EUROPEAN PHYSICAL SOCIETY HEP2019

European Physical Society
Conference on High Energy Physics

10-17 July 2019 - Ghent, Belgium

μ-e conversion and the Mu2e experiment at Fermilab

Eleonora Diociaiuti on behalf of the Mu2e collaboration
Tor Vergata University & LNF INFN

Università di Roma Tor Vergata

Mu2e

Fermilab

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Outline

- **Physics goal:**
  - **CLFV processes**
  - **Muonic atom related processes**
- **The Mu2e experiment:**
  - **the technique**
  - **the experimental setup**
- **Current status of construction**

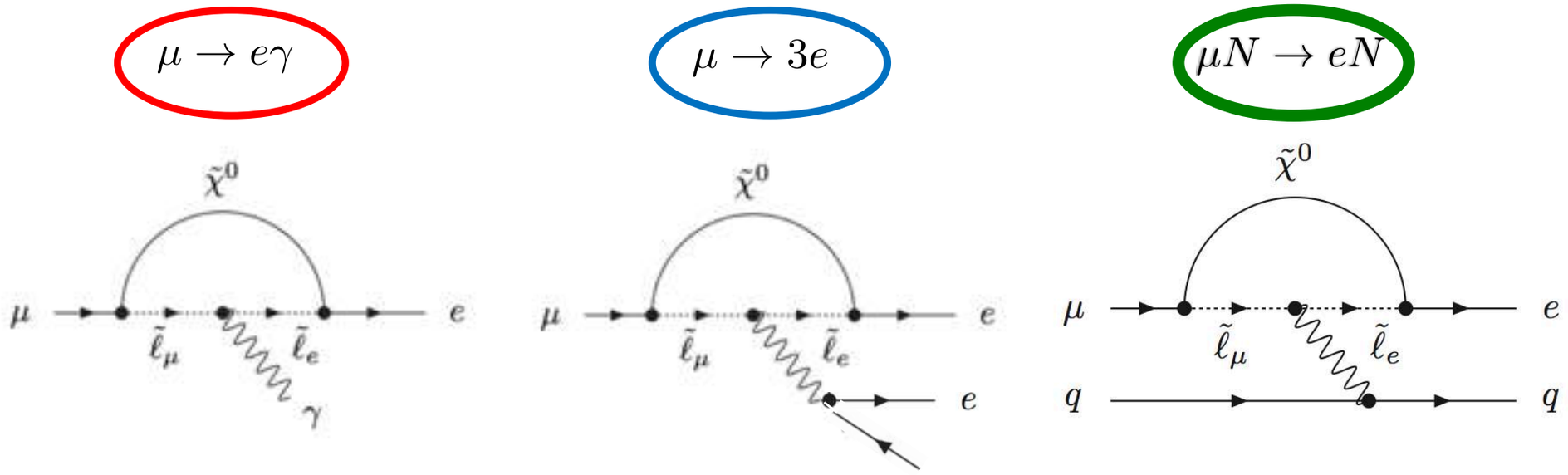
Charged Lepton Flavour Violation

- CLFV processes are forbidden in the Standard Model
- If the neutrino oscillations are included in a Minimal extension of the SM, CLFV processes are strongly suppressed ($\Delta M_\nu^4 / M_W^4 \sim 10^{-50}$)
- Different New Physics models predict rates observable for the current/next CLFV experiments

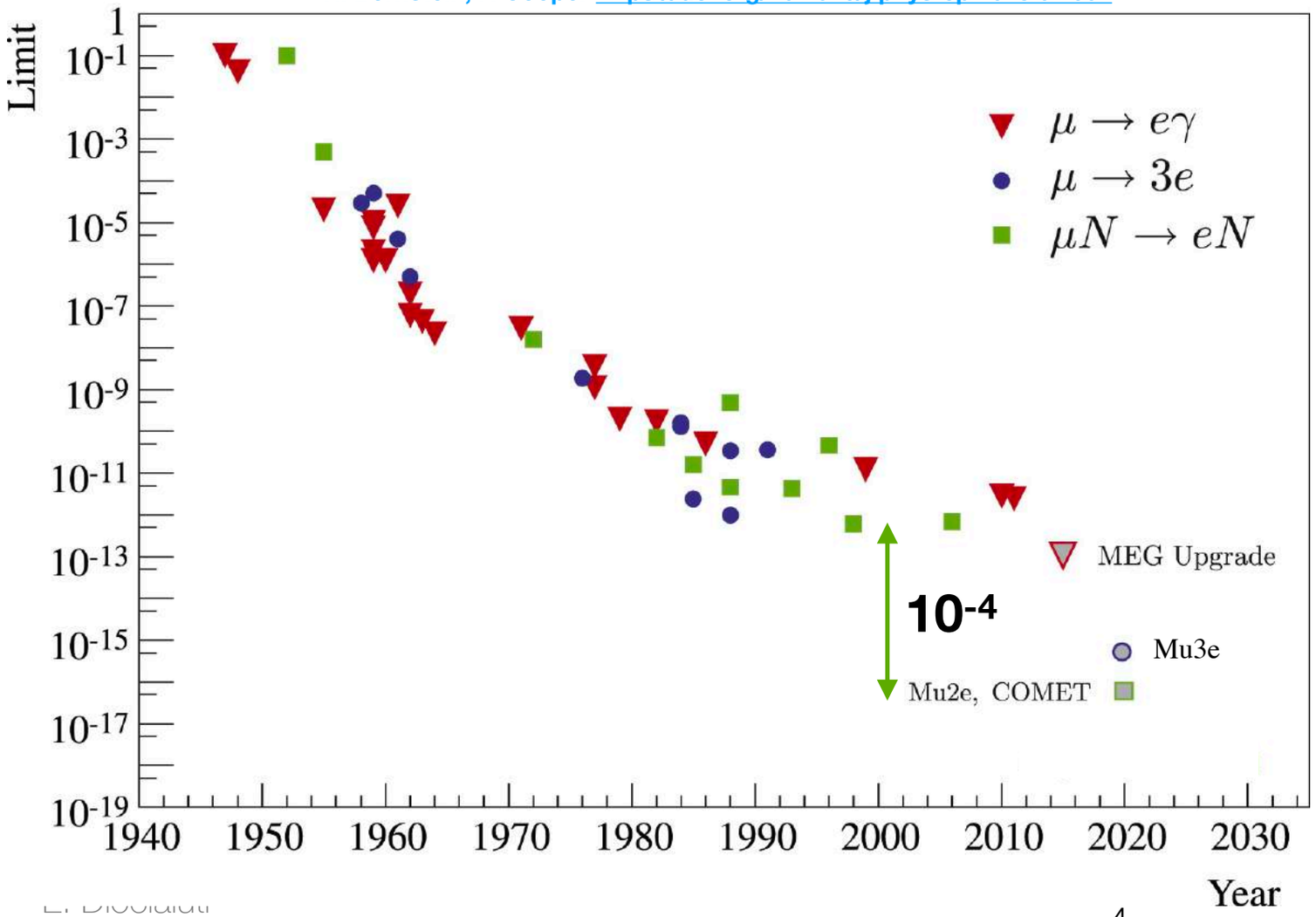
Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- N \to e^- N$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to e^-e^+e^-$	$< 2.7 \times 10^{-8}$
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$

- **Any observation will be a clear evidence of Physics Beyond the SM (BSM)**
- Muons ideal for CLFV searches
  - High intensity beams
  - Clean topologies

Muon CLFV - time line



R. Bernstein, P. Cooper https://doi.org/10.1016/j.physrep.2013.07.002



Current best limits:

BR(μ->eγ) < 4.2 ×10^{-13} MEG '16

BR(μ->3e) < 1 ×10^{-12} SINDRUM '98

$R_{\mu e}$ < 7 ×10^{-13} SINDRUM-II 2006

$R_{\mu e}$ ~ 8 x10^{-17} **Mu2e goal**

Mu2e Design

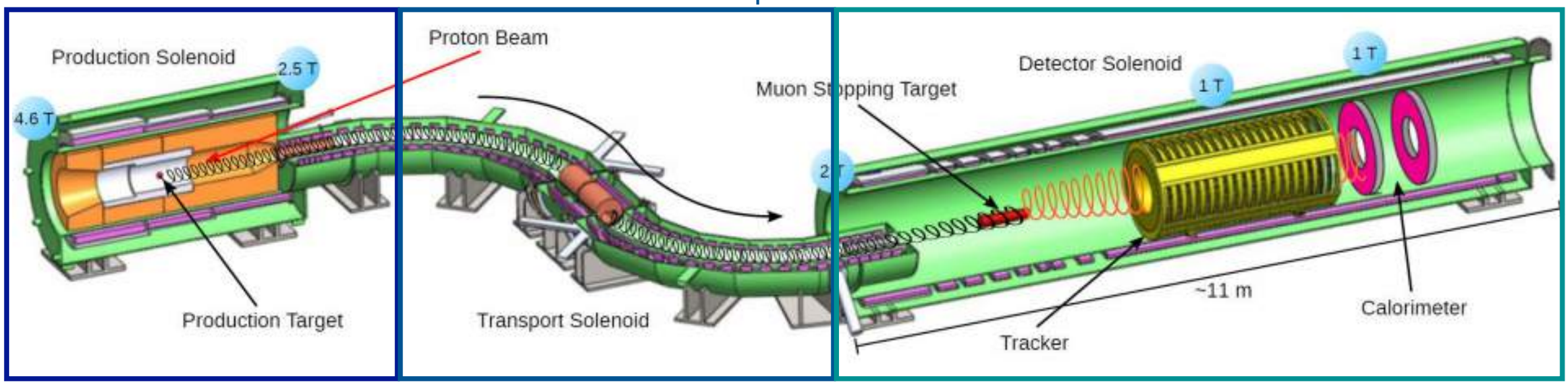
PRODUCTION SOLENOID

• 8 Gev Protons hitting the target and producing mostly π

•Graded magnetic field reflects slow forward π

TRANSPORT SOLENOID

- Selection and transport of low momentum μ^-
- Antiproton absorber in the mid-section



DETECTOR SOLENOID

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•Momentum measurement in the tracker and energy reconstruction with calorimeter

•CRV to veto cosmic rays events

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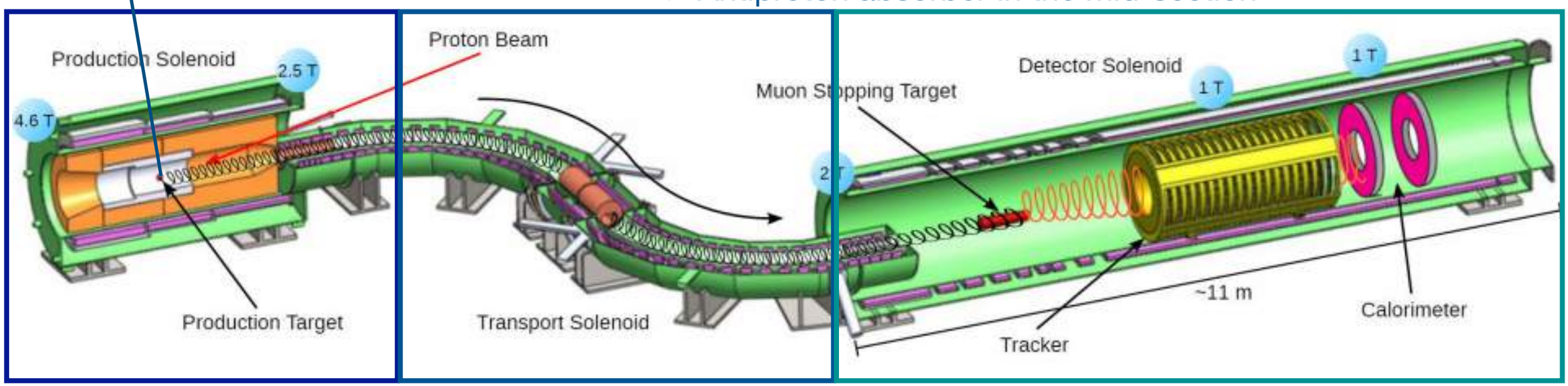

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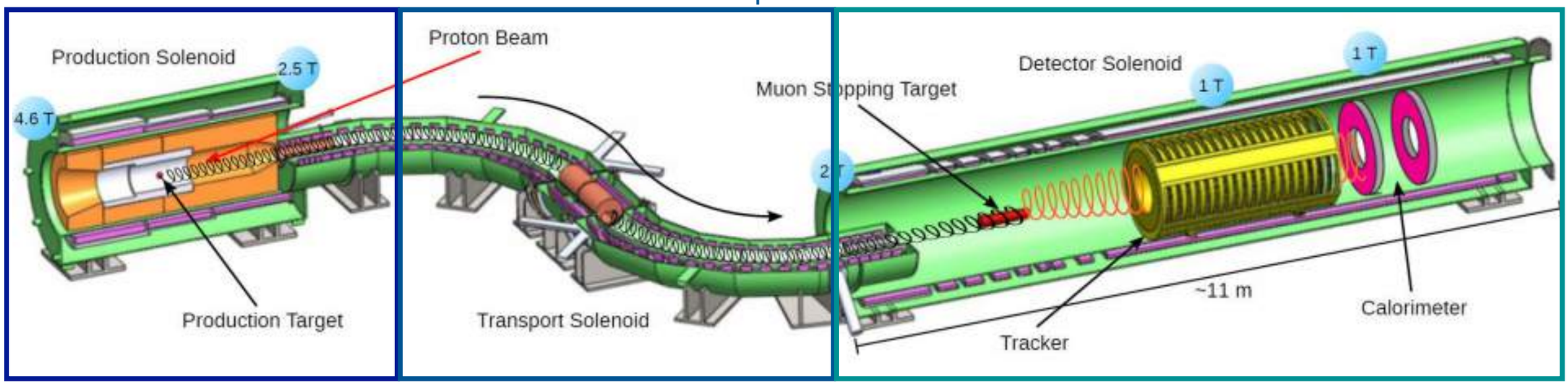

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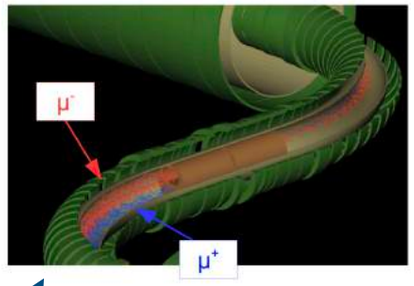

