Results from the EPICAL-2 Ultra-High Granularity Electromagnetic Calorimeter Prototype

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Introduction

• Digital calorimetry: count number of charged shower particles in sampling layers
  • Ideally: potential to reduce fluctuations from individual sampling layers
  • High granularity required due to high particle density

• State-of-the-art all-pixel calorimeter prototype
  • Follow up on proof of principle EPICAL-1 (JINST 13 (2018) P01014)
  • EPICAL-2: Si/W stack using ALPIDE sensors, detailed simulation in Allpix²

• Calorimetric performance from test-beam measurements
  • Detailed study at low energy (DESY)
  • First preliminary results from high energy (SPS)
New Digital Calorimeter Prototype – EPICAL-2

24 layers with each
- 3 mm W absorber
- 2 ALPIDE CMOS sensors
  - NIM A, 845:583–587, 2017
- ultra-thin flex cables (LTU Kharkiv)

29.24 x 26.88 µm² pixel size
active cross section 3 x 3 cm²
compact design: expect $R_M \approx 11$ mm

ALPIDE output via 1.2 Gb/s serial line
readout via 2 levels of FPGA
EPICAL-2 Measurements

- Cosmic muons (Utrecht University, 2020)
- Test beam DESY (Feb. 2020)
  - Electron/positron, $E = 1.0 - 5.8$ GeV
- H6 test beam SPS (Sept./Oct. 2021)
  - Mixed beam, $E = 20 - 80$ GeV
Allpix$^2$ Simulations

- Detailed implementation of ALPIDE sensor and detector geometry
- Good description of detector behaviour

Allpix$^2$: NIM A, 901:164–172, 2018
Event Displays

single electron event
5 GeV
raw data
colour → layer number
Sensor Calibration

- Use muons (from cosmics or in-beam) for relative calibration of sensors with different sensitivities
  - Expect identical response to muons in all layers in terms of hits and clusters
  - Ignore in-sensor variation of sensitivity
- Significant sensitivity variation observable in number of hits
- Minor variation in number of clusters
  - Number of clusters less susceptible to threshold variations
Detector Response

- Number of hits ($N_{\text{hits}}$) or number of clusters ($N_{\text{clus}}$) usable as response observable
  - Well defined peaks scaling with beam energy
- Allpix$^2$ simulation
  - Tuned to number of hits at 5 GeV
  - Very good description for hits at all energies
  - Good description for clusters
    - Sensitive to details of cluster algorithm
Energy Linearity

- Average response as a function of beam energy
  - Described by linear fit
    - Constrained to (0,0) by pedestal measurements
    - Behaviour reproduced by simulation
- Small apparent deviations from linearity in ratio
  - Perfect linearity in hits from simulation
  - Hits in data agree with EPICAL-1
    - Non-linearity in hits strongly influenced by uncertainty in DESY beam energy
      - NIM A, 922:265–286, 2019
    - Stronger non-linearity from $N_{\text{clus}}$
      - Reproduced in simulation
- Response consistent with full linearity at low energy
Resolution shows the expected behaviour for calorimeters

Experimental data likely contain a significant contribution from beam energy spread at DESY

“Particle counting” ($N_{\text{clus}}$) shows superior performance here

- Confirmed by simulations

Resolution from hits better than EPICAL-1 results

Resolution from $N_{\text{clus}}$ close to analog SiW ECAL (CALICE) physics prototype

NIM A 608:372-383, 2009

Cluster algorithm not yet optimised
Shower Profiles

- Longitudinal and lateral shower distributions show expected behaviour
  - Similar for $N_{\text{clus}}$ and $N_{\text{hits}}$

- Wealth of information to extract details of shower development: work in progress

- Hit density well below saturation limit at low energy
  - Maximum at 5 GeV: $\approx 300$ hits/mm$^2$
  - Saturation at 1272 hits/mm$^2$
  - Limit will be reached at high energy: correction required
SPS H6 Beam Composition

- Allows precise extraction of beam composition
- Hadron contamination of electron peak under control

- Detailed MC simulation (Allpix\textsuperscript{2}) describes all components of calorimetric energy spectra very well

![Graph showing SPS H6 Beam Composition]

EPICAL-2 preliminary
$E_{\text{beam}} = 80$ GeV
- test-beam data
- fit range
  - Allpix\textsuperscript{2} simulation of:
    - $\pi^+$
    - $K^+$
    - $p$
    - $e^-$
    - $\mu^+$
    - sum

N_devents
N
energy (GeV)

template contribution (%)
Energy Linearity at High Energy

- Electron peak position \( (N_{\text{hits}}) \) extracted for different beam energies
- Behaviour at high energy matches well to low energy
- Good linearity at high energy
  - Confirms observed non-linearity at DESY to be related to test beam properties
Energy Resolution at High Energy

- Results of preliminary analysis from SPS data:
  good energy resolution from $N_{\text{hits}}$
  - High energy (SPS) consistent with extrapolation from low energy (DESY)
- Work in progress:
  - $N_{\text{clus}}$ seen to yield better energy resolution at low energy, cluster algorithm needs to be adjusted for high energy
• Longitudinally integrated distribution makes separation challenging
• Much more information available in high-granularity 3D distributions
Application: Two-Shower Separation

- Full pixel detector information very powerful
  - Two-shower separation down to 1 mm should be possible
- Systematic studies to be done

EPICAL-2 preliminary
Allpix² simulation
30 GeV e⁻ + 250 GeV e⁻
1.2 mm separation
single event
Summary

• Digital calorimetry works
  • New prototype confirms findings with EPICAL-1
  • Much better performance of EPICAL-2
    • ALPIDE sensor: very low noise, readout speed compatible with modern experiments
  • Technology suitable for ALICE FoCal pixel layers

• Good energy linearity and resolution
  • Study limited by accelerator properties at DESY
  • To be confirmed at high energy – preliminary results very promising

• Very strong potential – so far “scratching the surface”
  • Use full 3D shower information for single- and multi-particle reconstruction
  • Improved jet measurements?
    • Study performance for particle flow algorithms
EPICAL-2 Team

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