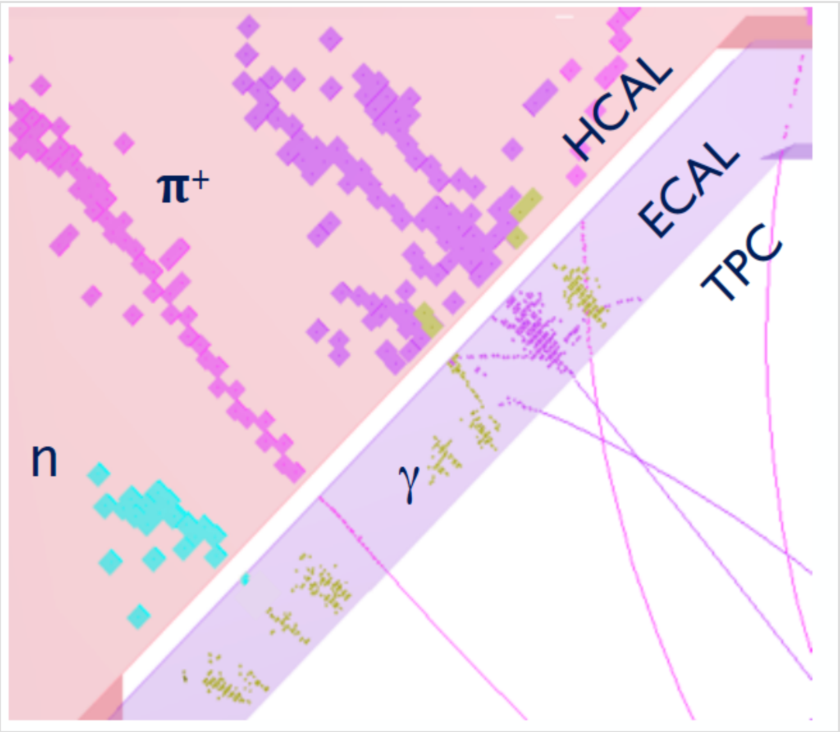
Software Compensation and Particle Flow



Katja Krüger (DESY)
for the CALICE collaboration

CHEF 2017
Lyon, 5 October 2017

HELMHOLTZ ASSOCIATION

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY

Outline

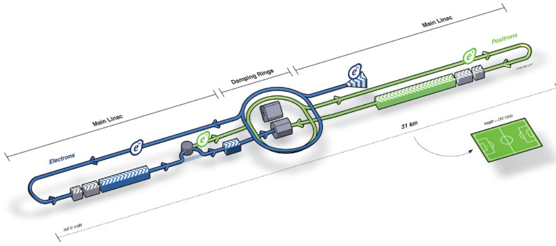
- Motivation
- Particle Flow Reconstruction & Software Compensation
- Software Compensation with Testbeam Data
- Software Compensation in PandoraPFA
  - Single Hadrons
  - Jets
  - Implications for the HCAL Granularity

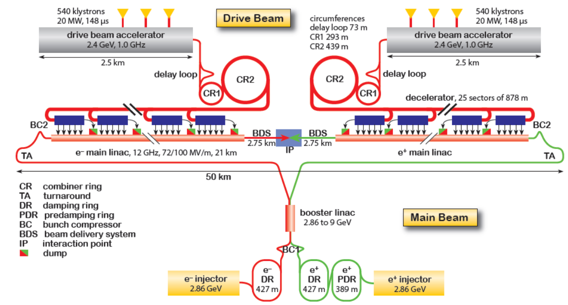
PandoraPFA results from arXiv:1705.10363, submitted to EPJC: based on a (generic) ILD detector for ILC

making use of the ILD software framework, only possible thanks to the work of many colleagues contributing to the development of ILD software!

Motivation: Future Linear Colliders

- future e+e- colliders offer unique physics possibilities
  - precise model-independent Higgs couplings
  - precision measurements of W, Z and top properties
  - indirect and direct searches for BSM physics
- ILC: under discussion in Japan
  - $\sqrt{s}$ up to 500 GeV, upgradeable to 1 TeV
  - 31 km long, superconducting RF cavities
- CLIC: developed at CERN
  - $\sqrt{s}$ up to 3 TeV
  - 50 km long, two-beam acceleration
- main interest for calorimeters at linear colliders: jet energies



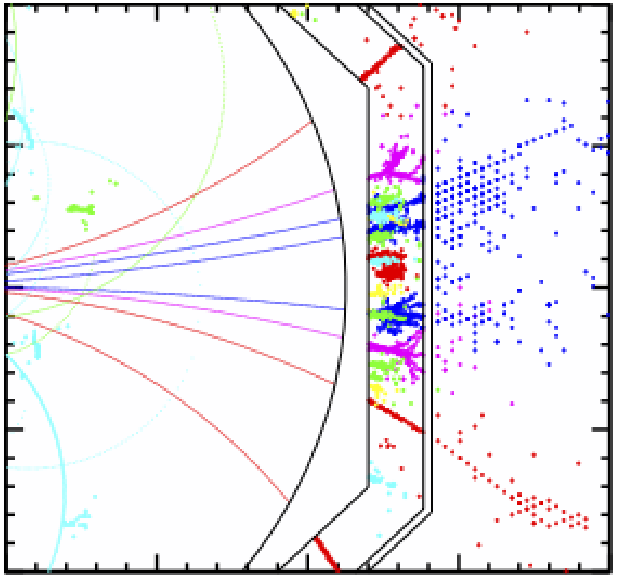


Physics Process	Measured Quantity	Critical System	Physical Magnitude	Required Performance
Zhh $Zh \to q\bar{q}b\bar{b}$ $Zh \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	3% to 4%

from ILC TDR

Particle Flow Reconstruction

- 3-4% jet energy resolution not possible with calorimeter information alone
  → use Particle Flow Algorithms
- Idea:
  for each individual particle in a jet, use the detector part with the best energy resolution



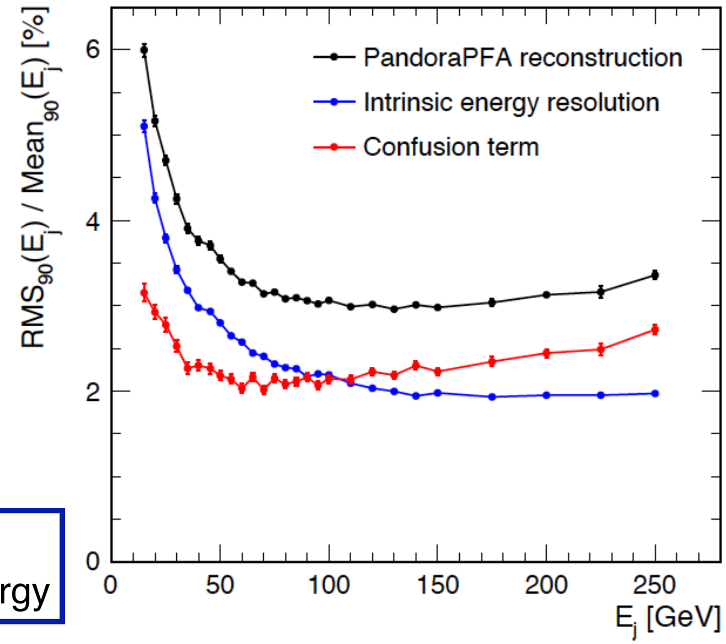
from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „typical“ jet:

		$(\sigma_{jet})^2$
~ 60% charged particles	tracking	$= (\sigma_{tracks})^2$
~ 30% photons	EM calorimeter	$+ (\sigma_{EMCalo})^2$
~ 10% neutral hadrons	HAD calorimeter	$+ (\sigma_{HADCalo})^2$
~ 1% neutrinos		$+ (\sigma_{loss})^2 + (\sigma_{confusion})^2$

Particle Flow Performance with PandoraPFA

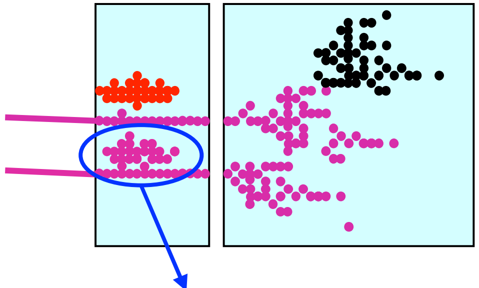
- separating the energy depositions of individual particles requires high granularity
- calorimeter energy resolution is still important
  - dominates for jets up to 100 GeV
  - contributes to resolving confusion



Pattern recognition based on topology and energy

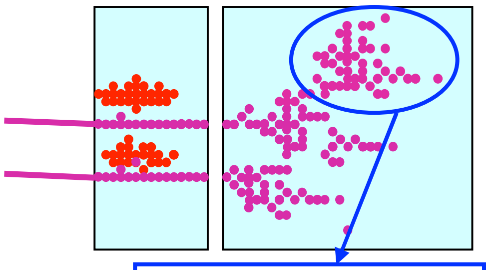
Types of confusion:

i) Photons



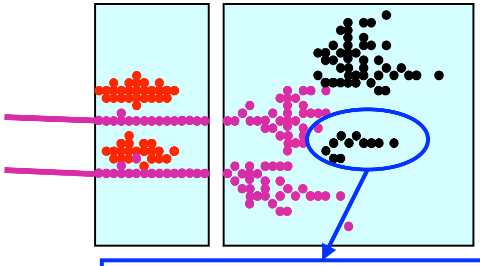
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



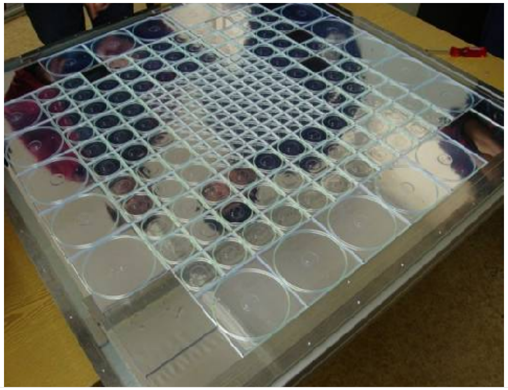
Reconstruct fragment as separate neutral hadron

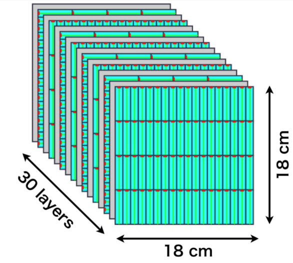
Particle Flow Reconstruction & Software Compensation

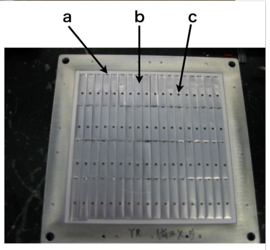
> CALICE collaboration develops highly granular calorimeters
  - optimised for particle flow reconstruction
  - high granularity can be useful for other tasks: pile-up mitigation, software compensation

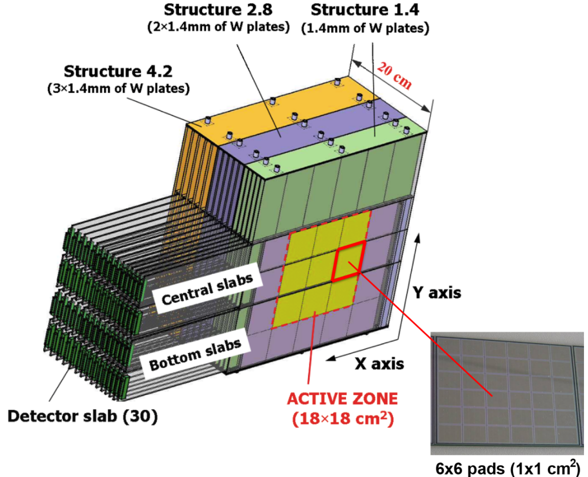
> CALICE prototypes shown in this talk:
  - AHCAL: scintillator-steel hadron calorimeter, 3*3 cm² scintillator tiles read out by SiPMs
  - ScECAL: scintillator-tungsten EM calorimeter, 4.5*1 cm² scintillator strips read out by SiPMs
  - SiECAL: silicon-tungsten EM calorimeter, 1*1 cm² silicon pads

> all these calorimeters are non-compensating
  - hadronic response is smaller than EM response
  - granularity can help to disentangle components of hadronic shower