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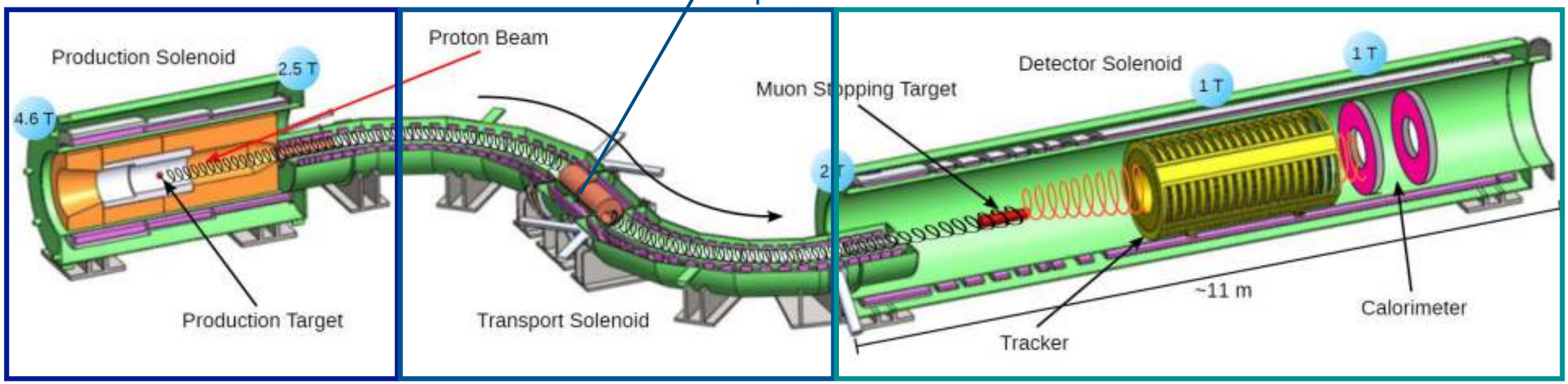

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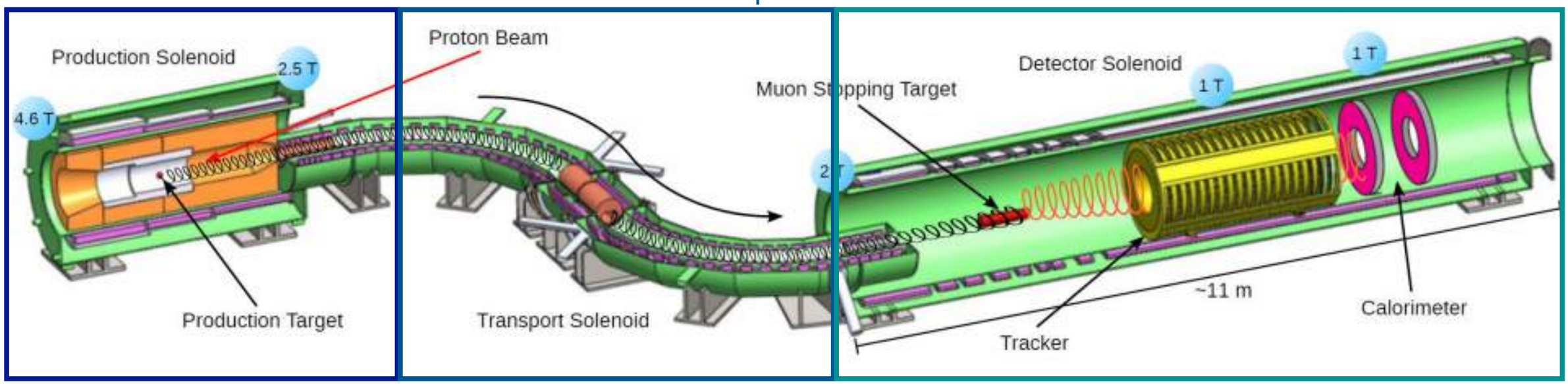

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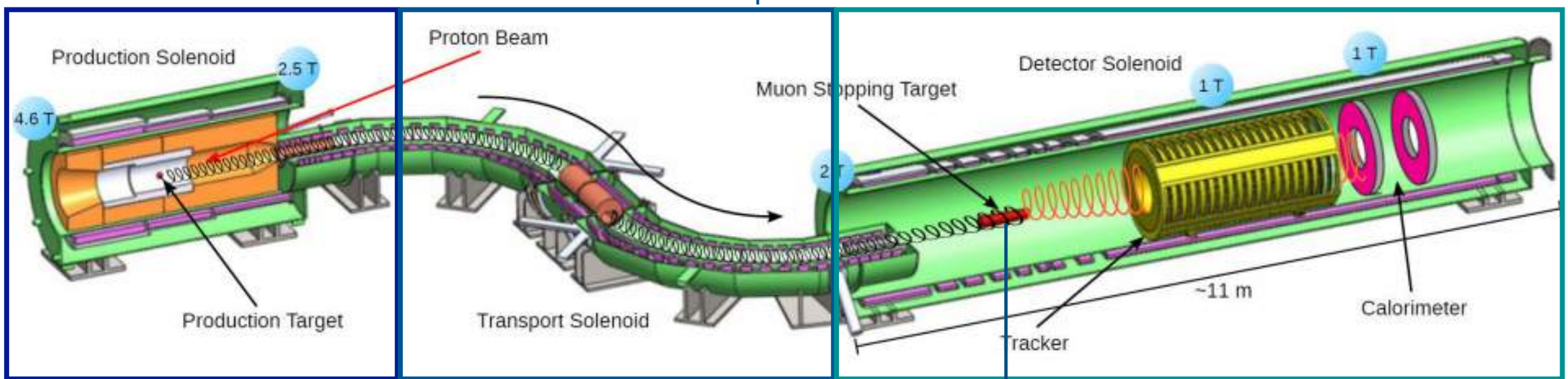

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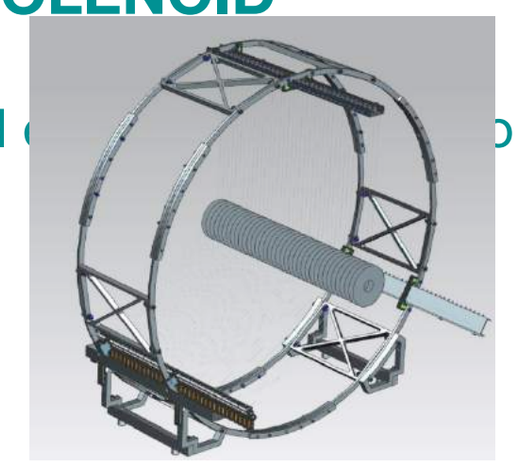

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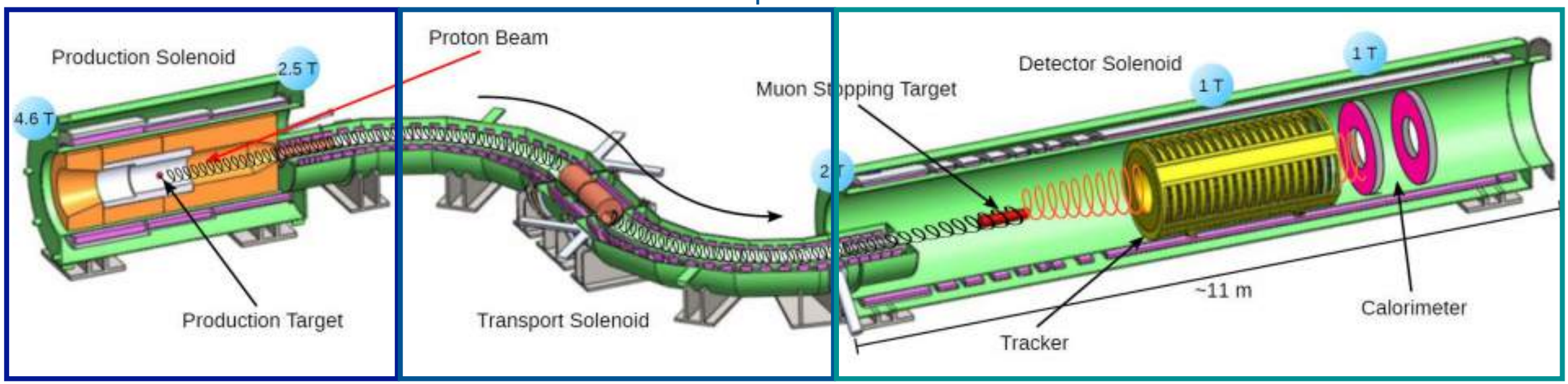

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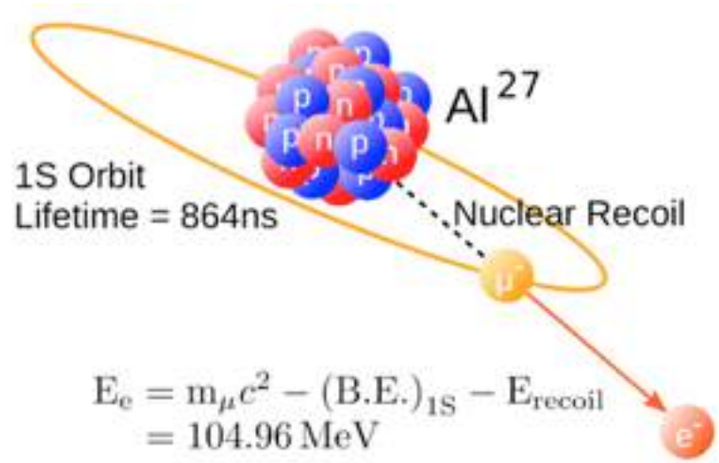
Experimental technique

Mu2e will look for coherent muon conversion into a muonic atom

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

- Low momentum μ beam (<100 MeV/c)
- High intensity pulsed rate
  - 10^{10} μ/s stopped on Al
- Stopped μ^- captured in atomic orbits
  - Cascade in the 1s state (~fs)

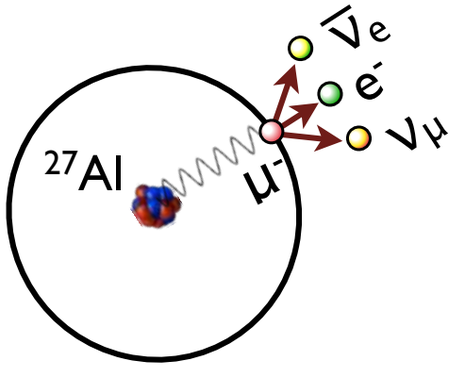
Conversion process



Signal

Decay in Orbit

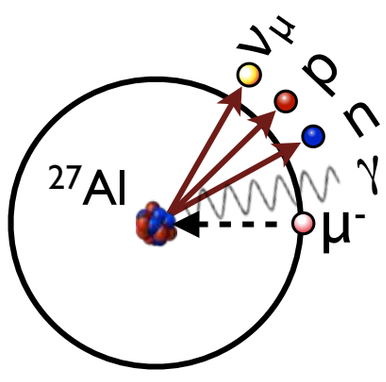
(BR=39%)



Background

Muon Capture

(BR=61%)



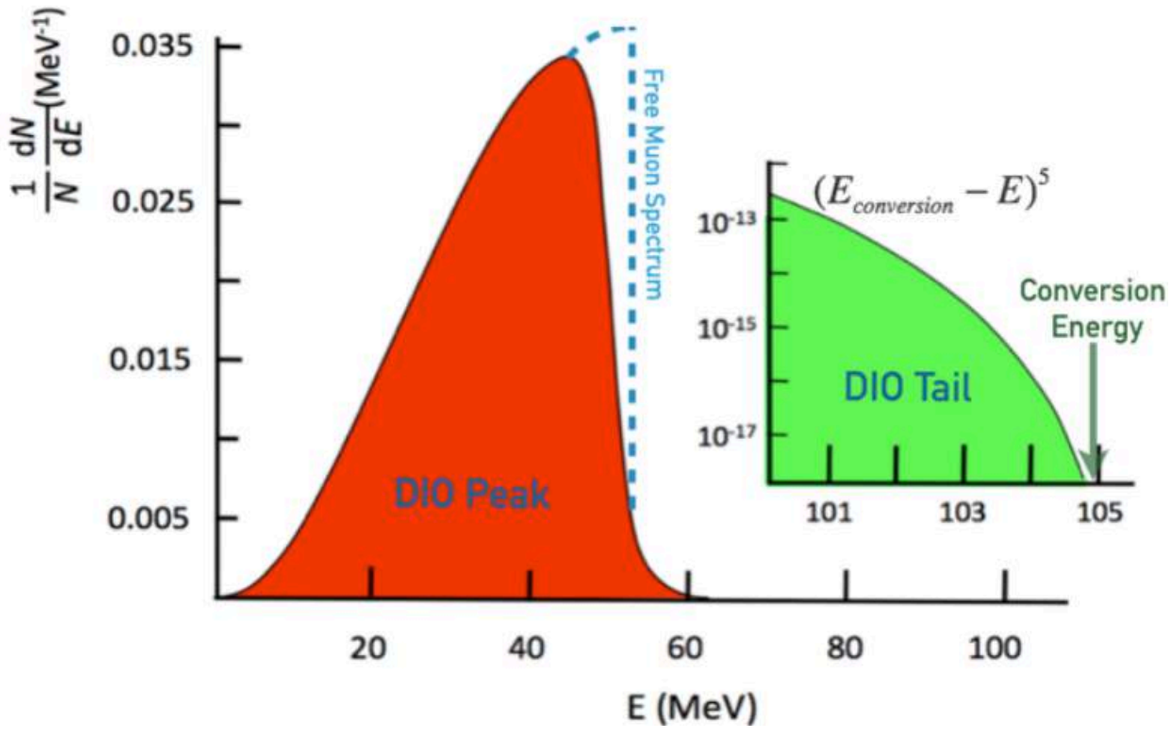
Normalisation

Mu2e will measure:

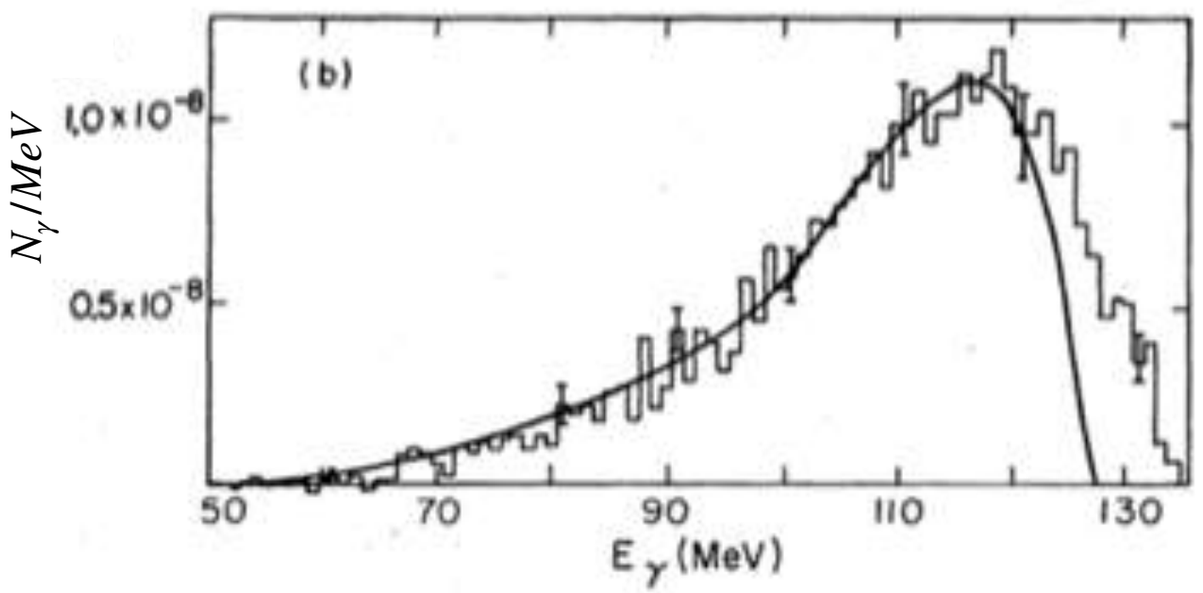
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

Main backgrounds

- **Intrinsic** *(scales with the stopped μ)*
  - Muon decay in obit
    $\mu^- + Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + Al$
  - Radiative μ capture
    $\mu^- + Al \rightarrow \nu_\mu + \gamma + Mg$



- **Cosmic Rays**
- **Late arriving from prompt processes**
  (scales with number of late protons)
  - Radiative π capture
    $\pi^- N \rightarrow \gamma N^*, \gamma \rightarrow e^+ e^-$
    $\pi^- N \rightarrow e^+ e^- N^*$
  - μ/π decay in flight
- **Antiproton annihilation**



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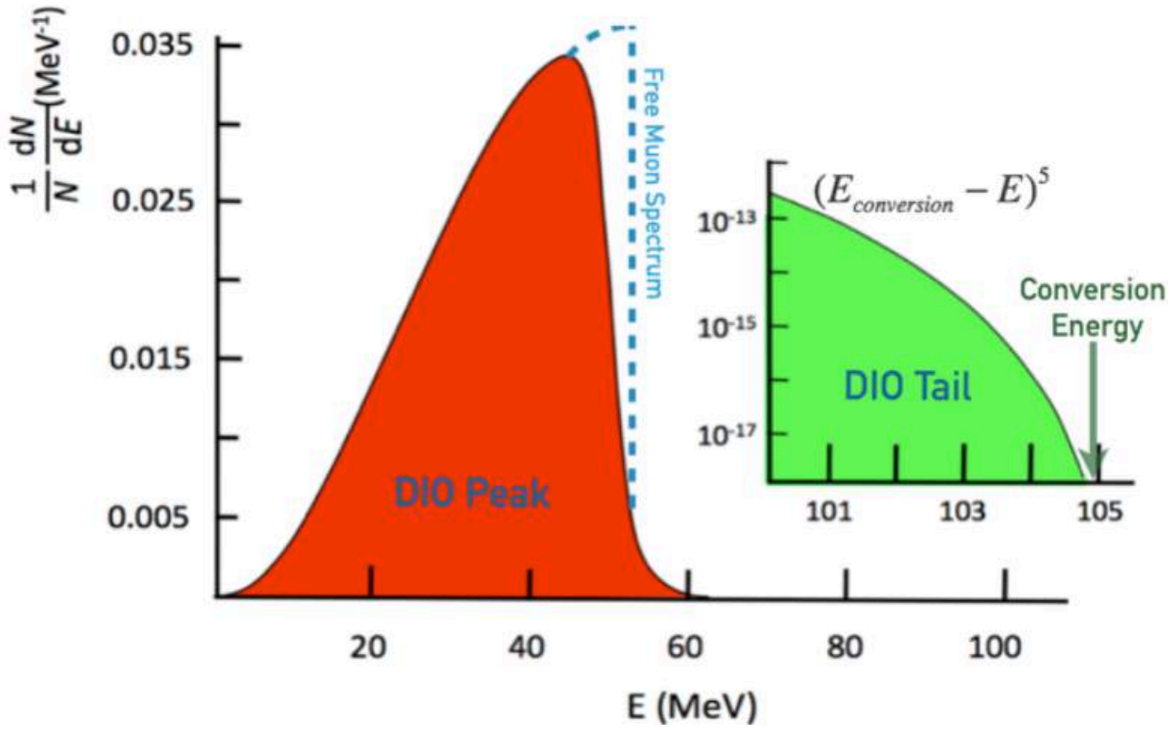

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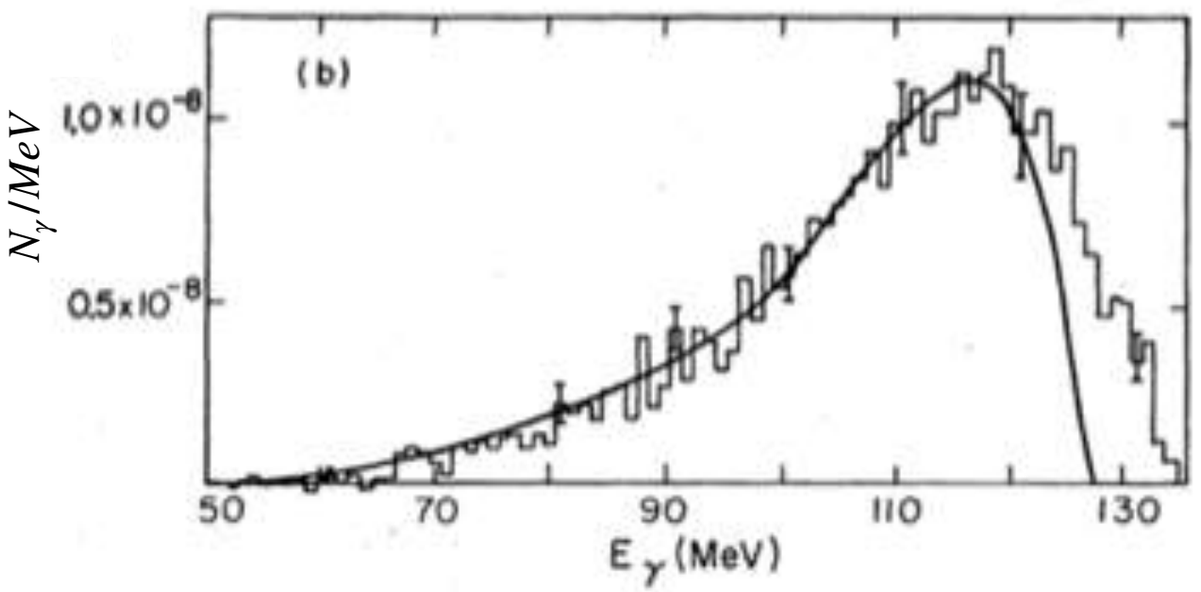


high performances tracker

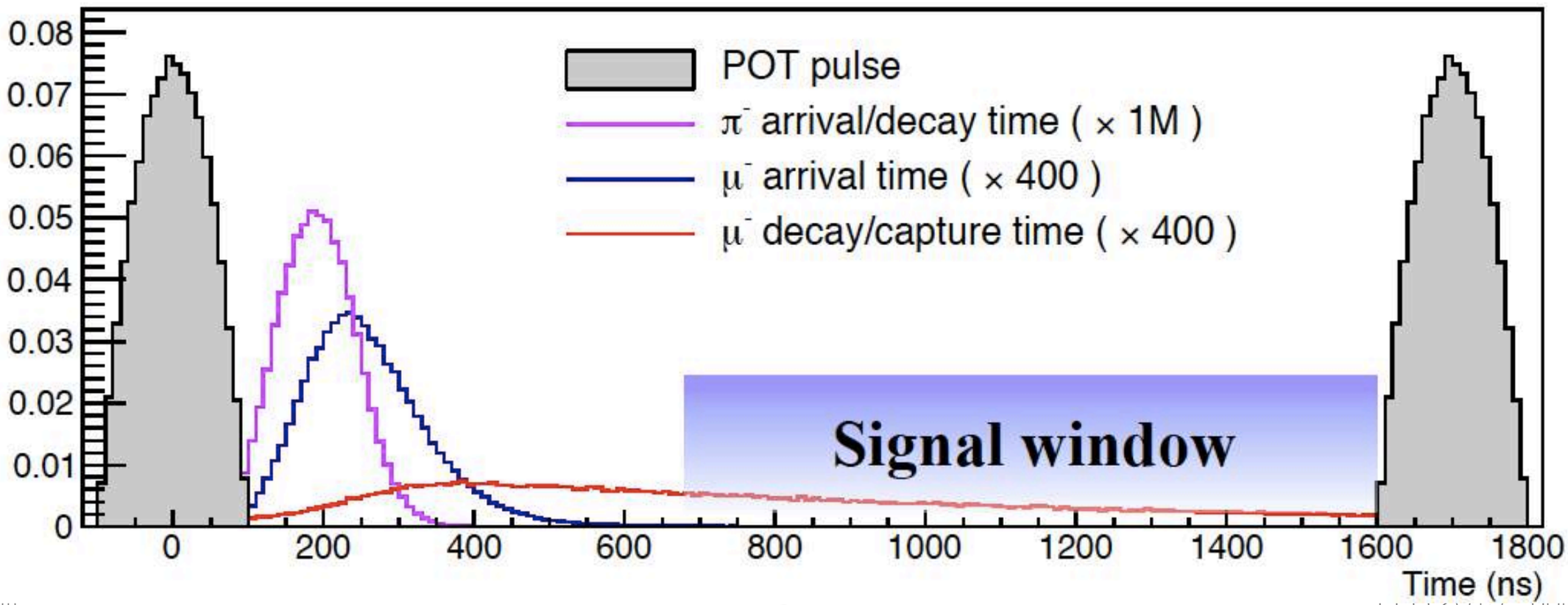
Cosmic Rays Veto

Pulsed beam

Antiproton Absorber

Minimising the main backgrounds

- The design of the Mu2e experiment is **optimised for the observation of CE events.**
- To get rid of low momentum particles (p<57 MeV) t**he tracker and the calorimeter presents a hole in the central part**
- **Muonic atomic life (τ = 864 ns) >> prompt backgrounds**
- Narrow pulsed proton beam
- **delayed signal window starting 700 ns after the initial proton pulse**



The Detectors

Aluminum target

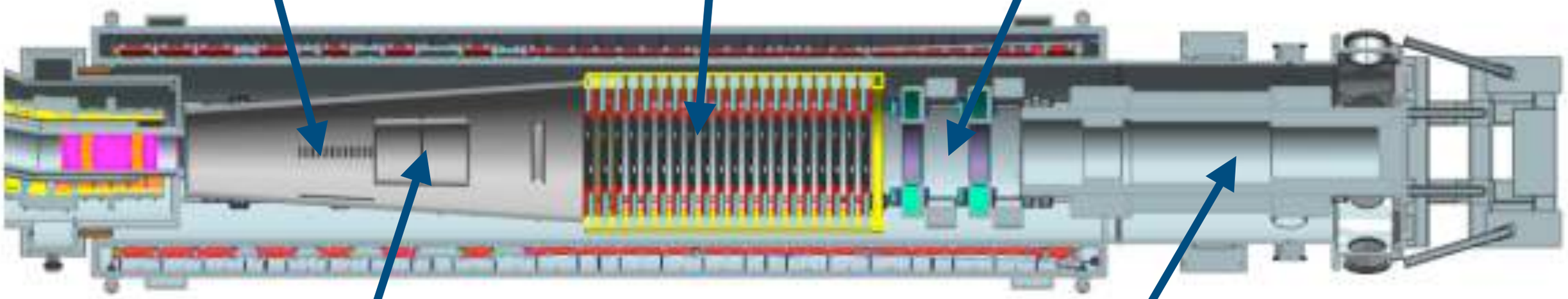
34 Al foils; the material choice is a compromise between the μ life time and E_{ce}

Calorimeter

2 disks of CsI crystals; used for Particle Identification; σ_E<10%

Tracker

~20k straw tubes; low mass detector with high performances (σ <200 keV/c)



Proton absorber

made of high-density polyethylene; designed in order to reduce proton flux on the tracker and minimize energy loss

Muon Beam Stop

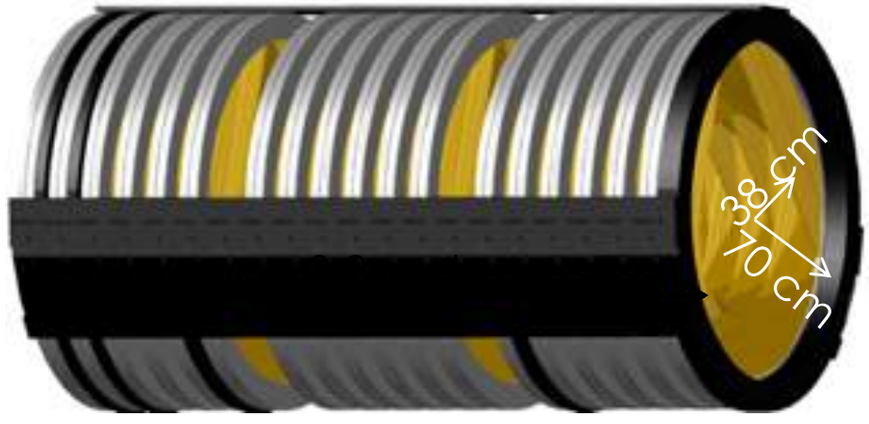
several concentric cylindrical structures of stainless steel and high density polyethylene; absorbs beam particles at the end of DS

