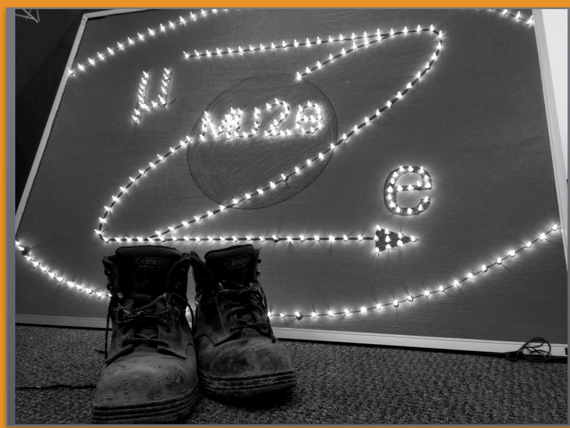

THE MU2E CRYSTAL CALORIMETER

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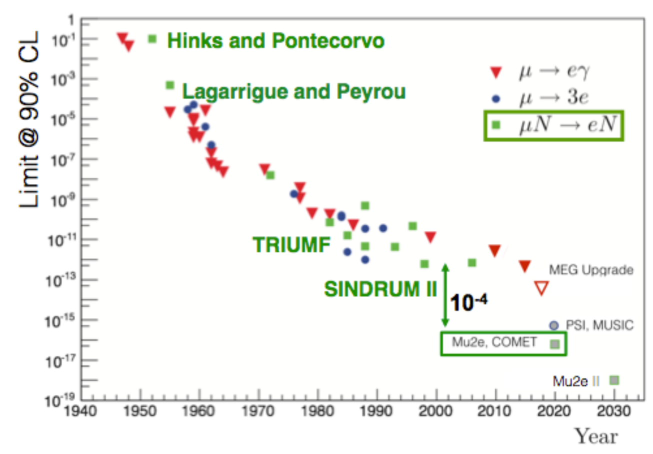
Abstract

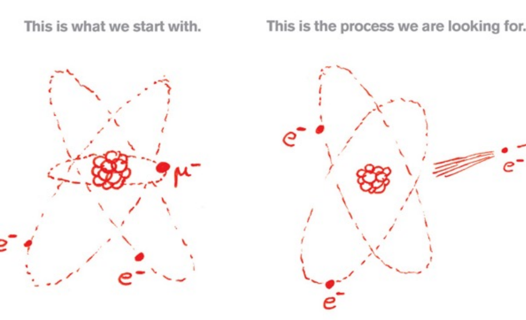
The Mu2e Experiment will search for coherent, neutrinoless conversion of muons into electrons in the field of a nucleus. Such a charged lepton flavor-violating reaction probes new physics at a scale inaccessible to direct searches at current high energy colliders. If no conversion events are observed in three years of running, Mu2e will set a limit on the ratio between the conversion rate and the capture rate, $R_{\mu e} < 6 \times 10^{-17}$ (@ 90% C.L.). The Mu2e calorimeter is composed of 1348 undoped CsI crystals coupled to large area UV-extended Silicon Photomultipliers. The calorimeter has to provide precise information on energy, timing and position. It should also be fast enough to handle the high background rate and it must operate at 10^{-4} Torr, in a 1T field and in a high radiation environment.

The Mu2e experiment

- Mu2e will search for neutrinoless coherent μ^- Al → e^- Al at a sensitivity level around 2.4×10^{-17}, improving by 10^4 the existing limit. SM: BR ($\mu \to e\gamma$) ~ $\Delta m_\nu^2 / M_W^2 < 10^{-54}$
- Search for muon conversion explores new physics sector and probes physics scales up to ~ 10^4 TeV
- Mu2e will detect and count the electrons coming from the conversion decay of a muon with respect to standard muon capture:

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

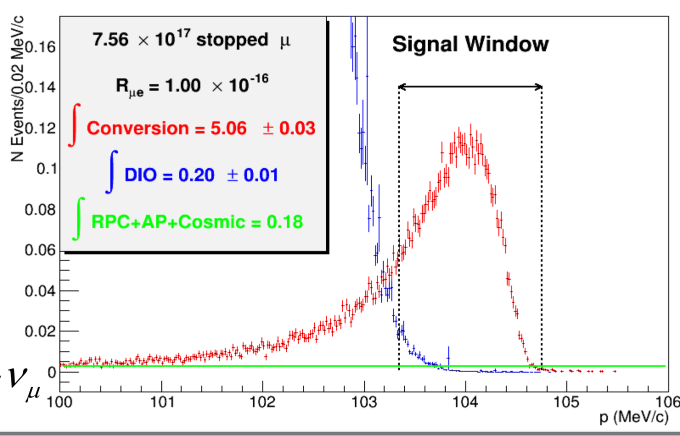




Conversion signature: **single electron** with a **mono-energetic spectrum** close to the muon rest mass.

