# Calorimetry R&D for the next generation of HEP collider experiments

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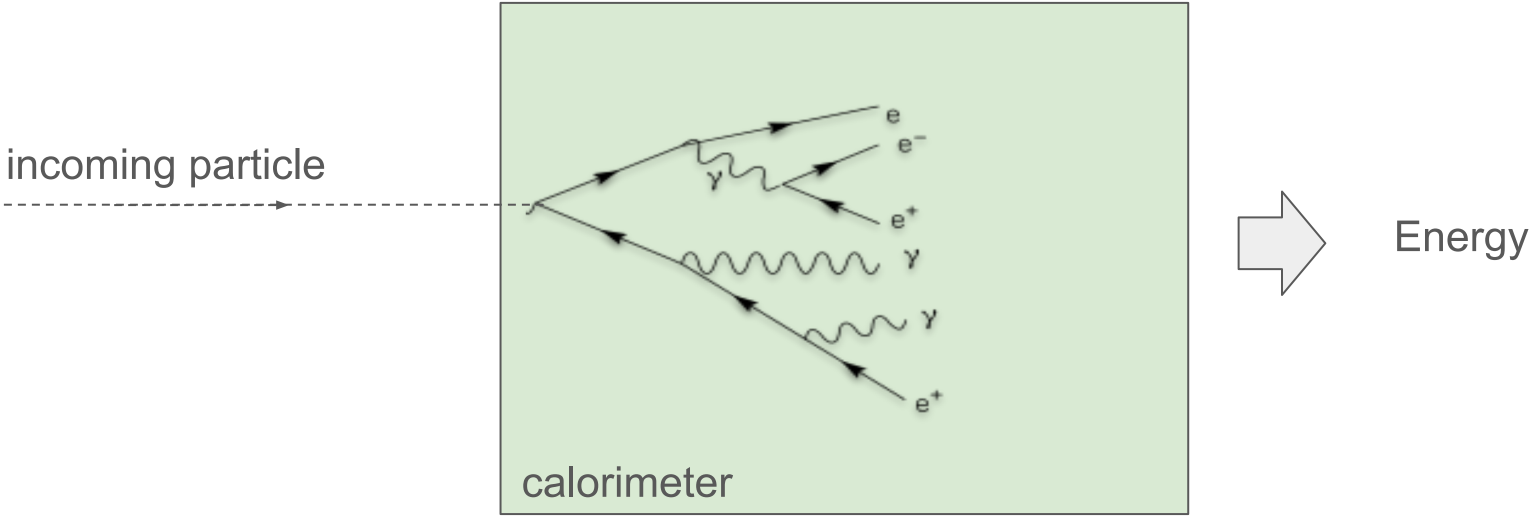
# Disclaimer

The landscape is broad:
this is a biased and non comprehensive overview

I pick a few examples to illustrate general needs and R&D trends

# A calorimeter for a theoretical physicists audience



*Measures the energy of a particle by fully stopping it and converting its energy into an electric signal*

# … and for an experimental physicists audience

CMS endcap calorimeter

**Removal of the CMS beam pipe (Image: Maximilien Brice/Julien Ordan/CERN)**

# Calorimetry at colliders

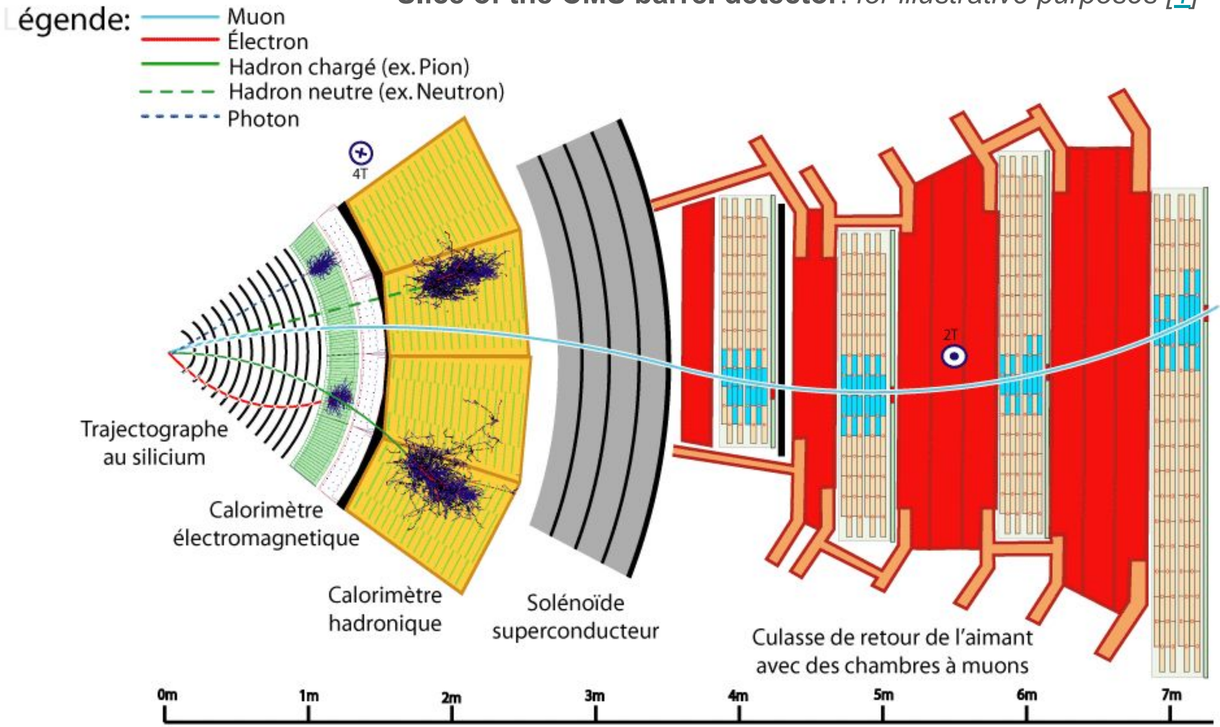
from state-of-the-art to R&D drivers

# **Calorimeters** at collider experiments

- **A central subsystem** to measure the **energy** of $e^{\pm}$, charged hadrons and mostly **neutral particles** (photons and neutral hadrons)!

- Often (but not necessarily) split into a EM and HAD section for **practical reasons** (size, cost, integration, performance requirements)

**Slice of the CMS barrel detector**: *for illustrative purposes [1]*

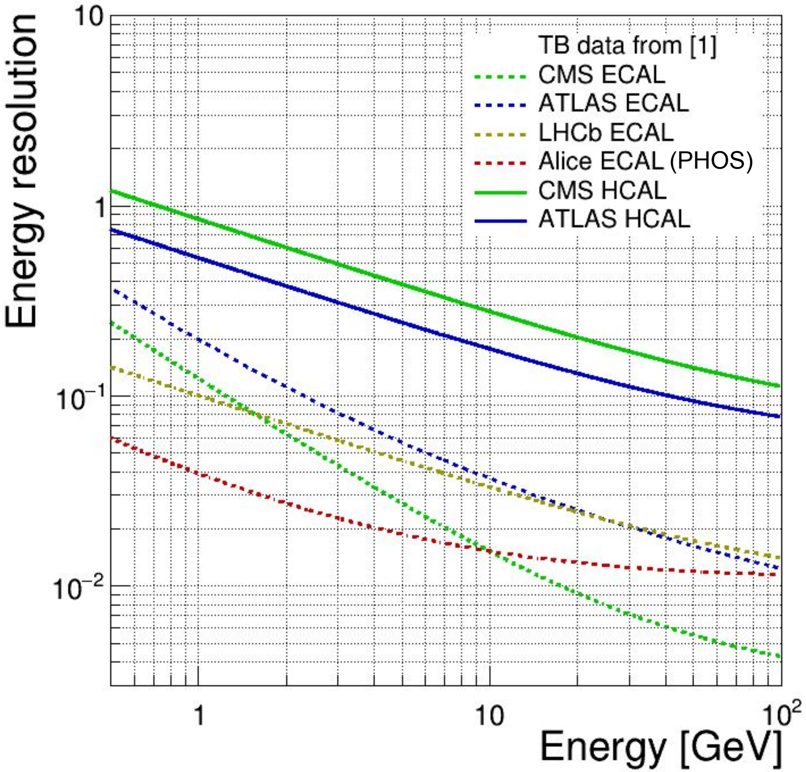


# **Energy resolution** - a usual benchmark

- Improves with particle energy
- Parameters depend on calorimeter design
- Large difference between EM and HAD calo

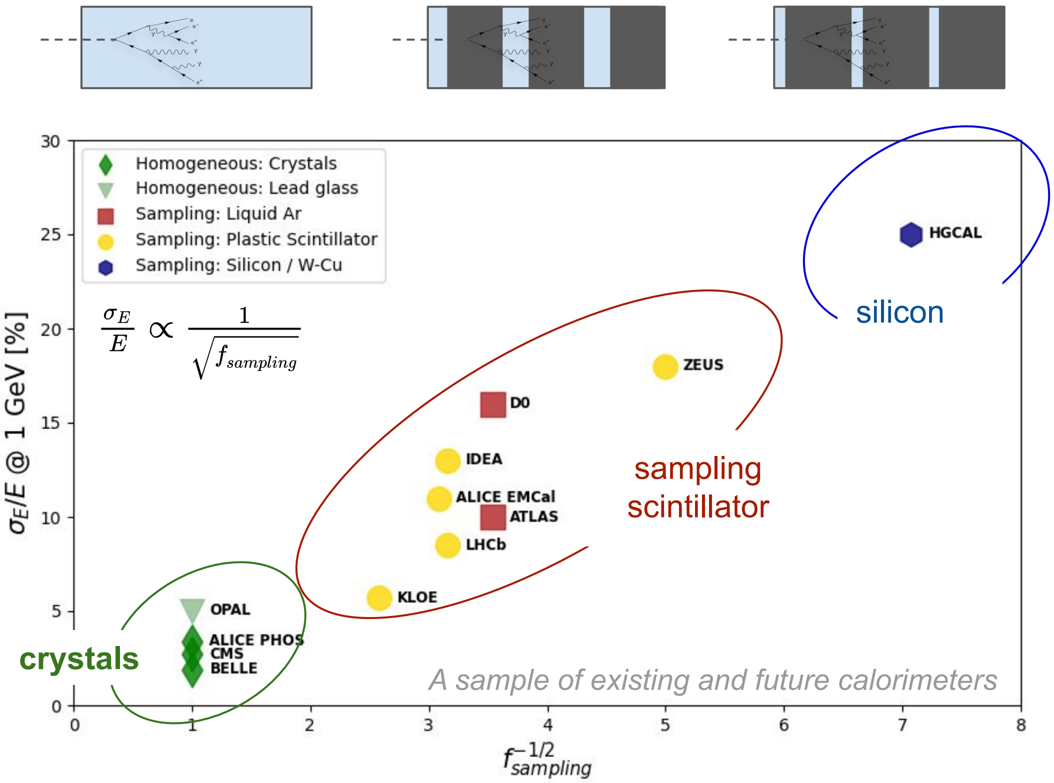
$$\frac{\sigma_E}{E} = \underbrace{\frac{A}{\sqrt{E}}}_{\text{stochastic}} \oplus \underbrace{\frac{B}{E}}_{\text{noise}} \oplus \underbrace{C}_{\text{constant}}$$

*TB Performance of LHC calorimeters [1]*



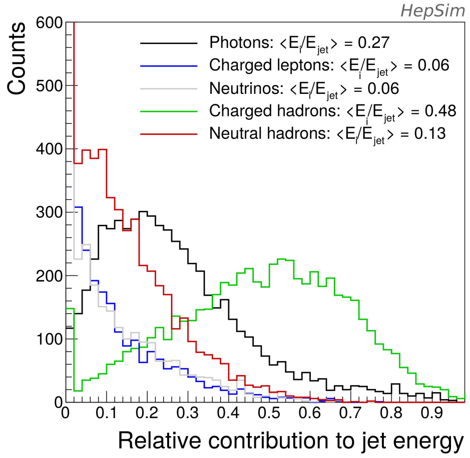
# **Performance drivers** in EM calorimeters

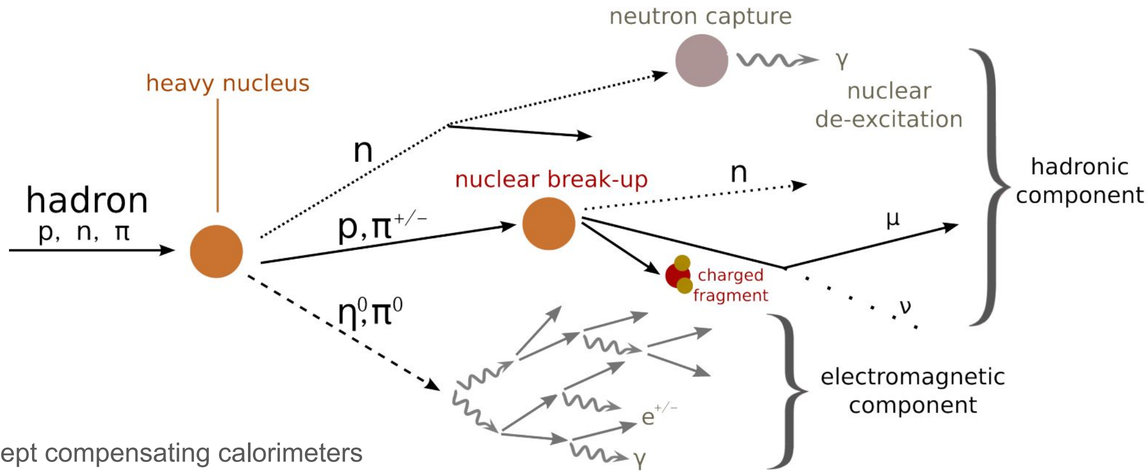
- **Homogeneous** calorimeters can provide the ultimate energy resolution (stochastic term)
  - Need high density active medium (e.g. crystals)
- **Sampling** calorimeters exploit a passive absorber to ‘stop’ particles
  - Intrinsically limited performance
  - More options for light and cheaper active media
- Electronic noise, calibration, stability, linearity are crucial aspects and can easily become limiting factors

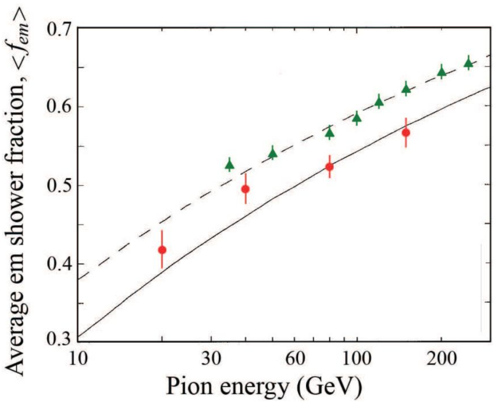


# **Limiting factors to hadron**/jet energy resolution

- Hadron showers and jets are complex objects
- Calorimeters typically* respond differently to the *EM* and *HAD* components of a shower
- The electromagnetic shower fraction (mostly $\pi^0$'s) increases with energy and sizably fluctuates event-by-event
  - → **Negative impact on linearity and resolution!**







*except compensating calorimeters

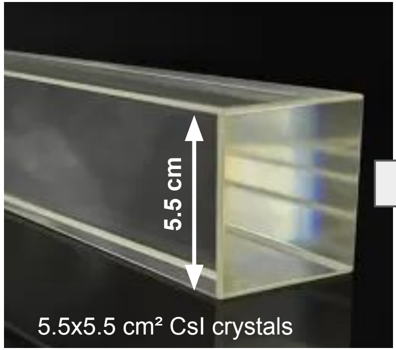
# Toward **6D calorimetry**

- **General trend** is to add more features into the calorimeter design, beyond the energy (**E**) measurement, toward a **6D** calorimetry concept:
  - **Position (x,y,z)**
    → down to O(1) mm w/ scintillators and O(50) μm w/ silicon
  - **Time (t)**
    → down to O(10) ps resolution
  - **Nature of the shower** (**S,C** ,...)
    → multi signal calorimetry: dual/triple readout

- Particle reconstruction combines information from all sub-detectors in a "particle flow approach" (PFA) and exploit new machine learning techniques

