Status of Mu2e experiment and INFN/LNF contributions

Stefano Miscetti
LNF, INFN, Italy
For the Mu2e INFN/LNF group

LNF Scientific Committee meeting,
Laboratori Nazionali di Frascati
9/May/2017

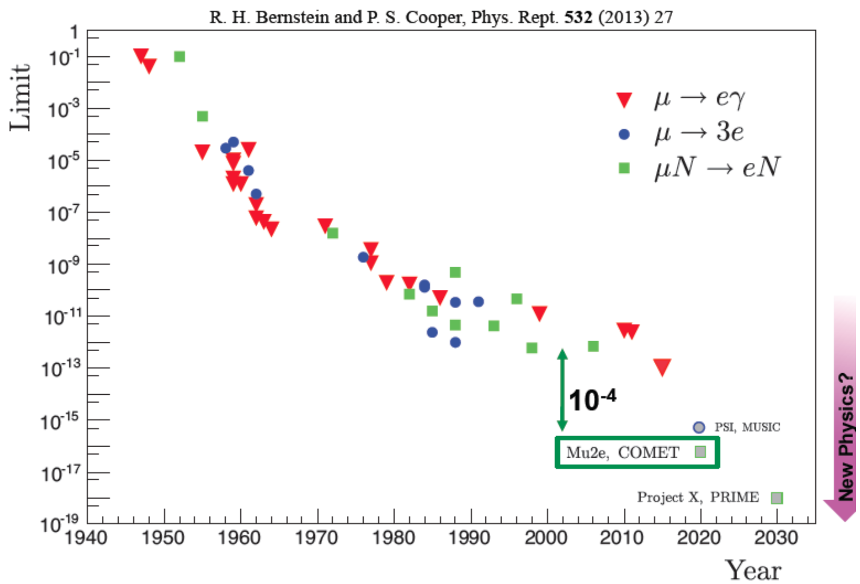
Mu2e

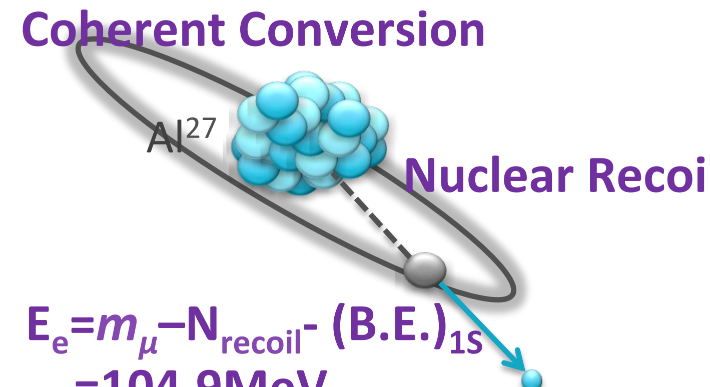
Layout of the talk

- Overview of Mu2e experiment
- Status of Mu2e and Mu2e Collaboration
- INFN group and INFN/LNF contributions
- Status of the Calorimeter system
- Pre-production: Crystals +SiPMs + FEE
- Status of Module-0
- Status of Full size Mockup
- Conclusions and plans

The Mu2e experiment: physics goal

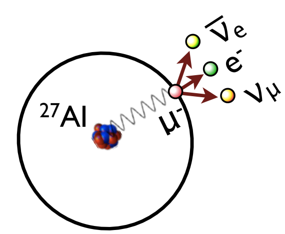
- Detect the CLFV process $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$ i.e. the coherent, neutrinoless **conversion of a muon to an electron** in the field of a nucleus.
- CLFV process. Negligible in the SM (10^{-52} assuming neutrino oscillations)
- **A clear CLFV signal is direct observation of new Physics**





$E_e = m_\mu - N_{recoil} - (B.E.)_{1S}$
$= 104.9\,MeV$

(BR=39%)



Mono energetic signal w.r.t. a fast falling spectrum from Decay In Orbit events (DIO)

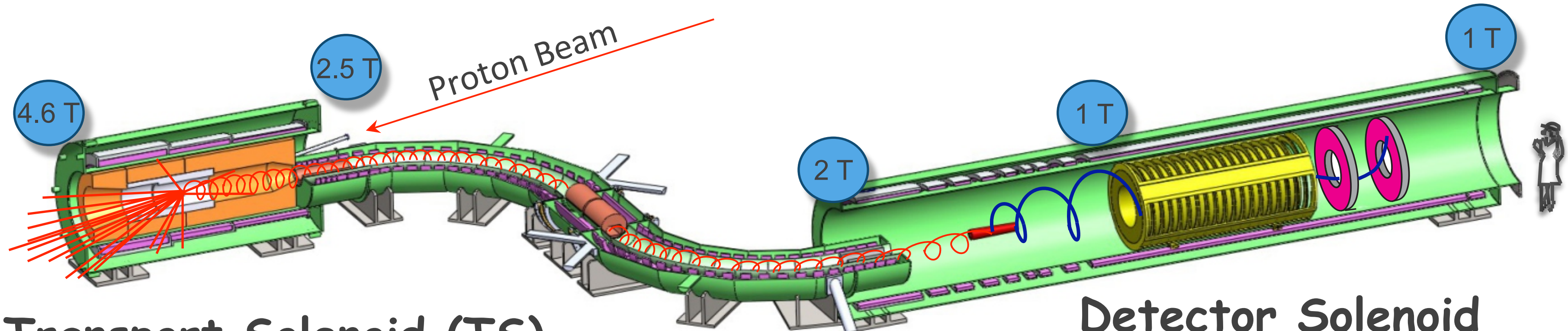
Mu2e goal: improve of 4 orders of magnitude the sensitivity w.r.t. previous Conversion experiment (Sindrum-II)

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

Mu2e: detector and full simulation for S/N

Production Target / Solenoid (PS)

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



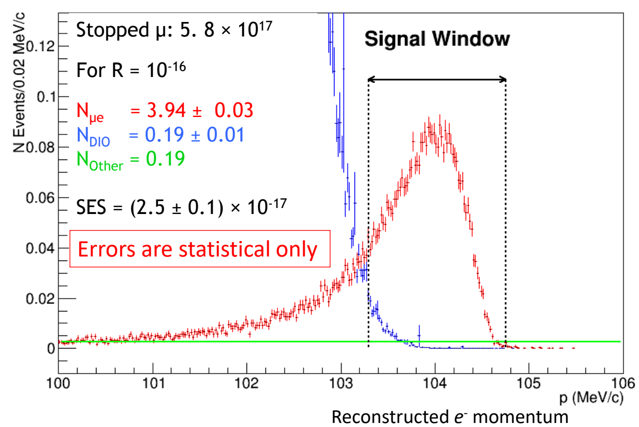
Transport Solenoid (TS)

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

Detector Solenoid

- Capture muons on Al target, Measure momentum in tracker and energy/time in calorimeter
- Cosmic Ray Veto detector surrounds the solenoid

For the sensitivity goal →
~ 6 x 10^{17} stopped muons
in 3 years run (6 x 10^{7} sec)
→ 10^{10} stopped muon/sec



@ Susy BR (10^{-15}) → expect 40 events with < 0.4 bkg
→ **Sensitivity to Mass scales up to thousands of TeV!!!**

Muon campus: Mu2e/g-2 → rendering 2013

Muon campus picture: Mu2e/g-2 → Feb-2017

The Mu2e Collaboration

~230 Scientists from 37 Institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, **Joint Institute of Nuclear Research Dubna,** Duke University, Fermi National Accelerator Laboratory, **Laboratori Nazionali di Frascati**, University of Houston**, Helmholtz-Zentrum Dresden-Rossendorf,** University of Illinois, **INFN Genova,** Lawrence Berkeley National Laboratory, **INFN Lecce, University Marconi Rome, Institute for High Energy Physics Protvino,** Kansas State University, Lewis University, **University of Liverpool, University College London,** University of Louisville, **University of Manchester,** University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, **INFN Pisa**, Purdue University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

Mu2e & INFN: group and contributions

Strong involvement of INFN group in two items:

(1) Calorimeter system: project leadership (S.Miscetti), design prototyping & construction, QA crystals/sensors, electronics and mechanics + Laser system.

(2) Construction of prototypes for the TS magnet and follow up for TS construction (ASG Superconducting) (INFN-Genova)

INFN group size

→ 35 people, 17 FTE

→ LNF composition (8 Researcher, 4 Engineers, 4 techs, 1 post doc, 2 PhD students) Total of 9 FTE.

INFN financial contribution so far:

- ❑ 500 kEuro for construction of TS proto
- ❑ 600 kEuro R&D calorimeter and I-tracker

Core contribution O(3 MEuro)

