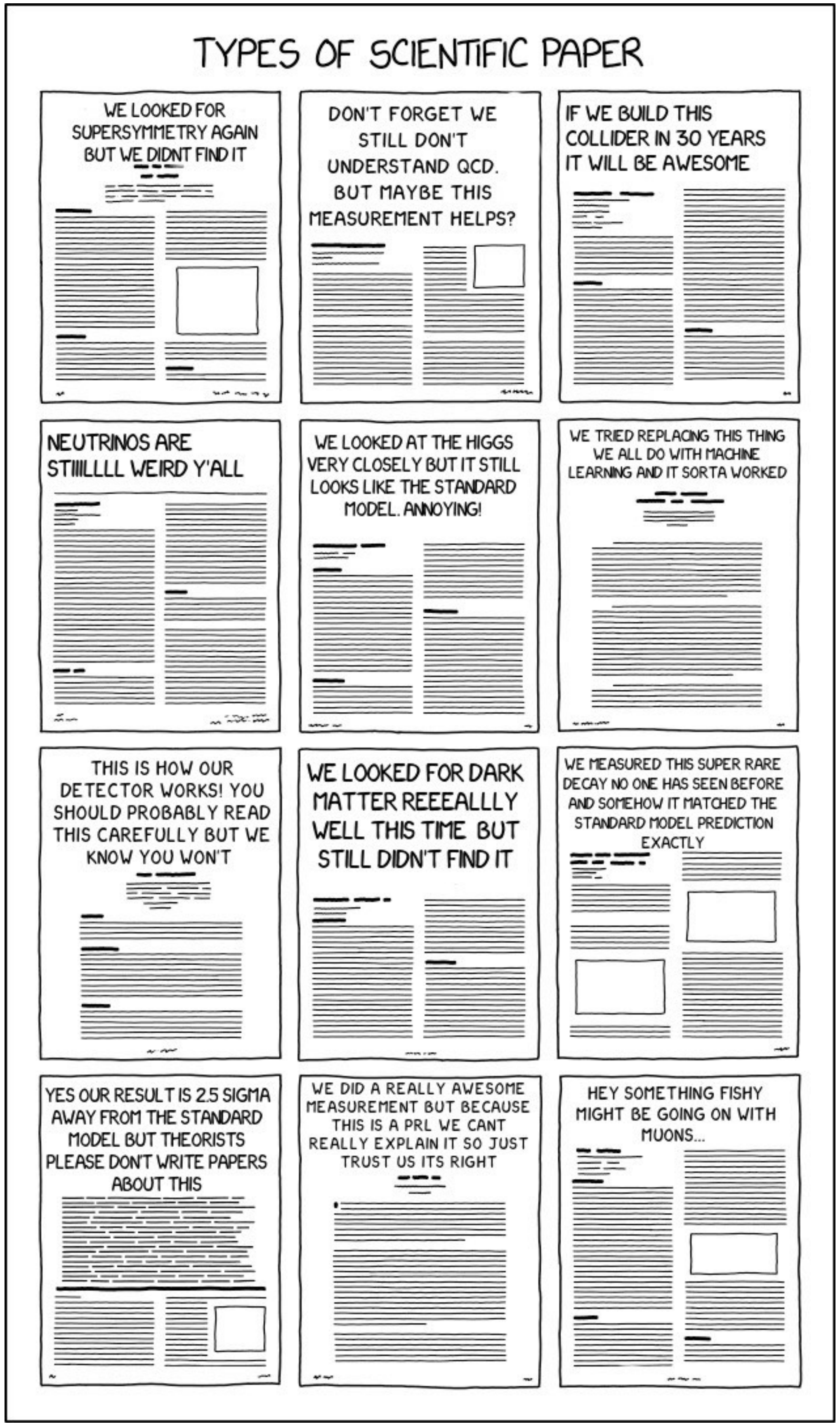
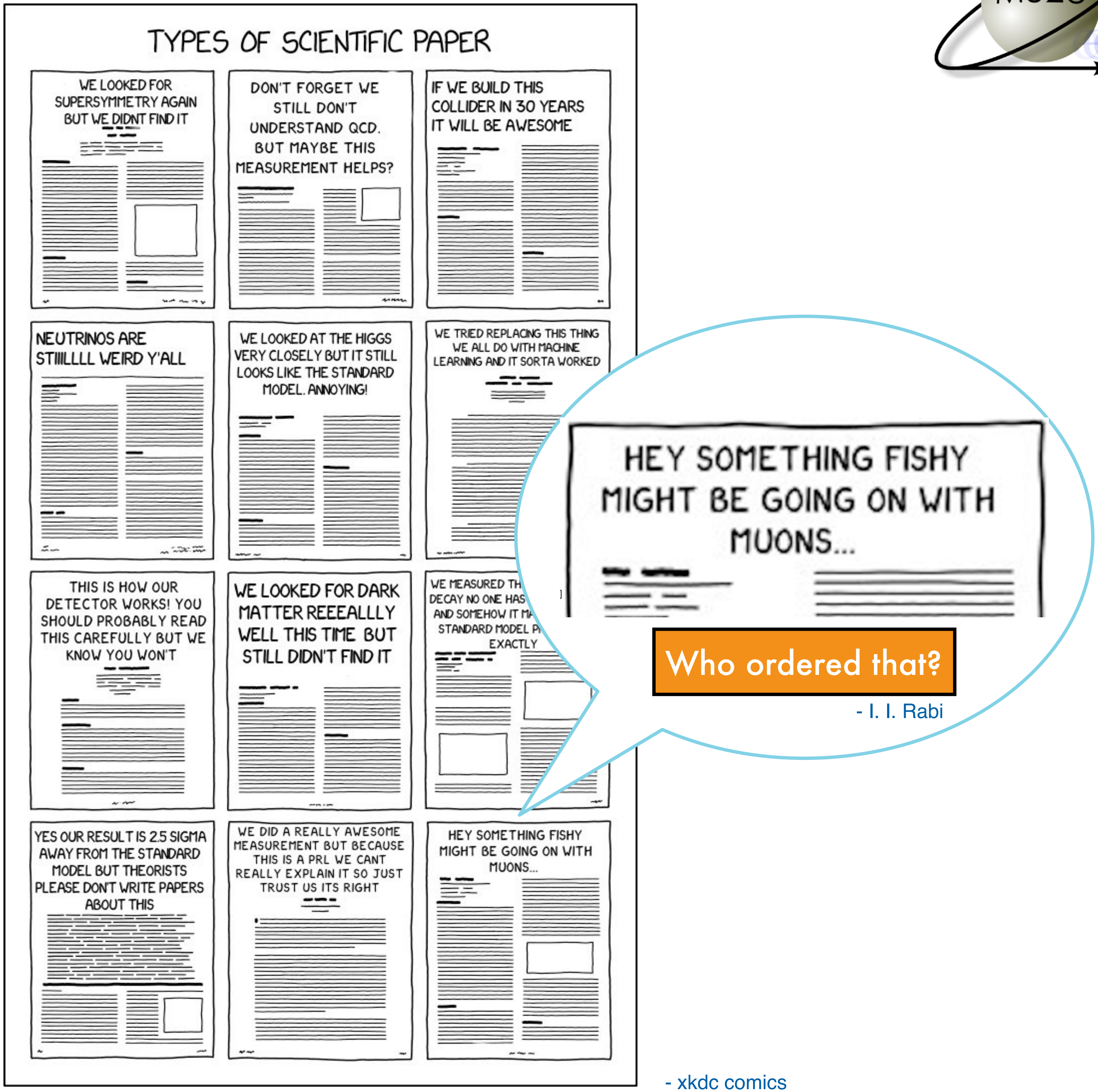
Mu2e Experiment

Mete Yucel on behalf of the Mu2e Collaboration
Users Meeting 2021
8/3/2021


TYPES OF SCIENTIFIC PAPER
WE LOOKED FOR SUPERSYMMETRY AGAIN BUT WE DIDNT FIND IT
DON'T FORGET WE STILL DON'T UNDERSTAND QCD. BUT MAYBE THIS MEASUREMENT HELPS?
IF WE BUILD THIS COLLIDER IN 30 YEARS IT WILL BE AWESOME
NEUTRINOS ARE STIIILLLL WEIRD Y'ALL
WE LOOKED AT THE HIGGS VERY CLOSELY BUT IT STILL LOOKS LIKE THE STANDARD MODEL. ANNOYING!
WE TRIED REPLACING THIS THING WE ALL DO WITH MACHINE LEARNING AND IT SORTA WORKED
THIS IS HOW OUR DETECTOR WORKS! YOU SHOULD PROBABLY READ THIS CAREFULLY BUT WE KNOW YOU WON'T
WE LOOKED FOR DARK MATTER REEEALLLY WELL THIS TIME BUT STILL DIDN'T FIND IT
WE MEASURED THIS SUPER RARE DECAY NO ONE HAS SEEN BEFORE AND SOMEHOW IT MATCHED THE STANDARD MODEL PREDICTION EXACTLY
YES OUR RESULT IS 2.5 SIGMA AWAY FROM THE STANDARD MODEL BUT THEORISTS PLEASE DON'T WRITE PAPERS ABOUT THIS
WE DID A REALLY AWESOME MEASUREMENT BUT BECAUSE THIS IS A PRL WE CANT REALLY EXPLAIN IT SO JUST TRUST US ITS RIGHT
HEY SOMETHING FISHY MIGHT BE GOING ON WITH MUONS...

- xkdc comics



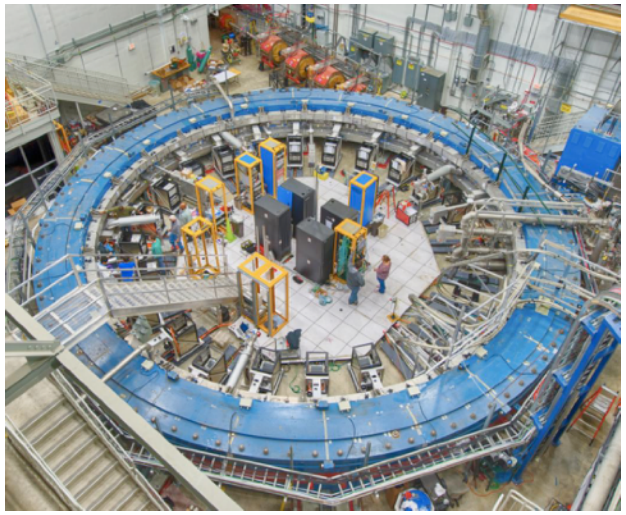
Who ordered that?

- I. I. Rabi

- xkdc comics

Muon mysteries

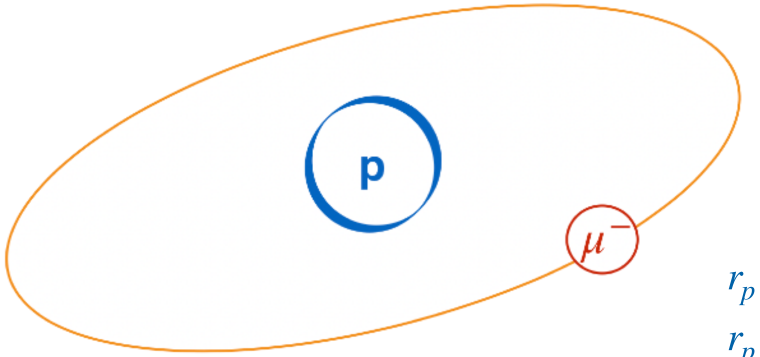
Muon a_μ



4.2σ difference with SM

(BNL, Fermilab)

Muonic atom



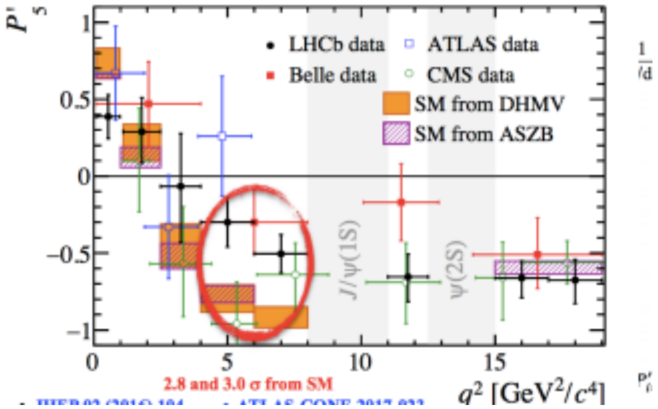
$r_p = 0.84 - 0.87$ fm

μ not a fat e^- ?

$r_p = 0.84184(67)$ fm (PSI μ result)

$r_p = 0.831(7)stat(12)syst$ fm (Jefferson Lab. e-p result)

Lepton universality in B



$b \to s\mu^+\mu^-$

3σ difference with SM

(LCHb, Belle)

Charged Lepton Flavor Violation

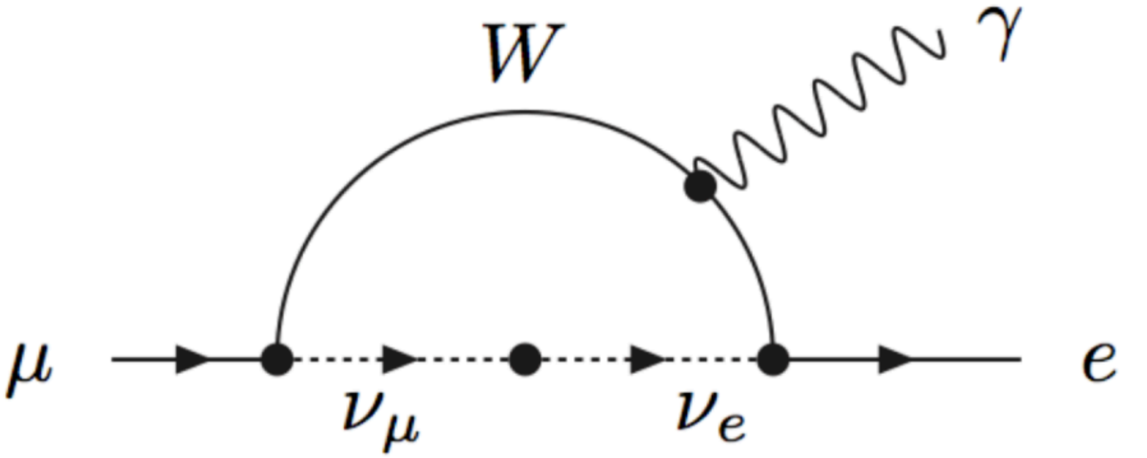
Today's topic

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; $\mu^- \to e^-$

Let's look at BR result for this process



$$\mathscr{B}(\mu^- \mathrm{Al} \to e^- \mathrm{Al}) \sim \mathscr{O}\ 10^{-52}$$

W. Marciano, T. Mori, M. Roney; https://doi.org/10.1146/annurev.nucl.58.110707.171126

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

- Searching for CLFV in the muon sector;

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

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

Motivation - What mass scale(Λ) Mu2e probes ?

