Riunione di Gruppo 1 - INFN Napoli

22 gennaio 2026

FCC report

Marcello Campajola

on behalf of the RD_FCC NA group

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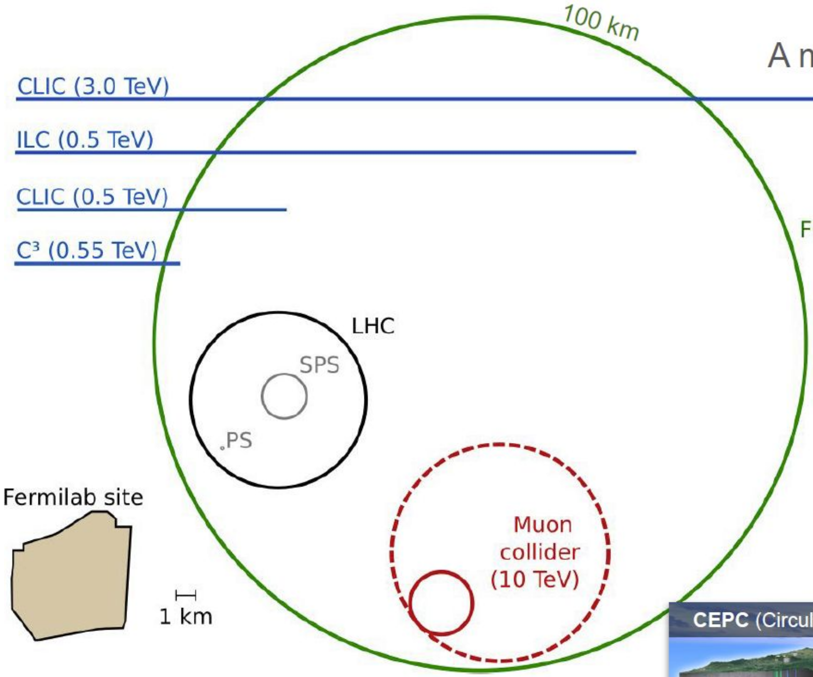
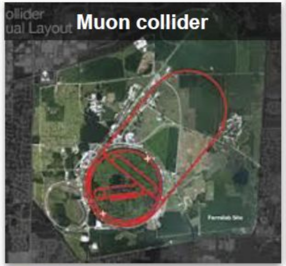
Outline

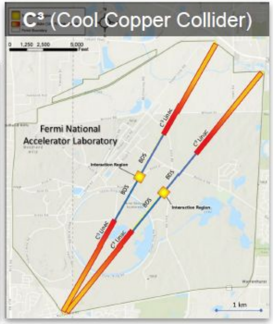
- **European Strategy for Particle Physics**
- **FCC project**
- **Napoli group ongoing activities**

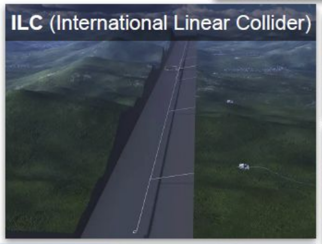
After the LHC - what’s next?

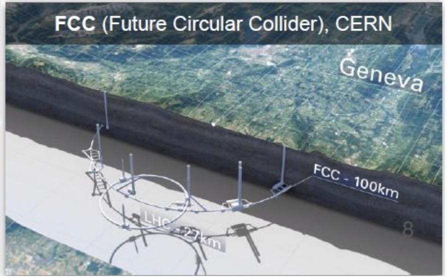


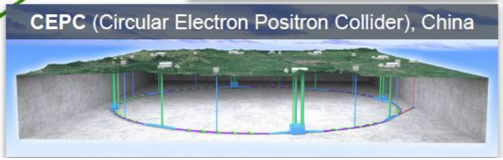
A major **civil engineering** challenge!











The European Strategy for Particle Physics (ESPP) update timeline

Inputs to the ESSP update process

Several inputs collected, and the technical readiness of the main projects analyzed.

Full report available: https://cds.cern.ch/record/2947728

- The FCC-ee feasibility plan is the only project to have received full green lights.

Project	Scope	TRL	R&D	Test facilities	Performance	Site preparation	Schedule	Cost	Risk
CLIC 380 GeV, 1.5 TeV		4 - 6 / 5.2							
FCC-ee 91-365 GeV		4 - 7 / 6.0							
FCC-hh 85 TeV		4 - 7 (Nb_3Sn) / 4.3 2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb_3Sn) / 5					Nb_3Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
LEP3 91 - 230 GeV		3 - 6 / 4.0							
LHeC: HL-LHC + 50 GeV ERL		3 - 6 / 4.5							
MC 3.2 TeV, 7.6 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							

Recommendations from the European Strategy Group

The European Strategy Group, after the Ascona drafting session, sent to CERN's Council its recommendations for the future large research infrastructure for Europe's HEP:

The recommendations is:

- ➔ **Plan A:**
  - ◆ **FCC-ee as the preferred option for the next flagship collider at CERN (cost: 15G€)**
- ➔ Plan B:
  - ◆ A descoped FCC-ee: no ttbar run, only two experiments and lower RF power (cost:12G€)

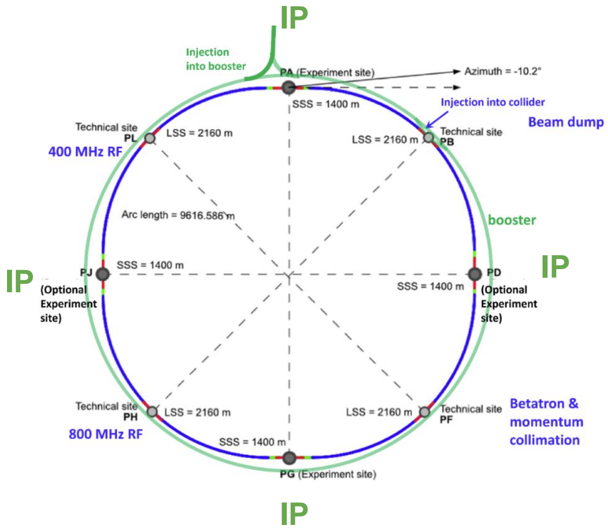
https://cds.cern.ch/record/2950671/files/CERN-ESU-2025-002.pdf

FCC-ee

A **91 km circumference** e+e- collider around the LHC area

Up to **4 interaction points**:

- possibility of specialised detectors to maximise physics reach



Planned to operate at **4 center of mass energies to** produce large statistics of the heaviest particles of the SM:

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

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

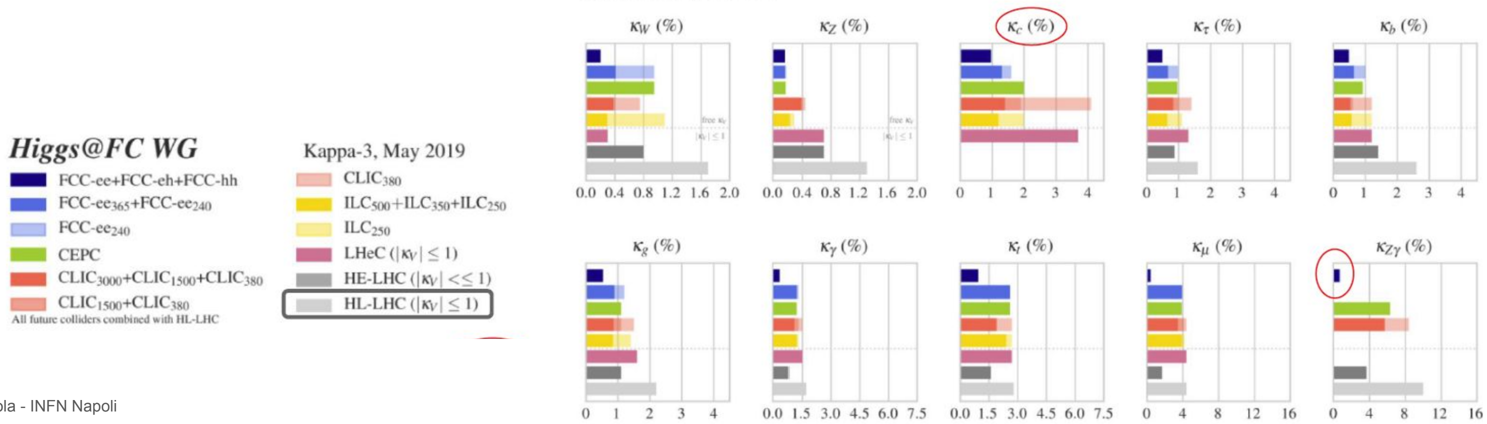
Precision Higgs physics:

- up to x 10 improvement on **Higgs coupling** (model-indep.) measurements over HL-LHC
- Model-independent measurement of the **Higgs boson width** with 1% precision
- Higgs self coupling below 10%

x 10-50 improvements on all **EW observables**

x10 target Belle II statistics for **heavy flavour physics**

Direct discovery potential for **feebly-interacting particles** over 5-100 GeV mass range



Where are we now?

FCC-ee Feasibility Study Report (FSR) successfully completed link

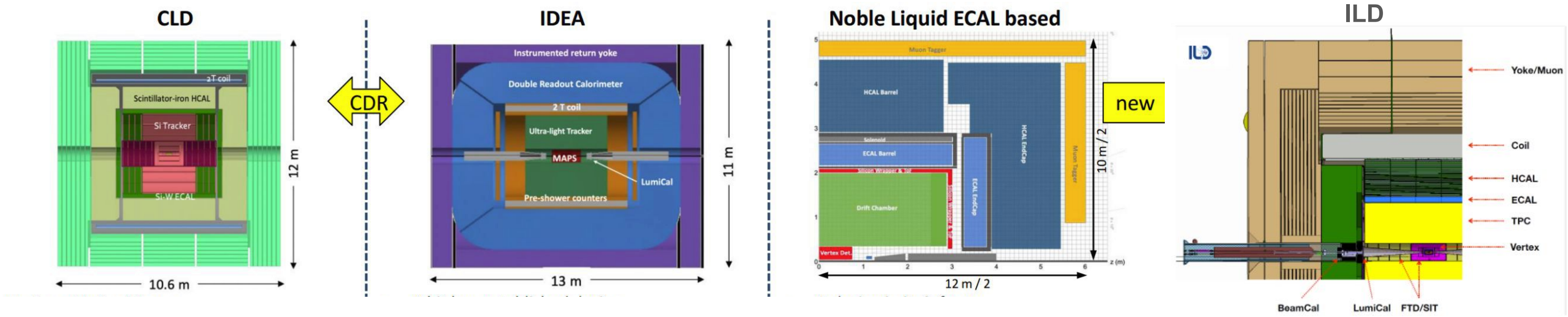
- 1: Physics, Experiments, Detectors
- 2: Accelerators, technical infrastructure and safety
- 3: Civil Engineering, Implementation and Sustainability


Future Circular Collider Feasibility Study Report
M. Benedikt, F. Zimmermann ... FCC Collaboration in The European Physical Journal C
Review | Open access | 24 December 2025 | Article: 1468

Future Circular Collider Feasibility Study Report
M. Benedikt, F. Zimmermann ... M. Zykova in The European Physical Journal Special Topics
Review | Open access | 17 November 2025 | Pages: 5713 – 6197

Future Circular Collider Feasibility Study Report
M. Benedikt, F. Zimmermann ... M. Zykova in The European Physical Journal Special Topics
Review | Open access | 13 October 2025 | Pages: 5113 – 5383

Ongoing work on the detector concepts.



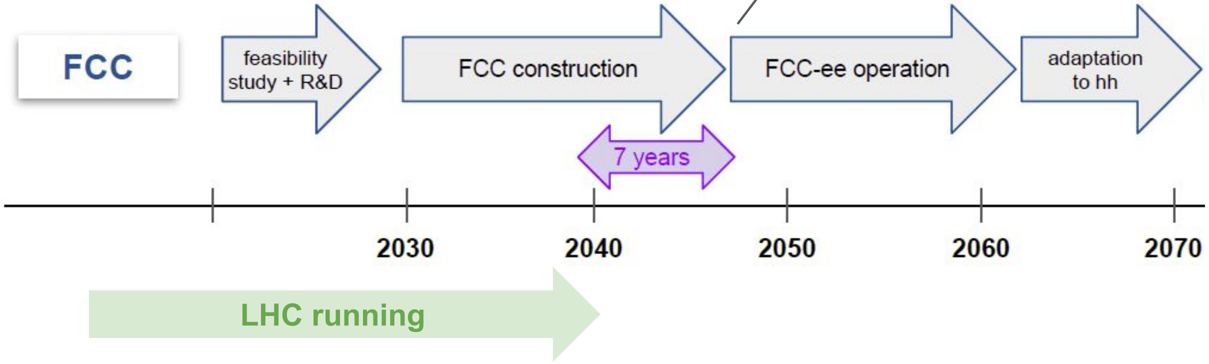
IDEA is the detector concept proposed by the INFN. CDR available (ArXiv)

What’s next?

Proposed FCC-ee project timeline

- 2027-28 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



RD_FCC

INFN is active on the FCC project since several year.

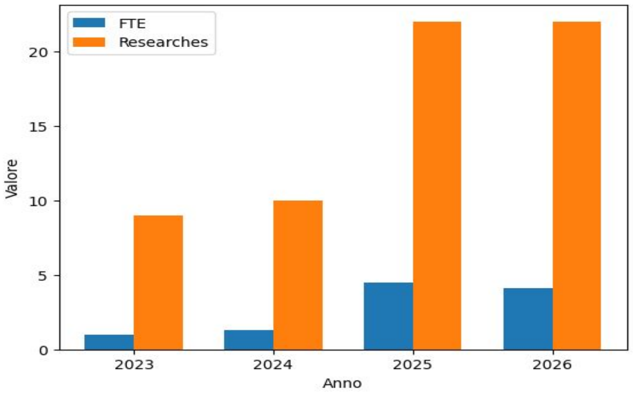
Involved on each aspect:

- **Physics studies**
- **Machine and accelerator**
- **Detector**
    - mainly on the IDEA detector concept (on each sub detector)
    - plus other R&Ds like MicroMegas, Tilecal etc for other detector concepts

NA group

Large interest of most of NA GR1

- 2023: 1 FTE, 9 researches
- 2024: 1.3 FTE, 10 researches
- 2025: 4.5 FTE, 22 researches
- 2026: 4.1 FTE, 21 researches



Anagrafica 2026

Cognome	Nome	Profilo	FTE
Alviggi	Maria Grazia	PO	20%
Boccanfuso	Daniele	PhD	100%
Borriello	Lucrezia	PhD	30%
Campajola	Marcello	R	10%
Cirotto	Francesco	RTD	15%
Confortini	Francesco	PhD	10%
Conventi	Francesco Alessandro	PA	15%
D'Avanzo	Antonio	PhD	10%
De Asmundis	Riccardo	PR	10%
De Nardo	Guglielmo	PO	10%
Della Pietra	Massimo	PA	25%
Di Donato	Camilla	PA	15%
Di Fraia	Carlo	PhD	10%
Favilla	Leonardo	PhD	10%
Francesconi	Marco	R	10%
Iengo	Paolo	PR	5%
Iorio	Alberto Orso Maria	PA	10%
Paolucci	Pierluigi	DR	30%
Perna	Simone	PhD	30%
Rossi	Elvira	PA	10%
Scamardella	Julia	PhD	30%

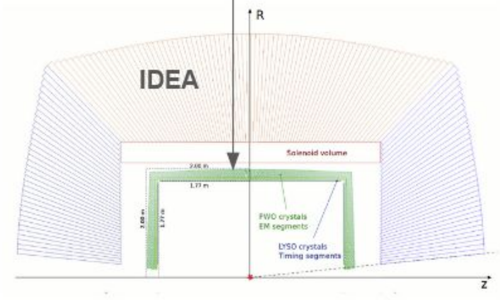
Resp. Locale

NA group

Involved on the detector and the accelerator WGs:

CALORIMETRY

dual readout ECAL R&D

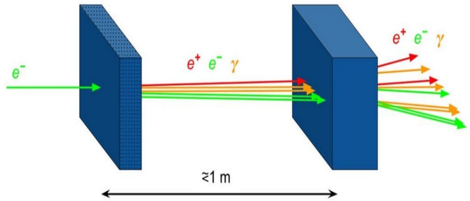


MUON detector

R&D on Resistive High granUlarity Micromegas

Positron source

R&D on oriented cristal based positron sources



Dual readout crystal calorimeter

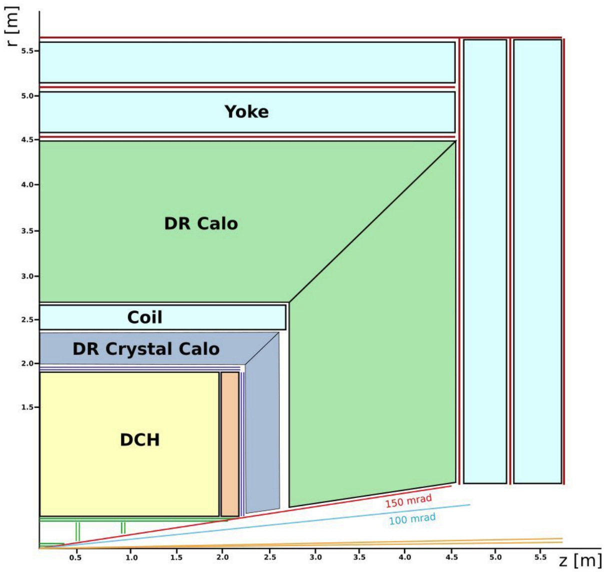
Calorimetry in the IDEA detector

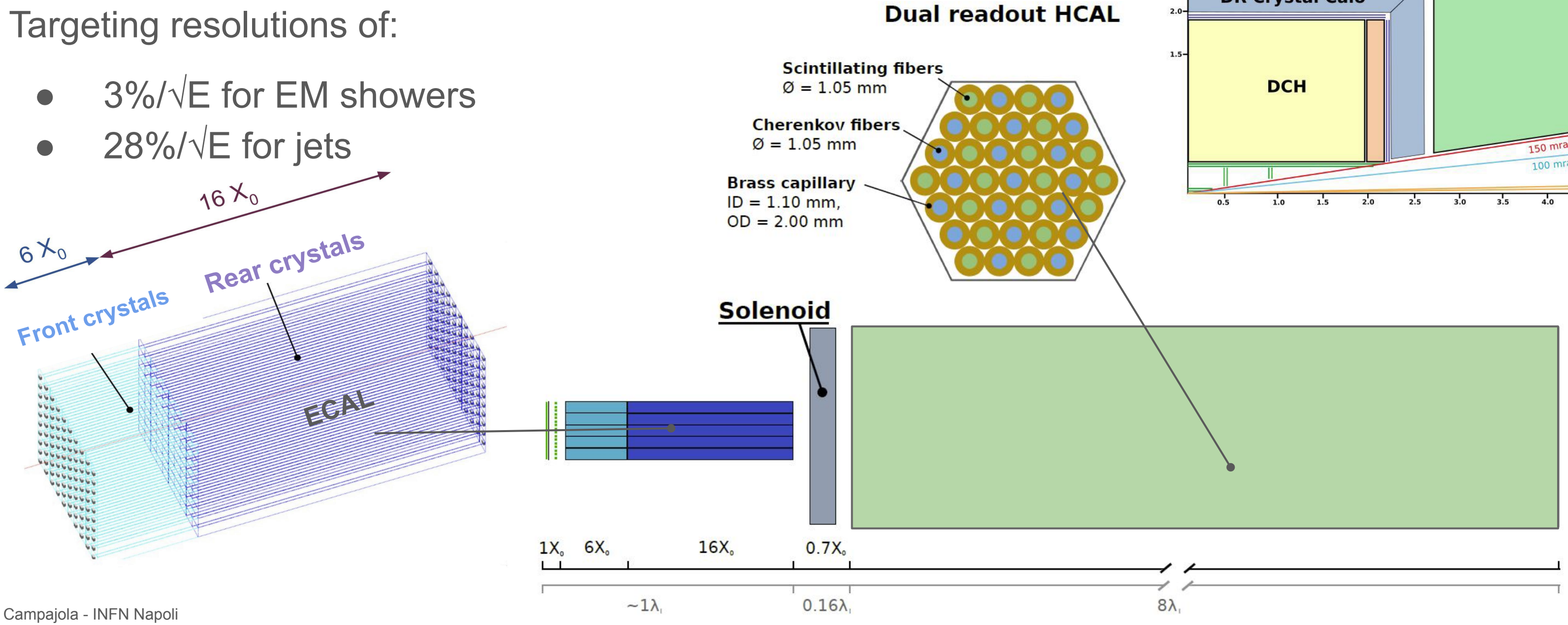
A two section dual readout calorimeter:

