Mu2e: status and perspectives

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What is μ→e conversion?

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

$$E_e = m_\mu c^2 - B_\mu(Z) - C(A) = 104.973 \text{ MeV}$$

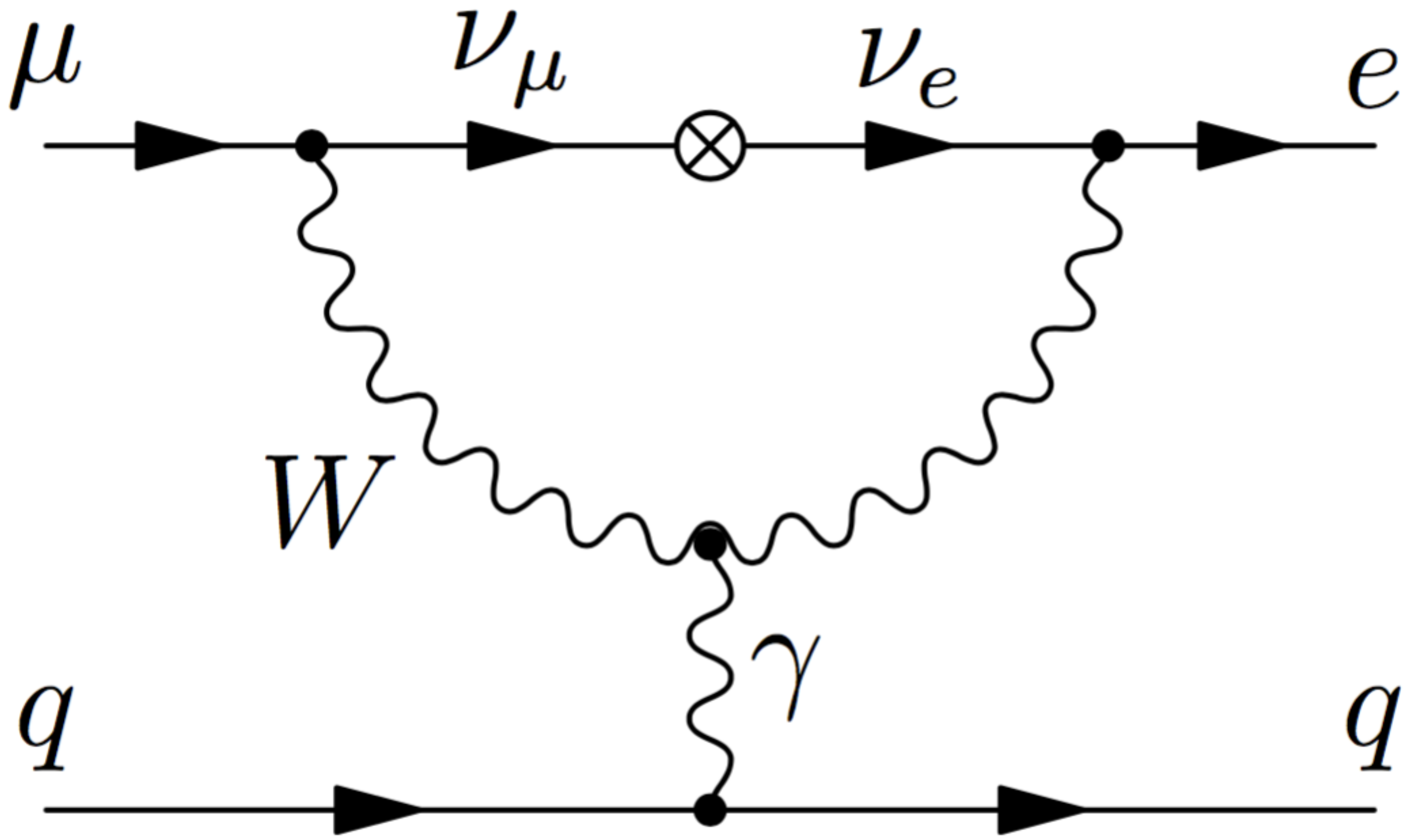
- for Aluminum: $\begin{cases} B_\mu(Z) \text{ is the muon binding energy (0.48 MeV)} \\ C(A) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

- Signal normalization:

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

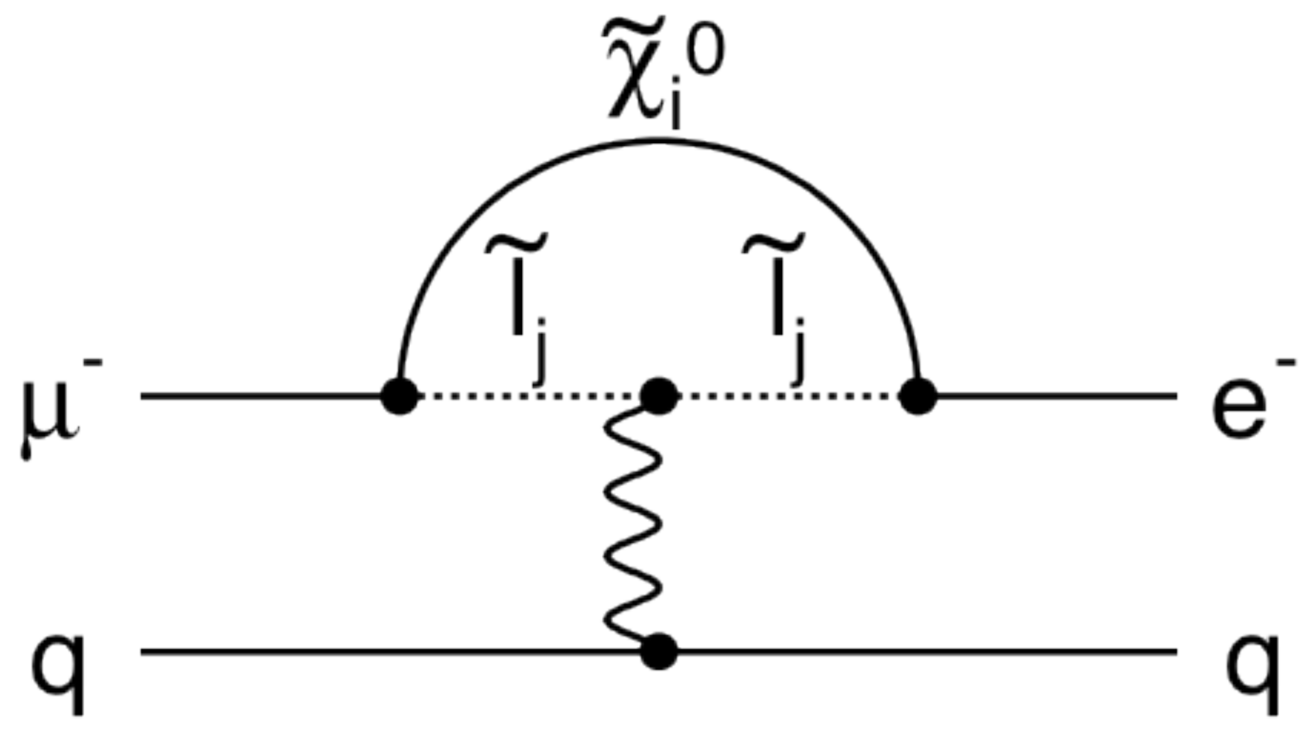
CLFV in the Standard Model

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

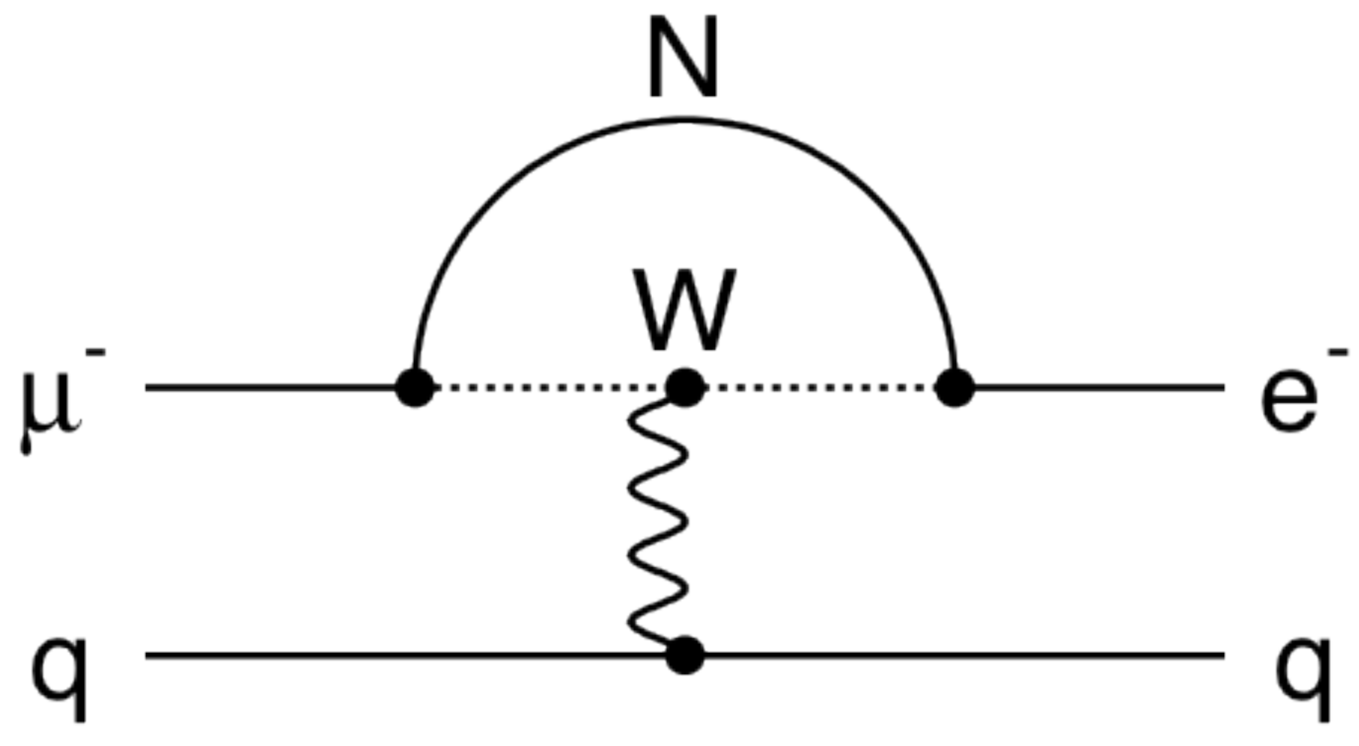


- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)

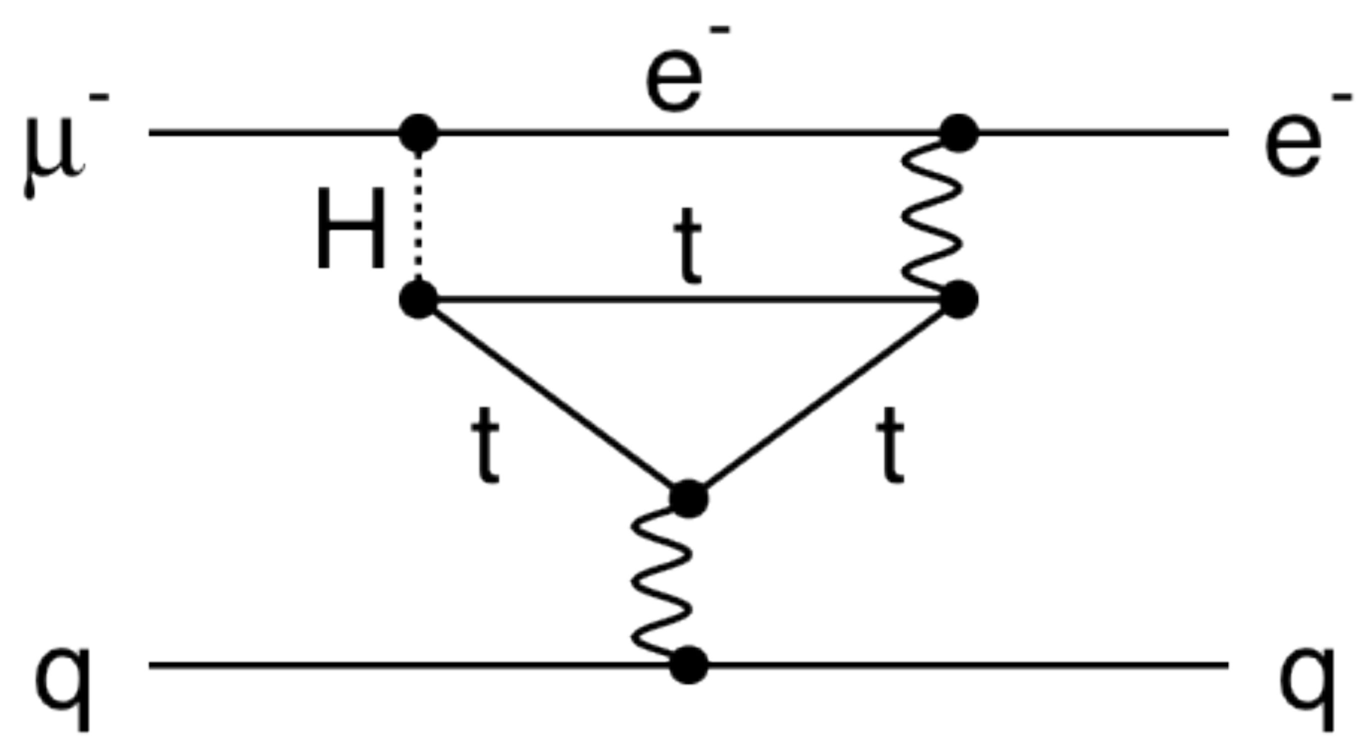
New Physics and μ→e



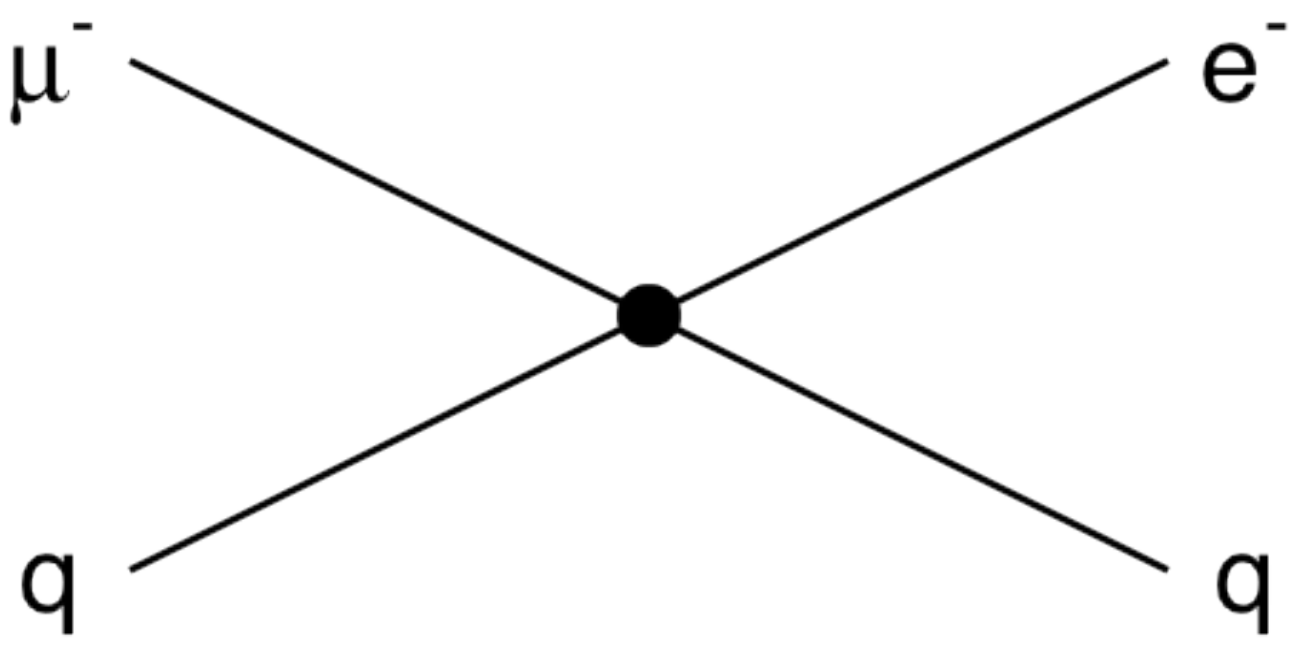
SUSY



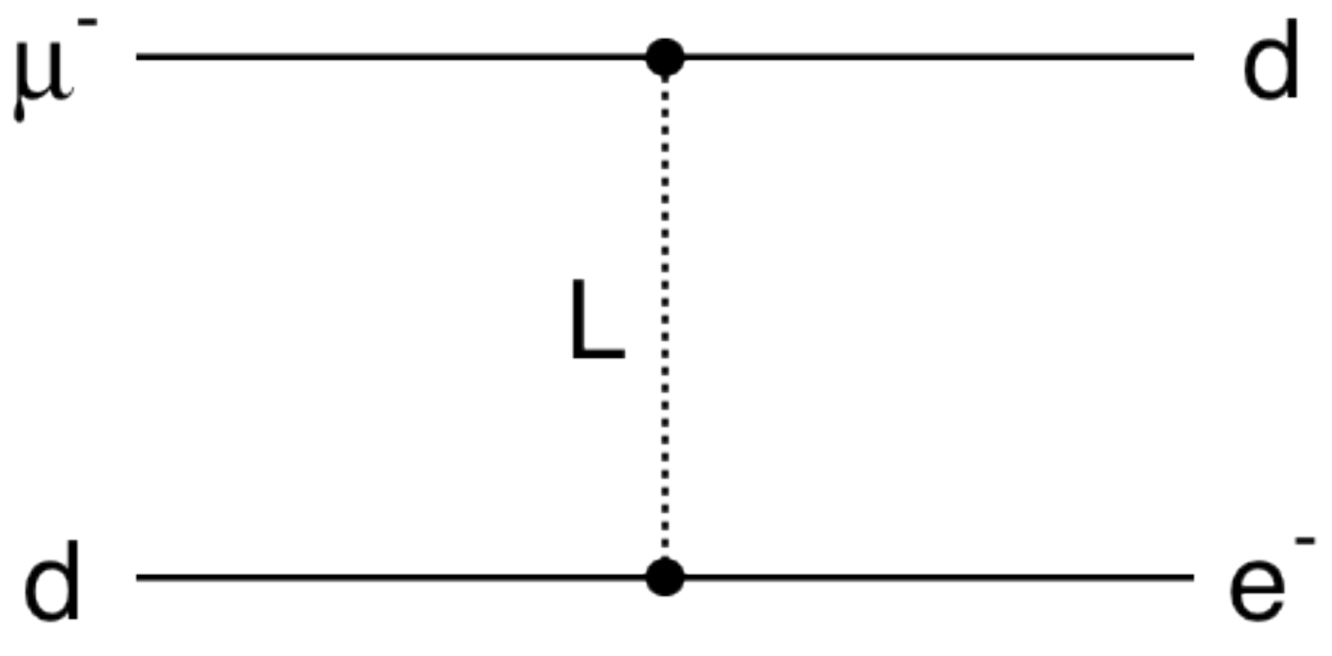
Heavy neutrino



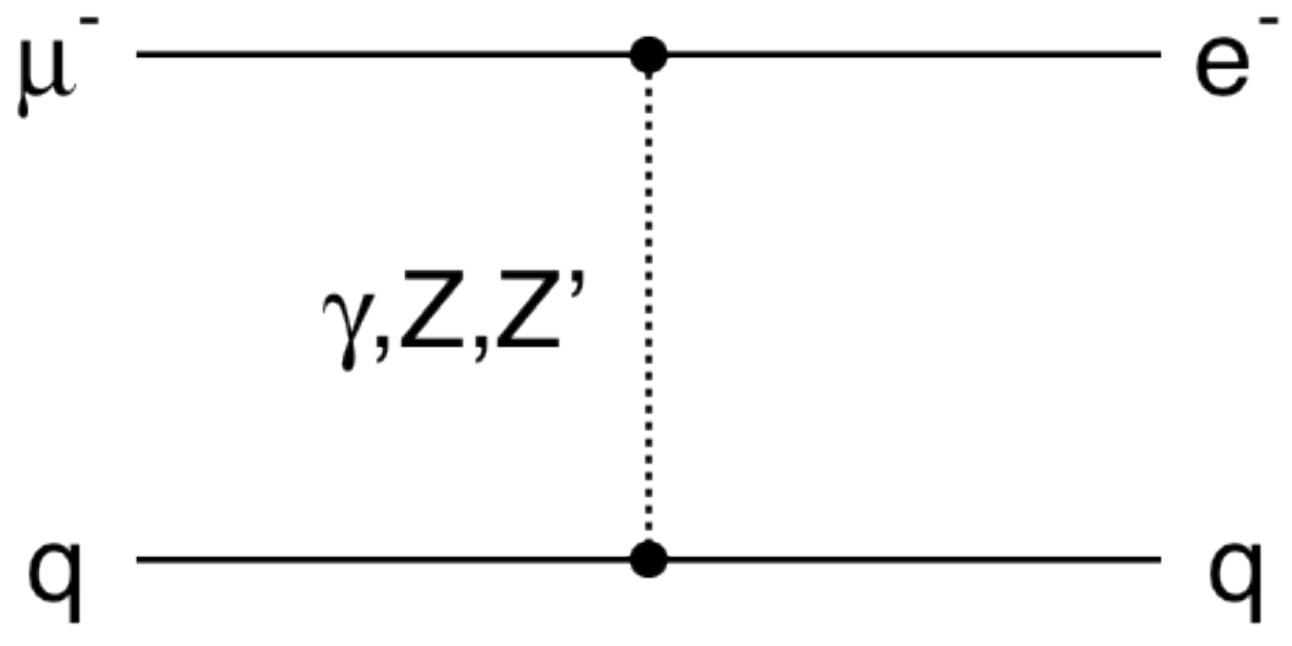
Two Higgs doublet



Compositeness



Leptoquarks



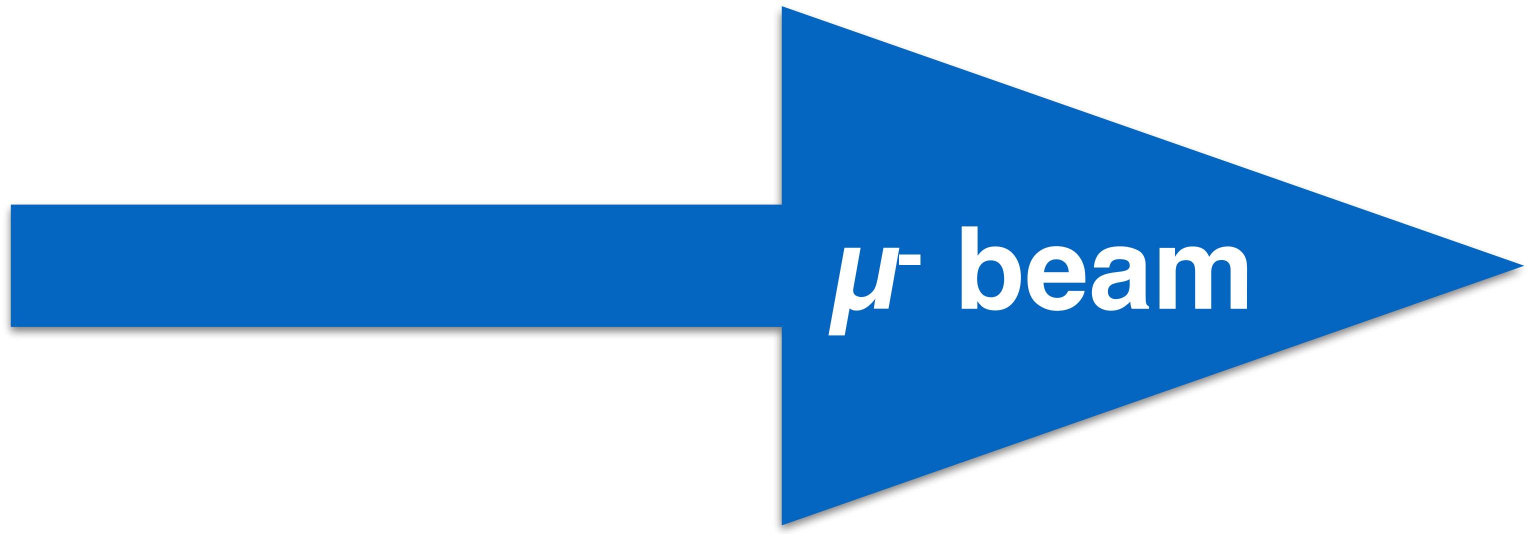
Z'/anomalous couplings

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

How to search for a μ2e conversion?

How to search for a μ2e conversion?

1. We need to produce lot of μ
   - ✓ ~10^{18} μ to meet the sensitivity goal



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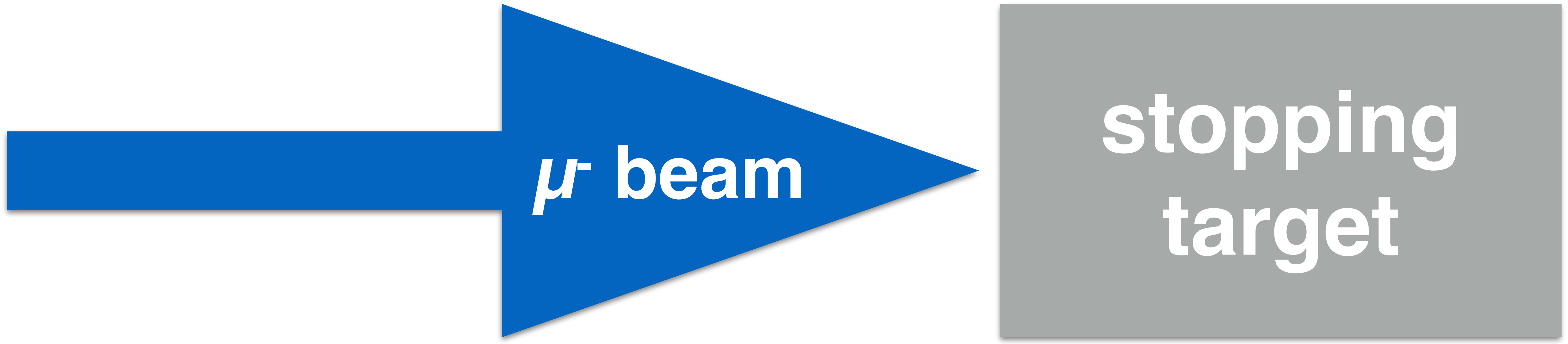
2. We need to stop the μ in a target

   ➡slow moving μ are preferable



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   ➡slow moving μ are preferable

3. We need to detect an e- @ E=105 MeV

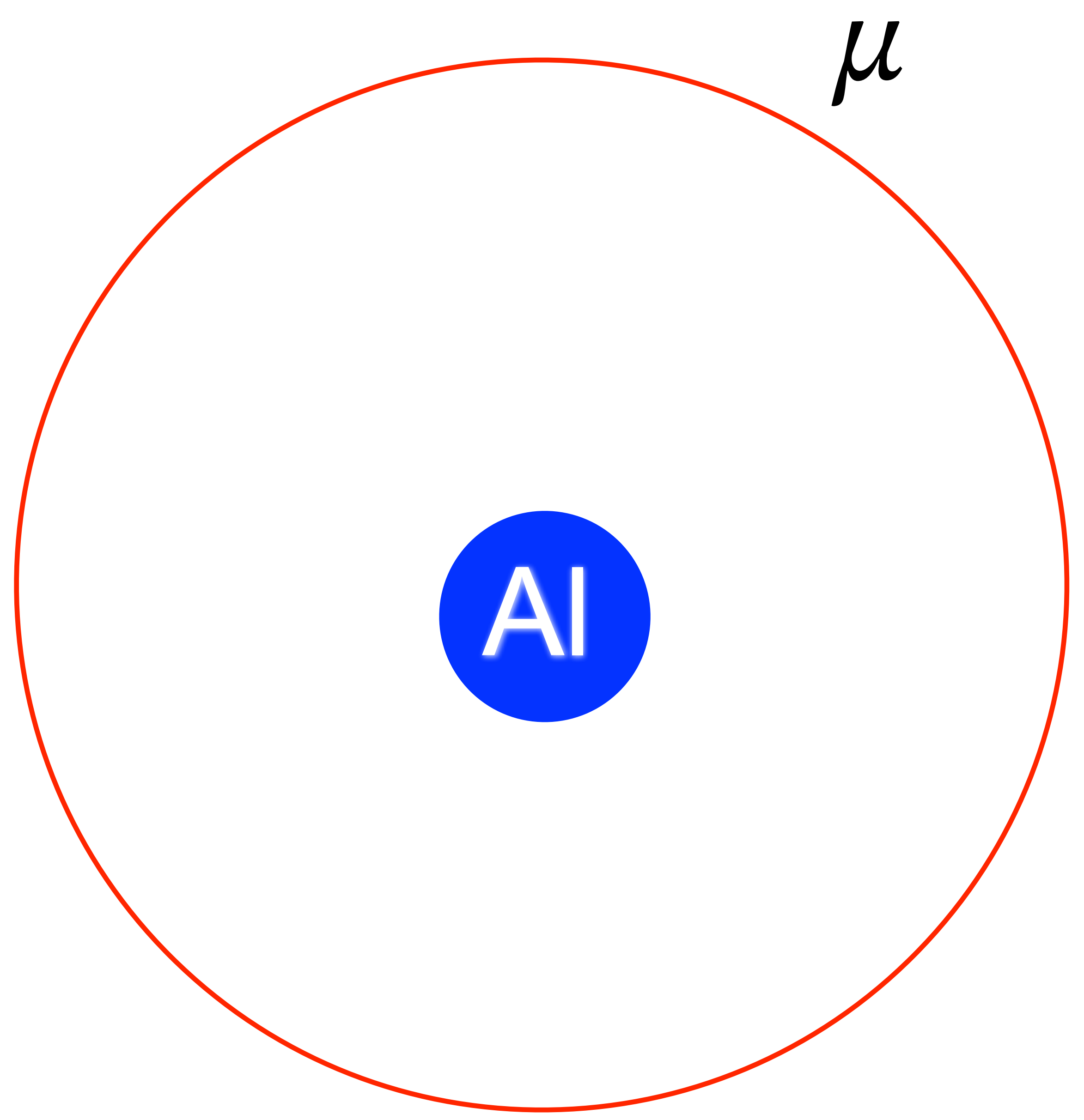
   ✓accuracy <1% to provide signal-to-background separation

Measuring 10^{-17} in collider units

- The captured muon is in a 1s state and the wave function overlaps the nucleus (*picture ~ to scale*)
- We can turn this into an effective luminosity
- Luminosity = density x velocity

$$|\psi(0)|^2 \times \alpha Z = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} = 8 \times 10^{43}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

- Times 10^{10} muons/sec x 2 μs lifetime
- **Effective Luminosity of 10^{48} cm^{-2}s^{-1}**

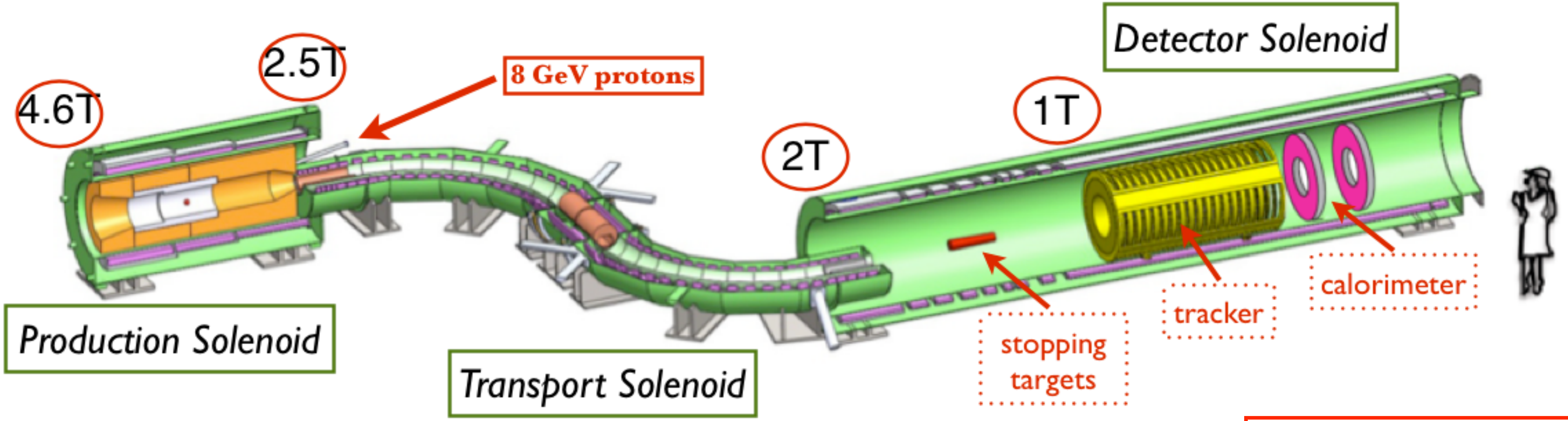


credits: B. Bernstein (rhbob@fnal.gov)

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
➡ Measure momentum in tracker and energy in calorimeter



from Lobashev idea

Transport Solenoid:
➡ Select low momentum, negative muons

Mu2e Detector

- *Proton absorber:*
  - ❖ made of high-density polyethylene
  - ❖ designed in order to reduce proton flux on the tracker and minimize energy loss

