Snowmass 2021
Instrumentation Frontier
IF06 - Calorimetry - Conveners

Andy White (UTA), Minfang Yeh (BNL), Rachel Yohay (Florida State)

February 18, 2022

Instrumentation Frontier
IF06 – Calorimetry – White Papers

1) **Collider**

- **Particle Flow Calorimetry for Future Colliders**

  Katja Kruger (DESY)
  Randi Ruchti (Notre Dame)

  Detailed outline received, initial writing assignments made.

  Plan for first draft by February 21 – review by LOIs until March 4
  Final version by March 10

- **Dual Readout Calorimetry for Future Colliders**

  Sarah Eno (Maryland)
  Franco Bedeschi (INFIN-Pisa)

  Draft created: https://www.overleaf.com/read/hvdmjvhpvdqk
  Author list expanded and outline agreed.
  Paper exists – now polishing (Nural Arcturin)

Particle Flow Calorimetry

White Paper Leaders: Katja Kruger, DESY and Randy Ruchti, Notre Dame

Abstract: Original motivation for PF calorimetry is to experimentally provide excellent jet energy resolution. Typically - jet energy resolution is relatively poor in conventional hadron calorimeters, but in particle flow calorimeters $\sigma/E < 5\%$ should be possible for a range of jet energies from ~50 GeV to ~250 GeV, important particularly for experiments at electron-positron colliders (ILC, CLIC, FCCee, CEPC). The high granularity, which is essential for PF calorimetry, can also be very beneficial for removal of background from pile-up on an event-by-event basis. This makes these calorimeters an attractive option also for hadron collider experiments, for example the HGCAL under construction for CMS for HL-LHC operations.

1. Introduction
2. Motivation for Particle Flow Calorimetry
    a. Scientific Objectives
        i. Measuring the energy of jets which includes understanding neutrals.
        ii. Vector Boson Reconstruction
        iii. Higgs Reconstruction
        iv. Tau Reconstruction
        v. Long lived particles (?)
    b. Resolution Concerns

Transcendental Preprint
February 14, 2022

Dual-Readout Calorimetry for Future Experiments Probing Fundamental Physics

ISTITUTO NAZIONALE DI FISICA NUCLEARE, SEZIONE DI PISA: PISA, ITALY

F. Bedeschi

U. MARYLAND, MD, USA

S. Eno

PRINCETON UNIVERSITY, NJ, USA

C. Tully

TEXAS TECH UNIVERSITY, TX, USA

Nural Akchurin

INFN & UNIVERSITY OF MILANO-BICOCCA, ITALY

M. Lucchini

INFN PAVIA, ITALY

R. Ferrari, G. Gaudio, G. Polesello

CERN, SWITZERLAND

L. Pezzotti

UNIVERSITY OF SUSSEX, UK

I. Vivarelli

INFN & UNIVERSITY OF ROMA LA SAPIENZA, ITALY

S. Giagu

INFN MILANO & UNIVERSITY OF INSUBRIA, COMO, ITALY

R. Santoro

KYUNGPOOK UNIVERSITY, S. KOREA

Sehwook Lee

OTHER

add more names

2 Calorimetry needs for future fundamental physics studies

In the DOE/NSF BRN [2], the calorimetry requirements are given in their Table 14, reproduced in Fig. 1 in this White Paper. Similar sets of requirements, designed specifically for future circular electron-positron colliders, are discussed in Refs. [1, 3]. The table links the calorimeter needs to physics goals via technical requirements (TRs). TRs 1.1-1.5 relate to measuring Higgs properties with sub-percent precision, Higgs self-coupling with 5% precision, Higgs connection to dark matter, and new particles and phenomena at the multi-TeV scale. TR 5.5 and 5.10 are related to flavor physics (search for new physics through rare flavor interactions, tests of the CKM quark mixing matrix description, studies of lepton flavor universality). TR 5.12 is related to charged lepton flavor violation studies. The Priority Research Directions 2 and 3 shown in Fig. 1 refer primarily to operation in hadron colliders, while PRD 1 is much more focused on electron-positron colliders. The latter are more likely to be available for experiments in the medium term future; this paper will then mainly discuss requirements for this type of future accelerators.

Priority Research Direction (PRD)	Technical Requirement (TR)
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	TR 1.3, TR 1.4, TR 5.5, TR 5.10, TR 5.12, TR 5.15
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	TR 1.4, TR 5.1, TR 5.10
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification	TR 1.3, TR 1.4, TR 5.7

Table 14: Summary of calorimetry Priority Research Directions to corresponding Technical Requirements.

