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

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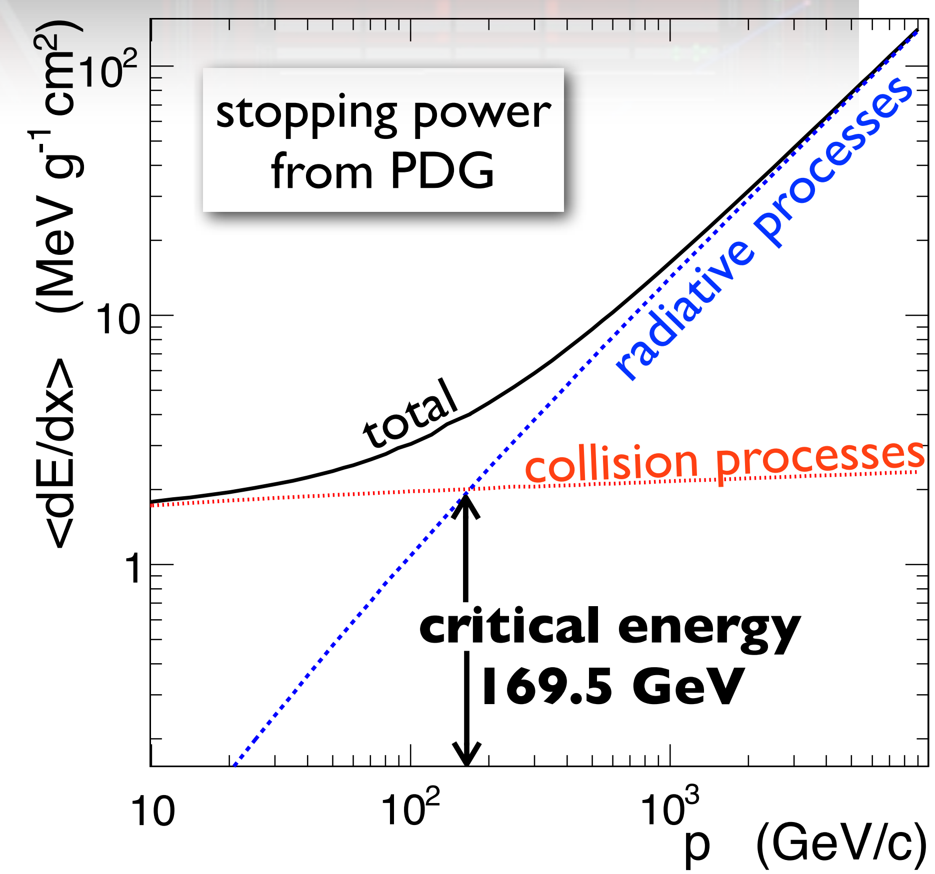
on behalf of the CMS collaboration

- Measurement setup
- Instrumental and containment effects
- Result of the measurement
- Summary

Introduction

- 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

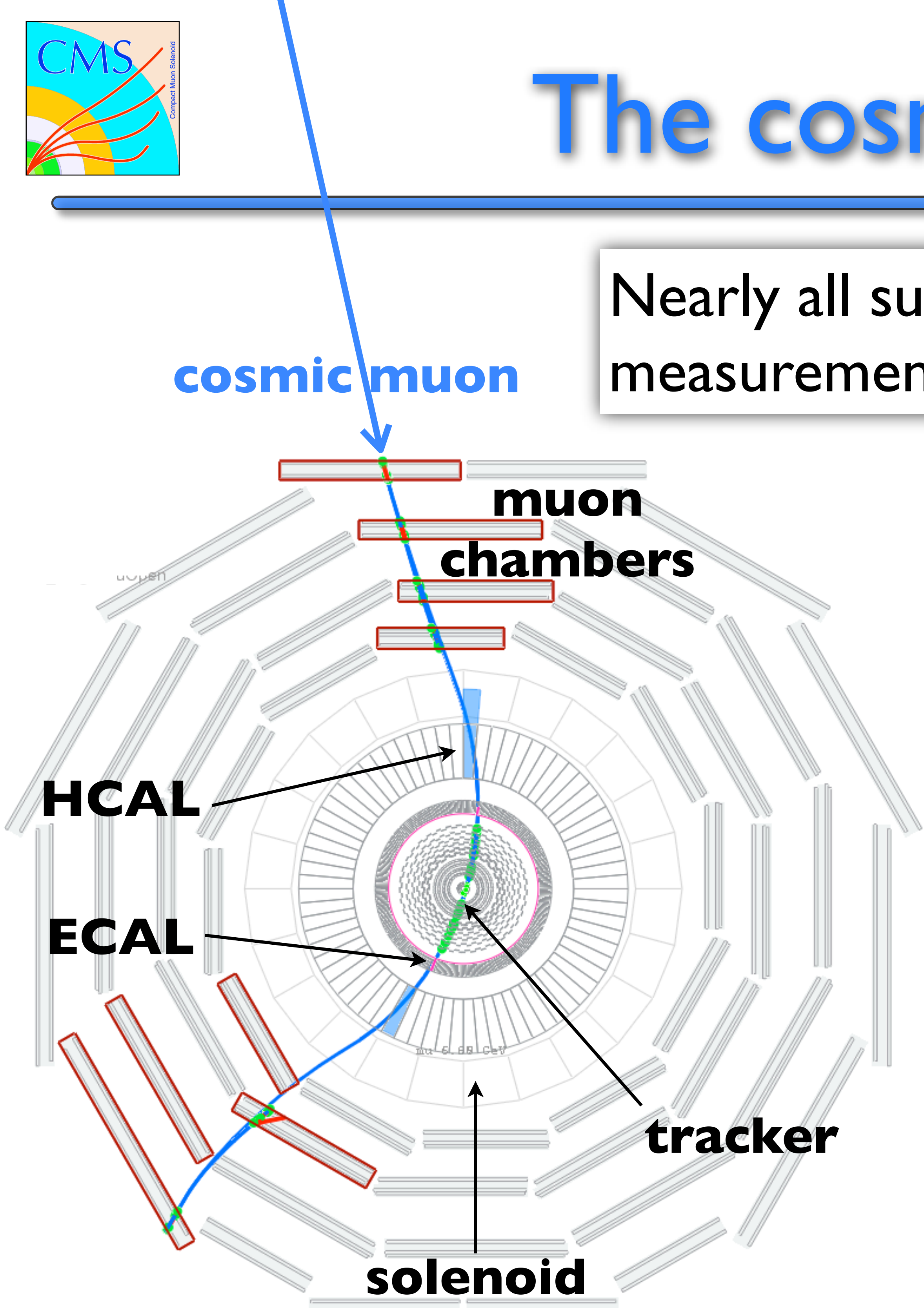
- With the data collected, we measured the specific energy loss (dE/dx) of muons in $PbWO_4$ (e.m. calorimeter) versus muon momentum and extracted:
  - a test of the energy scale of the calorimeter
  - a measurement of the muon critical energy in lead tungstate



