Particle Flow Calorimetry: Experimental Status and Technical Developments

Felix Sefkow
What we learnt from CALICE:

- **Introduction:**
  - testing PFLOW calorimetry

- **In real terms:**
  - Validate simulation
  - test algorithms
  - test technologies and establish feasibility
Understand particle flow performance

\[
\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} + 0.7 + 0.004E + 2.1 \left( \frac{E}{100} \right)^{+0.3}
\]

- Particle flow is always better
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too

<table>
<thead>
<tr>
<th>Tracking</th>
<th>Resolution</th>
<th>Leakage</th>
<th>Confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 %</td>
<td>3.0 %</td>
<td>0.7 %</td>
<td>0.8 %</td>
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<tr>
<td>0.7 %</td>
<td>2.0 %</td>
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<td>0.8 %</td>
<td>1.6 %</td>
<td>0.8 %</td>
<td>1.3 %</td>
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Calorimeter Only (ILD) vs. Particle Flow (ILD+PandoraPFA)

Particle Flow calorimetry: Experimental

Felix Sefkow
CALOR 2010, Beijing, May 10-14, 2010
How to test it experimentally?

• “Jets” from thin targets?
  – Would require magnet spectroscopy and large acceptance ECAL + HCAL
    • Simulation study
  – Multi-million $ experiment
  – and still inconclusive
    • need to control target losses and acceptance losses at 1-2% level
    • model dependence

• Factorize the problem: check the ingredients
  – simulation
  – algorithms
  – technical performance
Critical questions

• Are the basic detector **performance** predictions confirmed?
• Are the **shower parameters** well enough simulated to predict PFLOW?
• Is the **substructure** actually there and well modeled?
• Can one realize the potential of **software compensation** for gain and linearity?
• Can we verify the "**double track resolution**" of a tracking calorimeter?
• Are **detector effects** under control?
• Can we **calibrate** millions of cells and control stability?
• Can we build the detector without spoiling it by **dead material** everywhere?
• What are the relative merits of **different technologies** for PFLOW?
Technology tree

- mostly ILD, SiD
- ILC, CLIC
Overall status

- Major test beam campaigns at DESY, CERN and Fermilab
- 1st generation “physics” prototypes
- Mostly combined set-ups ECAL-HCAL

- Si W ECAL 2005-08
- Scint W ECAL 2007-09
- Scint Fe HCAL 2006-09
- RPC Fe HCAL to start end 2010

- 2nd generation “technical” prototypes: construction and commissioning ongoing, single or few layers
- Complete detectors to start with RPC-Fe HCAL 2011
- ECAL, Scint Fe HCAL later
Validation of the simulations
detector performance
shower models
ECAL options

- W Si or Sci: common mechanics, similar electronics
Pions in the SiW ECAL

- test Geant 4 predictions with 1 cm$^2$ granularity
- sensitive to shower decomposition
- favor recent G4 physics lists
- certainly not perfect - certainly not bad either!

Shower Components:

- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum
Present-day simulation quality requires good detector understanding to discriminate.

Fluctuations also well reproduced.

- **Fe Scint tile HCAL**
- **CALICE Preliminary**
- **2D profile from starting point**
- **Mean shower radius**
- **MC comparisons**
- **Physics prototypes in test beams provide unprecedented 3D information of the structure of hadronic showers**
- **Excellent possibilities for the validation and the further development of hadronic shower models in simulation codes (GEANT4)!**
Shower fine structure

- Could have the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already

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Particle Showers in a Highly Granular HCAL
CALOR2010, Beijing, China

Beam 25 GeV 

ECAL upstream
Summary on validation:

- The particle flow detectors perform as expected
  - support predictions for full-scale detector
- Geant 4 simulations not perfect, but also not as far off as feared a few years ago
  - fruitful close cooperation with model builders ongoing
- Predicted shower sub-structure is seen
  - detailed checks possible, benefits for all calorimeters
Test the algorithms with real data
Software compensation

- Poor man’s dream
- Significantly improved resolution AND linearity
- High granularity - many possibilities
Two-particle separation

- The “double-track resolution” of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Important: agreement data - simulation
  - sharing the same limitations

to be done with photons, too
Leakage estimation

- Infer leakage from seen part of shower topology and energy
- Multivariate techniques; striking potential
- Implications for detector optimization: implement in Pandora

Simulation, to be confirmed
Summary on algorithms

- Granularity is extremely powerful
- Energy resolution and imaging capabilities verified with data at sub-structure level
  - the main drivers of PFLOW performance
- Leakage estimation and software compensation not yet implemented in present Pandora
Test the technologies and establish feasibility
Calibration

- Study triggered by review of LC detector LOI
- Can you calibrate millions of channels and maintain stability?
  - not really a worry for Si, but could be an issue for scintillator

- 1. Simulate impact of statistic (uncorrelated) and systematic (correlated) calibration errors, find $\int L$ for in-situ calibration
  - PFLOW performance VERY robust w.r.t. channel-to-channel variations; coherent effects easy to control

- 2. Exercise in-situ methods (SiPM auto-calib, track segments) with test beam data from CERN and FNAL
  - transport calibration across the ocean and restore performance
Integration

• Sensor technology, precision mechanics
• Next: system engineering

• Industrialized ASIC development using common building blocks

• New operational challenges
  – power pulsing
  – on-detector zero suppression
  – real-time threshold monitoring
  – time measurement
Digital calorimetry

• MAPS DECAL: Tera-pixel
  – 1st sensor tests in e showers
• Digital and semi-digital hadron calorimeter
  – even higher granularity
  – suppress dE/dx fluct.
  – reduced n sensitivity
  – limited at high E?
• Small RPC proto successful
• Full-size RPC based prototypes underway

• Promising tests of GEM and MicroMEGAS based read-out modules

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CALICE 68. DESY PRC
High energy

- Particle flow also a promising option for CLIC energies
- Leakage expected to limit PFLOW performance
  - need $1 \lambda$ ECAL + $7 \lambda$ HCAL
- Tungsten absorber cost-competitive with larger coil - and less risky

- Test beam validation with scintillator and gas detectors

- More neutrons:
  - different model systematics
  - timing measurements
Summary on technologies

- a leap in several orders of magnitude in channel count
- new sensor technologies, new integration concepts
  - the latter is part of the feasibility demonstration
- progress towards realism:
  - realistic designs
  - realistic simulations
  - realistic cost
  - realistic proposal
- Digital calorimetry ready for exploration
Conclusion

• Particle flow calorimetry does not solve the inherent problems of hadron calorimeters

• But it holds the promise of providing a highly performant work-around

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\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left( \frac{E}{100} \right)^{+0.3} \%
\]

• Substantiated by test beam data
• Can be built