Muon4Future

Future μ→e conversion experiments

Gianantonio Pezzullo

Yale University

on behalf of the Mu2e-II collaboration

What is μ→e conversion?

- μ converts to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

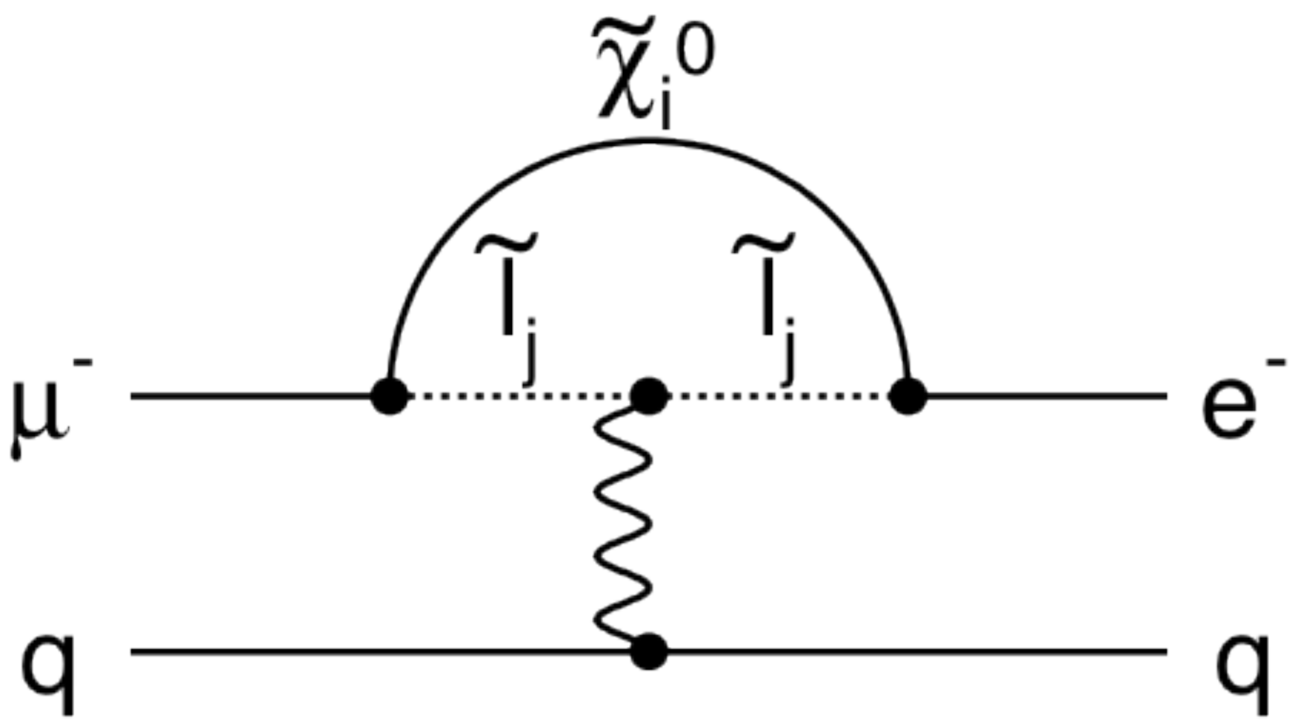
$$\mathrm{E}_e = \mathrm{m}_\mu \ \mathrm{c}^2 \text{ - } \mathrm{B}_\mu(\mathrm{Z}) \text{ - } \mathrm{C}(\mathrm{A}) = 104.973 \text{ MeV}$$

- for Aluminum: $\begin{cases} \mathrm{B}_\mu(\mathrm{Z}) \text{ is the muon binding energy (0.48 MeV)} \\ \mathrm{C}(\mathrm{A}) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

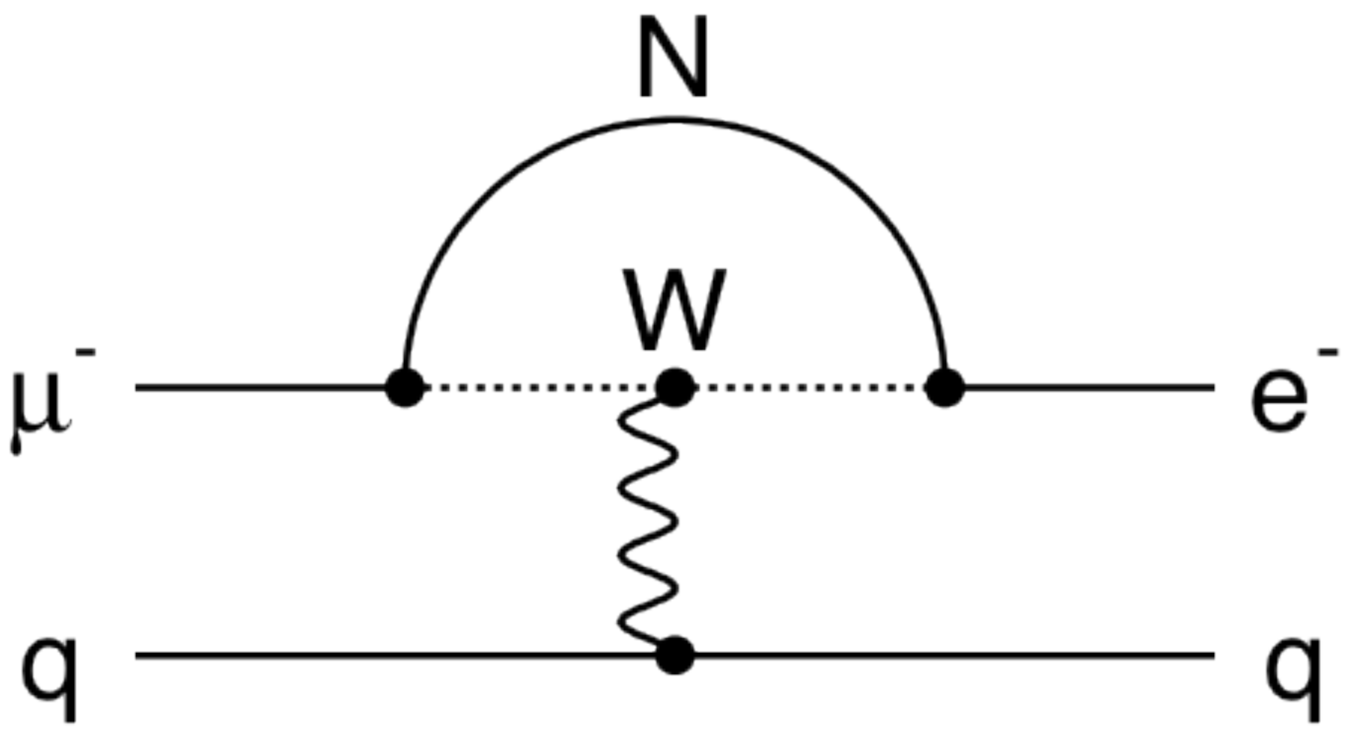
- Signal normalization:

$$\mathrm{R}_{\mu \mathrm{e}} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \mathrm{e}^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \text{all captures}\right)}$$

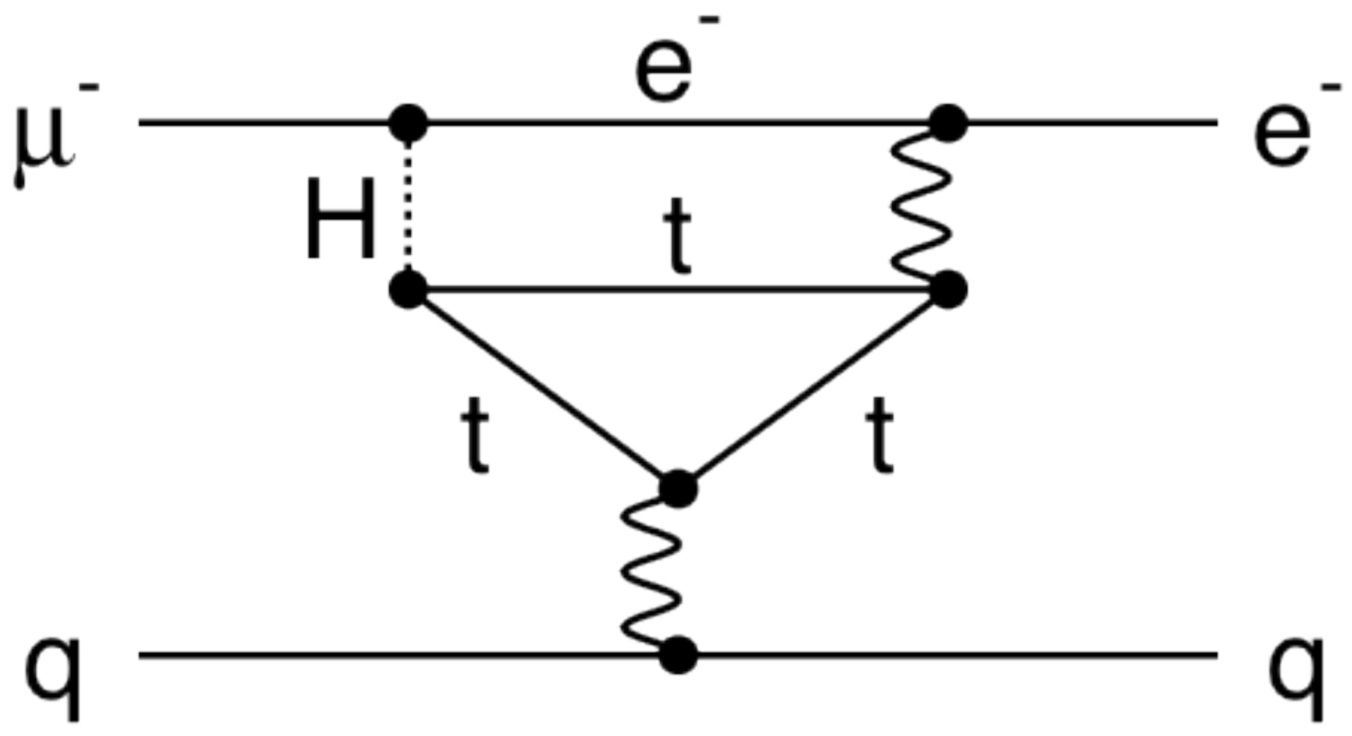
New Physics and μ→e



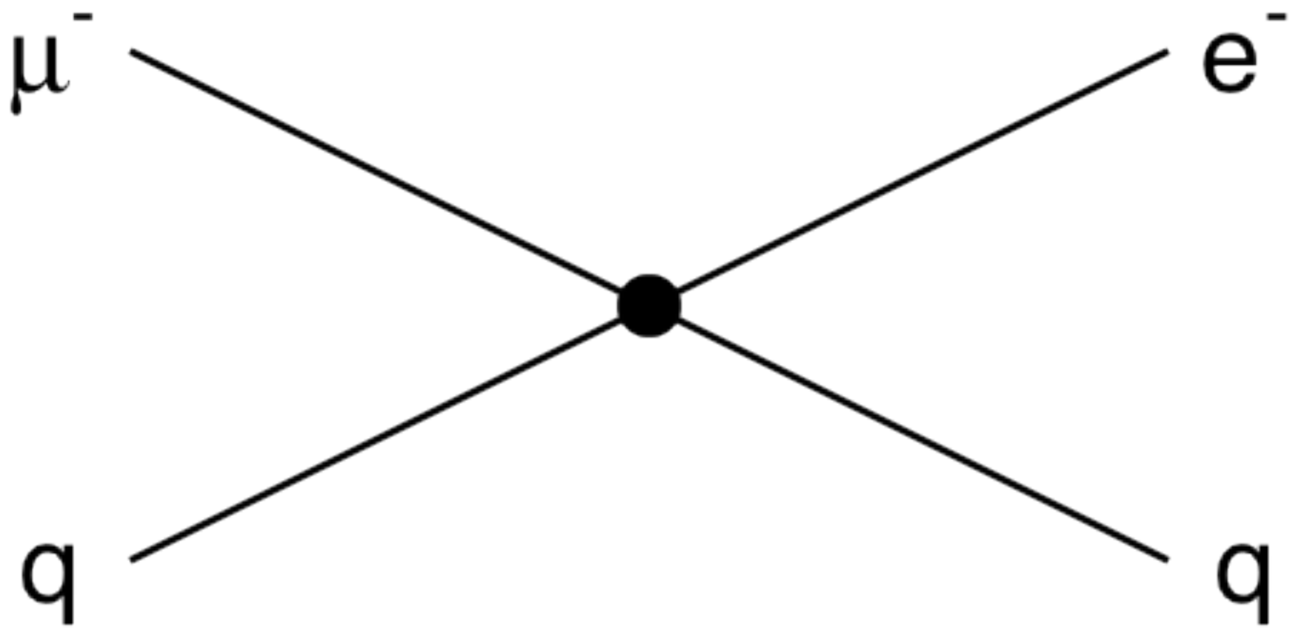
SUSY



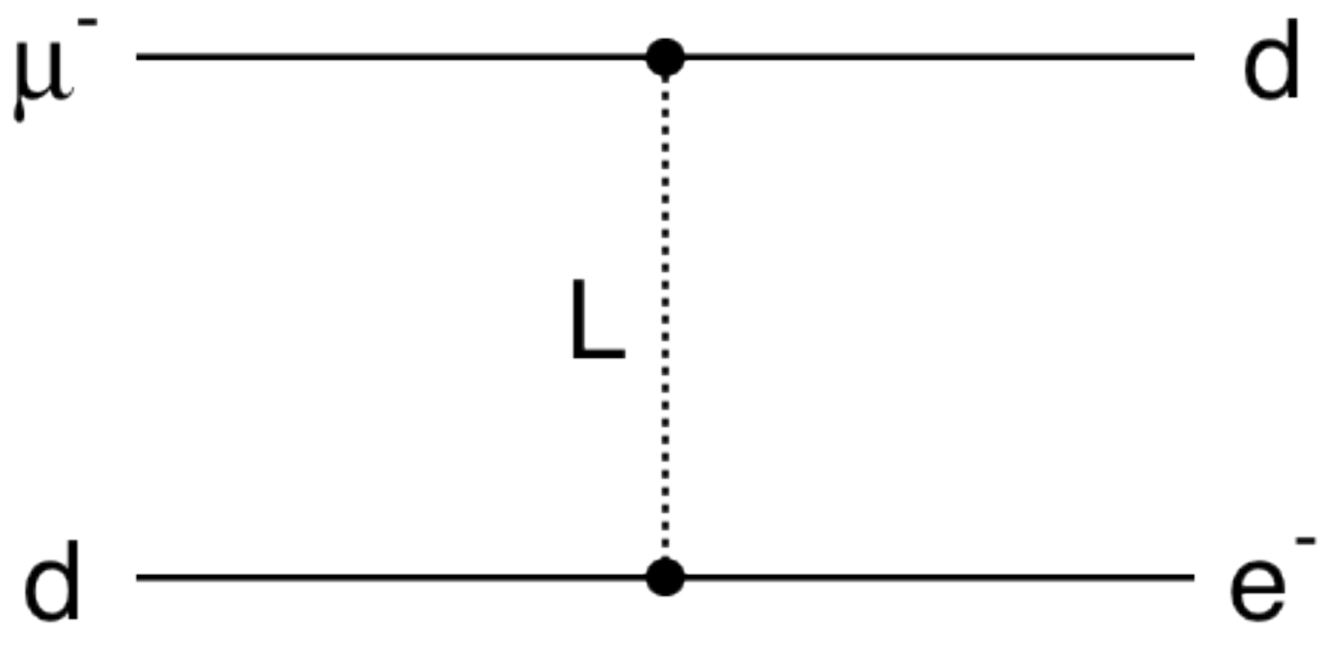
Heavy neutrino



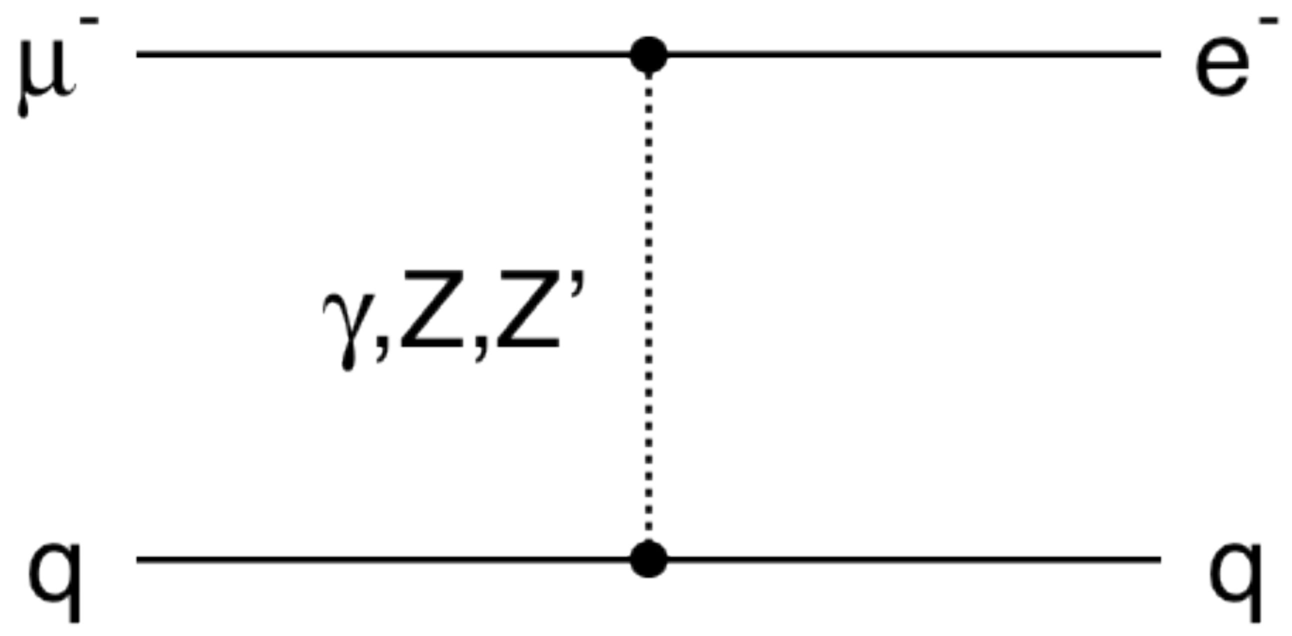
Two Higgs doublet



Compositeness



Leptoquarks



Z'/anomalous couplings

- Any signal observation would be an unambiguous sign of **New Physics**

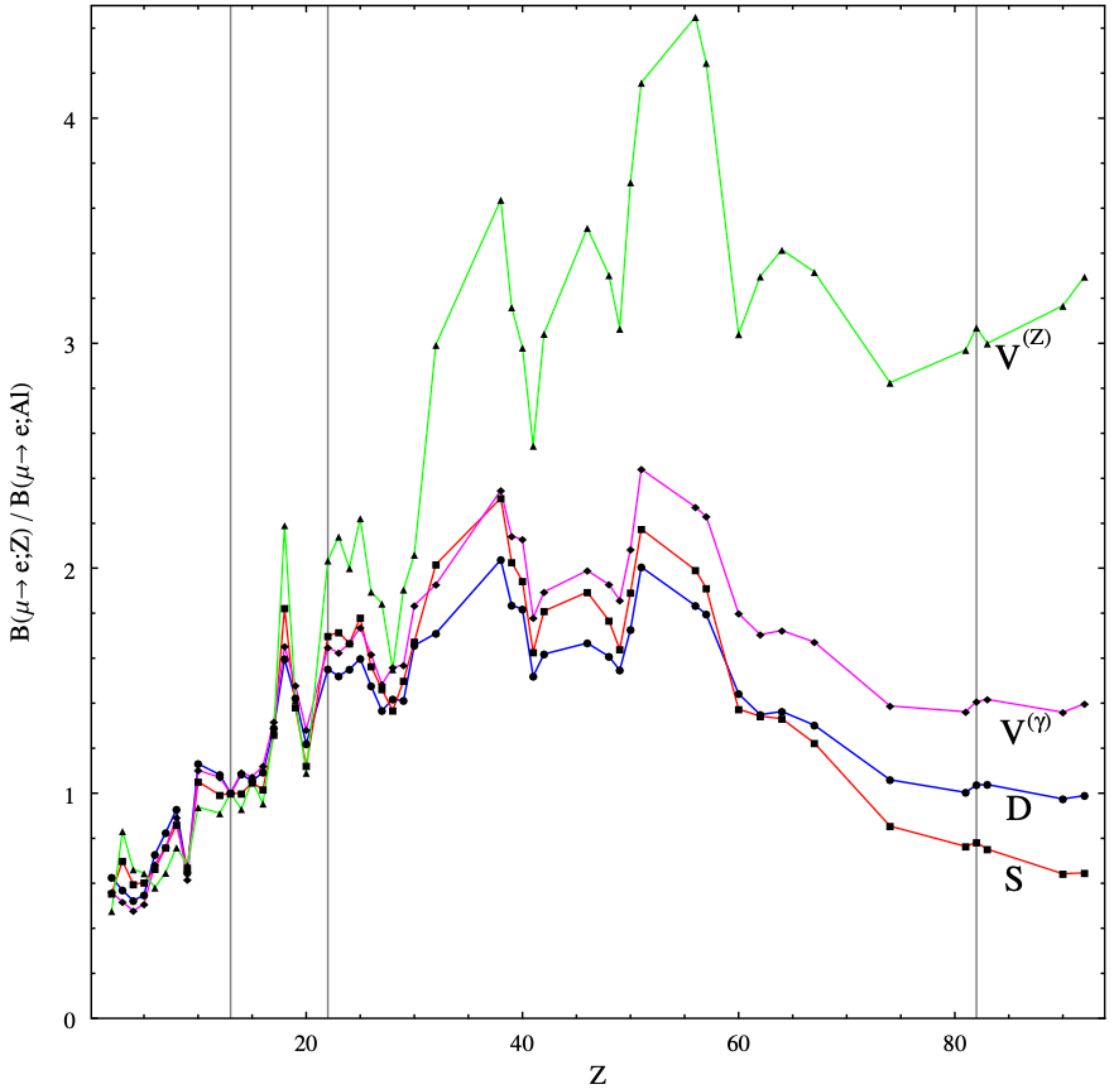
Motivation

- **$\mu \to e$ is the "golden channel" of CLFV**
  - Probes complementary regions of NP space
  - Measured rates can provide model discrimination

