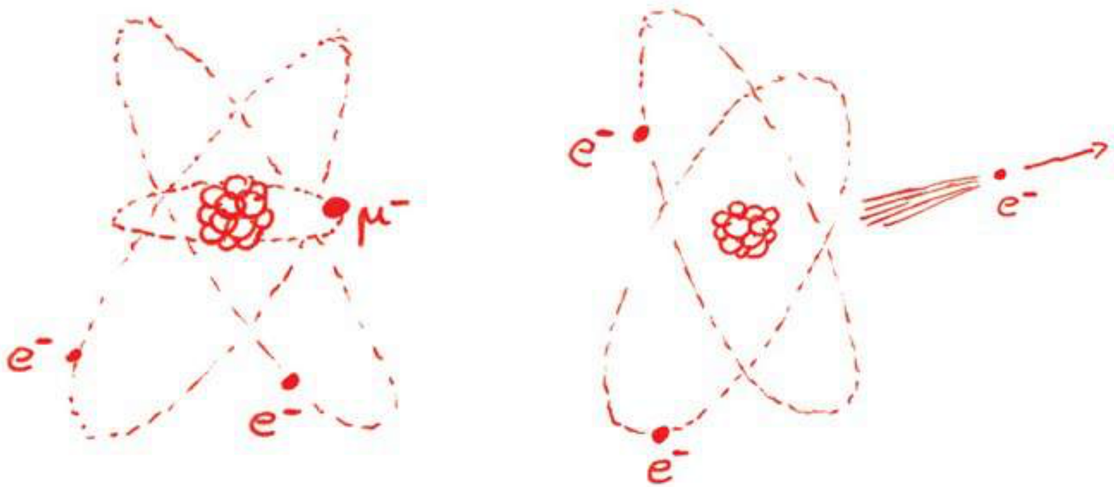
Mu2e crystal calorimeter

Design and Status

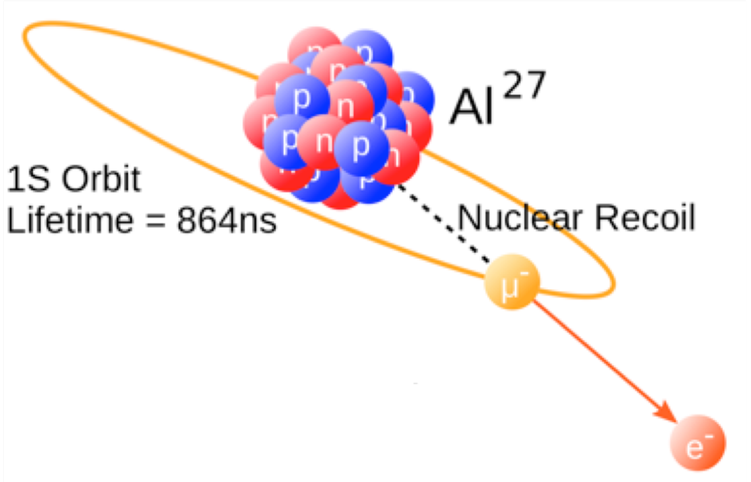


New Perspectives 2020
Fermilab, July 21

Daniele Paesani
INFN - LNF, Italy

Mu2e overview

$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96 MeV$$



μ-e conversion in the field of an Al nucleus

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \to e^- + N(A,Z)}{\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

total nuclear captures

(90% CL for ~ 10^{18} stopped muons over 3 years of running)

- Mu2e will search for coherent muon-to-electron conversion in the Coulomb field of an Al nucleus: $\mu^- Al \to e^- Al$
- CLFV processes are strongly suppressed by the SM but not forbidden: $BR(\mu \to e\gamma) \sim \Delta m_n^2 / M_W^2 < 10^{-54}$
- Mu2e will have discovery sensitivity over broad swath of BSM Physics parameter space

Some perspective

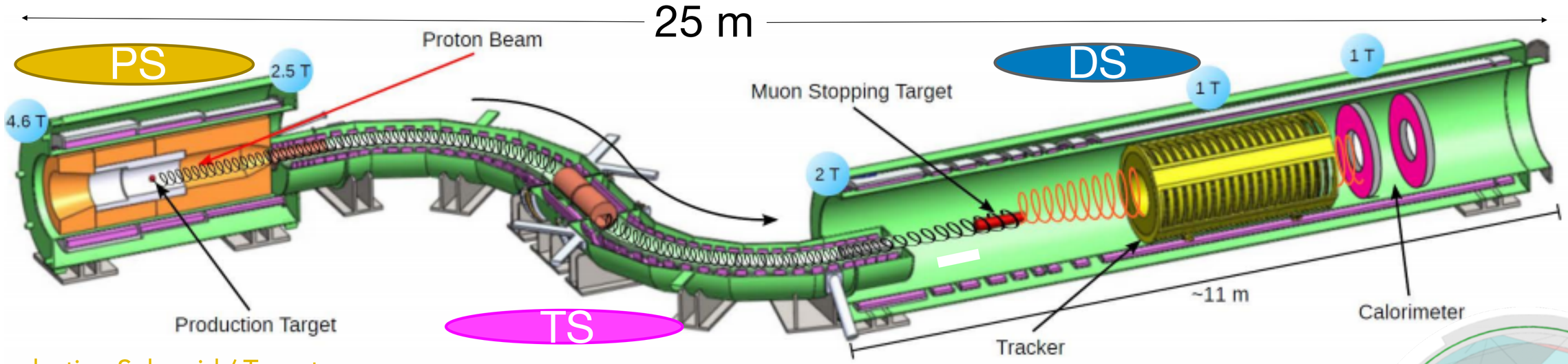
Probability of...	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (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 flipping 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

~90% C.L. goal

Single event sensitivity of Mu2e

Mu2e setup

1. Generate **high intensity PULSED** low momentum **μ^- beam**
2. Stop **μ in an Al** target → trapped in orbit around the nucleus
3. Look for an **excess around 105 MeV/c** in the electron momentum spectrum



Production Solenoid / Target

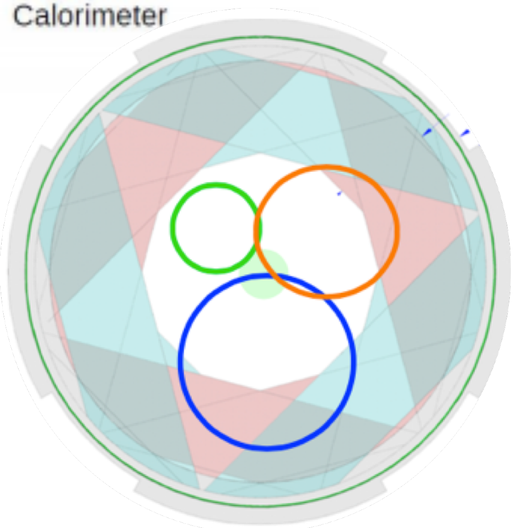
- Protons hitting target and producing mostly π

Transport Solenoid

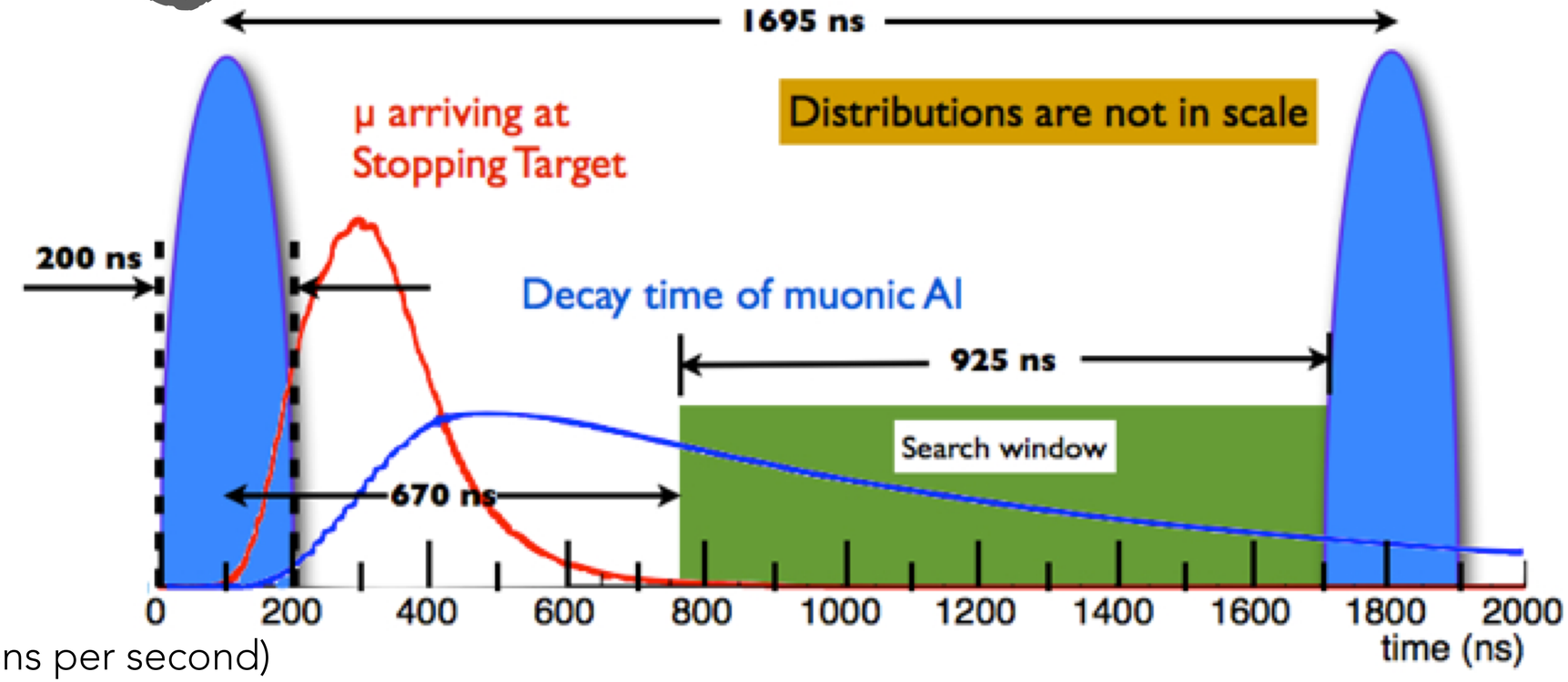
- Selects and transports low momentum μ^-
- Filter out neutral particles

Detector Solenoid: stopping target and detectors

- Stops μ^- on Al foils
- Measure momentum in tracker (< 200 keV/c @CE) and energy in calorimeter
- Events reconstructed by detectors optimized for 105 MeV/c momentum →

