Riunione di Gruppo 1 - INFN Napoli

16 gennaio 2025

FCC report

Marcello Campajola

on behalf of the RD_FCC NA group

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Università degli Studi di Napoli Federico II

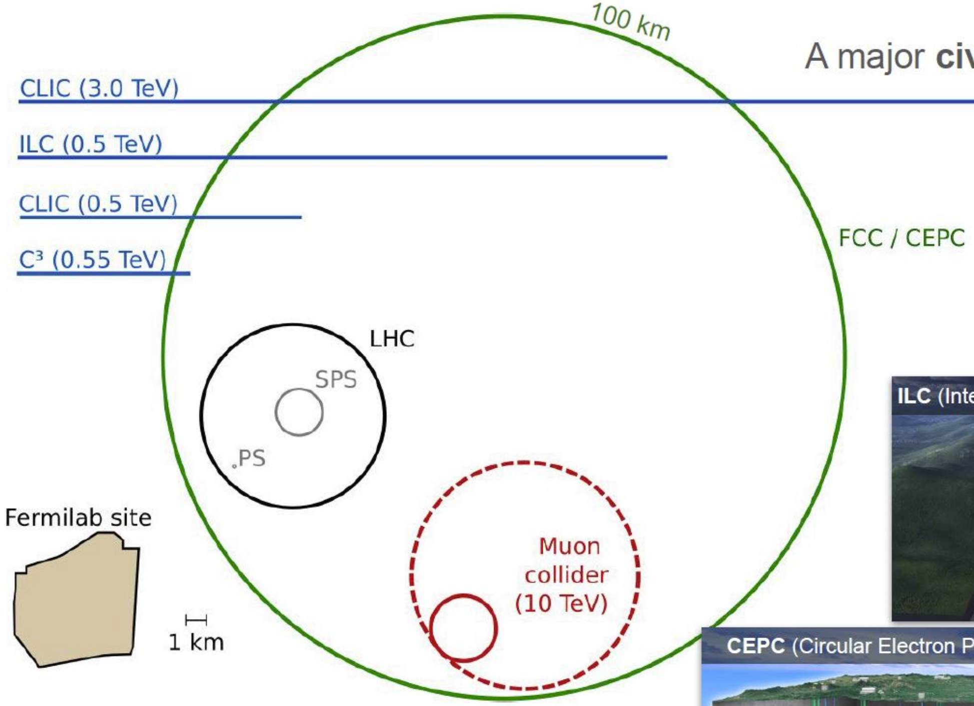
INFN NAPOLI

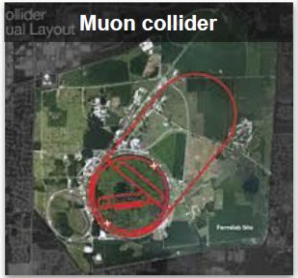
Outline

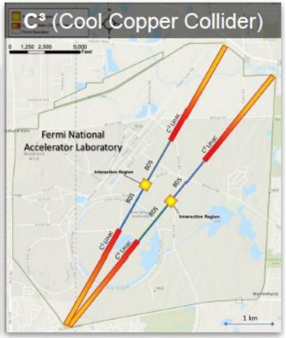
- **Future colliders and detector concepts**
- **Napoli group**
- **Ongoing activities**

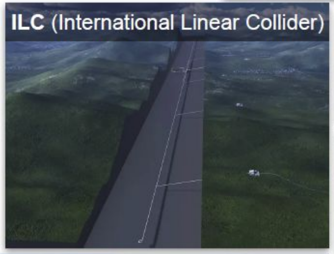
Beyond the LHC era - The XXI century collider

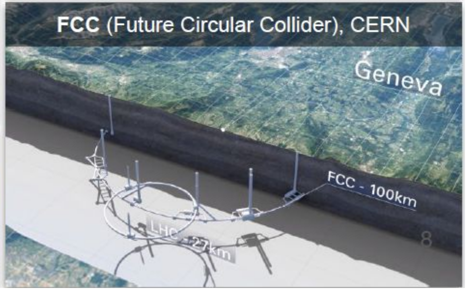
A major **civil engineering** challenge!

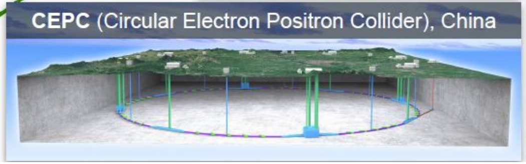




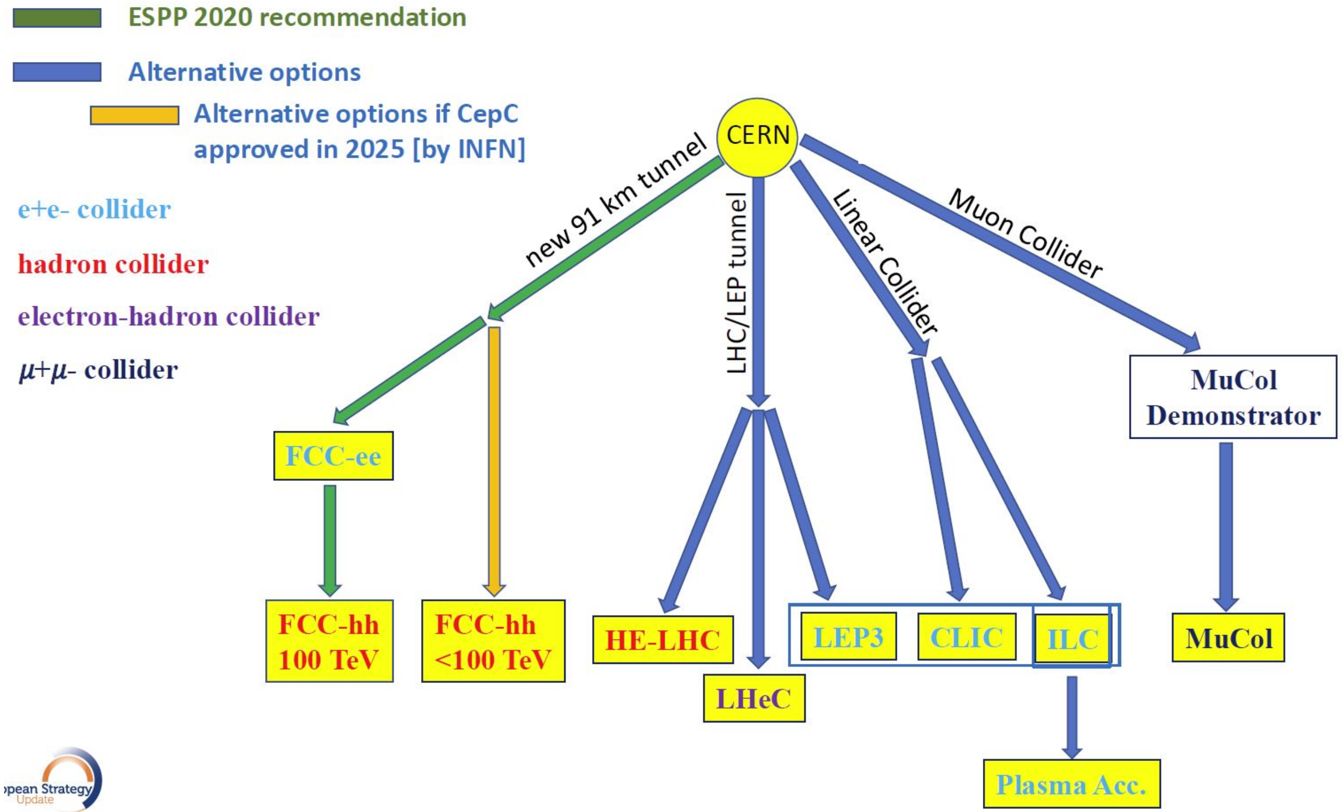








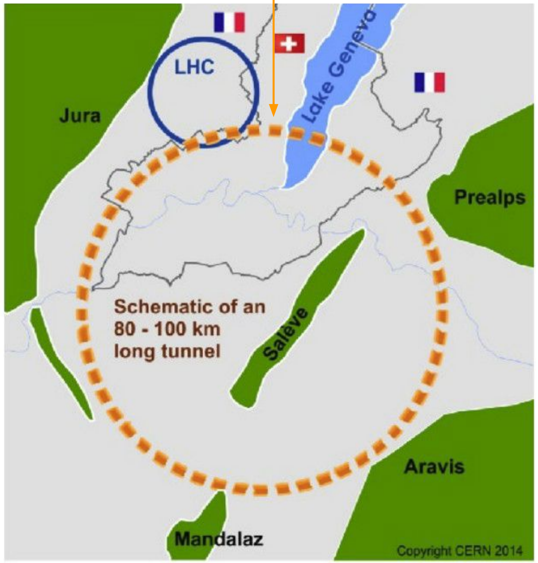
Future colliders: CERN preferred options



The FCC integrated program

The 2020 European Strategy concluded that an **e+e− Higgs factory is the highest priority next collider**.

➔ In 2021 CERN has launched the international **Future Circular Collider (FCC)** feasibility Study



FCC is a comprehensive long-term programme maximising physics opportunities:

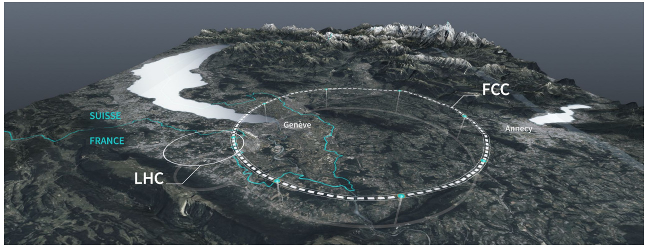
- **stage 1 (FCC-ee): an Higgs factory, electroweak and top factory at highest luminosities**
- **stage 2 (FCC-hh):** as natural continuation at energy frontier (~100 TeV)

intensity frontier

energy frontier

Both sharing same technical infrastructures

Stage 1: FCC-ee



A **91 km circumference** e+e- collider

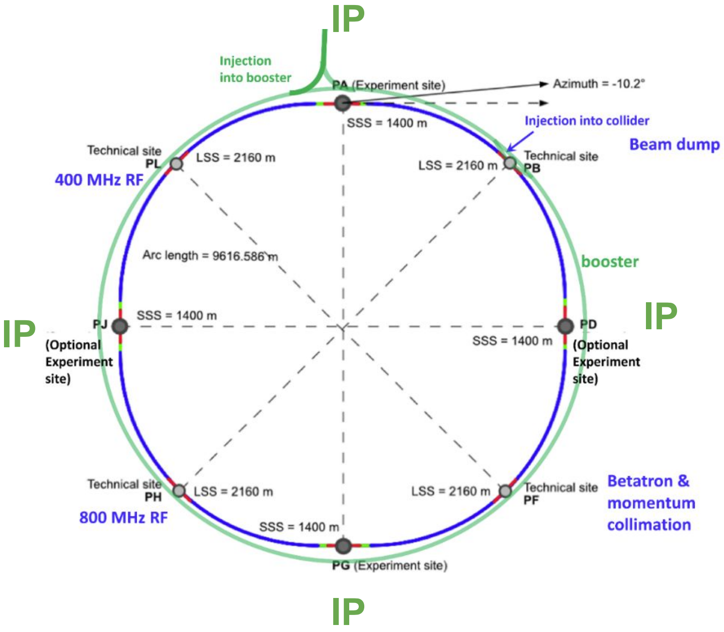
Up to **4 interaction points**:

- possibility of specialised detectors to maximise physics reach

Planned to operate at **4 center of mass energies:**

- **Z** pole (91 GeV)
- **WW** threshold (161 GeV)
- **ZH** production peak (240 GeV)
- **tt** threshold (365 GeV)

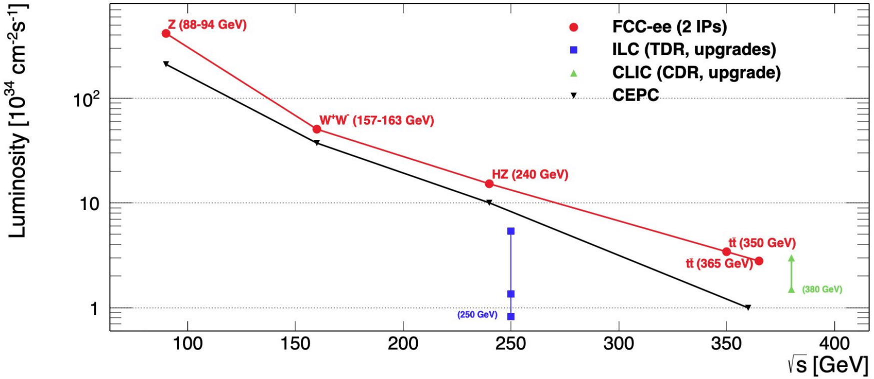
Design and parameters to **maximise luminosity** at all working points (e.g. > 10^{36} $cm^{-2}s^{-1}$ at the Z pole)



Energy range and Luminosity

Diverse programme with different priorities every few years

- produce all the heaviest particles of the Standard Model: **Z, W, H and top**

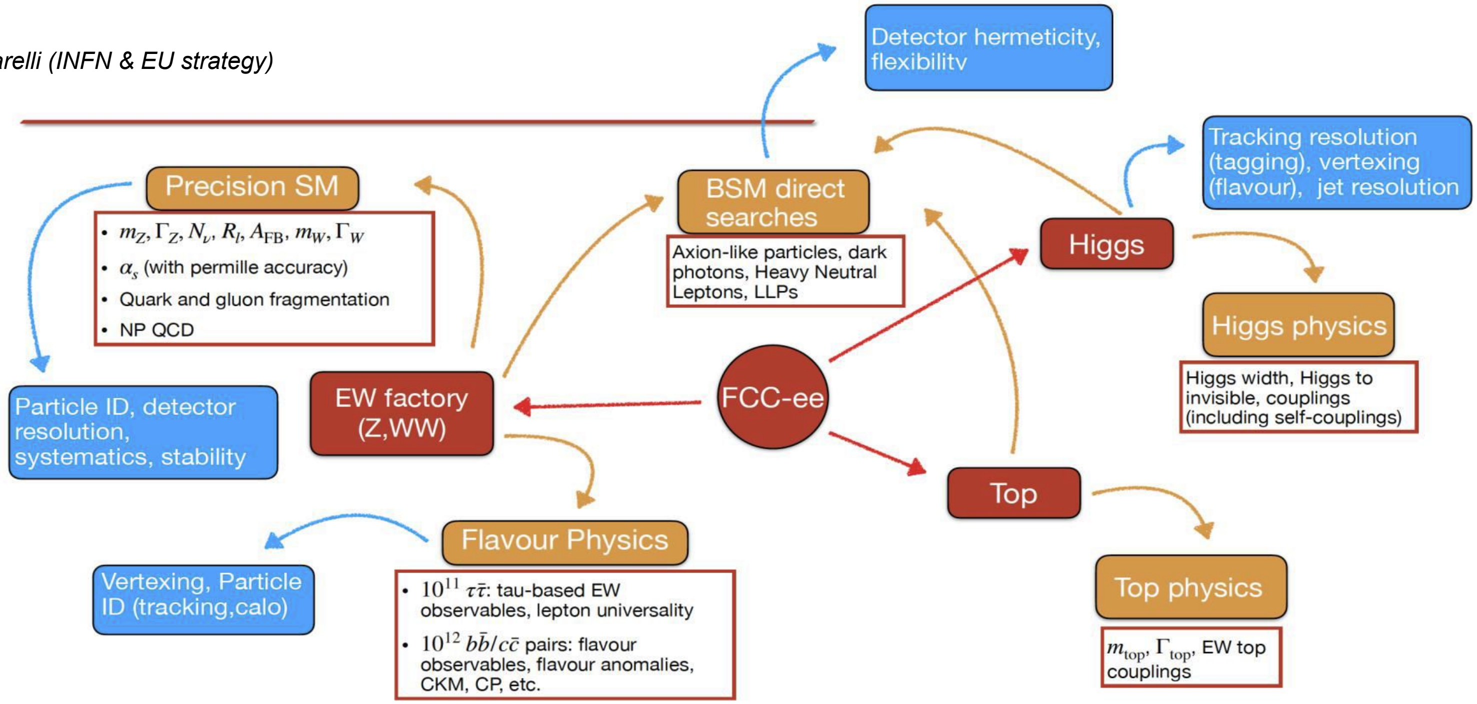


Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays	LEP x 10^5
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$
FCC-ee-H	3	240	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done

