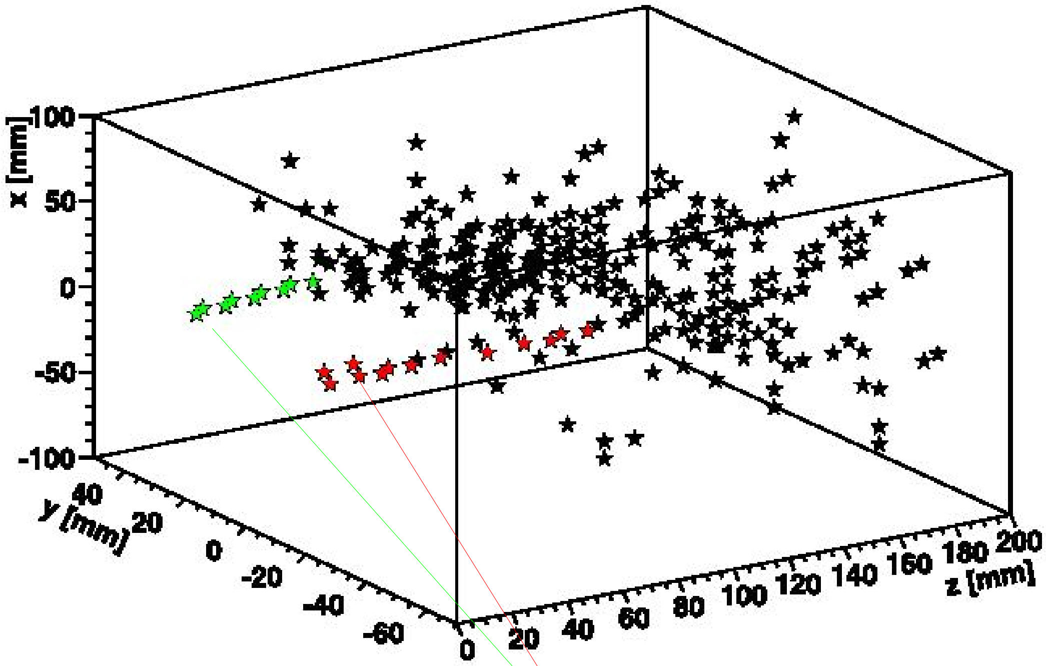
Exploiting the High Granularity I – Particle Separation

High granularity allows for application of advanced imaging processing techniques

