Hadronic energy reconstruction in the combined electromagnetic and hadronic calorimeter system of the CALICE Collaboration

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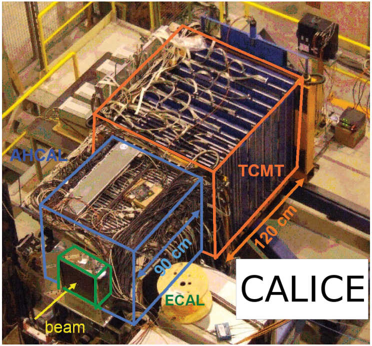
29th IMPRS Workshop
July 7th 2014

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

Calorimeter for ILC

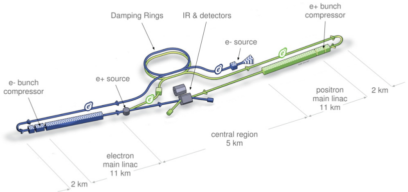
Overview



Future Linear Colliders

e^+e^--Colliders to complement LHC:

- Synchrotron radiation increases with E
  $\Rightarrow$ Only linear acc. can very reach high energies for e^+e^-



International Linear Collider (TDR published in 2013):

- Staged Implementation
  250 GeV, 350 GeV, 500 GeV
  (upgrade to 1 TeV possible)
- $\mathcal{L} = 2 \cdot 10^{34} \frac{1}{cm^2 s}$

Benefits for Physics:

- Exploration of Electroweak sector
- Model Independent Measurements
- Low Background

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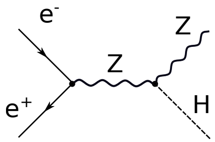
Calorimeter for ILC

Physics

Guaranteed Program

- Higgs measurements:
  - Couplings to fermions and bosons (including c, g)
  - Self-coupling
  - Total width
  - Top Yukawa coupling
- Top physics:
  - Measurements at threshold
  - Precise mass, width
- Precision physics:
  - Electroweak
  - QCD

One important measurement:



- Model-independent
- Identify Higgs production from Z recoil irrespective of Higgs decay

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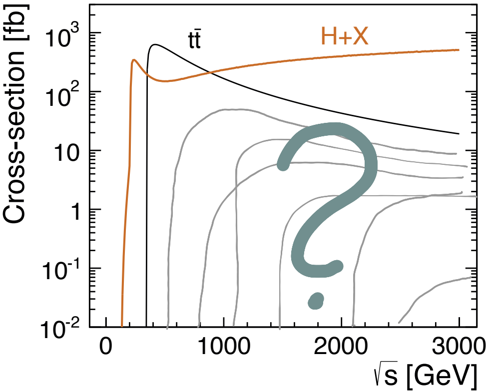
Physics

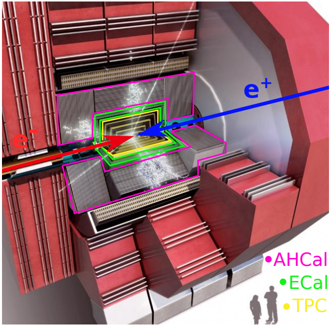
Possible Discoveries:

- Direct Production of new particles up to $\sqrt{s}/2$
- Indirect(Model-dependent) search for New Physics



Design of Detectors

- Vertex and TPC for precise tracking
- Electromagnetic calorimeter for γ and $e^- e^+$ energy
- Hadronic calorimeter for charged and neutral hadrons
  $\Rightarrow$ HCal energy resolution is **Bottleneck** for standard jet reconstruction
- Solenoid and return yoke



Higher precision:

- Combine tracking and calorimetry information $\Rightarrow$ Particle Flow
- Assignment $E_{deposit}$ to right particle crucial $\Rightarrow$ Requires high spatial resolution in calorimeters

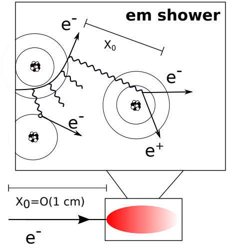
Particle Flow concept dictates calorimeter design

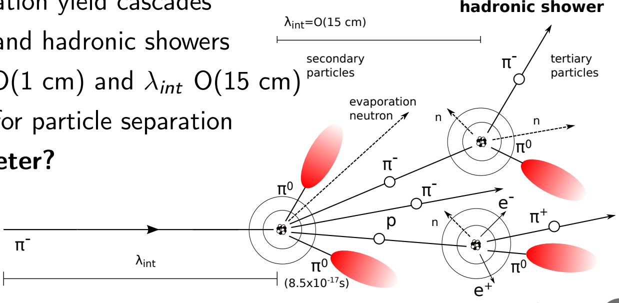
Calorimetry

Incoming particle:

- Destructive measurement: Total absorption
- Different interactions(Bremsstrahlung, pair production, inelastic hadronic interactions, spallation etc.)
- Particle multiplication yield cascades
- Electromagnetic and hadronic showers
- Governed by X_0 O(1 cm) and λ_{int} O(15 cm)
- High granularity for particle separation

Design of a Calorimeter?