To discriminate from standard decay in orbit signal we need a **high resolution spectrometer**

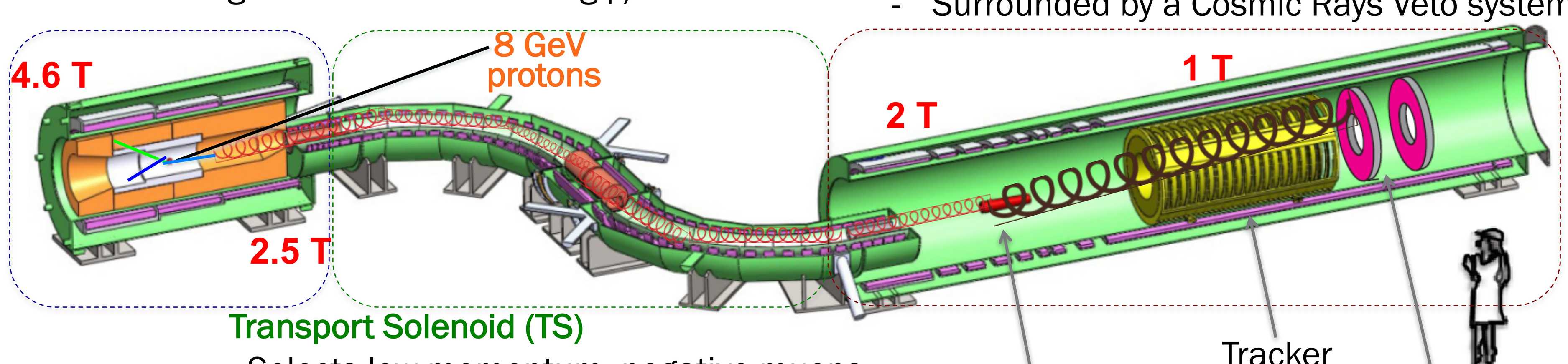
$$[\mu^- + A(N,Z)]^{1S}_{bound} \to A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$



Apparatus

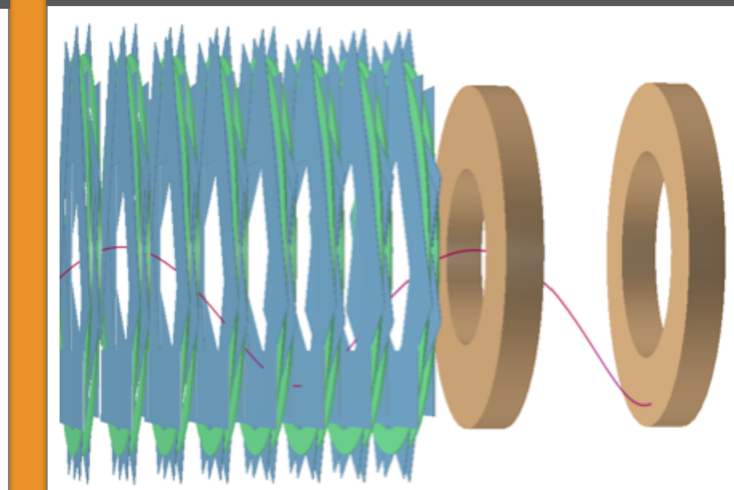
Production Solenoid (PS)
- 8 GeV Proton beam on Tungsten target
- Graded magnetic field for collecting μ/π

Detector Solenoid (DS)
- Capture μ on Al target
- Houses the detector system in 1 T B field
- Surrounded by a Cosmic Rays Veto system