http://pdg.lbl.gov/2009/AtomicNuclearProperties/index.html

The cosmic setup

Nearly all sub-detectors involved in the measurement of dE/dx vs p_μ in $PbWO_4$:

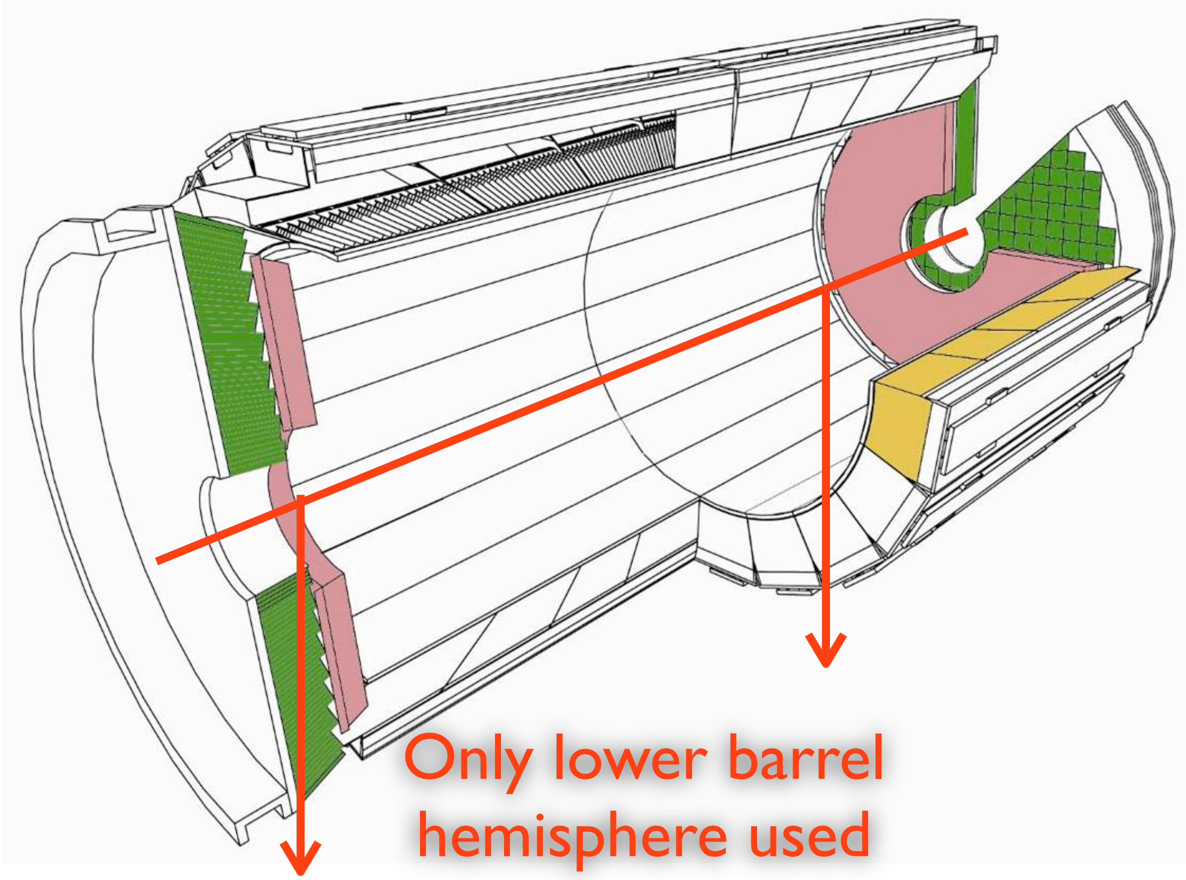


- Trigger: track segments from any <u>muon chamber</u> with any p_T
- dE: energy cluster in <u>ECAL</u> + corrections
- dx: track extrapolation from outermost <u>tracker</u> hit through <u>ECAL</u>
- p_μ: fit of <u>tracker</u> hits + <u>B field</u>
  - σ_p/p~10% for 1 TeV/c momentum muons

