Search for New Physics with the Mu2e experiment

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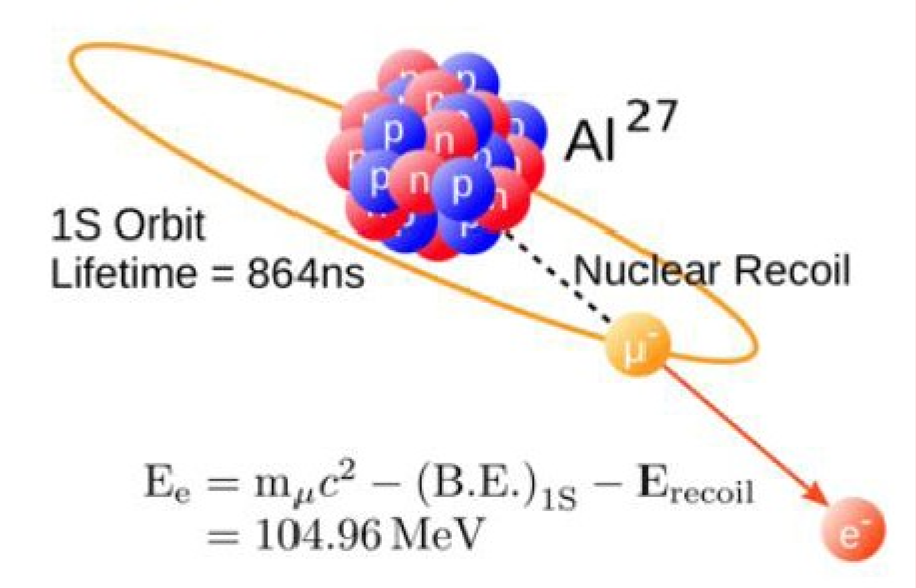
The Mu2e experiment

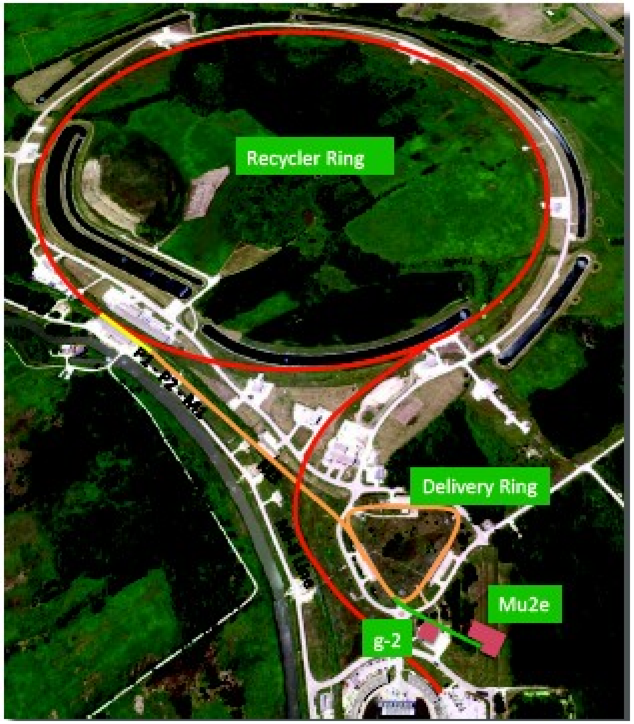
A search for **Charged Lepton Flavor Violation (CLFV)**

via the coherent conversion:

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



At Fermilab Muon Campus



Will improve by **a factor 10^4** the world best sensitivity (SINDRUM II) on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z)) \rightarrow \text{all muon captures})}$$

down to $3 \cdot 10^{-17}$

SM prediction is $O(10^{-54})$: any observation will be clear evidence for **New Physics**

Charged Lepton Flavour Violation search

Flavor is violated in quark mixing and in neutral lepton (neutrino) mixing: why not in charged leptons?

Long history of experiments looking for CLFV in muon sector but also in τ and K decays*

Best limits and expected improvements from muon sector:

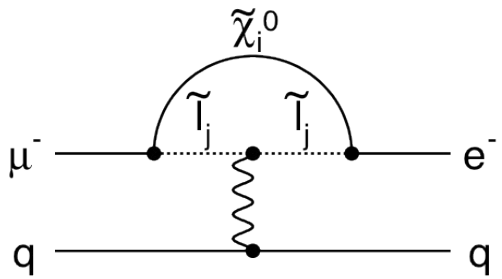
Process	Current limit	Next generation experiments
$\mu^+ \rightarrow e^+\gamma$	$BR < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^-e^+$	$BR < 1.0 \cdot 10^{-12}$	10^{-16} (PSI)
$\mu^- N \rightarrow e^- N$	$R_{\mu e} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

Many New Physics model predict rates observable by next generation experiments!

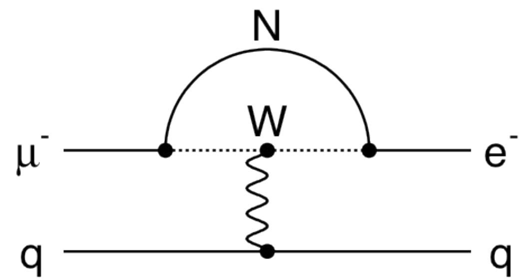
* See for example R.H Bernstein, P.S. Cooper Phys.Rept. 532 (2013) 27-64

New Physics contributions to CLFV

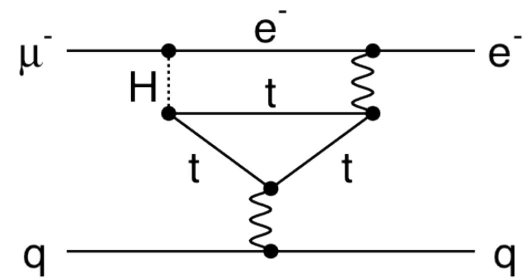
Loops



Supersymmetry

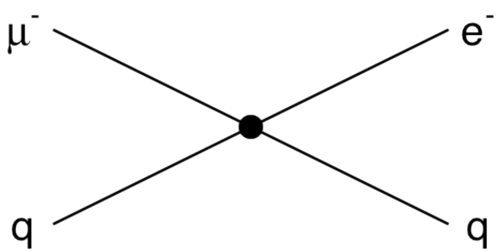


Heavy Neutrinos

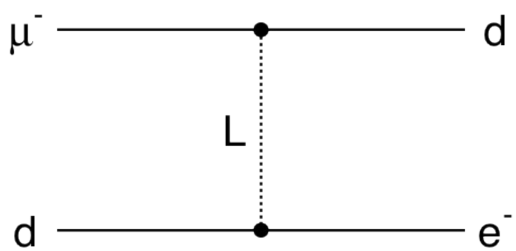


Two Higgs Doublets

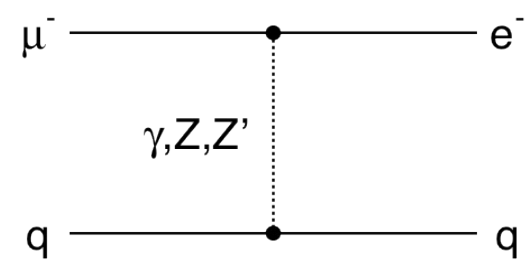
Contact Terms



Compositeness



Leptoquarks



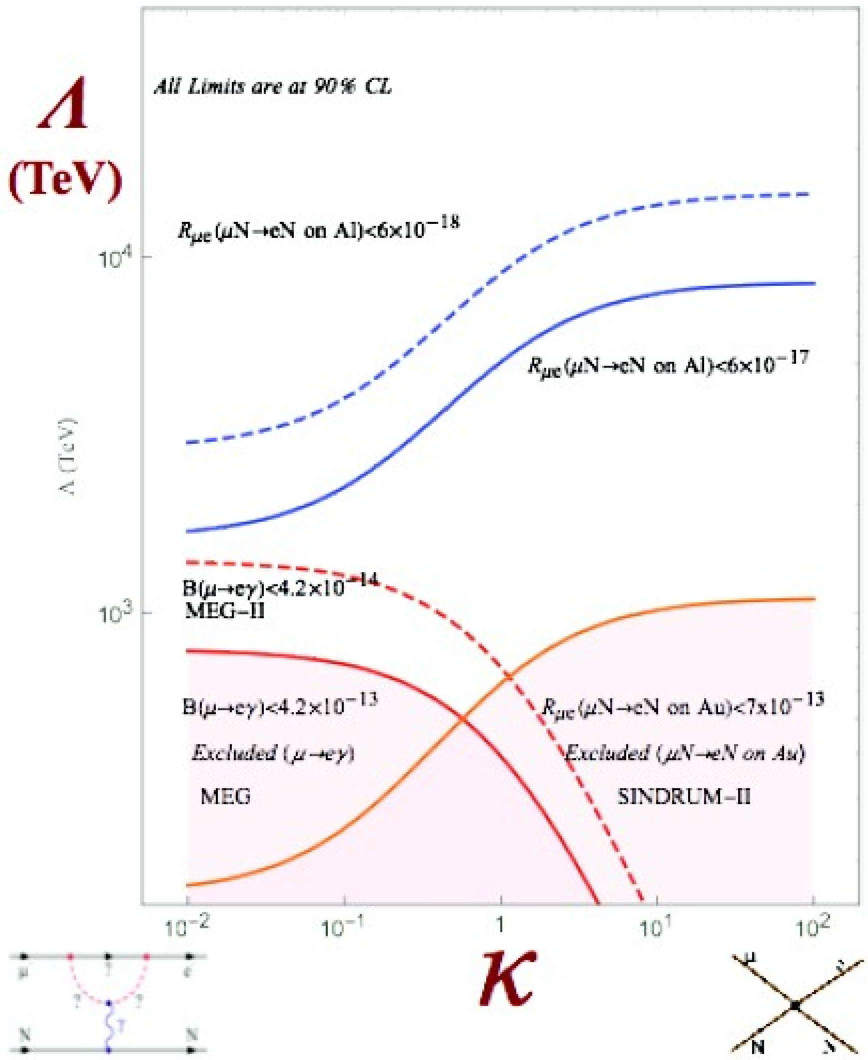
New Heavy Bosons /
Anomalous Couplings

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} \cdot \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \cdot \bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}\gamma^\mu q + \bar{e}\gamma^\mu e \right) + h.c.$$

