CLFV 2019

FERMILAB-SLIDES-19-

Mu2e: A Search for Charged Lepton Flavor Violation in $\mu^- N \rightarrow e^- N$ conversion with a Sensitivity < 10^{-16}

This document was prepared by Mu2e collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

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What is μ→e conversion?

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

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

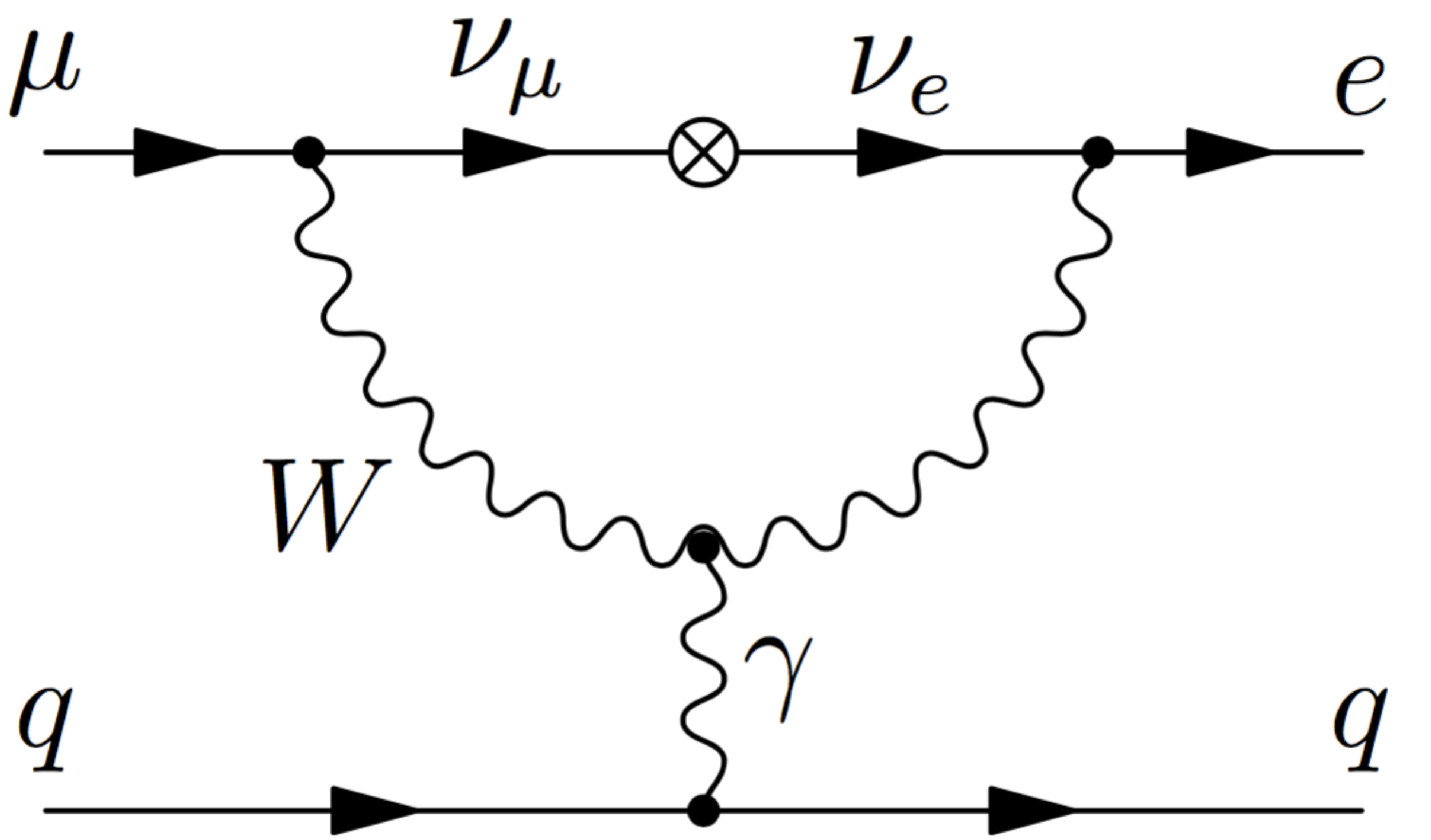
- for Aluminum: $\begin{cases} B_\mu(Z) \text{ is the muon binding energy (0.48 MeV)} \\ C(A) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

- Signal normalization:

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

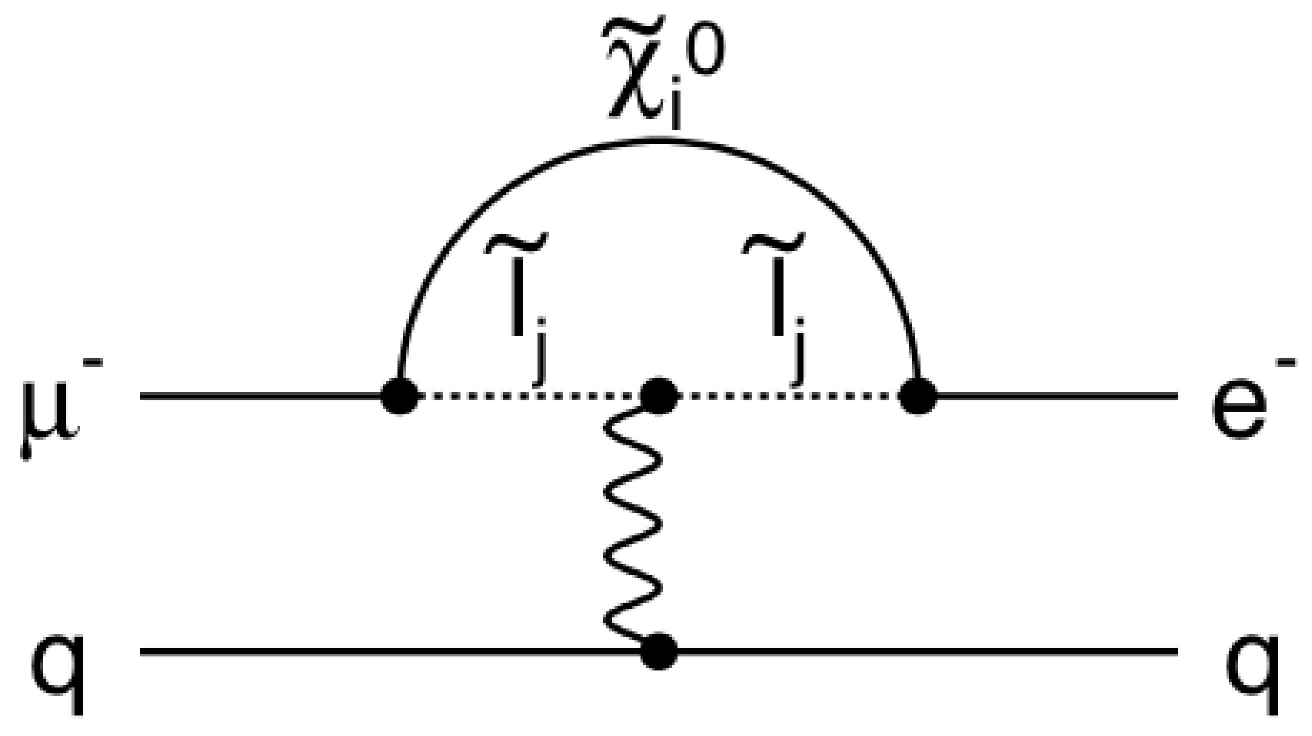
CLFV in the Standard Model

- **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}

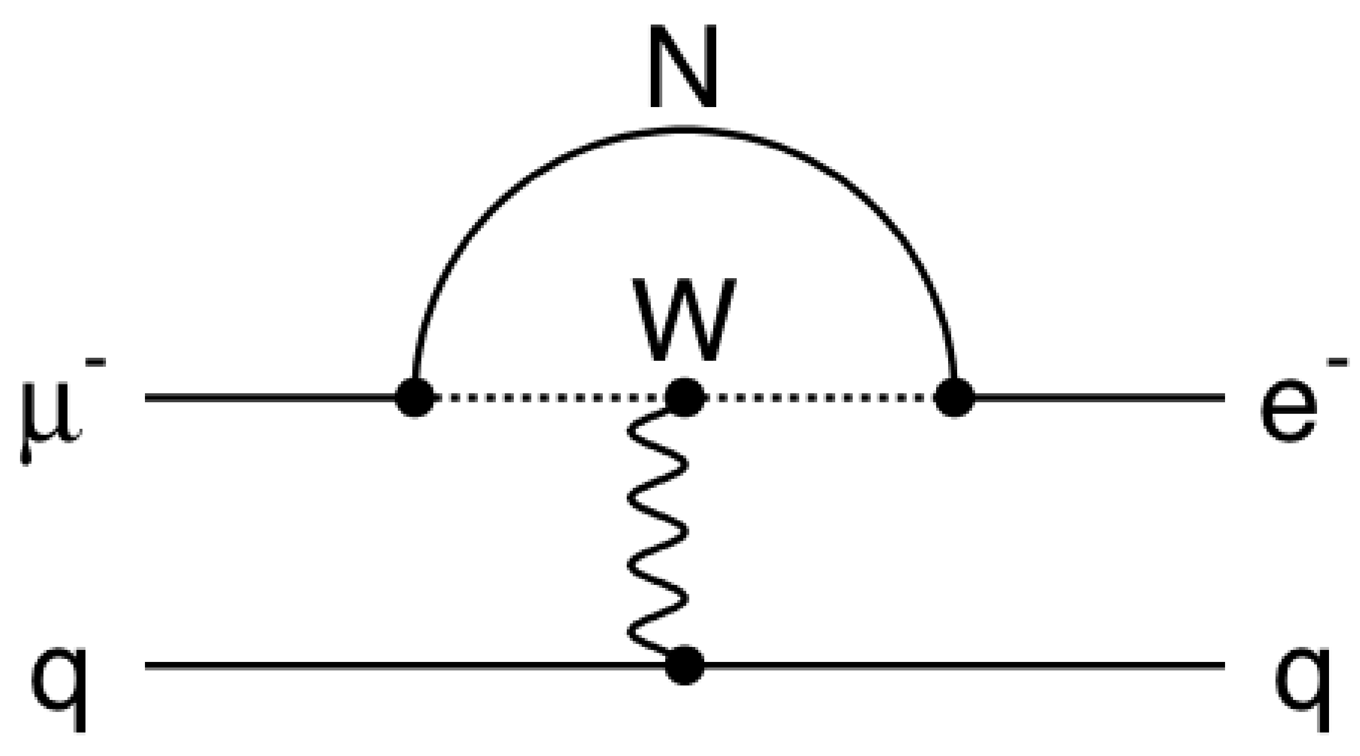


- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)

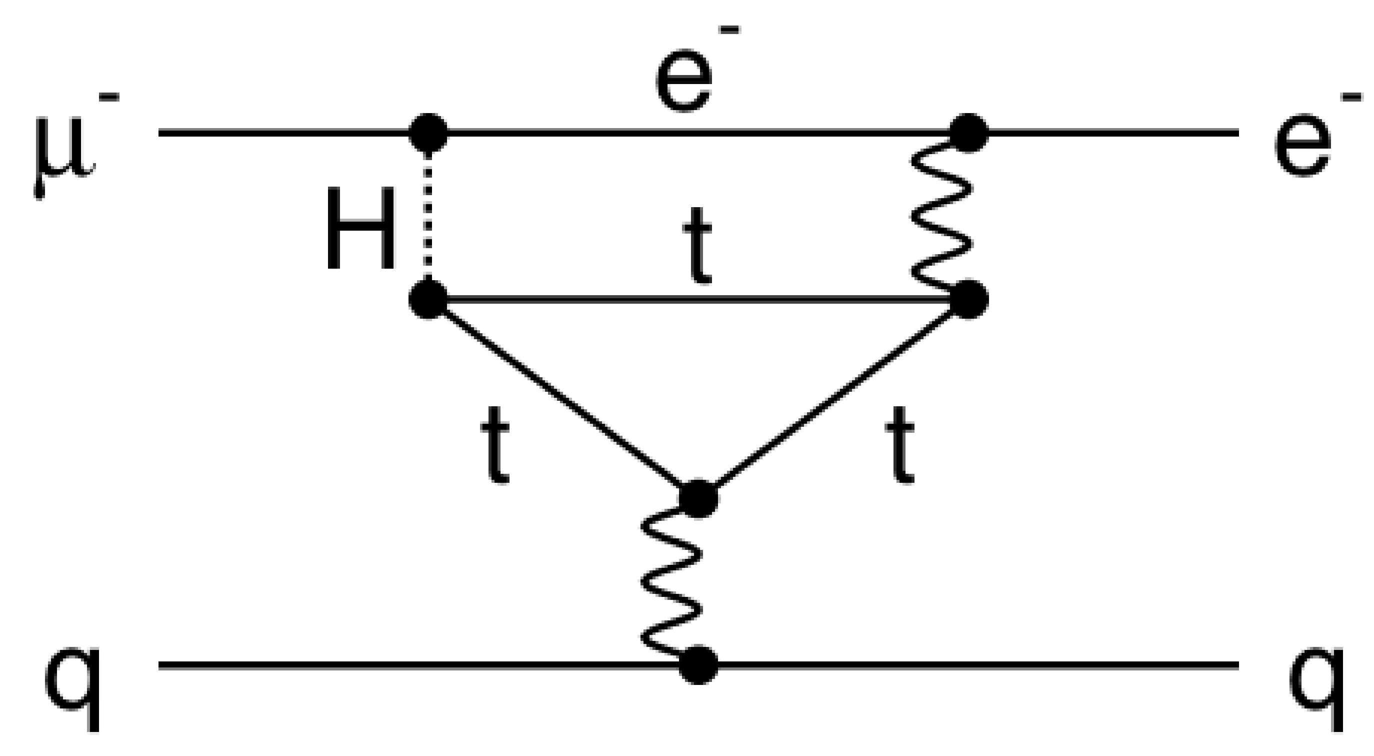
New Physics and μ→e



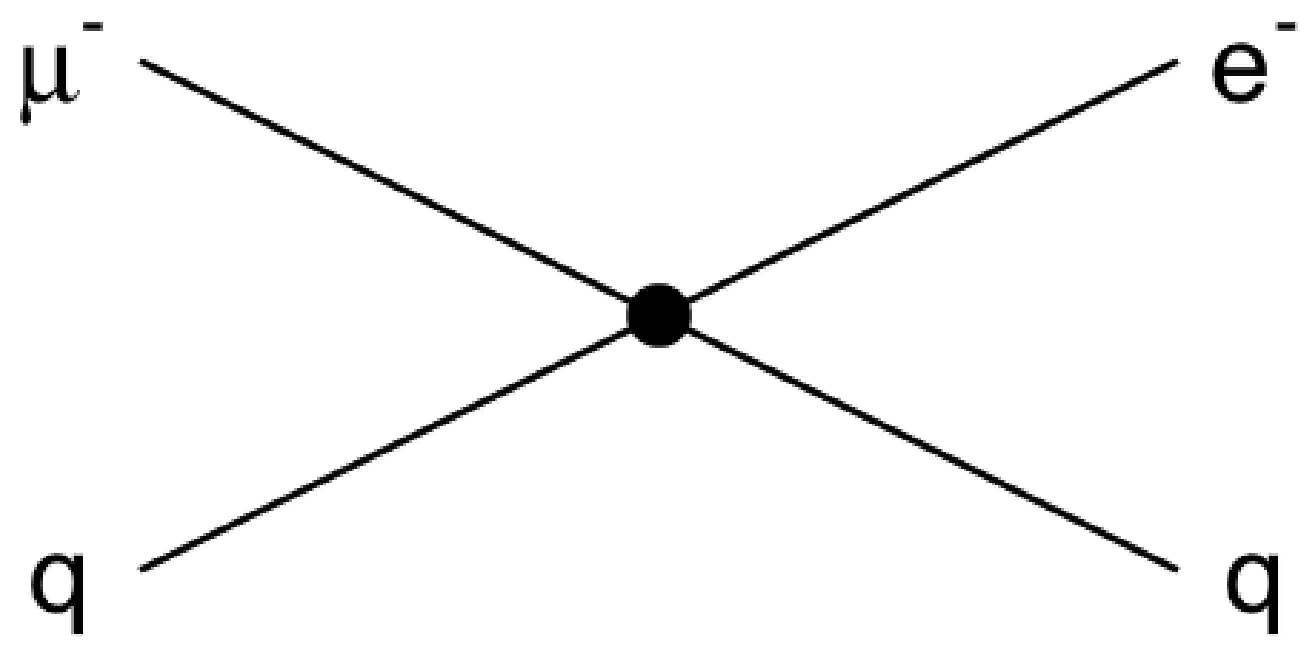
SUSY



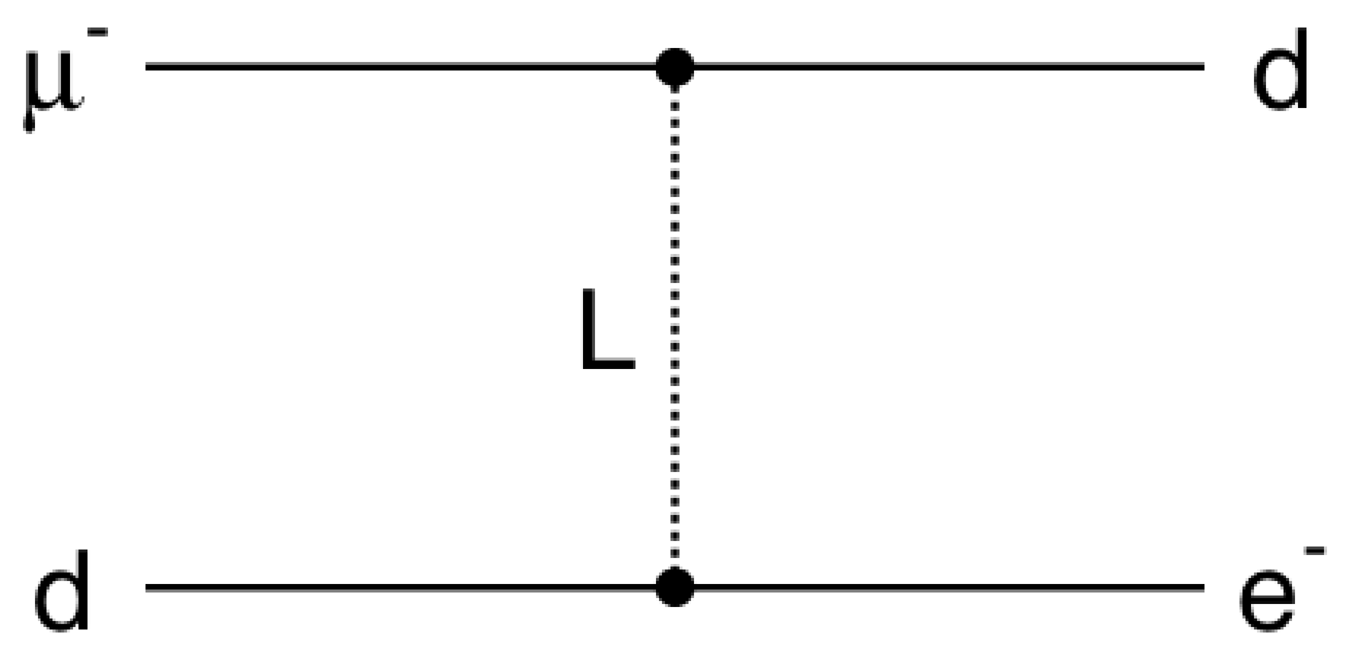
Heavy neutrino



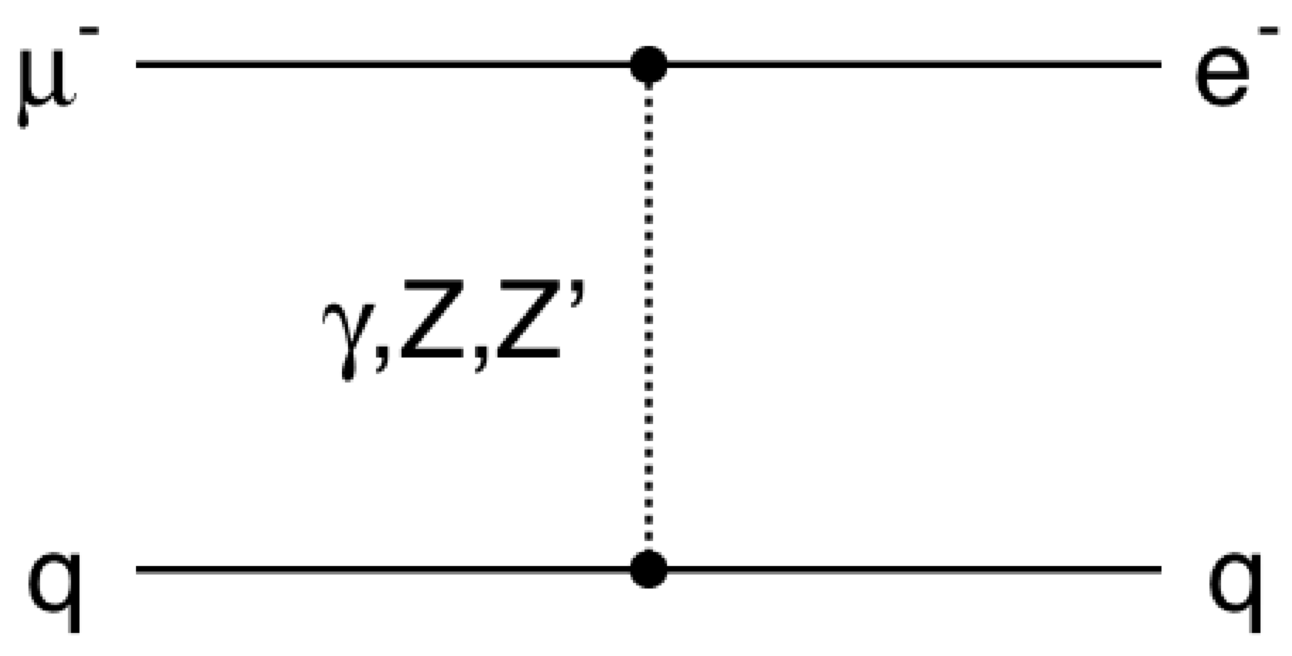
Two Higgs doublet



Compositeness



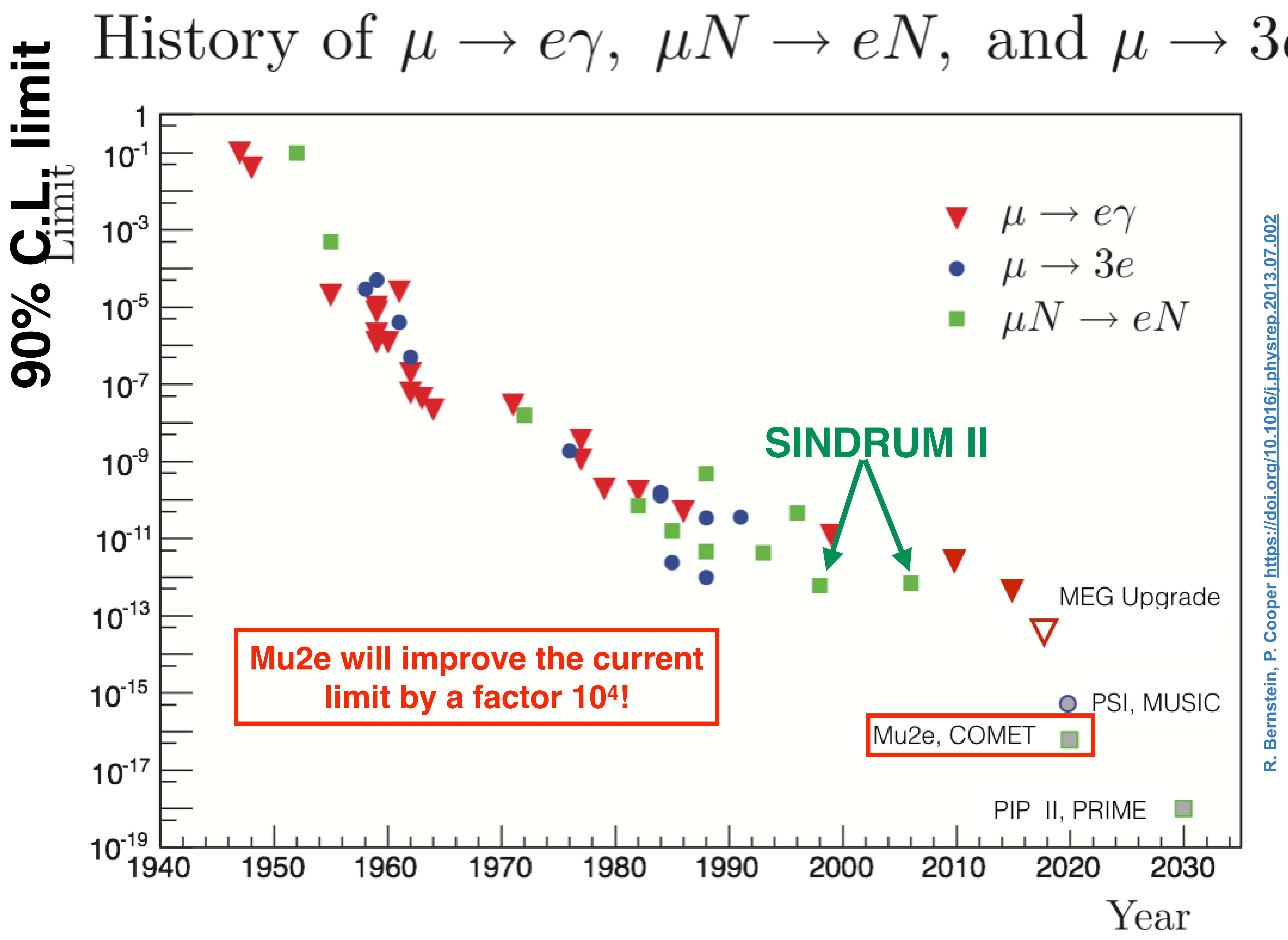
Leptoquarks



Z'/anomalous couplings

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

History of μ→e search



Experimental setup

Production Solenoid:

➡ Proton beam strikes target, producing mostly pions

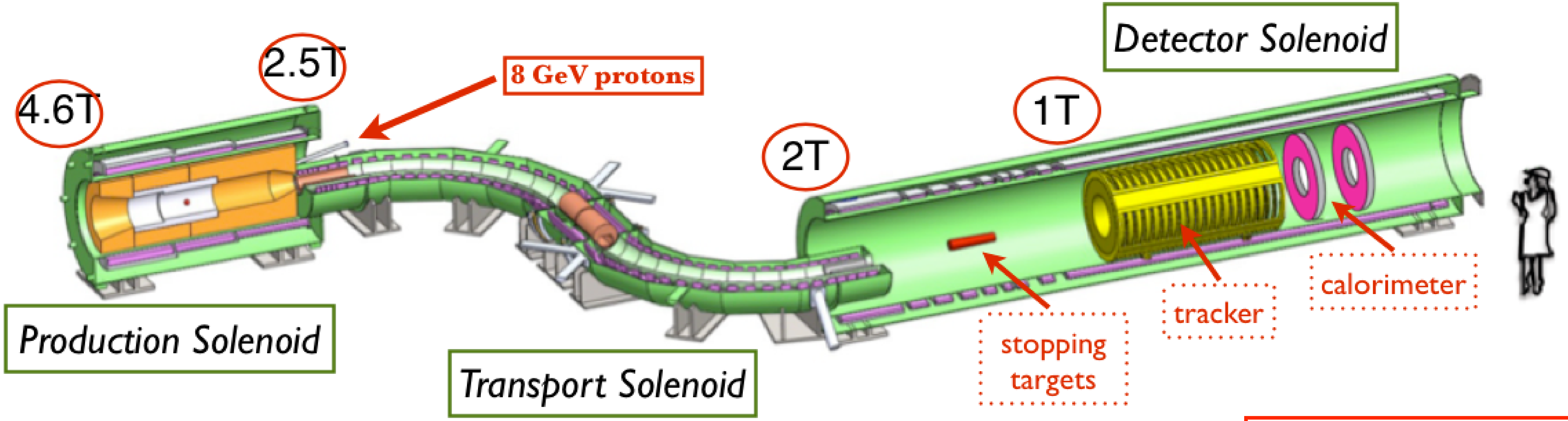
➡ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

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%): $\mu^- N \rightarrow e^- \bar{\nu}_e \nu_\mu N$, **background**
  - ➡ **capture** (61%): $\mu^- + N \rightarrow \nu_\mu + N'$, **normalization**
  - ➡ **conversion** (<10^{-13}): $\mu^- + N \rightarrow e^- + N$, **signal**

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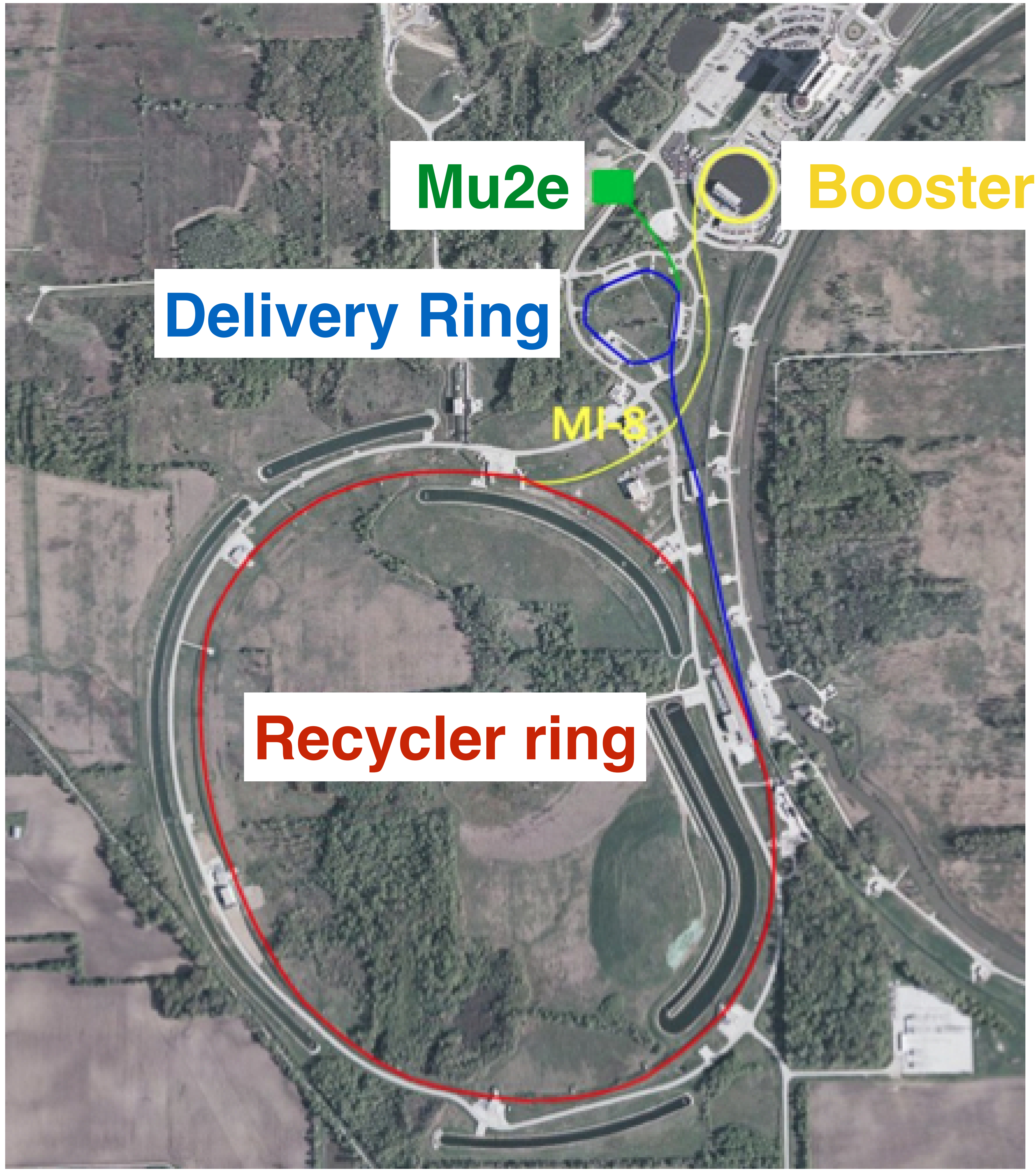
Mu2e beamline