A rich physics program

Benchmark physics channels: https://arxiv.org/abs/2401.07564

I. Vivarelli (INFN & EU strategy)



A rich physics program

Benchmark physics channels:
https://arxiv.org/abs/2401.07564

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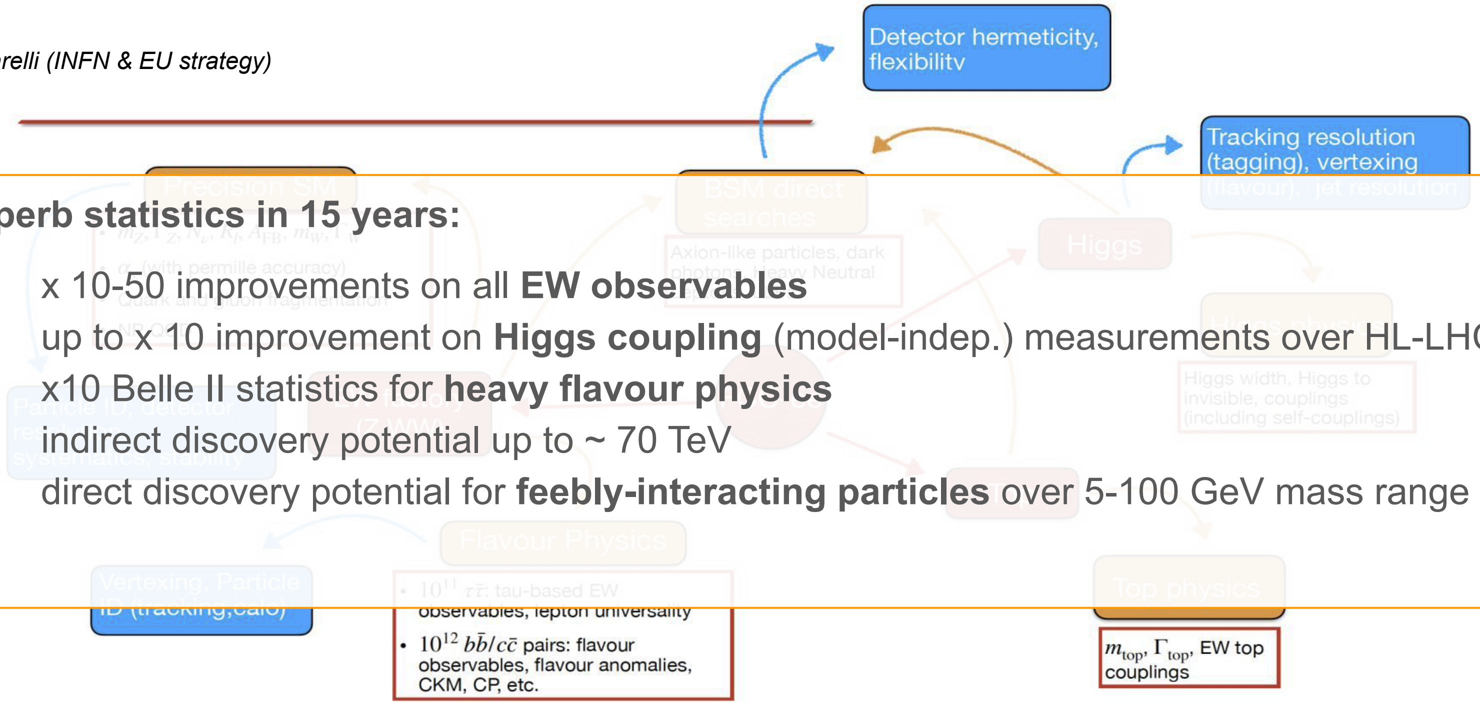


➔ **Superb statistics in 15 years:**

- x 10-50 improvements on all **EW observables**
- up to x 10 improvement on **Higgs coupling** (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for **heavy flavour physics**
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for **feebly-interacting particles** over 5-100 GeV mass range

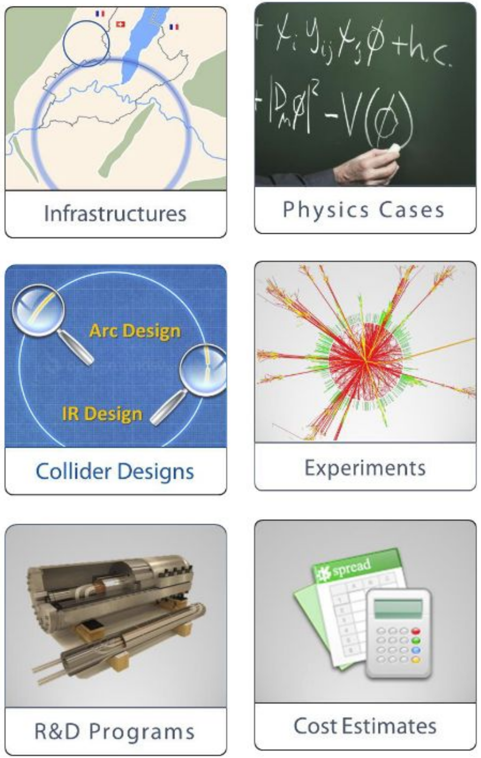
FCC: where are we now?

Ongoing processes in the HEP community to identify the detector requirements and their feasibilities for future collider experiments

Within 2025, completion of the FCC feasibility study document for the next European Strategy Update

- 1: Physics and Experiments
- 2: The integrated project
- 3: Implementation

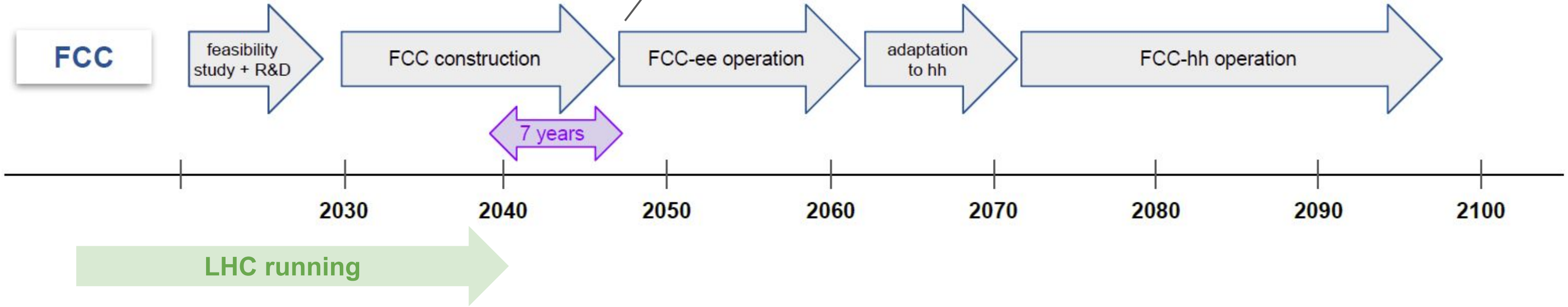
> Italy (INFN) very active on each aspect from the beginning



Proposed timeline

- 2027-2028, possible FCC project approval, start of civil engineering design contract
- 2031-32, possible start of civil engineering construction
- 2045 start of first collisions

FCC start expected a few years of the end of HL-LHC



Detector concepts and physics case drivers

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.

FCC-ee

Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

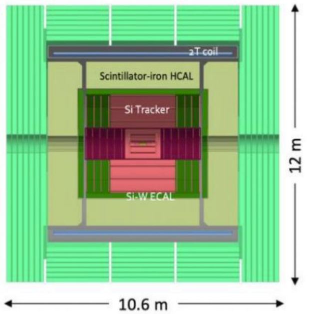
Several solutions with different pros and cons (next slide)

Baseline detector concepts for FCC

Three general purpose detector concepts proposed for FCC with different **technologies**

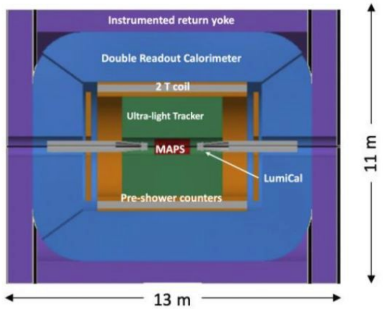
CDR

CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

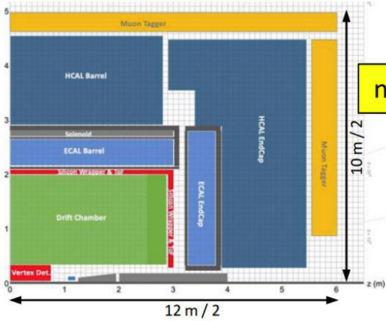
IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

new



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

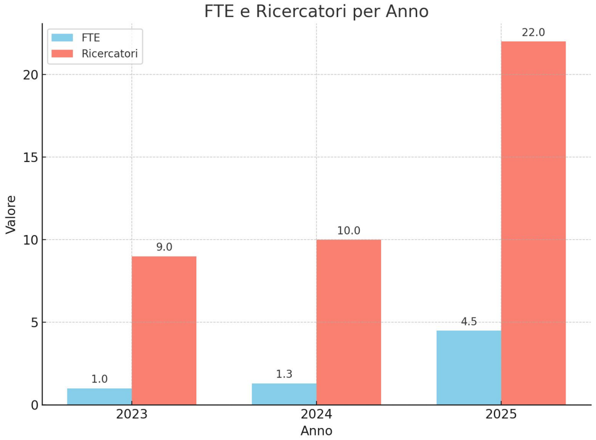
FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

Napoli group

Napoli joined RD_FCC in 2022

Large involvement from gr1, with an increasing trend.

- 2023: 1 FTE, 9 researches
- 2024: 1.3 FTE, 10 researches
- 2025: 4.5 FTE, 22 researches



Anagrafica in 2025

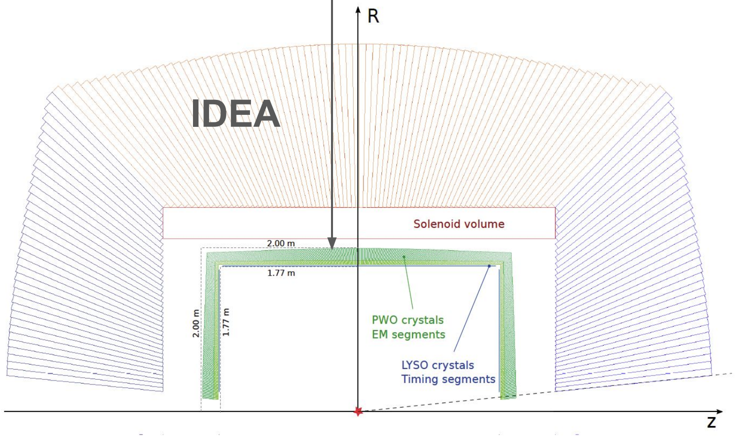
Name	Colonna1	Colonna2	FTE
Alviggi	Maria Grazia	PO	20%
Argiento	Benedetta	Borsista	50%
Boccanfuso	Daniele	PhD	100%
Borriello	Lucrezia	Borsista	100%
Campajola	Marcello	RTD	10%
Cirotto	Francesco	RTD	10%
Conventi	Francesco Alessandro	PA	10%
D'Avanzo	Antonio	PhD	10%
De Asmundis	Riccardo	PR	10%
De Nardo	Guglielmo	PO	10%
Della Pietra	Massimo	PA	25%
Di Donato	Camilla	PA	5%
Di Fraia	Carlo	PhD	10%
Favilla	Leonardo	PhD	10%
Francesconi	Marco	R	10%
Iengo	Paolo		10%
Iorio	Alberto Orso Maria	PA	10%
Izzo	Vincenzo		*
Paolucci	Pierluigi	DR	30%
Rossi	Biagio	R	10%
Rossi	Elvira	PA	10%
Sekhniaidze	Givi		5%

Resp. Locale (Paolucci)

Napoli group interests

CALORIMETRY

dual readout ECAL R&D



MUON detector

R&D on Resistive High granUlarity Micromegas

Key benchmarks for calorimetry

Jet energy resolution is a key benchmark of e+e- detector performance

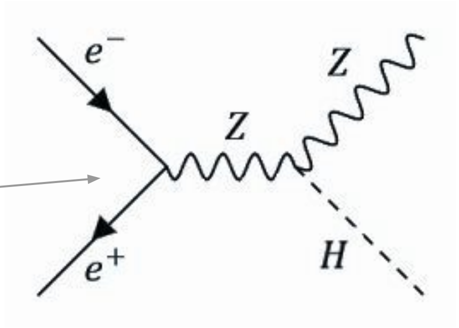
- Higgs production at **e+e- colliders** (@√s~250 GeV) is mainly through **higgsstrahlung**
  - **97%** of the SM higgsstrahlung signal has **jets in the final state**
- Need a calorimeter with **~30%/√E** (~3-4% @90 GeV) to distinguish jets from W or Z bosons

⇩

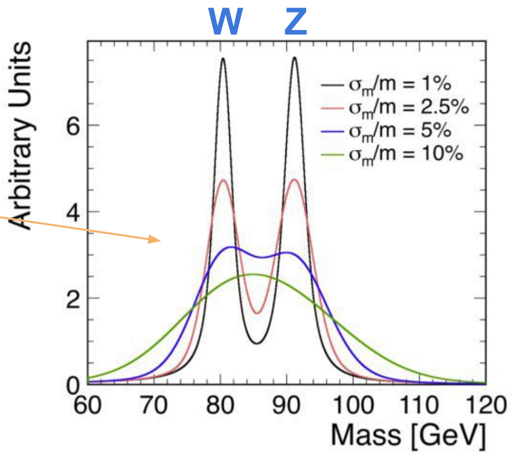
Hard to achieve with traditional calorimetry!

- Typical HCAL resolution >~50%/√E (e.g. ATLAS)

ℓℓ, νν, qq



ℓℓ, γγ, γZ, WW, ZZ



Key benchmarks for calorimetry

EM energy resolution equally important!

A **3%/√E EM energy resolution** has the potential to improve event reconstruction and expand the landscape of possible physics studies. E.g.

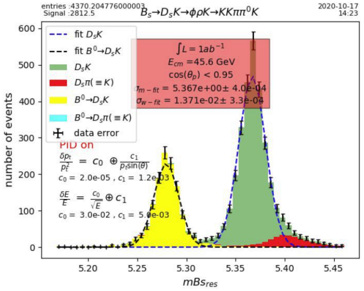
- Precision reconstruction of final states with **low energy photons (and π^0)**
  - reconstruction of exclusive b and tau decays
  - improve performance of jet clustering algorithms
- Reduce effect of **bremsstrahlung on electron resolution**

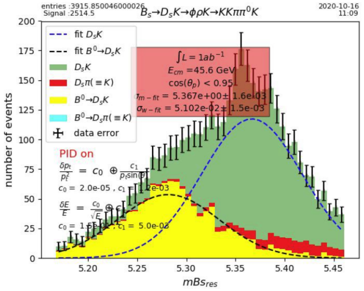
State of the art EM energy resolutions from homogeneous crystals: 1-2 %/√E

3%/√E

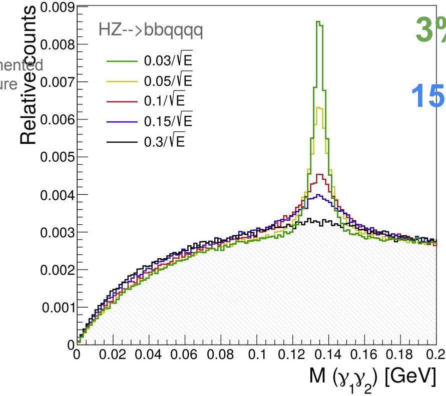
[R.Aleksan et al., Study of CP violation in B± decays to D0(D0)K± at FCCee, arXiv:2107.05311]

15%/√E





[M.Lucchini et al., New perspectives on segmented crystal calorimeters for future colliders, 2020 JINST 15 P11005]



3%/√E

15%/√E

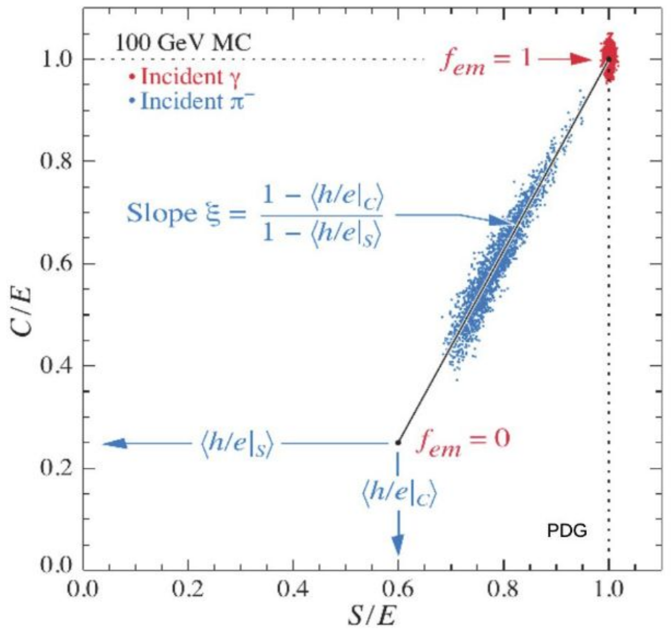
Dual readout strategy in crystals

Homogeneous crystal calorimeters promise excellent electron/γ energy resolution but have poor energy resolution for hadrons

Dual readout (DR) technique

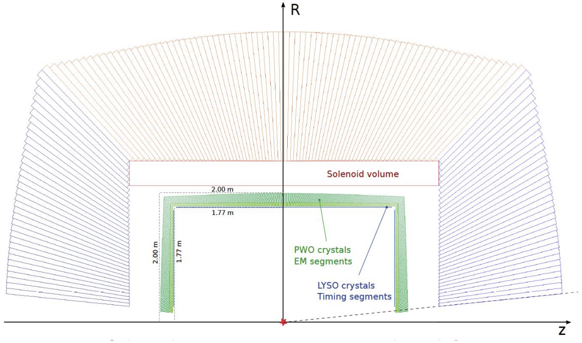
- quantify the electromagnetic fraction of hadronic showers via Cherenkov light
- Event-by-event response correction possible

R&D needed for demonstrating success of a dual readout combined crystals and sampling calorimeter for high resolution in EM and hadron calorimetry



S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002

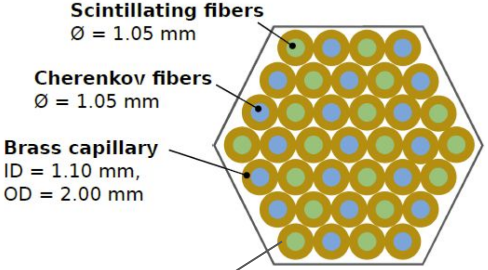
The IDEA detector



A two section hybrid DR calorimeter:

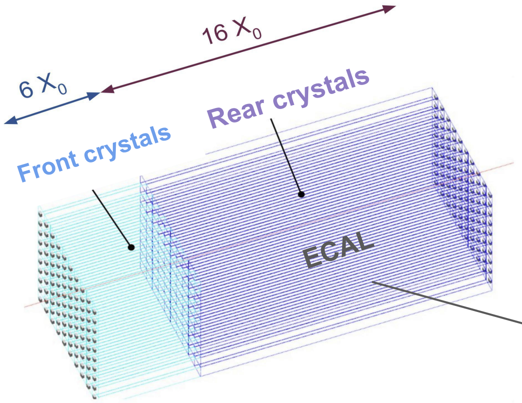
- dual-readout fiber hadronic calorimeter (**HCAL**)
- homogeneous dual-readout crystal EM calorimeter (**ECAL**)

