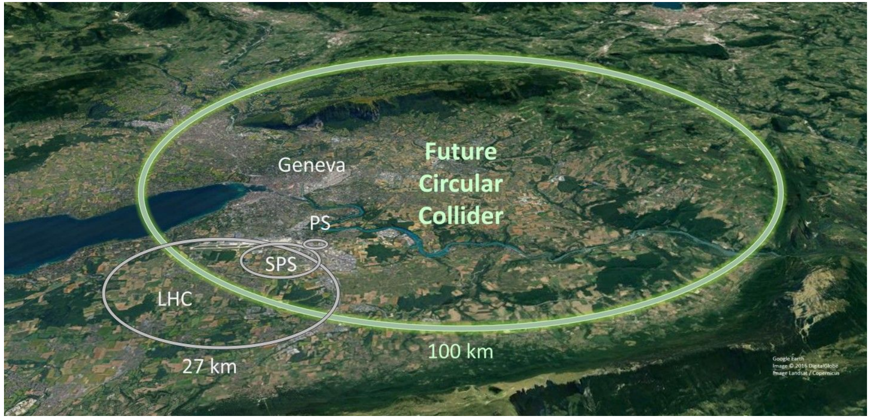
Bi-national conference on Detectors R&D

Dual readout calorimetry for experiment at future colliders

Material taken from several talks by dual readout community

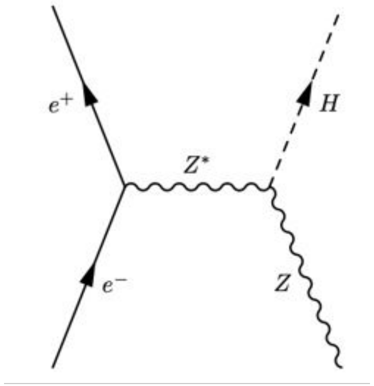
G. Gaudio
INFN-Pavia

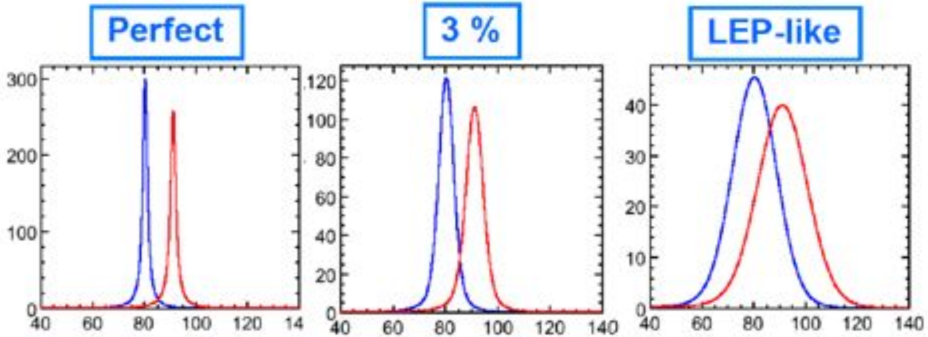
High Energy Resolution calorimeters



e+e-

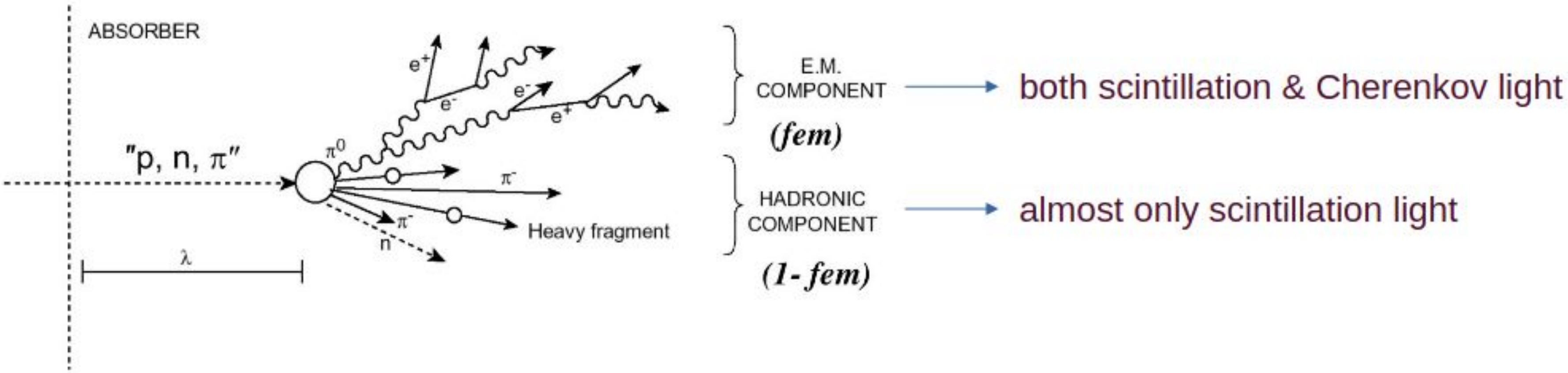
91.2 GeV Z-pole
161 GeV WW
240 GeV ZH
365 GeV tt





97% of the SM Higgsstrahlung signal has jets in the final states

Dual Readout technique



calorimeter response to em-component ≠ non-em response (e/h ≠ 1)

event-to-event fluctuations are large and non-Gaussian

<fem> depends on shower energy and age

Dual Readout Technique

Simultaneous measurement on event-by-event basis of elm fraction of hadron showers

$$S = [\, f_{em}\, e_S + (1 - f_{em})\, h_s \,] \times E$$
$$C = [\, f_{em}\, e_C + (1 - f_{em})\, h_c \,] \times E$$

→

$$S = [\, f_{em} + (h/e)_s \times (1 - f_{em}) \,] \times E$$
$$C = [\, f_{em} + (h/e)_c \times (1 - f_{em}) \,] \times E$$

