A relation between track length and deposited energy in homogeneous calorimeter by GEANT4 simulation at high energy

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bbjes from Higgs factory

- $E_{b\text{-jet}} \approx 50-100 \text{GeV}$ at HF
- Energy Resolution of Jets (JER) PFA is degraded
- due to HCAL E-resolution intrinsic
- PFA does work well at higher energies
- to improve Jet EReso. in 50-100 GeV region $E_{\text{particle}} < 10 \text{GeV}$

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Eparticle<10GeV

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Particle Flow Algorithm

- PFA requires 3D calorimeter
- with fine segmented cells
- to separate each particles
- JetER is dominated by HCAL R at lower energies
- intrinsic resolution of HCAL
- measure total hadrons best case
- hoping fine segmentation

ILD at 250GeV
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ILD at 250GeV

ee>ZH>jj+jbjb

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total measurements

- GEANT4 simulation 2mx2mx2m
  \[ \text{time cut} < 100\text{ns} \]
  \[ \text{Hadron model = FTFP-BERT} \]

- homogeneous CAL. for exam:
  \[ \lambda = 16, X_0 = 225 \]
  \[ \text{absorber: PbWO}_4 \]

- two measures from the calorimeter

- TL : Track length \( \propto \) Cherenkov

- ED : \( dE/dx \propto \) scintillation

- how much ER at best?
  
  no photon statistics

  \[ \text{green lines are neutrons} \]

  \[ 3 \text{ GeV pion} \]
ED and TL for 5GeV pi-

**ED** (MeV) resolution~13% @ 5GeV

- ED = sum of energy deposit
- ~ sum of scintillation lights in PbWO4

**TL** (mm) resolution~30% @ 5GeV

- TL = sum of track length
- ~ sum of Cherenkov lights in PbWO4
ED vs TL

- strong correlation between ED vs TL for 5GeV pi-

ED (MeV)

TL (mm)

- approx. in linear with constant term in ED
ED vs TL for π+

- Several energies (1, 5, 10, 20 GeV)

1 GeV, 5 GeV, 10 GeV, 20 GeV

ED (MeV) vs TL (mm)

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ED vs TL

- pion - (3, 5, 10, 20 GeV)
Constant slope for π⁺ and e⁻:

\[ ED = A(E) + B \times TL \]

MeV

ED (MeV)

TL (mm)

\( \pi \) & e

5 GeV

3 GeV

1 GeV

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slop of $\text{ED}$ and $\text{TL}$

- when fitted with linear
  $\text{ED} = A(E) + B \cdot \text{TL}$
- slope $= B$ is constant for all energies $E > 1\, \text{GeV}$
- no difference with $\pi^-$ and $\pi^+$

$B$: slope

- $A(E)$
- $\pi^+$
- $\pi^-$

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**Intercept of fitted line**

\[ ED = A(E) + B \times TL \]

- **Intercept (cut) \( A(E) \)** is
- **Linear with injected energies**
- Same to \( \pi^- \) and \( \pi^+ \)
- **Good linearity**

\[ y = 27.753 + 0.46088x \quad R=0.99996 \]

**\( \pi^+ \)**

A: **Intercept**

\[ y = 40.146 + 0.45714x \quad R=0.99995 \]

**\( \pi^- \)**

A: **Intercept**
Resolution

\[ ED = A(E) + B \times TL \]

- \[ B = \frac{(ED - A(E))}{TL} \]
- \( B \) is independent on \( E \)
- resolution of the calorimeter \( \sim \sigma_B/B \)

\[ \sigma_B/B \]

\[ 10\text{GeV } \pi^- \]

\[ 25\% \text{ @1GeV} \]
Energy resolution

\[ ED = A(E) + B^* TL \]

- energy resolution = \( \frac{\sigma_B}{B} \)
- \( \frac{\sigma_B}{B} \) scales in \( \frac{1}{\sqrt{E \text{(GeV)}}} \)
- kink at \( \sim 5 \text{GeV} \) due to
- Hadron model in G4

\[ \sigma_B/B \sim 25\% / \sqrt{E} \]

\[ 50, 20, 10, 5, 3, 1 \text{GeV} \]
EM response

$ED = A(E) + B \times TL$

- **ED vs TL**: 

