The Mu2e Experiment at Fermilab and the Calorimeter

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On behalf of the Mu2e Collaboration

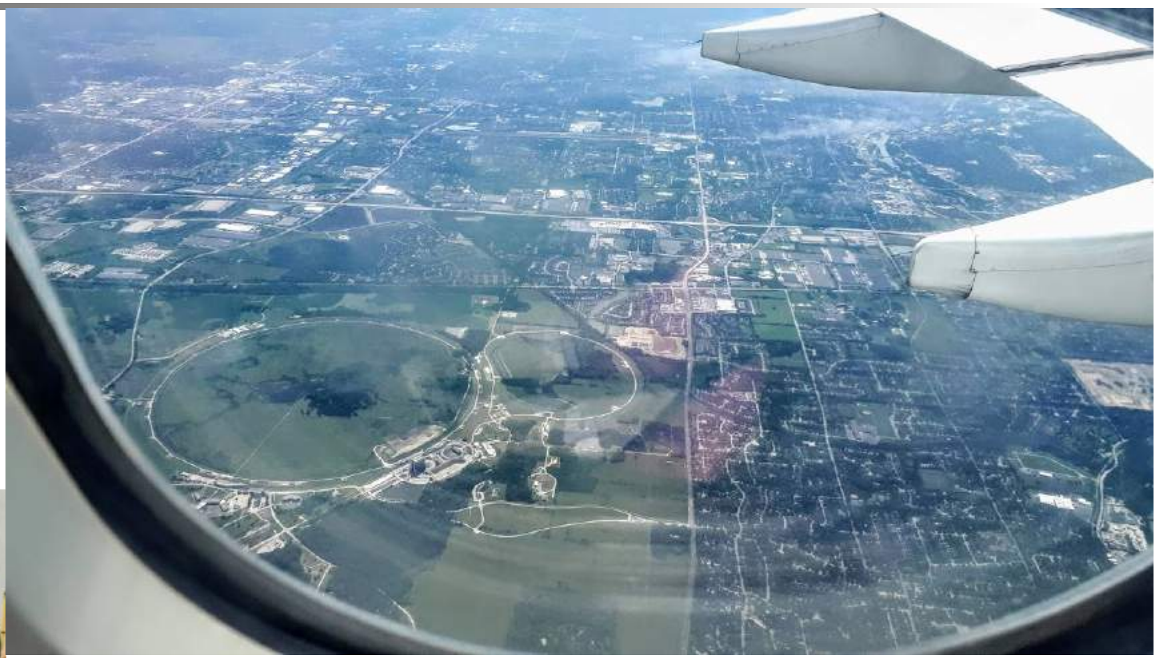
Joint Workshop on Future charm-tau Factory

Moscow, 24-28 Sep, 2019

Presentation outline

- Where, Why Muon 2 Electron conversion
- How, the experimental technique
- Accelerator complex
- A Little on the Tracker
- The undoped CsI+SiPM crystal Calorimeter
  - Crystals
  - Potosensors
  - mechanics
- Conclusions

The Mu2e collaboration @FNAL muon campus

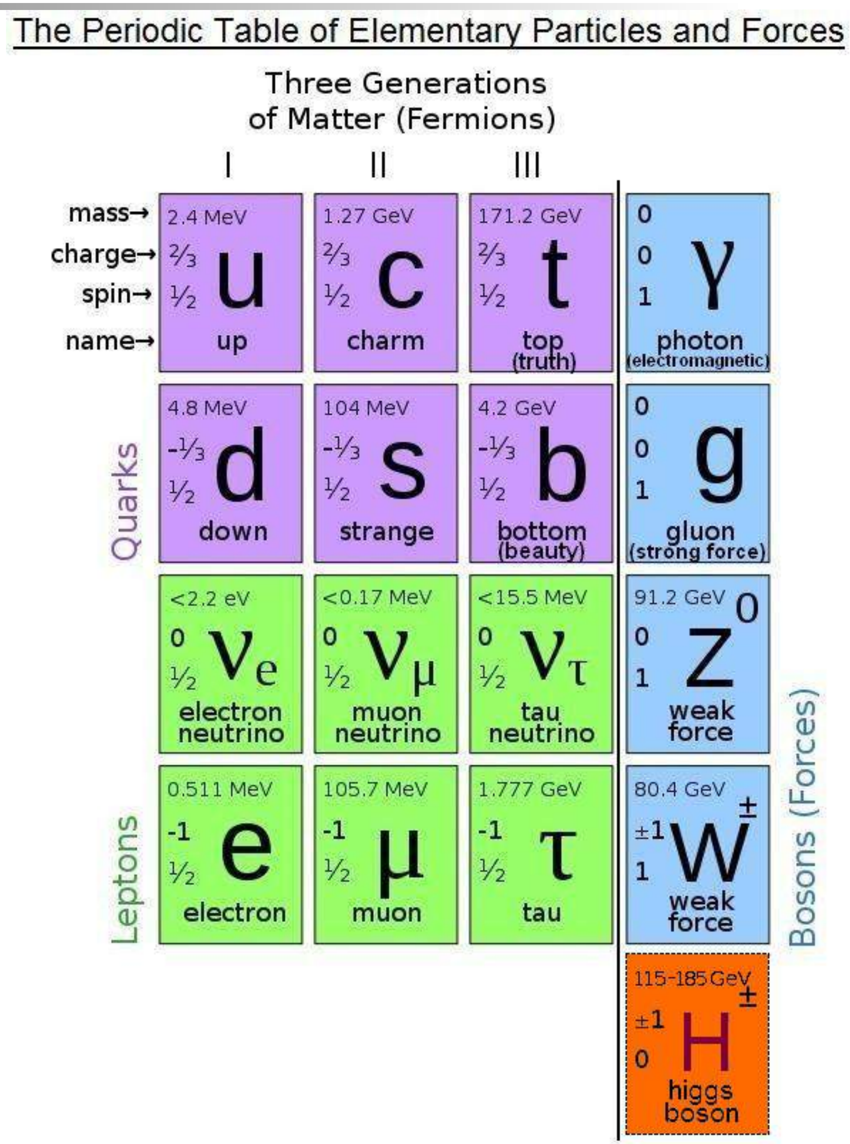


~230 Scientists from 37 Institutions

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

Intro

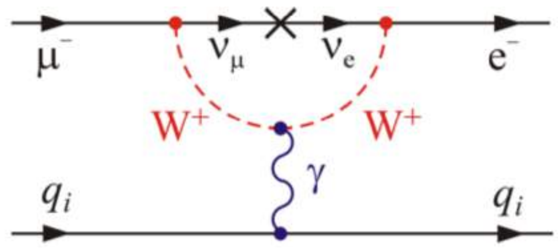
- We've known for a long time that quarks mix via W→ (Quark) Flavor Violation
  - Mixing strengths parameterized by Cabbibo-Kobayashi-Maskawa - CKM matrix
- In last 15 years we learned that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by Pontecorvo-Maki-Nakagawa-Sakata - PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)



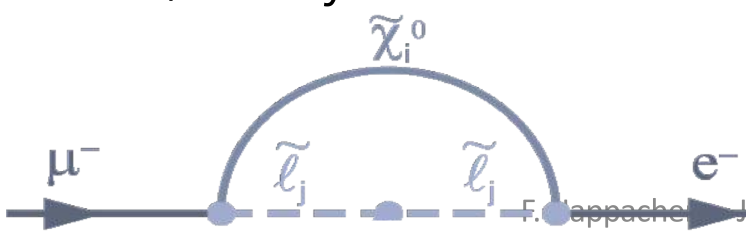
Why a Search for $\mu^- N \rightarrow e^- N$?

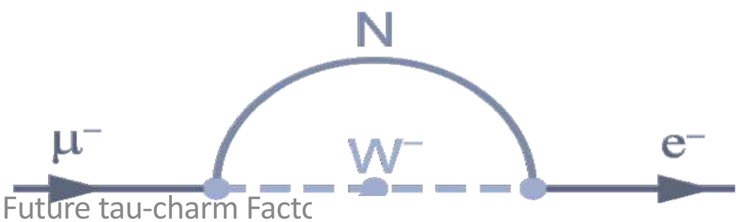
- Mu2e searches for muon-to-electron conversion in the coulomb field of a nucleus
- CLFV processes are strongly suppressed in the Standard Model
  - it is not forbidden due to neutrino oscillations
  - In practice $BR(\mu \rightarrow e\gamma) \sim \Delta m_\nu^2 / M_W^2 < 10^{-54}$

    thus not observable



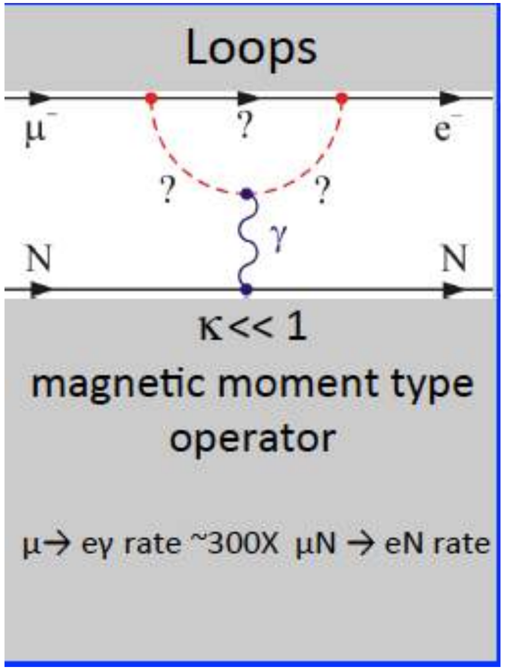
- BSM Physics could enhance CLFV rates to observable values
- Muon-to-electron conversion is similar but complementary to other CLFV processes as $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$.
- A detected signal would be evidence of physics beyond the SM (BSM) - Susy, Compositeness, Leptoquark, Heavy neutrinos, Second Higgs Doublet, Heavy Z'

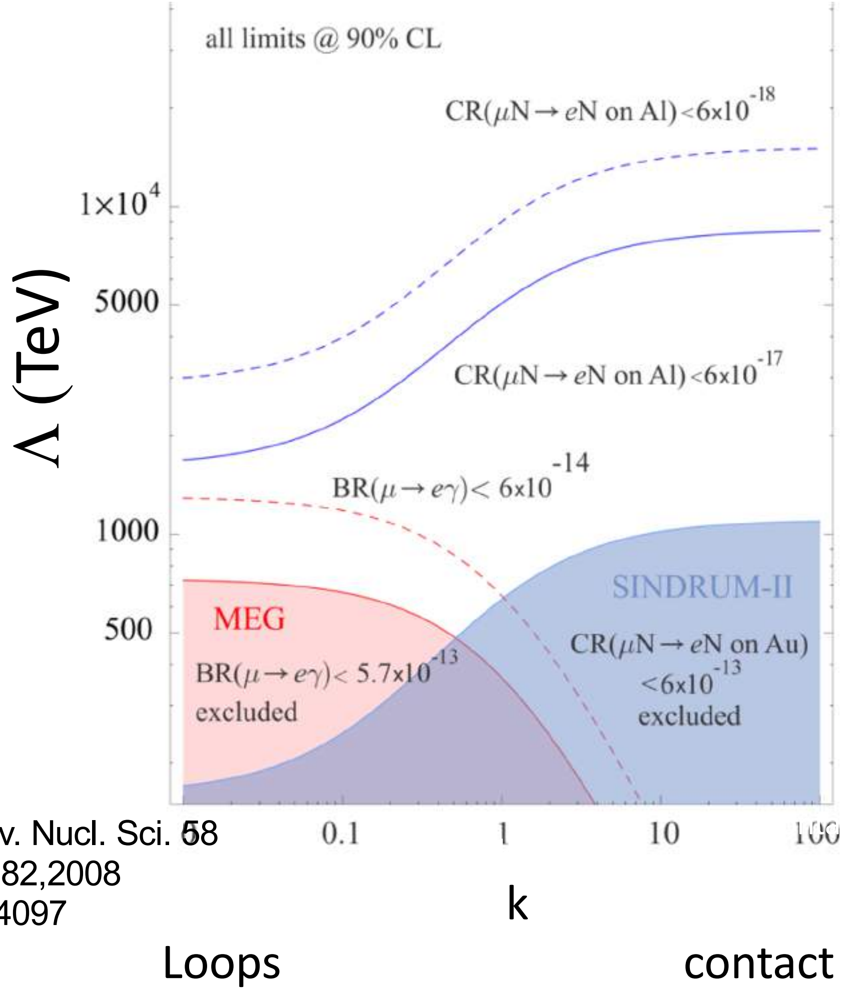


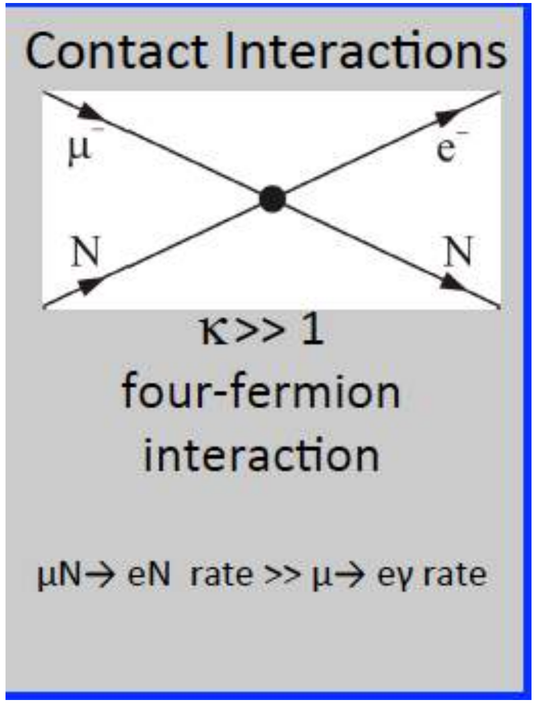


Mu2e Sensitivty

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







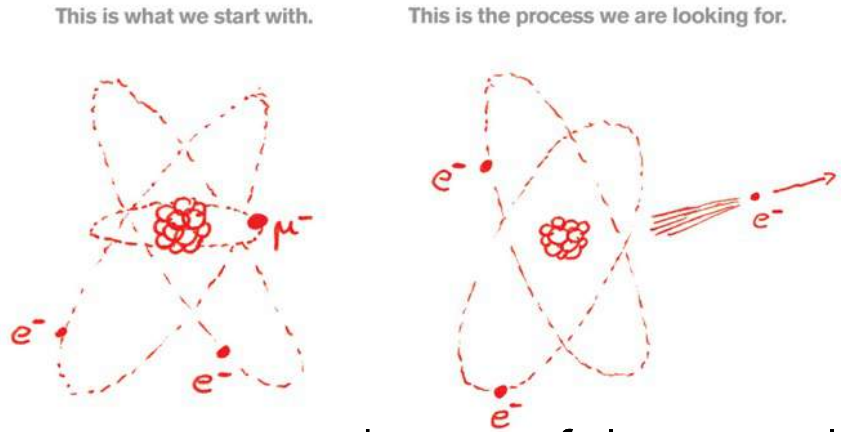
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

Mu2e Sensitivity best in all scenarios

What is Mu2e

– Will search the conversion of a muon into an electron after stopping it

$\mu^{-} Al \rightarrow e^{-} Al$



– Will use current the intense proton beam of the Fermilab accelerator complex to reach a single event sensitivity of ~2.5 x10^{-17} i.e. 10^{4} better than current world's best (Sindrum II)
– Will have *discovery* sensitivity over broad swath of BSM Physics parameter space
– Mu2e will detect and count the electrons coming from the conversion decay of a muon with respect to standard muon capture

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

As low probability as this!

