The Mu2e experiment at Fermilab and the Mu2e Calorimeter

ICHEP 2022, Bologna, Italy
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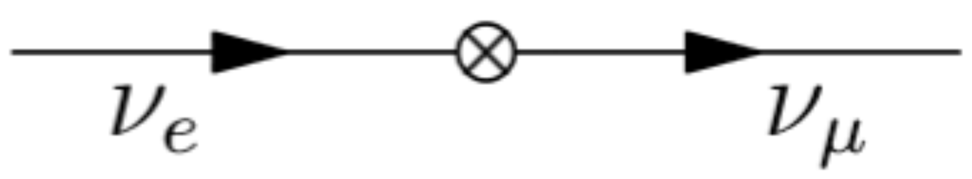
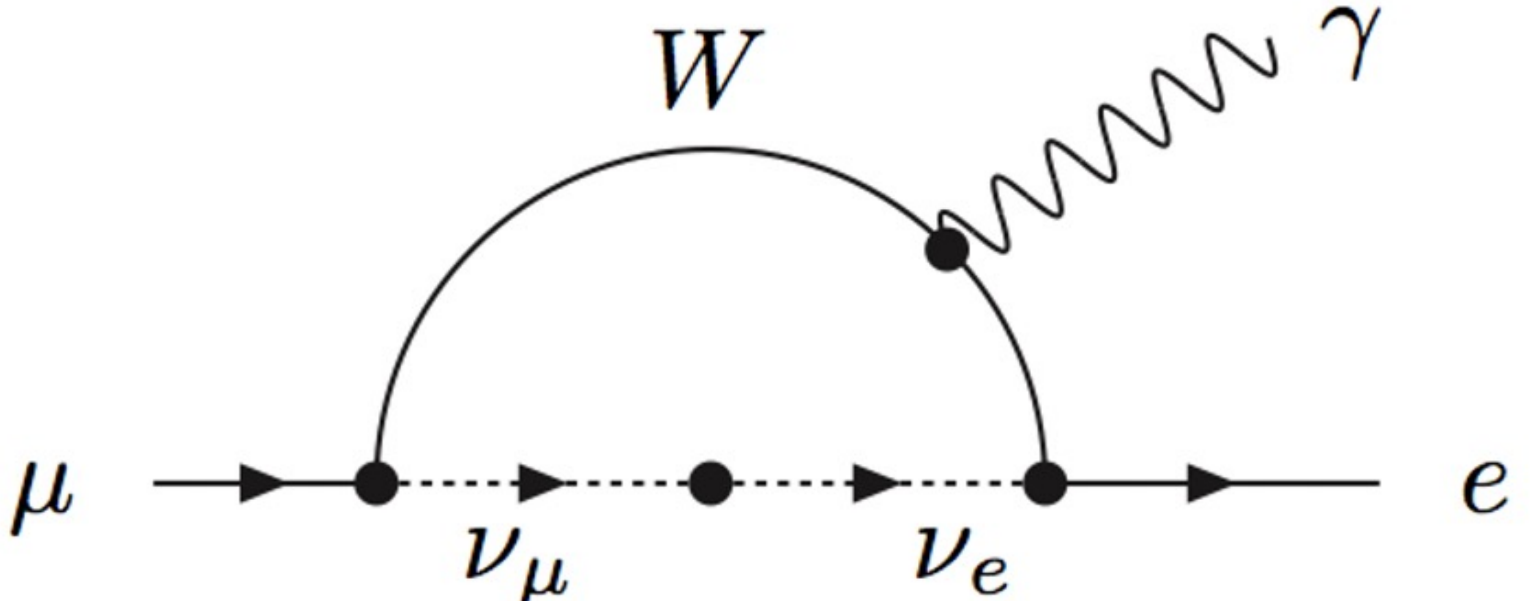
Charged Lepton Flavour Violation

Neutral lepton flavor violation (i.e. neutrino mixing) implies charged lepton flavor violation (CLFV) through neutrino mixing.



However, CLFV processes are strongly suppressed in the Standard Model.

BR($\mu \to e\,\gamma$) < 10^{-54} in the SM: negligible.

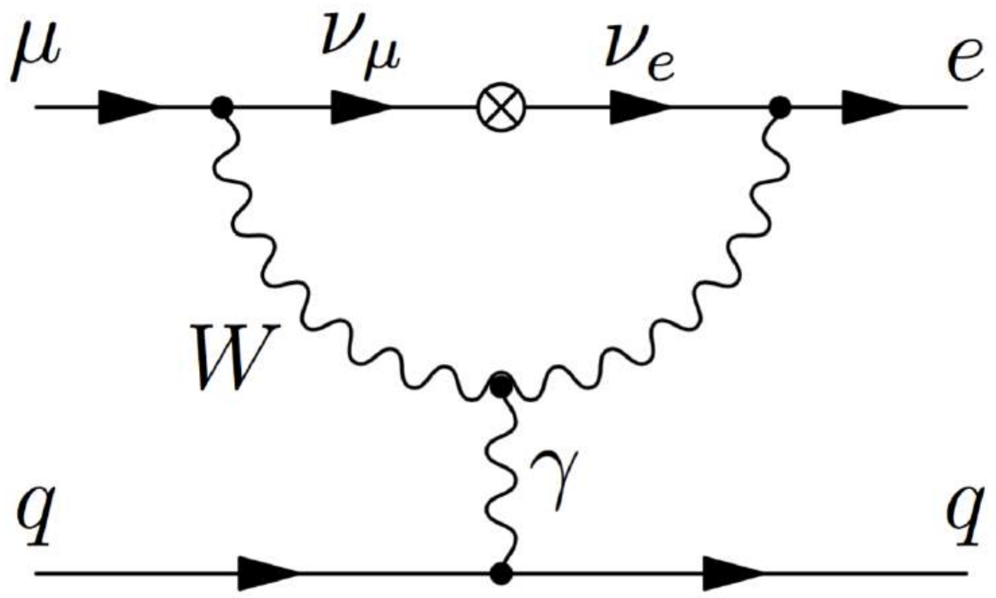


New Physics can enhance CLFV rates to observable values

Observation of CLFV is an unambiguous sign of New Physics

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

The Mu2e experiment @ FNAL (along with COMET in Japan) searches for muon-to-electron conversion in the coulomb field of a nucleus: *μ^- Al → e^- Al*

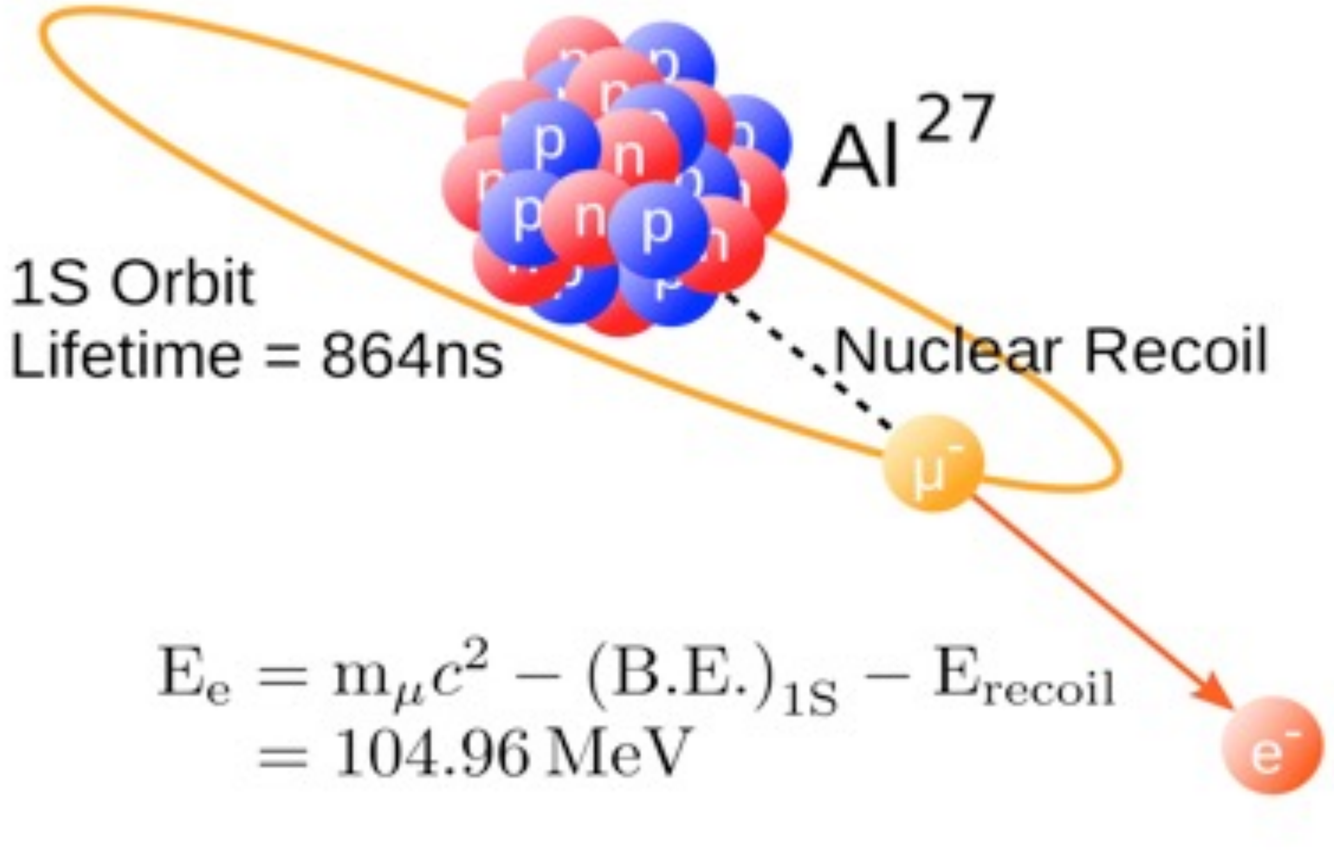


Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator

Experimental technique

1. **Produce muons** via protons hitting a fixed target
2. Stop low momentum **muons in Al target**
3. Wait for muon to convert into electron (t_m^{Al} = 864 ns) yielding a **105 MeV mono-energetic signal electron**

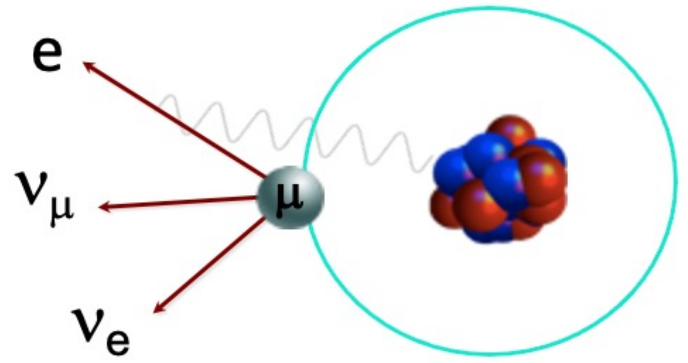
- **Mu2e measures the μ-e conversion/capture rate**
- **10^4 improvement of current experimental best limit**



Captured μ can undergo 3 processes:

