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

The collaboration

> 220 scientists from 38 institutions

Argonne National Laboratory, Boston University, 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 Nazionale di Frascati,** University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Michigan, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University

Outline

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

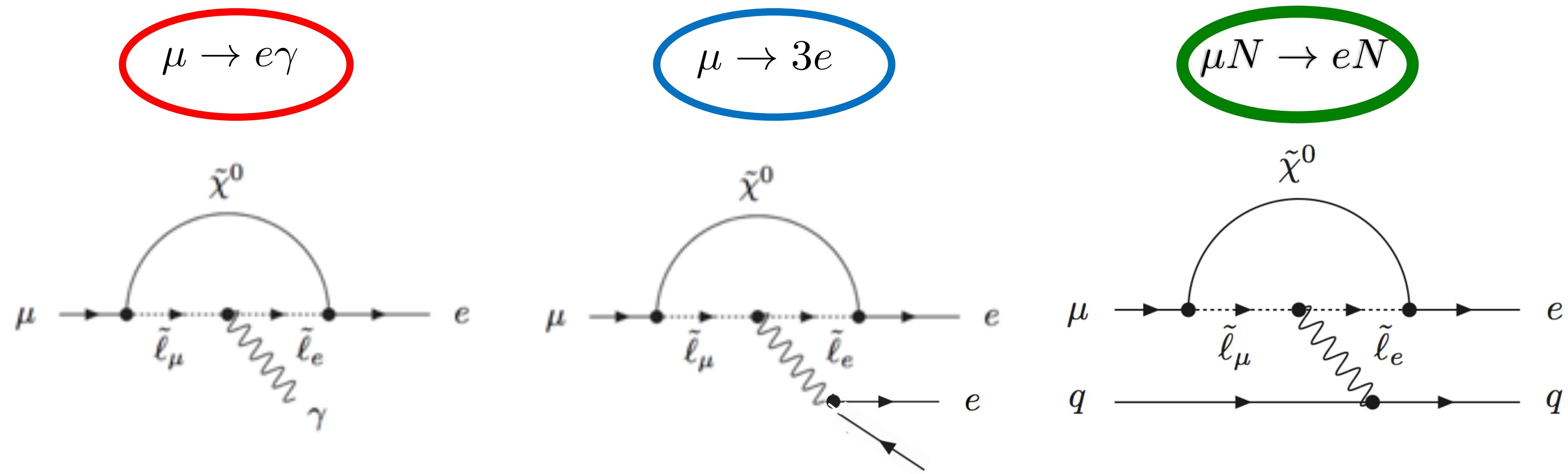
Charged Lepton Flavour Violation

- 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

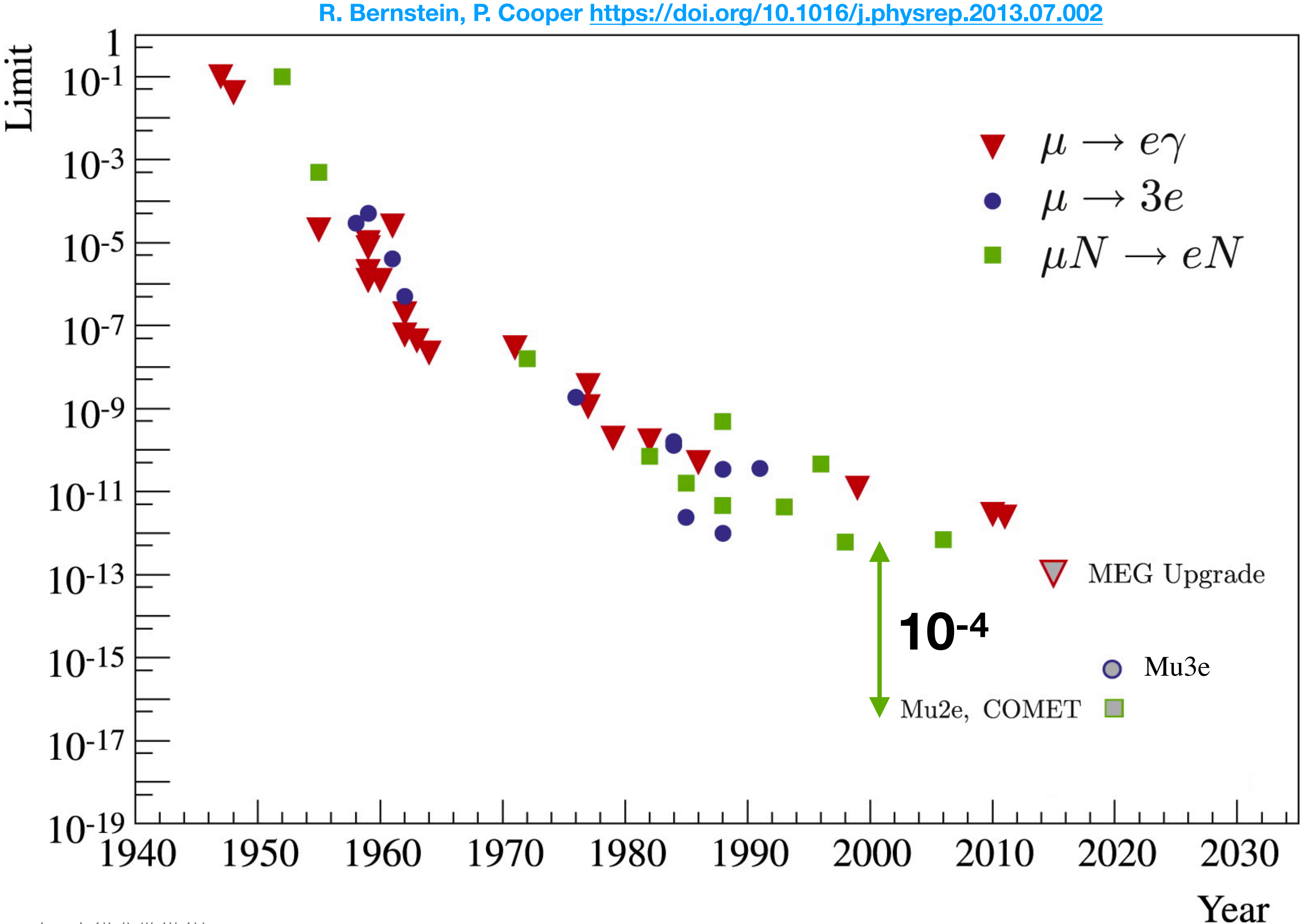
Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- N \to e^- N$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to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

- **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**

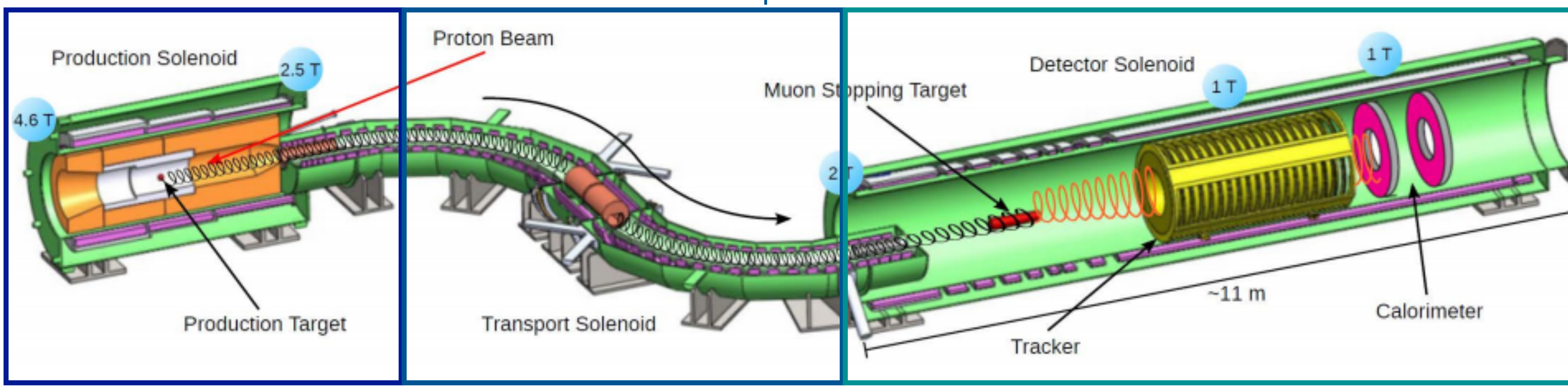
Mu2e Design

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

- Capture μ on the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic rays events

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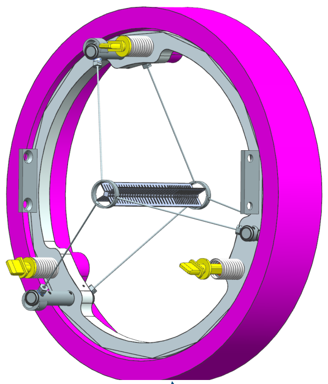

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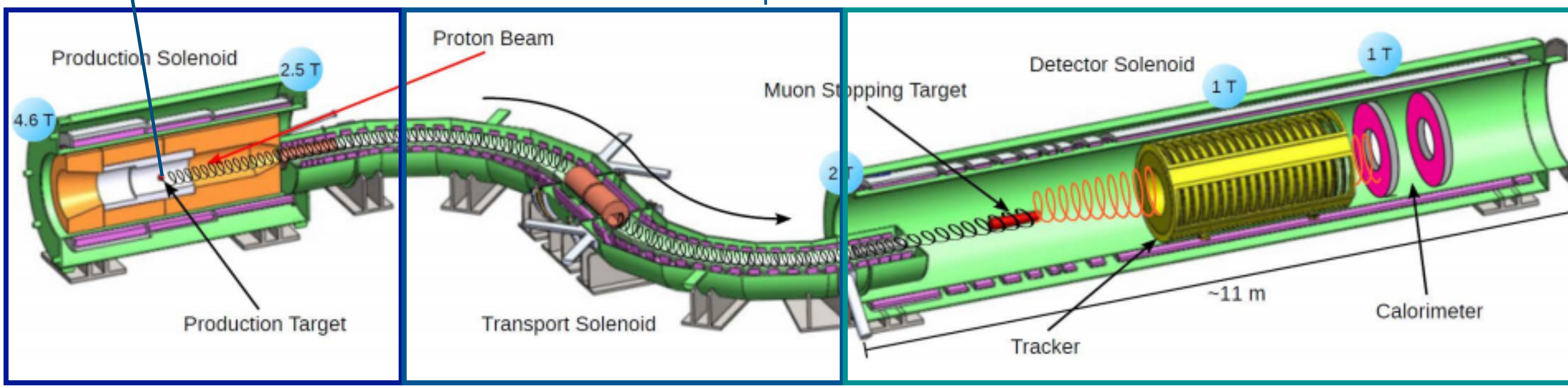

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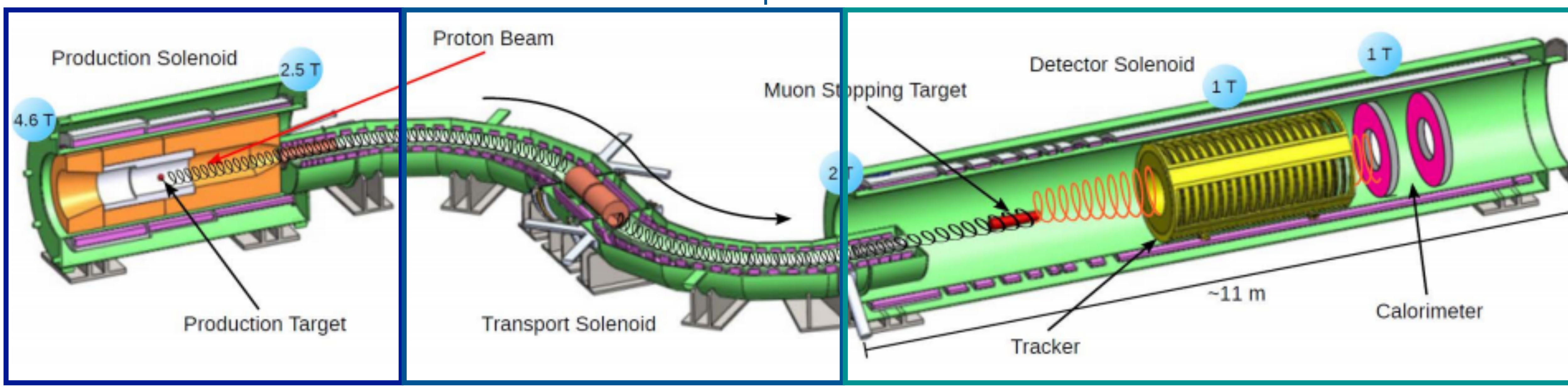

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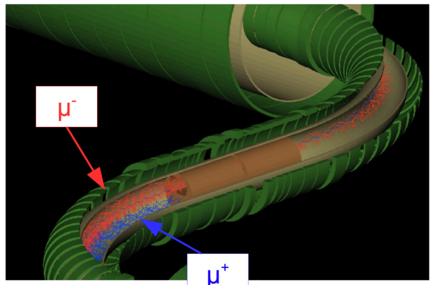

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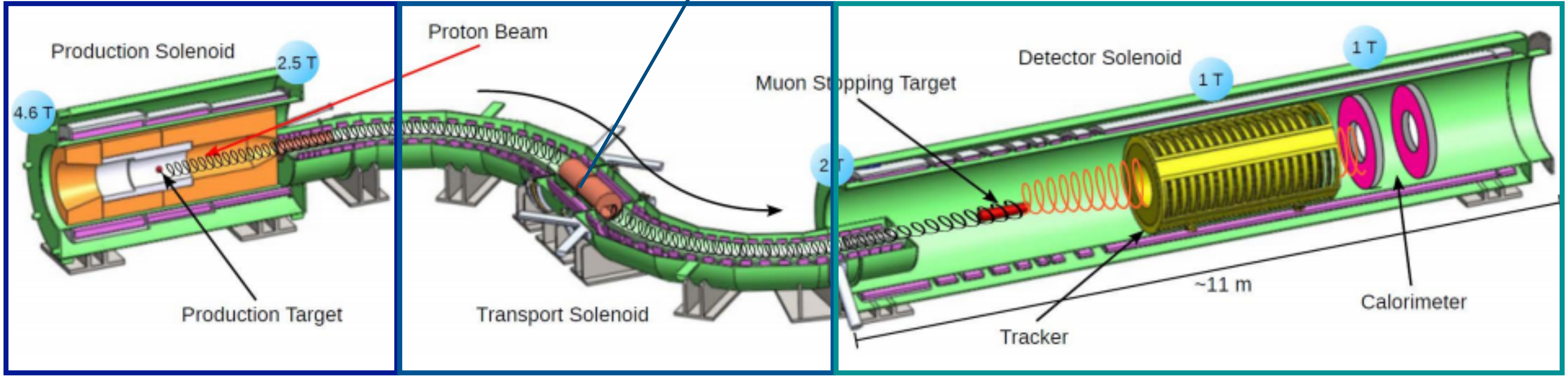