$$s = (h/e)_S$$
$$c = (h/e)_C$$

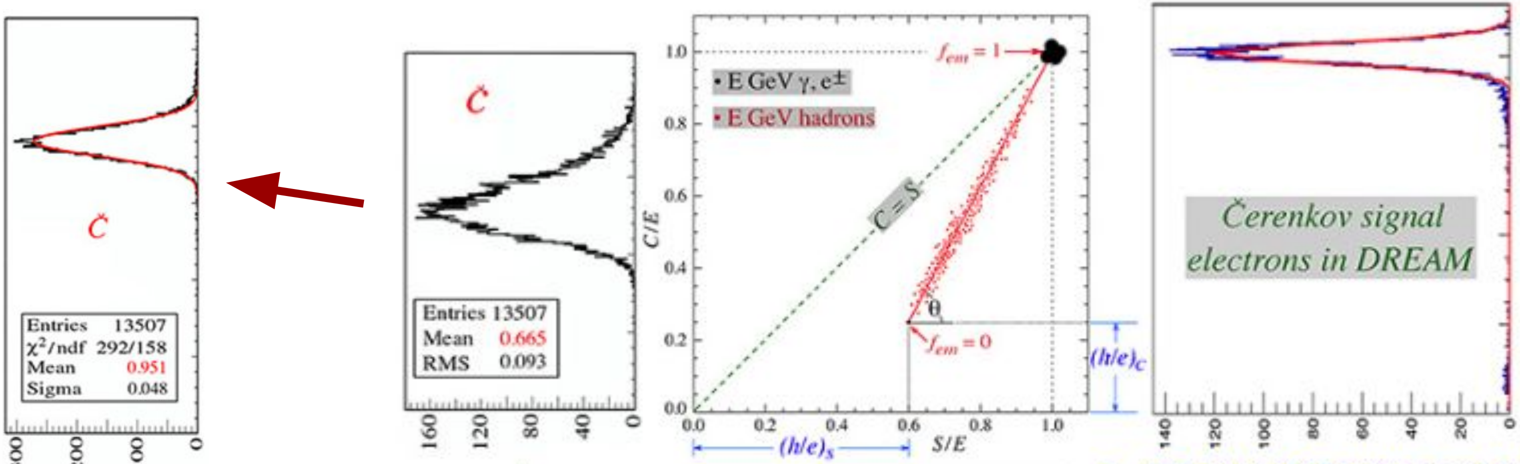
e/h ratio of the C (S) calorimeter structure (measured)

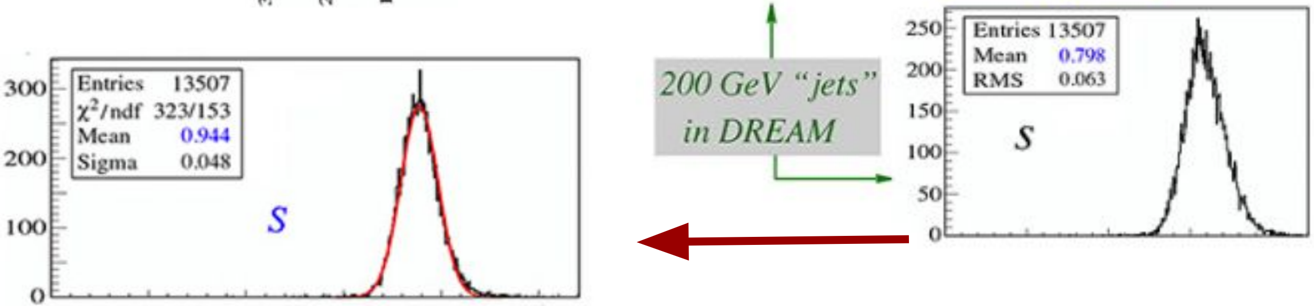
$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_c} = \frac{1 - s}{1 - c}$$

Solve the system with 2 equations and 2 unknowns (event per event) and calculate

$$f_{em} = \frac{c - s(C/S)}{(C/S)(1 - s) - (1 - c)} \qquad E = \frac{S - \chi C}{1 - \chi}$$

Dual Readout Technique

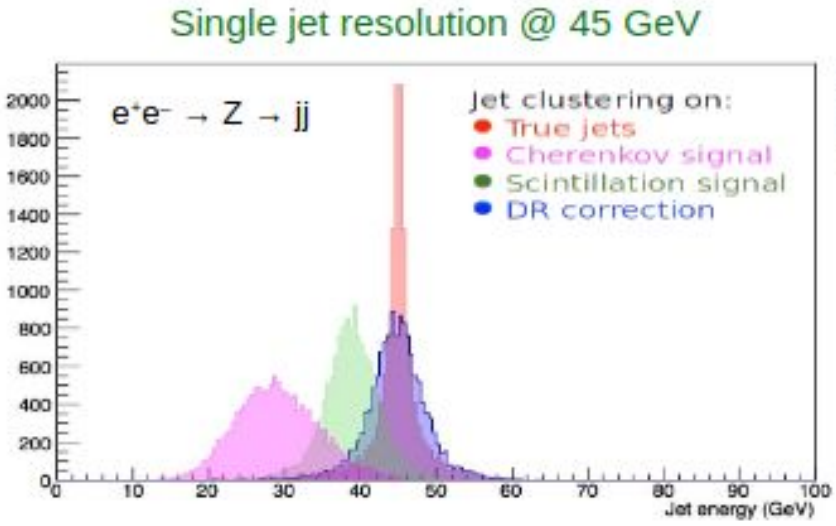


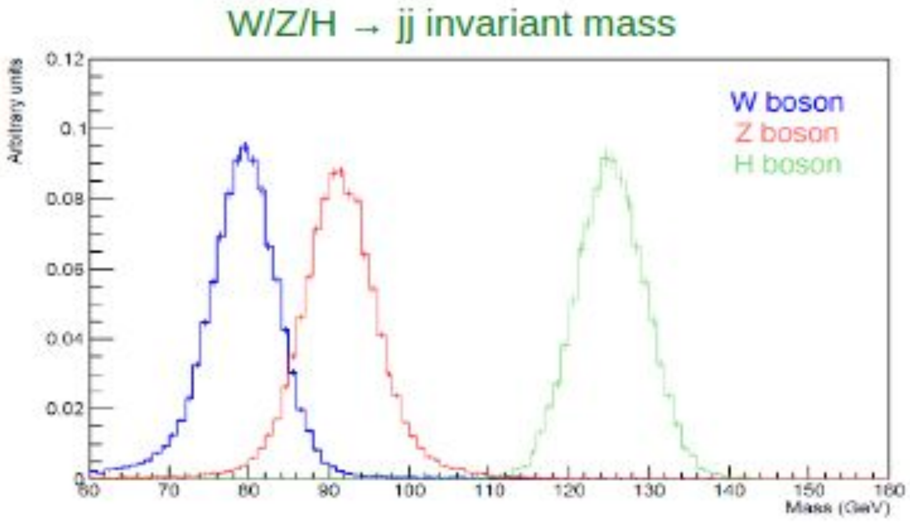


- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and Energy which one would obtain if fem=1 (em scale calibration)