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

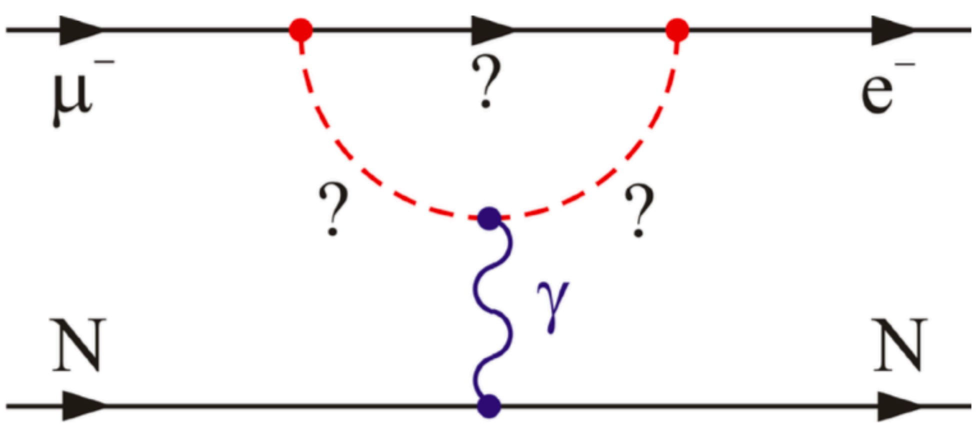
A. De Gouvea and P. Vogel; arXiv:1303.4097

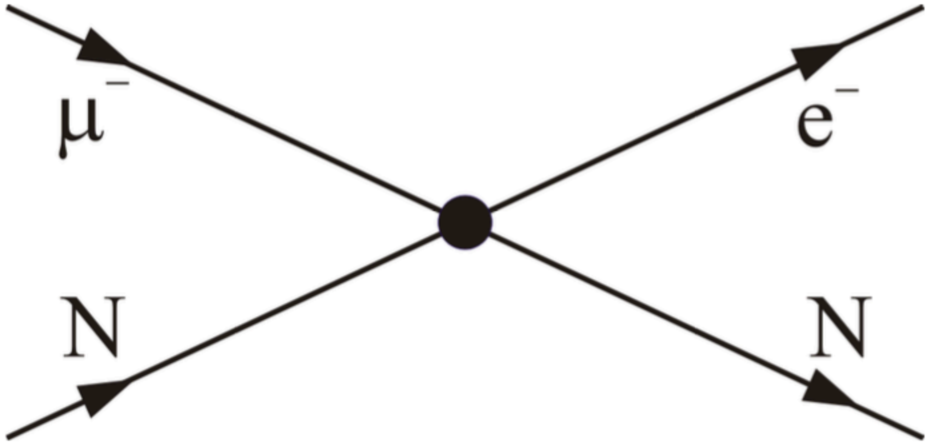
Lower κ is sensitive to the **loop** contributions to the $\mathscr{L}_{CLFV}$

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

$\kappa = 0$

$\kappa = \infty$





Supersymmetry & Heavy neutrinos

$\mu \to e\gamma$ contribution

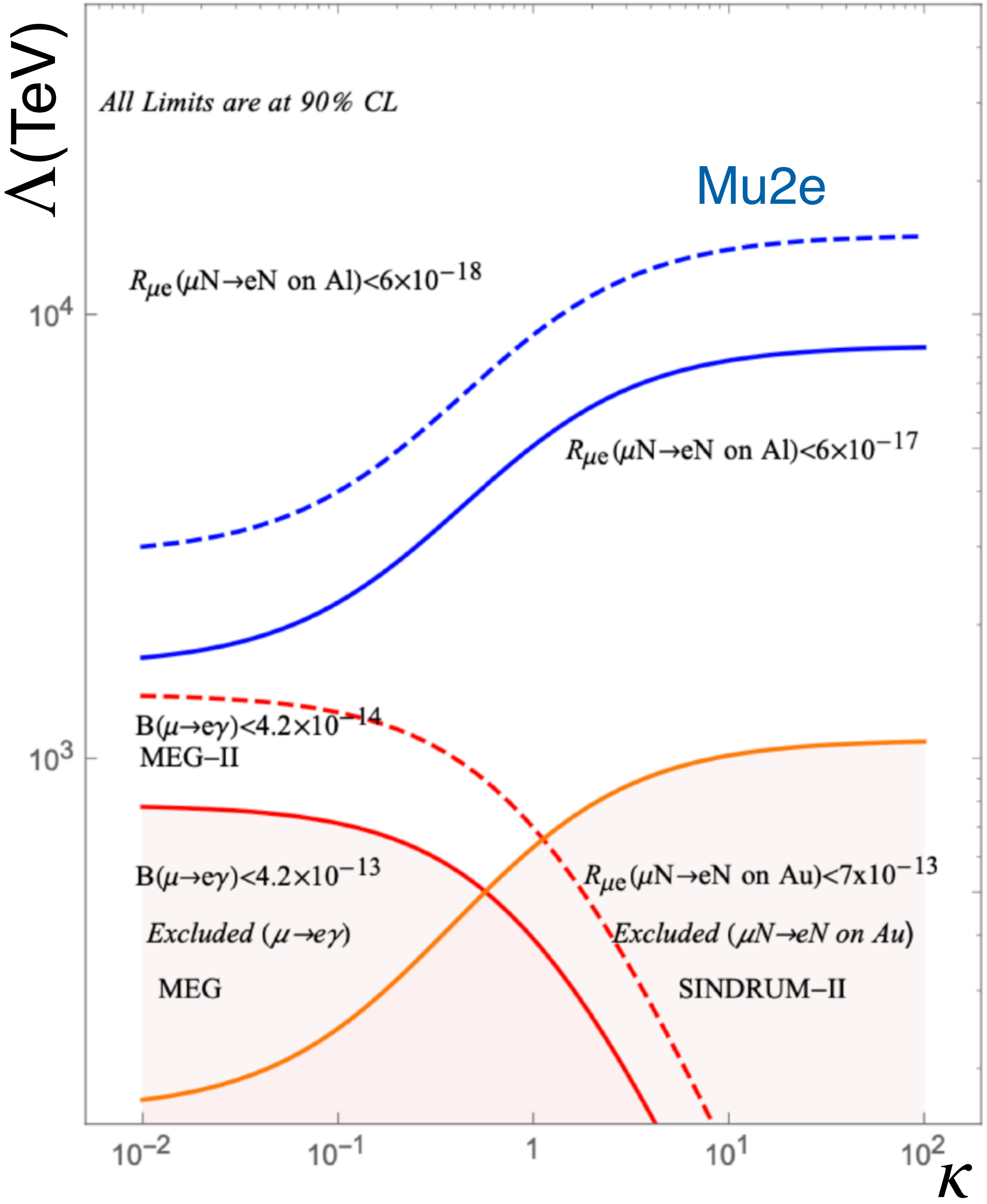
Leptoquarks, heavy Z …

No contribution from $\mu \to e\gamma$

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.



R. Bernstein, P. Cooper; arXiv:1307.5787

Mu2e signal

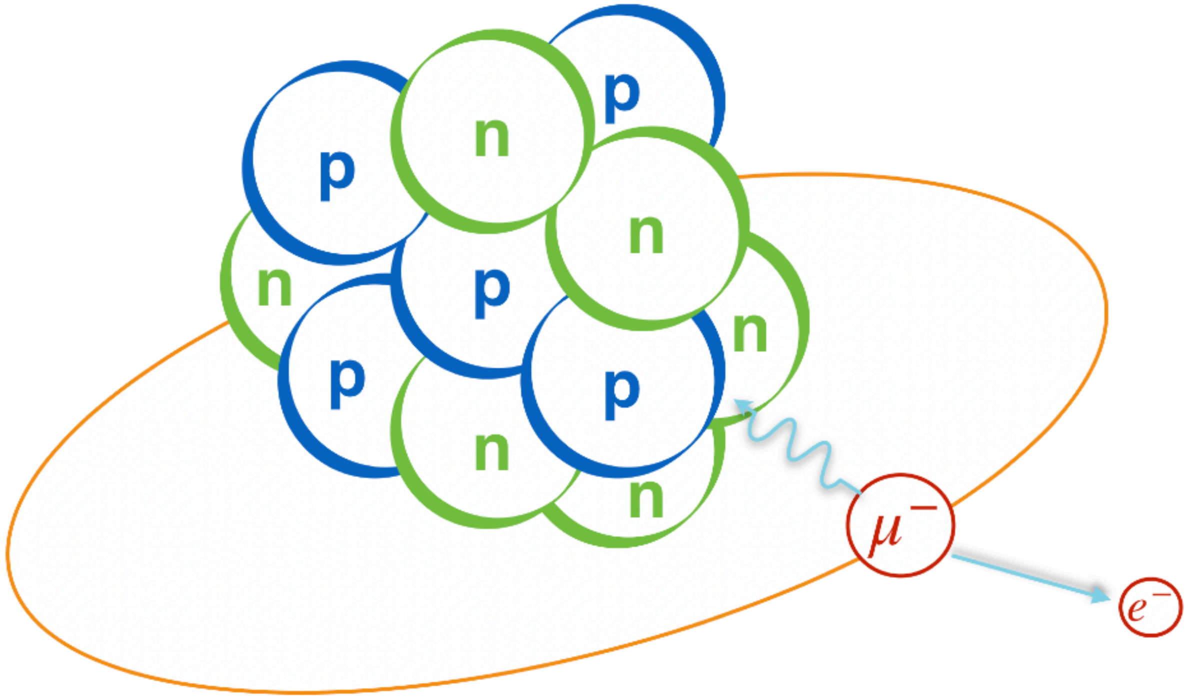
- Physics signal properties;
  - Coherent electron conversion.
  - Little energy lost to;
    - μ atomic binding energy $E_b = 0.48$ MeV.
    - Nuclear recoil $E_R = 0.21$ MeV.
  - **No neutrinos** are produced.
  - **Monoenergetic** e^- is **104.97 MeV.**

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 nucleus



Muonic Al lifetime = 864 ns

Conversion rate

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

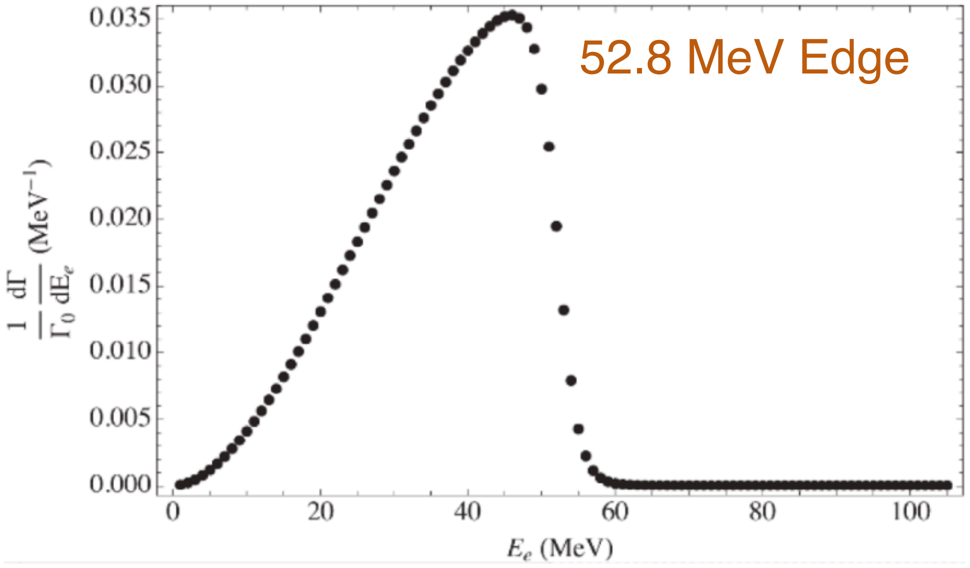
Mu2e goal $= 3 \times 10^{-17}$ SES

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

Backgrounds - DIO

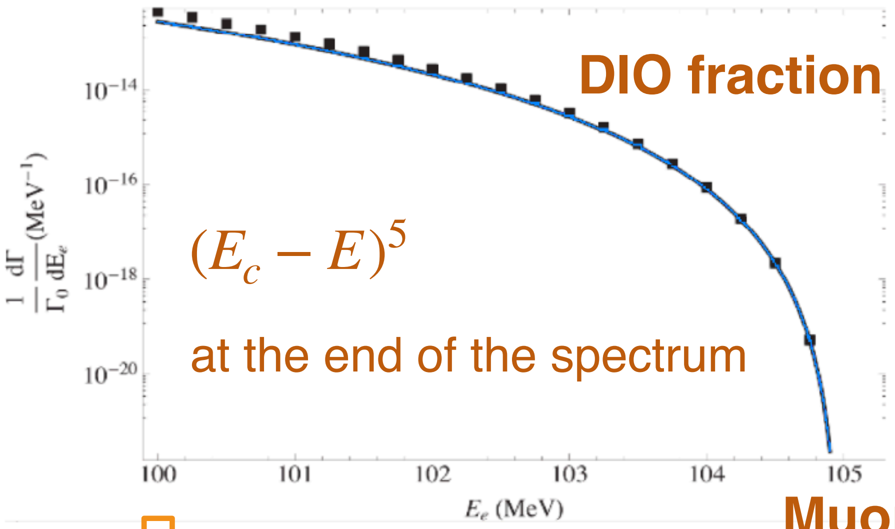
- Decay In Orbit(DIO).

Michel spectrum (μ decay in orbit)



52.8 MeV Edge

A. Czarnecki et. al; arXiv: 1106.4756v2



DIO fraction is 39% of decays

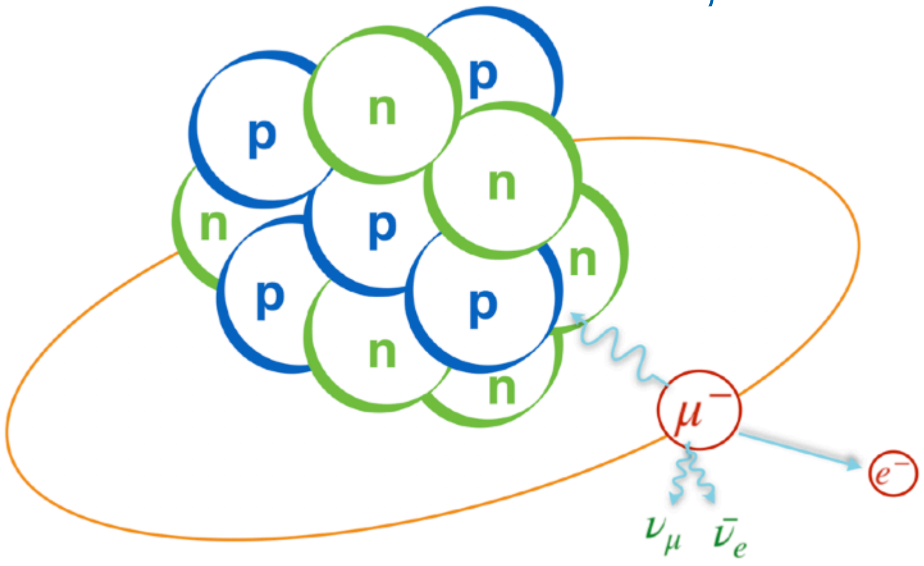
$(E_c - E)^5$

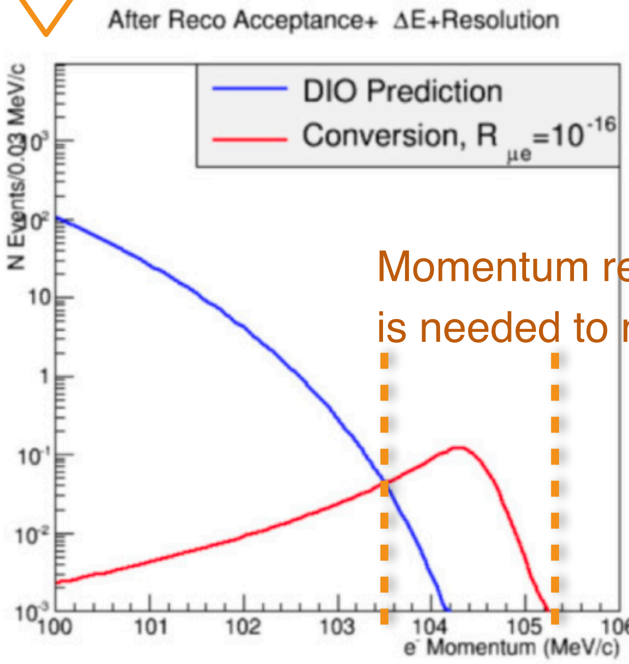
at the end of the spectrum

Muon mass 105.7 MeV

Plot conversion e^- on top

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





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.
- 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