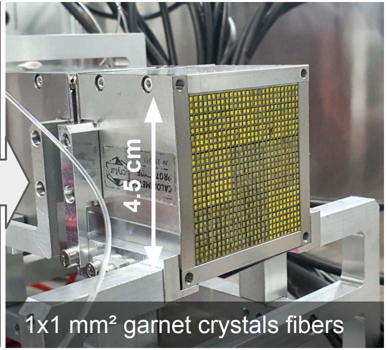
- New technologies offer many opportunities for novel calorimeter concepts → **need to define experiment requirements for collider-tailored optimization**

doi.org/10.1016/S0168-9002(00)00643-4

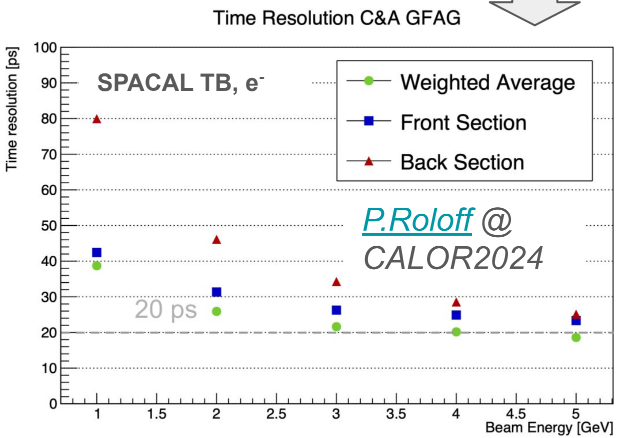


5.5x5.5 cm² CsI crystals

doi.org/10.1016/j.nima.2022.167629

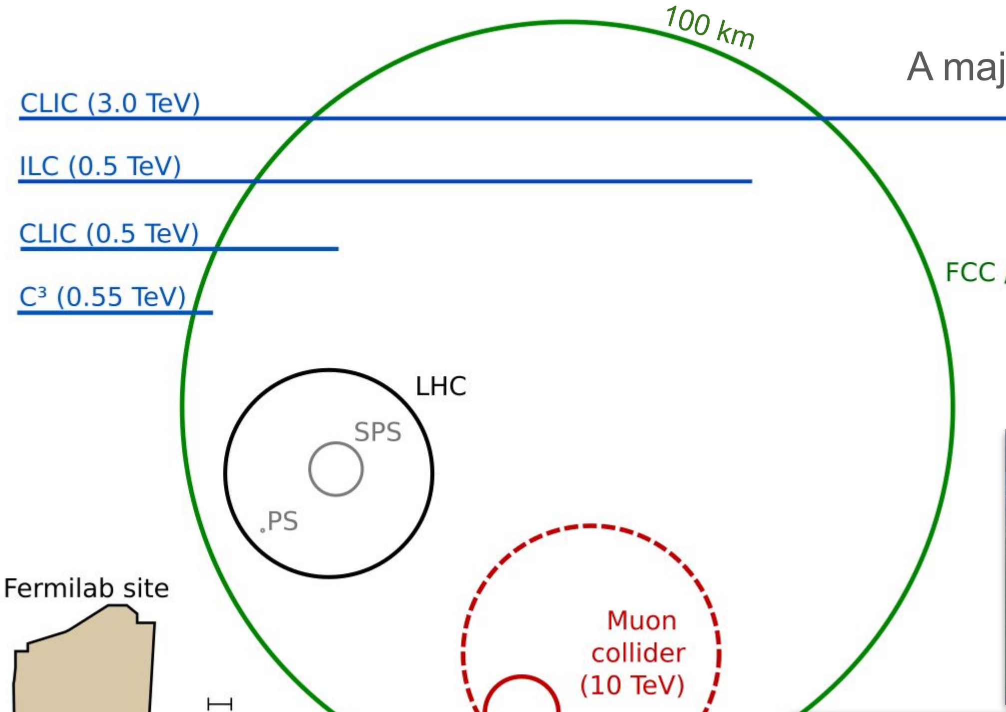


1x1 mm² garnet crystals fibers



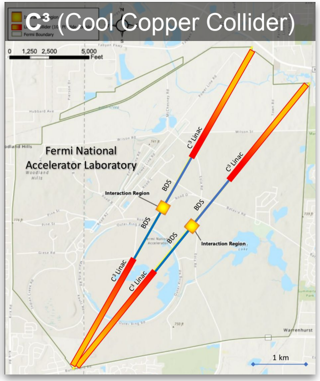
*P.Roloff @ CALOR2024*

# Future collider options on the table (for the XXI century)

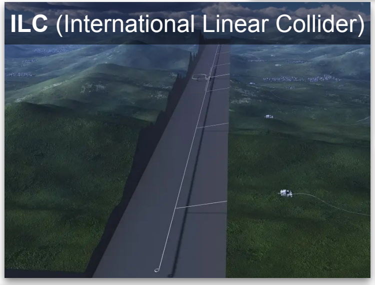


A major **civil engineering** challenge!

**Muon collider**

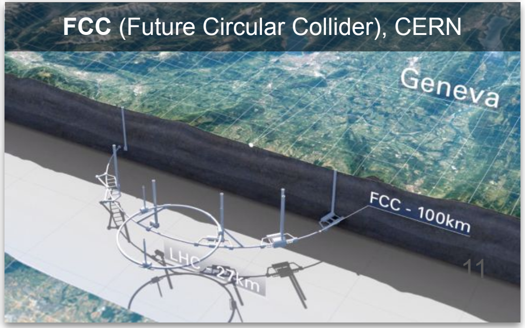


**C³** (Cool Copper Collider)

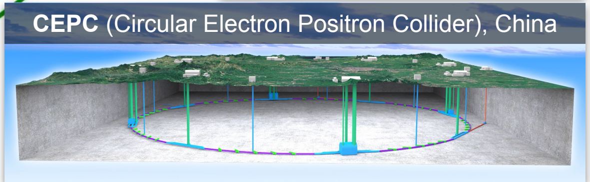


**ILC** (International Linear Collider)

**CLIC** (Compact Linear Collider)



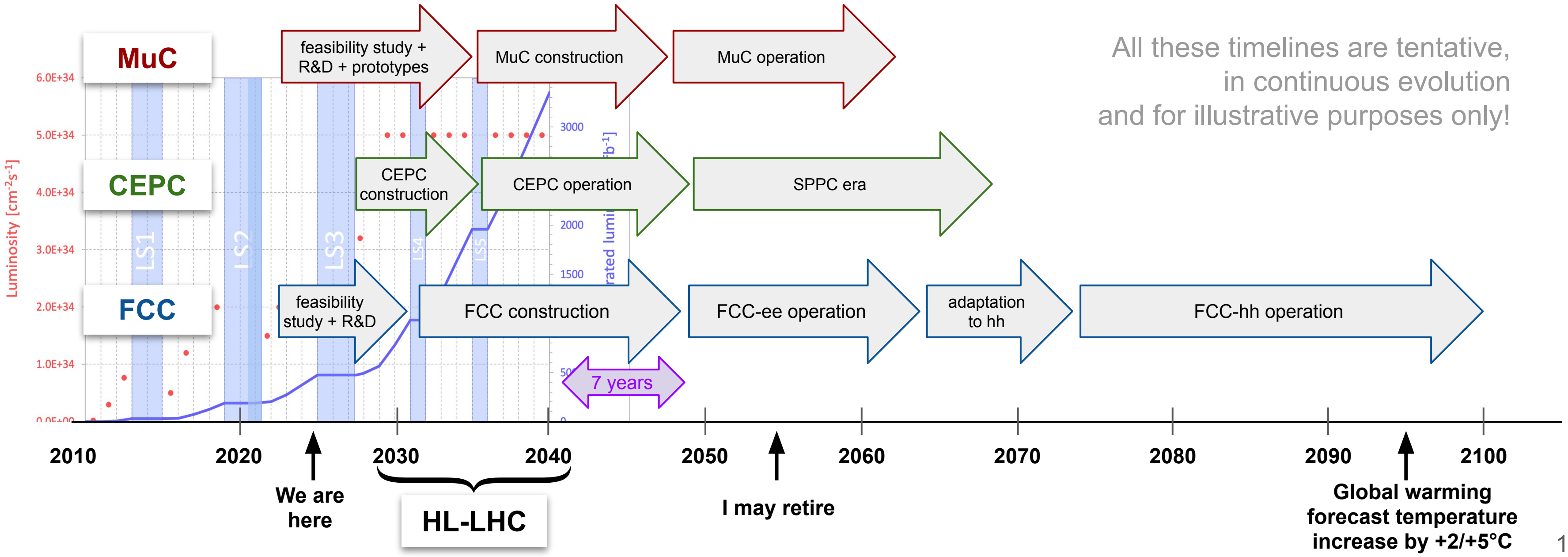
**FCC** (Future Circular Collider), CERN



**CEPC** (Circular Electron Positron Collider), China

# Tentative future collider **timelines**

- Project timelines spanning over many decades (a challenge for engagement)
- **Intense R&D phase on detectors in the next 5+ years!**



**MuC**

feasibility study + R&D + prototypes

MuC construction

MuC operation

**CEPC**

CEPC construction

CEPC operation

SPPC era

**FCC**

feasibility study + R&D

FCC construction

FCC-ee operation

adaptation to hh

FCC-hh operation

7 years

2010 2020 2030 2040 2050 2060 2070 2080 2090 2100

**We are here**

**HL-LHC**

**I may retire**

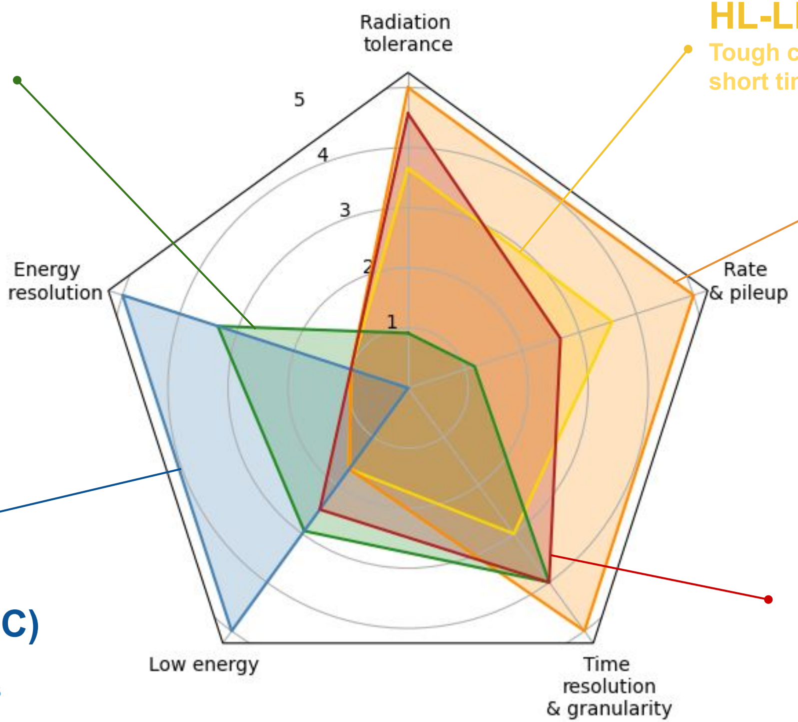
**Global warming forecast temperature increase by +2/+5°C**

All these timelines are tentative,
in continuous evolution
and for illustrative purposes only!

# Qualitative representation of **requirements** for calorimeters **at future colliders**

**$e^+e^-$ colliders**

Precision physics benefits from exploiting the best possible energy and time resolution



**HL-LHC**

**Tough challenges on a short timescale**

**FCC-hh**

Setting the toughest challenge on radiation tolerance and pileup conditions

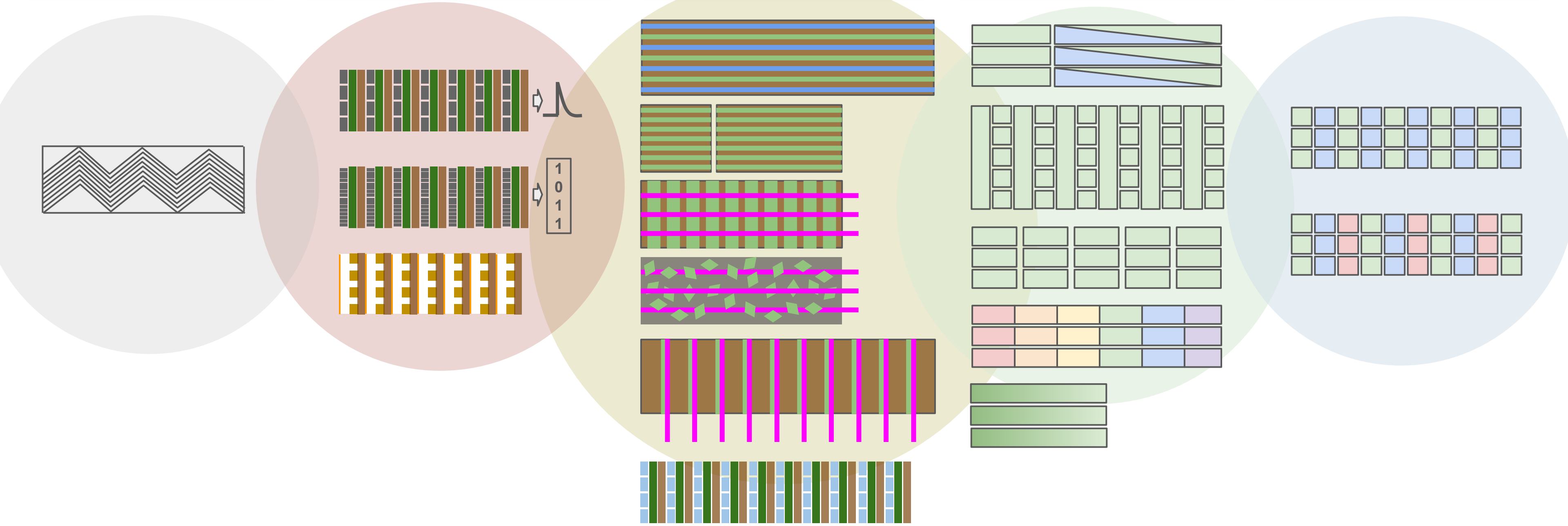
**Strong interaction experiments (e.g. EIC)**

Requiring the highest energy resolution for low energy photons

**$\mu^+\mu^-$ colliders**

High beam induced background and radiation levels, need for ambitious time resolution

# A broad and active R&D community (calorimeter ‘zoo’)



**Sampling calorimeters based on liquified noble gases (EM/HAD)**

**High granularity calorimeters based on semiconductors or gaseous detectors (EM/HAD)**

**Sampling calorimeters based on scintillators (EM/HAD)**

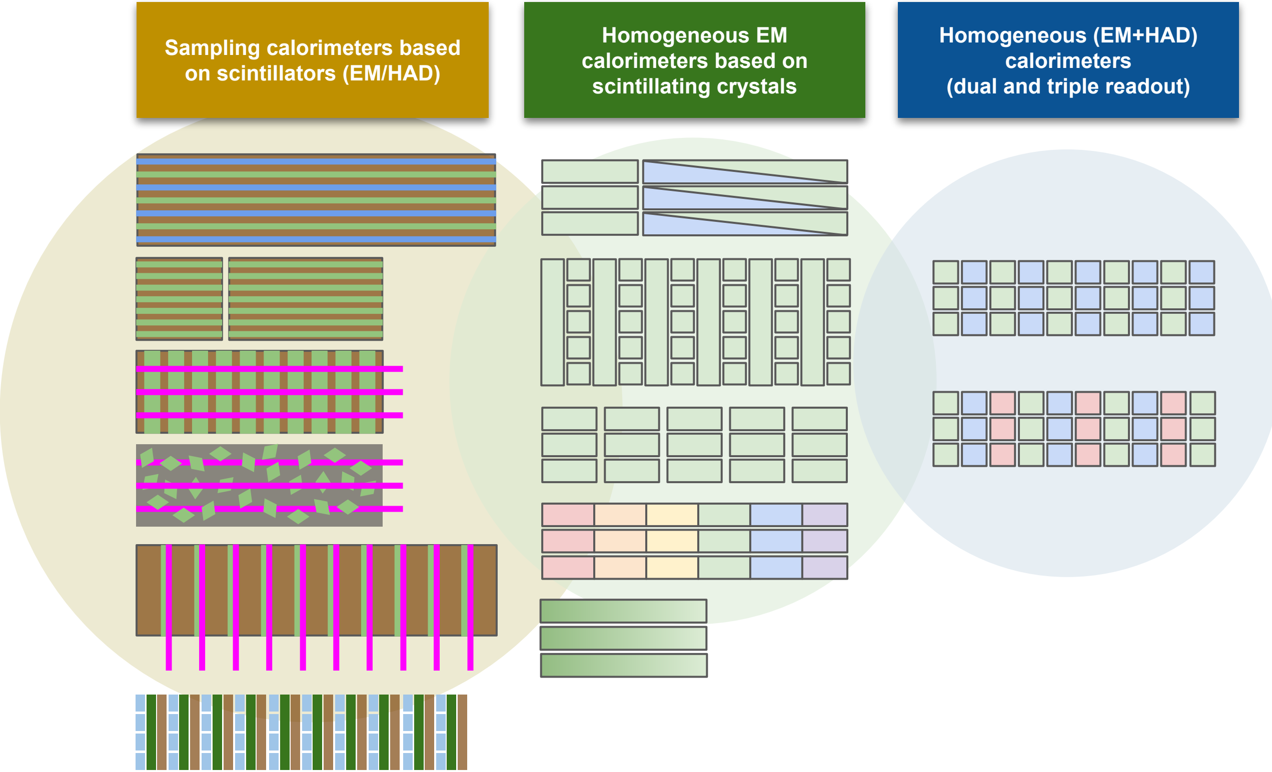
**Homogeneous EM calorimeters based on scintillating crystals**