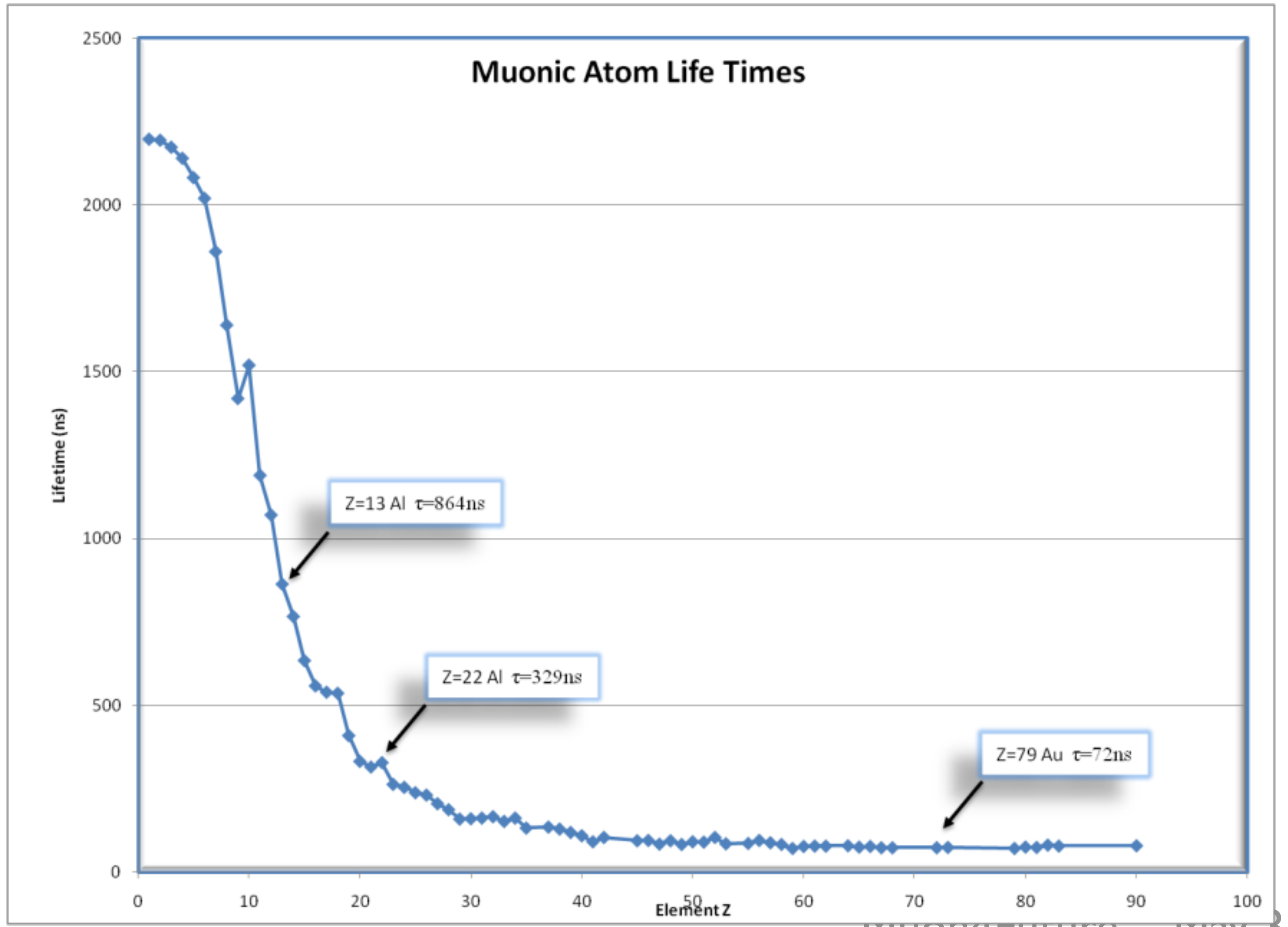
Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET), ~6x10-18 (Mu2e-II)

Model discrimination

- If we observe μ→e, we can measure the rate using different target materials to probe the underlying NP operator
- Mu2e(II) beam timing structure preclude high-Z materials due to short muonic atom lifetimes
  - Al(864 ns), Ti (330 ns), Au (73 ns)

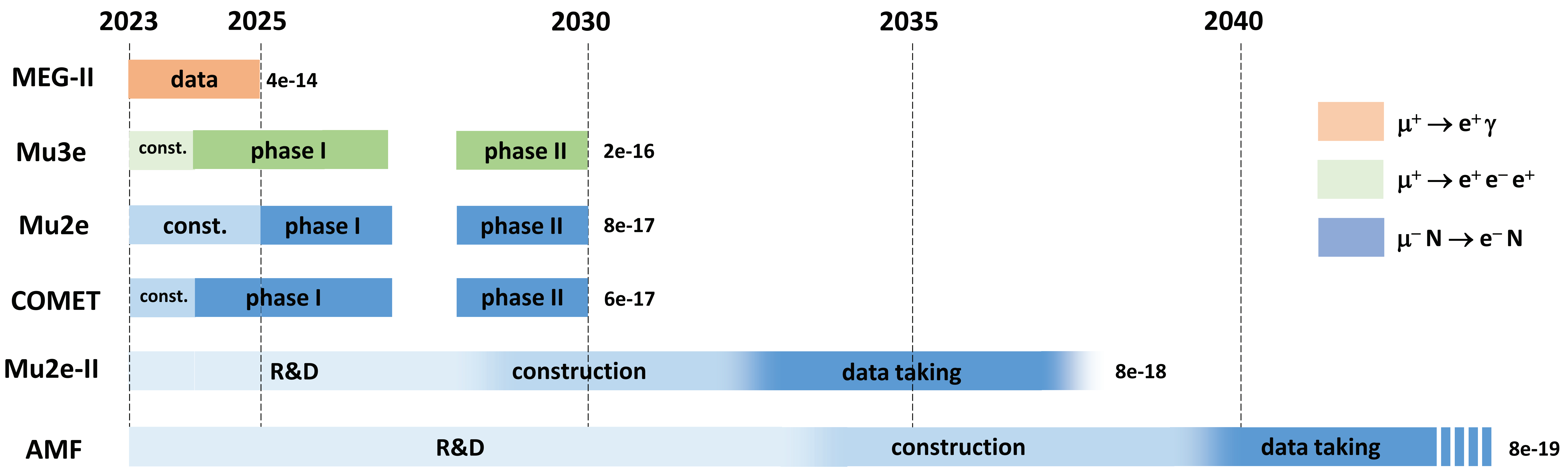


V. Cirigliano et al., Phys. Rev. D 80, 013002



Timescale

- Mu2e and COMET are under construction at Fermilab and J-PARK respectively
- Phase-I aims to reach x1,000 improvement w.r.t. the current best limit
- Phase-II will push the sensitivity at 6-8e-17



Mu2e experimental setup

Production Solenoid:

➡ Proton beam strikes target, producing mostly pions

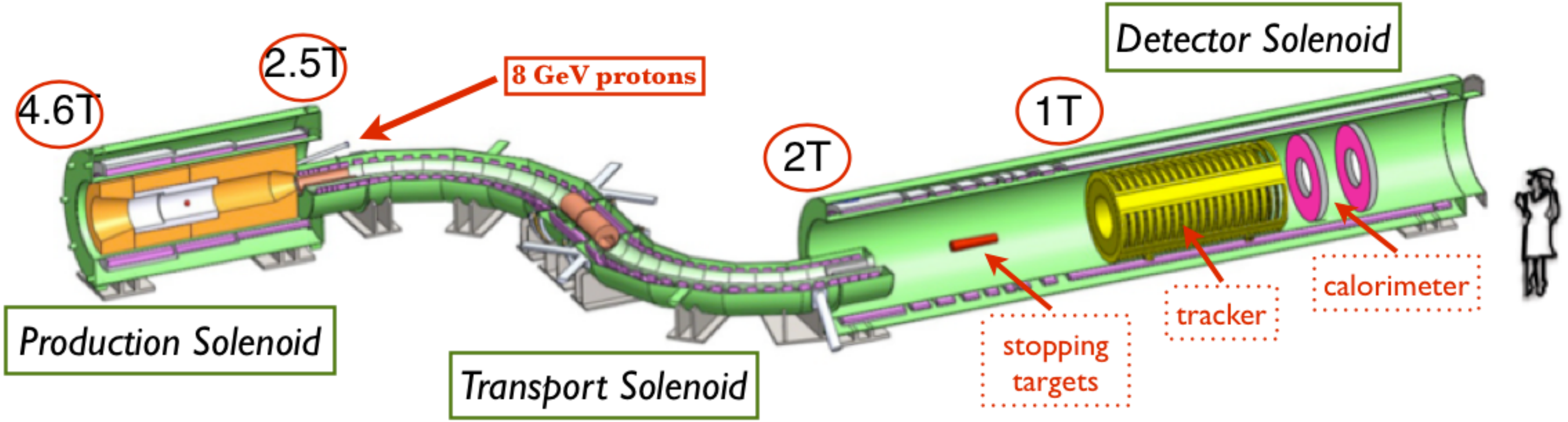
➡ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

Detector Solenoid:

➡ Capture muons on Al target

➡ Graded field "focuses" e^- in tracker fiducial volume

➡ Measure momentum in tracker and energy in calorimeter



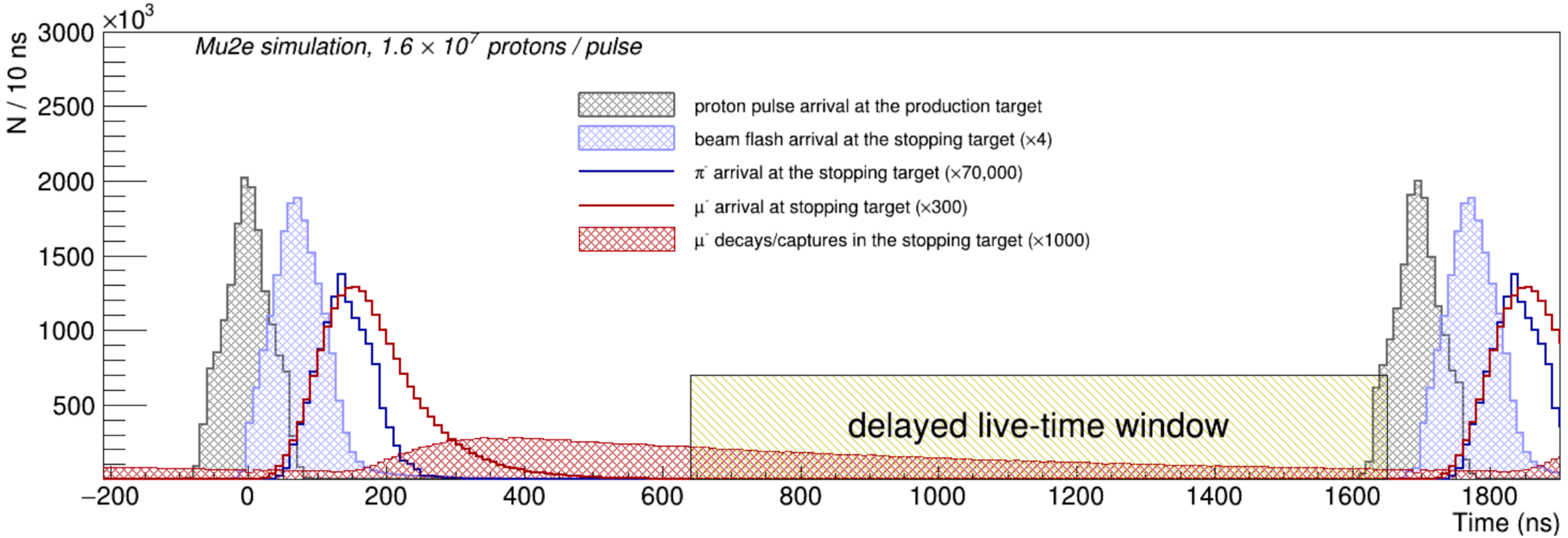
Transport Solenoid:

➡ Select low momentum, negative muons

Mu2e pulsed beam

- Beam period : 1.7 μs ~ 2 x τ_{μ}^{Al}
- DAQ gate start after ~400 ns from p beam arrival
- **out-of-time protons / in-time protons < 10^{-10}**

π are suppressed by 11 orders of magnitude before the DAQ gate

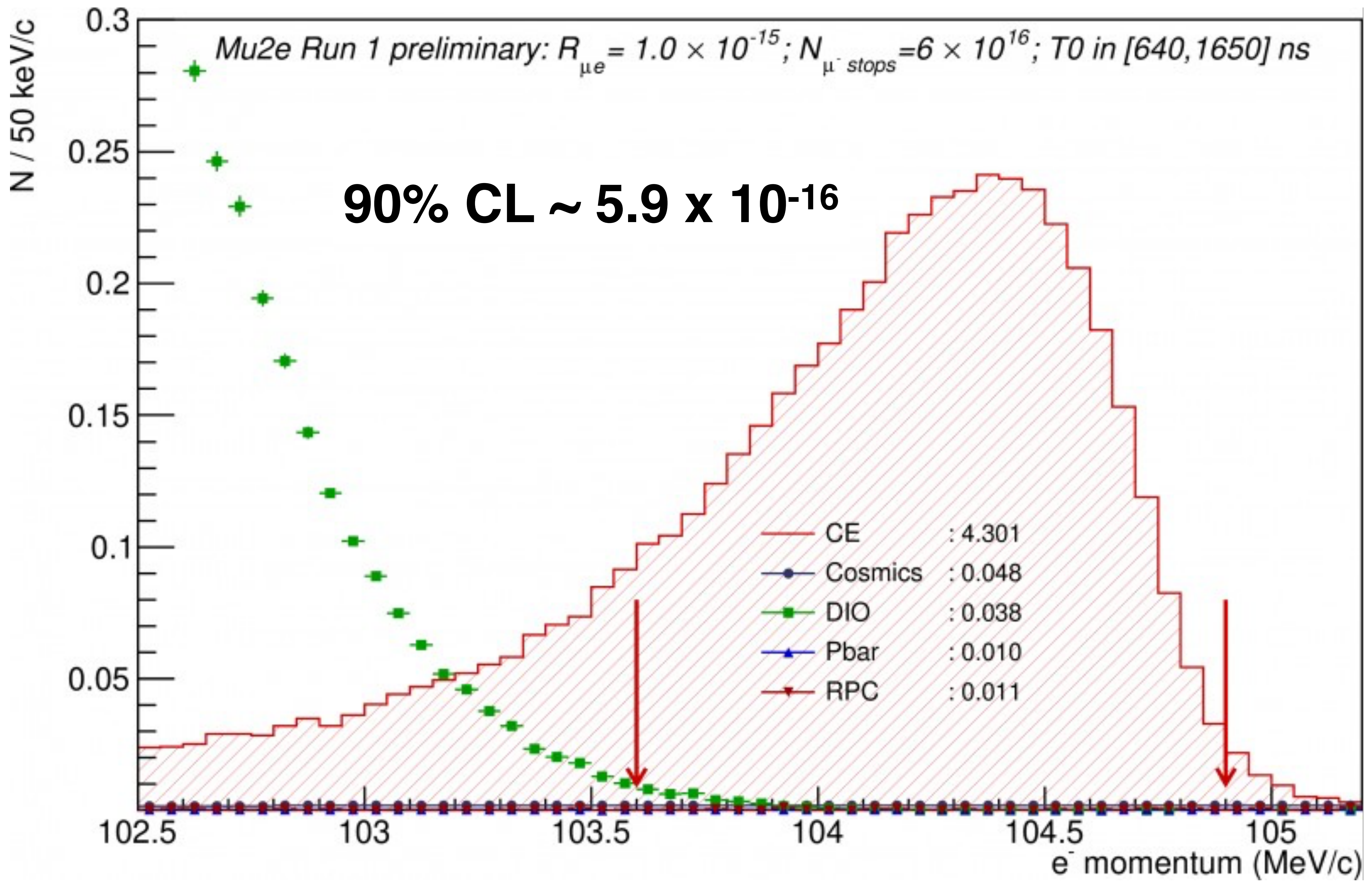


Mu2e Collaboration, arXiv: 2210.11380

Mu2e sensitivity

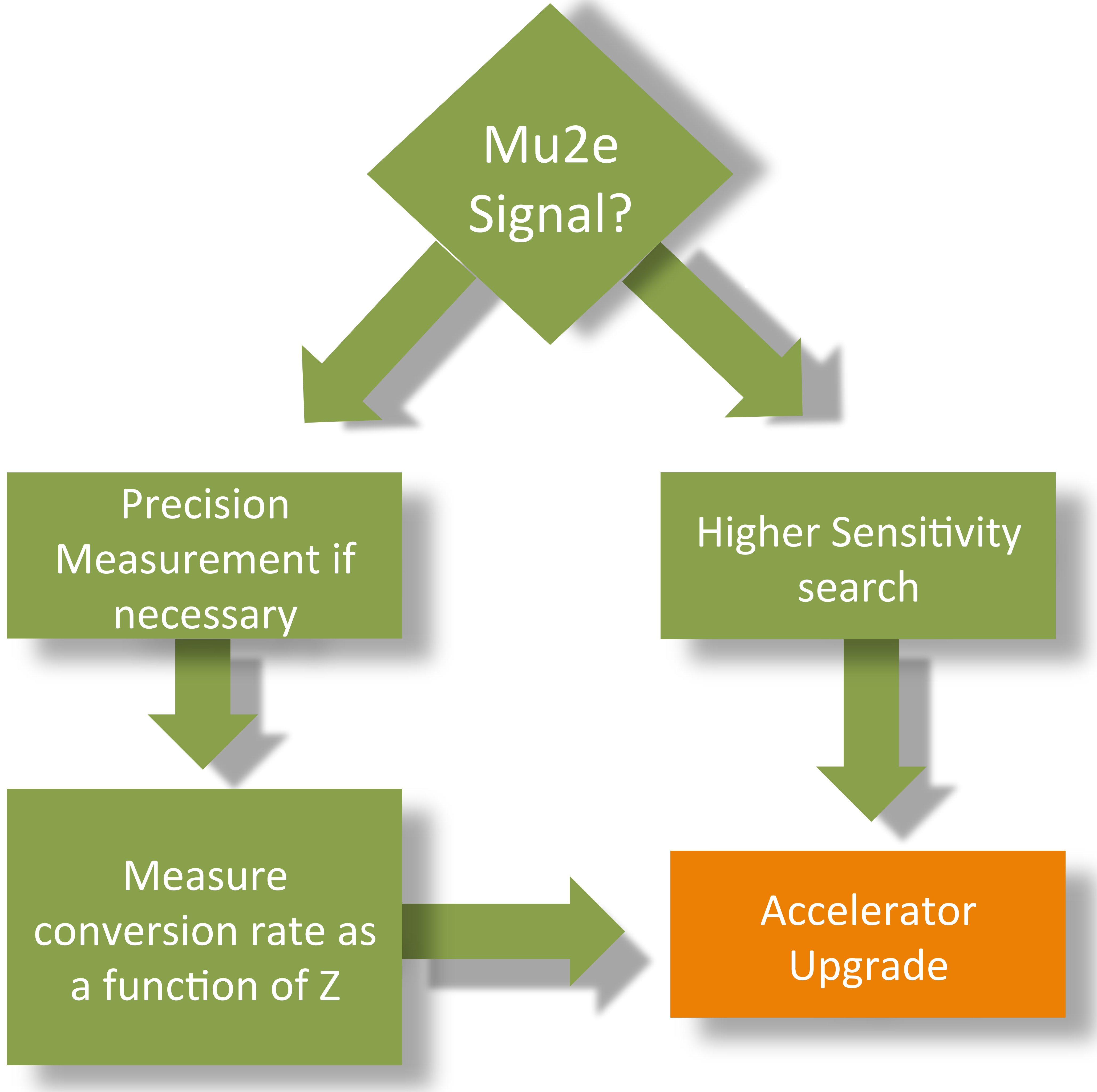
- **Run 1**: 2025-2026: 10^3 improvement over SINDRUM-II 90% CL limit
- PIP-II/LBNF shutdown scheduled for end of 2026
- Data-taking resumes early 2029: the goal is a x10^4 improvement over SINDRUM-II: (90% CL)

Channel	Mu2e Run 1 Background Expectation
Cosmics	0.047 ± 0.010 (stat) ± 0.009(syst)
DIO	0.038 ± 0.002 (stat)$^{+0.026}_{-0.016}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) $^{+0.010}_{-0.004}$ (syst)
RPC in-time	0.011 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time	negligibly small
RMC	negligibly small
Beam electrons	negligibly small
Total	0.106 ± 0.032 (stat$\oplus$syst)



Mu2e Run I sensitivity estimate

What's next?



- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons, thus an upgrade of the accelerator

Mu2e II

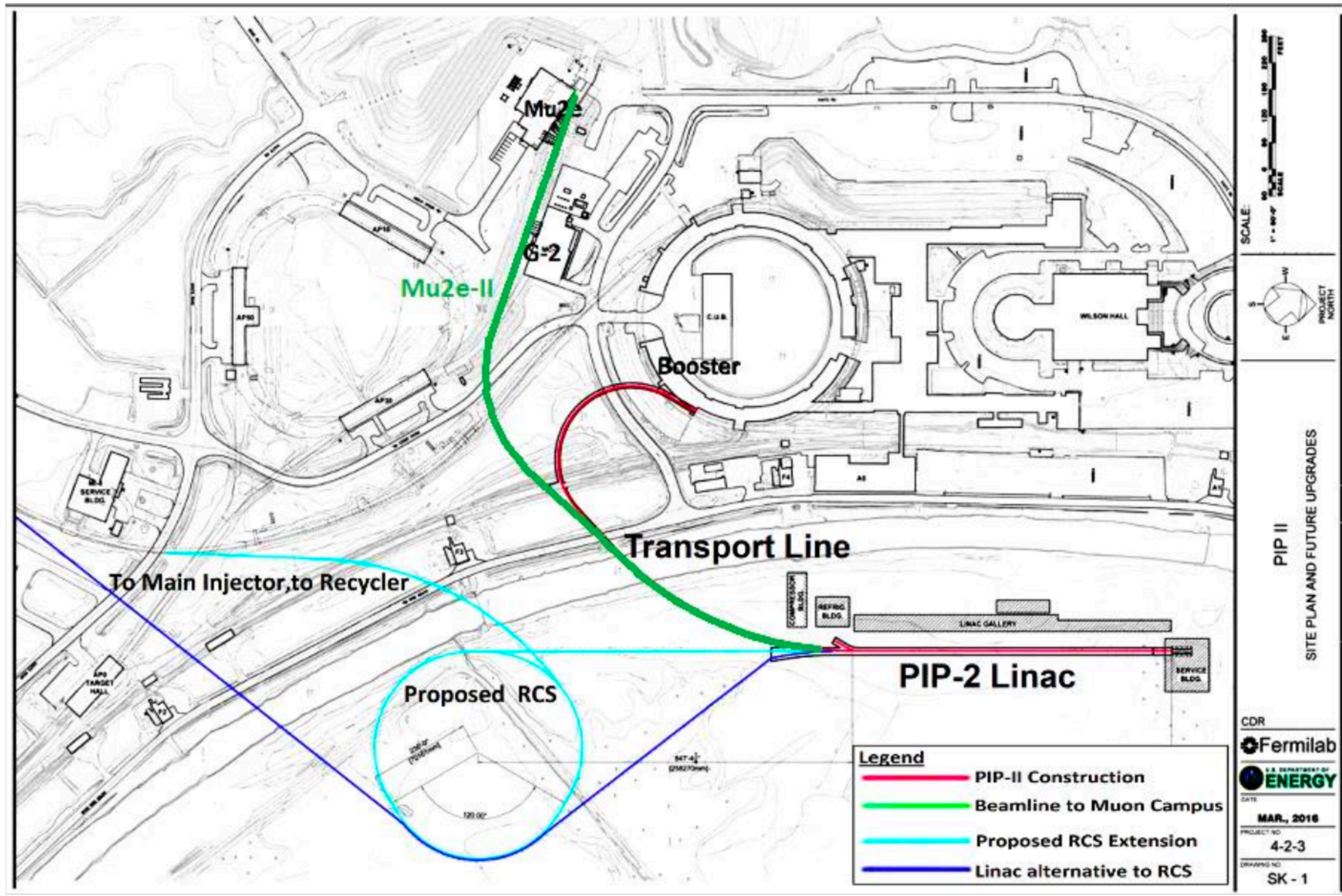
- **A proposed upgrade to the current Mu2e experiment that**
  - Uses ~100 kW of PIP-II 800 MeV protons
  - Leverages as much of Mu2e investment as reasonably possible
  - Achieves an order of magnitude improvement in sensitivity over Mu2e (i.e. probes $R_{\mu e}$ (90% C.L.) ~ 6e-18 level, extends Λ_{NP} reach by x2)
- **Timescale**
  - Could start a few years after end of Mu2e with conceptual design work already started
  - Data taking period: ~2035-2040
  - <u>R&D on critical items is needed now</u>

Mu2e II

- Studies of feasibility started a decade ago
  - Since then, multiple workshops and several study papers
- 2 Fermilab grants (LDRD) obtained so far: production target and tracker R&D
- 12 LOI's on Mu2e-II subsystems submitted to Snowmass
- **Snowmass White Paper** arXiv:2203.07569
  - 108 signatories from 34 institutes and 7 countries
  - Snowmass endorses the physics goal and recommends Mu2e-II as natural progression in the muon program

Mu2e-II proton beam from PIP II

- PIP-II designed to deliver 800 MeV H^- beam to the Booster
- Discussions ongoing to increase the beam energy up to 2-3 GeV
  - which is still below the pbar production threshold AND increase the π x-sec
- Mu2e-II will get a beam at upstream end of transfer line to Booster:
  - Need to build a beamline to deliver beam to M4 enclosure



Production Solenoid

- Stopped μ per watt comparable, 8 GeV vs 800 MeV
- Challenge: design a target that can handle very high heat and rad loads
  - Replace bronze heat and radiation shield with tungsten shield
- Not clear if PS will need to be replaced due to radiation damage or need for a larger radius to accommodate thicker shield
- Protons curve in field, injection path must be modified

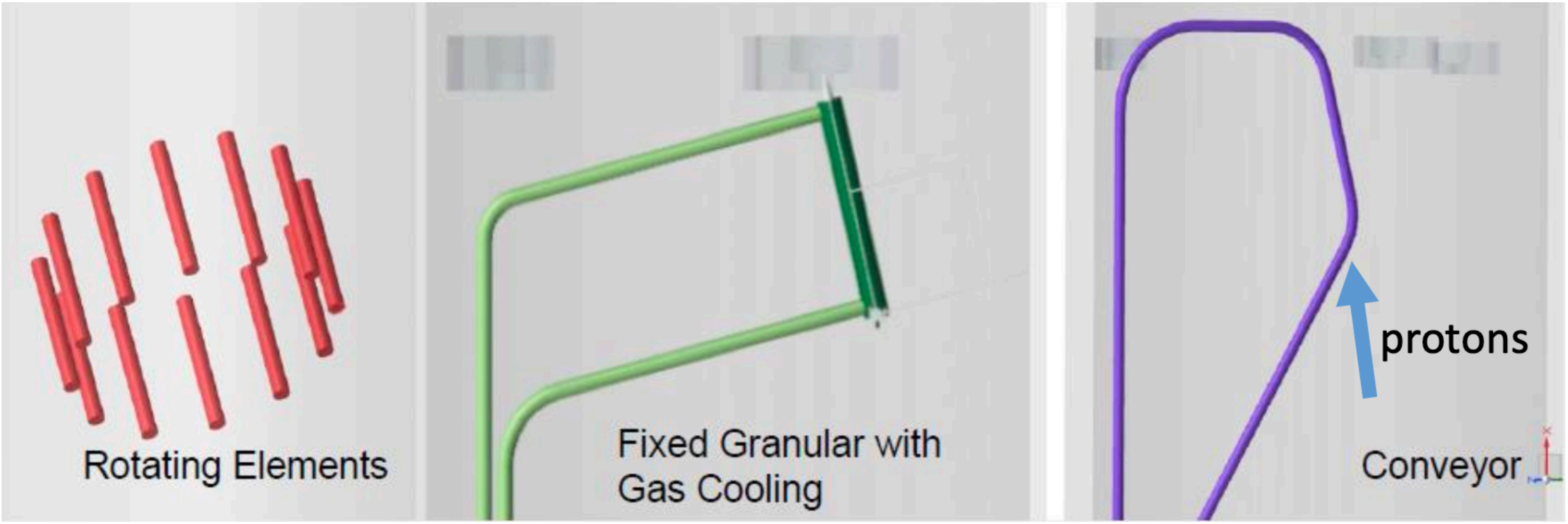

PS cold mass – inner shield dry run insertion


PS wires being routed to chimney area


PS outer cryostat components fit-up.

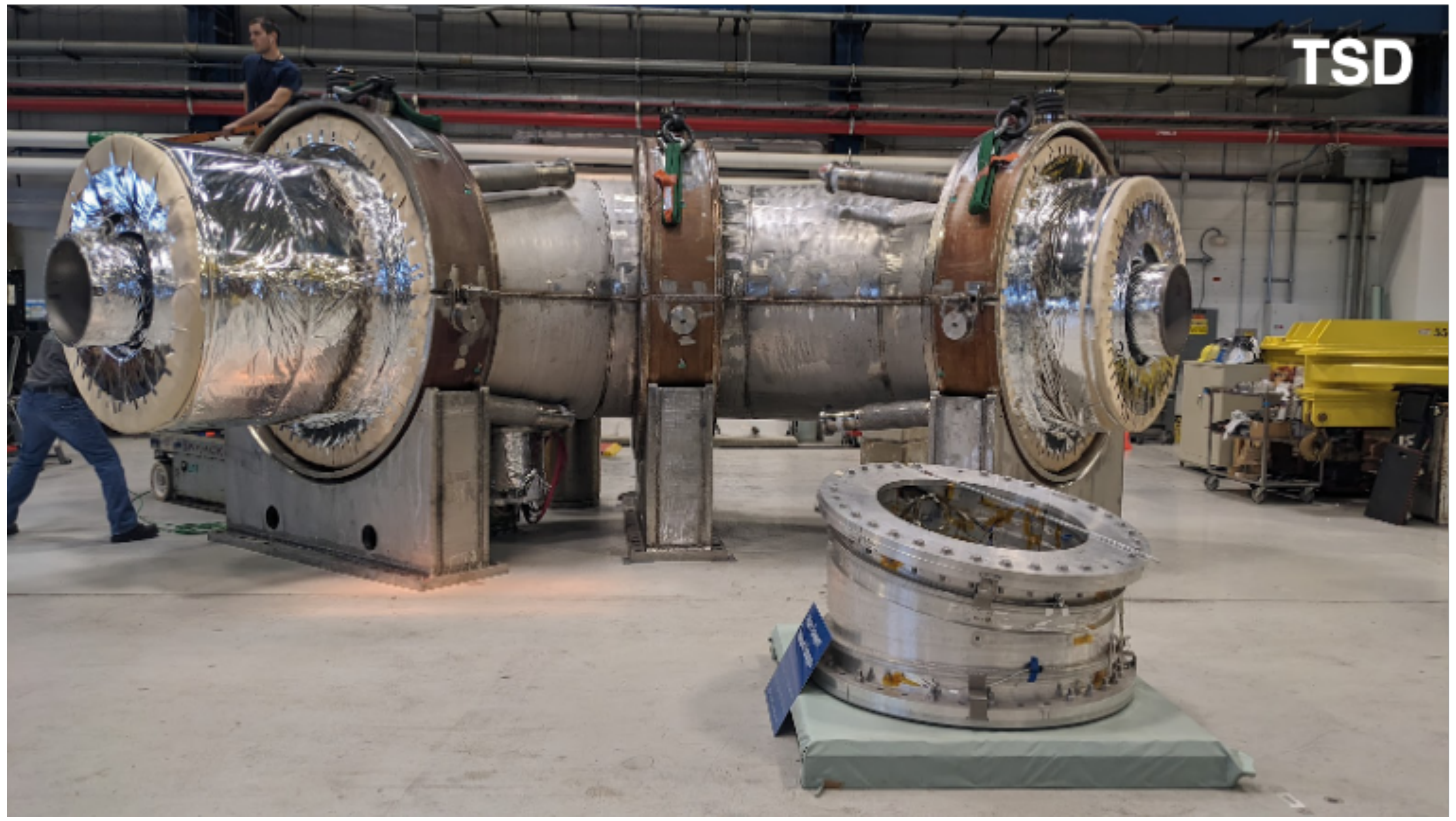
Mu2e-II Production Target

- Mu2e dumps ~1kW in a W target that is radiatively cooled, while for Mu2e-II, we will have ~15 kW in target
- Exploring different target materials: W, WC, SiC
  - Fermilab LDRD supports target investigations
- Conveyor prototype is current front-runner
- Simulations ongoing of μ-yield, thermal stress, radiation damage, residual activation, radiation and heat loads
- Synergy with other target groups e.g. muon collider, COMET, and AMF are being discussed



Transport Solenoid

- Delivery to Mu2e hall expected Oct 2023
- thin absorber in center can be removed - 800 MeV beam does not produce antiprotons
- No or minor changes anticipated for Mu2e-II upgrade
- Assumes upstream portion does not suffer excessive radiation damage from Mu2e operation
- For Mu2e-II: Perhaps we can reduce aperture to reduce average momentum of muons, stopping a larger fraction in a thin target and they will arrive later so more survive into live window



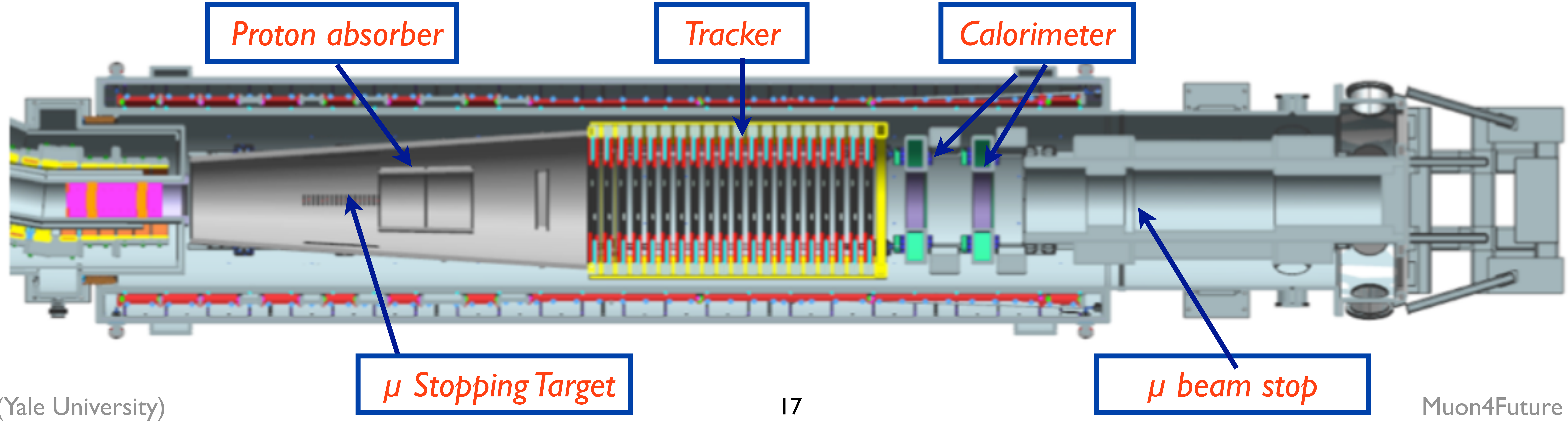
Detector Solenoid

Mu2e:

- 10/11 DS coils wound and epoxied
- Cold mass cryo supports prepared
- Delivery to Fermilab expected early 2024

Mu2eII:

- No changes necessary to the solenoid for Mu2e II
- Keep same detector arrangement as Mu2e