Loops

Contact terms

Mu2e sensitivity: 90% exclusion



Courtesy B. Bernstein

- Mu2e will probe Λ_{NP} ~ O(10^3 -10^4) TeV >> TeV

Mu2e sensitivity: discovery potential

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

★★★ = Discovery Sensitivity

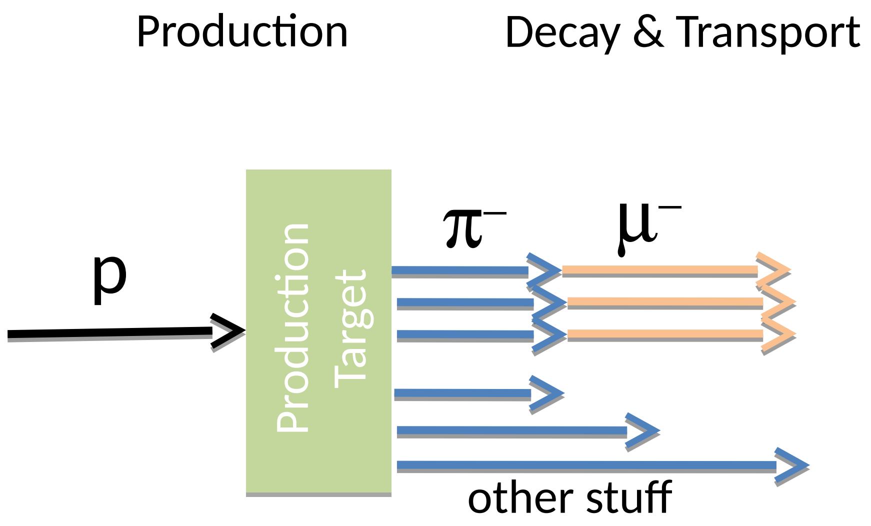
arXiv:0909.1333[hep-ph]

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

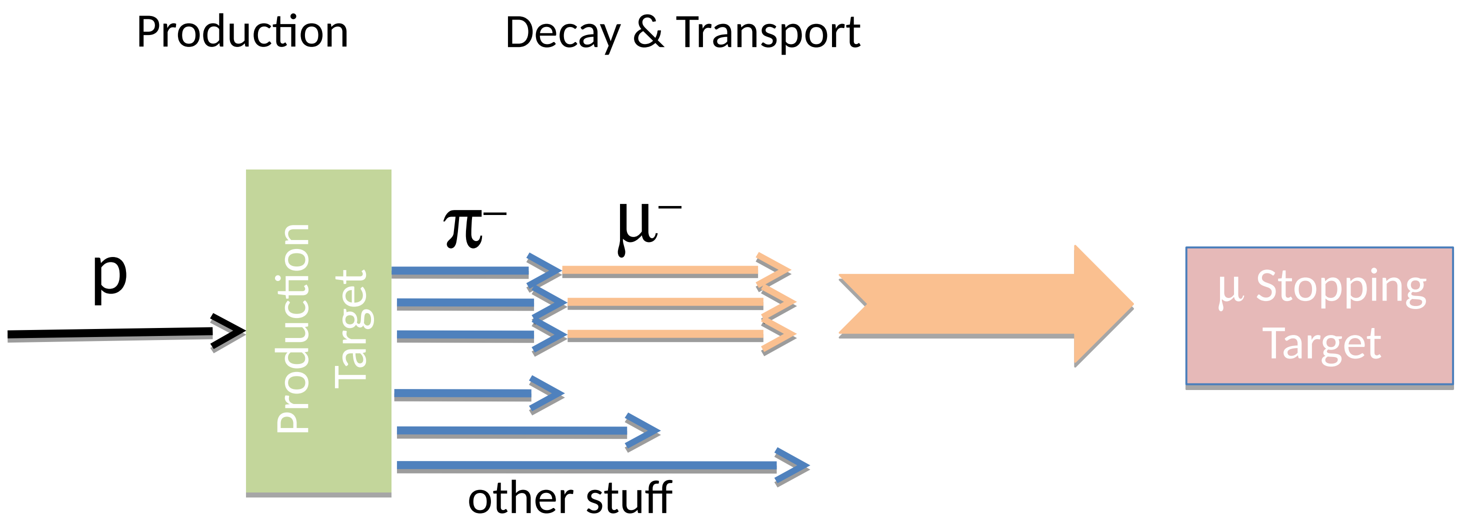
Comparison of sensitivity for various models

Mu2e concept



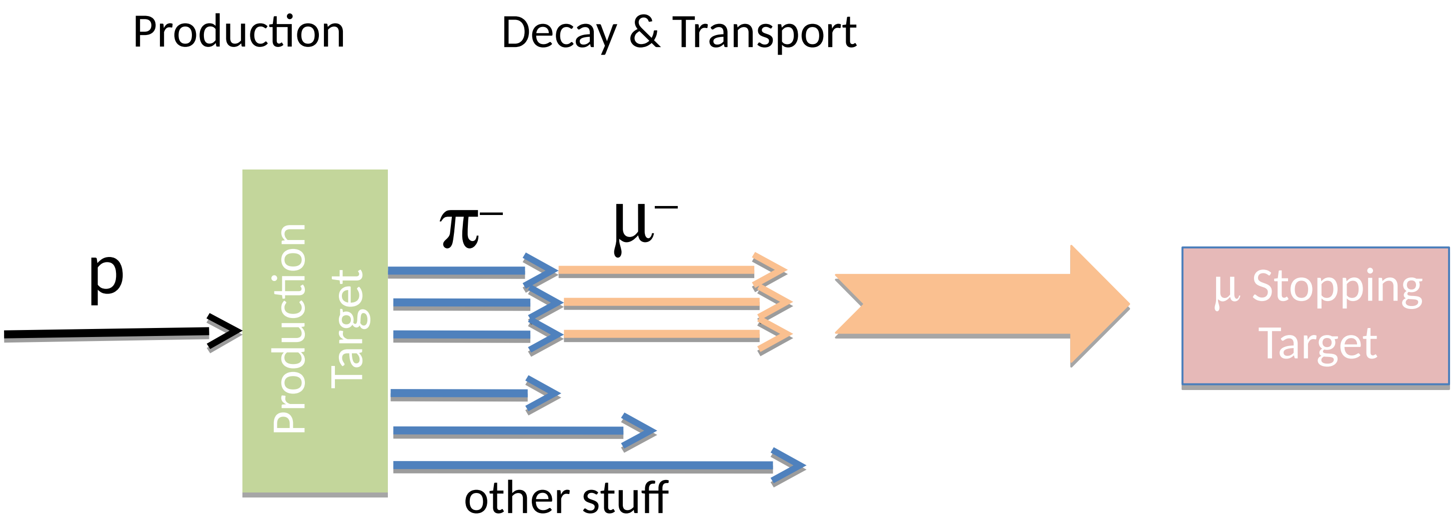
1) Generate a beam of low momentum muons

Mu2e concept



1) Generate a beam of low momentum muons
2) Stop the muons in a target (we'll use Al)

Mu2e concept

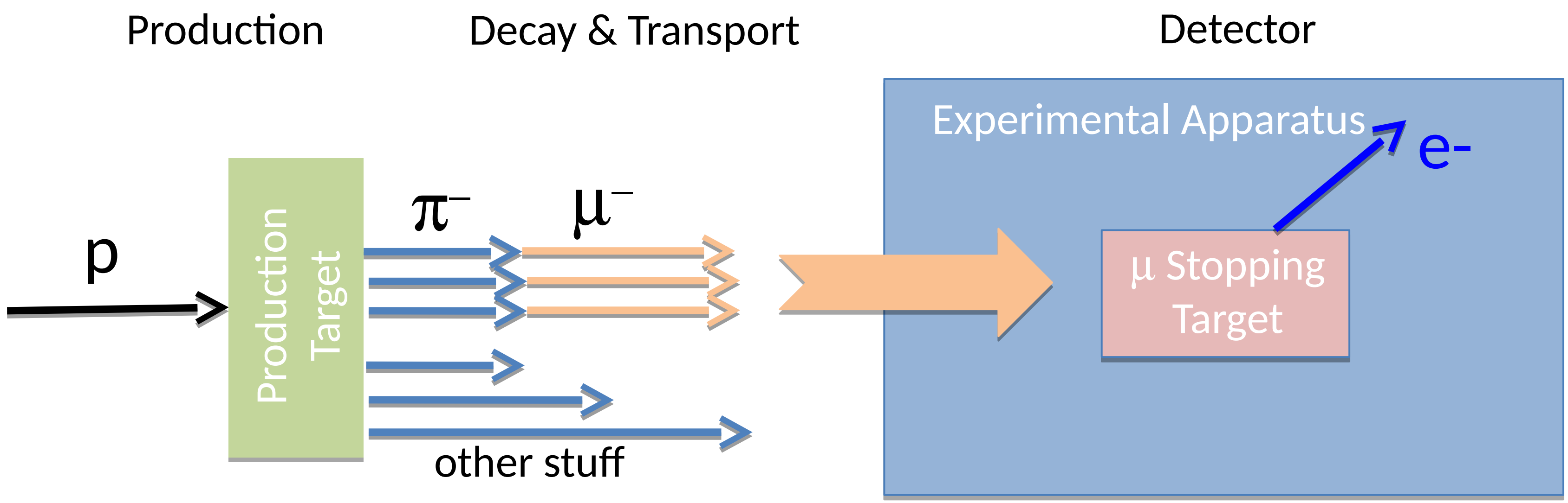


1) Generate a beam of low momentum muons
2) Stop the muons in a target (we'll use Al)

Muonic aluminum lifetime: τ_μ^{Al} = 864 ns

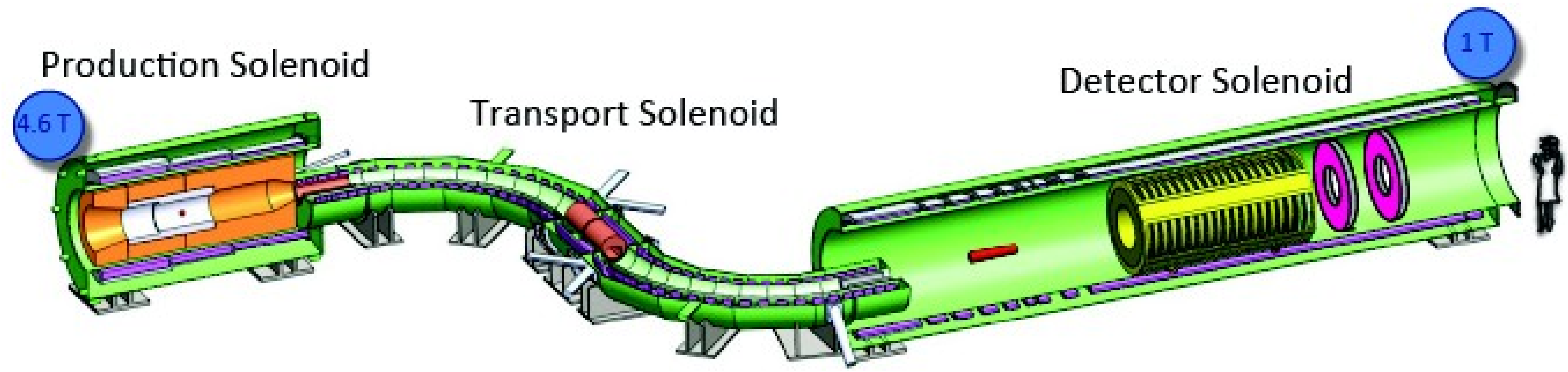
Large τ_μ^N important for discriminating background

Mu2e concept



1) Generate a beam of low momentum muons
2) Stop the muons in a target (we'll use Al)
3) Look for events consistent with $\mu^- N \rightarrow e^- N$
   - Monochromatic electron: $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$
   - For aluminum: E_e=104.96 MeV