Tracker

single panel

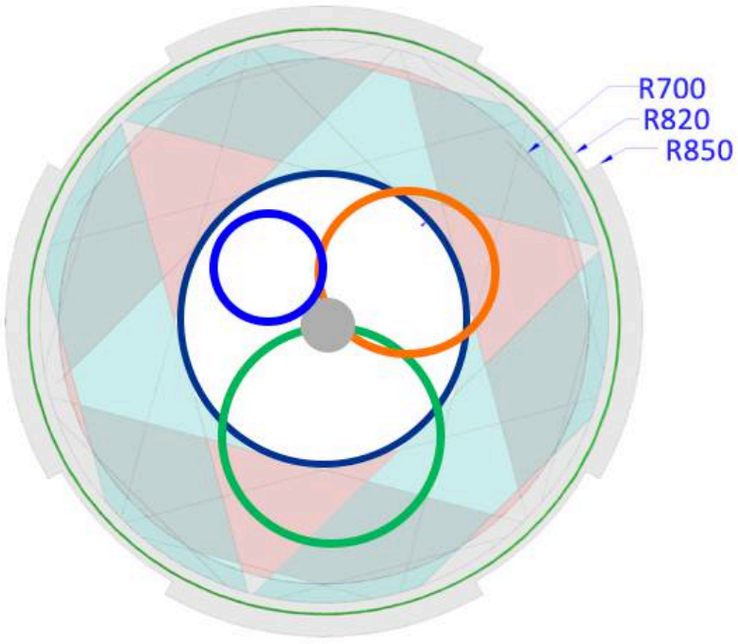
6 panels make a plane

2 planes make a station



- 3 m long, 1.4 diameter in a 1 T uniform B field
- 18 stations made of 20k straw drift tubes:
  - 5 mm diameter, 15 μm Mylar walls
  - Ar:CO_2 (80:20) with HV~1500V

hole in the center makes it blind to DIO

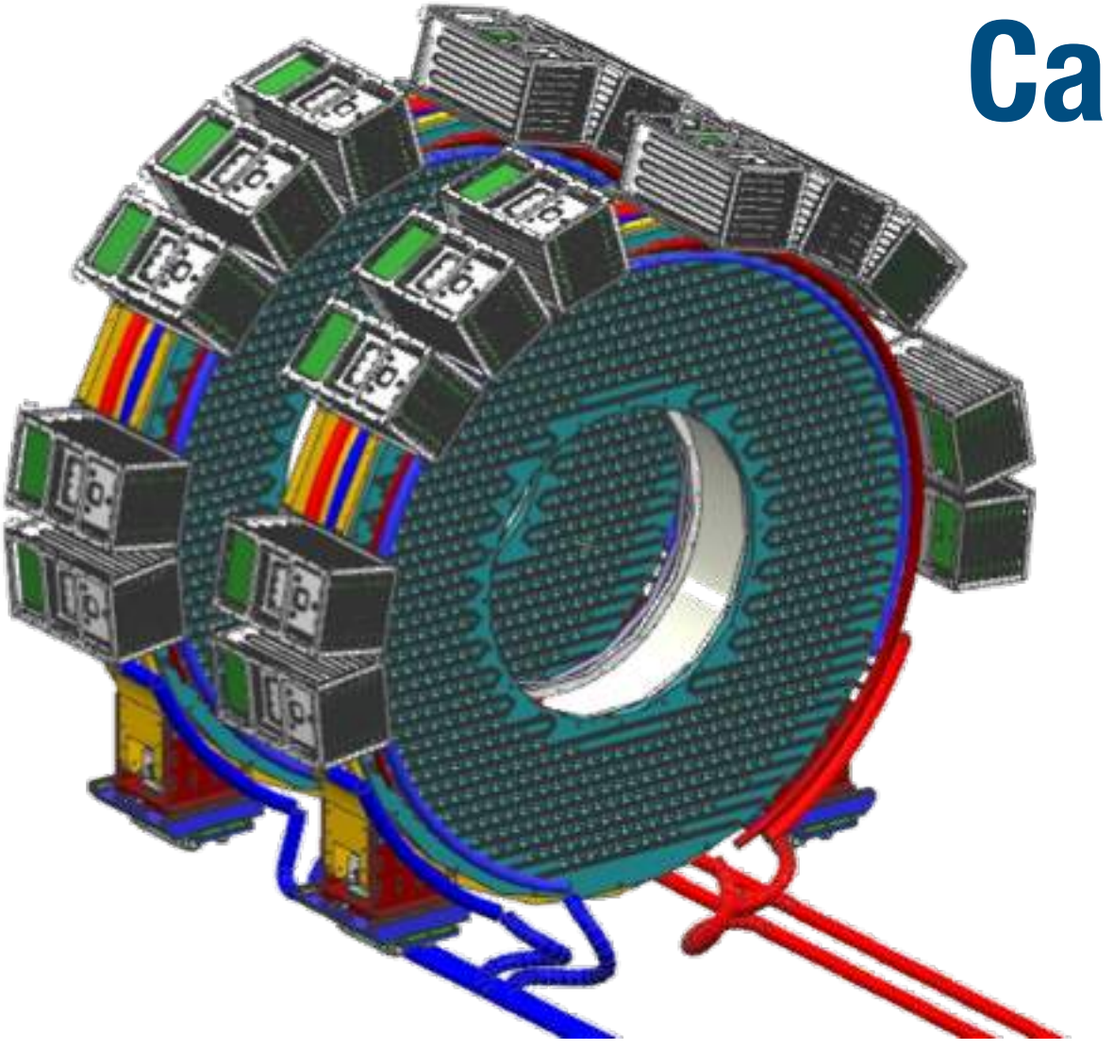


σ_p<180 keV/c @(100 MeV/c)

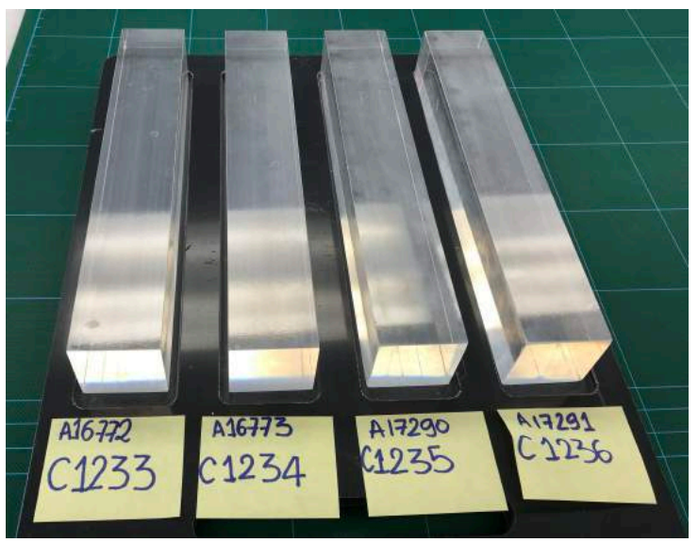
σ_t~ 1 ns

σ_x~100μm

Calorimeter



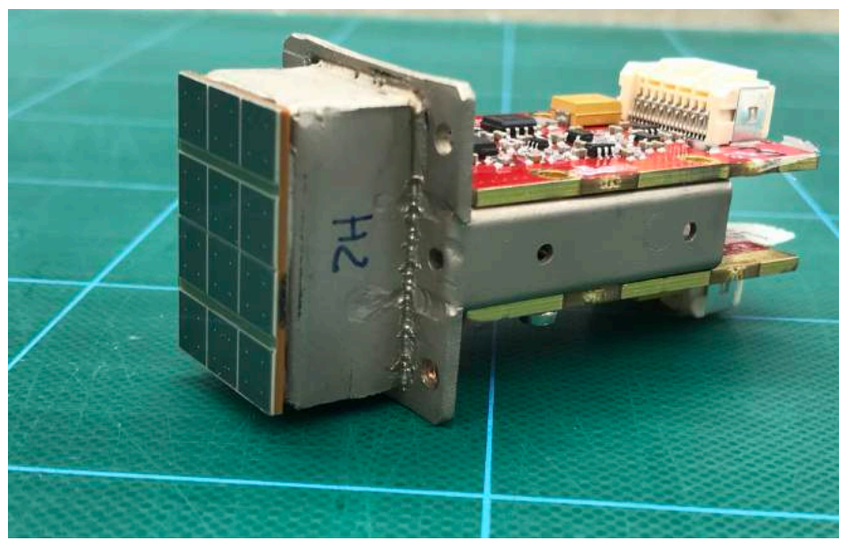
- 2 disks filled with 674 pure CsI crystals (34x34x200 mm^3) each
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- crystal read-out by 2 UV-extended SiPMs
- Analog FEE and electronics in near-by electronics crates
- Work in vacuum and B = 1T
- **PID: e/μ separation**
- **EMC seed track finder**
- **Standalone trigger**



$\sigma_E < 10\%$ (100 MeV/c)