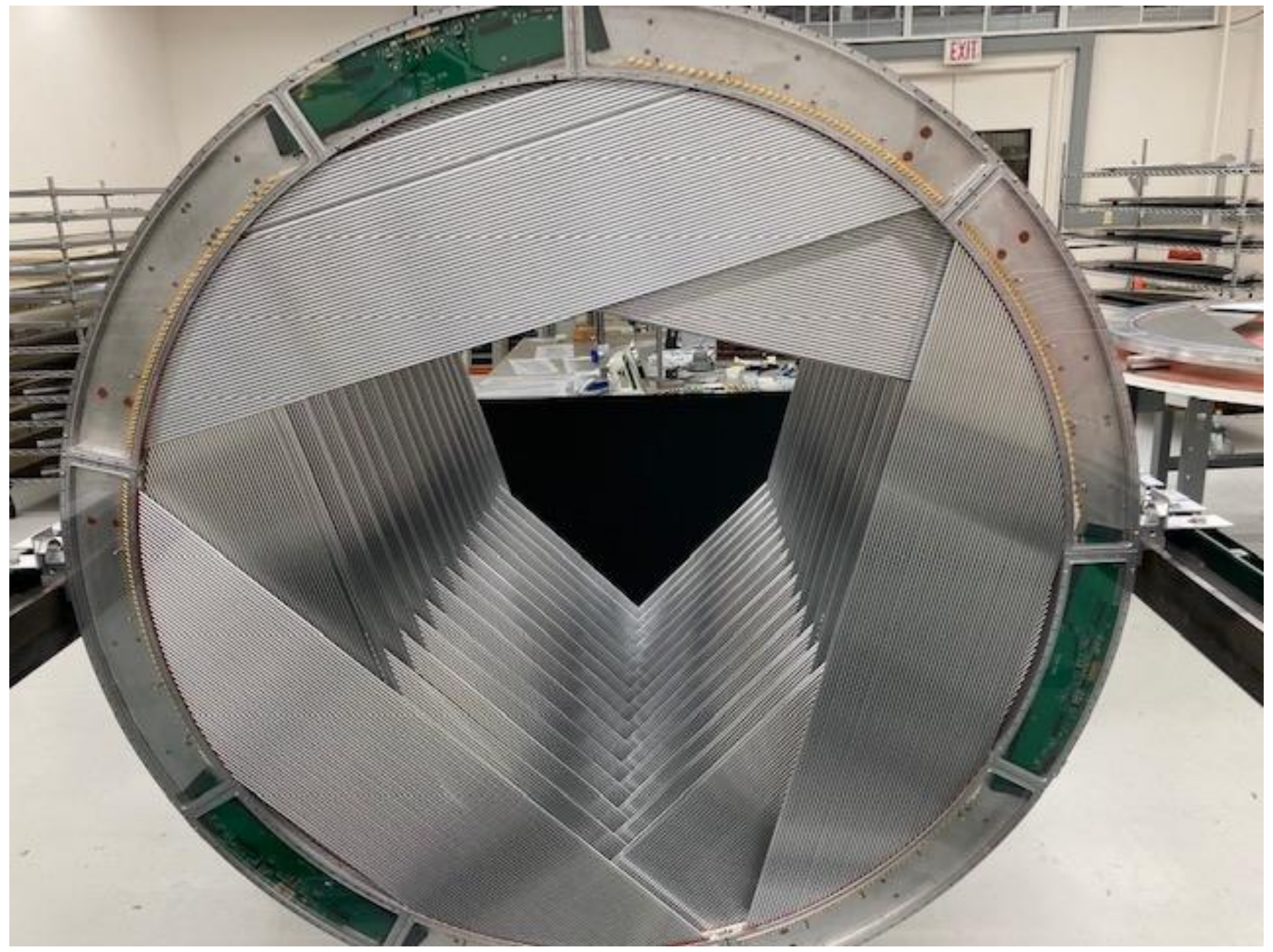


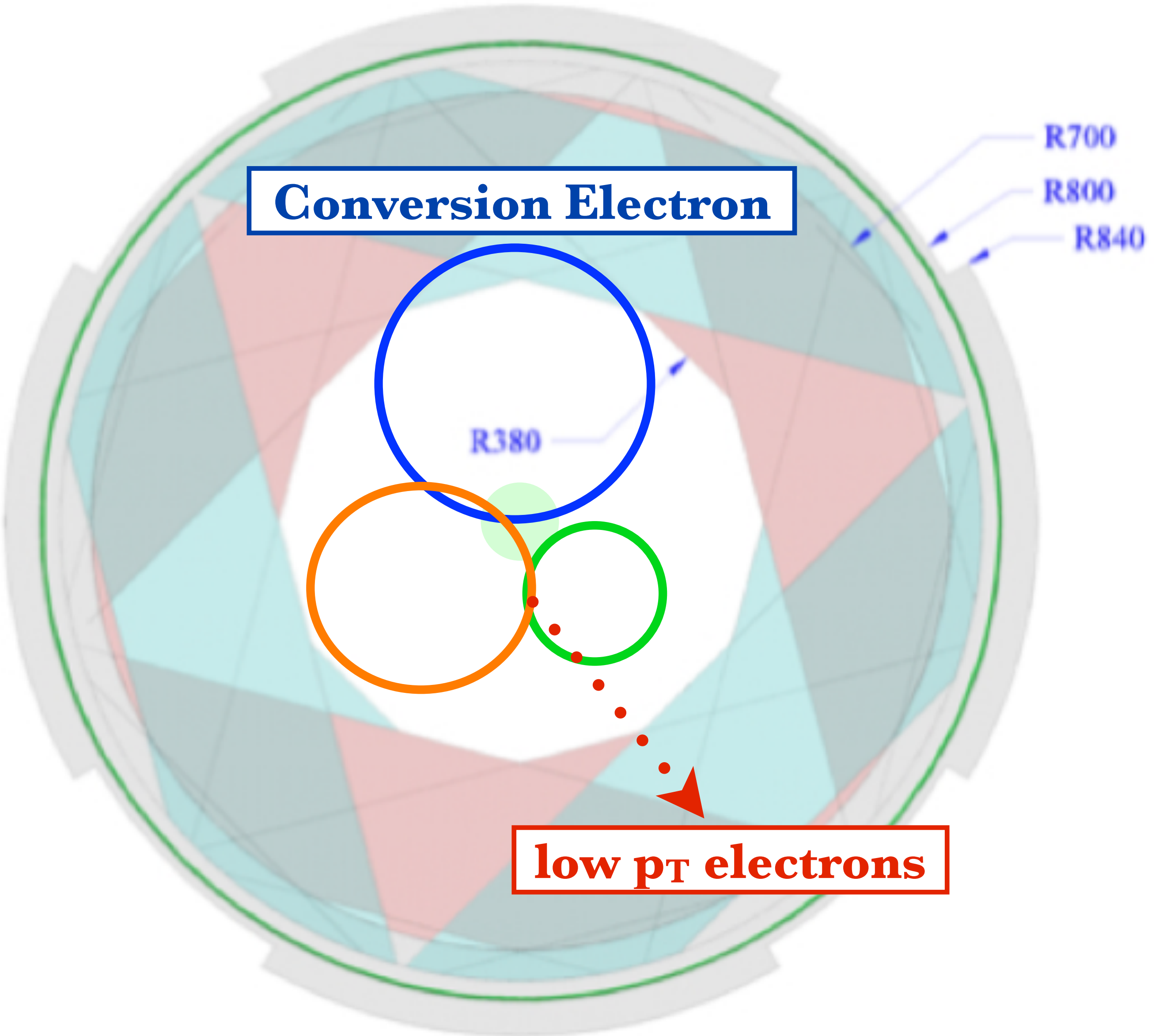
Mu2e-II
detector challenges

Mu2e Tracker design

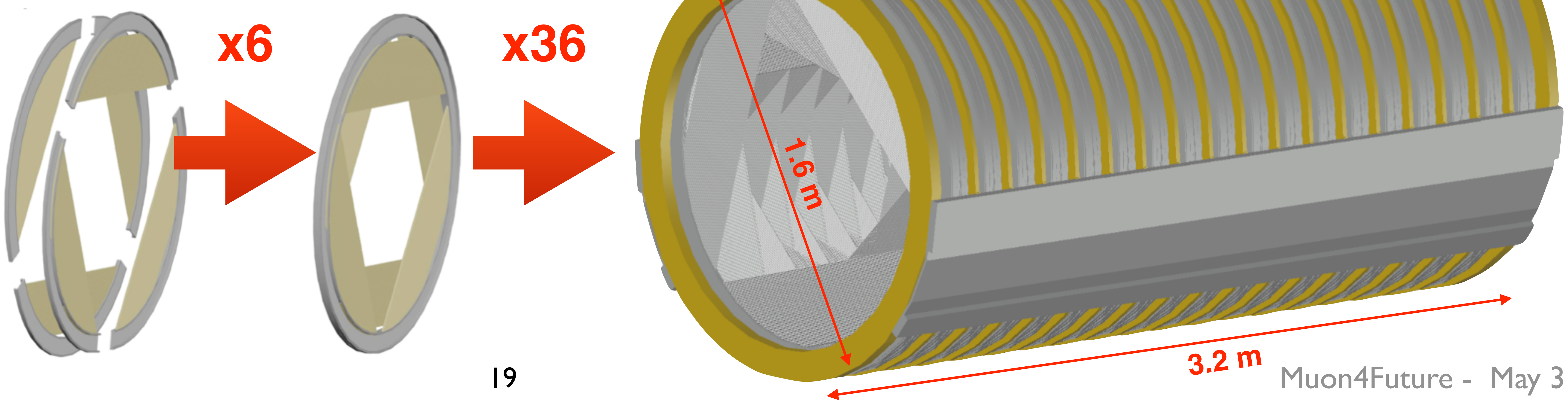
- 36 planes equally spaced with straws transverse to the beam
- Straw technology employed:
  - ✓ 5 mm diameter, 12 μm Mylar walls
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to **low** pT particles

Tracker assembly





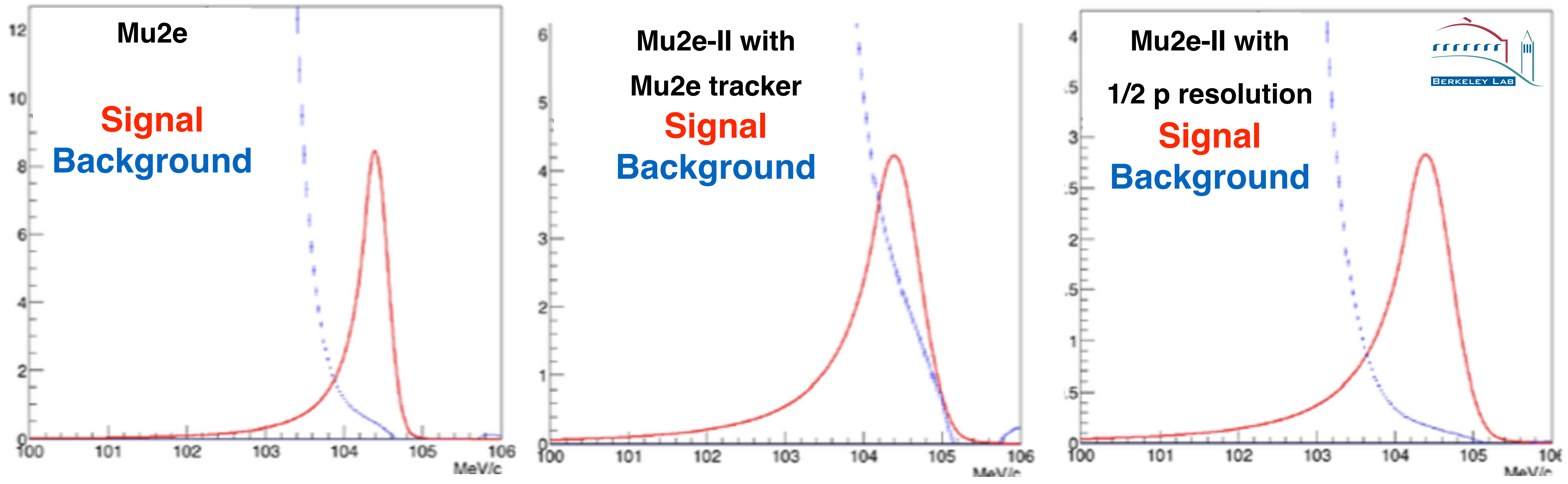
panel



Mu2e-II Tracker: challenges

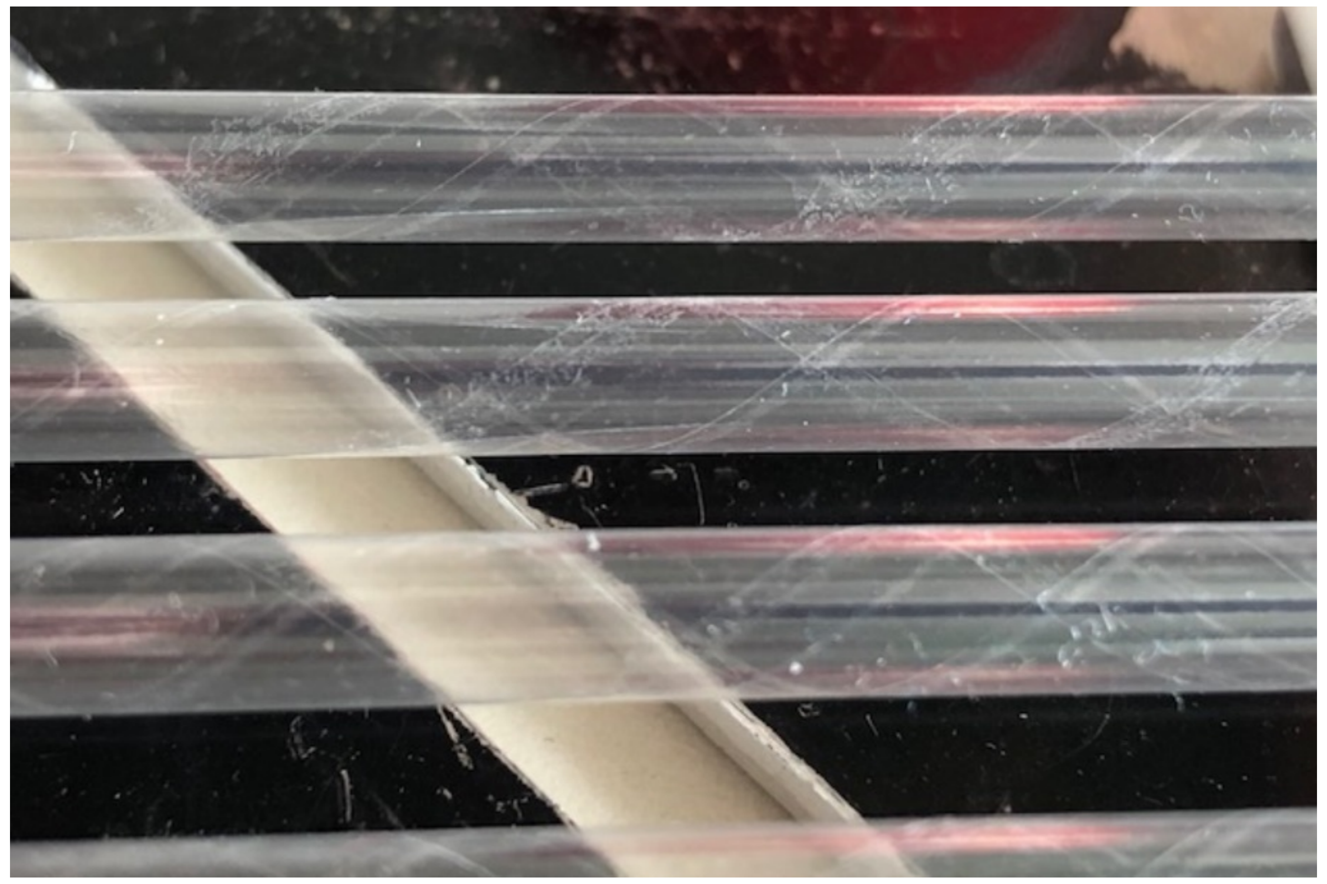
Challenges

- Increased radiation load in the electronics
- x4 higher intensity is expected to impact marginally the tracking efficiency (a few %)
- Increased momentum resolution requirement due to the higher DIO background level (~x10)
  - A toy MC study showed that the Mu2e tracker design doesn't provide discrimination
    - We need to reduce the material budget



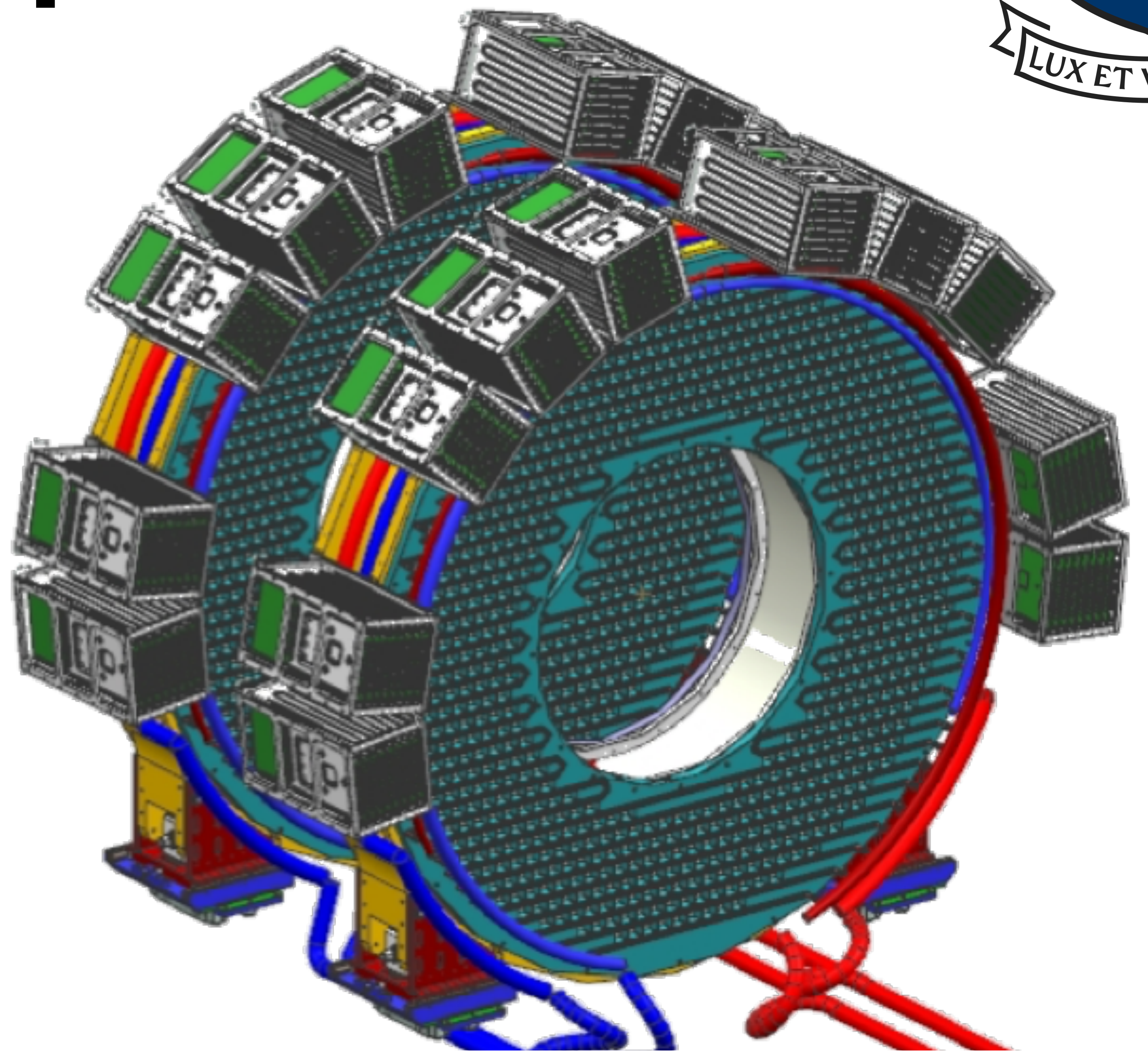
R&D:

- A LDRD @ Fermilab (Brendan Casey et al) is characterizing ultra-thin straw-tubes (3-8 μm)
  - Working with the same vendor that made the Mu2e straws
- Successful tests with 8 μm case:
  - Held 1 atm for multiple days
  - Survived 400 g tension without visible distortions
- Studying/testing also possible solutions for the support frame

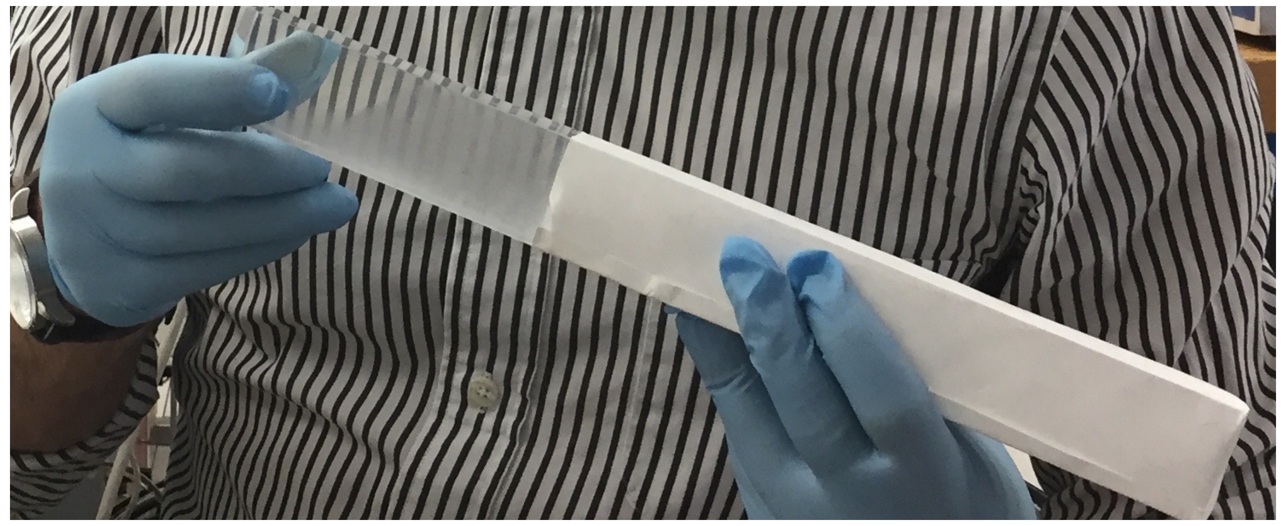


Mu2e Calorimeter design

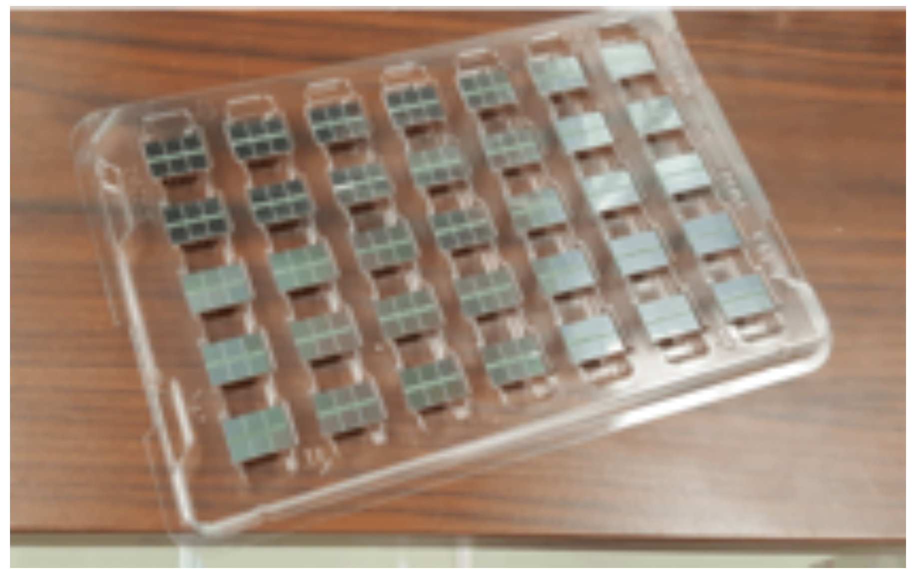
- 2 disks; each disk contains 630 undoped CsI crystals 20 x 3.4 x 3.4 cm^3
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- Readout system:
  - ➡ 2 large area SiPM-array/crystal
  - ➡ 12 bit, 200 MHz waveform-based digitizer boards