Mu2e Apparatus: 3 superconducting solenoids



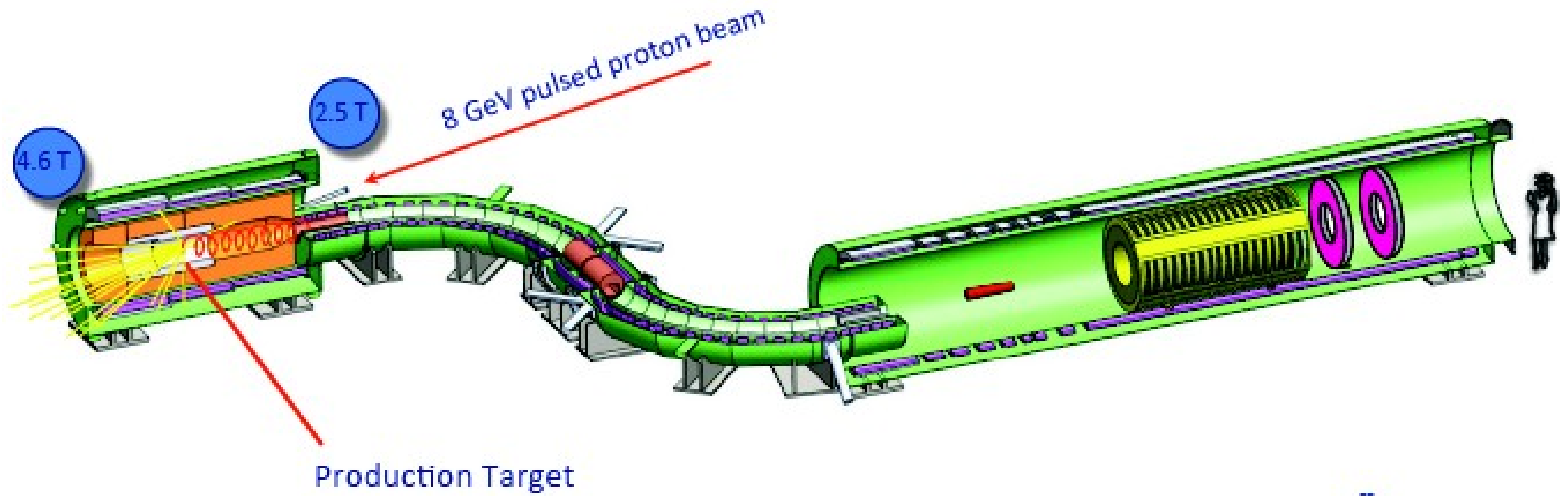
Magnetic field gradient is used to transport particles in the detector region

Evacuated to 10^{-5}-10^{-4} Torr

High neutron and ionizing radiation

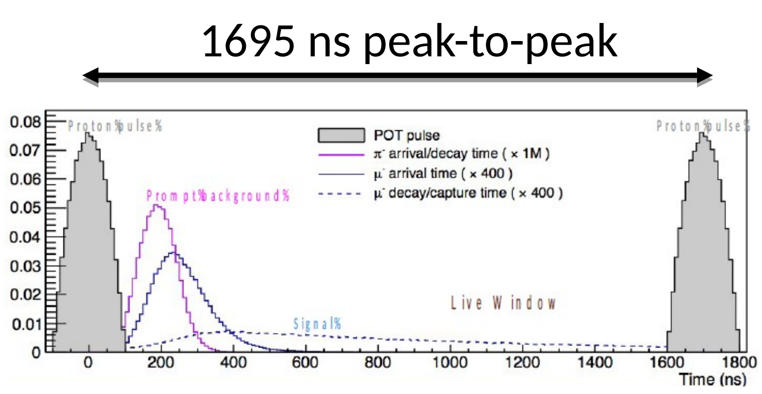
All components must be qualified to operate in these conditions

Mu2e Apparatus: production solenoid

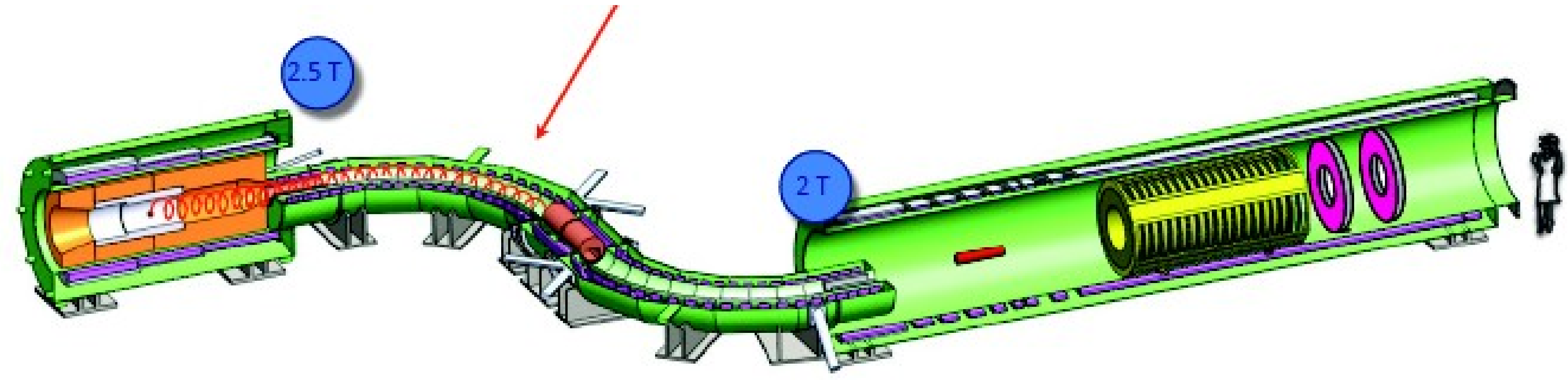


8 GeV protons interact with a tungsten production target to produce μ^- from π- decay: **3.6 ·10^{20} protons on target in 3 years**

Pulsed beam to allow an analysis time window (t>700 ns) suppressing prompt backgrounds from beam and pions. Fraction of protons out of bunch <10^{-10} measured by the 'extinction monitor' (not shown on the left)



Mu2e Apparatus: transport solenoid

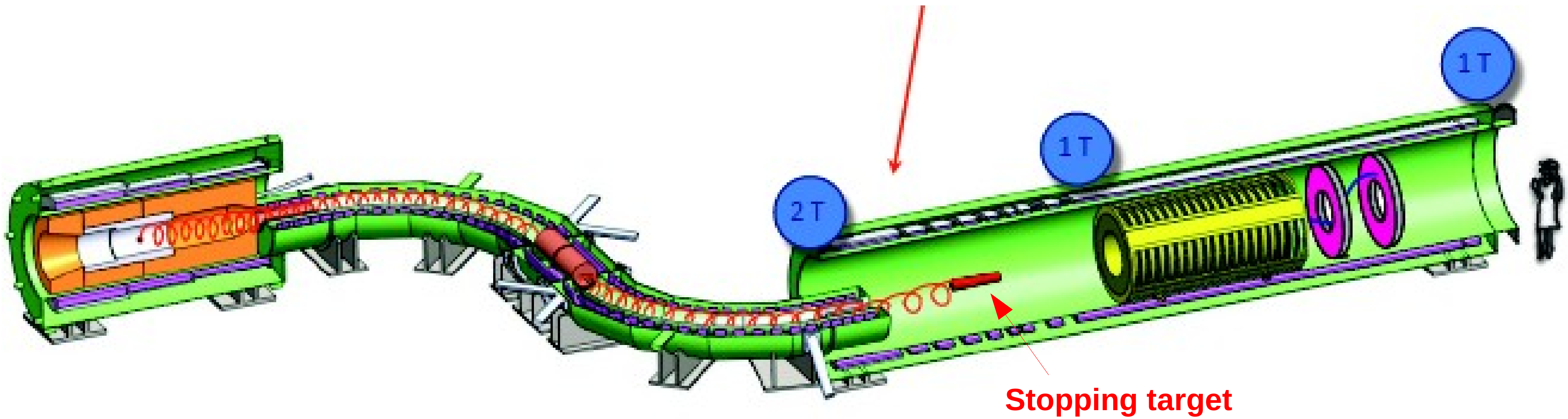


Field gradient captures π^- and subsequent μ^-

Collimators select negative particle charge and momentum range

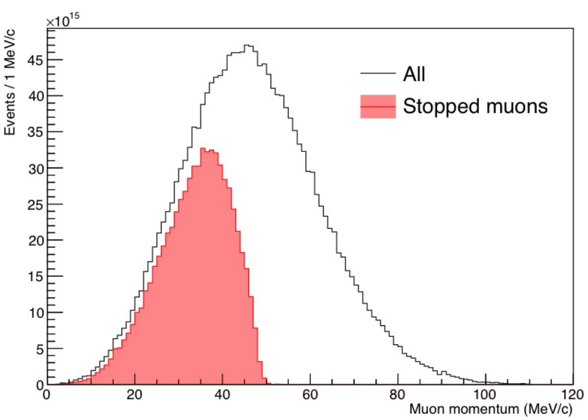
Be windows at beginning and in the middle to reduce antiproton contamination

Mu2e Apparatus: detector solenoid



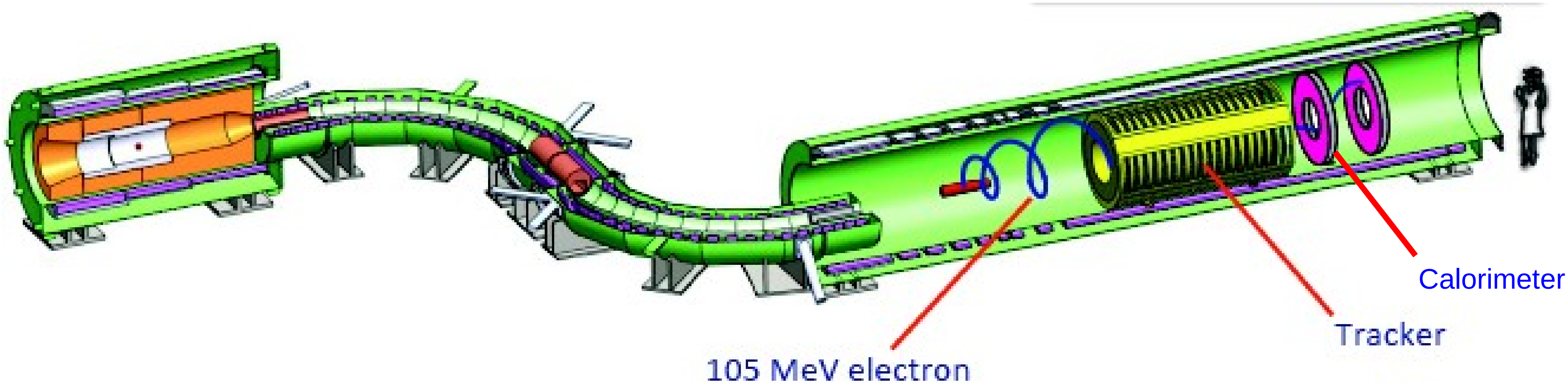
10^{10} Hz of muons stopped in 34 foils of Al:

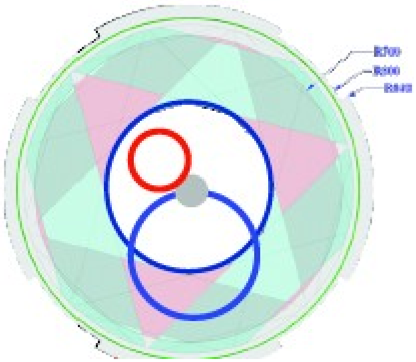
61% captured by Al nucleus
(normalization of $R_{\mu e}$)
39% decay in orbit (DIO)
Very few (!?!) eventually convert to e^-



Stopped muons momentum
(< 50 MeV/c)

Mu2e Apparatus: detector solenoid

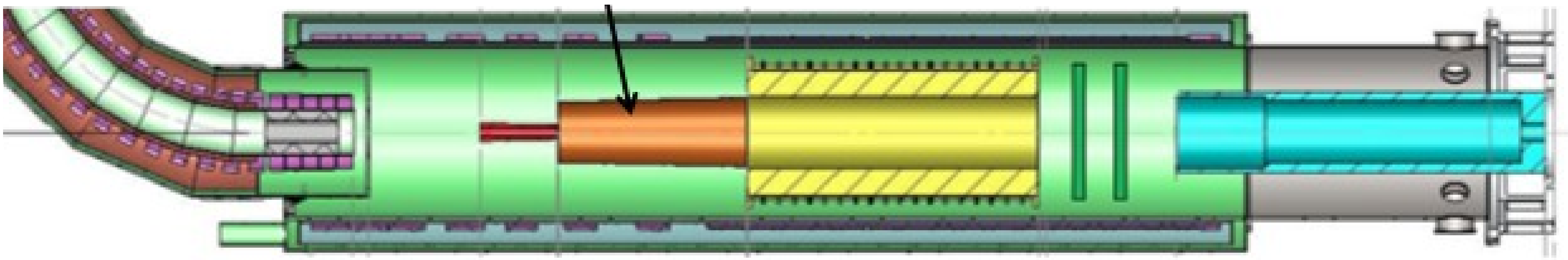




Upstream graded field improves acceptance and rejects backgrounds:
- high momentum particles are thrown away
- low momentum particles pass through tracker and calorimeter holes

Downstream uniform field to measure momentum

Mu2e Apparatus: detector solenoid



Proton absorber to reduce tracker occupancy

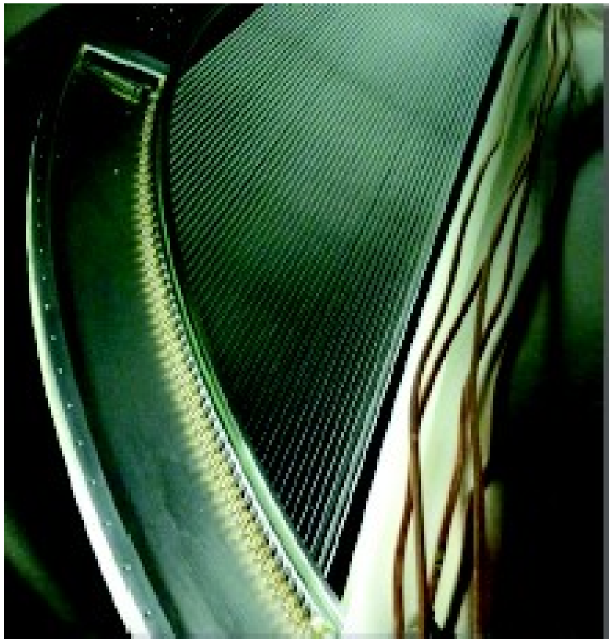
Beam stop to reduce back scattered particle flux

Not shown: Cosmic ray veto (around DS and part of TS)
Stopping target X and γ ray monitor (far on the right)

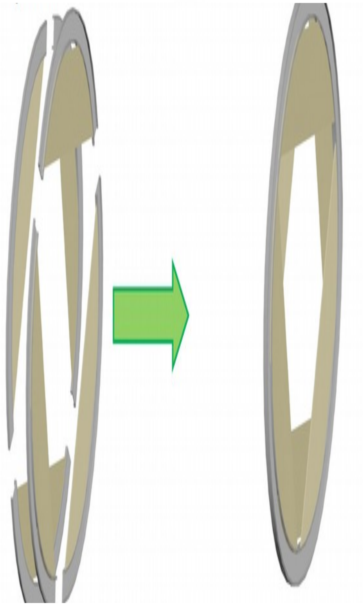
Mu2e detector: straw tracker

- 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/CO2 with HV < 1500 V

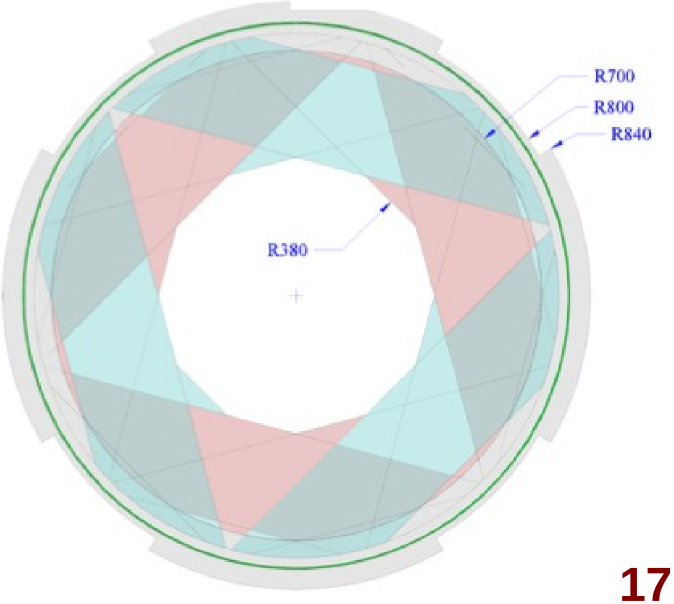
100 straws->1 panel



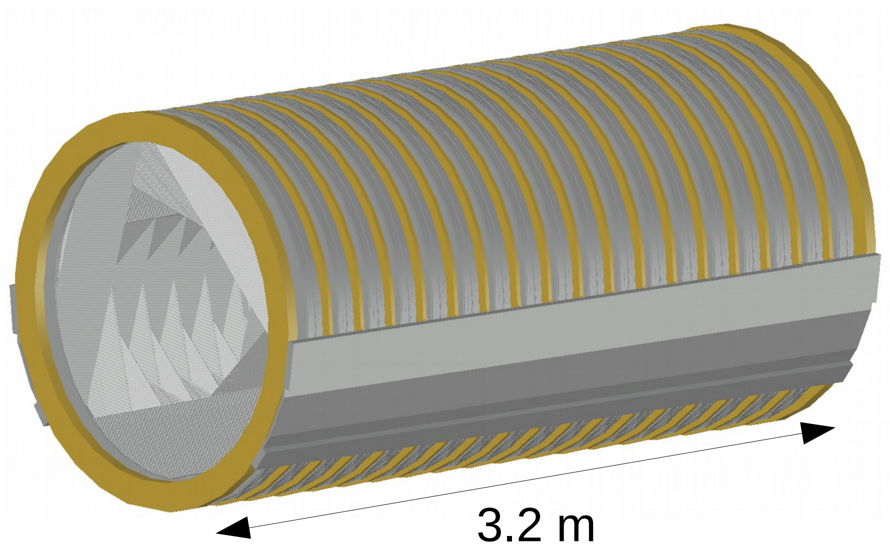
6 panels 1 plane



2 planes 1 station (stereo view)

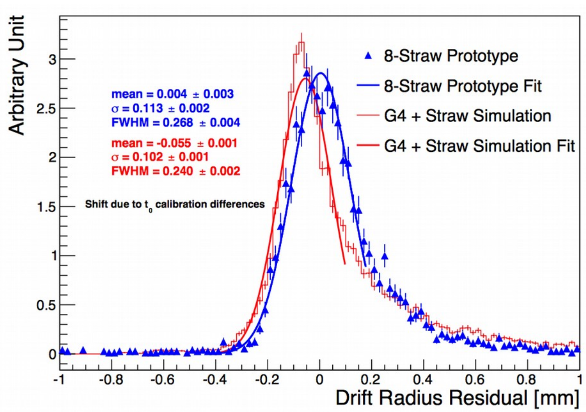


Mu2e detector: straw tracker



18 stations
Active volume: 38 < r < 70 cm
(blind to beam flash and >99% DIO)

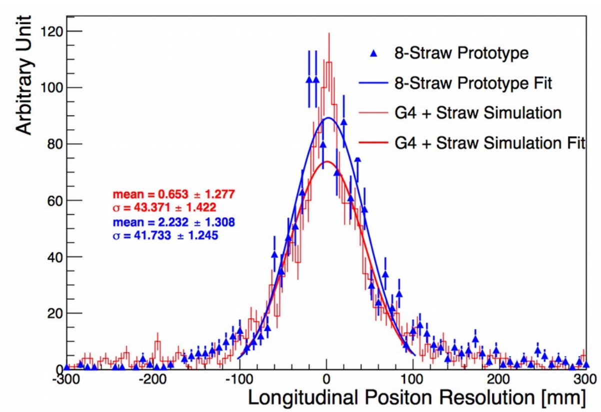
>20k straws total each read by 2 ADCs and 2 TDCs



Transverse Resolution
(Data vs MC)

$\sigma_{data} = 0.113 \pm 0.002$ mm

$\sigma_{MC} = 0.102 \pm 0.001$ mm

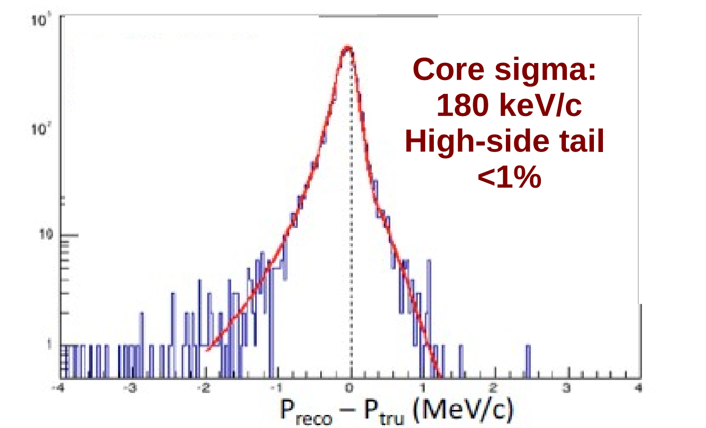


Longitudinal Resolution
(Data vs MC)