**Homogeneous (EM+HAD) calorimeters (dual and triple readout)**

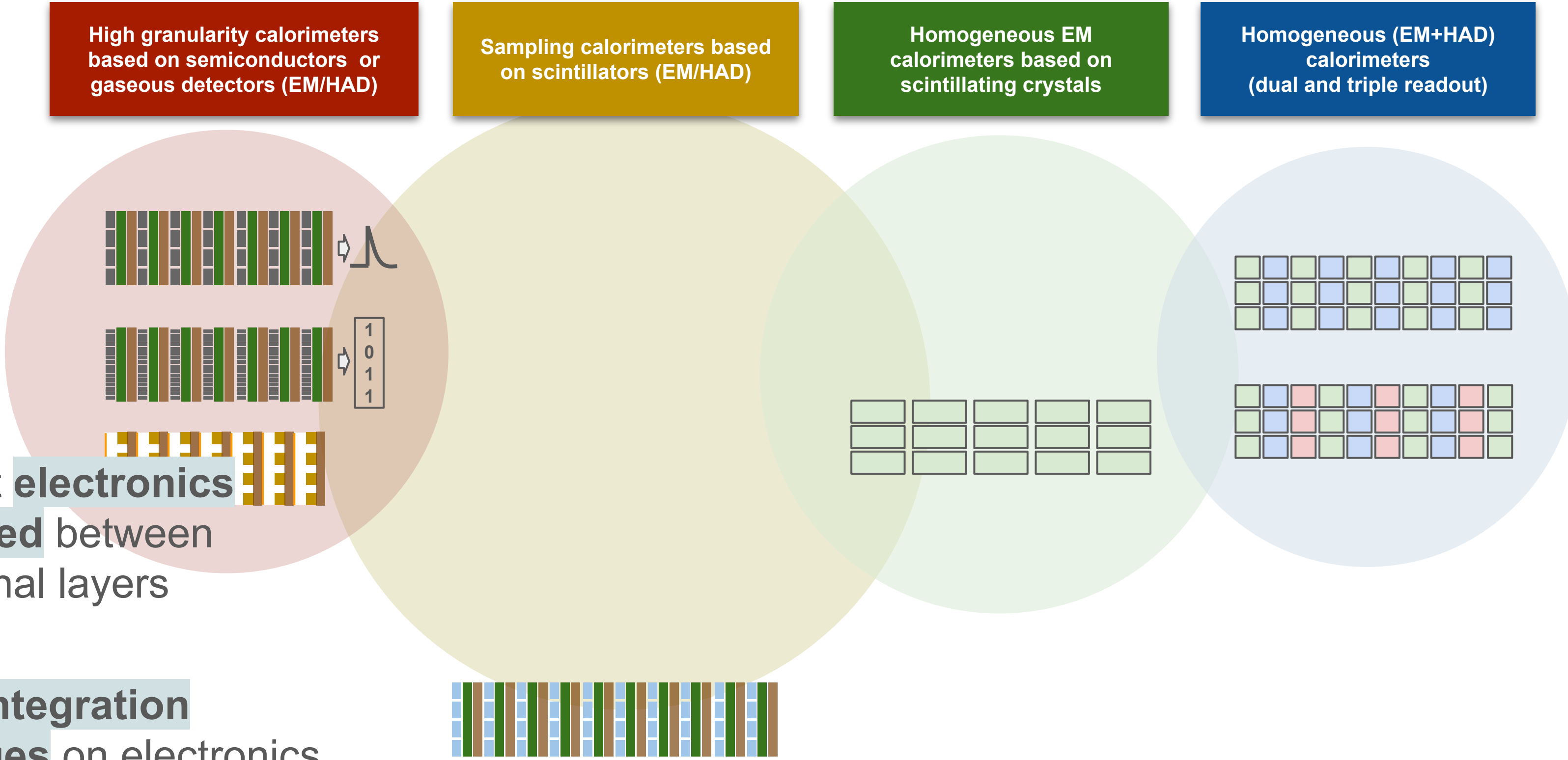
Check out the CALOR2024 conference and the DRD6 CERN Collaboration on calorimetry for more

# “Optical” calorimeters

- Exploit organic/inorganic scintillator to produce a **light signal** (and possibly as wavelength shifter)
- Use of **photodetector** (mostly **SiPMs**) for light readout
- Common synergies and R&D on active materials and photodetectors



# “Sandwich” calorimeters



**High granularity calorimeters based on semiconductors or gaseous detectors (EM/HAD)**

**Sampling calorimeters based on scintillators (EM/HAD)**

**Homogeneous EM calorimeters based on scintillating crystals**

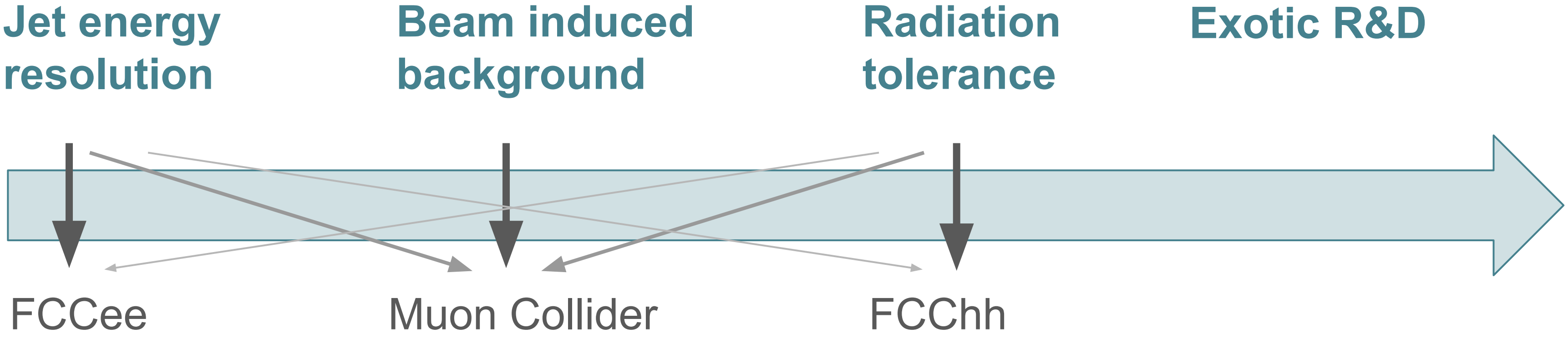
**Homogeneous (EM+HAD) calorimeters (dual and triple readout)**

- Compact **electronics embedded** between longitudinal layers

- Similar **integration challenges** on electronics, signal and services routing

# Rationale of the talk

- Many synergies and overlaps among different calorimeter concepts
- The same calorimeter concept can be used/optimized for different colliders
- A few examples on how **key challenges** are being addressed by R&D



**Jet energy resolution**

**Beam induced background**

**Radiation tolerance**

**Exotic R&D**

FCCee

Muon Collider

FCChh

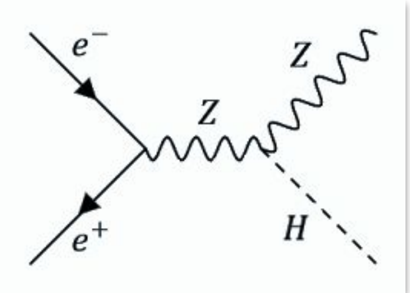
# Seeking the highest jet energy resolution

mostly for $e^+e^-$ colliders

# Jet energy resolution is a key benchmark

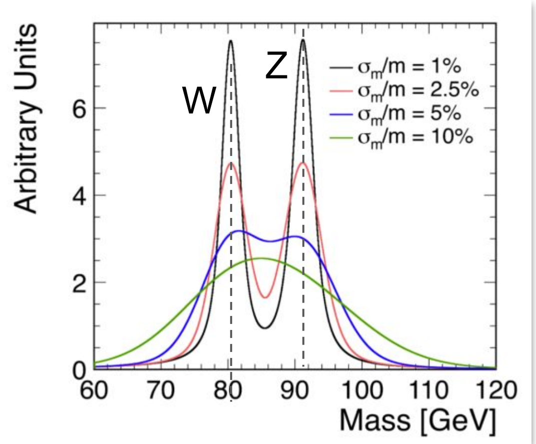
- Higgs production **at $e^+e^-$ colliders** (@$\sqrt{s}$~250 GeV) is mainly through Higgsstrahlung
- **97% of the Standard Model Higgsstrahlung signal has jets in the final state**
    - **~32%** with 2 jets
    - **~55%** with 4 jets
    - **~11%** with 6 jets
- A typical **jet resolution of ~30%/$\sqrt{E}$** (~3-4% @90 GeV) is **required** (e.g. to distinguish jets from W or Z bosons)
    - State of the art jet energy resolution at LHC ~2-3x worse (limited by the poor resolution of hadronic calorimeters)

Higgsstrahlung



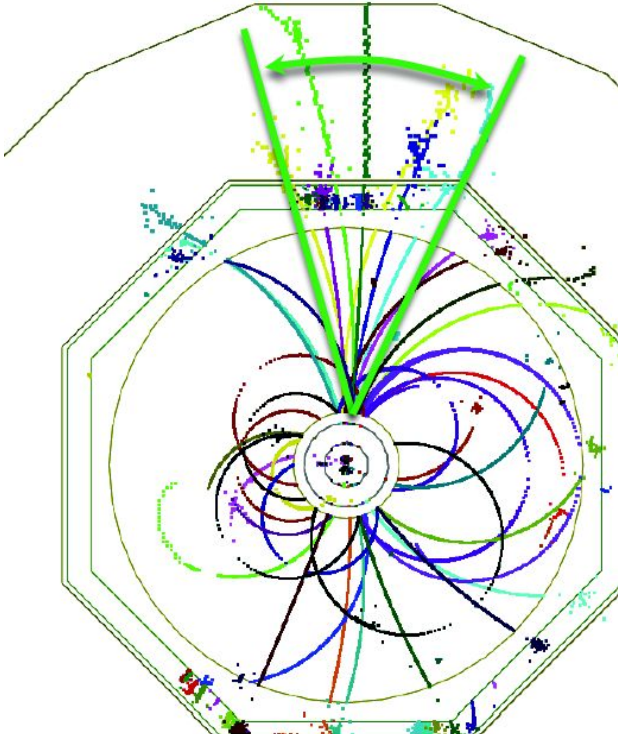
*ℓℓ, νν, qq*

*ℓℓ, γγ, γZ, WW, ZZ*



# Two historical approaches to tackle this challenge

## Particle Flow



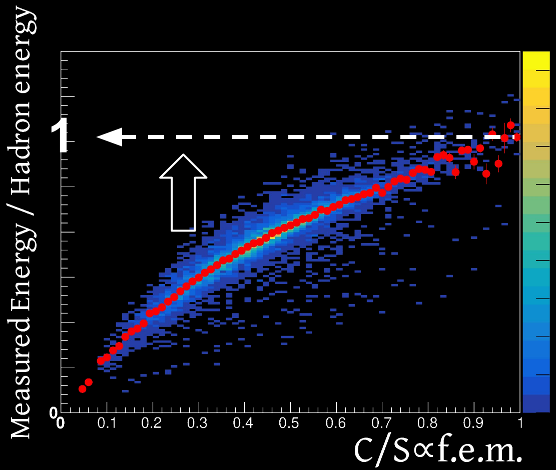
Use tracker to measure charged particles in the jet and the calorimeter for the neutrals

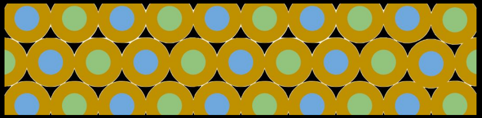
Requires excellent calorimeter granularity for an optimal matching of tracks to calorimeter hits

*New potential with machine learning, in use also at CMS*

## Dual-Readout

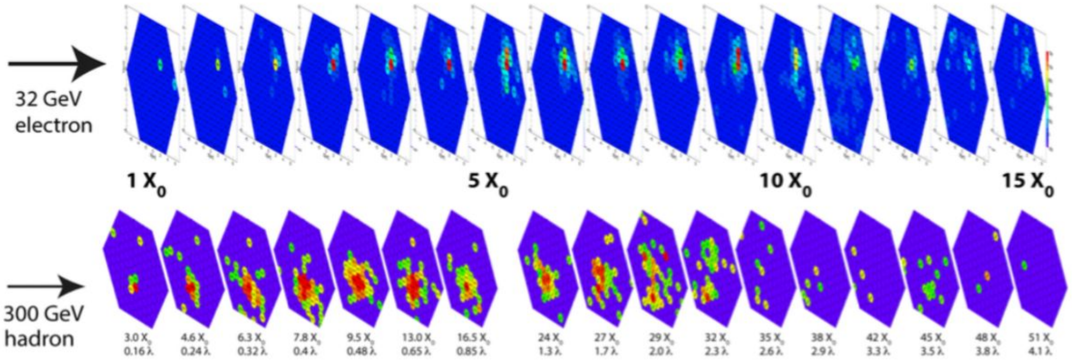
Correct for fluctuations of the electromagnetic shower fraction event-by-event by measuring simultaneously both the **S**cintillation and the **C**herenkov light, the latter being more intense for relativistic particles

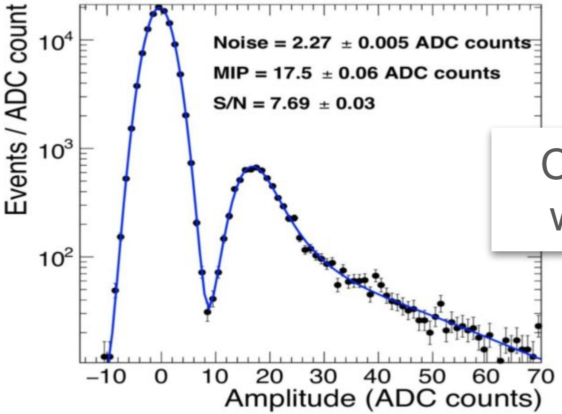




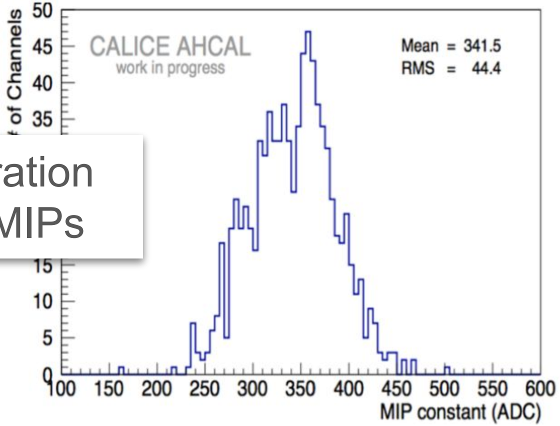
*Review paper here*

# **Particle flow** calorimetry





Calibration with MIPs



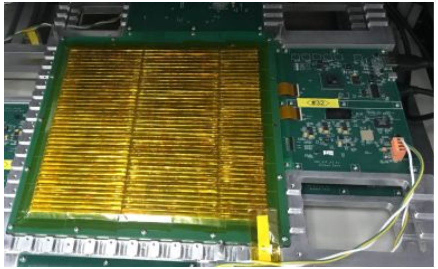
- **Granularity is more important than energy resolution**
- Lateral granularity should be below Molière radius in ECAL and HCAL
- In particular in the ECAL: small Molière radius to provide good two-shower separation
  - → dense absorbers and thin sensors
- **Sophisticated reconstruction software** needed [see ref]!