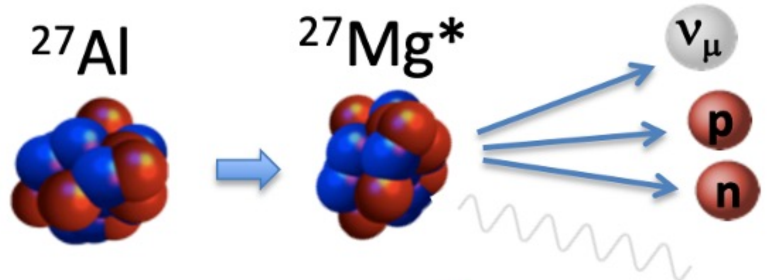
- Decay in orbit (39 % for Al) → intrinsic background

$$\mu^- + Al \to e^- \overline{\nu}_e \nu_\mu + Al$$



- Capture (61% for Al) → normalization

$$\mu^- + Al \to \nu_\mu + Mg^*$$



- Conversion ($<10^{-13}$) → our signal

$$\mu^- N \to e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1))}$$

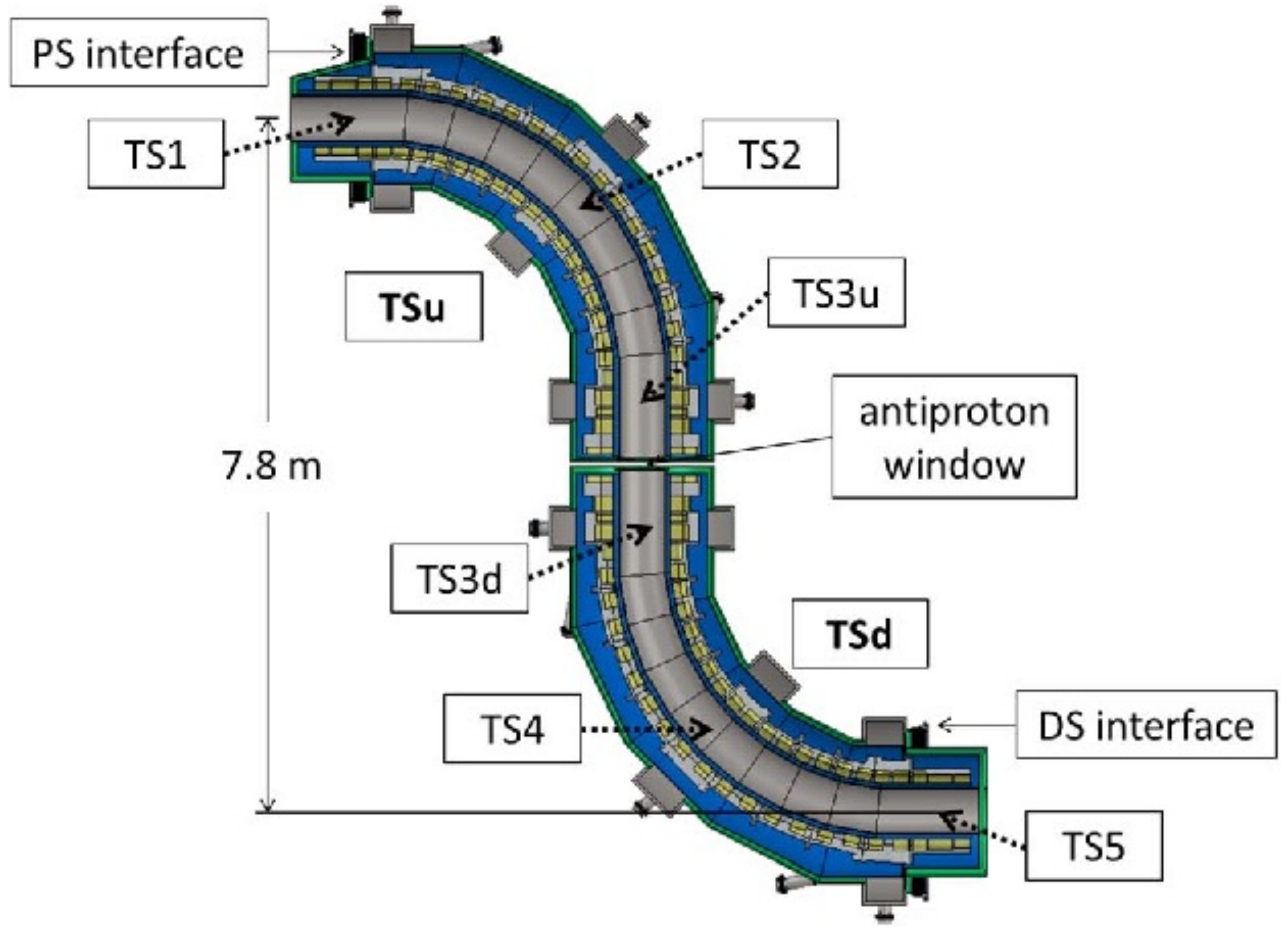
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1))} \leq 8 \times 10^{-17} (@\ 90\%CL)$$

Main backgrounds

1. **Intrinsic** (∝ μ stops): μ Decay in orbit, radiative μ captures
2. **Beam**: μ/π DIF, radiative π captures
3. **Other**: cosmics, misreconstructions

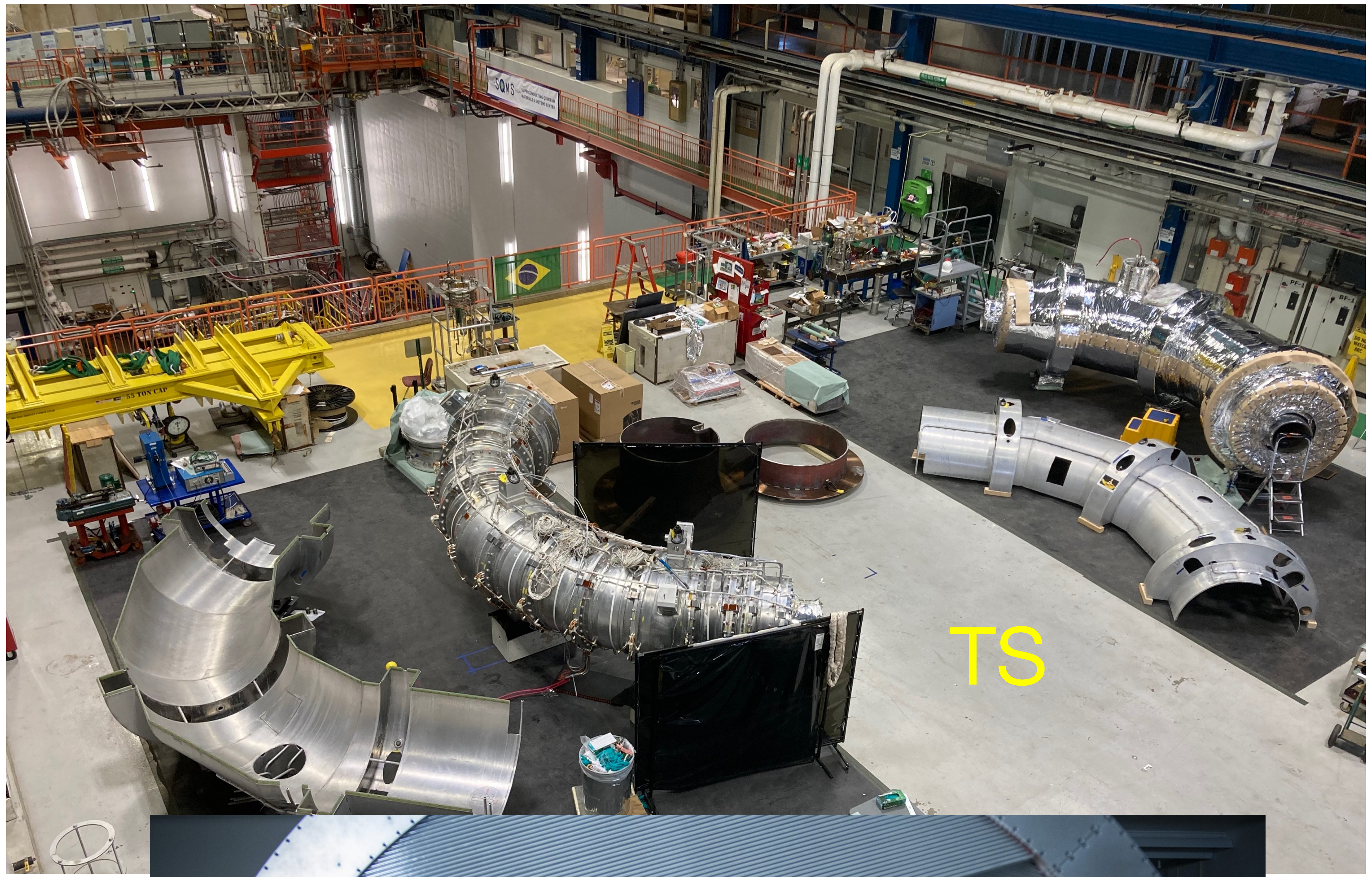
Experiment architecture

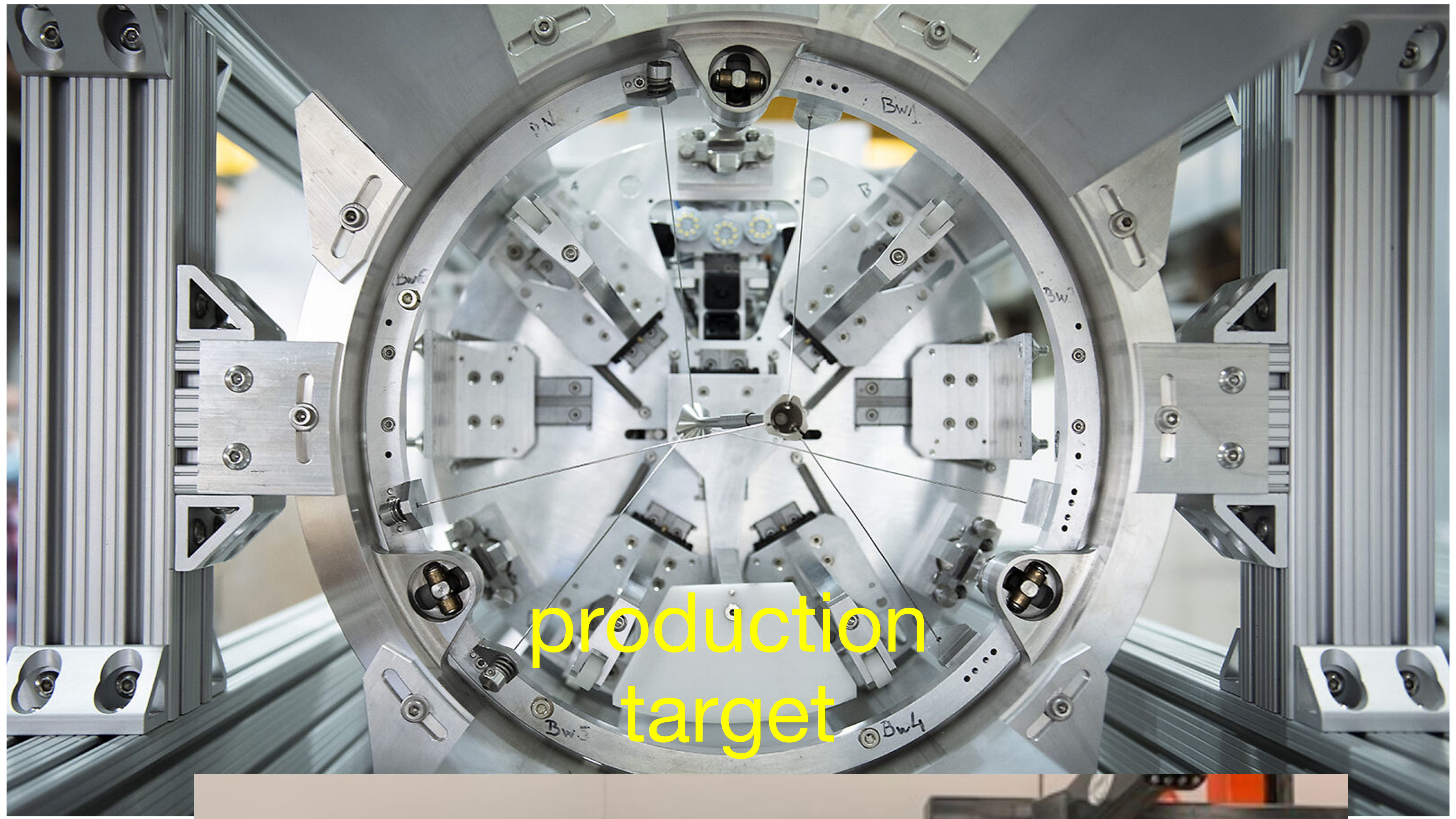
- 8 GeV proton beam
- W production target
- 200 ns proton pulse
- 1.7 us period
- POT produce mostly π
- μ^- from π^- decays