E.g. Hough Transformation

Events recorded in test beam





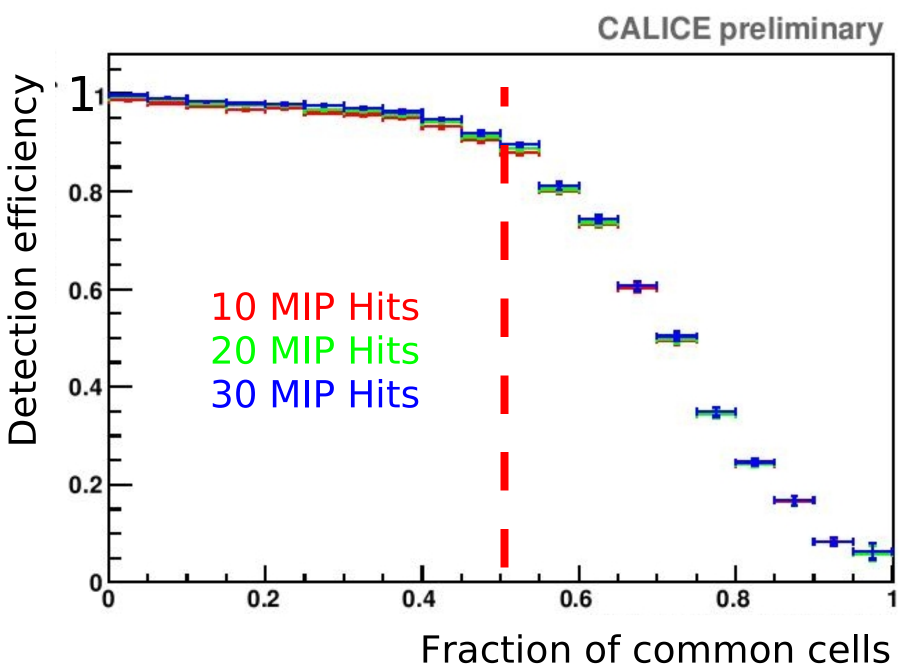
Two Pions entering the SiW Ecal

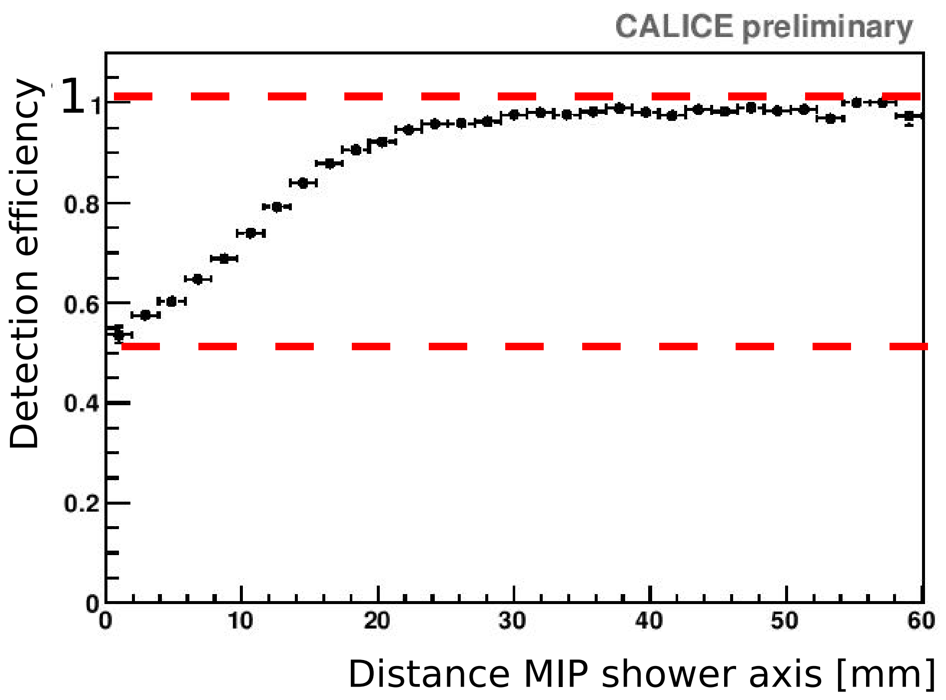
Secondary Muon within Electron Shower

Particle Separation – cont'd

Efficiency of Particle Separation

Separation MIP <-> Electron





E -> 100% for up to 50% shared hits

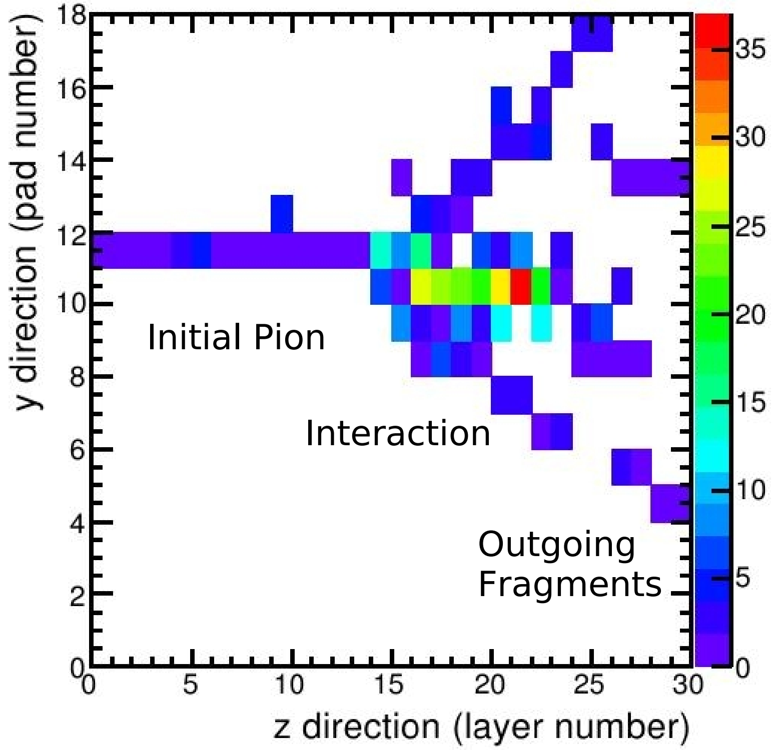
Independent of hits generated by MIP

Full separation for distances > 2.5 cm

Granularity and Hadronic Cascades

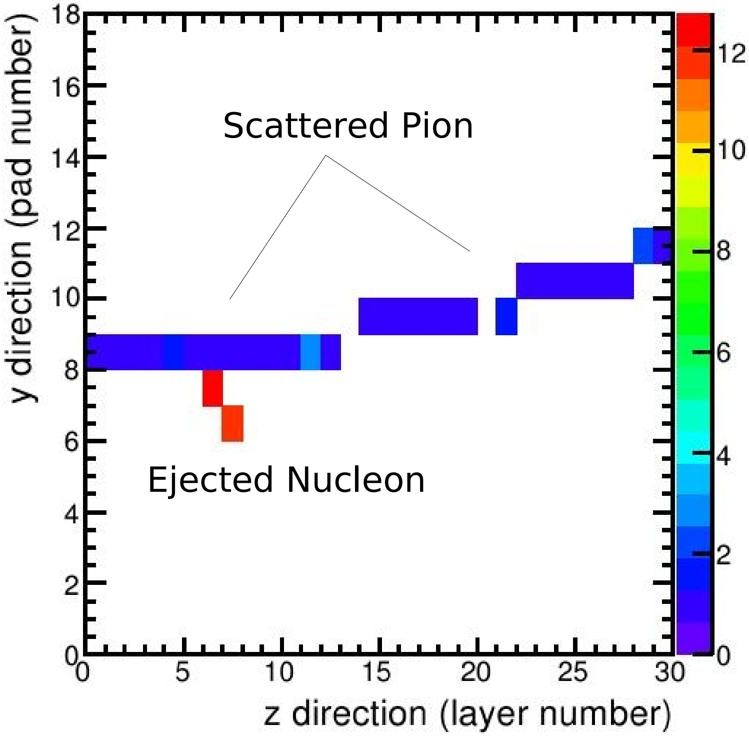
(Start of) Hadronic Showers in the SiW Ecal

