A Search for New Physics in the Lepton Sector: Charged Lepton Flavor Violation and the Mu2e Experiment

Mete Yucel on behalf of the Mu2e Collaboration

FPCP 2022

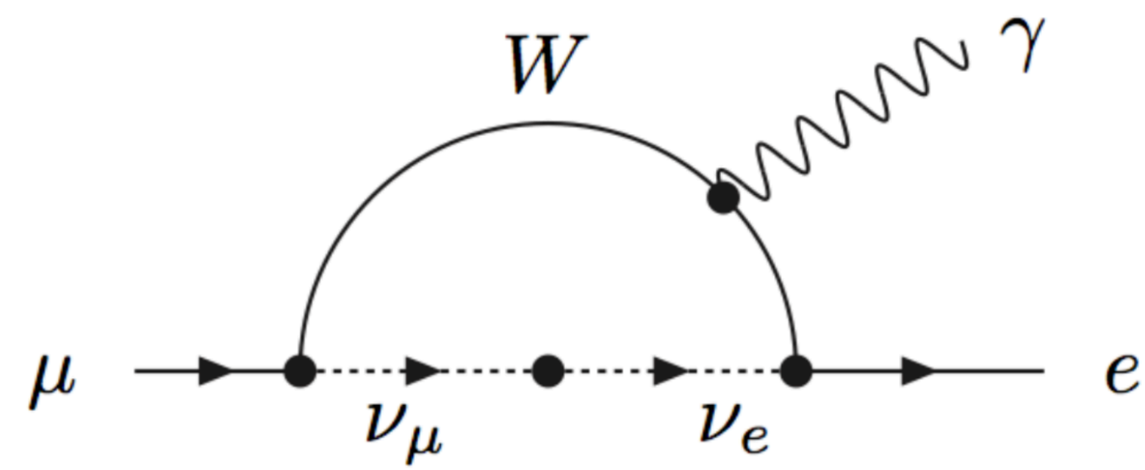
5/25/2022

Motivation - What is CLFV ?

CLFV (Charged Lepton Flavor Violation)

- Quarks mix, neutrinos mix, why don't we observe charged leptons mixing?
- Charged lepton flavor is not conserved.
  - As neutrino masses indicate.
- Let's look at SM process; $\mu^{\pm} \rightarrow e^{\pm} + \gamma$

  Let's look at BR result for this process



$$\mathscr{B}(\mu \rightarrow e\gamma) \sim \mathcal{O}\ 10^{-54}$$

Heavily suppressed in SM, perfect for searching for new physics !!!

- Searching for CLFV in the muon sector;

Experiment	Institute	Process
MEG II	PSI	$\mu^{\pm} \rightarrow e^{\pm} + \gamma$
Mu2e	FNAL	$\mu^{-} + N \rightarrow e^{-} + N$
COMET	JPARC	$\mu^{-} + N \rightarrow e^{-} + N$
Mu3e	PSI	$\mu^{\pm} \rightarrow e^{\pm} + e^{+} + e^{-}$

Mu2e focuses on the **neutrino-less conversion of the muon** in the presence of **Al nucleus**.

Motivation - What mass scale(Λ) Mu2e probes ?

$$\mathscr{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{e}\gamma^\mu e)$$

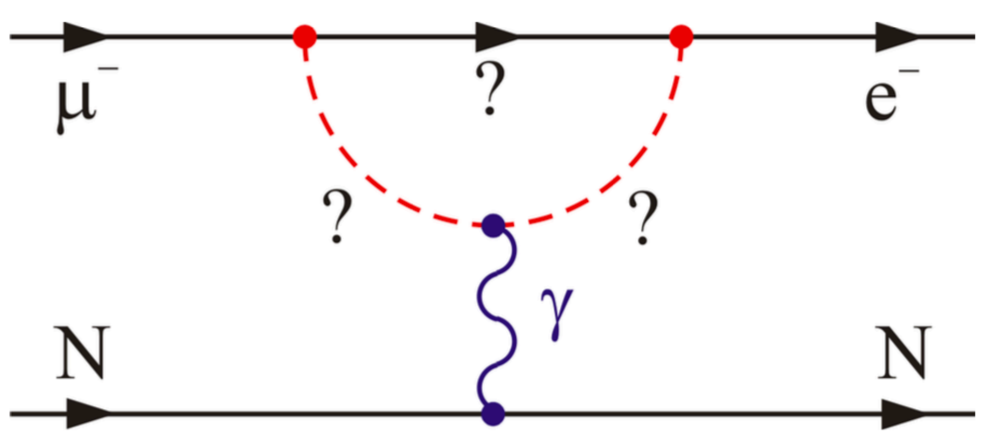
A. De Gouvea and P. Vogel; arXiv:1303.4097

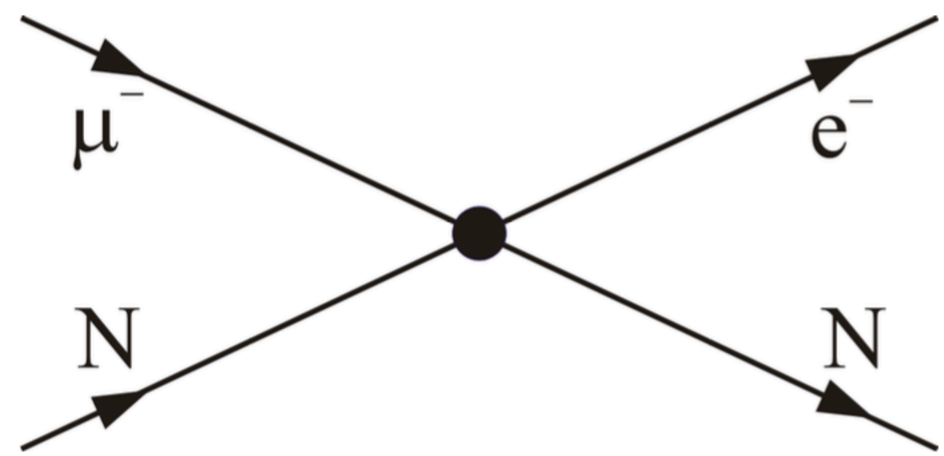
Lower κ is sensitive to the **loop** contributions to the $\mathscr{L}_{CLFV}$

Higher κ is sensitive to the **contact term** of the $\mathscr{L}_{CLFV}$

$\kappa = 0$

$\kappa = \infty$





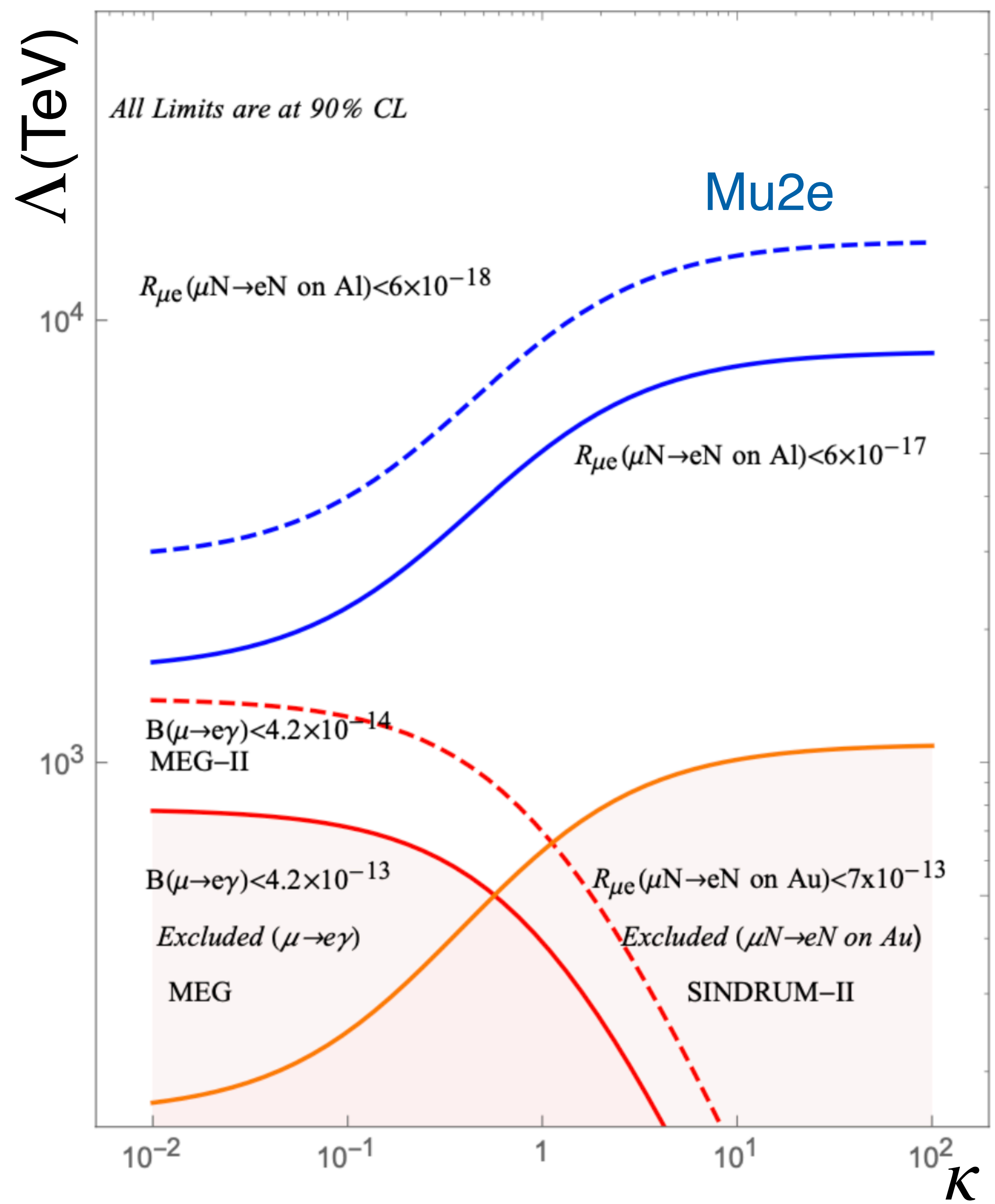
Supersymmetry & Heavy neutrinos
$\mu \rightarrow e\gamma$ **contribution**

Leptoquarks, heavy Z **...**
No contribution from $\mu \rightarrow e\gamma$

Motivation - Why is Mu2e unique?

- Mu2e probes Λ(mass scale) up to 10^4 TeV

- Advantage over collider experiments on probing rare process;
  - Free of SM backgrounds
  - Intense muon beams for high statistics.
  - High sensitivity to couplings.



