A LYSO Crystal Calorimeter for the Mu2e Experiment

Fabio Happacher
On behalf of the Mu2e Collaboration

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Presentation outline

- Concept and aim of the Mu2e experiment
- Mu2e layout
- Calorimeter requirements
- Calorimeter Design
- Calorimeter reconstruction skills
- Beam testing
- Conclusions

μ to e conversion: $\mu^- N \rightarrow e^- N$

Mu2e will probe the CLFV decay of a muon into an electron:

- It is allowed in SM if massive neutrino mixing is considered, but branching fractions are of O(10^{-54})
- Any signal would be a sign for new Physics: Susy, Compositeness, Leptoquark, Heavy neutrinos, Second Higgs Doublet, Heavy Z'

Mu2e will detect the electron coming from the decay of a muon in the field of a nucleus

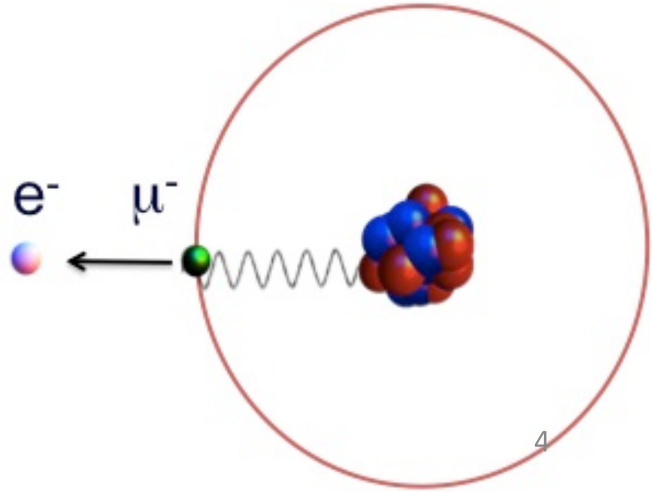
$$R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow capture} < 6 \times 10^{-17} \, (90\% \, C.L.)$$

Concept of Mu2e

μ^{-}'s are captured in a stopping target made of Al and falls to a 1S bound state ($\tau_{½}$= 864 ns) giving origin to:

- The muon decays in orbit (DIO): $\mu^{-} + Al \rightarrow e^{-}\bar{\nu}_e \nu_\mu + Al$ (40%)
- Muon capture: the wave function of muons and nuclei overlap, the nucleus can trap the muon: $\mu^{-} + Al \rightarrow \nu_\mu + Mg$ (60%)

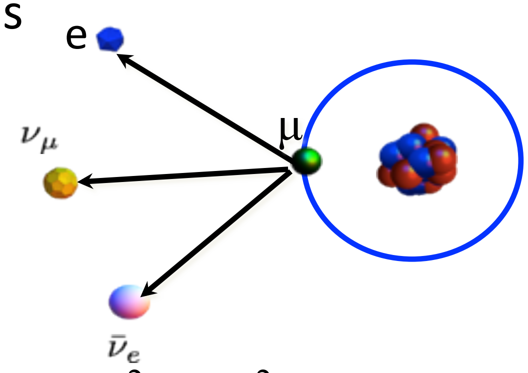
  generating a flux of p,n and γ
- Neutrinoless muon to electron conversion $\mu^{-} + Al \rightarrow e^{-} + Al$
  - Results in an electron of 104.97 MeV
  - $E_{CE} = m_\mu c^2 - B_\mu(Z=13) - C_\mu(A=27)$
    - M_μ muon mass, 105.66 MeV/c^2
    - B_μ binding energy of a muon in the 1S orbit of Al, 0.48 MeV
    - C_μ nuclear recoil of Al, 0.21 MeV



Muon from decay in orbit: DIO

- A **significant background comes** from Stopped Muons

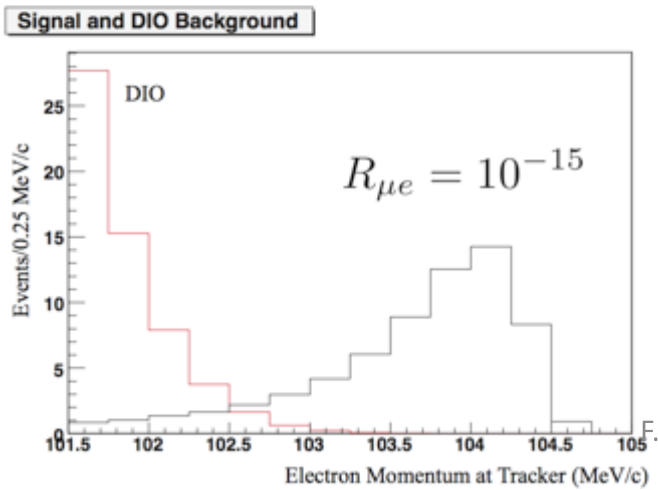
$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$



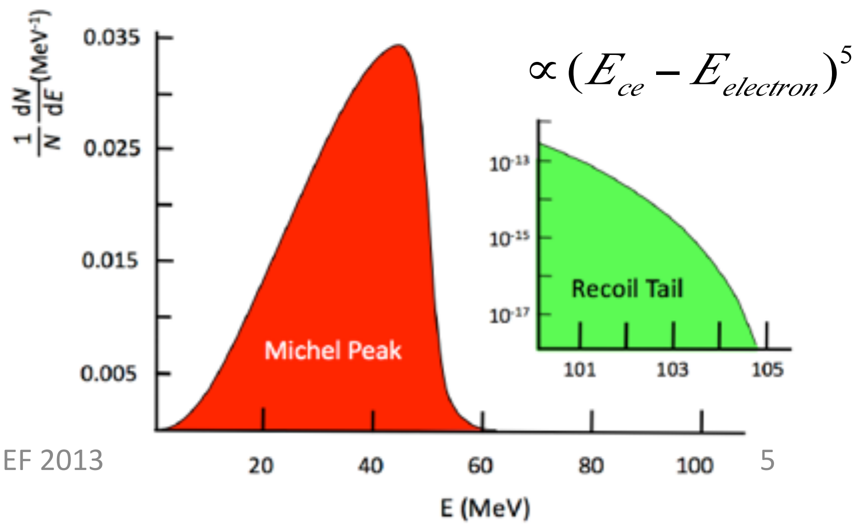
- Electrons from decay of bound muons (DIO)
- If the neutrinos are at rest the e⁻ can have exactly the conversion energy E_{CE}=104.97 MeV

$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

- **Recoil tail extends to conversion energy, with a rapidly falling spectrum near the endpoint**

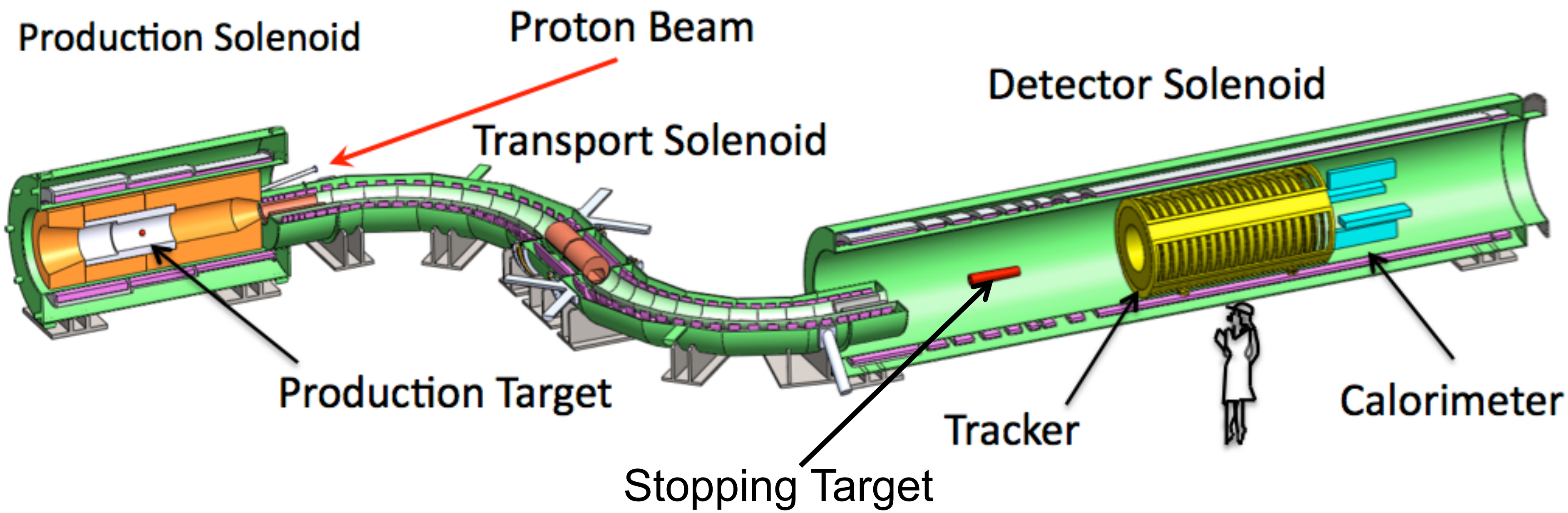


μ Decay in Orbit Spectrum for ^{27}Al



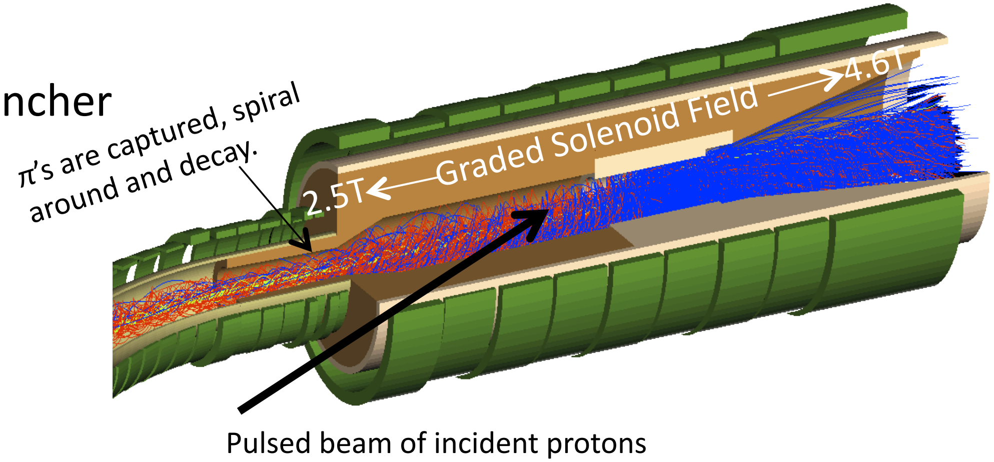
Mu2e Layout

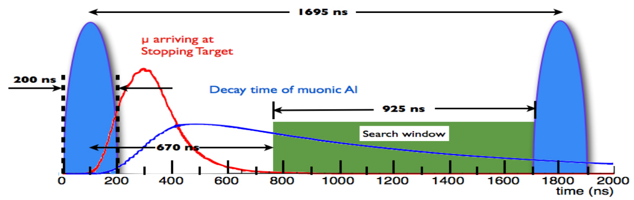
- Mu2e Solenoid System
  - Superconducting
    - Requires a cryogenic system
  - Inner bore evacuated to 10^{-4} Torr to limit background due to interactions of the charged particles with air

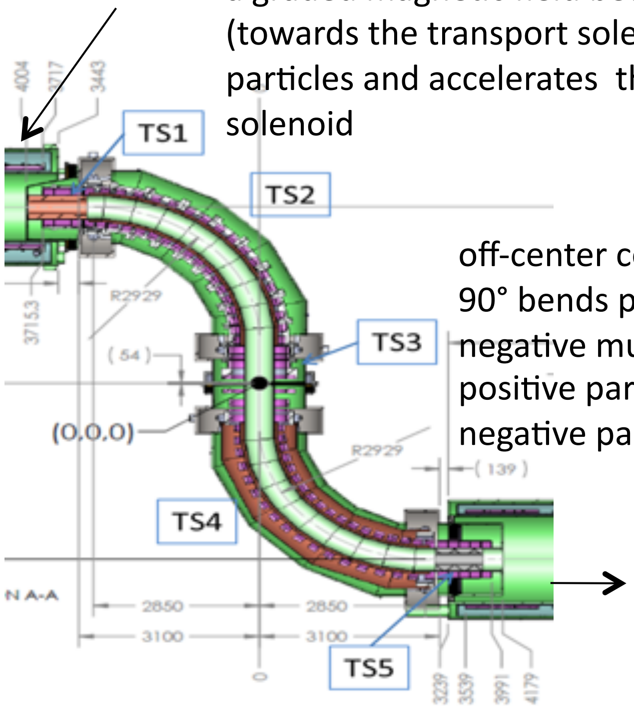


Mu2e Design

- Production Solenoid
  - Pulsed proton beam coming from Debuncher hit the target
    - 8 GeV protons
    - every 1695 ns / 200 ns width
  - Production target
    - tungsten rod, 16 cm long with a 3 mm radius
    - produces pions
  - Solenoid
    - a graded magnetic field between 4.6 T (at end) and 2.5 T (towards the transport solenoid) traps the charged particles and accelerates them toward the transport solenoid







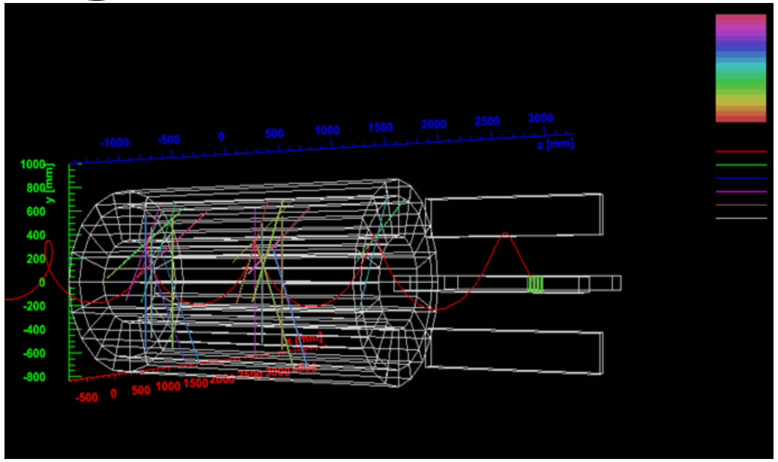
off-center central TS collimator and 90° bends passes low momentum negative muons and suppresses positive particle and high momentum negative particles.

Detector Solenoid

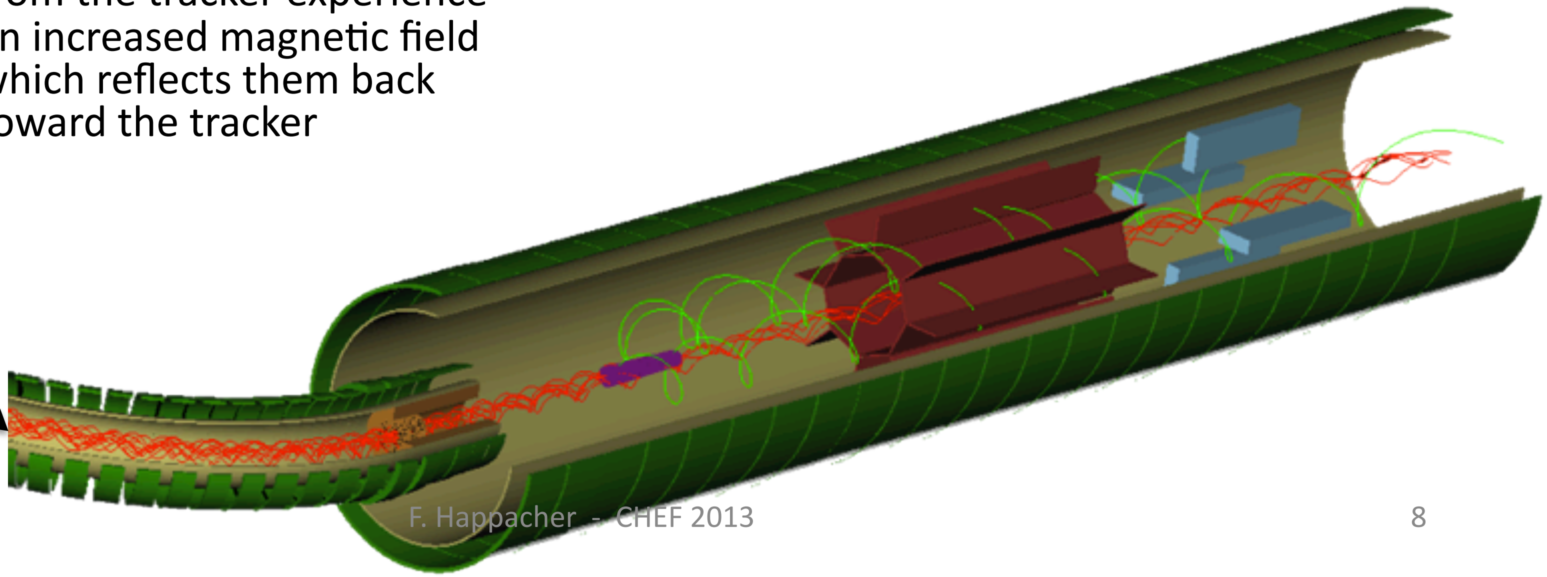
- Transport Solenoid
  - Graded magnetic from 2.5 T (at the production solenoid entrance) to 2.0 T (at the detector solenoid entrance)
    - Allows muons to travel on a helical path from the production solenoid to the detector solenoid
  - S-shaped to remove the detector solenoid out of the line of sight from the production solenoid
    - No neutral particles produced in the production solenoid enter the detector solenoid

Mu2e Design

- The Detector Solenoid houses the Al target and the two main detectors: the tracker and the calorimeter



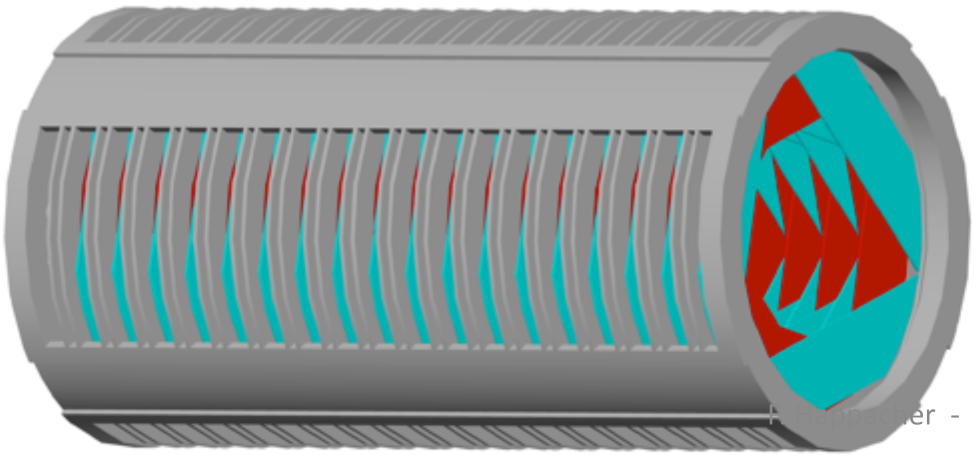
  - 17 Aluminum disks, 0.2 mm thick, radius between 83 mm (upstream) and 63 mm (downstream)
  - Surrounded by graded magnetic field from 2.0 T (upstream) to 1.0 T (downstream)
    - Conversion electrons will travel on a helical path toward the tracker and then hit the calorimeter
    - Electrons ejected away from the tracker experience an increased magnetic field which reflects them back toward the tracker

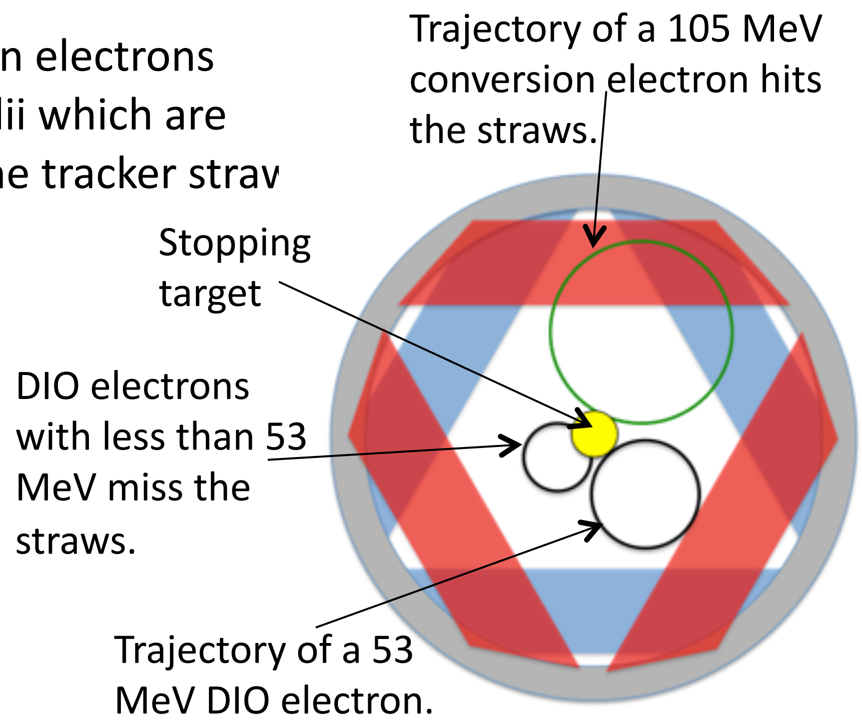


Mu2e Design

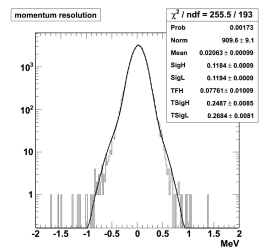
The Tracker

- Surrounded by a uniform 1 T magnetic field
- Conversion electrons will travel on a helical path through the tracker
- Measures the trajectories of conversion electrons
- Most decay-in-orbit electrons have radii which are so small so that they don't intercept the tracker strav (due their low energies)
- 3 m long
- Made of 21,600 straw drift tubes
  - 5 mm diameter tube, 15 μm thick walls
  - 334 mm to 1174 mm long
  - 25 μm diameter sense wire in the center





Cross sectional view of the Mu2e tracker



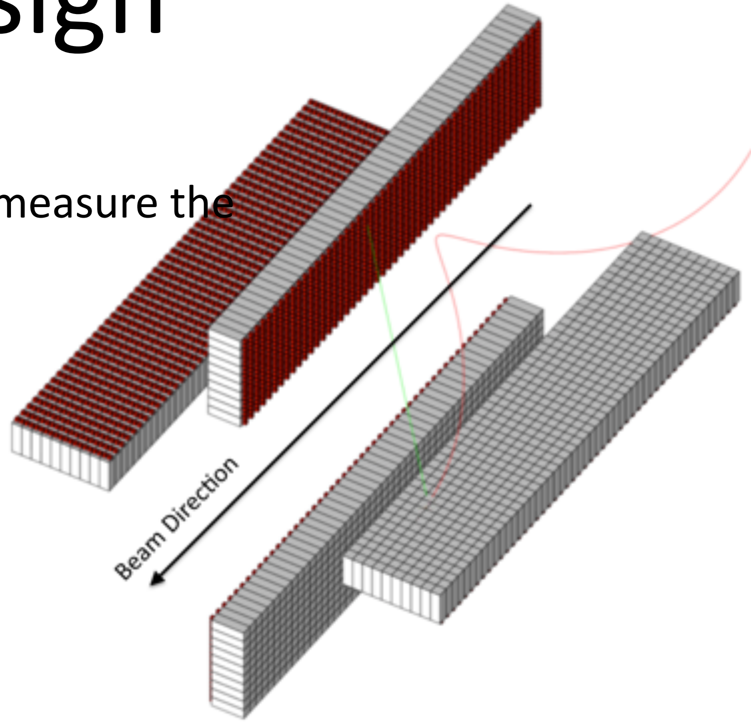
σ_P = 120 KeV/c

Mu2e Design

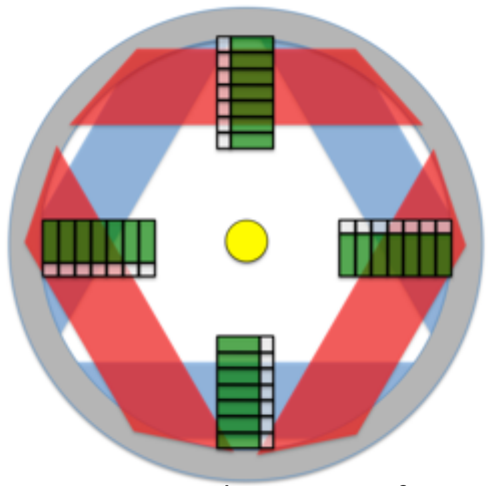
The Calorimeter

Provides a complementary and independent tool to measure the energy and trajectory of the electrons.

– Independent trigger (clustering energy deposits)
– Position resolution to match extrapolated tracks
– Time resolution to associate energy deposit to extrapolated track arrival time
– Track seeding
– Excellent energy resolution to match momentum resolution of the tracker
– PID

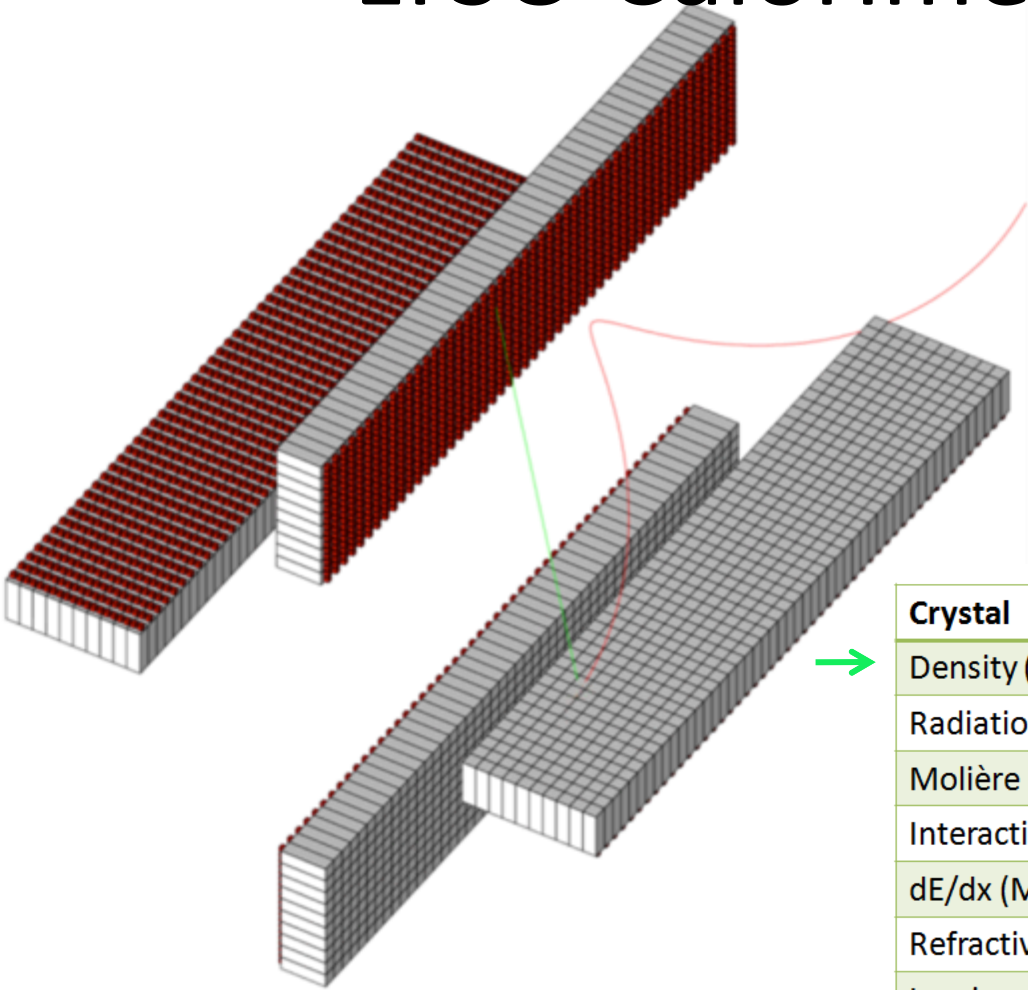


EMC Requirements and Performances	
Energy Resolution	O(2 % @100 MeV)
Time Resolution	< 1 ns
Spatial Resolution	≤ 1 cm
Radiation Dose	≈ 80 Gy/y
Magnetic Field	1 T
Potential Trigger	few kHz



Transverse plane view of tracker and calorimeter vanes

LYSO Calorimeter, CD1 baseline



1936 LYSO crystals arranged in in 4 vanes (11x44 crystals each) ~ 1.3 m long.

- Electrons spiral into the transverse, checkerboard face of the array.
- APDs and Front End Electronics (FEE) on back side.

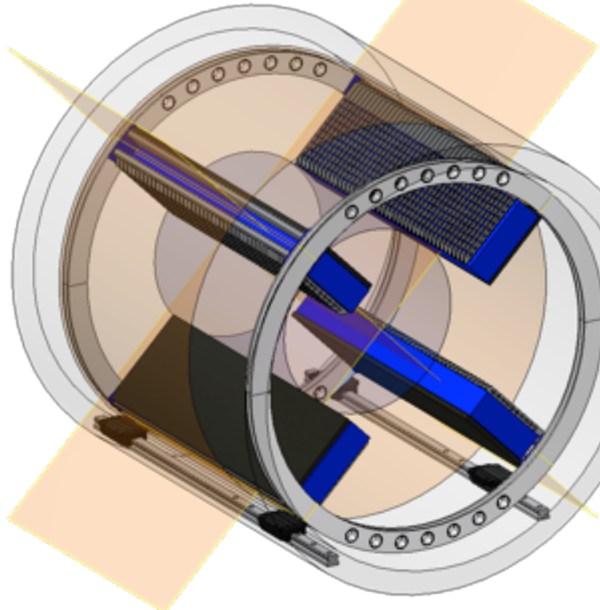
Crystal	LYSO	$PbWO_4$
Density (g/cm^3)	7.28	8.28
Radiation Length X_0(cm)	1.14	0.9
Molière Radius R_M(cm)	2.07	2.00
Interaction Length (cm)	20.9	20.7
dE/dx (MeV/cm)	10.0	13.0
Refractive Index at λ_{max}	1.82	2.20
Luminescence at peak (nm)	402	425, 420
Decay Time τ (ns)	40	30, 10
Light Yield (compared to NaI (Tl)) (%)	85	0.3, 0.1
d(LY)/dT (%/°C)	-0.2	-2.5
Hygroscopicity	None	None

@ -25°C

Calorimeter engineering

Until few weeks ago two competitor layouts: Vanes and Disks

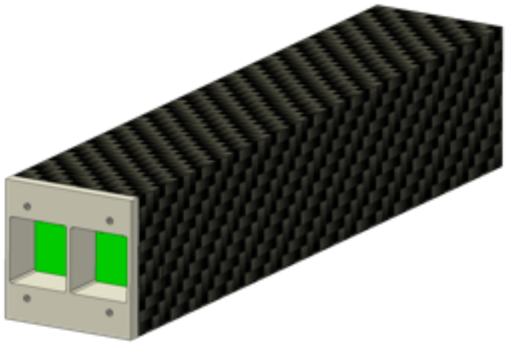
Vanes has been the baseline for long time:

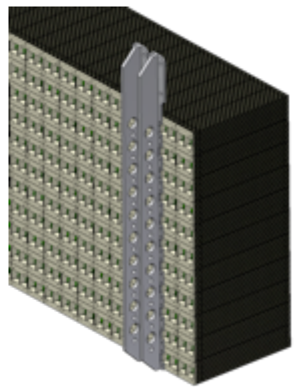


4 vanes of LYSO crystals

advanced design detailing

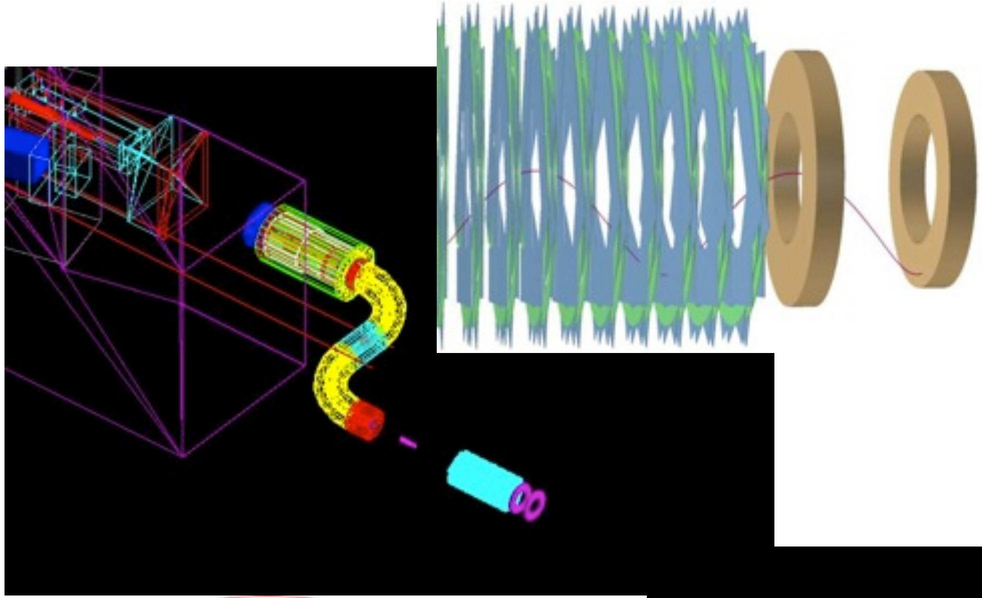
- Each vane is made of 11 by 44 crystals
- Crystal dimensions: $3 \times 3 \times 11$ cm^3
- Read out by avalanche photo diodes





- Crystal assembly with CF case + Tyvek + plastic caps (front and back)
- Crystal assembly dimension: 137mm x 30.4mm x 30.4mm
- 1+1 APD (AA size: 100mm^2 ; ED: 13.7mm x 14.5mm)
- CF/Iron Support Bars (Cantilever); max deflection Dx= 0,33 mm (free end)
- CF High Elastic Modulus >>> Dx = 0,15 mm

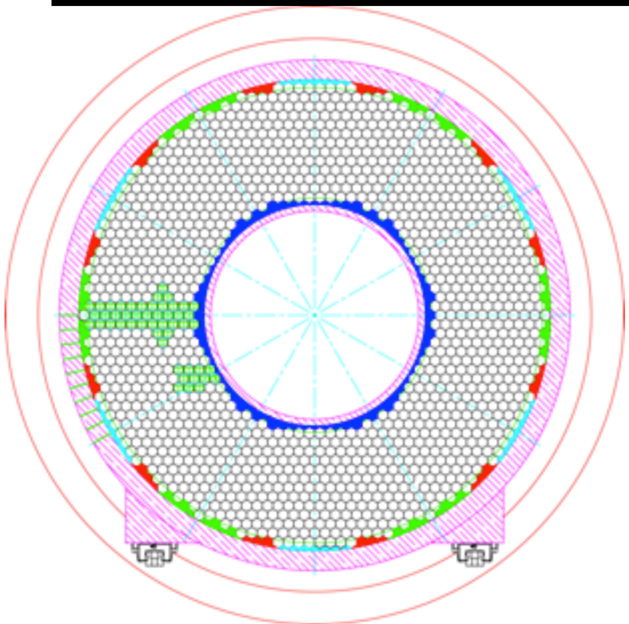
Calorimeter geometry: Disks

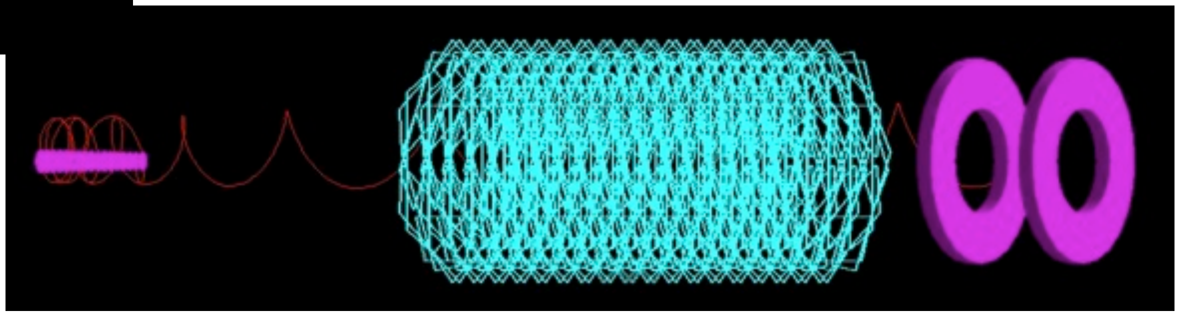


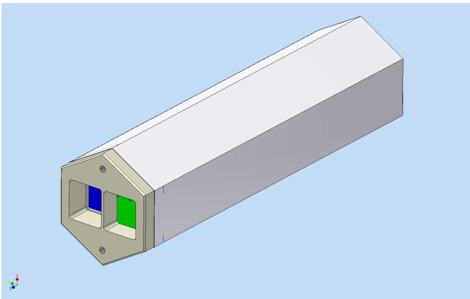
Baseline layout now, advantages:

- Slightly enhanced Efficiency
- Simplified Mechanics
- More shielded photosensors
- Same ene/time/spatial resolutions

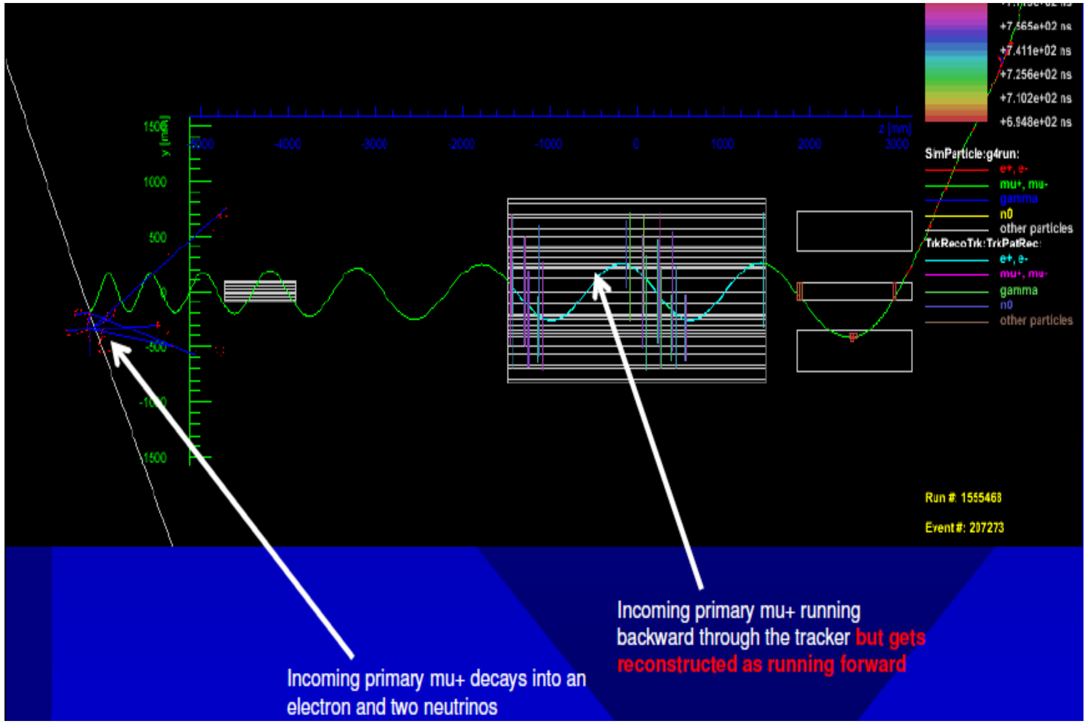
More radiation on the crystals





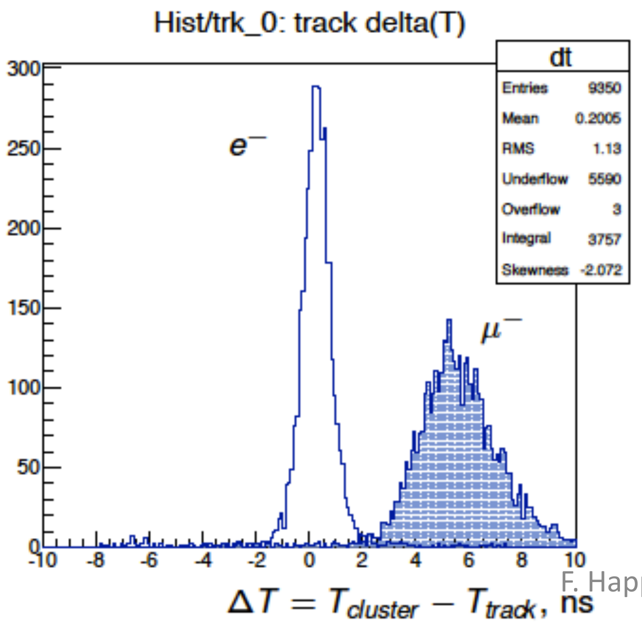


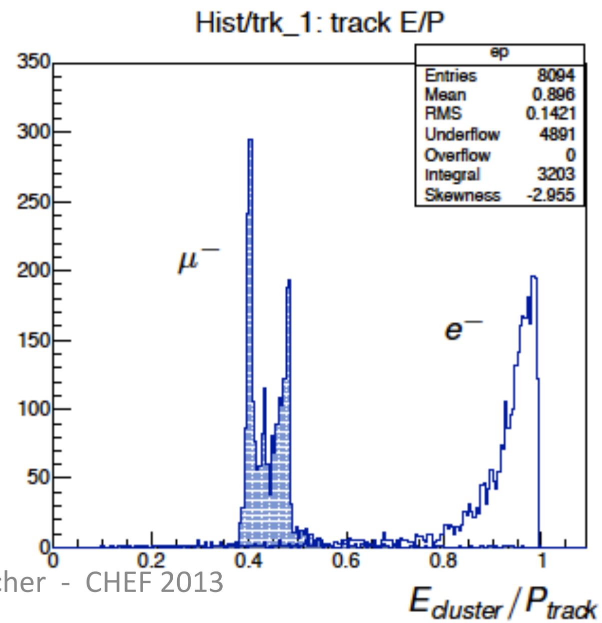
μ/e Separation



Compare 100 MeV electrons and muons assuming electron hypothesis in the track fit and in calorimeter acceptance

Combined with tracking, energy and time measurements provide 10^2 rejection factor for muons

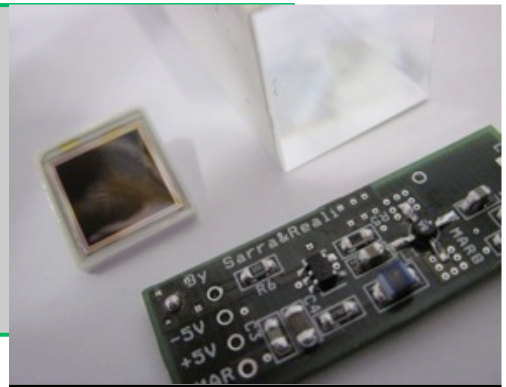


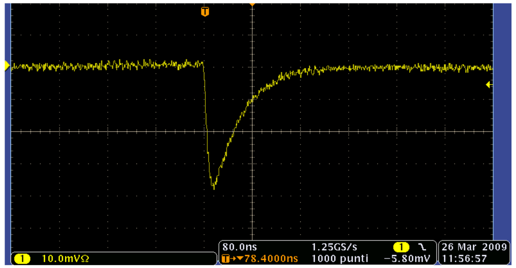


Photosensors

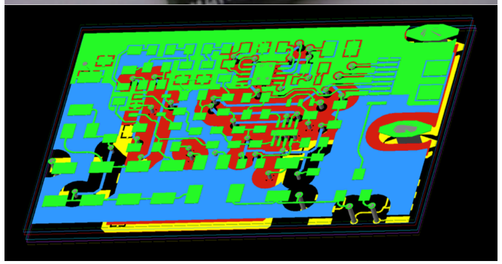
- ❑ BASELINE: Each crystal is readout with two large area APD's (10x10 mm^2)
  - → functional in 1 T field
  - → fast/proportional response
  - → gain from 50 to 1000
  - → large collection and quantum efficiencies

S8664-110
10x10 mm^2
-HV ~ 400 V
-G ~ 50-300

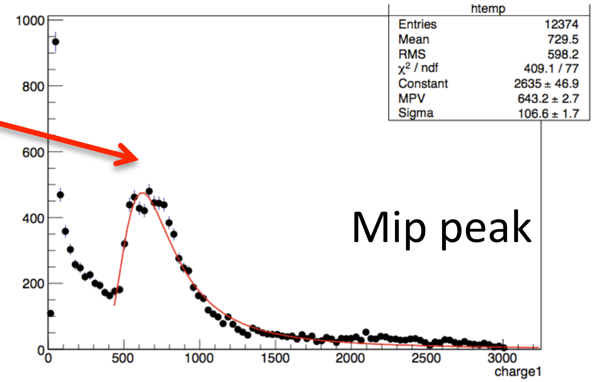




New preamplifier design
< 50 keV noise, integrated HV
linear regulator on PCB



- ❑ Large Area SIPM Candidates
  - ✧ Hamamatsu (Japan) 6x6 mm^2, 12x12 mm^2
  - ✧ IRST FBK (Italy) 4x4 mm^2
  - ✧ Sensl (Scotland) 6x6 mm^2,12x12 mm^2



New Sipm on the market with fast recovery time.
Help to disentangle overlapping digitized signal

Npe~7000 @ 15/20 MeV

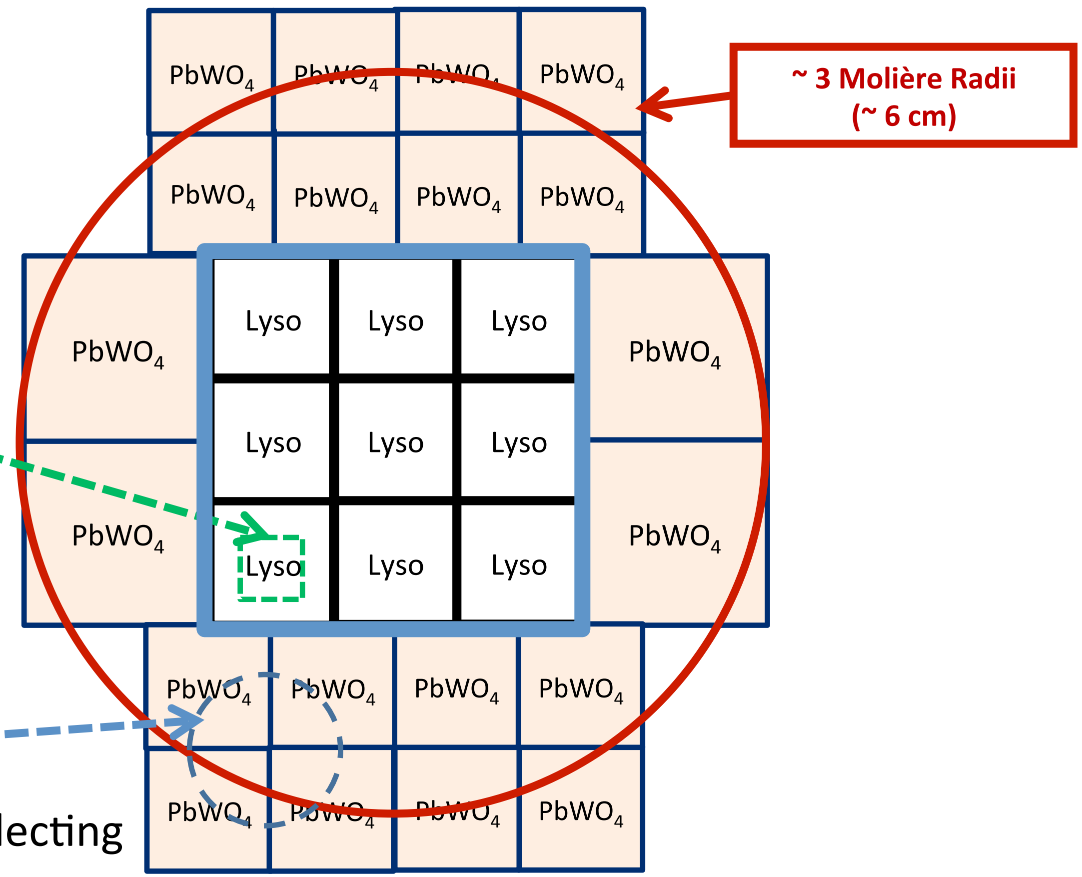
Test Beam @MAMI: Layout of the prototype

After a first test done at BTF(Beam Test Facility of LNF) with a small size prototype , a larger size matrix prototype has been built to be tested with a clean tagged photon beam (ΔP(FWHM) = 1 MeV) at MAMI (Mainz Microtron, Germany) facility.

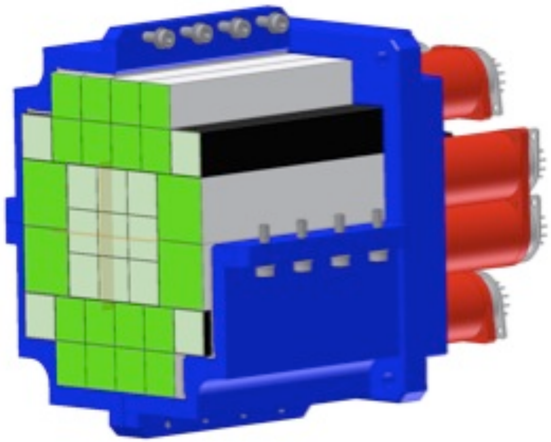
The prototype consists of

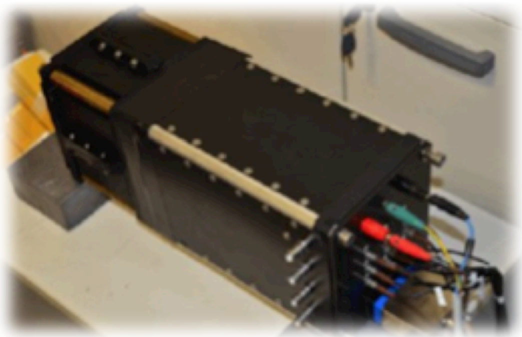
- An INNER MATRIX of 9 LYSO crystals
  - LYSO from (Shanghai) SICCAS High Technology Corporation
  - *$20x20x150\ mm^3$* →
  - readout by $10x10\ mm^2$ **APDs** Hamamatsu S8664-1010
- An OUTER MATRIX of 8 $PbWO_4$
  - for leakage recovery
  - crystals of mixed dimensions: 30 (40)x30(40)x130 mm^3
  - readout by **1 inch PMTs.**

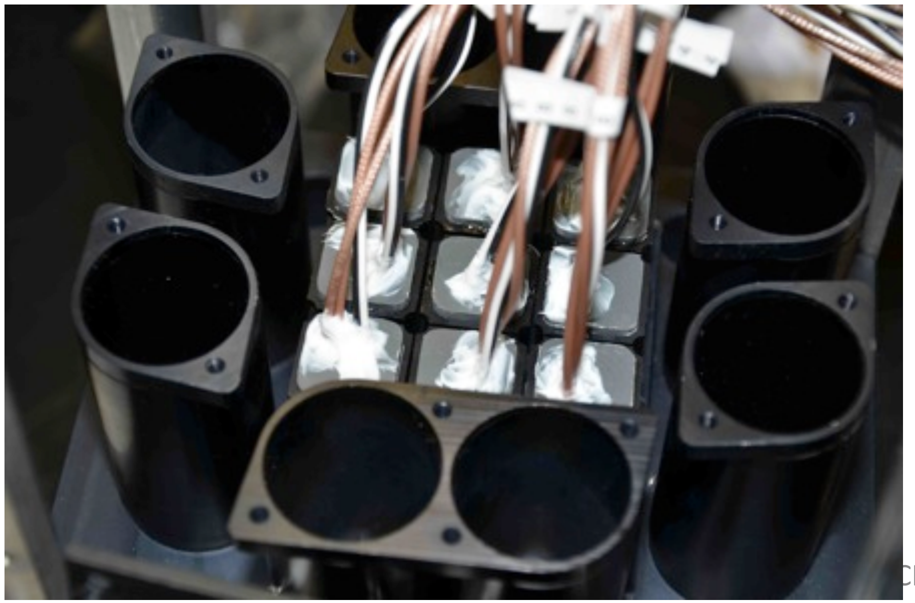
independently wrapped with 100 μm reflecting Tyvek



Prototyping and Beam Testing

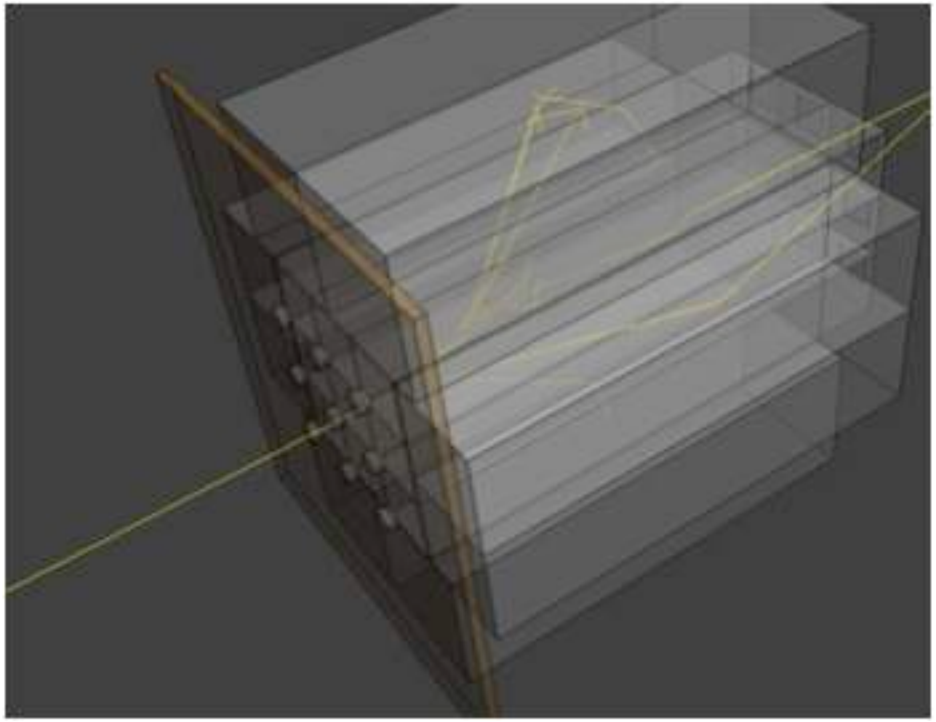


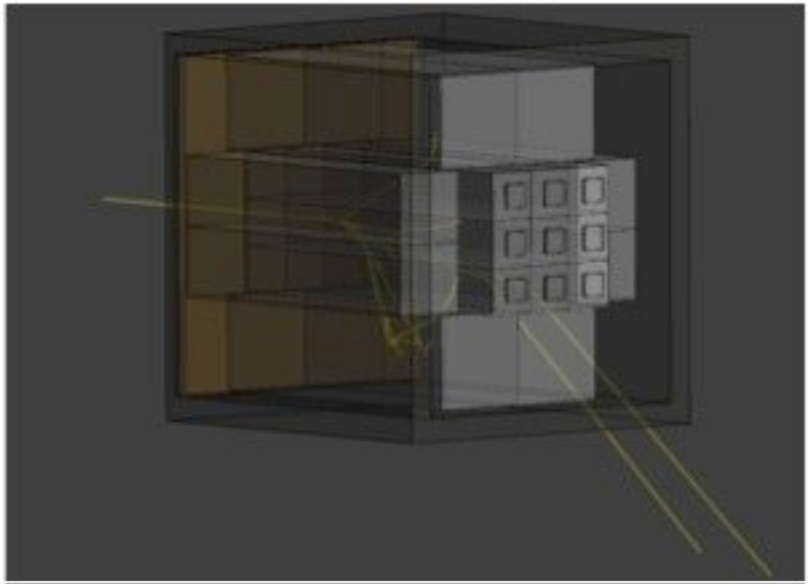


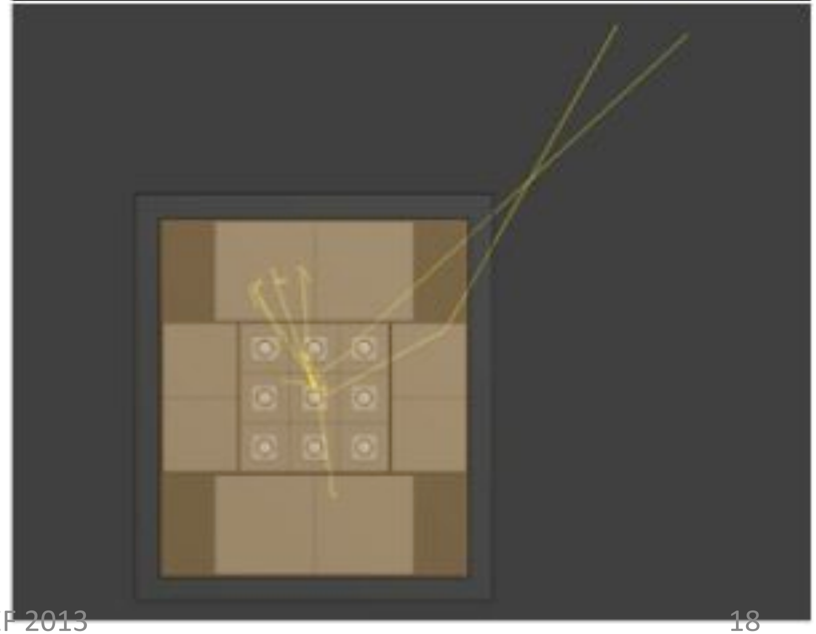


MC Simulation of Test Beam

- Detailed Geant-4 simulation used which respects all the construction features of the matrix: dimensions, positioning, photosensors (p.e., noise), 300 µm Tyvek wrapping, beam dimensions (8 mm diameter).
- Optical Photon Transportation has not been simulated.

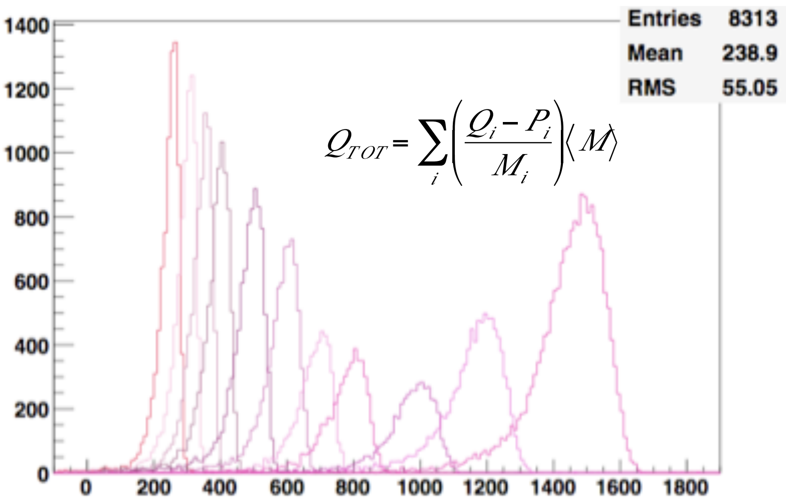


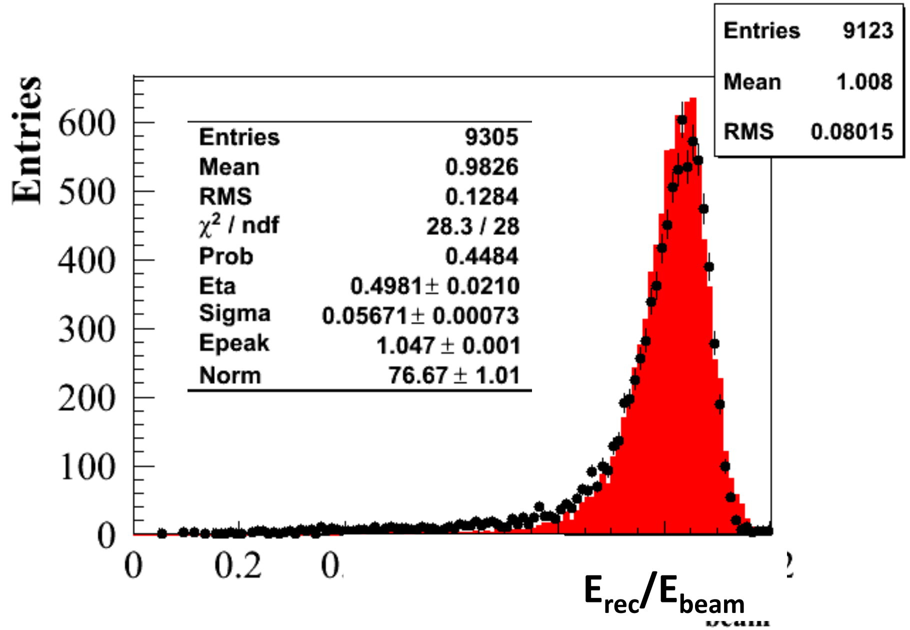


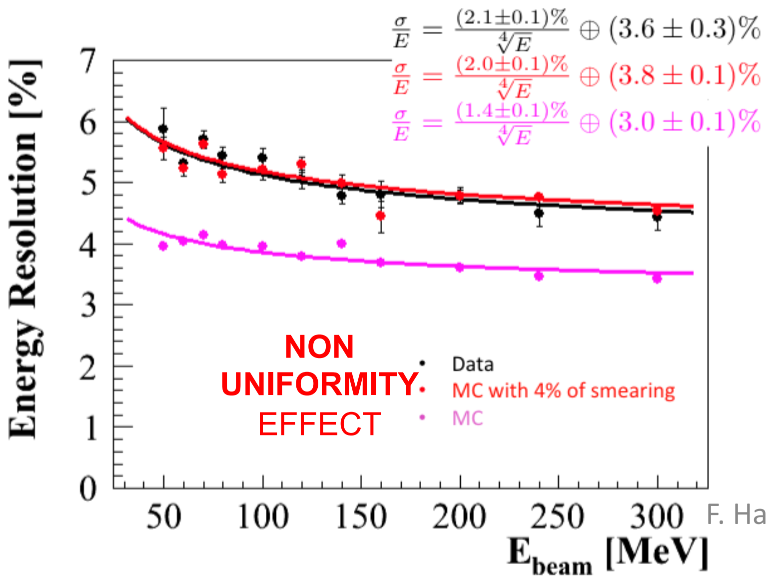


Beam Testing results

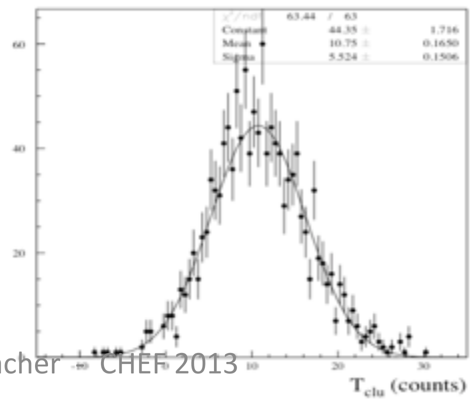
Energy scan between 40 and 300 MeV.

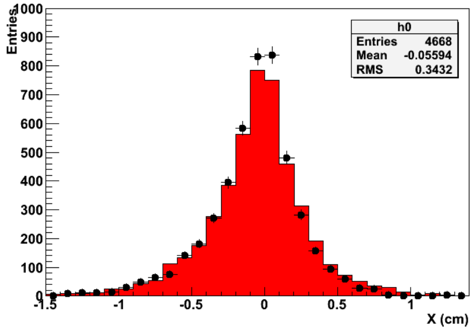






$\sigma_t \approx$ 290 ps @ 100 MeV





$\sigma_x \approx$ .3 cm @ 100 MeV

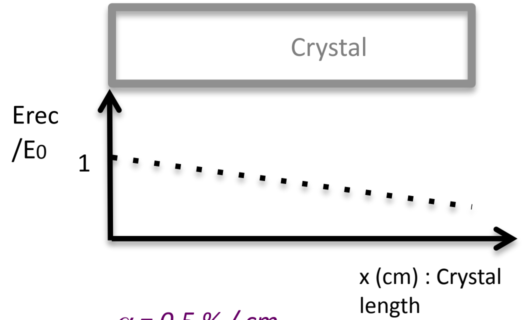
Contributions to the resolution

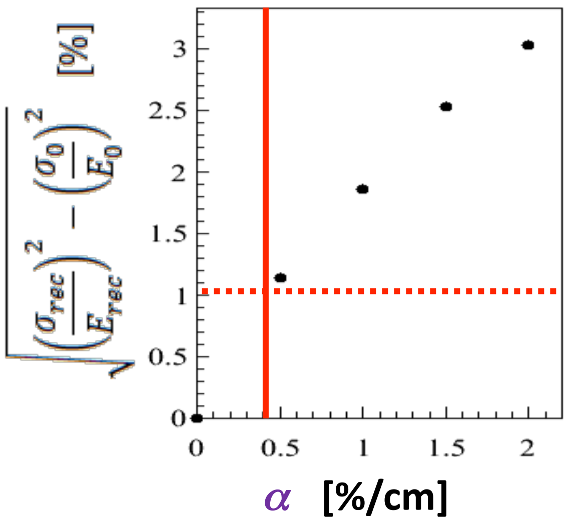
Resolution contributions studied by MC

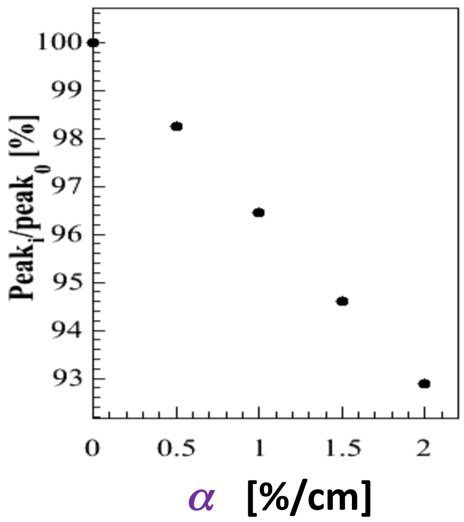
- **Longitudinal Response Uniformity (LRU) large**
- Negligible contributions:
  - Non-linearity response
  - Noise/crystal below 30 keV

LRU of crystal Light response inserted in the MC as

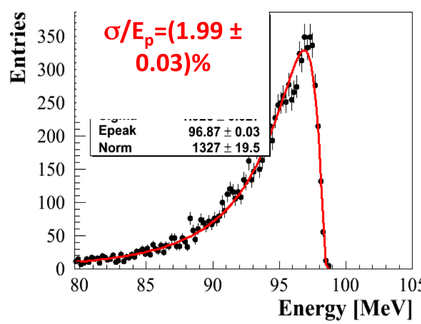
Erec/E0=1- α x ; α : LRU slope



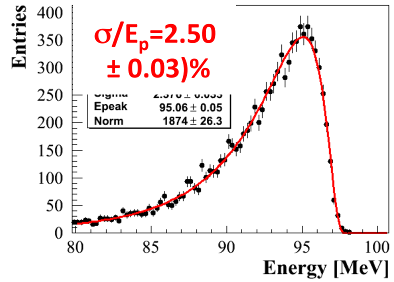




α = 0.5 % / cm



α = 1 % / cm



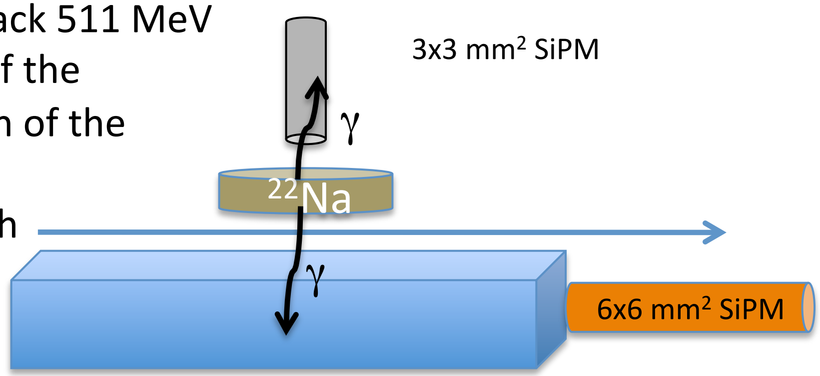
To keep under control the main contribution on the energy resolution it's vital to understand, test and control the longitudinal response of the crystals

need to keep LRU below 0.5 %/cm

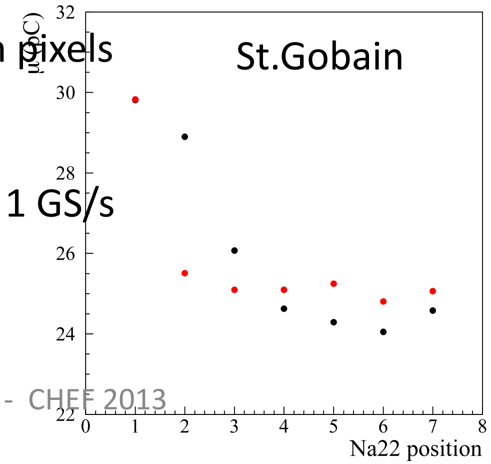
Crystal light response uniformity - LRU

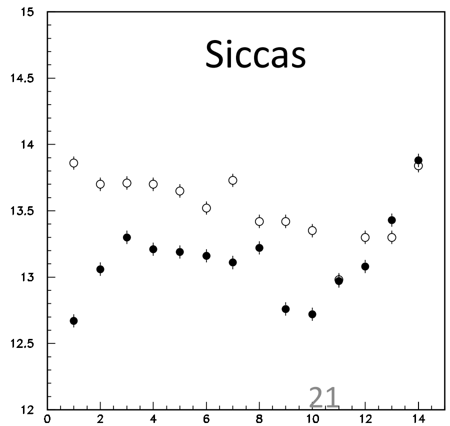
The Cerium doping in the LYSO crystals may not be uniformly distibuted causing fluctuations in the shower development; the Cerium deposition in the crystal is inhomogeneous following the axial growth of the initial ingot; also there is a tiny effect due to the light attenuation inside the crystal.
These two effects could cancel out if the photosensor is placed in the right position (i.e. edge of the crystal poorest in dopant).

We test the crystals using a ^{22}Na source; the two back-to-back 511 MeV photons are used to measure the light response uniformity of the crystal together with the light collection efficiency as function of the position of the radiation incidence along crystal.
To span the crystal length we tag one of the two photons with a finger, constraining the incidence direction along the crystal axis of the companion:



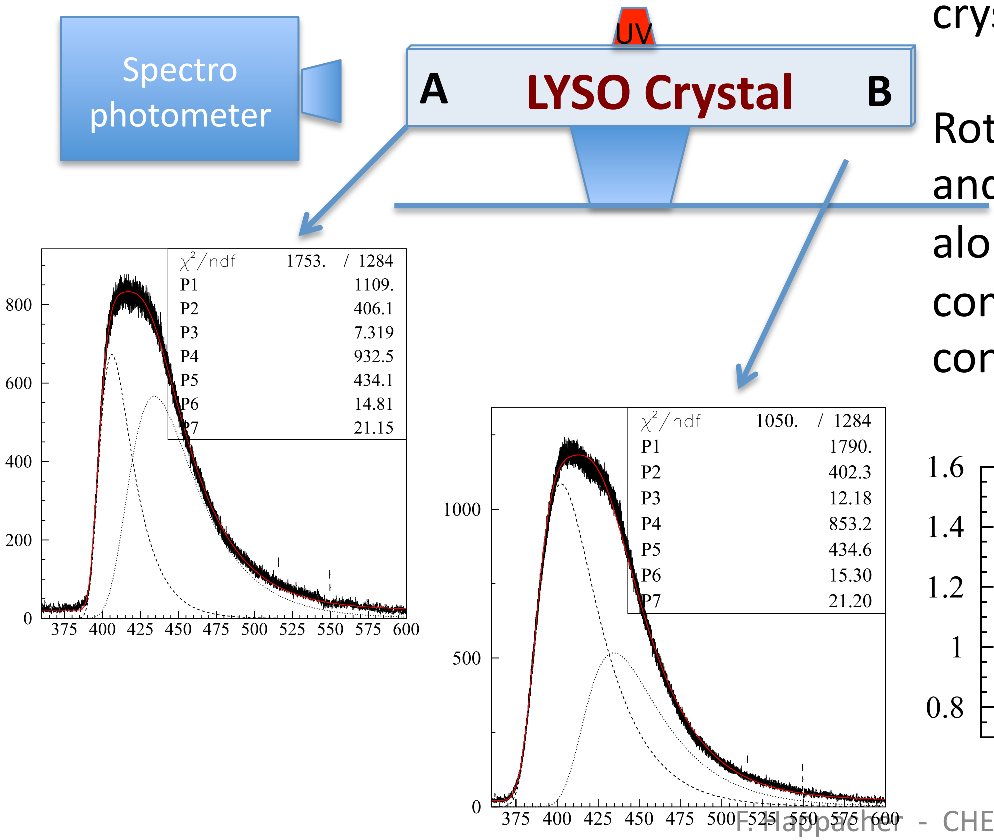
- ✧ Readout crystals using a 6x6 mm^2 MPPC with 25 μm pixels
- ✧ Tag/trigger with a "finger" made by a 3x3x15 mm^3 LYSO crystal and a 3x3 mm^2 MPPC.
- ✧ Digitization performed using a CAEN DT5751 10 bit 1 GS/s
- ✧ Manually movable source Sled





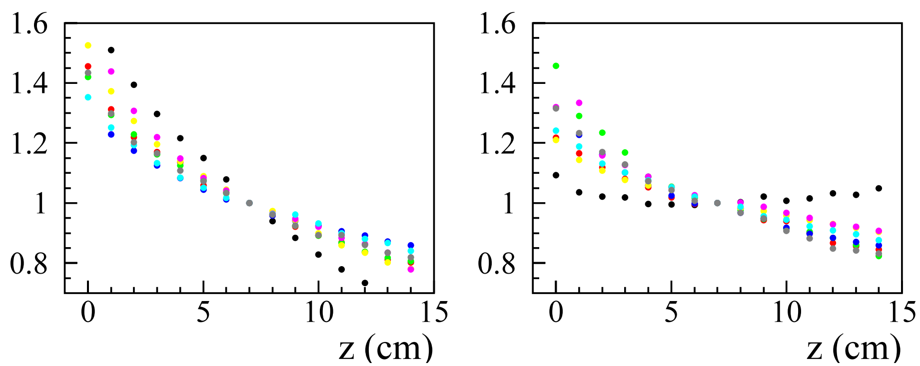
LRU - light emission

We use a spectrophotometer to study the emission and absorption of light components inside the LYSO crystal. We then fit the emission spectra with two Moyal function to extract the blue and green components.



The Blue light is more asorbed inside the crystal than the green

Rotating the crystal flattens the attenuation and indicates an increase in light yield along the crystal axis. For few crystals we se a compensation of the two effects: Cerium concentration and attenuation



Hardware Calibration System

Absolute energy calibration scale a' la BaBAr: Low energy neutrons (DT) irradiates Fluorinert Fluid that activates and is then pumped through pipes to the front face of the crystals

we are engineering this system

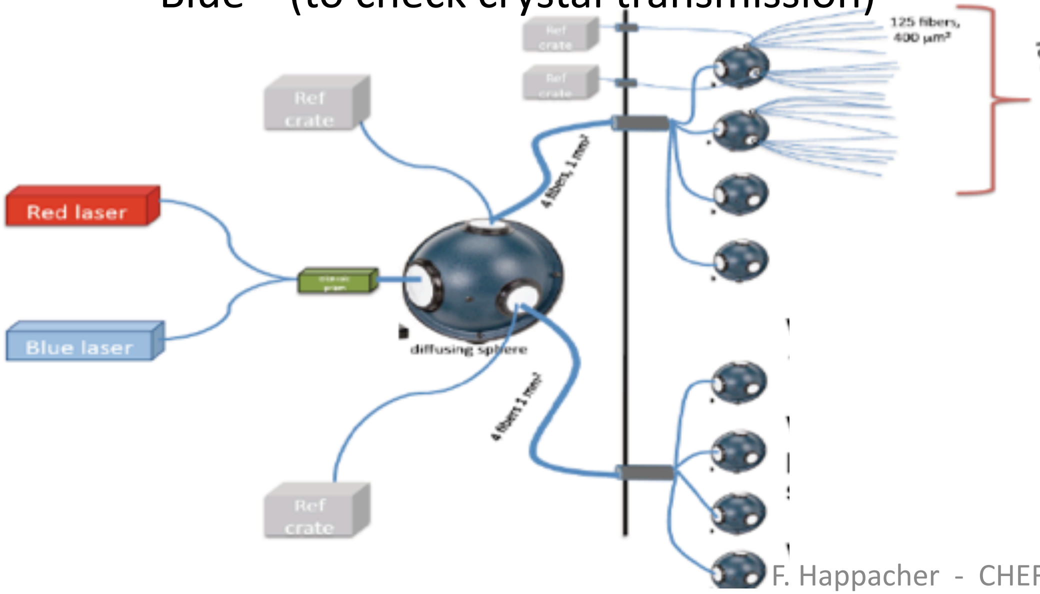
(weekly, ~ 30 min operation)

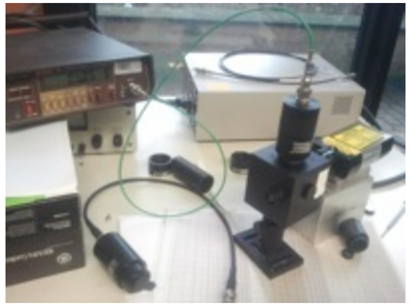
$$^{19}F + n \rightarrow \; ^{16}N + \alpha$$
$$^{16}N \rightarrow \; ^{16}O^{*} + \beta \qquad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^{*} \rightarrow \; ^{16}O + \gamma(6.13\ \mathrm{MeV})$$

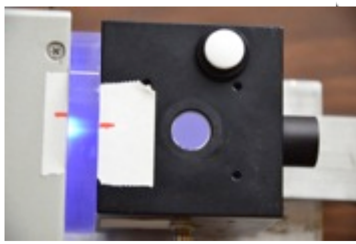
A laser/LED system to flash the crystal at different wave lenghts.

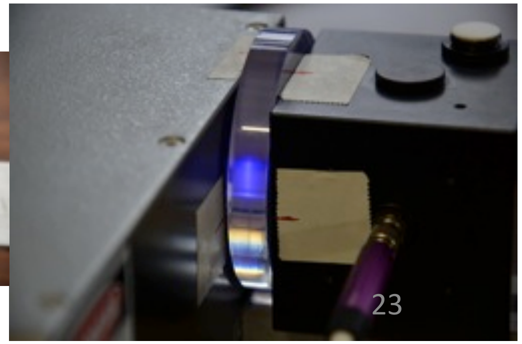
Light routed to the crystals through quarz fibers and monitored with reference pin diodes

- Green (to check the APD gain)
- Blue (to check crystal transmission)









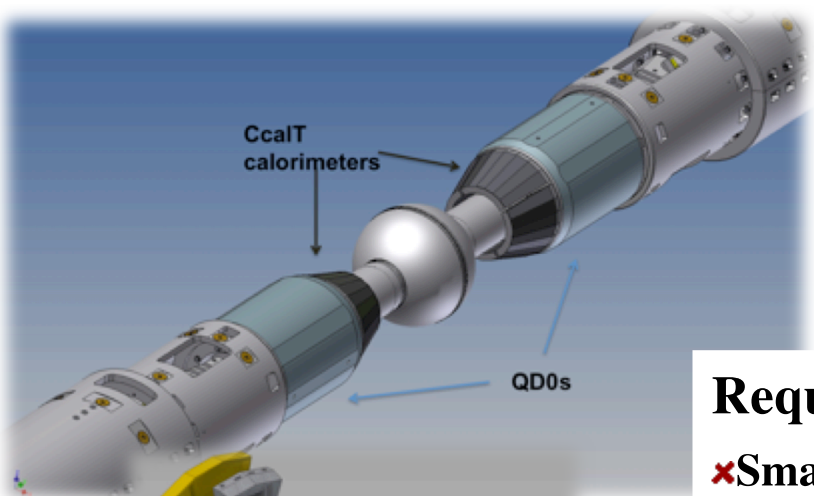
A real example: the CCALT @Kloe

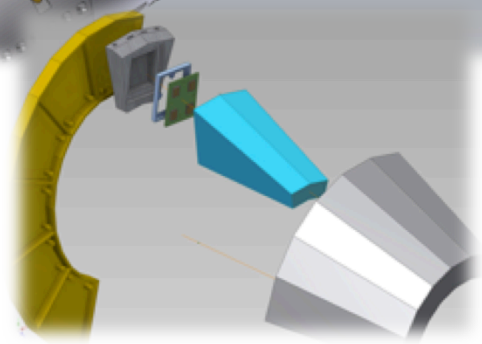
Goal: increase acceptance of the central calorimeter from 18 to 10 degrees, covering QD0 region

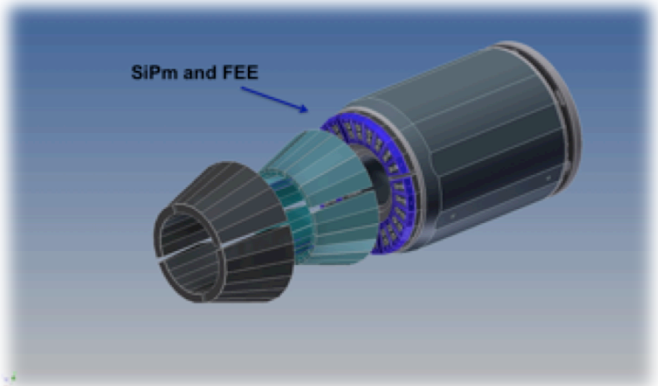
There are some physics items that can benefit from this upgrades, for instance:

✓The last KLOE measurement on BR($K_S \rightarrow \gamma\gamma$) → **(JHEP 0805:051,2008)**

3σ difference between KLOE and NA48. KLOE confirms O(p^4) prediction of ChPT.

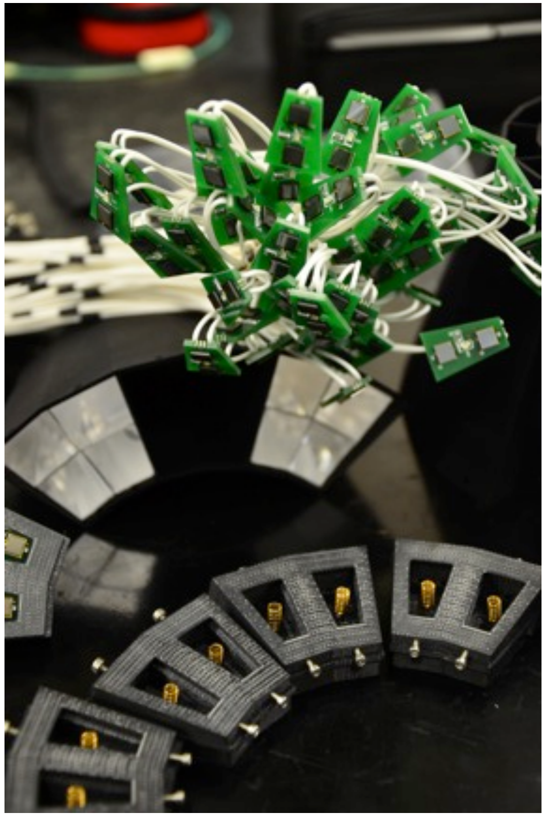


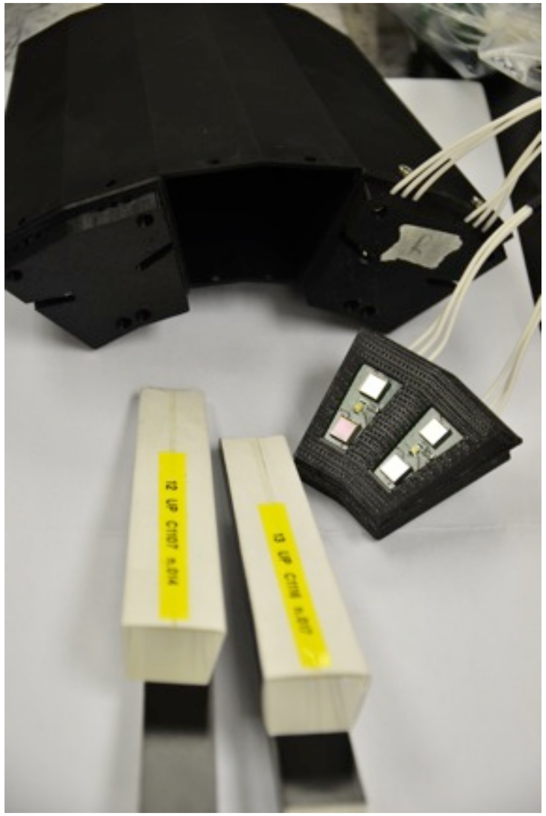


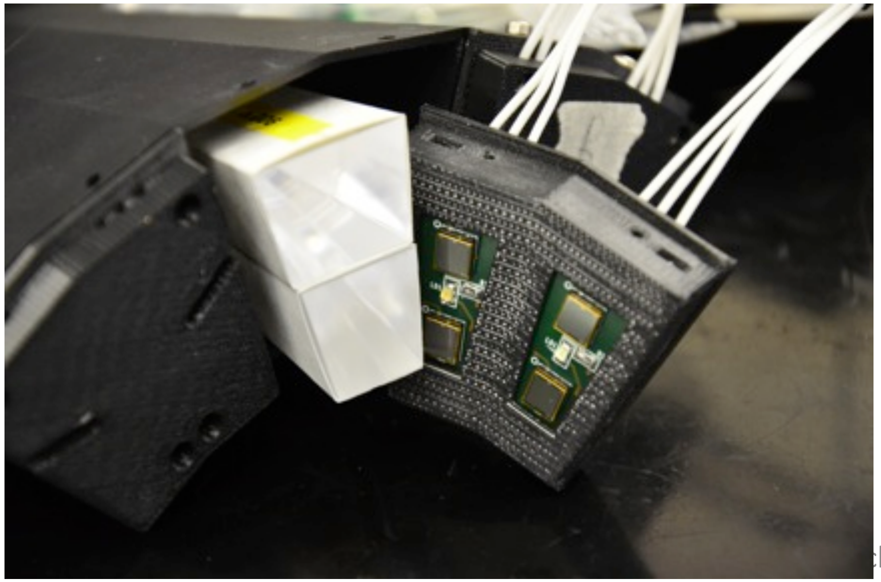


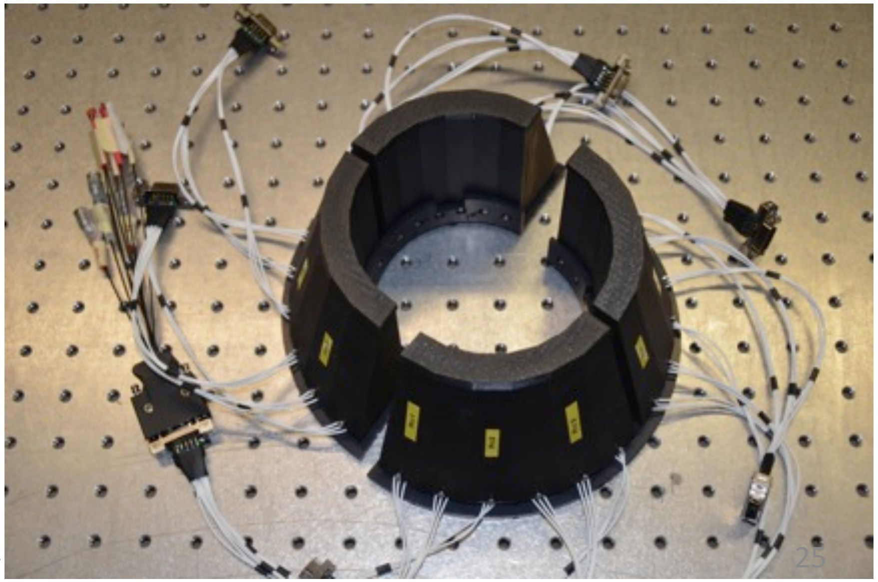
Requirements:

- **Small X_0 and Molière radius (limited available space)**
- **Accurate timing: 300-400 ps @ 20 MeV → bkg rejection**
- **High efficiency for 20-300 MeV photons**
- **Able to work inside 0.5 T magnetic field**
- **Position resolution of 2-3 mm**









Conclusions

- The design of the calorimeter based on Lyso + APD it's at a good stage
- The DISK geometry is the new baseline
- Photosensor choice between sipm and APD depend on noise and pile up separation capability
- Prototyping a more uniform matrix of 30 Lyso Crystals 30x30x130 mm^3 at LNF and Mami next autumn
- Development of a APD HV/preamp board under way
- Development of a custom digitization board in progress
- CD2 review expected for spring 2014