- *Tracker:*
  - ❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
  - ❖ Expected momentum resolution < 200 keV/c

- *Targets:*
  - ❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- *Calorimeter:*
  - ❖ 2 disks composed of undoped CsI crystals

- *Muon beam stop:*
  - ❖ made of several cylinders of different materials: stainless steel and polyethylene

Muonic atom

- Stopped μ⁻ is captured in atomic orbits
  ➡ quickly (~fs) cascades into 1S state

we detect these x-rays for measuring the # of captures

- Al radius ~4 fm
  ➡ significant overlap between the μ⁻ and nucleus wave-functions
- For a μ⁻ in orbit three processes may happen:
  ➡ **decay** (39%): $\mu^- N \to e^- \bar{\nu}_e \nu_\mu N$, **background**
  ➡ **capture** (61%): $\mu^- + N \to \nu_\mu + N'$, **normalization**
  ➡ **conversion** ($<10^{-13}$): $\mu^- + N \to e^- + N$, **signal**

Mu2e Detector

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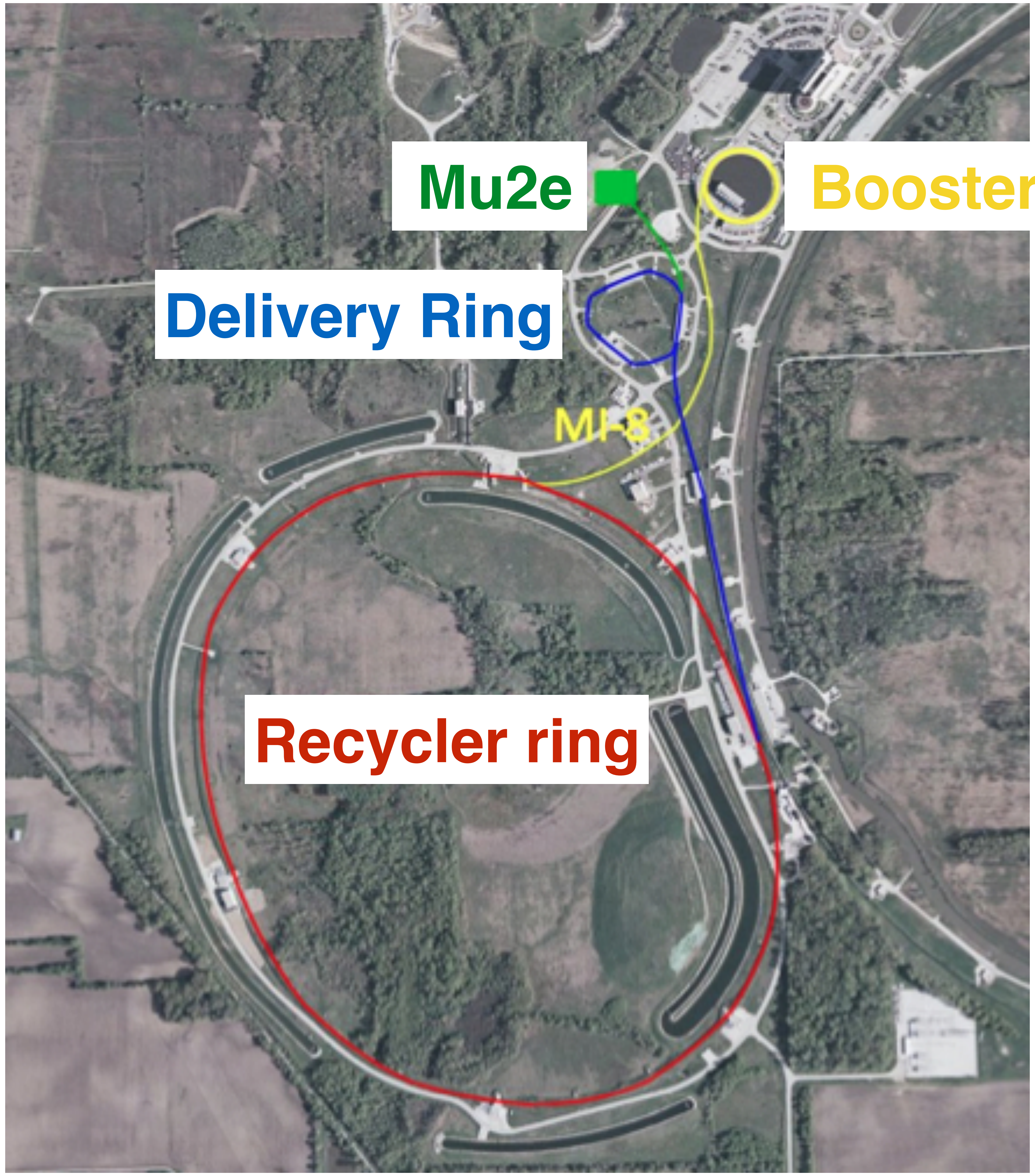
Mu2e beamline

Fermilab Muon campus

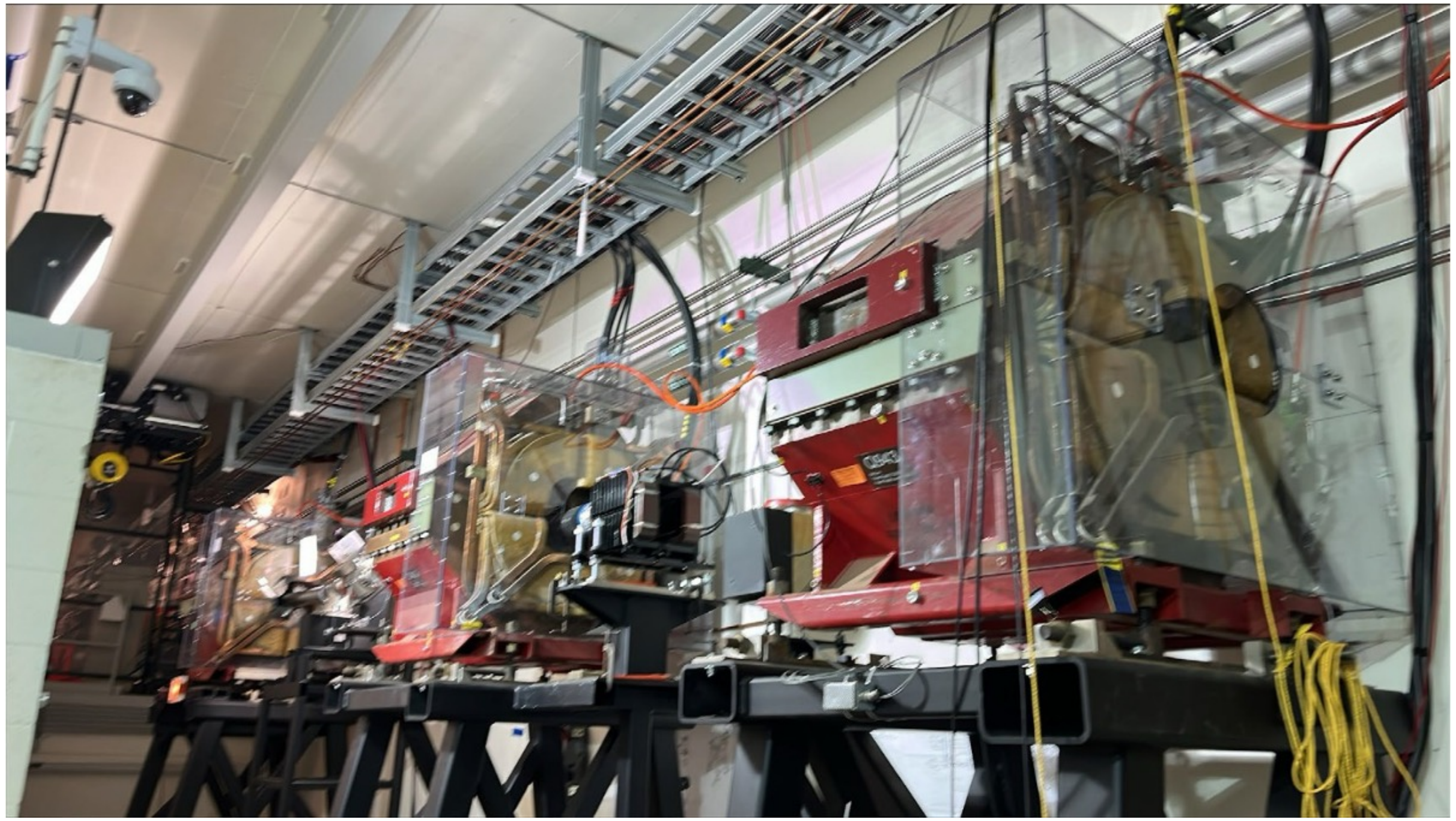
Mu2e proton beam



- 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
  - small loss to NOvA

Mu2e beamline

Built one AC dipole (pulsed beam), second one almost done, spare planned.



M4 Beam line dipole (small black) with quadrupoles (large red)

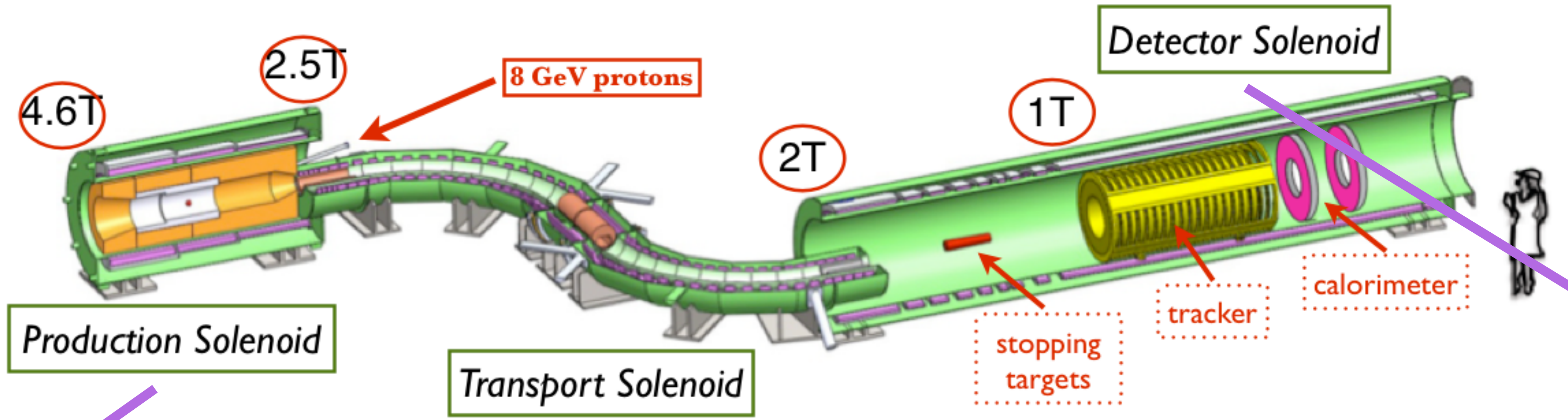
Mu2e Solenoids

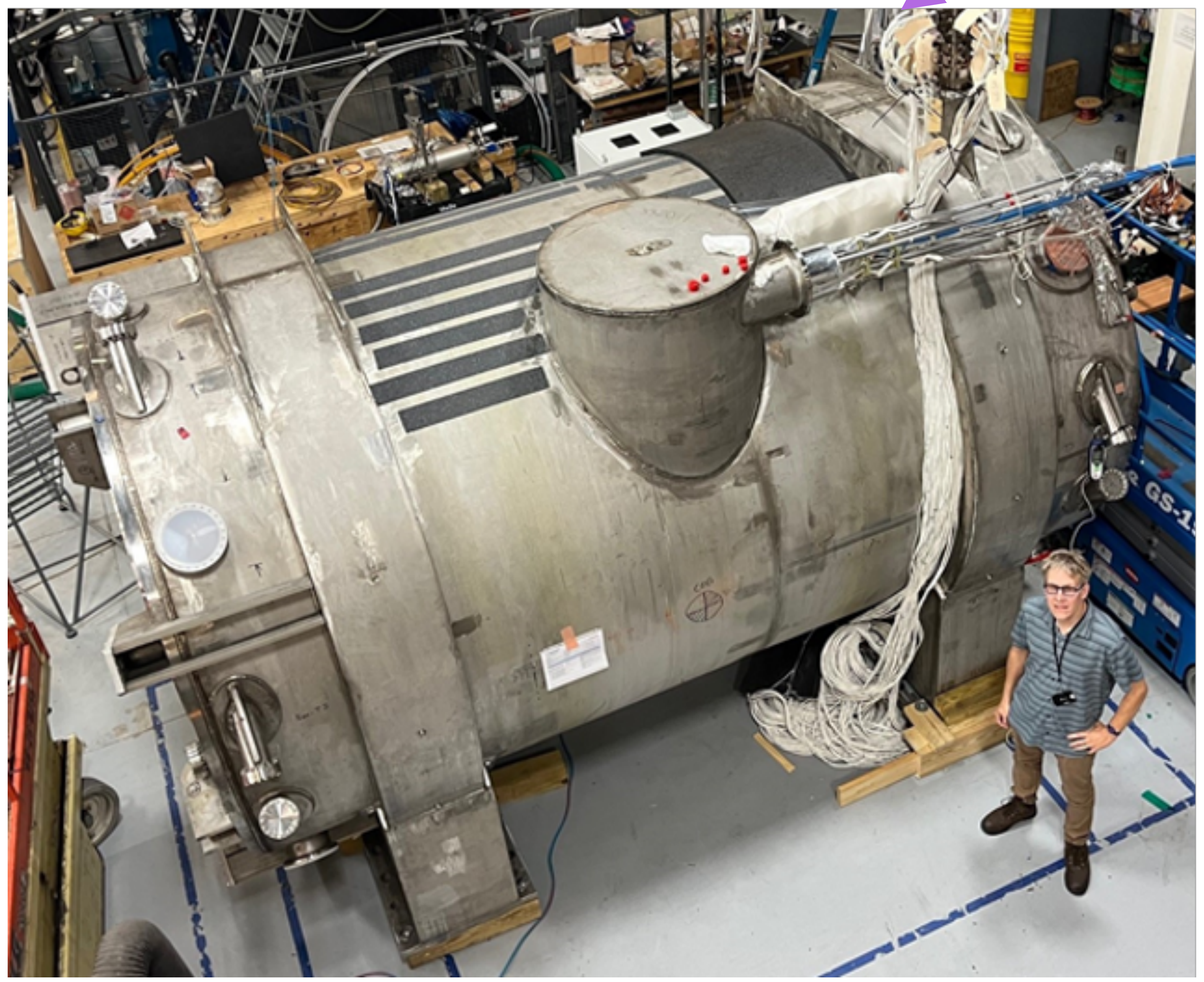
Mu2e solenoids summary

	Production	Transport	Detector
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	52	11
Conductor (km)	14	44	17
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

- PS, DS are being built by **General Atomics** (USA)
- TS is being built by **ASG** (Italy)

Solenoids status





PS inside the cold mass

TS is in the experimental hall

DS under construction

Backgrounds driving the experimental design

Physics background

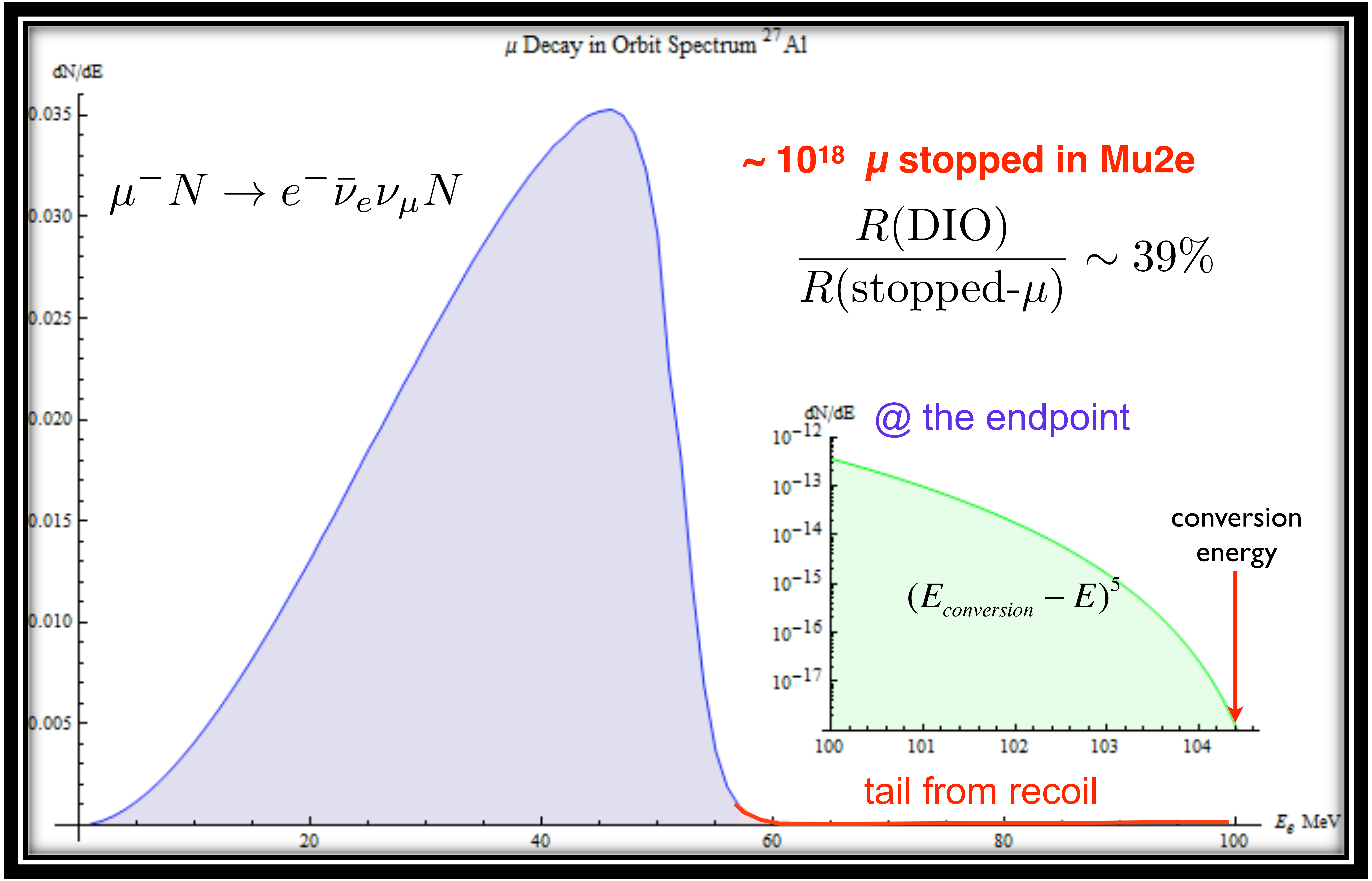
- **μ decay-in-orbit**

- Cosmic-induced background

- $\bar{p}$-induced background

- Radiative π capture

μ decay-in-orbit (DIO)



R. Szafron, A. Czarnecki https://doi.org/10.1016/j.physletb.2015.12.008

Physics background

- **μ decay-in-orbit:**

  ✓low-mass tracker with high performance

- Cosmic-induced background
- $\bar{p}$-induced background
- Radiative π capture

Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- **Cosmic-induced background:**

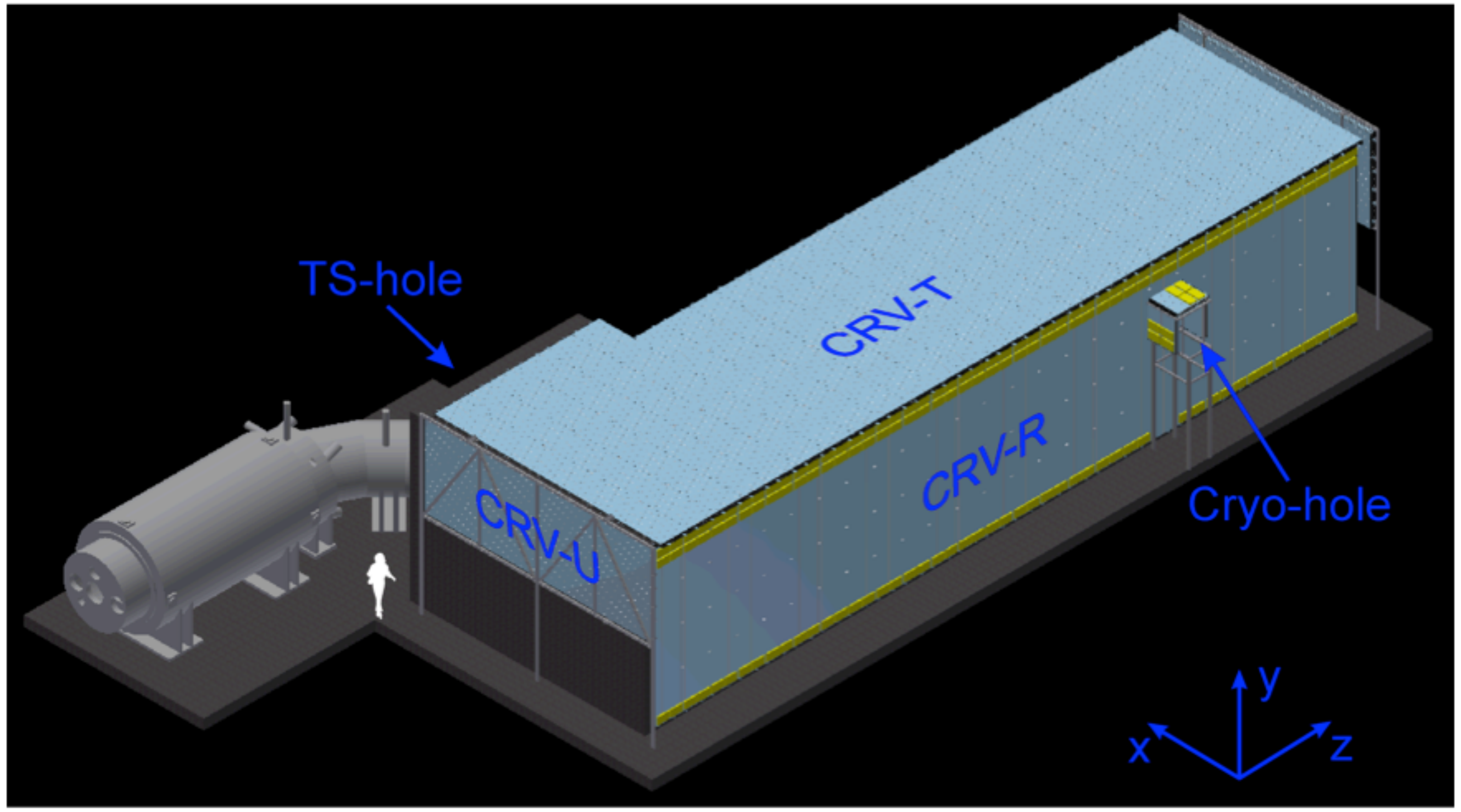
  ✓ **cosmic ray veto and Particle Identification (PID)**

- $\bar{p}$-induced background

- Radiative π capture

Cosmic Ray Veto

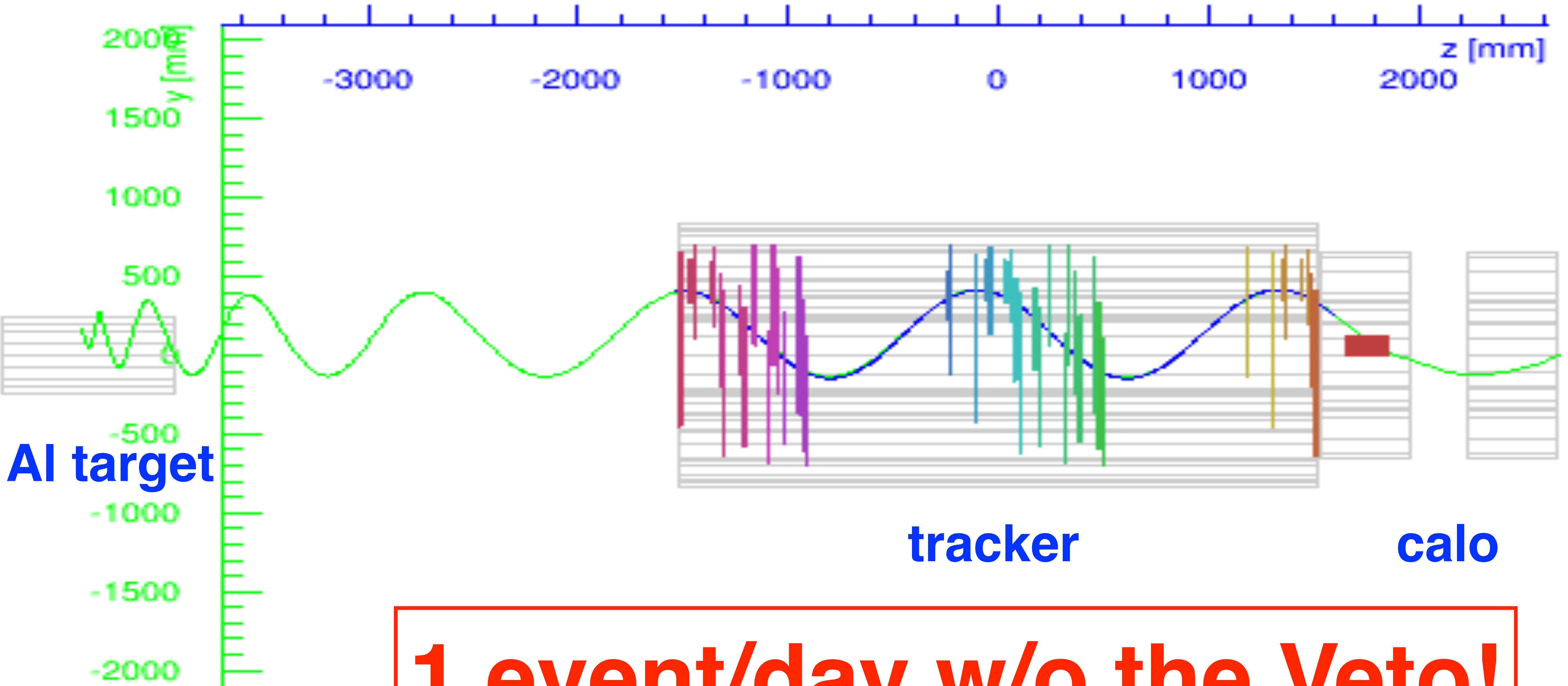
- Veto system covers entire DS and half TS
- 4 layers of scintillator
  - each bar is 5x2x~450 cm^3
  - 2 WLS fibers/bar
  - read out at both ends with SiPM
- required inefficiency ~ 10^{-4}



WLS fiber

Prototype

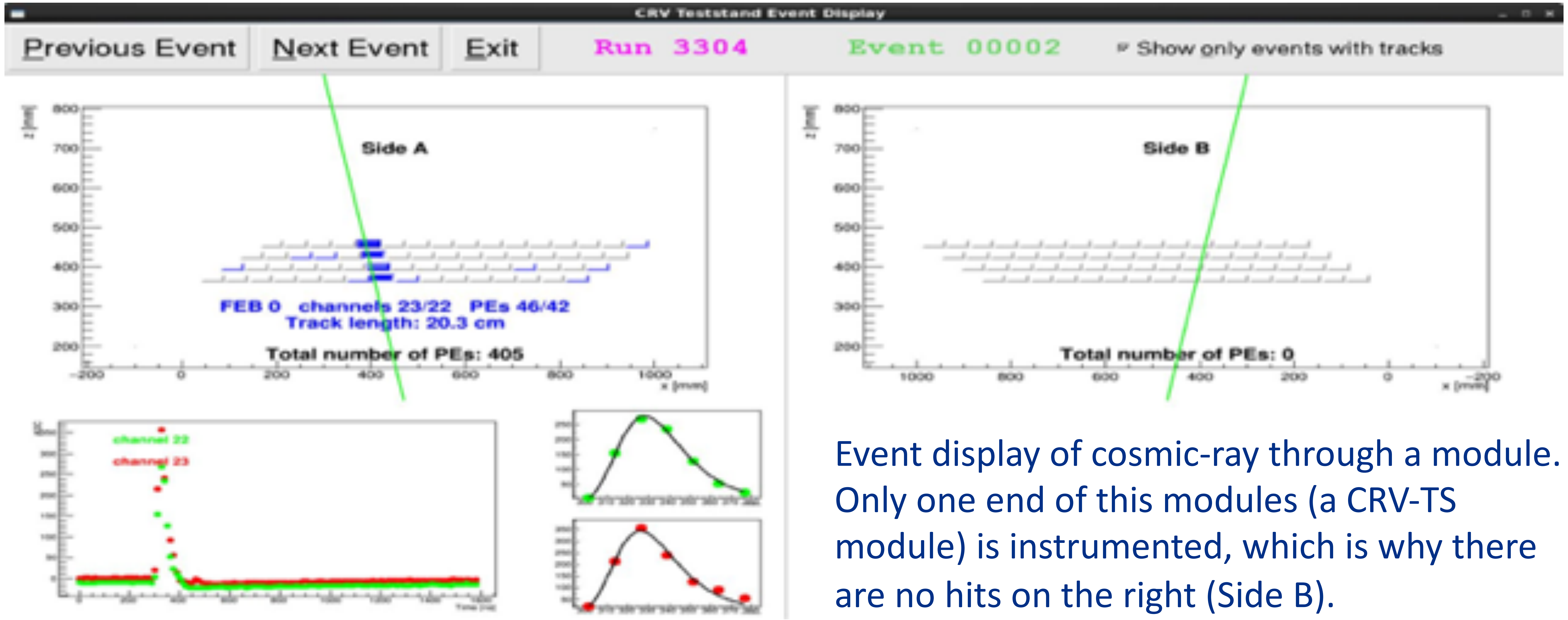
μ mimicking the CE



1 event/day w/o the Veto!

Cosmic Ray Veto construction

- We have fabricated all the modules
- QA test meet the requirements
- Electronics production underway
  - All SiPM tested
  - Front-End-Boards under construction @ Kansas State Univ



Event display of cosmic-ray through a module. Only one end of this modules (a CRV-TS module) is instrumented, which is why there are no hits on the right (Side B).