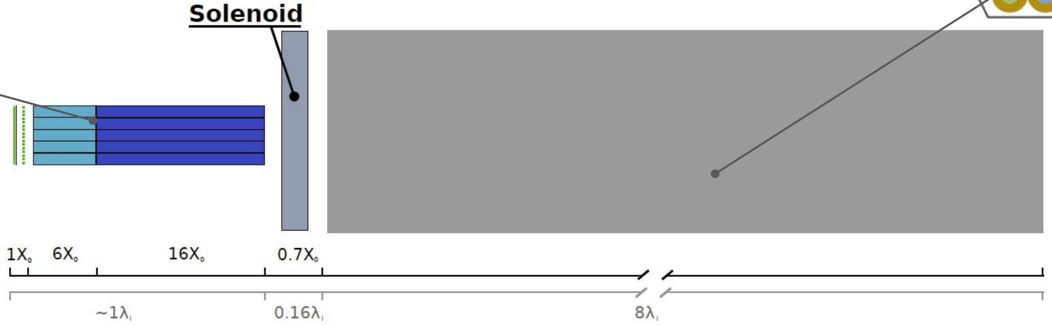
Dual readout HCAL



Targeting resolutions of

- **3%/√E EM**
- **28%/√E jets**



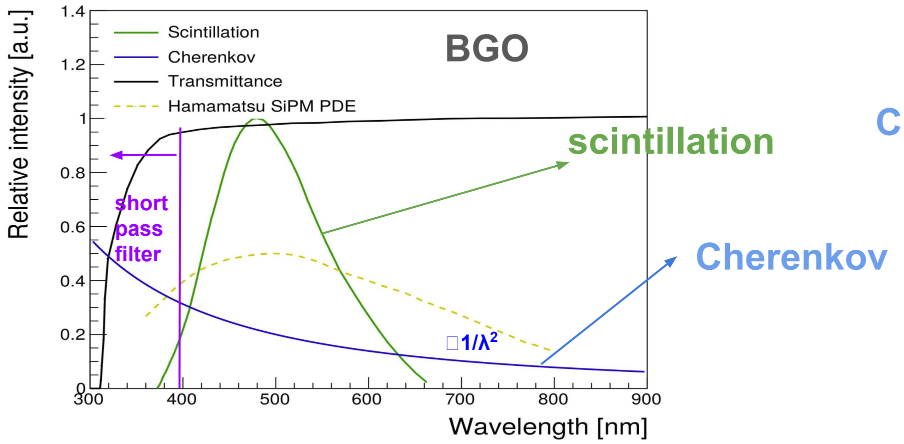


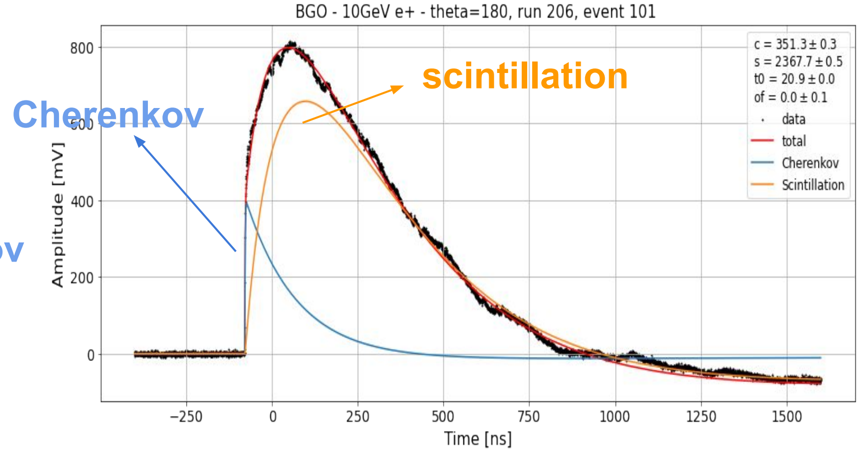
Dual readout strategy in crystals

Dual readout of scintillation and Cherenkov light from the same active element.

➔ **How? Exploit Cherenkov (C) and Scintillation (S) distinctive features:**

- C emission spectrum broader than S (use of filters and dedicated readout channels)
- C emission faster than S (use of pulse shape analysis)





IDEA ECAL

key design features:

- **high density crystals** (short X_0, small RM)
- **Fine** transverse and longitudinal **granularity**
- **SiPM readout** (cost effective)
- **Dual readout capability**

technological choices are active area of research

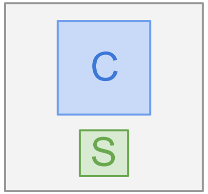
Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

Front crystal ECAL segment:

one SiPMs optimized for S detection

Rear crystal segment face



optical filter + 6x6 mm^2 SiPM with 50 μm cell size (large area and good pde)

3x3 mm^2 SiPM with 10 μm cell size (high dynamic range)

Feasibility of concept strongly depends on:

- Adequate statistics of C photoelectrons (> ~50 phe/GeV)
- Reasonably large S photoelectrons (> ~2000 phe/GeV)
- Sufficient separation of C from S light

IDEA ECAL

History and groups:

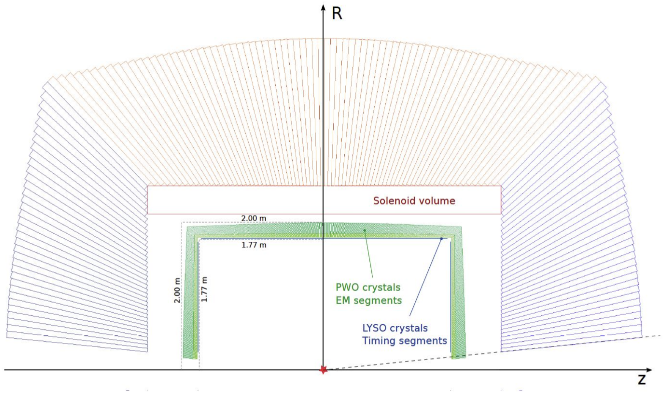
ECAL, initially proposed as an option, recently (2024) **elected in the baseline for the IDEA detector**

- **Activities formally included in the INFN RD_FCC WPs**

➔ **Results of the rump up of interest and R&D activities**

Main actors:

- Calvision (US)
- **INFN** (MIB, **NA**, PG)



Project goals aligned with strategic objectives of the **DRD6 collaboration** WP3 task 3.1.2

ECAL Napoli group

Working on ECAL activities at 360 degrees:

- **R&D on technologies and proof-of-principle of DR**
  - Identification of materials and methods
  - Proof-of-concept with lab measurements and test beams
- **Simulation studies**
- **Construction and testing of prototypes**

Laboratories and setup

Activities in loco exploit two test benches for SiPM characterizations, studies with cosmics and radioactive sources

Shared setup used for many Calorimetry R&D (Belle II, Nanocal AIDA_INNOVA, HetCal PRIN)

ABC (Atlas, Belle, CMS) space - 2H21

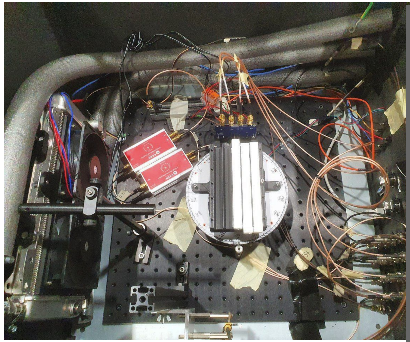
Hangar space

CERN TB

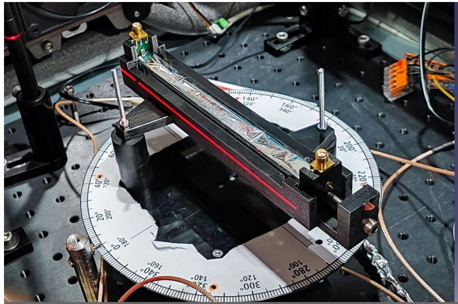
In July 2024 a **Test beam at CERN SPS H6** beam line prepared and **coordinated by MIB and Napoli** and with participation from Perugia, US and CERN

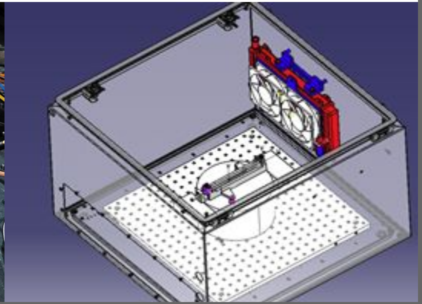
The focus was demonstrating/quantifying Cherenkov photon collection

- **tests with electrons (10-100 GeV), muons**, hadrons



TB crew

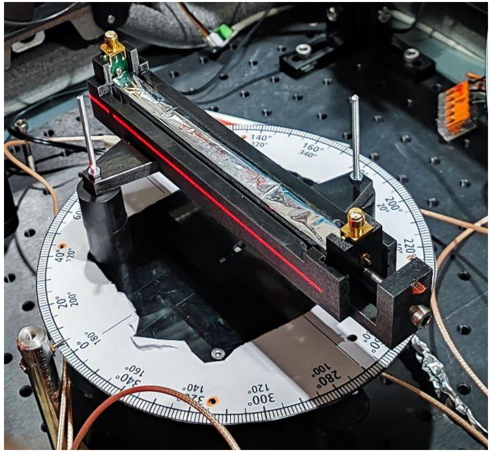




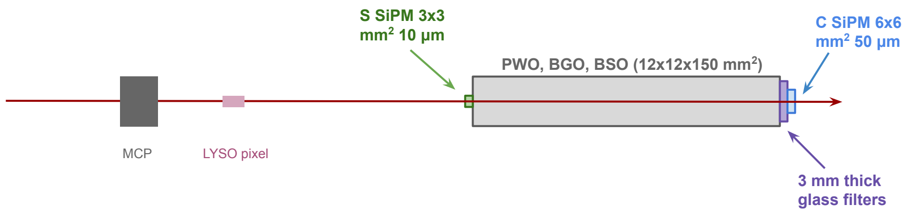
TB setup

CERN TB setup

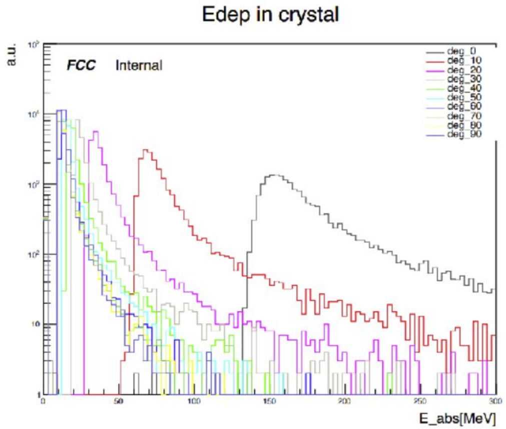
more in Lucrezia's and Antonio's talks



A single crystal setup with front rear readout:



- Tested a variety of filters and crystals (BGO, BSO, PWO)
- High bandwidth preamps and digitization w oscilloscope for pulse shape analysis
- Rotating stage for C/S study as a function of crystal-beam angle
- Dark box with temperature conditioning
- Geant4 simulation of the TB setup



Setup fully developed in Napoli with the help of our precious Services (Progettazione, Officina and SER)

Outcomes

Many bachelor and master theses

- J. Scamardella, Simulazione e analisi dati delle misure di una stazione di test per i calorimetri ai Future Colliders
- P. Amato, Studio delle prestazioni di cristalli calorimetrici a doppia lettura per futuri acceleratori circolari
- L. Borriello, Characterization of a cell prototype for a dual readout calorimeter proposal at the Future Circular Collider FCC-ee
- R. Corsini, Caratterizzazione di fotorivelatori SiPM per il calorimetro elettromagnetico al Future Circular Collider FCC
- B. Mantice, Simulazione e analisi dati di un prototipo di cella per un calorimetro di nuova generazione per il rivelatore IDEA al collisionatore FCC
- F. A. Diana: Studio e caratterizzazione di scintillatori a cristallo
- A. Calligari: Studio di Segnali Čerenkov e di Scintillazione in un Cristallo di BGO

Workshop and conferences:

- L. Borriello ‘Rivelatore IDEA concepito per futuri acceleratori’, IFAE 2024
- M. Campajola, ‘Highlight from CERN test beam’, Italy-France FCC workshop 2024
- Oral contribution accepted at VCI 2025

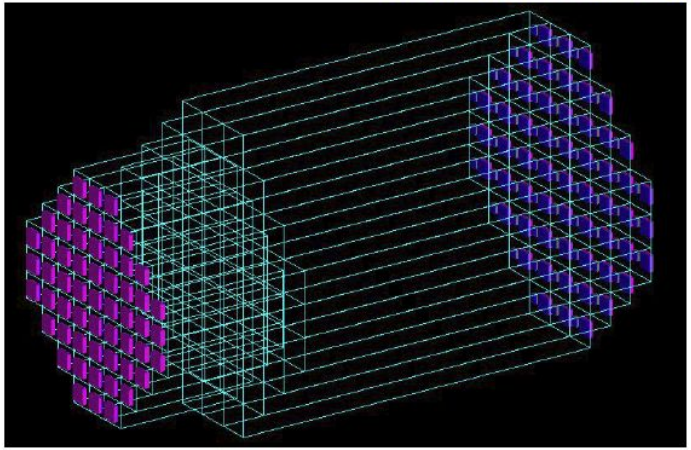
Towards a multi-channel prototype

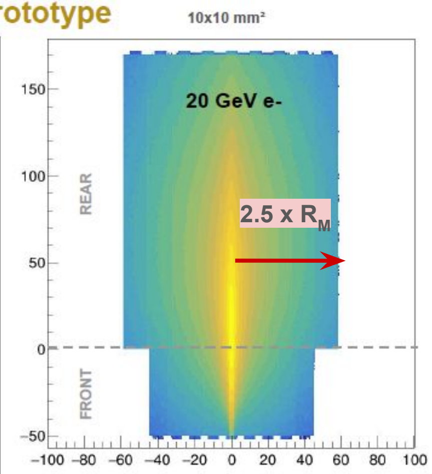
What's next?

Beam test results will inform the choice of a **baseline technologies**

Than, build a full containment EM calorimeter prototype (9x9)

Geant4 simulation of prototype





single sensor test with various flavors of crystal, filters and SiPMs

full containment EM calorimetric module prototype (9x9 matrix) using most promising technologies

combined test beam with fibre calorimeter prototype

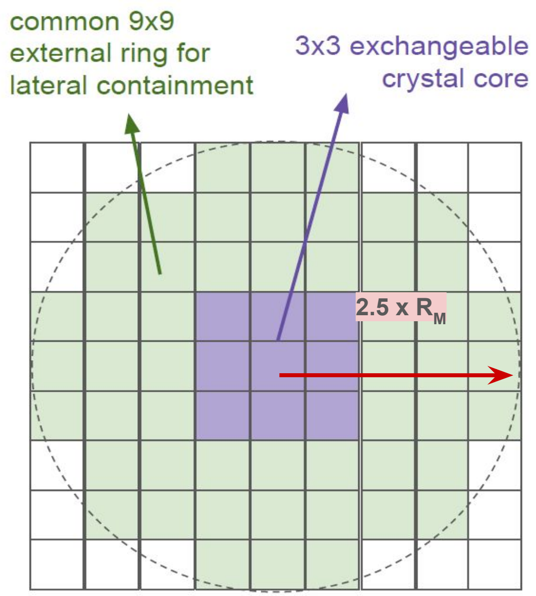
2024 — 2025 — 2026

Towards a multi-channel prototype

Napoli fully committed on a 9x9 matrix realization:

- Mechanical structure prototyping, DAQ and realization of a complementary technology (BGO or BSO) core module

- **Prototype assembling and testing expected from 2025 on, in the Hangar space**



Plan for a **test of the prototype on beam at CERN in the second half of 2025**

- 2-week test beam slot requested at SPS (H6) for late September 2025
    - deliverables: linearity, containment and EM energy resolution

Resistive High granUlarity Micromegas (RHUM)

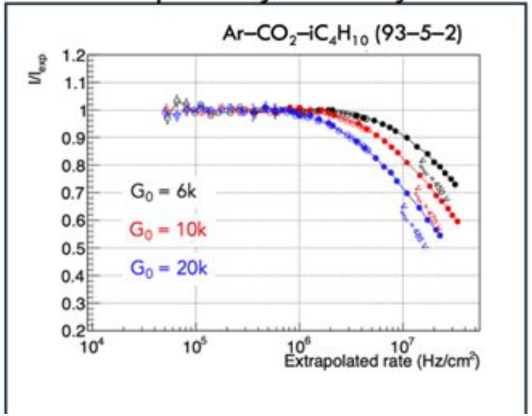
For about 10 years, the Napoli group, in collaboration with Roma3, has developed **resistive MicroMegas with pad readout**.

- performances achieved: ~100% efficiency, ~100 μm spatial resolution, and <10 ns time resolution, even at fluxes up to 10 MHz/cm².