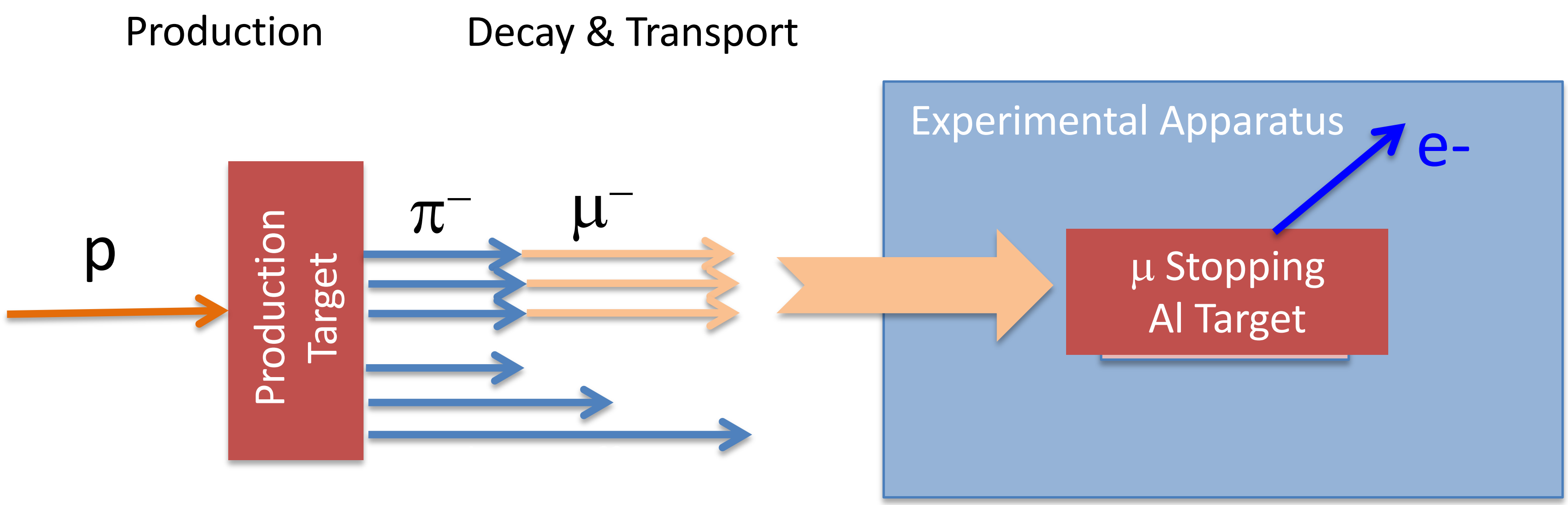
Some Perspective

1,000,000,000,000,000,000

= number of stopped Mu2e muons

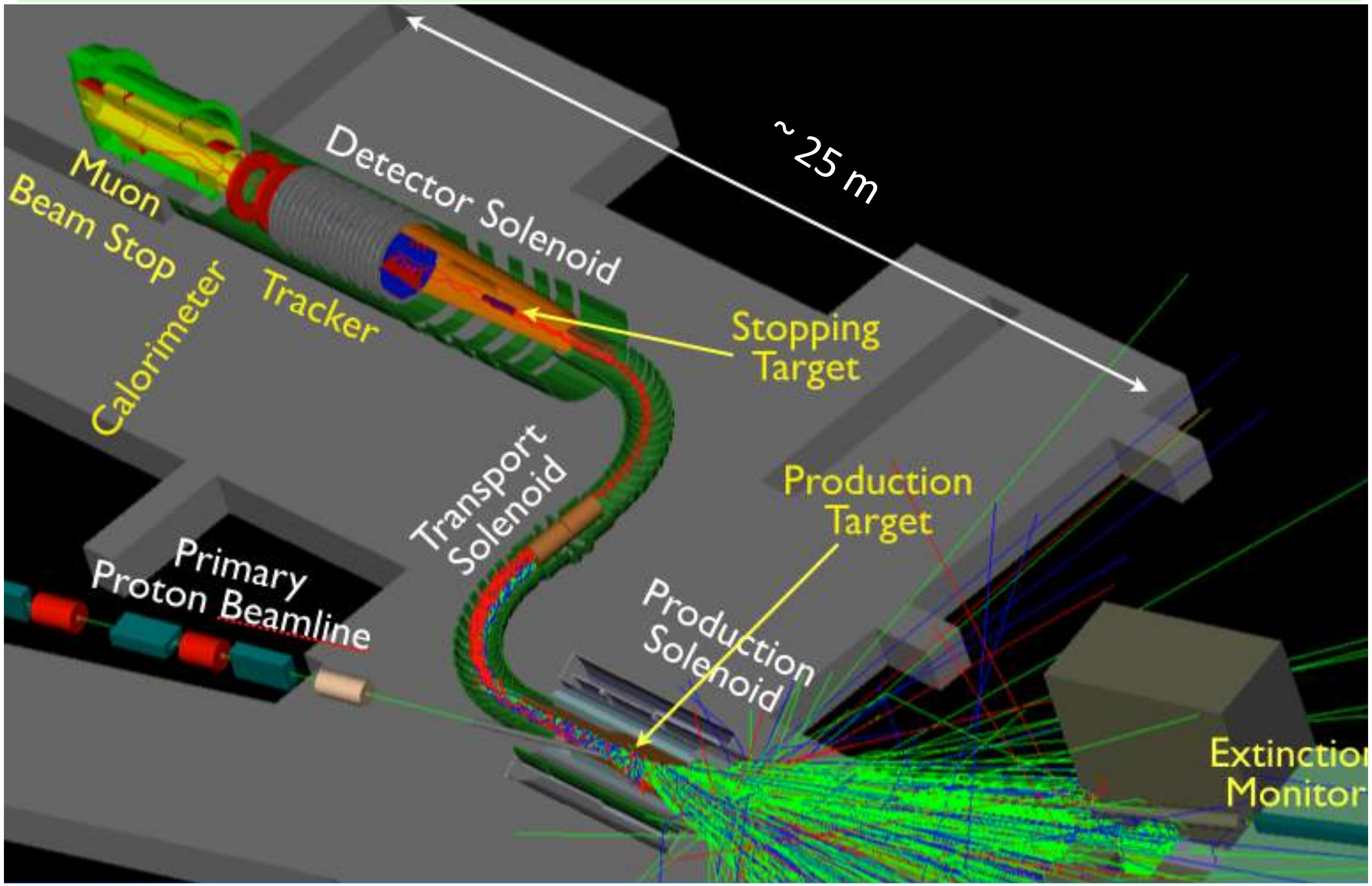
= number of grains of sand on earth's beaches

Mu2e Concept in a sketch



From the cartoons …. To real tough life

Mu2e Experimental Apparatus



- Derived from MELC concept originated by Lobashev and Djilkibaev in 1989

Muonic Al atom

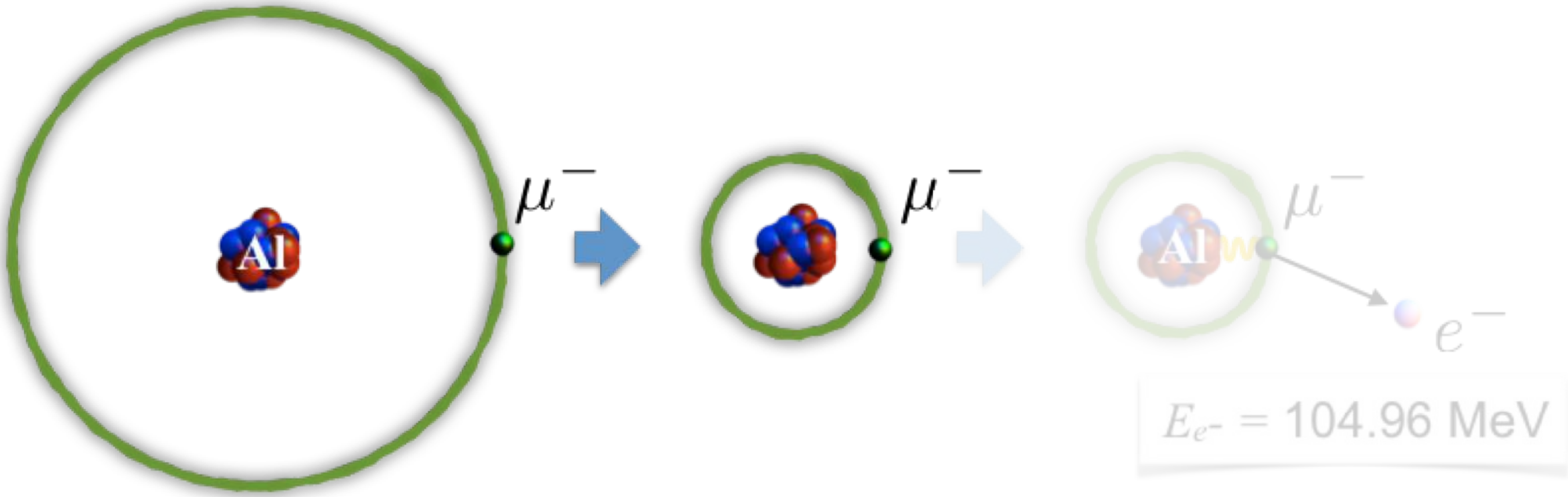
Before going to the experimental setup, a look to the topology of the events we are dealing with.

- Low momentum μ^- is captured in atomic orbit
  - Quickly (~fs) cascades to 1*s* state emitting *X*-rays
- Bohr radius ~20 fm (for aluminum)
  - Significant overlap of μ^- and Nucleus wave functions
- Once in 1s state, 3 main process (might) take place
  - Conversion : $\mu^- N(A,Z) \rightarrow e^- N(A,Z)$ (signal)
  - Muon Capture : $\mu^- N(A,Z) \rightarrow \nu N^*(A,Z\text{-}1)$ (61%) (normalization)
  - Decay : $\mu^- N(A,Z) \rightarrow e^- \nu\nu N(A,Z)$ (39%) (main bkg)

Mu2e Measurement factors

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

- Muon is trapped on Aluminum

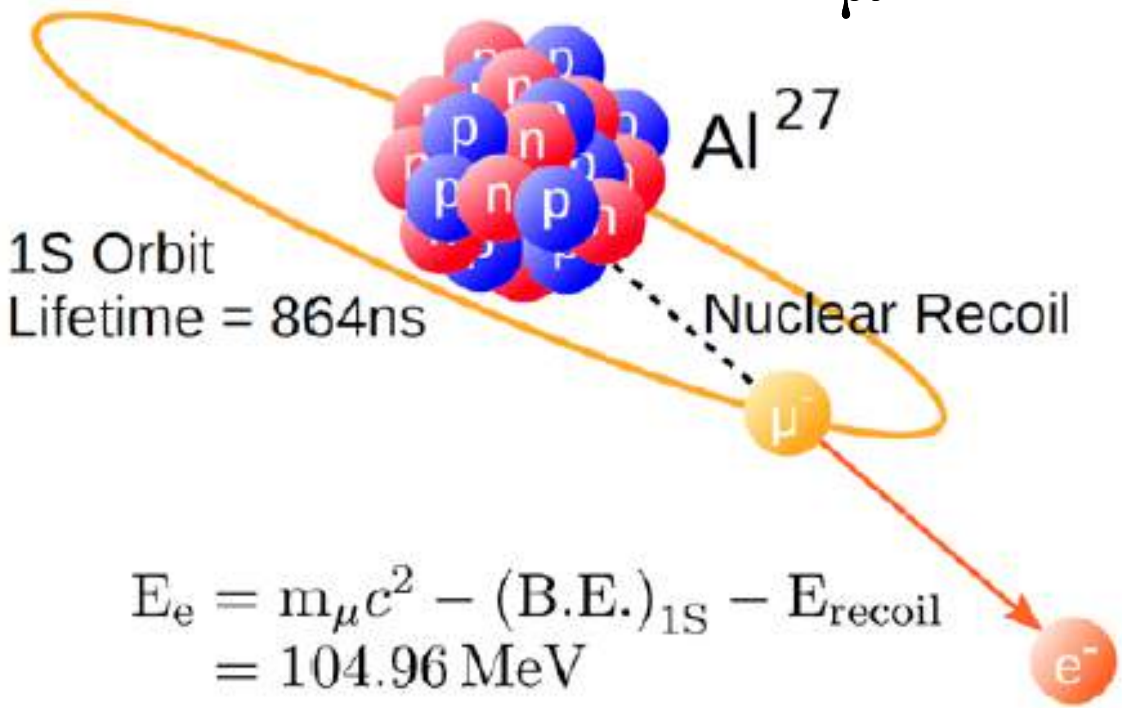


and…

The numerator, i.e. **the signal**

…neutrinoless converts to an electron with a mono energetic spectrum close to the muon rest mass. Clear signature