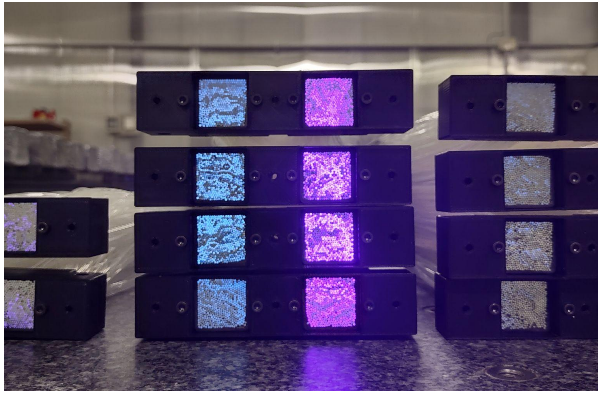
Expected performances @FCC-ee

- ✦ Gaussian resolution
- ✦ Adequate separation of W / Z / H



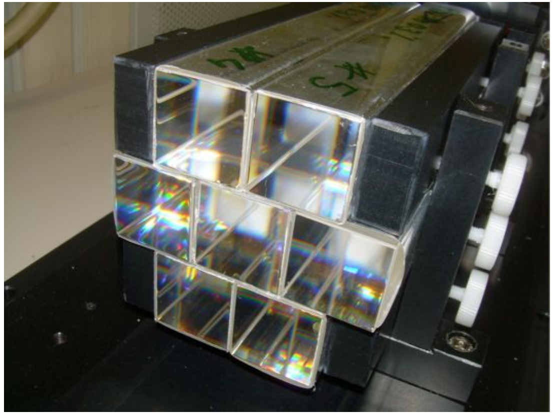


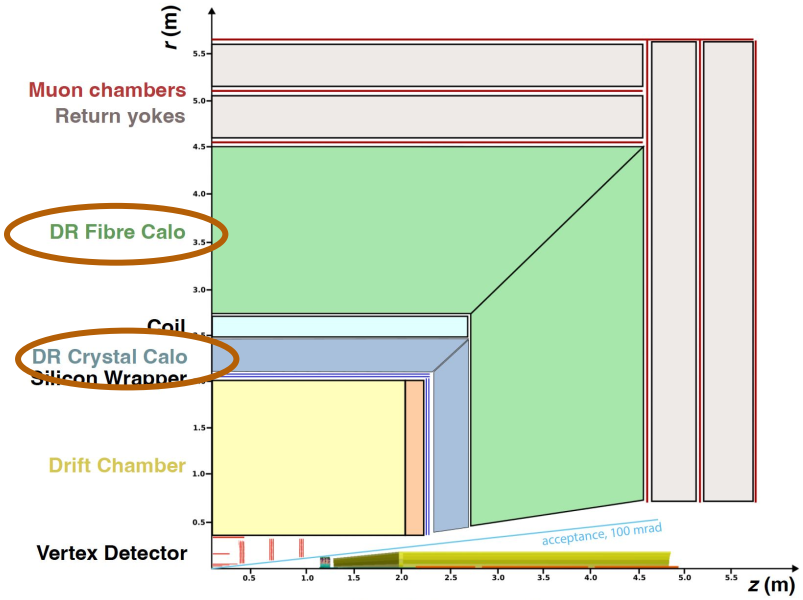
Dual readout in practice



Using different media (e.g. Fibres)

Disentangling the 2 signals in the same media





IDEA @ FCC
New baseline option

drdcalo

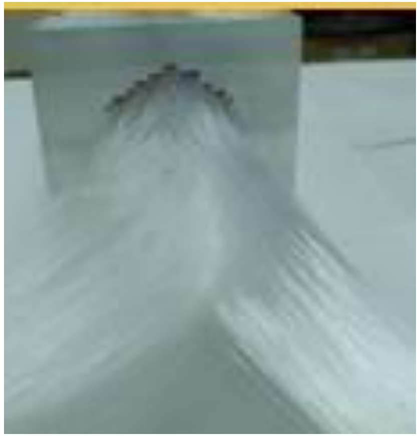
Fiber dual readout calorimeter

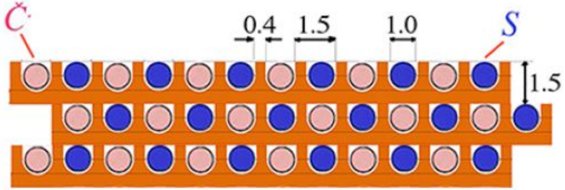
Different generation of prototypes with increasing complexity

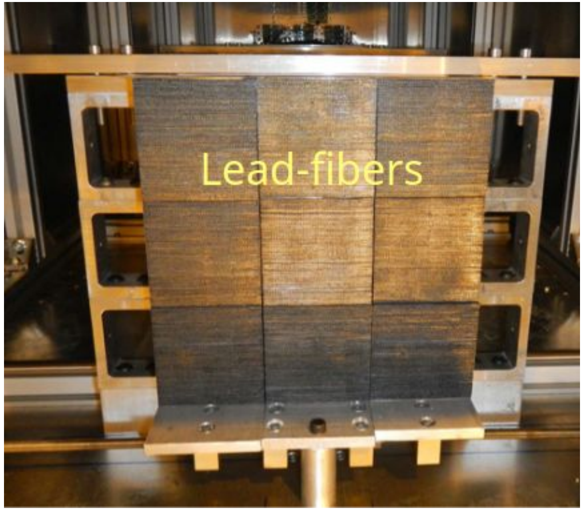
Originally meant as unsegmented ECAL and HCAL

- DREAM module and lead demonstrators: **proof of concept**
- Capillary tube “EM-Size” calo: **SiPM integrazione**
- HiDRa: **full containment with scalable construction technique**
- DREAM++: **adding timing** for longitudinal segmentation and PID
- **ML approach** to better reconstruct shower features (PID)

Proof of concept







2003 - 11 **DREAM Cu-fiber**

NIM A 533 (2005) 305
NIM A 536 (2005) 29
NIM A 537 (2005) 537
NIM A 548 (2005) 336
NIM A 550 (2005) 185
NIM A 581 (2007) 643
NIM A 598 (2009) 422