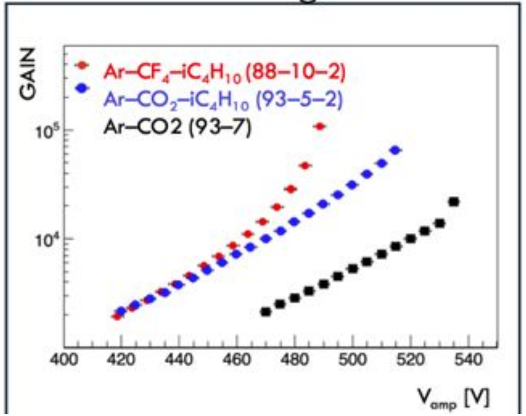
The latest R&D project, RHUM (CSN V), concluded in 2024 with excellent results.

more in Simone's talk

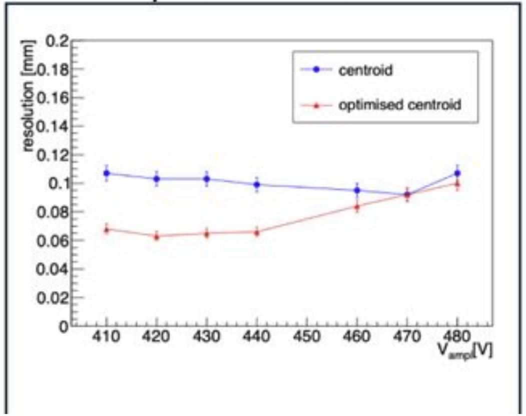
Rate capability vs X-ray flux



Gain for different gas mixtures



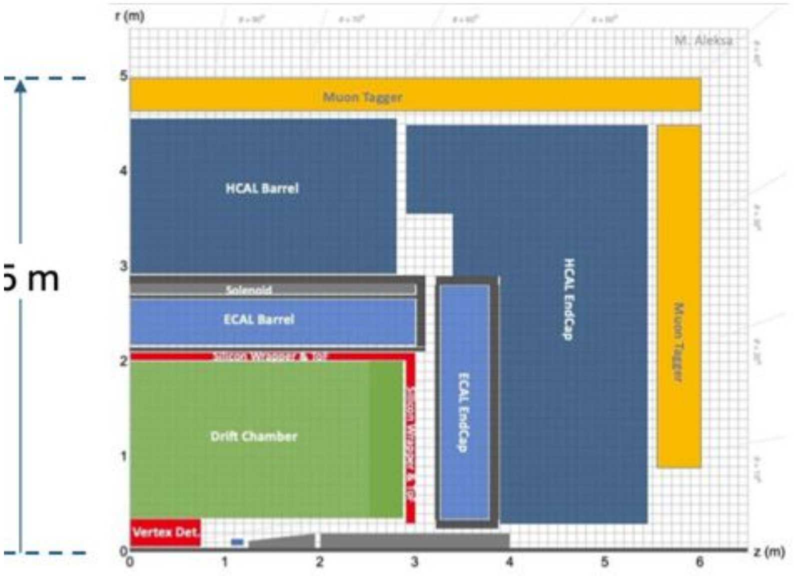
Spatial resolution



MicroMegas and FCC

The new generation of High-Performance Resistive-MicroMegas is fully aligned with the ECFA Roadmap and included in the DRD1 on gas detectors as one of the most promising MPGD technologies.

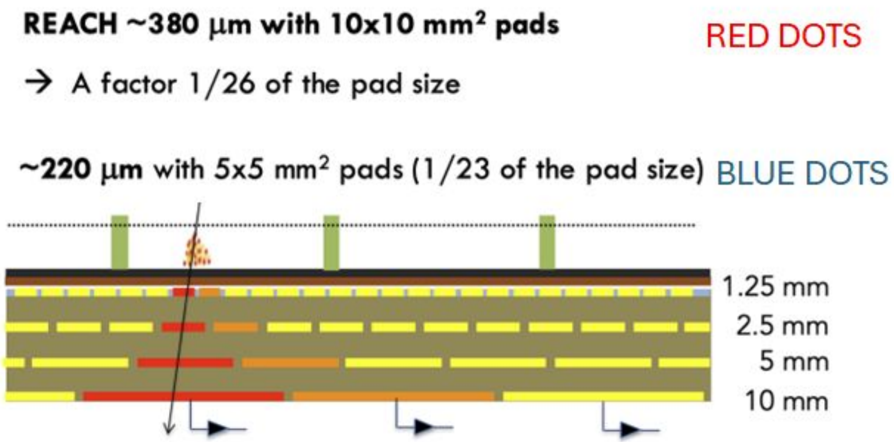
Expression of Interest submitted for **ALLEGRO muon detection and tagging system**

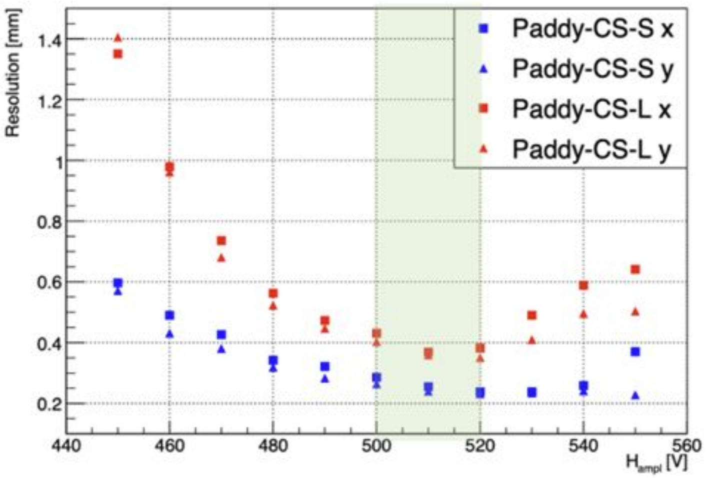


Paddy Micromegas for FCC-ee

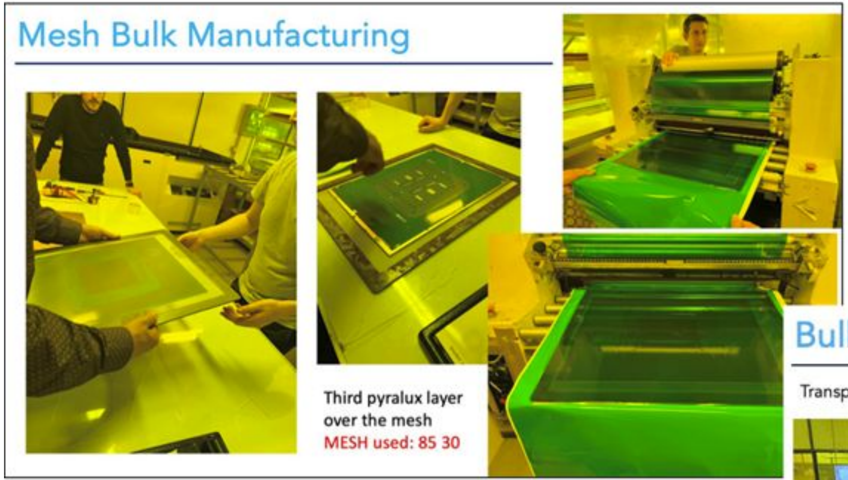
At FCC-ee low muon fluxes expected in the muon spectrometers/taggers: similar to LEP, dramatically lower than in HL-LHC and FCC-hh.

- **a new prototype using "capacitive sharing"** developed: fewer readout channels, still good spatial resolution, and reduced production costs.





MicroMegas production in industry

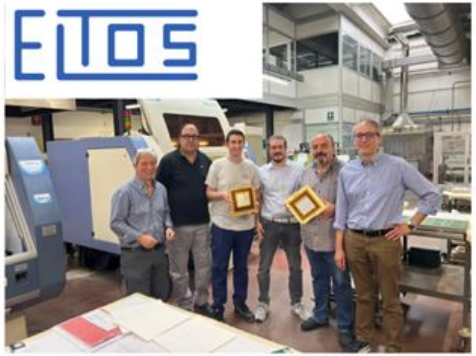


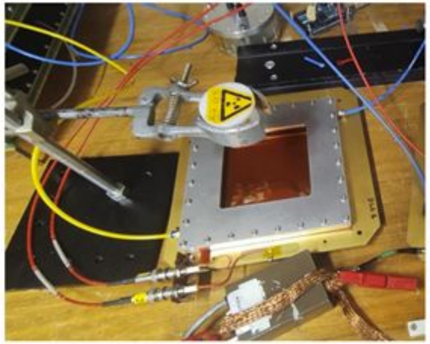
a technology transfer for the production of MM using the bulk technique, previously achievable only at the CERN Workshop, began a couple of years ago with ELTOS, a PCB manufacturer based in Arezzo.

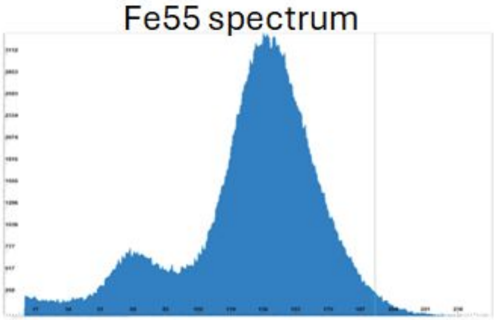
in June 2024, a second series of reduced-size prototypes was produced, and funding was secured in Naples for the production of larger-size prototypes in 2025.

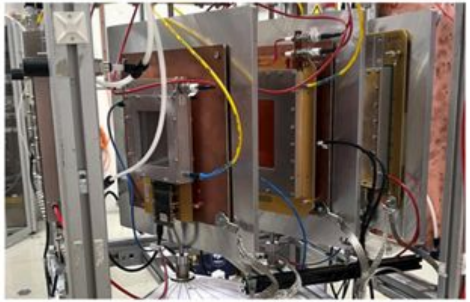
MicroMegas production in industry

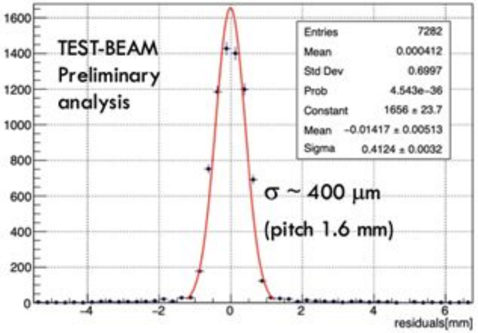
First promising results with X-ray sources and Test Beam

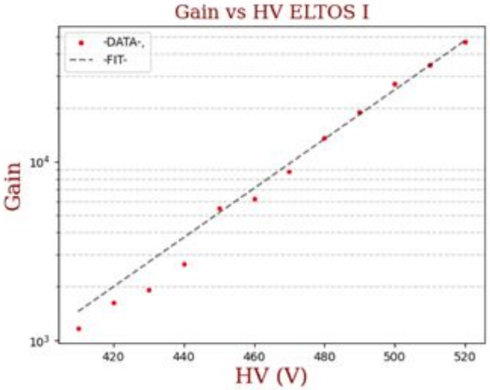












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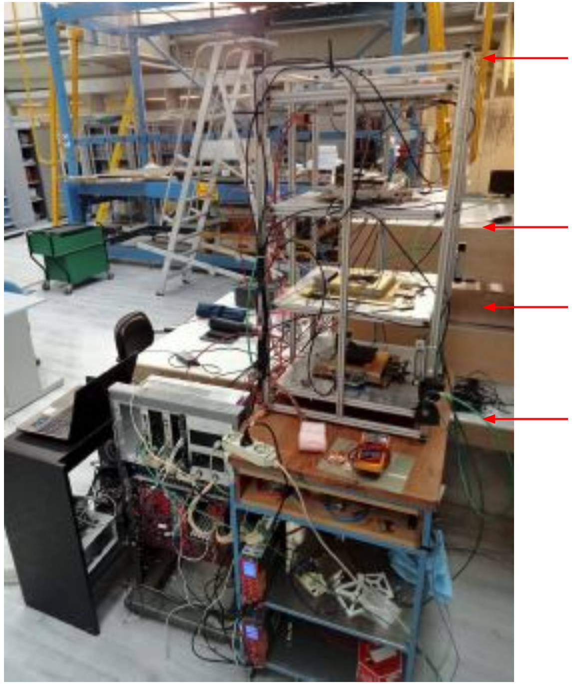
MicroMegas: Napoli test bench

Test bench in the hangar allows for testing one or more MM prototypes by tracking cosmic rays and acquiring Front-end signals with two different chips: APV25 and VMM.

- cosmic ray tracker capable of tracking with a single-plane resolution of approximately 100 μm over an area of a few cm².

Possible synergies for tracking in lab and at beam test for the ECAL group.



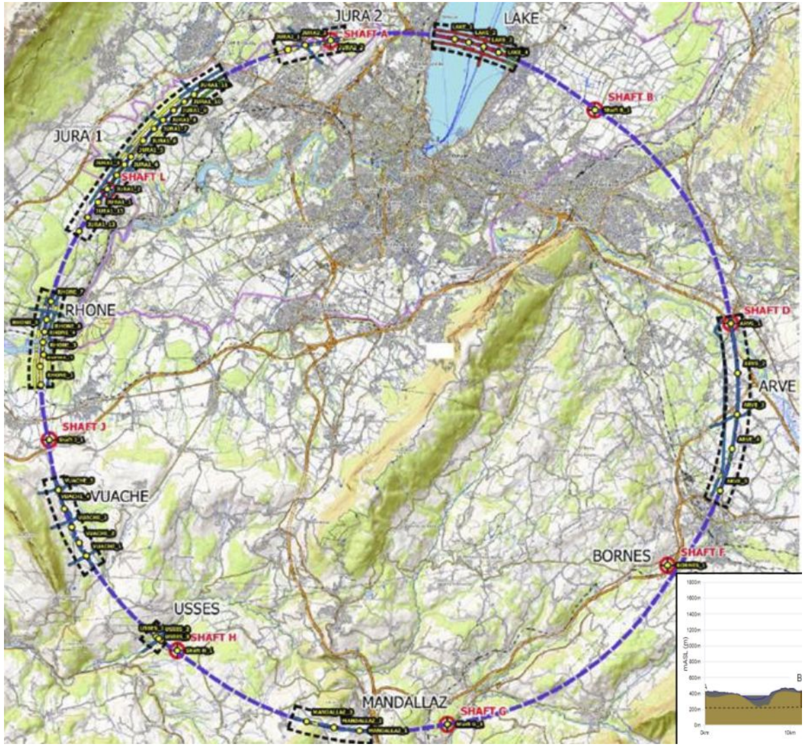
Thank you

Backup

FCC: where are we now?

First series of site investigation to identify exact location of geological interfaces

- total of ~ 30 drillings and ~100 km seismic lines
- 50-70% available for Feasibility Study report
- vertical position and inclination of the tunnel



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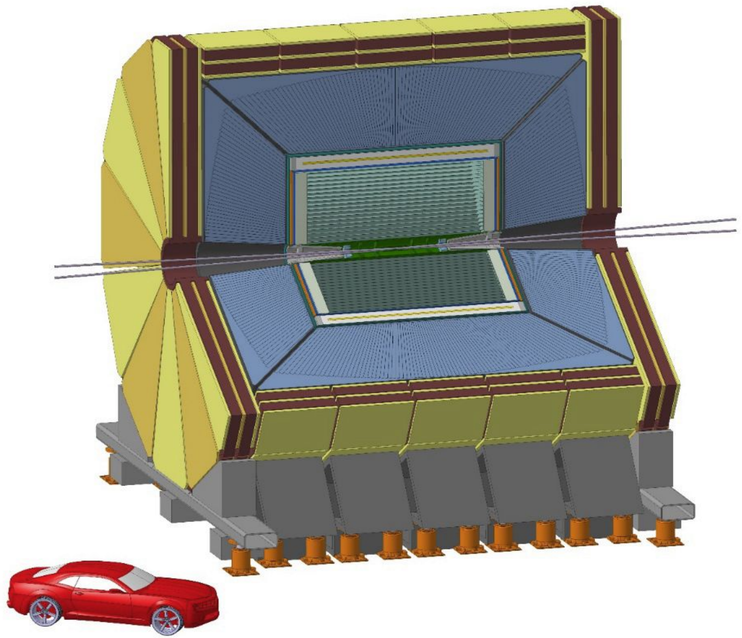
The IDEA detector

INFN very active on the IDEA detector concept and its sub-detectors



New, innovative, possibly more cost effective concept details here

- Silicon vertex detector
- Short-drift, ultra-light wire chamber
- Hybrid dual-readout calorimeter
- Thin and light solenoid coil inside calorimeter system
- Small magnet ⇒ small yoke
- Muon system made of 3 layers of μ-RWELL detectors in the return yoke

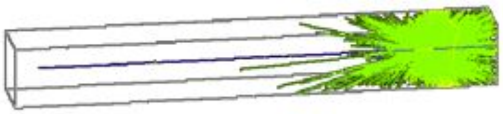
R&D activities

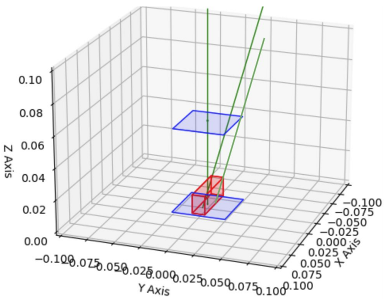
Laboratory benches exploiting radioactive sources, excited photoluminescence and cosmic rays for single calorimetric cell

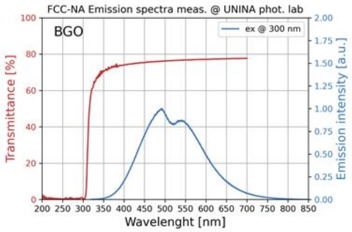
- **investigation** of:
  - Scintillating crystals
  - Absorptive optical filters to isolate the Cherenkov light
  - SiPMs technologies

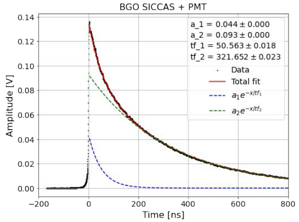
collaboration with our Optics colleagues: A. Sasso, G. Rusciano

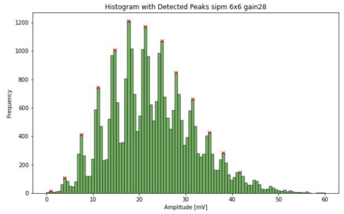
- **simulation** with single crystal geometry
- **prototypes testing**