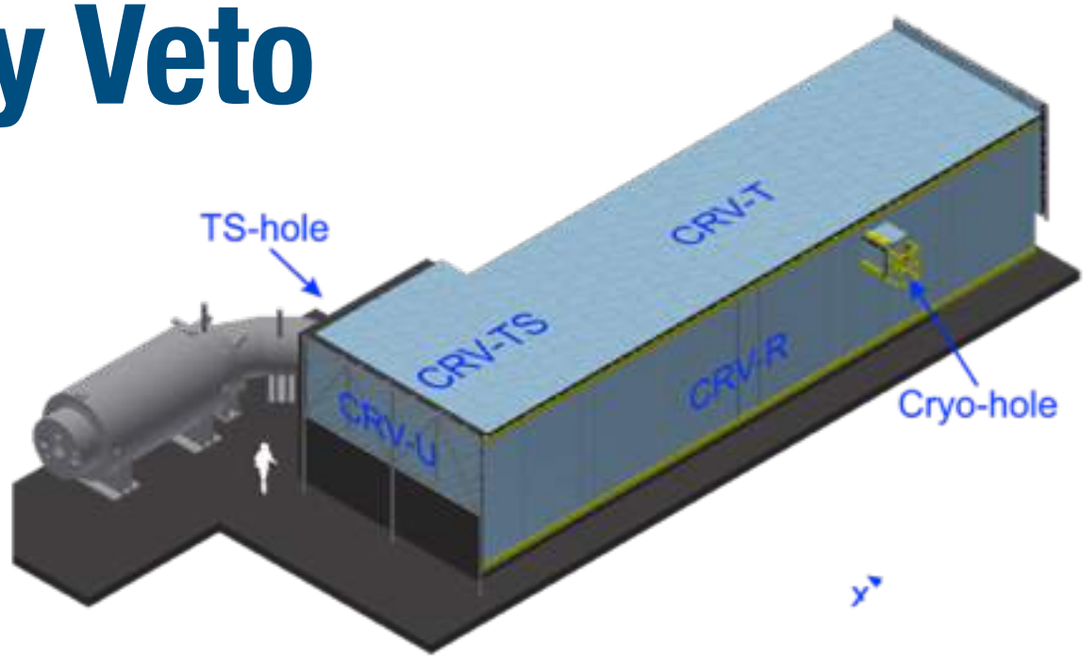
$\sigma_t \sim 500$ ps

$\sigma_x \leq 1$ cm

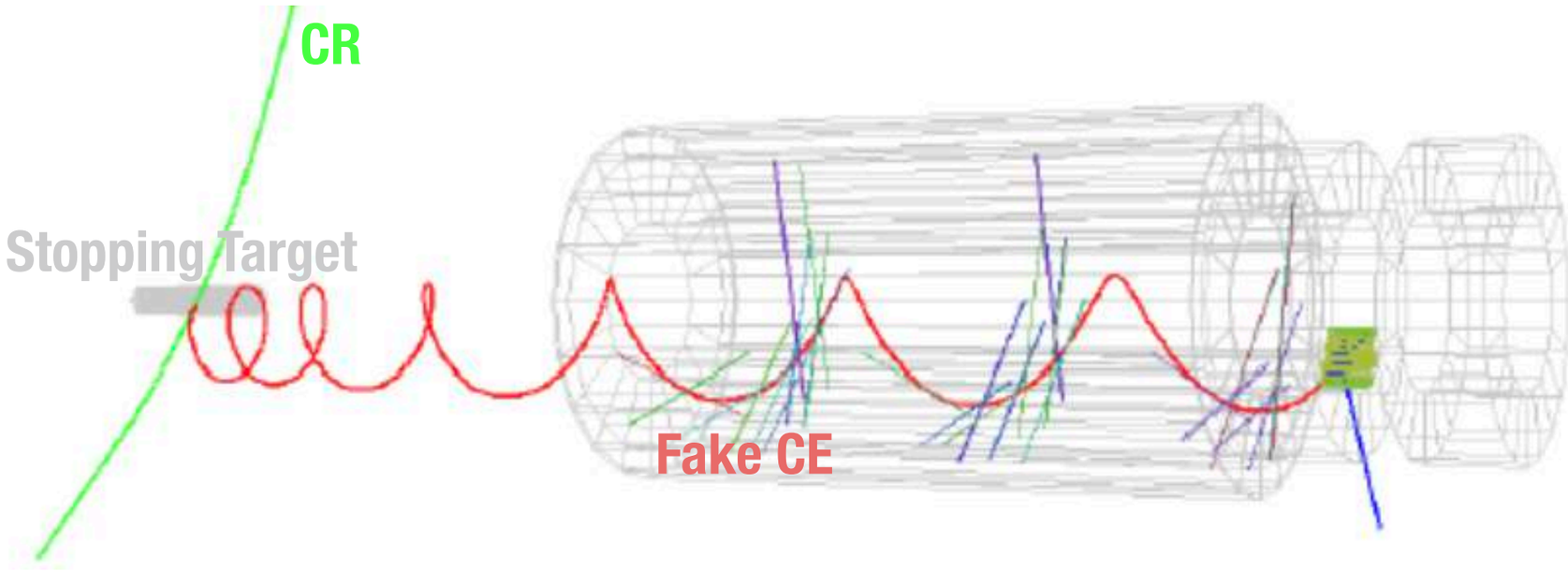


Cosmic Ray Veto

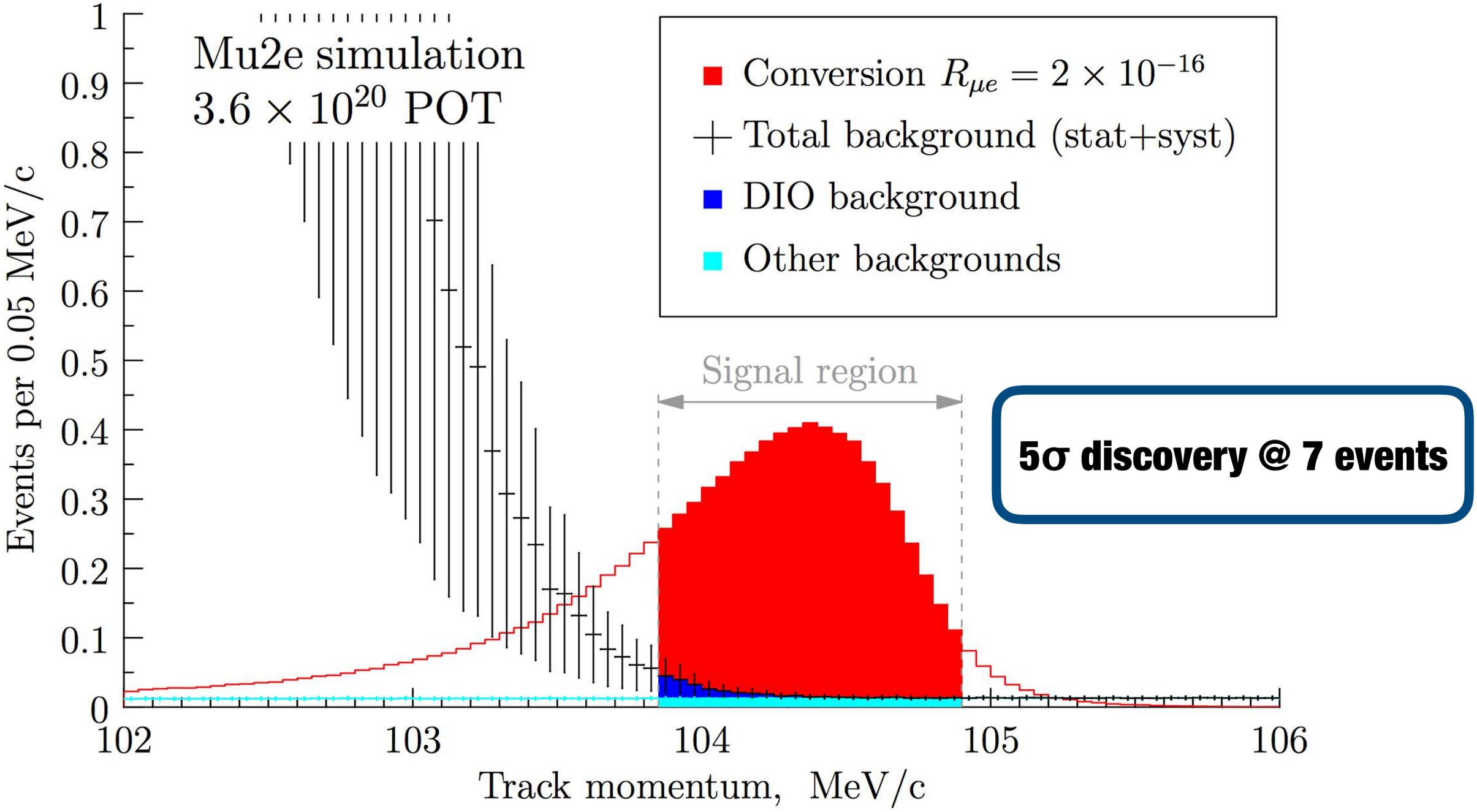
- CRs main source of backgrounds
  - 1 fake CE event per day
- CRV cover whole DS and part of TS
- passive shield and active veto
  - Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPMs



- excellent muon veto efficiency (99.99%)



Mu2e sensitivity

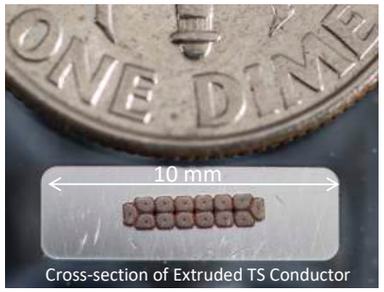


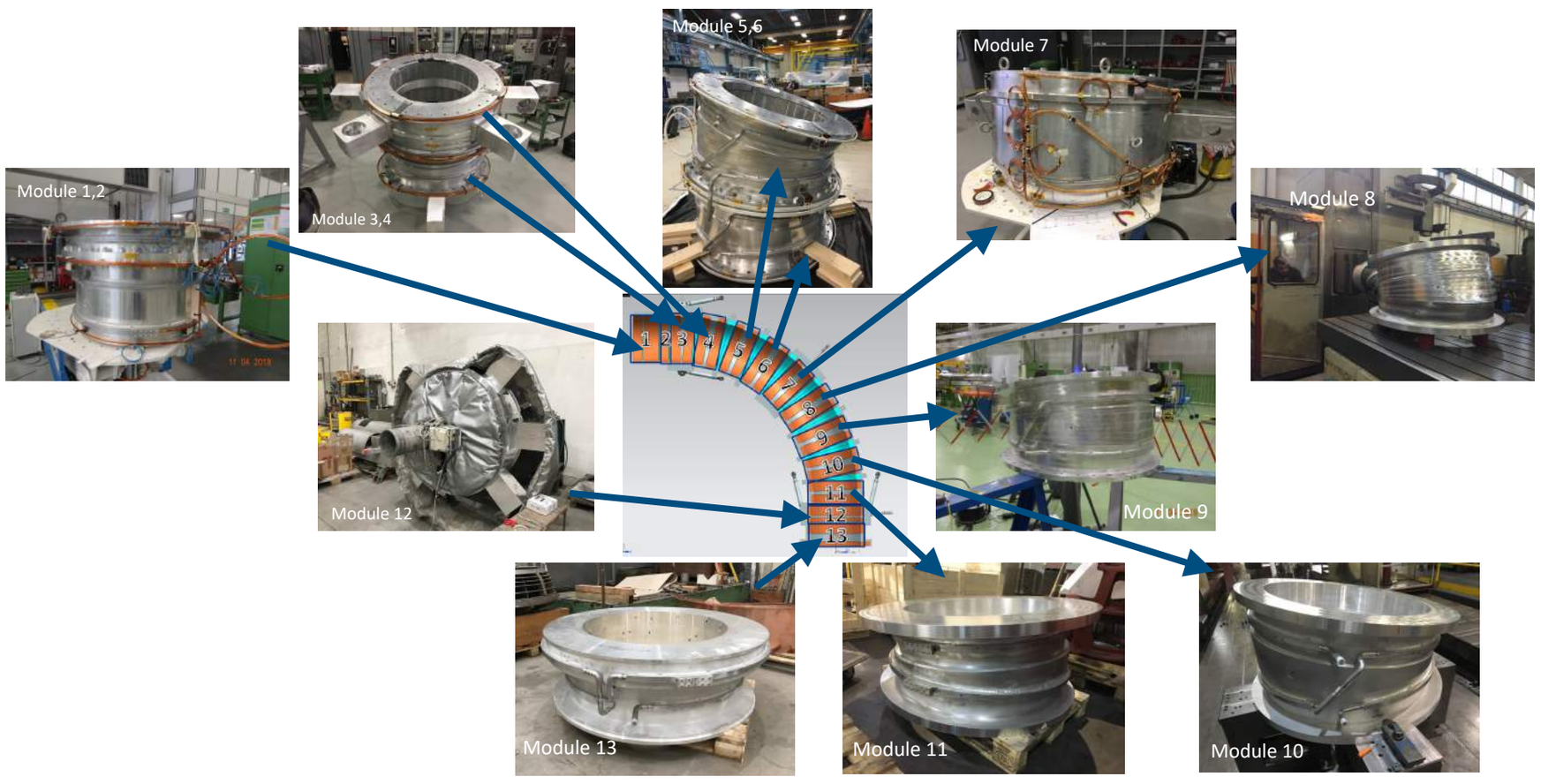
5σ discovery @ 7 events

Discovery sensitivity accomplished with 3 years of run and background suppression to <0.4 event total

Status of construction - Solenoids

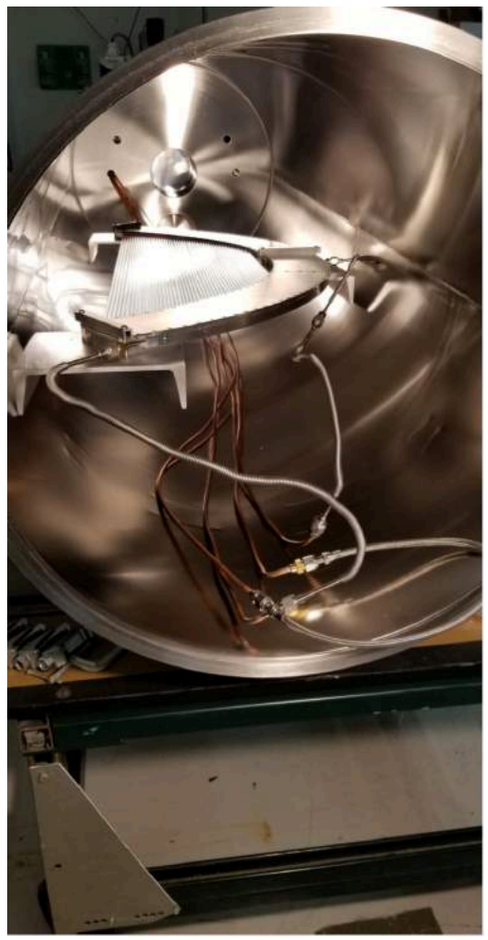
- Conductor construction completed
- Winding procedure of the PS and DS started
- 1/2 TS completed and the modules are now under test

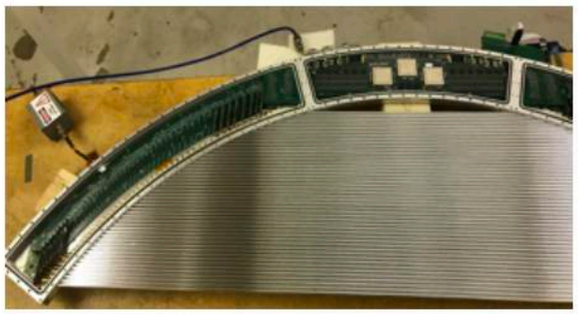




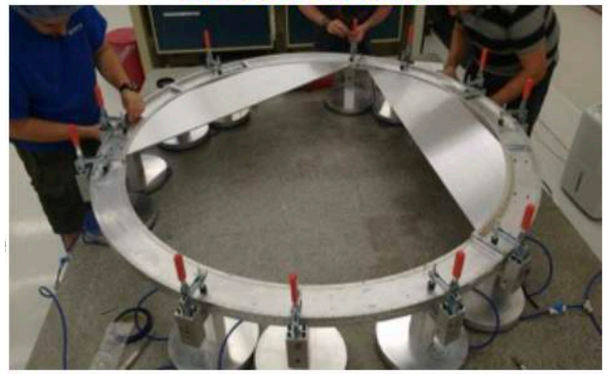
Status of the construction -Tracker

- Straws production completed
- Panel production will start in August
- preparing for a beam test @ Fermilab in the fall





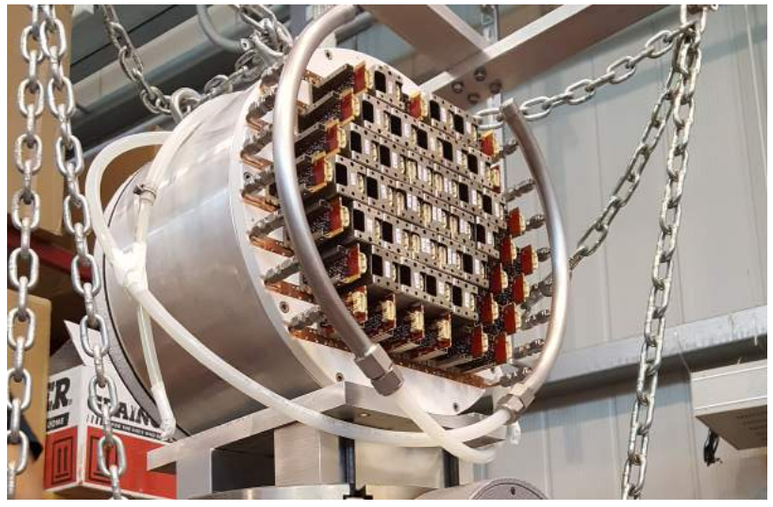
Panel w/Front-End Electronics



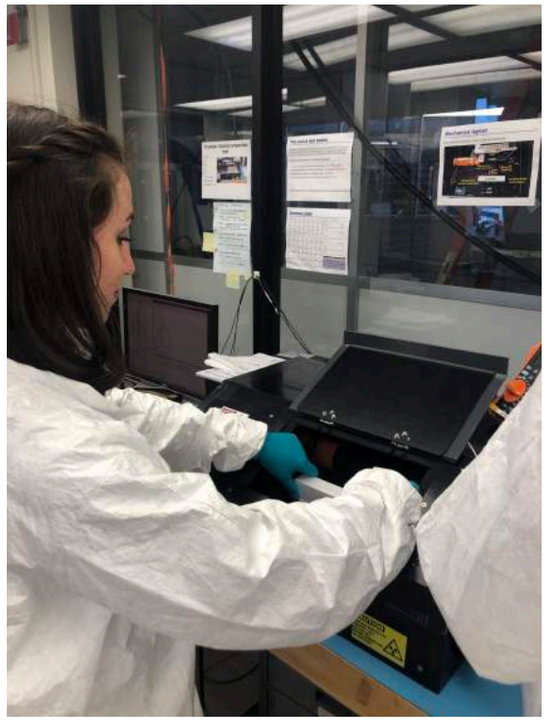
Two panels installed in plane

Panel: Straw Installation

Status of the construction - Calorimeter



- Test beam on a large size prototype
  - good energy and time resolution
- QA on SiPMs completed
- 1100/1400 crystals tested
  - end of test 10-2019
- Slice test of the whole electronics chain completed
- board design being upgraded to include rad-hard components