Complex and Impressive



Inelastic Reaction in SiW Ecal

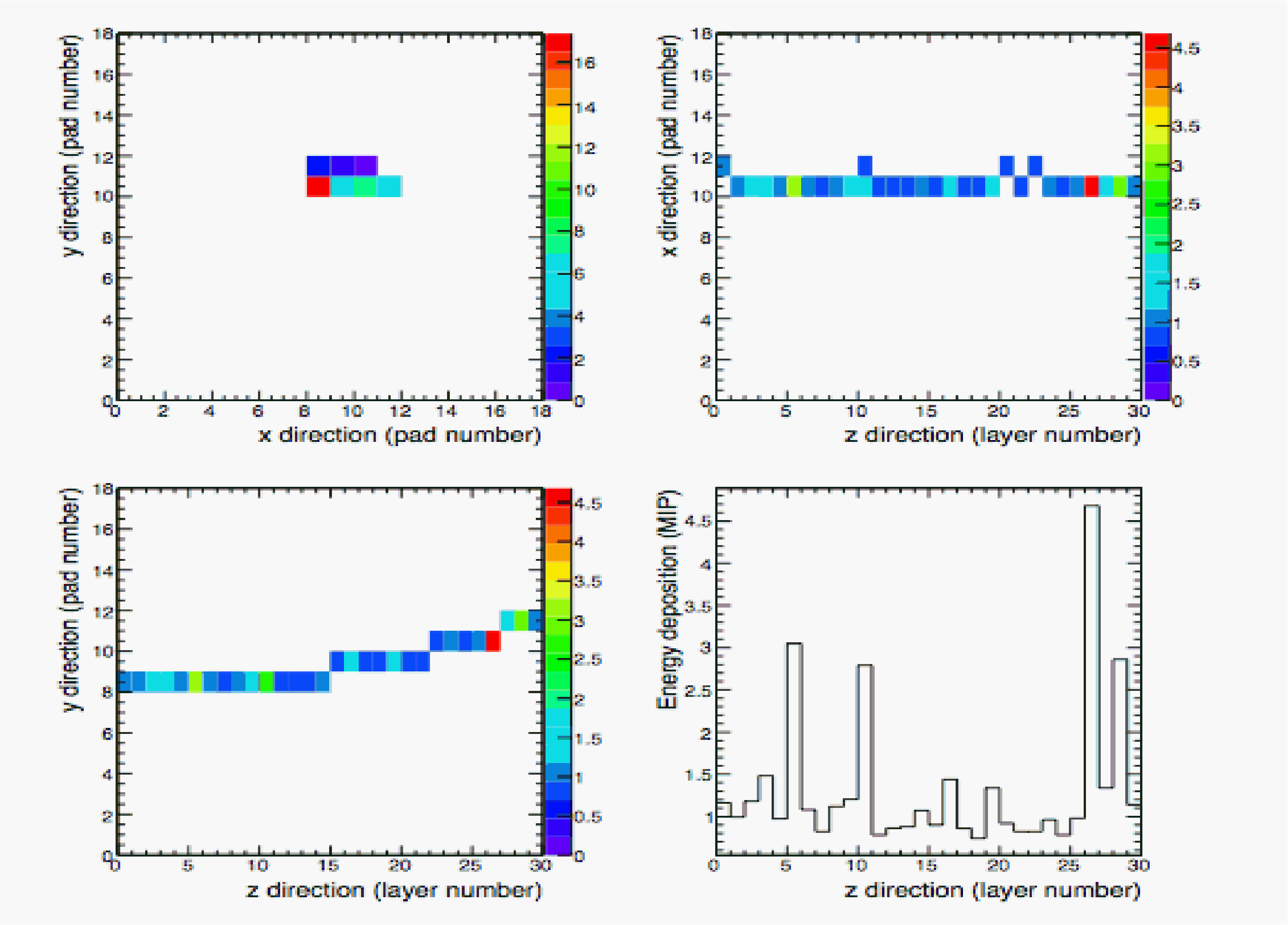
Simple but Nice



Nucleon Ejection in SiW Ecal

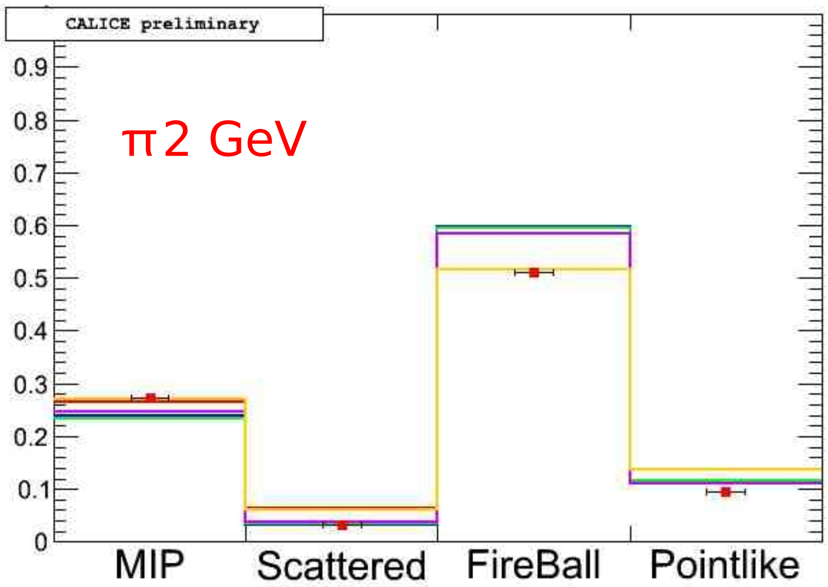
High granularity permits detailed view into hadronic shower