Fermilab Muon campus

Mu2e proton beam



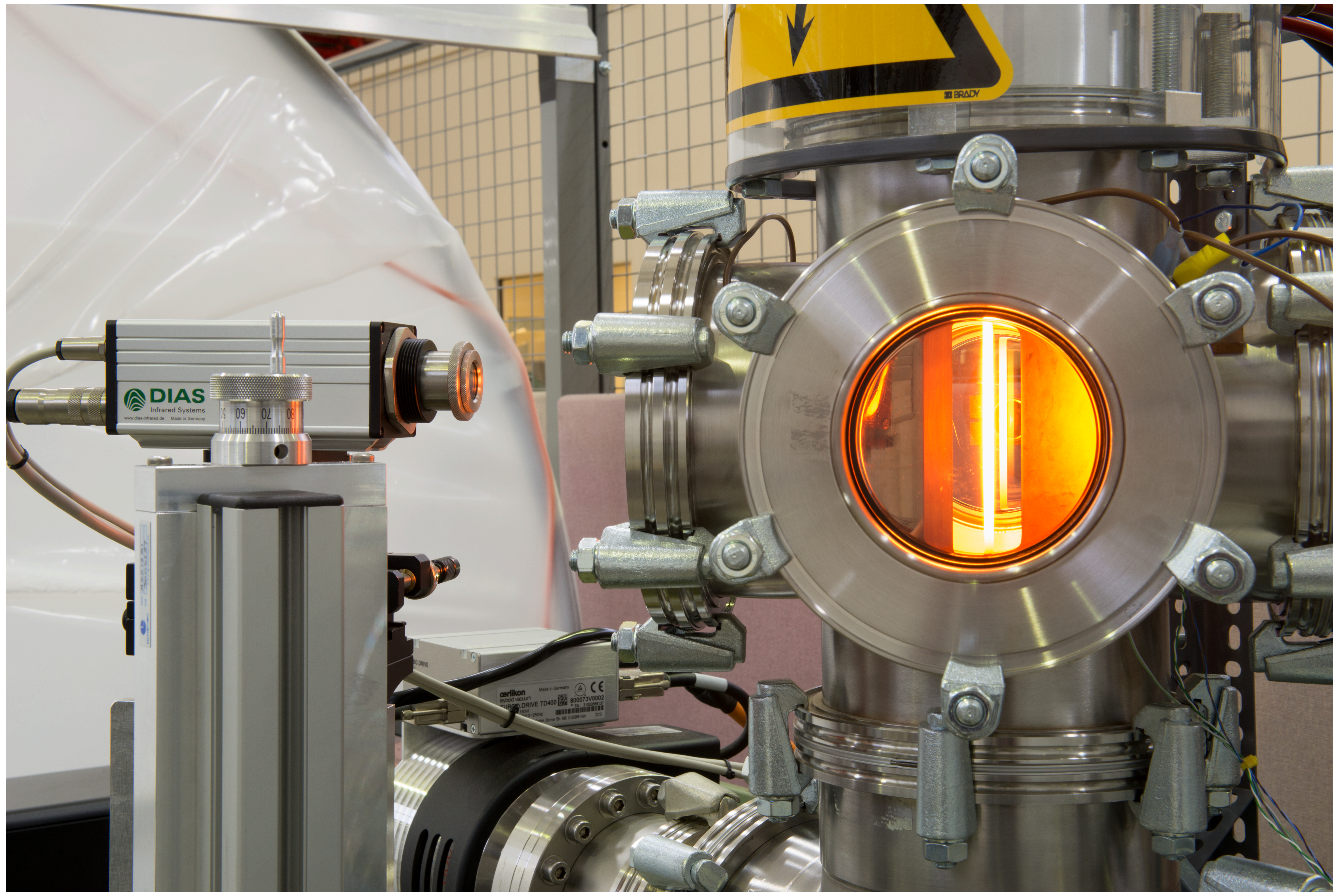
- Mu2e will use 8 GeV protons from the Booster
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons
- Mu2e will collect data simultaneously with NOvA and short baseline program
  - small loss to NOvA

Mu2e beamline

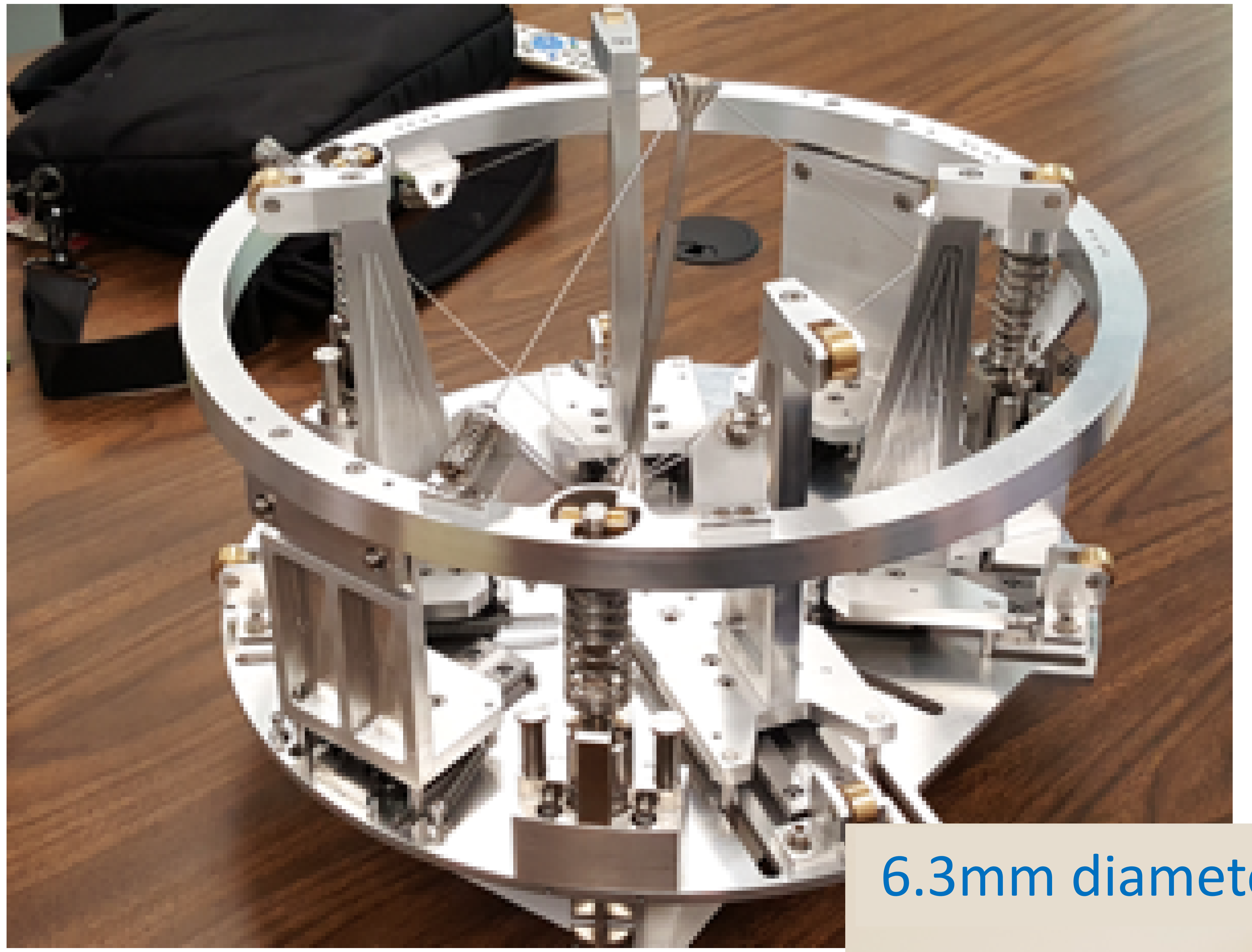
- Installation of beam magnets well along:
  - vacuum system
  - instrumentation upstream of the diagnostic absorber in progress

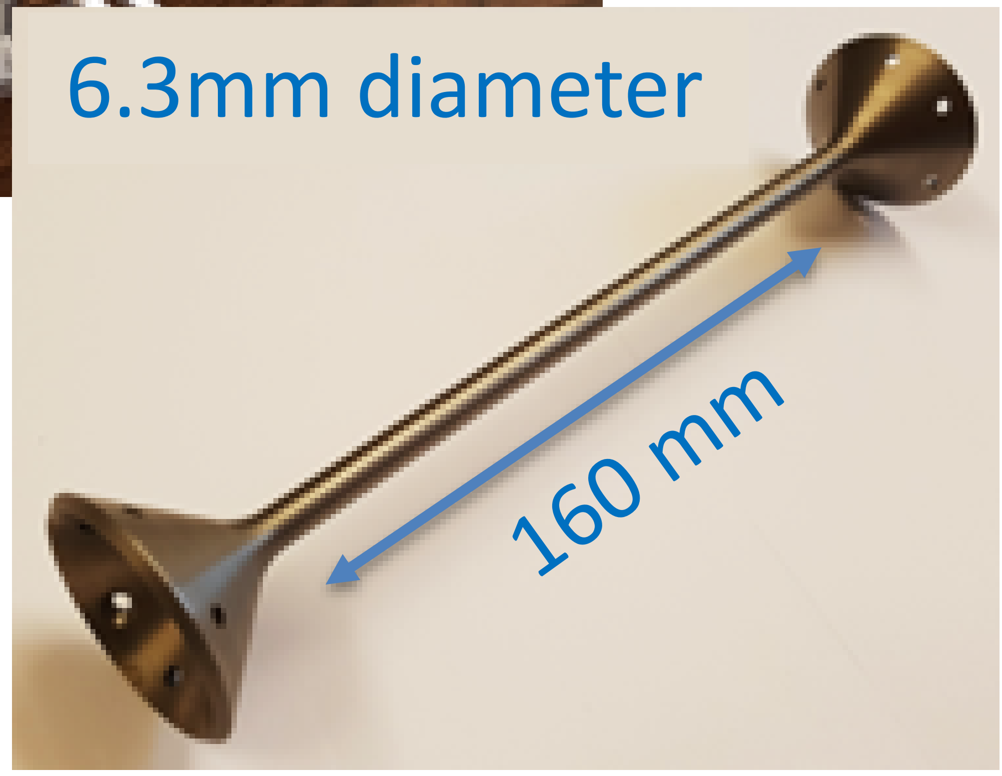
Mu2e production target

Testing @ Rutherford-Appleton Lab (UK)



Target End-of-Arm tooling @ Fermilab





- Target design being finalized in the fall

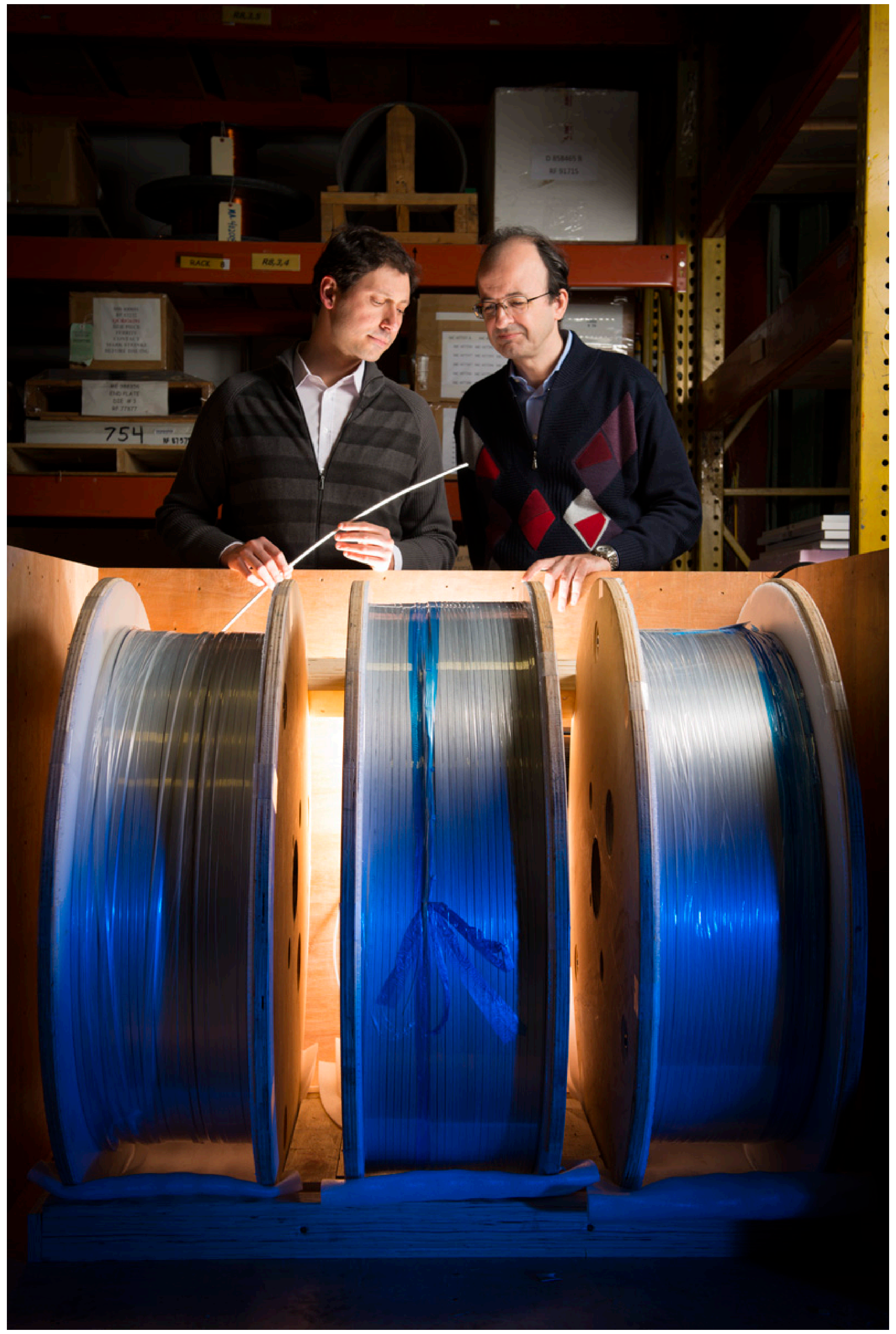
Mu2e Solenoids

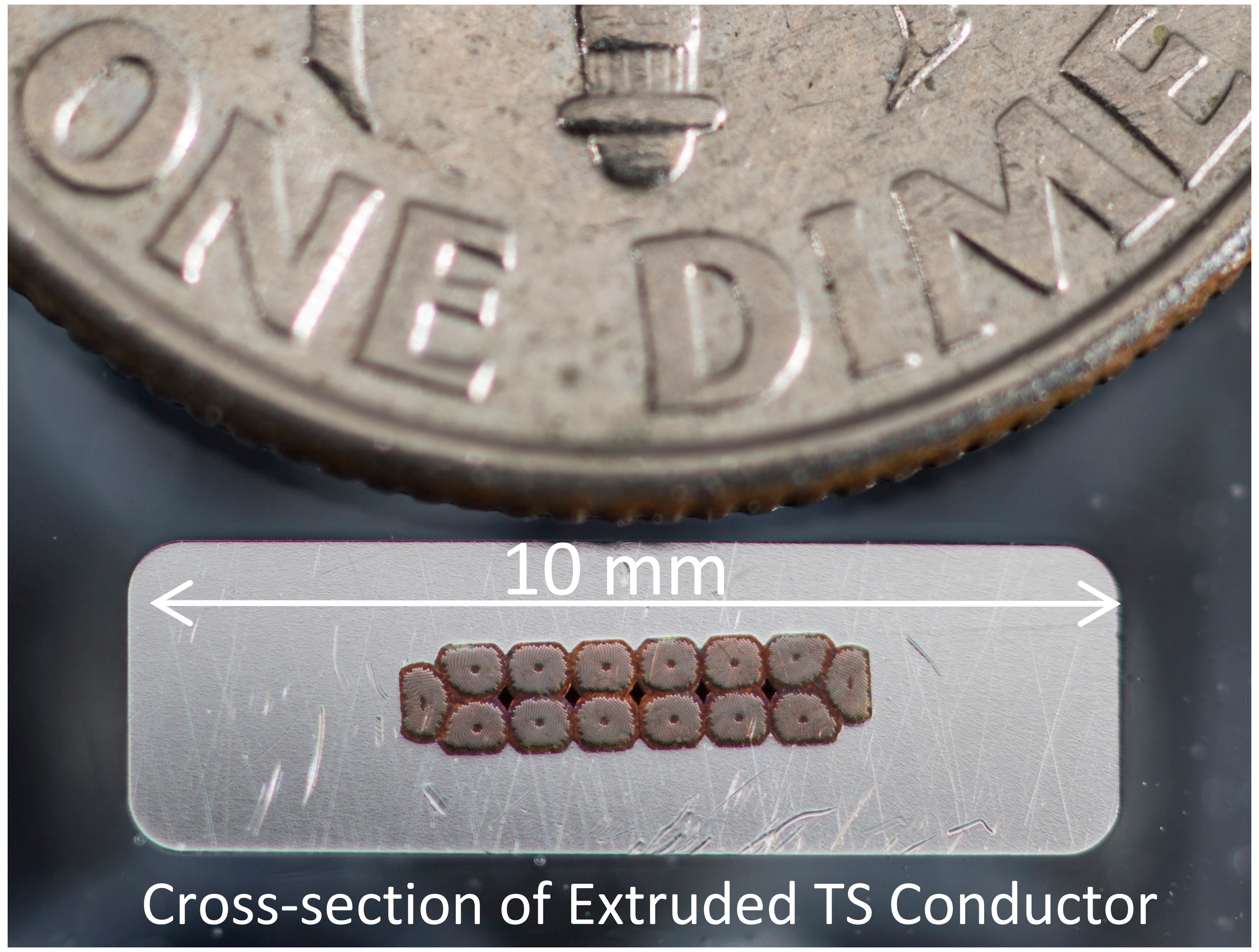
Mu2e solenoids summary

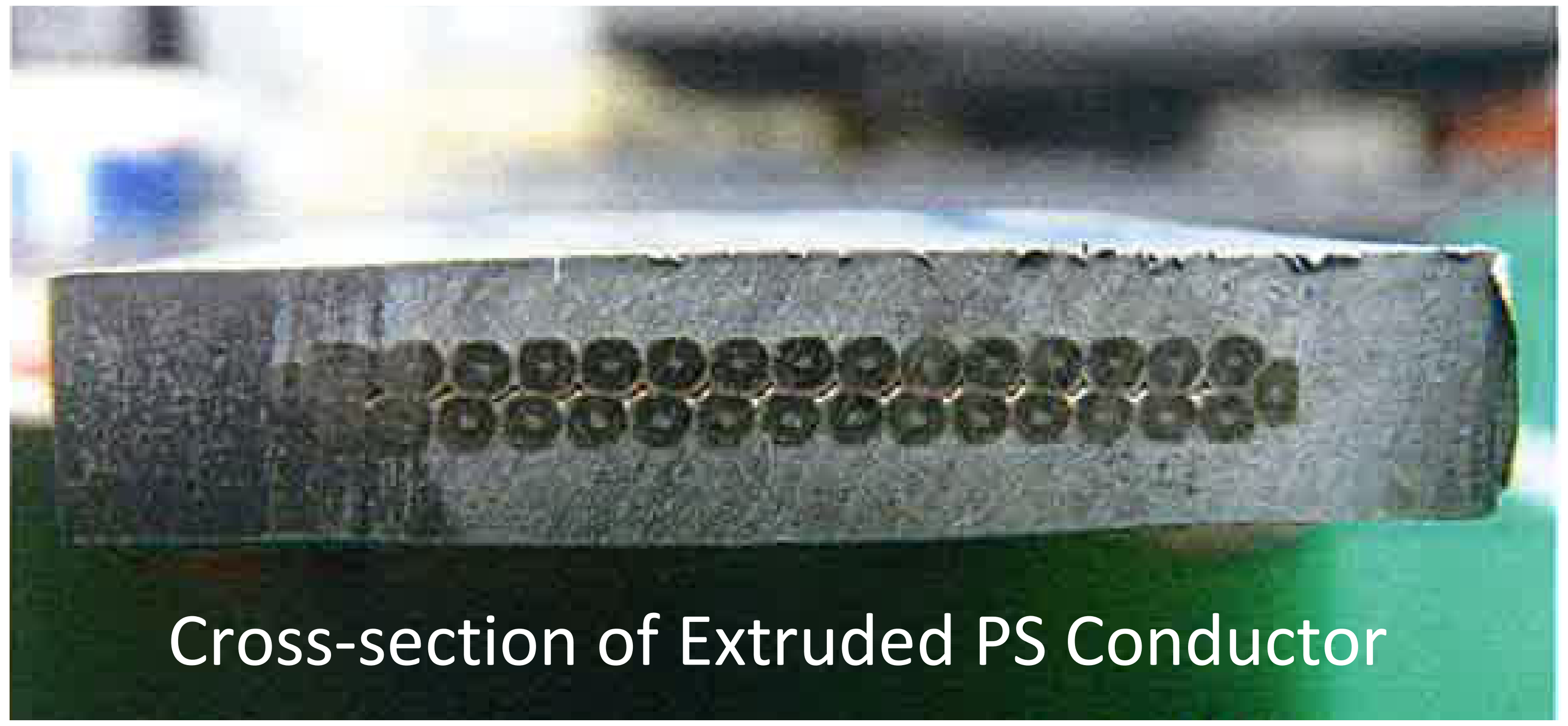
	Production	Transport	Detector
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	52	11
Conductor (km)	14	44	17
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

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

Mu2e superconductor





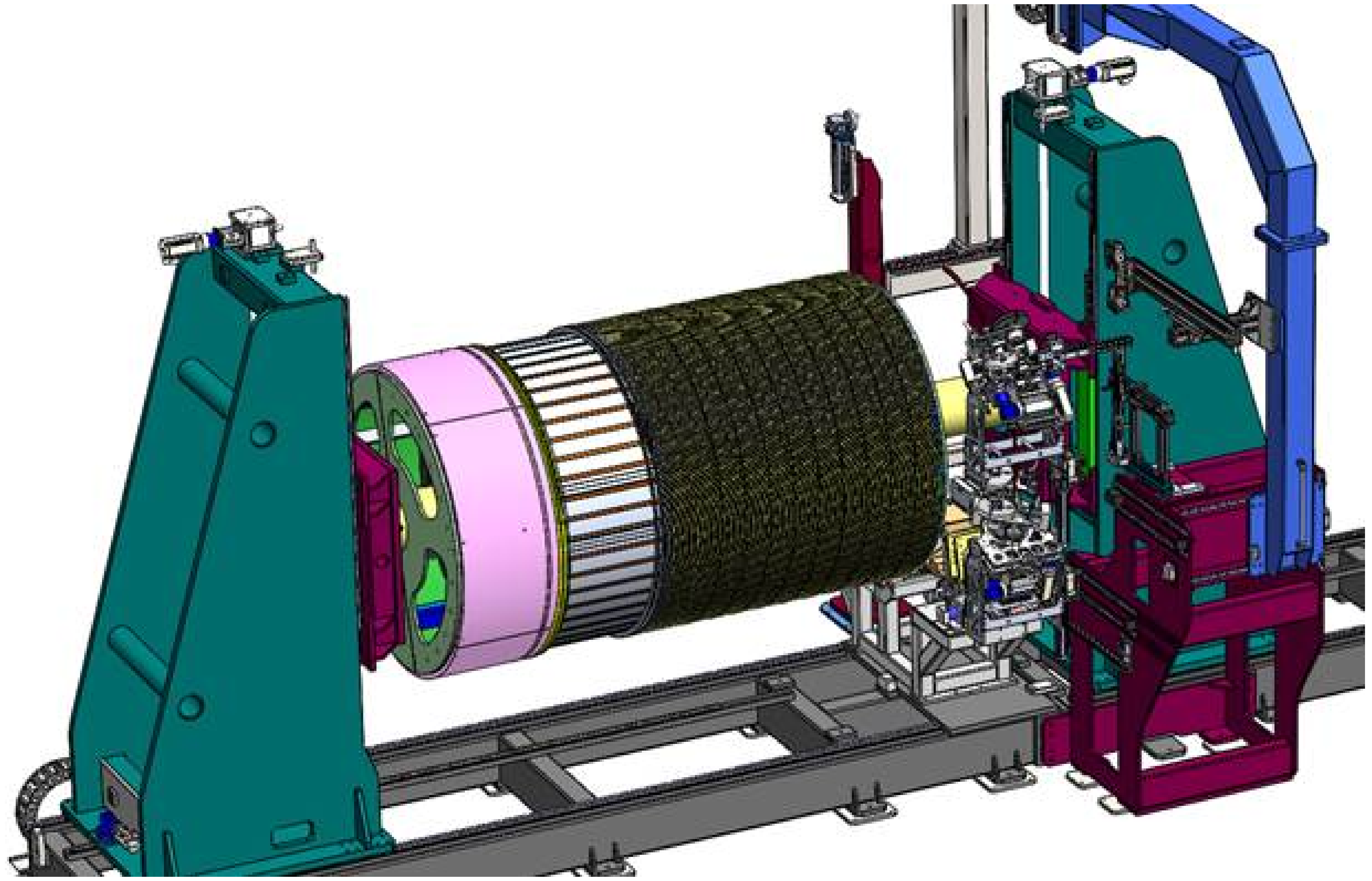


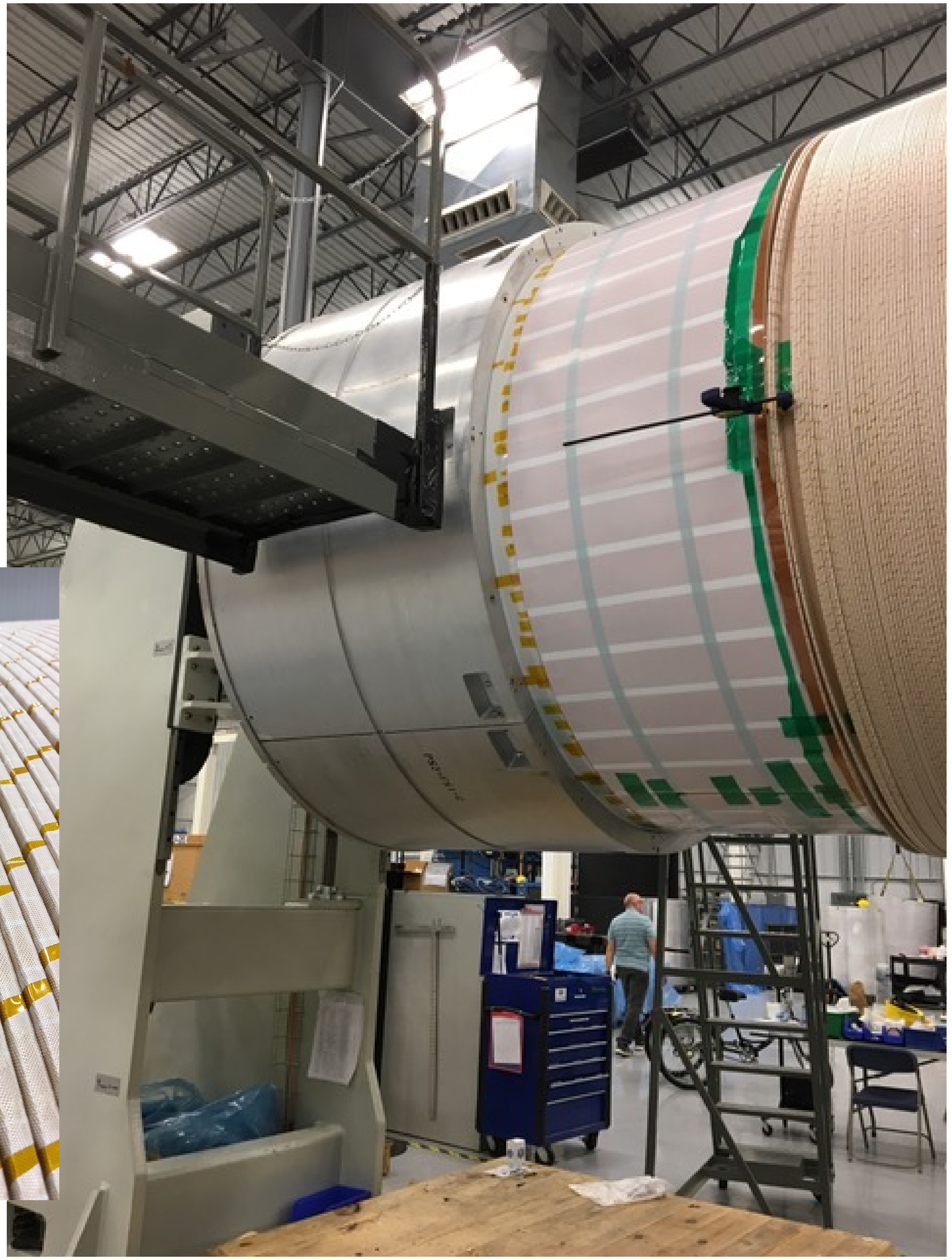
- Conductor production is complete

Production Solenoid

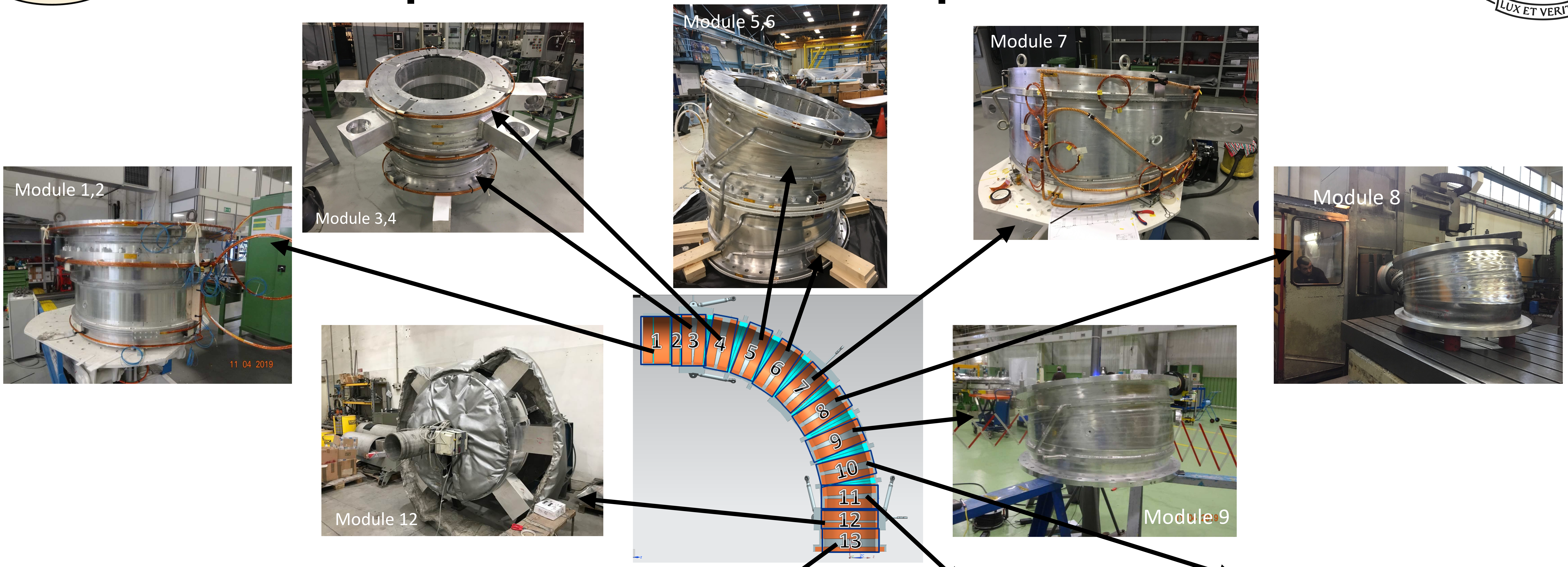
- Winding machine developed by General Atomics
- Demonstrator with a small 70-70 coil was successful
- Winding of the PS began in April of the current year

