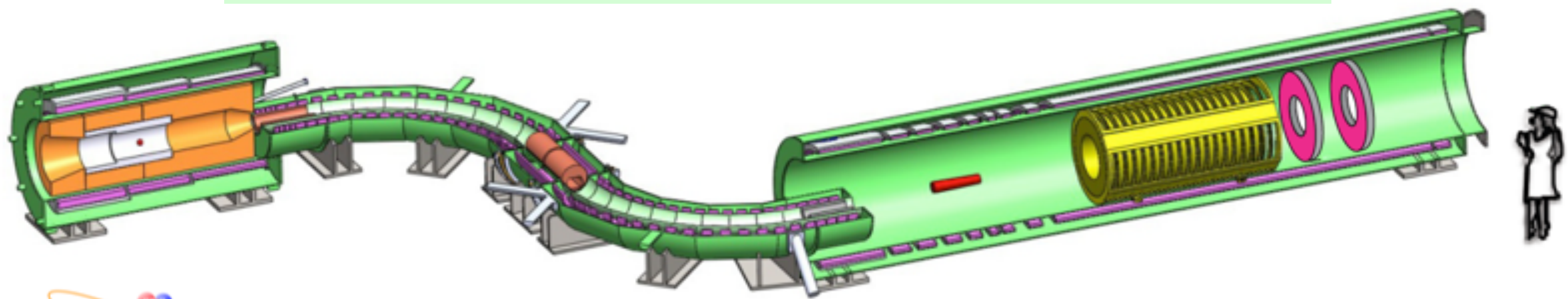
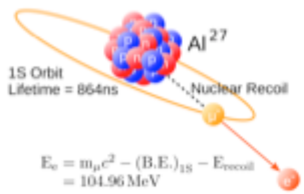
The Mu2e experiment @ FNAL





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2nd lecture @
University
“La Sapienza”
Rome, Italy
19 January 2016

Lezione 2: The Detector

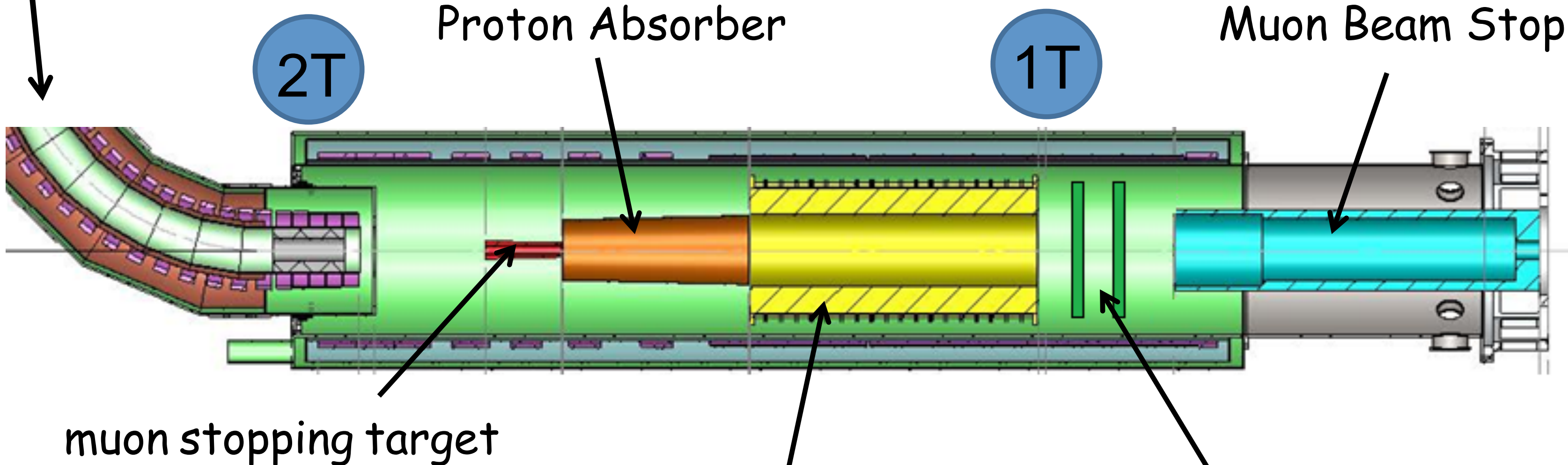
- **MU2E tracker**
  → Requirements and design considerations
  → Straws vs Cylindrical
  → Baseline tracking
  → CE reconstruction

- **MU2E Calorimeter**
  → Requirements and design considerations
  → Crystal choice: LYSO vs BaF_2/CSI
  → Irradiation tests
  → CsI+MPPC
  → Test Beam results

- **Conclusions**

Detector Solenoid

Graded field "reflects" downstream a fraction of conversion electrons emitted upstream



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

For the sensitivity goal → ~ 6 x 10^{17} stopped muons

For 3 year run , 6 x 10^{7} sec → 10^{10} stopped muon/sec

Tracking Design considerations

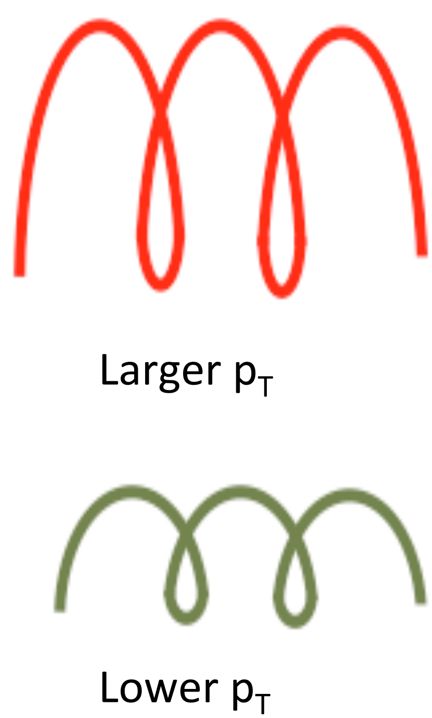
- High reconstruction efficiency for Conversion Electron (CE)
- High momentum resolution @ 100 MeV

In order to do so:

→ Minimize multiple scattering (small material budget)
→ High efficiency on single point
→ Good single point space resolution
→ Require many points/track (> 20)

- Axial B(field) = 10 kG = 1 T (uniform)
- Higher P_T = 100 MeV
- ρ_{max} (m)= P_T/(0.3 B) = 0.1 (GeV)/0.3x1 (T)
  → 0. 33 m = 33 cm

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\,\frac{\sigma_y p_\perp}{(0.3BL^2)} \quad \mathbf{(m, GeV/c, T)}$$



"back on the envelope" resolution

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\frac{\sigma_y p_\perp}{(0.3BL^2)} \quad \text{(m, GeV/c, T)}$$

(P_T example = 100 MeV = 0.1 GeV)

1) SPATIAL RESOLUTION CONTRIBUTION

- **N(hits) per track = 40, B(Field) = 1 T, L = 0.3 x 2π = 2 m, Sy = 200 μm**
- SQRT(720/44) xσ (point) x 0.1 / (0.3 x 1 x 4)

  → 4 x σ(point) x 0.1 x 0.8 = 0.3 x Sy (m) ~ 60 x 10^{-6} = 0.6 x 10^{-4} = 0.06 permil

  → @ 100 MeV → 0.06 x 100 keV = 6 keV

2) MULTIPLE SCATTERING CONTRIBUTION

- Sy (m.s.) = L sin0 x Theta_rms =
- Theta_rms =13 MeV/P(MeV) x SQRT(L(X0))

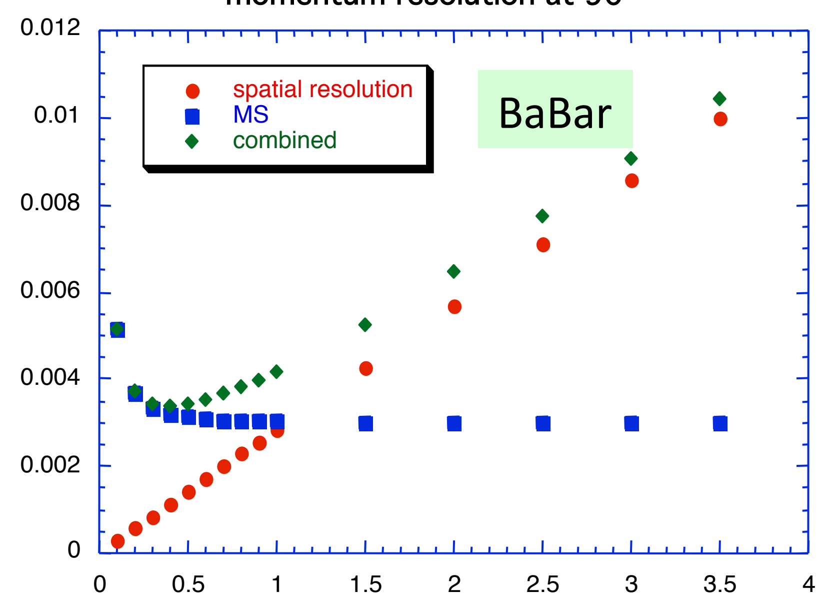
  → @ 100 MeV and 1% X0

  → Theta_rms = 0.13 x SQRT(10^{-2})

  → 0.13 x 0.1 = 0.013
- **Sy (m.s.) = 1,3 cm**

  50 times larger than space resolution
- **σ(p)/p = 0.06 x 50 permil = 0.003**

momentum resolution at 90⁰

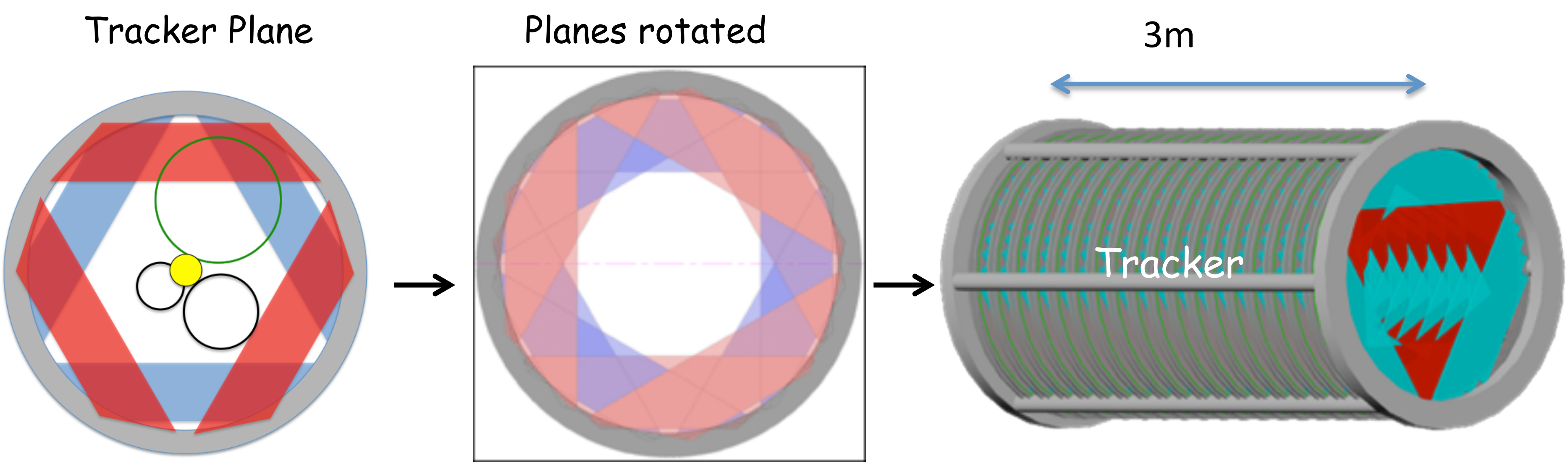


Design Alternatives: TT

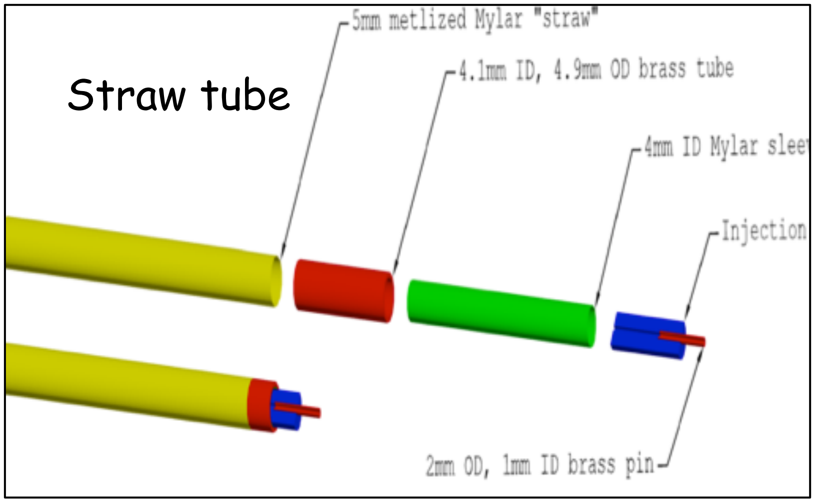
- Tracker made of arrays of straw drift tubes (red/blue stripes in tracker stations)

- ~ 20000 tubes arranged in planes on stations, the tracker has 18 stations.

- Tracking at high radius ensures operability (beam flash produces a lot of low momentum particles, large DIO background. Most of this background miss the tracker.)

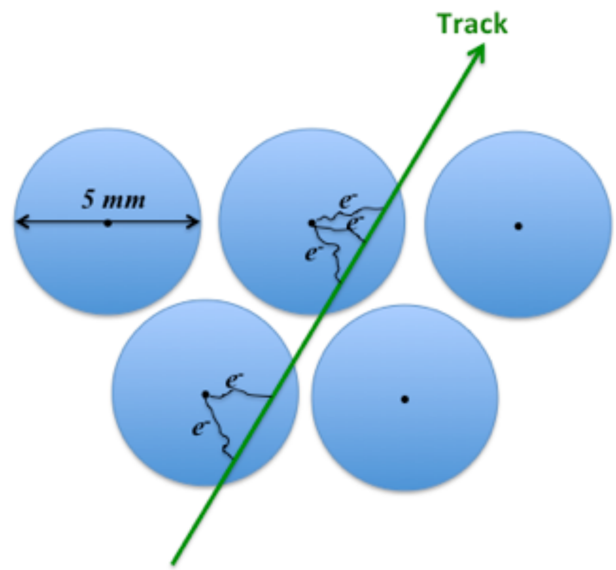


Design Alternatives: TT



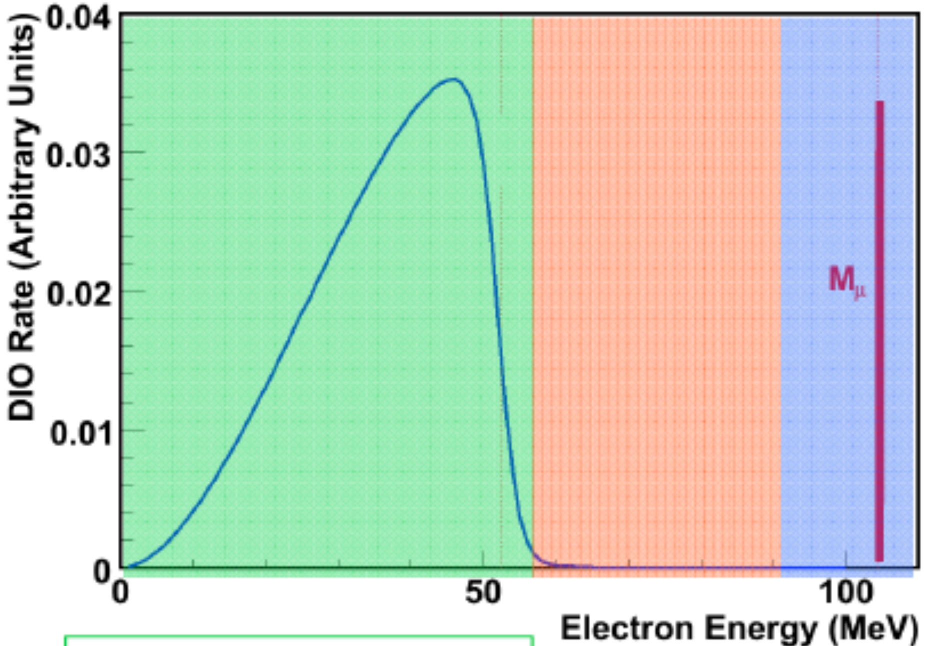
Straw Diameter	5 mm
Straw Length	430 – 1200 mm, 910 mm average
Straw Wall	15 μm Mylar (2×6.25μm plus adhesive)
Straw Metallization	500Å aluminum, inner and outer surface 200Å gold overlaid on inner surface
Gas Volume (straws only)	$4 \cdot 10^8$ mm³ (0.4 m³)
Sense wire	25 μm gold-plated tungsten
Drift Gas	$Ar{:}CO_2$, 80:20
Gas gain	$3\text{-}5 \cdot 10^4$ (exact value to be set later)
Detector Length	3196 mm (3051 mm active)
Detector Diameter	1620 mm (1400 mm active)

- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm)**



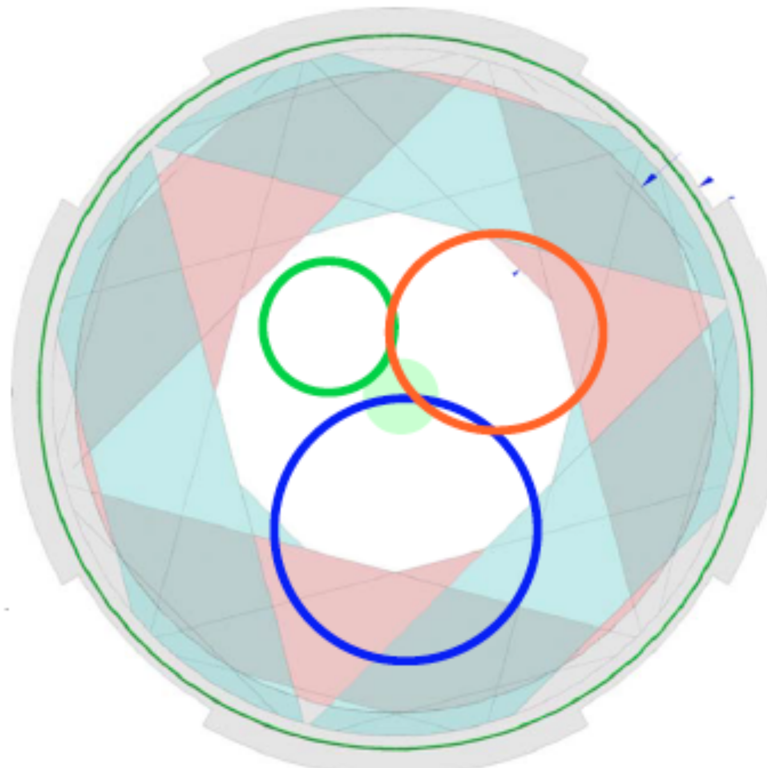
Tracking Pattern idea

reconstructable tracks



no hits in tracker

some hits tracker, tracks not reconstructable.



