The calorimeter project for the Mu2e experiment

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On behalf of the Mu2e Collaboration

Frontier Detectors for Frontier Physics
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La Biodola, Isola d'Elba (Italy)
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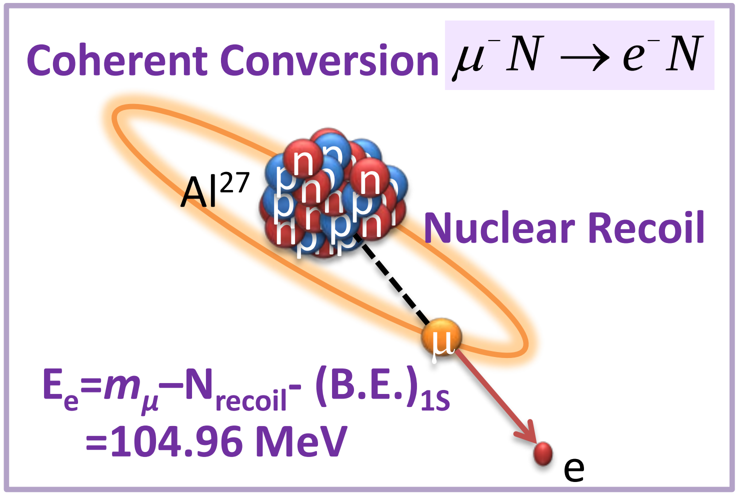
Outline

- The Mu2e experiment
- Electromagnetic Calorimeter (EMC) Requirements
- Conceptual Design
- Reconstruction Capabilities
- Test Beam: Data/MC comparisons
- Technical Details
- Summary

The Mu2e experiment



- Detect **conversion of a muon to an electron** in the field of a nucleus

$$\mu^- + N \rightarrow e^- + N$$

- Charge Lepton Flavor Violation (CLFV) process
- In the Standard Model, BR($\mu^- N \rightarrow e^- N$)~$10^{-54}$
- Any signal is a compelling evidence of New Physics

- **MU2E Goal** $$R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow capture} < 6 \times 10^{-17}\ (90\%\ C.L.)$$

- **Current limits** (SINDRUM II at PSI) : $R_{\mu e} < 4.3 \times 10^{-12}$ (Ti), $R_{\mu e} < 7 \times 10^{-13}$ (Au)

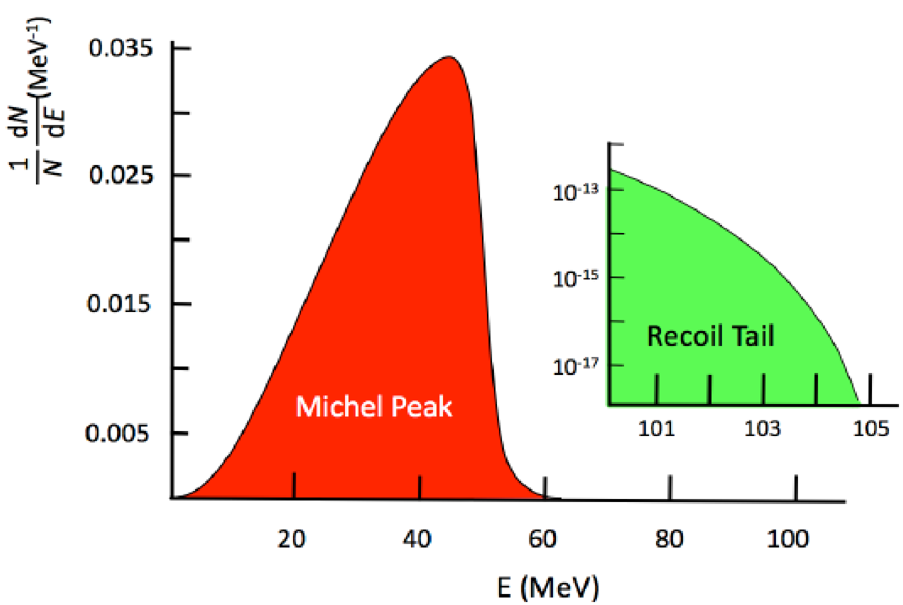
Muon Decay In Orbit (DIO)

- A **significant background** from Stopped Muons

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

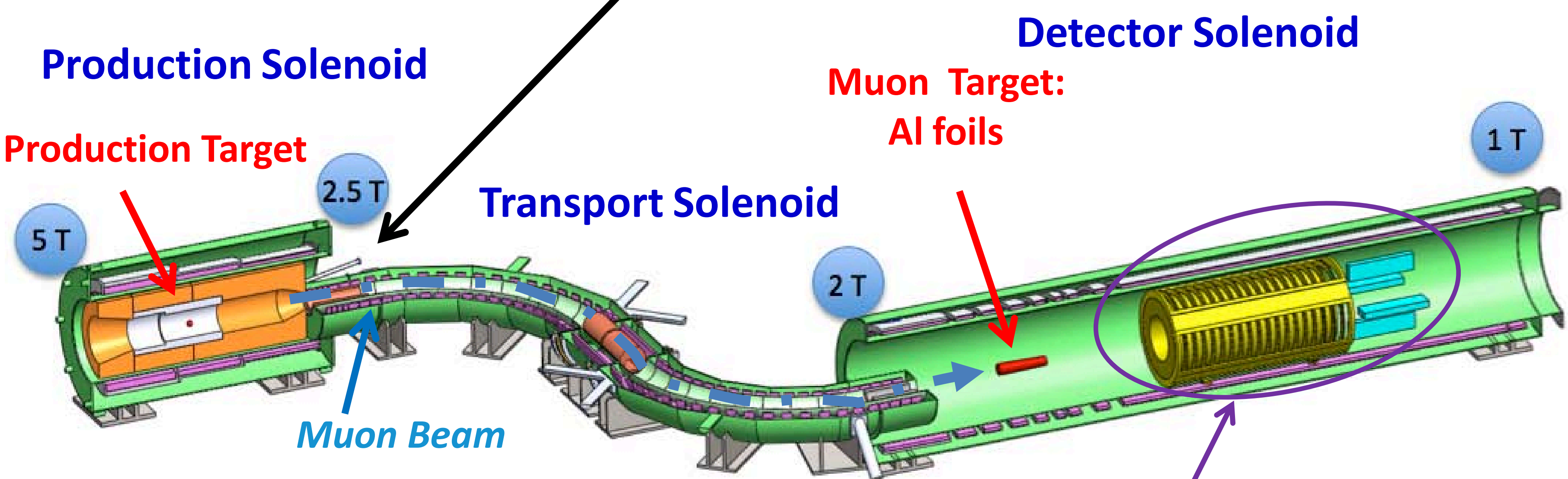
- Electrons from **decay of bound muons (DIO) ,**
- **Recoil tail extends to conversion energy, with a rapidly falling spectrum near the endpoint** $prob \sim (E_{conv} - E)^5$

μ Decay in Orbit Spectrum for ^{27}Al



The Mu2e apparatus

Pulsed Proton Beam:
8 GeV protons produced by the Fermilab accelerator



DETECTORS:

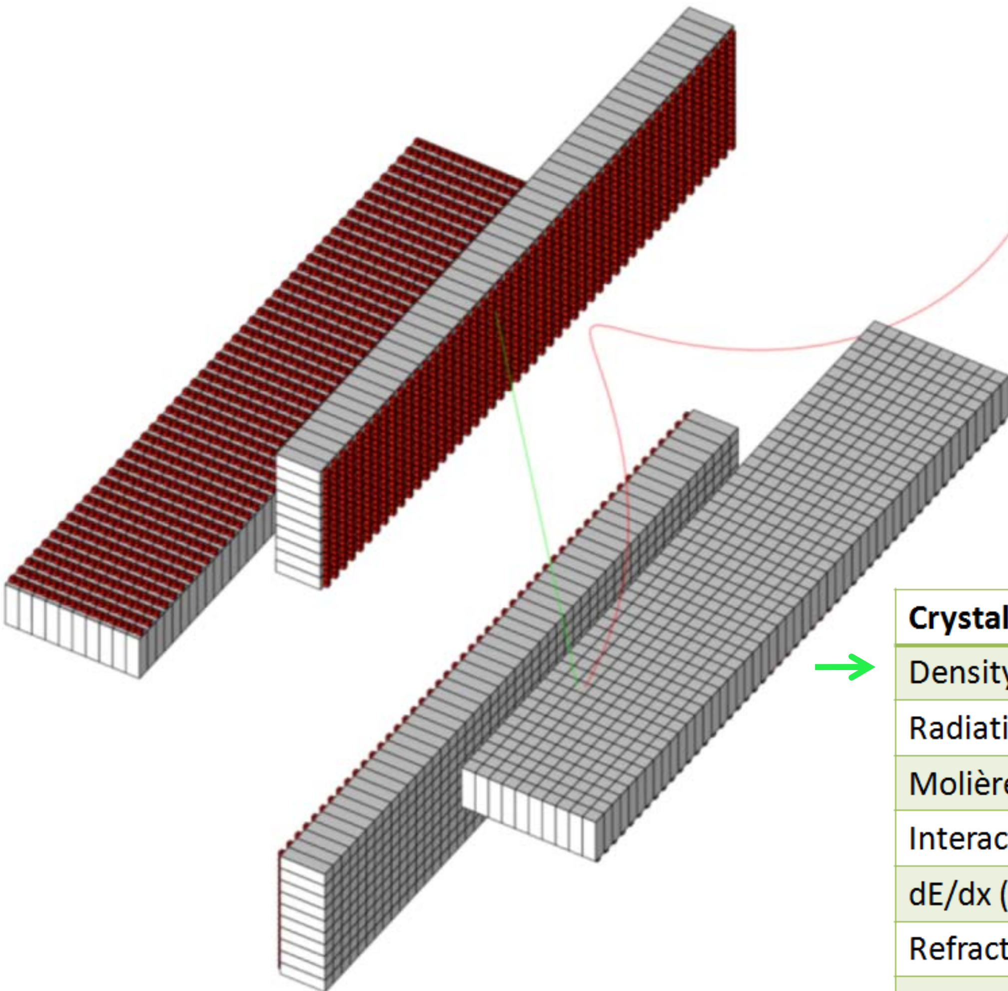
- ▶ **Tracker** measures *e*- momentum with excellent intrinsic resolution (sigma core 115 keV/c , sigma tail 176 keV/c)
- ▶ **Calorimeter** after the tracker to confirm the signal

EMC Requirements

The calorimeter will be used to confirm that a reconstructed track is well measured, well identified conversion electron candidate and was not created by a spurious combination of hits in the tracker.

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

EMC Baseline Design



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

EMC Trigger Role

The EMC could be used to trigger /filter events in order to:

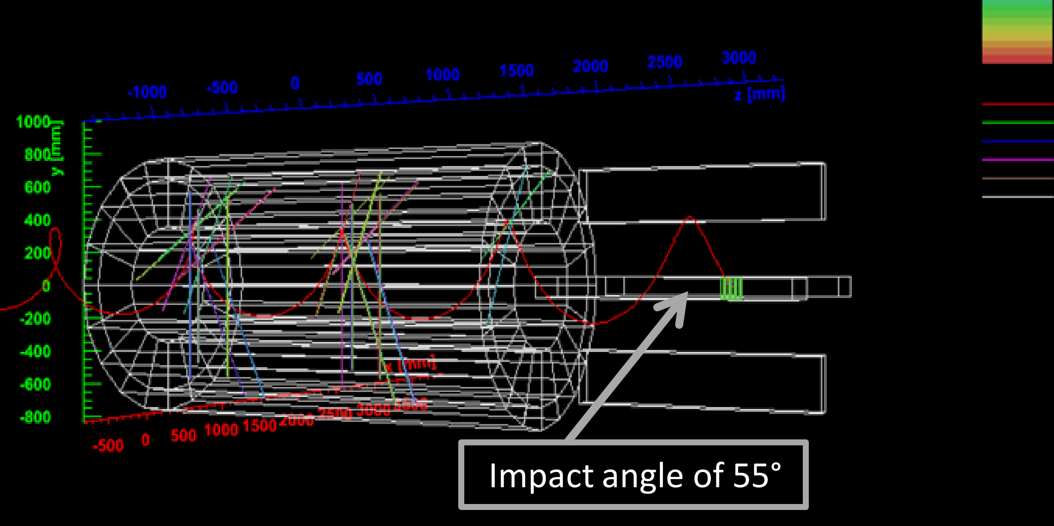
(i) reduce the writing on disk by a large amount (x200) in order to bring the 0.3 AB/year to O(few PB) storage (Tier1-like)

(ii) or reduce the Data Throughput from the detectors from 30 GB/s
→ few 100 MB/s

✧ **Keep high efficiency for signal events.**

✧ **To test it 100 k events with Signal and DIO (a significant bkg) have been simulated**

Mu2e events and trigger



✓ Event Display for a pure single event.

The trigger must isolate candidate conversion electrons from <u>background</u>

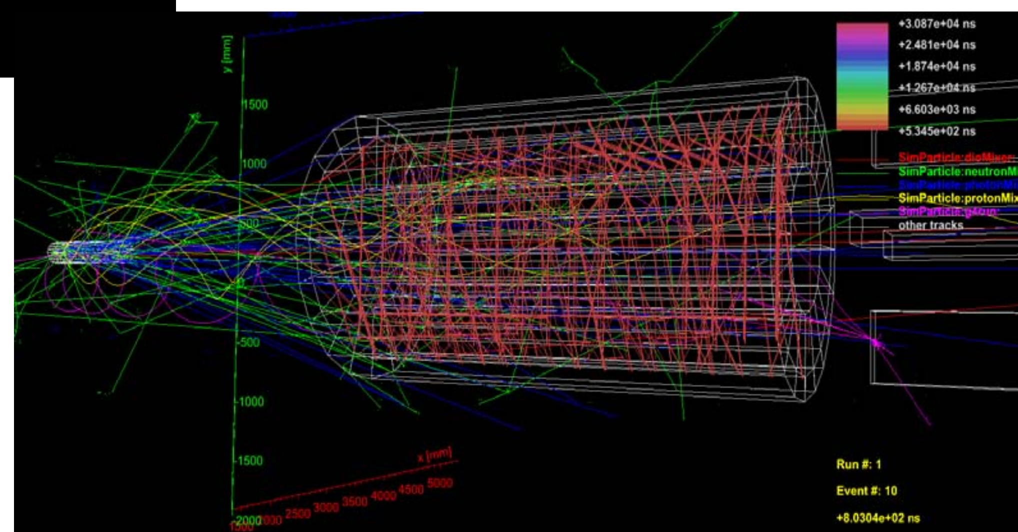
(n, p, γ from muon capture and beamflash)

- <u>Tracker-based trigger</u>

Organize tracker hits into tracks at FPGA level –difficult due to large number of hits

- <u>Calorimeter-based trigger</u>

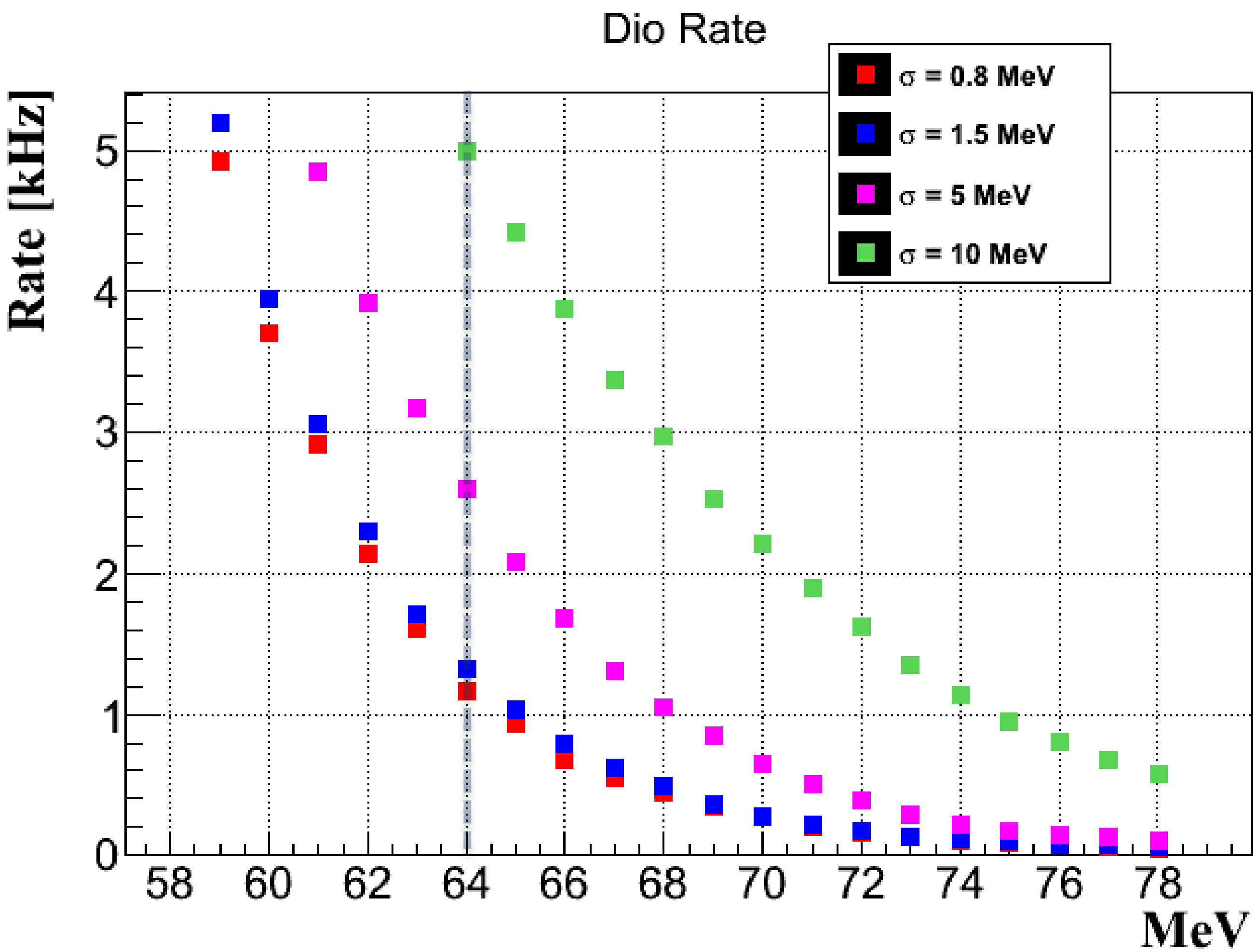
Organize crystal hits into clusters at FPGA level – straightforward, since most background hits are low energy (O(MeV))



