Atlas Electromagnetic Calorimeter

Master-Seminar WS16/17
Particle tracking and identification at high rates
Test predictions of theories on particle physics (Standard Model), including search for Higgs boson and its properties. Search for new particles predicted by supersymmetric theories.
Standard Model

- SM predicts W,Z to have vanishing masses
- However short range of weak interaction suggests W,Z to be massive
  - Confirmed 1983 at CERN SPS
- Englert-Brout-Higgs mechanism
Outline

• Higgs

• Calorimetry

• ATLAS electromagnetic Calorimeter

• Result
Higgs boson production at LHC

- LHC p-p luminosity:
  \[ 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1} \]

- Production:
  \[ \sigma \approx 10 \, \text{pb} = 10^{36} \, \text{cm}^2 \]

- \( \Rightarrow \) about 100 Higgs Bosons per second
Higgs boson decay channels

- Most promising channel for Higgs detection due to separation from background
- $\sigma(pp \rightarrow H \rightarrow \gamma\gamma) \approx 50 \text{ fb}$
QCD background

• Irreducible γγ-background

⇒ Detector requirement:

Excellent mass resolution of 1%

Angular contribution better than energy resolution
Mass resolution

\[ \left( \frac{m_H}{0} \right) = \left( \frac{E_{\gamma_1}}{p_{\gamma_1}} \right) + \left( \frac{E_{\gamma_2}}{p_{\gamma_2}} \right) \]

Rest frame \hspace{1cm} Detector frame

\[ m_H^2 = 2 E_{\gamma_1} E_{\gamma_2} (1 - \cos(\varphi)) \]

Higgs is approximately at rest:

\[ E_{\gamma_1} \approx E_{\gamma_2} \quad (1 - \cos(\varphi)) \approx \left( 2 - \frac{(\varphi - \pi)^2}{2} \right) \]

\[ \Rightarrow \Delta m_H (\varphi \approx \pi) \approx E_\gamma \frac{\pi}{2} \cdot \Delta \varphi \]

\[ \frac{\Delta m_H}{m_H} = 1\% \Rightarrow \Delta m_H \approx 1.25GeV \]

\[ \Rightarrow \Delta \varphi \underset{\leq}{\sim} \frac{1.25GeV \cdot 2}{\pi \cdot E_\gamma (\approx 62GeV)} = 0.01rad \]

\[ \Rightarrow \text{Detector requirement:} \]

\[ \Delta \varphi \leq 50mrad/\sqrt{E(GeV)} \]
QCD background

- Irreducible $\gamma\gamma$-background
  \[ \sigma_{\text{irrback}} \approx 100 \sigma_{H \to \gamma\gamma} \]

- $\gamma$/jet and jet/jet background (reducible)
  \[ \sigma_{jj+jj} \approx 10^6 \sigma_{H \to \gamma\gamma} \]

- Need jet rejection of \( R_j > 10^3 \) at \( \varepsilon_\gamma > 80\% \) to get \( \sigma_{jj+jj} \ll \sigma_{H \to \gamma\gamma} \)

⇒ Detector requirement:
Excellent particle identification and jet separation (high granularity)
Additional detector requirements

• High efficiency (for rare processes like H->γγ)

• Reconstruction capability and dynamic range from 1GeV (b-physics) to 5TeV (Z’/W’-decays)

• Total thickness of at least 24 radiation length

• Energy scale precision of 0.1%
Calorimeter

- Dense absorber material to “fully” absorb incident particle
- Active material to produce output signal proportional to input energy
Sampling calorimeter

- Absorber and active material can be the same (e.g. CsI, lead glass), or (more commonly) different:

  e.g. Pb
  -> Energy deposit

  e.g. scintillator (light output) or liquid argon (ionisation)
  -> Signal generation
Longitudinal shower development

- After $t$ radiation length, the number of particles is
  \[ N(t) \approx 2^t \]

- Average energy of shower particle is
  \[ E(t) \approx E_0 / 2^t \]

- Shower has maximum number of particle when critical energy is reached

- => shower maximum at
  \[ t_{\text{max}} \approx \frac{\ln(E_0 / E_c)}{\ln(2)} \]

For example:

\[
\begin{align*}
t_{\text{max}} (E_0 = 100 GeV) & \approx 11.5 X_0 \\
t_{\text{max}} (E_0 = 3 TeV) & \approx 16.4 X_0
\end{align*}
\]
Transverse shower development

• Emission of Bremsstrahlung under small angle

\[ \langle \Theta^2 \rangle \approx \frac{m}{E} = \frac{1}{\gamma^2} \]

• Multiple scattering dominates transverse shower development. Moliere theory (3d):

\[ \langle \Theta^2 \rangle = \left( \frac{21.2 \text{MeV}}{\beta \rho c} \right)^2 t \]

\[ R_M = \sqrt{\langle \Theta^2 \rangle_{x=x_0} X_0 \approx \frac{21 \text{MeV}}{E_c} X_0} \quad (=9.5\text{cm for liquid argon}) \]