$\sigma_{data} = 42 \pm 1$ mm

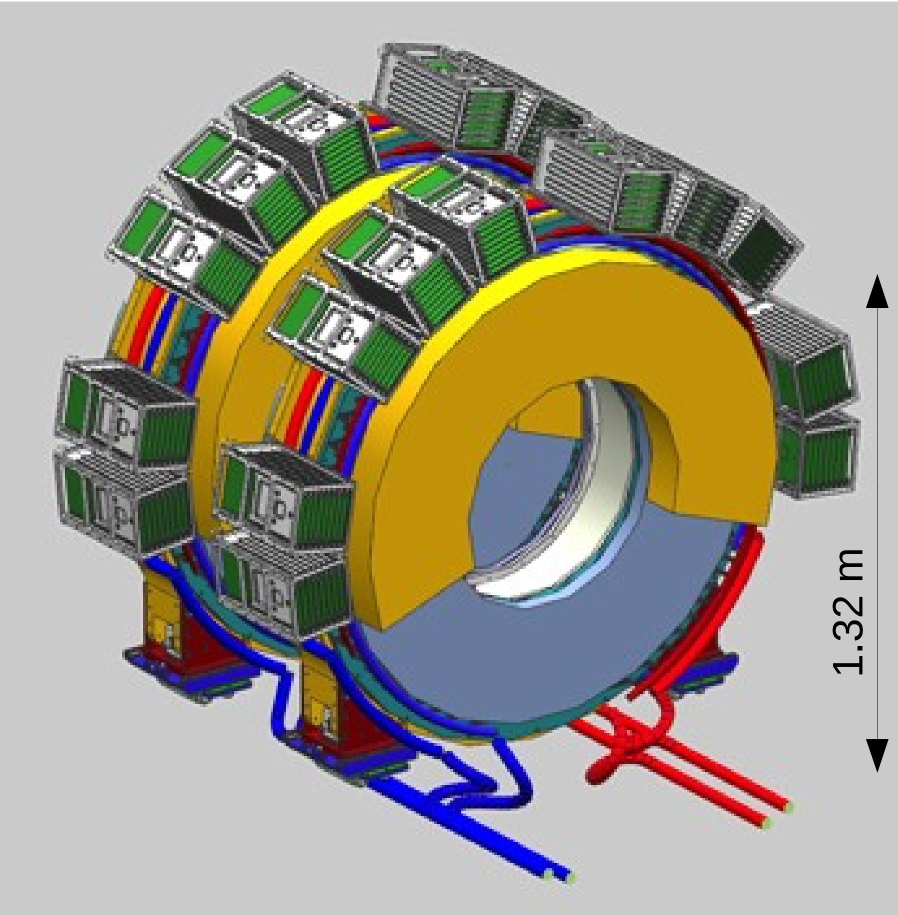
$\sigma_{MC} = 43 \pm 1$ mm

Momentum resolution



σ_p~180keV/c **σ_t~1 ns**

Mu2e detector: crystal calorimeter



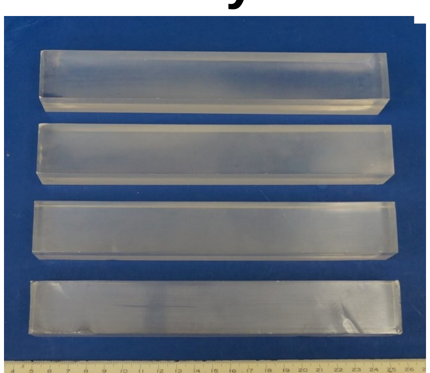
2 disks spaced by 70 cm
($\sim\lambda/2$ of e^- trajectory in r-z plane)
Active volume: 37 < r< 66 cm

1 disk: 674 undoped CsI crystals
($3.4 \times 3.4 \times 20$ cm^3)

1 crystal: 2 channels
($1.4 \times 2 cm^2$ SiPM arrays cooled at 0^o C)

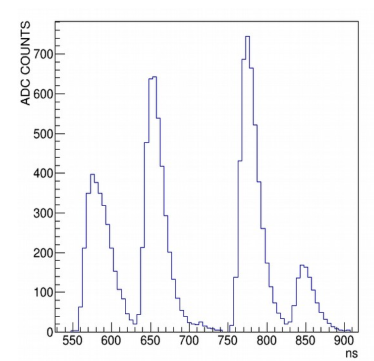
Analog FEE on SiPM back
Digital electronics on external crates

CsI crystals

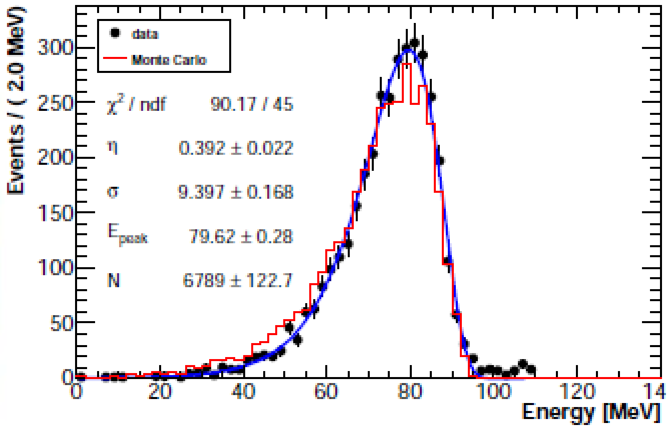


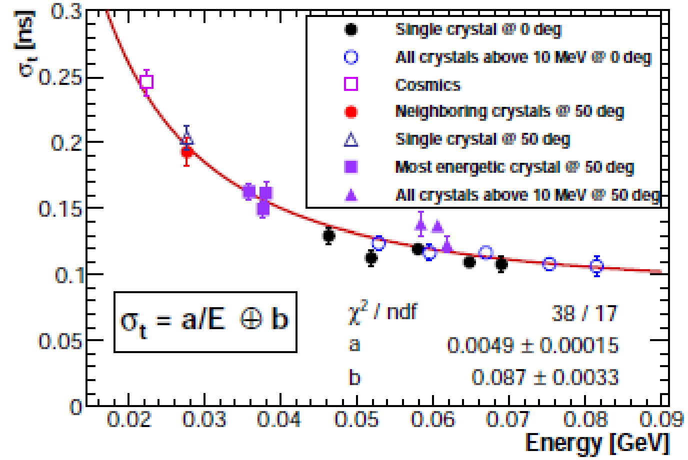
SiPM arrays: 2x3 6x6 cm^2 cells

digitized signal



Mu2e detector: crystal calorimeter





2015 beam test results: **$\sigma(E)/E$ ~7% @50°** **$\sigma(t)$~120 ps @50°**

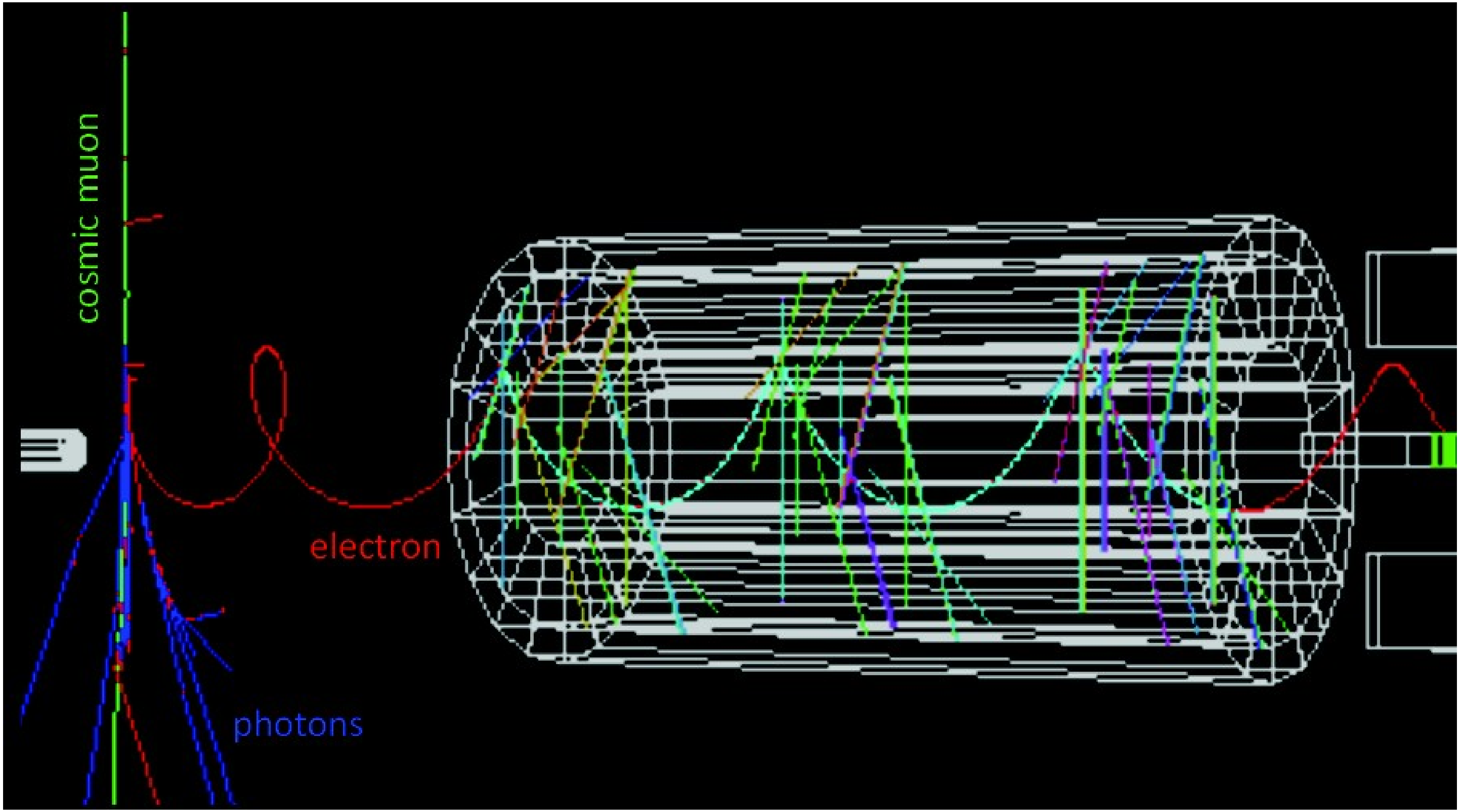
(dominated by lateral leakage)

2017: Module 0 prototype
with 51 CsI crystals and 58 SiPMs
and cooling

First test with close to final FEE and
not final digital electronics
already reached requested energy and
time resolution