- Homogeneous segmented crystal EM calorimeter (**ECAL**)
- Fiber hadronic calorimeter (**HCAL**)

Targeting resolutions of:

- 3%/√E for EM showers
- 28%/√E for jets





IDEA ECAL

ECAL officially introduced in the IDEA baseline since March 2025

- segmented crystals readout with SiPM, and providing **dual readout capabilities**

Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

R&D activity at 360 degrees:

- Simulation studies (from standalone to full sim)
- R&D on technology and proof-of-principle
- Prototyping of a calorimetric module

➔ **NA, MIB and PG groups involved**

Front crystal ECAL segment:

one SiPMs optimized for S detection

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

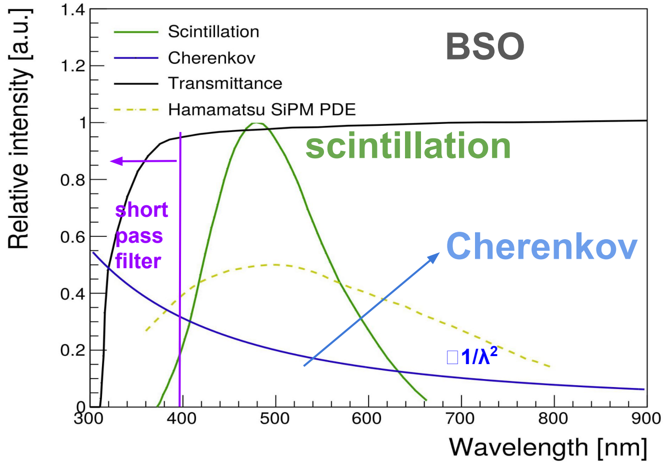
Dual readout strategy in BSO

Cherenkov window in the 320-380 nm region where there’s no scintillation light

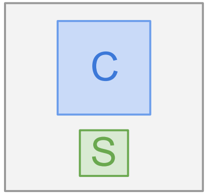
- use of UV optical filters on a dedicated readout channel

Cherenkov emission faster than Scintillation one (decay rate is 100 ns)

- use of pulse shape analysis to disentangle the contributions



crystal face



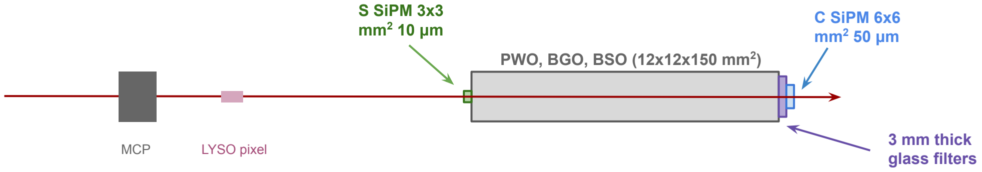
optical filter + 6x6 mm² SiPM with 50 µm cell size (large area and good pde)

3x3 mm² SiPM with 10 µm cell size (high dynamic range)

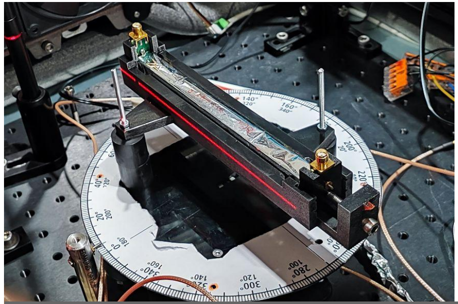
2024 test beam results

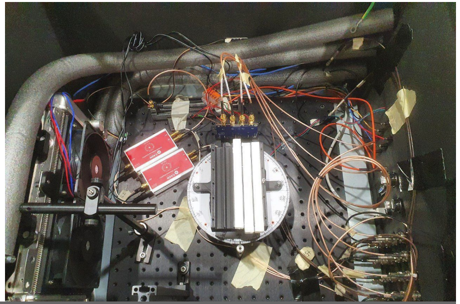
In July 2024 a **Test beam at CERN SPS H6** beam line prepared and **coordinated by Napoli and MIB** and with participation from Perugia, US and CERN

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



TB crew



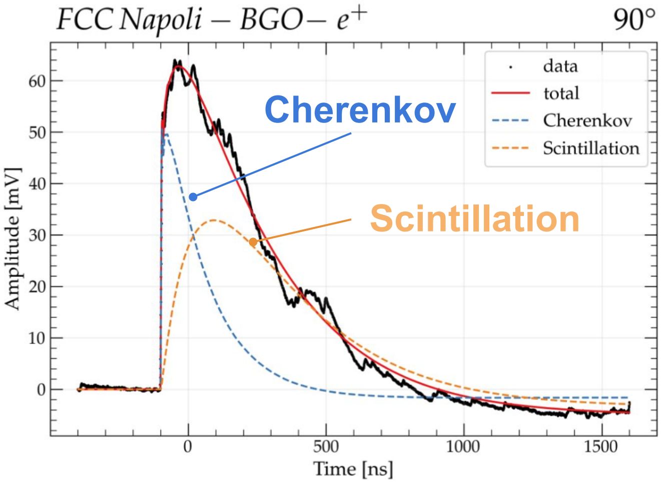


TB setup

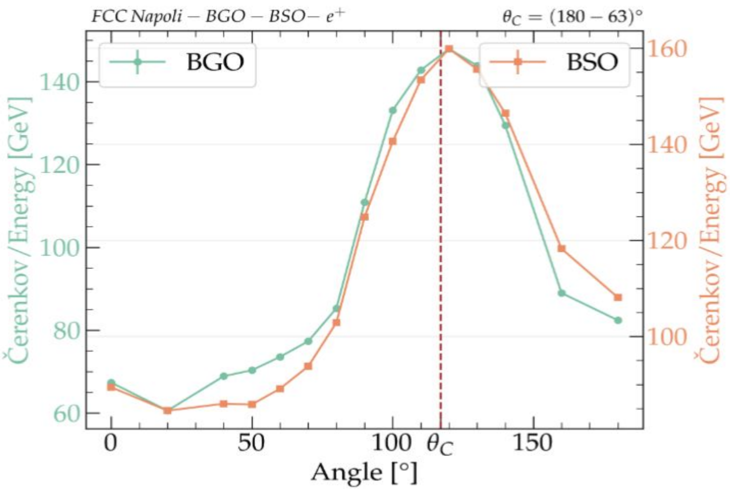
2024 test beam results

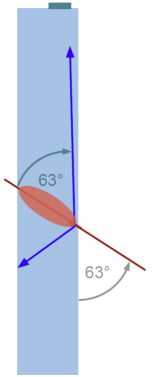
First demonstration of cherenkov/scintillation light separation in BGO and BSO crystals readout with SiPM

Template pulse shape fitting of SiPM+filter signal in BSO yields a good estimate of the cherenkov signal



Angular dependence of C/S peaks as expected around the cherenkov cone emission angle (~63°)



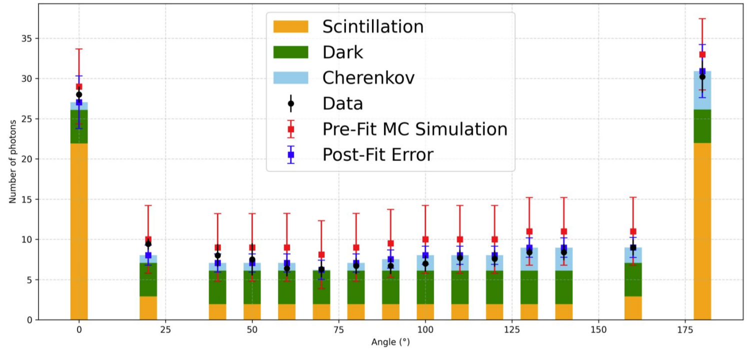


2024 test beam results

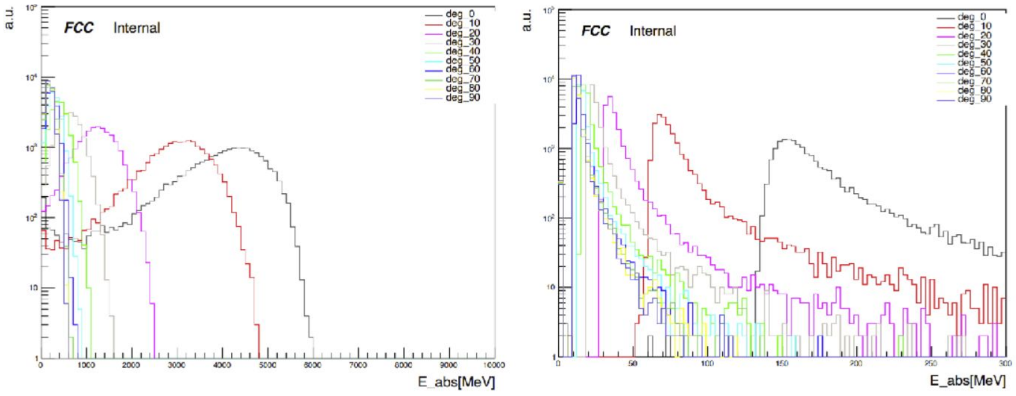
Setup of a standalone Geant4 simulation (including optical transport!)

- 2024 TB data useful input to tune the simulation parameters

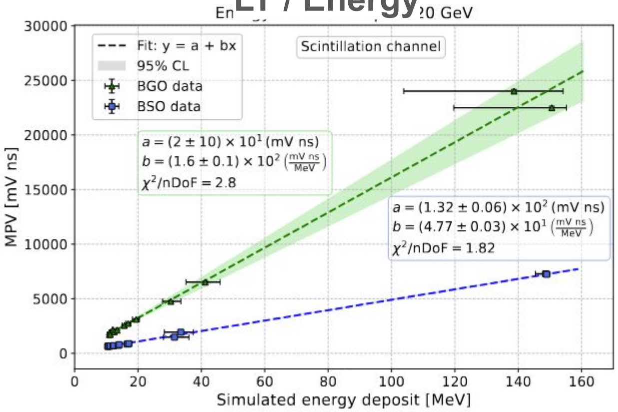
LY in simulation and data



deposited energy simulation



LY / Energy



2025 test beam

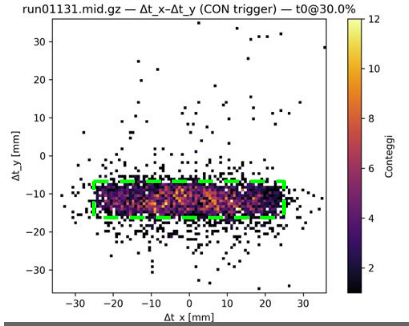
more details in Daniele's talk

New test beam at CERN SPS H6 in September 2025 (NA, MIB and PG)

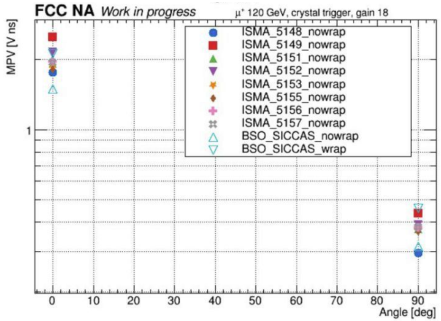
Aim was testing again DR with an improved setup and using scalable readout electronics, testing other producer crystals, and testing linearity in front-rear segment configuration.

Results (analysis still ongoing) will inform us about prototype design optimization

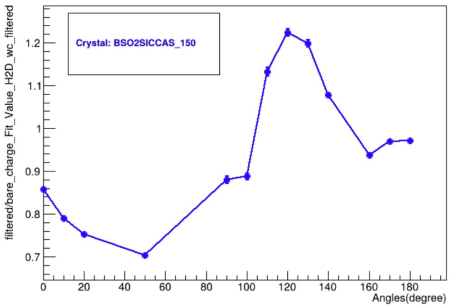
TB crew



DWC hits



crystal's LY



C/S scan

Outcomes in 2025

Journal paper in preparation

To be submitted to JINST or NIMA

Students involvement:

- 1 master (Julia) + 1 ongoing (Valeria)
- 3 PhD projects sinergic with FCC

Conferences:

- Double-readout crystal calorimetry for IDEA”, IDF 2025, Sestri Levante 2025, M. Francesconi
- Test beam of a cell prototype for a dual readout-calorimeter proposal at the Future Circular Collider FCC-ee”, 13th edition of the Beam Telescopes and Test Beams Workshop, Valenzia 2025, L. Borriello

Contribution to the IDEA CDR [arXiv:2502.21223v2]

Measurement of Cherenkov and Scintillation light in a single-crystal cell for a dual-readout electromagnetic calorimeter prototype at future colliders

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Abstract

We report on the separation of Cherenkov and scintillation light components in BGO and BSO homogeneous crystals using a dual-readout technique. A compact setup based on silicon photomultipliers (SiPM) readout was developed, providing an efficient and granular detection system. The setup was tested with high-energy positron and muon beams at the CERN SPS North Area. By exploiting differences in emission timing and wavelength, we demonstrate the feasibility of detecting and distinguishing Cherenkov photons from scintillation ones in such crystals. These results represent a key validation step for the development of a dual-readout electromagnetic calorimeter as foreseen in the IDEA detector concept for a future e^+e^- Higgs factory.

Keywords: Calorimetry, Dual-readout, Crystals, Cherenkov, Silicon Photomultipliers

Contents

1. Introduction

Future particle physics experiments require significant improvements in detector performance and the development of innovative technologies. A notable example is that of a Higgs factory based on an e^+e^- collider, such as the proposed CEPC or FCC-ee projects (1; 2; 3). In such facilities, excellent hadronic and jet energy resolution is crucial for reconstructing multi-jet final states, a key aspect in studies of Higgs boson properties and other precision measurements.

Dual-readout calorimetry (4; 5) represents a promising approach toward meeting these requirements. By separately measuring scintillation and Cherenkov light during shower development, the electromagnetic (EM) fraction of a hadronic shower can be determined and corrected event-by-event. This enables a significant improvement of the hadronic energy resolution. A widely studied implementation of this concept involves sampling calorimeters that combine scintillating and quartz fibers embedded in high-Z absorbers. This approach has been successfully investigated in over more than two decades R&D (6; 7; 8; 9; 10; 11) including recent developments such as the HYDRA prototype (12; 13; 14), demonstrating hadronic energy resolutions at the level of ~ $30\%/\sqrt{E}$. However, the intrinsic sampling fluctuation of these detectors limits their EM resolution to about $15\%/\sqrt{E}$, which is significantly worse than what is typically achieved with homogeneous crystal calorimeters.

To simultaneously achieve excellent electromagnetic and hadronic energy resolutions, the IDEA detector concept for FCC-ee (15) proposes a hybrid calorimetric approach: a segmented homogeneous crystal electromagnetic section, followed by a sampling hadronic calorimeter, both using dual-readout technique. The electromagnetic section employs high-density scintillating crystals with a total depth of $22X_0$, targeting an electromagnetic energy resolution better than $3\%/\sqrt{E}$. A high-granularity design is adopted, with transverse cell size of the order of $1\times1\ cm^2$ and two-layer longitudinal segmentation, in order to enhance particle identification and enable efficient particle flow reconstruction (16). The inclusion of a traditional elec-

Preprint submitted to Nuclear Physics A *January 20, 2026*

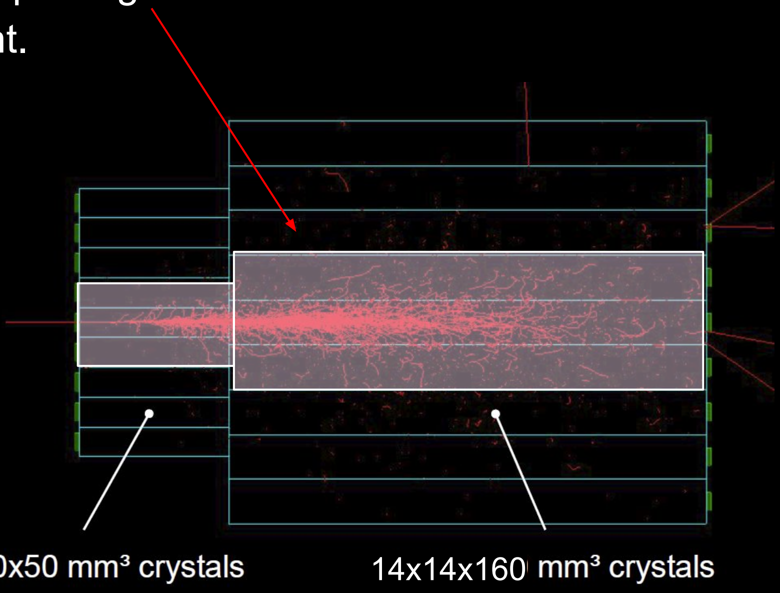
Towards a multi-channel prototype

In the 2026, NA will build and test a **3x3 BSO matrix prototype** exploiting filter and waveform based discrimination of scintillation and Cherenkov signal.