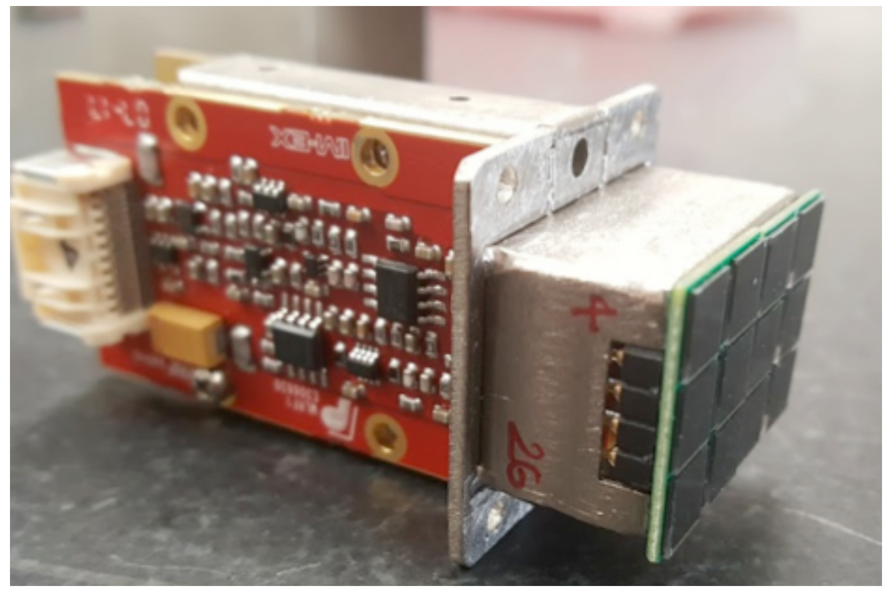


undoped CsI

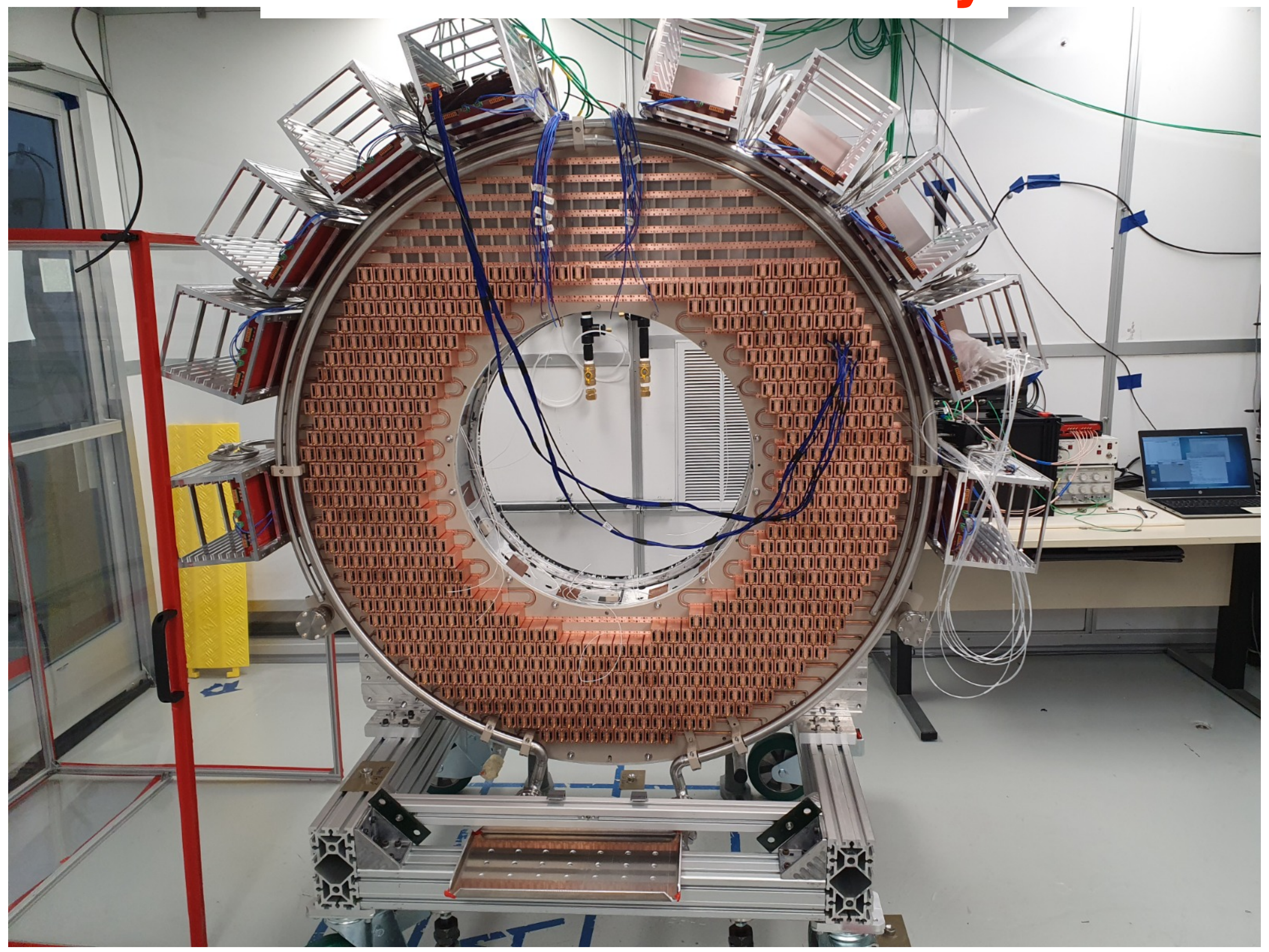


SiPM array





calorimeter assembly



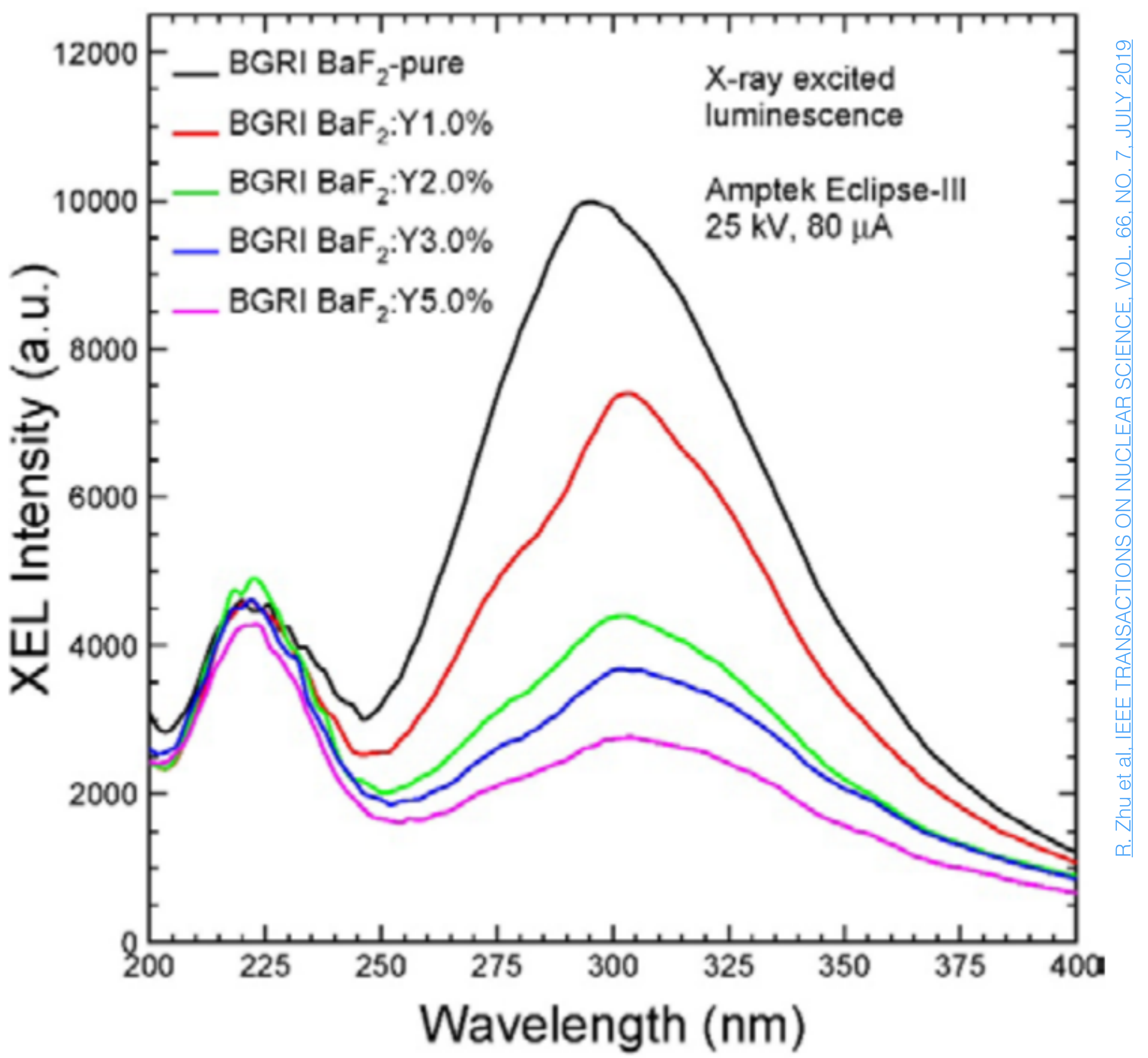
Mu2e-II calorimeter: crystal R&D

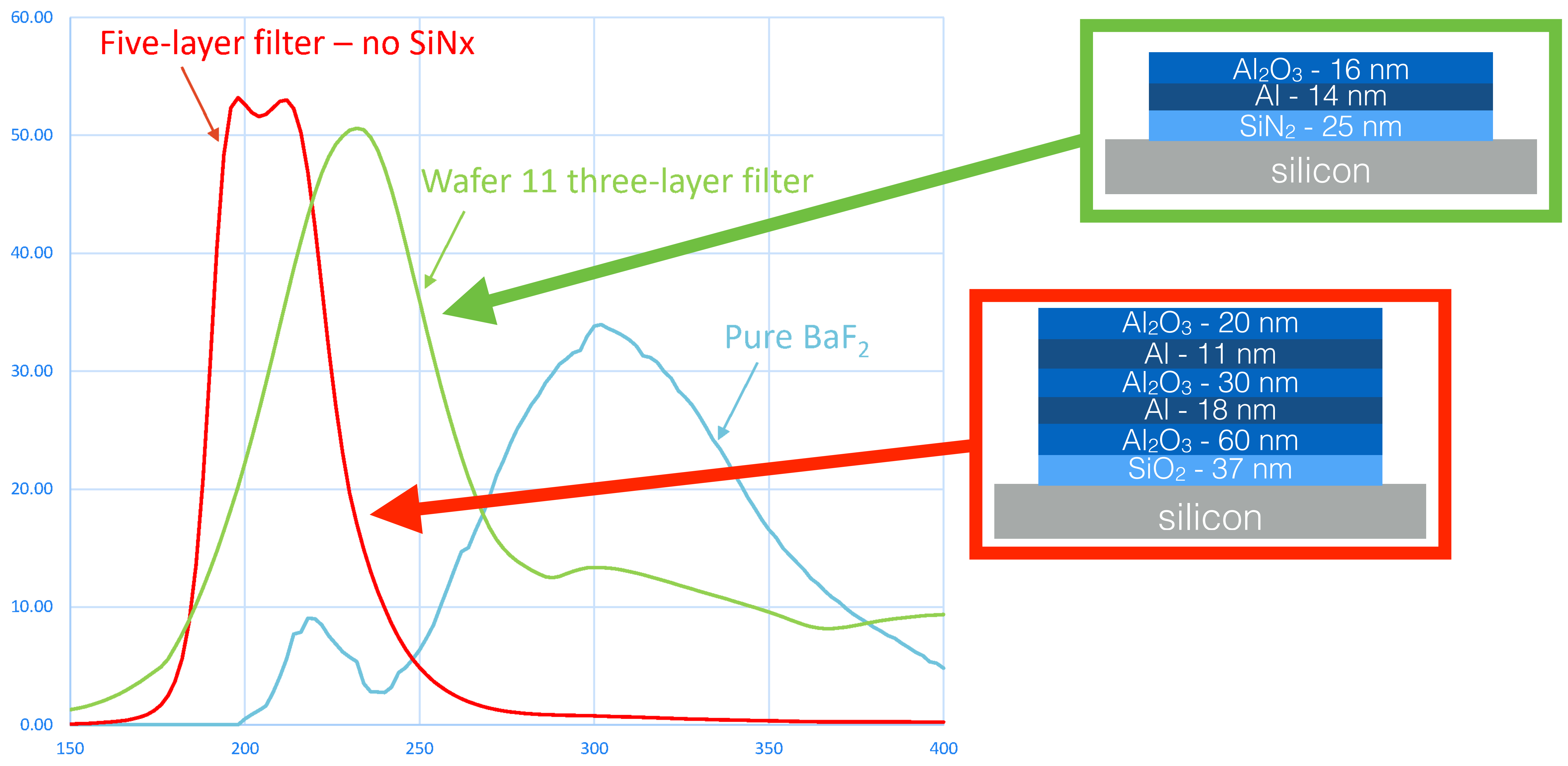
- Rad-hard issues for the CsI in the Mu2e-II case: ~10kGy/year
- Larger occupancy requires a faster crystal

Proposed solution:

- BaF_2 crystals
- Caltech-JPL-FBK consortium working on delivering developing a special coating for SiPMs
  - Sandwich of Al, SiN_2 and Al_2O_3 layers deposited on the active material

Crystal	CsI(pure)	BaF_2	BaF_2(Y)
Density [nm]	4.51	4.89	4.89
Hygroscopicity	Slight	None	None
λ_{peak} [nm]	420 310	300 220	300 220
Light Yield [% NaI(Tl)]	3.6 1.1	42 4.8	1.7 4.8
Decay Time [ns]	30 6	600 0.5	600 0.5

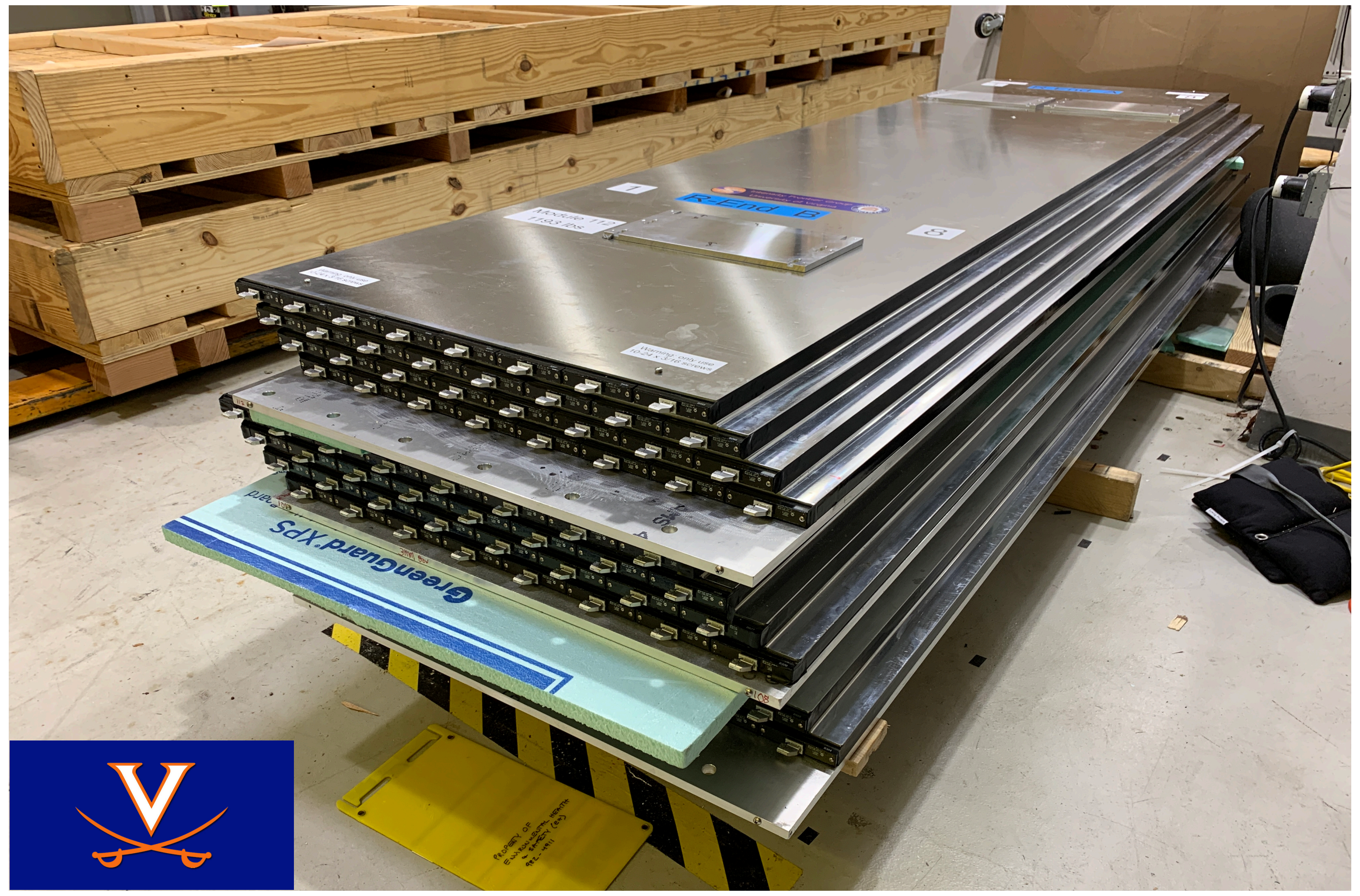


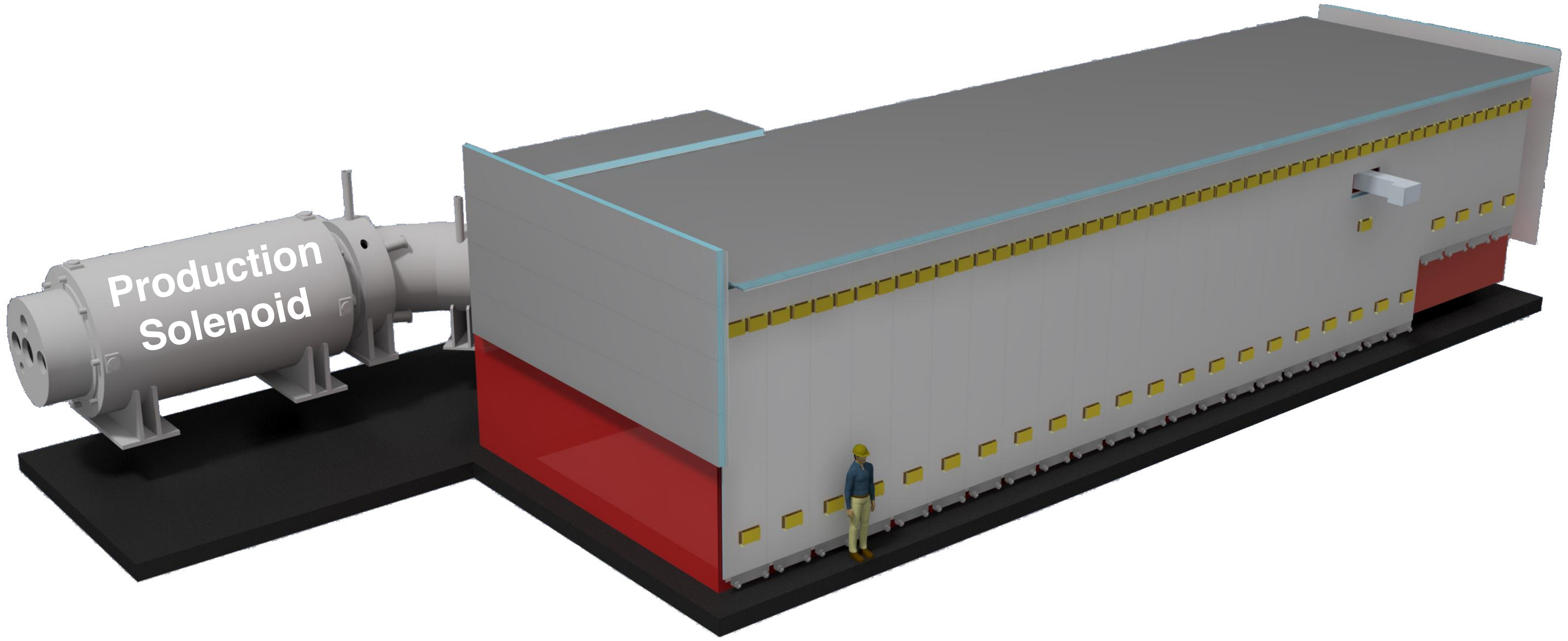


Cosmic Ray Veto

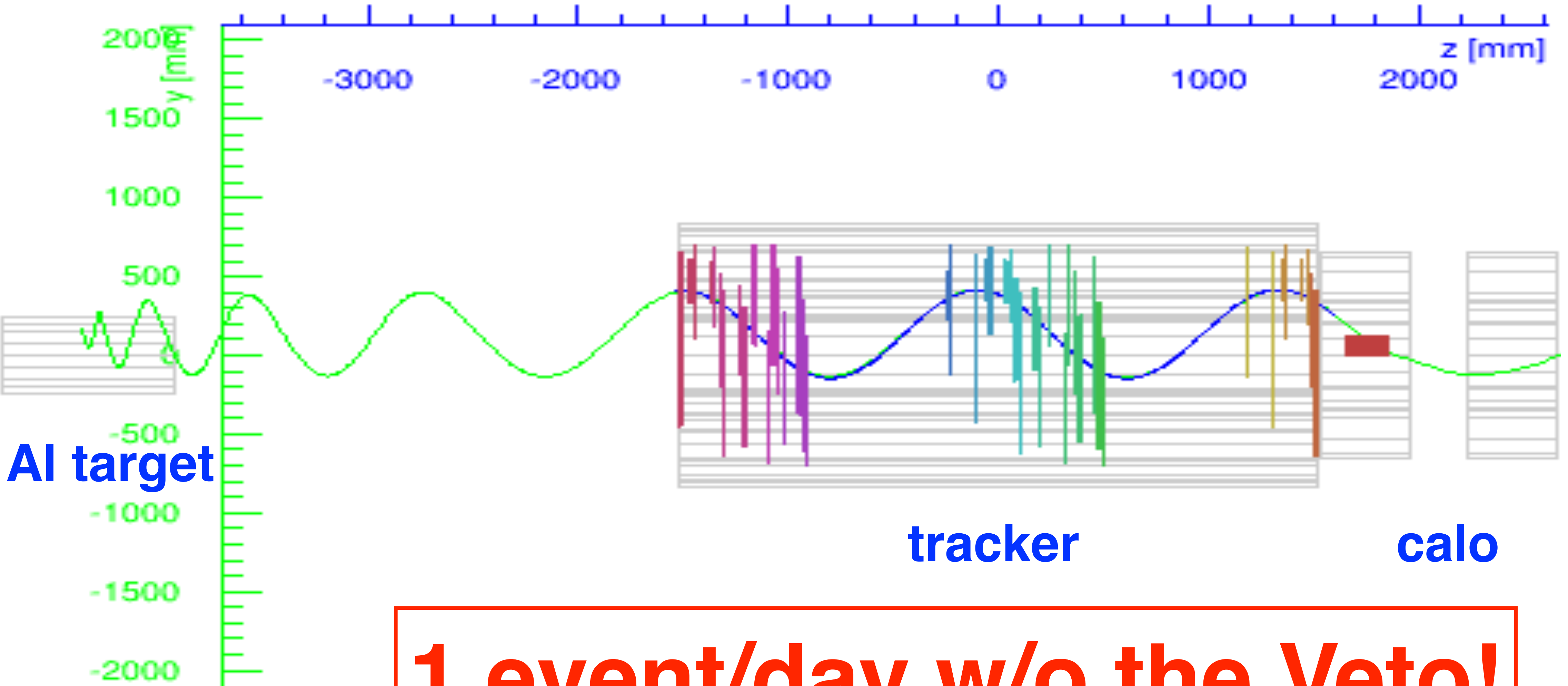
- Veto system covers entire DS and half TS
- 4 layers of scintillator
  - each bar is 5x2x~450 cm^3
  - 2 WLS fibers per bar
  - read out at both ends with SiPM
- required inefficiency ~ 10^{-4}