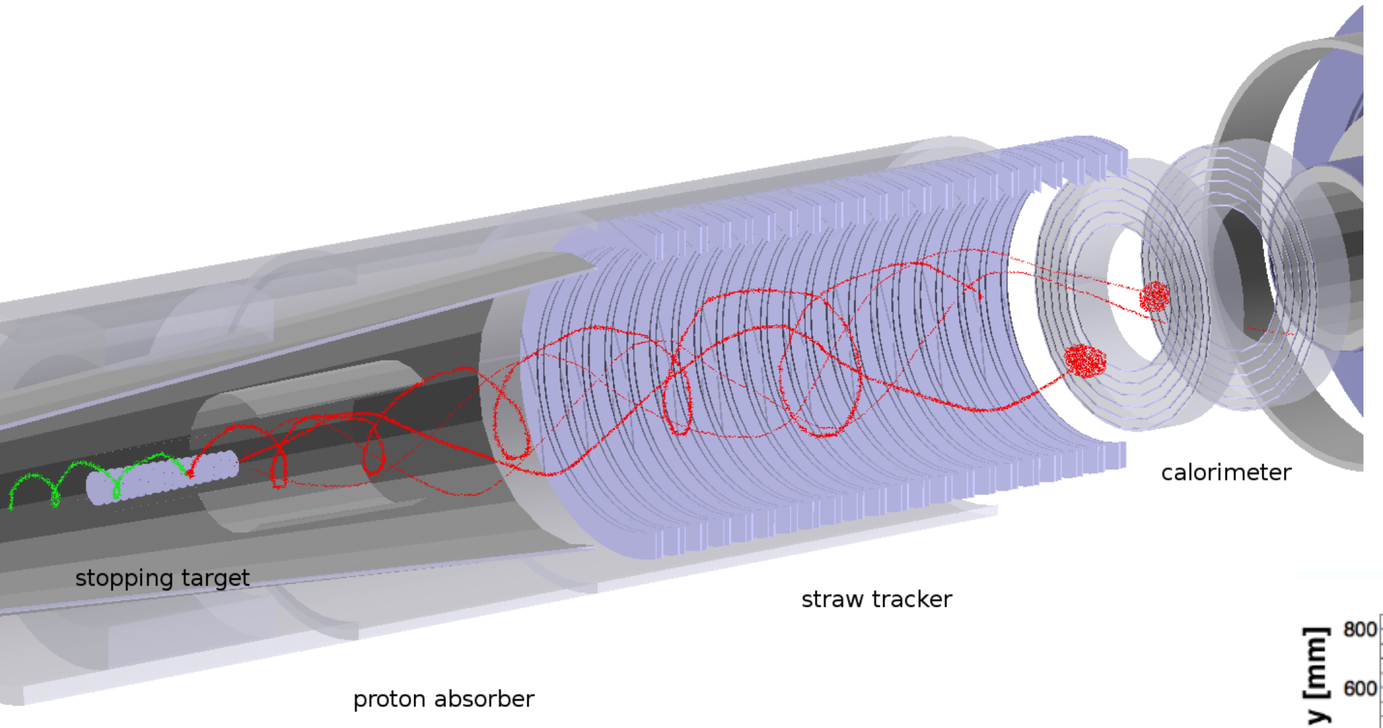


Mu2e timing and bkg



- Proton bunch → FW ~ 200 ns pulse
- ~ 20,000 muons per bunch (10^{10} muons per second)
- μ reach the stopping target in ~250 ns
- Stopped μ lifetime in 1S Al **~864 ns**
- **Prompt bkg** → protons, unstopped muons, stopped and unstopped pions
- Late protons noise -> **10^{10} beam extinction needed**
- Pions from late p → RPC prompt bkg (t_{pi}^{Al} = 26 ns)
- Mainly DIO (and CR) background during observation window

Calorimeter requirements



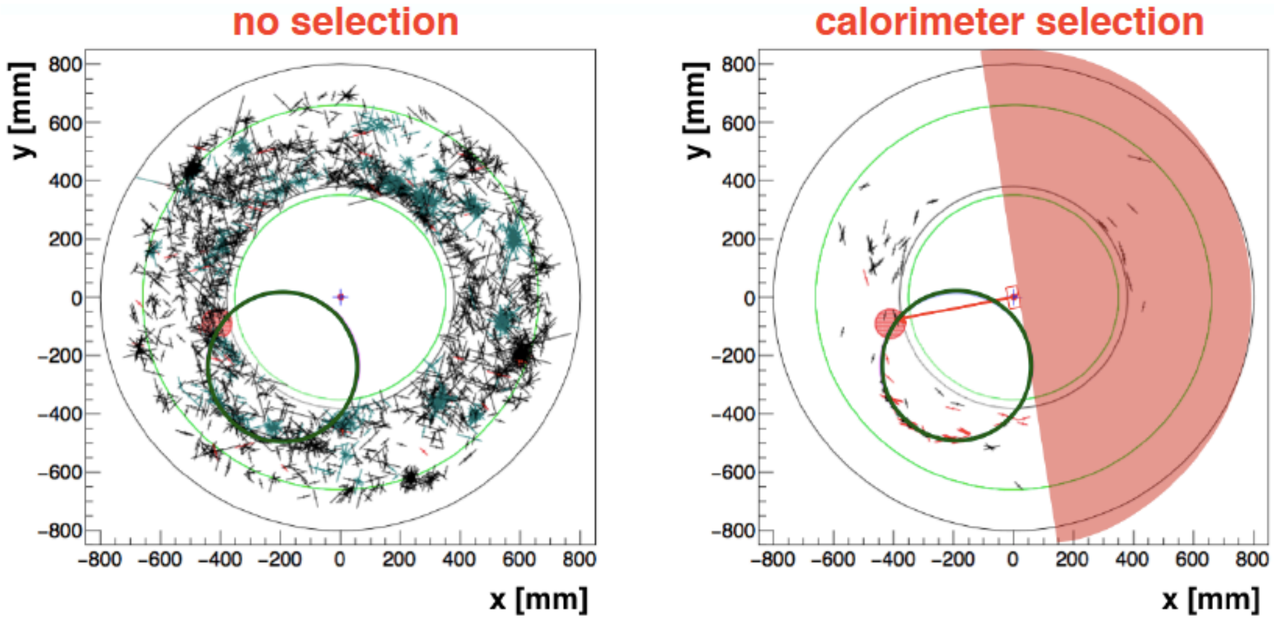
- PID: **e/μ separation** (μ rejection of 200)
- Cluster seeding for track finding
- Scintillation emission **τ**< 40 ns
- Standalone **on-line trigger capability**
- 1 T B-field and 10^{-4} mbar operating environment
- 1 year minimum continuos operation time

resolution @ 105 MeV

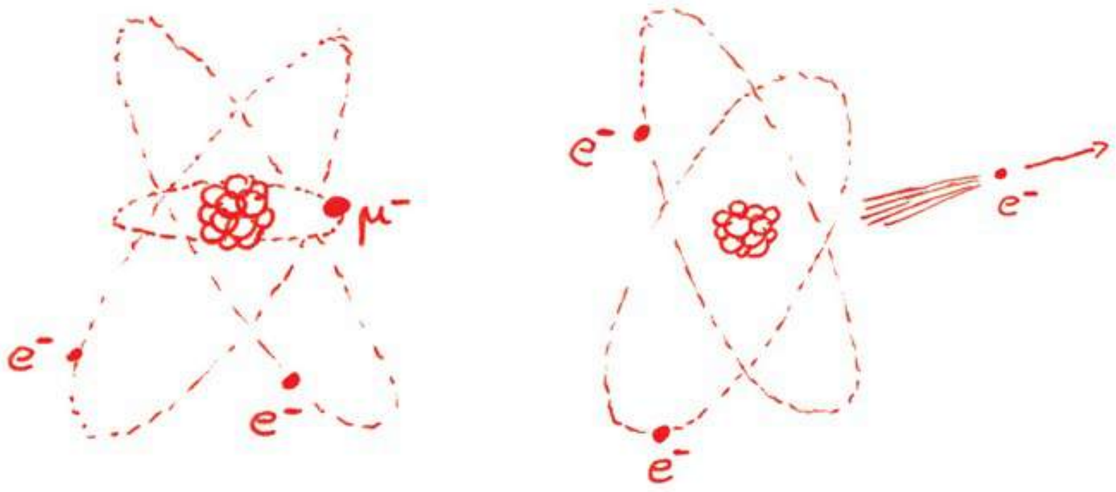
- $\sigma_E/E = \mathcal{O}(10\%)$
- $\sigma_T < 500$ ps
- $\sigma_{X,Y} \leq 10$ mm

rad hardness

- 100 krad (45 krad) dose for crystals (sensors)
- 3×10^{12} n_{1MeV}/cm^2 for crystals
- 1.2×10^{12} n_{1MeV}/cm^2 for sensors
- Radiation induced readout noise < 0.6 MeV

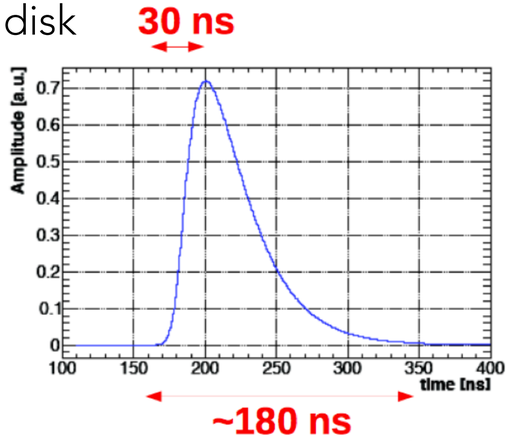


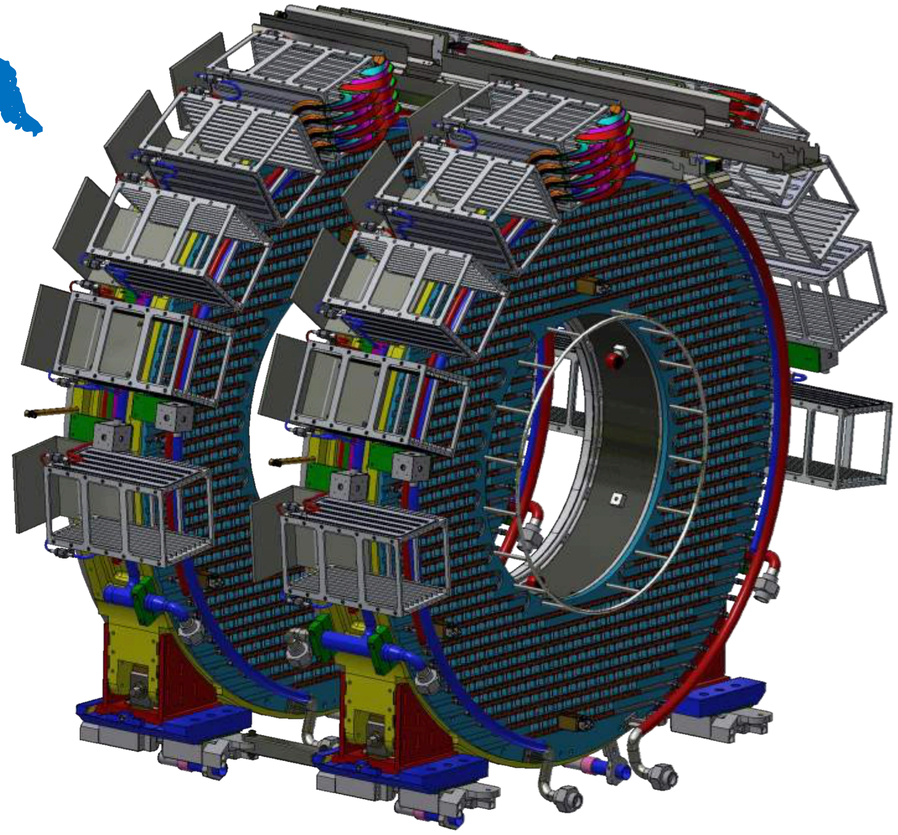
How are we going to achieve such precision and stability?