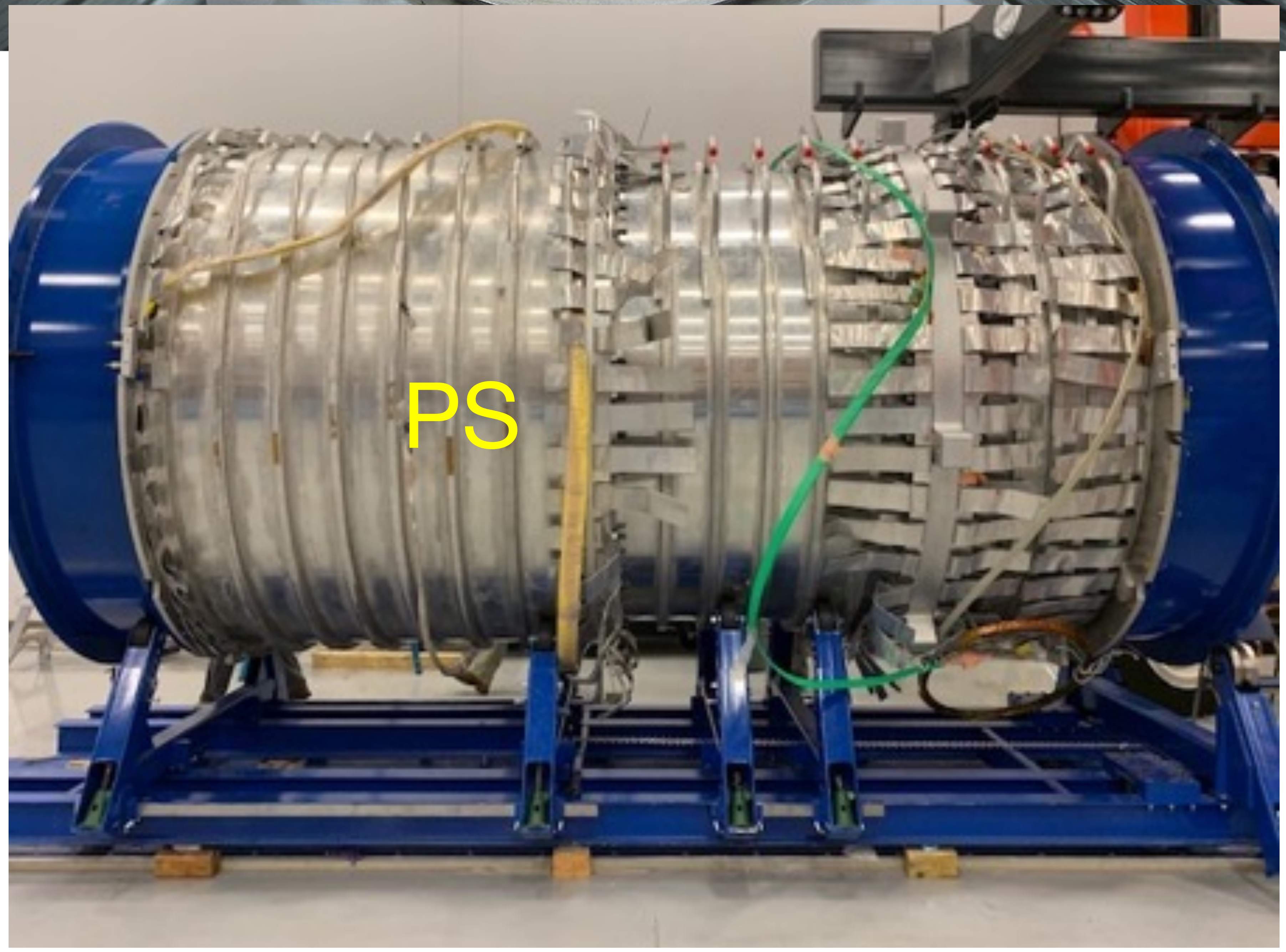


- **10^{10} μ/s selected and transported**
- **25 metres long Al-stab Nb-Ti superconductor system**
- Low momentum pulsed (20k μ^- /bunch) muon beam
- High resolution (< 200 keV/c) straw-tube tracker
- Electromagnetic calorimeter

Work in progress



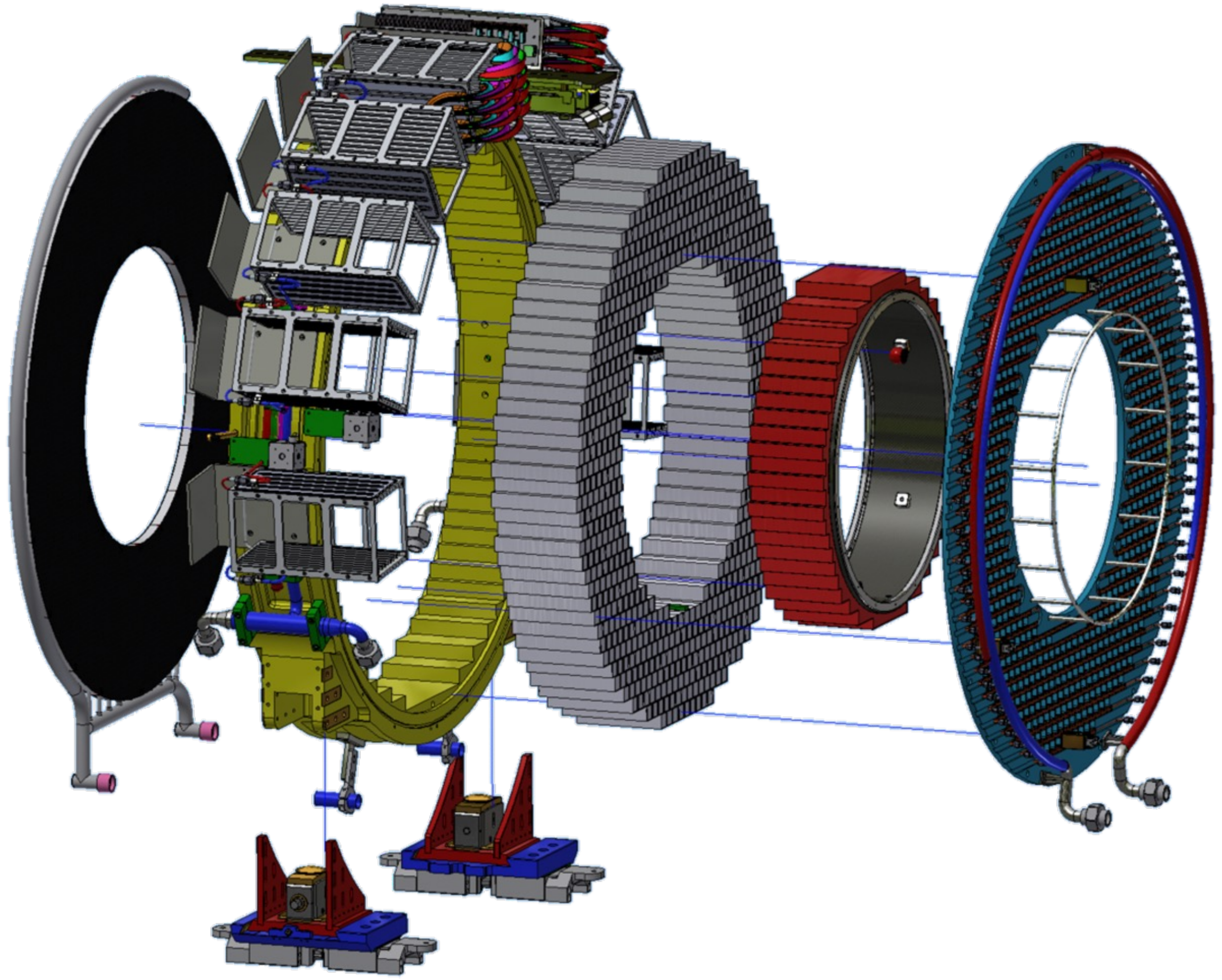




Detector solenoid

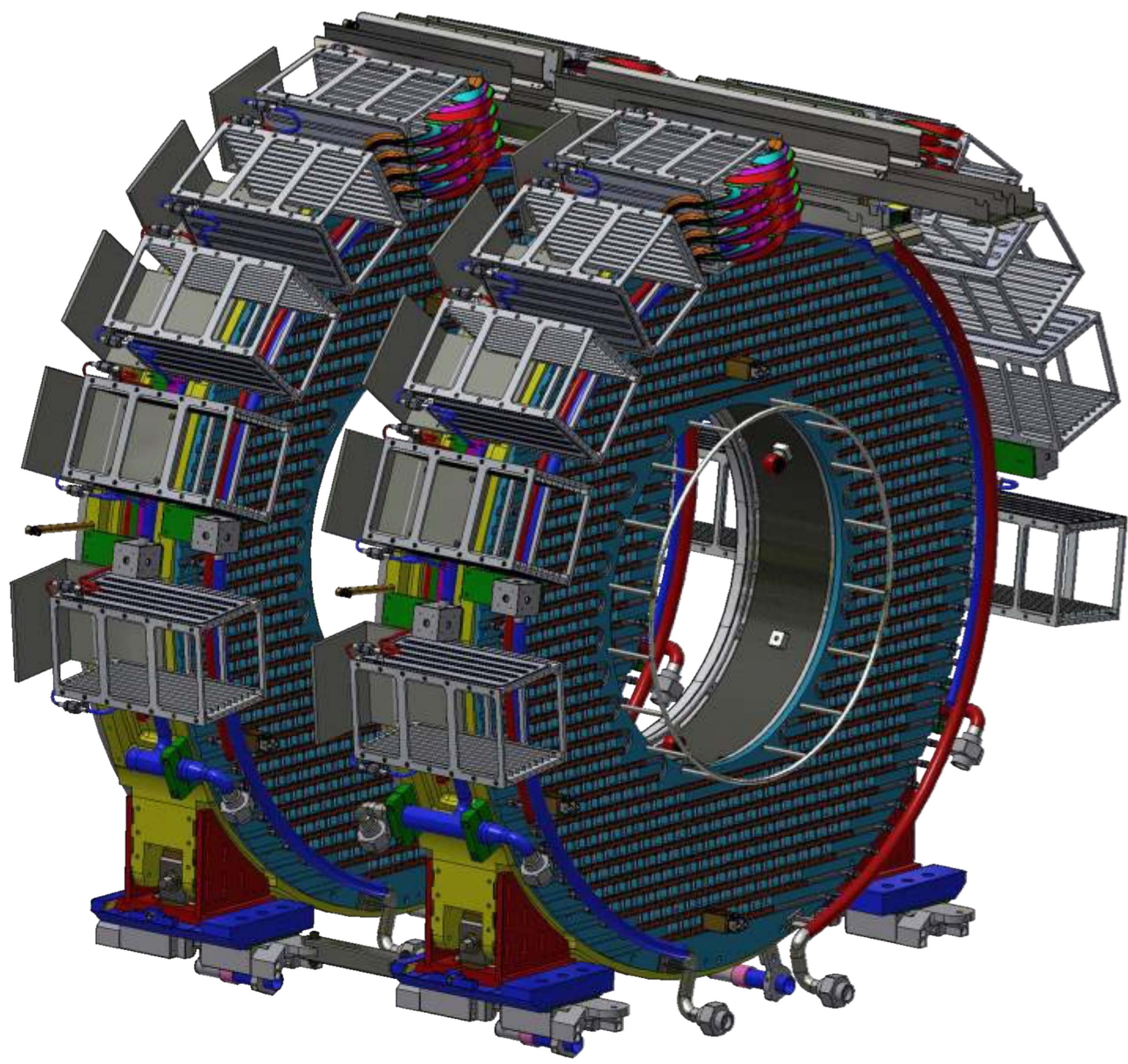
34 Al foils; Aluminum selected mainly for the muon lifetime in capture events (**864 ns)** that matches nicely the prompt separation in the Mu2e beam structure.