Mu2e: status of the experiment

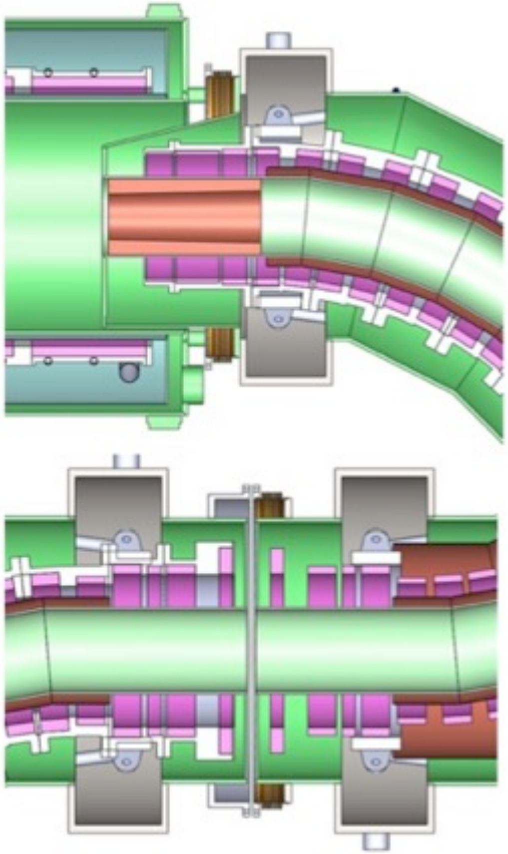
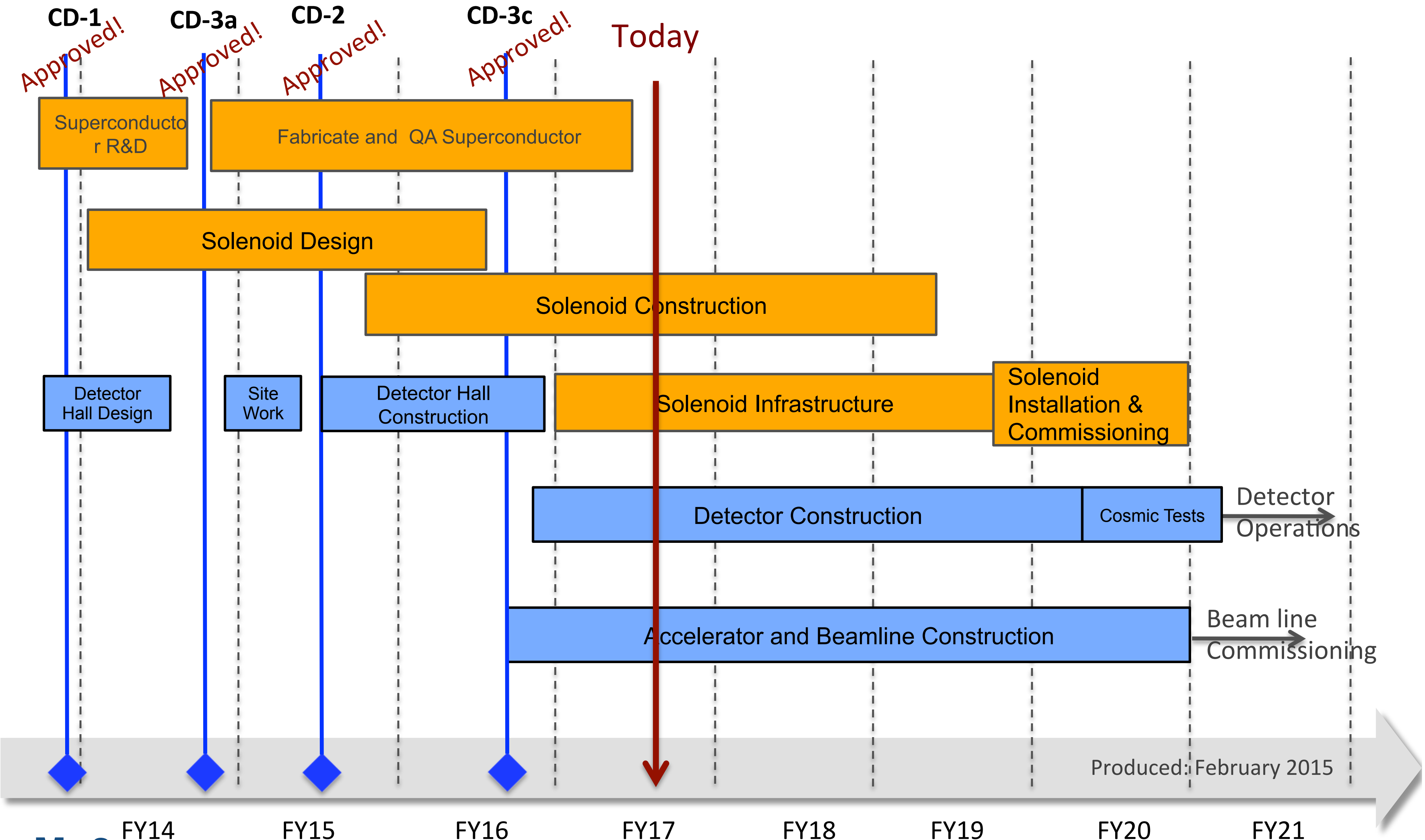


Figure 7.25. TSu Cryostat Interfaces. Top: TSu-PS interface; Bottom; TSu-TSd interface.

- Civil construction completed
- 70 km of Superconducting Coils procured
- Solenoid designs and bids finalized.
- DS/PS to GA (USA), TS to ASG Superconducting (Italy).
- TS fabrication has begun. PS, DS fabrication ready to start.

Mu2e Project Schedule



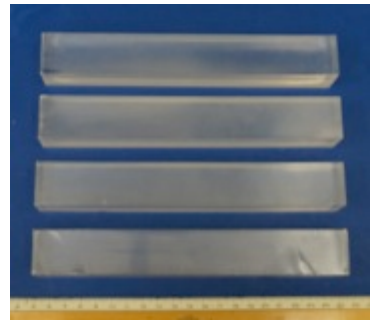
Calorimeter System → where are we now?

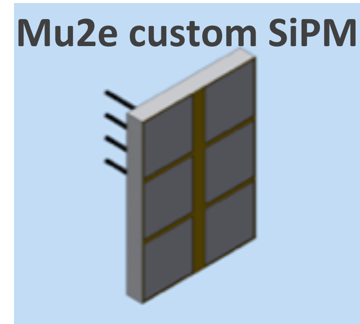
- Technology Choice Review → July 2015
  INFN favorite solution (CsI + MPPC) adopted Dec. 2016
- Design Review → Feb 2016
- Director review for CD3-C → April 2016
- CD3c → June 2016 → **CD3c approval , July 2016**
- **INFN/Fermilab signature of Statement of Work → Oct 2016**
- Final Design Report: December 2016
- **Mechanical review: March 2017**

✓ Pre-production started after CD3c
✓ Now proceeding with Module-0/Mockup
✓ Continuing Irradiation Program (FNG/Casaccia/HZDR)
✓ Upcoming reviews for Construction Readiness (CRR) under planning (2017/2018) → start of production

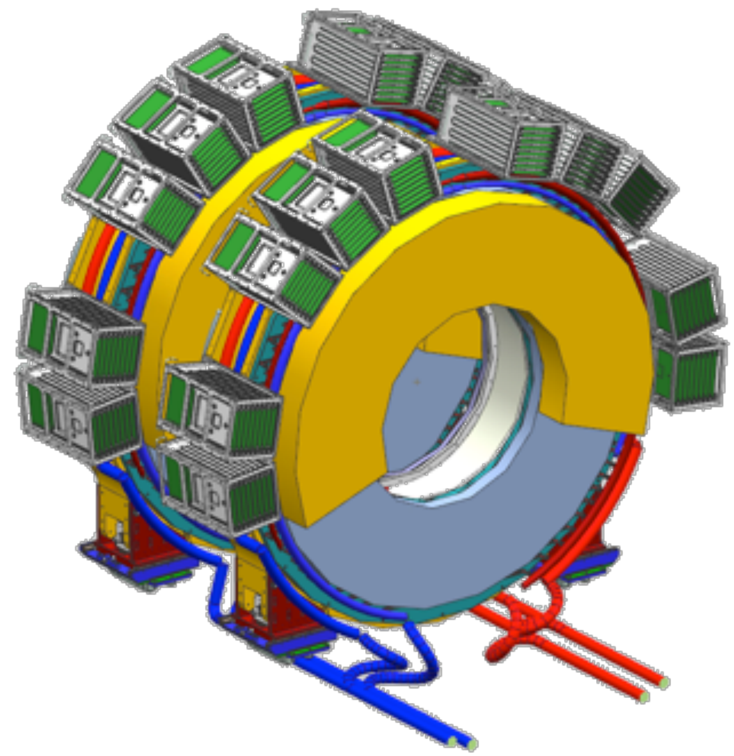
The Mu2e calorimeter Final Design

The Mu2e Calorimeter is a state of the art detector consisting of two disks with 674 34x34x200 mm^3 CsI square crystals:

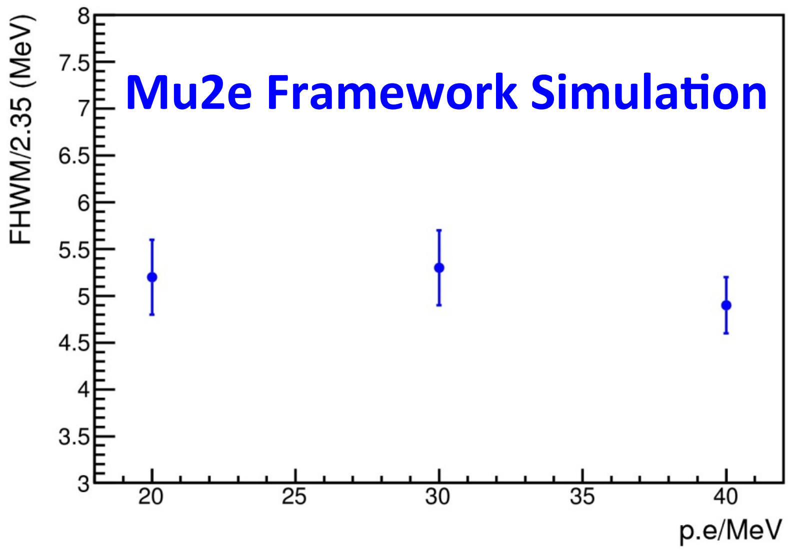




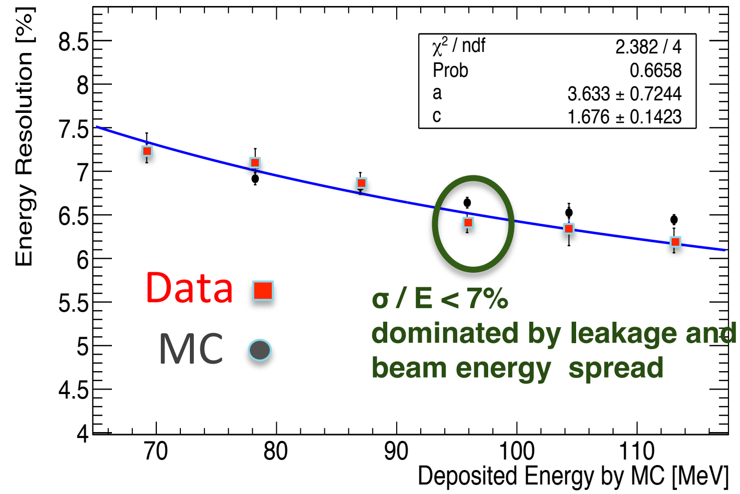
- → R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
- → Each crystal is readout by two large area UV extended SIPM's (14x20 mm^2)
- → Analog FEE is on the SiPM and digital electronics located in near-by electronics crates
- → Radioactive source and laser system provide absolute calibration and monitoring capability



