CD-2 Review: Mu2e Calorimeter

Stefano Miscetti
LNF INFN, Italy
Calorimeter L2 Manager
10/21/2014

Mu2e

Calorimeter Team leaders

- Stefano Miscetti - L2 Manager, LNF
  - 10 years experience in operating the CDF Hadron calorimeter
  - 20+ years experience in construction and operation of KLOE calorimeter. KLOE-2 Technical Manager 2006-2013 → Experience in crystal calorimeters.
  - L2 manager of Mu2e calorimeter since 2009.
- David Hitlin – Deputy L2 Manager, Caltech
  - 40+ years experience in calorimetry. Responsible for design and construction of Liquid Argon calorimeter for Mark-II and SLD and BaBar crystal calorimeter.
  - Spokeperson of E92, MarkII, MarkIII and BaBar experiments.
  - L2 deputy of Mu2e calorimeter since 2011.
- Ren Yuan Zhu – Crystal expert, Caltech
  - 30+ years experience in crystal testing, crystal calorimetry and calibration.
  - Worldwide recognized as crystal and calorimeter expert (PDG).
  - Responsible of crystal laboratory of Caltech.

Calorimeter Team Organization

475.7 Calorimeter
L2: S. Miscetti (LNF)
Deputy: D. Hitlin (Caltech)

- **475.7.1 Project Management**
  L3 – S. Miscetti – (LNF)
  CAM – D. Hitlin
- **475.7.2 Crystals**
  L3 – D. Hitlin (Caltech)
  CAM - D. Hitlin
- **475.7.3 Mechanics**
  L3 – F. Happacher (LNF)
- **475.7.4 Photosensors**
  L3 – I. Sarra (LNF)
  CAM – D. Hitlin
- **475.7.5 Digitizer**
  L3 – F. Spinella (Pisa)
  CAM – D. Hitlin
- **475.7.6 Calibration**
  L3 – F. Porter (Caltech)
  CAM – D. Hitlin
- **475.7.7 Frontend electronics and power**
  L3 – G. Corradi (LNF)
- **475.7.8 Assembly and Installation**
  L3 – A. Saputi (LNF)
  CAM – D. Hitlin

- ❑ MoU agreement in progress between INFN and JINR.
- ❑ DOE/INFN sharing proposed

Requirements

The calorimeter requirements are described in DOCDB-864

The calorimeter, EMC, should:

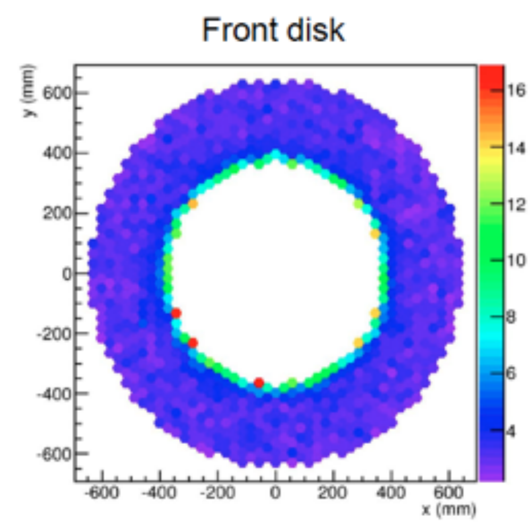
- Provide information that, in combination with information from the tracker, can distinguish electrons from muons and pions;
- Provide a clean, independent, software trigger, based on energy deposition;
- Have large acceptance for signal electrons;
- Provide a “seed" to improve track pattern recognition.

Function in the unique mu2e environment:

→ Sustain a Ionization Dose of < 12 krad/year per crystal and a fluence of $\approx 10^{12}$ n/cm^2/year

→ Work in a B field of 1 Tesla

→ Work in a high rate environment (from 5-12% occupancy @ 1 MeV threshold)

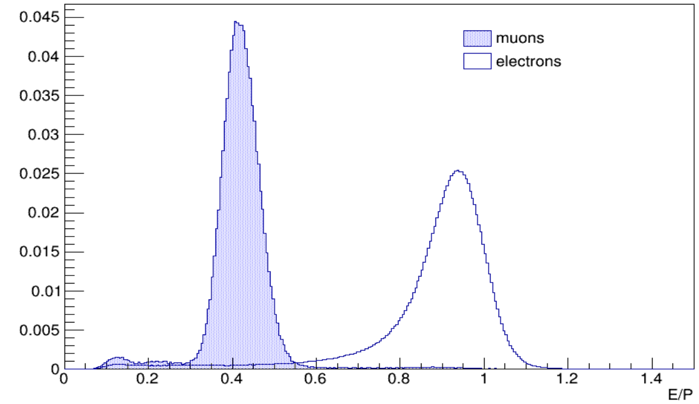


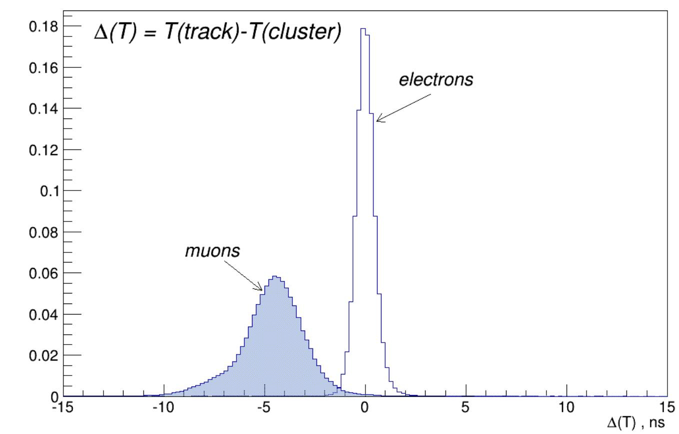
Requirements.1 – PID mu/e

- ❑ Simulation shows that, after full Track Selection 1 muon that cannot **be vetoed by the CRV** is reconstructed as a CE.

- ❑ Need to keep the background of these muons faking electrons negligible (below 0.01 events)

→ muon rejection of 200 while keeping highest possible efficiency





Rejection/efficiency evaluated with a log-likelihood based on Eclu/P and $\Delta T = T_{trk}-T_{clu}$.
Toy MC adds gaussian spread on calorimeter energy and timing response

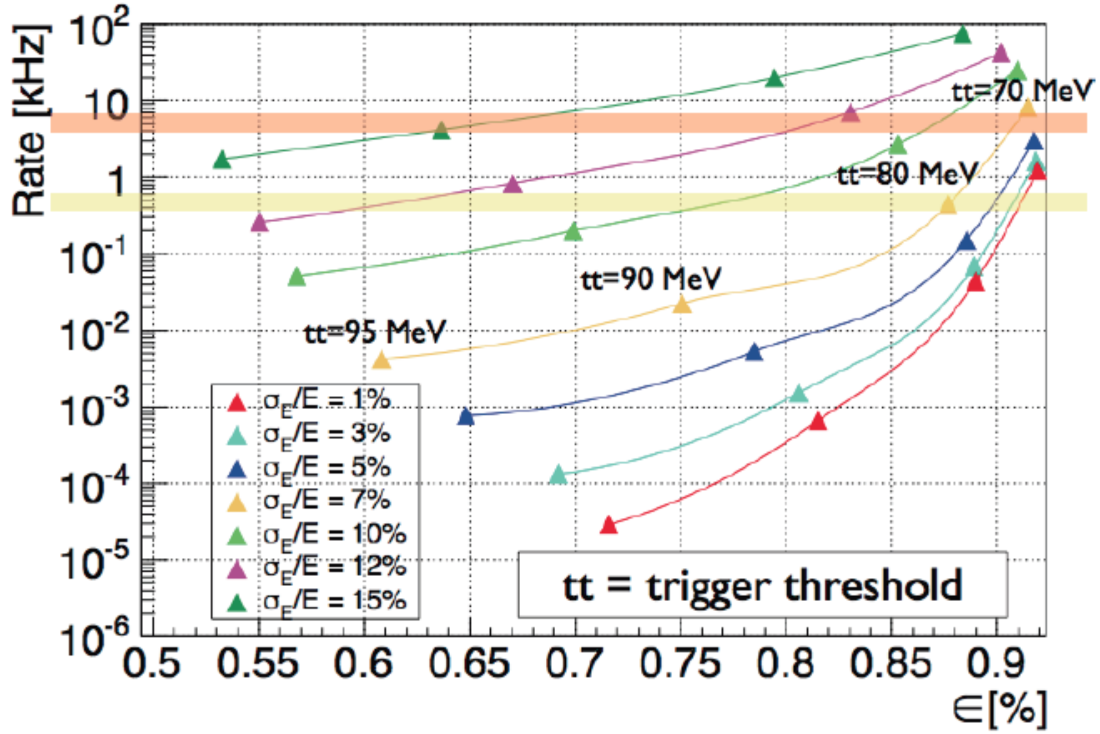
→ Energy res. 5% and time res. < 500 ps look as a reasonable choice.

Requirements.2 – trigger

- ❑ Fast and track-independent HLT selection based on EMC cluster reconstruction.

- ❑ **Reduce storage rate to 2 kHz (5 PB/year) .**

- ❑ Toy MC suggests a calorimeter with < 7% energy resolution.