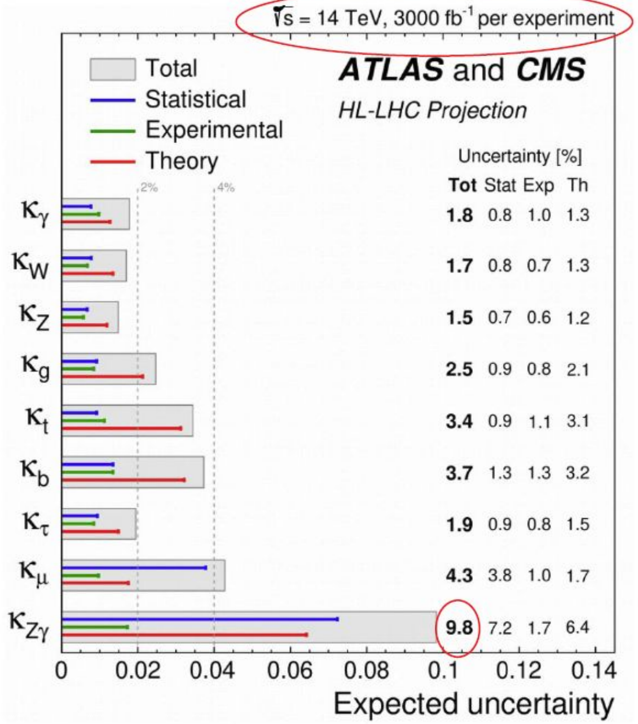
Precision Higgs physics

The physics reach of HL-LHC

- **Estimated precision at the end of HL-LHC**
  - **O(2−4%) precision** on the couplings to W, Z, and 3rd generation fermions
  - **Higgs width** indirectly measurable at **~17%** ($ZZ \rightarrow 4$ lepton channel)
  - Higgs-boson **self-coupling** probed with **O(50%)** precision

- **What will not be achieved**
  - Couplings to u, d, s, c quarks still not accessible at the LHC directly

170 million Higgs bosons
120 thousand Higgs-boson pairs



CERN Yellow Report on the Physics at the HL-LHC:
https://cds.cern.ch/record/2703572?ln=en

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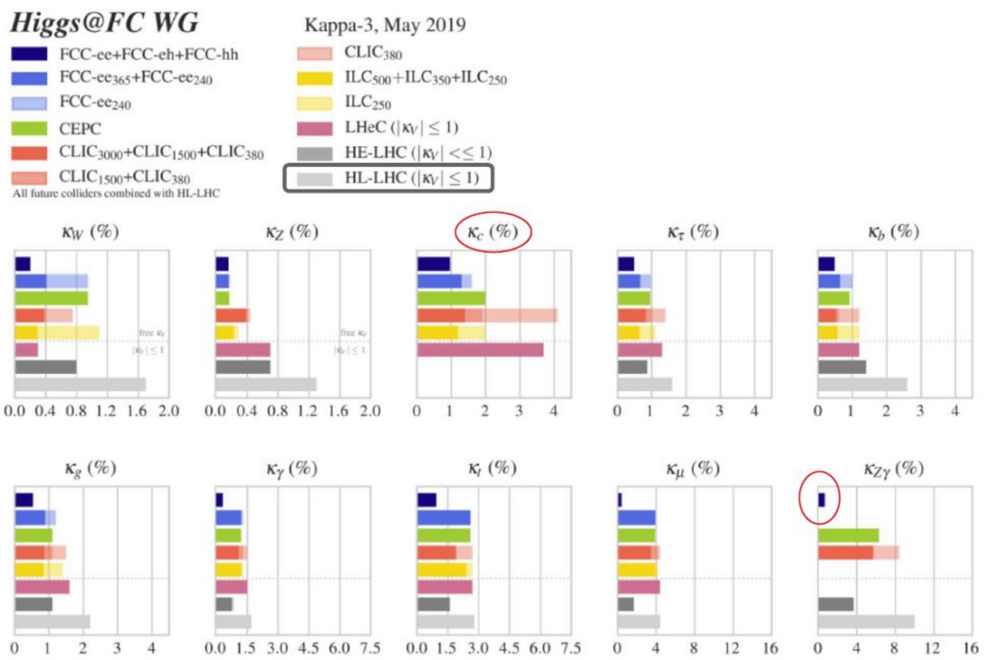
Precision Higgs physics



- **An e^+e^- Higgs factory can measure these couplings with smaller uncertainties** than HL-LHC due to:
  - Better knowledge of the momentum of the incoming particles
  - Smaller background environments
  - Better detector resolutions

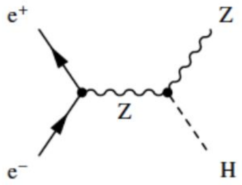
- Model-independent measurements of the **Higgs boson width to the 1% level** (invariant mass of $Z \to e^+e^-$ recoil in Higgsstralhung)

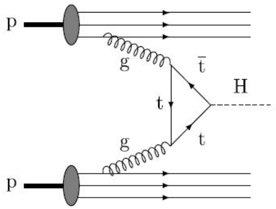
- **Higgs self-coupling below 10%**

Stage 1: FCC-ee

FCC

e^+e^- VS pp COLLISIONS - THE BASIC





e^+e^- collisions	p-p collisions
e^+/e^- are point-like → Initial state well defined (E, $\mathbf{p}$), polarisation → High-precision measurements	**Proton is compound object** → Initial state not known event-by-event → Limits achievable precision
Clean experimental environment → Trigger-less readout → Low radiation levels	**High rates of QCD backgrounds** → Complex triggering schemes → High levels of radiation
Superior sensitivity for **electro-weak states**	High cross-sections for **colored-states**
- At lower energies (≲ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.** - Higher energy (>1TeV) e^+e^- requires **linear** collider.	High-energy **circular** pp colliders feasible

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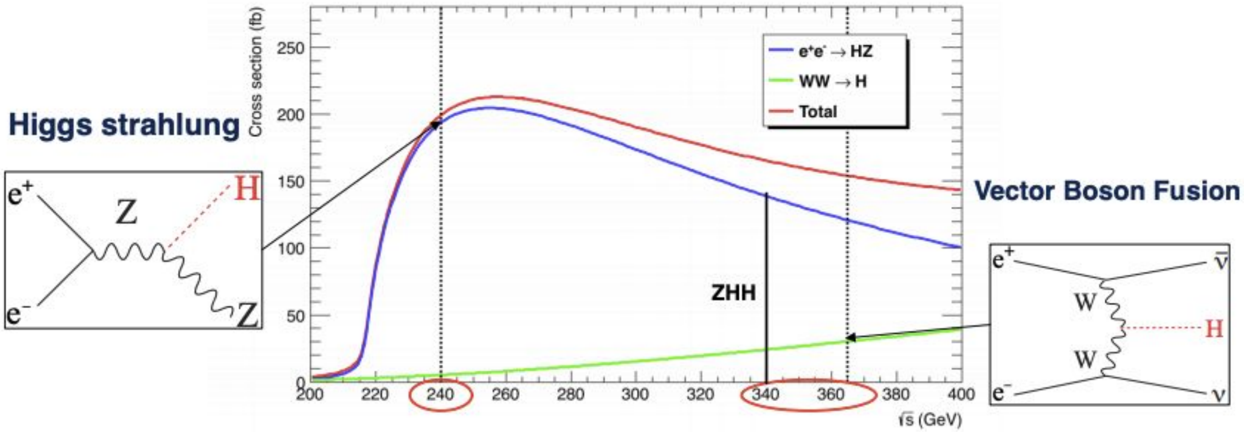
Precision Higgs physics

Higgs boson production through Higgs strahlung and VBF

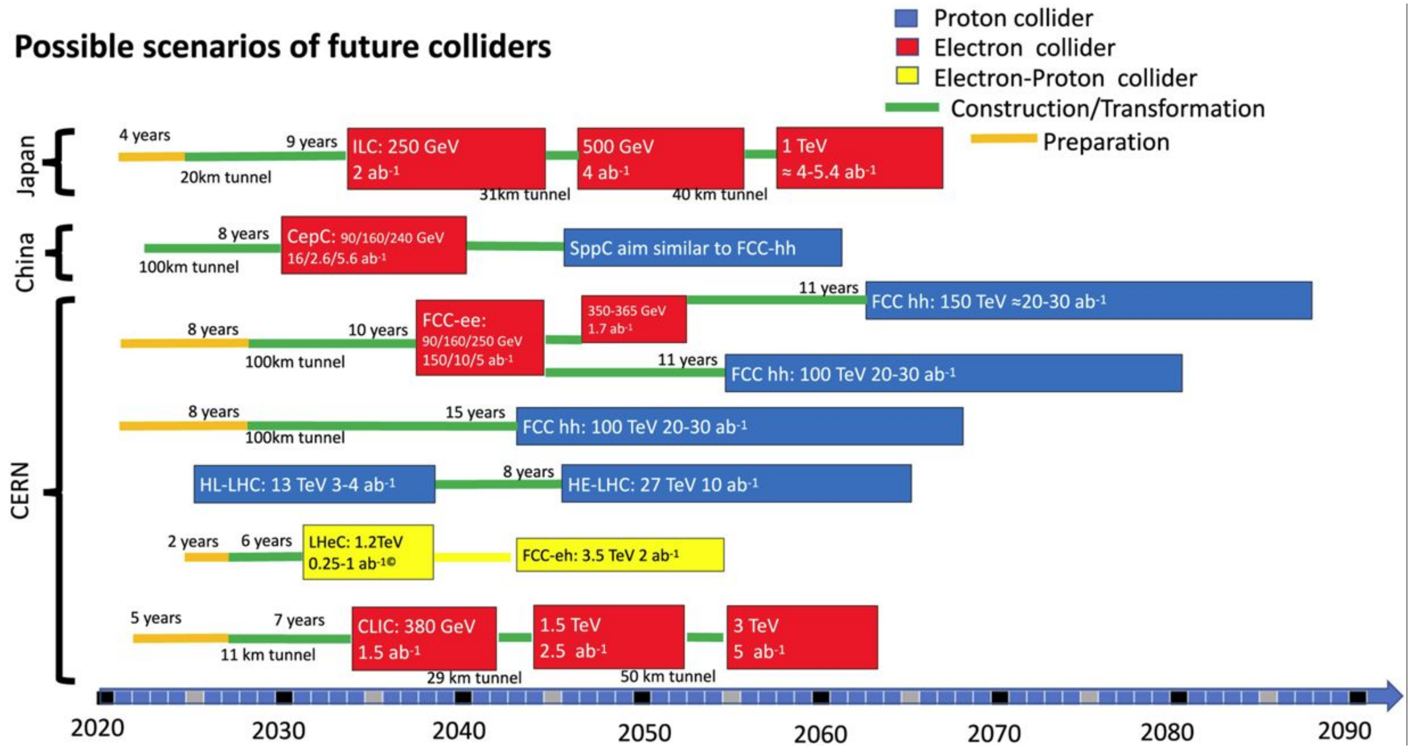


- maximum ZH cross section value at √s = 255 GeV
- luminosity drops with √s at constant ISR dissipation power

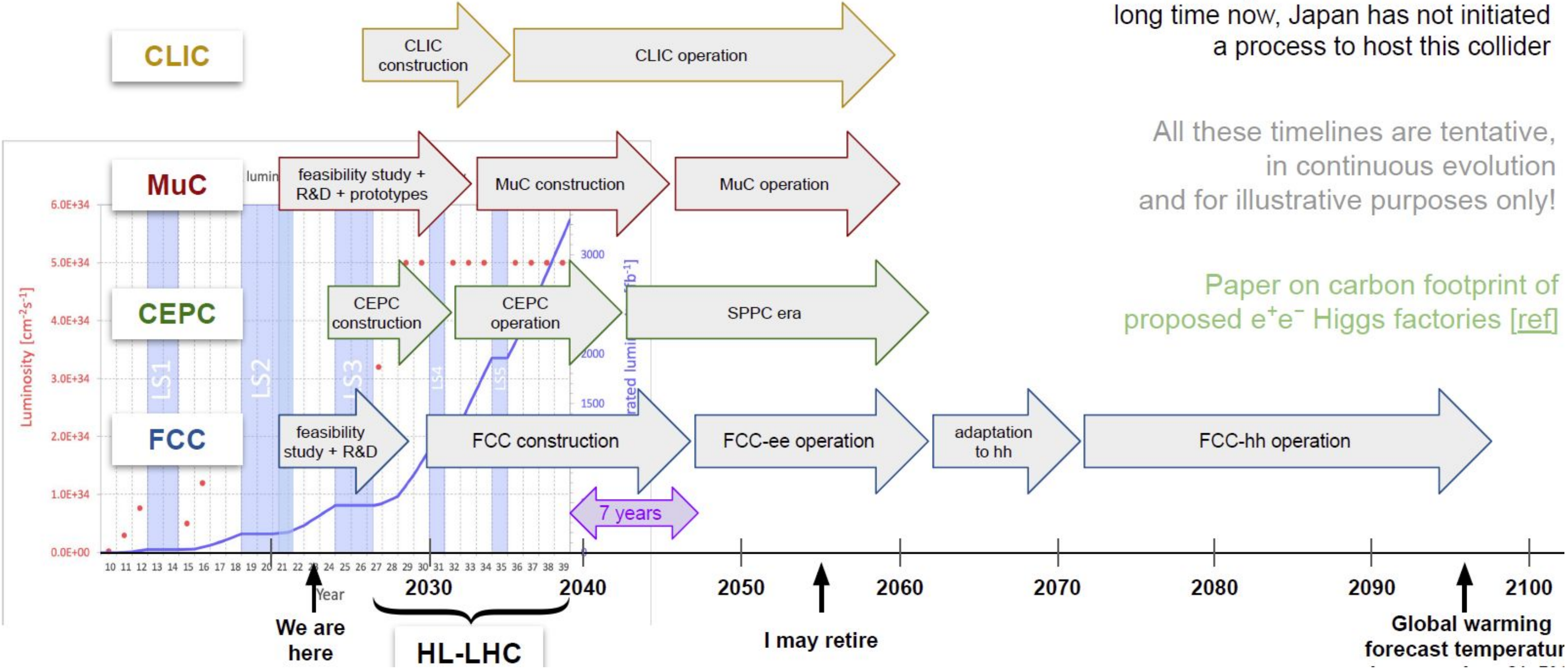
maximum event production at √s = 240 GeV

- higher energy points available for other physics targets (top physics), but they can be used to improve Higgs measurements (in particular Γ_H and Higgs self-coupling)

Proposed future collider timelines



Proposed future collider timelines



long time now, Japan has not initiated a process to host this collider

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

Paper on carbon footprint of proposed e^+e^- Higgs factories [ref]

The detector challenge

The physics case drivers

	Critical detector	Requirement	Comments
$ZH \to \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2 \cdot 10^{-5}$	But also precision EW, flavour, BSM
$H \to b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu\text{m}]$	Additional case study: $B \to K^*\tau\tau$
$H \to gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{jet})}{E_{jet}} \sim 4\,\%$ (at $E_{jet} \sim 50$ GeV)	Also BSM and missing energy reconstruction
$H \to \gamma\gamma$	ECAL	$\frac{\sigma(E_\gamma)}{E_\gamma} \sim \frac{10-15\,\%}{\sqrt{E_\gamma}}$	But flavour physics may need better EM energy resolution

one problem –several solutions with different pros and cons

Benchmark physics channels:
https://arxiv.org/abs/2401.07564

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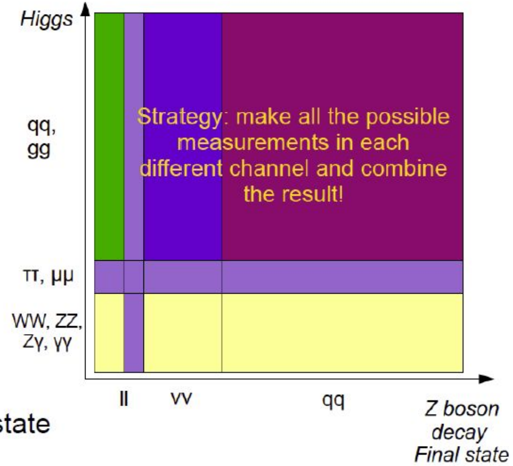
Precision Higgs physics

- SM Higgs

Slide borrowed from Manqi Ruan (LCWS 2019, Sendai, Japan)

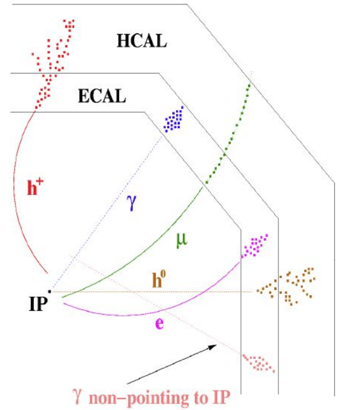
  - *0 jets: 3%:* *Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)*
  - *2 jets: 32%*
    - *Z→qq, H→0 jets. 70%*10% = 7%*
    - *Z→ll, νν; H→2 jets. 30%*70% = 21%*
    - *Z→ll, νν; H→WW/ZZ→semi-leptonic. 3.6%*
  - *4 jets: 55%*
    - *Z→qq, H→2 jets. 70%*70% = 49%*
    - *Z→ll, νν; H→WW/ZZ→4 jets. 30%*15% = 4.5%*
  - *6 jets: 11%*
    - *Z→qq, H→WW/ZZ→4 jets. 70%*15% = 11%*

2/3 (4 jets + 6 jets)



- **97%** of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: include all the SM Higgs decay modes
- **2/3** need color-singlet identification: grouping the hadronic final state particles into color-singlets
- Jet is important for EW measurements & jet clustering is essential for **differential** measurements

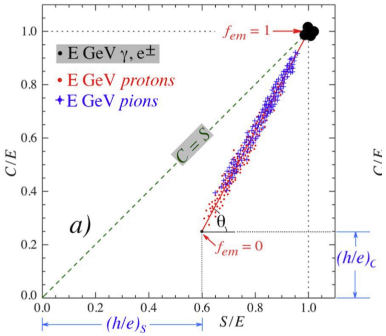
Challenges of hadronic calorimetry



Two general approaches to cure it

- **Particle-flow**: use track info to measure charged jet fragments and calorimeter data mainly for the measurement of neutral particles. Requires fine (transverse) granularity to separate showers

- **Dual-readout:** use proxy for invisible E component of hadron showers. Effectively use an evt-by-evt proxy for EM fraction of hadronic showers. More moderate requirements on granularity.