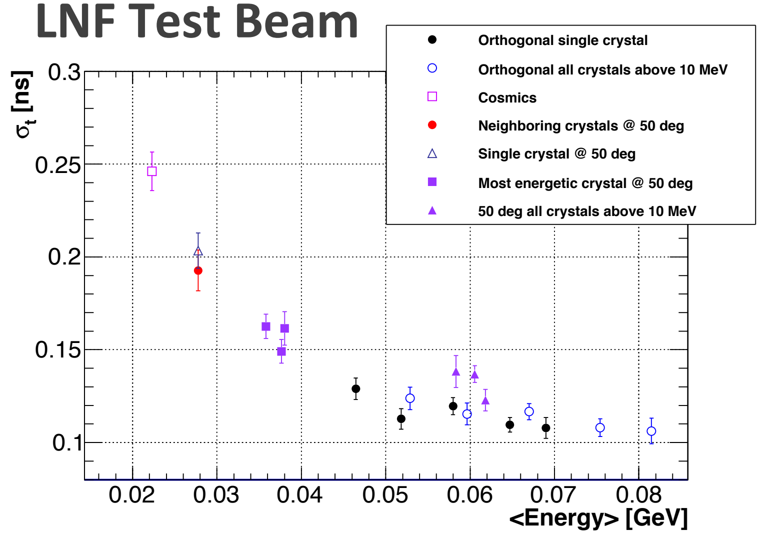
Design → meeting the requirements



LNF Test Beam



LNF Test Beam



- Simulation performed as a function of LY and many other variables → **CsI+SIPM match requirements.**
- Test beam with e⁻ @ BTF, LNF 80 to 130 MeV. 3x3 array of 30x30x200 mm³ CsI + MPPC used
- Good energy (7%) and timing (110 ps) resolution
  Exp tests → Matching EMC requirements

Pre-production of crystals & Mu2e SiPMs

The 2 largest bids (3 and 1 M$) are the ones for Crystals and photo-sensors

- Same technique of "competitive bid" used for both bids:

  → **Pre-production to rank the vendors. Final choice 40% cost, 60% technical**

For crystals, **the international bid has been prepared @ FNAL:**

- 6 vendors participated St.Gobain, Siccas, Amcrys, OptoMaterial, Hilger, Khineng.
  3 vendors selected for preproduction

  St. Gobain, Siccas, Amcrys
- We have received 24 pieces/each for module-0 (Oct-Dec 2016)

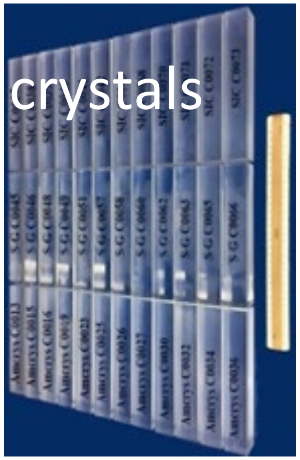
For the Mu2e SiPMs, the international bid has been prepared @ INFN:

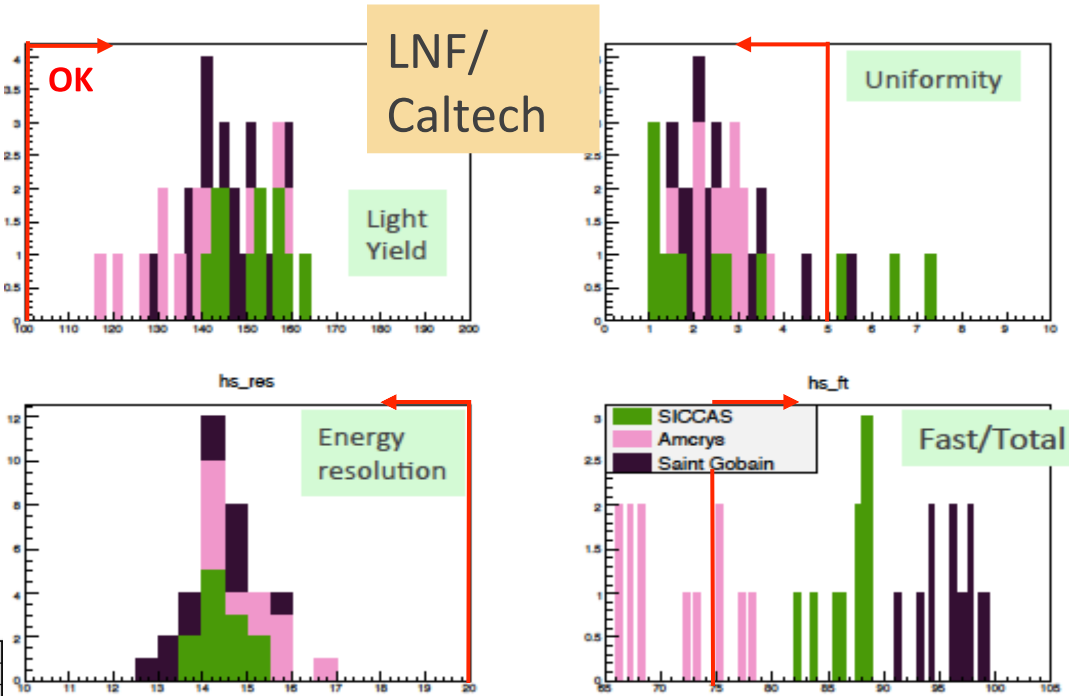
- 3 vendors participated, **3 vendors selected for preproduction**

  Hamamatsu, SensL, FBK. Each of them produced 50 prototypes
- Delivered on schedule in the middle of October

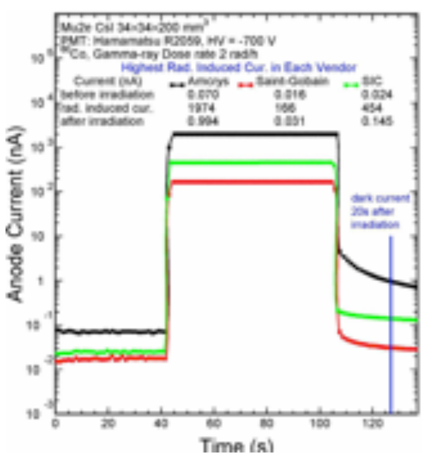
  → We have spent > 4 months for the QA evaluation (irradiation/MTTF)

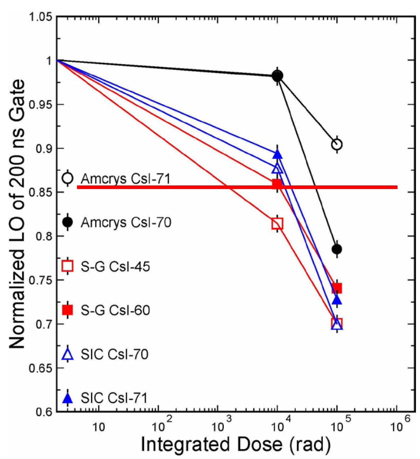
QA of undoped CsI crystals

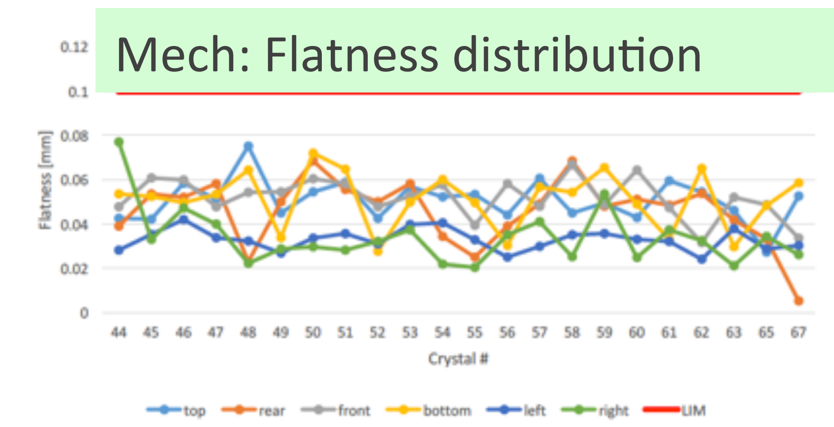




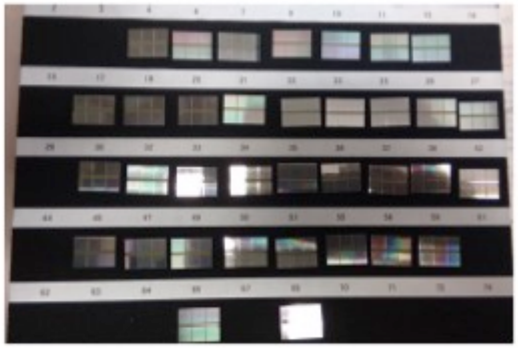
Radiation Induced Noise & Radiation Damage