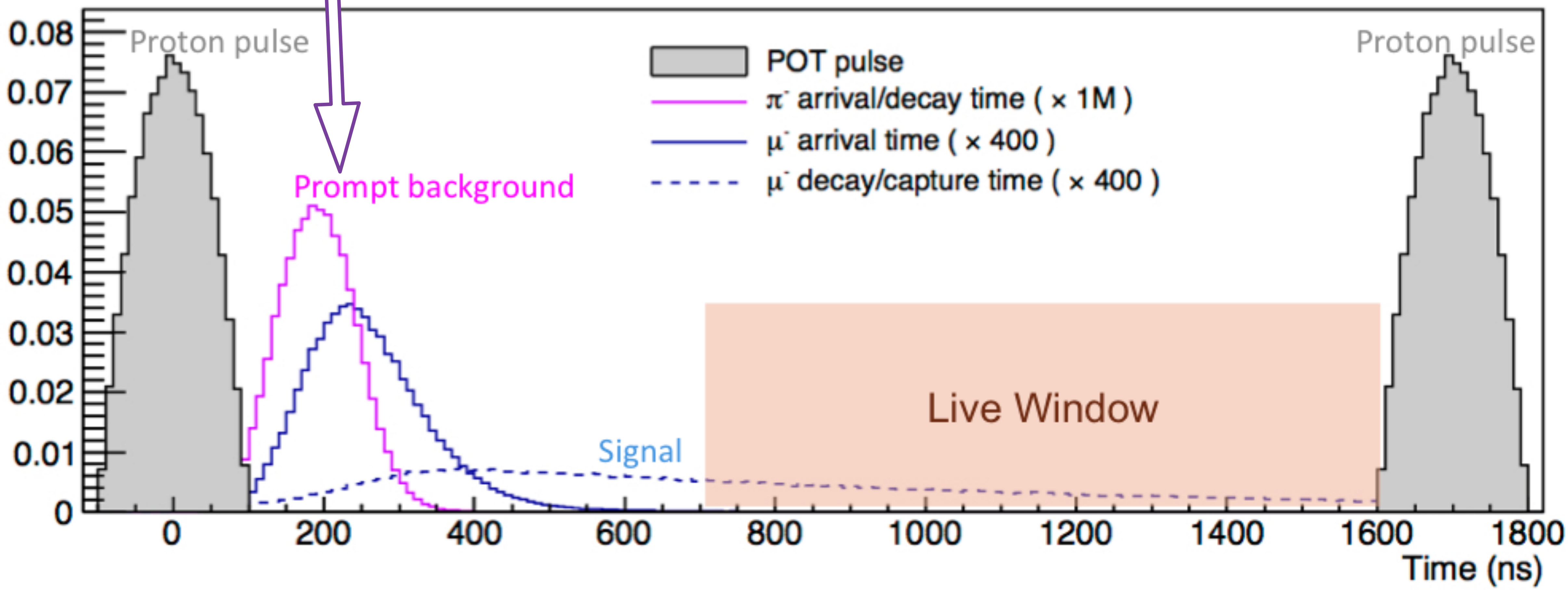
Background suppression: Radiative Pion Capture + other beam related bg

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

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

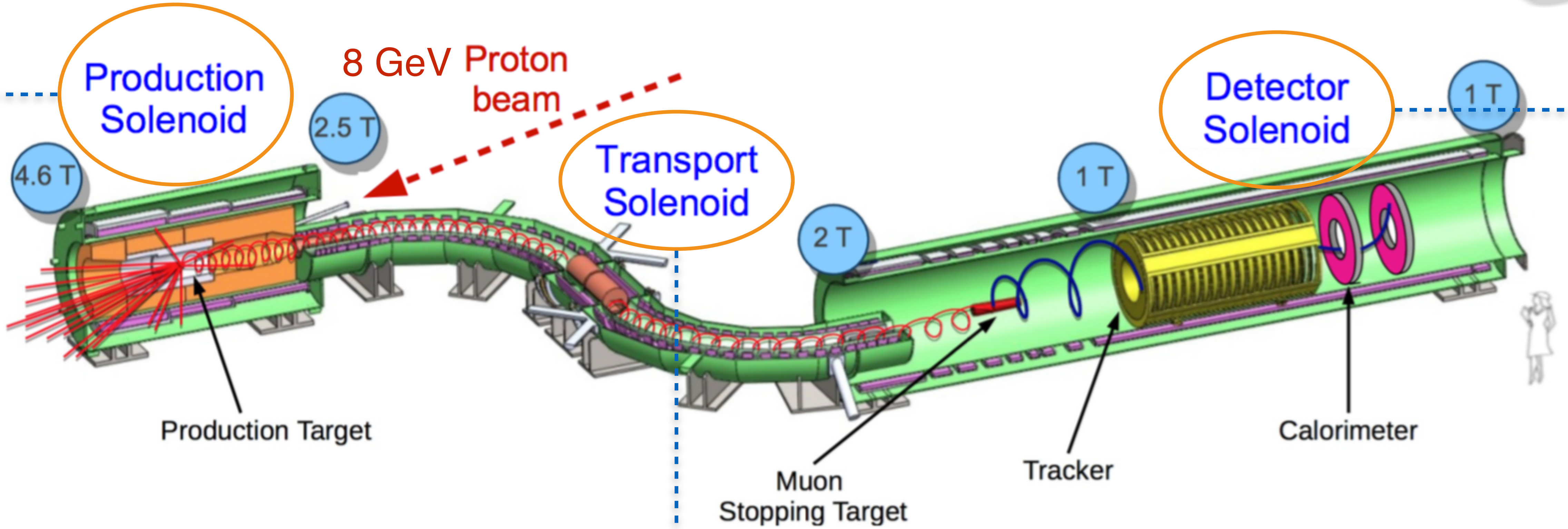
e^- with enough momentum can fake conversion events

- 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

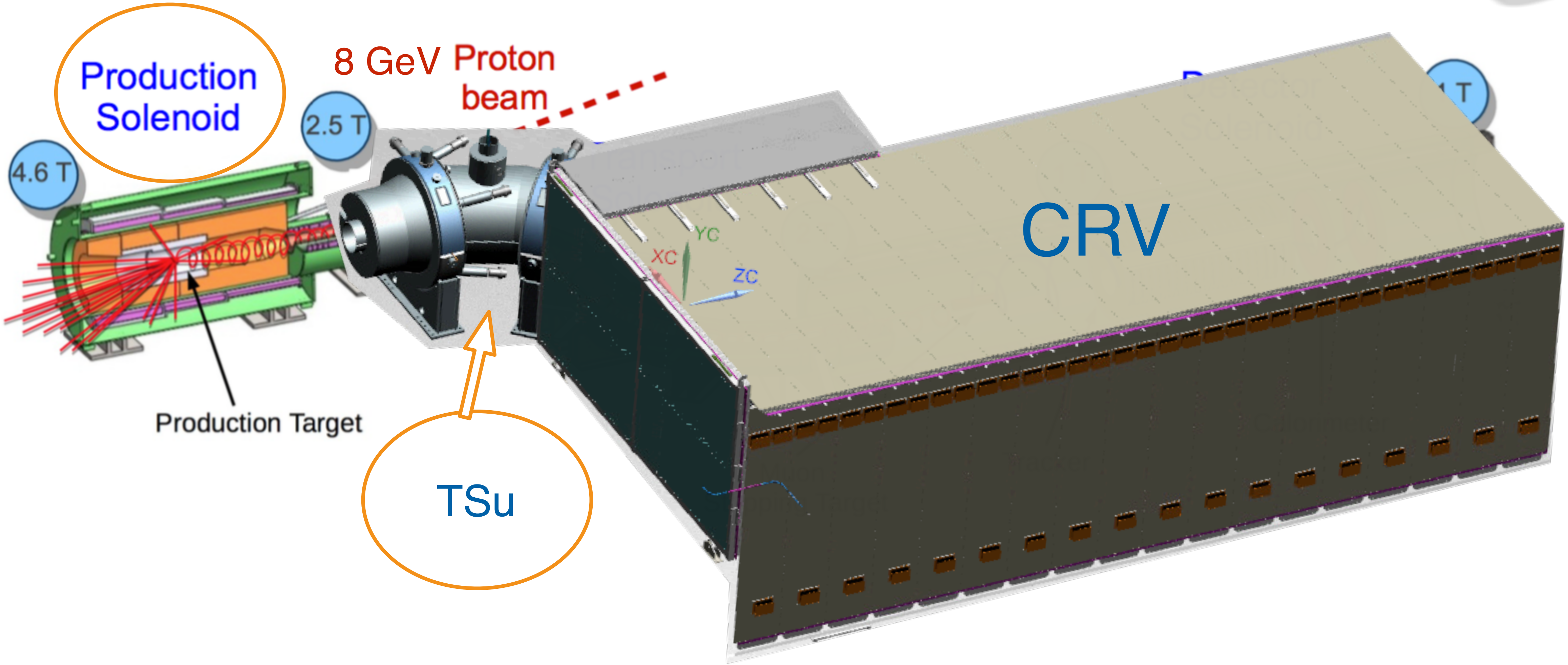
NbTi Superconducting Magnets



- 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

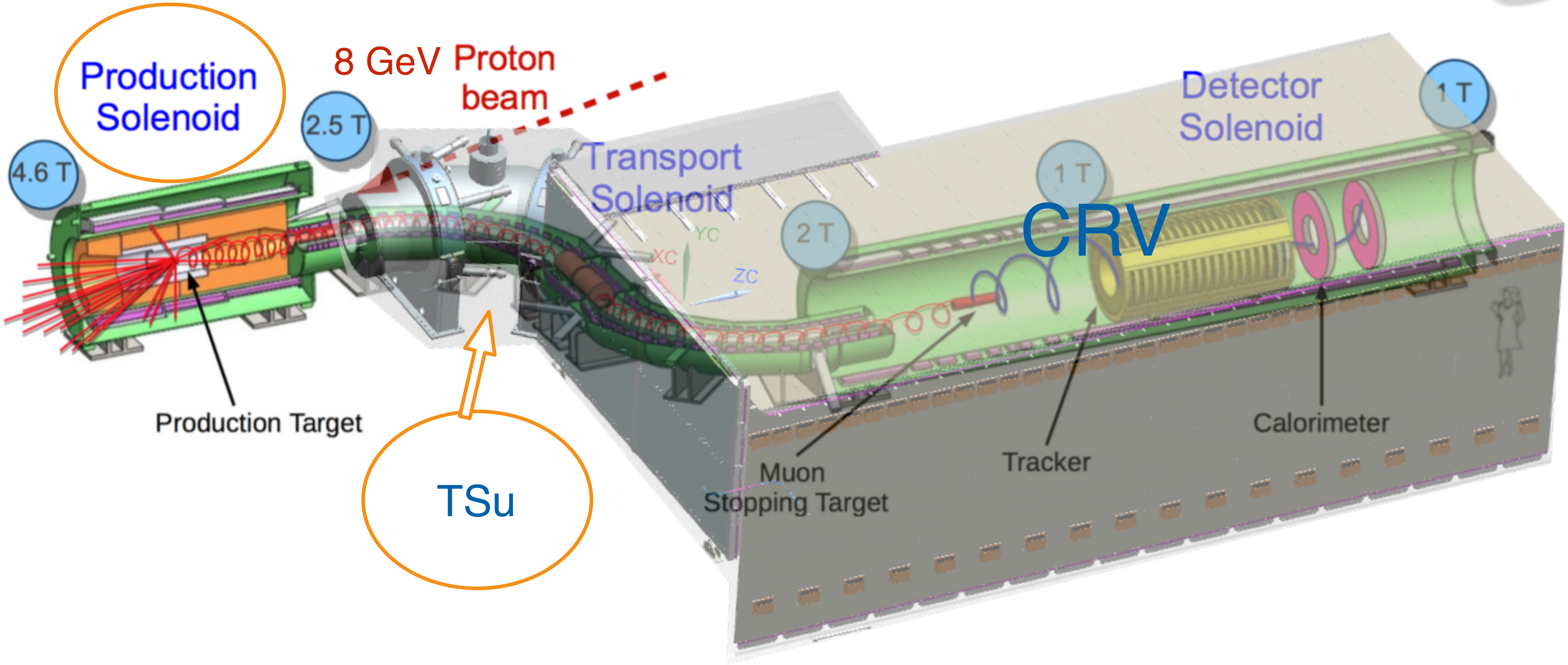
NbTi Superconducting Magnets



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

Solenoids - progress

- Production Solenoid (PS)
- Detector Solenoid (DS)
- Transport Solenoid (TSu,TSd)

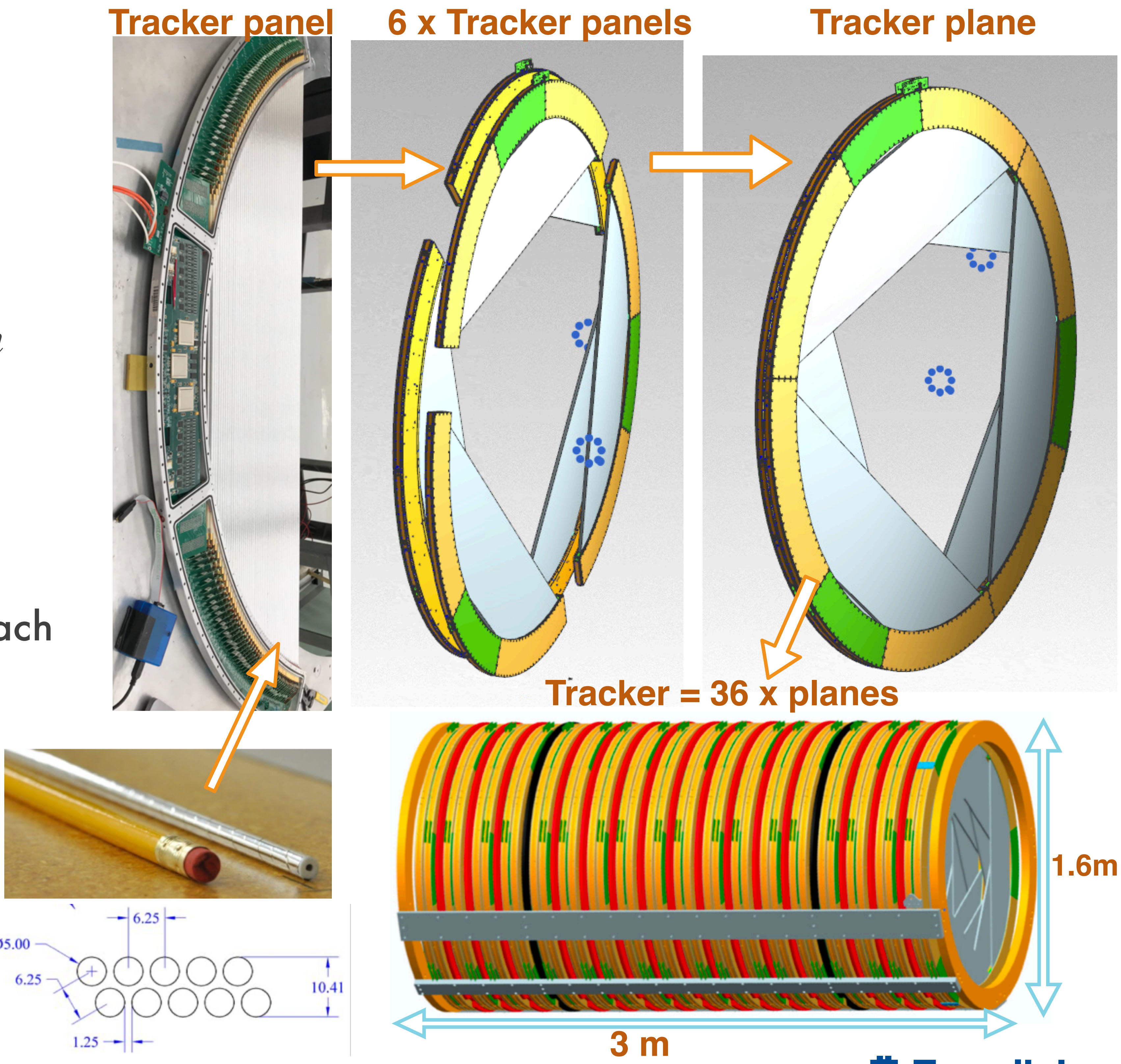
Coil production

1. Winding superconducting coils.
2. Vacuum pressure impregnation(VPI).
3. Shell insertion.
4. Cold test of the unit.

Tracker

Background suppression: DIO

- Main detection element of Mu2e.
- Low mass tracker using straw drift tubes running ArCO2(80/20).
- Tracker kept 15 psid with solenoid.
- 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