CRV modules





μ mimicking the CE

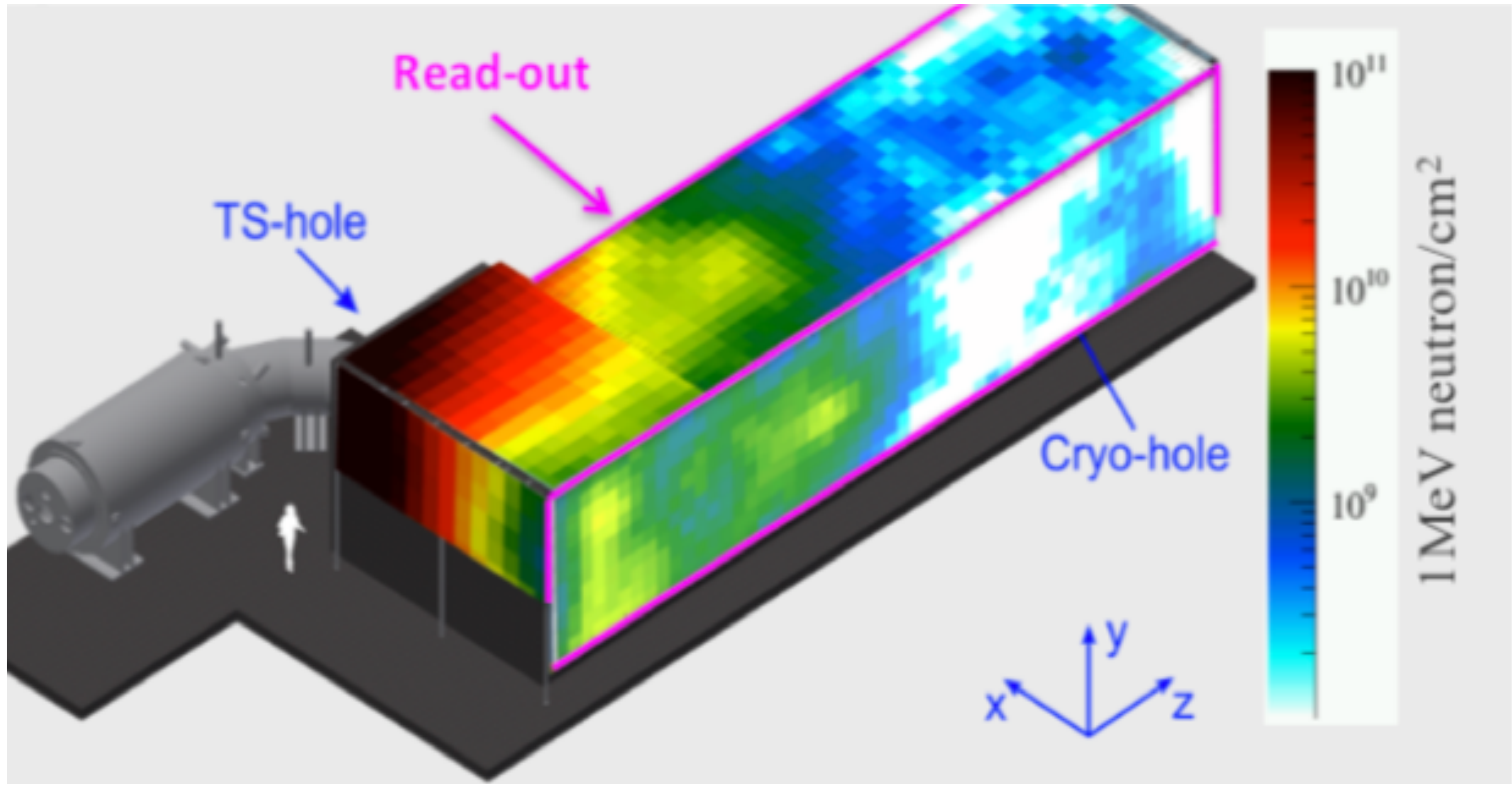


1 event/day w/o the Veto!

Mu2e-II Cosmic Ray Veto

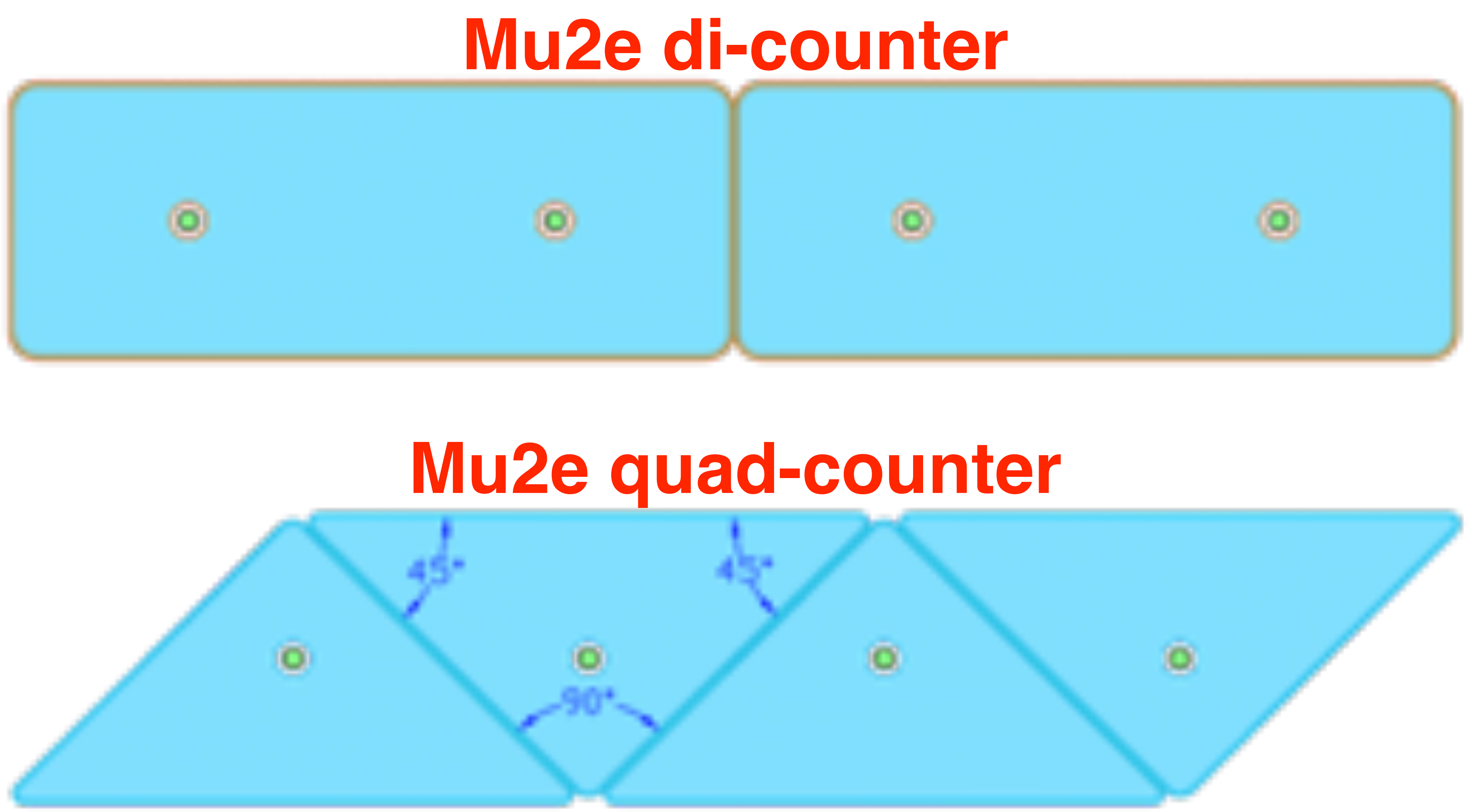
Challenges:

- **Increased live time:** ~x3 higher
- **Light yield degradation:** expected scintillator light yield will be significantly less
- **Noise rates**: expect ~x3 higher noise rates caused by increased beam intensity
- **Radiation damage** to the readout chain close to becoming an issue
- **Rate** issues in hot regions is expected to be already at the limit



Proposed solutions:

- Novel counter design with triangular bars:
  - Improved efficiency due to reduced gaps
  - lower rate per channel
- Replace the counters and SiPMs
- Improve the CRV shielding (Boron loaded concrete)
- Use RPC in the region with expected higher rates?



Summary

- Mu2e-II is a proposed upgrade to Mu2e with strong physics motivations
- PIP-II will provide the possibility of a x10 improvement over the expected Mu2e sensitivity
- Mu2e-II experimental conditions will face technological challenges for all detector systems
  - Working groups already started Monte Carlo studies to address most of the issues
  - Various projects (also LDRDs) already started and others have been proposed
- **If approved, Mu2e-II expects to start data taking in the early 2030's**
- **More info:** `http://mu2eiiwiki.fnal.gov`

backup slides

Mu2e-II TDAQ system

Increased data rate, more background and more detector channels:

- ~x10 data rate
- ~x3 event size
- 3000:1 rejection is needed to stay within ~14 PB/year

Considerations:

- Reduced time with no-beam to read out large front-end buffers
- Radiation tolerances requirements for the readout-controller-boards

Solution:

- 2-level TDAQ system based on FPGA pre-processing and trigger primitives

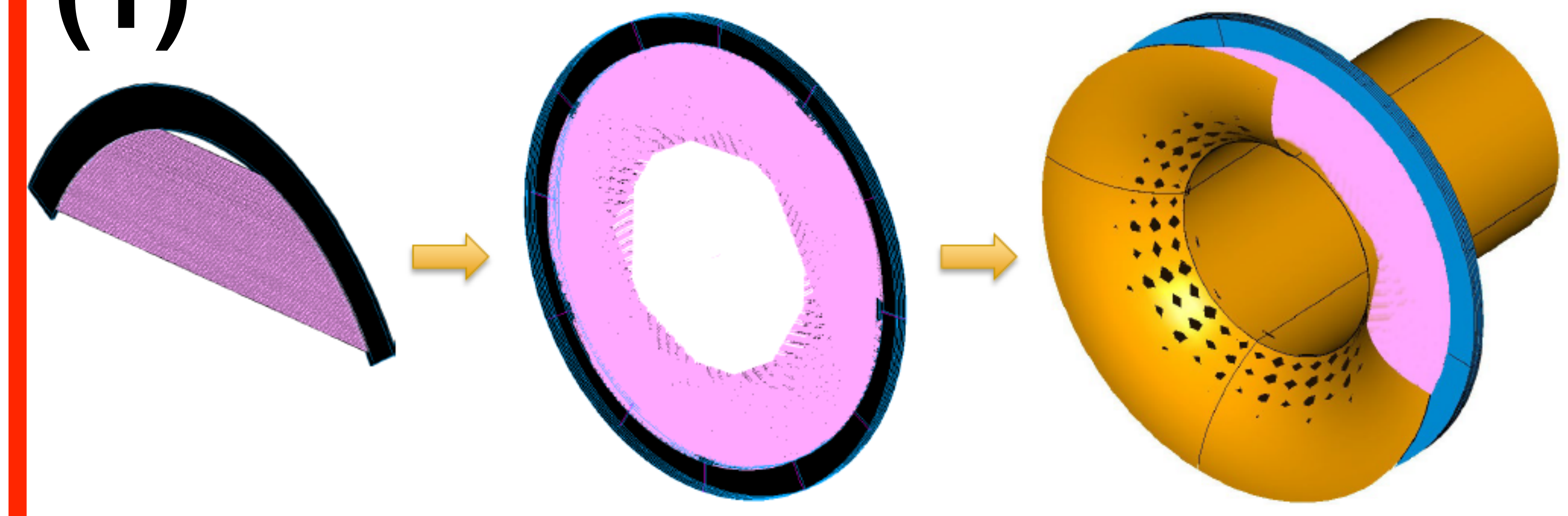
Mu2e-II proton beam specs

	Mu2e	Mu2e-II	Comments
Source	slow extracted from the Delivery Ring	H^- directly from PIP-II linac	Mu2e-II will need to strip H^- ions upstream of the production target
Beam energy	8	0.8	Optimal beam energy 1-3 GeV
Total POT	3.6E+20	4.5E+22	
Lifetime [yr]	3	3	
Run time [s/yr]	2E+07	2E+07	
Duty factor	25%	>90%	This has a large impact in the TDAQ system
p pulse width	250	100	
p pulse spacing	1695	1700	
Extinction	1E-10	1E-11	Ratio of out:in time protons
Average beam power [kW]	8	100	

Mu2e-II Tracker: alternatives

1. Use wire or thin metallized foils for the cathode + house the panels in a unique gas vessel
2. Drift chamber based on the MEG-II design
3. Employ light Si or MPGD modules in a disk geometry

(1)



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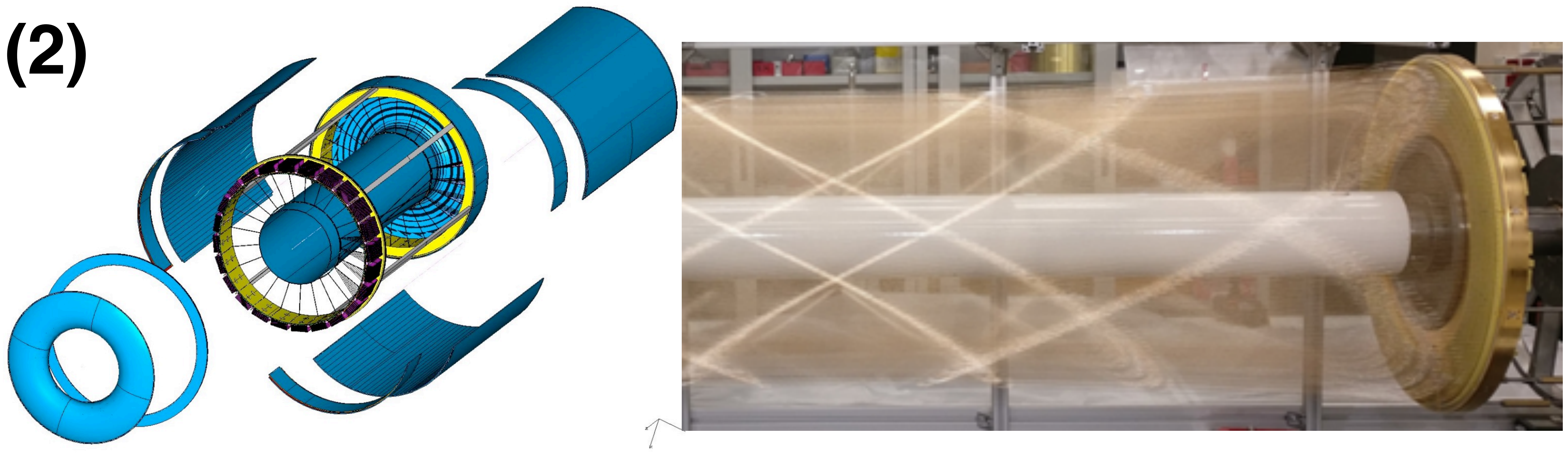

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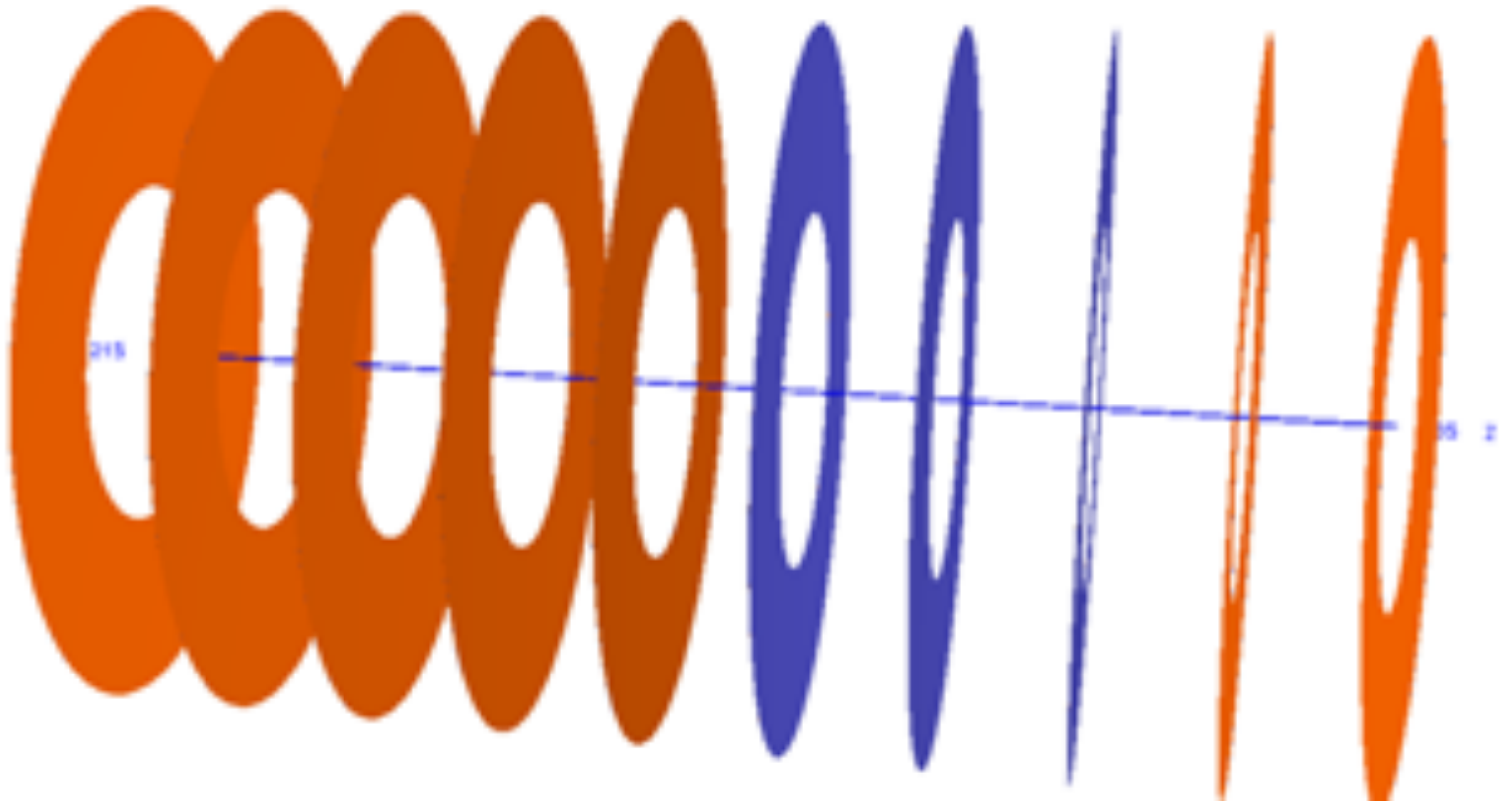


Motivation

- **CLFV is a unique probe of New Physics parameter space**
  - Next gen experiments planned in EU, Asia and the USA
  - Probes complementary regions of NP space
  - Measured rates can provide model discrimination

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu \to eee)}{\mathrm{BR}(\mu \to e\gamma)}$	$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

L. Calibbi, G. Signorelli, arXiv:1709.00294

Mu2e sensitivity

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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