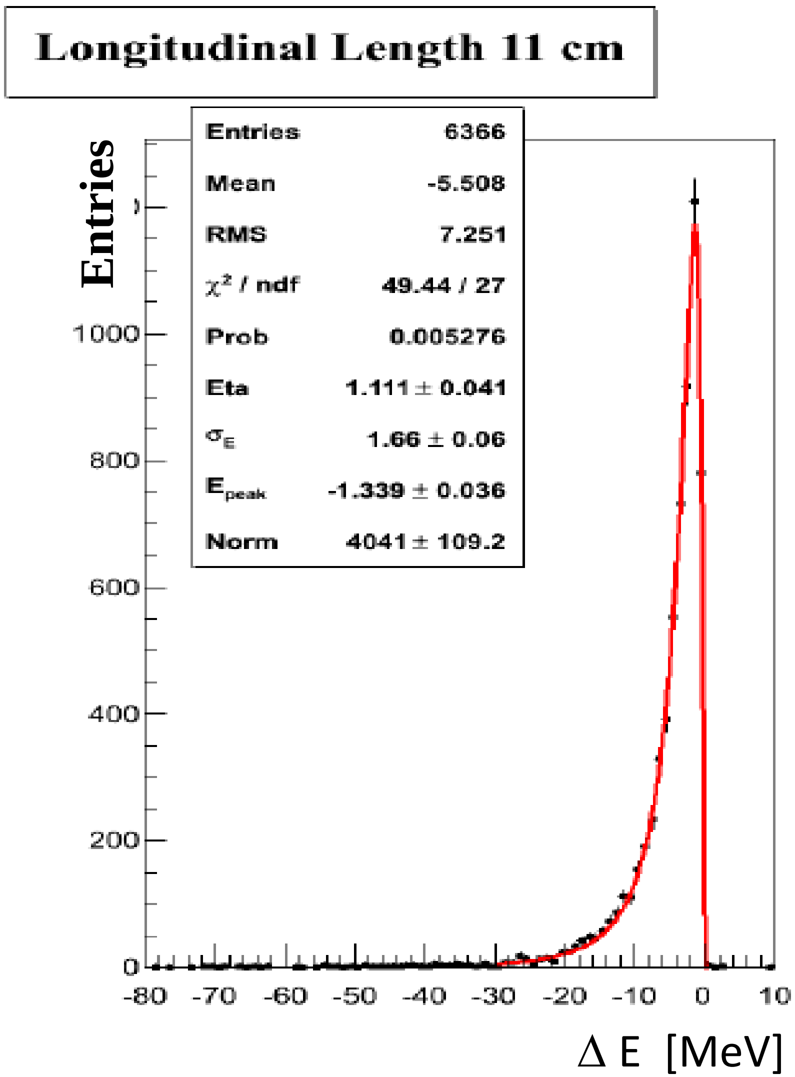
✓ Sig. + Bkg : ZOOM

EMC Trigger Capabilities

- ❑ Trigger algorithm just applies thresholds on reconstructed clusters
- ❑ 91% efficiency @ 64 MeV
- ❑ **DIO Rate reduction of 120: 200 kHz →1.5 kHz in Standalone Trigger Mode.**
- ❑ Rejection/efficiency depends on energy resolution



Intrinsic EMC Resolution in Mu2e



✧ 10k events simulated

By optimizing the vane dimension w.r.t to cost and resolution we found that:

<u>Resolution slightly depends on crystal length</u>

- **11 cm is a reasonable choice**
- Final vane dimensions:

11x44 crystals, $3x3x11\ cm^3$.

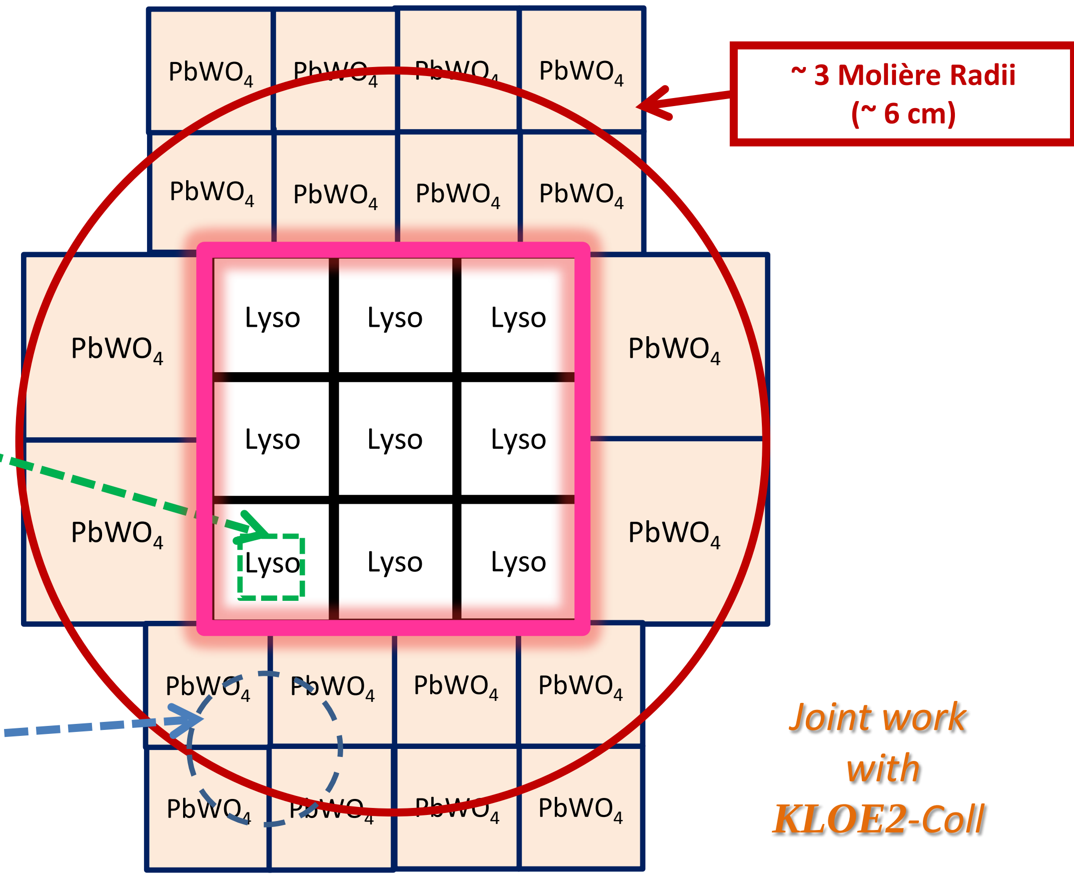
Test Beam @ MAMI: Layout of the prototype

After a first test done in 2009 at BTF(Beam Test Facility of LNF) with a smaller size prototype , a larger size matrix prototype has been built to test it with a clean tagged photon beam* at MAMI (Mainz Microtron, Germany) facility (March 2011).

The prototype consists of

1) An **INNER MATRIX** of 9 LYSO crystals
   - new LYSO from (Shanghai) SICCAS High Technology Corporation
   - *20x20x150 mm³* →
   - readout by 10x10 mm² **APDs** Hamamatsu S8664-1010

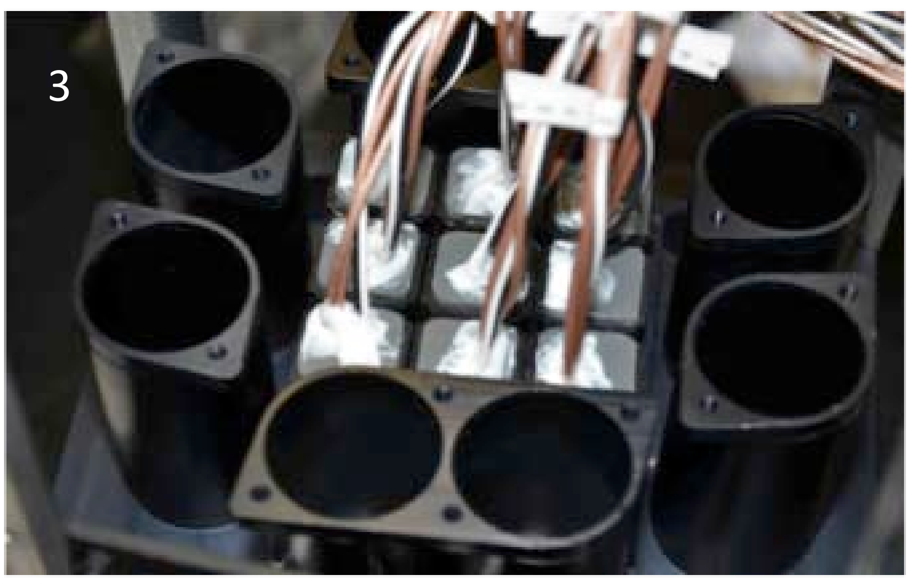
2) An OUTER MATRIX of 8 $PbWO_4$
   - for leakage recovery
   - crystals of mixed dimensions: 30(40)x30(40)x130 mm³
   - readout by **1 inch PMTs.**



Joint work with ***KLOE2-Coll***

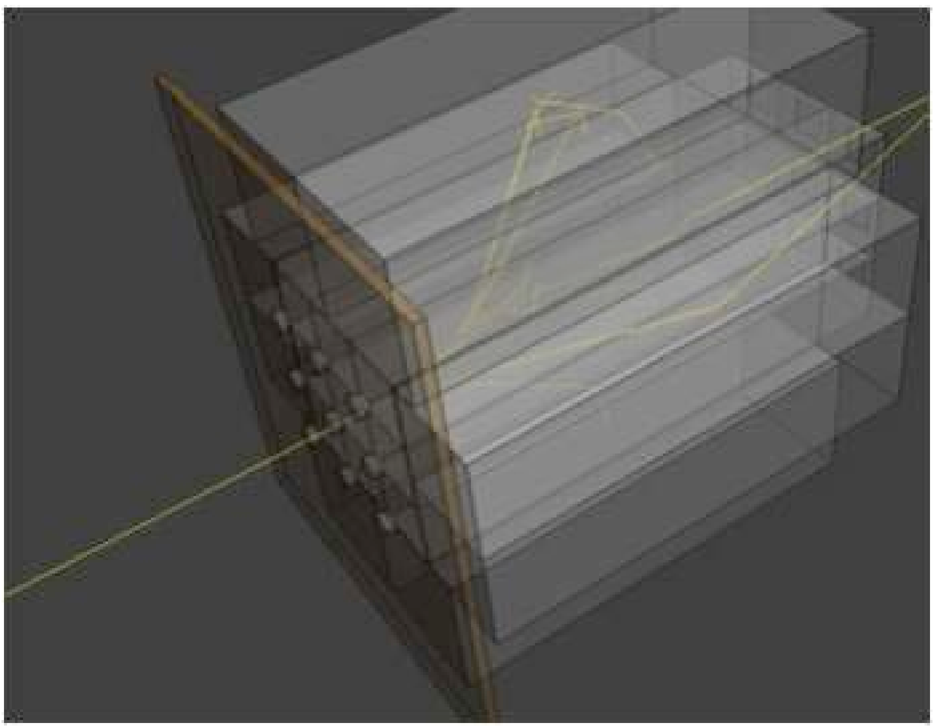
*Tagged photon beam with excellent ΔP(FWHM) = 1 MeV

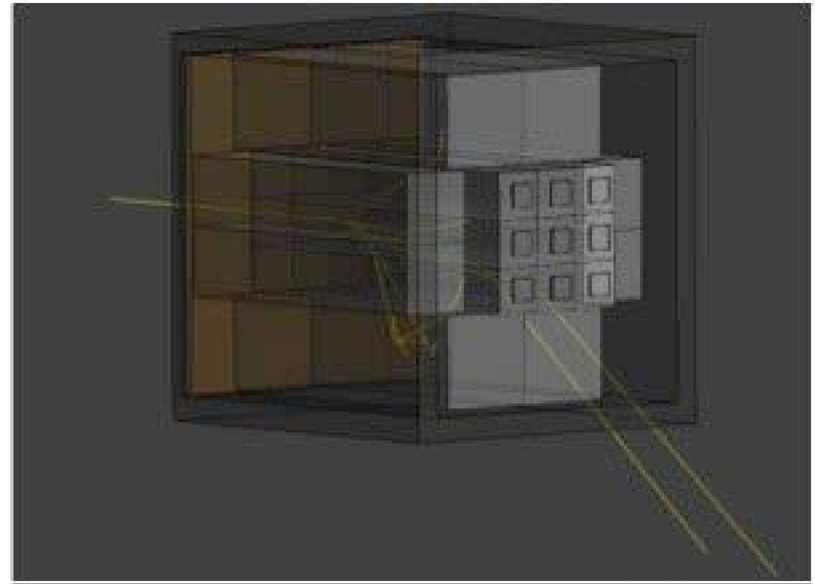
Matrix: stages of assembly

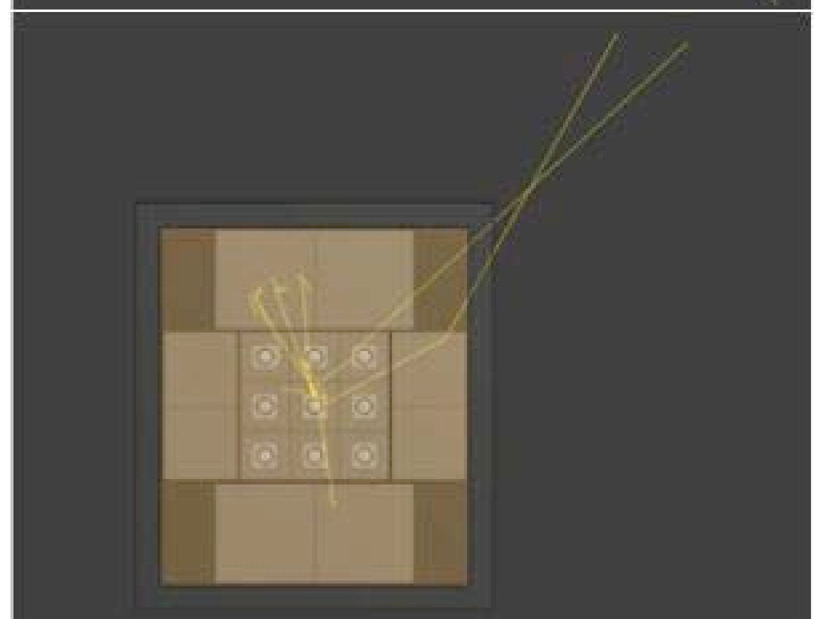


MC Simulation of Test Beam

- 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.