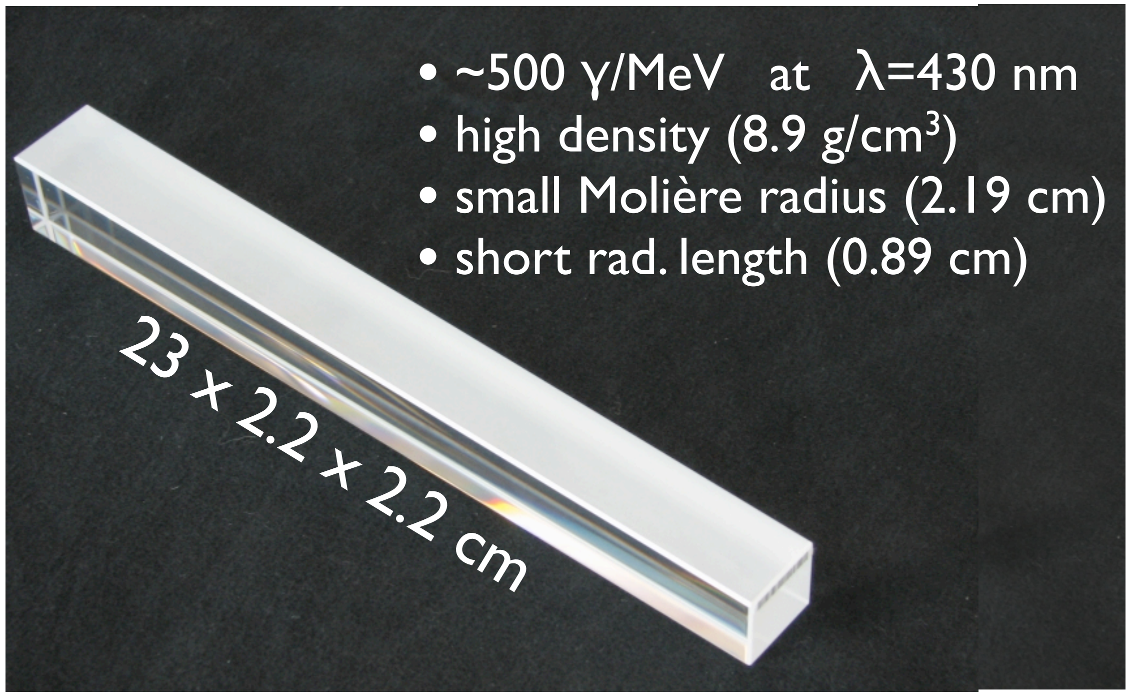
- Only muon deposits in lower ECAL half-barrel used to measure ‹dE/dx›
  - muon momentum measured in the tracker <u>upstream</u> energy loss

The electromagnetic calorimeter

- ECAL: scintillating calorimeter made of lead tungstate crystals ($PbWO_4$)
- 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)

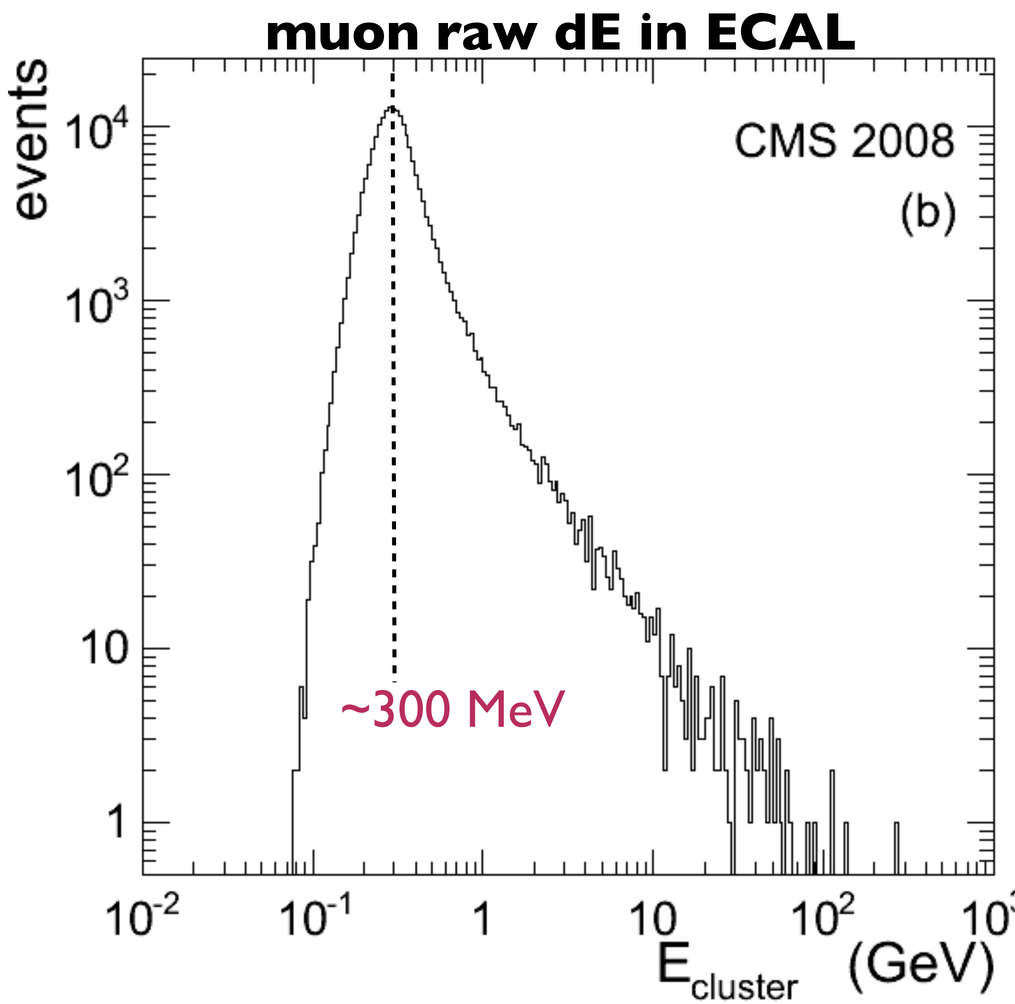


- ECAL global energy scale fixed with a 120 GeV electron beam (TB 2006)