Test with final electronics in next months

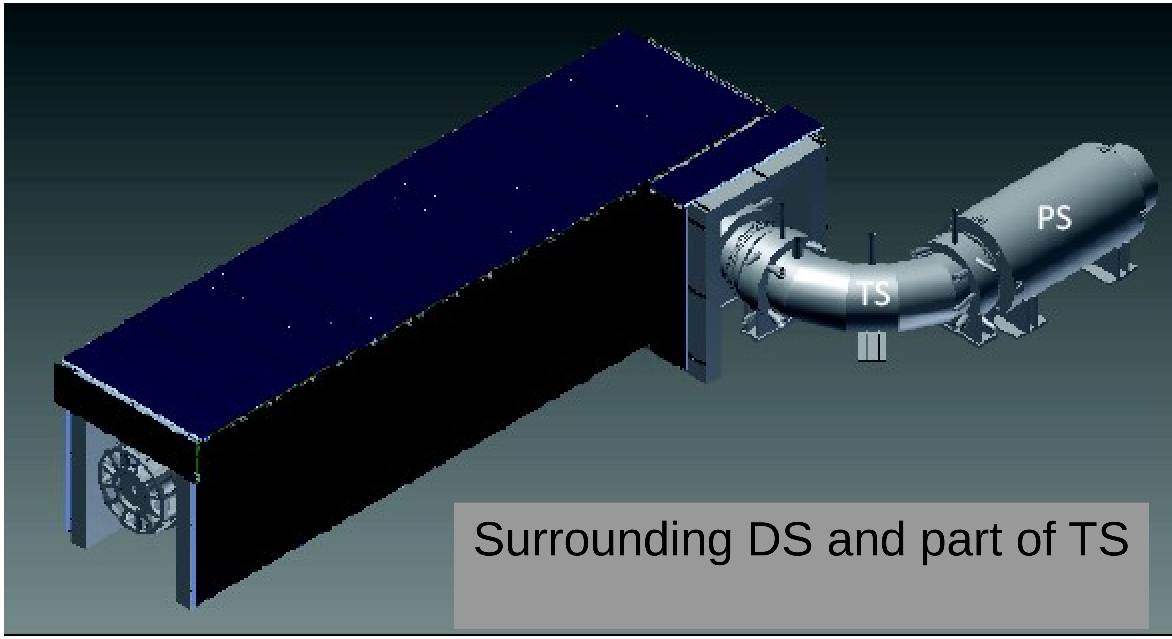
Mu2e detector: cosmic ray rejection



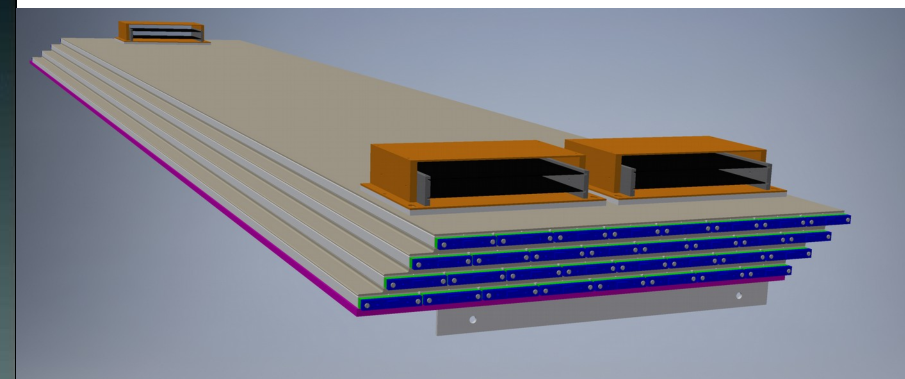
1 cosmic ray per day can produce a ~105 MeV/c electron

Need a veto system with a rejection factor O(10^4)

Mu2e detector: cosmic ray veto



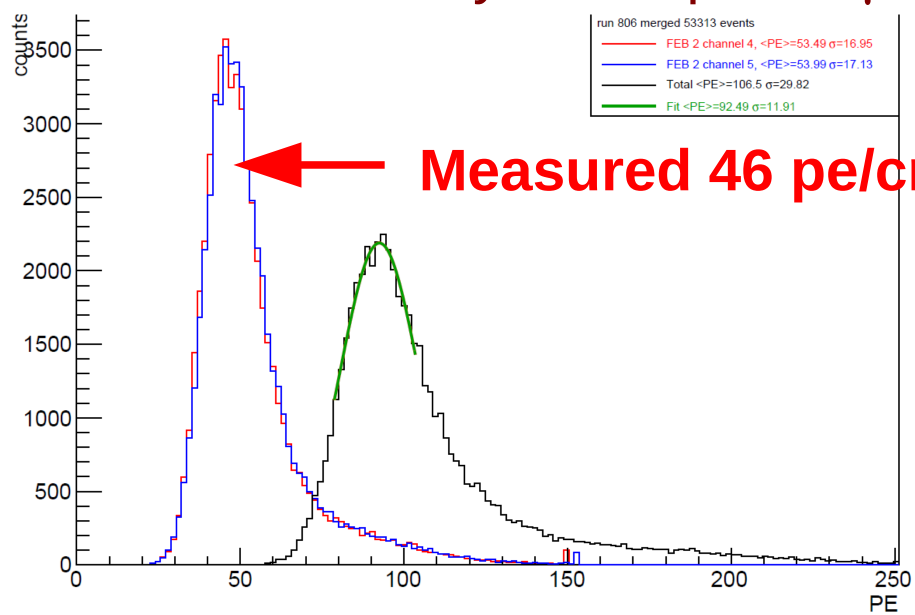
Dead time<10% (requires shielding)



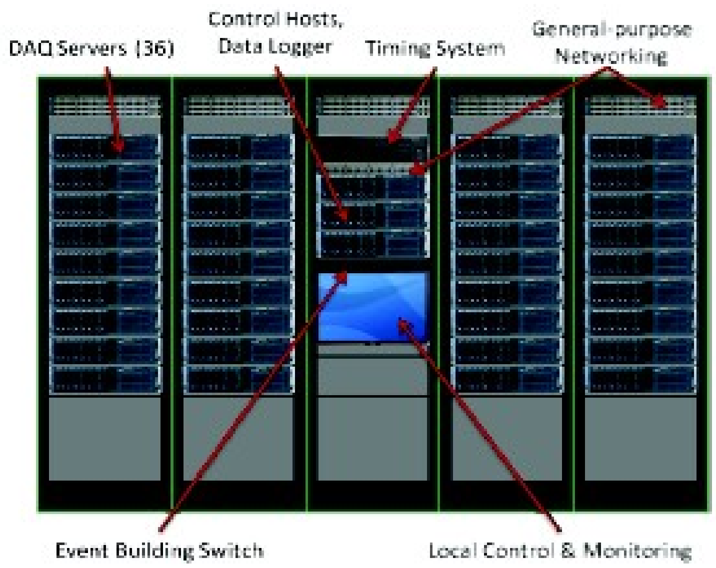
4 overlapping layers of scintillator bars 5x2x90-660cm^3

light collected by 2 WLS fibers (1.4 mm) read by 2x2 mm^2 SiPM at each end (not the ones close to the holes)

10^{-4} inefficiency -> 26 pe/cm μ@1 m



Mu2e trigger and DAQ



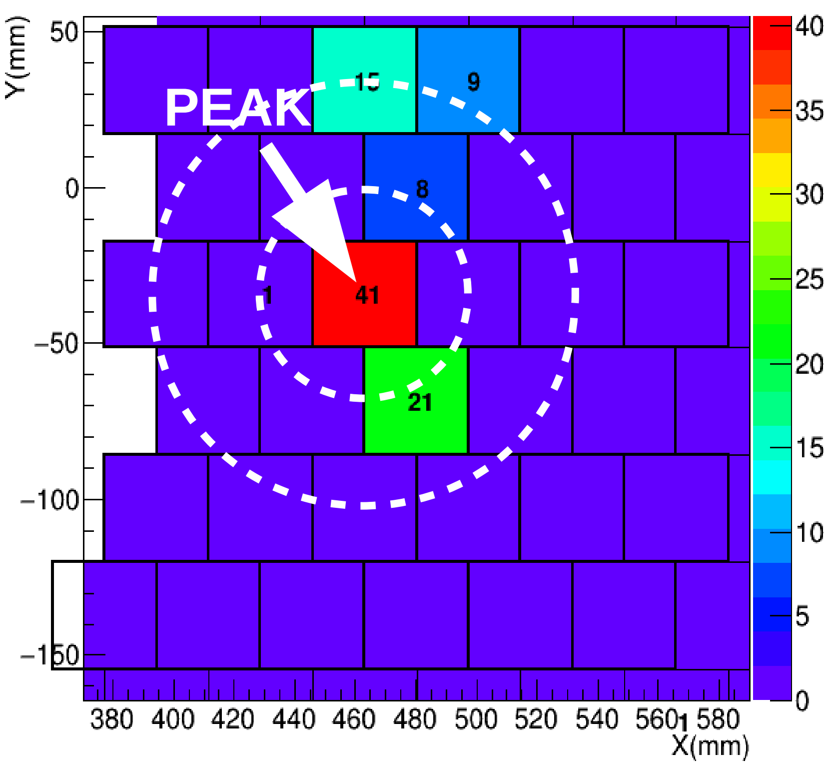
Acquire:

- events (1.7 μs microbunch) with an high momentum electron within tracker acceptance within 500-1700 ns from proton pulse

- calibration events

Bandwidth from average event size: ~31GB/s

Storage limit: 7 PB/y ~ 0.7 GB/s



<u>Trigger requirements:</u>

Event rate suppression: ~100

Event processing time: < 3.6 ms

<u>Trigger Example</u>

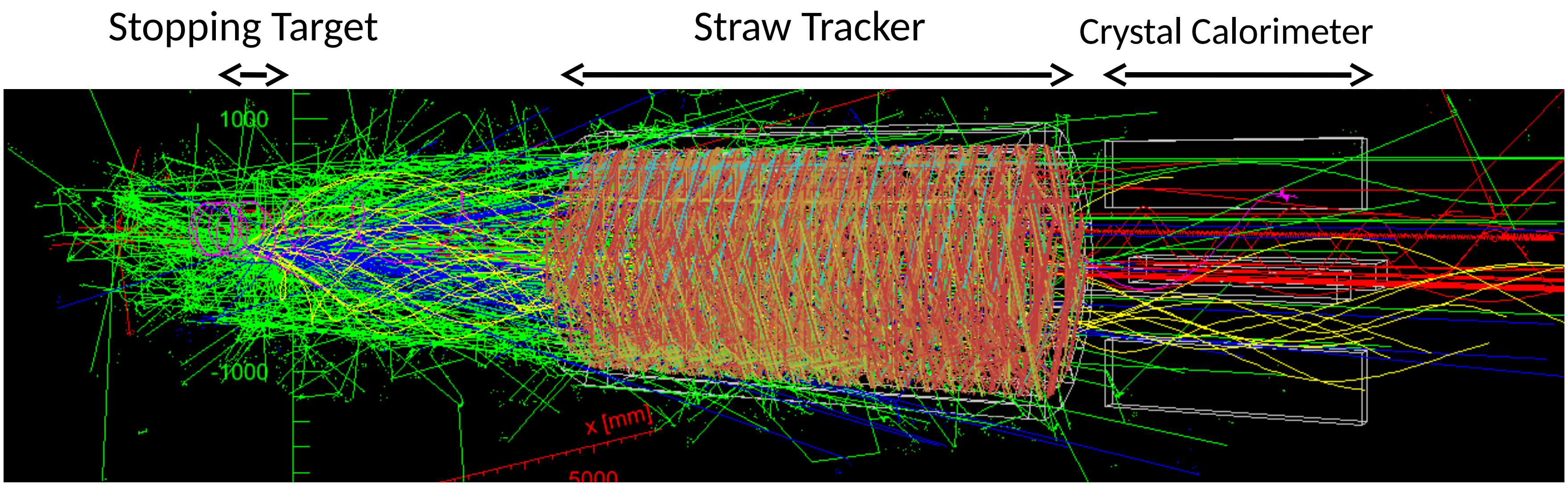
Calorimeter trigger using shower peak amplitude, time and position and highest energy deposits in neighbour crystals:

Efficiency on physics dataset: 85-90%

Rejection factor: 100

Processing time: 1 ms

Mu2e track reconstruction

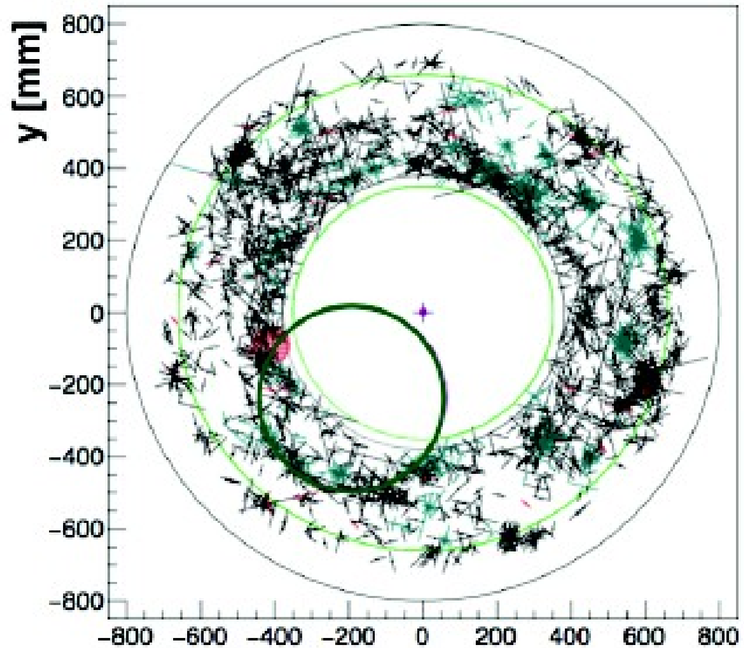


A typical Mu2e tracker event integrated over 500-1695 ns window

Hits filtered according to their time, energy and position
Low momentum electrons hits rejected by dedicated algorithm
Candidate tracks searched by grouping hits in 50 ns time windows

Mu2e track reconstruction

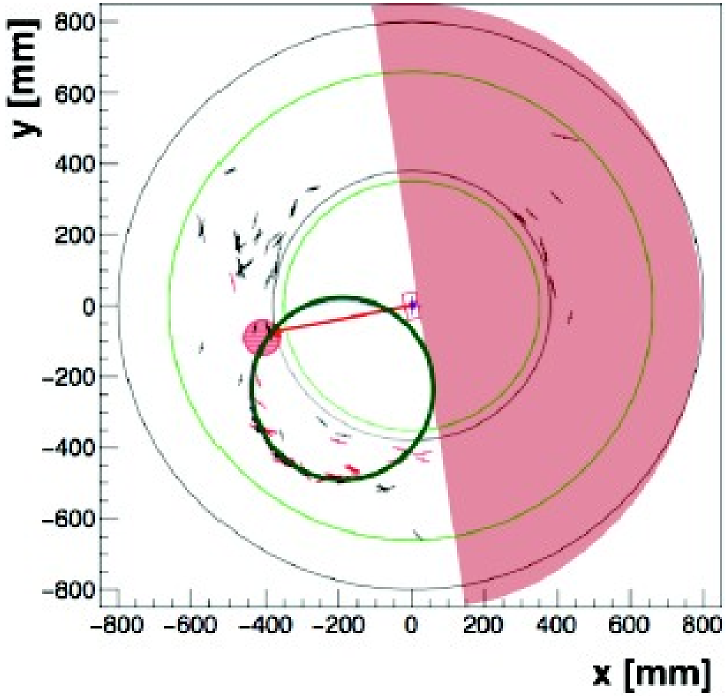
1.7 μs event (no hit selection)

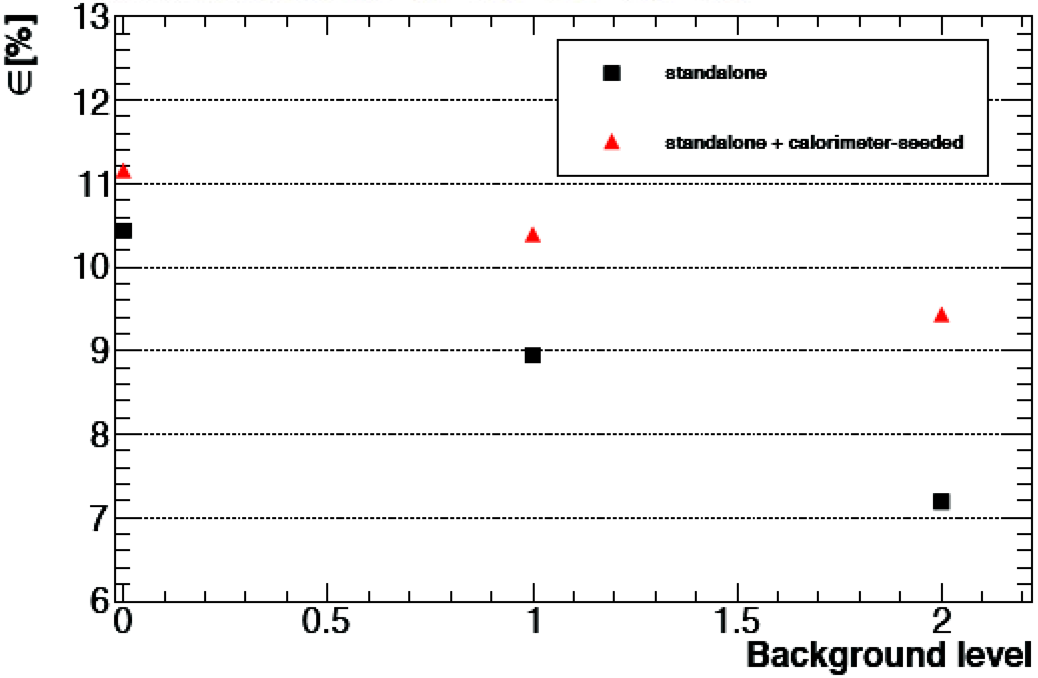


Select tracker hits matching time and position of ECAL cluster

→

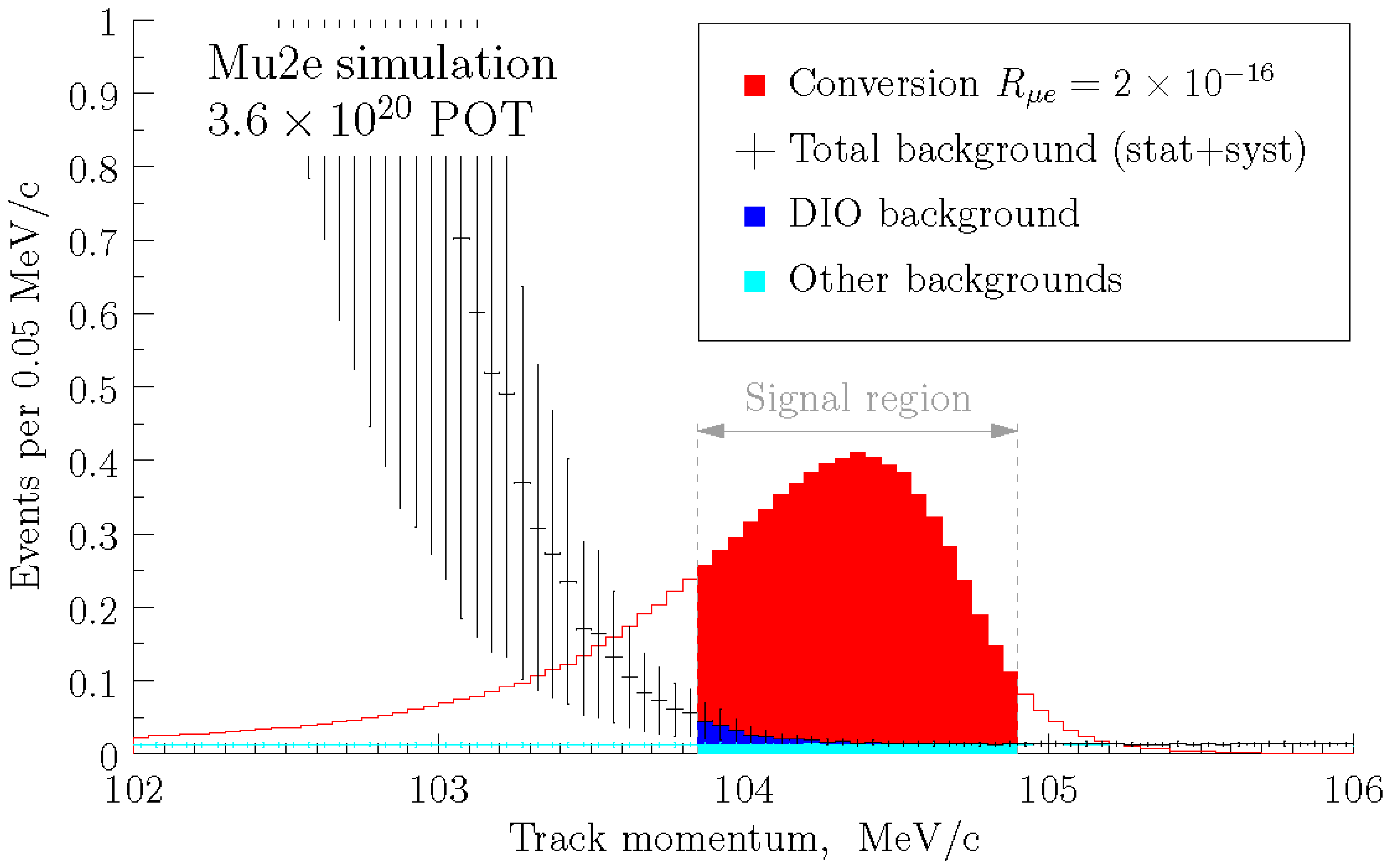
1.7 μs event (ECAL hit selection)