Completed modules stored @ Fermilab

Vertical slice test @ Fermilab

Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- Cosmic-induced background:

  ✓ cosmic ray veto and Particle Identification (PID)

- **$\bar{p}$-induced background**

  ✓ absorbers in the beam line to stop the $\bar{p}$

- Radiative π capture

Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- Cosmic-induced background:

  ✓ cosmic ray veto and Particle Identification (PID)

- $\bar{p}$-induced background

  ✓ absorbers in the beam line to stop the $\bar{p}$

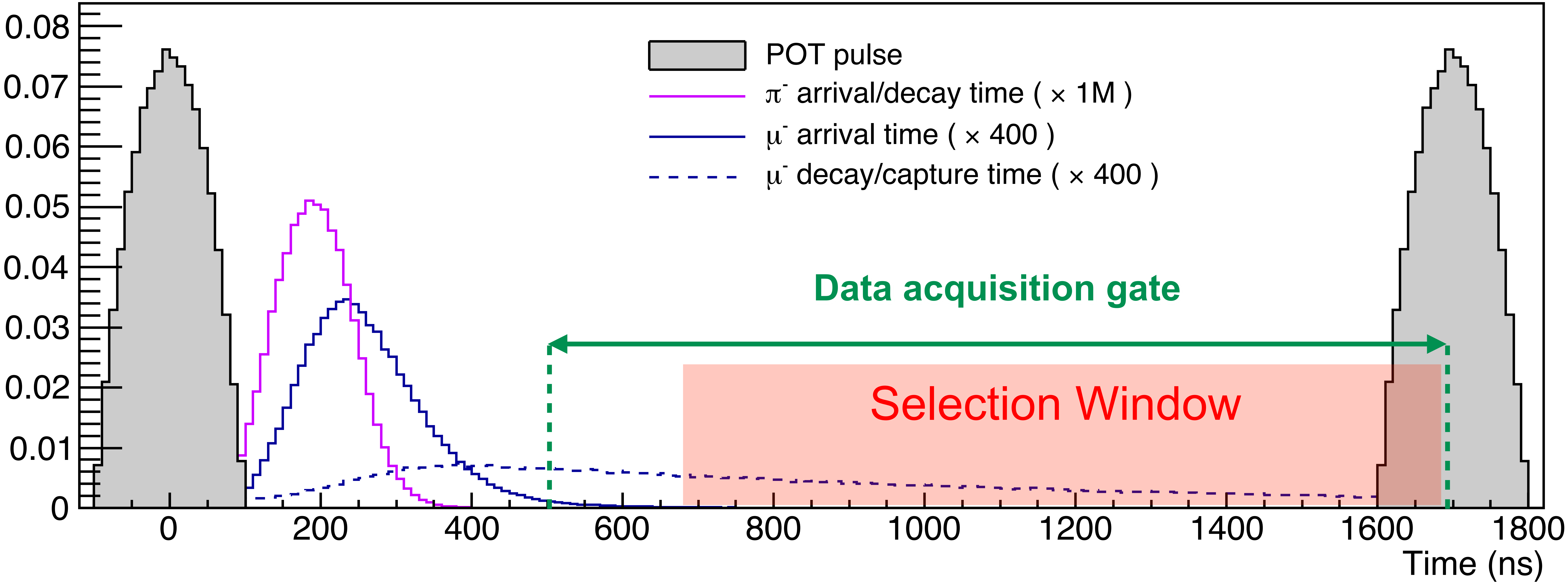
- **Radiative π capture: $\pi^- N_Z \rightarrow N^*_{Z-1}\,\gamma$, asymmetric $\gamma \rightarrow e^- e^+$**

  ✓ pulsed beam and extinction of out-of-time protons

Pulsed beam

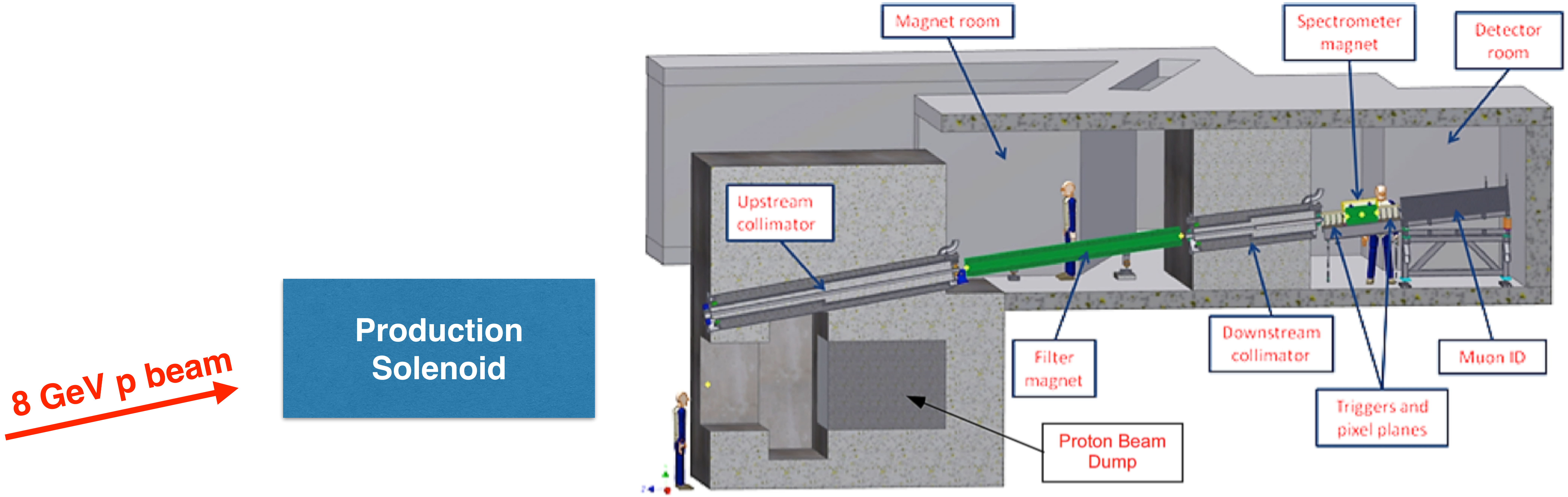
- Beam period : 1.7 μs ~ 2 x τ_{μ}^{Al}
- Beam intensity: 3.9 x 10^7 p/bunch
- duty cycle : ~ 30%
- **out-of-time protons / in-time protons < 10^{-10}**

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



Extinction of out-of-time protons

- The RF structure of the Recycler provides some "intrinsic" extinction:
  - **Intrinsic extinction ~10^{-5}**
- A custom-made AC dipole placed just upstream of the PS provides additional extinction:
  - **AC dipole extinction ~ 10^{-6} - 10^{-7}**
- Together they provide a total extinction:
  - **Total extinction ~ 10^{-11} - 10^{-12}**
- Extinction measured using a detector system: Si-pixel + sampling EMC

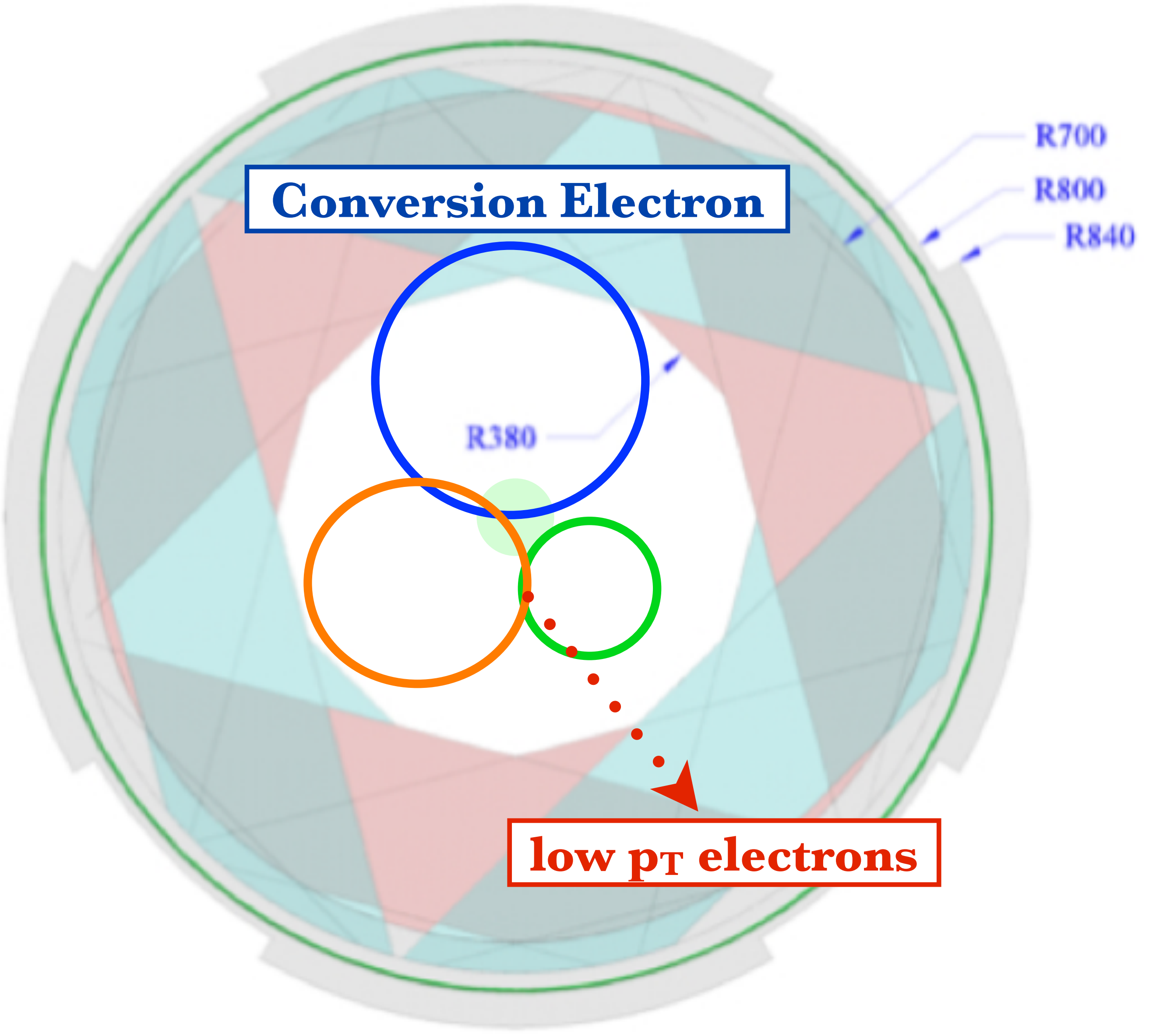


Mu2e detectors

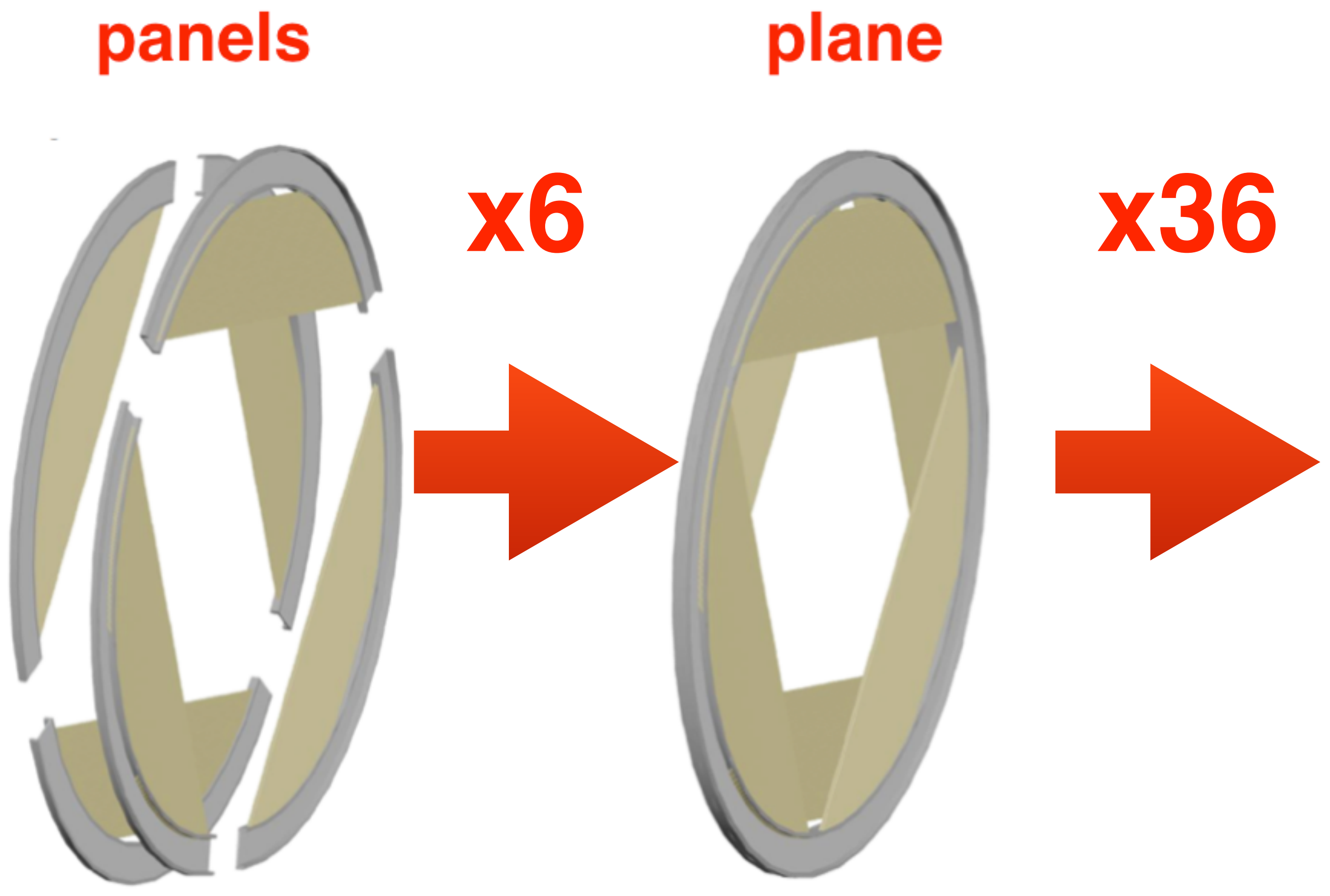
Tracker design

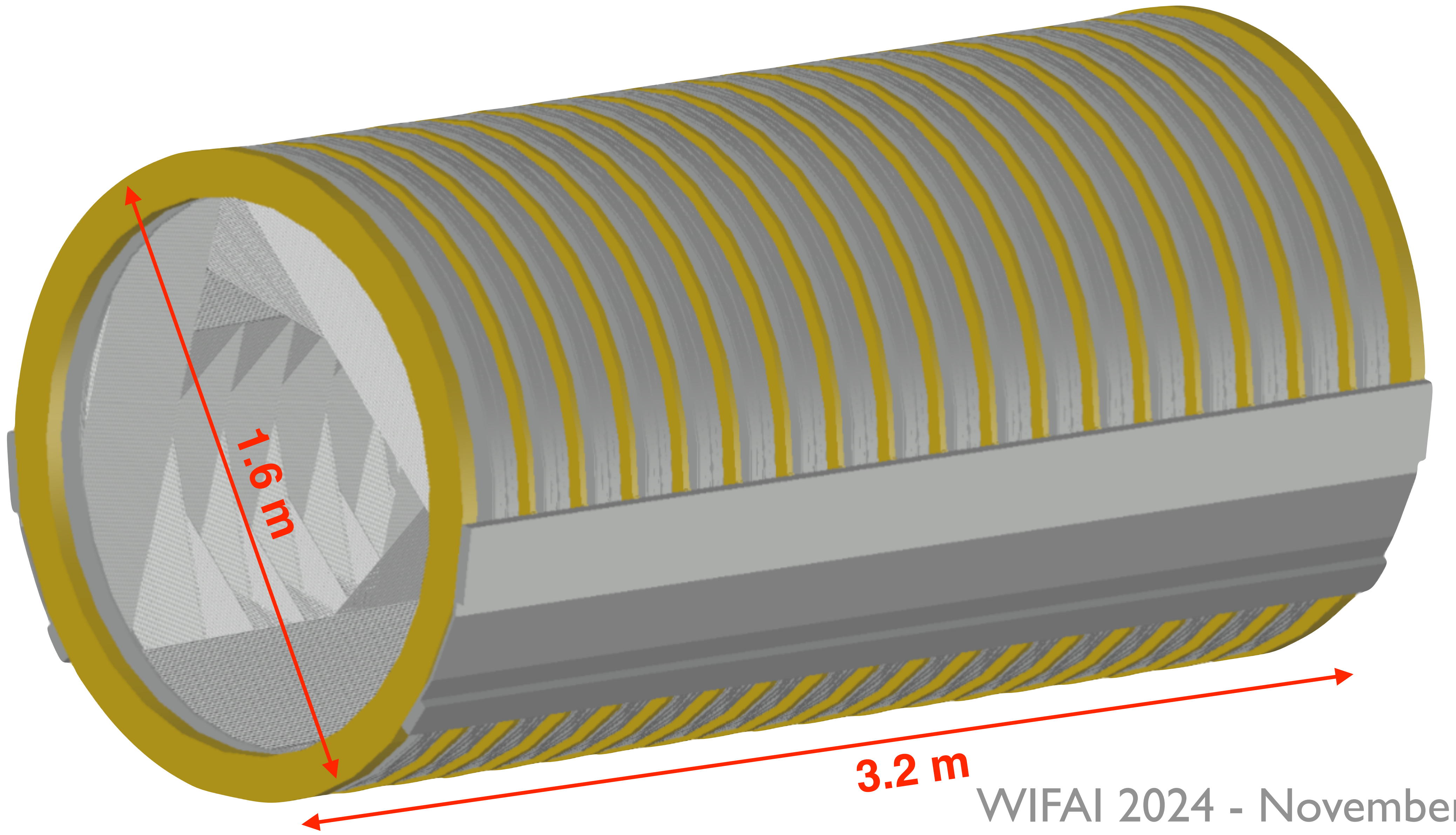
- 36 planes equally spaced with straws transverse to the beam
- Straw technology employed:
  - ✓ 5 mm diameter, 12 μm Mylar walls
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to **low** pT particles, only ~10^5 DIO remain

Straw-tube



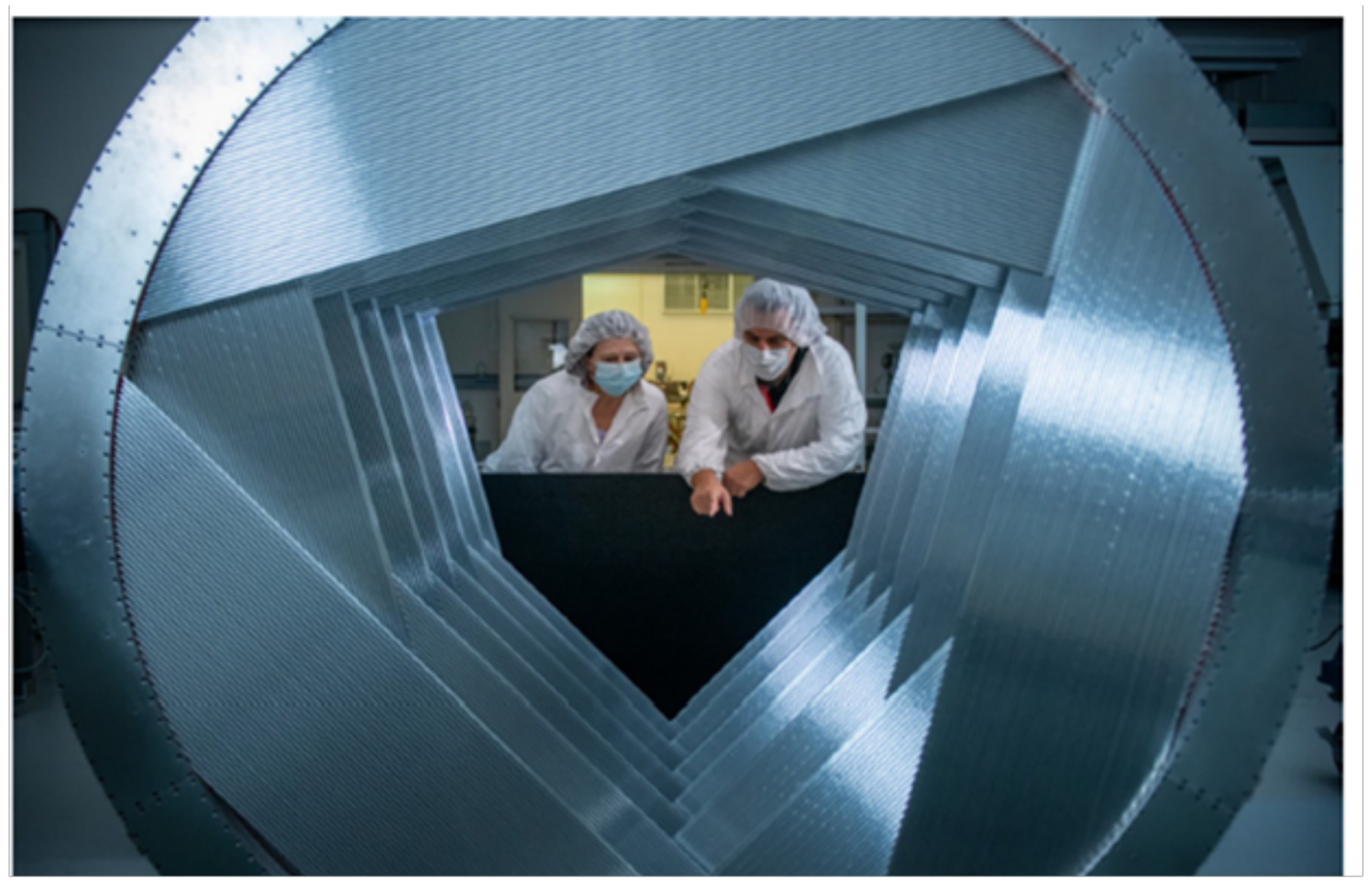
panel

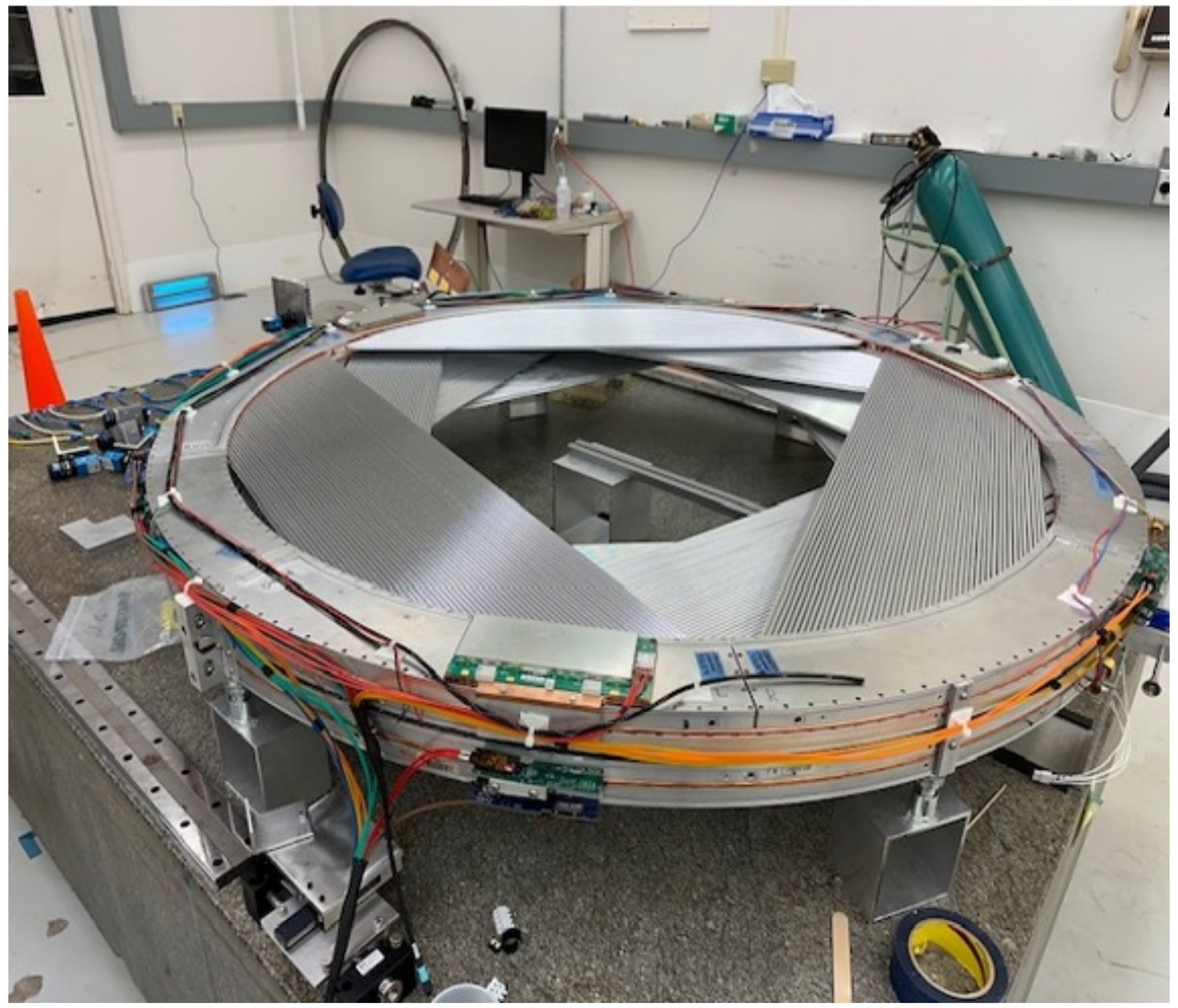




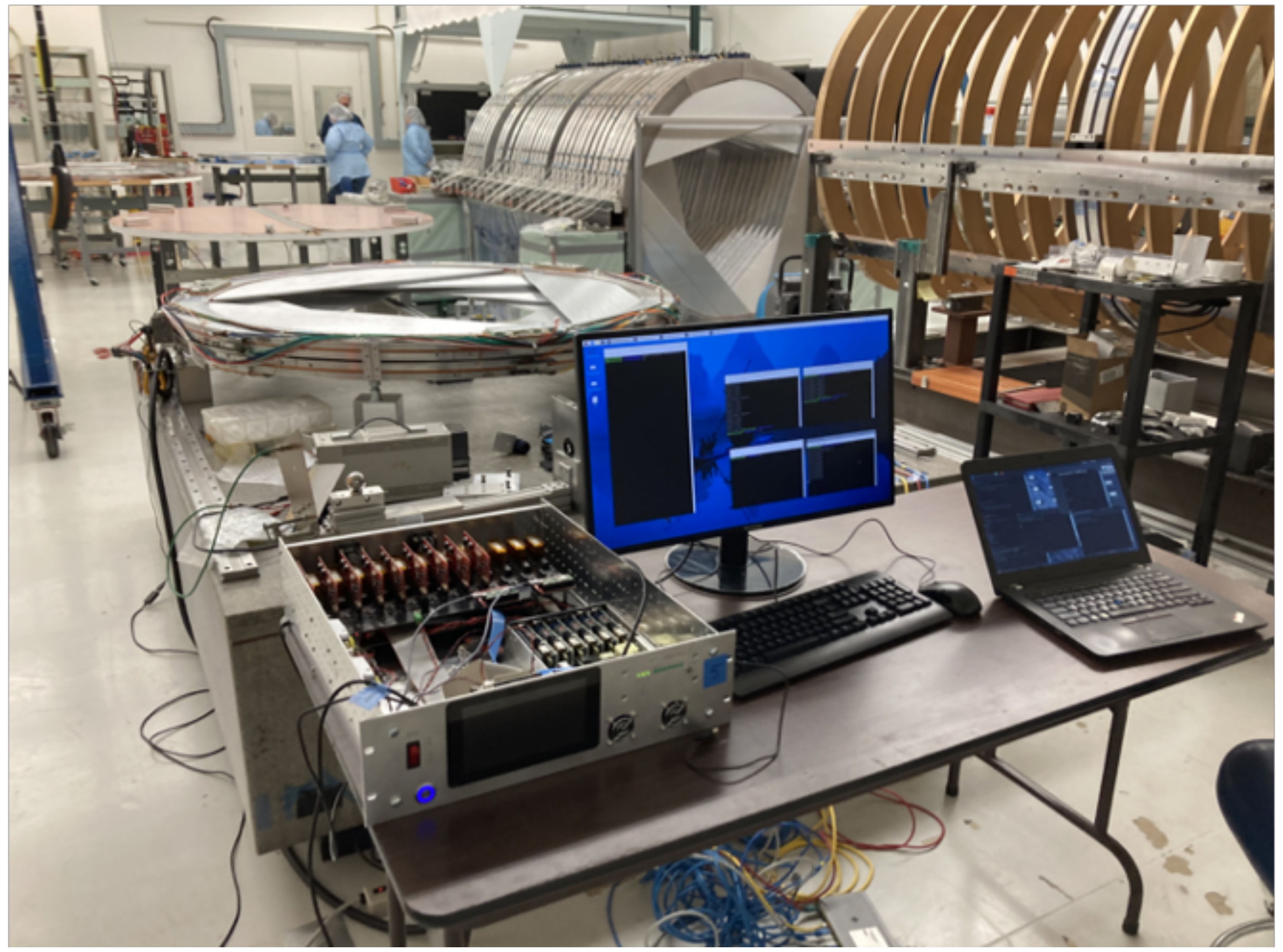
Tracker construction

- Tracker Assembly @ Fermilab
- Plane Assembly (36 planes needed)
- Plane construction nearly completed
- Electronics installation into planes
- On track to complete in December 2024





Tracker station



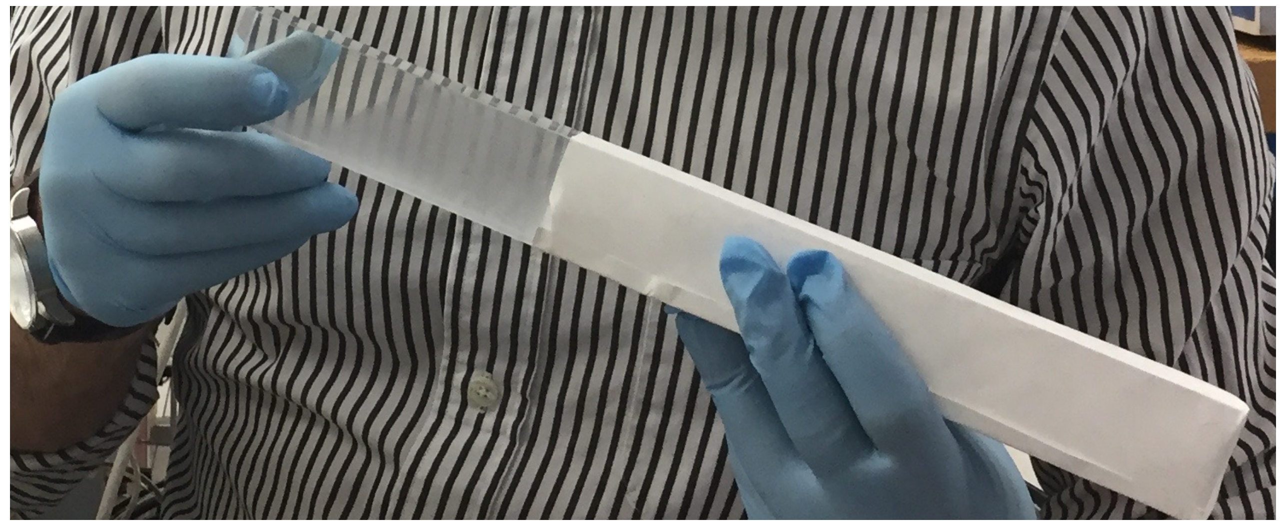
DAQ test station

Long-term leak test

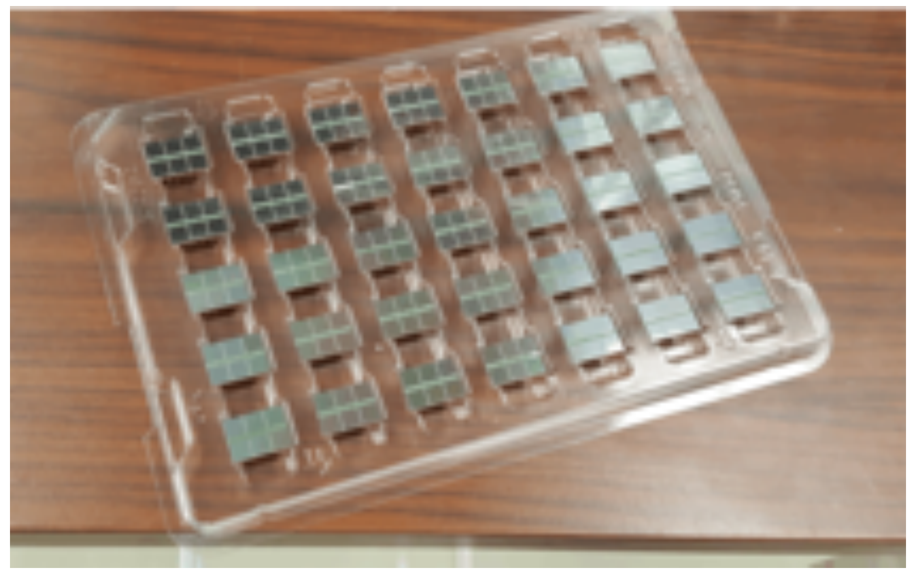
Calorimeter design

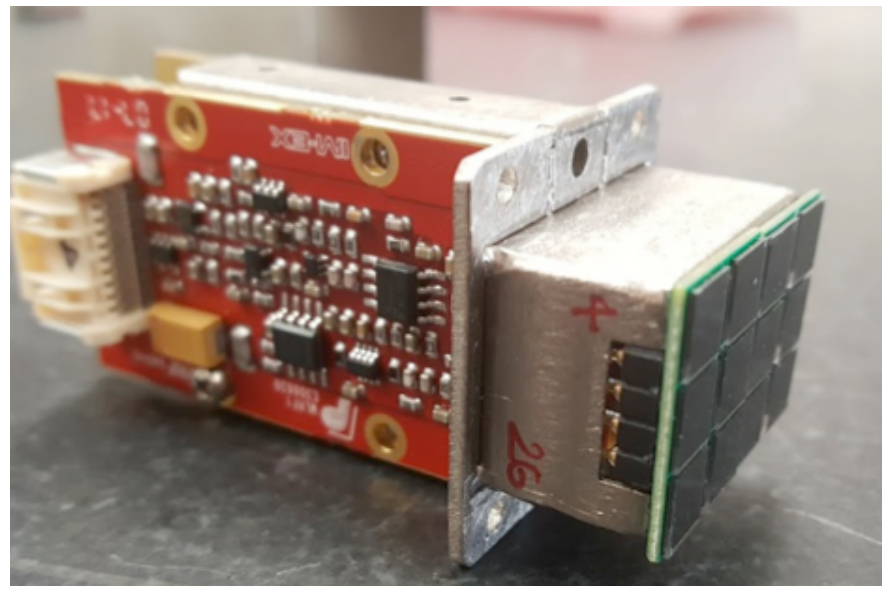
- 2 disks; each disk contains 930 undoped CsI crystals 20 x 3.3 x 3.3 cm^3
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- Readout system:
  - ➡ 2 large area SiPM-array/crystal
  - ➡ 12 bit, 200 MHz waveform-based digitizer boards