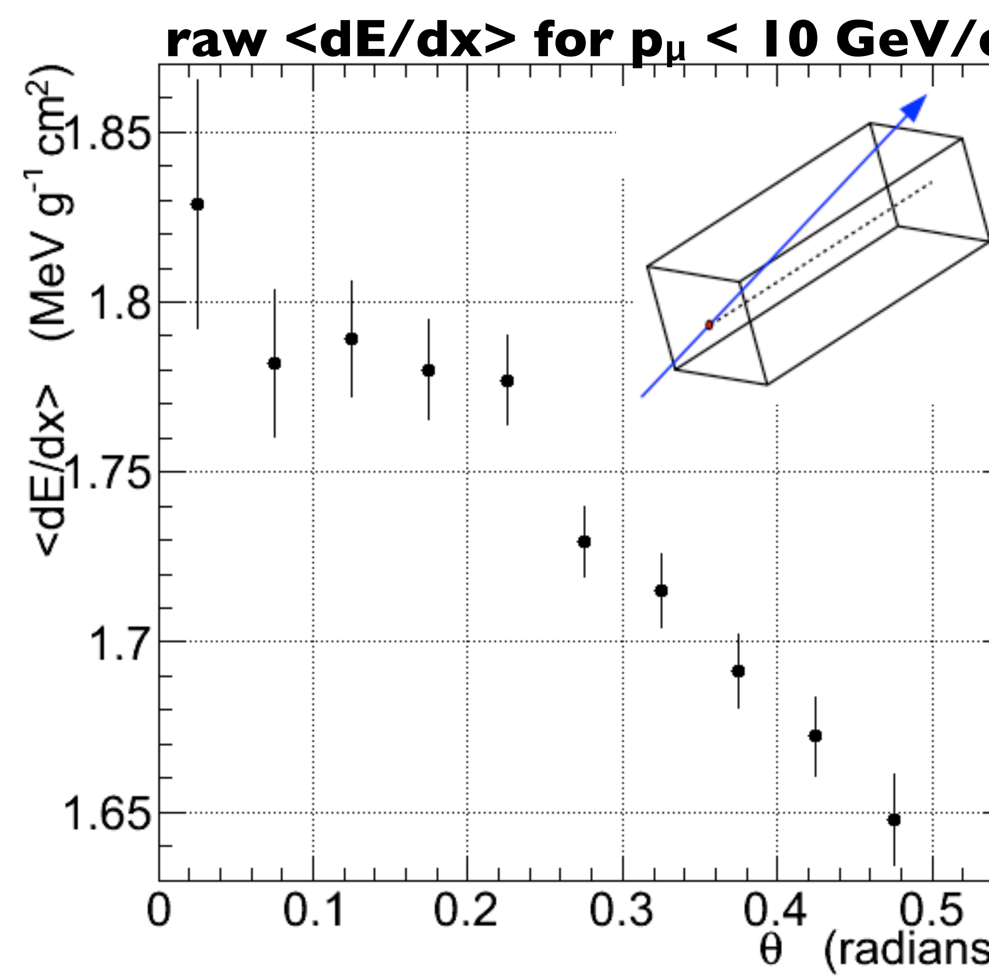


- This analysis probes energy ranges down to 300 MeV, far less than what ECAL is designed for!
  - for a m.i.p. muon, dE in ECAL is approximatively $1.5\ \mathrm{MeV\ cm^2\ g^{-1}} \times 23\ \mathrm{cm} \times 8.9\ \mathrm{g\ cm^{-3}}$ ~300 MeV

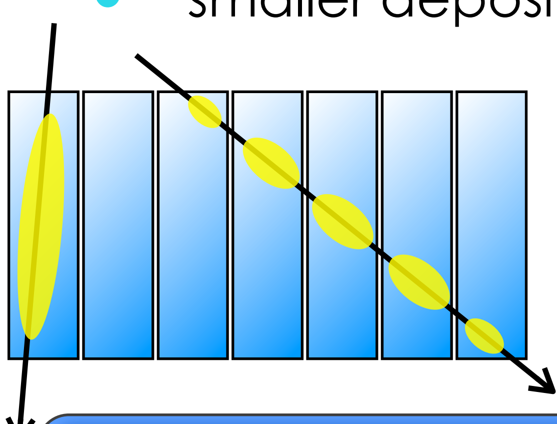
Instrumental effects



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



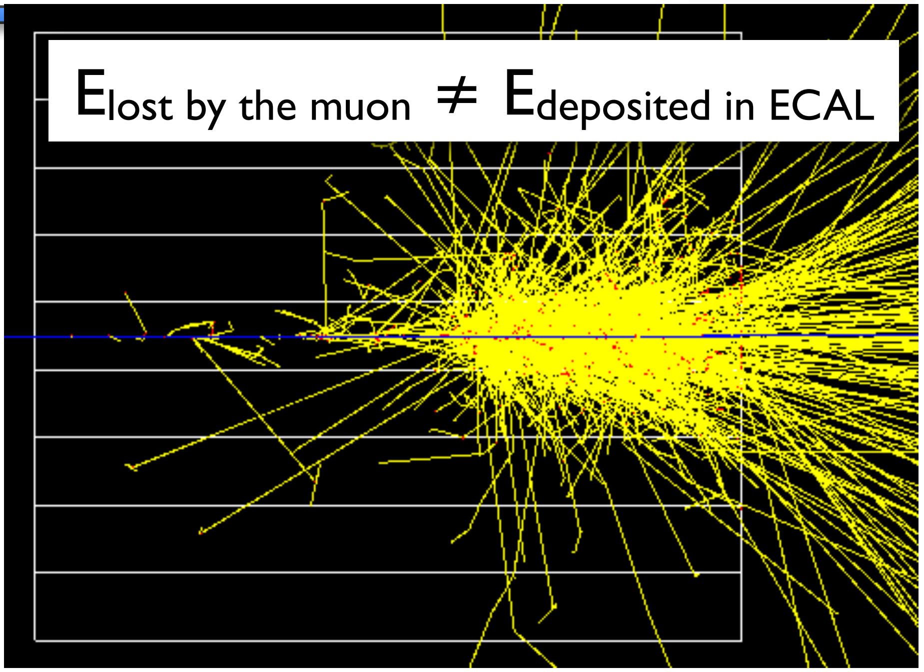
- Biases in energy reconstruction depend on the <u>angle muon-crystal</u>:
  - smaller deposit from skewed muons → threshold effect



Corrections to raw energy depositions have been extracted from data

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:



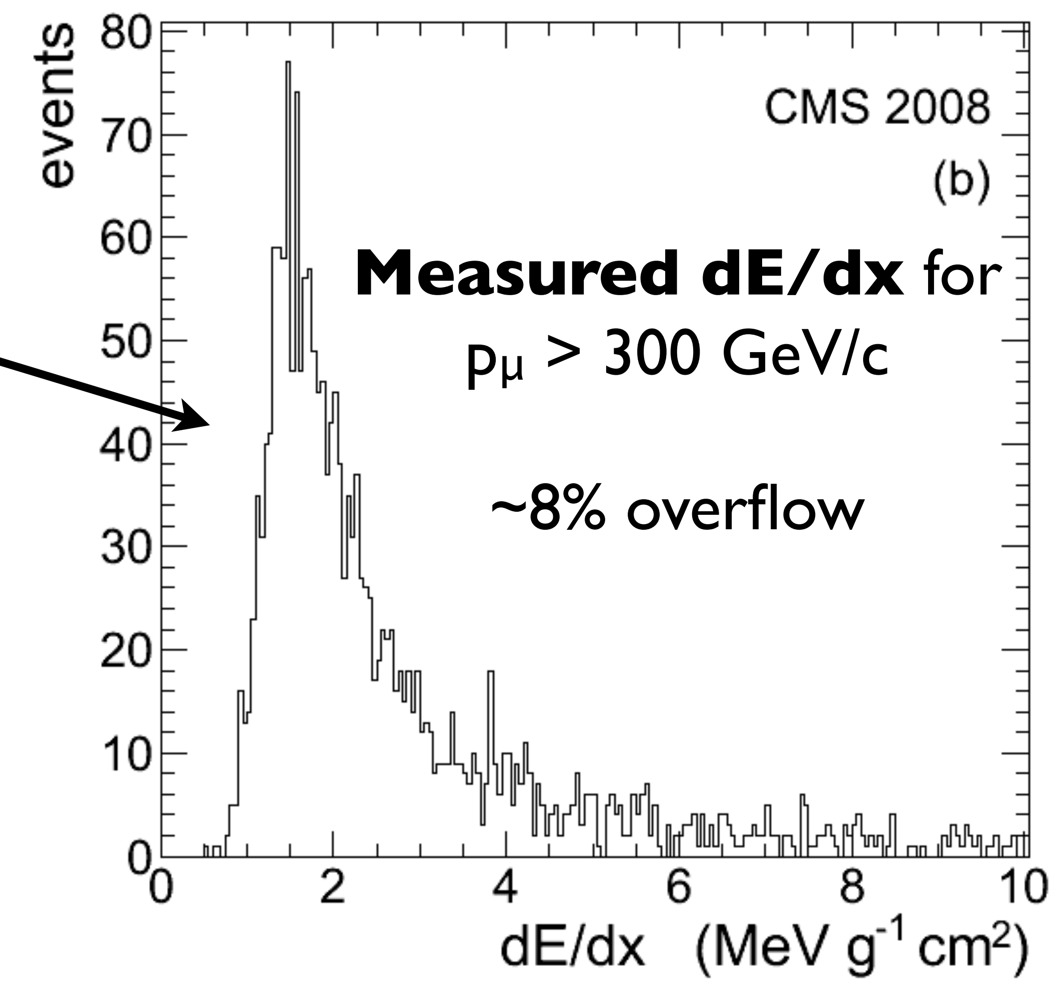
- <u>Low energy - collisional processes dominating:</u>
  - no differences found (within 1%) in ⟨dE/dx⟩ in upper and lower ECAL hemisphere, although different upstream material budget (HCAL / tracker)
    - → tracker material is thick enough to compensate rear losses
  - assume no net correction for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

- <u>High energy - radiative processes dominating:</u>
  - leakage corrections from a <u>dedicated Geant4</u> simulation, in <u>two limit configurations</u>:
    - no upstream material budget
    - all tracker mat. budget in front of ECAL
  - correction applied is the average of the two cases, systematic uncertainty is half the difference

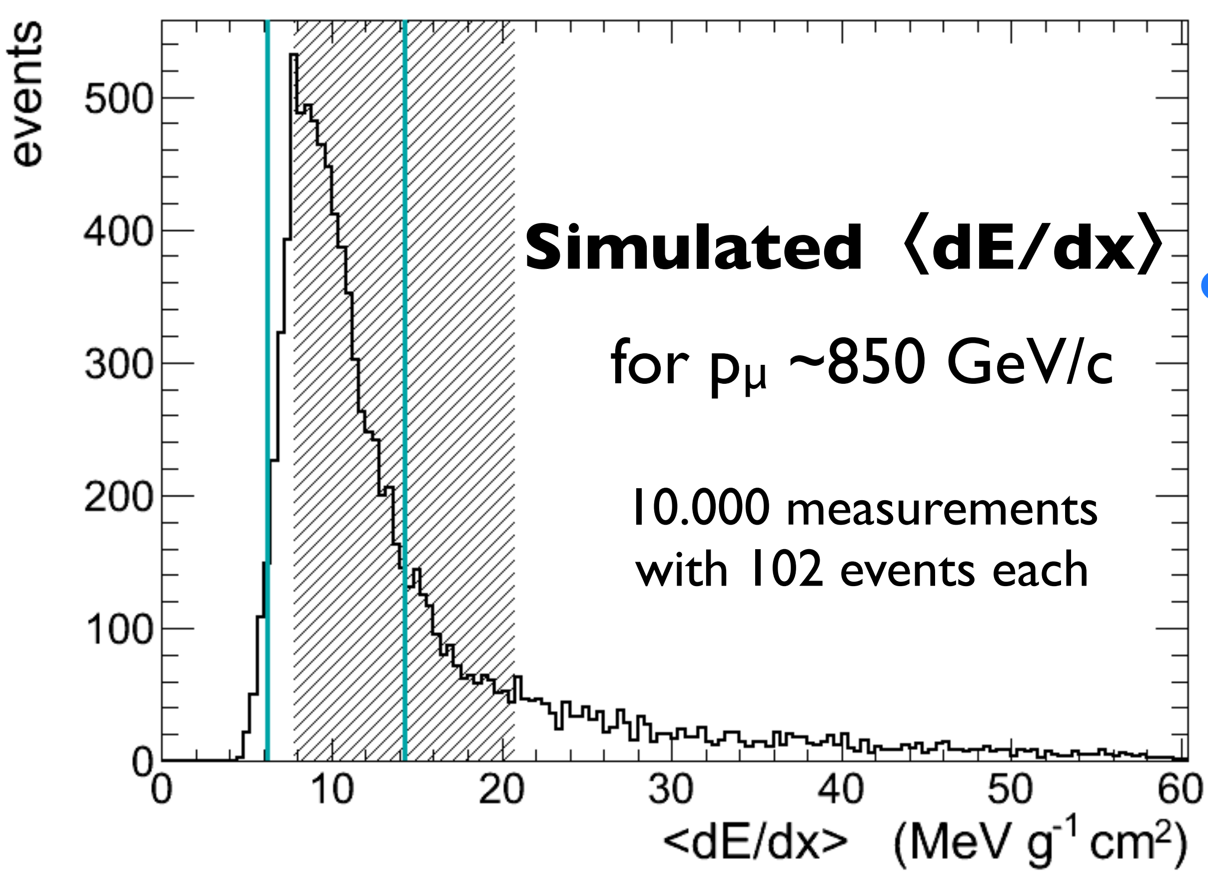
<u>Leakage correction factors:</u>
(14.5±2.5)% @ 170 GeV/c
(28±5)% @ 1 TeV/c