Plan to test also BSO EM energy resolution by replacing the **central core** of the PWO matrix which allow achieving shower containment.

Possible test together with the HCAL

Two test beams allocated in May and July, at PS and SPS, respectively



Marcello Campajola - INFN Napoli

AI-LEGS: Algorithms for Imaging of Low Energy Gamma rays in Space

AI-LEGIS project synergic with the crystal and muon R&D
2 PhD positions founded at U. Parthenope

ICSC Spoke-3

A. D'Avanzo, F. Betta, A. Buono, M. Bossa, F.Cirotto, Francesco Conventi, C. Di Donato, P. Di Donato, F. Gargano, E. Rossi

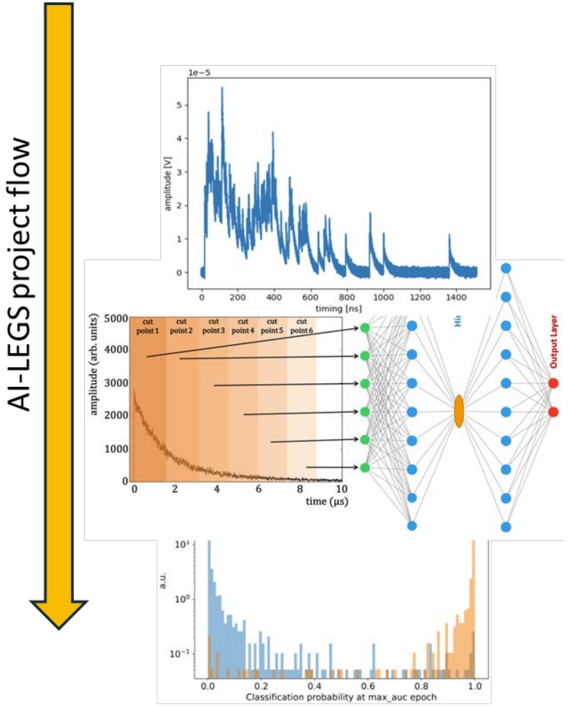
- **The goal of this project is to develop and test a DL algorithm based for low energy gamma ray imaging in space calorimeters:**

- Require a detailed MonteCarlo simulation of the experimental setup→ HEP sw tools (Geant4) + simulation of detector response
- Develop and test different ML architecture for gamma vs background PSD
- The proposed algorithms have been implemented and verified on CPU and GPU accelerated architectures to demonstrate the feasibility of using this algorithm in on-line applications as a trigger system.

➢ Geant4 code run on INFN Naples IBiSCo (Infrastructure for BIg data and Scientific COmputing) cluster → 3 machines available for use of multithreading Geant4 implementation (128 cores)

➢ IBiSCo also provides a GPUs cluster, consisting of 6 (nodes) x 2 GPUs

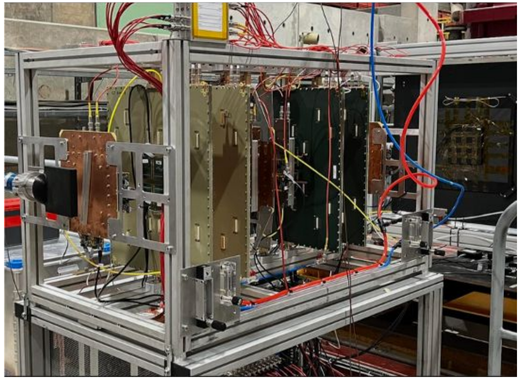
➢ CUDA support allows the use of Pytorch tensors allocated on GPU, thus speeding up the training process in case of further developing of more complex architectures for the ML task



Resistive Micromegas for MuonSystems at FCC-ee

slides from M. Della Pietra

Expression of Interest for ALLEGRO Muon System



Napoli & Roma3 INFN Groups

Mariagrazia Alviggi, Michela Biglietti, Kacper Chmiel, **Massimo Della Pietra**, **Camilla Di Donato**, Roberto Di Nardo, Ada Farilla, Mauro Iodice, **Paolo Iengo**, Romano Orlandini, **Simone Perna**, **Givi Sekhniaidze.**

Paolo has been appointed as Contact Person for ALLEGRO Muon System

The R&D proposal on Resistive Micromegas for Muon Systems for experimentsat FCC-ee was presented in 2024 and has been part of the **RD_FCC** activities since 2025 (LINK)

- **EoI ID0084 Resistive Micromegas detectors for Muon systems at FCC-ee**
- Presented to the 8th FCC Physics Workshop at CERN Satellite meeting 13-17 January 2025 (LINK)
- It represents one of the possible solutions, either on its own or in combinationwith multiple technologies for the IDEA muon system and/or ALLEGRO.
- EoI for ALLEGRO Muon System in March 2025
- https://indico.cern.ch/event/1475630/contributions/6214315/subcontributions/516749/attachments/2973058/5232866/Allegro_Micromegas_kickoff_22Nov2024_v2.pdf
- https://indico.cern.ch/event/1439855/contributions/6461614/attachments/3045992/5381959/ALLEGRO_Full_Detector_Concept_EoI-ESU-Mar27-2025.pdf

Requirements for Muon Systems @ FCC-ee

Similar dimensions for the Muon detectors for ALLEGRO and IDEA:

- ➔ Total surface Barrel: ~315 m2
- ➔ Total surface Both endcaps: ~2x75 m2 = 150 m2
- ➔ Tot surface: ~500 m2
- ➔ 3 - 4 layers for 100% efficiency / redundancy and tracking → 1500 - 2000 m2

Facilitate production by combining different technologies (e.g., Barrel/Endcap)

Requirements still to be studied in detail.

At the moment, only educated guess for Muon detection with tagging/tracking capabilities

- ➔ low-rate capability < 1 kHz/cm2
- ➔ Spatial resolution: 300 - 500 \mum in both coordinates or asymmetric (~ 0.2 mm / 1mm) for LLP tracking (?)
- ➔ Time resolution: few ns - 10 ns
- ➔ Efficiency: close to 100%
- ➔ Sustainable gas mixture

This low-rate drove the idea of capacitive-sharing layout to join 2D resistive MM detector high performances (robustness and high spatial resolution) with a reasonable number of read-out channels

Towards application for FCC-ee: Capacitive sharing

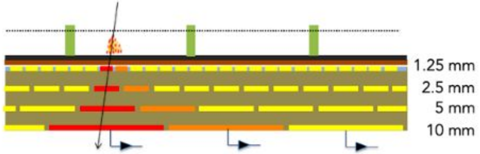
In 2024: Feasibility study of the Capacitive sharing concept

Leverage high-rate experience to create robust, simplified resistive Micromegas for **medium/low-rate environments** and large areas, like the FCC-ee muon system, at a reduced cost.

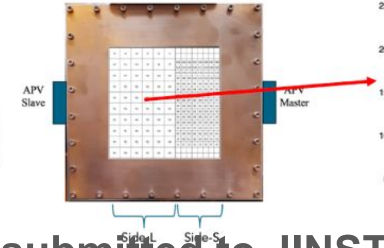
Medium/Low-rate Version – Capacitive Sharing

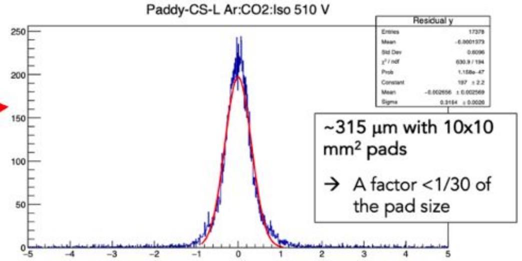
Concept from R. De Oliveira and K. Gnanvo et al., NIMA 1047 (2023) 167782)

SINGLE LAYER DLC Layout implementing the "capacitive sharing" concept, aiming at preserving good spatial resolution with a reduced number of readout channels:
Charge shared in large readout pads through the capacitive coupling between stack of layers of pads.



First Micromegas Prototype Built implementing the Capacitive Sharing layout





~315 µm with 10x10 mm^2 pads

→ A factor <1/30 of the pad size

Paper submitted to JINST

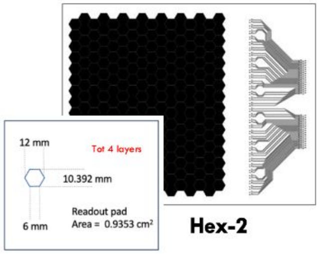
In 2025:

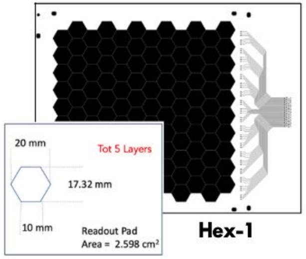
- **CS with larger area**

Two 40x50 cm2 chambers with different layout (rectangular or squared pads) and 3 layer of capacitive sharing

- **CS With Hexagonal pad shape**

Two chambers of medium area (20x20 cm2) with also a stack of 4 and 5 capacitive

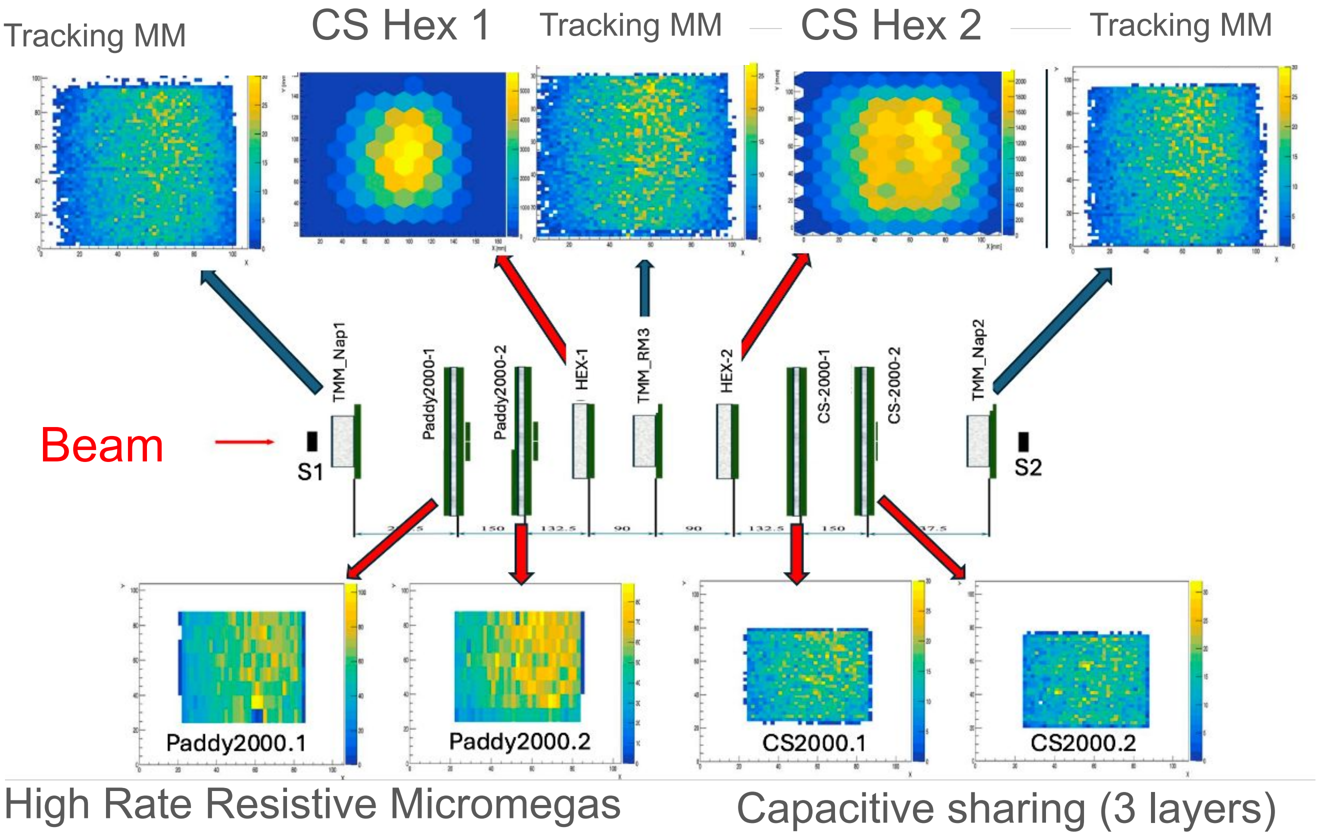




Tot number of pads: 256
Diameter of pads:
- internal layer: 1.5 mm
- Readout layer: 12 mm
- **Area readout pad: 0.94 cm²**

Tot number of pads: 120
Diameter of pads:
- internal layer: 1.25 mm
- Readout layer: 20 mm
- **Area readout pad: 2.6 cm²**

Preliminary test beam results (Nov. 2025)



All Resistive Micromegas
- 3 trackers
- 6 Detectors under test

Gas Mixtures:
- Ar-CO2-iC4H10 (93-5-2) [Nominal]
- Ar-CF4-iC4H10 (88-10-2)
- Ar-iC4H10 (98-2)

Front-end/DAQ:
- APV25 / SRS

Trigger:
- Two scintillators 10x10 cm2

Preliminary results: Standard vs Capacitive-sharing MM

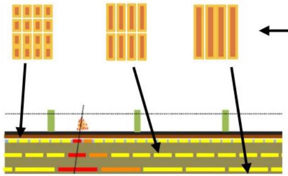
STANDARD

Pad pattern
Readout layer:
1x8 mm^2

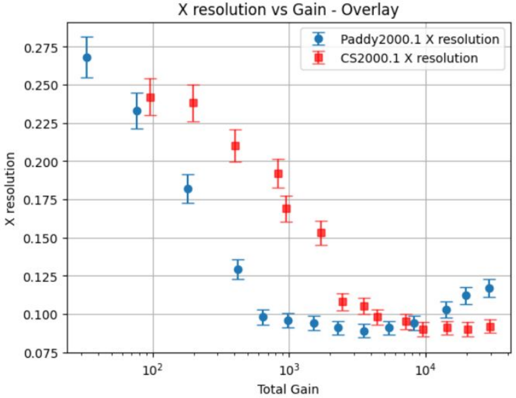
1st layer: 1x2 mm^2

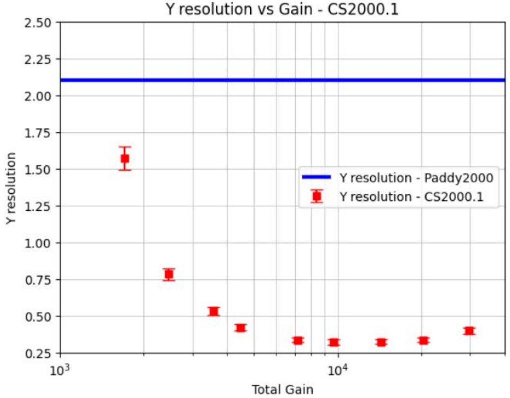
2nd layer: 1x4 mm^2

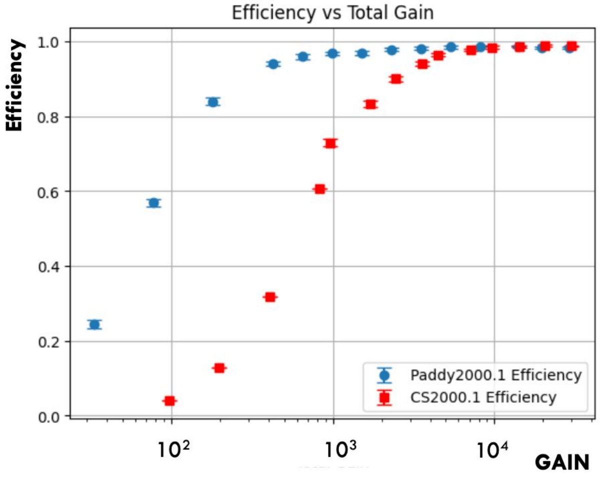
CS



Pad pattern
Readout layer:
1x8 mm^2



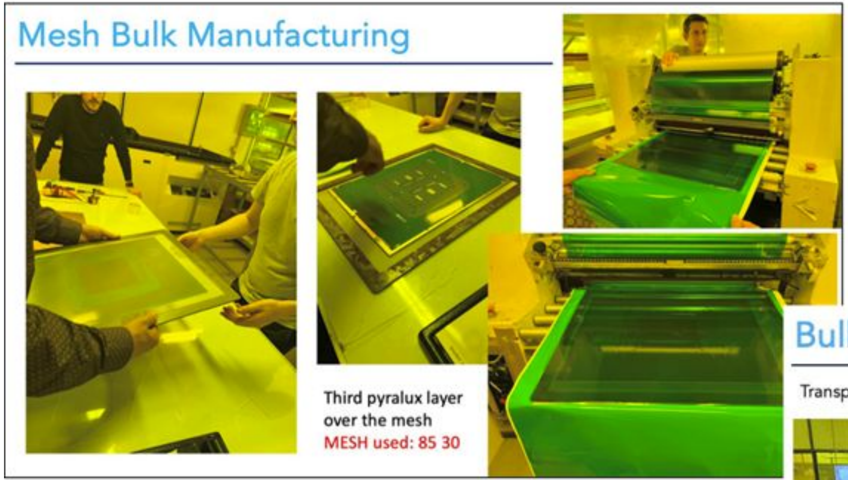




CS detector reaches full efficiency with higher gain as expected

X Coordinate - Same segmentation (1 mm pitch) resolution = 80 micron
Y Coordinate - standard 2.2 mm (8 mm pitch) CS 300 micron (1/27 pad pitch)

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.

Production of new prototypes ongoing:

Large bulk MM-chambers produced last week: to be tested.