Figure 1: Table 14 from Ref. [2] giving the US priorities in calorimetry.

The associated production of a Z and a Higgs boson in e^+e^- collisions at 240 GeV is one of the key processes to be studied in detail at future colliders. Over 90% of the possible final states contain hadronic jets. One third has two jets, while the rest have four or six. It is therefore straightforward that good jet resolution is a very important feature of any detector to be deployed at these accelerators. In particular this generates strong requirements on the performance of the calorimeters. Jet resolution is relevant in many specific analyses, for instance: 1) Higgs recoil mass from Z decaying to two jets, to be distinguished from hadronic decays of pair-produced W's or Z's; 2) classification of specific Higgs decay final states, in particular separation of $H \to W^+W^-$ from $H \to ZZ$ when W's or Z's decay to two jets [4]. At higher energies the separation between the vector boson fusion process $H\nu\nu$ from ZH associated production with $Z \to \nu\nu$, which is important in the determination of the Higgs width, also relies on good jet energy resolution [3].

Typical ElectroMagnetic (EM) resolutions in high granularity particle flow calorimeters are $\sim$15%/$\sqrt{E}$ and $\sim$10%/$\sqrt{E}$ in Liquid Argon or dual-readout sampling calorimeters respectively [1]. The hadronic jet resolution is not significantly affected by improving this level of precision, although it has been shown that photon association to π^0 and therefore to jets is strongly improved with state-of-the-art EM resolutions from homogeneous calorimetry in the 3-5%/$\sqrt{E}$ range [5]. The sampling calorimeter resolutions are also sufficient to detect

3 Short review of the dual-readout concept

In this section, we briefly review why ancillary information can improve shower resolutions. Hadronic showers involve inelastic interactions of hadrons with nuclei. The breakup of the nuclei consumes some of the kinetic energy of the incident particle, and produces many different types of secondary particles, including charged and neutral pions, heavy-ion fragments, strange mesons, photons, etc. The signal generated by a hadronic shower is lower in general compared to that of an electron/photon ("EM" shower) of the same energy due to *invisible energy losses* from e.g. nuclear binding energies, neutrinos, and particles with small inelastic cross sections such as neutrons escaping the detector or depositing energy outside of the sampling window. A variety of other effects also contribute to the lower detector response to hadronic showers. The amount of missing (invisible) energy is correlated with the number of inelastic nuclear collisions. Maximal information calorimetry finds measurable quantities that are correlated with the missing energy to make shower-by-shower corrections.

4.1 The IDEA detector and its spaghetti calorimeter

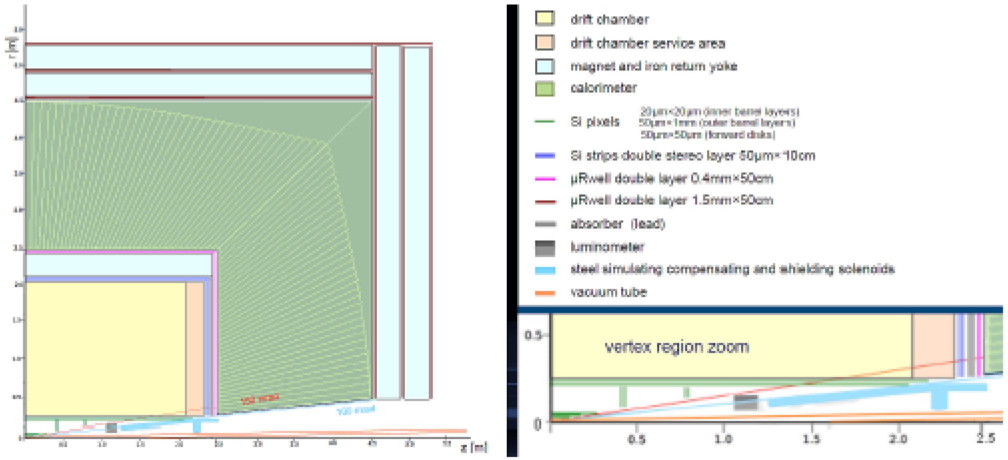

Figure 6: Cross section of the proposed layout for the IDEA detector concept.