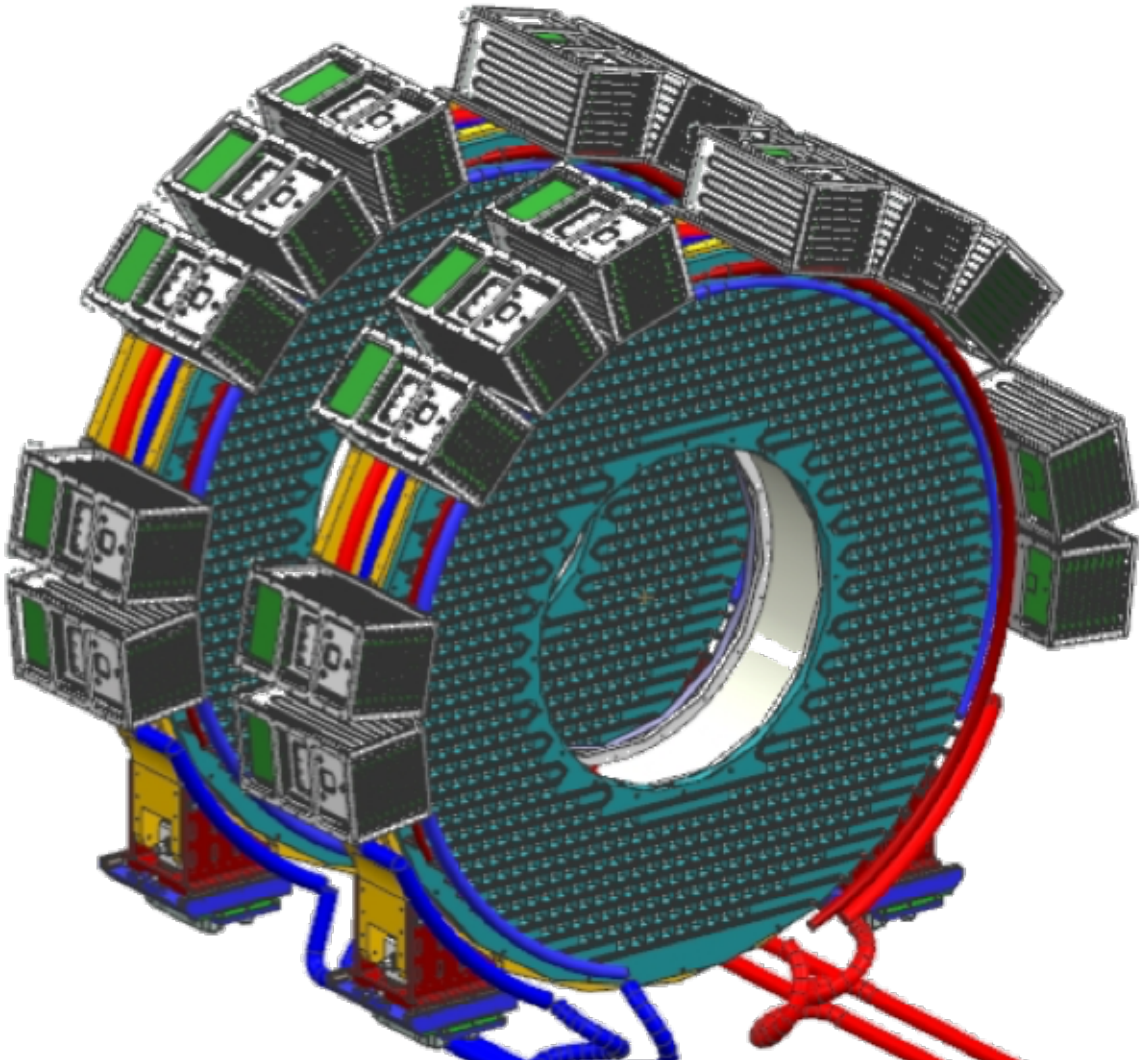
undoped CsI



SiPM array

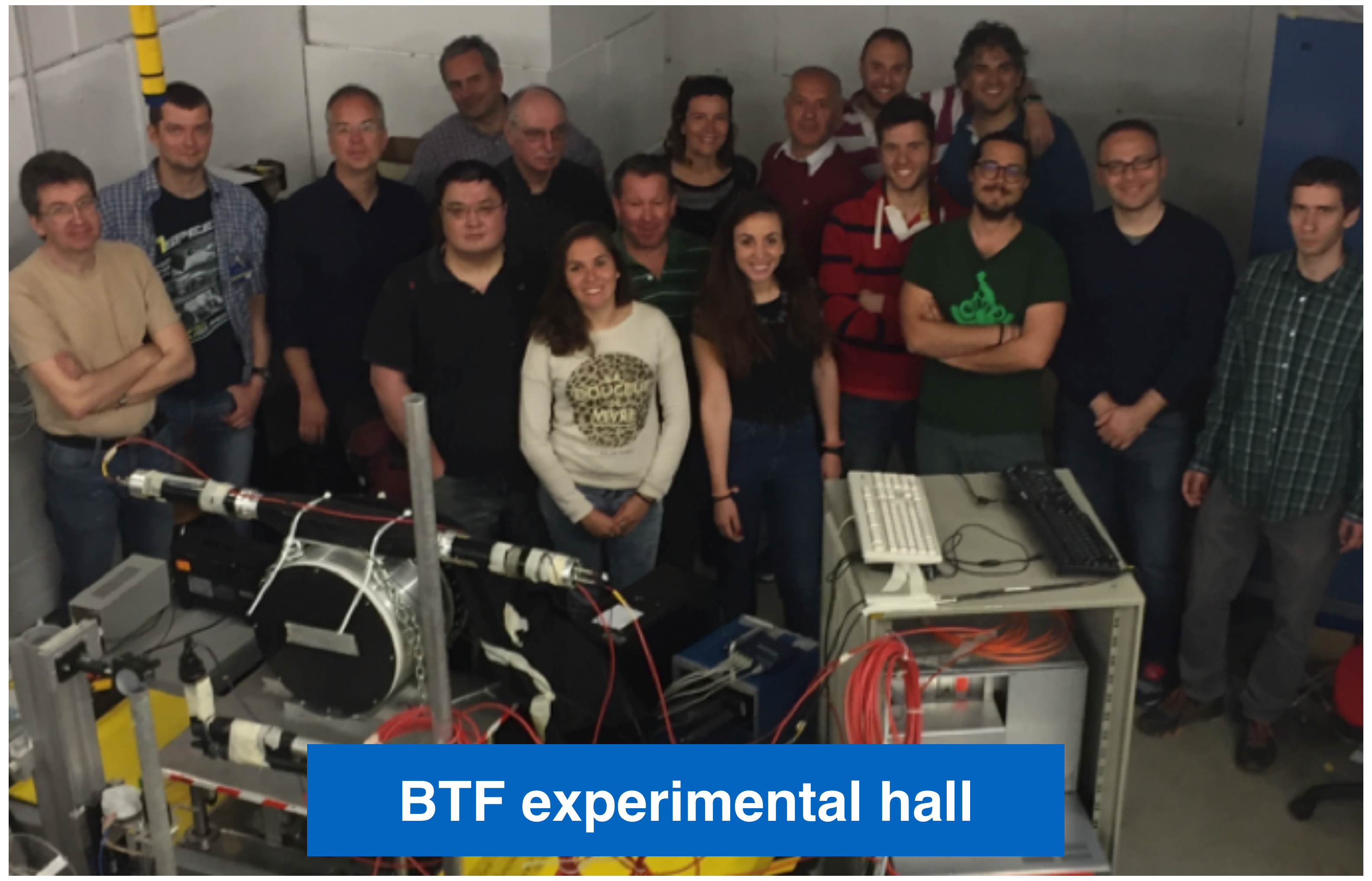


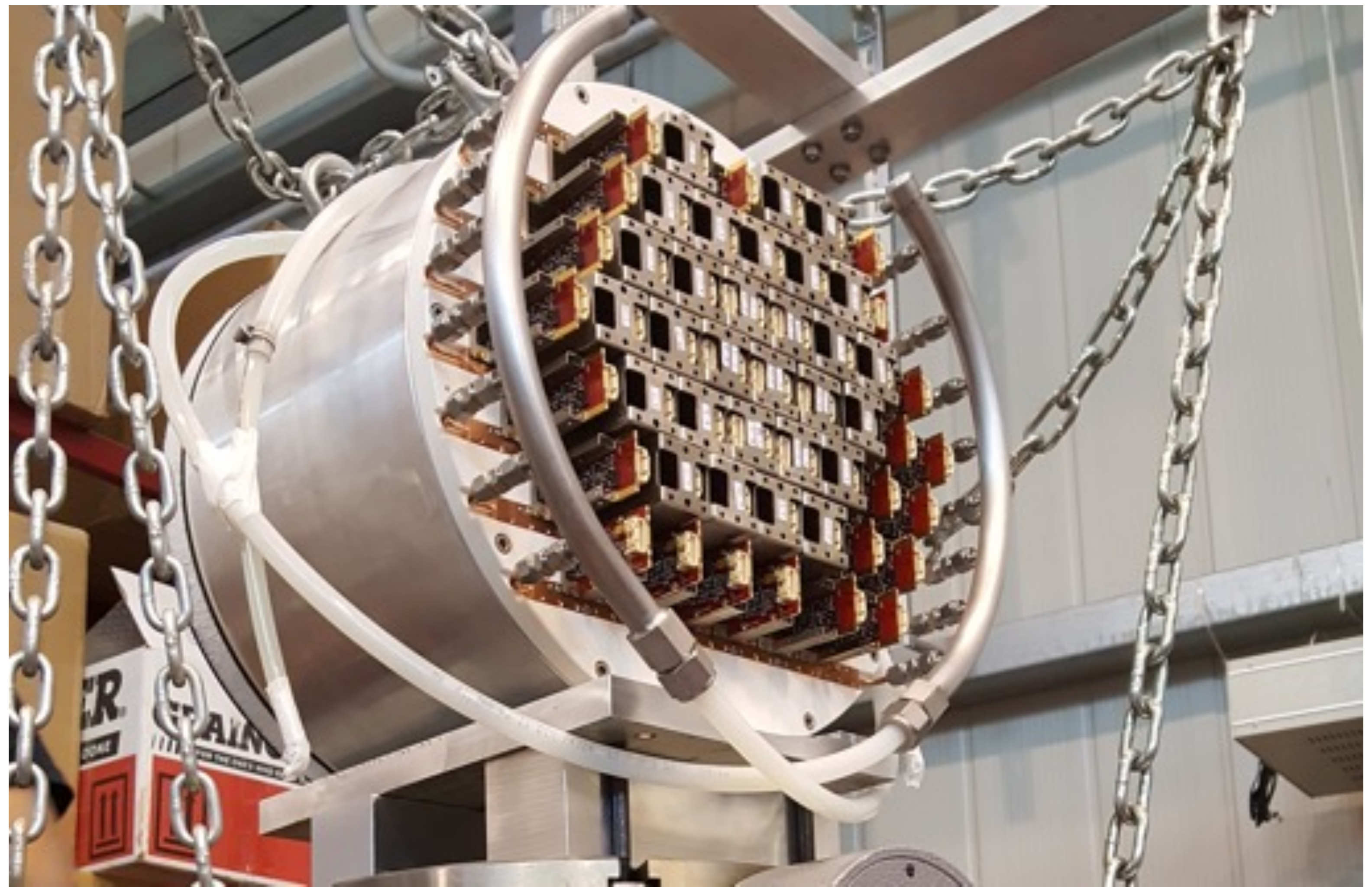


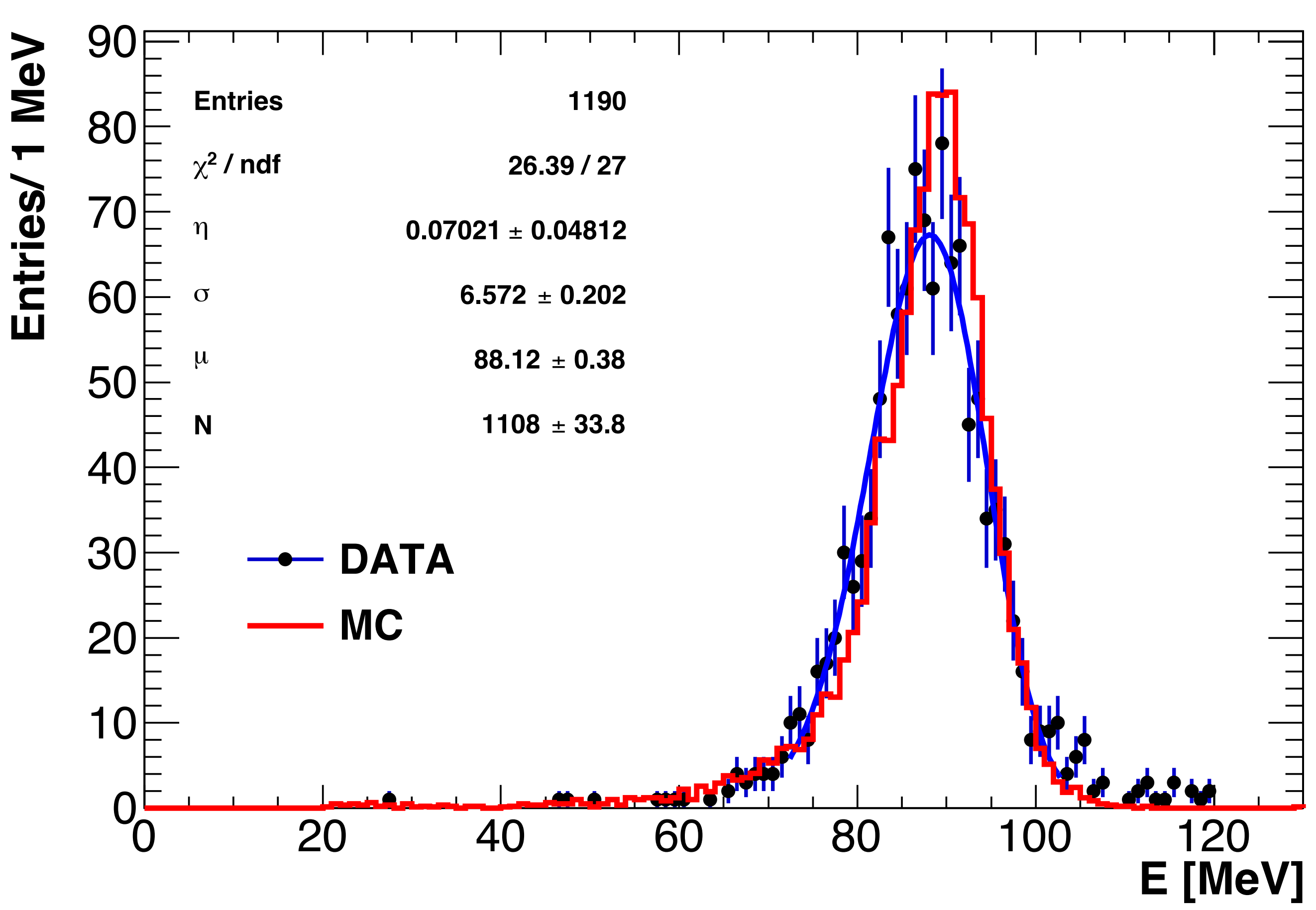


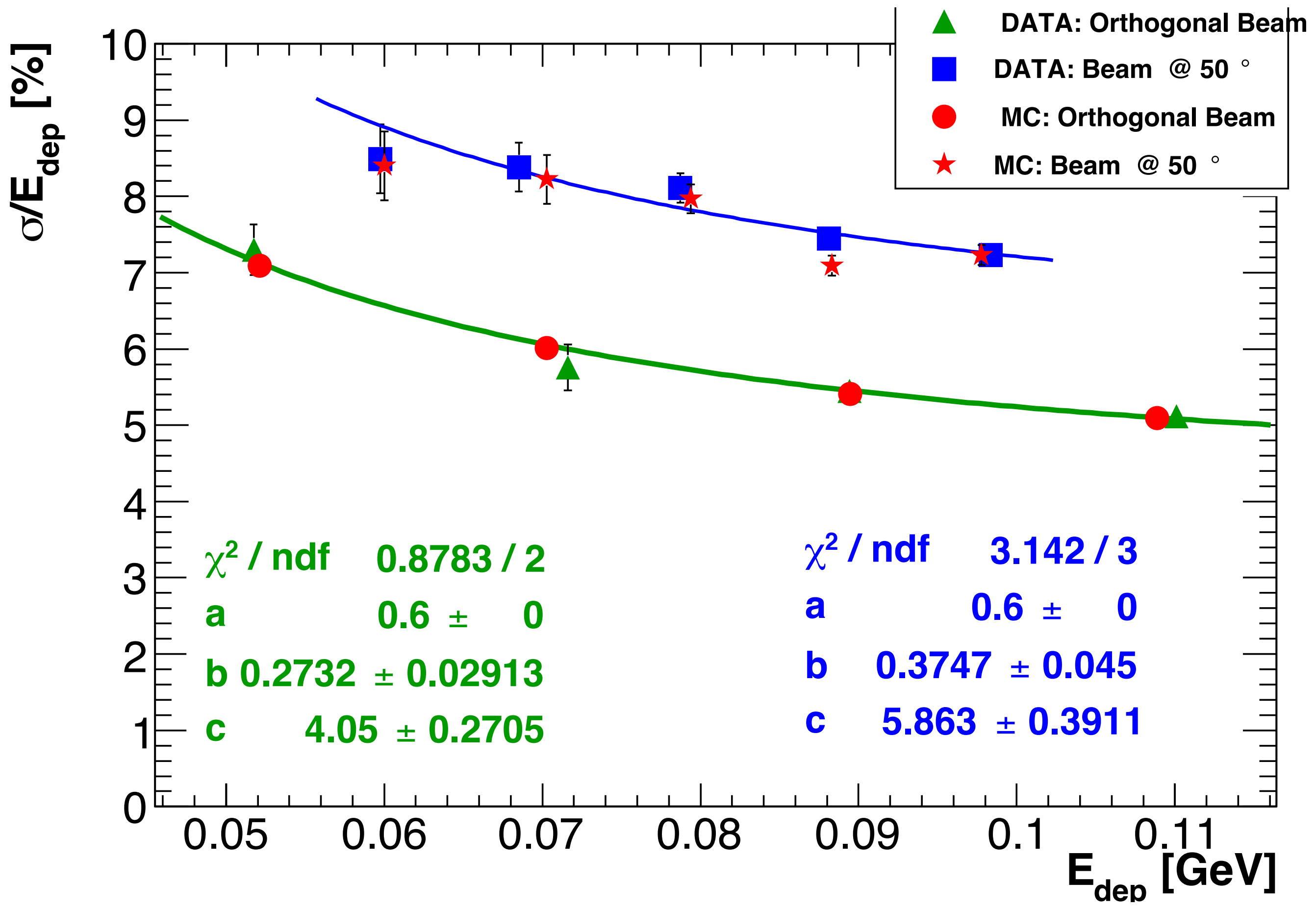
Calorimeter R&D

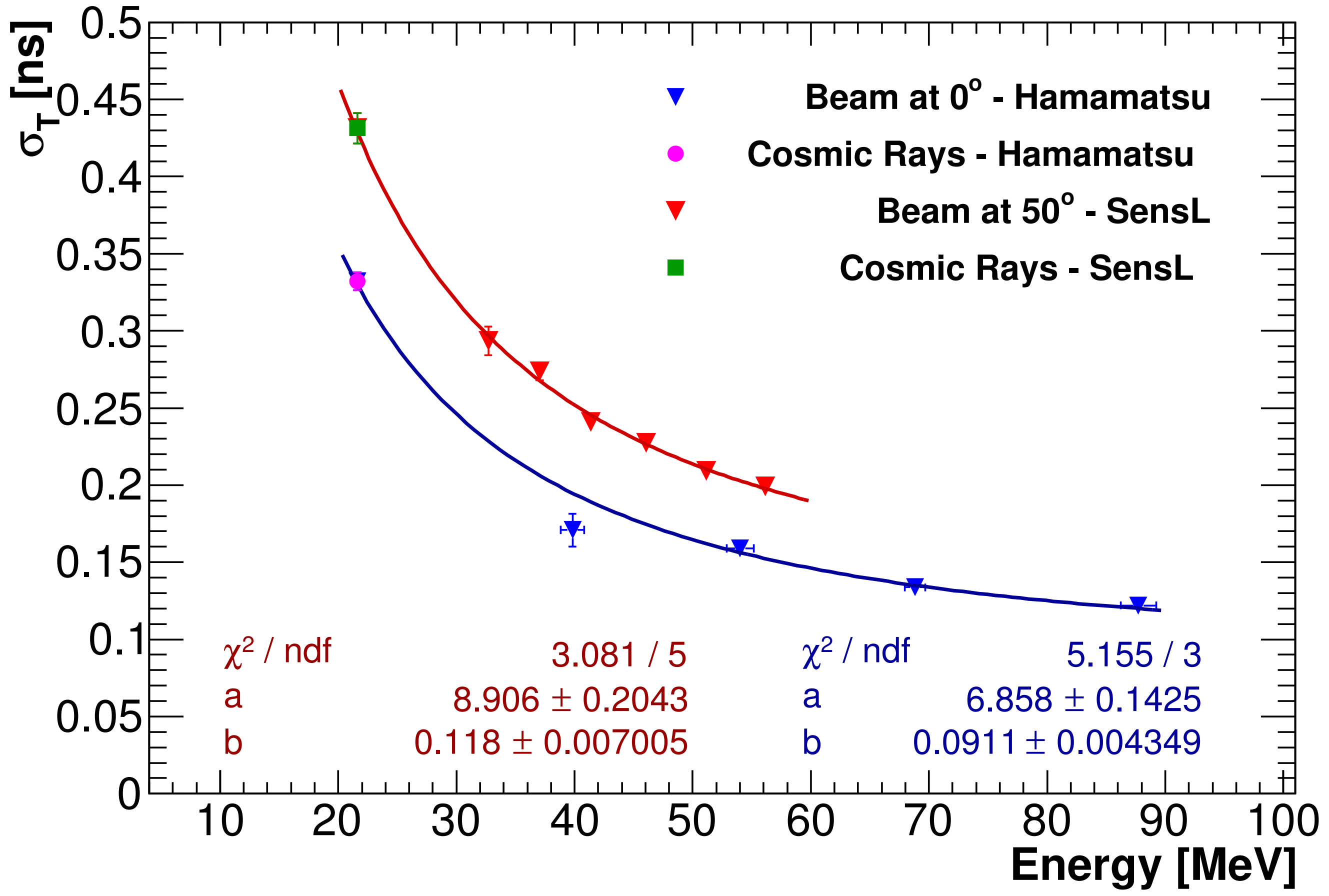
- Large prototype: 51crystals + 102 SiPM + 102 FEE boards
- Beam test successfully performed @ BTF in Frascati using e$^-$ beam