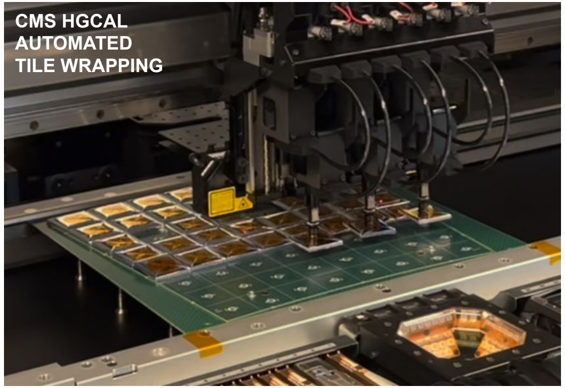
*D.Barney, CERN Seminar*

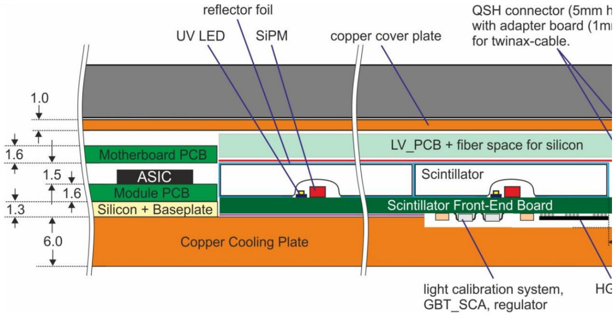
# High granularity with **plastic scintillators**

- Plastic scintillator tiles (2-30 cm²) or strips readout with small SiPMs (1x1 - 3x3 mm²)
- Light collection efficiency optimized through dome like shape and wrapping with reflector
- Many developments within the CALICE collaboration (Sc-ECAL)
- Being used for the CMS HGCAL hadronic calorimeter endcap HL-LHC upgrade


5x42 mm Sc-ECAL strip

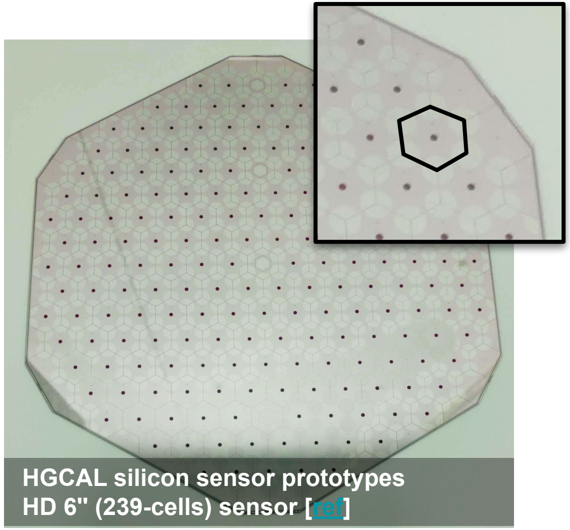


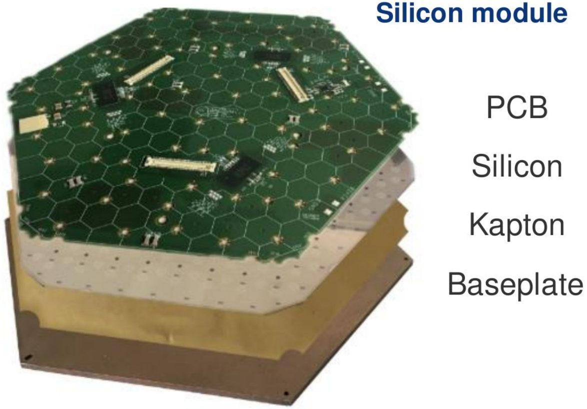

CMS HGCAL
AUTOMATED
TILE WRAPPING

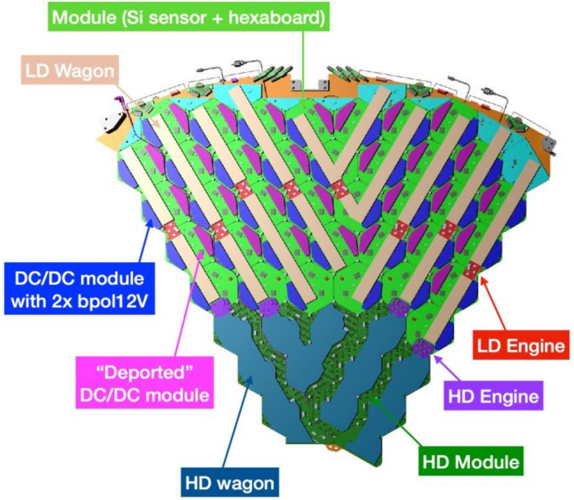


# High granularity with **semiconductors**

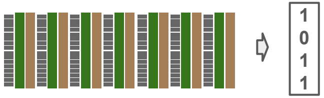
- Capitalizing decades of R&D within the CALICE (SiW-ECAL/AHCAL) collaboration, the CMS HGCAL uses silicon sensors for ECAL and HCAL endcaps, R&D continues
- HGCAL: granularity 0.5-1.2 cm² hexagonal cells, 6M channels, 600 m², 24+21 layers
- High complexity of services in each layer: power, cable routing, cooling


**HGCAL silicon sensor prototypes**
**HD 6" (239-cells) sensor [ref]**



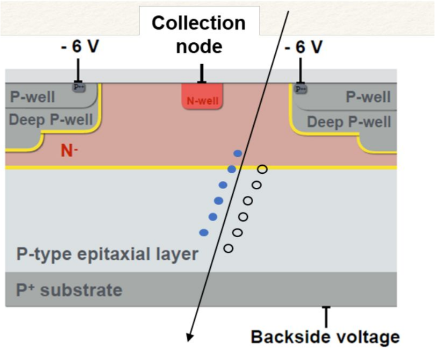


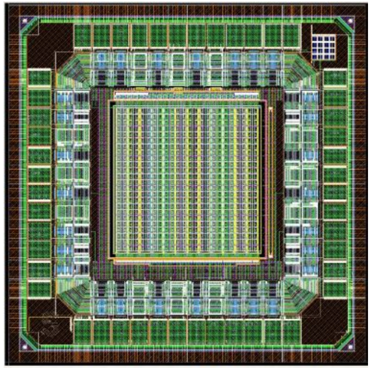
# Ultimate granularity with **CMOS MAPS**

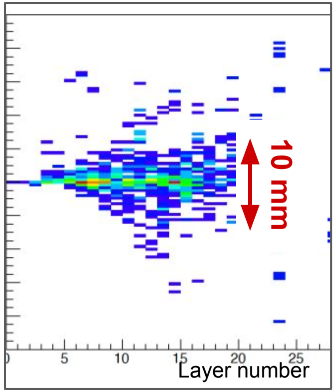


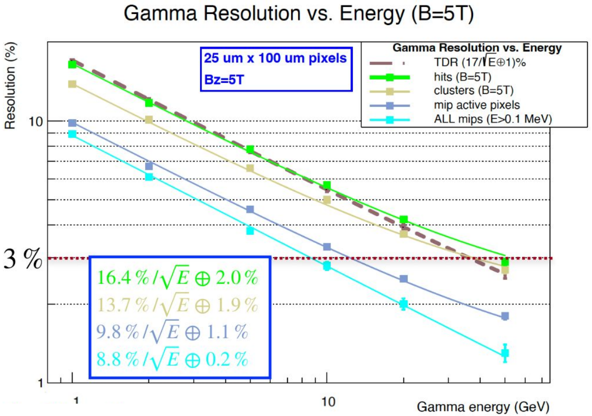
- Further boost the granularity by factor $10^4$ using SiD Digital ECal Based on Monolithic Active Pixel Sensors (MAPS) with down to 25x50 µm² size
- A **fully digital approach**: each pixel is read out with 1 bit resolution → energy measurement from hit counting
- Main challenges: reconstruction algorithms, reduce CMOS power consumption by ~1 order of magnitude (currently at ~10 mW/cm²)

*J.Brau @ CALOR2024*







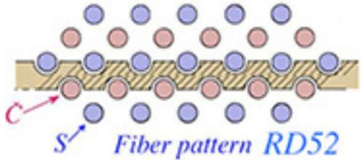


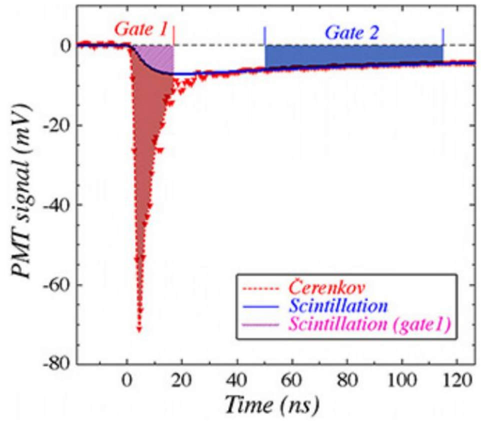
# **Dual-readout** calorimetry

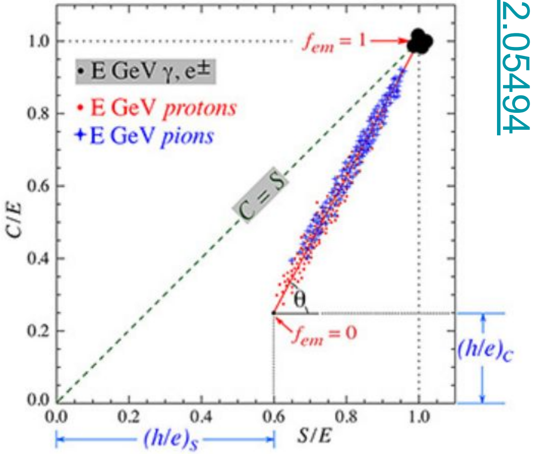
- EM fraction of the shower contains more relativistic particles → on average a larger Cherenkov signal is produced → can be used a proxy of $f_{em}$
- Cherenkov measured either using a different material (non scintillating) or based on pulse shape
- **Event by event correction of the reconstructed energy based on the S/C signal** ratio recover the linearity of the calorimeter and improve its resolution

Calculate characteristic constants of the calorimeter ⇨ $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_C} \sim 0.3$

Calculate corrected energy ⇨ $E = \dfrac{S-\chi C}{1-\chi}$

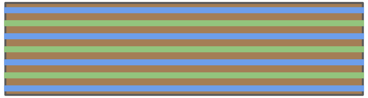




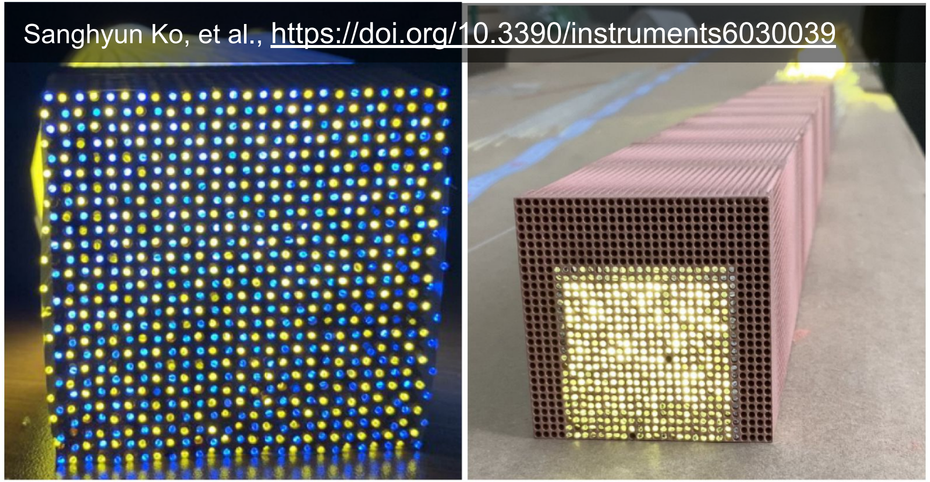


https://arxiv.org/abs/1712.05494

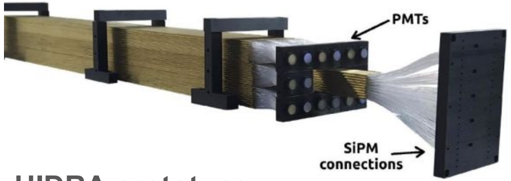
# Dual-readout **fiber calorimeter prototyping**



- **Long standing R&D, prototyping and proof-of-principle** (from DREAM to HIDRA)
- Fitting clear PMMA (C) and plastic scintillator fibers (S) inside an absorber groove (or inside brass capillaries which are then glued together)
- Potential transverse granularity down to ~1 mm with single fiber readout with SiPMs
- No longitudinal segmentation

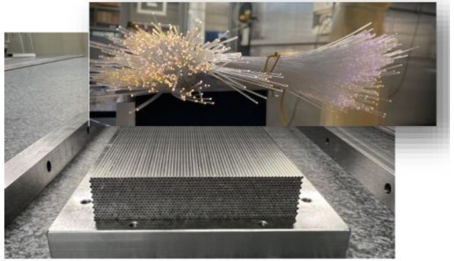


Sanghyun Ko, et al., https://doi.org/10.3390/instruments6030039

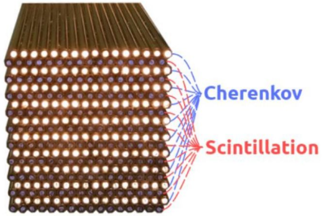


**HIDRA prototype**

*N.Valle at CALOR2024*



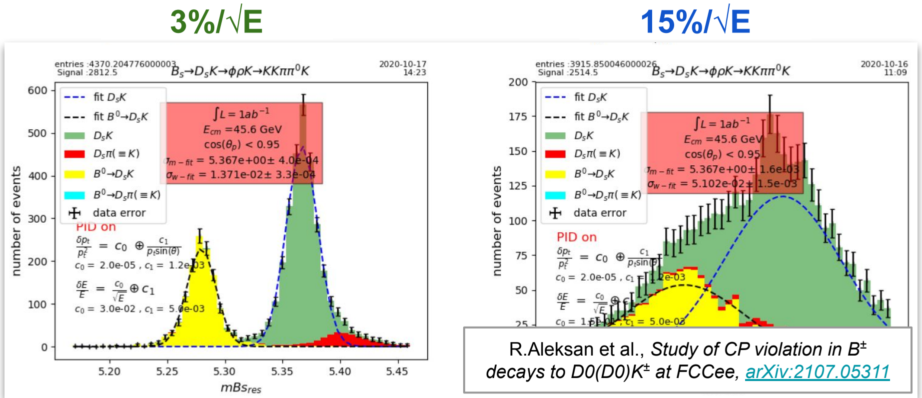
**DREAM prototype**



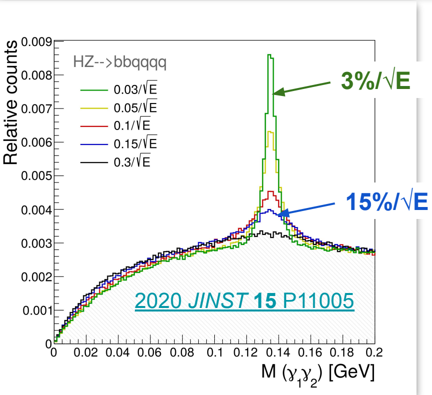
# Potential for **high EM energy resolution**

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 $\pi^0$'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)



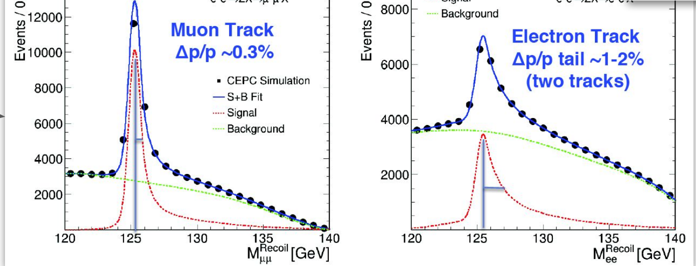
R.Aleksan et al., *Study of CP violation in B± decays to D0(D0)K± at FCCee, arXiv:2107.05311*



2020 *JINST* **15** P11005

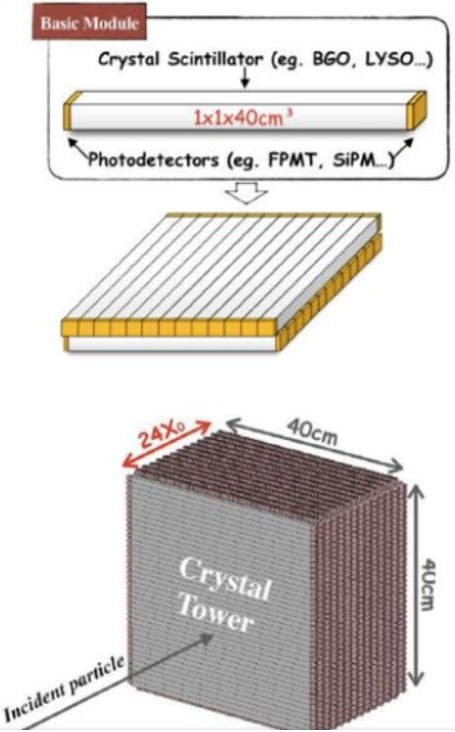
Z→μ⁺μ⁻ Recoil

Z→e⁺e⁻ Recoil

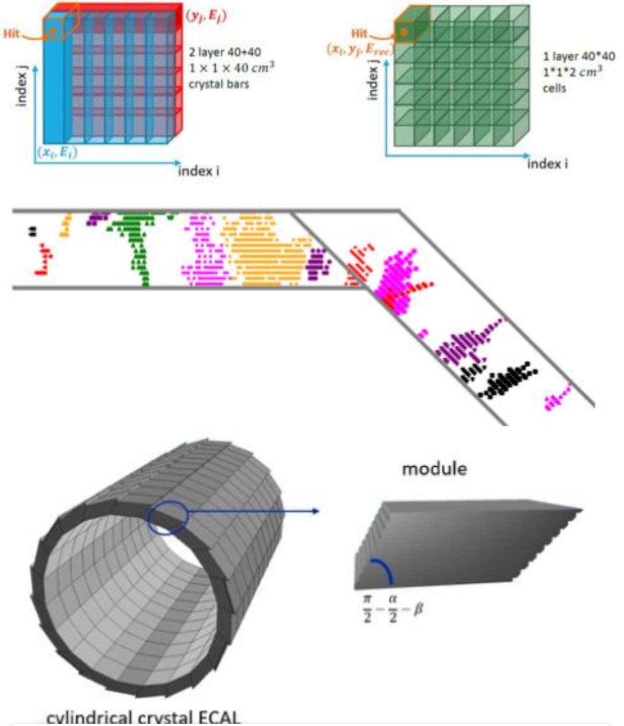


*Example from CEPC CDR*

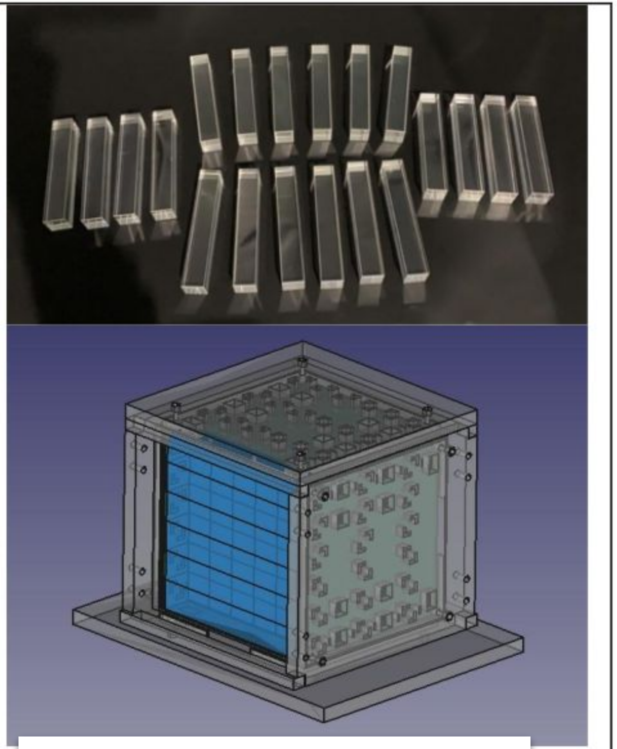
# **High Granularity Crystal** Calorimeter (HGCCAL)