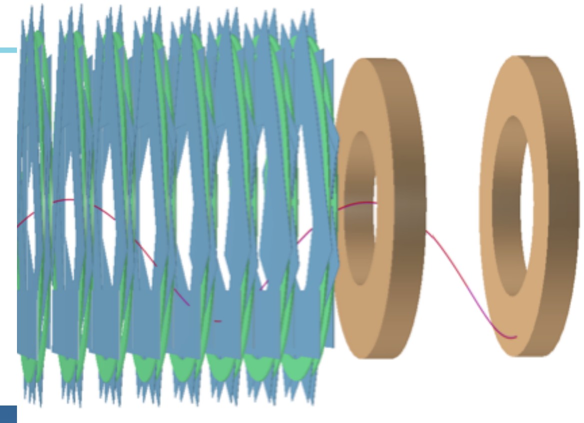


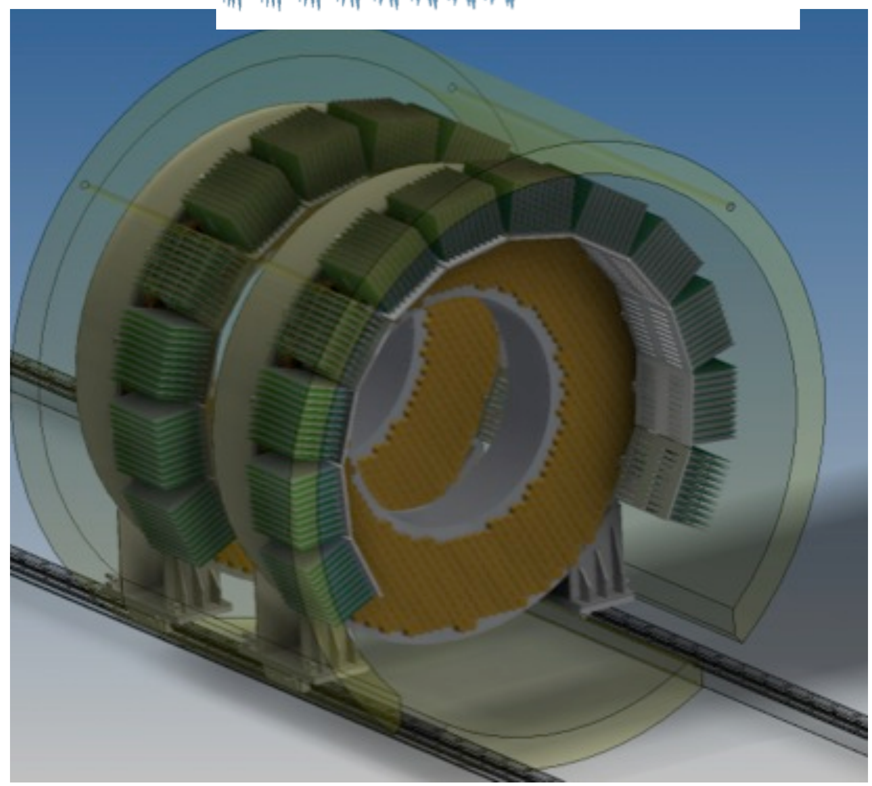
These constraints translate to calorimeter specifications of:
98% acceptance for CE tracks, O(5%) energy resolution
O(1 cm) position resolution and a time resolution < 0.5 ns.

Calorimeter Layout

The Calorimeter consists of two disks with 1650 BaF_2 hexagonal crystals:

- → R_{inner} = 351 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
- → The distance between disks is optimized at ½ wavelength (70 cm)
- → Each crystal is readout by two large area APD's (9x9 mm^2) (3300 total)
- → Analog FEE and digitial electronics are located in near-by electronics crates
- → Radioactive source and laser systems provide absolute calibration as well as fast and reliable monitoring capability





475.07.02: crystals

Barium Fluoride (BaF_2)

- Radiation hard, non-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
- Crystal dimension: hexagonal faces of 33 mm across flats, 200 mm length (10 X_0)

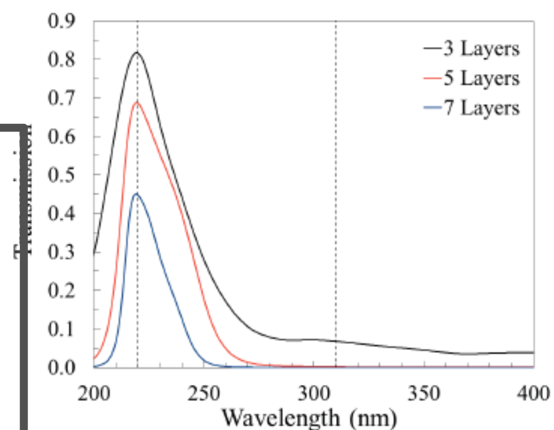
	BaF_2
Density (g/cm^3)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.29)% / °C

Breakout talk: R.Y.Zhu

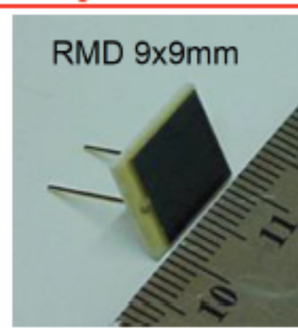
475.07.04: photo-sensors

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

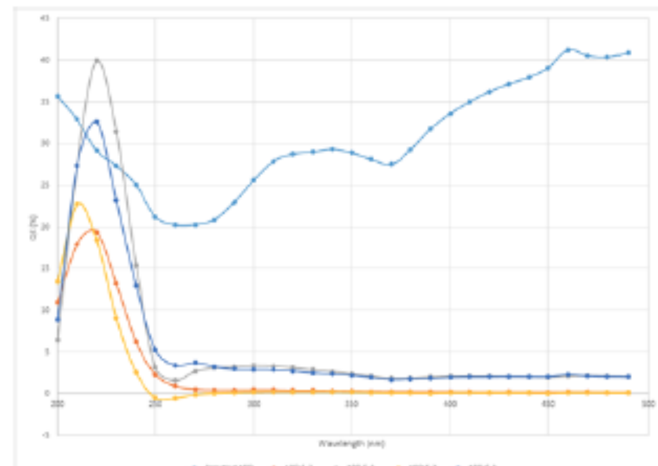
- ✓ 60% QE @ 220 nm
- ✓ ~ 0.1 % QE @ 300 nm
- ✓ capacitance ~ 60 pF (1/5 of Ham S8664)
- ✓ HV ~ 1800 V
- ✓ Operation Gain ~ 500
- ✓ Decay time ~ 25 ns.



deltadoped APD from RMD

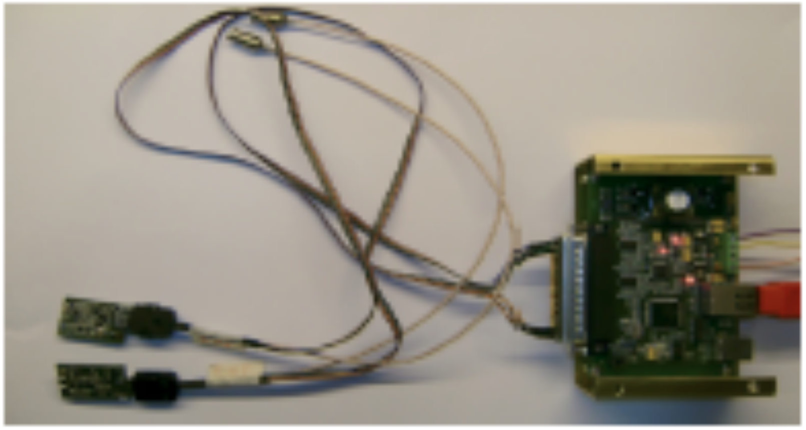


Tests on few prototypes with ALD applied proved that "solar" blindness works

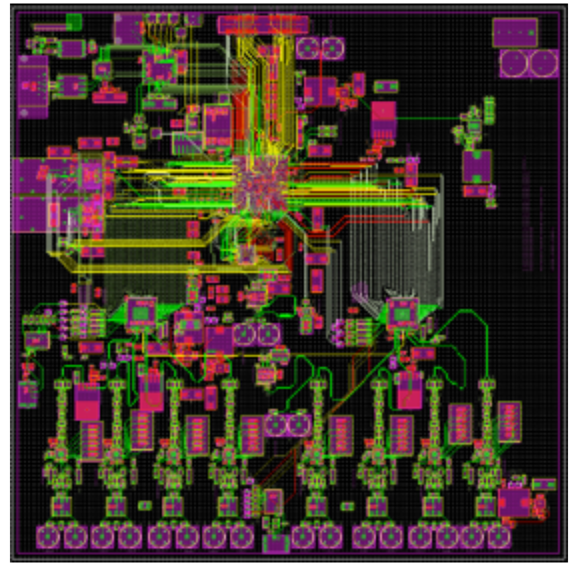


Breakout talk:
D.Hitlin

Calorimeter FEE & Readout



- FEE is a discrete chips connected to the photo-sensor: V preamp & Local V-bias regulator.
- 16 FEE channels driven by an ARM-controller to generate/distribute Vbias, Low Voltages
- 50 FEE channels and 5 ARM controllers produced by INFN- Frascati for test beam array.
- **New development in progress to adapt this FEE to the BaF_2 crystals.**

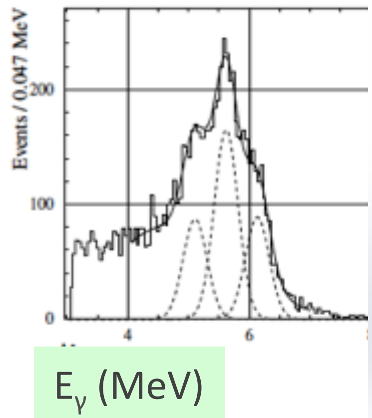


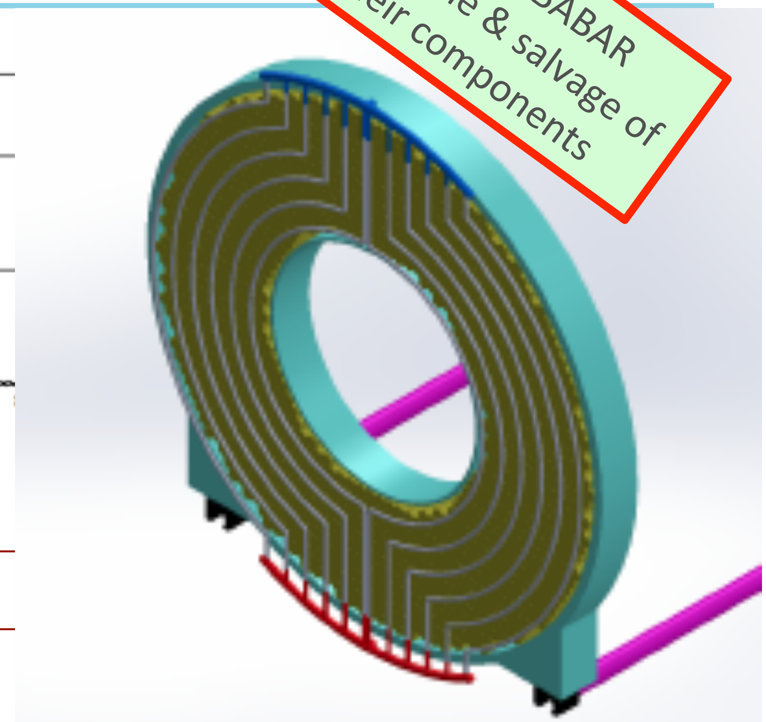
- Digitizer board with 32 channels 12 bit resolution, 200 msps, Smart Fusion-2 FPGA.
- 5 prototypes 8 channels under construction at University of Illinois
- **Design of final digitizer under way as a joint project between INFN Pisa and University of Illinois.**

Breakout talks:
G.Corradi/G.Pezzullo

475.07.06 Calibration system

- Neutrons from a Deuterium-Tritium (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 few minutes. Linearity.
- Final experiment scale (E/P) is set using DIO's.