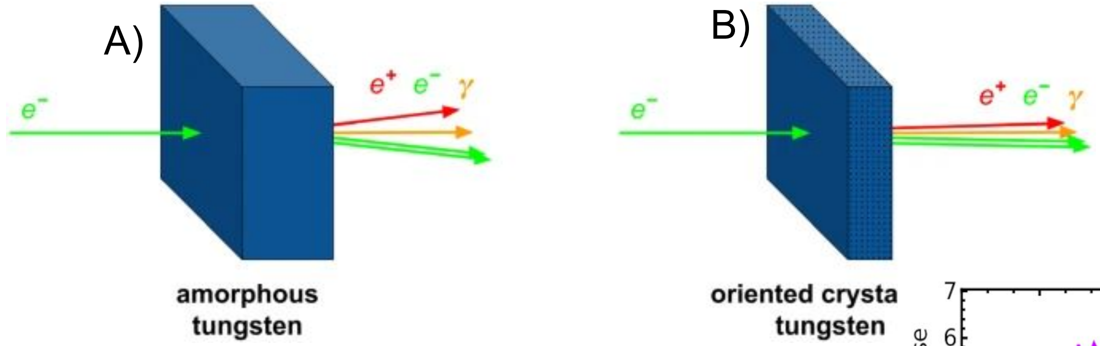
FCC-ee positron source (e+BOOST)

slides from O. Iorio

Progetto e+BOOST per sorgente di positroni

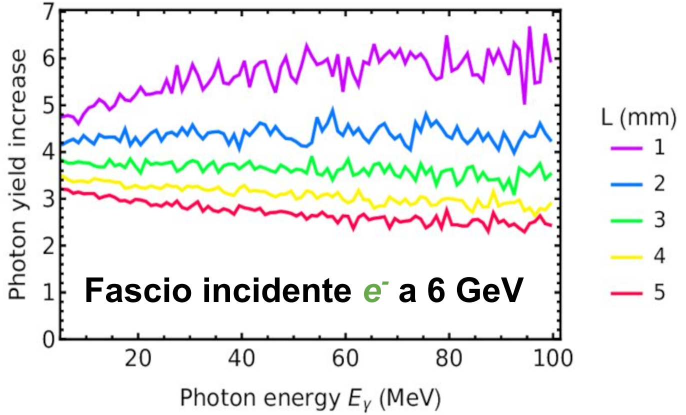
Progetto per migliorare la possibile sorgente di positroni di FCC-ee:

A) metodo "classico" di generazione positroni è bombardare un cristallo amorfo con e^-. Si ottengono fotoni che vanno convertiti in coppie. Ci sono limiti di **heat load e di energia depositata nel bersaglio**



B) metodo proposto nel prin: usare *cristalli orientati*:

- e- nella direzione dell'asse "incanalati" in forti campi elettrici
- produzione "radiazione coerente" - tutto il cristallo interagisce
- aumento fotoni prodotti a parità di lunghezza



Gruppo di Napoli coinvolto assieme a Ferrara e Insubria:

- O. Iorio (co-PI prin e+BOOST PRIN2022-2022Y87K7X)
- D. Boccanfuso (PhD SSM)
- S. Perna (PhD U.Parthenope)

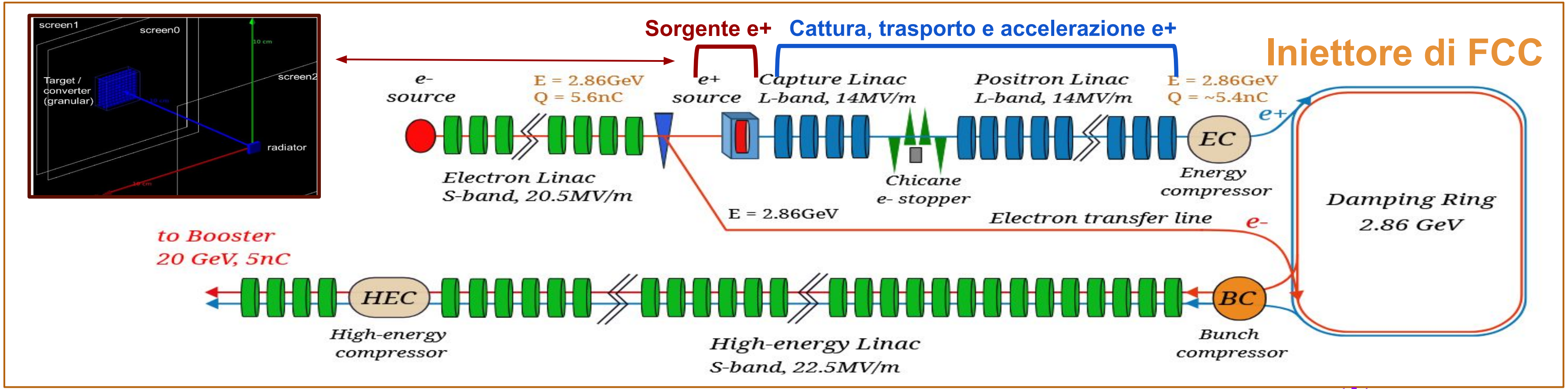
Funded by the European Union NextGenerationEU

Studio performances su FCC-ee

Attività prima fase: studio di performances

→ Si è simulato l'iniettore di FCC con una combinazione di

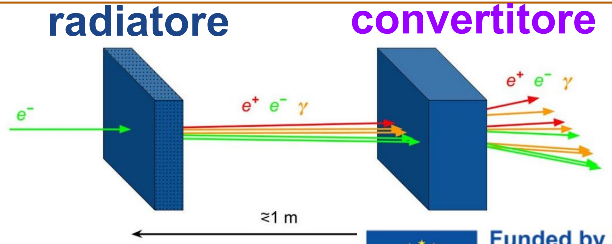
- **Geant4** per la parte di sorgente (Napoli, Ferrara)
- **RFTrack** per il **trasporto sorgente-anello di accumulazione** (sviluppato dall' IJCLab)



Challenge: dispersione angolare dovuta al trasporto

Soluzione: sorgente ibrida in due fasi:

- **radiatore** (cristallo orientato sottile)
- **convertitore** (cristallo amorfo spesso)



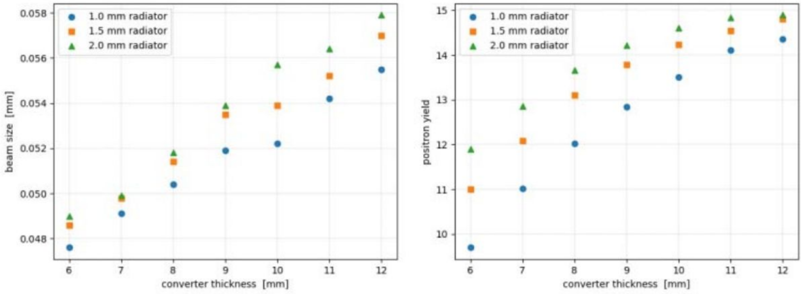
Funded by the European Union
NextGenerationEU

Risultati studi di performance

Ottimizzazione delle dimensioni radiatore/converter:

Per fasci ad energia 6 GeV - Il Nuovo Cimento 48 C (2025) 108 (D. Boccanfuso et al.)

Primi studi al variare della size delle dimensioni relative:



Confronto con una **sorgente convenzionale:**

Source type	Accepted Yield	PEDD [J/g/pulse]	Deposited Power [kW]
Conventional	7.0	7.67	1.13
Converter 7.0 mm	6.33	7.43	0.47
Converter 9.0 mm	7.22	6.88	0.65
Converter 12.0 mm	7.72	6.50	0.99

Per fasci a 2.86 GeV: NIMA 1075 (2025) 170412 (F. Alharthi et al.)

Parameter	Conventional	Crystal-based
Target thickness [mm]	15	12
e^+ production rate	7.1	7.6
Accepted yield at the DR	3.03	3.36
Primary e^- bunch charge [nC]	4.46	4.0
Deposited power in the target [kW]	1.14	0.98
PEDD in the target [J/g]	6.99	6.76

Parametri di merito/demerito:

+ Resa di positroni iniziale
+ Resa di positroni all'AdA
- Carica del fascio e- necessaria
- Potenza persa nel bersaglio
- Densità di energia max nel bersaglio (PEDD)

Funded by the European Union NextGenerationEU

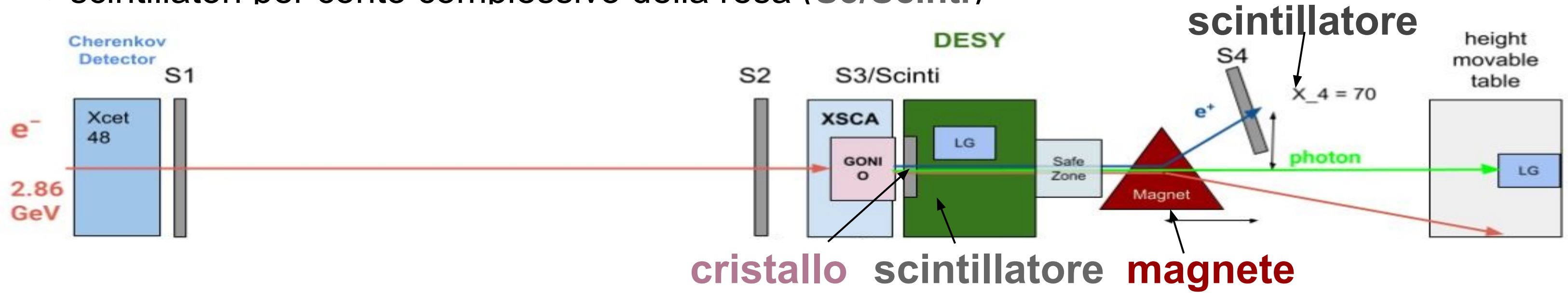
Test beam 2025

Messa in prova della resa di positroni reale:

→ Fascio di **e^- di 2.86 GeV** al sito di Meyrin incidente su un **cristallo situato su goniometro**

→ **campo magnetico** per curvare i positroni e rivelatore ad hoc (**S4**)

→ scintillatori per conto complessivo della resa (**S3/Scinti**)

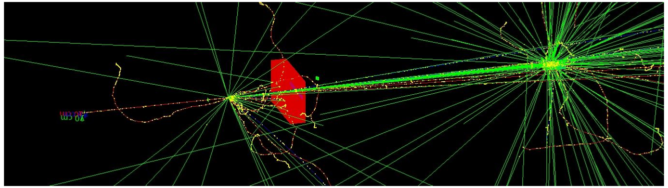


Presa dati a giugno 2025 → paper WIP

Simone Perna

Setup ottimizzato da studi MC

→ In particolare campo magnetico per massimizzare l'accettanza positroni su S4



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Piani per il futuro

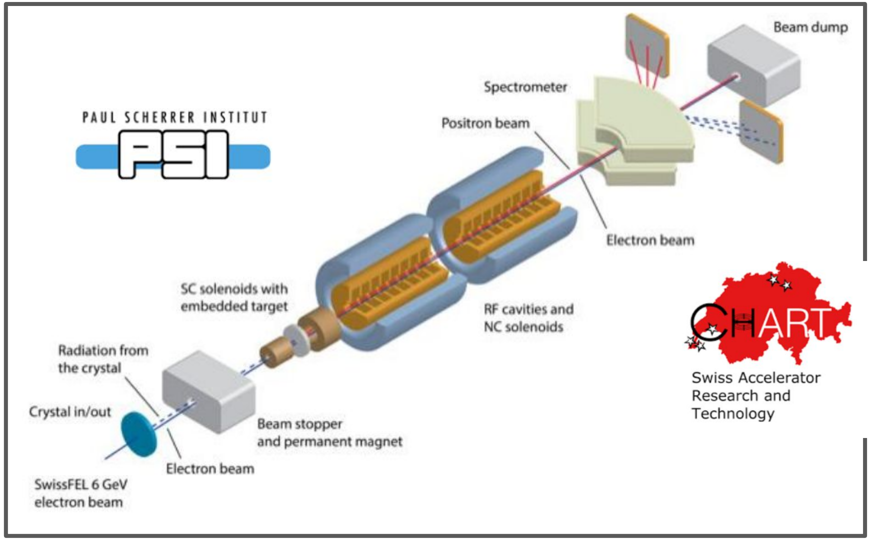
Nei prossimi ~5 anni:

→ Finalizzare lavoro su **risultati test beam 2025**

→ Studi di iniettore in diverse configurazioni (cristallo singolo, ibrida etc) a valle dei risultati ottenuti

→ Realizzazione di un **prototipo di iniettore di FCC** presso il **PSI**

Collaborazione **INFN** - **CHART** Svizzero su **progetto PSS** approvato l'anno scorso



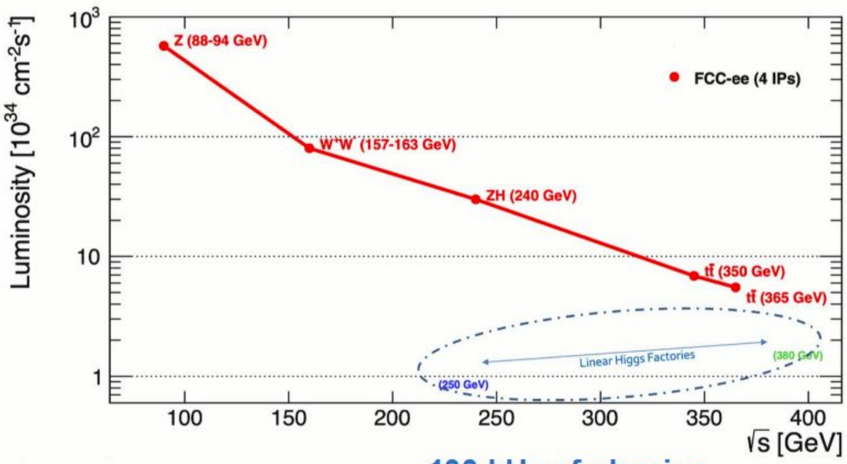
Pagina di CHART:

https://www.psi.ch/en/cas/fcc-ee-injector-design-and-psi-positron-source-pss-project

Thank you

Backup

Machine luminosity for physics at FCC-ee

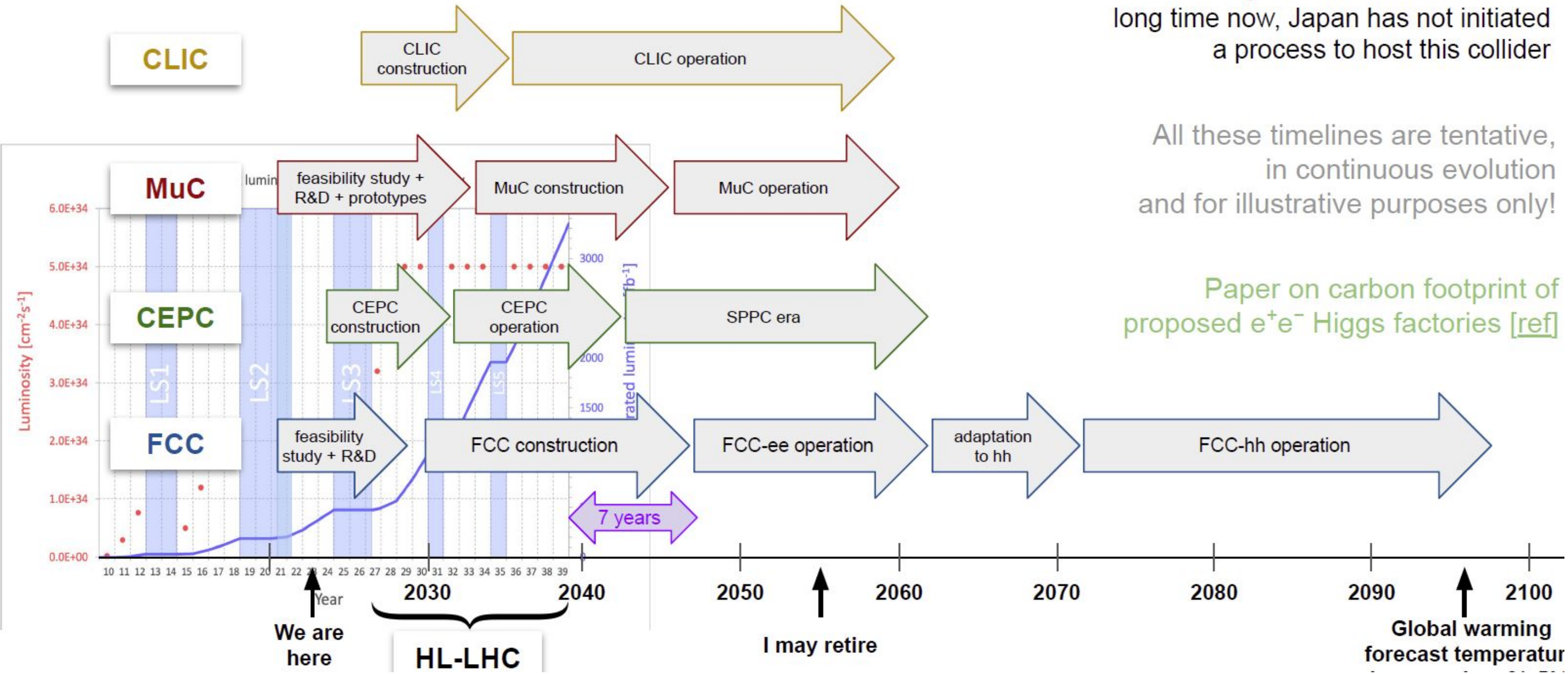


- Higgs factory:
  - 2.2×10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory:
  - 6×10^{12} $e^+e^- \rightarrow Z$ (LEPx10^5)
  - 2.4×10^8 $e+e^- \rightarrow W^+W^-$
  - 2×10^6 $e^+e^- \rightarrow tt$
- Flavor factory:
  - 5×10^{12} $e^+e^- \rightarrow bb, cc$
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$

~100 kHz of physics data at the Z pole

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

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]

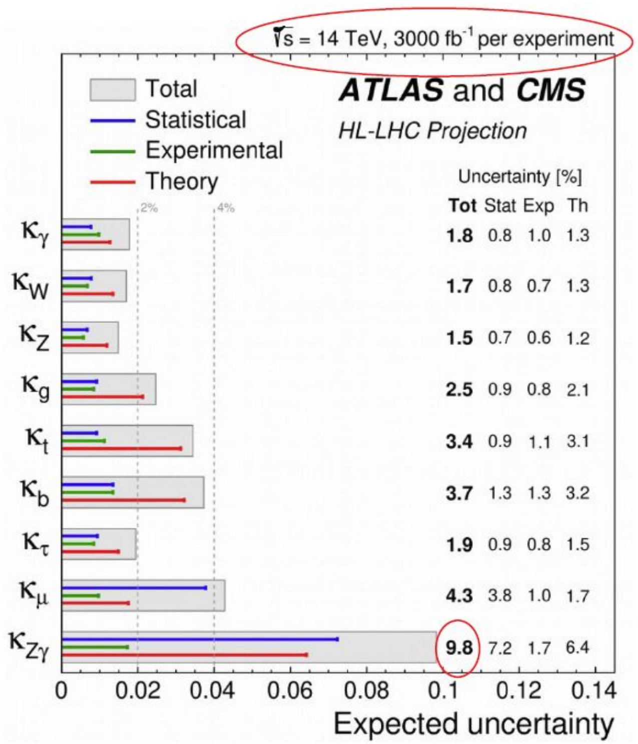
Precision Higgs physics

170 million Higgs bosons
120 thousand Higgs-boson pairs

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 → 4 lepton channel)
  - Higgs-boson **self-coupling** probed with **O(50%)** precision

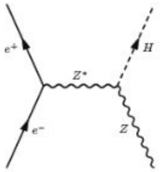
- **What will <u>not</u> be achieved**
  - Couplings to u, d, s, c quarks still not accessible at the LHC directly