EM calorimeter module: a grid of ~1x1x40cm³ crystal bars readout with SiPMs

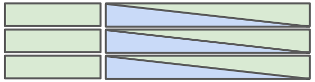


**Advanced simulation and reconstruction studies with dedicated ARBOR PFA**

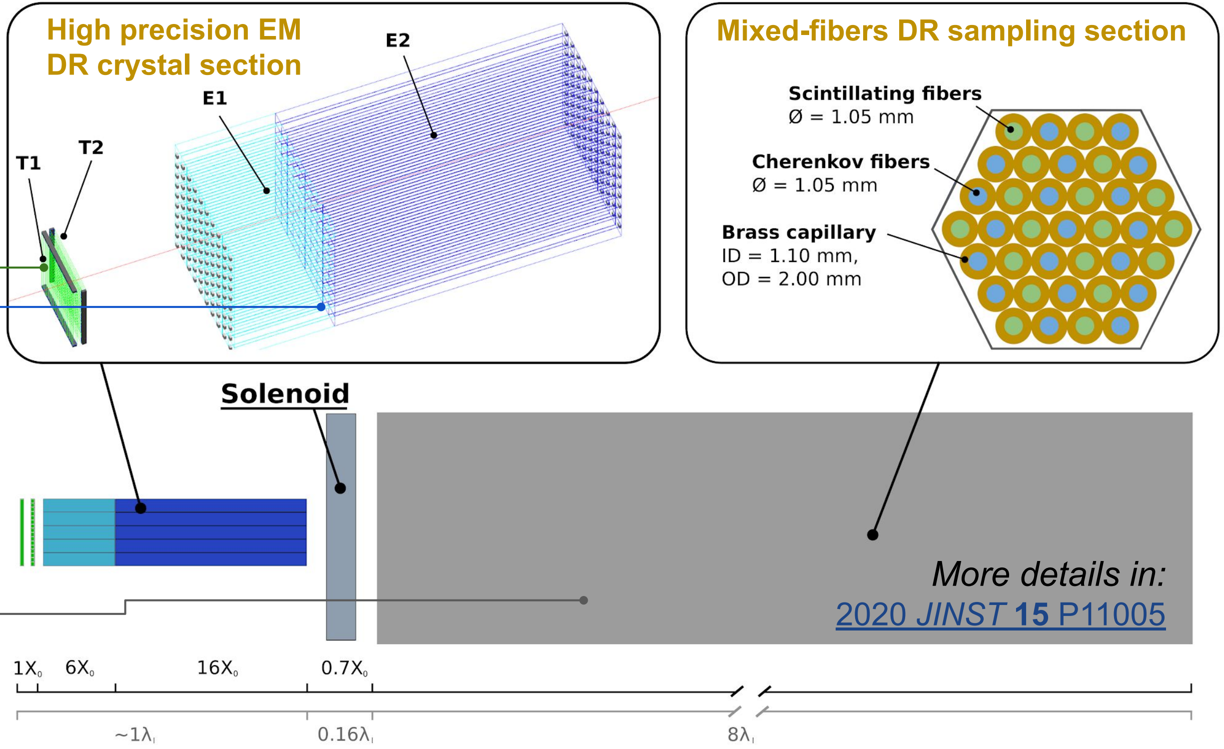


Hardware developments on crystals, SiPMs, prototypes [*See CALOR 2024*]

# **Dual-readout segmented crystal** calorimeter



- **Timing layers** $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~1$X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~6$X_0$)
  - Rear segment (~16$X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~0.7$X_0$
- **HCAL layer** $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

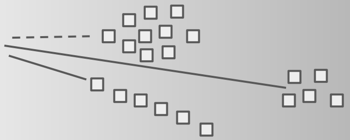


*More details in:*
2020 *JINST* **15** P11005

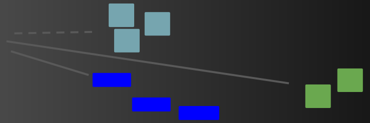
R&D for FCC, baseline for the IDEA detector concept [arXiv:2502.21223]

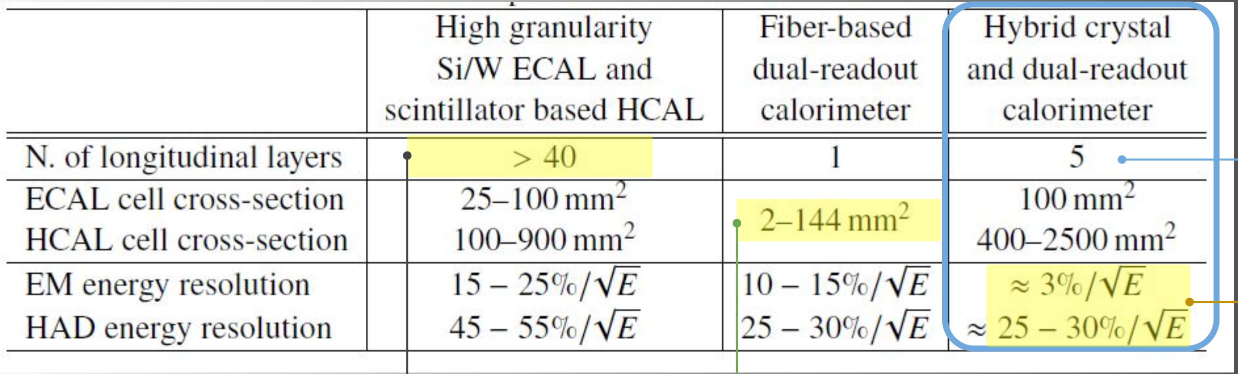
# The two approaches can be merged

## Particle Flow



## Dual-Readout





| | High granularity Si/W ECAL and scintillator based HCAL | Fiber-based dual-readout calorimeter | Hybrid crystal and dual-readout calorimeter |
|---|---|---|---|
| N. of longitudinal layers | $> 40$ | 1 | 5 |
| ECAL cell cross-section<br>HCAL cell cross-section | $25$–$100\,\text{mm}^2$<br>$100$–$900\,\text{mm}^2$ | $2$–$144\,\text{mm}^2$ | $100\,\text{mm}^2$<br>$400$–$2500\,\text{mm}^2$ |
| EM energy resolution<br>HAD energy resolution | $15 - 25\%/\sqrt{E}$<br>$45 - 55\%/\sqrt{E}$ | $10 - 15\%/\sqrt{E}$<br>$25 - 30\%/\sqrt{E}$ | $\approx 3\%/\sqrt{E}$<br>$\approx 25 - 30\%/\sqrt{E}$ |

Moderate longitudinal segmentation (helpful to identify and measure the $\pi^0$ component of jets)

Highest energy resolution and linearity

Highest longitudinal segmentation

Highest transverse segmentation: full potential (e.g. using neural networks) yet unexplored

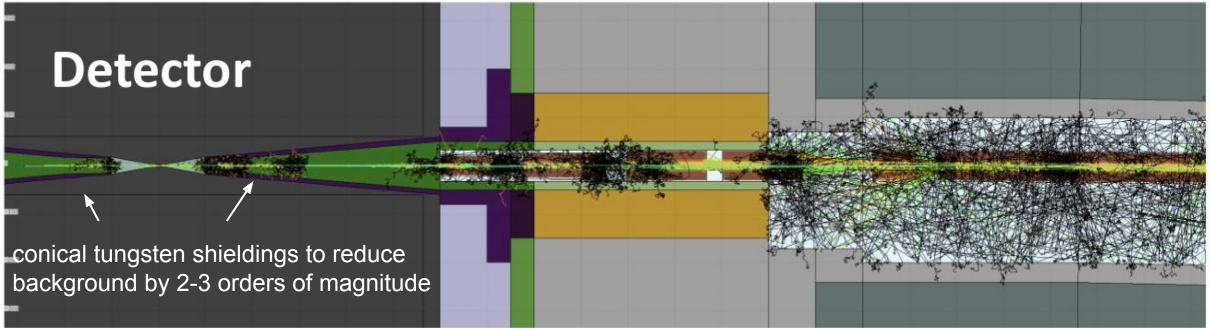
See DR-protoPFA algorithm
/doi.org/10.1088/1748-0221/17/06/P06008

# Beam induced background challenge

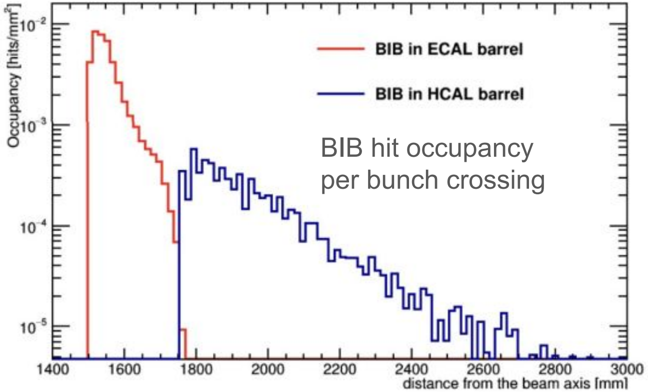
at muon colliders

# **Beam induced background** at a muon collider

- Muon decay products generate an intense flux of “beam-induced background (BIB) particles
    - low momentum, displaced origin and asynchronous time of arrival
- **Strategy**:
    - **High granularity** to reduce the overlap of BIB particles in the same calorimeter cell
    - **Excellent timing** (of the order of 100 ps) to reduce the out-of-time component of the BIB
    - **Longitudinal segmentation** to distinguish the signal showers from ‘fake’ BIB showers
    - **Energy resolution** better than 10%/√*E*
- Baseline is a Si-W ECAL, but also cost-effective alternatives with less channels under study

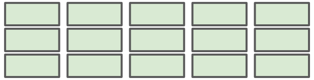


conical tungsten shieldings to reduce background by 2-3 orders of magnitude

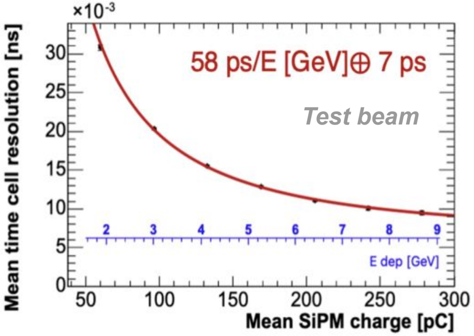


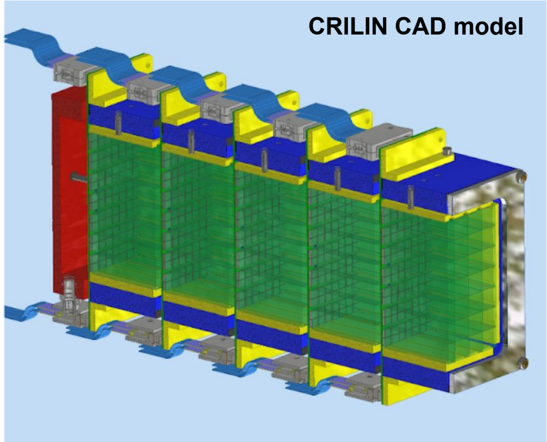
BIB hit occupancy per bunch crossing

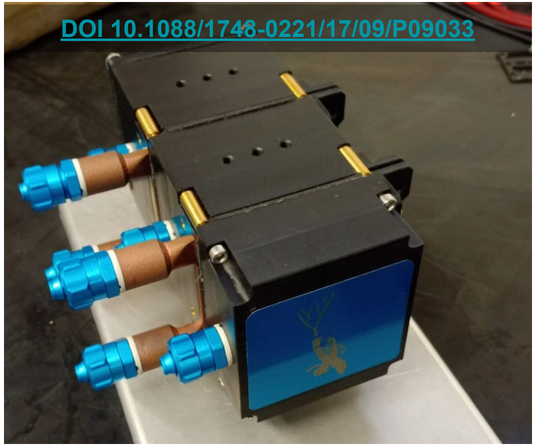
# A semi-homogeneous CRystal calorImeter with Longitudinal InformatioN (**CRILIN**)



- **Longitudinal segmentation** to mitigate the beam induced background (BIB)
- **Time resolution** in the sub 100 ps domain
- **Advanced prototyping**
  - 5 longitudinal layers, UF-**PWO** / **PbF$_2$** crystal size: 1x1x4 cm³
  - 3x3 mm² UV extended 10μm SiPMs readout

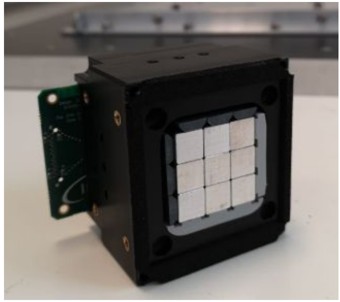


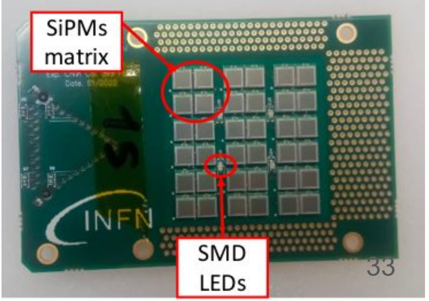




DOI 10.1088/1748-0221/17/09/P09033

Modular architecture based on stackable modules



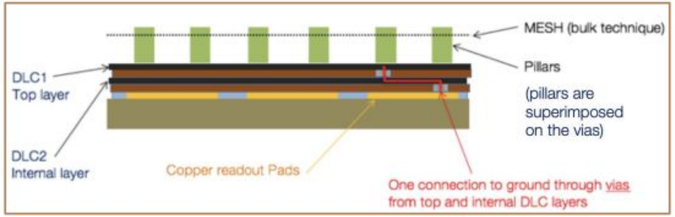


# An **MPGD** based sampling HCAL

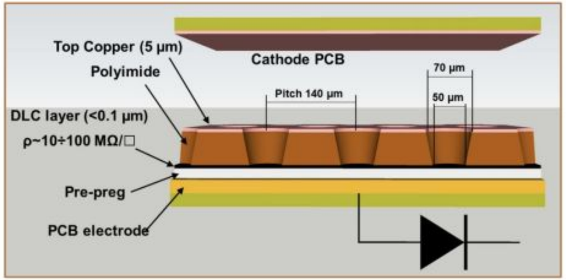
*L.Longo at ICHEP 2024*

- **Micro-pattern gaseous detectors** (MPGD) as readout layers for a sampling hadronic calorimeter at a muon collider
  - 60 layers, ~1cm² cells
  - Energy resolution ~60%/√E
- **Key features at a muon collider**:
  - High rate capability ~O(MHz/cm²)
  - High granularity ~O(100 um)
  - Radiation hardness
- Various technologies on the table:
  - Resistive MicroMegas
  - µRWELL
  - RPWELL

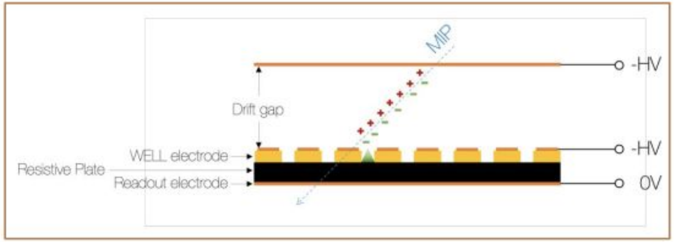
**Micromegas (MM)**



**µRWELL**



**RPWELL**



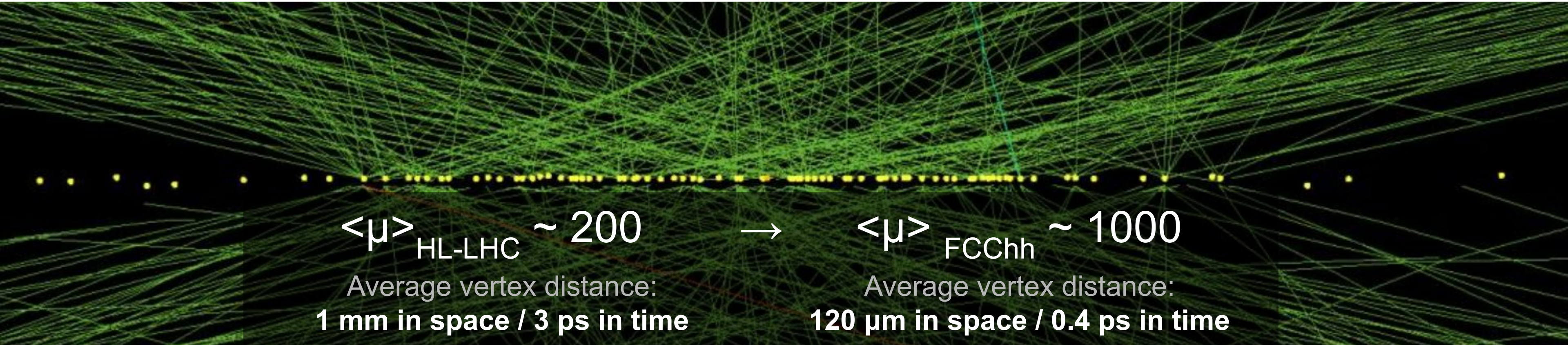
# Unimaginable radiation and pile-up levels

FCChh ~ 10x HL-LHC

# **Pileup**: multiple interactions per bunch crossing

- Vertex identification requires the aid from timing (as for HL-LHC but better)
- **State-of-the-art**: Crystal+SiPMs and LGADs → O(30 ps) for CMS and ATLAS at HL-LHC
- FCChh requires timing of tracks at the <10 ps level

- **Timing needed also in calorimeters** for pileup rejection from calorimetric clusters
  - O(25ps) to reduce pile-up by factor 5
  - O(5ps) to reduce pile-up by factor 25
  - It is not too far from state-of-the-art… if it wasn't for the radiation hardness issue!