Winding machine

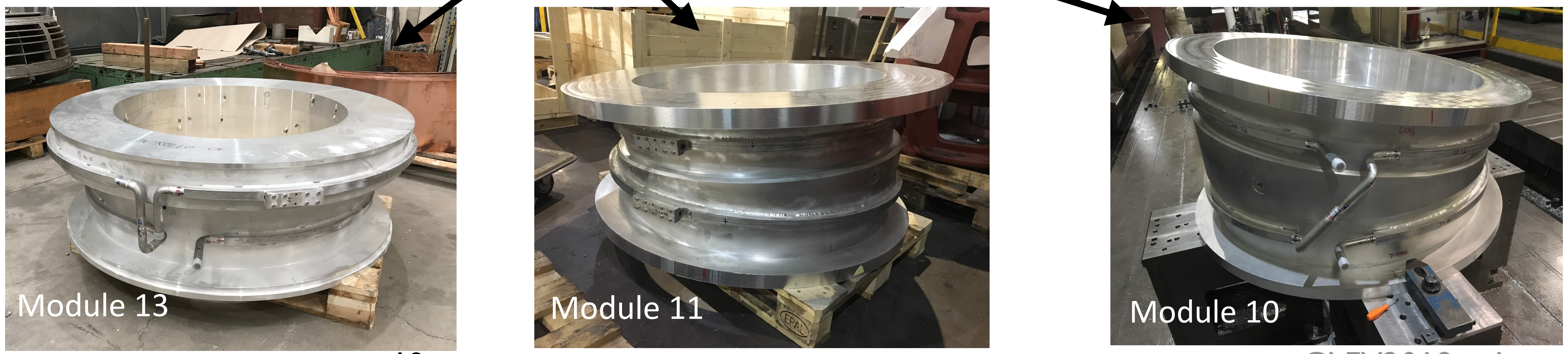




Transport Solenoid - Upstream side

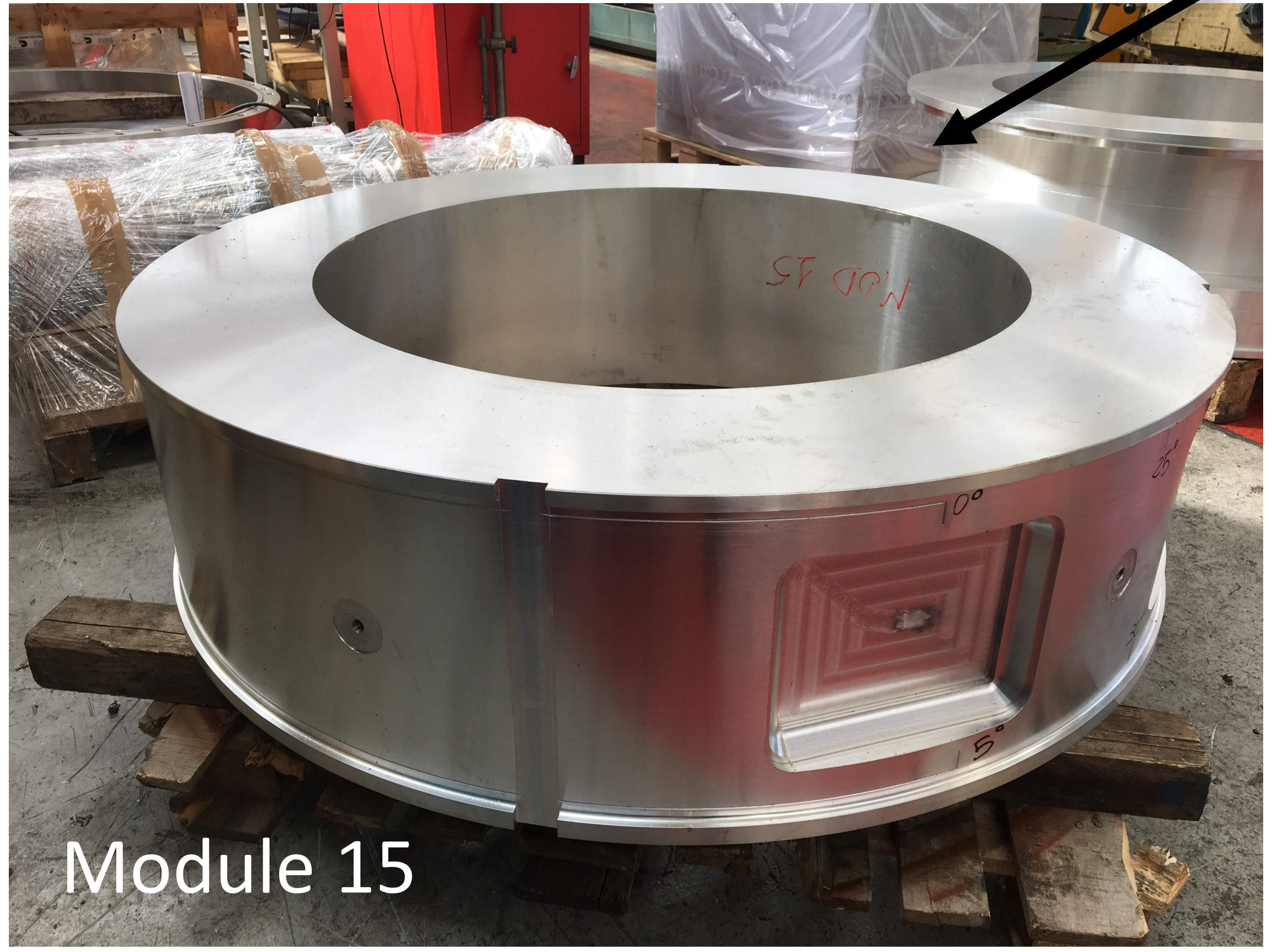


- Upstream side of the TS has been completed and the modules are now under test

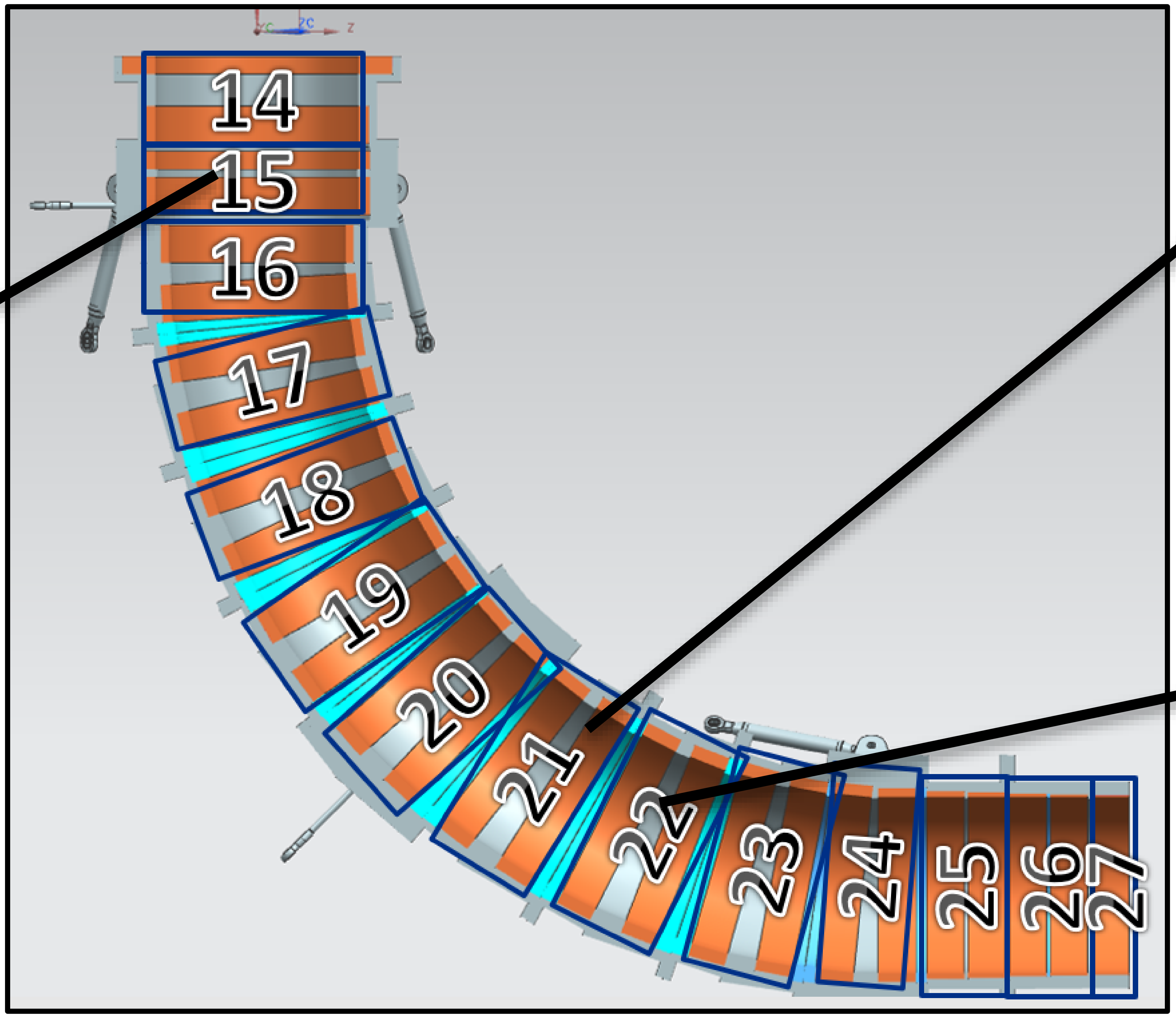


Transport Solenoid


Module 14


Module 15

- Work on the downstream section has started

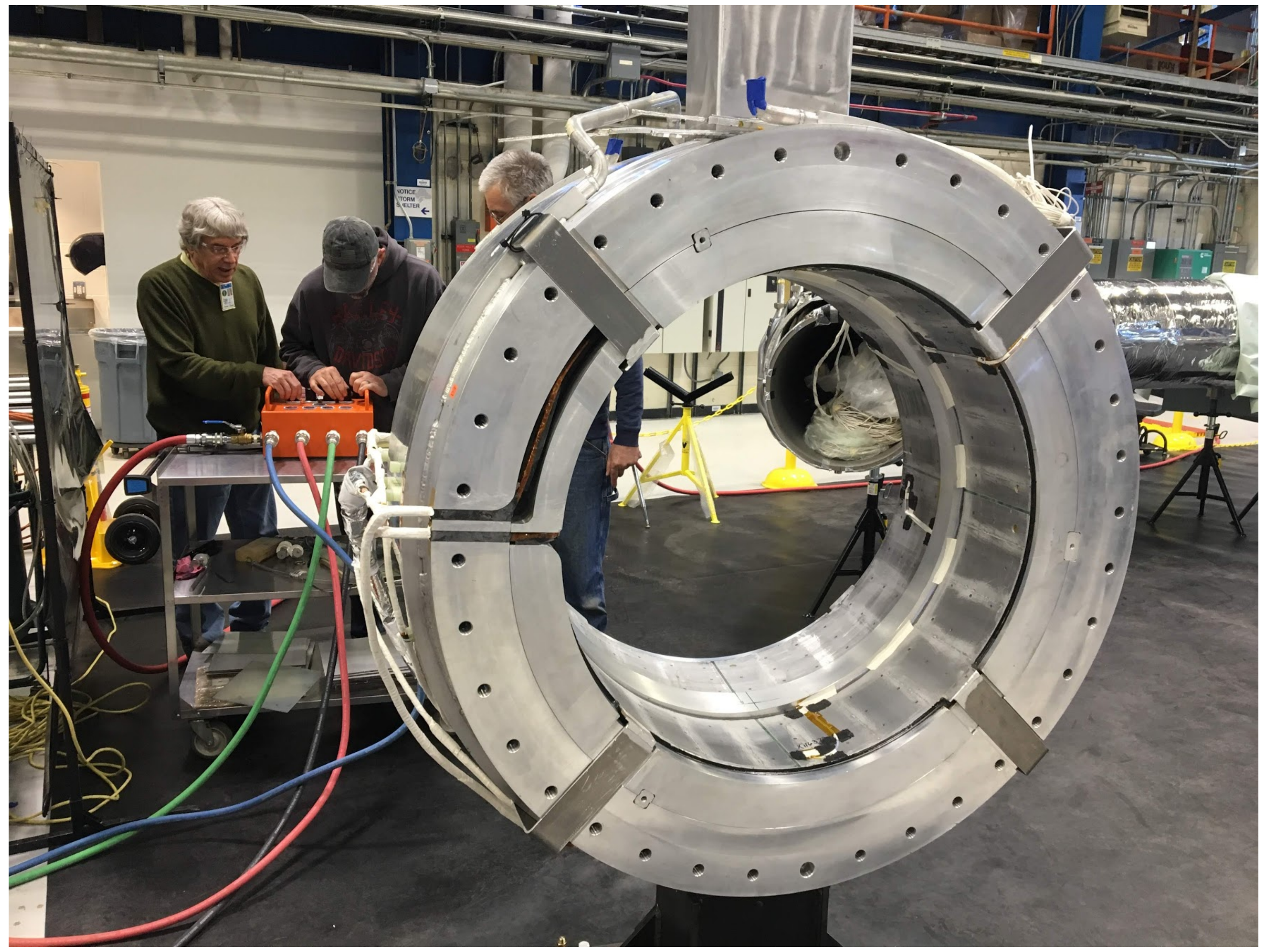


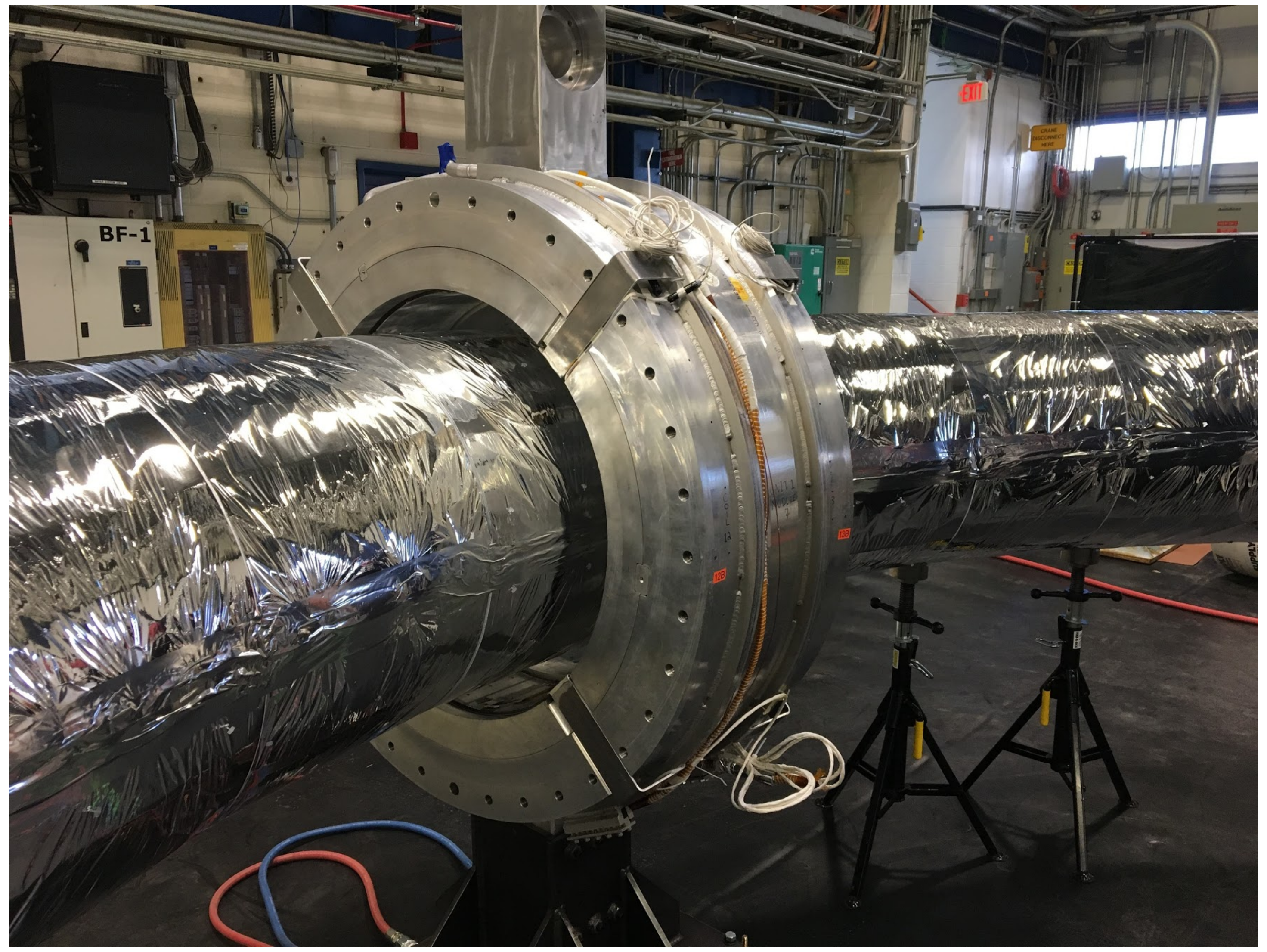

Module 21


Module 22

Cold mass assembly @ Fermilab

- First test unit assembled on warm bore
- Alignment is ongoing



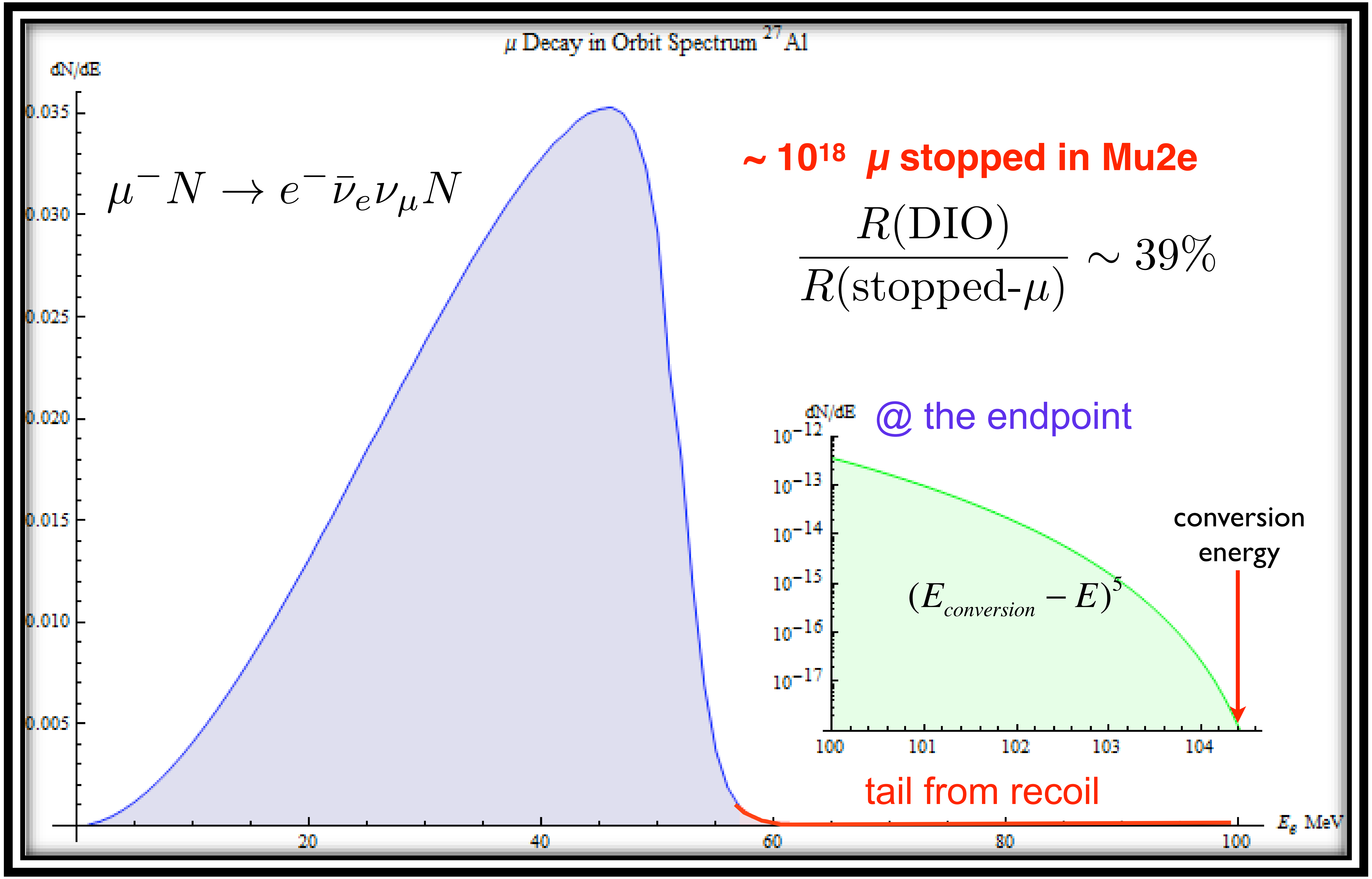


Backgrounds driving the experimental design

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

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Physics background

- μ decay-in-orbit:

  ✓ low-mass tracker with high performance

- **Cosmic-induced background:**

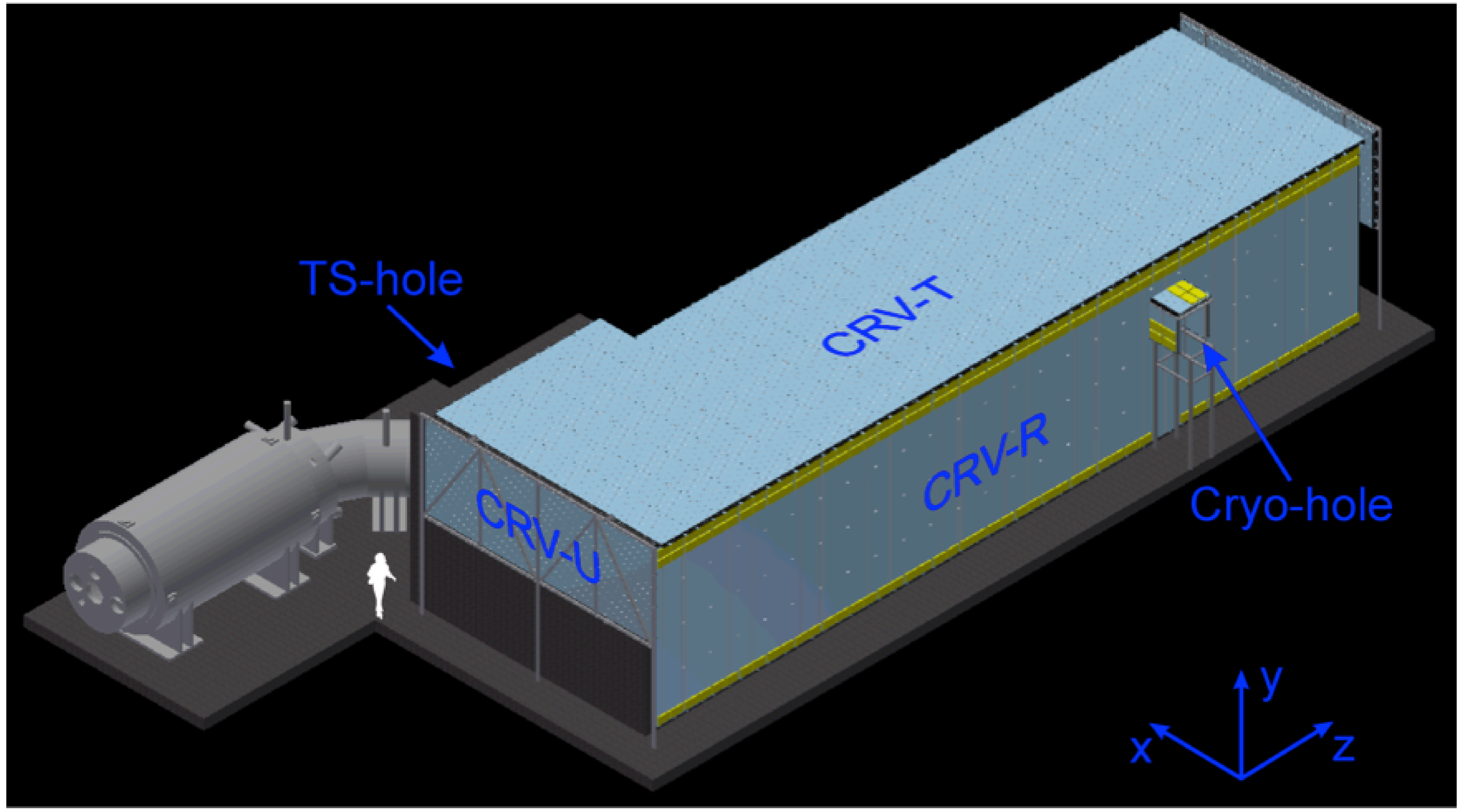
  ✓ cosmic ray veto and Particle Identification (PID)

- $\bar{p}$-induced background

- Radiative π capture

Cosmic Ray Veto

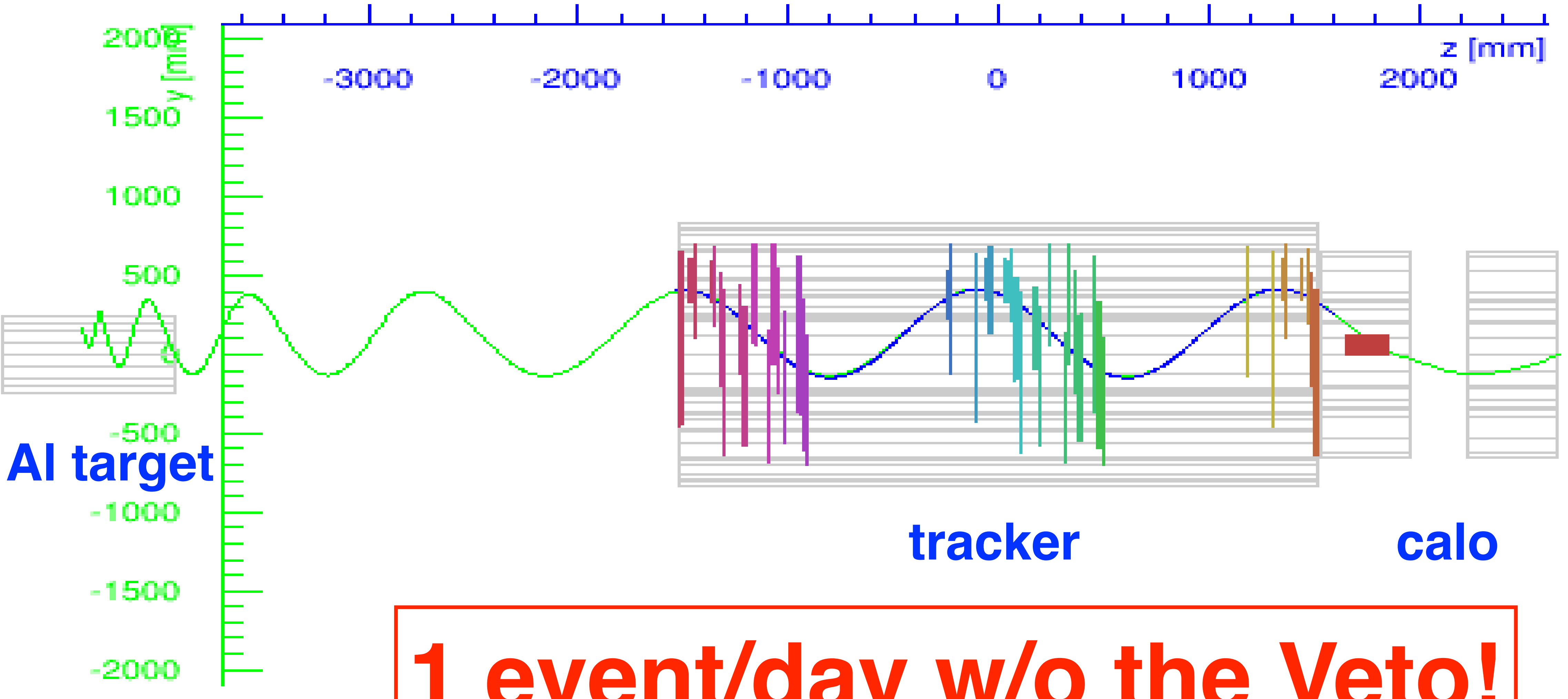
- Veto system covers entire DS and half TS
- 4 layers of scintillator
  - each bar is 5x2x~450 cm^3
  - 2 WLS fibers/bar
  - read out at both ends with SiPM
- required inefficiency ~ 10^{-4}



WLS fiber

Prototype

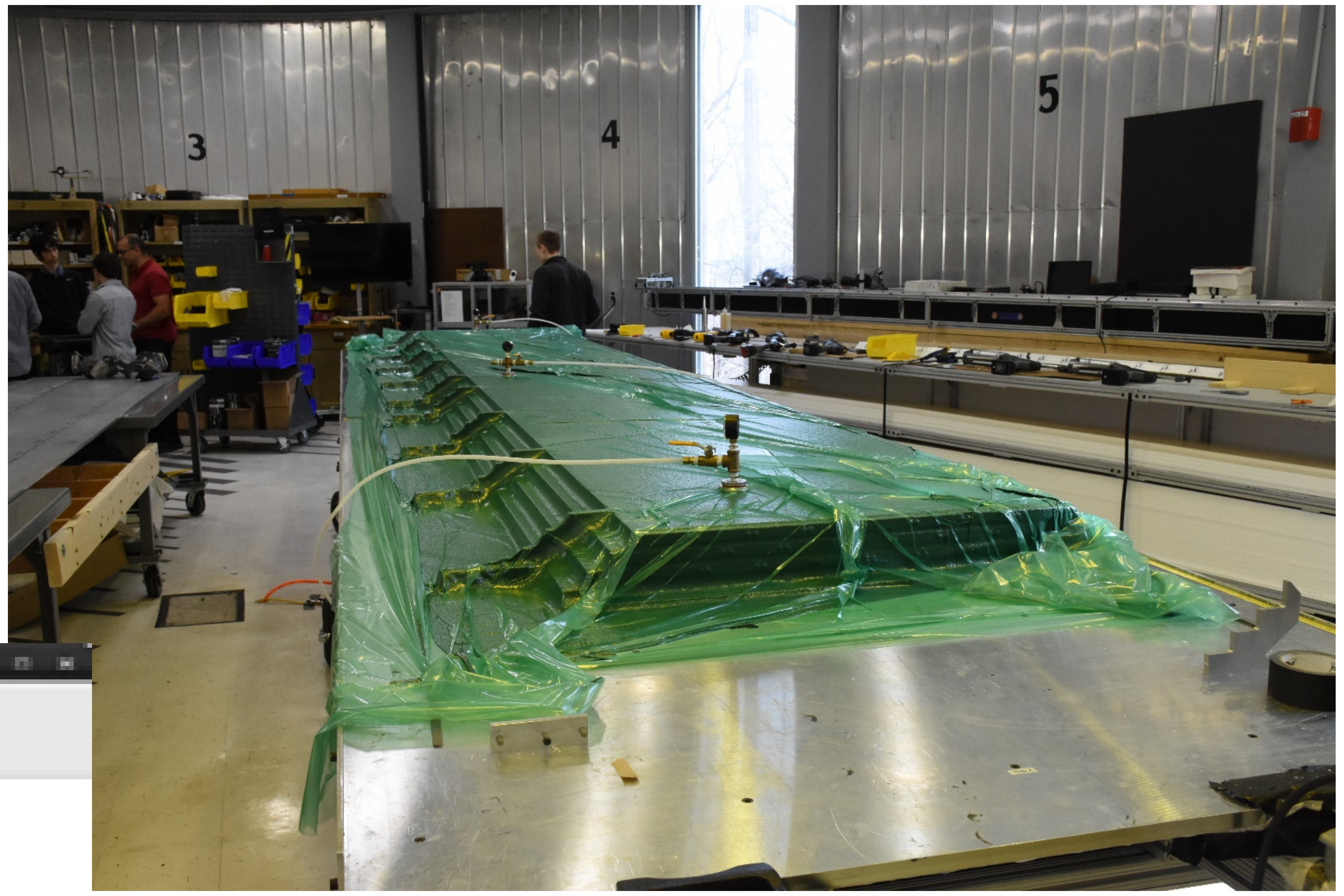
μ mimicking the CE



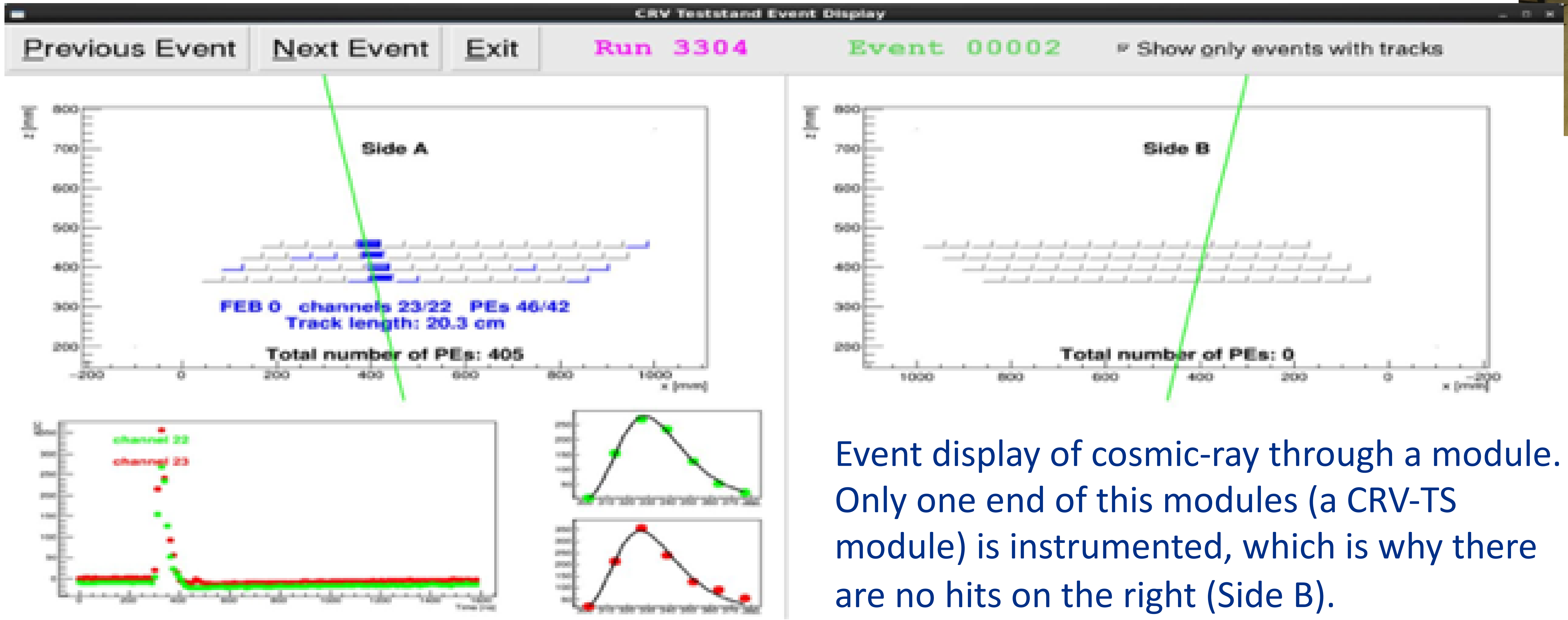
1 event/day w/o the Veto!