beam's-eye view of the tracker

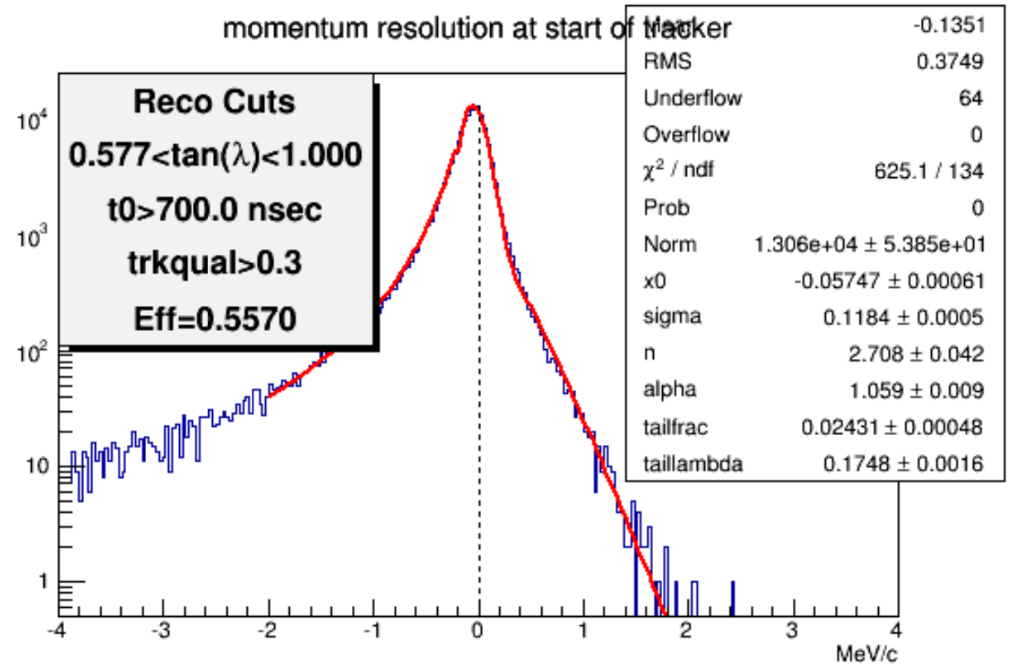
TT Performance

Pattern Recognition based on
***BABAR* Kalman Filter algorithm**

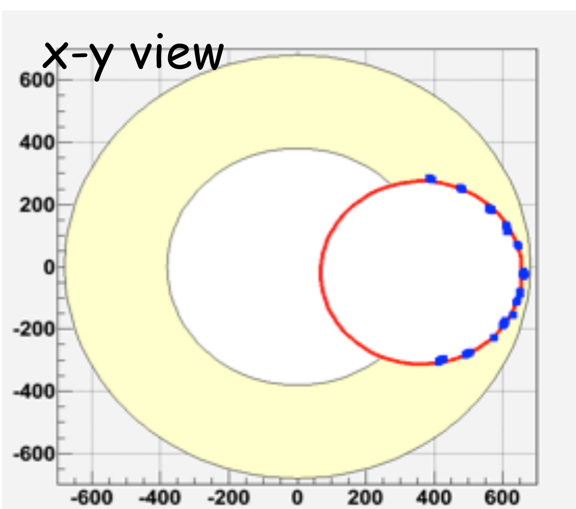
No significant contribution of
mis-reconstructed background

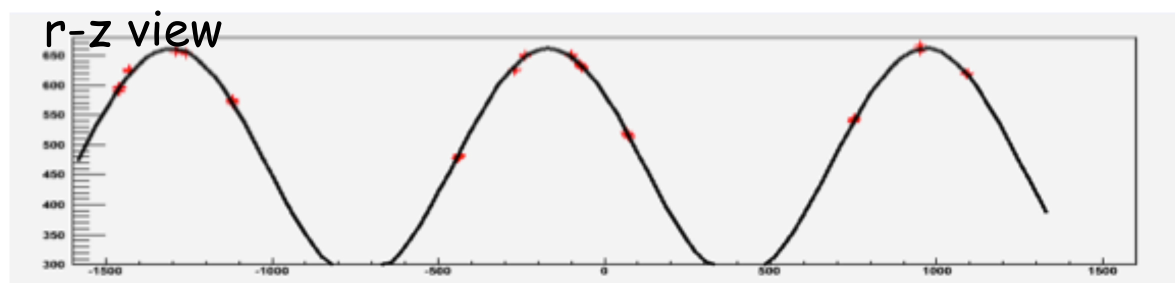
Momentum resolution

core σ~120 keV
tail σ~175 keV (2.5%)



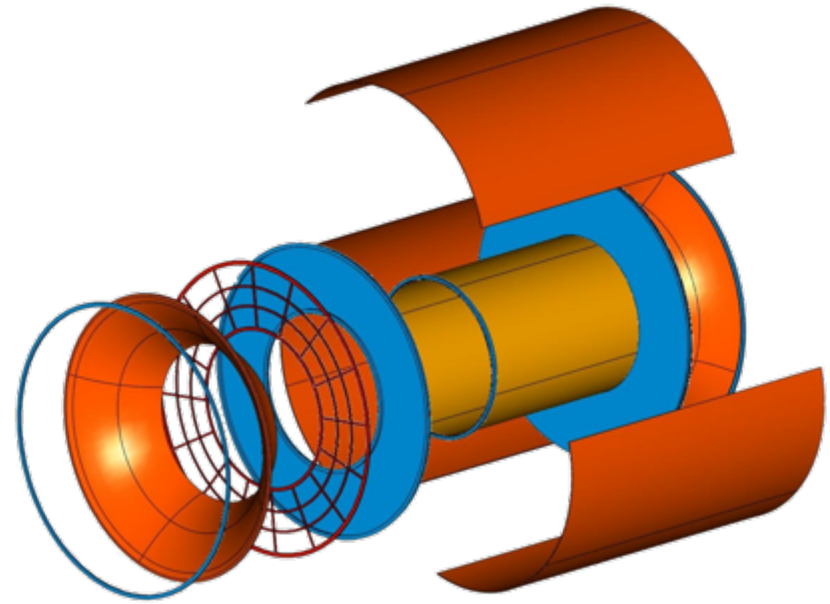
Fit: Crystal Ball + exponential



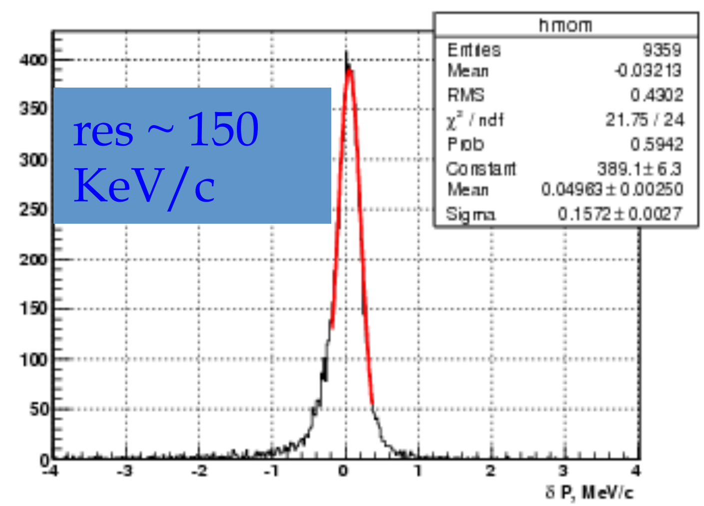


Design alternatives: IT

Detector Element	Composition	g/cm²	X/X_0 [‰]
EndCap (Gas envelope)	4 plies x 60 μm	0.04	1
Inner Cylinder (Gas envelope)	Sandwich of two 120 μm C-fiber skin and 5mm spacer (0.04g/cm³)	0.05	1.2
Wire anchoring + first electronics parts	in average equivalent to 500 μm of C	0.11	2.5
Wires	~ 15000 20 μm Mo (sense) ~ 80000 40 μm Al (Field) (mass equivalent for 1m of track)	0.036	6.3
Gas	Helium based gas mixture (90% He 10% isoButane) (mass equivalent for 1m of track)	0.045	1.2



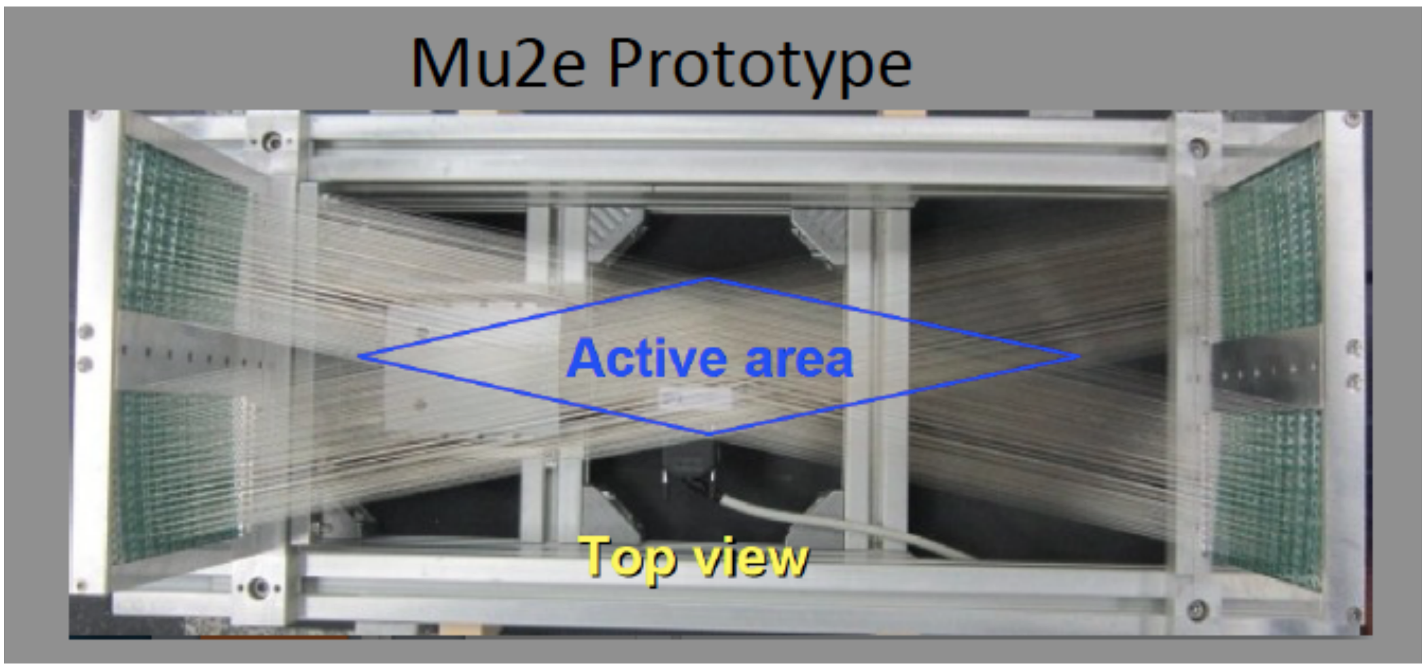
- Large area Drift Chamber (Helium based) a-la KLOE with 15000 sense wires (Vd = 20 μm/ns)
- Small Drift cells (< 1 cm²) → reduce drift time < 200 ns
- Stereo/Stereo layers
- Total amount of budget material/track → 7% X_0
- Much larger number of points/track ~ 200
- Much simpler pattern recognition than TT



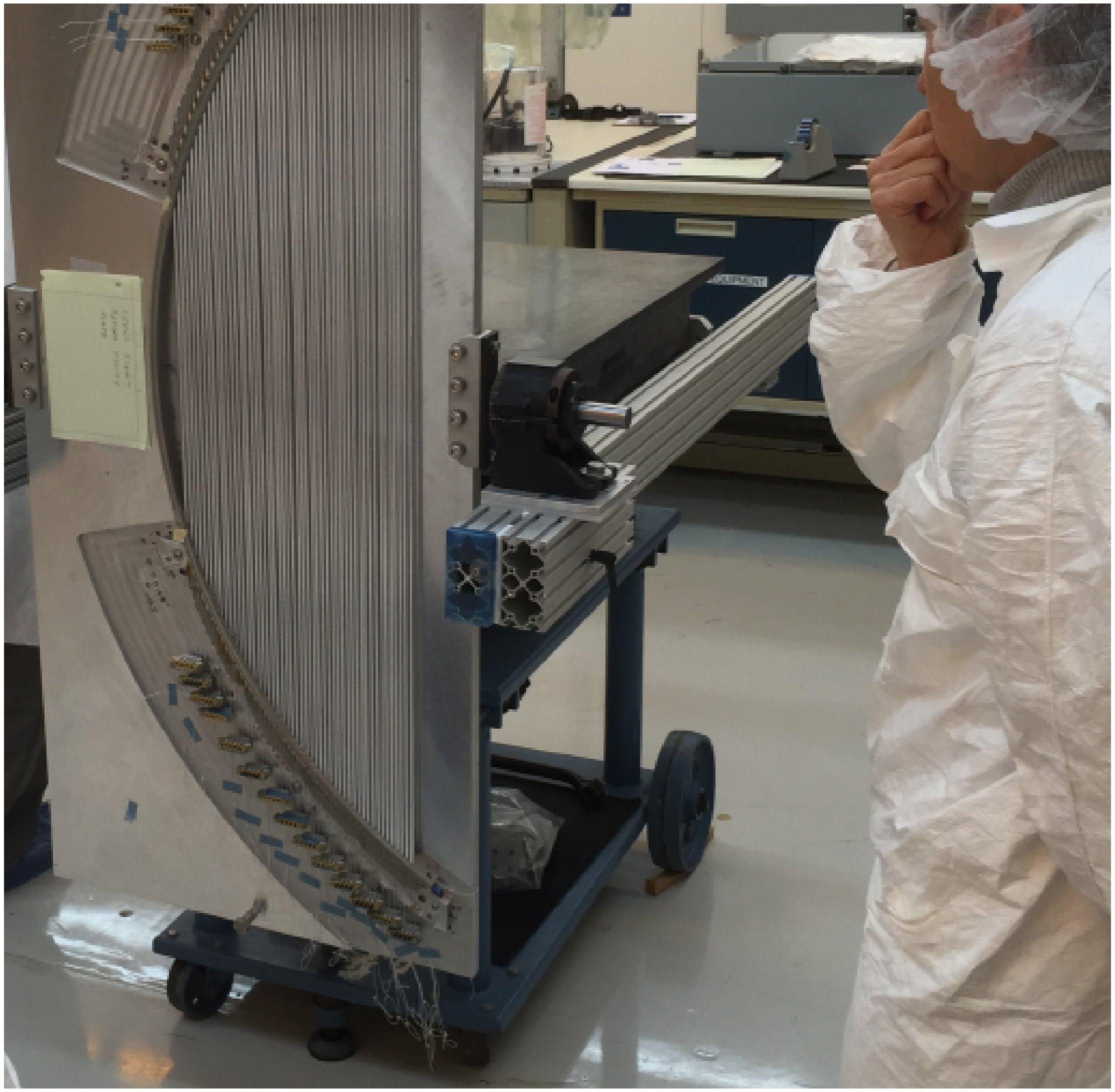
Final Technology choice for tracking

- **Similar reconstruction performances found by review committee:**
  IT → easier pattern recognition, similar performance, slightly higher material budget
  TT → less material, smaller number of hits, reconstruction proven to be working on full simulated data set with environmental background added

- **Final choice related to the preparation for CD-2 review of scheduling and cost**
- R&D on IT prototype has not been lost → the built prototype and wiring techniques are now used for the construction of MEG-upgrade drift chamber!



Tracking Status

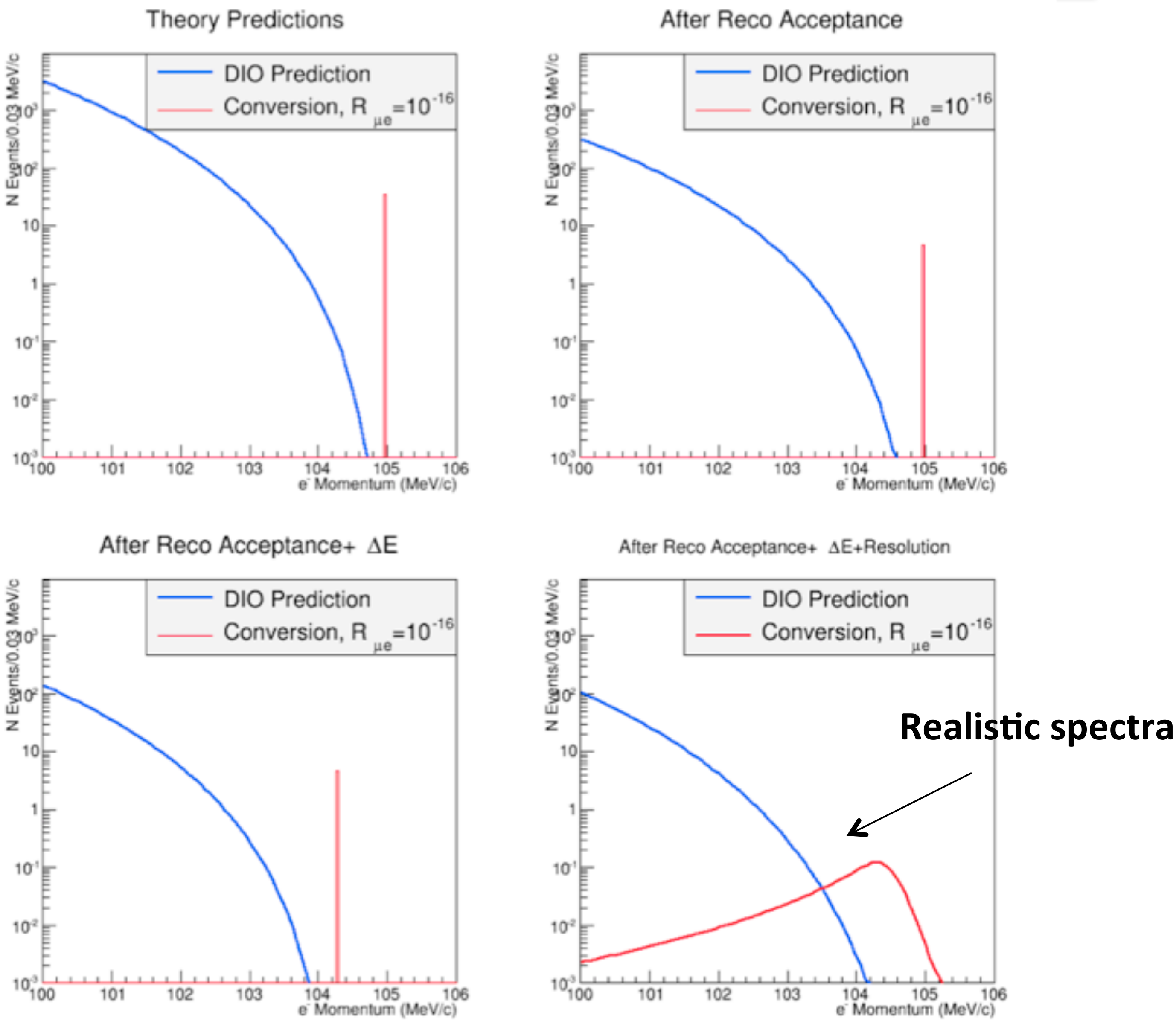


Progressing well.