A. De Gouvea and P. Vogel; arXiv:1303.4097

Mu2e signal

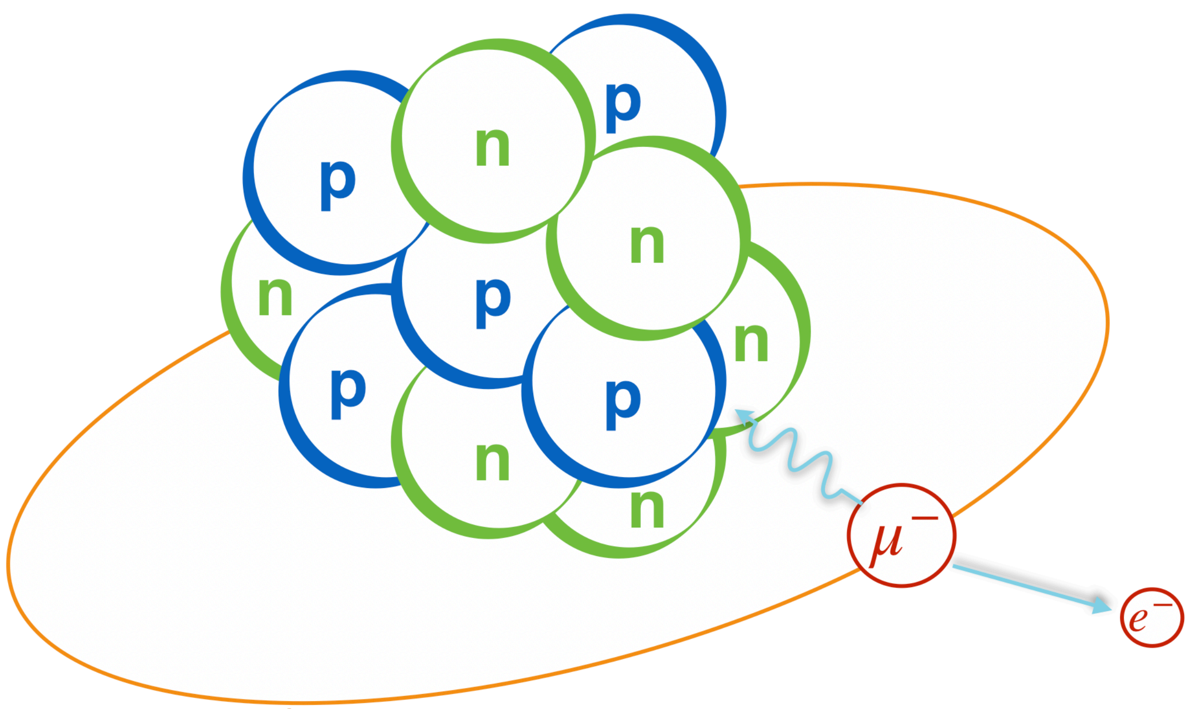
- Physics signal properties;
  - Coherent electron conversion
  - Little energy lost to
    - μ atomic binding energy $E_b = 0.48$ MeV
    - Nuclear recoil $E_R = 0.21$ MeV
  - **No neutrinos** are produced
  - **Monoenergetic** e^- is **104.97 MeV**

Coherent electron conversion with Al

$$\mu^- + {}^{27}Al \rightarrow e^- + {}^{27}Al$$

$$E_{e^-} = M_{\mu^-} - E_b - E_{recoil} = 104.97 \text{ MeV}$$

Aluminum nuclei



Muonic Al lifetime = 864 ns

Conversion rate

$$R_{\mu e} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow All\ captures)}$$

Mu2e goal = 3×10^{-17} SES

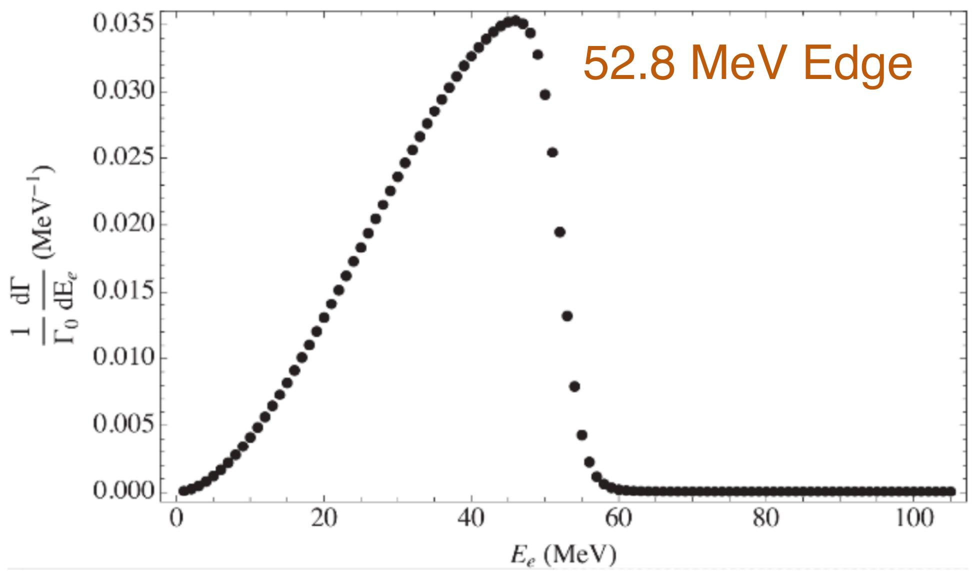
$\times 10^4$ improvement over SINDRUM-II

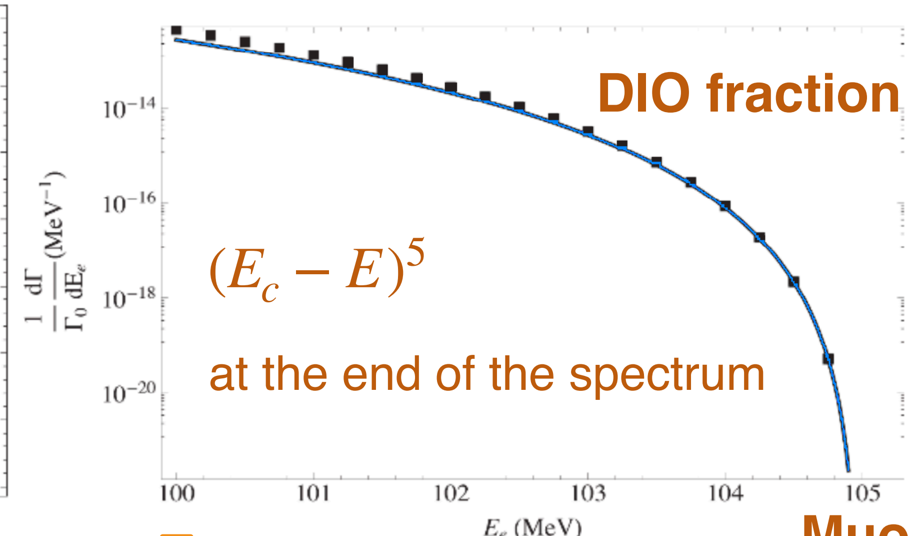
Backgrounds - DIO

- Decay In Orbit(DIO)

Michel spectrum (μ decay in orbit)

A. Czarnecki et. al; arXiv: 1106.4756v2





DIO fraction is 39% of decays

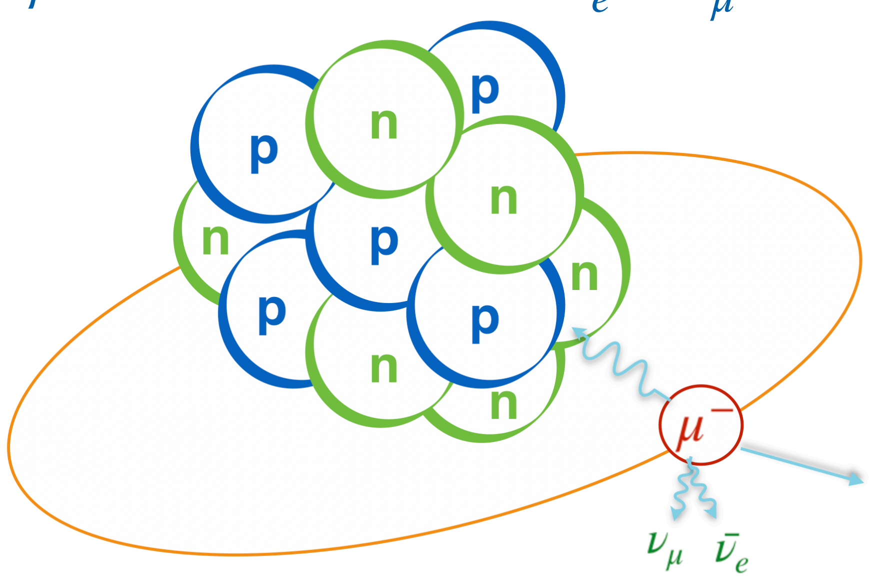
$(E_c - E)^5$

at the end of the spectrum

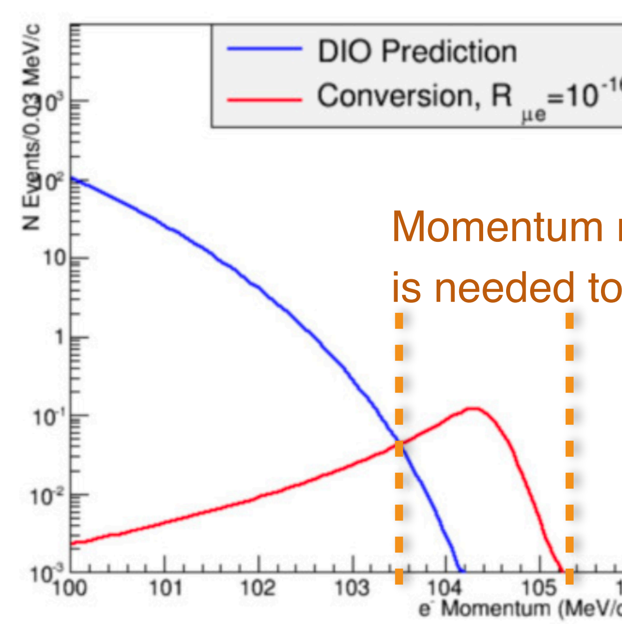
Muon mass 105.7 MeV

Plot conversion e^- on top

$$\mu^- + {}^{27}Al \rightarrow + e^- + \bar{\nu}_e + \nu_\mu + {}^{27}Al$$



After Reco Acceptance+ ΔE+Resolution



Momentum res. < **180 keV/c** is needed to make the separation

Design principles

How to get 10^4 improvement over SINDRUM II & SES 3×10^{-17}

1. High intensity pulsed muon beam.
   - High statistics.
   - Introduces beam related backgrounds !!!
2. High resolution on the momentum
   - Separation of 105 MeV/c conversion e^- from DIO e^- tail.
   - Low mass straw drift detector with 180 keV/c resolution for 105 MeV/c e^-.
   - Couple with EM calorimeter to complement tracker.
3. Background suppression of <1 event for the experiment.
   - Blind to low momentum particles.
   - 10^{-10} extinction factor for out-of-time protons.
   - Event window separation with pulsed muon beam.
   - Cosmic ray veto.

Beam related bg;
- π/μ decay in flight
- Radiative pion capture
- Antiproton annihilation

Cosmics;
- 1 conversion like e^- per day.
  - μ misidentified as e^-
  - Decay in flight
  - Interaction with detector material
- 99.99% veto efficiency is needed !

Live Event Window

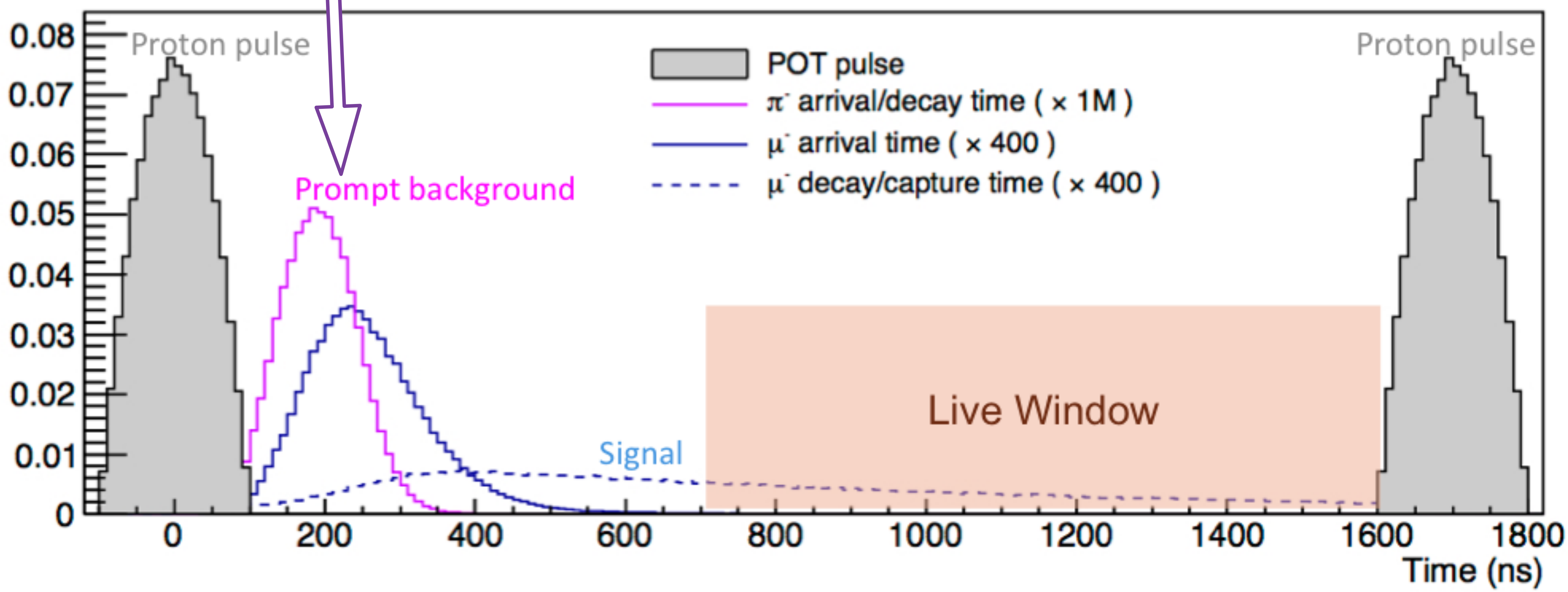
Background suppression: Radiative Pion Capture + other beam related bg