Cosmic Ray Veto construction

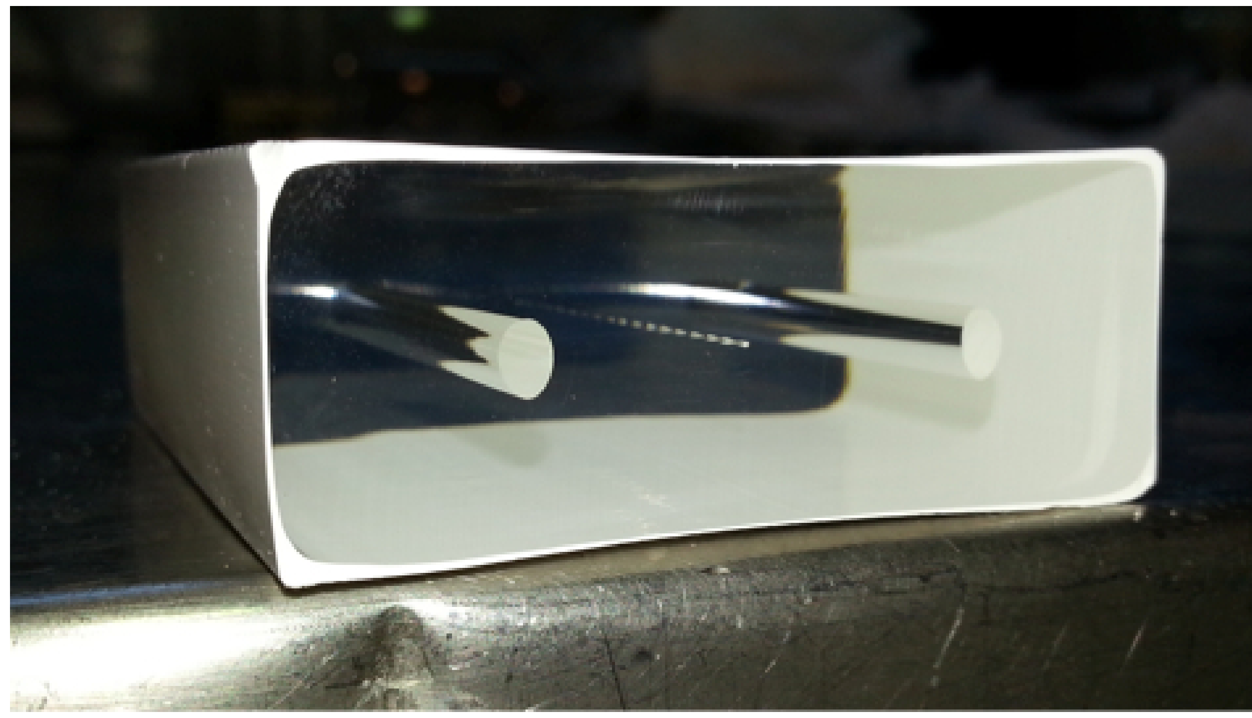
- We have fabricated 4 pilot production modules
- QA test meet the requirements
- Electronics production underway
  - ~30% of the SiPM tested
  - Front-End-Boards will be produced @ Kansas State Univ



First module being vacuum bagged.



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).



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 $\bar{p}$

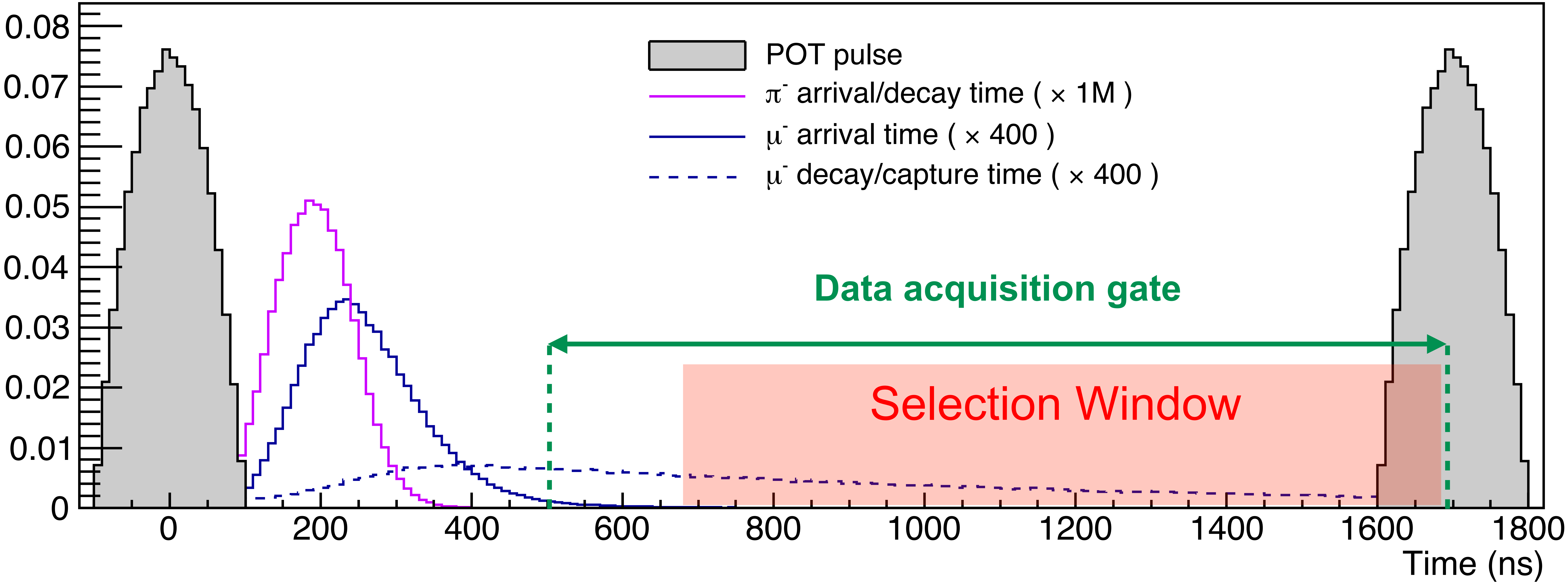
- **Radiative π capture: $\pi^- N_Z \rightarrow N^*_{Z-1}\, \gamma$, asymmetric $\gamma \rightarrow e^- e^+$**

  ✓ 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}**

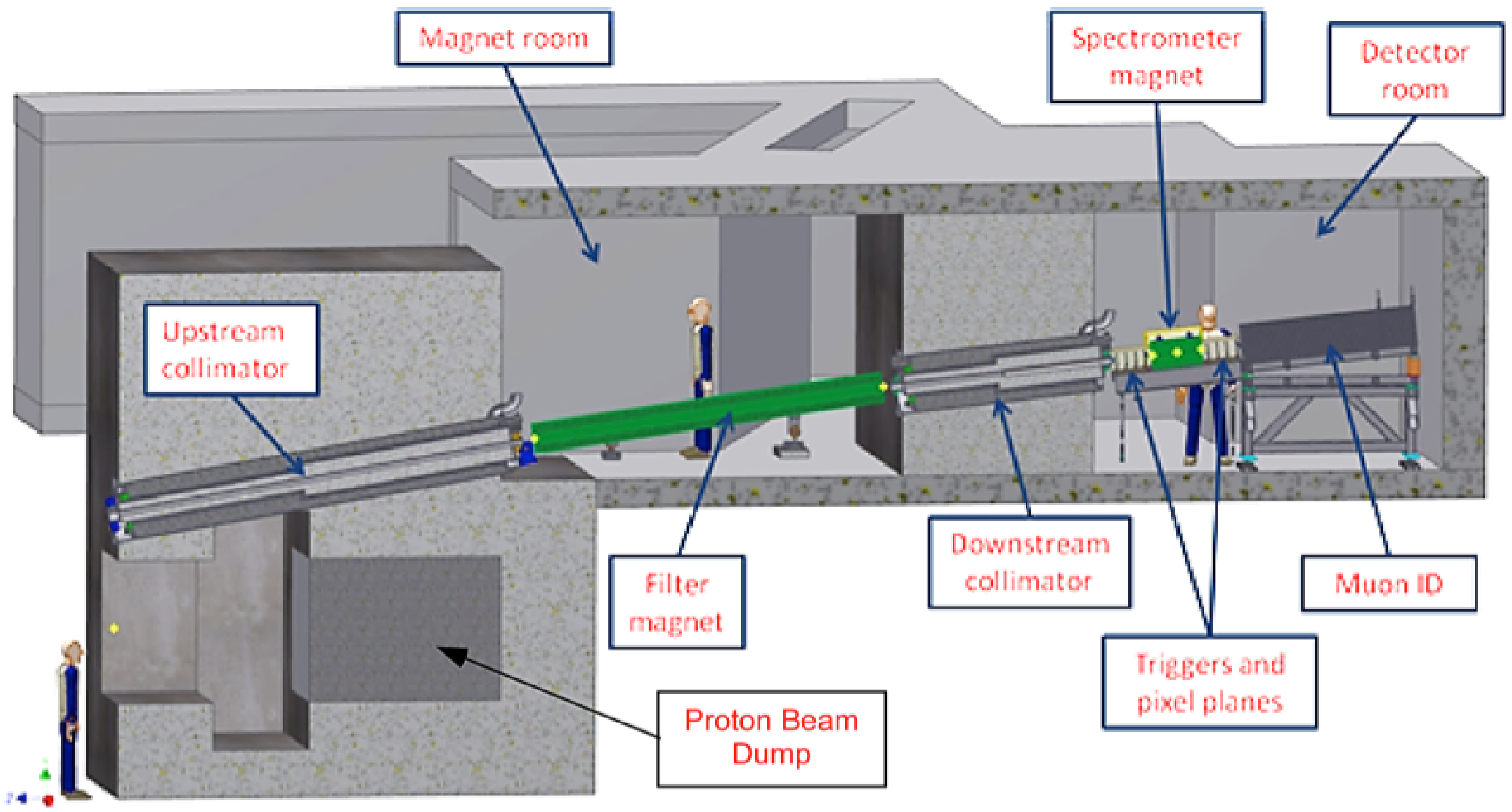
π are suppressed by 11 orders of magnitude before the DAQ window



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

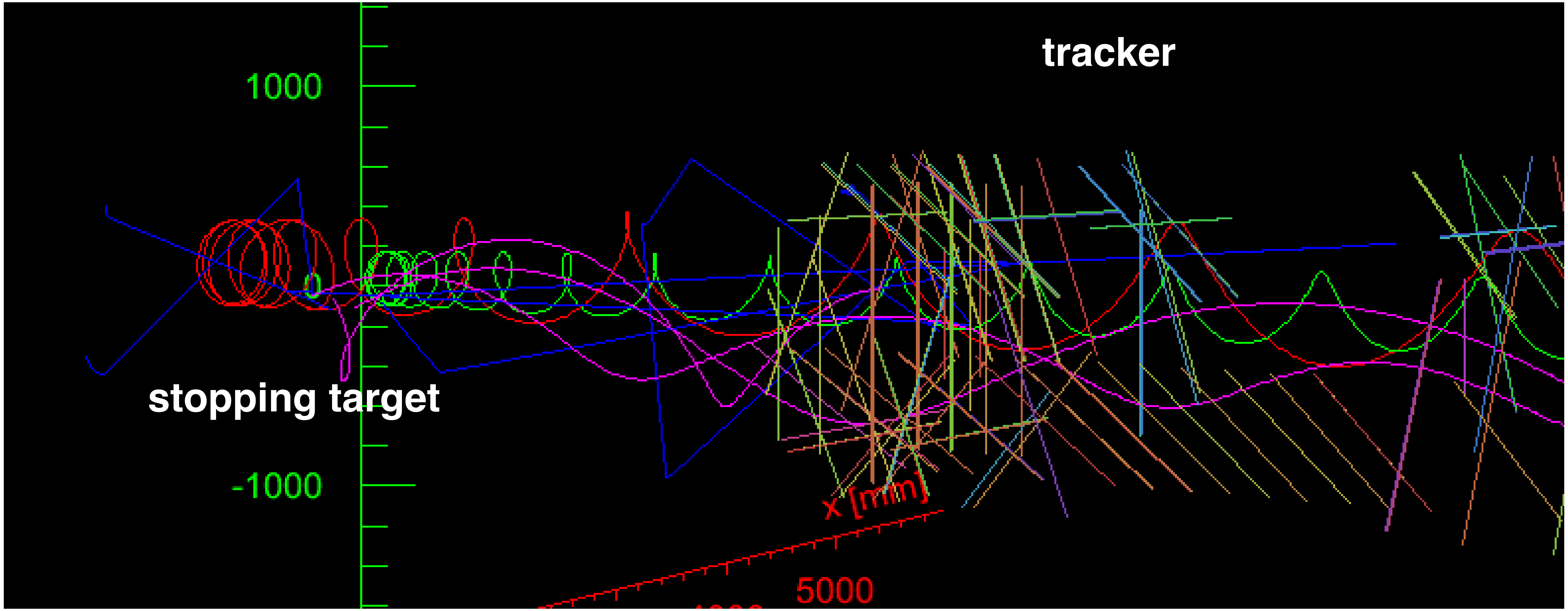
Production Solenoid



Mu2e detectors

Tracker Requirements

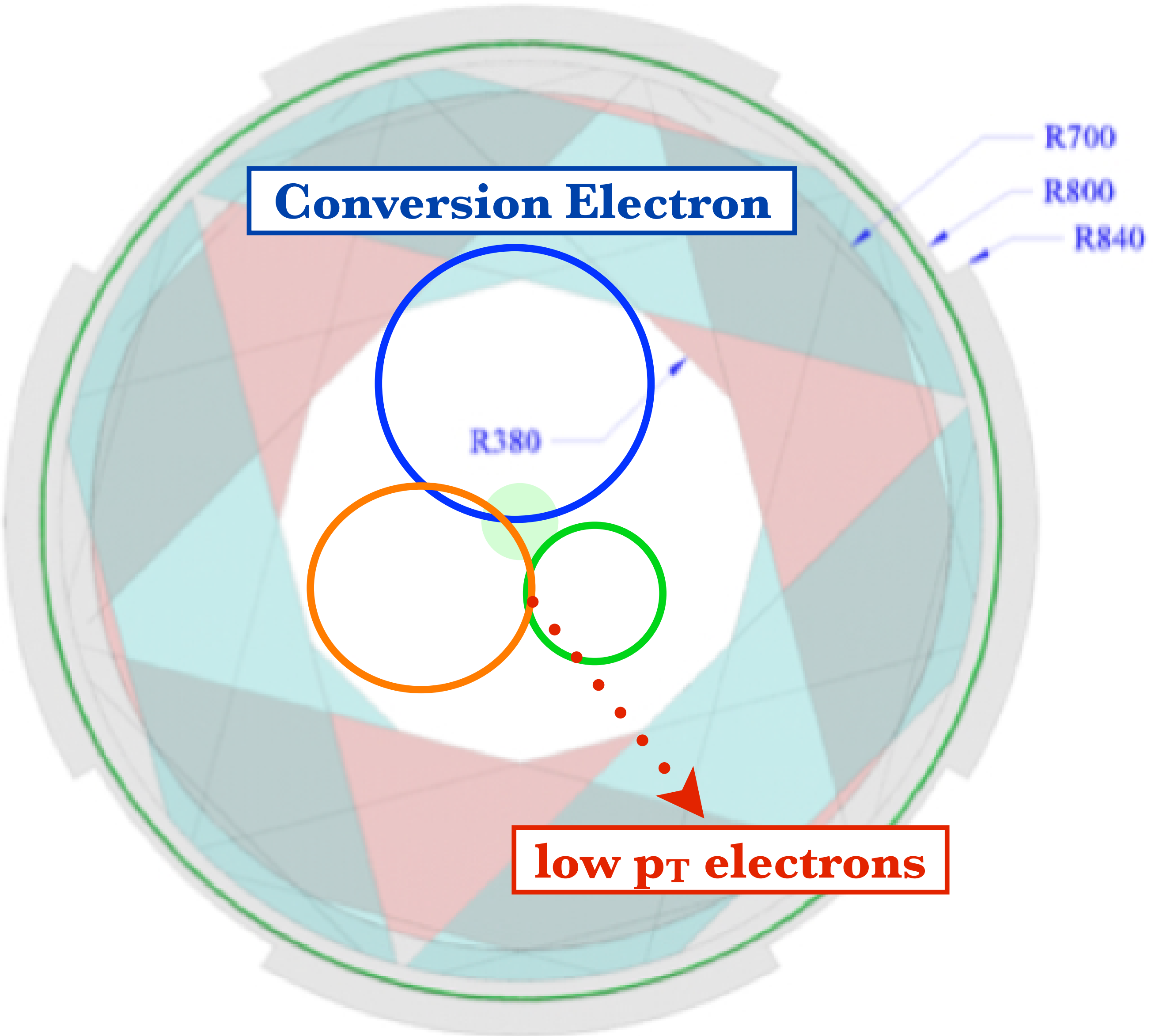
- measure p with resolution < 200 keV/c
- work in 1 T field and 10^{-4} Torr vacuum



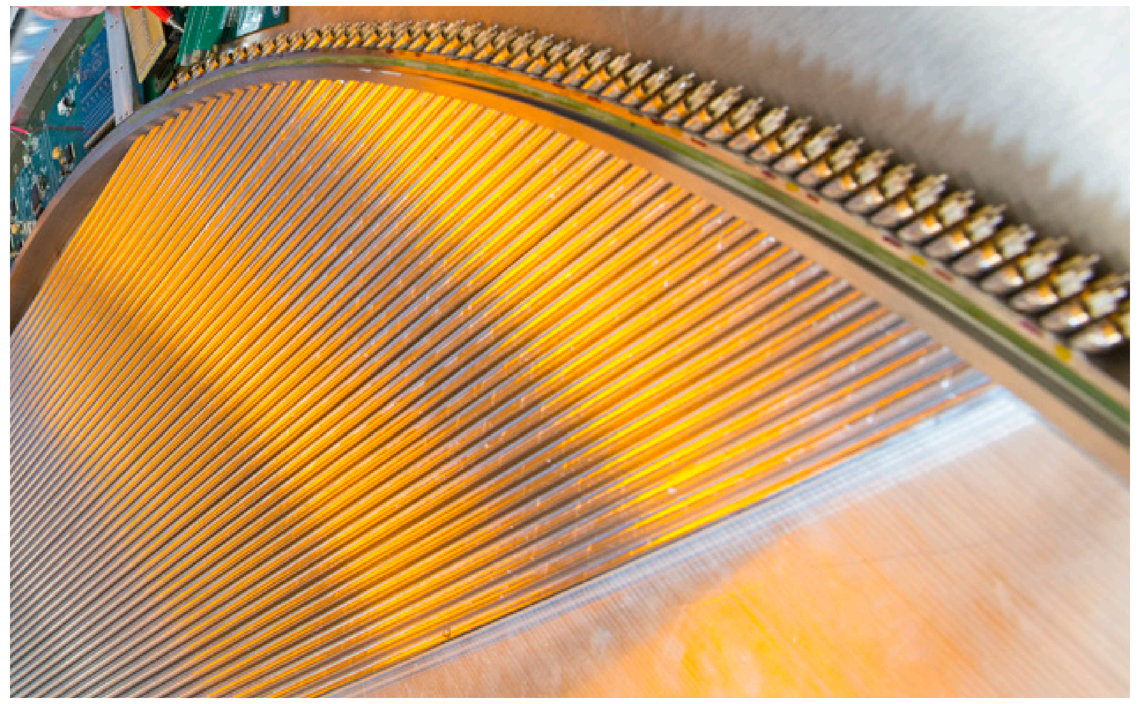
Tracker design

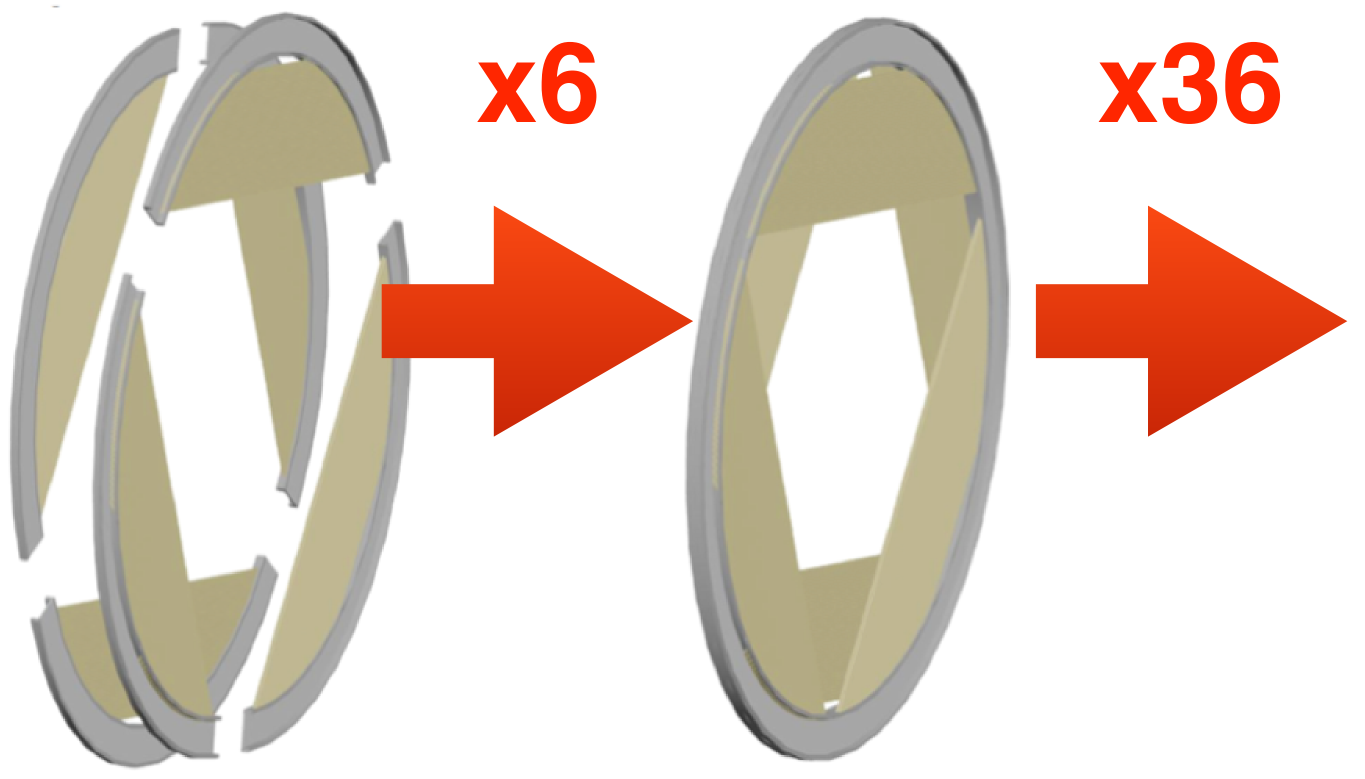
- 36 planes equally spaced with straws transverse to the beam
- Straw technology employed:
  - ✓ 5 mm diameter, 12 μm Mylar walls
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to **low** pT particles, only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