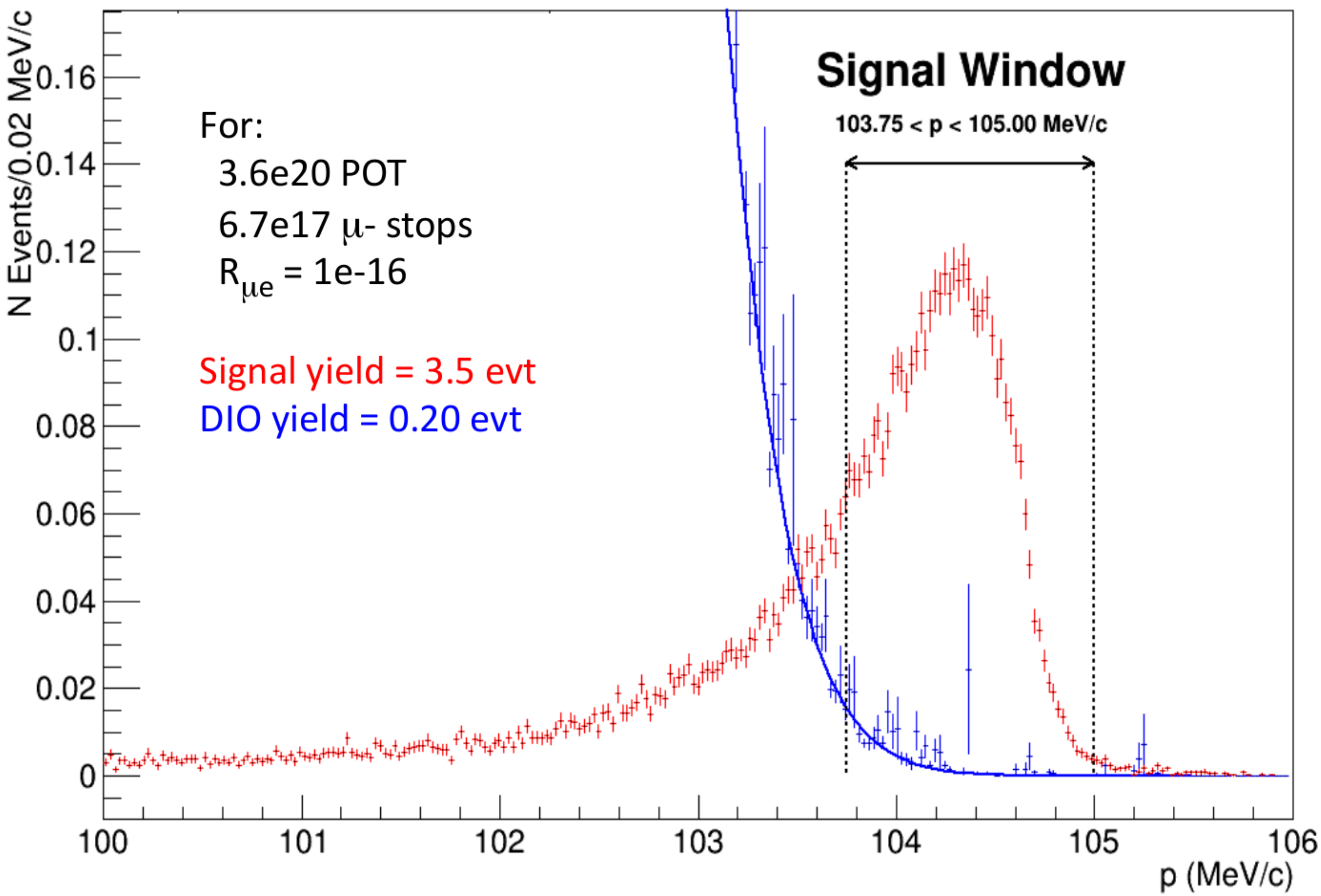
→ Mechanical properties and gas permeability properties meet Mu2e requirements.

→ Designs of support, FEE and services exist.

Tracking performances

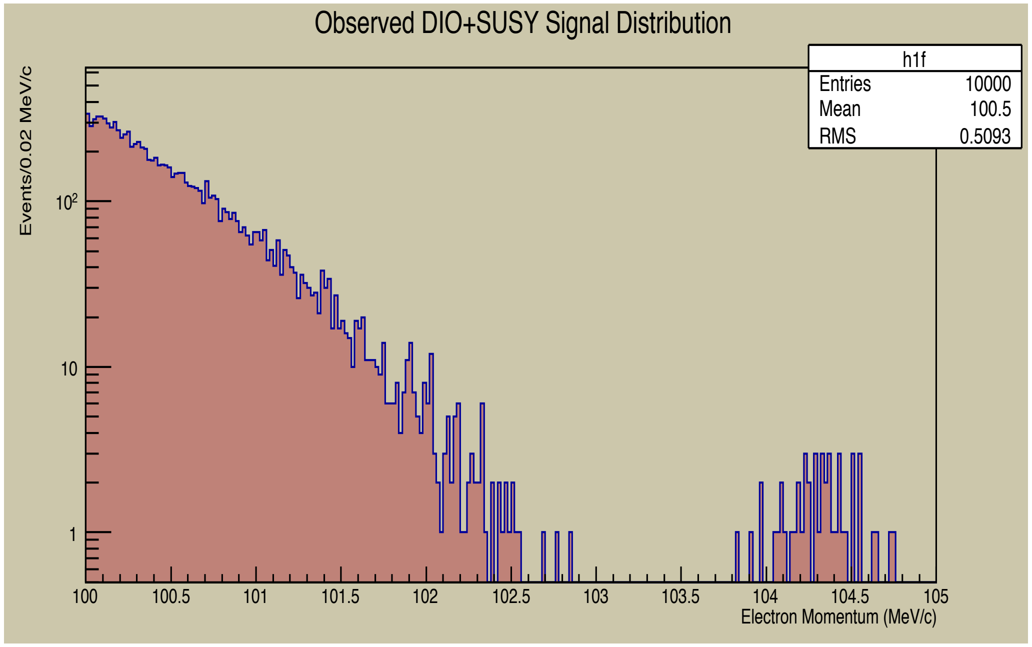


Signal extraction



Other background and SUSY Example

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10



- **The Bottom Line:**
- **Very low background: < 0.5 event**
- **Single event sensitivity: $R_{\mu e} \sim 2.5\times10^{-17}$**
- **Typical SUSY Signal: ~40 events for $R_{\mu e} = 10^{-15}$**

This is a very “low” probability search …

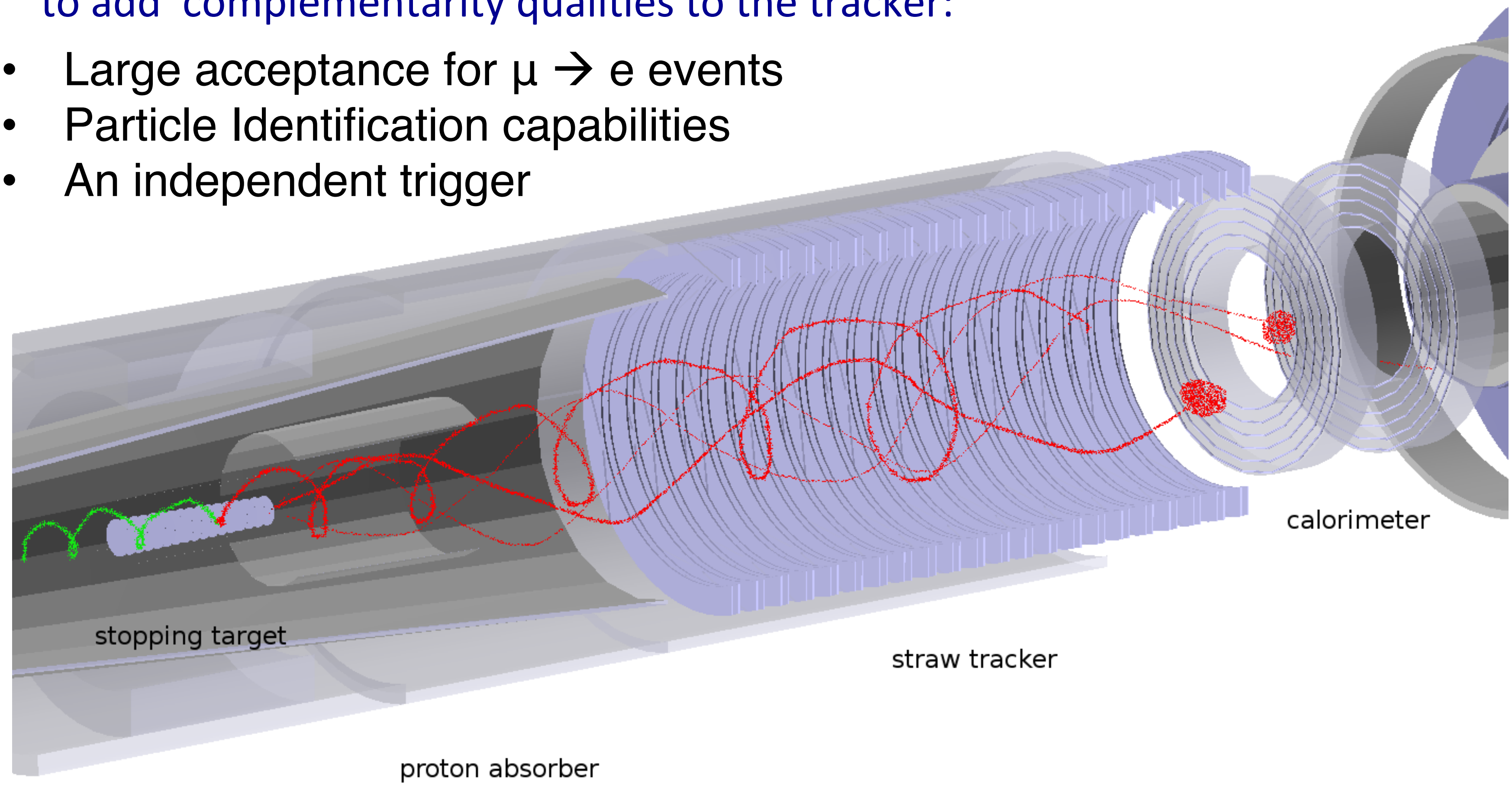
Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flpping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

As low probability as this!

Calorimeter Requirements

In order to add redundancy to this “super-rare” search, the calorimeter has to add complementarity qualities to the tracker:

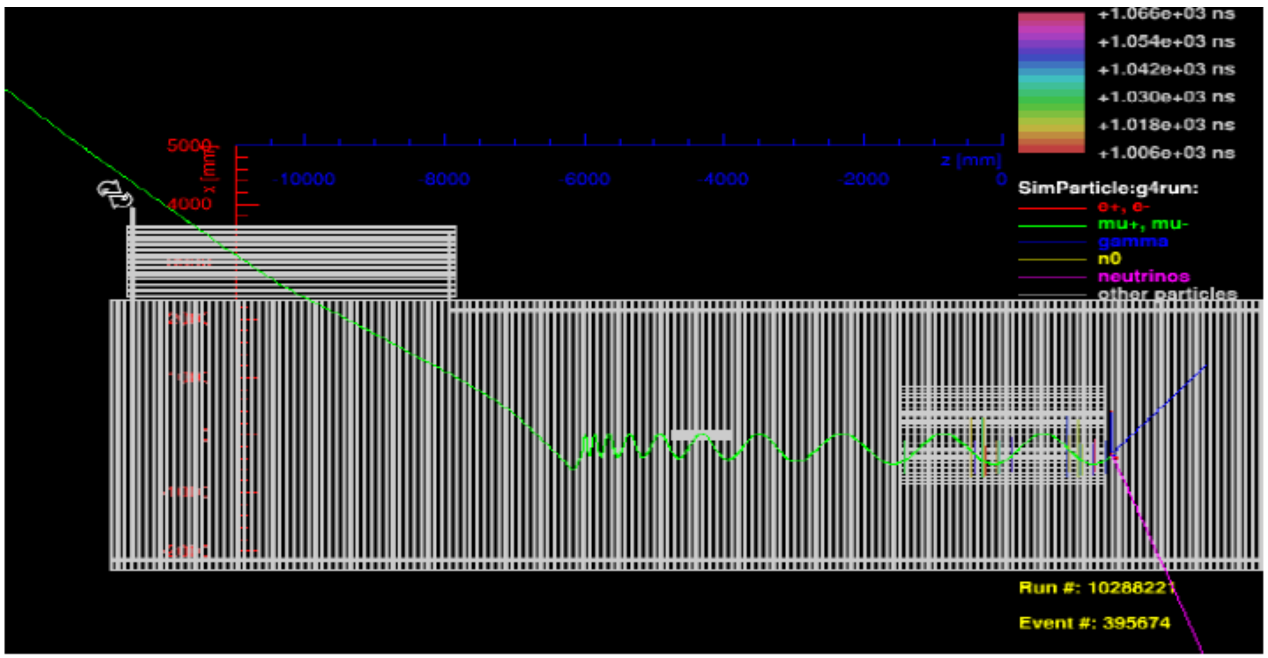
- Large acceptance for μ → e events
- Particle Identification capabilities
- An independent trigger



- “seeds” to improve track finding efficiency at high occupancy
- Resistant to radiation dose and working in vacuum @ 10^{-4} Torr

PID – Requirement #1

- CRV studies showed:
  - Assuming a CRV inefficiency of 10^{-4}
  - To have < 0.1 “fake” events from atmospheric particles
  - A μ rejection factor ~ 200 is needed

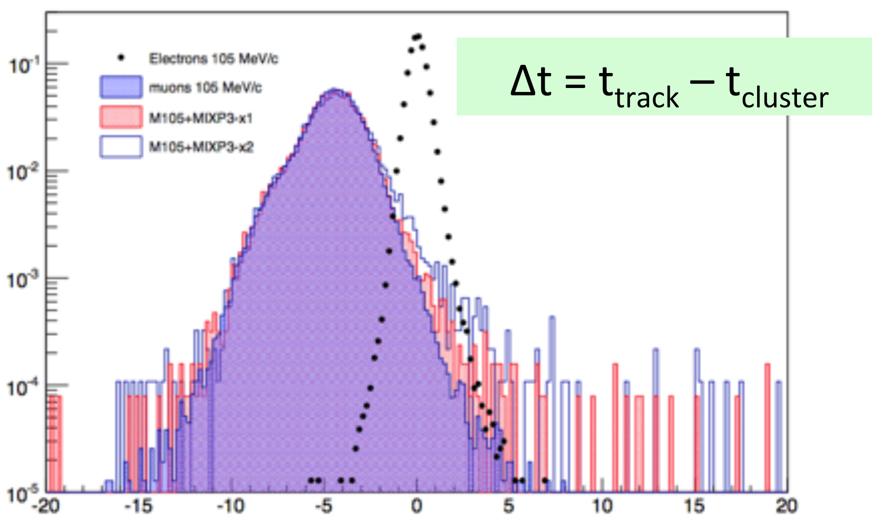


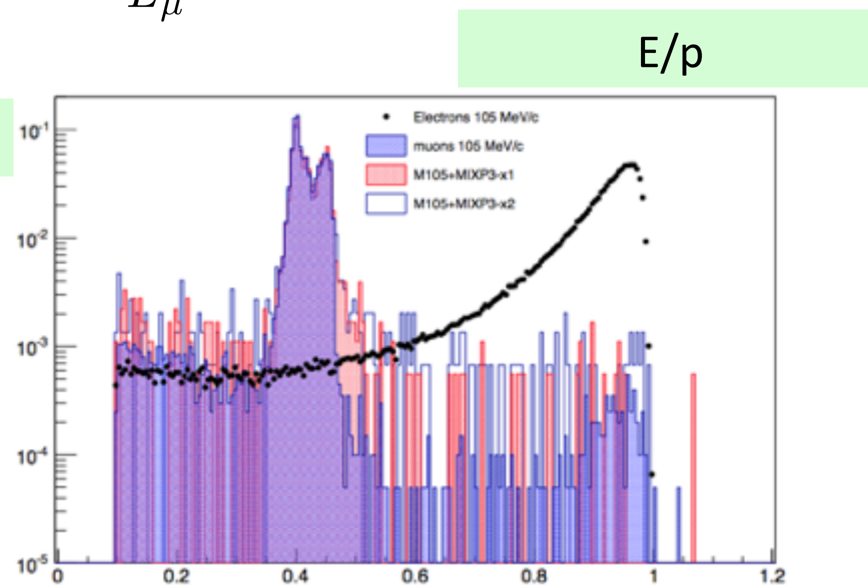
Event display: μ^- mimicking the signal

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
  - Use the likelihood ratio: $\ln L_{e/\mu} = \ln \frac{L_e}{L_\mu} = \ln L_e - \ln L_\mu$





PID – Resolutions vs e⁻ efficiency

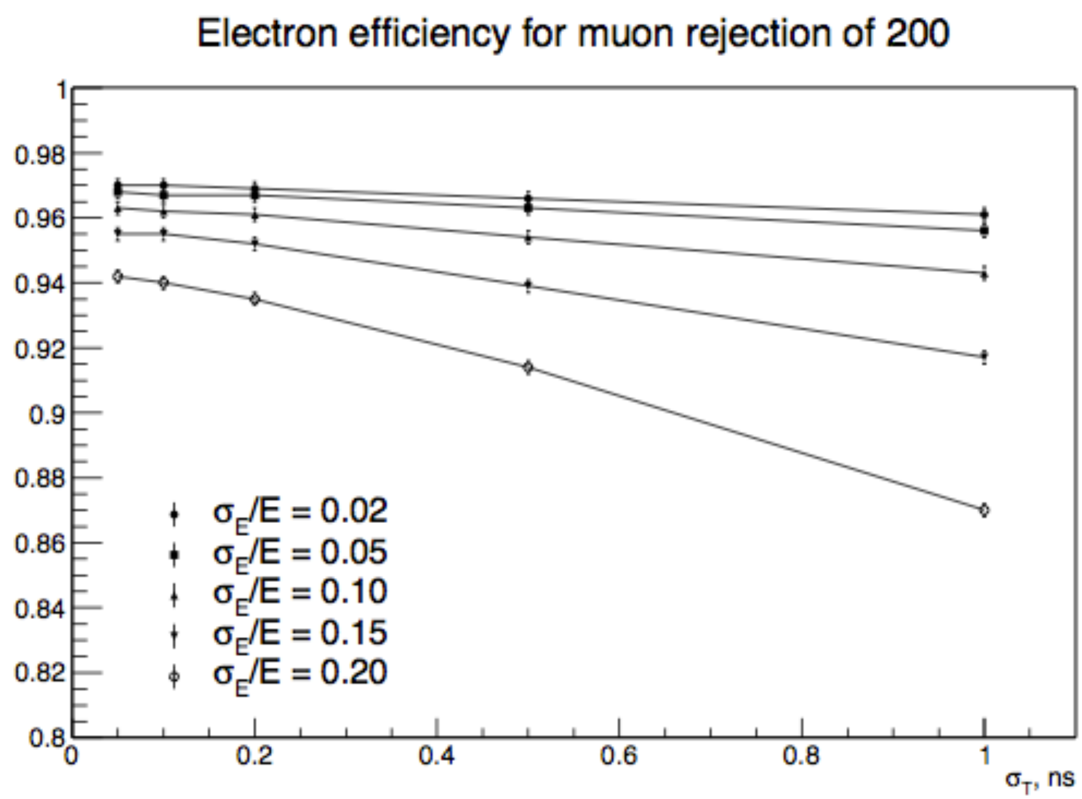
- TOY MC used to estimate, **assuming no accidental activity**, what is the range of calorimeter resolutions that are matching our requirements.

- **Simple convolution with Gaussians performed both for timing and energy**.