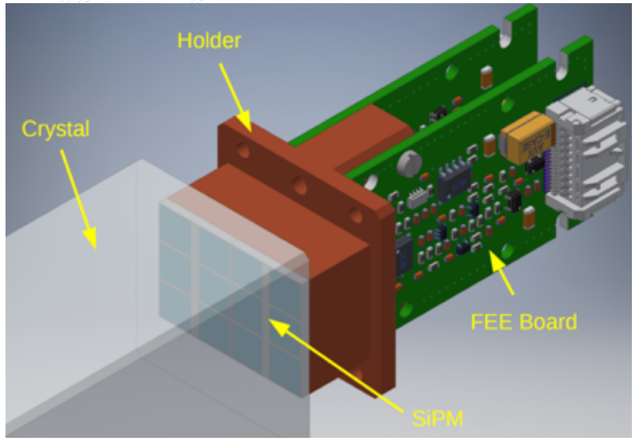


Calorimeter design

- Two annular disks
- 674 undoped CsI (34 x 34 x 200) mm^3 square crystals per disk
- Depth = 10 X_0 (200 mm) and spacing = 70 cm







readout

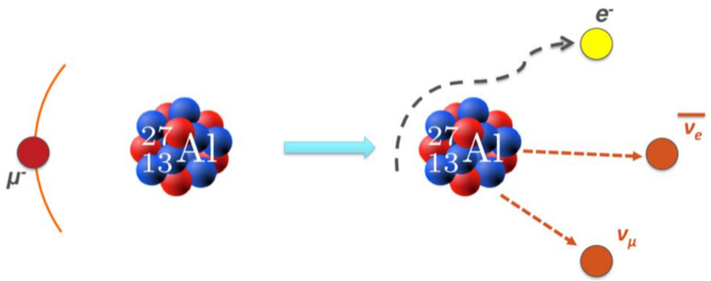
- 2 large area UV-extended SiPMs per crystal
- Shaped signal: 50 ns RT and 200 ns FW
- Individually programmable bias voltages
- Dirac DAQ board (20 ch @ 200 Msps)

embedded calibration systems

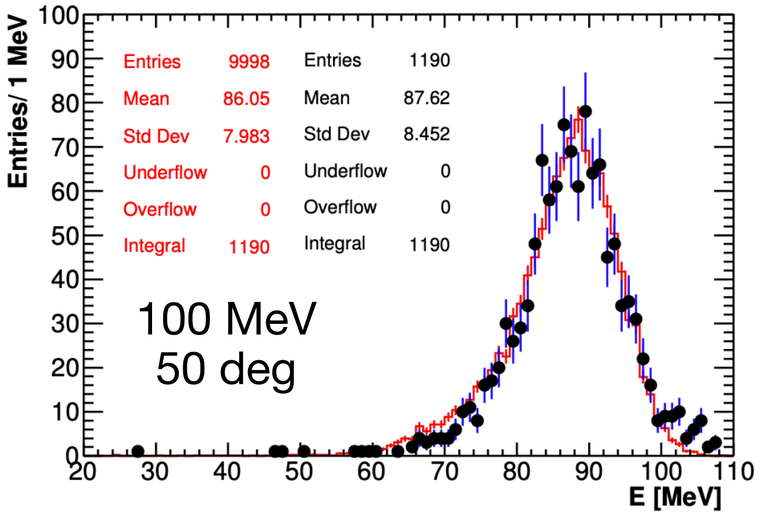
- 530 nm laser for SiPM gain equalisation
- Radio source emitting 6 MeV photons for crystal equalisation

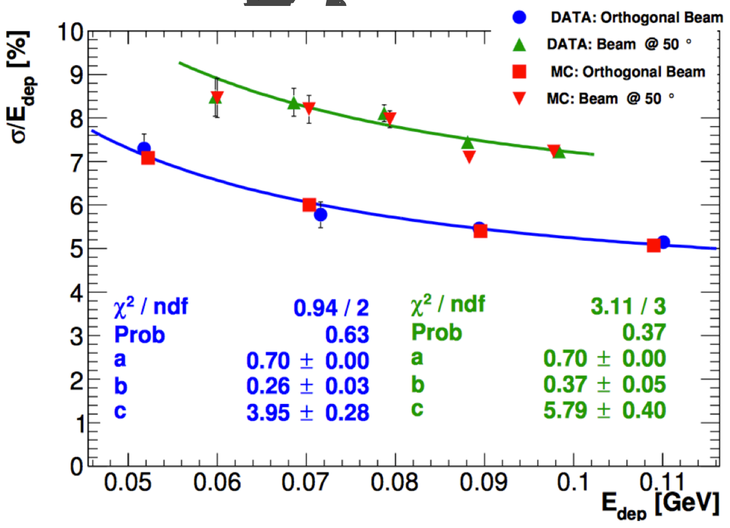
other calibration systems

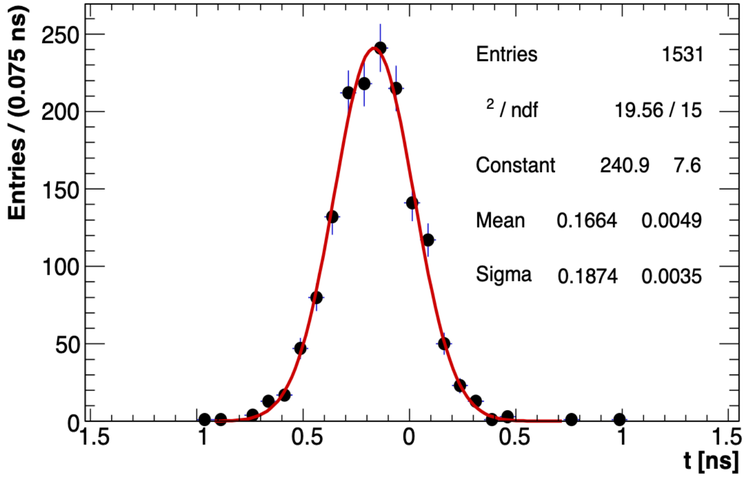
- Cosmic based calibration at ~ 21 MeV (MIPs)
- IPA DIO e^- w/ ~ 40 MeV peak (useful for the first disk)
- Target DIO e^- up to 100 MeV
- DIO e- runs w/ reduced B-field (adjusted acceptance to increase statistics) and extrapolation to 1 T

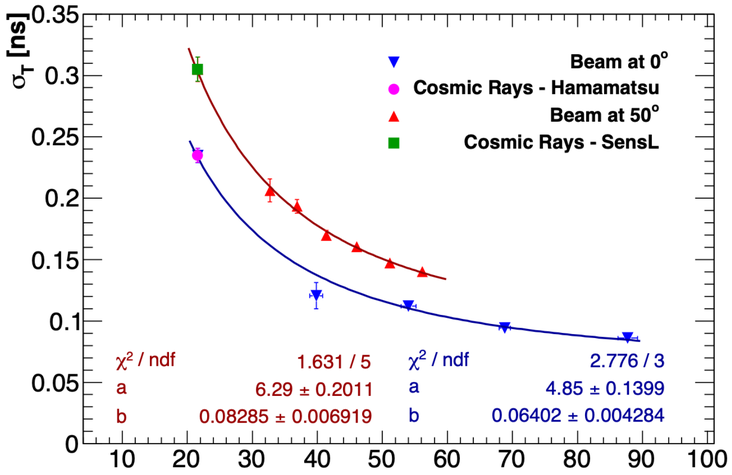


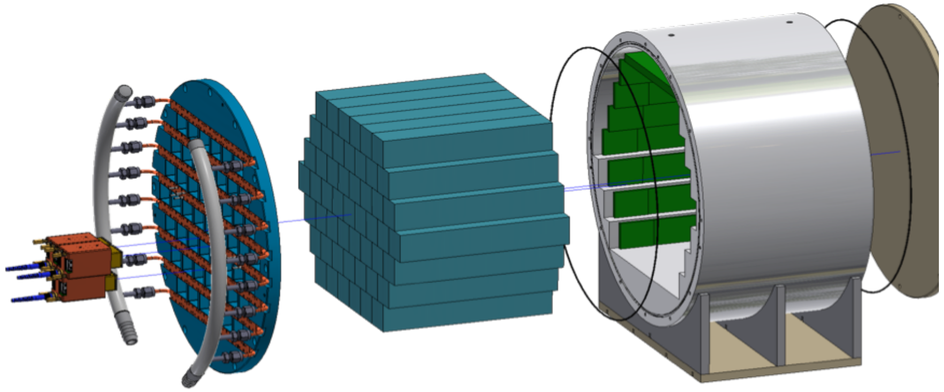
Design validation S1 CHS prototype TB











Energy response

- Single particle selection
- MIPs Equalisation & E-scale
- 100 MeV e- beam impinging @ 0° and 50°
- LY/SiPM = 30 pe/MeV
- Great Data-MC agreement

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

$$\sigma_T = a/E \oplus b$$

Time response

- Log-normal fit on leading edge
- 5% CF discrimination
- σ (T1) ~ 130 ps @ Ebeam = 100 MeV

Production status

Crystals QA

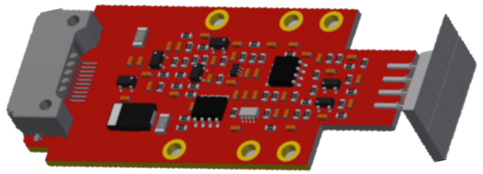
- > 85% crystals already tested (1300/1500)
- Production completion within 2021
- QC check on LRU, resolution, slow component and RIN, OK
- Excellent dimensional specs (CMM tested)