$$\mu^- + Al \rightarrow e^- + Al$$

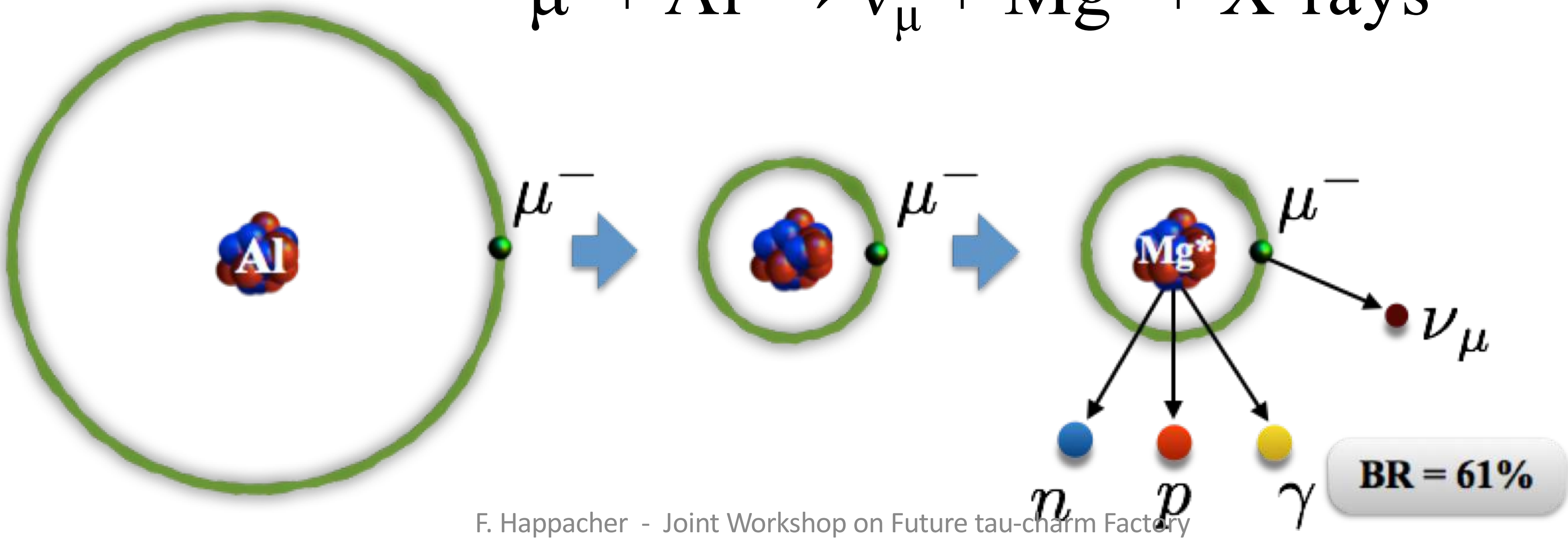


<u>But…</u>

The denominator, i.e. the normalization

…61 % of the time, interacts with the Aluminum nucleus to form Magnesium. We know well the X ray emissions of capture processes and relative rates: we measure their rate and know how many muons have been stopped

$$\mu^- + Al \rightarrow \nu_\mu + Mg^* + X\text{-rays}$$



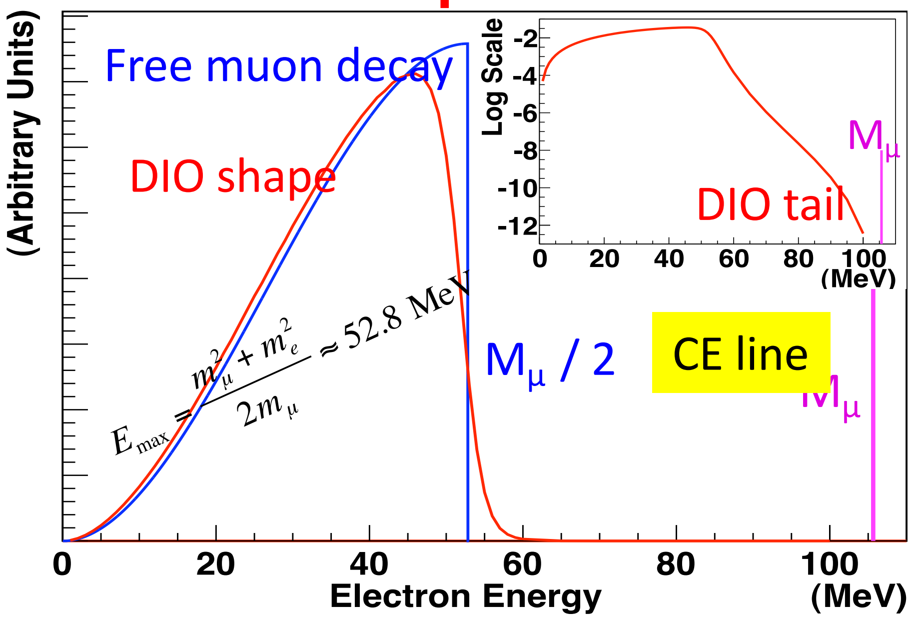
Mu2e irreducible background

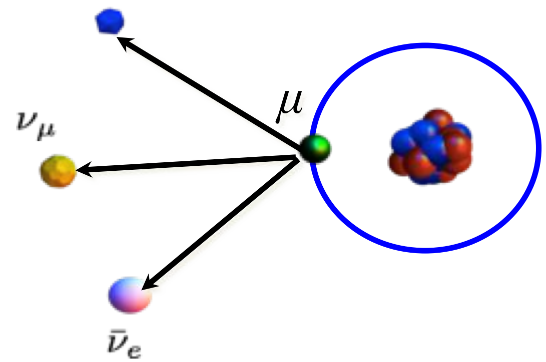
Unfortunately, 39 % of the time, muons can also:

Weak Decay in orbit (DIO): $[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$

- The Michel spectrum is distorted by the presence of the nucleus
- If the neutrinos are at rest the e⁻ can have exactly the conversion energy E_{CE}=104.97 MeV, contaminating the signal region
- Electron spectrum has tail out to 104.96 MeV
- Accounts for ~55% of total background

Drives exp. resolution





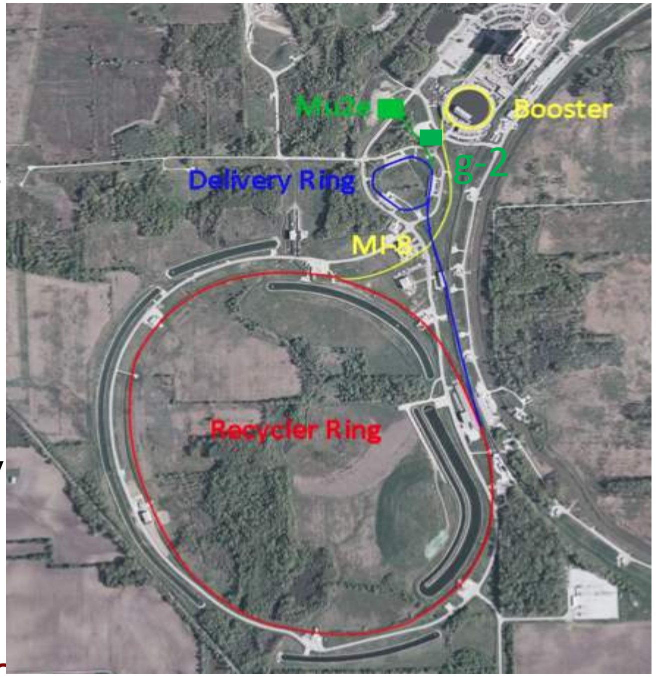
Separation of ~few 100 keV for $R_{\mu e} = 10^{-16}$

Accelerator & proton extinction

- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Booster: 21 batches of 4×10^{12} of 8 GeV protons every $1/15^{th}$ second
- Booster "batch" is injected into the Recycler ring and re-bunched into 4 smaller bunches
- These are extracted one at a time to the Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure → pulses of ~3×10^7 protons each, separated by 1.7 μs
- **Proton Extinction** between bunches

  $(N_p$ out of bunch$)/(N_p$ in bunch$)$
  - Internal: momentum scraping and bunch formation
  - External: oscillating AC dipole

  Accelerator models show that this combination ensures ~ 10^{-12}

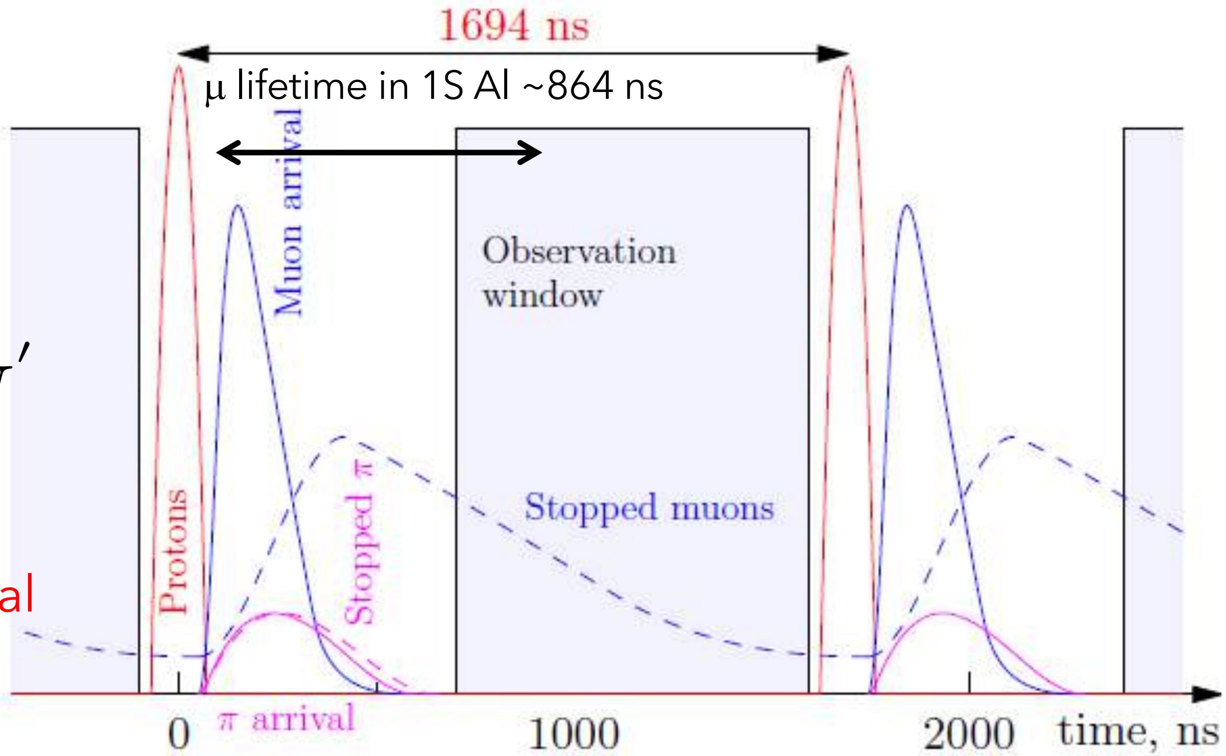


Pulsed beam structure

- Pions from late protons can undergo radiative capture (RPC) (τ_π^{Al} = 26 ns)

$$\pi^- + N \to \gamma_{e^+e^-} + N^{'}$$

γ energy up to m_π , peak at 110 KeV. One electron can mimic signal



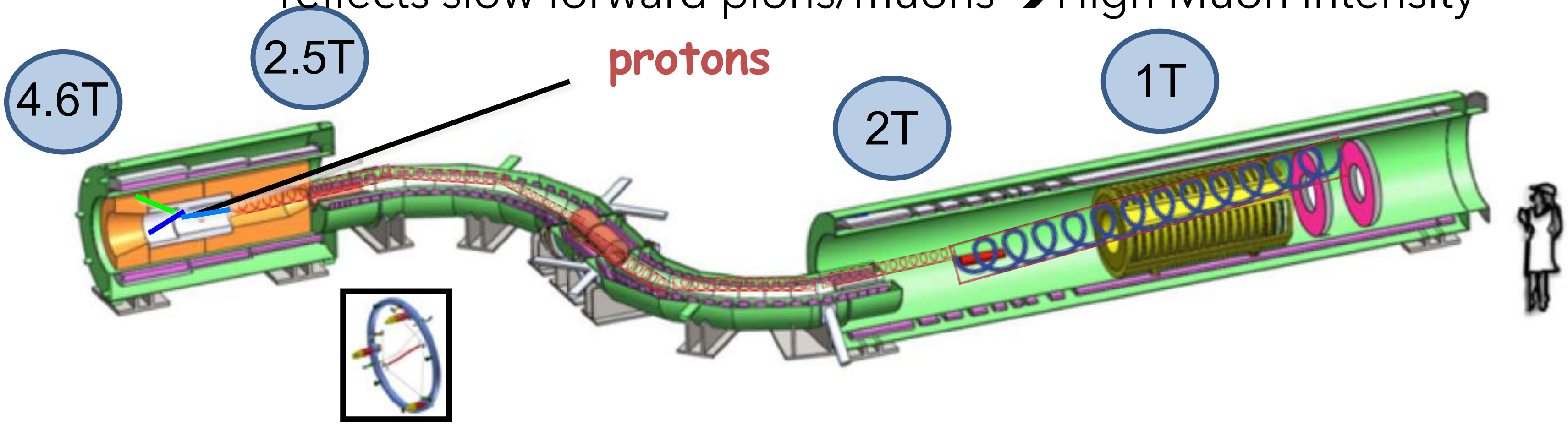
- Use the fact that muonic atomic lifetime >> prompt background
  Need a pulsed beam to wait for prompt background to reach acceptable levels
  → Fermilab accelerator complex provides ideal pulse spacing
  a 700 ns delay reduces pion background by $>10^{-9}$

- Out of time protons are also a problem->prompt bkg arriving late
  To keep background low we need proton extinction extintion$<10^{-10}$

Muon Beam-line

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 ➔High Muon intensity



→ Heat and radiation shielding
→ Tungsten target.

