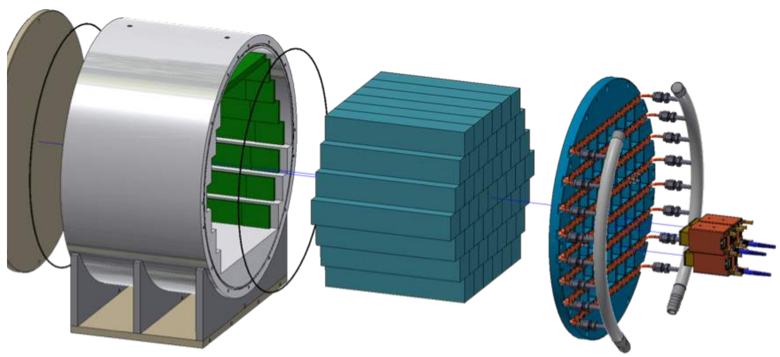
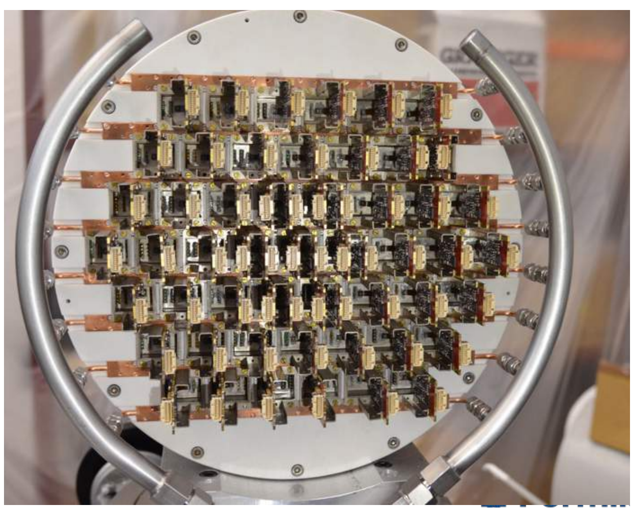
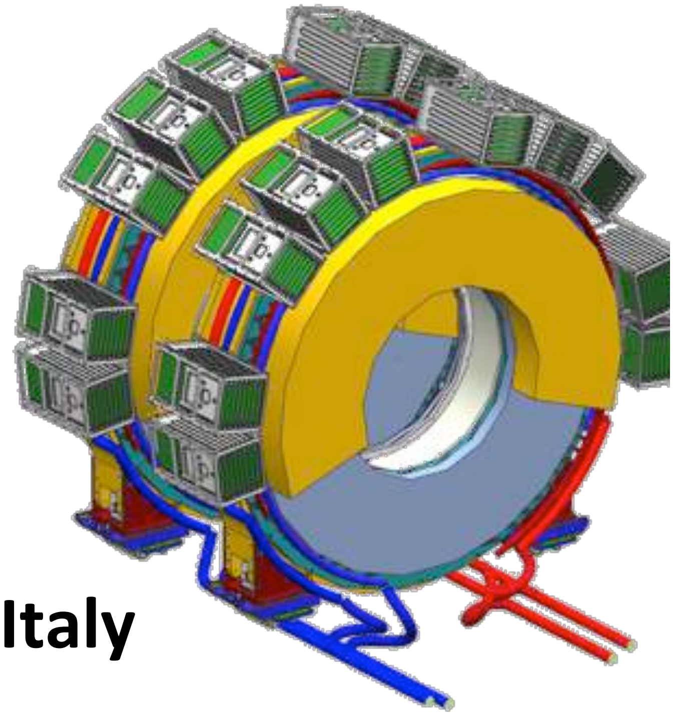
The Mu2e Calorimeter







S.Miscetti
LNF/INFN Frascati, Italy

Lectures for US/EU FNAL
Summer Students
FERMILAB - 3 August 2017

Outline of the lecture

- **Introduction of calorimetry**

  A calorimetry primer
  → Electromagnetic showers
  → Homogenous calorimetry
  → Scintillation crystals
  → Photodetectors

- ***An example: the MU2E Calorimeter***
  → Requirements and design considerations
  → Crystal choice: LYSO vs BaF_2/CSI
  → Simulation and prototyping
  → Pre-production of crystals and MU2E SiPMs
  → Irradiation tests
  → Experimental tests
  → Engineering design and Module-0
  → "in-situ" Calibration

- **Conclusions**

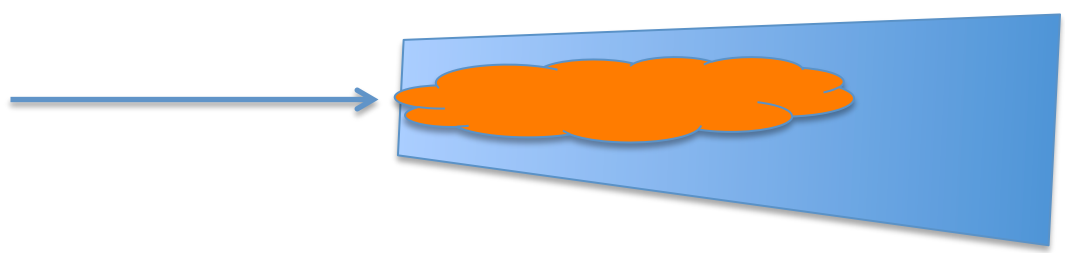
What is a calorimeter ? (1)

- The main usage of a calorimeter (HEP) **is to measure the particle energy.**

- They typically do this by means of totally absorbing energy in the calorimeter material **(destructive measurement)**

- **What kind of particle can be measured ?**
  neutral and charged
  - em calorimeter (photons, π^0, electrons)
  - hadron calorimeters (n, p, $\pi^{+/-}$,K, Jets …..)

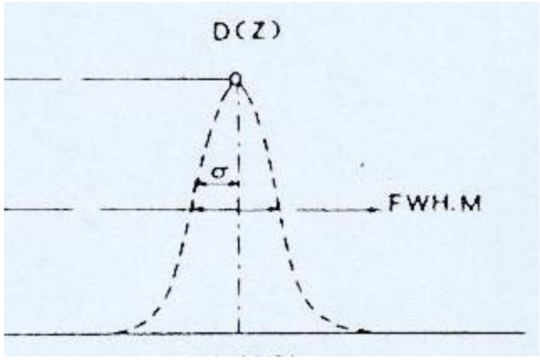
- **Basic assumption of the response → Linearity**
  Q (response pC) = a (Calib Constant) x Ep (Particle Energy)



What is a calorimeter ? (2)

Calorimeter and trackers are complementary in HEP.
Many good reasons to have it one in your detector:

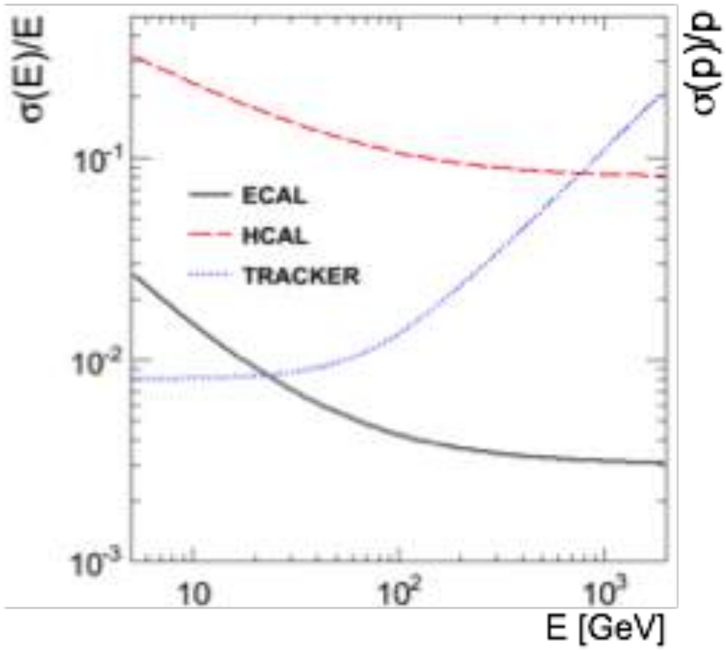
- **Energy resolution improves for increasing energy** (like k/sqrt(Ep), stochastic measurement)



- **Tracker momentum resolution deteriorates** for increasing momentum (larger sagitta errors)

- **Calorimeters can be extremely fast** and easy to be **used for triggering**.

- **Tracking + calorimeter helps:**
  → **PID** (ex photons/e, e/pi-mu, …)
  → **Energy flow**
  (i.e. tracking correction of energy deposits to improve Jets determination ..
  Started CDF , CMS-Atlas improved



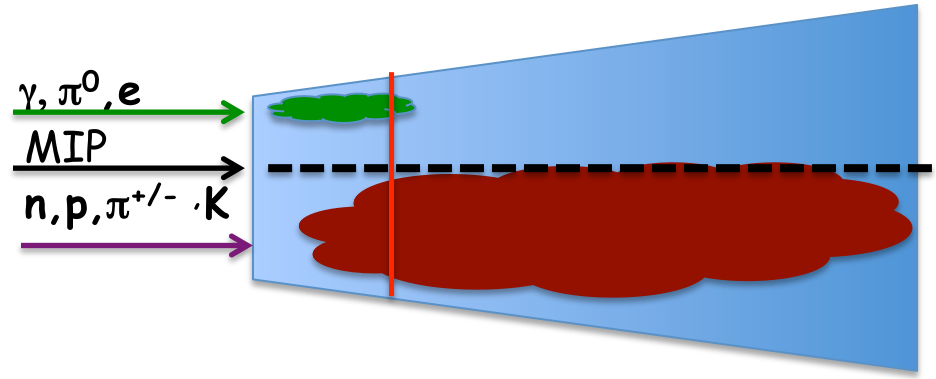
- **In 4−π detectors also missing energy** becomes very important **(neutrinos)**

How many kinds of calorimeter?

Calorimeters have assumed any form since they were born but basic sub-division remains for dimension scale and methods of operation:

→ **Electromagnetic, Hadronic**

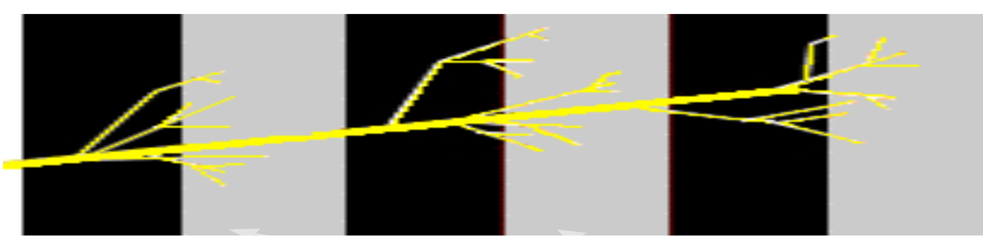
E.M. …. well described shower
radiation length (X_0)
Had .. Not well described shower
interaction length (Lambda)

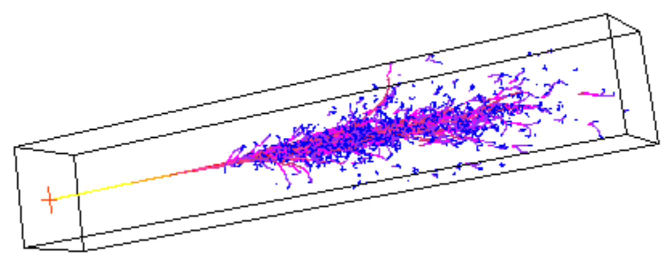


→ **Heterogeneous, Homogeneous**

Heterogenous: Sampling signal in active material, mostly absorbed in passive material. **Possibility of longitudinal segmentation. Many choices.**
Can be both EM and hadronic. Poor resolution.

Homegenous: signal is fully absorbed in active material.
Small longitudinal segmentation. Limited choice of material. Expensive.
Cannot be hadronic calorimeter. Very good resolution.





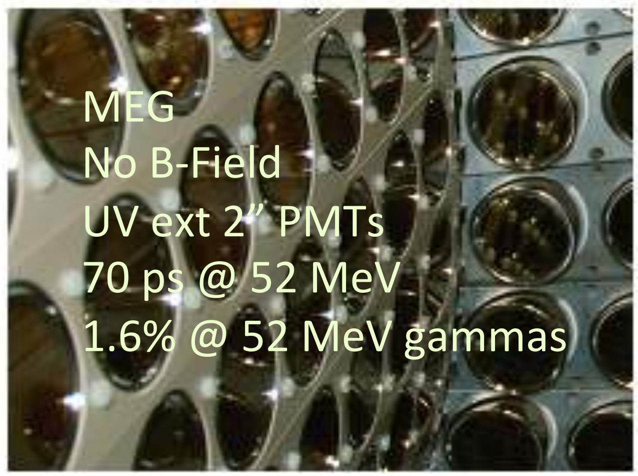
Concentrate on one category

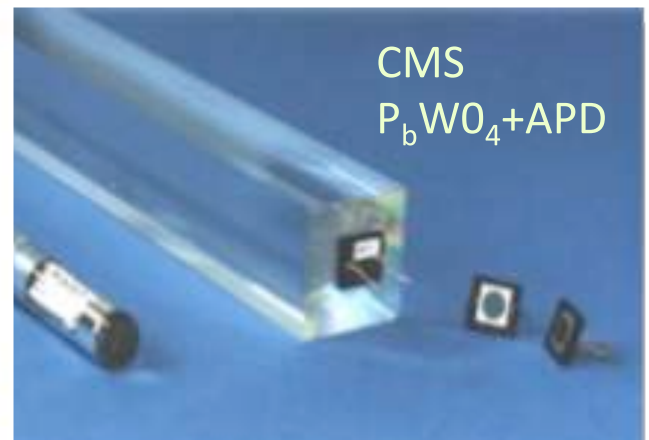
Today we describe only Electromagnetic , homogeneous! Why?

At Mu2e, the signal is a mono-energetic electron of 105 MeV.

Many possible "on-paper" solutions depending on requirements:

- High sampling heterogeneous calorimeter (KLOE-like)
- Homegeneous Liquid Xenon (MEG-like)
- Homogeneous Crystal like detector (kTeV, BaBar, CMS …)





$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{0.125}{E(GeV)} \oplus 0.3\%$$

Primer of EM showers (1)

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

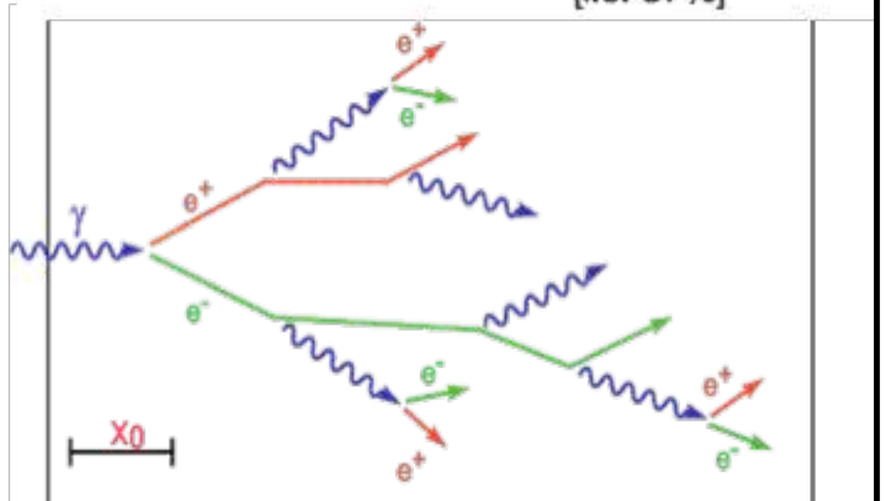
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only $(1/e)^{th}$ of its primary energy ...
[i.e. 37%]



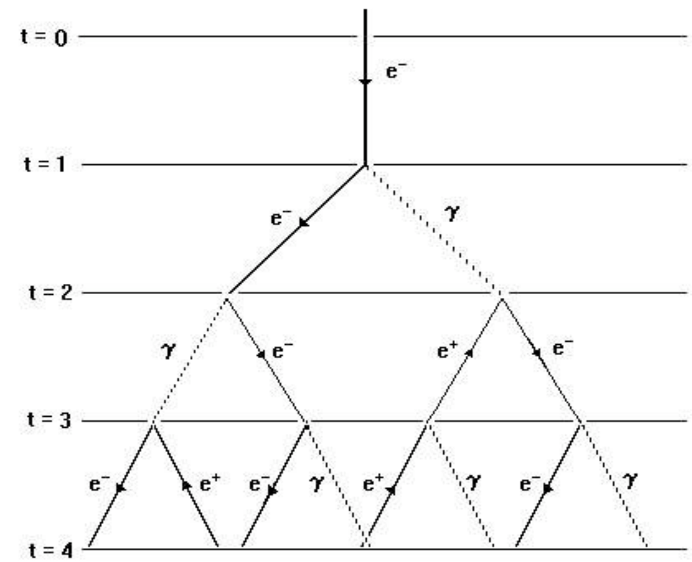
Primer of EM showers (2)

An alternating sequence of interactions creates a cascade

Simplified shower model [Heitler]

$E > E_c$: shower development governed by X_0

- e^- loses energy via Bremsstrahlung
- γ pair production with ***mean free path 9/7 X_0***



- N. particles doubles every X_0 of material,
- Energy gets reduced by 2 @ each iteration
- Shower continues until the particles energy reaches E_c

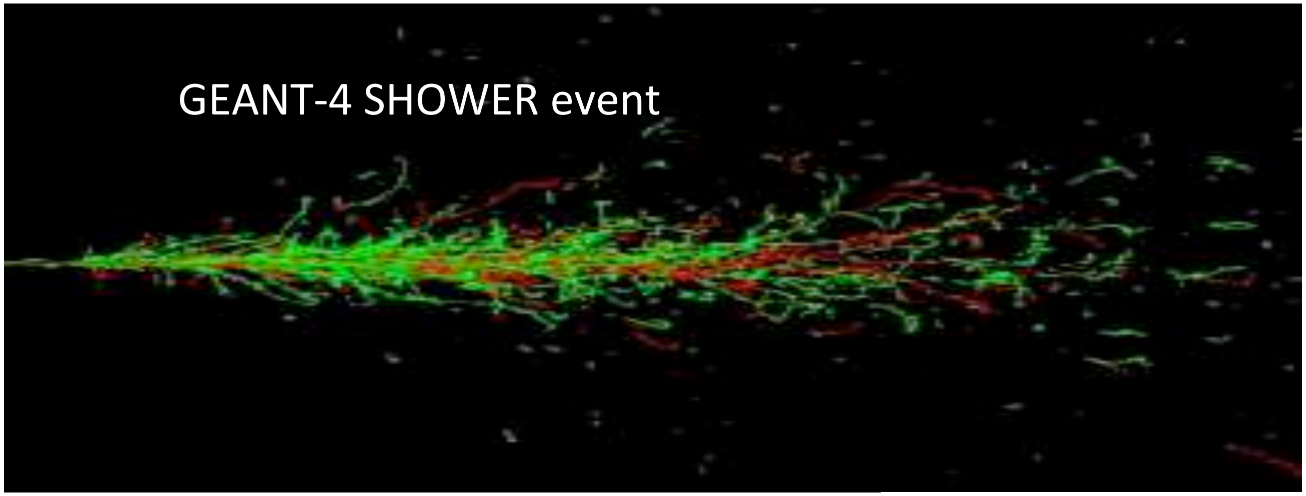
$$E_c \approx \frac{610\,\mathrm{MeV}}{Z+1.24}$$

$$N_{max} = 2^{t_{max}} = \frac{E_0}{E_c}$$

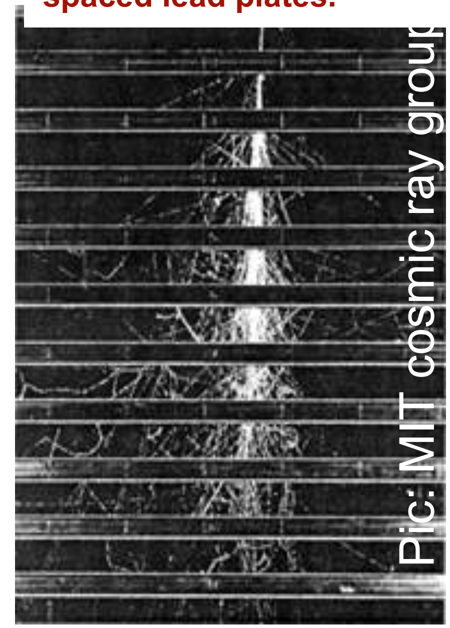
Shower max @ tmax = $\ln(E_0/E_c)/\ln 2$
After this point dE/dx, Compton and photoelectric effects take over. Shower energy deposition diminishes and then stops. It is referred as shower tail.

t (95 %)= [t(max) + 0.008 Z + 9.6] in X_0 units

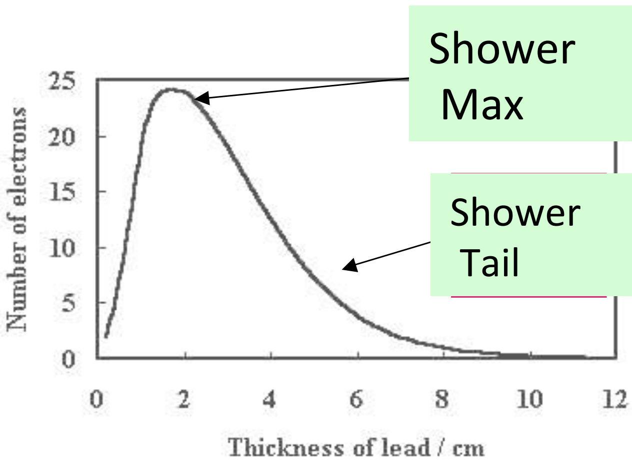
Primer of EM showers (3)



Cloud chamber photo of EM cascade between spaced lead plates.