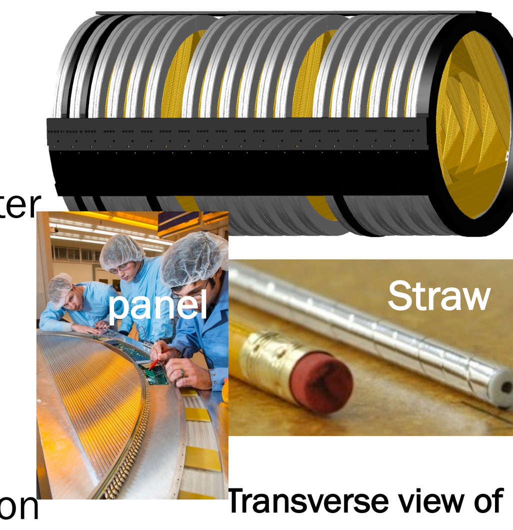


Transport Solenoid (TS)
- Selects low momentum, negative muons
- Antiproton absorber in the mid-section

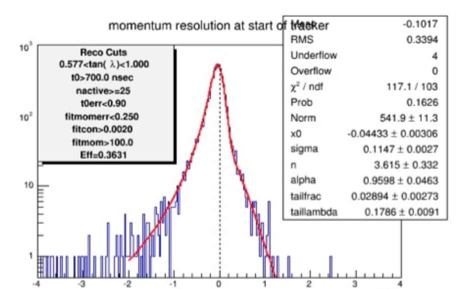
Detector system and Calorimeter design

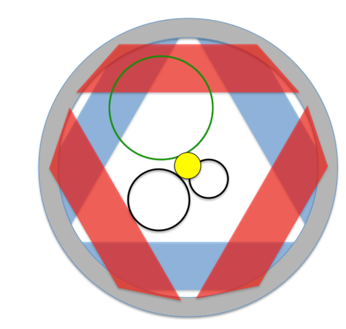


Tracker
- Low mass straw drift tubes transverse to secondary beam
- 15 μm thickness, 5 mm diameter, length 430 – 1120 mm
- Dual-ended readout,
- ~ 20000 tubes arranged in planes on 18 stations
- 115 keV/c momentum resolution



Calorimeter requirements
- Particle Identification to distinguish e/mu
- Seed for track pattern recognition
- Tracking independent trigger
- Work in 1 T field and 10^{-4} Torr vacuum
- Radiation hard up to 100 krad, 10^{12} n/cm²/year





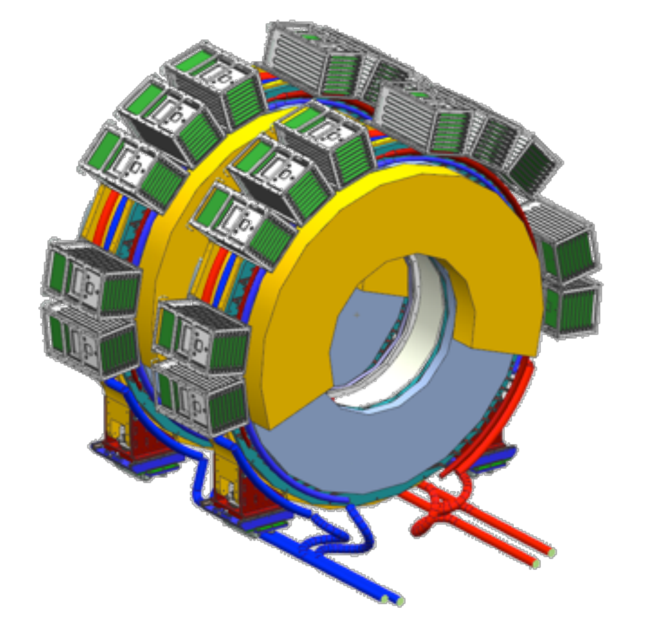
Transverse view of a tracker station

Calorimeter choice

High granularity crystal based calorimeter with:
- **σ/E of O(5%)** and **time resolution < 500 ps**
- **Position resolution of O(1 cm)**
- Almost full acceptance for conversion signal @ 100 MeV

Disks geometry
- 2 disks: each disk containing 674 un-doped CsI crystals of 20 x 3.4 x 3.4 cm³ dimension
- Disk separation ~ 75 cm
- Inner/outer radii: 37.4/66 cm
- Readout system:
  2 custom arrays of 2x3 6x6 mm² SiPMs/crystal
  1 FEE/SiPM-array
  12 bit, 200 Msps waveform digitizer boards (WD)