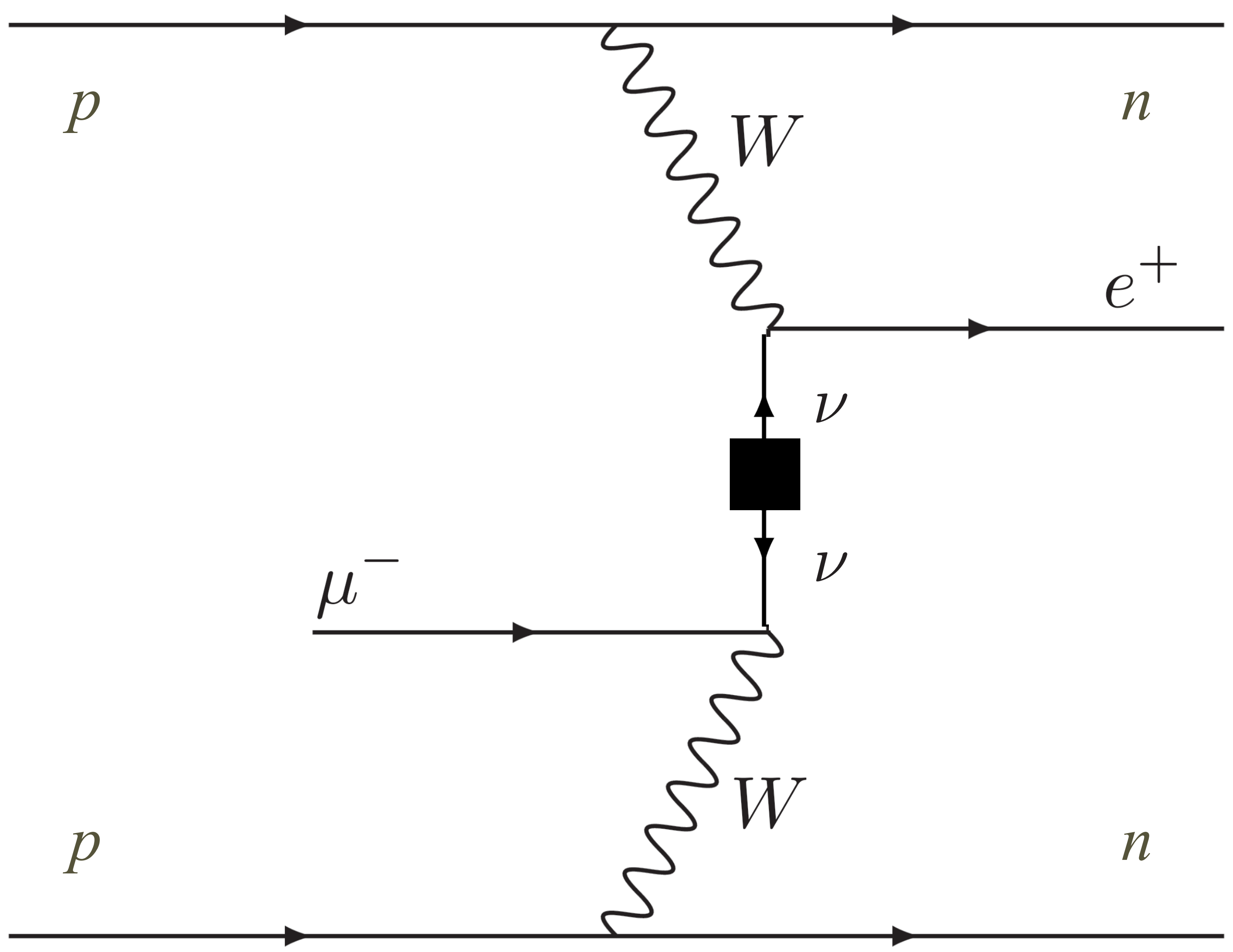
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

arXiv:0909.1333[hep-ph]

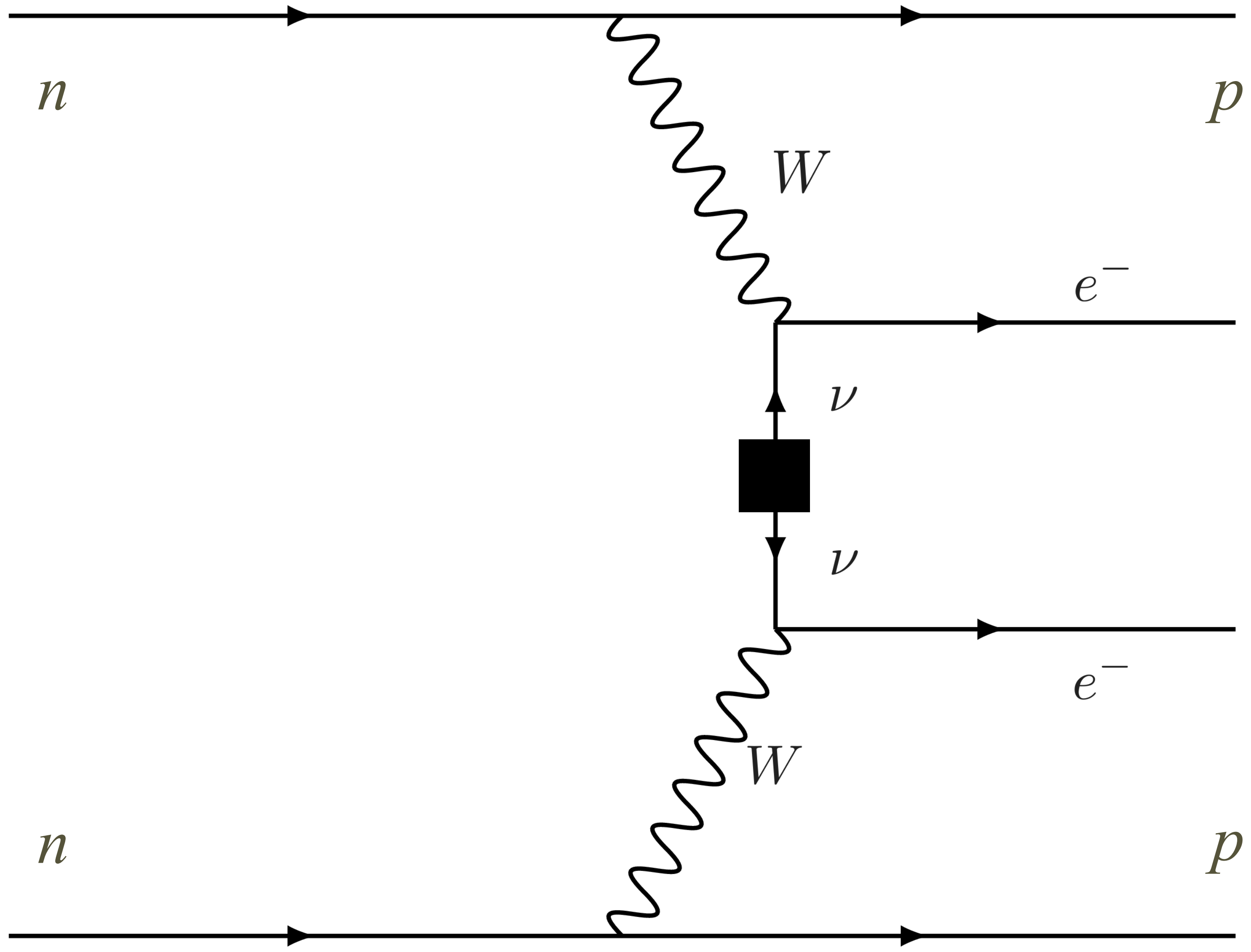
$\mu^- N \rightarrow e^+ N^*$ conversion search

- While 0νββ has the greatest sensitivity to new ultraviolet energy scales, its rate might be suppressed by the new physics relationship to lepton flavor
  ✓ $\mu^- \rightarrow e^+$ conversion offers a complementary probe of lepton-number-violating physics
- Mu2e Run I SES on $R_{\mu e+}$ of 4×10^{-16}, which is ~x5,000 better than the current best limit

μ^- N→e^+ N*

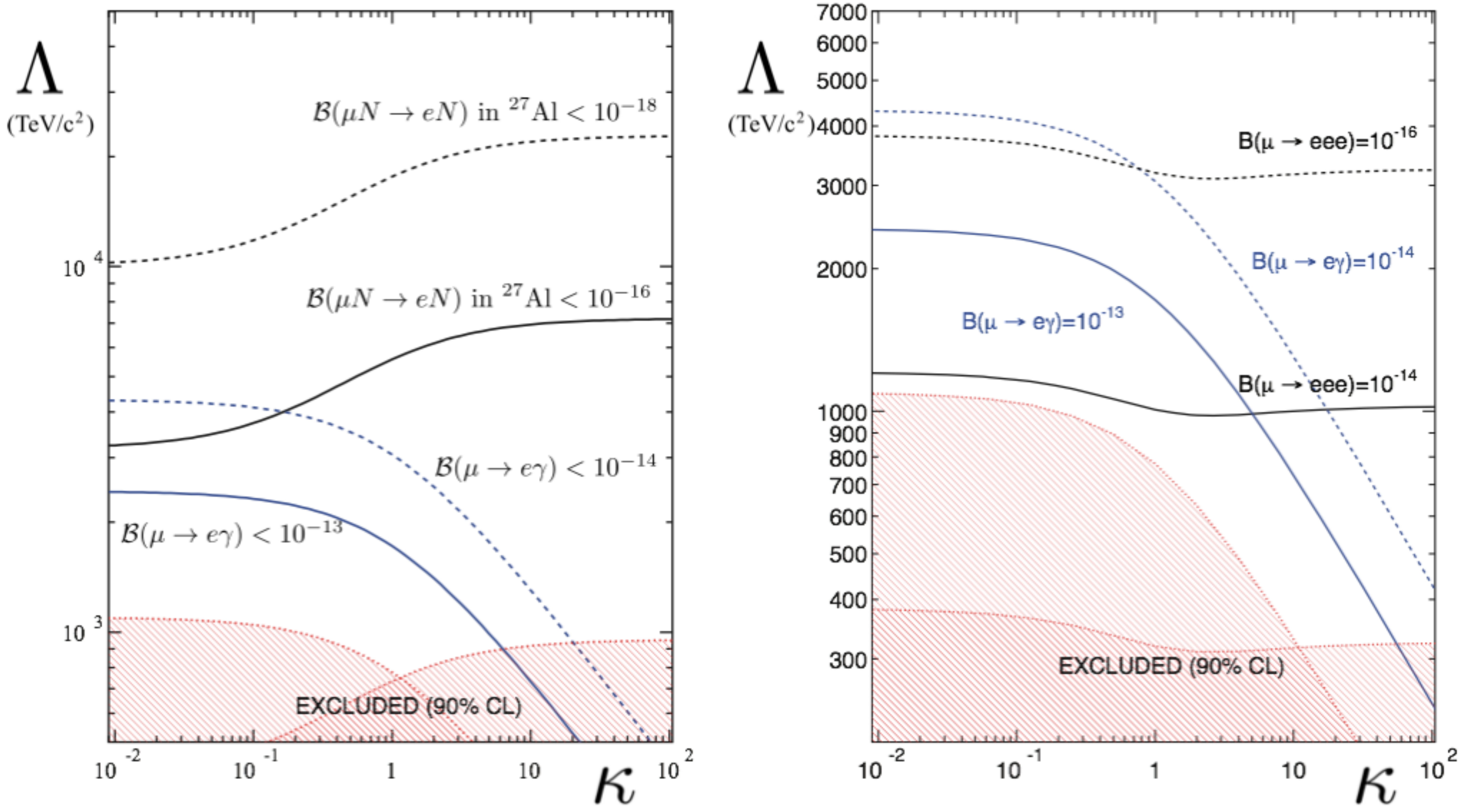


0νββ decay



- Useful references: Phys. Rev. D 95.115010, arxiv-161.00032, arxiv-1705.07464, arxiv-1609.09088

Model independent Lagrangian



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

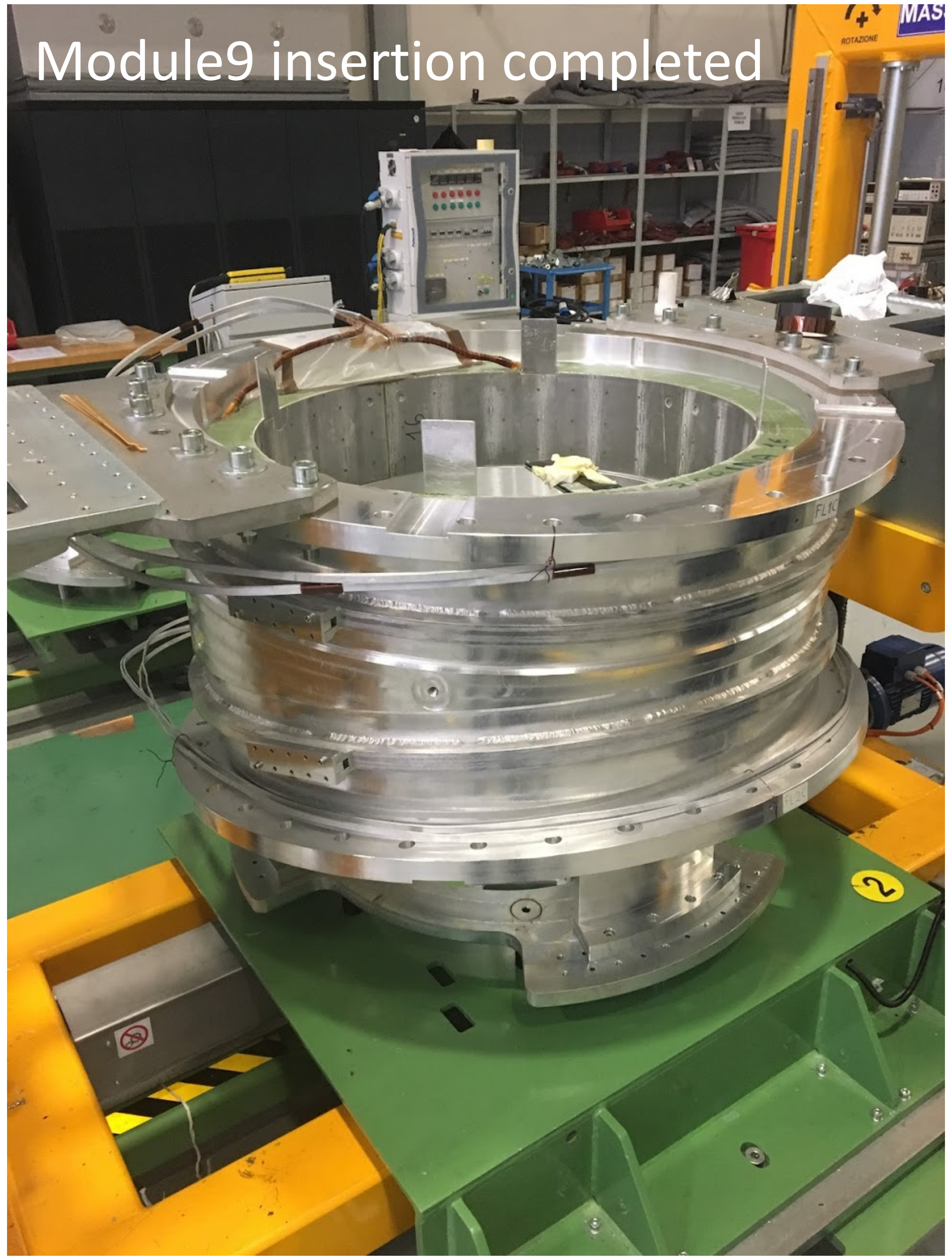
“dipole term” **“contact term”**

Mu2e TDAQ specs

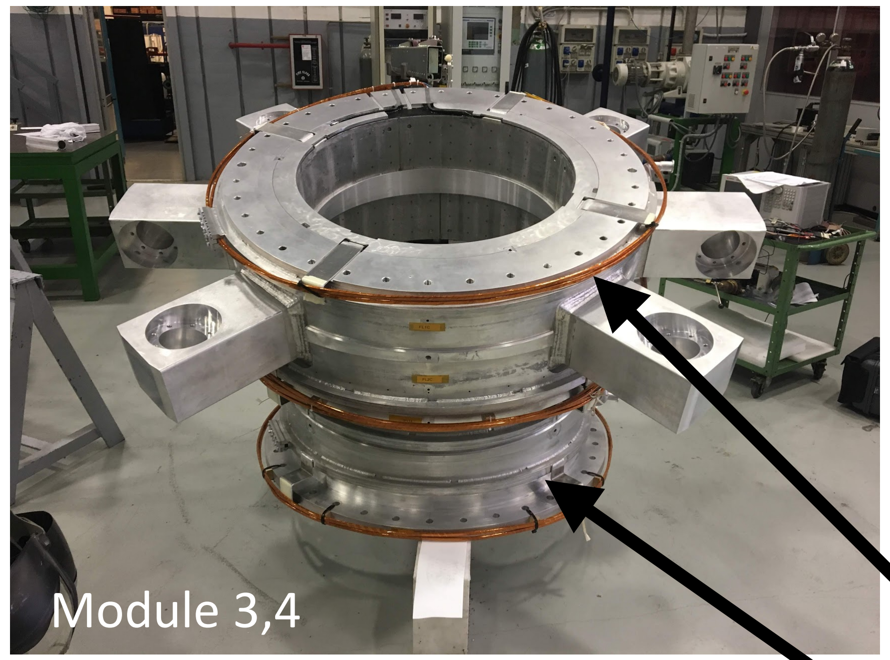
Parameter	Value
DAQ Servers	36
Detector Optical Links	216
System Bandwidth	40 GBytes/s
Online Processing	40 TFLOPS
Input Event Size (average)	120 Kbytes
Input Event Rate	192 KHz
Input Data Rate	35 GBytes/s
Rejection Factor	$\geq$ 100
Output Event Size (average)	130 Kbytes
Output Event Rate	$\leq$ 2 KHz
Output Data Rate	$\leq$ 260 MBytes/s
Offline Storage	$\sim$ 7 PBytes/y