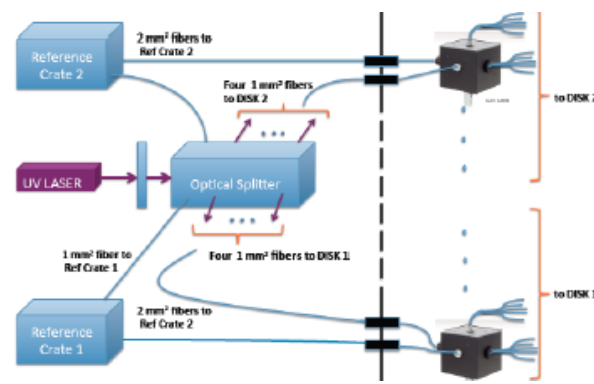
Based on BABAR scheme & salvage of their components

neutron generator: $d + t \rightarrow n(14.2\ \text{MeV}) + {}^4\text{He}$

$$
\begin{aligned}
{}^{19}F + n \rightarrow\ & {}^{16}N + \alpha \\
{}^{16}N \rightarrow\ & {}^{16}O^* + \beta \quad t_{1/2} = 7\ \text{s} \\
& {}^{16}O^* \rightarrow {}^{16}O + \gamma(6.13\ \text{MeV})
\end{aligned}
$$

Laser system adapted from CMS calibration system.

UV light to monitor continuously the variation of the photosensor gain (in-kind INFN)



Breakout talk: F.Porter

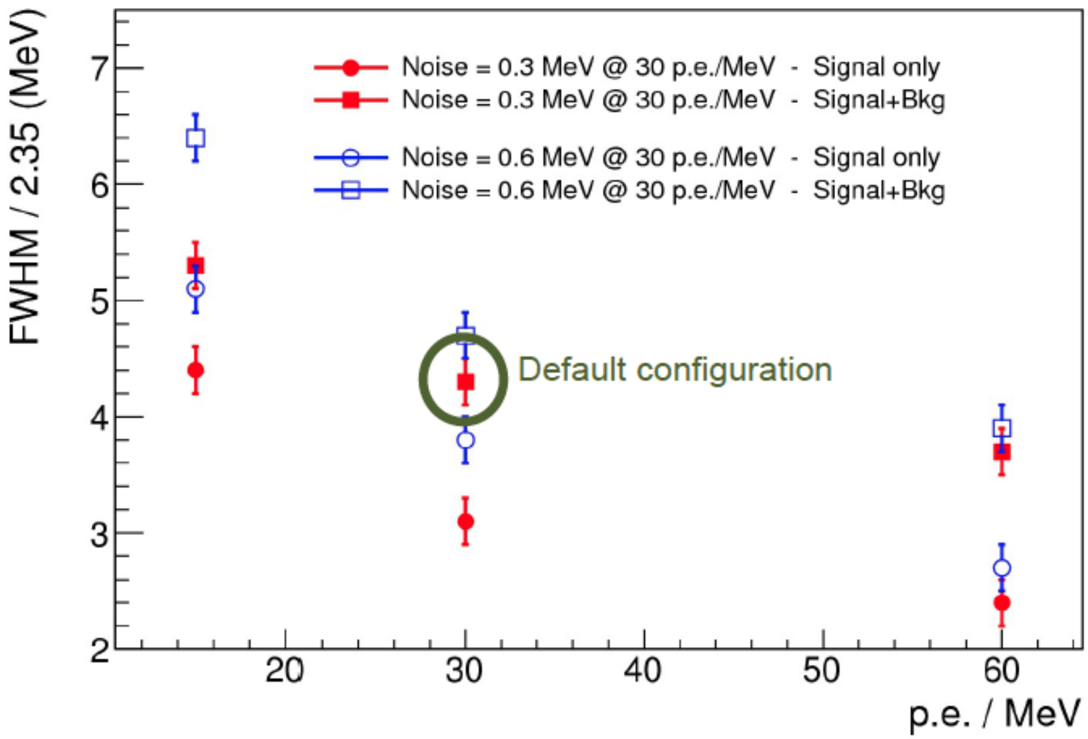
Improvements since CD-1

Two significant improvements happened since CD-1:

- **Geometry has been modified from Vanes to Disks**
  - → (+) Larger acceptance
  - → (+) Identical response and acceptance for electrons and positrons
  - → (+) Easier mechanics
  - → (-) More background on the crystals
  - → (+) Better shielding for photo-sensors

- **Baseline crystal has been changed from LYSO to BaF_2**
  - → (+) BaF_2 Is less expensive than LYSO (its cost increases x 2.5 since CD-1) but it still matches requirements.
  - → (+) The BaF_2 is faster, it could be used for Mu2e-II sustaining a x10 increase in the rate.

Performance: Energy resolution



Breakout talk: B.Echenard

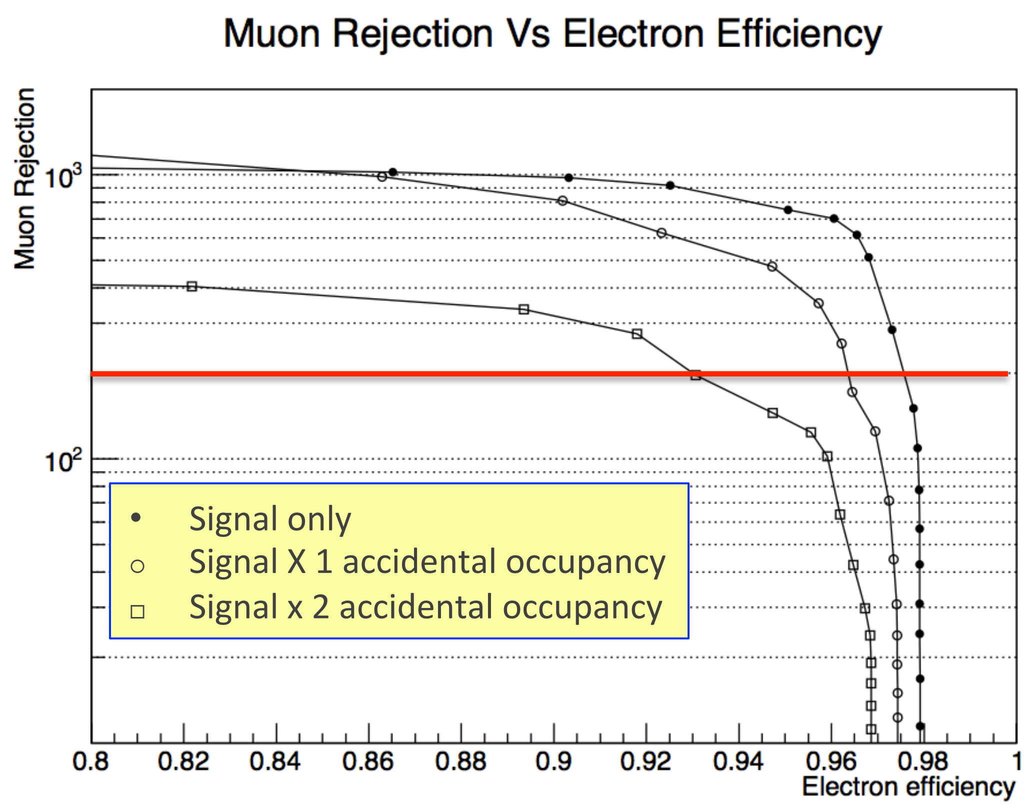
- ❑ L.Y.=30 pe/MeV from crystal measurement with PMT scaled by APD area and Q.E (1.3%)
- ❑ Electronics noise of 300 keV by scaling down measurement for LYSO and RMD/Hamamatsu APD properties → adds another relevant term to the resolution (1.3%).
- ❑ 2% leakage and albedo
- ❑ Pileup contributes additional 3 % to the total resolution.

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**

Quality Assurance

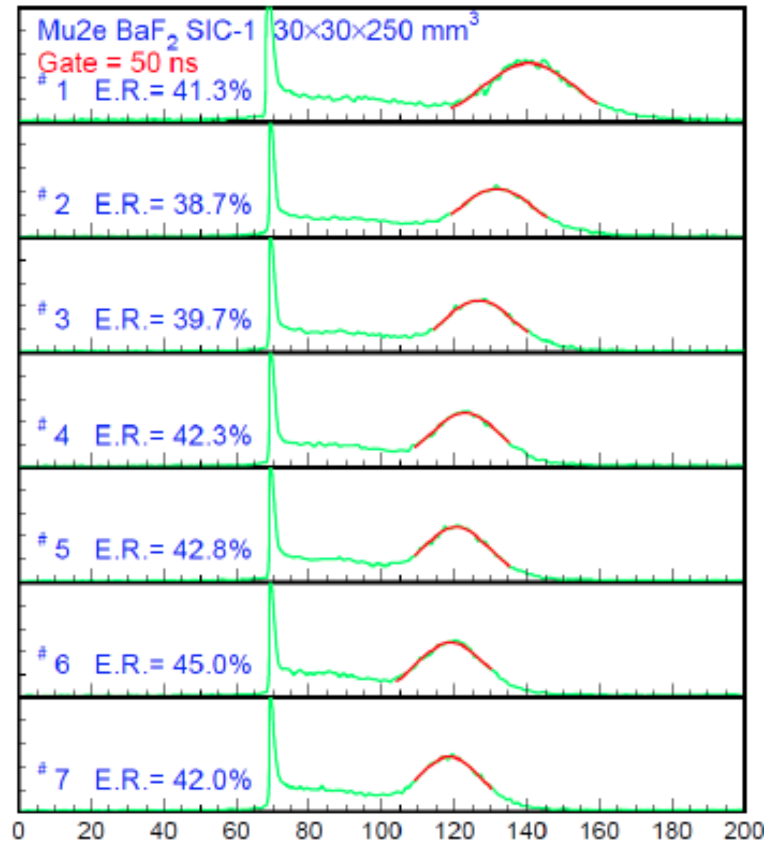
❑ QA stations for crystals and photo-sensors exist in INFN and Caltech. Crystal stations are being modified to adapt to the BaF_2 deep UV emission. **Feedback with vendor ensure meeting specifications.**

→ 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



Integration and Interfaces

- The Calorimeter has external interfaces to the Muon Beamline, Conventional Construction, DAQ and the tracking system.
- Internal interfaces between mechanics and crystals, FEE and calibration systems …
- Internal and external interfaces identified and described in Calorimeter Interface document, available on Review site (docdb # 2195).
- Participation in bi-weekly integration meetings.
- Formal sign-off between owners of all external interfaces as part of final design requirements.