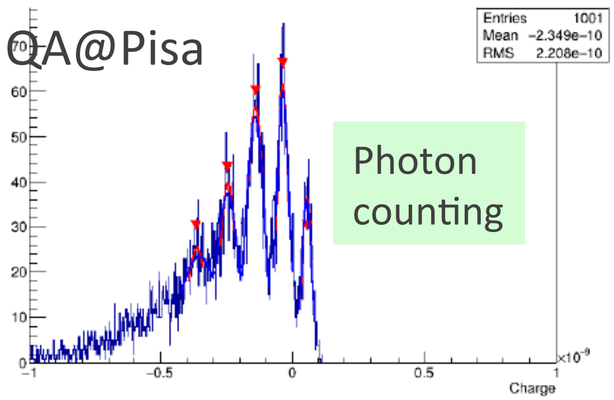


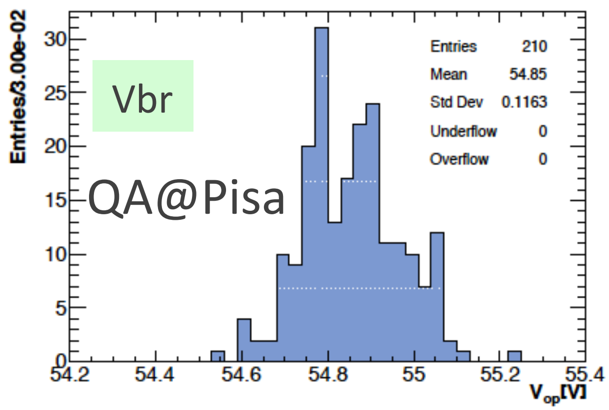


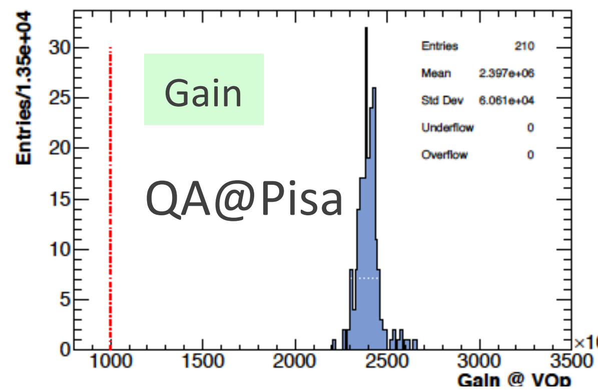


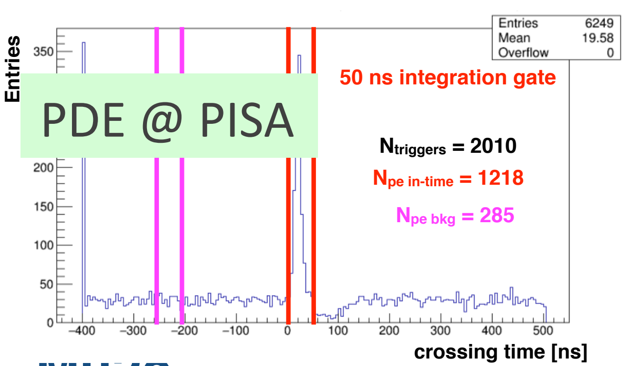
QA of Mu2e custom SiPMs

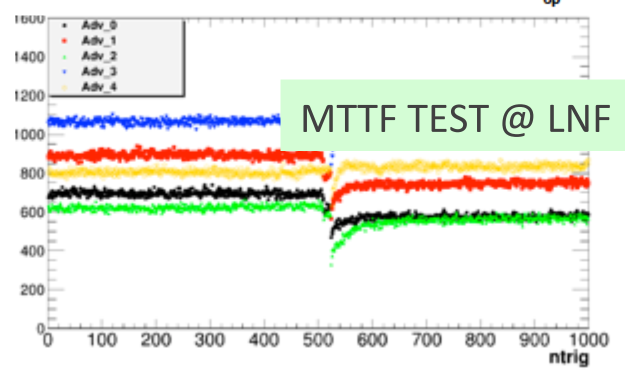


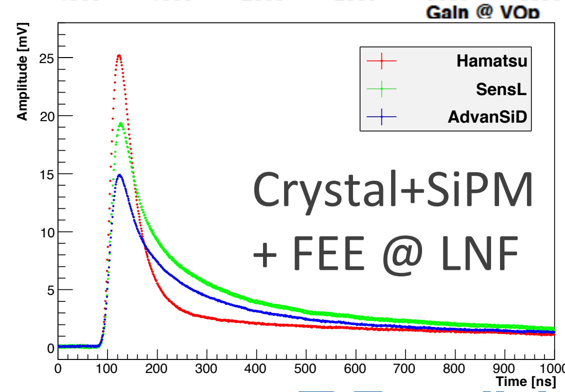










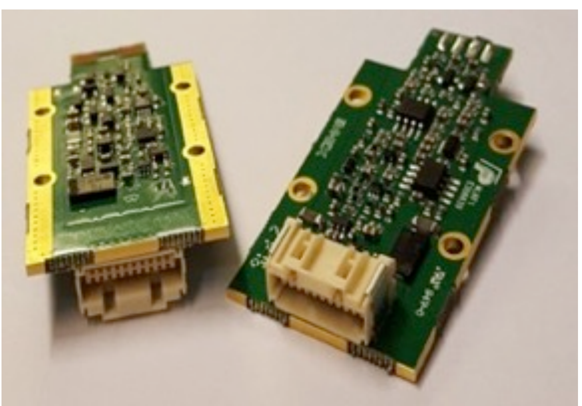


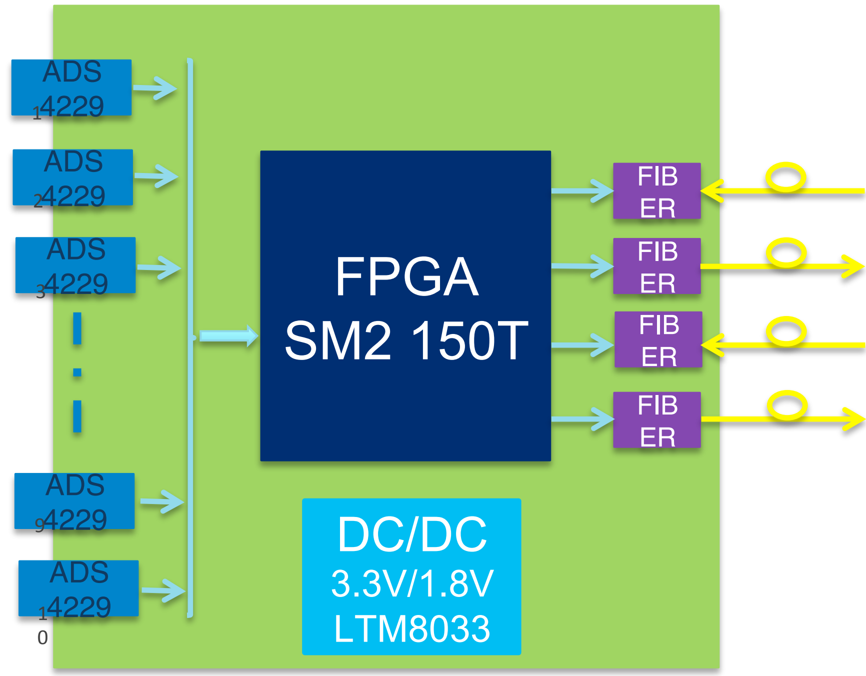
Pre-production status: FEE/WD

The electronics is composed of 3 parts:

1) The FEE chips closed to the sensors (amplification, HV regulation) (SEA-LNF)
2) The Mezzanine Board (MB) to set/read HV, T and Idark (SEA-LNF)
3) The Waveform Digitizer (WD) board to digitize the signals at 200 Msps (Pisa)

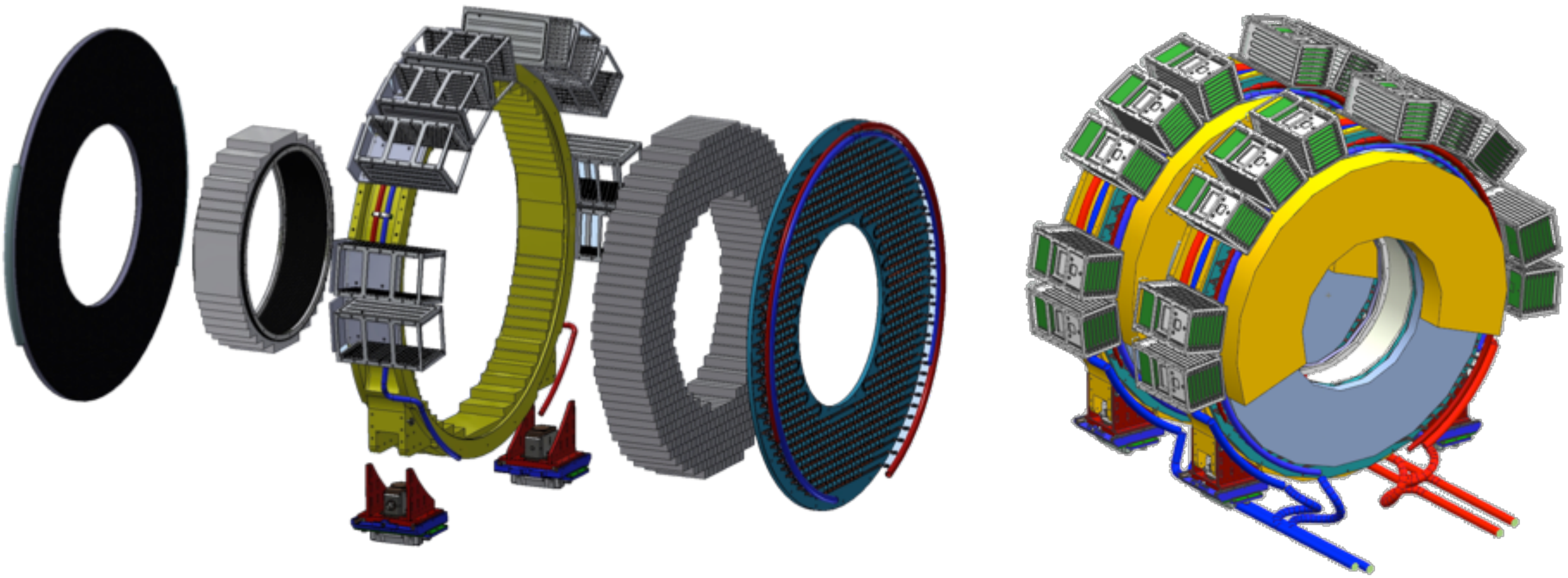
- ✓ 130 FEE pieces produced
- ✓ 5 MBs produced
- ✓ WD design completed.
- ✓ WD PCB in routing.
- ✓ 2 WD prototypes under construction





