Use of Particle Flow Algorithms in a Dual Readout Crystal Calorimeter

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Summary
Motivation

- Development of clear, dense crystals (PbWO, BGO, PbF, . . .) with both scintillator and cerenkov response
  - Cerenkov response is prompt, short $\lambda$
  - Scintillator response has longer time, longer $\lambda$

7-9 g/cc densities -> 5-6 $\lambda_i$ total absorption crystal calorimetry in, e.g., CDF barrel calorimeter volume

- Development of photodetectors (SiPM, APD, . . .)
  - for scintillator response, small area (1 mm$^2$) SiPMs
  - for cerenkov response, development of (thin) large area (~1 inch$^2$) detectors

On-crystal photodetectors -> highly segmented and granular calorimeter

Cerenkov/scintillator response ratio correction optimizes energy resolution of calorimeter objects

Resulting high-purity particle shower content per calorimeter cell

-> Use of PFA algorithms to categorize clusters
Dual Readout Calorimeter Detector Parameters

**Dual Readout Calorimeter in SiD02 Shell (Barrel and EC)**

| DR ECAL | DR HCAL |
|---------|---------|
| 3 cm x 3 cm x 3 cm BGO | 5 cm x 5 cm x 6 cm BGO |
| 8 layers – 21.4 $X_0$ (1.1 $\lambda_I$) | 17 layers – 4.6 $\lambda_I$ |
| 127 cm IR – 151 cm OR | 151 cm IR – 253 cm OR |
| Scin/Ceren analog hits | Scin/Ceren analog hits |

**Muon Chambers**
- 11 layers

**Total Absorption Crystal Calorimeter**
- 25 total layers of BGO
- 5.6 $\lambda_I$ in barrel
Threshold/Timing Cuts on Calorimeter hits

e^+e^- \rightarrow ZZ \rightarrow \nu\nuqq \ @ \ 500 \ GeV

Scintillator Hits

dE/dx \sim 30, 60 \ MeV \ per \ mip
Threshold \sim 1/50 \ mip
Timing \ t<100 \ ns

Cerenkov Hits

Similar (magnitude) threshold
Timing \ t<100 \ ns
Electron Calibration for Scintillator, Cerenkov

10 GeV electrons

$\sigma/E = 0.017$ Scintillator
$\sigma/E = 0.052$ Cerenkov

$S = 1.004 \times s_{\text{raw}}$
$C = 7692 \times c_{\text{raw}}$
Cerenkov/Scintillator Correction for Hadrons

S/E slices in em fraction (C/S) bins

5, 10, 20, 50, 100 GeV pions

Note: for a visible fraction S/E, fluctuations in shower em fraction > fluctuations in had fraction at any fixed em fraction

S (e calibrated scintillator response)
- em and had visible energy

C (e calibrated cerenkov response)
- em part of shower

C/S ~ em fraction of visible energy

S/E = total fraction of energy seen

S/E slices in em fraction (C/S) bins

Scint over E bin .15
- Entries: 304
- Mean: 0.57547
- Rms: 0.555732

Scint over E bin .25
- Entries: 475
- Mean: 0.605937
- Rms: 0.563289

Scint over E bin .35
- Entries: 608
- Mean: 0.623591
- Rms: 0.582522

Scint over E bin .45
- Entries: 1225
- Mean: 0.663942
- Rms: 0.596844

Scint over E bin .55
- Entries: 1782
- Mean: 0.706982
- Rms: 0.623386

Scint over E bin .65
- Entries: 2579
- Mean: 0.741667
- Rms: 0.691175

Scint over E bin .75
- Entries: 3256
- Mean: 0.76332
- Rms: 0.693478

Scint over E bin .85
- Entries: 2667
- Mean: 0.62118
- Rms: 0.672199

Scint over E bin .95
- Entries: 1111
- Mean: 0.95115
- Rms: 0.74116
Polynomial Correction Functions: \( E = \frac{S}{P_n} \)

- \( P_1 = 0.315 + 0.684(C/S) \)
- \( P_2 = 0.677 - 0.439(C/S) + 0.762(C/S)^2 \)
- \( P_3 = 0.506 + 0.608(C/S) - 1.050(C/S)^2 - 0.935(C/S)^3 \)
- \( P_4 = 0.577 - 0.149(C/S) + 1.464(C/S)^2 - 2.302(C/S)^3 + 1.410(C/S)^4 \)

- \( \text{em fraction} = 1 \)
- \( S/E, C/S = 1 \)
- \( \rightarrow \) calibration

- Missing part of had fraction

- Mean and \( \sigma/\text{mean} \) of fit in each C/S bin plotted
- \( \rightarrow \) resolution improves with em fraction
Corrected Pion Scintillator signal using P3 Polynomial

\(\sigma/E \sim 0.08\)

\(\sigma/E \sim 0.07\)

\(\sigma/E \sim 0.05\)