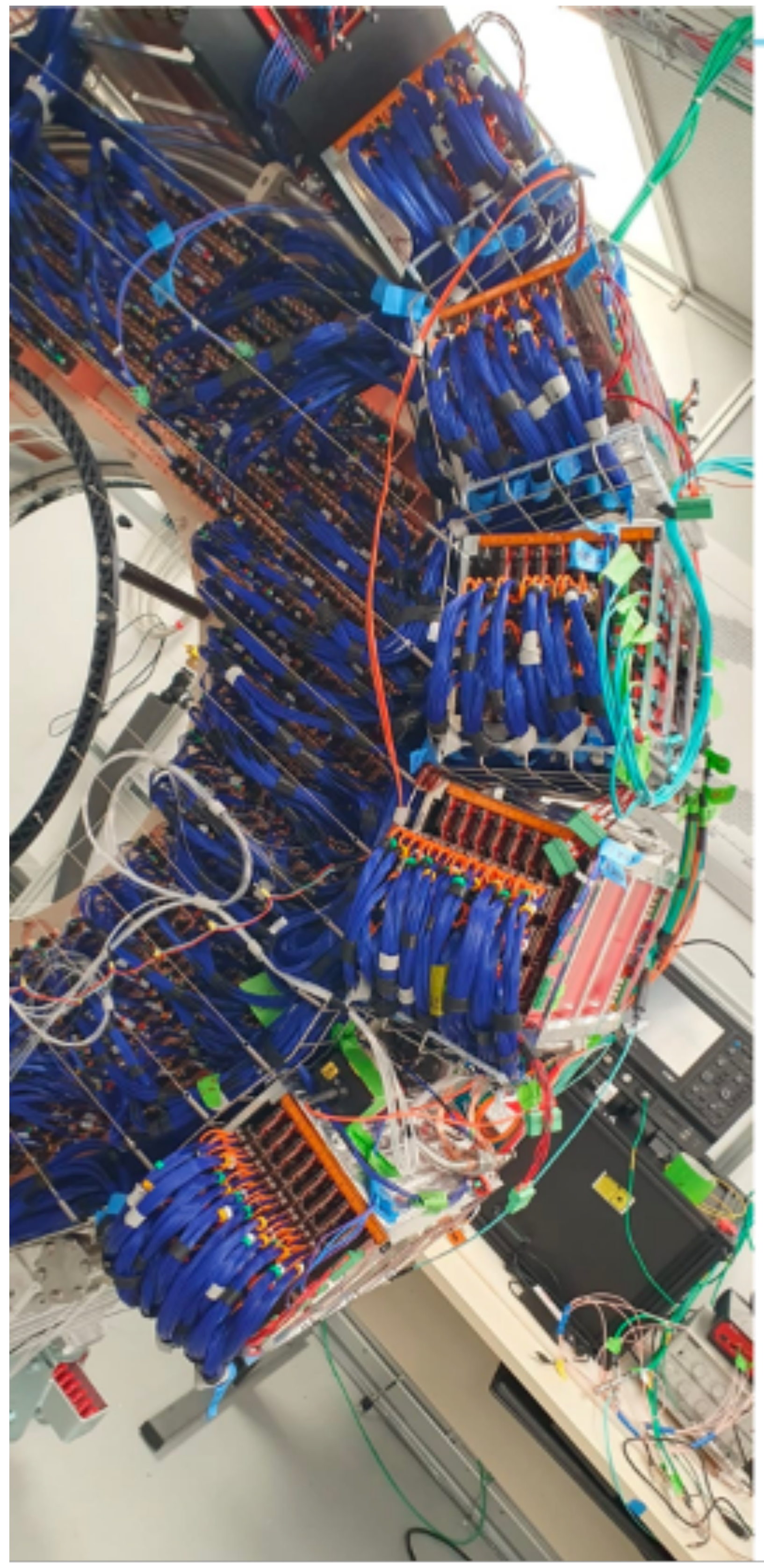


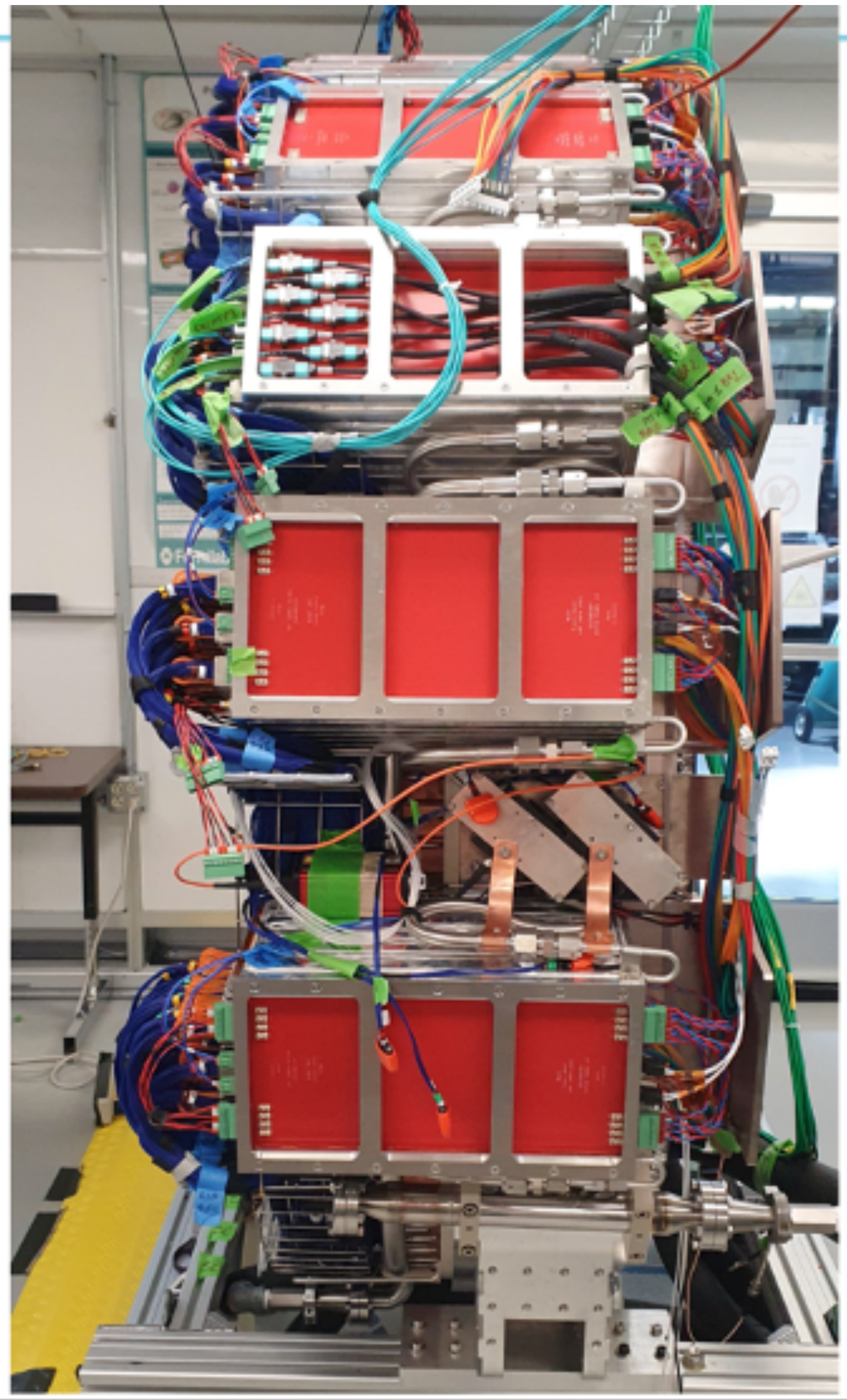


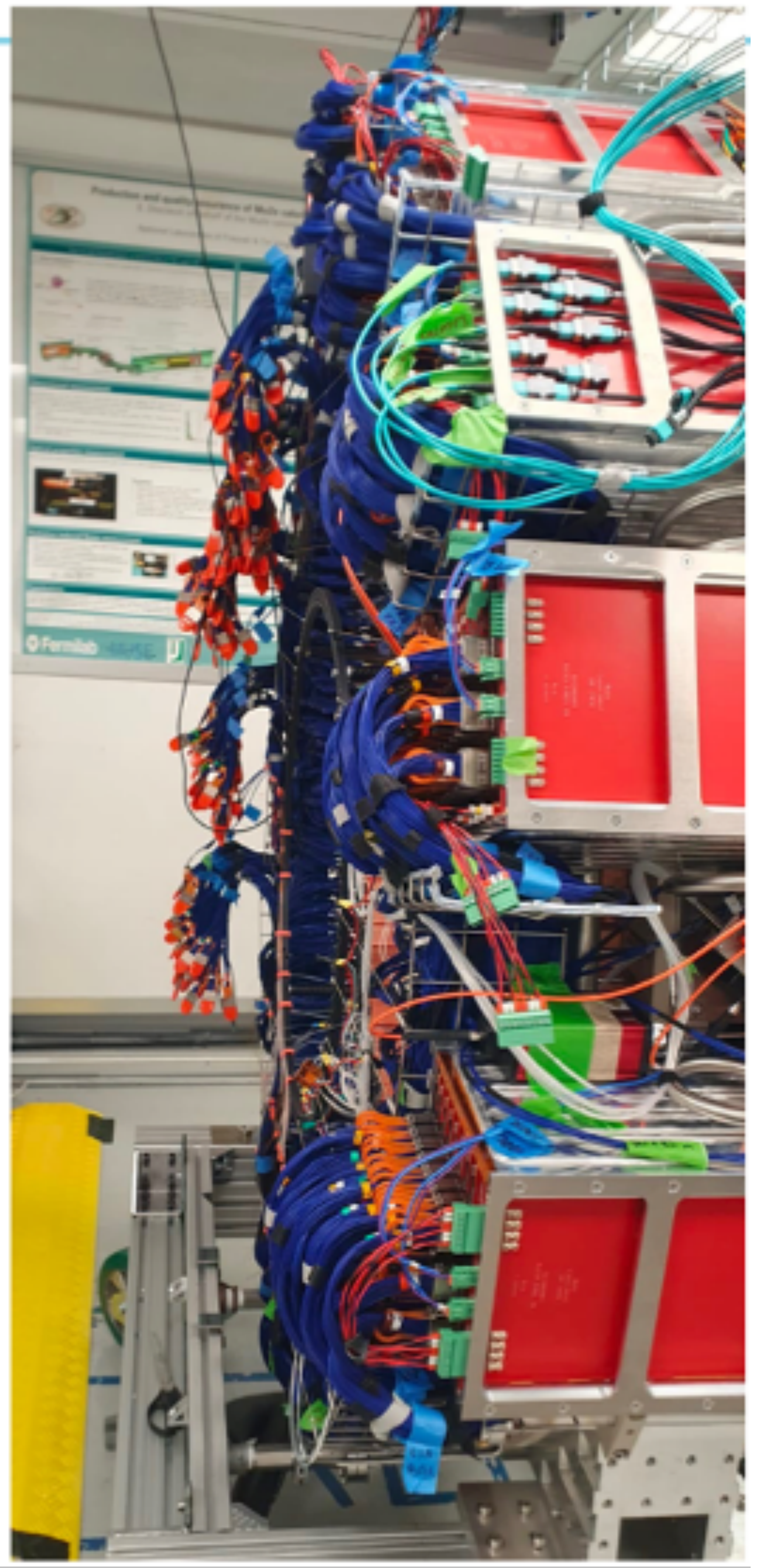


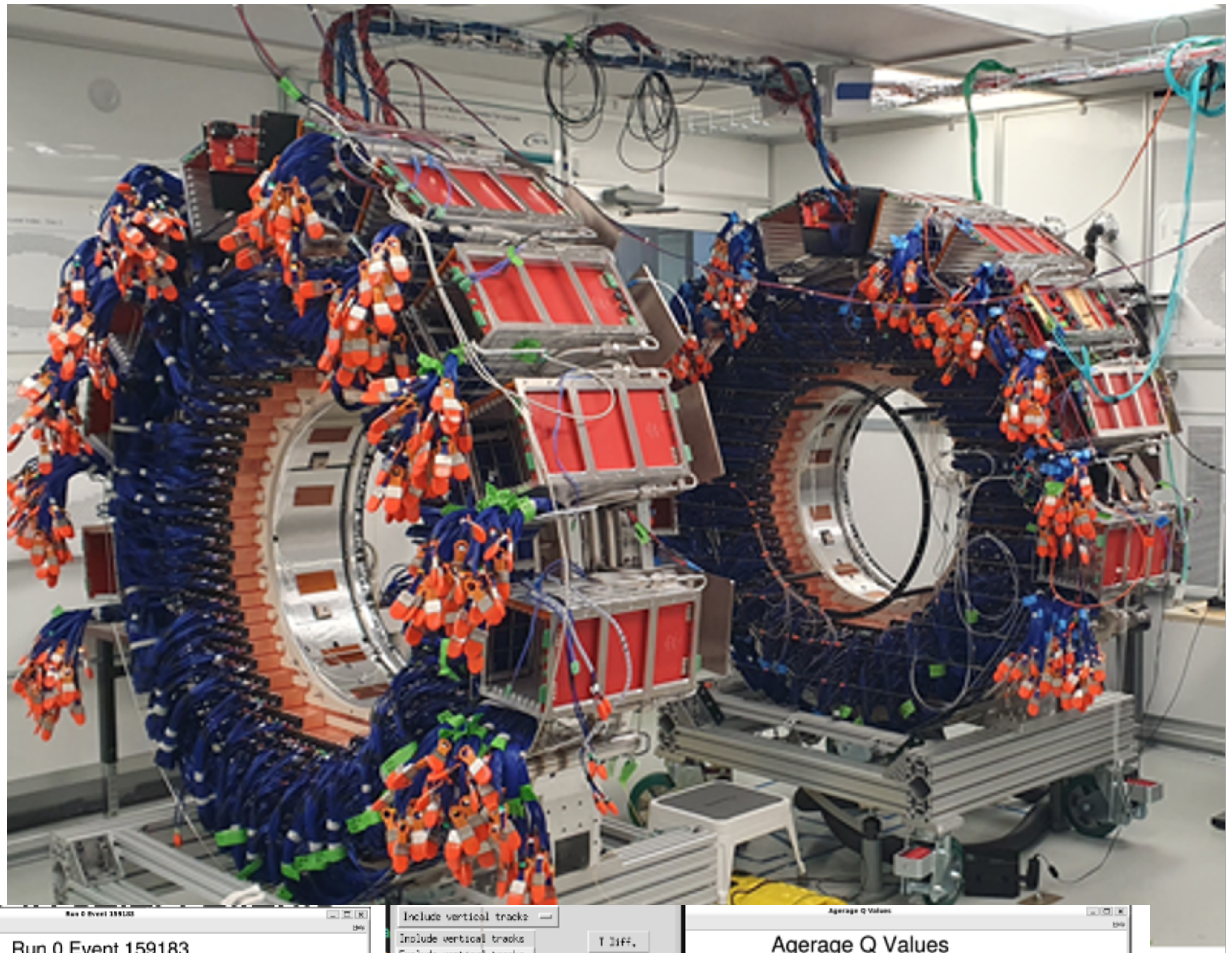
Calorimeter construction

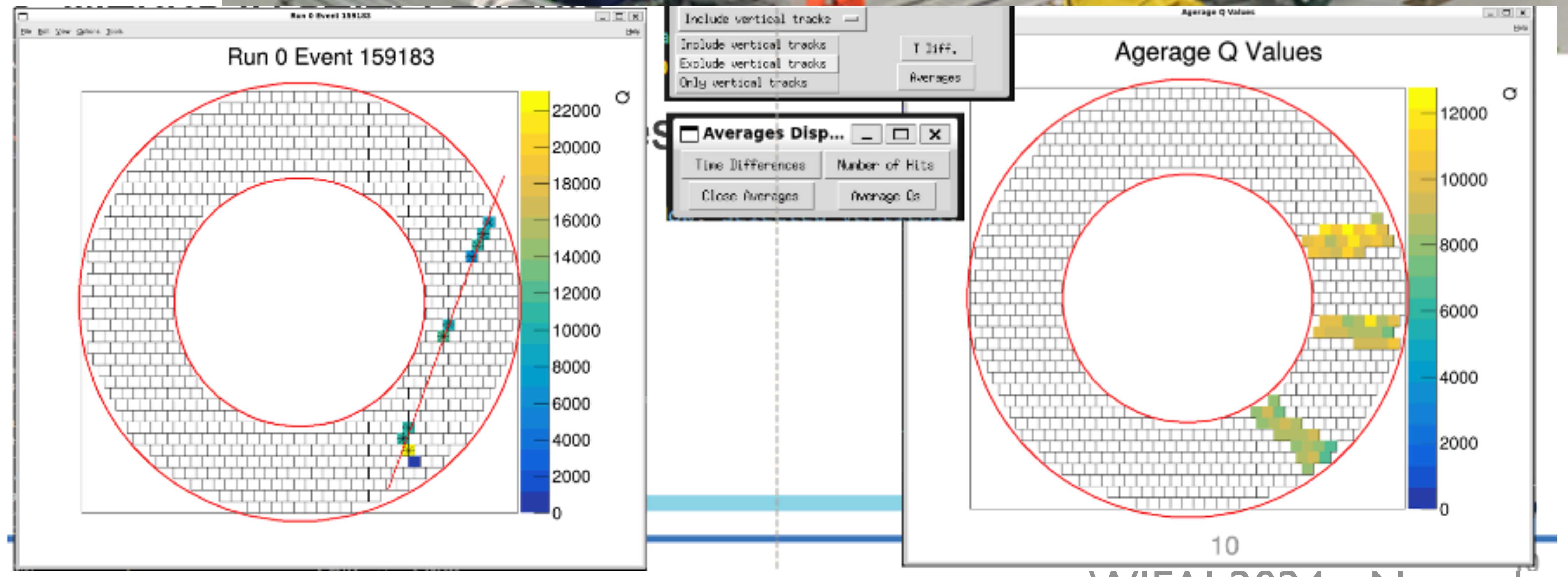
- Calorimeter disks fully cabled!
- Checking signals with cosmics and laser pulses
- On track to be ready to move disks early next year









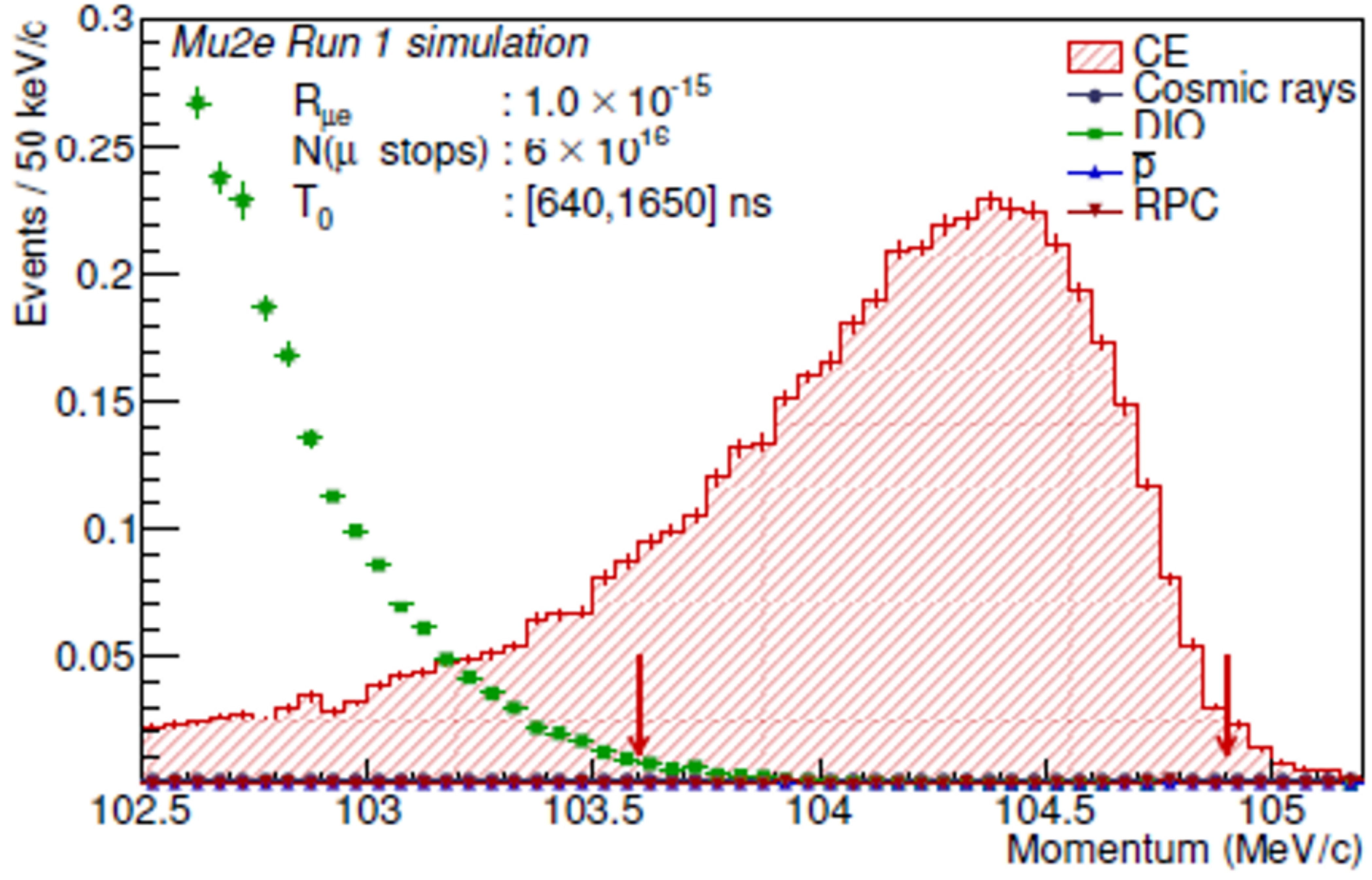


Mu2e Sensitivity

Mu2e sensitivity

- For Run I, assuming 6×10^{16} stopped muons, we expect a SES of 2.4×10^{-16}
- Largest background contributions coning from Cosmic rays induced events and DIO electrons

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1$ (stat) $^{+0.1}_{-0.3}$ (syst)) $\times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

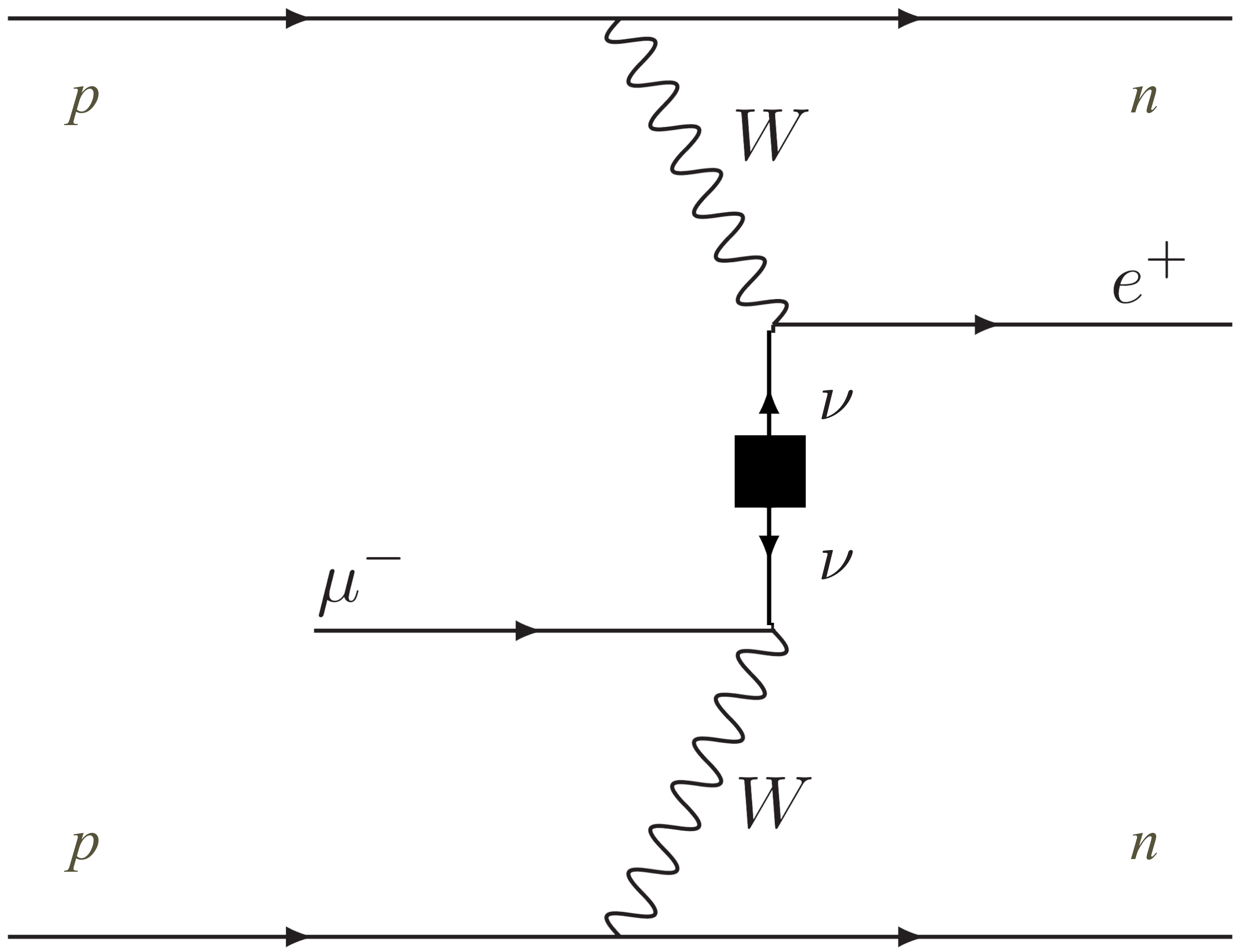


Universe 2023, 9, 54

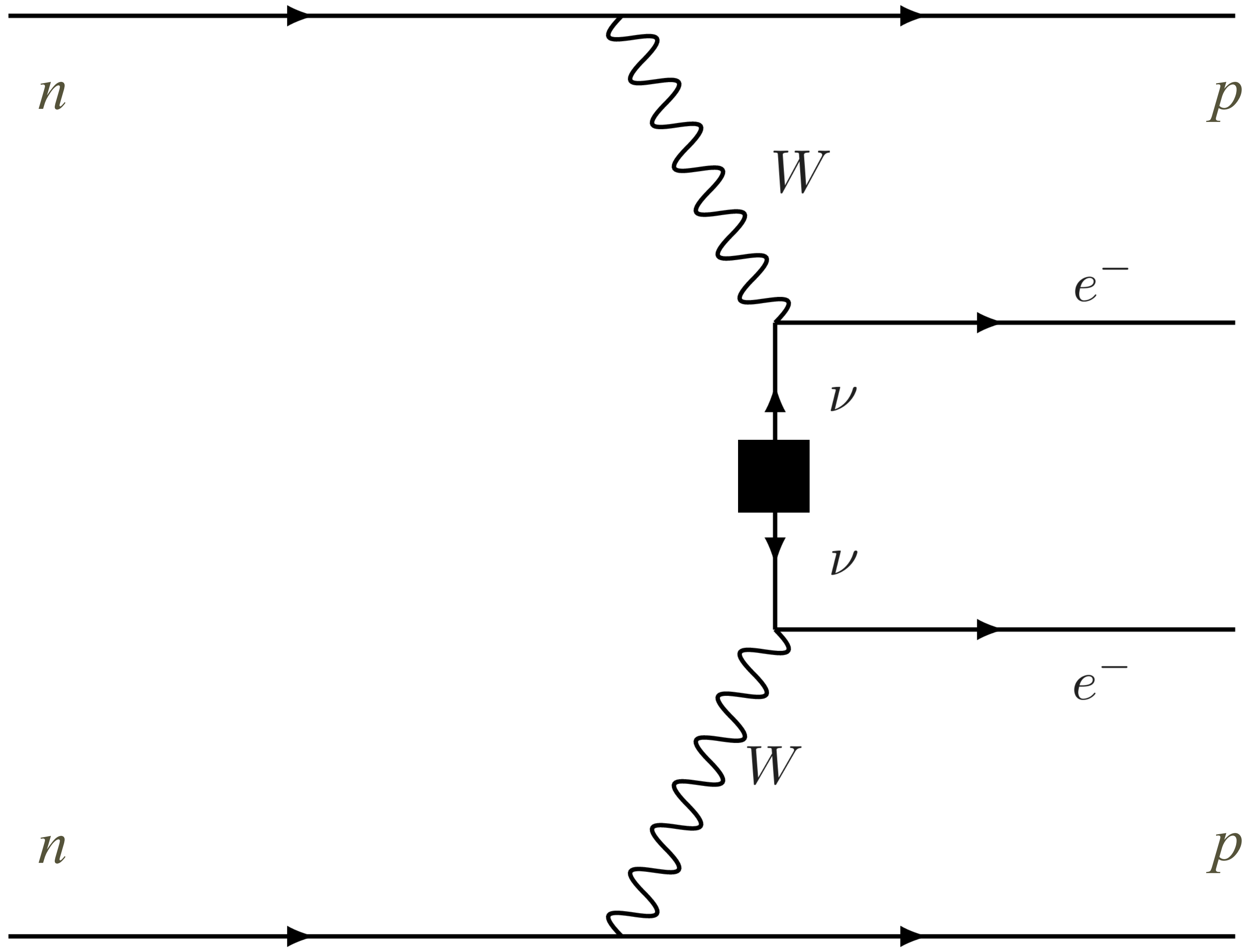
$\mu^- N \rightarrow e^+ N^*$ conversion search

- 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

μ^- N→e+ N*



0νββ decay



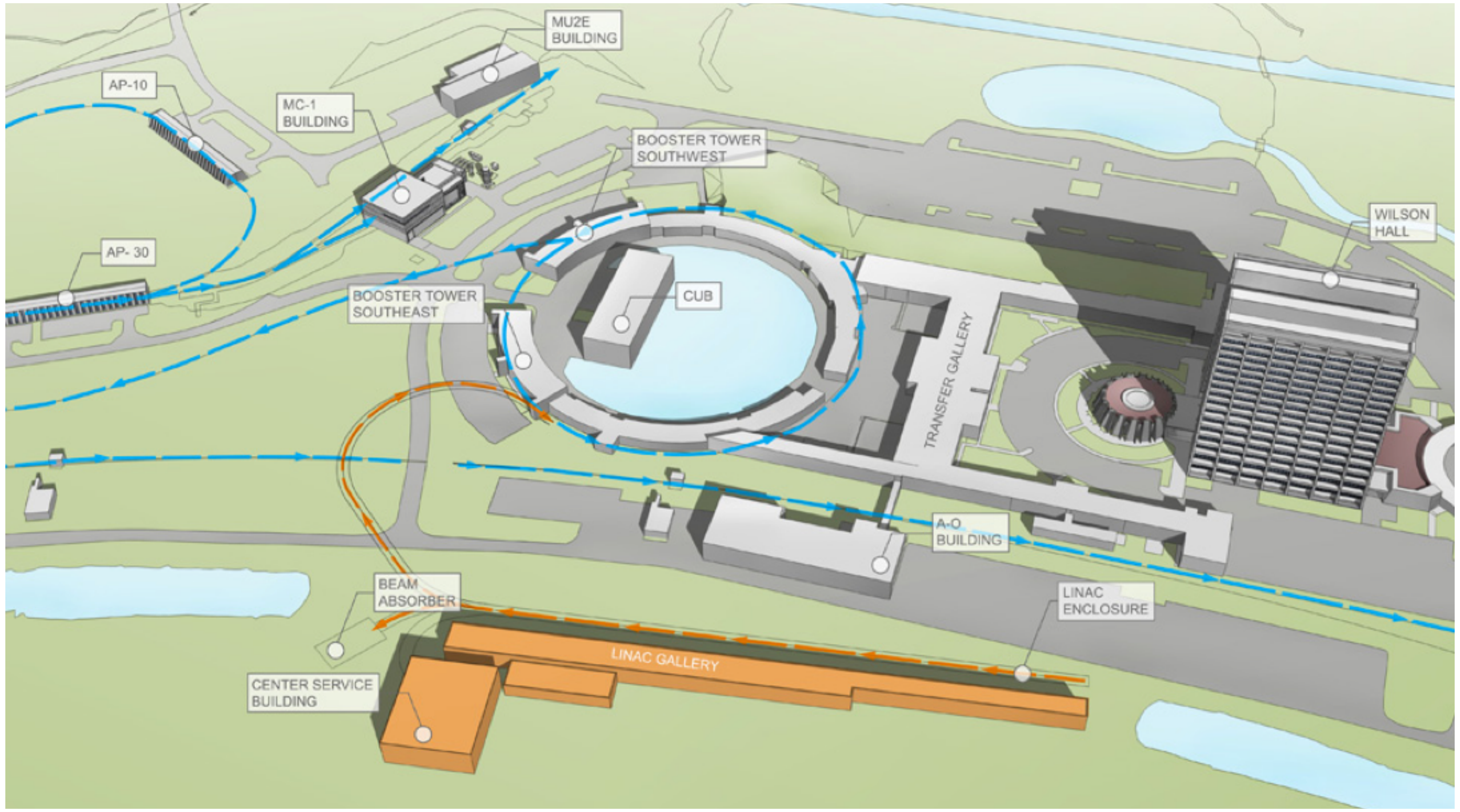
- Useful references: Phys. Rev. D 95.115010, arxiv-161.00032, arxiv-1705.07464, arxiv-1609.09088

Mu2e II

- Studies for x10 improvement with Ti look promising and will be continued; EOI written (1307.1168 and EOI at 1802.02599)
- We need detector and solenoid improvements

  ➡may need new production solenoid to handle lower energy beam and higher power

- FNAL PIP-II natural for both pulsed and non-pulsed CLFV, could do $\mu^- N \rightarrow e^\pm N$, $\mu \rightarrow e\,\gamma$, $\mu \rightarrow 3e$, $\mu^- e^- \rightarrow e^- e^-$ at one facility



Summary

- Mu2e will improve the sensitivity by four orders of magnitude
- Provides discovery capabilities over a wide range of theories BSM
- **Commissioning expected in 2025**
- **More info: http://mu2e.fnal.gov**

backup slides

Constrains on Higgs

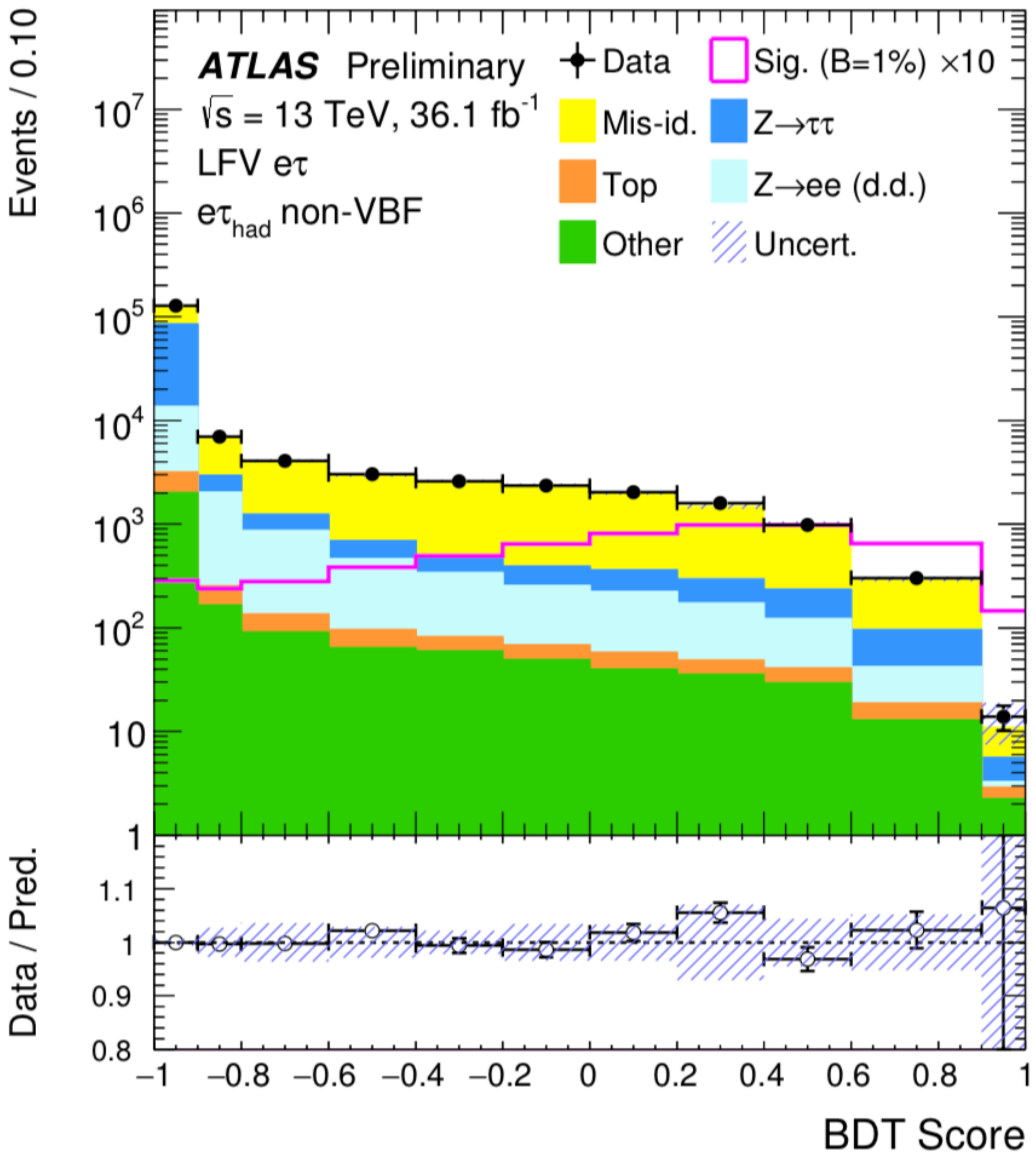
- **Muons** provide strong limits on LFV Higgs decays for 1st and 2nd generations
- **But not if tau involved:** 1st-3rd or 2nd-3rd

$$\begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

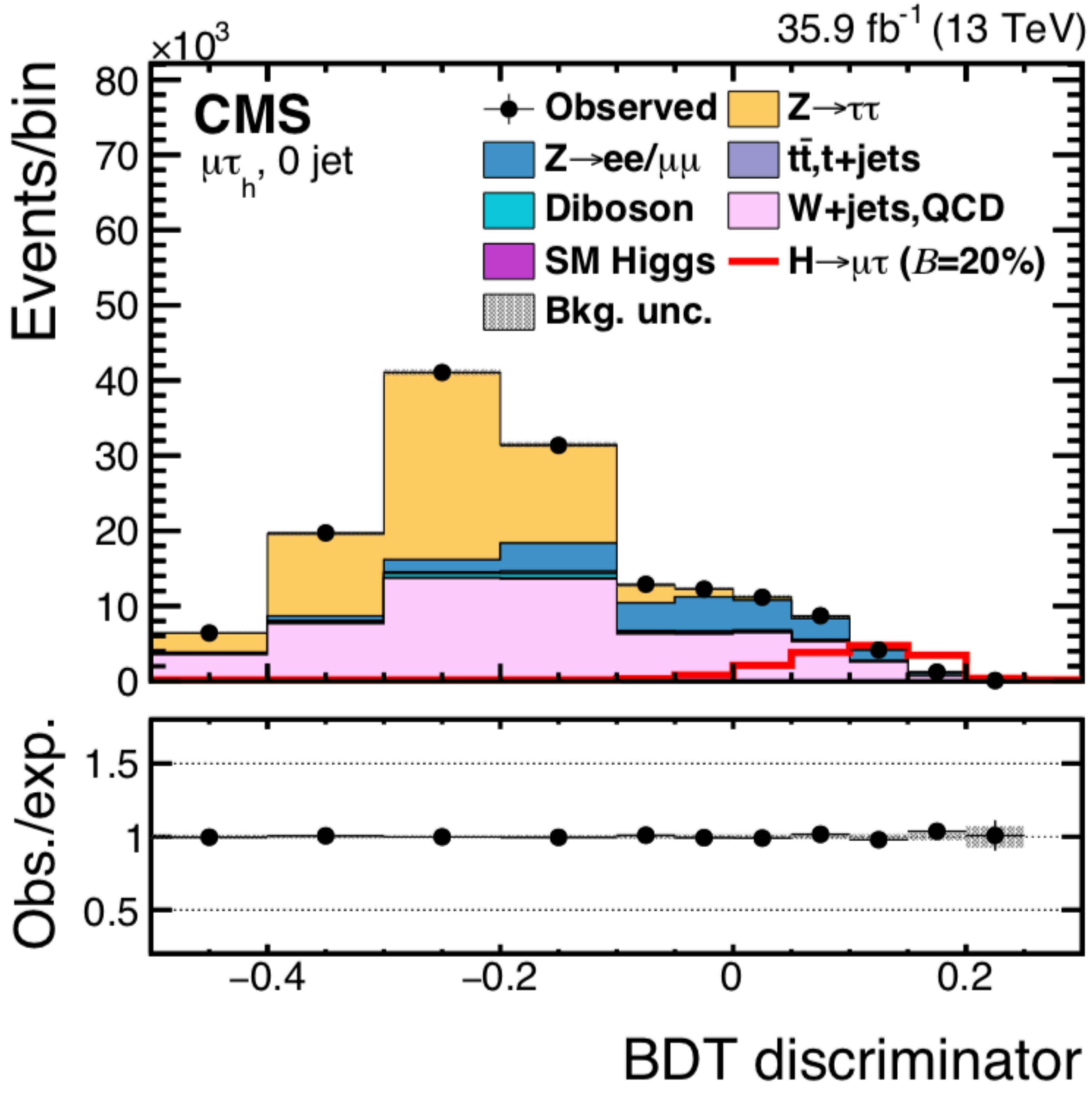
Hiroshi Okada, et al: arxiv.org/pdf/1604.01948.pdf

CLFV at CMS & ATLAS

- Similar final states as in $H\rightarrow\tau\tau$: search for $H\rightarrow e\tau$ and $H\rightarrow\mu\tau$
- 95% C.L. limits from likelihood fit are Br($H\rightarrow e\tau$) < 0.47% and Br($H\rightarrow\mu\tau$) < 0.25%