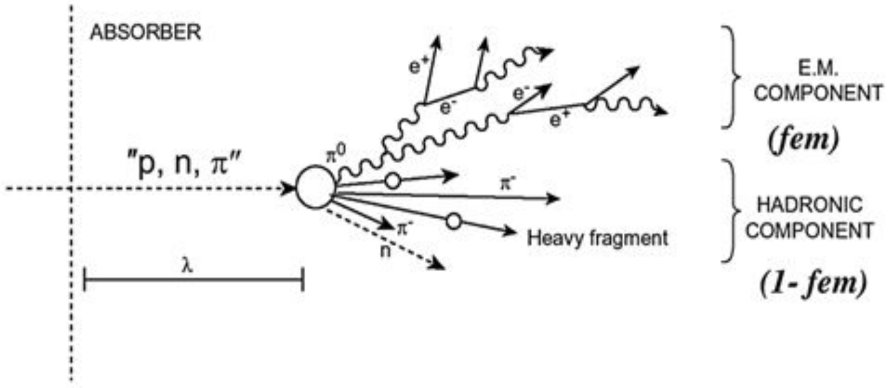


Complementary and also compatible with each other

Challenges of hadronic calorimetry

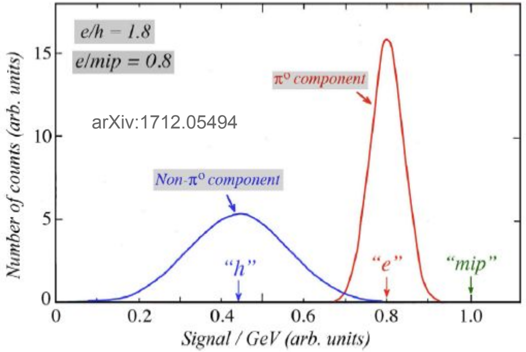
Hadronic calorimetry is hard!

- hadronic showers include a **pure EM component with large E dependence and fluctuations**
- purely hadronic component can result in significant amount of **invisible energy** (binding energy, neutrons, neutrinos, ...)



➔ **different response (e/h>1) and fem fluctuations degrade resolution**

- **Strategies to mitigate this effect by design need to be adopted**



Dual-readout calorimetry

Dual readout technique: by reading two calorimetric signals with different h/e, the **fem can be measured event by event** and the compensation can be achieved off-line.

Need to measure simultaneously:

- **Scintillation S** signals: sensitive to all charged particles
- **Cherenkov C** signals: sensitive to relativistic charged particles (electrons mainly)

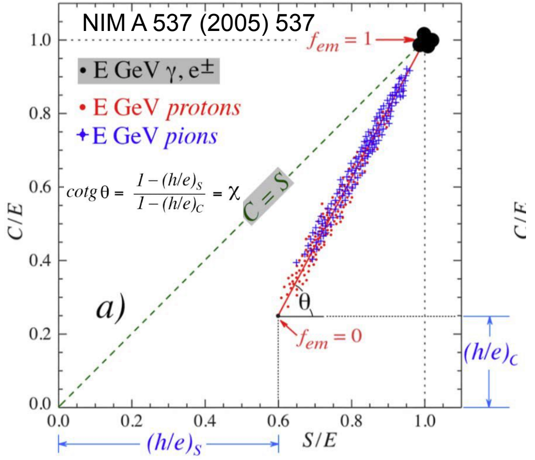
$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi}$$

$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

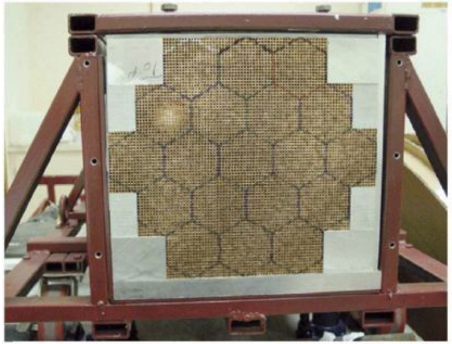
χ does not depend from energy and particle type.
It is detector dependent: it can be measured on beam tests

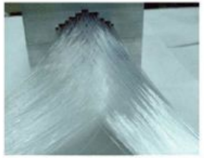


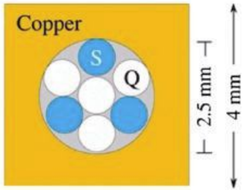
Dual-readout calorimetry on work

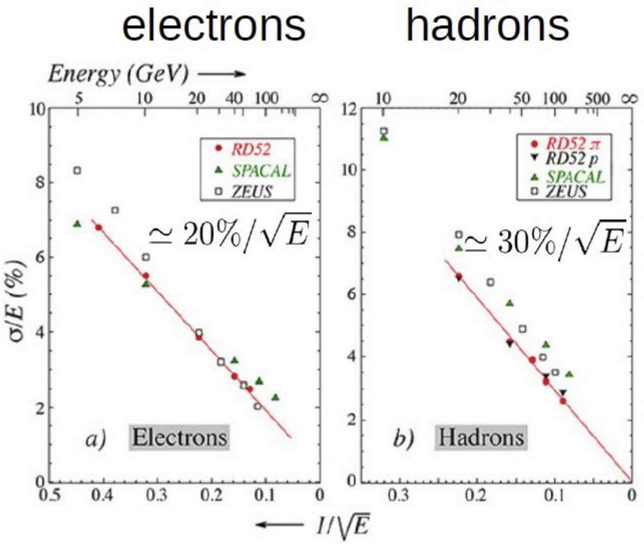
Dual Readout technique successfully demonstrated in **sampling fiber calorimeters** with quartz and scintillating fibers to measure Ĉ and S signals

➔ **impressive hadron performance have been demonstrated : 30%/√E**





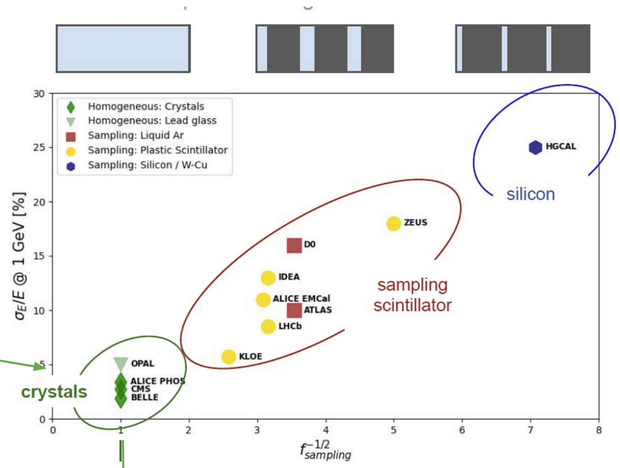




DREAM/RD52 collaboration

The dual-readout method in a hybrid calorimeter

- For a DR fiber calorimeter EM energy resolutions are mediocre at the best 15%, due to poor sampling fractions.
- State of the art EM energy resolutions from homogeneous crystals: 1-2 %/√E



Technology (Experiment)	Depth	Energy resolution
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$
CsI(Tl) (BaBar)	$16\text{–}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$

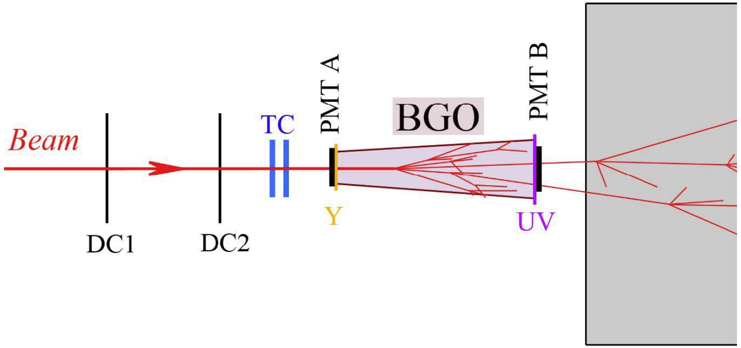
any solution?

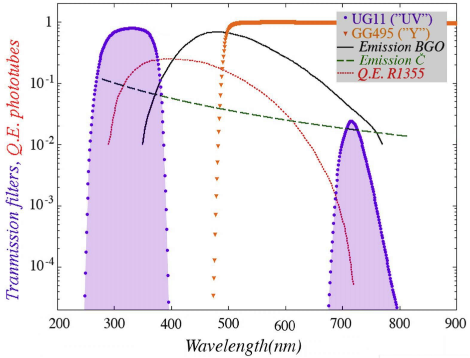
➔ combine the best of both (hadronic and EM) worlds with an **hybrid dual-readout crystal and fiber calorimeter**

Dual readout strategy in crystals

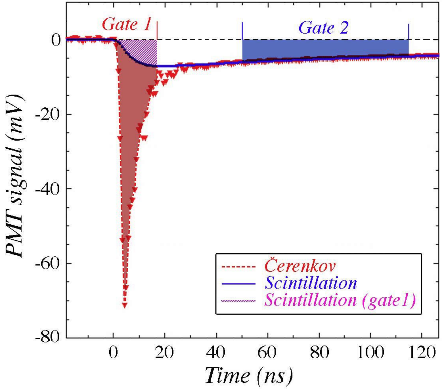
DREAM/RD52 demonstrated DRO proof-of-concept in crystals

- Used PMTs, optical filters and timing to separate C and S signals
- Resolution dominated by photon detection statistics
- Improvements needed on efficiency, λ range of light collection
- Not pursued further:
  - Cost with PMT readout
  - Limited wavelength sensitivity
  - ‘acceptable’ EM resolution demonstrated in fiber calorimeter for goals of the day





Nucl. Instr. And Meth. A 595 (2008) 359

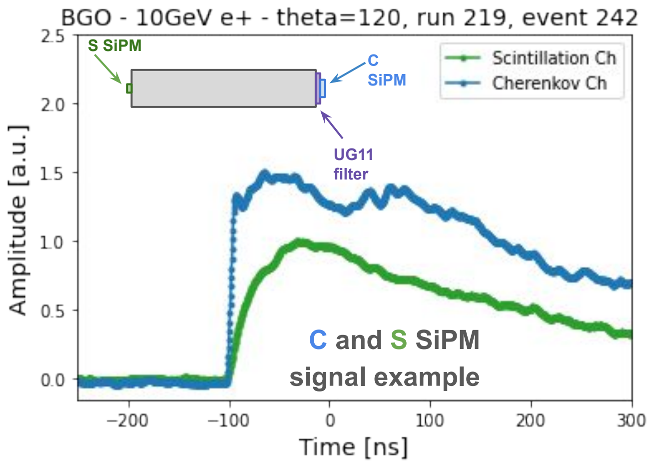


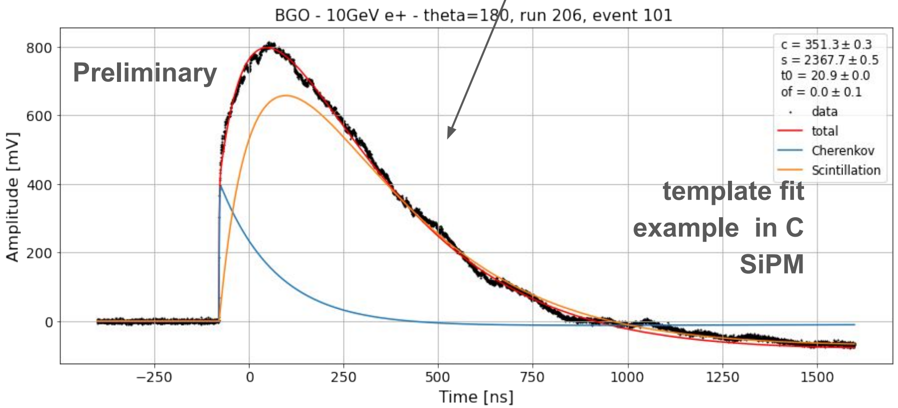
Nucl. Instr. And Meth. A 598 (2009) 710

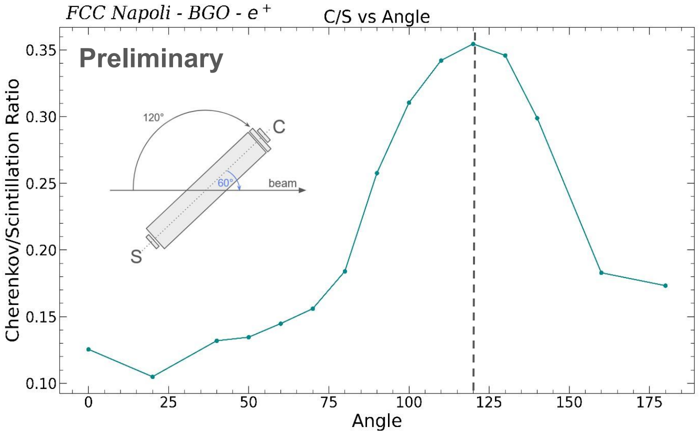
Highlights from CERN TB

Pulse shape analysis studies with BGO

- **Different pulse shapes in SiPMs w and w/o filter**
  - C contribution on the rise time clearly observable
- Nice discrimination of **C** vs **S** phe with a template* fit on the C SiPM

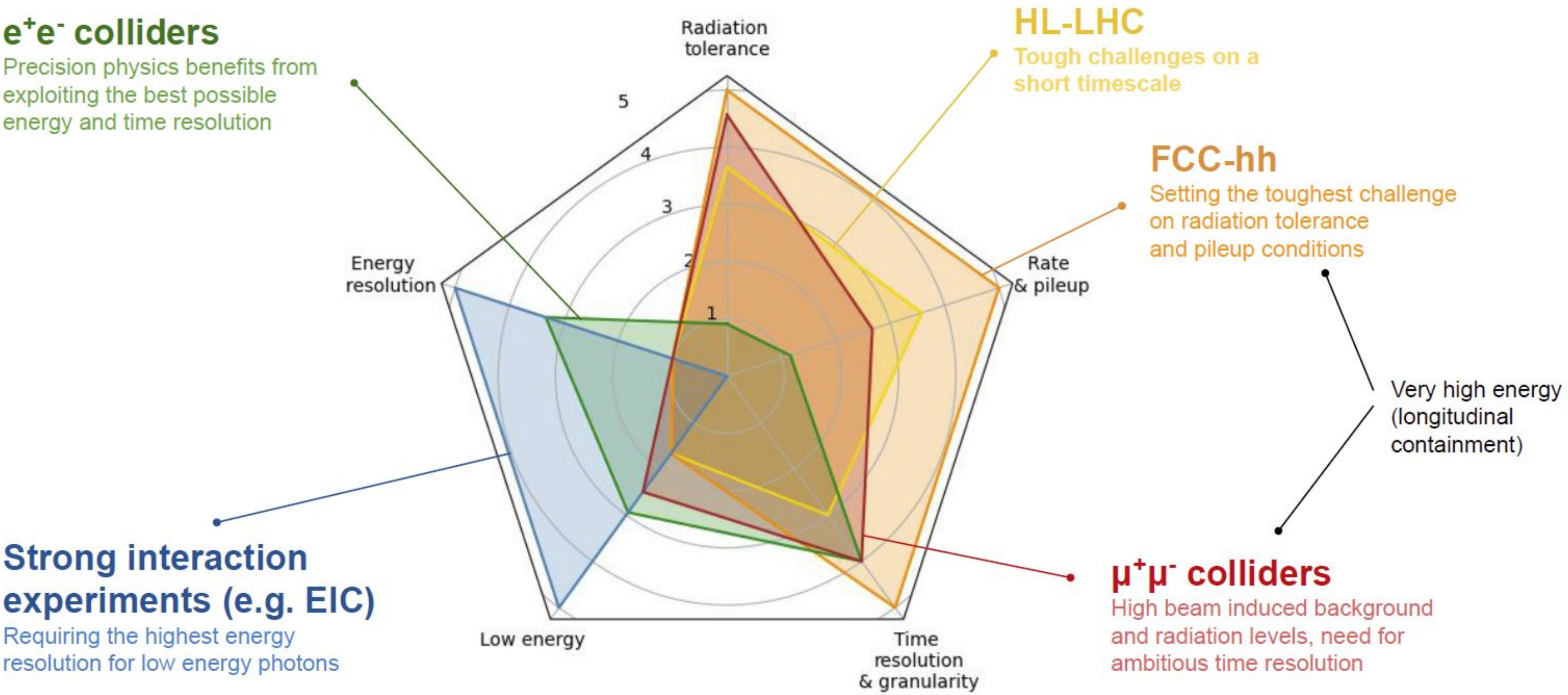






*templates from SiPM+electronic single phe shape convolution with arrival time distributions

Requirements for calorimetry at future colliders



Dual readout strategy

Crystal transparency where Cerenkov light is most intense (near UV) is poor. So feasibility of concept strongly depends on:

- **Adequate statistics of C photoelectrons** (> ~50 phe/GeV)
- **Reasonably large S photoelectrons** (> ~2000 phe/GeV)
- **Sufficient separation of C from S light**
  - Wavelength digitization for timing/pulse shape discriminators

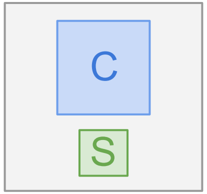
Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

Front crystal ECAL segment:

one SiPMs optimized for S detection

Rear crystal segment face



optical filter + 6x6 mm^2 SiPM with 50 μm cell size (large area and good pde)

3x3 mm^2 SiPM with 10 μm cell size (high dynamic range)

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

Including a **dual-readout** in the crystal EM calorimeter section enables the use of DR method in a hybrid calorimeter configuration

