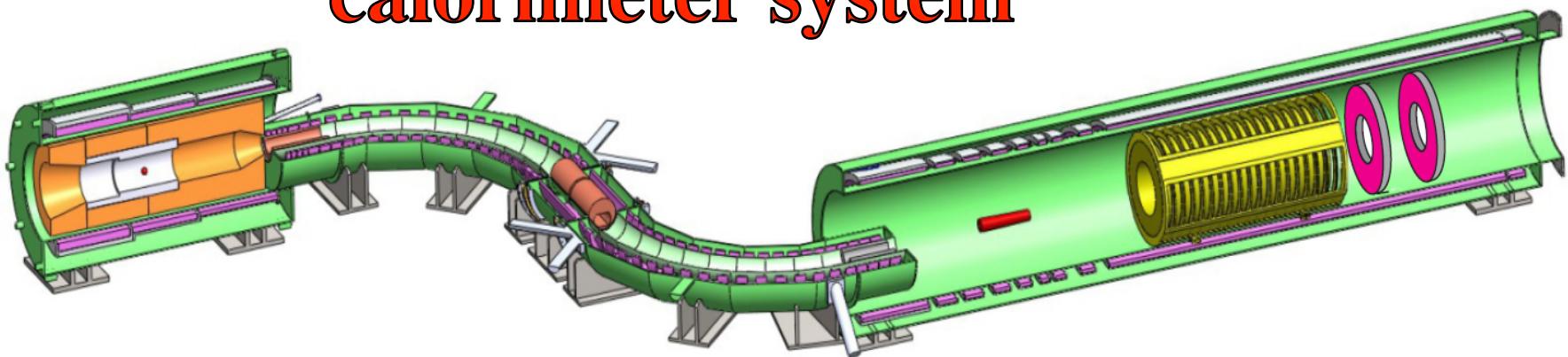


# Progress status for the Mu2e calorimeter system



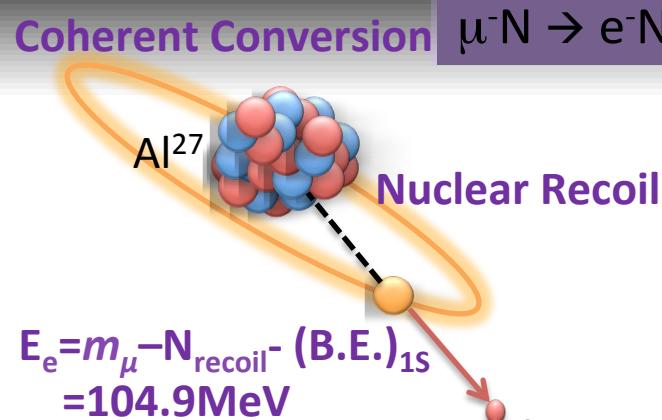
Ivano Sarra  
LNF -INFN-  
on behalf of Mu2e calorimeter group  
Tipp2014  
Amsterdam – June 6, 2014

# Outline

## The Mu2e experiment

- The Solenoids
  - Cosmic Rays Veto, Tracker, Calorimeter
- 
- ✓ The Crystal Calorimeter
    - Calorimeter requirements
    - Calorimeter baseline
    - Calorimeter performances
- 
- ✓ Parallel studies
    - Backup alternative
    - R&D on LYSO

# The Mu2e experiment



Detect the CLFV process  $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$  i.e. the coherent, neutrinoless **conversion of a muon to an electron** in the field of a nucleus.

## ➤ Goal of Mu2e:

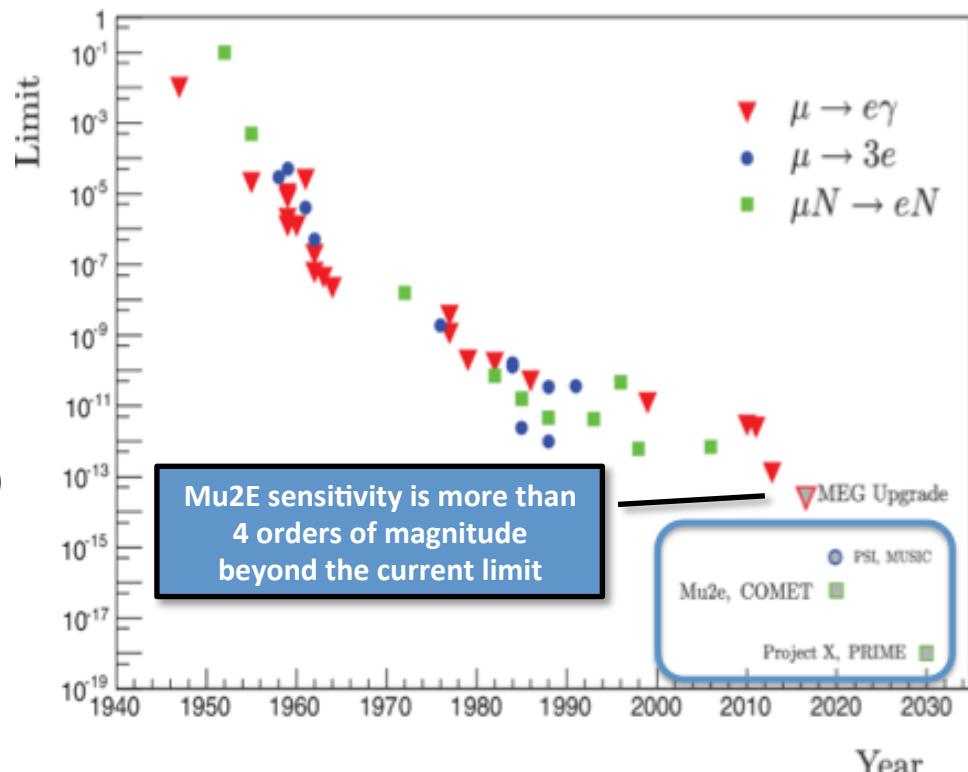
Measure the rate of conversion relative to ordinary muon capture on the nucleus:

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

with a single event sensitivity (SES) of  $2.5 \times 10^{-17}$

## ➤ Current limits (SINDRUM II at PSI) :

$$R_{\text{me}} < 4.3 \times 10^{-12} \text{ (Ti)}, R_{\text{me}} < 7 \times 10^{-13} \text{ (Au)}$$



# The Mu2e experiment layout

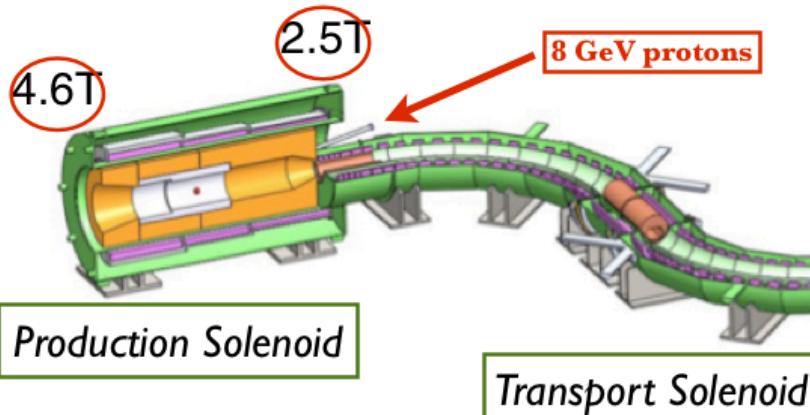


## • Production Solenoid:

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

## • Detector Solenoid:

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field “reflects” downstream conversion electrons emitted upstream

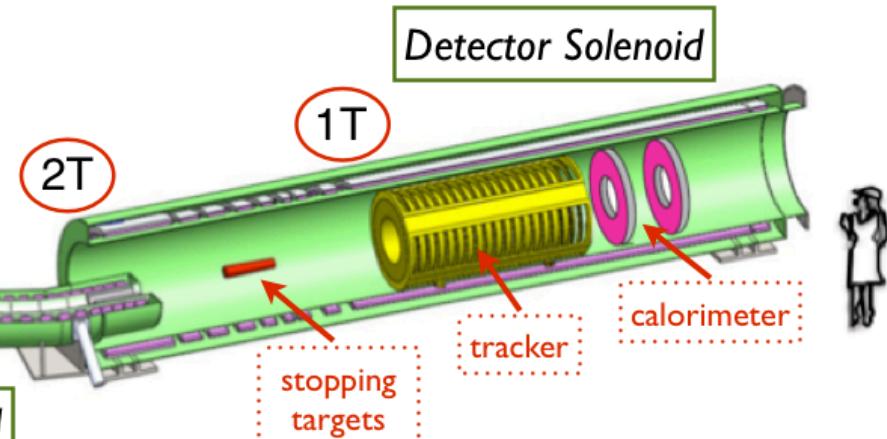


Production Solenoid

Transport Solenoid

## • Transport Solenoid:

- Select low momentum, negative muons
- Antiproton absorber in the mid-section



Detector Solenoid

stopping targets

tracker

calorimeter

## • Targets:

- ❖ 17 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

## • Tracker:

- ❖ ~25000 tubes arranged in planes on stations, the tracker has 20 stations
- ❖ Expected momentum resolution  $\sim 120 \text{ keV}/c$



# The Calorimeter Group



Boston University  
Brookhaven National Laboratory  
University of California, Berkeley and  
Lawrence Berkeley National Laboratory  
University of California, Irvine

## **California Institute of Technology**

City University of New York  
Duke University

Fermilab

University of Houston

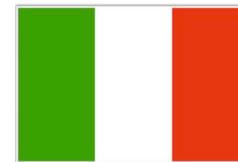
## **University of Illinois, Urbana-Champaign**

Lewis University  
University of Massachusetts, Amherst  
Muons, Inc.  
Northern Illinois University  
Northwestern University  
Pacific Northwest National Laboratory  
Purdue University  
Rice University  
University of Virginia  
University of Washington, Seattle

<http://mu2e.fnal.gov>



**JINR, Dubna**  
**Institute for Nuclear Research, Moscow**



**Laboratori Nazionale di Frascati**  
INFN Genova  
**INFN Lecce and Università del Salento**  
**Istituto G. Marconi Roma**  
**INFN Pisa**  
Universita di Udine and INFN Trieste/Udine

Mu2e collaboration:  
~135 members from 28 institutions  
**Calorimeter Group:**  
**~25 members from 7 institutions**

# Calorimeter requirements

- Provide a quality check on the reconstructed track
- Helpful tool to perform the pattern recognition of tracks
- Particle identification: muon rejection factor > 200
- Filter the events at HLT independently from the tracker

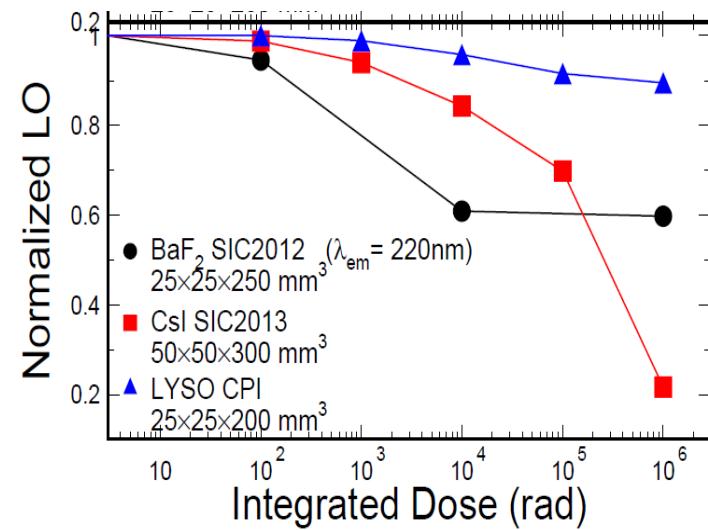
Survive in the Mu2e environment:

- ◆ Operable in 1 T magnetic field
  - ◆ Radiation hard ( $\sim 10$  kRad/year/crystal)
- 
- ✓ energy with a resolution of  $O(5$  MeV)
  - ✓ time with a resolution  $\leq 0.5$  ns
  - ✓ impact position with a resolution  $\sim 1$  cm

# Calorimeter crystal history

- CDR choice LYSO: small  $X_0$ , high light yield, expensive ( $\rightarrow$ very expensive)
- TDR choice BaF<sub>2</sub>: larger  $X_0$ , lower light yield (in the deep UV), very fast component at 220 nm, readout R&D required, cheaper than LYSO
- TDR backup CsI: larger  $X_0$ , lower light yield (in the near UV), fast component at 310 nm, readout MPPC, cheaper than BaF<sub>2</sub>

Crystal	BaF <sub>2</sub>	LYSO	CsI
Density (g/cm <sup>3</sup> )	4.89	7.28	4.51
Radiation length (cm) $X_0$	2.03	1.14	1.86
Molière radius (cm) Rm	3.10	2.07	3.57
Interaction length (cm)	30.7	20.9	39.3
$dE/dx$ (MeV/cm)	6.5	10.0	5.56
Refractive Index at $\lambda_{\max}$	1.50	1.82	1.95
Peak luminescence (nm)	220, 300	402	310
Decay time $\tau$ (ns)	0.9, 650	40	26
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	3.6
Light yield variation with temperature (% / °C)	0.1, -1.9	-0.2	-1.4
Hygroscopicity	None	None	Slight



# Calorimeter baseline

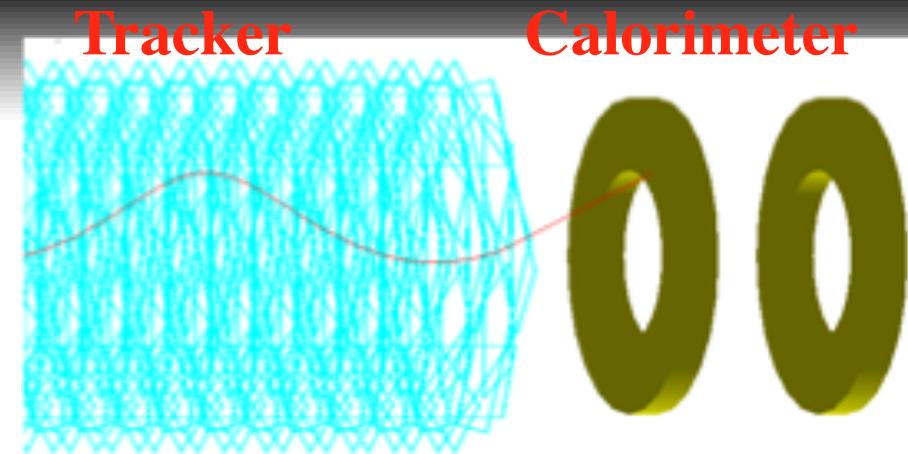
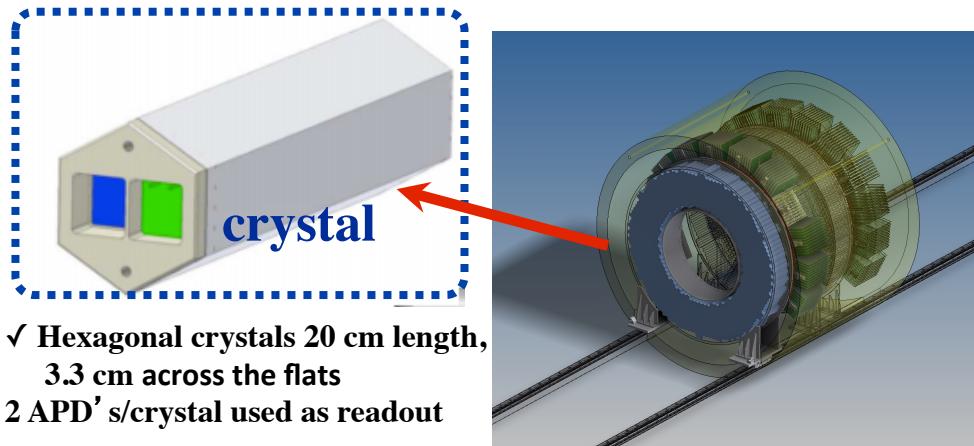
After an optimization study done with simulation:

- ✓ The baseline design consists of two disks with a 92% acceptance;

