Measurement of the Muon Stopping Power in Lead Tungstate with the Electromagnetic Calorimeter in CMS

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on behalf of the CMS collaboration

• Measurement setup
• Instrumental and containment effects
• Result of the measurement
• Summary
In Fall 2008, the CMS collaboration conducted a month-long data-taking exercise:

- **commission** the experiment for extended operation
- test the **solenoid at 3.8 T**
- collect ~300 M **cosmic triggers** for sub-detector performance studies

With the data collected, we measured the **specific energy loss** (dE/dx) of muons in PbWO$_4$ (e.m. calorimeter) versus muon momentum and extracted:

- a test of the **energy scale** of the calorimeter
- a measurement of the muon **critical energy** in lead tungstate
The cosmic setup

Nearly all sub-detectors involved in the measurement of $dE/dx$ vs $p_\mu$ in PbWO$_4$:

- **Trigger**: track segments from any muon chamber with any $p_T$
- **$dE$**: energy cluster in ECAL + corrections
- **$dx$**: track extrapolation from outermost tracker hit through ECAL
- **$p_\mu$**: fit of tracker hits + B field
  - $\sigma_p/p \sim 10\%$ for 1 TeV/c momentum muons

- Only muon deposits in lower ECAL half-barrel used to measure $\langle dE/dx \rangle$
  - muon momentum measured in the tracker upstream energy loss
The electromagnetic calorimeter

- ECAL: scintillating calorimeter made of lead tungstate crystals (PbWO₄)
- Scintillating light detected by 2 APD on the rear face of each crystal (barrel)
  - APD gain set to 200 for runs of interest for this analysis (4x w.r.t. operation condition @ LHC)

- ECAL global energy scale fixed with a 120 GeV electron beam (TB 2006)

- This analysis probes energy ranges down to 300 MeV, far less than what ECAL is designed for!
  - for a m.i.p. muon, dE in ECAL is approximatively 1.5 MeV cm² g⁻¹ x 23 cm x 8.9 g cm⁻³ ~300 MeV
Instrumental effects

- Energy released by muons in ECAL is reconstructed via a clustering algorithm
  - collects deposits in a 5x5 matrix above threshold
- Raw dE/dx is affected by instrumental biases:
  - single channel noise fluctuations
  - thresholds in readout/clustering processes

- Biases in energy reconstruction depend on the angle muon-crystal:
  - smaller deposit from skewed muons → threshold effect

Corrections to raw energy depositions have been extracted from data

raw \langle dE/dx \rangle \text{ for } p_{\mu} < 10 \text{ GeV/c}
Energy containment effects

• Muons in ECAL ≠ electrons in ECAL
• rear leakage of energy due to secondaries produced all along the muon path
• rear leakage is (partly) compensated by showers initiated in the material upstream the crystals
• two different regimes depending on the muon energy:

  • Low energy - collisional processes dominating:
  • no differences found (within 1%) in \( \langle dE/dx \rangle \) in upper and lower ECAL hemisphere, although different upstream material budget (HCAL / tracker)
    • tracker material is thick enough to compensate rear losses
  • assume no net correction for collisional processes and 1% as systematic uncertainty on correction

  • High energy - radiative processes dominating:
  • leakage corrections from a dedicated Geant4 simulation, in two limit configurations:
    • correction applied is the average of the two cases, systematic uncertainty is half the difference

  Leakage correction factors:
  (14.5±2.5)% @ 170 GeV/c
  (28±5)% @ 1 TeV/c

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The $dE/dx$ measurement

- For high-energy muons ($p_\mu \geq 300$ GeV/c), the probability density function for $\langle dE/dx \rangle$ is non-gaussian:
  - p.d.f. for single-event $dE/dx$ is highly skewed
  - very low statistics in each bin

- $\text{RMS}/\sqrt{N}$ is not a good estimator for the statistic error

**Simulated $\langle dE/dx \rangle$**

for $p_\mu \sim 850$ GeV/c

10,000 measurements with 102 events each

- Use the “expected” statistic error instead:
  - reproduce 10,000 times the outcome of the measurement for each experimental bin with Geant4
  - interval discarding 16% for each p.d.f. tail
  - smallest interval containing 68% of measurements