Interfaces understood and under control.

Risks

- 3 Calorimeter risks in risk registry
  - All risks mitigated to the extent possible
  - 3 threats
    - 2 high
    - 1 low
    - 0 retired risks
- Detailed mitigation plans for all risks, documented in risk forms on docdb and linked from Risk Register (docdb 4320)
- **All risks understood and under control.**
- Details in breakout session.

ES&H

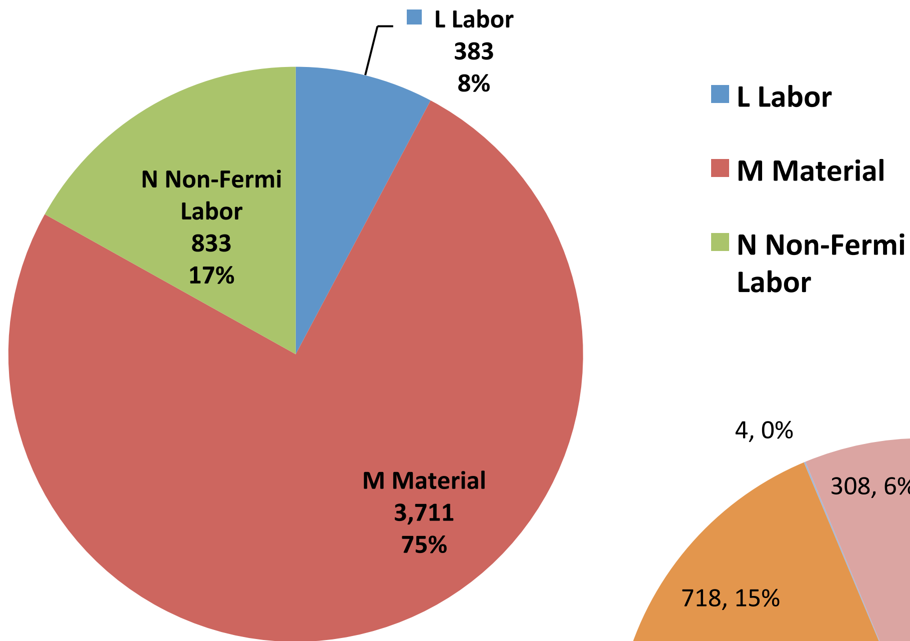
- Calorimeter has standard detector related issues that are common at Fermilab
  - Electrical hazards from both High and Low voltage.
  - Mechanical hazards (calorimeter is heavy)
  - Toxic materials
    - Epoxy may be used to assemble calorimeter (attach APDs).
  - **Activated Fluorinert with a neutron generator used as Source system.**
    - Operation of the source in a remote control in a no access condition
    - Shielding and interlock the neutron generator
    - Compute the maximum exposure in case of a fluid leak
    - **Used in BaBar @ SLAC.**
  - **Lasers used as part of a flasher system.**
    - Laser will be enclosed.
- These hazards are discussed in the Mu2 Hazard Analysis document (Mu2e-doc-675).

Calorimeter DOE Cost Table

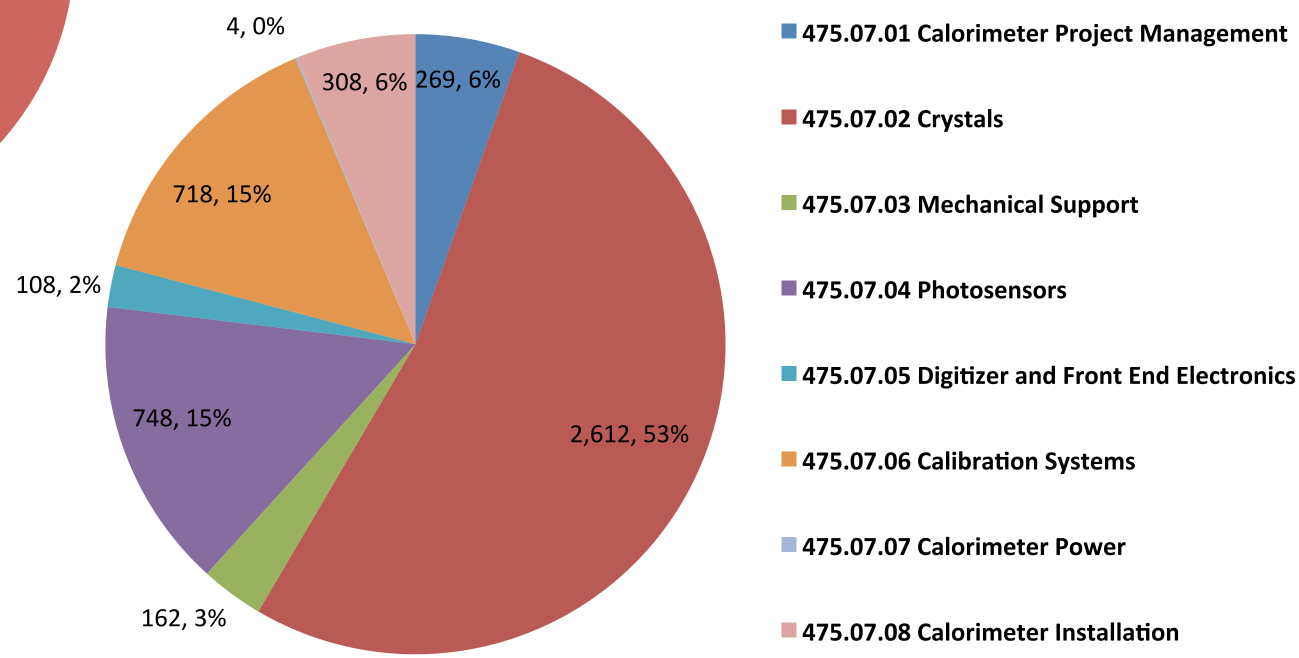
	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency on (on remaining budget)	Total Cost
475.07 Calorimeter						
475.07.01 Calorimeter Project Management	262	7	269	31	21%	300
475.07.02 Crystals	2.557	54	2.612	433	17%	3.045
475.07.03 Mechanical Support	162		162	32	20%	195
475.07.04 Photosensors	748		748	302	47%	1.050
475.07.05 Digitizer and Front End Electronics	108		108		0%	108
475.07.06 Calibration Systems	660	58	718	206	37%	923
475.07.07 Calorimeter Power		4	4	1	30%	5
475.07.08 Calorimeter Installation	47	260	308	108	35%	416
475.07.99 Risk Based Contingency				51	-	51
Grand Total	4.544	383	4.928	1.164	26%	6.092

It assumes INFN pays 1/3 of Crystals, ½ of Photosensors and provide
In-kind the Laser system, the mechanics, and all FEE/Digitizer electronics