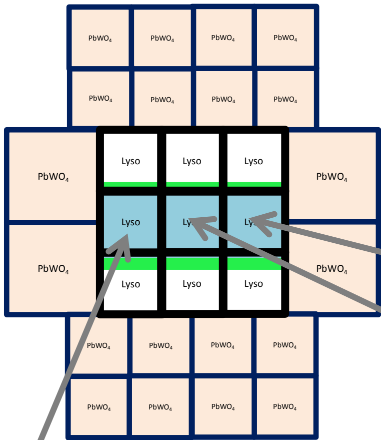


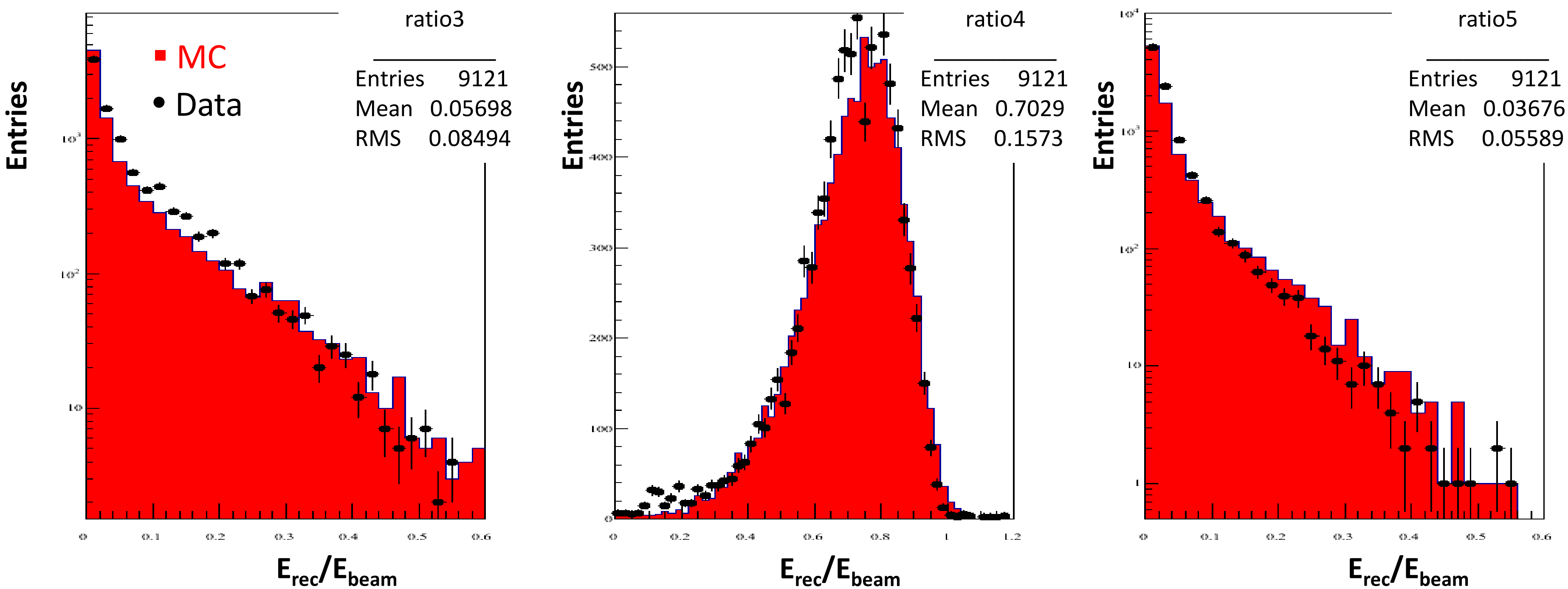


Data/MC comparison

Ebeam=100 MeV; on center

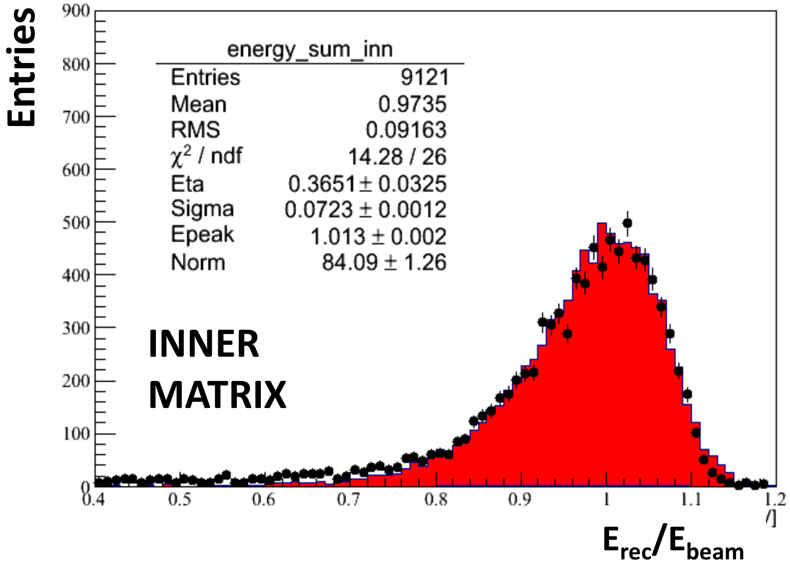
Analysis of Test Beam data completed with full calibration of external matrix by means of an horizontal scan with photons.

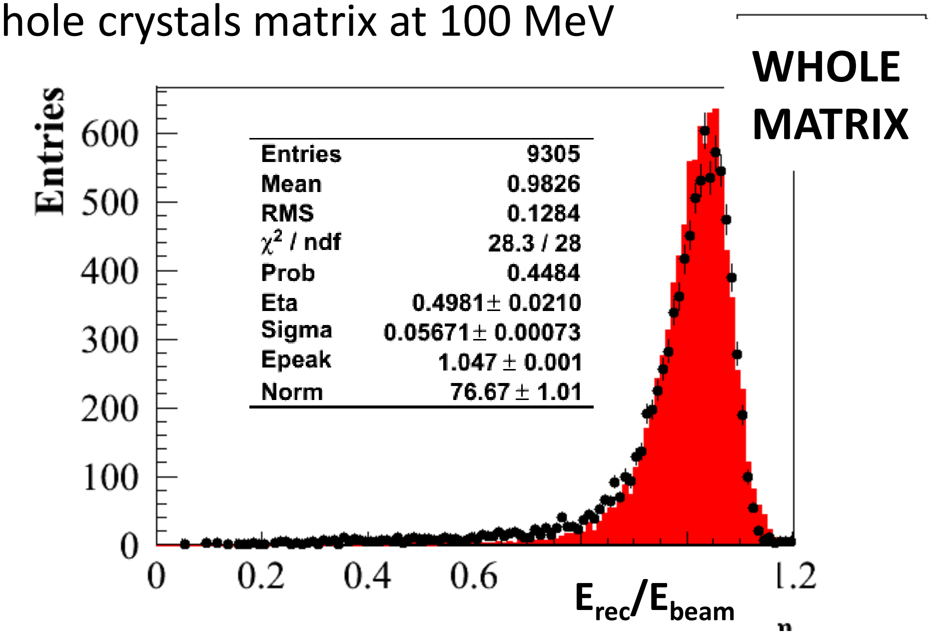


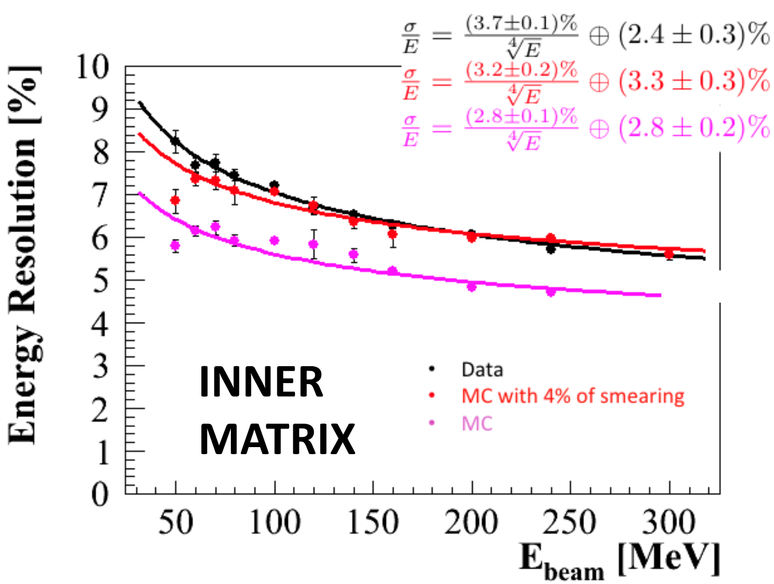


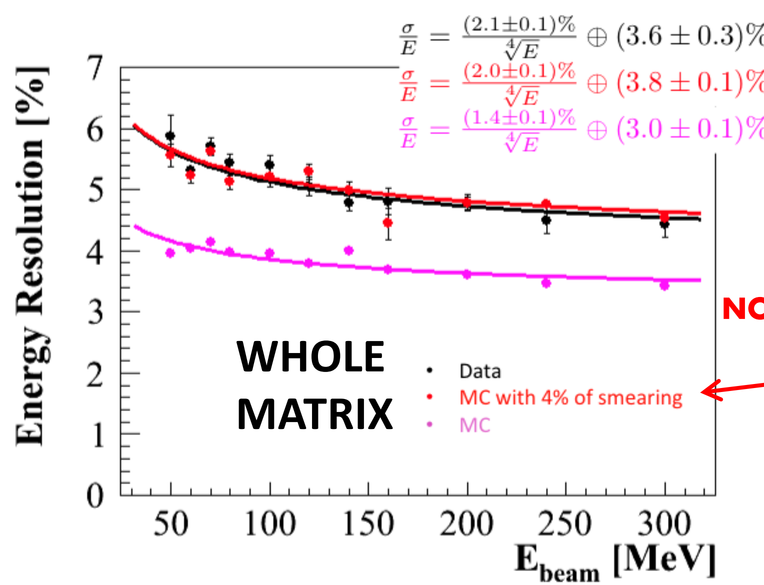
Data-MC comparison:Esum/Ebeam and σ_E/E

Energy Sum in the inner and in the whole crystals matrix at 100 MeV









NON-UNIFORMITY EFFECT

Contributions to resolution

Resolution contributions studied by MC

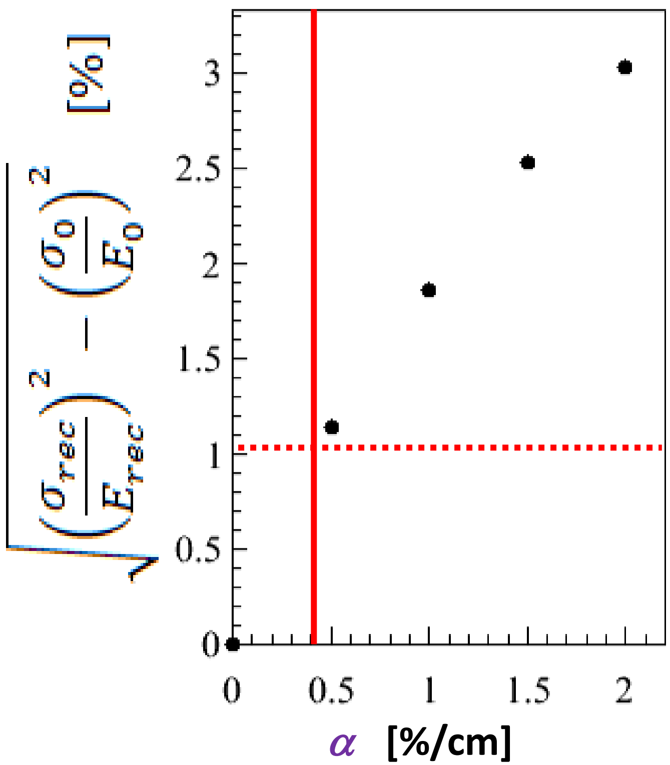
- **Longitudinal Response Uniformity (LRU) large**
- Negligible contributions:
  - Non-linearity response
  - Noise/crystal below 30 keV

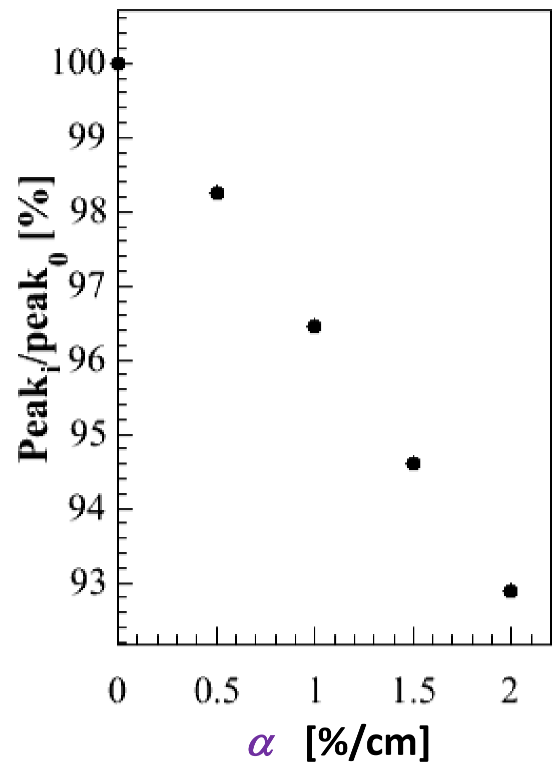
LRU of crystal Light response inserted in the MC as

Erec/E0=1- α x

α : LRU slope

Conclusions: need to keep LRU below 5 %





Photosensors and Noise

Each crystal readout with two large area APDs

→ functional in 1 T field
→ fast/proportional response with gain from 50 to 1000
→ large collection and quantum efficiencies

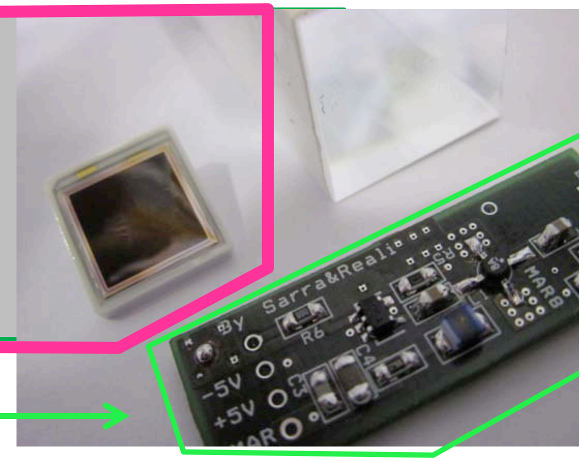
Candidate:

Hamamatsu Photonics(Japan) S8664-110 APD

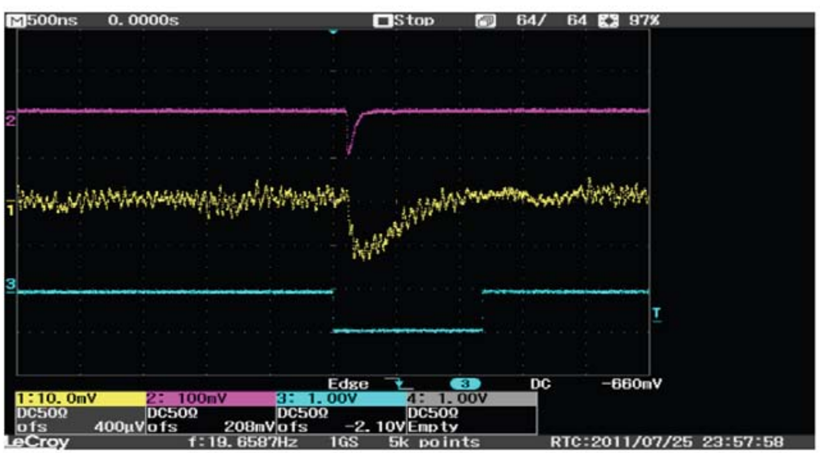
followed by a low noise **preamplifier**