Calorimeter at a glance



Tasks

- PID capabilities w/ e^-/μ rejection factor > 200
- Stand alone online trigger capability (HLT)
- Cluster-based seeding for track finding
- Large acceptance for conversion electrons



Requirements

- energy resolution $\sigma_E/E = O(10\,\%)$ @ 100 MeV
- timing resolution $\sigma(t) < 500$ ps @ 100 MeV
- Fast signal for Pileup and Timing
- $\sigma_{xy} < 1$ cm

Operating environment

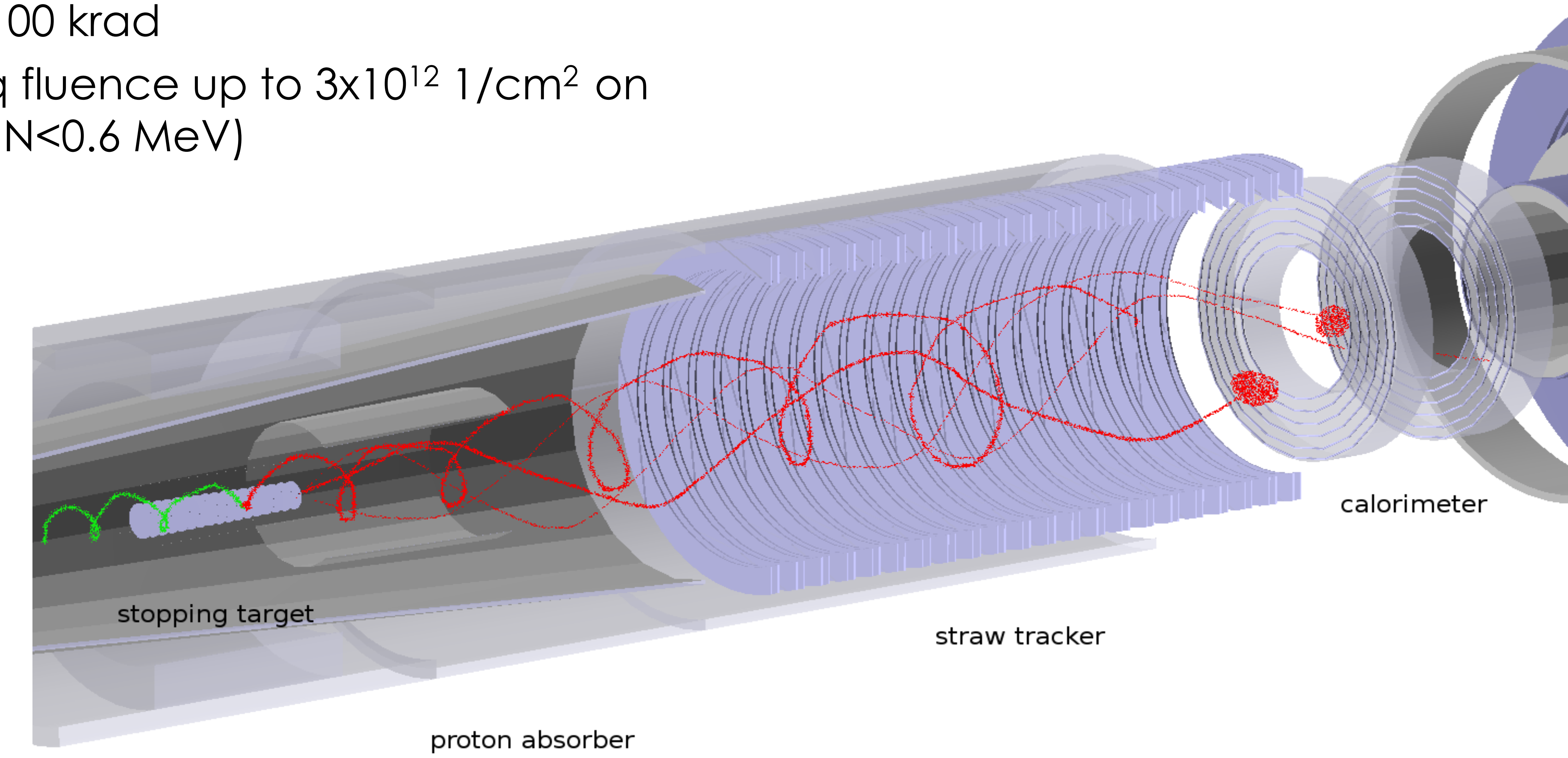
- 1 T B-field
- 10^{-4} mbar vacuum
- TID up to 100 krad
- 1MeV-neq fluence up to 3×10^{12} 1/cm^2 on crystals (RIN<0.6 MeV)

Calorimeter architecture

- Two annular disks w/ 674 undoped CsI 34 x 34 x 200 mm^3 crystals each
- 10 X_0 (200 mm) crystal depth and 70 disk cm spacing
- 30 cm inner disk bore, 66 cm outer bore
- Readout via 2 large area UV-extended SiPMs per crystal
- SiPM + FEE fluid cooling down to –10° C

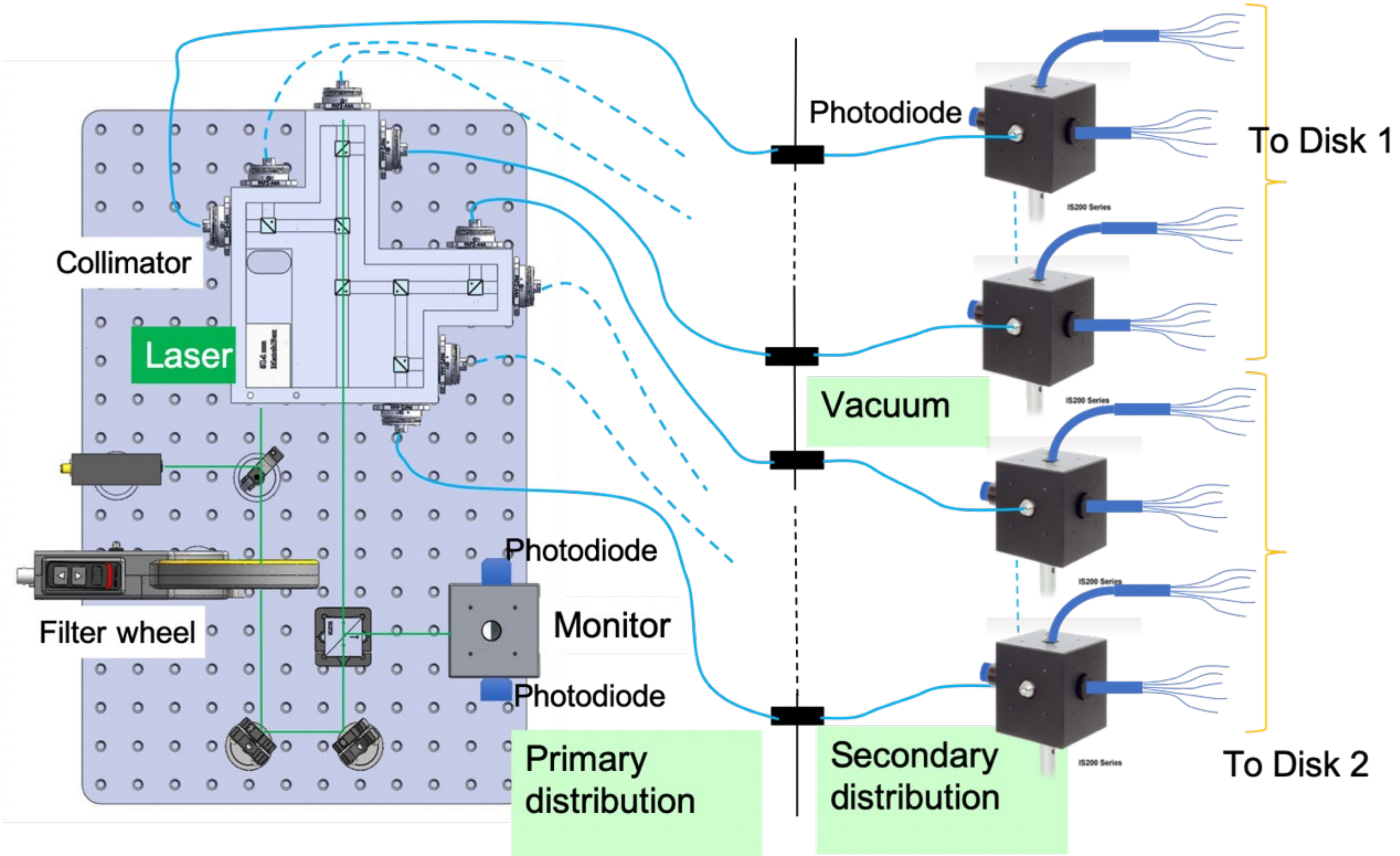
Calibration methods

- 530 nm laser for SiPM gain monitoring, equalisation and timing alignment
- Liquid radio source for crystal equalisation w/ 6 MeV photon
- In-situ calibration with crossing MIPs, DIO's and other physics processes



Calibration systems

$$^{19}F + n \rightarrow {}^{16}N + \alpha$$
$$^{16}N \rightarrow {}^{16}O^{*} + \beta \quad t_{1/2} = 7\ s$$
$$^{16}O^{*} \rightarrow {}^{16}O + \gamma(6.13\ \text{MeV})$$

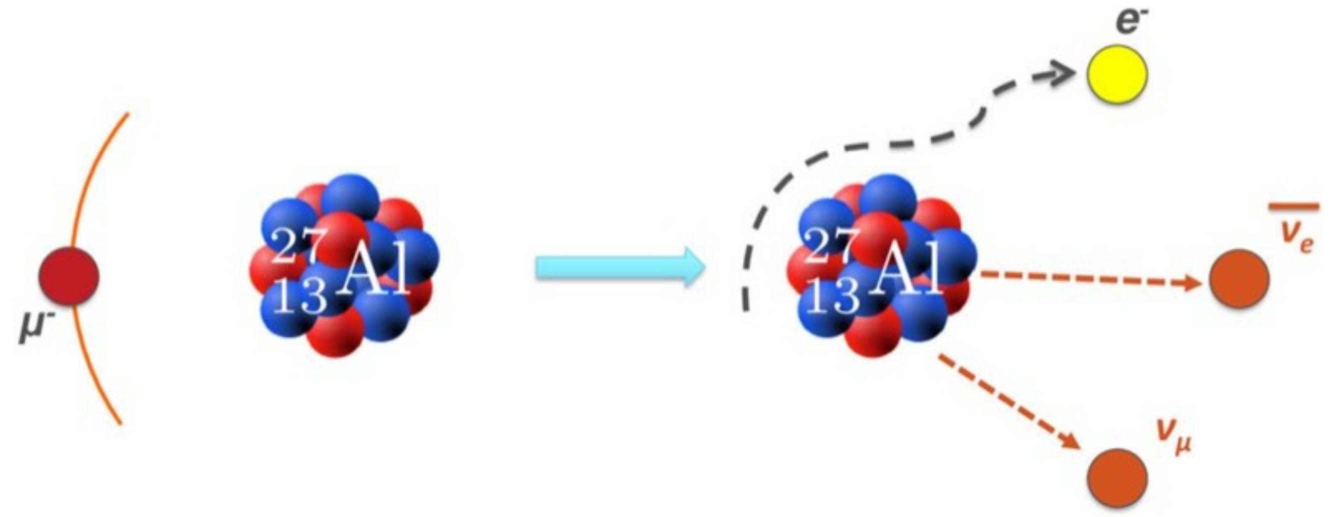


embedded calibration systems

- 530 nm picosecond **laser system** for SiPM **gain equalisation, monitoring and timing alignment**
- Fluorinert-based **liquid radio source** emitting 6 MeV photons for crystal equalisation

other calibration systems

- Crossing **cosmic MIPs** based calibration at ~ 21 MeV
- **DIO** e⁻
- Radiative pion/muon captures