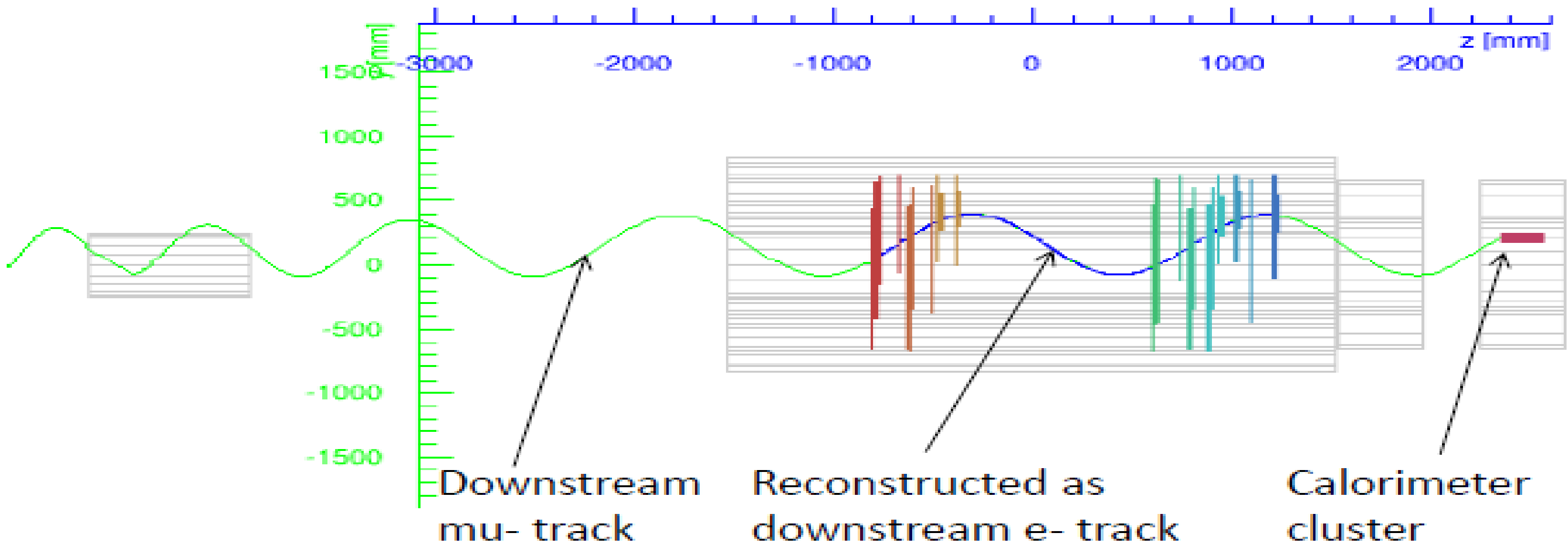


Calorimeter information helps track reconstruction and makes it more stable against background level

DIO background: 0.2 events in 3 years



Cosmic muons background



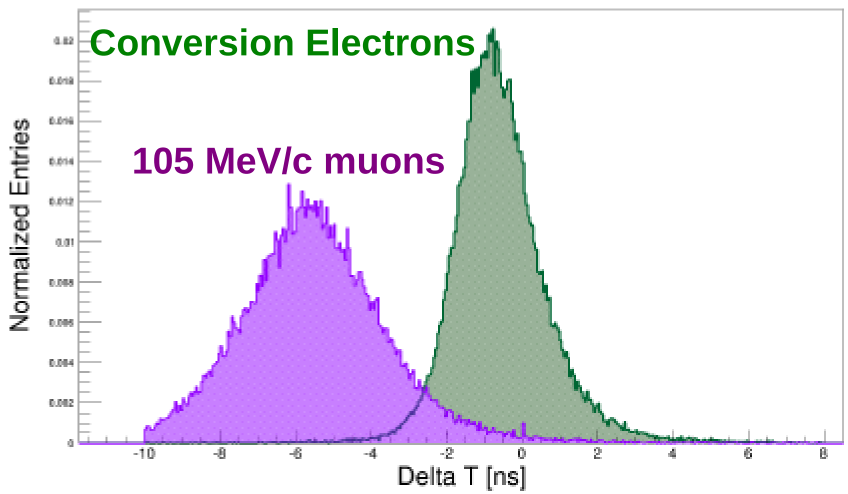
Muons can elude Cosmic ray veto entering through the hole at the TS entrance

10 times more than cosmic induced e^- background: can be suppressed by particle identification

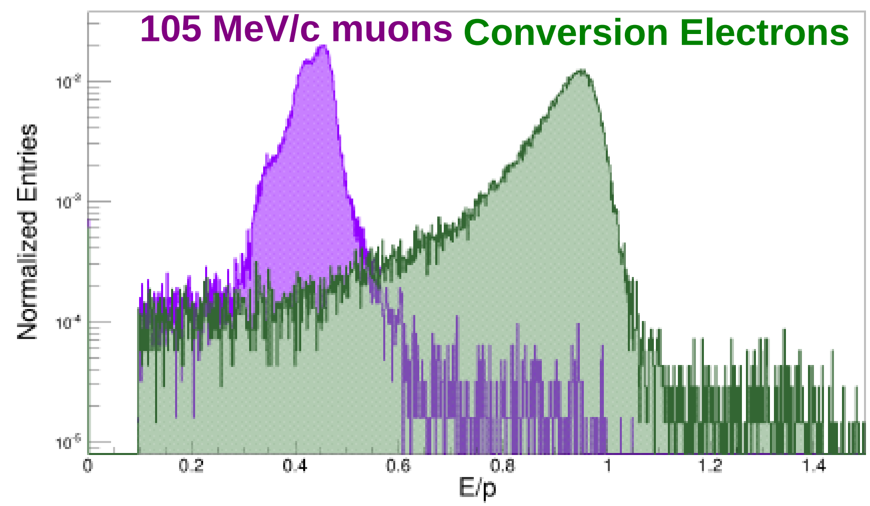
Mu2e particle identification

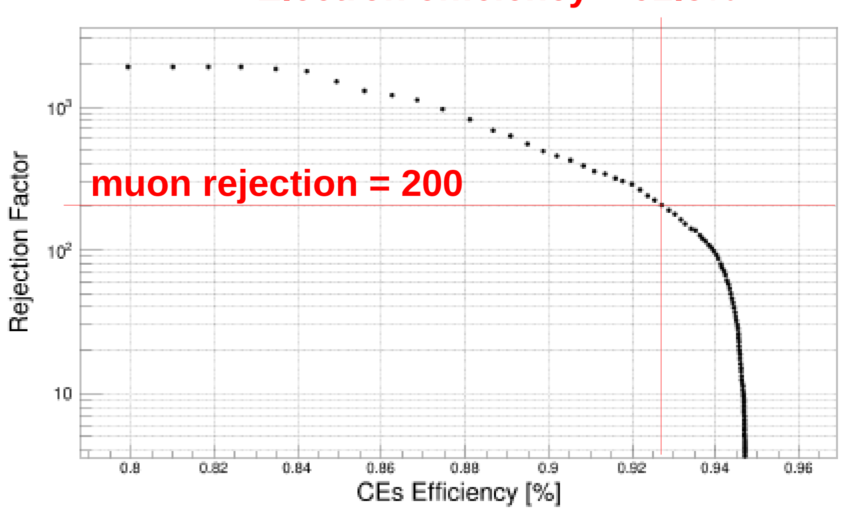
Tracker track – calorimeter cluster association + likelihood using:

time matching



Energy/momentum ratio





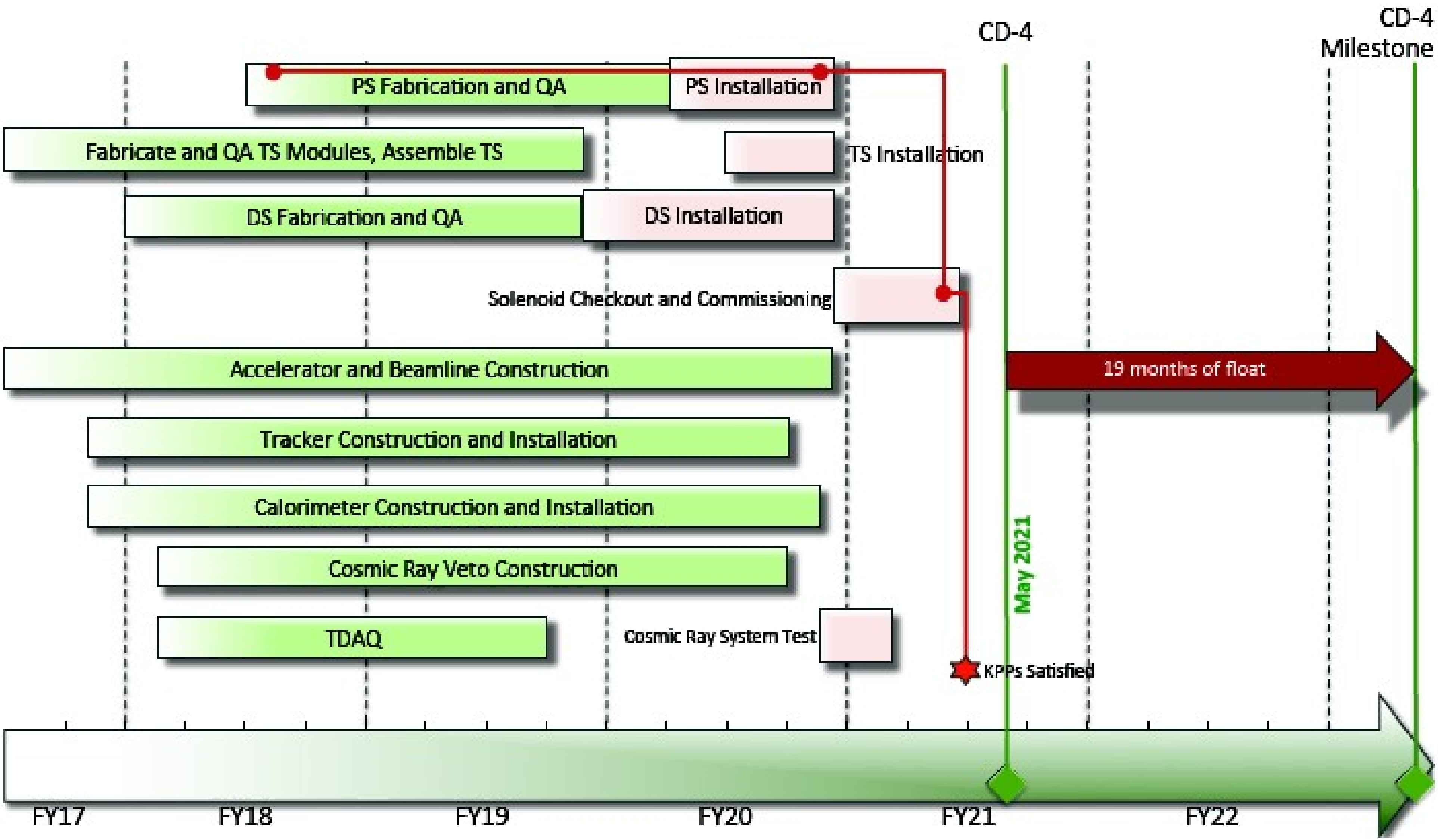
Rejection factor 200 makes cosmic muon background negligible wrt cosmic induced electron background

Mu2e background after 3 years ($3.6x10^{20}$ POT)

Process	Event Yield	comment
DIO	0.14±0.11	
RMC	<0.004	Kinematically suppressed
Pion capture	0.025±0.003	Cross section can be measured
Muon DIF	<0.003	
Pion DIF	0.001± 0.001	
Beam electrons	$(2.5\pm1.2)x10^{-4}$	Assumes 10^{-10} extinction factor
Antiprotons	0.05±0.02	
Cosmic rays	0.25±0.07	
Total	**0.5±0.1**	

Single Event Sensitivity = [3.01±0.03(stat)±0.41(syst)]$x10^{-17}$

Mu2e schedule



Conclusions

Mu2e experiment:

- is expected to improve the sensitivity for CLFV muon conversion to electrons by a factor of 10^4
- provides *discovery capability* over wide range of New Physics models
- is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments
- is progressing on schedule: will begin commissioning in 2020