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

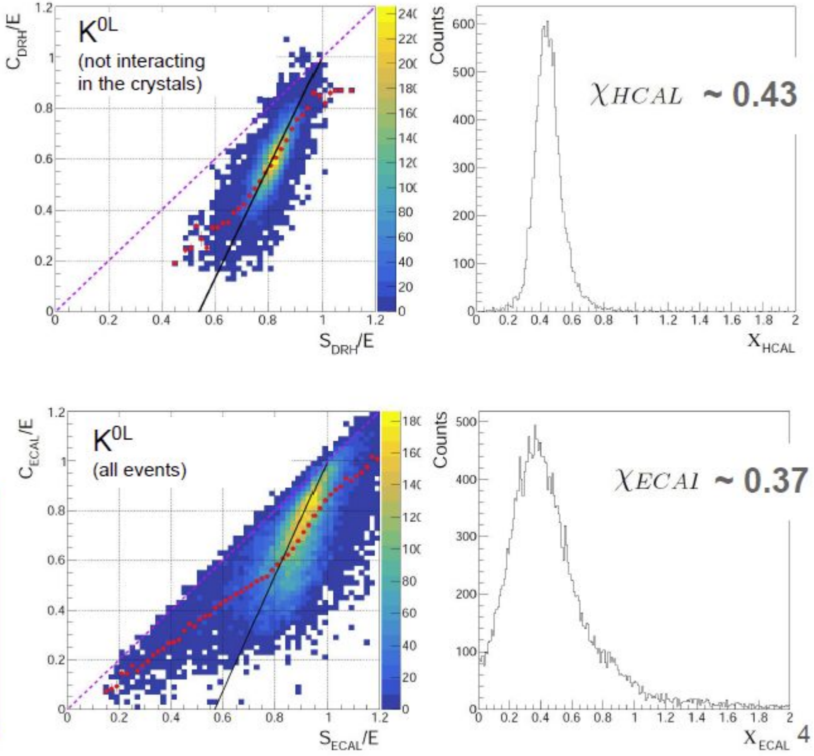
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

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

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

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

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



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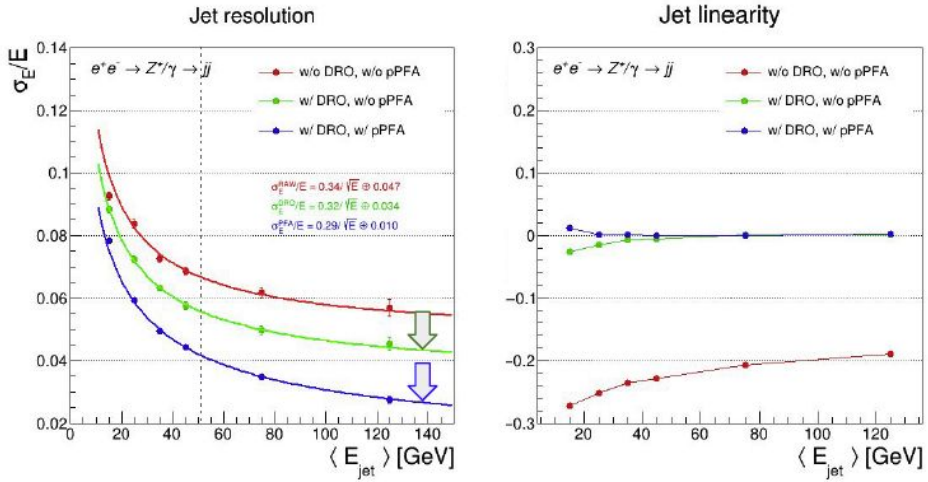
from Marco L. slides at *IDEA Study Group meeting*

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 $e^+e^- \to Z^* \to jj$ events (at different center-of-mass energies):

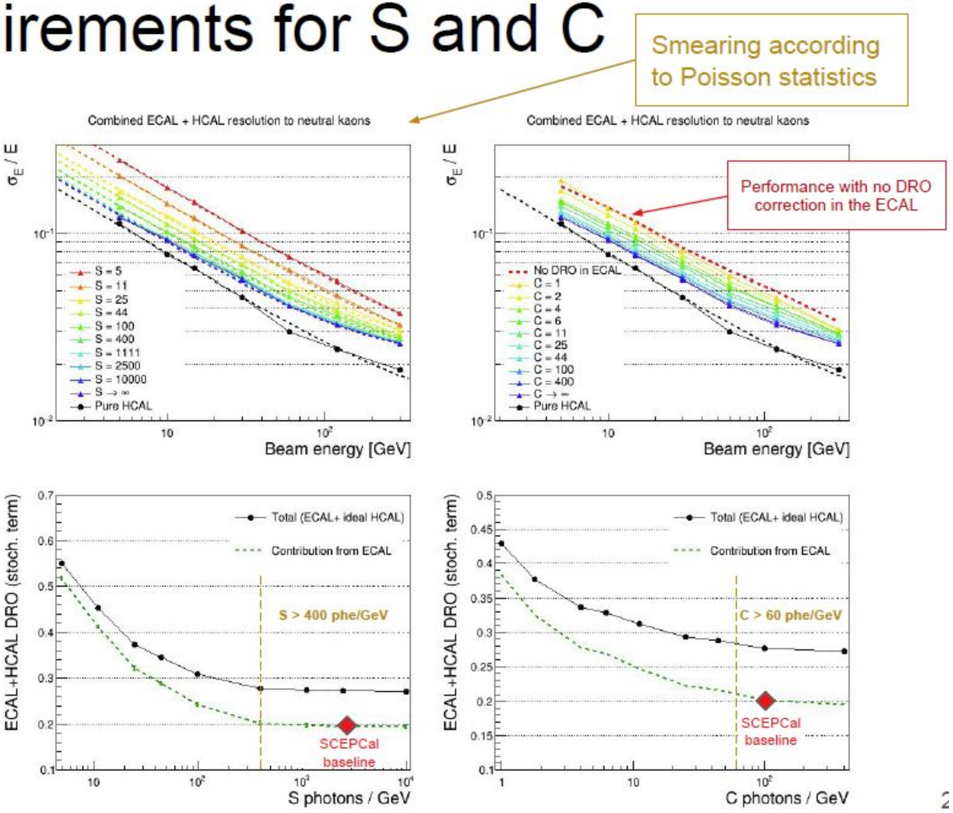
- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



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

Photo-statistic requirements for S and C

- 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
- **Baseline layout choices** (granularity and SiPM size) to **provide sufficient light collection efficiency** in Geant4
  - Need experimental validation with lab and beam tests



Dual readout ECAL: overview

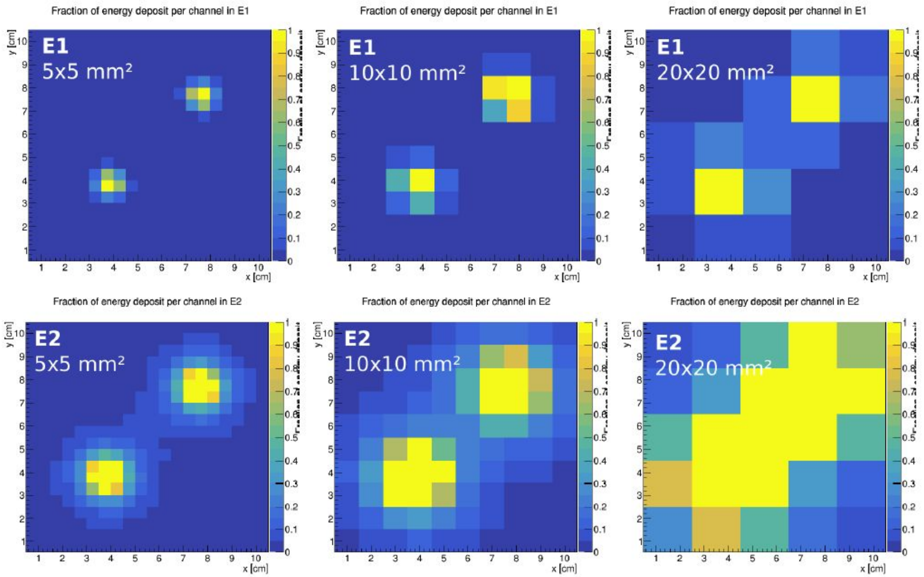


Figure 14. Transverse separation of two photons emitted with an angle of about 3 degrees, in the front and rear layer of the crystal ECAL (with PbWO crystals), for different scenarios of transverse segmentation ($5 \times 5\,\mathrm{mm}^2$, $10 \times 10\,\mathrm{mm}^2$, $20 \times 20\,\mathrm{mm}^2$).

arXiv:2203.04312v2

Dual readout ECAL: overview

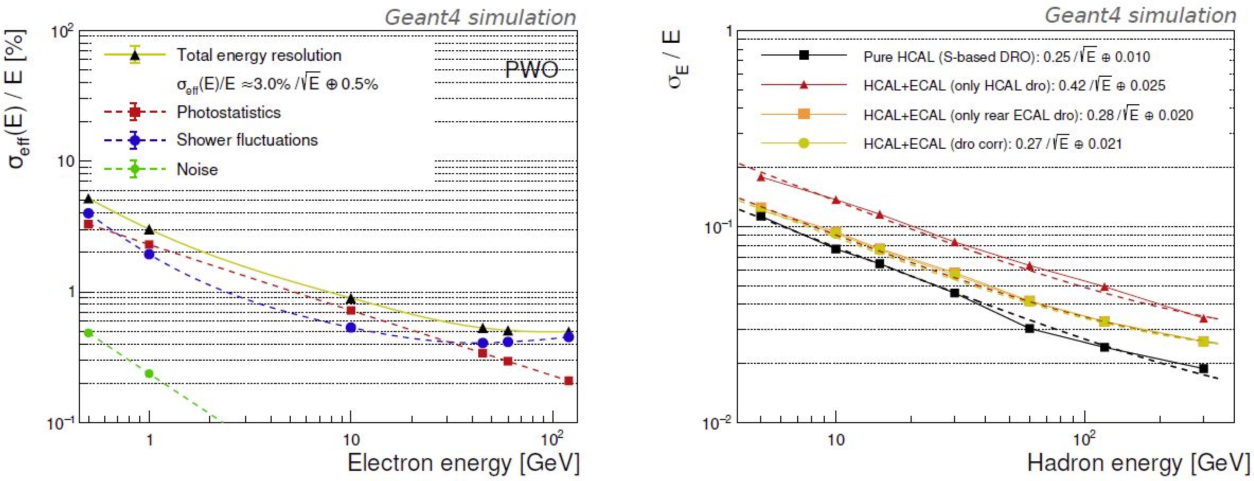
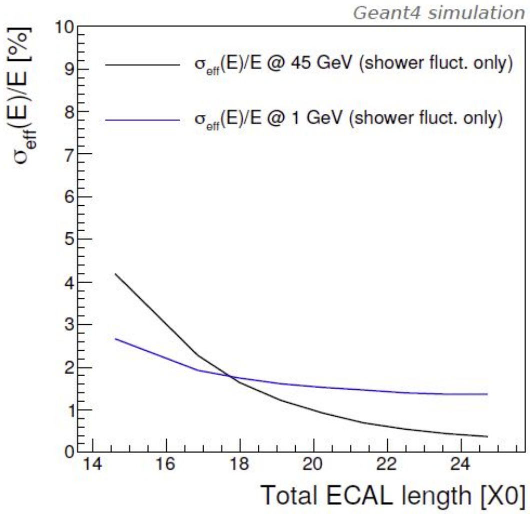


Figure 15: Simulated resolutions for a combined dual-readout crystal ECAL and a dual-readout spaghetti HCAL from Ref. [5], for a pure dual-readout spaghetti, for that with a conventional crystal EM, and that with a dual-readout crystal EM calorimeter. Note that the energies of particles produced at electron-positron Higgs factories are mostly below 20 GeV, and so this is the most relevant part of the hadronic resolution. The average energy of a charged pion is 3 GeV [5]. On average, 13% of the jet energy is from neutral hadrons [5]. Shown are EM (left) and hadronic (right) resolutions.

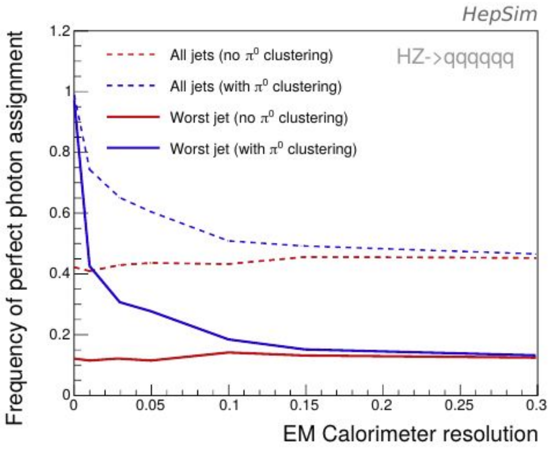
Dual readout ECAL: overview

arXiv:2203.04312v2

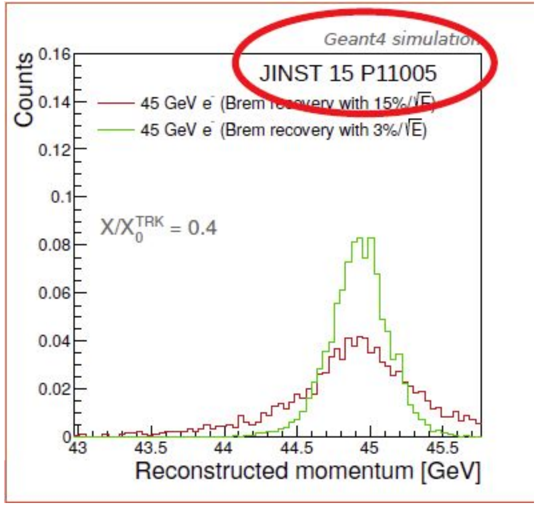


Dual readout ECAL: overview

arXiv:2203.04312v2



photon matching in 6 jet event:
w/ π0 clustering
w/o π0 clustering



electron energy w/ brem. recovery
vs ECAL resolution

ECAL key design features

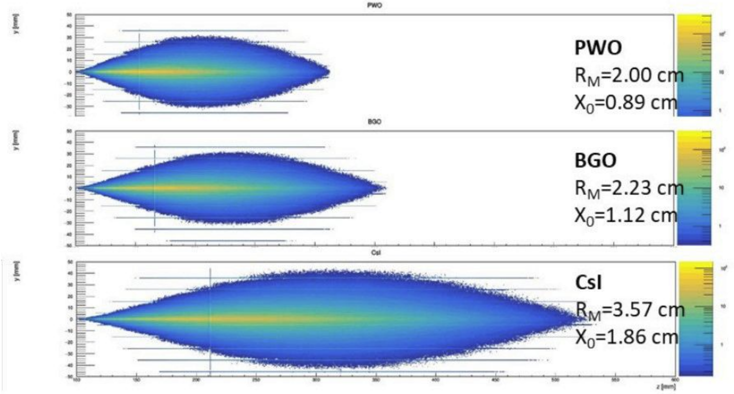
Crystal requirements:

- good calorimetric properties (short X0, small RM)
- Fast signal, cost effective
- reasonable Ĉ/S ratio

Crystal	Density g/cm²	X_0 cm	λ_I cm	R_M cm	Relative Yield	Decay time ns	Refractive index
$PbWO_4$	8.3	0.89	20.9	2.00	1.0	10	2.20
BGO	7.1	1.12	22.7	2.23	70	300	2.15
BSO	6.8	1.15	23.4	2.33	14	100	2.15
CsI	4.5	1.86	39.3	3.57	550	1220	1.94

PbWO4, BGO and BSO are good candidates

Longitudinal shower profiles



- PWO: Fastest, most compact;
- CsI: the brightest, least compact
- BGO: in between the two

R&D activities

First activities **focus on understanding photon collection in single crystal configuration with various technological choices (crystals, filters, SiPMs, front end)**

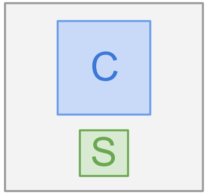
Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

Front crystal ECAL segment:

one SiPMs optimized for S detection

Rear crystal segment face



optical filter + 6x6 mm^2 SiPM with 50 μm cell size (large area and good pde)

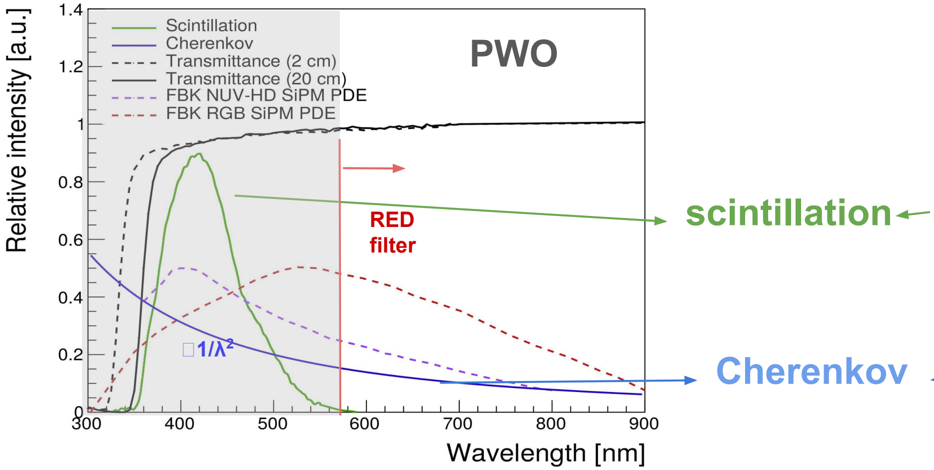
3x3 mm^2 SiPM with 10 μm cell size (high dynamic range)

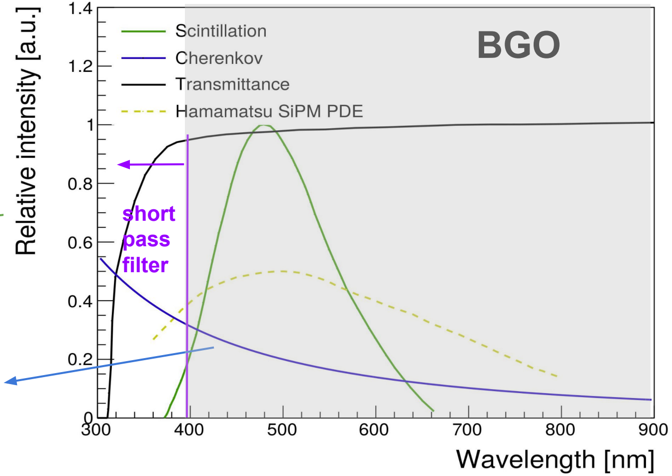
Dual readout strategy in crystals

Simultaneous readout of scintillation and Cherenkov light from the same active element.