RPC : $\pi^- + N \rightarrow \gamma + N'$

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

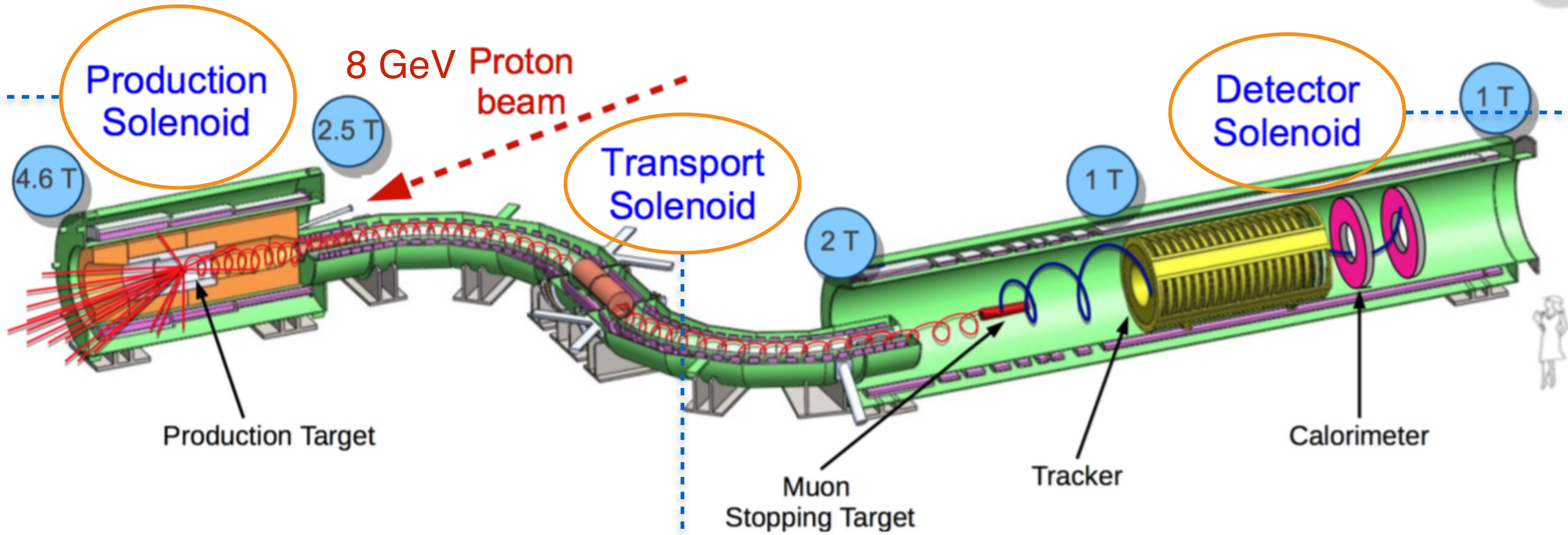
e^- with enough momentum can fake conversion events

- 8 GeV pulsed proton beam @ 1695 ns intervals.
- We wait 700 ns before taking C.E data to avoid most of the **prompt** background
  - Muonic Al lifetime = 864 ns.
- Out of time protons/ beam < 10^{-10}



Solenoids

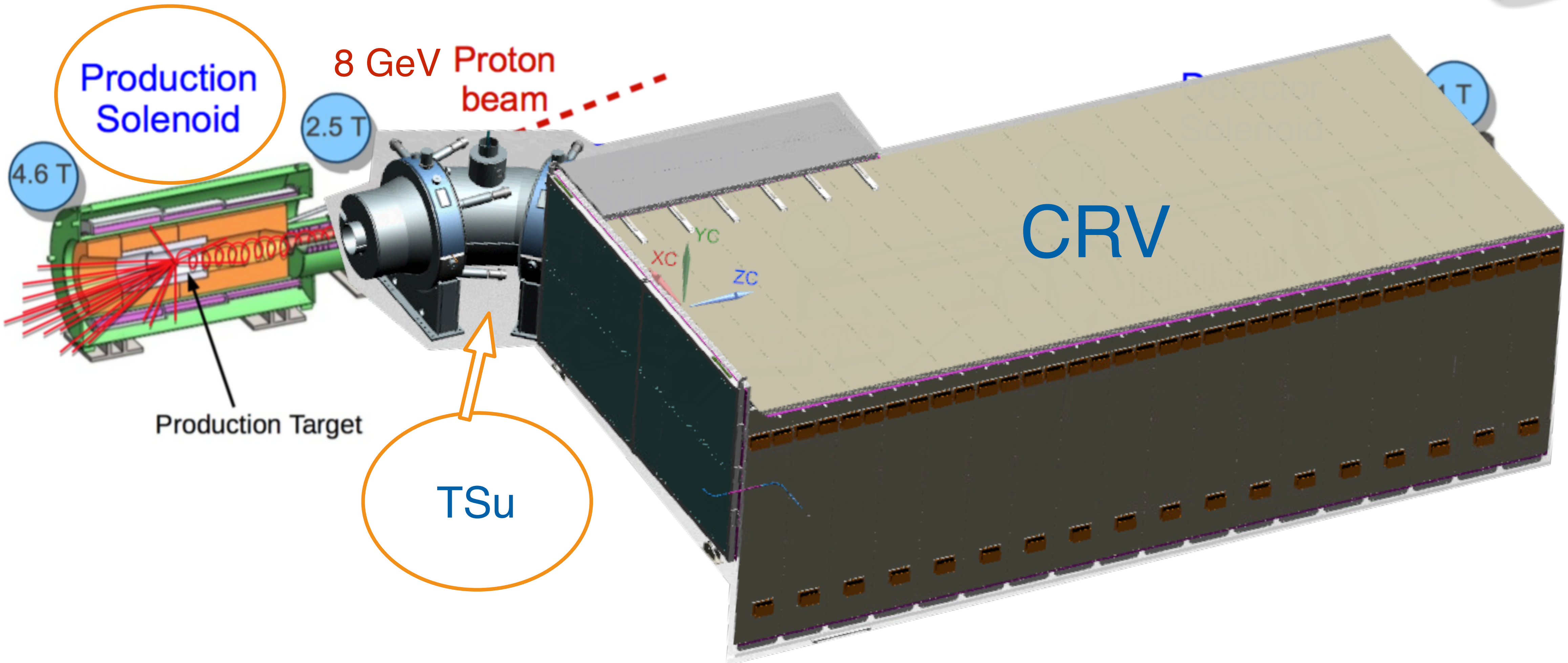
NbTi Superconducting Magnets



- Direct low momentum pions/muons to transport solenoid.
- S-shaped geometry with collimators select low momentum and negatively charged particles.
- Houses muon stopping target, tracker & calorimeter.

Solenoids + Cosmic Ray Veto(CRV) + Shielding

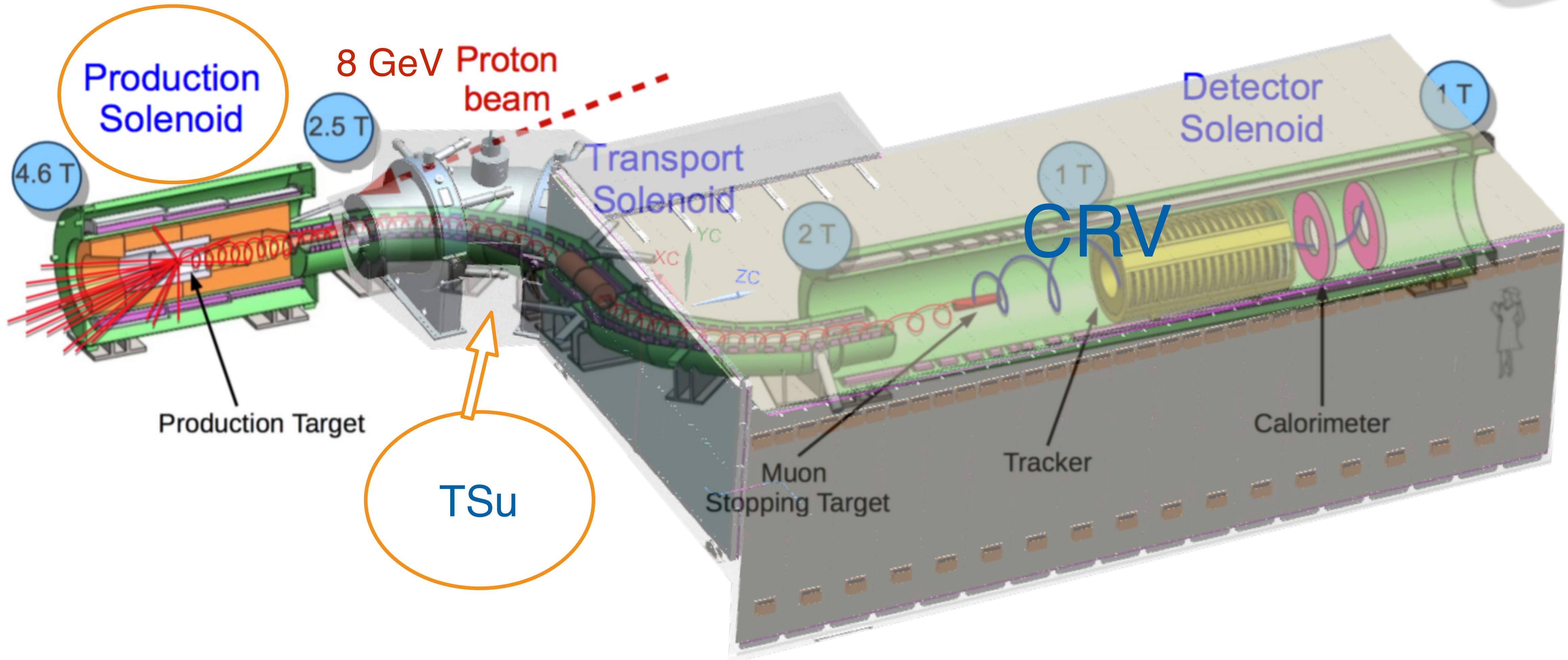
NbTi Superconducting Magnets



Cosmic Ray Veto covers all of DS and some of TS

Solenoids + Cosmic Ray Veto(CRV) + Shielding

NbTi Superconducting Magnets



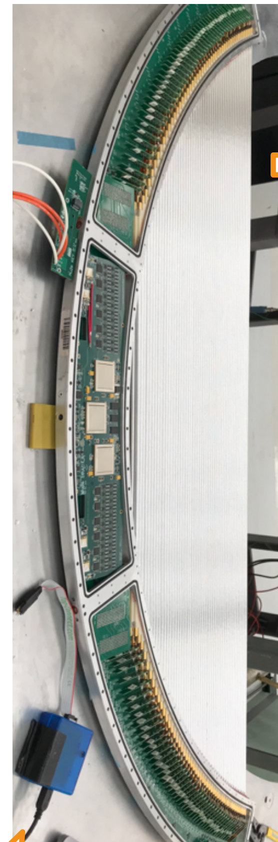
Cosmic Ray Veto covers all of DS and some of TS

Tracker

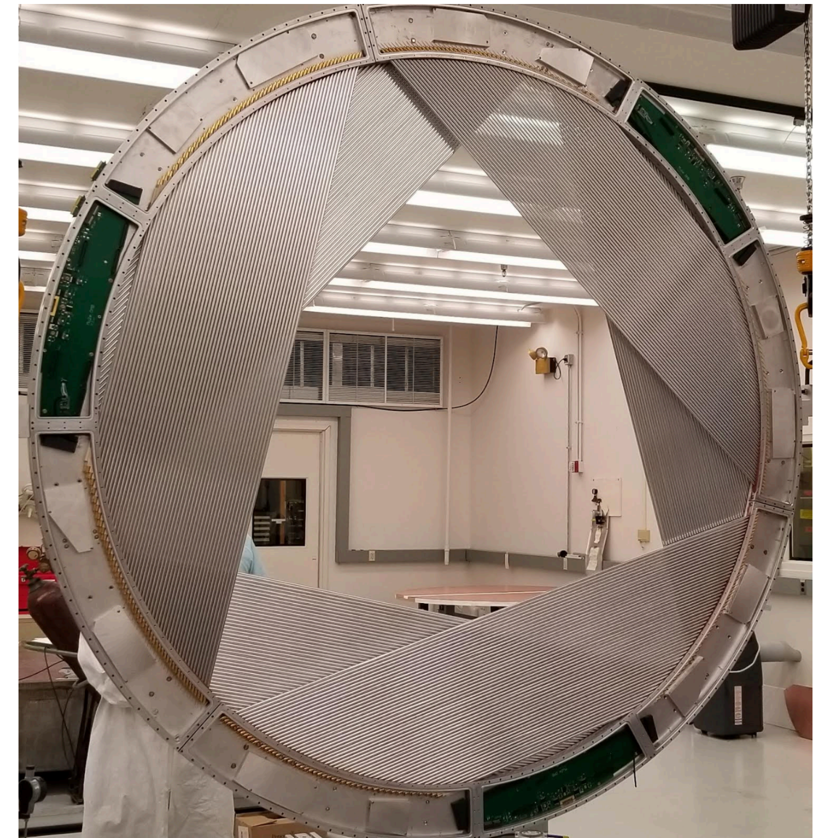
Background suppression: DIO

- Main detection element of Mu2e.
- Low mass tracker using straw drift tubes running ArCO2(80/20).
- 25 μm Tungsten wire as the anode.
- 21600 x 5 mm OD metalized 15 μm thick walled Mylar straws;
  - Inner coat provides cathode
  - Outer coat provides shielding and reduces leaks.
- Highly segmented -> 36 planes -> each made from 6 panels.
- Momentum resolution < 180 keV/c.