Calorimeter disks

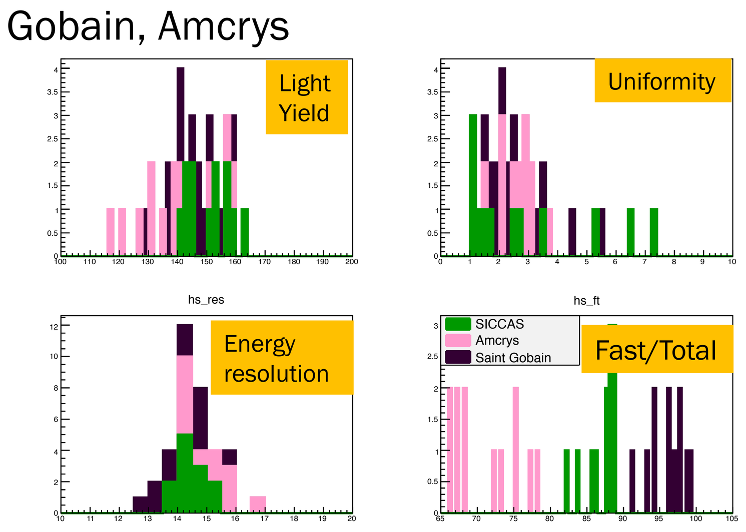


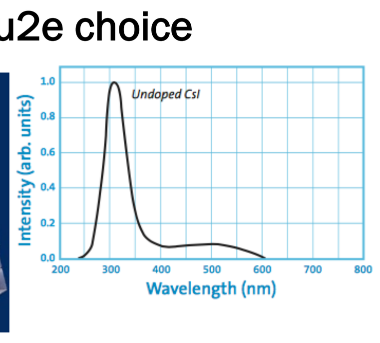
Undoped CsI Crystals

Mu2e crystals requirements
- High light output (LY) > 100 pe/MeV
- Longitudinal response uniformity < 5 %
- Fast signal with small slow component: τ < 40 ns, F/T > 75%
- Radiation hard with LY loss < 40% for:
  Ionization dose: 100 krad
  Neutrons: 10^{12} n/cm²
  Small radiation induced readout noise: < 0.6 MeV

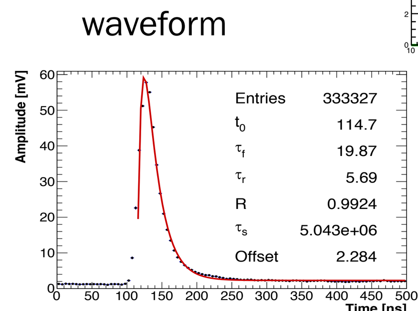
Undoped CsI is the Mu2e choice

60 preproduction crystals from 3 different vendors: Siccas, St. Gobain, Amcrys

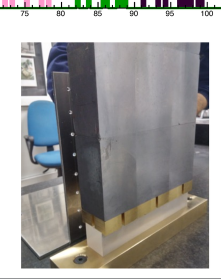




CsI + UV PMT waveform



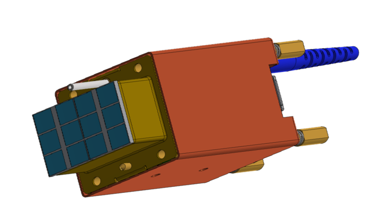
Mechanical stress test
45 Kg dead load

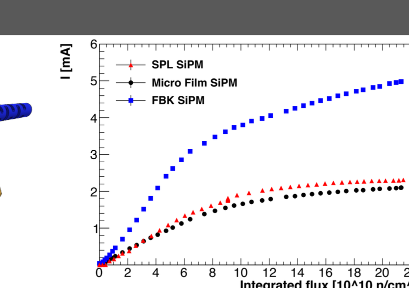


Silicon Photomultipliers, SiPMs

Solid state photodetectors, such as SiPMs, able to work inside the 1 T axial magnetic field

Requirements:
- High quantum efficiency @ 315 nm
- High gain, fast signal, low noise
- Large active area to maximize pe/MeV collected; 2 Sipm/crystal
- Withstand a radiation environment of 3×10^{11} n/cm² @ 1 MeV_{eq} and 20 krad of dose