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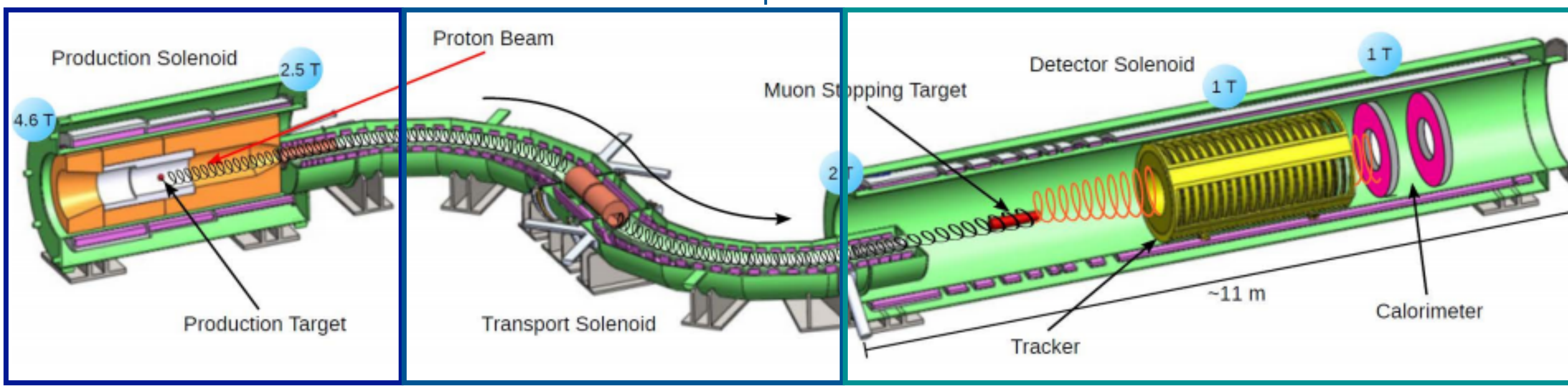

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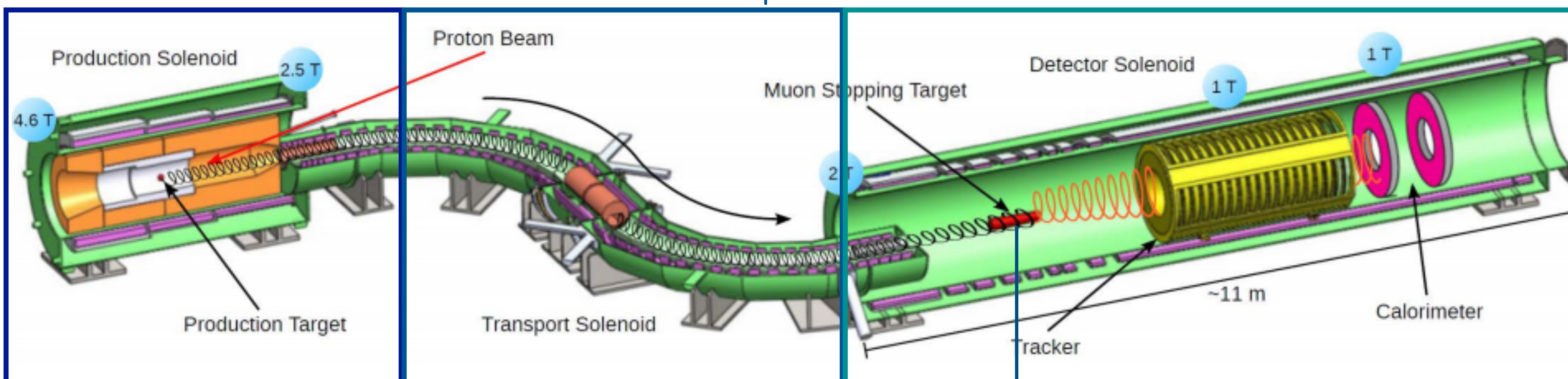

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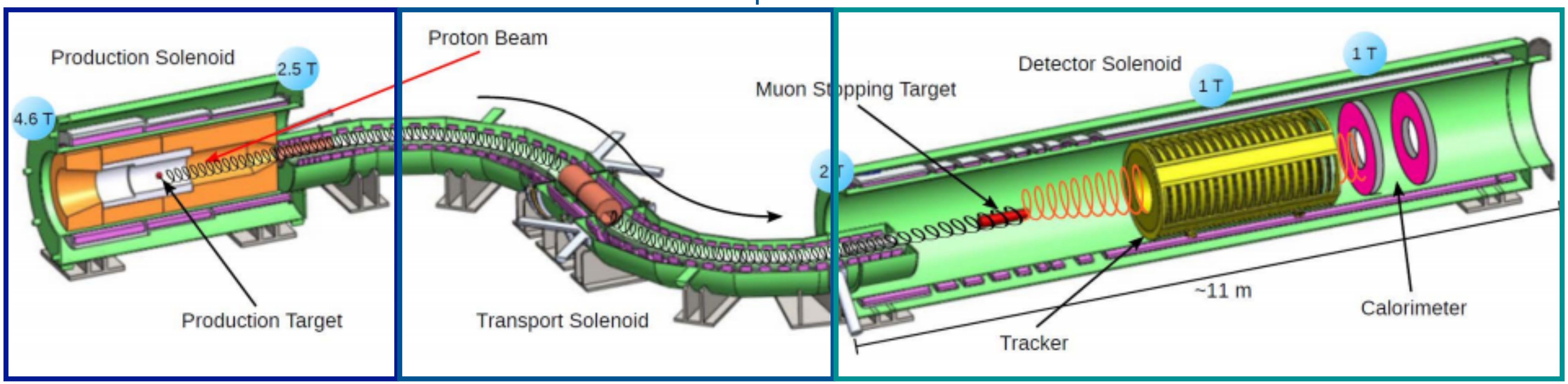

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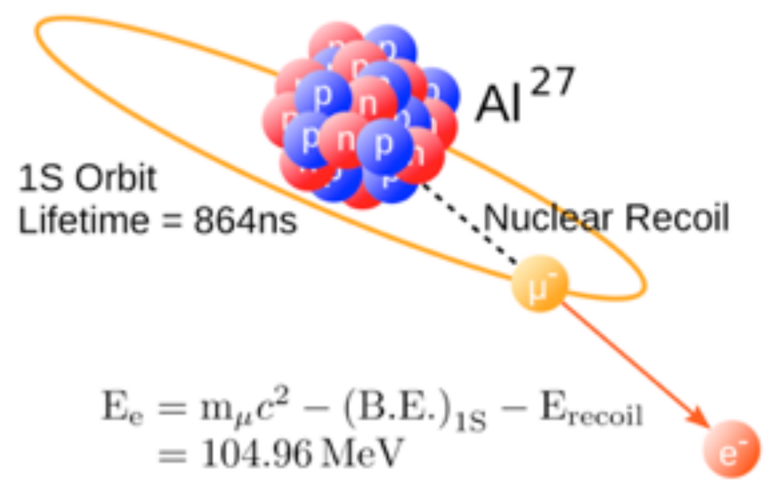
Experimental technique

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)

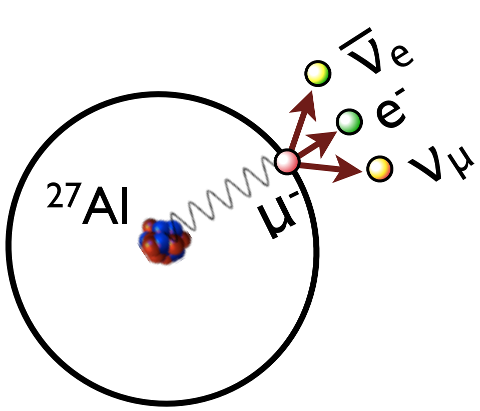
Conversion process



Signal

Decay in Orbit

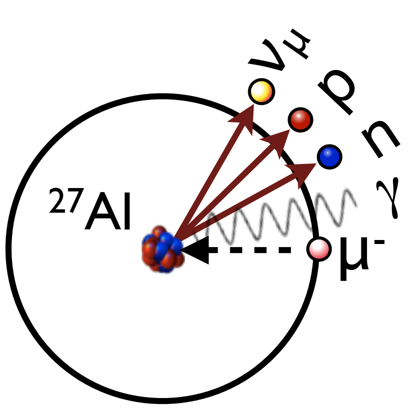
(BR=39%)



Background

Muon Capture

(BR=61%)



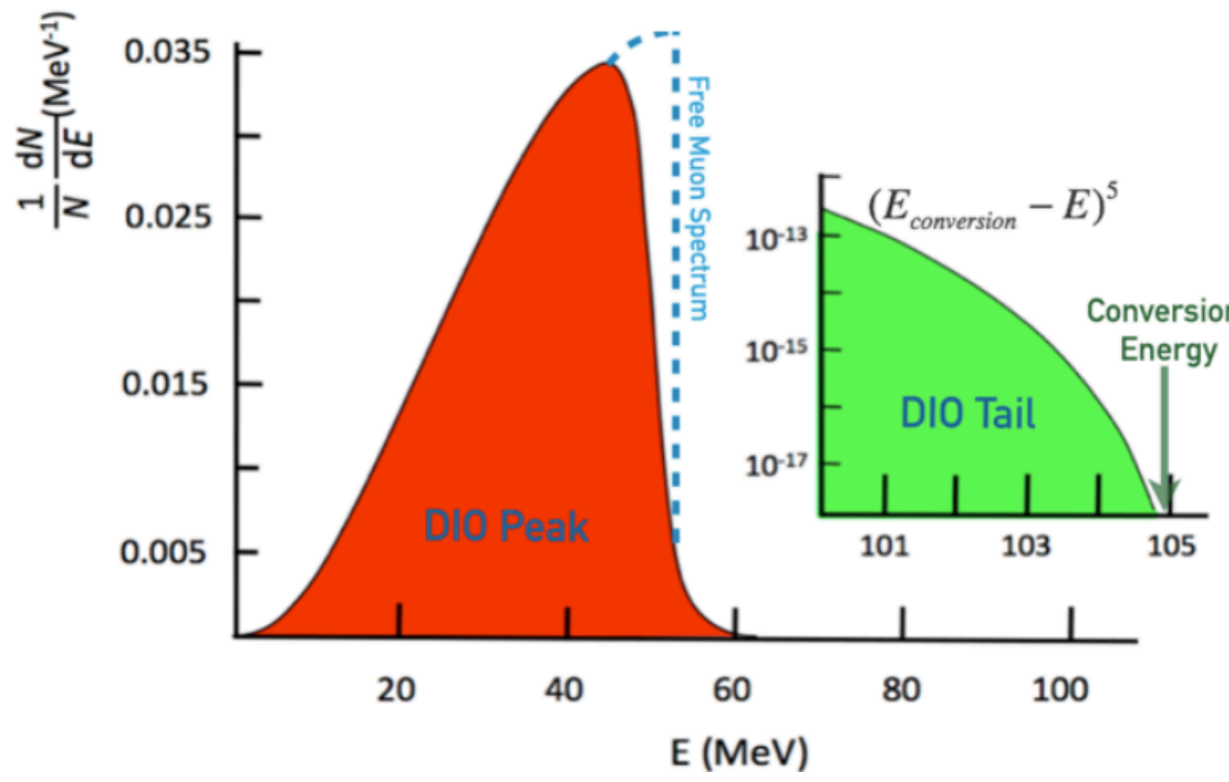
Normalisation

Mu2e will measure:

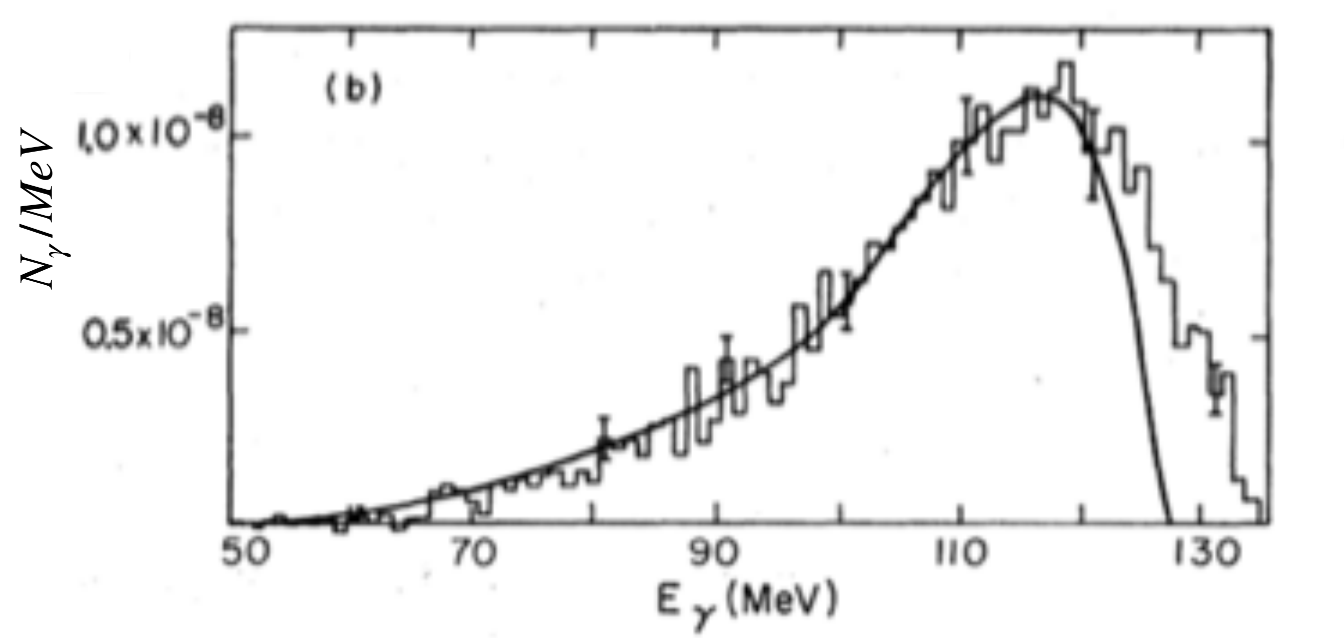
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$