- ✓ each disk contains 930 hexagonal BaF<sub>2</sub> crystals

- ✓ Disk separation ~ 70 cm

- ✓ Inner/outer radii: 35.1/66 cm



Caltech/JPL/RMDinc consortium is doing intense R&D for developing a modified delta-doped RMD large area APD which incorporates an atomic layer deposition antireflection filter for providing:

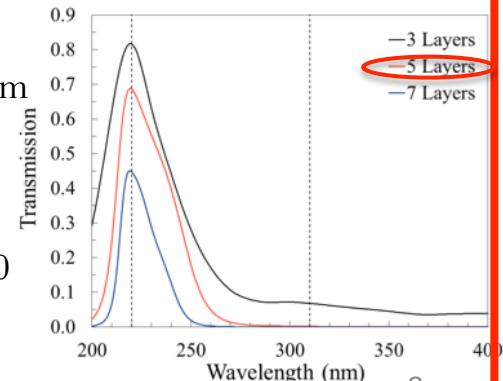
- ✓ 70% QE @ 220 nm (wavelength of the fast component)

- ✓ ~0.1% QE @ 300 nm

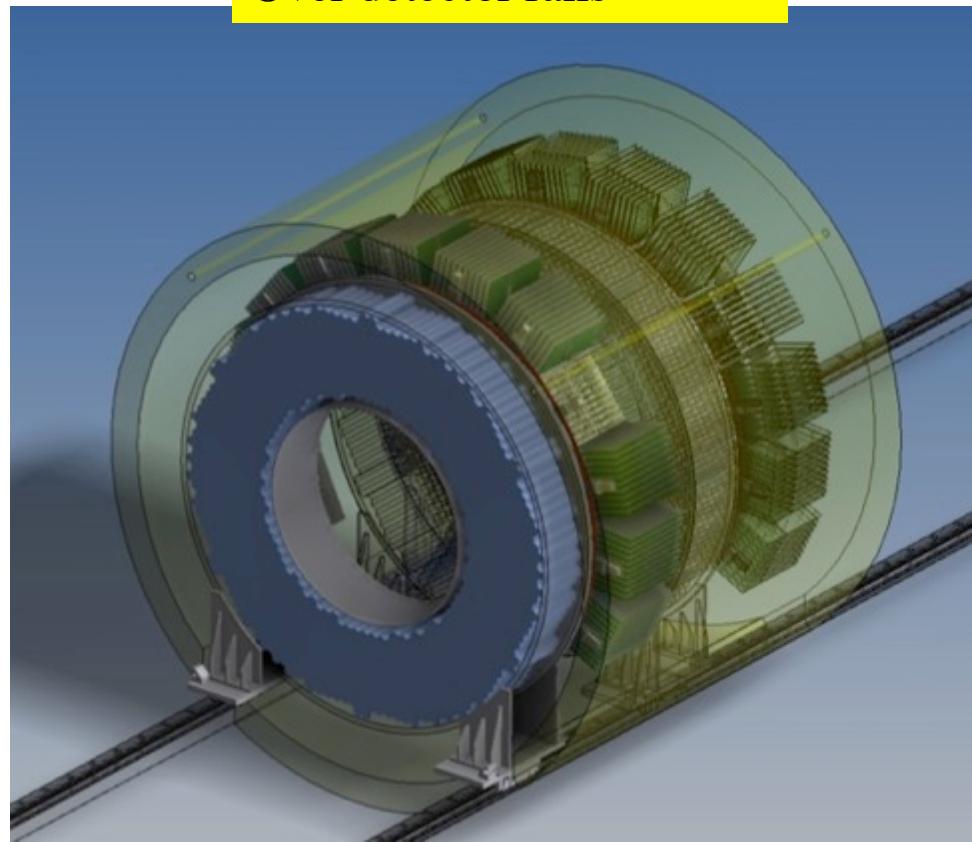
- ✓ capacitance ~ 60 pF

- ✓ operation gain ~ 500

- ✓ HV 1800 V

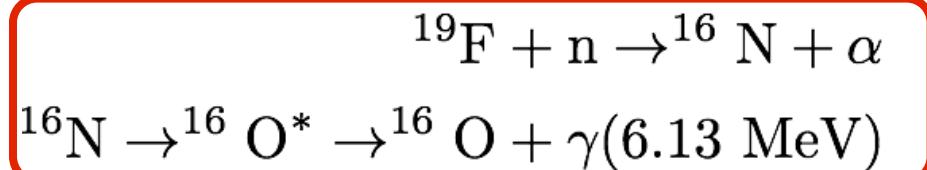


# Mechanics

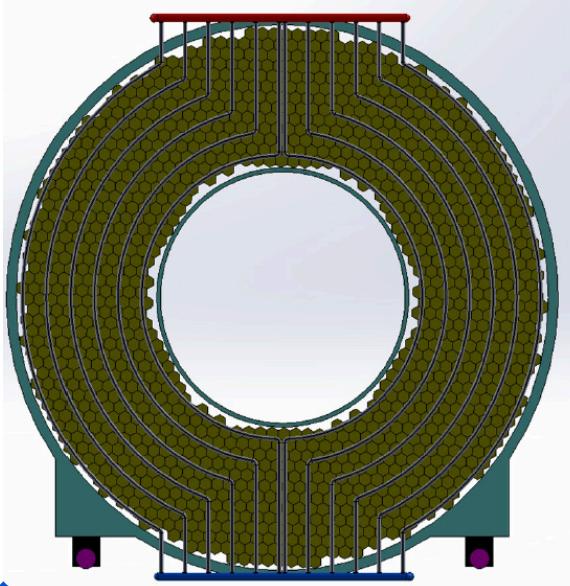


# Calibration system

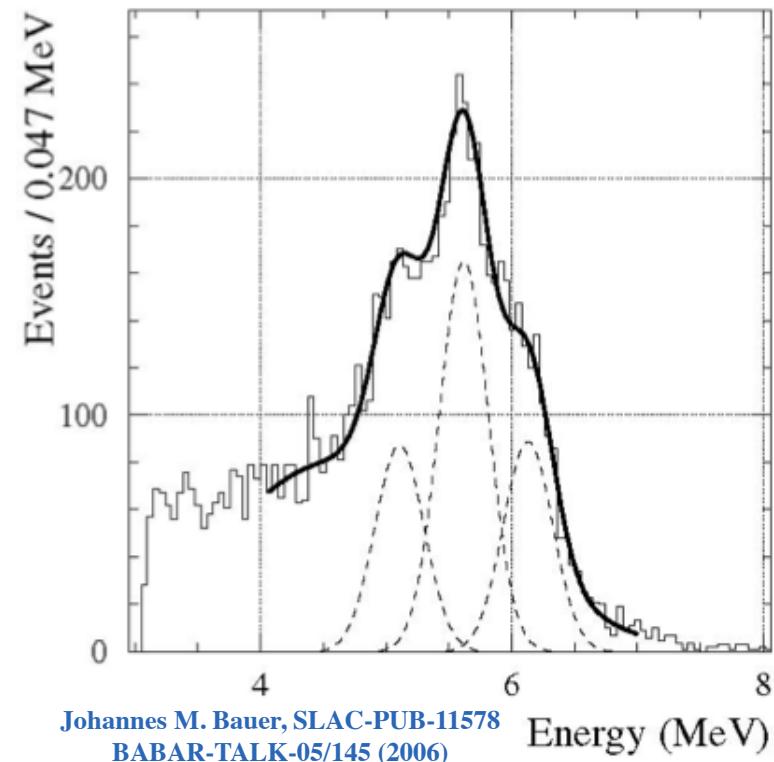
The equalization in response of the crystals, an energy scale and a check of linearity are provided by a liquid source system ( $\text{C}_8\text{F}_{18}$ )



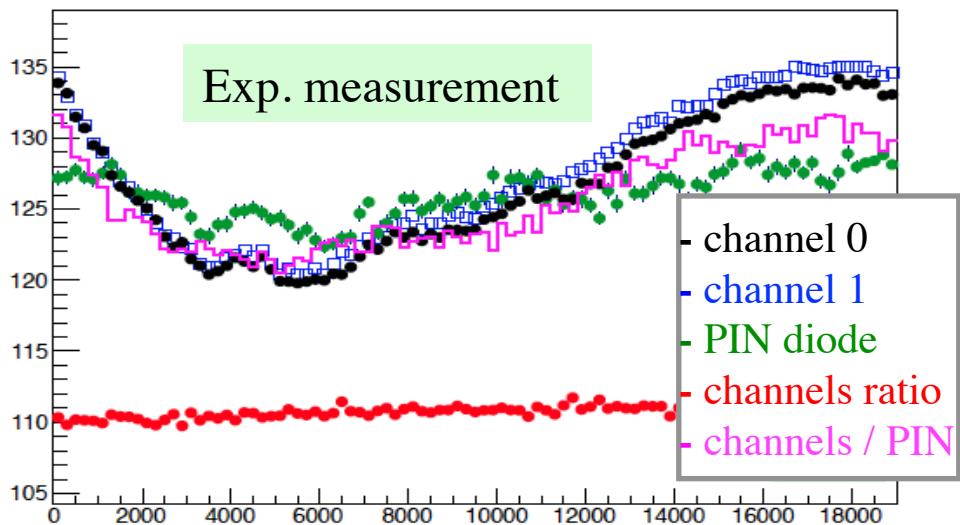
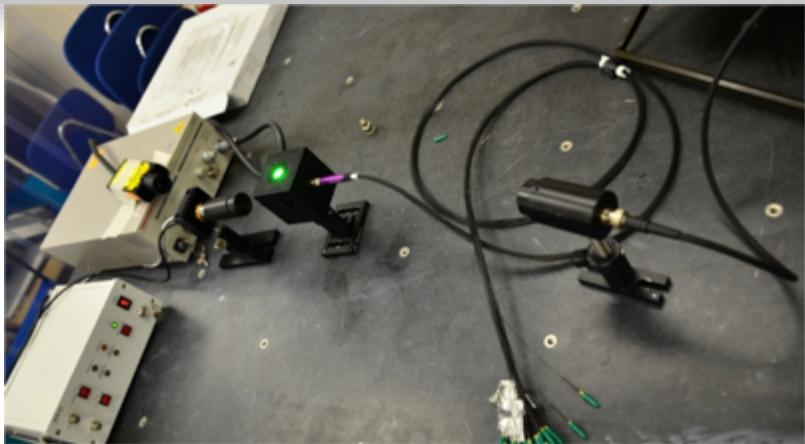
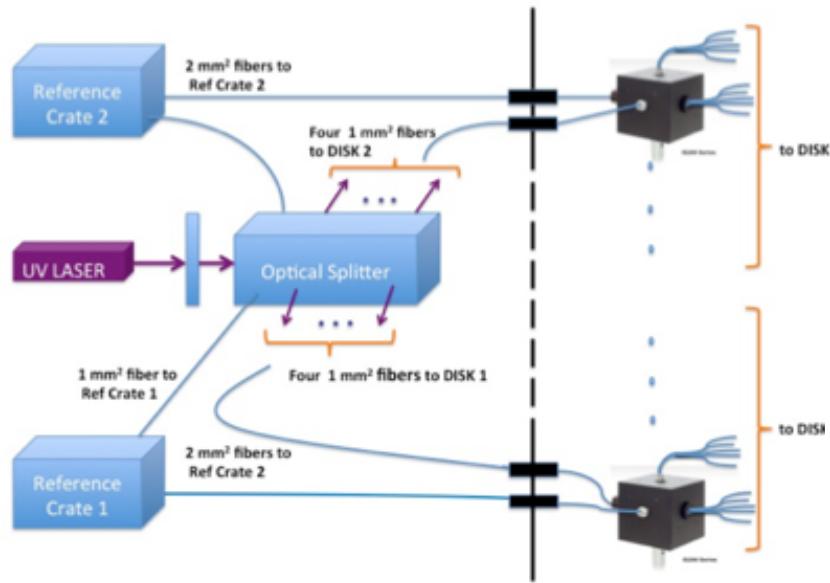
## Liquid source circuit



- ✓ 12 Al pipes
- ✓ 0.5 mm thickness
- ✓ ~1 cm diameter
- ✓ length 1.5 - 1.7 m



# Monitoring system

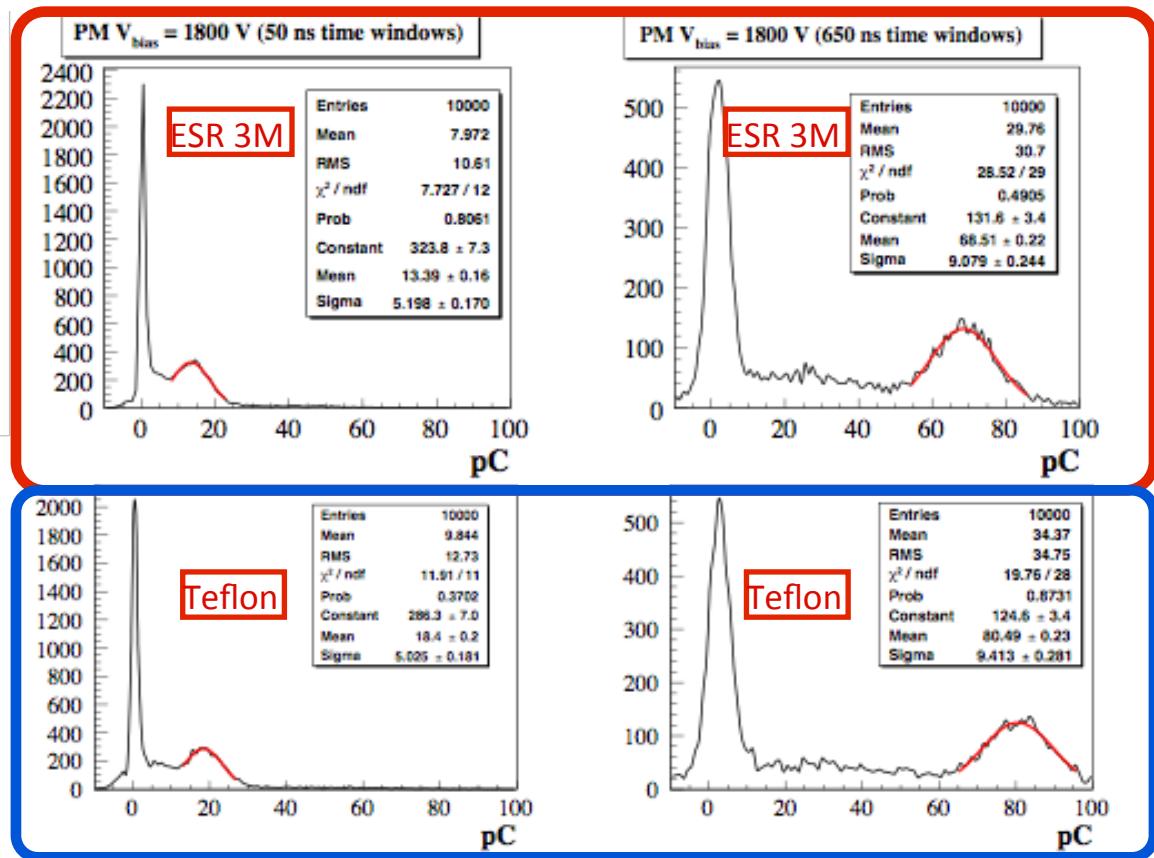


- **Npe ~30000 at end of distribution chain as measured with prototype laser and calorimeter system.**

# Testing BaF<sub>2</sub>

First tests with BaF<sub>2</sub> 30x30x230 mm<sup>3</sup> crystals by Siccas with:

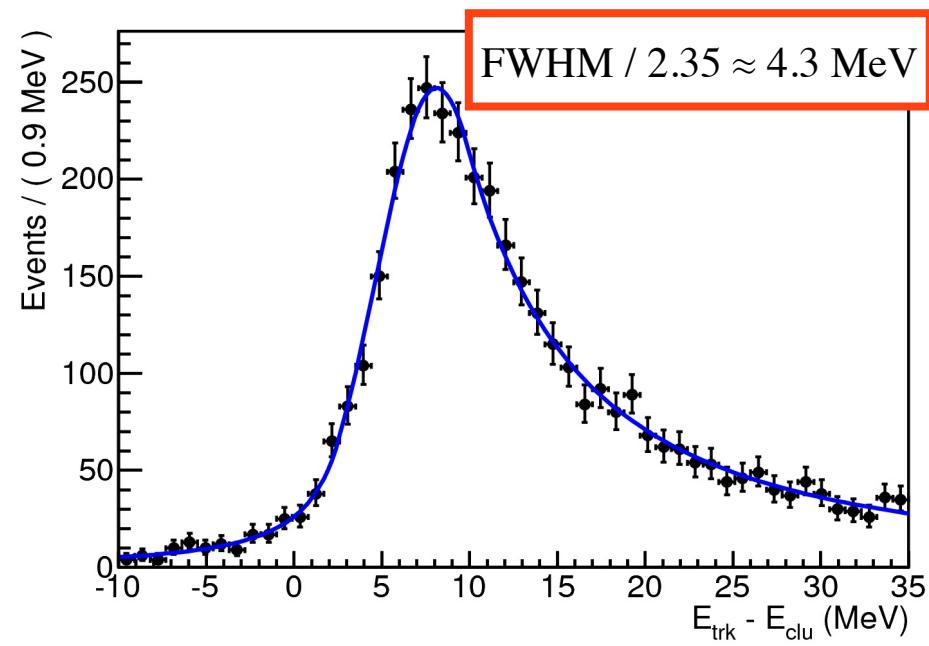
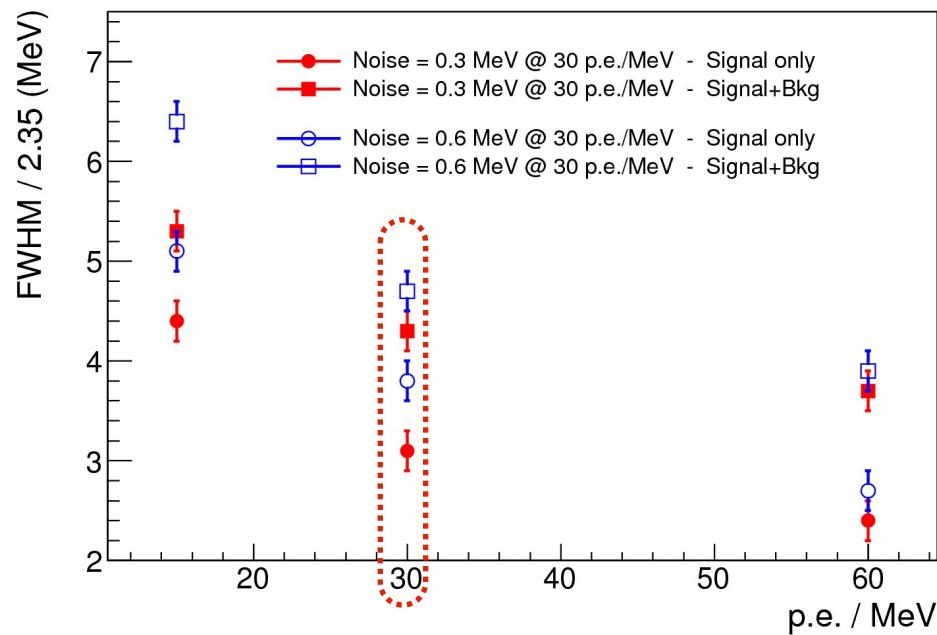
- **NO GREASE**
  - teflon and ESR 3M
  - EMI PM @ V<sub>bias</sub> = 1800 V,  
gain =  $3.8 \times 10^6$   
QE ~ 30% @ 210 nm
  - Na<sup>22</sup> source
- Light yield** ~ 70-72 pe/MeV
- Scaling to APD and using optical grease ~ **30 - 32 pe/MeV per photosensor** (for the fast component using 50 ns)



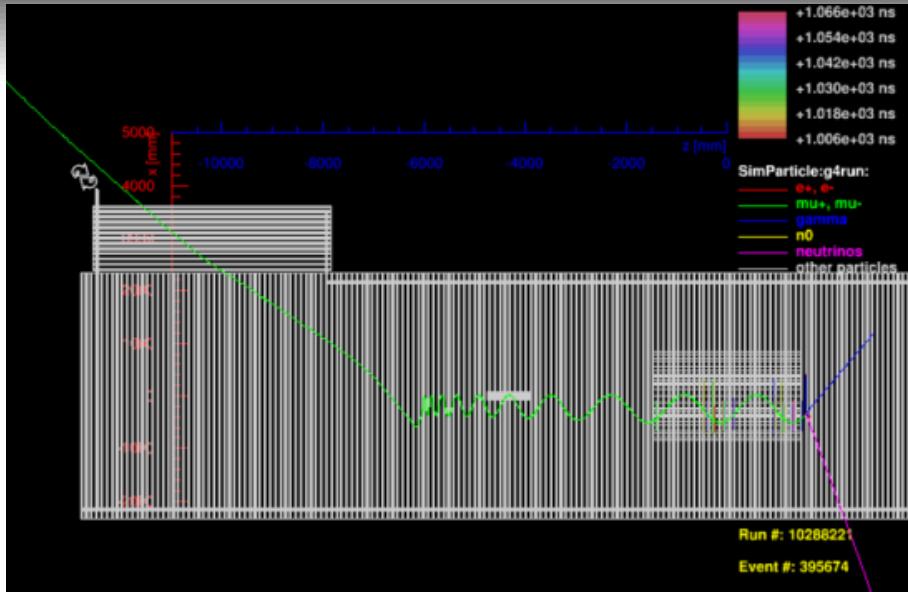
# Calorimeter performances

- Full GEANT4 simulation performed for signal events ( $\sim 30\text{pe}/\text{MeV/APD}$ )
- Simulation with backgrounds included is under study
- 300 keV a threshold @ 1 MeV will be applied

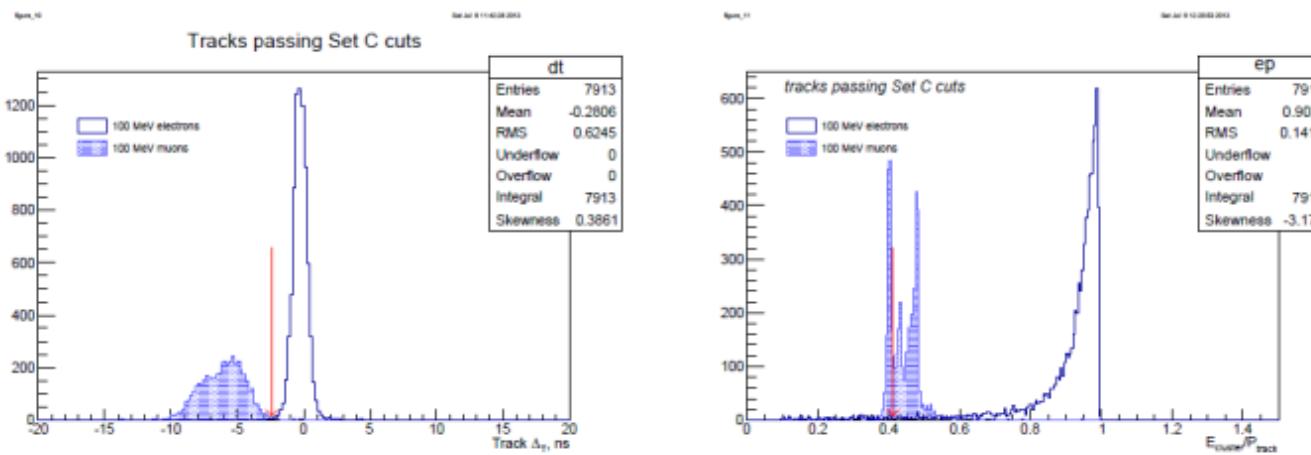
## Energy resolution BaF<sub>2</sub>



# Particle ID: The “Ralf event”



- In massive MC runs to optimize the CRV, an event was found that evaded the CRV, passed through the target and the tracker, and stopped in the calorimeter
- The calorimeter, however, provides substantial additional background rejection, through  $\mu/e$  PID, with a combination of timing information and  $E/p$



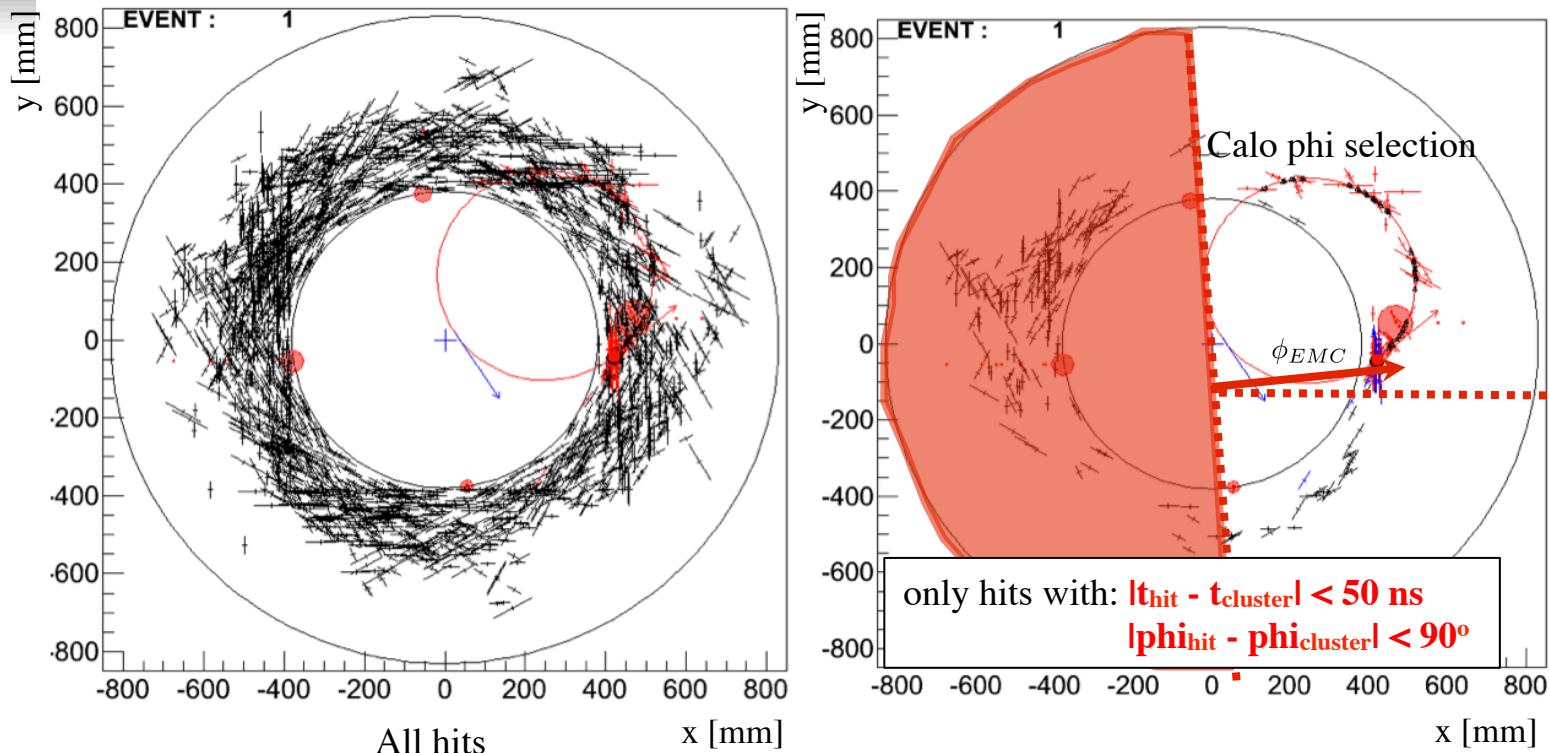
**Calorimeter timing and energy deposition provide excellent muon rejection:**

**$\epsilon > 99\%$ ,  
muon rejection  $\sim 200$ .**

# Cal-track Pattern recognition



Transverse view of the Detector Solenoid: signal mixed with all background



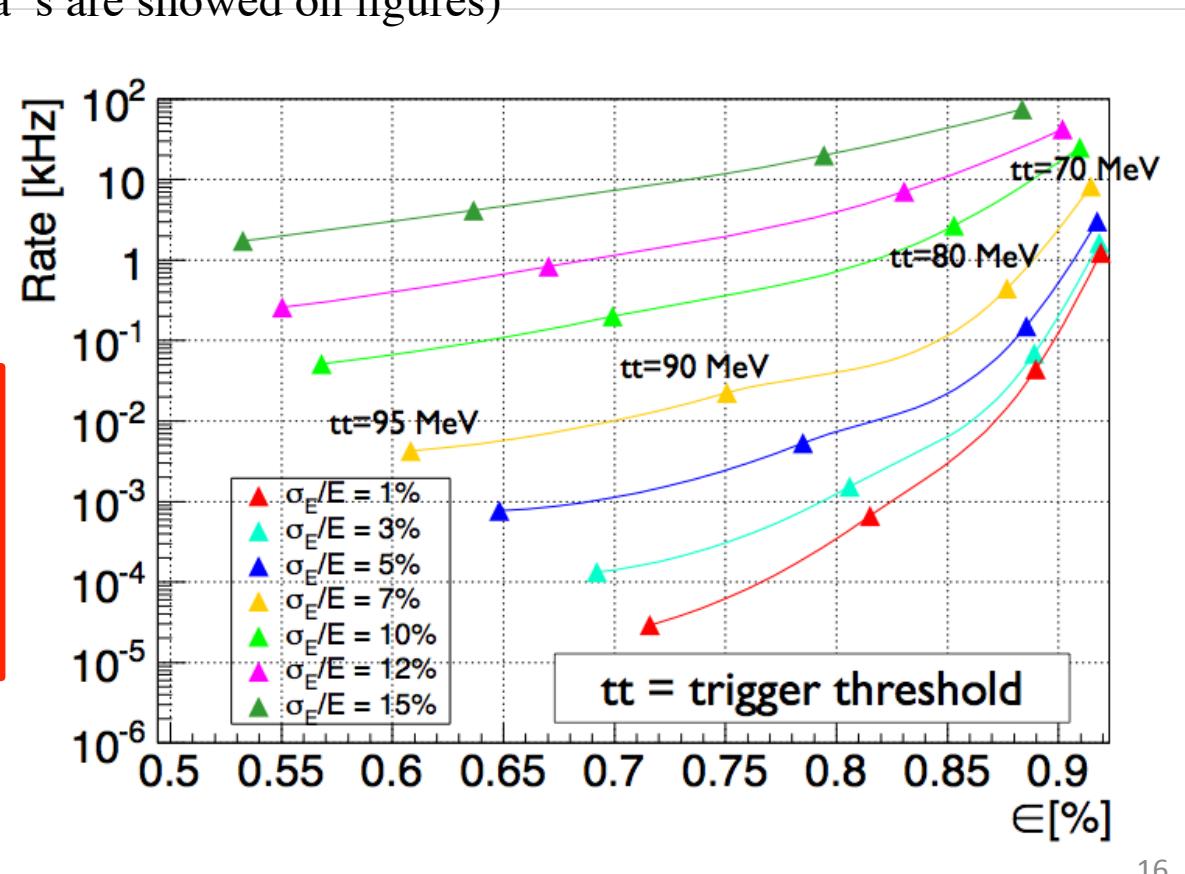
- ✓ Red bullets are EM clusters positions (bullet size is proportional to the energy deposited), the red line is the Conversion electron helix
- ✓ Crosses represent tracker hits position

Cal-track finding increases efficiency on finding CE tracks from 10% to 11.2%

# Trigger algorithm and rates

- ✓ The trigger algorithm (HLT) applies a threshold on the reconstructed cluster energy
- Signal efficiency and DIO rate were studied convoluting simulations results with Gaussian functions (sigma's are showed on figures)

As an example by putting the threshold @ 70 MeV one gets ~92% efficiency and ~2 kHz of DIO rate with 5% energy resolution.