Nice sinergy/feedback with PADME group for electronics development

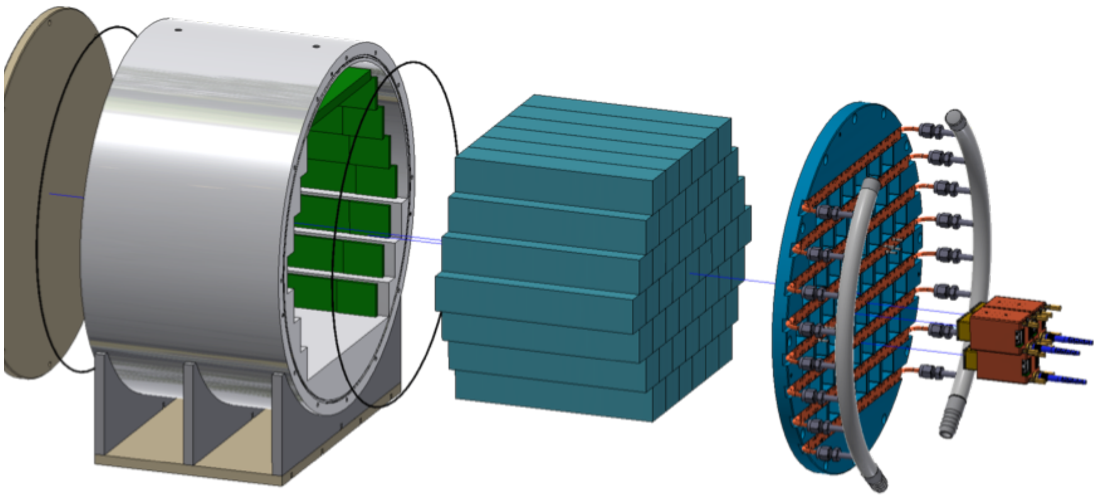
Engineering design: Mechanical system



Fully integrated design:

→ Completion of FEA calculation for mech. Structure
→ Calculation and definition of Composite structure
→ Improved cooling plate for FEE/SiPM
→ Thermal calculation of SiPM temperature
→ Improved FEE/SiPM holder
→ First layout of FEE cable routing and integration of services in 3D model

The Module-0 : from CAD to reality



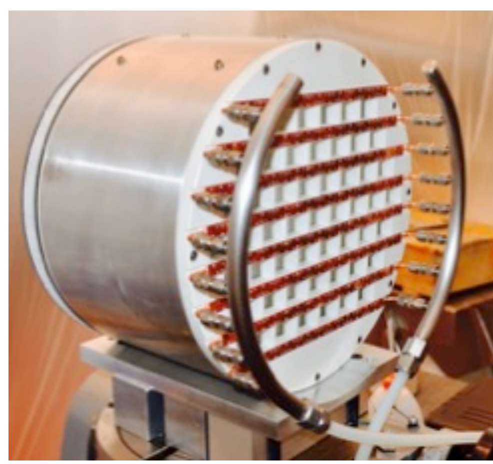
A large size prototype of the disk with final components.

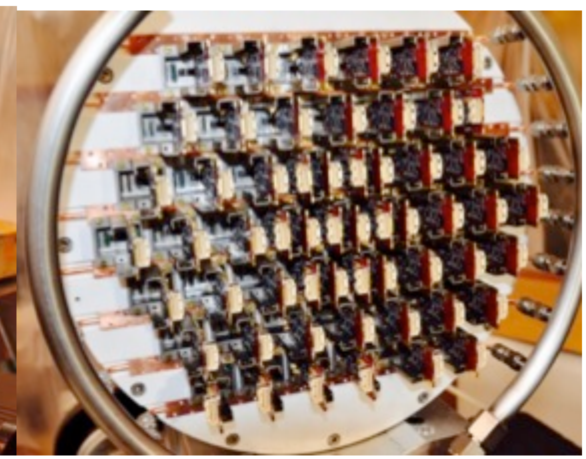
- 51 crystals, 102 sensors,
- 102 FEE chips, cooling

lines and readout.

- Completed 2 weeks ago

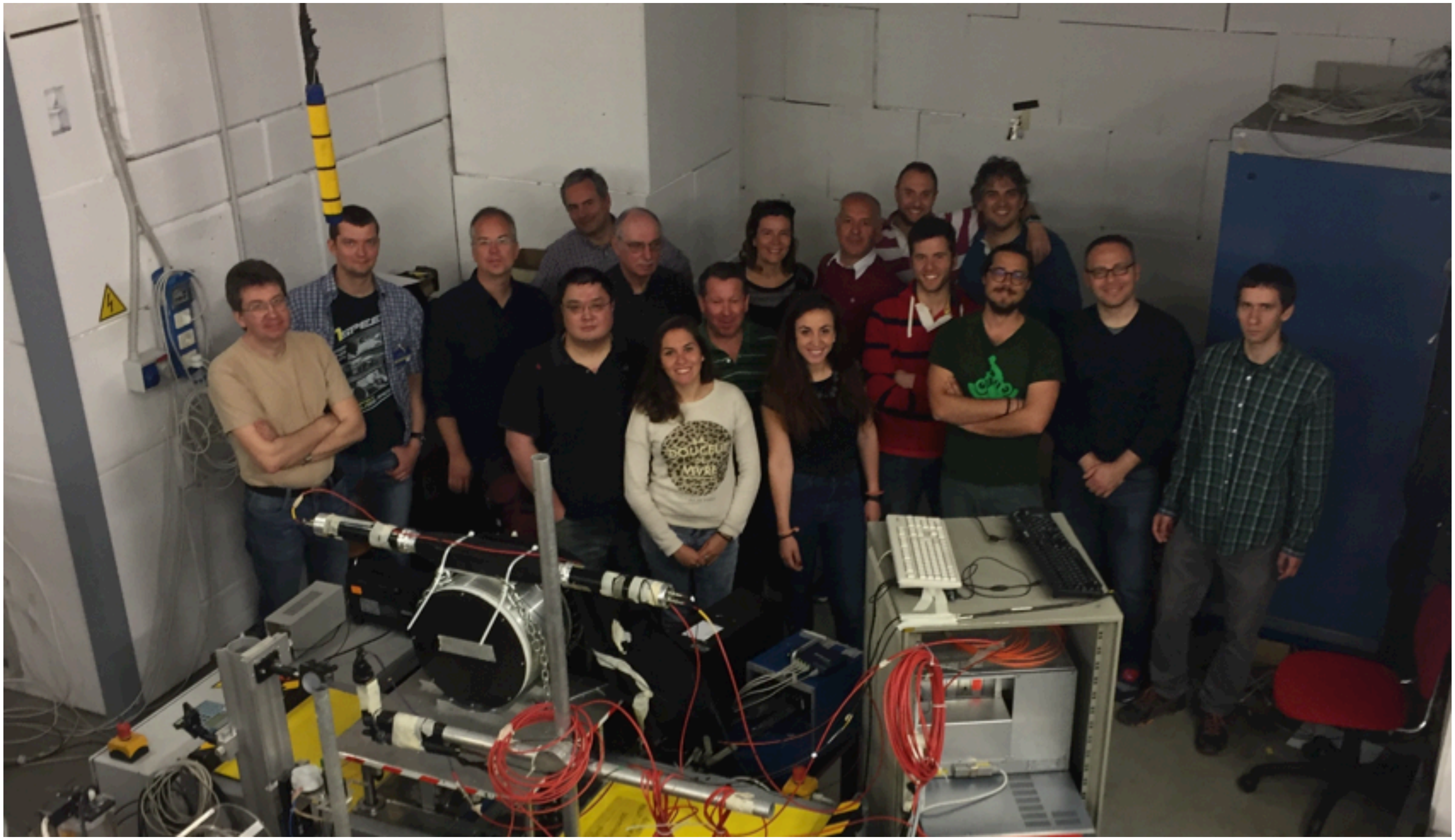
A great achievement!



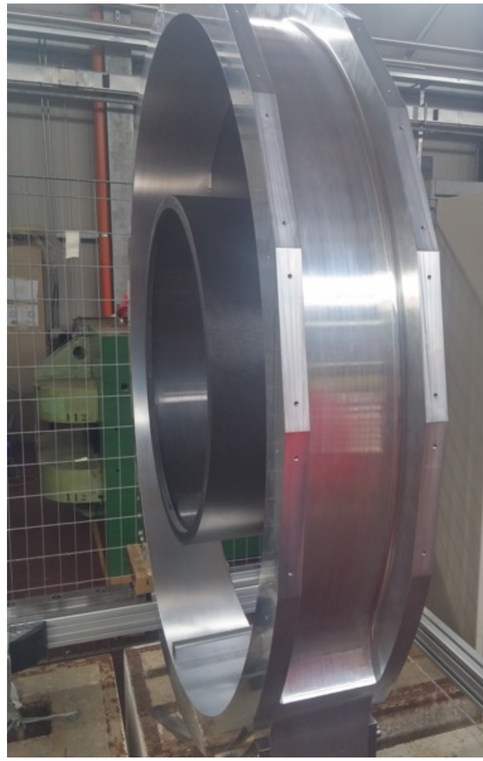
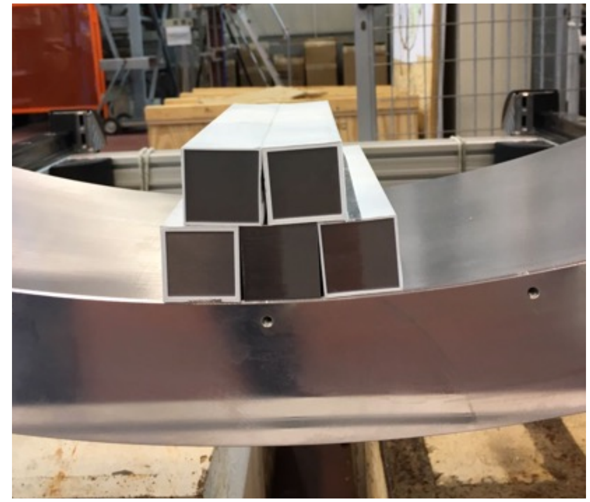


Test beam of Module-0

Last Friday, module- 0 has been transported to the area for an electron beam test @ LNF.
16 people (INFN, Caltech, JINR) are working on this test that is being carried out this week.