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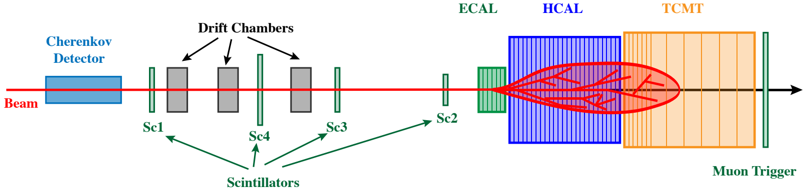
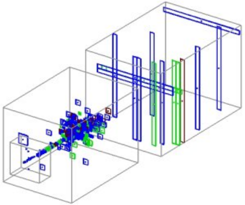
Calorimeter for ILC

CALICE Prototype



Highly Granular Sampling Calorimeters:

- Most energy deposited in absorber plates
- Conversion factor needed $E_{seen} \cdot C = E_{total}$
- Three different sub-detectors
  $\Rightarrow$ Inter-calibration
- 20000 Channels



Two ways for energy reconstruction

Basic Reconstruction

Calorimetry is counting of shower particles:

- $E \propto N \Rightarrow E_{toal} = \sum_{ECalhits} E_{hit} \cdot \omega$
- ω accounts for sampling fraction!
- Introduce one weight per sub-detector
- ω_{ECal}, ω_{HCal} and ω_{TCMT} account for inter calibration

Determination of calibration factors?

Use of χ^2 minimization procedure

$$\chi^2 = \sum_{events} \left(\sum_{ECalhits} E_{hit}\omega_{ECal} + \sum_{AHCalhits} E_{hit}\omega_{AHCal} + \sum_{TCMThits} E_{hit}\omega_{TCMT} - E_{beam} \right)^2$$

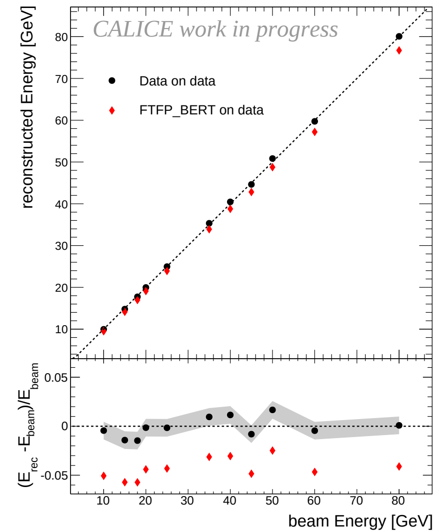
Reconstructed Energy

Calib. factors calculated with data and MC:

- Energy independent calibration factors
- Data reconstructed with factors from MC
  $\Rightarrow$ Constant offset
- MC does not perfectly reproduce visible energy

ECal	0.0049	$\frac{GeV}{MIP}$
AHCal	0.029	$\frac{GeV}{MIP}$
TCMT	0.031	$\frac{GeV}{MIP}$

Table: Factors from data



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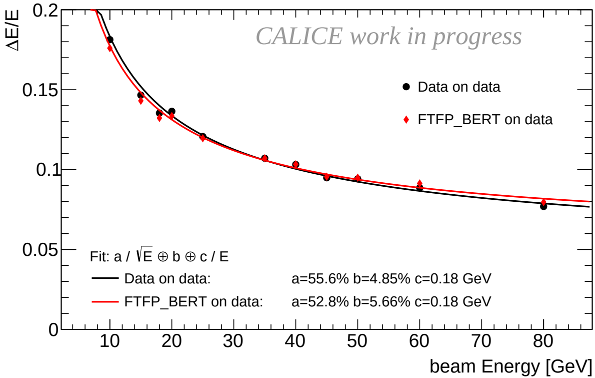
Resolution

Resolution	=	Stochastic Term	Constant Term	Noise Termn

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- Weights from FTFP_BERT and Data on same level
- Atlas: $\approx \frac{45\%}{\sqrt{E}}$
  CMS: $\approx \frac{100\%}{\sqrt{E}}$



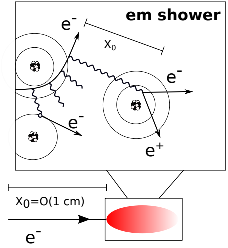
Enhance the resolution?