# Backup alternative: CsI + MPPC

The selected alternative for BaF<sub>2</sub> is pure CsI + MPPC (by Hamamatsu, PDE  $\sim 5\%$  @ 310 nm). First tests with 30x30x200 mm<sup>3</sup> pure CsI crystals have been made:

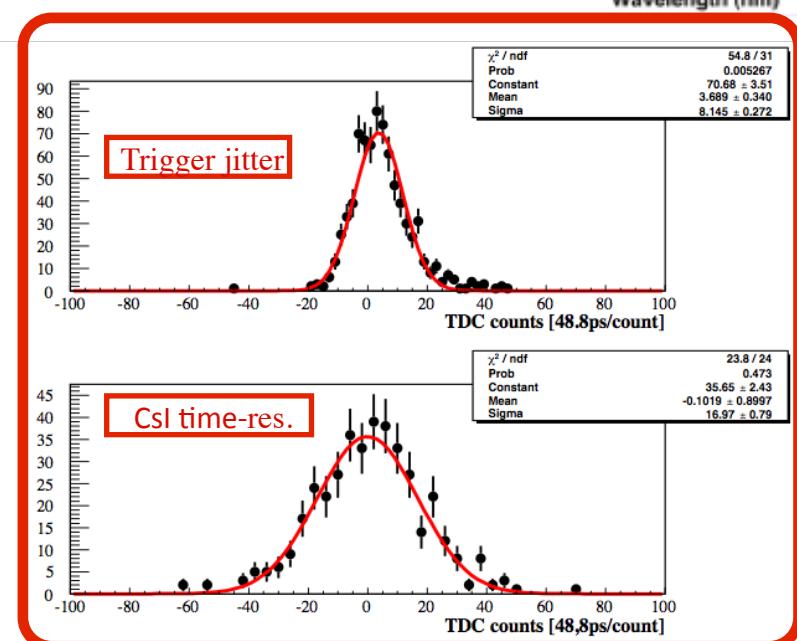
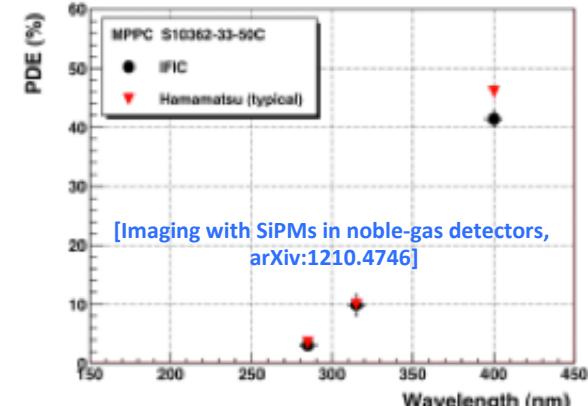
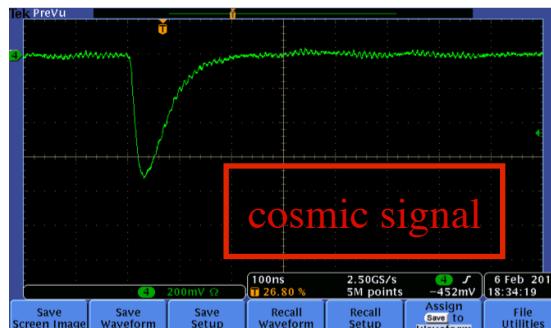
- Silicon paste 7 by Rhodorsil, Teflon wrapping
- one MPPC matrix (16 MPPCs of 3x3 mm<sup>2</sup>) with:

- analog sum of 16 anodes
- 1-pole filter for shaping

- Trigger made by two small plastic scintillators

✓ time resolution  $\sim 720$  ps after trigger jitter correction

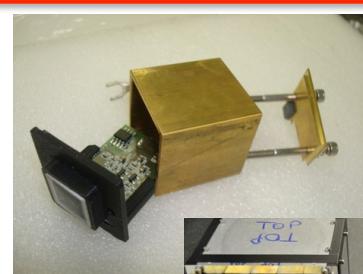
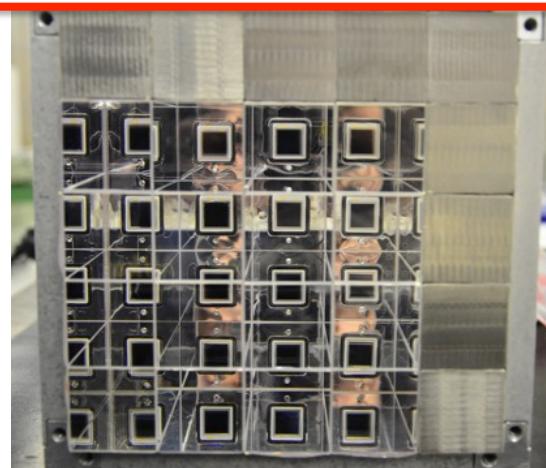
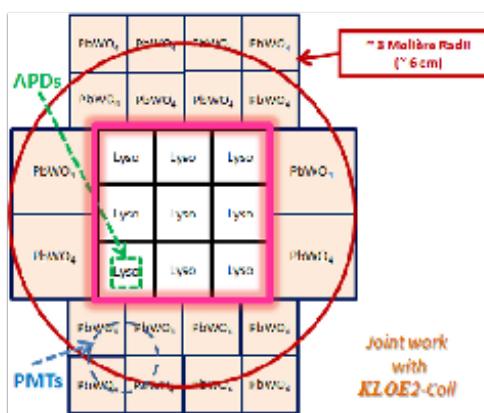
(@  $\sim 18$  MeV, dE/dx  $\sim 5.6$  MeV/cm)



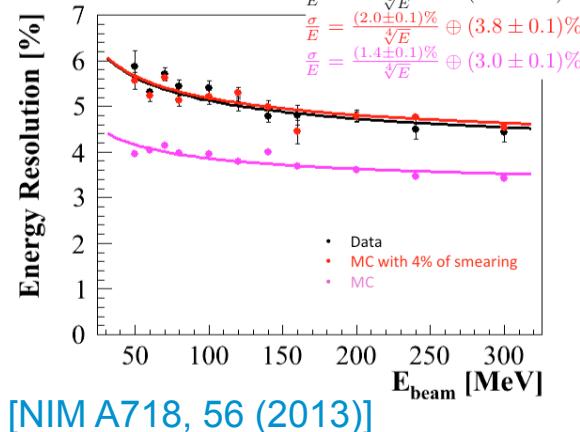
# R&D on LYSO

Test Beam (2011) at MAMI (Mainz Microtron, Germany) with a clean tagged photon.

- An inner matrix of 9 LYSO crystals  
20×20×150 mm<sup>3</sup>
- An outer matrix of PbWO<sub>4</sub> crystals
- **New matrix of 25 LYSO crystals**  
30x30x130 mm<sup>3</sup> built. Tests with cosmic rays and laser-monitoring-system are ongoing

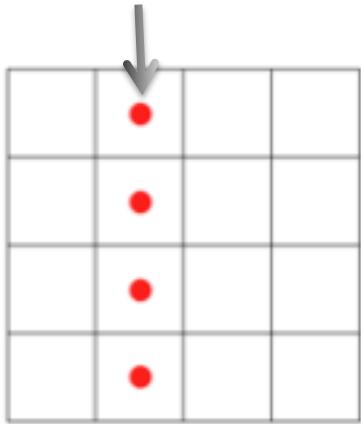


APD + ampl  
BOX



# Test with cosmic rays

**Preselection applied**  
one full column with empty  
neighbors.



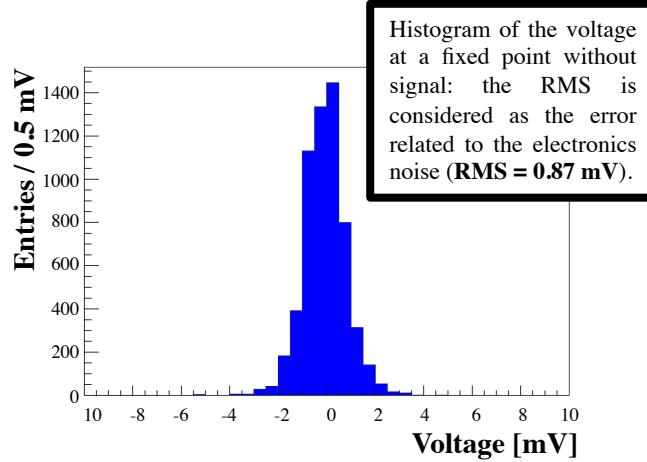
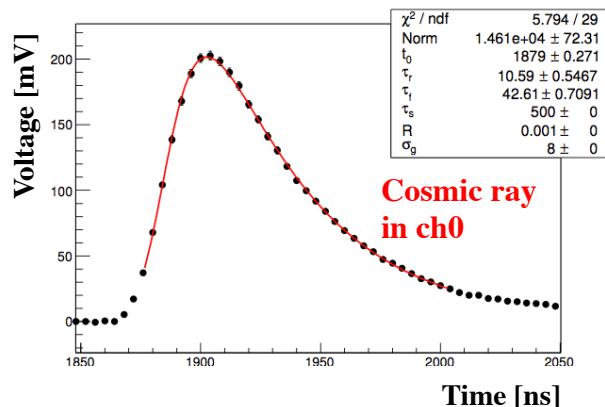
## Voltage Error:

- Electronic noise: 0.87 mV
- Digitizer:  $0.5 \text{ mV} \approx 2\text{V}/2^{12}$   
(2 V: full scale, 12: number of bits)
- Photoelectrons fluctuation:  
 $N'_{pe} = N_{pe} \cdot Q(\Delta V)/Q_{tot}$   
 $N_{pe}$ : number of photoelectrons  
 $(\geq 75000 \text{ for a 30 MeV MIP})$   
 $Q(\Delta V)$ : binned charge at voltage  $V$   
 $Q_{tot}$ : total signal charge.

$$\delta_{\Delta V} = 0.87 \text{ mV} \oplus 0.5 \text{ mV} \oplus \frac{1}{\sqrt{N_{pe}}} \cdot \Delta V$$

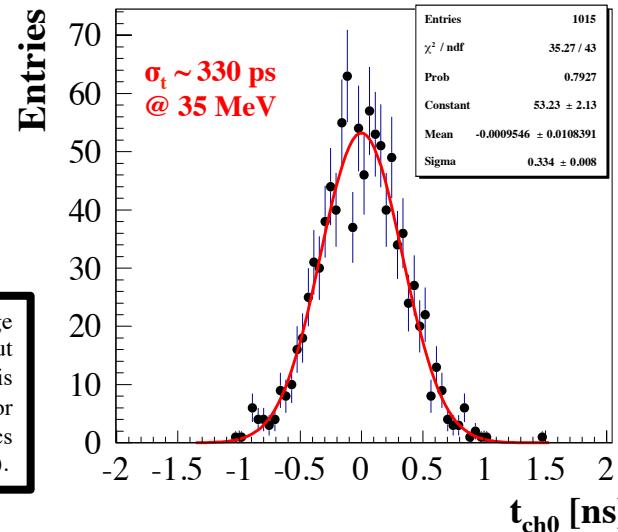
## Fit for a MIP event

The waveform is parametrized with three exponential parts, one rising and two decaying, convoluted with a gaussian



We calculate the difference between the reconstructed  $t_{max}$  for ch0 and the charge weighted average of the  $t_{max}$  for ch2 and ch3

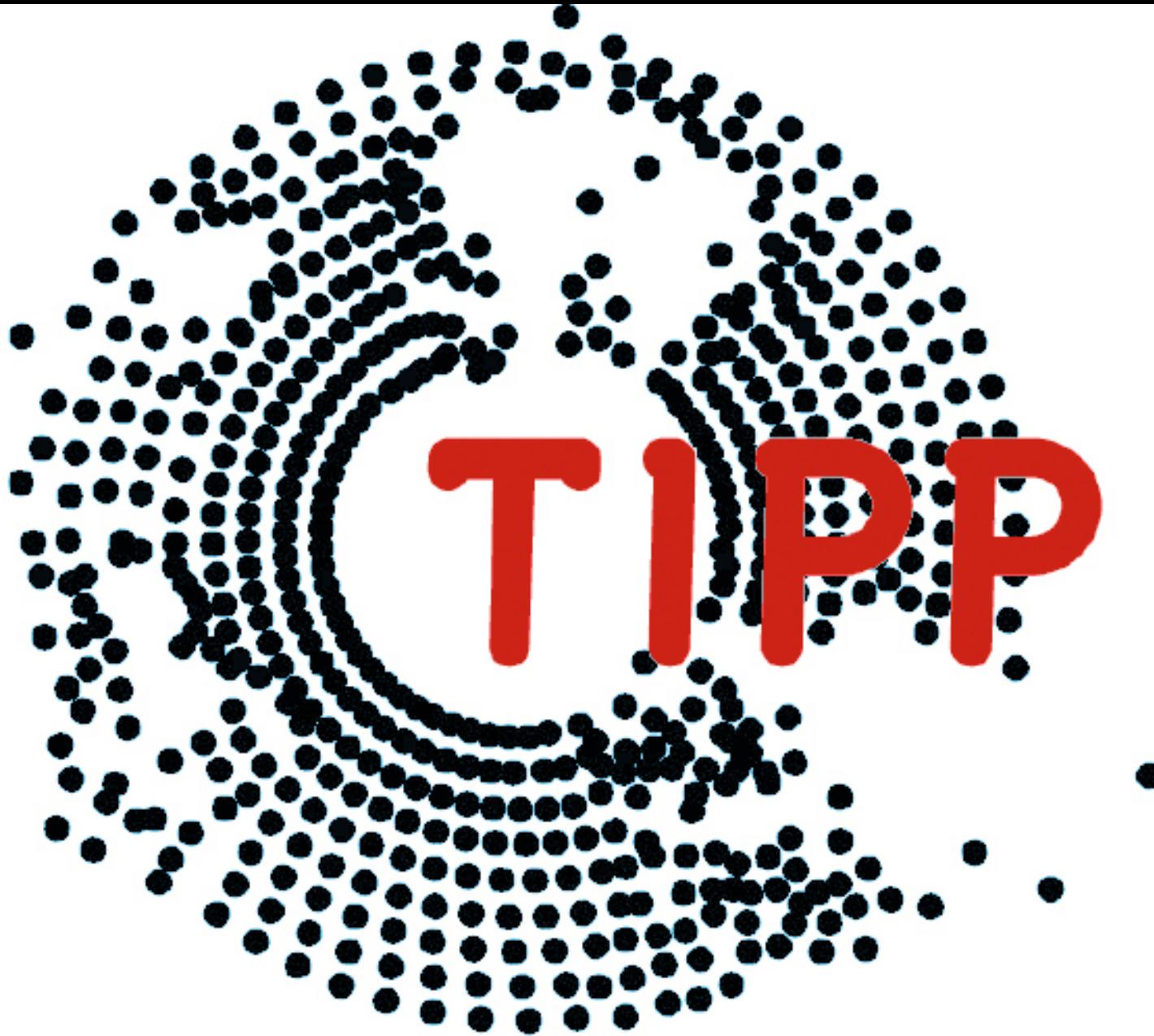
$$t_{ch0} = t_{max_0} - \frac{\sum_{i=2,3} t_{max_i} E_i}{\sum_{i=2,3} E_i}$$



# Conclusions

- ✓ The design of the MU2E calorimeter is being completed.  
It consists of two disks of 930 hexagonal BaF<sub>2</sub> crystals that should grant 5% energy, 500 ps timing and 1 cm position resolutions.
- The EMC characteristics will allow a powerful PID, HLT filtering and a successful HLT filter stage.
- R&D on the photosensors development is in progress
- A final technology choice is planned for next spring when the BaF<sub>2</sub> readout with new RMD APD will be compared with the CsI readout with the enanchched UV MPPC.
- ❑ To complete the R&D on LYSO, a new test beam is planned with the photon beam at MAMI in September 2014. Other test beam measurements are planned with new matrix prototype of BaF<sub>2</sub> or CsI under construction.

SPARE



TIPP'14

# What is $\mu^-$ Conversion?

- The neutrino-less conversion of a muon to an electron in the field of a nucleus is a particularly interesting example of an LFV process involving charged leptons.