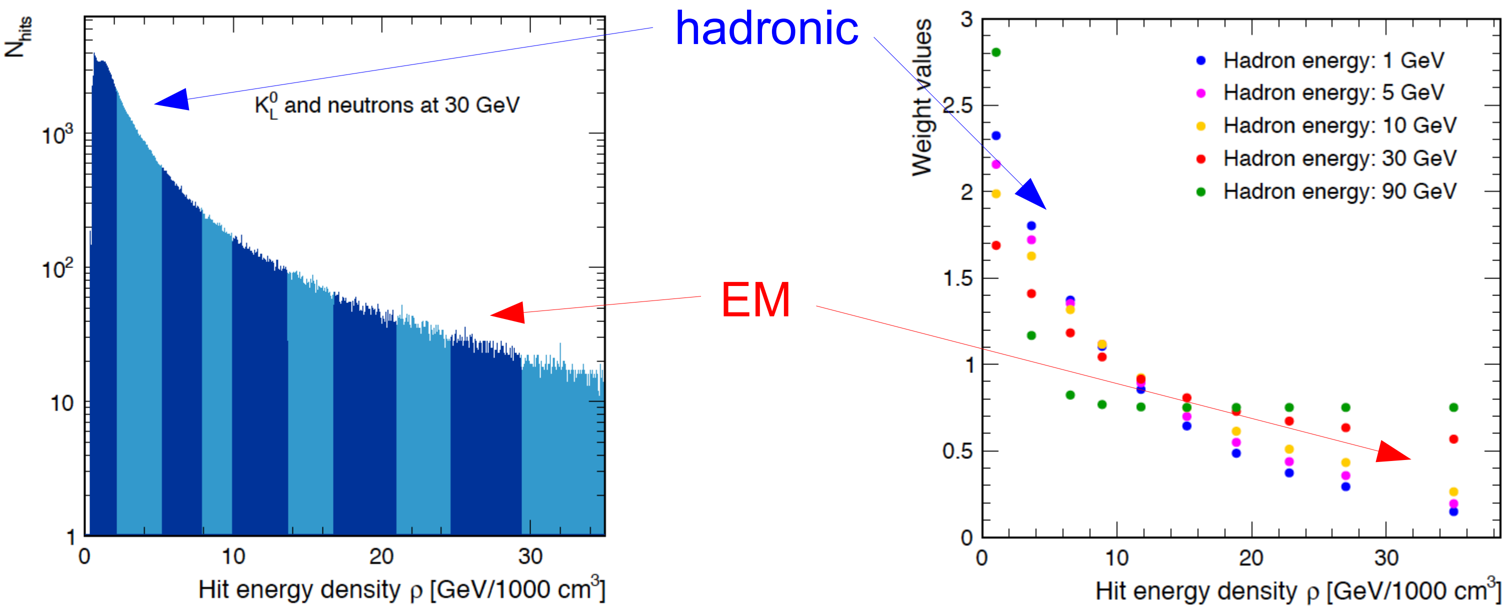




Software Compensation Logic

- correlate:
  - high energy-density (ρ) hits with EM sub-shower
  - low energy-density hits with hadronic shower component
- weight:
  - decrease weight for EM hits
  - increase weight for hadronic hits
  - weights depend on cluster energy, use simple energy sum as estimator (no prior knowledge from beam information)

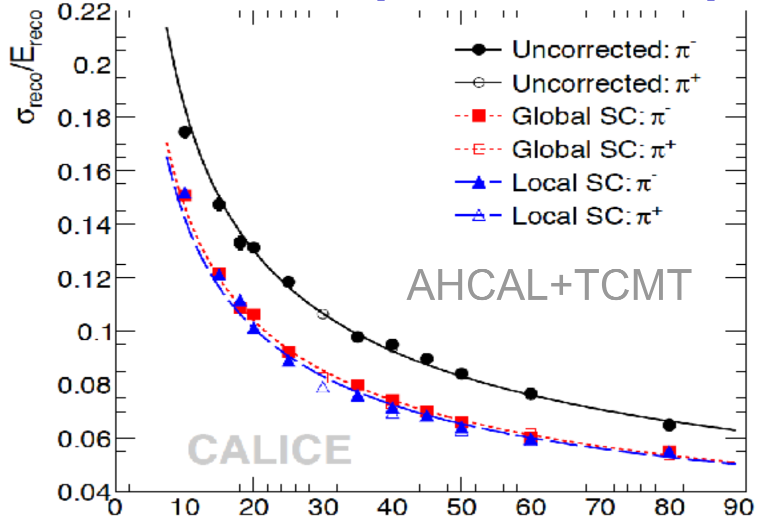
$$E_{SC} = \sum_{\text{hits}} E_{ECAL} + \sum_{\text{bin } i} (E^i_{HCAL} \times \omega(\rho_i))$$

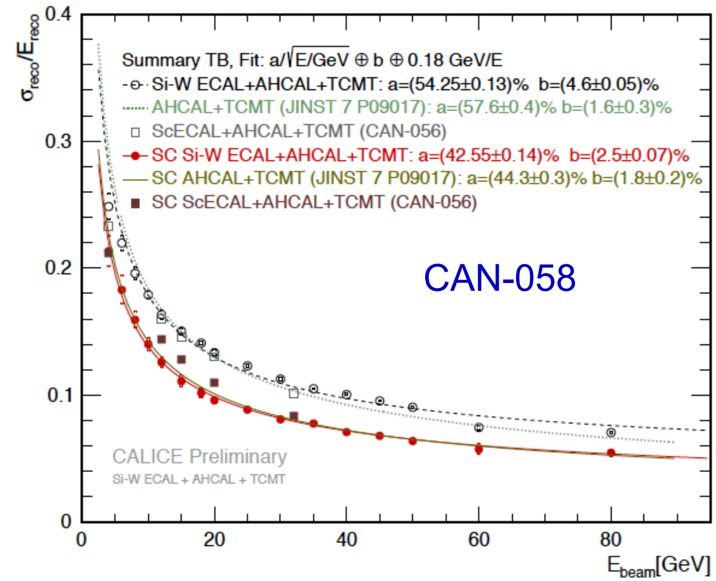


Software Compensation with Testbeam Data

- software compensation for single pions with CALICE AHCAL
  - improvement for hadronic energy resolution by ~20% in the energy range 10 to 80 GeV
- software compensation for single pions with combined calorimeters:
  - ScECAL + AHCAL
  - SiECAL + AHCAL
  - improvement for hadronic energy resolution by 10 to 30%
  - similar improvement in both configurations
  - more details in talk by Yasmine Israeli on Tuesday