6 x Tracker panels

Tracker plane

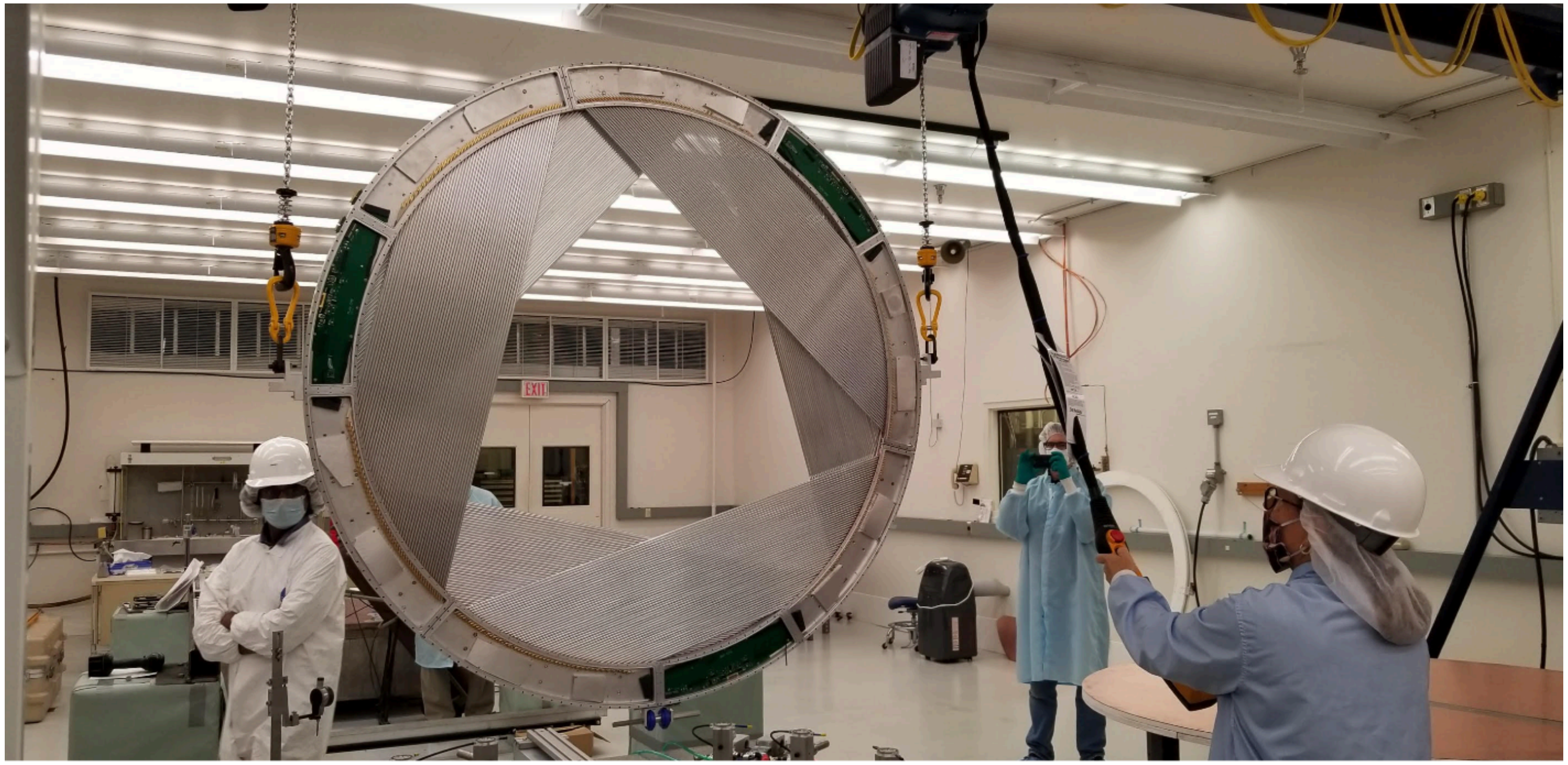
Tracker = 36 x planes

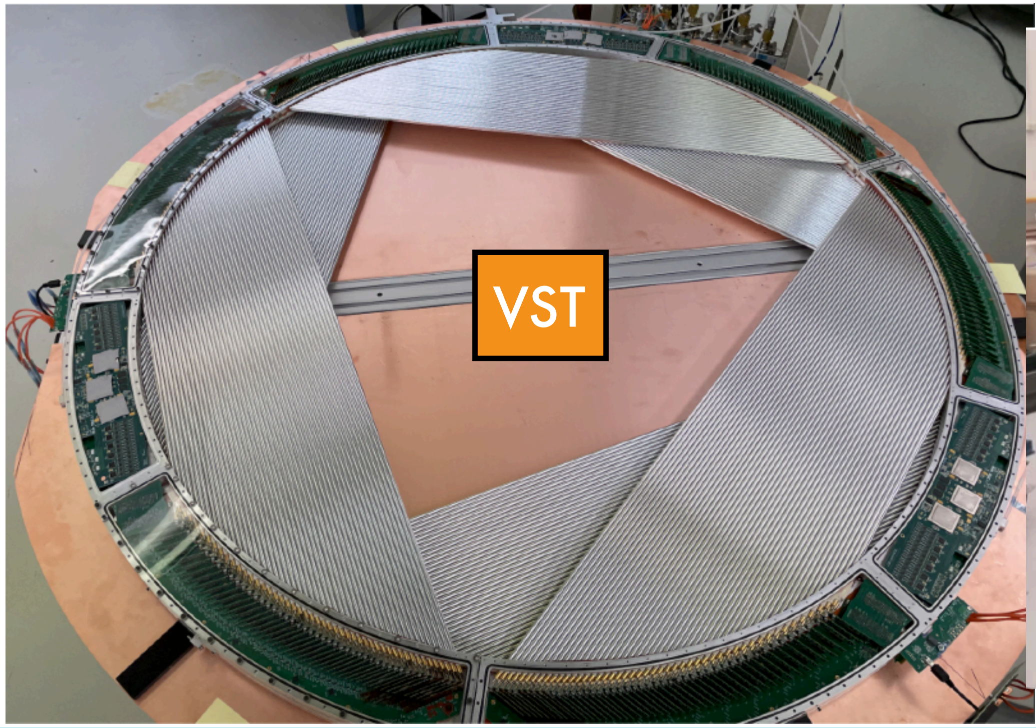
21600 x straws

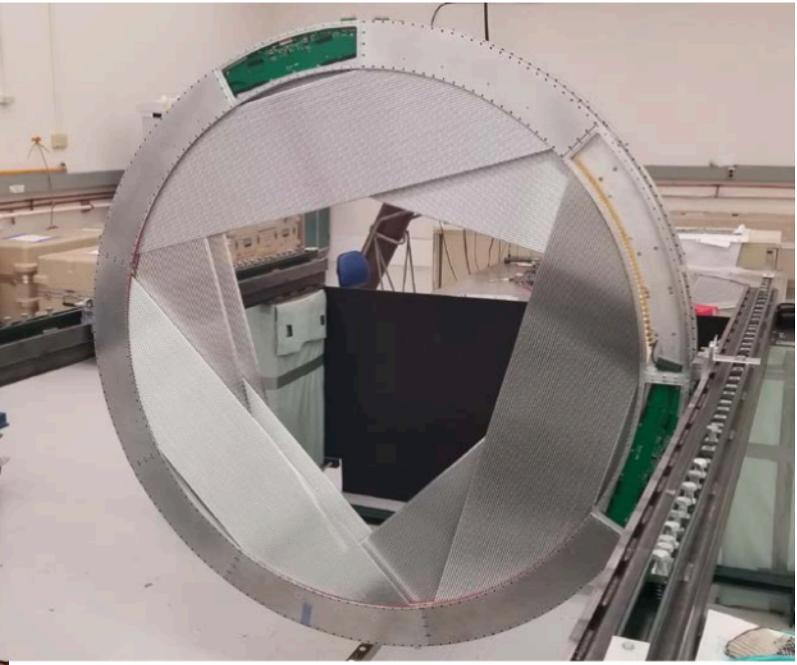
Double layered
96 per tracker panel

Tracker - progress

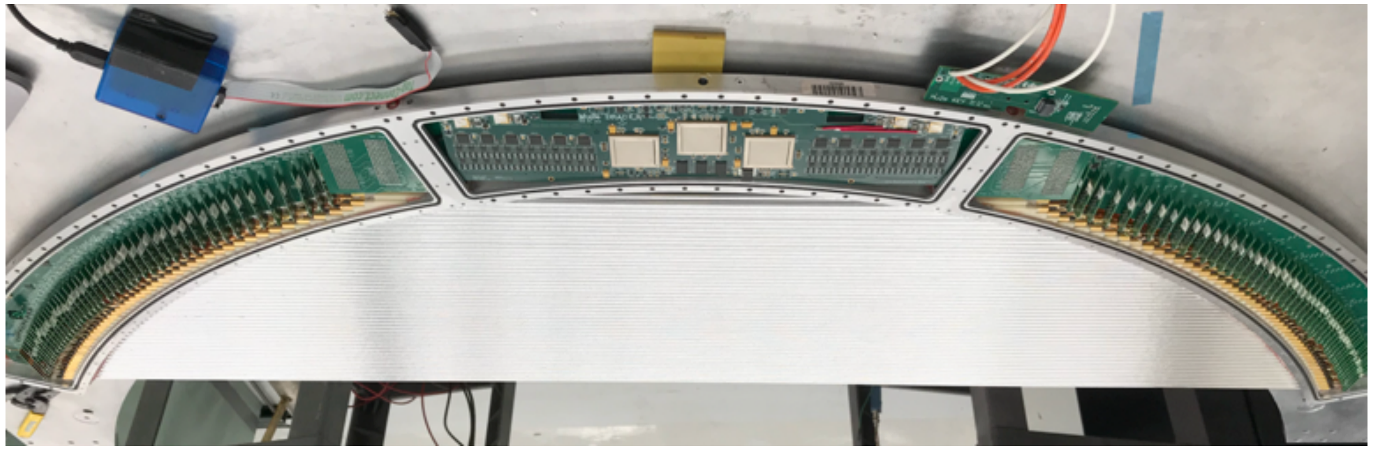
- **120/240** tracker panels are produced.
- **6/36** planes produced.
- Vertical slice test(a test of complete tracker plane with production electronics) of the first plane has been ongoing since Jan-2021.
- Test in vertical orientation will be conducted soon.