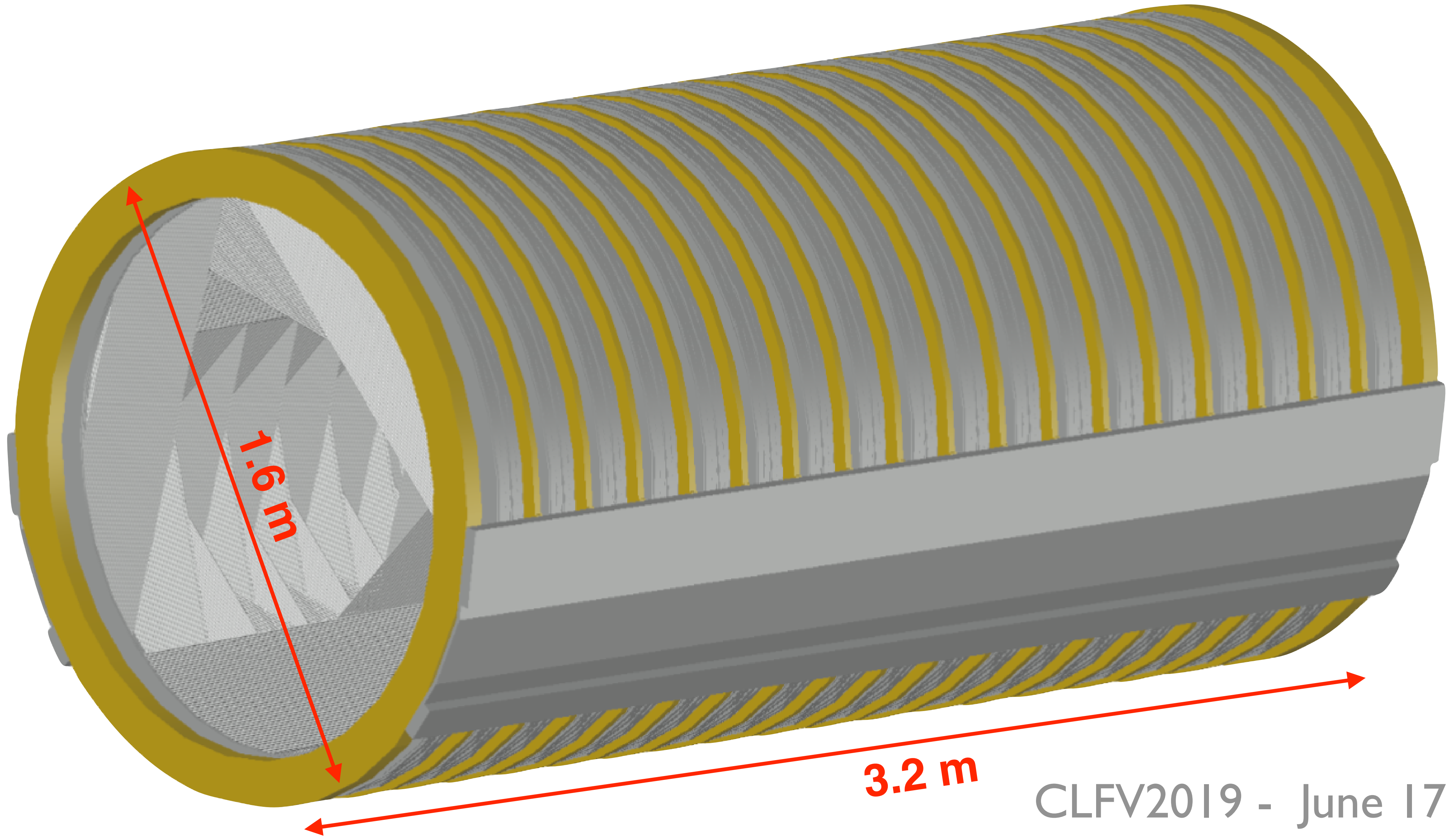
Straw-tube



panel

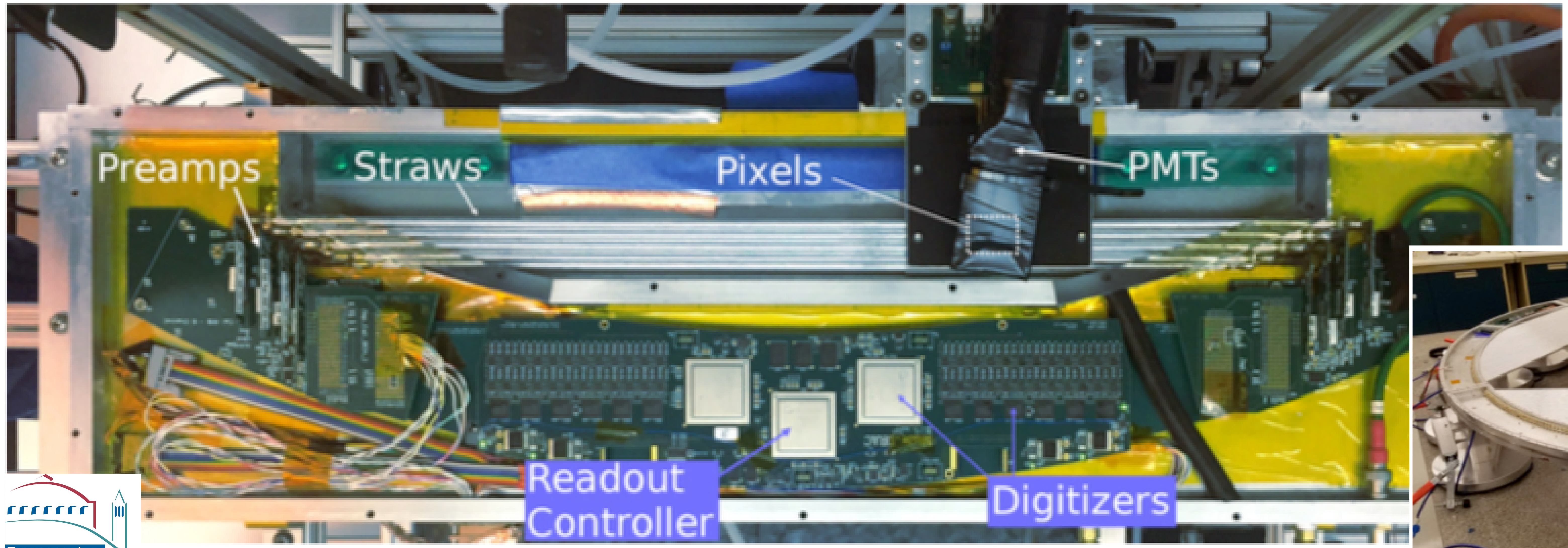




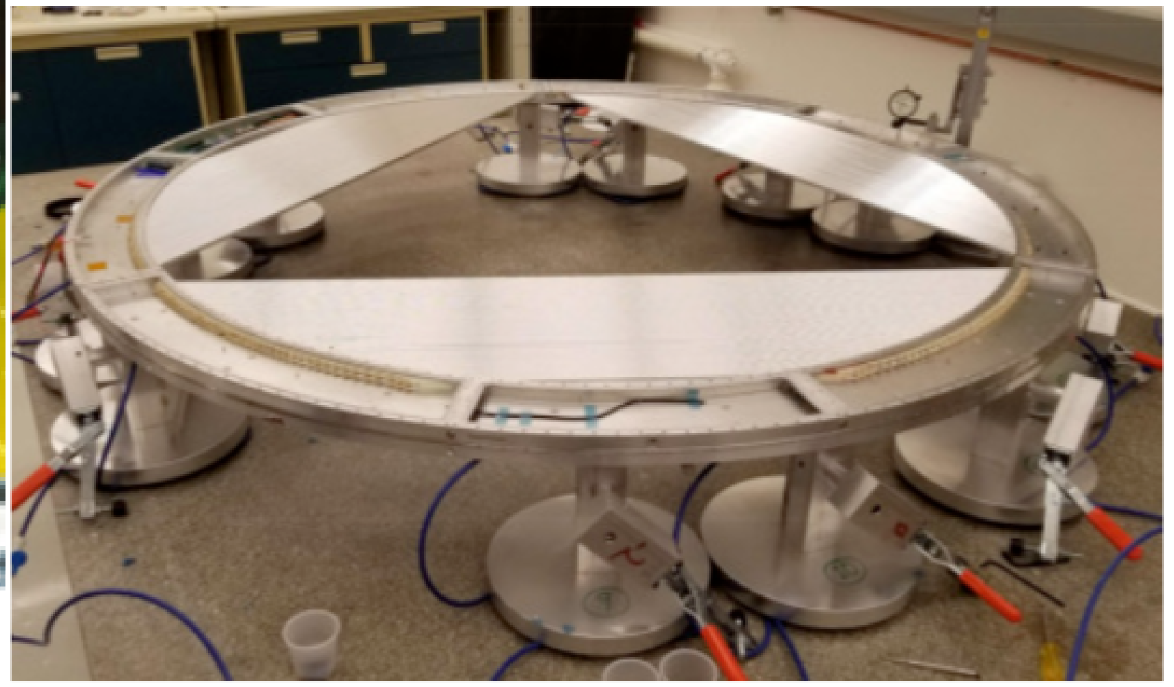


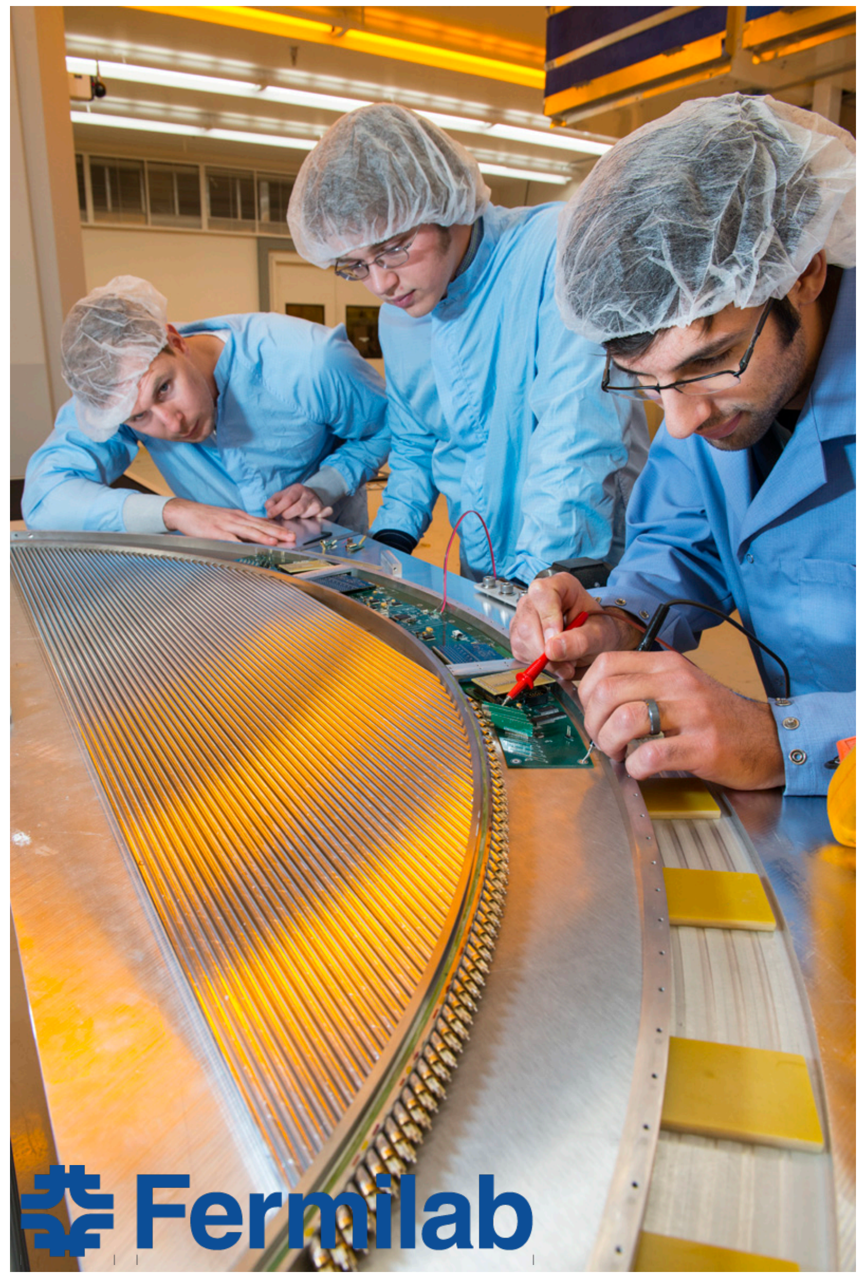
Tracker R&D

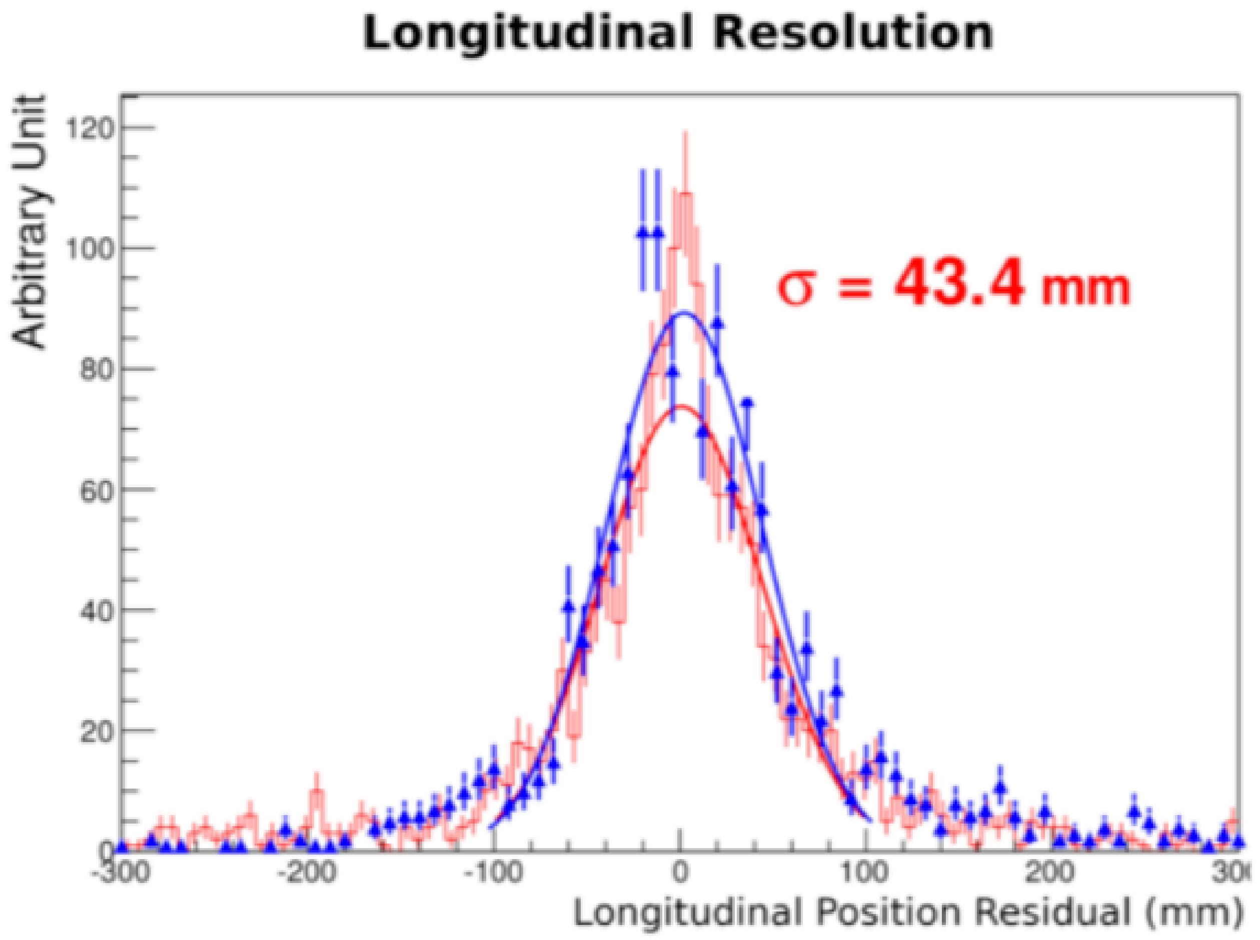
panel prototype

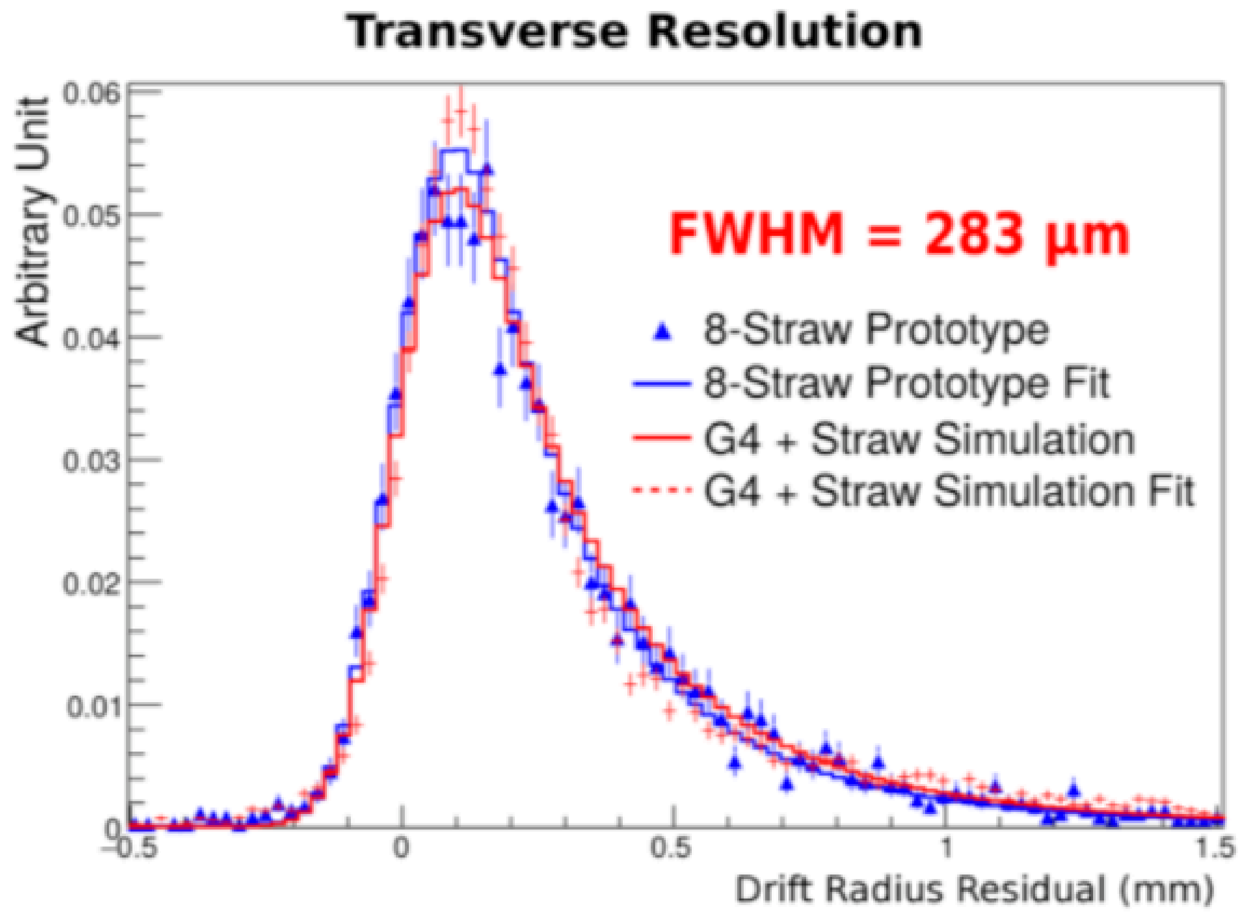


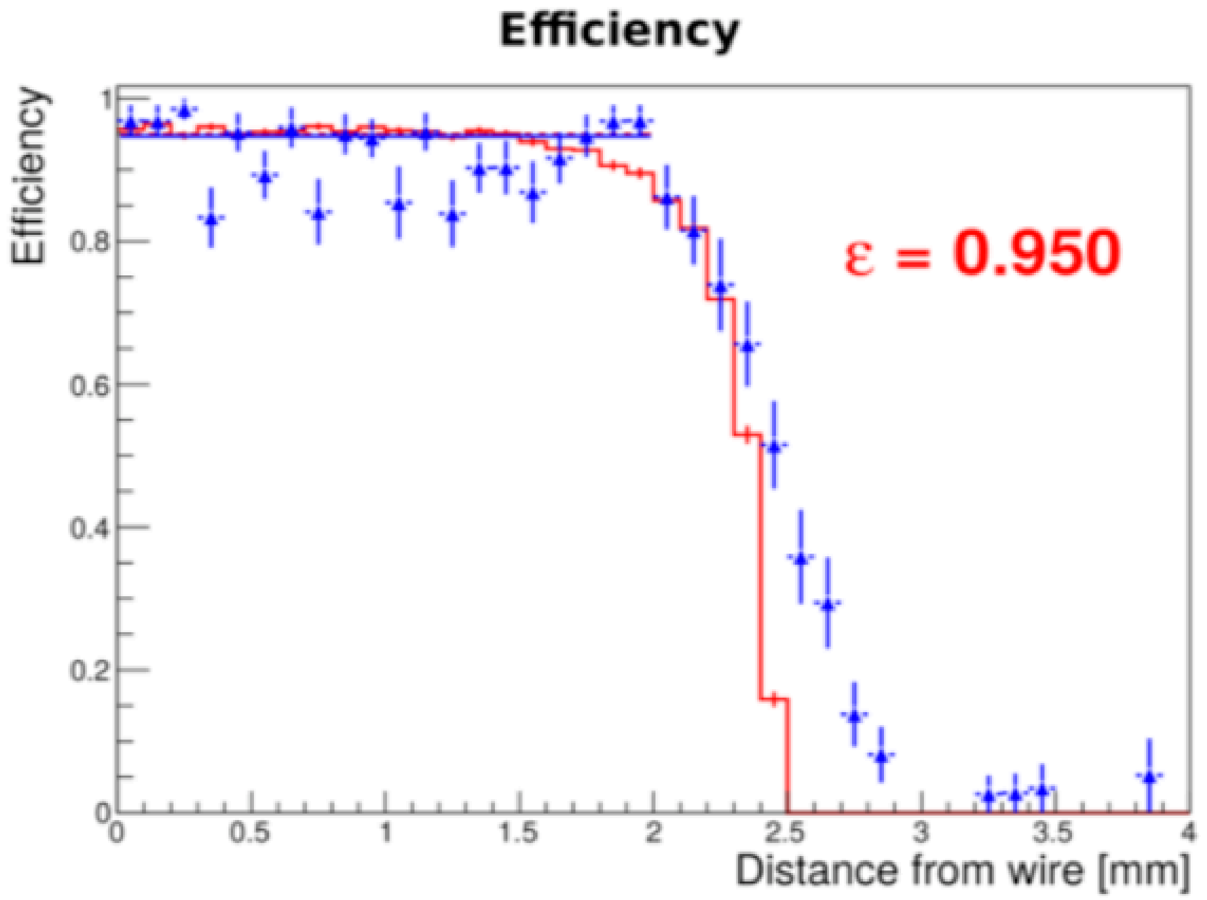
plane







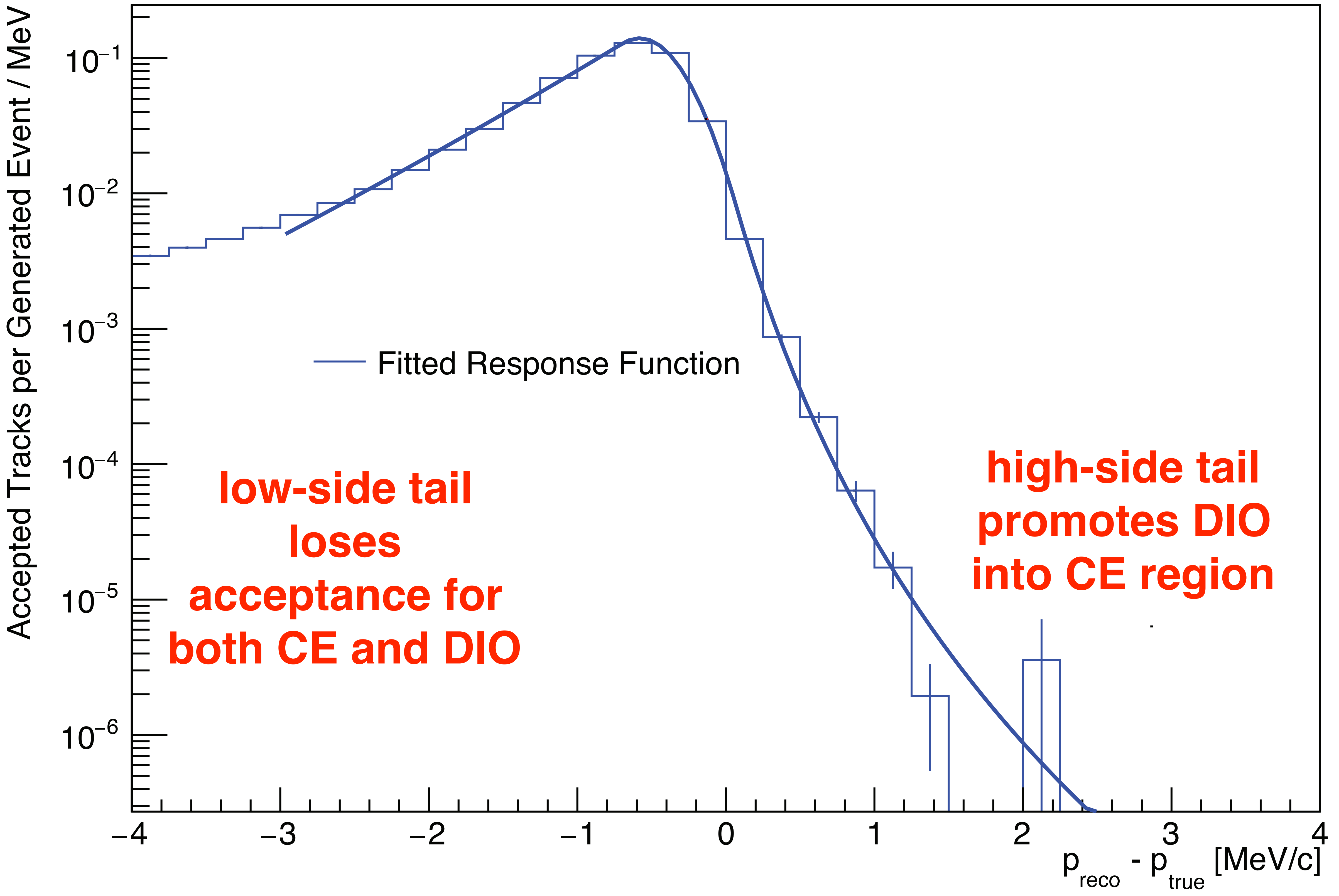




Tracker resolution

- 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

peak is below zero because of energy loss in the stopping target region



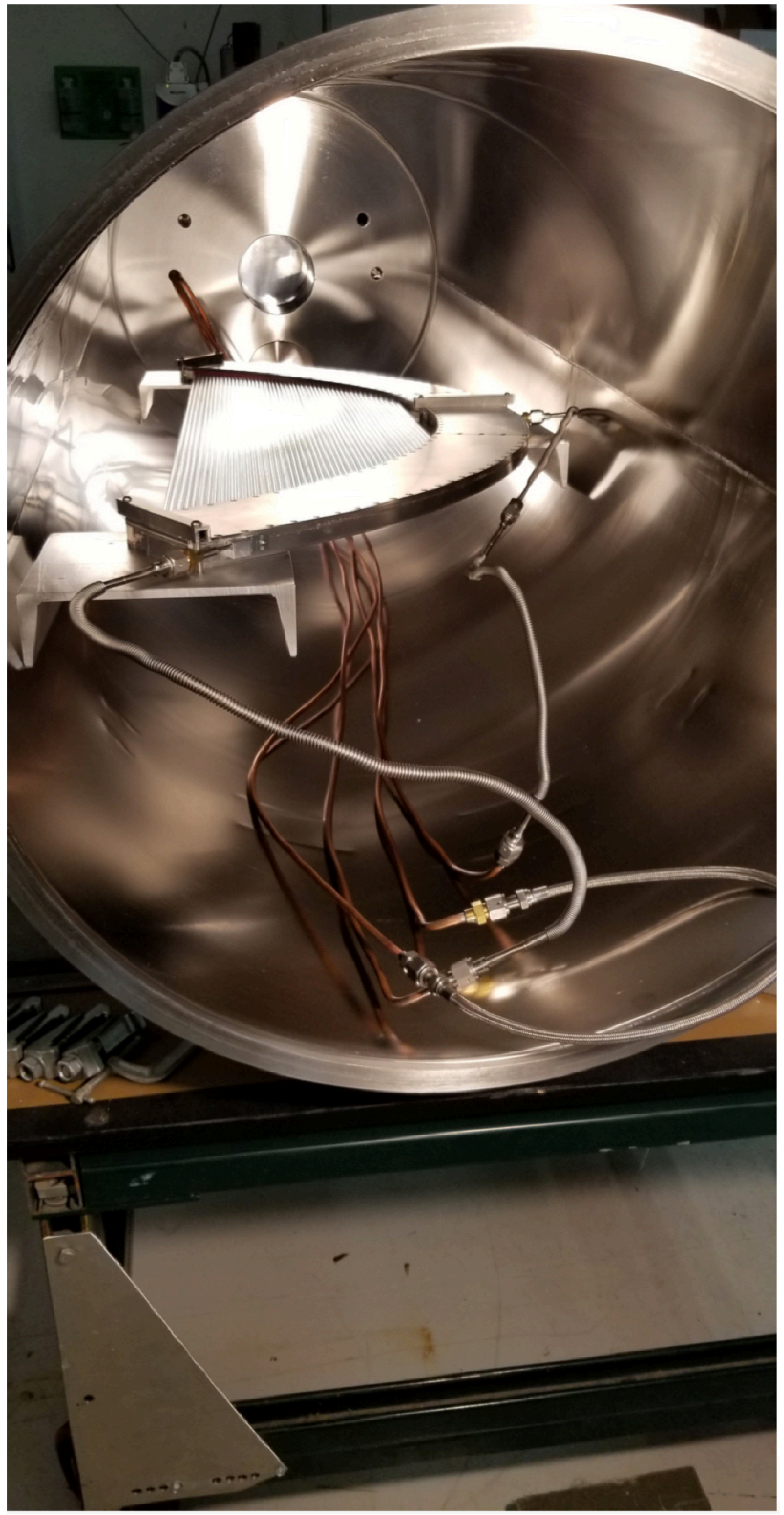
reconstructed - true momentum [MeV/c]

Tracker construction

- 12 pre-production under construction (10 out of 12 already done)
  ✓ useful step for doing final mech optimization
- preparing for a beam test @ Fermilab in the fall

panel assembly & test @ Univ of Minnesota

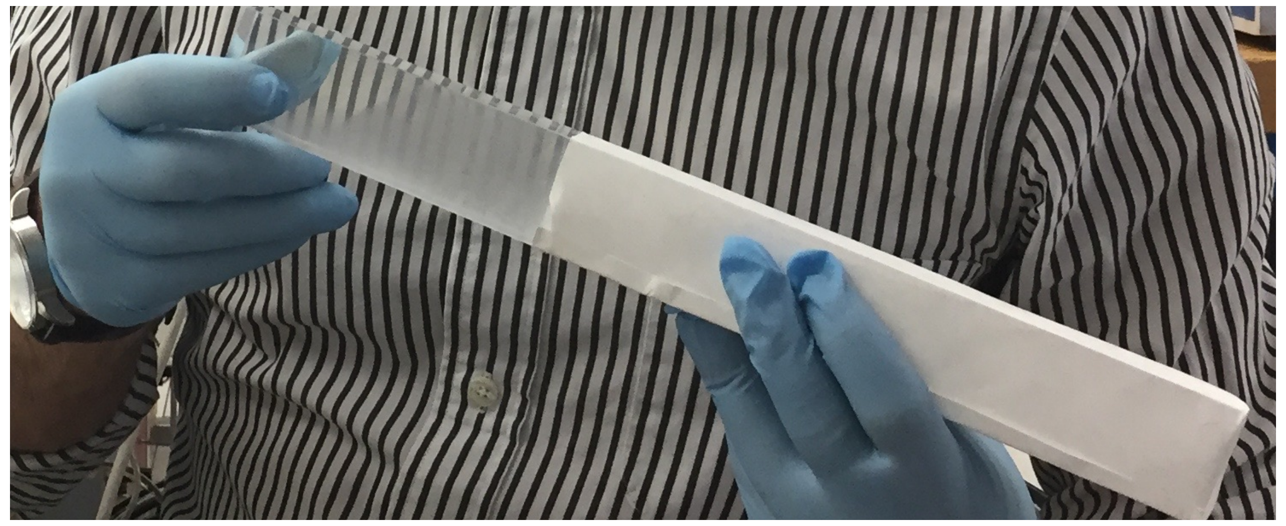
vacuum test @ Fermilab



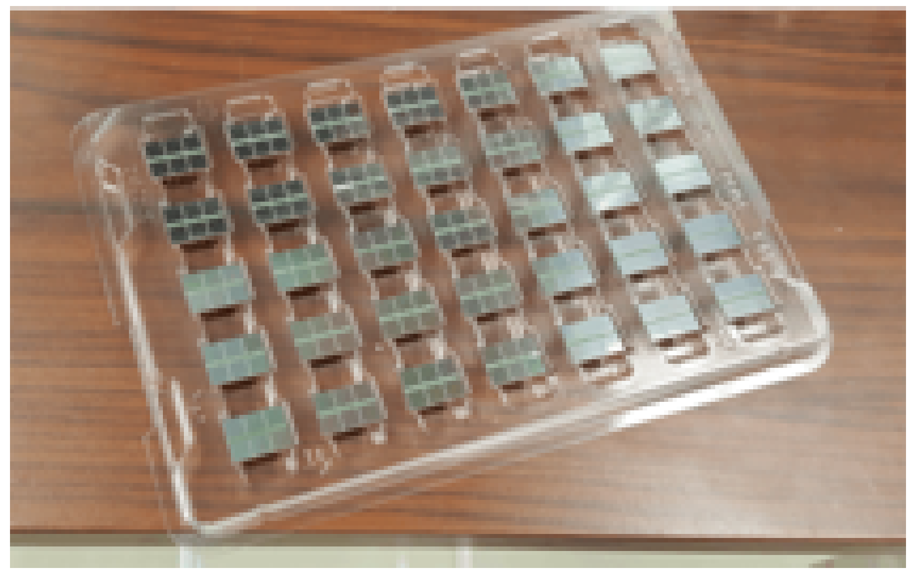
Calorimeter design

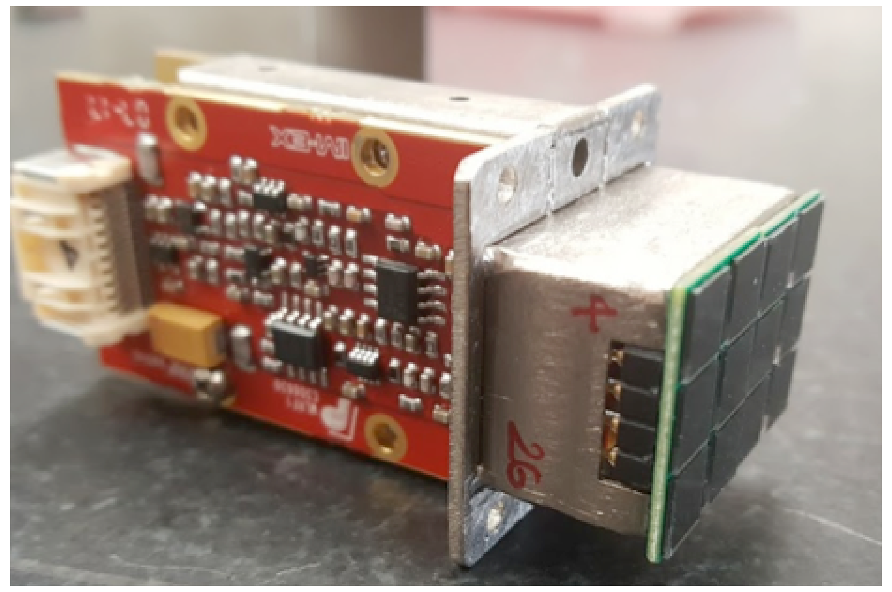
- 2 disks; each disk contains 930 undoped CsI crystals 20 x 3.3 x 3.3 cm^3
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- Readout system:
  - ➡ 2 large area SiPM-array/crystal
  - ➡ 12 bit, 200 MHz waveform-based digitizer boards