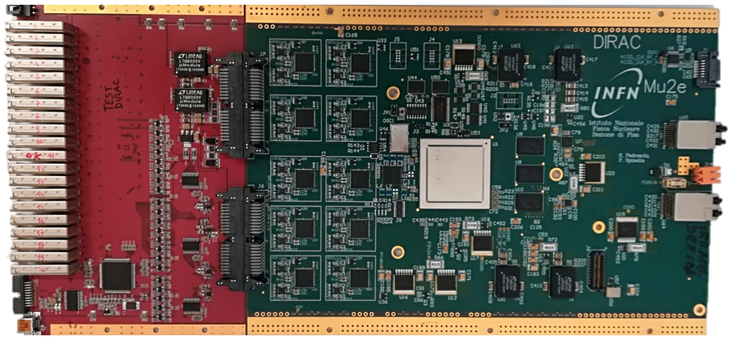
SiPM QA

- Production phase concluded (4000 pcs of Mu2e-SiPMs) by HAMAMATSU
- 6 cells individually tested (Vbr, Idark, Gain x PDE)
- Irradiation with ~1×10^{12} neutrons/cm^2 (MTTF) test on 5 (15) SiPMs/batch

FEE & DAQ

- 25 pieces of FEE PCBs developed and tested (production due in late 2020)
- Signal shaper, gain and ADC/DACs settings ultimated
- FEE showed excellent behavior for 100 krad TID (60 Co γ source)
- MB and DIRAC design completed
- Rad-hard and SEU tests on ARM controller OK, B-field test OK
- Firmware almost completed

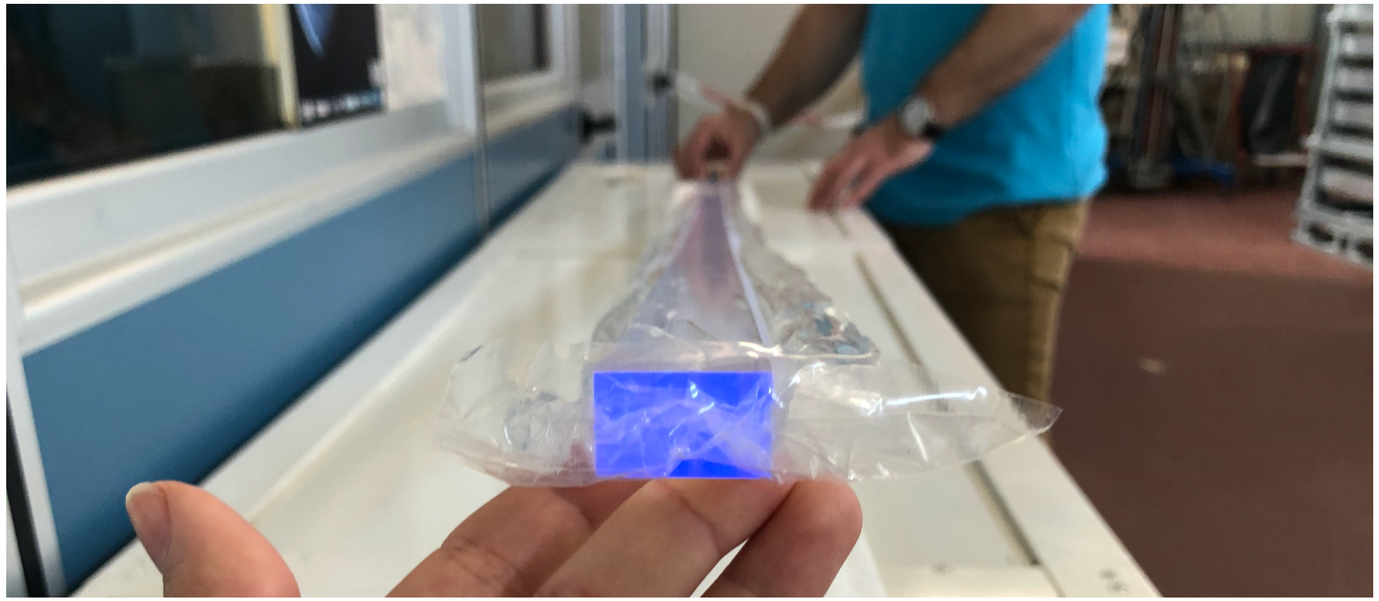


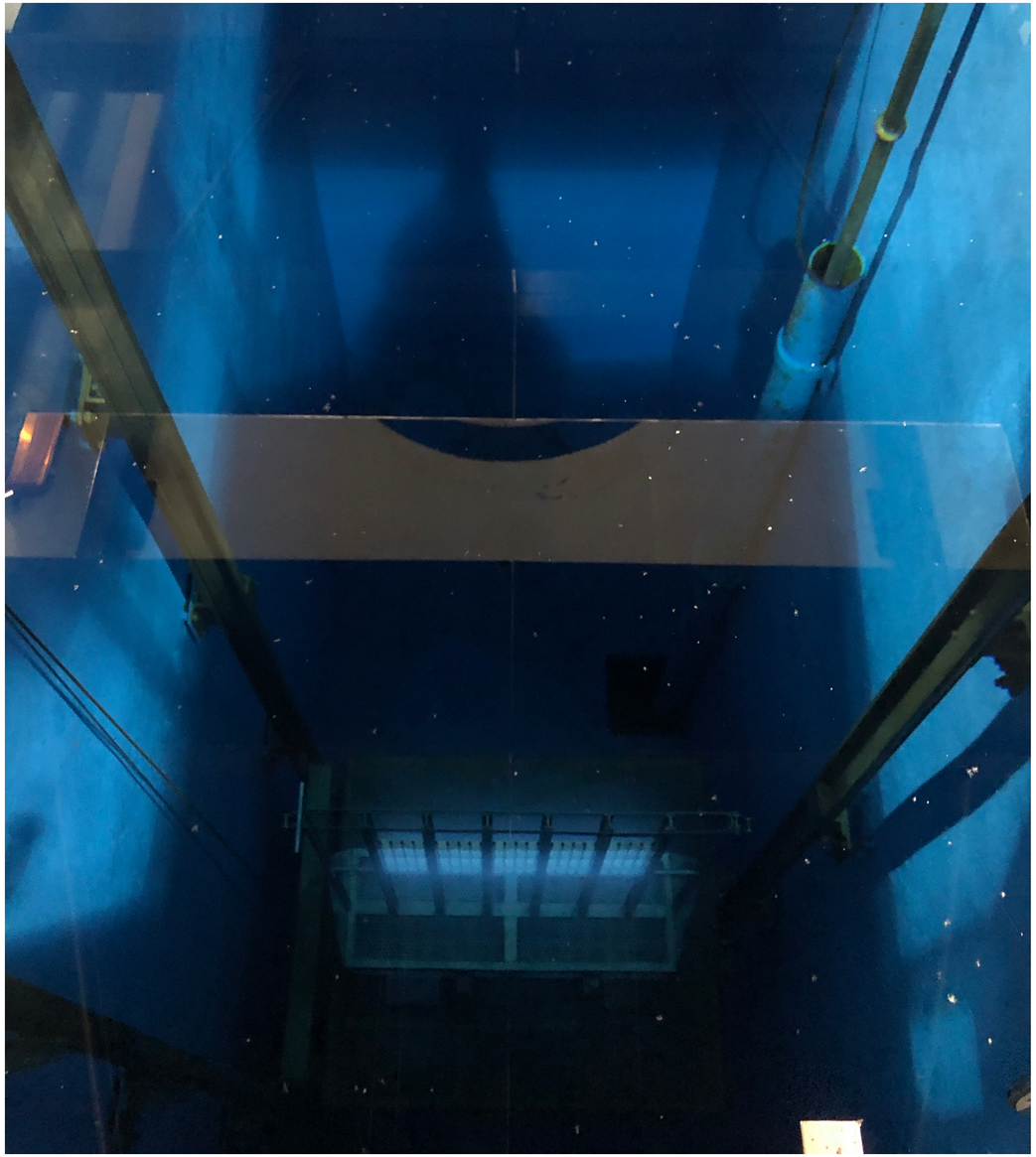


Mechanical

- Mechanical structure design is final
- Al disks has been milled

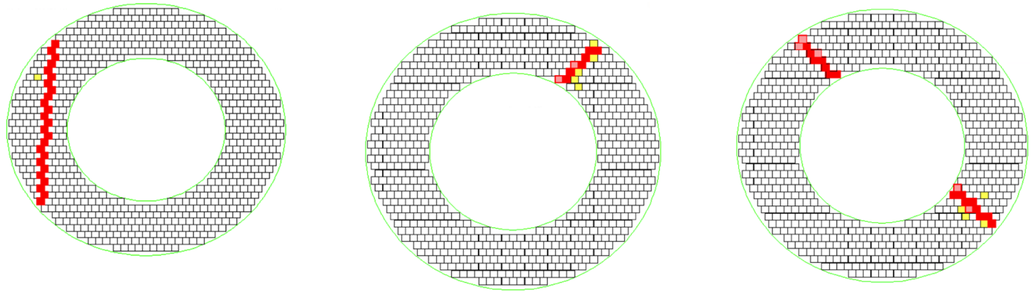
Meantime at LNF...