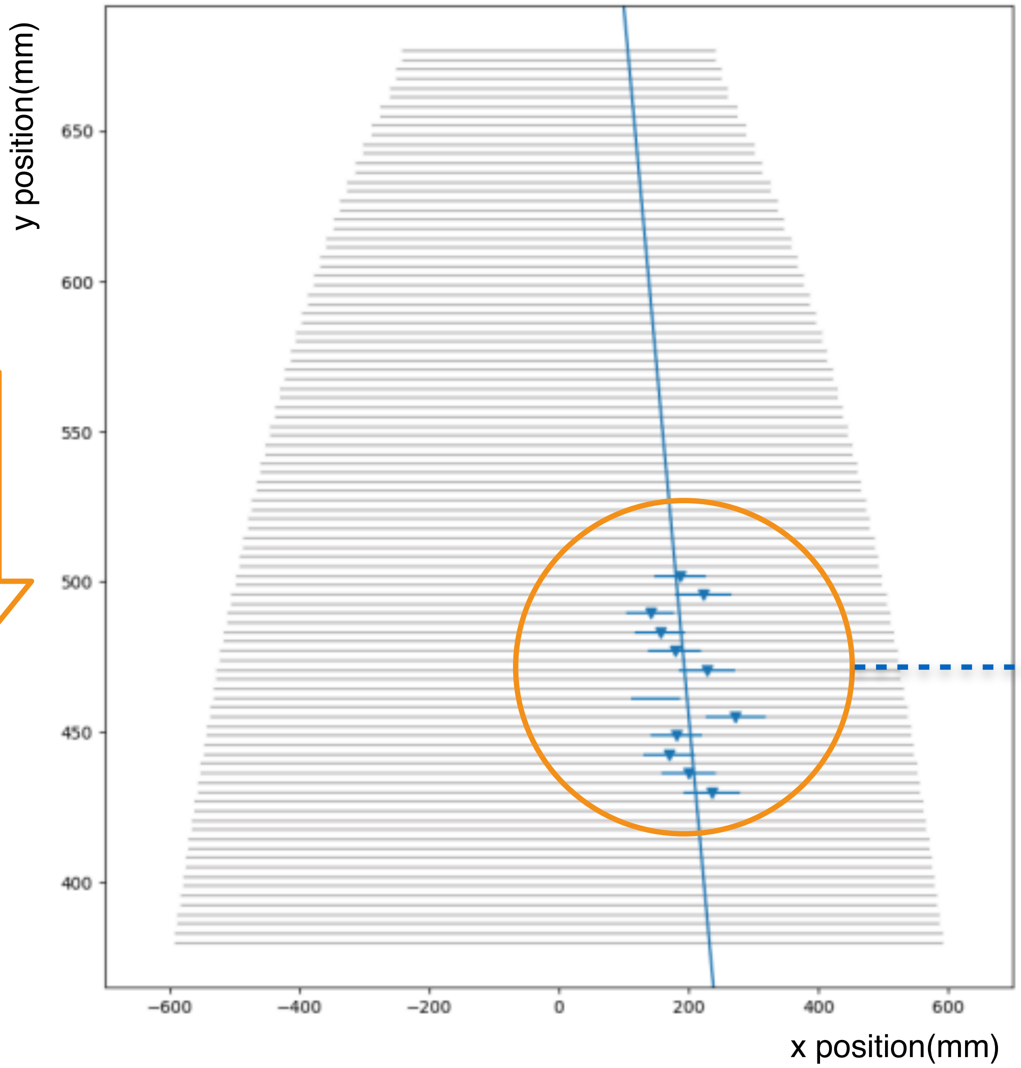




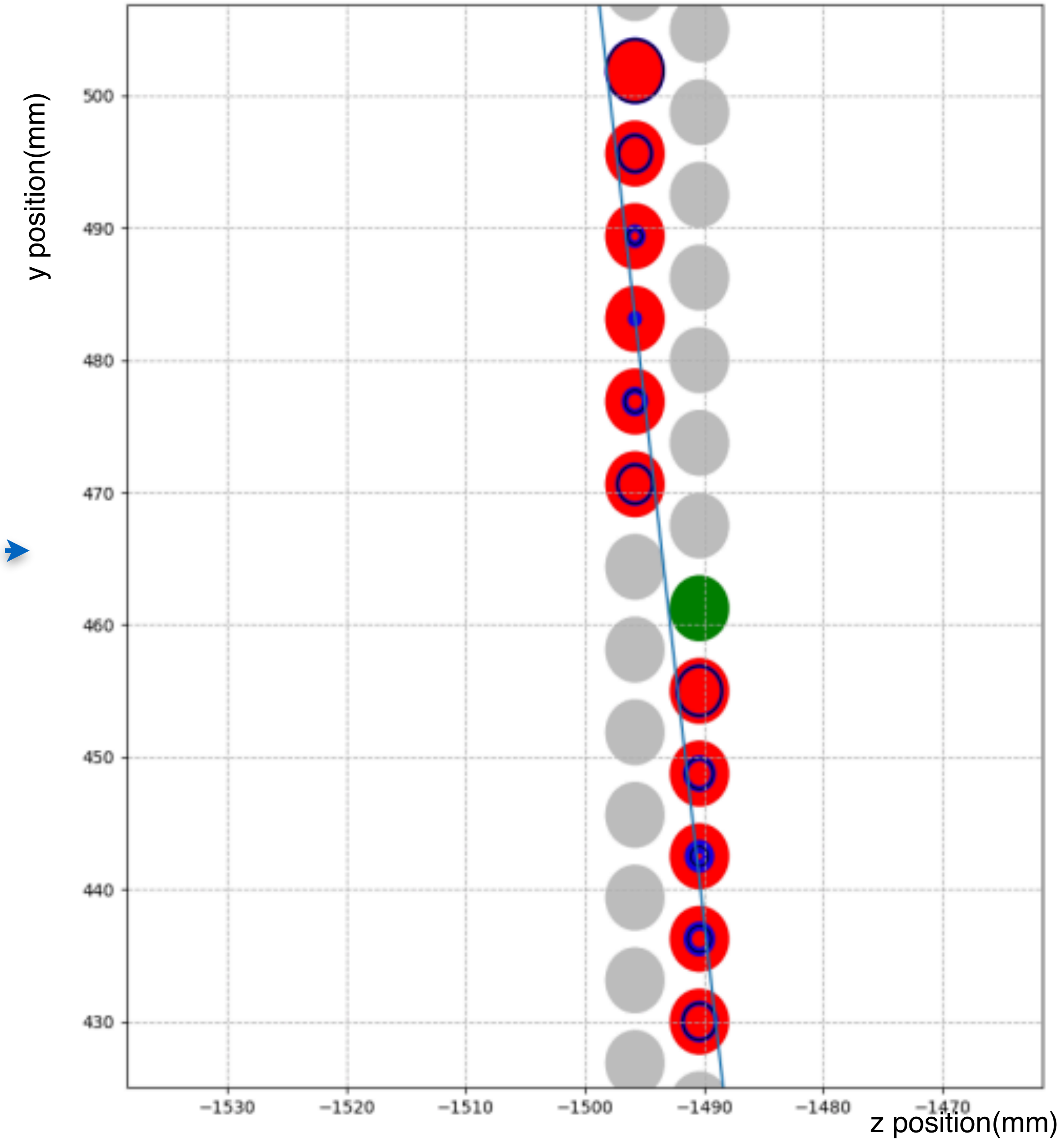
Cosmic track reconstruction



Short to long straws



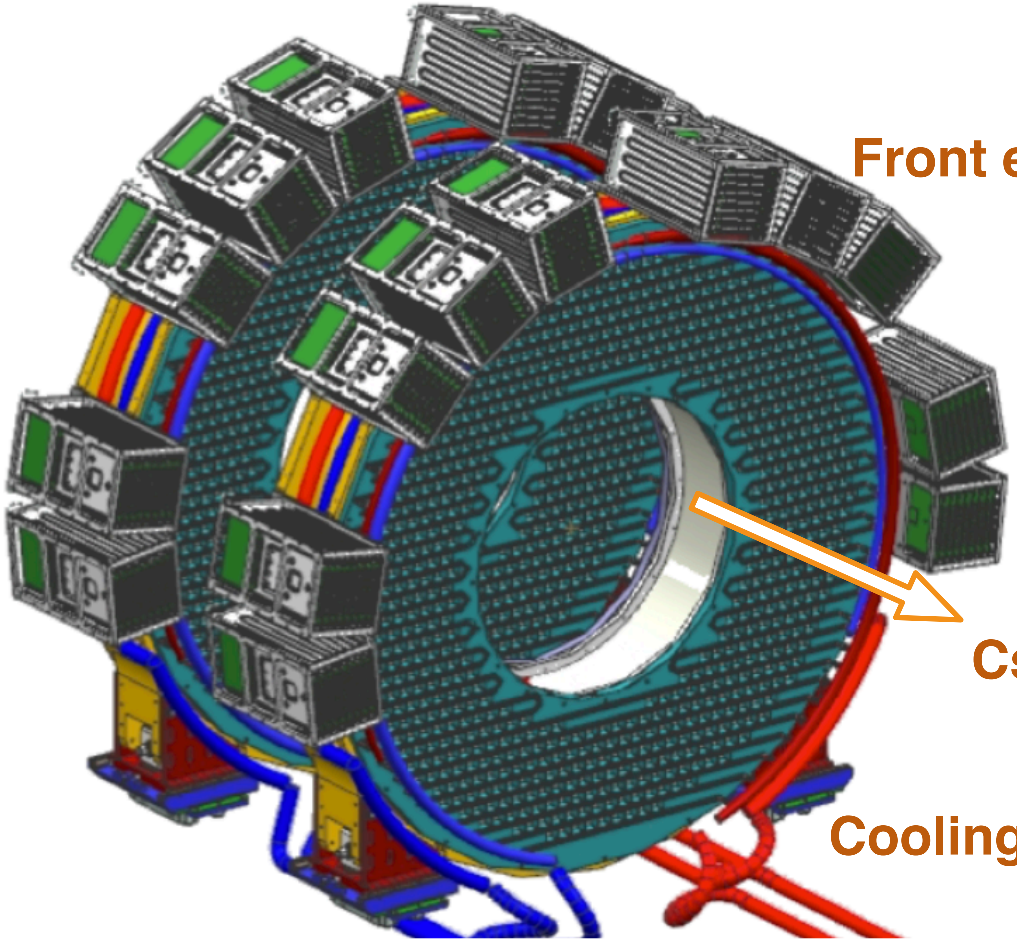
Panel orientation



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

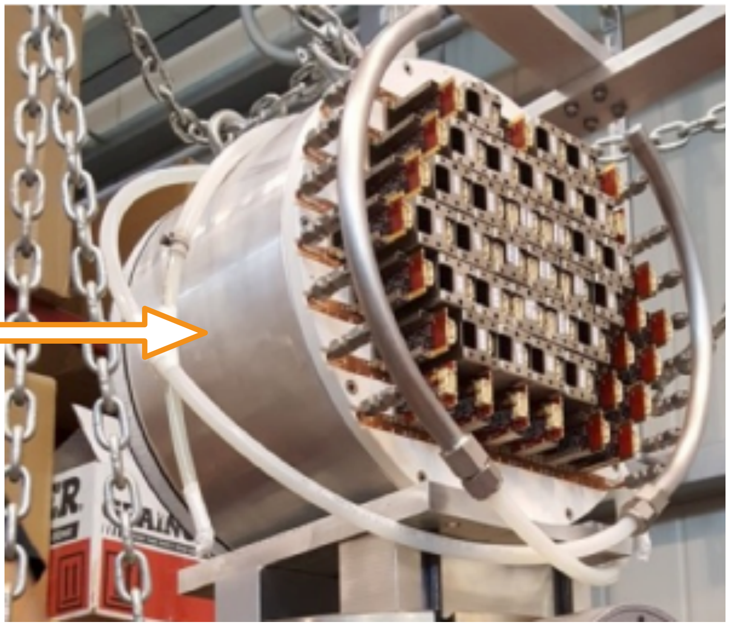


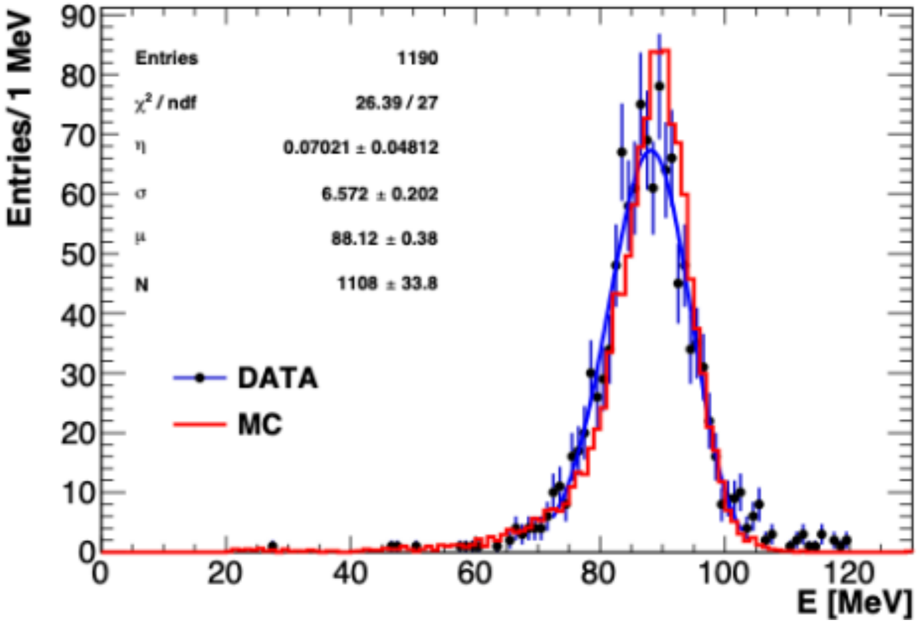
Front end electronics

CsI crystals

Cooling

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

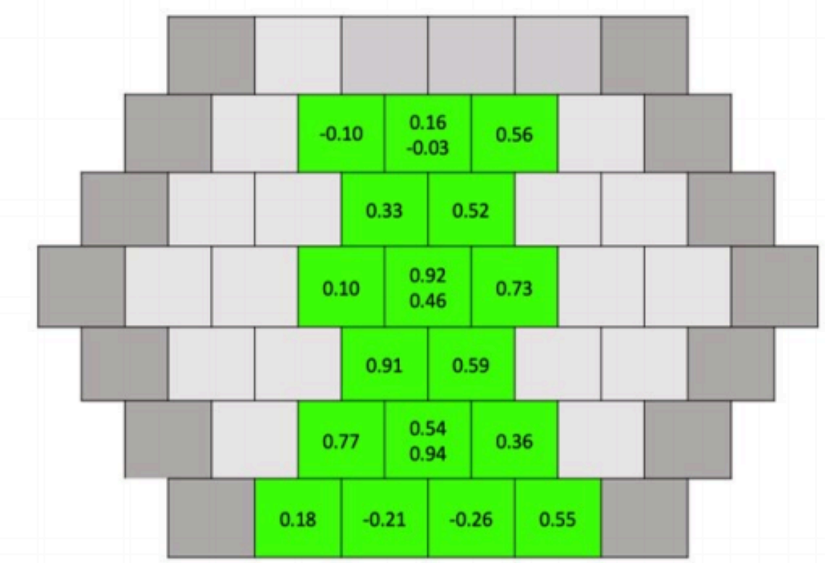


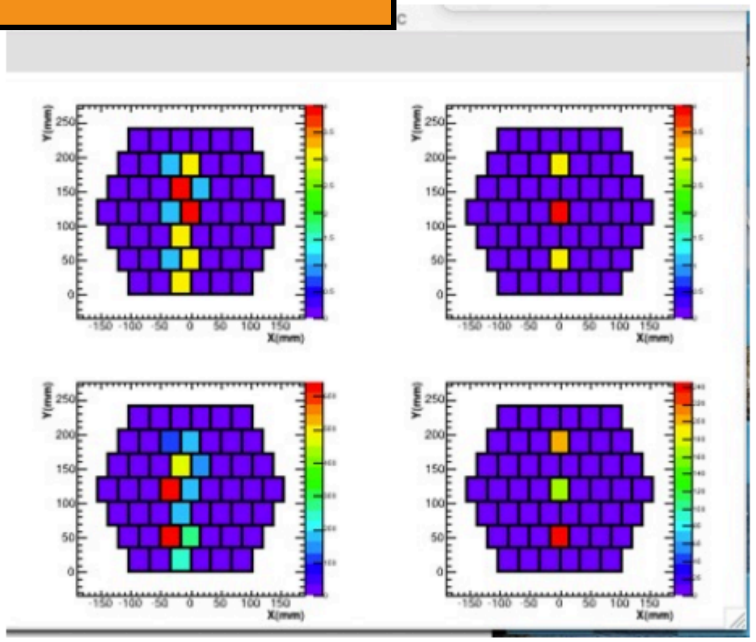


Calorimeter - progress

- Production of CsI crystals are finished.
- FEE production finished, QC in progress.
- 3950 SiPMs are completed and accepted with 1.2% rejection rate.
- DIRAC installed on Module-0 May 11 and tested.

Module 0 with DIRAC and readout

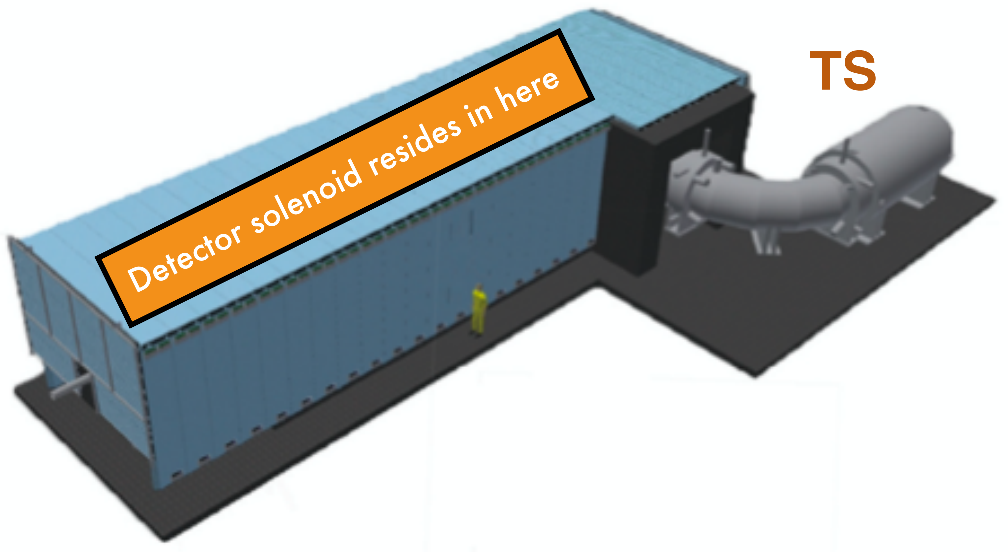


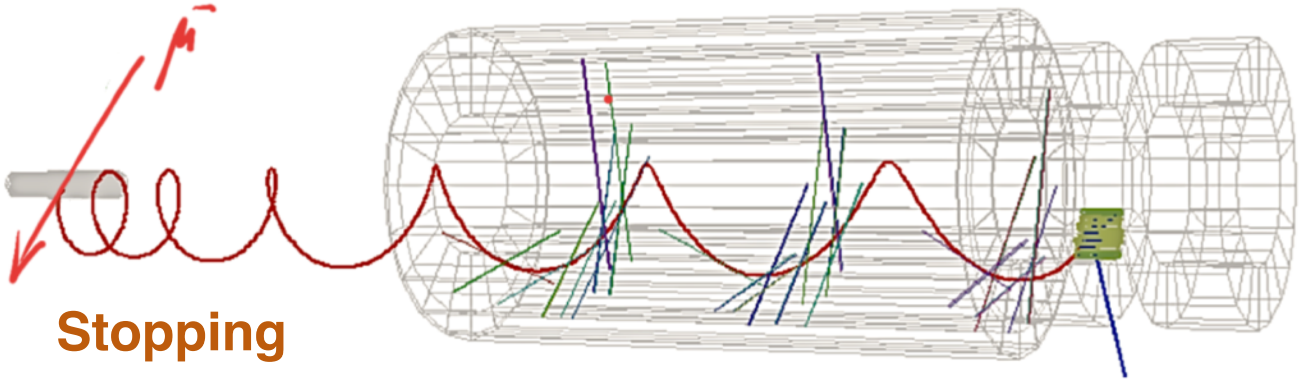


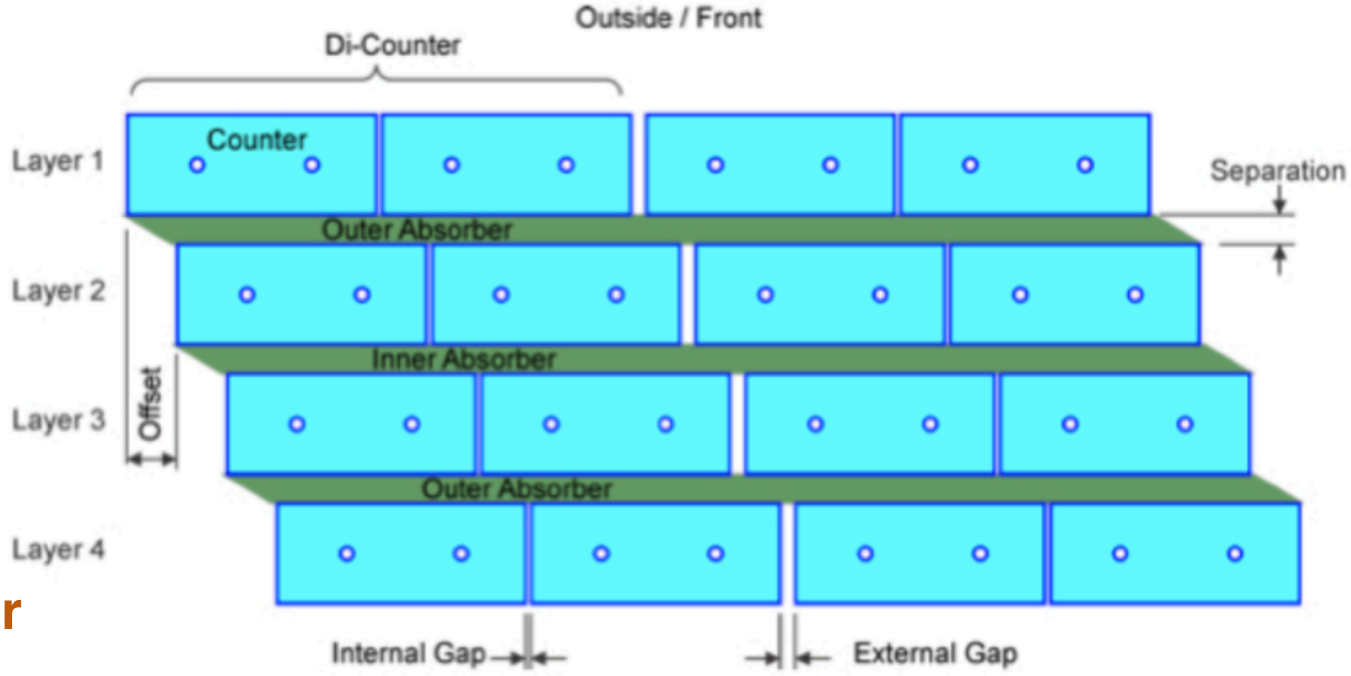
Cosmic Ray Veto

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 TiO2 sandwiched between Al absorbers.
- 4 overlapping layers of scintillators.
  - 3 layer coincidence veto.
- Readout through WLS fibers & 2x2 mm^2 SiPMs on both ends.





