Calorimetry for lepton colliders: experience and activities of the LPI-MEPhI-MIPT group

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Lepton colliders – precision frontier

Relies on unprecedented jet energy resolution 3-4%

e.g. to distinguish dijets from W and Z hadronic decays and achieve physics goals

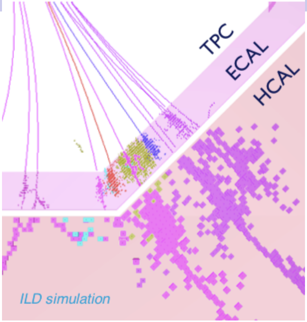
Main tool: Particle Flow reconstruction

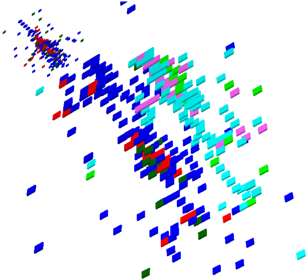
- inherited from Energy Flow approach at LEP
- assumes possibility to disentangle contributions from different particles within jets
- **requires high longitudinal and transverse calorimeter segmentation — highly granular calorimeters**
  - experimentally tested by the CALICE collaboration
  - accepted for CMS HGCAL for HL-LHC

PF approach invention

Our colleague was among the inventors of PF approach *[V.L. Morgunov, Proc of CALOR02, Pasadena, 70 (2002)]*

and among the developers of the first reconstruction algorithms for highly granular calorimeters *[V. Morgunov & A. Raspereza, LCWS2004, Paris (2004)]*





Superimposed events from the CALICE AHCAL test beam

Contribution to LC calorimetry

CALICE collaboration – calorimeters for LC

pioneered developments of highly granular calorimeter concepts

- member of the group is a co-founder of the CALICE collaboration
- our group actively working in CALICE since 2005 for R&D and data analysis
  - scintillator production by industrial partners was done in cooperation with experts from our group
  - colleagues from our group participated in the development of SiPM test procedures
- member of the group was a Chair of the CALICE Speakers Bureau during 4 years
- 6 from 25 CALICE papers with key contribution from our group members

Focus of our group in CALICE activities

R&D of highly granular scintillator-steel hadron calorimeters with SiPM

- the first physics prototype and next-generation technological prototype
- scintillator tiles development and production
- calorimeter assembly and SiPM tests
- calorimeter calibration
- participation in beam tests

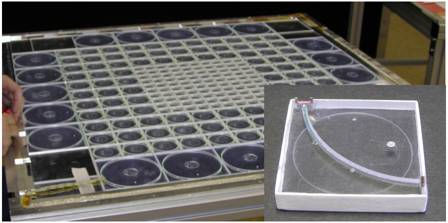
Data analysis

- calorimeter-based particle ID for test beam event selection
- shower start finder
- a novel software compensation algorithm
- hadronic shower shapes investigation
- validation of Geant4 models

R&D and tests of CALICE scint-SiPM analog hadron calorimeters

First physics prototype

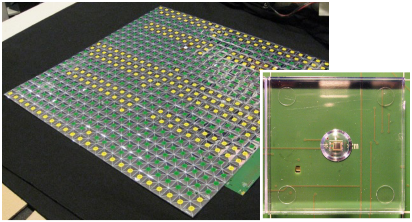
- sampling, 38 layers, **~5.3λ_I**
- sensor: **scintillator + WLS fiber + SiPM**
  - **~8000 moulded tiles (UNIPLAST, Russia) and SiPMs from PULSAR (Russia)**
  - transverse size: ~90×90 cm^2
  - **3×3, 6×6, 12×12 cm^2 tiles, 5-mm thick**
  - side coating against crosstalk
- absorber: **steel (tungsten)**, 2(1)-cm thick
- external electronic boards
- test beams in 2006–2011 (DESY, CERN, FNAL), e, μ and hadrons, 1–120 GeV
- **Successful proof-of-principle!**



[JINST 5 (2010) P05004], [JINST 6 (2011) P04003]