Transport Solenoid (TS)

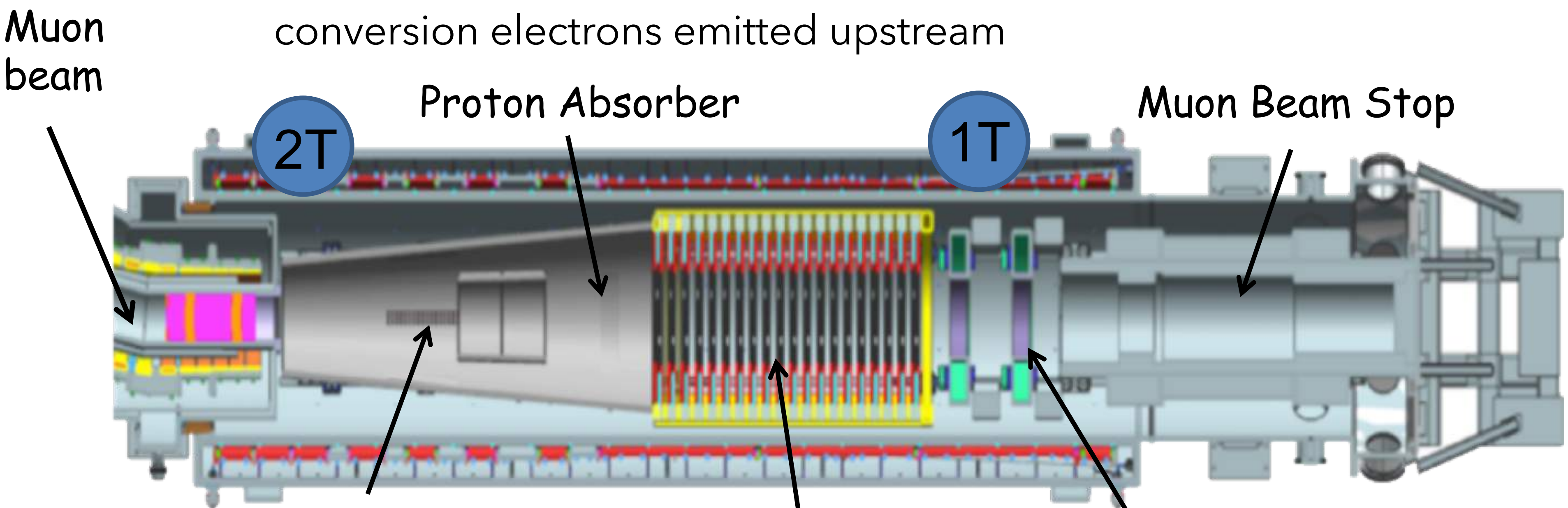
Collimator selects low momentum, negative muons
Antiproton absorber in the mid-section
S-shape eliminates photons and neutrons

Target, Detector and Solenoid (DS)

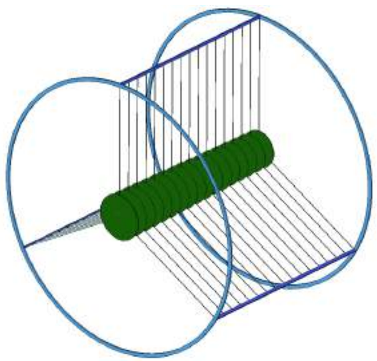
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Detector Solenoid

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



34 Al foils; Aluminum choice dictated by the bound muon lifetime (**864 ns**) that nicely matches the the Mu2e pulsed beam structure for prompts' separation

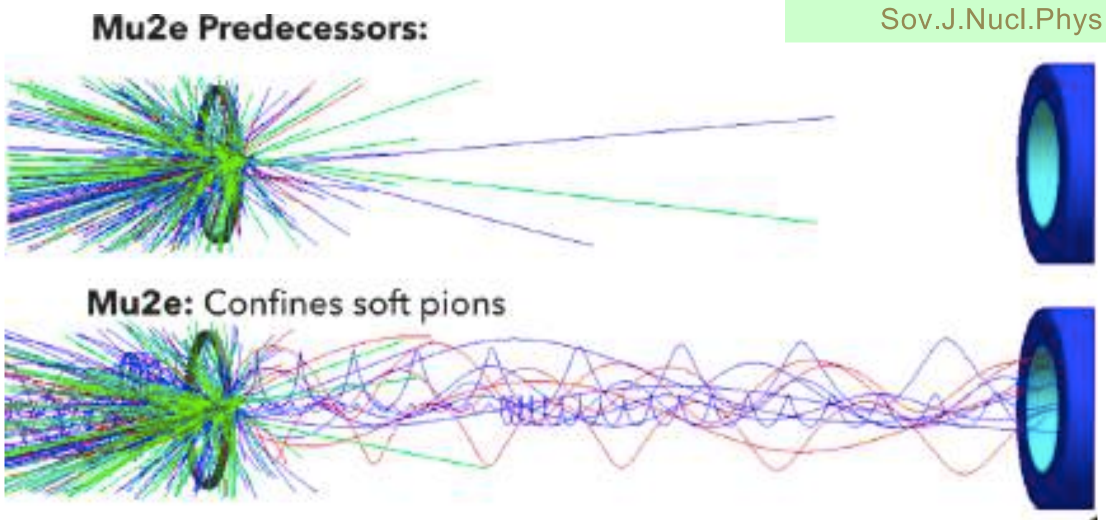


Sensitivity goal →
~ 6 x 10^{17} stopped muons
3 year runs , 6 x 10^7 sec →
10^{10} stopped muon/sec

the keys to Mu2e Success

- ❑ **High intensity pulsed proton beam**
  - Narrow proton pulses (< ± 125 ns)
  - Very few out-of-time protons (< 10^{-10})
  - 3×10^7 proton/pulse.
- ❑ **High efficiency in transporting muon to Al target**
  - Need of a sophisticated magnet with gradient fields
- ❑ **Excellent detector for 100 MeV electrons**
  - → Excellent momentum resolution (< 200 keV core)
  - → Calorimeter for PID, triggering and track seeding
  - → High Cosmic Ray Veto (CRV) efficiency (>99.99%)
  - → Thin anti-proton annihilation window(s)

Concept by Lobashev and Djilkibaev
Sov.J.Nucl.Phys. 49, 384 (1989)



Status of PS/DS construction

- PS/DS Cryostats being completed @ Joseph Oat
  (GA Subcontract)

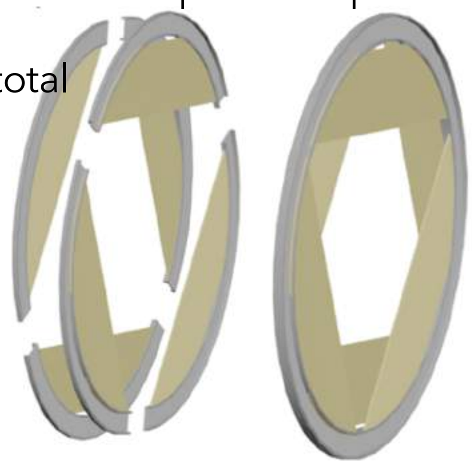
The Mu2e Tracker

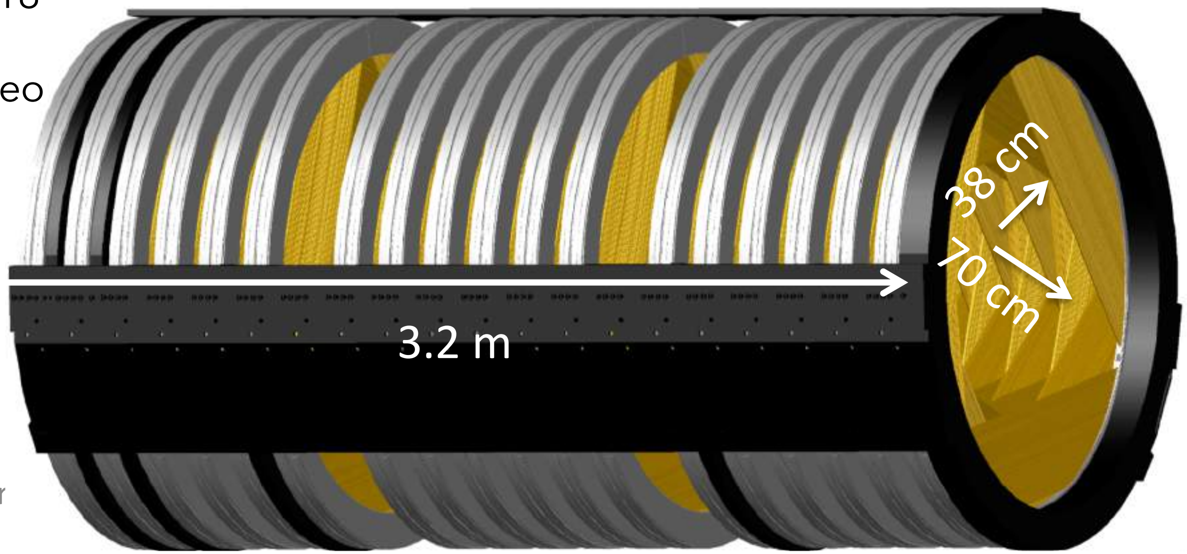
Detector requirements:

1. Small amount of budget material, maximizing X_0
2. σ_p < 115 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm^2 in live window
   - Beam flash of 3 MHz/cm^2
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

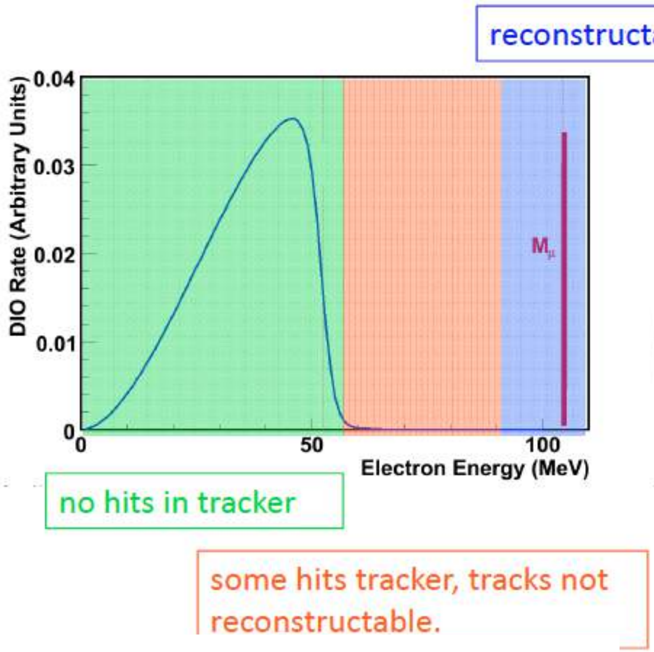
- dual ended TDC/ADC readout large Radii
- 5 mm diameter straw
- Spiral wound
- Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 @ 1 atm with HV < 1500 V

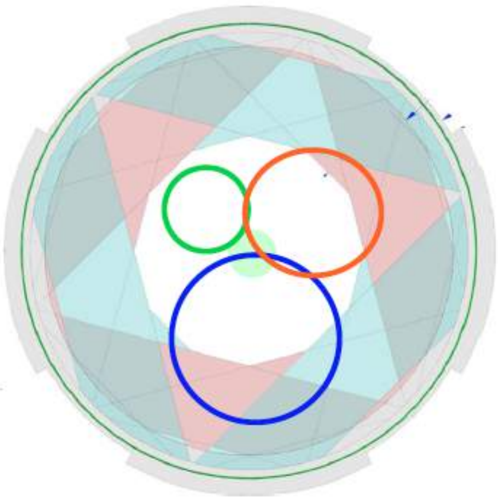
- Self-supporting "panel" consists of 100 straws
- 6 panels assembled to make a "plane"
- 2 planes assembled to make a "station" -> 18 stations
- Rotation of panels and planes improves stereo information
- >20k straws total