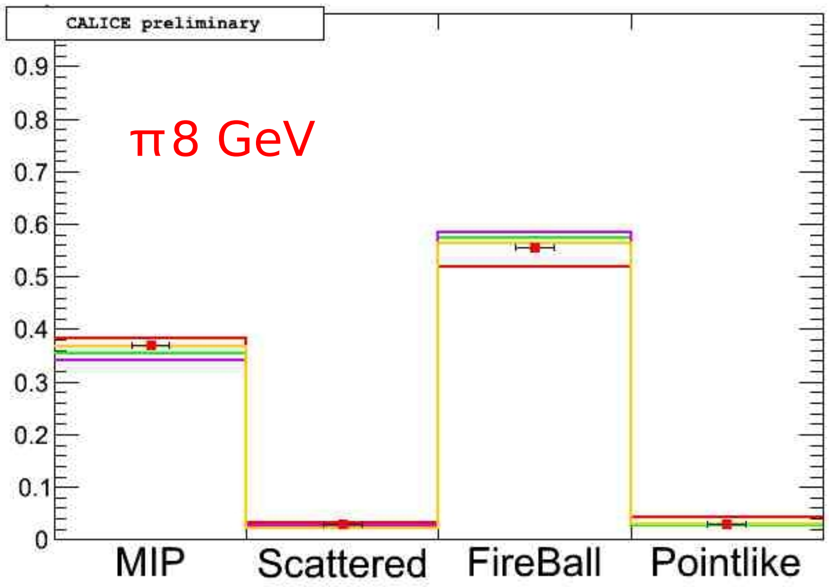
Elastic Scattering



Types of interactions of hadrons

Modern Bubble Chamber



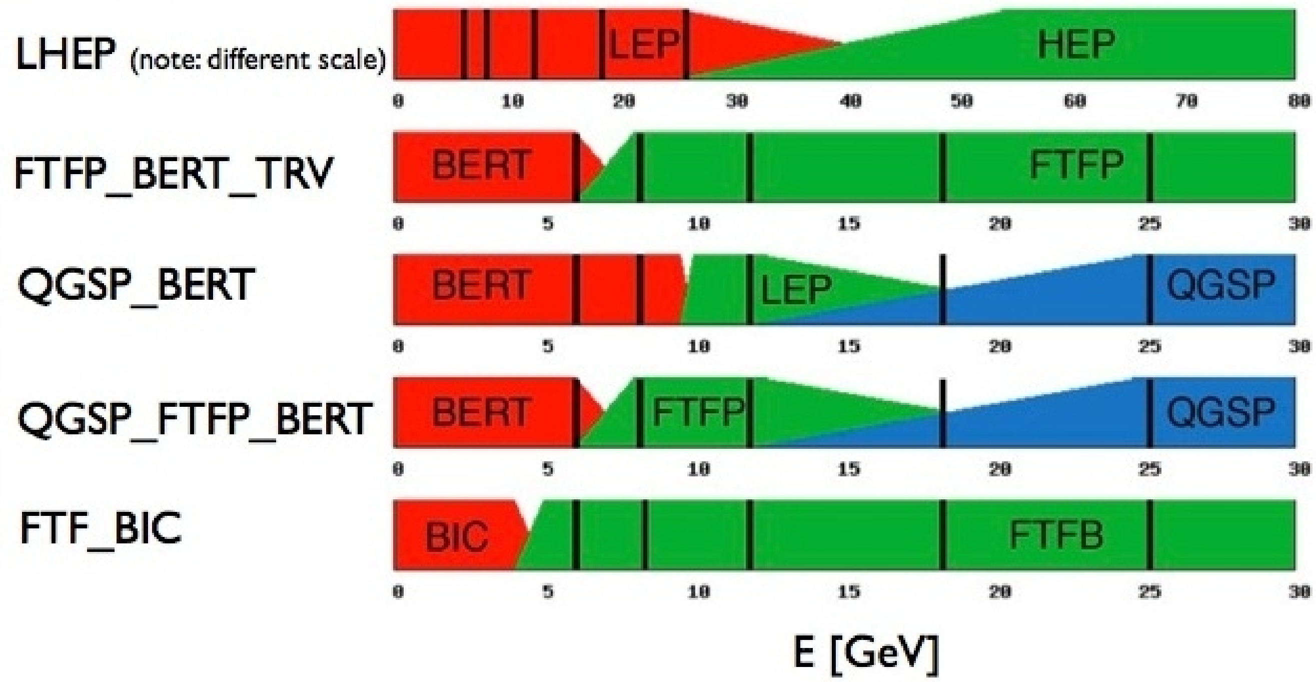


- Classification of hadronic interactions

- Large potential for application of pattern recognition algorithms or learning algorithms
  Basic Question: "How many particles are in the calorimeter"

Hadronic models in GEANT4

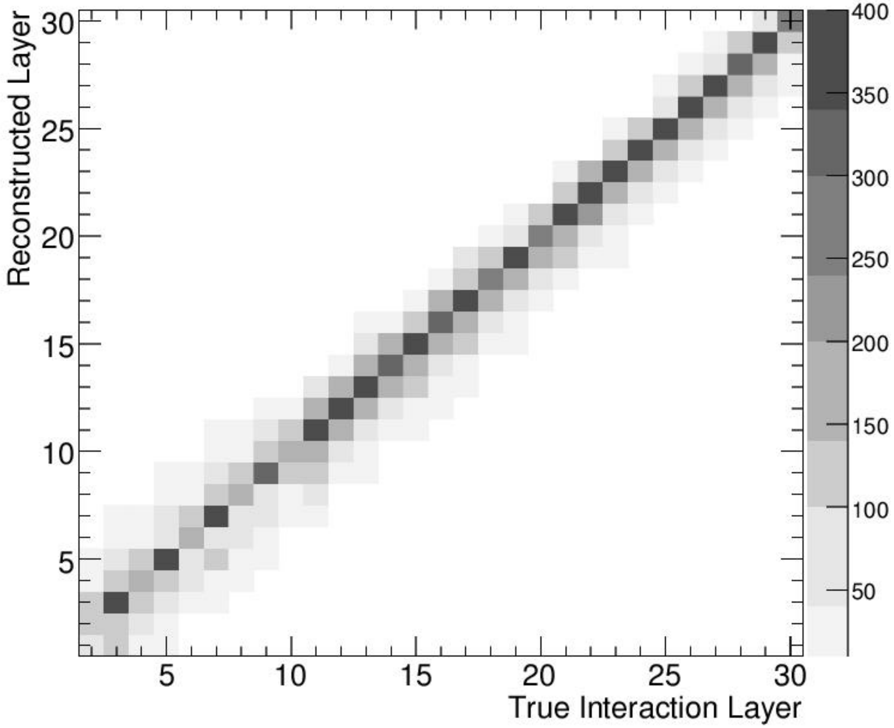
Variety of models available to describe hadronic showers



Discriminative power by high granularity !?
“Series of thin targets” (See A. Dotti's talk on G4)

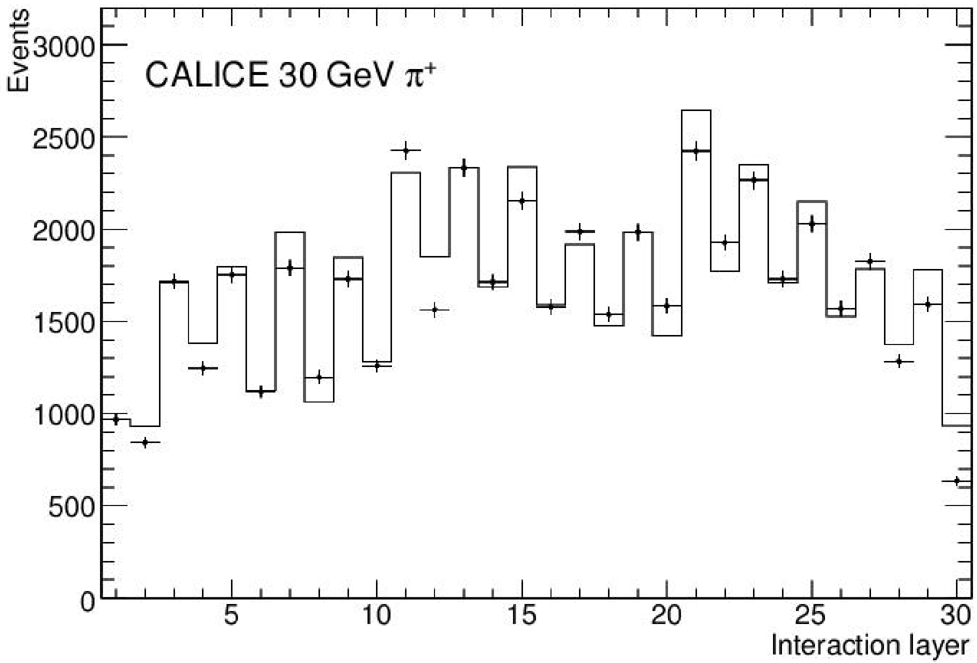
Finding the Interaction in the SiW Ecal

Correlation:
True Interaction <-> Found Interaction



Determination precise to two layers
(Overall Layer thickness ~7mm max.)