• 95% of shower contained in \( 2R_M \)
Energy resolution

- Resolution of a sampling calorimeter usually takes the form:

\[ \frac{\sigma}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c \]

- **Noise term**
  - Electronic noise
  - Signal pileup

  Dominates at low energies

- **Sampling term**
  - Choice of absorber
  - Choice of active material
  - Thickness of sampling layers

  Typically most important in 10-100 GeV energy range

- **Constant term**
  - Depth of detector
  - Detector non-uniformities
  - Cracks
  - Dead material

  Dominates at high energies
Energy resolution

\[ \frac{\sigma}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c \approx 1\% \]

• Sampling term: \( \approx 10\%/\sqrt{E}(GeV) \)

• Constant term: < 0.7%
ATLAS Detector

44 m long
22 m high
7000 tons
Electromagnetic Calorimeter
Electromagnetic barrel calorimeter
Accordion structure

- Allows for better coverage of detector volume
- High voltage copper layer inductively coupled to kapton electrode
- Stainless steel for mechanic stability and better surface
Accordion structure
Segmentation

• Segmentation in $\eta$ by etching of electrodes
• Segmentation in $\phi$ by sampling of accordion plates
• Two longitudinal segments plus third segmentation as event trigger
• 190,000 channels
Angular resolution

- Position in $\phi$ is measured in the second sampling by using $3 \times 7$ square towers
  - Allows reconstruction of azimuthal angle of photons together with vertex transverse position

- Position in $\eta$ is measured in first (3 strips) and second sampling (3x3) square towers
  \[ \sigma_\eta < 1.5 mm / \sqrt{E(\text{GeV})} \]
Pointing

\[ Z_{1,2} = \frac{\rho_{1,2}}{\tan(\Theta_{1,2})} = \rho_{1,2} \sinh(\eta_{1,2}) \approx 175.92 \text{ cm} \]

\[ Z_V = \frac{Z_1 \rho_2 - Z_2 \rho_1}{\rho_2 - \rho_1} \]

Obtained z-resolution:

\[ \sigma_Z \approx 4 \text{ cm} \]
Material buget

Need presampler to correct for missing energy deposited in dead material!
Presampler

- 1.1cm active LAr layer in front of Barrel calorimeter
- 5mm active LAr layer in front of end-cap calorimeter
- Scintillator slab in crack between barrel and end-cap
- Allows reconstruction of missing energy deposited in front of calorimeter (inner detector, cryostat walls, etc...)

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Energy resolution - Sampling term

For $\eta<1.1$, sampling term <10% obtained

For $\eta>1.1$, energy resolution is worse due to larger amount of dead material
Constant term

• Construction tolerances and the calibration system ensure that the response is locally uniform, with a constant term < 0.5% over regions of size $d\eta \times d\phi = 0.2 \times 0.4$

• Need to intercalibrate 384 regions of such size, within 0.5% in order to achieve a desired global constant term of < 0.7%.
Calibration

- Use Electron pairs from Z boson decays (well known mass and width) to intercalibrate regions
- Result: 0.4% region–to–region dispersion obtained with about 250 electrons per region
- Can be transferred to photon energy scale
- Also: Achieve absolute energy scale precision to 0.1%

03.02.2017
Daniel Ryklin
## Overall constant term

<table>
<thead>
<tr>
<th>Sources</th>
<th>Contribution to constant term</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanics (short-range)</strong></td>
<td></td>
</tr>
<tr>
<td>Absorber tolerances</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td>Liquid gap tolerances</td>
<td>&lt; 0.15%</td>
</tr>
<tr>
<td>Residual $\phi$-modulation</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td>Residual of the sampling fraction correction (end-cap only)</td>
<td>~ 0.35%</td>
</tr>
<tr>
<td><strong>Calibration (short-range)</strong></td>
<td></td>
</tr>
<tr>
<td>Amplitude accuracy</td>
<td>&lt; 0.25%</td>
</tr>
<tr>
<td>Readout stability</td>
<td>~ 0.1%</td>
</tr>
<tr>
<td>Difference between calibration and physics signals (inductance, changing drift time, etc. [2-6])</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td><strong>Others (long-range)</strong></td>
<td></td>
</tr>
<tr>
<td>Time dependence of charge measured in liquid (impurities)</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Liquid density - temperature gradients</td>
<td>~ 0.2%</td>
</tr>
<tr>
<td>HV variations</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Others (material, etc.)</td>
<td>?</td>
</tr>
<tr>
<td><strong>Total (quadratic sum)</strong></td>
<td></td>
</tr>
<tr>
<td>barrel</td>
<td>~ 0.55%</td>
</tr>
<tr>
<td>end-cap</td>
<td>~ 0.65%</td>
</tr>
</tbody>
</table>
Obtained mass resolution

- Energy resolution
  - Sampling term \( \approx 10\% / \sqrt{E(\text{Gev})} \)
  - Constant Term \(< 0.7\%\)