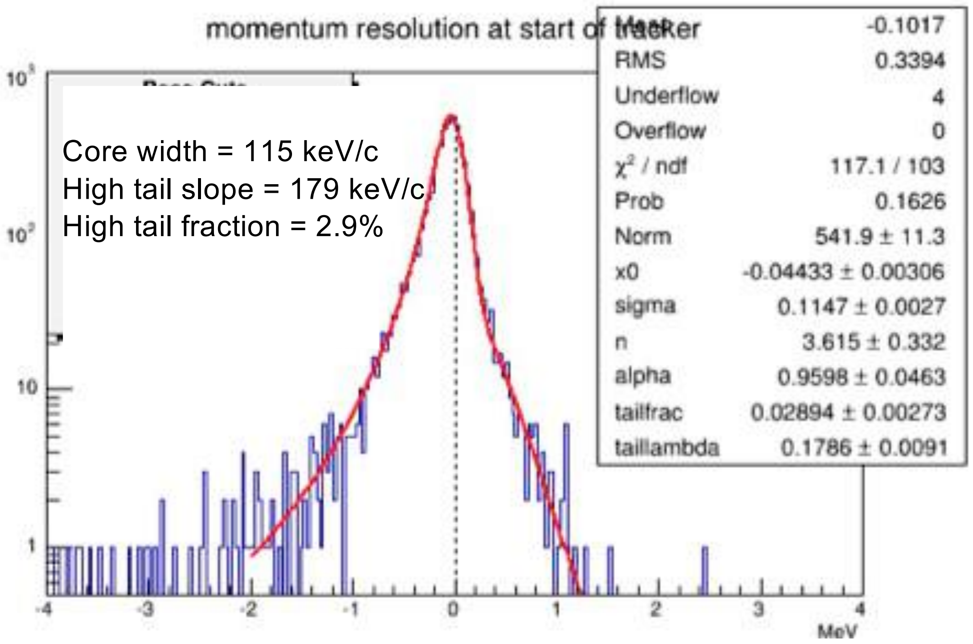


The Mu2e Tracker



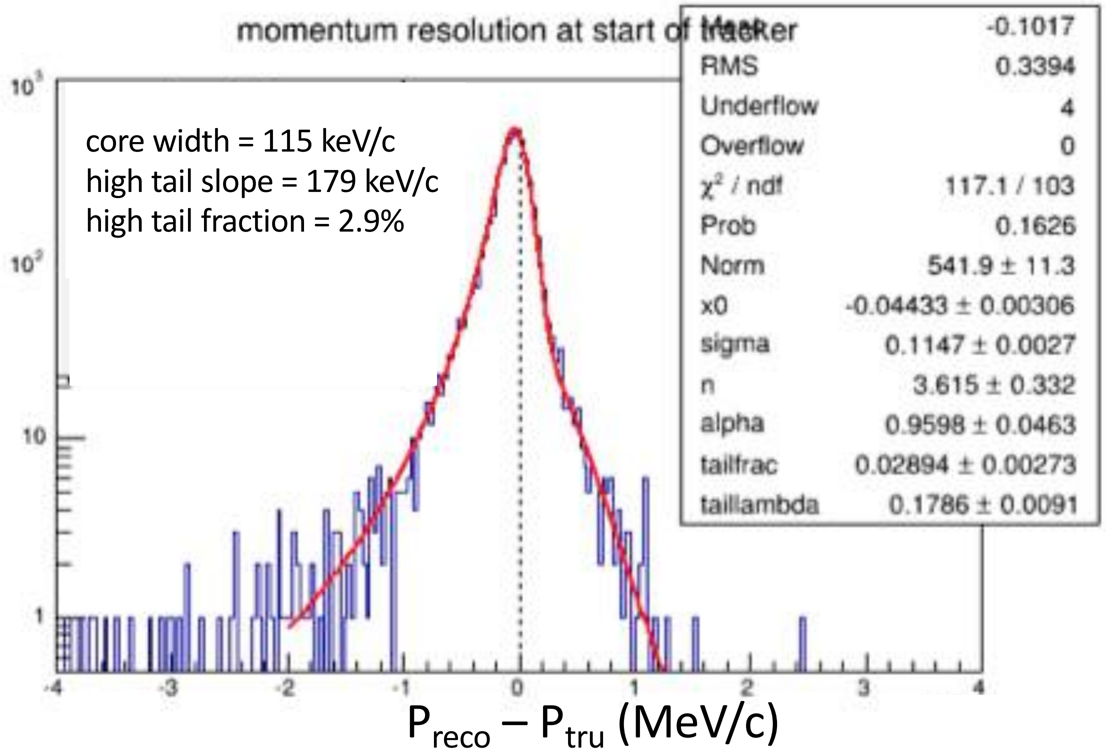


beam's-eye view of the tracker



- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum
- Performance well within physics requirements 115 keV/c momentum resolution

Mu2e Tracker Performance



- Performance well within physics requirements 115 keV/c momentum resolution

The Mu2e calorimeter

The calorimeter has to:

- Provide high e^- reconstruction efficiency for μ rejection of 200
- Provide cluster-based additional seeding for track finding
- Provide online software trigger capability
- Stand the radiation environment of Mu2e
- Operate for 1 year w.o. interruption in DS w/o reducing performance

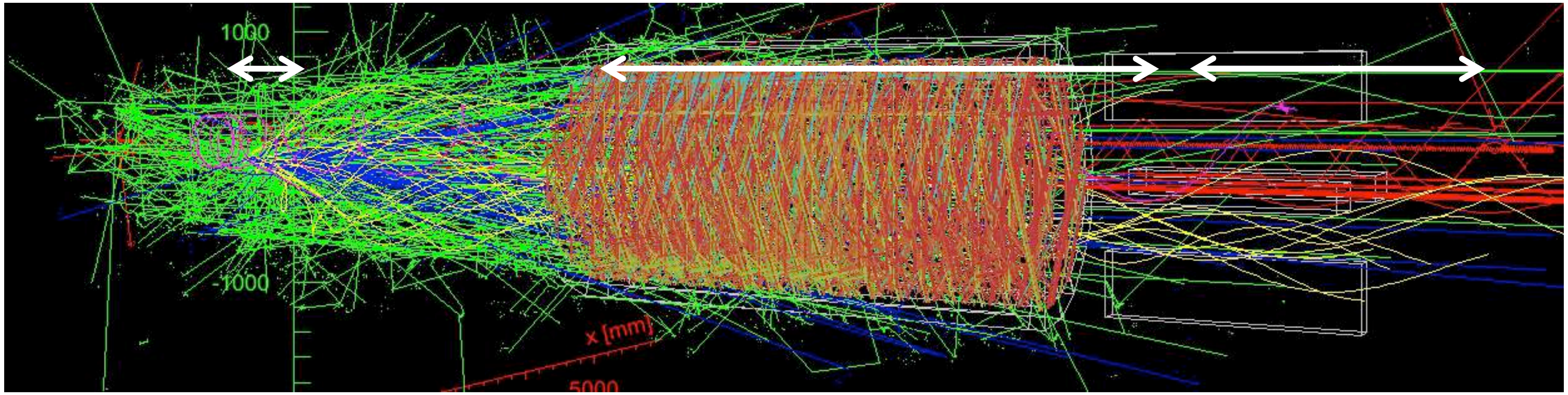
the calorimeter needs to fulfill the following

→ Provide energy resolution σ_E/E of O(5 %)
→ **Provide timing resolution $\sigma(t)$ < 200 ps**
→ Provide position resolution < 1 cm
→ Provide almost full acceptance for CE signal @ 100 MeV
→ Redundancy in FEE and photo-sensors

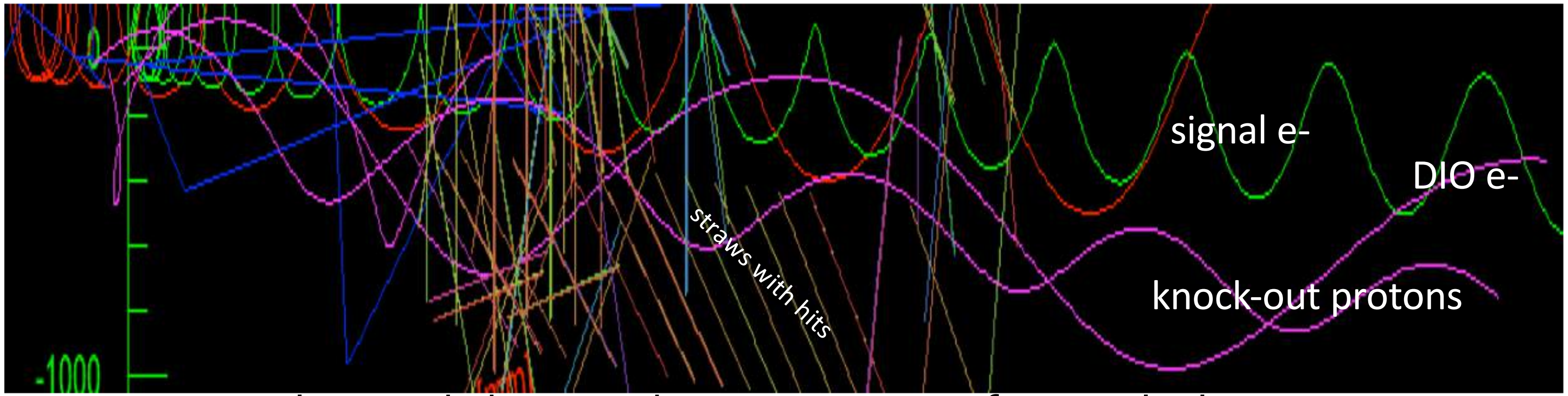
A crystal based disk calorimeter

Mu2e Pattern Recognition

Stopping Target Straw Tracker Crystal Calorimeter



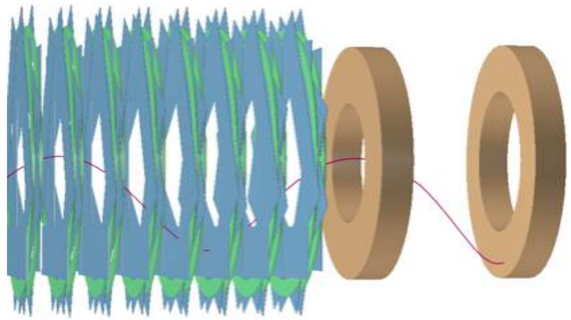
A signal electron, together with all the other interactions



particles with hits within +/-50 ns of signal electron t_{mean}

The Mu2e Calorimeter

High granularity crystal based homogeneous calorimeter with:



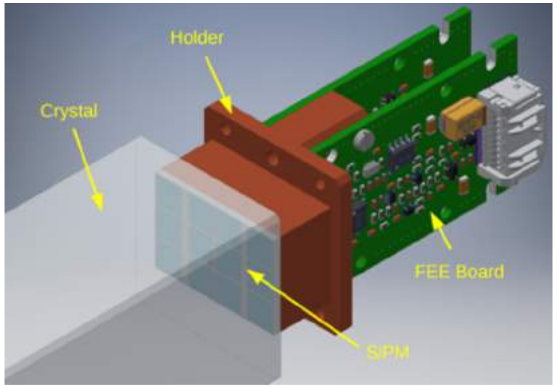
- 2 Disks (Annuli) geometry to optimize acceptance for spiraling electrons
- Crystals with high Light Yield for timing/energy resolution → **LY(photosensors) > 30 pe/MeV**
- **2 photo-sensors/preamps/crystal** for redundancy and reduce MTTF requirement → now set to 1 million hours/SIPM
- Fast signal for Pileup and Timing resolution → **τ of emission < 40 ns + Fast preamps**
- **Fast WFD to disentangle signals in pileup**
- **Crystal dimension optimized** to accommodate in DS envelope
  → reduce number of photo-sensor, FEE, WFD (cost and bandwidth) while keeping pileup under control and position resolution < 1 cm.
- Crystals and sensors should work in 1 T B-field and in vacuum of 10^{-4} Torr and:
  → **Crystals survive TID of 90 krad and a neutron fluency of 3×10^{12} n_{1MeV}/cm²**
  → **Photo-sensors survive 45 krad and a neutron fluency of 1.2×10^{12} n_{1MeV}/cm²**

The Mu2e Calorimeter

The two Calorimeter annuli contain 674 34x34x200 mm^3 un doped CsI crystals each

- → R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
- → Disks separated by 75 cm, half helix length

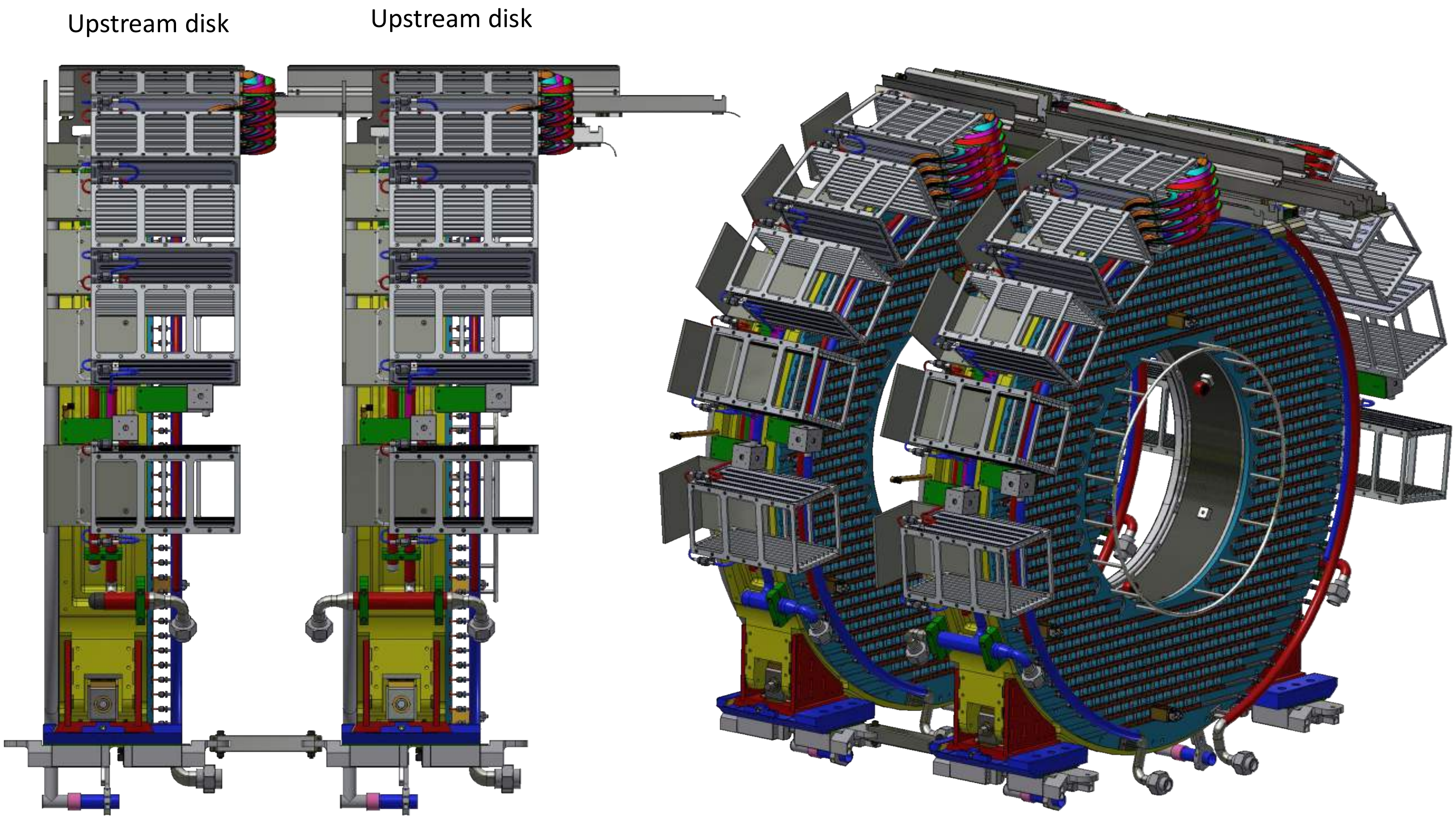
- → Each crystal is readout by two array UV extended SIPM's (14x20 mm^2) maximizing light collection.
  PDE=30% @ CsI emission peak =315 nm.
  GAIN ~10^6