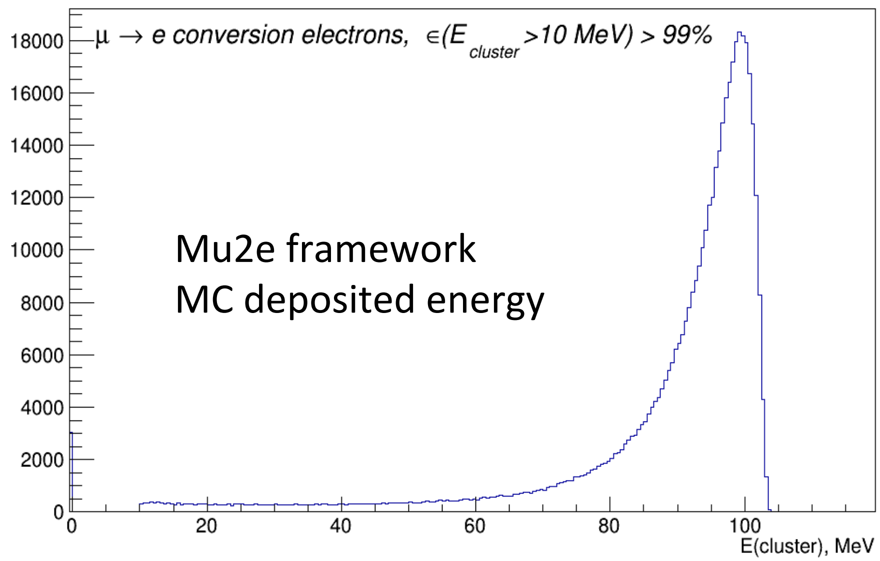
- The e- efficiency drops off by an acceptable 2.5% in the following resolution ranges:

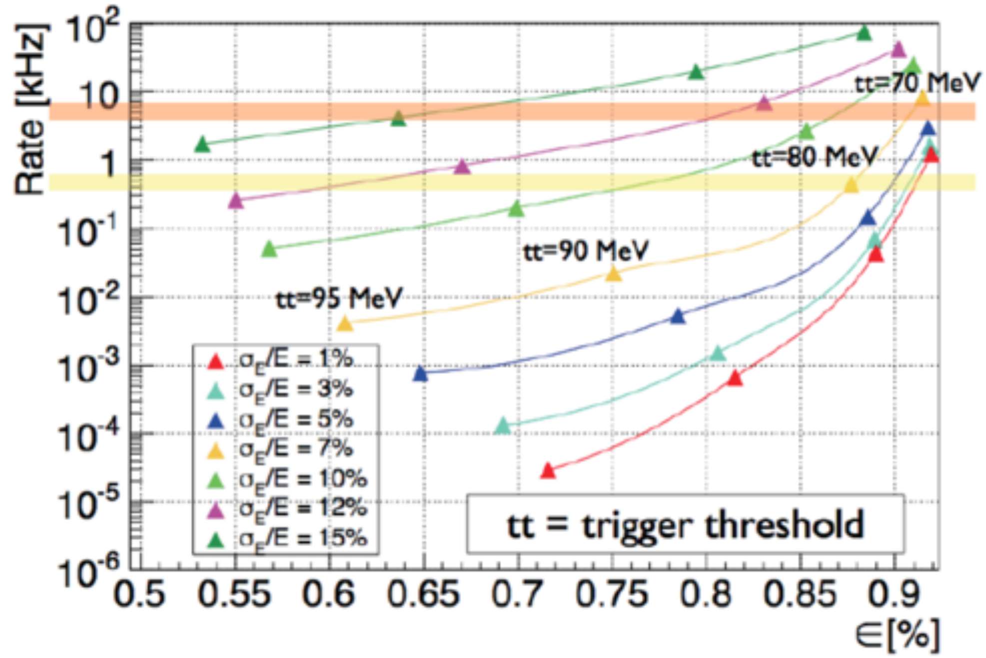
$$\sigma_E/E < 0.1$$

$$\sigma_t < 0.5 \text{ ns}$$



Calorimeter-based Trigger



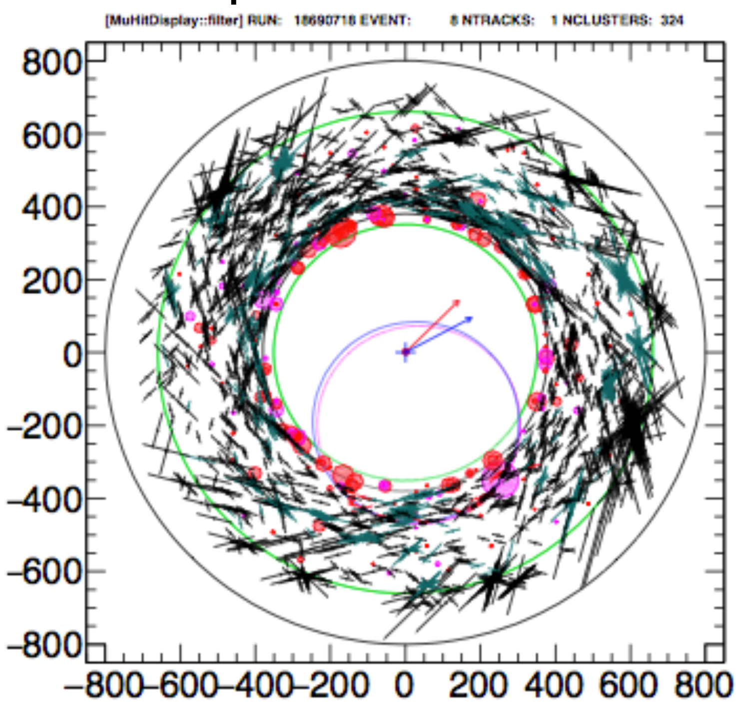


- acceptance: > 99% of events with good tracks have a cluster E > 10 MeV
- **standalone calorimeter-based online trigger needed**
  - tracker momentum calibration (i.e., $\pi^+ \rightarrow e\nu$) needs a non-tracker trigger
  - DAQ bandwidth limitations
- Trigger logic: a cluster with E > E(min)
- ε(CE) = 90% @ 2 KHz requires σ(E)/E < 7%

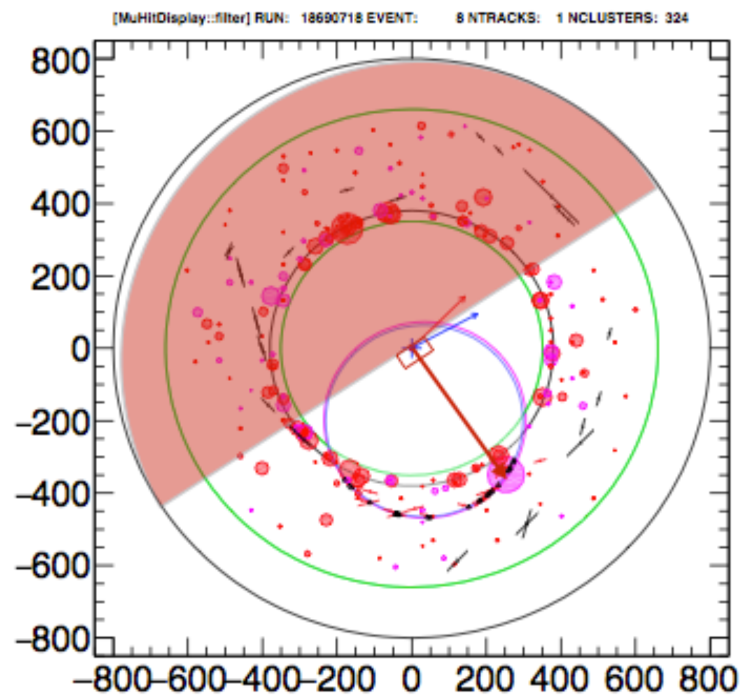
Track seeding

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

ce + spurious hits: no selection



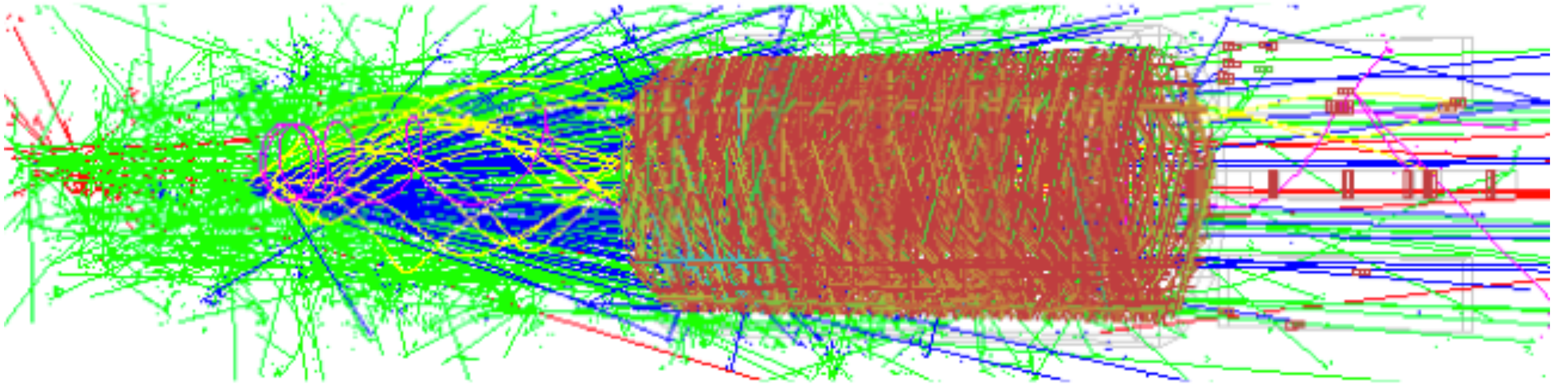
ce + spurious hits: calo selection



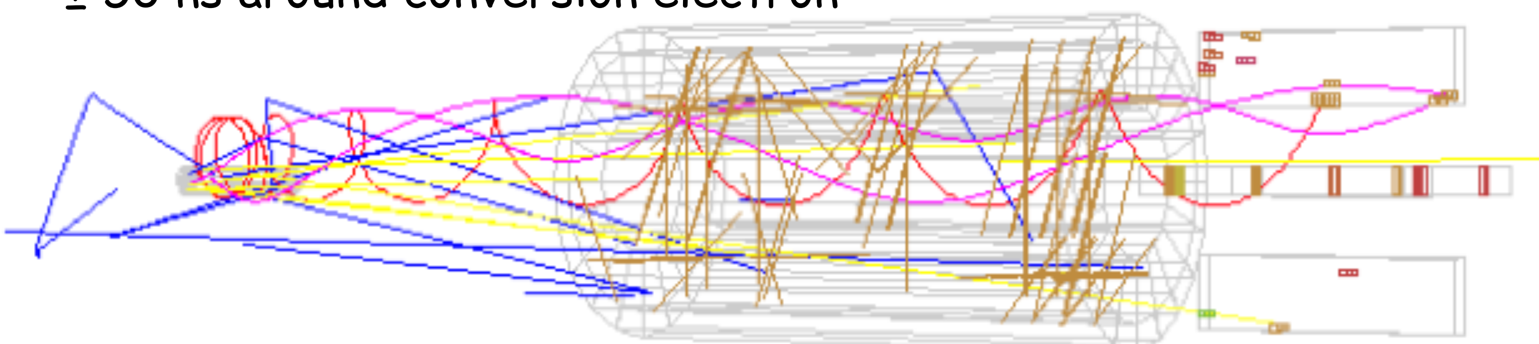
Fitting a helix to the selected tracker hits and calorimeter cluster increases the tracking efficiency by 9%

A single MicroBunch event

500 – 1695 ns window

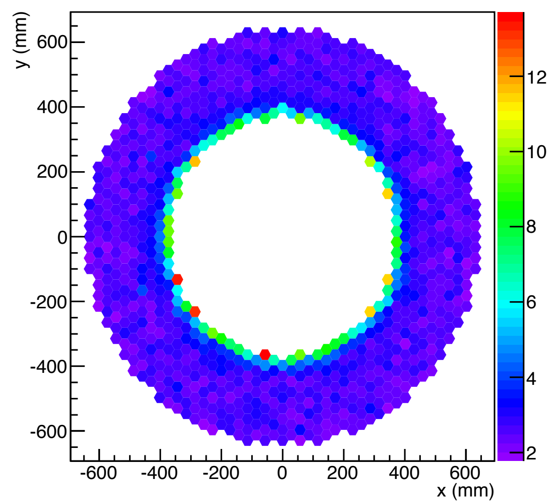


± 50 ns around conversion electron

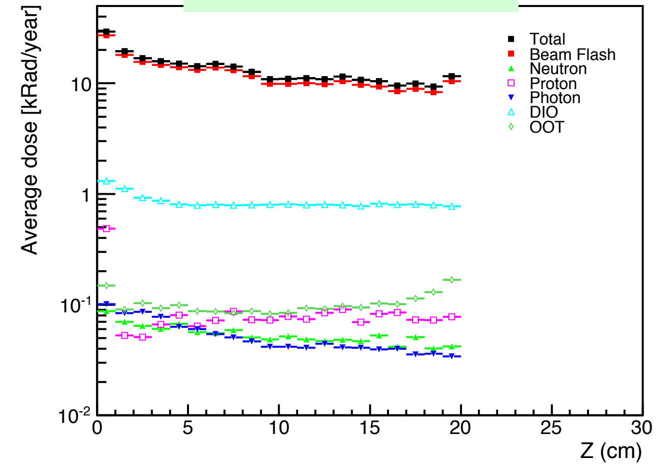


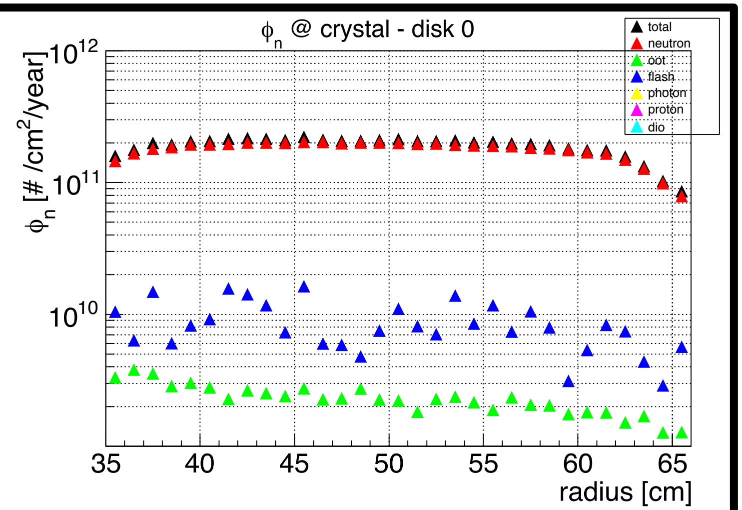
Radiation hardness (simulation)

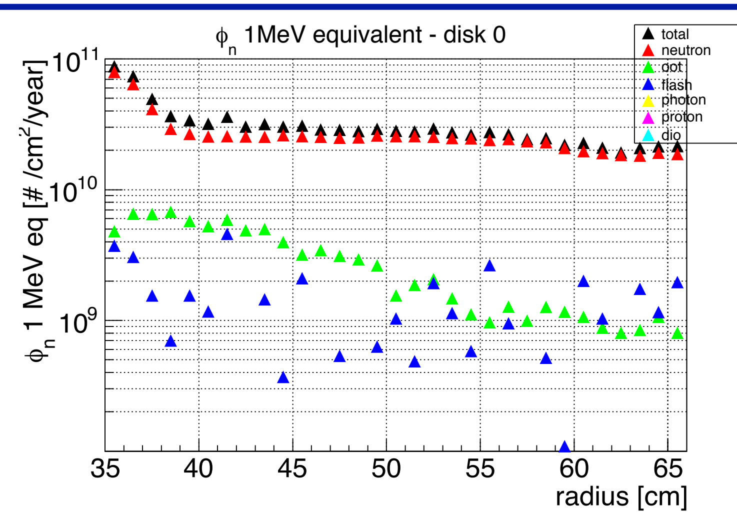
- ❑ Radiation dose driven by Beam flash (300 ns from interaction on target). **Dose from Muon capture x 10 smaller**
- ❑ Strongly limited to inner radius (up to 400 mm)
- ❑ **Highest dose/year ~ 10 krad**
- ❑ **Highest n flux/year on crys. ~ 2×10^{11} n/cm^2**
- ❑ **Highest dose/year on APD ~ 6×10^{10}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



Radius = 36 cm







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

Summary of Calorimeter Requirements

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

In order to do so the calorimeter should:

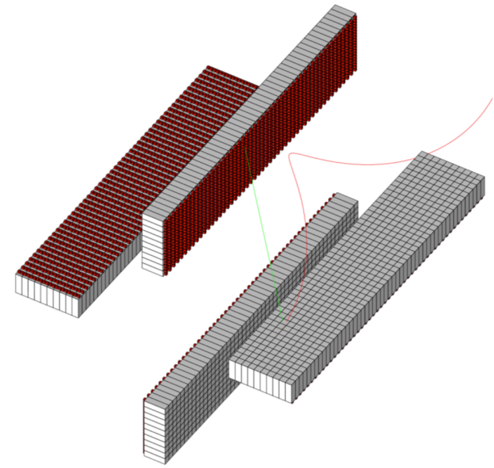
→ Provide energy resolution σ_E/E of O(5 %)
→ Provide timing resolution σ(t) < 500 ps
→ Provide position resolution < 1 cm

→ Crystals survive a radiation dose of 100 krad and
a neutron fluence of 10^{12} n/cm^2

→ Photo-sensors survive a neutron fluence of 3×10^{11} n_1MeV/cm^2

Calorimeter system: Specifications & layout

Calorimeter choice: High granularity crystal based calorimeter



Disk geometry vs "Vanes"

(+) better acceptance

(+) simpler to change kind of crystals (X_0 i.e. length)

(+) simpler mechanics

(-) more radiation on crystals

(+) less radiation on photo-sensors

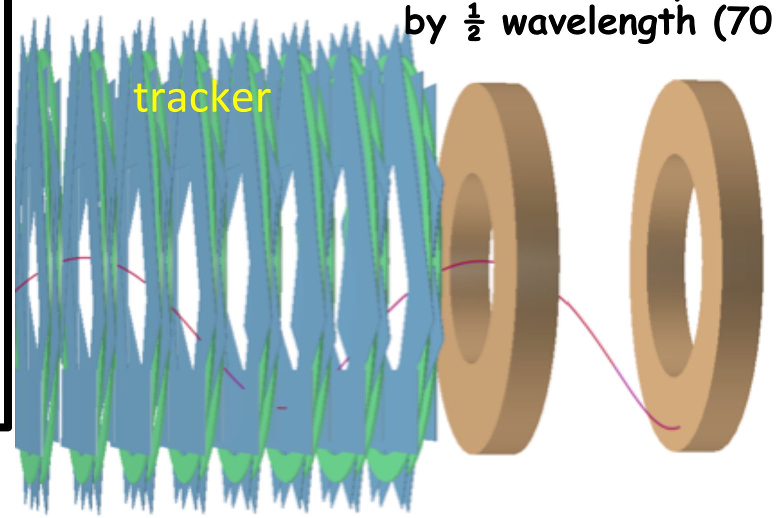
(+) Charge symmetric, can measure $\mu^- N \rightarrow e^+ N$

Square vs Hexagonal crystals

(+) minor cost, same light yield

(-) less favorable packing for mechanics

Two disks separated by ½ wavelength (70 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)

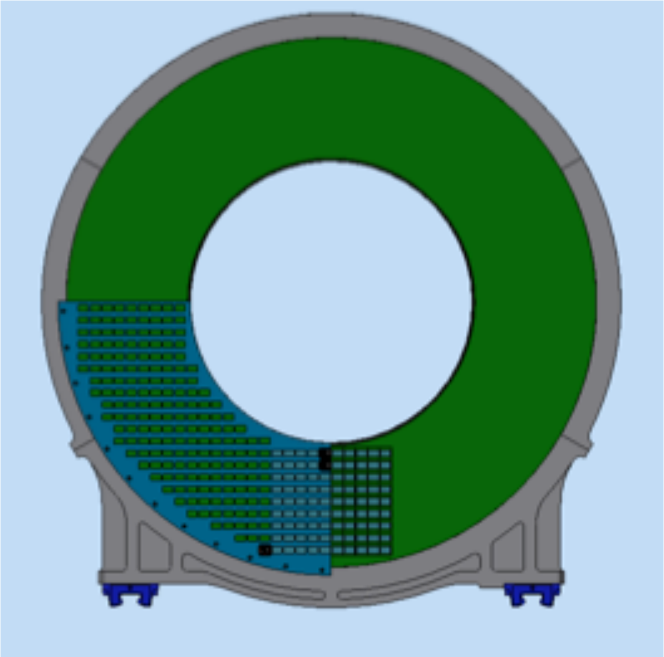
Baseline for EDR

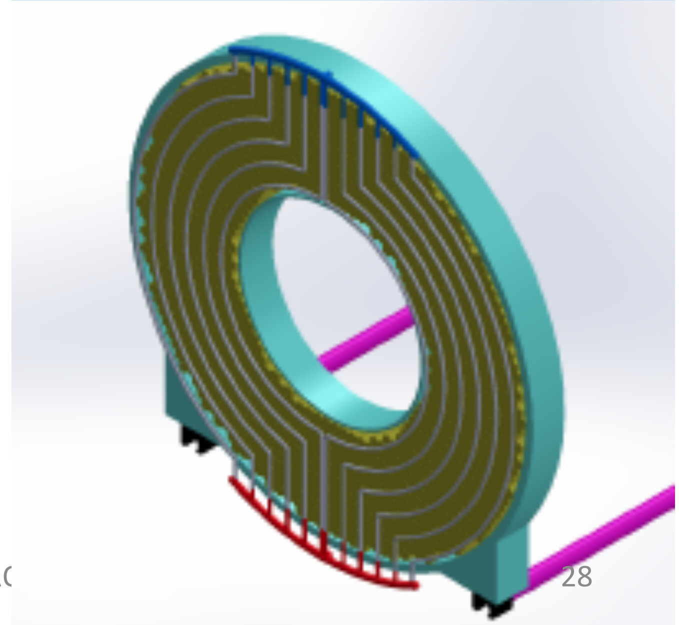
- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

Disk Calorimeter Layout

The Calorimeter consists of two disks with 1650 square crystals (30x30x200) mm^3

- ❑ R_{IN} = 351 mm, R_{OUT} = 660 mm
  Depth = 10 X_0 (200 mm)
- ❑ Each crystal readout by two silicon photosensors (3300 total) for redundancy
- ❑ Analog FEE and digital electronics located in near-by electronics crates
- ❑ Radioactive source and laser systems provide absolute calibration as well as fast and reliable monitoring capability.