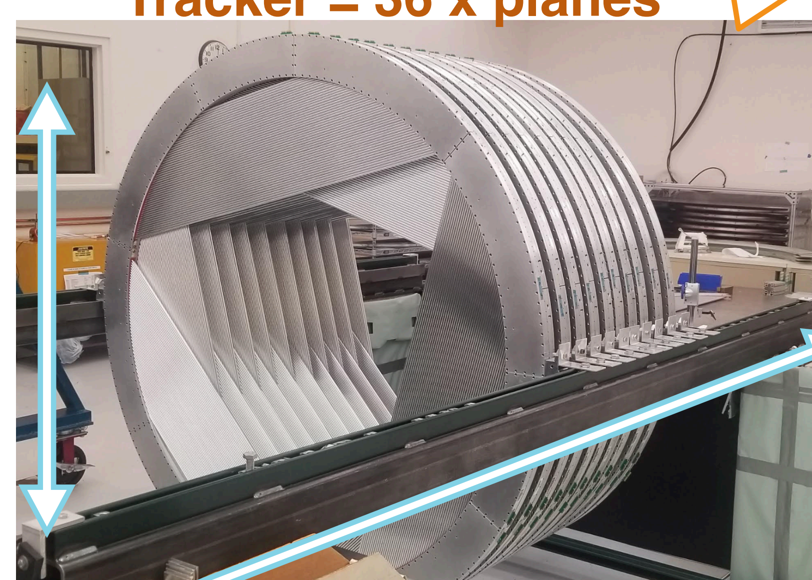
Tracker panel



Tracker plane



Tracker = 36 x planes

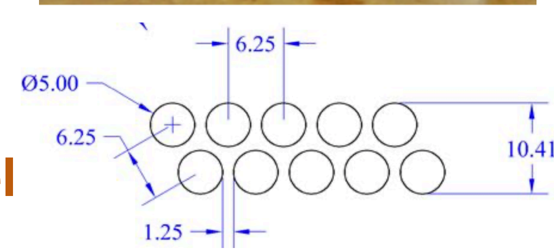


1.6m

3 m

21600 x straws

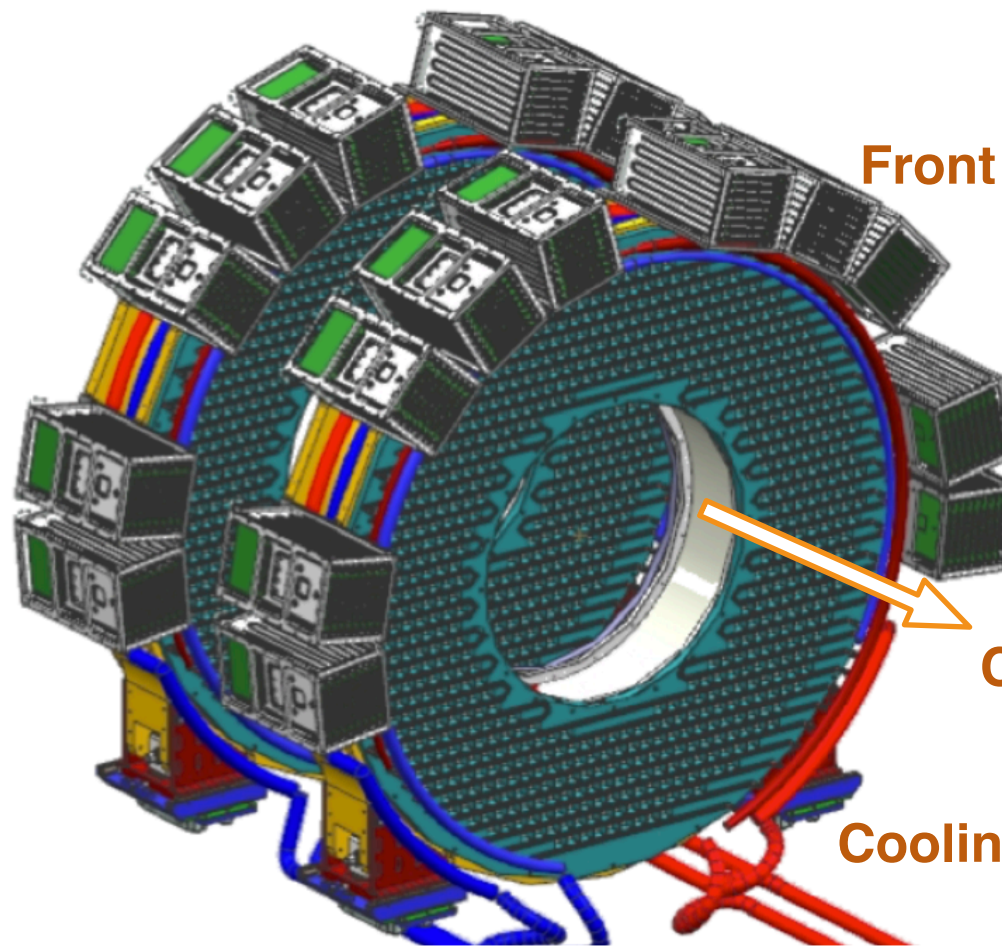
Double layered
96 per tracker panel



EM Calorimeter

- 1348 CsI crystals;
  - 3.4x3.4 cm surface area
  - 20 cm in length.
- Readout by SiPMs.
- Annular design like tracker with hole in the middle.
- Distance between two disks = 70 cm
  - half wavelength of electron’s path
- Provides
  - Seed to complement tracking.
  - 0.5 ns time resolution.
  - particle ID, 10% energy resolution.
  - Position, 1 cm spatial resolution.

2 disk annular design with hole

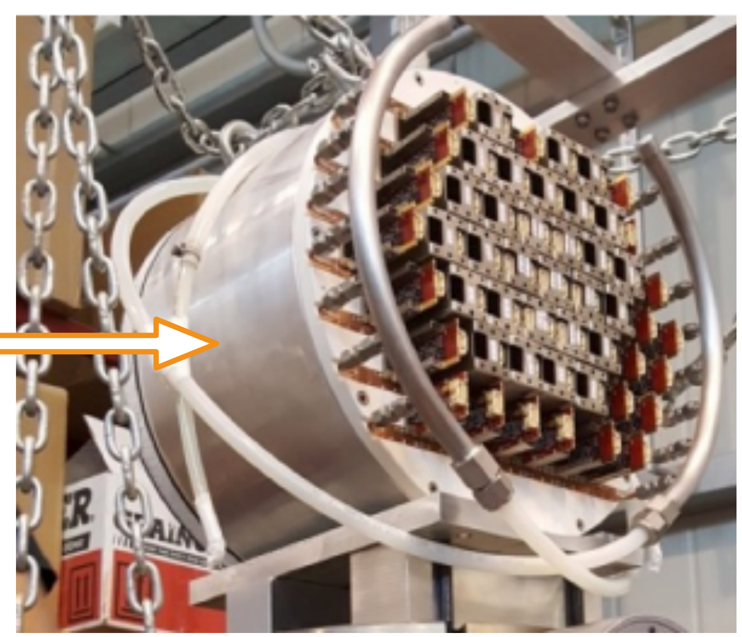


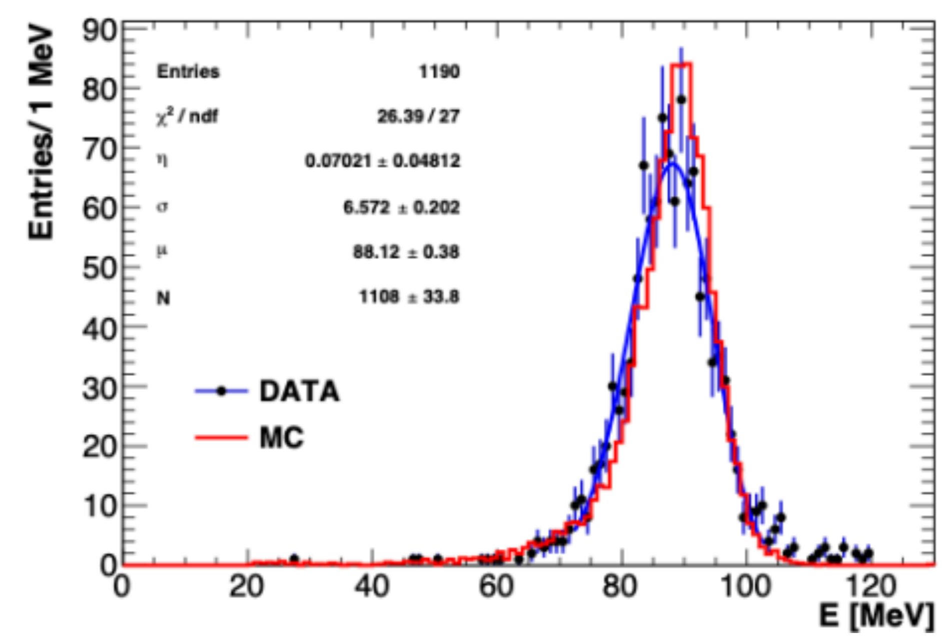
Front end electronics

CsI crystals

Cooling

- **Prototype using 51 CsI crystals & 102 SiPMs**
- **5.4% at 100 MeV energy resolution**
- **Timing resolution < 150 ps**

