Highly sensitive, low-temperature sensors

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Introduction

(main) Low Temperature Detectors technologies

- semiconductors
  - Neutron Transmutation Doped (NTD) Germanium

- superconductors
  - Transition Edge Sensors (TES)
  - Microwave Kinetic Inductance Detectors (MKIDs)

- others
  - Magnetic Metallic Calorimeters

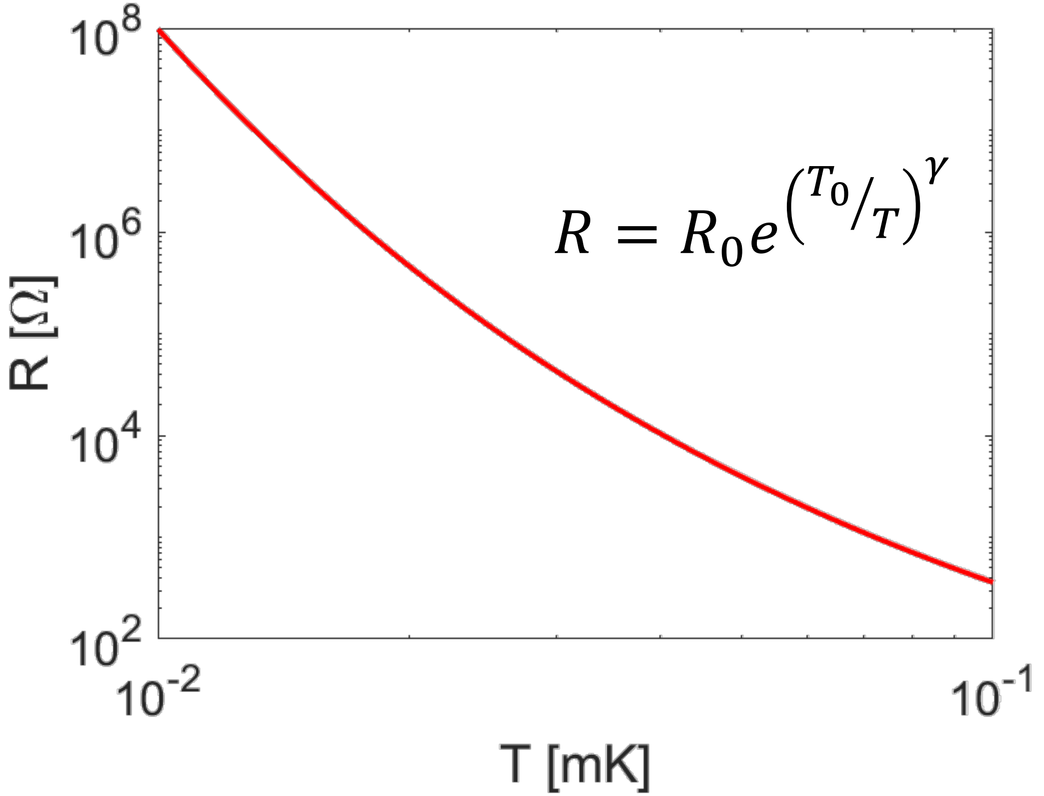
Neutron Transmutation Doped (NTD) Germanium sensors

- well **established technology**
- conduction band engineered to have **large sensitivity at very low temperature** (~10 mK)
- coupled to large crystals (see I. Nutini's talk) for **rare event searches**
- current biased → electro-thermal feedback → **thermal stability**
- **great energy resolution** $\Delta E \approx \mathcal{O}(\text{keV})$ @ MeV
- also coupled to thin absorbers, to **detect light** (particle identification)
- large impedance → signal integration (stray capacitance) → **slow signals**

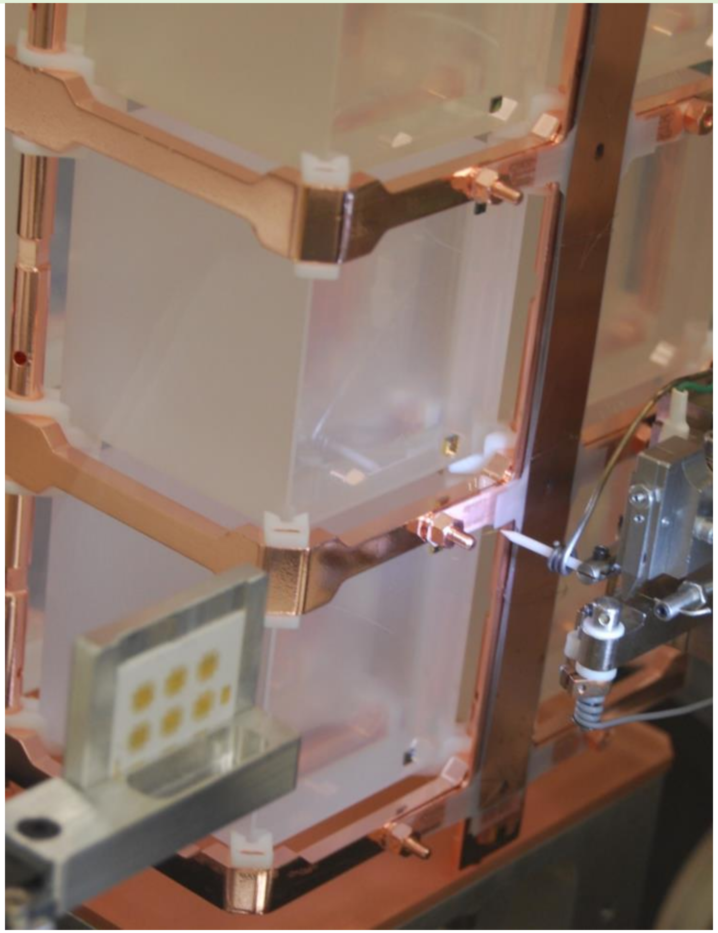
⬇

aims:

- ➢ decrease heat capacity to increase sensitivity
- ➢ increase thermal coupling to light absorber (eutectic bonding?)

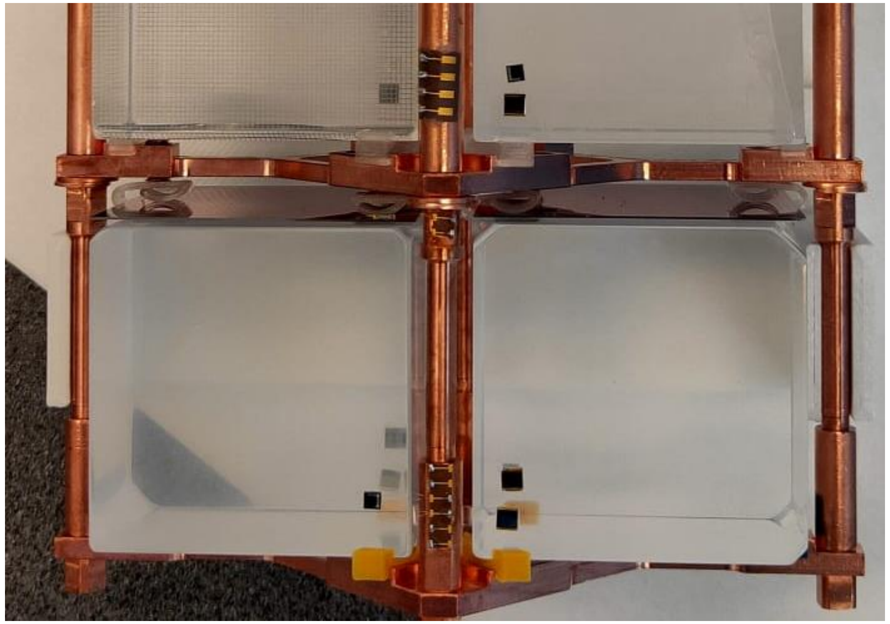


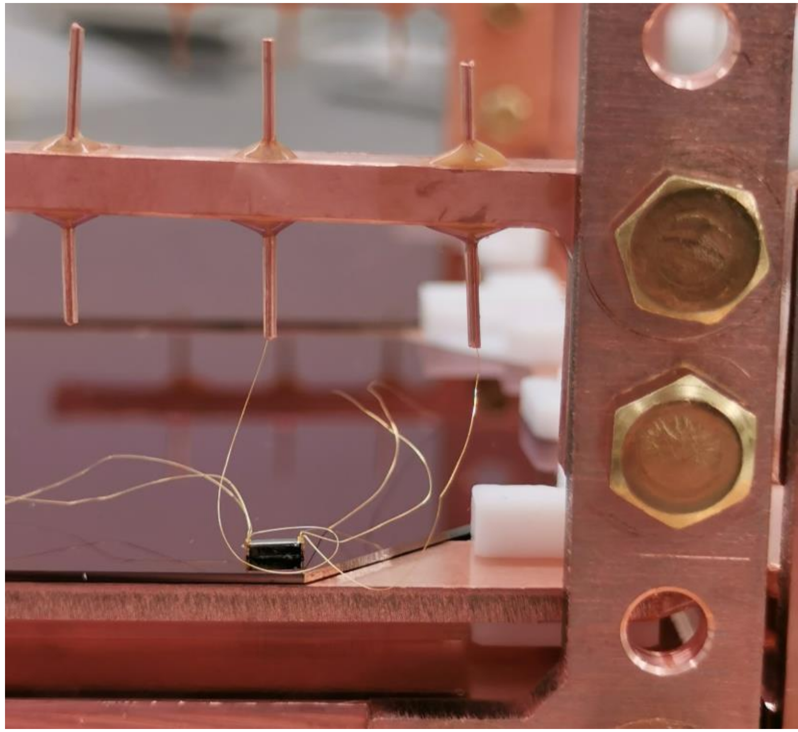
Neutron Transmutation Doped (NTD) Germanium sensors



CUORE

CUPID (thermal channel)

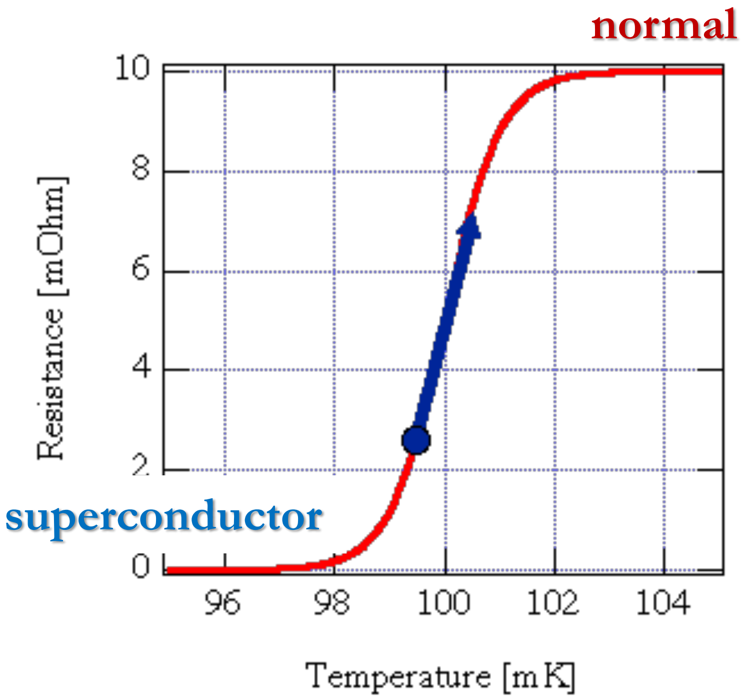


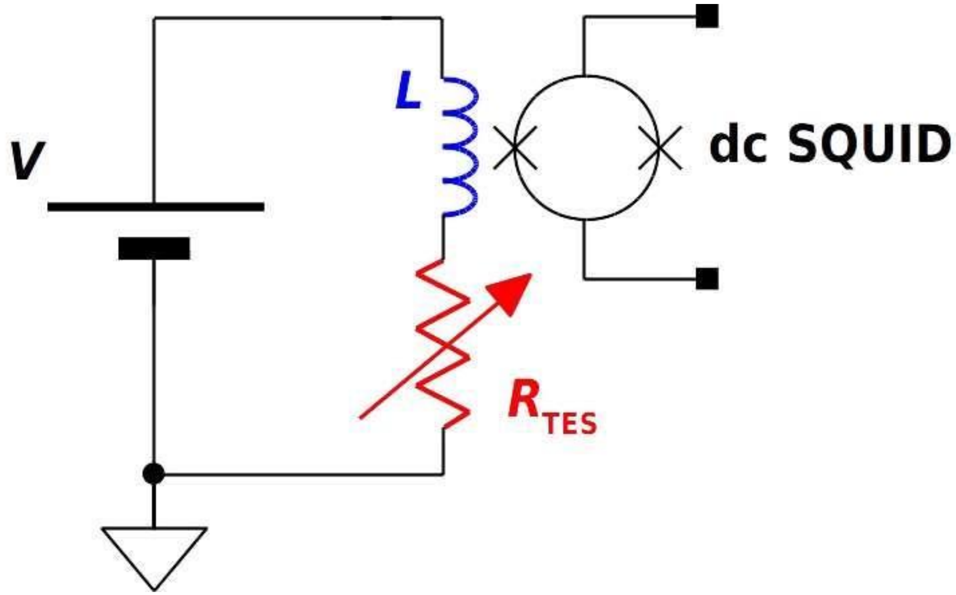


CUPID (light channel)

Transition Edge Sensors (TESs)

- superconductive films within transition at $T = T_c$ → high sensitivity → **high energy resolution** $\Delta E \approx \mathcal{O}$(eV) @ keV
- thermodynamic limit $\sigma_E^2 \approx \xi^2 k_B T^2 C(T) \xrightarrow{if\ C \propto T} \propto T_c^3$
- metal/superconductor bilayers: Mo/Cu, Ti/Au, Ir/Au, Ti/Al, … → **tunable T_c** (20÷200) mK
- voltage biased → electro-thermal feedback → **thermal stability**
- **intrinsically fast**, but ultimately time profile tuned by L/R to match bandwidth
- low impedance → SQUID readout → **multiplexing schemes** for large arrays (TDM, FDM, CDM, μwave mux)
- narrow transition region → **limited dynamics**





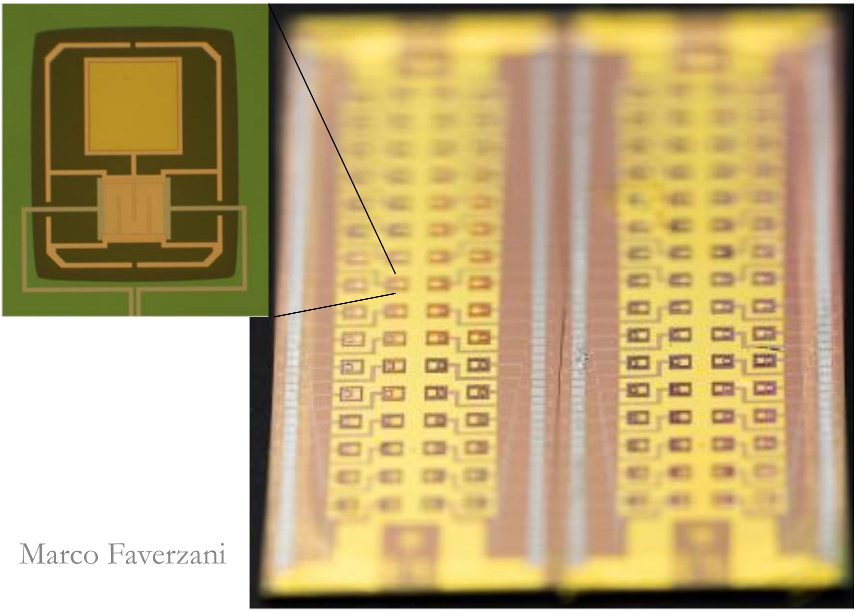
Transition Edge Sensors (TESs)

- direct (and calorimetric) assessment of neutrino mass
  - measurement of decay energy in a beta process

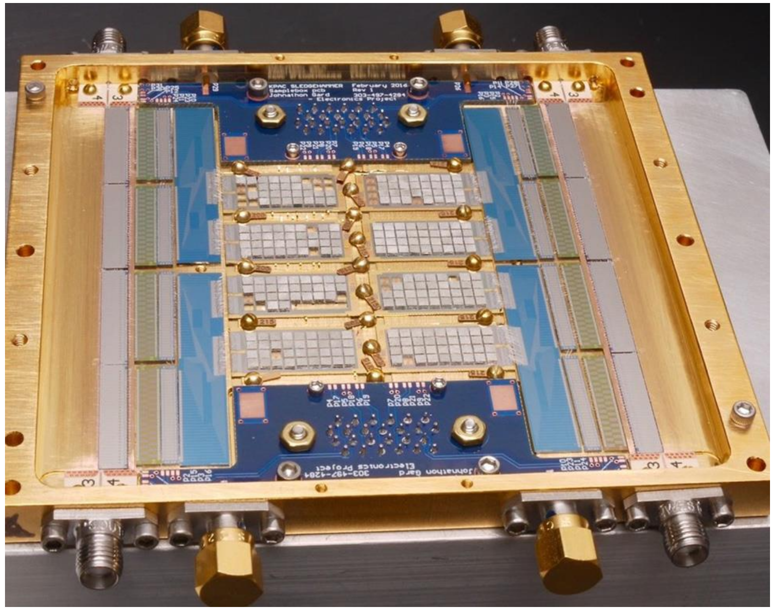
- dark matter searches
  - nuclear recoils due to WIMPs scatter

- photon detection
  - X-ray spectroscopy, single photon detection, CMB (bolometers)

HOLMES



SLEDGEHAMMER



Micorwave Kinetic Inductance Detectors (MKIDs)

pair breaking detectors:
$E = h\nu > 2\Delta$ (≈ meV)

⬇

increase in quasiparticles
$N_{qp} \approx \eta\, h\nu/\Delta$
change in sheet impedance $Z_s = R_s + i\omega L_s$

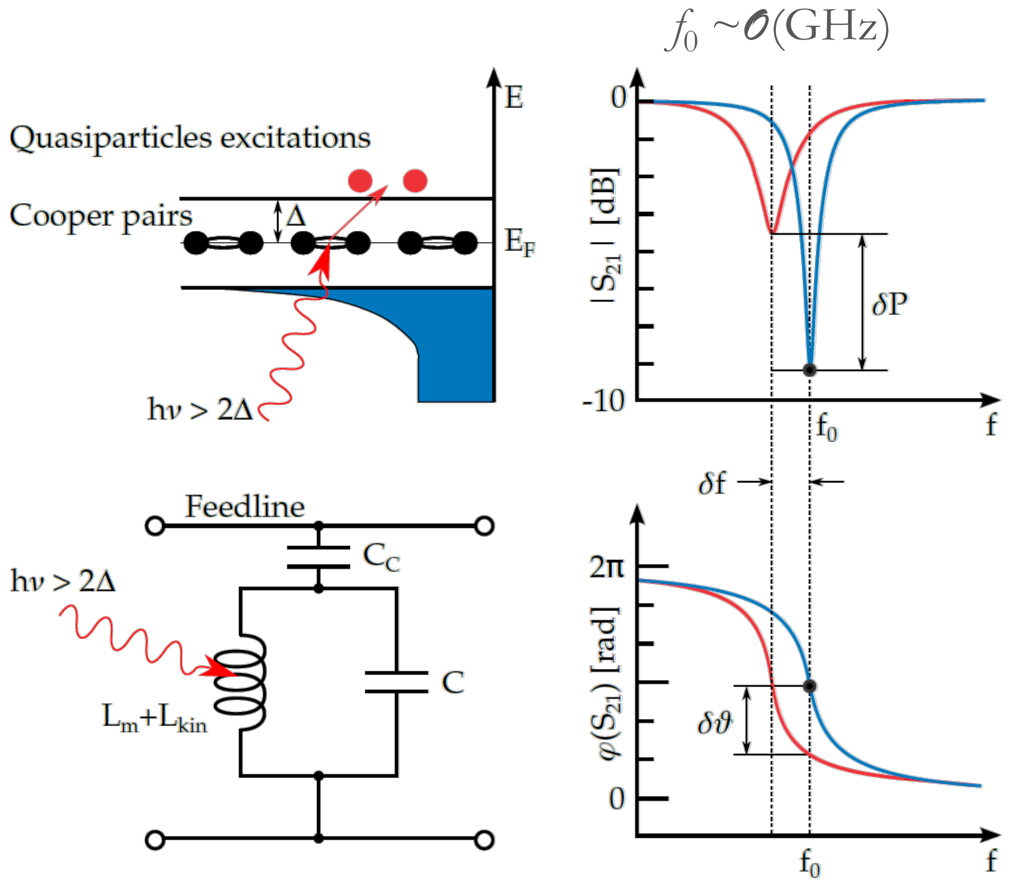
⬇

$$\frac{\delta f_r}{f_r} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \alpha\frac{\delta R_s}{\omega L_s}$$

α = *surface inductance fraction*

⬇

relaxation time after qp recombination time τ_{qp}



Nature, 425:817 (2003)

demonstrated single photon detection $\Delta E_{FWHM} \approx$ 0.5 eV @ 0.8 eV
J Low Temp Phys 199, 73–79 (2020)

MKIDs operated in thermal mode

equivalence of temperature change and external pair breaking

J Low Temp Phys (2008) 151: 557–563

radiation interacts in absorber coupled to the sensor

sensor detects increase of absorber's temperature $\Delta T \approx h\nu/C$

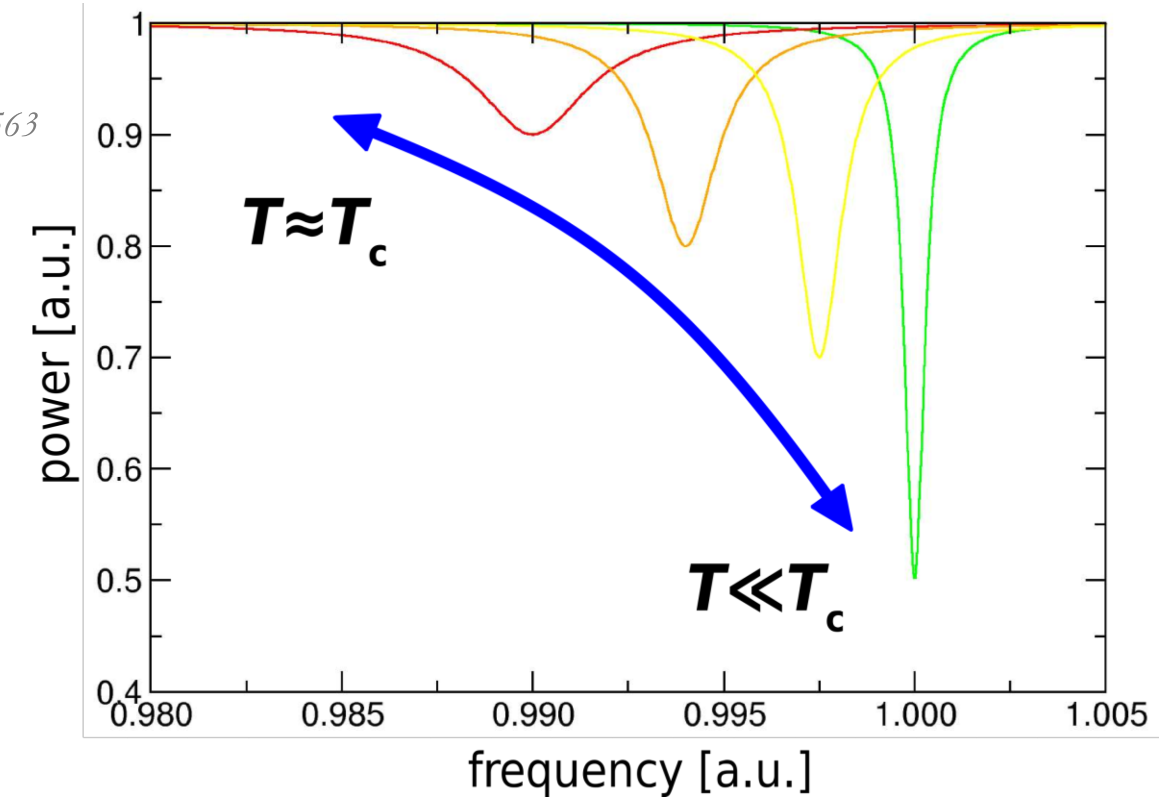
$$n_{qp} = 2N_0\sqrt{2\pi kT\Delta}e^{-\frac{\Delta}{kT}}$$

⬇

$$\frac{\delta f_r}{f_r} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \alpha\frac{\delta R_s}{\omega L_s}$$

⬇

thermal relaxation time $\tau = C/G$



possible TES replacement?

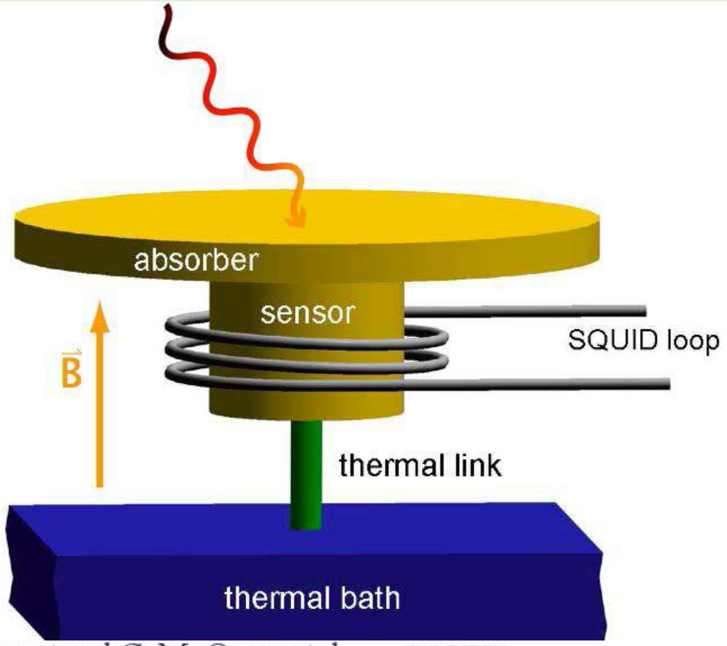
- in principle $\Delta E \approx$ thermodynamic limit
- simple read-out
- natural multiplexing

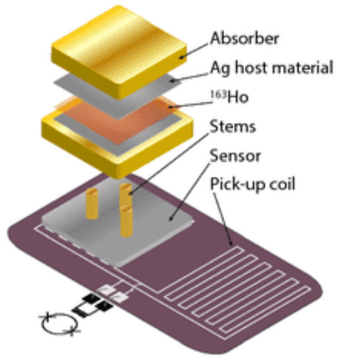
so far $\Delta E = 75$ eV @ 5.9 keV

Appl. Phys. Lett. 106, 251103 (2015)

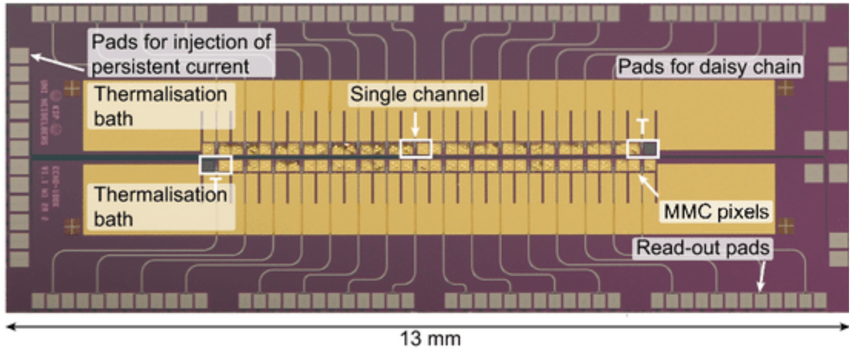
Magnetic MicroCalorimeters

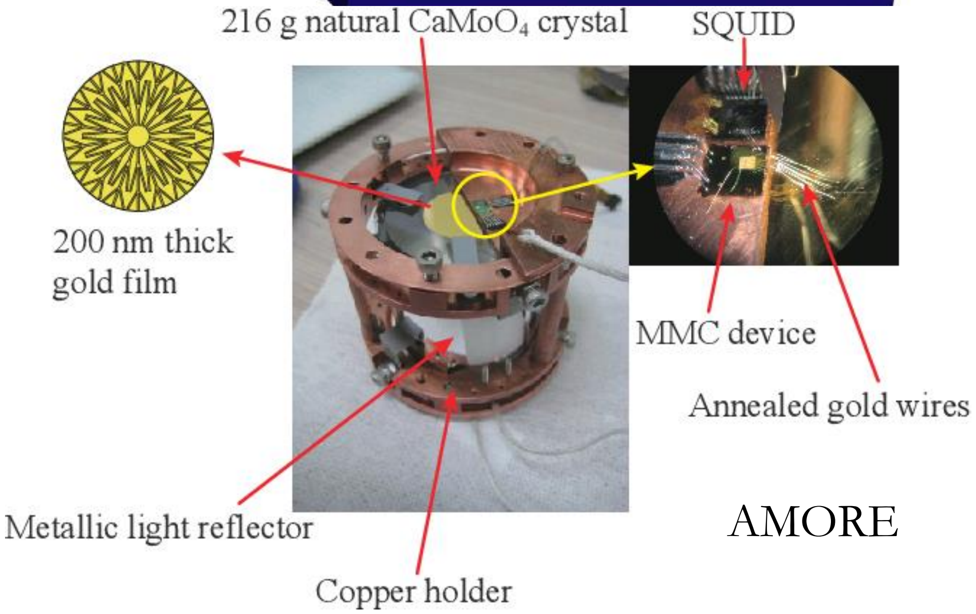
- paramagnetic temperature sensors (Au:Er, Ag:Er, …): **$\delta E \rightarrow \delta M \rightarrow \delta\phi$**
- dc-DQUID readout
  - **high energy resolution**
  - **fast rise** time ≈ 100 ns
- **high linearity**
- **no power dissipation** in the sensor
- possible **frequency multiplexing**





ECHO

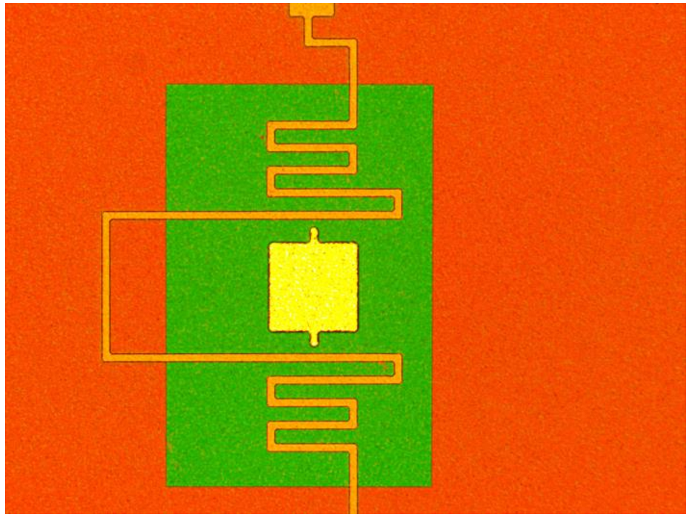




AMORE

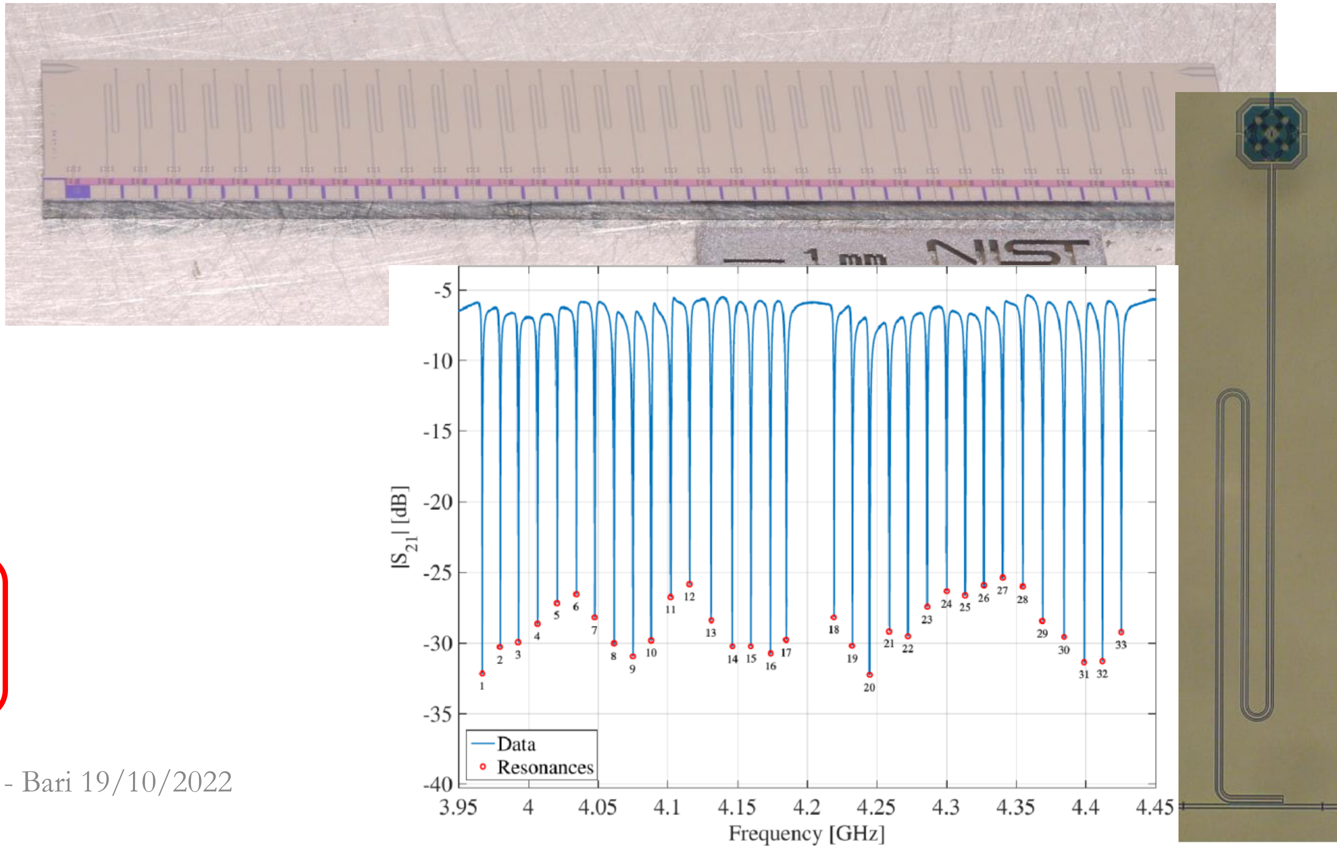
Future challenges

- **NTDs:**
  - decrease sensors' heat capacity as much as possible
  - improve coupling to the absorber
- **MKIDs**
  - R&D
  - …



- **Sensors and readout techniques strongly synergetic with quantum technologies!**

- **TESs**
  - multiplexed readout: $\mathcal{O}(10^6)$ detectors, $\tau_R \sim \mu s$
  - large scale producing facility closely related to Italian community
- **MMCs**
  - demonstration of multiplexed readout



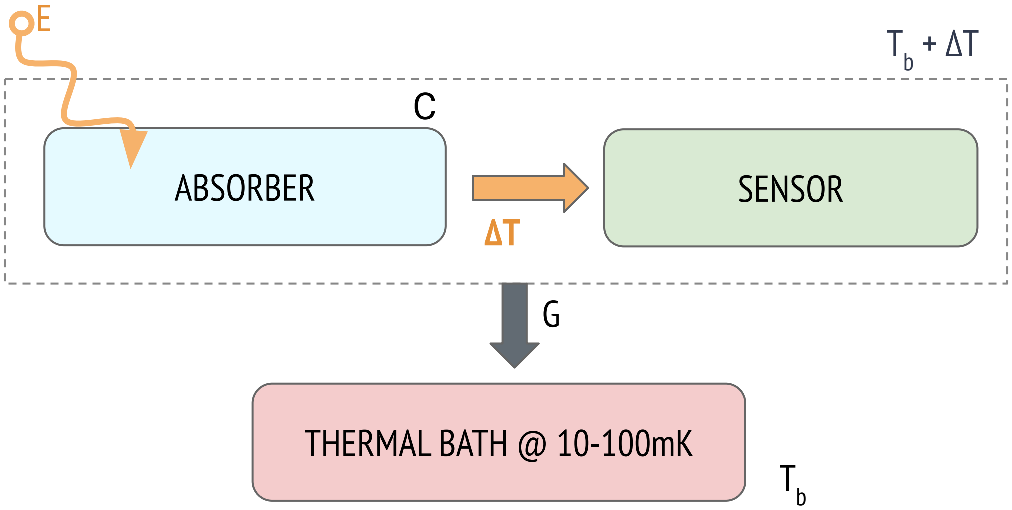
Absorber crystals for cryogenic detectors: status and challenges

IFD 2022 Workshop - ‘Calorimeters’ session

Oct.19th, 2022 - Bari

Irene Nutini (UniMiB - INFN MiB)

Cryogenic detectors



Absorber crystal:

- Energy deposition ⟶ phonons/heat ⟶ **$\Delta T = E/C$**
- Completely **active**
- Wide choice of absorber compounds depending on the physics case
- **Macro (O(g,cm)) vs. micro (O(mg,100μ))**
- Monolithic vs Composite detectors

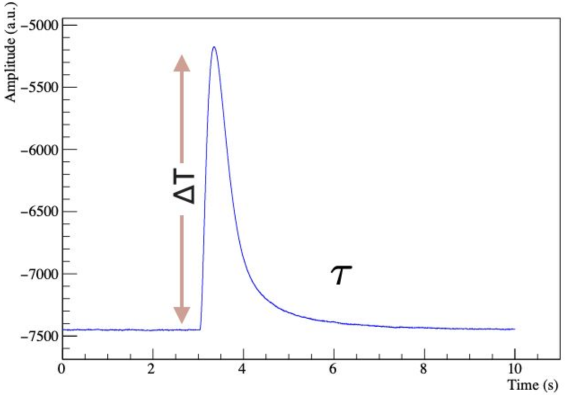
Temperature sensor:

See talk from M. Faverzani

Absorber crystals at low temperatures: heat capacity

The role of the heat capacity:
sensitivity, thermalization time & energy resolution

$\Delta T = E/C$ | **$\tau = C/G$** | **$\Delta E \sim \sqrt{C} \times T$ (intr. therm. limit)**

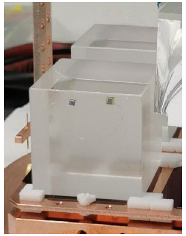


$C(T) = c_{tot}(T) \times M$

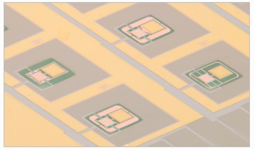
$c_{tot}(T)$ [for T << 1K]: lattice ($\sim T^3$)
+ electric ($\sim T$ for metals, $\sim T^{-1} \times \exp(a/T)$ for supercond, 0 for semicond)
+ magnetic ($\sim T^{-2}$ dipole/shottky)

Choice of crystal compounds:

- Dielectric and diamagnetic for macro (eg. TeO_2, Li_2MoO_4, ZnSe, $CaMoO_4$)
- Metals (eg. Au) or dielectric (eg. $AgReO_4$) for micro



Li_2MoO_4



^{163}Ho:Au layer

Cryogenic detectors: applications in particle physics

Macro calorimeters

Neutrinoless ββ decay
Majorana nature of neutrino

Rare event search: **large mass of ββ emitter (ton-scale)** and low background

High energy resolution: ~5-10 keV @2-3 MeV-scale

CUORE

CUPID

AMoRE
Advanced Mo-based Rare process Experiment

Direct Dark Matter searches

Rare event search: **large mass (different elements)**, low background

Low energy thresholds: 0.1-1 keV

COSINUS

CRESST
Cryogenic Rare Event Search with Superconducting Thermometers

Micro calorimeters

Spectral shape of β decay/EC
Neutrino mass

High β source activity (uniformly spread among multiple channels)

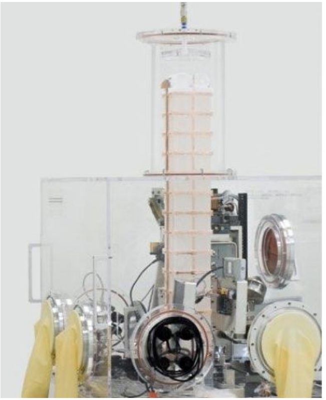
Optimal energy resolution:
~ eV @ 3 keV

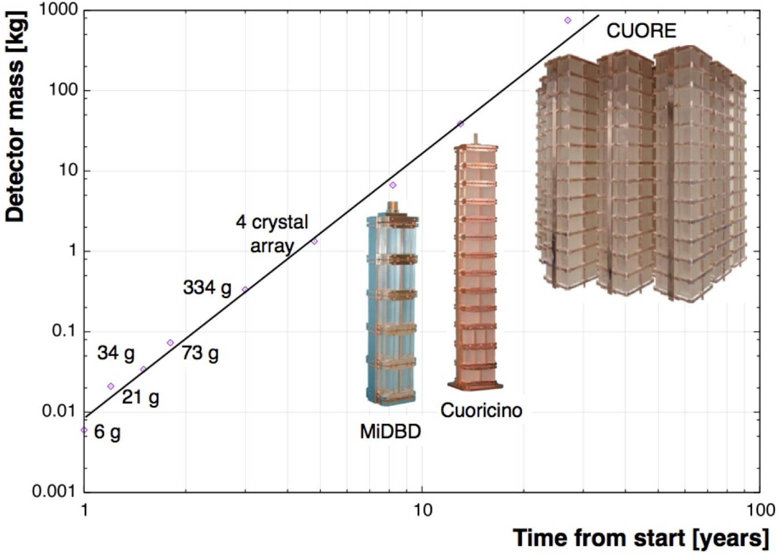
HOLMES

ECHo

Macro calorimeters for rare events

- Crystal structure:
  resistance to thermal & mechanical stress
- Crystal growth:
  ⟶ Scalability and reproducibility on a 1000 detectors / 1 ton mass scale (eg. CUORE)
  ⟶ Radiopurity of different compounds and different growth procedures
- Avoid re-contamination during handling and assembly





Macro calorimeters: pile-up in the absorber

Large crystals enriched in ββ isotope

- Enrichment process: risks of contamination
- **2nuββ pile-up in the absorber** and its contribution to background in 0nuββ ROI

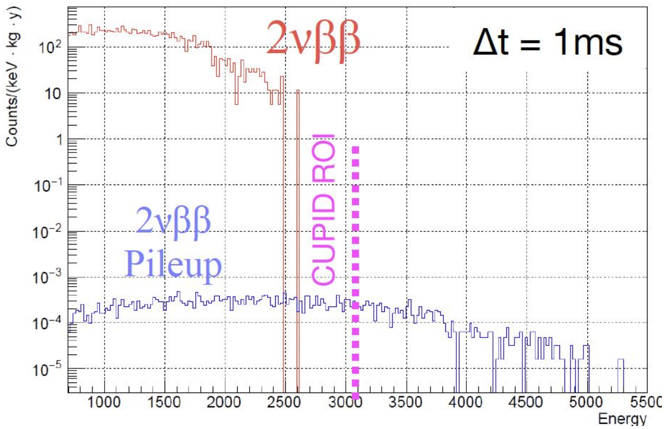
  Mo-based detectors:

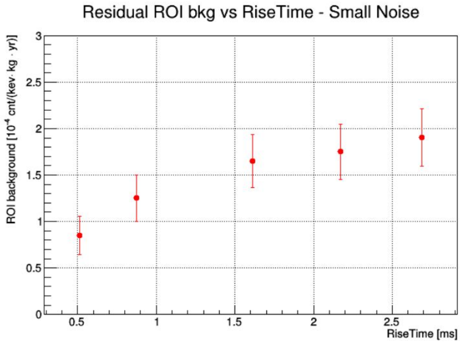
  ^{100}Mo 2νββ fast decay time = 7.1 × 10^{18} yr

  3 mHz rate 2νββ for CUPID detectors

  (300g Li_2MoO_4 enriched at > 95% in ^{100}Mo)

  ⟶ optimize and improve the time resolution of the detectors (RT & dt)

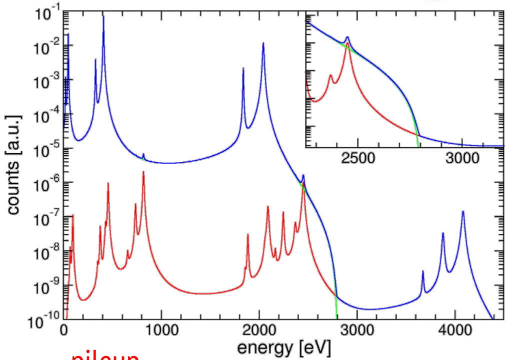




Micro calorimeters: pile-up in the absorber

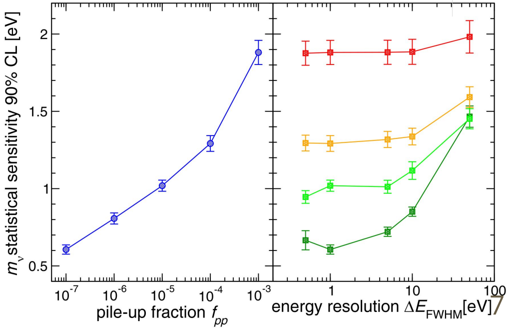
High activity source in substrate

- Source realization line: technical challenges for realizing high activities and for ensuring **uniform** irradiation over substrates with ~10^6 micro-detectors (**~100Bq/det**)
- High quantity of ^{163}Ho isotope and **effect on thermal capacitance**
- **Pile-up** is a major **systematics**, but its impact on sensitivity can be mitigated via optimal dt ~1 us of micro-calos



MC Simulation

pileup

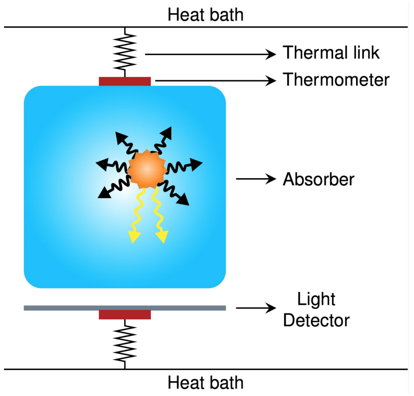


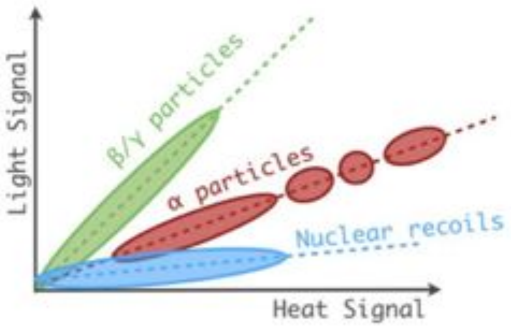
(sx) N_{ev} 10^{14}, dE 1eV
(dx) f_{Pu} 10^{-7}, 10^{-5}, 10^{-4}, 10^{-3}

Scintillating cryogenic crystals

Double readout: heat & light

→ **PID** for background discrimination





Scintillating compounds

Examples: Li_2MoO_4, ZnSe, $CaMoO_4$, … (ββ decay); NaI, $CaWO_4$, … (Dark Matter)

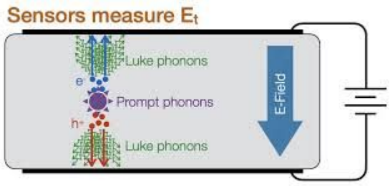
Generally **intrinsic scintillators** → vacancies/defects as luminescent centers: challenge of reproducible light emission among multiple crystals

Characterization of scintillation processes at low T → **traps**: reduced/delayed light emission and effect on heat channel

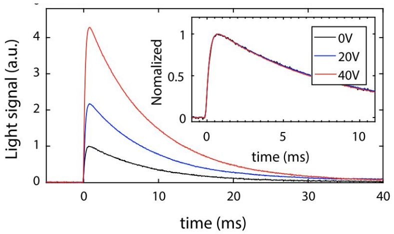
Scintillating cryogenic crystals

Strategies for **improving the information from scintillation light** at 10mK

- Light emission: crystal doping
- Light collection: coating of surfaces ⟶ reflective coating of scintillating absorber + anti-reflective coating of Light Detectors
- Improve the sensitivity of the Light detector:
    - Improve LD internal gain - Neganov-Luke effect
    - Better coupling LD to thermal sensor (eg. eutectic bonding)



Neganov-Luke effect

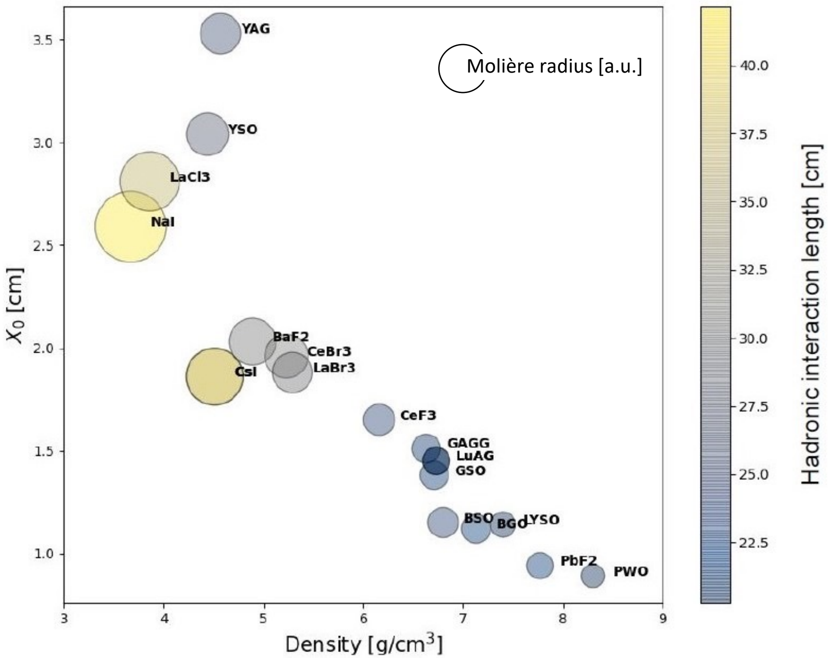


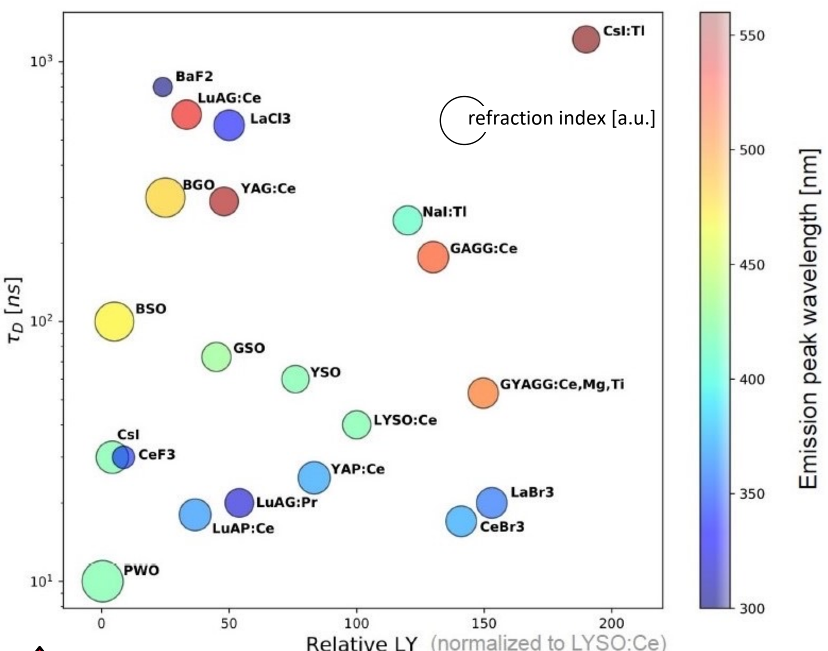
News and prospects of crystal scintillators

(rapidfire talk)

Ioan Dafinei
INFN Sezione di Roma and GSSI

HEP calorimetry





<u>the hardest work has already been done</u>

currently is available a large variety of crystals ready to satisfy most experimental needs

- energy resolution
- time resolution
- sampling factor
- irradiation endurance

a possible user will (only ☺) have to take care of detector construction

- handling
- packaging
- transport
- certification
- storage

Recommended reading:
<u>Marco Lucchini</u>, "Crystal Calorimetry", ECFA Detector R&D Roadmap Symposium
https://indico.cern.ch/event/999820/contributions/4200695/attachments/2241036/3799740/2021_05_07_ECFA_TF6_Lucchini_CrystalCalorimetry.pdf

Marco Lucchini

(few of) crystal candidates

	BGO	PWO	CeF3	LYSO:Ce	GAGG:Ce	YSO:Ce	YAP:Ce	LuAG:Ce	LuYAP:Ce	YAG:Yb	YAP:Yb
LY (normalised)	25	0.5	15	100	115	80	9 32	35 48	16 15	0.36	0.19
decay time (ns)	300	30 10	30 8	40	53	75	191 25	820 50	1485 36	4.00	1.50
emission peak (nm)	480	425 420	340 310	428	520	420	370	520	385	350	350
refractive index	2.15	2.20	1.62	1.82	1.87	1.80	1.94	1.84	1.90	1.83	1.94
dE/dX (MeV/cm)	8.00	10.10	8.00	9.55	8.96	6.57	8.05	9.22	9.82	7.01	8.05
radiation length (cm)	1.12	0.89	1.68	1.14	1.63	3.10	2.77	1.45	1.37	3.53	2.77
Molière radius (cm)	2.23	2.00	2.60	2.07	2.20	2.93	2.40	2.15	2.01	2.76	2.40
Z_{eff}	72.90	74.50	50.87	64.80	51.80	33.30	31.90	60.30	58.60	30.00	31.90
density (g/cm^3)	7.13	8.30	6.16	7.40	6.50	4.44	5.35	6.76	7.20	4.56	5.35
melting point (°C)	1050	1123	1443	2050	1850	2070	1870	2060	1930	1940	1870

$Bi_4Ge_3O_{12}$ (BGO)
$2 \cdot Bi_2O_3 + 3 \cdot GeO_2 \rightarrow Bi_4Ge_3O_{12}$
Bismuth Germanate

$PbWO_4$ (PWO)
$PbO + WO_3 \rightarrow PbWO_4$
Lead Tungstate

$(Lu_{(1-x)}Y_x)_2SiO_5$:Ce (LYSO:Ce)
$(Y_2O_3)_x + (Lu_2O_3)_{(1-x)} + SiO_2 + (CeO_2)^* \rightarrow (Lu_{(1-x)}Y_x)_2SiO_5$:Ce
Cerium doped, Lutetium Yttrium Oxy-Orthosilicate

$Gd_3Al_2Ga_3O_{12}$ (GAGG)
$3 \cdot Gd_2O_3 + 3 \cdot Ga_2O_3 + 2 \cdot Al_2O_3 \rightarrow 2 \cdot Gd_3Al_2Ga_3O_{12}$
Gadolinium Gallium Aluminum Garnet

Y_2SiO_5 (YSO)
$Y_2O_3 + SiO_2 \rightarrow Y_2SiO_5$
Yttrium Orthosilicate

$YAlO_3$ (YAP)
$Y_2O_3 + Al_2O_3 \rightarrow 2 \cdot YAlO_3$
Yttrium Aluminum Perovskite

Recommended reading:
Marco Lucchini, "Scintillating crystals at particle colliders trends, challenges, perspectives"
SCINT 2022: 16th Int. Conference on Scintillating Materials & their Applications
https://cernbox.cern.ch/index.php/s/JWX4o5NZYKyWr9x

Feasibility issues

- readiness of crystals with requested characteristics
- bringing crystals of a producer portfolio to ECAL requests
  - scintillation characteristics
  - shape and dimensions
  - radiation hardness
- implementation of large-scale production
  - building a dedicated production facility or expansion of an existing one (quite large investment in both cases)
  - after the end of production:
    - difficult dismantling or reuse of the production facility
    - difficult retraining of the manpower
- reception and quality control facility at the beneficiary

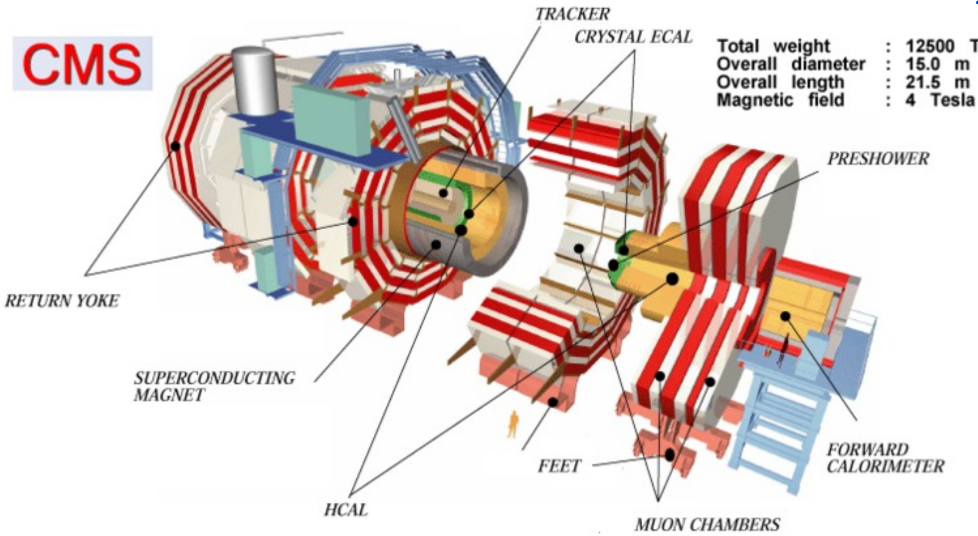
NB: the construction of the calorimeter itself will be another problem, to be discussed/solved separately, including the decision to make it in-house or through outsourcing

Lessons learned from previous experiences

example of ECAL-CMS

- **R&D was needed to find the best suited crystal**
  - **RD18 CERN and The Crystal Clear Collaboration:** ***https://crystalclearcollaboration.web.cern.ch/***
  - **SCINT (series of conferences):** ***http://scint.univlyon1.fr/icap_website/view/2324***
- **finally, the crystal choice was driven not only by technical/scientific motivations (total costs and feasibility played a very important role)**
- **two regional centers were set up for the construction of the modules and the assembly of the ECAL super modules (in Rome and at CERN)**

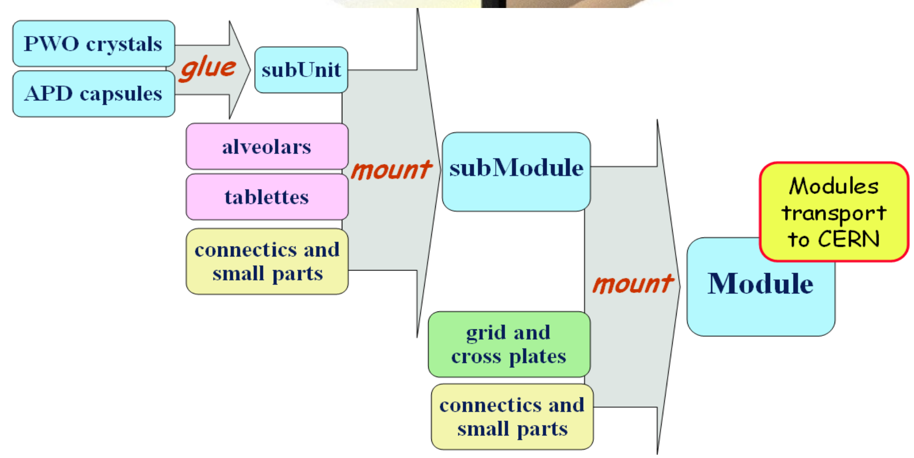
From a small laboratory set-up to a full scale calorimeter



CMS: 75848 Xtals $PbWO_4$
~78000 kg

ECAL Barrel
- 61 200 crystals
- 61 200 capsules APD
- 6120 alveolars
- 6120 tablets
- 6120 SubModules
- 144 Modules
- 36 SuperModules

Regional Centre
ECAL-CMS
Italy



capacity reached in the final phase: 50 crystals/day
(i.e. 50 subunits, 5 submodules, etc.)

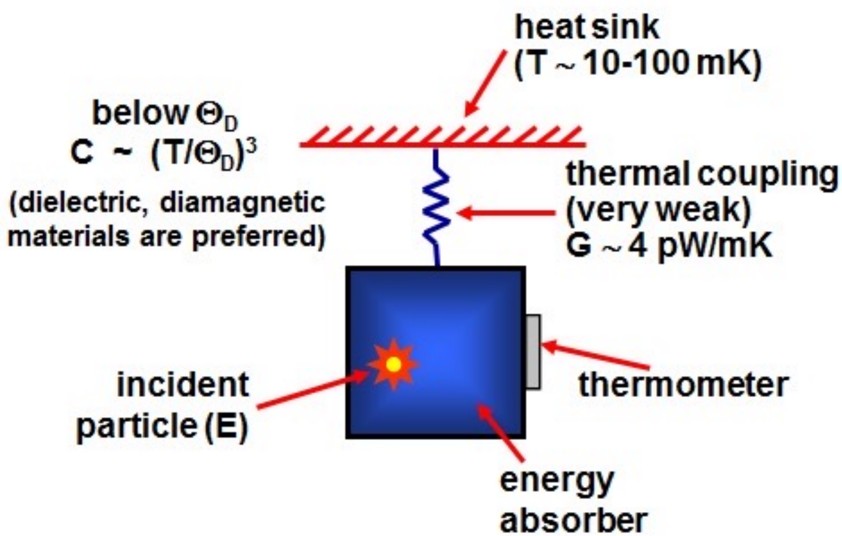
Crystals for the bolometer technique in Rare Events Physics

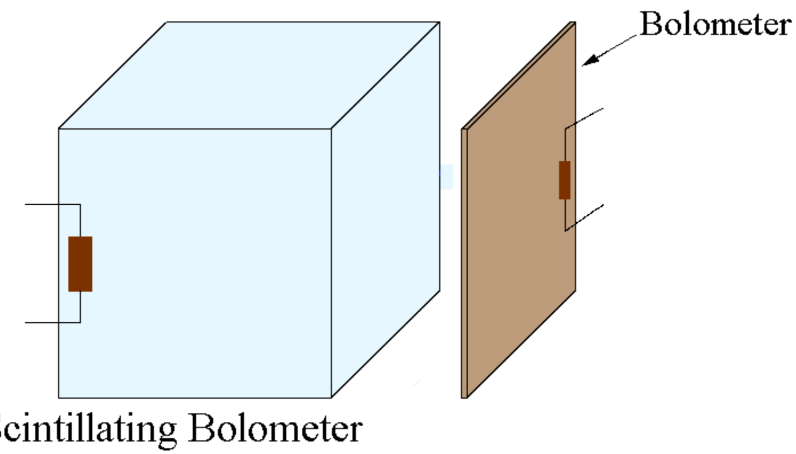
Bolometer:

Highly sensitive calorimeter operated at cryogenic temperature (~10 mK)
Energy deposits are measured as temperature variations of the absorber.
If the absorber is also an efficient scintillator the energy is converted into heat + light.

Main features:

- high energy resolution O(1/1000)
- high detection efficiency (for DBD, source = detector)
- background-free experiments become possible
- large choice of materials
- scalable to large masses





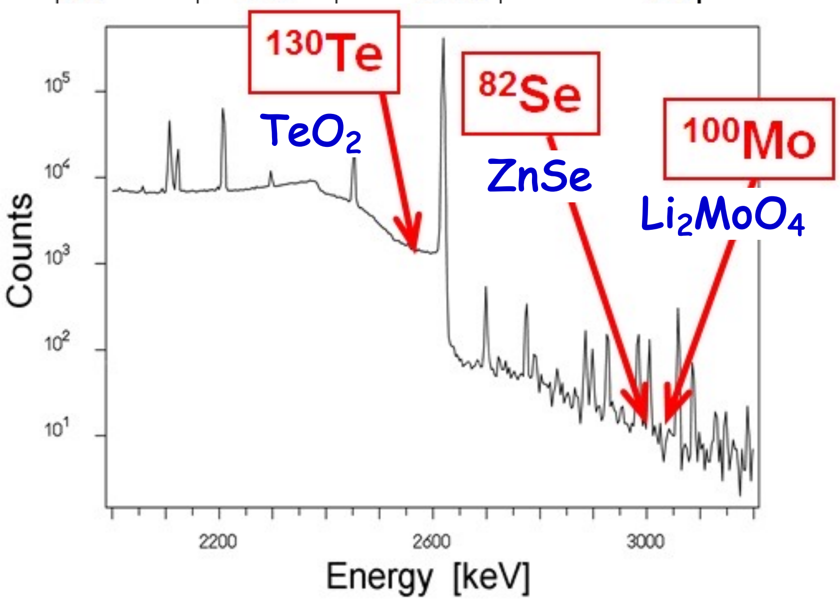
background-free experiments become possible!

Recommended reading:

CUORE	https://cuore.lngs.infn.it/
CUPID-0	https://cupid-0.lngs.infn.it/
CUPID	https://www.lngs.infn.it/en/pages/cupid-en
CRESST	https://www.lngs.infn.it/it/cresst
COSINUS	https://www.lngs.infn.it/en/cosinus-eng

crystals for 0vDBD

element	isotope	end point energy (MeV)	abundance (%)
Ca	48	4.271	0.187
Ge	76	2.039	7.8
Se	82	2.995	8.8
Zr	94	1.145	17.4
Zr	96	3.350	2.8
Mo	100	3.034	9.7
Pd	110	2.013	11.7
Cd	116	2.802	7.5
Te	130	2.527	24.6
Xe	136	2.457	8.9
Nd	150	3.367	5.6



main (CUPID) candidates today

crystals for DM

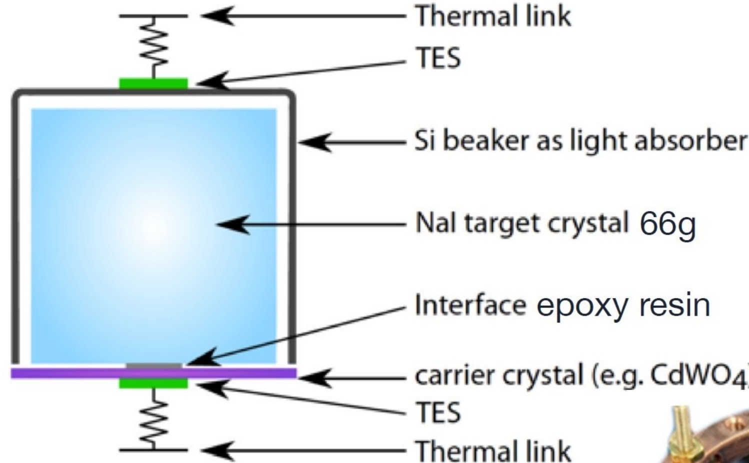
in principle, any crystal would do...

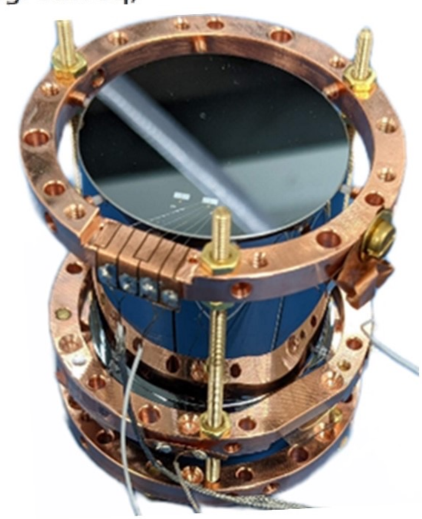
$CaWO_4$ ⟶ CRESST

TeO_2 ⟶ CUORE

NaI ⟶ COSINUS

...few limitations (no paramagnetic...)



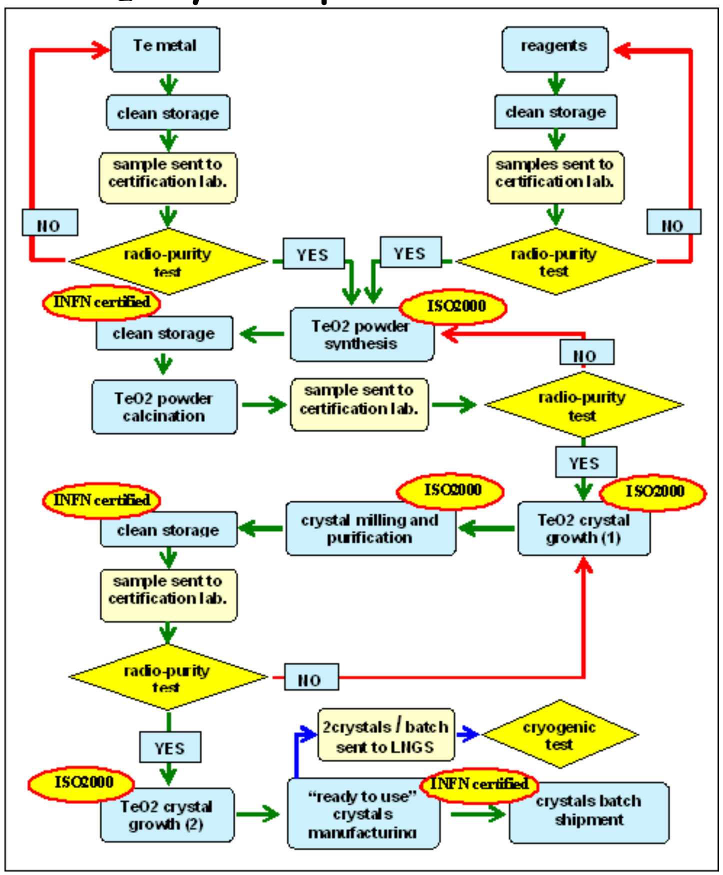


previous experience

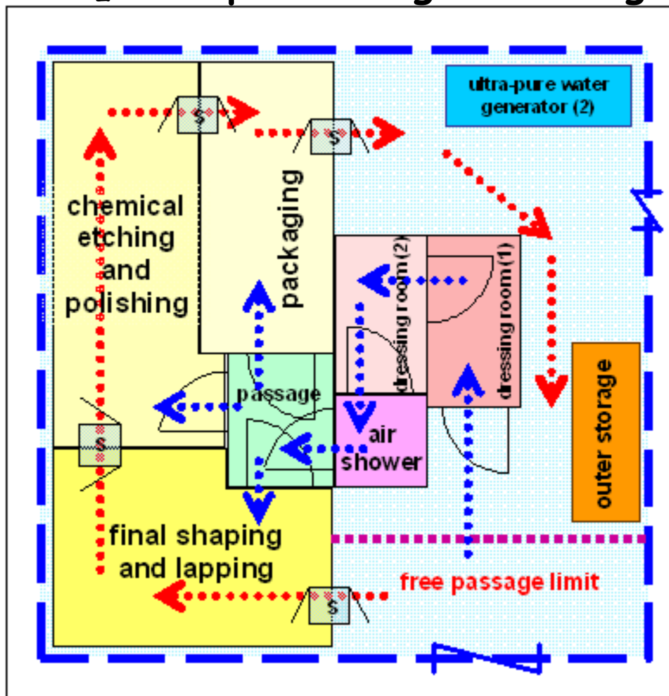
TeO_2 crystals for CUORE

radio-purity insurance

certification procedure during TeO_2 crystals production



SICCAS/INFN Clean Room for TeO_2 final processing at Jiading



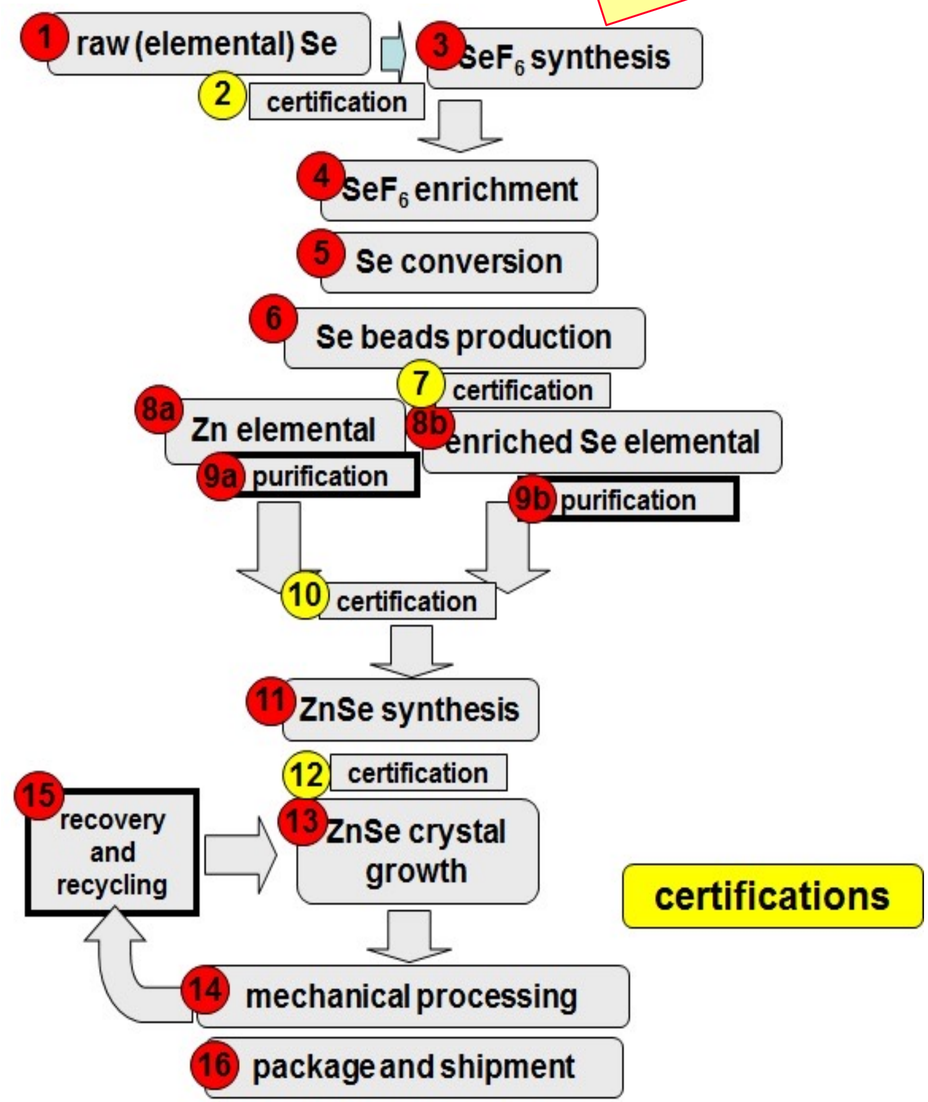
Journal of Crystal Growth 312 (2010), 2999-3008

Production of high purity TeO_2 single crystals for the study of neutrinoless double beta decay

previous experience

$Zn^{82}Se$ crystals for CUPID-0

similar for any crystal candidate



enrichment: ^{82}Se from 8.82% to 96.30% (made at URENCO, Almelo, Holland)

$Zn^{82}Se$ synthesis and crystal growth: made at ISMA Kharkiv Ukraine with strong INFN contribution

final processing (cutting and polishing): made at LNGS, INFN Italy

production yields:

synthesis: 98.35%

(99.55% at S-1, 99.40% at VTT and 99.40% at HTT)

crystal growth*: 95%

cutting*: 96,72%

shaping and polishing*: 99%

____

* including recovered material for recycling

Journal of Crystal Growth 475 (2017) 158–170
Production of ^{82}Se enriched Zinc Selenide (ZnSe) crystals for the study of neutrinoless double beta decay

Crystals, how to proceed?

keep updated!

the scintillator crystal science is very dynamic

- **SCINT2022**

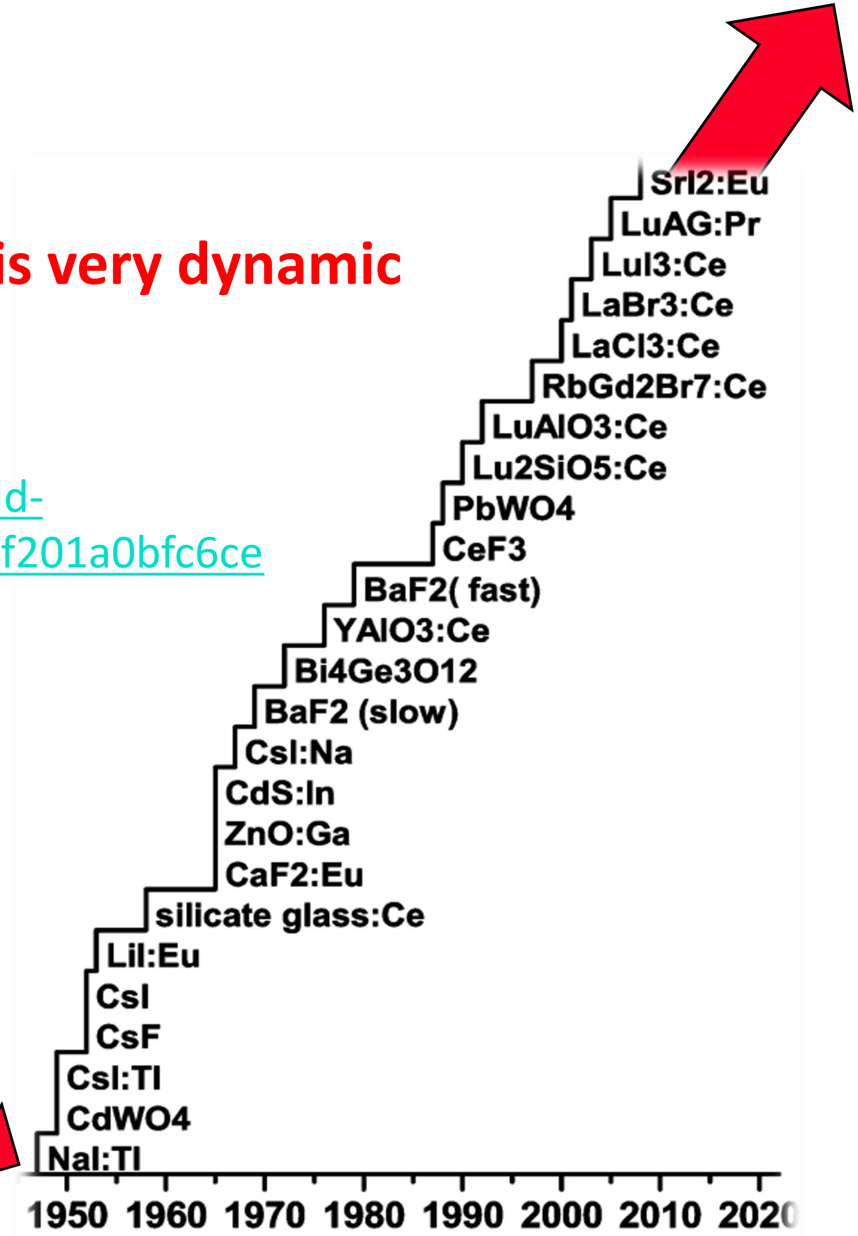
https://web.cvent.com/event/b707dc85-ddc6-4a0d-89dd-c1ef679ed3ce/websitePage:645d57e4-75eb-4769-b2c0-f201a0bfc6ce

- **IEEE NSC**

2022 IEEE NSSC, 05-12 November 2022, Milano, Italy

https://nssmic.ieee.org/2022/program/

1948: NaI:Tl scintillator
Robert Hofstadter
(Nobel prize 1961)



P. Dorenbos, IEEE Trans.Nucl.Sc., VOL. 57, NO. 3, p.1162

Crystals, how to proceed?

scintillating crystal manufacturers follow the evolution of crystal science very closely and often develop their own R&D programs for new crystals

Global Scintillation Crystals Market Research Report 2022

https://www.marketresearch.com/QYResearch-Group-v3531/Global-Scintillation-Crystals-Research-31907475/

The global Scintillation Crystals market was valued at USD 157.92 million in 2021 and it is expected to reach USD 219.04million by the end of 2028, growing at a CAGR* of 4.74% between 2022 and 2028. In terms of volume, the global ScintillationCrystals Production was 765.29 Ton in 2021, and it is predicted to reach 1,152.99 Ton in 2028.

**Compound Annual Growth Rate (CAGR), is the mean annual growth rate of an investment over a specified period of time longer than one year.*

Main producers

- ***Saint-Gobain Crystals***
- ***Hilger Crystals+RMD***
- ***Alpha Spectra***
- ***Amcrys***
- ***Shanghai SICCAS***
- ***Scionix***
- ***Inrad Optics***
- ***Scitlion Technology***
- ***Kinheng Crystal***
- ***Shalom Electro-optics***
- ***IRay Technology***
- ***Anhui Crystro Crystal Materials***

concluding remarks

- electromagnetic calorimetry is one of the most exciting fields in experimental physics
- lately, the conditions have matured for performant ECAL construction based on scintillating crystals (*the same goes for large mK bolometers*)
- many things have changed though, compared to thirty years ago when the ECAL-CMS project started (*and 20 years from starting of CUORE*)
- the strategies to be applied will be different when deciding the construction of new experiments using crystal-based ECALs or large-scale (one ton) bolometric experiments
    - market survey
    - check pros and cons of a possible "in-house" production
    - search for possible geo-political opportunities

Acknowledgements
This work is supported by PRIN 2017 Linea A, Settore ERC PE2_3
Advanced techniques for a next generation cryogenic Double Beta Decay experiment - ID n. 2017FJZMCJ_004, CUP D14I17000180001

THE CALORIMETERS OF MU2E AND MEG EXPERIMENTS

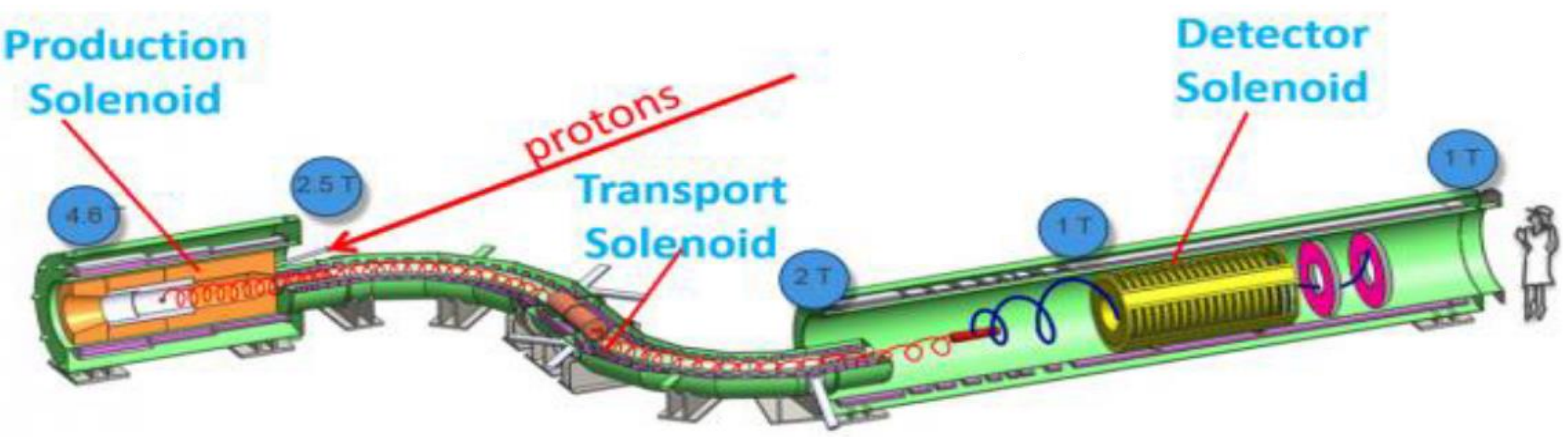
Ruben Gargiulo – INFN Frascati National Laboratories

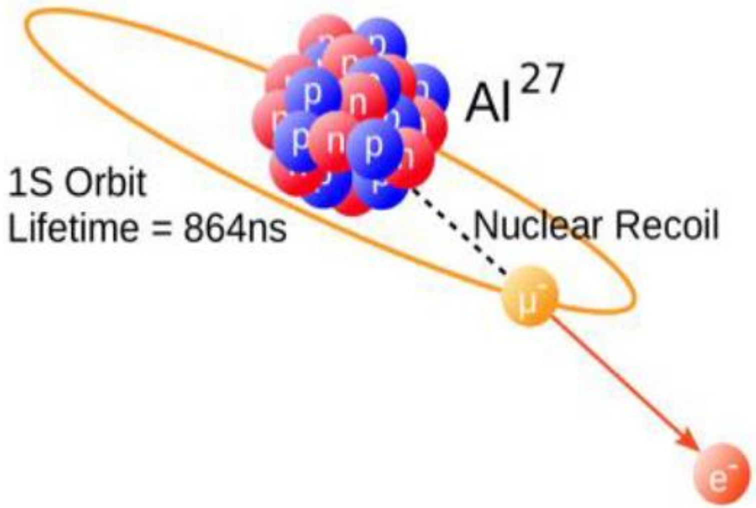
Bari – INFN Future Detectors 2022 – 17/19 October 2022

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

THE MU2E EXPERIMENT

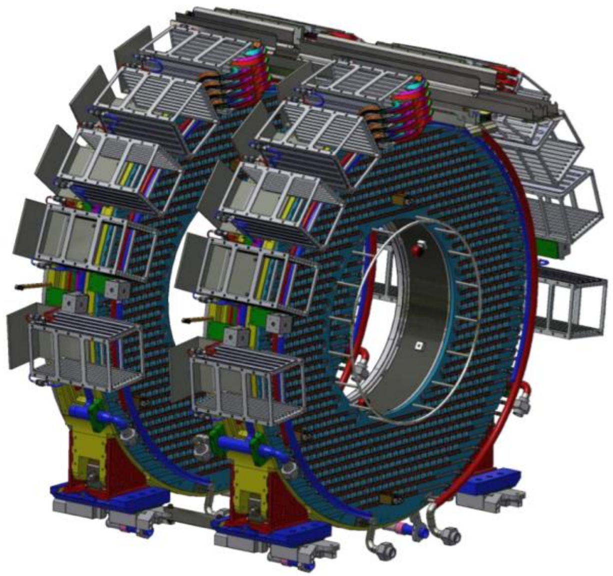
- In construction at Fermilab, Mu2e will search for $\mu^- \rightarrow e^-$ conversions in muonic atoms. This process:
  - happens in a coherent nuclear interaction, with the emission of an e^- with $E_e \sim 105$ MeV $= m_\mu$
  - is a Charged Lepton Flavor Violation (CLFV), unobservable in the Standard Model, so any observation is a New Physics evidence
- Mu2e will measure $R_{\mu e}$ = #conversions / #nuclear captures. The single-event sensitivity is 2.2×10^{-17} , i.e. a $\times 10^4$ improvement
- Over 10^{10} μ^-/s stopped in an aluminium target for three years, with a magnetic transportation and selection system
- 1.7 us pulsed beam to reject prompt backgrounds + hermetic veto with scintillators to reject cosmic-ray backgrounds by a factor 10^4
- Conversion electrons observed by a very precise straw-tube tracker and a fast calorimeter

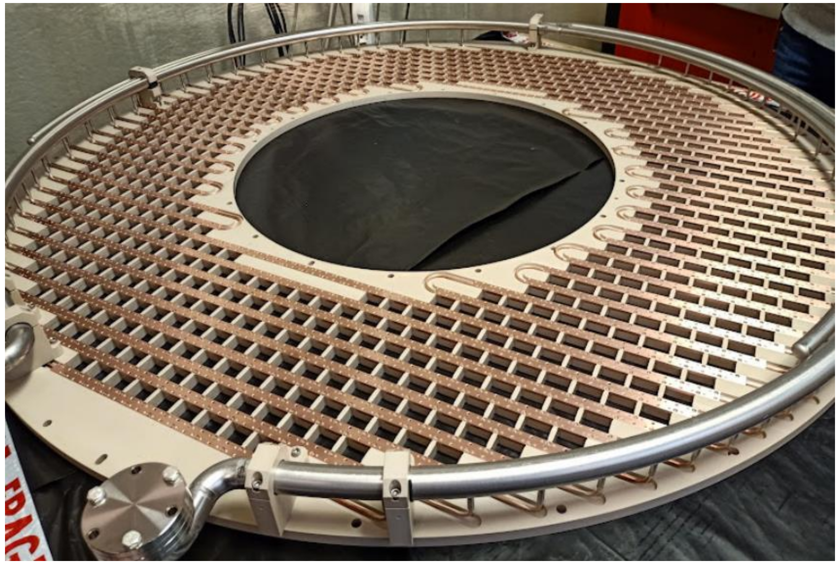


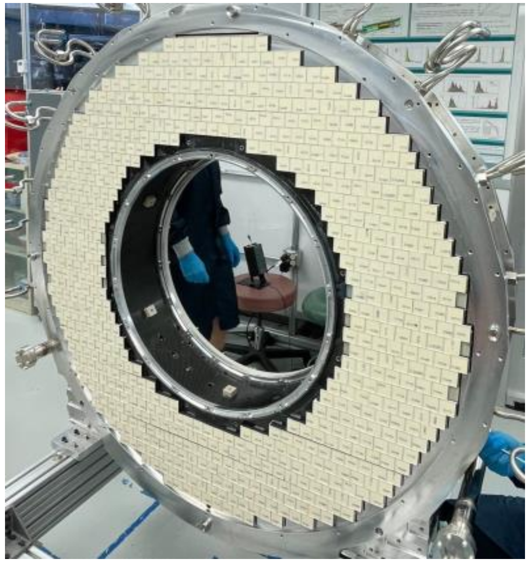


MU2E CALORIMETER OVERVIEW

- Very precise Mu2e tracker (σ_p<200 keV/c) not sufficient for Mu2e aims → Calorimeter needed to provide:
  - Stand-alone trigger — Track-seeding — Electron/muon separation for cosmic-rays rejection
- Physics requirements: σ_E /E <10% , σ_t < 500 ps and good pileup handling → Granular calorimeter with fast pure CsI crystals
- High particle fluxes (20 kHz/cm^2) in a very harsh environment (50 krad total ionizing dose):
  - 1T magnetic field → Silicon sensors
  - 320 nm CsI light → Custom UV-extended SiPMs
  - Intense low-p beam background → Two annular disks
  - High neutron fluence (3 x 10^{12} n_{1MeV} /cm^2) → SiPM operated at -10°C
  - 10^{-4} Torr vacuum → Low outgassing components and powerful cooling system
  - Detector accessible once in 6 months → Redundant readout with 2 SiPM arrays

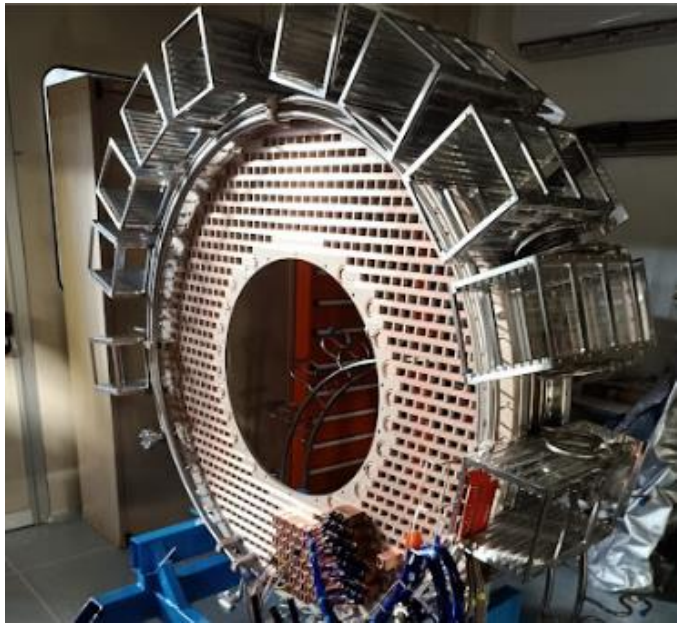


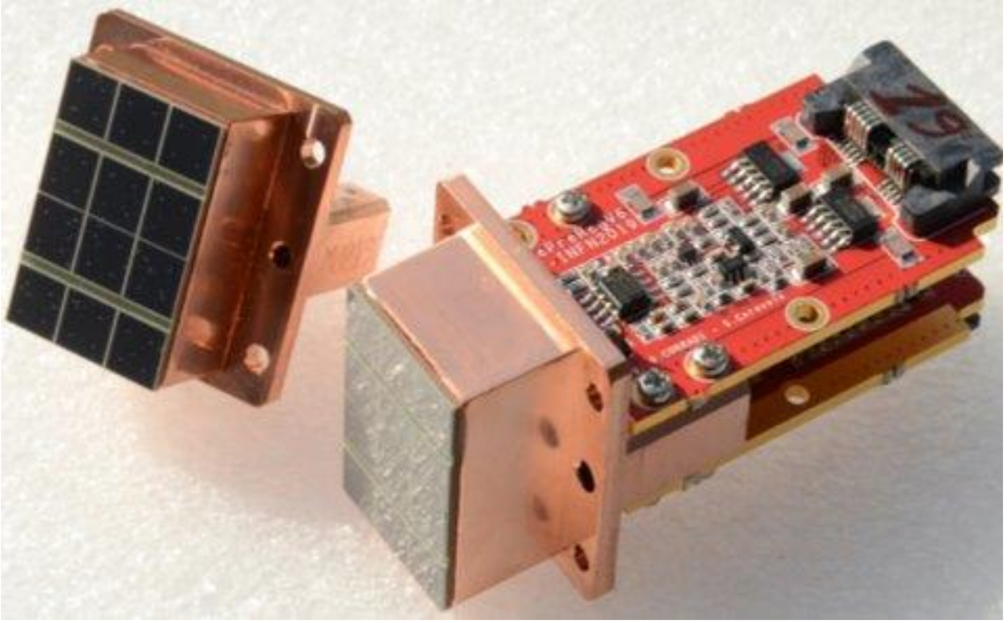


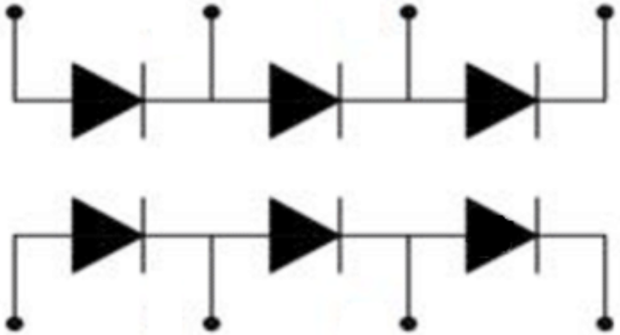


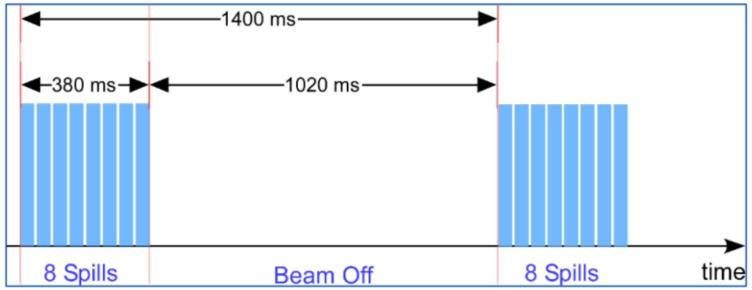
MU2E CALORIMETER DAQ

- Good pile-up handling needed → Scintillation τ<30 ns — Two series of 3 SiPMs to reduce capacitance — Fast preamps in front-end electronic boards
- 2700 channels with 200 MHz 12 bit digitizers in **D**I**gital** **R**e**A**dout **C**ontrollers
  - 140 DIRAC boards (20 ch. each) with FPGAs for zero-suppression, pile-up handling and throughput reduction, housed in electronics crates
- 8GB/s calorimeter DAQ output, with Mu2e maximum storage limit of 0.7GB/s
  - Online trigger based on PC servers and exploiting beam-off periods



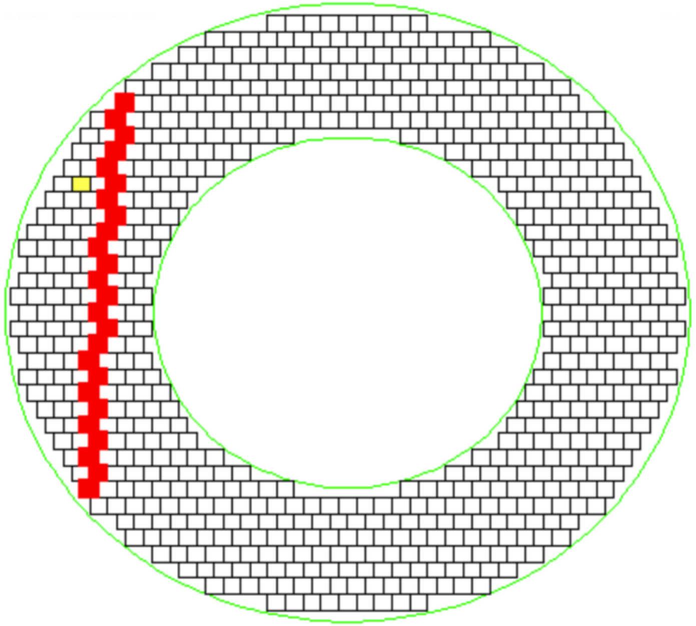


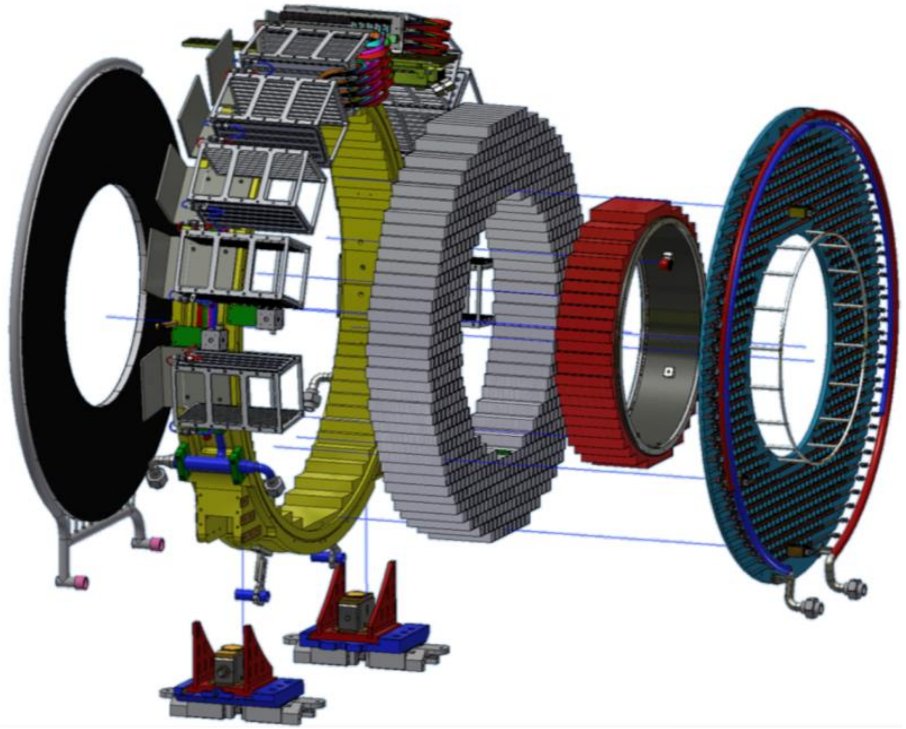


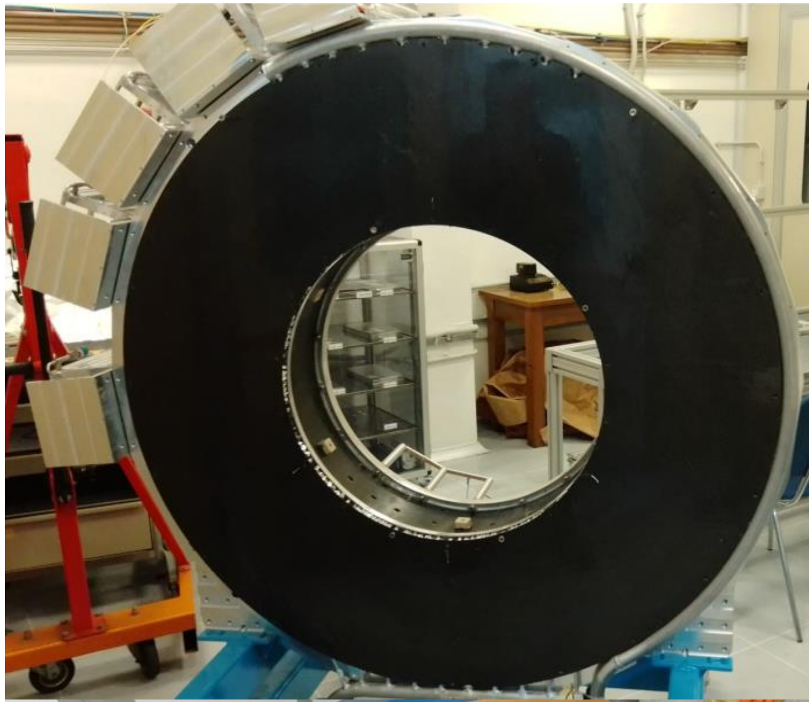


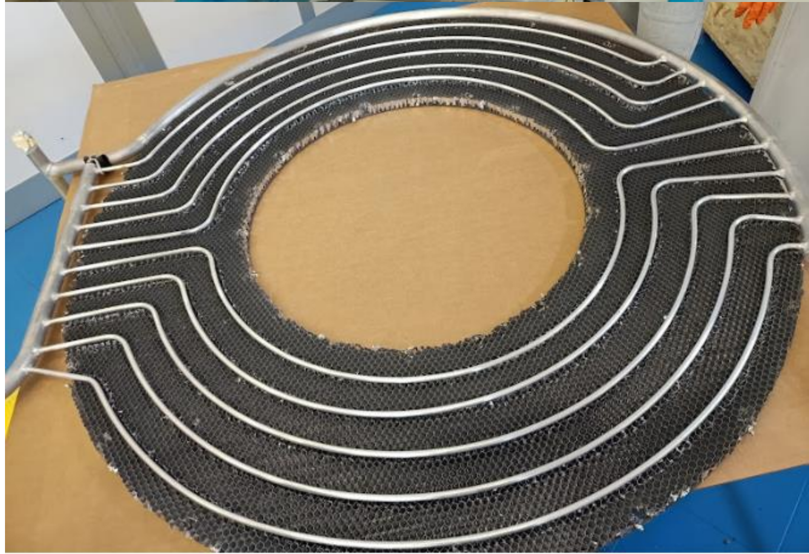
MU2E CALORIMETER CALIBRATION

- High stability required at run time → Multiple calibration methods available:
  - SiPM+FEE Gain monitor using a green laser light transported with optical fibers
  - Cosmic rays calibration, for energy equalization and time-offset alignments
  - Low energy 6 MeV gamma rays from fluorine-containing liquid activated with a neutron DT generator
    - Low material-budget carbon-fiber/aluminium honeycomb front plate with integrated pipes



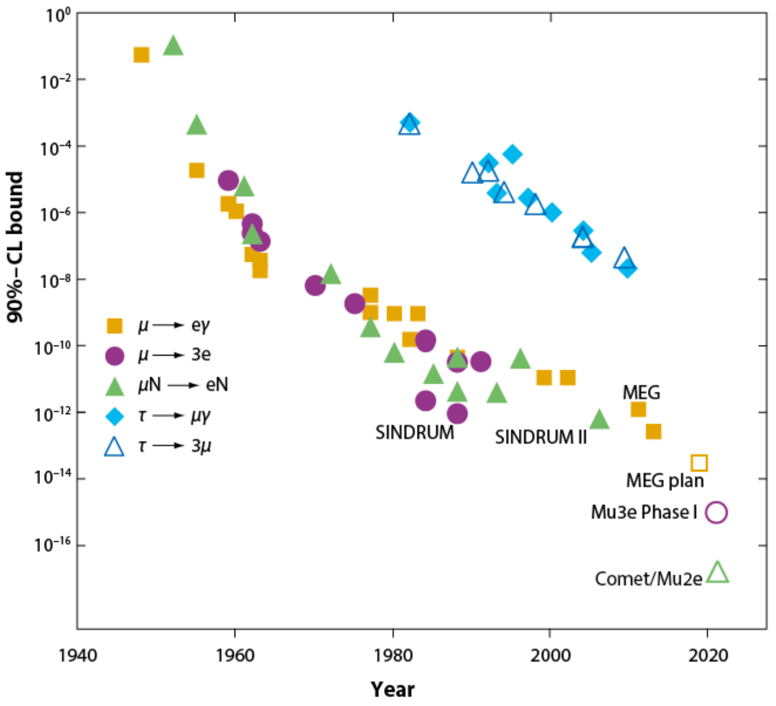


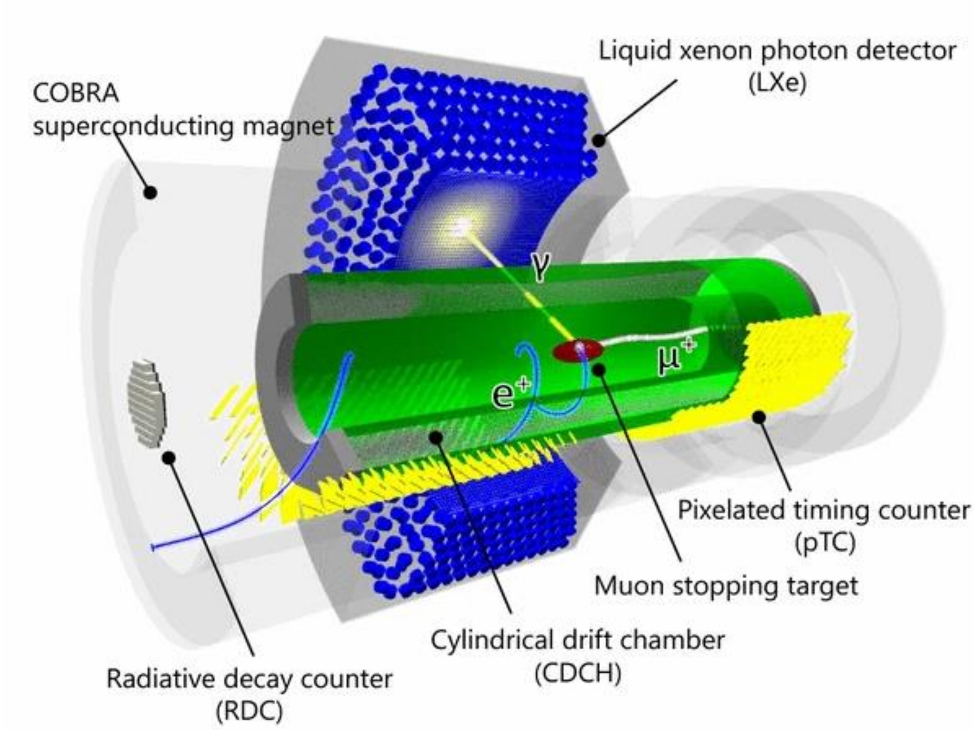




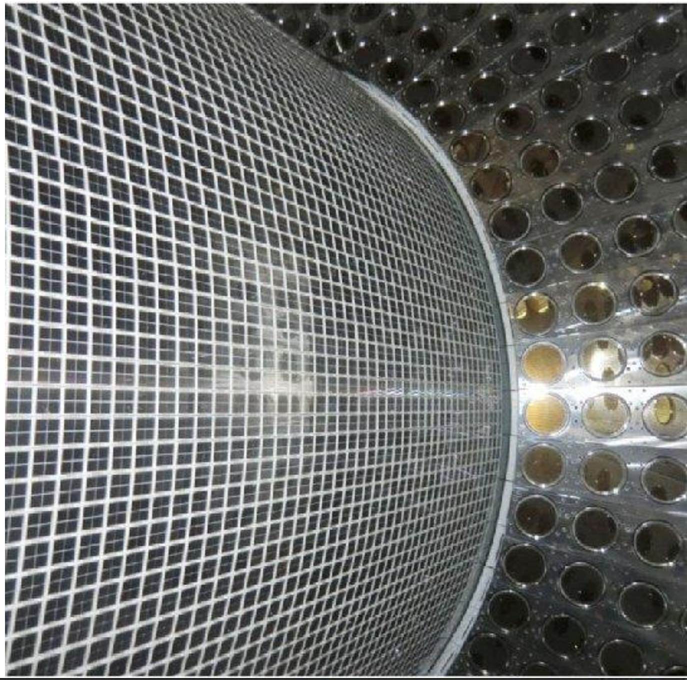
COMPARISON WITH MEG/MEG-II

- Muon to Electron Gamma CLFV search at PSI, looking for the $\mu^+ \to e^+ \gamma$ decay
- MEG published a limit on the branching ratio at a level of 10^{-13}, MEG-II (in commissioning) will improve by a factor 10
- MEG-II observes a signal → Mu2e also should see a bump, but converse not true
- Over 7×10^7 μ^+/s stopped in a plastic target (no muonic atoms), to fix the kinematics
- ~53 MeV conversion positrons and photons observed with Drift Chamber + Pixelated Timing Counter + Gamma Detector

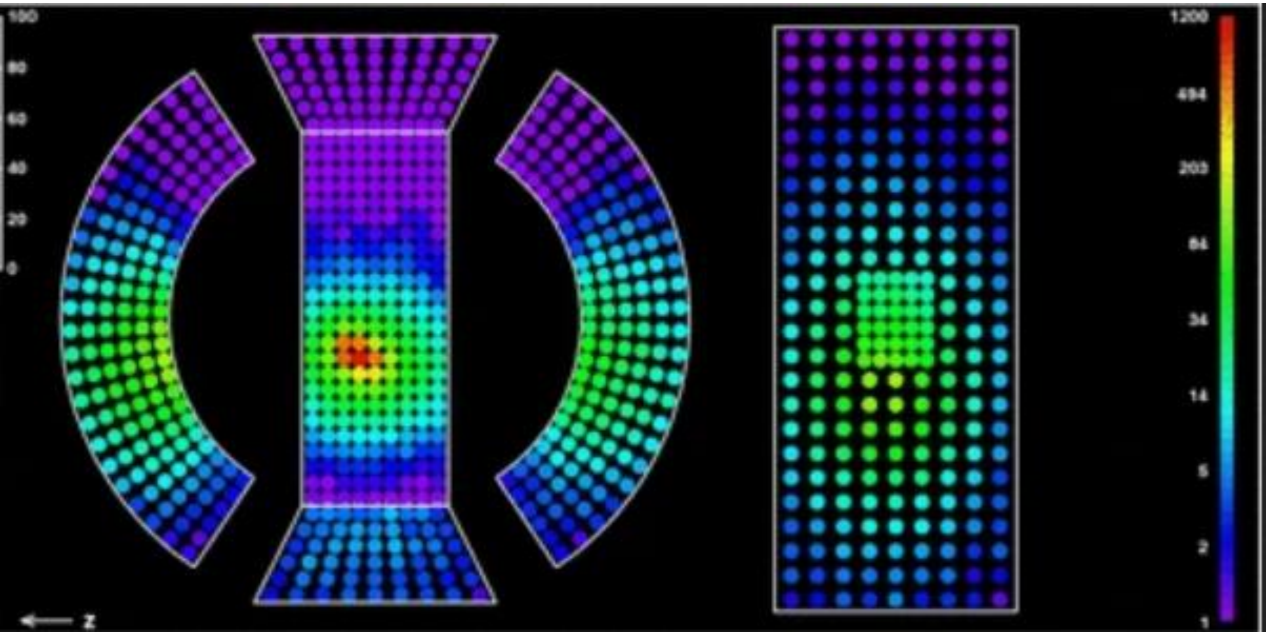


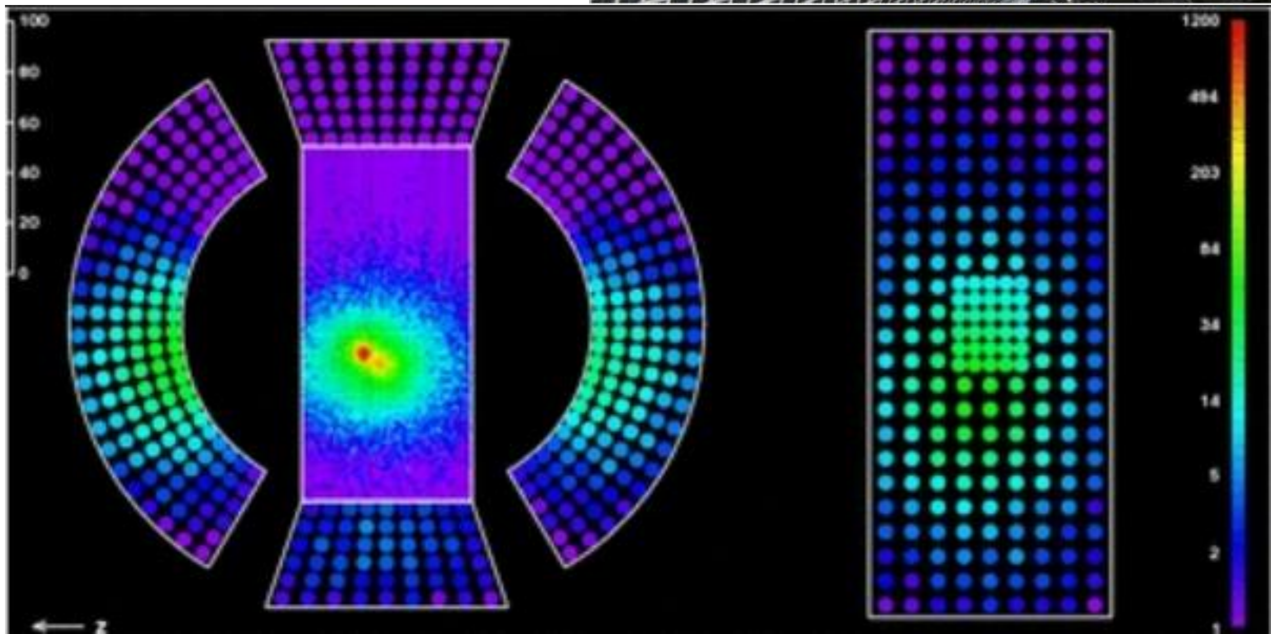


MEG-II CALORIMETER OVERVIEW



- High energy resolution (~1%) needed at ~53 MeV → Homogeneous calorimeter
- Photons-only detector → No energy loss in the walls → Scintillating liquid calorimeter suitable
- High rates → Liquid Xenon (fastest scintillating noble gas with ~180 nm light emission, 2.2 ns singlet lifetime and 27 ns triplet lifetime)
- Non-uniform response reduction → Substitution of MEG PMTs in the inner region with custom VUV-extended SiPMs





R&D for innovative calorimeters with optical readout

Matthew Moulson and Ivano Sarra, INFN Frascati
for the INFN Frascati – Ferrara – Padova – Torino groups

IFD 2022: INFN Workshop on Future Detector (19 October 2022)

-

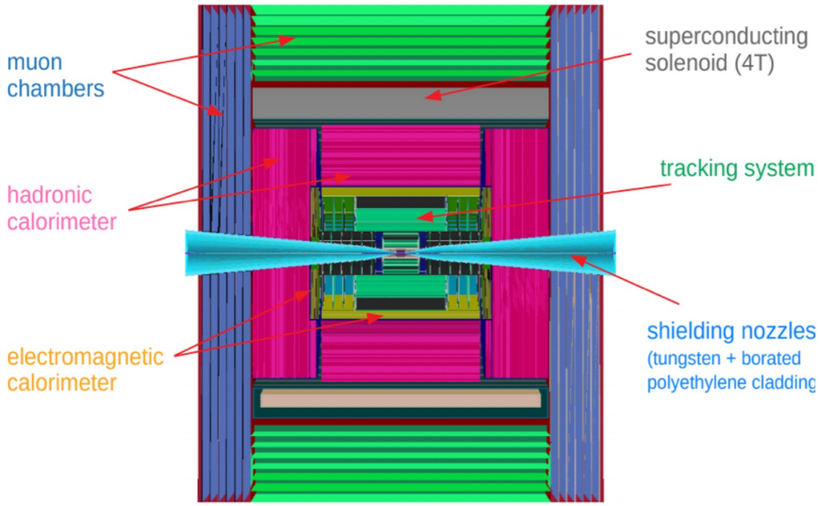
The case of Muon Collider

- At the ECAL barrel surface the BIB flux is 300 particles/cm^2, most of them are photons with <E>=1.7 MeV.
- The BIB produces most of the hits in the first centimeters of the calorimeter

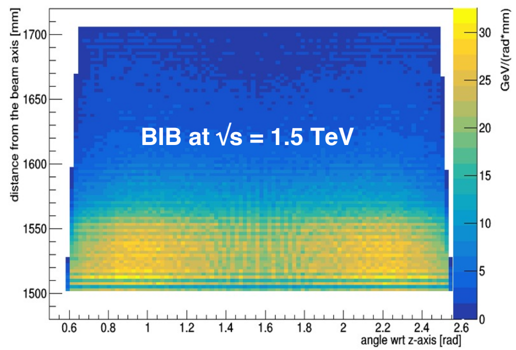
Timing and longitudinal segmentation play a key role in BIB suppression
→ **fast response** (small integration window) is essentially to **reduce energy contribution** from BIB

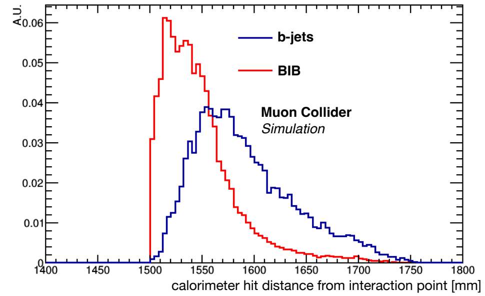
- Since the BIB hits are out-of-time w.r.t. the bunch crossing, a **measurement of the hit time performed cell-by-cell** can be used to **remove most of the BIB:**

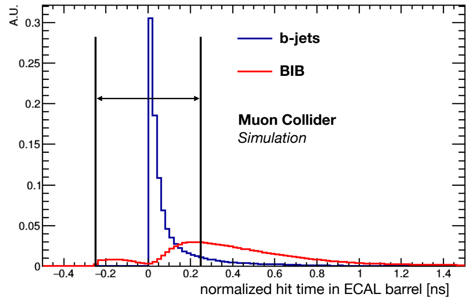
Actual design of the ECAL:
40 layers of 1.9 mm W absorber
+ silicon pad sensors
(~64M channels for the Barrel)
- 5x5 mm^2 cell granularity
- 22 X_0 (1 λ_i)



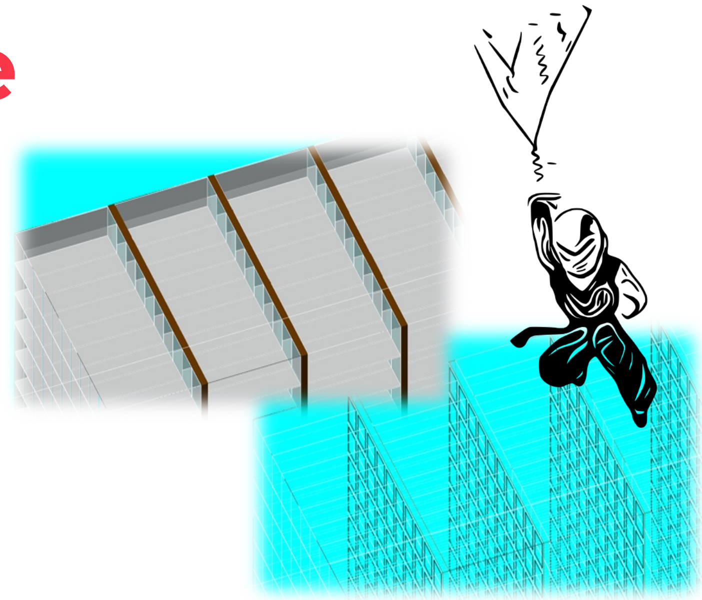
Energy released in ECAL barrel by one BIB bunch crossing



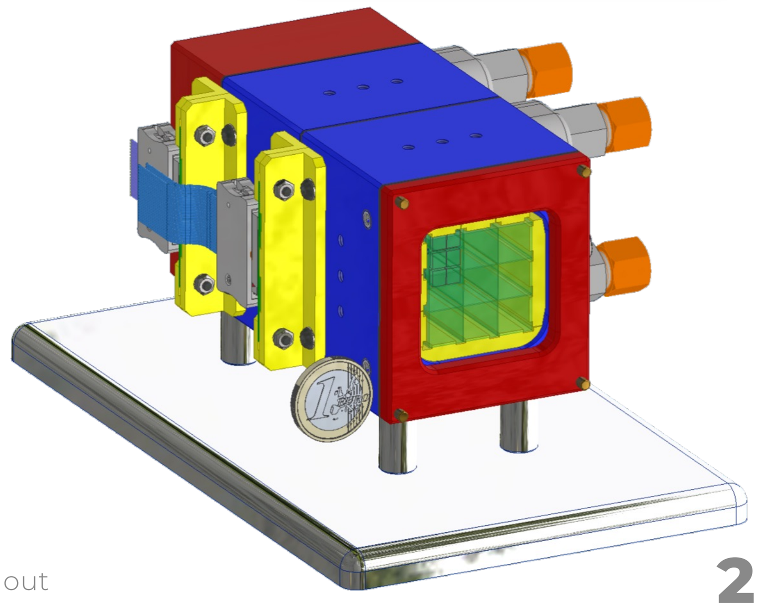




Crilin prototype

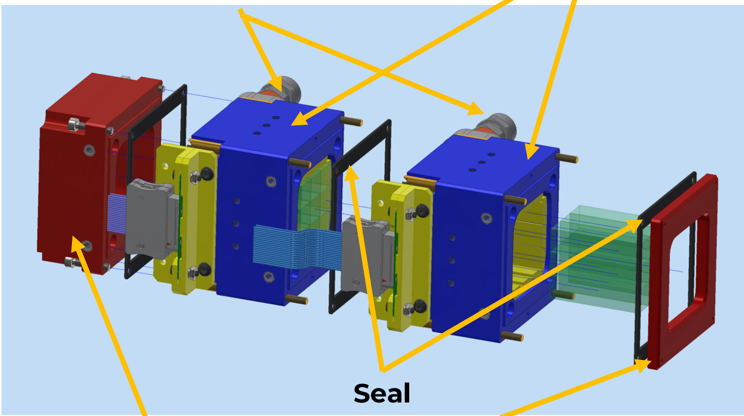


- Crilin (Crystal calorimeter with longitudinal information) represent a **valid** and **cheaper backup solution**
  - Based **on Lead Fluoride** (PbF_2) crystals readout by **2 series of two UV-extended 10µm pixel SiPMs each.**
  - Crystal dimensions are 10x10x40mm^3 and the surface area of each SiPM is 3x3 mm^2, to closely match the crystal surface.
  - Modular architecture based on stackable submodules

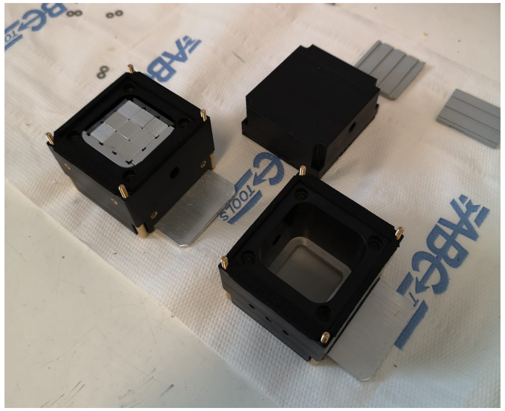


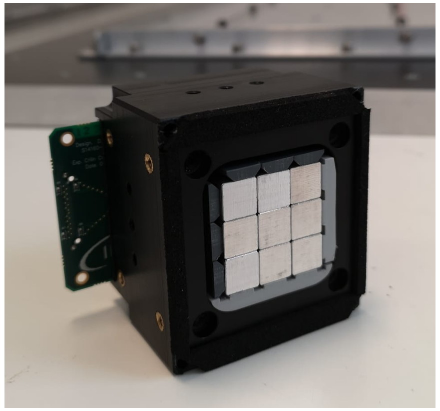
- **Proto-1:** 2 submodules assembled by bolting, each composed **of 3x3 crystals+36 SiPMS** (2 channel per crystal)
  - light-tight case which also embeds the front-end electronic boards and the heat exchanger needed to cool down the SiPMs.
  - SiPMs are connected via 50-ohm micro-coaxial transmission lines to a microprocessor-controlled Mezzanine Board which provides signal amplification and shaping, along with all slow control

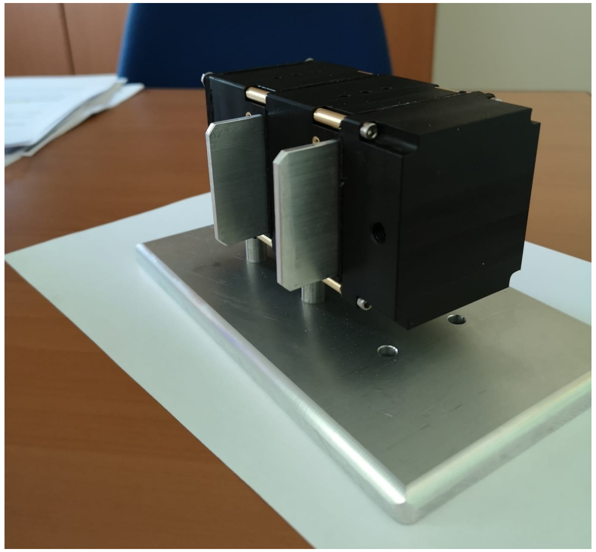
Mechanics and cooling system

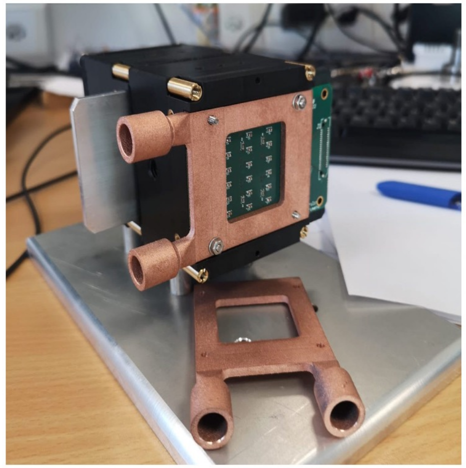


- Total heat load estimated: **350 mW per crystal** (two readout channels)
- Cold plate heat **exchanger** made of copper mounted over the electronic board.
- **Glycol based water solution** passing through the deep drilled channels.









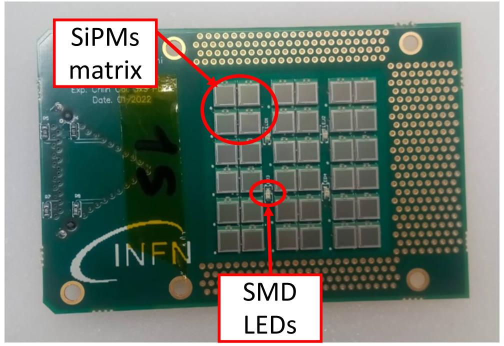
Copper exchanger

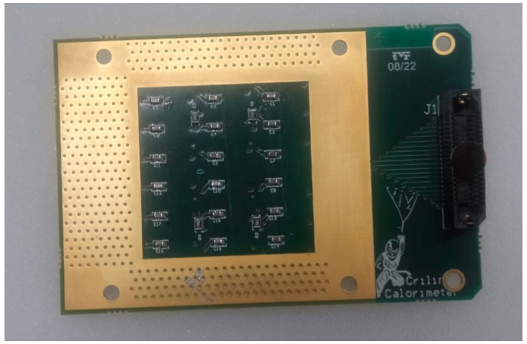
Electronics
SiPMs Board and FEE/Controller

The SiPMs board is made of:

- 36 **10 μm Hamamatsu SiPMs**

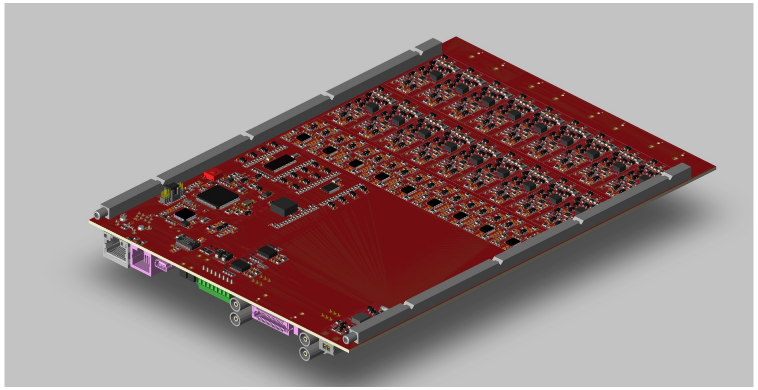
  ⟶ each crystal has **two separate readout channels connected in series**.

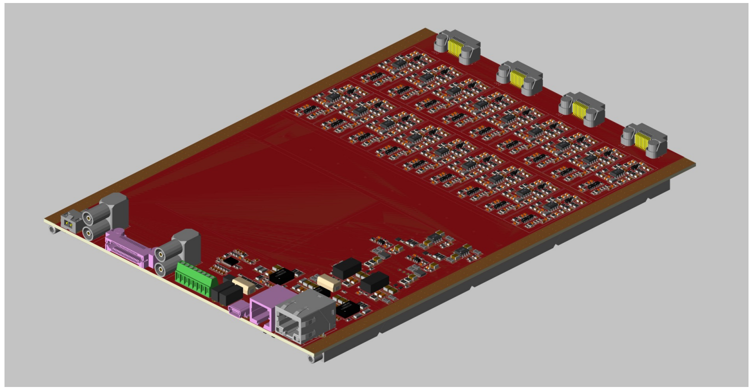




- Four SMD blue LEDs nested between the photosensor packages.

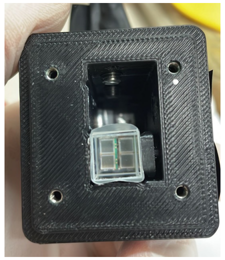
- Controller - 18 Front End electronics channels → under production

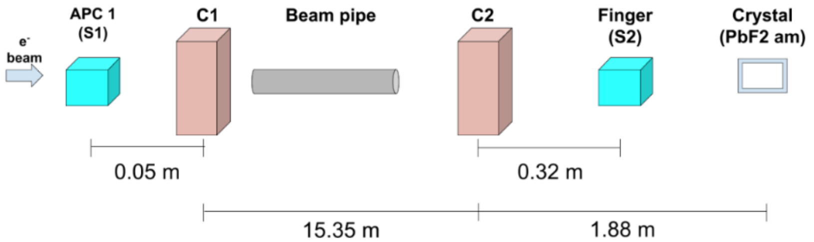




Test beam: PbF_2 and PWO-UF

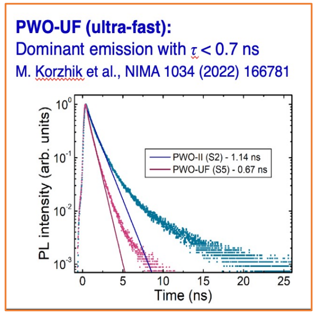
- Validate CRILIN readout electronics and readout scheme
- Study systematics of light collection in small crystals with high *n*
- Measure time resolution achievable for PbF_2 and PWO-UF





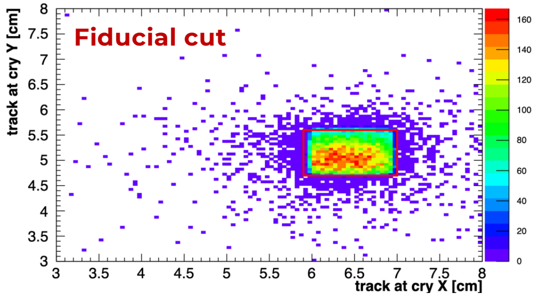
- 80 GeV electrons beam
- Tracking with C1 C2 silicon strips
- Start trigger with S2 scintillator
- Signals digitized at **5 GS/s**

For reference

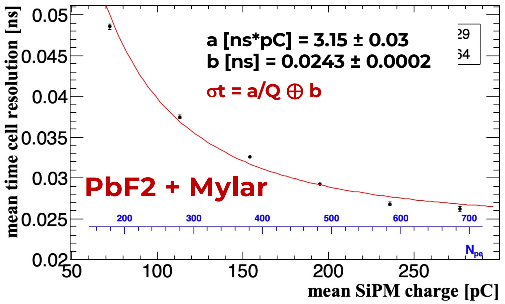


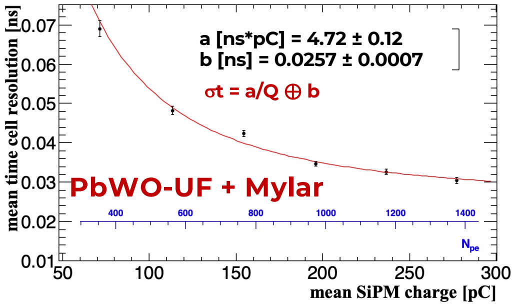
Very Preliminary

Deposited energy vs 1 single particle in C1 and C2



Time Resolution per charge slices after asymmetry correction

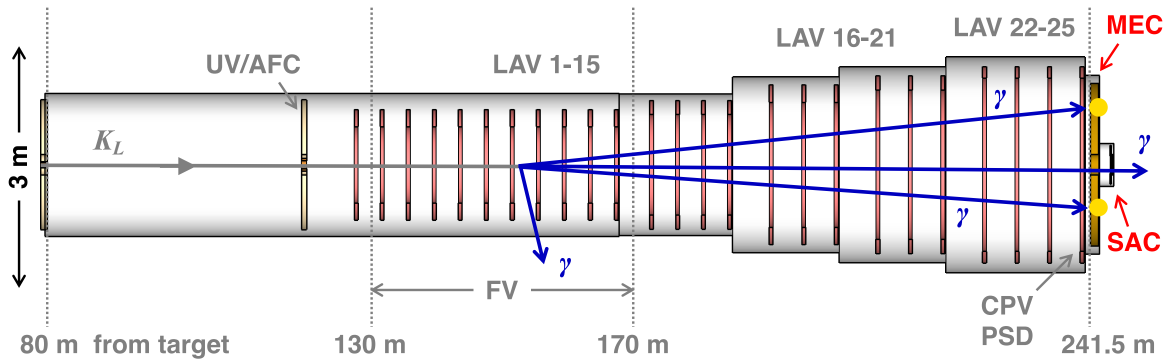




Attenuator of -6dB used for PWO-UF → Double of LY respect to the PbF2

Innovative calorimeters for KLEVER

- **KLEVER will measure BR($K_L \to \pi^0 \nu\nu$) ~ 3 10^{-11}**
Must reject decays with extra photons ($K_L \to \pi^0\pi^0$) at 10^{-8} level!



Small-angle calorimeter (SAC)
- Rejects extra photons escaping through beam pipe
- Sits directly in neutral hadron beam
- Must be transparent to 450 MHz of beam neutrons

- **Good photon detection efficiency for *E*>5 GeV**
- **Excellent time resolution (<< 100 ps)**
- **Radiation resistant**

Synergy with Crilin

Compact, ultra-fast crystal calorimeter

Main electromagnetic calorimeter (MEC)
- Reconstructs π^0 in $K_L \to \pi^0 \nu\nu$ decays
- Rejects events with extra photons
- Establishes event time (total event rate ~ 100 MHz!)

- **Excellent photon detection efficiency**
- **Excellent time resolution (< 100 ps)**
- **Radiation resistant**

High-performance Shashlyk calorimeter

NanoCal project: AIDAinnova WP13.5 (Blue Sky)

Realize first calorimeter with NC scintillators:

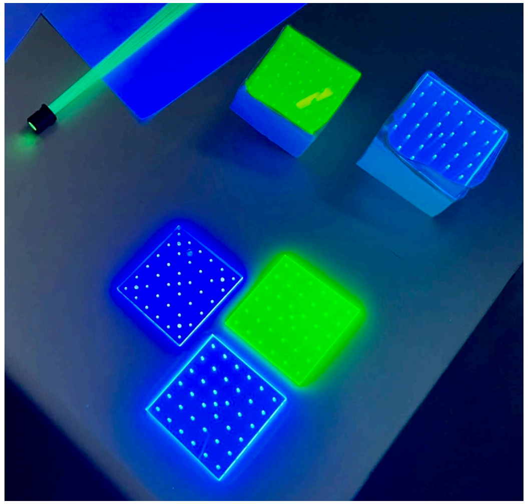
$CsPbBr_3$, 0.05-0.2% w/w in UV-cured PMMA
- 50% of light emitted in components with τ < 0.5 ns
- Radiation hard to O(1 MGy)
- **Light yield? O(few k) photons/MeV deposit?**

Nano composite scintillators for shashlyk

KLEVER

Quantum dots used as emitters for bright, ultrafast, robust scintillators:

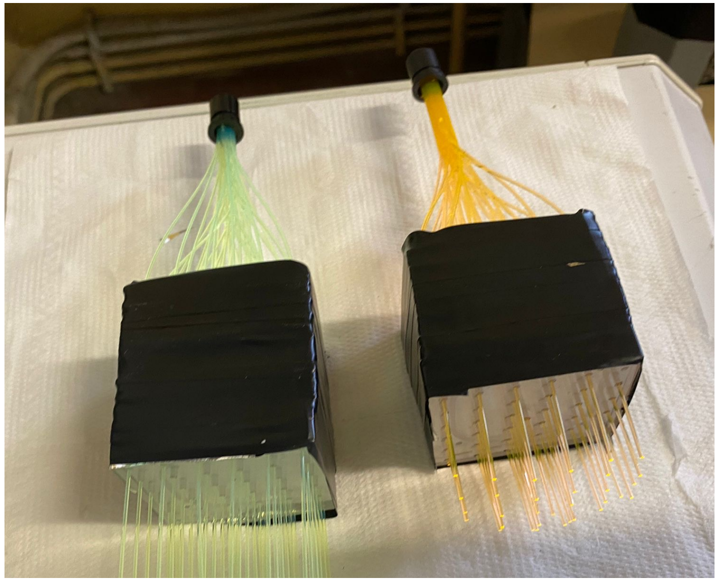
- Calorimetry
- Timing-plane detectors



Trial production of tiles in Protvino format (55×55 mm^2)

- Two identical modules, 12 layers, very fine sampling
- *Comparison of performance with conventional scintillator before constructing full-scale prototype*

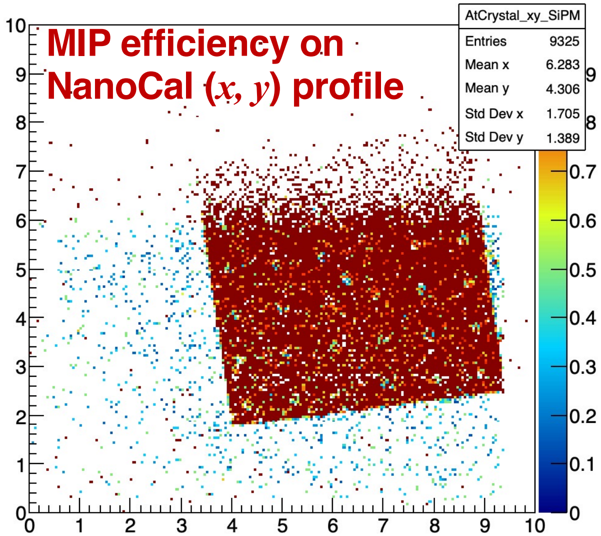
- Both have 12 fine sampling layers: 0.6 mm Pb + 3 mm scintillator
- Each 1.3X_0 in depth: expected mip energy deposit = 10 MeV
- Each read out with a single Hamamatsu 13360-6050 SiPM

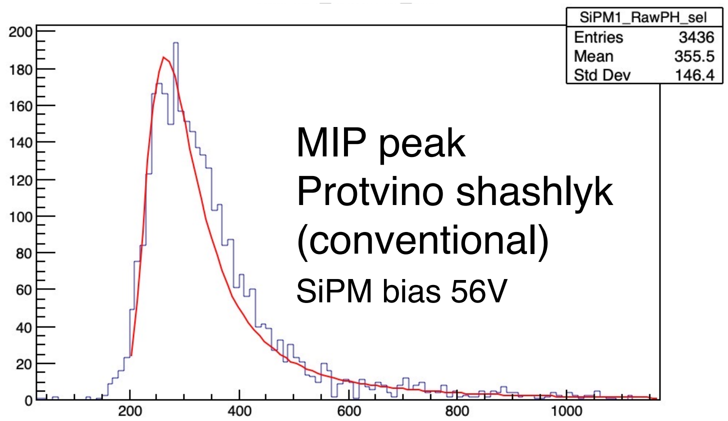


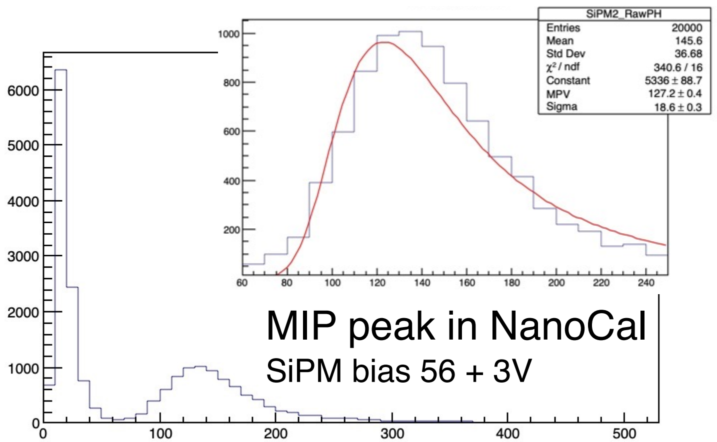
Nano Cal scintillator
PMMA
0.2% $CsPbBr_3$
Kuraray O-2(100) fibers

Protvino scintillator
Polystyrene
1.5% PTP/0.04% POPOP
Kuraray Y-11(200) fibers

Shashlyks: Conventional vs NanoCal







Preliminary (undigested) observations:

- NanoCal signal output significantly smaller than Protvino (x10?)
- **NanoCal time resolution for mips 30% worse than Protvino**
  Correlated with signal output: less light = worse resolution

Influence of fibers

- QE of SiPM drops by 25% from 480 → 550 nm
- Don't know relative LY of O-2 vs Y11 fibers

Also need direct measurements of NanoCal vs. Protvino scintillator

Combining **Dual-Readout** Crystals and Fibers in a **Hybrid Calorimeter** for the IDEA Experiment

Marco Lucchini

INFN & University of Milano-Bicocca

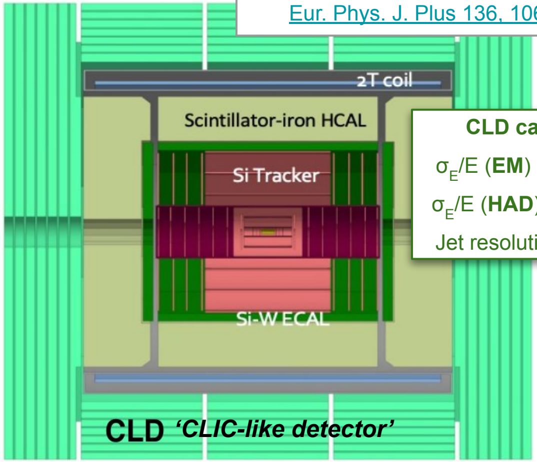
*On behalf of the **IDEA calorimeter group***

Current baseline detector concepts for future e^+e^- colliders

Two main baseline concepts for general purpose detectors at future e^+e^- colliders (have been around since a while):

- **CLD**: Sampling calorimeters with silicon / plastic scintillators active elements interleaved with tungsten / steel
  - Exploiting high granularity for particle flow algorithms (combining tracker and calorimeter exploiting topological information)
- **IDEA**: Sampling calorimeters with ~2 m long scintillating (plastic) and cherenkov fibers inside absorber groove
  - Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)

M.Aleksa et al., *Calorimetry at FCC-ee*, Eur. Phys. J. Plus 136, 1066 (2021)

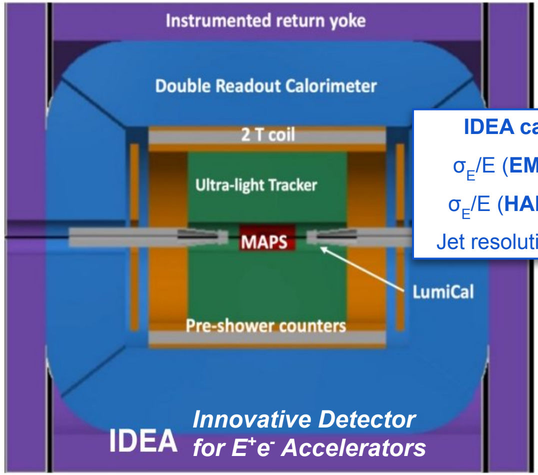


CLD calorimeter

σ_E/E (**EM**) ~15-17%/√E

σ_E/E (**HAD**) ~45-50%/√E

Jet resolution ~ 30%/√E



IDEA calorimeter

σ_E/E (**EM**) ~11%/√E

σ_E/E (**HAD**) ~30%/√E

Jet resolution ~ 30%/√E

Current baseline detector concepts for future e^+e^- colliders

Two main baseline concepts for general purpose detectors at future e^+e^- colliders (have been around since a while):

- **CLD**: Sampling calorimeters with silicon / plastic scintillators active elements interleaved with tungsten / steel
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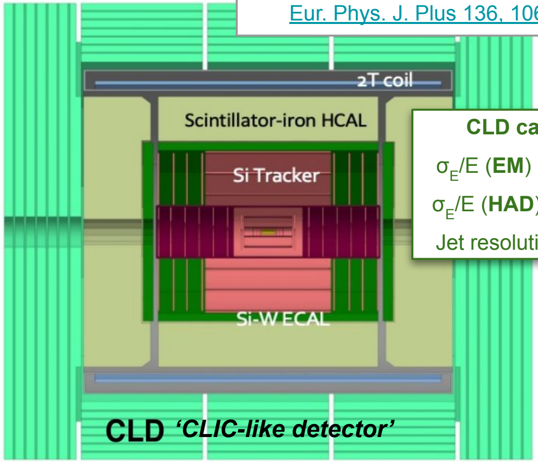
- **IDEA**: Sampling calorimeters with ~2 m long scintillating (plastic) and cherenkov fibers inside absorber groove
  - Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)

- **EM energy resolution is far from that of state-of-the-art homogeneous crystal calorimeters (1-3%/√E)**

M.Aleksa et al., *Calorimetry at FCC-ee*, Eur. Phys. J. Plus 136, 1066 (2021)



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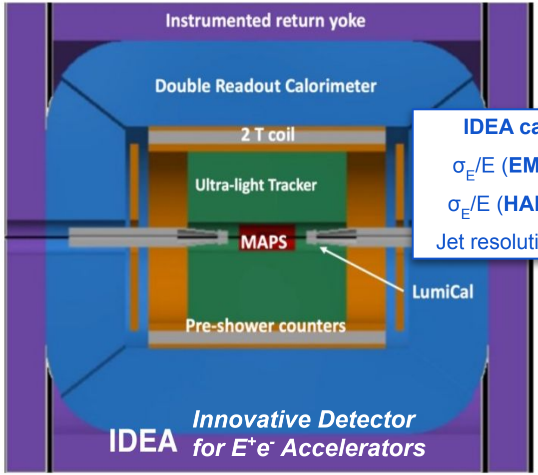


IDEA calorimeter

σ_E/E (**EM**) ~11%/√E

σ_E/E (**HAD**) ~30%/√E

Jet resolution ~ 30%/√E

Potential for high EM energy resolution

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

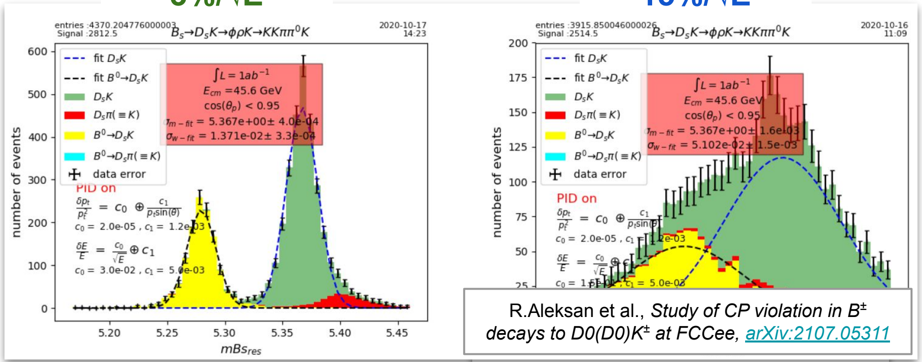
Potential for high EM energy resolution

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

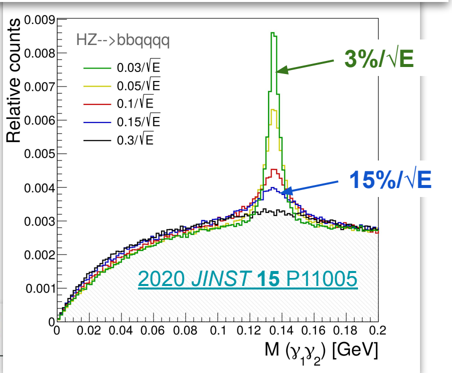
- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

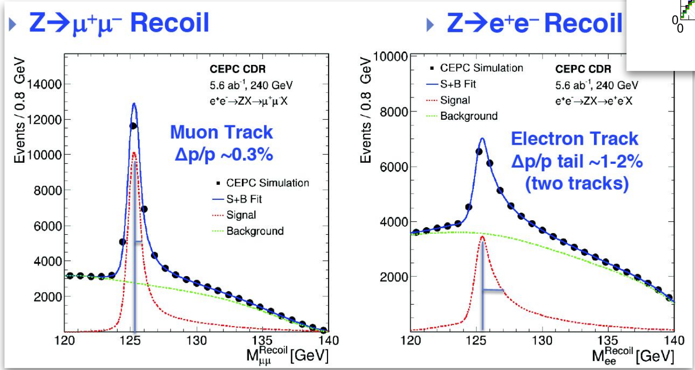
3%/√E

15%/√E



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





Example from CEPC CDR

Technological progress in the field of scintillators and photodetectors has **enabled** the design of **a cost-effective and highly performant calorimeter**

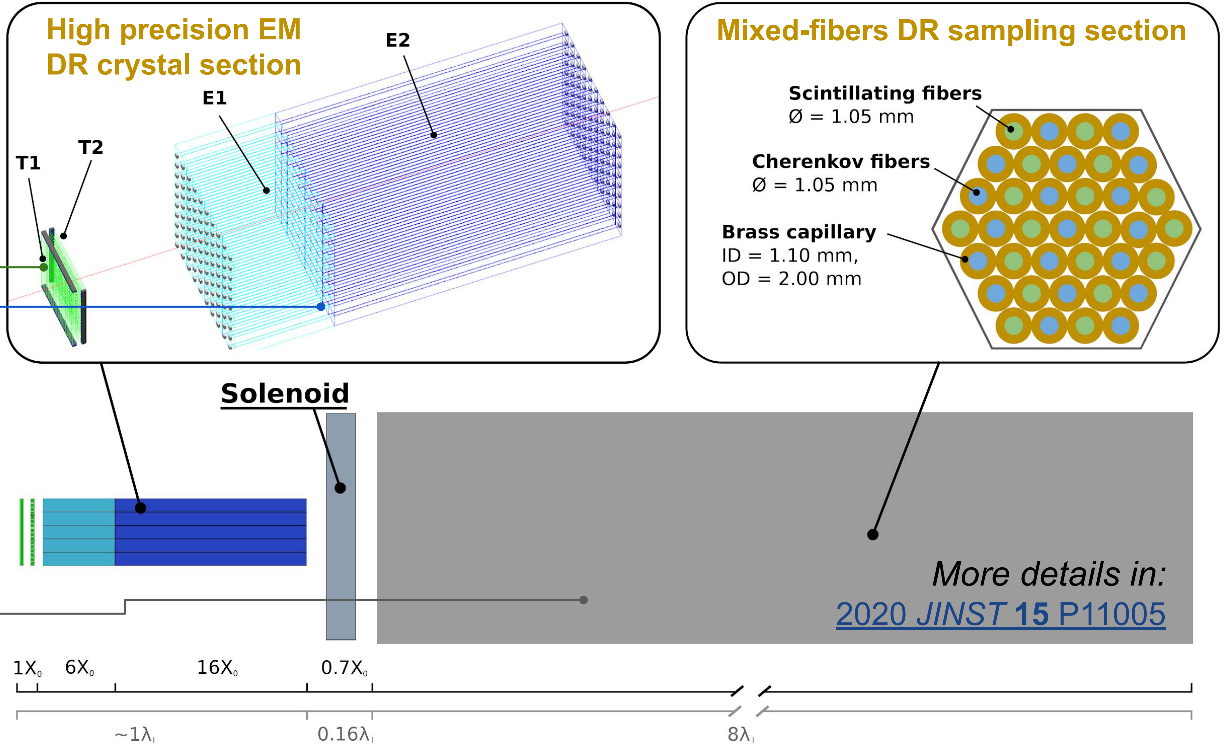
- **Excellent energy resolution to photons and neutral hadrons**
  (~3%/√E and ~30%/√E respectively)
- **Separate readout of scintillation and Cherenkov light**
  (to exploit dual-readout technique for hadron resolution and linearity)
- **Longitudinal and transverse segmentation**
  (to provide more handles for particle flow algorithms)
- **Energy resolution at the level of 4-3% for 50-100 GeV jets**
- **Precise time tagging for both MIPs and EM showers**
  (time resolution better than 30 ps)

"Maximum information" calorimetry
(**6D**: x,y,z,t,E,C/S)

Conceptual layout

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

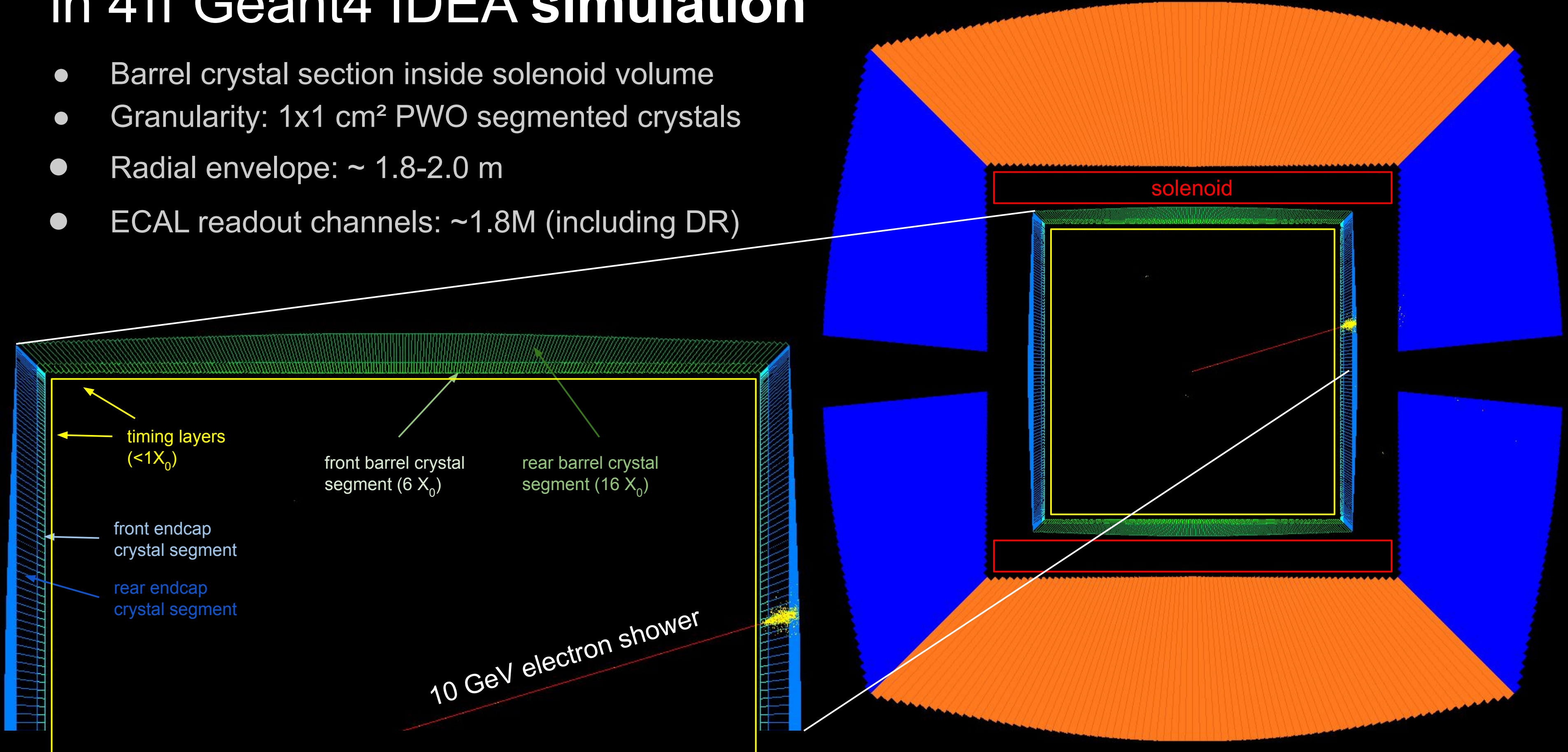
- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  -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



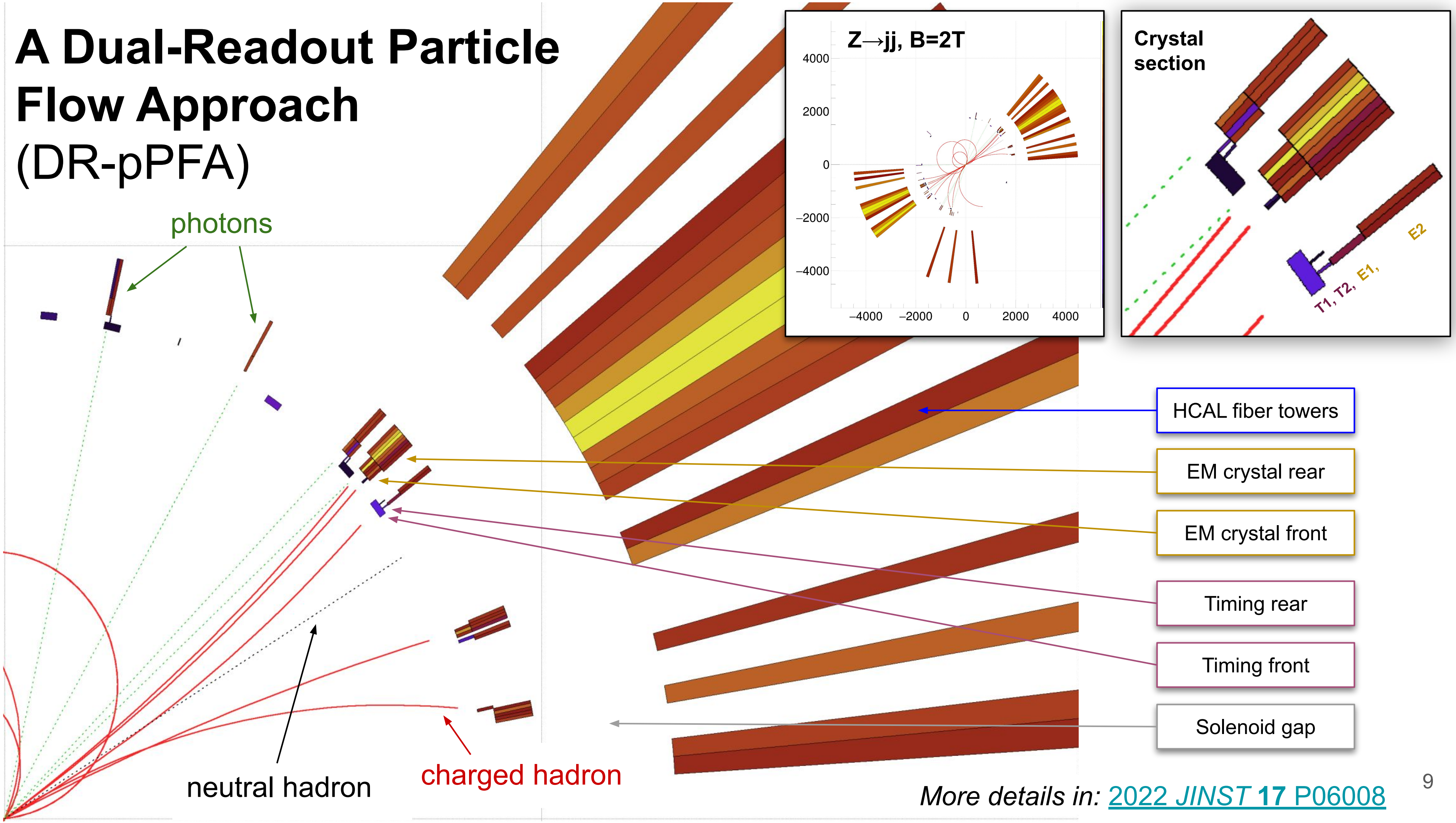
More details in: [2020 *JINST* **15** P11005]

Integration of crystal EM calorimeter in 4π Geant4 IDEA **simulation**

- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: ~1.8M (including DR)



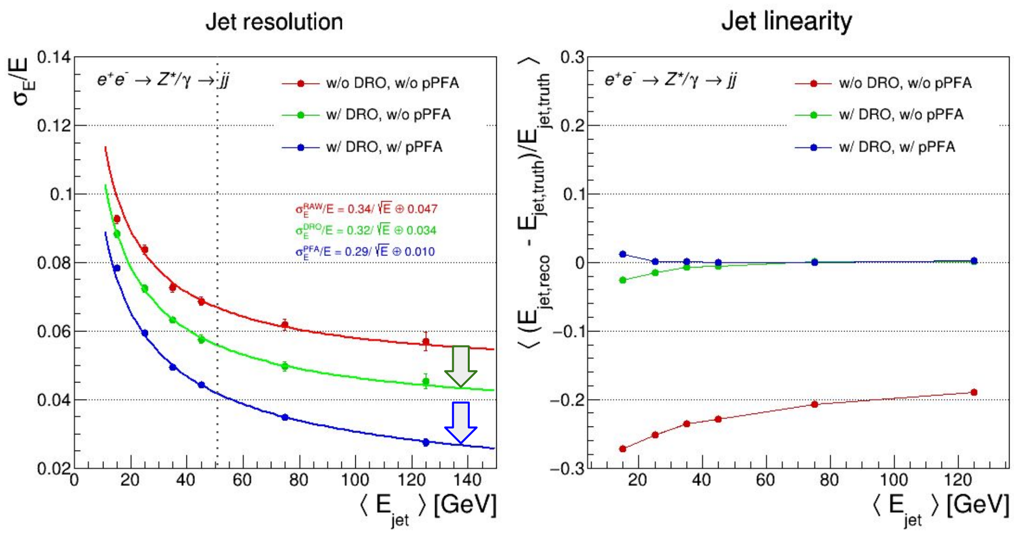
A Dual-Readout Particle Flow Approach
(DR-pPFA)



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

Jet resolution: with and without DR-pPFA

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



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

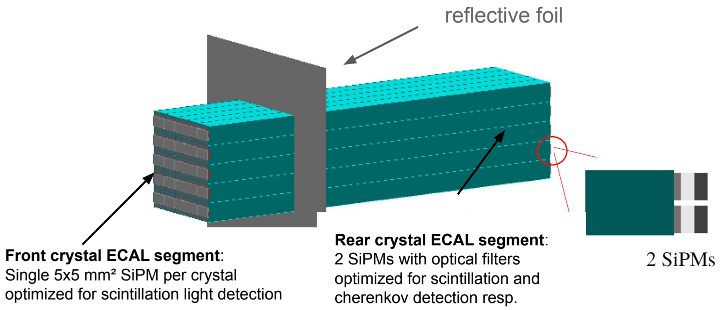
- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA

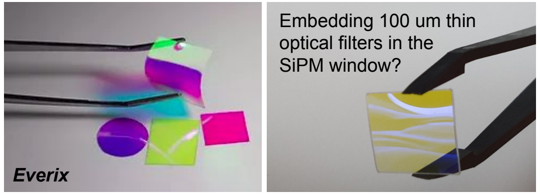
Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

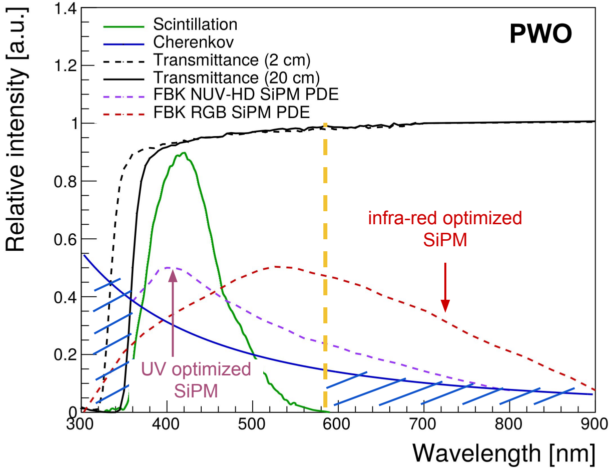
Ongoing R&D activities on the EM crystal section

- **Key R&D challenges**:
  - Crystal **readout with SiPMs**
    → challenging dynamic range and photon sensitivity
  - Multi-signal readout challenges:
    - Reasonable scintillation and cherenkov light yields
    - **Good separation of scintillation and cherenkov signals**
      → e.g. based on wavelength (thin filters)
  - Main crystal candidates are PWO, BGO, BSO because of their high Cherenkov yield and density

- Interest and efforts are ramping up within the IDEA calorimeter group and the CalVision project in the US

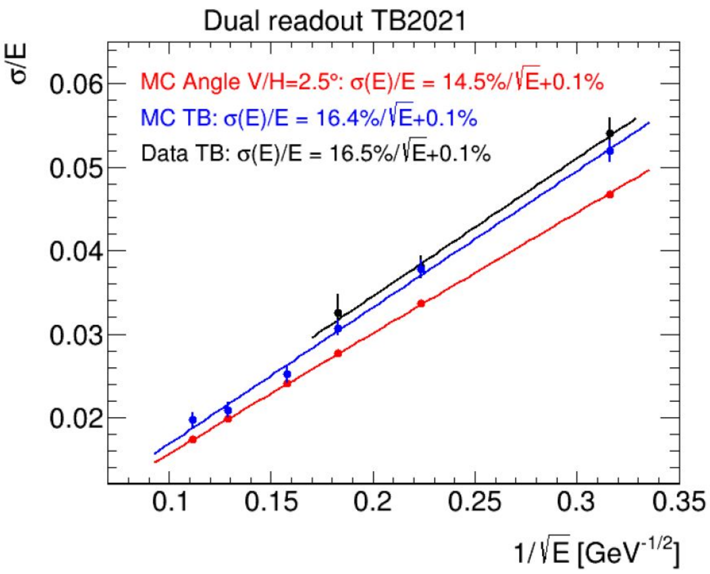


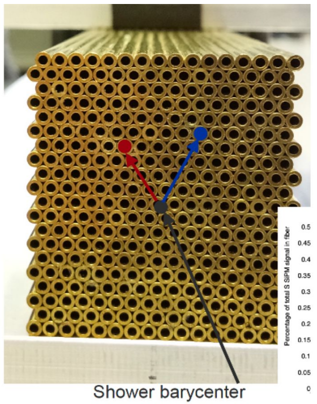


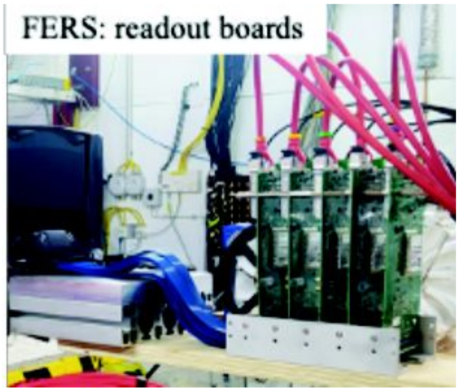


Test beam results from IDEA fiber calorimeter prototype

- **EM-size prototype** (10x10x100 cm^3) put on beam in 2021
- Basic calorimeter unit: one **brass capillary** tube of 2 mm external diameter hosting a fiber of 1 mm diameter







Summary

- EM energy resolution at the 1-3%/√E level can **expand the physics potential of e^+e^- collider experiments** providing enhanced sensitivity to low energy photons
- A **dual-readout hybrid calorimeter** (homogeneous crystals + fibers in brass tubes) **can meet the requirements of EM, HAD and jet energy resolution** (through the development of dedicated dual-readout particle flow algorithms)
- **Growing international collaborative efforts** to address **R&D challenges** and development of simulation tools to optimize a cost-effective calorimeter design

MPDG-based calorimeter for future colliders

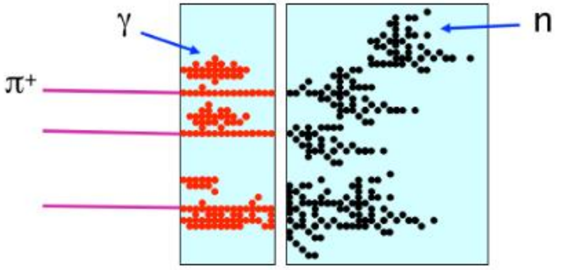
Anna Stamerra

INFN Workshop on Future Detectors

Bari, 19 Ottobre 2022

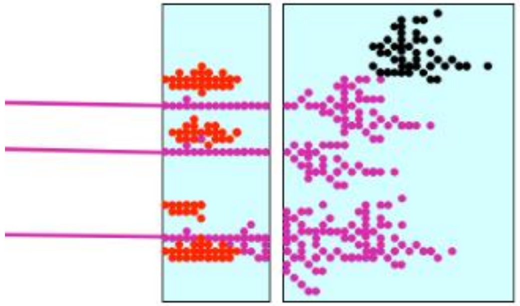
Particle-Flow Calorimetry

Future high-energy lepton colliders require optimal jet energy resolution: $\sigma_E/E < 3.5\%$



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

Traditional calorimetric approach
- Jet-energy is measured as a whole
- Measured from ECAL + HCAL
- ~ 70 % of jet energy measured in HCAL with poor resolution (<60%)



$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

PFlow calorimetric approach
- Reconstruct individual particles of the jets
- Exploiting the most accurate subdetector system
- ~ 10 % of jet-energy carried by long-lived neutral hadrons is measured in HCAL

HCal requirements**:** longitudinal and transverse **fine granularity** to separate neutral hadrons from nearby charged particles

J. Marshall, M. Thomson
arXiv:1308.4537

Proposal: MPGD-based HCAL

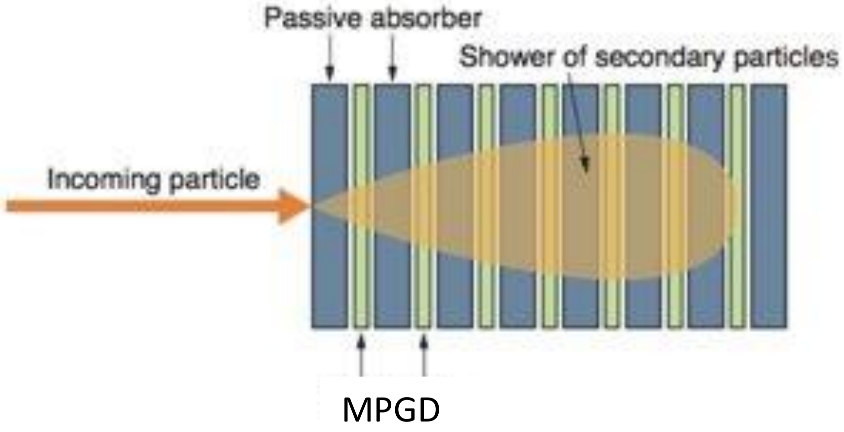
The **CALICE collaboration**(*) already proposed the use of gas detectors (RPCs, GEMs and Micromegas) as active layers for hadron calorimetry to implement **digital** and **semi-digital** readout options.

Micro Pattern Gas Detectors (MPGD) based HCAL

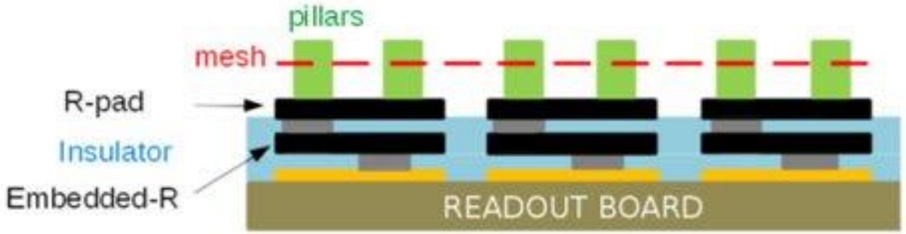
- High rate capability (up to 10 MHz/cm^2)
- Allow high granularity
- Flexible space resolution (> 60 μm)
- Time resolution of the order of tens of ns
- Low cost to instrument large area
- Use of environmental-friendly gas mixtures

- **μRWell** and resistive **Micromegas** as best candidates to mitigate effects due to discharge in the gas

MPGD-based HCAL layout



Micromegas detector layout

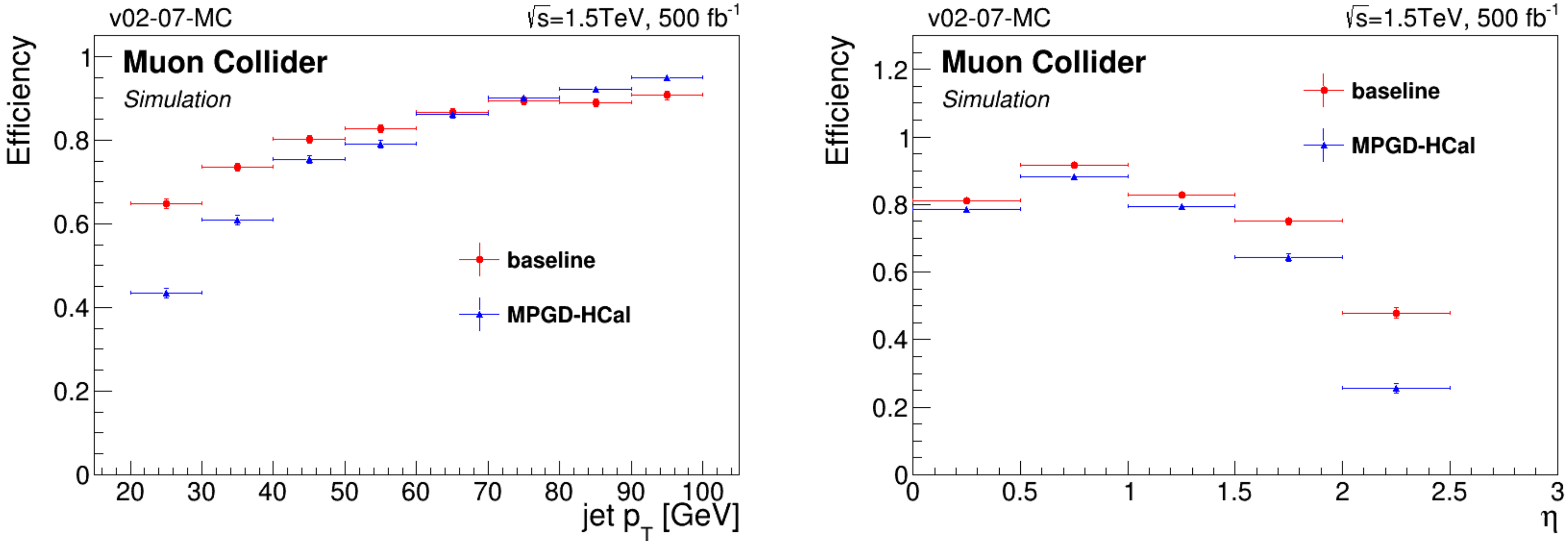


(*)arXiv:1901.08818

MPGD-based HCal at Muon Collider

Baseline: Scintillators + Steel

PRELIMINARY

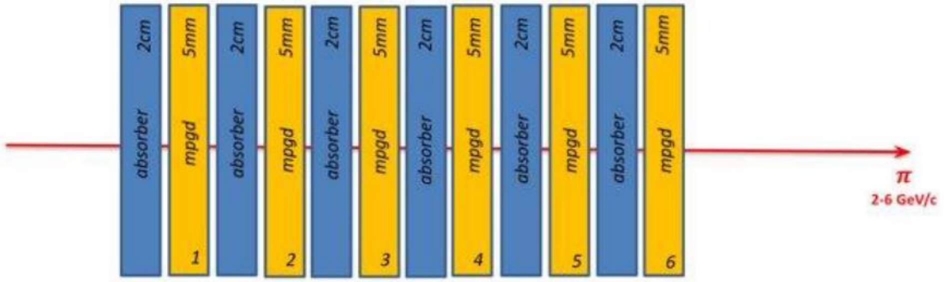


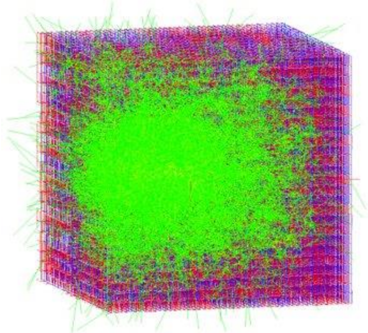
The jet reconstruction efficiency estimated with the MPGD-HCal is comparable to the baseline one.

MPGD-based HCal at Muon Collider – GEANT4 studies

Implemented geometry

- Layers of alternating
  - 2 cm of Steel (absorber)
  - 5 mm of Ar/CO2 (active gap)
- Granularity given by cell of 1x1 cm²

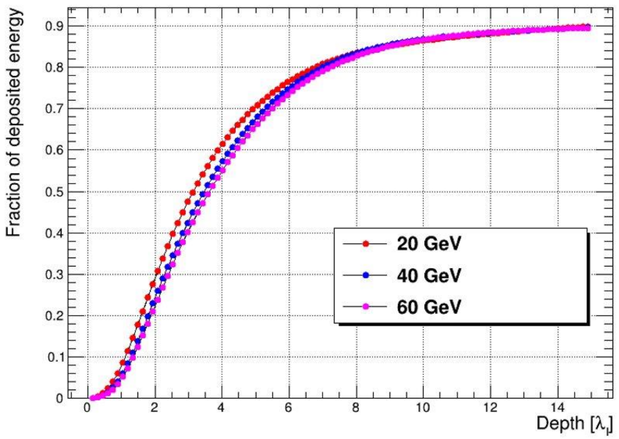




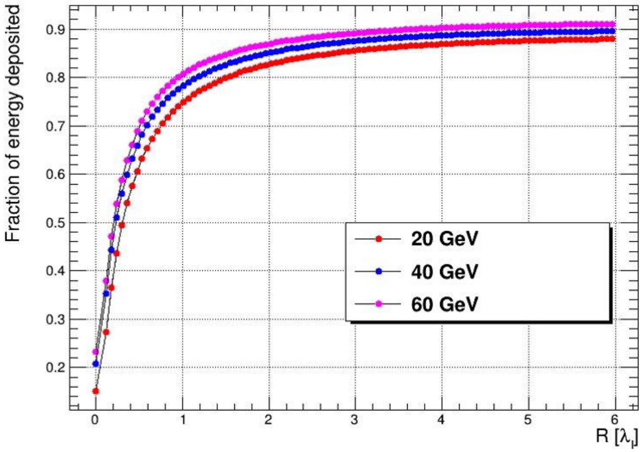
Digital readout simulated

PRELIMINARY

Shower longitudinal containment

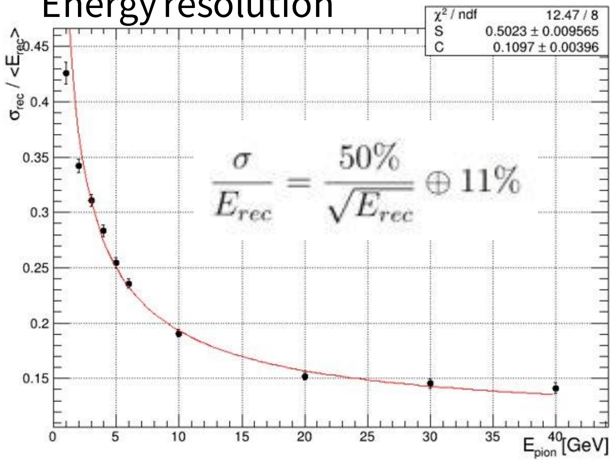


Shower lateral containment



90% shower **containment** in 14 $\boldsymbol{\lambda}_I$ depth and 3 $\boldsymbol{\lambda}_I$ radius

Energy resolution



HCAL Experimental Prototype

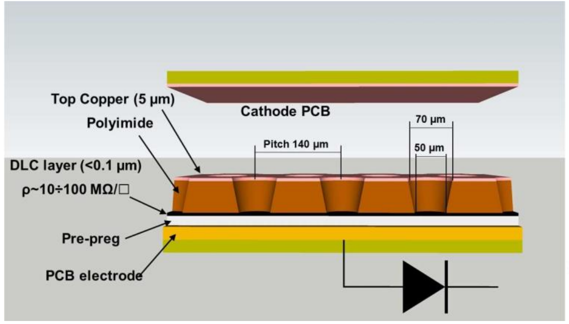
A small scale prototype exploiting last generation resistive MPGDs is under construction
GOAL: validate the simulations with test beam (MIPs with energies between 1 to 6 GeV)

- **6 active layers** made of state of the art resistive MPGDs
  - Resistive **µ-RWell** and **MicroMegas**
  - 20x20 cm^2 with 1 cm^2 pad size

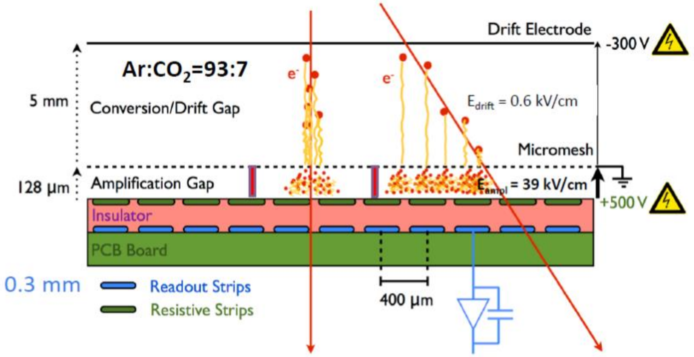
- For Read Out 32 channels **FATIC**(*) asic
  - for timing and charge measurements of the hits
  - It is possible to emulate semi-digital readout

- **Plans for the prototype**
  - Test Micromegas and µRWELL prototypes
  - Build HCal prototype
  - Test under beam irradiation

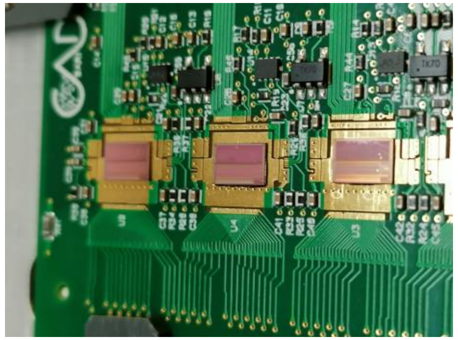
µ-RWell



Resistive Micromegas



FATIC chips



(*)DOI: 10.1109/IWASI.2019.8791274

INFN BARI
Istituto Nazionale di Fisica Nucleare

INFN Workshop on Future Detectors 2022

“Quantum-dot light emitters for chromatic calorimetry”

Anna Colaleo, Antonello Pellecchia, Federica Maria Simone,
Raffaella Radogna, Piet Verwilligen
INFN Bari

IFD 2022, 17-19 Ottobre, Bari

Motivations

Potential of quantum sensing

- the possible applications are incredibly varied
- within few years from the laboratory to real-world/ commercial
- many advantages over traditional semiconductors: compact size, fast operation, superior transport and optical properties

Why QT for HEP?

- increasingly **ambitious physics targets** require **dedicated detector R&D**

R&D for future calorimeters:

- **Demanding needs** from HEP: radiation-hard, enhanced electromagnetic energy and timing resolution, high-granularity with multi-dimensional RO for particle-flow
- R&D with existing technologies can potentially meet this **challenge** at the cost of a high complexity of the readout system

Technology-driven ('blue-sky') R&D to **push detectors beyond state-of-the-art**

Low Dimensional materials for scintillating detectors

Conventional semiconductor bulk material:

- continuous conduction and valence band

→ broad spectrum

- typical 1 photon/Mev/ps (LYSO)

→ small yield from fast signal component

Nanocrystals (NC) 1 - 10 nm size:

- discrete energy levels
- energy gap depends on size **[keypoint]**

→ tuning of opto-electronic properties, such as for instance the

emission wavelength

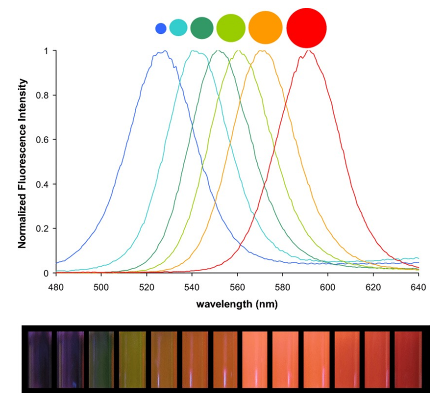
- In direct-band-gap-engineered semiconductor NCs:

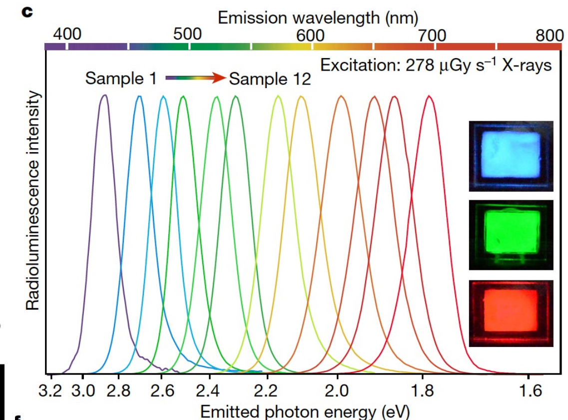
→ **scintillation decay times below 1 ns**

Limitations:

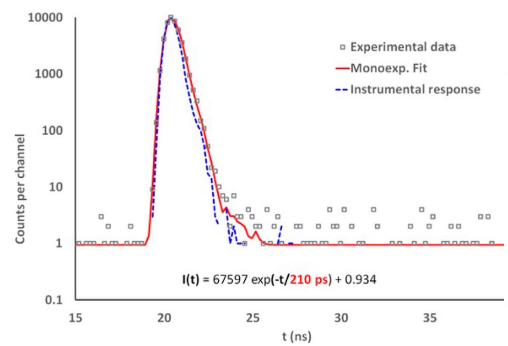
- small energy deposited
- low stopping power
- self-absorption

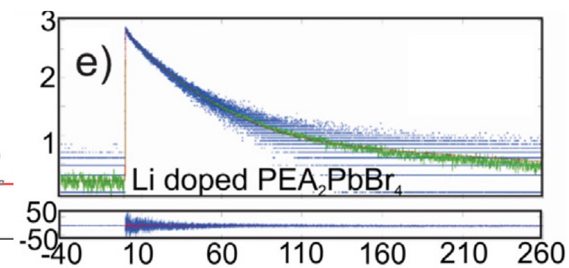
→ **combine bulk scintillators and NCs**



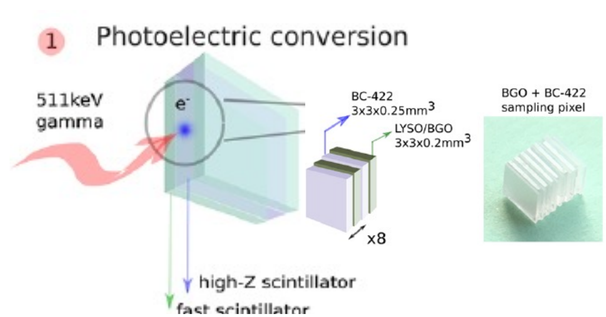


Tunable luminescence spectra of the perovskite QDs under X-ray [https://doi.org/10.1038/s41586-018-0451-1]





Scintillation light time decay. Left: ZnO(Ga) under irradiation by X-rays [doi:10.1016/j.optmat.2015.07.001]. Right: Li-doped PEA_2PbBr_4 [doi:10.1063/5.0093606]

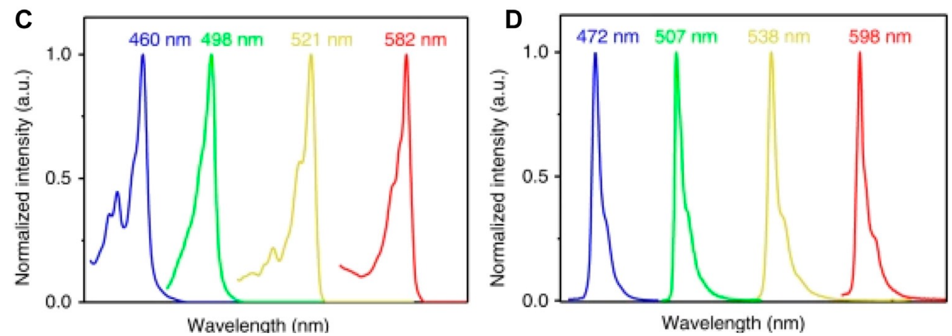


Left: fast plastic BC-422 layers combined with high-Z LYSO as proof-of-principle [doi: 10.1088/1361-6560/ab18b3]. Right: Quantum-dot doped polymer [doi:10.1016/j.radmeas.2018.02.008]

Chromatic calorimeter

- High tunability and narrow emission bandwidth of NCs
- Possibility to combine NCs with bulk scintillators

→ **idea of chromatic calorimeter**



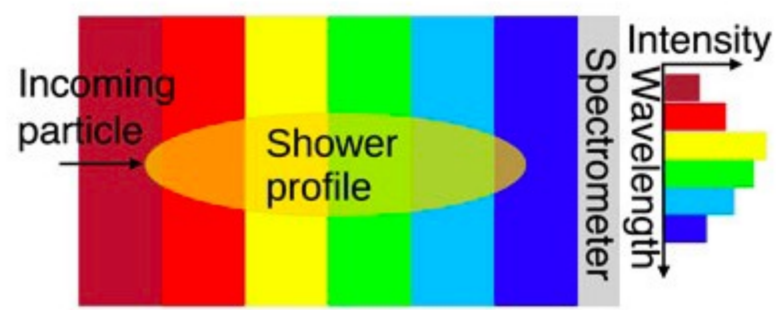
Normalized UV-vis absorption (C) and photoluminescence (D) spectra of triangular carbon quantum dots [doi:10.1038/s41467-018-04635-5]

Single high-Z material doped with NCs with different emission wavelengths (wl)

- longest wl towards the beginning
- shortest wl towards the end

→ **longitudinal tomography of the shower profile**
- → particle ID
- → high-granularity

→ **potentially fast response**
- → trigger



Chromatic calorimeter sketch [doi:10.3389/fphy.2022.887738]

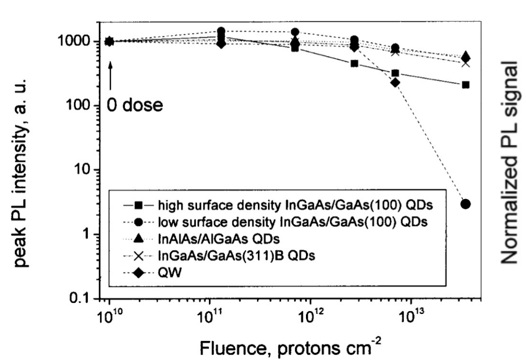
Many technological challenges

- radiation hardness of nano materials
- readout electronics
- light guiding → transparency (self-absorption)
- light yield
  - bulk doping technique
  - NC density, device geometry

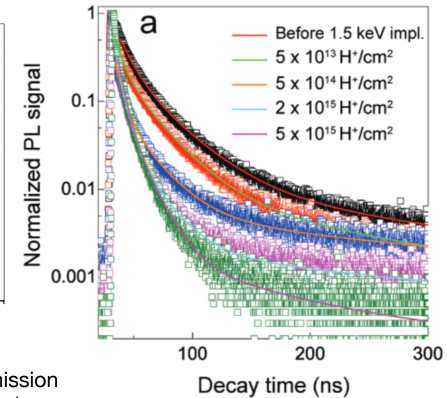
R&D needed to make this real

1) Access radiation hardness of nano materials (perovskites, QDs, quantum wells)

- few studies with protons and HIP in literature
- damage depends on metamaterial structure
- → systematic studies for different NC families and deposition/doping techniques



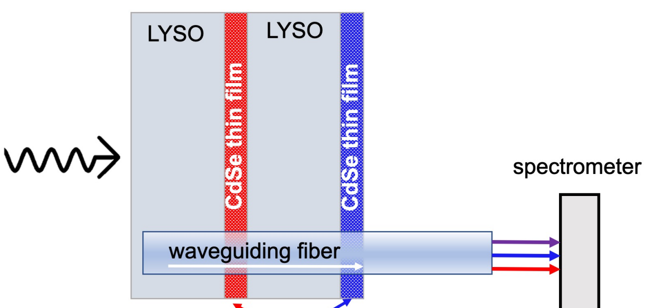
Effects of proton irradiation on luminescence emission and carrier dynamics of self-assembled III-V quantum dots [DOI:10.1109/TNS.2002.806018]

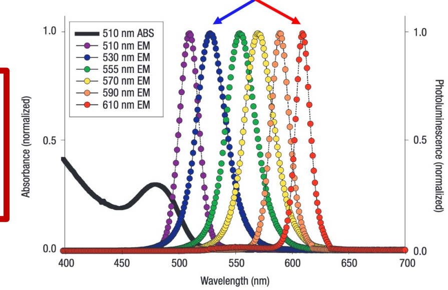


PL after proton-irradiation on CdSe/CdS Core/Shell Quantum Dots [**doi.org/10.1002/adfm.201904501**].

2) Proof-of-principle device

- simplified layered structures
- use «well»-known materials (LYSO bulk, CdSe/CdS QDs)
- → prove that different layers are resolved
- → assess light guide design (one fiber, array)
- → measure PL time resolved spectrum and yield





https://doi.org/10.1038/nmat1390

A great technical challenge
→ enhanced QT expertise in the HEP community

Compact calorimeter based on oriented crystals

Speaker:
Alessia Selmi
On behalf of the **INFN STORM/OREO Collaboration**

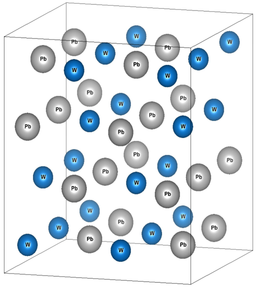
IDF2022- INFN workshop on Future Detectors
Oct 17 – 19, 2022
Bari

Acknowledgement to CSN5 Ricerca Tecnologica

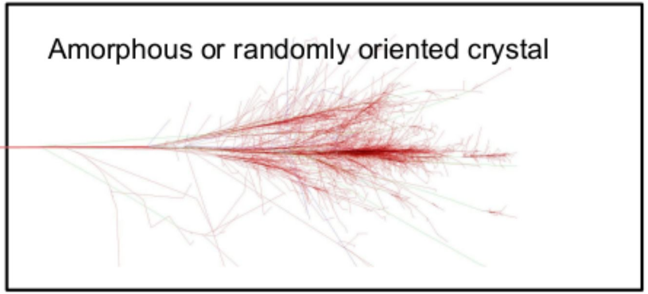
INFN

UNIVERSITÀ DEGLI STUDI DELL'INSUBRIA

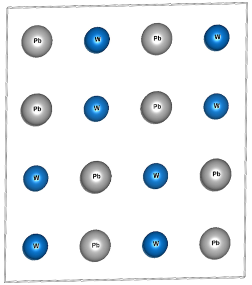
Randomly oriented crystal



Particle



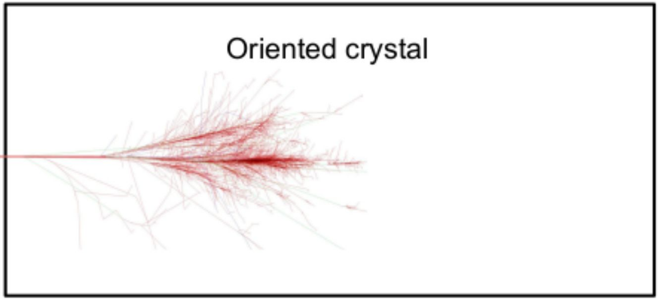
Oriented crystals



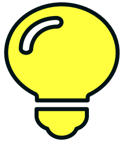
Axial orientation

Strong Field

Particle



Reduction of the radiation length X_0
in comparison with amorphous media

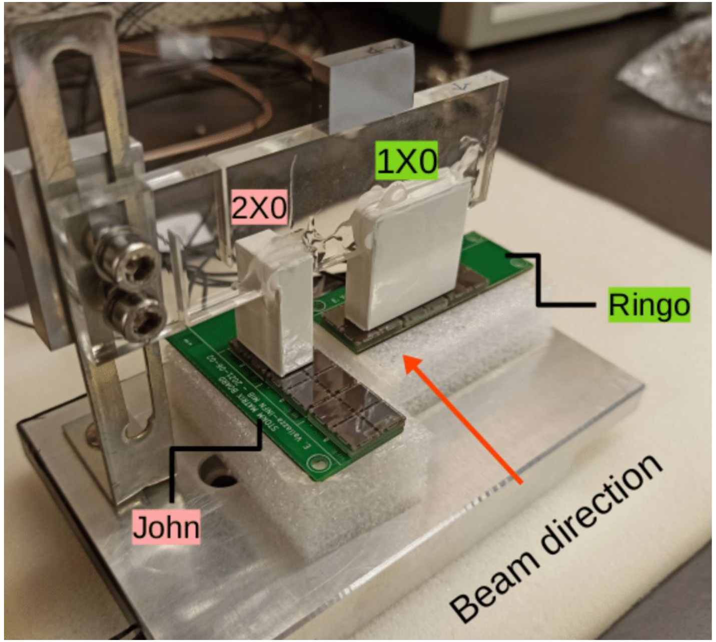


Compact calorimeter!

STORM (STrOng cRistalline electroMagnetic field)

beamtest on the H2 line at the CERN SPS, North Area, CERN

with 120 GeV electrons



PWO crystals

	$1\ X_0$	$2\ X_0$
axis	<001>	<100>
interatomic pitch	12.020 Å	5.456 Å
U_0	~600 eV	~700 eV
Θ_0	~1 mrad	~1 mrad
strong field ($\chi = 1$)	~ 30 GeV	~ 30 GeV

$1\ X_0$ $0.9 \times 3 \times 3\ cm^3$

Produced by The Institute for Nuclear Problems, Belarusian State University, Minsk

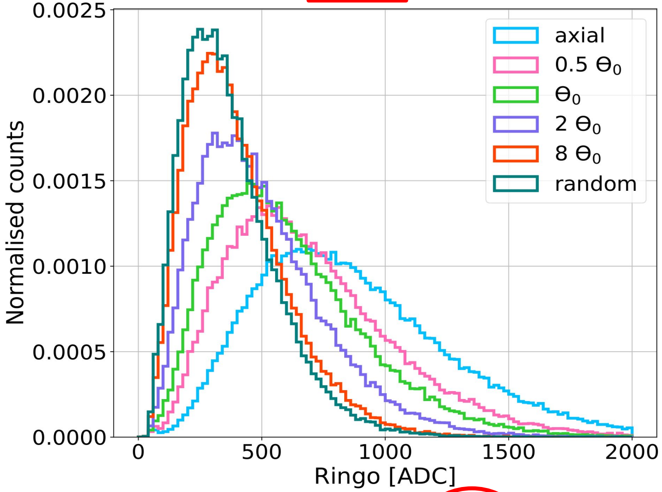
$2\ X_0$ $1.8 \times 0.9 \times 2.7\ cm^3$

Produced by Molecular Technology GmbH (Moltech), Berlin

Energy deposited in crystals (ADC units)

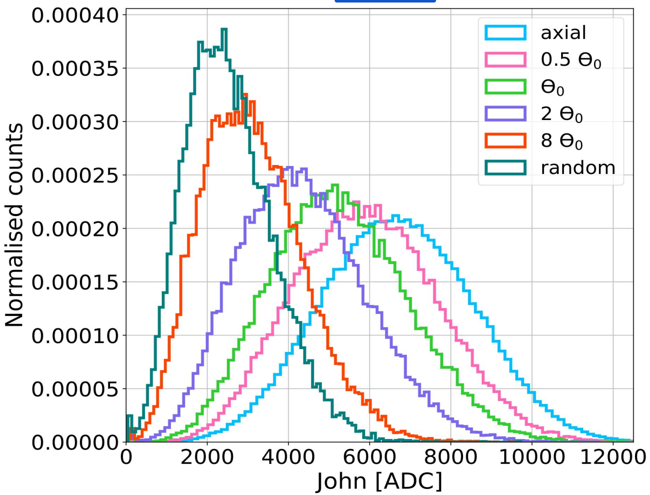
$$\Theta_0 = \frac{U_0}{mc^2} \sim \text{mrad}$$

$1X_0$



$$E_{Ax} \sim 2.5\, E_{Rn}$$

$2X_0$

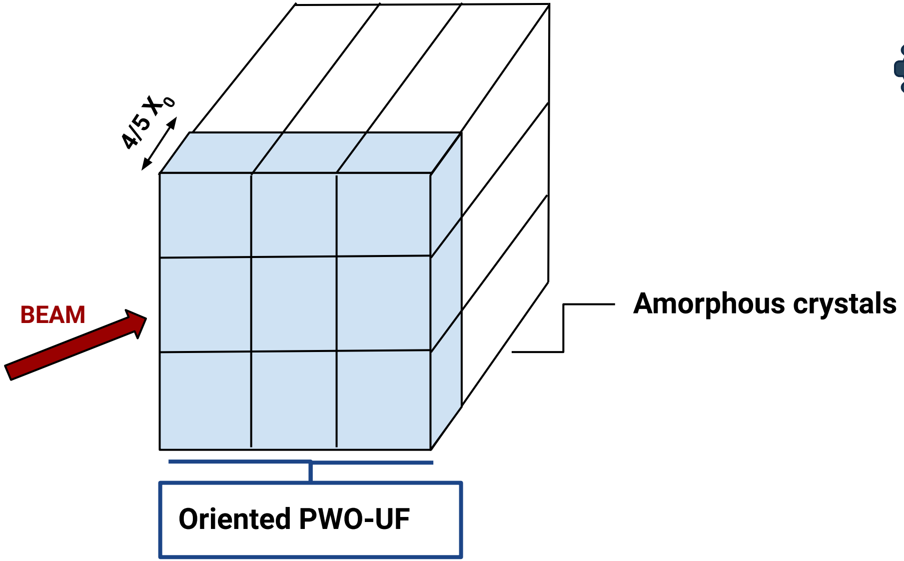


$$E_{Ax} \sim 3\, E_{Rn}$$

Decrease of $\mathbf{X_0}$ of around 30%

OREO - ORiEnted calOrimeter

National Coordinator
Laura Bandiera, INFN FE



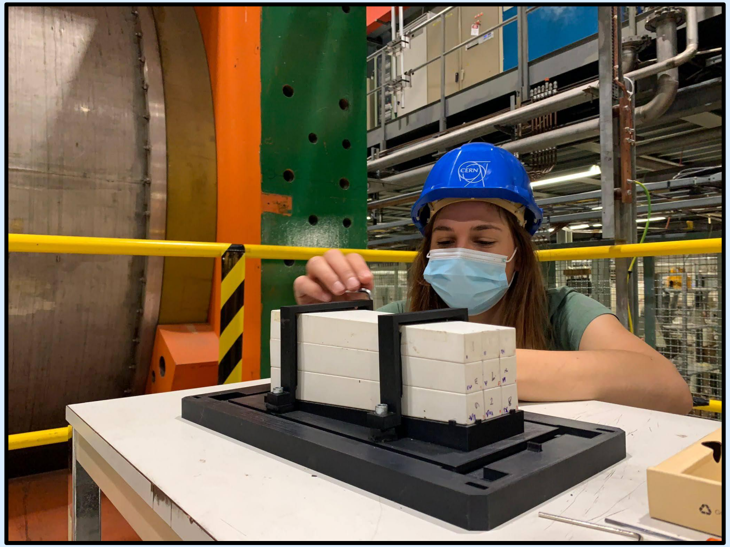
Prototype of compact crystal based calorimeter

3x3 matrix of oriented PWO-UF readout by SiPMs

GOAL

Prove that it's possible **to contain e.m. showers in a reduced volume/weight** and cost

Thanks for the attention



The Demonstrator of the instrumented decay tunnel for the ENUBET monitored neutrino beam

IFD2022 - Bari, Italy
19th October 2022

Università degli Studi di Padova
INFN, Sezione di Padova

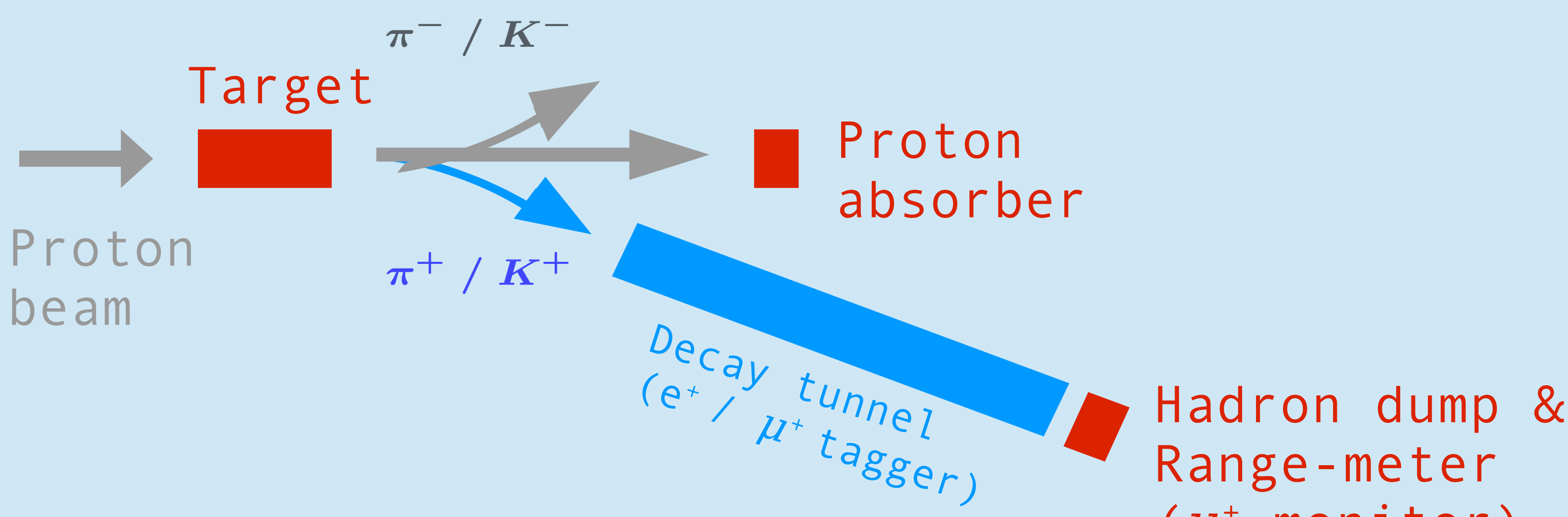
Fabio Iacob
on behalf of the NP06/ENUBET collaboration

NP06/ENUBET

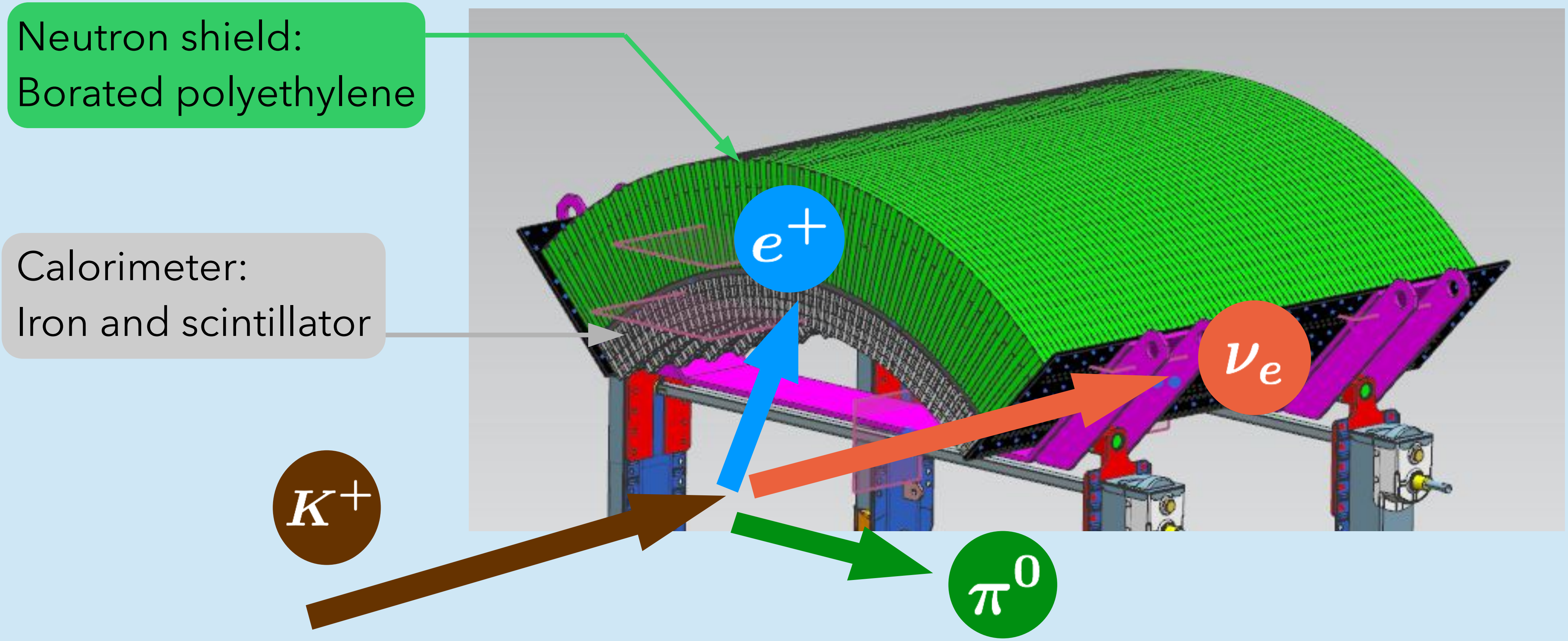
NP06: CERN Neutrino Platform experiment number 6.
ENUBET: Enhanced NeUtrino BEams from Kaon Tagging.

GOAL: develop a new monitored neutrino beam in which the flux and flavor composition are known at 1% level, and the energy with O(10%) precision.

SCIENTIFIC JUSTIFICATION: the monitored neutrino beam enables a programme of precise cross-sections measurements, which are useful to other neutrino experiments (e.g.: DUNE, Hyper-Kamiokande).



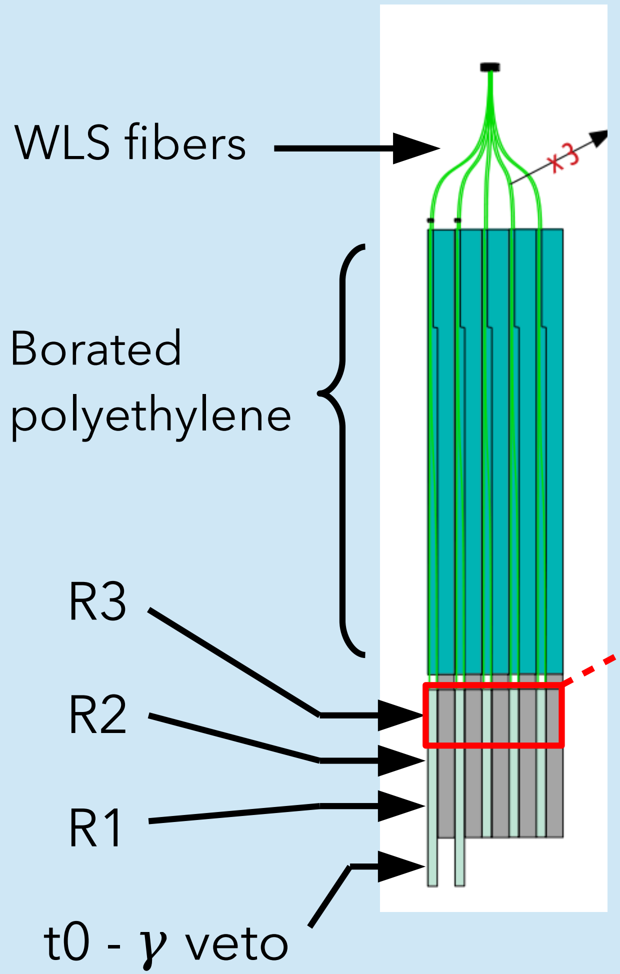
Demonstrator

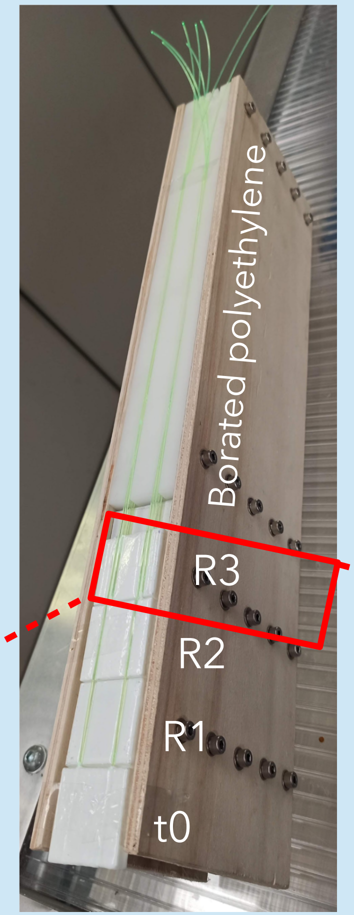


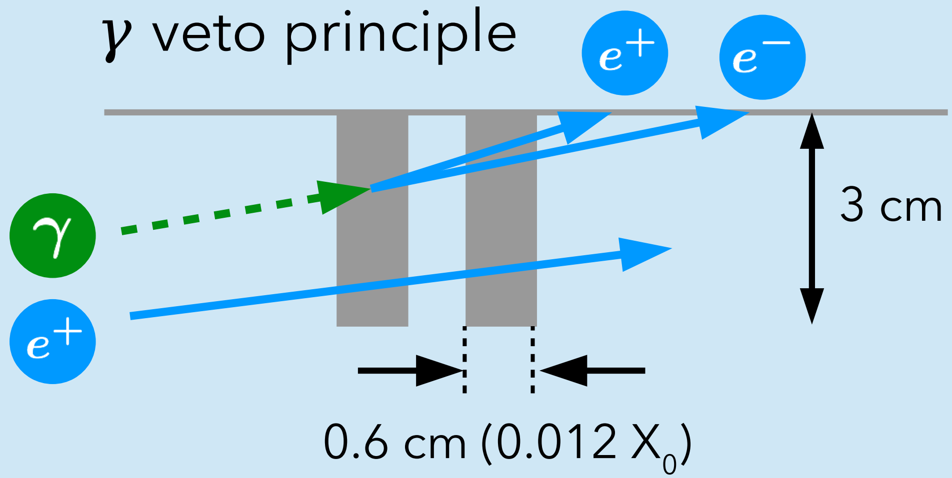
Hardware deliverable: tagger demonstrator (portion of instrumented decay tunnel).

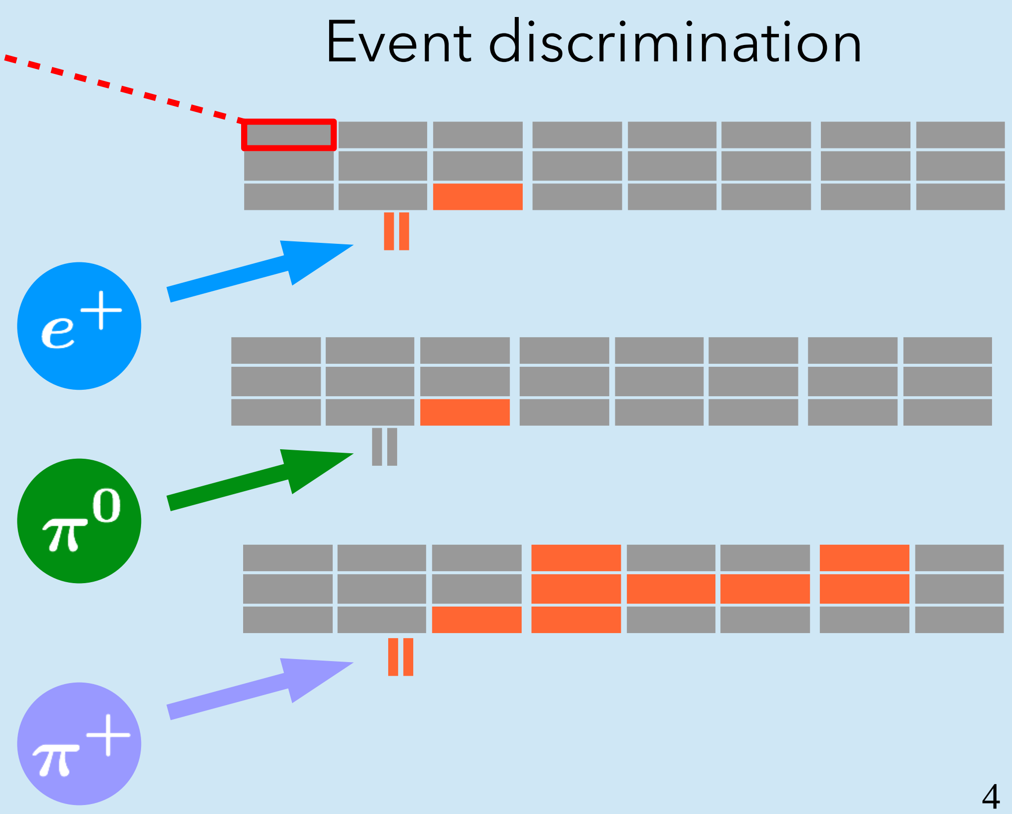
- Should tag positron in coincidence with electron neutrino
- e / μ / π discrimination capabilities
- Quarter of circle x 1.65 m length

Demonstrator azimuthal sector

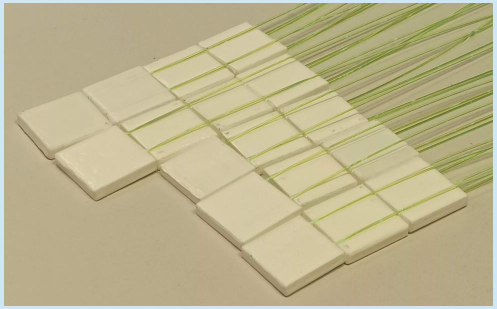






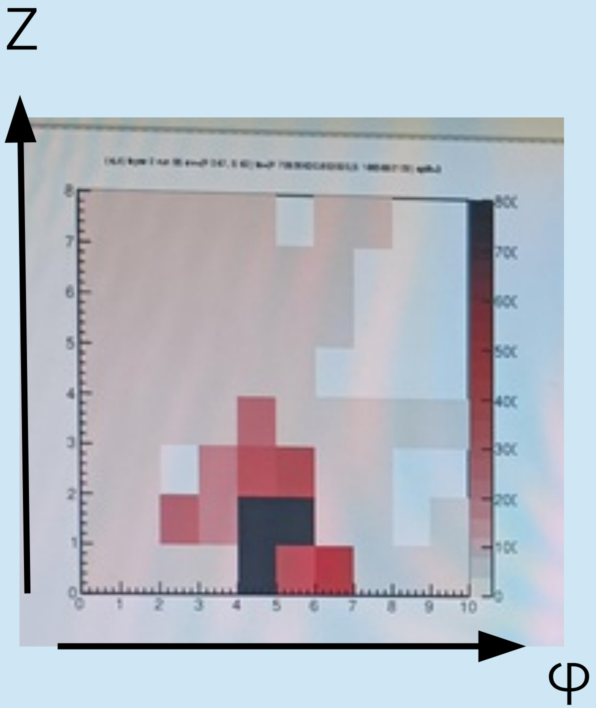


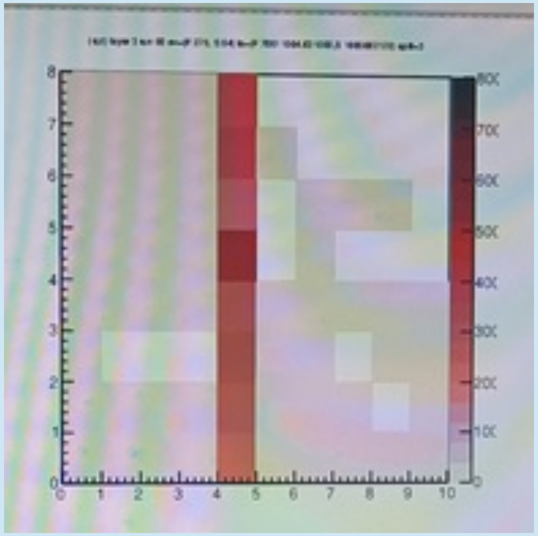
Scintillator tiles and WLS fibers

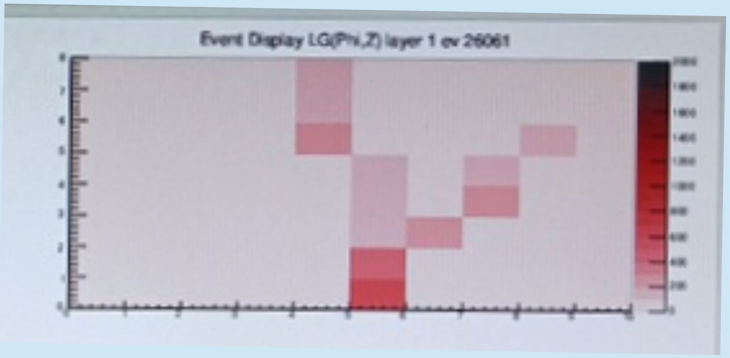


Events at CERN PS T9

3 - 16 October 2022 test beam at CERN PS T9

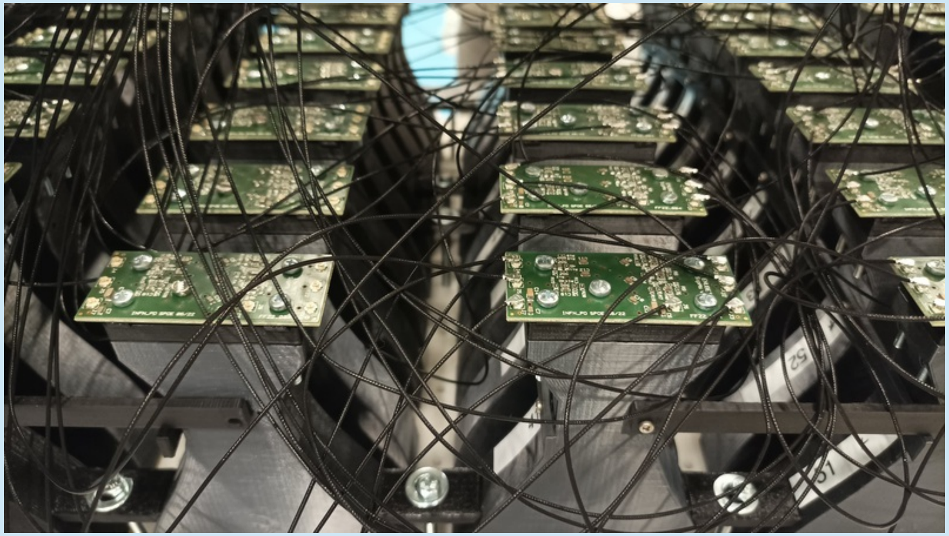




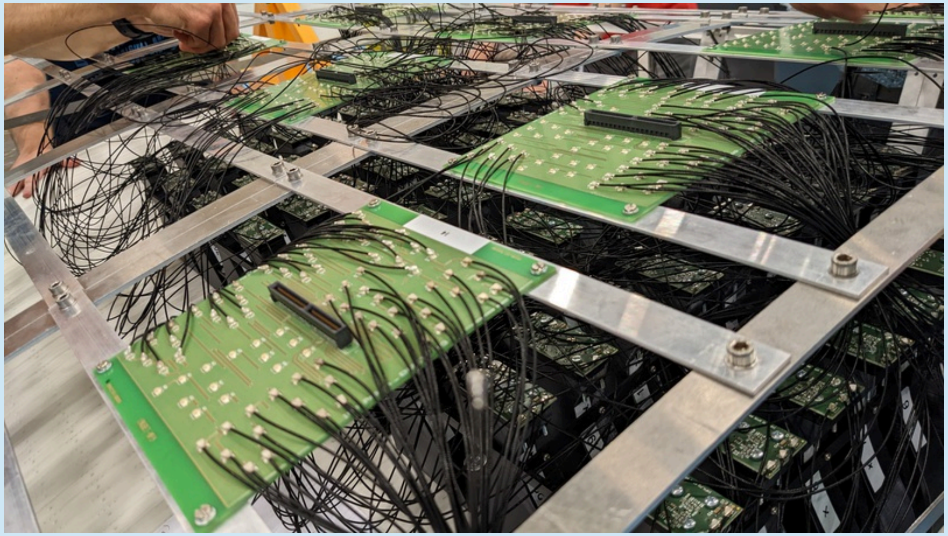


PRELIMINARY! e / μ / π discrimination
from energy deposit and event topology

Demonstrator at CERN PS T9



SiPM boards



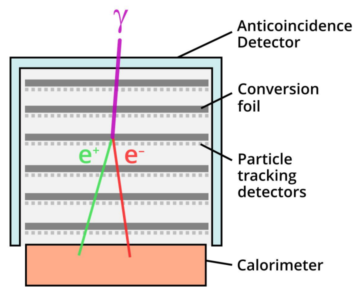
Interface boards

Readout

Demonstrator

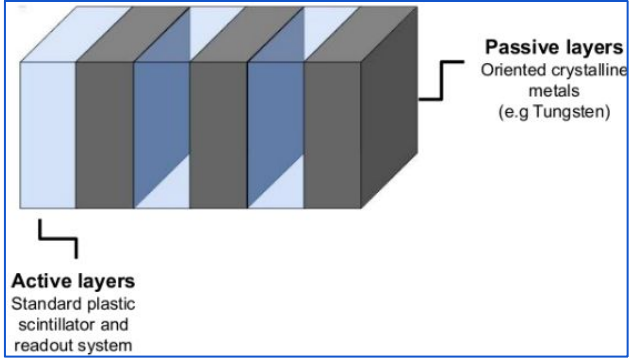
80 SiPM boards
400 SiPMs
1360 tiles
~1.5 km fiber

Possible applications

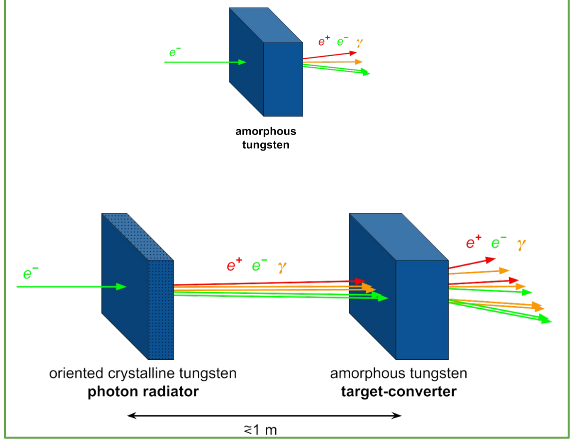


Source-pointing γ-ray telescope

Sampling and homogeneous calorimeter for fixed-target experiments



Intense positron source



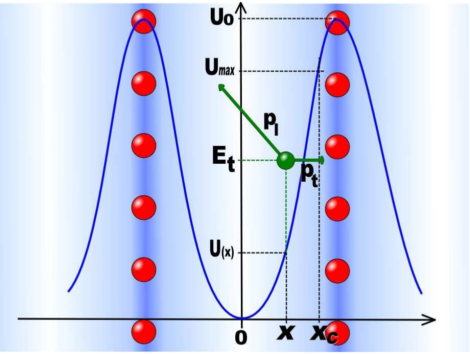
Light particles interaction with oriented crystals

Misalignment crystal → e^+/e^- → incoherent bremsstrahlung

But what happens if the crystal is oriented?

1912 → J.Stark introduced the idea that the crystalline lattice may modify the motion of charged particles

1965 → J.Lindhard → **axial / planar channeling**



e+ planar channeling

Critical angle → $$\theta_c = \sqrt{\frac{U_0}{pv}}$$ →

It depends on:
- the input energy
- the material

At 120 GeV for Tungsten →

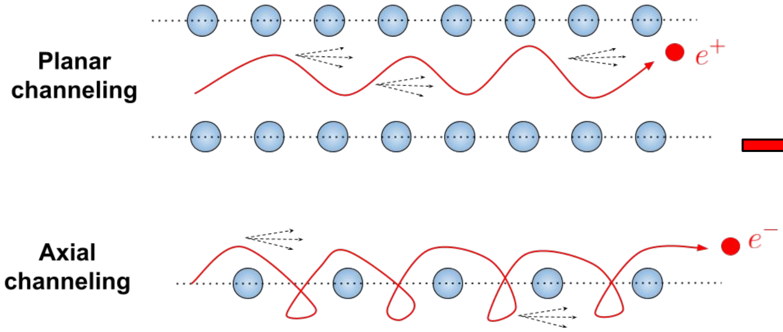
Planar : $\theta_c = 31\ \mu\text{rad}$

Axial : $\theta_c = 110\ \mu\text{rad}$

1976

M.Kumakhov demonstrated that the crystalline lattice modifies the features of the electromagnetic processes inside the crystal

The periodicity of the planar/axial channeling motion leads to the coherent emission of photons



This leads to an enhancement in the radiation emission with respect to the case of amorphous medium (incoherent bremsstrahlung)

Intense radiation source!

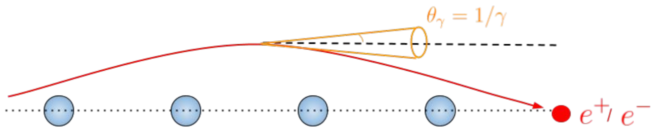
At high energies (about tens of GeV) → **STRONG FIELD REGIME**

$$\chi = \frac{\gamma E}{E_0} > 1$$

- Lorentz factor: γ
- Field experienced by the electron in its rest frame: E
- QED critical electric field: $E_0 \sim 1.3 \cdot 10^{18} \ \frac{V}{m}$

The particle experiences a field that can be considered constant along the string → **Constant Field Approximation (CFA)**

Strong field (CFA)



→ Large enhancement of radiation emission and pair-production

Angular range

$$\Theta_0 = \frac{U_0}{mc^2}$$

→ Does not depend on particle energy

For Tungsten 120 GeV

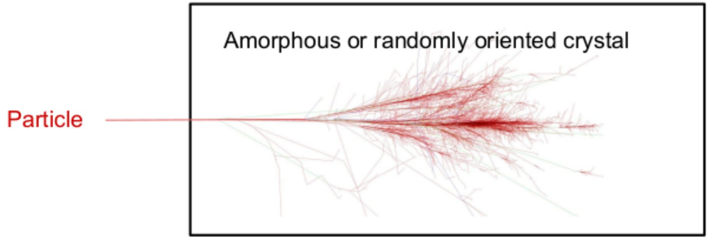
$$\Theta_0 = 1.2 \text{ mrad}$$

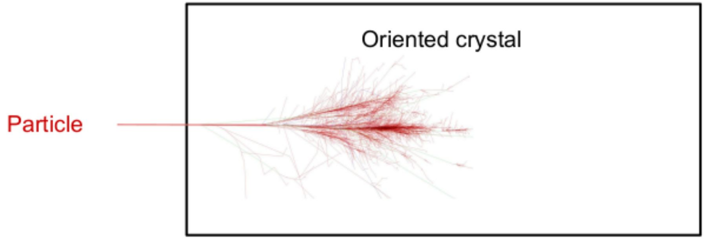
VS

$$\theta_c = 110 \ \mu\text{rad}$$

Large enhancement of radiation emission and pair-production → **acceleration of the electromagnetic shower** → Described in terms of the radiation length X_0:

X_0 is the mean distance over which a high energy electron loses all but 1/e of its energy via bremsstrahlung.



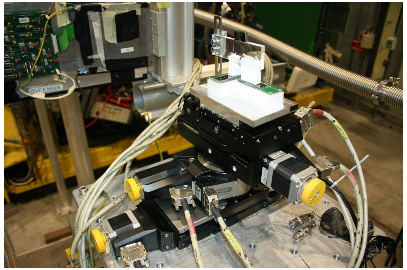


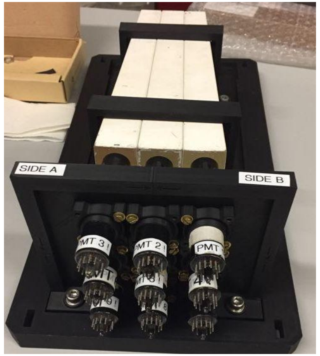
→ **reduction of the radiation length in comparison with amorphous media**

Compact calorimeter!

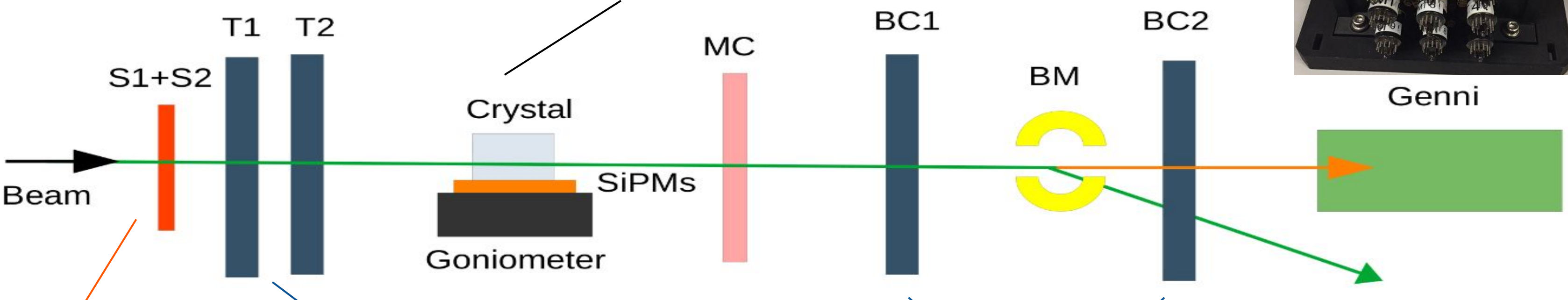
The electromagnetic shower starts before in the oriented crystal!

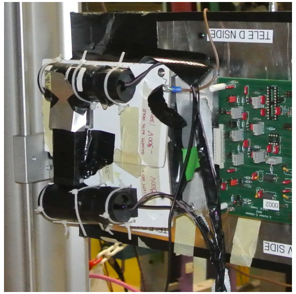
The experimental setup



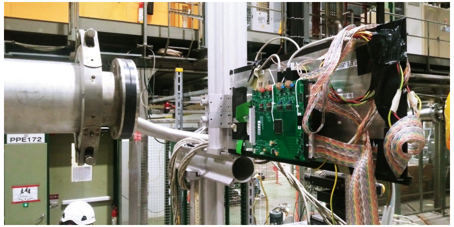


Genni

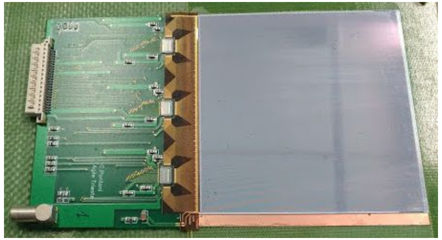




Trigger system



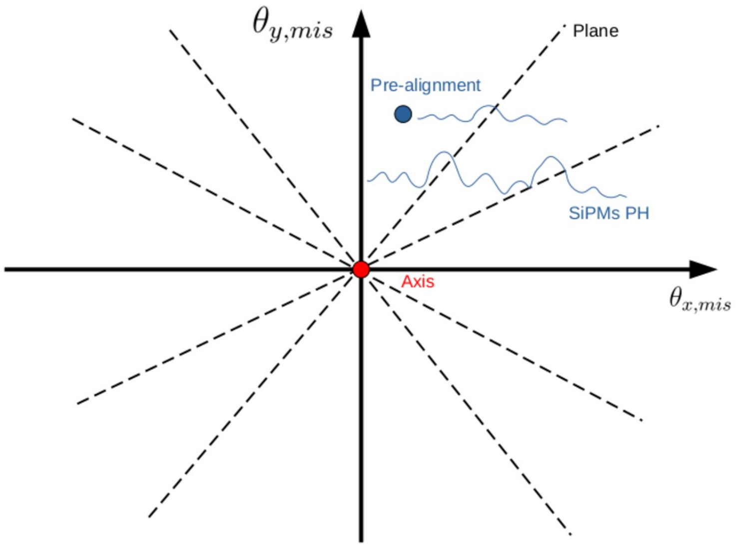
Tracking system



Tracking system

The fine alignment

The stereogram

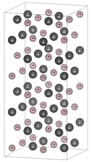


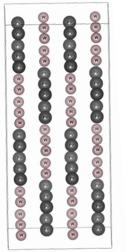
The stereogram has been reconstructed with the experimental data using the output signal of the Ringo ($1X_0$ crystal) and John ($2X_0$ crystal) SiPMs and of the multiplicity counter

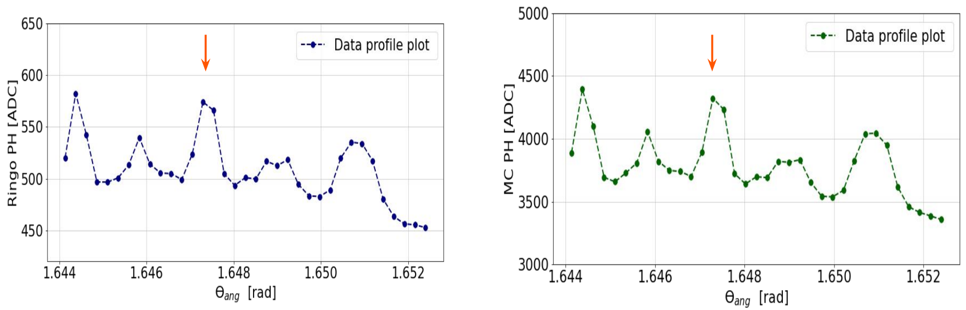
The PH of the SiPMs and the one of the multiplicity counter are expected to be larger when the beam is aligned with respect to the axis; a smaller enhancement is expected when it is aligned with planes

θ_{mis} → the angle between the particle trajectory and the crystalline sample

The stereogram reconstruction → Ringo (1X0 crystal) and MC

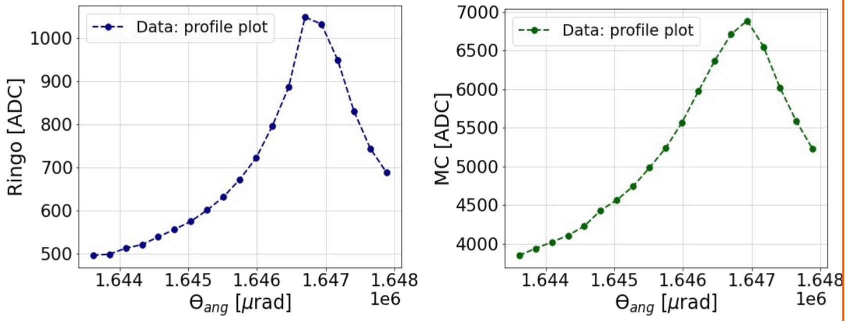


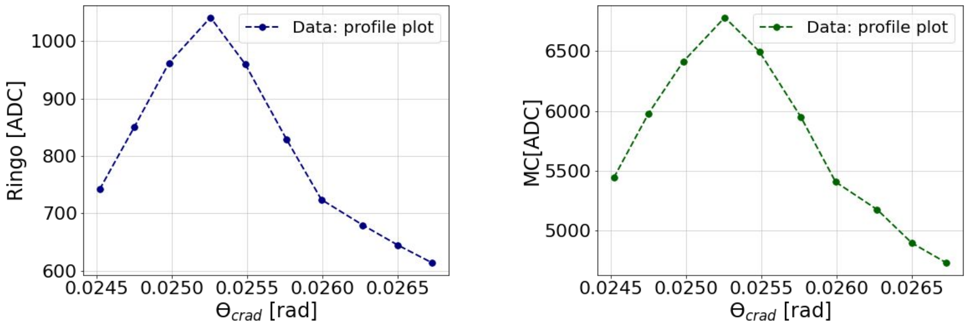




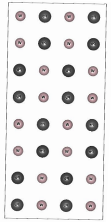
1° angular scan

2° angular scan



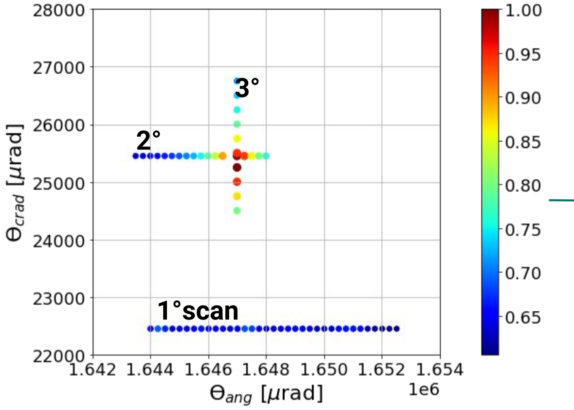


3° cradle scan

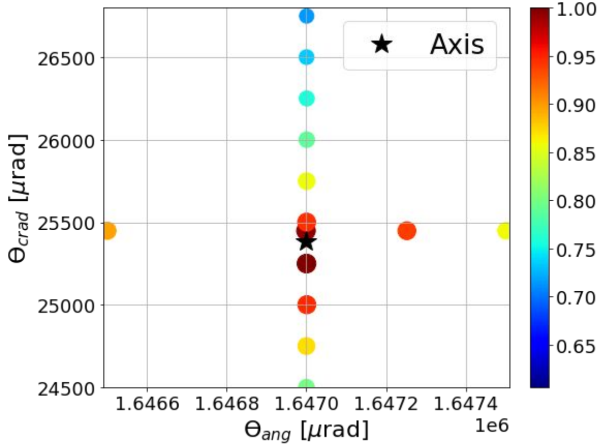


The complete stereogram

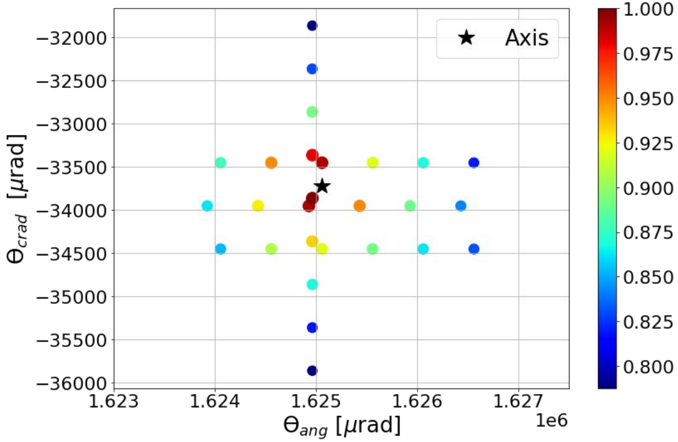
Ringo
($1X_0$ crystal)



Zoom

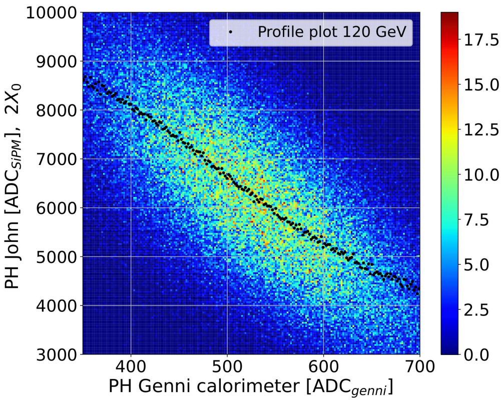


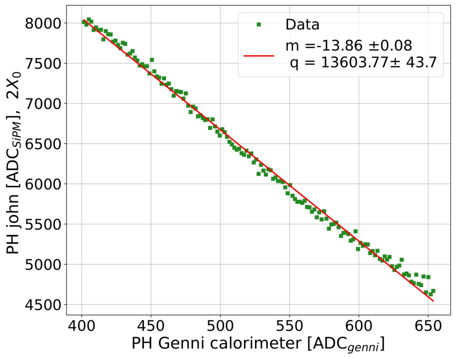
John
($2X_0$ crystal)



Each dot represents the normalized mean value of the PH of Ringo and John. The axis has been chosen between the two points with the higher PH values

SiPMs PH correlation with calorimeter signal



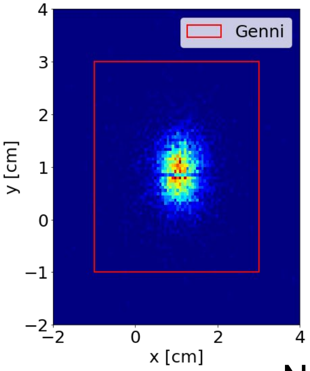


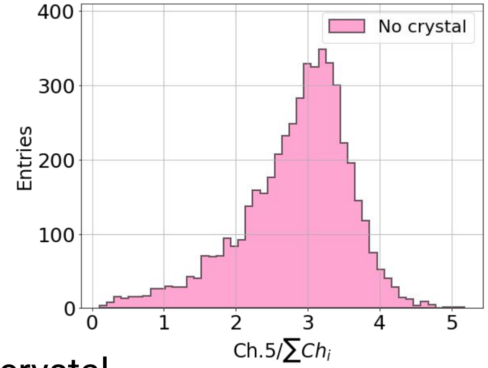
The two signals are anti-correlated

$$E_{TOT} = E_{SiPM} + E_{Genni}$$

Can I calibrate the SiPMs?

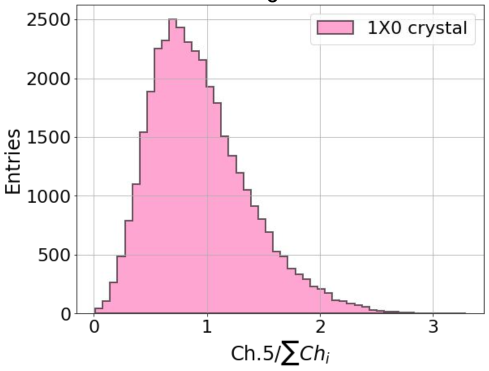
NOT SO EASY



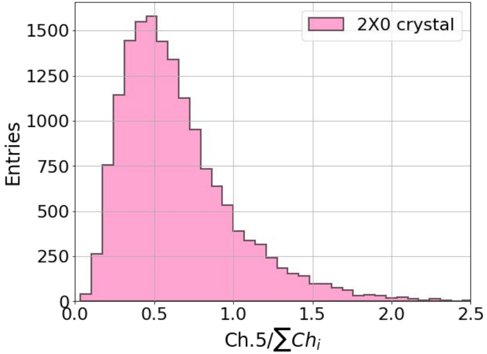


No crystal

1X_0

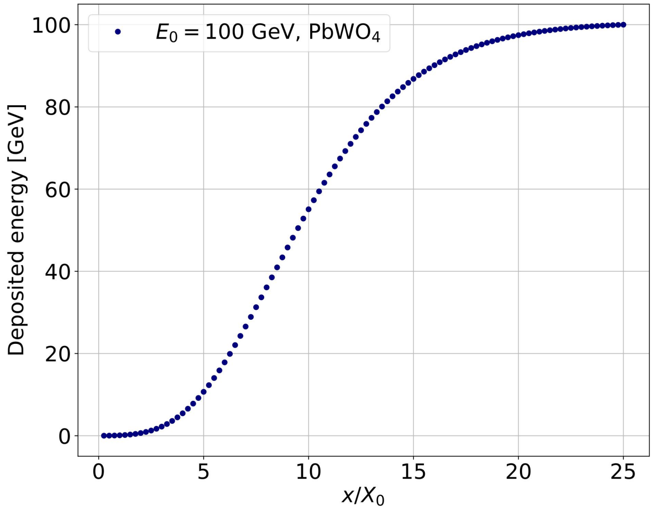


2X_0



A Monte Carlo simulation is needed

Evaluation of the radiation length reduction



Cumulative deposited energy as a function of the thickness of the detector in units of X_0 for a 100 GeV electron beam impinging on a PWO crystal

Extrapolated from the curve

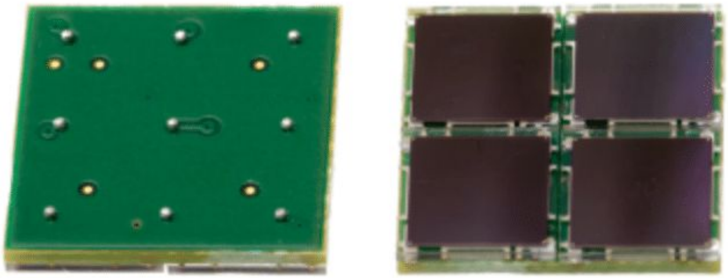
	Deposited energy random	Deposited energy axial	Thickness in X_0 in axial	Thickness increase
1 X_0	100 MeV	250 MeV	1.41	41%
2 X_0	650 MeV	1.9 GeV	2.87	43%

Decrease of **X_0** of around 30%

- It depends on the input energy
- Compact calorimeter
- Particle ID in the calorimeter itself

Features of ARRAYC-60035-4P-BGA

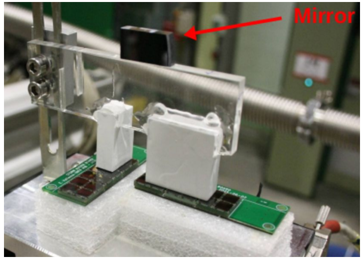
Array size	Sensor type	Readout	Board Size	Sensor pitch	Nr. of connections
2	60035	Sensor	14.3×14.2 mm^2	7.2 mm	3×3 BGA

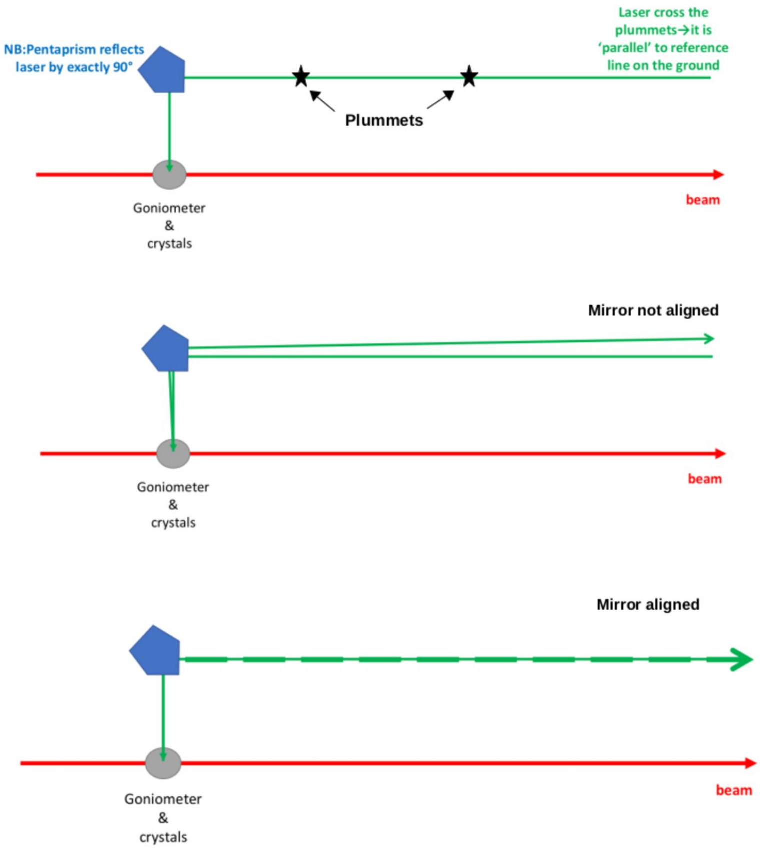


squared pixel dimensions = 35×35 μm^2
C-series dimensions = 6x6 mm^2

Pixel n° ~ 116000

The pre-alignment procedure ⟶ performed using a laser and several mirrors





1. Crystalline sample + holder and mirror are placed on the goniometer on the beamline
2. Two plummets, set on a reference line drawn parallel with respect to the beam, are used to align the laser
3. A pentaprism, positioned in front of the crystal, reflects the laser light of exactly 90° on the reference mirror on the holder
4. The mirror is aligned using the goniometer so that the laser returns along the same path
5. The mirror is aligned with the beam by rotating the holder of 90°
6. The crystalline sample is aligned with the beam using an offset measured previously in the laboratory