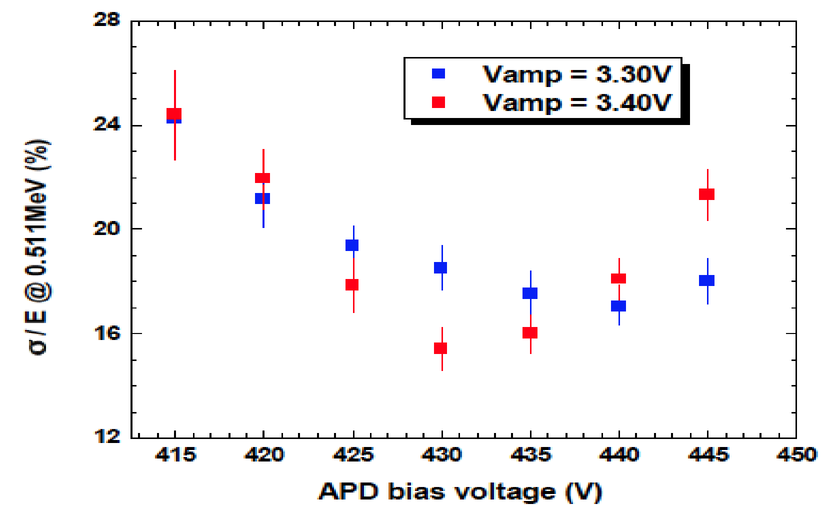
with ENC ~ 4000 e-

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



LYSO test with ^{22}Na source; Equivalent Noise Energy about 30 keV





EMC Baseline Structure

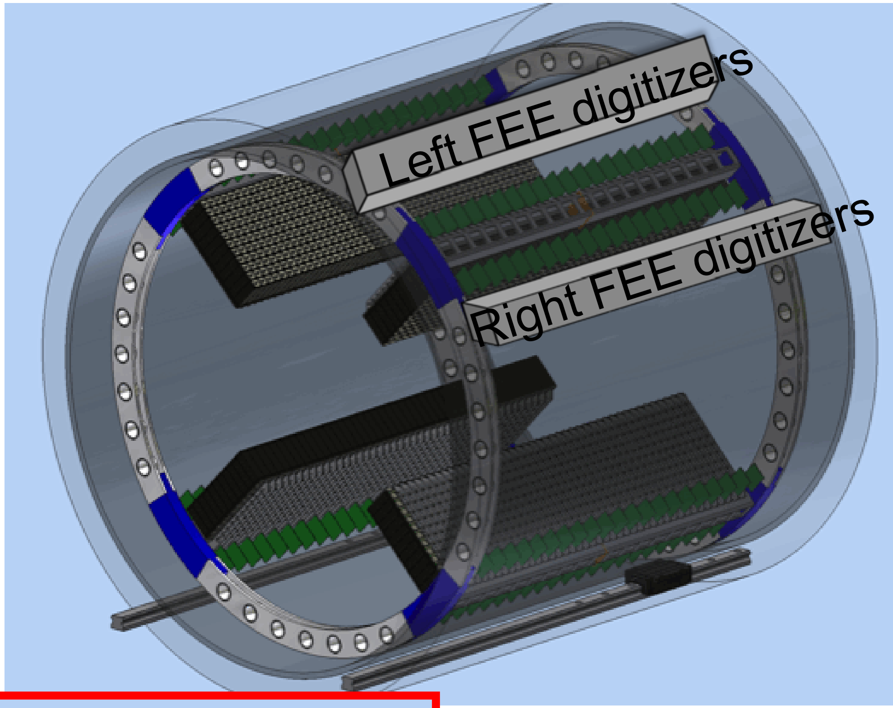
◆ 4 vanes suspended in a Barrel support structure inside the Detector Solenoid

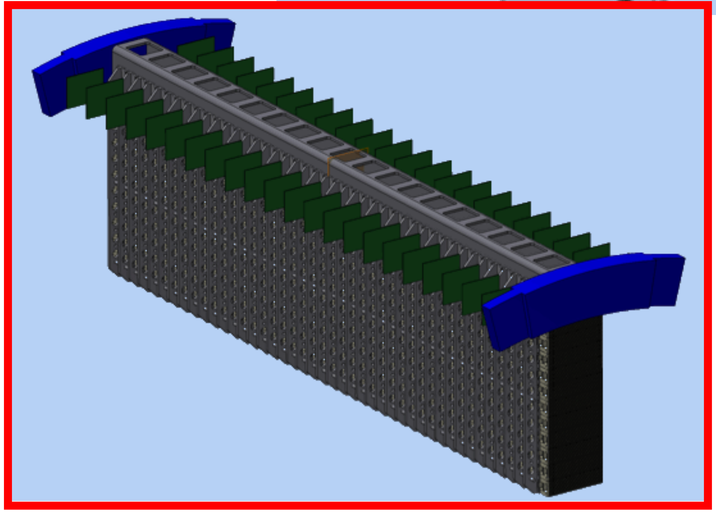
◆ Each Vane $(33x136x11)cm^3$ is a matrix composed by 484 crystal

◆ Each crystal is inside a Carbon Fiber case (cell) with two APDs readout

◆ FEE on the rear face close to APDs

◆ Digitizers inside the Detector Solenoid





Calibration and monitoring

Source: Absolute Calibration

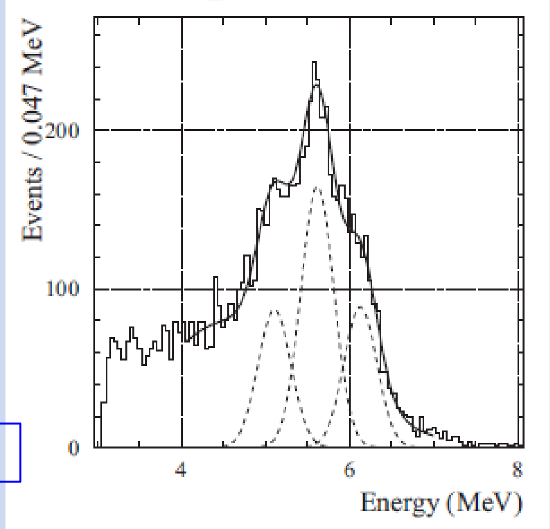
Activated Fluorinert™ FC-77 (C_8F_{18});
Pumped through tubes in the front face of crystals

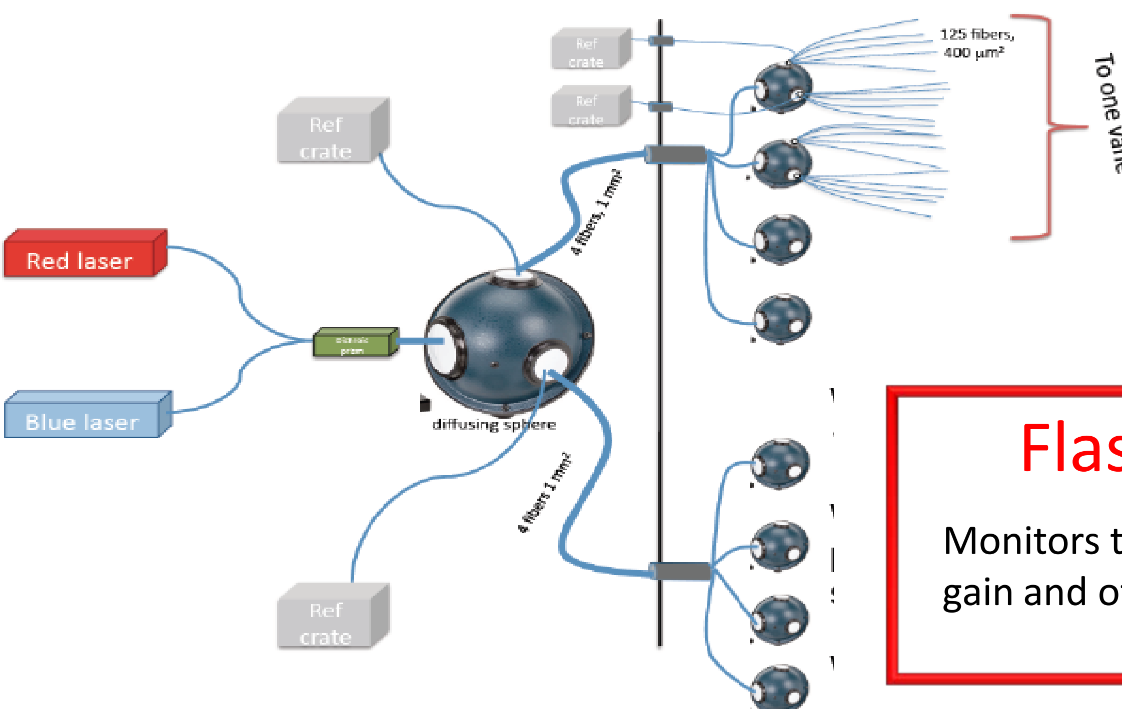
Decay process: $^{19}F + n \rightarrow {}^{16}N + \alpha$

$^{16}N \rightarrow {}^{16}O^* + e^- + \bar{\nu}_e$ $t_{1/2} = 7$ s

$^{16}O^* \rightarrow {}^{16}O + \gamma$ (E_γ = 6.13 MeV)

BaBar: Nucl.Instrum.Meth. A479 (2002) 1-116, SLAC-PUB-8569, BABAR-PUB-01-08,



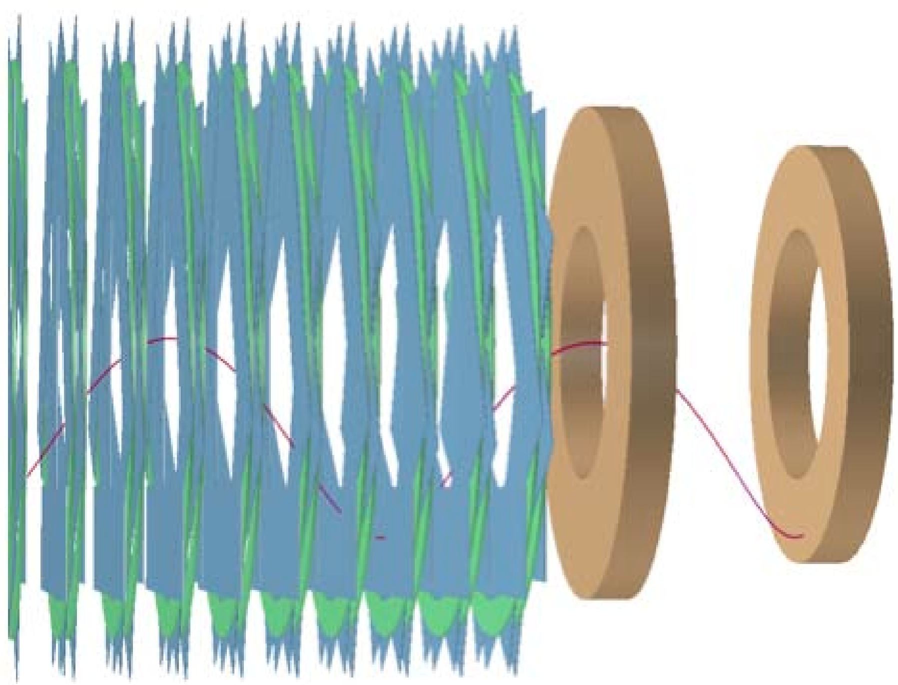


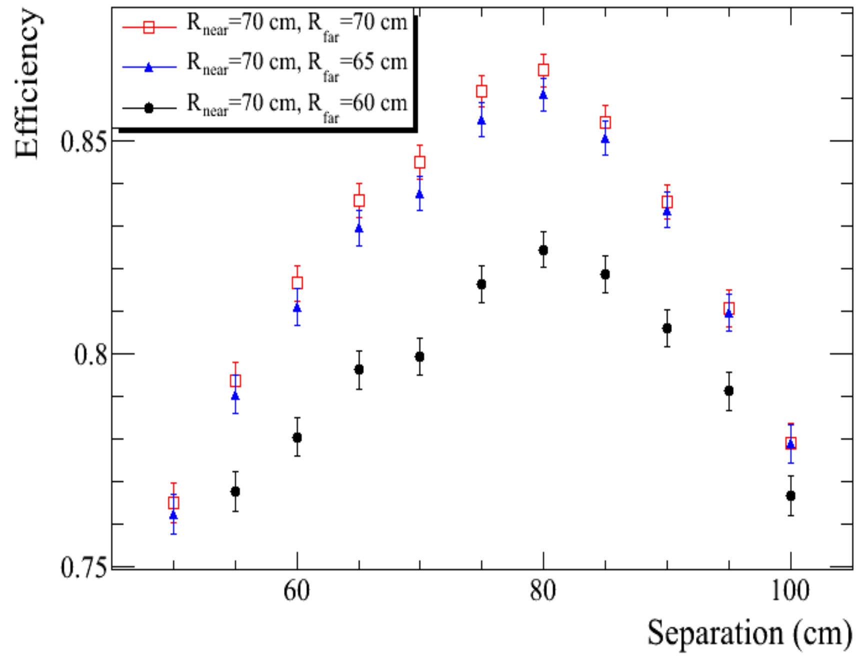
500 fibers total
440 to vane, remainig
to ref crates and spares

Flasher system

Monitors the variation of the photo-sensor gain and of the crystals transmittance

Alternative: Disk Geometry





- Two disks downstream the T-tracker separated by ~ ½ of the wavelength of the spiraling electrons.
- Impact angle of conversion electron similar to the vane case (~ 50 degrees)
- Increasing geometrical acceptance: 72 % (vanes) → 85 % (disks)

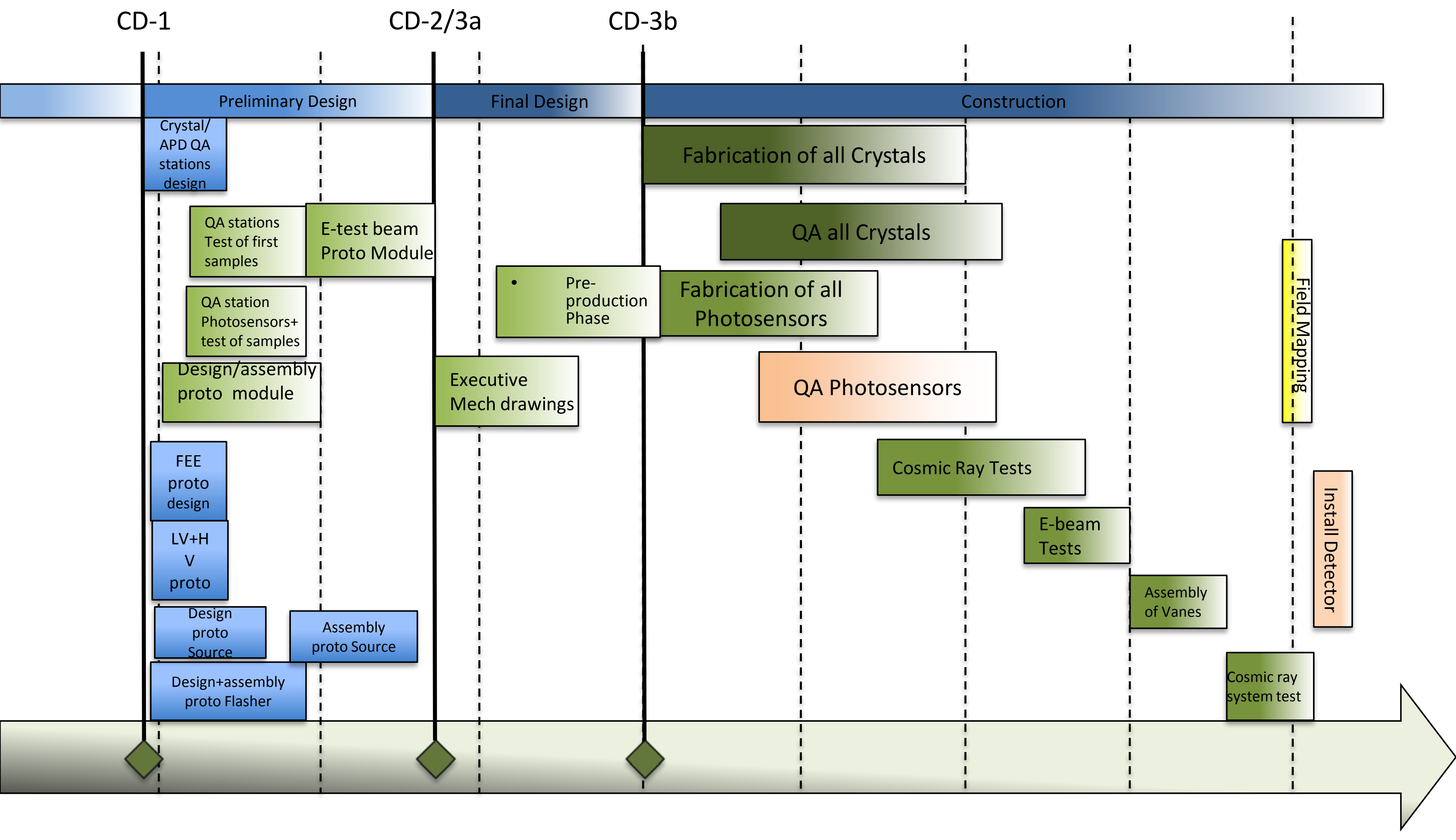
Summary & conclusions

The **Mu2e EMC can provide a trigger greatly reducing DAQ rate and will confirm the conversion electron signal w.r.t. the one coming from the tracker system.**

- Results from tests and simulation are encouraging.
- Prototypes of calorimeter, FEE and HV are being developed.
  Plans for digitizers/mechanics exist.
- Alternative geometries are under evaluation to improve acceptance.
- First version of clustering tested. Background rejection studies in progress.
- R&D plans layout to improve crystal uniformities and Quality Control.
- New test beams under discussion with larger size prototypes.