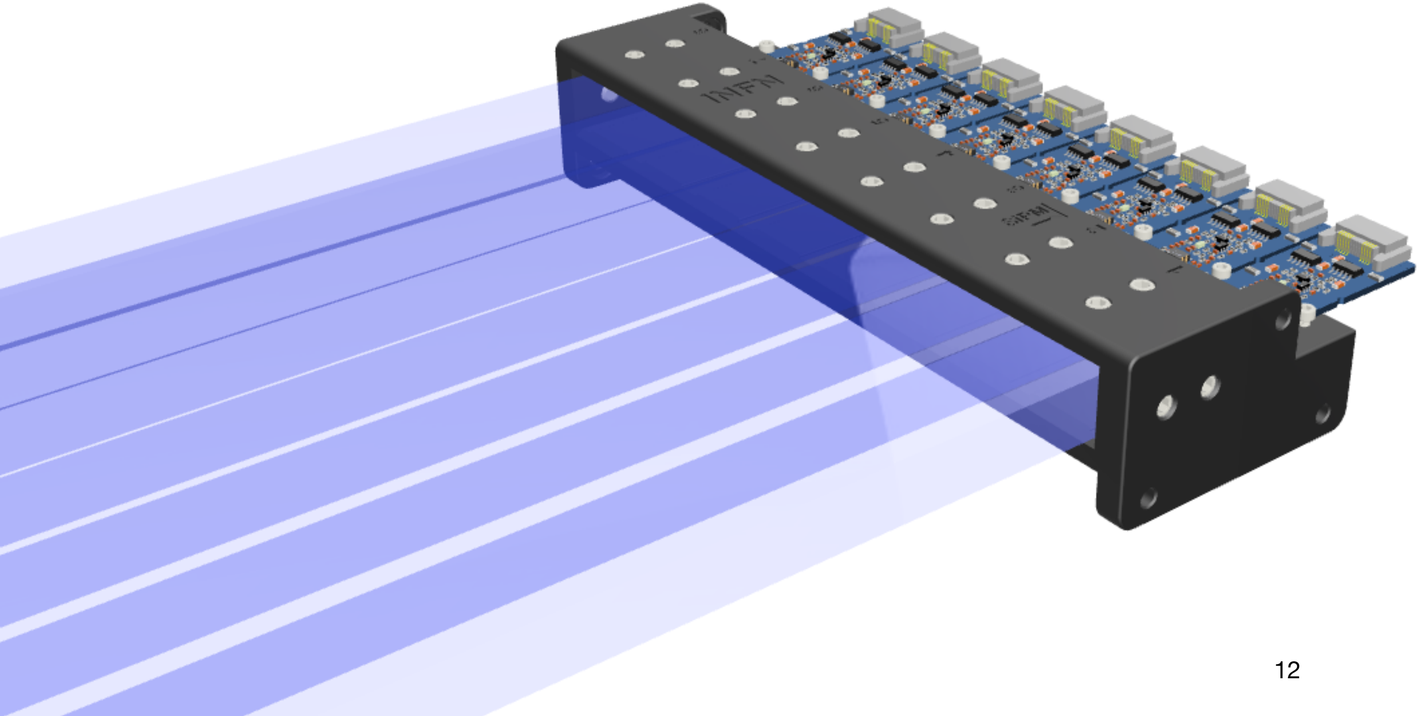




MIP offline calibration and CRT

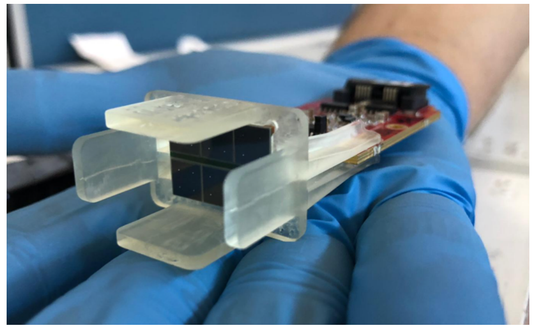
- Each calorimeter disk will be tested before installation using the CRT
- Equalisation and calibration of the energy response @ 21 MeV (MIPs)
- TOF for time offset alignment
- T0s calibration at a level below 10 ps (RMS)
- Crystals LRU
- Study of timing resolution dependence on crystals z-axis
- About 6 hours completion time





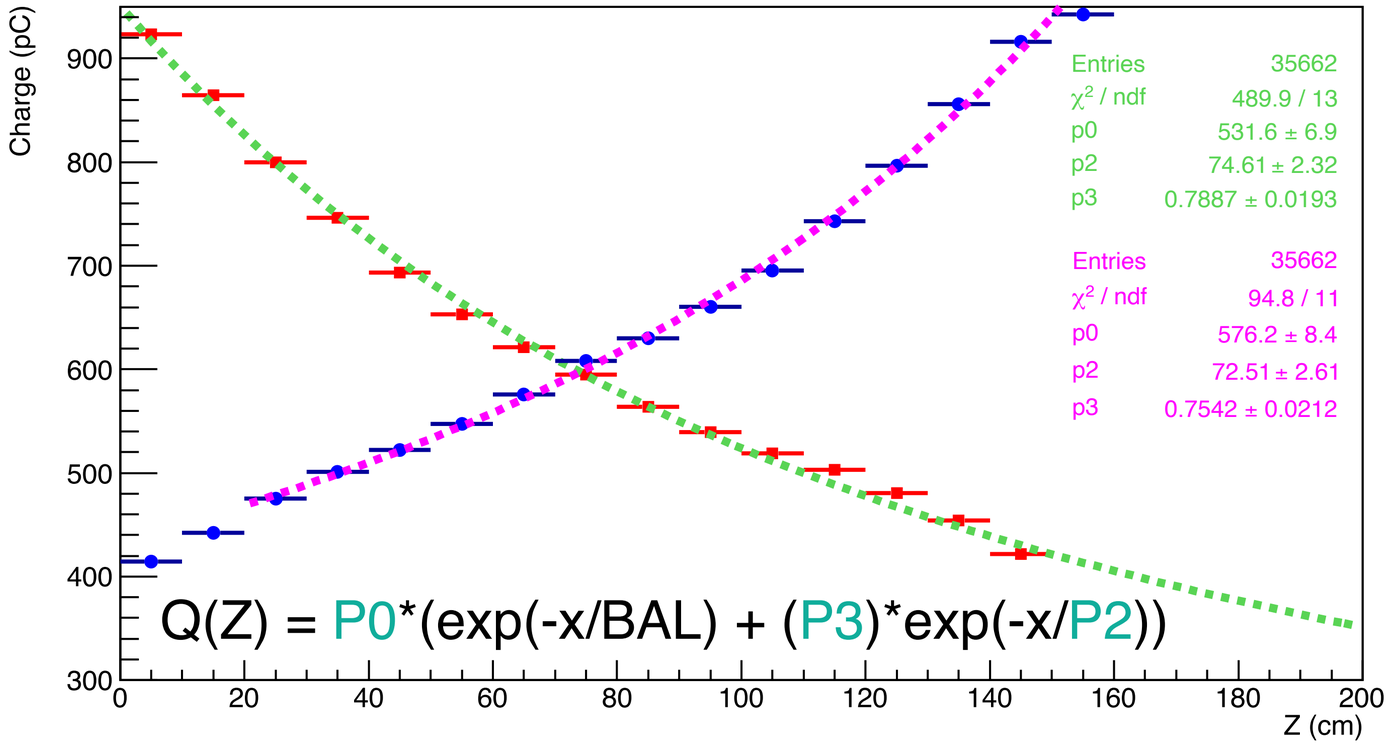
Cosmic Ray Tagger overview

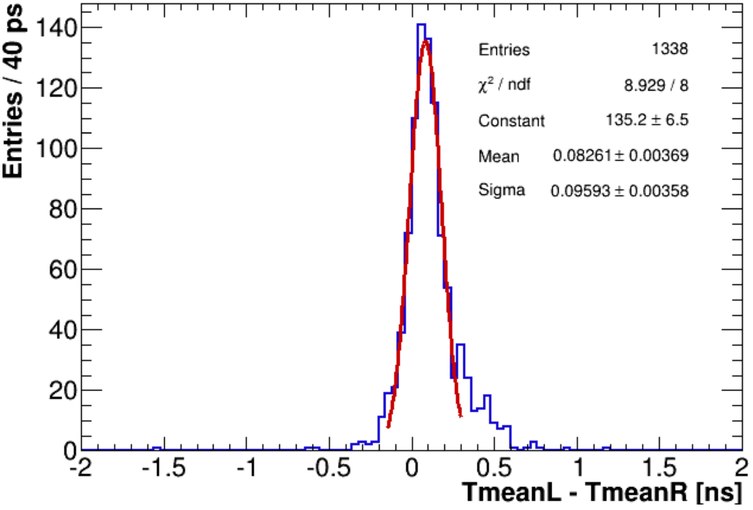
- 2 layers of 8 EJ200 scintillating bars
- double readout w/ Mu2e SiPM + FEE
- LO of 10000 photons/MeV
- fast 900 ps scintillation time
- 3800 mm attenuation length
- 15x25x1600mm3 dimensions
- Tyvek wrapping

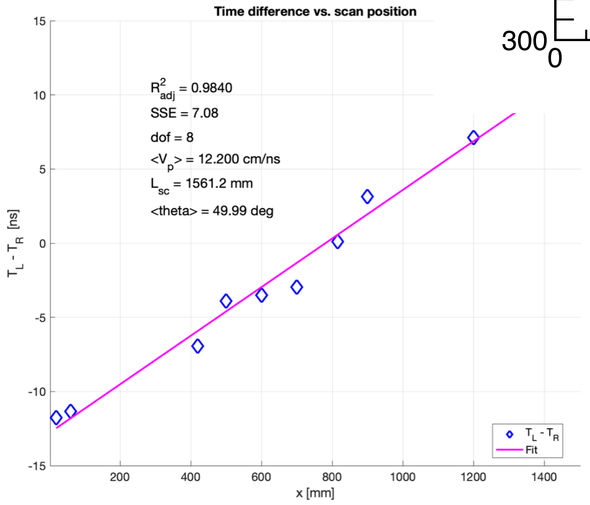


CRT single bar test

- 330 pe/MeV LY (@ L/2)
- Signal time by template fit
- Fitted light propagation speed <Vp> = 12.2 cm/ns
- Propagation angle <θ> = acos (n*V/c) = 49.99 deg
- Sigma (TL-TR) ~ 100 ps
- Time resolution ~ 100 ps / sqrt(2) ~ 70 ps
- Longitudinal resolution = V_f*sigma/2 ~ 6 mm
- Fitted technical **attenuation length 260-280 cm**