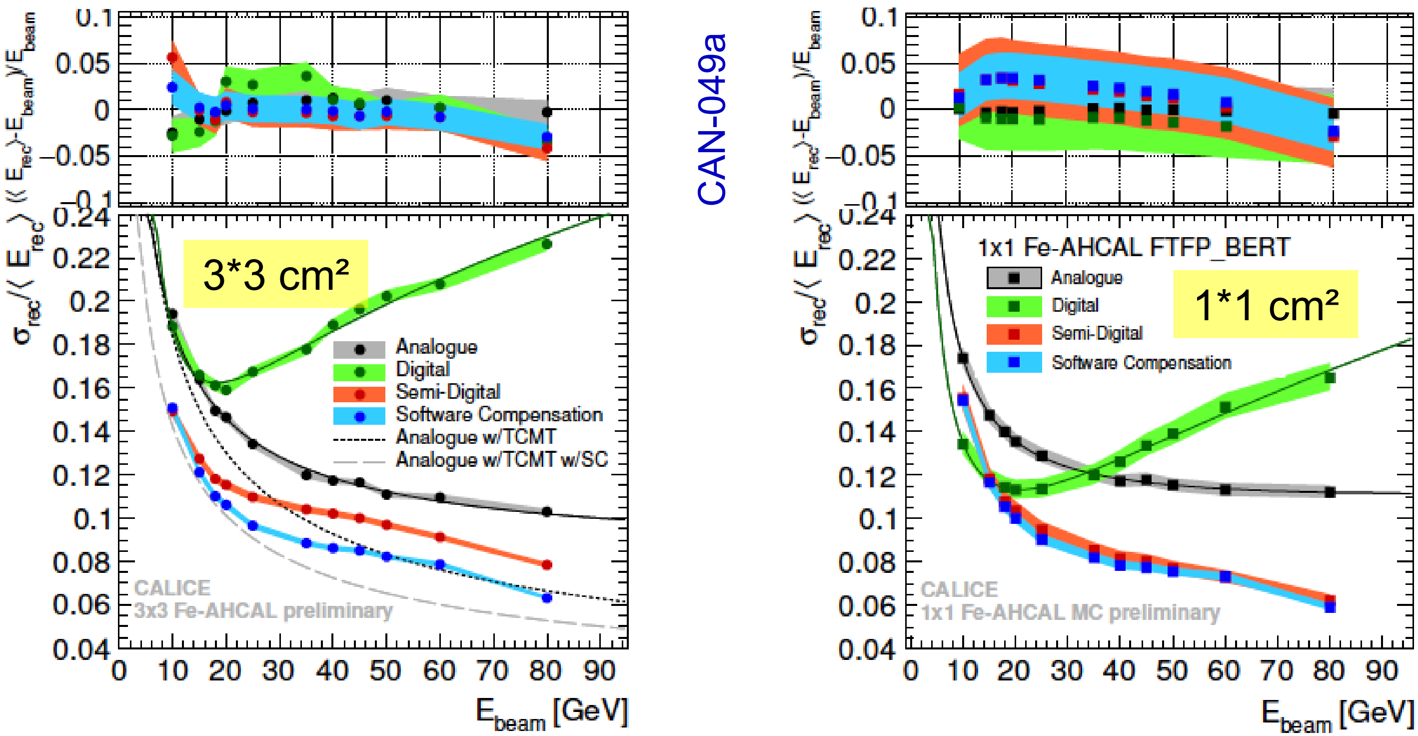
[arXiv: 1207.4210v2]





Software Compensation for Single Pions: Granularity

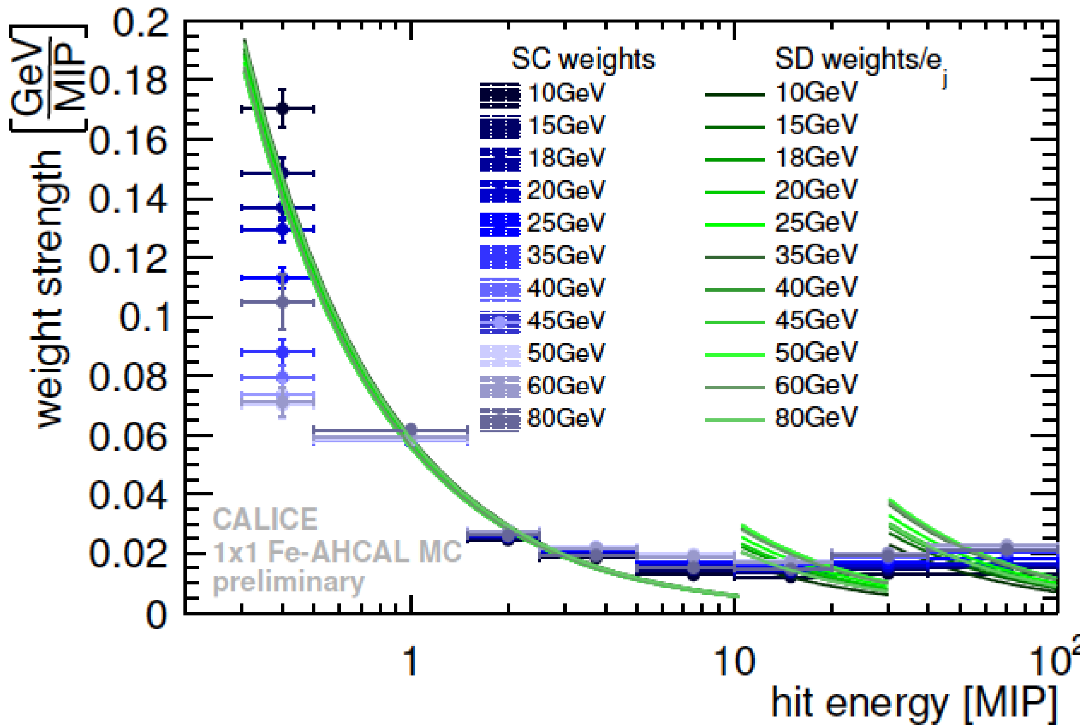
- interplay of reconstruction method and granularity
- AHCAL with 3*3 cm² tiles
  - Software Compensation better than semi-digital reco better than simple sum
- simulated AHCAL with 1*1 cm² tiles
  - Software Compensation for 1*1 cm² tiles not better than for 3*3 cm²
  - Software Compensation and semi-digital reco reach the same resolution



simulation 1*1 cm² scintillator tiles

Software Compensation for Single Pions: Weighting Method

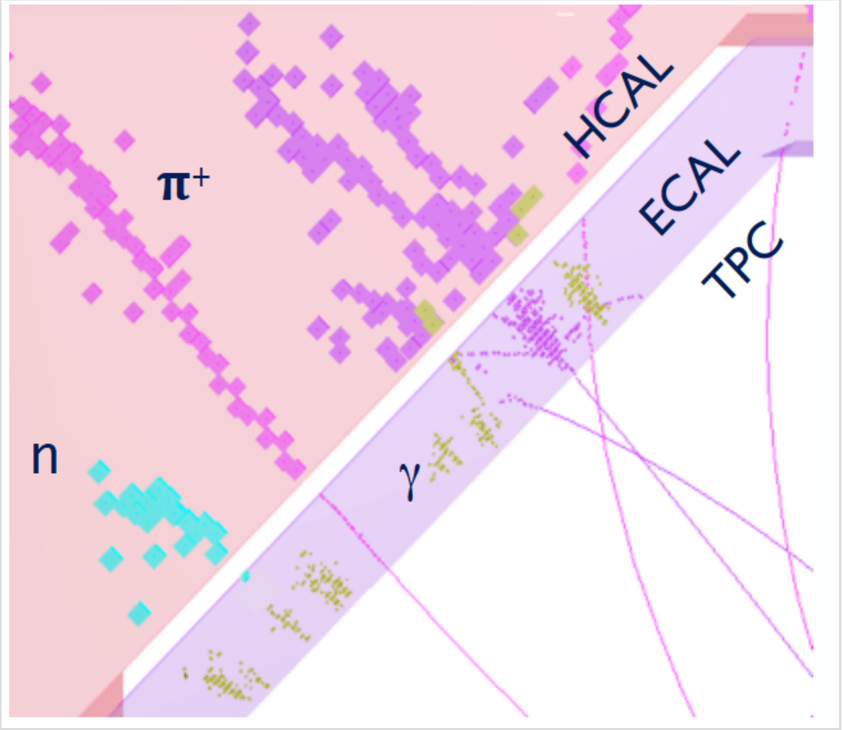
- different methods for software compensation for single pions with AHCAL
  - constant weight in each energy density bin
  - energy-density-dependent weight in each bin
    → for $\omega=1/\rho$ this is the same as counting hits
  - → corresponds to semi-digital readout (with arbitrary number of thresholds)
- not only energy resolutions, but also weights very similar for both methods