Rad Hardness Tests/Plans

Irradiation tests of crystals

→ Caltech Laboratory

→ ENEA Calliope Facility (Co^{60}) …

large irradiation possible

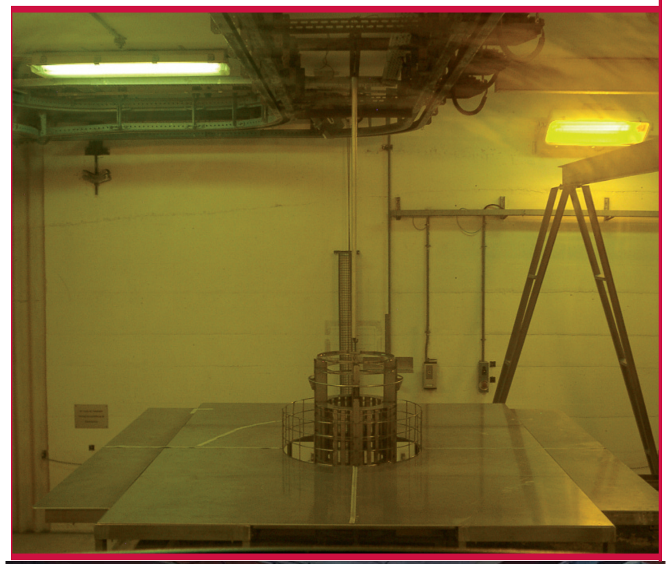
up to 0.3 10^{15} Bq

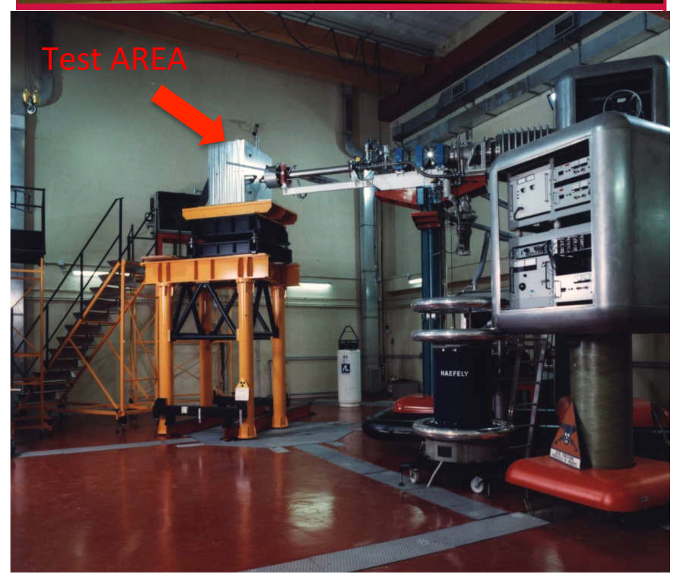
Irradiation tests with neutrons on crystals , APD and SiPM

→ Caltech Laboratory with Cf-252 source (2.5 MeV n)

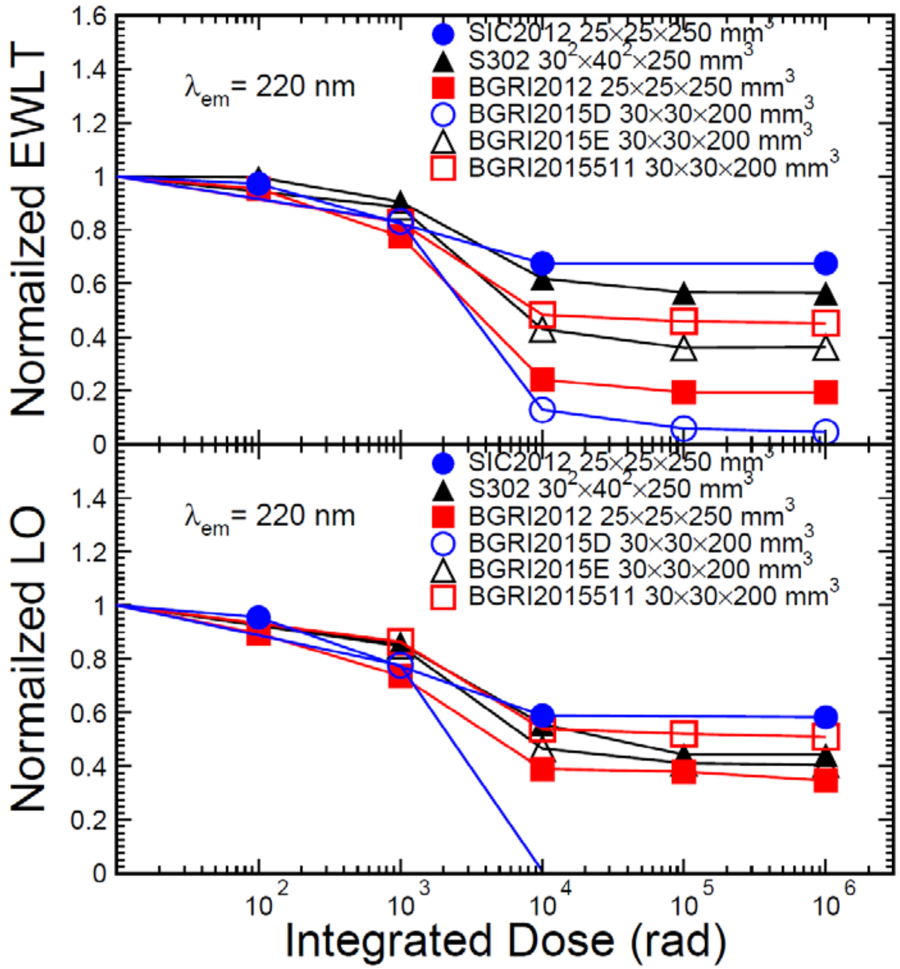
→ ENEA FNG (Frascati Neutron Generator) with 14 MeV n

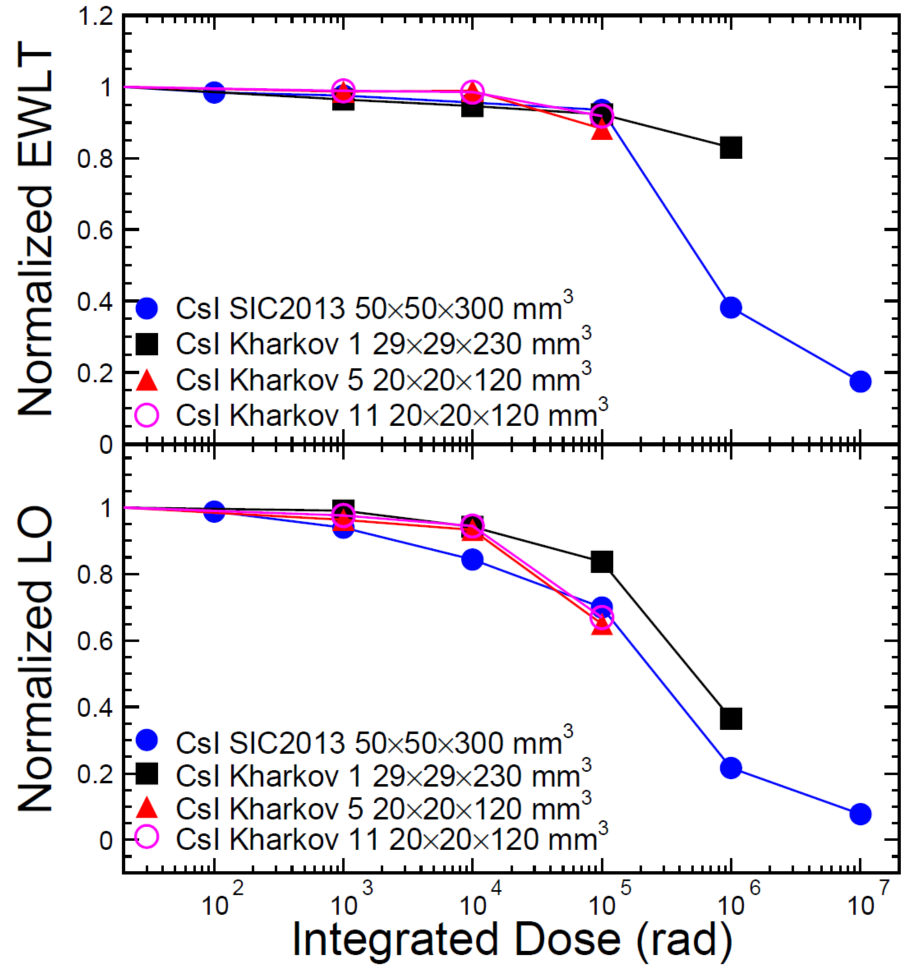
→ Irradiation under planning with p @ Los Alamos and with 1 MeV n @ NElbe (HZDR)





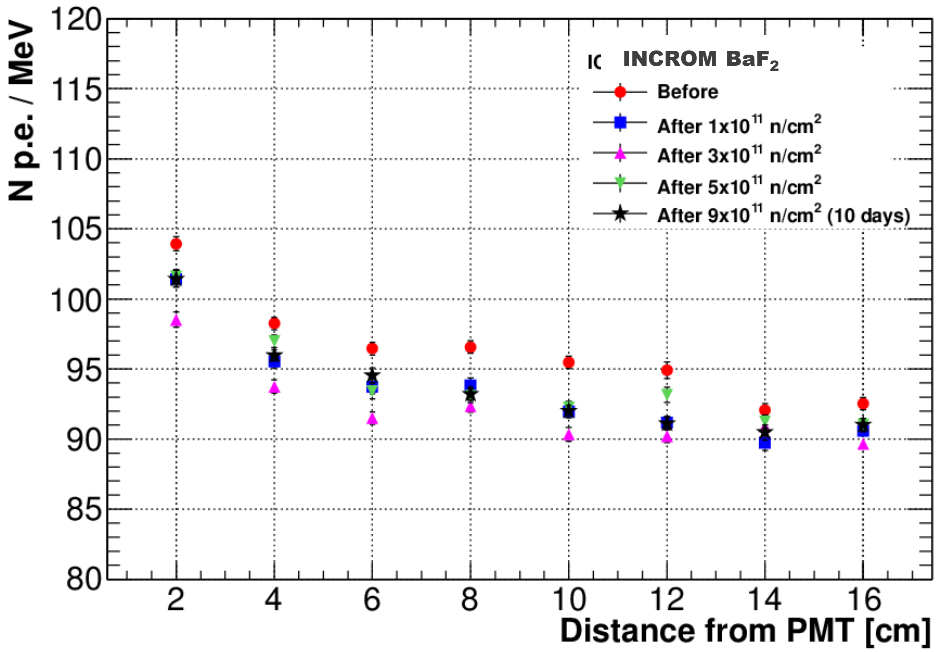
Crystal radiation hardness: dose



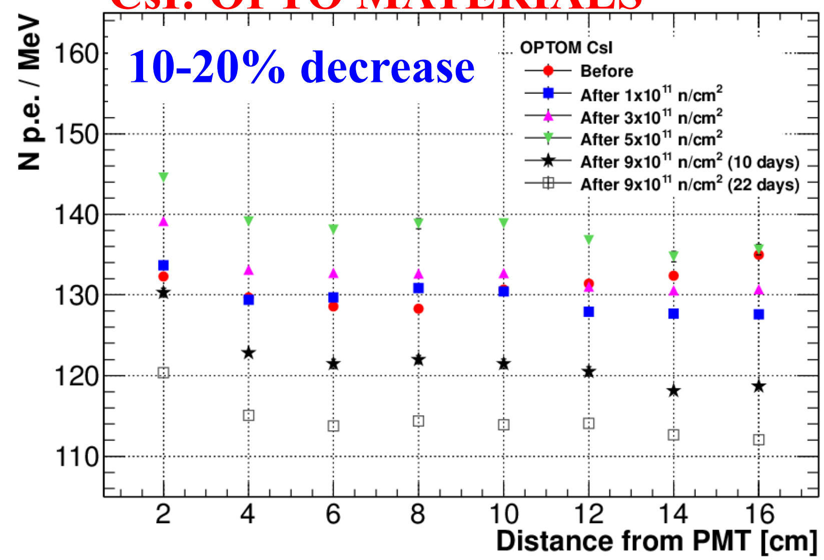


- Both crystals rad-hard for expected dose in Mu2e-I
- No recover from annealing
- BaF_2 loses more light in the first 10/100 krad, then it stabilizes

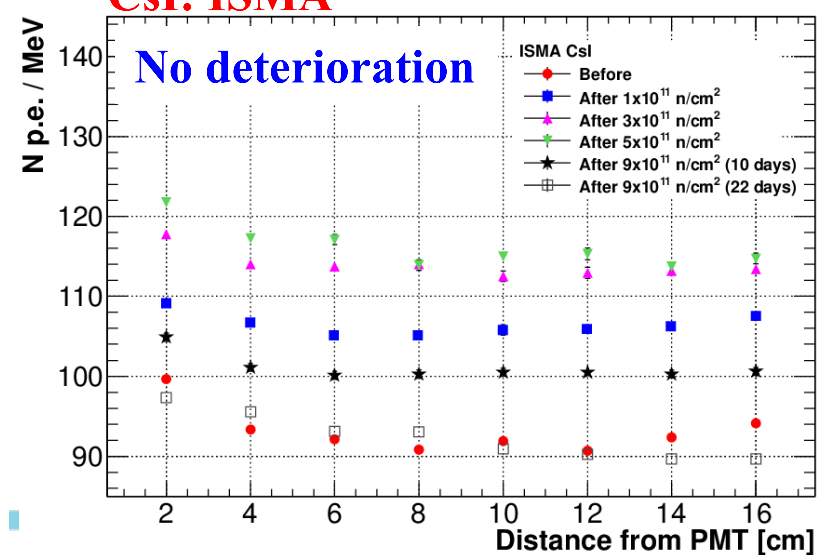
Crystal radiation hardness: neutrons



CsI: OPTO MATERIALS



CsI: ISMA

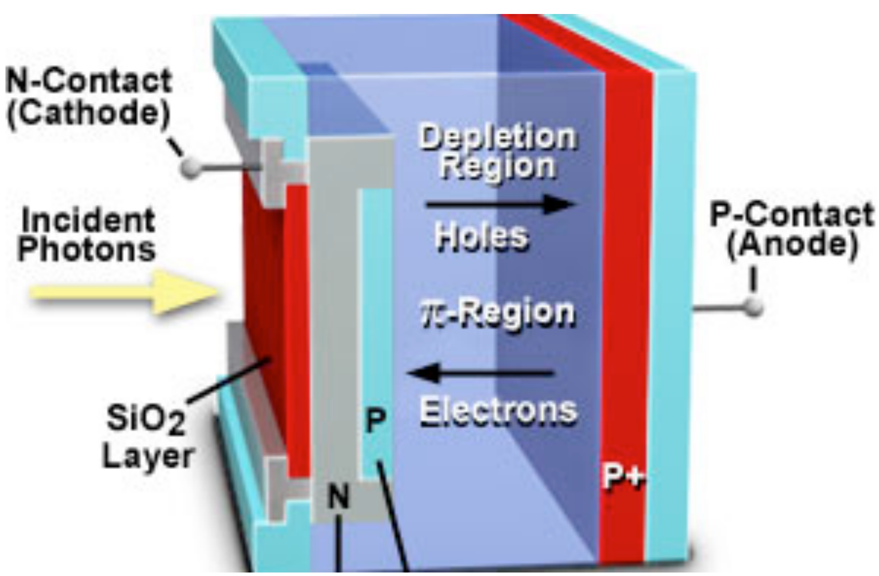


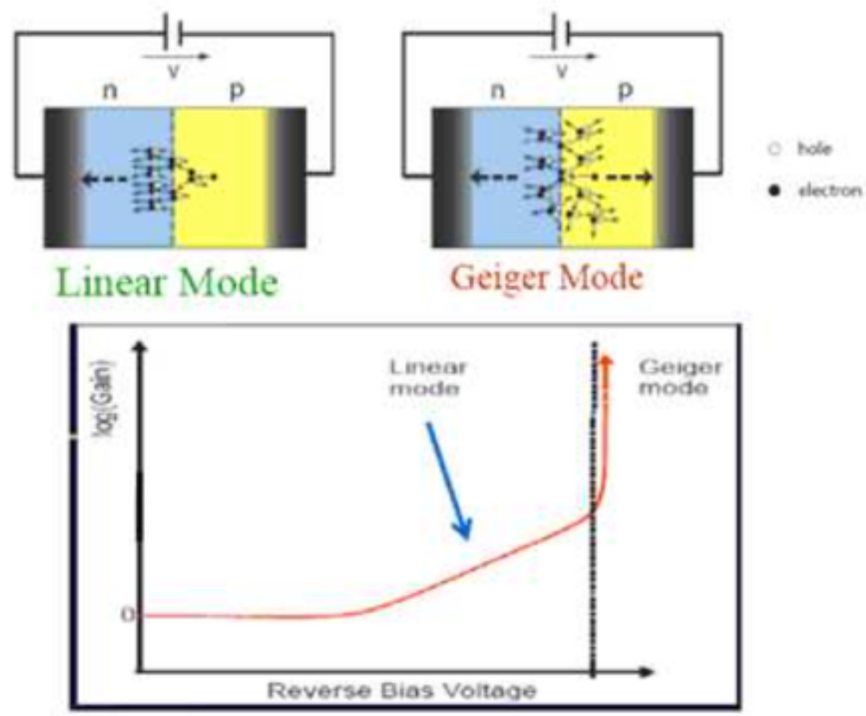
- Both crystals are radiation hard for the expected flux of neutrons.
- Losses in transmittance and LY contained at the 10% level