Distribution of found interaction layers



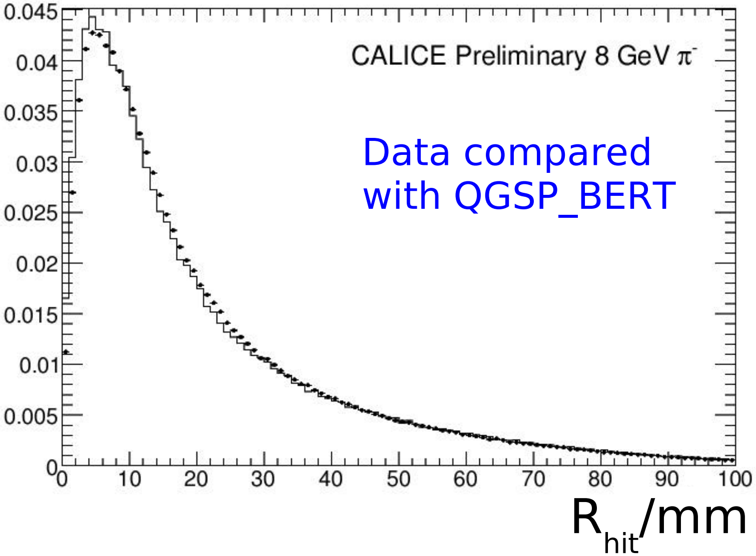
Good agreement between Data and Simulation (G4, here QGSP_BERT)

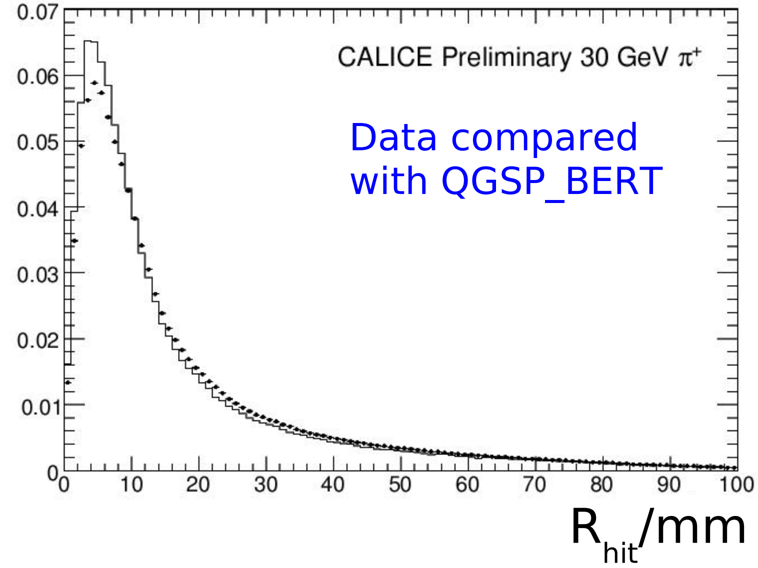
Granularity allow for resolving interaction layer with high resolution
High energy cross sections well implemented in G4 simulation

Transversal Shower Profiles and Shower Radius

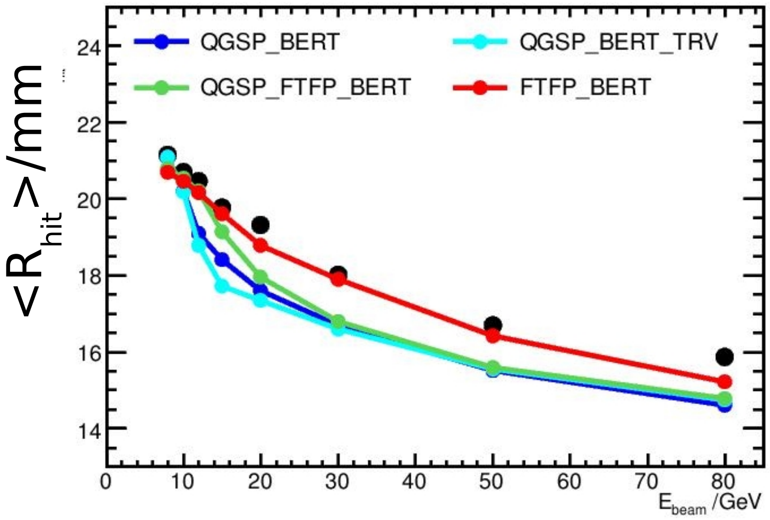
Affects overlap of showers <-> Importance for PFA