**Measured $dE/dx$ for $p_\mu > 300$ GeV/c**

~8% overflow
Result of the analysis

- 8.8 x 10^7 initial triggers reduced to a final statistics of 2.5 x 10^5 events, divided into 20 logarithmic bins
- 5 GeV/c < p_μ < 1 TeV/c
- angle(μ-crystal axis) < 0.5
- ΔE/p_μ < 1
- no deposits in upper ECAL hemisphere bigger than 500 MeV

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Fit of experimental points

- Binned maximum likelihood fit of experimental points with

\[(dE/dx)_{\text{meas}} = \alpha \cdot [(dE/dx)_{\text{coll}} + \beta \cdot (dE/dx)_{\text{rad}}]\]

\[\alpha = 1.004^{+0.002}_{-0.003}(\text{stat.}) \pm 0.019(\text{syst.})\]
\[\beta = 1.07^{+0.05}_{-0.04}(\text{stat.}) \pm 0.06(\text{syst.})\]

- Agreement between data and theory at low energy at 2.0\%_{\text{stat.}} +_{\text{syst.}} level
  - 1.9\% systematic uncertainty:
    - 1.2\% from uncertainty on energy scale dependence on angle and clustering
    - 1.0\% from uncertainty in containment corrections for collisional processes

- Extract critical energy value from \(\beta\) \(\rightarrow\) \(E_C = 160^{+5}_{-6}(\text{stat.}) \pm 8(\text{syst.})\) GeV
  - 8 GeV systematic uncertainty:
    - 4.5 GeV from uncertainty in containment corrections for radiative processes
    - 6 GeV from stability of fit from bias correction and variation of analysis cuts (mainly angle mu-crystal)
Conclusions

- Measurement of muon stopping power in PbWO$_4$ performed over a wide muon momentum range - 5 GeV/c → 1 TeV/c

- In the region $p_\mu < 20$ GeV/c:
  - average energy deposits ~300 MeV (collisional processes)
  - agreement at 2% level between the measured stopping power and the calculated values
  - the energy scale of the detector, previously determined with 120 GeV/c electrons, is confirmed down to the sub-GeV scale

- From a fit of the experimental points up to $p_\mu = 1$ TeV/c:
  - first measurement of the muon critical energy
  - $E_C = 160^{+5}_{-6}(\text{stat.}) \pm 8(\text{syst.})$ GeV, in agreement with expectation from theory (169.5 GeV)
Backup slides
Readout and energy reconstruction

- On-line data reduction is based on
  - Zero Suppression (ZS): only channels above the ZS threshold (~20 MeV) are read out
  - Selective Readout (SR): full readout of high-interest regions - a matrix of 3x3 trigger towers is read out (5x5 crystals each), centered on a trigger tower with at least 170 MeV

- Energy deposited by muons in ECAL is reconstructed via a clustering algorithm

![Measured energy spectrum of muon ΔE in ECAL](image)

- start from a seed: 1 channel > 139.5 MeV or 2 adjacent channels > 46.5 MeV
- cluster together channels above 18.5 MeV in a 5x5 matrix centered on the seed

- Events vs. cluster energy (E_cluster) in GeV

- ~300 MeV
Instrumental effects

Aligned muons ($\alpha < 0.1$):
- SR is dominant over ZS (in ~90% of cases muons deposit > 170 MeV) → all channels are read out
- positive bias in $\Delta E$ measurement from upper noise fluctuations clustered together with signal
- Average noise per channel during cosmic runs measured to be ~1 ADC = 9.3 MeV
  - this reflects into a cluster energy bias of ~14.7 MeV

Skewed muons ($\alpha > 0.1$)
- ZS more frequent: higher threshold → smaller positive bias
- shorter track segments in single crystals → negative bias from deposits under threshold

Correct data for these effects:
- normalize raw $(dE/dx)_{\text{coll}}$ vs. angle to small-angle value through a fit of observed trend
- subtract estimated noise bias of 14.7 MeV

Central fit: plateau up to 0.1 rad + linear fit
Systematics: estimated from the two limit cases
no plateau / plateau up to 0.2