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**



Main backgrounds

- **Intrinsic** *(scales w... the stopped μ)*
  - Muon dec... orbit
    $\mu^- + ... e^- + \bar{\nu}_e + \nu_\mu + Al$
  - ...diative μ capture
    $\mu^- + Al \to \nu_\mu ... + Mg$

high performances tracker

- **Cosmi... ays**

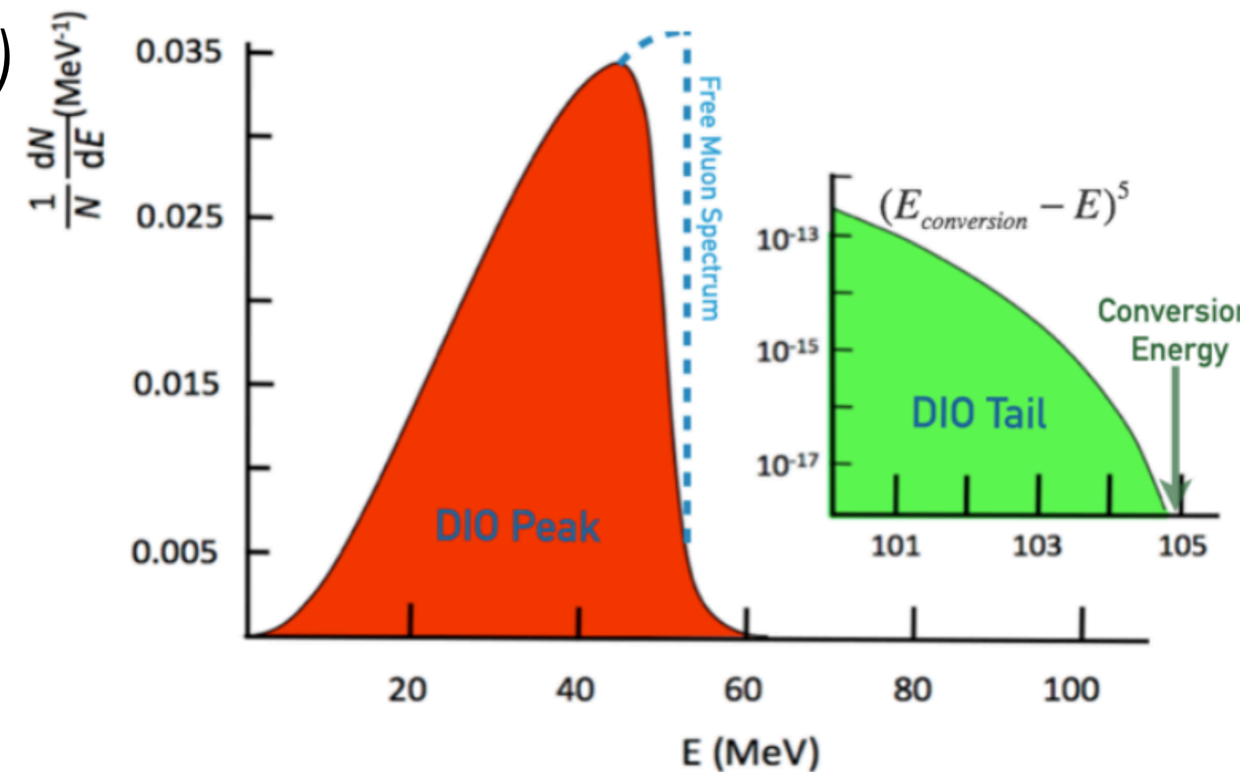
Cosmic Rays Veto

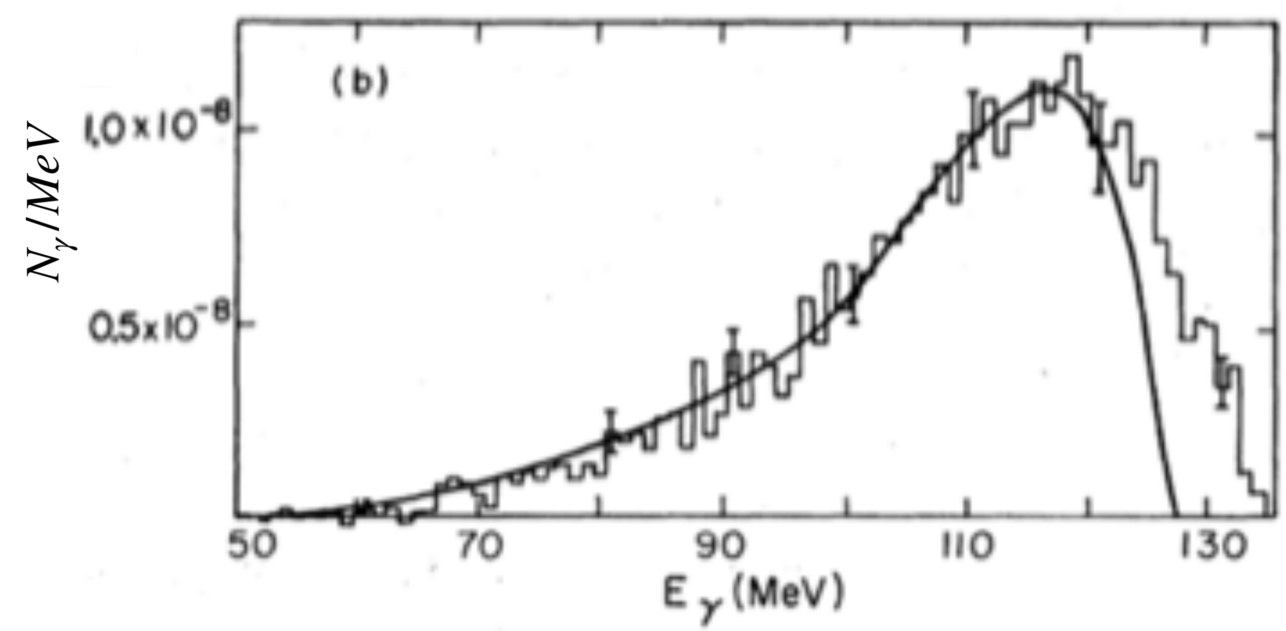
- **Lat... arriving from prompt processes**
  (scales with ...ber of late protons)
  - Ra... π capture
    $\pi ... \to \gamma N*, \gamma \to e^+e^-$
    $\pi^- N \to e^+e^- N*$
  - μ/π decay in fl...

Pulsed beam

- **Antiproto... nihilation**

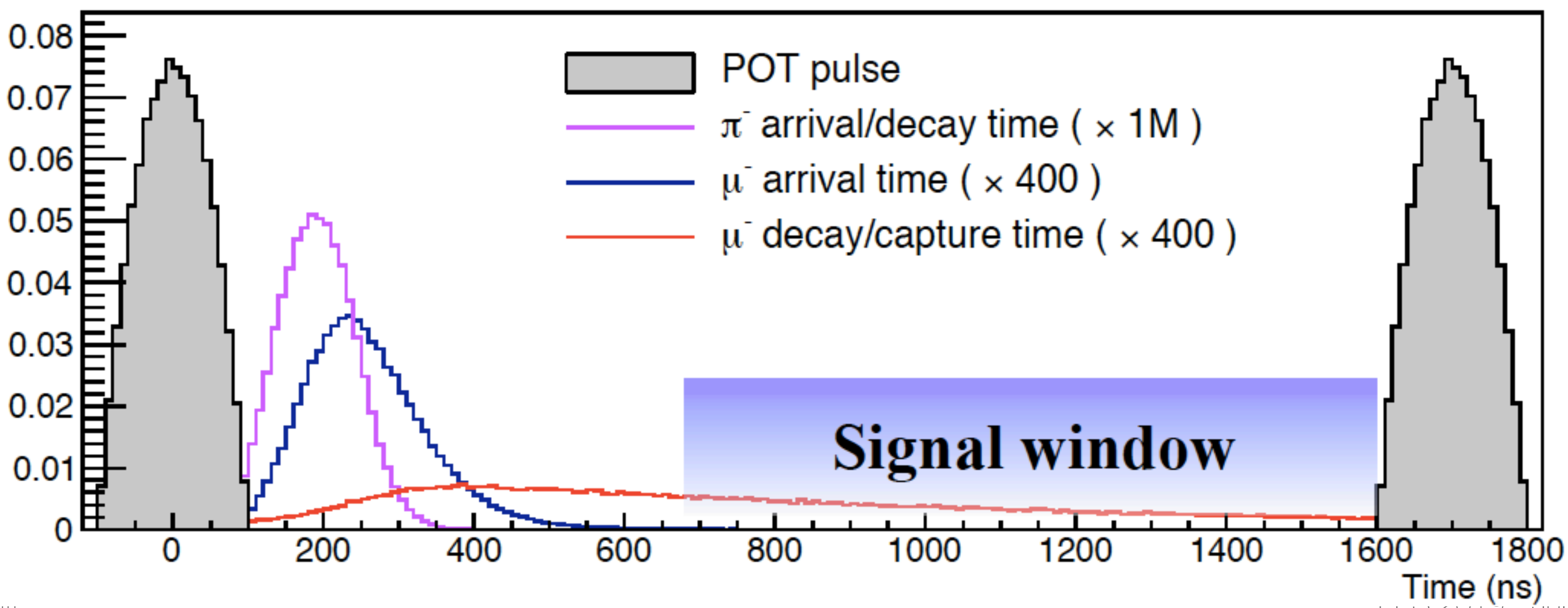
Antiproton Absorber





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) **the 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

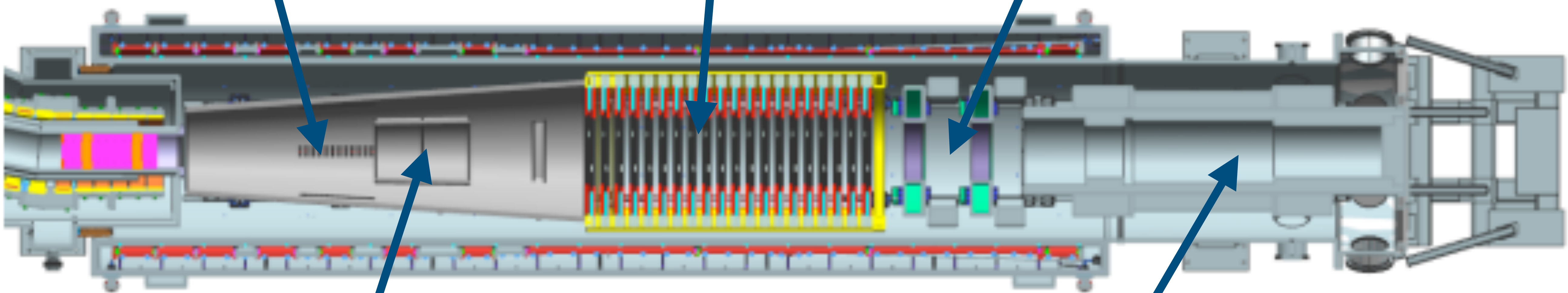
34 Al foils; the material choice is a compromise between the μ life time and E_{ce}

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

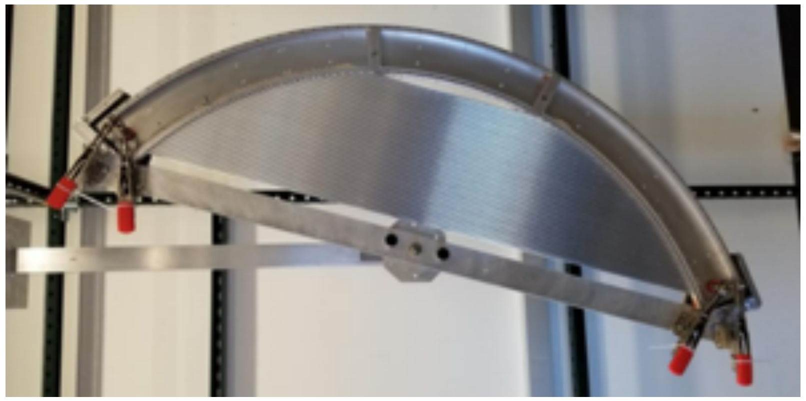
made of high-density polyethylene; designed in order to reduce proton flux on the tracker and minimize energy loss

Muon Beam Stop

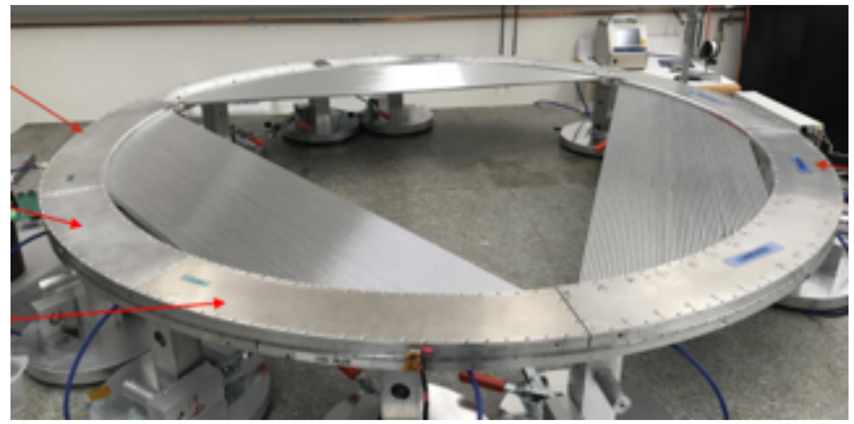
several concentric cylindrical structures of stainless steel and high density polyethylene; absorbs beam particles at the end of DS