CAN-049a

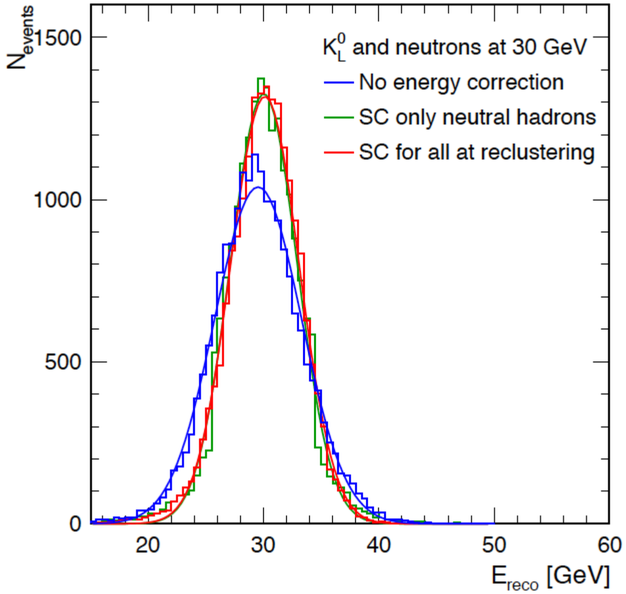
Software Compensation in Particle Flow Reconstruction

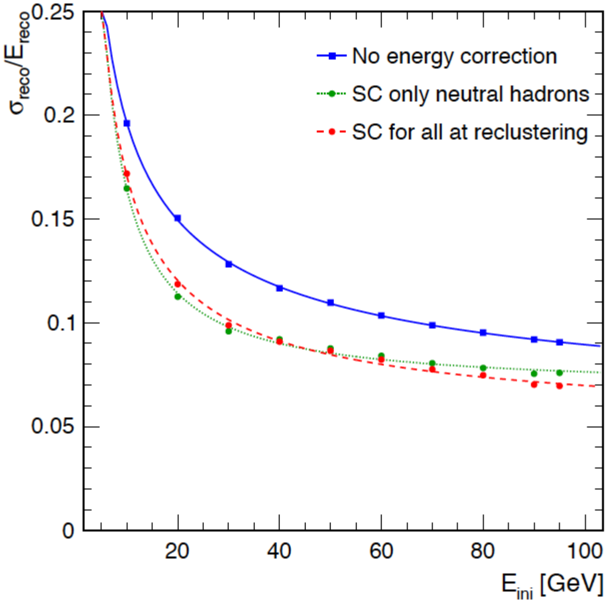
- software compensation successfully tested for single hadrons in testbeam data
- possible improvements due to software compensation in particle flow reconstruction
  1) better single neutral hadron energy reconstruction
  2) better track – cluster matching leading to less confusion
- implementation in PandoraPFA particle flow reconstruction
  - in the cluster energy estimation: 1)
  - in the pattern recognition reconstruction: 1) and 2)
- studies shown are done with simulation of (generic) ILD detector



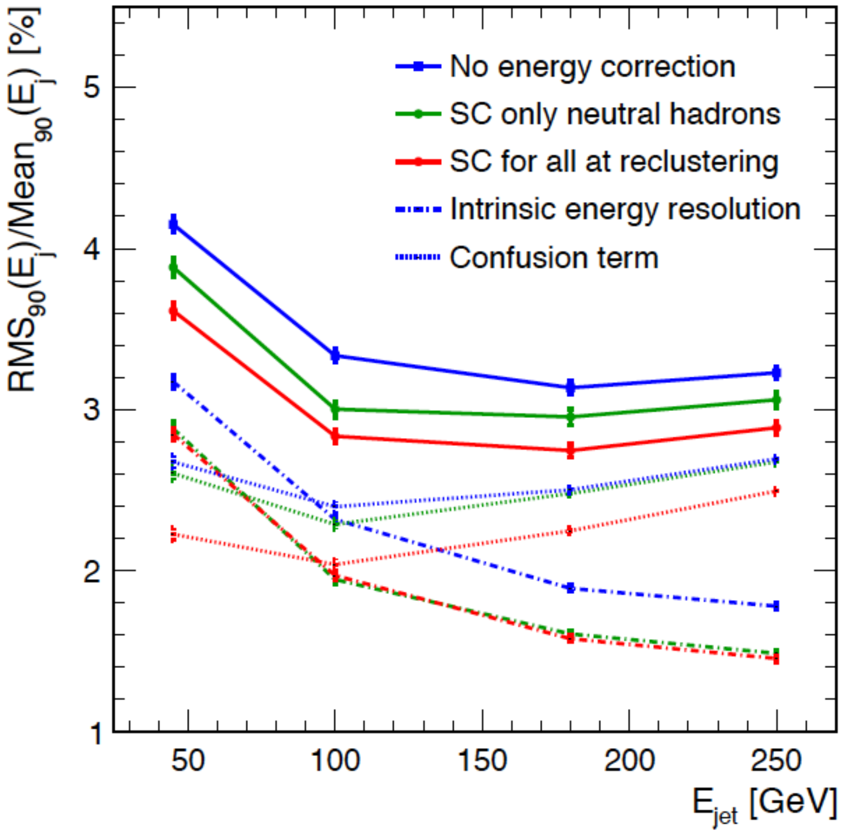
Software Compensation in PandoraPFA: Single Hadrons

- application of software compensation in PandoraPFA to simulated single neutral hadrons (K0L, n)
- significant improvement in the cluster energy estimation
  - as expected: very similar in size for application in cluster energy estimation only and for application also in pattern recognition
  - improvement of ~20% consistent with AHCAL testbeam data