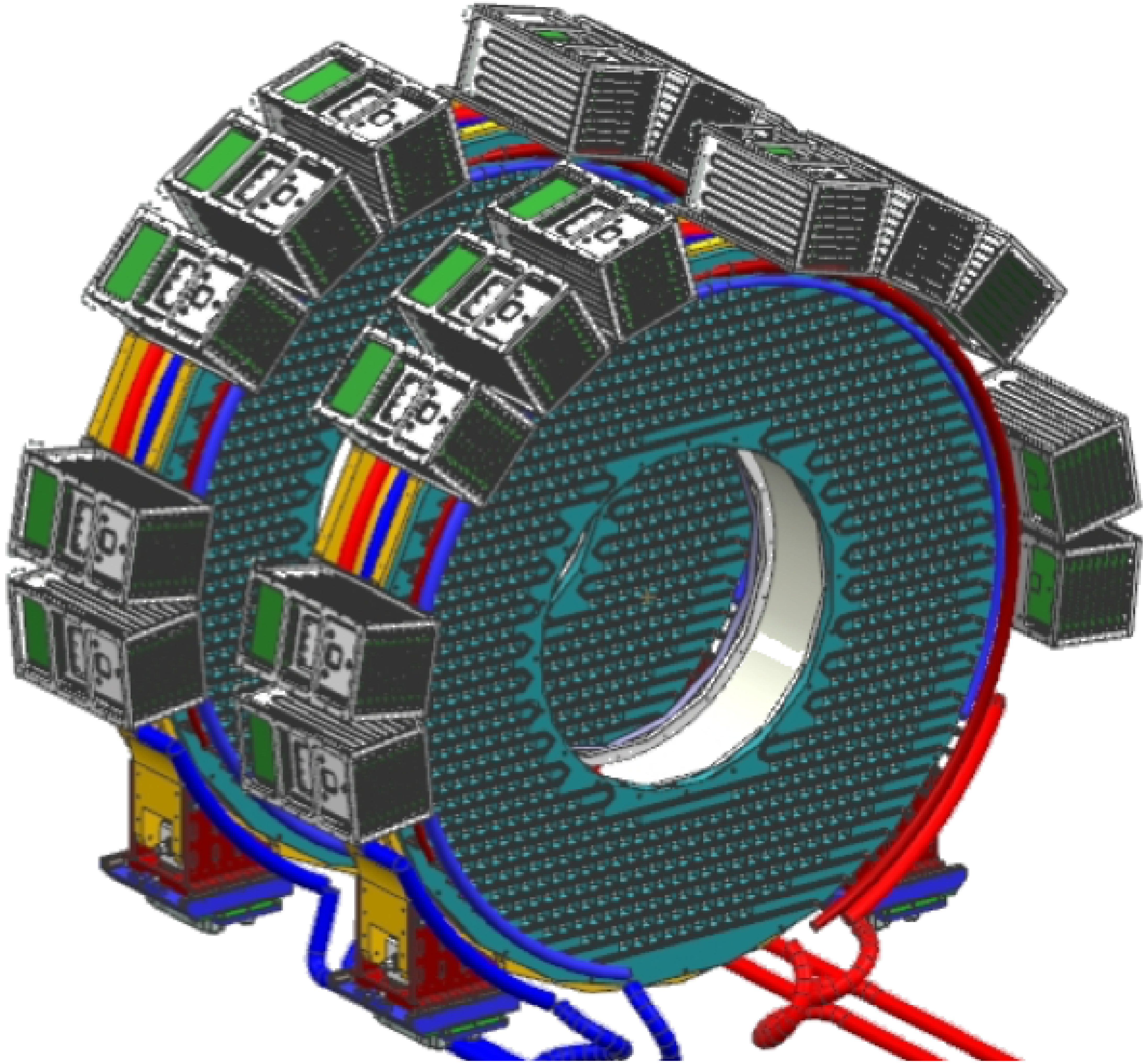
undoped CsI



SiPM array

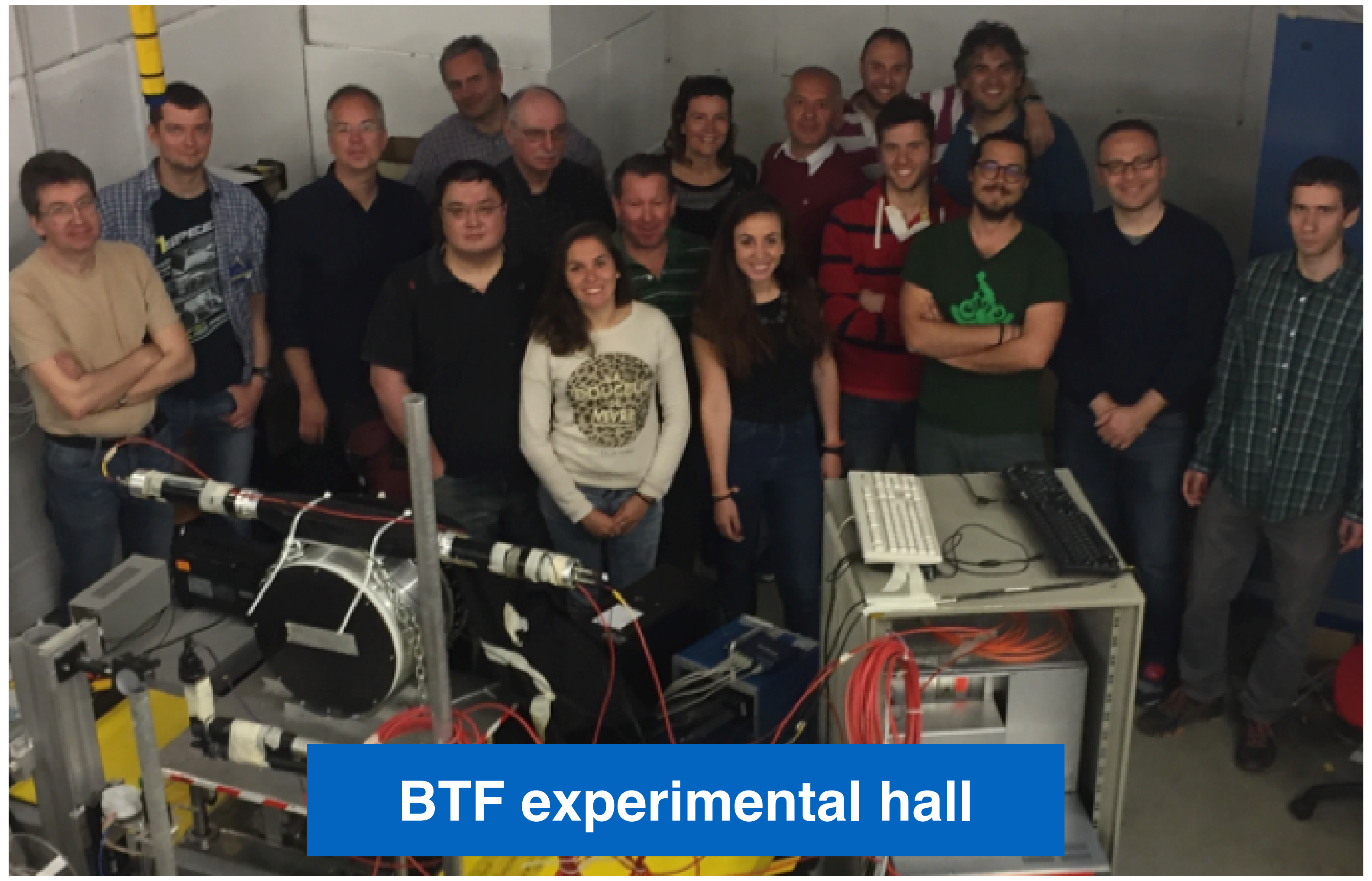


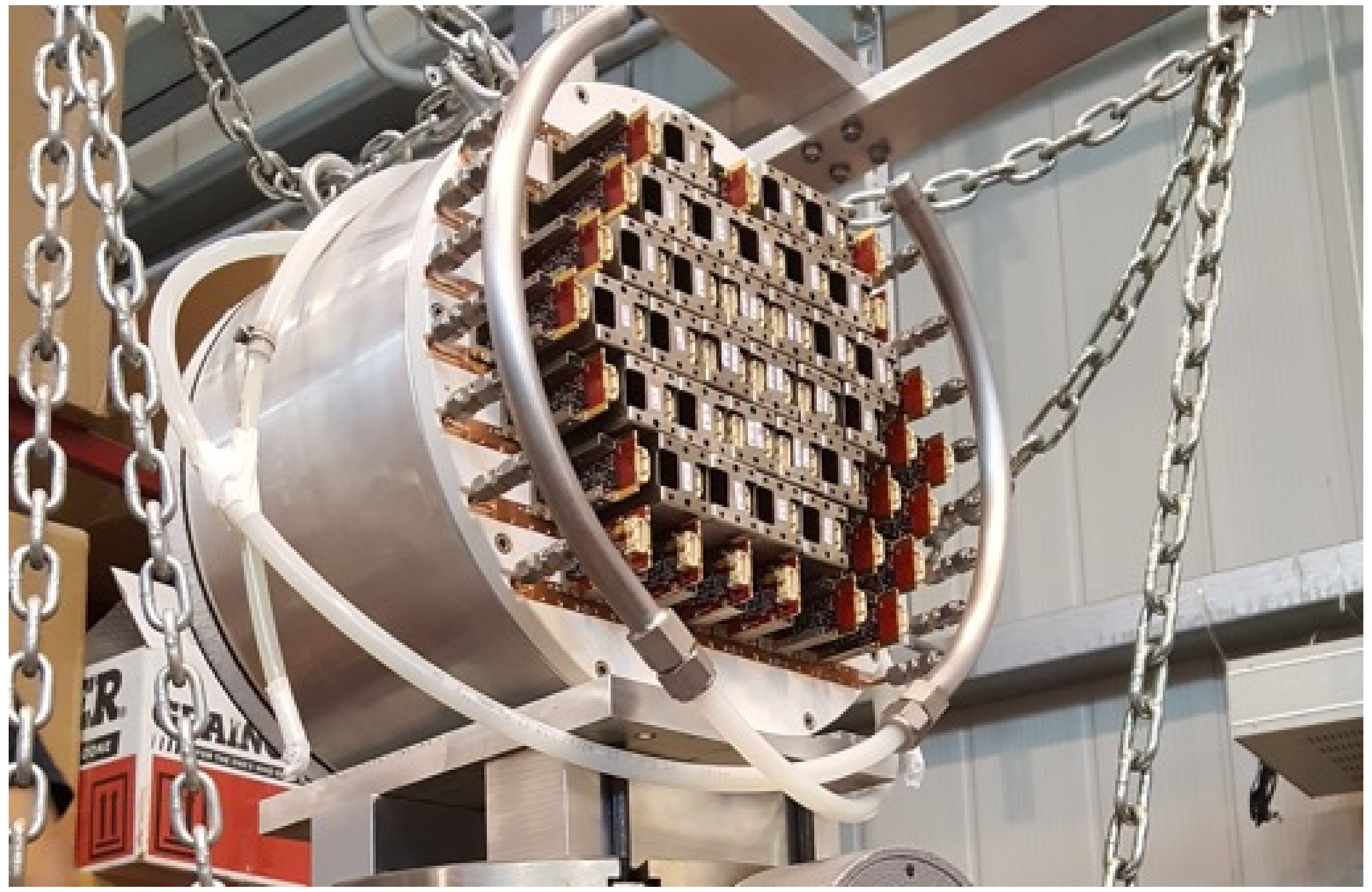


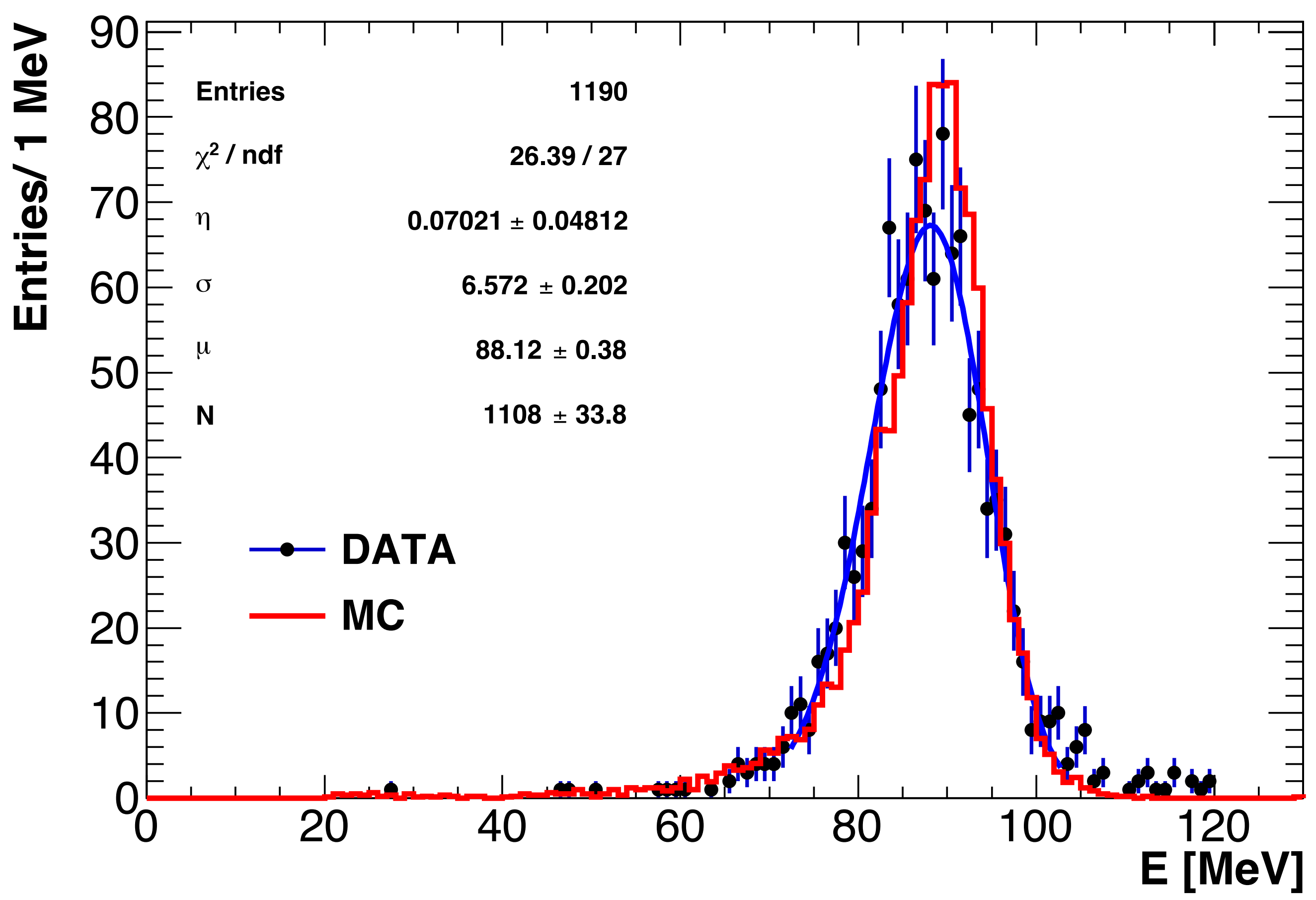


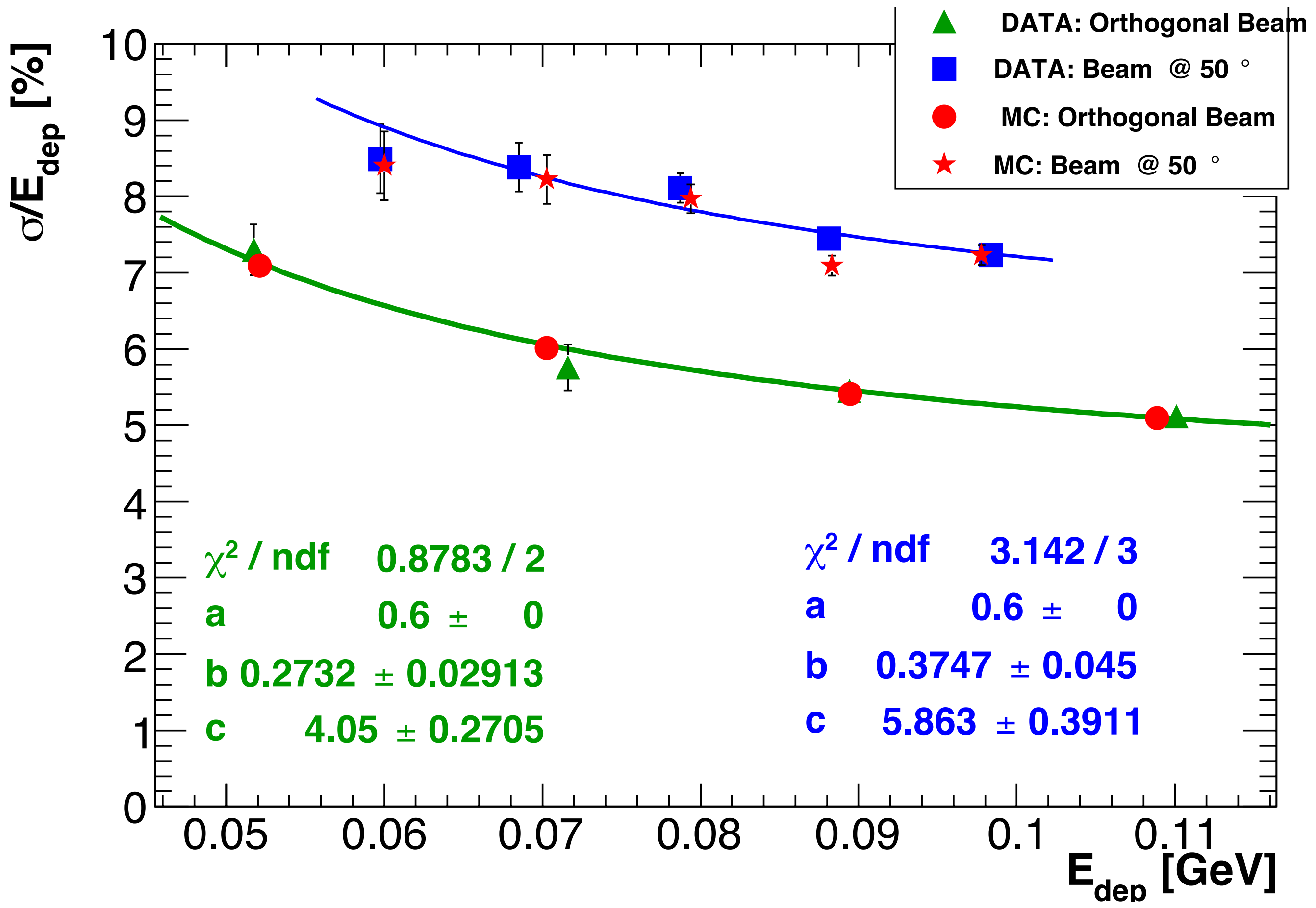
Calorimeter R&D

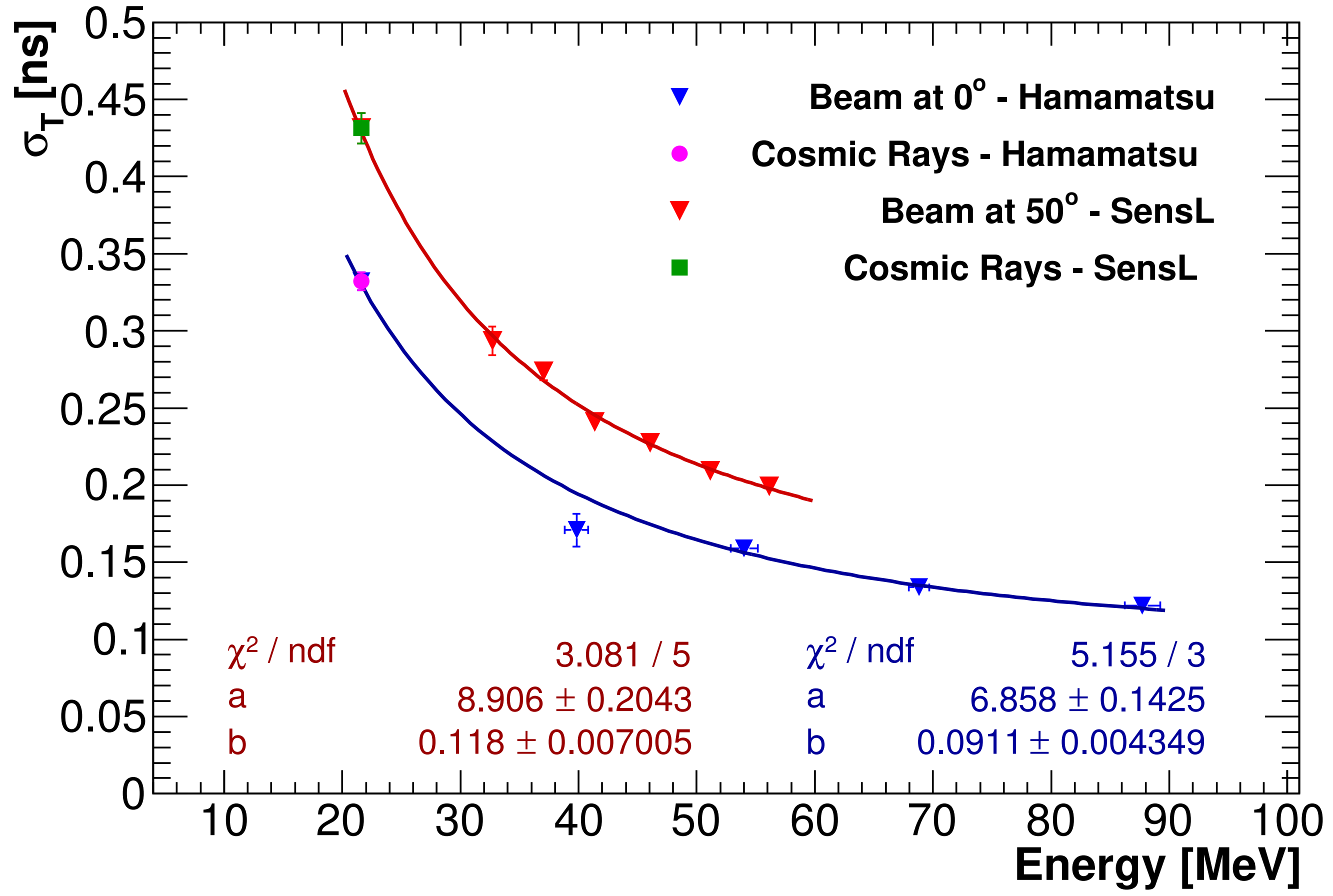
- Large prototype: 51crystals + 102 SiPM + 102 FEE boards
- Beam test successfully performed @ BTF in Frascati using e$^-$ beam







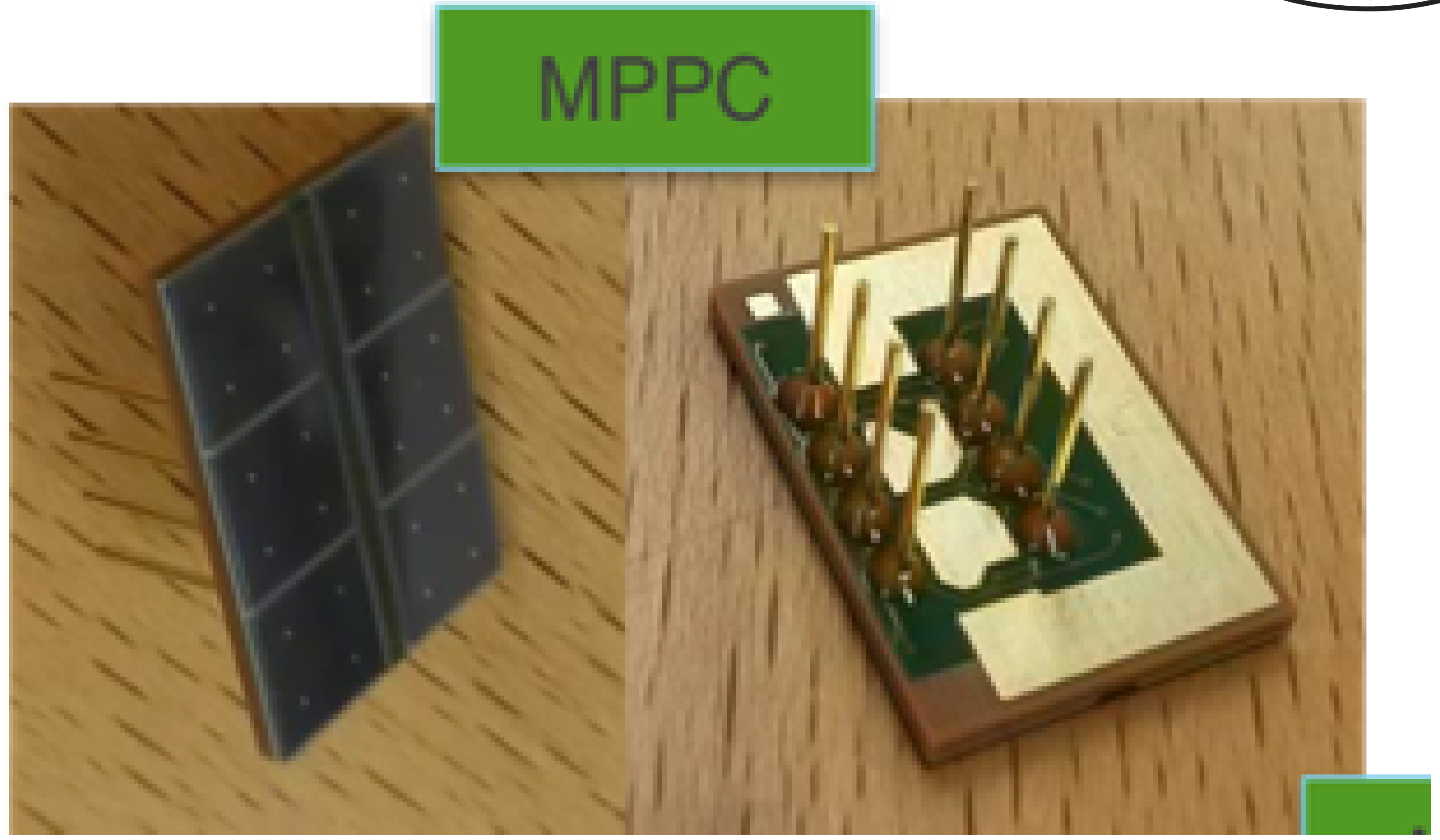




Electronics procurement

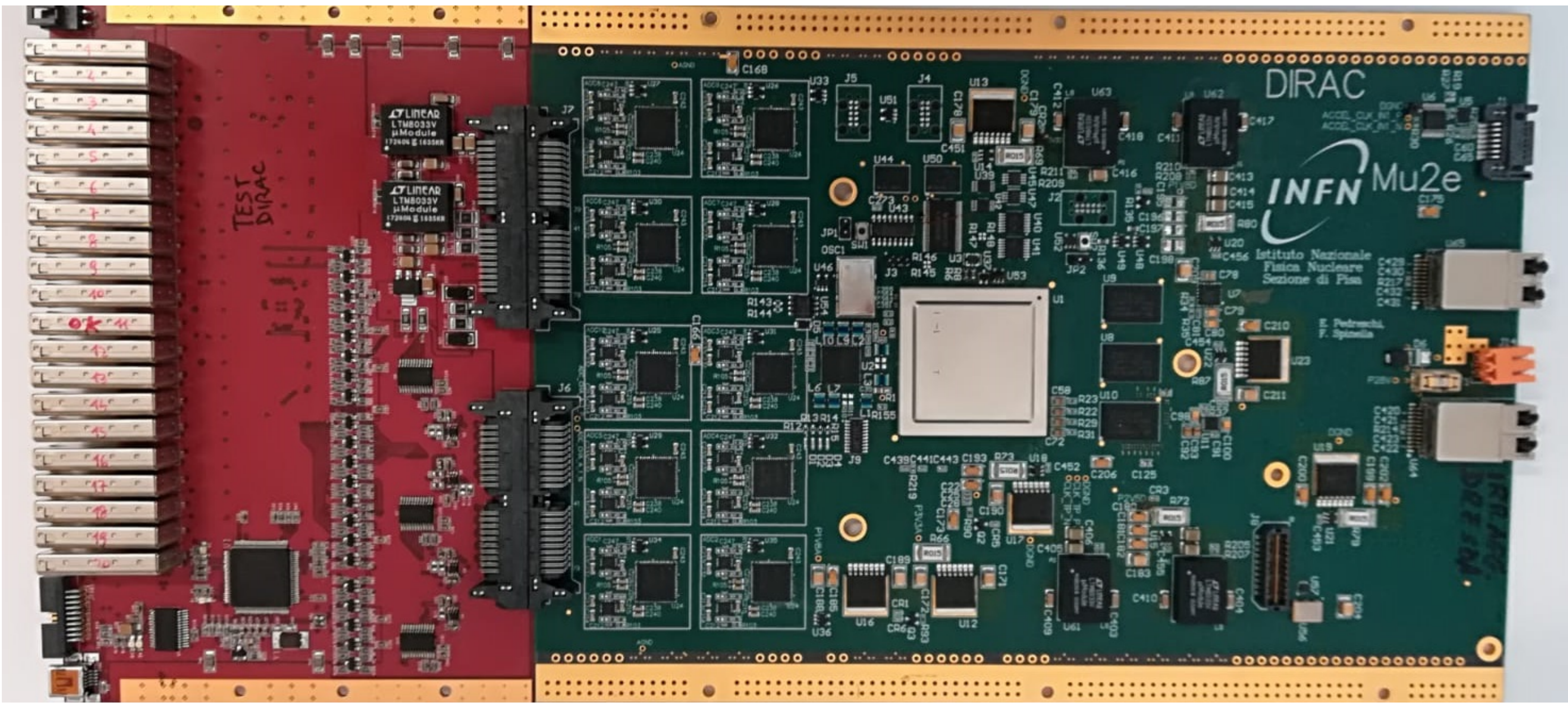
Photosensors

- 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

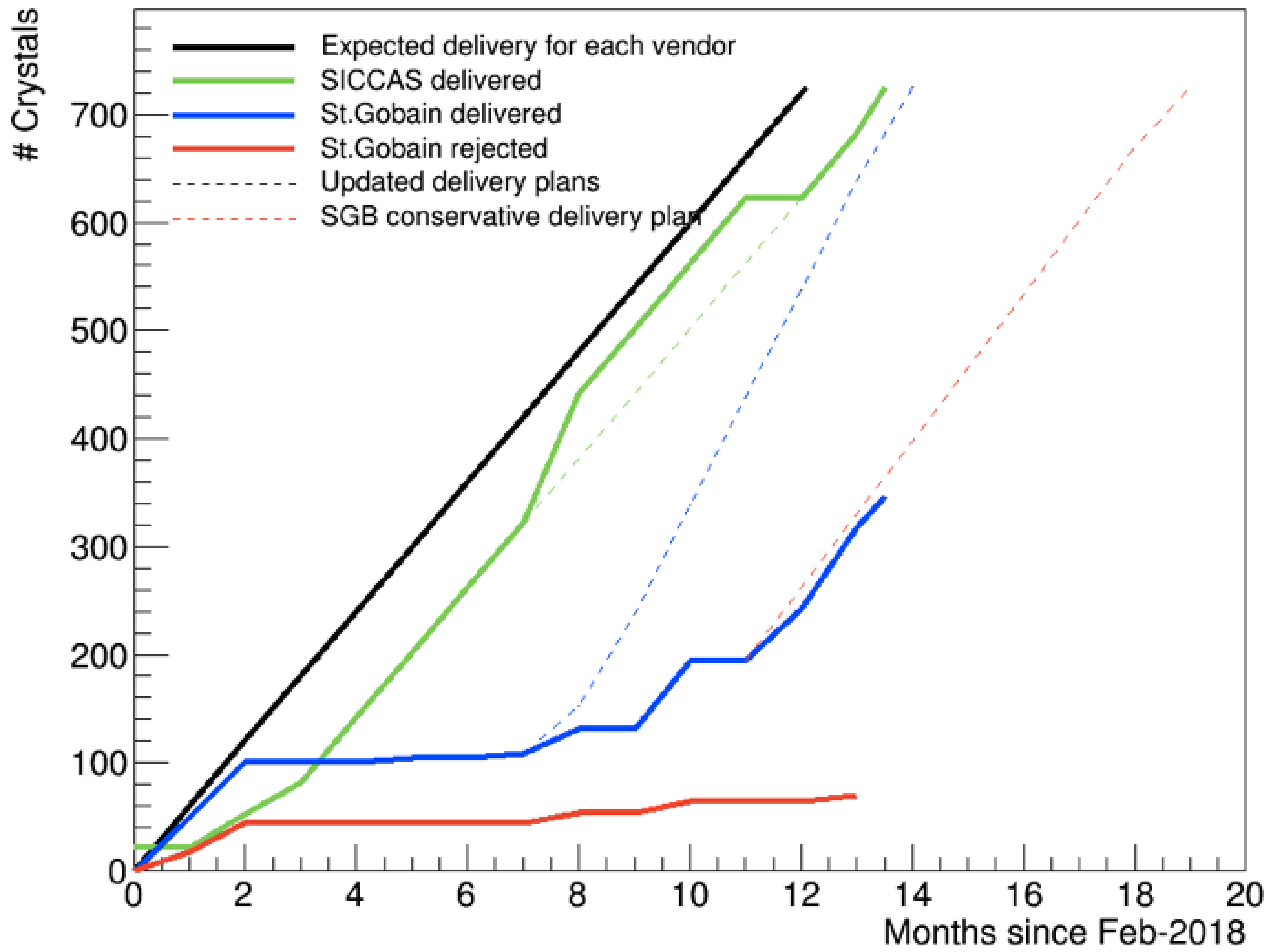
- Slice test of the whole electronics chain completed
- board design being upgraded to include rad-hard components
  - ➡ FPGA -> PolarFire, from Microsemi
  - ➡ DCDC converter -> LTM-8053
  - ➡ Optical transceiver -> VTRx from CERN