Silicon Photosensors

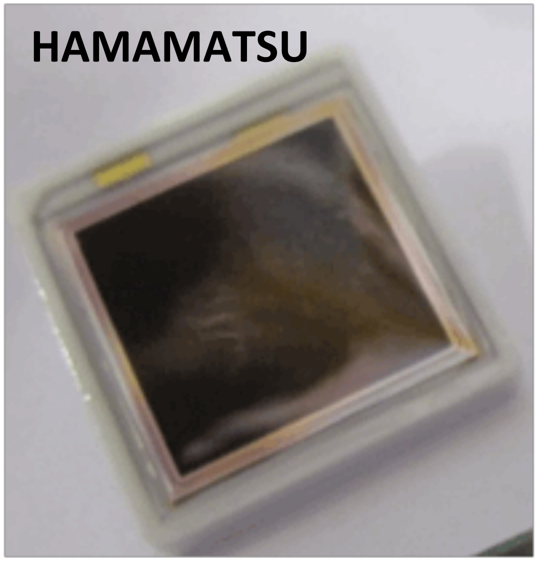
- A silicon photo-sensor is "in practice" a reverse Silicon N-P junction with a photo sensitive layer where "photo"electrons are extracted.
- The reverse bias helps to create a large depleted region and reduce to negligible values the "dark current", Id, i.e. the current seen without any signal in input
- **3 work regimes:**

→ **Photodiode (G=1)** all e- produced in the photosensitive layer are collected at the anode.
→ **APD (G=50-2000)** , or Avalanche Photodiode, working in proportional regime and
→ **Geiger APD (G=10^5-10^6)** working in Geiger mode

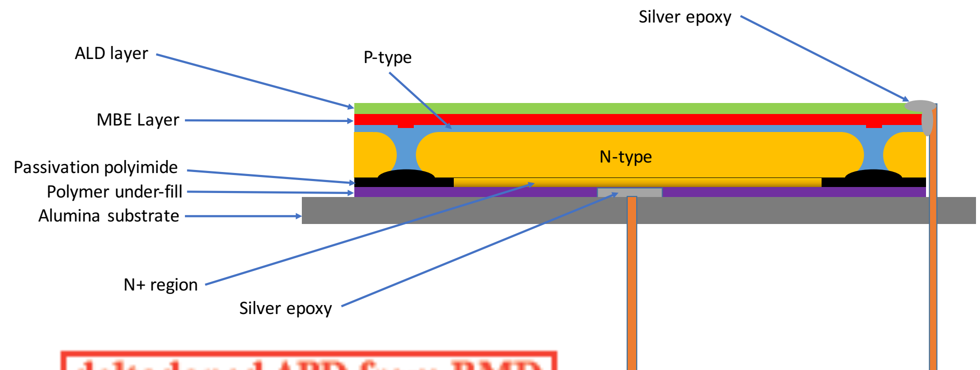




Different kind of APDs

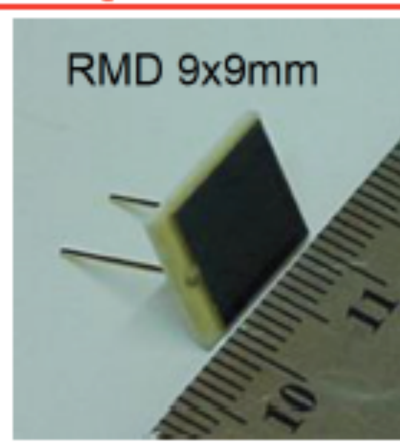


- CT from 80 to 270 pF
- Id from 5-50 to 10-100 nA
- Quantum Efficiency on Blue ~ 70%
- Typical Gain ~ 50
- Operation Voltage ~ 400 V



- ✓ 60% QE @ 220 nm
- ✓ ~ 0.1 % QE @ 300 nm
- ✓ capacitance ~ 60 pF (1/5 of Ham S8664)
- ✓ HV ~ 1800 V
- ✓ Operation Gain ~ 500
- ✓ Decay time ~ 25 ns.

deltadoped APD from RMD

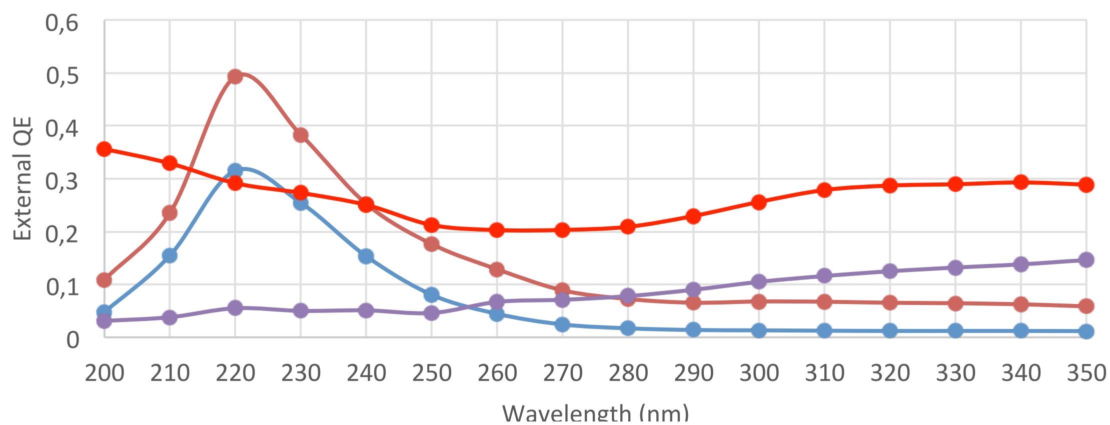


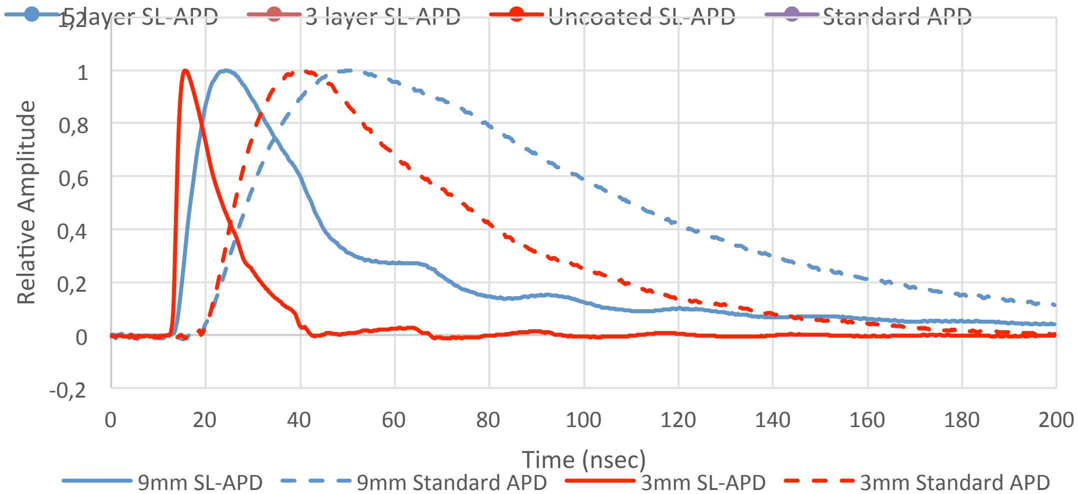
Solar Blind APDs

A Caltech/JPL/RMD consortium formed to develop a Large area RMD APD **into a super-lattice APD with high Q.E. @ 220 nm** incorporating also **an Atomic Layer Deposition antireflection filter** to reduce efficiency for wavelength > 300 nm.

SL - SB APD developed to get light from BaF2 Crystals:

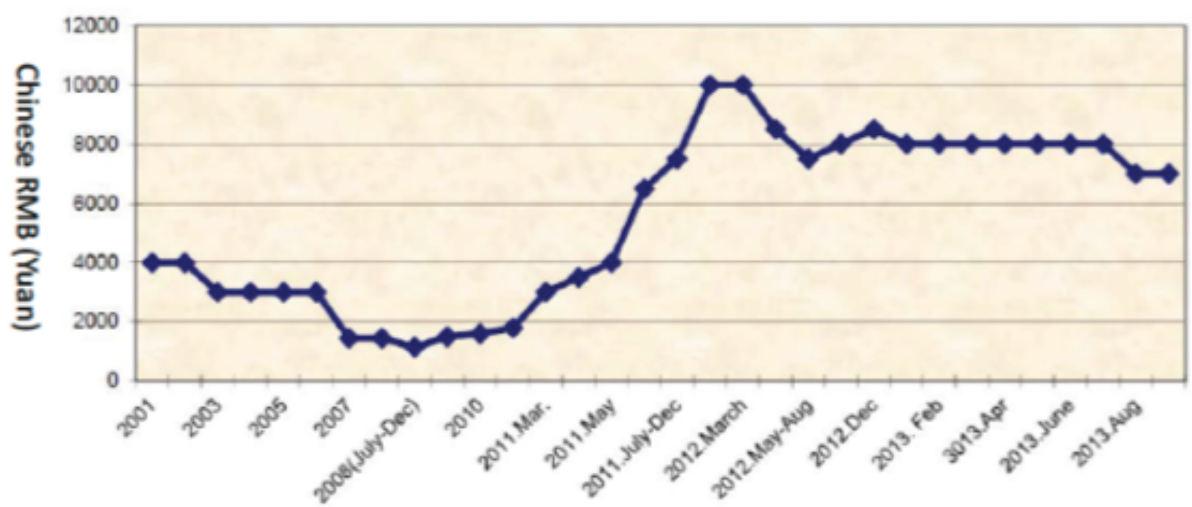
- 0,9 ns light @ 220 nm
- 600 ns light @ > 280 nm



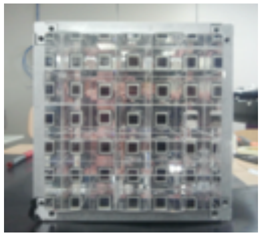


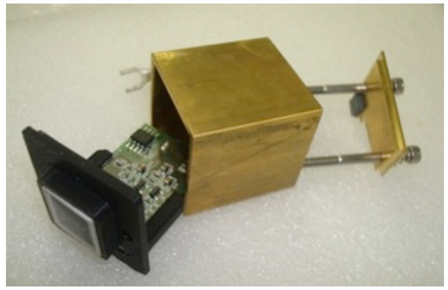
INFN Calo R&D (2013-2014)

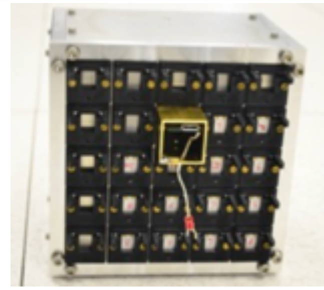
- Simulation/reconstruction of clusters + calorimeter based seed for tracking
- Design and construction of 2 (LYSO + APD) calorimeter prototypes
- Control stations for characterization of crystals and photo-sensors
- Design/construction/operation of 50 FEE amplifiers/Voltage regulator + 5 ARM based controller (SEA LNF) + 5 WF prototype (Illinois/Pisa)
- 1 Laser prototype (green light + distribution system)
- **Change on technology and R&D due to sudden LYSO cost increase (x 3) in 2012-2013.**

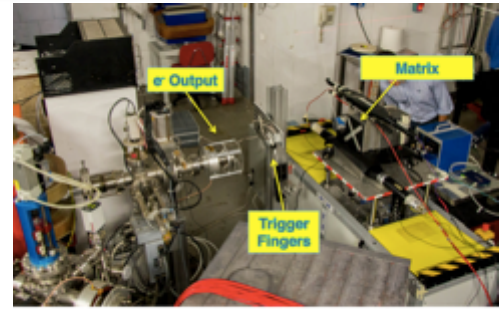


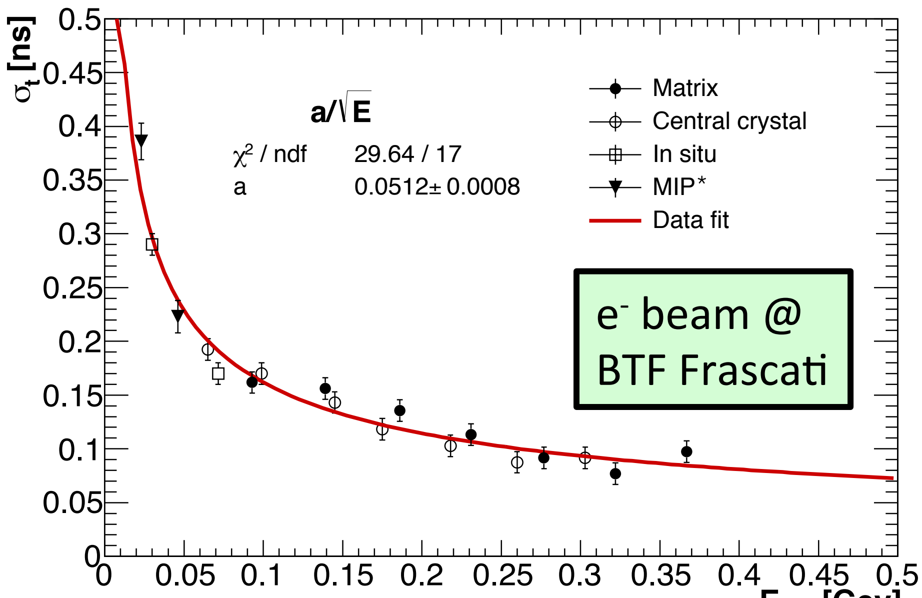
LYSO Legacy



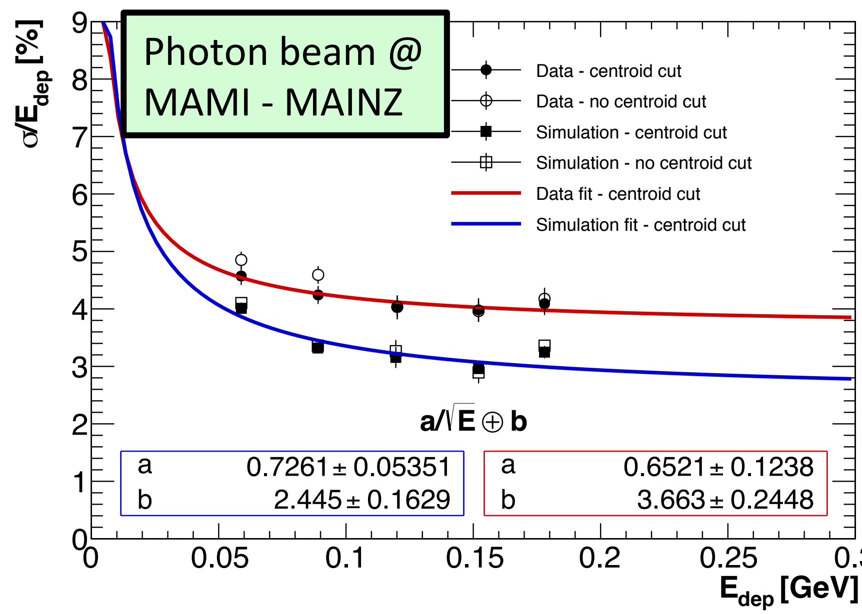








*Time resolution with MIPs from Mu2e DocDB 4409



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

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

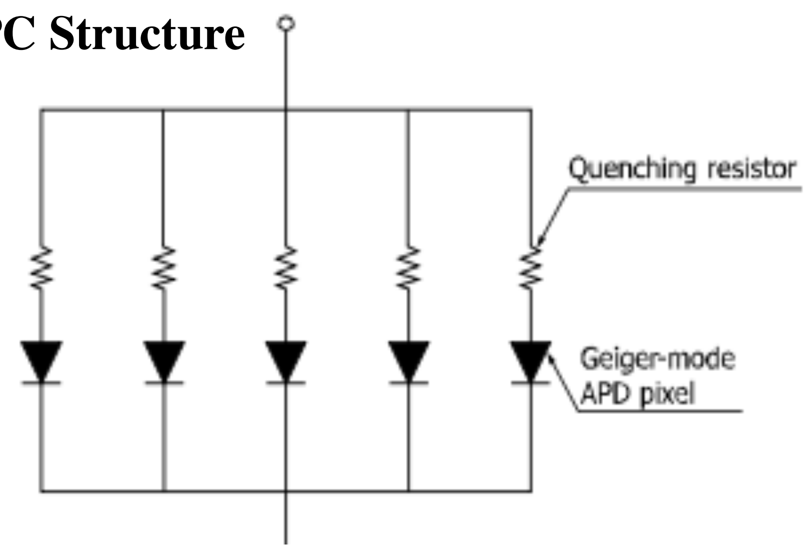
Noise term *b* considered negligible (~0.1% in quadrature).

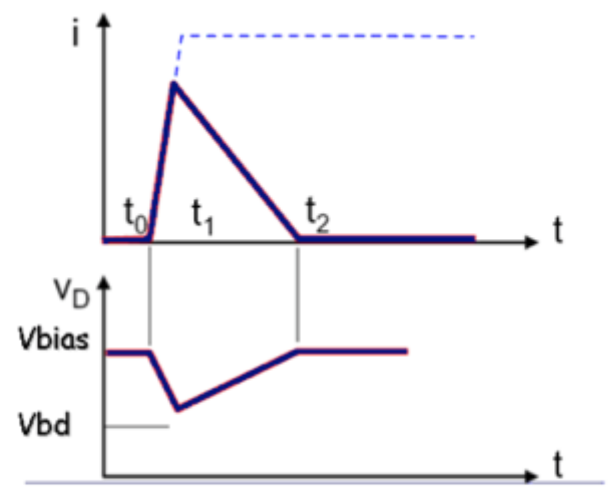
Silicon PMT (1)

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

- The Geiger mode allows obtaining a **large output by the discharge even when detecting a single photon**. Once the Geiger discharge begins, it continues as long as the electric field is maintained.
- One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with each APD pixel. This quickly stops the multiplication in the APD since a voltage drop occurs when the output current flows.

MPPC Structure





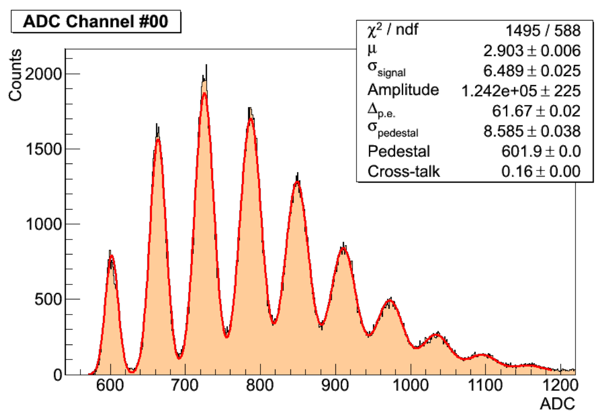
Silicon PMT (2)

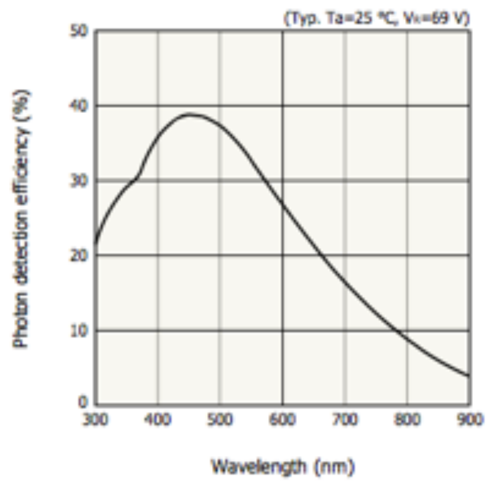
The basic SIPM element (pixel) is a combination of the Geiger-APD and quenching resistor

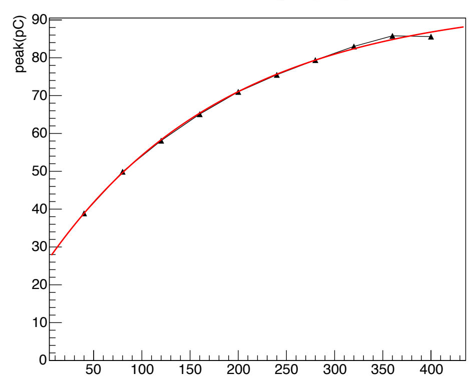
→ a large number of these pixels are electrically connected and arranged in two dimensions;

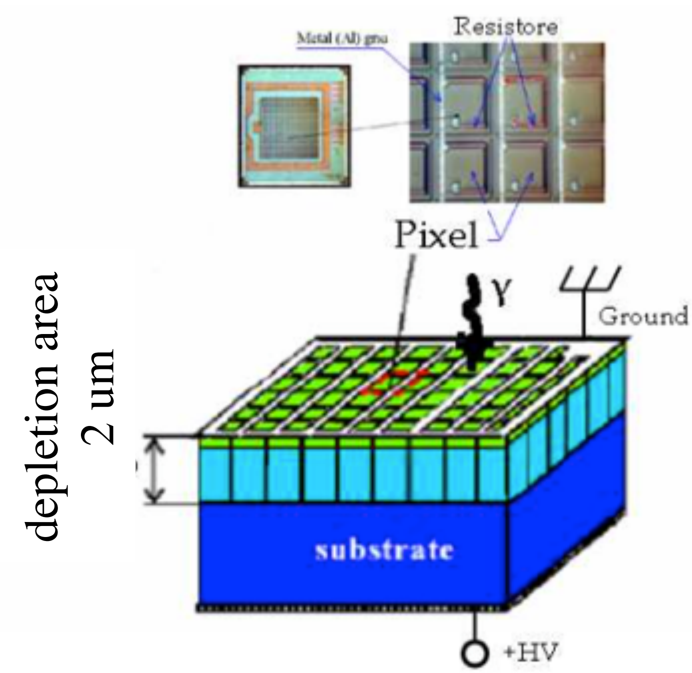
→ Each pixel generates a pulse of the same amplitude when it detects a photon .