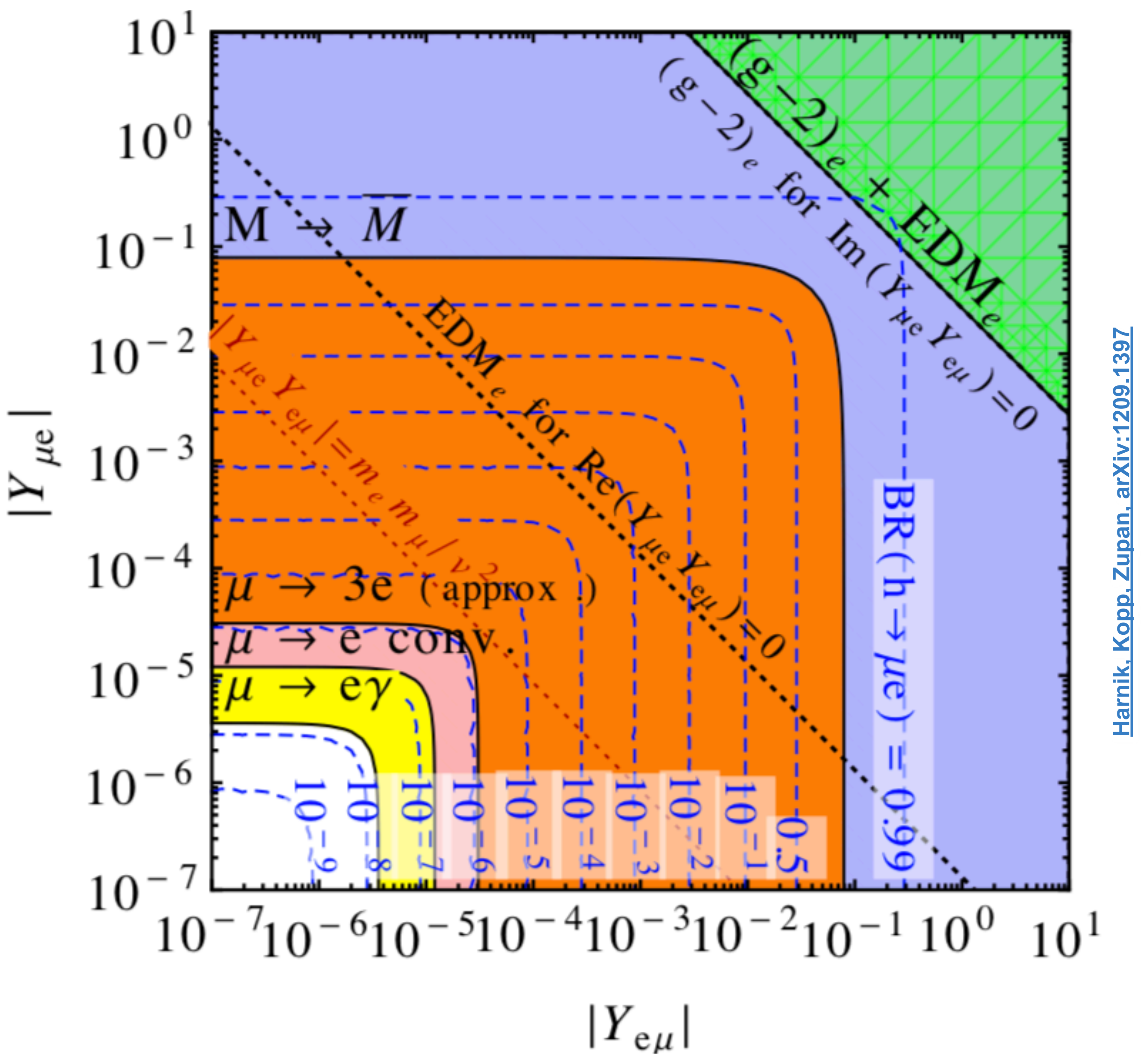


ATLAS_CONF Note 2019 013

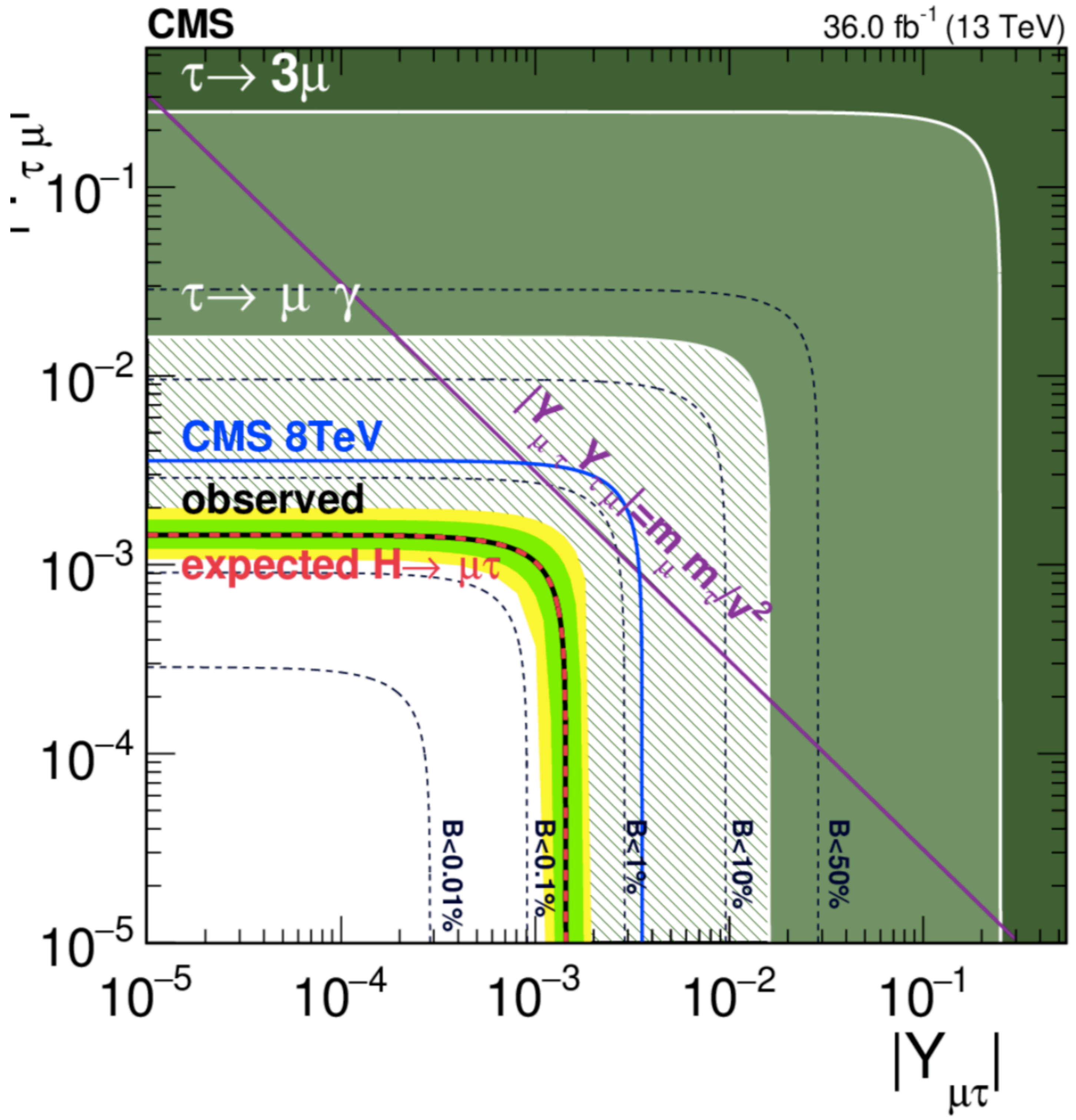


CMS, Sirunyan, A.M., Tumasyan, A. et al. J. High Energ. Phys. (2018) 2018: 1.

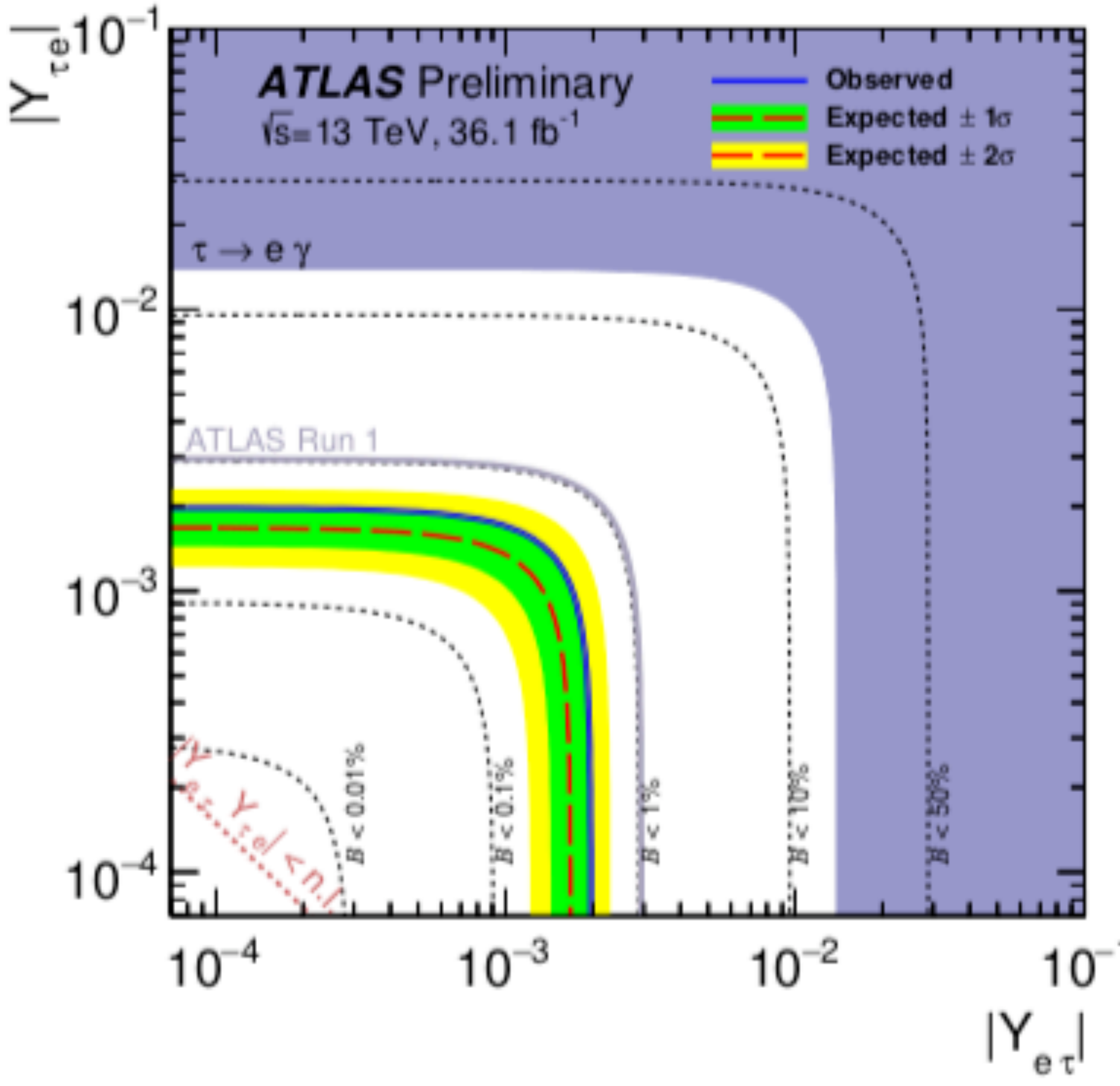
LHC/Direct searches



Harnik, Kopp, Zupan, arXiv:1209.1397



CMS, Sirunyan, A.M., Tumasyan, A. et al. J. High Energ. Phys. (2018) 2018: 1.



ATLAS, CONF Note 2019 013

- $H \to \mu e < 0.36 \times 10^{-3}$ @ 95% C.L. (CMS)
- $H \to e\tau <$ (0.61/0.47)% @ 95% C.L. (CMS/ATLAS)
- $H \to \mu\tau <$ (0.25/0.28)% @ 95% C.L. (CMS/ATLAS)

Flavor Violation

- We've known for a long time that quarks mix

✓**Mixing strengths parameterized by V_{CKM}**

$$\mathrm{V_{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- In last 15 years also neutrinos (neutral leptons) mixing was measured

✓**Mixing strengths parameterized by PMNS matrix**

- **Is there violation for charged leptons?**

Charged Lepton Flavor Violating processes

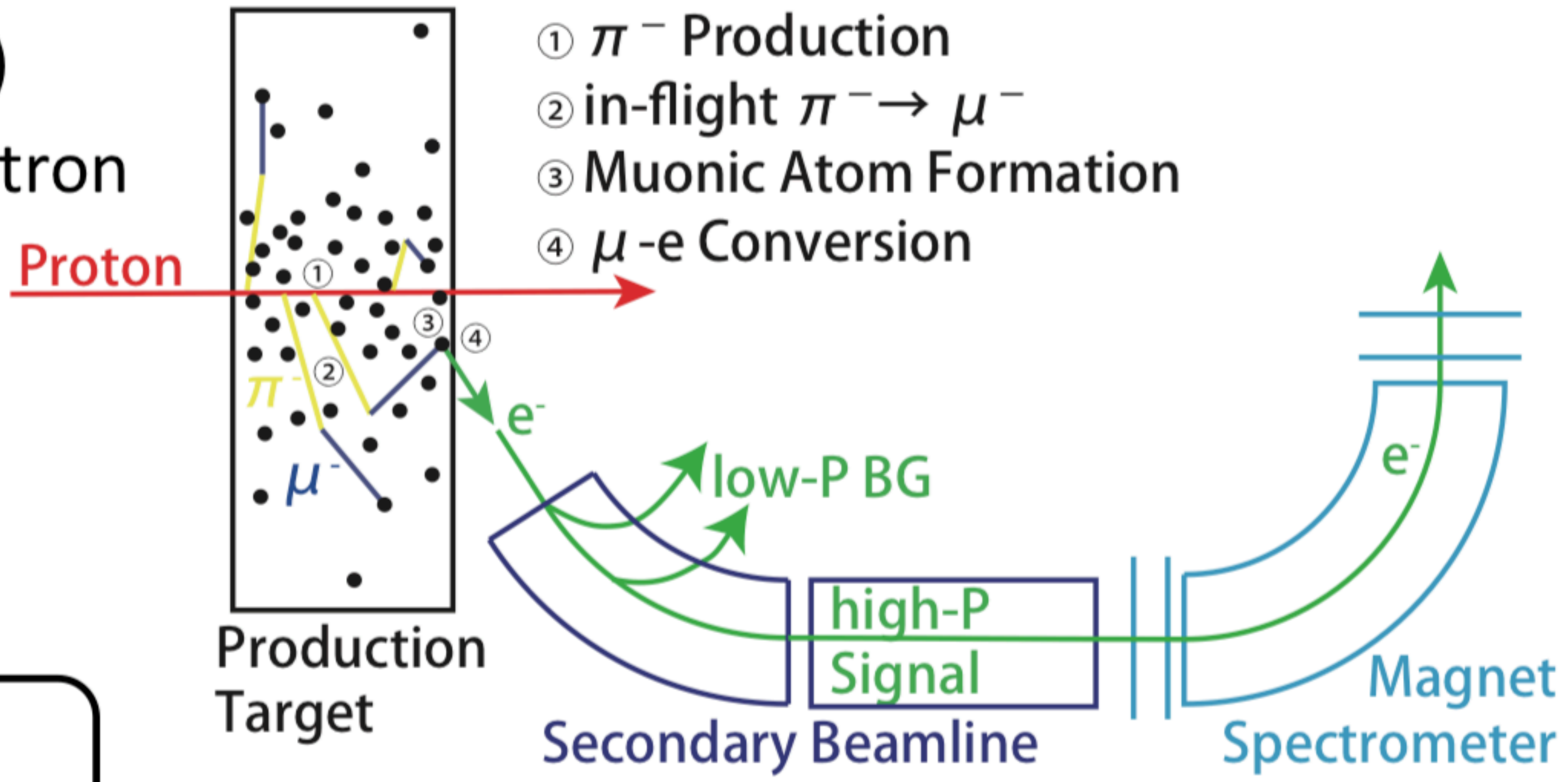
Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$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

- Global interest in CLFV

Mu2e competitors

DeeMe experiment

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed：~1μS
- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - Pulsed Proton beam
      - Prompt timing

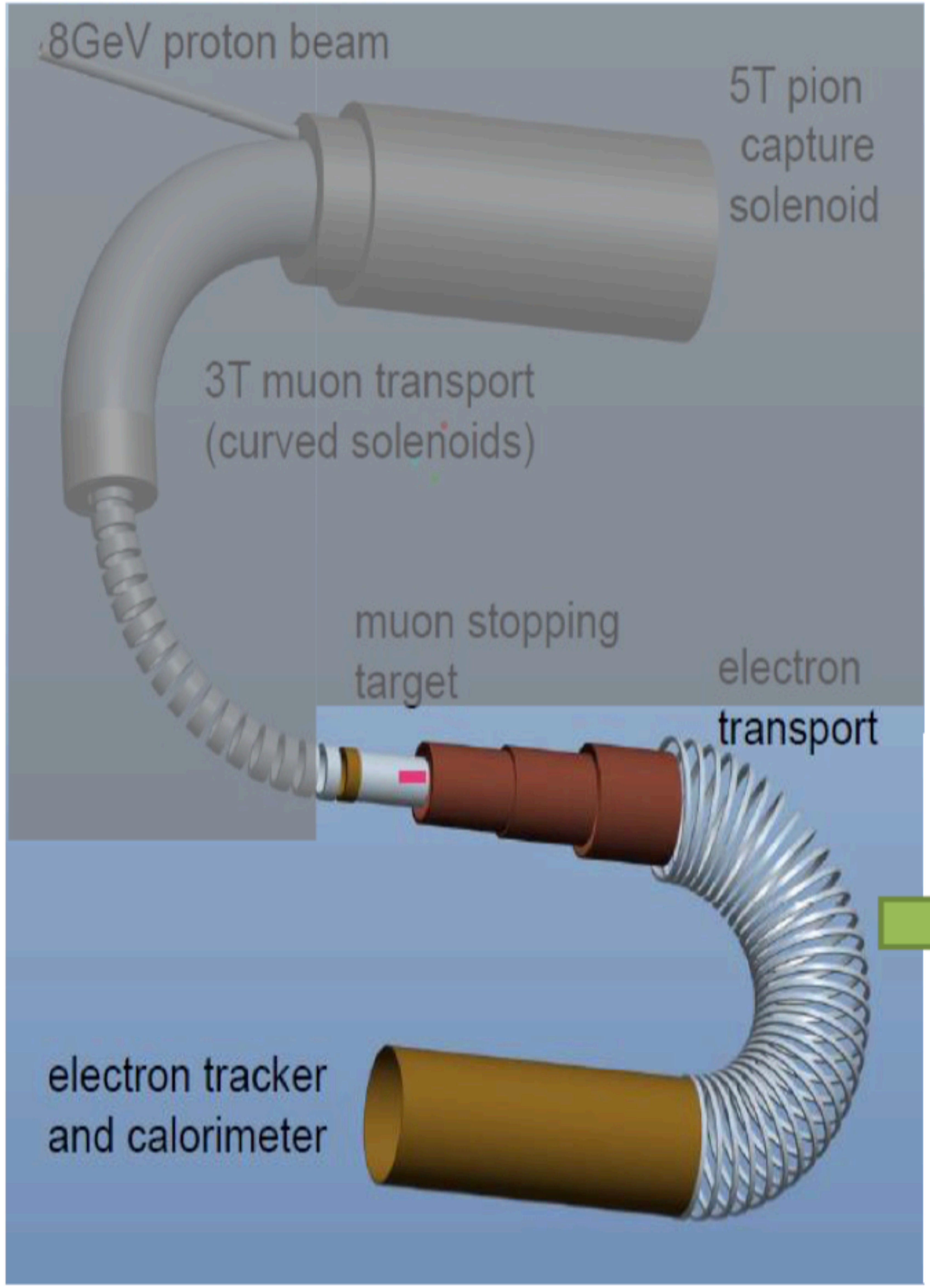


- Low Energy main part: suppressed by the beamline.
- High Energy tail: Magnet Spectrometer (Δp < 0.5%)

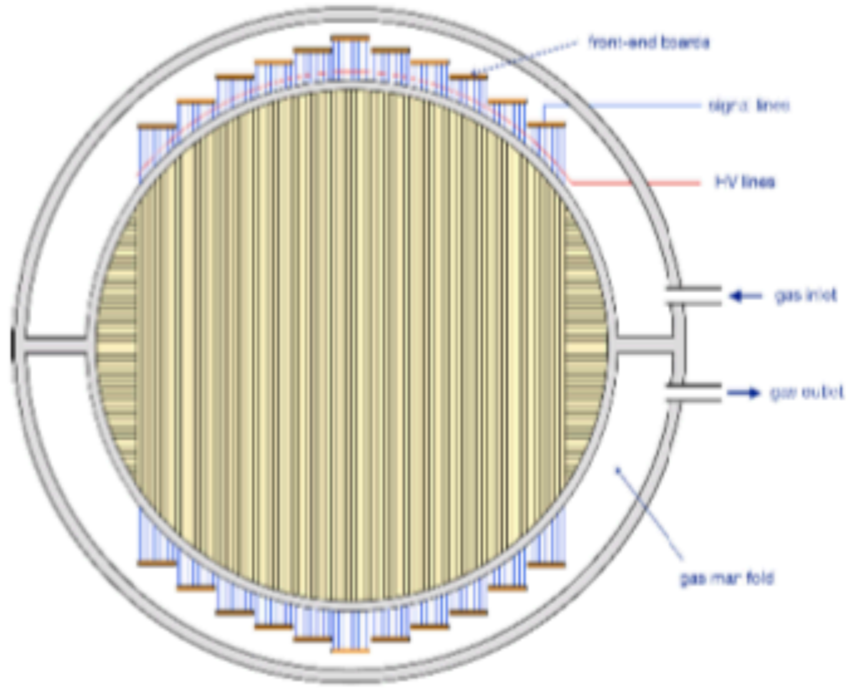
- Main pulse burst: State-of-the-art MWPC that becomes operational quickly after a burst.
- Delayed-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{DP} << 10^{-17}$.

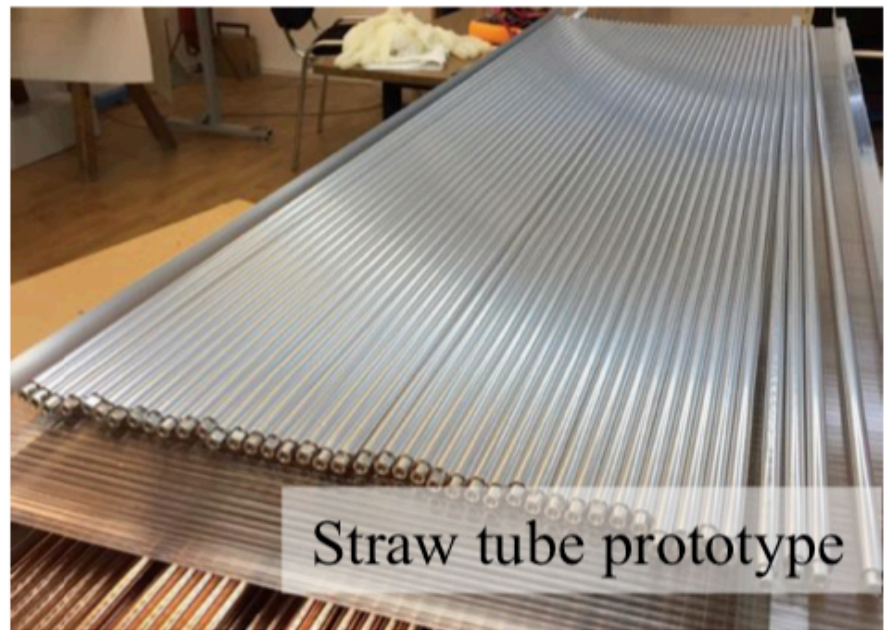
M. Aoki, Presentation @ CLFV2019

COMET

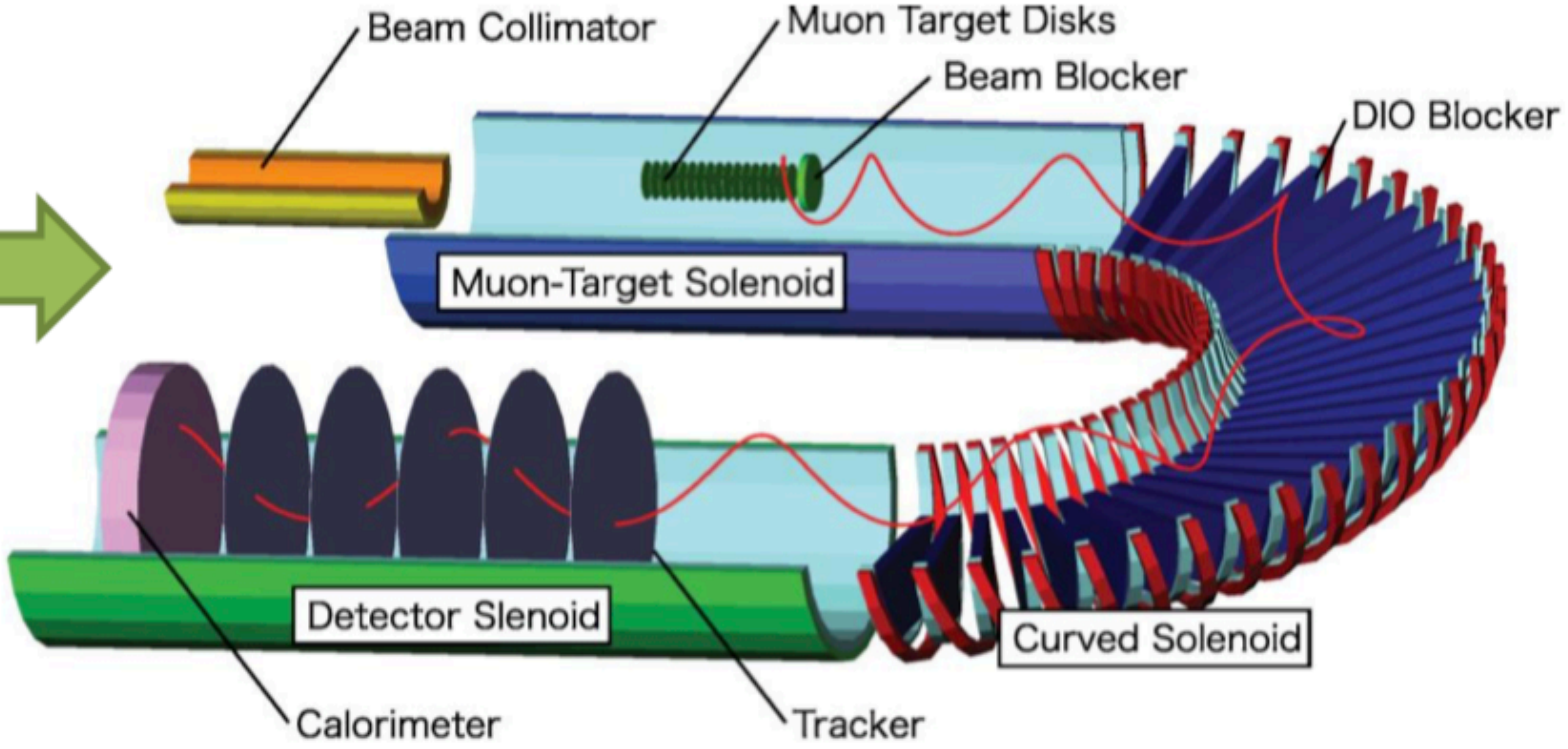


- Use straw tracker to measure the momentum
  - Really light: put in vacuum, 12 micro meter thin straw





- Electromagnetic calorimeter
  - Providing trigger, TOF and PID



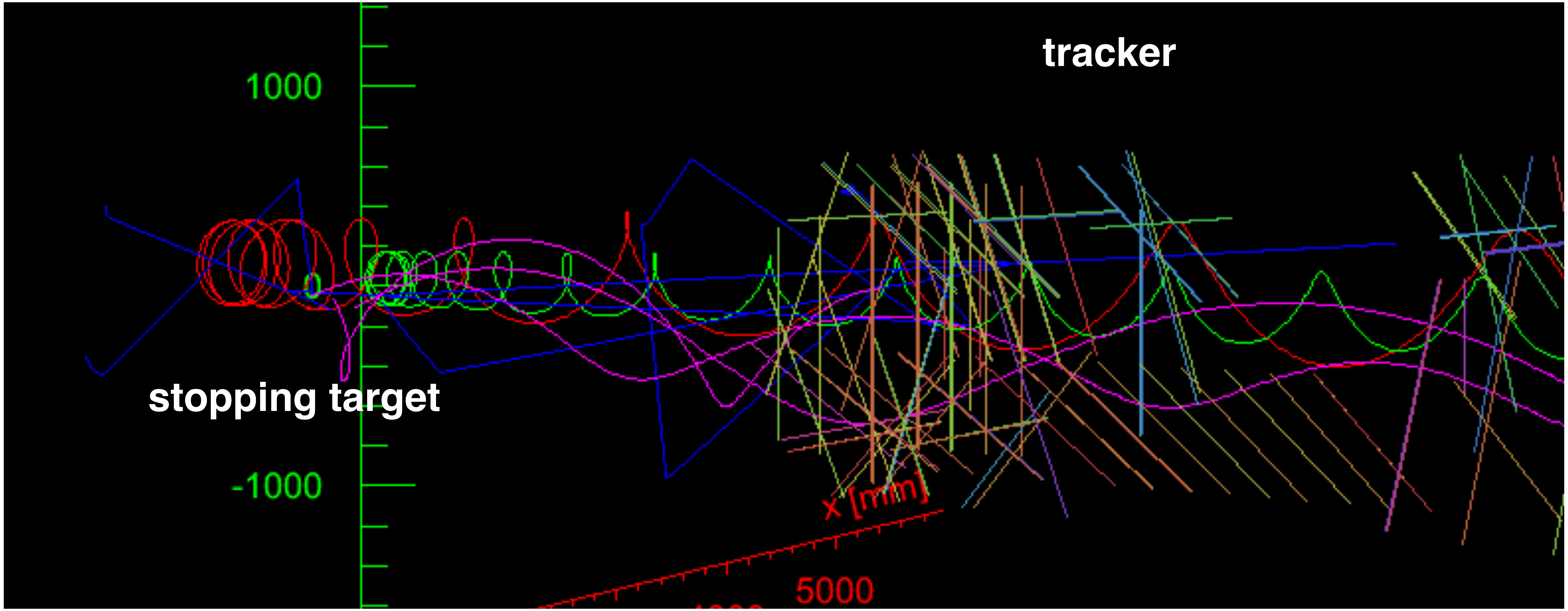
Wu Chen, Presentation @ CLFV2019

14

Track reconstruction

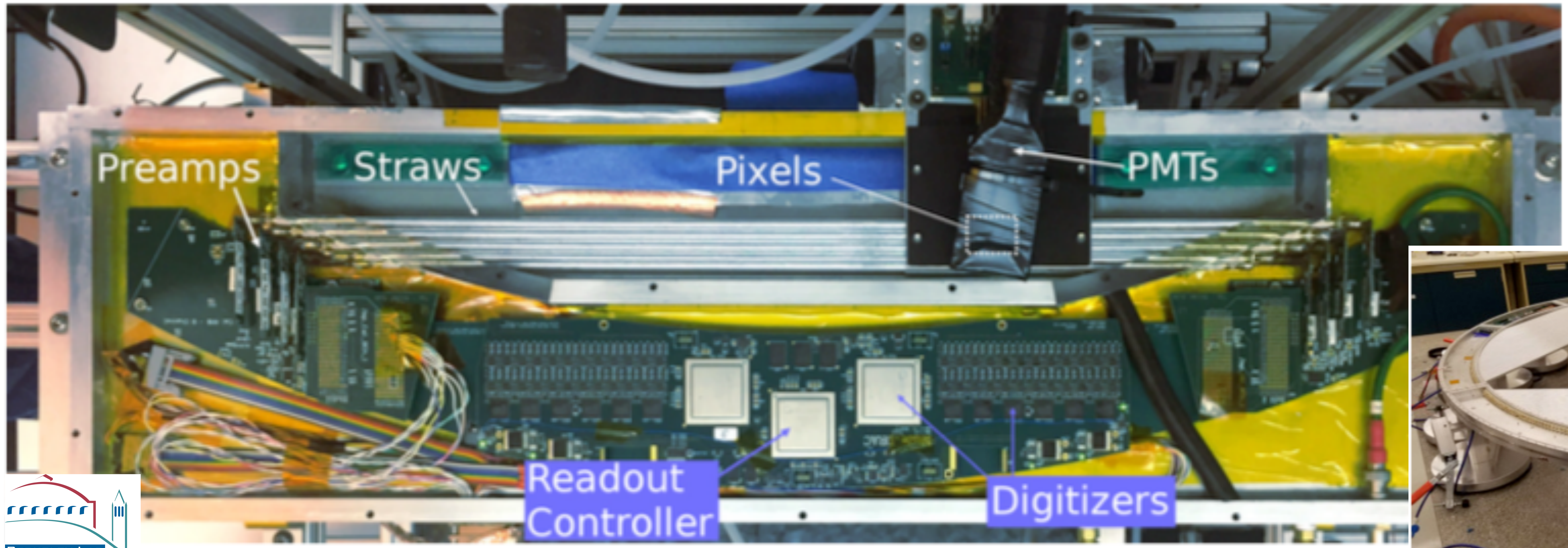
Tracker Requirements

- Measure p with resolution < 200 keV/c
- Work in 1 T field and 10^{-4} Torr vacuum