Backup

Schedule



CD-1
CD-2/3a
CD-3b
Preliminary Design
Final Design
Construction
Crystal/ APD QA stations design
QA stations Test of first samples
E-test beam Proto Module
QA station Photosensors+ test of samples
Design/assembly proto module
FEE proto design
LV+HV proto
Design proto Source
Assembly proto Source
Design+assembly proto Flasher
Pre-production Phase
Executive Mech drawings
Fabrication of all Crystals
QA all Crystals
Fabrication of all Photosensors
QA Photosensors
Cosmic Ray Tests
E-beam Tests
Assembly of Vanes
Cosmic ray system test
Field Mapping
Install Detector

$\mu^- N \rightarrow e^- N$ and $\mu^+ \rightarrow e^+\gamma$

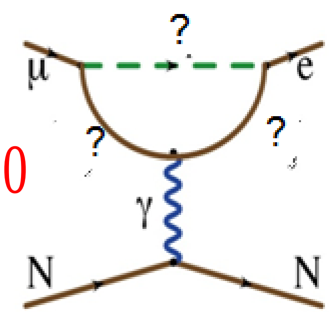
Model independent CLFV Lagrangian:

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

Λ sets the energy scale

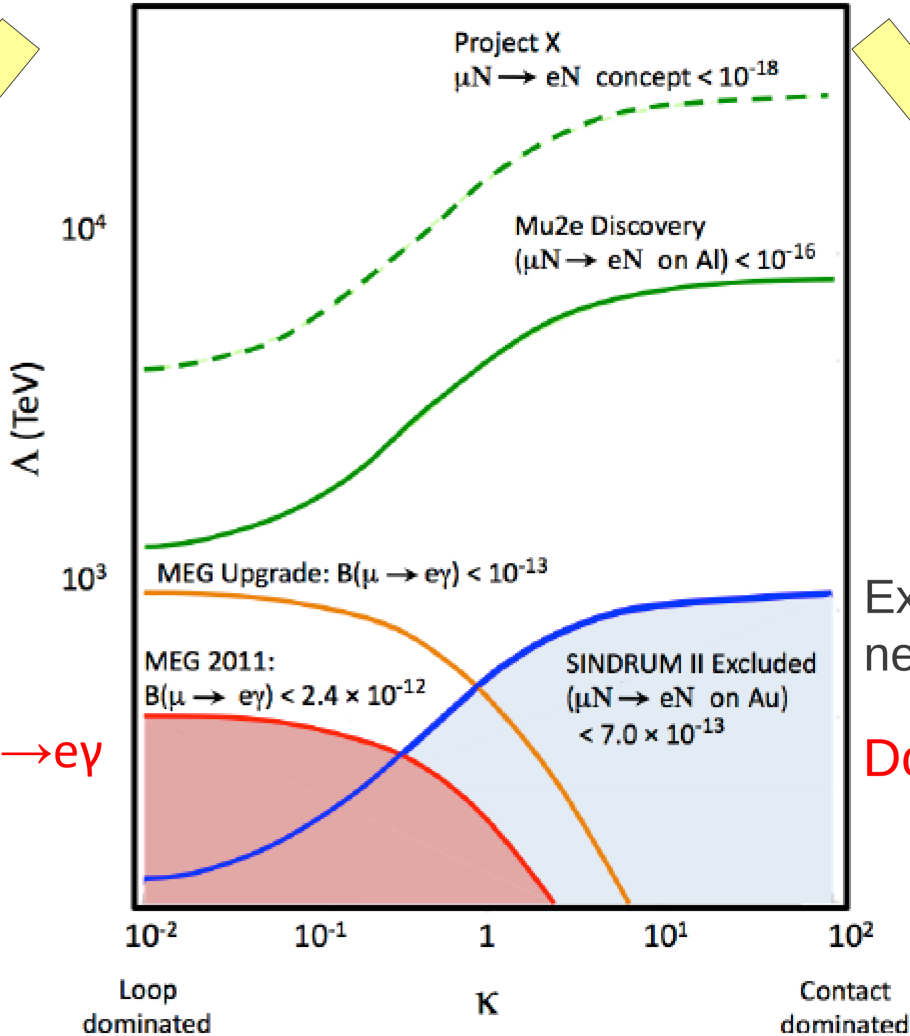
κ magnetic moment type operator: controls relative weights of terms

$\kappa = 0$

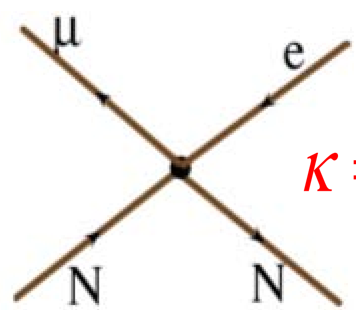


Supersymmetry and Heavy Neutrinos

Also contributes to $\mu\rightarrow e\gamma$



$\kappa = \infty$



Exchange of a massive new particle

Does not produce $\mu\rightarrow e\gamma$

$\mu\rightarrow e$ likely has the greatest potential experimental sensitivity for CLFV

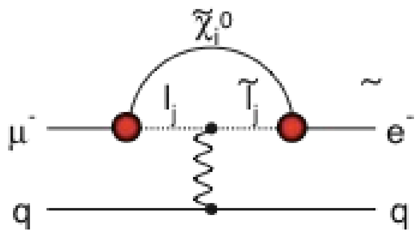
Experimental Advantage of $\mu \rightarrow e$

- Production of lots of muons is relatively easy
- Conversion electron energy, 105 MeV, is far above the bulk of low energy decay electron background. Considerable improvement in the ultimate sensitivity is quite possible.
- With additional improvements in detectors, beam line, fluxes, it may be possible to get $R_{\mu e} < 10^{-18}$ or better (with Project X and detector upgrades).
- **Contrast with $\mu \rightarrow e\gamma$:**
  - Method: look for back-to-back 53 MeV electron and photon
  - e and γ energies are right at the maximum flux of electron energies from ordinary muon decay. There can be a significant rate of accidental coincidence between Michel electrons and photons from other events, or from radiative muon decay. These backgrounds are believed to limit future improvements in achievable limits on the branching ratio.

New Physics scenarios for the μ --> e conversion

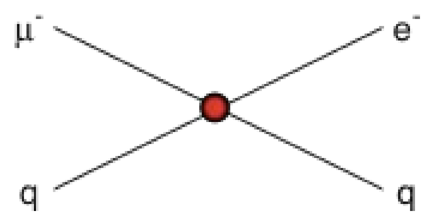
Supersymmetry

rate ~ 10^{-15}



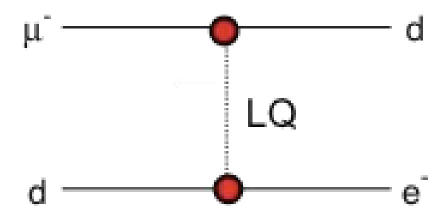
Compositeness

Λ_c ~ 3000 TeV

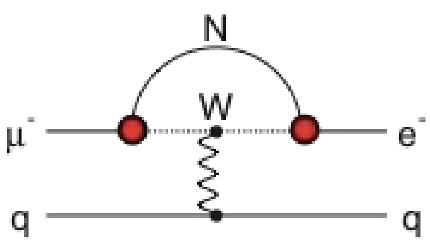


Leptoquark

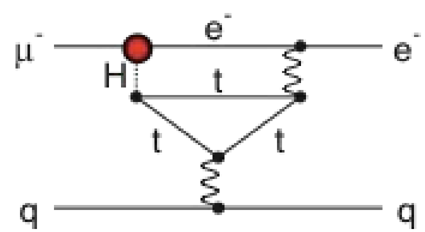
$M_{LQ} =$
$3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



Heavy Neutrinos

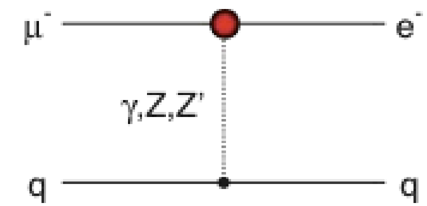


Second Higgs Doublet



Heavy Z' Anomal. Z Coupling

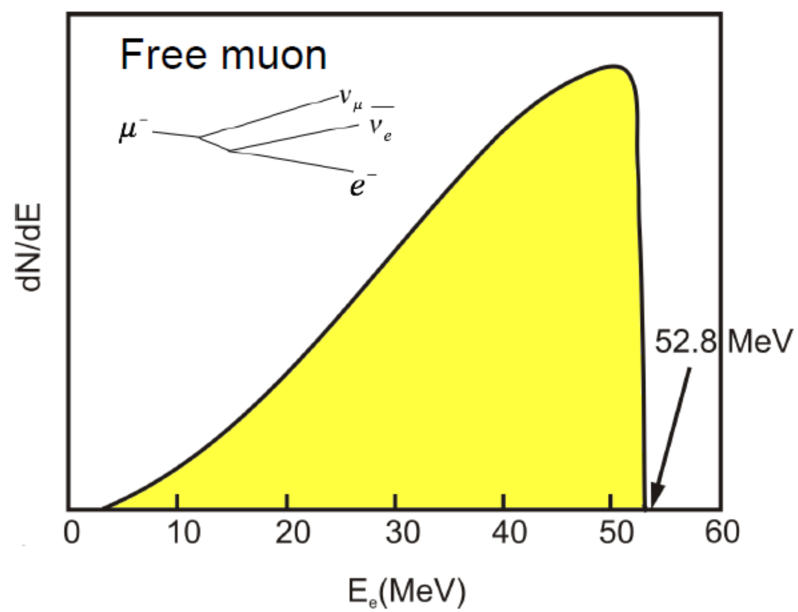
$M_{Z'} = 3000$ TeV/c^2

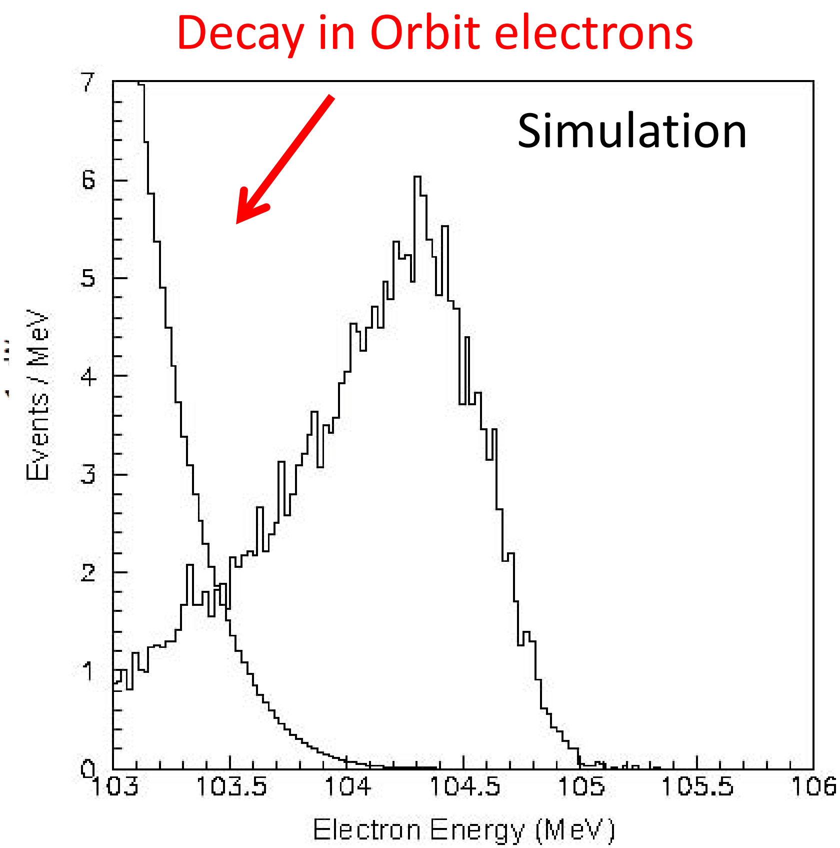


From W. Marciano.
also see Flavour physics of leptons and dipole moments, arXiv:0801.1826

Backgrounds

- Muon Decay In Orbit (DIO)





- High resolution in order to avoid this kind of bkg

- Radiative pion capture
- Radiative muon capture

Back

Some potential backgrounds

1 Electrons from muon decay bound in atomic orbit: max energy is same as conversion electron energy $E_e(\max) = E_{ce} = 105 MeV$

- Probability falls rapidly near endpoint, $\propto (E_e - E)^5$
- This background can be separated from conversion electrons with good electron energy resolution: Require <1 MeV FWHM for Mu2e, $R<10^{-16}$
- Vast majority of decay electrons are < 53 MeV, well below conversion electron energy- big advantage over $\mu \rightarrow e\gamma$
- This is an example of a 'Delayed' background

2 Radiative pion capture, followed by photon conversion

$\pi^- + (A,Z) \rightarrow (A,Z-1) + \gamma$, E_γ ~ 140 MeV

- This is an example of a 'Prompt' background
- Possibility of ~105 MeV conversion electrons ⇒ strong suppression of pions is required

3 Flux of low energy protons, neutrons, gammas from ordinary muon capture on stopping target nuclei- can lead to tracking errors.

4 Beam electrons ~100 MeV

- Suppress with collimators in muon beam line
- Most traverse beam line quickly during muon injection

5 Cosmic rays- suppress with shielding and 4π veto

Prompt Background and Choice of Z

chosen Z based on tradeoff between rate and lifetime: **longer lived reduces prompt backgrounds**

Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

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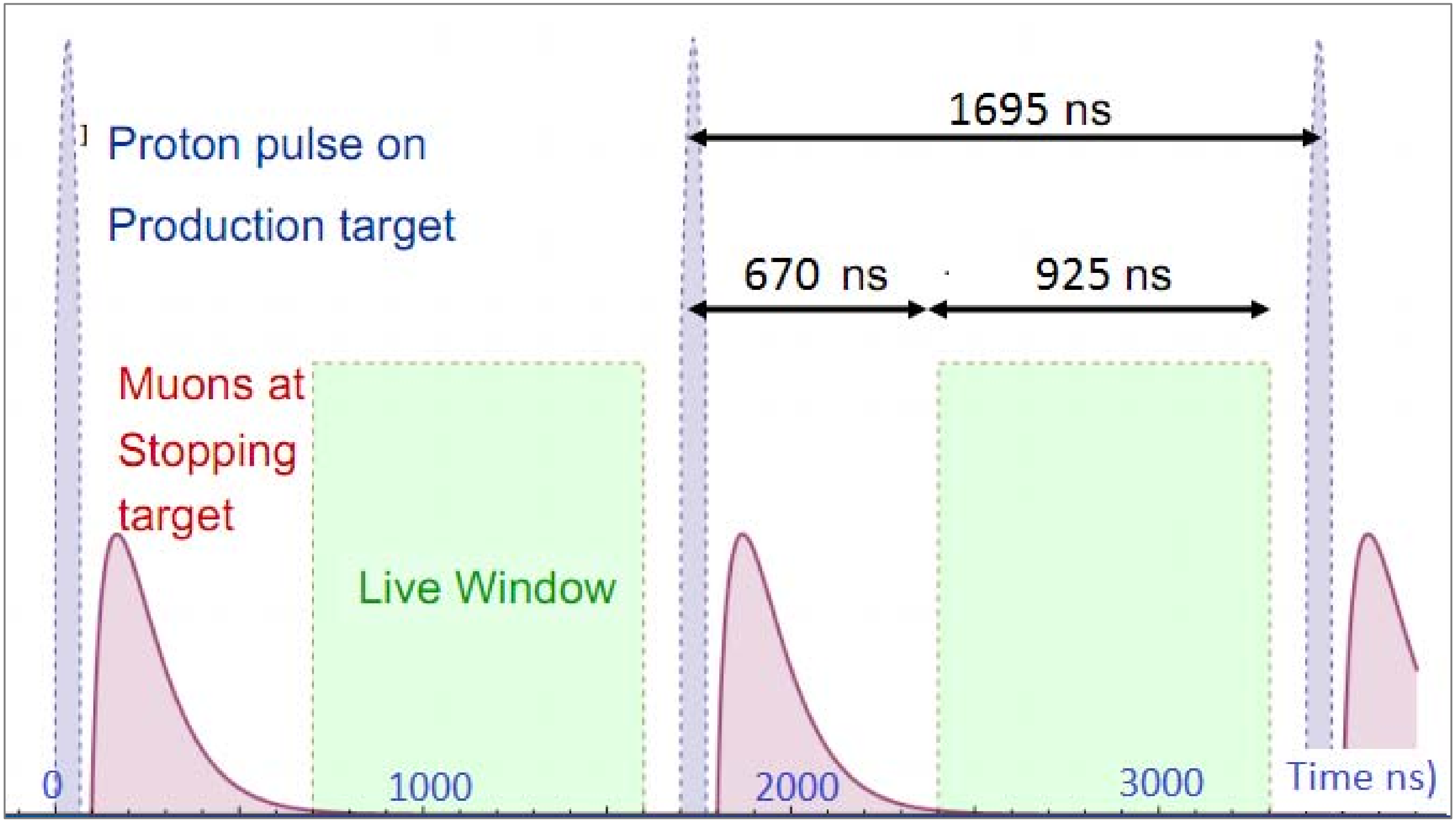
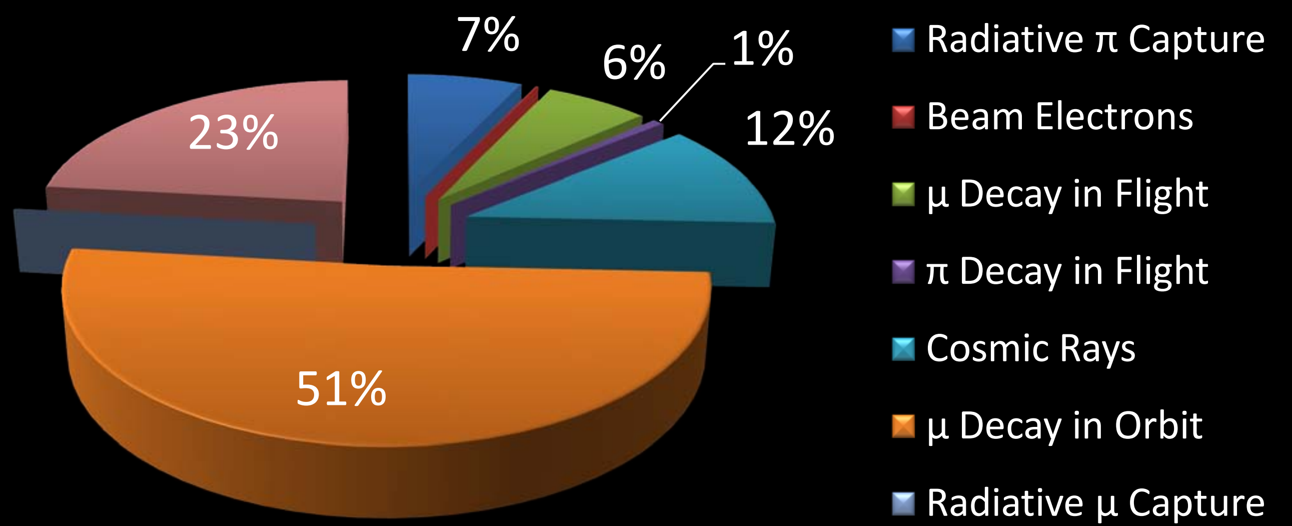
Pulsed Beam