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









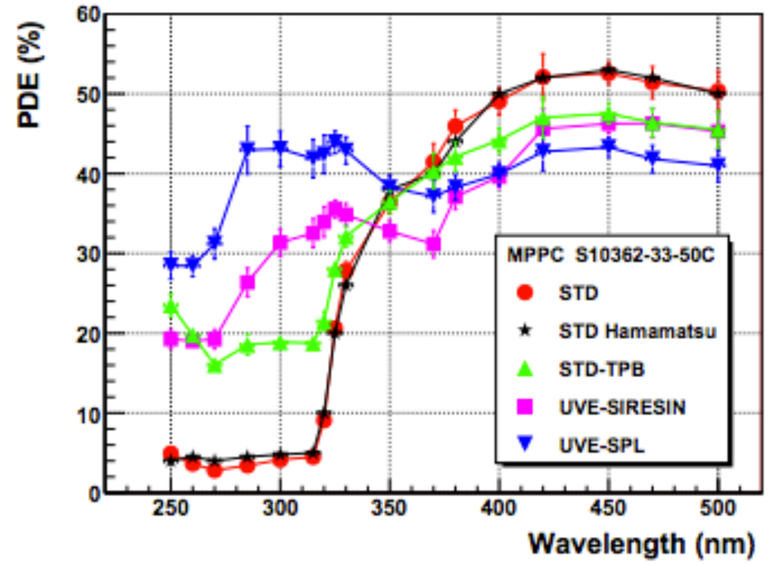
- ➢ Single photon counting
- ➢ Photon Detection Efficiency
- ➢ "Intrinsic" not-linearity on the response.

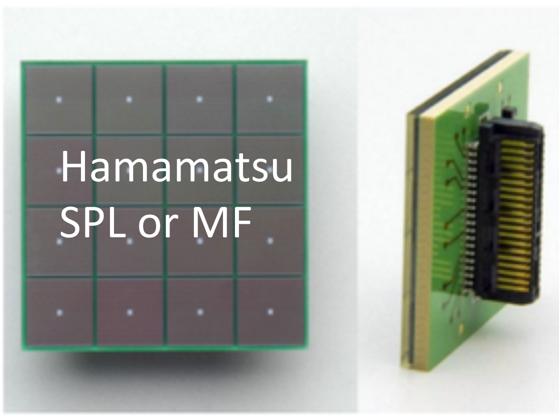
UV extended SiPM

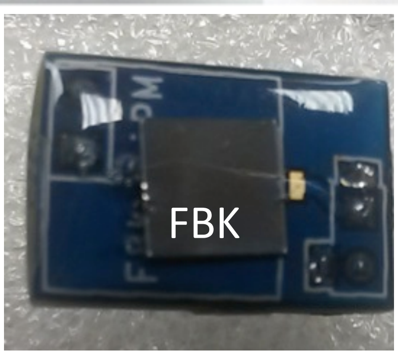
The PDE of UV-enhanced MPPC is higher than the standard one:

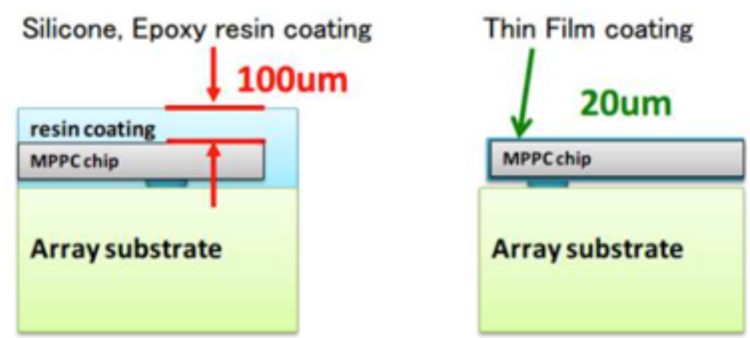
Imaging with SiPMs in noble-gas detectors:
arXiv 1210.4746

- → **30-40% @ 310 nm (CsI pure wavelength)**
- → **with new silicon resin window**
- → **Gain = 10^6**
- → **Reduced cross talk and dark current**
- → **possibility to work up to 3-4 volt above the V_{op}**







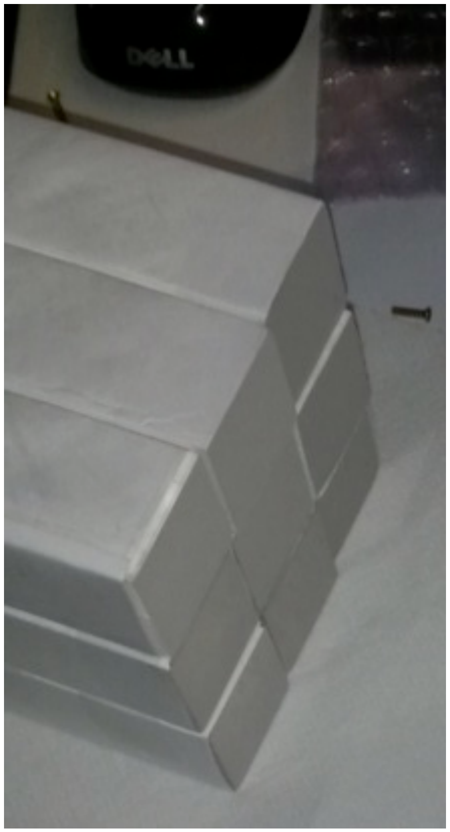


■merit
- robust to the mechanical shock
- easy handling (during assy.)
- superior transparency in UV region
  - silicone resin coating type -

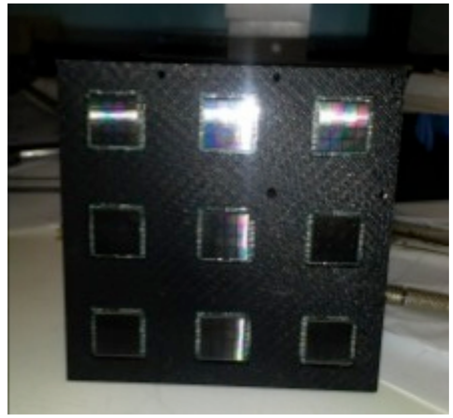
■merit
- tough coating
  (mechanical shock should be avoided)
- superior transparency in UV region
- cross-talk suppression in the coating
- super flatness (minimum bending)

Array of CsI+ UV extended SPL SiPM

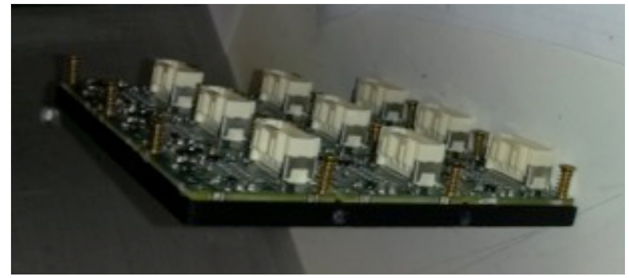
100 μm Tyvek reflective wrapping



MPPC lodgments created by means of PVC 3D print

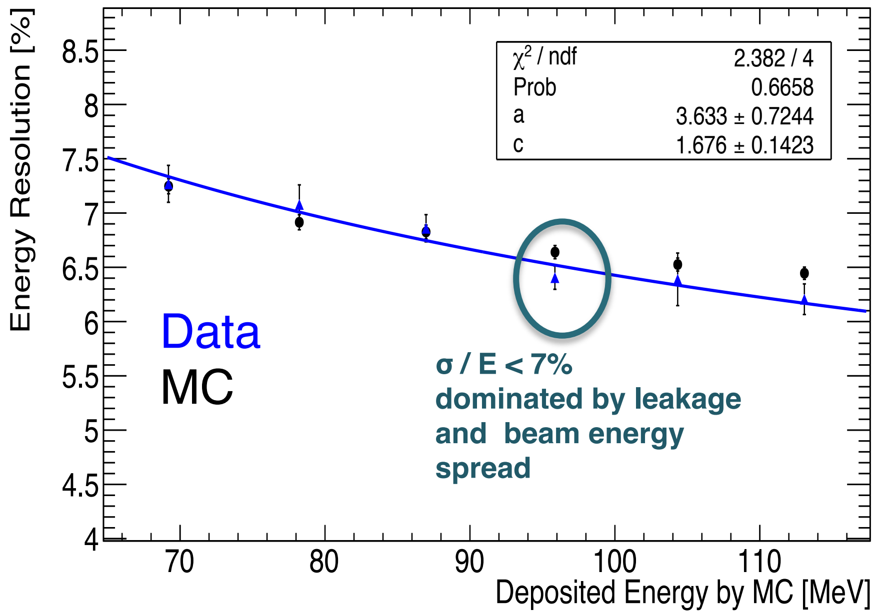


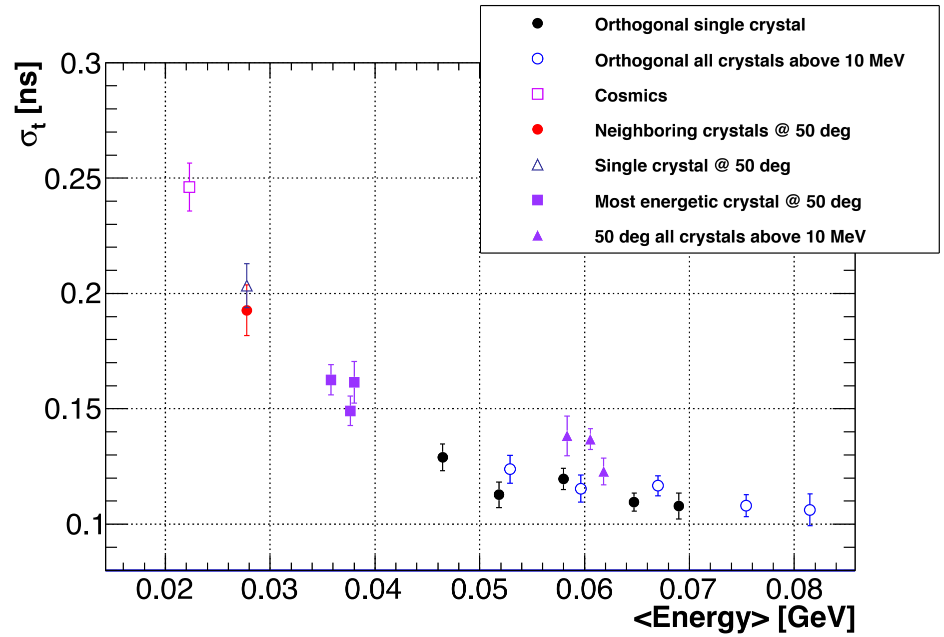
Electronics FEE: analog adder of the 16 anodes/MPPC



Optical coupling with Silicon Paste grease + 50% light output
High transmittance @ 310 nm

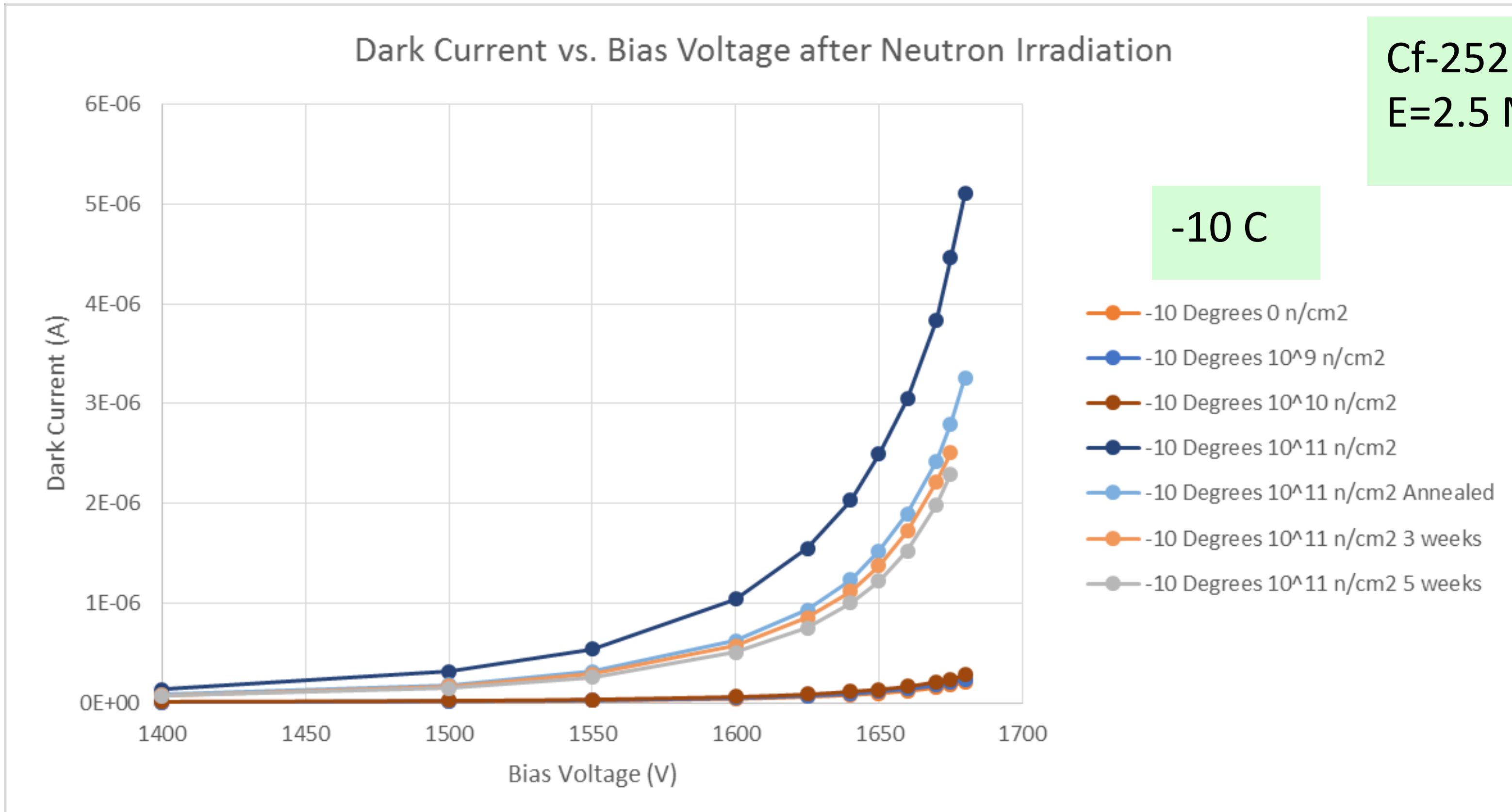
CsI+SiPM test with e- beam





- Test beam with e- beam @ BTF, LNF from 80 to 130 MeV.
- Good energy (7%) and timing (110 ps) resolution measured.
- Matching results with the one obtained with the LYSO array

Irradiation of photosensors: APD

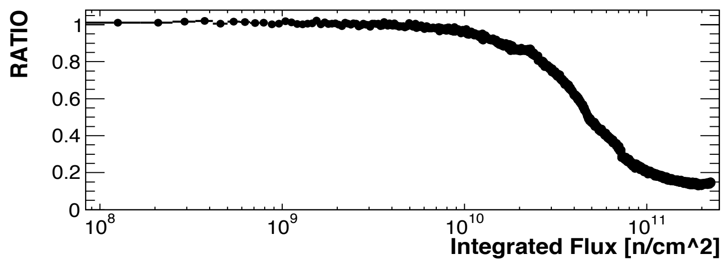


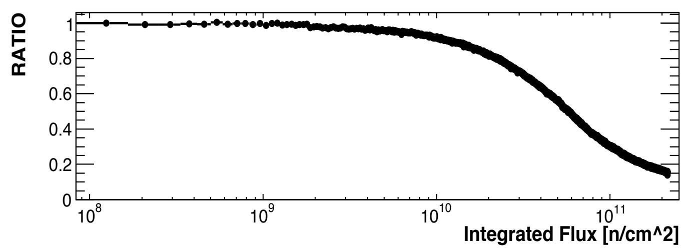
Cf-252
E=2.5 MeV

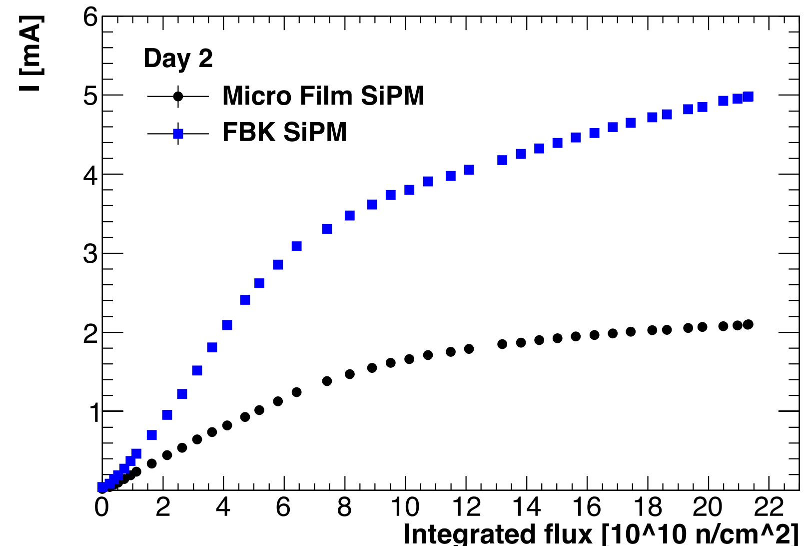
-10 C

- Dark current increases up to a factor of 15 when exposed to a neutron fluency of 10^{11} n/cm^2 and 5 weeks annealing.
- Another factor of 3 needed to reach safety margins.
- No bias applied to the APD when irradiated

Irradiation of photosensors: SiPM







Reported current for FBK SiPM has been corrected by a factor of 4, due to the different active area.