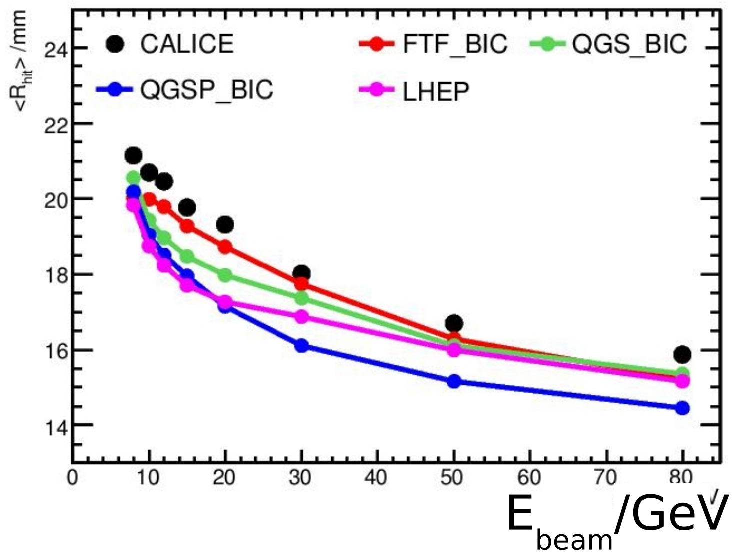
Transverse Profiles





Shower Radius

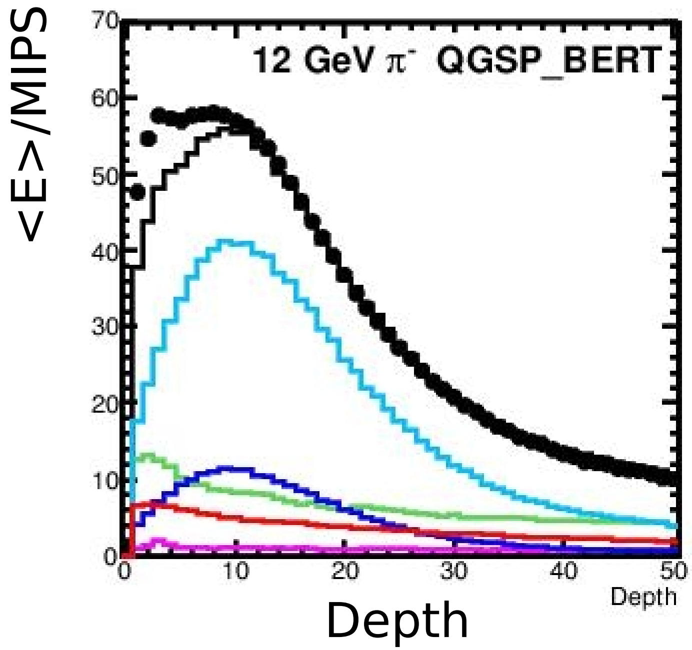


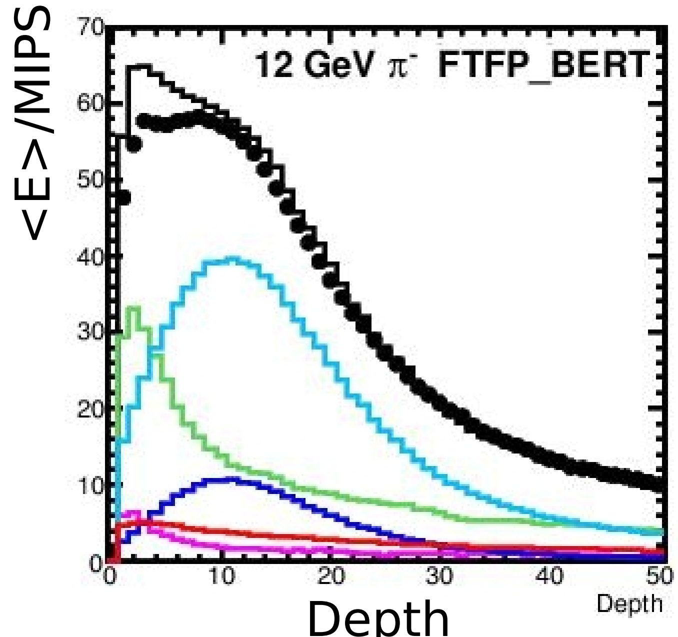


Small Energy ok for 'BERT' models
Towards high energy: Underestimation of Content in SiW Ecal
Relatively small difference between models (~15%)

Longitudinal Energy Profiles

Sensitivity to different shower components





Shower Components:

- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum

Significant Difference between Models

- Particularly for short range component (protons)

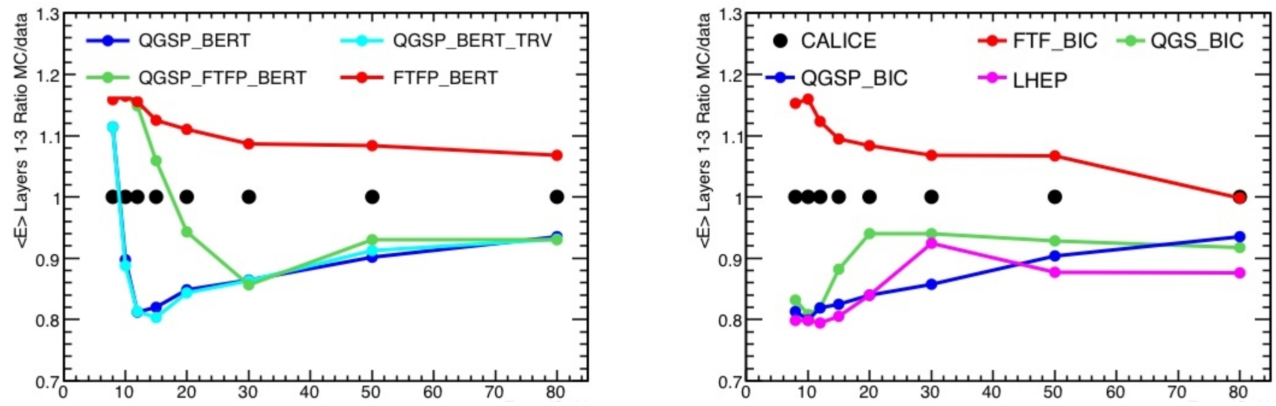
Granularity of SiW Ecal allows (some) disentangling of components