Stop  $\mu^-$  in atoms:  $\mu^- \rightarrow 1s$  state

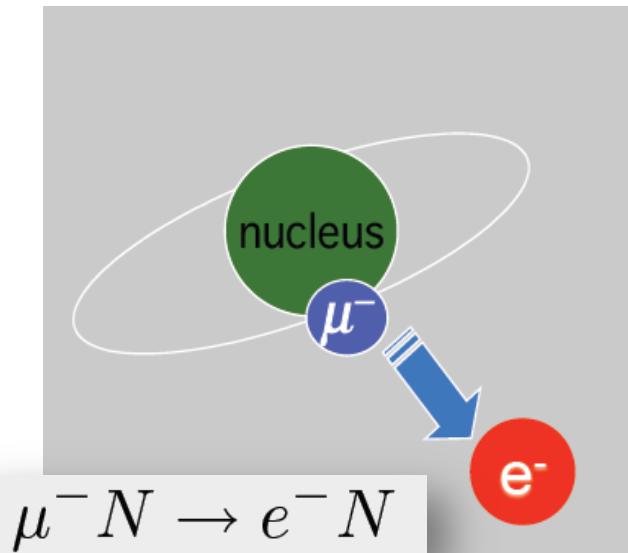
1. Capture:  $\mu^- N \rightarrow \nu_\mu N'$  (60%)

2. Decay:  $\mu^- N \rightarrow e^- \bar{\nu}_\mu \bar{\nu}_e$  (40%)

3. Coherent Conversion:

A Single Monoenergetic Electron

If  $N = Al$ ,  $E_e = m_\mu - BE = 105. MeV$



- In the Standard Model, such conversions would take place through higher order Feynman diagrams involving virtual neutrino mixing, *at a rate far below the threshold of any currently conceivable experiment* .

$$BR_{SM}(\mu^- N \rightarrow e^- N) \approx 10^{-56}$$

# Beyond the SM

- Any detectable signal would be a definite signature, even if indirect, of new dynamics at very high energy scales.

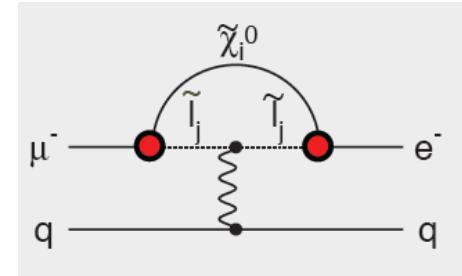
Sensitive to mass scales up to  $O(10^4 \text{ TeV})$

The Mu2e experiment is designed to search for the signature of a captured muon converting to an electron through the exchange of virtual particles with an Aluminum nucleus:

Supersymmetry  
rate  $\sim 10^{-15}$

## Mu2e goal

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z)) \rightarrow e^- + N(A, Z)}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon capture})} \leq 6 \times 10^{-17} \text{ (@90%CL)}$$



Mu2e will start data taking at Fermilab in the second half of 2019

# Experimental Technique

## Normalize to Capture:

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

Negatively charged muons that stop in matter are quickly trapped and form muonic atoms:

Al turns  
into Mg

- The muon cascades to 1s orbital by electromagnetic transitions (**X-rays provide the stop rate.** This rate will be measured with a germanium detector downstream near the beam dump).

After capture,

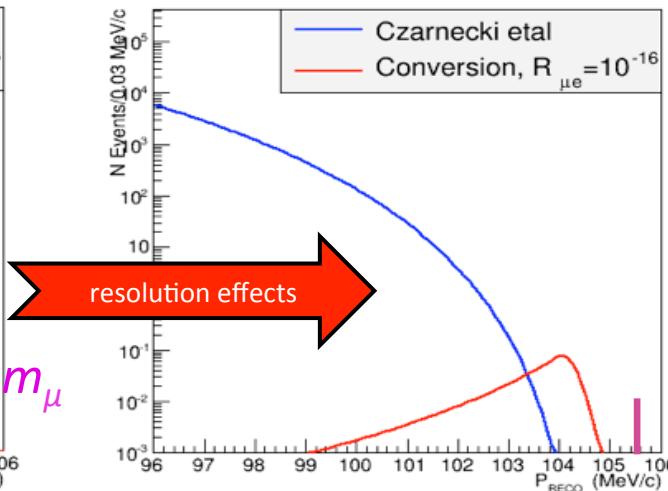
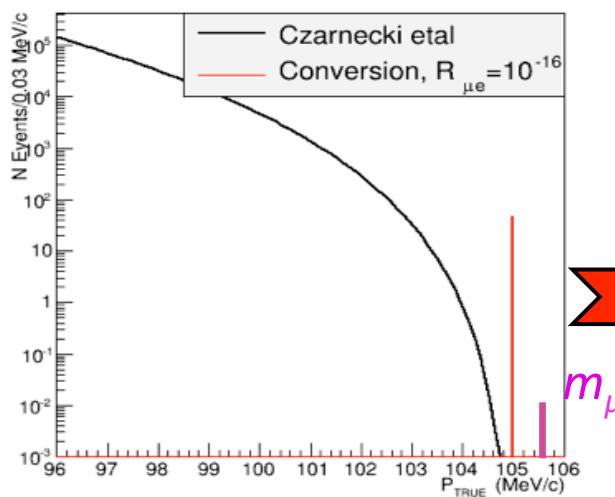
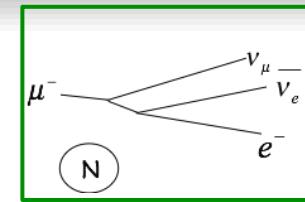
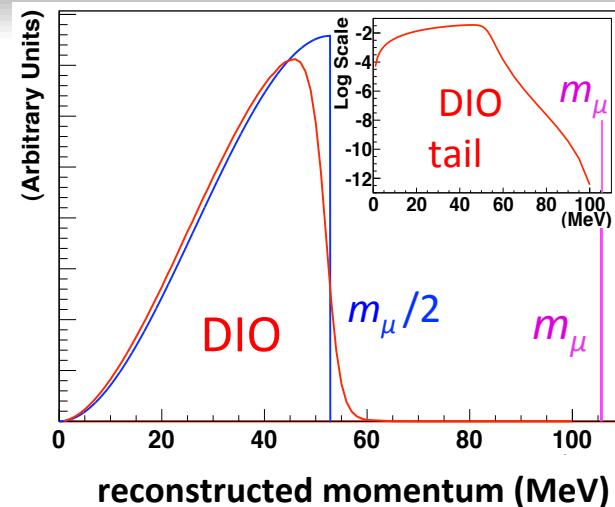
- $\text{Mg} \rightarrow \text{Al}$  by a 2.6 MeV  $\beta$  followed by  $\gamma$  that could be used to measure capture rate.

# Physics backgrounds

Background	Rejection method
<i>Electrons from muon decay-in-orbit (DIO)</i>	<i>Good momentum and energy resolution</i>
<i>Cosmic induced background</i>	<i>Cosmic ray veto and PID</i>
<i>Antiproton induced background</i>	<i>Anti-proton absorber in the TS</i>
<i>Radiative pion capture and muon decay-in-flight</i>	<i>Pulsed beam and delayed time signal window</i>

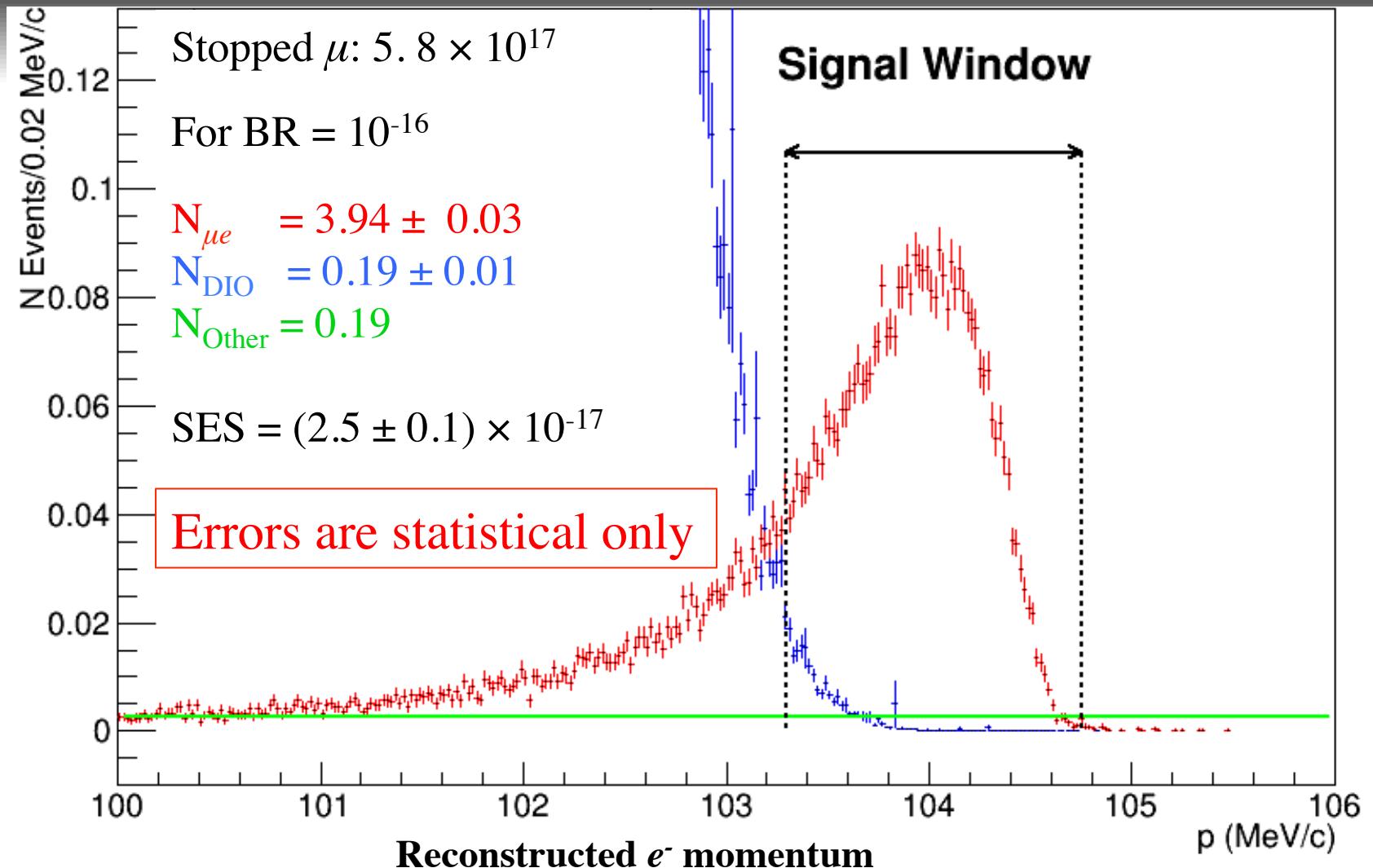
# The dominant background: muon decay in orbit (DIO)

- The tail of the DIOs falls as  $(E_{\text{Endpoint}} - E_e)^5$
- Separation of a few hundred keV for  $\text{BR}_{\mu e} = 10^{-16}$



**Resolution effects  
extend the DIO  
endpoint into the  
signal region**

# Signal sensitivity for a 3 Year Run



# CLFV has actually been seen in California



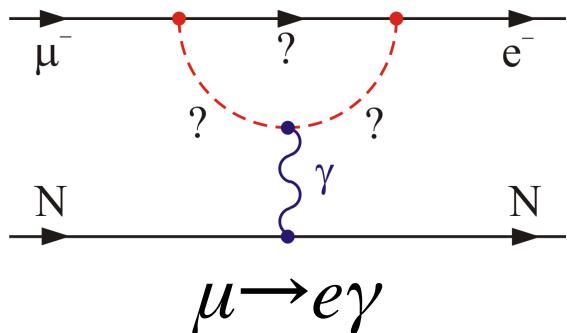
## Mu2e goal

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z)) \rightarrow e^- + N(A, Z)}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon capture})} \leq 6 \times 10^{-17} \text{ (@90%CL)}$$

**Mu2e will start data taking at Fermilab in the second half of 2019**

# Two types of amplitudes contribute

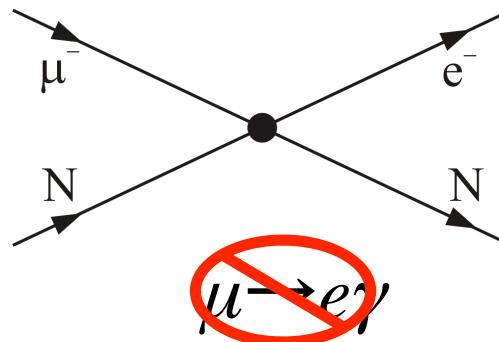
Loops



$$\mu N \rightarrow e N$$

$$\mu \rightarrow eee$$

Contact terms



$$\mu N \rightarrow e N$$

$$\mu \rightarrow eee$$

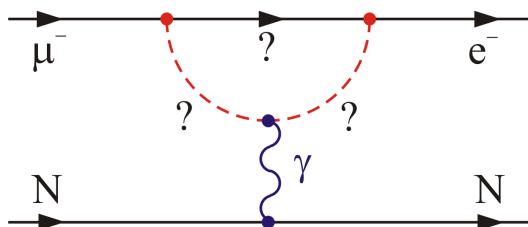
Effective Lagrangian

$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

# Sensitivity to high mass scales

$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

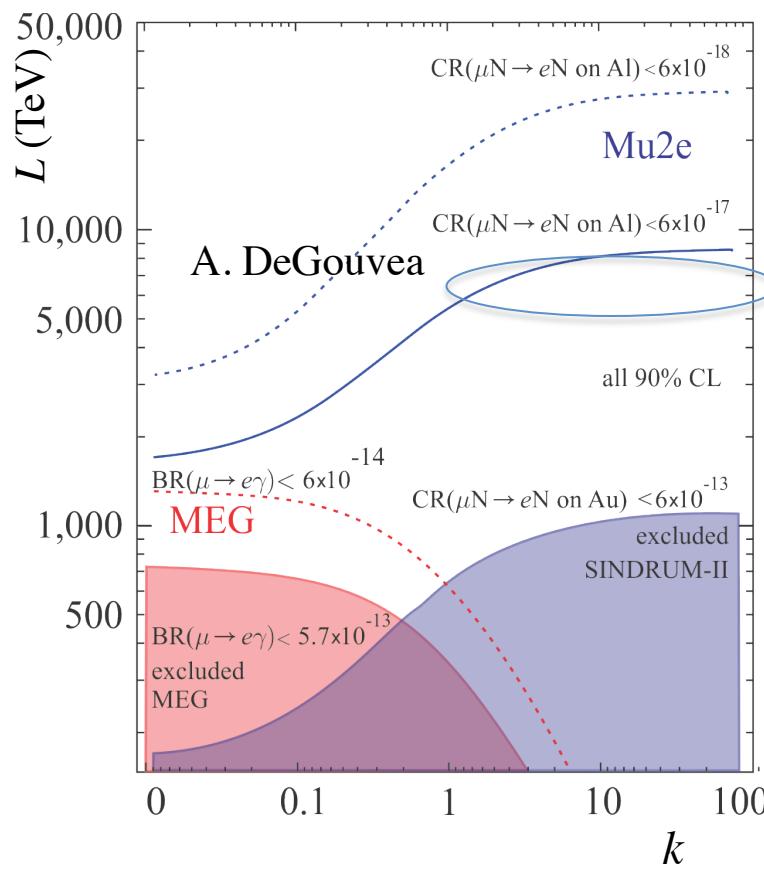
Loops dominate for  $k \ll 1$



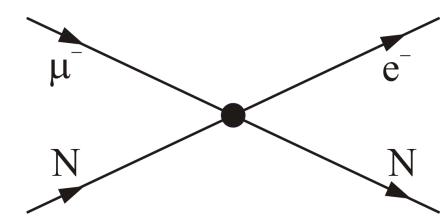
$\mu \rightarrow e\gamma$

$\mu N \rightarrow eN$

$\mu \rightarrow eee$



Contact terms dominate for  $k \gg 1$



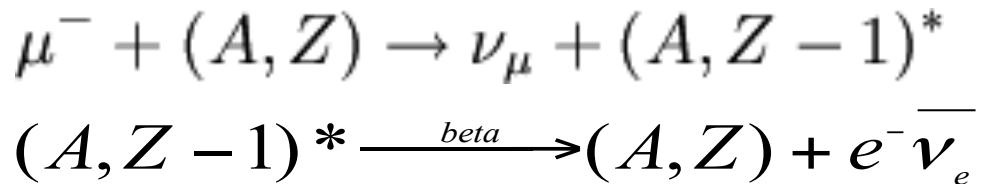
~~$\mu \rightarrow e\gamma$~~

$\mu N \rightarrow eN$

$\mu \rightarrow eee$

# Muonic Atom

- Quando un muone con carica negativa si arresta all'interno di un materiale, viene attratto dal nucleo di un atomo, e rapidamente viene catturato. Successivamente, la particella scenderà attraverso i vari livelli energetici fino a giungere al livello ad energia minima, chiamato *1S*. L'energia emessa durante questo processo, chiamato *cascata muonica*, porterà all'emissione di raggi X, ma i dettagli dell'emissione dipendono dalla natura chimica e fisica del materiale assorbente.
- Dato che la massa del muone è molto maggiore di quella dell'elettrone, la sua orbita sarà molto più vicina al nucleo che non quella di un elettrone: nello stato *1S* il raggio orbitale sarà sicuramente confrontabile col raggio di distribuzione di carica nucleare.
- Pertanto, esisterà una certa probabilità che il muone venga catturato da un protone del nucleo. L'atomo tornerà stabile attraverso decadimento beta del neutrone