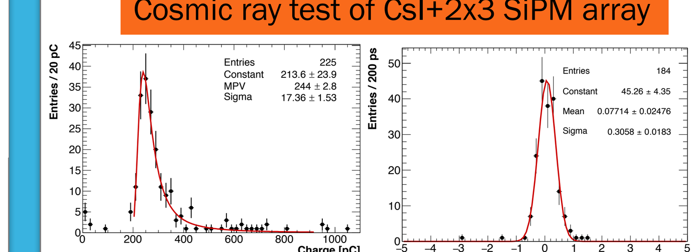




Neutron test

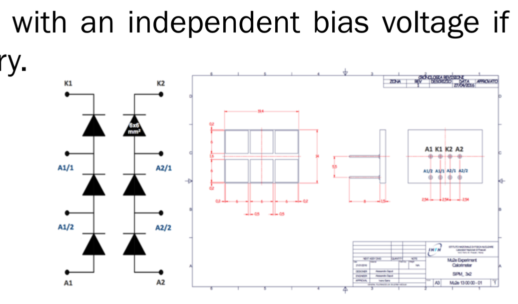
I_{dark} increase due to neutron and dose induced damage is still acceptable, but requires cooling down the SIPM to ~ 0 ◦C

Cosmic ray test of CsI+2x3 SiPM array

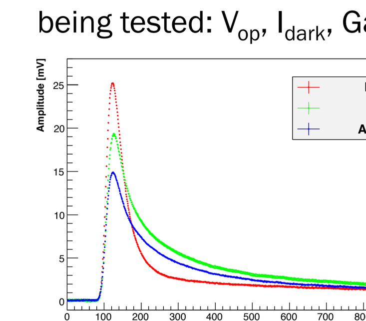


Final resolution for 1 MIP (~20 MeV) → ~ 170 ps

Custom design: 2x3 array of individual 6x6 mm² monolithic UV extended SiPM's (thin film, silicone resin). We will read out the sum of the two series. Each series could be powered with an independent bias voltage if necessary.



Prepoduction SiPM from 3 different vendors, Hamamtsu, Sensl, Advansid being tested: V_{op}, I_{dark}, Gain, PDE@Vop



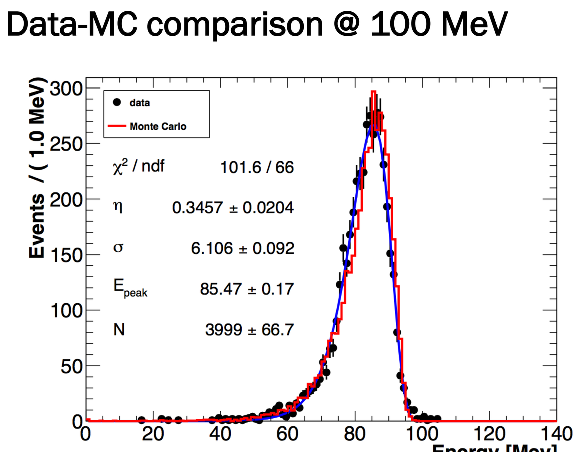
Pulse Shape @ 511 MeV

Calorimeter prototype performances

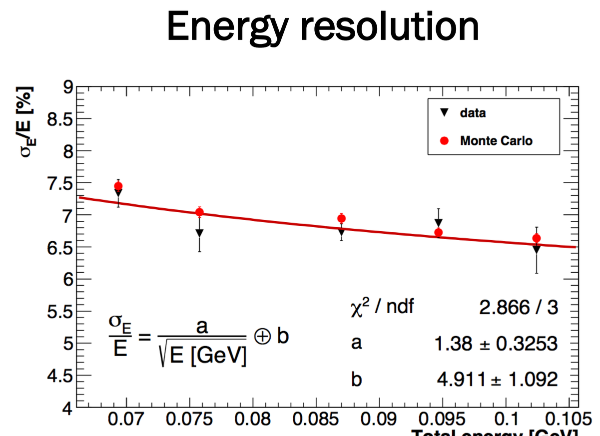
Prototype:
- A 3 x 3 array of undoped CsI crystals 3 x 3 x 20 cm³ coupled to Hamamatsu SiPMs
- Beam orthogonal or at 50° to the prototype face
- Beam energy: 80 - 120 MeV (in 10 MeV steps)