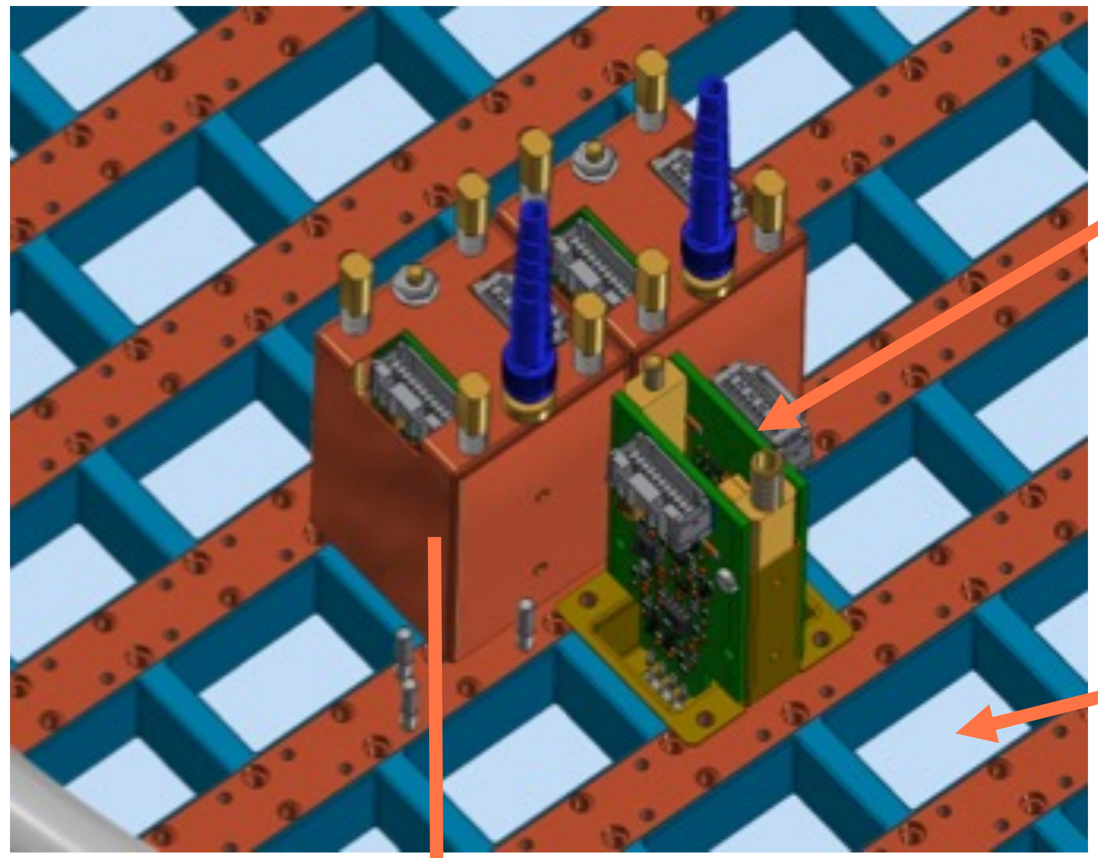
Signal chain overview

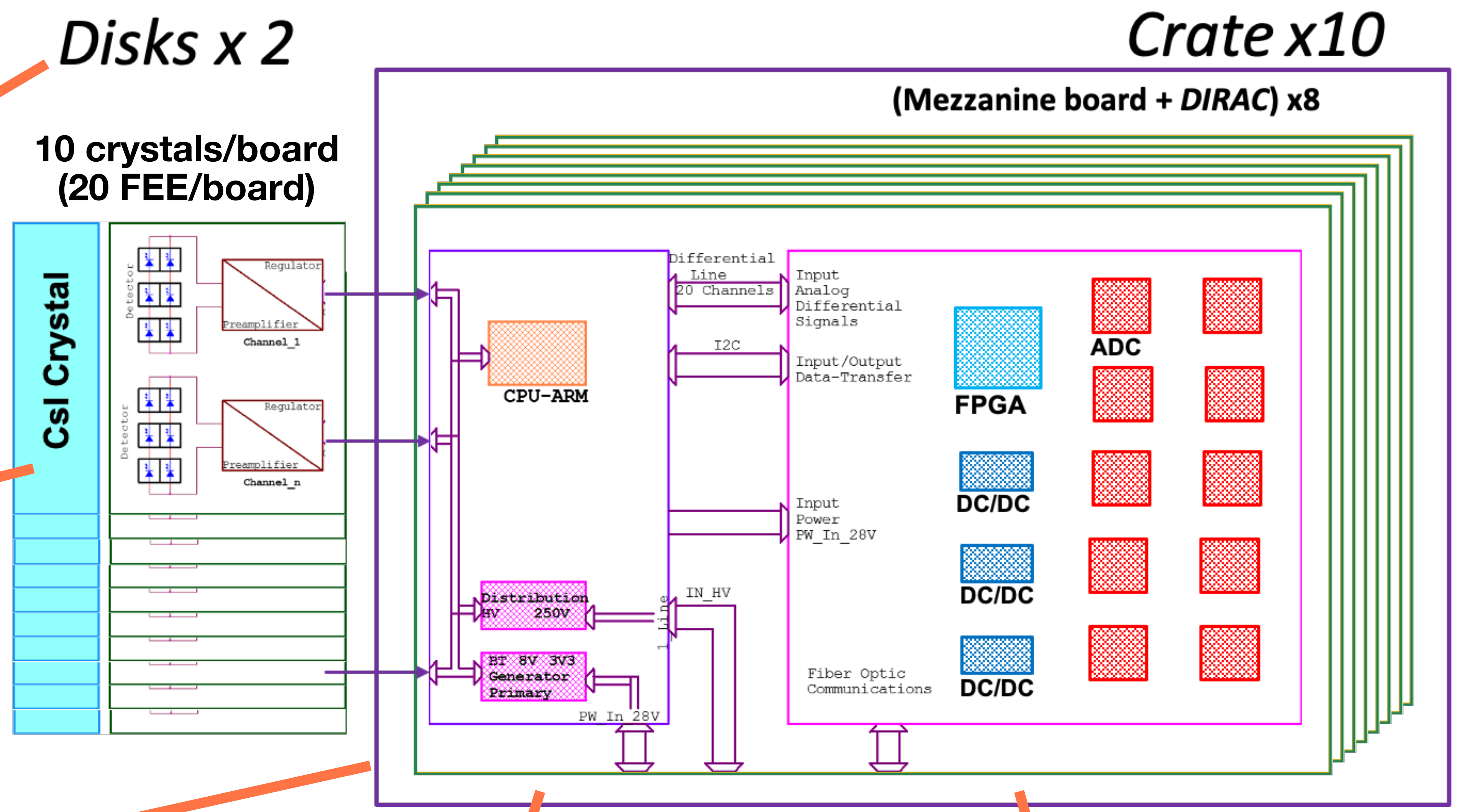
- 2700 readout channels w/ fully custom readout chain (from SiPM to DAQ)
- 10 electronics crates/disk (280 boards total)
- SiPM cooling to -10 °C

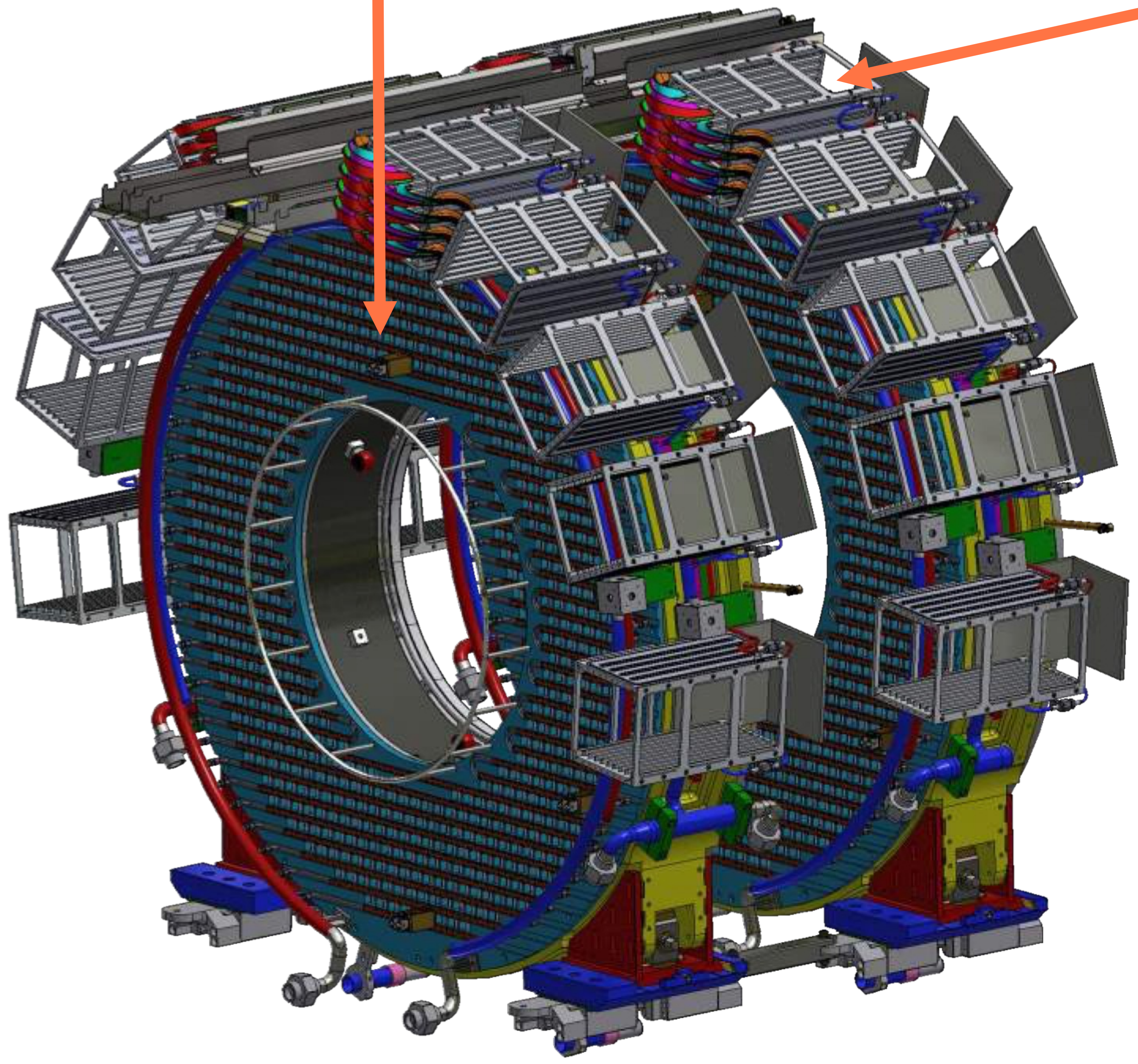
- **2700 Read-Out Units**
  - Two fully independent readout channels per cry
  - 2 large-area UV-extended SiPM
  - **2 Front-End Electronics (FEE) boards**
    - SiPM amplification and shaping
    - Digitally controlled SiPM monitoring and biasing

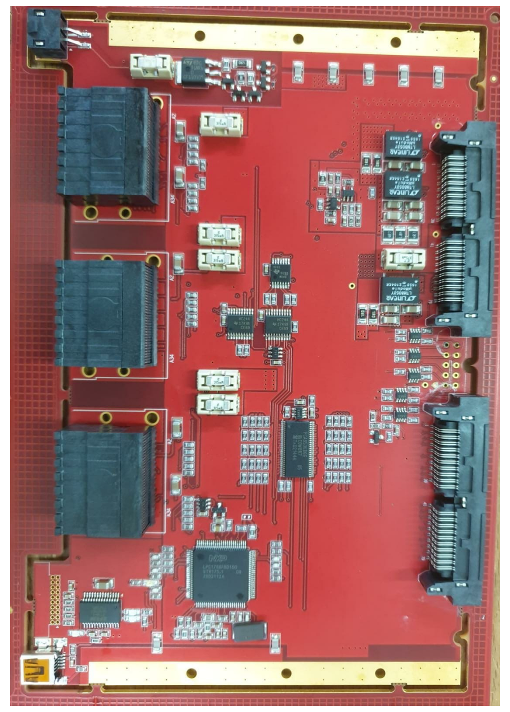
- **140 Mezzanine Boards (MB)**
  - Slow-control distribution
  - FEE power distribution
  - ARM-microprocessor based