DOE Calorimeter Cost Breakdown



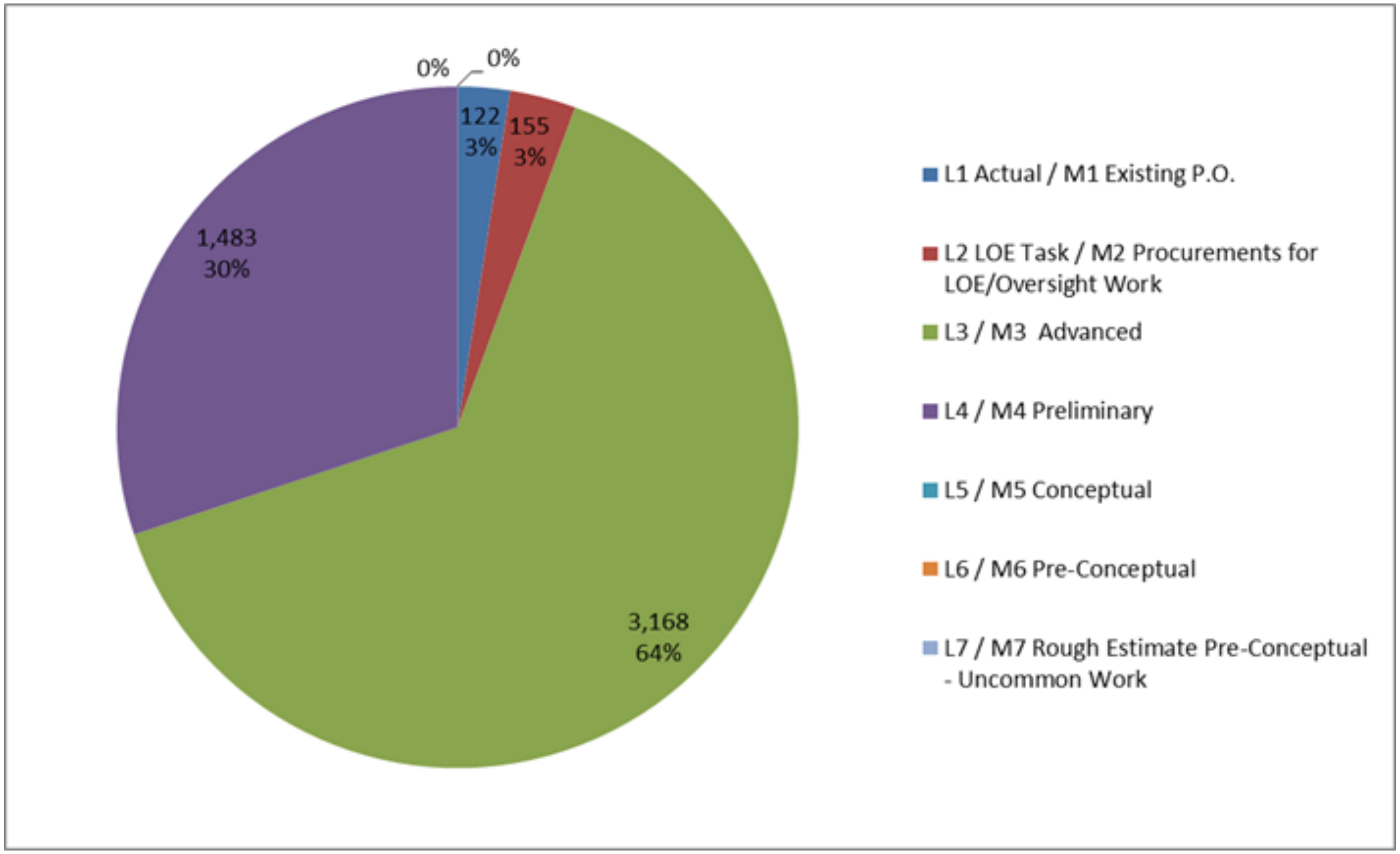
BASE COST in AY$K



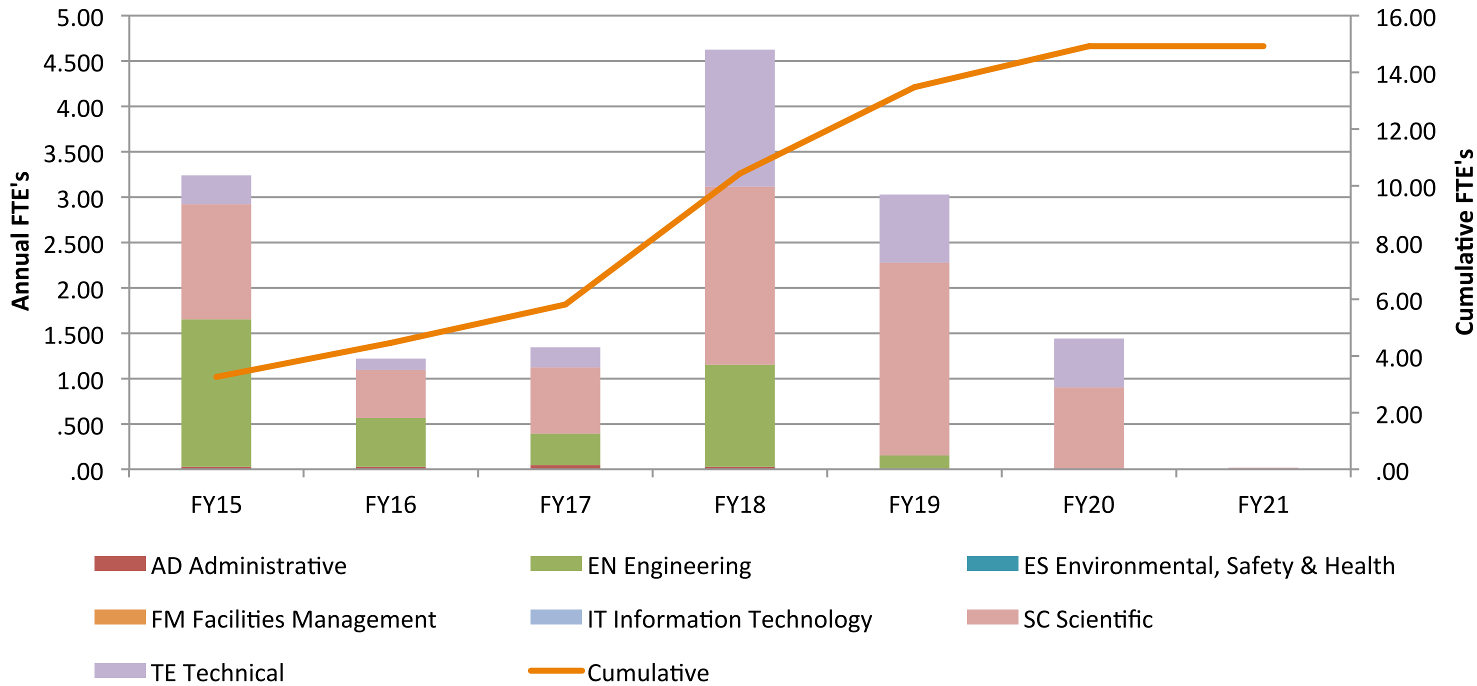
Quality of Estimate

Sum of Value	
Estimate Type	Total
L1 Actual / M1 Existing P.O.	122
L2 LOE Task	155
L3 / M3 Advanced	3.168
L4 / M4 Preliminary	1.483

100% of estimate
are at, or better than,
the preliminary level



DOE Labor Resources by FY

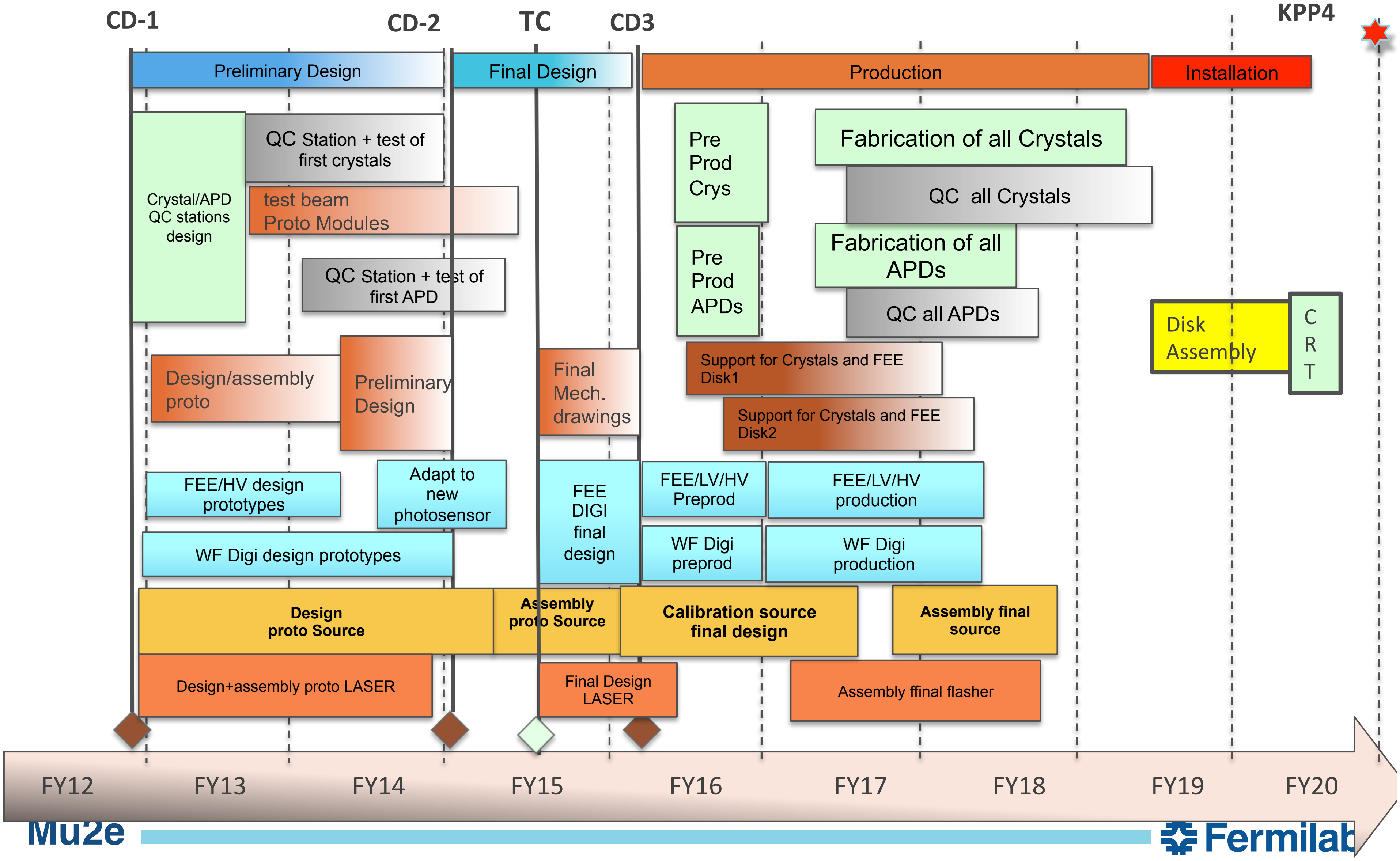


- Labor peaks in 2015 to get final design and pre-production ready
- Second labor peak in 2018 due to QC and assembly

Major Calorimeter Milestones

1. 47507.2.001783 **Technology choice for crystals/photosensors** 4 May 2015
2. 47507.5.001401 **INFN delivers final FEE design** 22 Oct. 2015
3. 47507.2.001980 **DOE Reviews production crystal contract** 9 Jun. 2016
4. 47507.2.011986 **PO issued for production crystals** 3 Jan. 2017
5. 47507.4.000700 **PO issued for production photo-sensors** 29 Mar. 2017
6. 47507.6.001510 **PO issued for source system material** 4 Aug. 2017
7. 47507.4.000790 **QC of all photo-sensors complete** 10 Aug. 2018
8. 47507.5.001522 **INFN delivers FEE electronics** 23 May 2018
9. 47507.2.092161 **Survey of production crystals complete** 13 Mar 2019
10. 47507.8.002410 **Ready for cosmic ray system test** 28 May 2020