4.2 Dual readout with crystal calorimeters

Recently a consortium of US Universities and National laboratories (Oak Ridge, FNAL, Argonne, Maryland, Princeton, Virginia, Texas Tech, Caltech, Michigan, MIT, Purdue) has revived the RD52 research on dual-readout of homogeneous crystals. A crystal EM calorimeter used in conjunction with a spaghetti-type dual-readout hadron calorimeter could have both excellent resolution for electrons and photons and state-of-the-art hadron and jet resolutions. The proposal was inspired by Ref. [5], which proposed a detector called *SCEPCAL*. Such a calorimeter could be built on the time scales of future Higgs factories such as ILC, FCC-ee, and the muon collider. Collaboration members are also interested in longer term dual-readout R&D, which will be discussed in Sections 5.5 and 5.6.

5 Future R&D activities

5.1 IDEA collaboration prototype plans

Unprecedented jet energy resolutions required by future Electroweek factories seem to be reachable with a fibre-sampling Dual-Readout (DR) calorimeter, ad described in 4.1. Despite the dual-readout principle has been proved experimentally with seeveral test beams, many technical problems are still open, and a dedicated R&D is needed to build a hadronic-size prototype and finally assess the performance that could be reached.

6 Executive Summary

this is the all important 1.5 page executive summary that will go into the actual snowmass report

Future collider detectors are tasked with resolving at higher precision the information content of Higgs boson events and a wealth of potential new physics processes with the possibility to shed light on the nature of the fundamental interactions and on the origin of dark matter in the universe. Calorimeters have a central role in bringing together electromagnetic, charged and neutral hadron information with the central tracker and muon systems

Instrumentation Frontier
IF06 – Calorimetry – White Papers

1) **Collider (cont.)**

- **Precision Timing for Collider Experiment based Calorimetry**

  Frank Simon (MPP Munich)
  Sergei Chekanov (ANL)

  Structure of document agreed.
  Building author/contributor list
  Draft created: https://www.overleaf.com/project/615b6678cb069afe6b799d14
  Interacting with LOIs, paper on track

2) Neutrino

- **Calorimeter Techniques and Materials for Neutrino Experiments**

  Milind Diwan (BNL)
  Jae Yu (UTA)

  Separate document for IF06, NF10 preferred by IF liaison (Mayly Sanchez)
  No update

Argonne NATIONAL LABORATORY

Status of the White paper:

Precision Timing for Collider Experiment based Calorimetry

Contact: S.Chekanov, F.Simon

Goals: to discuss physics cases and requirements for precision timing for electromagnetic (ECAL) and hadronic (HCAL) calorimeters for future particle-collision experiments

Status

Overleaf draft is created: https://www.overleaf.com/project/615b6678cb069afe6b799d14

Table of content

- **(1) Introduction**
- **(2) Physics case**
  - Event and object reconstruction
  - Shower reconstruction and PFA (~2 pages)
  - Particle identification (1 page)
  - Pileup mitigation (1 page)
- **(3) System options**
  - Volume timing
  - Timing layers (2 pages added from a contributed paper)
  - Possible technologies

Table of content (cont.)

Technology candidates for timing layers:

➔ Low-Gain Avalanche Detectors (LGADs)
➔ Ultra-fast silicon monolithic sensors using the CMOS
➔ Depleted Monolithic Active Pixel Sensor (DMAPS)
➔ Micro channel plate (MCP)
➔ Sampling calorimeters based on a Lutetium-yttrium oxyorthosilicate (LYSO)

Technology candidates for volume timing:

➔ Various options of silicon sensors
➔ Plastic scintillator tiles or strips with SiPM readout
➔ Resistive plate chambers, in particular multi-gap RPCs
➔ Highly granular crystal-based detectors

Technology candidated for TM

IF6-neutrino-summary

Milind Diwan[1] and Jaehoon Yu[2]

[1] *Brookhaven National Laboratory*

[2] *University of Texas at Arlington*

(Dated: January 2022)

I. INTRODUCTION

This is the summary of calorimeter technologies intended for neutrino detection. As all neutrino detectors are calorimeters of some kind, this is a vast subject area and the 9 letters of intent submitted under the IF6 designation do not do justice to this subject. The same LOIs also appear in neutrino frontier subgroup NF10 where there are 94 entries. The NF10 LOIs are more comprehensive regarding neutrino instrumentation. Radio detection of neutrinos in covered in IF10 with 11 entries.

We will summarize the 9 LOIs submitted to IF6-neutrinos, although this represents only a fraction of the effort ongoing in the community.

With six neutrino types (three flavors for neutrinos and anti-neutrinos), and a vast range of energies from natural and man-made sources, there is potential for a very large number of detector technologies. Before a summary of the letters of intent in this area, we will classify the types of neutrino calorimeters in terms of their capability.