Emits X-rays on the way down:

• •

66 keV, 3d-2p, intensity 62.5%

347 keV, 2p-1s, intensity 79.7%

How Can We Detect these X-Rays?: Stopping Target Monitor,

# Why Mu2e is unique?

**Muon to electron conversion is a unique probe for BSM:**

◆ **Broad discovery sensitivity across all models:**

- Sensitivity to the same physics of MEG but with better mass reach
- Sensitivity to physics that MEG is not
- If MEG observes a signal, MU2E does it with improved statistics.  
**Ratio of the BR allows to pin-down physics model**
- If MEG does not observe a signal, MU2E has still a reach to do so.  
**In a long run, it can also improve further with PIP-2**

◆ **Sensitivity to  $\lambda$  up to 10.000 TeV beyond any imaginable accelerator**

# (WhatNext?) Mu2e ... Mu2e-II

**Project-X re-imagined to match  
Budget constraints:**

## 1) PIP-2 plans:

- 1 MW at LNBE at start (2025)
- 2 MW at regime at LNBE
- **x 10 at Mu2e**

[Projectx-docdb.fnal.gov/cgi-bin/  
ShowDocument?docid=1232](http://Projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232)  
CLVF-snowmass → Arxiv.1311.5278  
Mu2e-2 → Arxiv.1307.1168v2.pdf

## 2) Depending on the beam

**Structure available:**

study Z dependence  
if signal is observed

## 3) If no signal is observed

Use x 10 events in Mu2e-2  
Minor modifications of the  
detector →  $\text{BR} < 6 \times 10^{-18}$

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, arXiv:0904.0957 [hep-ph];  
Phys. Rev. D80 (2009) 013002

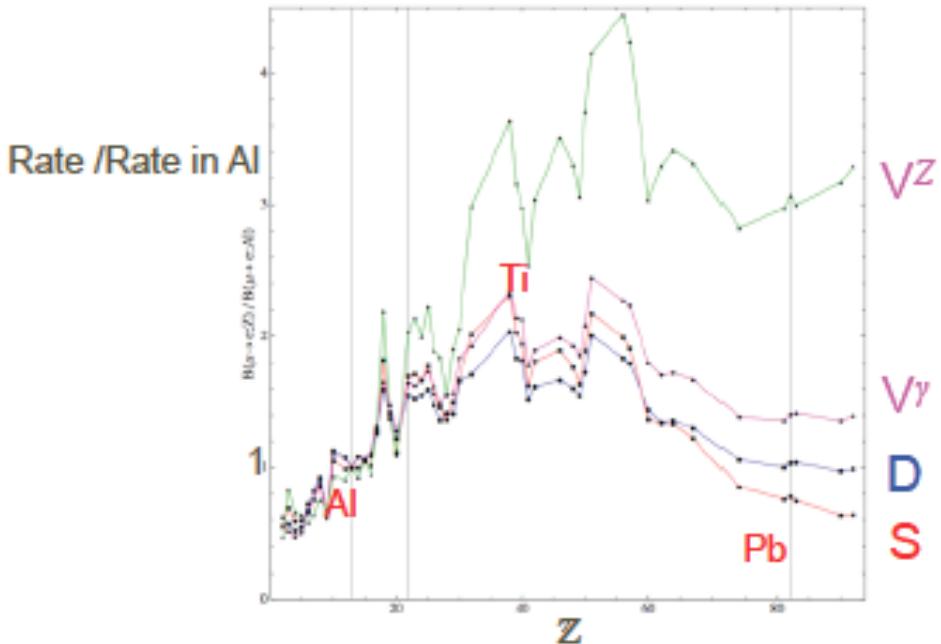
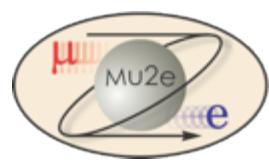


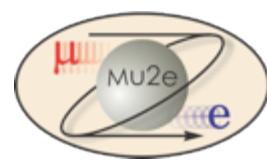
Figure 3: Target dependence of the  $\mu \rightarrow e$  conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ( $Z = 13$ ) versus the atomic number  $Z$  for the four theoretical models described in the text:  $D$  (blue),  $S$  (red),  $V^{(\gamma)}$  (magenta),  $V^{(Z)}$  (green). The vertical lines correspond to  $Z = 13$  (Al),  $Z = 22$  (Ti), and  $Z = 83$  (Pb).

# Mu2e Schedule and plans



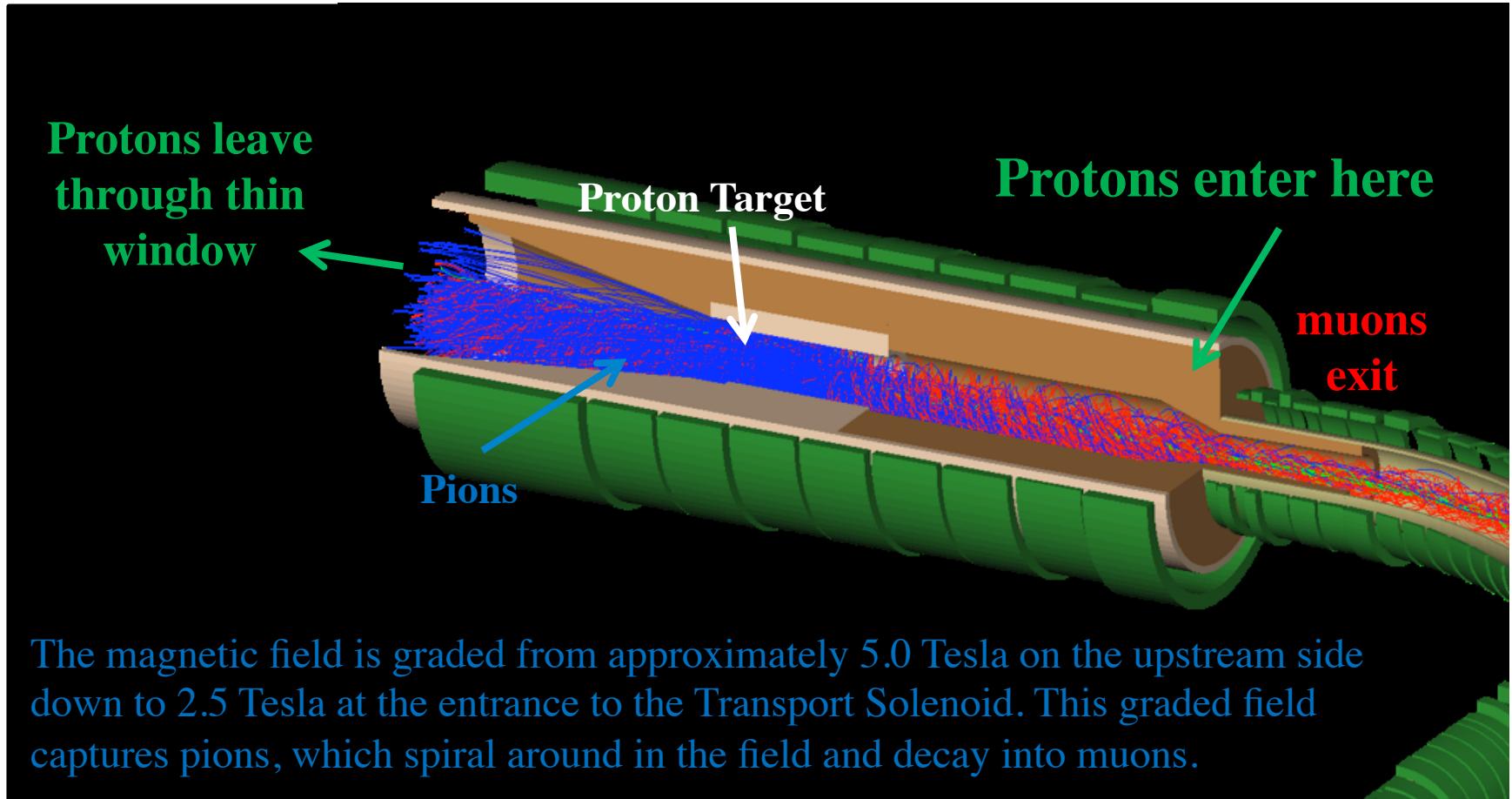
- CD-0 in November 2009, CD-1 in July 2012
- **Scheduled CD-3a in FY2014-Q2 → Done**
  - Order production lengths of solenoid superconductor (long lead item)
- **Scheduled CD2/3 in FY2014-Q3**
  - Start on building, proceed expeditiously with solenoid fabrication
  
- Obtain R&D lengths of all conductor types
- Develop a Reference Design for the solenoids and solicit bids from industry for their Final Design & Fabrication.
- Complete necessary studies to specify baseline
  - Shielding designs + Building drawings
  - Detector R&D and test beam studies

# Production Solenoid

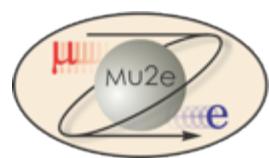


**Protons enter opposite to outgoing muons:**

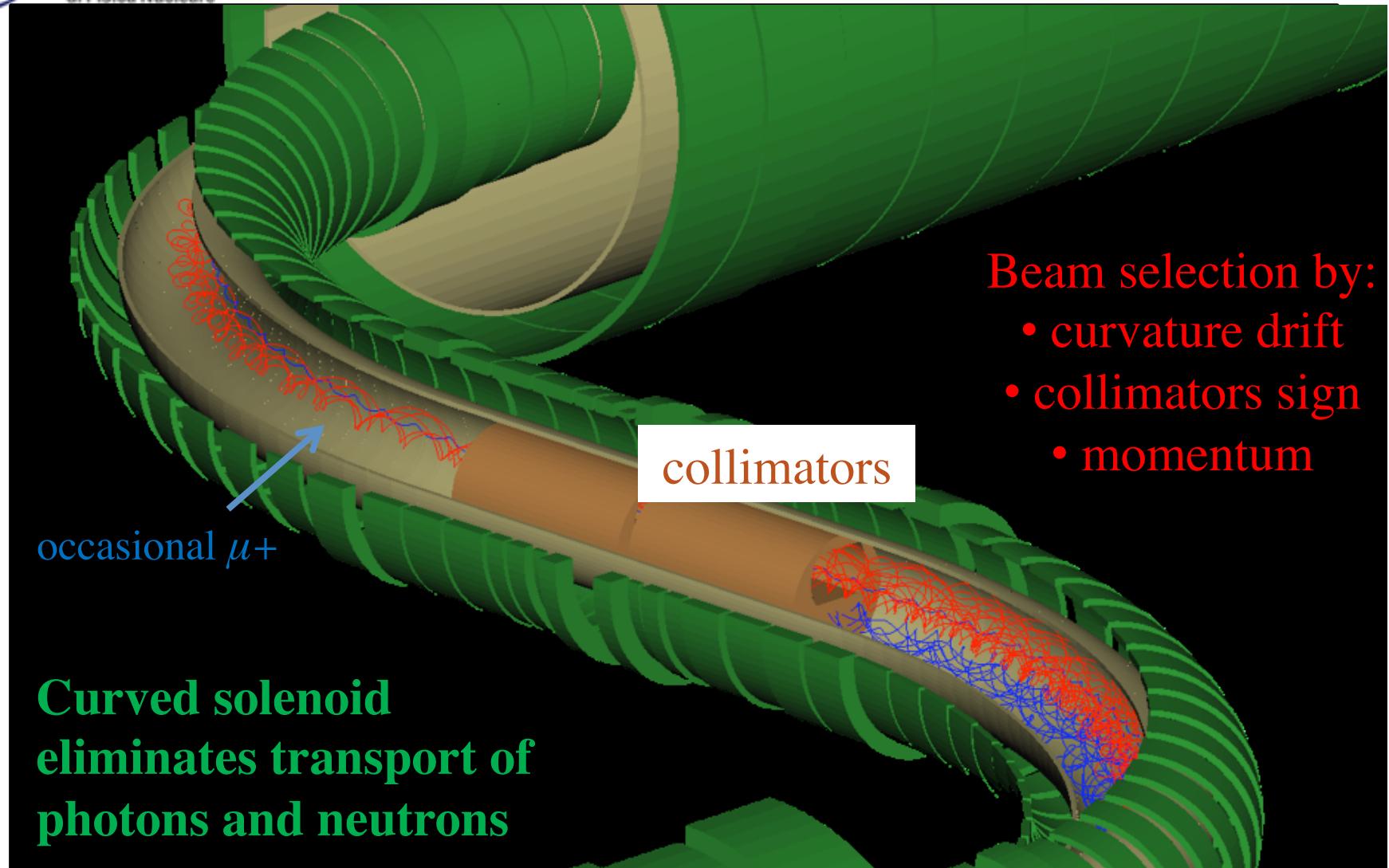
This is a central idea to remove prompt background



# Transport Solenoid



Istituto Nazionale  
di Fisica Nucleare



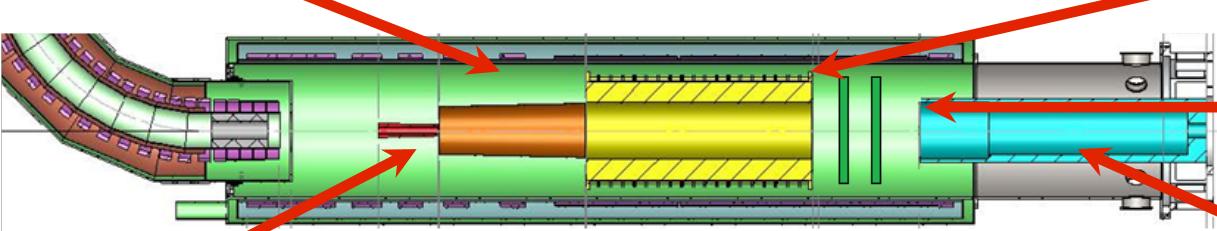
# Detector Region

- **Proton absorber:**

- ❖ made of high-density polyethylene
- ❖ designed in order to reduce proton flux on the tracker and minimize energy loss

- **Tracker:**

- ❖ ~25000 tubes arranged in planes on stations, the tracker has 22 stations
- ❖ Expected momentum resolution  $\sim 120 \text{ keV}/c$



- **Targets:**

- ❖ 17 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- **Calorimeter:**

- ❖ 2 disks composed of  $\text{BaF}_2$  crystals and separated by 1/2 wavelength

- **Muon beam stop:**

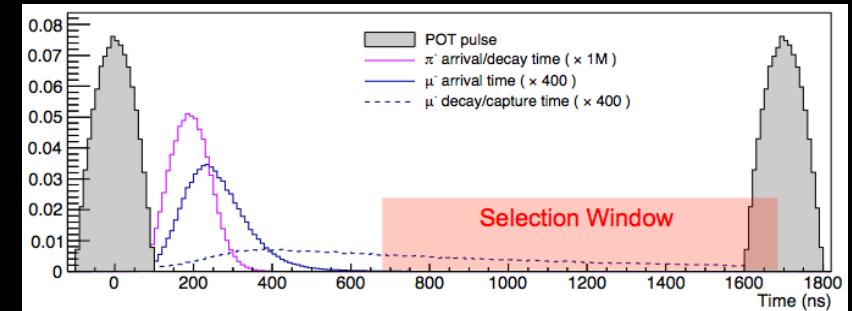
- ❖ made of several cylinders of different materials: stainless steel, lead and high density polyethylene

choose Z based on tradeoff between rate and lifetime:

**longer lived reduces prompt backgrounds**

Nucleus	$R_{\mu e}(Z) / R_{\mu e}(\text{Al})$	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

## Beam structure



# Backgrounds for a 3 Year Run

Source	Events	Comment
DIO	$0.20 \pm 0.06$	
Anti-proton capture	$0.10 \pm 0.06$	
Radiative $\pi^-$ capture*	$0.04 \pm 0.02$	from protons during detection time
Beam electrons*	$0.001 \pm 0.001$	
$\mu$ decay in flight*	$0.010 \pm 0.005$	with e- scatter in target
Cosmic ray induced	$0.050 \pm 0.013$	assumes $10^{-4}$ veto inefficiency
Total	$0.4 \pm 0.1$	

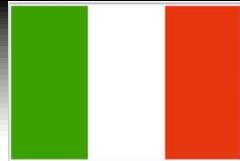
All values preliminary; some are statistical error only.