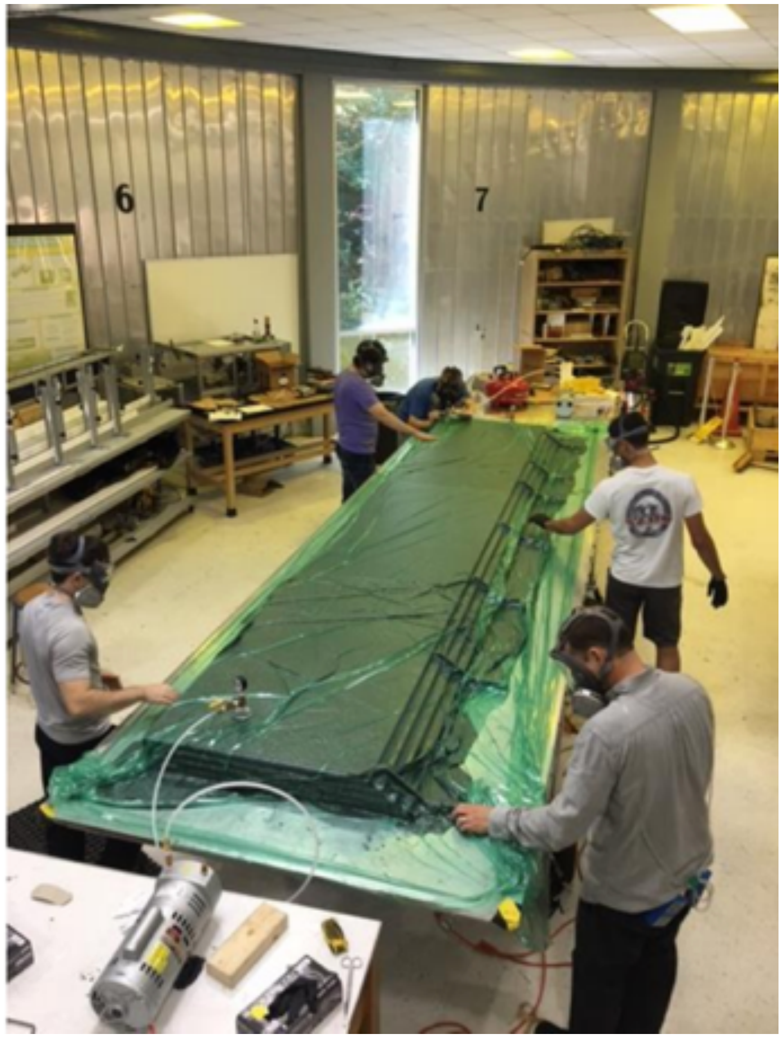


CRV - progress

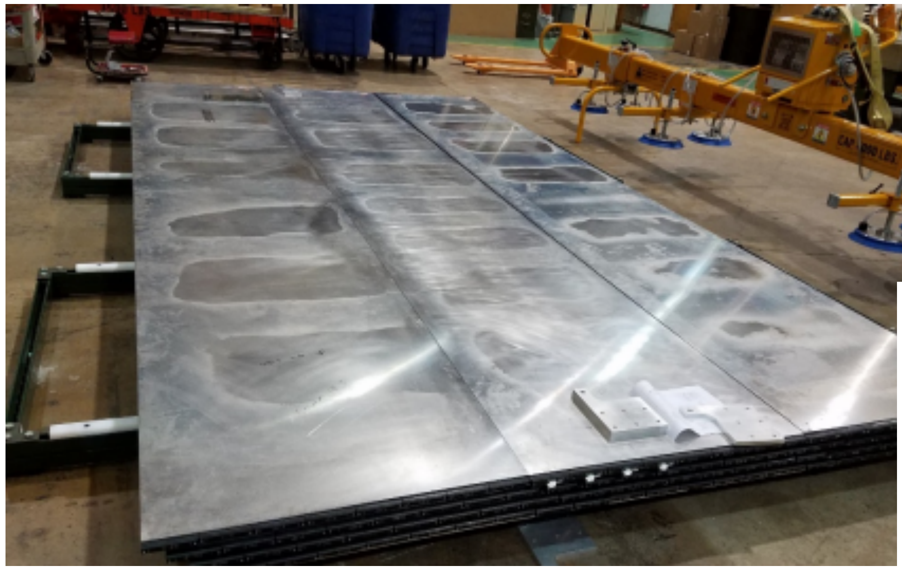
- **100%** SiPMs tested, 99% yield.
- **1760/2688** di-counters(58%) produced.
- **52/83** production modules(63%) are completed.

Vertical modules

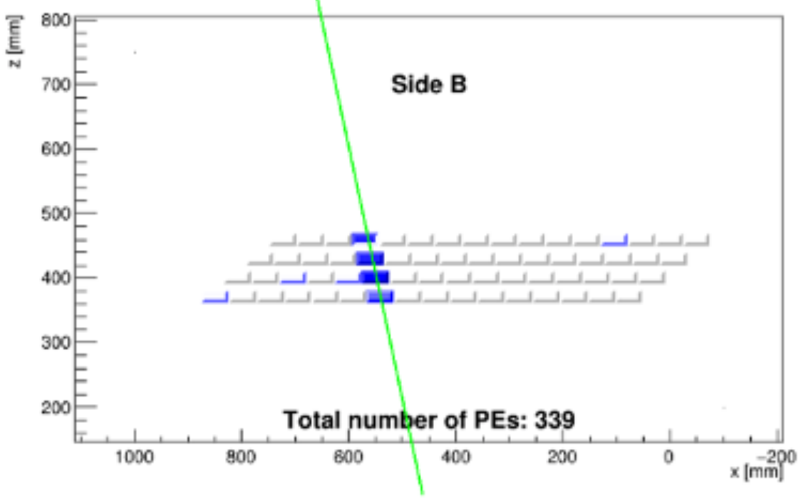
CRV module vacuum bagged



Side modules



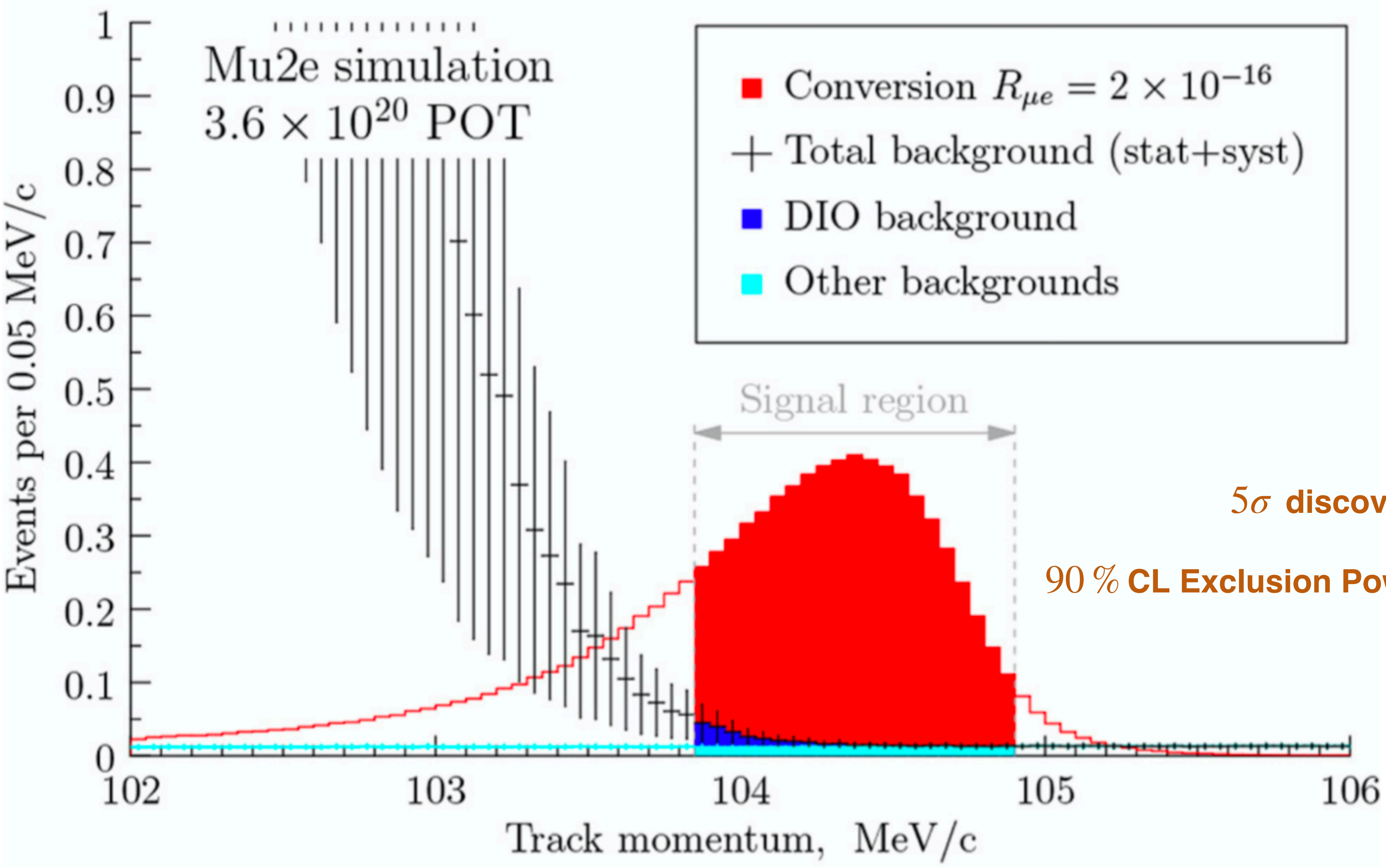
Module testing ongoing



Major backgrounds summary

	Process	*Estimated yield(events)*
Intrinsic	*Muon DIO*	0.144 ± 0.028(stat) ± 0.11(syst)
Beam related prompt	*RPC*	0.021 ± 0.001(stat) ± 0.002(syst)
	Antiproton induced	0.040 ± 0.001(stat) ± 0.020(syst)
Other	*Cosmic ray induced*	0.209 ± 0.022(stat) ± 0.055(syst)
	TOTAL	0.41 ± 0.13(stat+syst)

Sensitivity

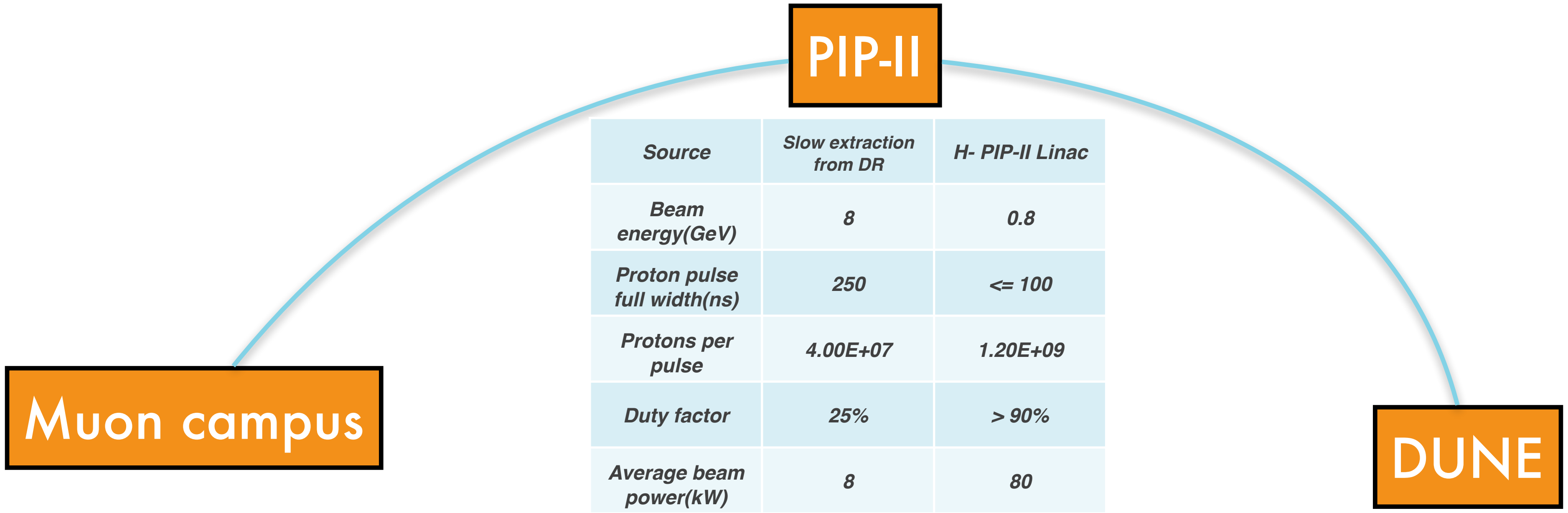


5σ **discovery** : $R_{\mu e} \geq 2 \times 10^{-16}$

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

7 events are needed for 5σ

Future experiments



PIP-II

Source	Slow extraction from DR	H- PIP-II Linac
Beam energy(GeV)	8	0.8
Proton pulse full width(ns)	250	<= 100
Protons per pulse	4.00E+07	1.20E+09
Duty factor	25%	> 90%
Average beam power(kW)	8	80

Muon campus

- Mu2e-II.
- EDM experiments.
  - μ, p probes dark matter/ dark energy.
- Muonium/Dimuonium.
- PRISM.
  - Slow muons to supply new CLFV programs.

DUNE

Not the topic of this talk

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 2022.
  - Start physics data taking in 2025.
  - $\times 1000$ improvement over current limit by 2026.
  - LBNF/PIP-II shutdown.
  - $\times 10000$ improvement over current limit by the end of the decade.
- Great progress so far from all subsystems.
- Next 2 years will see a big effort on building and commissioning the detector.