The calorimeter full size Mockup


- Mockup is standing on its feet
- CF rings mounted
- Crystal supports being prepared
- 700 Fake crystals being wrapped

EU funding/Dissemination for LNF group

- **Since 2015, members of MU2E LNF/INFN group have:**
- → got CD3c done, INFN budget for EMC construction O(3 MEuro)
  - → **won a European RISE call for work at Muon Campus (MUSE)** started January 2016 (1.7 MEuro budget) → (S.Giovannella, LNF)
  - → **received 2017 "Award for Seal of Excellence"** for Proposal Nausicaa for MSCA Individual Fellowhips → (I. Sarra, LNF)
  - → **won the fellowship E.Pancini** 2015 (I.Sarra, LNF)
  - → **received prices for best poster** a La Biodola 2015 (R.Donghia)
  - → **received an ARAP prize** as Master students (R.Donghia, E.Diociaiuti)
- **Disseminated Information in 2016:**
  - → 7 papers (1 IEEE, 4 NIM, 1 EPJ web Conf, 1 Nuovo Cimento C)
  - → Talks delivered by 10 people.
  - → 2 Master Thesis

Tomorrow at 14:30, LNF Seminar by Mu2e Spokeperson Doug Glenzinsky

Conclusions

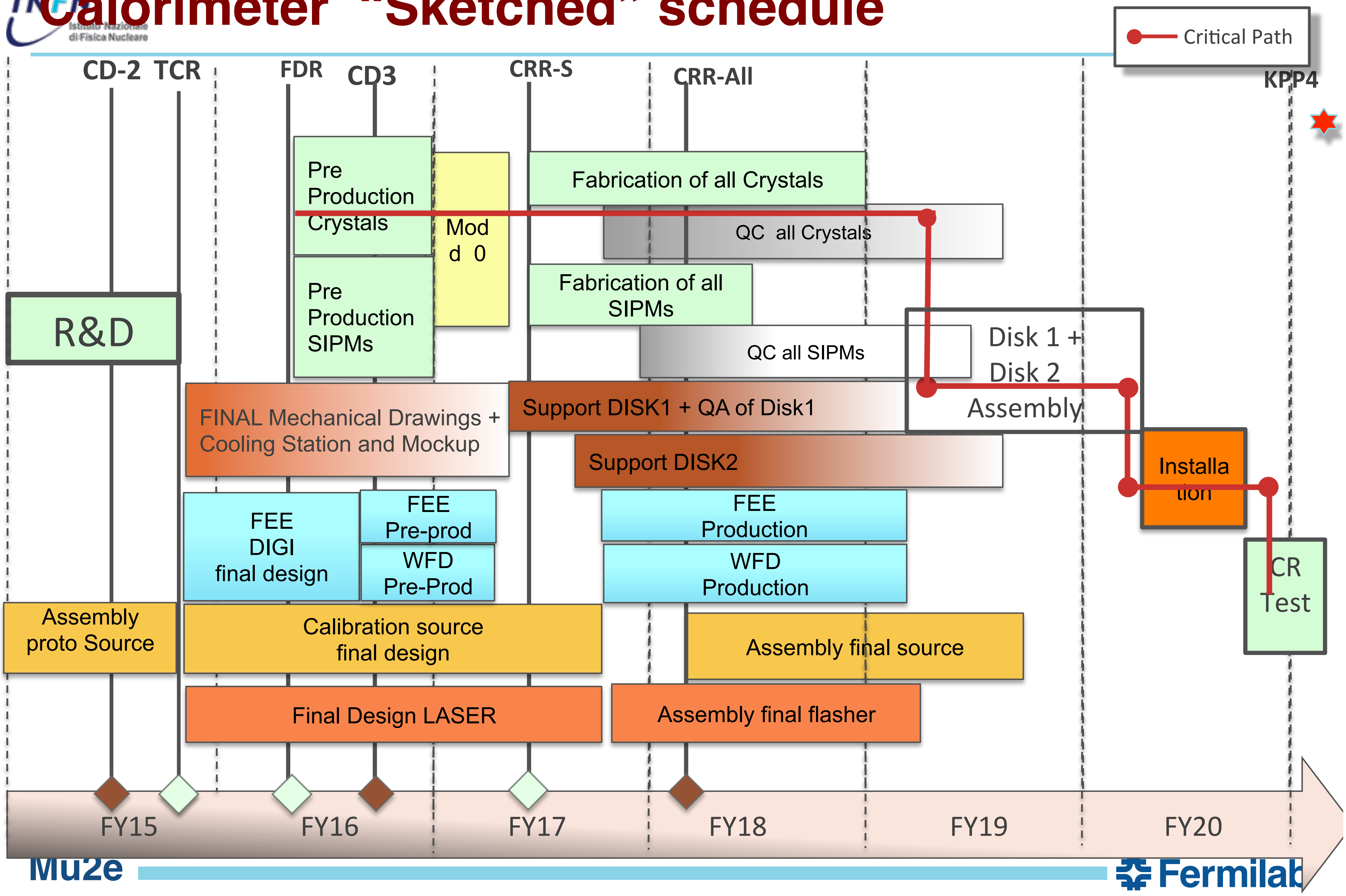
- The Mu2e experiment is a high precision CLFV experiment looking for physics BSM with high complementarity to other programs
- Mu2e Civil Construction and production of Superconducting cables done
- Mu2e Solenoid construction started
- DOE CD3-C approved → INFN has signed the SOW for EMC construction
  Contribution of INFN and LNF are fundamental for this operation.
- Calorimeter is progressing quickly toward construction:
  - → Pre-production for crystals, SiPMs and FEE completed.
  - → WD in progress. Cables selected. Outgassing in progress.
  - → **MODULE-0 COMPLETED .. TEST BEAM IN PROGRESS THIS WEEK @ BTF**
  - → **Full Size Mockup exists, proceeds with assembly**

NEXT STEPS:

- CRR review for crystals/SiPMs → June 2017 → **Complete BIDs this summer**
- CRR review for whole calorimeter after Slice test → beginning 2018.
- **Start up of Disk Assembly**

Additional Information

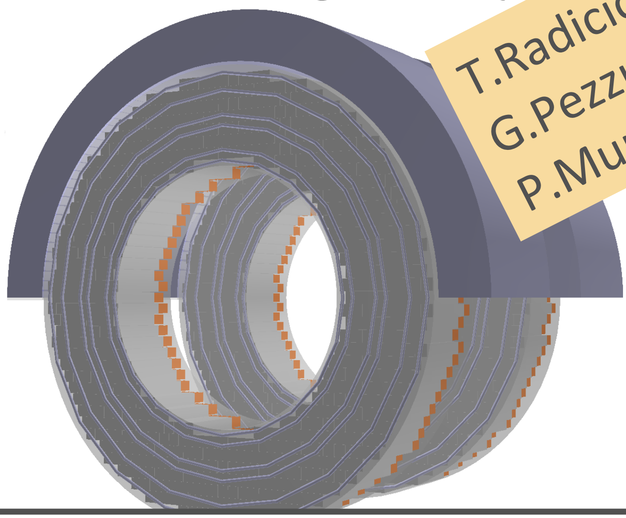
Calorimeter "Sketched" schedule



Geometry description on simulation

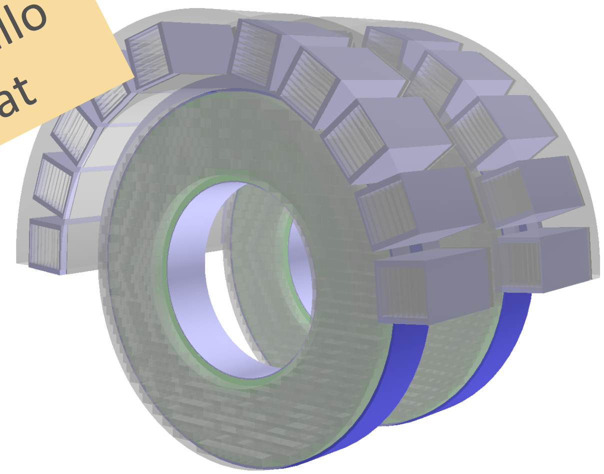
MUSE

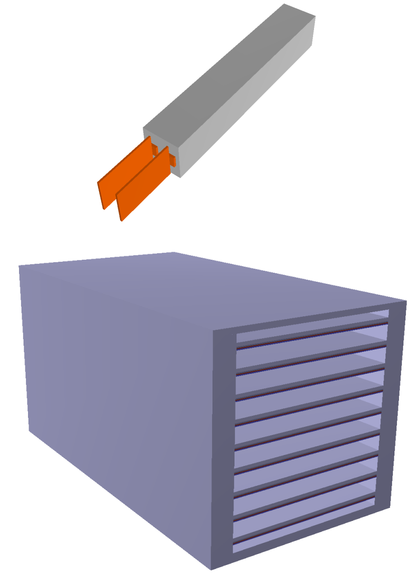
Current geometry



T.Radicioni,
G.Pezzullo
P.Murat

Improved geometry

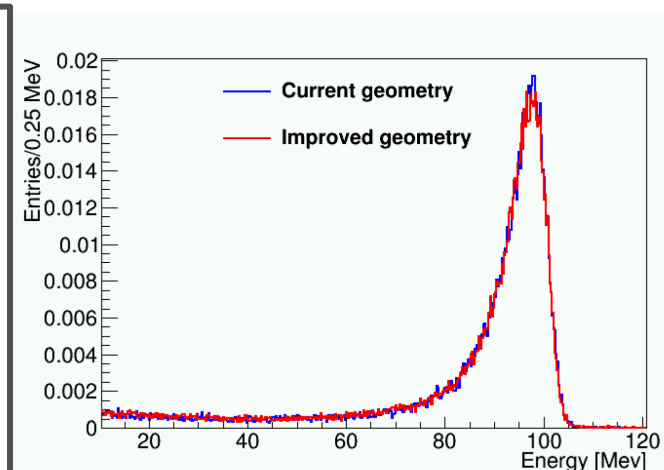




Detailed description of passive materials added to simulation:

- SiPM sensors and FEE cards
- Inner CF Ring
- Aluminum Structural support
- Source piping
- FEE crates and FEE boards

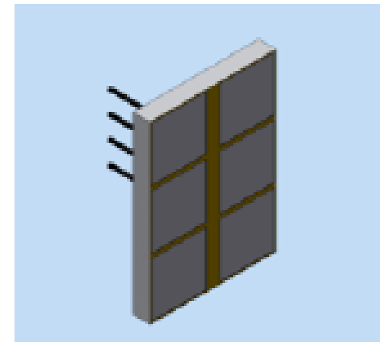
Goals are to allow a more realistic DOSE studies in electronics and sensors and check stability of calorimeter performance.