$\Rightarrow$ **Local Software Compensation**

The Idea of Software Compensation

Electromagnetic showers:

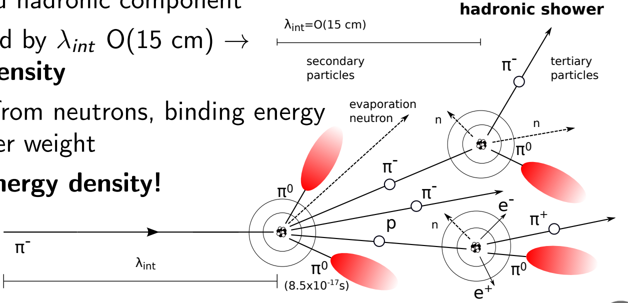
- Solely composed of γ, e^- $\rightarrow$ $E_{visivle} \propto E_{deposit}$
- Large number of particles in each events
- Governed by X_0 O(1 cm) $\rightarrow$ **Large Energy Density**



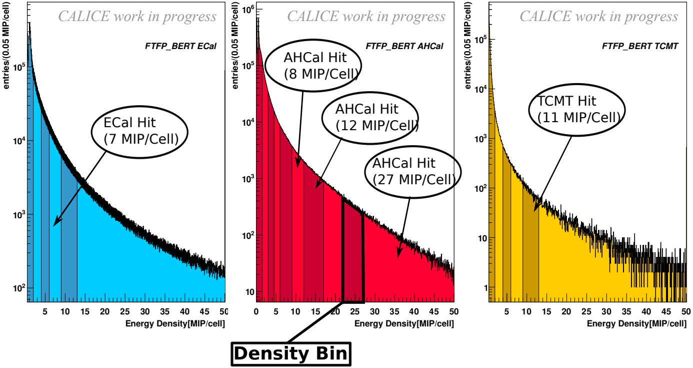
Hadronic showers:

- $\pi^0 \rightarrow \gamma\gamma$: em und hadronic component
- Hadronic governed by λ_{int} O(15 cm) $\rightarrow$ **Small Energy Density**
- Unseen deposits from neutrons, binding energy etc. $\rightarrow$ need larger weight

Classify hit by it's energy density!



The Implementation of Software Compensation



Assign each **Density Bin** it's own calibration factor

now 6 ω_i in ECal, 10 ω_j AHCal and 6 ω_k in TCMT $\Rightarrow$ 22 factors
i,j,k: Density Bin indexes

The Implementation of Software Compensation

Determination of $\omega_{i,j,k}$ via Minimization:

- Small Density Bin Index
  $\Rightarrow$ Small energy density
  $\Rightarrow$ More likely hadronic
  $\Rightarrow$ Higher weight
- Factors change with E_{beam}
  $\Rightarrow \omega_{i,j,k}(E_{beam})$
- Iterative Parameterization

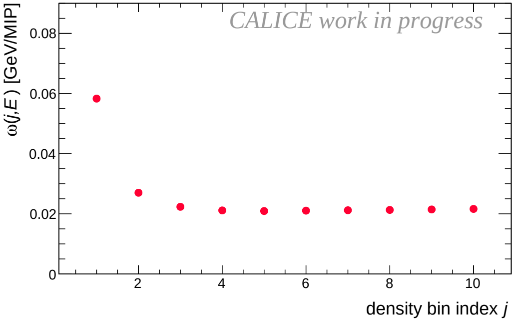
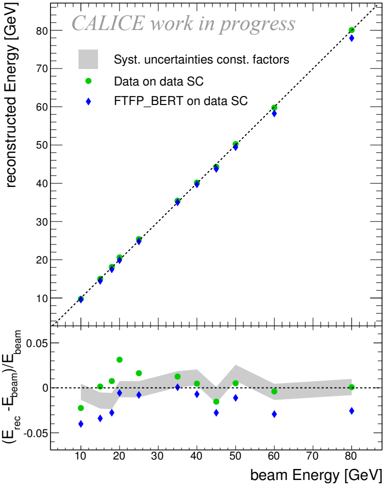


Figure: CALICE work in progress

Reconstructed Energy

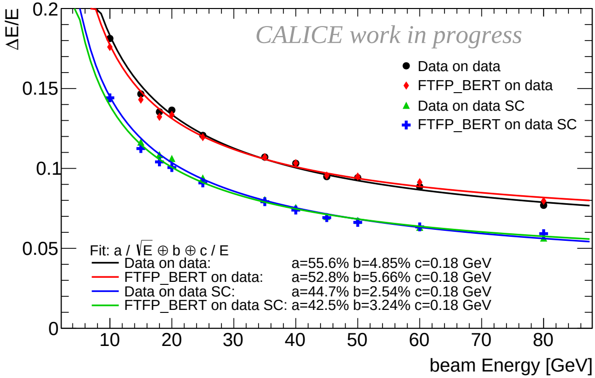
Calib. factors again calculated from data and FTFP_BERT:

- Reconstructed energy for MC factors again too low
- Offset decreased to ≈ 1-2%



Resolution

- Data and MC show good agreement
- Gain in resolution



Software Compensation clearly increases resolution

$$\frac{\sigma(E)}{E_{Reco}} \propto 55.6\% \Rightarrow 44.7\%,\ 4.85\% \Rightarrow 2.54\%$$

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Summary

- Calorimeter systems play important role at future linear collider detectors
- Calibration of sub-detectors possible with three constant factors
- Discrimination by energy density
  ⇒ Successful application of Software Compensation enhances Resolution
- Large progress in the simulation of hadronic showers
  ⇒ Results from Simulations and Data on comparable level

Still missing:

- Updated Monte Carlos

Possible next step:

- Further improve at low energies
- Expand analysis to low energy Fermilab data

Backup

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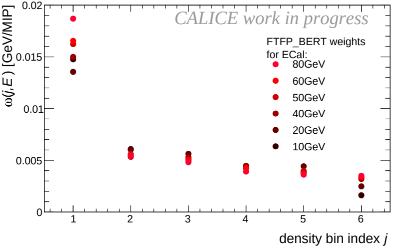
Calorimeter for ILC

Run list from CAN-35

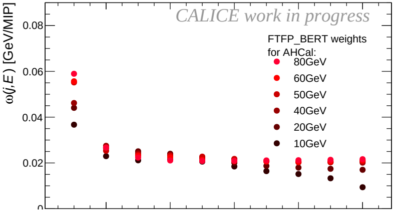
Table: List of used data runs.

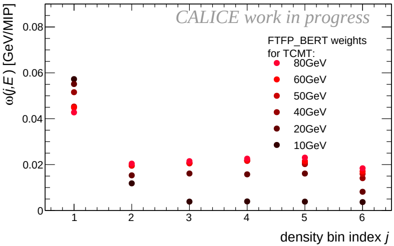
run number	particle type	beam energy, GeV
330332	π^-	10
330643	π^-	10
330777	π^-	10
330850	π^-	10
330328	π^-	15
330327	π^-	18
330649	π^-	20
330771	π^-	20
330325	π^-	25
330650	π^-	25
331298	π^+	30
331340	π^+	30
330551	π^-	35
330960	π^-	35
330390	π^-	40
330412	π^-	40
330560	π^-	40
331338	π^+	40
331339	π^+	40
330550	π^-	45
330559	π^-	45
330961	π^-	45
330391	π^-	50
330558	π^-	50
331335	π^+	50
331282	π^+	60
331333	π^+	60
331334	π^+	60
331556	π^-	60
331568	π^-	60
331655	π^-	60
331664	π^-	60
330392	π^-	80
330962	π^-	80
331280	π^+	80
331324	π^+	80
331554	π^-	80
331567	π^-	80
331654	π^-	80

Energy Dependence of Weights



$$\omega(j,E) = p_1(E)Exp^{(p_2(\mathbf{E})*\mathbf{j})} + p_3(E)$$





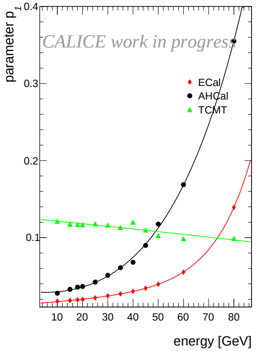
Parameterization

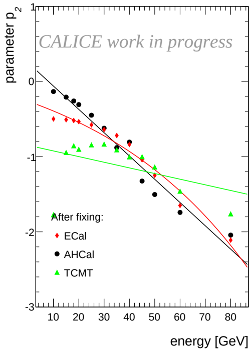
Iterative Procedure:

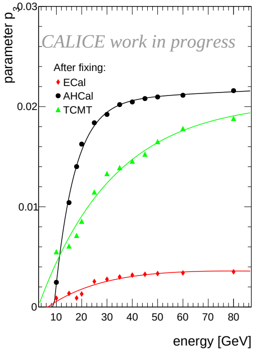
1. Minimize
2. Fix parameter 3
3. Minimize
4. Fix parameter 2
5. Minimize

ForExample :

- $p_1(E) = c_1 + E * c_2 + c_3 * Exp^{c_4 * E}$
- $p_2(E) = b_1 * E + b_2$
- $p_3(E) = a_1 * (1 - Exp^{a_2 * E}) + a_3$







Constant calib. factors from FTFP_BERT

ECal	0.004675	$\frac{GeV}{MIP}$
AHCal	0.02796	$\frac{GeV}{MIP}$
TCMT	0.02216	$\frac{GeV}{MIP}$

Table: Factors from FTFP_BERT

ECal	0.0049	$\frac{GeV}{MIP}$
AHCal	0.029	$\frac{GeV}{MIP}$
TCMT	0.0309	$\frac{GeV}{MIP}$

Table: Factors from data