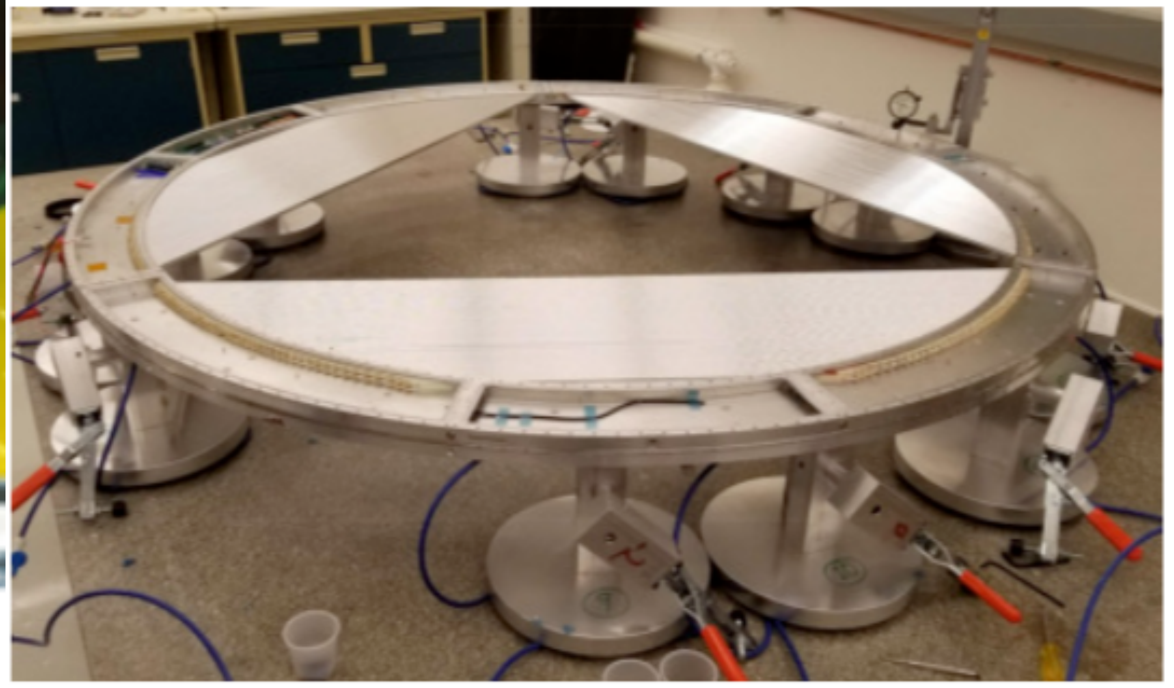


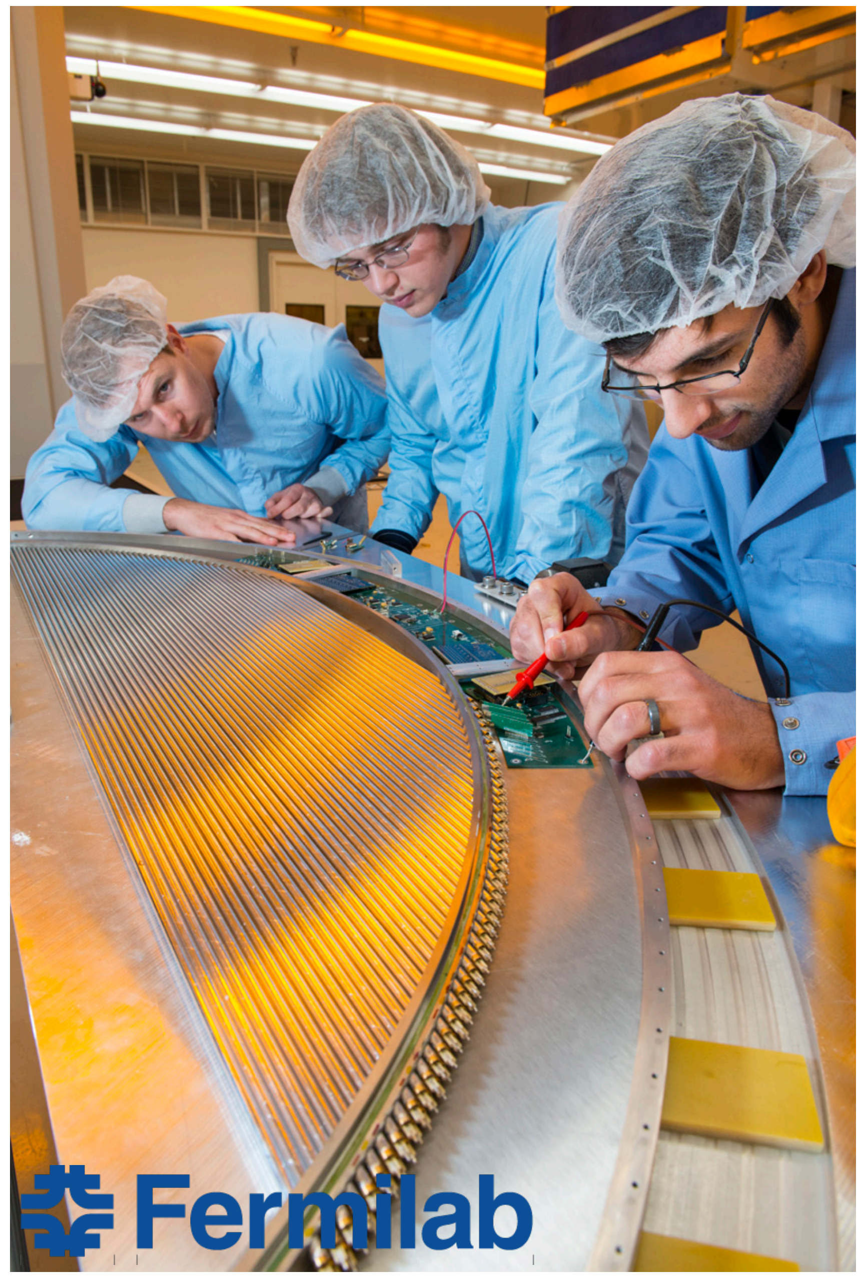
Tracker R&D

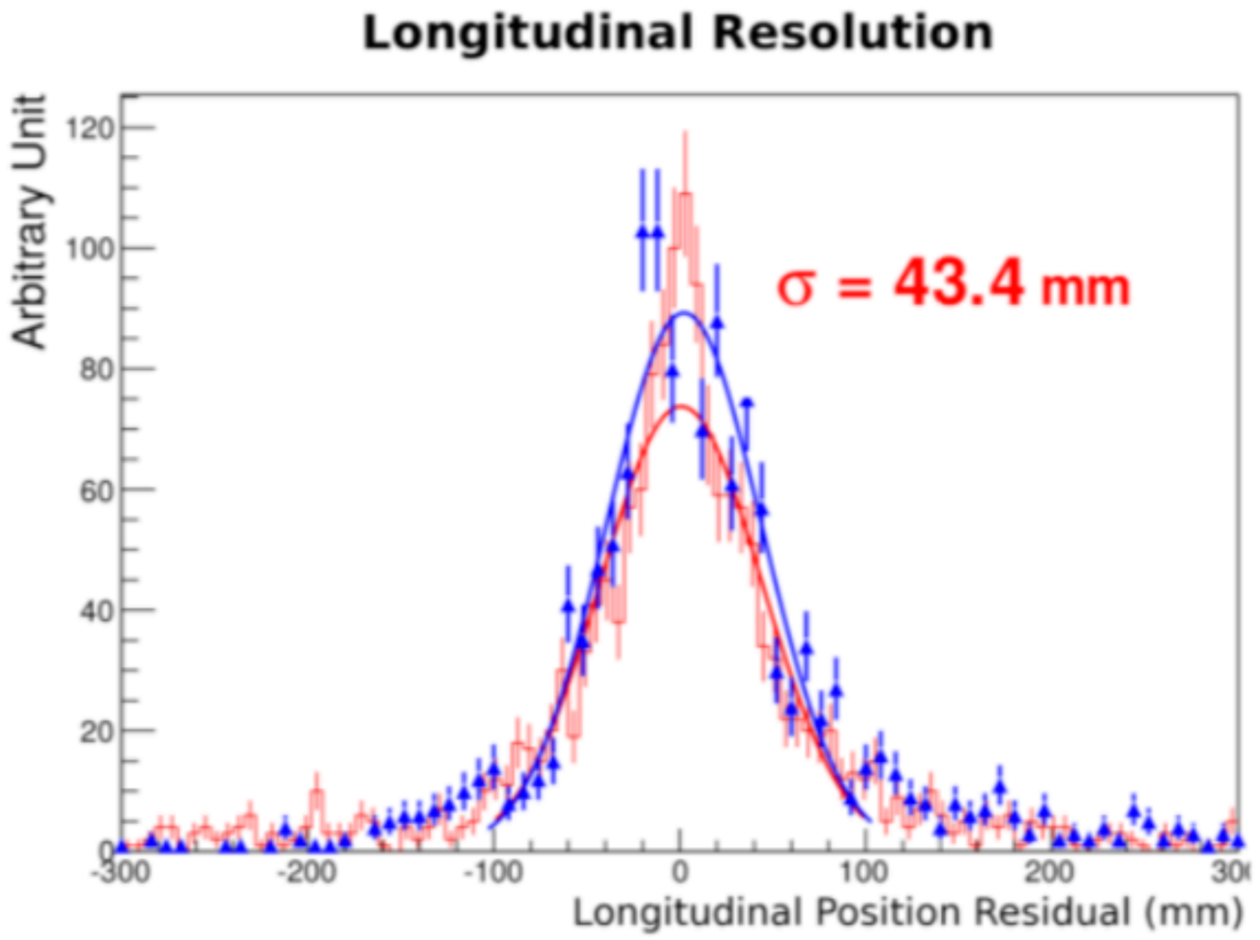
panel prototype

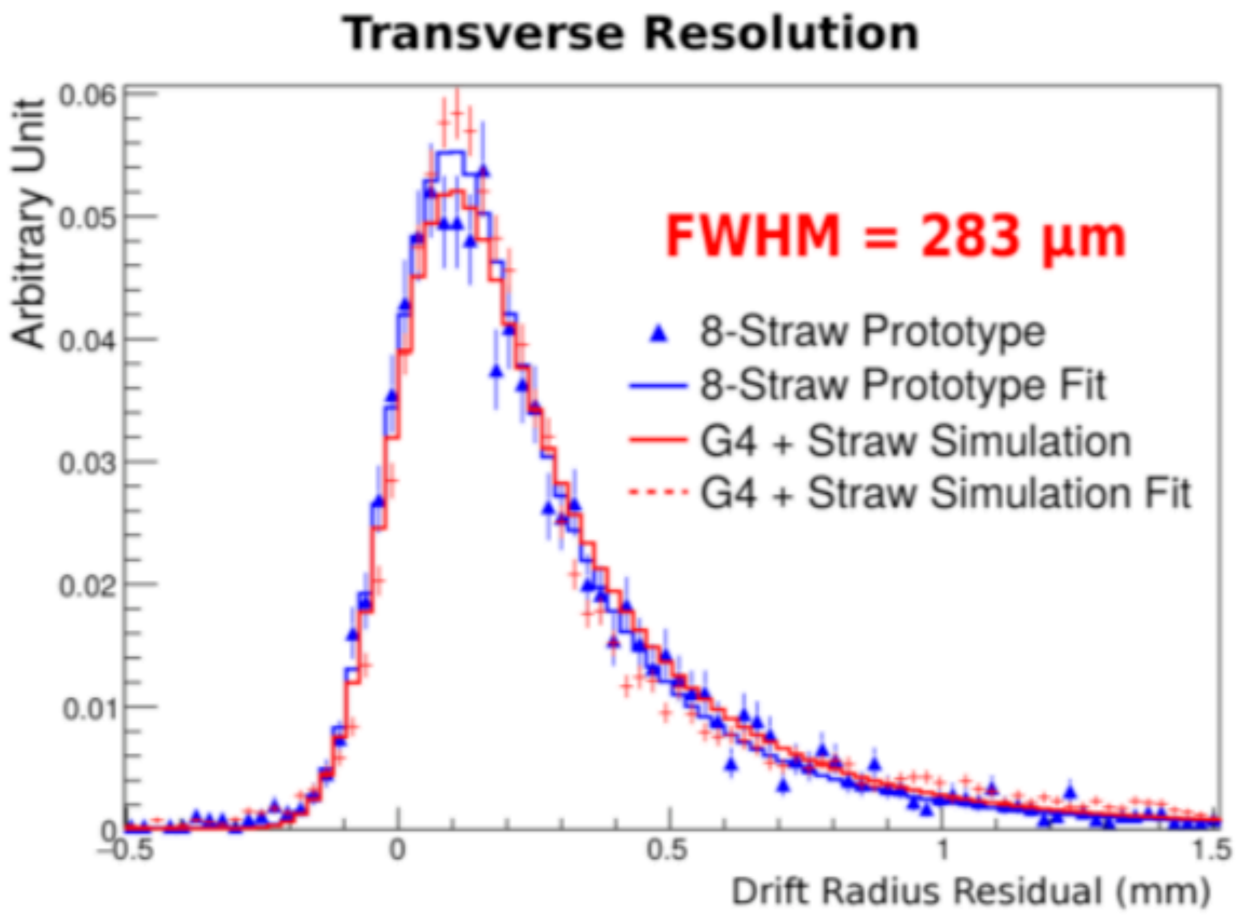


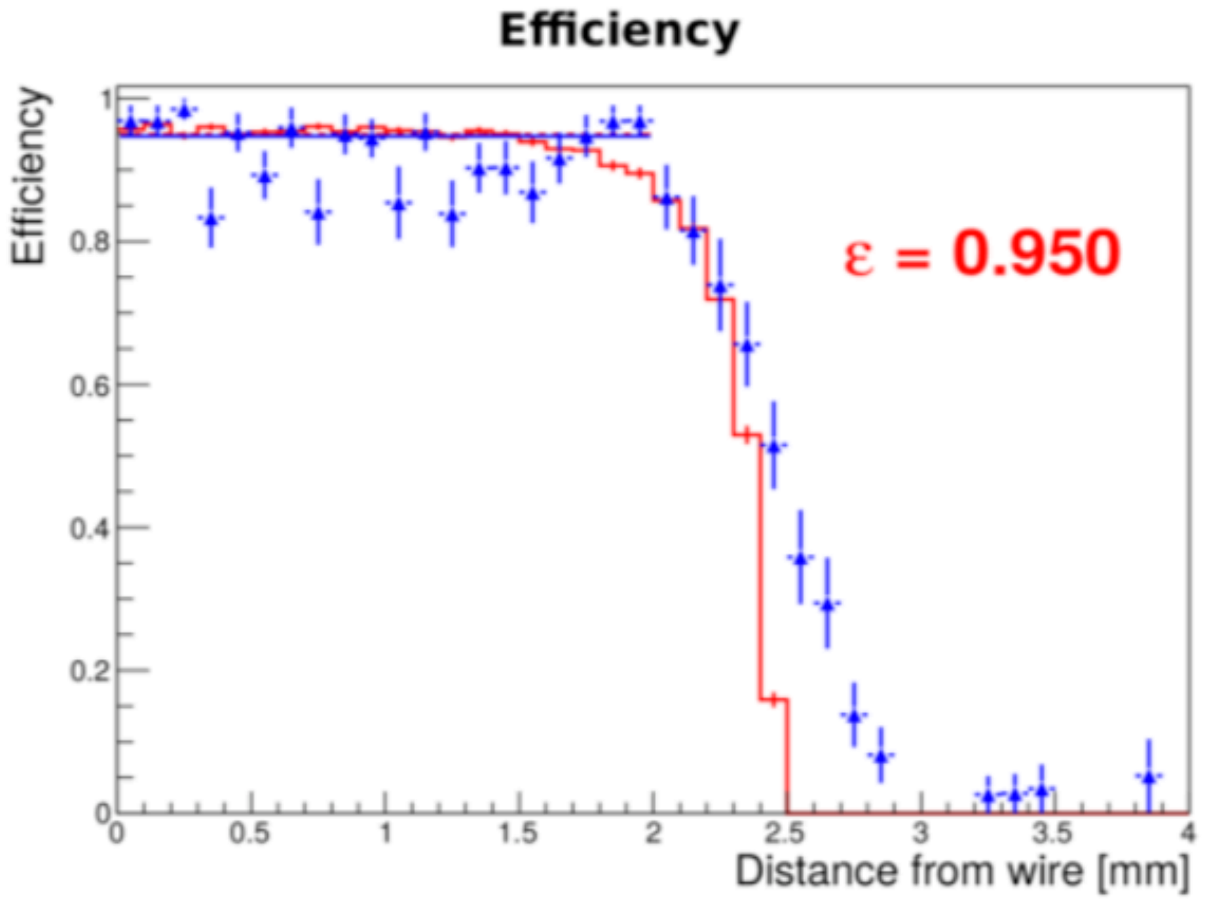
plane





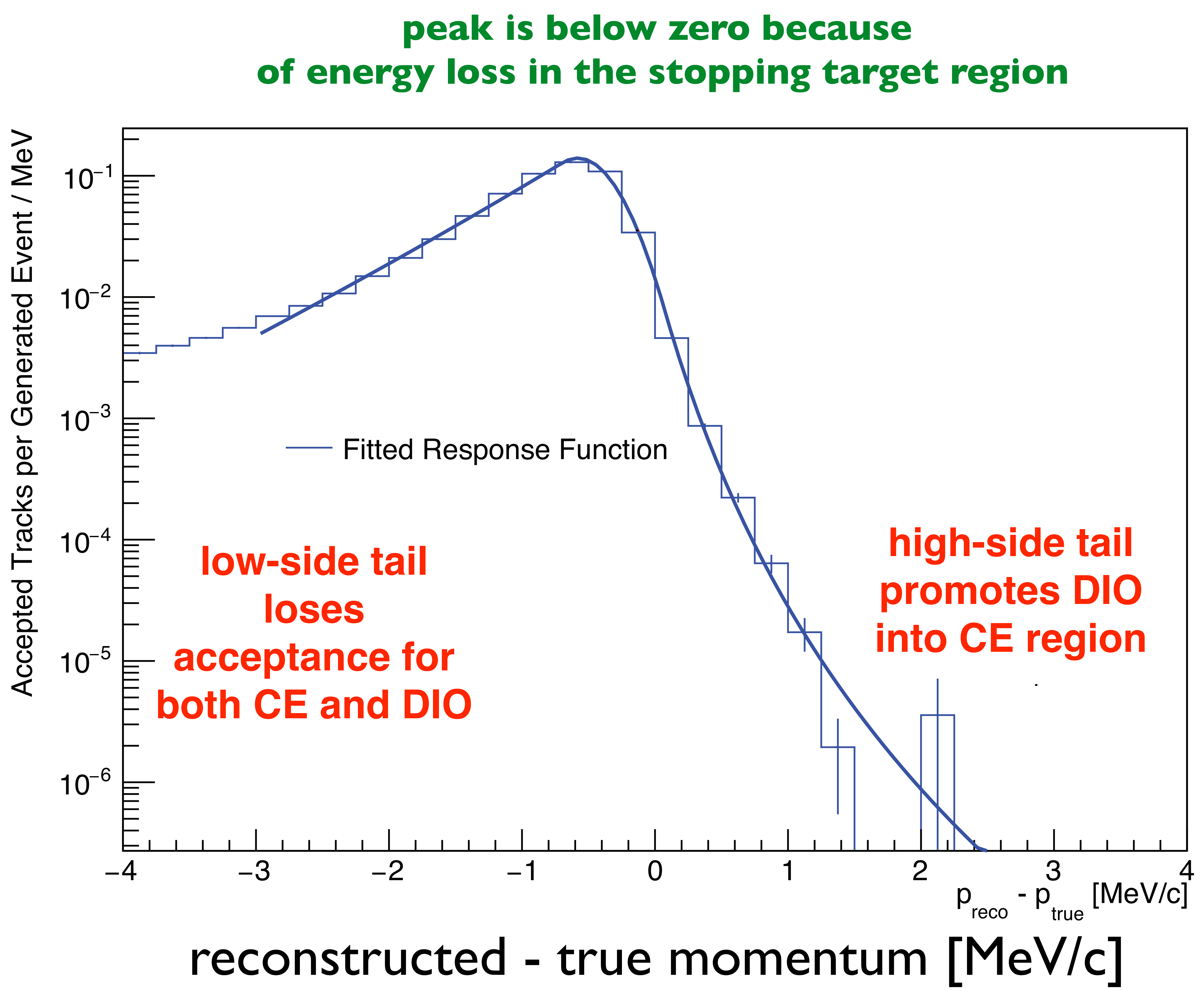






Tracker resolution

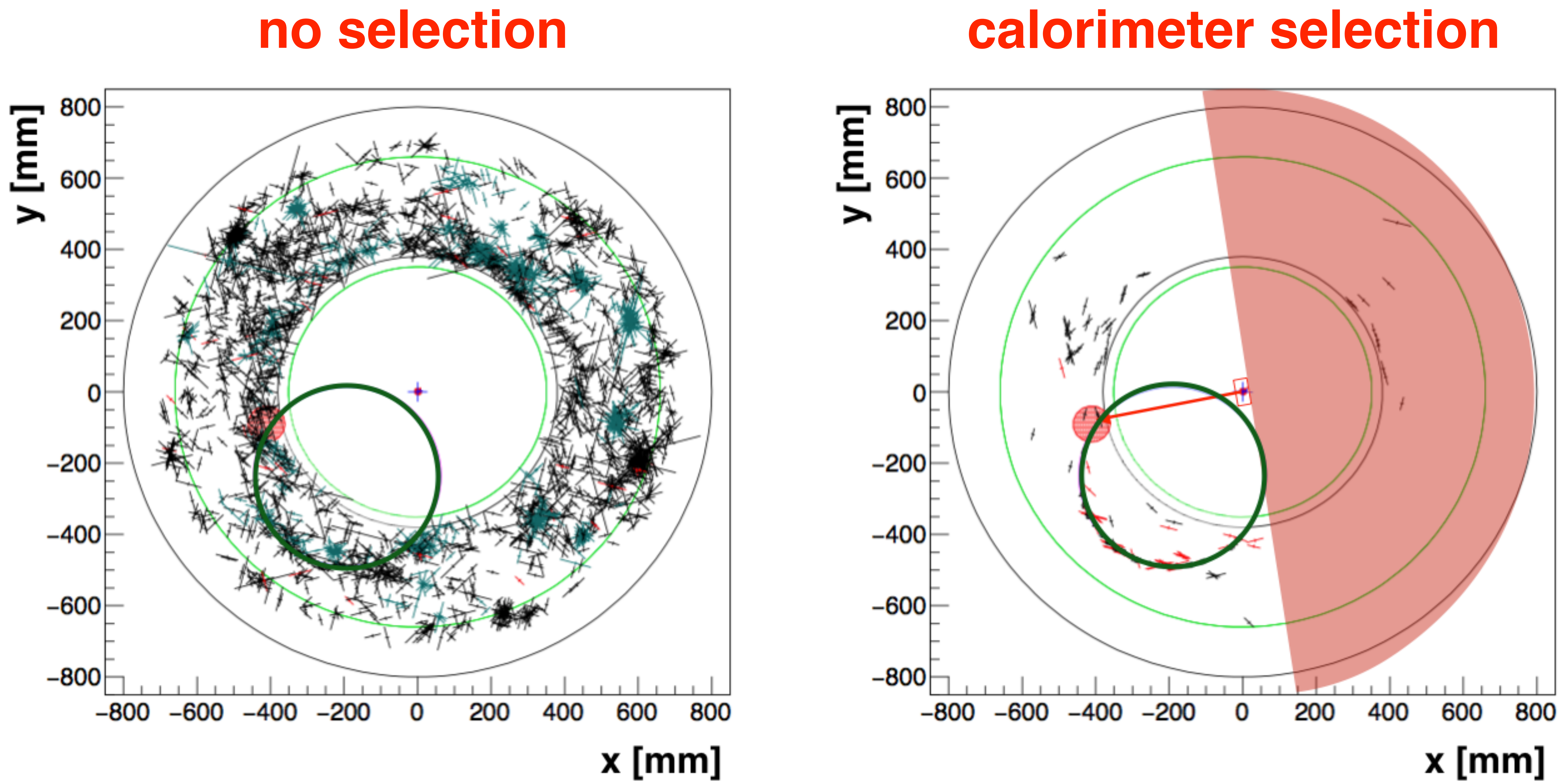
- Decays-in-orbit can enter the Conversion Electron signal region in two ways:
  - ➡ Both DIO and CE lose energy by ionization and bremsstrahlung in the stopping target region
    - ✓ Roughly equal amount of radiation, ionization
    - ✓ Both CE and DIO lose an average of about 600 keV in a stochastic distribution; some DIO lose very little energy so some DIO near the endpoint stay in the signal region
  - ➡ A "high-side" tail in the momentum resolution promotes DIOs into the signal region and can dominate the DIO background. Therefore excellent tracker resolution is essential
    - ✓ and is why we use measured distributions and a "first-principles" simulation with charge-cluster formation and electronics included



Track search

Track reconstruction workflow:

1. pattern recognition: search for a group of hits correlated in time and forming a helicoidal trajectory
2. global 3D track fit: uses B-field map and computes a unique chi2
3. Kalman based fit: takes into account E losses and Multiple Scattering



- The first two stages exploit the online Trigger selection (~4 ms/event)

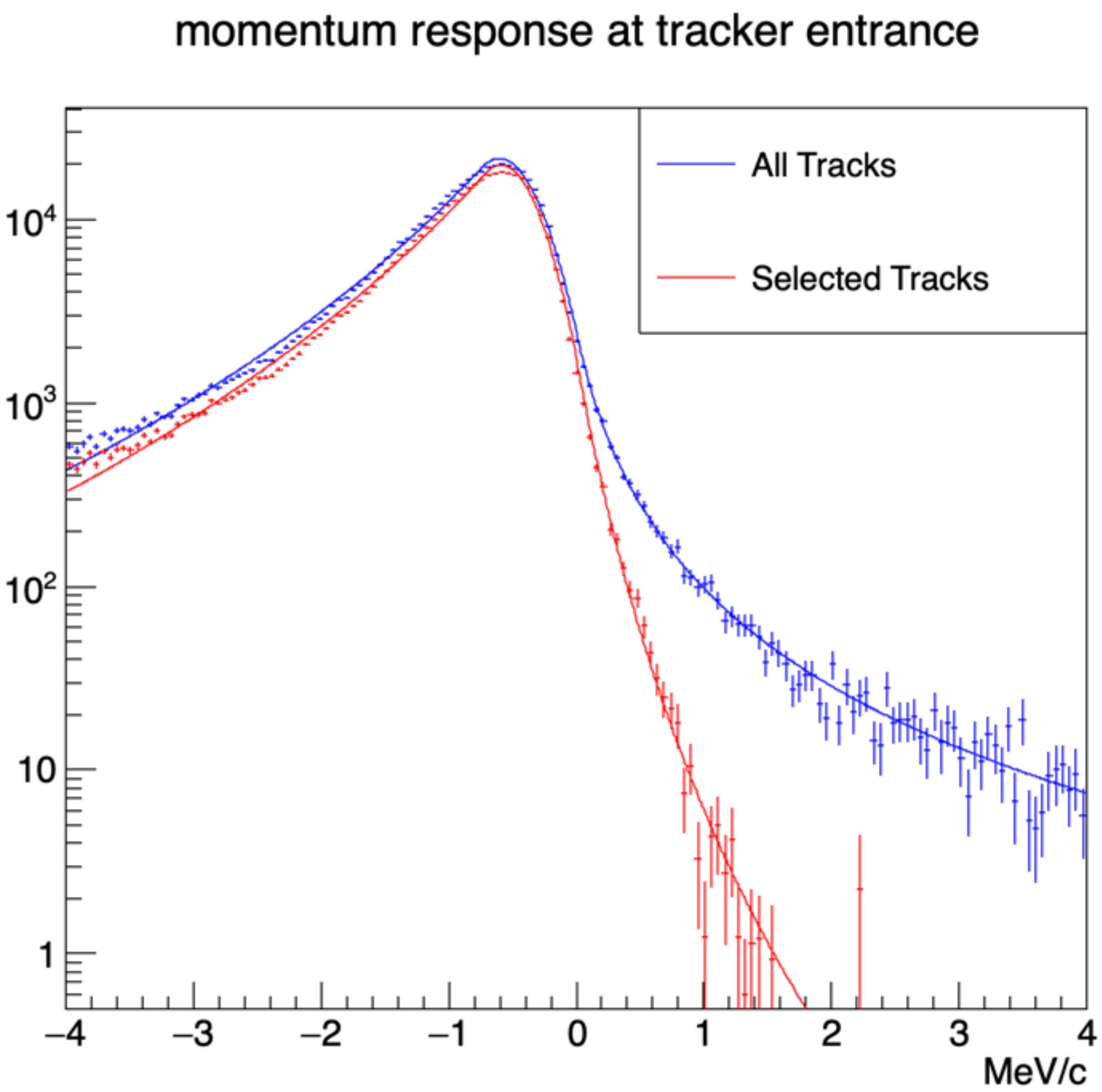
Trigger system

- Stream data in time slice to the TDAQ farm (CPU+FPGA)
  ➡ Mu2e is expected to have one of the largest data rate at Fermilab
- We are in charge of developing the Trigger Menu of the experiment
  ✓ **Primary**: CE(+/-), High Energy Photon
  ✓ **Support**: efficiency, performance measurements and monitoring
  ✓ **Calibration**: multiple triggers for sub-detectors
  ✓ **Backup**: less efficient set of triggers that require fewer resources

Experiment	Data rate (GB/s)	# BoardReaders	# EventBuilders	Reduction factor
DUNE 35ton	0.1	24	16	1
Darkside-50	0.5	12	16	~5
LArIAT	0.3	1	1	1
Mu2e	33	36	~500	~100
protoDUNE-SP	3	~80	10-20	1
SBND	0.4	~20	10-20	1
ICARUS	0.4	~20	10-20	1

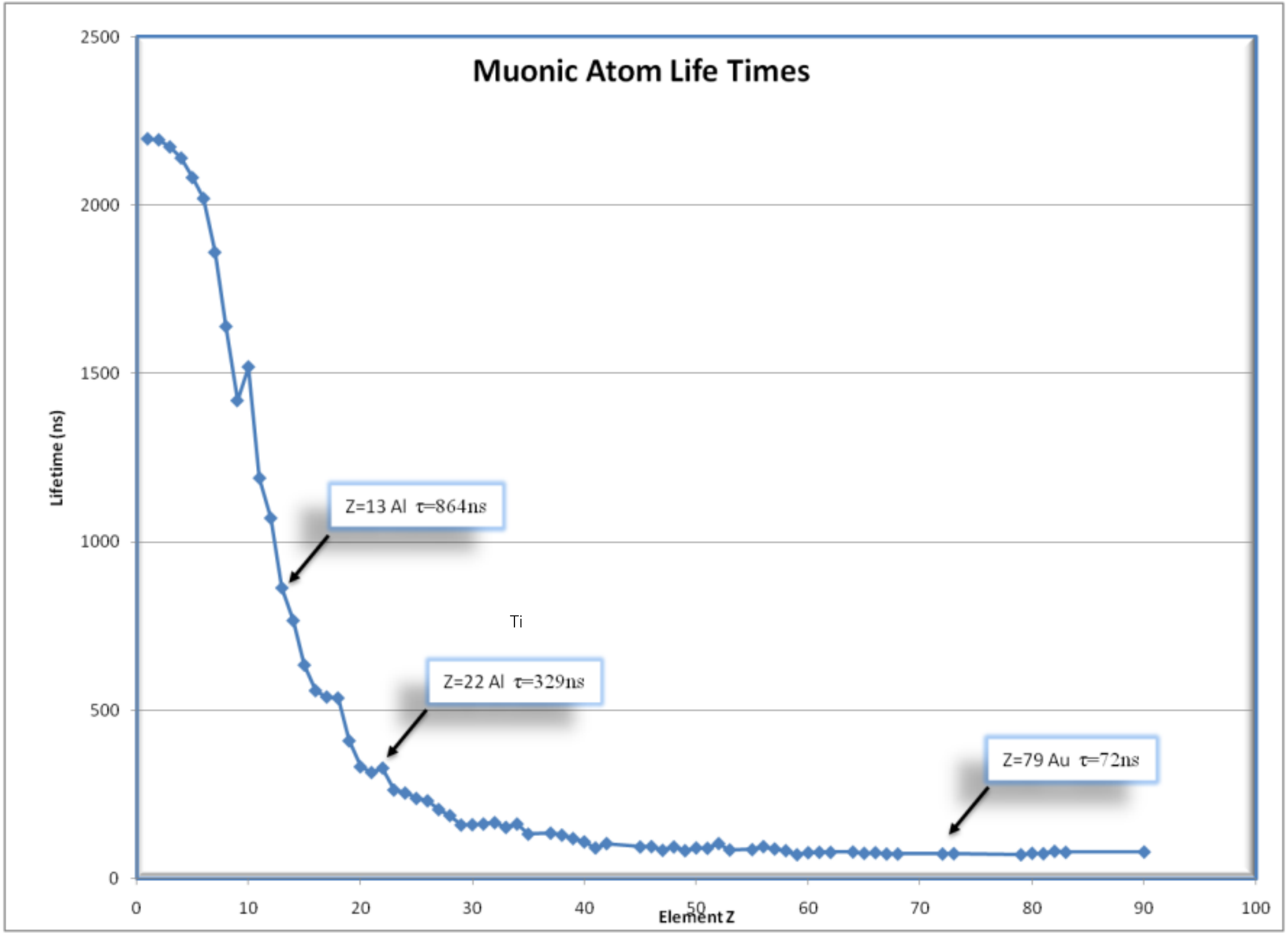
FERMILAB-CONF-17-066-CD

Track selection



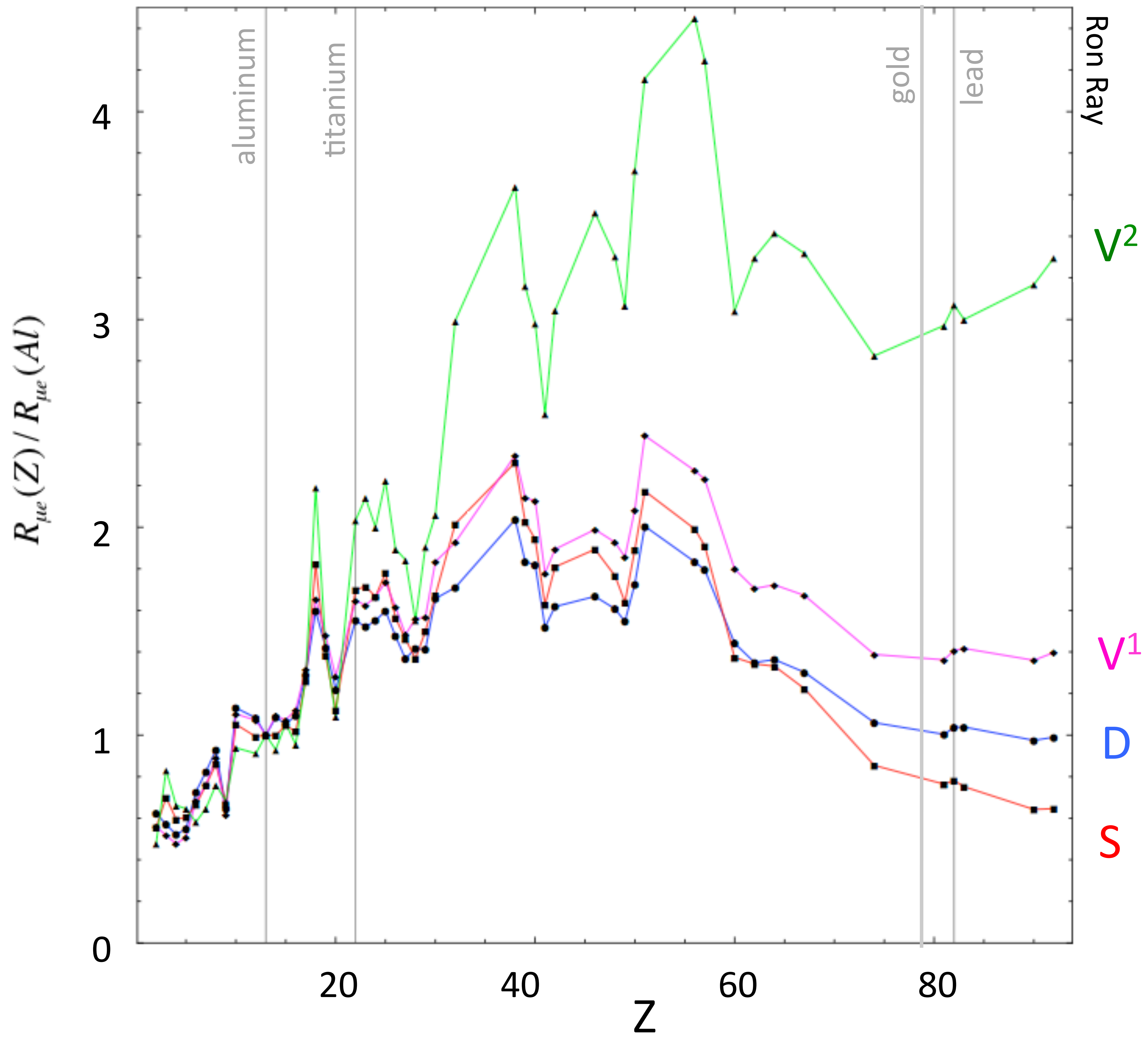
- MVA-based selection allows us to suppress the tracks where the p was overestimated