The dE/dx measurement

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



- RMS/√N is not a good estimator for the statistic error

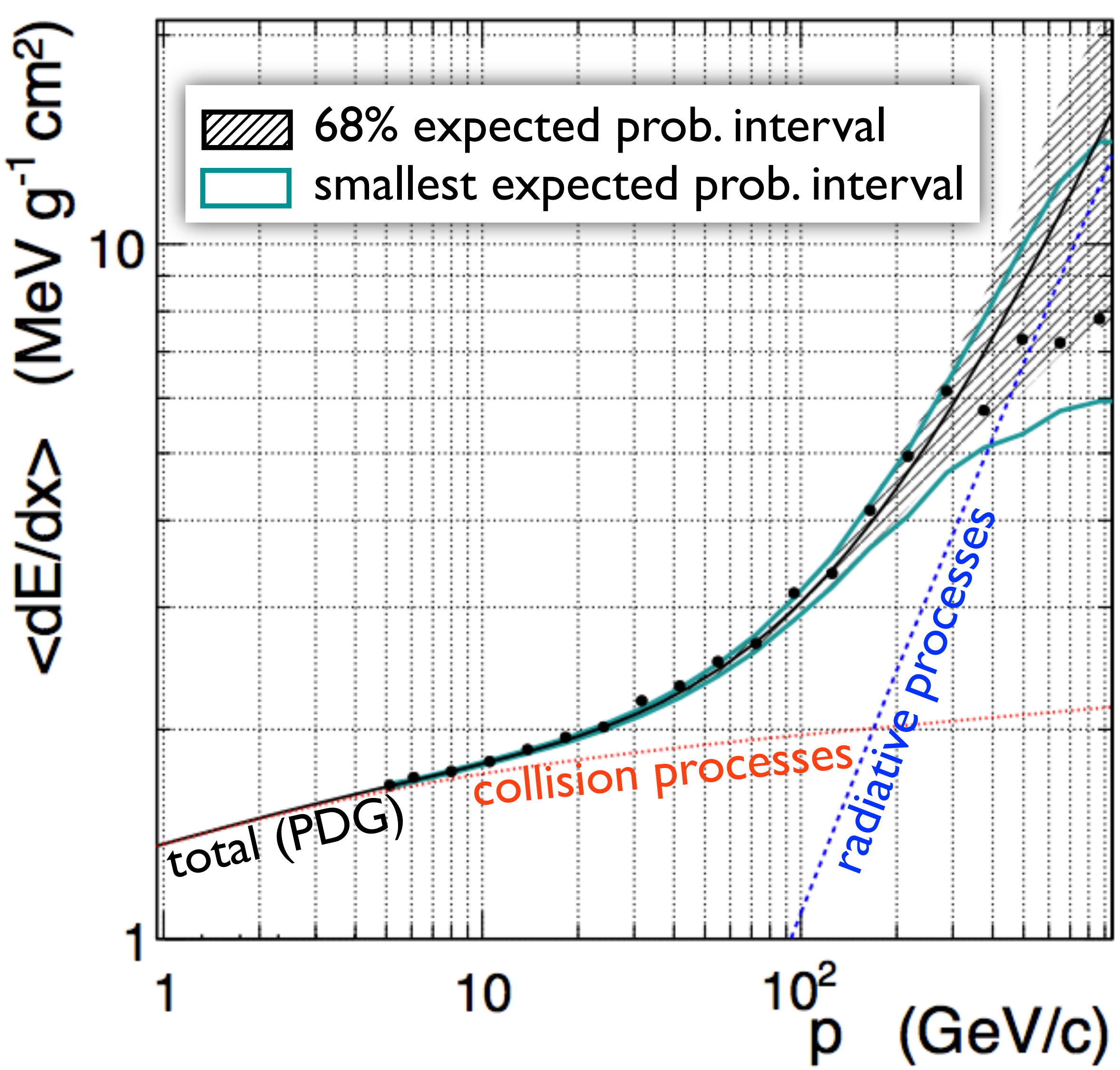


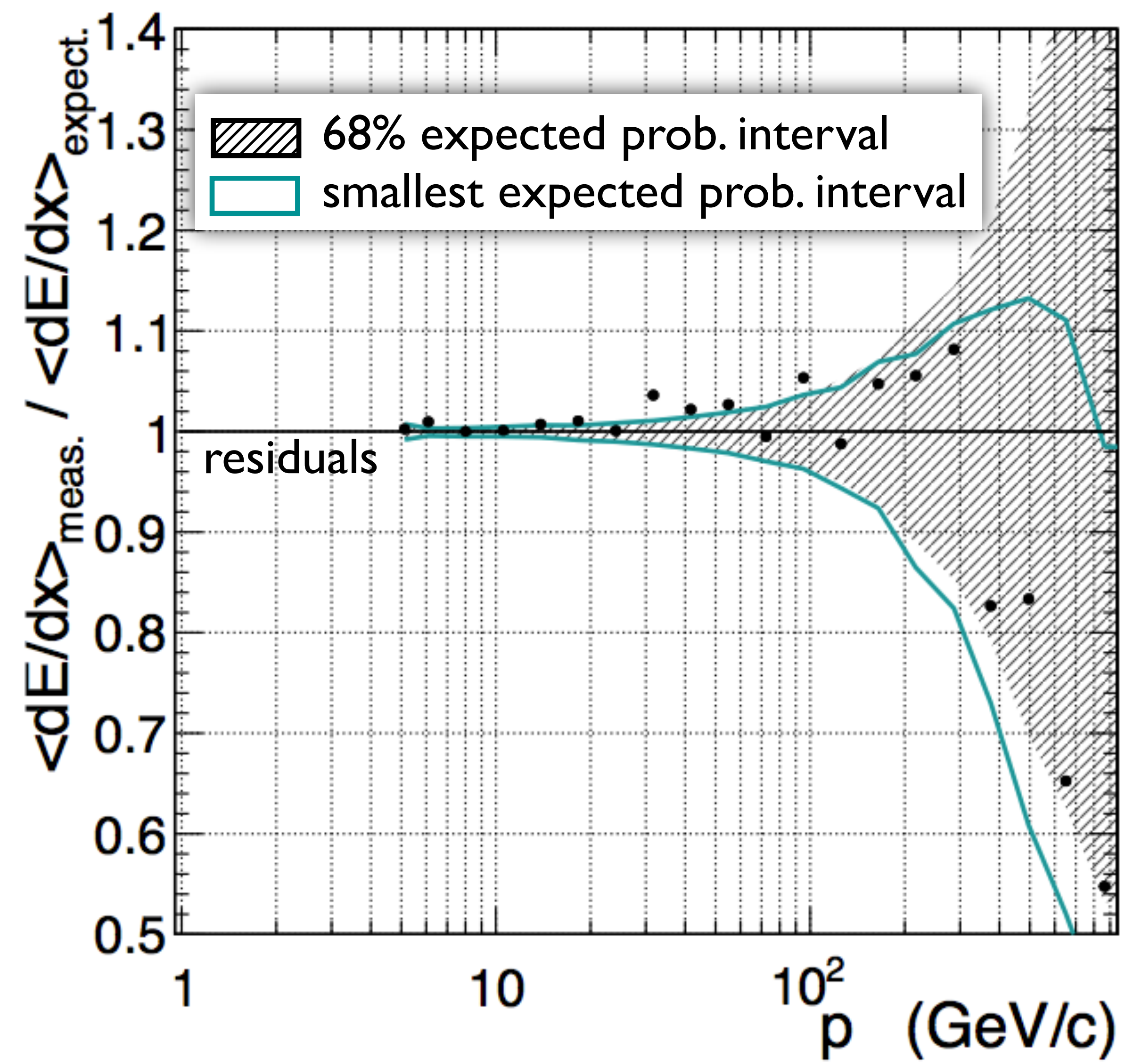
- Use the "expected" statistic error instead:
  - reproduce 10.000 times the outcome of the measurement for each experimental bin with Geant4
  - interval discarding 16% for each p.d.f. tail
  - smallest interval containing 68% of measurements

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
- $\Delta E/p_\mu < 1$
- no deposits in upper ECAL hemisphere bigger than 500 MeV





Fit of experimental points

- Binned maximum likelihood fit of experimental points with

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

$$\alpha = 1.004^{+0.002}_{-0.003}(stat.) \pm 0.019(syst.)$$

$$\beta = 1.07^{+0.05}_{-0.04}(stat.) \pm 0.06(syst.)$$

- Agreement between data and theory at low energy at 2.0%$^{stat.+syst.}$ 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 β → $E_C = 160^{+5}_{-6}(stat.) \pm 8(syst.)$ 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)