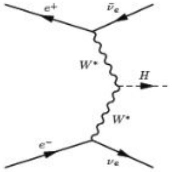


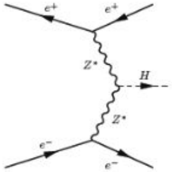
CERN Yellow Report on the Physics at the HL-LHC: https://cds.cern.ch/record/2703572?ln=en

Higgs production at FCC-ee

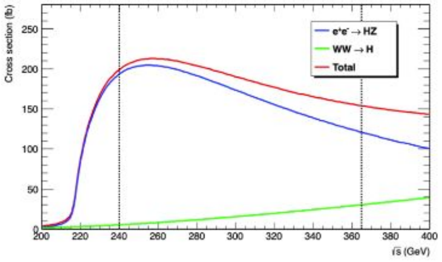
Higgs-strahlung or $e^+e^- \rightarrow ZH$







VBF production: $e^+e^- \rightarrow \nu\nu H$ (W fusion)
$e^+e^- \rightarrow He^+e^-$ (Z fusion)

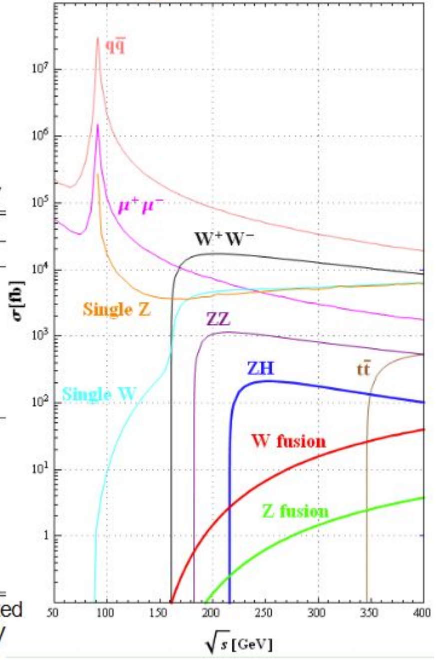


$\sqrt{s}$ = 240.0 GeV

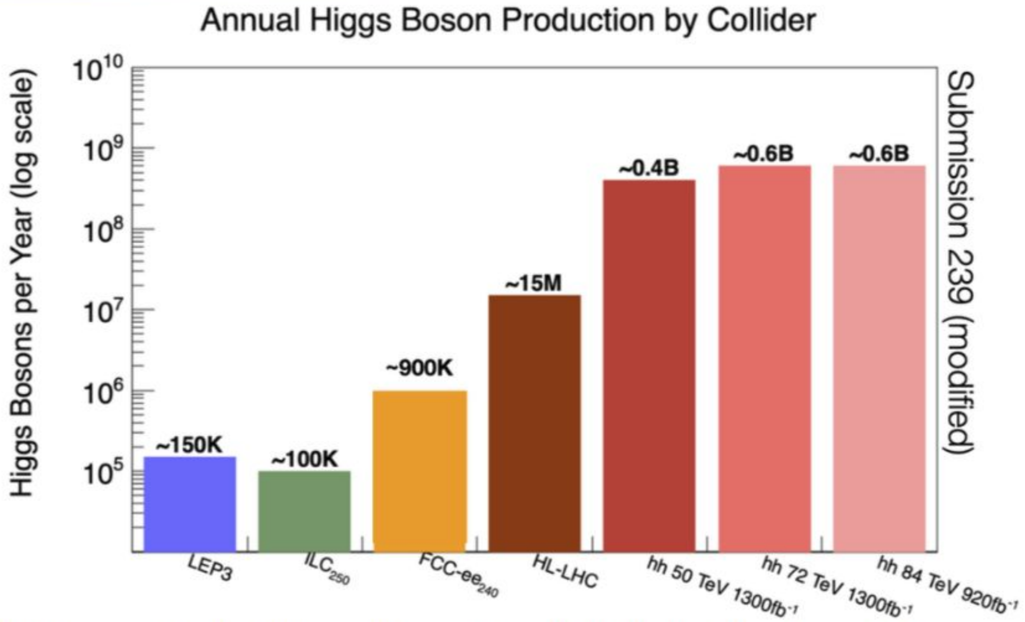
Process	Cross section
Higgs boson production, cross section in fb	
$e^+e^- \rightarrow ZH$	212
$e^+e^- \rightarrow \nu\bar{\nu}H$	6.72
$e^+e^- \rightarrow e^+e^-H$	0.63
Total	219
Background processes, cross section in pb	
$e^+e^- \rightarrow e^+e^-$ (Bhabha)	25.1
$e^+e^- \rightarrow q\bar{q}$	50.2
$e^+e^- \rightarrow \mu\mu$ (or $\tau\tau$)	4.40
$e^+e^- \rightarrow WW$	15.4
$e^+e^- \rightarrow ZZ$	1.03
$e^+e^- \rightarrow eeZ$	4.73
$e^+e^- \rightarrow e\nu W$	5.14

$\mathcal{L}$= 10.8 ab^{-1} in 3 years with 4 detectors located at 4 interaction points (IPs), at $\sqrt{s}$=240 GeV

Background sources



Higgs yield at colliders

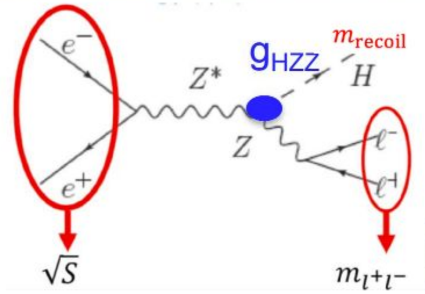


- e^+e^- colliders produce less Higgs bosons than the LHC, but they benefit from precise knowledge of initial stage and a "clean" experimental environment.
- *pp* colliders allow measurements of rare decays

- e^+e^- and *pp* colliders are complementary to fully explore the Higgs sector

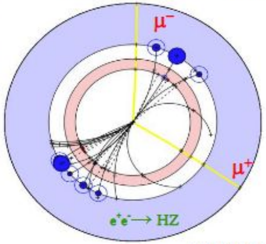
Global strategy for Higgs studies

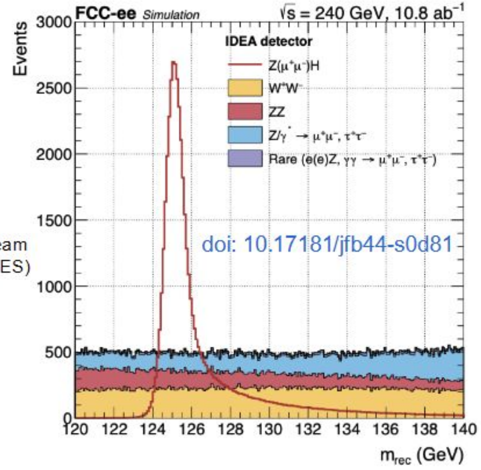
Eur. Phys. J. Plus 137(1), 23 (2022)



$\sigma(e^+e^- \rightarrow HZ) \propto g^2_{HZZ}$

ZH events tagged by the Z, without reconstructing the Higgs decay. Unique to lepton colliders.





e.g. when $Z \rightarrow$ leptons :

$$m^2_{\text{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

affected by the Beam Energy Spread (BES) and Initial State Radiation (ISR)

A fit to the recoil mass distribution allows:

- measurement of $\sigma(ZH)$ independent of the Higgs decay mode with **0.31 %** uncertainty. Hence an absolute determination on g_{HZZ}

  → **$\delta g_{HZZ}/g_{HZZ}$ ~ 0.1-0.2 %** (also including Z→had)

- a precise meas. of the **Higgs mass → $\delta m_H/m_H$ ~ O(MeV)** (w.r.t **20 MeV for HL-LHC**)

Easiest case: $Z \rightarrow$ lep.

- $Z \rightarrow$ had: more careful design of the analysis

N. De Filippis RD_FCC meeting, November 18, 2025 10

Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

$$\sigma_{ZH} \times \mathcal{B}(H \to X\bar{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

H → ZZ* provides Γ_H : $\frac{\sigma(e^+e^- \to ZH)}{BR(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{SM} \times \Gamma_H$

→ **$\delta\Gamma_H / \Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, …

→ deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

Select events with H → "nothing" → deduce Γ(H→invisible)

→ **$\delta g_{XX}/g_{XX}$ ~ 1 %**

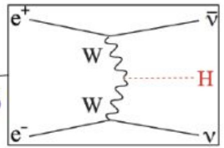
a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

$$\sigma_{H\nu_e\bar{\nu}_e} \times \mathcal{B}(H \to X\bar{X}) \propto \frac{g^2_{HWW} \times g^2_{HXX}}{\Gamma_H}$$

First ννH → ννbb ~ $g_{HWW}^2\, g_{Hbb}^2 / \Gamma_H$

- ννbb / (ZH(bb) ZH(WW) ~ g_{HZZ}^4 / Γ_H = R → Γ_H precision at 1%



Then do ννH →ννWW ~ g_{HWW}^4 / Γ_H

- R / ννWW ~ g_{HWW}^4 / g_{HZZ}^4
- g_{HWW} precision to few permil

At the end: Higgs couplings and Γ_H extracted from a glob fit to all σ x BR (Kappa framework, SMEFT framework)

N. De Filippis RD_FCC meeting, November 18, 2025 11

Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

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→ **$\delta\Gamma_H / \Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, …

→ deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

Select events with H → "nothing" → deduce Γ(H→invisible)

→ **$\delta g_{XX}/g_{XX}$ ~ 1 %**

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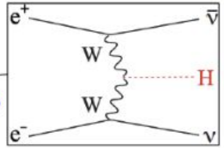
First ννH → ννbb ~ g_{HWW}^2 g_{Hbb}^2 / Γ_H

- ννbb / (ZH(bb) ZH(WW) ~ g_{HZZ}^4 / Γ_H = R → Γ_H precision at 1%

Then do ννH →ννWW ~ g_{HWW}^4 / Γ_H

- R / ννWW ~ g_{HWW}^4 / g_{HZZ}^4
- g_{HWW} precision to few permil

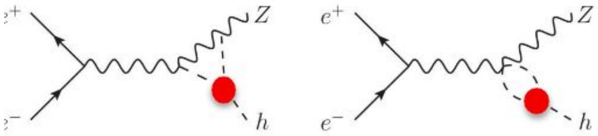


At the end: Higgs couplings and Γ_H extracted from a global fit to all σ x BR (Kappa framework, SMEFT framework)

Higgs self coupling at FCC-ee ($\sqrt{s}$ < 500 GeV)

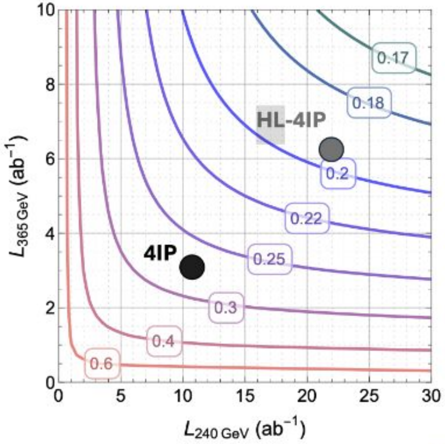
NB: 365 GeV → ZHH threshold, but too low ZHH x-secti

λ_3 affects single-Higgs prod at NLO



e.g. 100% variation on λ_3 modifies σ(ZH) by ~ 2% at 240 GeV and ~ 0.5% at 365 Ge
Larger than / comparable with the exp. precision on σ(ZH)

Precise measurement of σ(ZH) constrains a combination of λ_3 and g_{HZZ}.
Measurements at two values of $\sqrt{s}$ needed to determine separately λ_3 and g_{HZZ}.



- Recent: 4 IPs. Running at $\sqrt{s}$ = 240 and 365 GeV

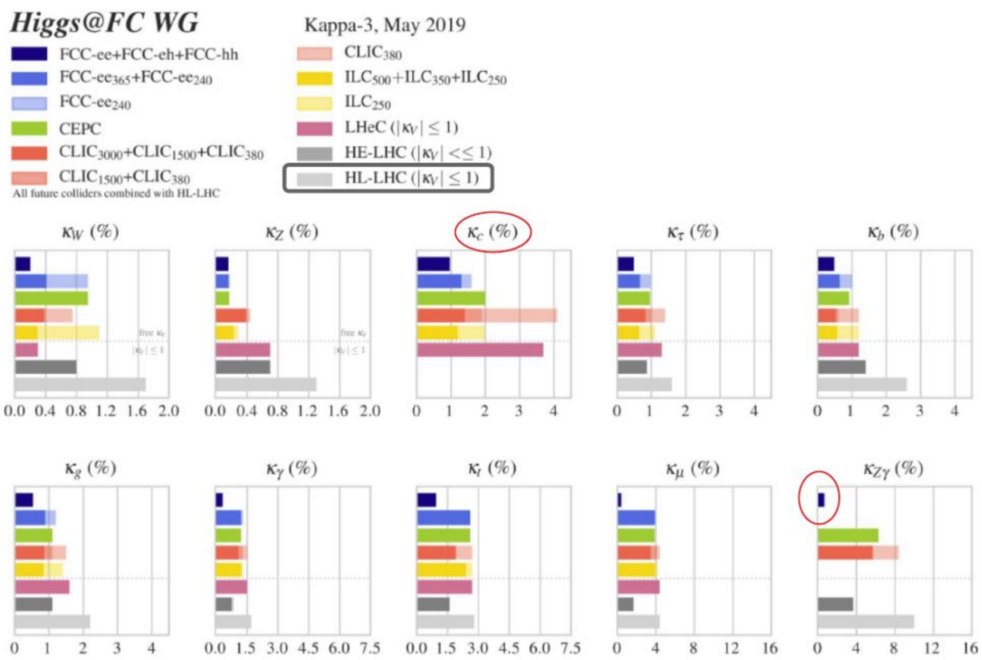
→ **$\delta\kappa_\lambda$ ~ 28% for FCC-ee**
~ 18% (combining with HL-LHC)

arXiv:2505.00272v1

With 4 IPs: 5σ observation of λ_3 within reach with 15 years of operation at FCC-ee

N. De Filippis RD_FCC meeting, November 18, 2025 22

Precision Higgs physics



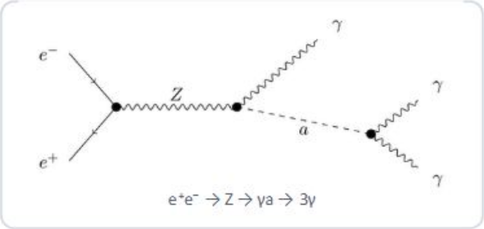
- **An e^+e^- Higgs factory can measure these couplings with smaller uncertainties** than HL-LHC due to:
  - Better knowledge of the momentum of the incoming particles
  - Smaller background environments
  - Better detector resolutions
- Model-independent measurements of the **Higgs boson width to the 1% level** (invariant mass of $Z \rightarrow e^+e^-$ recoil in Higgsstralhung)
- **Higgs self-coupling below 10%**

Missing Energy
Characteristic of invisible decays (Higgs → invis, Z→ γ + invis, ,$A' \rightarrow$ dark matter, etc.). Need excellent hermiticity.

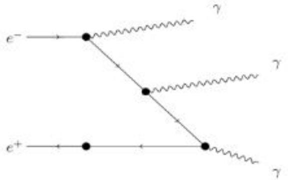
Displaced Vertices (LLPs)
Vertex detector: high granularity silicon pixels to locate decay ~10 μm accuracy.
Tracking volume: large radius to catch late decays.
Low beam backgrounds at FCC-ee simplify LLP searches.

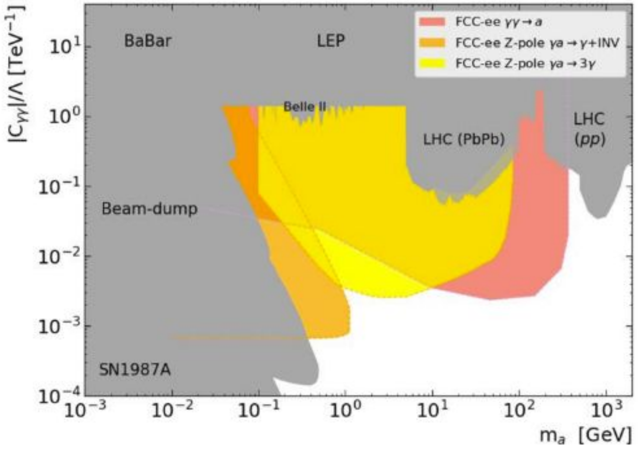
Resonances
Peaks in invariant mass distributions (e.g. dilepton resonances from A').
Requires high resolution tracking/calorimetry to distinguish narrow bumps.
Also large statistics and controlled systematics

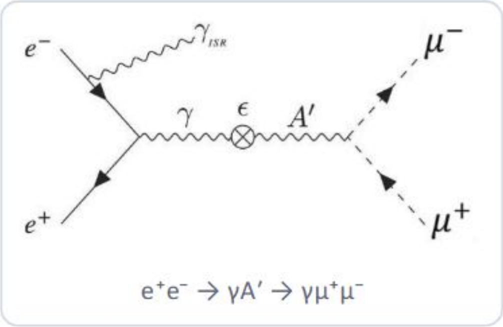
Trigger/Timing
FCC-ee can likely run trigger-less. Picosecond timing layers in calorimeter and tracking can tag delayed decays and remove background

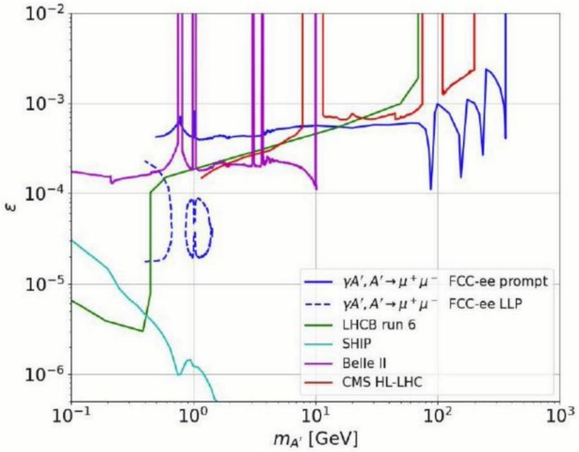


ALP Background: $e^+e^- \to \gamma\gamma\gamma$









Detector requirements from physics case drivers

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/$\sqrt{E}$ 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 $\mu\mu$)
- Stability of B-field to 10^{-6} : stability of $\sqrt{s}$ meast.

Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ $\sqrt{E}$ 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 $\rightarrow$ νN, with N decaying late

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

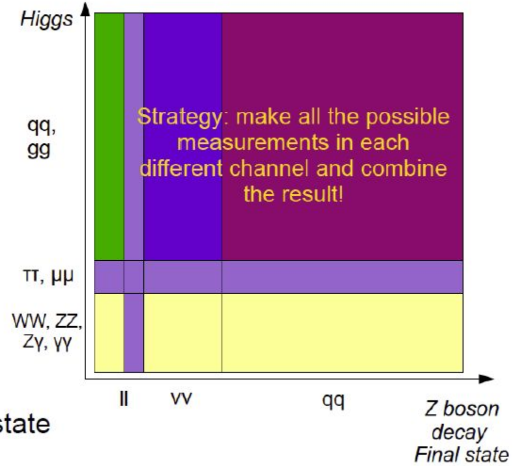
Precision Higgs physics

- 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

Key benchmarks for calorimetry

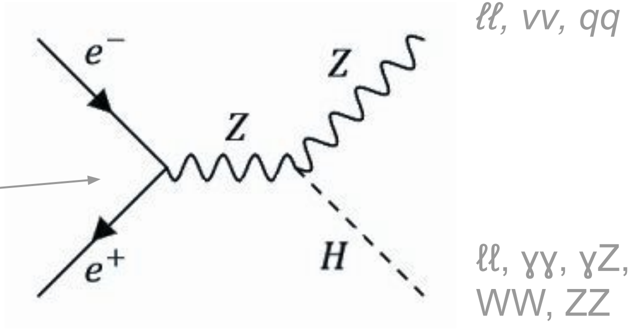
Jet energy resolution is a key benchmark of e+e- detector performance

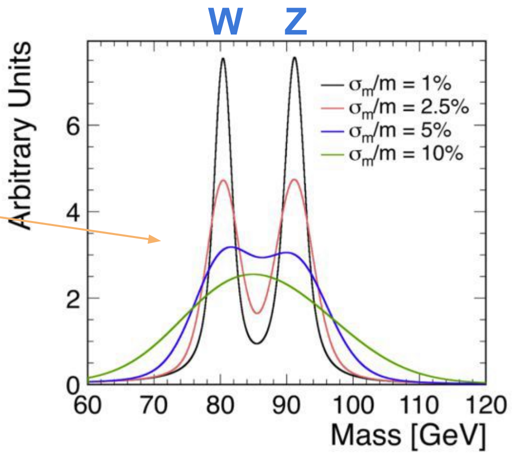
- Higgs production at **e+e- colliders** (@√s~250 GeV) is mainly through **higgsstrahlung**
  - **97%** of the SM higgsstrahlung signal has **jets in the final state**
- Need a calorimeter with **~30%/√E** (~3-4% @90 GeV) to distinguish jets from W or Z bosons

⇩

Hard to achieve with traditional calorimetry!

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





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.

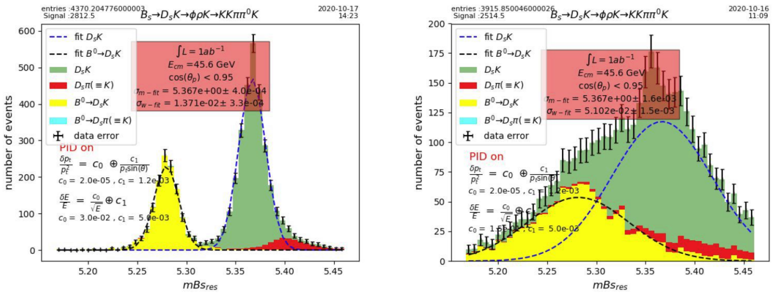
- Precision reconstruction of final states with **low energy photons (and π^0)**
  - reconstruction of exclusive b and tau decays
  - improve performance of jet clustering algorithms
- Reduce effect of **bremsstrahlung on electron resolution**

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

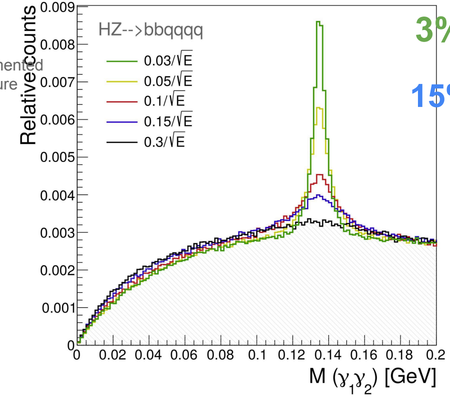
3%/√E

[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

The detector challenge

The physics case drivers

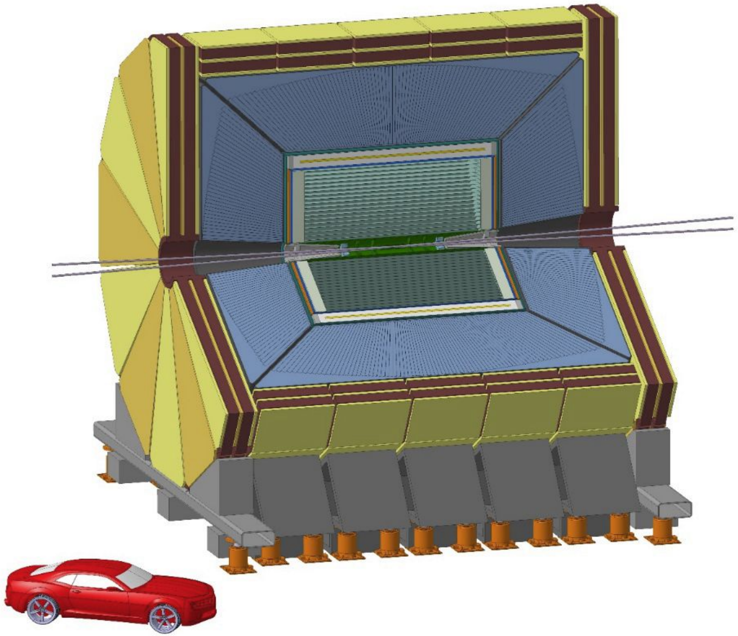
	Critical detector	Requirement	Comments
$ZH \to \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2 \cdot 10^{-5}$	But also precision EW, flavour, BSM
$H \to b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu\text{m}]$	Additional 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

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

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 29×29 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				CMS	
	Barrel LAr/Tile		End-cap LAr			
	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

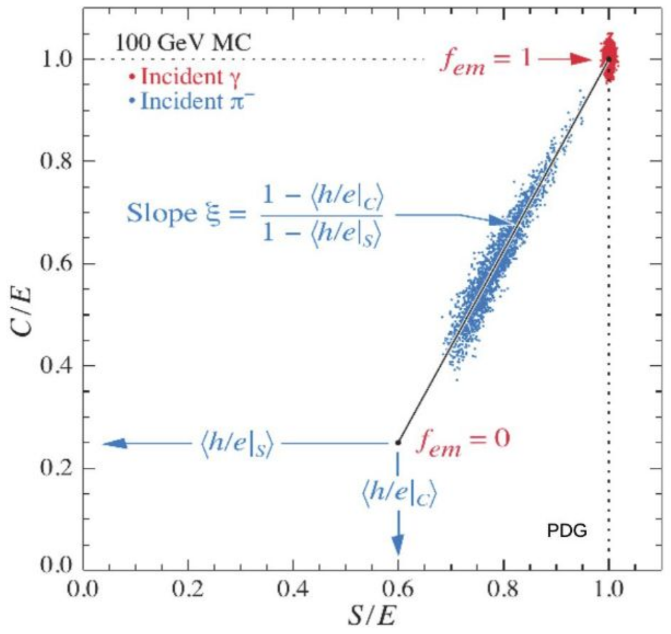
Dual readout strategy in crystals

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

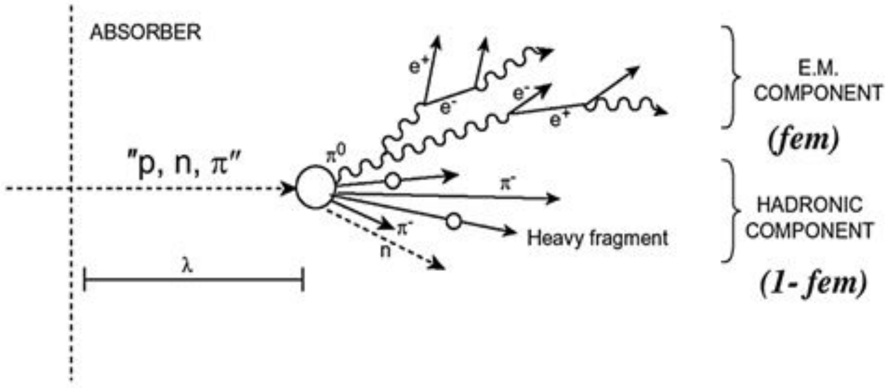


S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002

Challenges of hadronic calorimetry

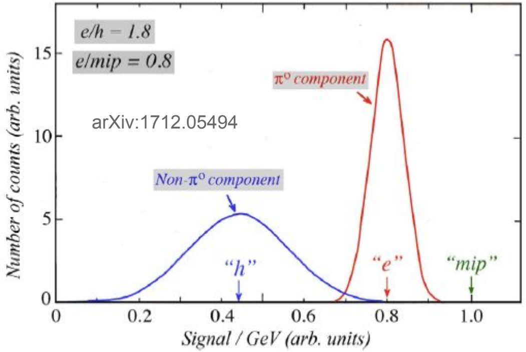
Hadronic calorimetry is hard!

- 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)

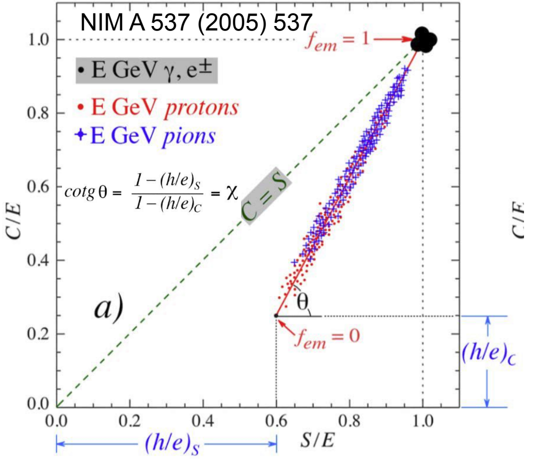
$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

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

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

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

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



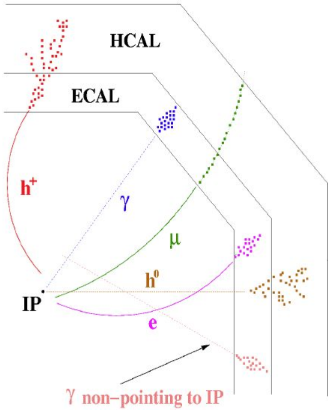
Challenges of hadronic calorimetry

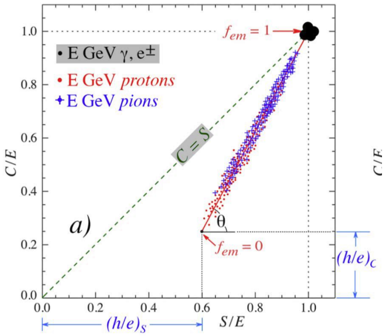
Two general approaches to cure it

- **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

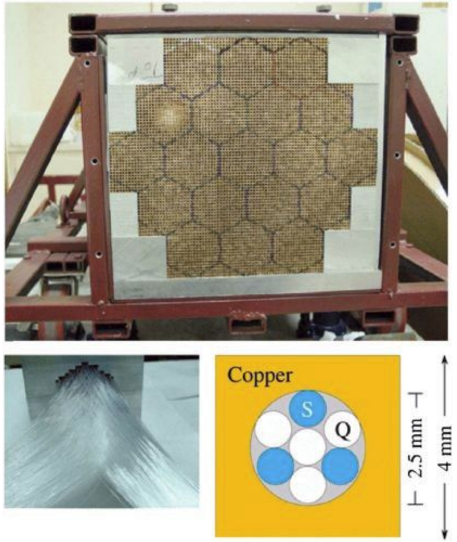


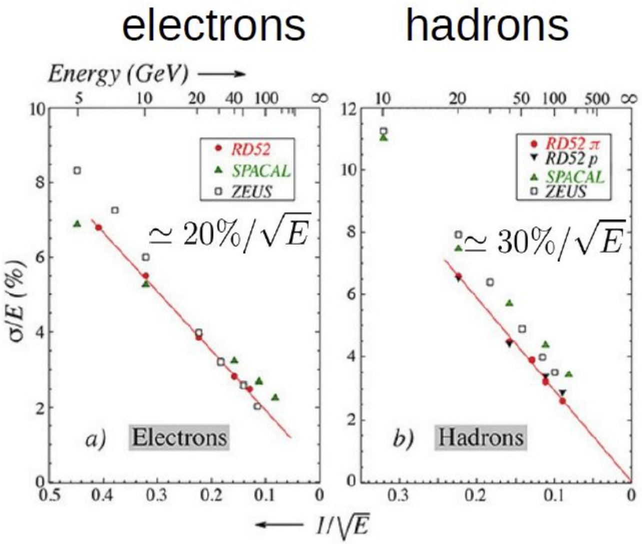


Dual-readout calorimetry on work

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**

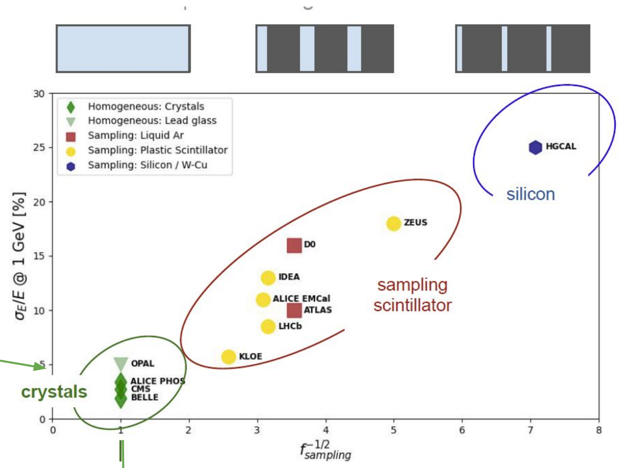




DREAM/RD52 collaboration

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



any solution?

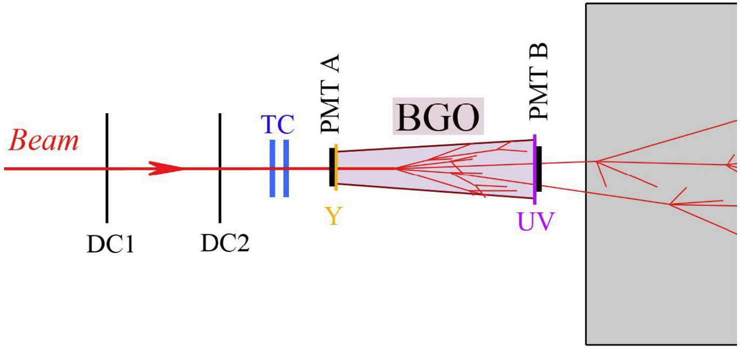
➔ combine the best of both (hadronic and EM) worlds with an **hybrid dual-readout crystal and fiber calorimeter**

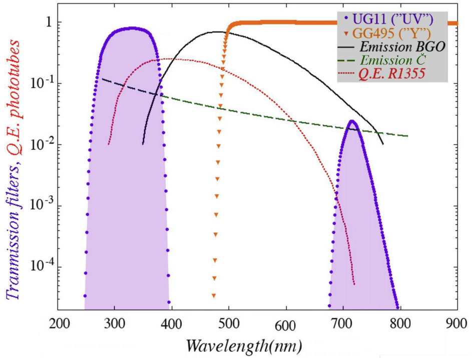
Technology (Experiment)	Depth	Energy resolution
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$

Dual readout strategy in crystals

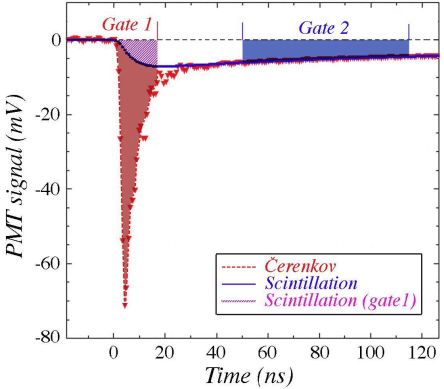
DREAM/RD52 demonstrated DRO proof-of-concept in crystals