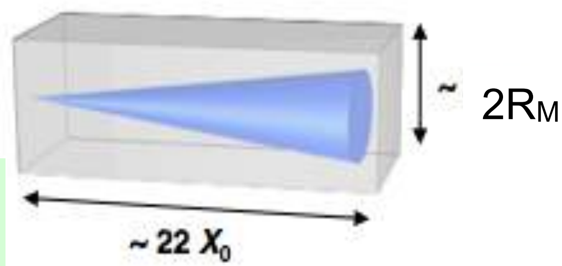
Longitudinal development



$$dE/dt = E_0\, ct^{\alpha} \exp(-\beta t)$$

$$t = X/X_0$$

Transverse development



Multiple scattering dominates in Transverse development

$$R_M = \frac{21\,\text{MeV}}{E_c(MeV)} X_0 \quad [g/cm^2]$$

75% E_0 in $1R_M$;
95% in $2R_M$;
99% in $3.5R_M$

Signal generation

1. A particle deposits its full energy in the calorimeter media
2. The energy is converted into a measurable signal

(charge / light / sound / heat)

The most used materials → gases / semiconductors / scintillators ……

- semiconductors: dE/dx or photon-absorption + drift of e-h — **eV per e-hole pair**
- gases: dE/dx or photon-absorption + charge diffusion — **20-40 eV per e-ion pair**
- scintillators: dE/dx or photon-absorption + light emission — **400-1000 eV per photon**

generated charges or photons yield the measurable signal:
statistical process = the more the better !

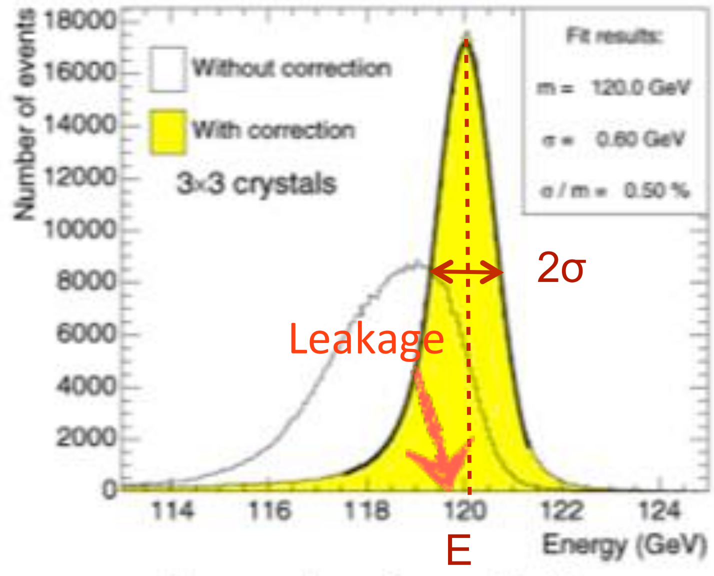
Energy Resolution terms

- The **energy resolution** is parametrized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

or

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



- **Stochastic term a**
  - $E \propto N \rightarrow \sigma \propto 1/\sqrt{N}$: all statistical effects contribute
    i.e. intrinsic and sampling fluctuations, photoelectron statistics

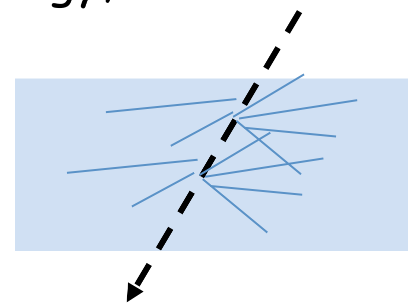
- **Noise term b** (energy independent term) relevant at low E
  - Electronic noise, radioactivity

- **Constant term c** (linearly dependent of energy) dominates at high E
  - inhomogeneities, calibration uncertainties, radiation damage, (leakage), …

Scintillation process

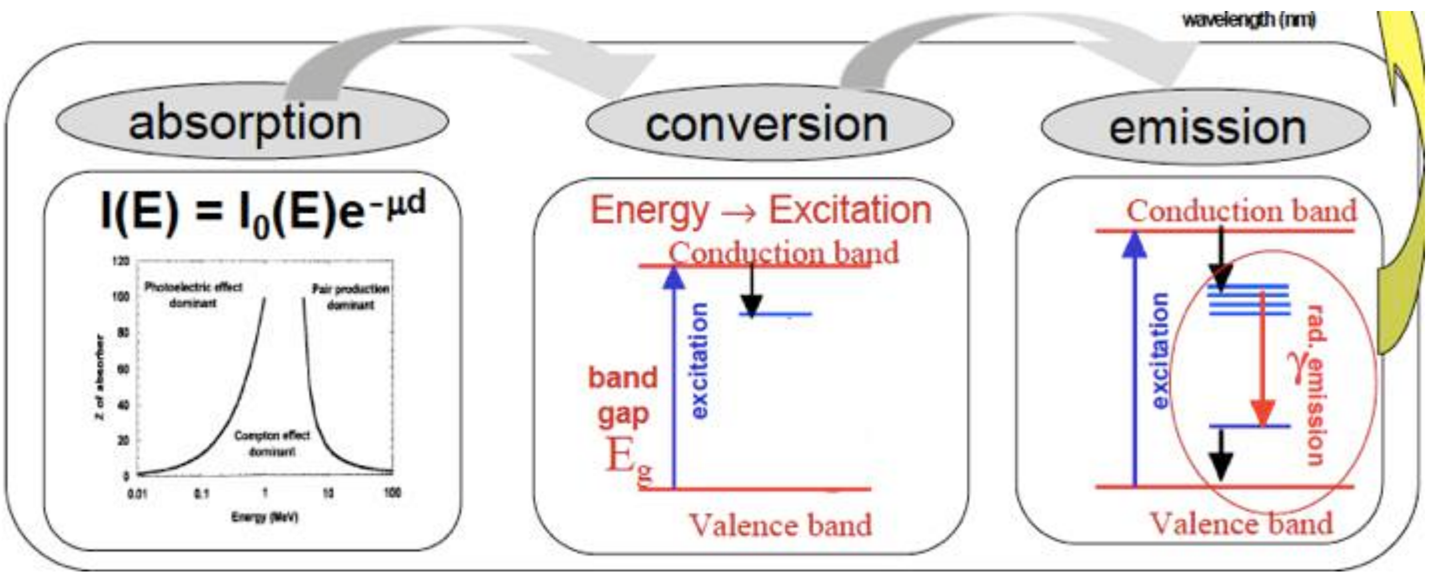
Basic principle: a charged particle crossing a scintillator loses energy, exciting atoms or molecules of the material

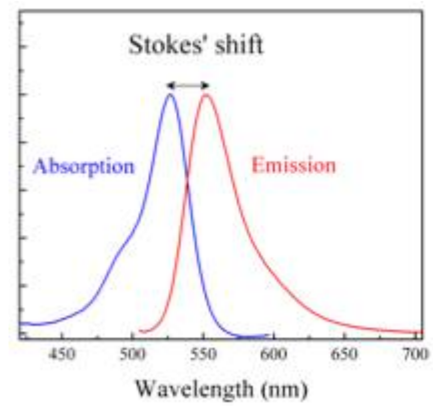
➪ **photon emission** (UV-visible) follows



Light emission:

- can be instantaneous, $<10^{-8}$ s, (fluorescence) or delayed, ms to hours(phosphorescence)
- Has one or two exponential decay time t_D (fast, fast/slow)





$\lambda_{em} > \lambda_{ex}$

Scintillators: characteristics

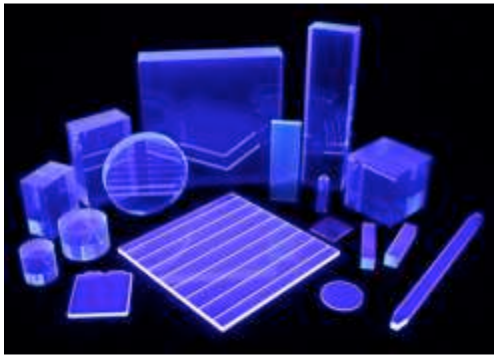
Relevant characteristics for particle detection:

- ✗ Light Yield (LY) number of photons produced for a given absorbed energy
- ✗ Transparency to the emitted radiation
- ✗ Spectral emission compatible with light detectors (photosensors), where light is collected and then converted into electrons via photo-electric effect
- ✗ Linearity of response
- ✗ Time response
- ✗ Density, X_0, Rm

Types of scintillators

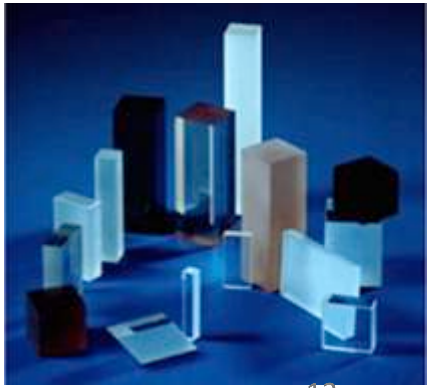
Organic scintillators

- ✗ Complex organic molecules (typically soluted in plastics materials) where UV light is emitted after excitation of molecular levels. Other molecules (wave length shifters) are then added to transfer light into visible radiation
  - ➢ **Fast emission time** (2.5-10 ns)
  - ➢ **Low scintillation efficiency** (< 2 k photons / MeV)
  - ➢ **Low density** (1 g/cm^3)
  - ➢ Can be easily **machined to any shape (fibers)**



Inorganic scintillators

- ✗ Crystals (alkali, alkaline earth and rare earth), usually doped with impurities uniformly dispersed throughout the crystal lattice
  - ➢ **High scintillation efficiency** (10-70 k photons / MeV)
  - ➢ **Slow emission time** (100-600 ns)
  - ➢ **High density** (4-7 g/cm^3)



Crystals for HEP

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3
Melting Point (°C)	651	621	621	1280	1050	2050	1123
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20
Hygroscopicity	Yes	Slight	Slight	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10
★ Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5

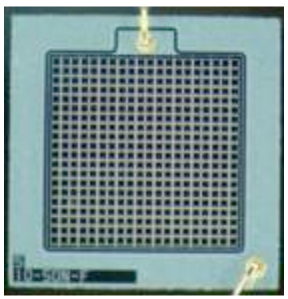
Broad variety of scintillator parameters: relative importance depends on the application

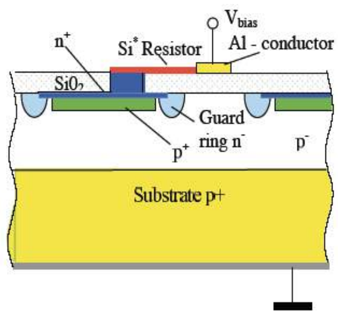
★ Typical LY of NaI ~ 40000 γ/MeV

Detecting the light: Photosensors

Light is guided to a photo-detector (i.e. photomultiplier tube, silicon photomultiplier) and converted into charge:

- Conversion of a photon into electrons via photo-electric effect
- Amplification of the electron signal by factor 10^5-10^6 via secondary emissions on dynodes or avalanche multiplication in silicon





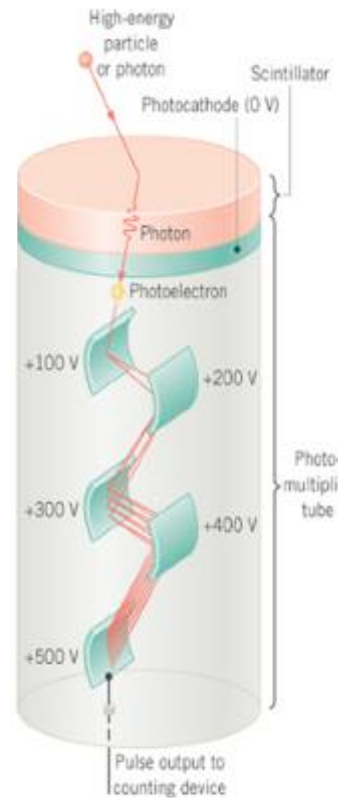
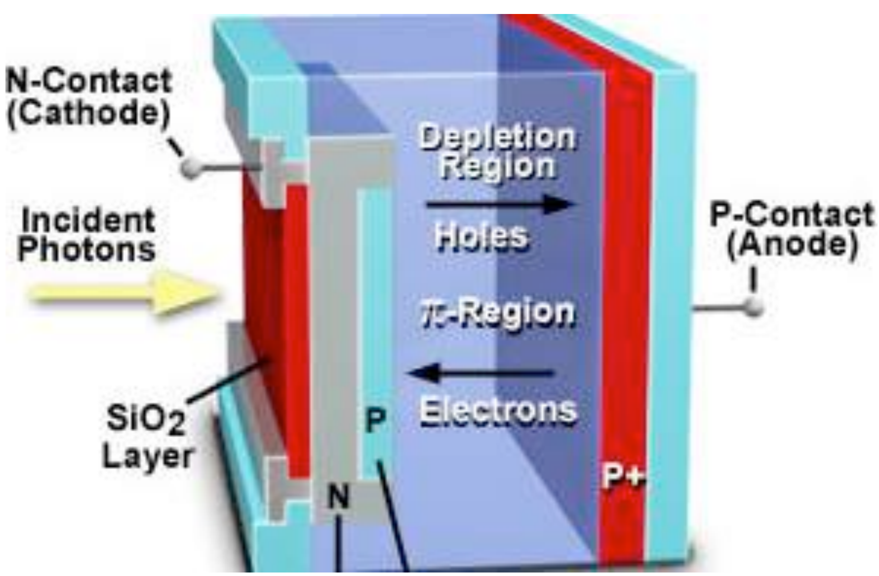


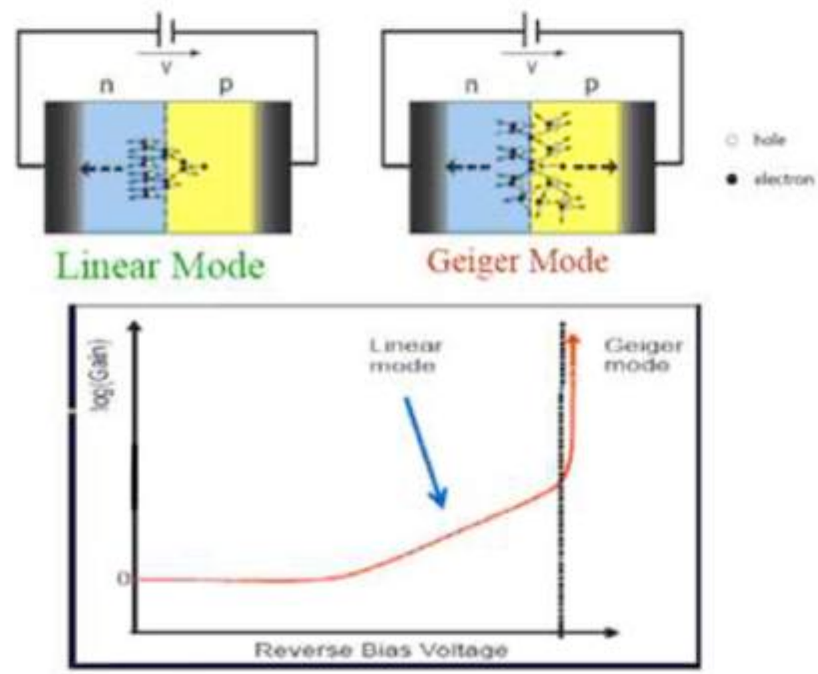
Photo-detector requirements:

- cover a large range of wave lengths (UV to IR)
- good efficiencies, single photon detection possible
- cover large active areas (SuperKamiokande O 46cm)
- **PMT (SiPM) are (not) sensitive to B-Field**

Silicon Photosensors

- A silicon photo-sensor is "in practice" a reverse Silicon N-P junction with a photo sensitive layer where "photo-electrons" are extracted.
- The reverse bias helps to create a large depleted region and reduce to negligible values the "dark current", Id, i.e. the current seen without any signal in input
- **3 work regimes:**
  → **Photodiode (G=1)** all e- produced in the photosensitive layer are collected at the anode.
  → **APD (G=50-2000)** , or Avalanche Photodiode, working in proportional regime and
  → **Geiger APD (G=10^5-10^6)** working in Geiger mode





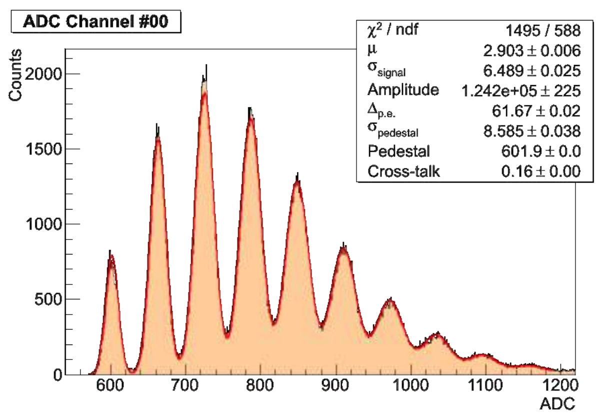
Silicon Photomultipliers (SiPM)

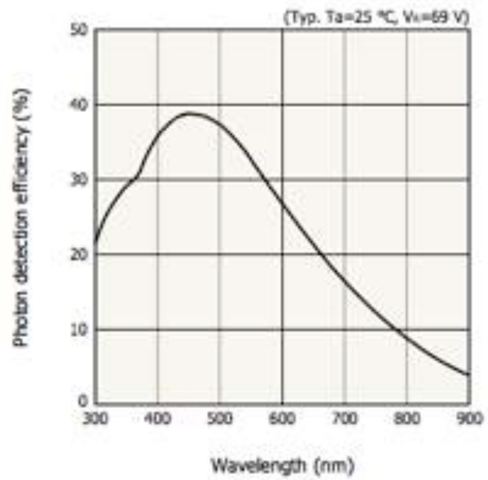
The basic SIPM element (pixel) is a combination of Geiger-APDs and quenching resistors

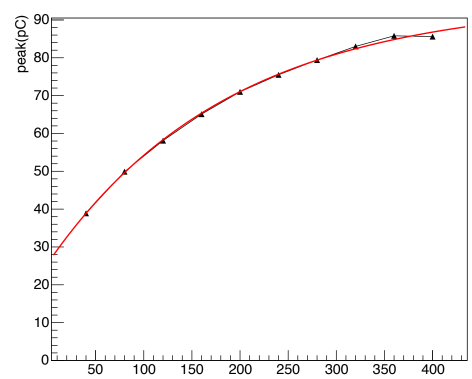
→ a large number of pixels are electrically connected and arranged in two dimensions;

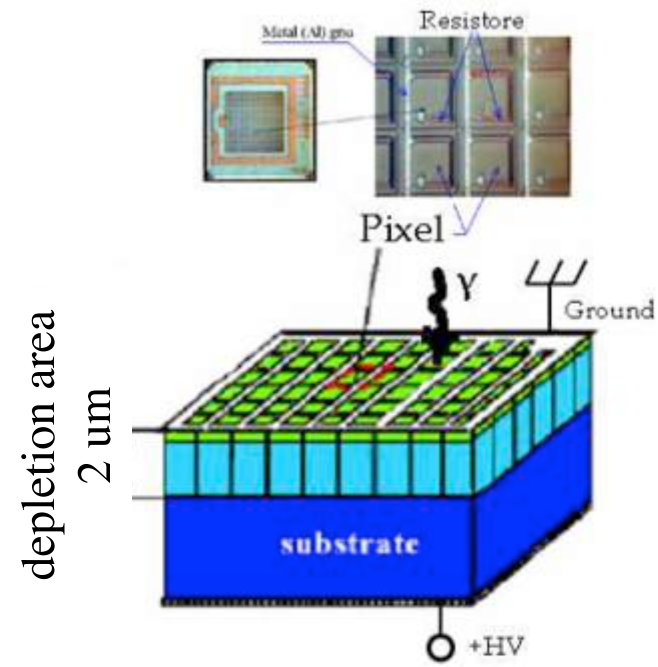
→ Each pixel generates a pulse of the same amplitude when it detects a photon .

→ The output signal from multiple pixels is the superimposition of single pixel pulses.







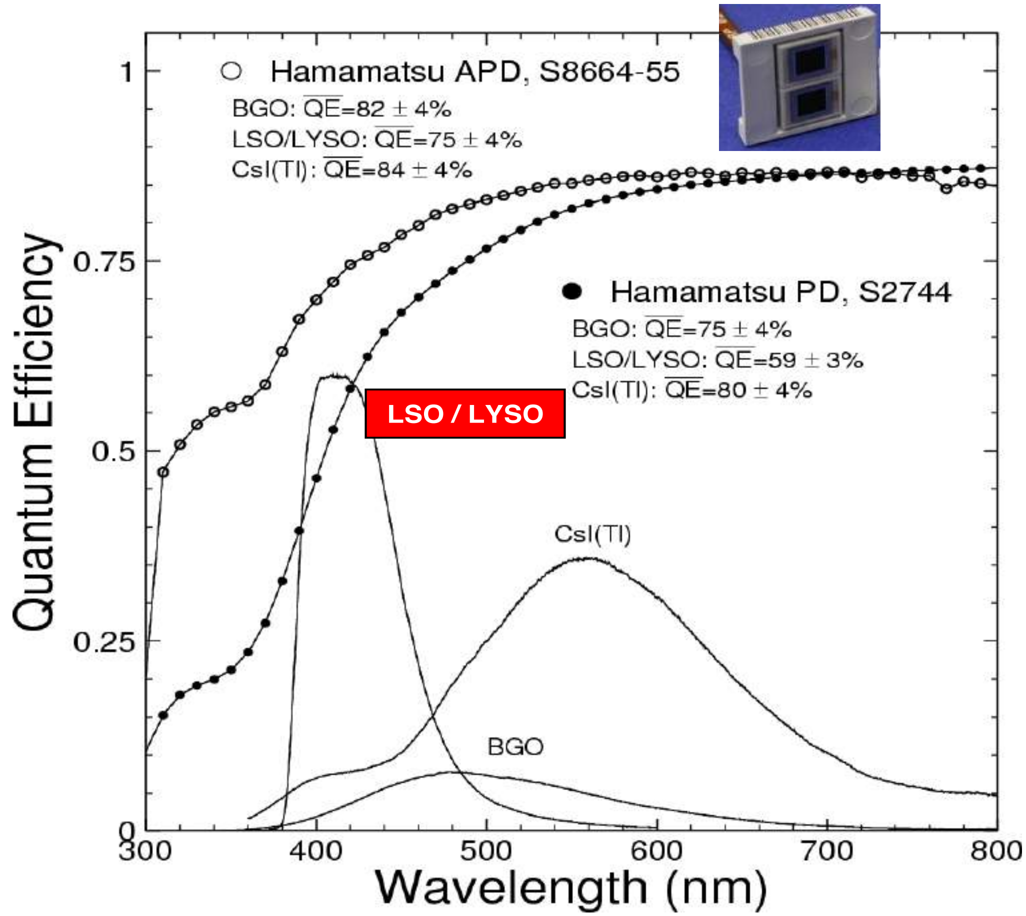


- Single photon counting
- Photon Detection Efficiency
- "Intrinsic" not-linearity on the response.

Photosensors & Scintillator matching

Coupling scintillator light emission spectrum to Quantum Efficiency of photosensors is essential

Crystals with λ > 400 nm well match with standard bi-alcali PMT and APD

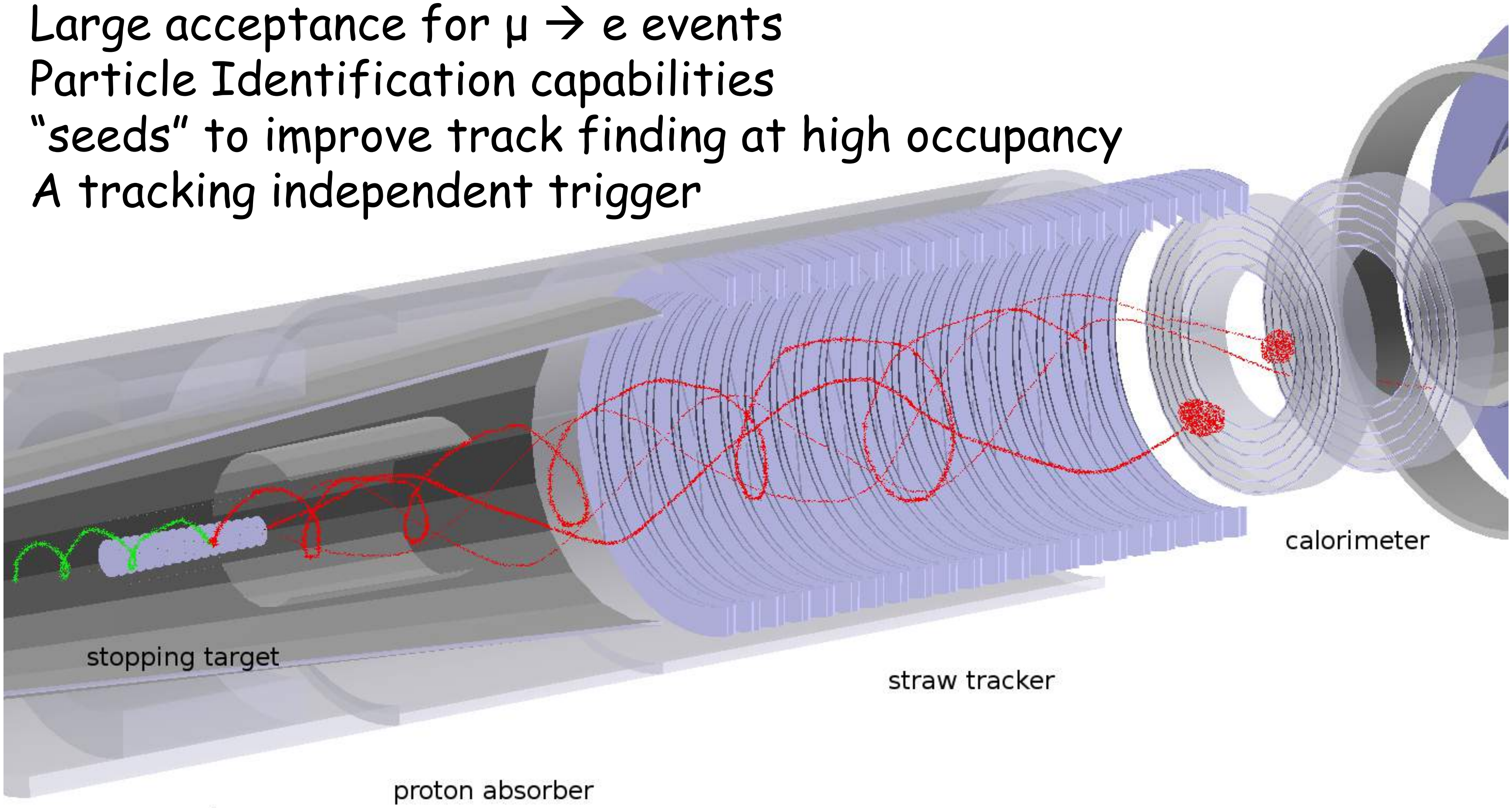


Design and details of the Mu2e calorimeter system

Calorimeter Requirements

In order to add redundancy to the muon to electron conversion search, the calorimeter has to add complementarity qualities to the tracker system:

- Large acceptance for μ → e events
- Particle Identification capabilities
- "seeds" to improve track finding at high occupancy
- A tracking independent trigger



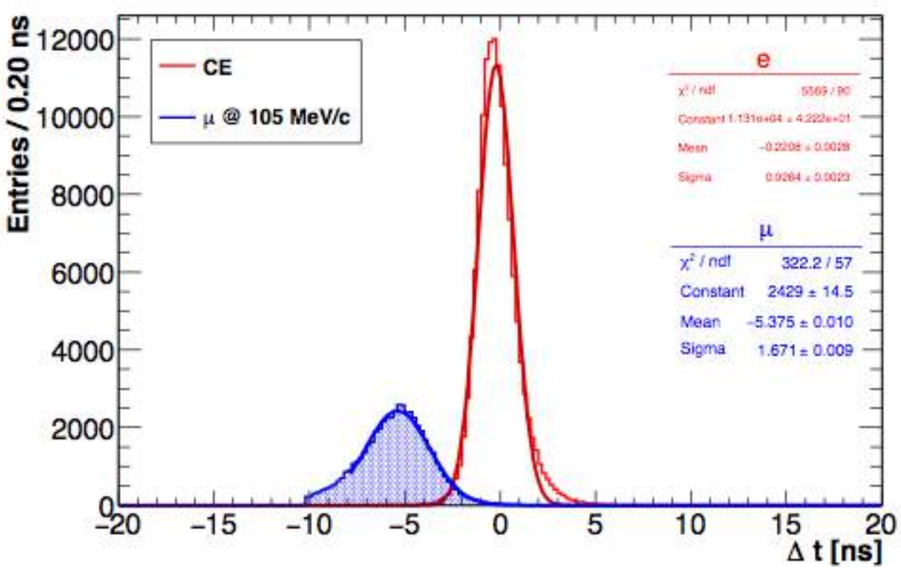
- + of course .. resistant to radiation and working in vacuum @ 10^{-4} Torr

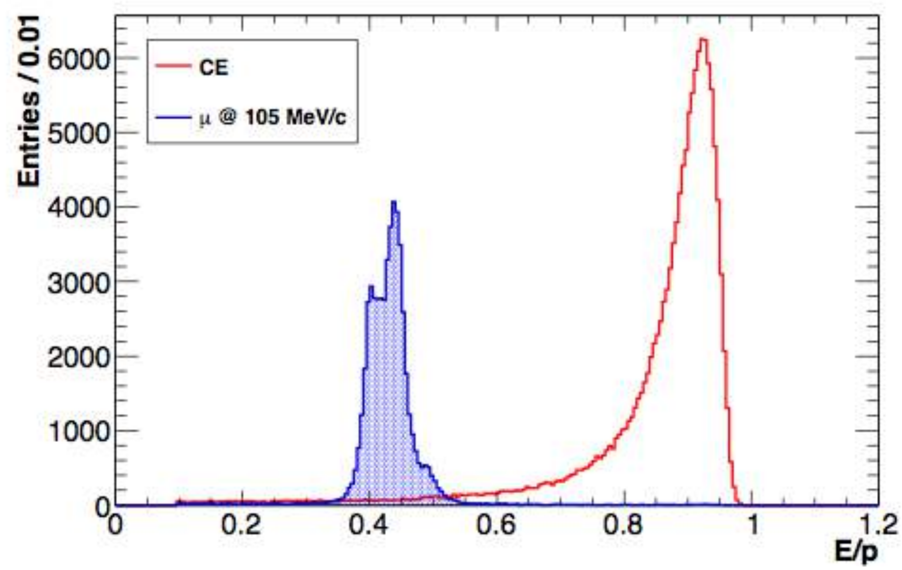
PID calorimeter-tracker – basic idea

$$\beta = \frac{p}{E} \sim 0.7, \;\; E_{kin} = E - m \sim 40\ \mathrm{MeV}$$

Compare the reconstructed track and calorimeter information:

- $E_{cluster}/p_{track}$ & $\Delta t = t_{track} - t_{cluster}$,
- Build a likelihood for e- and mu- using distribution on E/p and Δt

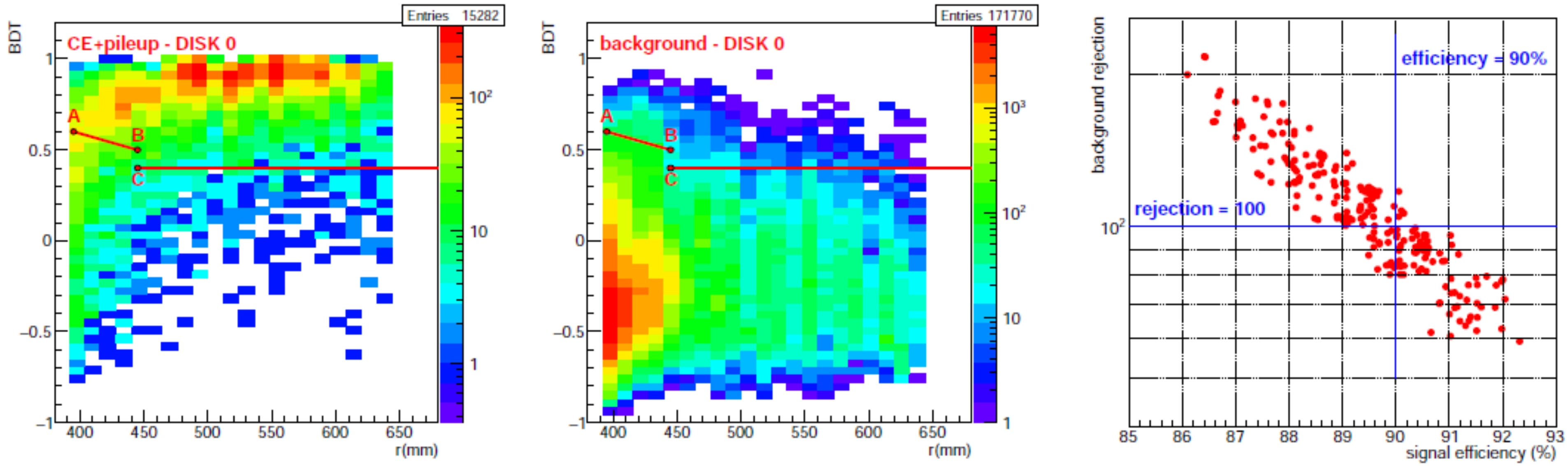




Get very high efficiency (> 95%) with Rejection factor > 200

→ Needs energy res 5-10 % and timing < 500 ps.

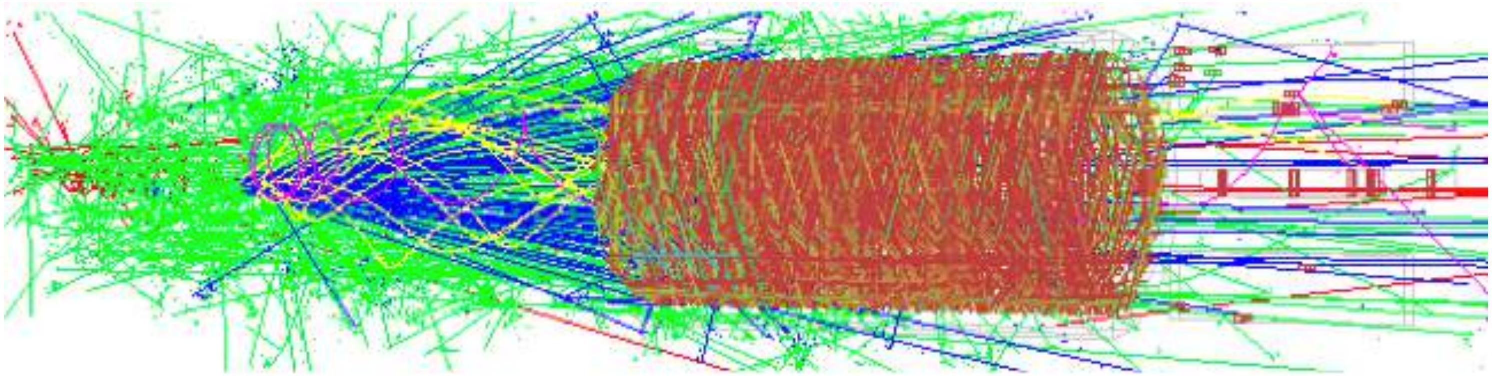
Calorimeter-based Trigger



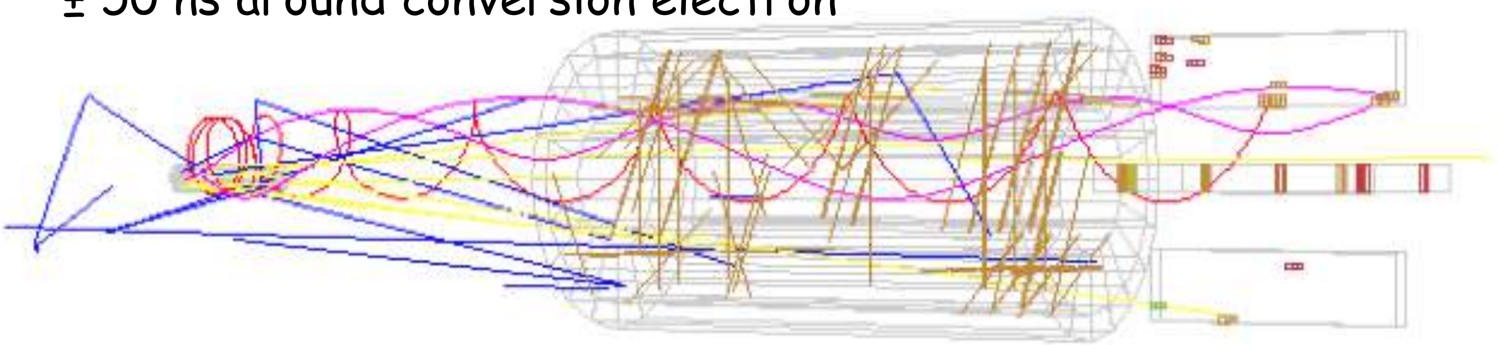
- acceptance: > 90% of events with good tracks have a cluster E > 60 MeV
- **standalone calorimeter-based Online Trigger needed**
  - Tracker momentum calibration (i.e., $\pi^+ \rightarrow e\nu$)
  - Measurement of tracking efficiency
  - DAQ storage limitations → 100 times reduction of background events
  - Fast algorithm

EMC based track seeding

500 – 1695 ns window



± 50 ns around conversion electron



The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters → simplification of the pattern recognition.

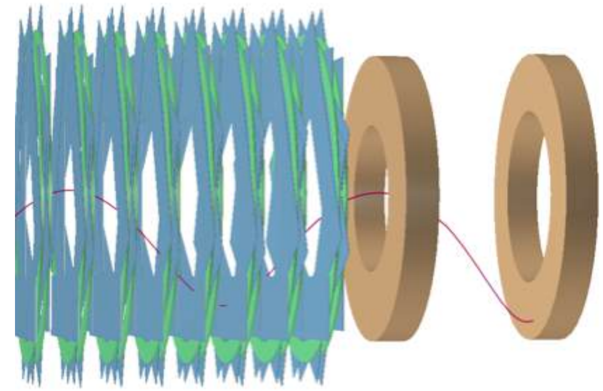
Calorimeter Requirements

- Provide high e^- reconstruction efficiency for μ rejection of 200
- Provide online trigger capability (HLT)
- Provide cluster-based seeding for track finding

In order to do so the calorimeter should:

→ Have high acceptance and efficiency for 105 MeV electrons
→ Provide energy resolution σ_E/E of O(5 %)
→ Provide timing resolution $\sigma(t) < 500$ ps
→ Provide position resolution < 1 cm
→ Work in vacuum
→ Survive the harsh radiation environment
→ Allow to work without interruption for 1 year in the DS

Derived technical requirements



- 2 Disks (Annuli) geometry
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 20 pe/MeV**
- **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → **1 million hours/SIPM**
- Fast signal for Pileup and Timing → **τ of emission < 40 ns + Fast preamps**
- **Fast Digitization (WD) to disentangle signals in pileup**
- Calorimeter should work in 1 T B-field and in vacuum of 10^{-4} Torr and:
  → **Crystals should survive a dose of 90 krad and a neutron fluence of 3×10^{12} n/cm^2**
  → **Photo-sensors should survive 45 krad a neutron fluence of 1.2×10^{12} n_1MeV/cm^2**

Safety Factor = 3
5 years of run

- **DOSE on FEE/WD up to 90 krad**

Safety Factor = 12
5 years of run

Crystal Choice

	~~LYSO~~	~~BaF_2~~	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310

LYSO
CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF_2)
BASELINE-TDR

- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be "solar"-blind
- Medium cost 10$/cc

CsI(pure)
FINAL CHOICE

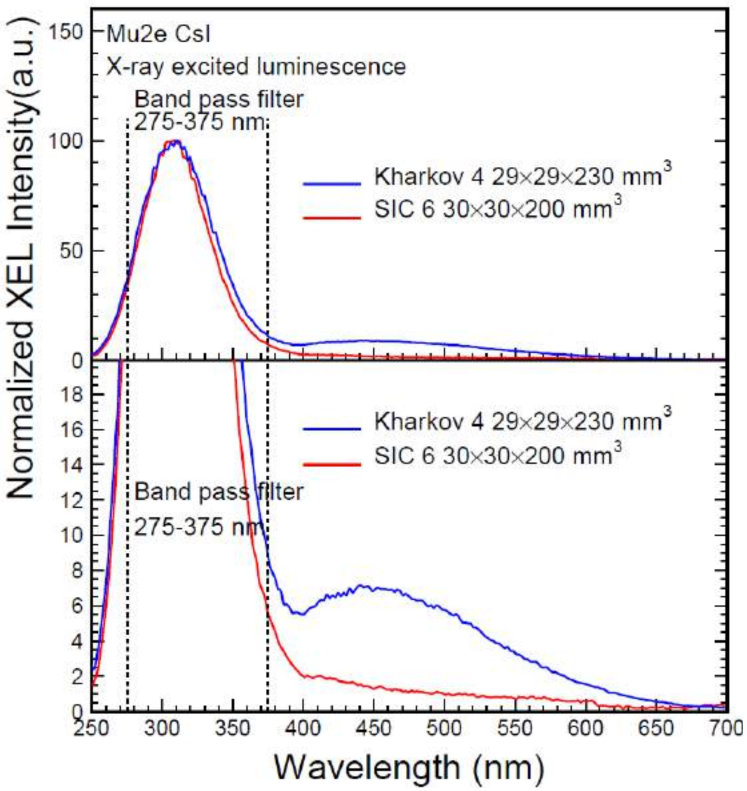
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

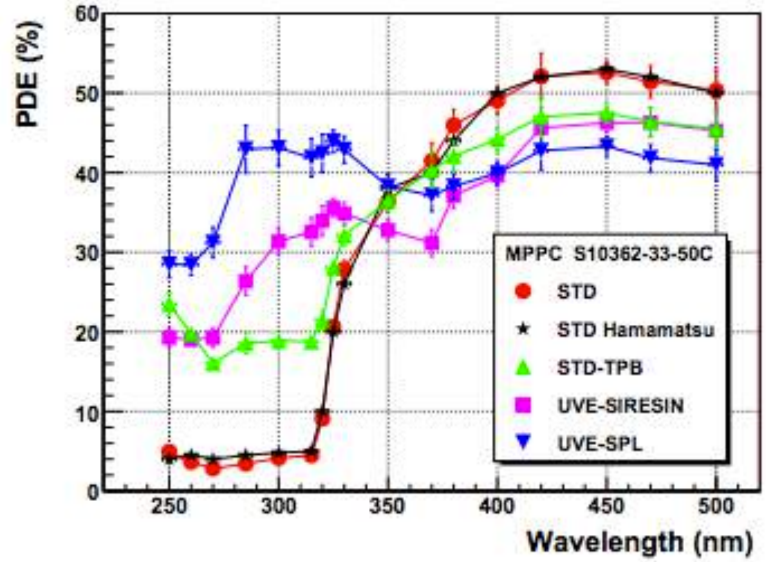
UV extended SiPM

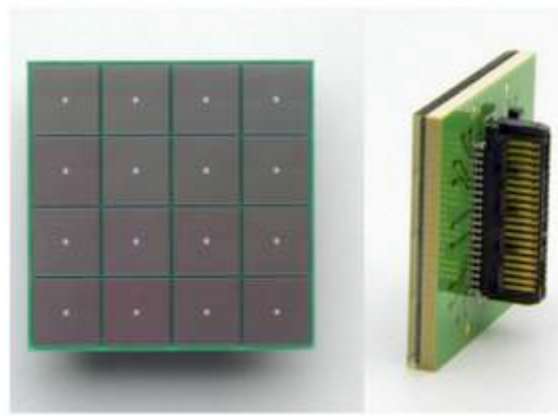
The PDE of UV-enhanced MPPC is higher below 350 nm

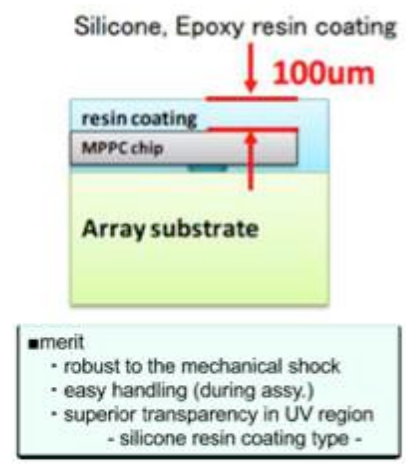
Imaging with SiPMs in noble-gas detectors: arXiv 1210.4746

- → **30-40% @ 310 nm (CsI pure wavelength)**
- → **New silicon resin window**
- → **TSV readout, Gain = 10^6**







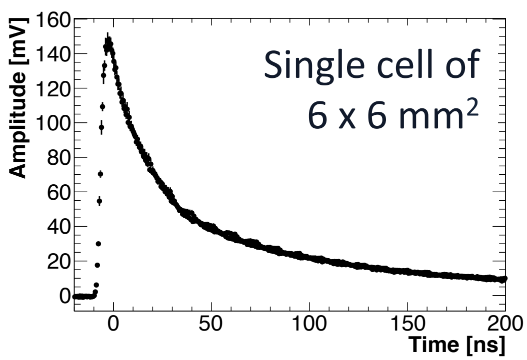


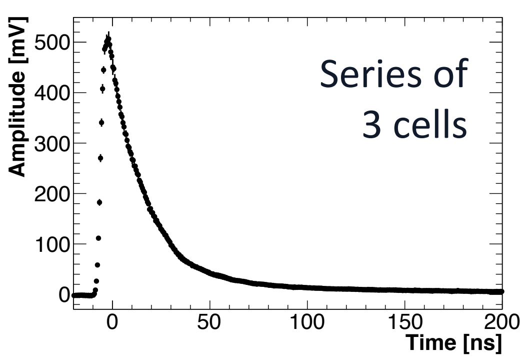
Mu2e custom SiPMs design

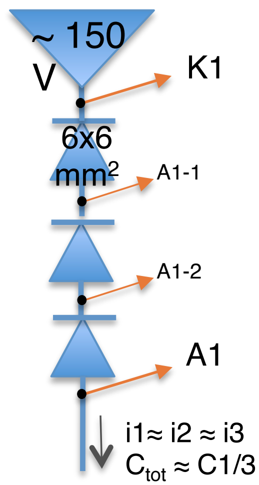
Mu2e custom silicon photosensors:

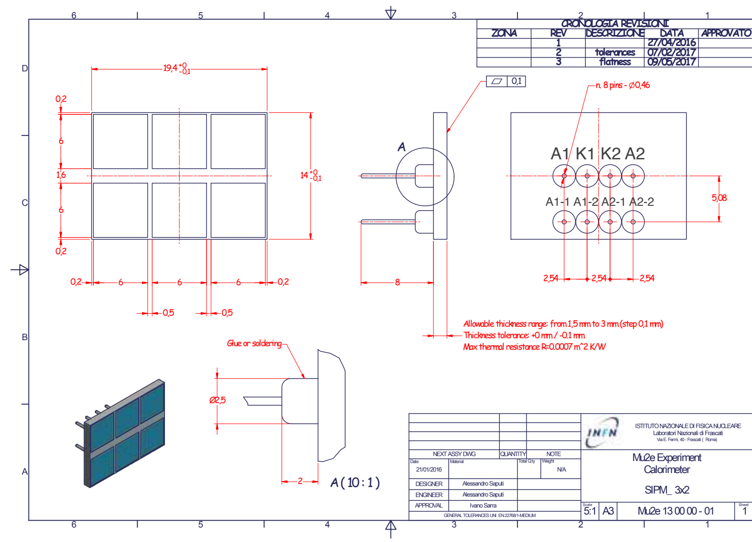
→ **2 arrays of 3 6 x 6 mm² UV-extended SiPMs for a total active area (12x18) mm²**

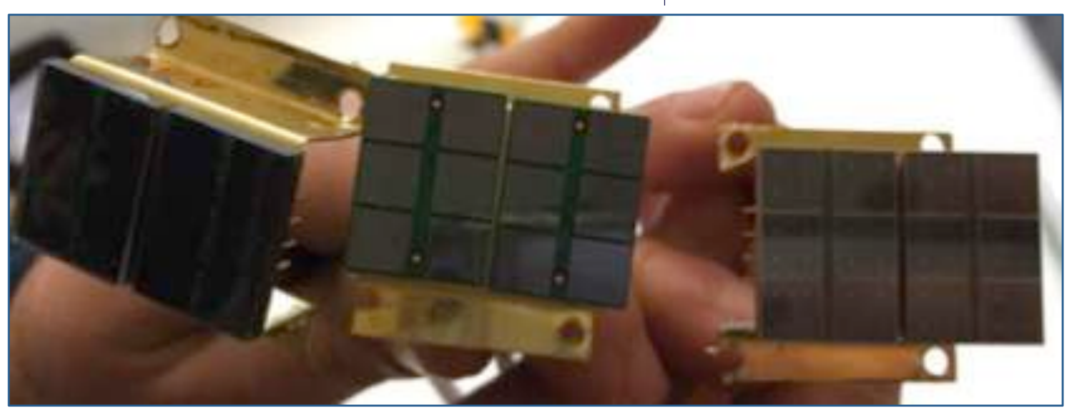
The series configuration reduces the overall capacity and allows to generate narrower signals





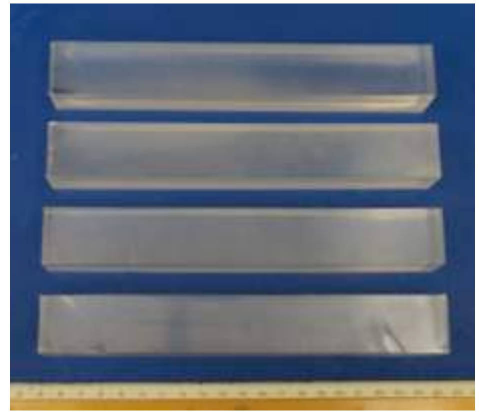


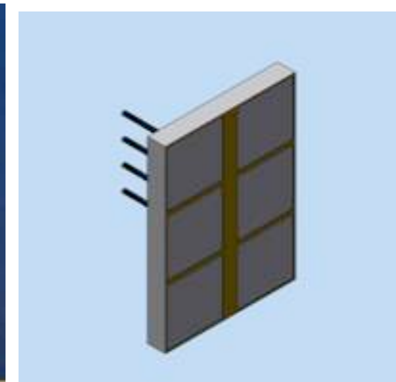




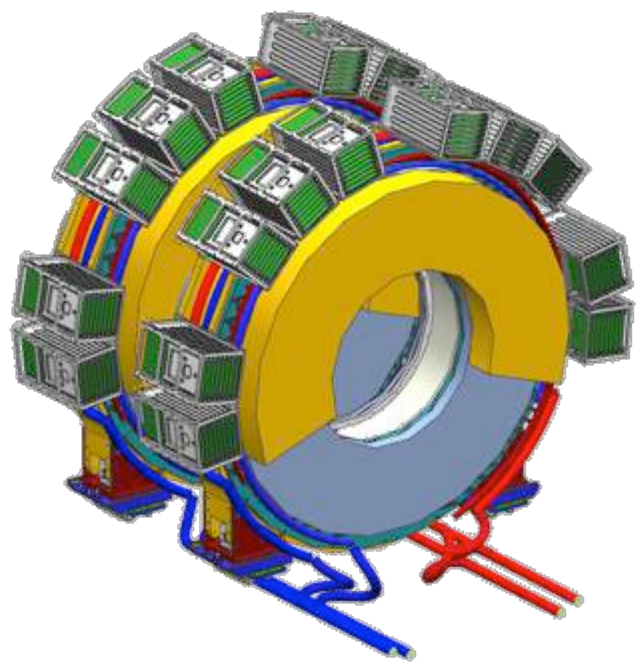
Mu2e Calorimeter Design

The Mu2e Calorimeter consists of two disks with 674 un-doped CsI 34x34x200 mm^3 square crystals:



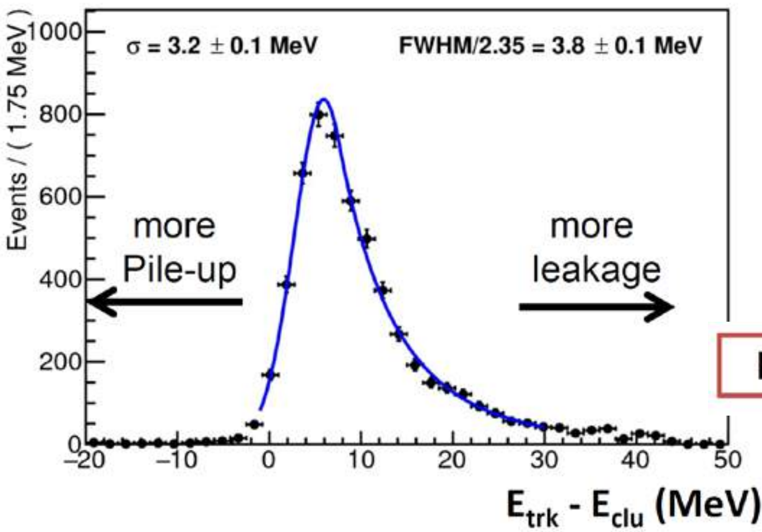


- Each crystal is readout by two large area UV extended Mu2e SiPM's (14x20 mm^2)
- Analog FEE is on the SiPM and digital electronics is located in near-by electronics crates
- Radioactive source and laser system provide absolute calibration and monitoring capability

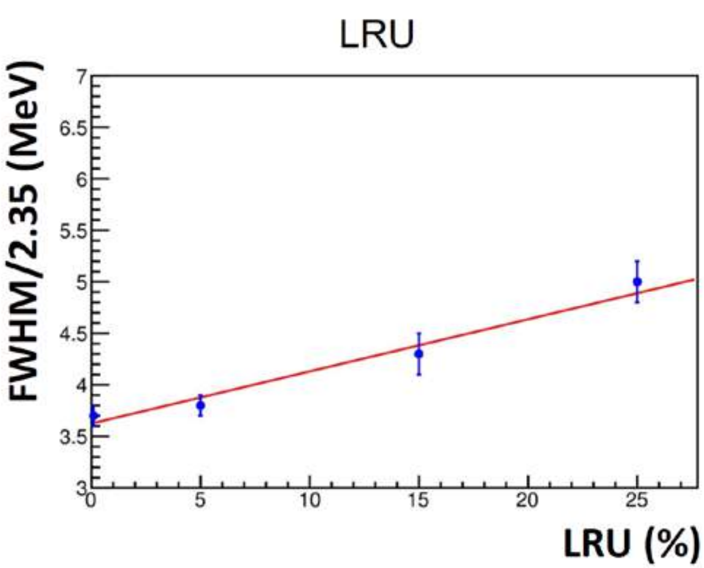


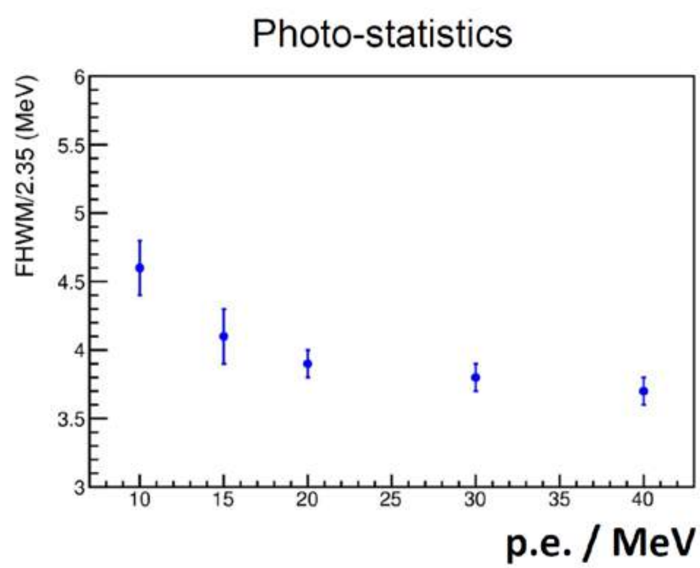
Simulated performances

Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery



FWHM / 2.35 = 3.8 ± 0.1 MeV

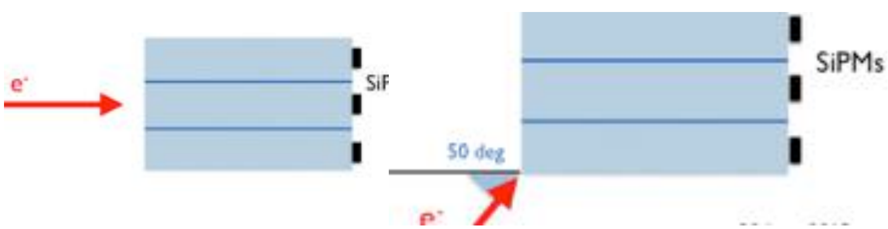


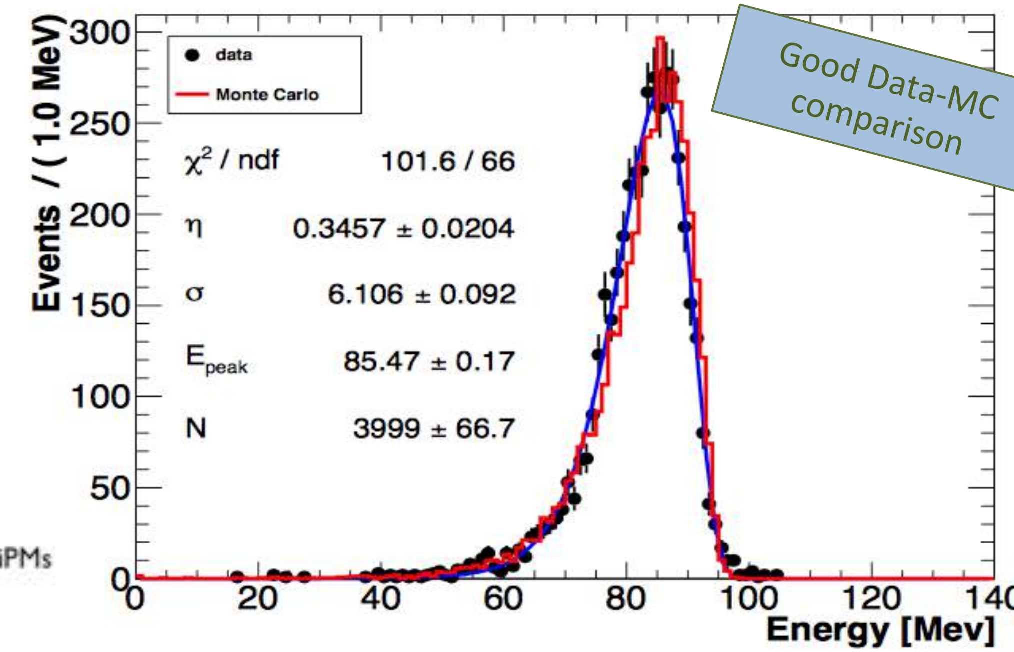


Small size prototype (1)

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of 30×30×200 mm^2 undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm^2 with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

JINST 12 (2017) P05007

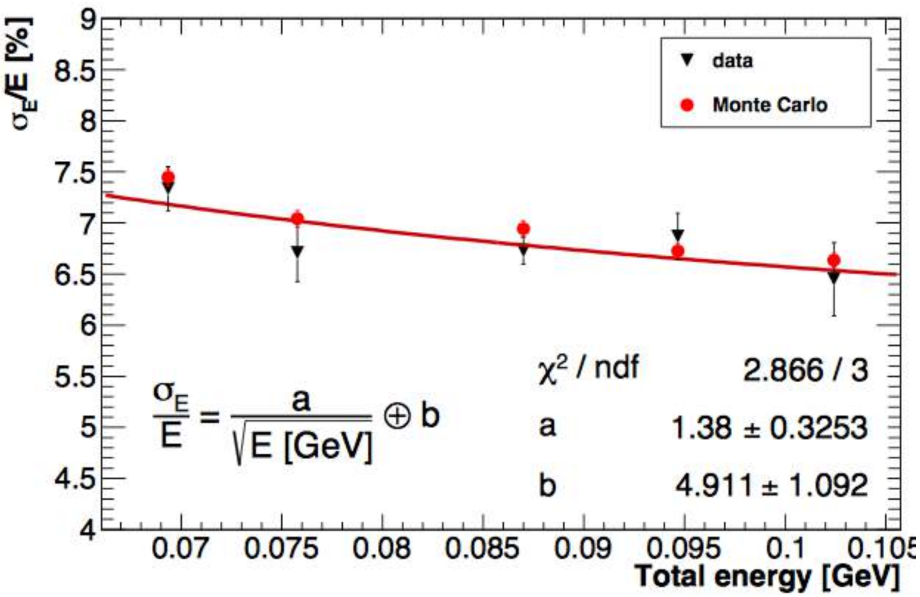


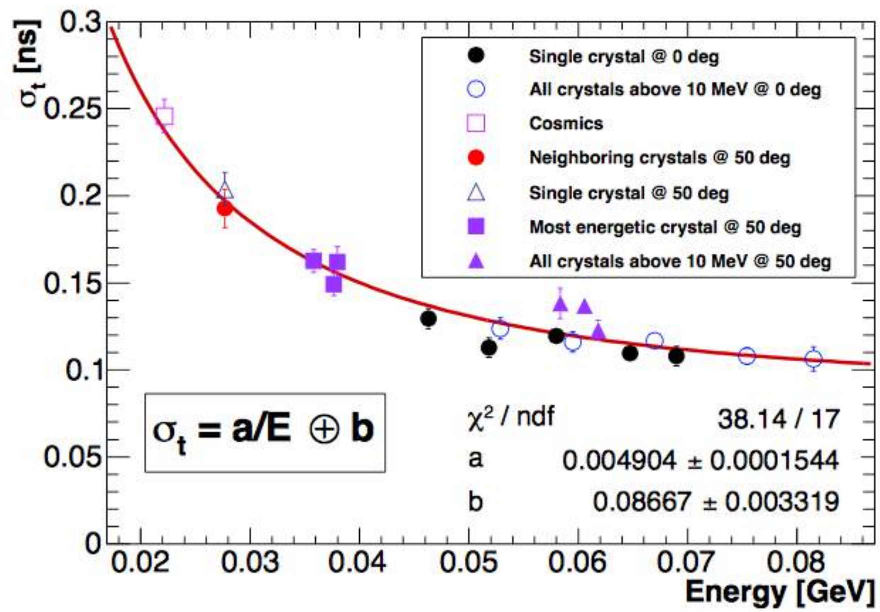


Good Data-MC comparison

Small Size prototype (2)

JINST 12 (2017) P05007





σ_E ~ 6.5% at 100 MeV **σ_T ~ 110 ps at 100 MeV**

Significant leakage contribution due to the matrix dimensions

1 year long R&D phase for the final test of the option CsI + UV extended SiPM

PRE-PRODUCTION

72 crystals + 150 SiPM + 150 FEE chips completed in 2016

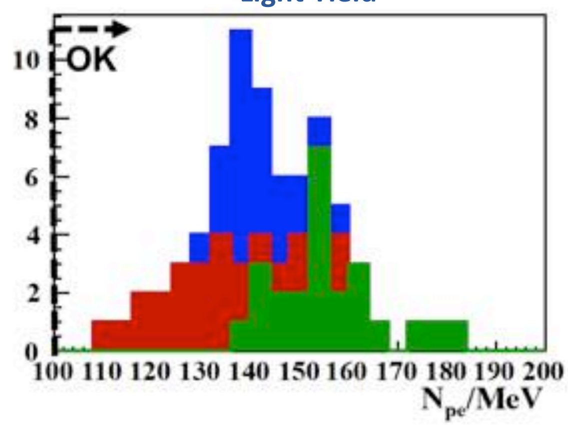
Crystals pre-production

- 24 crystals from three different vendors: **SICCAS**, **Amcrys**, **Saint Gobain**
- Optical properties tested with 511 keV γ's along the crystal axis
- Crystals wrapped with 150 μm of Tyvek and coupled to an UV-extended PMT

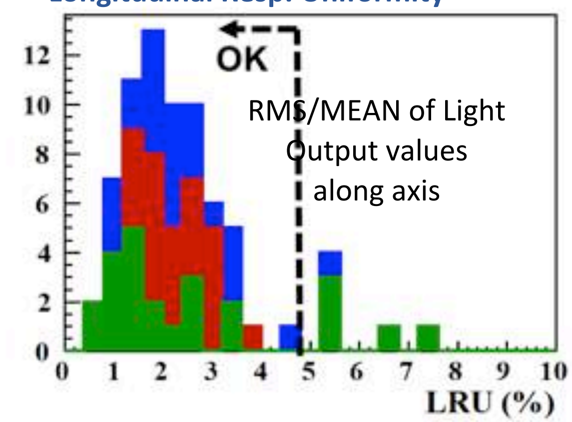
Un-doped CsI crystals perform well

- ❑ **Excellent LRU and LY:**
  - -100 pe/MeV with PMT readout
  - - LRU < 5%
- ❑ τ of 30 ns with small slow component
- ❑ **Radiation hardness OK for Mu2e**
  Smaller than 40% LY loss
  @ 100 krad
- ❑ Small Radiation Induced Noise (Phosphorescence)

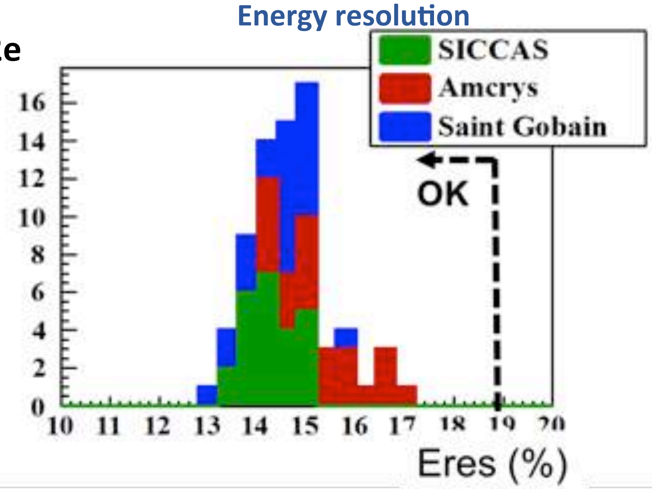
Light Yield



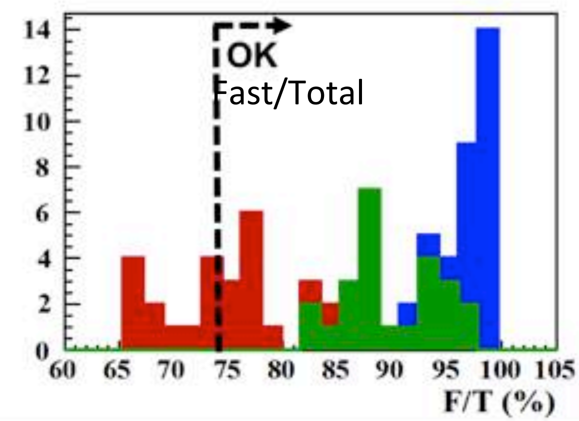
Longitudinal Resp. Uniformity



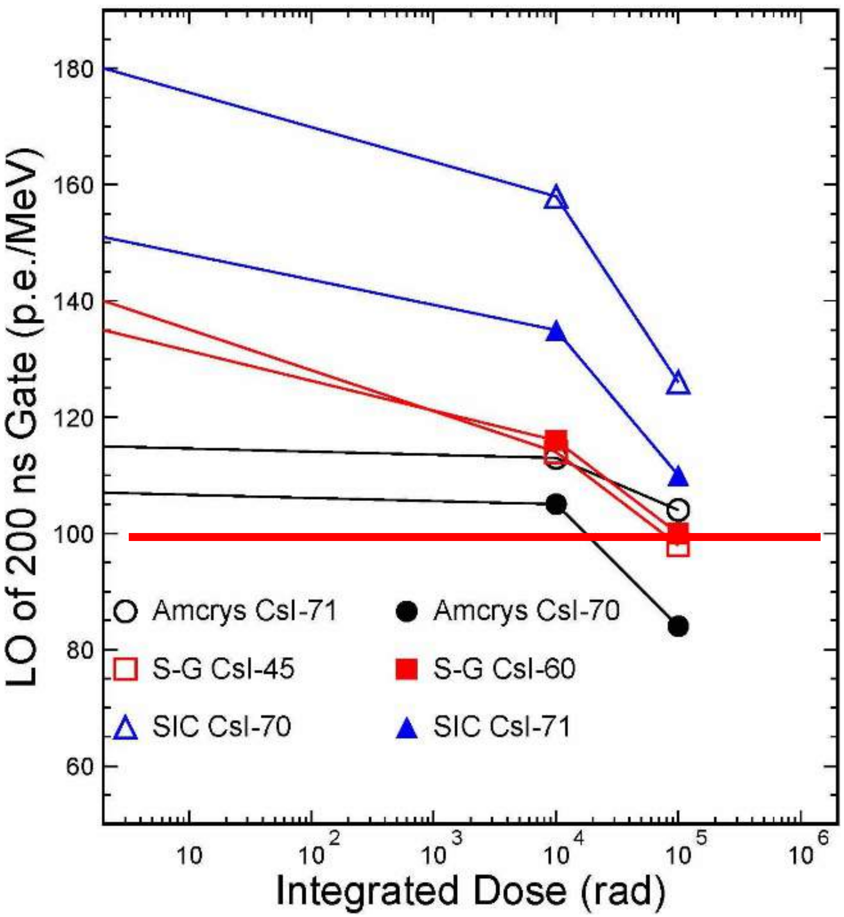
Energy resolution

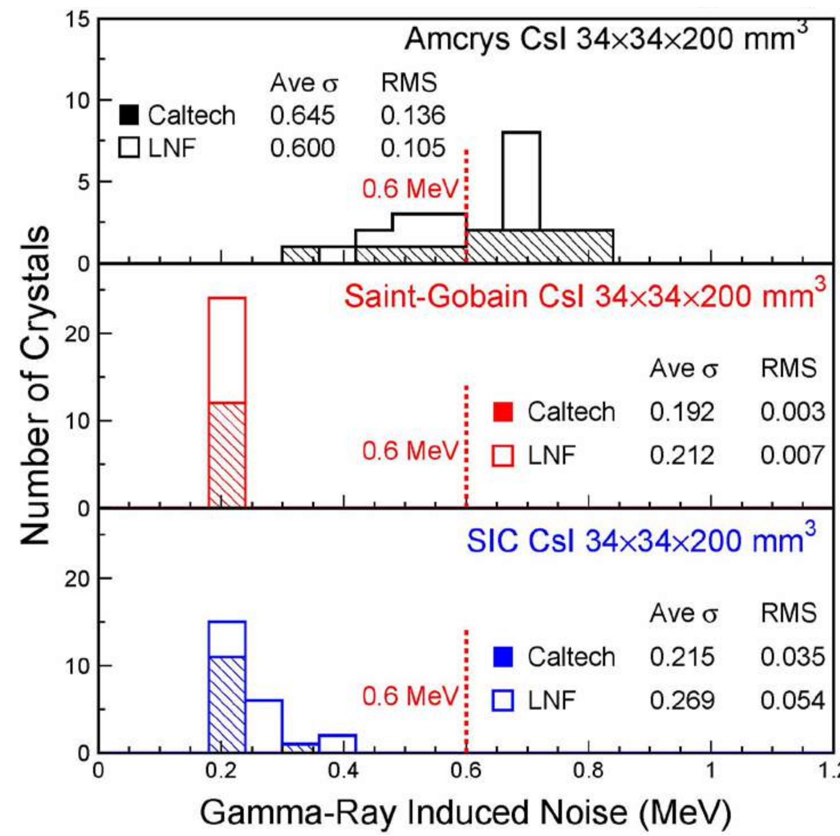


Q(200 ns)/Q(3000 ns)



Radiation hardness: dose & neutrons



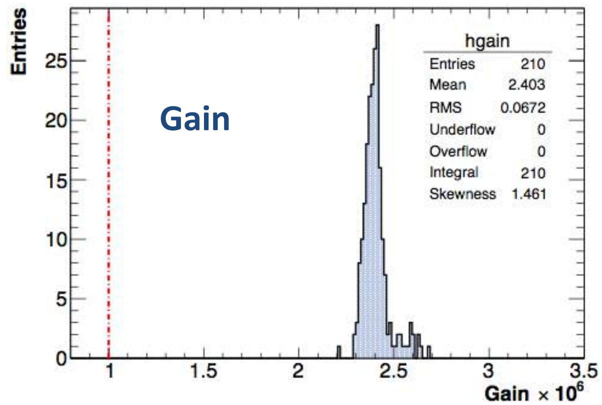


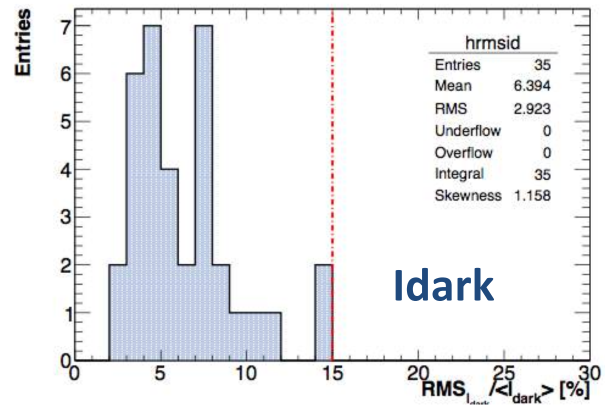
- CsI crystals rad-hard for expected dose in Mu2e-I
- No recovery after annealing
- RIN is larger for ionizing dose than for neutrons

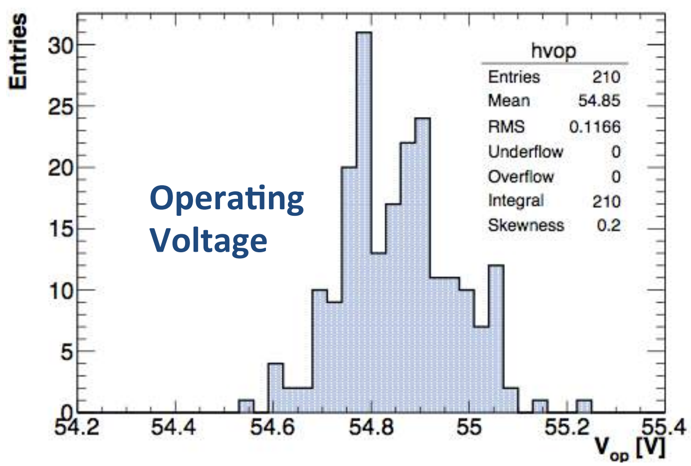
Pre-production of SiPMs

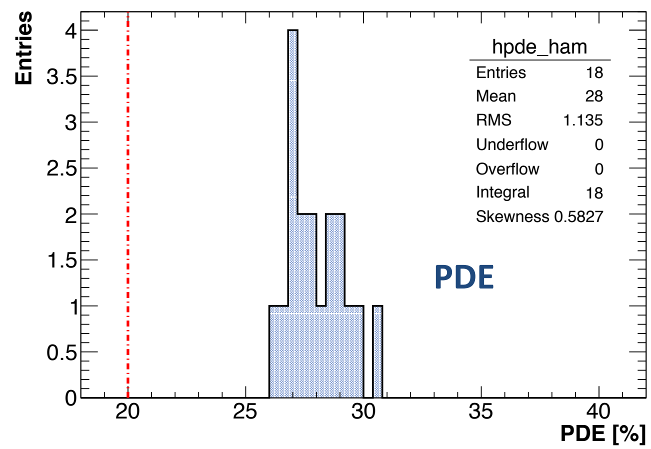
150 Pre-production photo-sensors:

- 3×50 Mu2e pre-production SiPMs from Hamamatsu, SenSl and AdvanSiD
- 3×35 were fully characterized for all six cells in the array



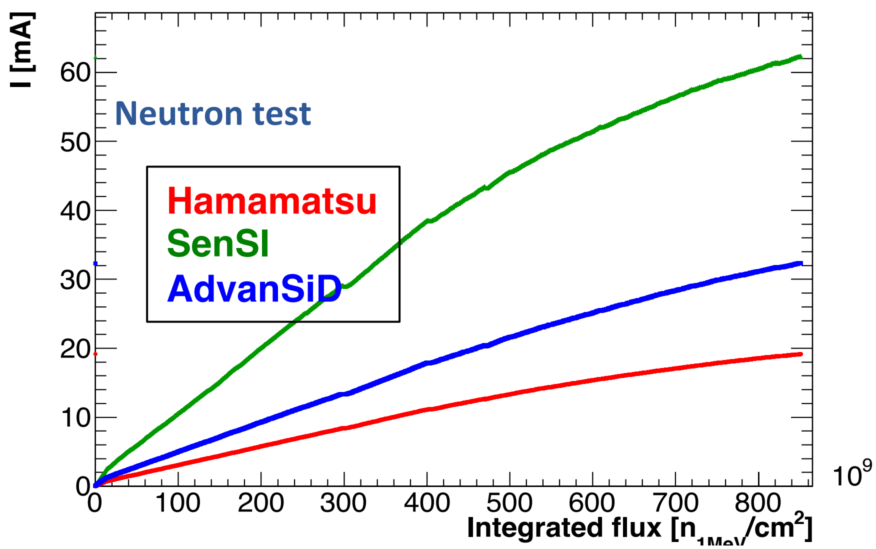


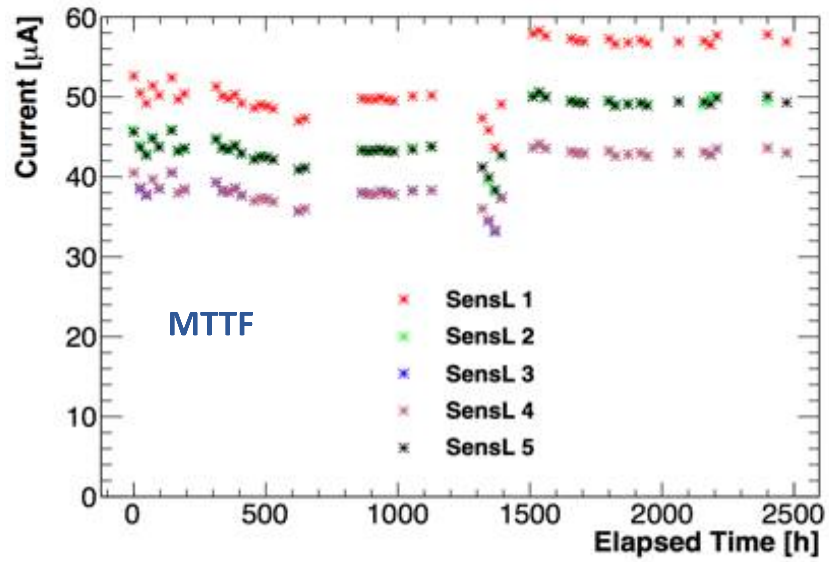




Irradiation and MTTF of SiPMs

- ✓ 1 sample/vendor have been exposed to neutron flux up to 8.5×10^{11} n_{1MeVeq}/cm^2 (@ 20˚C)
- ✓ 5 samples per vendor have been used to estimate the mean time to failure value
  Requirement: grant an MTTF of 1 million hours when operating at 0 °C





In Mu2e SiPMs will operate @ 0 ˚C

→ a decrease of 10 °C in SiPMs temperature corresponds to a I_d decrease of 50%
→ Lower V_{op} also helps to decrease I_d

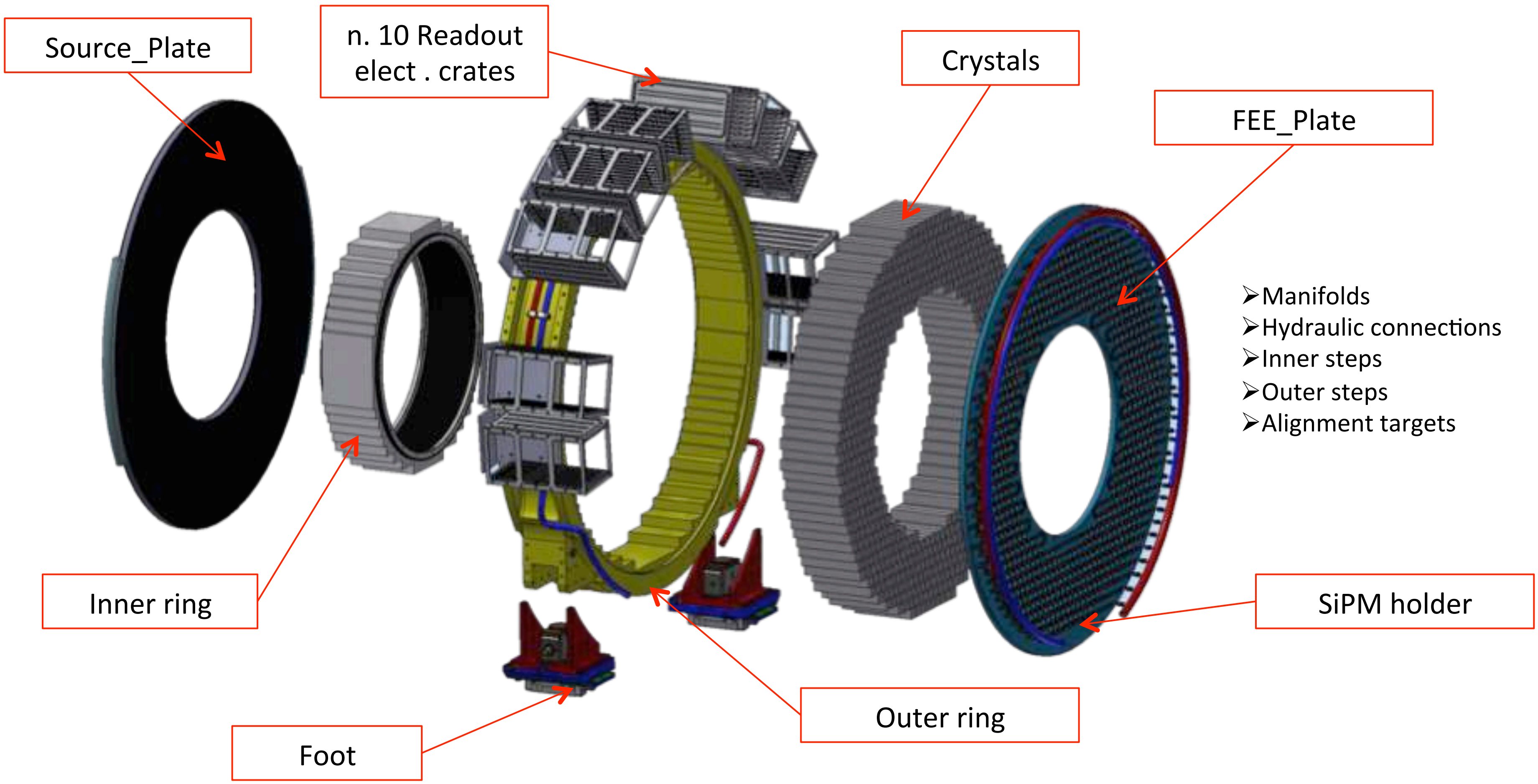
Thumb Rule: -1 V, 10% loss, -2V 40% loss

- MTTF evaluated operating SiPMs @ 50˚C for 3.5 months
- No dead channels observed

MTTF ≥ 6×10^5 hours

Engineering design

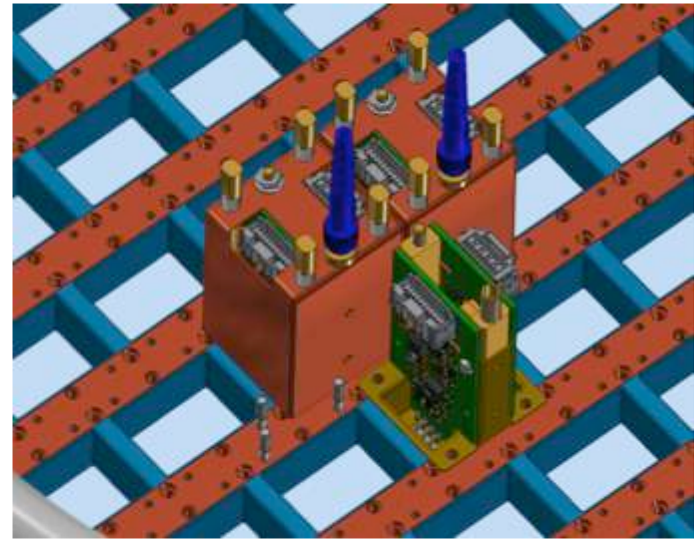
The calorimeter consists of two disks each one composed of:

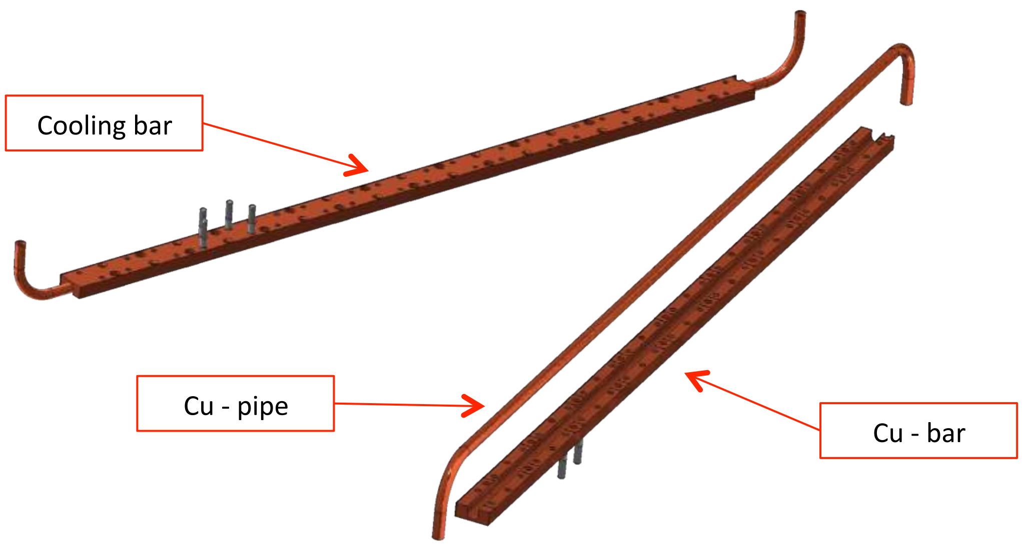


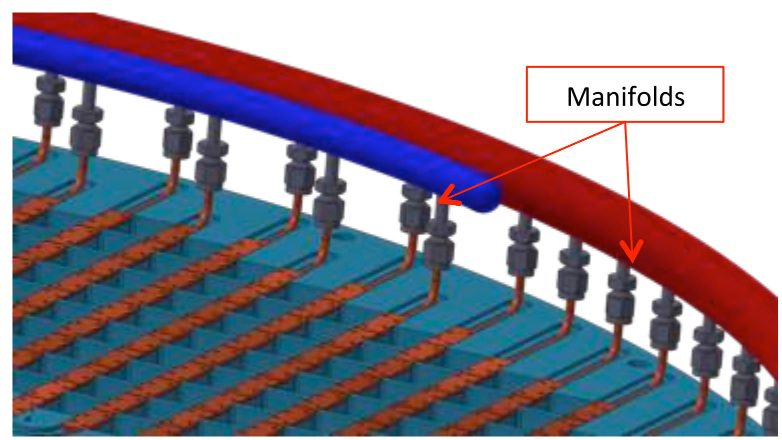
- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets

End-plate design and Cooling

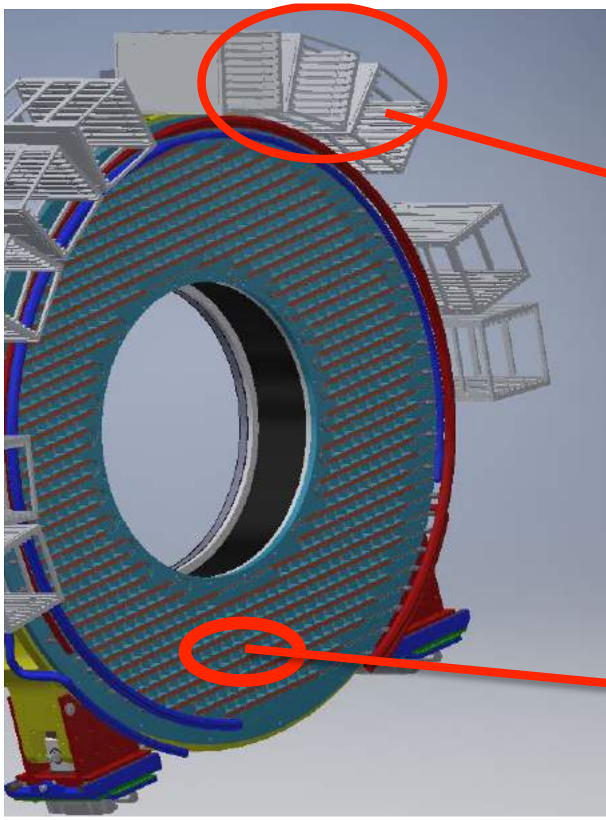
- The FEE plate houses the Front End electronics and photosensors holders and provides cooling.
- The coolant runs inside the cooling channels, at ~ -10°C.
- The manifolds are jointed to the cooling channels by means of tube fittings (Swagelok type).
- The SiPM holders are bolted to the cooling channels by means four stud screws. It is in thermal contact with the cooling channels.
- The plate is thermally isolated from the outer ring and from the crystals.
- Thermal simulation indicates SiPM to run at 2.7 °C

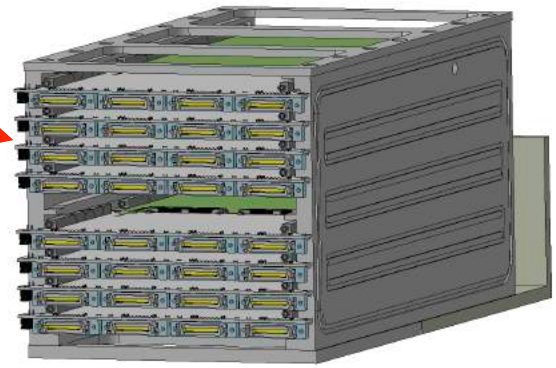


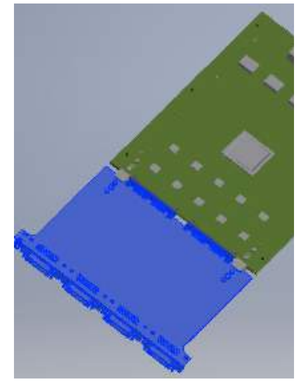




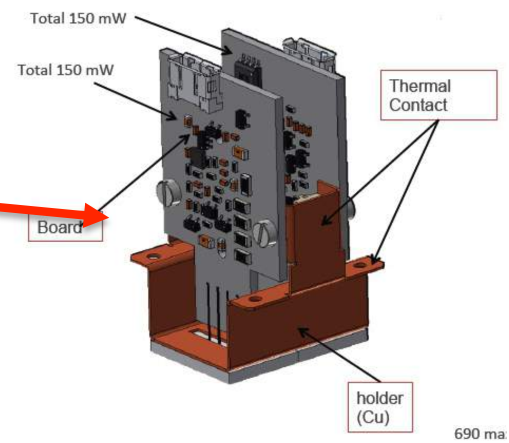
FEE and Digitization scheme

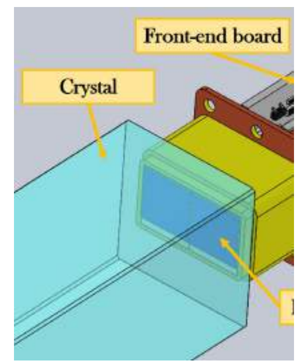






Front-end



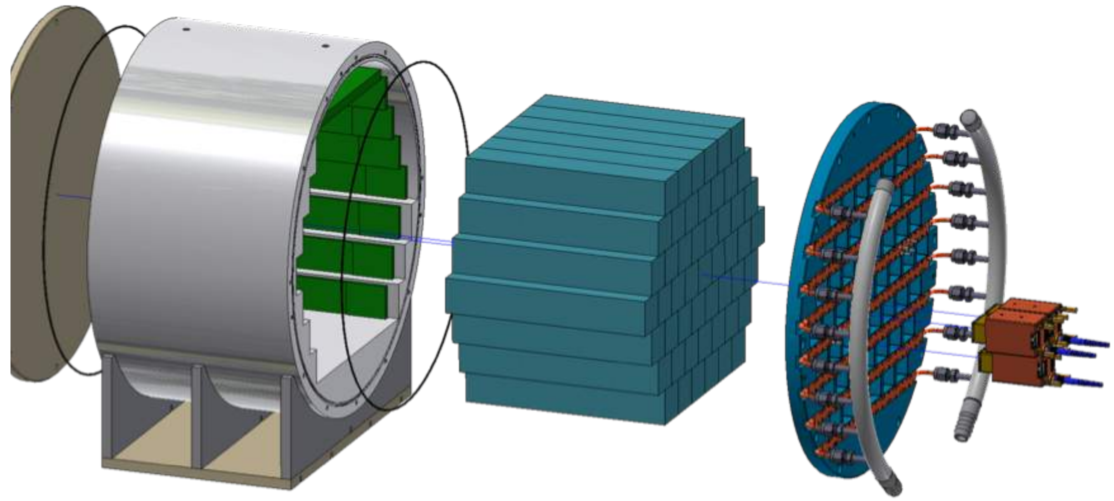


- ✓ 1 FEE chip (amplification and HV regulation) locally on the SiPM pins
- ✓ Completely independent Left/Right amplification, HV & readout for Left/Right SiPMs
- ✓ 8 (Digitizer+Mezzanine) boards in 10 crates. Each board is 20 ch format.
- ✓ Alternate Left and Right boards.
- ✓ Digitizer @ 200 Msps (5 ns binning), Mezzanine to set/read HV of each SiPM

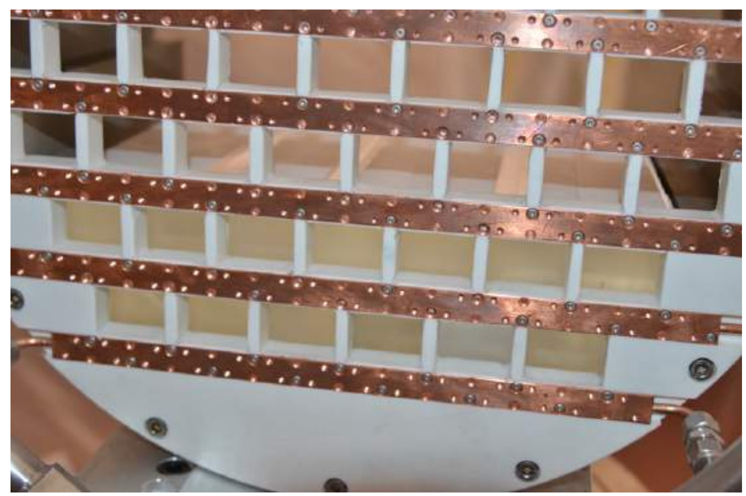
Module-0 preparation: Step-0

Large size prototype of
the disk assembled April 2017

- 51 crystals, 102 sensors,
- 102 FEE chips
- Cooling lines and readout.

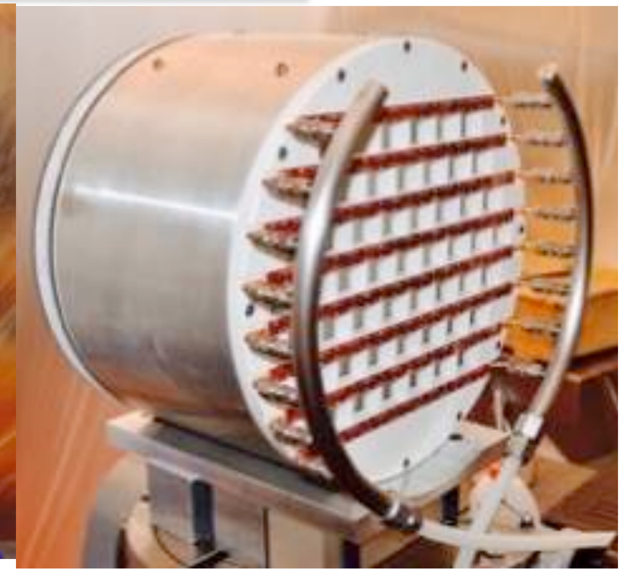


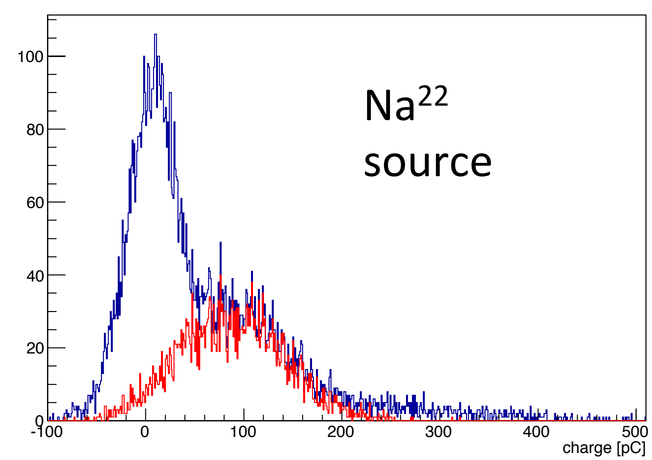
Assembly of back disk in ZEDEX on Al support disk



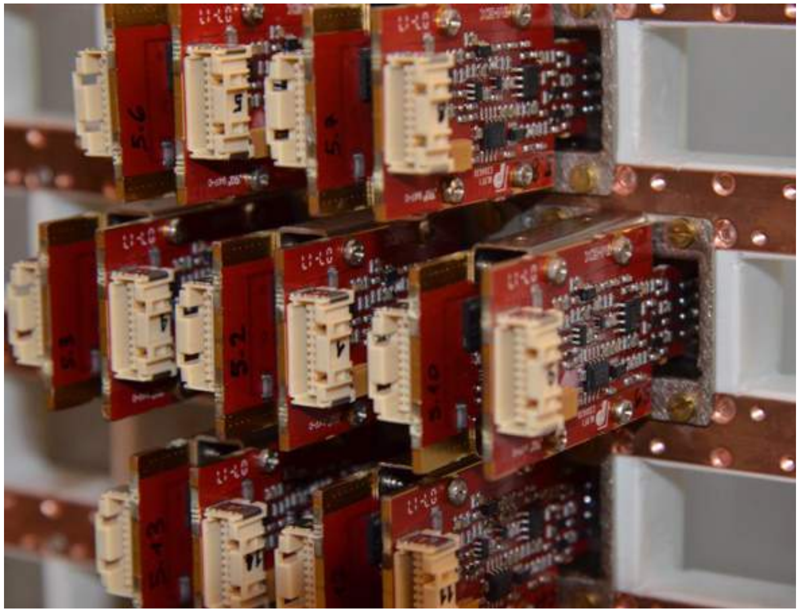
Module-0 preparation: step-1

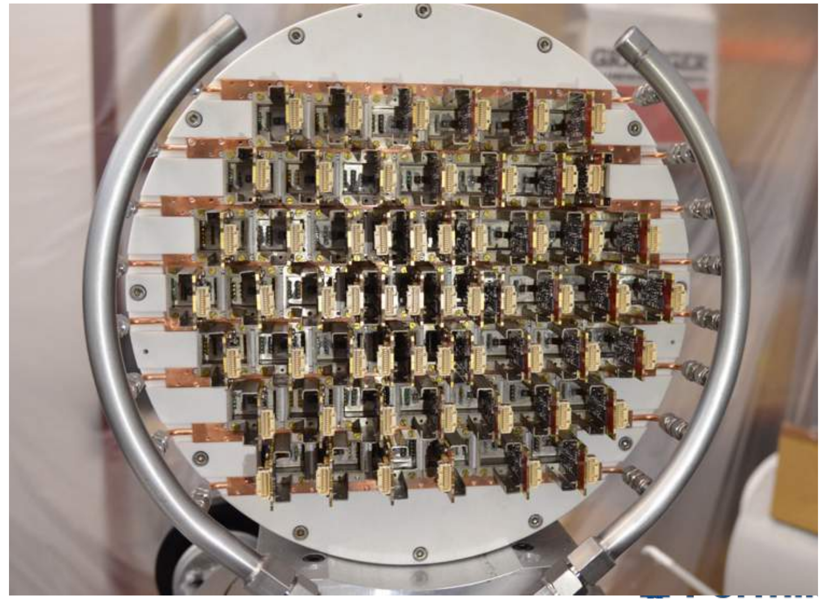
- Insertion of wrapped crystals
- Check of cooling lines
- Glueing of SiPMs on SiPM holdr
- Add FEE





Module-0 preparation: step-2



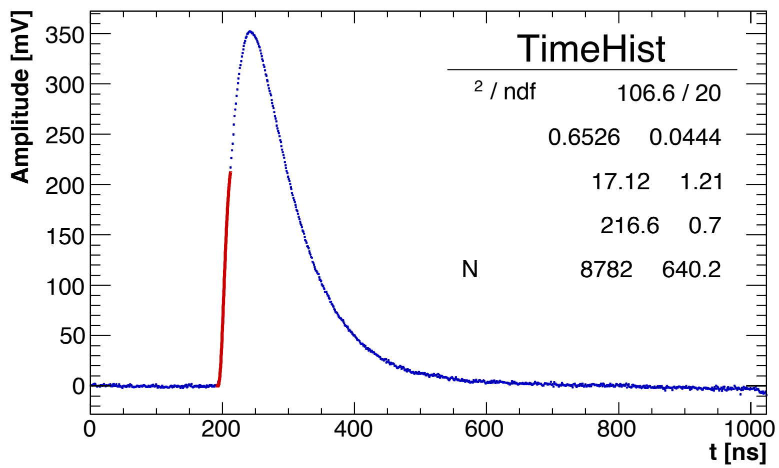


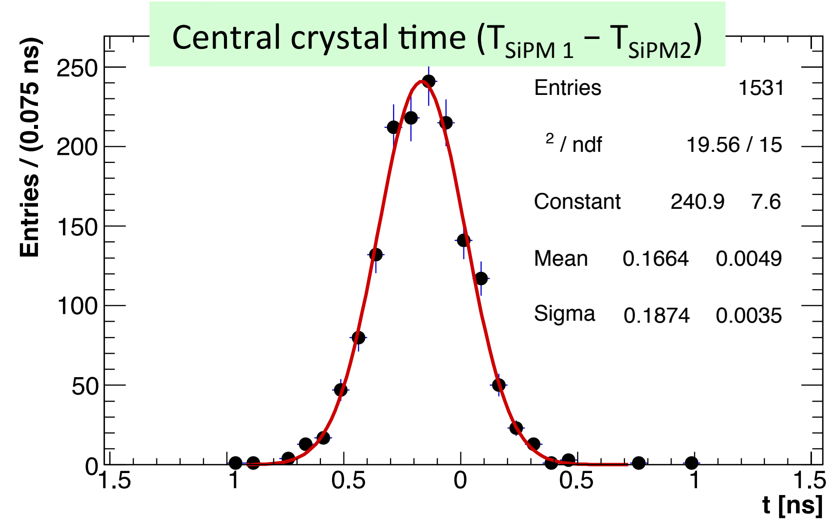
- Mount SiPM+FEE on back plate.
- Readout with 4 NIM Mboard 16 channel each
- Total readout of 58 channels.
  The 7 central crystals had two FEE chips (and cable)/Holder
- Final readout via 2 CAEN WD (DRS4) chips, 32 channels, 1 Gsps

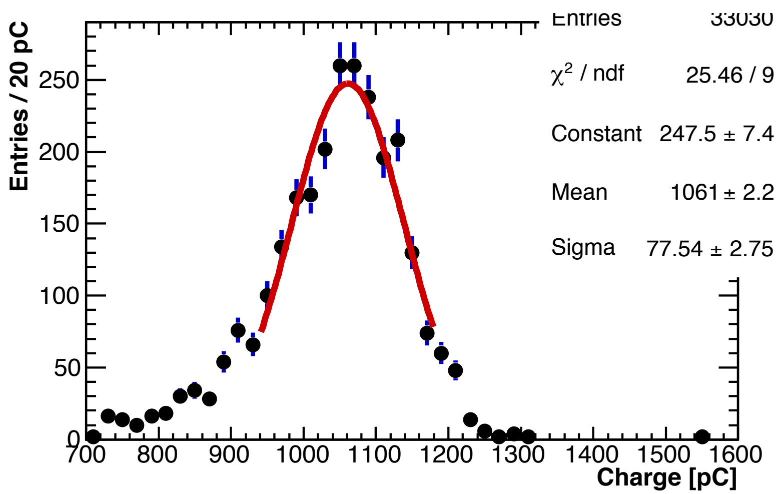
Test Beam of Module-0

Module- 0 has been transported to the area for an electron beam test @ LNF.
16 people (INFN, Caltech, JINR) worked on this test beam **May 8-15 2017**

Test Beam preliminary results







$\sigma_{(T1+T2)/2}$ ~ 94 ps
@ E_{beam} = 100 MeV

- Log-normal fit on leading edge, Constant Fraction method used (CF = 5%)
- Calibration completed for first ring around central crystal
- Noise in Test beam too high to extend clustering after first ring
- Data quality allowed to extract preliminary resolution in agreement with small size prototype

σ_E ~ 7.3% within 1° ring
@ E_{beam} = 100 MeV

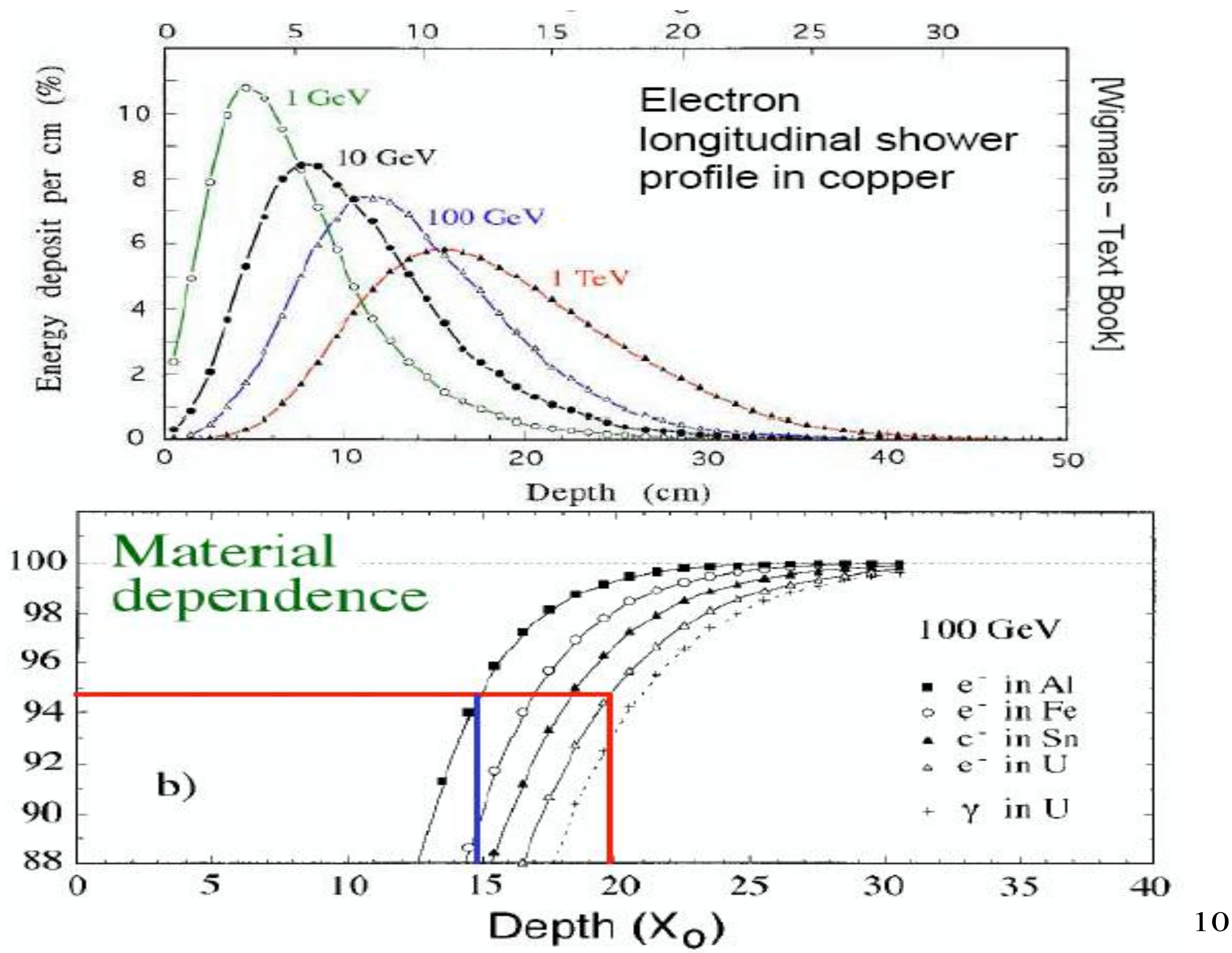
Conclusions

- Yes .. I tried to convince you that in an experiment it is very useful to have a calorimeter!!
- Mu2e calorimeter is a state of the art Crystal Calorimeter with excellent energy (5 %) and timing (< 50 ps) resolution and great pileup solving capability.
- **The most demanding request is to do all of the above in presence of 1 T field, under vacuum and in a radiation harsh environment.**

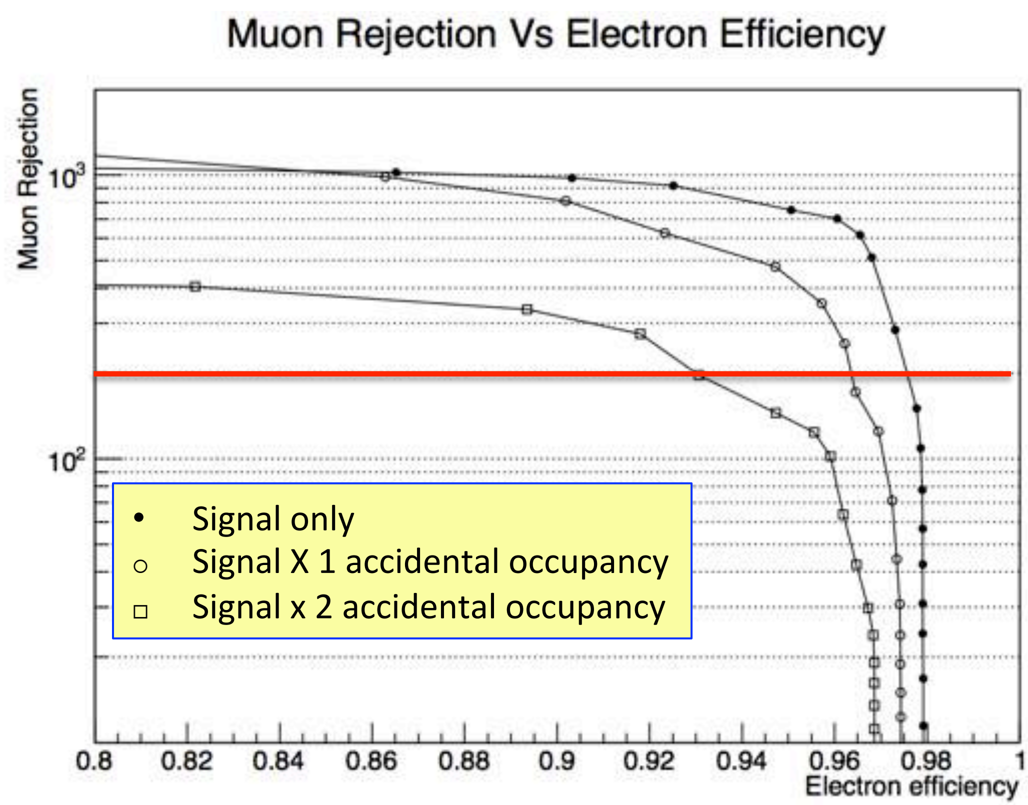
  → Engineering of cooling and calorimeter mechanics is crucial
  → SiPM will work under neutron irradiation only if cooled down to 0 C
- **FEE and Digitizer have also a very demanding engineering**
- Pre-production of crystals and SiPM done → production under way
- **Module-0 has been built → Full Size Mockup underway**
- **Schedule is to start assembly first real disk in fall 2018.**

ADDITIONAL MATERIAL

Longitudinal development



Performance: PID (muon vs electrons)

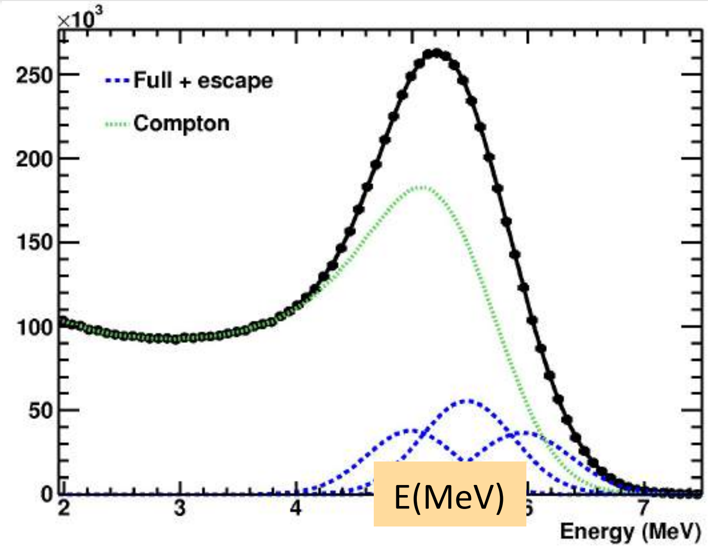


- ❑ Full simulation with pileup background included.
- ❑ Pre-selection based on track to cluster matching (space & time).
- ❑ PID is based on LogLikelihood with E/P and ΔT

✓ For a muon rejection of 200 → **Electron ID efficiency is 98%**
✓ Adding pre-selection cuts → **Total PID efficiency is > 93% with twice the exp. background**

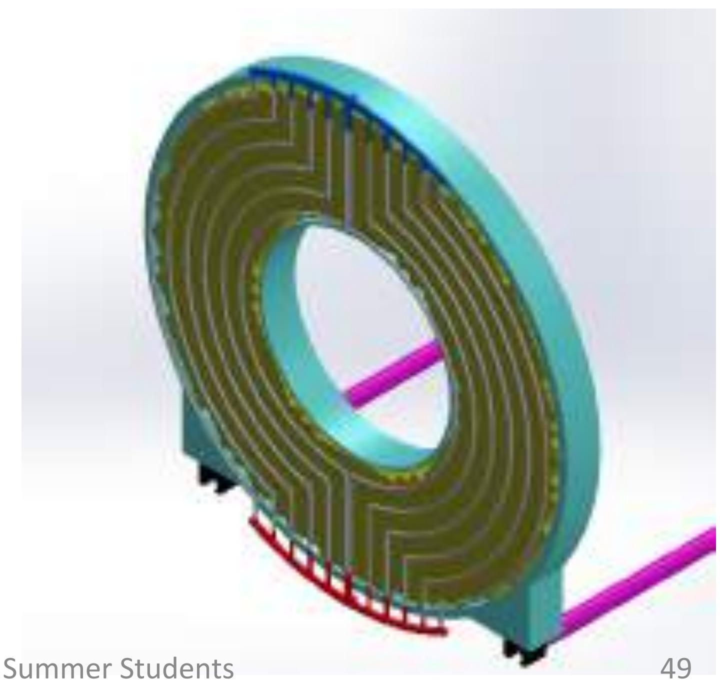
Calibration and monitoring system (1)

- Neutrons from a DT generator adjacent to the Detector irradiate a fluorine rich fluid (Fluorinert).
- The activated liquid is piped to the front face of the disks.
- Few per mil energy scale in a few minutes.
- Final experiment scale (E/P) is set using DIO's.



Based on BABAR scheme & salvage of their components

→ Salvage of BABAR DT generator done @ Caltech
→ Integration of pump, mechanics and controls done
→ **First tests done in summer 2015**



Calibration and monitoring system (2)

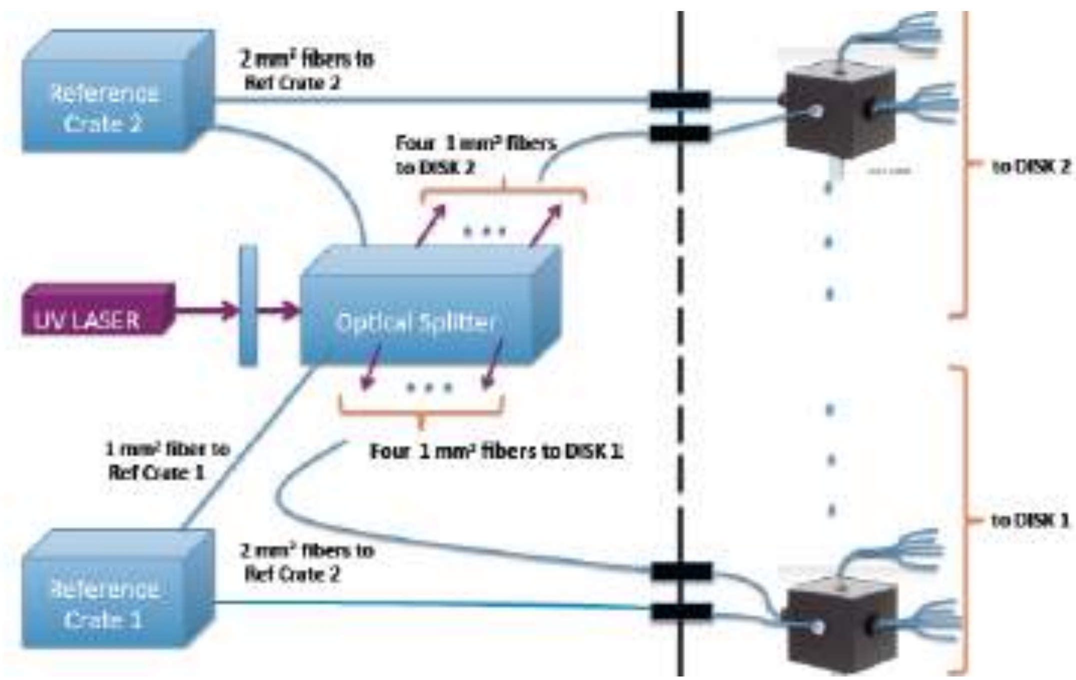
Laser system adapted from CMS calibration system.
UV light to monitor continuously the variation of the APD gain and as the first tool for calibrating the timing offsets

→ Green laser prototype used for LYSO test.

→ Distribution system with Silica optical fibers developed

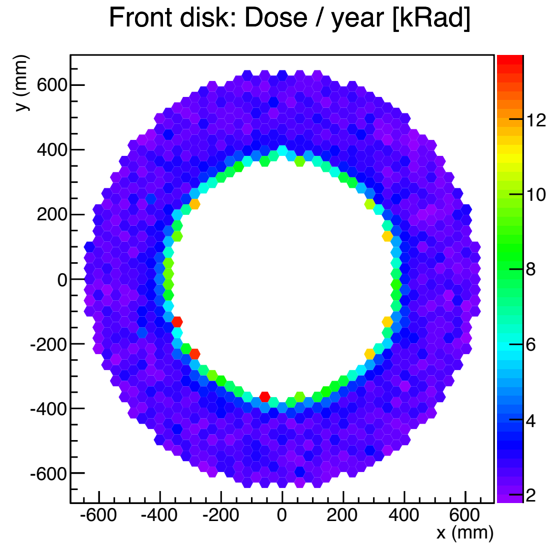
→ Successful

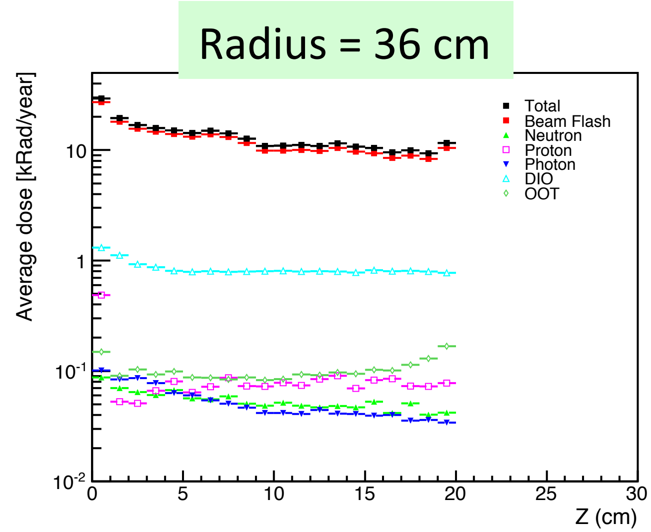
→ **UV laser and monitoring system still to be optimized.**

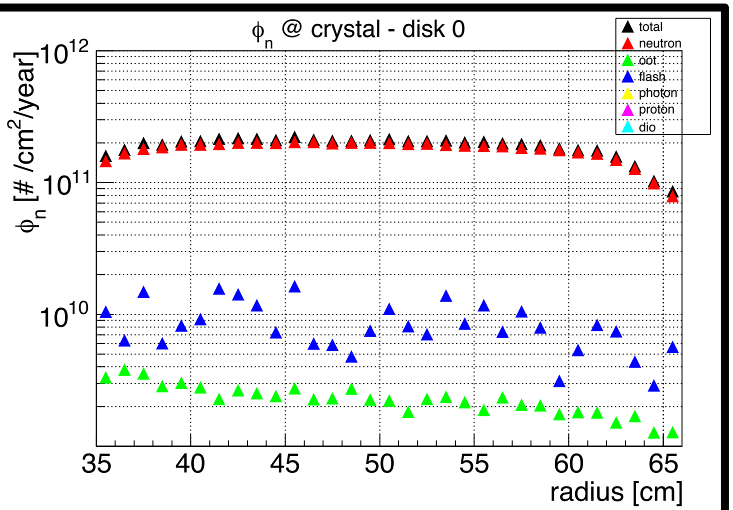


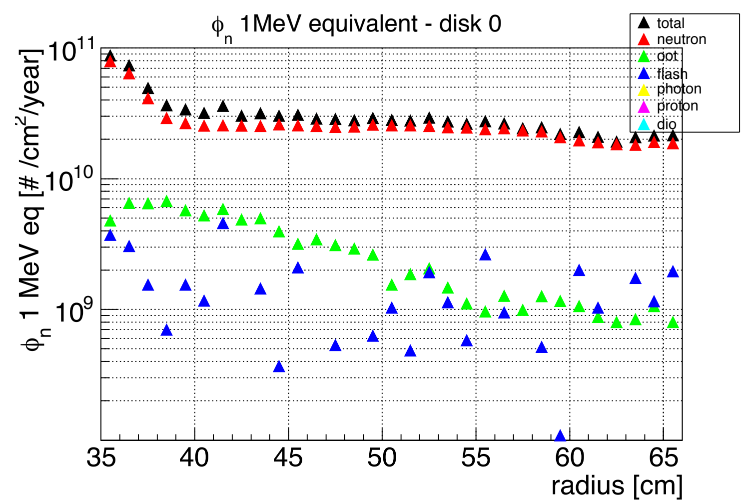
Radiation hardness (simulation)

- Radiation dose driven by Beam flash (300 ns from interaction on target). **Dose from Muon capture x 10 smaller**
- Strongly limited to inner radius (up to 400 mm)
- **Highest dose/year ~ 10 krad**
- **Highest n flux/year on crys. ~ 2×10^{11} n/cm^2**
- **Highest dose/year on APD ~ 6×10^{10} n_1Meveq/cm^2**









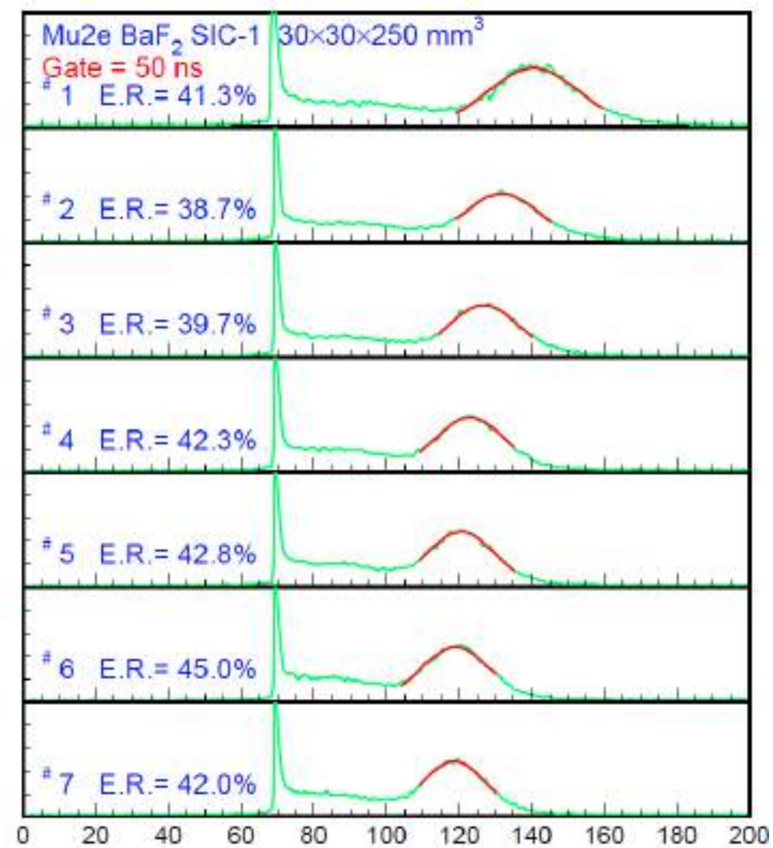
Rad-Hard test: qualify crystals up to 100 krad , 10^{12} n/cm^2
Qualify photo-sensors up to 10^{11} --- 3×10^{11} n_1MeV/cm^2

Quality Assurance

❑QA stations for crystals and photo-sensors exist in INFN and Caltech. Crystal stations are being modified to adapt to the BaF_2 deep UV emission. **Feedback with vendor ensure meeting specifications.**

→ Test longitudinal transmittance, light yield response to a ^{22}Na source and measurement of longitudinal uniformity for all crystals

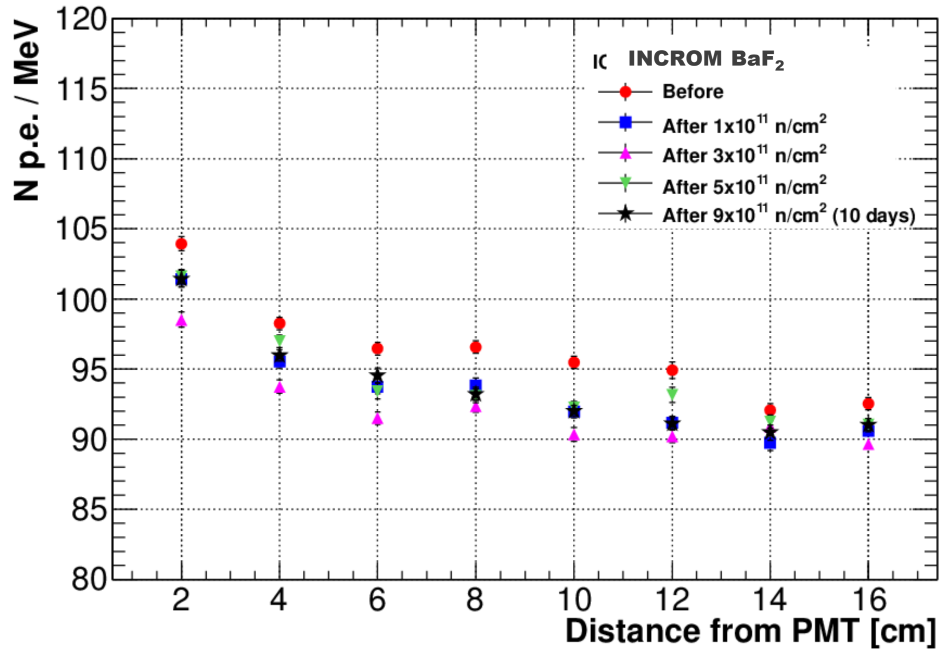
→ Measurement of gain, I-leakage and their dependence on Vbias for each photo-sensor;



❑Bench test planned for the FEE and Digitizer systems.

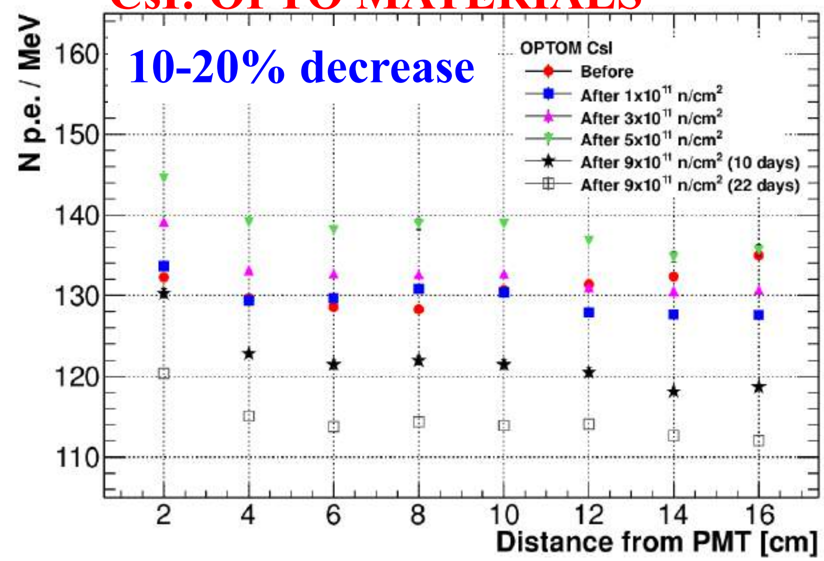
❑Burn in test for HV system

Crystal radiation hardness: neutrons

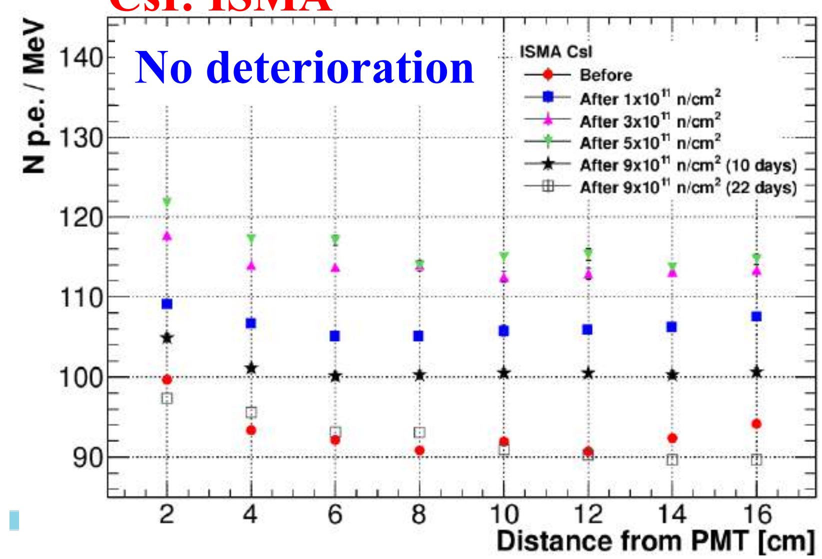


- Both crystals are radiation hard for the expected flux of neutrons.
- Losses in transmittance and LY contained at the 10% level

CsI: OPTO MATERIALS



CsI: ISMA



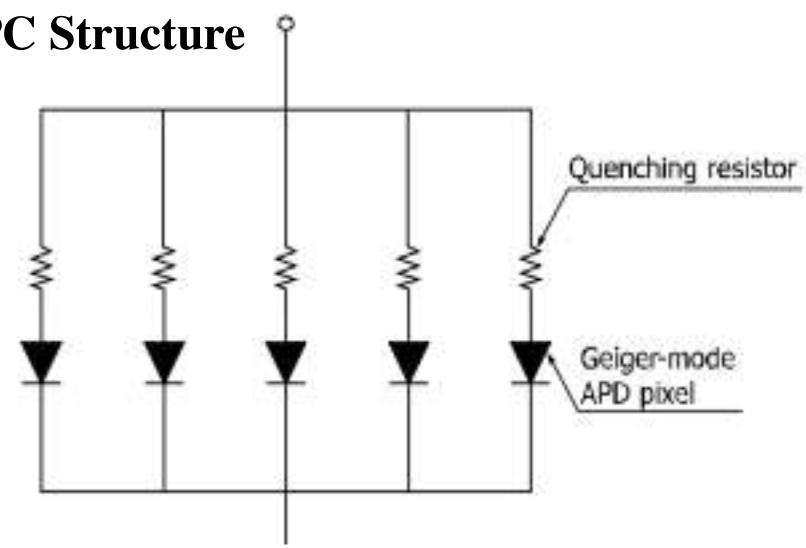
Silicon PMT : quenching

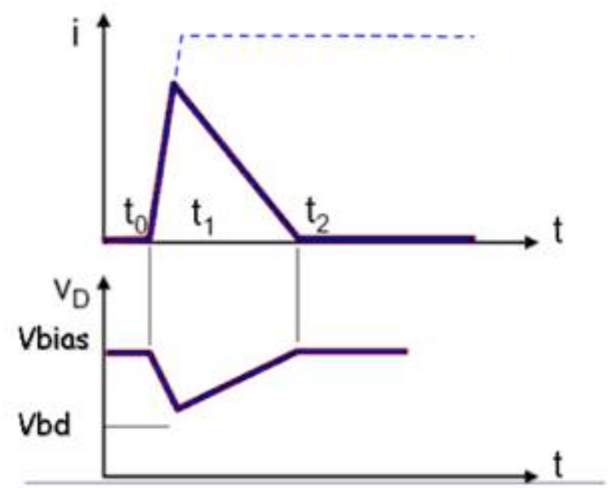
- The MPPC (multi-pixel photon counter) is one of the devices called silicon photomultipliers (SiPM) or Geiger APD. It is a photon-counting device **that uses multiple APD pixels operating in Geiger mode;**

- The Geiger mode allows obtaining a **large output by the discharge even when detecting a single photon**. Once the Geiger discharge begins, it continues as long as the electric field is maintained.

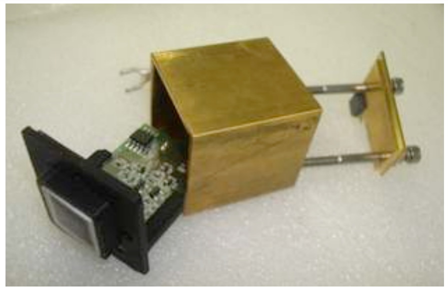
- One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with each APD pixel. This quickly stops the multiplication in the APD since a voltage drop occurs when the output current flows.

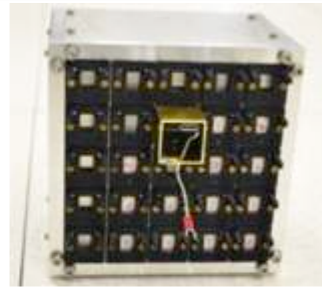
MPPC Structure

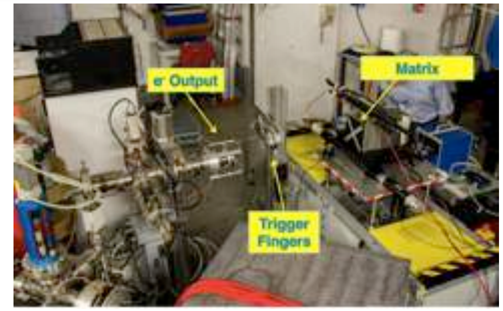


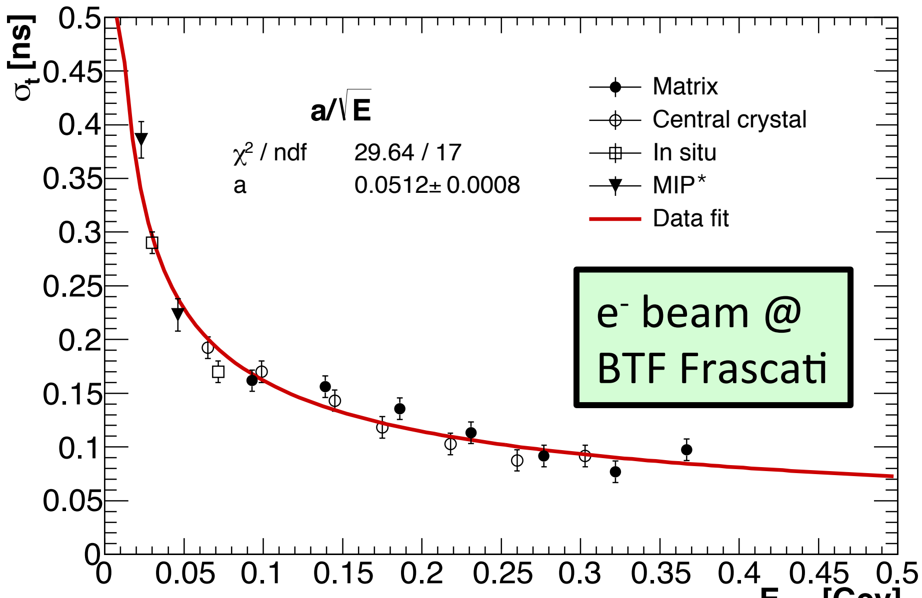


LYSO Legacy

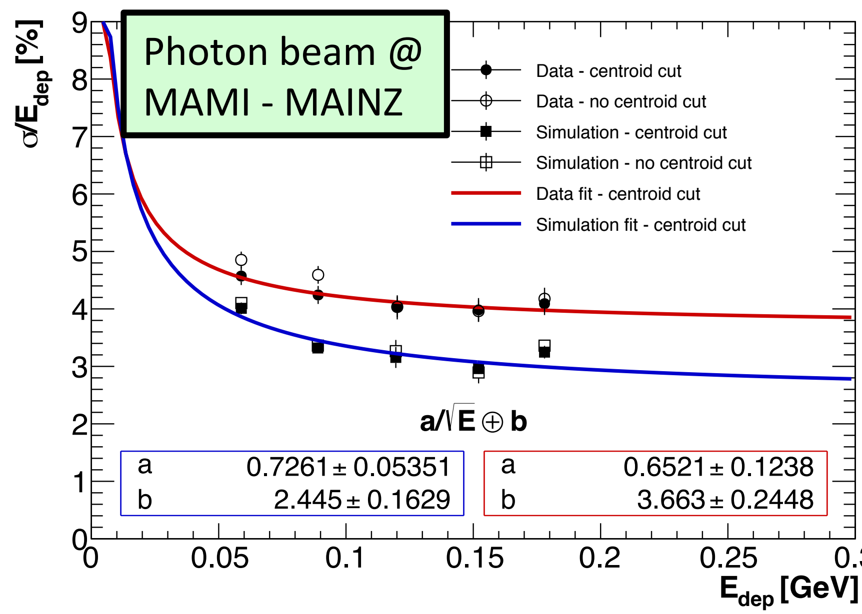








*Time resolution with MIPs from Mu2e DocDB 4409



σ_T = 51 ps/sqrt(E/GeV) compare with KLOE ~ 55 ps/sqrt(E/GeV)

Energy resolution as a function of the energy deposition fitted with the function:

~ 4% @ 100 MeV

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

Noise term *b* considered negligible (~0.1% in quadrature).