Calorimeter schedule



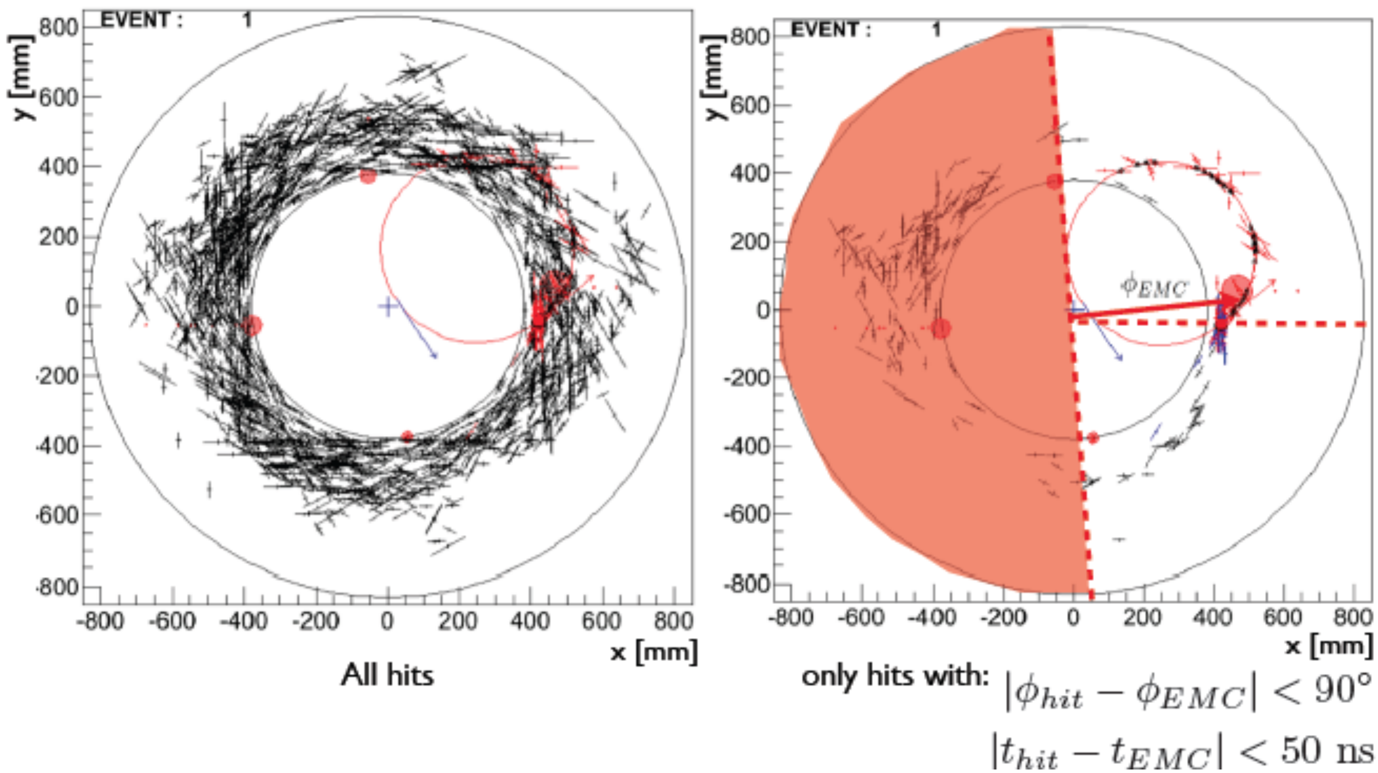
Summary

- The Calorimeter has a Baseline design (BaF_2 crystals in disk geometry readout with "solar-blind" APDs) that fully satisfies requirements.
- The Calorimeter cost estimates are completed:
  - → 100 % of the cost understood at a preliminary design level or higher;
  - → Risks are understood, mitigated to the extent possible and are under control;
- Interfaces are identified and defined;
- Resource needs understood. Responsibility are divided between US and Italian groups: discussions on INFN funding are well advanced.
- ES&H embedded into all aspects of the Project;
- Responded to all recommendations from previous reviews.

Calorimeter is ready for CD-2.

Additional Material

Requirements.2 – assisting the tracker



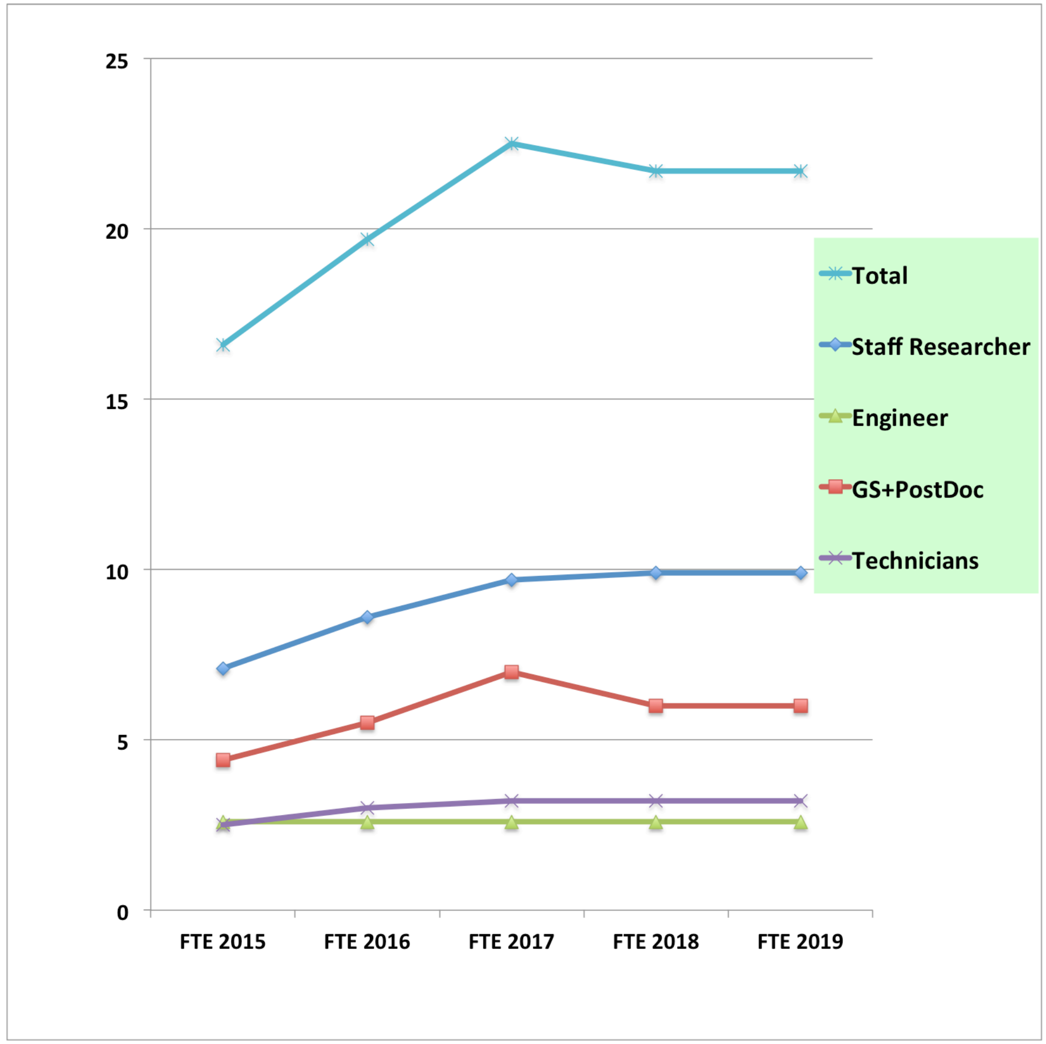
- ✓ **Pattern recognition of tracks improves when requiring "Straw" hits in time** (50 ns window) and space connected with the most energetic cluster.
- ✓ **Calorimeter assisted tracking increases of +12% the overall signal** reconstruction efficiency and provides stability as a function of background rate.

INFN Calorimeter proposed Scope

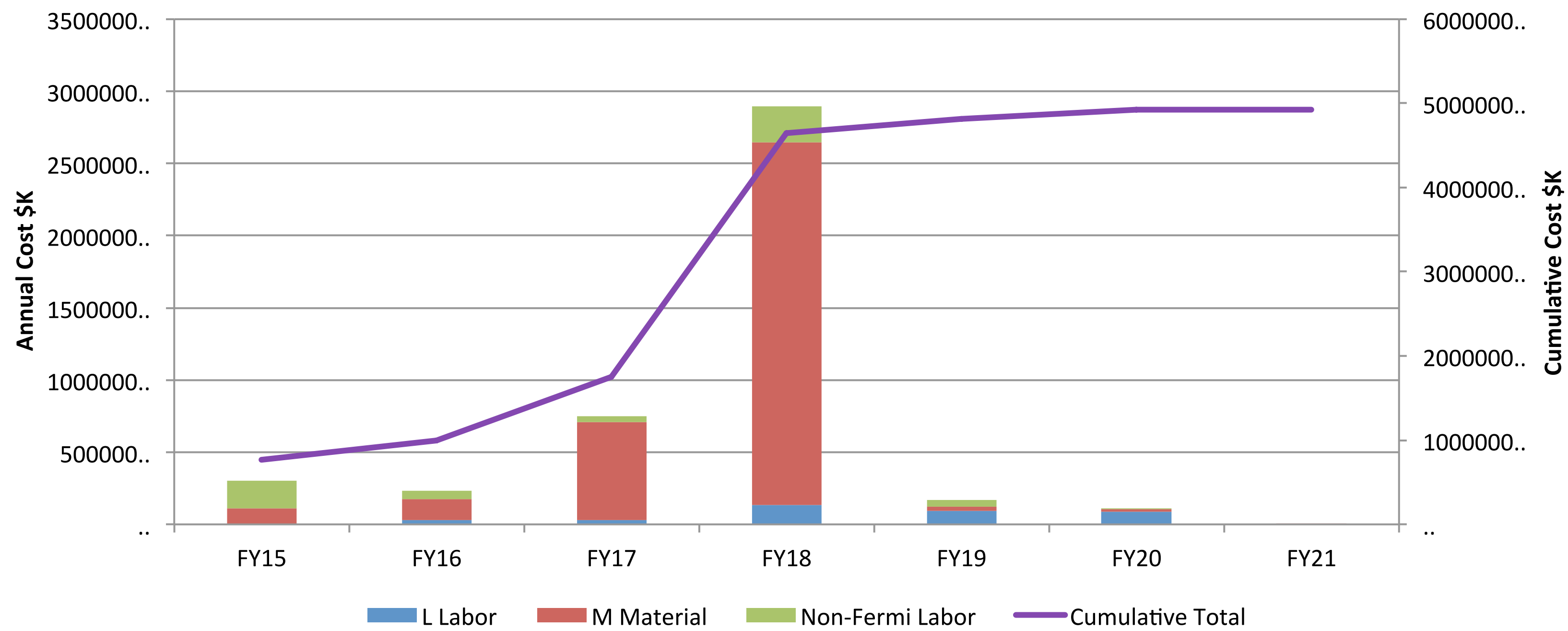
- The INFN Mu2e group submitted to INFN CSN1 (National Scientific Committee 1: HEP experiments at particle accelerators) a proposal which envisages the commitment of the group to take responsibility for the following four items of the calorimeter project:
  1) Design, procurement and assembly of the mechanical support
  2) Design, procurement and assembly of the FEE
  3) Design, procurement and assembly of the waveform digitizer
  4) Design, procurement and assembly of the laser calibration system
- In addition, the group also proposed to contribute on the core investment with a share of 50% of the photosensors and 1/3 of the crystals.
- **CSN1 expressed support to the first four commitments listed above**
- A decision on the investment level for crystals and photosensors is deferred, pending the outcome of the Technology Choice Review (TCR) for the calorimeter, currently scheduled for May 2015
- The INFN financial commitment will be scrutinized by the INFN Technical-Scientific Committee (CTS) , whose review of the proposal should start on June 2015, after the Mu2e TCR, with an expected decision taken by October/November 2015 (in time for CD-3)