Tracker

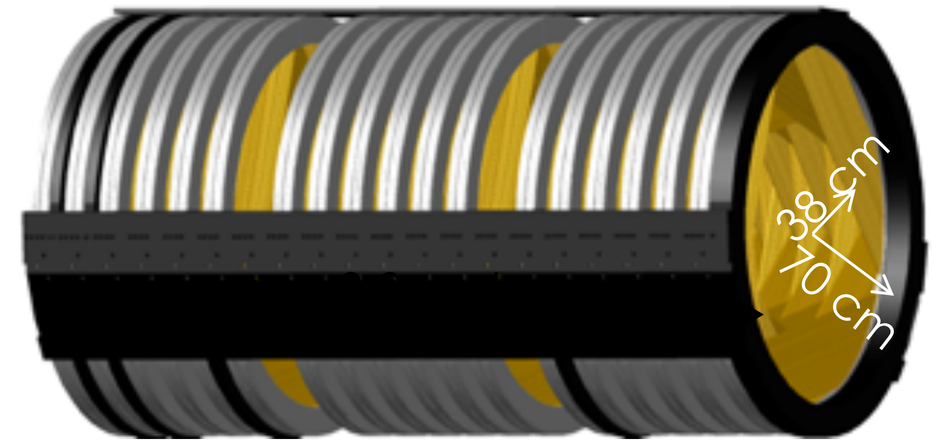
single panel



6 panels make a plane



2 planes make a station



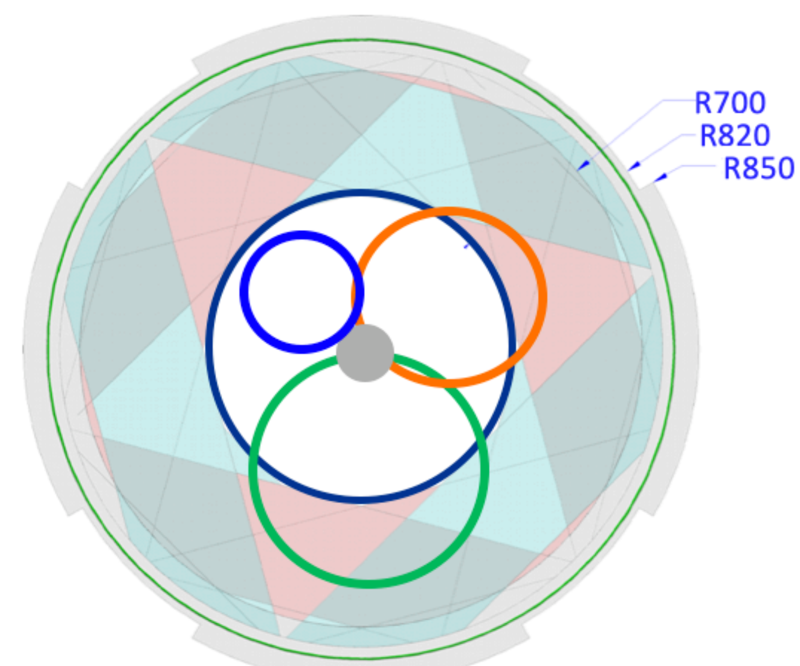
- 3 m long, 1.4 diameter in a 1 T uniform B field
- 18 stations made of 20k straw drift tubes:
  - 5 mm diameter, 15 µm Mylar walls
  - Ar:CO_2 (80:20) with HV~1500V

σ_p<180 keV/c @(100 MeV/c)

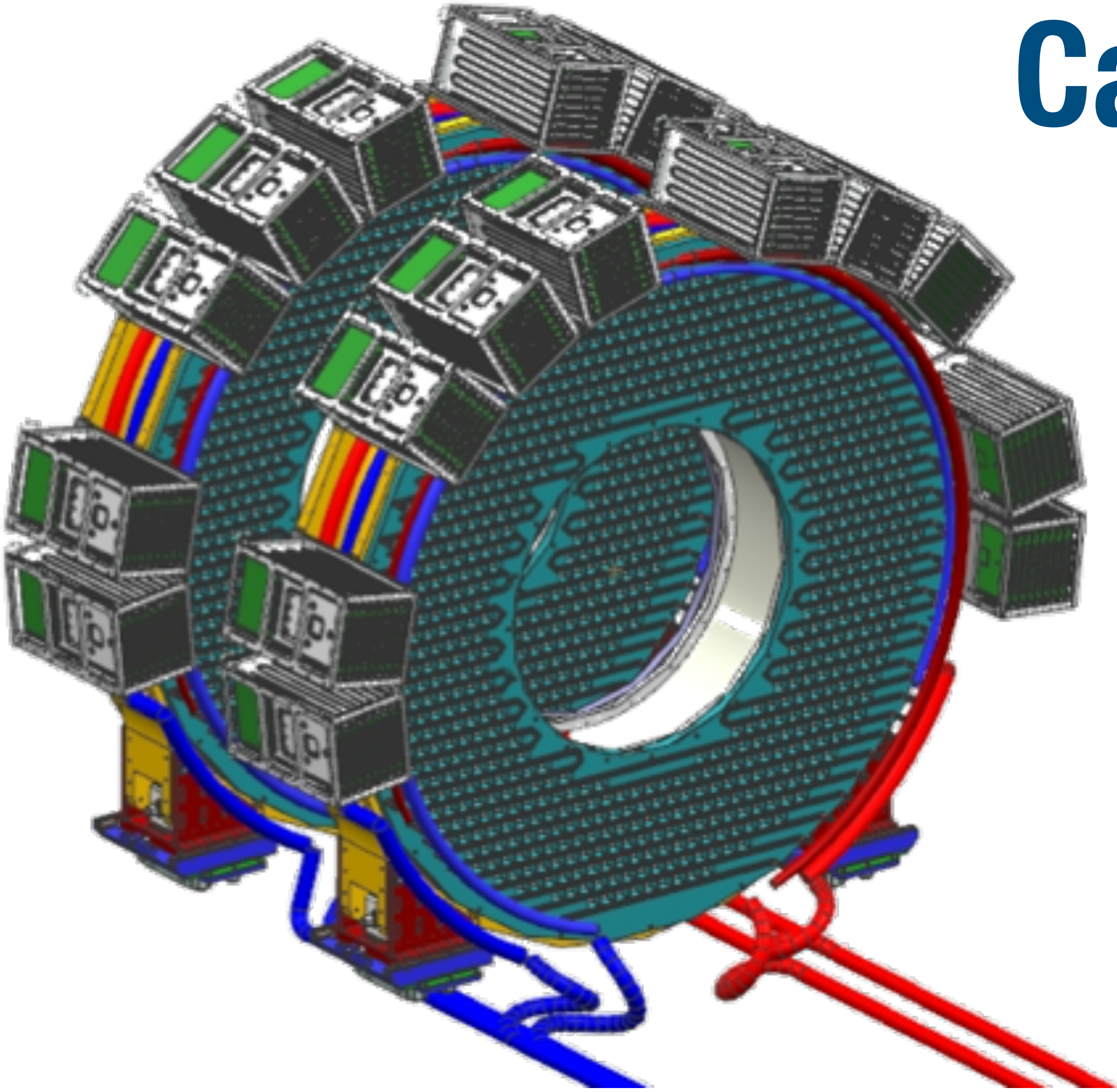
σ_t~ 1 ns

σ_x~100µm

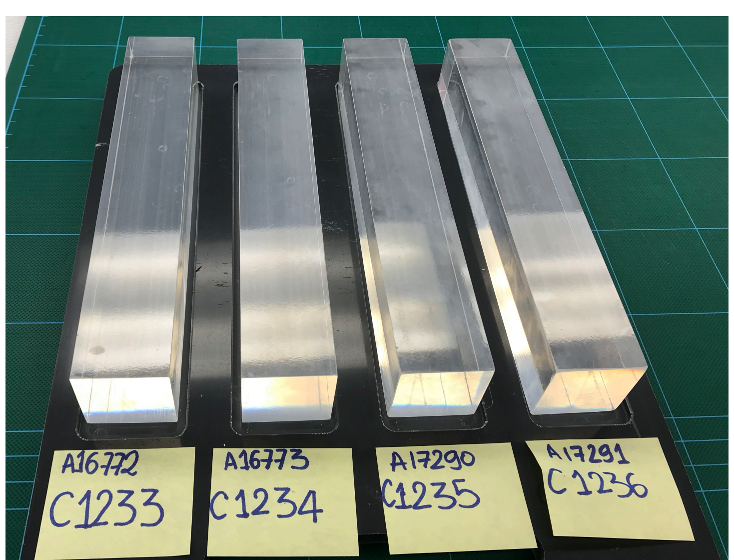
hole in the center makes it blind to DIO



Calorimeter



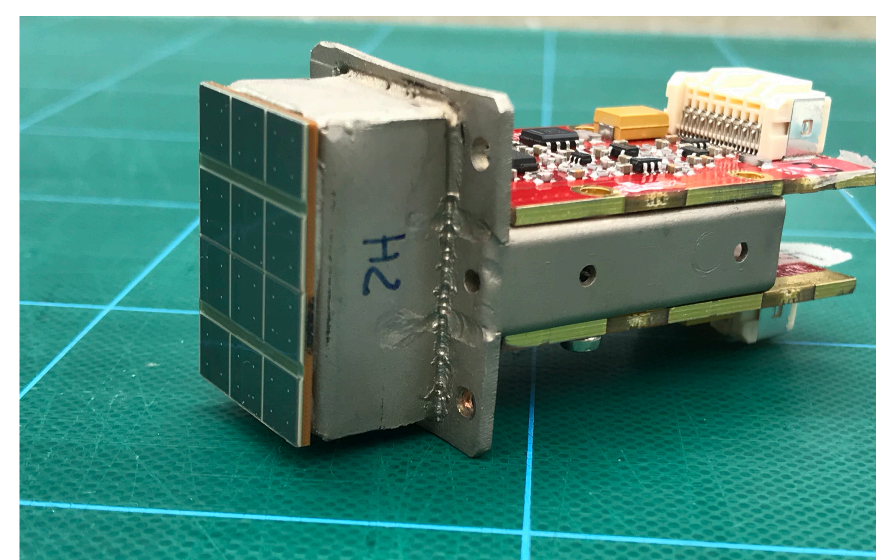
- 2 disks filled with 674 pure CsI crystals ($34 \times 34 \times 200$ mm^3) each
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- crystal read-out by 2 UV-extended SiPMs
- Analog FEE and electronics in near-by electronics crates
- Work in vacuum and B = 1T
- **PID: e/μ separation**
- **EMC seed track finder**
- **Standalone trigger**



σ_E < 10% (100 MeV/c)