Status of the construction - Calorimeter

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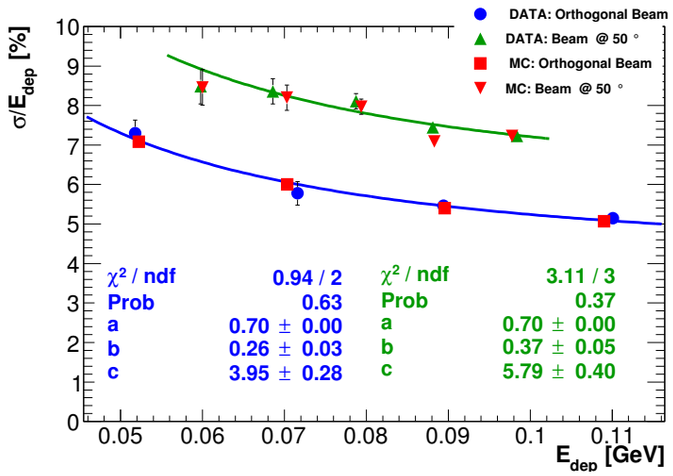
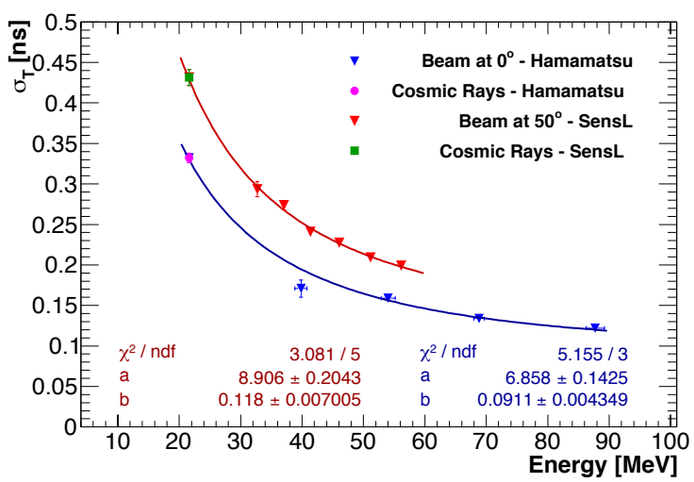
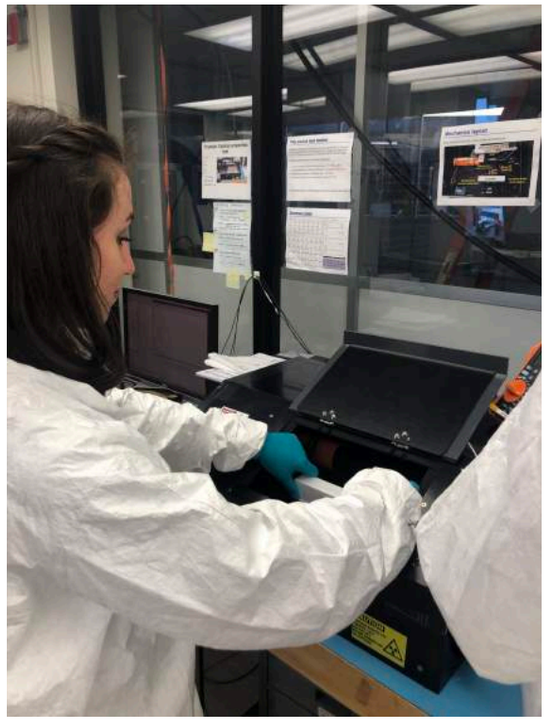
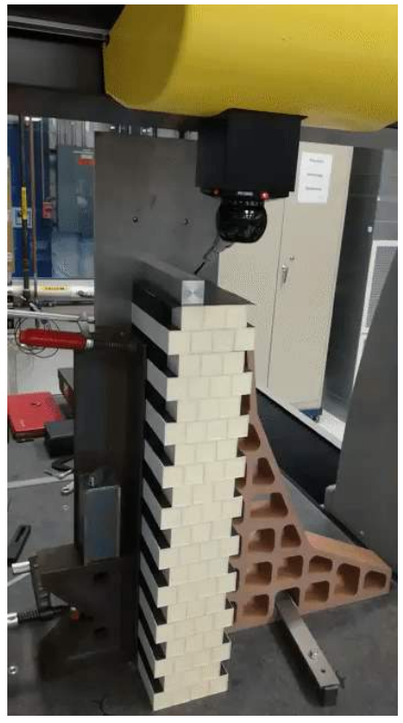


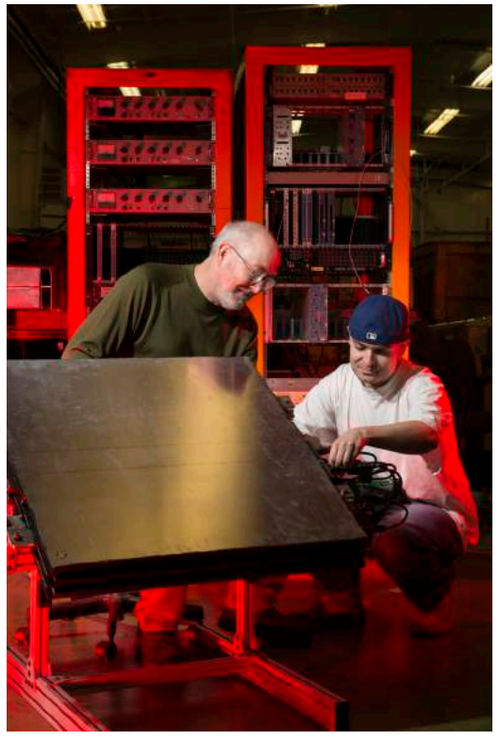






Status of the construction - CRV

- Di-counter production started June 2018
  - Half production is done
- pre-production modules completed
- pre-production module tested
- analysis ongoing



Conclusion

- The Mu2e experiment is a discovery experiment looking for the CLFV process of a coherent conversion of muon into electron
- Mu2e will improve the sensitivity on conversion experiment of ~ **4 orders of magnitude** up to 10000 TeV mass scale
- It provides discovery capabilities over a wide range on NP model
- Construction phase: 2017-2020
- Installation in 2021
- Commissioning phase will begin in 2022
- Start thinking about Mu2e-II —>increase x10 the intensity and the sensitivity


EUROPEAN PHYSICAL SOCIETY
EPS
HEP2019
European Physical Society
Conference on High Energy Physics
10-17 July 2019 - Ghent, Belgium

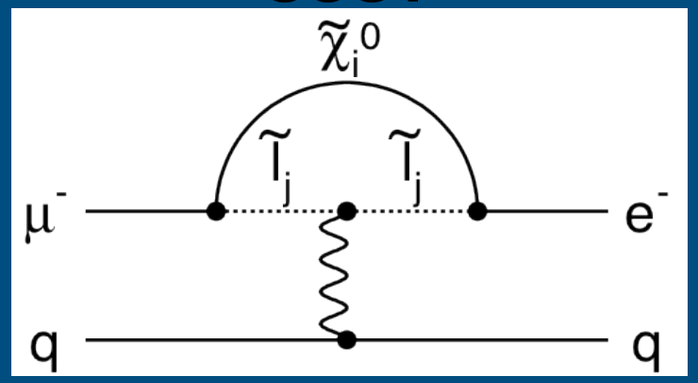
Spares

Muon CLFV - BSM theory

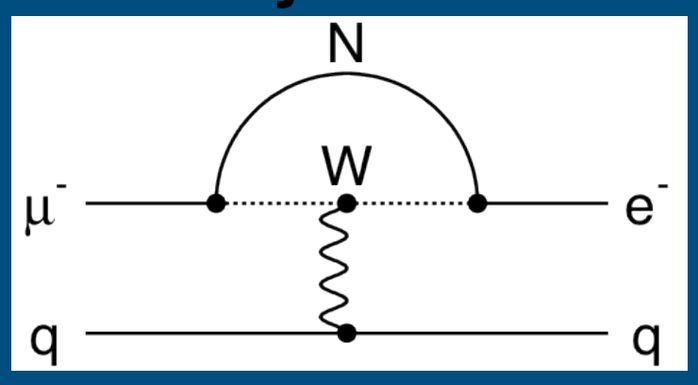
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