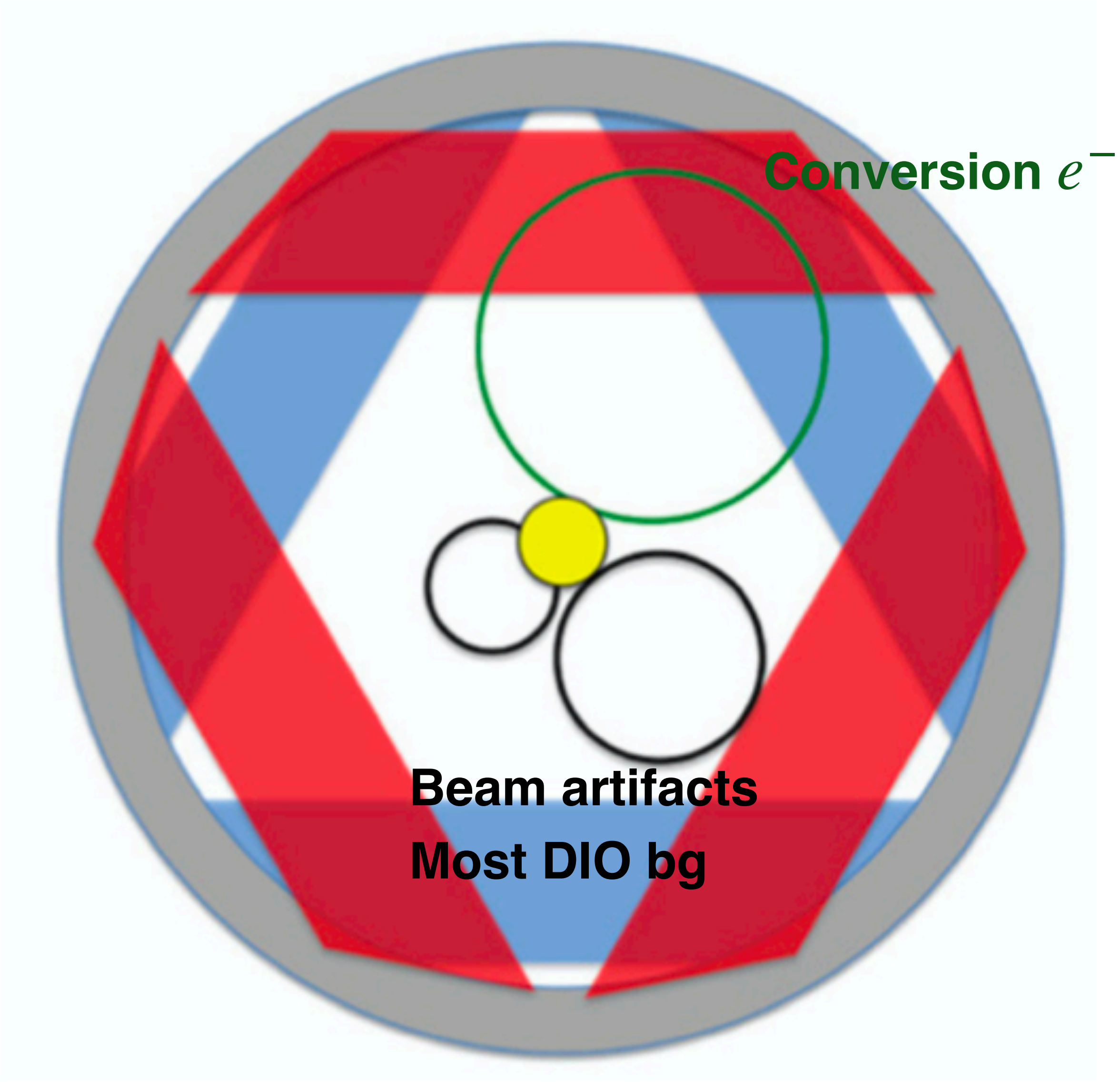
Hope for an in person meeting next time!

Thanks for listening

BACKUP

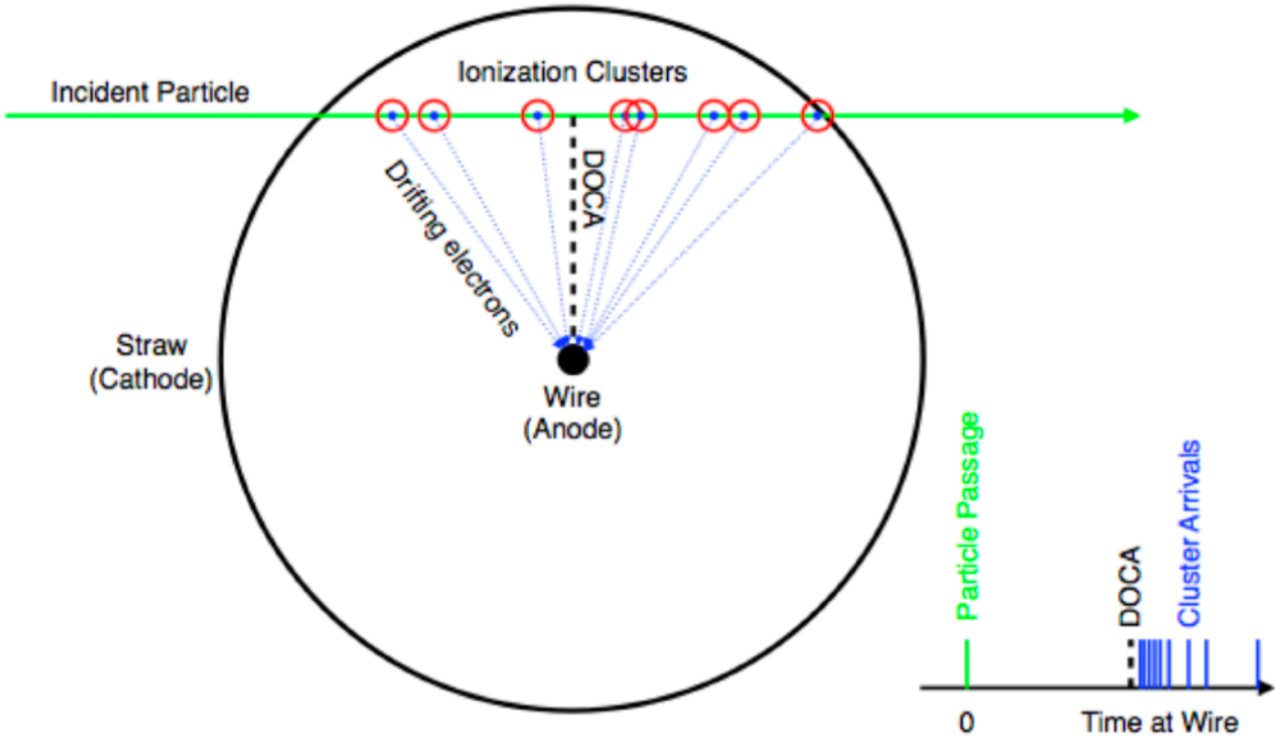
Tracker hole in the middle design

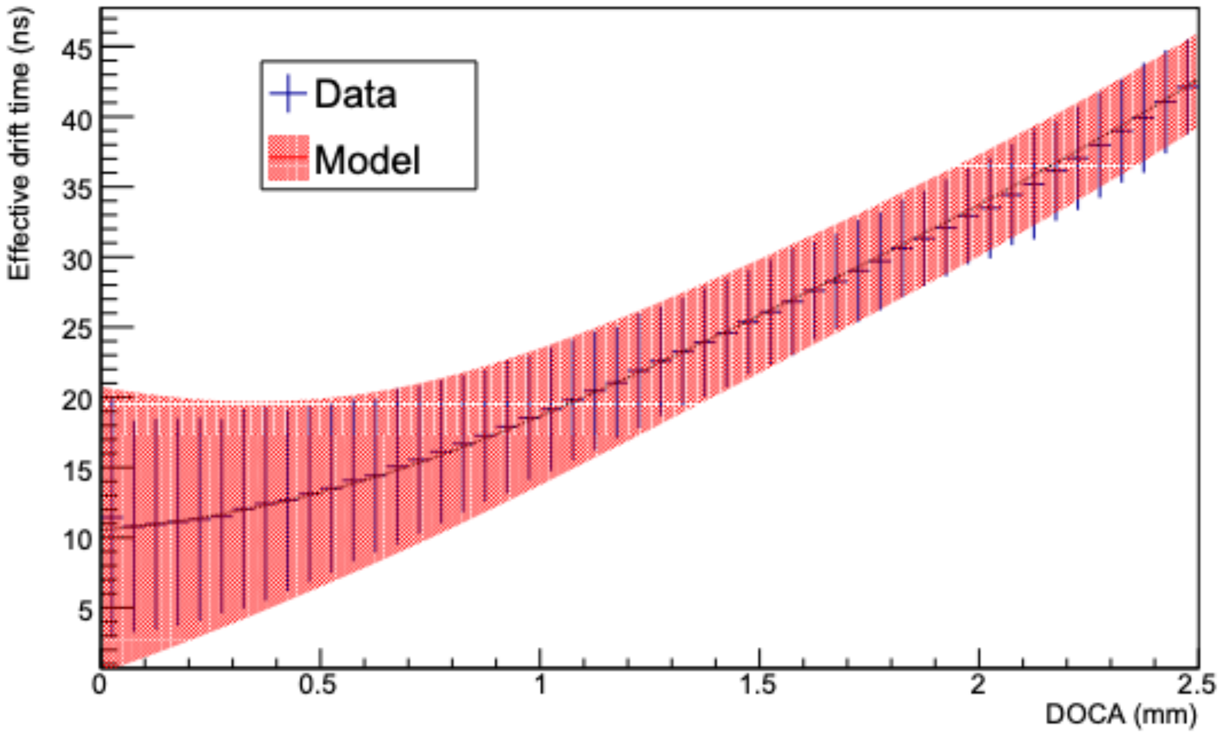
- Center(<400 mm) is empty to make the detector blind against most DIO electrons, beam artifacts.



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.

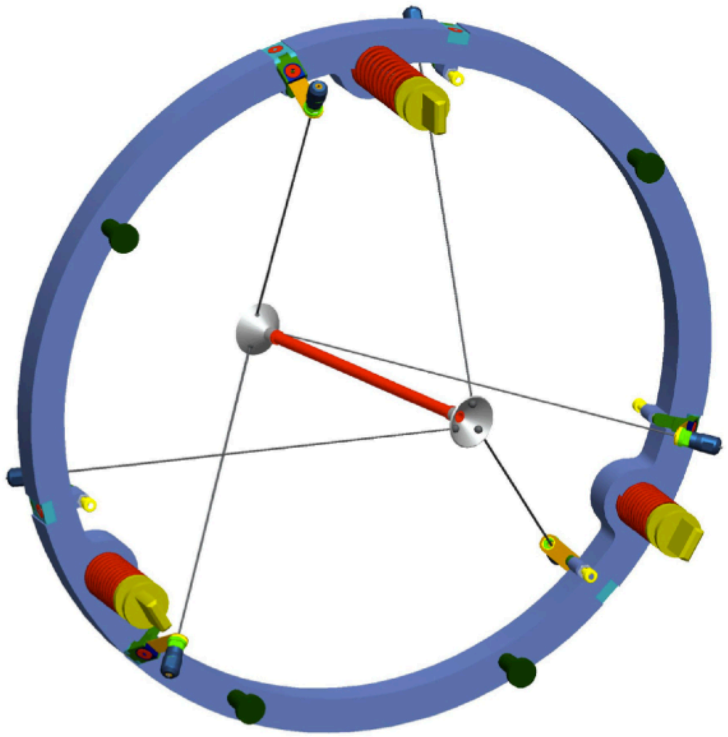




Targets

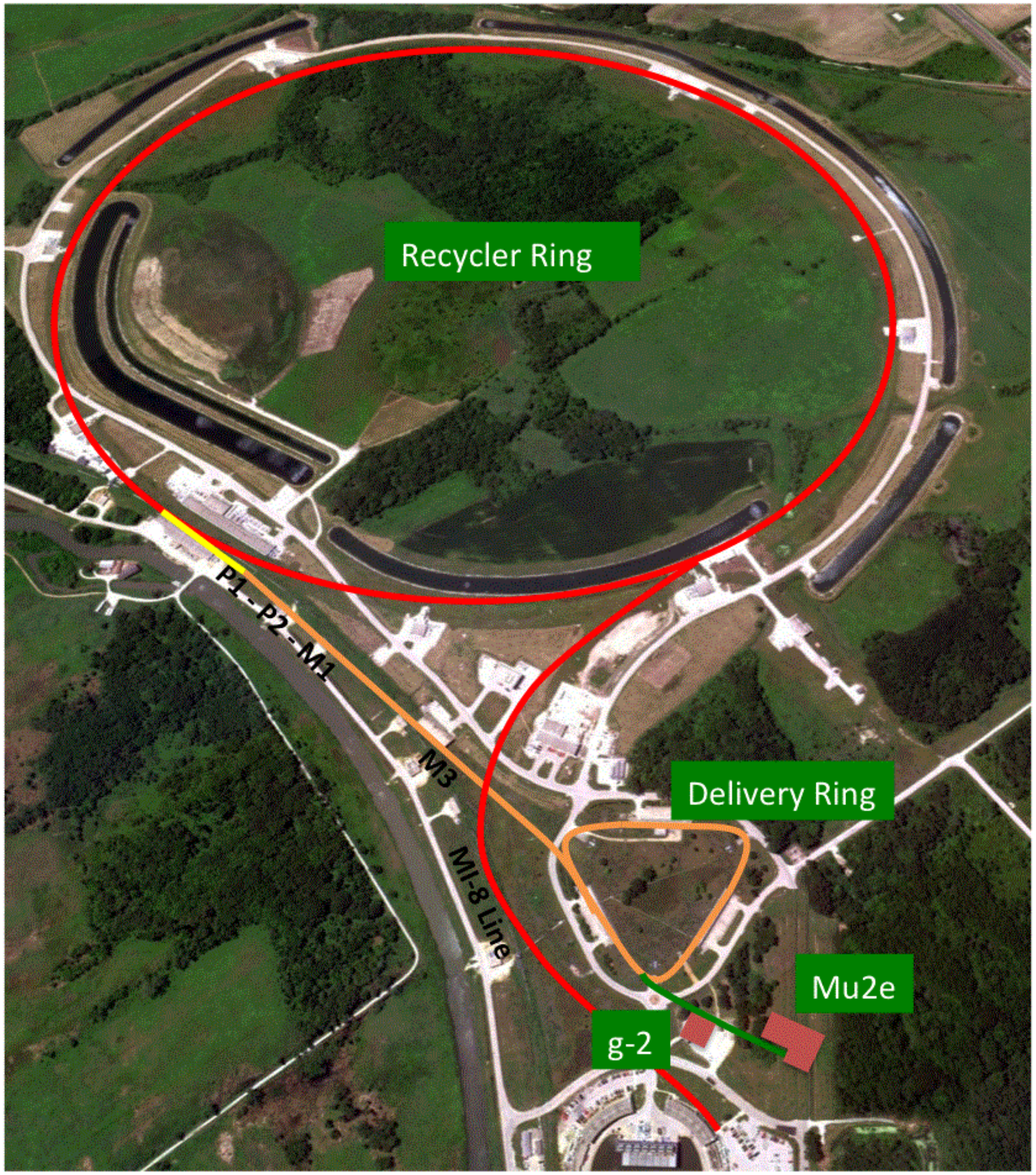
- Production target
  - Tungsten
  - Suspended on spokes
  - Minimize scattering & π absorption
  - 1400 msec beam cycles
  - 630 W power absorption
  - 2000 K temperature
  - Operate 1 year

- 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.