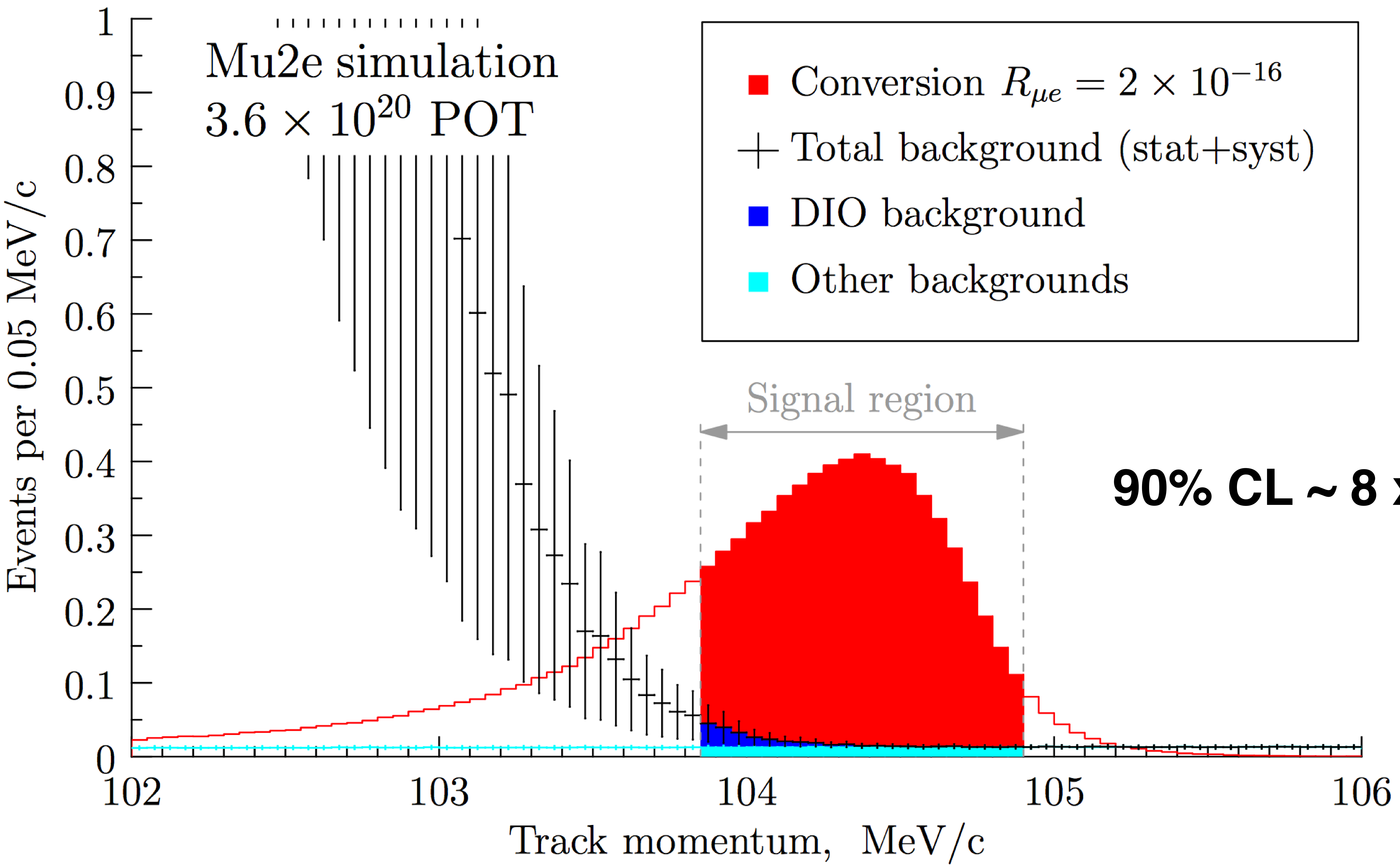
Crystal procurement

- Two separate vendors used:
  - SICCAS
  - St. Gobain
- **SICCAS** delivered 725/725 crystals with a small rejection factor (~4%)
- **St. Gobain** reached a stable point. Expected delivery end on October 2019

	SICCAS	St.Gobain	Total
Arrived	725+13	347	1085
CMM + inspection	725+13	242	980
Sent to Caltech	214	73	287
Back to Vendor	13	44	57
Irradiation at Caltech	10	2	12

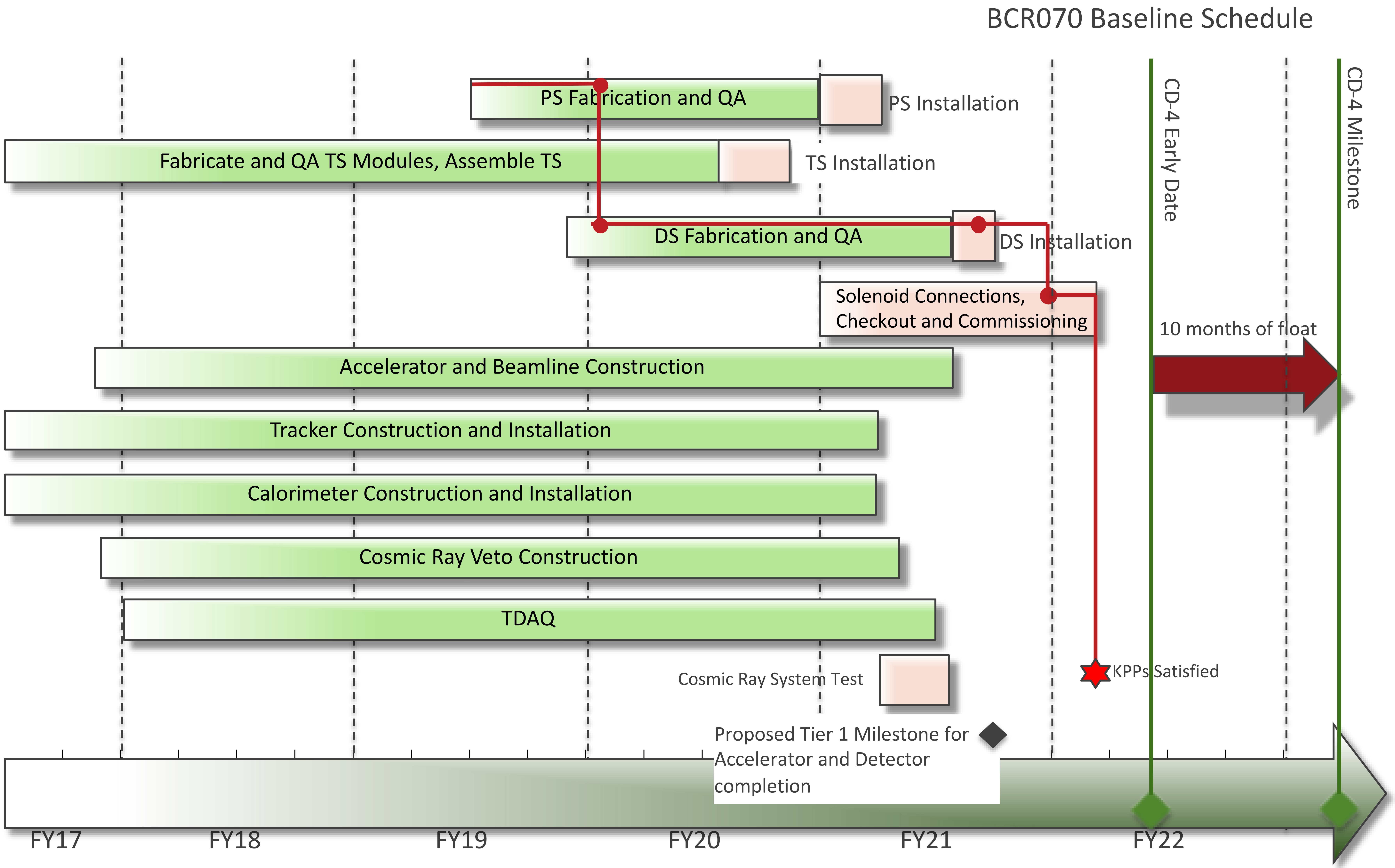


Mu2e sensitivity



90% CL ~ 8 x 10-17

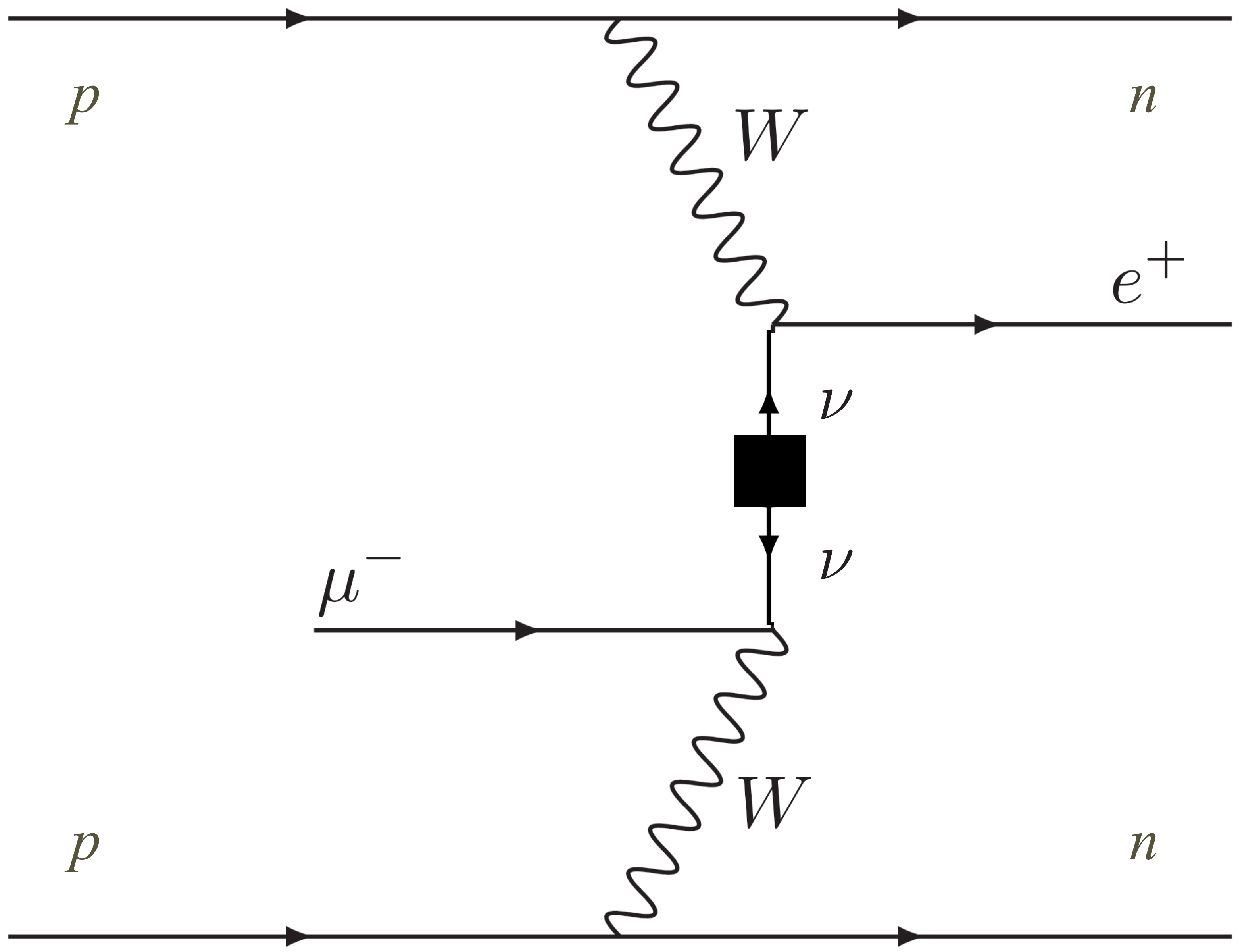
Mu2e Schedule



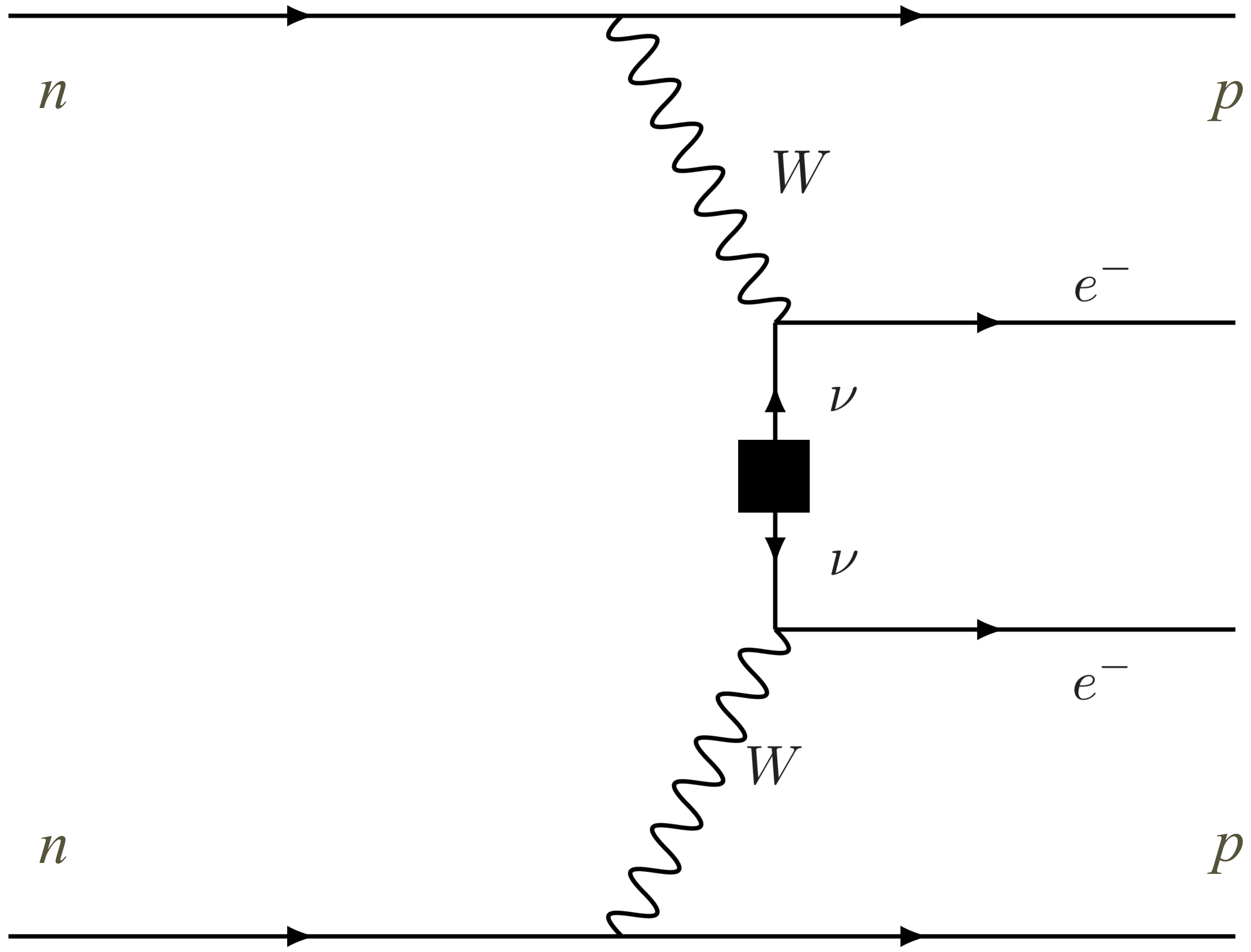
$\mu^- N \to e^+ N^*$ conversion search

- While 0νββ has the greatest sensitivity to new ultraviolet energy scales, its rate might be suppressed by the new physics relationship to lepton flavor
  ✓ $\mu^- \to e^+$ conversion offers a complementary probe of lepton-number-violating physics

μ^- N→e⁺ N*



0νββ decay



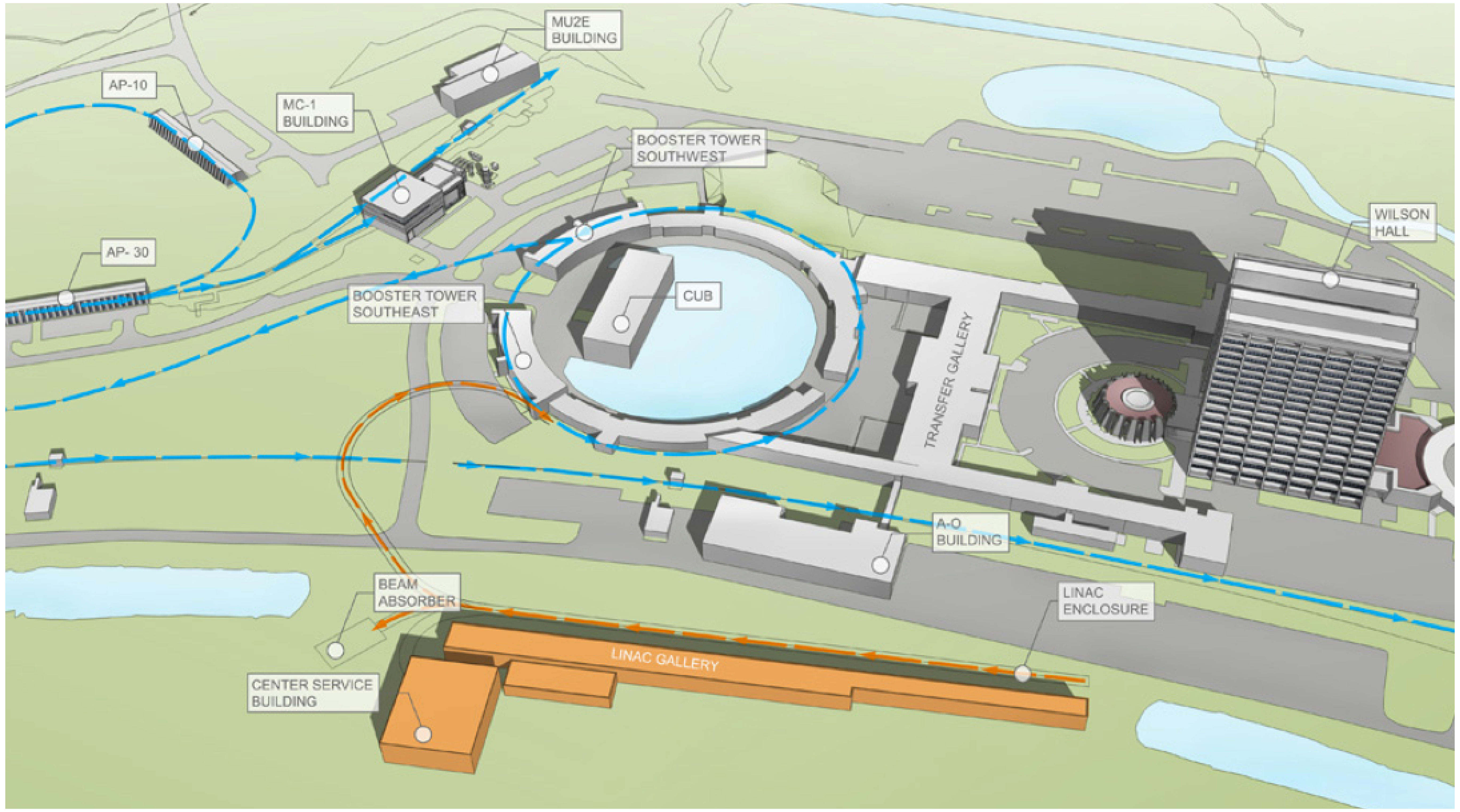
- Useful references: Phys. Rev. D 95.115010, arxiv-161.00032, arxiv-1705.07464, arxiv-1609.09088

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 $\mu^- N \to e^\pm N$, $\mu \to e\,\gamma$, $\mu \to 3e$, $\mu^- e^- \to e^- e^-$ at one facility



Summary

- Mu2e will improve the sensitivity by four orders of magnitude
- Provides discovery capabilities over a wide range of theories BSM
- R&D mature with detectors under construction
- **commissioning expected in 2022**
- **More info:** http://mu2e.fnal.gov

backup slides

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

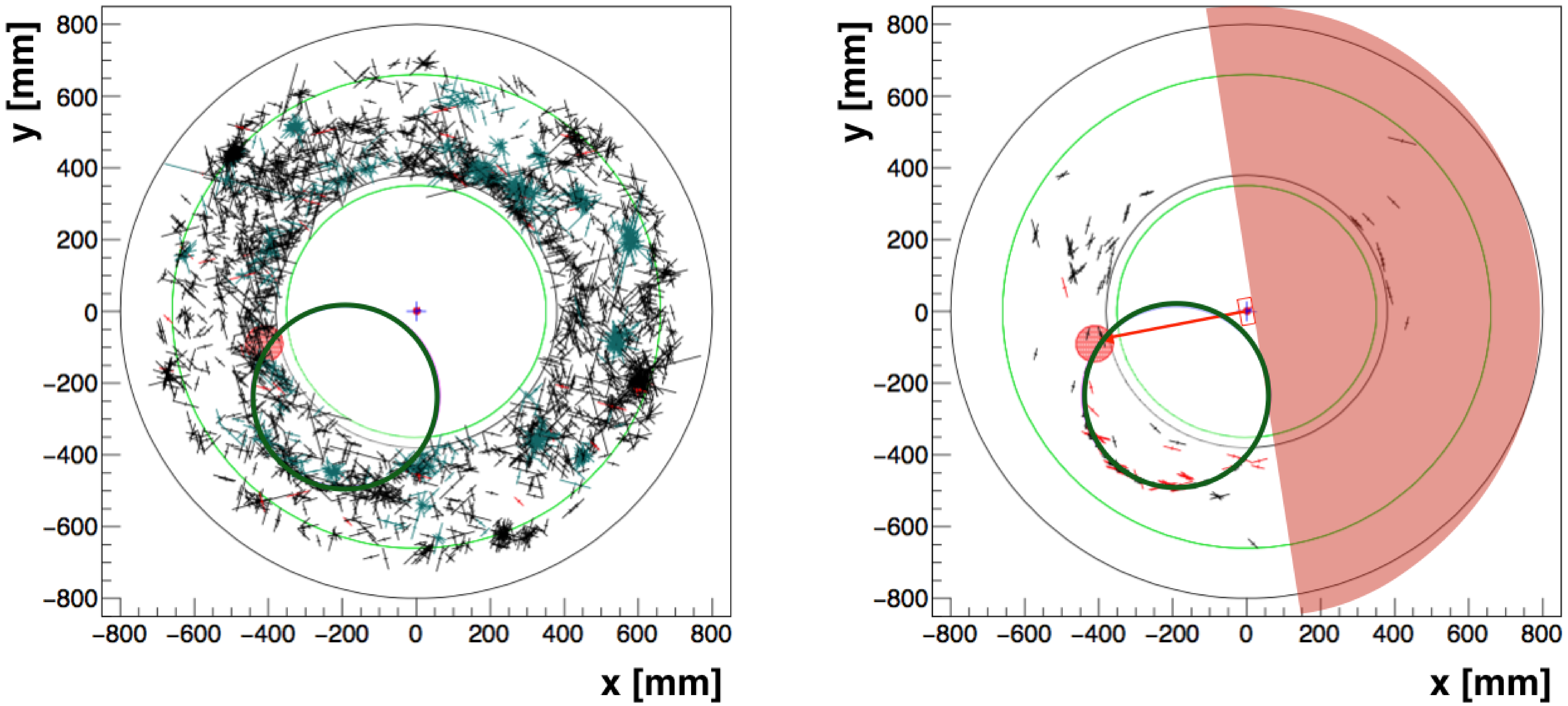
Track reconstruction

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

no selection **calorimeter selection**



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

Trigger system

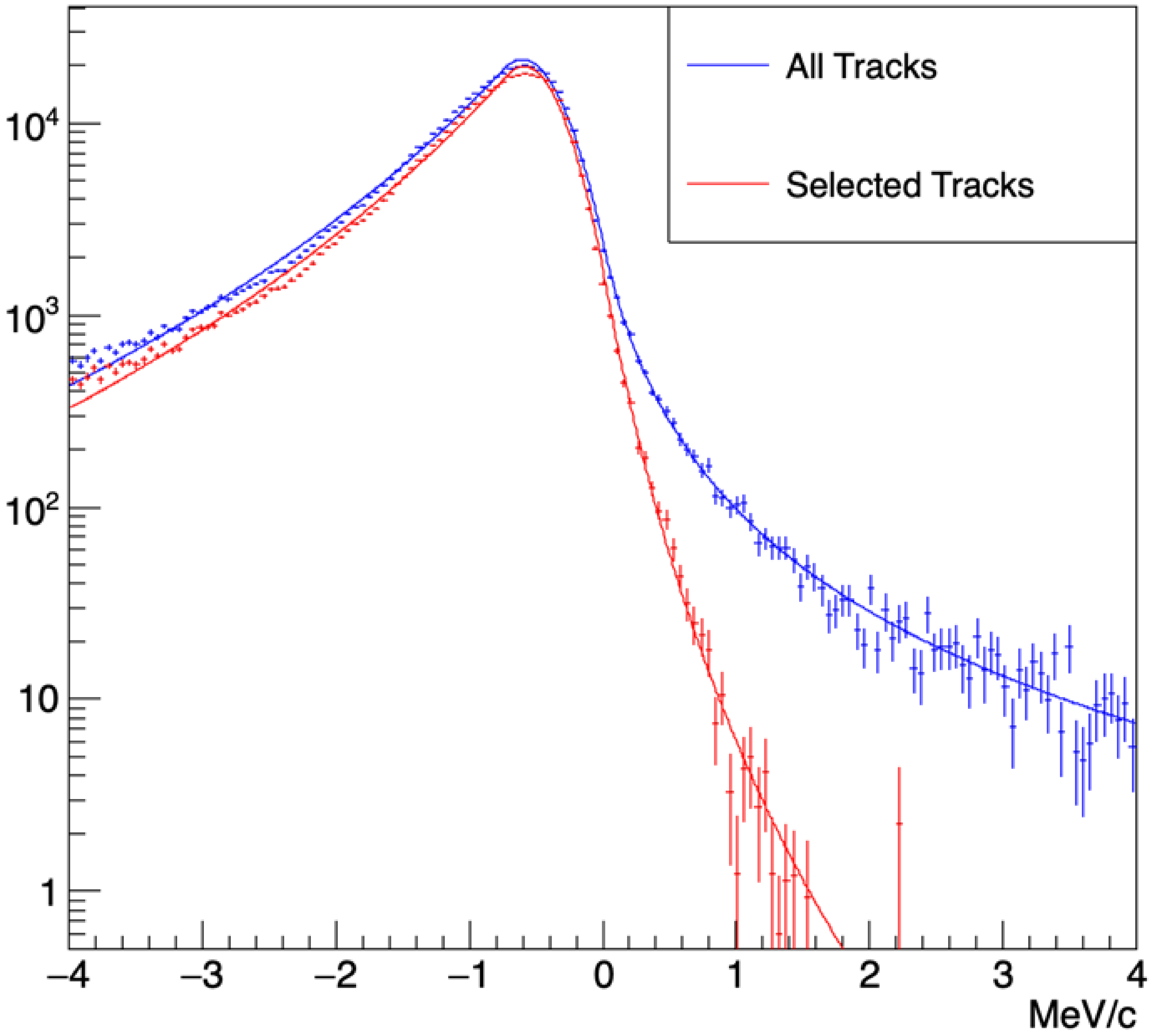
- Stream data in time slice to the TDAQ farm (CPU+FPGA)
  ➡ Mu2e is expected to have one of the largest data rate at Fermilab
- We are in charge of developing the Trigger Menu of the experiment
  ✓ **Primary**: CE(+/-), High Energy Photon
  ✓ **Support**: efficiency, performance measurements and monitoring
  ✓ **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

momentum response at tracker entrance



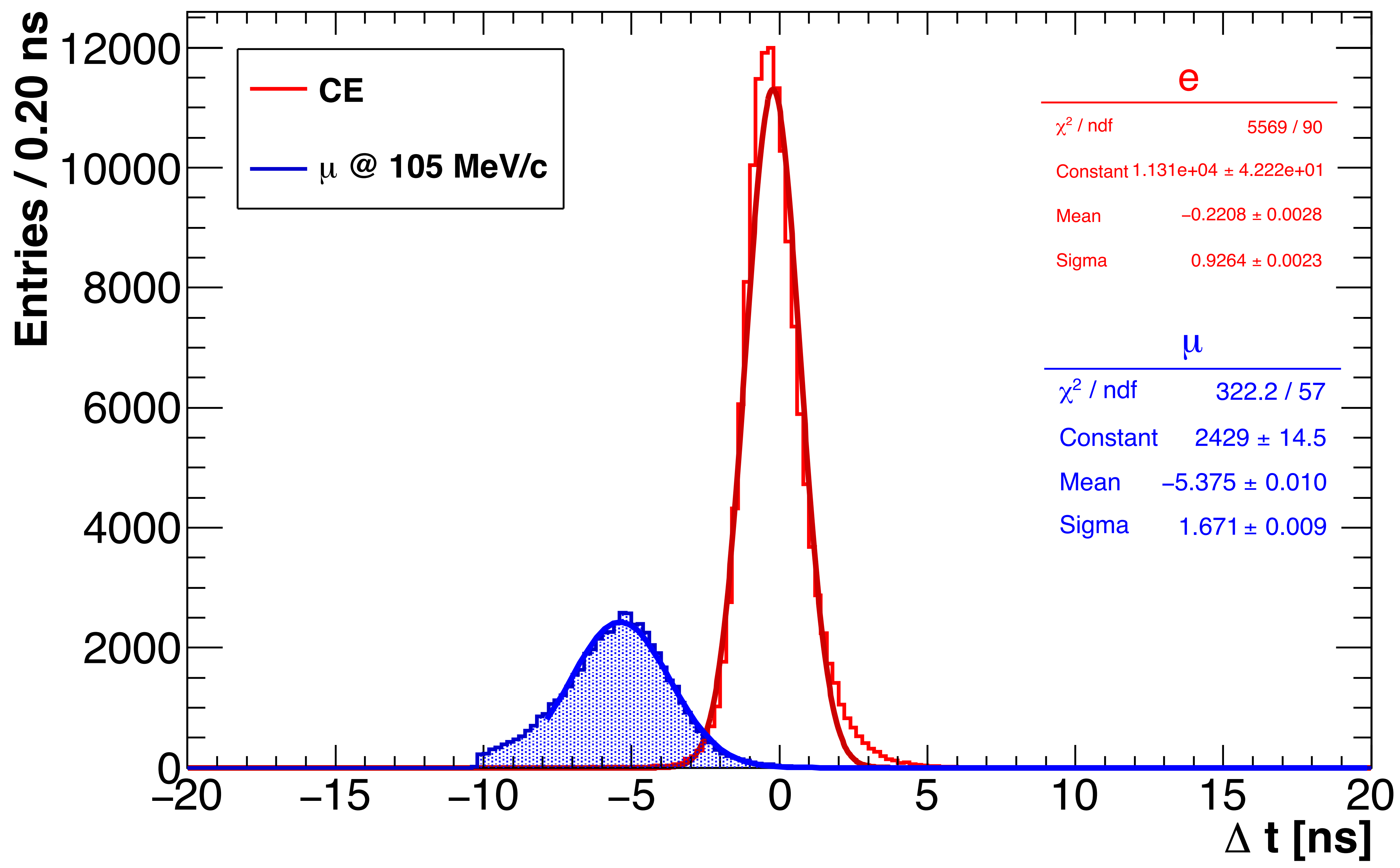
- MVA-based selection allows us to suppress the tracks where the p was overestimated