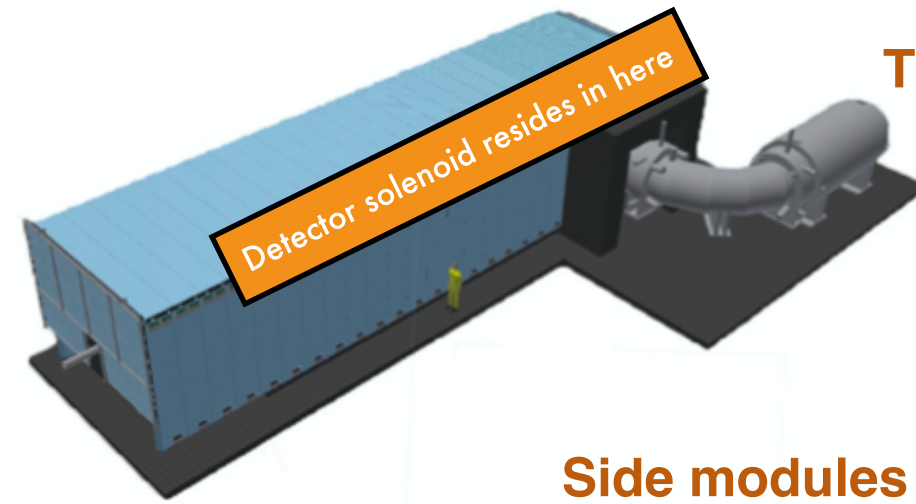




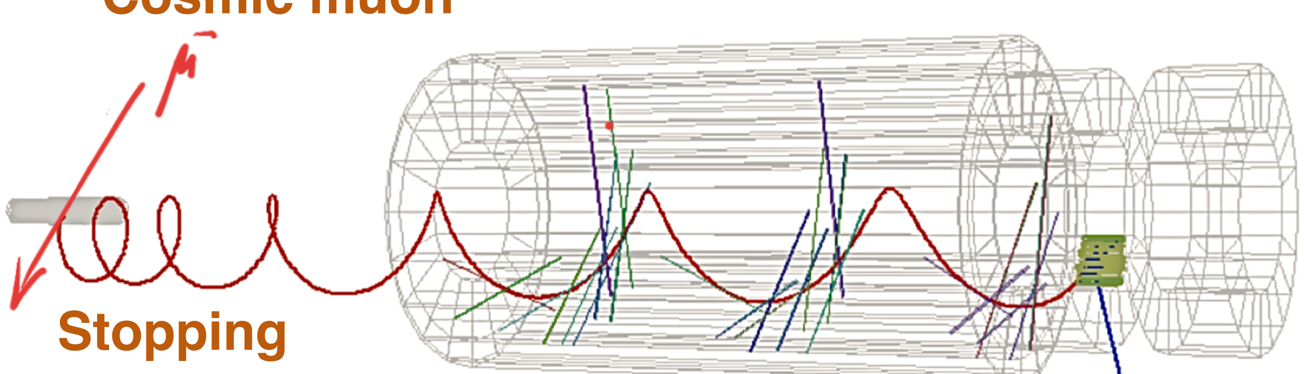
Cosmic Ray Veto

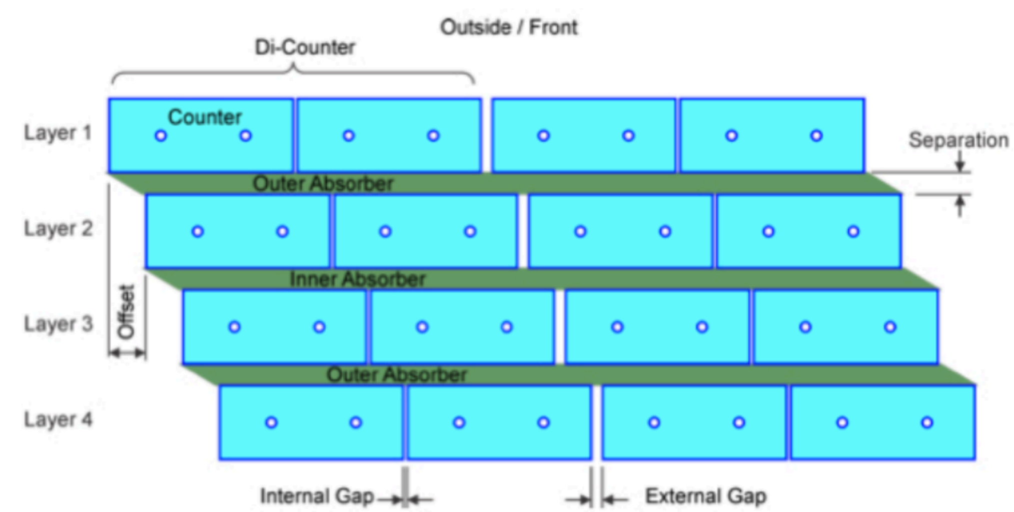
Background suppression: Cosmics

- Unvetoed cosmic background ~= 1 bg event per day.
- Covers all DS and part of TS.
- 337 m^2 surface area.
- Polystyrene scintillators coated with TiO_2 sandwiched between Al absorbers.
- 4 overlapping layers of scintillators.
  - 3 layer coincidence veto
- Readout through WLS fibers & 2x2 mm^2 SiPMs on both ends.



Side modules

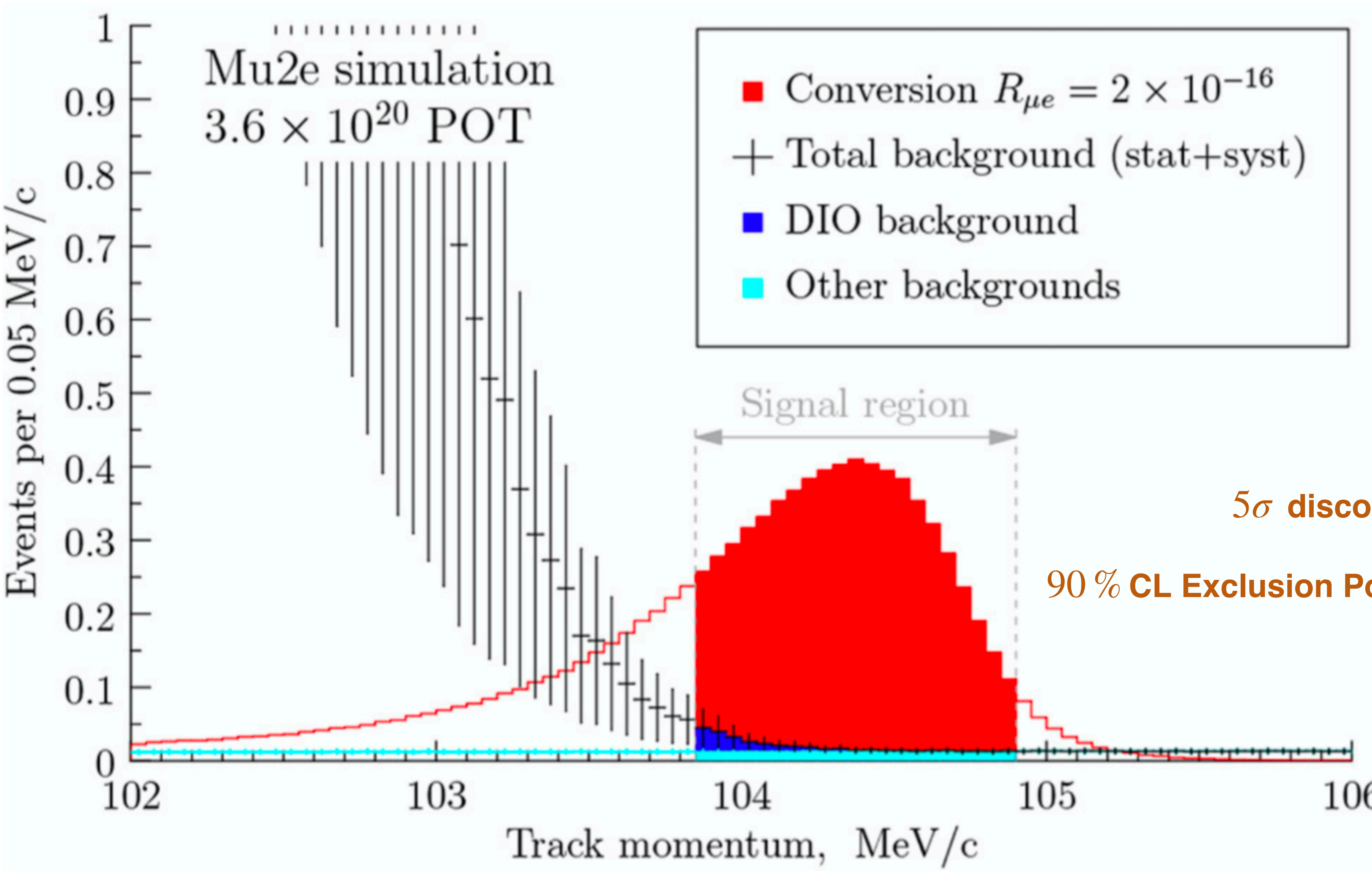




Background summary

Category	Process	Estimated yield(events)
Intrinsic	Muon DIO	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
	RMC	$0.000^{+0.004}_{-0.000}$
Beam related prompt	RPC	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
	Muon DIF	< 0.003
	Pion DIF	$0.001 \pm < 0.001$
	Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Other	Antiproton induced	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
	Cosmic ray induced	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
	TOTAL	**0.41** $\pm 0.13(\text{stat+syst})$

Sensitivity



5σ **discovery** : $R_{\mu e} \geq 2 \times 10^{-16}$

$90\,\%$ **CL Exclusion Power** : $R_{\mu e} \geq 8 \times 10^{-17}$

7 events are needed for 5σ

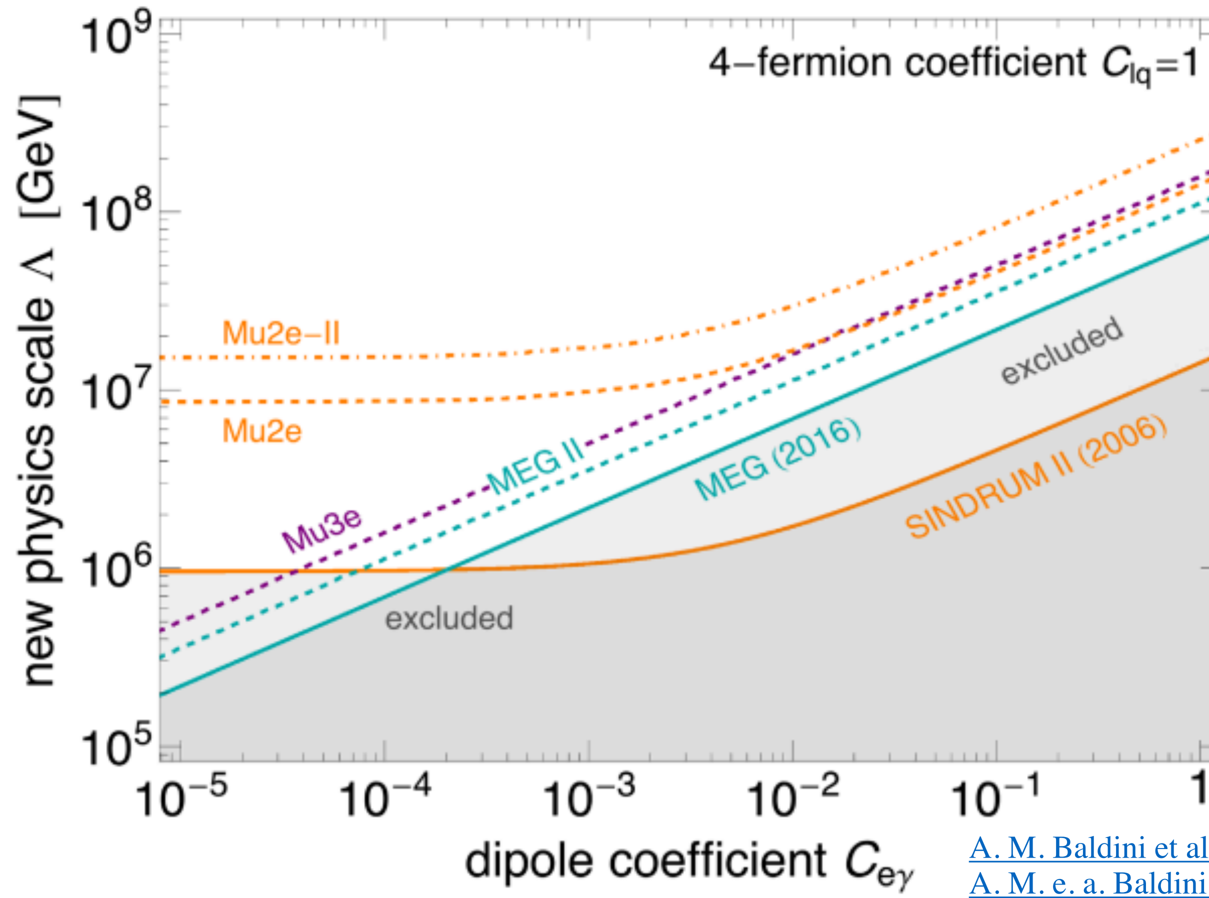
Mu2e-II with PIP-II beam line

Increasing Mu2e capability

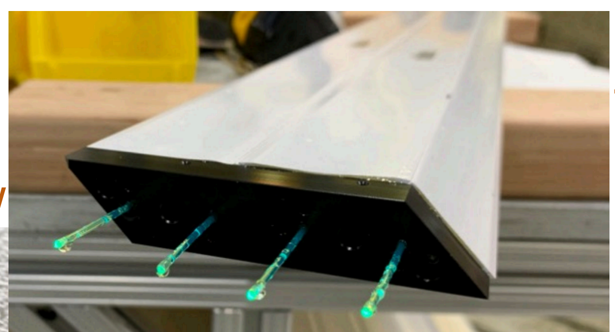
- Improve sensitivity.
- Probe higher mass scale.