Next-generation technological prototype

- sampling, 38 layers, **~4.5λ_I**
- sensor: **scintillator+SiPM**(direct readout)
  - **~22000 moulded tiles** produced by **UNIPLAST factory** in **Russia**
  - transverse size: ~72×72 cm^2
  - **3×3 cm^2 tiles, 3-mm thick**
  - each tile wrapped in reflective foil
- absorber: **steel**, 2-cm thick
- embedded electronics
- test beams in 2018 at CERN, electrons, muons and hadrons, 10–200 GeV
- **Technology ready for mass production!**



[JINST 18 (2023) P11018]

Example of analyses performed by group members

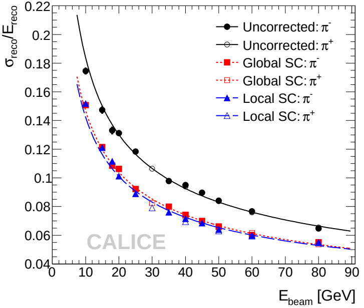
A novel technique of software compensation to improve energy resolution

$$E^{\text{event}}_{\text{SCglobal}} = C_{\text{trk}} \cdot \sum_{t=1}^{N_{\text{trk}}} e_t + E^{\text{event}}_{\text{cor}} \cdot P(a_G, E^{\text{event}}_{\text{cor}})$$

$$E^{\text{event}}_{\text{cor}} = \sum_{s=1}^{M} C_s \cdot W^{\text{event}}_s \cdot \sum_{i}^{N_s} e_{is}$$

- Weights W^{event}_s are calculated from hit energy spectrum shape.
- Coefficients a_G of second-order polynomial P are estimated from test beam data.

[JINST 7 P09017 (2012)]



Improvement ∼**15–25%** for single hadrons

Published CALICE analyses with dominated contribution from group members

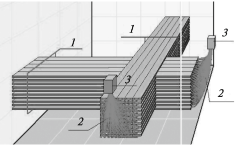
- **first demonstration of PF approach using CALICE test beam data** *[JINST 6 (2011) P07005]*
- comparison of pion and proton response of CALICE AHCAL *[JINST 10 (2015) P04014]*
- shower shape analysis *[JINST 11 (2016) P06013]*

Experience in calorimetry and detectors for particle physics

CMS experiment at LHC

Calibration of the hadron calorimeter in situ with isolated hadrons from collisions, development of the new approach of correction for pileup *[JINST 13 (2018) 03, C03025]*

DANSS experiment at Kalinin power plant



DANSS detector design

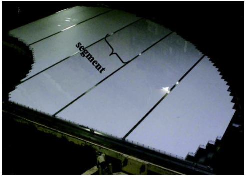
Development, construction, assembly, optimisation, calibration and monitoring of the DANSS detector:

- 2500 1-meter long scintillator counters
- SiPM and PMT readout
- *[Phys.Part.Nucl.Lett. 15 (2018) 3, 272-283]*

Belle II experiment at SuperKEKb

Participation in the development and construction of the KLM system:

- scintillator strips with SiPM readout:
  - 16800 strips produced for two KLM endcaps
  - 75 strips (4 cm width) / sector
  - the longest strip 2.8 m; the shortest 0.6 m
- *[JINST 12 (2017) C07035]*



KLM Endcap assembly

Ongoing and planned activities

Test of digitisation scheme and other parameters for simulations of the CALICE AHCAL technological prototype

Development of machine-learning-based approach for prediction of hadronic shower properties using calorimetric observables *[JINST 17 (2022) P10031]*

Application of machine learning for Geant4 models validation with CALICE test beam data; preliminary Monte Carlo study in *[Phys.Atom.Nucl. 86 (2023) 4, 551-556]*

CMS HGCAL: cosmic tests of the SiPM-on-tile elements at different temperatures

Upgrade of DANSS detector with new strips and photodetectors

Development of particle ID system (base on Focusing-Aerogel Ring-Imaging CHerenkov detector) for Super Charm-Tau Factory project

We are looking forward to apply our experience and best practices in CEPC developments