- $A(E)$ shows good linearity

- $B$ is const. at $E > 100\text{MeV}$

- $B$ is same as $\sim \pi + e/h \approx 1$

$E\text{MeV}$ vs $TL(\text{mm})$

10 GeV $e^{-}$

- $B(\text{MeV/mm})$

$B(\text{MeV/mm})$

$E_{e^{-}}(\text{MeV})$

$E_{e^{-}}(\text{MeV})$

$1\% @ 1\text{GeV}$
how to measure

- energy resolution ~ 25%/ sqrt(E)
- from ED and TL
- use heavy crystal such as PbWO4
- ED ~ dE/dx ~ scintillation lights
- TL ~ Cherenkov lights
- MPPC+air coupling: scintillation
- MPPC+glue: Cherenkov + scintillation

due to total reflection of Cherenkov angle

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how to measure

- energy
- from $E_{D}$
- use head
- $E_{D} \sim dE$
- TL $\sim$ Cherenkov
- MPPC+air
- MPPC+glue

due to total reflection of Cherenkov angle

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summary and outlook

- homogeneous calorimeter is simulated
- found a linear relation between \( \text{ED} \) and \( \text{TL} \)
  \[
  \text{ED} = A(E) + B \times \text{TL}
  \]
- good linearity by intercept \( A(E) \)
- fine energy resolution \( B \) for pions, no photon stat.
- \( \text{ED} \sim \) scintillation light
- \( \text{TL} \sim \) Cherenkov light
- test calorimeter with \( \text{PbWO4} \)

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• reason of intercept
• muon+ : <200MeV uniform injection
• non-linear response close to 0=ED
• due to Bragg curve
discussion

- electron cases are tested
- $A/E_e \sim \text{const. at } E_e > 100\text{MeV}$ where EM shower dominates
- at lower $E_e$, close to zero
PFA performance

- PFA utilises
- tracker for charged
- ECAL for photons
- HCAL for KoL
- can separate W and Z
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![Graphs showing Mjj vs. mjj and events distribution.]

- Jet E res.
- W/Z sep
- perfect
- 3.1%
- 2.9%
- 2.6%
- 2.3%
- 2.0%
- 1.1%

- Defined as effective Gaussian equivalent
- Mass resolution
- jet energy resolution give decent W/Z separation
- 3 – 4%
- for W/Z separation, not much to gain beyond this as limited by W/Z widths
- sets a reasonable choice for Lepton Collider jet energy
- minimal goal ~3.5%

- Mainz, February 2013
- Mark Thomson

- What motivates the jet energy requirements at a future LC?
- In part, depends on physics..
- Likely to be primarily interested in di-jet mass resolution
- For a narrow resonance, want best possible di-jet mass res.
+ strong desire to separate W/Z hadronic decays

- e – e
- W/$\gamma$
- w
- q
- q
- q
- q

- e.g.
- Calorimetry at a Future Collider
- m$_{jj}$
- m$_{jj}$
- m$_{jj}$
- jet energy resolution
track length vs Nchernenkov light

- nice correlation: we can use track length instead of number of cherenkov light which consume CPU power for simulation

track length

300 p.e.
particle energy in jet

- particle energy distribution
- $E < 10$ GeV dominating

![Graph showing particle energy distribution for different categories: photon, charged, neutral hadron. The x-axis represents particle energy (GeV) and the y-axis represents entries. The table on the right shows ID, entries, mean, and RMS values for the data.]
# PbWO4

Scintillation properties of lead tungstate (PbWO4) crystals:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ((g/cm^3))</td>
<td>8.28</td>
</tr>
<tr>
<td>Radiation length ((cm))</td>
<td>0.92</td>
</tr>
<tr>
<td>Decay constant ((ns))</td>
<td>6/30</td>
</tr>
<tr>
<td>Emission peak ((nm))</td>
<td>440/530</td>
</tr>
<tr>
<td>Light yield (%) of NaI:Tl</td>
<td>0.5</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1123</td>
</tr>
<tr>
<td>Hardness ((\mu\Omega))</td>
<td>/</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>2.16</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>none</td>
</tr>
<tr>
<td>Cleavage</td>
<td>101</td>
</tr>
</tbody>
</table>