Loop Term

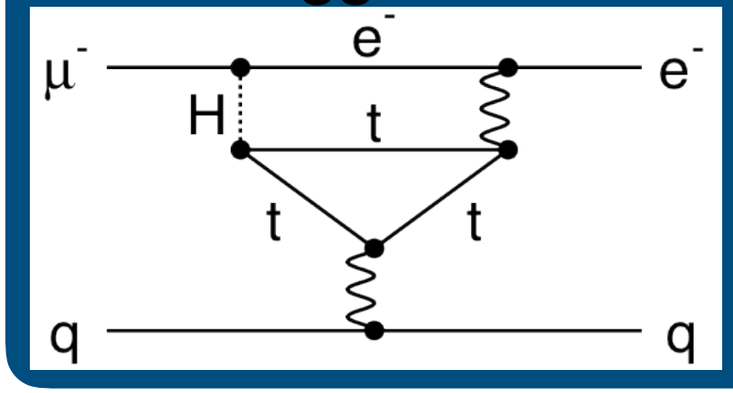
SUSY



Heavy neutrino

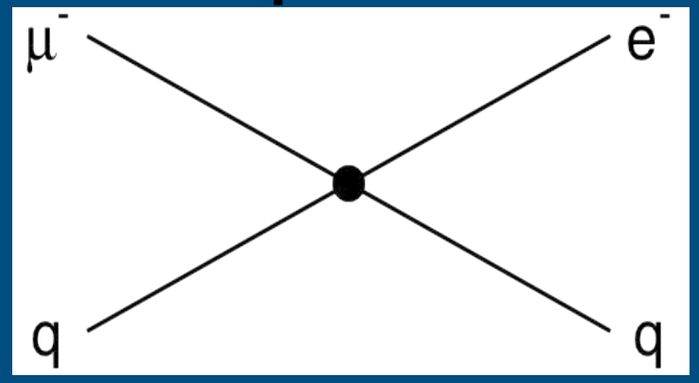


Two Higgs doublet

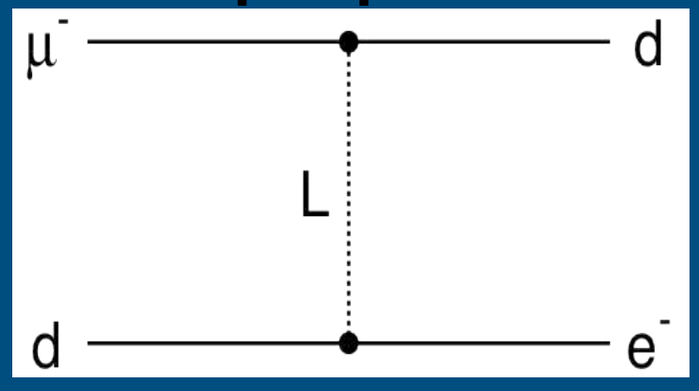


Contact Term

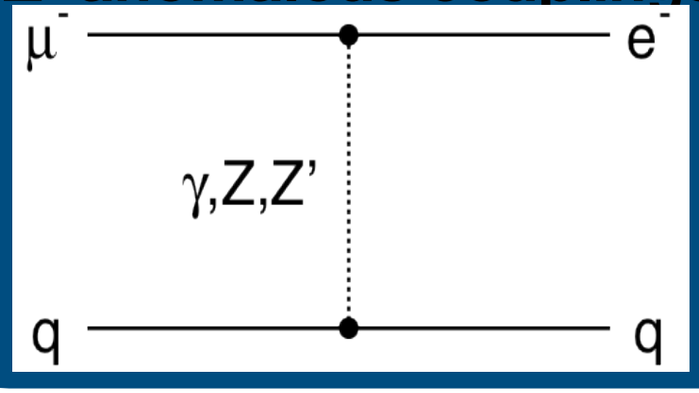
Compositeness



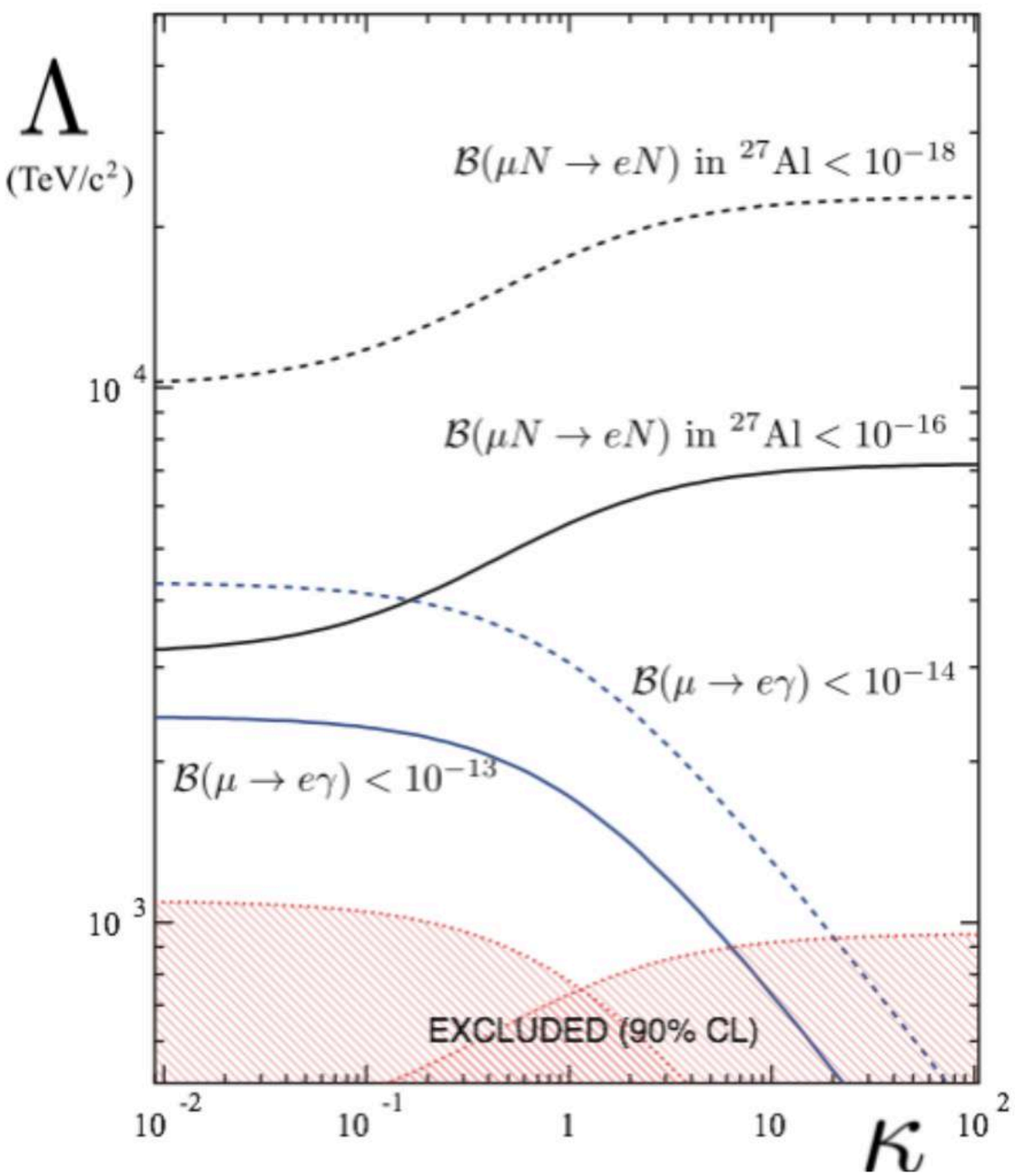
Leptoquarks

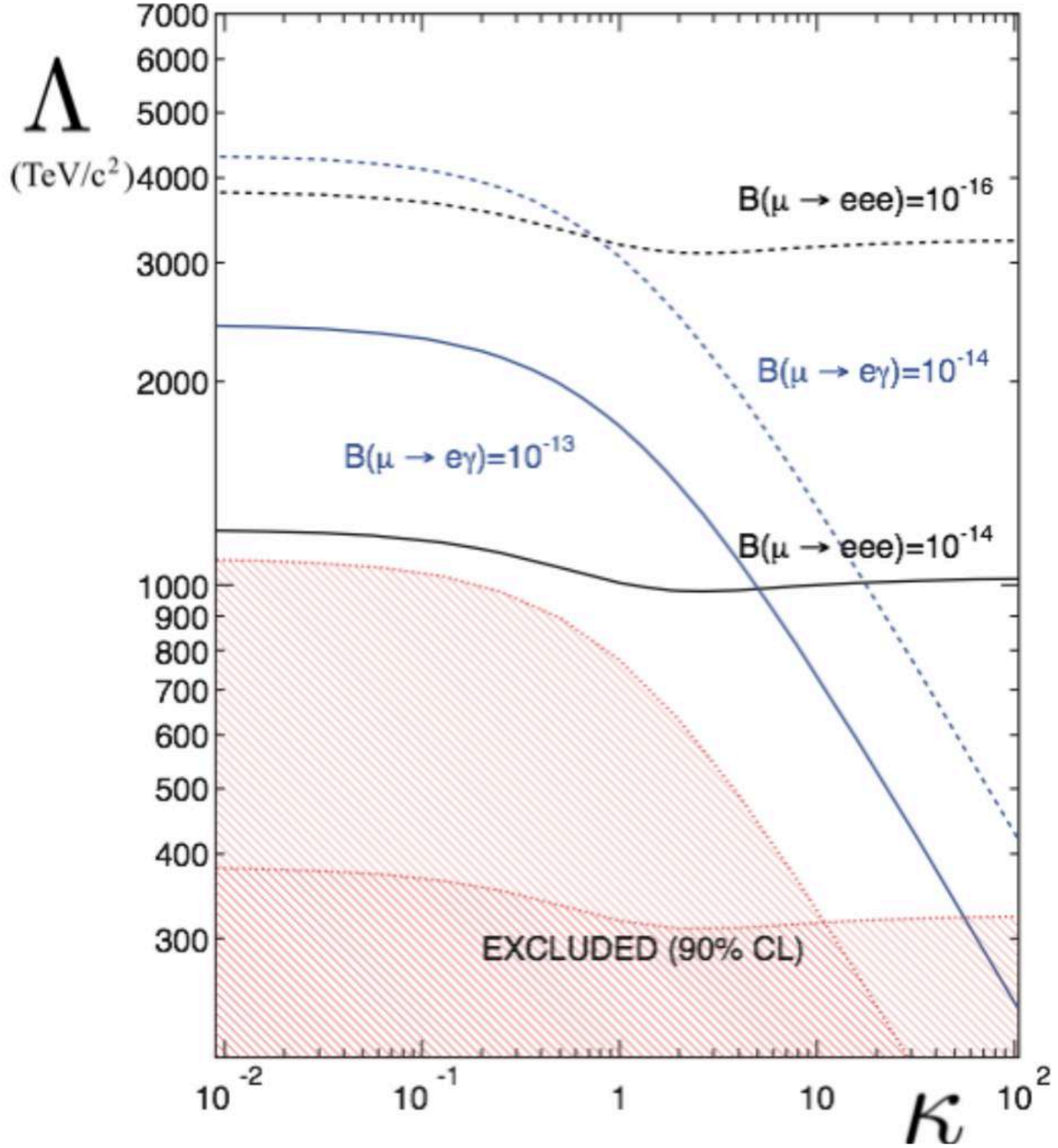


Z' anomalous couplings



Interval searches





SUSY benchmark point

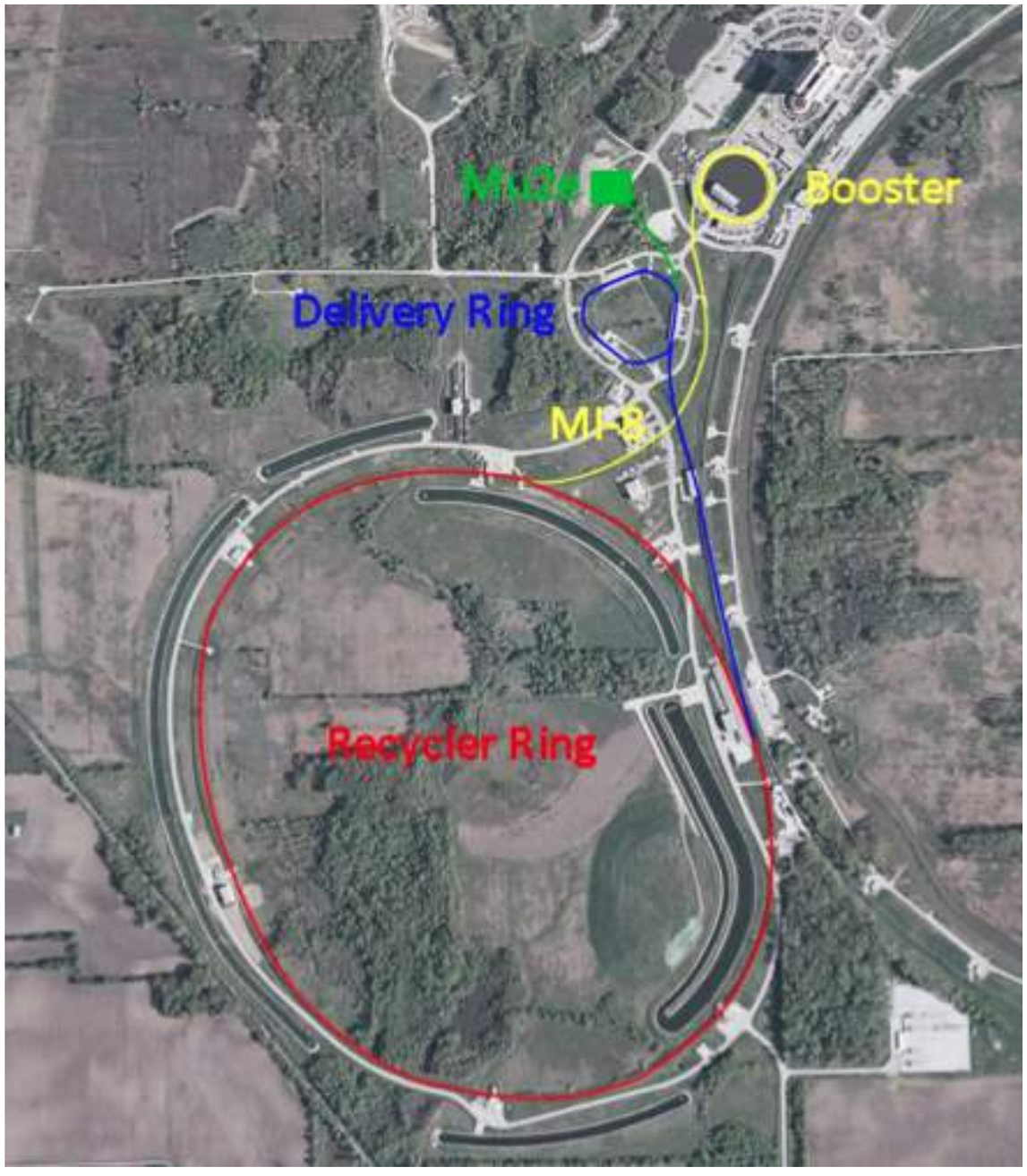
W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

★★★ = Discovery Sensitivity

	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.

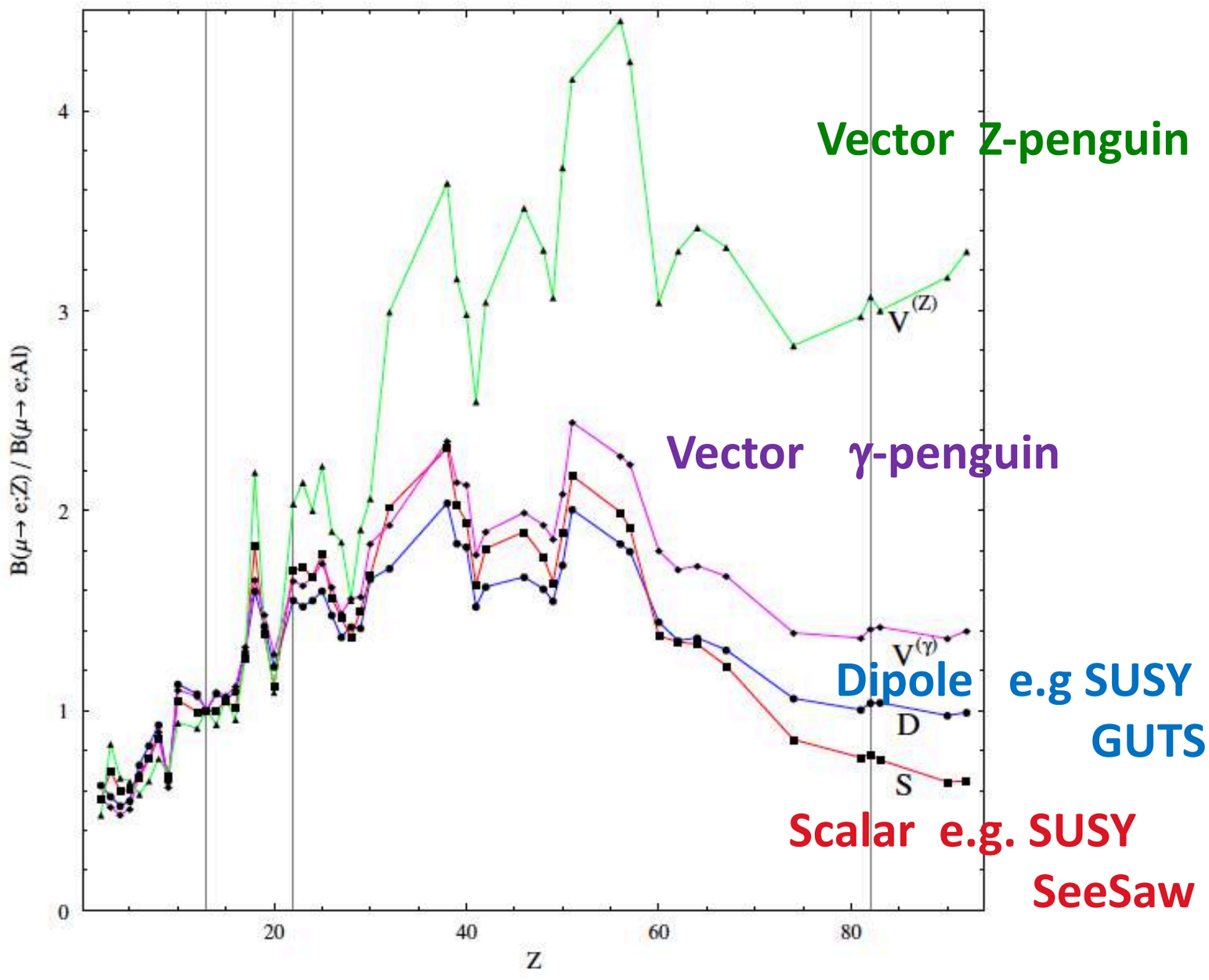
Proton beam



- Mu2e will use 8 GeV protons from the Booster
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons
- Mu2e will collect data **simultaneously** with NOvA and short baseline program
- 5% loss

Model Discrimination

We obtain model discriminating power on underlying physics mechanism by comparing CLFV rates on different stopping targets



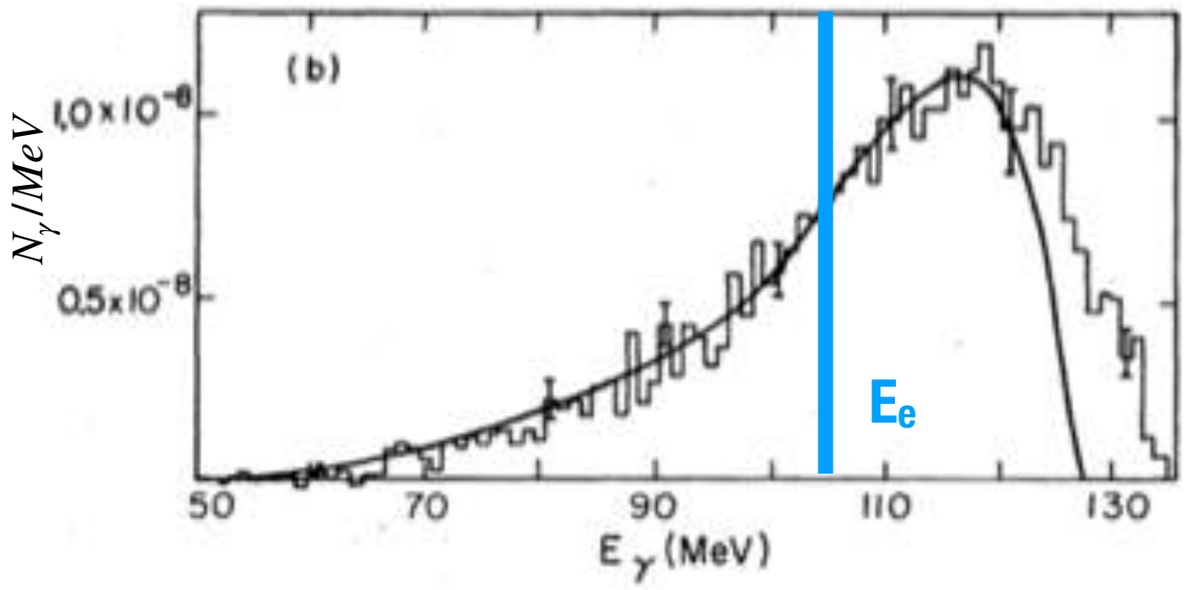
Prompt background

Radiative pion capture:

Non-decayed pion reaches stopping target, is radiatively captured, then photon converts:

$$\pi^- N \to \gamma N$$

$$\gamma \to e^- e^+$$

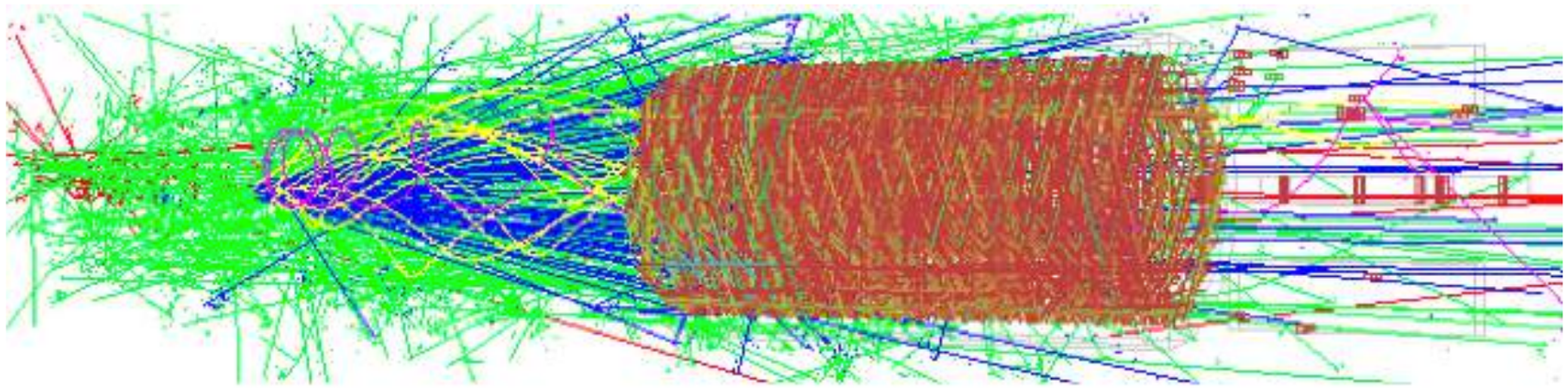


The electron can have momentum in signal window, and mimic conversion event.