Expanding upon Mu2e goals

- Change targets.
- Focus on excluding/including models.
- $\mu^- + N \rightarrow e^+ + N'$
- $\mu \rightarrow eX$

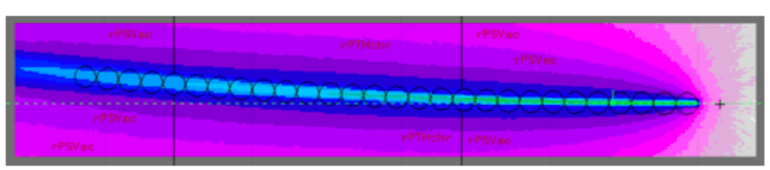


A. M. Baldini et al., [1605.05081]
A. M. e. a. Baldini, [1801.04688]
A. Blondel et al. , [1301.6113]



Triangular CRV scintillators

8 μm Tracker straw



Carbide production target

hep-ex > arXiv: 2203.07569

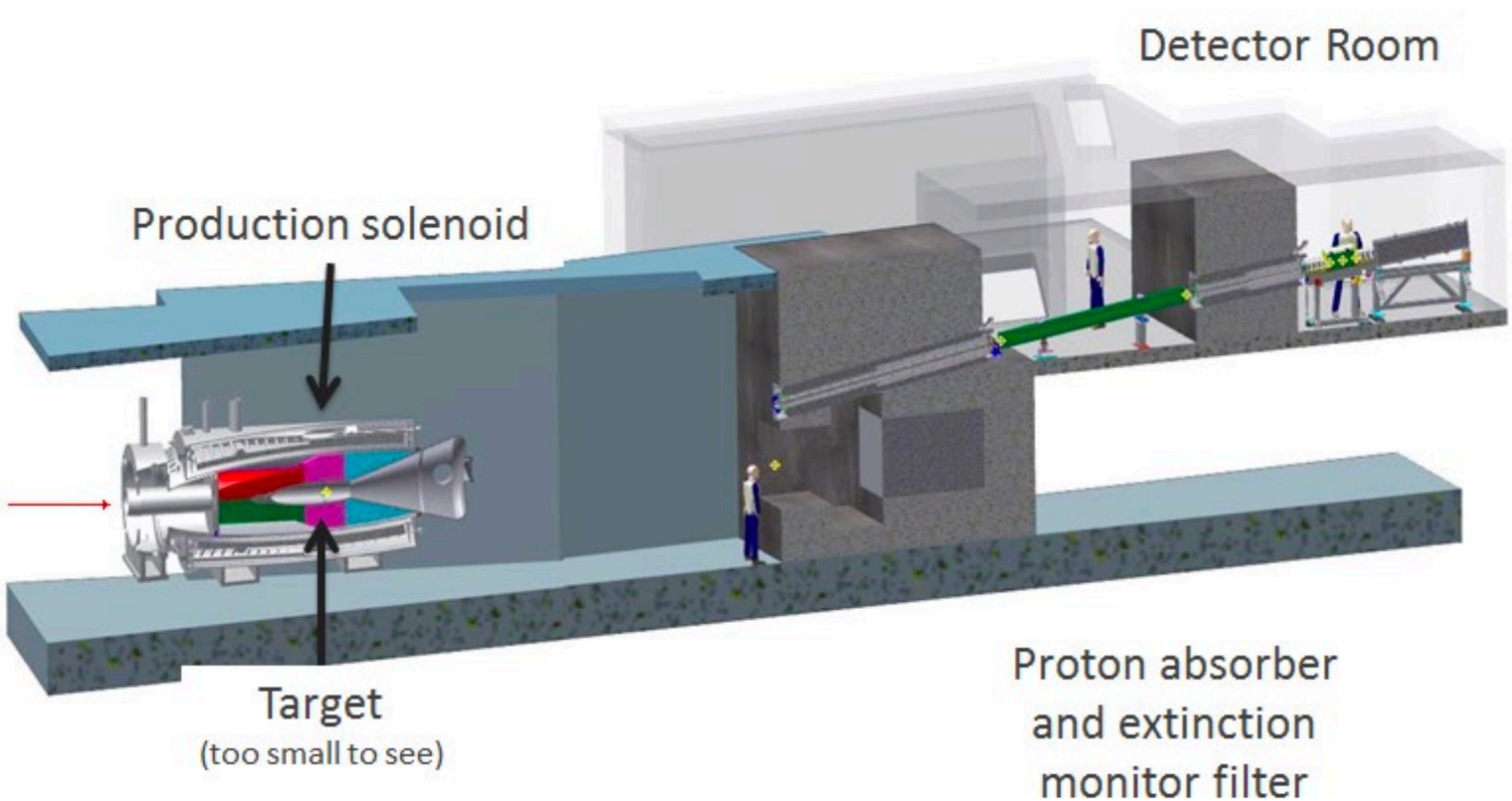
Parameter	Mu2e	Mu2e-II
Proton source	Slow extraction from DR	PIP-II Linac
Proton kinetic energy	8 GeV	0.8 GeV
Beam Power for expt.	8 kW	100 kW
Protons/s	6.25×10^{12}	7.8×10^{14}
Pulse Cycle Length	1.693 μs	1.693 μs
Proton rms emittance	2.7	0.25
Proton geometric emittance	0.29	0.16
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}
Stopped μ per cycle		1.2×10^5

Summary

- Mu2e will improve current limit on conversion rate by 10^4 @ SES $= 3 \times 10^{-17}$.
- Will probe mass scales up to 10^4 TeV.
- Current schedule;
  - Installation and commissioning starting in 2023.
  - Beam commissioning and physics data taking 2026.
  - $\times 1000$ improvement over current limit by 2027.
  - LBNF/PIP-II shutdown.
  - $\times 10000$ improvement over current limit by the end of the decade.
- Next 2 years will see a big effort on building and commissioning the detector.