$\langle\mu\rangle_{\text{HL-LHC}} \sim 200$ → $\langle\mu\rangle_{\text{FCChh}} \sim 1000$

Average vertex distance:
**1 mm in space / 3 ps in time**

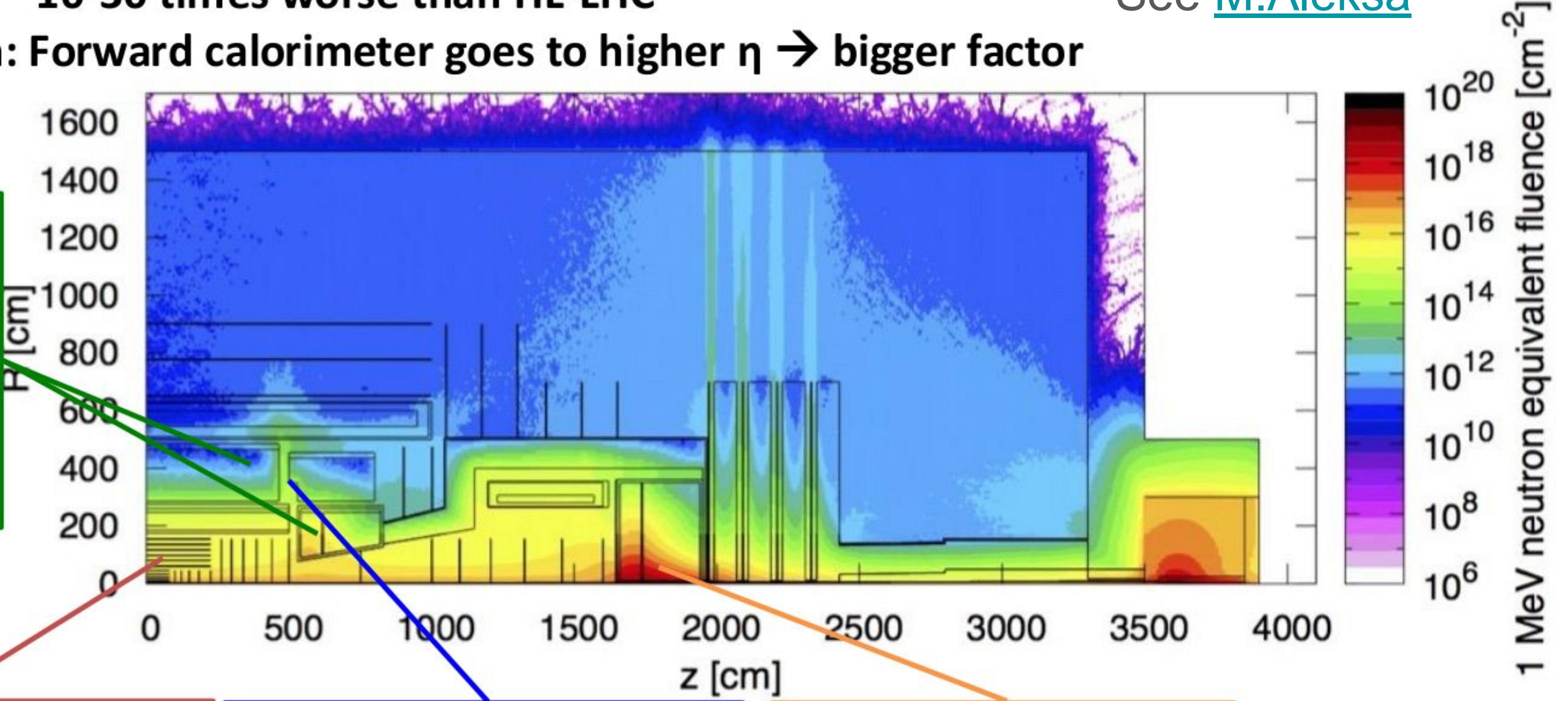
Average vertex distance:
**120 μm in space / 0.4 ps in time**

# 1 MeV Neutron Equivalent Fluence for 30ab$^{-1}$

**Generally ~10-30 times worse than HL-LHC**

**Exception: Forward calorimeter goes to higher η → bigger factor**

See M.Aleksa



Barrel calorimeter:

EM-calo: 4 $10^{15}$ cm$^{-2}$

HAD-calo: 4 $10^{14}$ cm$^{-2}$

End-cap calorimeter:

EM-calo: 2.5 $10^{16}$ cm$^{-2}$

HAD-calo: 1.5 $10^{16}$ cm$^{-2}$

Central tracker:

- first IB layer (2.5 cm ): ~5-6 $10^{17}$ cm$^{-2}$
- external part: ~5 $10^{15}$ cm$^{-2}$

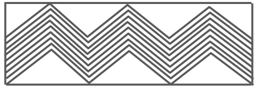
Calorimeter gap:

from $10^{16}$ cm$^{-2}$ to $10^{14}$ cm$^{-2}$

Forward calorimeters:

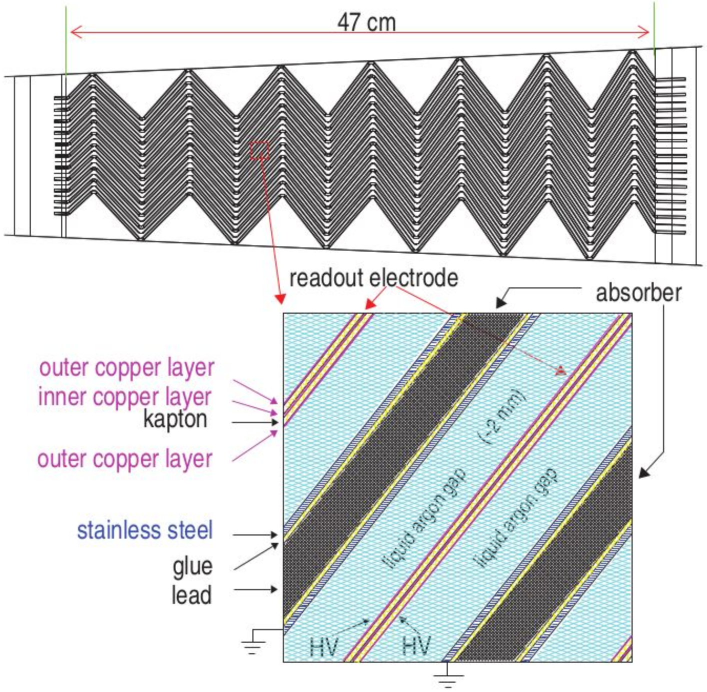
~5 $10^{18}$ cm$^{-2}$ for both the EM and the HAD-calo

# High Granularity **Liquid Argon** Calorimeter



- Current baseline candidate for FCChh calorimetry in the highest fluence regions:
  - Liquid Argon (LAr) with Pb absorbers for ECAL
  - Liquid Kripton with W-Cu for higher density in the endcap HCAL and forward calorimeters
- Active material is **intrinsically radiation tolerant**
- R&D for FCC ongoing to boost granularity and performance → ALLEGRO detector concept
  - EM Energy resolution at the 7-8%/$\sqrt{E}$ level
  - Longitudinal segmentation: 11 layers
  - Transverse segmentation:
    - $\Delta\theta$ ~ 10 (2.5) mrad for regular (strip) cells
    - $\Delta\phi$ ~ 8 mrad

*Accordion structure of the ATLAS LAr Calorimeter*

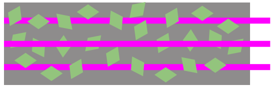


*https://ieeexplore.ieee.org/document/6728060*

# “Exotic R&D”

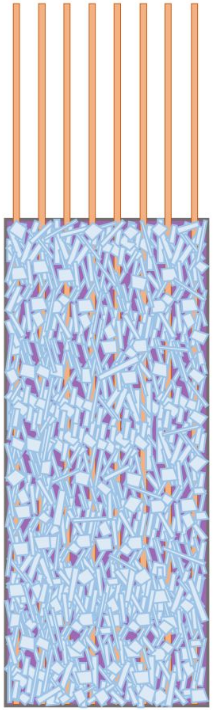
for a colorful ending

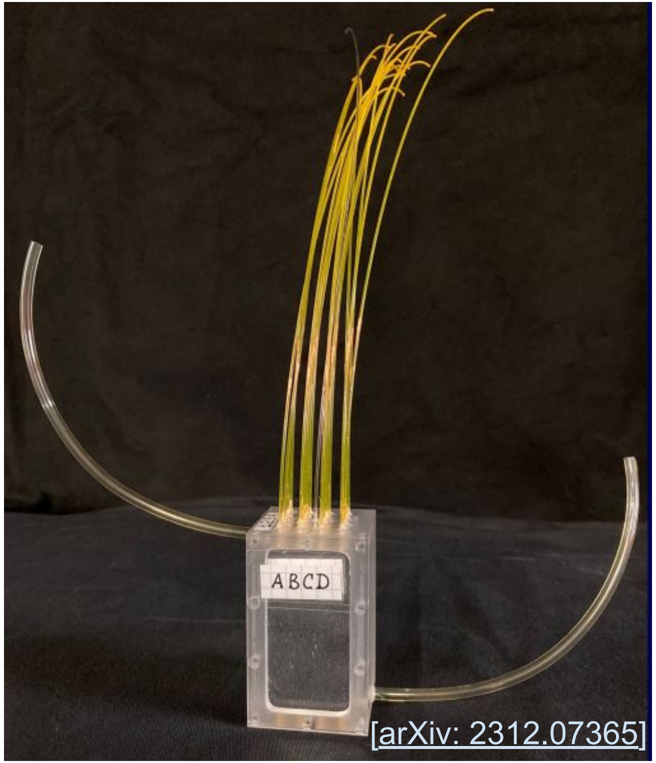
# **GRAiNITA** calorimeter



- A high sampling EM calorimeter made of a dishomogeneous medium:
    - **Grains** of high density crystal readout by wavelength shifting fibers and SiPMs
    - **ZnWO4/BGO** 1 mm$^2$ cubes immersed in liquid
    - Target ~1-2%/$\sqrt{E}$ as homogeneous crystal calorimeters but at a competitive cost!
    - Inspired by *LiquidO* for neutrino detector
      *[A. Cabrera et al. LiquidO Commun Phys 4, 273 (2021) ]*

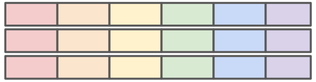
[ref]



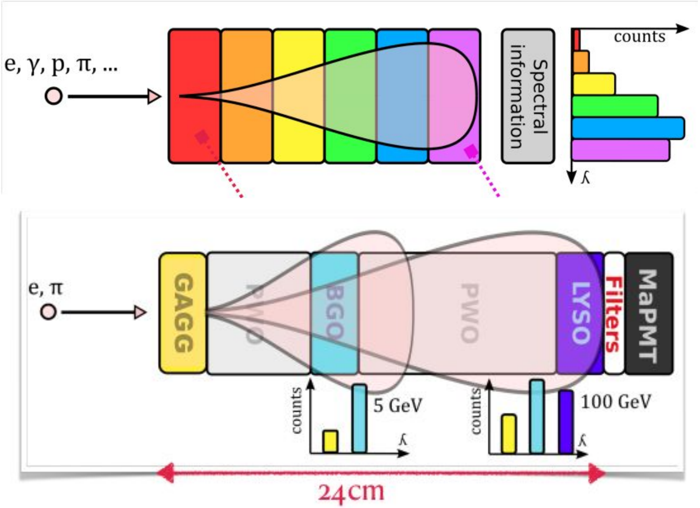


[arXiv: 2312.07365]

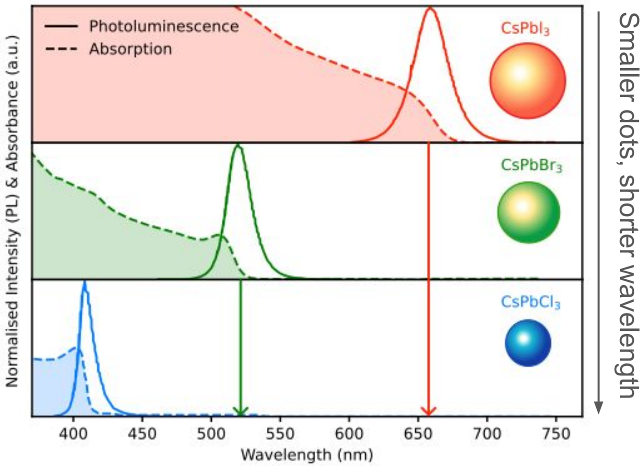
# **Chromatic** calorimeter

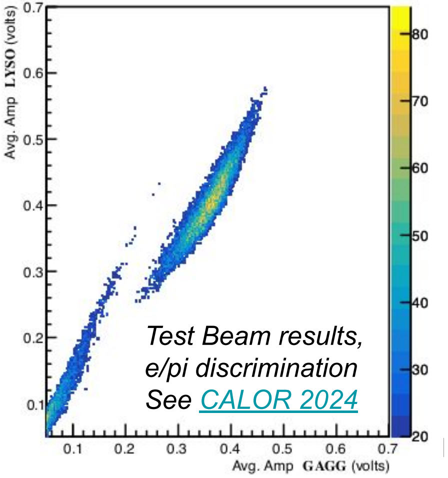


- Use different scintillating materials along the scintillator module to follow the shower propagation and a detector capable of discriminating different emission λ
    - Absorption and emission of the “crystal” stack have to be one directional transparent
- ‘High sampling’ calorimeter with single photodetector layer at the back yielding a **virtual longitudinal segmentation**



Y. Haddad, N U, Boston, USA
(based on data from: Zheng, W. et al, Nat Commun 9, 3462 (2018))

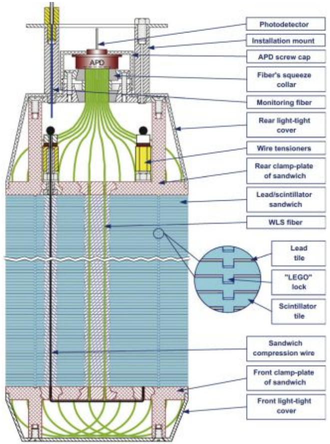




*Test Beam results, e/pi discrimination*
*See CALOR 2024*

# **Nanocrystal**-based sampling calorimeters

- NanoCal project exploiting semiconductor nanocrystals **quantum dots** (e.g. CsPbBr3) inside a polymeric matrix to build for fine sampling calorimeters
  - Extreme flexibility in wavelength and scintillation time (<1ns) depending on dot size (1-10 nm)
  - Generally cheaper and easier to produce than inorganic scintillators
- Challenges:
  - Achieve sufficient energy transfer from host matrix to quantum dots, avoid self-absorption




M.Soldani @ CALOR2024

Development of nanocomposite scintillators for use in high-energy physics
DOI:10.48550/arXiv.2407.10915

# **Takeaway** message

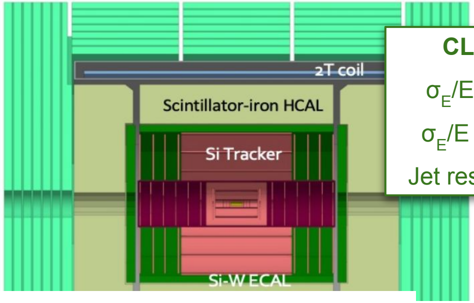
- **A broad and active community** on calorimetry R&D (e.g. organized in CERN DRD6)
    - Recent technological developments enabled **a ‘zoo’ of novel calorimeter designs**
    - Desired performance for FCCee physics goals is within reach
    - Major challenges for a muon collider or FCChh require targeted R&D

- While this talk was focused on conceptual layouts and R&D, the real challenge for calorimeters is to **move from small prototypes to large scale system** addressing:
    - Integration aspects, services, cost, power consumption
    - Demonstrate a reliable calibration strategy and system stability

# Additional material

# Mainstream detector concepts for future **$e^+e^-$ colliders**

- **CLD**: Exploiting high granularity for particle flow algorithms with Silicon sensor and Tungsten absorber for a compact ECAL and plastic scintillator+absorber in the HCAL.
- **IDEA**: Exploiting a hybrid crystal-fiber dual-readout approach (with homogeneous crystals for ECAL and a mixture of scintillating and “Cherenkov” fibers inside an absorber groove for HCAL).
- **ALLEGRO:** Including a noble liquid (LAr) sampling calorimeter for the ECAL and a scintillator tile calorimeter for HCAL. Reasonable granularity and segmentation for particle flow algorithms.