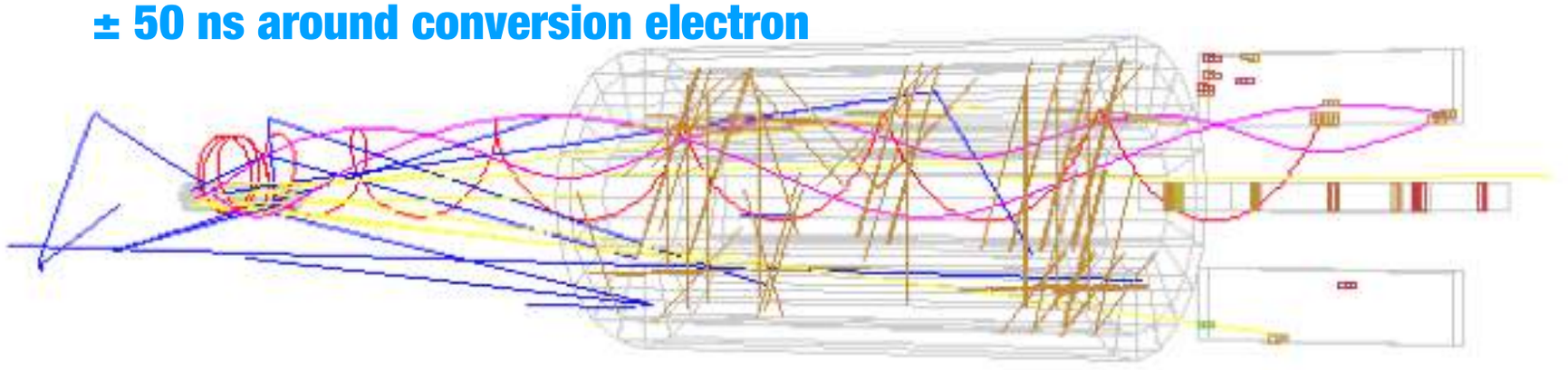
Simply wait until their rates are lowered before initiating live window to look for signal

A typical event

500 -1695 ns windows



± 50 ns around conversion electron



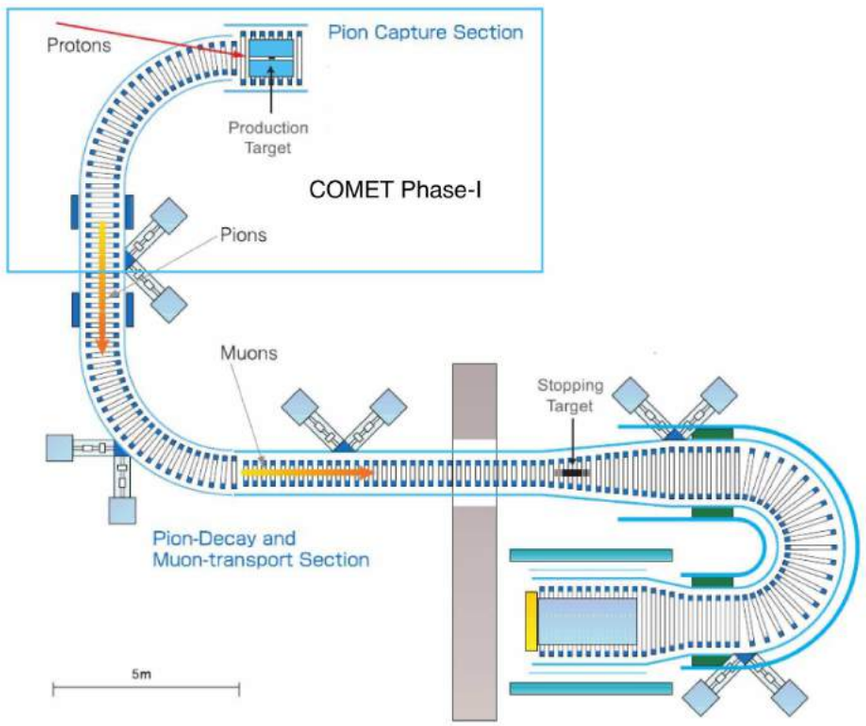
- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → **simpler pattern recognition**

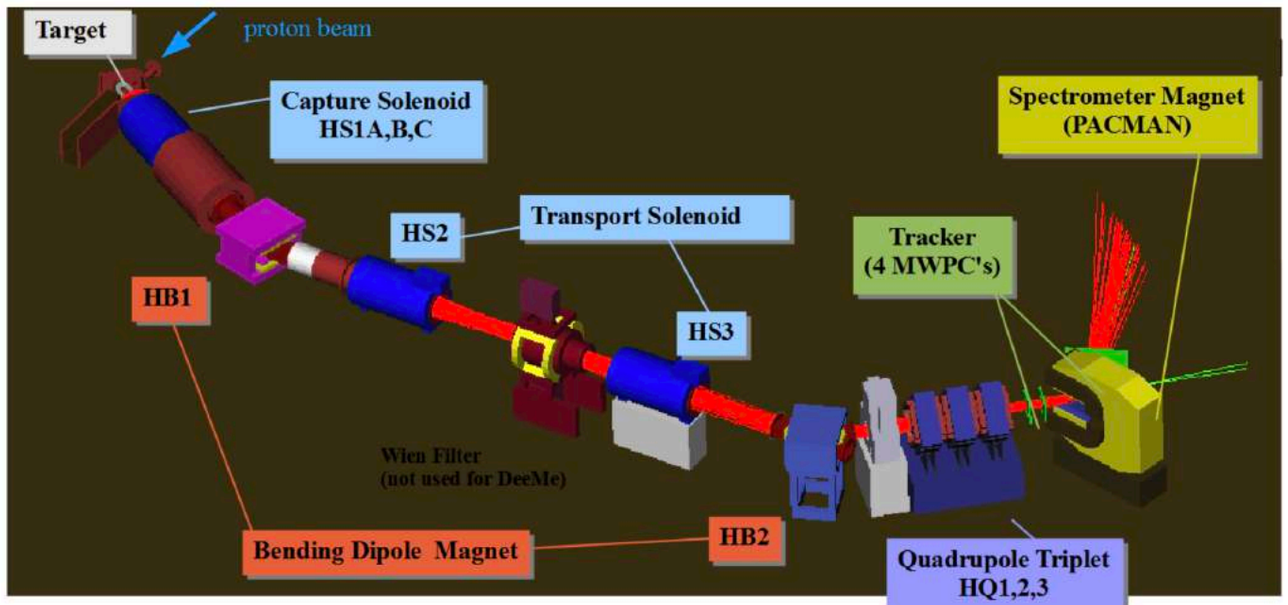
Background summary

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.14 (0.11)
	Radiative μ Capture	<0.001
Late Arriving	Radiative π Capture	0.025(0.003)
	Beam electrons	2.5E-4
	μ Decay in Flight	<0.003
	π Decay in Flight	0.001
Miscellaneous	Anti-proton induced	0.047(0.024)
	Cosmic Ray induced	0.247(0.055)
Total Background		0.46(0.11)

- 3 years at 1.2×10^{20} protons/year (8 kW beam power)
- Expect <0.5 background event in 3 years

competitor experiments @ J-Park

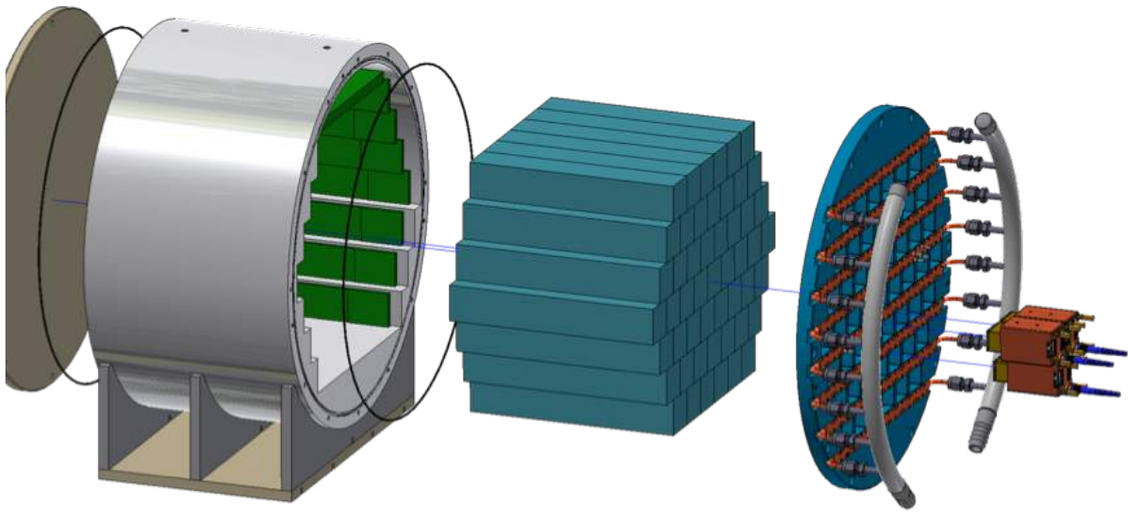




- Al target:
  - SES : 3 x10^{-15} (Phase I)
  - SES : 2 x10^{-15} (Phase II)
- Phase I is now under construction
- Directly measure the muon beam with prototypes of Phase-II detector.

- Graphite target: SES<10^{-13}
- SiC target:SES<10^{-15}
- Construction of detector system completed:
  - spectrometer from TRIUMF
  - tracker

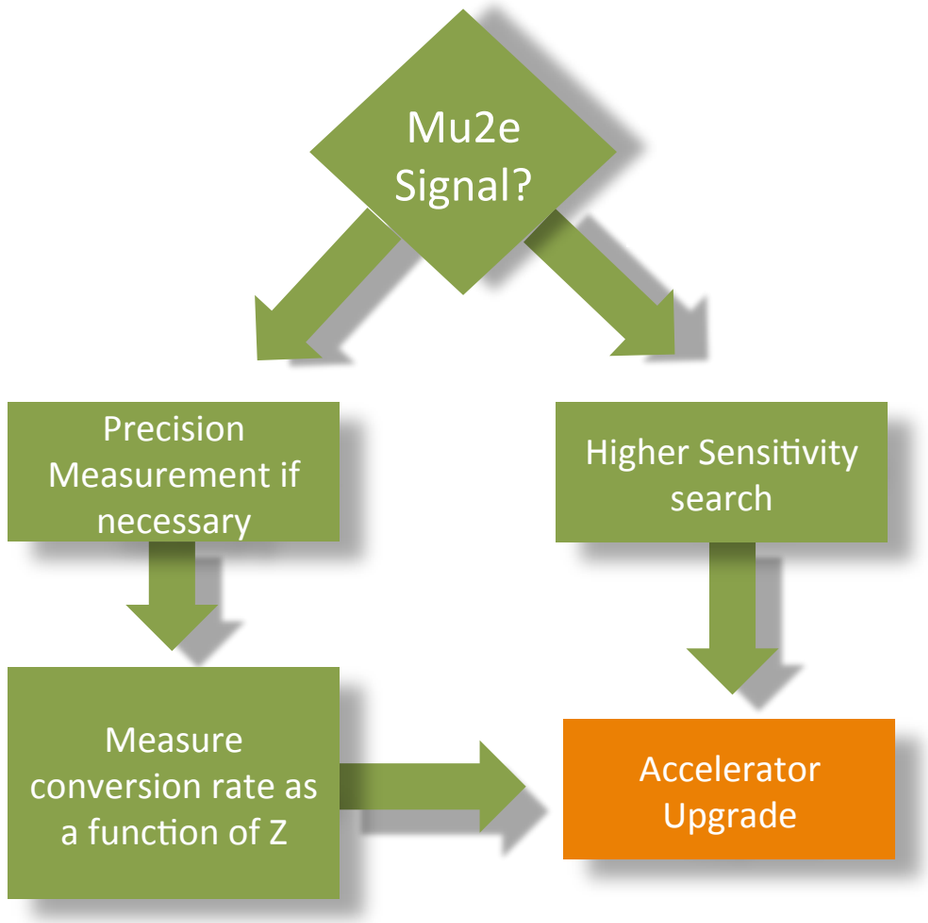
Calorimeter TB



Large size prototype: 51 crystals coupled to 102 sensors

- Goals:
  - Test performances
  - Test integration and assembly procedures
  - Operate under vacuum, low temperature and irradiation test
- e- beam (60-120)MeV
  - Orthogonal and tilted (~50º) configuration
  - Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

Mu2e signal?



- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons
    upgrade accelerator
  - ✓ **Snowmass** white paper,
    arXiv:1802.02599