\* scales with extinction: values in table assume extinction =  $10^{-10}$

# The Mu2e Collaboration



Boston University  
Brookhaven National Laboratory  
University of California, Berkeley and  
Lawrence Berkeley National Laboratory  
University of California, Irvine  
California Institute of Technology  
City University of New York  
Duke University  
Fermilab  
University of Houston  
University of Illinois, Urbana-Champaign  
Lewis University  
University of Massachusetts, Amherst  
Muons, Inc.  
Northern Illinois University  
Northwestern University  
Pacific Northwest National Laboratory  
Purdue University  
Rice University  
University of Virginia  
University of Washington, Seattle



Laboratori Nazionali di Frascati  
INFN Genova  
INFN Lecce and Università del Salento  
Istituto G. Marconi Roma  
INFN Pisa  
Università di Udine and INFN Trieste/Udine



JINR, Dubna  
Institute for Nuclear Research, Moscow

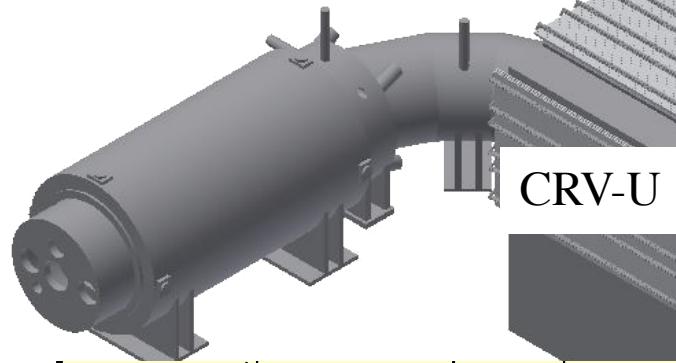
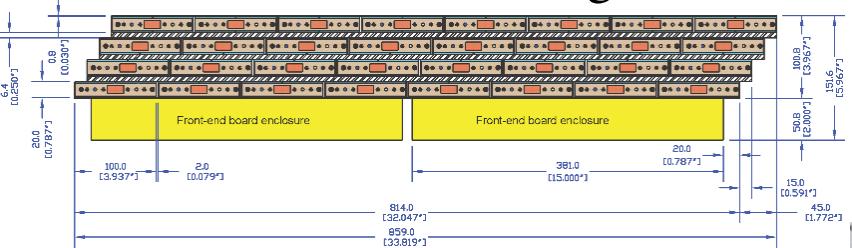


<http://mu2e.fnal.gov>

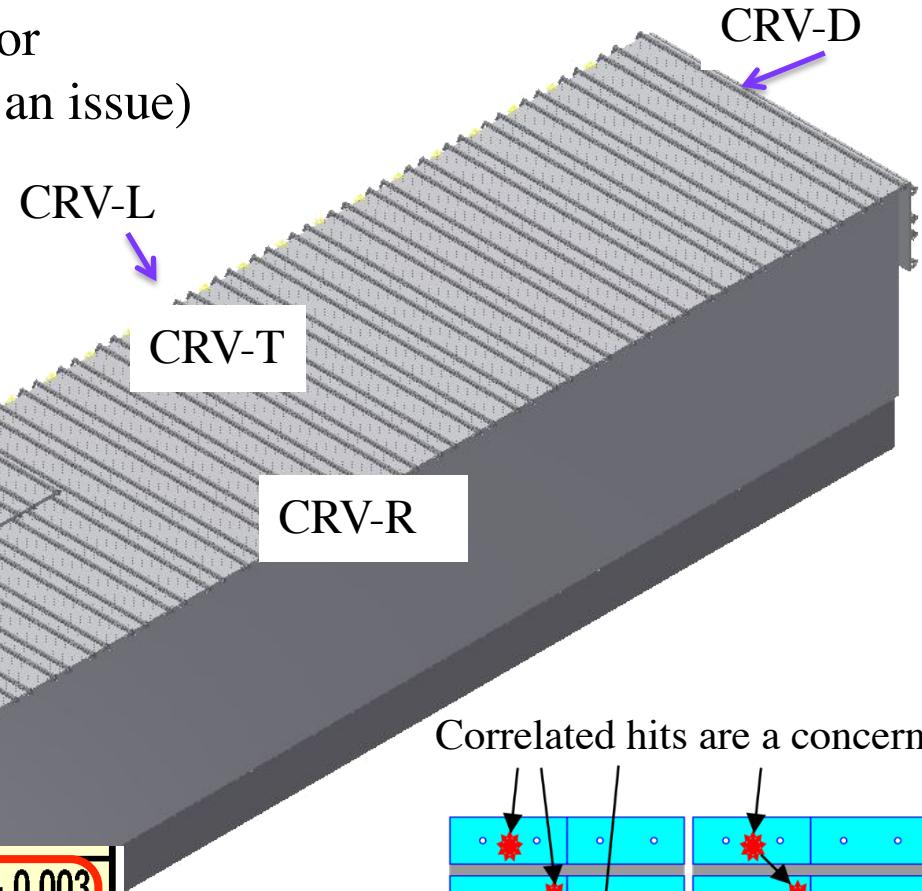
135 members from 28 institutions

# Detector solenoid is surrounded by a cosmic ray veto (CRV)

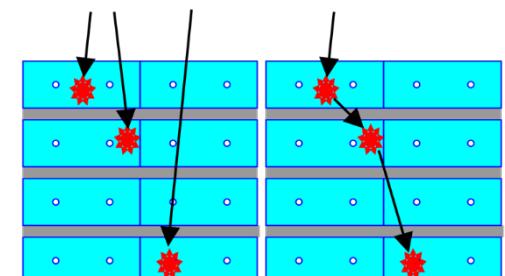
- Four layers of extruded plastic scintillator
- Fiber/SiPM readout (neutron damage is an issue)
- Al and concrete shielding



Desired number of background events	$0.050 \pm 0.003$
Required CR veto inefficiency	4.11E-05
90% CL CR veto inefficiency	3.83E-05



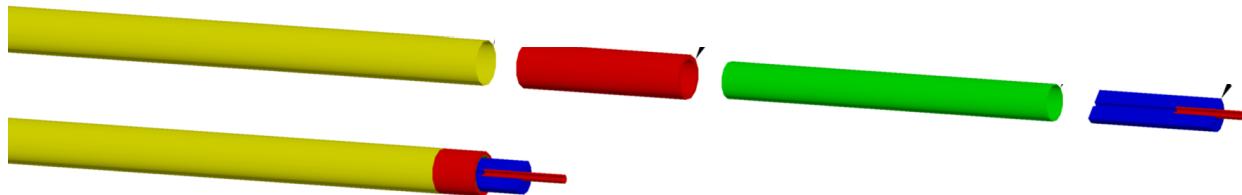
Correlated hits are a concern



# Tracker: straw tubes operating in vacuum -1

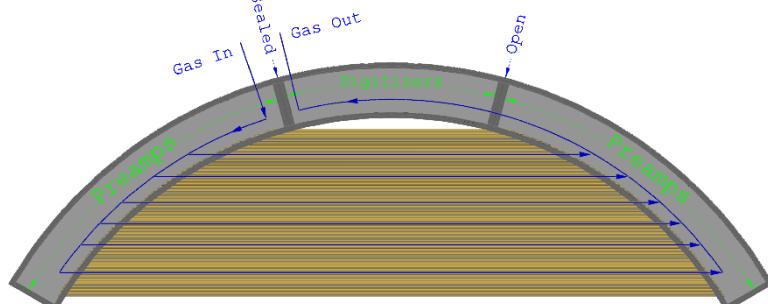
1 Straws: 5 mm OD; 15  $\mu\text{m}$  metalized mylar wall.

Custom ASIC for time division:  $\sigma \approx 5 \text{ mm}$  at straw center



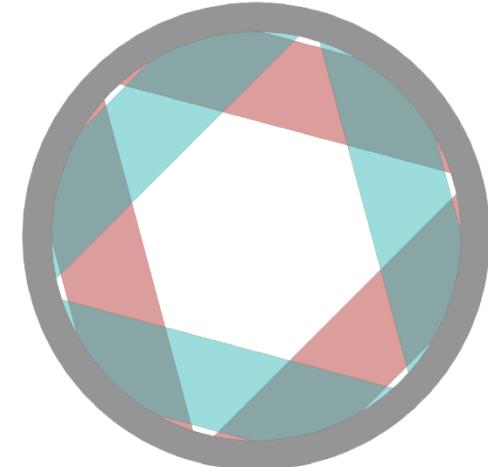
2

Panel: 2 layers, 48 straws each



3

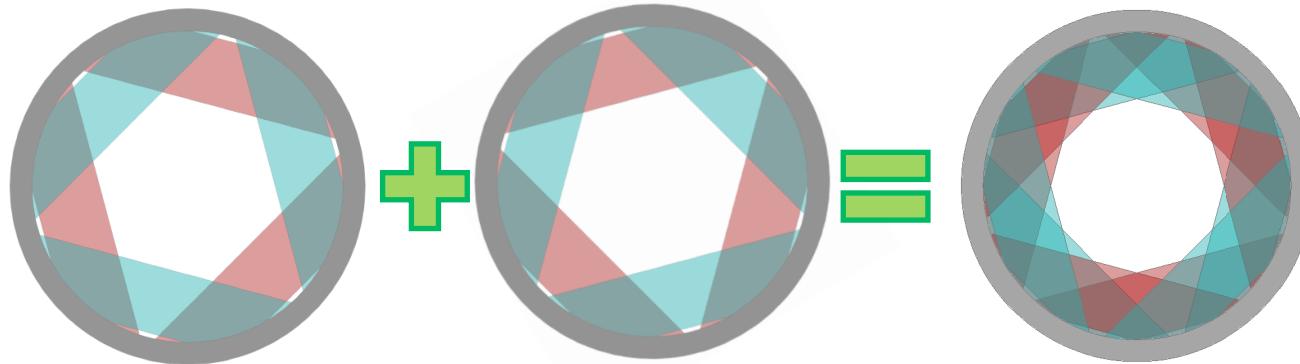
Plane: 6 self supporting panels



# Tracker: straw tubes operating in vacuum -2

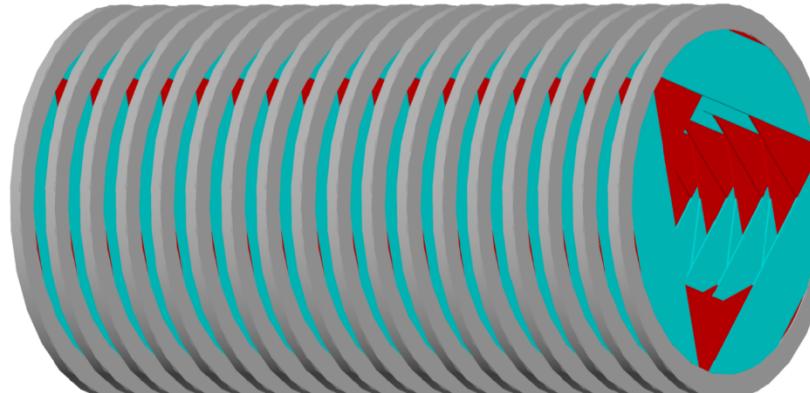
4

Station: 2 planes; relative rotation under study



5

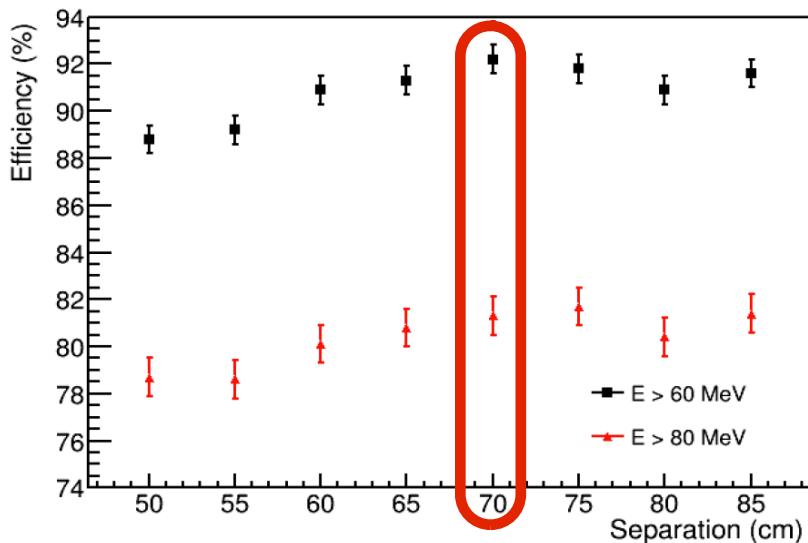
Tracker: 22 stations (# and rotations still being optimized)



# Design optimization

Crystal size (mm)	Disk Radii in / out (cm)	# crystals	Empty volume in / out (mm <sup>3</sup> )	Crystal vol. (cm <sup>3</sup> )	Efficiency (%)
31	359.1 / 643	966	28772.2 / 54288.1	168830	90.5 ± 0.6
31	359.1 / 672.3	1110	28772.2 / 54508.3	193998	90.4 ± 0.6
32	340.1 / 663.5	1044	29098.3 / 57184.3	194424	92.2 ± 0.6
32	371 / 663.5	966	29801.2 / 57184.3	179898	90.2 ± 0.6
33	351 / 660	930	30243.4 / 67178.5	184188	92.2 ± 0.6
34	361.2 / 647.3	798	32992.5 / 68438.1	167769	90.4 ± 0.6

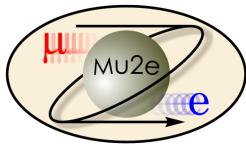
(some of the configuration tested)



Optimization has been performed relative to the tracker

$$\text{Efficiency} = \frac{\#\text{reco-tracks with } E_{EMC} > 60 \text{ MeV}}{\#\text{reco-tracks}}$$