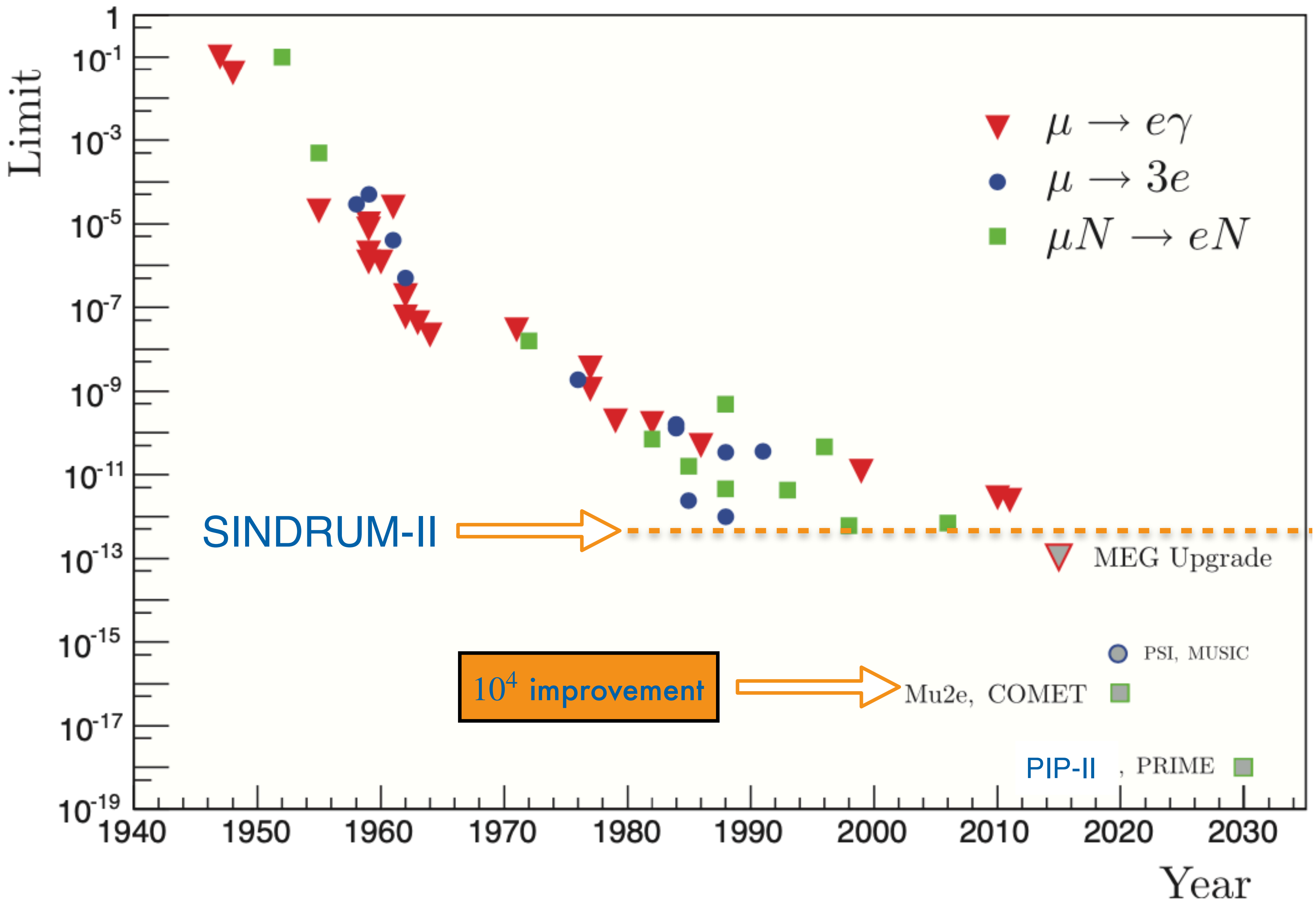


Beam delivery

- 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.
- 3.9×10^{7} POT per bunch.
- 3.6×10^{20} POT total



Muon searches history



SINDRUM-II

10^4 improvement

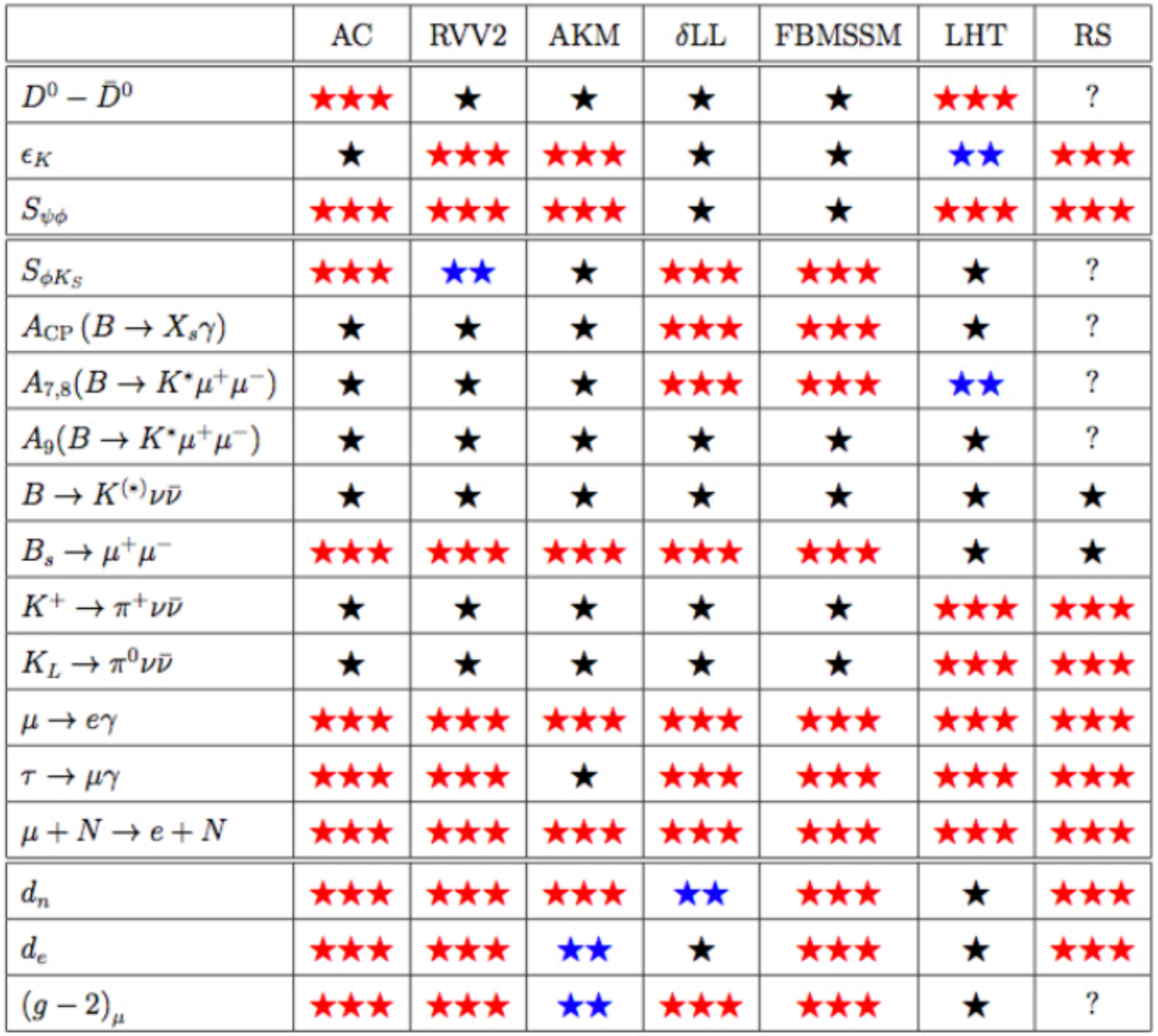
PIP-II

R. Bernstein, P. Cooper; arXiv:1307.5787

CLFV processes sensitivity to BSM

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

★★★ = Discovery Sensitivity

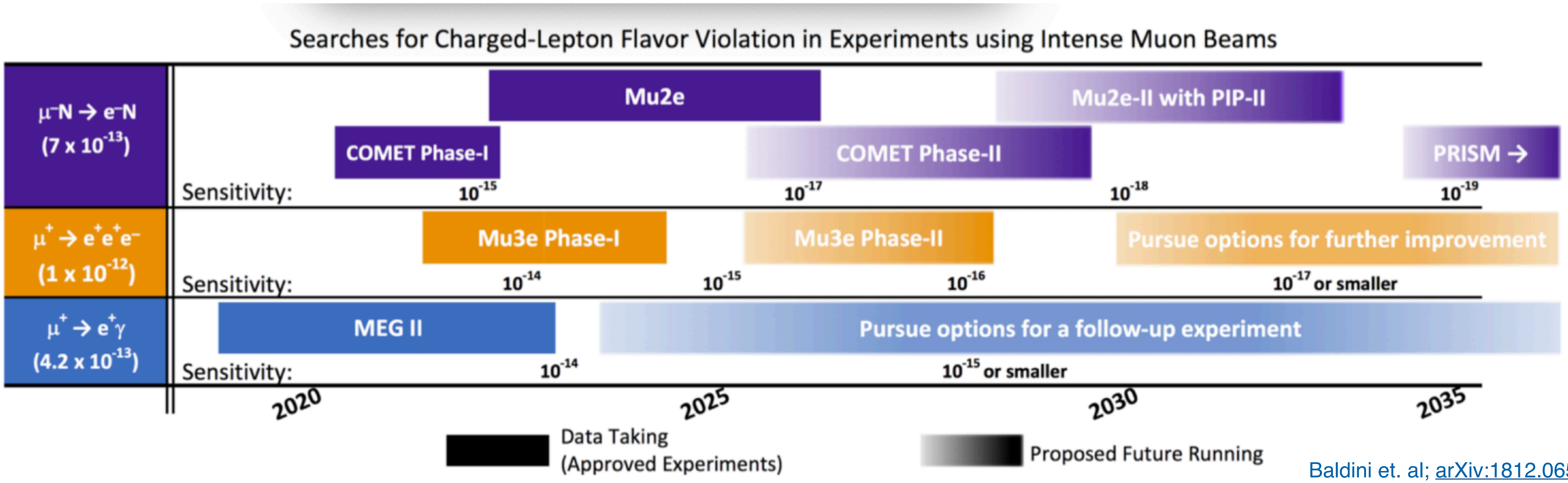


	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★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

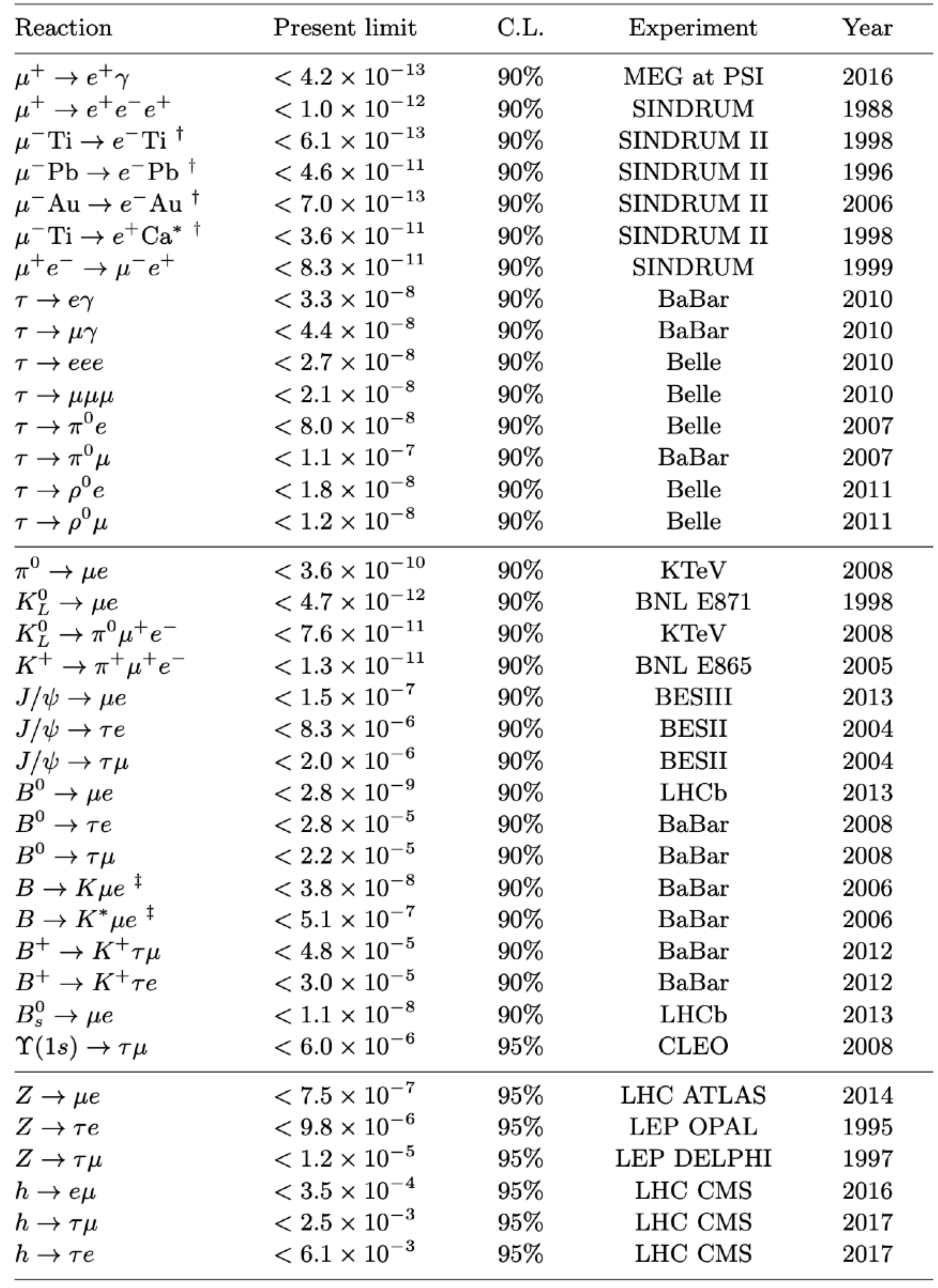
arXiv:0909.1333[hep-ph]

Looking forward in muon searches



Baldini et. al; arXiv:1812.06540v1

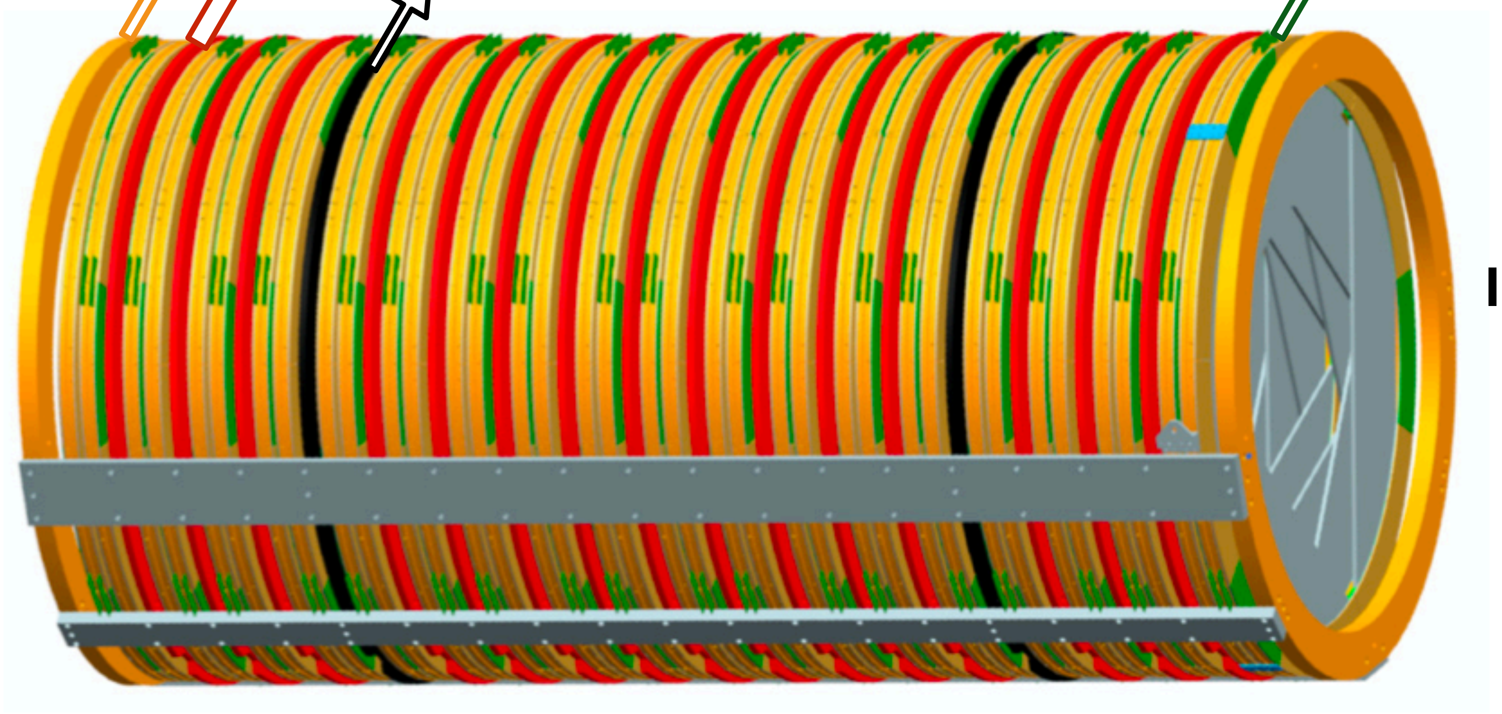
CLFV experimental limits



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
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	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



End disks x 2

Absorber disks x 15

Support rings x 2

Tracker planes x 36

Incoming beam