- → TYVEK + tedlar wrapping
- → Analog FEE is onboard to the SiPM (amplification and shaping) and digital electronics located in electronics crates (200 MhZ sampling)
- → Cooling system – SiPM cooling, Electronic dissipation

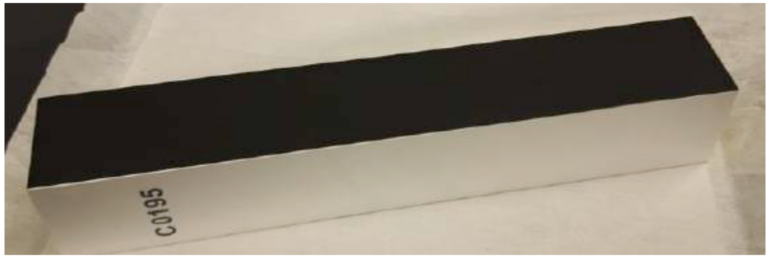
- → Radioactive source and laser system provide absolute calibration and monitoring capability

Calorimeter layout

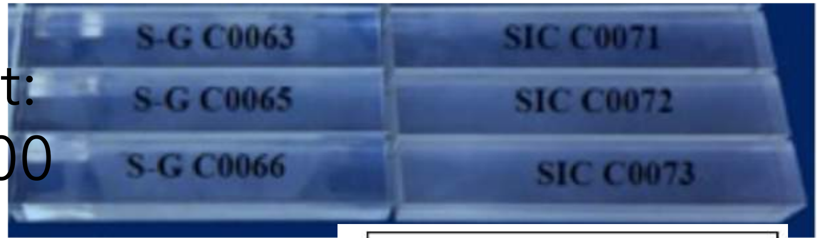


Crystal requirements

- High light output (LO) > 100 p.e./MeV by standard bialkali PMT with air gap and crystal wrapped with 150 μm Tyvek paper



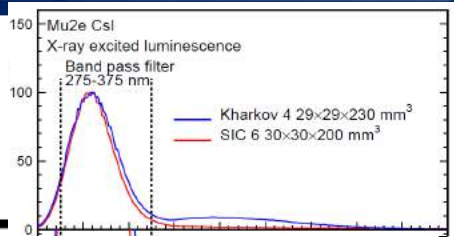
- Good light response uniformity (LRU) < 10 %



- Fast signal with small slow component: τ < 40 ns and F/T = F(Integral in 200 ns)/T(Integral in 3000 ns) >75%

$

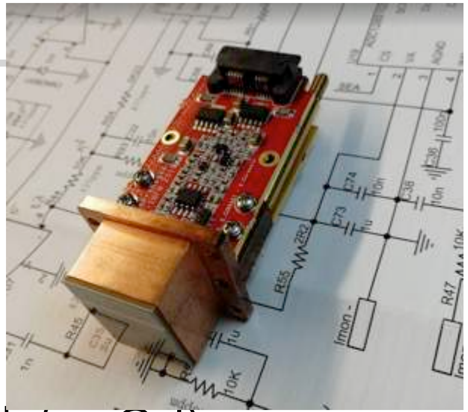
	~~LYSO~~	~~BaF2~~	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**RMD APD**	SiPM
Wavelength [nm]	402	**220**/300	310



CsI(pure)

- Adequate radiation hardness
- Slightly hygroscopic
- 30 ns emission time, small slow component.
- Emits @ 310 nm.
- Comparable LY of fast component of BaF_2.
- Lower cost (6-8 $/cc)

SiPM Requirements



(R0) Work in B-field of 1 Tesla → **Silicon photomultiplier**

(R1) Have a high quantum efficiency @ 315 nm (the emission peak for CsI) and a large active area to maximize the number of collected photoelectrons → **20-30 pe/MeV with SiPM readout**

(R2) Have a high gain, fast signal and low noise;

(R3) Withstand a radiation environment of **~6 x10^{11}** n/cm^2 @ 1 MeV$_{eq}$ and ~**30 krad** for photons (for 5 years and a factor 3 of safety);

(R4) Work in vacuum at 10^{-4} Torr;

(R5) Have sufficient reliability to allow operation for 1 year w.o. interruption;

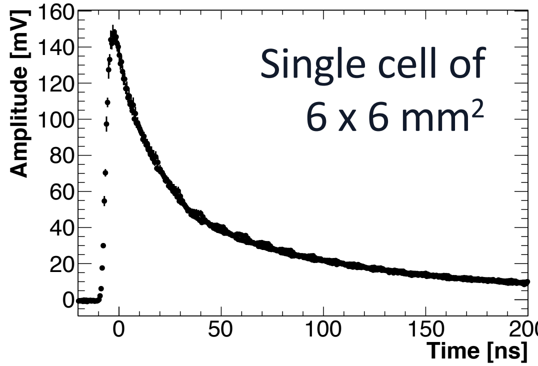
(R6) Allow replacement of photosensors after 1 year of running if needed

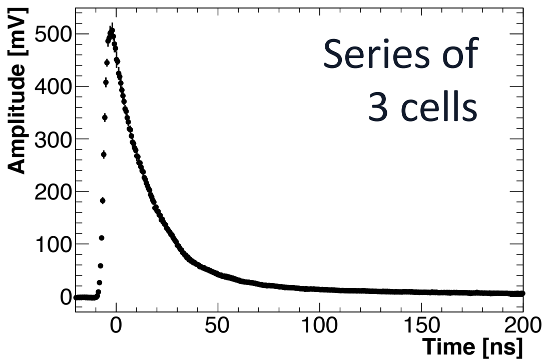
SiPMs

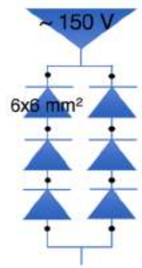
Mu2e custom silicon photosensors from Hamamtsu:

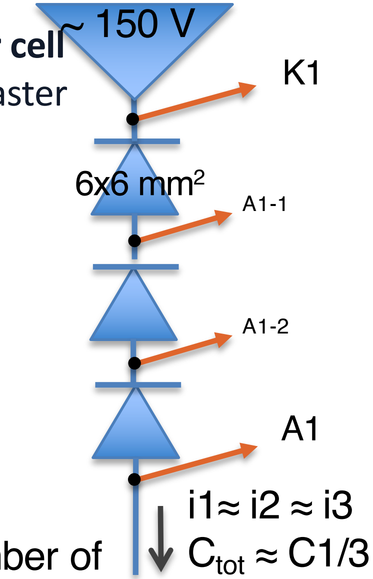
→ **2 arrays of 3 6 x 6 mm² UV-extended SiPMs: total area (12x18) mm² 1400 pixels (50 mm) per cell**

2 arrays arranged in parallel. The readout series configuration reduces the overall capacitance→faster signals







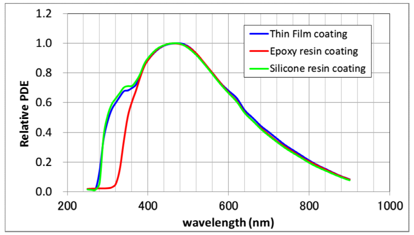


We have chosen a modular SiPM layout to enlarge the active area and maximize the number of collected photoelectrons.

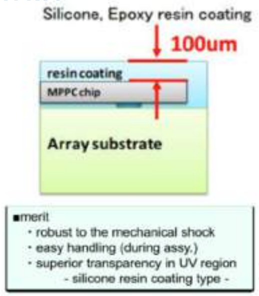
To replace sensors and reduce outgassing we coupled the sensors to the crystal with an air-gap **while satisfying the p.e./MeV requirement with a single photosensor**. Two SiPMs/crystal are used for redundancy;

SiPM + crystal configuration achieving

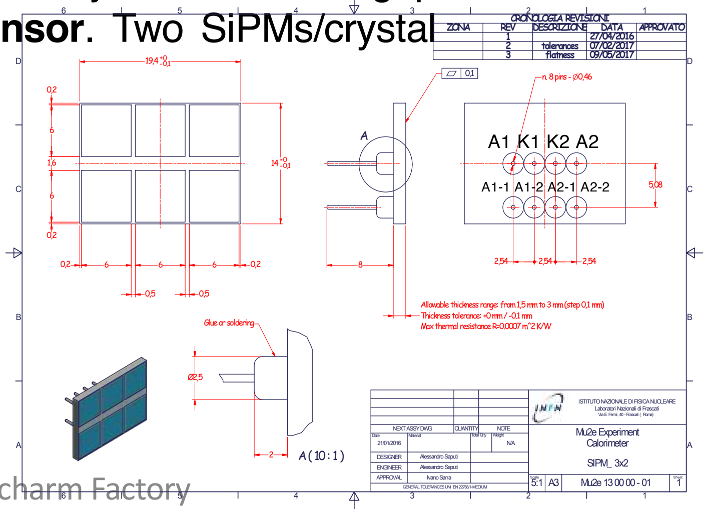
→ ~ 30 (20) p.e/MeV with (without) optical grease with Tyvek-wrapped crystals



Thin Film coating and Silicon resin coating has PDE advantage in UV region.



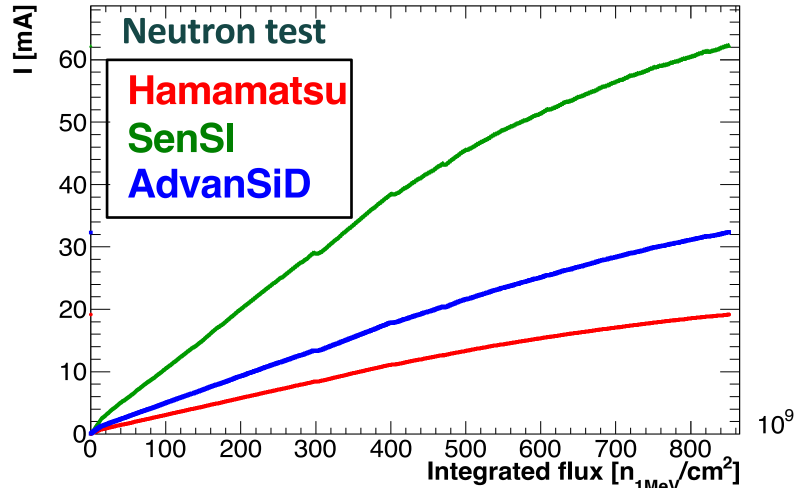
UV extended thin silicone layer instead of epoxy



SiPM irradiation

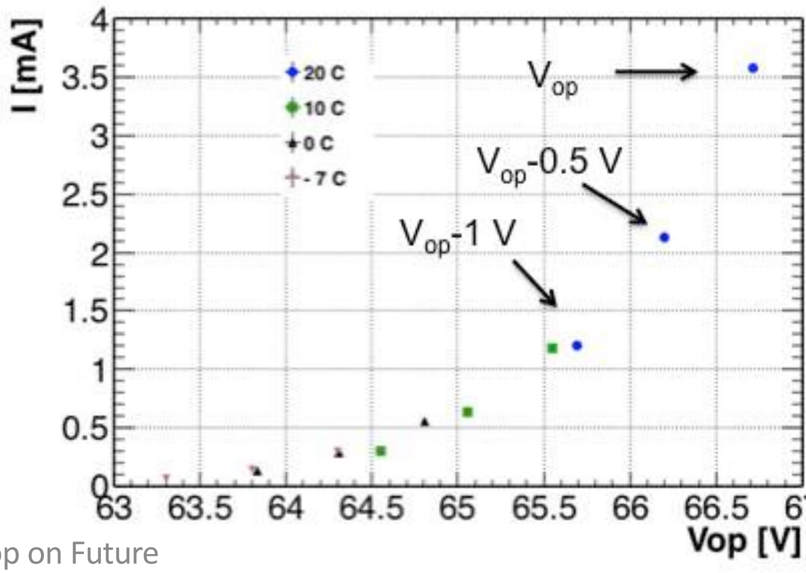
SiPM irradiated at ENEA Casaccia with 20krad ^{60}Co photon source producing negligible effect on the response and on leakage current

- Neutron irradiation tested at ENEA Frascati (FNG) with 14 MeV neutrons.
- Total flux 2.2x10^{11} n/cm^2 (2.2 times the experiment lifetime neutron dose)
- Leakage current increases to too high values. Need to cool at lower temperatures the sensors.