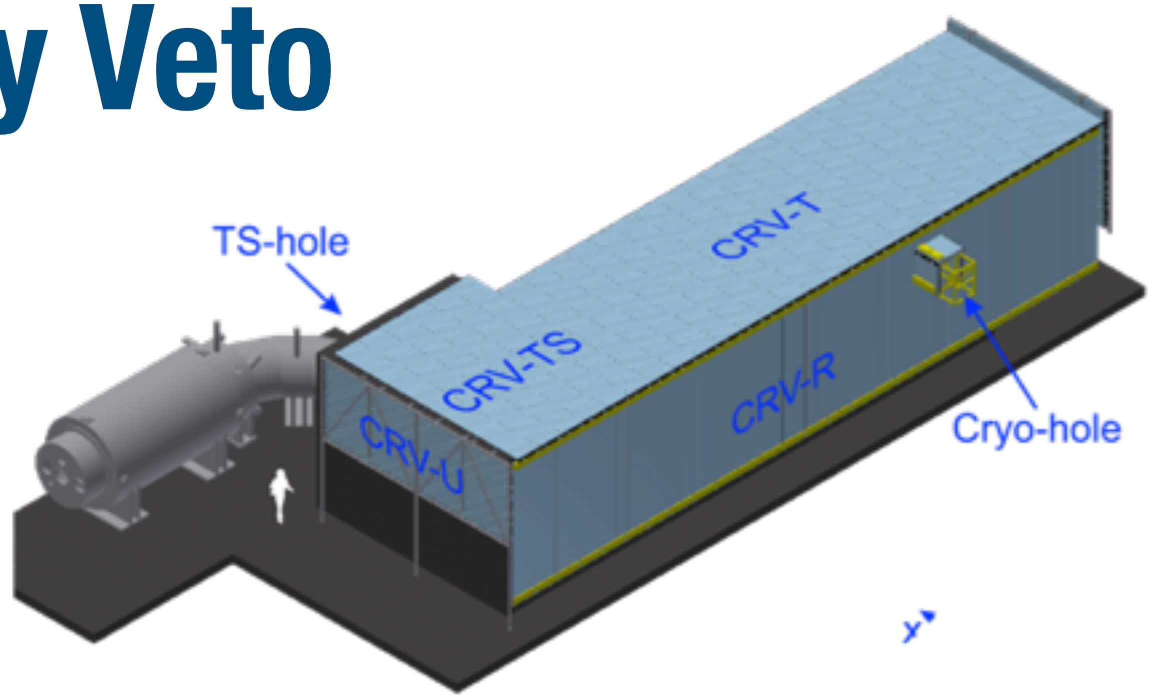
σ_t ~ 500 ps

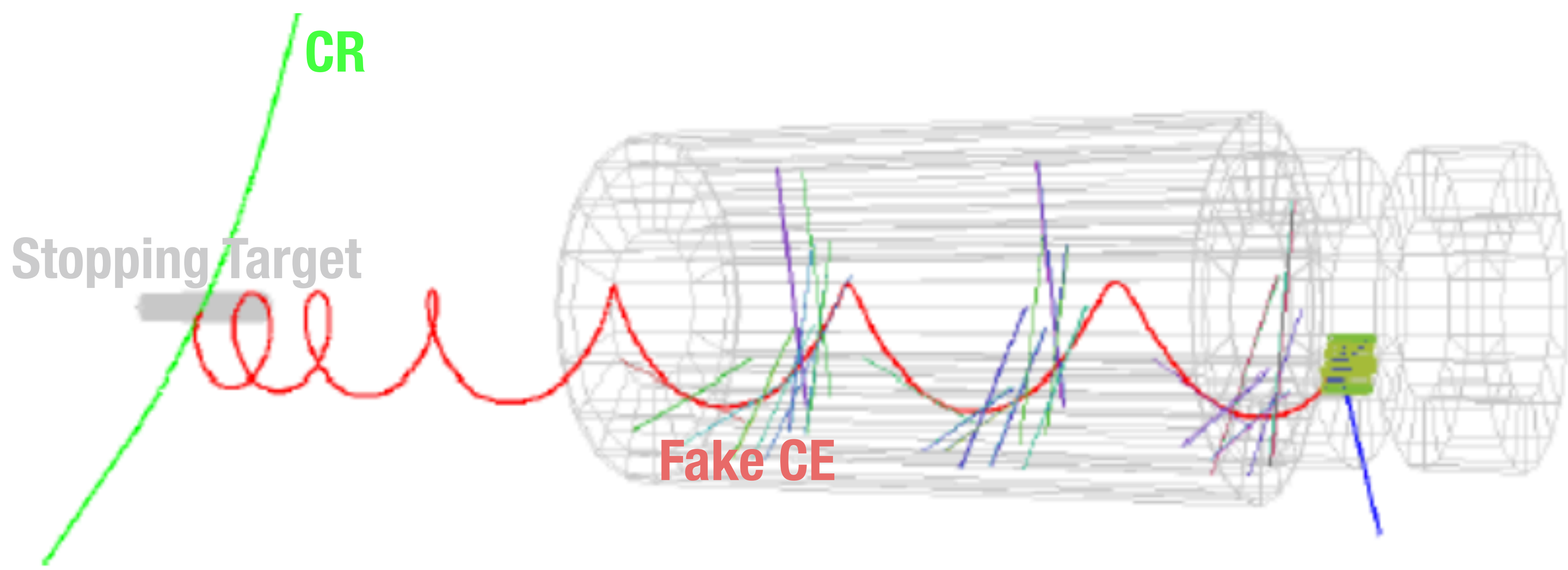
$\sigma_x \leq$ 1 cm



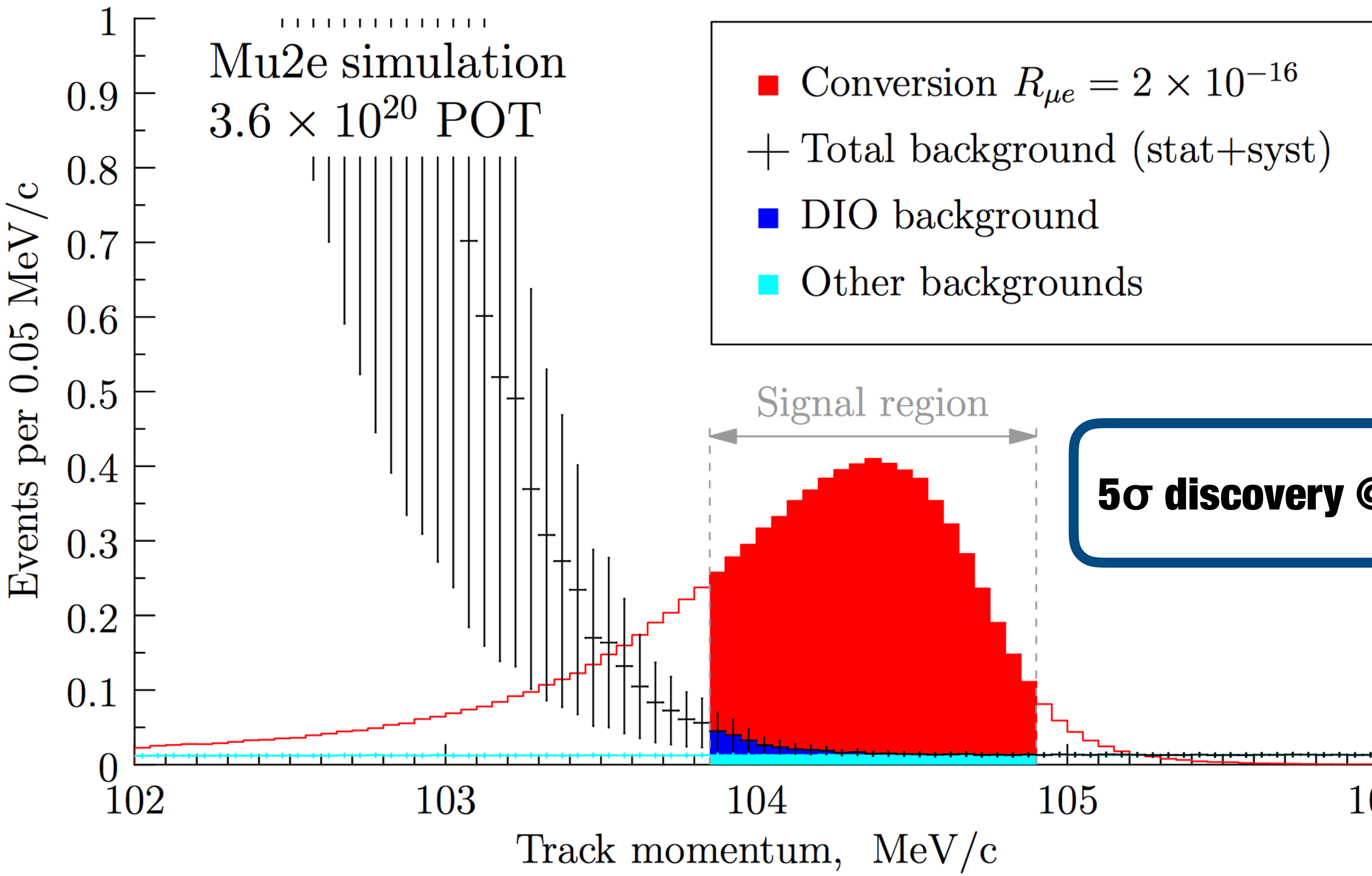
Cosmic Ray Veto

- 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

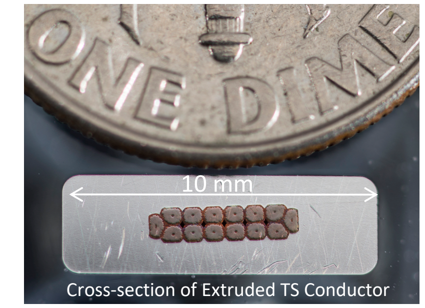


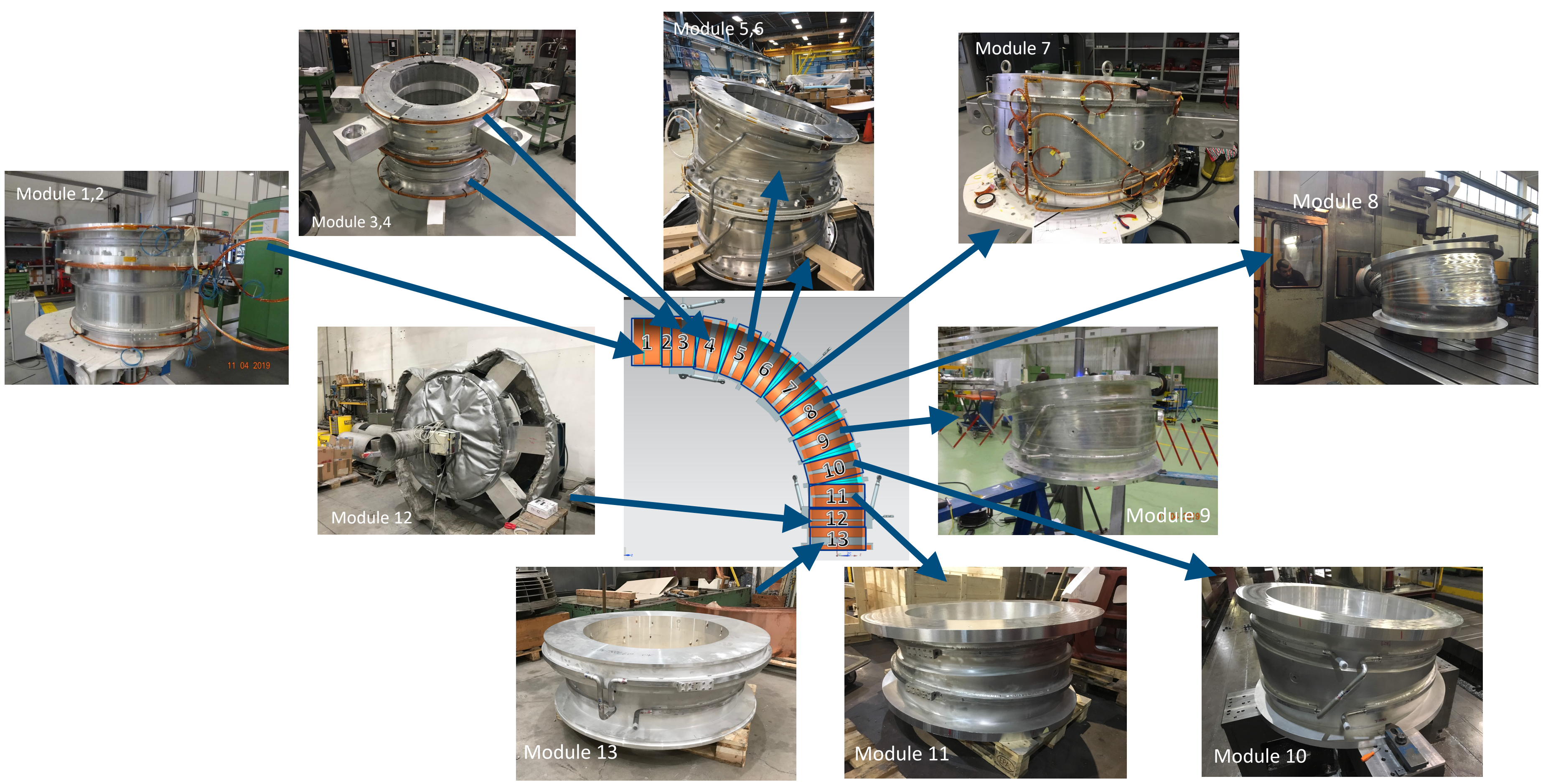
5σ discovery @ 7 events

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

Status of construction - Solenoids

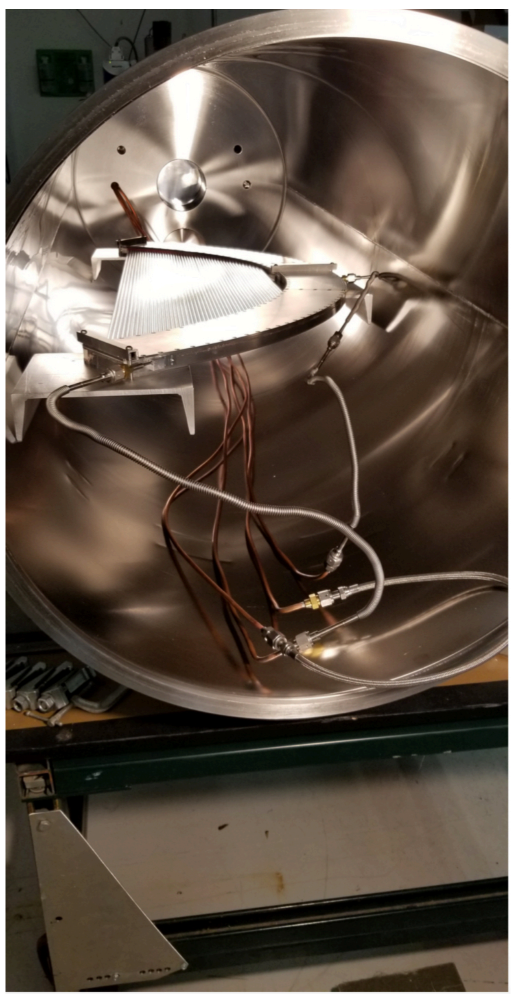
- Conductor construction completed
- Winding procedure of the PS and DS started
- 1/2 TS completed and the modules are now under test