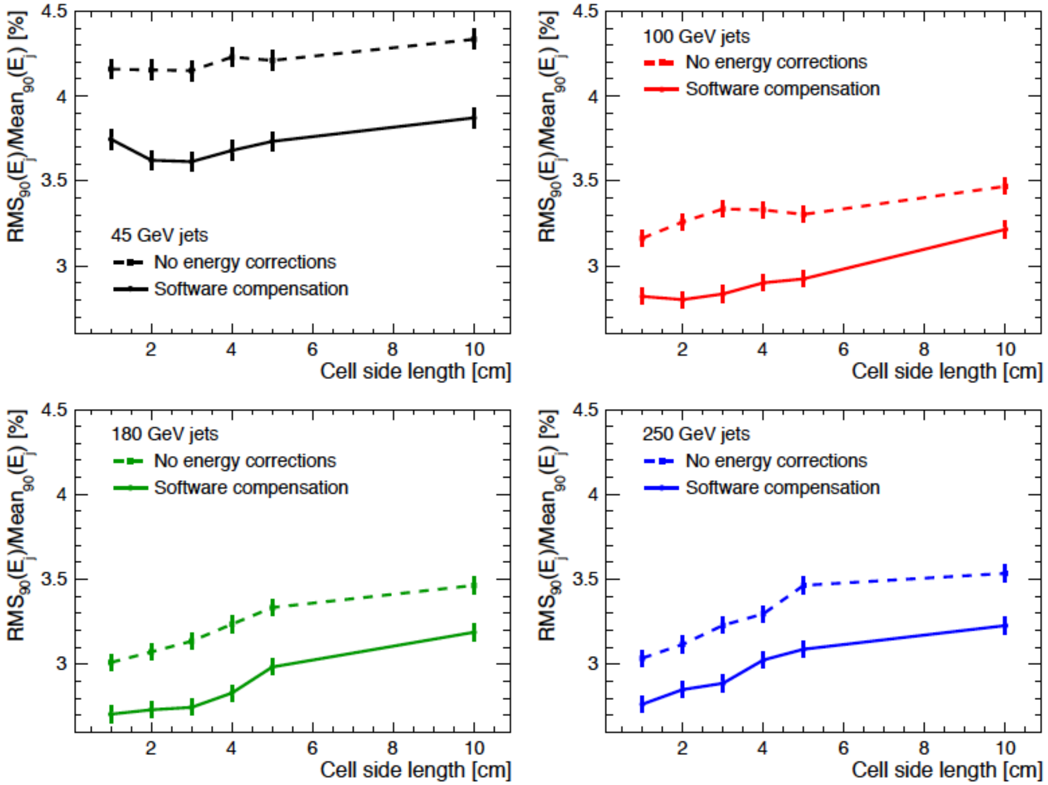
Software Compensation in PandoraPFA: Jets



- application of software compensation in PandoraPFA to simulated *uds* jets
- significant improvement in the jet energy resolution (JER)
  - contribution of the intrinsic energy resolution to the JER: effect similar to single hadrons
  - confusion term only affected by application of software compensation in pattern recognition
  - total JER: application in pattern recognition clearly better than application in cluster energy estimation only

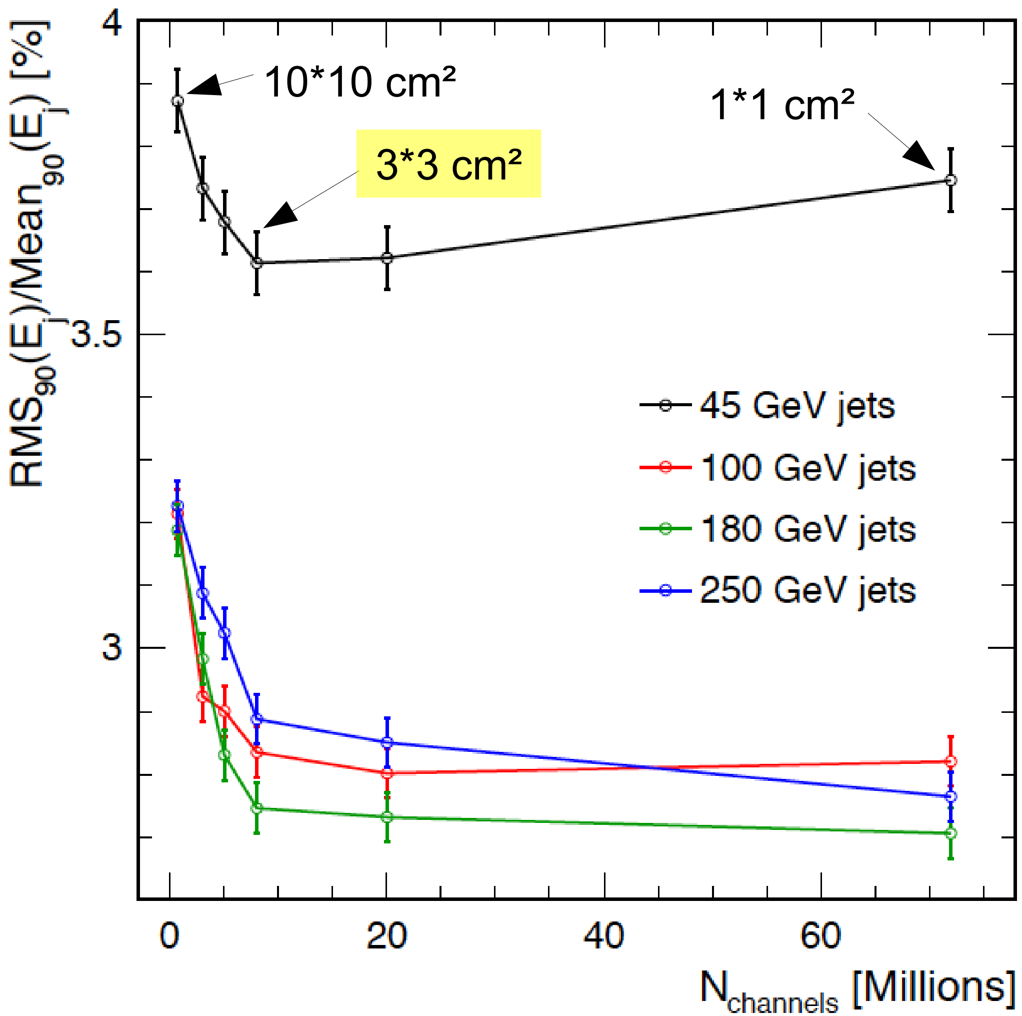
Software Compensation for Jets: Granularity

- granularity has an effect on pattern recognition in PandoraPFA
- software compensation leads to similar improvements for all granularities and all jet energies
  - weights need to be optimised for each cell size



Software Compensation for Jets: Number of Cells

- jet energy resolution with software compensation as function of the number of HCAL channels in ILD
  - number of channels is relevant for total cost
- original choice of 3*3 cm² is still very reasonable