Energy and time measurements
- Energy reconstructed by numerical integration of the waveform
- Time reconstructed by fitting the waveform leading edge, and setting the time at a fixed fraction of the max pulse-height

Data-MC comparison @ 100 MeV

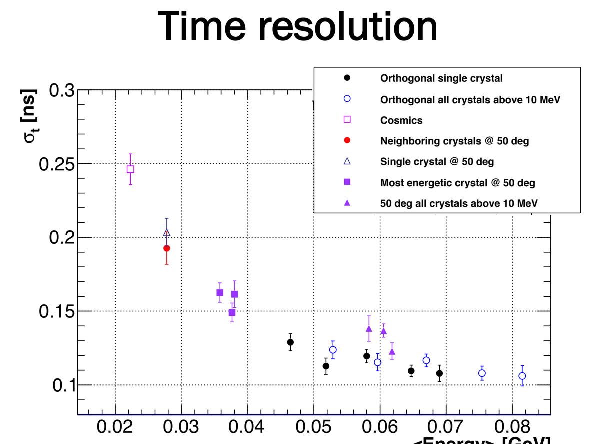


Energy resolution



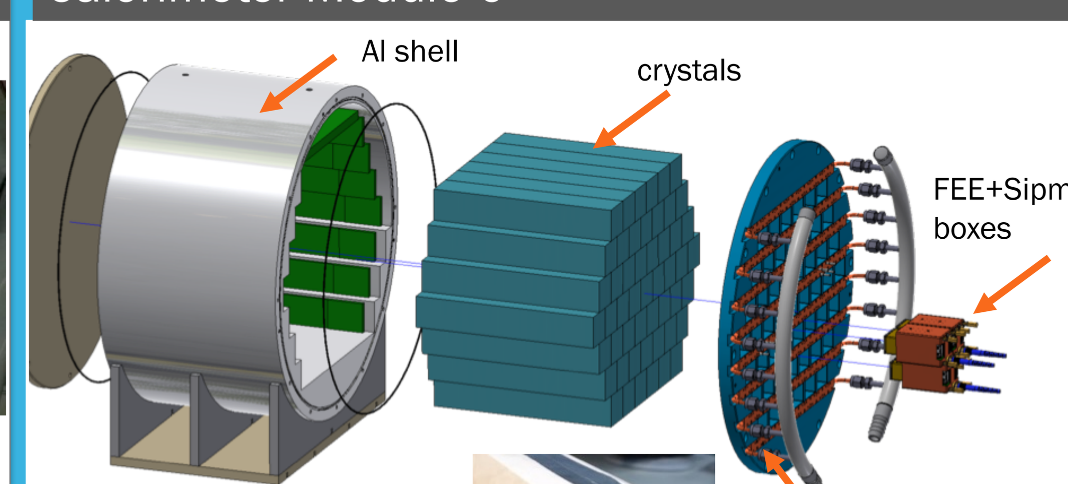
Energy resolution ranges between 6.5 to 7.5 % dominated by leakage