- 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

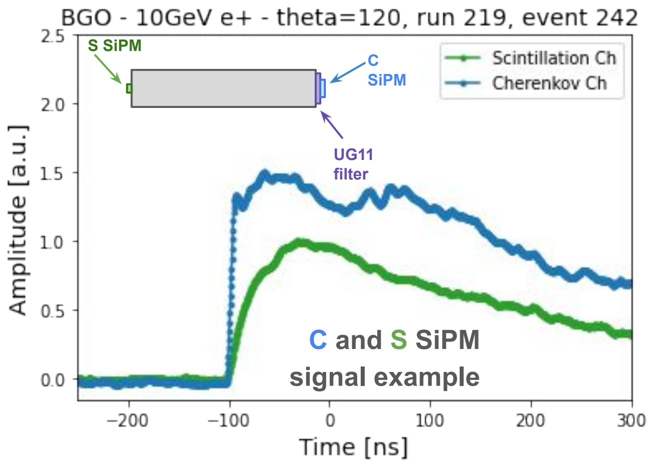


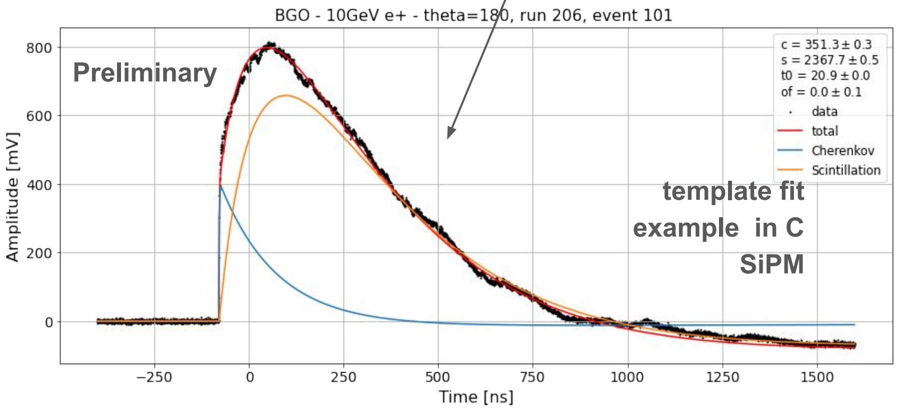
Nucl. Instr. And Meth. A 598 (2009) 710

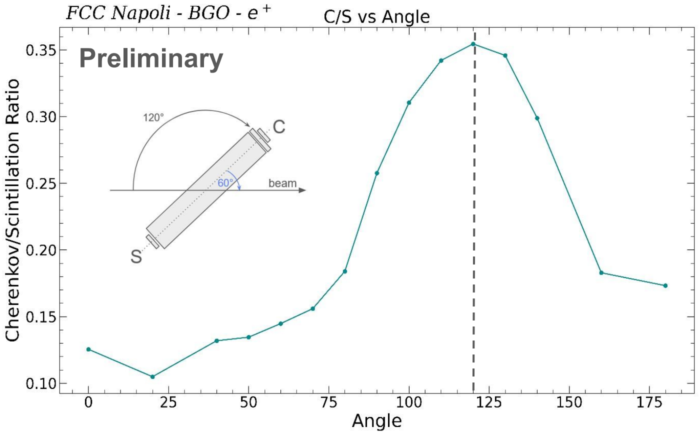
Highlights from CERN TB

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

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

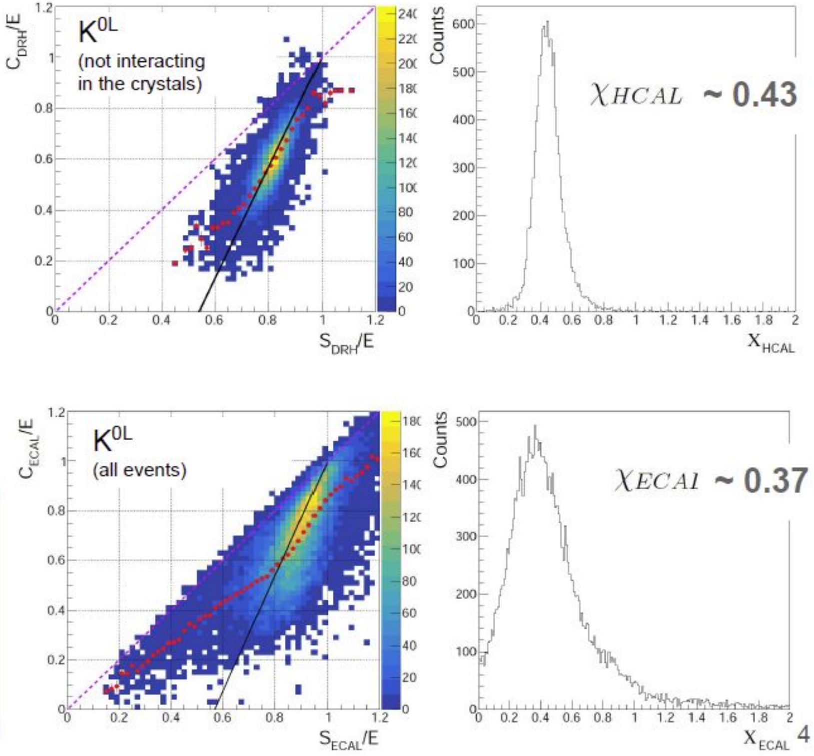
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

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

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

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

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

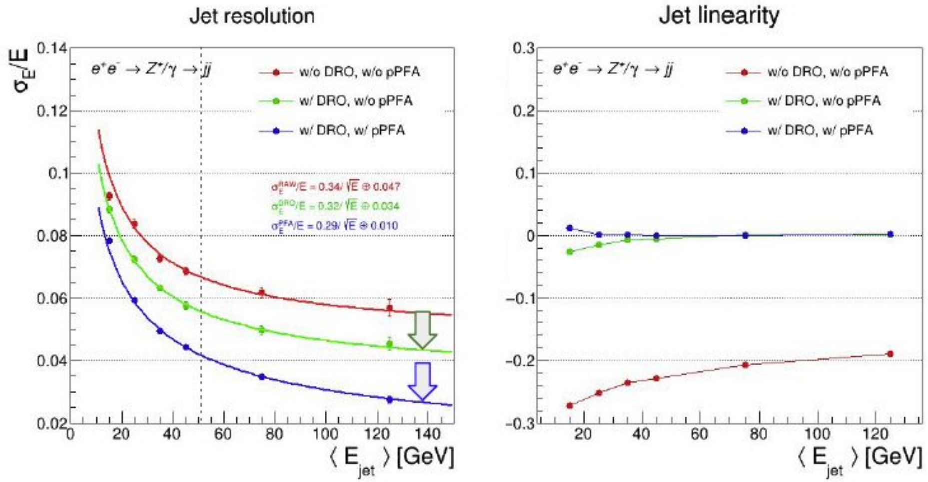


Jet resolution: with and without DR-pPFA

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):

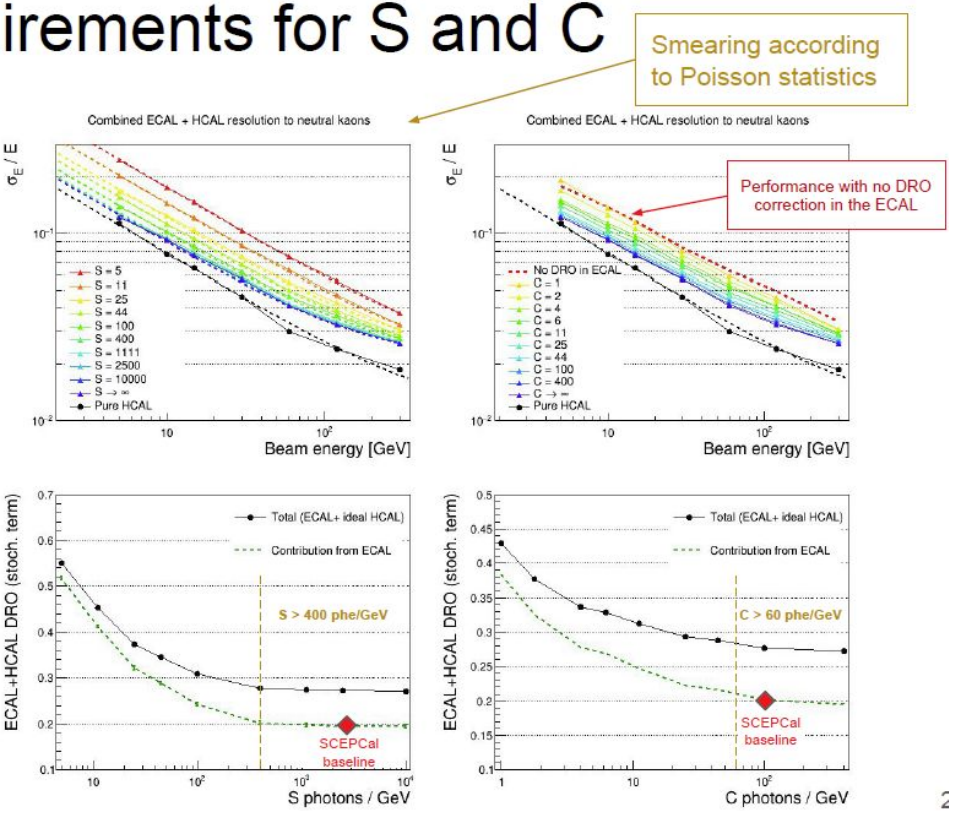
- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



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

arXiv:2203.04312v2

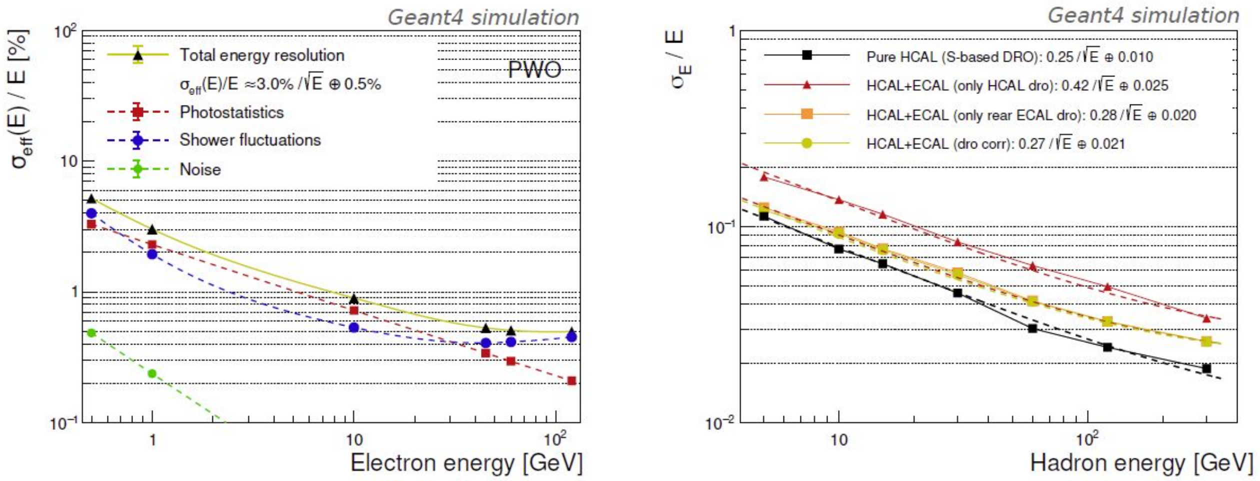


Figure 15: Simulated resolutions for a combined dual-readout crystal ECAL and a dual-readout spaghetti HCAL from Ref. [5], for a pure dual-readout spaghetti, for that with a conventional crystal EM, and that with a dual-readout crystal EM calorimeter. Note that the energies of particles produced at electron-positron 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.

ECAL key design features

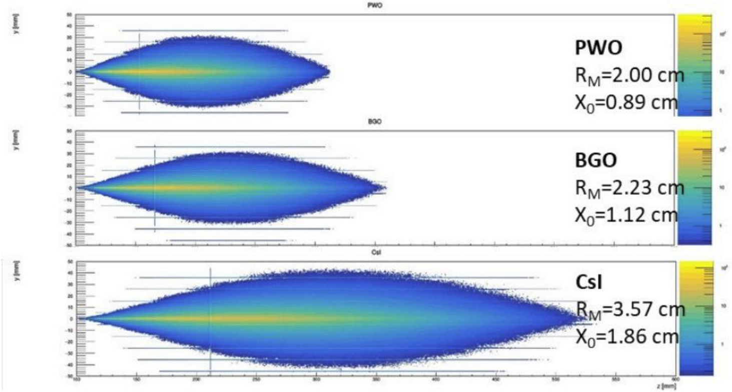
Crystal requirements:

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

Crystal	Density g/cm^2	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



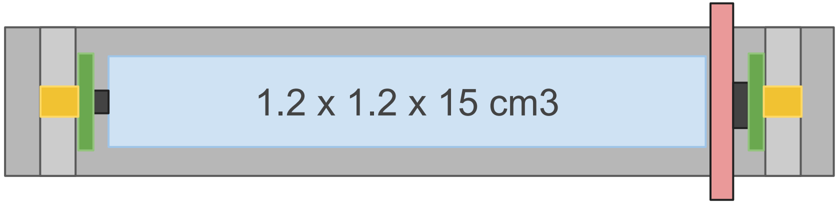
- PWO: Fastest, most compact;
- CsI: the brightest, least compact
- BGO: in between the two

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)



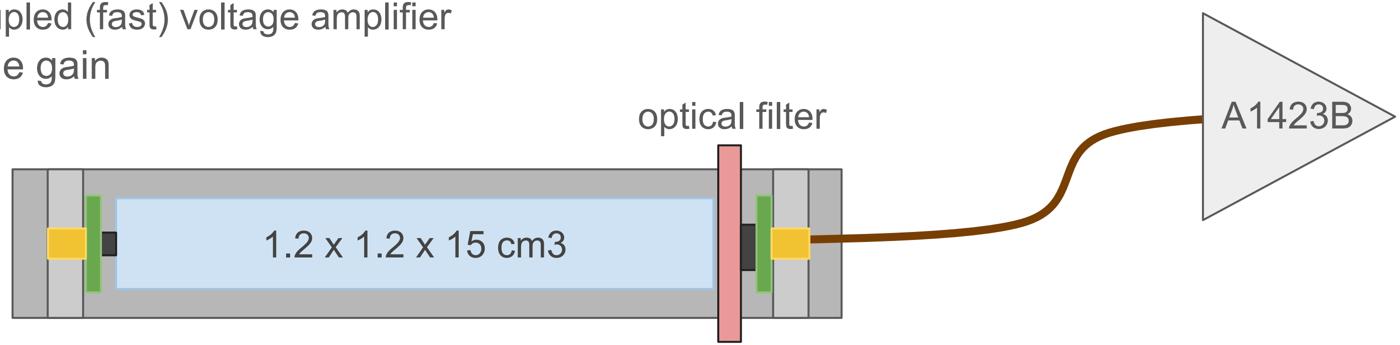
Scintillation side
SiPM 3x3 mm2
HPK S14160-3010

Cherenkov side
SiPM 6x6 mm2
HPK S14160-6050

SiPM front end (Setup B)

2x CAEN A1423B Wide band (1.5 GHz) preamplifier

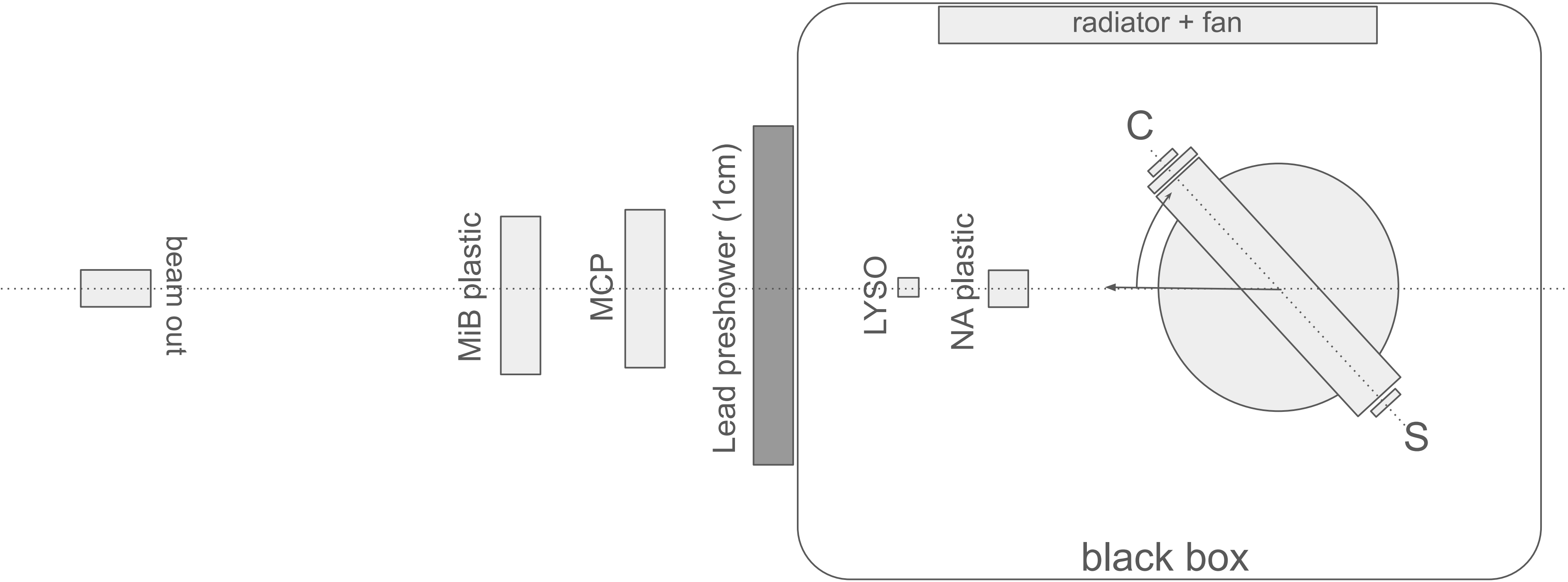
- AC coupled (fast) voltage amplifier
- Variable gain



Scintillation side
SiPM 3x3 mm2
HPK S14160-3010

Cherenkov side
SiPM 6x6 mm2
HPK S14160-6050

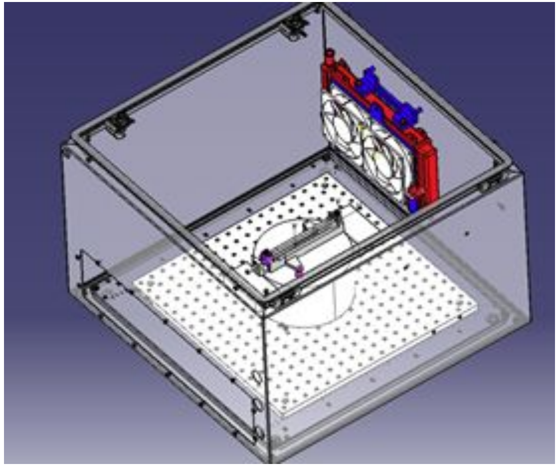
Setup schematic

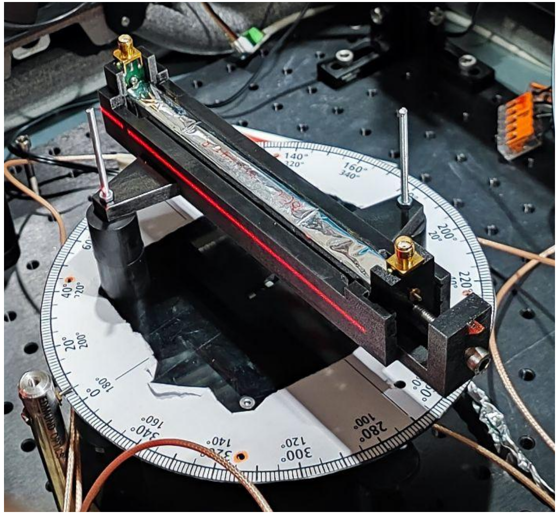


Setup mechanics

- 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

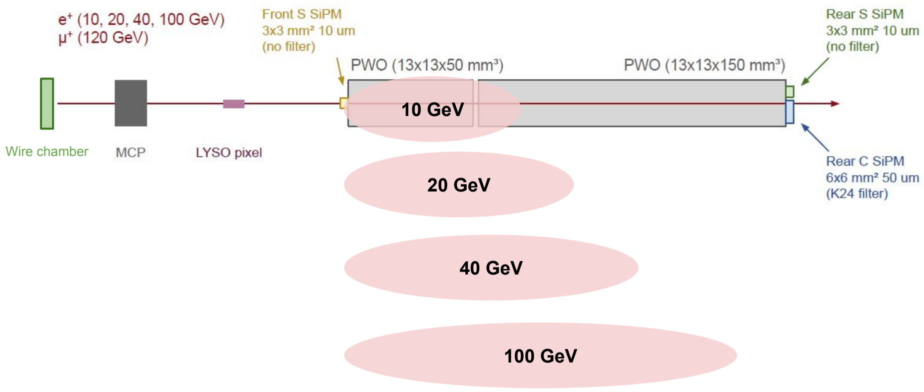


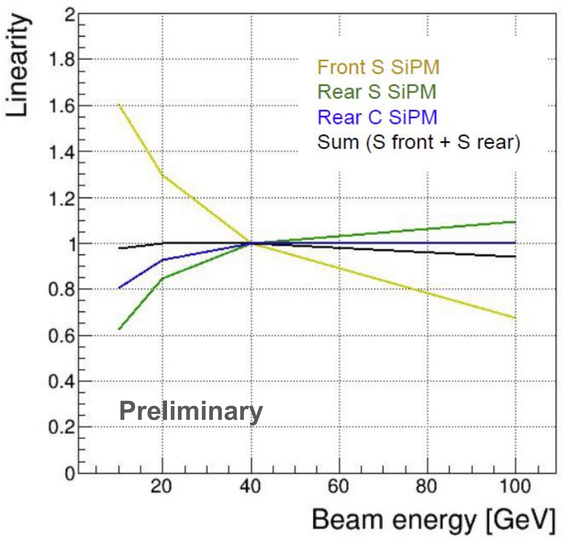


Highlights from CERN TB

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**





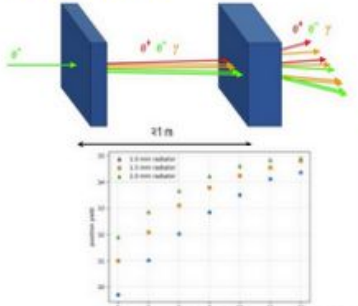
Studio performances su FCC-ee (versione 1slide)

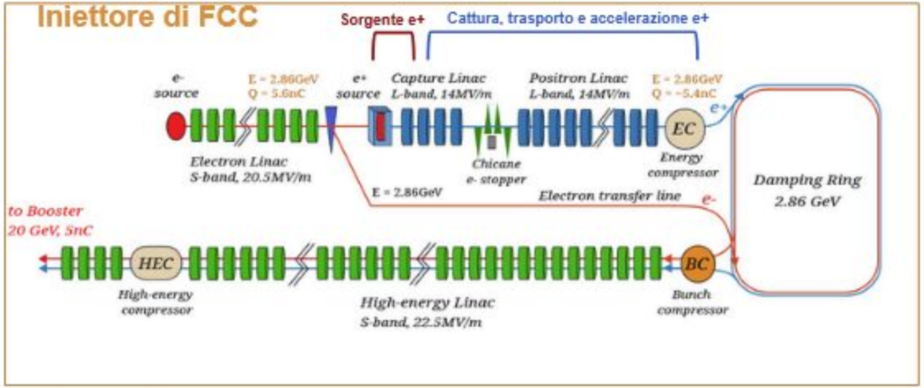
Attività prima fase: studio di performances

→ Si è simulato l'iniettore di FCC con una combinazione di

- **Geant4** per la parte di sorgente (Napoli, Ferrara)
- **RFTrack** (sviluppato dall' IJCLab) per il **trasporto sorgente-anello di accumulazione**

Studi di schema ibrido per fasci ad energia 6 GeV in [Il Nuovo Cimento 48 C (2025) 108]:





...FCC-ee e^+ source optimization results.

Parameter	Conventional	Crystal-based
Target thickness [mm]	15	12
e^+ production rate	7.1	7.6
Accepted yield at the DR	3.03	3.36
Primary e^- bunch charge [nC]	4.46	4.0
Deposited power in the target [kW]	1.14	0.98
PEDD in the target [J/g]	6.99	6.76

Risultati per fasci di 2.86 GeV in [NIMA 1075 (2025) 170412]

Parametri di merito: **miglior produzione e rate in arrivo**

Fattori soppressi con successo: **carica necessaria, potenza / energia max nel bersaglio**

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Riferimenti

Prodotti del PRIN:

Study of a high intensity positron source based on oriented crystals, D. Boccanfuso et al.

Il Nuovo Cimento 48 C (2025) 108

FCC-ee positron source from conventional to crystal-based, F.Alharthi et al.
NIMA 1075 (2025) 170412

Letteratura introduttiva al progetto:

Geant4 simulation model of electromagnetic processes in oriented crystals for accelerator physics

https://arxiv.org/abs/2303.04385

Crystal-based pair production for a lepton collider positron source

https://link.springer.com/article/10.1140/epjc/s10052-022-10666-6

Letteratura precedente in materia:

A positron source using channeling in crystals for linear colliders

https://www.worldscientific.com/doi/abs/10.1142/S0217751X10049955

Experimental study of a crystal positron source

https://www.sciencedirect.com/science/article/pii/S0370269301013958

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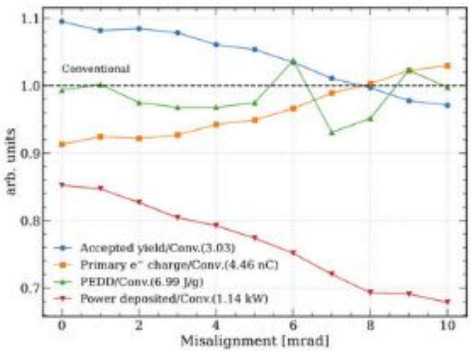
Altri risultati:

Studi di allineamento

→ La struttura dell'injector prevede una distanza minima di 1m tra radiatore e convertitore

→ Si è studiata la dipendenza dall' **allineamento rispetto alla direzione di channeling**

→ risultati restano buoni entro l'errore sperimentale atteso sull'allineamento



Altri confronti: SuperKEKB

→ FCC avrà una yield 9 volte quella di SuperKEKB (con il convenzionale)

→ Potrebbe fare meglio almeno di un ulteriore ~10% in yield al DR secondo i risultati di e+BOOST

Parameter	SuperKEKB [3]	FCC-ee
Primary e^- energy [GeV]	3.5	2.86
Target thickness [mm]	14	15
Matching device, maximum field on the target [T]	4.4	12
Maximum RF cavity aperture [mm]	30	60
Accepted e^+ yield at DR per GeV	0.114	1.05

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Prin e+BOOST

Intense positron source Based On Oriented crySTals - e+BOOST

Sviluppo di una sorgente di elettroni-positroni basato su una tecnologia a cristalli orientati

Gruppi coinvolti:

INFN Ferrara

Responsabile: Laura Bandiera (Ricercatore INFN, **PI**),

Partecipanti: Susanna Bertelli (Tecnologo), Marco Romagnoni (Assegnista)

UniInsubria

Responsabile: Michela Prest (PO)

Partecipanti: Luca Bomben (Dottorando)

Federico II

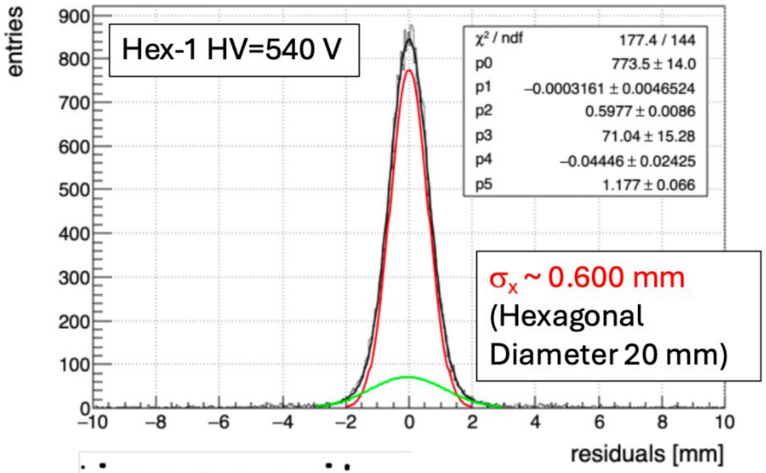
Responsabile : Orso Iorio (PA, Co-PI)

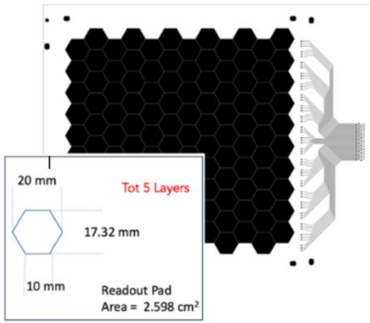
Partecipanti : A. De Iorio (Assegnista), F. Carnevali (Dottorando) A. Cagnotta (Dottorando)

Funded by the European Union NextGenerationEU

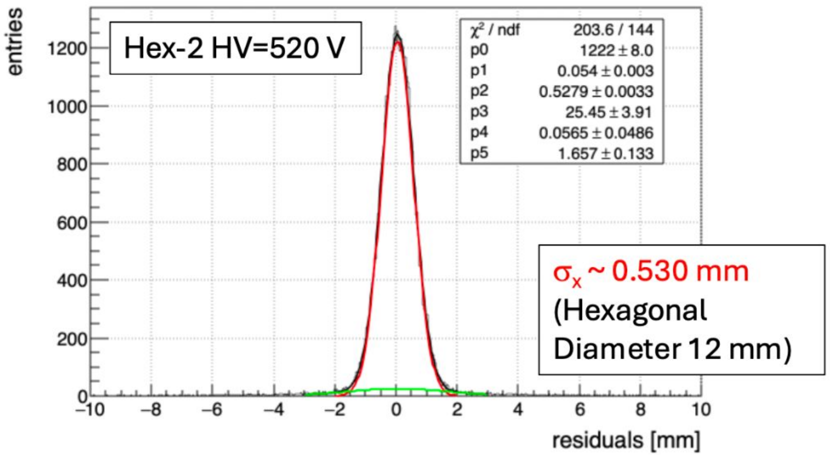
Capacitive-Sharing MM

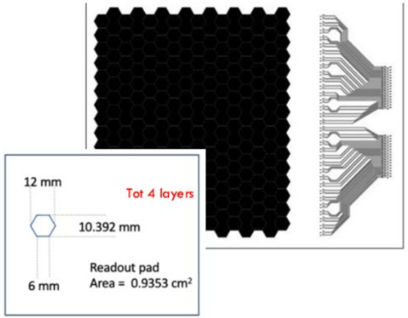
HEX Spatial Resolution – Hex-1 Vs Hex-2 (i.e. 5 layers Vs 4 layers)





Hex1

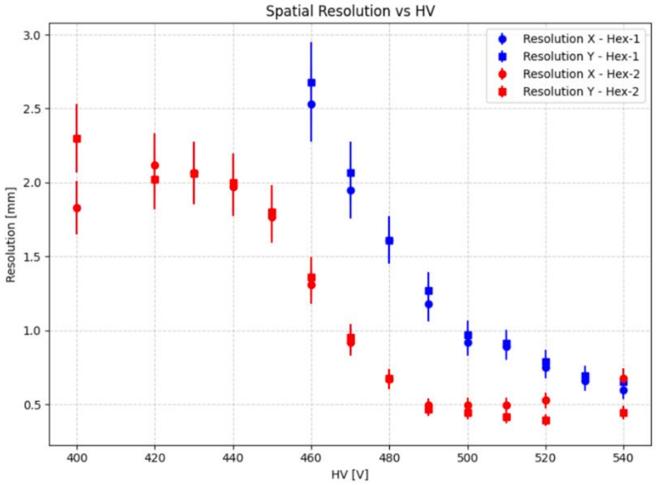


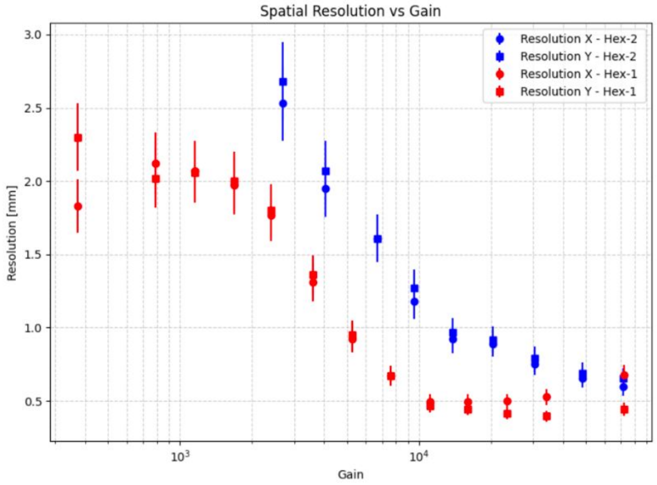


Hex2

Capacitive-Sharing MM

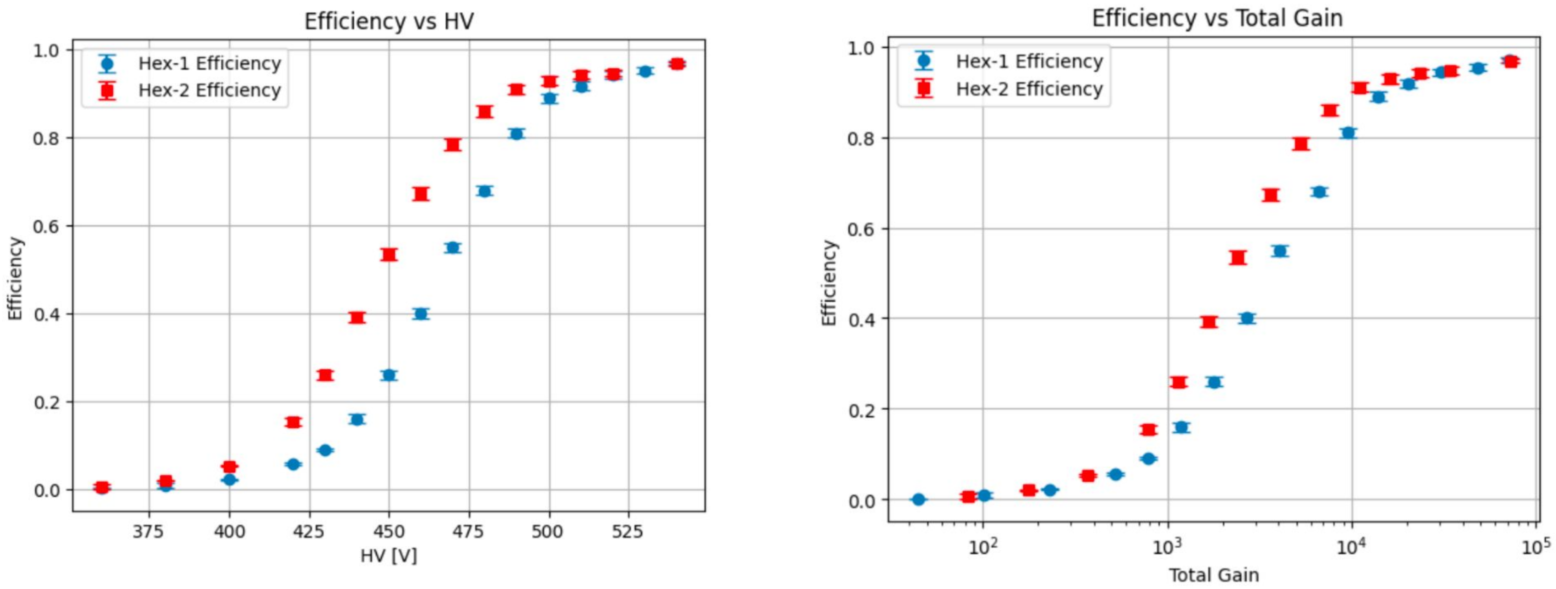
HEX Spatial Resolution – Hex-1 Vs Hex-2 (i.e. 5 layers Vs 4 layers)





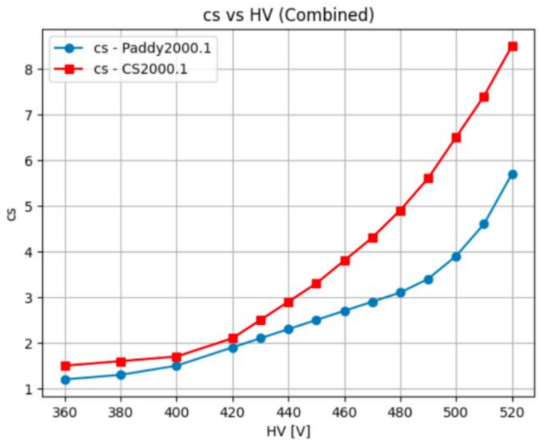
Capacitive-Sharing MM

HEX EFFICIENCY – Hex-1 Vs Hex-2 (i.e. 5 layers Vs 4 layers)



Capacitive-Sharing MM

Cluster-size



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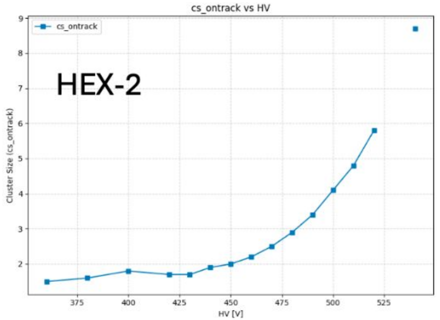
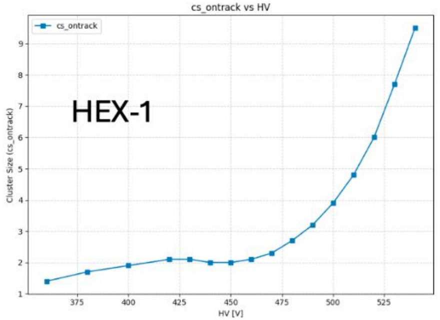
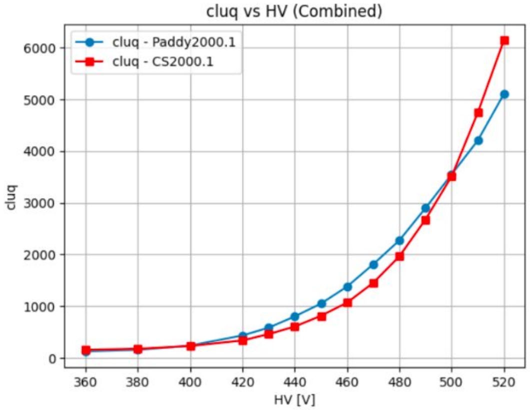




Capacitive-Sharing MM

Cluster Charge –



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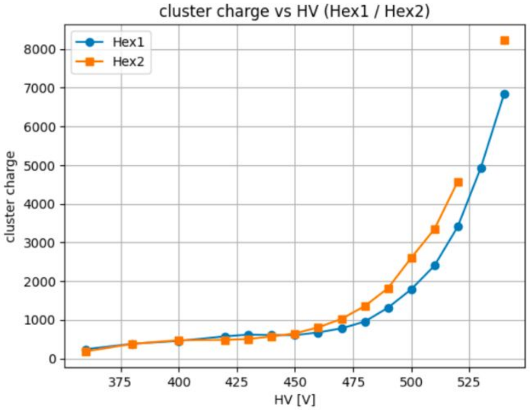

HEX

Standard MM

Time resolution