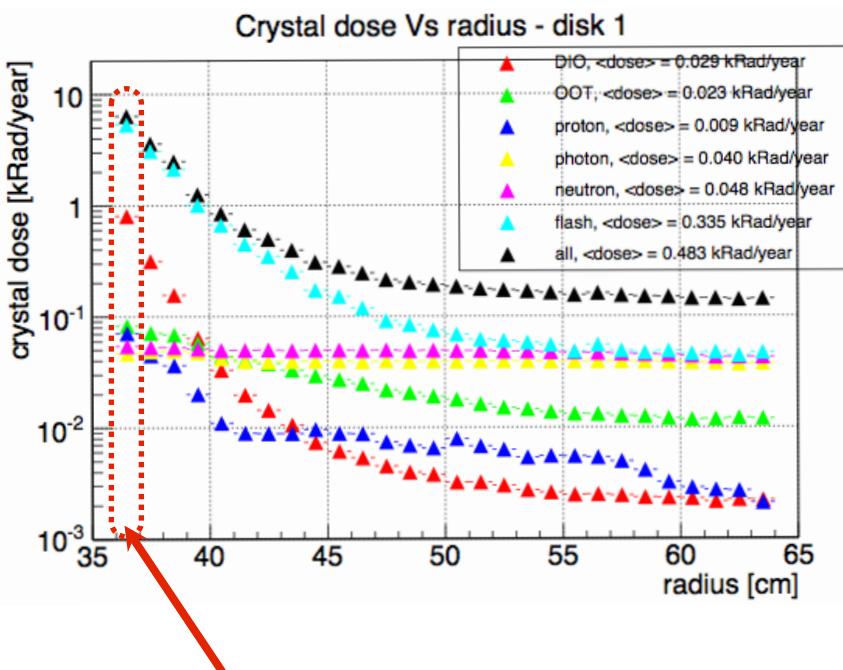
- ✓ Disk separation is maximized with a distance  $\sim 1/2$  wavelength of the Conversion electron



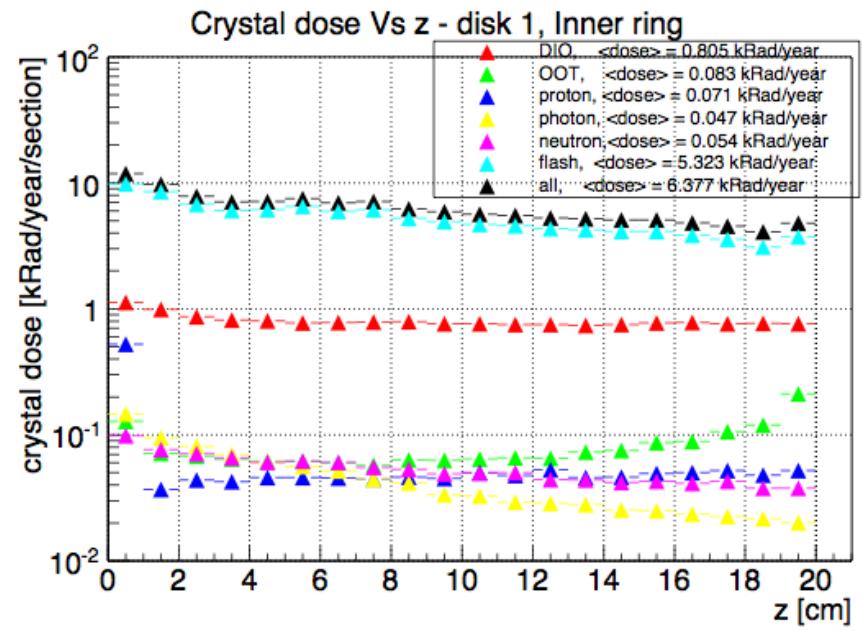
# Mu2e radiation environment



- Calorimeter dose has been studied simulating all the expected backgrounds
- Two observables to look at:
  - ✓  $\langle \text{crystal dose} \rangle$  Vs radius
  - ✓ crystal dose along the crystal



Inner ring

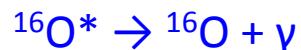


# Sorgente di calibrazione

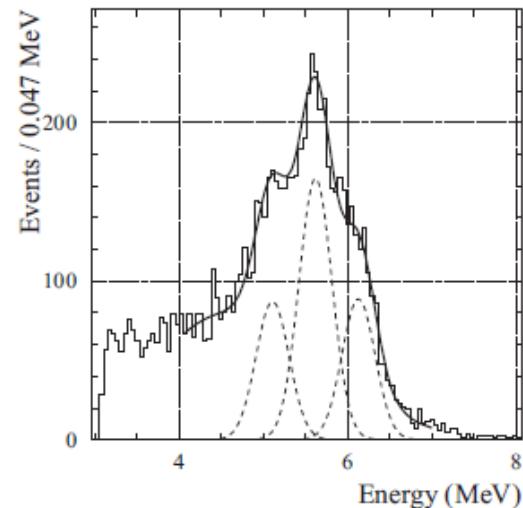
Sorgente utilizzata: Fluorinert™ FC-77 ( $C_8F_{18}$ )

Liquido inerte ricco di fluoro che viene attivato con neutroni

La catena di decadimento innescata è:



$$(E\gamma = 6.13 \text{ MeV})$$



Il Fluorinert irradiato viene pompato attraverso tubicini fino ai cristalli (faccia frontale dell'ECAL). I fotoni emessi nel decadimento incidono con un rate di 40 Hz per cristallo. Le energie sono misurate con il sistema di acquisizione dati.



I neutroni sono prodotti da un generatore DT.

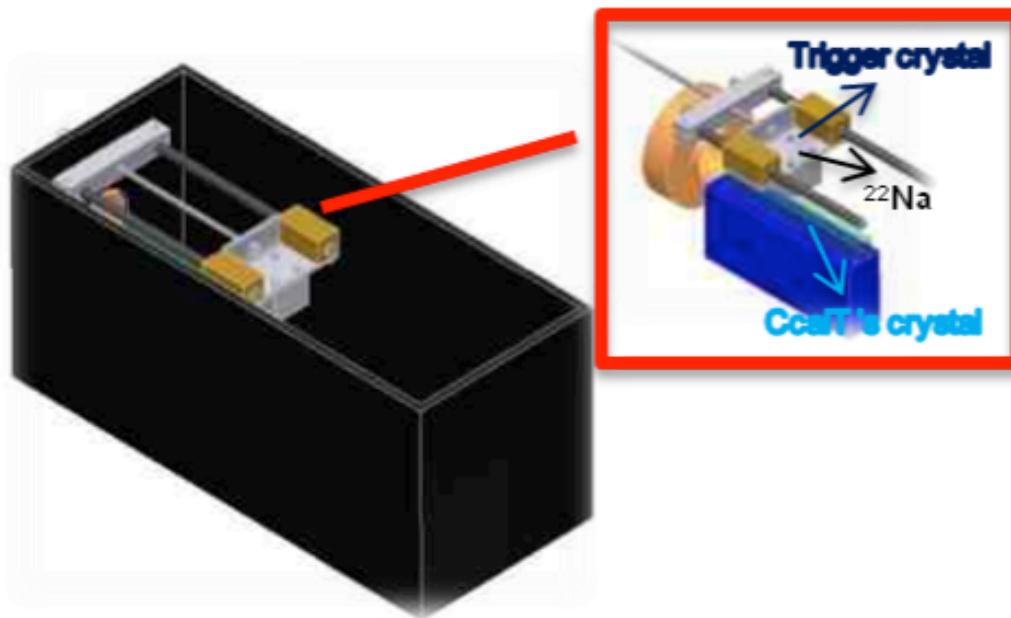
Questo dispositivo produce neutroni facendo collidere deuteroni su un bersaglio di trizio:  $d + t \rightarrow n(14.2 \text{ MeV}) + \alpha$

Rate =  $10^9 \text{ n/s}$

# Test Environment

The trigger has been provided by a Lyso Crystal 3x3x15 mm<sup>3</sup> readout by Hamamatsu SiPm 3x3 mm<sup>2</sup> (50 μm<sup>2</sup> pixel area)

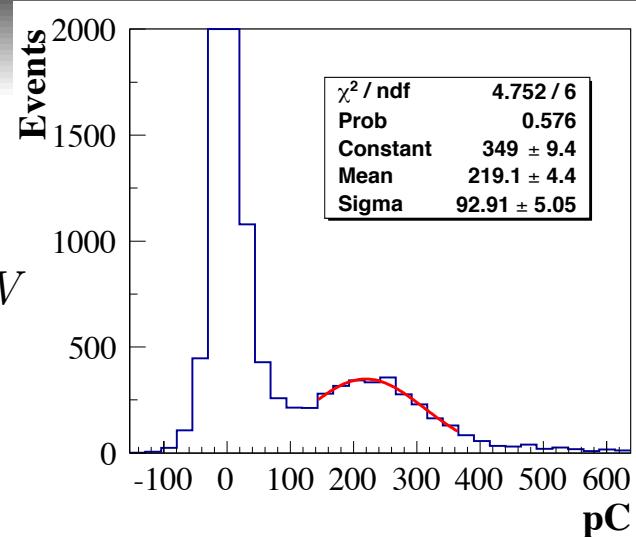
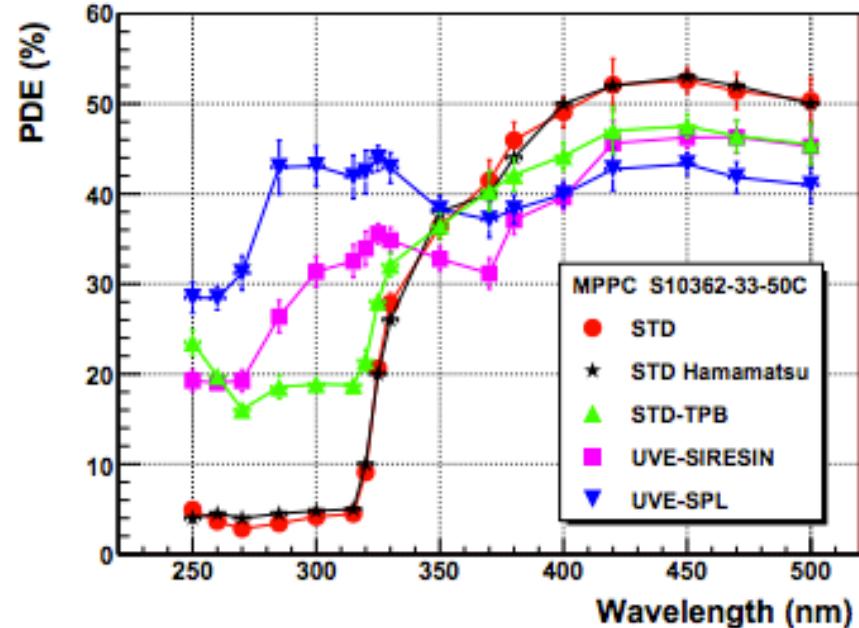
- 2" PM UV by EMI as readout for the test of the crystals has been used
- Analog Signals has been acquired with a 1 GHz / 10 bits Flash ADC by CAEN



# CsI + MPPC -2-

$$N_{pe} = \frac{Q_{mean}}{e^- \cdot G_{MPPC}(6.5 \times 10^5) \cdot G_{amp.}(3) \cdot 18MeV} \sim 45pe/MeV$$

UV enhanced MPPC



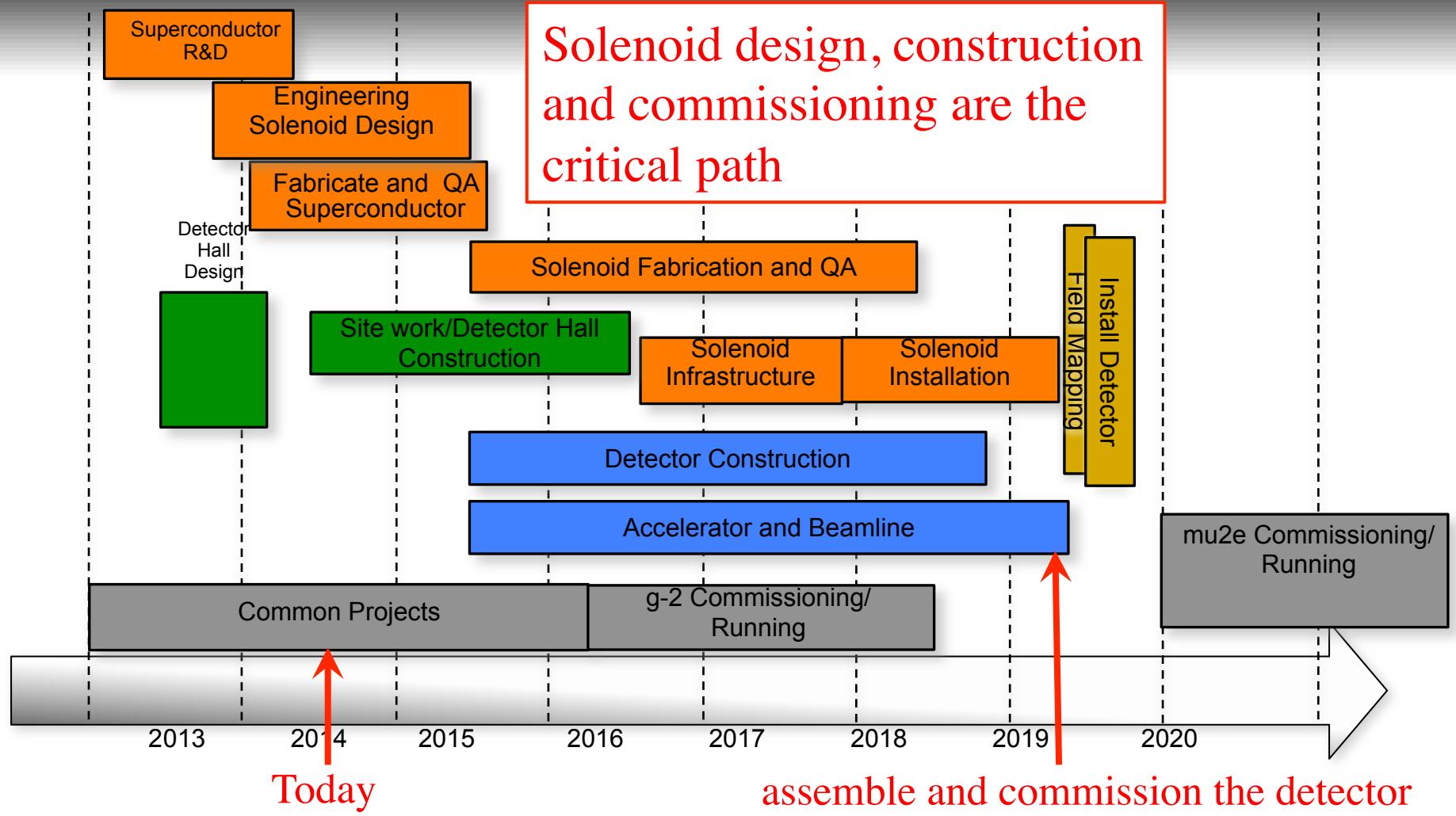
- The PDE of the TPB-coated MPPC is similar to the PDE of the UV enhanced MPPCs at 315 nm and is 30% lower at 285 nm;
- The response level of the UV-enhanced and TPB-coated (wavelength shifter, tetraphenyl butadiene) MPPCs in the UV range is significantly higher than the response level of the standard MPPC

*Imaging with SiPMs in noble-gas detectors  
arXiv:1210.4746*

# Crystal alternatives

Scintillation properties of CeF <sub>3</sub> crystal	BaF <sub>2</sub> crystal:	CsI-purecrystals
Density(g.cm-3)	Density(g.cm-3)	Density(g.cm-3)
6.16	4.88	4.51
Radiation length(cm)	Radiation length(cm)	Radiation length(cm)
1.7	2.03	2.43
Decay constant(ns)	Decay constant(us)	Decay constant(us)
5/30	0.8ns/630ns	16
Emission peak(nm)	Emission peak(nm)	Emission peak(nm)
310/340	220/310	315
Light yield(%NaI:Tl)	Light yield(%NaI:Tl)	Light yield(%NaI:Tl)
4-5	8/32	4-6
Melting point(°C)	Melting point(°C)	Melting point(°C)
1443	1280	621
Hardness(Mho)	Hardness(Mho)	Hardness(Mho)
4	3	2
refractive Index	refractive Index	refractive Index
1.68	1.56	1.95
Hygroscopicity	Hygroscopicity	Hygroscopicity
none	slightly	Slightly
Cleavage	Cleavage	Cleavage
001	(111)	none

# Mu2e schedule



Calendar Year