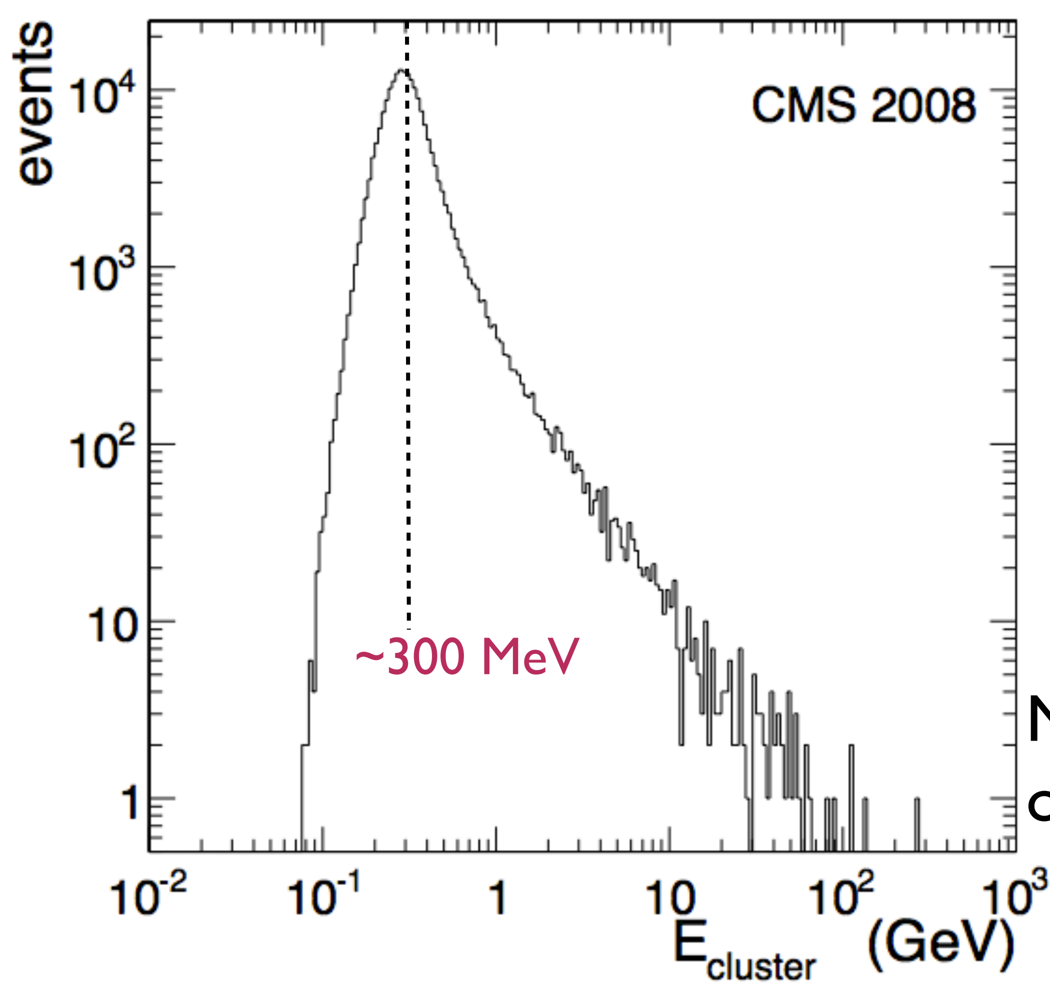
Backup slides

Readout and energy reconstruction

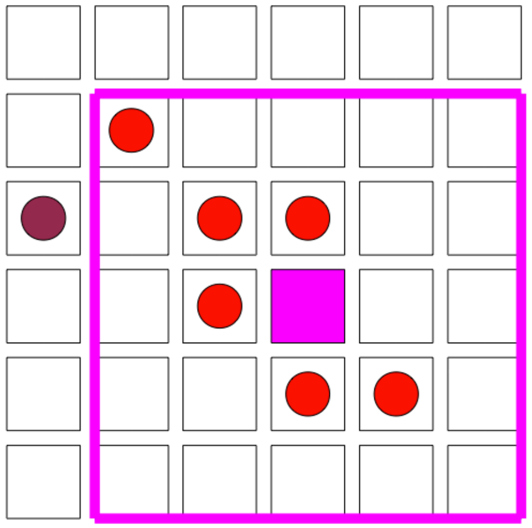
- On-line data reduction is based on
  - Zero Suppression (ZS): only channels above the ZS threshold (~20 MeV) are read out
  - Selective Readout (SR): full readout of high-interest regions - a matrix of 3x3 trigger towers is read out (5x5 crystals each), centered on a trigger tower with at least 170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

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

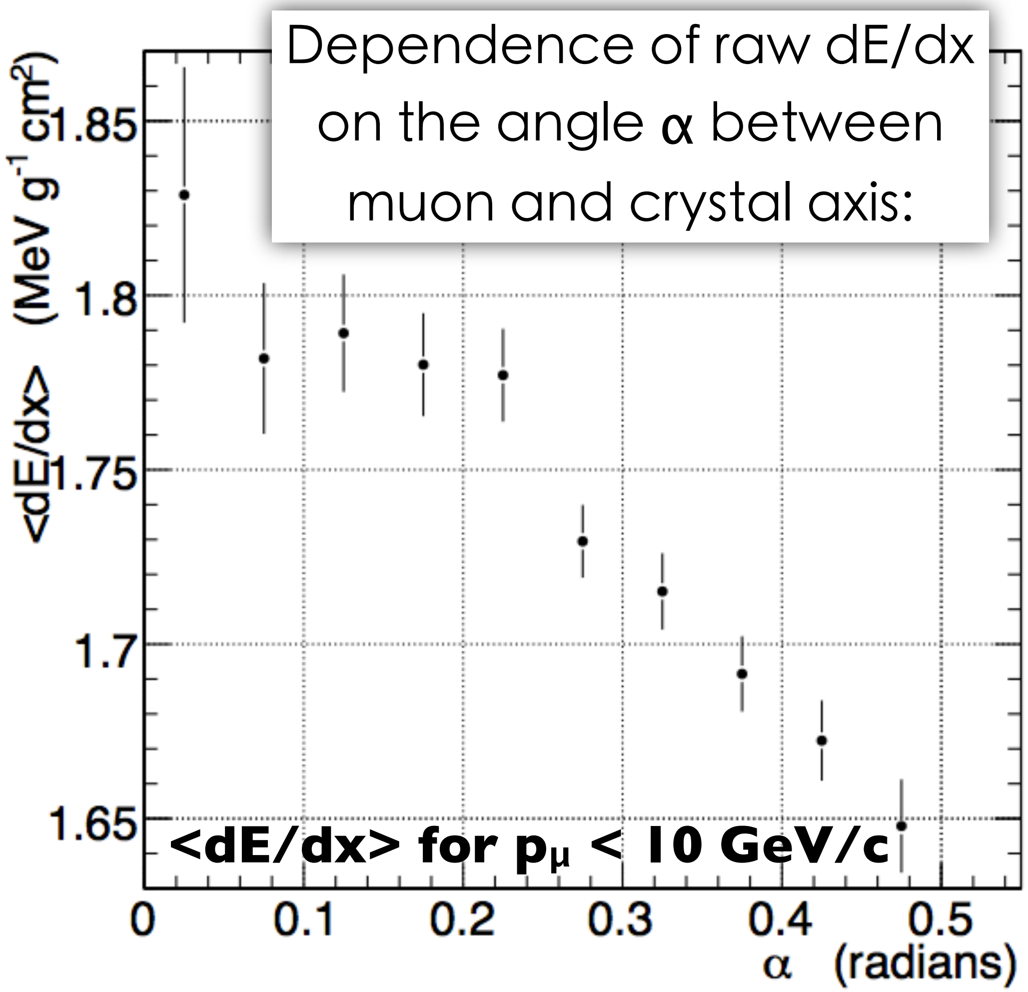
> • start from a **seed**: 1 channel > 139.5 MeV or 2 adjacent channels > 46.5 MeV
> • cluster together channels above **18.5 MeV** in a 5x5 matrix centered on the seed



Measured energy spectrum of muon ΔE in ECAL



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 ΔE 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 $(dE/dx)_{coll}$ 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