2010 **Pb - Tile DRC**

INST 9, (2014) C05009

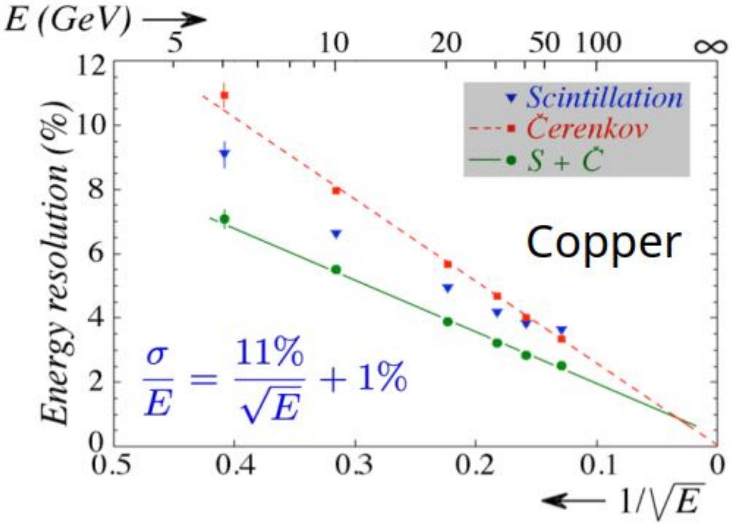
2012- 16 **Cu, Pb Fiber DRC**

NIM A 762 (2014) 110
NIM A 735 (2014) 120
NIM A 735 (2014) 130
NIM A 808 (2016) 41

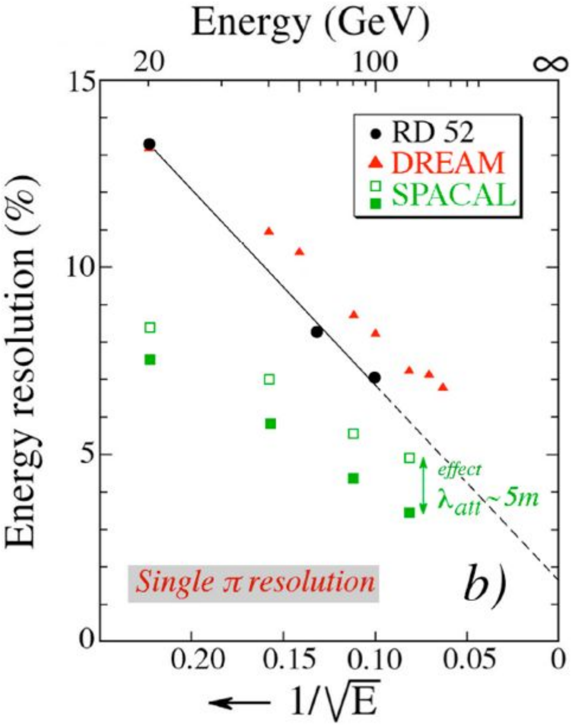
DREAM coll

RD52 coll

Proof of concept



EM resolution



$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

Expected to improve (based on MC simulation) by including corrections on:
- light attenuation
- lateral leakage

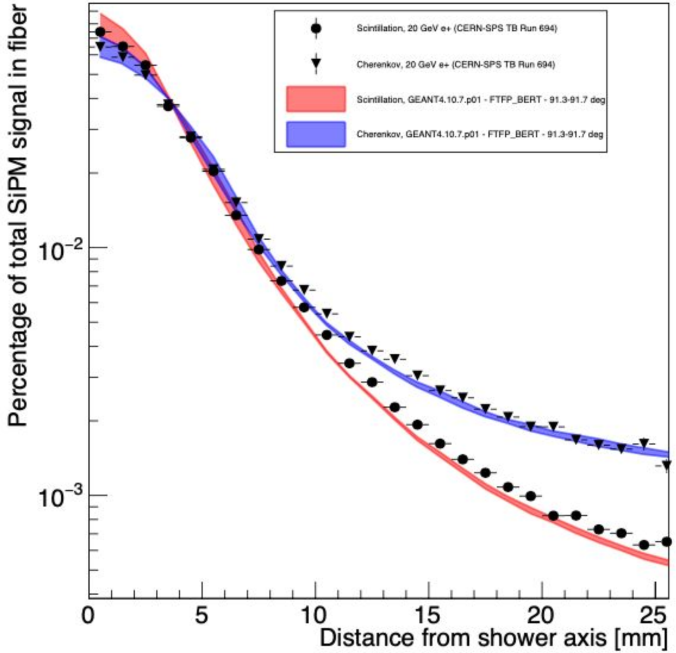
HAD resolution

Dual readout with High Granularity

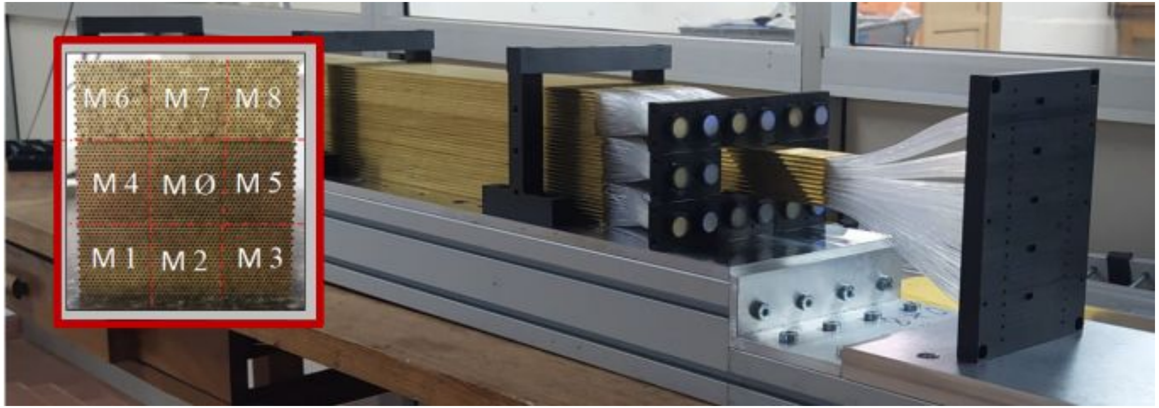
- SiPM advantages:
  - compact readout (no fibres sticking out)
  - operation in magnetic field
  - larger light yield (# of Čerenkov p.e. limits resolution)
  - very high readout granularity → particle flow “friendly”

- SiPM (potential) disadvantages:
  - signal saturation (digital light detector)
  - cross talk between Čerenkov and scintillation signals
  - dynamic range
  - instrumental effects (stability, afterpulsing, ...)