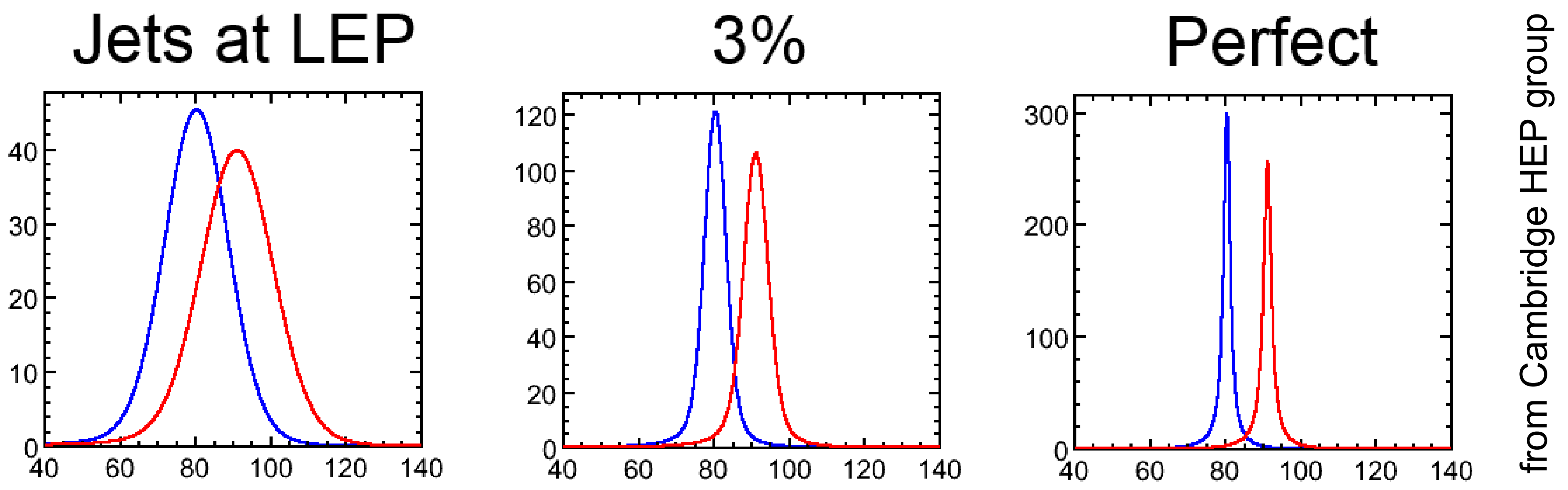
Summary

- highly granular calorimeters developed for Particle Flow reconstruction allow for Software Compensation
- beneficial effects of Software Compensation demonstrated with testbeam data of CALICE AHCAL without and with ECAL in front
  - improvements of 10% to 20% compared to simple energy summing
- Software Compensation in PandoraPFA Particle Flow reconstruction contributes in 2 places
  - single particle resolution for neutral hadrons
  - track – cluster matching in pattern recognition
- consistent improvements with Software Compensation in PandoraPFA for single particles and jets, both contributions equally relevant for jets
- no significant impact on granularity optimisation: choice of 3*3 cm for ILD AHCAL very reasonable

Backup

Why 3-4% jet energy resolution?

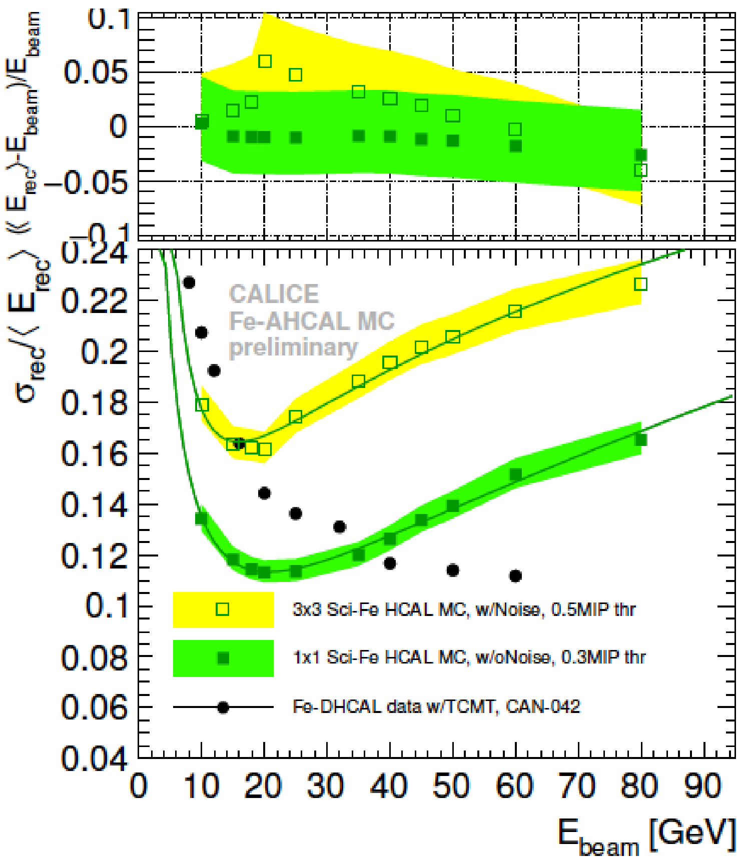
- goal: distinguish the decays $W \rightarrow jet\ jet$ and $Z \rightarrow jet\ jet$ by their reconstructed mass

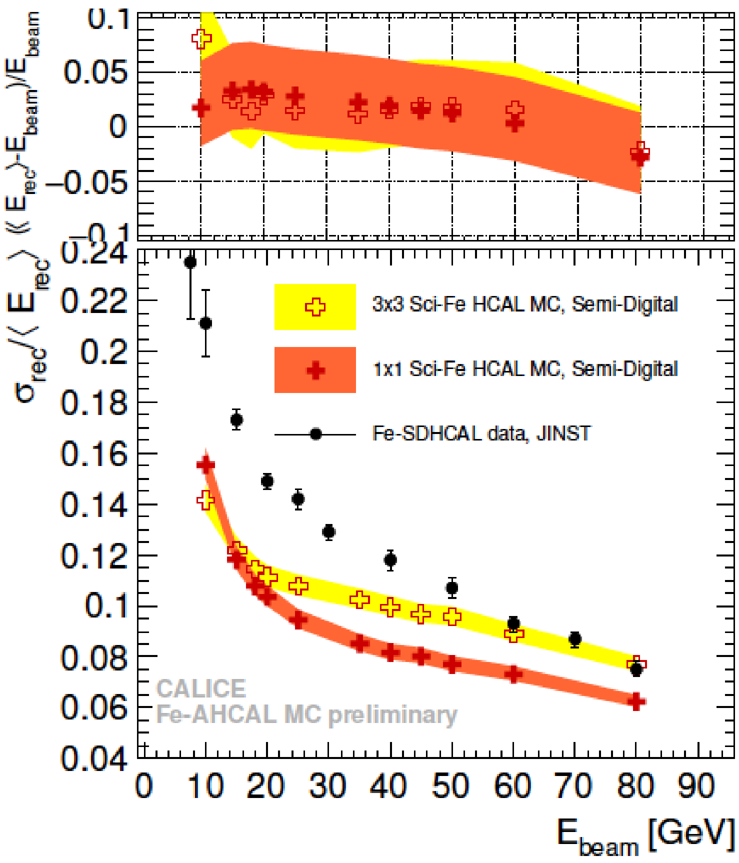


- required resolution: $\sigma(E_{jet})/E_{jet} \approx$ 3-4%
- interesting jet energy range: $E_{jet} \approx$ 40 to 500 GeV
- not possible with calorimeter information alone