BACKUP

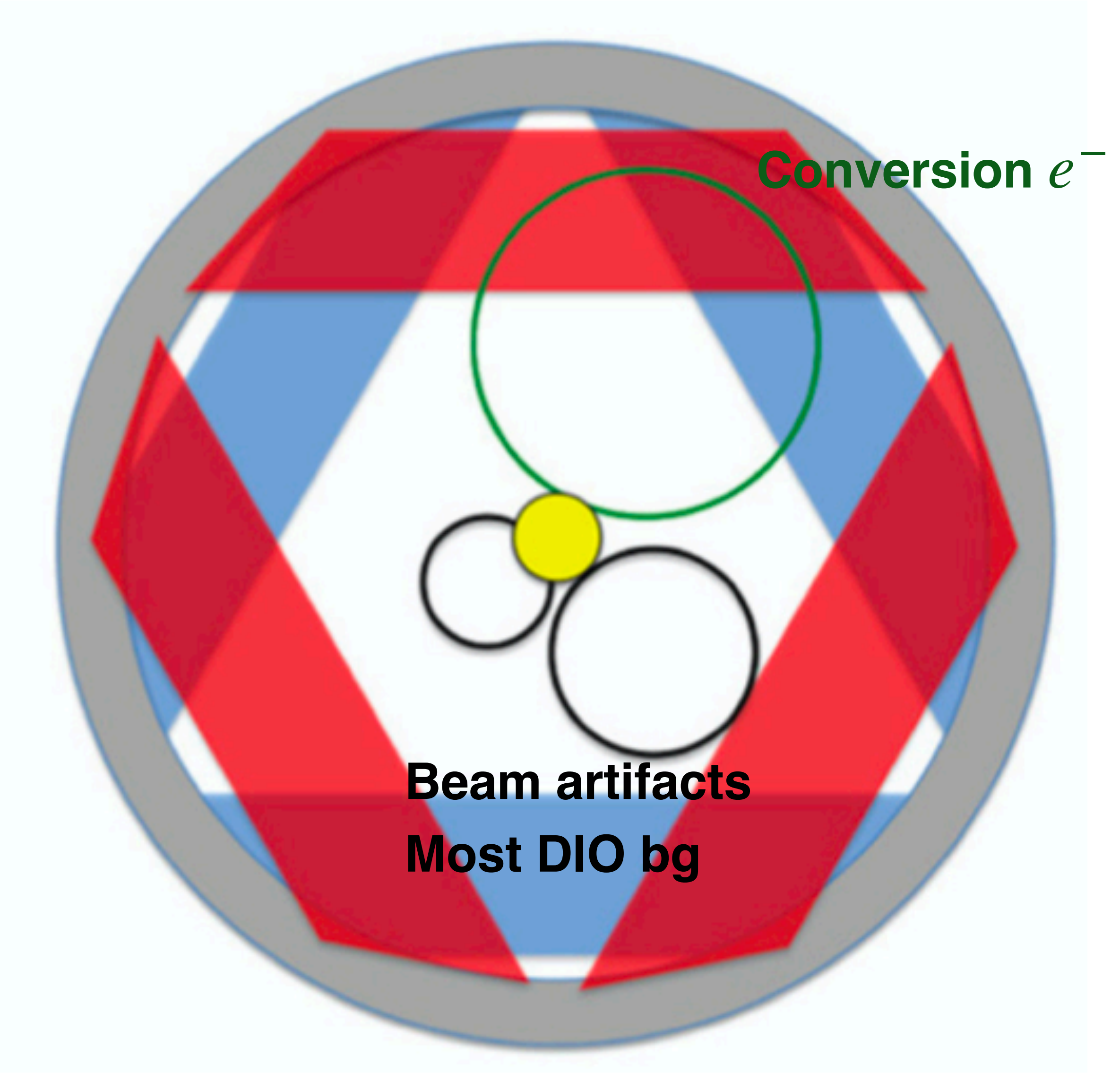
Extinction monitor



Mu2e Extinction monitor

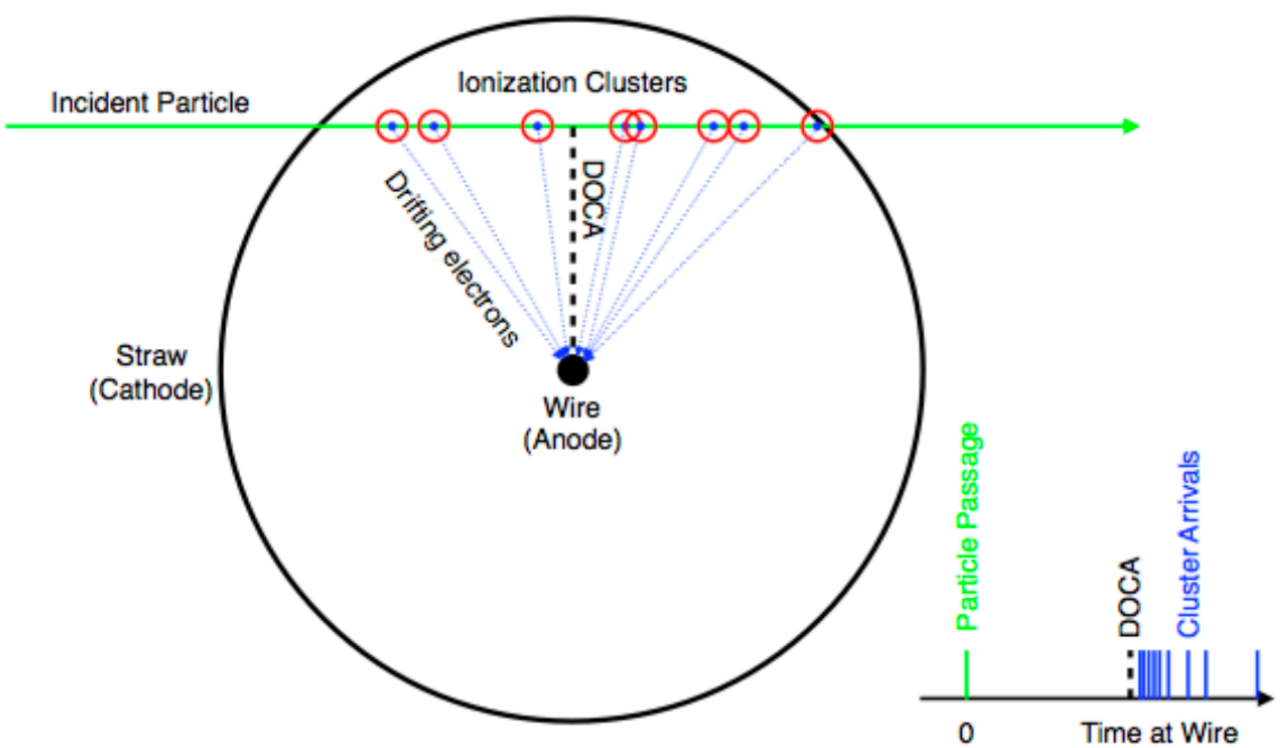
Tracker hole in the middle design

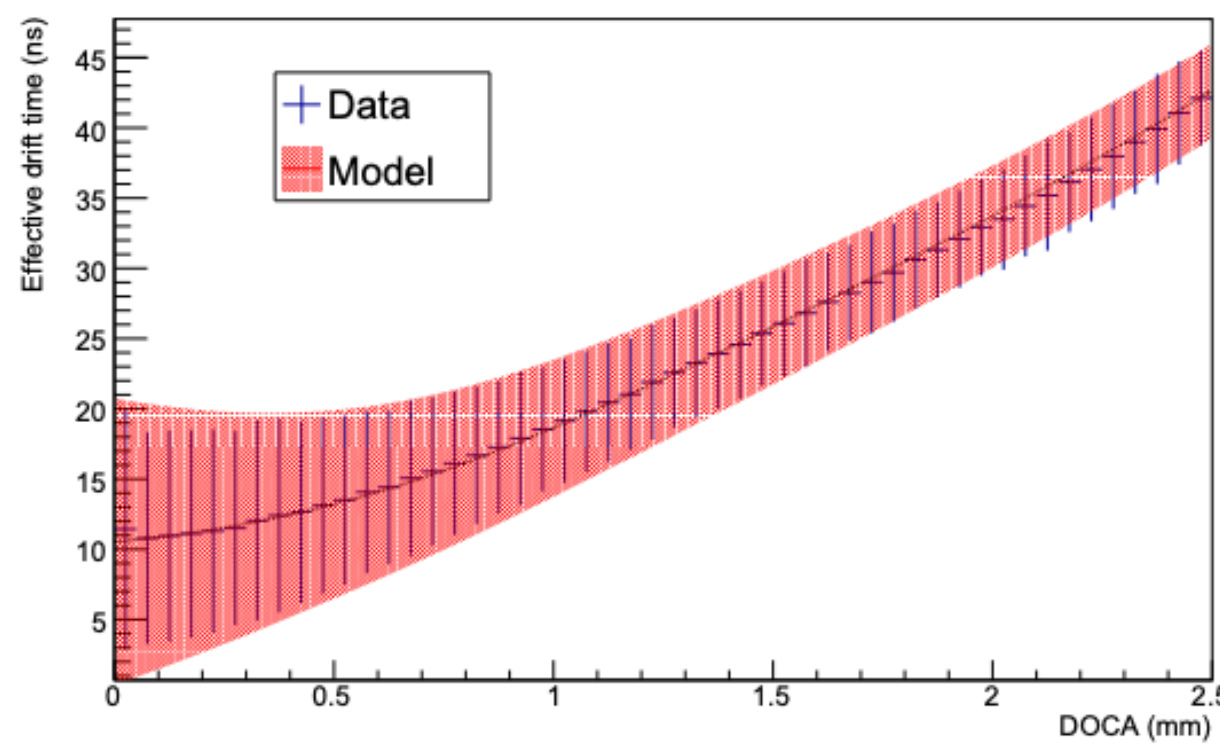
- Center(<400 mm) is empty to make the detector blind against most DIO electrons, beam artifacts.



Cosmic run with tracker panel

- Data was taken May 2020 with production tracker panel.
- DOCA(distance of closes approach) is determined to compute drift time.





Targets

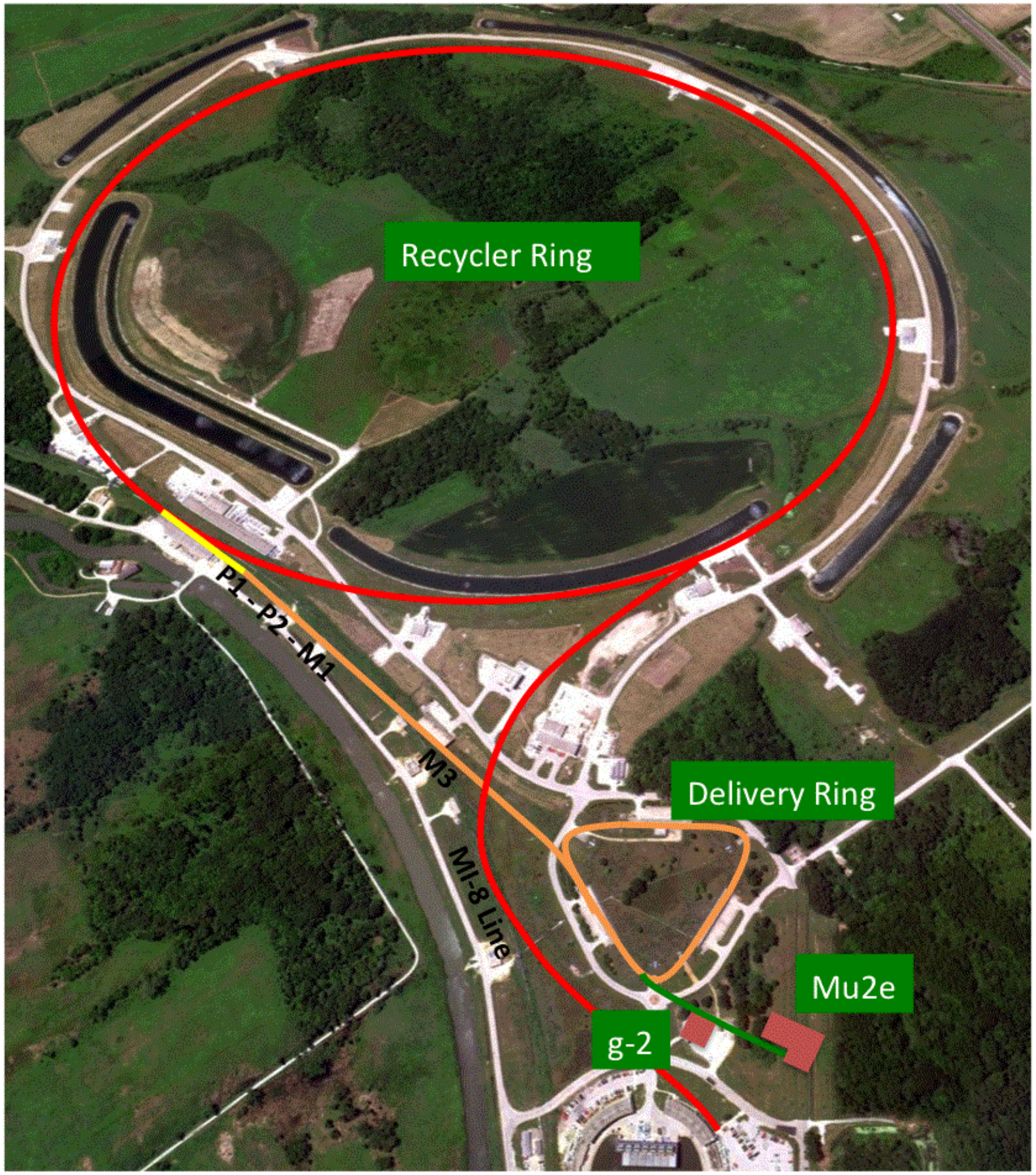
- Production target
  - Tungsten
  - Suspended on spokes
  - Minimize scattering & π absorption
  - 1400 msec beam cycles
  - 630 W power absorption
  - 2000 K temperature
  - Operate 1 year

- Stopping target
  - 37 high purity Al disks
  - Each 100 μm thick, 150 mm OD, 40 mm ID.
  - 740 mm in length.
  - Suspended with 76 μm diameter gold plated W wires.

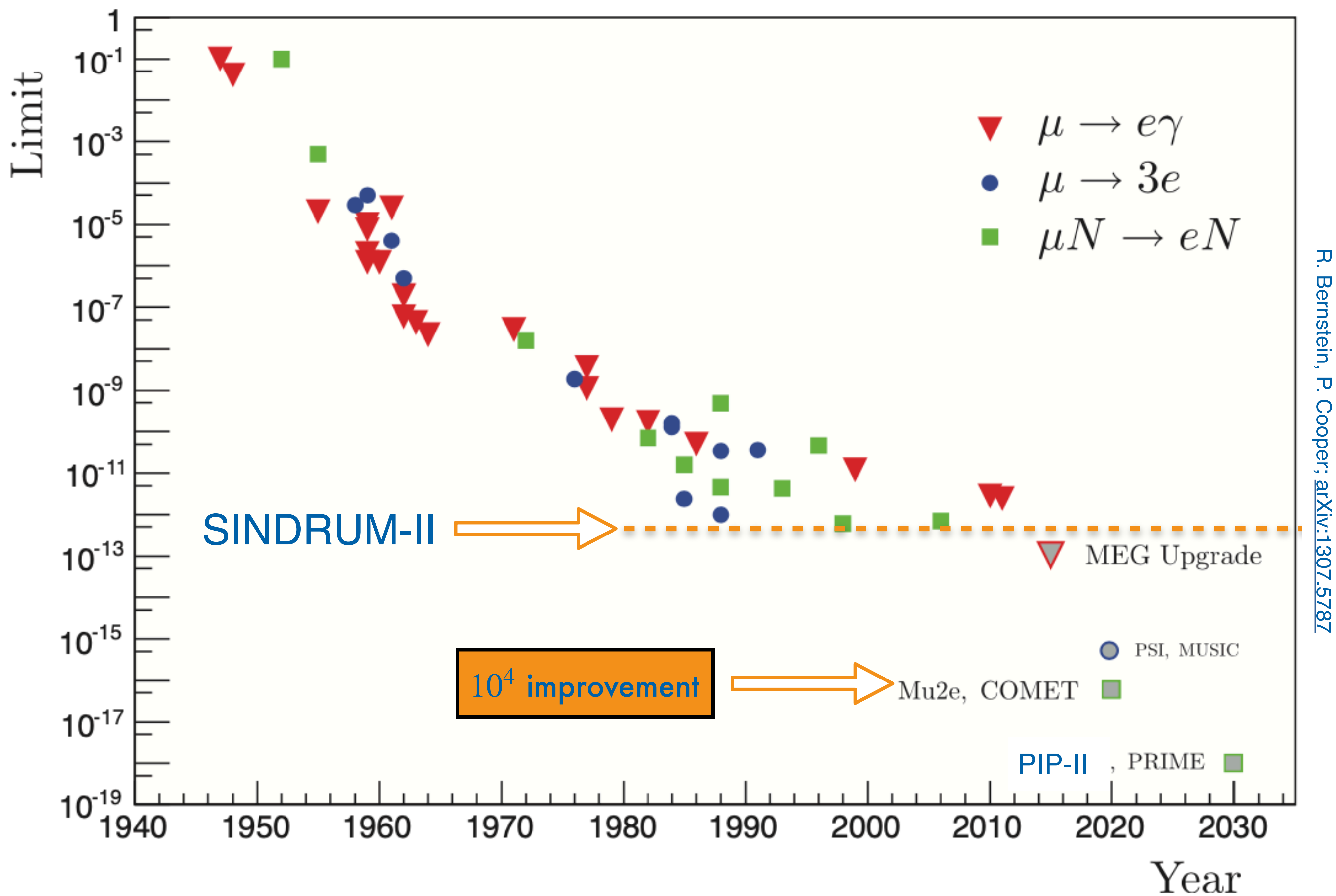
Fermilab

Beam delivery

- 8 GeV protons are transferred to DR(delivery ring) from recycler.
- 2.5 MHz bunches.
- Protons are extracted from DR and sent to Mu2e in 1695 ns intervals.
- $3.9\mathrm{x}10^{7}$ POT per bunch.
- $3.6\mathrm{x}10^{20}$ POT total