- Angular resolution
  - \( \sigma_{\phi} \approx 15\text{mm} / \sqrt{E(\text{GeV})} \)
  - \( \sigma_{\eta} < 1.5\text{mm} / \sqrt{E(\text{GeV})} \)

- Vertex reconstruction (pointing)
  \( \sigma_{Z} \approx 4\text{cm} \)

- \( \Rightarrow \sigma_{m_{\gamma\gamma}} = 1.3\text{GeV} \) for 100GeV Higgs
Jet-separation

\[ \eta = 0 \]
Photon/Jet separation criteria

- The energy deposited in the hadronic calorimeter, in a region of size $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$ (2 $\times$ 2 cells) behind the electromagnetic cluster smaller than 500 MeV.
- Energy leaking outside the 3 $\times$ 5 tower cluster into a region of 7 $\times$ 7 towers smaller than 10% of the shower energy.
- Four most energetic towers of the cluster contain more than 65% of the cluster energy.
- The shower width was required to be compatible with the size of a single EM shower.
photon/jet separation

• Cuts were optimized as function of $\eta$
  – 90% Photon efficiency
• Obtained rejection factors:
  $R_{jet} \approx 1200$  For low pT sample
  $R_{jet} \approx 2500$  For high pT sample
• Additional factor of 3 needed for $\pi_0$
Photon/$\pi_0$ separation

- The probability of interaction in the first compartment is larger in the case of a $\pi^0$ decay (two photons) than of a single photon.
Photons/$\pi_0$ separation

- The strip with the largest energy is searched for inside a window of size $\Delta \eta \times \Delta \phi = 0.125 \times 0.2$ centered on the shower position.
- A second local maximum is then searched for inside the same window.
- Its transverse energy is computed using three strips.
- A cut on this transverse energy is used to remove $\pi_0$ decays where the two photons are well separated from each other.
\[ \frac{E_7 - E_3}{E_3} \text{ is computed} \]

E3 (resp. E7) is the energy contained in 3 (resp. 7) strips centered on the strip with the largest energy.
Photon/$\pi_0$ separation

- Using three strips (the most energetic one and its two neighbors) the shower width in $\eta$ is calculated. The width (in strip units) is plotted for photons and $\pi^0$'s, as a function of the shower position inside the hit strip.
Overall rejection factor

- With additional Rejection factor of $\approx 3$ for $\pi_0$ rejection, needed overall factor of 5000 is achieved
RESULT
Result

- July 2012 CERN published evidence of Higgs-like particle

- $m_H = 125,98 \pm 0.50 GeV$

- Nobel price 2013 for Francois Englert and Peter Higgs
Summary

• Higgs particle was predicted to give masses to Z and W bosons

• To find Higgs, need excellent detector
  – 1% mass resolution
  – angular resolution \( \leq 50 \text{mrad/}\sqrt{E(GeV)} \) and vertex reconstruction
  – Rejection of QCD Background (high granularity)
  – High efficiency

• ATLAS EM calorimeter
  – Accordion shape sampling calorimeter (lead, LAr)
  – 190000 channels, 3 longitudinal samplings, \( \eta \)-strips for \( \pi_0 \)-rejection
  – Presampler

• \( \Rightarrow \) Higgs discovered! \( m_H = 125.98 \pm 0.50 \text{GeV} \)
Resources


- https://www.hep.ucl.ac.uk/~sstef/EMCalo.html
- http://irfu.cea.fr/Images/astImg/2236_1.jpg
- http://hep.wits.ac.za/images/higgsphys/higgsBranchA.png
- https://inspirehep.net/record/1353076/files/em_shower.png
- https://www.researchgate.net/profile/Prakash_Mathews/publication/51931541/figure/fig2/AS:269528702689281@1441272058478/Figure-1Feynman-diagrams-contributing-to-the-subprocess-qqng-where-the-dashed-line.png
- http://sites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
- http://images.slideplayer.com/8/2402174/slides/slide_34.jpg
Energy loss

- At high energy
  - Electron looses energy mainly via Bremsstrahlung
  - Photons mainly via pair creation
Accordion structure

- varying the bend angles, as well as the length of the folds between bends, as a function of radius
  - constant sampling fraction as a function of radius
  - full projectivity in $\phi$
  - minimal density variation in $\phi$

- Sagging of plates due to gravity has to be taken into account
  - Small systematic phase shift
Crack regions

Regions, where the detector response is deteriorated with respect to the rest of the acceptance
• The transition between the two half-barrel calorimeters at \( \eta = 0 \).
• The transition between the barrel and the end-cap calorimeters at \( \eta \sim 1.45 \).
• The transition between the outer and the inner wheel of the end-cap calorimeter at \( \eta = 2.5 \).

These regions must be kept at the level of less than 10% of the total calorimeter coverage, not to significantly deteriorate the discovery potential for rare signals
Crack regions

In the region $1.45 < |\eta| < 1.55$ the energy lost in the material in front of the calorimeter is too large to be efficiently recovered with a presampler.

--> slab of scintillator in between the barrel and the end-cap