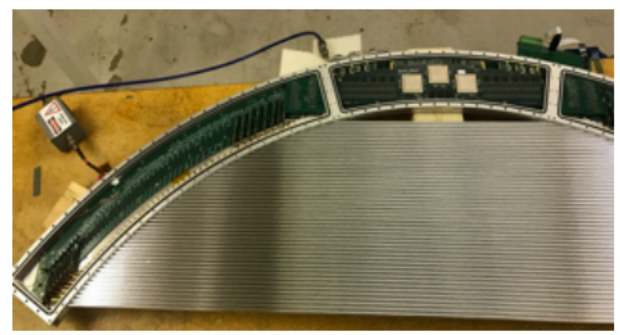




Status of the construction -Tracker

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



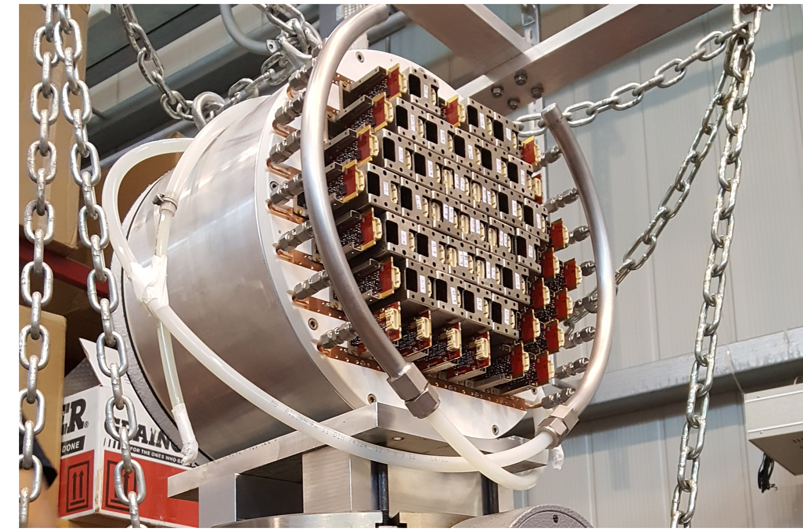


Panel w/Front-End Electronics

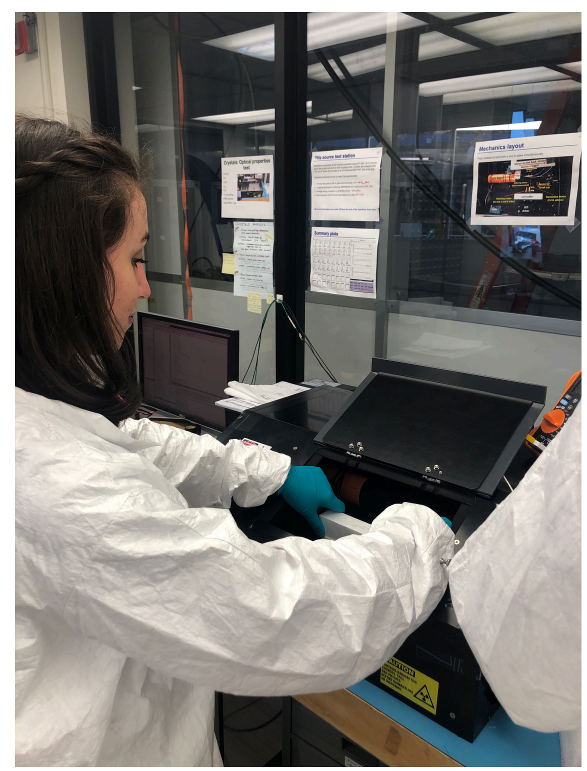
Two panels installed in plane

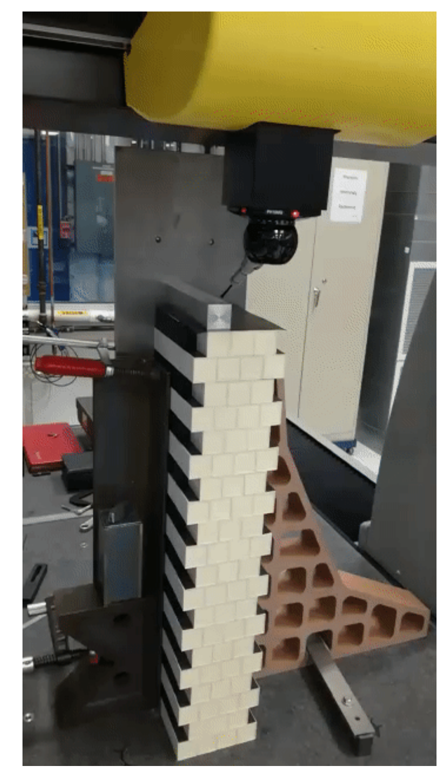
Panel: Straw Installation

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





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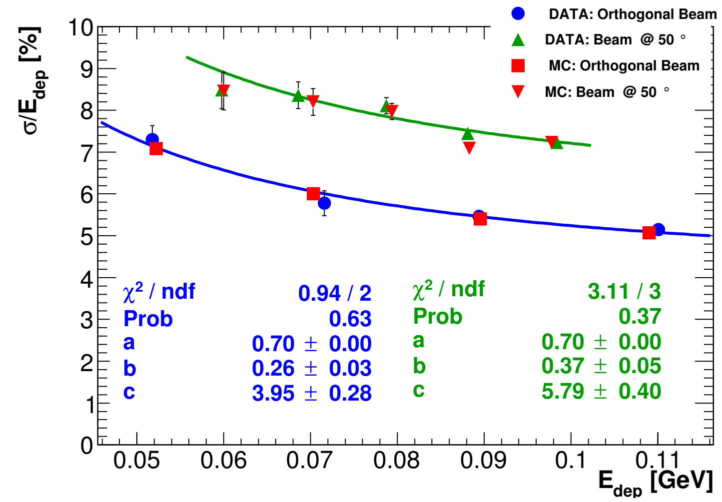
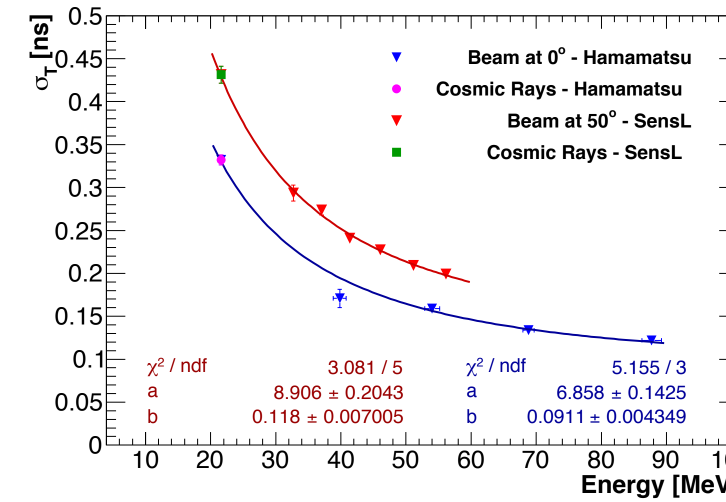
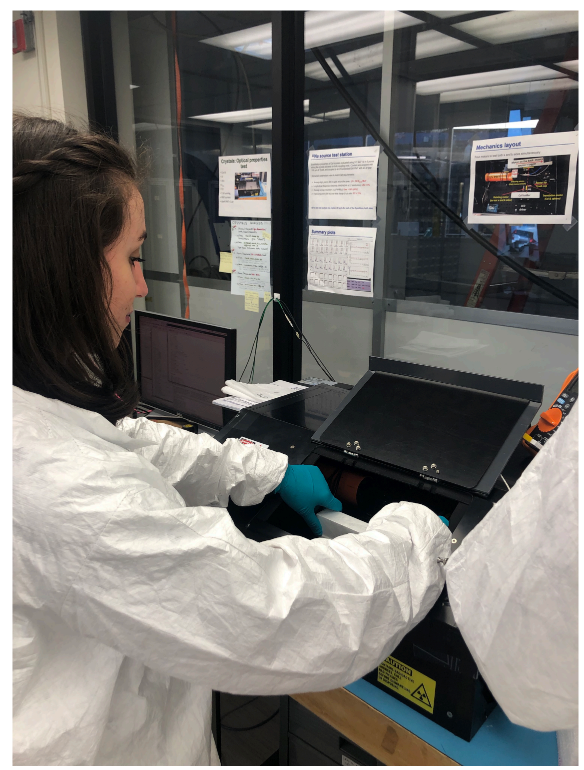
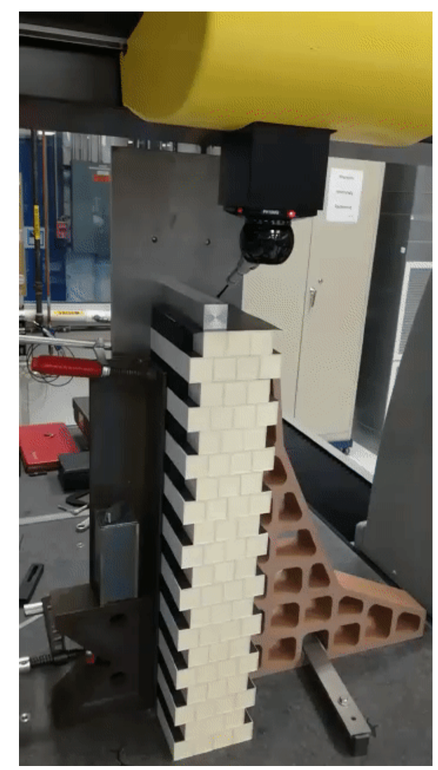


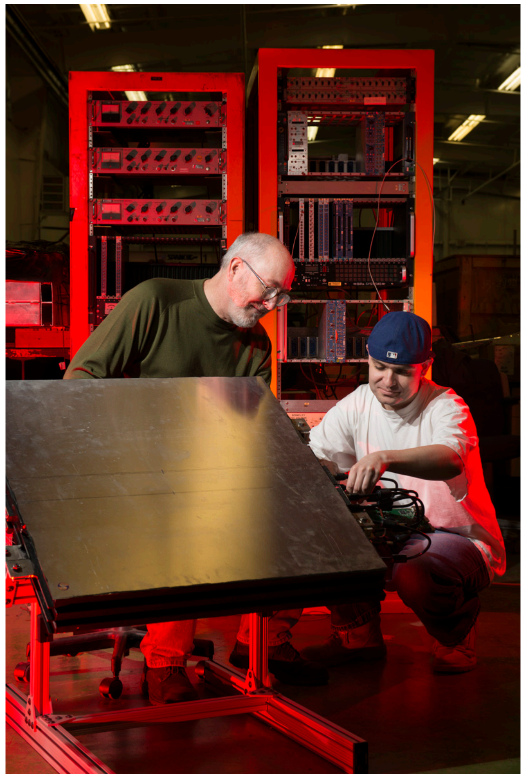






Status of the construction - CRV

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



First module being vacuum bagged.

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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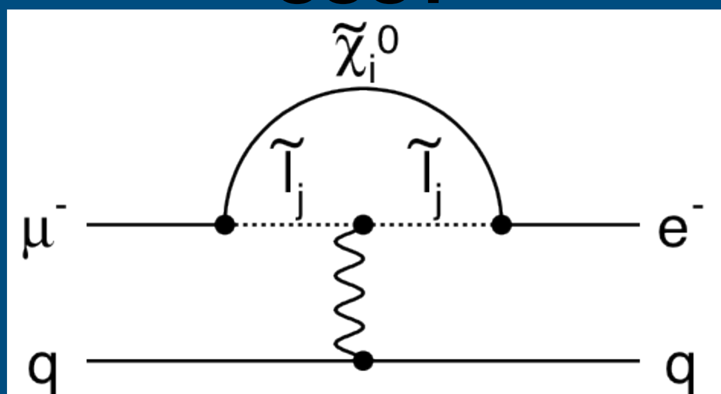
Spares

Muon CLFV - BSM theory

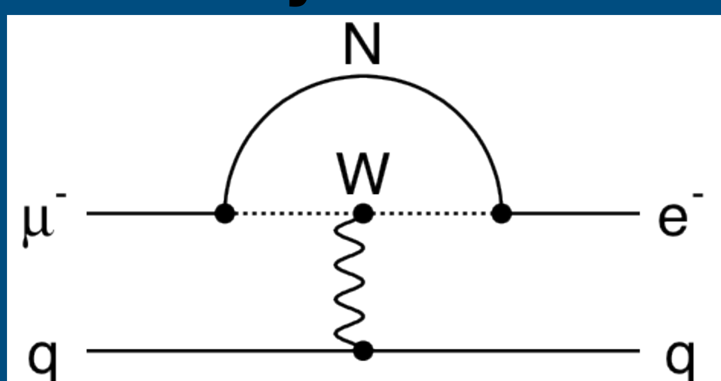
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