✓Pulsed beam reduces prompt bkgs



Backgrounds estimates for the Mu2e experiment



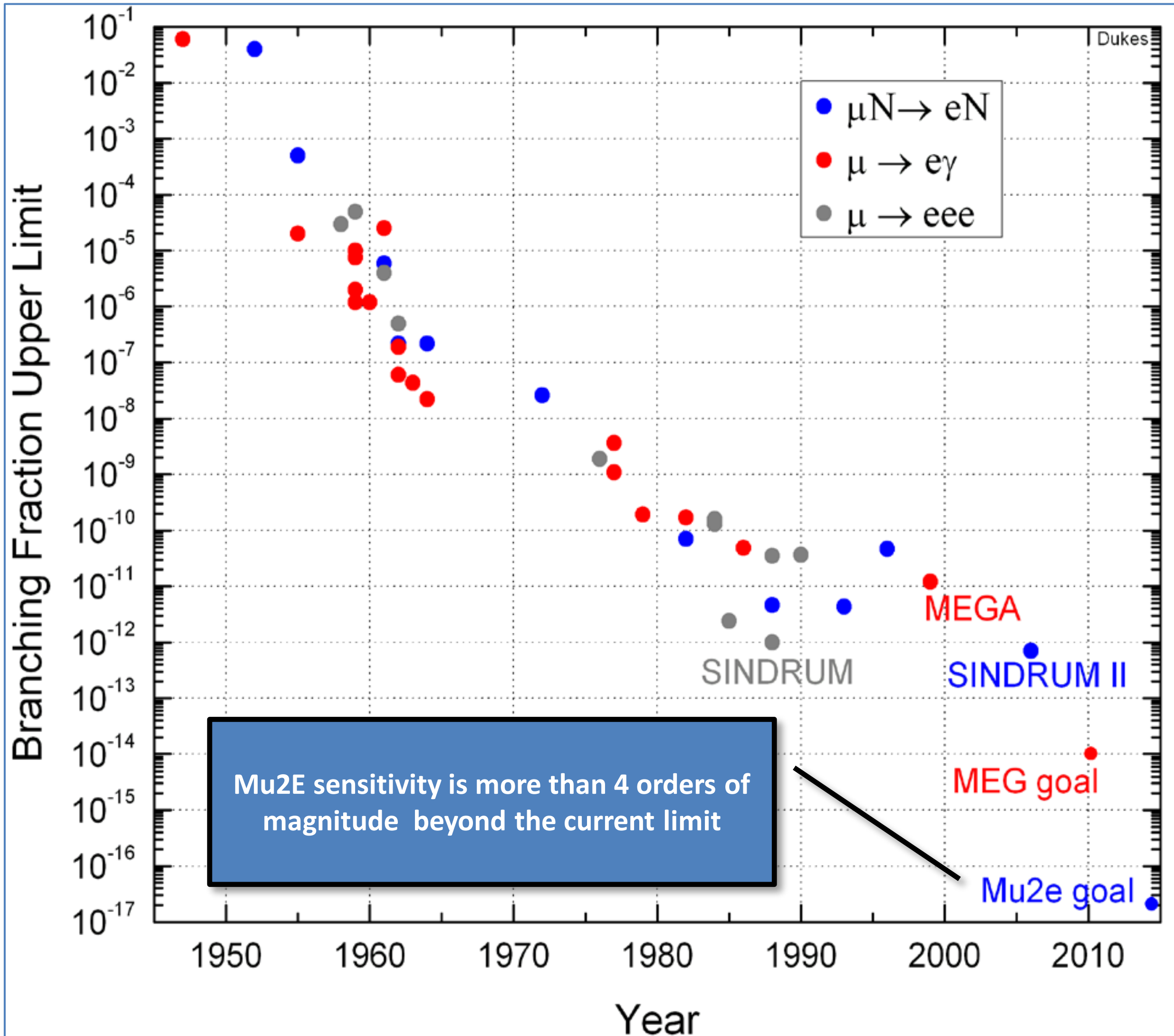
Category	Source	Bkg estimate
Intrinsic	μ Decay in Orbit	0.22 ± 0.06
	Radiative μ Capture	$< 2 \times 10^{-6}$
Late Arriving	Radiative π Capture	0.030 ± 0.007
	Beam Electrons	0.0006 ± 0.0003
	μ Decay in Flight	0.027 ± 0.013
	π Decay in Flight	0.0030 ± 0.0015
Miscellaneous	Cosmic Rays	0.050 ± 0.025
	Antiprotons Induced	0.100 ± 0.035
TOTAL		0.45 ± 0.08

Table from Mu2e-Doc 1169-v8

The expected sensitivities

Parameter	Value
Running time @ 2×10^{7} s/yr	3 years
Protons on target per year	1.2×10^{20}
μ– stops in stopping target per proton on target	0.0016
μ– capture probability	0.609
Fraction of muon captures in live time window	0.507
Electron Trigger, Selection, and Fitting Efficiency in Live Window (note 0.507×0.10 = .0525	0.10
Single-event sensitivity with Current Algorithms	5.4×10^{-17}
Goal	**2.4×10^{-17}**

Currents Limits



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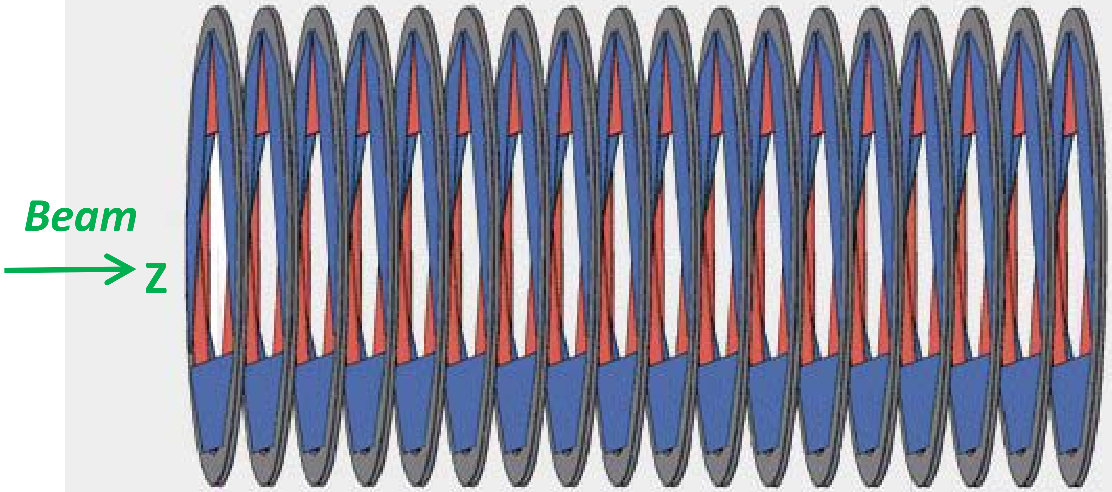
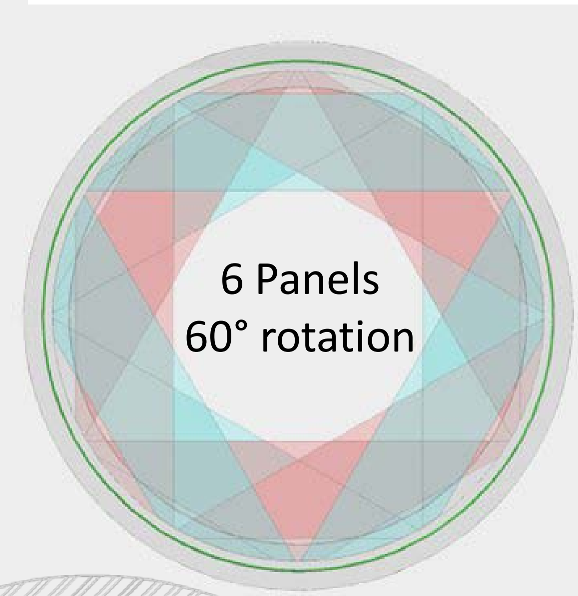
$T_{ransverse}$-tracker

18 “stations” spanning ~3 m length

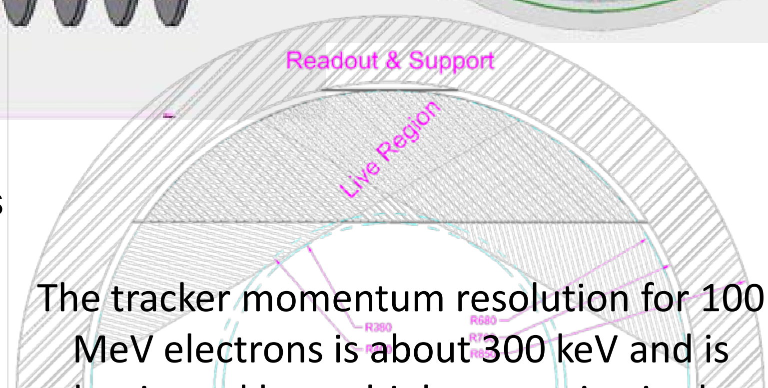




- 18 **stations**
- Each station has 2 **planes** … 36 planes
- Each plane has 6 **panels** … 216 panels
- Each panel has 2 **layers** … 412 layers
- Each layer has 50 straws …

  21,600 straws
- Two readout channels per straw …

  43,200 readout channels



The tracker momentum resolution for 100 MeV electrons is about 300 keV and is dominated by multiple scattering in the tracker.

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Crystals for HEP (High Energy Physics)

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	PWO(Y)	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (°C)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	0.89	1.14	1.38
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.00	2.07	2.23
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.7	20.9	22.2
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	2.20	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	425 420	402	440
Decay Time [b] (ns)	230	1250	30 6	630 0.9	300	30 10	40	60
Light Yield [b,c] (%)	100	165	3.6 1.1	36 3.4	21	0.29 .083	83	30
d(LY)/dT [b] (%/ °C)	-0.2	0.3	-1.3	-1.3	-0.9	-2.7	-0.2	-0.1
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV	TAPS (L*) (GEM)	L3 BELLE PANDA?	CMS ALICE PrimEx PANDA?	Super B?	-

a. at peak of emission; b. up/low row: slow/fast component; c. PMT QE taken out.

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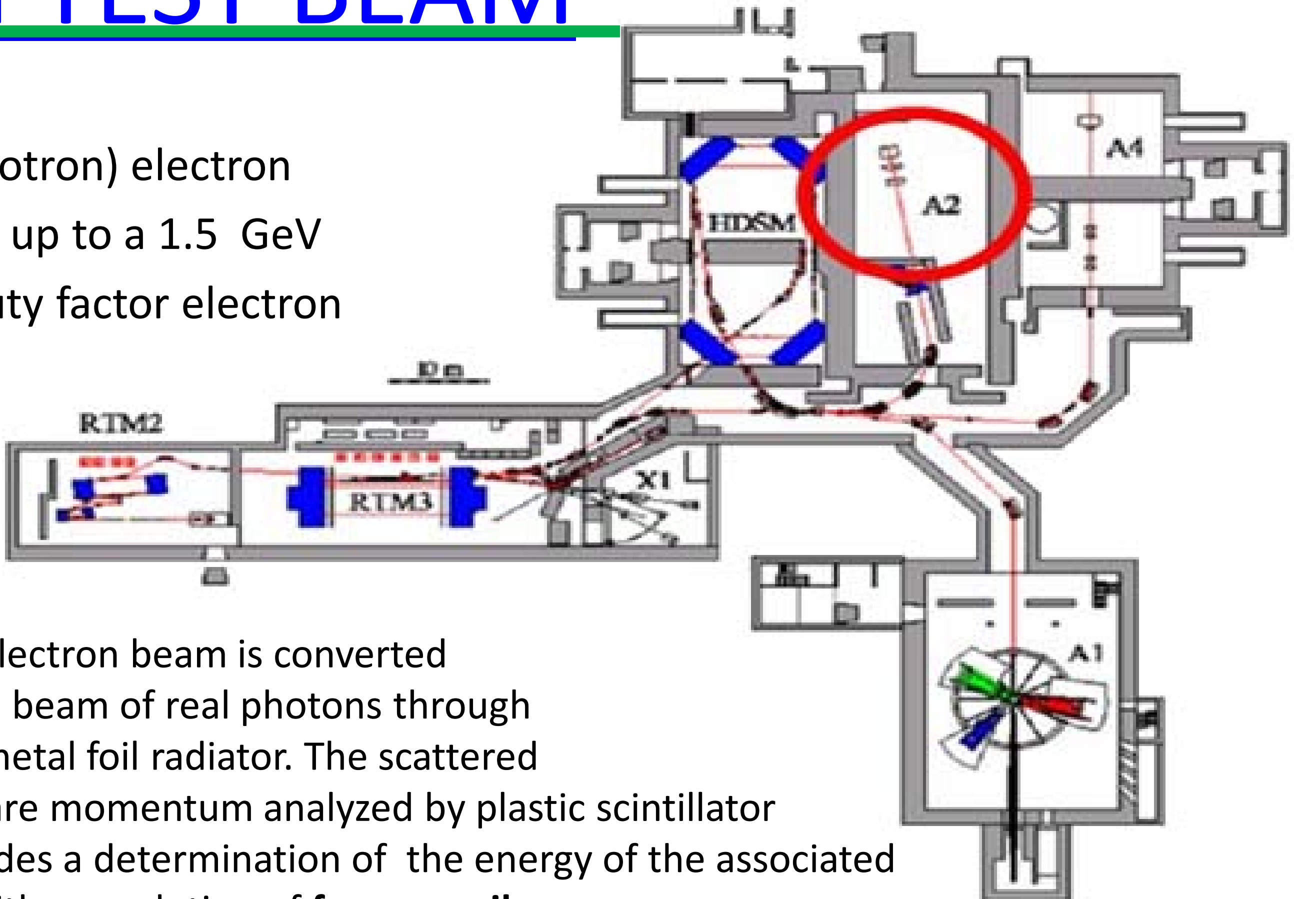
Light Yield del NaI ~ 40000 γ/MeV

MAMI TEST BEAM

The MAMI (Mainz Microtron) electron beam facility produces up to a 1.5 GeV High quality ~100% duty factor electron beam.