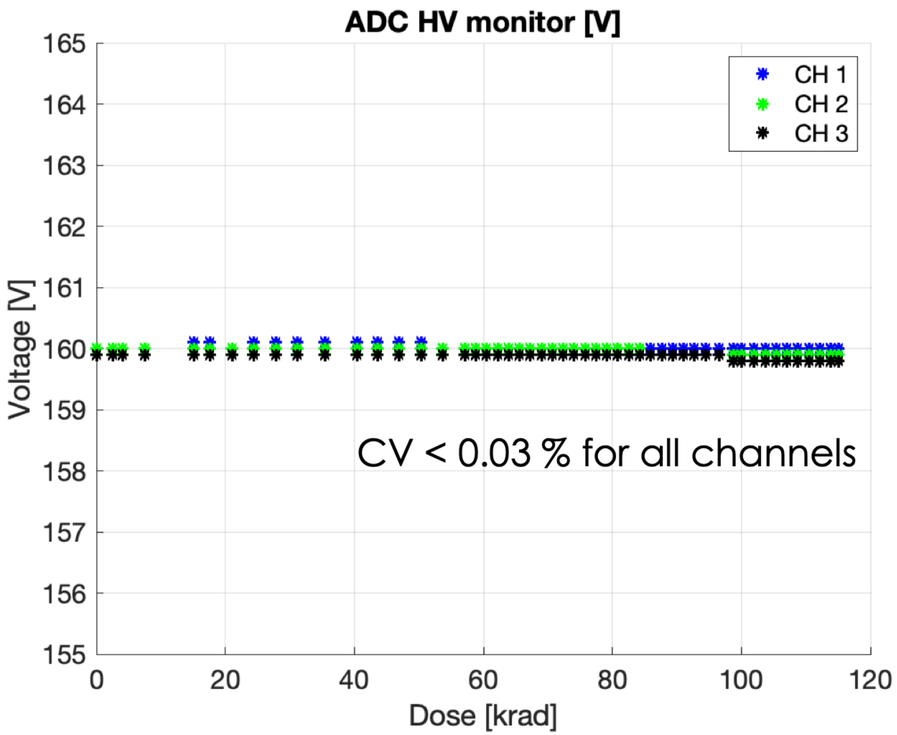


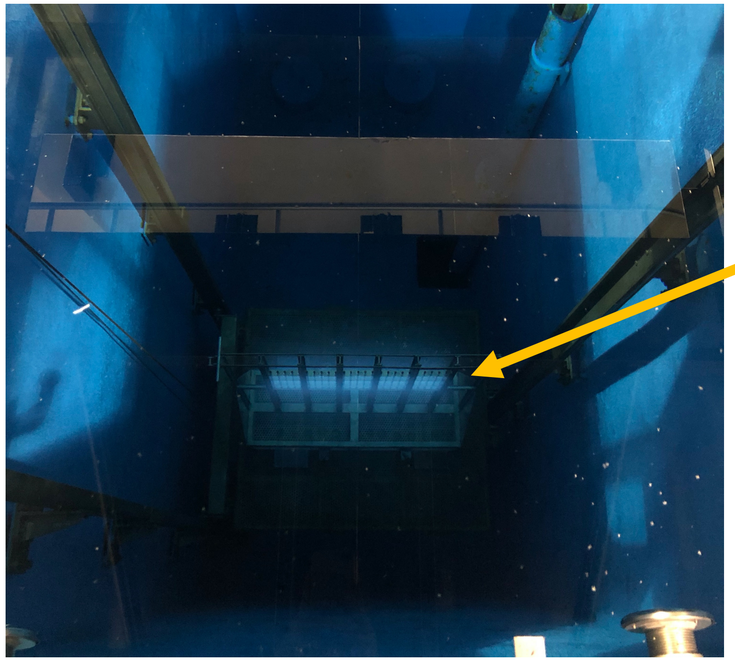
Next steps

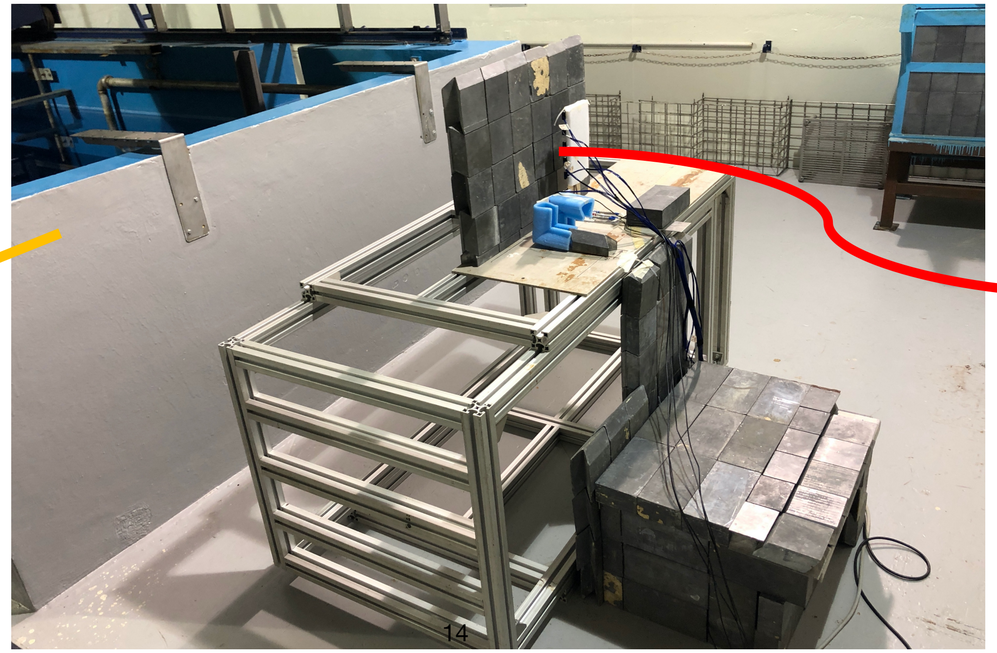
- Mechanical design of the CRT is being finalised
- Mechanical assembly due in september
- Disks calibration @ SiDET due in late 2021

FEE rad hardness

- TID test @ Calliope facility (60Co γ source)
- 100 krad integrated dose over 136 h
- Safety factor of 3 over 3 y run
- Linear regulator showed excellent stability
- ADCs & DACs showed excellent stability
- Mosfet performance ok







Design phase is concluded.

Installation due in mid 2021...

What to expect in the future?

Mu2e – what if ?

Signal?

Yes

Let's party!

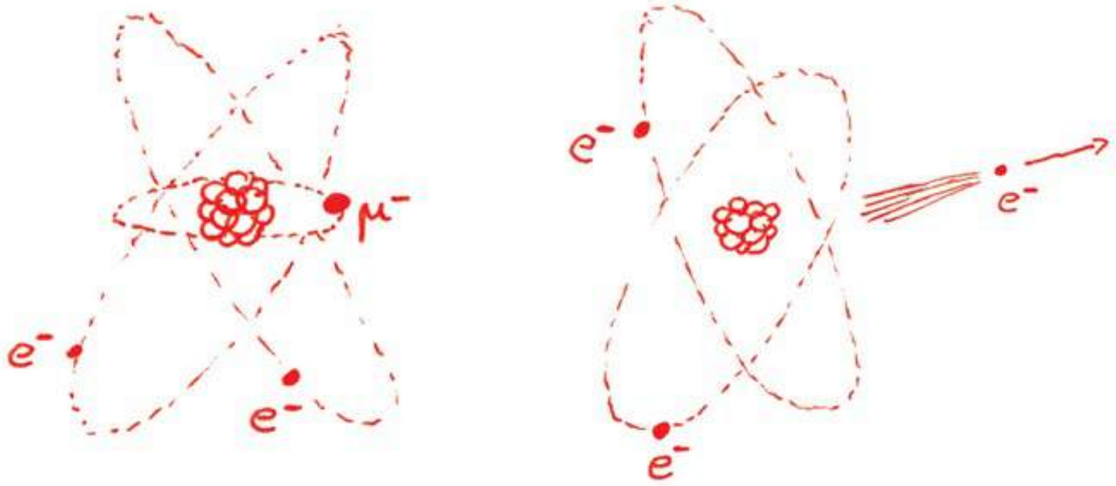
Change the target to study the underlying NP

Upgrade proton source and detector to achieve precision

No

Higher rates, background must decrease to measure $R_{\mu e}$ at 10^{-18}

Upgrade proton source and detector to improve sensitivity



THANKS FOR YOUR ATTENTION !

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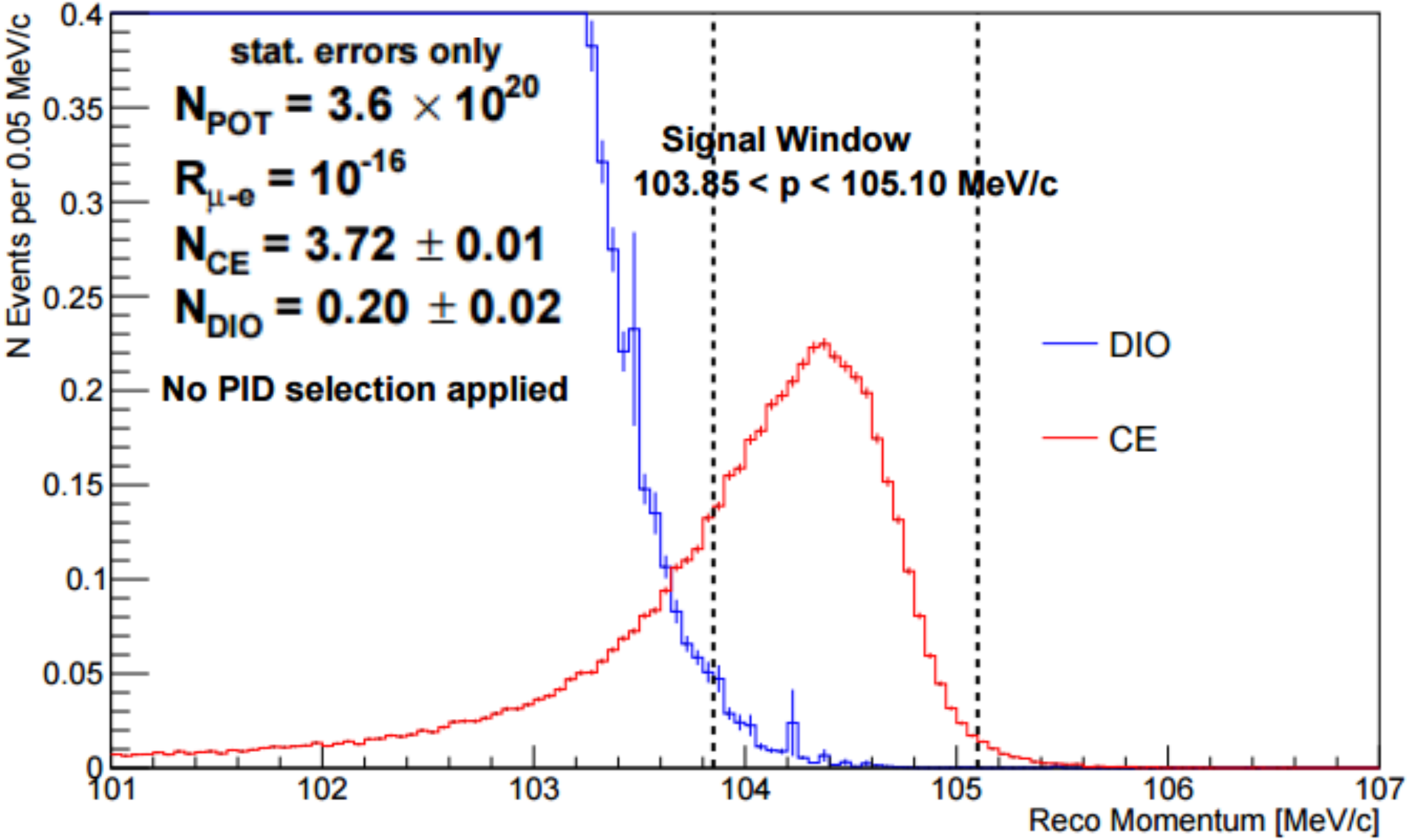
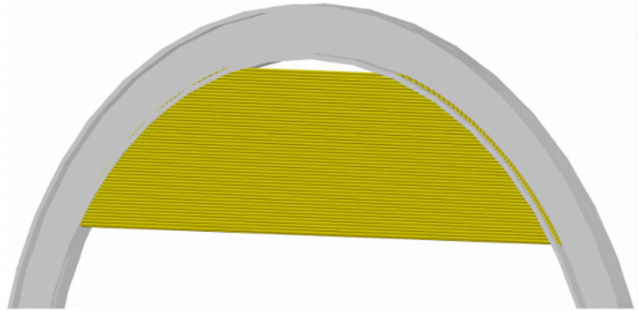
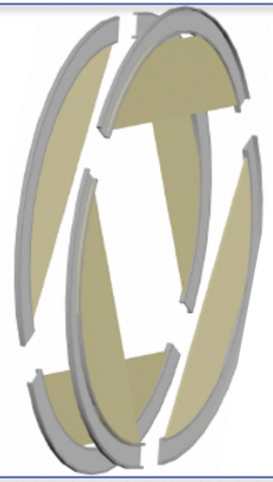
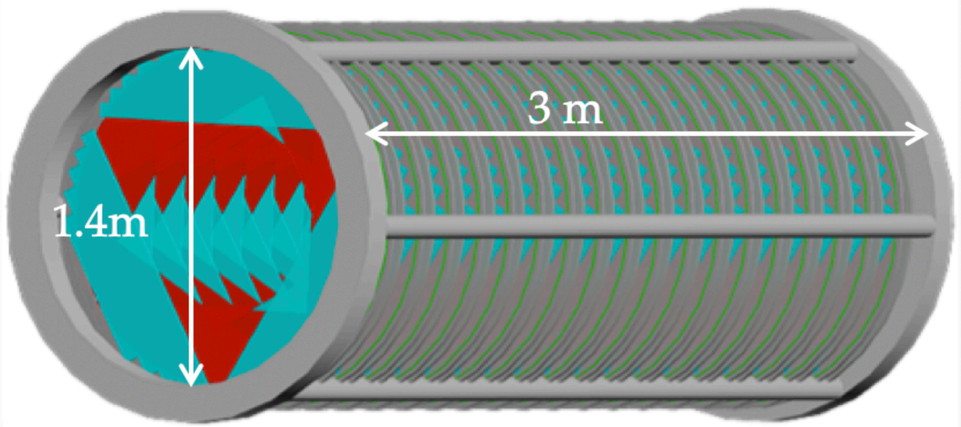
Backup slides