For a neutron fluence equivalent to 2.2 times the experiment lifetime, the signal peak decreases from:

- ~250 to 30 mV for SPL
- ~ 400 mV to 50 mV for MF

For the innermost layer a larger amplification value can be used (e.g. from 10 to 20)

The current increased from

- **16 uA up to 2 mA (MF)**
- **100 uA up to 2.2 mA (SPL)**
- **86/4 uA up to 19/4 ~5 mA (FBK)**

Running conditions

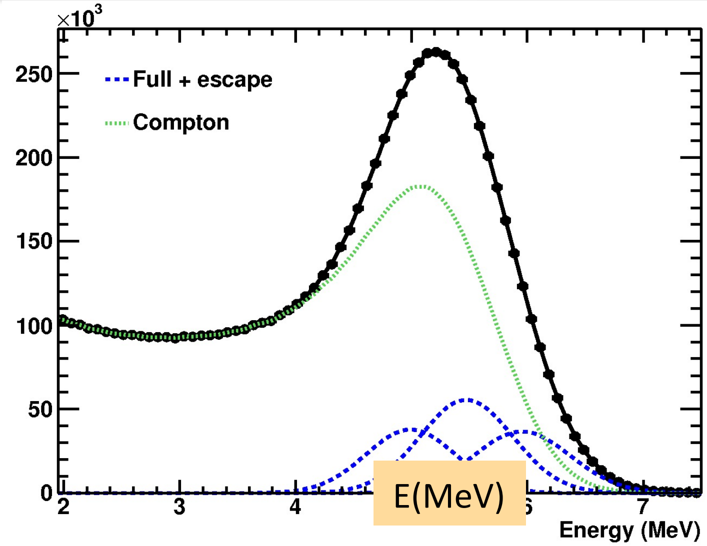
- **APD : work @ -15 °C**
  → After irradiation w.o. bias, noise increases of a factor 15
  A factor of > 200 observed when irradiated @ 1/5 of Vop
  → Noise term too high at RT
  → Reliability improved in the last months but still an issue
  → low signal, large noise

- **SiPM: work @ RT**
  → After irradiation, innermost layer need to go to 0 °C
  → Reliability is not an issue
  → can be customized to better shape (rectangular?)
  → High gain, small noise

The SiPM is the final choice

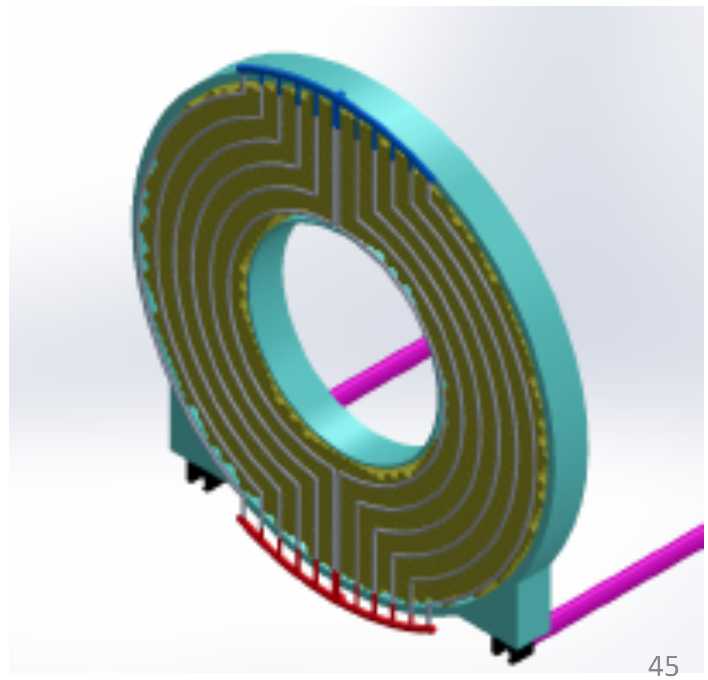
Calibration and monitoring system (1)

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



Based on BABAR scheme & salvage of their components

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



Calibration and monitoring system (2)

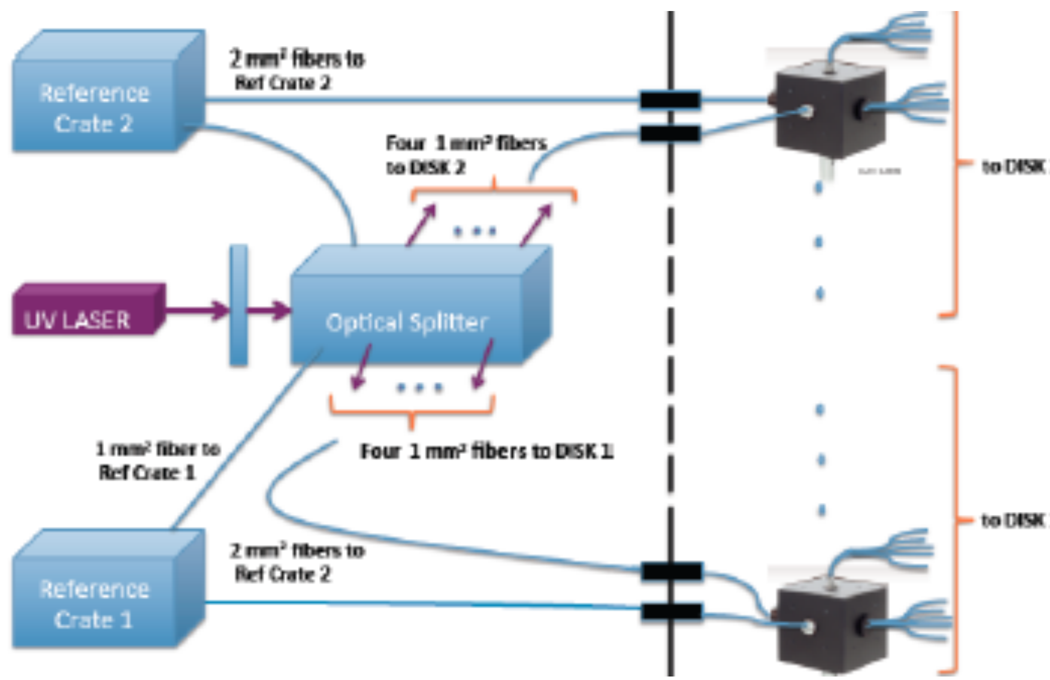
Laser system adapted from CMS calibration system.
UV light to monitor continuously the variation of the APD gain and as the first tool for calibrating the timing offsets

→ Green laser prototype used for LYSO test.

→ Distribution system with Silica optical fibers developed

→ Successful

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



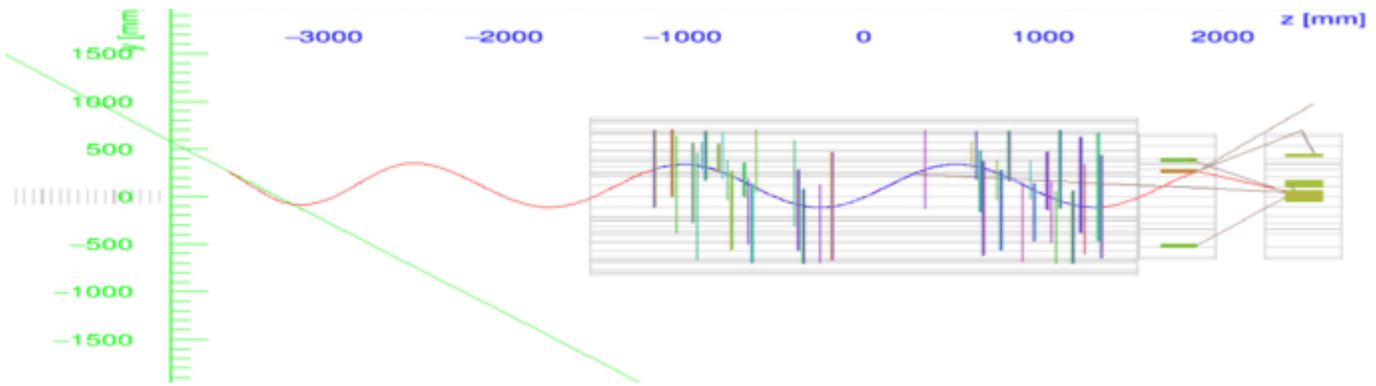
Conclusions

- Muon conversion experiments (CLFV in general) are excellent tools to look for new physics (BSM).
- They belong to the Intensity Frontier searches and are complementary to searches @ colliders while exploring a mass scale not directly accessible.
- The design of the Mu2e experiment is under way and In the next years an intense phase of construction and tests are scheduled.
- Mu2e offers a lot of opportunities for brilliant students to participate to a state of the art, world class, experiment in USA.
- Summer Schools @ FNAL are available: https://www.unipi.it/index.php/students/item/5153-summer-student-at-fermilab

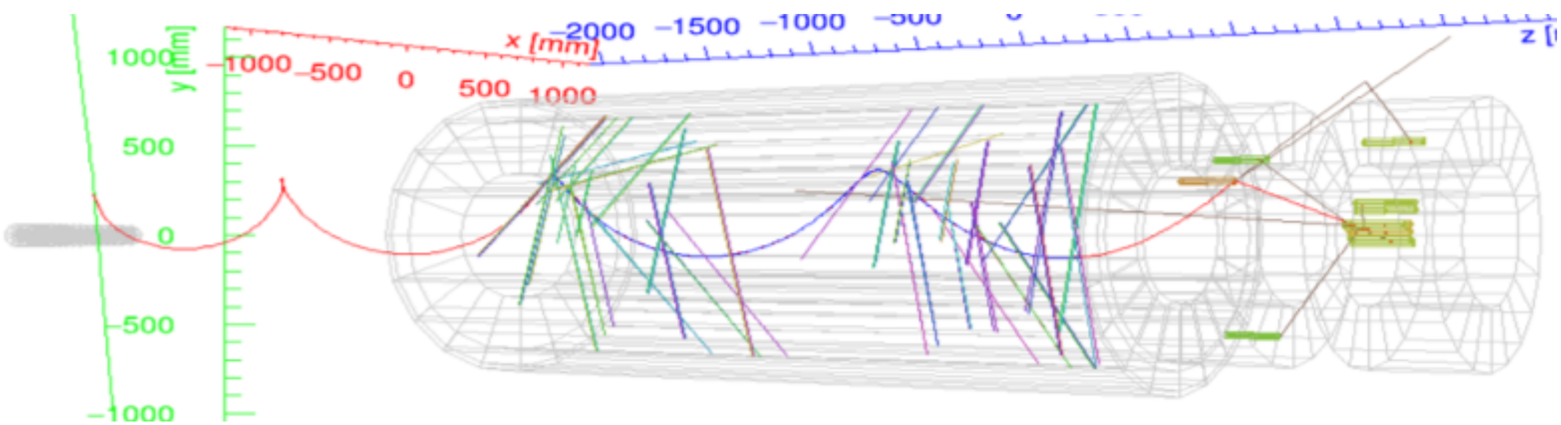
ADDITIONAL MATERIAL

Cosmic Ray Veto

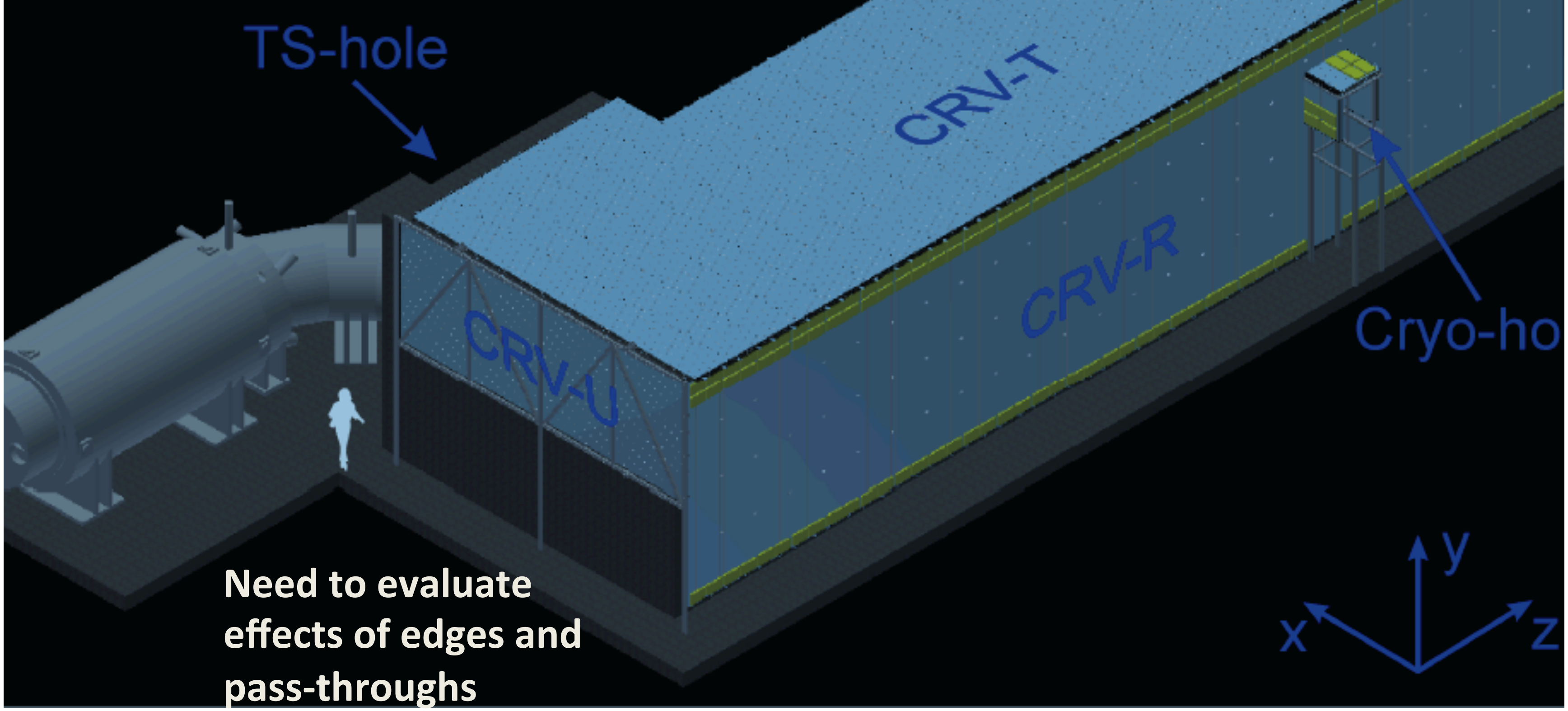
The Cosmic Ray Veto (CRV)



- **Cosmic ray muons and interaction products can fake conversion electrons at a rate of ~1 per day**



- **Cosmic Ray Veto made of layers of plastic scintillator bars surrounding detectors and transport region.**
- **Time resolution ~5ns**
- **Veto efficiency over 99.99%**



Need to evaluate effects of edges and pass-throughs

Quality Assurance

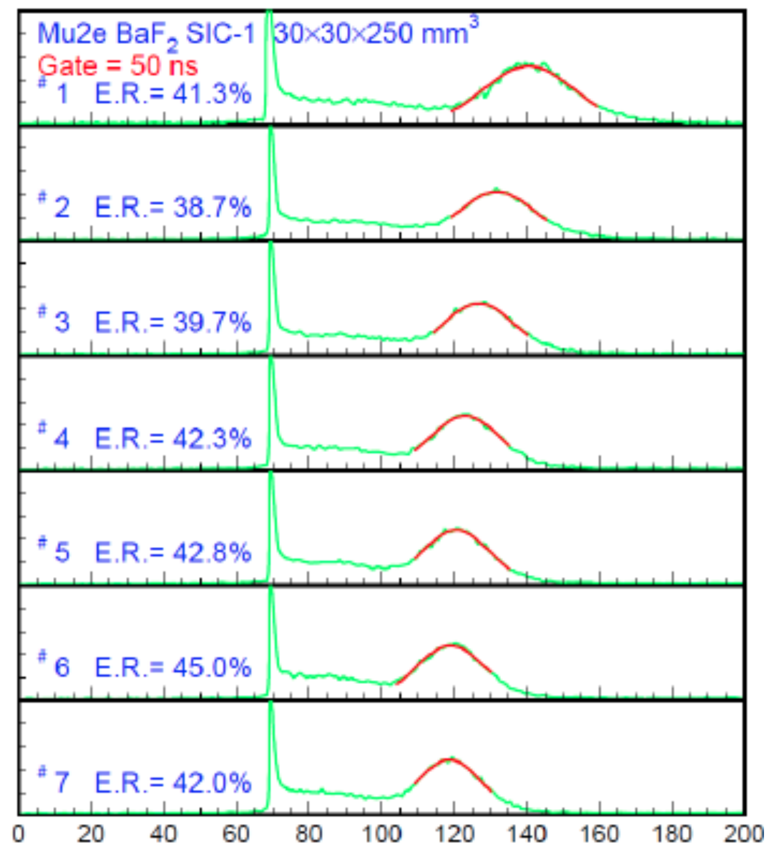
❑QA stations for crystals and photo-sensors exist in INFN and Caltech. Crystal stations are being modified to adapt to the BaF_2 deep UV emission. **Feedback with vendor ensure meeting specifications.**

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

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

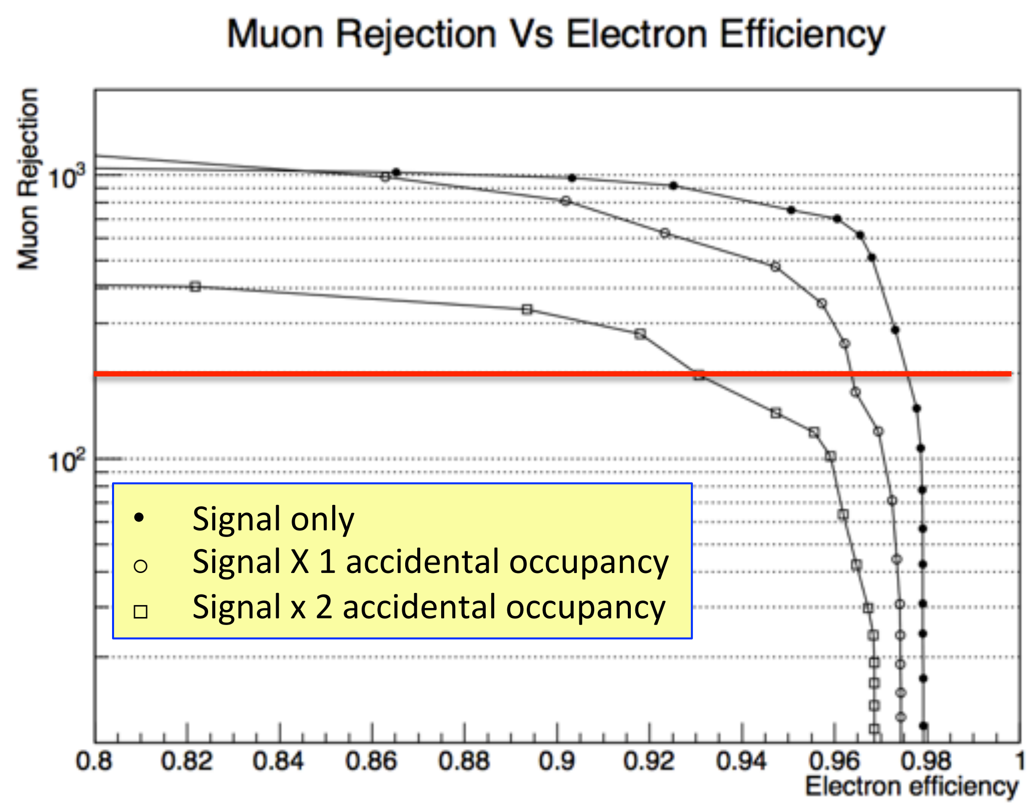
❑Bench test planned for the FEE and Digitizer systems.

❑Burn in test for HV system



Performance: PID (muon vs electrons)

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



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