# Integration of a high EM resolution crystal calorimeter within the IDEA DRO calorimeter

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#### Marco Lucchini INFN & University of Milano-Bicocca

A growing effort with the IDEA DRO Calorimeter group



"Maximum information crystal calorimetry" for a hybrid dual-readout calorimeter system at e<sup>+</sup>e<sup>-</sup> colliders

#### **Design drivers:**



Excellent energy resolution to photons and neutral hadrons (~3%/ $\sqrt{E}$  and ~30%/ $\sqrt{E}$  respectively)



**Separate readout of scintillation and Cherenkov light** (for integration with a dual-readout hadron calorimeter)

**Longitudinal and transverse segmentation** (to provide more handles for particle flow algorithms)

**Precise time tagging for both MIPs and EM showers** (time resolution better than 30 ps)

More details in: 2020 JINST **15** P11005

## **Performance highlights** at an e<sup>+</sup>e<sup>-</sup> collider

See dedicated talk at the "Performance session" on Thursday 11th

Highlights **summary**:

- Recovery of bremsstrahlung photons to improve the resolution of the recoil mass signal in Higgstrahung events from Z→ee decays to about 80% of that from Z→ µµ decays
- Clustering of π<sup>0</sup> photons ahead of jet clustering algorithms to reduce angular spread of jet particles in 4-6-jet event topologies
- Use of dual readout in particle flow algorithm
   to achieve ~3% jet energy resolution at the Z/W boson masses
- Extend the coverage for physics studies to include **final states with low energy photons** (e.g. B-physics, see <u>R.Aleksan's slides at 4th FCC workshop</u>)

## Layout overview

- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget



#### **Dual-readout** in PWO and BGO/BSO crystals

- Dual readout needed only on rear segment
- Strategy can be customized for a given crystal choice (e.g. 2 SiPMs + optical filters on the rear crystal segment)
- Sensitivity to cherenkov photons in both the UV and infrared region with Silicon Photomultipliers



**PWO** 



#### Integration of the crystal calorimeter option in the $4\pi$ Geant4 IDEA simulation

- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm<sup>2</sup> PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: 1.8M (including DRO)

front endcap crystal segment

timing layers (<1X\_)

rear endcap

front barrel crystal segment (6 X<sub>o</sub>)

rear barrel crystal segment (16 X<sub>o</sub>)

10 GeV electron shower

## Energy resolution for **EM particles**

- Contributions to energy resolution:
  - Shower fluctuations
    - Longitudinal leakage
    - Tracker material budget
    - Services for front layers readout
  - Photostatistics
    - Tunable parameter depending on:
      - SiPM choice
      - Crystal choice
  - Noise
    - Negligible with SiPMs
      - High gain devices (~10<sup>5</sup>)
      - Small dark count rate within signal integration time window



#### The dual-readout method in a hybrid calorimeter

- 1. Apply the DRO correction on the energy deposits in the crystal and fiber segments first
- 2. Sum up the corrected energy from both segments

$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL}C_{HCAL}}{1 - \chi_{HCAL}}$$

$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL}C_{ECAL}}{1 - \chi_{ECAL}}$$

$$E_{total} = E_{HCAL} + E_{ECAL}$$

$$\chi_{HCAL} = \frac{1 - (h/e)_s^{HCAL}}{1 - (h/e)_c^{HCAL}}$$

$$\chi_{ECAL} = \frac{1 - (h/e)_s^{ECAL}}{1 - (h/e)_c^{ECAL}}$$



#### Energy resolution for neutral hadrons

- Dual-readout method confirms its applicability to a hybrid calorimeter system
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter



## Calorimeter cost/performance optimization

- Integration of crystals section for EM particles with IDEA calorimeter offers room for overall detector cost optimization
  - Reduce sampling fraction and readout granularity in the hadronic segment (fibers-absorber sampling calorimeter) with limited impact on hadron resolution [e.g. increase of the brass tube outer diameter (OD) to 3-3.5 mm]
  - Relative channel reduction and cost decrease approximately with ~1/OD<sup>2</sup>



#### Jet reconstruction with a dual-readout calorimeter

#### Calorimeter only approach:

- Jet clustering (FASTJET Durham  $k_T$ ) using all calorimeter hits:
  - Both Scintillation and Cherenkov signals
  - Both for the ECAL (crystals) and the HCAL (fiber sampling)
- Apply a dual-readout correction based on the S and C components clustered within each jet



0.04

0.02

**Comparable "calorimeter only" jet resolution of ~5.5% at 50 GeV** achieved with the baseline IDEA calorimeter and with the addition of a dual-readout segmented crystals section

#### Dual-Readout Particle Flow Algorithm for jet reconstruction

- Maximally exploit the information from the **crystal ECAL** for classification of EM clusters and use it **as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter hits
- Exploit the **high resolution and linear response** of the hybrid **dual-readout** calorimeter to improve precision of the track-calo hits matching in a particle flow approach