➔ **How? Exploit Cherenkov (C) and Scintillation (S) distinctive features:**

- **C emission spectrum broader than S** → **Use of optical filters and dedicated readout sensors to separate C and S**



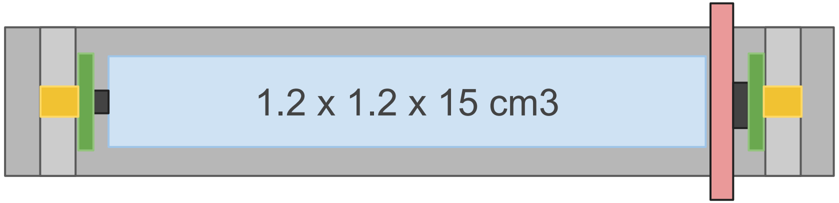


Crystals, Filters and SiPM (setup B)

Absorptive colored glass filter (SCHOTT) on the Cherenkov side

- **long pass:** OG550**,** RG-610, RG-665, RG-715 + KODAK thin film 580 nm → PWO
- **short pass:** UG11 → BGO, BSO, CsI

optical filter → (d = 25.4 mm, t = 3 mm)



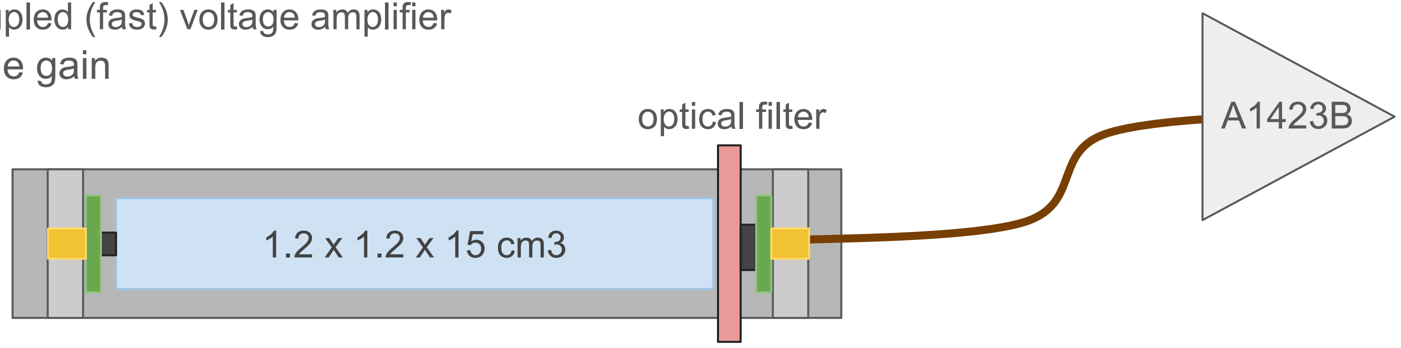
Scintillation side
SiPM 3x3 mm2
HPK S14160-3010

Cherenkov side
SiPM 6x6 mm2
HPK S14160-6050

SiPM front end (Setup B)

2x CAEN A1423B Wide band (1.5 GHz) preamplifier

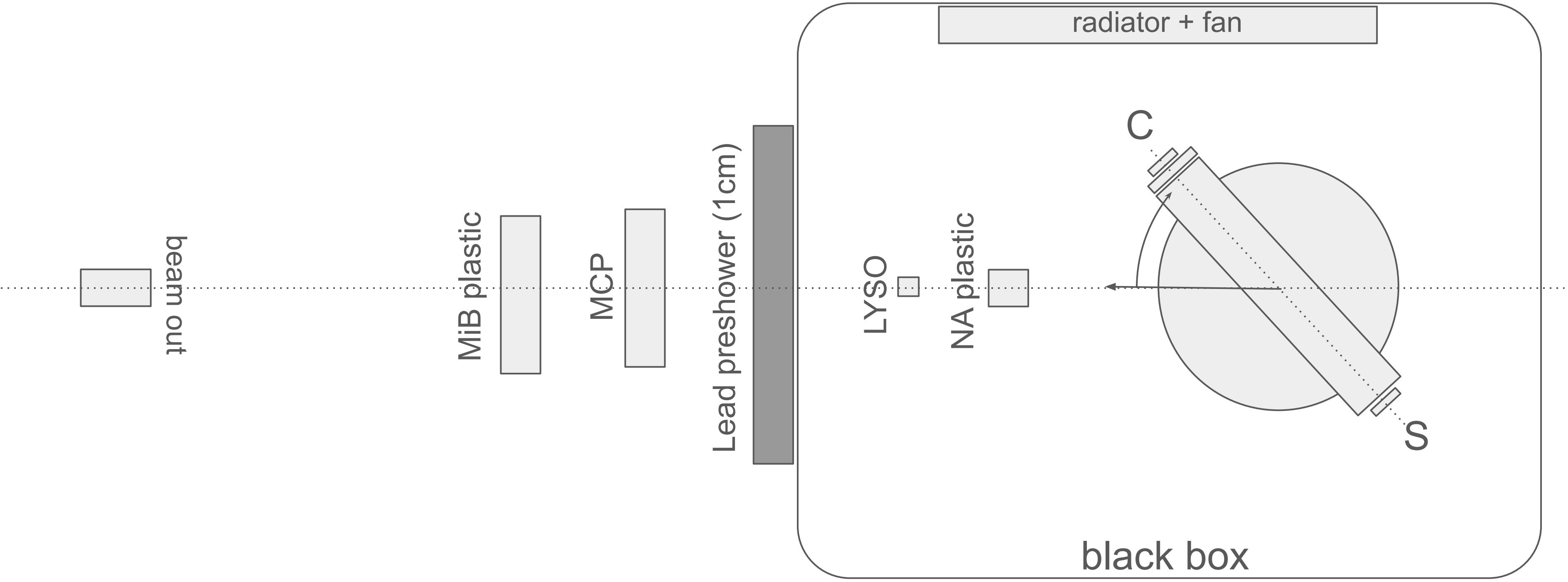
- AC coupled (fast) voltage amplifier
- Variable gain



Scintillation side
SiPM 3x3 mm2
HPK S14160-3010

Cherenkov side
SiPM 6x6 mm2
HPK S14160-6050

Setup schematic

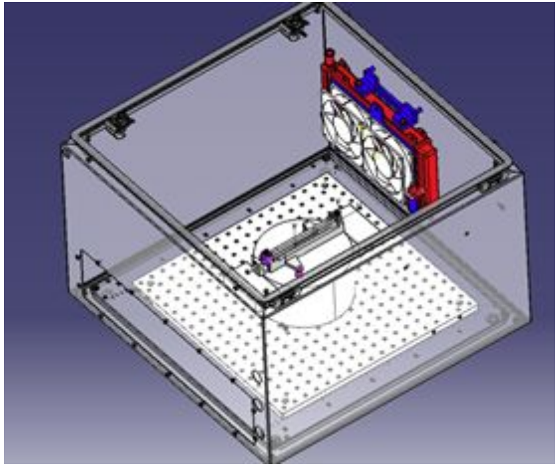


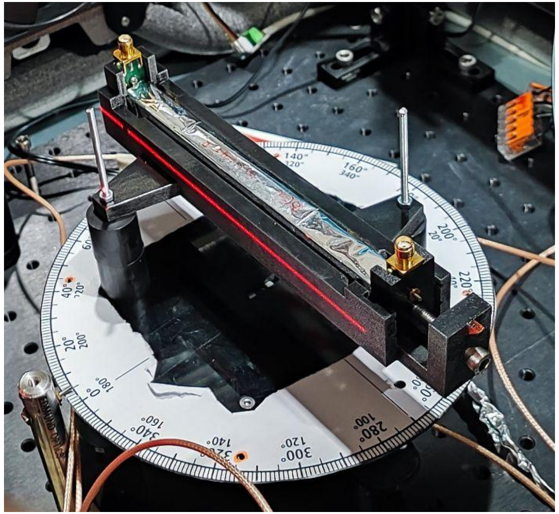
Marcello Campajola - INFN Napoli and UNINA

Setup mechanics

- Stainless steel box (1.5mm thickness) 40 x 60 x 60 cm3;
- Internal nitrile insulation (2 mm);
- Thorlabs perforated aluminum bench 45x45 cm2;
- Homemade rotator from: top diameter 15 cm;
- 3D printed crystal and sipm holder;
- Flange with feedthrough connectors;

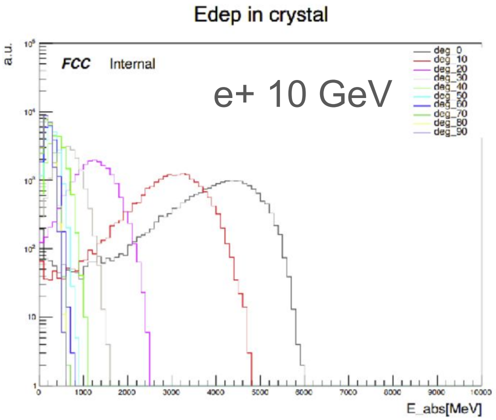
- Box temperature conditioning with internal radiator with fans connected to an external LAUDA chiller;
- Internal temperature sensor + PID software feedback to the chiller for temperature stabilization;
  - □ stable operations at 23° C

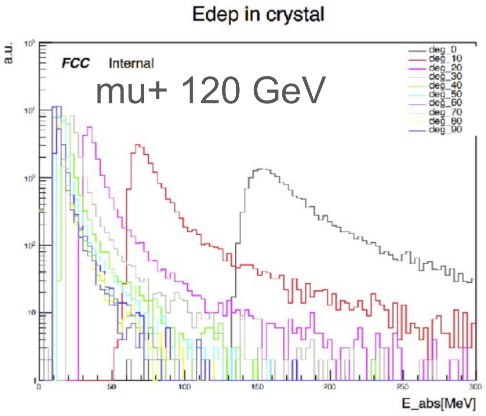


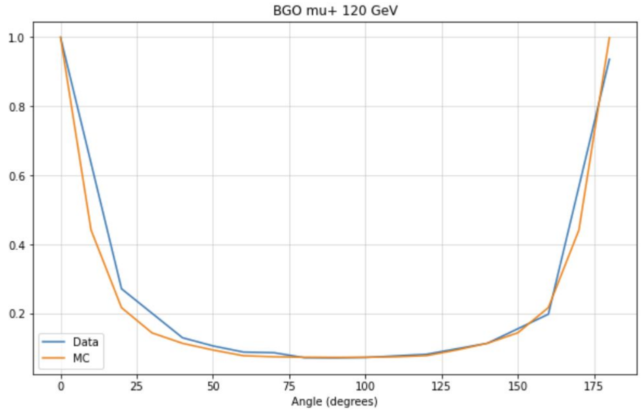


Simulation

- **Recent effort from NA to work on Geant4 simulation of TB setup B**
- Useful in this data analysis and for the prototyping of the full containment module



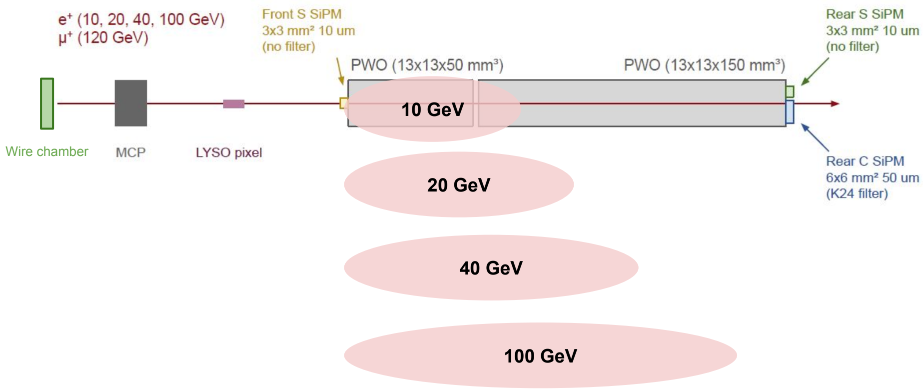




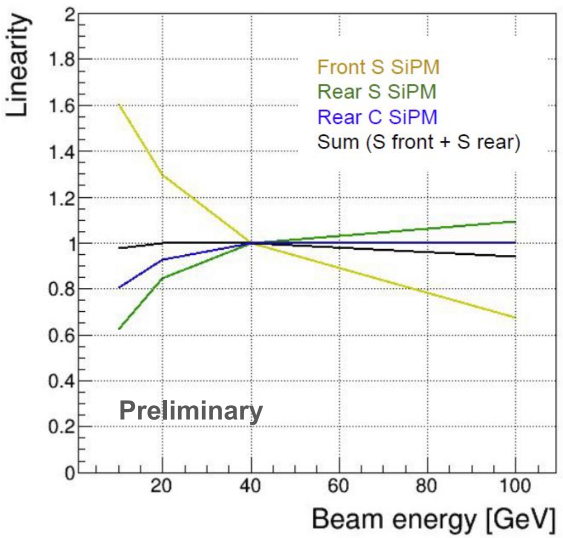
Highlights from CERN TB

Energy scan to study linearity with electron runs with setup A (PWO)

- Signal of front and rear scintillation SiPMs change as shower energy increases and shower maximum moves towards the rear crystal



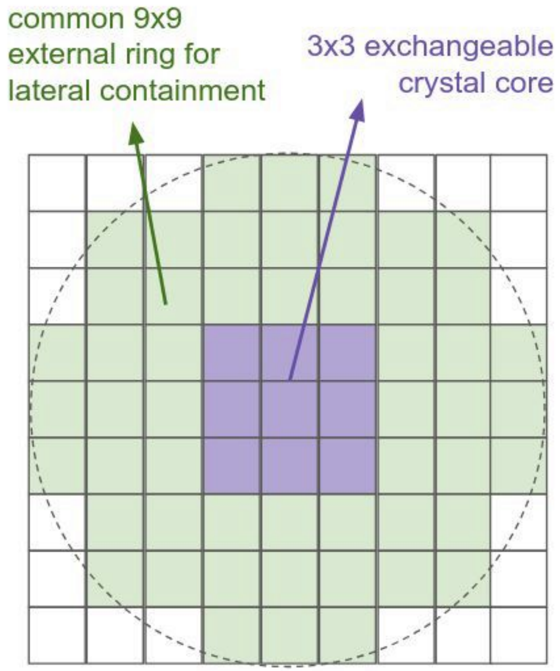
- **Combination of front and rear SiPMs yields reasonable linearity**



Towards a multi-channel prototype

Plan to build two main prototypes using complementary technologies:

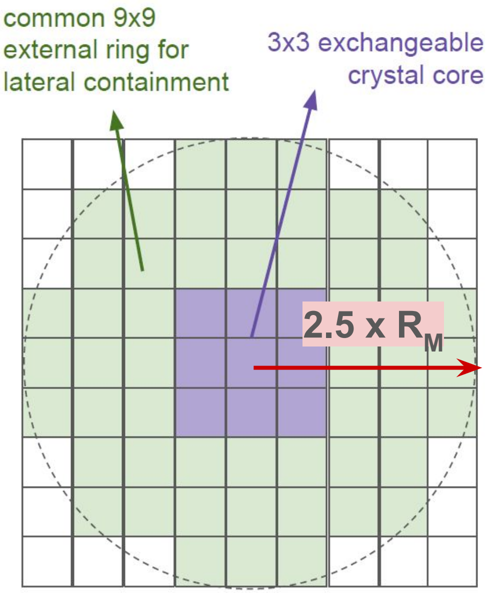
- **PWO-based:**
  - fast crystal (10 ns)
  - shortest X0 and smaller RM
  - readout of cherenkov photons in the infrared region
- **BGO-based:**
  - slower crystal (300 ns) but larger scintillation light output,
  - readout of cherenkov photons possible also in the UV region
  - C/S discrimination through pulse shape possible



Summary and work plan

- R&D* and proof-of-principle of a dual readout ECAL concept is ongoing
  - large efforts in 2023/24 with a series of beam tests on single crystal modules (@ CERN, + DESY, FNAL*)
  - **team of analyst working test beam data analysis and G4 simulation**
    - **first positive results**
- Plan* is to achieve the demonstration of this calorimetric technique using a full scale EM calorimeter prototype by the next 1-2 years.

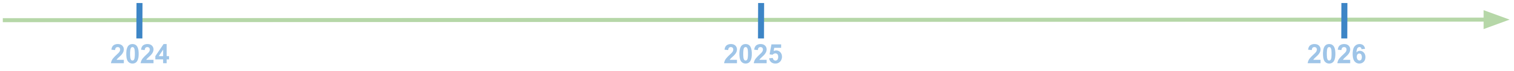
*similar/complementary R&D activities and plans also from US (see in the backup)



single sensor test with various flavors of crystal, filters and SiPMs

full containment EM calorimetric module prototype (10x10 matrix) using most promising technologies

combined test beam with fibre calorimeter prototype



Atlas/CMS ECAL resolutions

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term a	10%	10 to 12%	3%	5.5%
Local constant term b	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of $29 \times 29\ mm^2$. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

Atlas/CMS HCAL resolutions

TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS					
	Barrel LAr/Tile		End-cap LAr		CMS	
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV