Frascati Detector School

LNF, 21-22-23 March 2018

Calorimetry @ low energies

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Principles

Simulation

Operation

FEE

DAQ

Hands-on Laboratory

Commissioning

Calibration

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LOC: G. Bencivenni, D. Domenici, G. Felici, S. Miscetti

Outline of the lecture

Calorimetry at O (GeV) level

→ Particle Factories

→ Rare searches

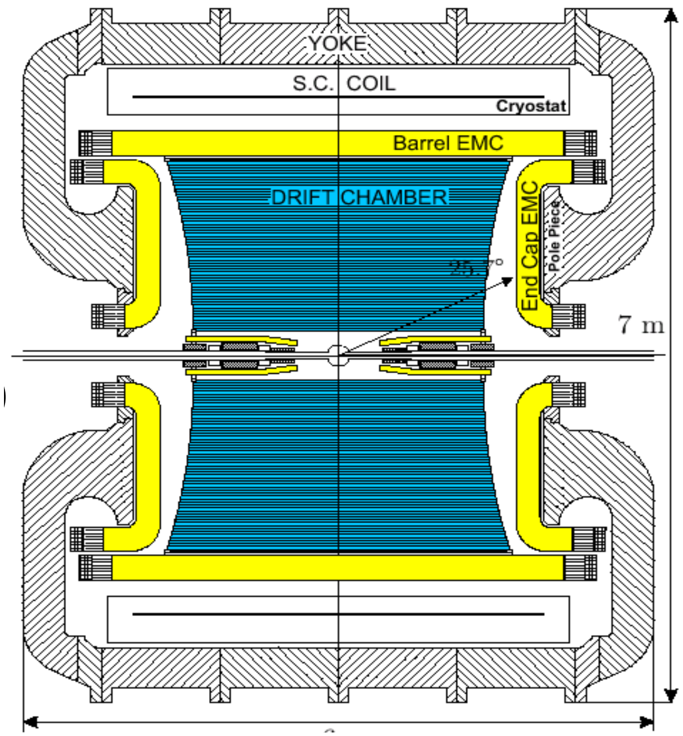
..... essentially EM calorimeters

Three Golden Examples

- ❑ Kaon/hadron physics: KLOE Lead/Scifi EMC
- ❑ LFV searches:
  - → MEG/MEG-upgrade: Liquid Xenon + PMT/SiPMs
  - → MU2E: CsI + SiPMs

Conclusions

KLOE at DAϕNE - the Frascati ϕ Factory

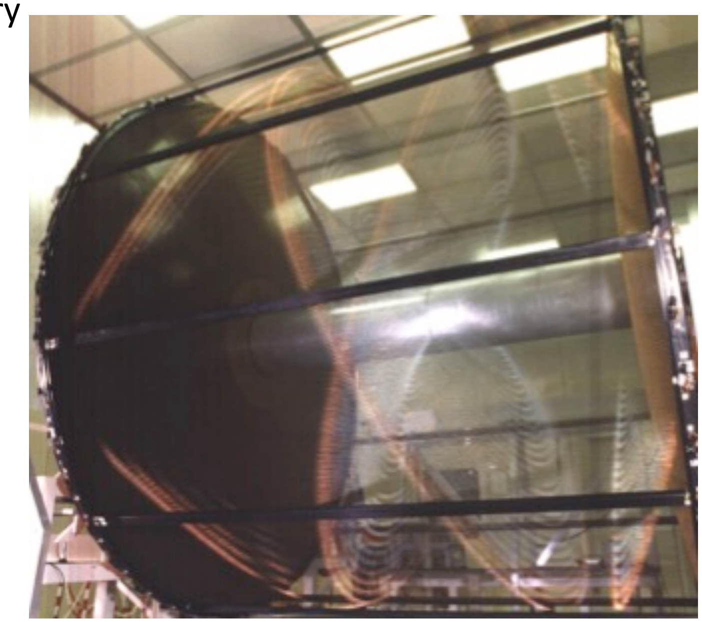


Process	Cross section (μb)
$e^+e^- \to \phi$	≈ 3
$e^+e^- \to e^+e^-(\gamma)$	6.2 ($\theta > 20°$)
$e^+e^- \to \mu^+\mu^-(\gamma)$	0.1
$e^+e^- \to \pi^+\pi^-(\gamma)$	0.05

ϕ Branching Ratios	
K^+K^-	49.1%
K_SK_L	34.3%
$\rho\pi + \pi^+\pi^-\pi^0$	15.4%
$\eta\gamma$	1.3%
$\eta'\gamma$	$O(10^{-4})$
$f_0(980)\gamma$	$O(10^{-4})$
$a_0(980)\gamma$	$O(10^{-4})$

Kaon physics
- CP violation
- Vus,BR measurements
- Quantum Interferometry

Light hadron spectroscopy
Hadronic Cross section

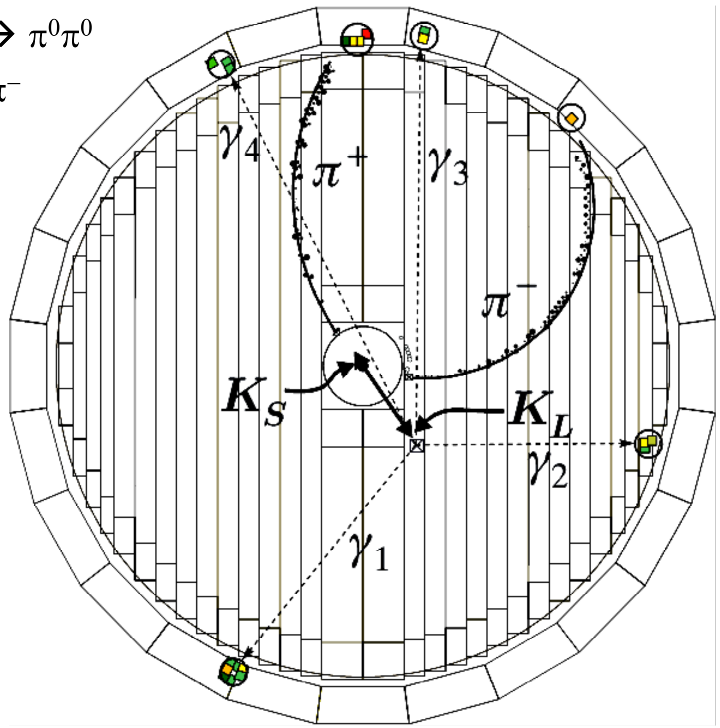


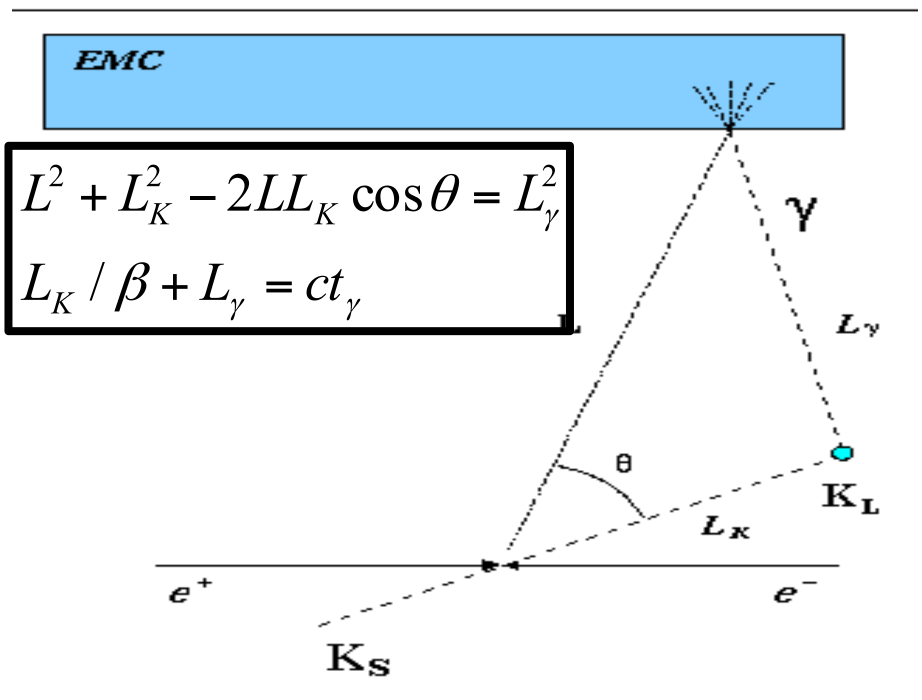
- KLOE experiment required a high performing detector joining high precision tracking with well performing calorimetry
- **Luminosity few 10^{32} cm-2sec^{-1}, L of 2.5/fb (KLOE-2 5/fb)**

- **Largest size tracker in the world**. **He based gas mixture.**
  Stereo angle wires. **1 MeV resolution on Kaon masses**.
  → **0.4% momentum resolution at 500 MeV.**

A High Sampling Calorimeter

$\phi \rightarrow K_S K_L \rightarrow \pi^0\pi^0$
$\rightarrow \pi^+\pi^-$





$$L^2 + L_K^2 - 2LL_K \cos\theta = L_\gamma^2$$
$$L_K / \beta + L_\gamma = ct_\gamma$$

- ❑ Calorimeter Requirements: reconstruct with high efficiency and good resolution both "prompt" hadronic decays (from the IP) and K_L decays in 2/3 π^0 in the large K_L decay volume (~ 4 m diameter) of the KLOE Drit Chamber
- ❑ This translated in a long list of technical specs difficult to fulfill in 1995 (20 years ago). Driving need was **to reconstruct neutral vertex with 1 cm accuracy.**
  In other words, 100 ps resolution, 10's of ps of timing accuracy (1-2 mm boundaries) for 20-300 MeV photons.

A High Sampling Calorimeter

- Hermeticity (photons counting 2 π^0 vs 3 π^0)
- Efficiency for low energy photons (Eγ < 300 MeV down to 3 MeV)
- Energy resolution of O (5 % /SQRT(E/GeV))
- Time resolution of O (50 ps/SQRT(E/GeV))
- Fast response for triggering (signals of O (100 ns))
- Charge particle identification (π vs μ vs K^+)
- Measurement of K_L interaction on the calorimeter
- Identification of $K_L \rightarrow 2\pi^0$ decay vertex (Timing and position)

Two solutions explored:

1) Crystal calorimeter such as CsI(Tl)
2) High sampling lead-fiber calorimetry (Chosen Solution)

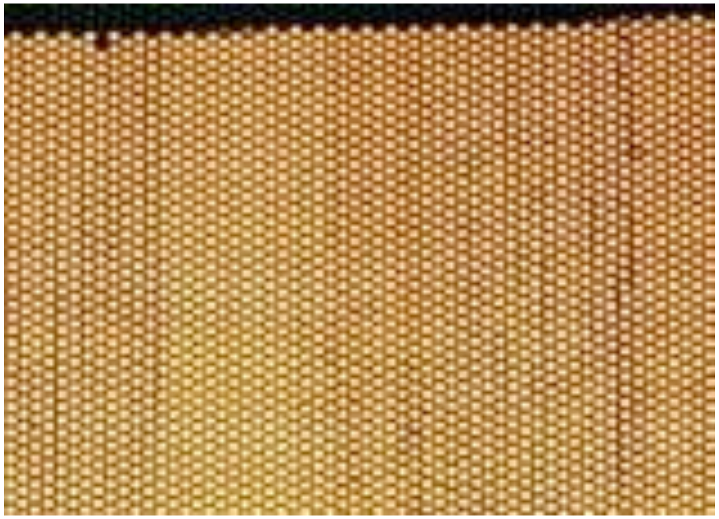
Cheaper, faster, better timing resolution (at the time)

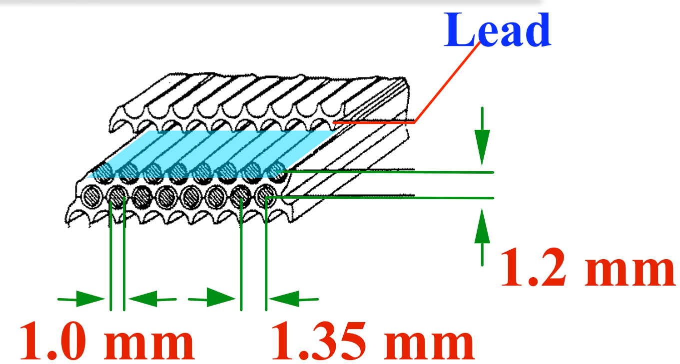
A Posteriori

→ CsI(Tl) could not have granted rejection of the few MHz machine bkg in EndCaps

→ Csi(Tl) has better energy resolution but worse position resolution ..
No improvements available with kinematic fitting

Details of the KLOE EMC structure





Fiber:Lead:Glue volume = 48:42:10
Lead Thickness 500 um ($d/X_0 = 0.1$)
1 mm diameter fibers

The advantage of this choice resides in the highly uniform and high frequency of sampling.

Fibers positioned on the vertices of an equilateral triangle.

From "sampling" formula (even assuming Ec=600 MeV/Z) → **σ(E)/E (slabs) = 7 %**

Sampling frequency gets a factor of two larger than than for alternated slabs of fibers/lead

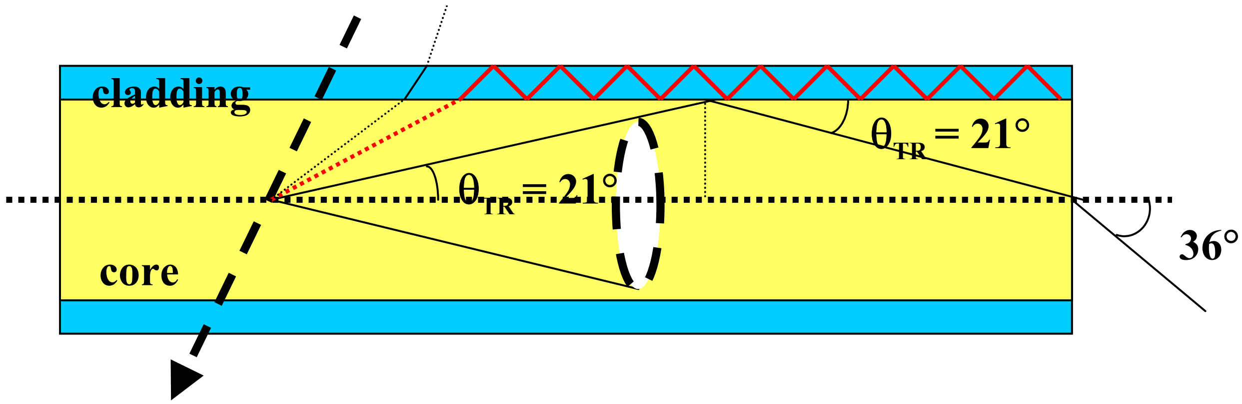
→ Energy resolution improved by 1/sqrt(2) → **TB proven 4.-4.5 % energy resol.**

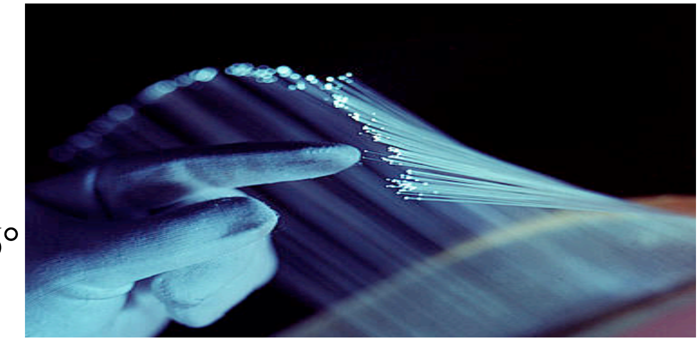
→ Nice optical connection between lights and photo-sensors.

→ Flexible for shapes .. allowed to position PMT inside 0.5 T field

→ Able to build 3D reconstruction of objects

Scintillating fibers



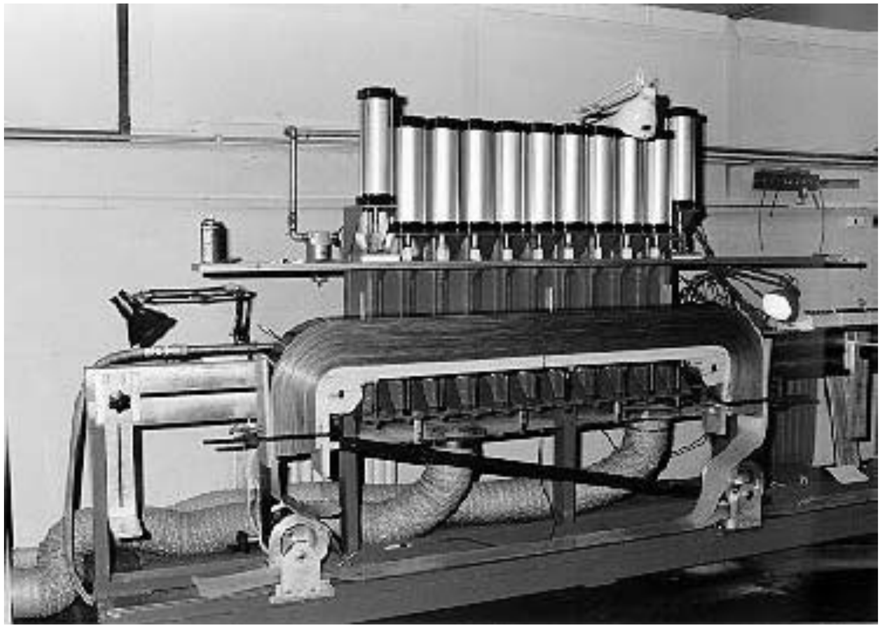


- "Scintillating optical fibers" are constituted by a scintillating "core" (Polistyrene) with refractive index (η) of 1,6 protected by one (or two) external claddings (plexiglass) with lower η (1,5)
- Due to internal reflection, The trapping angle is of 21° so that the light travels practically at small angle inside the fiber. Opening angle in air contact < 40°
- Small value of light collection at the edges (3 %)
- **Large values of attenuation lengths > 250 cm (long detectors)**
- **Small value of timing dispersion along fiber axis**
- Fibers both scintillating on Blue or WLS (on green) exist

KLOE fibers specs:
- ✓ 1 mm diameter
- ✓ 4 m length
- ✓ λopt = 410 nm
- ✓ τ = 2.5 ns
- ✓ LY of 4-5 pe/MiP
- ✓ λatt = 350 cm

KLOE has got in its detector more than 15,000 km of optical fibers.
Long production from two firms: Kurarary (Japan), PoLiHiTech (Italy)

Assembly Station …

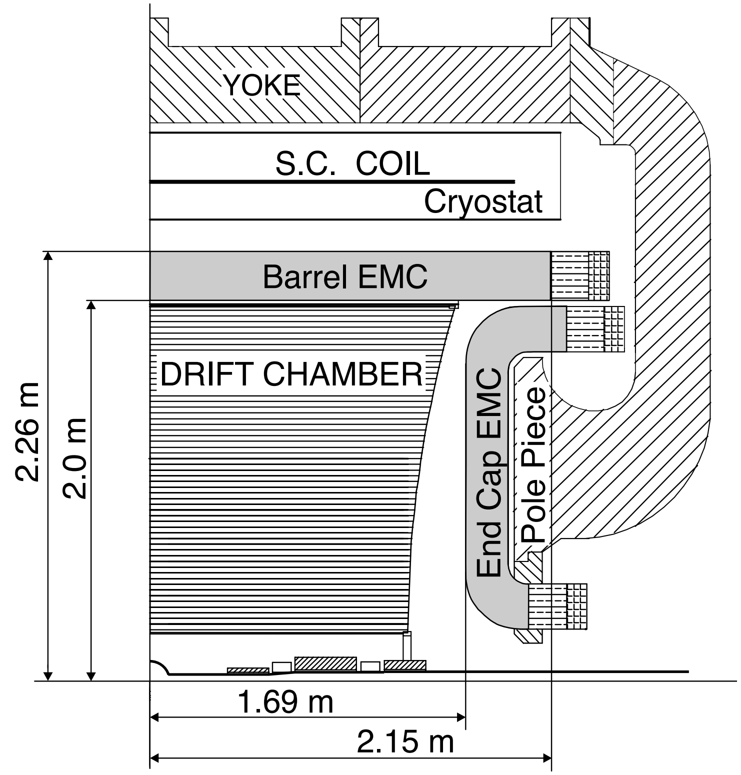


Assembly station for End-Cap modules

Curing time of few hours between 0.5 mm grooved plates (obtained by a grooving machine) and fibers with Epoxy glue.
Pressure of 1.1 atm applied each 10 layers.

Properties of the resulting structure:

Lead : Fiber : Glue volume ratio	= **42 : 48 : 10**
Density	= **5 g / cm³**
Radiation Length	= **1.5 cm**
Module thickness	= **23 cm (~ 15 r.l.)**



Flexible lead/scifi composite for:

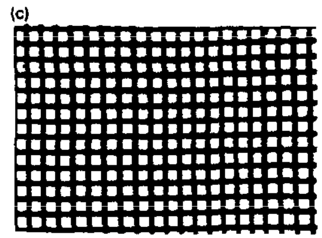
→ **Curvature**. It allows to put PMT in smaller B-Field area
→ **Length.** It allows to build 4.3 m long barrels

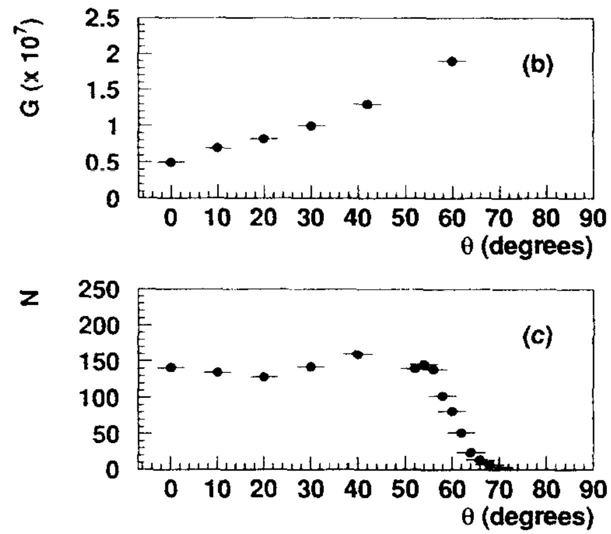
Light guides , PMTs used and readout

Mesh Dinodes PMT (HPK R5960)

→ first PMT working in B-Field due to grid geometry @ **EndCap at B=0.2 T, θ= 30°**

→ Fast Transit Time spread < 100 ps/p.e., $G=4x10^6$, $\varepsilon q(420\ nm) = 25\%$





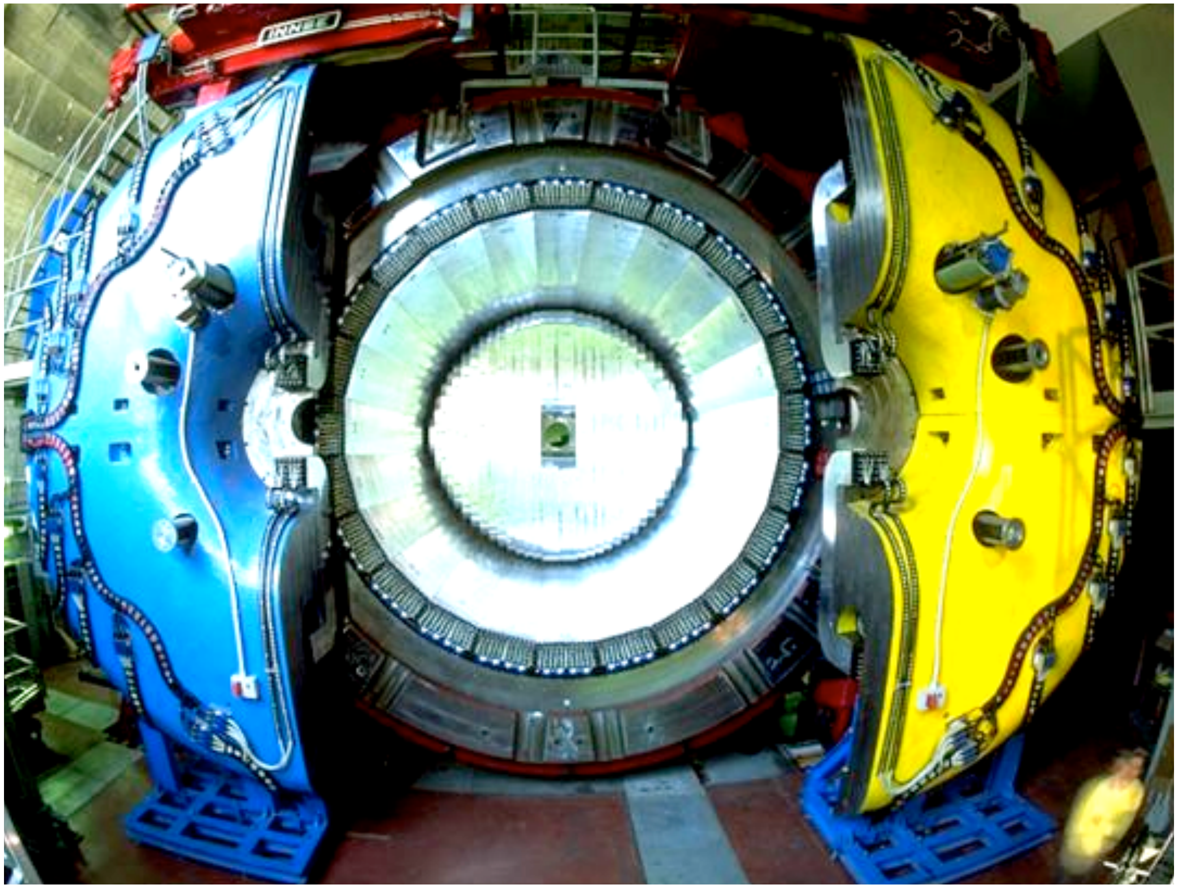
- Optical connection of $4.4^2\ cm^2$ → 3.7 cm diameter PMTs with Bicron optical grease
- Light collection better than 90% i.e. >> basic area ratio loss (50%), LY= (1-2 pe/MeV)

→ **Liouville Theorem in action by means of Winston Cone and trapping angle in fibers**

- 5 Layers of readout along the shower dept (Transversal readout)
- Longitudinal reconstruction along fiber axis with difference of timing

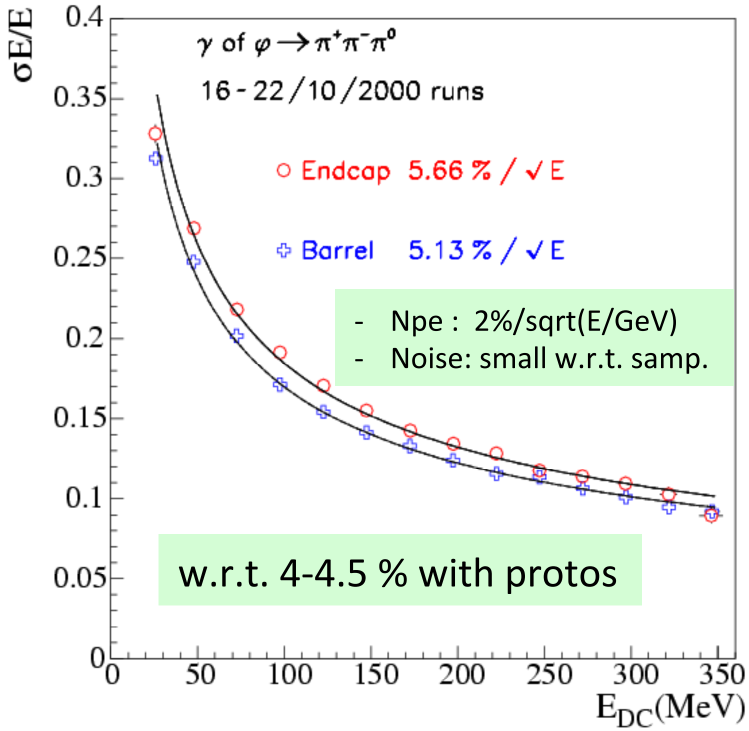
Ta Z reconstruction = Vf x (Ta-Tb)/2 → Sigma(z) = Vf x Sigma(t) Tb Vf = c/η = 5 ns/m

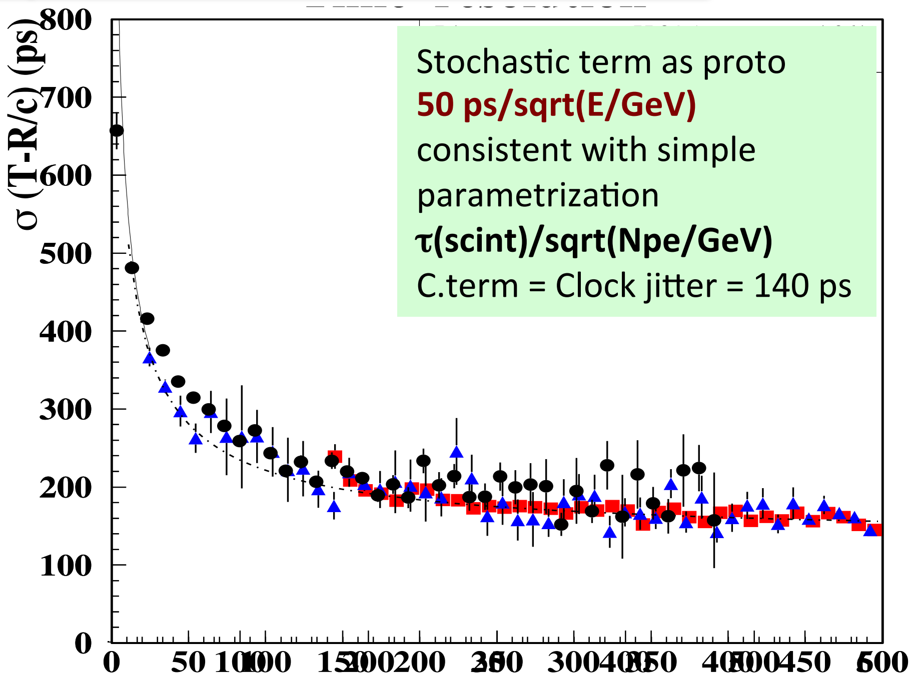
Final detector before inserting DC



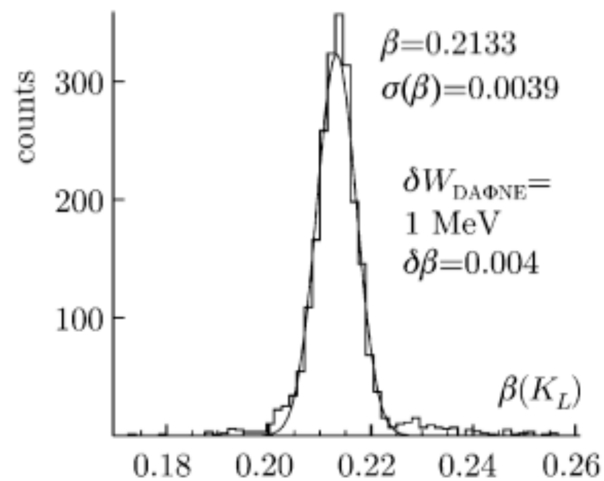
- ✓ Barrel with 24 wedges, Length of 430 cm.
- ✓ EndCaps of curved shape to cover 98% the solid angle and the Barrel-EndCaps
- ✓ **N(PMTs) = 5000.** Double sampling ADC, 50 ps TDC
- ✓ Position resolution: 1 cm in transversal position , 1.2 cm/sqrt(E/GeV) along fiber axis

KLOE EMC performance



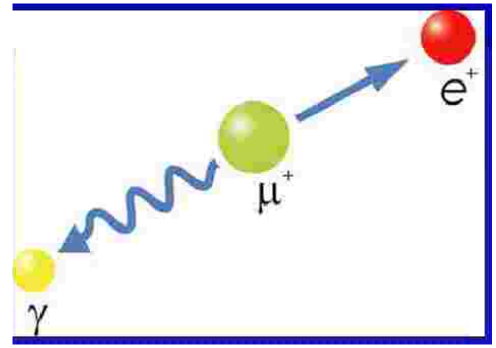


- ✓ Nice reconstruction of invariant masses (15 MeV resolution on π^0 masses)
- ✓ Kinematic fitting improved masses (**2-3 MeV resolution on π^0 masses**) thanks to good position reconstruction (1 cm)
- ✓ Identification of K_L interacting on calorimeter with precise measurement of their speed

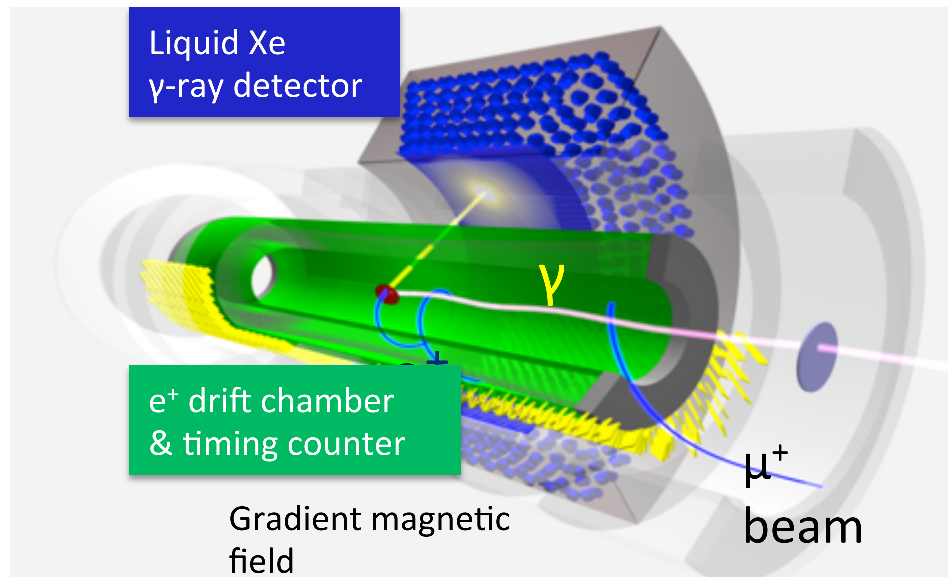


MEG Liquid Xenon Calorimeter

- Charge Lepton Flavor Violation search
  SM Forbidden $\mu \rightarrow e\gamma$ decay in flight
  $E_e = E_\gamma$ = 52.8 MeV, Te = T



- **Backgrounds:**
  1) **Accidental coincidence**
  Look for a signal over background with good resolution of all detectors proportional to I^2
  2) Radiative Muon decays
  1/10 of accidental coincidences proportional to I



- Event rate of muon stop **10^7 u/sec**

- Calorimeter for photon detection only

Needs for very precise calorimetry, both on energy and timing
→ to compare $\Delta P(e-\gamma) = P_e - P_\gamma$ e $\Delta T(e-\gamma) = T_e - T_\gamma$

MEG Calorimeter: basic design

MEG Design energy resolution of **$\sigma(E)/E$ =1 % at 52.8 MeV**

Looking only at statistical power → No noise, No leakage, Negligible Intrinsic fluctuation
$\sigma(E)/E = 1/\mathrm{sqrt}(Npe)$ → Npe → $(0.01)^{-2}$ = 10000 pe @ 50 MeV → 200 pe/MeV
$N\gamma$ /MeV = Npe/GeV/εq → 6000 γ/MeV → for εq of 10%, collection 30%

	NaI	BGO	GSO	LSO	LXe	Lar	Lkr
ρ (g/cm^3)	3.7	7.1	6.7	7.4	3.0	1.4	2.4
Rel LY	100	15	20-40	45-70	73	70	55
Tau (nsec)	230	300	60	40	2.2, 34	6, 1000	2, 91

- ❑ Liquid scintillators offer a comparable LO with the best of scintillating crystals

- ❑ MEG selected LXe for high LY and fast emission → **Good for timing resolution**
  Rough estimate → 34 ns/sqrt(Npe) @ 58 MeV
  LY (LXe) = 40000 γ/MeV, Npe > 2000 pe/MeV → σ_T < 100 ps

- ❑ **Liquid scintillators are uniform, negligible-small intrinsic resolution**

MEG Calorimeter: pro and contra

900 l of Liquid Xenon

846 2" UV-PMT soaked in liquid

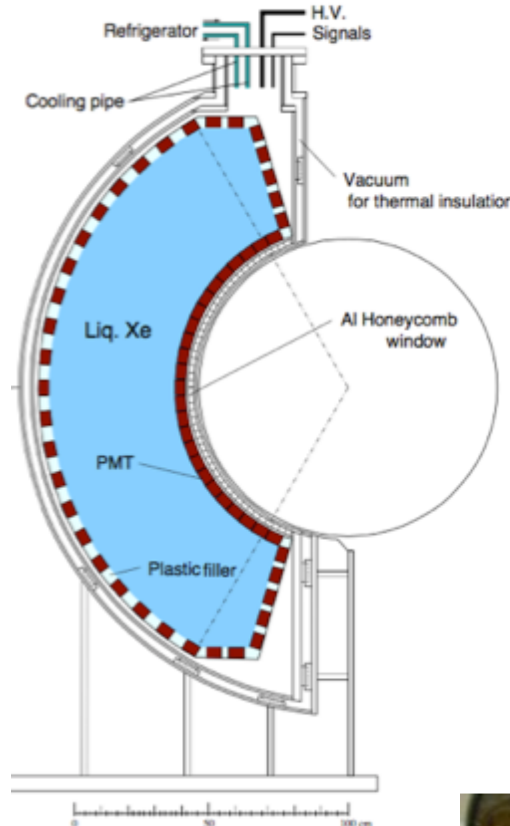
Waveform analysis for Pileup

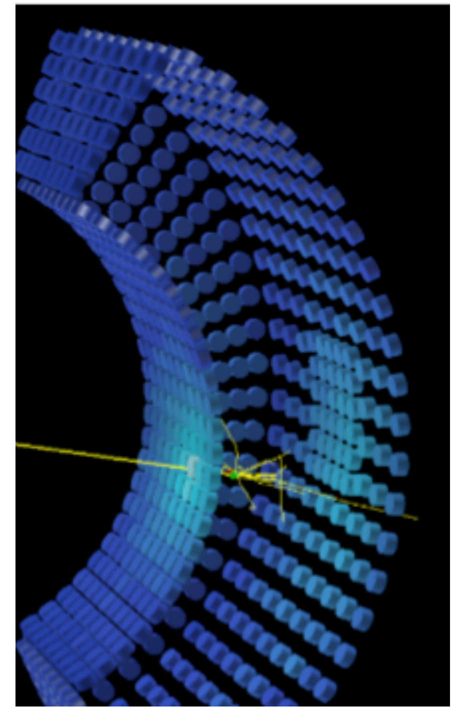
Advantages of Lxe

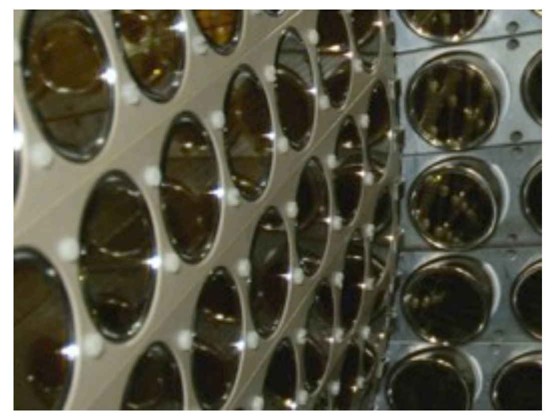
- Only scintillation light,
  very high LY (~75% of NaI)
  40000 photons/MeV
- Fast scintillation time
  (τ_{decay}= 2,4, 45 ns for γ-ray)
- High stopping power (X_0= 2.8 cm)
- **Uniform (liquid)**

Disadvantages of LXe

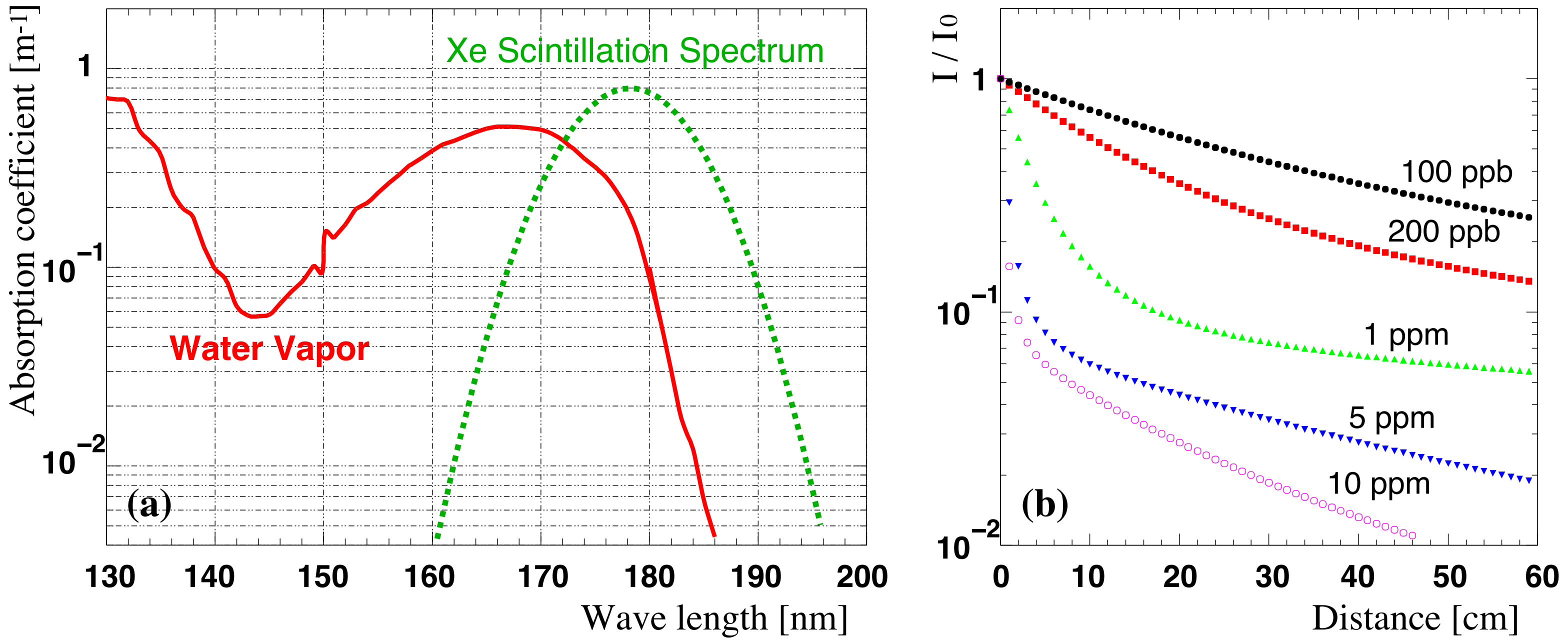
- VUV Scintillation light (λ=175nm)
- Low temperature (165 K) to keep liquid state
- Purification system: removal of H_2O/O_2 contamination)

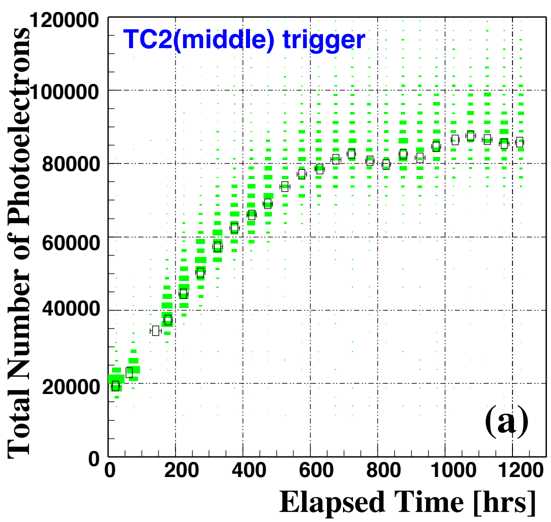






MEG Calorimeter: VUV light absorption





Water vapor is the worst contaminant in Lxe absorbing large part of the emitted photons @ 180 nm. **When improving purity**

→ Attenuation length improves up to 100 cm

→ Light yield greatly increases

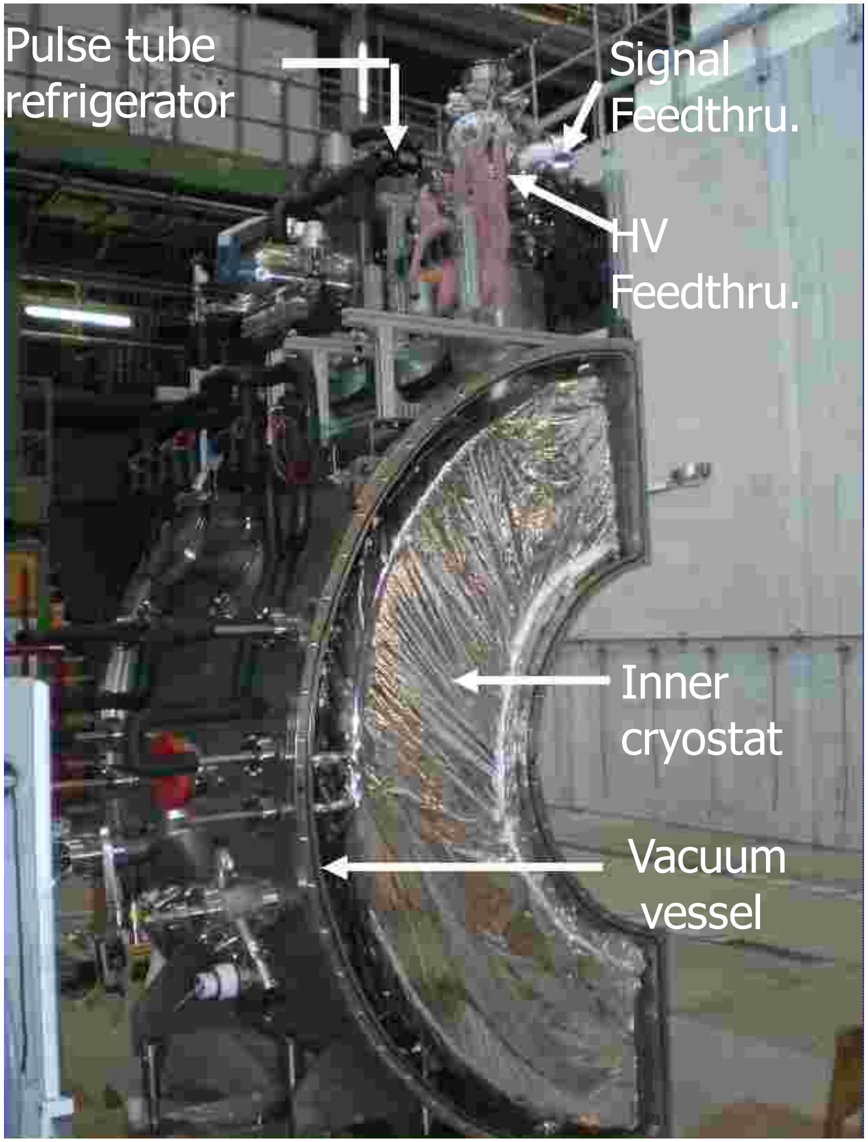
→ Reduced fluctuation along collection

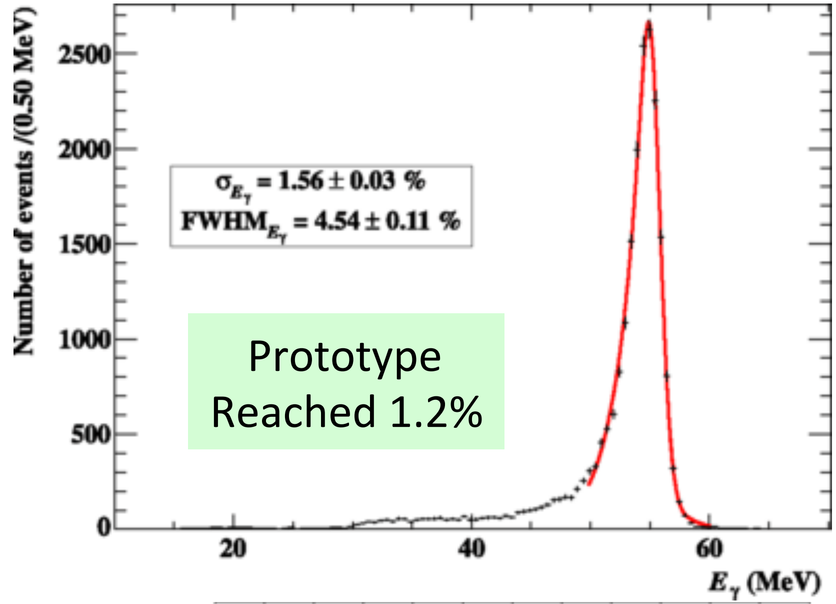
According to simulation → Attenuation lengths at this level enough to reach resolution of 1.2%

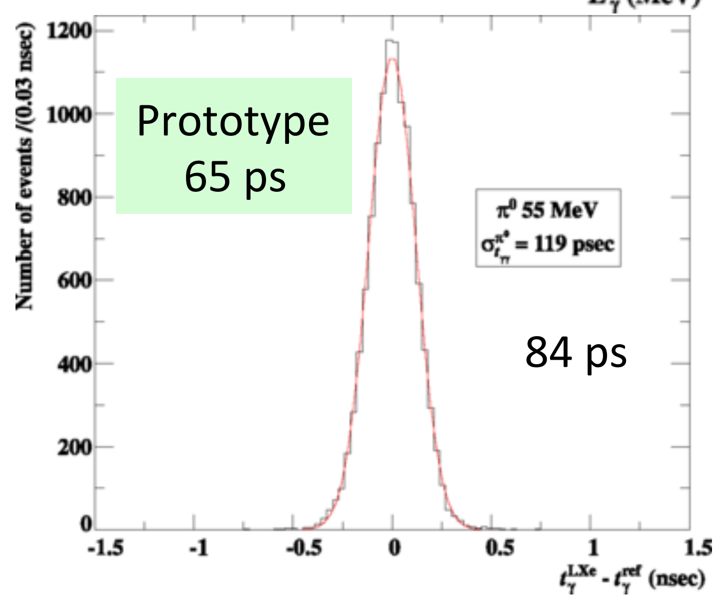
MEG Calorimeter: construction

PMTs are installed into PMT holders
PMT holders are installed into PMT support structure

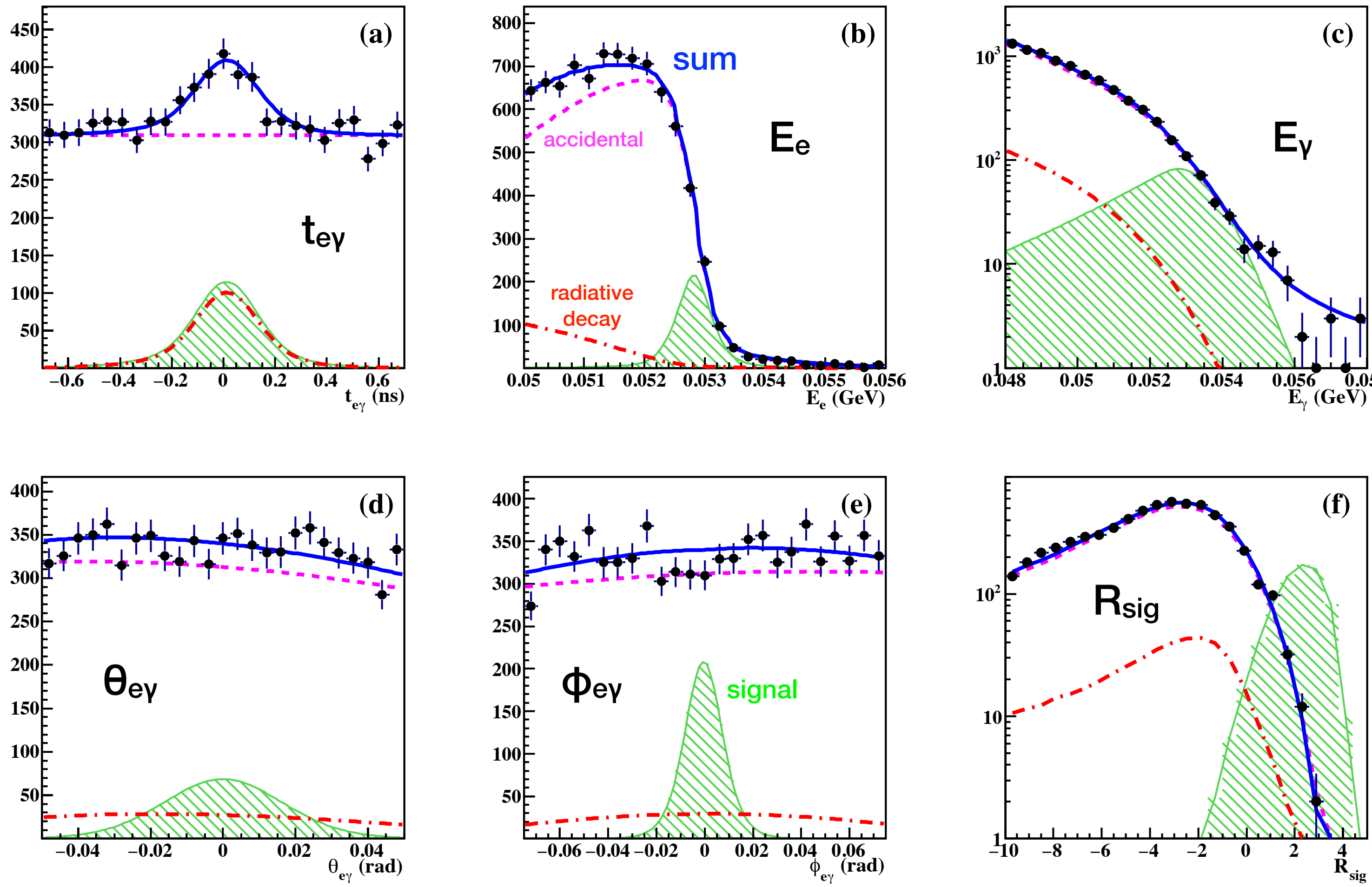
MEG Calorimeter: performances







MEG detector: reconstruction



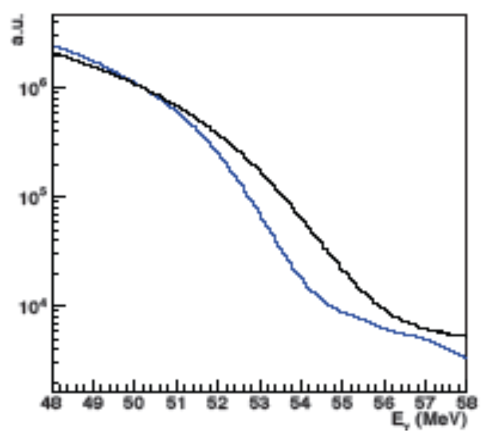
MEG upgrade: detector improvement

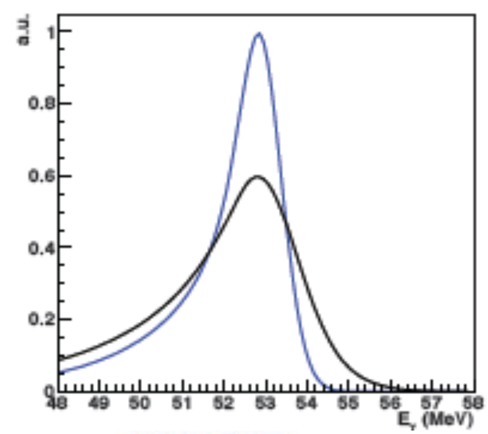
- New run expected in coming years to improve muon statistics

- Strong improvement on all detector components to improve rejection of Accidental Coincidences

- Goal is to improve sensitivity on CLFV of a factor of 10 down to BR of 4×10^{-14}

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

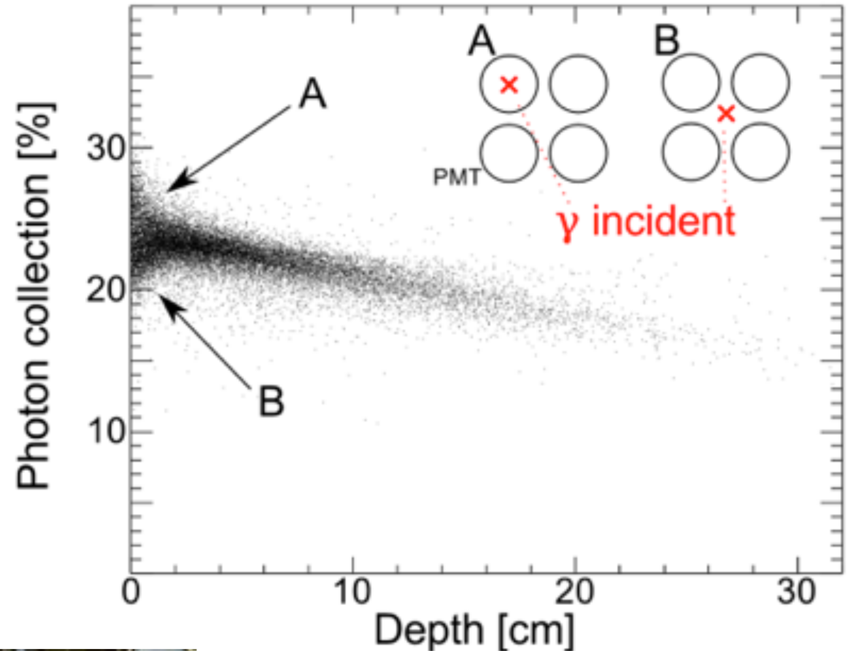


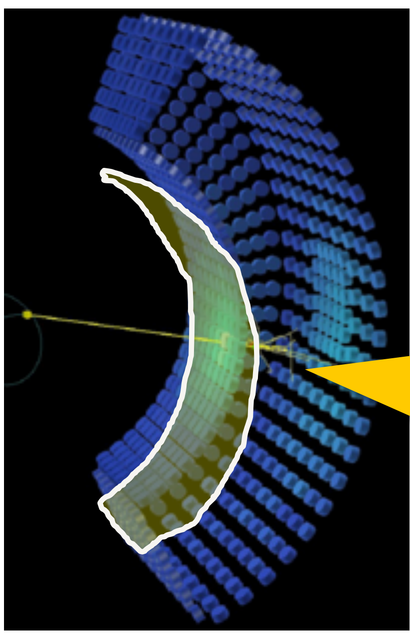


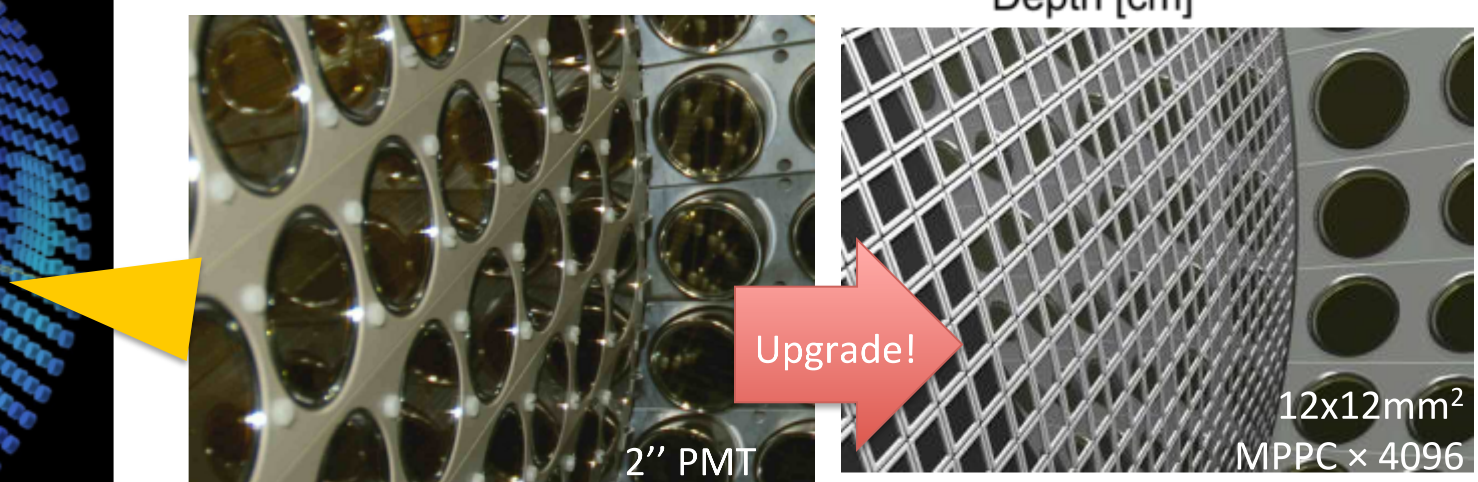
MEG-II: Calorimeter Upgrade

Calo-upgrade: reach the 1% res. target
Resolution limited by the non-uniformity of the photon collection efficiency.

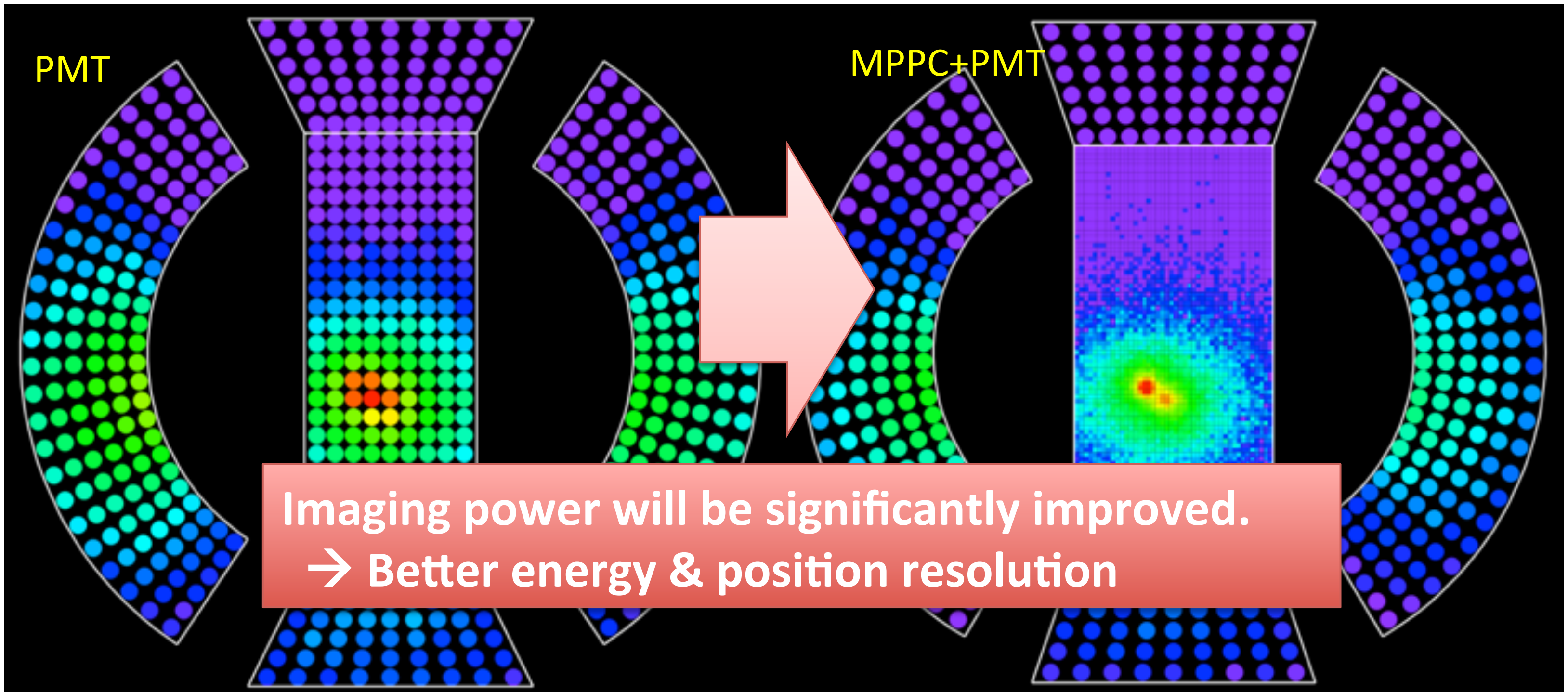
→ **Replace the PMTs at the γ incident face with 12x12 mm² MPPCs.**

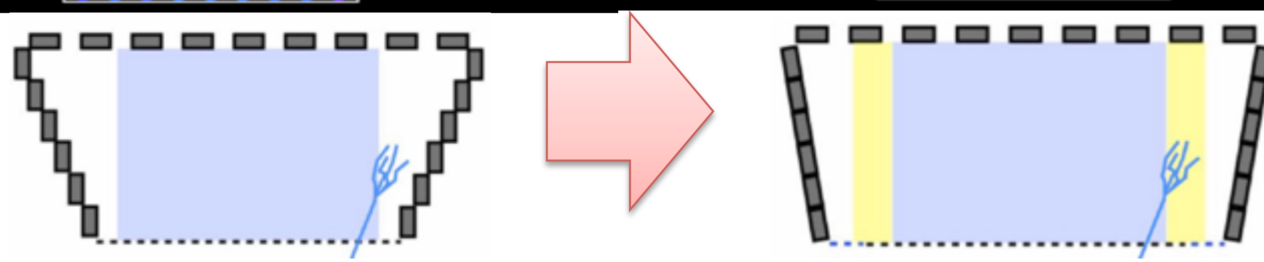






MEG-II: Calorimeter Upgrade

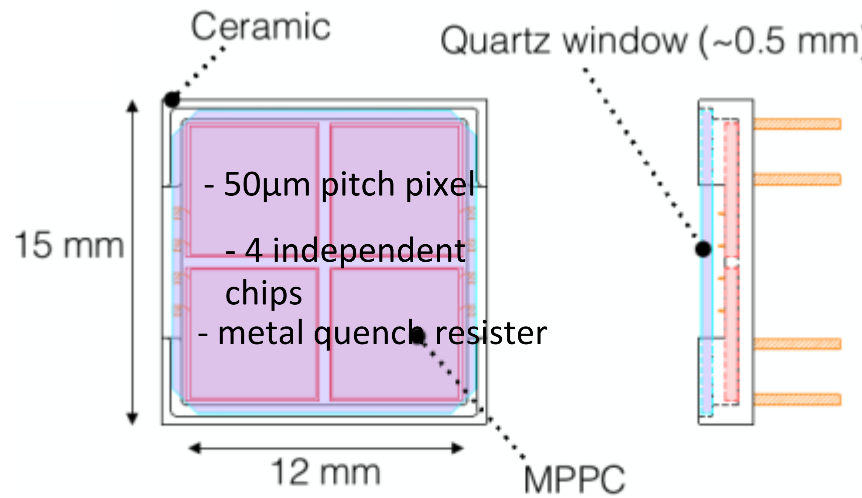




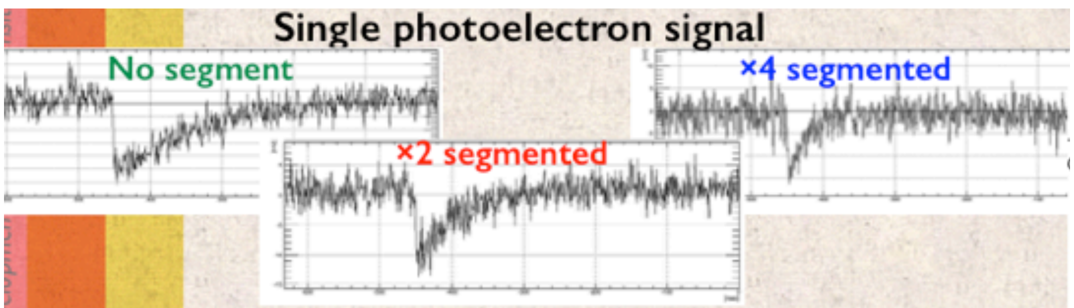
The layout of the PMTs will also change.
→ less energy leakage, better uniformity

VUV SiPMs

- **Sensitive to VUV-light**
  → Protection coating is removed, VUV-transparent quartz window is used for protection.



- **Series configuration of cells to reduce overall quenching time**



	Non-segmented	×2 segmented	×4 segmented
Fall time	135ns ⇨	49ns	25ns

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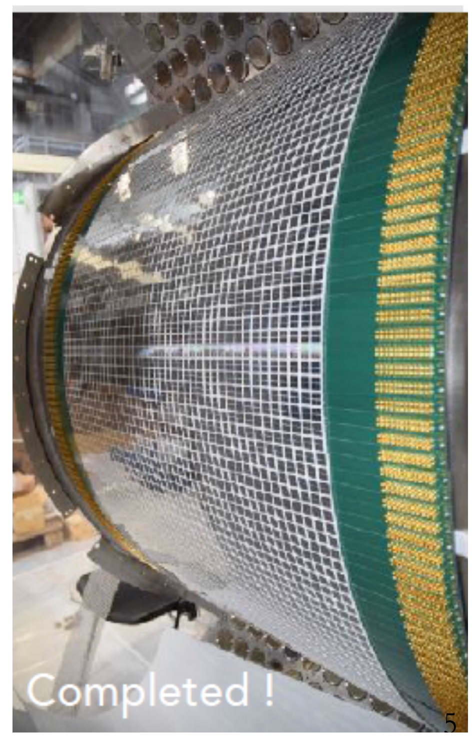
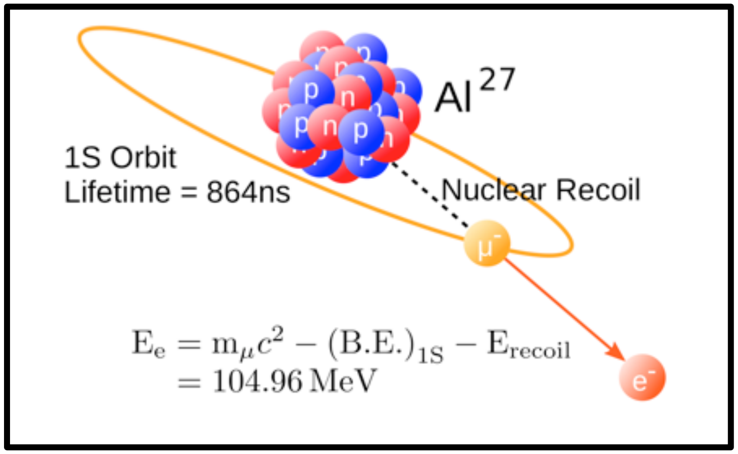
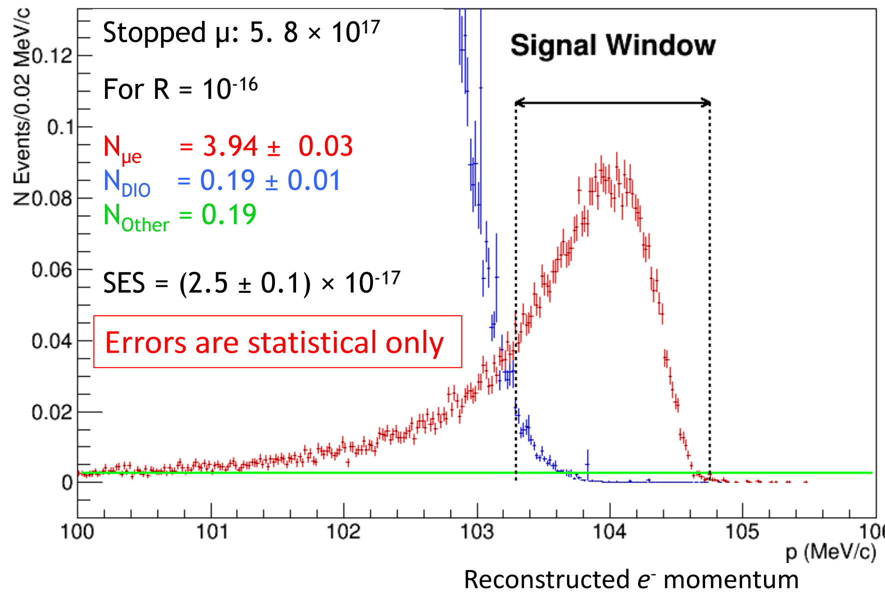


Mu2e search: High Intensity CLFV

Mu2e search for the Muon to electron conversion in the field of an Aluminium nucleus.





- ❑ Extremely high rate: **muon beam of 10 GHz** stopping on aluminum target
- ❑ Pulsed beam with 1.8 usec structure
- ❑ Conversion Signal close to end point of background
- ❑ High rate of neutrons and dose (10^{12} n/cm^2, 100 krad)
- ❑ Need to work under vacuum (10^{-4} Torr) + 1 T field

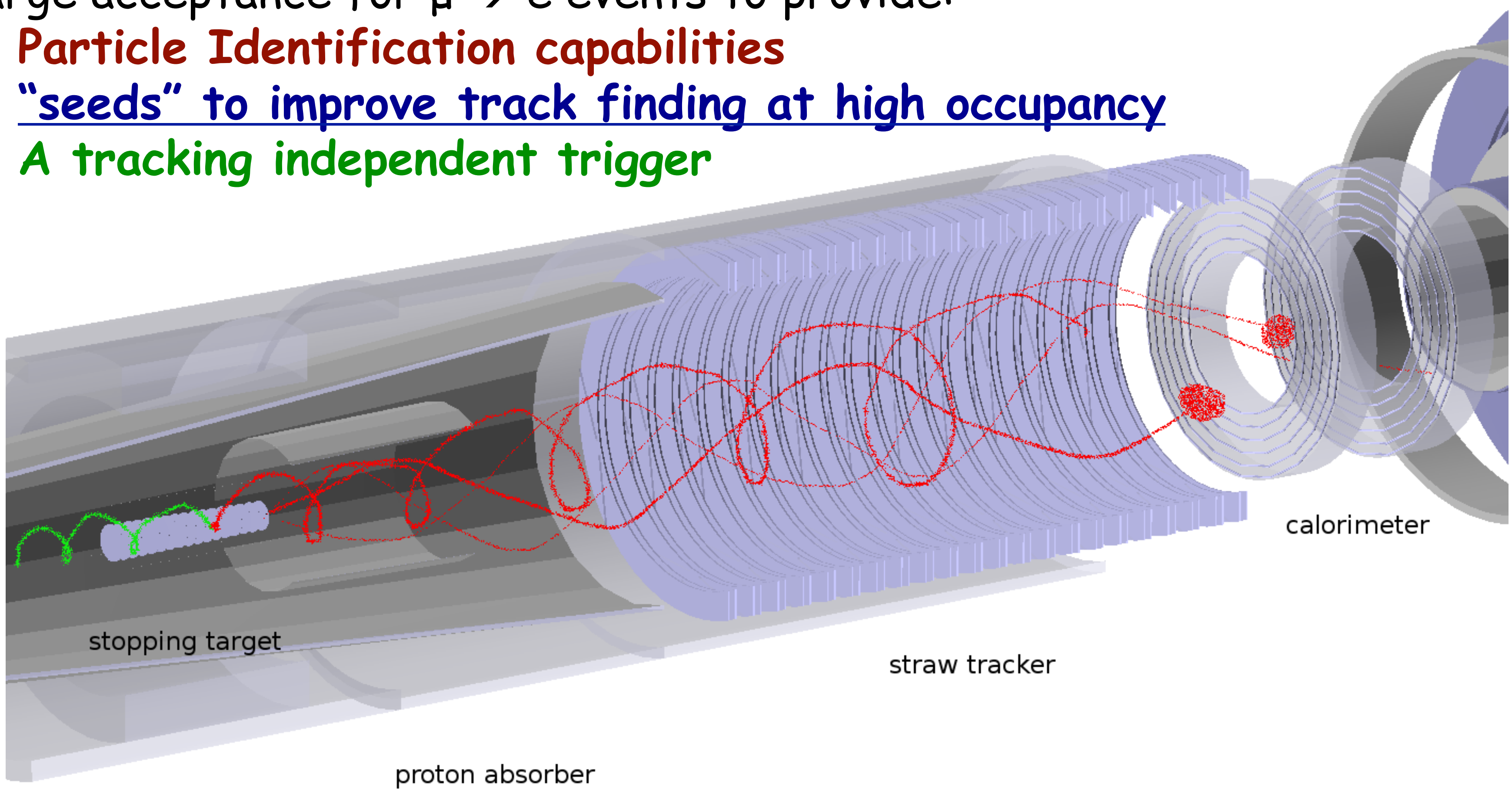
NEED of extremely light and precise tracker → 200 keV at 100 MeV

Why calorimetry at Mu2e ?

The calorimeter adds complementary qualities to the tracker system:

Large acceptance for μ → e events to provide:

- **Particle Identification capabilities**
- **"seeds" to improve track finding at high occupancy**
- **A tracking independent trigger**



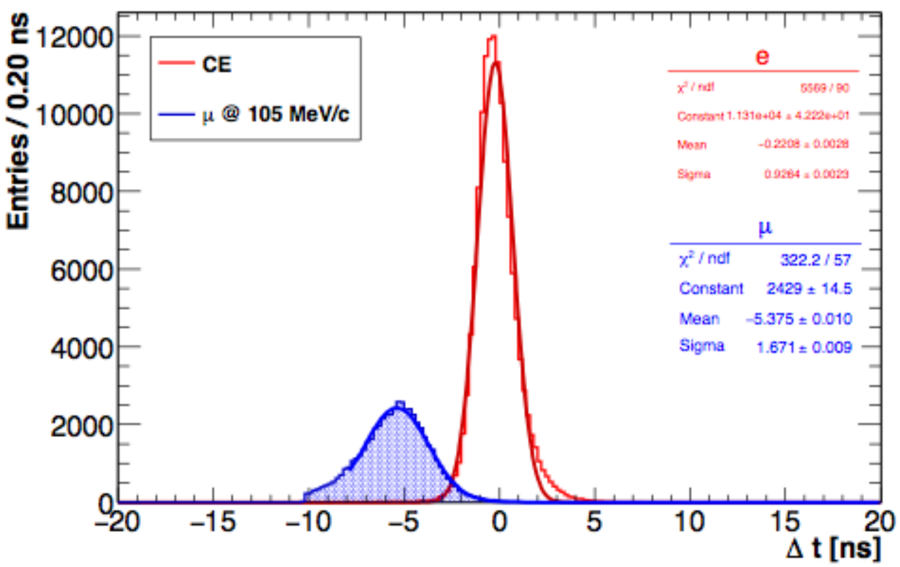
+ .. resistant to radiation and working in 1T field and @ 10^{-4} Torr vacuum

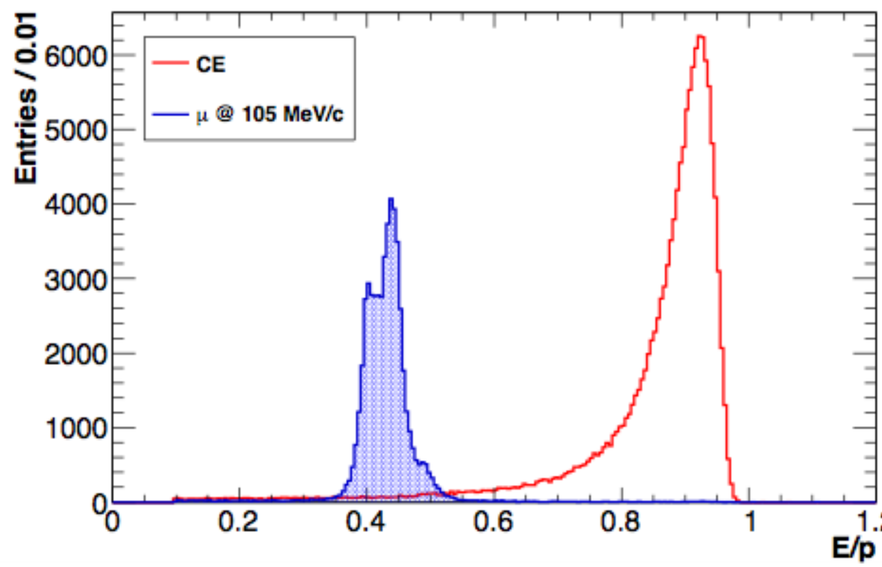
PID calorimeter-tracker – basic idea

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

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



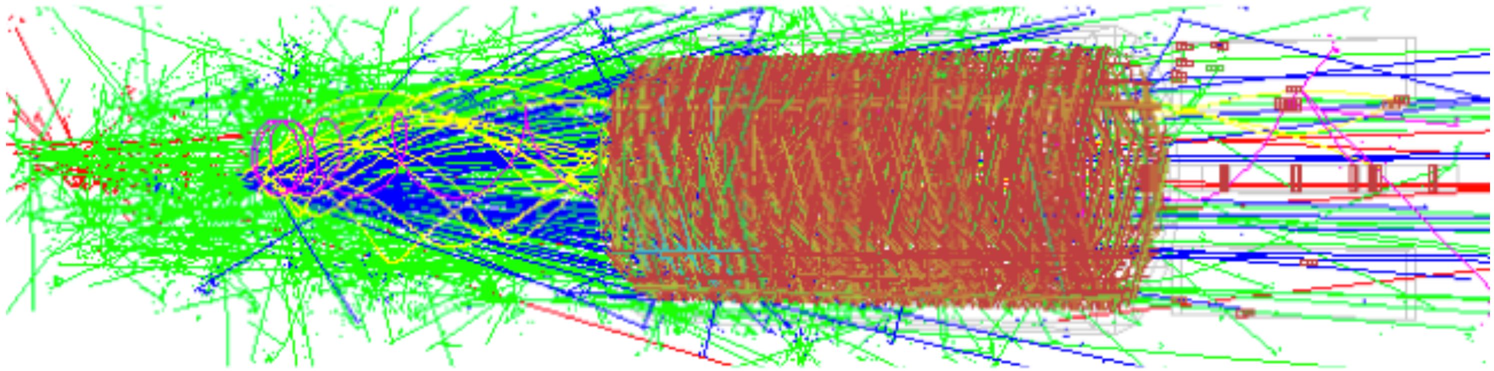


Get very high efficiency (> 95%) with Rejection factor > 200

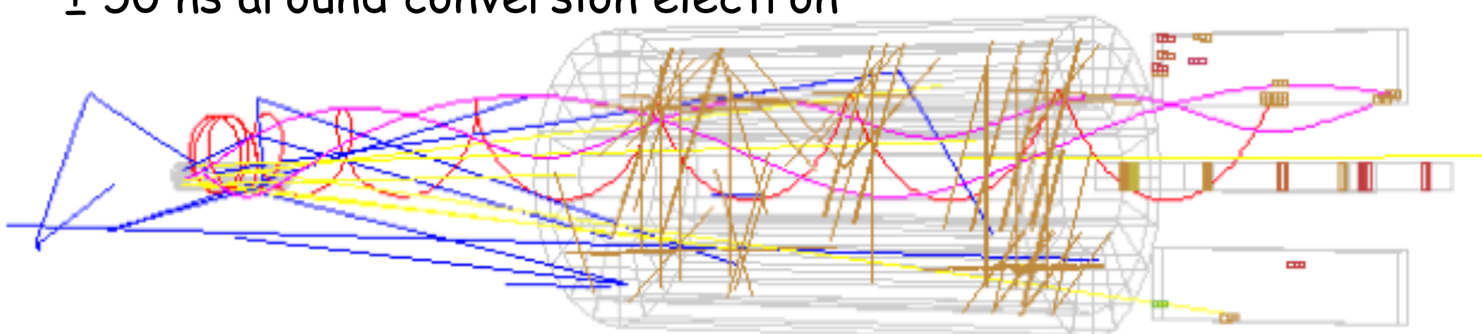
→ Needs energy res 5-10 % and timing < 500 ps.

EMC based track seeding

500 – 1695 ns window



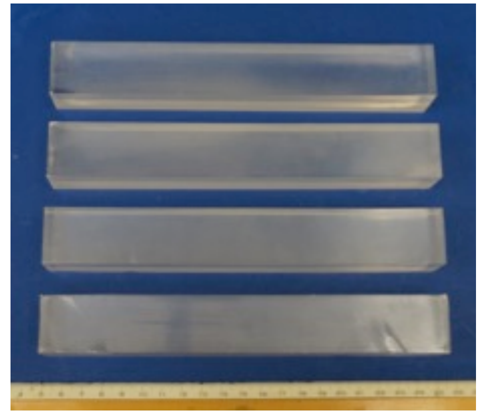
± 50 ns around conversion electron

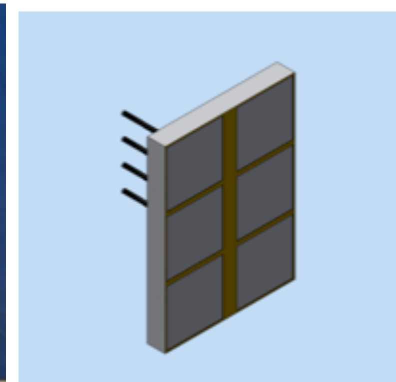


The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters → simplification/improvement of pattern recognition.

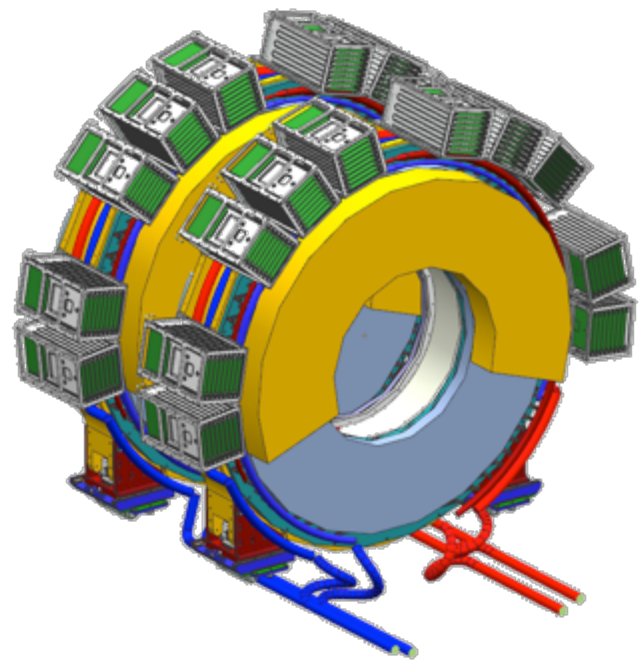
Mu2e Calorimeter Design

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. Waveform analysis for pileup.
- Radioactive source and laser system provide absolute calibration and monitoring capability



High efficiency for 105 MeV electrons and:

→ Provide energy resolution σ_E/E of O(5 %)

→ Provide timing resolution $\sigma(t) < 500$ ps

→ Provide position resolution < 1 cm

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

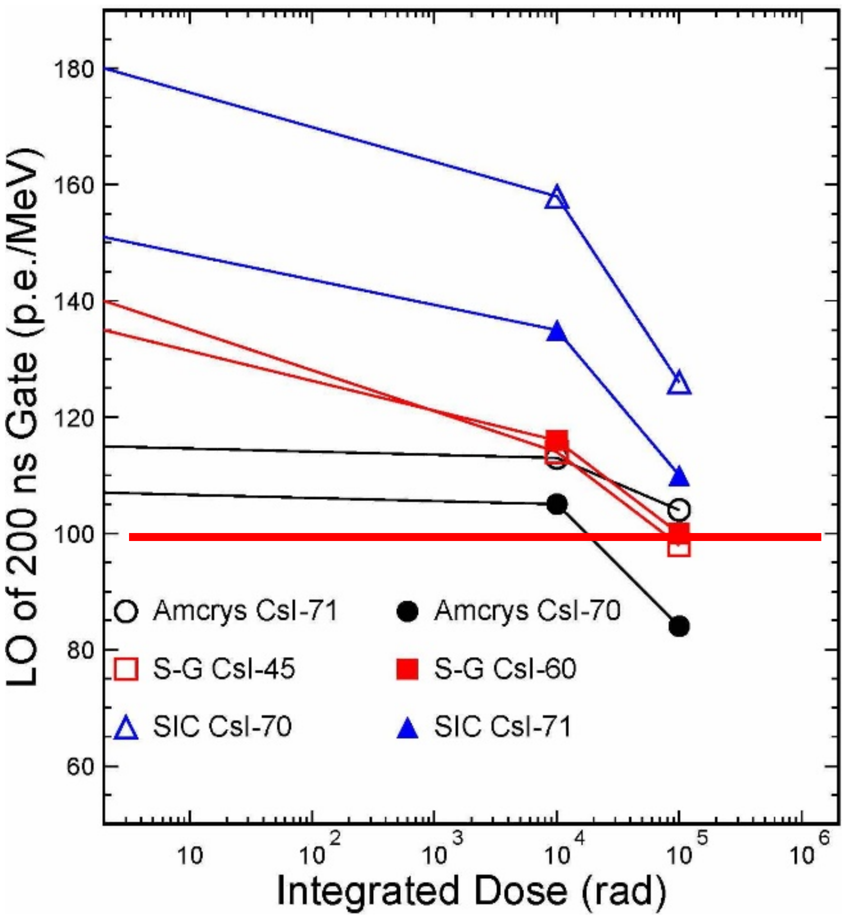
- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be "solar"-blind
- Medium cost 10$/cc

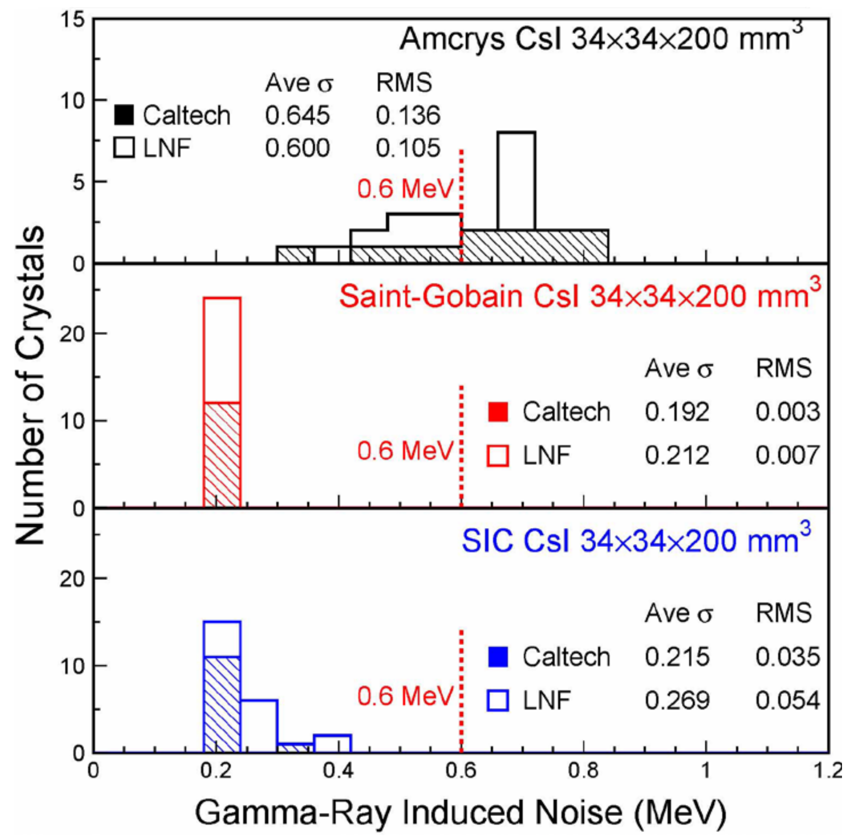
CsI(pure)

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)

Radiation hardness: dose & neutrons





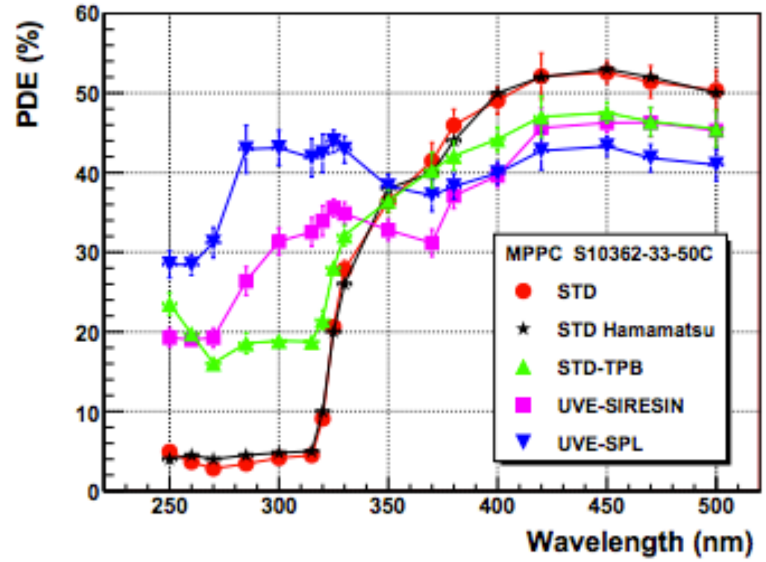
- CsI crystals rad-hard for expected dose in Mu2e-I
- No recovery after annealing
- Radiation Induce Noise (phosporescence) is larger for ionizing dose than for neutrons

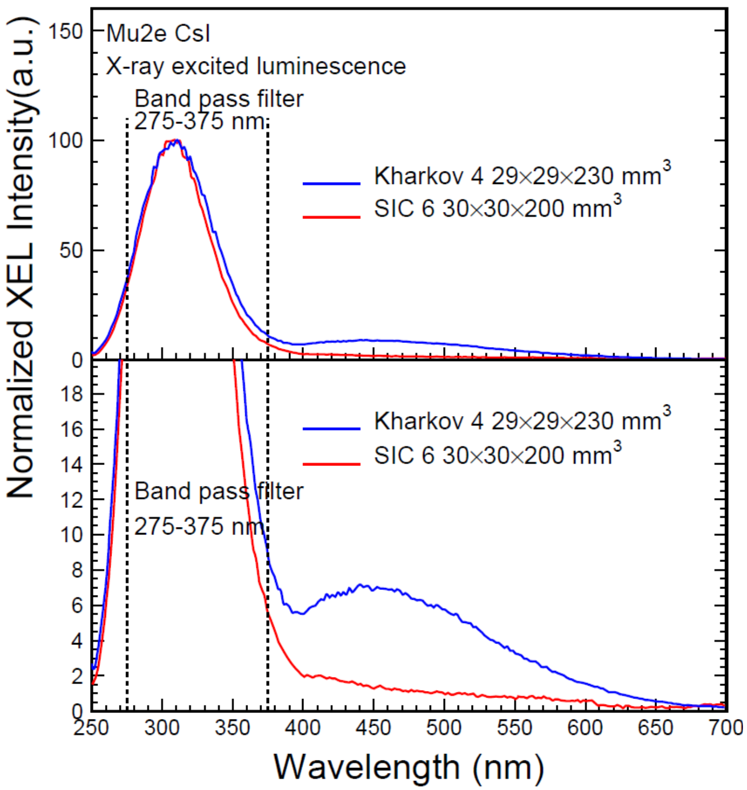
UV extended SiPM

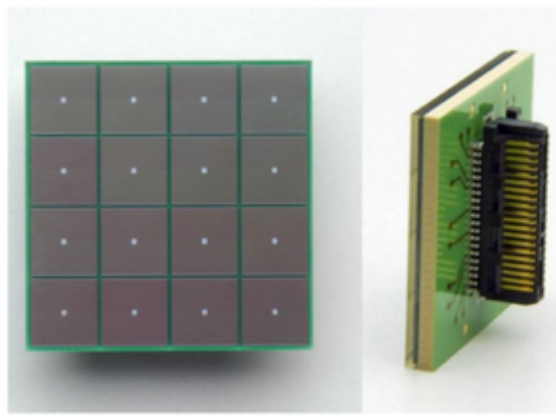
The PDE of UV-enhanced MPPC is higher below 350 nm

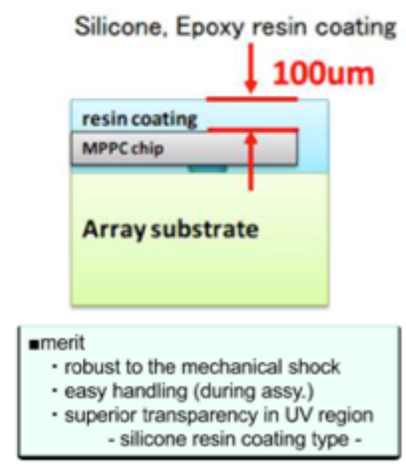
Imaging with SiPMs in noble-gas detectors: arXiv 1210.4746

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







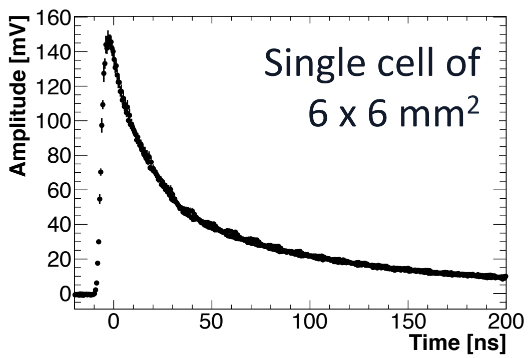


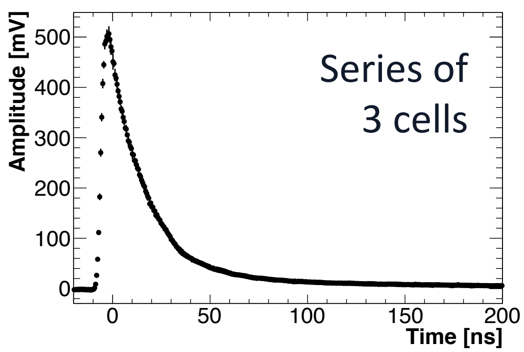
Mu2e custom SiPMs design

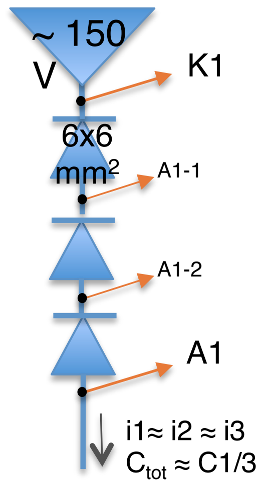
Mu2e custom silicon photosensors:

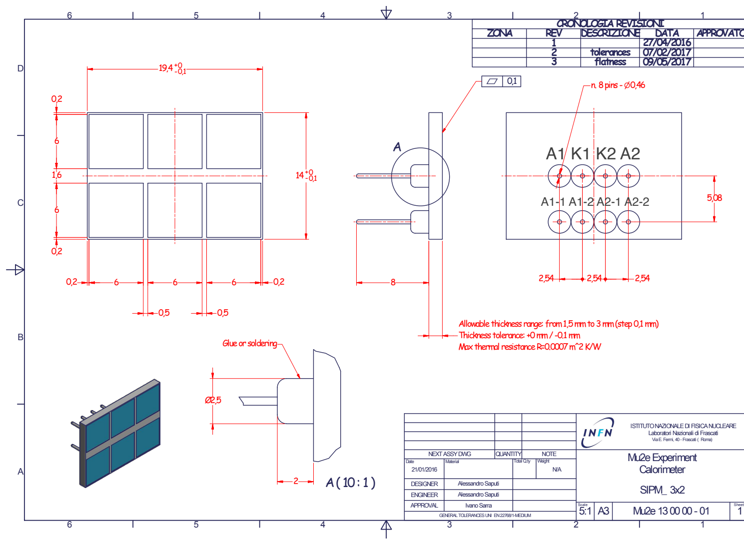
→ **2 arrays of 3 6 x 6 mm² UV-extended SiPMs for a total active area (12x18) mm²**

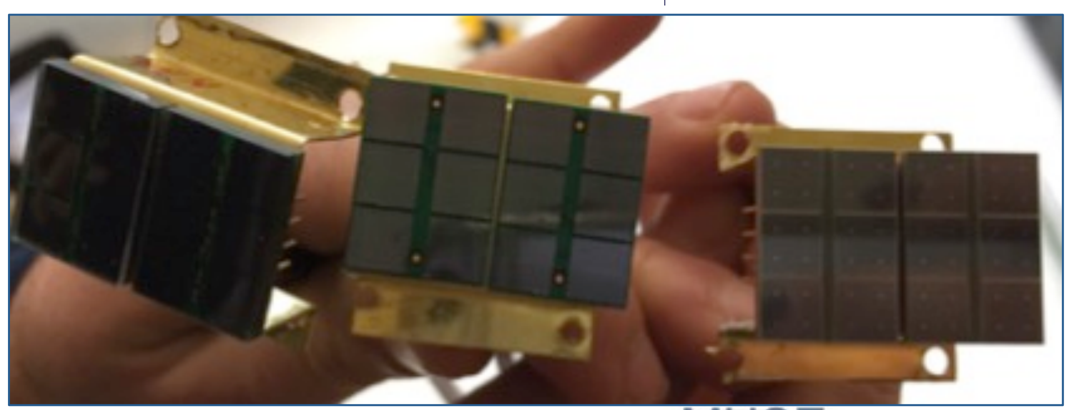
The series configuration reduces the overall capacity and allows to generate narrower signals





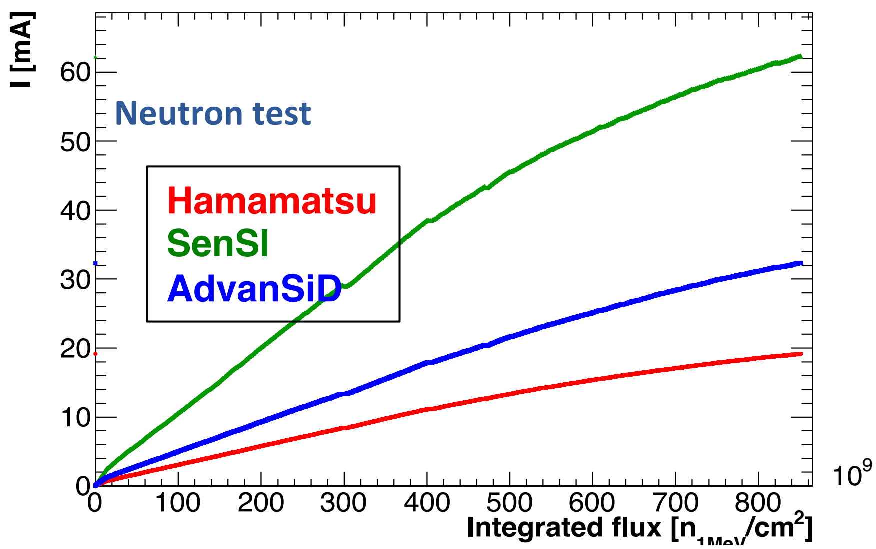


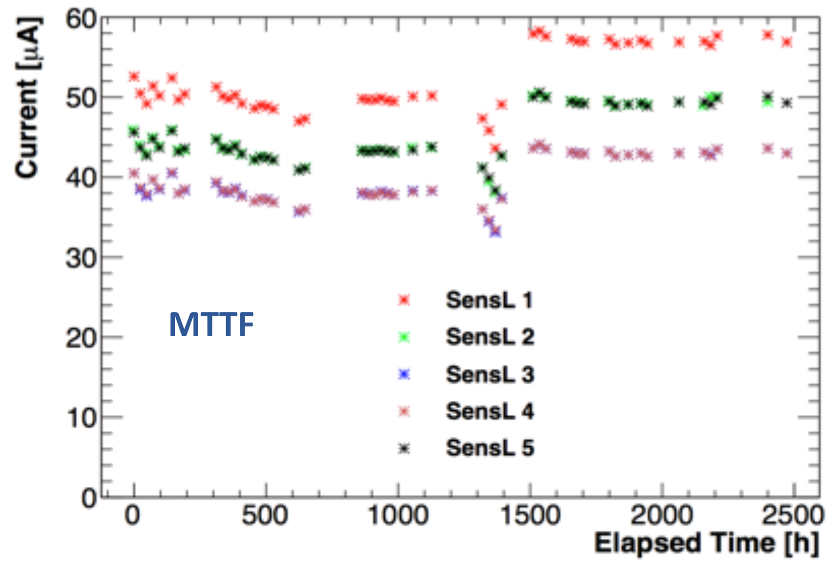




Irradiation and MTTF of SiPMs

- ✓ 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

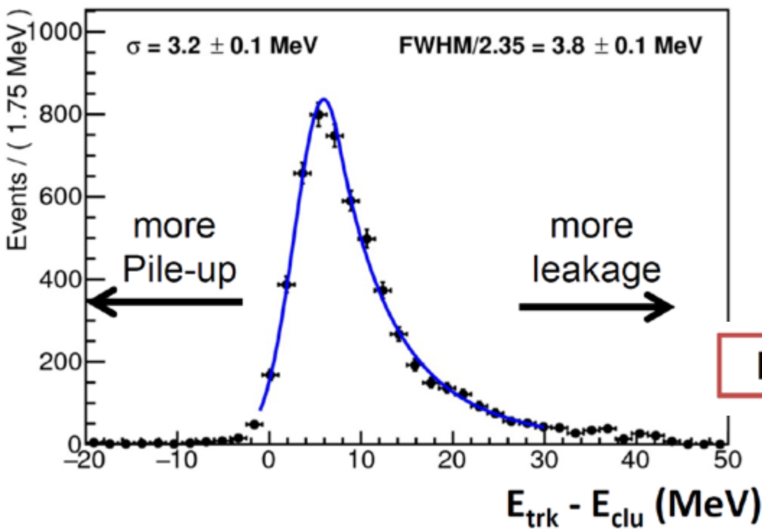
→ a decrease of 10 °C in SiPMs temperature corresponds to a I_d decrease of 50%
→ Lower V_{op} also helps to decrease I_d

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

- MTTF evaluated operating SiPMs @ 65 C
- No dead channels observed

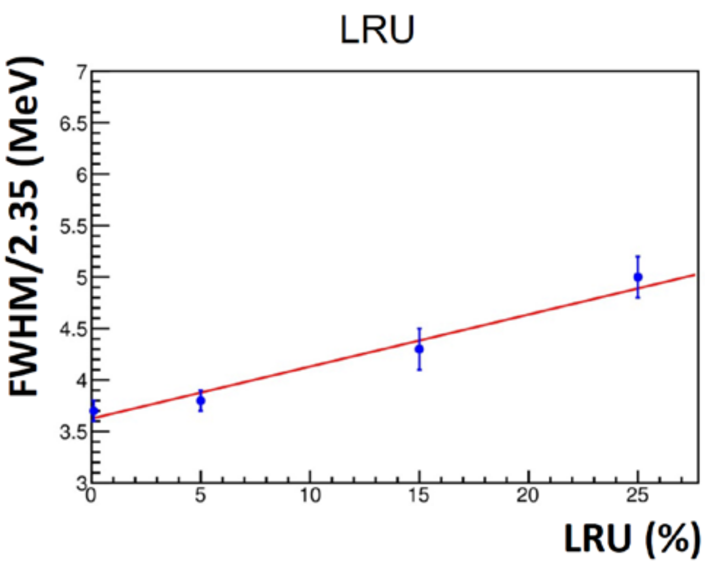
MTTF ≥ 10^6 hours

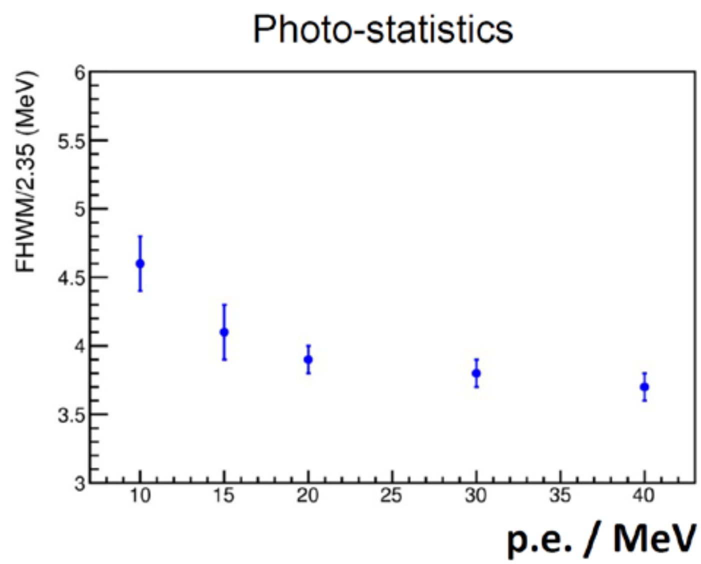
Simulated performances



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

FWHM / 2.35 = 3.8 ± 0.1 MeV

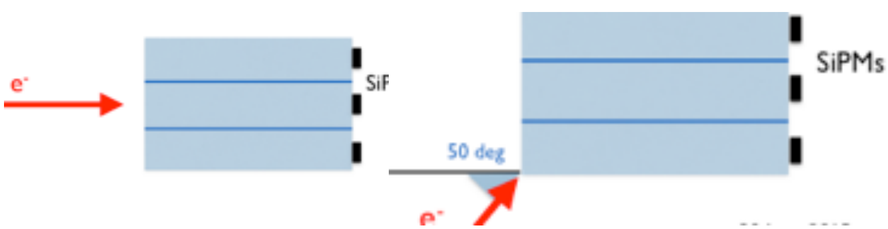


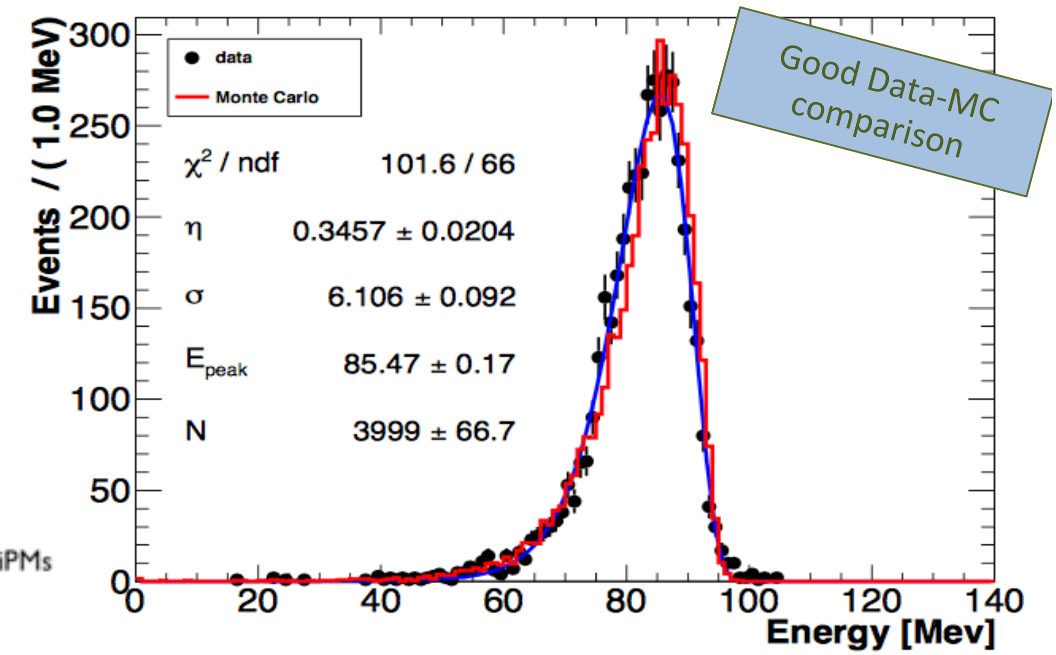


Mu2e small size prototype

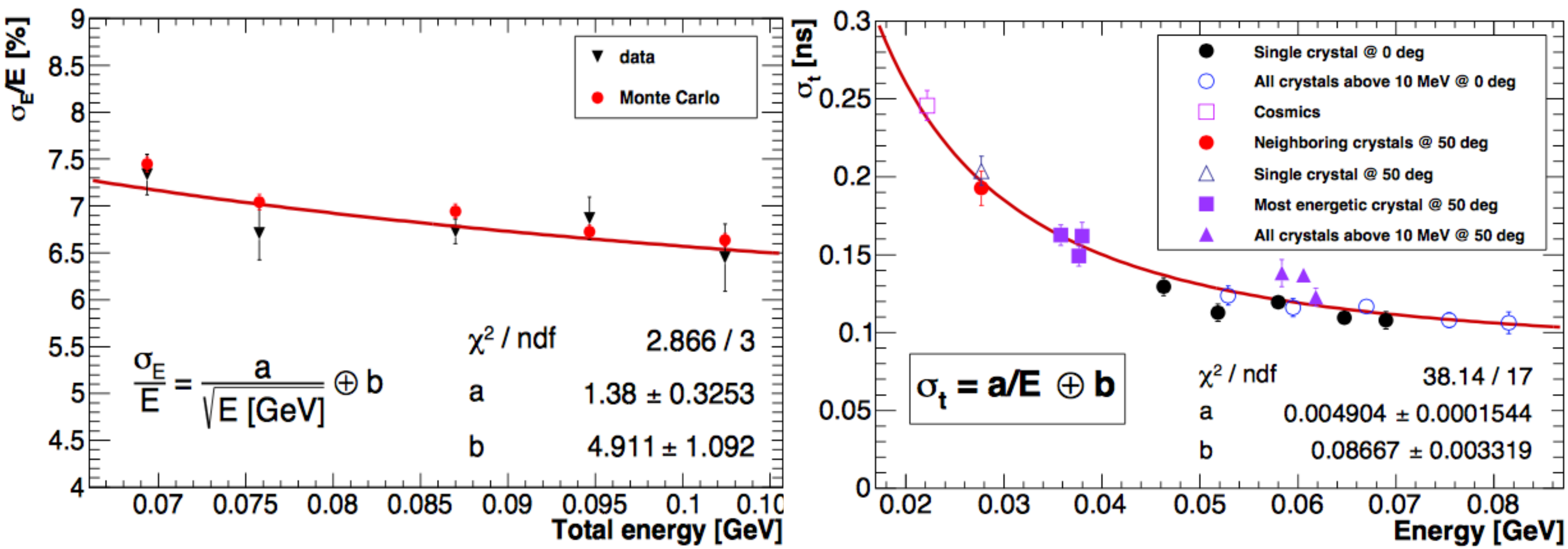
- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of 30×30×200 mm^2 undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm^2 with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

JINST 12 (2017) P05007





Mu2e small size prototype



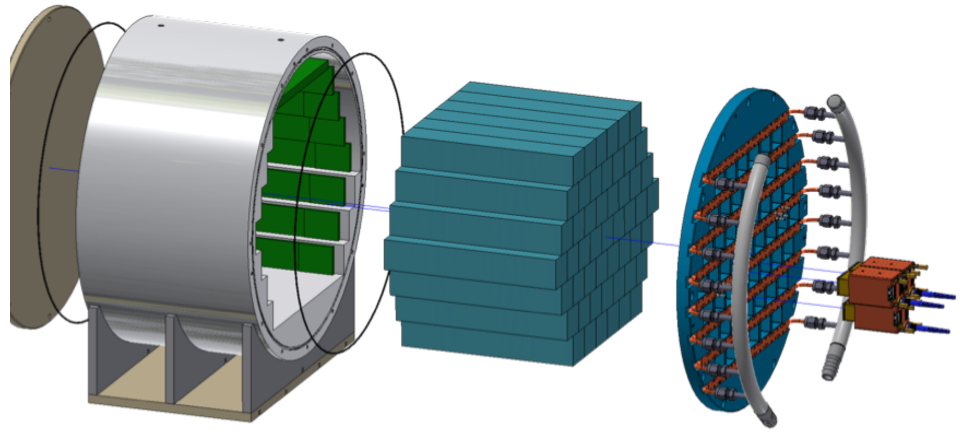
σ_E ~ 6.5% at 100 MeV **σ_T ~ 110 ps at 100 MeV**

Significant leakage contribution due to the matrix dimensions

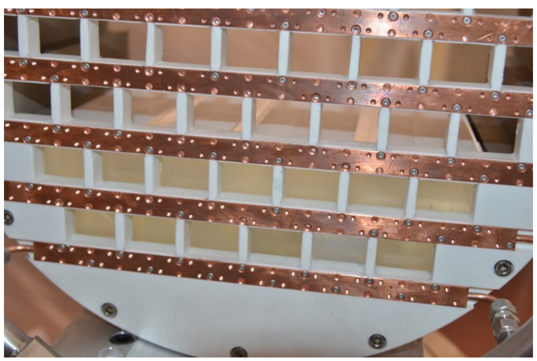
Module-0 prototype

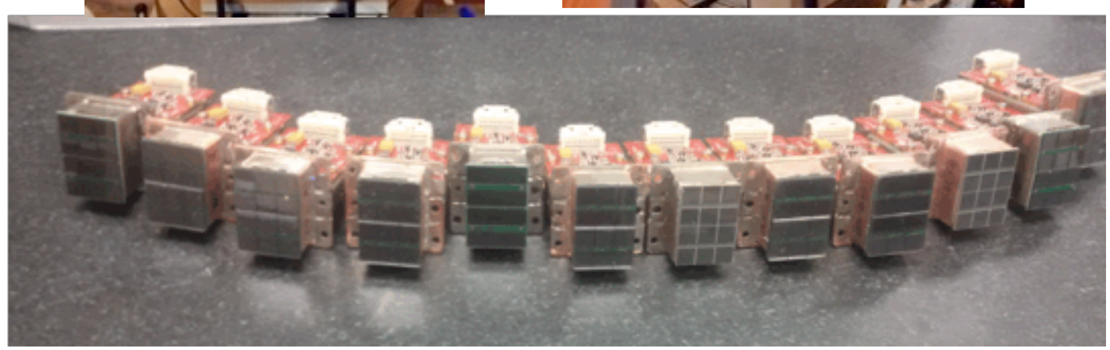
Large size prototype of
the disk assembled April 2017

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



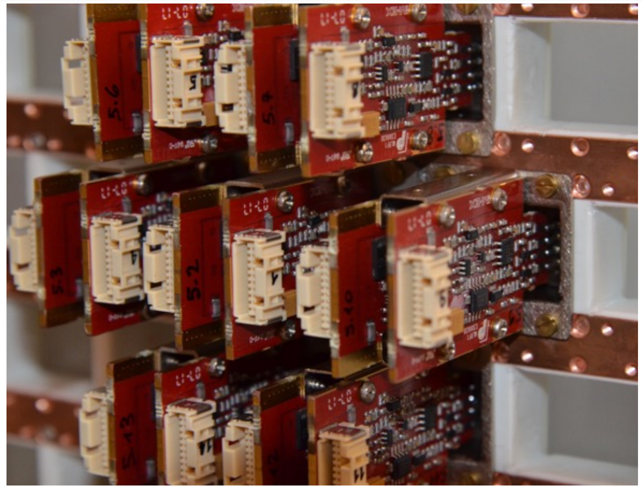
Assembly of back disk in
ZEDEX on Al support disk

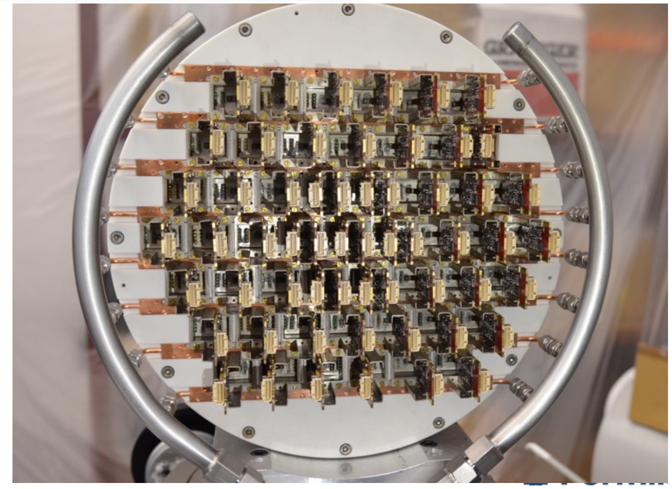


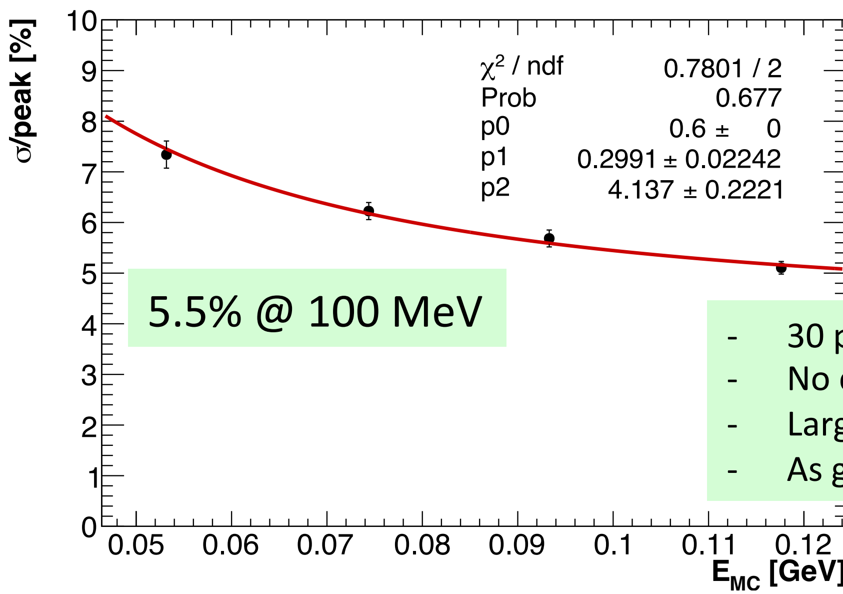


Module-0: test beam results

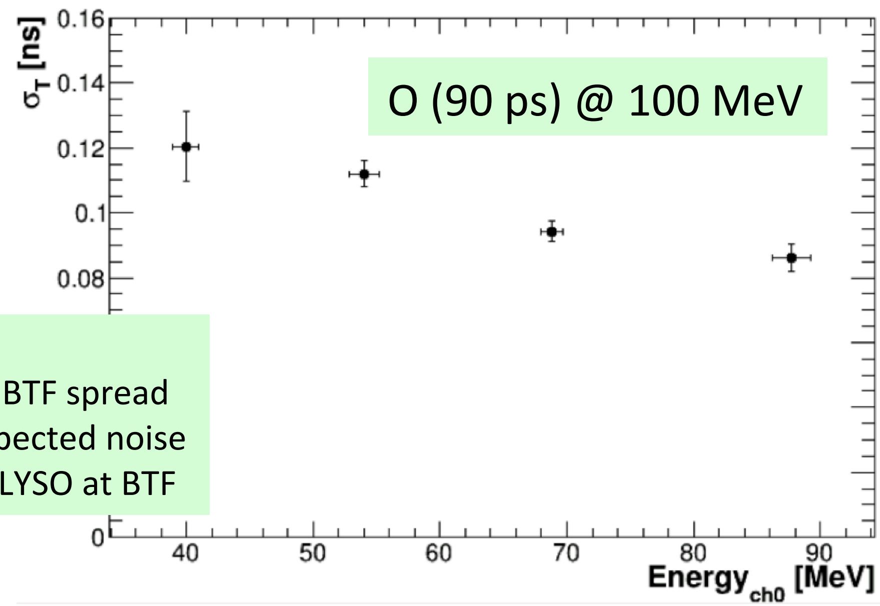
- Tested at BTF @ 50 Hz
- **No optical grease**
- Final shapes and components
- Running at 20 °C
- Now working under vacuum and 0 °C
- **New sets of test planned w neutrons, high rate beams**







5.5% @ 100 MeV



O (90 ps) @ 100 MeV

- 30 pe/MeV
- No corr for BTF spread
- Large unexpected noise
- As good as LYSO at BTF

Working on data at 50 degrees angle to simulate Conversion Electrons

Conclusions

- Albeit **at low energy (< GeV)** tracking systems ARE fundamentally more precise than a calorimeter **YET there are many reasons to built calorimeters:**
  → (obvious) Photon reconstruction
  → Fast triggering & Particle Identification
  → Resolving pileup in high intensity

- Nowadays highest precision in HEP calorimeter at low energies comes from liquid Xe (Ar, Kp) thanks to their homogeneity and high scintillating properties. **They can be extremely fast.**

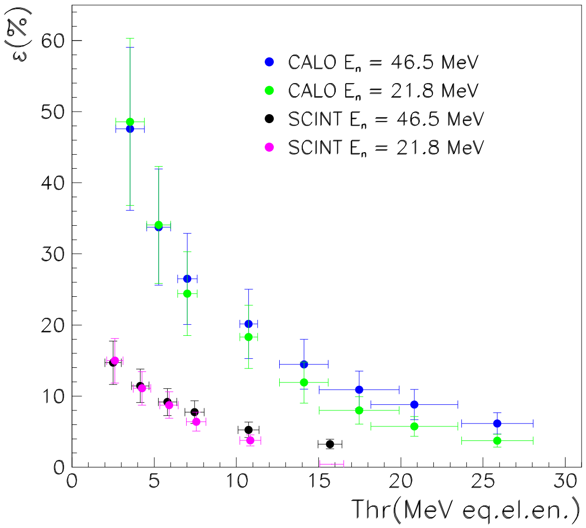
- Crystal calorimetry is "reborn" at low energies (also in presence of large B-fields) thanks to the great improvement on the photosensor side.

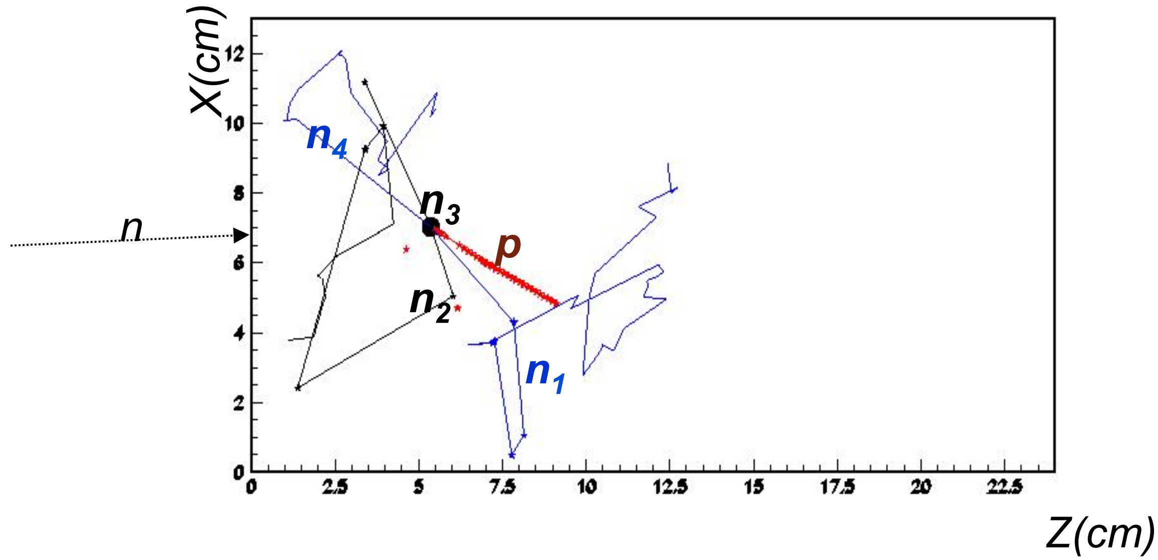
→ **large area SiPMs are now almost similar to PMTs (size, cost, .. noise).**
→ **SiPMs are also improving their PDE in the UV regions.**

They are getting better and better as noise term and as rad-hard resistance are concerned → thus opening the road to work at really high intensity

ADDITIONAL MATERIAL

KLONE = KLOe NEutron detection





- Detection of *n* of few to few hundreds MeV is traditionally performed with **organic scintillators** (el.scattering of *n* on H atoms produces protons detected by the scintillator) ⇒ **efficiency or O(1%/cm)**
- High-Z material improves neutron efficiency [NIM A297 (1990), NIM A338 (1994) NIM B192 (2002)]
- A KLOE Calo Small Size prototype tested at "The Svedberg Laboratory" (TSL) of Uppsala (October 2006 and June 2007) with 22, 46 and 174 MeV neutron beam.
- **<u>IMPROVED EFFICIENCY (x 4) with respect to an equivalent "thickness" of scintillator slab.</u>**
- Full FLUKA simulation performed:

  → suggest huge inelastic production of secondary neutrons at lower energy in the lead

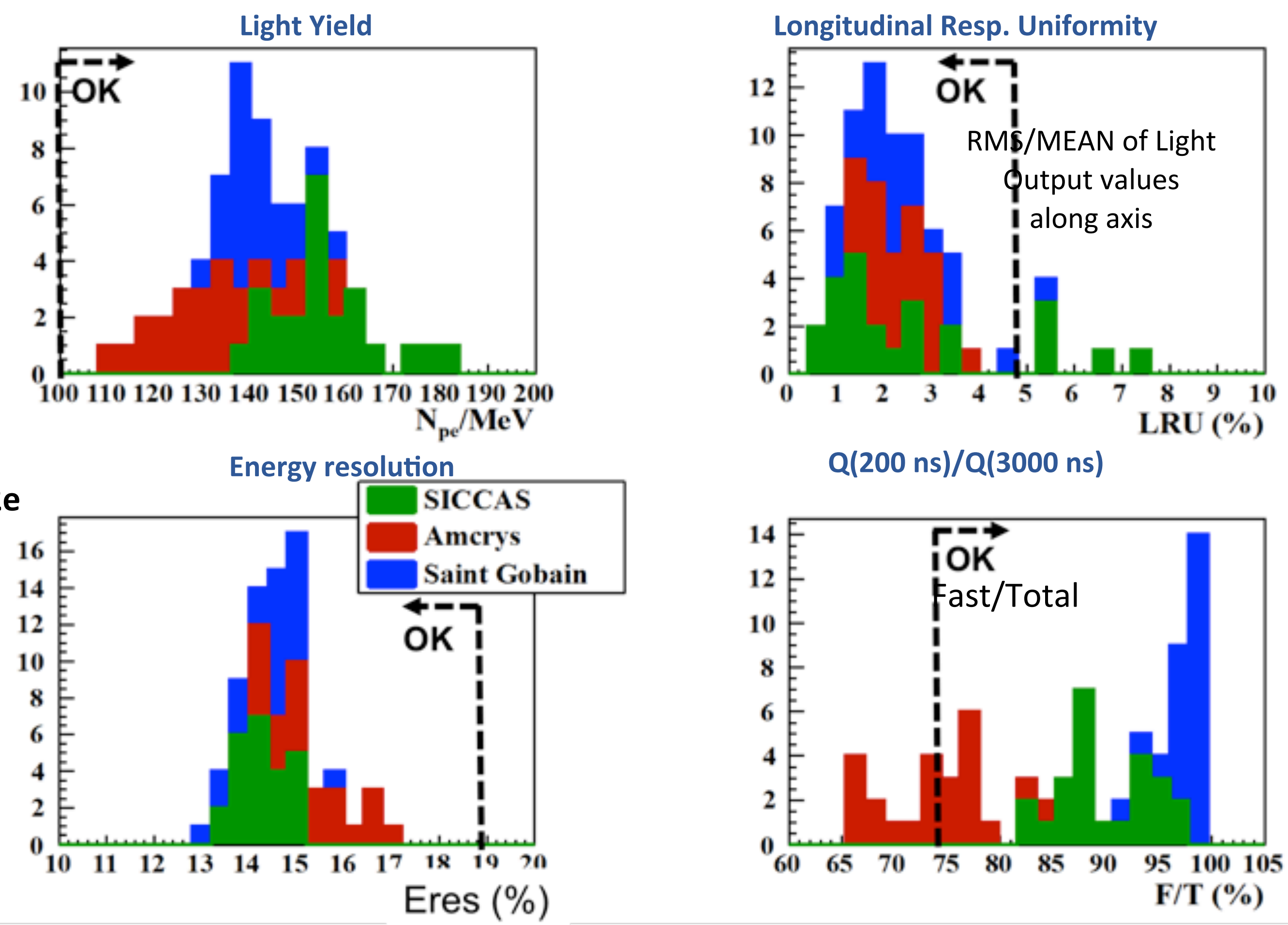
  → they are accompanied by em fraction and protons. Then producing signals on scintillation side

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

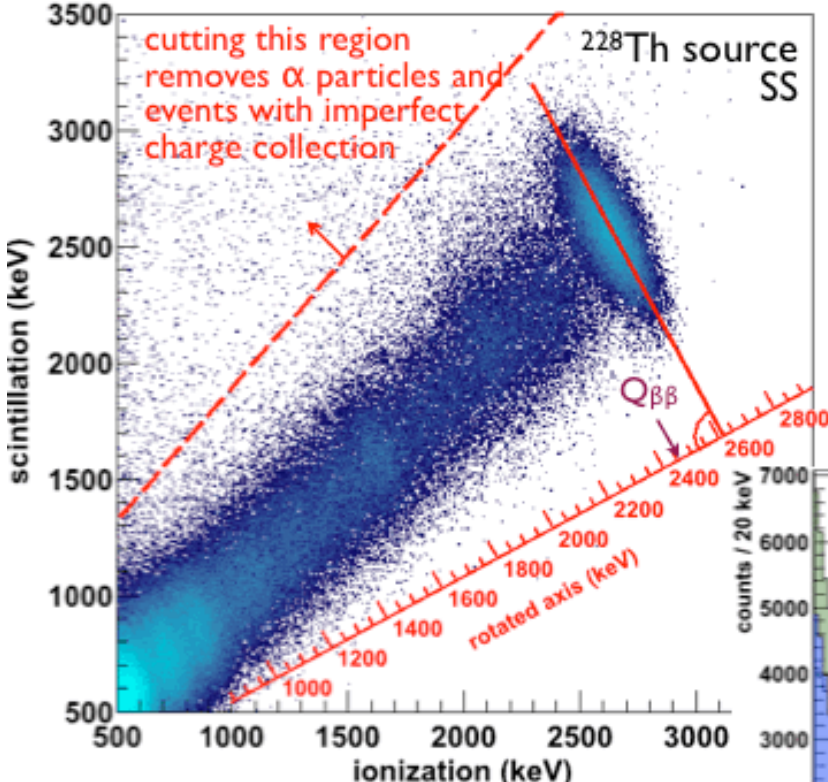
- ❑ **Excellent LRU and LY:**
  -100 pe/MeV with PMT readout
  - LRU < 5%
- ❑ τ of 30 ns with small slow component
- ❑ **Radiation hardness OK for Mu2e**
  Smaller than 40% LY loss
  @ 100 krad
- ❑ Small Radiation Induced Noise (Phosphorescence)



EXO: Liquid Xe, Ionization & Scintillation

EXO: Liquid Xe, Ionization & Scintillation

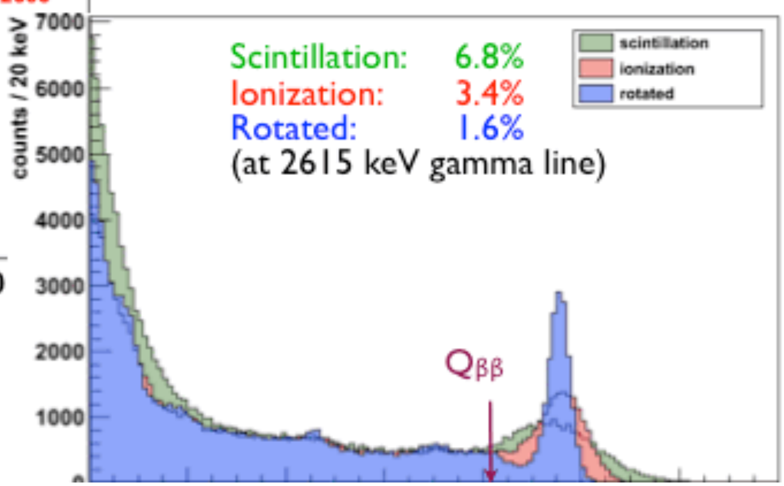
- Ngamma = E_deposited/Wph
- Wph = W /(1 + Nexcitation/Nionizing)
- W is average energy for e-ion pair production , Nexciton and Nionization



Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

E. Conti et al. Phys. Rev. B 68 (2003) 054201

Use projection onto a rotated axis to determine event energy



Rotation angle chosen to optimize energy resolution at 2615 keV

Liquid Xenon LY, Tau

Table 2
(a) Decay times for fast (τ_S) and the slow (τ_T) components of scintillation light from liquid Ar, Kr and Xe excited by 1 MeV electrons. τ_R, the recombination time, and the intensity ratios I_S/I_T of fast component to the slow components are also shown. All decay times are in ns
(b) Decay times for fast (τ_S) and the slow (τ_T) component of scintillation light from liquid Ar, and Xe excited by α-particles. The intensity ratios I_S/I_T of the fast component to the slow component are also shown. All decay times are in ns

(a)	Liquid Ar	Liquid Kr	Liquid Xe
τ_S	6.3 ± 0.2^a ns (5.0 ± 0.2 ns for $E = 6$ kV/cm)^b 6 ± 2^b	2.0 ± 0.2^a ns (2.1 ± 0.3 ns for $E = 4$ kV/cm)^b	(2.2 ± 0.3 ns for $E = 4$ kV/cm)^b
τ_T	1020 ± 60^a, 1590 ± 100^b ns (860 ± 30 ns for $E = 6$ kV/cm)^b	91 ± 2^b ns (80 ± 3 ns for $E = 4$ kV/cm)^b	34 ± 2^b ns (27 ± 1 ns for $E = 4$ kV/cm)^b
τ_R	< 1 ns		45^a ns
I_S/I_T	0.083^b (0.045 for $E = 6$ kV/cm)^b 0.3^a	0.01^b (0.02 for $E = 4$ kV/cm)^b	0.05 for $E = 4$ kV/cm)^b

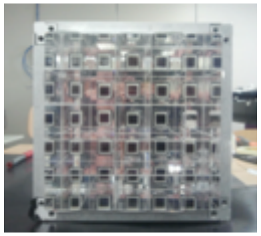
(b)	Liquid Ar	Liquid Xe
τ_S	7.7 ± 1.0^a ns $\sim 5^b$ ns	4.3 ± 0.6^a ns 3^c ns
τ_T	1660 ± 100^a ns 1200 ± 100^b ns	22 ± 1.5^a ns 22^a ns
I_S/I_T	1.3^a	0.45 ± 0.07^a 1.5^a ns

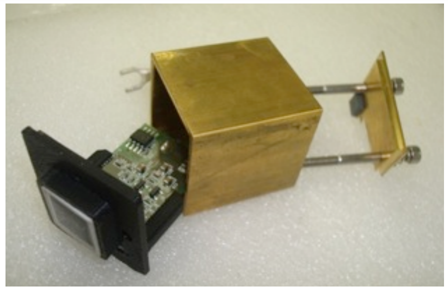
Liquid Xenon LY

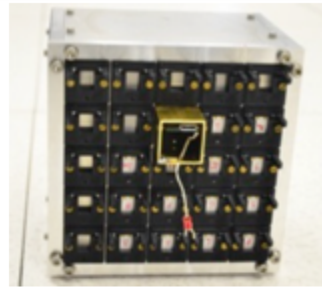
Table 1
Measurements and estimates of the average energy needed to produce a scintillation photon, W_{ph}(eV) in liquid Xe

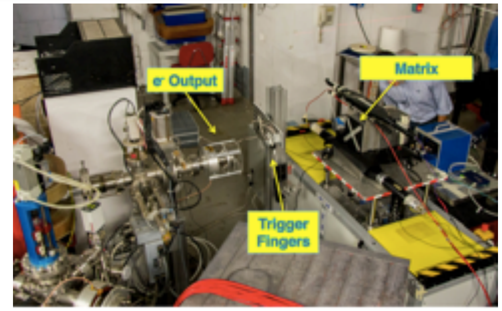
Liquid rare gas	Relativistic electrons	α-particles	Relativistic heavy particles (W'_{ph} (eV))
Ar	25.1 ± 2.5	27.5 ± 2.8	19.5 ± 2.0
Xe	23.7 ± 2.4	19.6 ± 2.0	14.7 ± 1.5
	(< 35)[a]	(16.3 ± 0.3)[b]	
	(67 ± 22)[c]	(39.2)[d]	
	(29.6 ± 1.8)[e]		
	(14.2)[f], $(12.5, 12.3)$[g]		
	(42 ± 0.6)[h]		
NaI(Tl)	$(17.2 \pm 0.4, 16.5 \pm 0.4)$[i]		

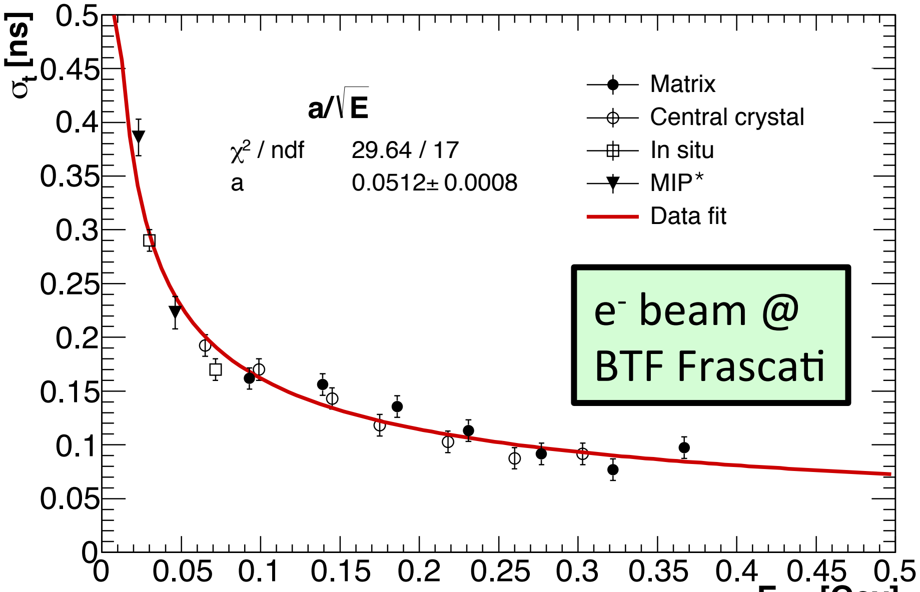
LYSO Legacy



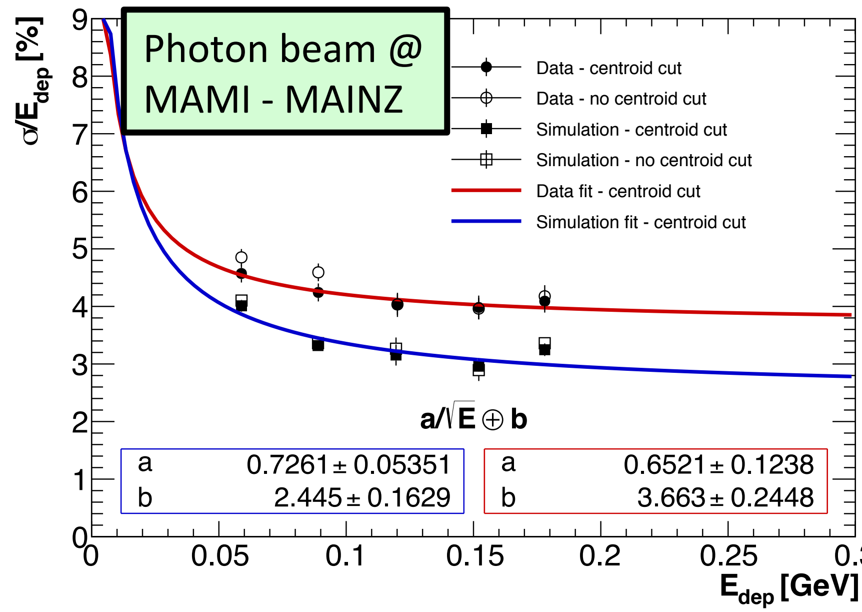








*Time resolution with MIPs from Mu2e DocDB 4409



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).