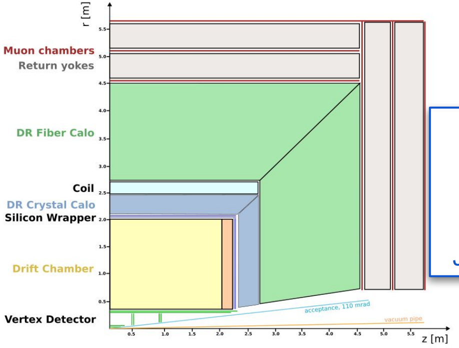


**CLD calorimeter**

$\sigma_E/E$ (**EM**) ~16%/√E

$\sigma_E/E$ (**HAD**) ~45%/√E

Jet resolution ~ 30%/√E

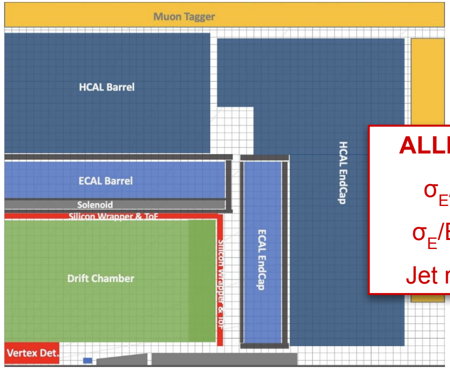


**IDEA calorimeter**

$\sigma_E/E$ (**EM**) ~3%/√E

$\sigma_E/E$ (**HAD**) ~30%/√E

Jet resolution ~ 30%/√E



**ALLEGRO calorimeter**

$\sigma_E/E$ (**EM**) ~8%/√E

$\sigma_E/E$ (**HAD**) ~37%/√E

Jet resolution ~ ?%/√E

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

1. Evaluate the χ-factor for the crystal and fiber section
2. Apply the DRO correction on the energy deposits in the crystal and fiber segment independently
3. Sum up the corrected energy from both segments

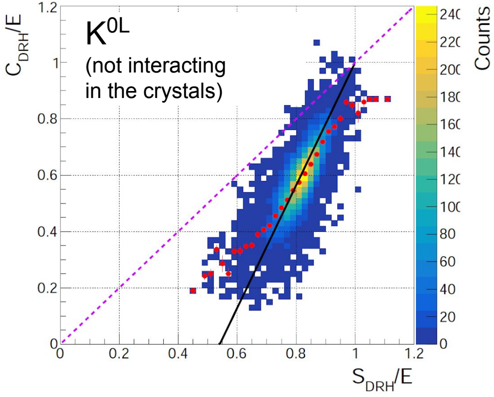
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

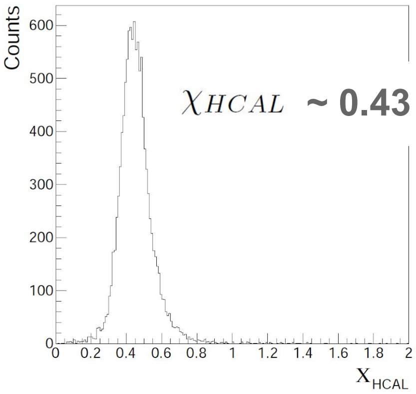
$$\chi_{ECAL} = \frac{1-(h/e)_s^{ECAL}}{1-(h/e)_c^{ECAL}}$$

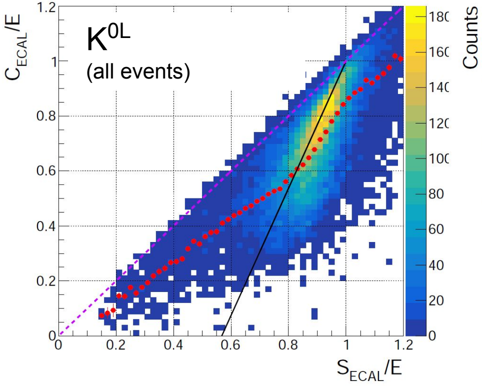
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1-\chi_{HCAL}}$$

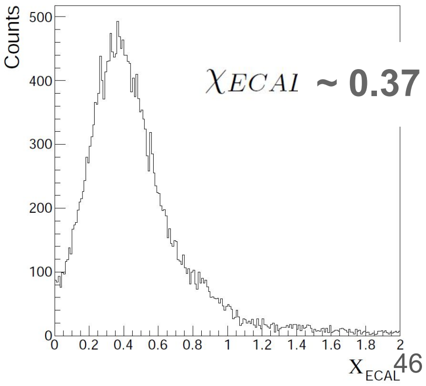
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1-\chi_{ECAL}}$$

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

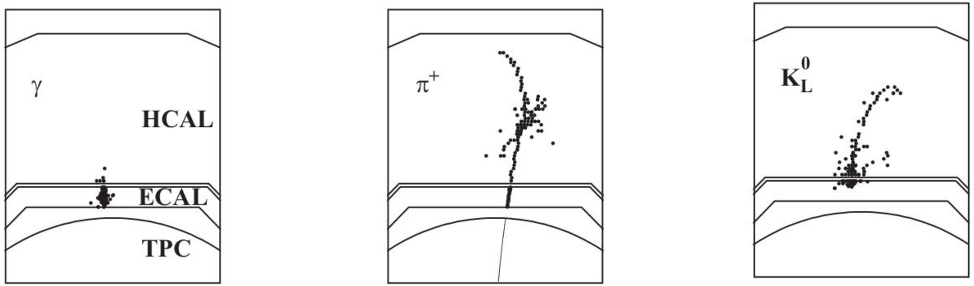




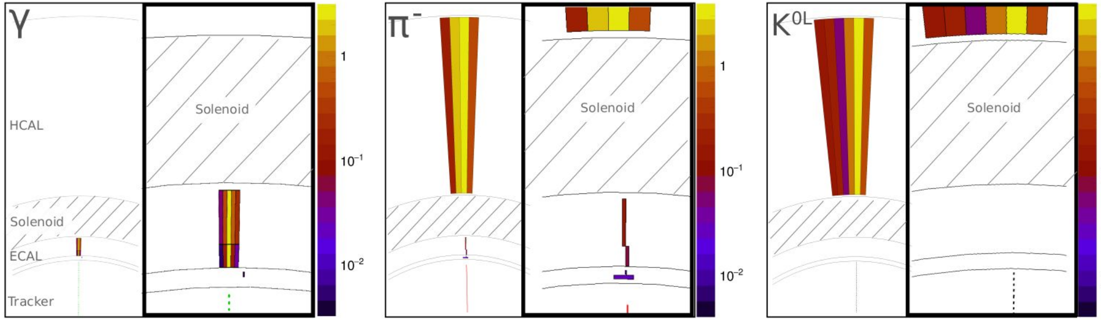




# Single particle identification through ‘hits-topology’



Typical PFA with Si-W high granularity calorimeter



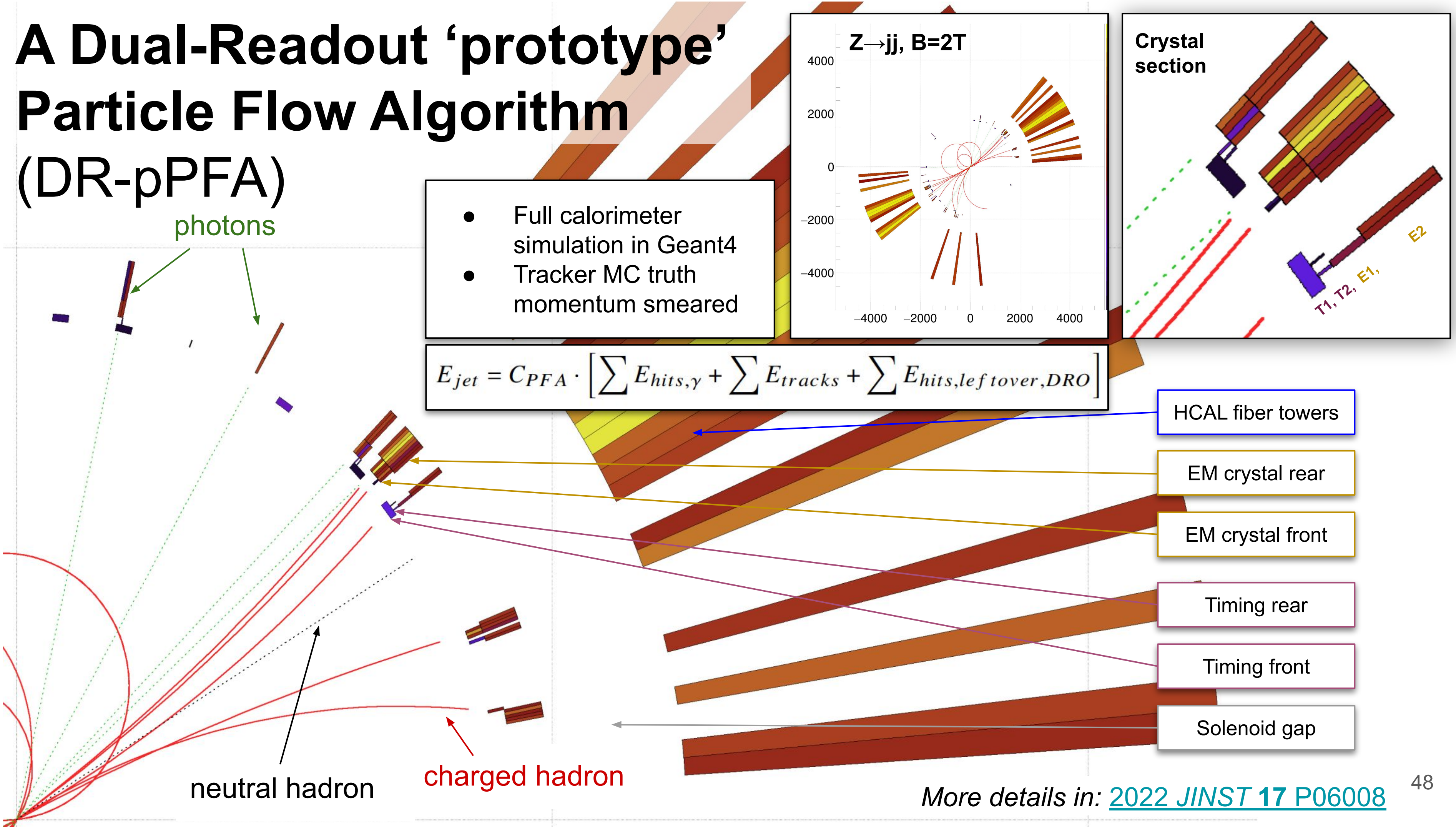
DR-pPFA with high resolution DRO calorimeter

**A moderate longitudinal segmentation, fine transverse granularity and the highest energy resolution for single particle identification**

# A Dual-Readout ‘prototype’ Particle Flow Algorithm (DR-pPFA)

- Full calorimeter simulation in Geant4
- Tracker MC truth momentum smeared

$$E_{jet} = C_{PFA} \cdot \left[\sum E_{hits,\gamma} + \sum E_{tracks} + \sum E_{hits,leftover,DRO}\right]$$



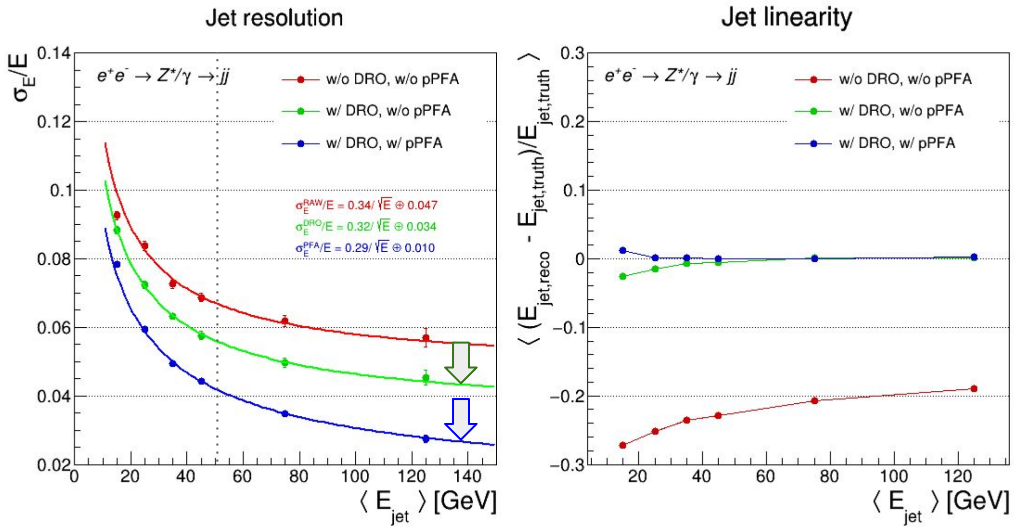
*More details in:* [*2022 JINST* **17** P06008]

# **Jet resolution**: with and without DR-pPFA

*More details in:*
2022 *JINST* **17** P06008

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

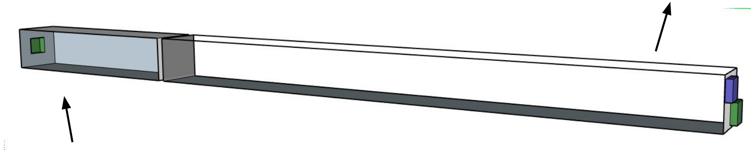


**Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV**

# **Implementation** of dual-readout in the crystal section

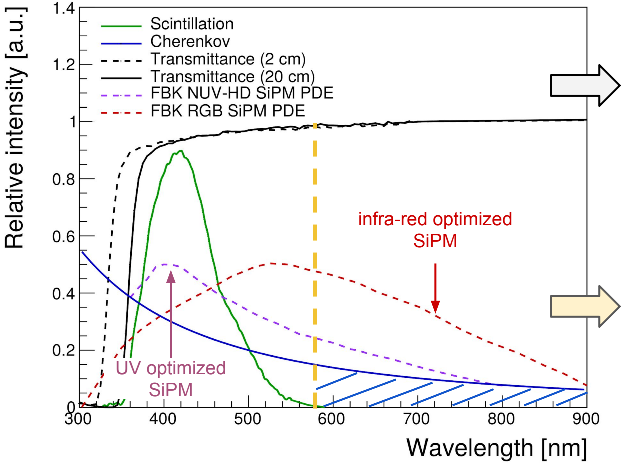
- Simultaneous readout of scintillation and Cherenkov light from the rear segment with dedicated SiPMs+wavelength filters

**Rear crystal ECAL segment**: Two 4x4 mm² SiPMs with optical filters optimized for scintillation and cherenkov detection resp.