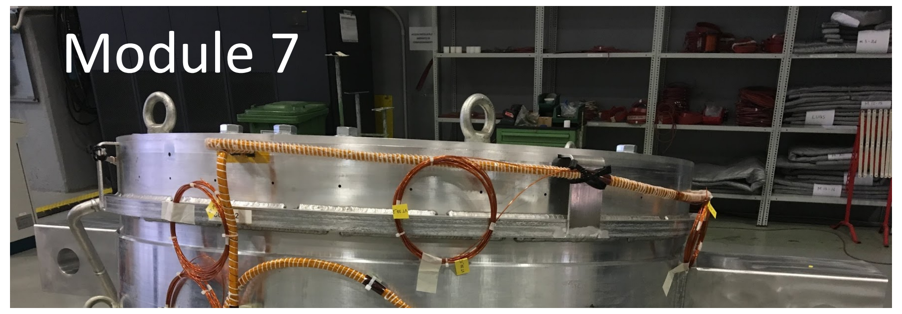
Cold mass tests @ Fermilab

- Cold test is performed for all the modules at Fermilab

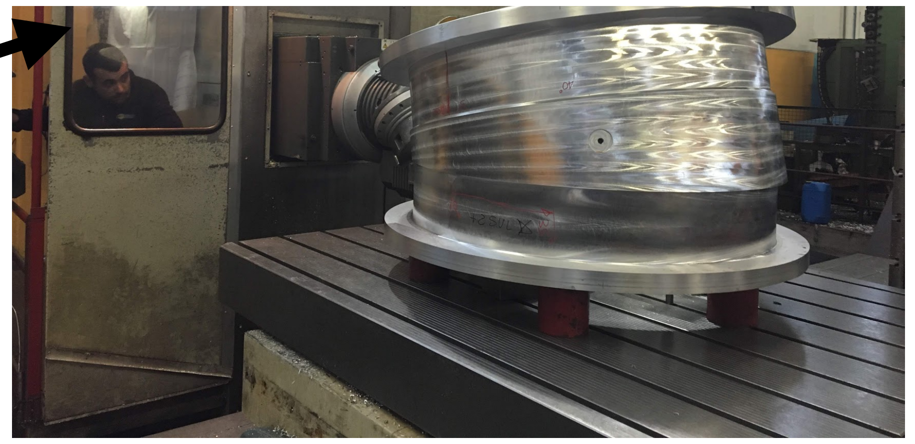


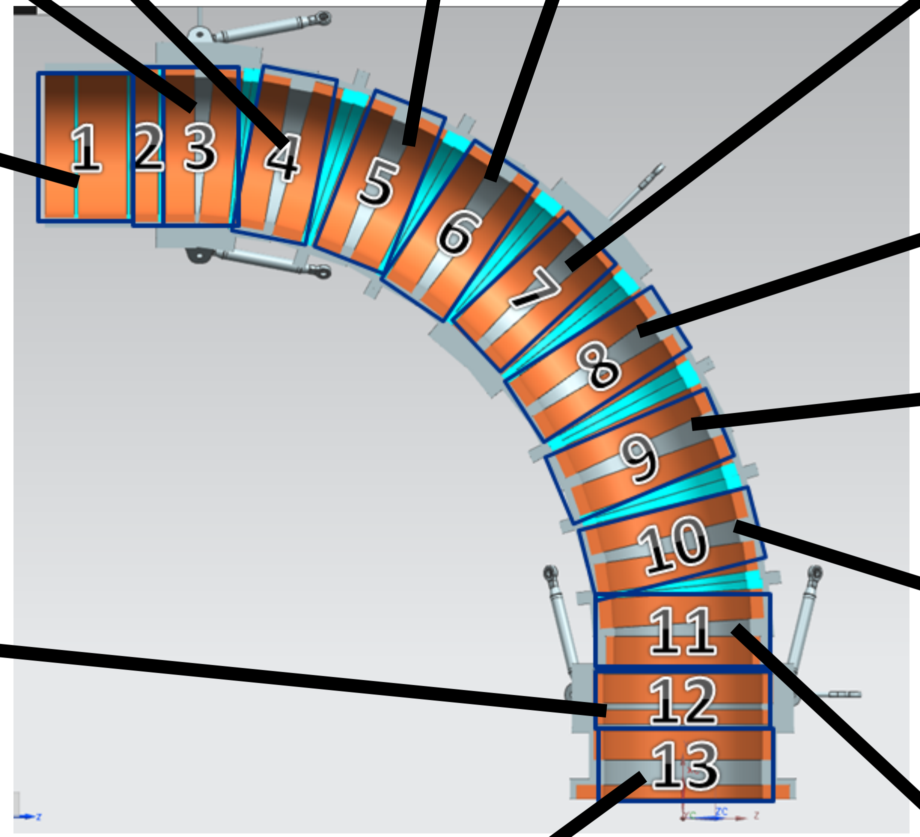
Transport Solenoid - Upstream side



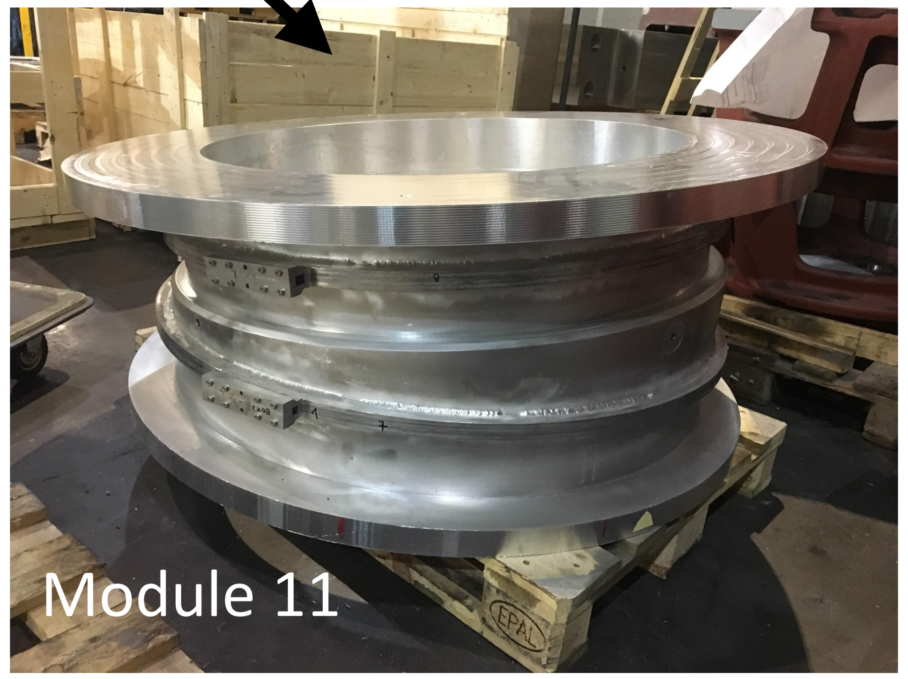


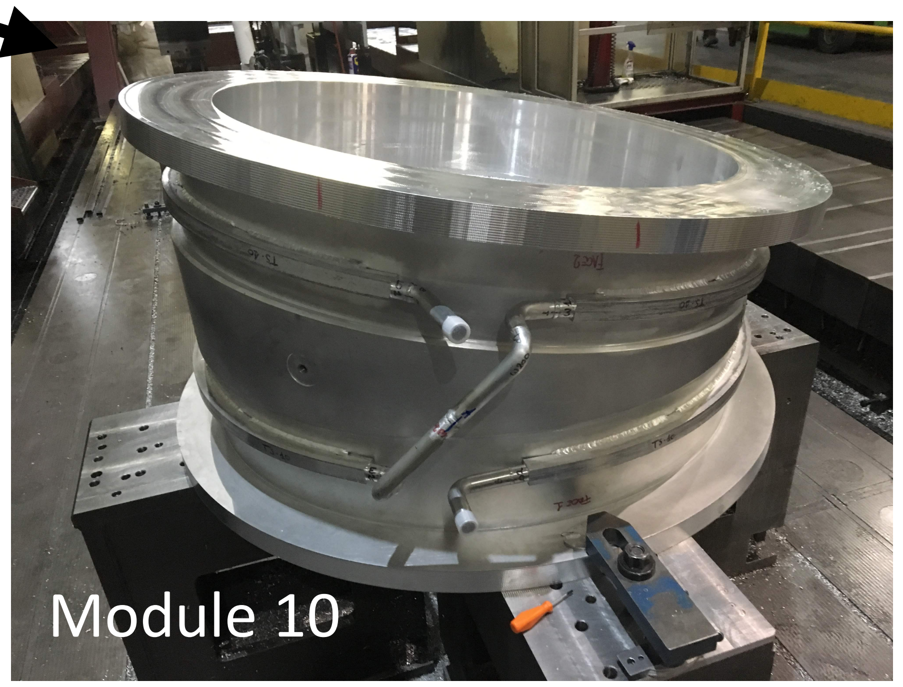
back in 2019...



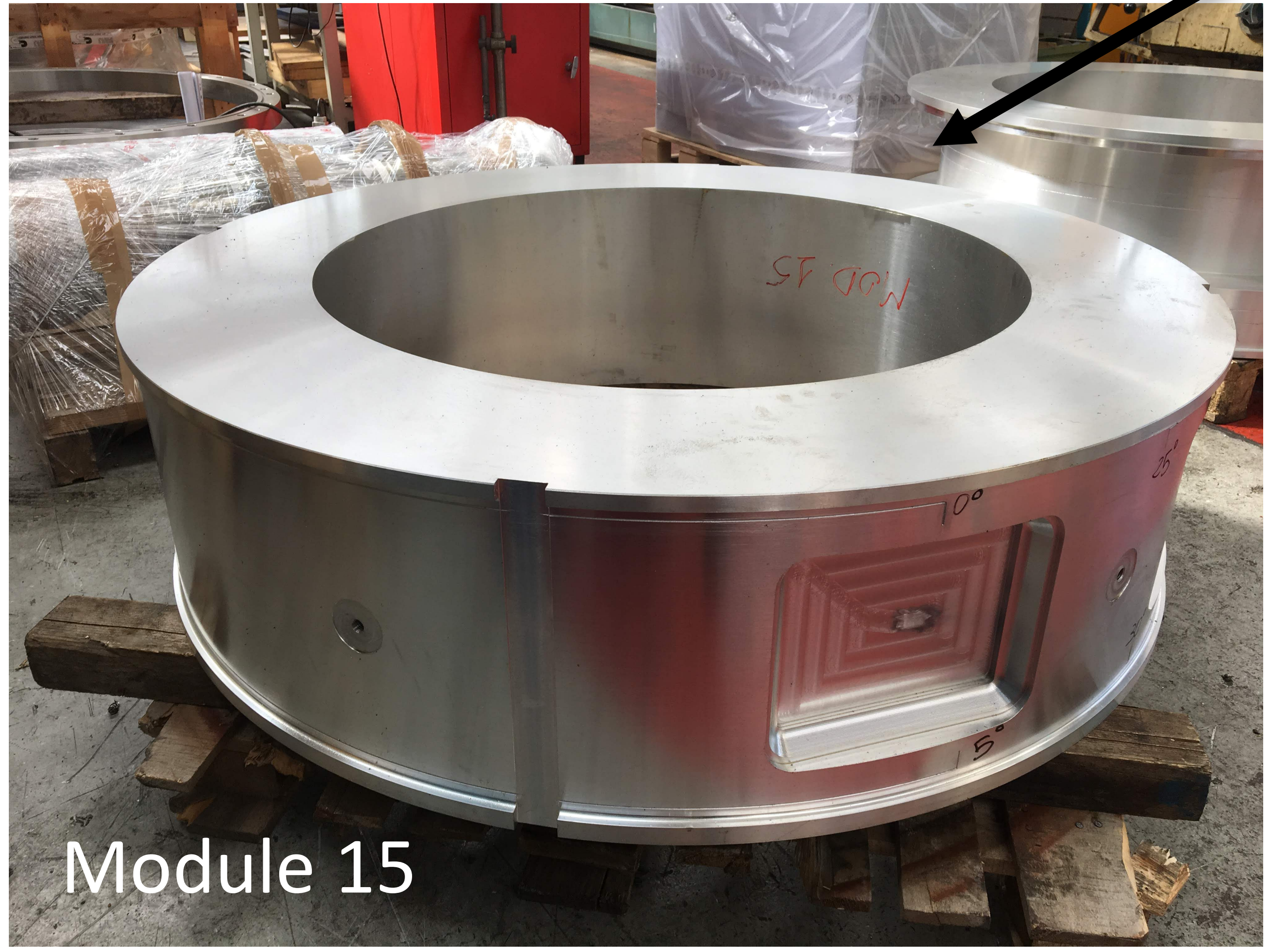


- Upstream side of the TS has been completed and the modules are now under test

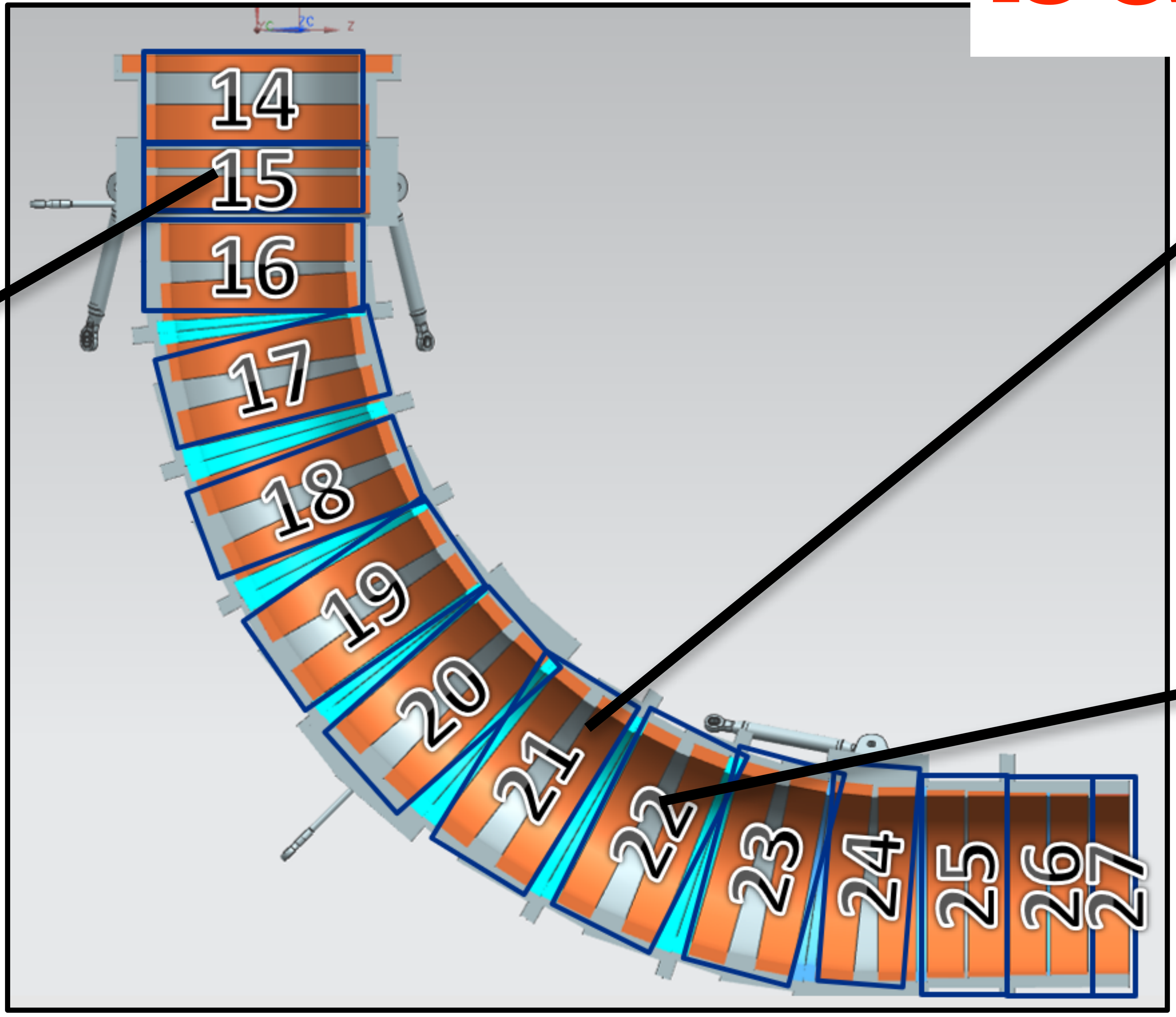




Transport Solenoid

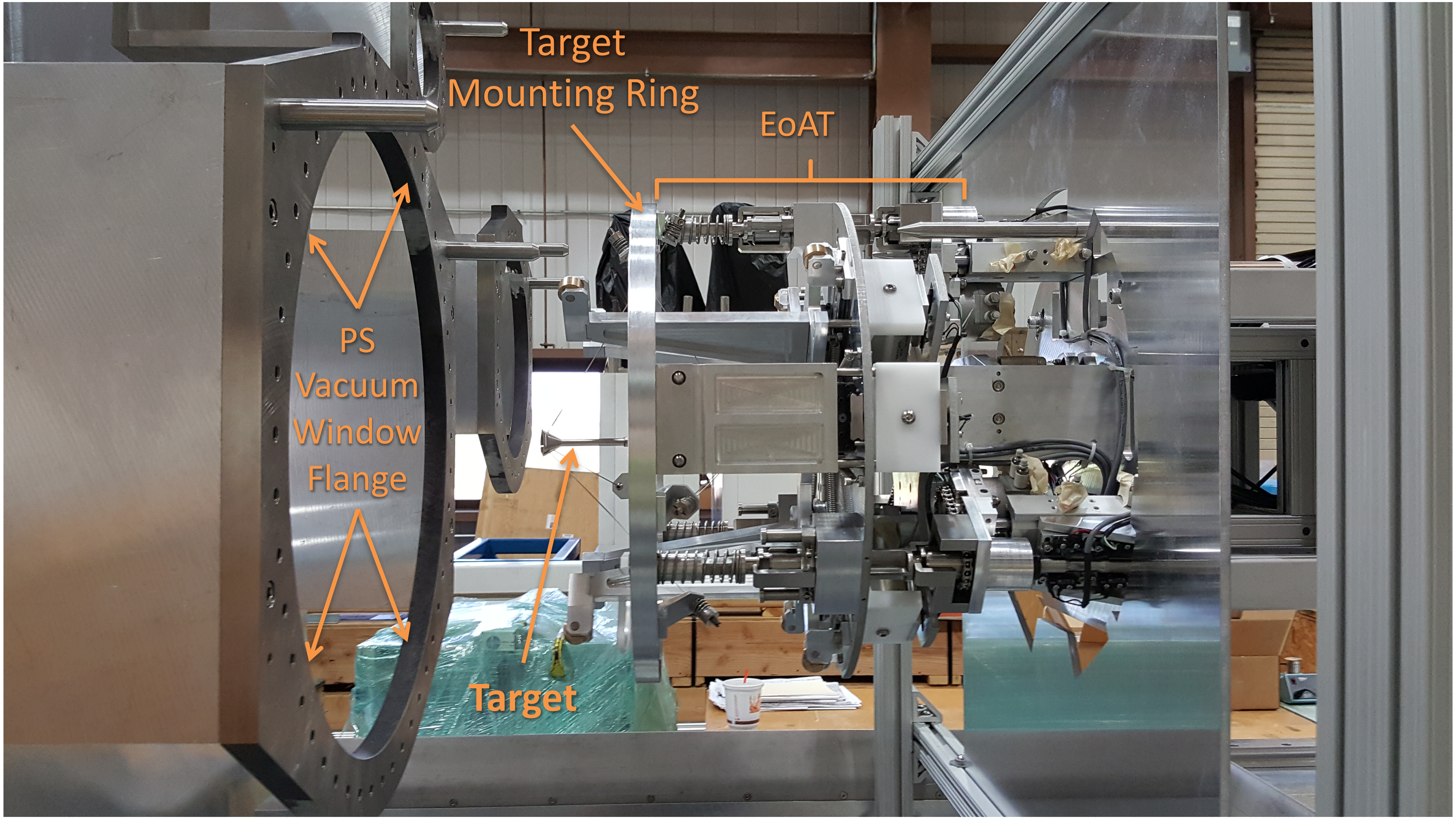


- Work on the downstream section has started



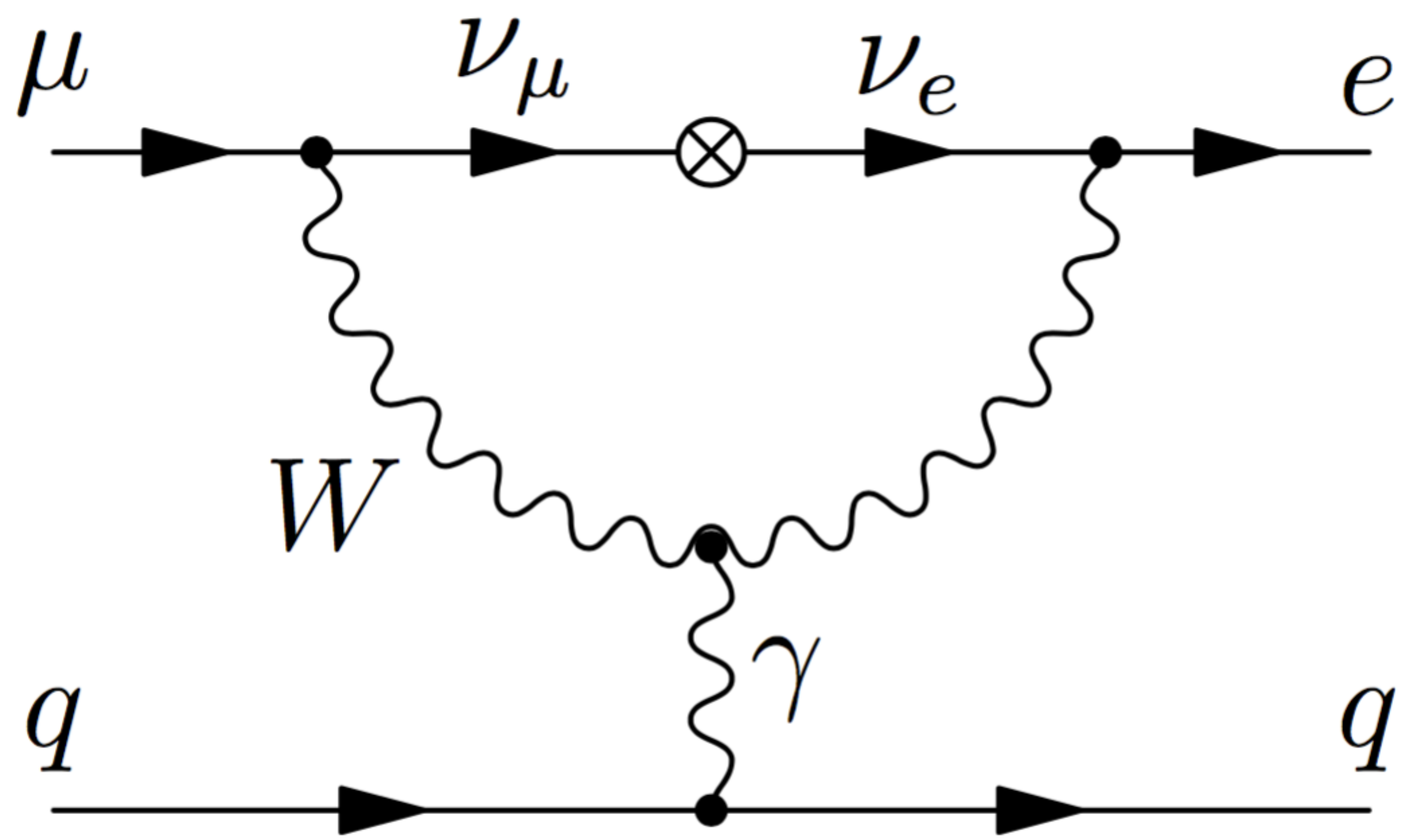
back in 2019...

Testing Handling Robot



CLFV in the Standard Model

- **CLFV** process forbidden in the **Standard Model (SM)**
- μ conversion in the extended-SM is introduced by the **neutrino masses and mixing** at a negligible level ~ 10^{-52}



- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)