Muon searches history



CLFV processes sensitivity to BSM

★★★ = Discovery Sensitivity

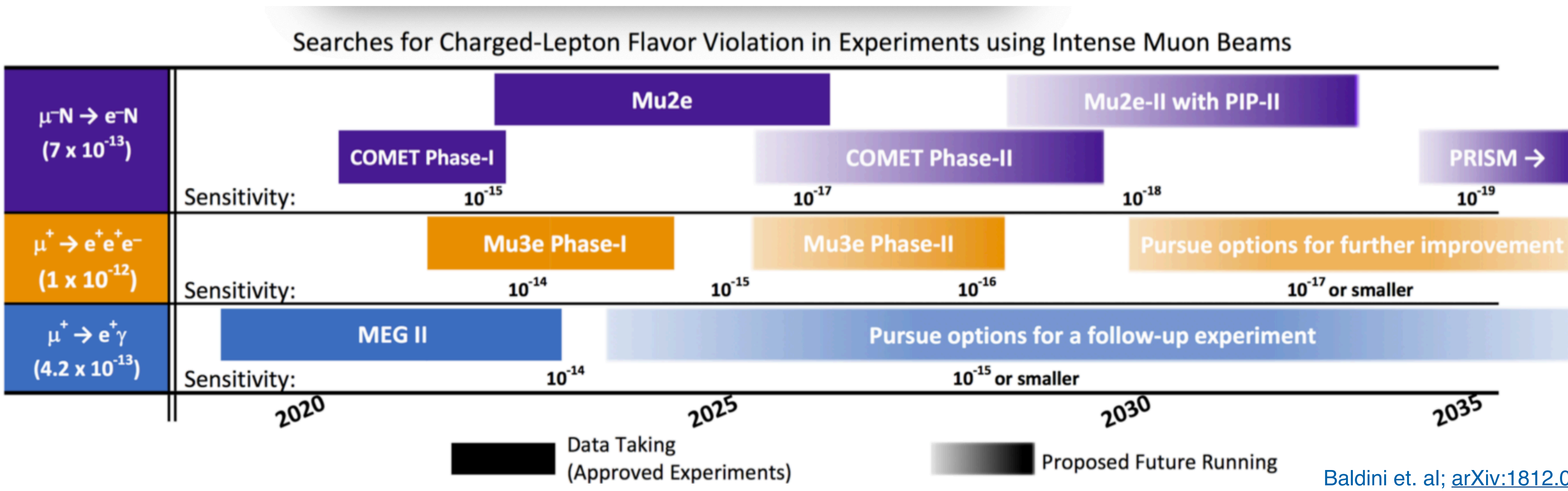
W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	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.

arXiv:0909.1333[hep-ph]

Looking forward in muon searches



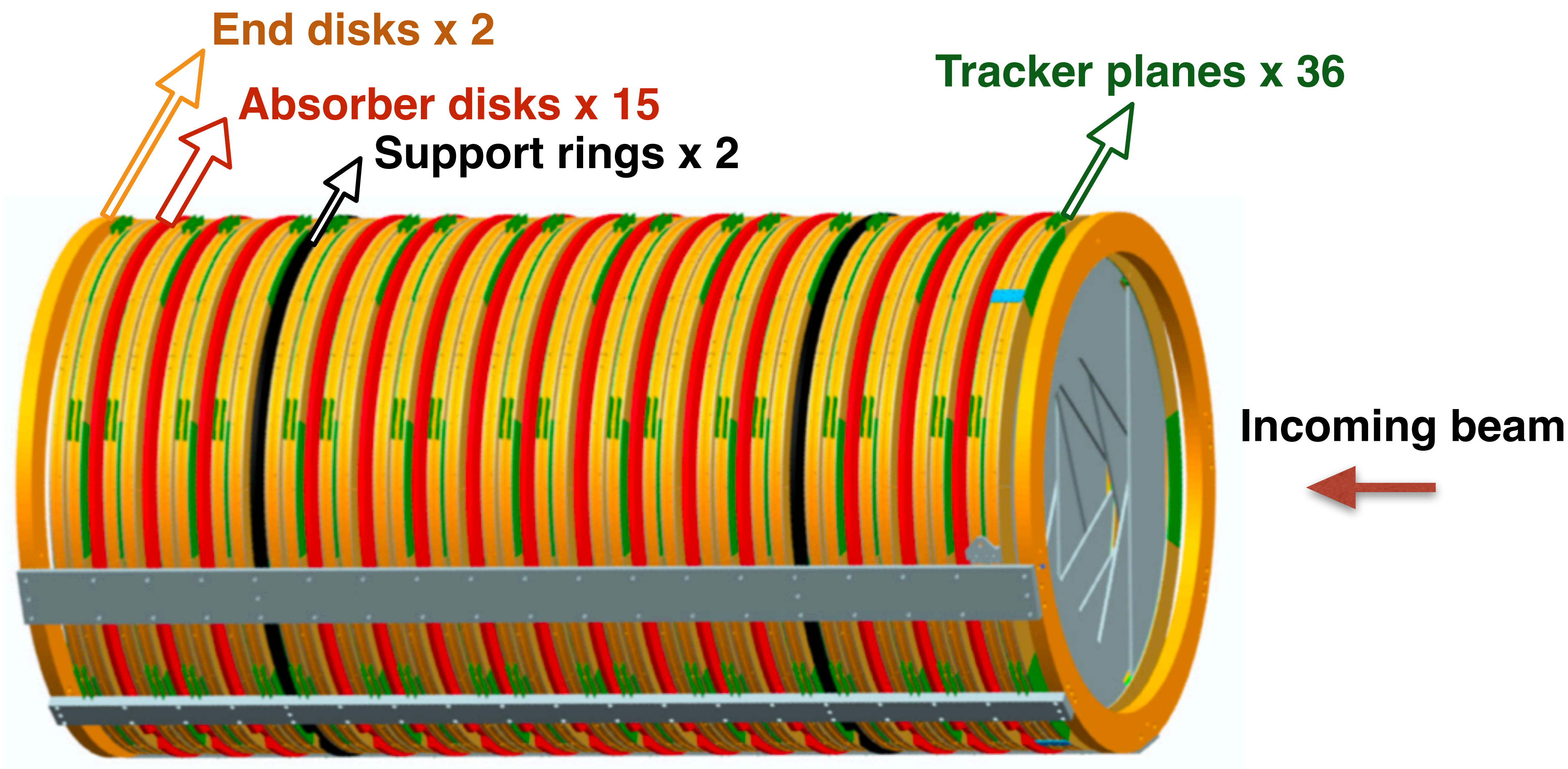
Baldini et. al; arXiv:1812.06540v1

CLFV experimental limits

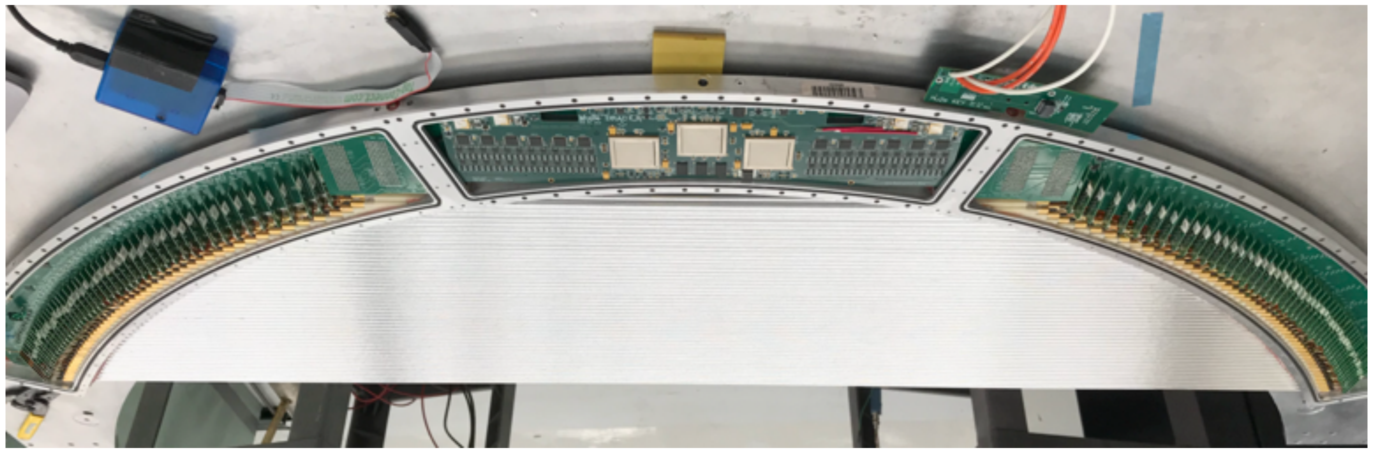
Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\mu^-\text{Ti} \to e^-\text{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\text{Pb} \to e^-\text{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\text{Au} \to e^-\text{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\text{Ti} \to e^+\text{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004
$J/\psi \to \tau\mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008
$B^0 \to \tau\mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008
$B \to K\mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006
$B \to K^*\mu e$ ‡	$< 5.1 \times 10^{-7}$	90%	BaBar	2006
$B^+ \to K^+\tau\mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012
$B^+ \to K^+\tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013
$\Upsilon(1s) \to \tau\mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017

L. Calibbi and G. Signorelli; arXiv:1709.00294v2

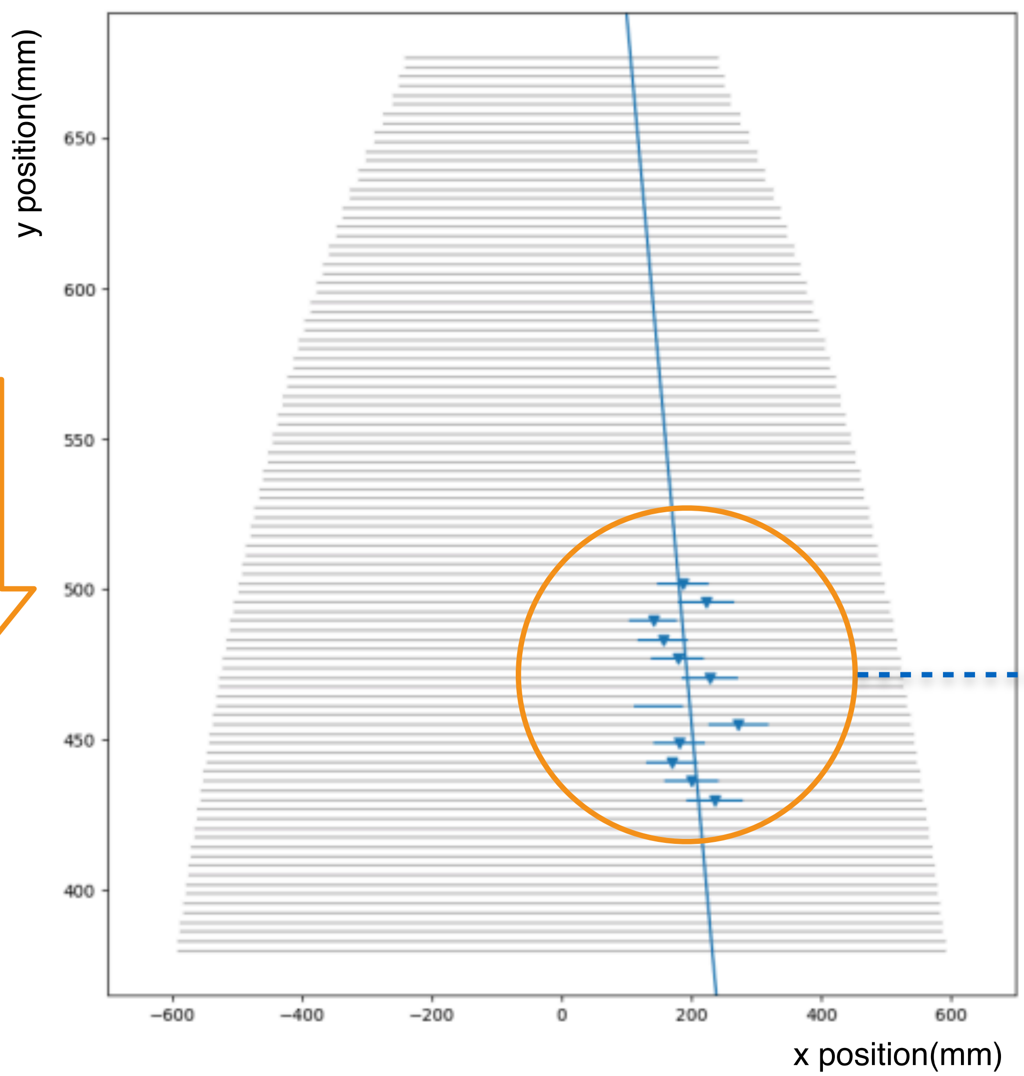
Tracker Frame



Cosmic track reconstruction



Short to long straws



Panel orientation