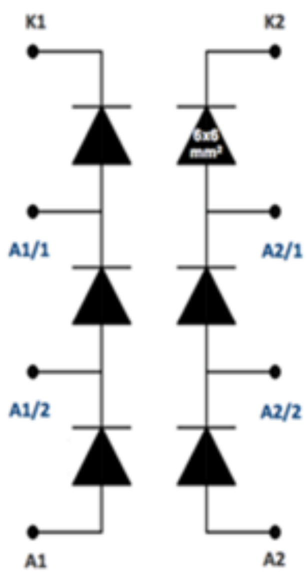
The Mu2e “custom” SiPMs

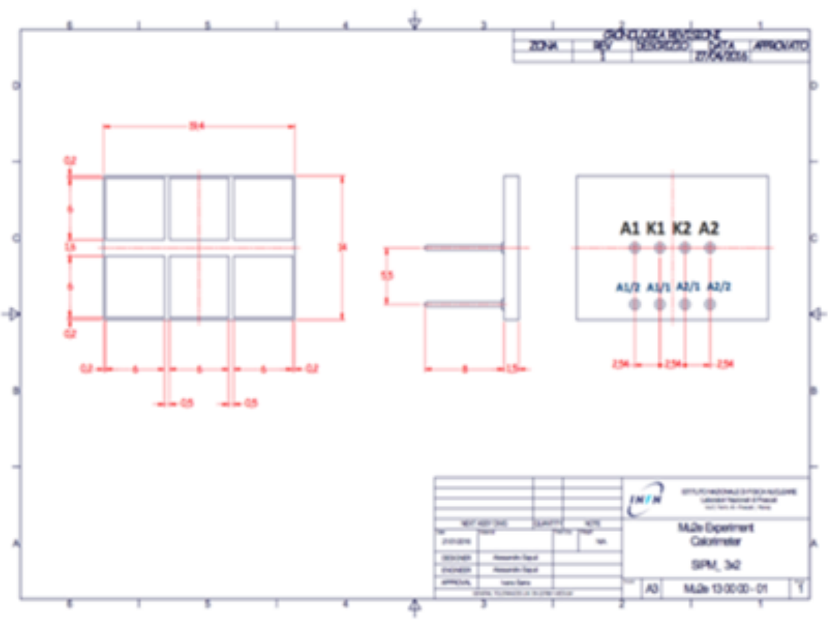
- We have chosen a modular SiPM layout to enlarge the active area, maximizing the number of collected photoelectrons.

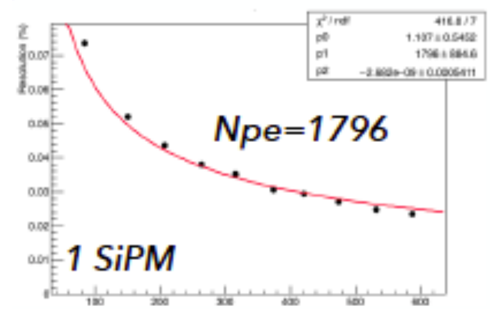
- The crystal dimension, increased from 30x30 to 34x34 mm², accommodates two arrays of 3 individual 6x6 mm² monolithic UV extended SiPM’s in series → Lower C, better time signals.

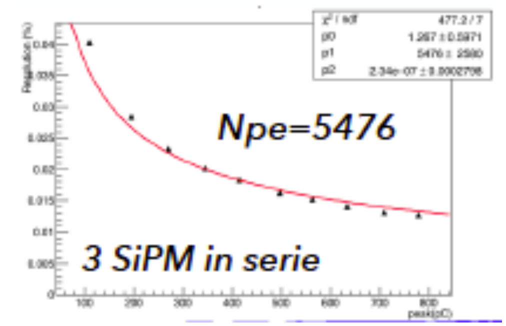


This layout allows us to use an air-gap while satisfying the p.e./MeV requirement with a single photosensor. Two SiPMs/crystal used for redundancy.







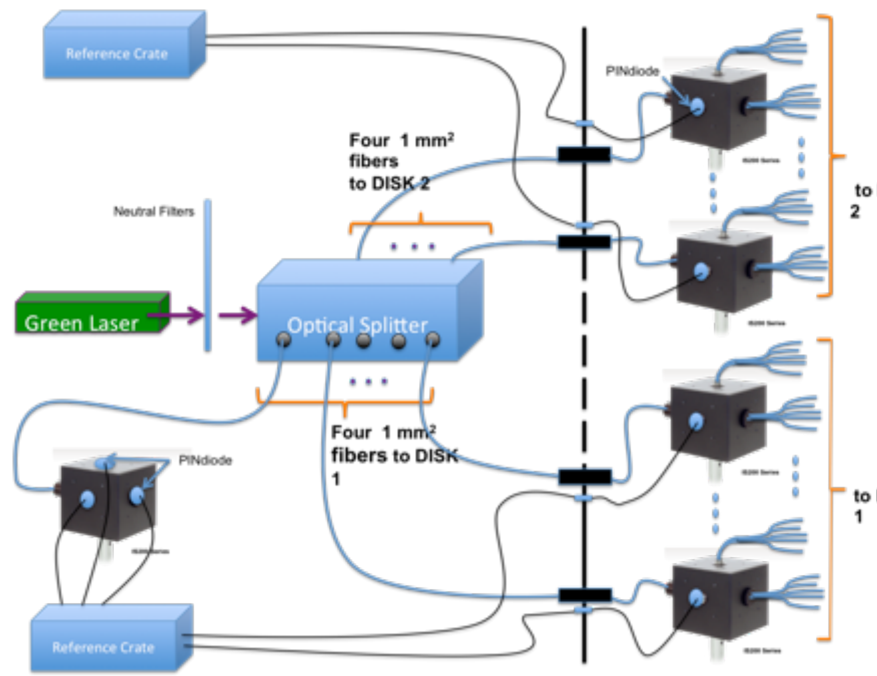


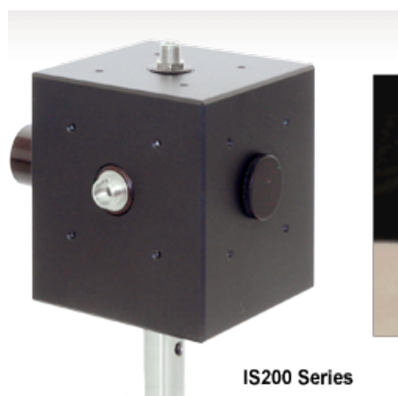
The Mu2e calorimeter calibration system

- The Laser calibration system has the goal to monitor the changes of the SiPM gain and of their resolution by distributing 315 nm Laser light to each sensor.

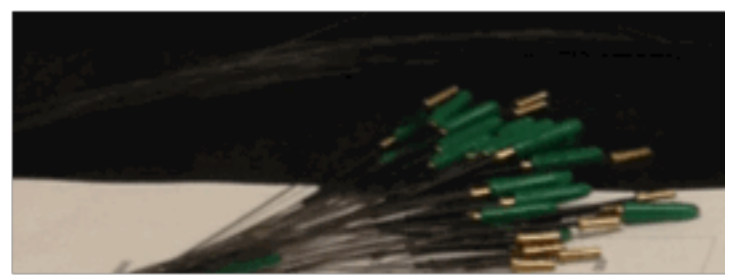
- The distribution system is based on optical lenses and diffusing sphere.

- It will monitor also the timing performances providing a first calibration of T0s.





IS200 Series



(WhatNext?) Mu2e → Mu2e-II

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:

→ 1 MW at LNBF at start (2025)
→ 2 MW at regime at LNBF
→ **x 10 at Mu2e**

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-II

Minor modifications of the detector → **BR < 6 x 10^{-18}**

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

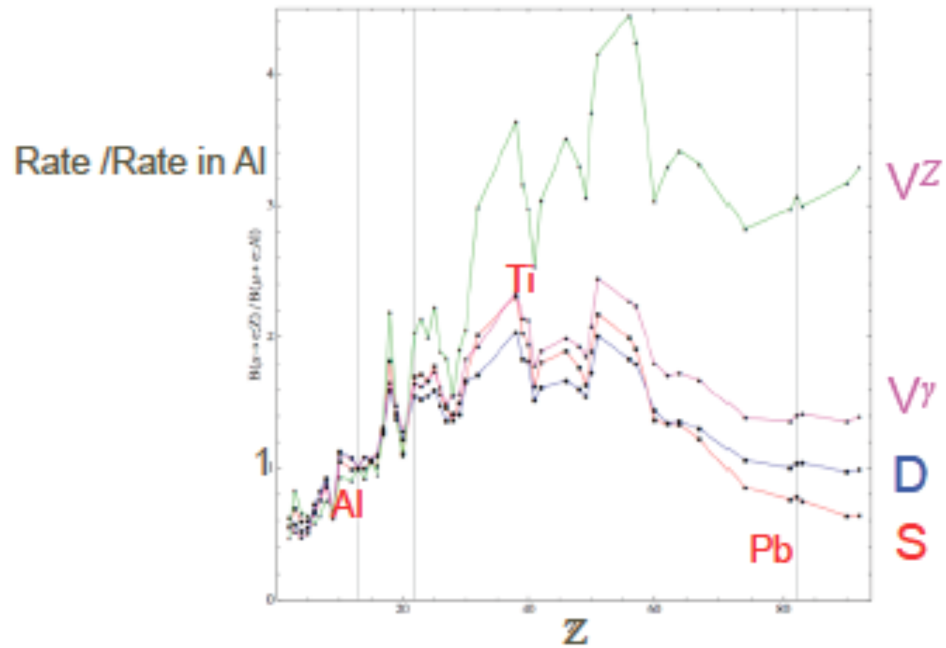


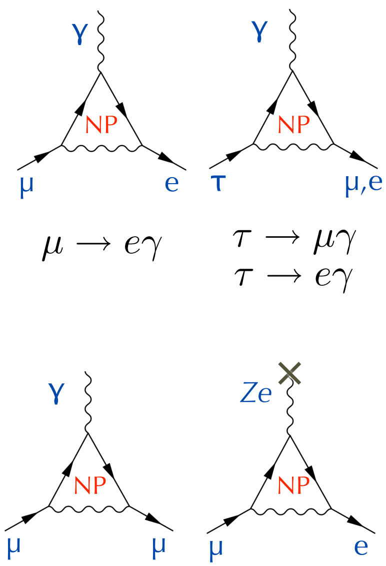
Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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