  → use Particle Flow Algorithms

Comparison of Single Hadron Energy Resolutions



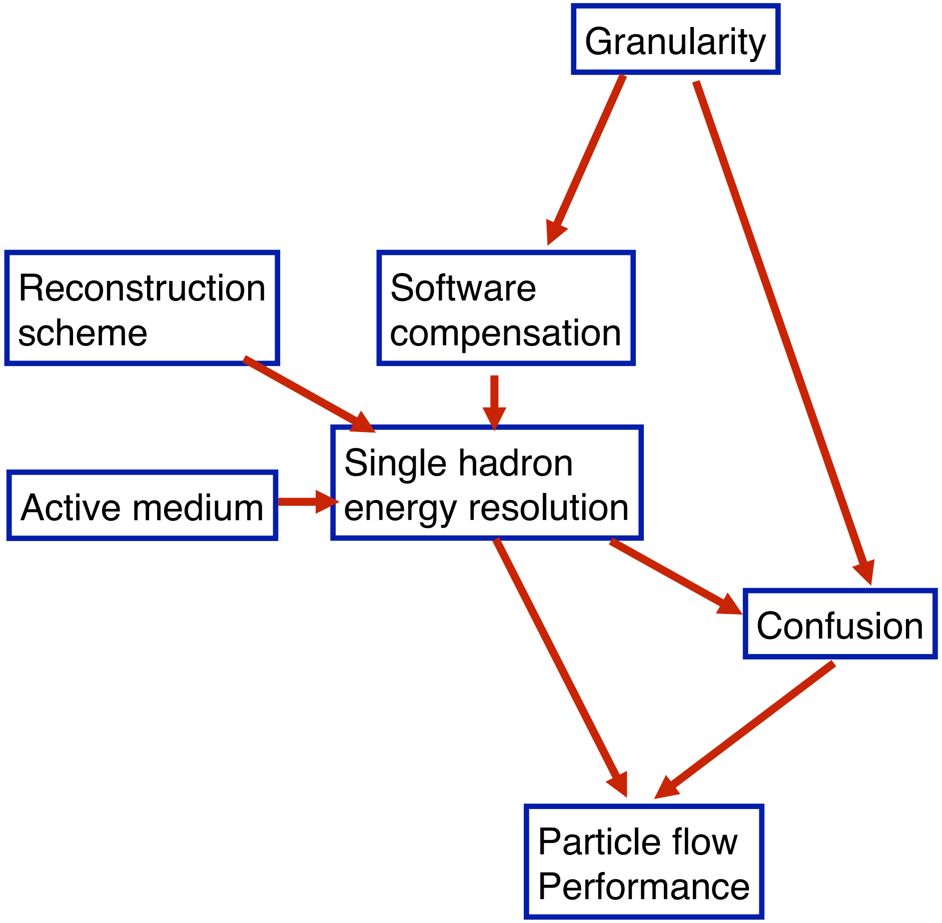


Software version and configuration

- **Detector model**: ILD_o1_v06
- **Reconstruction software**: ilcsoft_v01-17-07 combined with PandoraPFA version v02-09-00:
  - PandoraSDK v02-03-01
  - LCContent v02-04-00 including software compensation in LCPlugins and hits information registration for software compensation weight training in LCUtility
  - PandoraMonitoring v02-03-00

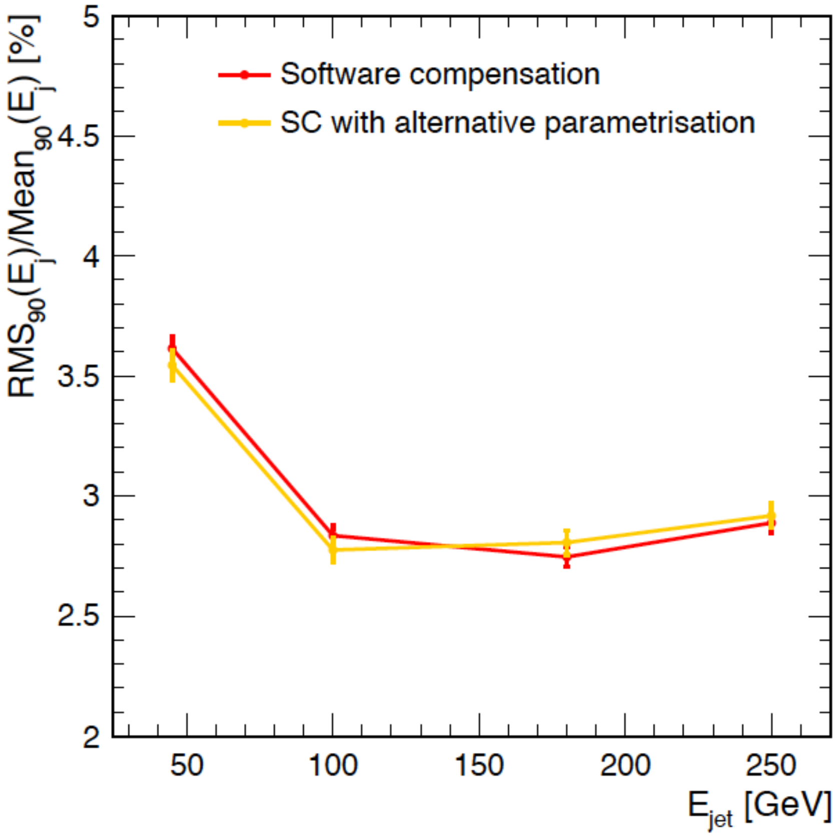
- **Digitiser**: ILDCaloDigi with realistic options for ECAL and HCAL
- **Calibration constants** optimised using PandoraAnalysis toolkit
- **Timing cut**: 100 *ns*

Software Compensation, Particle Flow and Granularity



Software Compensation for Jets: Weighting Method

- application of software compensation in PandoraPFA to simulated *uds* jets
- test different weighting methods in software compensation
  - "classic" software compensation: force exponential dependence of weights on ρ
  - alternative: parametrize weights for each ρ bin individually
- energy resolution for jets is nearly identical for the two weighting methods



Single Particle Resolution vs. Jet Energy Resolution

- example: ZEUS high-resolution uranium–scintillator calorimeter, compensating
- very good single particle resolution for hadrons: $35\%/\sqrt{E}$
- jet energy resolution can be extracted from Z → jets measurement:
  - Gaussian core width of mass distribution: 6%
  - assumption: Z decay at rest
  - $\sigma_{Ejet}/\sqrt{Ejet} = \sigma_m/\sqrt{m}$
  - $\sigma_{Ejet}/Ejet = 57\%/\sqrt{Ejet}$
- good single particle resolution does not directly translate into good JER

Physics Letters B 718 (2013) 915–921