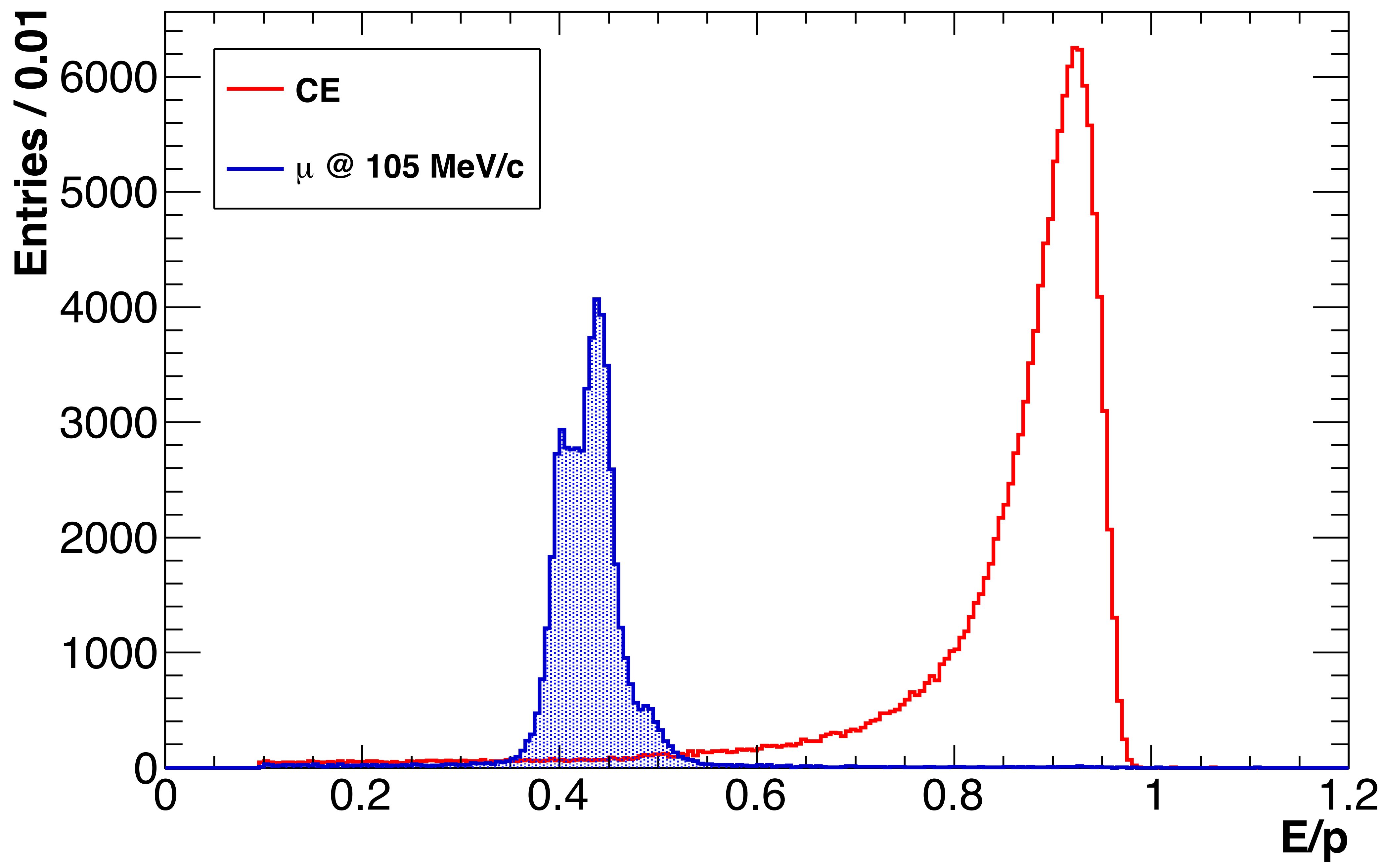
Particle identification

Cosmic μ rejection

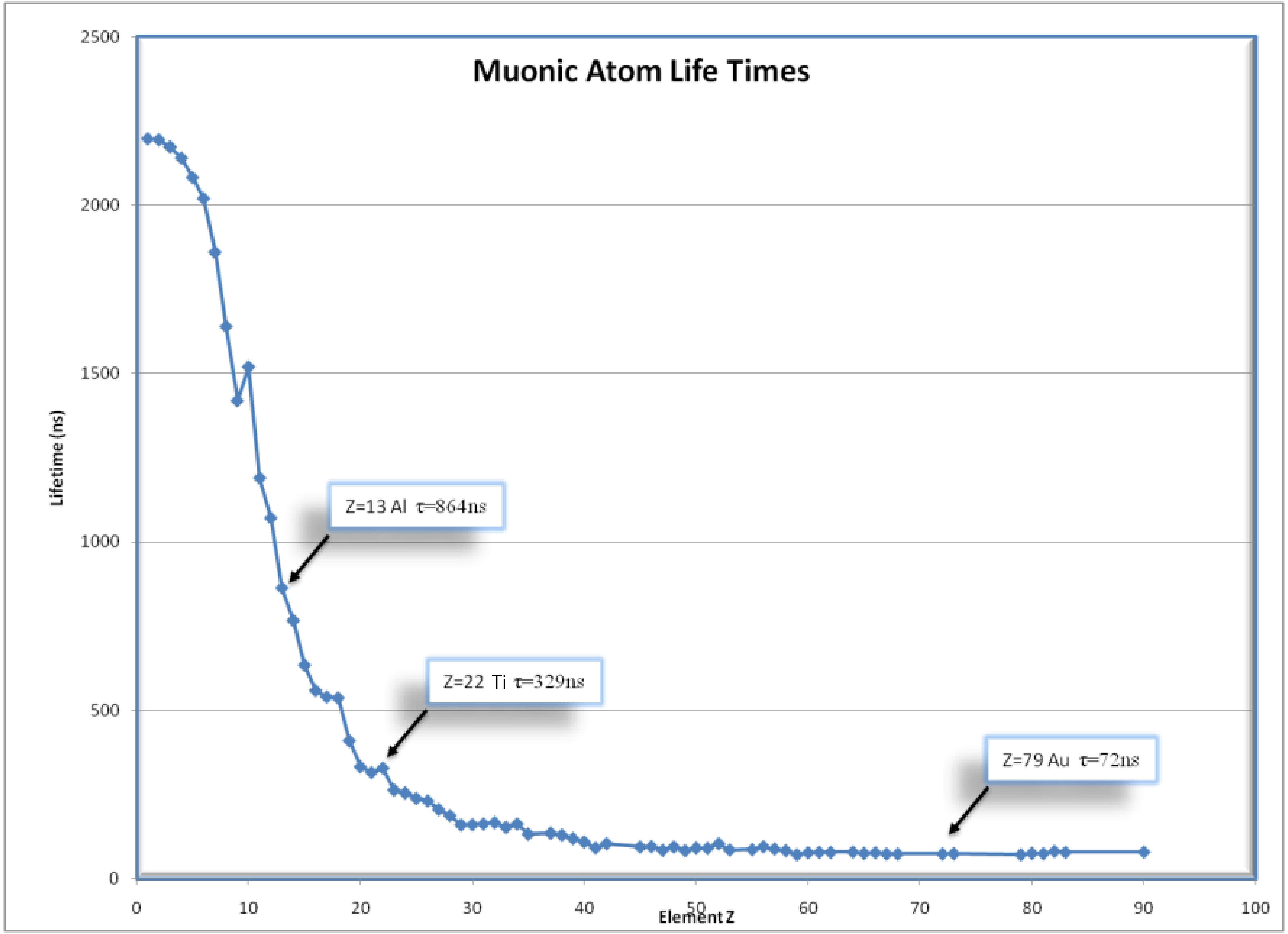
- 105 MeV/c e- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines $\Delta t = t_{track} - t_{cluster}$ and E/p:

$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta \mathrm{t}) + \ln P_{e,\mu}(\mathrm{E/p})$$



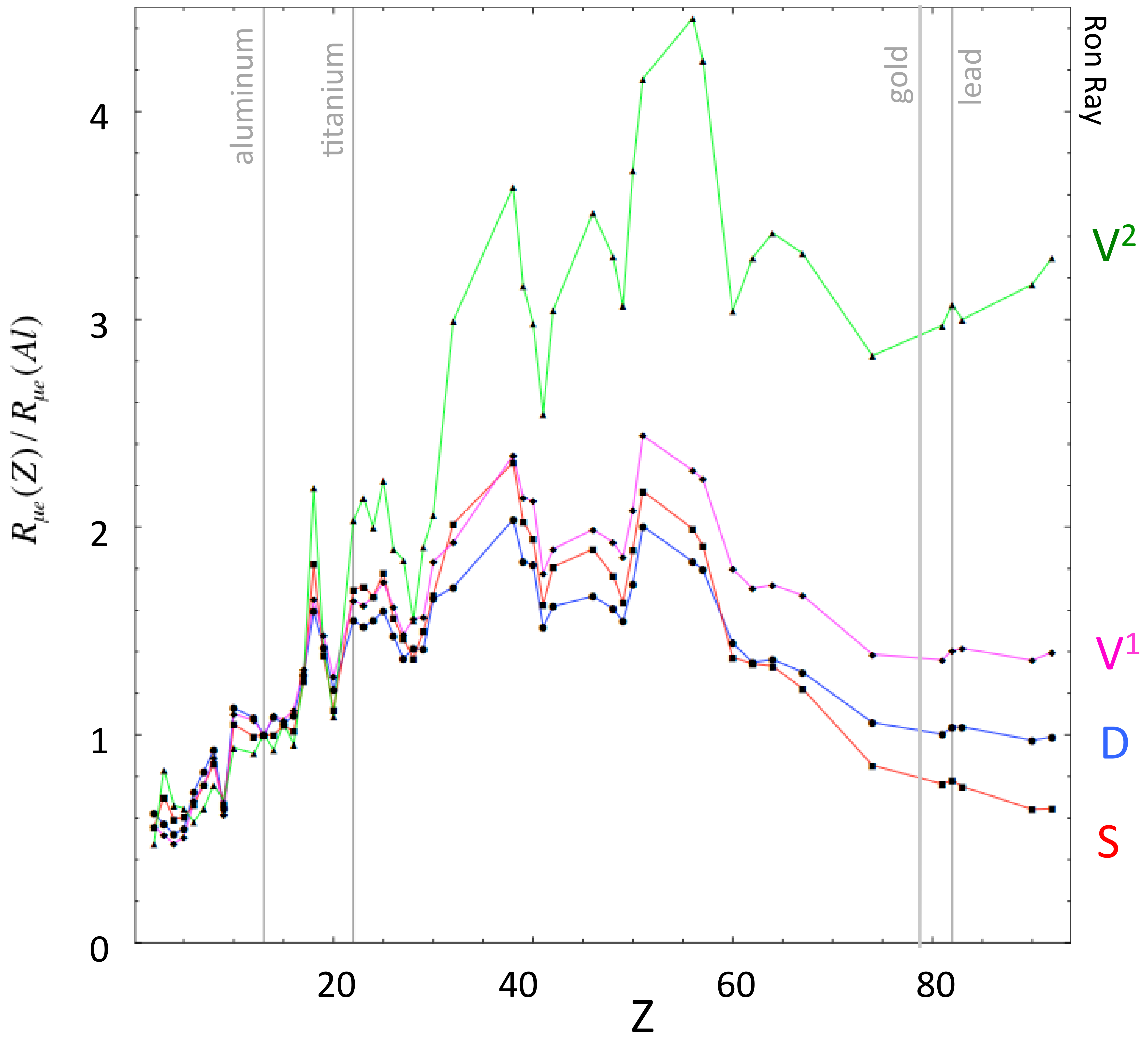


Muonic atom life times



$R_{\mu e}$ 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

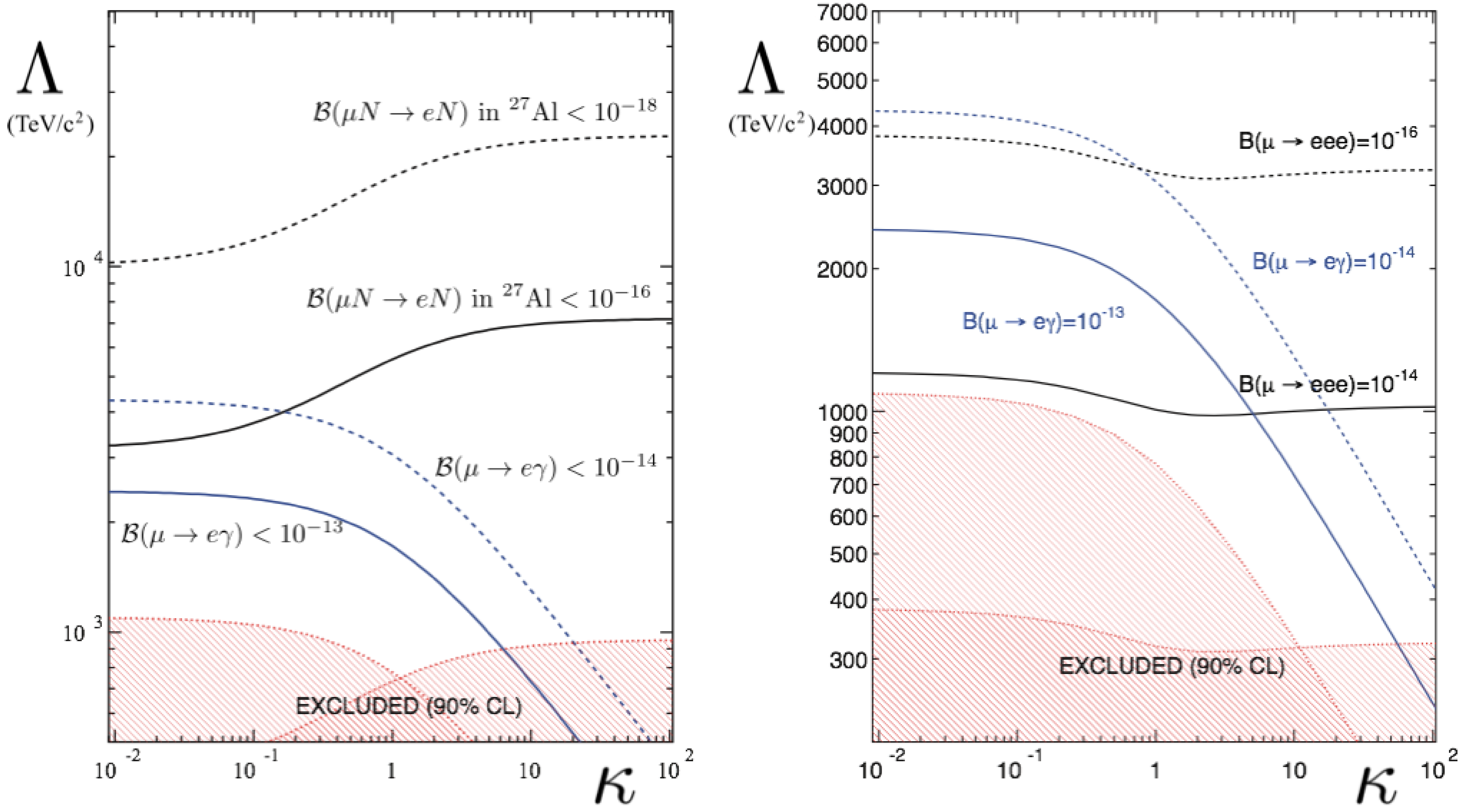
★★★ = Discovery Sensitivity

	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]

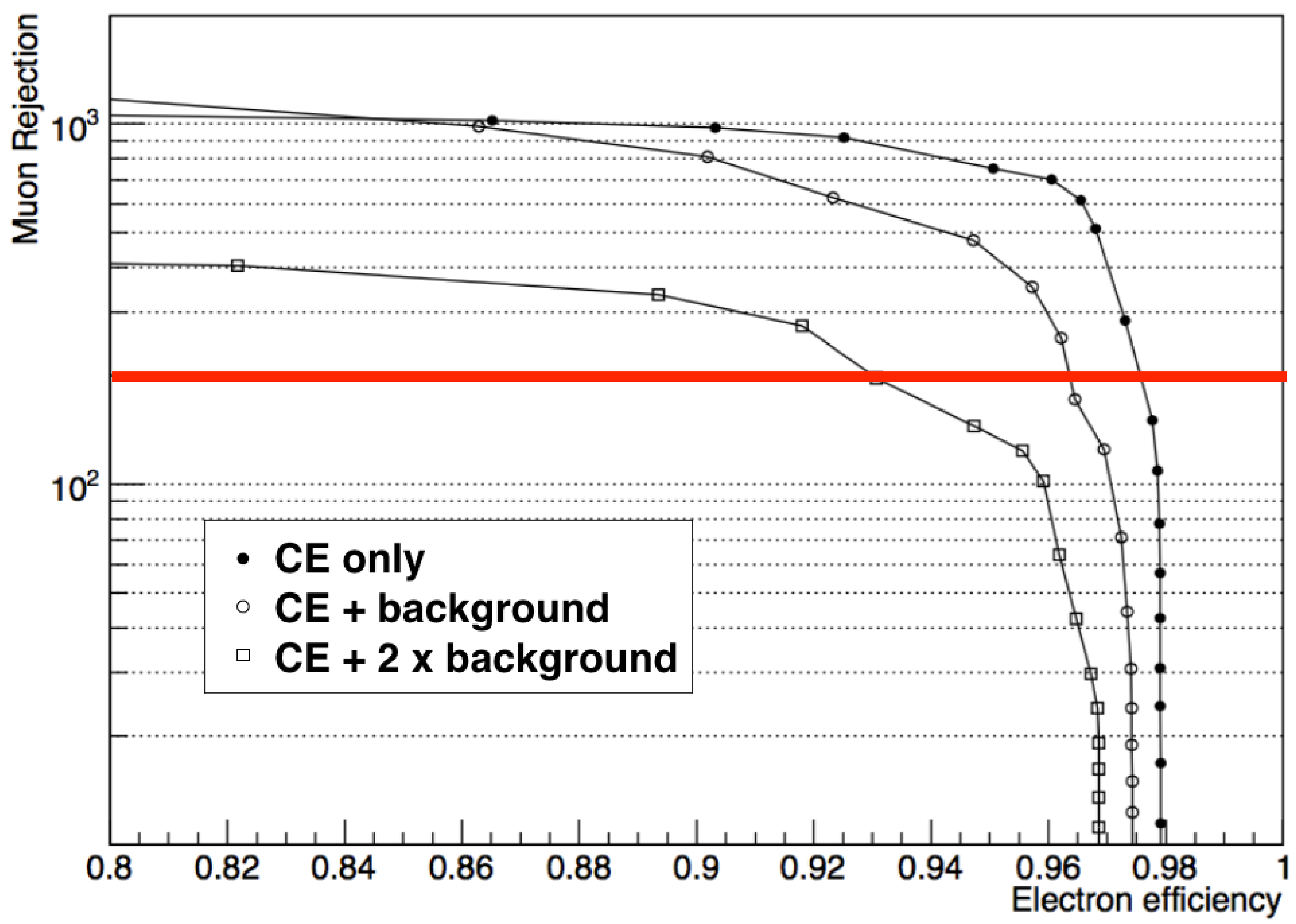
Model independent Lagrangian

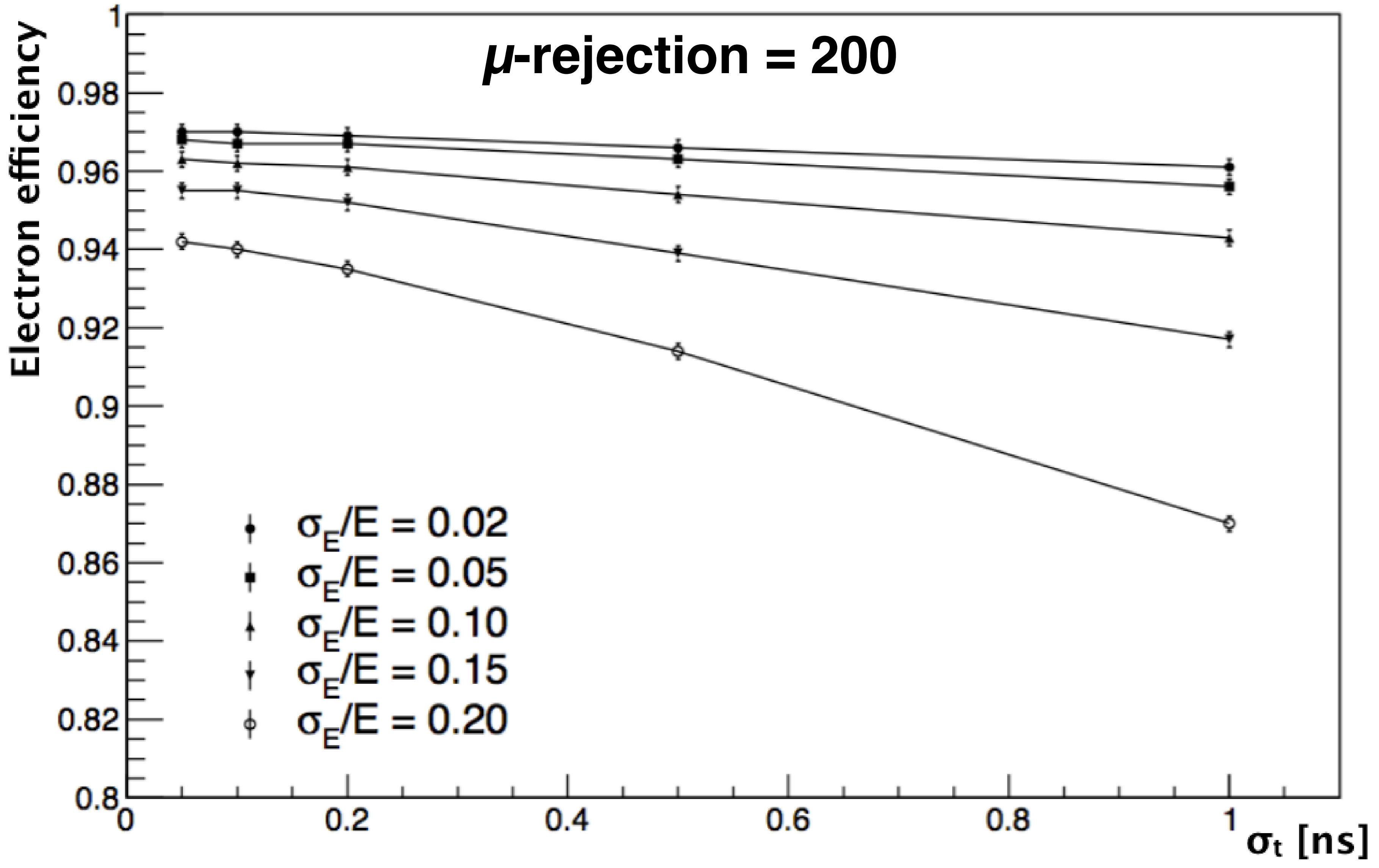


$$L_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right)$$

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

PID performance





- A muon-rejection of 200 corresponds to a cut at ln $L_{e/\mu}$ > 1.5 and an e^- efficiency of ~ 96%
- In the range $\sigma_E/E<10\%$ and $\sigma_t<0.5$ ns the e^- ϵ varies by less than 2%

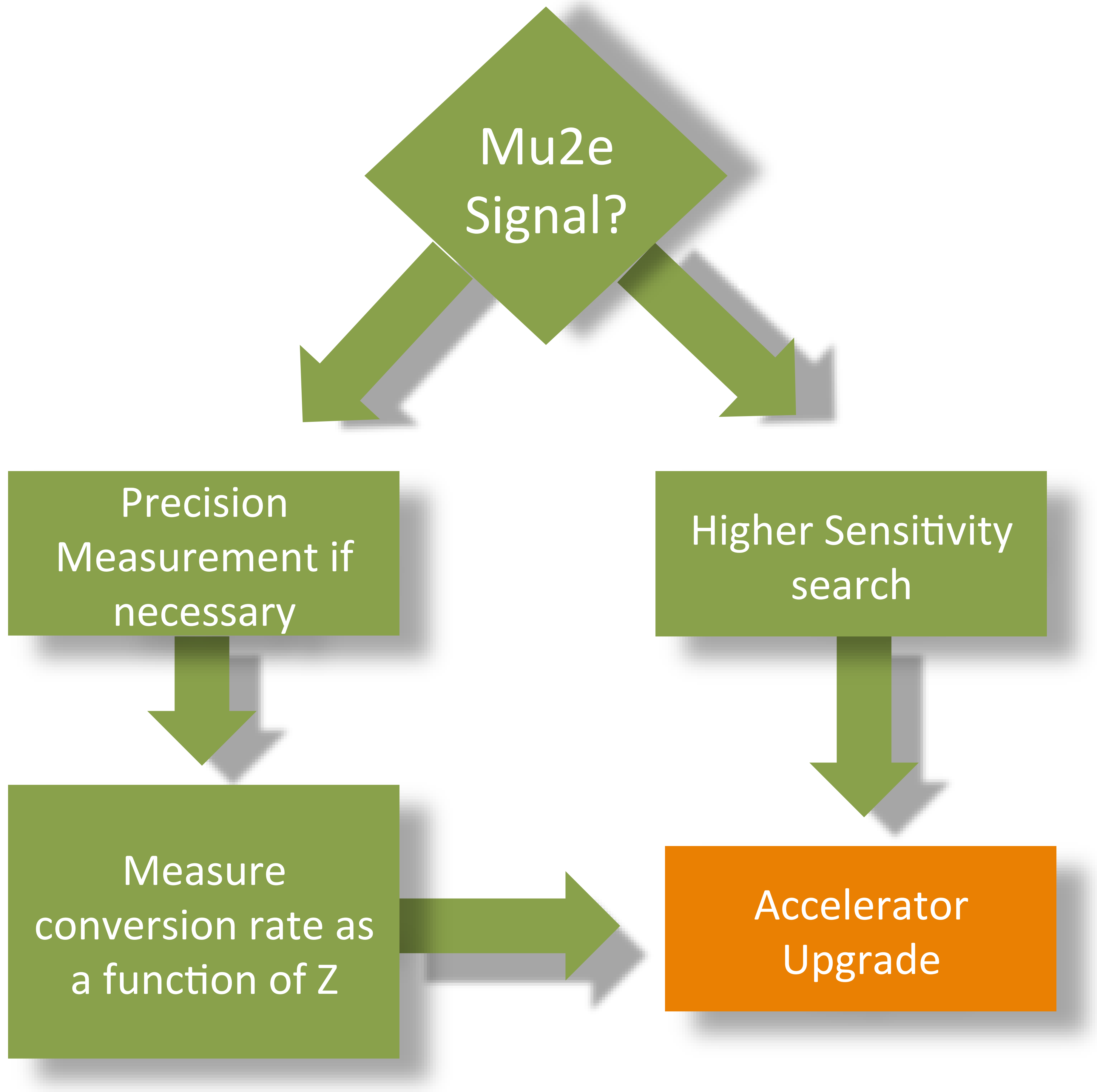
CLFV limits I

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

Mu2e signal?



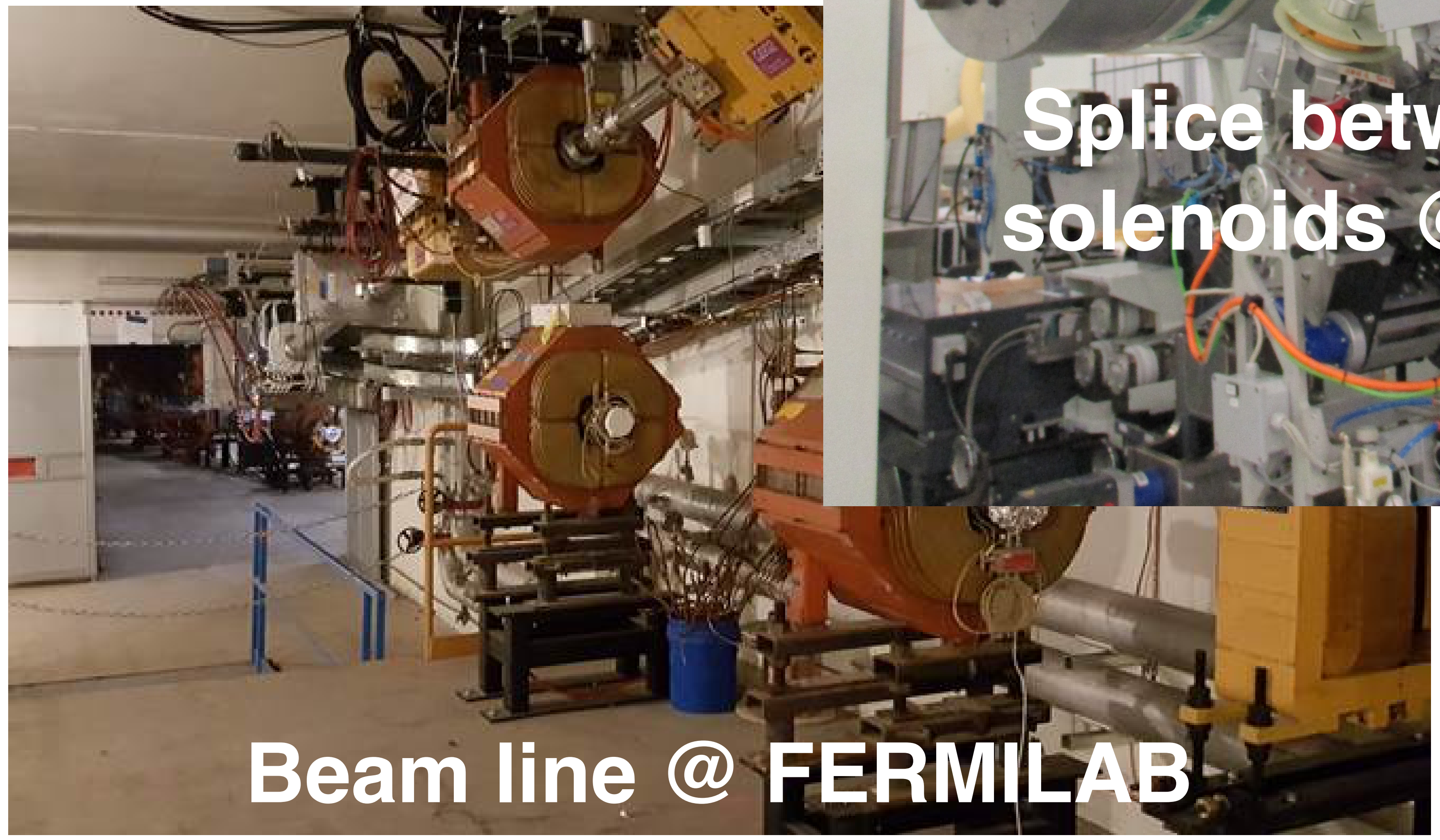
- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons upgrade accelerator
  - ✓ **Snowmass** white paper, arXiv:1802.02599

Pictures


North face


Splice between
solenoids @ GA


Coils module @ ASG

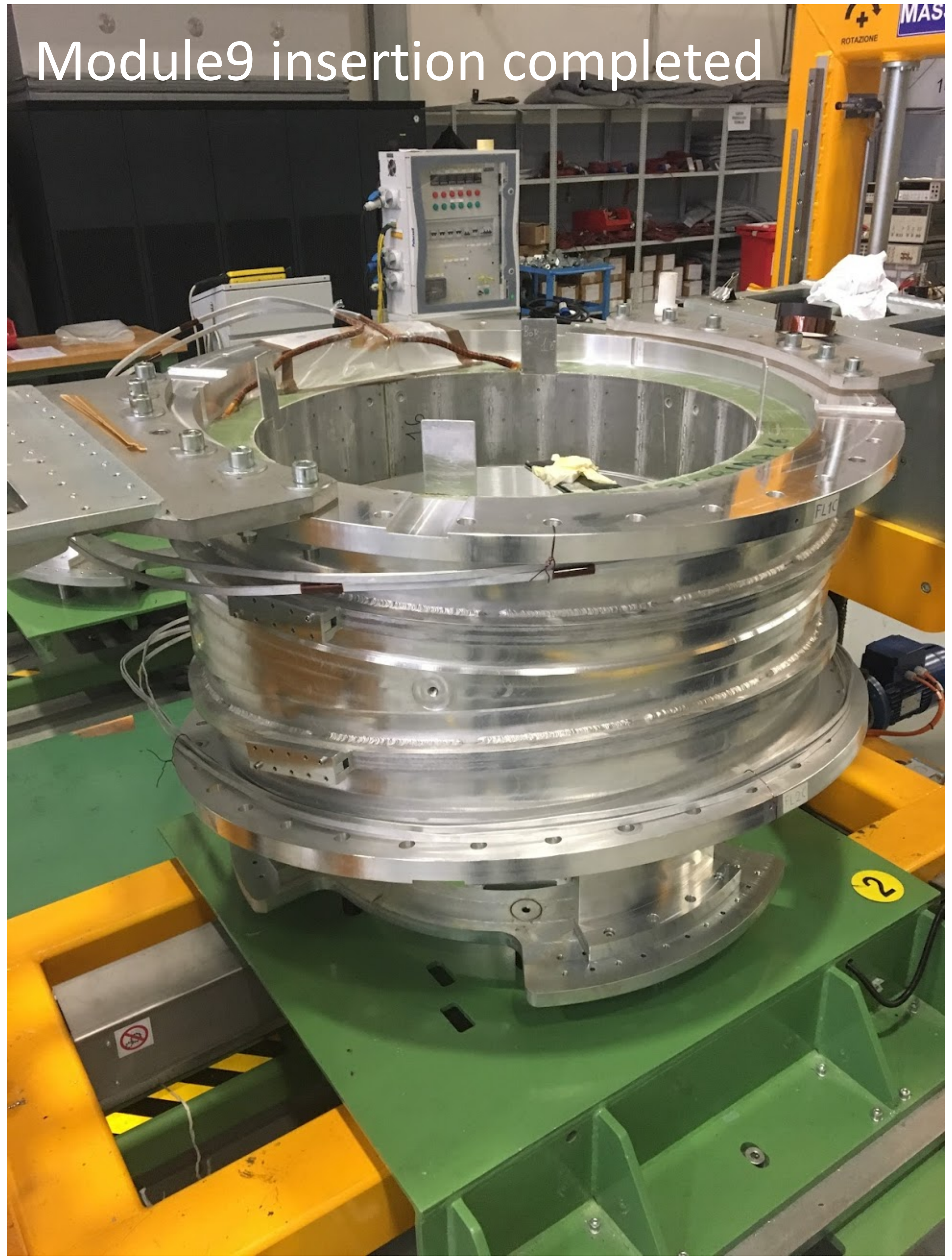

Beam line @ FERMILAB

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



Testing Handling Robot