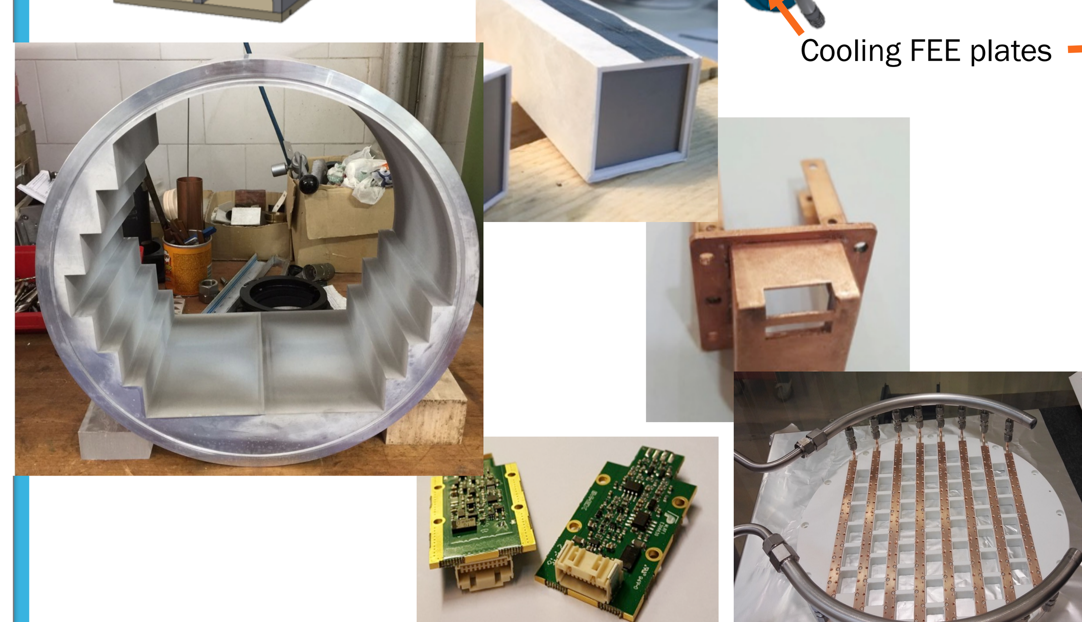
Time resolution



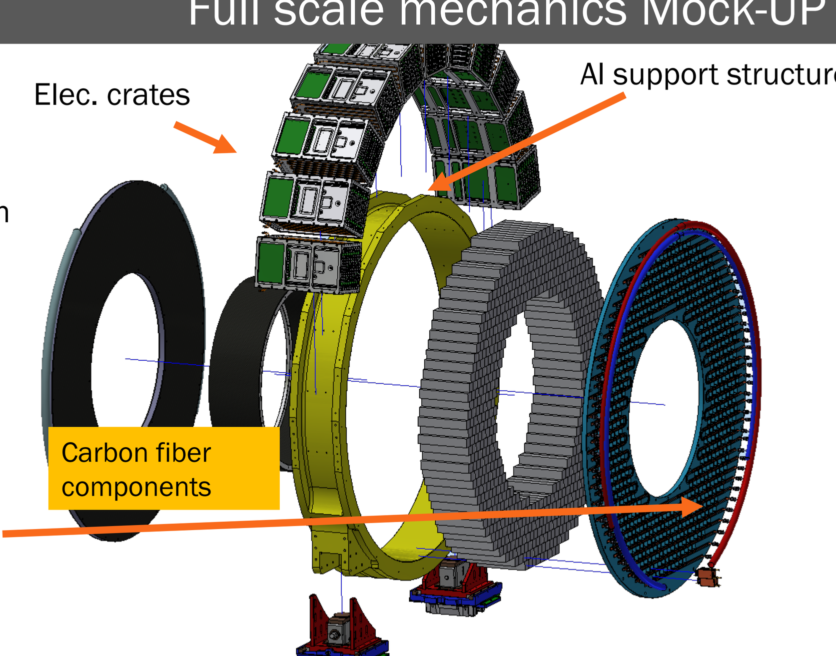
Time resolution 110 ps @100 Mev

Calorimeter Module-0





Full scale mechanics Mock-UP



Conclusions

Results from 2 years long R&D phase show that undoped CsI crystals perform well providing fast signals for the Mu2e requirements, good LY, LRU and a small slow component. The new generation of UV extended SiPMs is a good match to CsI crystals. The selected match of crystals and sensors shows good radiation hardness for the expected doses in Mu2e.

The beam test results well satisfy the Mu2 calorimeter requirements: time resolution better than 200 ps @ 100 MeV; energy resolution of about 7% @ 100 MeV (due to leakage).

An additional gain factor of √2 on timing is expected given the double SiPM readout. A test beam with a larger prototype with final characteristics, Module-0, is planned in Spring of 2017:
- 51 crystals coupled to 2 SiPM with final FEE and digital readout will be exposed to a 100 MeV electron beam at the Frascati Beam Test Facility.
- A beam test with module-0 will be repeated after exposing it to a large neutron flux and radiation dose.

The construction of the Module-0 is underway, most of the parts are being manifactured and it will be assembled in March 2017

We are building a full scale Mock-Up of the calorimeter mechanics to optimize the assembly procedures and the cooling system for SiPM and Front End Electronics

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