In the facility hall A2 the electron beam is converted to an intense (~10^8 γ sec^{-1}) beam of real photons through bremsstrahlung in a thin metal foil radiator. The scattered electrons in this process are momentum analyzed by plastic scintillator spectrometer which provides a determination of the energy of the associated bremsstrahlung photon with a resolution of **few per mil**.

- Tagged photon beam with excellent ΔP(FWHM) = 1 MeV
- Selectable rate (from few kHz to MHz) & energy 20-380 MeV
- photon beam spot on calorimeter of ~ 8 mm of diameter

MAMI data taking

- We ran the tagged photon beam at the lowest available energies (20 – 380 MeV) at rates of
  10 kHz, writing on disk at 10-20 Hz.

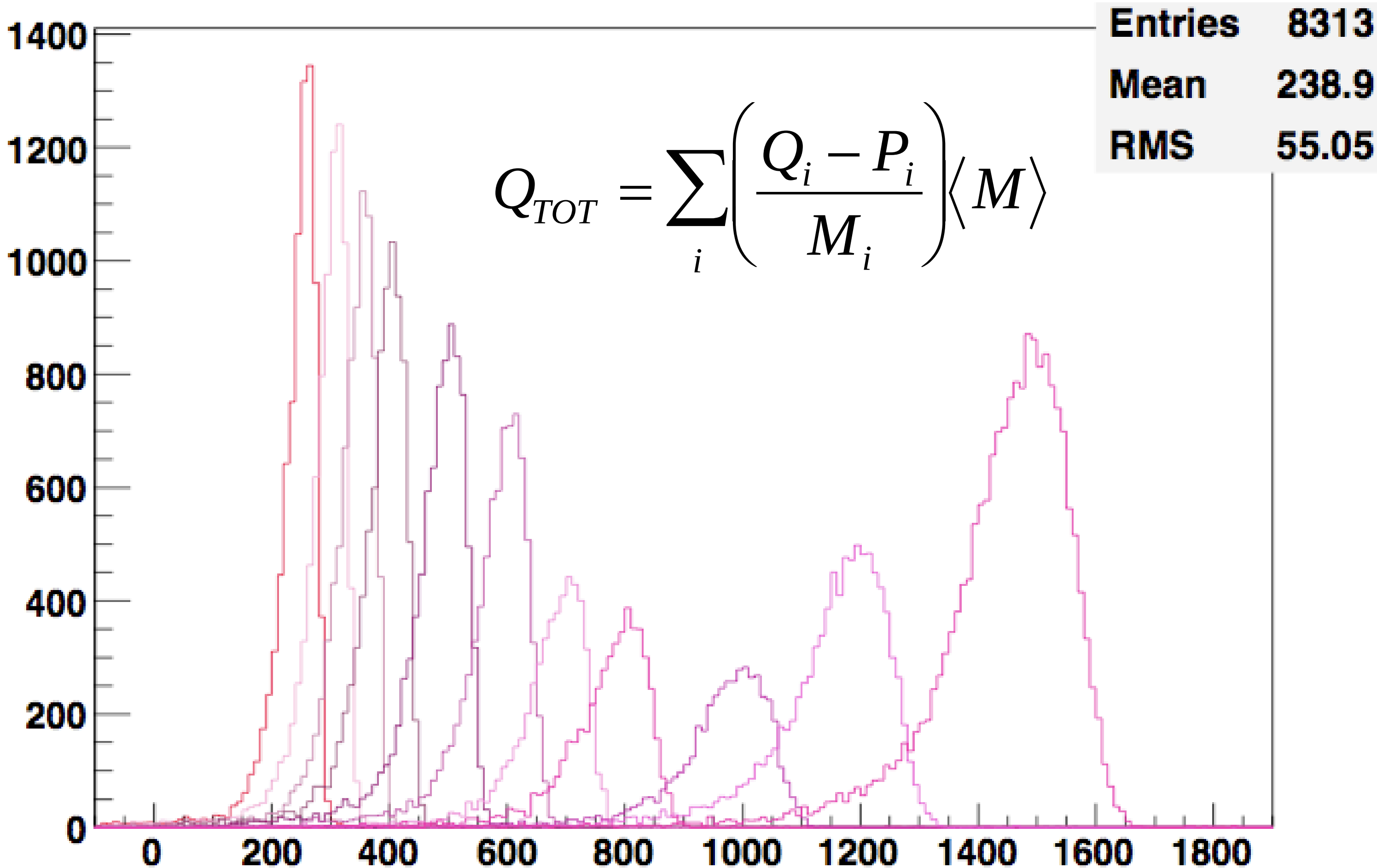
- We triggered events with a coincidence between the discriminated sum of the matrix and the reference tagging signal

- We took 10000 events/point for two days

- Energy and position scans performed

Energy scan

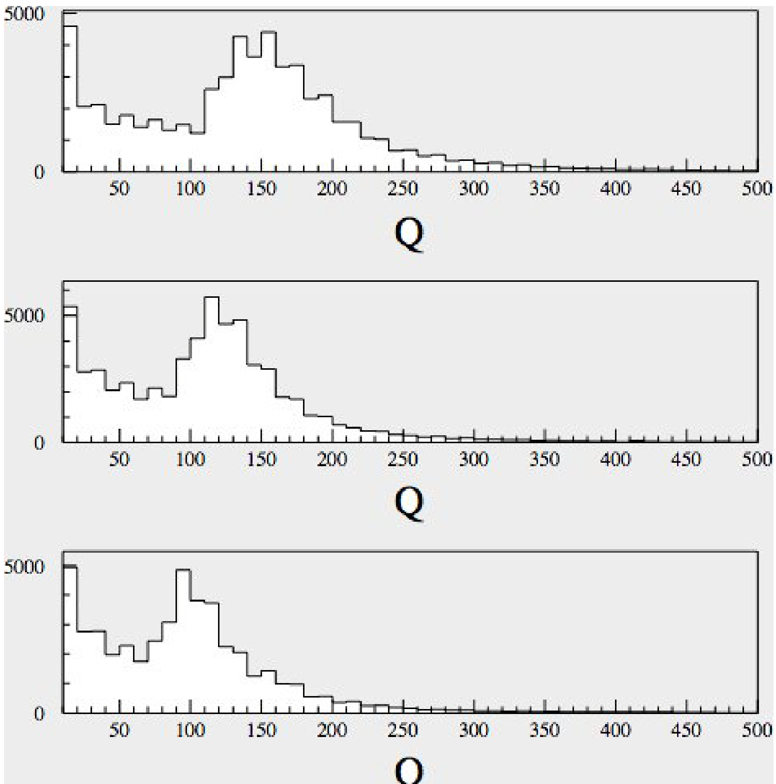
We have selected 14 energies between 40 and 300 MeV.

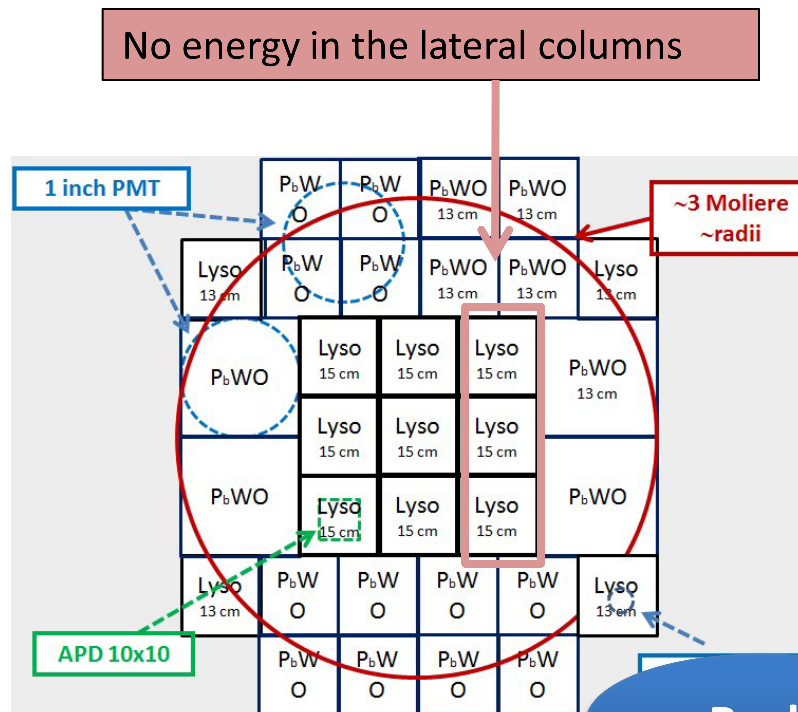


$$Q_{TOT} = \sum_i \left(\frac{Q_i - P_i}{M_i} \right) \langle M \rangle$$

CR test (Inner Matrix) - Calibration

- CR test for the equalization of response carried out (T~ 24 °C) by triggering with an external scintillation counter on top of the prototype.
- clean-up the events by selecting “clean” fired columns for the inner matrix.
- Calibration of the single channel at a level of 2%
- M(APD) ~ 120
- Average MIP ~ 100-120 counts





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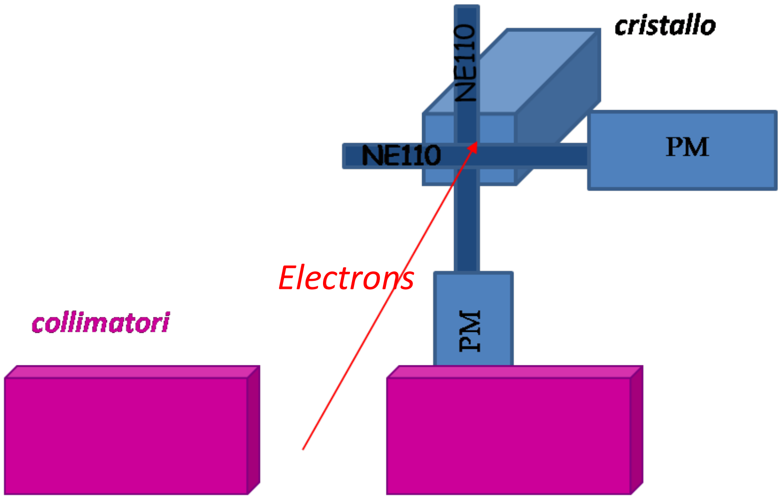
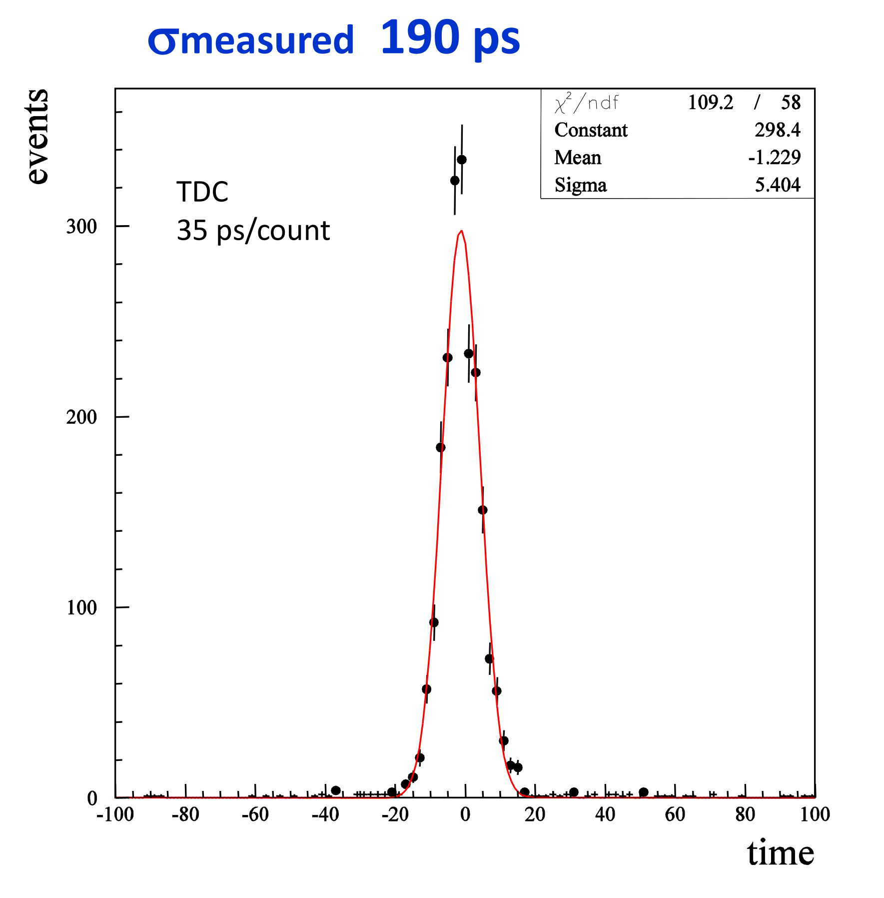
LYSO: Test with electrons

Results with 500 MeV electrons at Beam Test Facility of Frascati (2009)



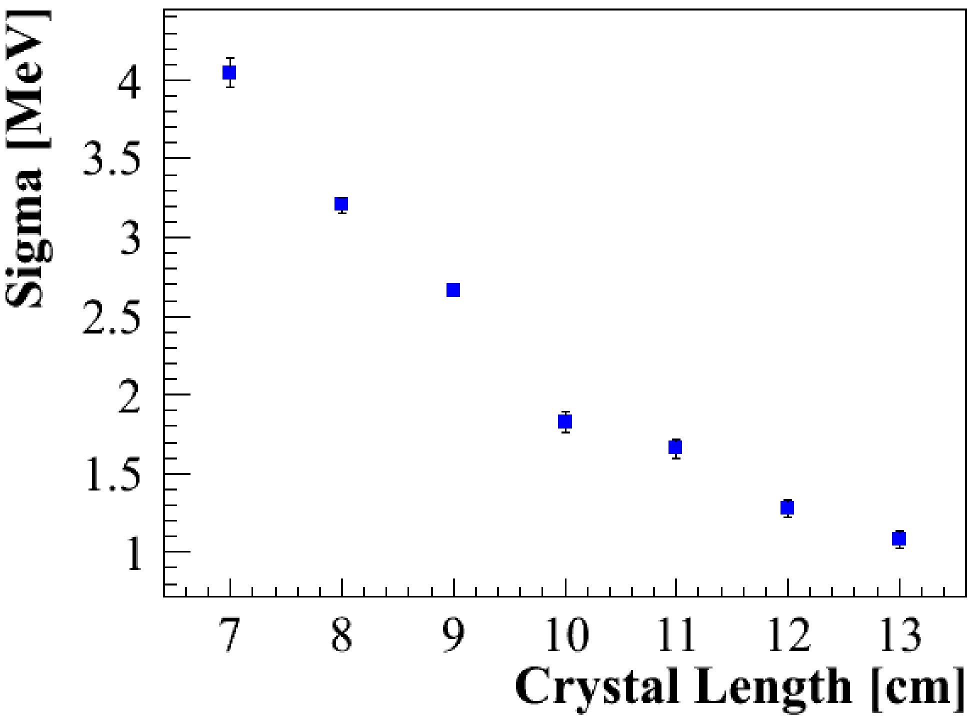


Time resolution

$$\sigma_T = \sqrt{\sigma_{meas}^2 - \frac{1}{2}\sigma_{jitter}^2}$$

90 ps (120 ps) @ 500 MeV (100 MeV).