#### CNNs for **particle ID** with segmented crystal calorimeter



- Use Convolutional Neural Networks to exploit the crystal transverse + longitudinal segmentation and the **high sampling fraction** (=1 in a homogenous calorimeter) for classification of EM clusters
- Using the crystal EM section only, a good classification of EM clusters can be achieved:
  - $\pi^{\pm}/e^{\pm}$ 0
    - $e^{\pm}$  ID with ~99.9% efficiency at 0.4%  $\pi^{\pm}$  mis-ID probability
  - $\pi^0/\gamma$ 0
    - Distinguish photons from  $\pi^0$  with an efficiency higher than 95% at mis-ID probability smaller than 5%
  - $\circ$  K<sup>0,L</sup>/y
    - Distinguish EM and HAD neutral clusters in crystal section (i.e. clusters with no charge track pointing to it) as an early step in particle flow algorithm

#### Crystal longitudinal segmentation matters

• Tangible improvements in particle ID from the longitudinal ECAL segmentation, i.e. **two crystal segments** (front and rear) instead of a single crystal cell

Single particle gun events with uniform energy distribution in the range 1-100 GeV, 100k events for each type of particle





## Jet resolution: with and without DR-pPFA

Jet energy resolution and linearity as a function of jet energy in off-shell  $e^+e^- \rightarrow Z^* \rightarrow jj$  events (at different center-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach  $\rightarrow$  3-4% for jet energies above 50 GeV

#### Summary

- A cost-effective integration of a segmented dual-readout crystal calorimeter within the IDEA fiber calorimeter results in a highly performant hybrid calorimeter system suitable for future e<sup>+</sup>e<sup>-</sup> colliders
- Performance studies show promising results:
  - **Excellent EM, HAD and jet resolution** by combining the DRO information from different calorimeter segments (homogeneous crystals & sampling fibers)
  - **Particle identification capabilities enhanced** by the longitudinal segmentation in the crystal section and by the dual-readout information
  - Combination of the DRO information with a simplified particle flow algorithm shows additional improvement to the jet energy resolution achieving 3-4% for E<sub>iet</sub> > 50 GeV

#### Additional material

#### Some crystal options

- **PWO**: the most compact, the fastest
- BGO/BSO: parameters tunable by adjusting the Si-fraction
- CsI: the less compact, the slowest, the brightest





Crystal	Density g/cm³	λ <sub>ι</sub> cm	X <sub>0</sub> cm	R <sub>M</sub> cm	Refractive index, n	Relative LY @ RT	Decay time ns	Photon density (LY / τ <sub>D</sub> ) ph/ns	<b>dLY/dT</b> (% / °C)	Cost (10 m³) Est. \$/cm³	Cost*X <sub>0</sub> Est. \$/cm²
PWO	8.3	20.9	0.89	2.00	2.2	1	10	0.10	-2.5	8	7.1
BGO	7.1	22.7	1.12	2.23	2.15	70	300	0.23	-0.9	7	7.8
BSO	6.8	23.4	1.15	2.33	2.15	14	100	0.14		6.8	7.8
Csl	4.5	39.3	1.86	3.57	1.96	550	1220	0.45	+0.4	4.3	8.0











#### Photo-statistic requirements for S and C

#### Smearing according to Poisson statistics

- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV
- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV
- SCEPCal layout choices (granularity and SiPM size) provide sufficient light collection efficiency
  - Need experimental validation with lab and beam tests







C photons / GeV

#### Recovery of Bremsstrahlung photons

- Reconstruction of the Higgs boson mass and width from the recoil mass of the Z boson is a key tool at e<sup>+</sup>e<sup>-</sup> colliders
- Potential to improve the resolution of the recoil mass signal from Z→ee decays to about 80% of that from Z→ µµ decays [with Brem photon recovery at EM resolution of 3%/√E]

> Z→e+e- Recoil

#### Example from <u>CEPC CDR</u>

> Z→µ<sup>+</sup>µ<sup>-</sup> Recoil





More on calo geometry and single particle performance

#### Segmentation of calorimeter

#### • ECAL

- Radius: 1800-2000 mm
- Segmentation in theta:
  - barrel: 2x180 = 360
  - endcap: 179 rings
- Segmentation in phi:
  - barrel: 1360 rotations around the beam axis
  - endcap: tuned for each ring to have ~1x1 cm<sup>2</sup> crystals
- HCAL
  - Radius: 2500-4500 mm
  - Segmentation in phi: 252
  - Segmentation in theta: nominal



## Signals

Hits in MIP timing layers:
 t1, t2, E1, E2

• Hits in EM shower layers:

$$S_{F} = \mathcal{P}(E_{dep,F} \cdot LY \cdot \epsilon_{S})$$

$$S_{R} = \mathcal{P}(E_{dep,R} \cdot LY \cdot \epsilon_{S})$$

$$S = S_{F} + S_{R}$$

$$C = C_{R} = \mathcal{P}(N_{cher,prod,R} \cdot \epsilon_{C})$$
Cherenkov signal from only the rear segment

Scintillation signal and time stamp from both layers

#### Angular resolution

 T1+T2: 0.3-1.0 mm spatial resolution along z with the MIP timing layer grid (muons)

• E1+E2: 0.3-0.45 mrad angular resolution for EM particles using center of gravity of the shower (photons)



#### Energy resolution for EM particles



Some shower leakage beyond 200 GeV

#### Response to single charged pions

- Sample of charged pions of "low energy" to understand the expected calorimeter response to the charged pions within the jets
- Strong non-linearity without DRO correction
- Some residual non-linearity for very low energies after DRO