Loop Term

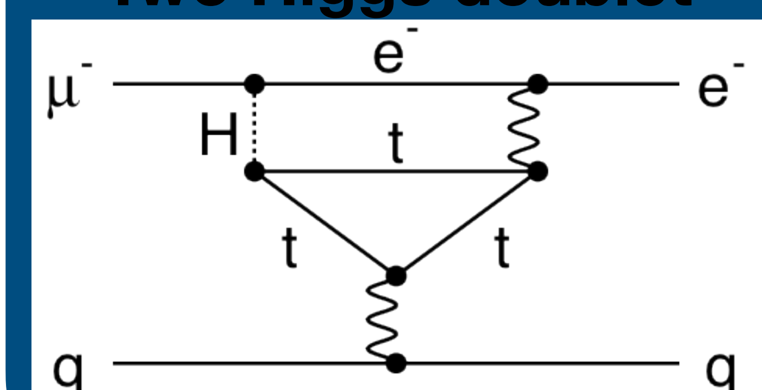
SUSY



Heavy neutrino

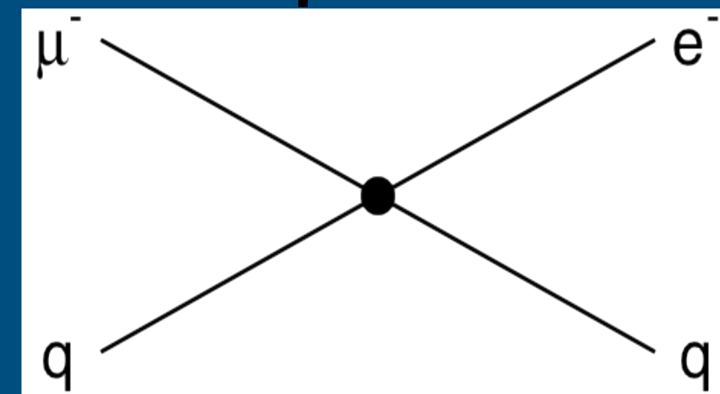


Two Higgs doublet

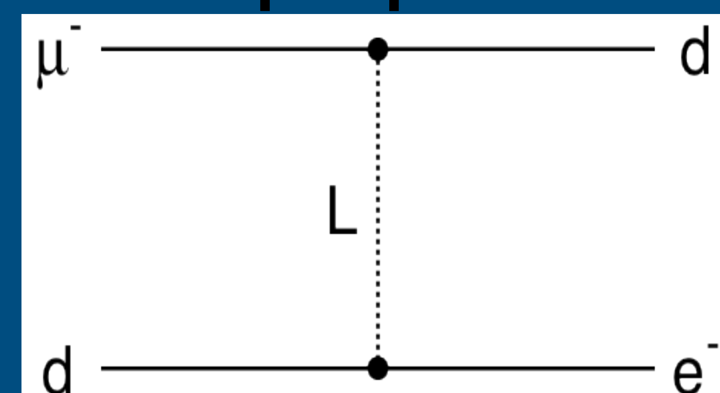


Contact Term

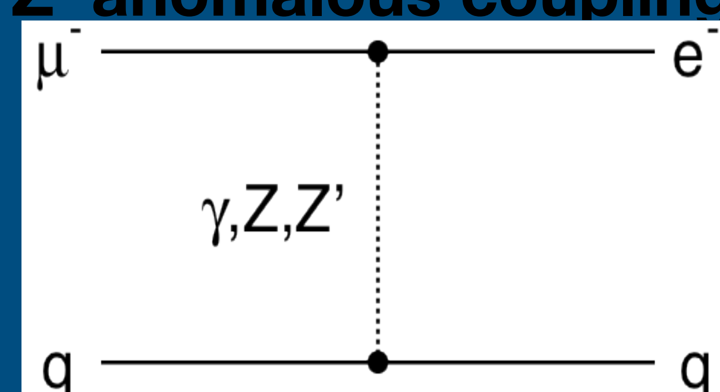
Compositeness



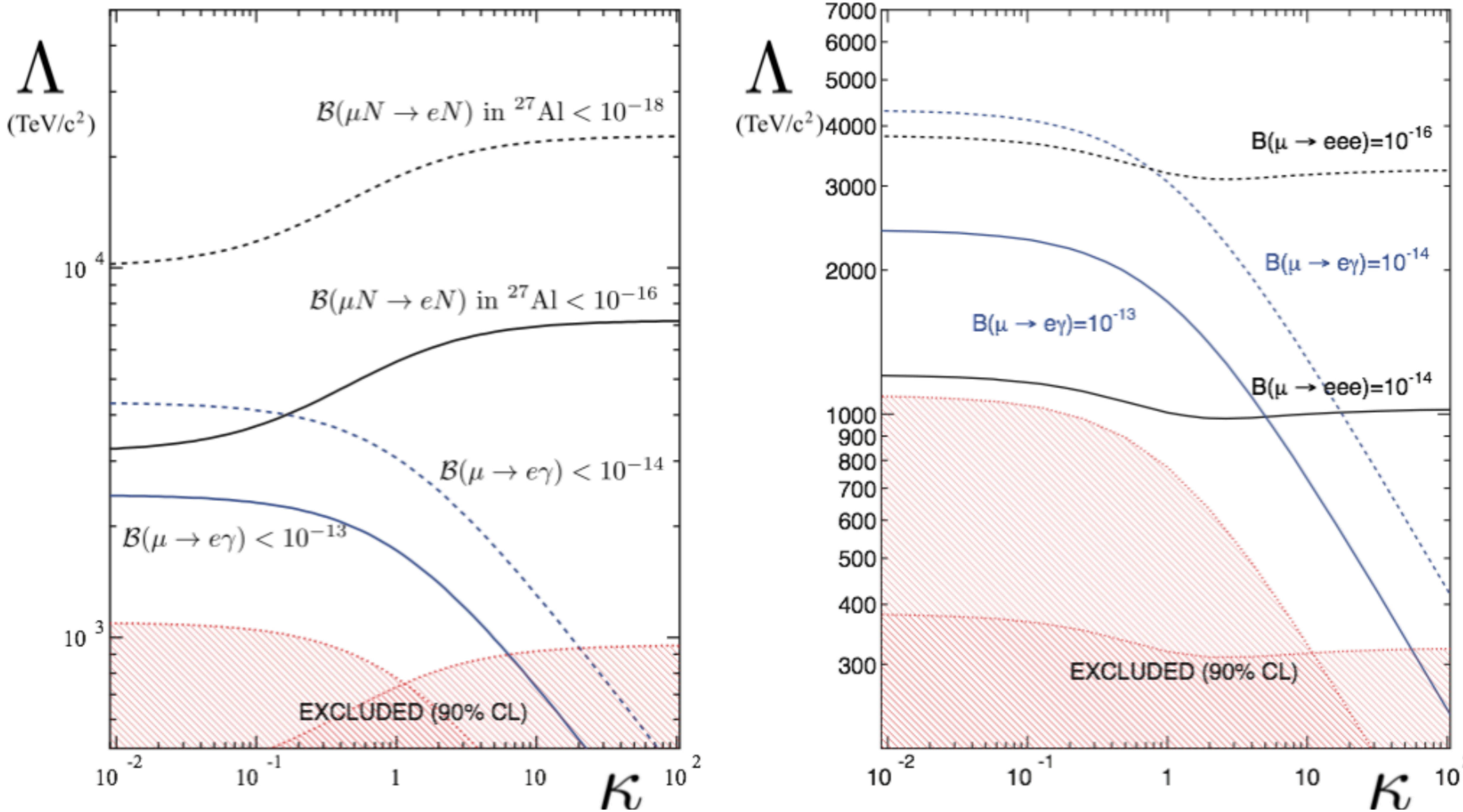
Leptoquarks



Z' anomalous couplings



Interval searches



SUSY benchmark point

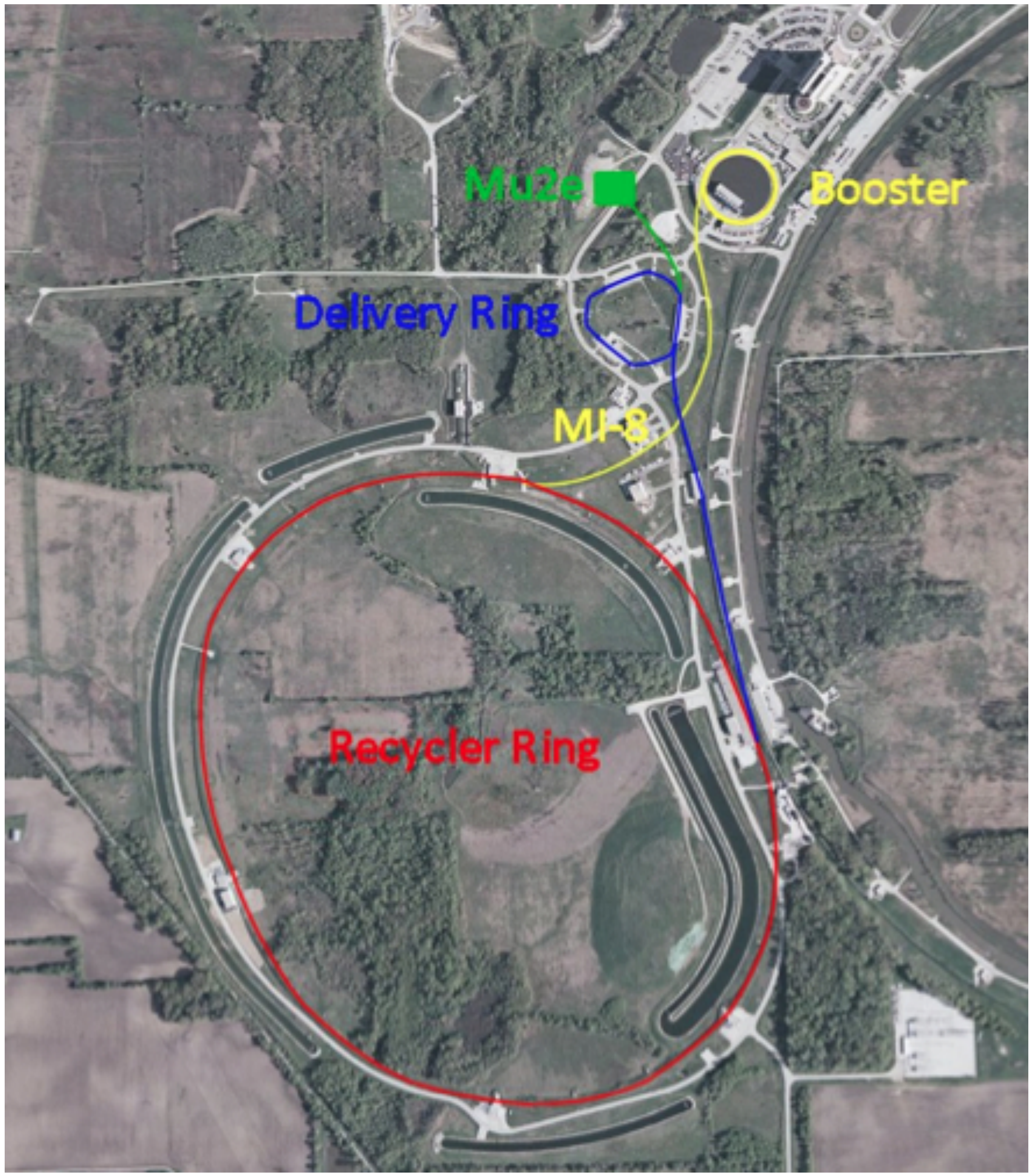
W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

★★★ = 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.

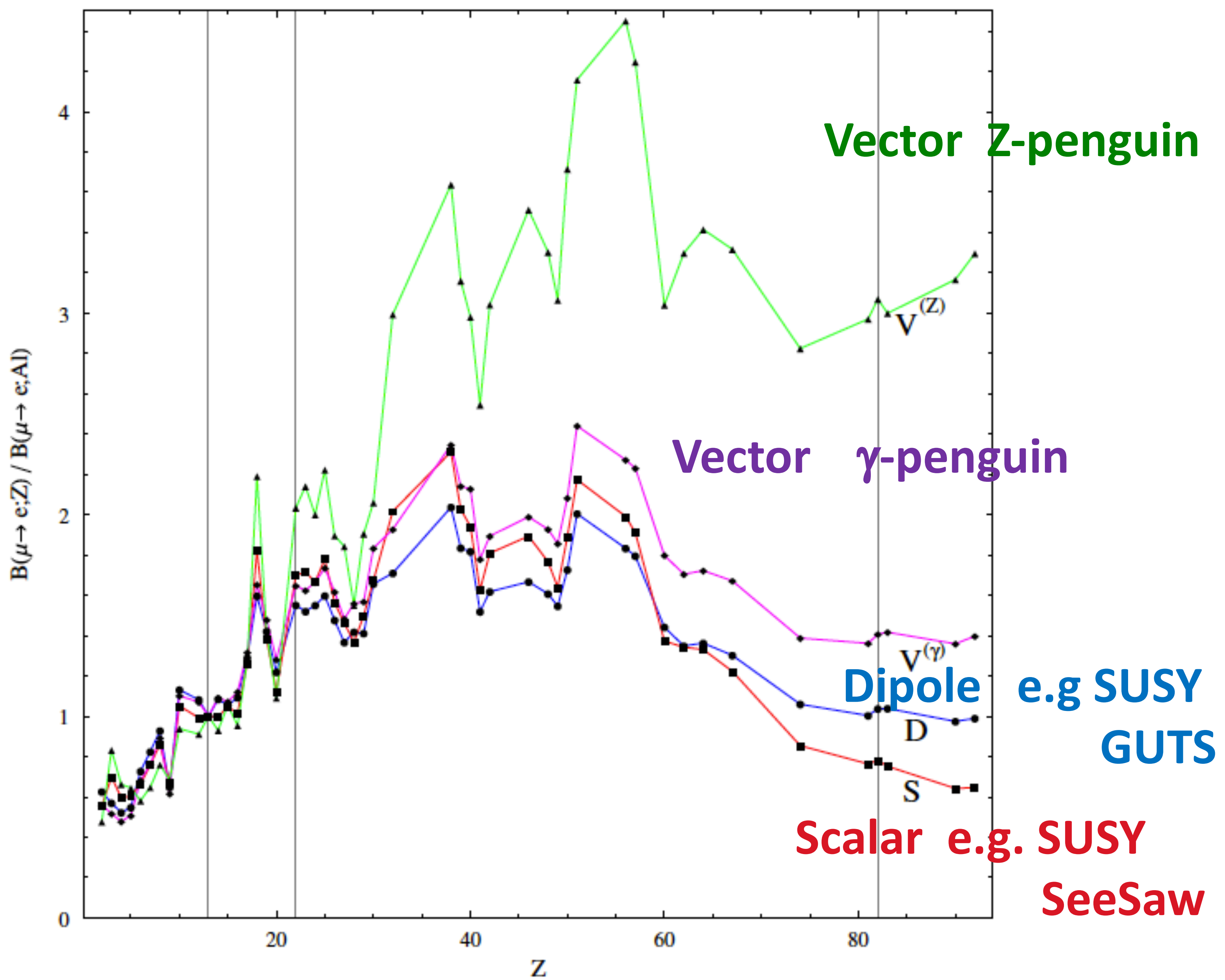
Proton beam



- 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



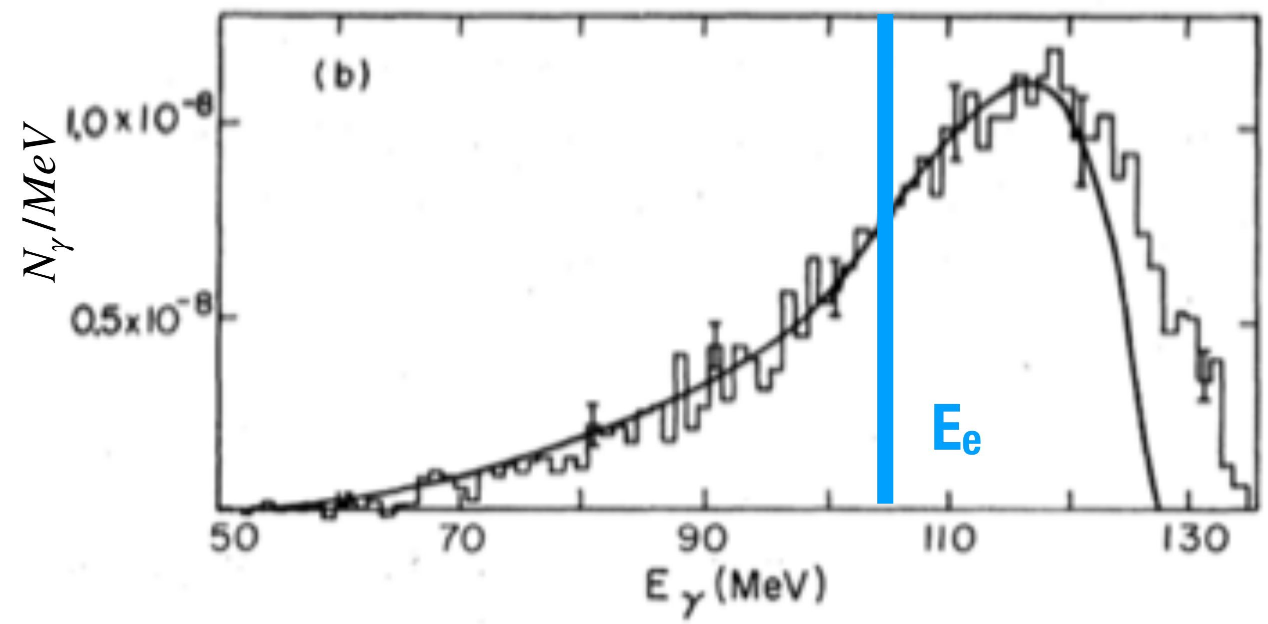
Prompt background

Radiative pion capture:

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

$$\pi^- N \rightarrow \gamma N$$

$$\gamma \rightarrow e^- e^+$$

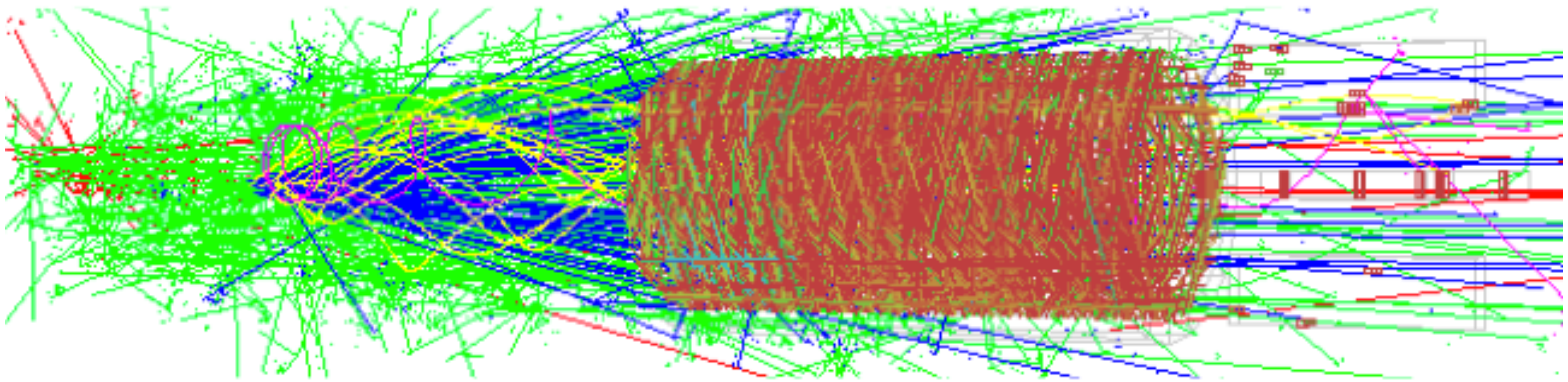


The electron can have momentum in signal window, and mimic conversion event.