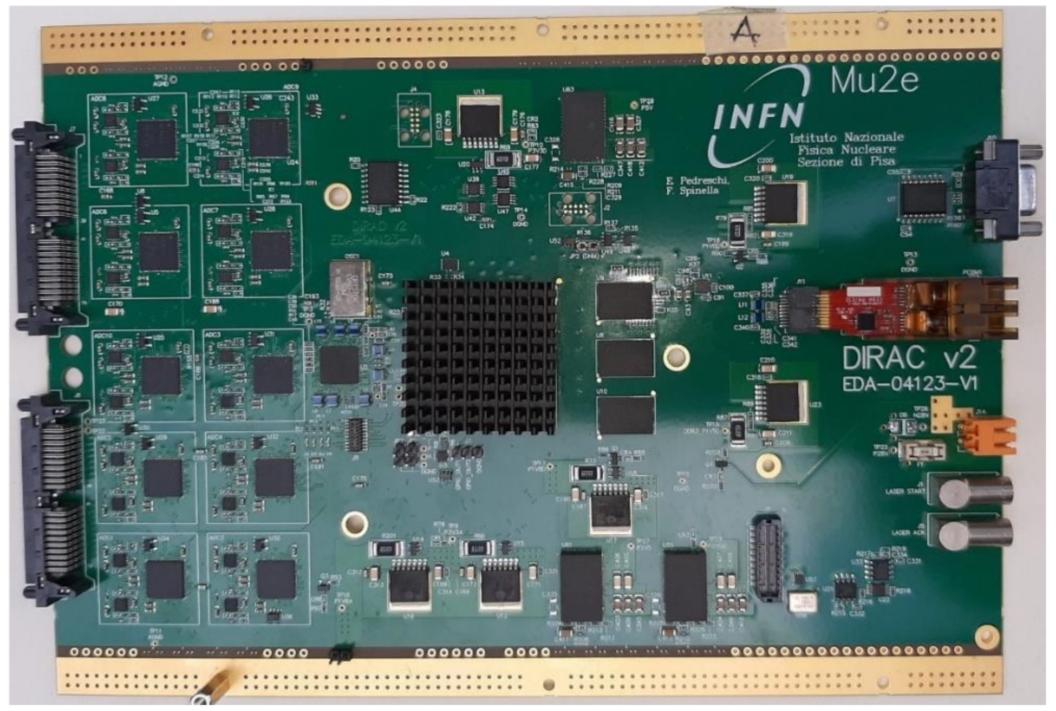
- **140 custom digitiser boards (DIRAC)**
  - Signal digitisation @ 200 Msps w/ 12-bit flash ADC
  - Digitisation to allow good signal reconstruction despite the high expected pileup
  - *PolarFire* rad-hard FPGA
  - VTRX 10 Gbps optical link to Detector Control System
  - DIRAC v3 prototype ready





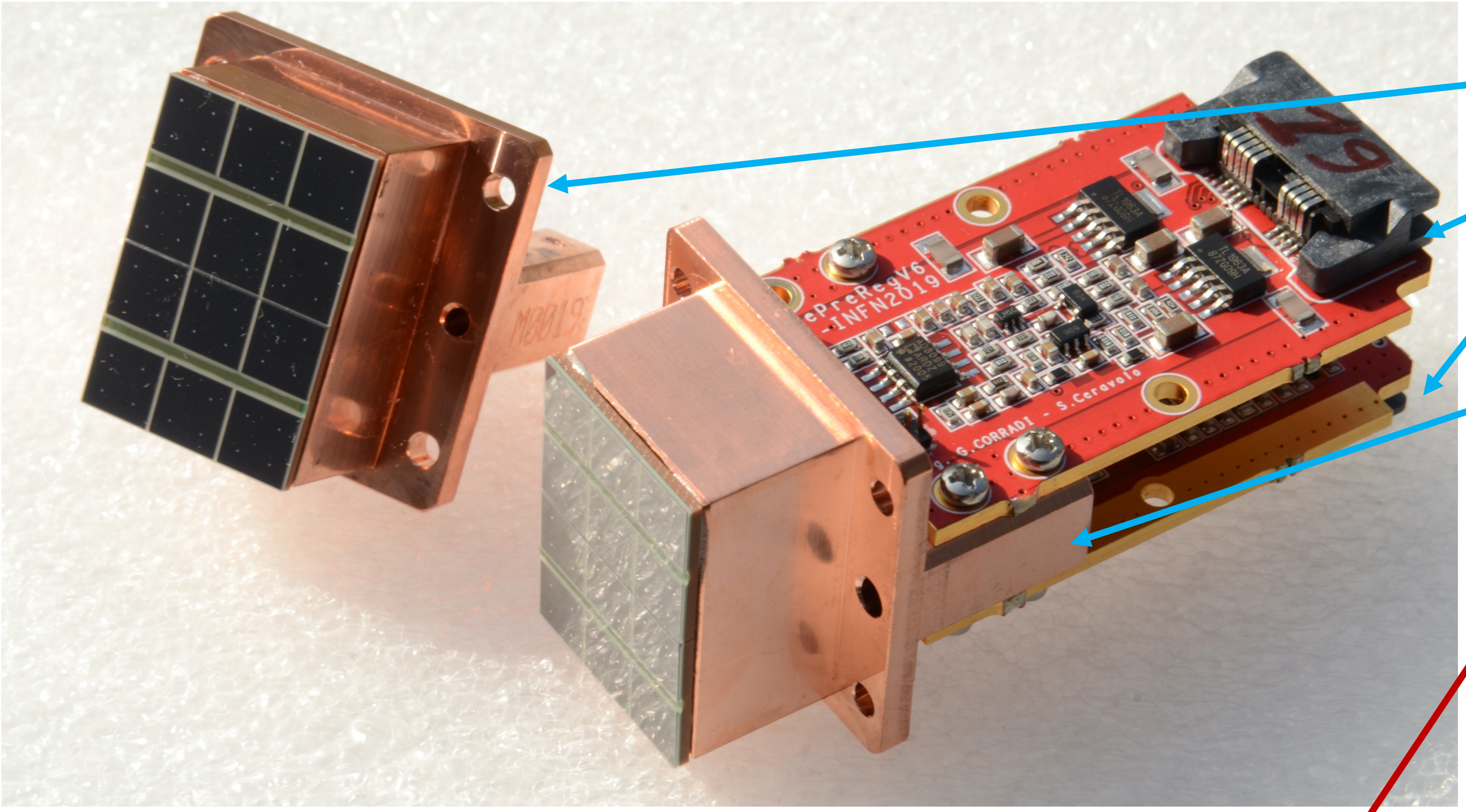






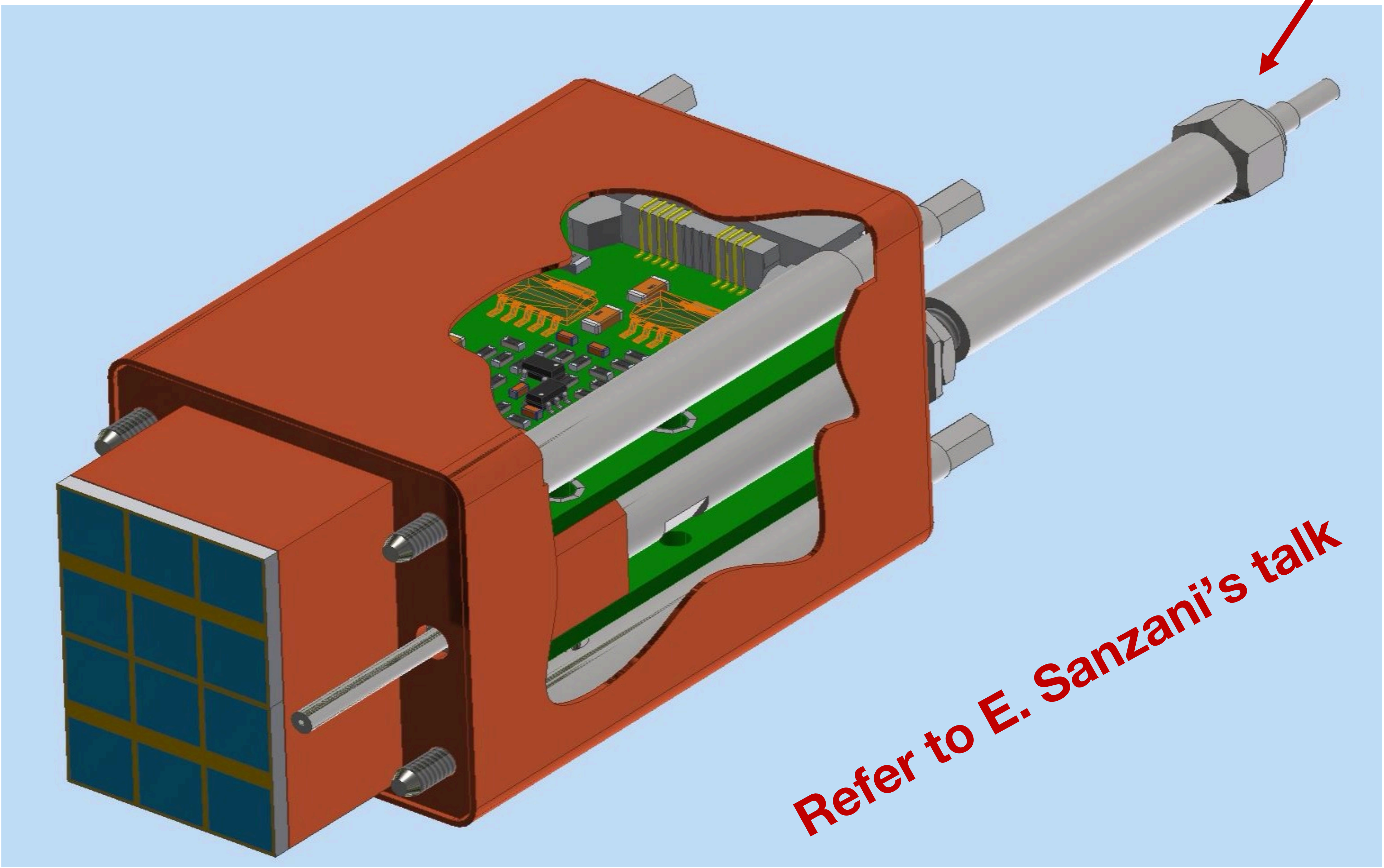
In this talk we will mainly focus on **FEE** and **MB** systems (currently in production)