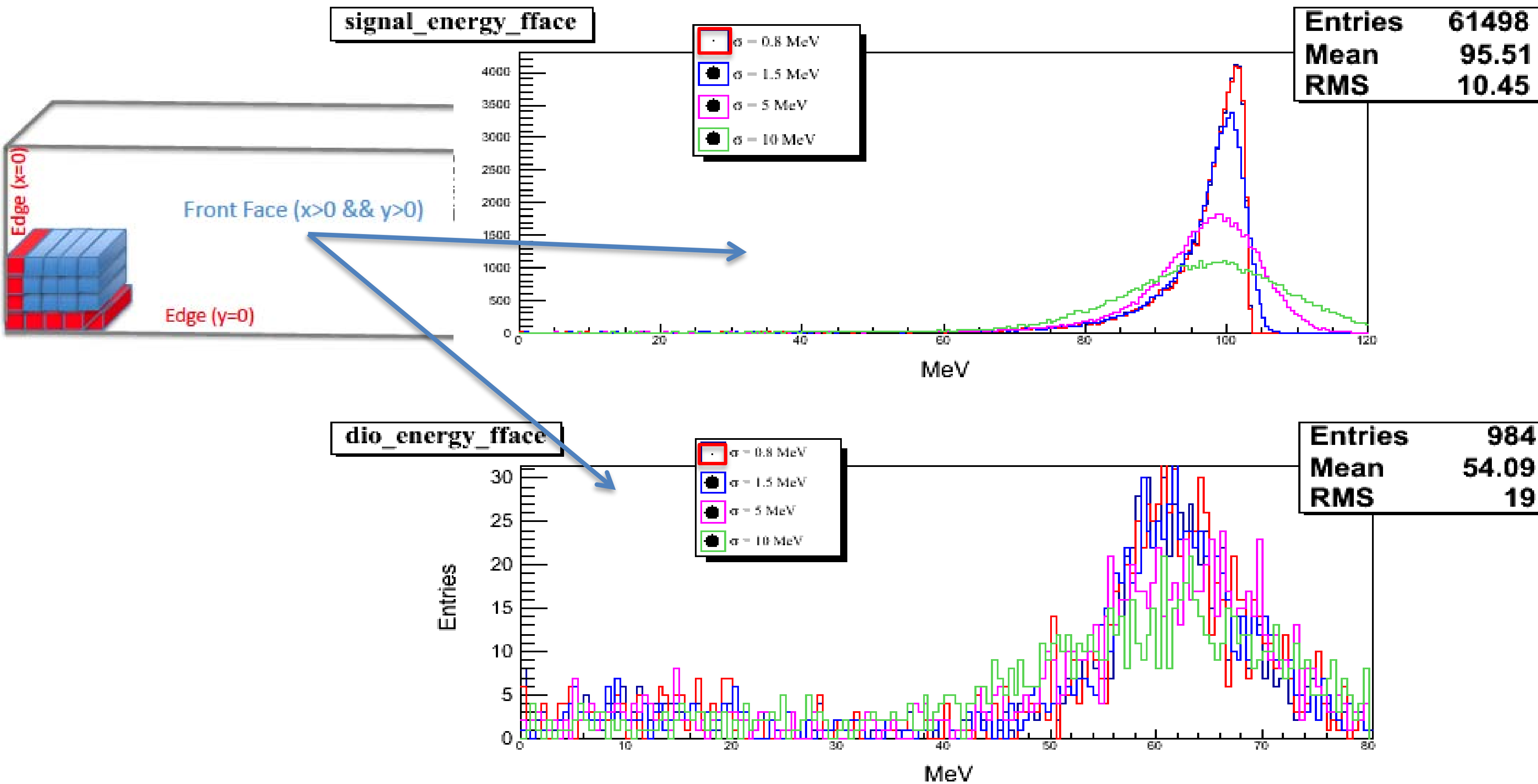
Resolution vs crystals length



- 10k events simulated
- We select events in fiducial region → energy with Maximum Energy deposition should not be in the Innermost Row or in the Edge Column towards target.
- We get reconstructed acceptance ~ 72%.

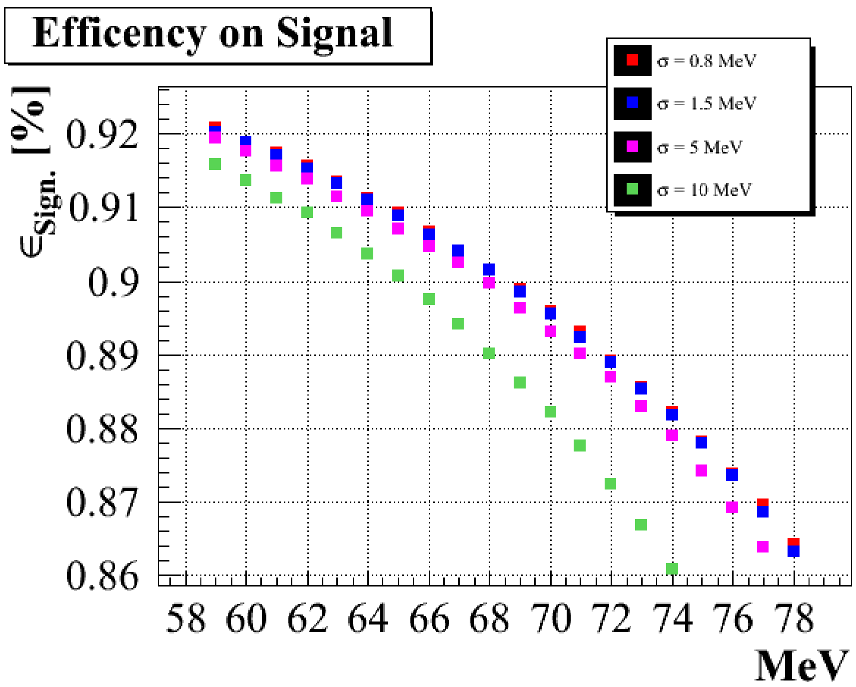
Resolution slightly depends on crystal length; 11 cm is a reasonable choice w.r.t. $/perfomances

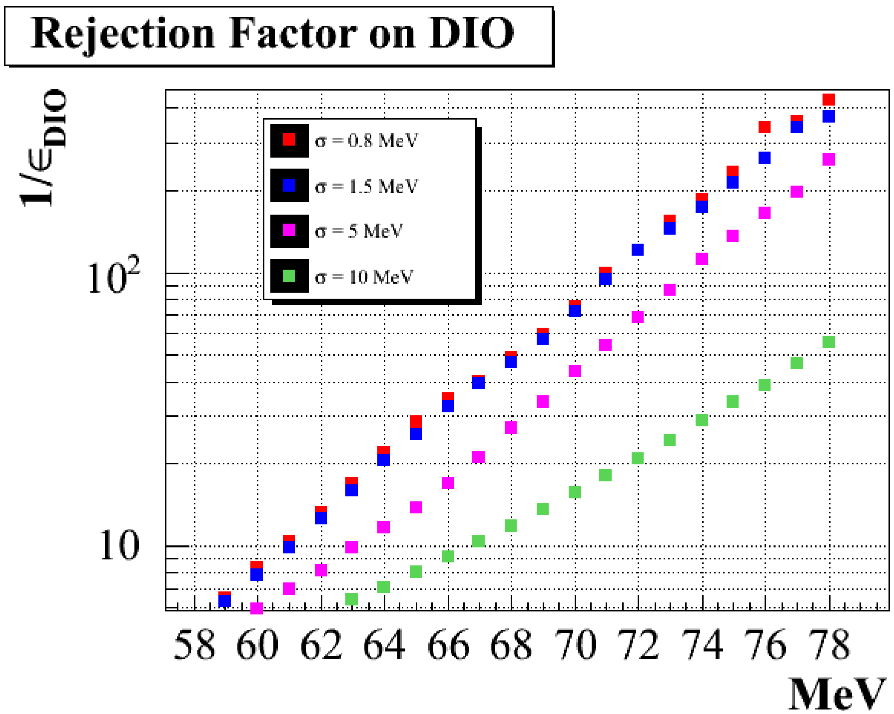
Trigger algorithm: energy distribution on front face



90700 generated events with cosTheta(-0.5:0.5) and 20 hits in the Tracker:
→ 61500 (70%) events on the Front Face and 27500 (30%) events on the Edges
Assuming to be able to discriminate DIO from signal, on both ECAL places→ **Effi ~ 98%**

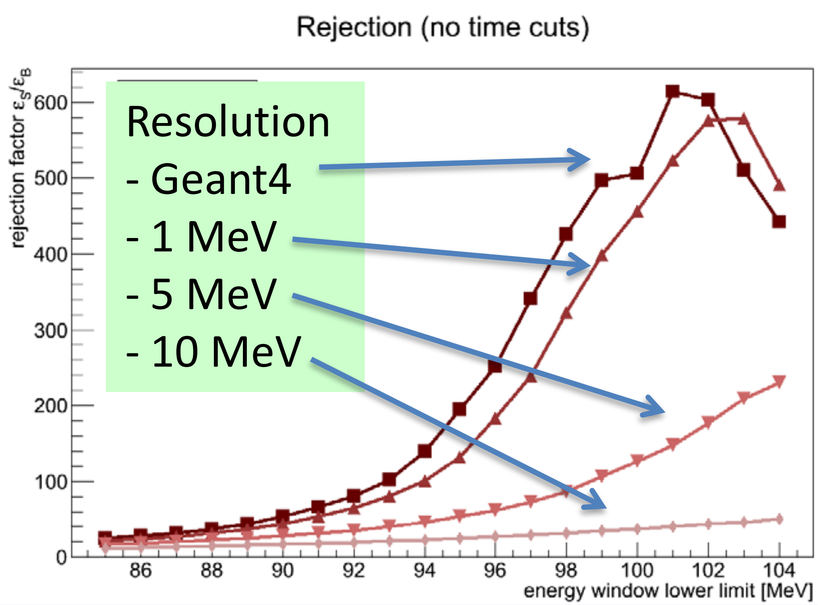
EMC Trigger

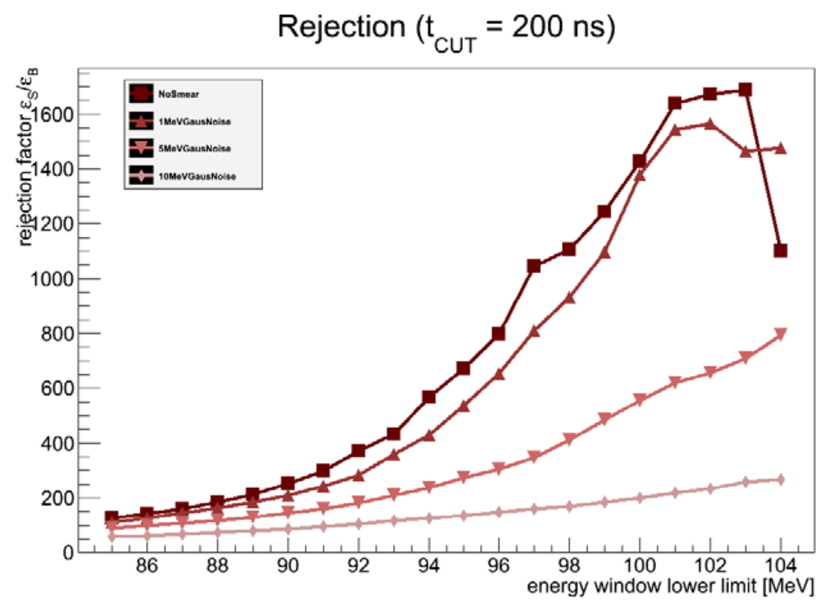




- ❑ **91% efficiency @ 64 MeV**
- ❑ Rejection/efficiency depends on energy resolution

Particle ID: Muon rejection





- ✧ **To distinguish 105 MeV/c μ- from e- we can use both time of flight in conjunction with the tracker determination or use particle ID into the calorimeter**

- ▪ **Calorimeter PID relies on the smaller energy deposition of μ- w.r.t. e- by applying a cut on the total cluster energy.**

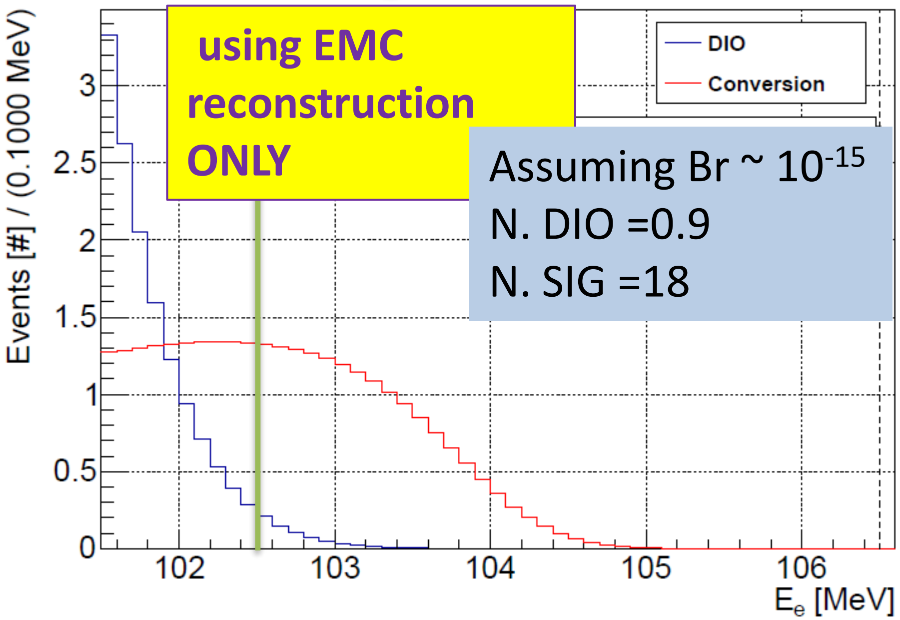
- ✧ In average the energy distribution peaks to 44 MeV with a long tail due to nuclear products from capture or decay to electrons. Adding also a cut in the charge integration time (200 ns) , a further reduction is obtained

Log Gaussian

$$\frac{df}{dE} = \frac{\eta}{\sqrt{2\pi} \cdot \sigma_E \cdot s_0} \cdot e^{-\frac{1}{2}\left\{\left[\frac{\ln\left[1 - \frac{\eta}{\sigma_E} \cdot \left(E - E_{peak}\right)\right]}{s_0}\right]^2 + s_0^2\right\}}$$

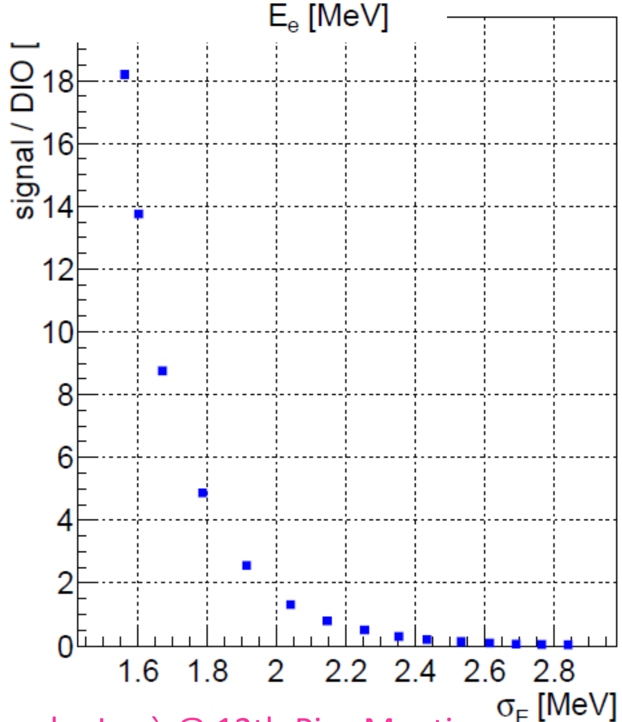
η= asym, σ= FWHM/2.35

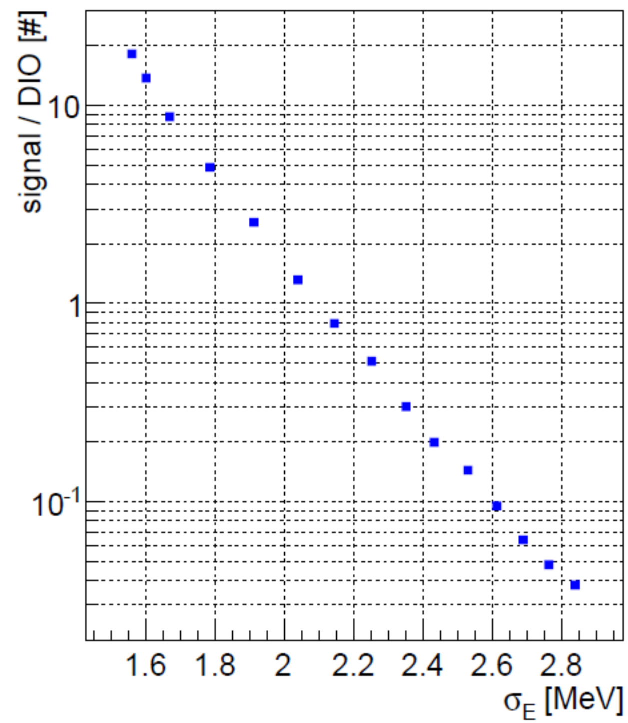
Signal and DIO vs EMC Resolution



By convoluting the **DIO** and Sig spectra with different EMC energy resolution

Dependence of the signal to DIO ratio on the σ_E values





Costs

- DOE 4.6 M$:

– 2.6 M$ MATERIALS (1.6 M$ crystals)

– 2 M$ labor

- NOT DOE 5.3 M$ (+ 30% contingengy)

- 3.2 M$ Crystals