Further studies for shower decomposition are ongoing

Energy depositions in different calorimeter depths

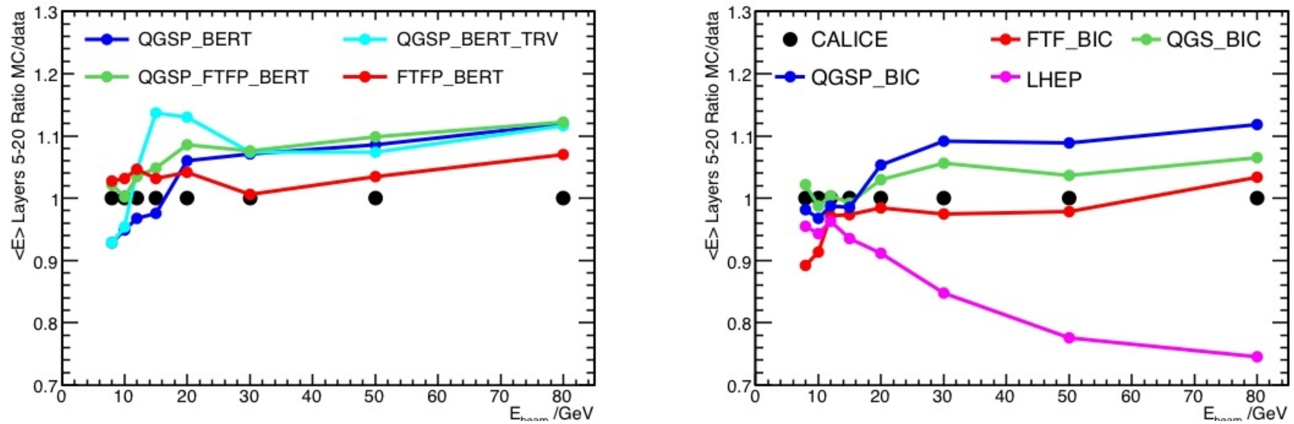
Layer 1-3:

Nuclear breakup



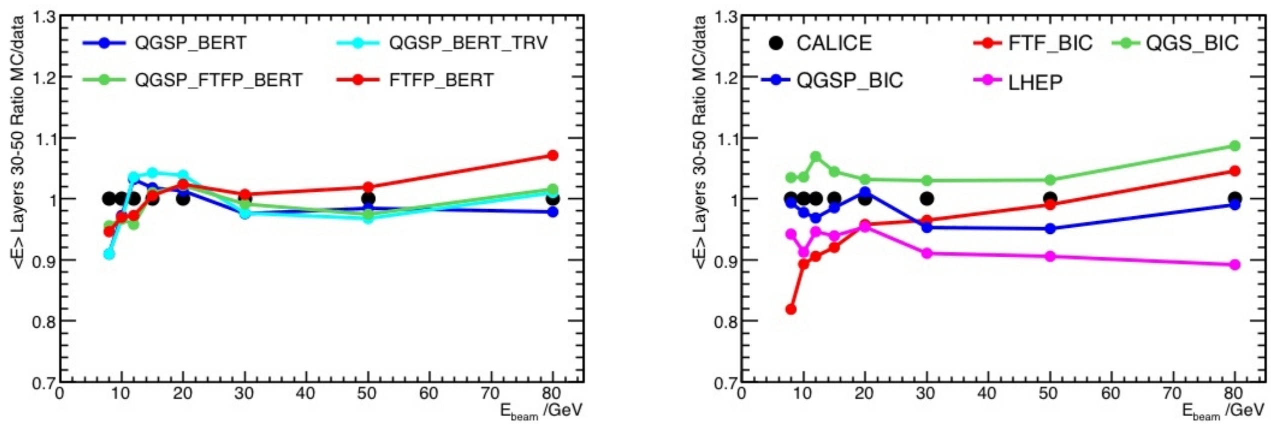
Layer 5-20:

elm. component



Layer 30-50:

Shower hadrons



Summary and Outlook

- Successful R&D for a highly granular electromagnetic calorimeter

- Detector concept is built on Particle Flow

<u>Physics Prototype</u> (2005-2009):
- Energy resolution ~17%/√E
- Signal to Noise Ratio ~8/1
- Stable calibration

<u>Technological Prototype</u> (2010-...):
- Mechanical concept validated with demonstrator
- Silicon Wafer technology at hand
- Front End Electronics will be challenging
  Embedded into calorimeter layers, power pulsing

- Capacity of separating particles impressively demonstrated by test beam analysis

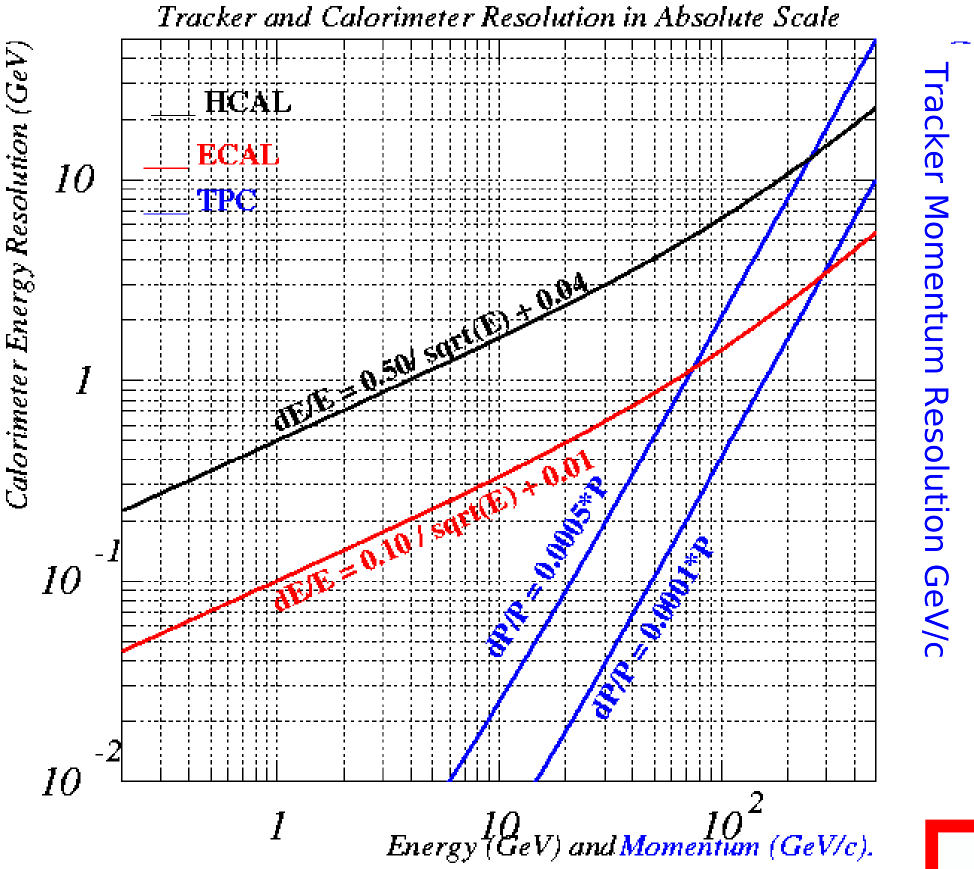
- Unprecedented realistic views into hadronic showers thanks to high granularity
  'Modern bubble chamber'

- Coping with vast amount of information is challenging
  The harvest is just starting

Backup Slides

Jet Energy Resolution

Final state contains high energetic jets from e.g. Z,W decays
Need to reconstruct the jet energy to the utmost precision !