INFN expected Labor resources by year

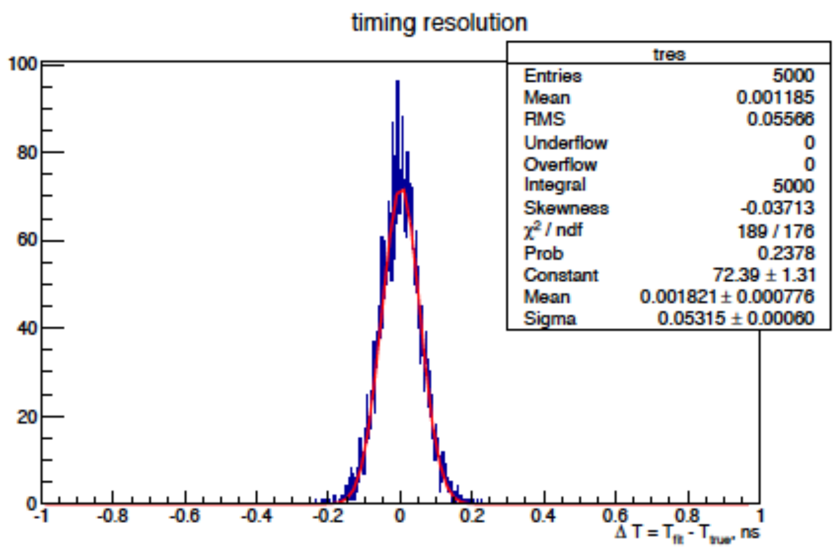
- INFN Mu2e group plans to contribute on labor for all the INFN supported items.
- The group plans also to constribute to the installation.
- The expected profile of INFN FTE vs year is shown in the attached figure.
- Note: INFN FY starts on January 1st

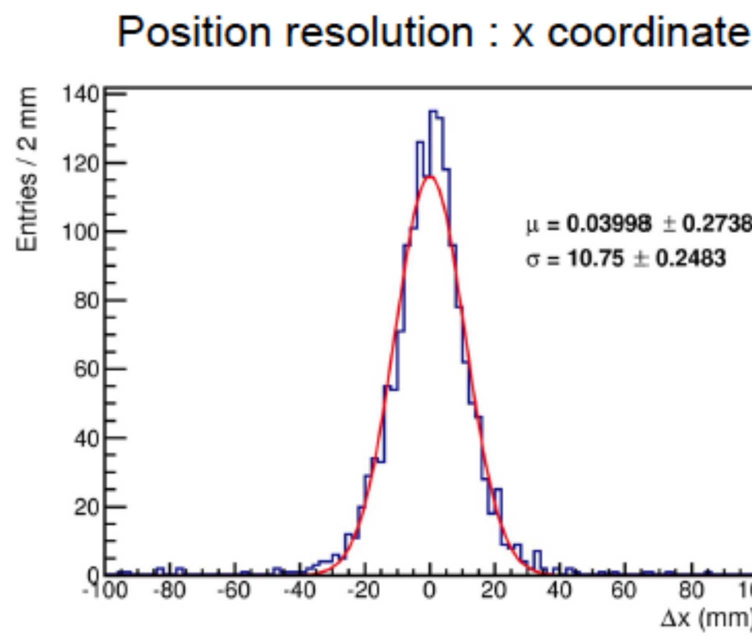


Labor/Material spending profile



BaF_2 Performance: Timing & space resolution

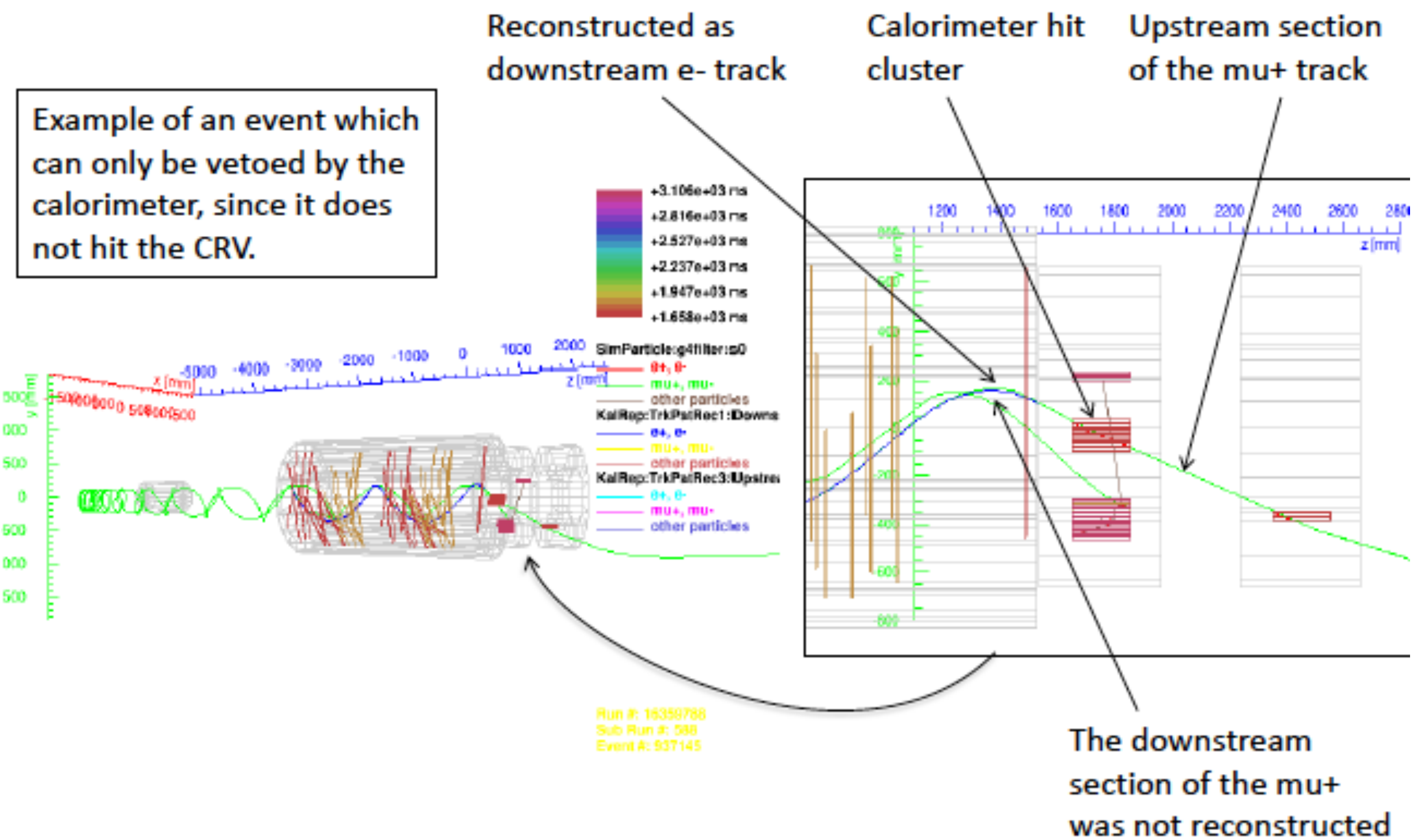




- ✓ Electronic noise contribution to T-Res estimated by simulating & fitting the signal shape with noise → **50 ps.**
- ✓ Contribution of pulse shape stability and trigger jitter expected to be small.
- ✓ Shower time fluctuation < L/v_light (1 ns/sqrt(12)) **should be < 280 ps.**

Calorimeter Cluster centroid (log weighted) at shower max.