CERN SPS 20 GeV e^+ - GEANT4 (log scale)



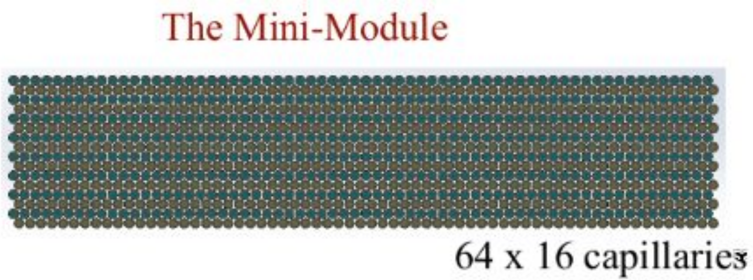
Dual readout with High Granularity



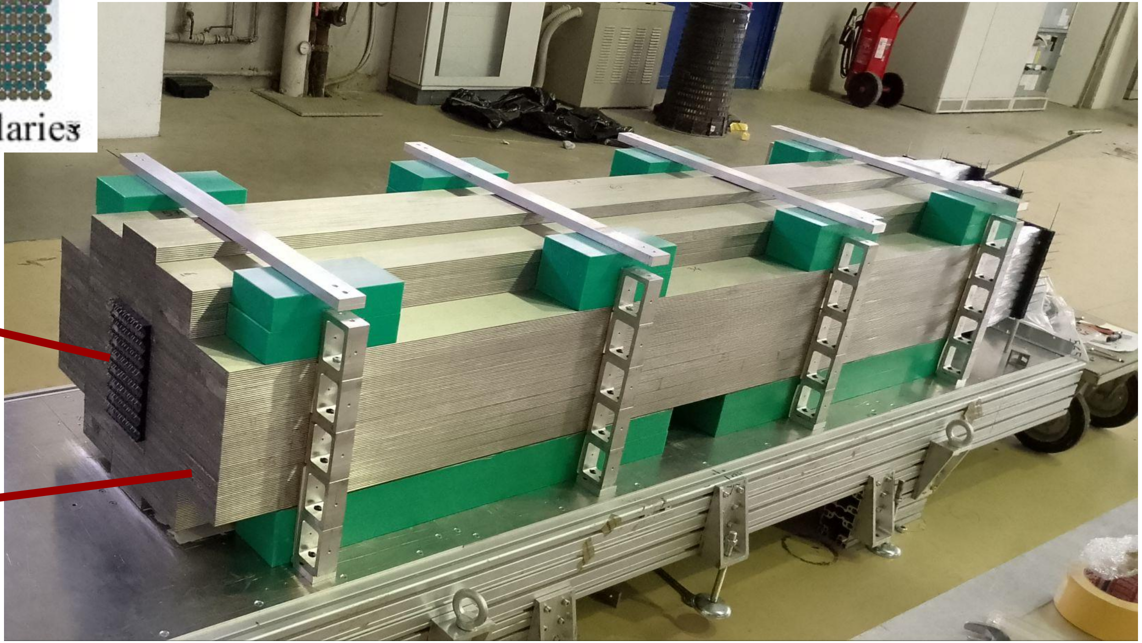
10x10 cm^2 divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S fibres)

Capillary:
2mm OD, 1.1 mm ID
Material: Brass

HiDRa: full containment high granularity



Grant INFN CSNV

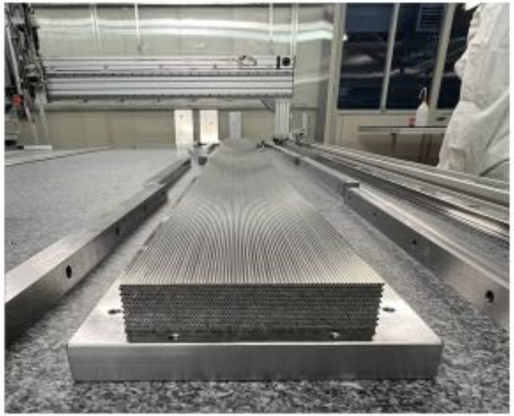


High-granular core
(~ 10k SiPM)

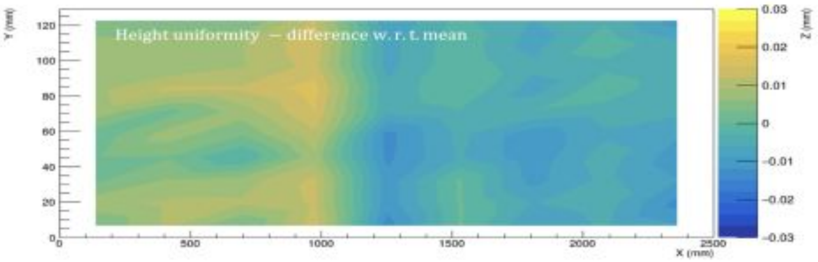
70 minimodules readout
by PMT (2 each)

HiDRa: full containment high granularity

Semi-automatic system for planarity measurement: 90 measurements per minimodule



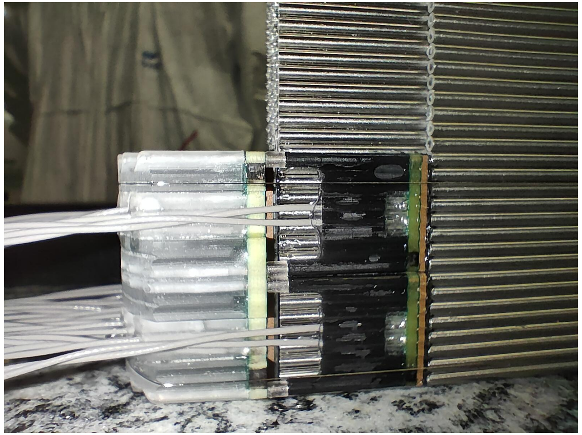
O(10 μm) precision on minimodule height (calor2024)

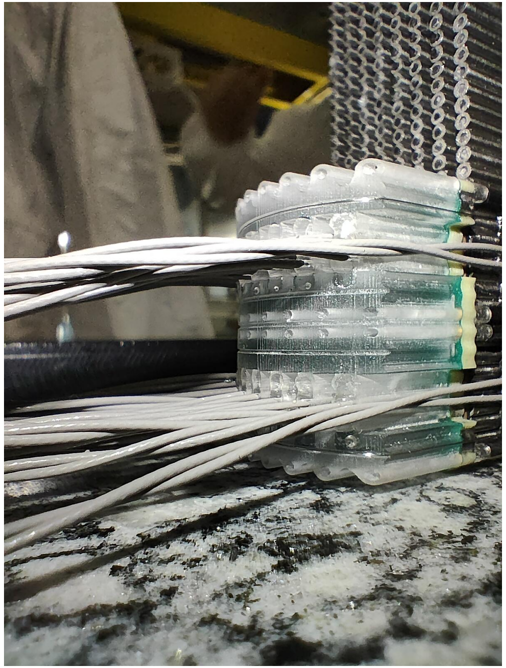


- Reliable and scalable construction technique
- Bottleneck: fibre insertions (too much time consuming
    - Ideas on how to overcome this problems under study