Jet energy carried by …

- Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$)): 65%
  Most precise measurement by Tracker
  Up to 100 GeV

- Photons: 25%
  Measurement by Electromagnetic Calorimeter (ECAL)

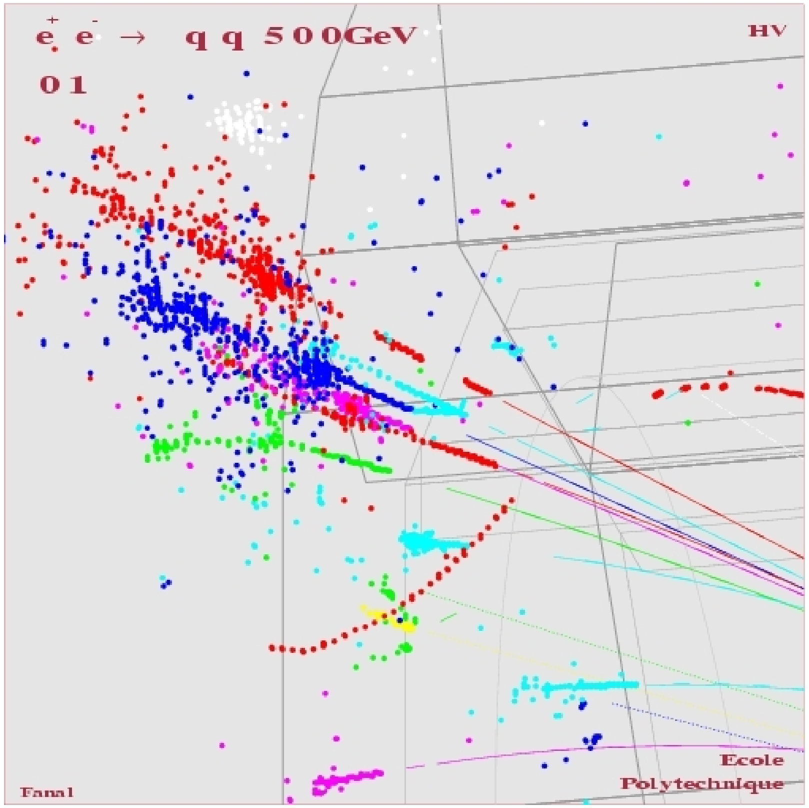
- Neutral Hadrons: 10%
  Measurement by Hadronic Calorimeter (HCAL) and ECAL

$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$

Confusion Term

- Base measurement as much as possible on measurement of charged particles in tracking devices

- Separate of signals by charged and neutral particles in calorimeter



- Complicated topology by (hadronic) showers

- Correct assignment of energy nearly impossible

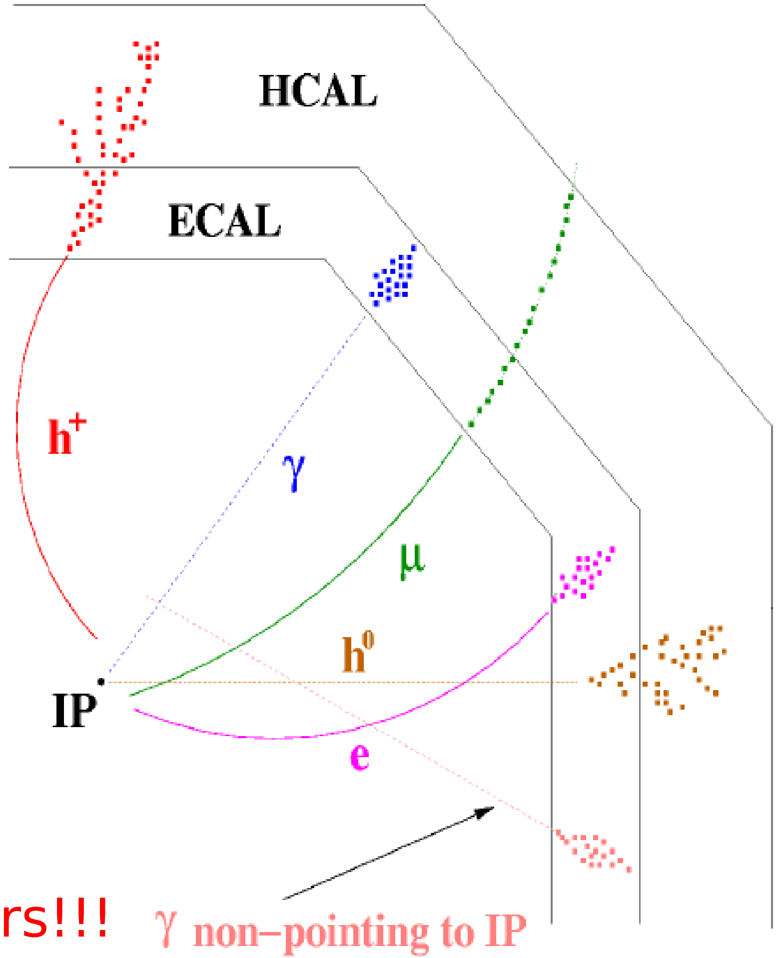
$\Rightarrow$ Confusion Term

Need to minimize the confusion term as much as possible !!!

Detector and Calorimeter Concept – Particle Flow

Jet energy measurement by measurement of **individual particles**
Maximal exploitation of precise tracking measurement

- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- “no” material in front of calorimeters
  - stay inside coil
- small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping showers



Physics Goals at the ILC demand the
Construction of Highly Granular Calorimeters!!!
Emphasis on tracking capabilities of calorimeters