Mu2e vs MEG/MEG upgrade

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

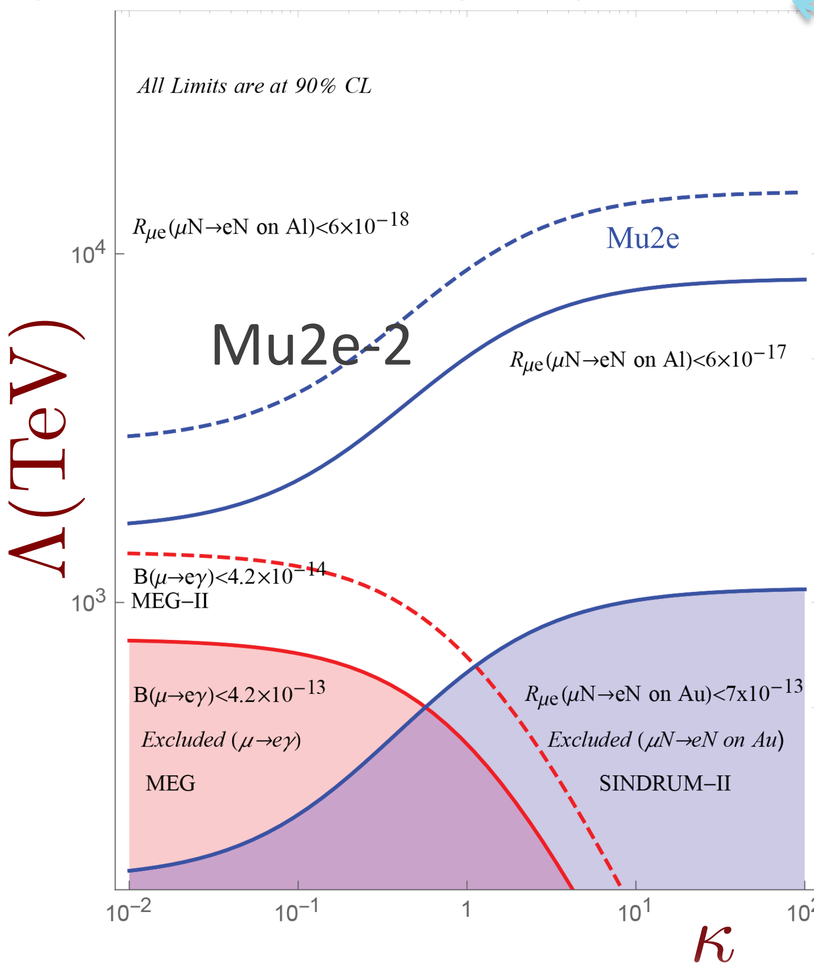
LOOP TERM

$\kappa \ll 1$



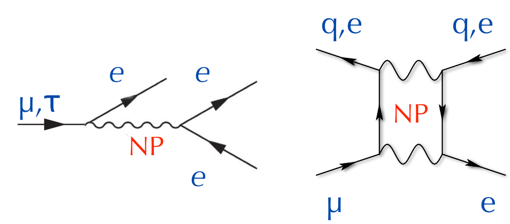
$\mu \to e\gamma$ $\quad \tau \to \mu\gamma$, $\tau \to e\gamma$

$(g-2)_\mu$ $\quad \mu^-\mathcal{N} \to e^-\mathcal{N}$



CONTACT TERM

$\kappa \gg 1$

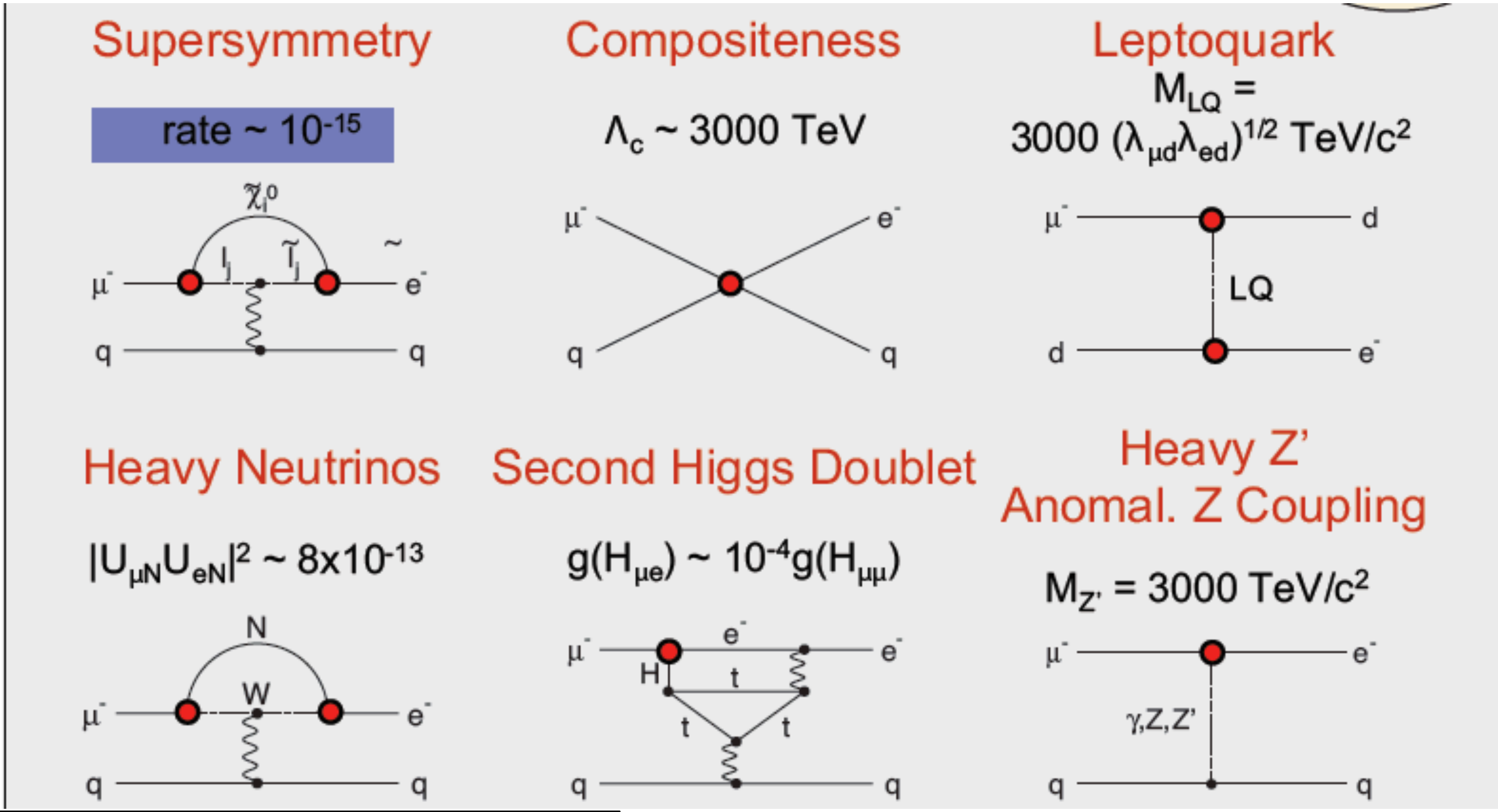


$\mu \to eee$

$\mu^-\mathcal{N} \to e^-\mathcal{N}$

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

Mu2e physics reach & goal



Sensitivity reach:
10^4 improvement with respect to previous muon to electron conversion experiment (Sindrum-II)

Test of Physics BSM:
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

SUSY benchmark points vs LHC

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		SPS 1b		SPS 2		SPS 3		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
BR($\mu \to e\,\gamma$)	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
BR($\mu \to e\,e\,e$)	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
CR($\mu \to e$ in Ti)	*$2.0 \cdot 10^{-15}$*	*$2.4 \cdot 10^{-14}$*	*$2.6 \cdot 10^{-15}$*	*$7.6 \cdot 10^{-14}$*	*$1.0 \cdot 10^{-16}$*	*$6.7 \cdot 10^{-16}$*	*$1.0 \cdot 10^{-16}$*	*$8.4 \cdot 10^{-16}$*	$\mathcal{O}(10^{-18})$
BR($\tau \to e\,\gamma$)	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
BR($\tau \to e\,e\,e$)	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
BR($\tau \to \mu\,\gamma$)	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	*$7.8 \cdot 10^{-10}$*	$2.7 \cdot 10^{-12}$	*$6.0 \cdot 10^{-10}$*	$\mathcal{O}(10^{-9})$
BR($\tau \to \mu\,\mu\,\mu$)	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

Muon to electron conversion 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/mu3e but with better mass reach

  → Sensitivity to physics that MEG/mu3e are not

  → If MEG/mu3e observe a signal, MU2E/COMET do it with improved statistics.
  Ratio of the BR allows to pin-down physics model

  → If MEG/mu3e do not observe a signal, MU2E/COMET have still a reach to do so.
  In a long run, it can also improve further (MU2E-II) with the proton improvement plan (PIP-2)

- **Sensitivity to Λ (mass scale) up to thousands of TeV beyond any current existing accelerator**