SiPM integration

1 SiPM per Fibre (2mm pitch!)
8 SiPM grouped together (analogic sum)

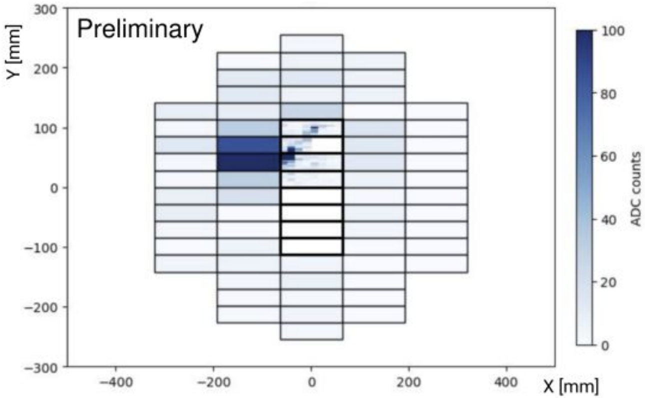




Microboard for Cherenkov (Hamamatsu S16676-15) and macroboard for Scintillanting (HamamatsuS16676-10)

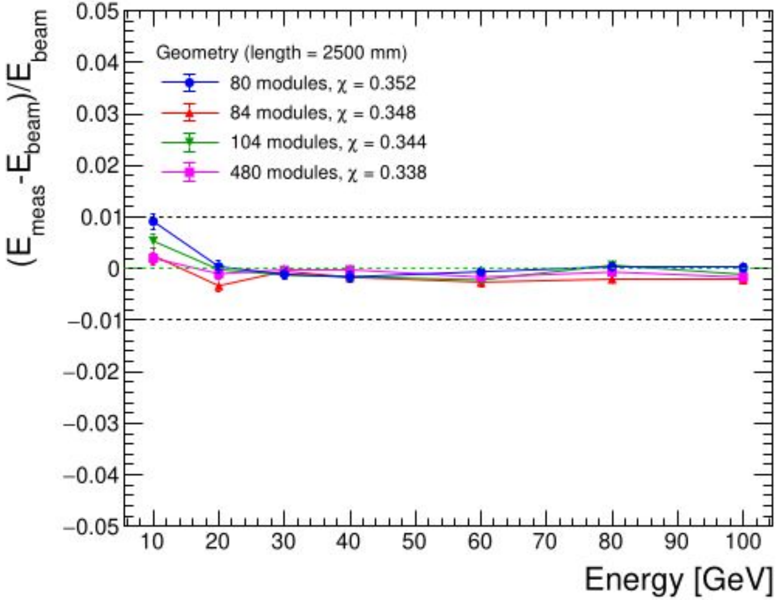
Test beam 2025 @CERN SPS

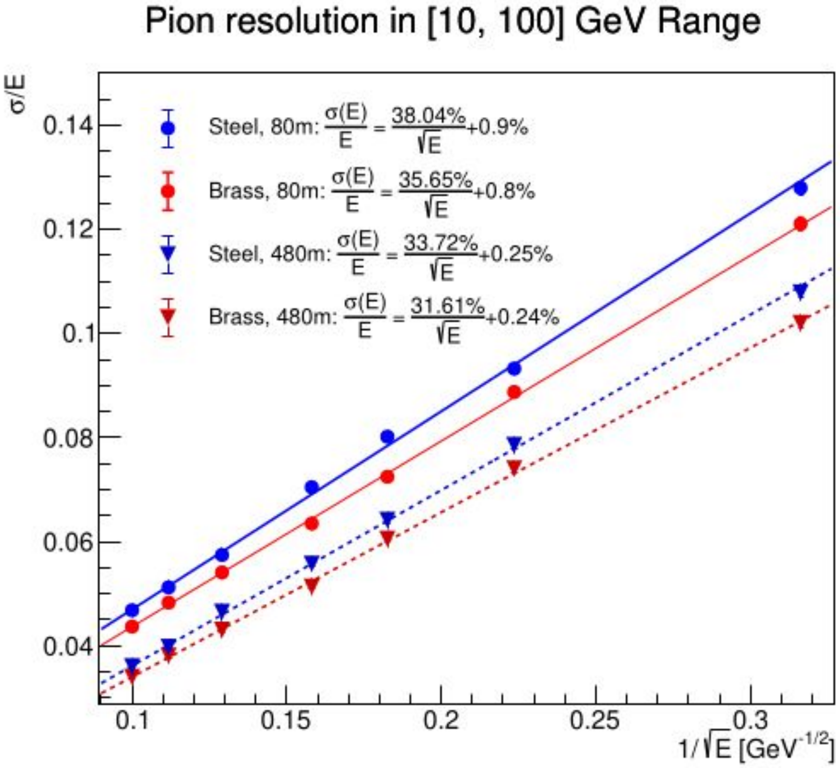
Response to electron, muon, pion
Energy resolution
Data analysis started



drdcalo

HiDRA expected performance (GEANT4 sim)





drdcalo

Adding timing info

Start with Traditional Dual Readout

Excellent individual hadron energy resolution

Increase granularity in the XY plane

in the XY plane:

- Fine shower shape structure in the XY plane;
- resolve confusion matrix for particle-flow

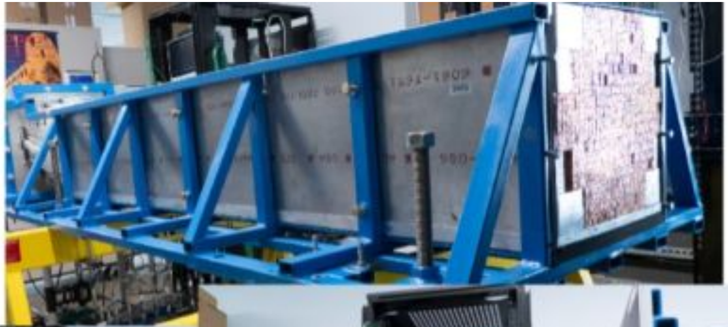
Longitudinal segmentation from Precise Timing

in the Z axis:

- Traditional fiber-based calorimeter did not utilize the timing information
- But thanks to developments on SiPM, electronics, and ML, we can possibly recover the lost timing (longitudinal) information

HG-DREAM (US effort within DRCAL)

- High Granularity
- Fast readout with excellent time resolution:
  - SiPM
  - Advanced electronics for fast readout
  - advanced algorithms for both fast online processing and accurate offline reconstruction