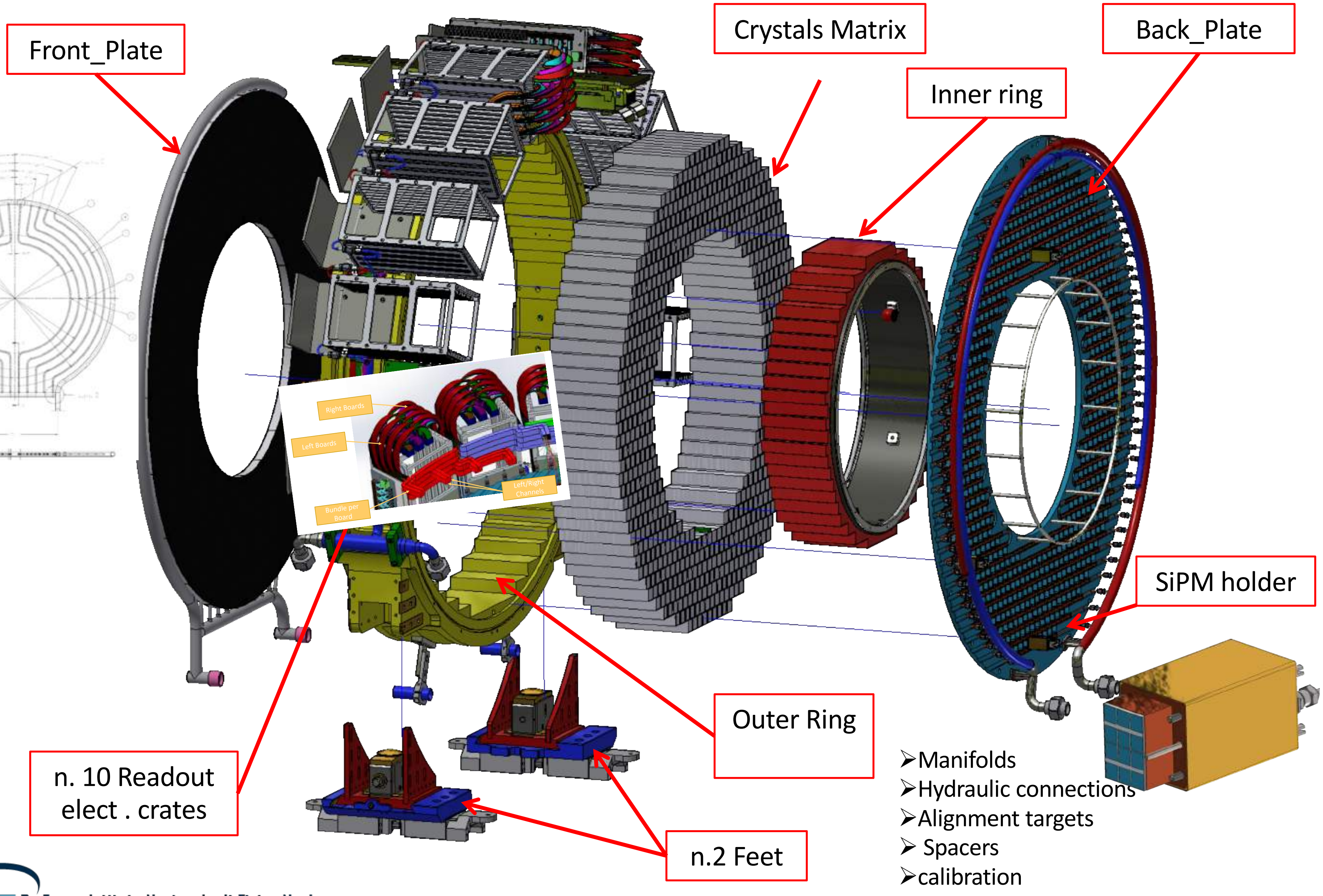


By measuring the dependence of the leakage current as a function of temperature, we observe a factor of 10 reduction in Idark when working at T = 0 °C that is acceptable.
keeping the leakage current < 2 mA up to **1E^{12} n/cm^2**:

We need to reduce the X2 gain…and 15% of PDE



Calorimeter Mechanics



- Manifolds
- Hydraulic connections
- Alignment targets
- Spacers
- calibration

nil volentibus

Calorimeter mechanics

The calorimeter mechanics needs to fulfill the following main requirements:

- respect both the assigned envelope and clearances;
- be quite stiff (max deformation 0.01 mm) minimizing stresses on crystals;
- minimize the passive material;
- operate in vacuum and magnetic field;
- allow an adjustment along X and Y axis;
- allow the access for maintenance.
- comply with the clearances of the muon beamline geometry
- correctly interface with Tracker and other components of the detector solenoid

Furthermore, the calorimeter structure has to host:

- The SiPMs, the FrontEnd electronics, the Mezzanine (HV/LV) controllers boards and the Digitizers board;
- The cooling system needed to cool down the SiPMs and extract the heat dissipated by the readout/voltage supply/digitizer electronics;
- the source and laser calibration systems;
- all services (cables, fibers and pipes)
- the alignment references.

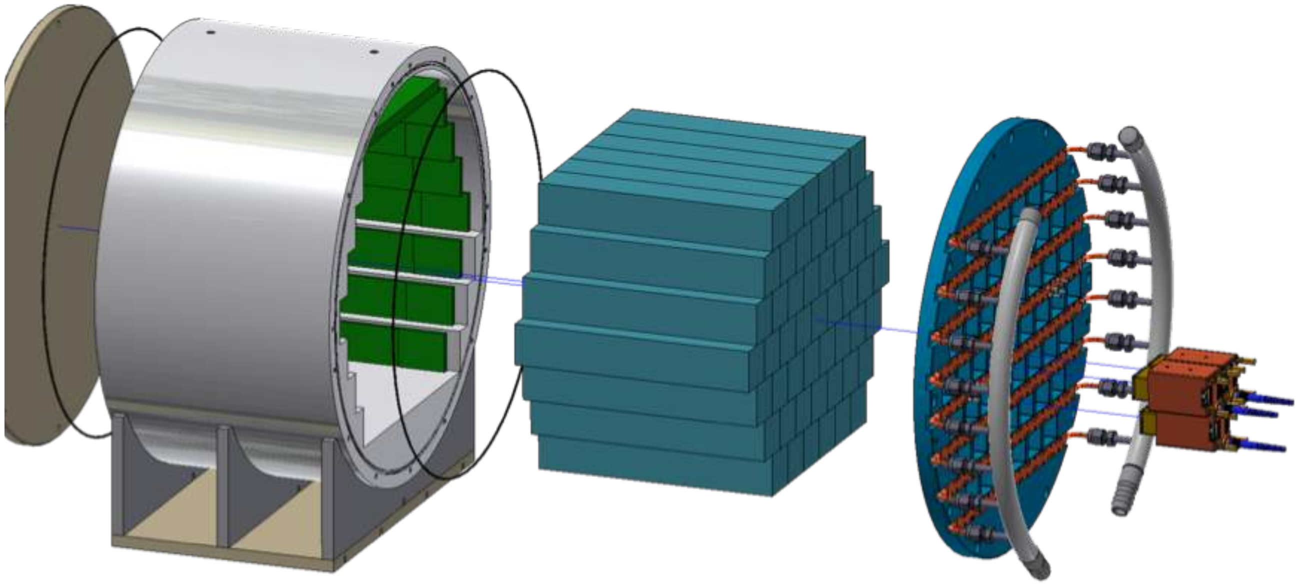
Module 0

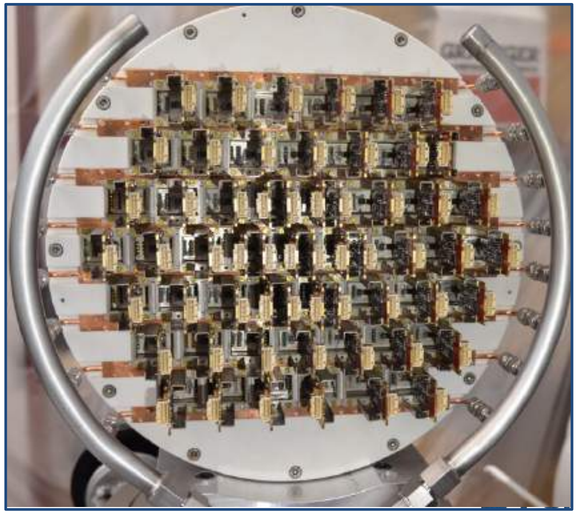
Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**

Mechanics and cooling system similar to the final ones

but smaller scale → Main goals:

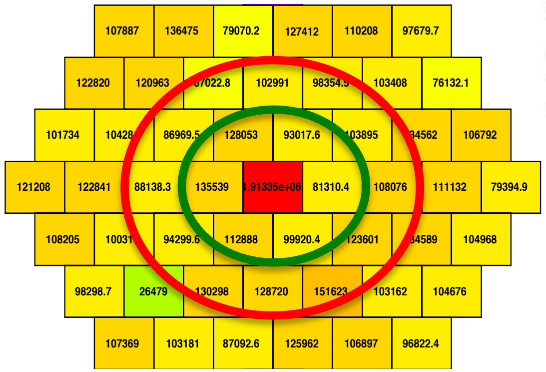
- Integration and assembly procedures
- Test beam May 2017, **60-120 MeV** ***e***$^-$ (**@ 0° and @ 50°**)
- Work under vacuum, low temperature, irradiation test

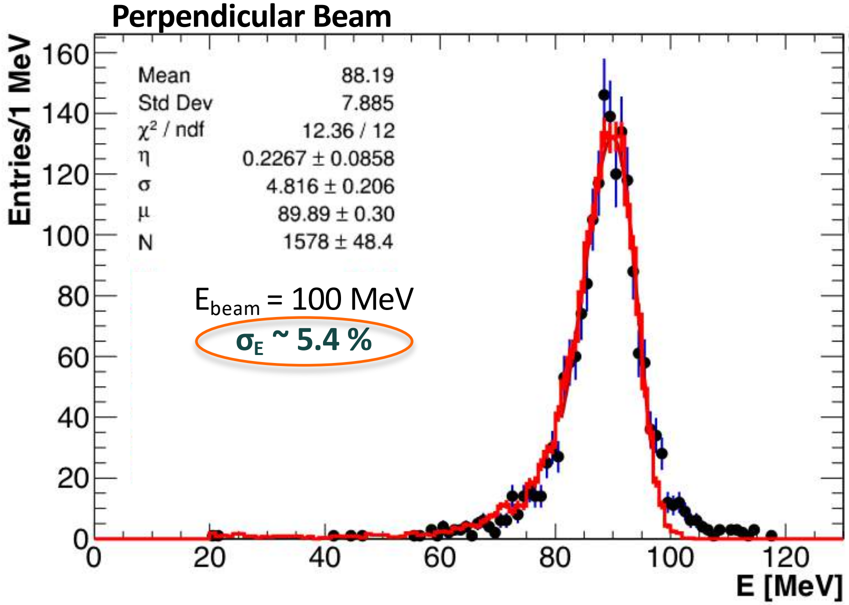


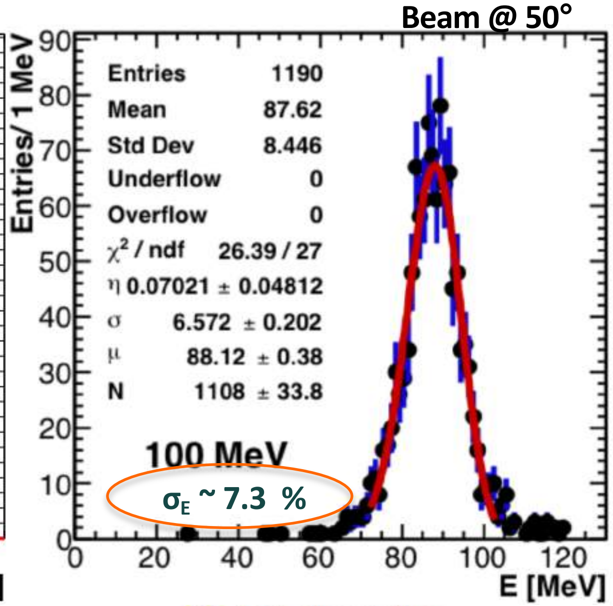


Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

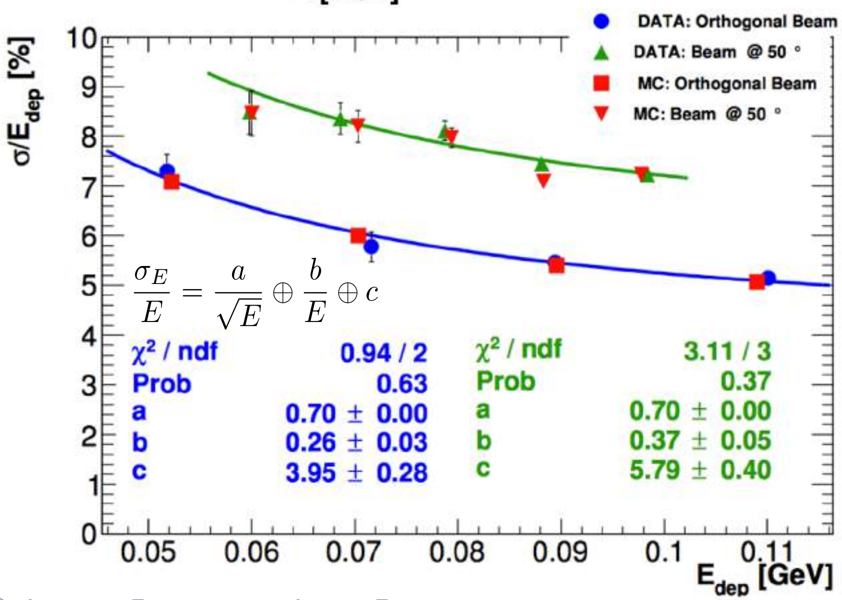
Module 0 - Energy resolution



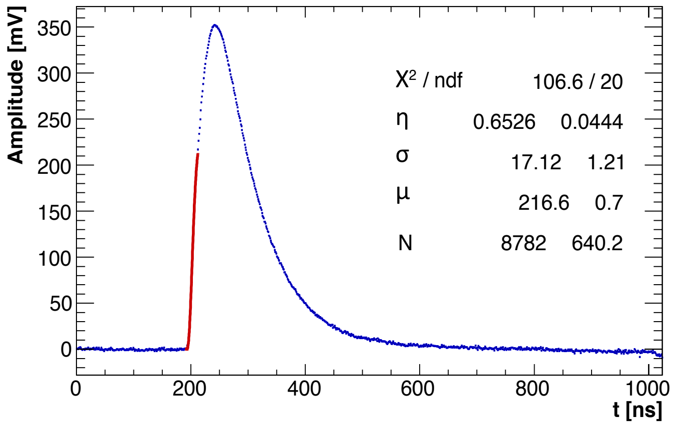


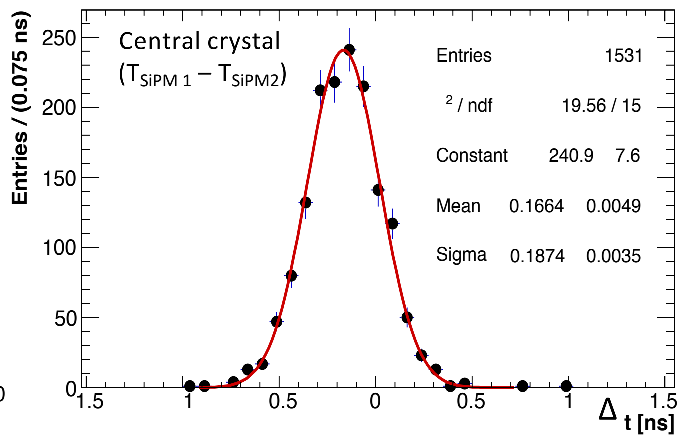


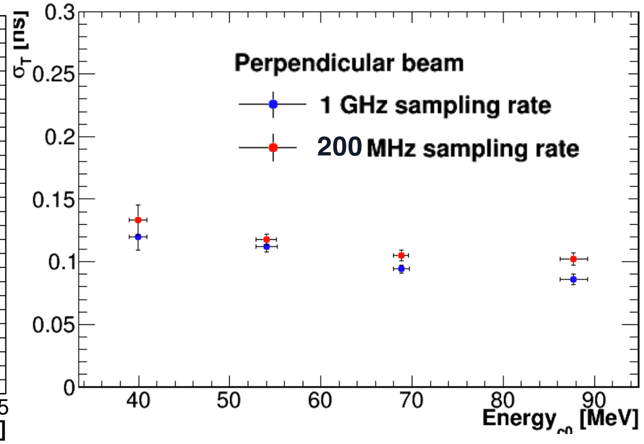
- Single particle selection
- Equalization and E-scale
  - MIPs
  - 100 MeV e⁻ beam, up to ring **2**
- Threshold applied @ 3 σ (Noise)
- LY/SiPM = 30 pe/MeV
- **Great Data-MC agreement**