CE spectrum


stat. errors only
$N_{POT} = 3.6 \times 10^{20}$
$R_{\mu\text{-}e} = 10^{-16}$
$N_{CE} = 3.72 \pm 0.01$
$N_{DIO} = 0.20 \pm 0.02$
No PID selection applied
Signal Window
103.85 < p < 105.10 MeV/c
DIO
CE
N Events per 0.05 MeV/c
Reco Momentum [MeV/c]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
101
102
103
104
105
106
107

Tracker design

Straw tubes on a panel	One station	Tracker Structure
		

- ~ 20000 straw drift tubes, divided in 18 stations, 2 planes/station
- Each straw is 5 mm diameter, with 25 μm sense wire, 15 μm thick mylar walls
- 3 m long, 1.4 m diameter, in a uniform 1 T magnetic field

Momentum resolution < 170 keV/c (@ 100 MeV/c)

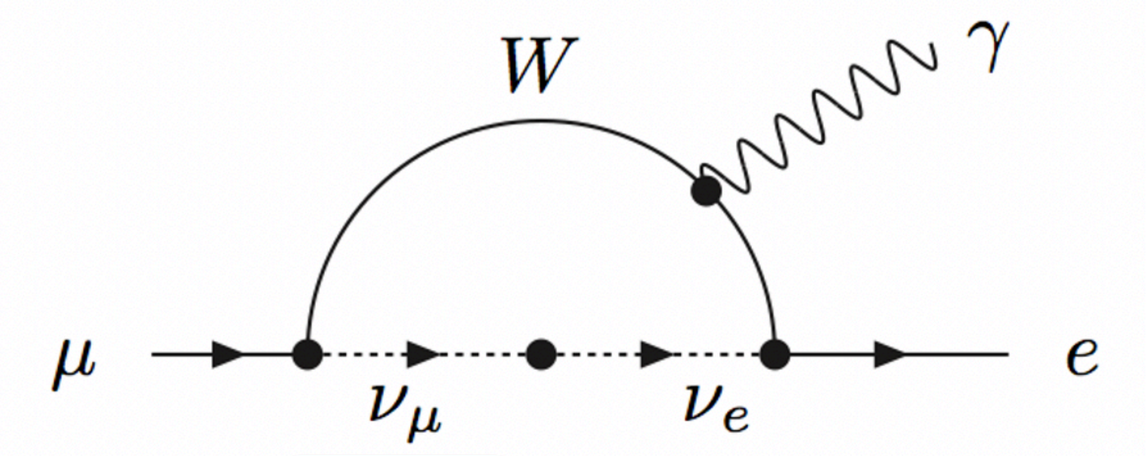
Timing resolution ~ 1 ns

Spatial resolution ~ 100 μm

CLFV loop interaction

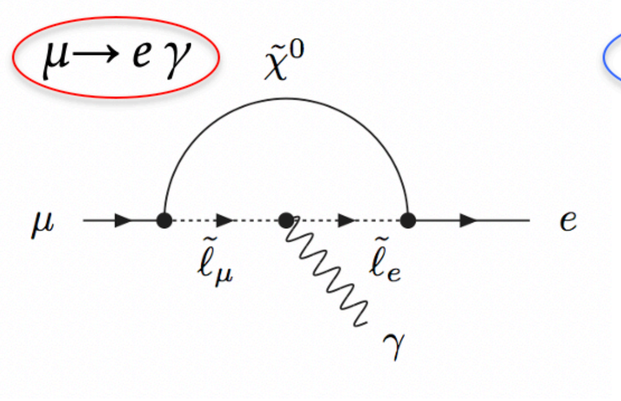
With neutrino mass, we know that lepton flavor is not conserved

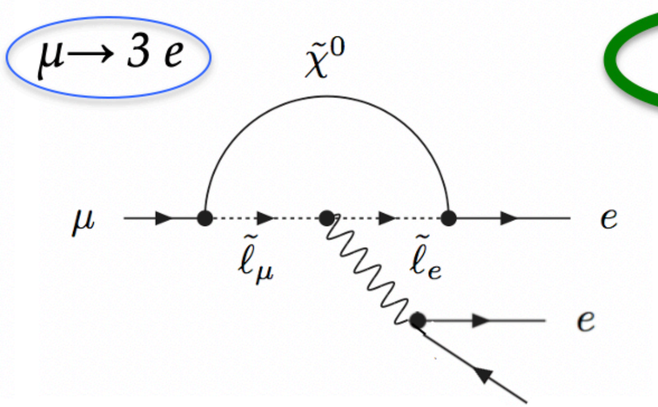
The SM CLFV process would be strongly suppressed:

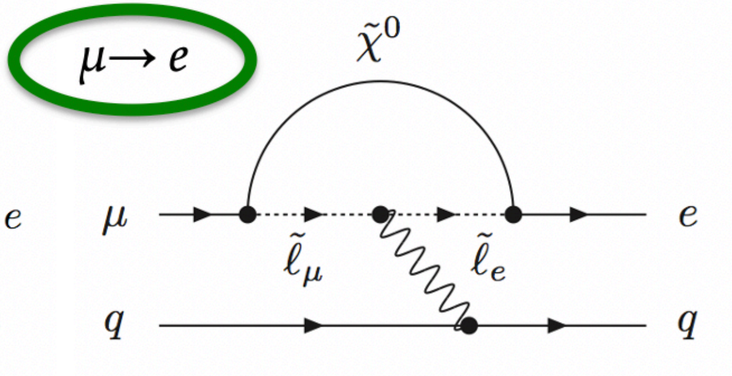


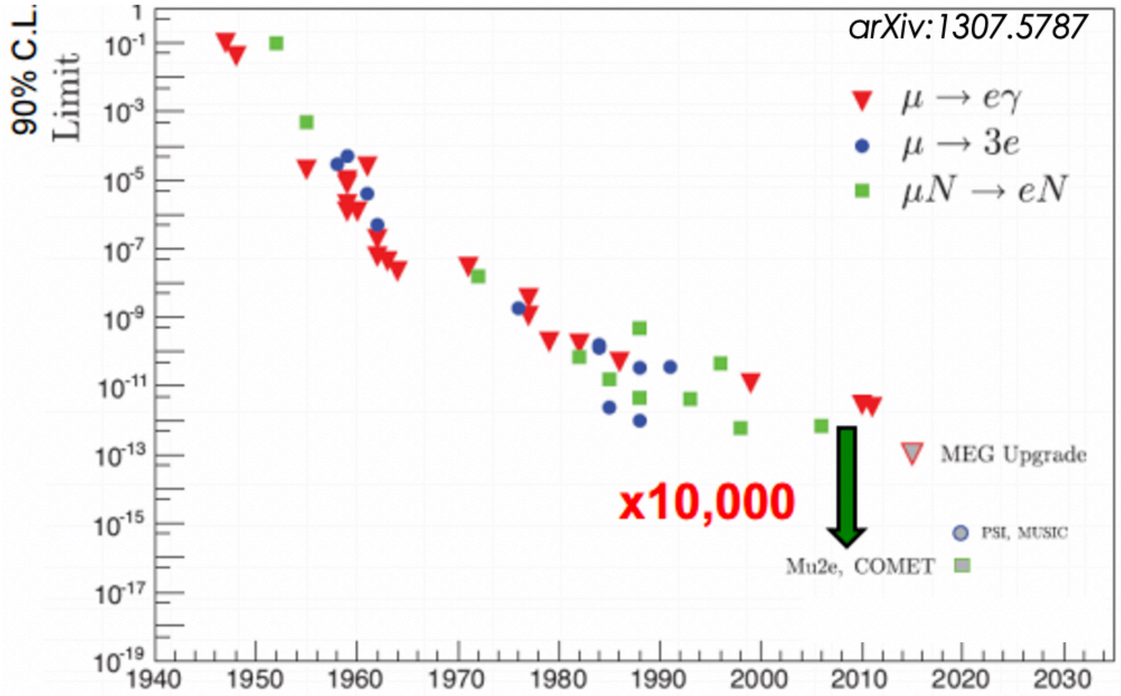
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}$$

CLFV history









Current best limits:

BR(μ→eγ) < 5.7 x 10^{-13} MEG2013

BR(μ→3e) < 1 x 10^{-12} SINDRUM1988

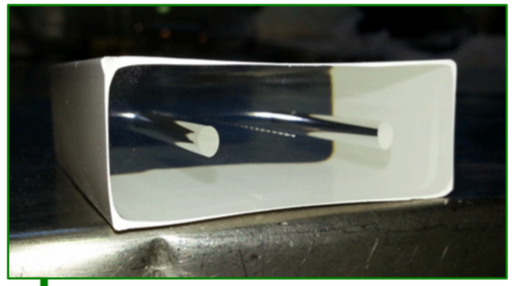
$R_{\mu e}$ < 6.1 x 10^{-13} SINDRUM-II 2006

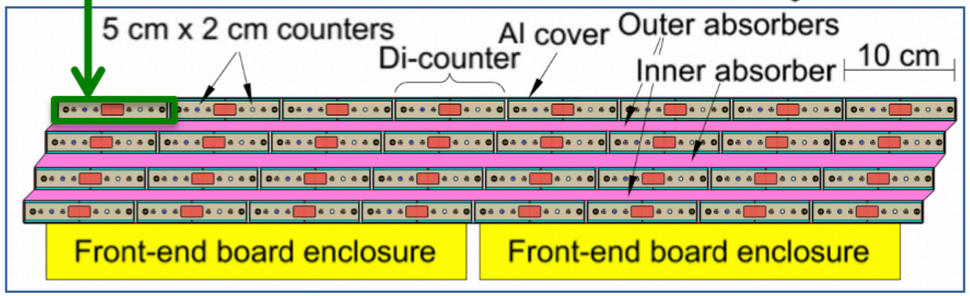
$R_{\mu e}$ = few x 10^{-17} Mu2e goal

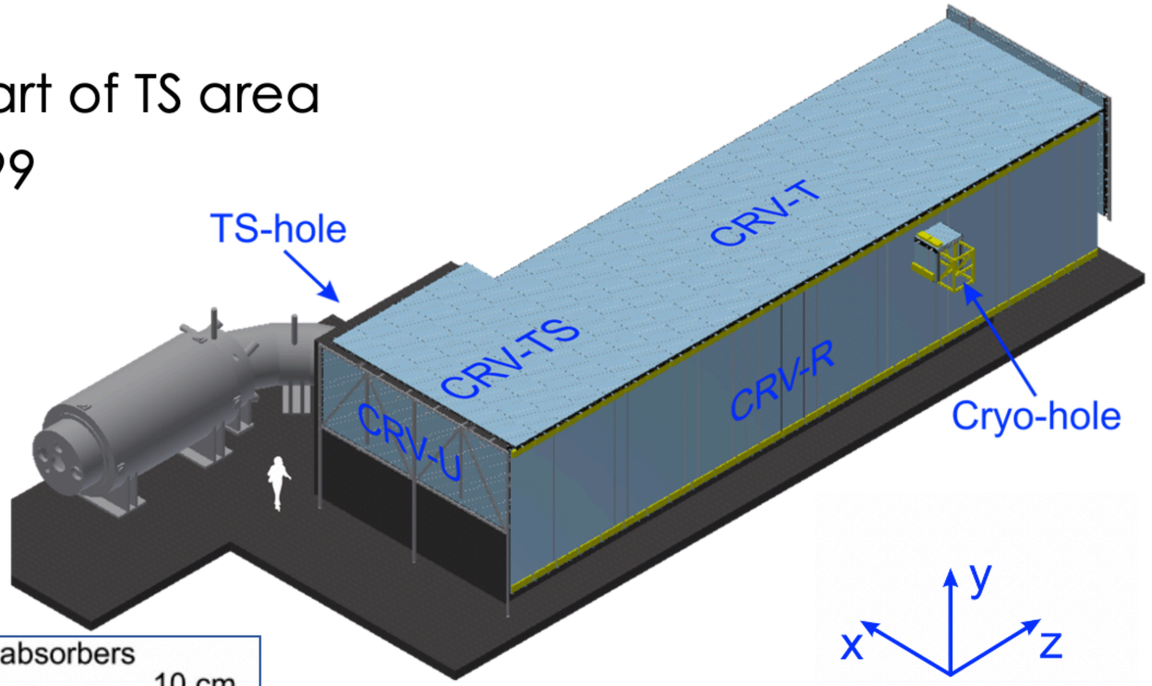
Cosmic Ray Veto

Cosmic Rays are a major sources of background → CRV required

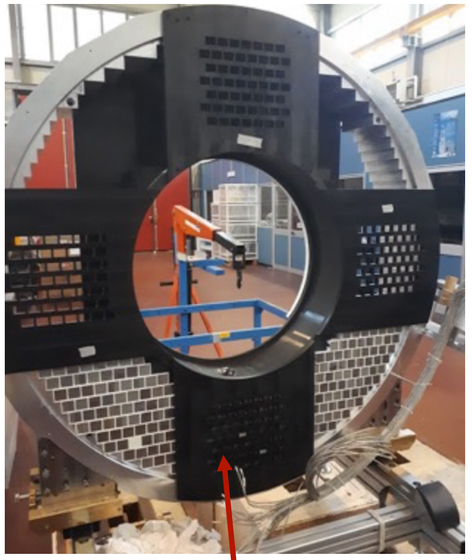
- Composed of 4 layers of overlapping scintillators (a coincidence of 3 out of 4 is used)
- Placed around DS and part of TS area
- Required efficiency: 0.9999

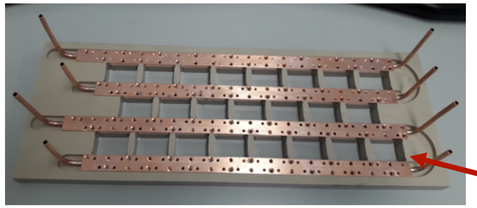


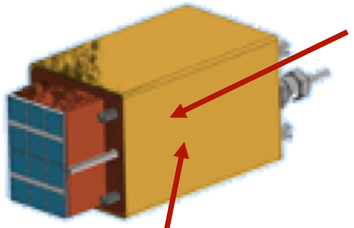
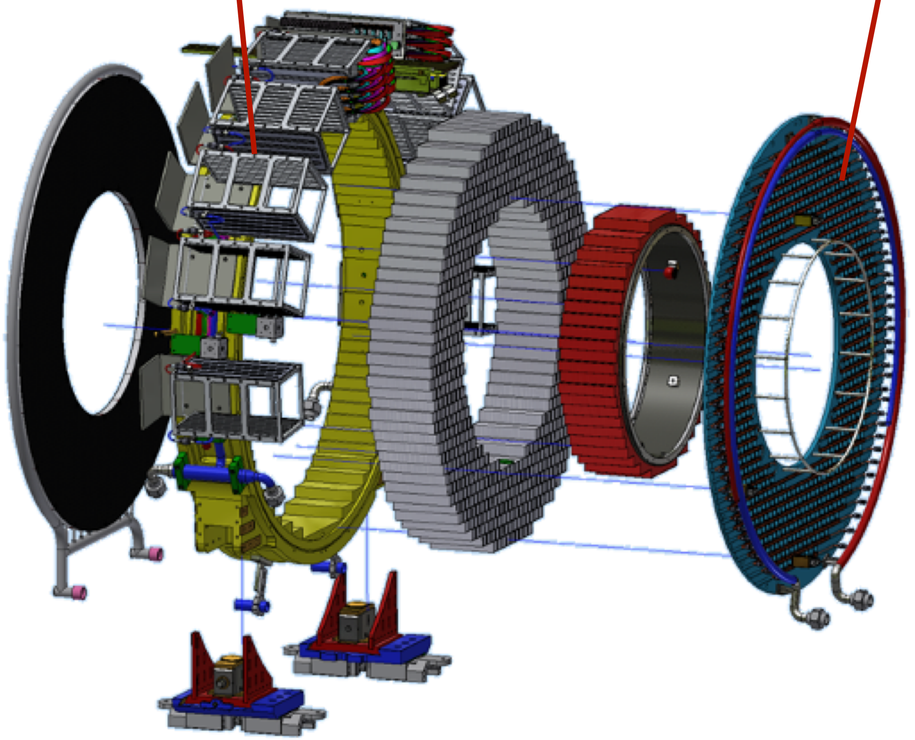
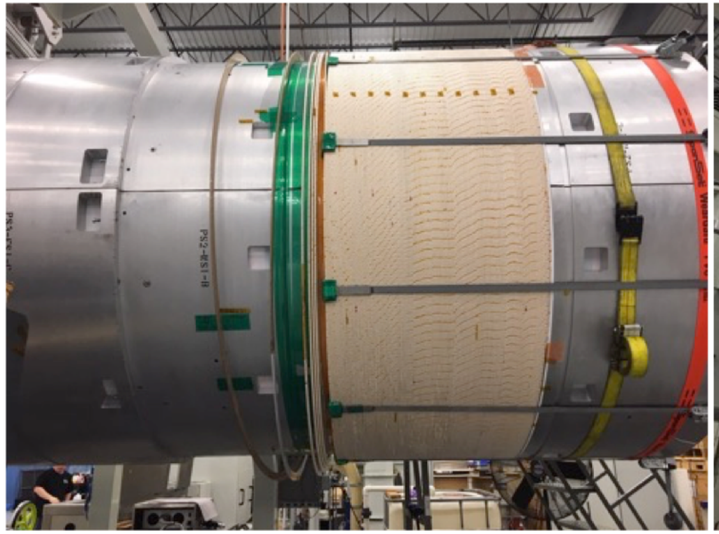
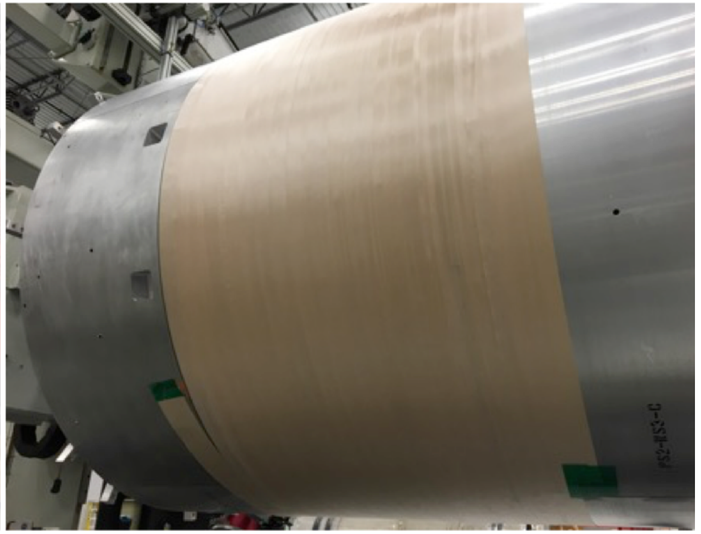




Mechanical design







1. Composite inner barrel
2. PEEK back panel for holding and housing cooling system
3. FEA completed: good stability, small stress on legs
4. FEE crates connected to the external cylinder
5. Two integrated calibration systems
6. Crystals stacked inside the outer SS ring