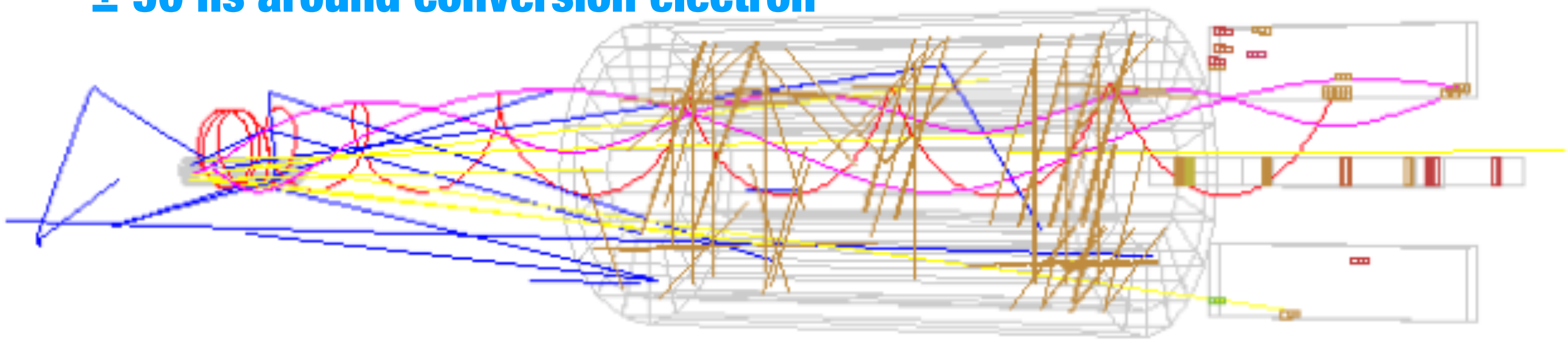
Simply wait until their rates are lowered before initiating live window to look for signal

A typical event

500 -1695 ns windows



± 50 ns around conversion electron



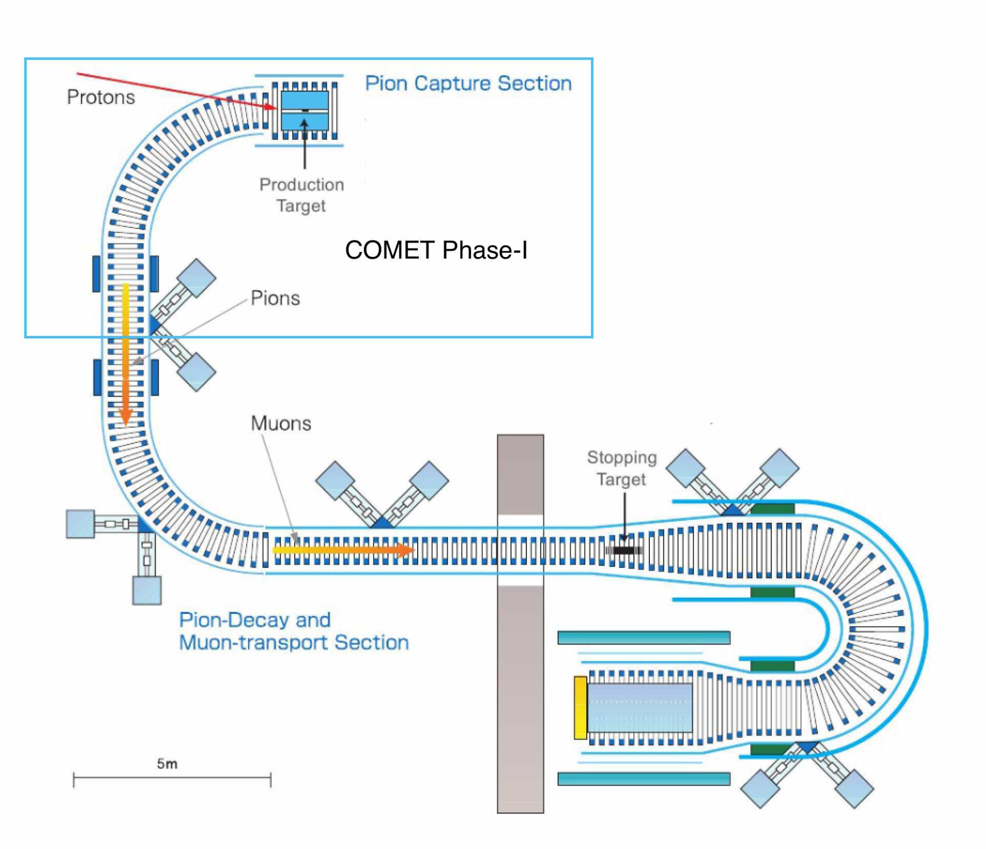
- Search for tracking hits with time and azimuthal angle compatible with the calorimeter clusters ($|\Delta T| < 50$ ns) → **simpler pattern recognition**

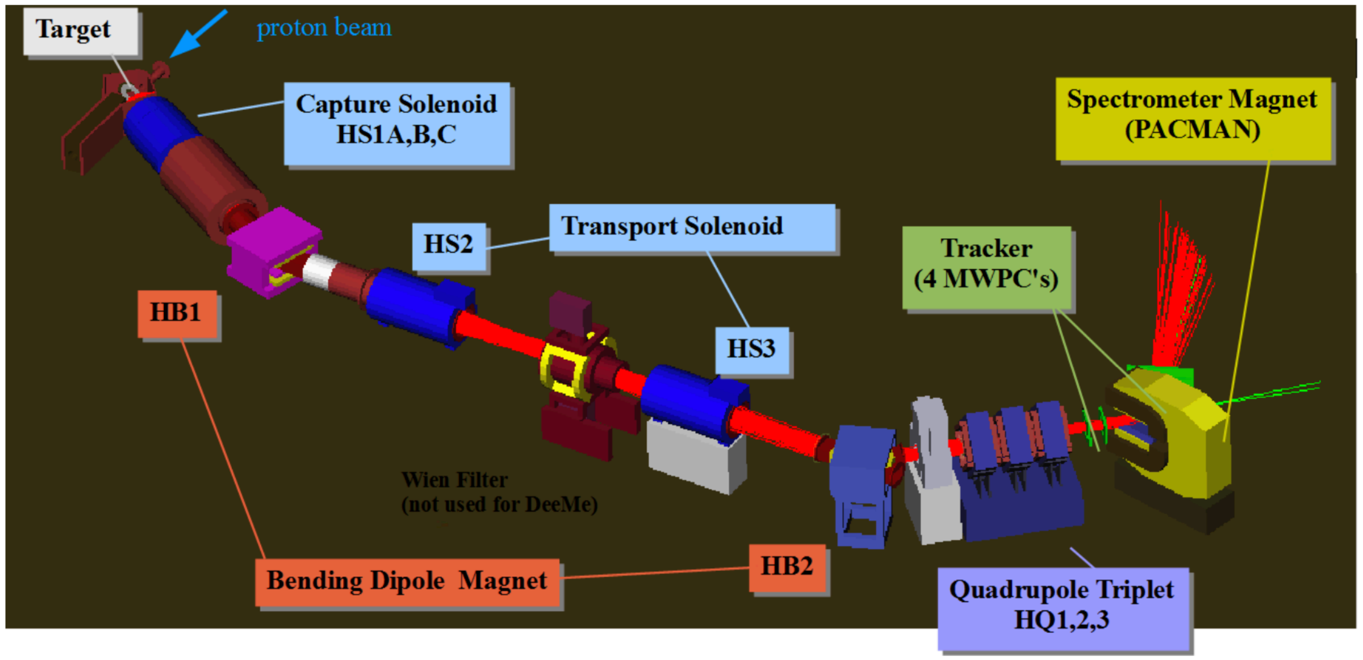
Background summary

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

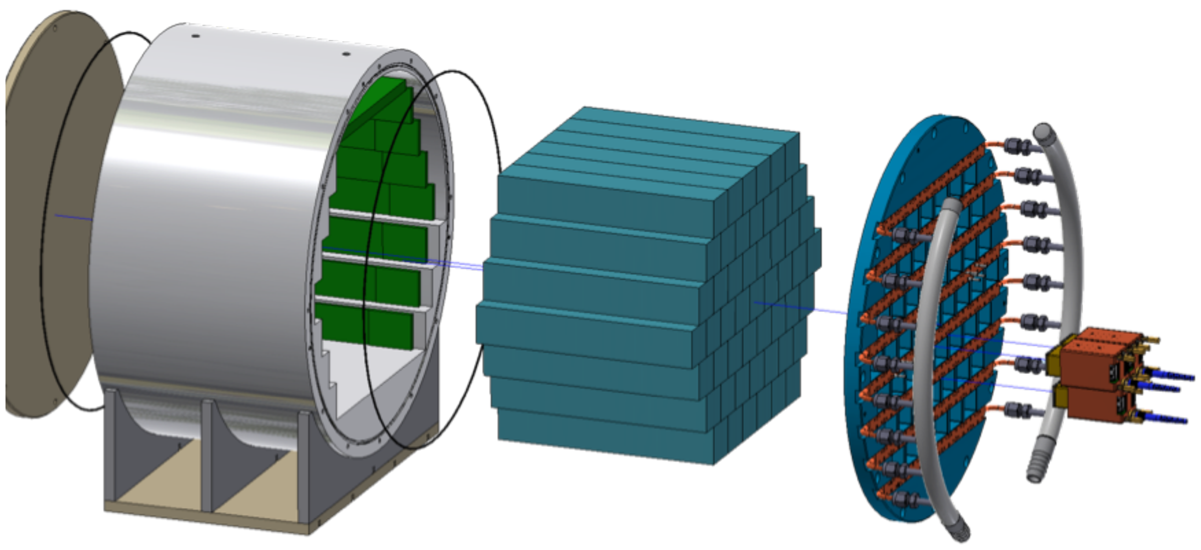




- Al target:
  - SES : 3 x10^{-15} (Phase I)
  - SES : 2 x10^{-15} (Phase II)
- Phase I is now under construction
- Directly measure the muon beam with prototypes of Phase-II detector.

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

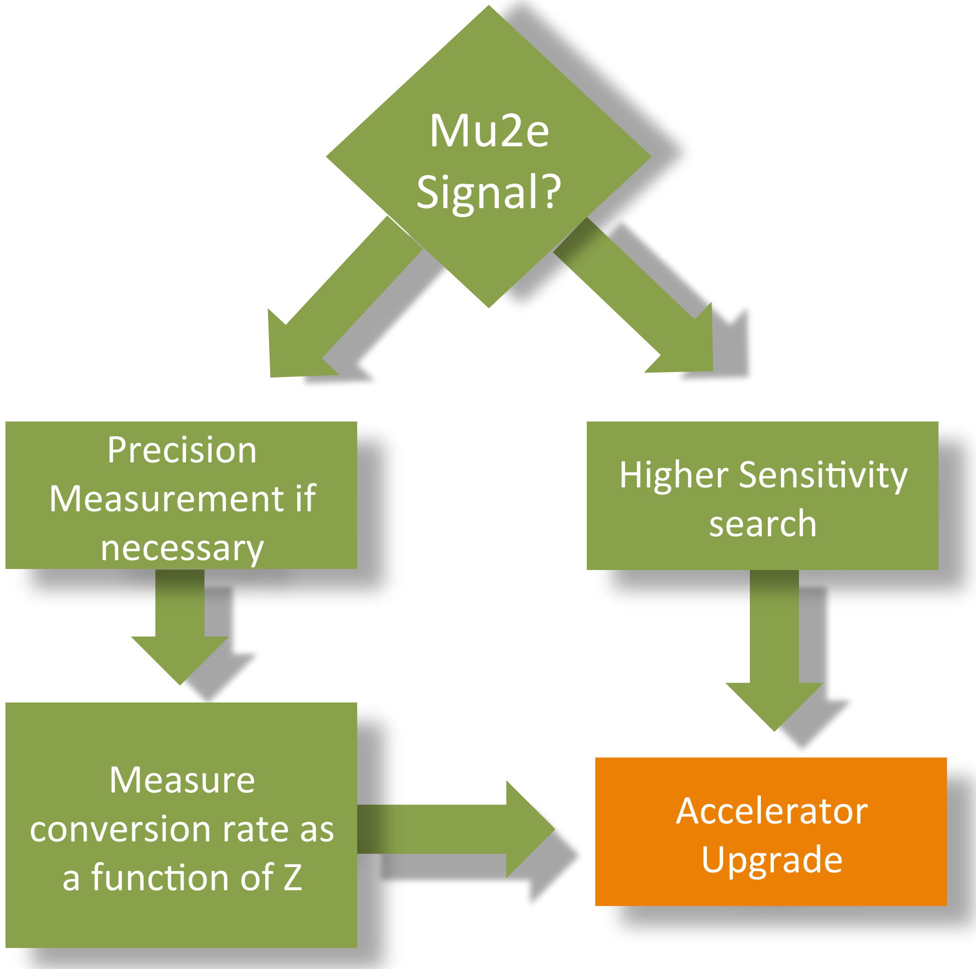
Calorimeter TB



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