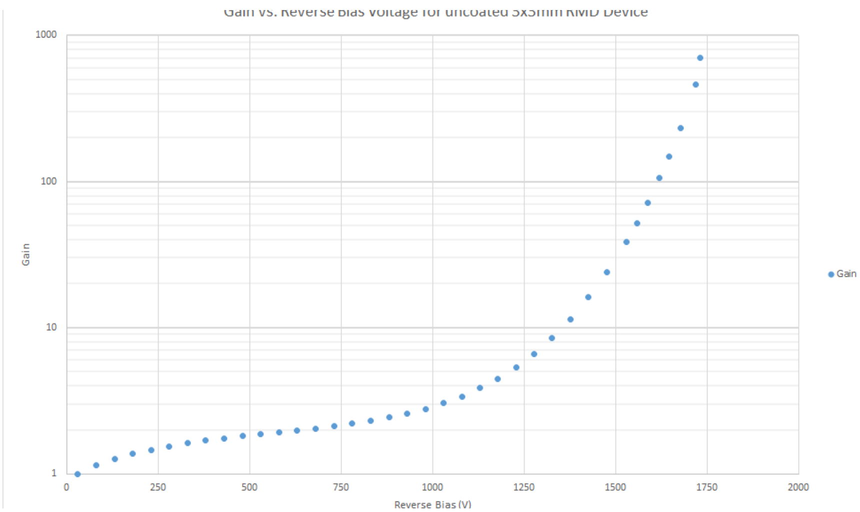
Requirements – PID

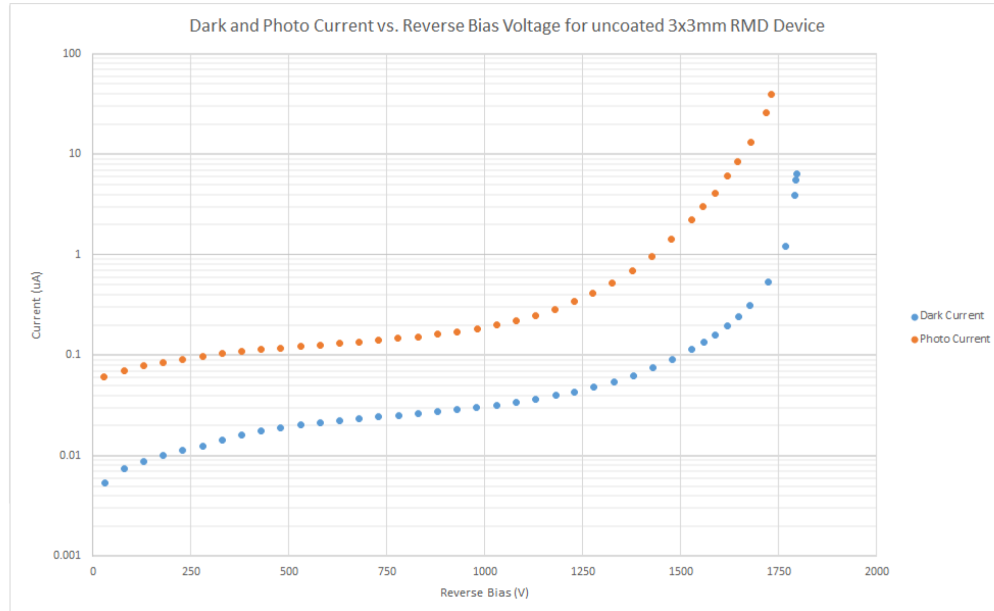


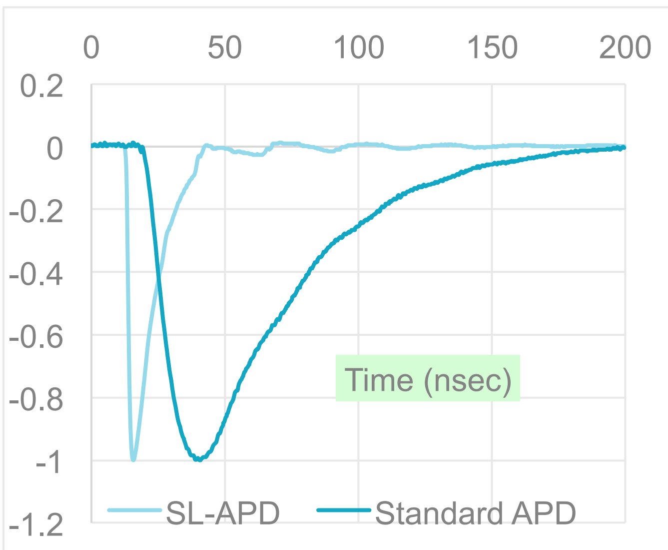
-- Simulation of CR events faking electrons carried out by the CRV group → 9 events Not Vetoed : (6 mu-, downstream) (3 mu+,upstream)

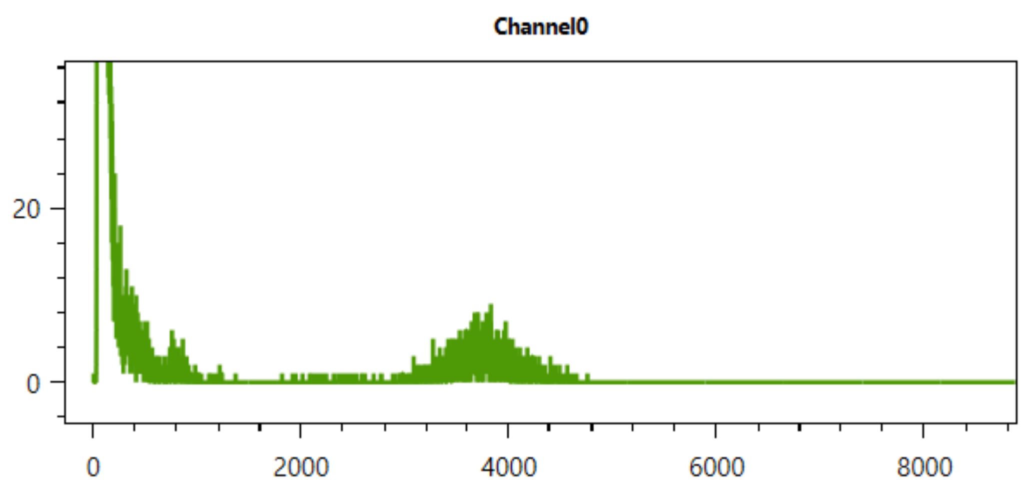
-- Applying the CutC selection → they correspond to 1.1 events

APD RMD/JPL Caltech status: 1 (3x3 mm^2)









Remaining work before CD-3

- BaF_2 crystals perform as expected (light yield with PMT ~ 100-160 pe/MeV), however RMD/JPL APD RMD to be produced to show matching their design specifications. First prototypes (3x3 mm^2) give positive indications.

  → Modification of FEE to adapt to RMD/JPL APD under way.
  To be completed for beginning 2015.

- **Internal Technology Choice review** to be held middle 2015 to test baseline option and compare with backup solution (pure CsI and MPPC).

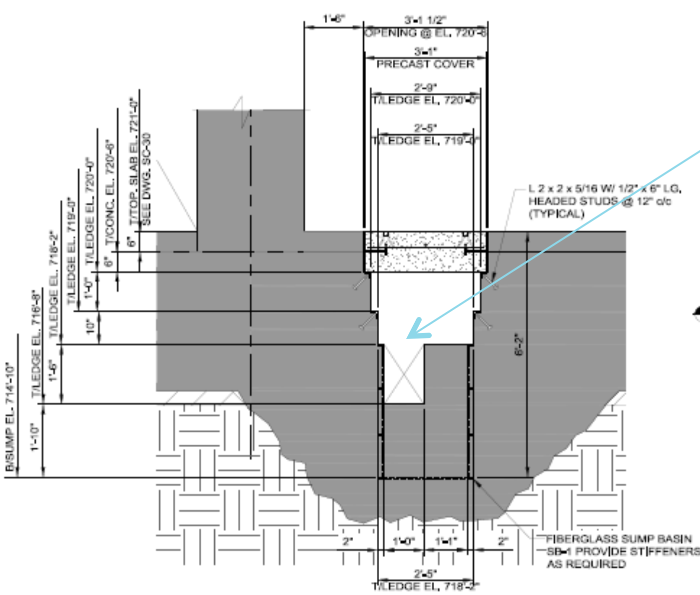
- Mockup of smaller size Disk to test mechanics and mounting scheme.

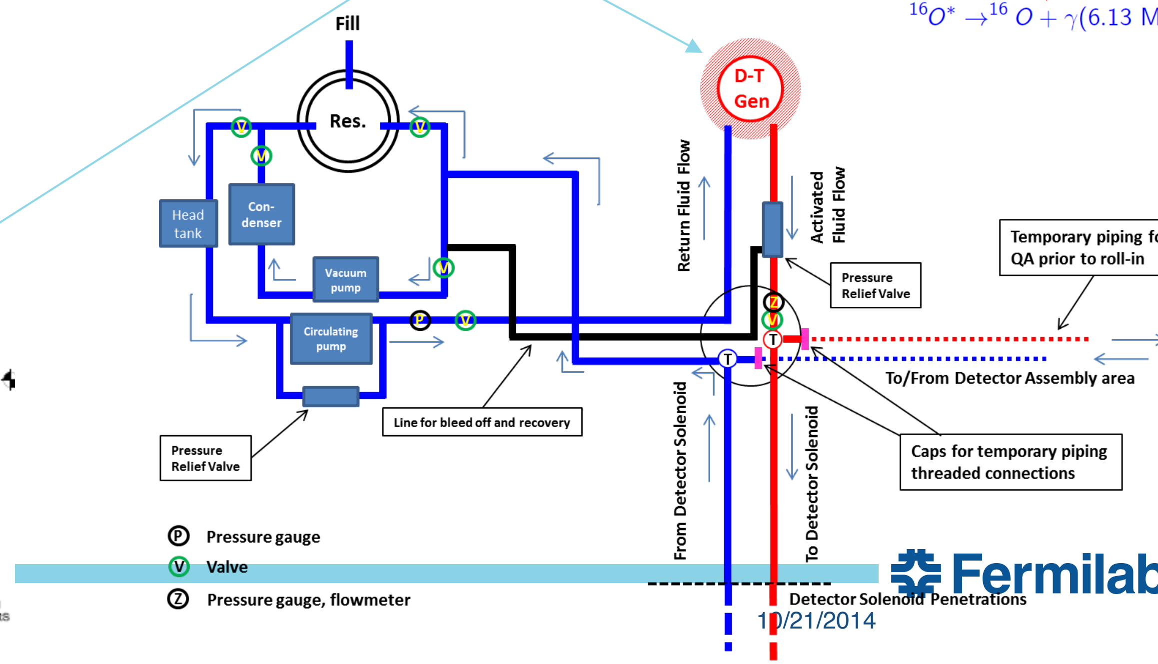
- Adapt QA stations/Laser to final crystal and photo-sensors

Mu2e Ecal Source Calibration

- Ecal absolute energy calibration with a source of known-energy, known-path photons allows monitoring for changes in crystal gain and measurements of noise in energy units, along with an initial set of calorimeter gain settings prior to first beam
- Mu2e Ecal source calibration system is based on a similar system salvaged from SLAC/BaBar
- Salvage items were delivered to Caltech about two weeks ago for refurbishment and development into the system to be deployed at FNAL
- Support for the source calib system has recently been integrated into the detector hall design and work begun to integrate with Ecal mechanics

$$^{19}F + n \rightarrow \; ^{16}N \; + \alpha$$
$$^{16}N \; \rightarrow \; ^{16}O^{*} + \beta \quad t_{1/2} = 7\text{ s}$$
$$^{16}O^{*} \rightarrow ^{16} O + \gamma(6.13\text{ MeV})$$





Risks

- CAL-108, **INFN cannot deliver full in-kind scope**
  → parallel path of approval being followed. Solid R&D contribution established.
  → 6th July 2014, CSN1 approved INFN participation in Mu2e, acknowledge strong physics case and relevant contribution to the Detector.

- CAL-148, **Cannot develop UV-extended solid state photodetectors that is blind to longer wavelengths**
  → Active R&D being followed → Blindness have been proven
  → work on backup solution followed by INFN (CsI+MPPC)

- CAL-170 , US/Russia relations could impact the purchase of the calibration system DT generator in FY2017/2018
  → It is reasonable to expect that normal commercial relation will be re-established on that time scale.
  → There is (a more expensive) US vendor.