Identifying Electromagnetic Showers in the Forward Hadron Calorimeter

CMS · LHC · CERN

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The Compact Muon Solenoid (CMS)

- Weight: 14,000 tons
- Length: 21.6 meters
- Radius: 7.5 meters
- Field: 3.8 tesla
The Forward Hadron Calorimeter (HF)

- Steel absorber plates and quartz fibers run parallel to the beam-line.
- HF detects Cherenkov radiation produced in these fibers.
- PMTs detect energy absorbed by long and short fibers separately.
- The quartz fibers are of two different lengths —
  - **Long:** begin at inner face of detector, extend 1.65 m.
  - **Short:** begin 0.22 m from inner face, extend 1.43 m.
What is Cherenkov Light?

- When a high-energy charged particle enters the detector, it moves at speed $v > c/n$, the speed of light in that material.

- Creates a light cone which is sent into the PMTs.

- Produces bluish glow.
2011 $Z \rightarrow e^+e^-$ LHC Data

**Signal:** Double $e$ events with invariant mass in the $Z$ range, $70 \text{ GeV}/c^2 \leq m \leq 120 \text{ GeV}/c^2$.

**Background:** Jets that survive loose $e$ cuts in $Z$ mass window.

One electron received in HF, second received in barrel.
What are Jets?

- Collisions produce quarks, which carry color charge.
- Quarks must combine to form hadrons.
- Jets, groups of hadronized quarks, spray our detector.
- Hadrons in jets are much heavier than the $e^-, e^+$ we detect.
How Do We Identify Detected Particles?

- Inner face of HF detector is divided into cells.
- **Seeds:** cells that absorb $E_T > 5 \text{ GeV}$ in the long fibers.
- Form clusters around seeds,
  - Seed: red
  - $3 \times 3$: red + green
  - $5 \times 5$: red + green + blue
  - Core: red + highest $E$ neighbor
- For each cell in a cluster, store
  1. Long-fiber energy,
  2. Short-fiber energy.
Measuring Transverse Shower Shape

Lateral Containment

\[ E_{9/25} = \frac{\sum_{3 \times 3} \text{total energy}}{\sum_{5 \times 5} \text{total energy}} \]

Heavy particles spread out in collisions while light particles remain laterally dense ⇒

EM: \[ E_{9/25} \to 1, \]
Jets: \[ E_{9/25} \text{ is lower.} \]

Transverse Shape

\[ E_{C/9} = \frac{\sum_{\text{core}} \text{long-fiber energy}}{\sum_{3 \times 3} \text{long-fiber energy}} \]

Using the same reasoning,

EM: \[ E_{C/9} \to 1, \]
Jets: \[ E_{C/9} \text{ is lower.} \]
Measuring Longitudinal Shower Shape

Longitudinal Shape

\[ E_{S/L} = \frac{\sum_{3 \times 3} \text{short-fiber energy}}{\sum_{3 \times 3} \text{long-fiber energy}} \]

The 0.22 m steel gap between the inner face of HF and the short fibers is

**EM:** 12.5 radiation lengths \( \Rightarrow \)

\( E_{S/L} \) is small,

**Jets:** 1.3 interaction lengths \( \Rightarrow \)

\( E_{S/L} \approx 1/2. \)
Inadequacy of Current Methods

Signal Isolation in the Present-day LHC: $\mathcal{L} \approx 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

Lateral Containment: $E_{9/25} \geq 0.94$,

Two-dimensional Shape: $E_{C/9} - 1.125 \cdot E_{S/L} \geq 0.2$,

- Increase in beam luminosity $\mathcal{L}$ will create more frequent events and more pileup (uninteresting secondary interactions).
- Creates need for tighter cuts.
- Tighter cuts expose faults in the current method of signal isolation —
  1. Energy-dependent efficiency,
  2. Failure of longitudinal shower-shape cuts.

$\begin{align*}
2011 \quad \mathcal{L} &\quad \rightarrow \quad 2012 \quad 5\mathcal{L} &\quad \rightarrow \quad 2014 \quad 10\mathcal{L} &\quad \rightarrow \quad 2020 \quad 20\mathcal{L}
\end{align*}$
A Problem with the Longitudinal Cut

- Penetration depth depends on total shower energy.
- Using the variable
  \[ E_L = \sum_{3 \times 3} \text{long-fiber energy}, \]
  proportional to total shower energy, we can study this effect graphically.
- An \( E_{S/L} \) cut removes mainly high-energy EM events — their penetration depth disguises them as jets.
To eliminate this dependency, we send $E_{S/L} \mapsto E_{S/L}^{\text{cor}}$ as follows.

1. Fit the points in the plot of $E_{S/L}$ v. $\log (E_L / 100 \text{ GeV})$ to a line, $y = mx + b$.
2. Rotate the data clockwise by $\tan^{-1}(m)$ so that the fit line becomes the $x$-axis.
3. Call the new $y$-value of each entry $E_{S/L}^{\text{cor}}$.

$E_{S/L}^{\text{cor}}$ measures deviation of penetration depth from that of a typical electron with similar $E$. 

Data: Signal
Optimizing the Longitudinal Cut

- In comparing the effectiveness of different cuts, we use

**Signal Efficiency**
\[
\text{Signal Efficiency} = \frac{\text{# of signal events surviving cut}}{\text{total # of signal events}}
\]

**Background Rejection**
\[
\text{Background Rejection} = \frac{\text{# of background events failing cut}}{\text{total # of background events}}
\]

- For all values of signal efficiency, the \( E_{S/L}^{\text{corr}} \) cut performs better than the \( E_{S/L} \) cut.
Optimizing the Two-dimensional Cut

\[ E_{C/9} - m \cdot E_{S/L}^{cor} > C_{2d}. \]

- An algorithm optimizes the choices of \( m, C_{2d} \), choosing a diagonal cut-line:

For all values of signal efficiency, the new 2D cut performs better than the \( E_{C/9} \) cut.
Conclusion

1. Improved the effectiveness of the longitudinal shower-shape cut by removing the energy dependency from the $E_{S/L}$ variable.

   \[ E_{S/L} \mapsto E_{S/L}^{\text{cor}} \]

2. Introduced a new 2D shower-shape cut that out-performs the $E_{C/9}$ cut, which was previously most effective for tight cuts.

   \[ E_{C/9} - m \cdot E_{S/L}^{\text{cor}} > C_{2d} \]
Questions?