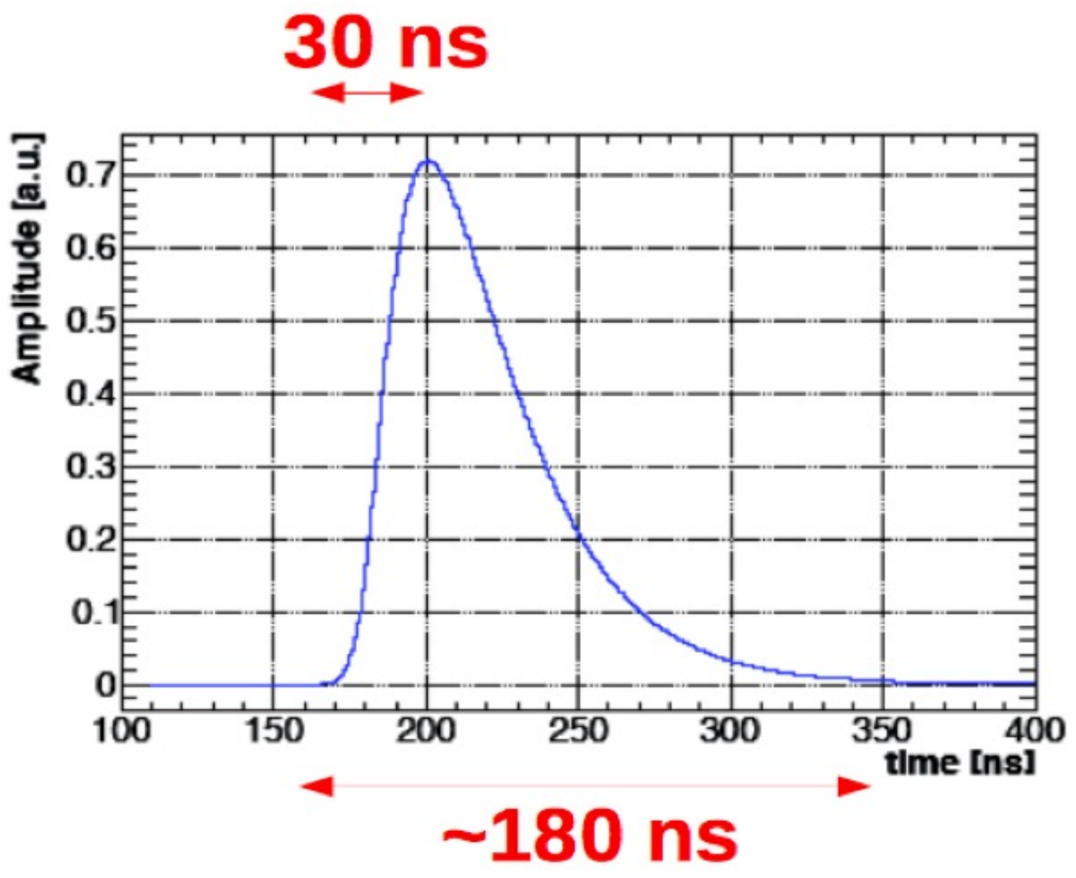
Read-out units

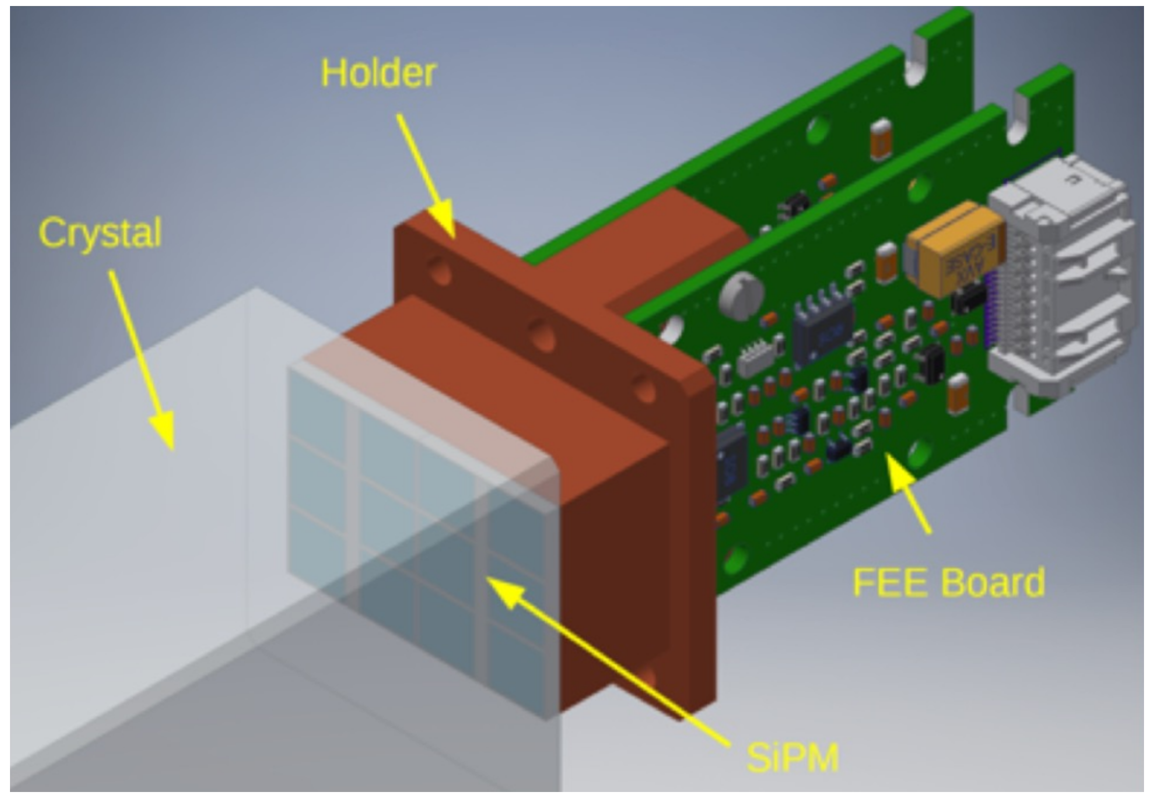


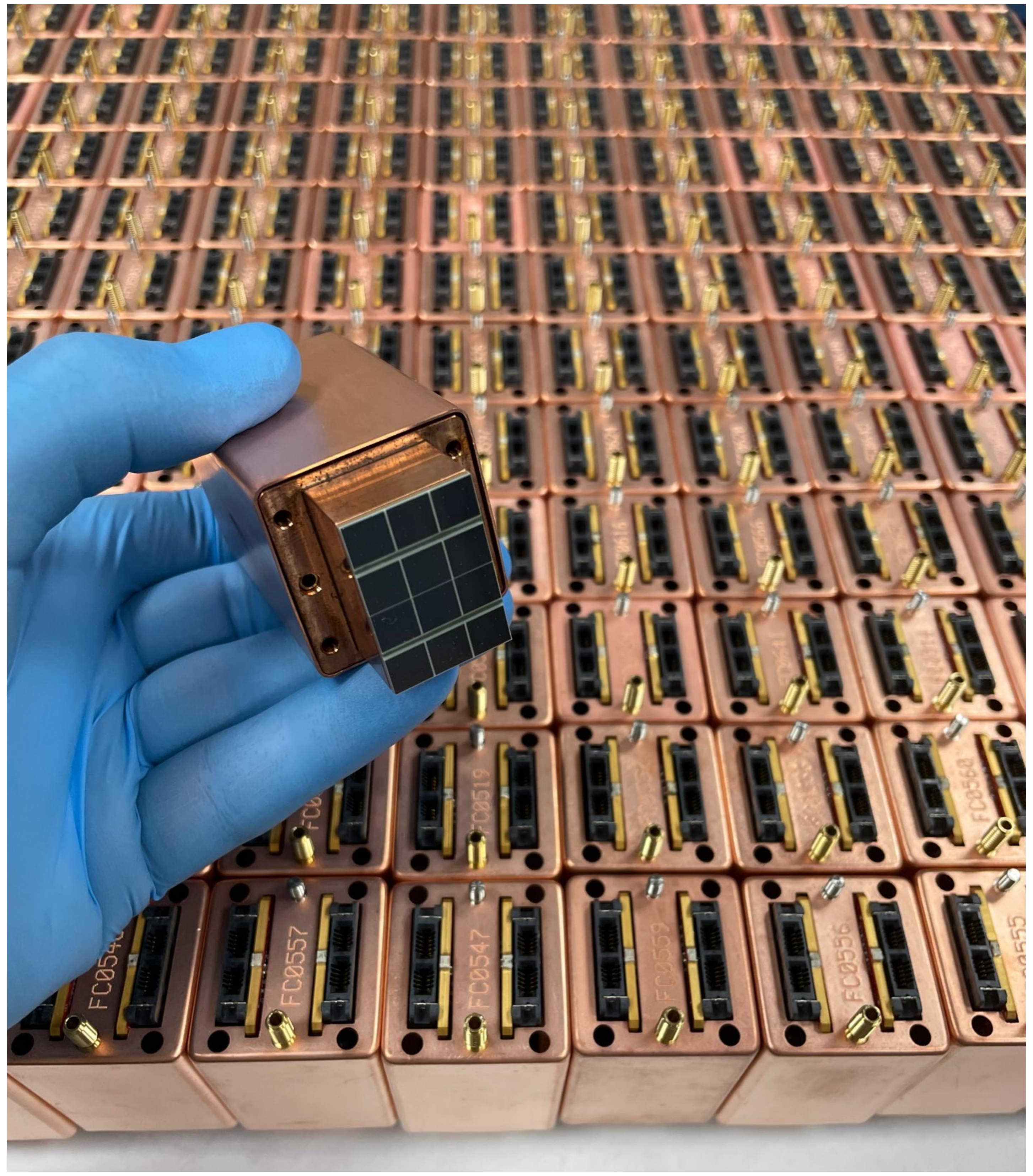
- Two custom large area UV-extended SiPMs
- Two independent readout channels per crystal
- Fully integrated FEE + slow control board

- Thermal block for SiPM cooling
- Fibre optic coupler for laser system distribution