**Front crystal ECAL segment**: Single 5x5 mm² SiPM per crystal optimized for scintillation light detection

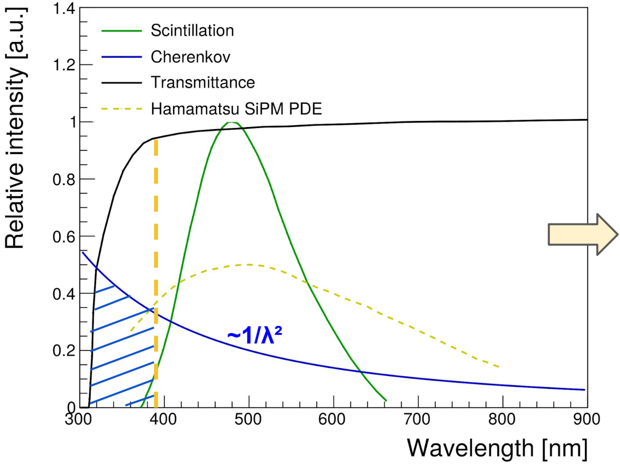
**PWO**



Estimated:
- >2000 phe/GeV for scintillation photons
- >100 phe/GeV for Cherenkov photons

Cherenkov photons above scintillation peak are much less affected by self-absorption

**BGO / BSO**



BGO/BSO have larger stokes shift, i.e. a wider range of transparency for 'UV Cherenkov'

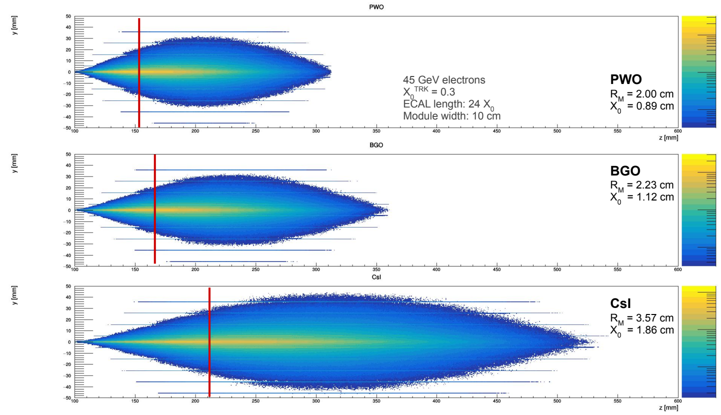
# Some crystal options

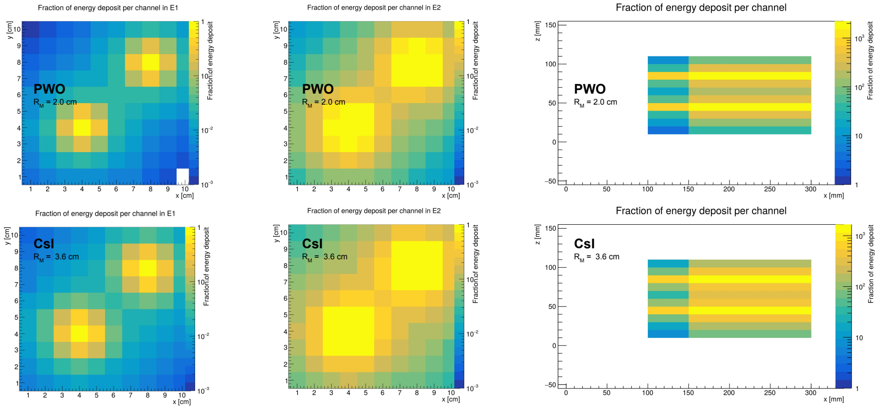
- **PWO**: the most compact, the fastest
- BGO/BSO: parameters tunable by adjusting the Si-fraction
- CsI: the less compact, the slowest, the brightest

better for PFA ⇧

⇩ better stochastic term

| Crystal | Density g/cm³ | $\lambda_I$ cm | $X_0$ cm | $R_M$ cm | Refractive index, n | Relative LY @ RT | Decay time ns | Photon density (LY / $\tau_D$) ph/ns | dLY/dT (% / °C) | Cost (10 m³) Est. \$/cm³ | Cost*$X_0$ 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 |
| **CsI** | 4.5 | 39.3 | 1.86 | 3.57 | 1.96 | 550 | 1220 | 0.45 | +0.4 | 4.3 | 8.0 |





# Oriented crystal calorimeter (**OREO**)

- Acceleration of the electromagnetic shower longitudinal development if the crystal axis is oriented with the incoming particle [see slides and ref]
- One could expect to see an effect for specific angles in CMS ECAL crystals, e.g.:
    - Larger signals for e.m. showers that are not longitudinally contained (>200 GeV)
    - Changes in transverse shower profile (R9/R25)
    - Different non linearity of energy response in crystals with low transparency

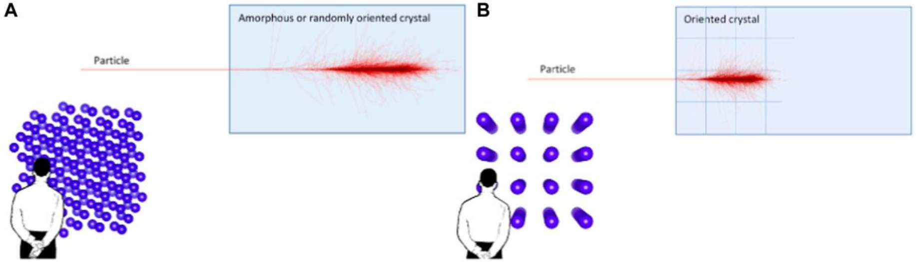


FIGURE 2
**(A)** Sketch of the electromagnetic shower in an amorphous material or a randomly-oriented crystal. **(B)** Sketch of a more compact electromagnetic shower in the same material but with the first layers made of crystals oriented with the beam direction along their strong axial field.

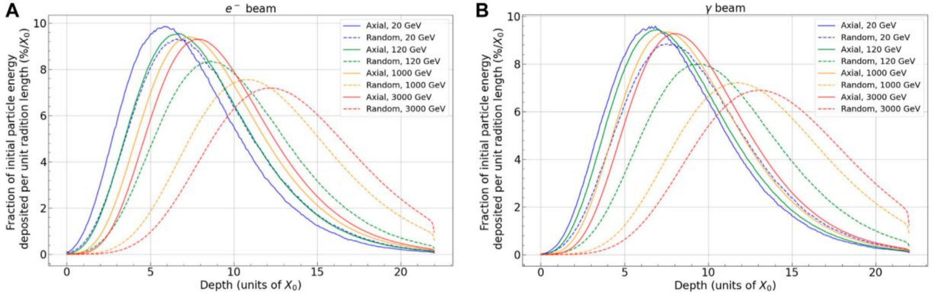
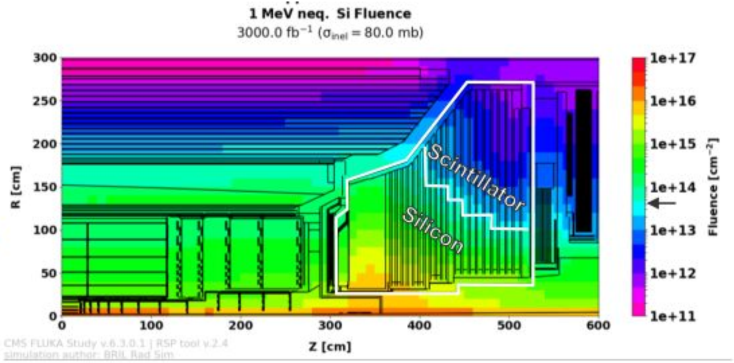


FIGURE 7
Simulated fraction of initial particle energy deposited per radiation length in electromagnetic showers initiated by electrons **(A)** and photons **(B)** as a function of the penetration depth in randomly (dashed lines) and axially (<001>) oriented (solid lines) PWO crystals.

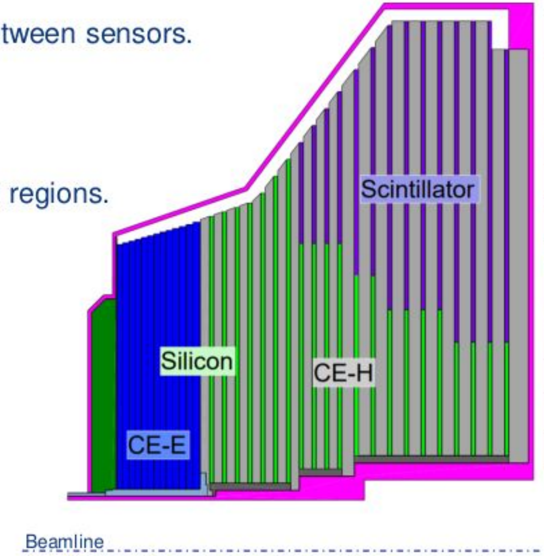
# Proposed Detector – HGCAL



- HGCAL needs to fit in the envelope of the previous calorimeters (EE and HE) and provide **high granularity, radiation-tolerance (2 MGy), and efficient readout.**
- Each HGCAL is **5.4 m in diameter** and weighs about **230 tonnes.**
- The **electromagnetic part (CE-E)** is designed with fine longitudinal resolution, and thin absorber layers of lead and CuW/copper between the active layers.
- The **hadronic part (CE-H)** has thick stainless-steel absorbers between sensors.
- Active sensors cover **≈1000 m² total over both endcaps.**
  - **Silicon sensors** as active material in the front sections.
  - Plastic **scintillator tiles**, read out by SiPMs, in lower radiation regions.
- **Challenges:**
  - **Engineering (electronics, mechanical, and thermal).**
  - **Data transmission,** and level-1 (L1) trigger formation.

This presentation

See presentations by Aidan Grummer (front-end electronics and readout) and Stavros Mallios (back-end electronics).
Andre Stahl will be presenting reconstruction and performance.



HGCAL cross-section (~axisymmetric)

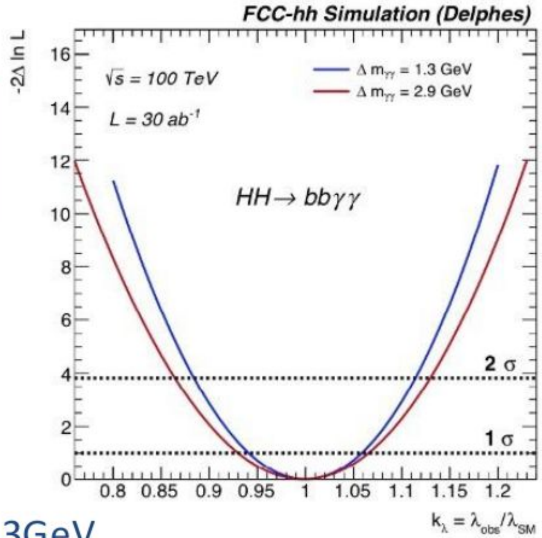
| Both Endcaps | Silicon | Scintillator |
|---|---|---|
| Area | ~620 m² | ~370 m² |
| Channel Size | 0.5 – 1.2 cm² | 4 – 30 cm² |
| # Channels | ~6M | ~280k |
| # Modules | ~26k | ~4k |
| Op. Temp. | -35 °C | -35 °C |

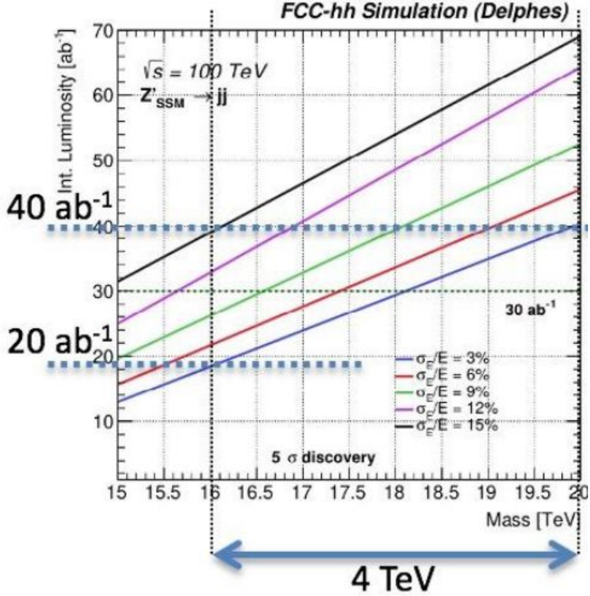
| Per Endcap | CE-E | CE-H Si | CE-H Si+Scint. |
|---|---|---|---|
| Absorber | Pb, CuW, Cu | SS, Cu | |
| Depth | 27.7 $X_0$ | 10 λ | |
| Layers | 26 | 7 | 14 |
| Weight | 23 t | 205 t | |

# Physics Benchmarks – Detector Requirements

**Calorimetry – Improving resolution with higher energy!**

$$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$





**Higgs self-coupling** $\delta\lambda/\lambda$ = 7% for $\Delta m_{\gamma\gamma} <$ 3GeV

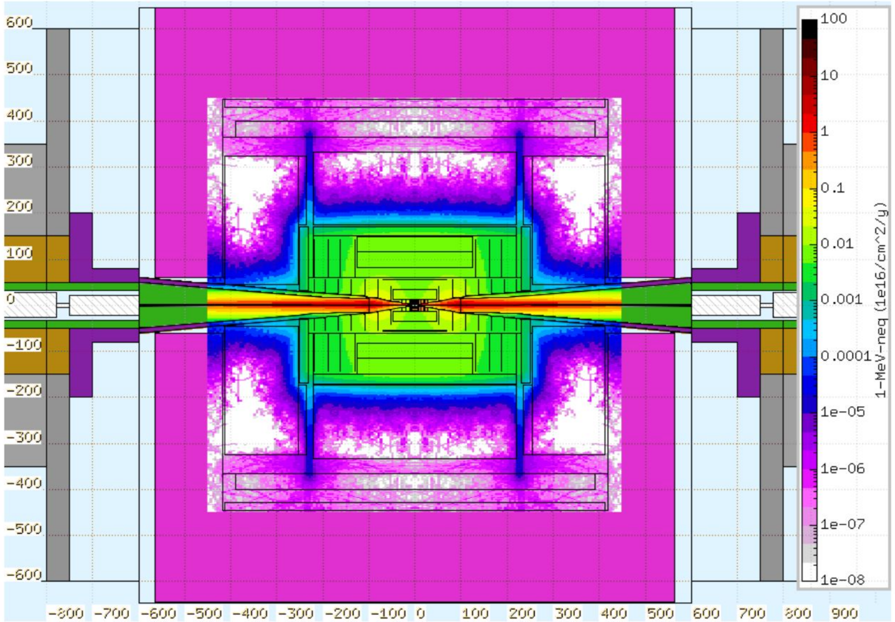
- → **EM-calorimeter resolution**
  **sampl. term *a ≈ 10%* and noise term *b < 1.5GeV* (including pile-up)!**

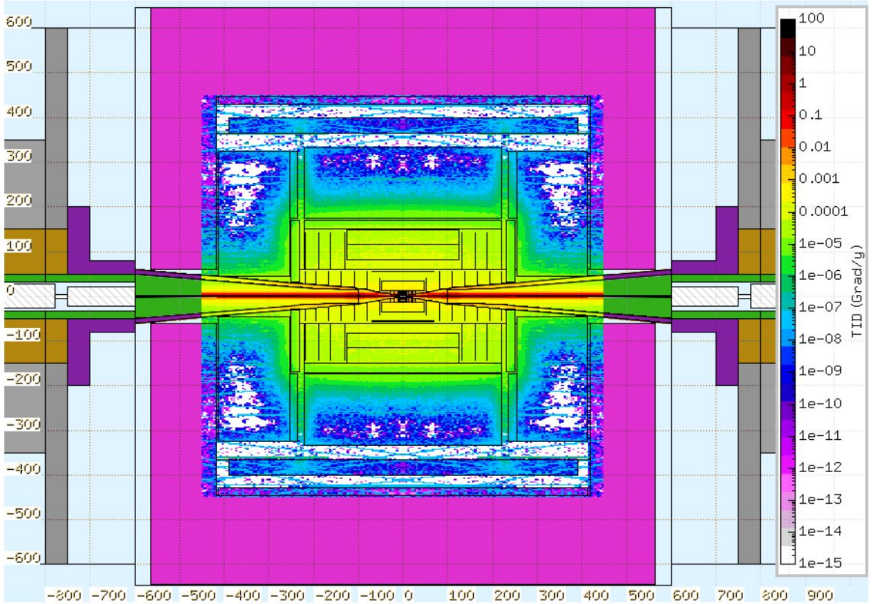
**Di-jet resonances:** HCAL constant term of *c* = 3% instead of 15%**:** extend discovery potential by 4TeV (or same disc. pot. for 50% lumi)

- → **full shower containment is mandatory !**
- → Large **HCAL depth (~ 12 $\lambda_{int}$)!**

Better detector performance could compensate decreased HH statistics at 80 TeV

# Muon collider radiation levels (1 year of operation)





https://doi.org/10.1088/1748-0221/17/09/P09033

# Radiation hardness constraints

- No state-of-the-art optical calorimetry technology (scintillators/photodetectors) could survive → much R&D need
  - The CMS Barrel Timing Layers **SiPMs** will be facing 2x$10^{14}$ 1 MeV/neq at HL-LHC
    - → Exploiting thermal annealing and operation at -45°C [see [2023 JINST 18 P08020]]
    - → Still need 1-2 orders of magnitude better for FCChh calorimeters
  - R&D on radiation tolerant inorganic scintillators (LYSO, GAGG) and a new generation of rad-hard SiPM exploiting larger band gap GaIn structure → [RADICAL] calorimeter

- Radiation damage in HGCAL silicon sensors also an issue, tested up to fluences of $10^{16}$ 1 MeV neq/cm² for HGCAL [https://indico.cern.ch/event/1395691/]

*C. Hu et al., J. Phys.: Conference Series 1162, 012020 (2019)*