E (GeV)
DiJet Mass: $e^+e^- \rightarrow ZZ \rightarrow qq\nu\nu$ @ 500 GeV

C/S correction per jet
No PFA

$\Delta M/M = 0.076$

$\Delta E/E = 0.036$
No leakage correction yet
Cluster and C/S corrections

~7 clusters per pion, many small fragments

Fit gives mean of ~20 GeV
$\sigma/E \sim 24\%/\sqrt{E}$
PFA Possibility? - MC Particle Contribution to DR Cal Cells

Scintillator Hit Collections

All Hits

Multiple Particles

Cerenkov Hit Collections

All Hits

Multiple Particles
Mip Cluster/Interaction SpacePoint Algorithm

Interaction spacepoint defines the start of showering and the end point of the track \( \rightarrow \) used for \( \Delta M \) correction on jets.
$e^+e^- \rightarrow ZZ \rightarrow \nu\nu qq$ @ 500 GeV

Contains perfect reconstructed particles (from MC gen and sim) and C/S-corrected Clusters with 4-hit minimum
PFA Performance – Track/CAL Cluster Match

\[ e^+e^- \rightarrow ZZ \]
\[ \rightarrow \nu\bar{\nu}qq \text{ @ } 500 \text{ GeV} \]

# tracks = # mip clus
(but sometimes start of shower is layer 0, so mip cluster has 0 hits)

Track Core clusters lie on extrapolated track

Clusters pointing to the end of the mip cluster (ILSP Clusters) are rare after cores are removed

4.3 Tracks per event (19%) are matched to clusters by PFA
PFA Cluster Purities

$e^+e^- \rightarrow ZZ$
$
\rightarrow \nu\nuqq @ 500 \text{ GeV}$

Purity of mip clusters is $> 98\%$

Purity of core clusters $\sim 90\%$

Purity of ILSP clusters is $> 96\%$

Final $E/p$ range for matched clusters determined by CAL resolution for charged pions
e^{+}e^{-} \rightarrow ZZ \rightarrow \nu\nuqq @ 500 \text{ GeV}

Mip clusters, core clusters, pointing clusters, and shower clusters

Final Track/Cal Cluster matches
-> Track 4-vectors are used in PFA, clusters are removed
Difference -> DiJet Mass – qq Mass

C/S-corrected Clusters

\[ \sigma/M = 0.068 \]

PFA-enhanced Clusters

\[ \sigma/M = 0.059 \]

13% improvement
PFA Template developed for SiD and variants:

- Fully modular construction
- Common IO for all modules:
  - Mip-finding/Track Endpoint, Cluster Algorithms, Cluster pointing, Core cluster matching, Track-Shower association, Cut-based photon ID, H-Matrix photon ID, Neutral hadron finding

All modules run on both Dual Readout collections with zero -> minimal modifications

First use of PFA: Mip-finder Track endpoint determination -> \( \Delta M \) correction from charged particles in event (see Adam Para’s talk later) or per jet

Same parameters as for SiD, only modification was to change collection names
Effect of $\Delta M$ Correction on Jet Masses

All-Track $\Delta M$ for C/S-corrected cluster jets

Unmatched Track $\Delta M$ for C/S-corrected + PFA jets

Use of PFA results in smaller mass per jet
DiJet Mass + $\Delta M$ Correction

$e^+e^- \rightarrow ZZ\rightarrow \nu\nu q\bar{q} @ 500$ GeV

C/S-corrected Clusters

$\sigma/M = 0.075$

19% improvement

PFA-enhanced Clusters

$\sigma/M = 0.061$
Difference -> DiJet Mass – qq Mass + $\Delta M$ Correction

C/S-corrected Clusters
$\sigma/M = 0.062$

PFA-enhanced Clusters
$\sigma/M = 0.059$

5% improvement
e^+e^- \rightarrow ZZ \rightarrow \nu\nuqq @ 500$ GeV

C/S-corrected Cluster RPs

C/S-corrected Clus
PFA Tracks + C/S-corrected Cluster RPs

4 Track/Cluster matches found

e^+e^- \rightarrow ZZ \rightarrow \nu\nuq\bar{q} @ 500 \text{ GeV}
Summary

- A total absorption calorimeter using dense crystals and employing dual readout of both scintillator and cerenkov light has been simulated and used to study high energy e+e- interactions.

- Because of the high segmentation and granularity of the crystal calorimeter configuration, high purity of particle contribution per calorimeter cell was obtained -> PFA approach to event reconstruction.

- Dual Readout corrections were applied to pion shower fragments from a NN cluster algorithm, resulting in an energy resolution stochastic term of $\sim 24%/\sqrt{E}$ for single pions.

- Modular PFAs developed for a pixelized sandwich calorimeter have been used without modification in the crystal calorimeter including:
  
  - Determination of the starting layer of hadron showers
  - Matching of core clusters to tracks
  - Cluster pointing algorithms
  - Iterative track shower association with E/p evaluation

- Using the PFA-enhanced approach along with the DR corrections to clusters and mass corrections to jets, improvement of the dijet mass resolution in the range of 5-19% has been obtained when compared to the non-PFA reconstruction.