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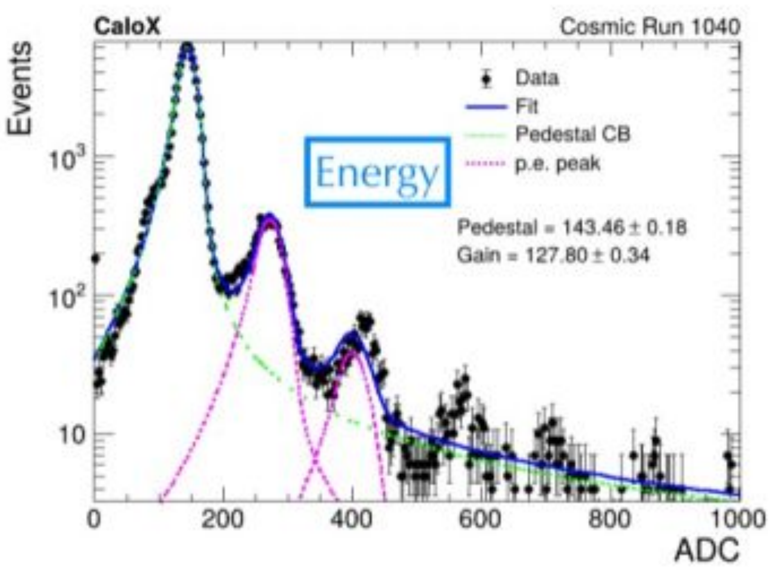
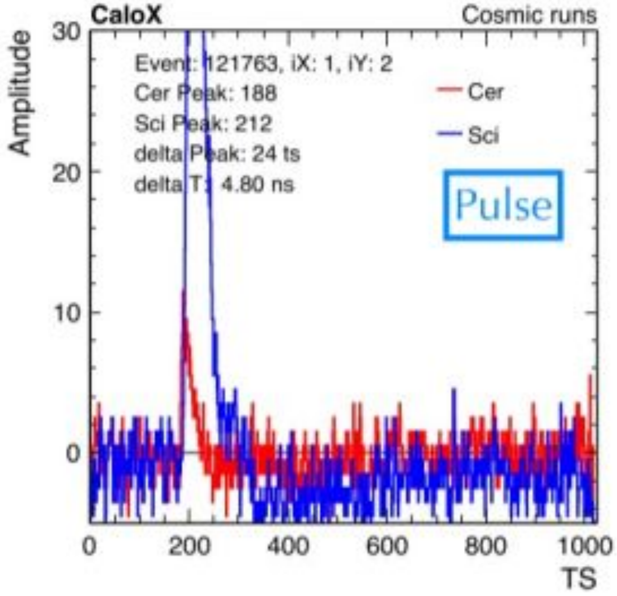
HG-DREAM (US effort within DRCAL)





- Outputs from Cosmic runs. Left: FERS readout (energy). Can observe pedestal + individual photon peaks
- Right: DRS readout of pulses. (One time slice is 200ps)
  - Cherenkov signals (red) smaller than Scintillation signals
  - Cherenkov signals faster than Scintillation signals

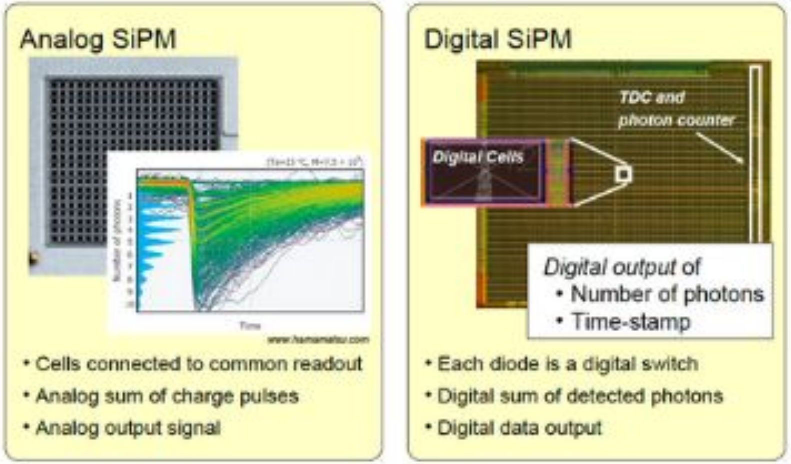
What we have/know as of today

- proof of concept of dual-readout technique
- solid and scalable assembly technique
- integration technique for HG detector
- timing information benefit
- SW description in DD4HEP => entering the FCCSW era

What we still need to do (not exhaustive)

- Solve fiber issues for scalability
- Calibration technique
- Projective geometry and engineering
- Scalability of readout electronics
- Full exploitation of ML approach

Digital SiPM



https://indico.gsi.de/event/2099/contributions/6718/attachments/5430/6692/DIRC2013_Philips_Haemisch.pdf

With dSiPM there is no need for analogue signal post-processing

- **SPAD array in CMOS technologies may offer the following benefits:**
  - to embed complex functions in the same substrate (e.g. SPAD masking, counting, TDCs);
  - the design of the front-end electronics can be optimized to preserve signal integrity (especially useful for timing)
  - the monolithic structure simplifies the assembly for large area detectors
  - development costs can be kept relatively low if the design is based on standard process

Digital SiPM @ ASPIDES

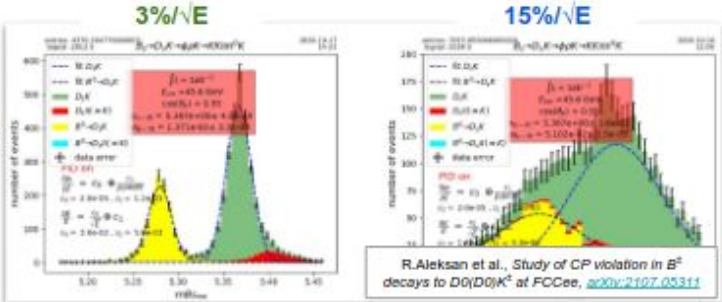
- ASPIDES: two-year CSN 5 project, coordinated by L. Ratti (INFN-PV)
- Goal: development of monolithic SiPMs in CMOS technology detectors with embedded functionalities (dSiPM)
  - Photon counting with wide dynamic range (30 pitch)
  - Fully digital output
  - ToA and ToT with resolution better than 100 ps
  - Threshold adjustment capabilities for noise rejection
  - Possibility to enable/disable individual microcells and global signal to enable/disable array
- Study of radiation damage and operation at cryogenic temperatures
- Modelling of new SPAD devices with improved performance in radiation environment and at cryogenic temperatures
- Submission planned for Q4 2025 (LFoundry 110 nm, 6 metal layers)

Boosting EM resolution

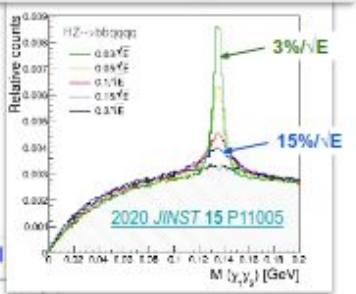
High EM energy resolution potential at e+e- Higgs factories