Muonic atom life times



$R_{\mu e}$ rate vs Z

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



Mu2e sensitivity

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

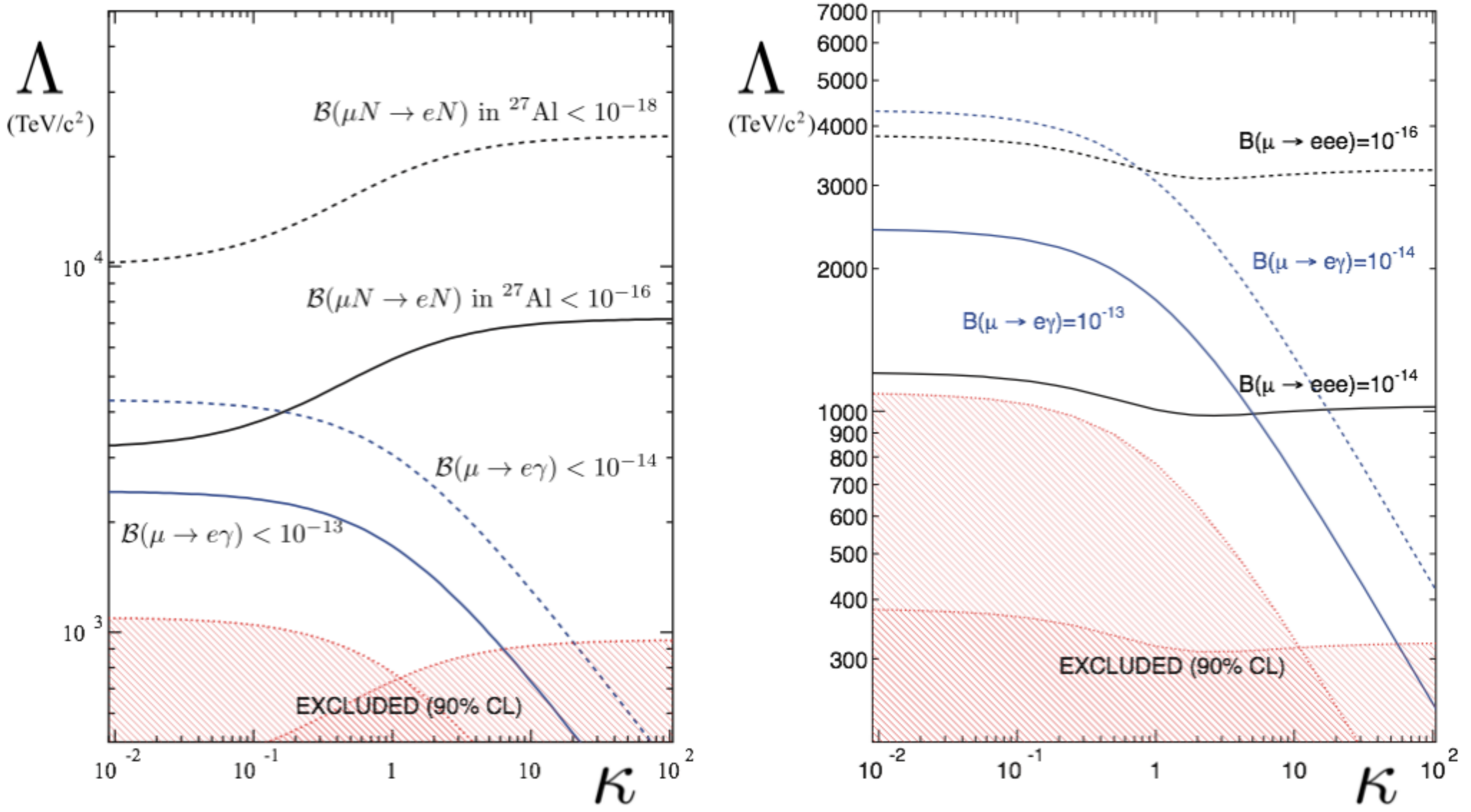
★★★ = Discovery Sensitivity

	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]

Model independent Lagrangian



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

"dipole term" **"contact term"**

CLFV limits I

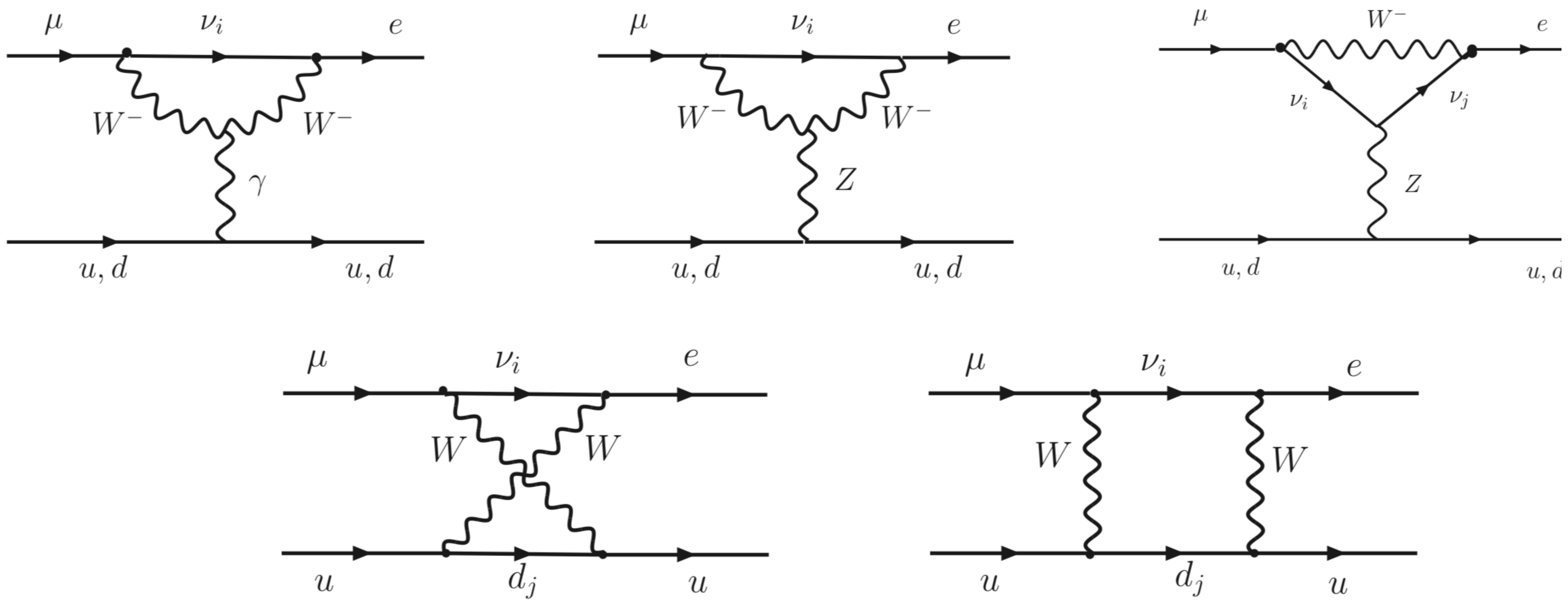
Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$< 1.7 \times 10^{-12}$
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 3.0 \times 10^{-13}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to e^-e^+e^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-\mu^+\mu^-$	$< 2.1 \times 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$< 1.8 \times 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$< 1.7 \times 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$< 1.5 \times 10^{-8}$

CLFV limits 2

Process	Upper limit
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$
$K_L^0 \to \pi^0 \mu^+ e^-$	$< 4.4 \times 10^{-10}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau \mu$	$< 1.2 \times 10^{-6}$

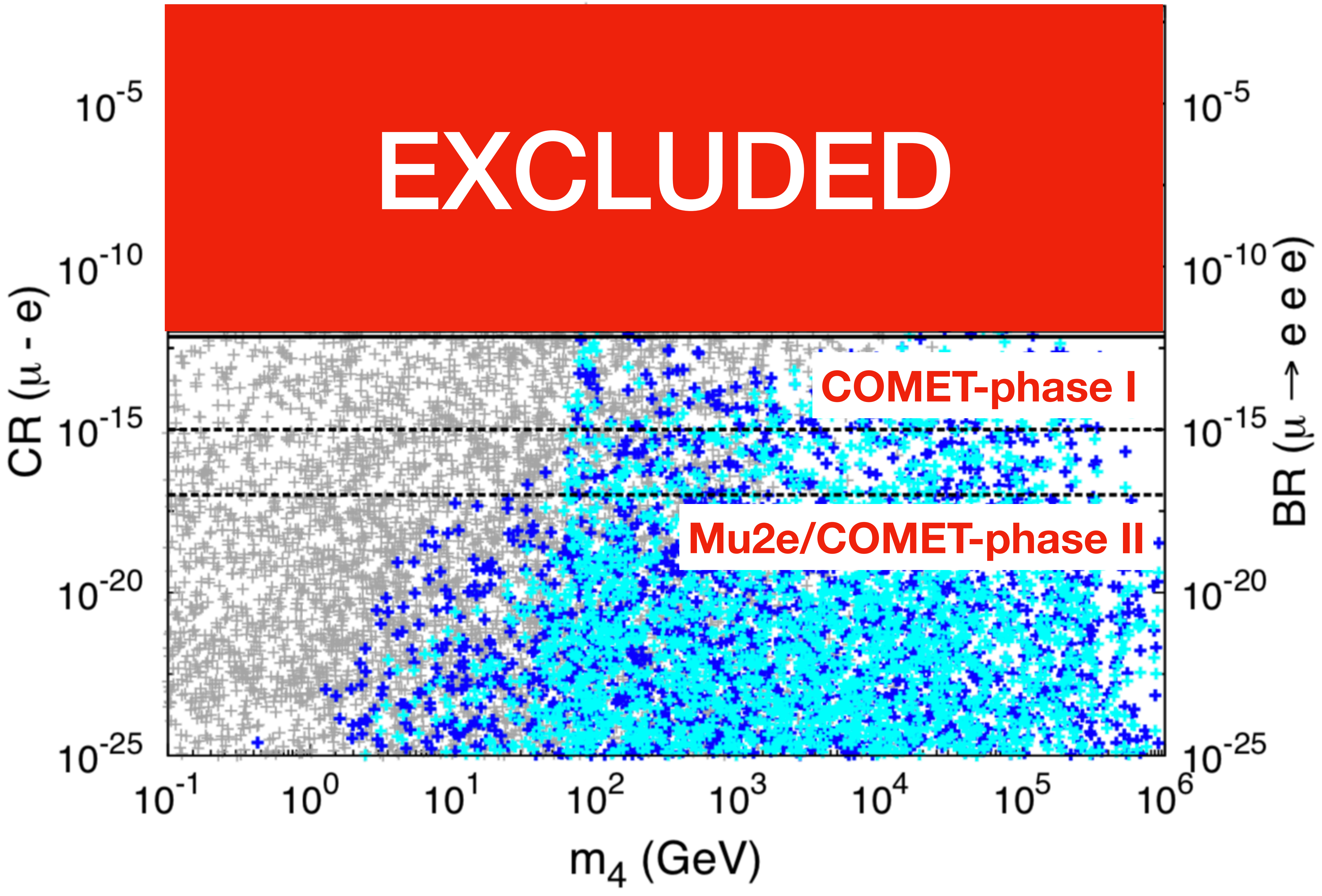
Sterile neutrinos and CLFV

- MiniBooNE @ Fermilab observed an interesting hint: **PRL 121, 201801 (2018)**
- Effect on Lepton Universality and W and Z vertex
- Sterile neutrino can contribute to CLFV processes



- Contributions to μ2e conversion
- *i*=1,2,3,**4** while *j*=1,2,3

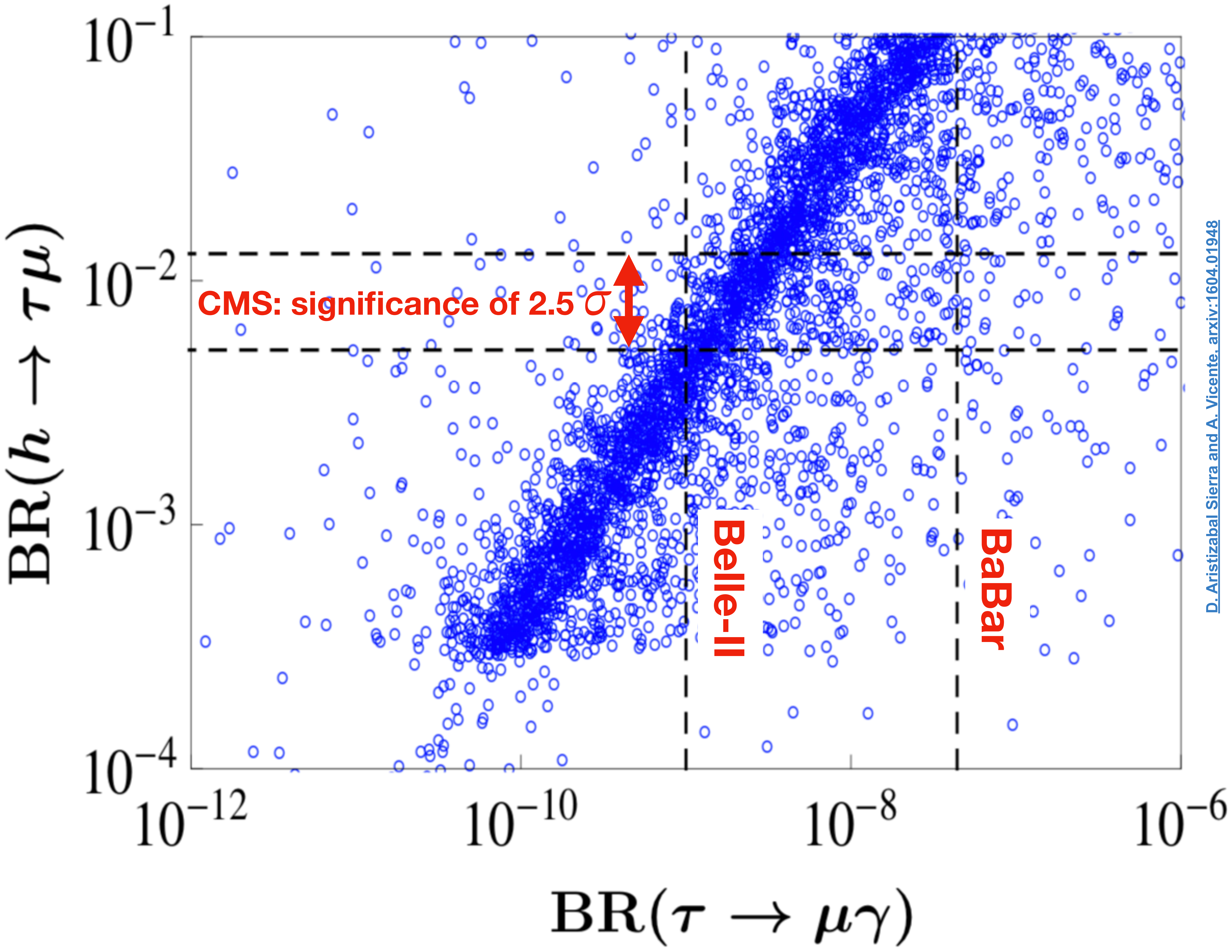
Abada, V. De Romeri, A. M. Teixeira arXiv:1510.06657



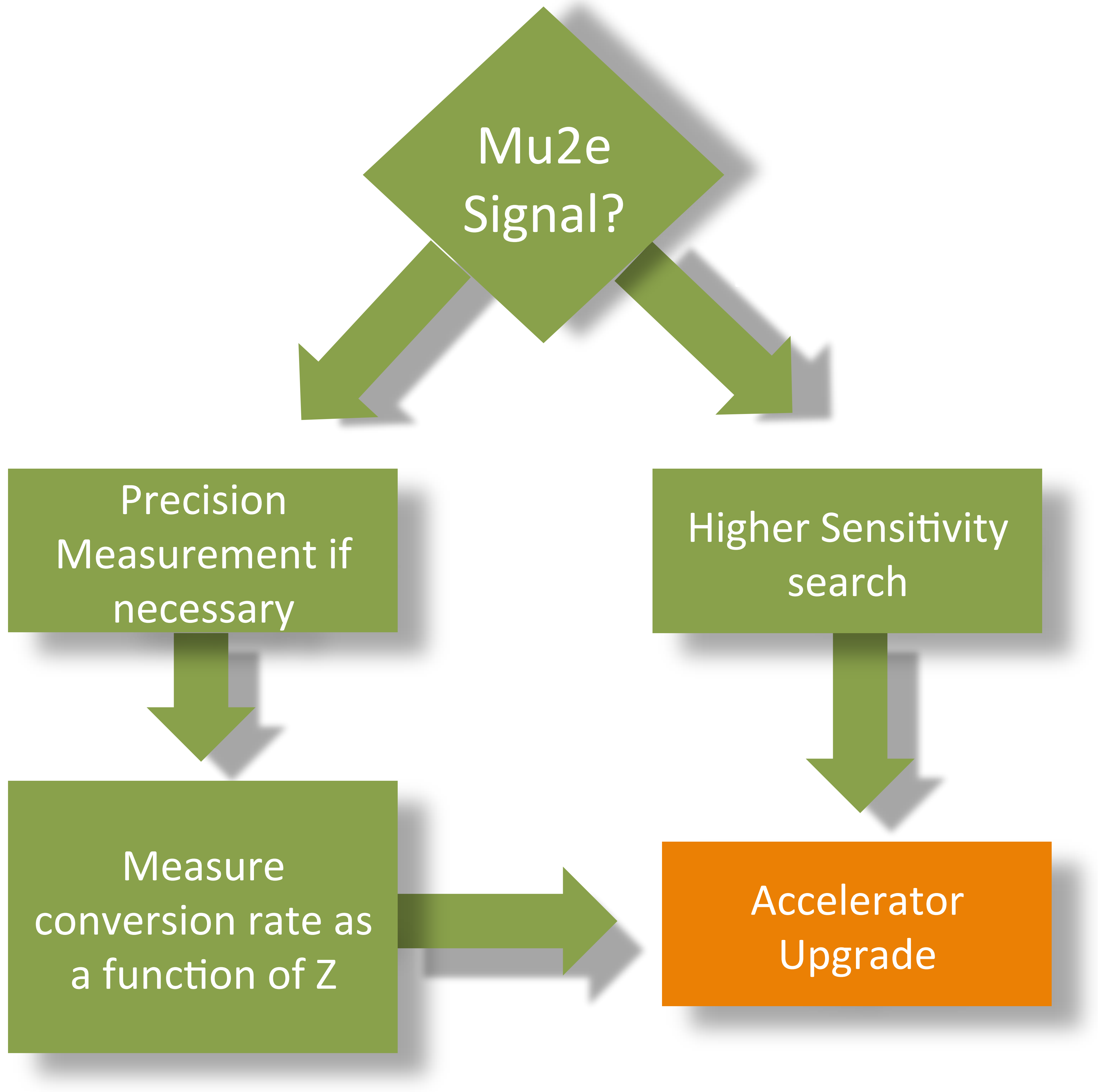
Two Higgs doublet models

- Induces flavor violation in both quarks and leptons
  - coupling constants $\rho_{ij} \propto \sqrt{m_i m_j}$
  - automatically suppresses 1st and 2nd generation coupling!

$$\mathrm{BR}(h \to \tau\mu) = \frac{m_h}{8\pi\Gamma_h}\left(|g_{h\tau\mu}|^2 + |g_{h\mu\tau}|^2\right)$$



Mu2e signal?

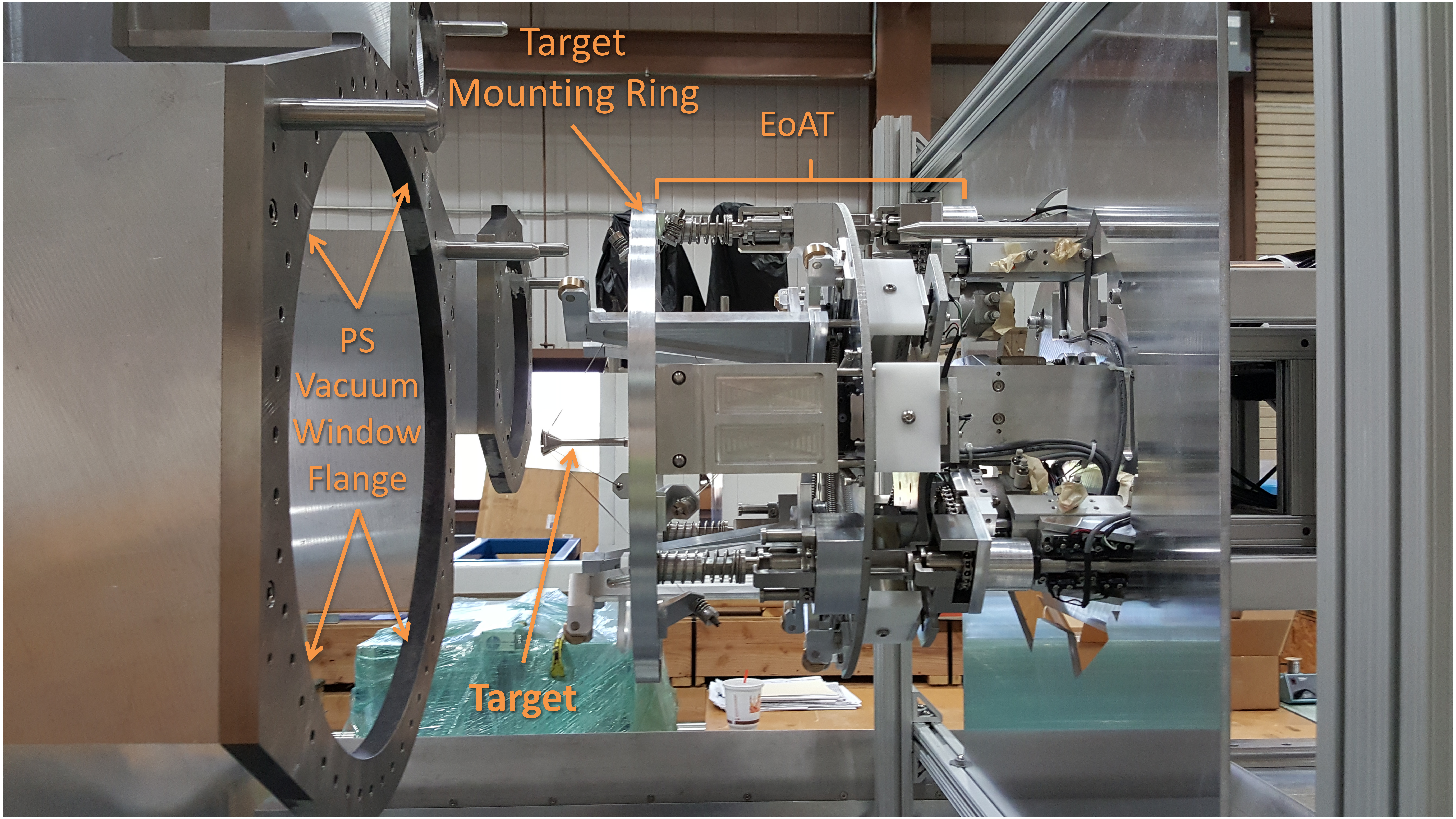


- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons upgrade accelerator
  - ✓ **Snowmass** white paper, arXiv:1802.02599

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

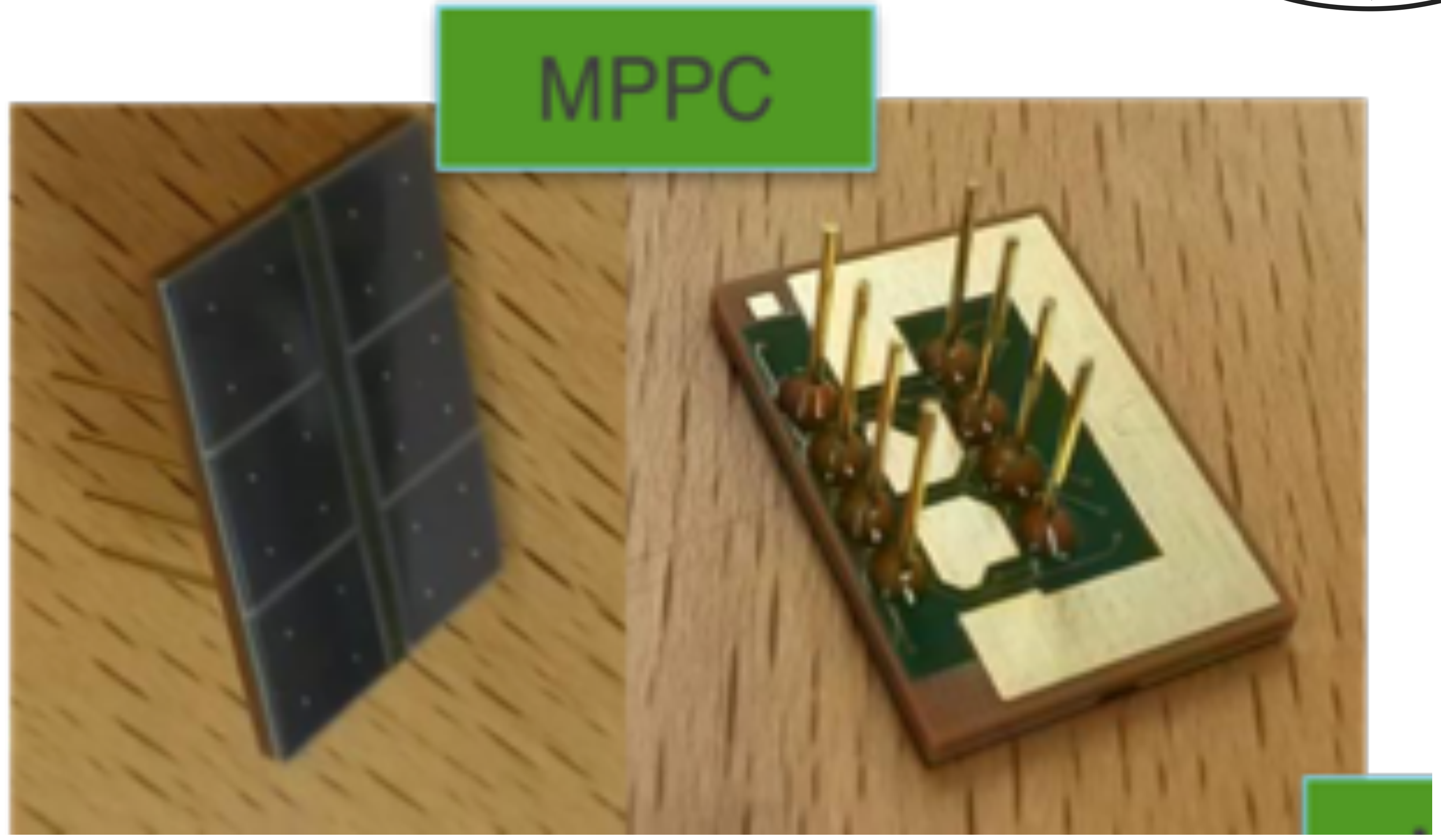
Testing Handling Robot



Electronics procurement

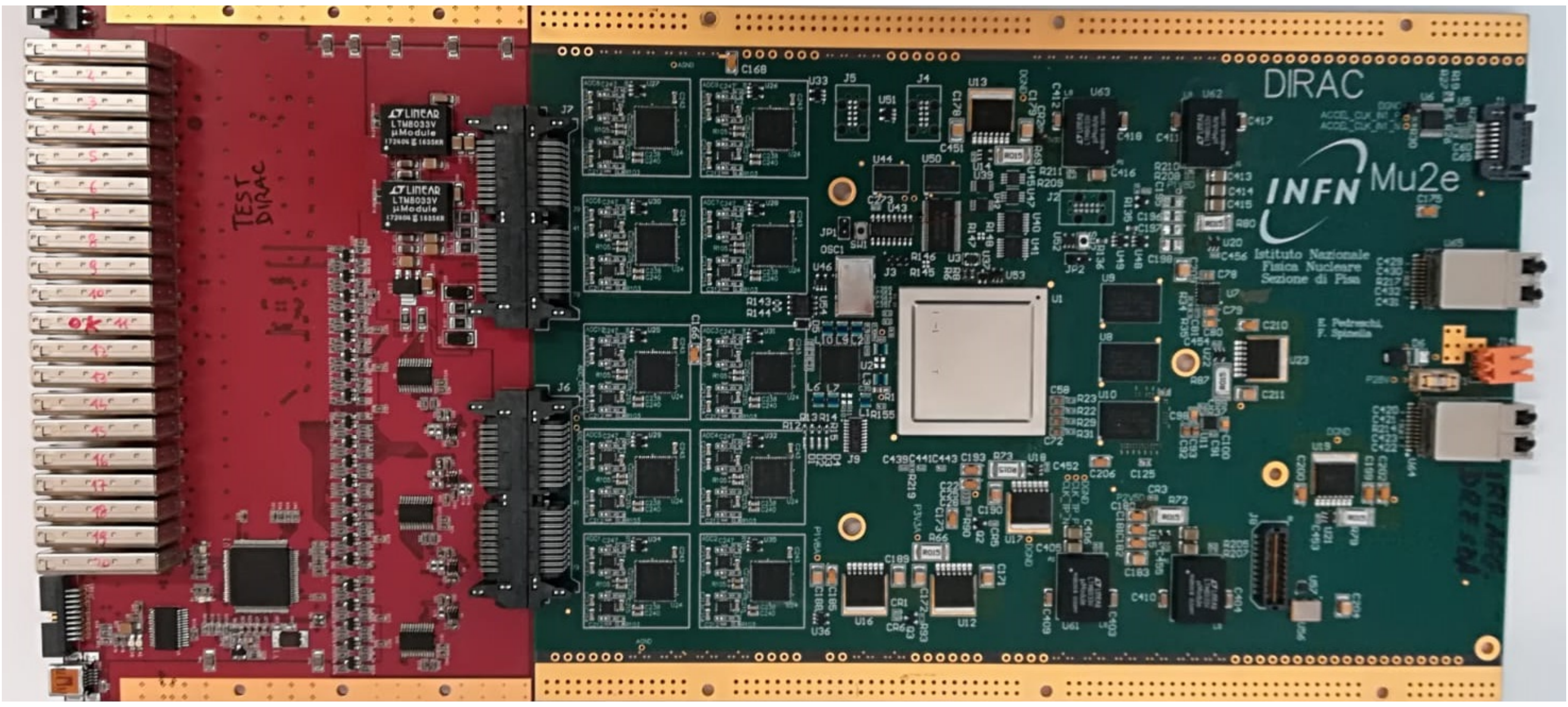
Photosensors

- We developed custom SiPM-array design with Hamamatsu
- 2812 SiPM delivered (100%)
  ➡ ~0.7 % rejected
- >92% tested successfully so far
- Expected end of QA test is September 2019



Digitizer

- Slice test of the whole electronics chain completed
- board design being upgraded to include rad-hard components
  ➡ FPGA -> PolarFire, from Microsemi
  ➡ DCDC converter -> LTM-8053
  ➡ Optical transceiver -> VTRx from CERN



Mu2e Schedule