Module 0 - Time resolution

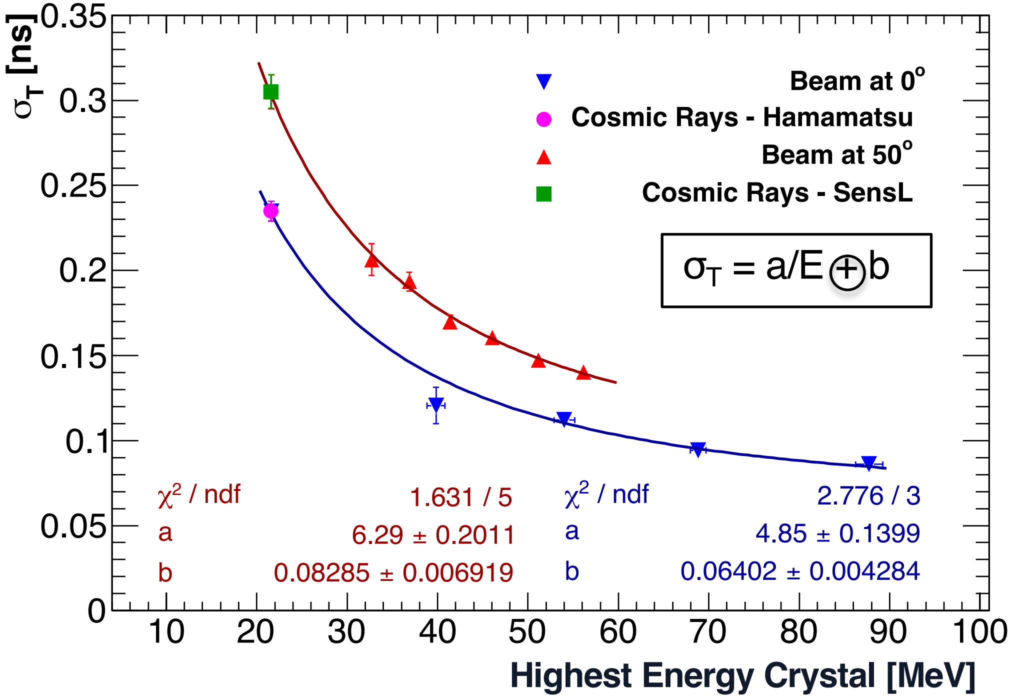




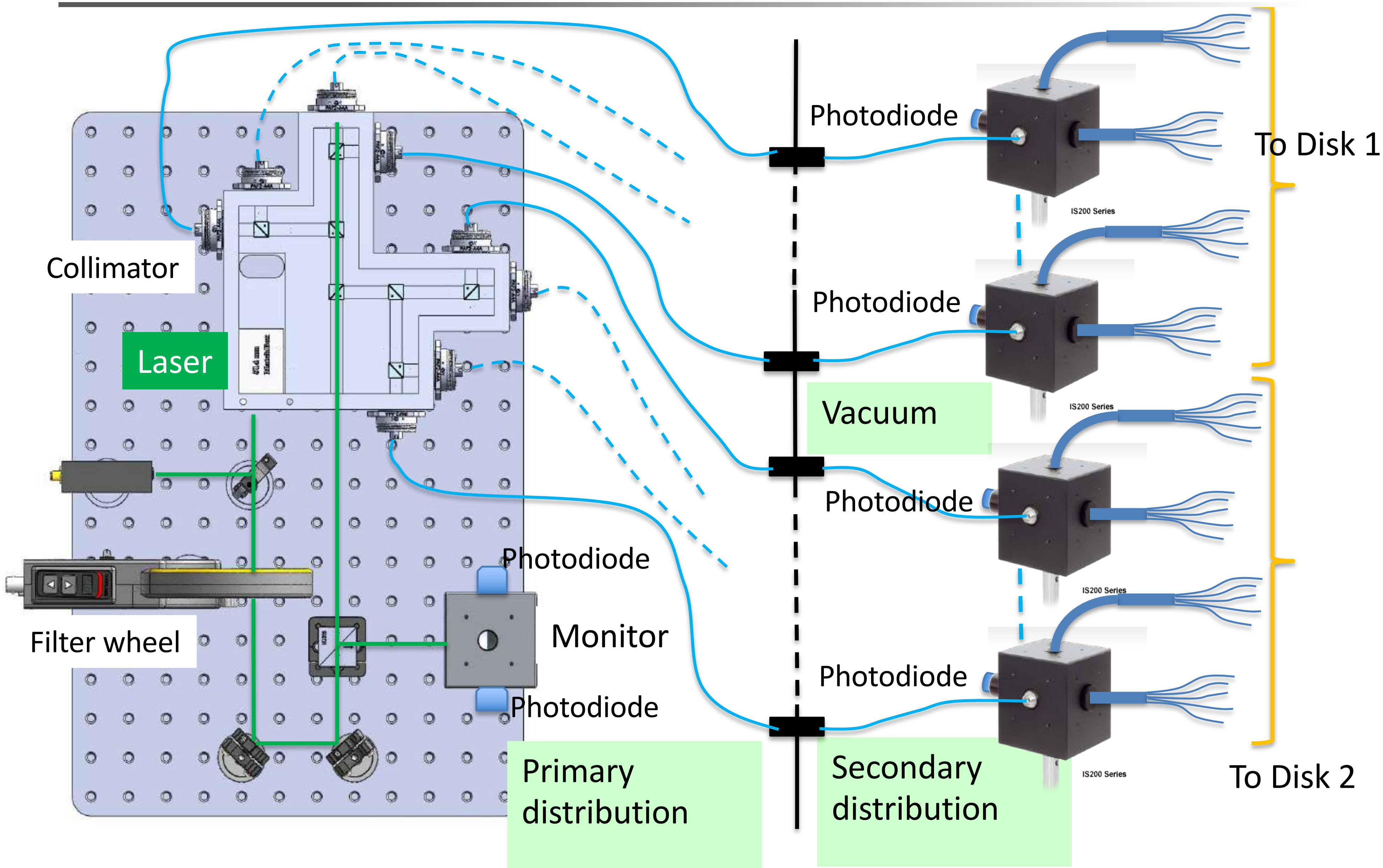


- Single particle selection
- Log-normal fit on leading edge
- Constant Fraction method used
  → CF = 5%

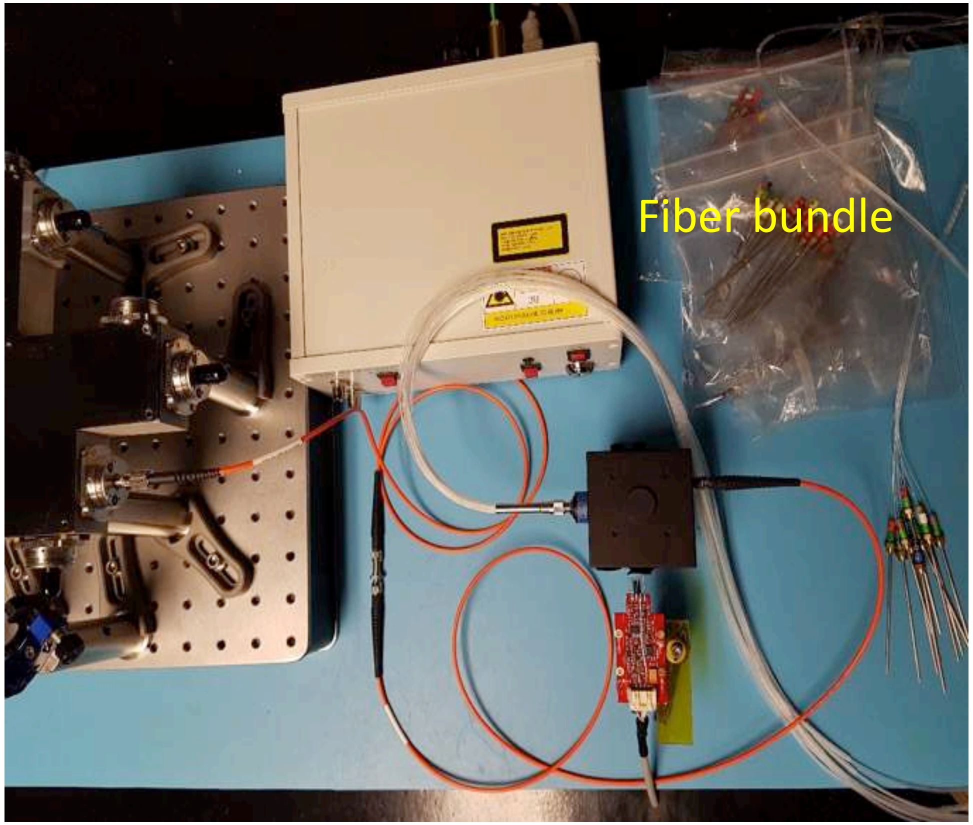
σ (T1) ~ 130 ps
@ E_{beam} = 100 MeV

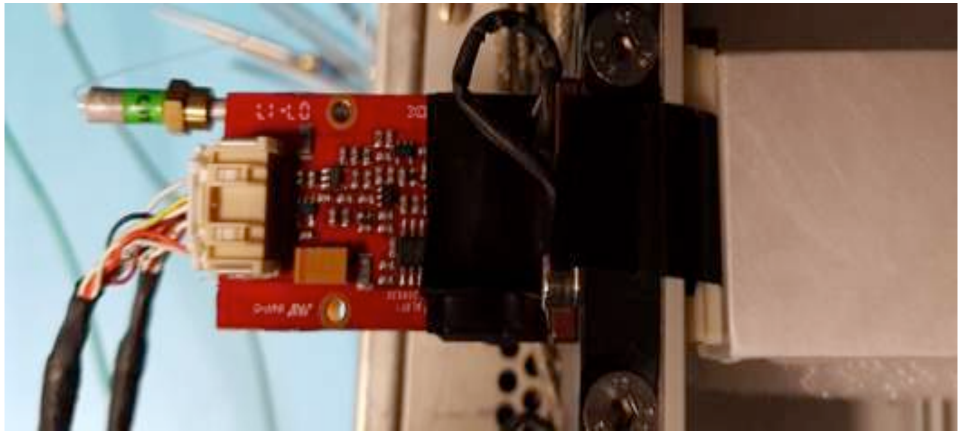


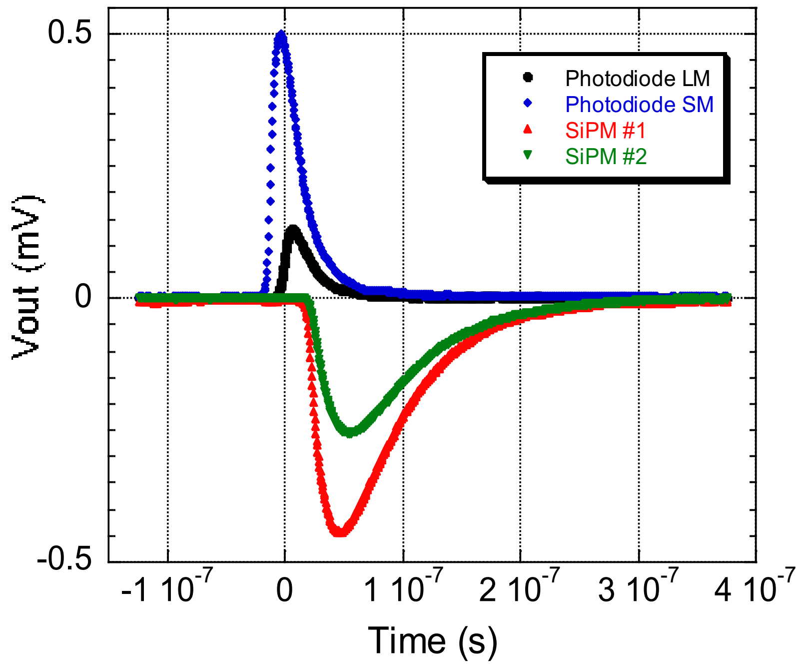
Laser System Scheme



Realistic Laser tests







Summary and Conclusions

- Mu2e improves sensitivity by a factor of 10^4 SINDRUM II limit
  - Reach Sindrum-II sensitivity in 100 min, x10 in 17 hours , x100 in 7 days, x10000 in 700 days
- Provides discovery capability over a wide range of NP

- calorimeter concluded its prototyping phase satisfying the Mu2e requirements:
  - **Un-doped CsI crystals perform well – 80% arrived and QA tested**
    - **Excellent LRU and LY** > 20 pe/MeV (SiPM+Tyvek wrapping), τ of 30 ns
    - **Radiation hardness OK**: 40% LY loss at 100 krad
  - **Mu2e SiPMs quality OK – All arrived and QA tested**
    - High gain, high PDE, low I_{dark}, low RMS spread in array
    - SiPMs performance after **irradiation OK → require 0 ° C cooling**
  - **Calorimeter prototypes** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**
- Calorimeter production phase started March 2018
- Production will end in October 2019, FEE production middle 2020
- Calorimeter assembly at beginning of 2020
- **Calorimeter installation in Mu2e experimental hall planned for 2020**