The most important criteria for a neutrino detector is the cost per unit volume or mass. This criteria leads to selection of inexpensive target mass such as rock, ice, water or liquid argon with readout of charge or light on the surface of the detector. Surface readout, rather than volume readout, reduces the number of electronic channels. However, the energy range and the particle identification requirements determine the technology that can be used in terms of target mass, tracking, and energy resolution.

We separate the calorimetric technologies in several groups corresponding to these criteria: 1) mass scale (low mass (< 1 kg) to high mass > 1000ton), 2) electromagnetic energy threshold (low threshold (< 10 MeV) to high threshold (> 1 TeV)), 3) Tracking capability or spatial resolution (capable of separating tracks or not), 4) Particle identification capability (identification of taus, muons, and electrons), and finally 5) capability to measure muon charge. These five categories can be used to define the capabilities of a detector technology. The science to be addressed then depends on the source of flux; its location, intensity, and timing characteristics.

II. SUMMARY OF LETTERS OF INTENT

Several LOI's are presented related to the DUNE/LBNF project. *Michael_Mooney-192* proposes techniques for precision calibration of large liquid argon TPC's. *Jim-110* and *C.K_Jung-118* are proposals for R&D and application a 3D tracking calorimeter of modest size as a near detector for DUNE. The detector would be made from scintillation plastics read out by fibers that extend in 3 Cartesian coordinates. Such a detector would be useful for 3D reconstruction of ~ 1 GeV neutrinos and placed inside a superconducting magnet for track momentum measurement.

Instrumentation Frontier
IF06 – Calorimetry – White Papers – cont.

3) **Dark Matter**

- **New Calorimeter Techniques and Materials for Dark Matter Detection**

  David Winn (Fairfield)
  Rick Gaitskell (Brown)

  General calorimetry notes/outline received.
  Paper worked out

4) **Materials**

- **Materials for Future Calorimeters**

  Ren-Yuan Zhu (Caltech)
  Minfang Yeh (BNL)

  Detailed outline received.
  Contributors (+invitees) from LOIs identified.
  Targeting Jan 7 for first responses from contributors.
  Draft ready for review at end of February

New Calorimeter Techniques and Materials for Dark Matter Detection

Items for SnowMass on Calorimetry

Calorimetry per se covers a large range of Techniques, Properties, and Issues:

- Energy depositions: meV's (superconducting/DM); ~10 TeV (accelerators), 10^{21} eV astrophysics.
- Energy Resolution: fractions of % –> 150%/√E
- Dynamic range: exceeding 6 orders of magnitude
- Rates/Pileup: ~1 per year to GHz
- Time resolution: ~few ms to few picoseconds
- Radiation Requirements:~0 to GRads per year, 10^{18} n/cm^2 at 5000 fb^{-1} $\eta>5$
- Material purities approaching 0.01 ppb levels
- Raw Data rates up to GByte/s
- Sensitivity/selectivity/ID to variety of particles: γ<–>IR, ν, n, e±, charged hadrons, anti-protons.
- Sizes: ~10's μm to ~10^{10} m^3 – Masses ~ 10 MTonnes
- Hermeticity
- Front-End electronics and digitizing: speed, rad resistance, in-situ operation for tile/Energy-flow
- Reliability/MTBF up to decades.
- Environments: deep ice and ocean, to ~5km below grade, to earth orbit environment, to solar system
- Shock and vibration from nanoN to many g's.
- Cost

Materials for Future Calorimeters

Ren-yuan Zhu and Minfang Yeh

Current and Planned Projects

- Calorimetry concept and design
- What are the current calorimetry usages and requirements?
  - Review DOE Basic Research Needs (BRN) for HEP instrumentation, December 2019 [1]
  - Current ongoing experiments
- What materials are available with pros/cons
  - engineering analysis on performance vs cost & availability

Key Issues and Onwards

- Review CPAD HEP instrumentation frontier workshop in March 2021 [2]
- Preferable materials with high density, better optical property, high light-yield and fast/short light pulse (and low cost)
  - high density → increased stopping power
  - high light-yield → energy and spatial resolution → improved reconstruction
  - high optical transmission → enhanced signal efficacy
- Novel calorimeter concepts with new materials.
  - A Radical consortium proposed to develop a ultracompact, radiation hard and fast-timing

Snowmass 2021
for Instrumentation Frontier/Calorimetry

- Drafts ready by end of February (except Neutrino paper)
- Review by conveners/iterate with authors
- Final versions in early March
- …submission to archive