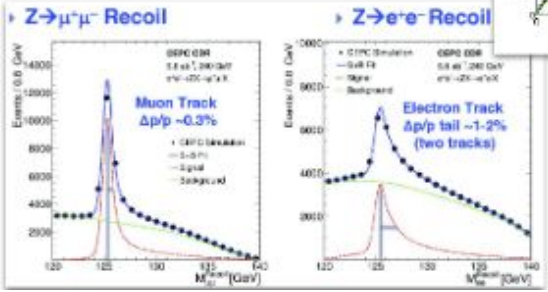
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)



R.Aleksan et al., *Study of CP violation in $B^\pm$ decays to D0(D0)K$^\pm$ at FCCee*, arXiv:2107.05311





Example from CEPC CDR

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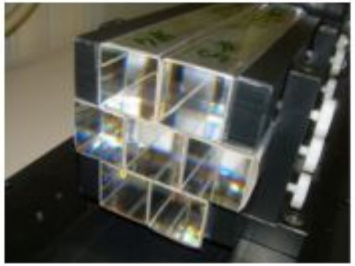
Dual readout in crystal calorimeters

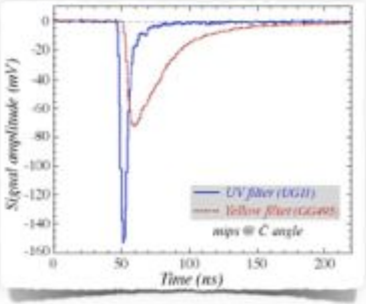
Requirements for using crystals in dual readout based calorimeter:

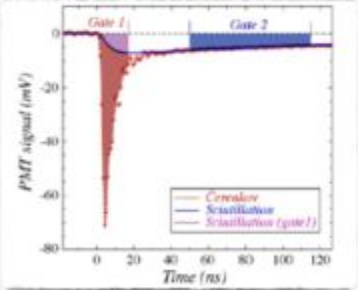
- Good Čerenkov vs Scintillation separation
- Response uniformity
- High light yield (to reduce contribution of p.e. fluctuation to the resolution)



Separation can be achieved by:

- optical filters: exploit different spectral region of Č and S
- time integration: exploit different time structure of Č and S





In order to have the best possible separation a crystal must have a scintillation emission:

* in a wavelength region far from the Cherenkov one
* with a decay time of order of hundreds of nanoseconds
* not too bright to get a good C/S ratio (<50% BGO emission)

Combined ECAL+HCAL Dual Readout

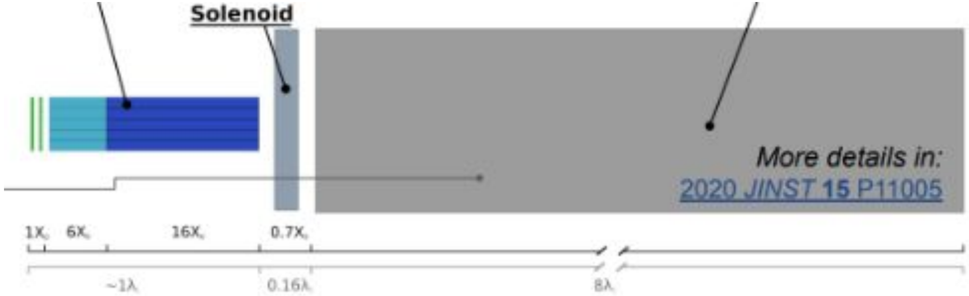
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$

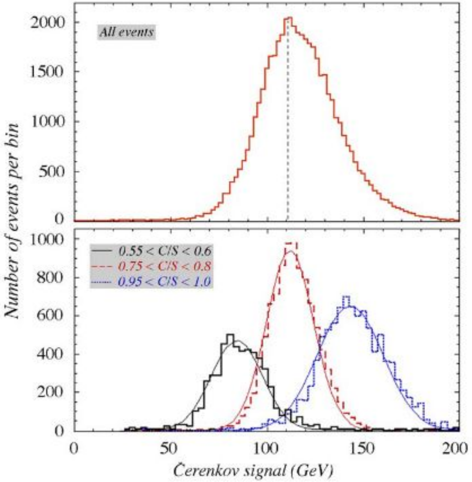
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$

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

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

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

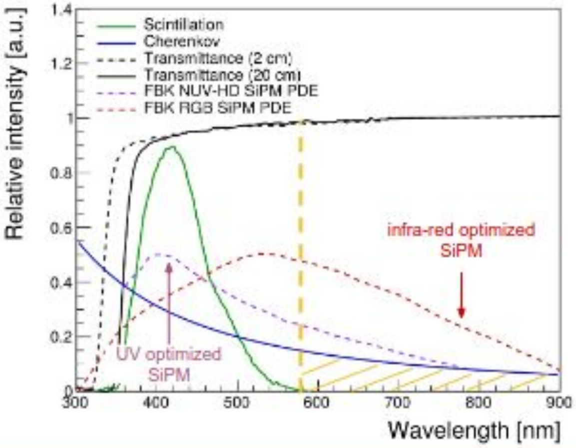




Strategies for DR in crystal calorimeters

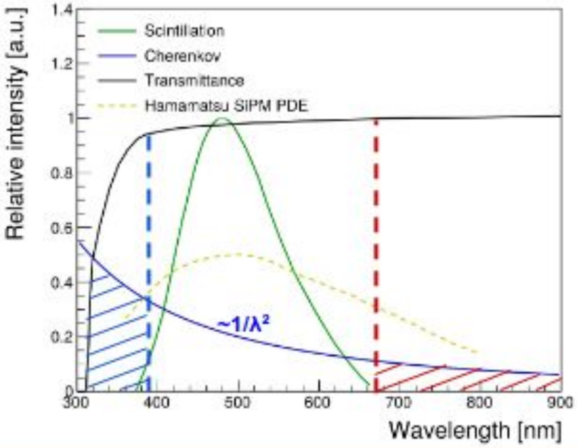
PWO (λ-based)

- Highest refractive index, lowest R_M and X_0
- Low light yield at 420 nm → easier to filter out scintillation light with a dedicated SiPM+optical filter and detect C photons at λ>580 nm
- Fast decay time (~10 ns) → hard to separate S and C using pulse shape



BG(S)O (λ+t-based)

- Higher light yield (10-30x PWO) at 480 nm
  → excellent photostatistics
  → harder to filter out scintillation photons
  → narrower band for infrared C photon detection (λ>680 nm)
- Wider transparency band for 'UV Cherenkov' (λ∈[320,380] nm)
- Slow decay time (~100-300 ns) → can separate S/C with timing



Outlook

Mature and tested technique for improving energy resolution

Suitable for future accelerator experiment

Aligned with the strategic objectives identified in the ECFA R&D roadmap and part of DRD6 collaboration (DRDCalo)

Interest in the technique is growing

Still open questions to be addressed