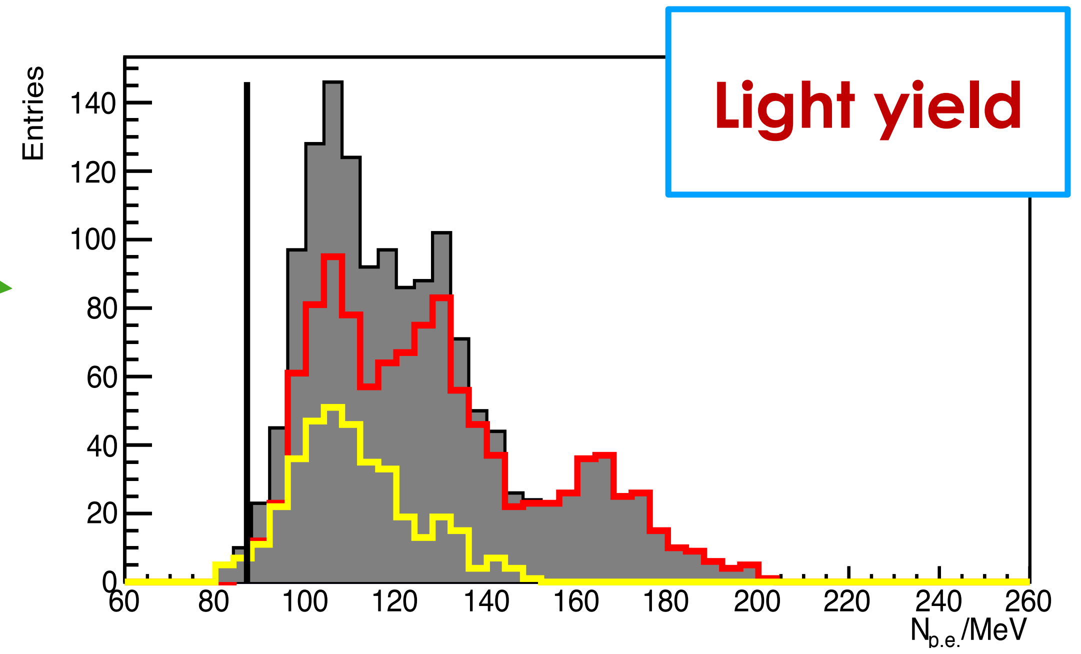


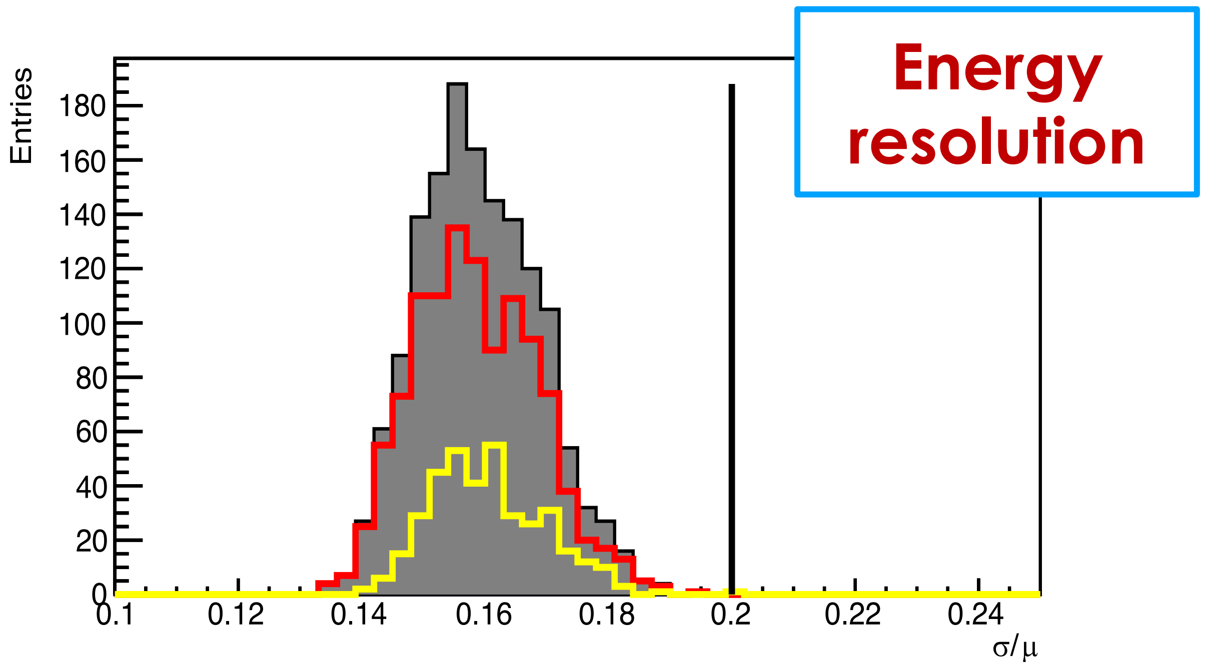


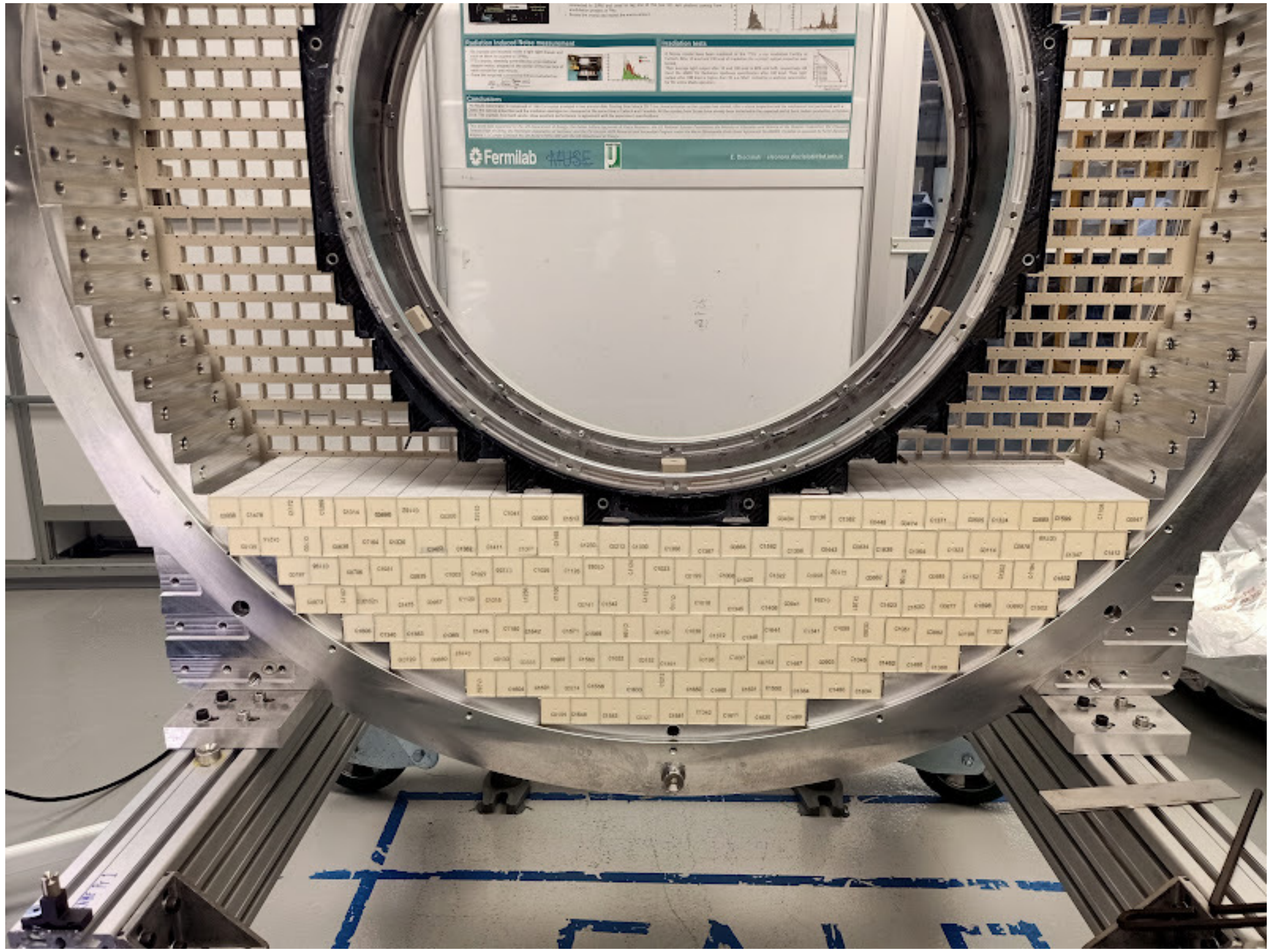
Calorimeter production status

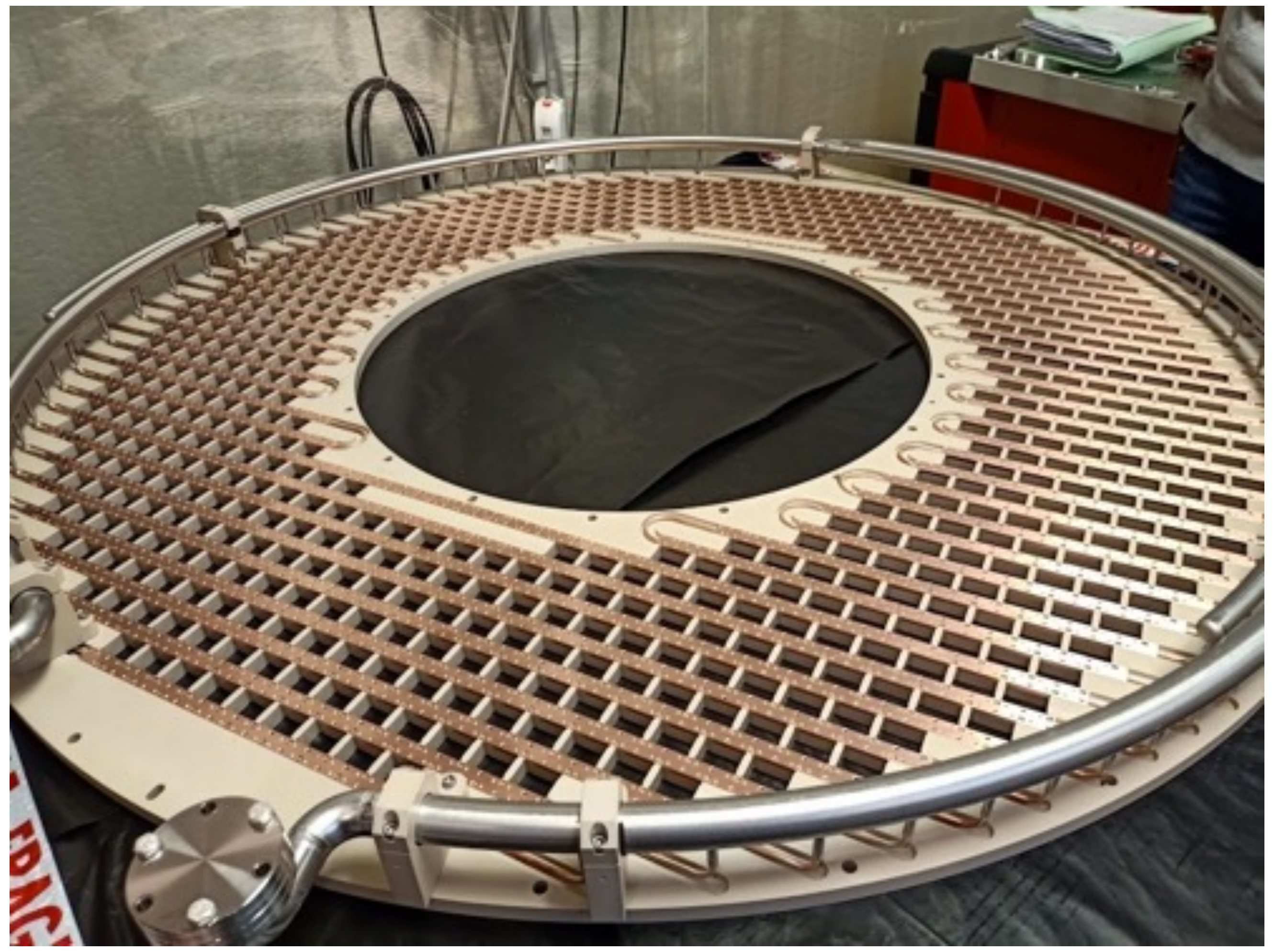
- **Crystals** production and QC (LY, LRU, F/T, RIN) started in 2018 → completed in 2020 ✅
- **SiPM** production and QC (Vbr, Idark, TNID irradiation) completed in 2019 ✅
- **Front-end boards** production ended in late 2021 ✅
- **Read-out units** assembly and QC in progress → refer to E. Sanzani's talk
- **Mechanics** production is being finalised
- Digital electronics production in progress

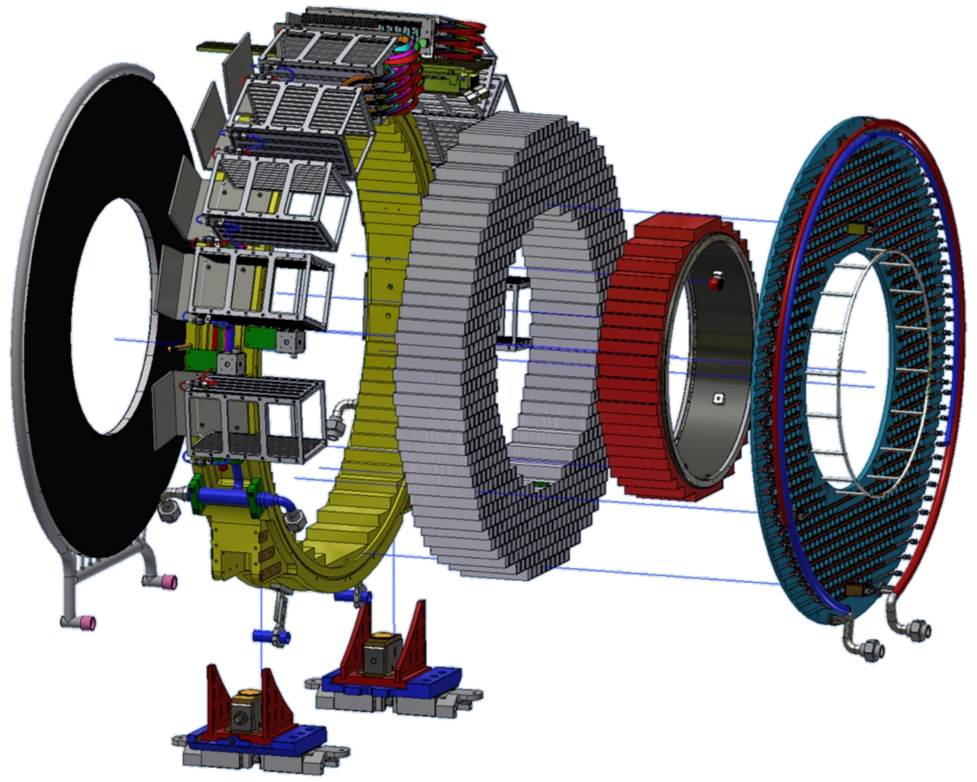
- Assembly of the Calo downstream disk is at SiDet, Fermilab: **crystal outgassing, stacking** and **alignment** in progress, mechanical structure preloading → 1/3 disk completed



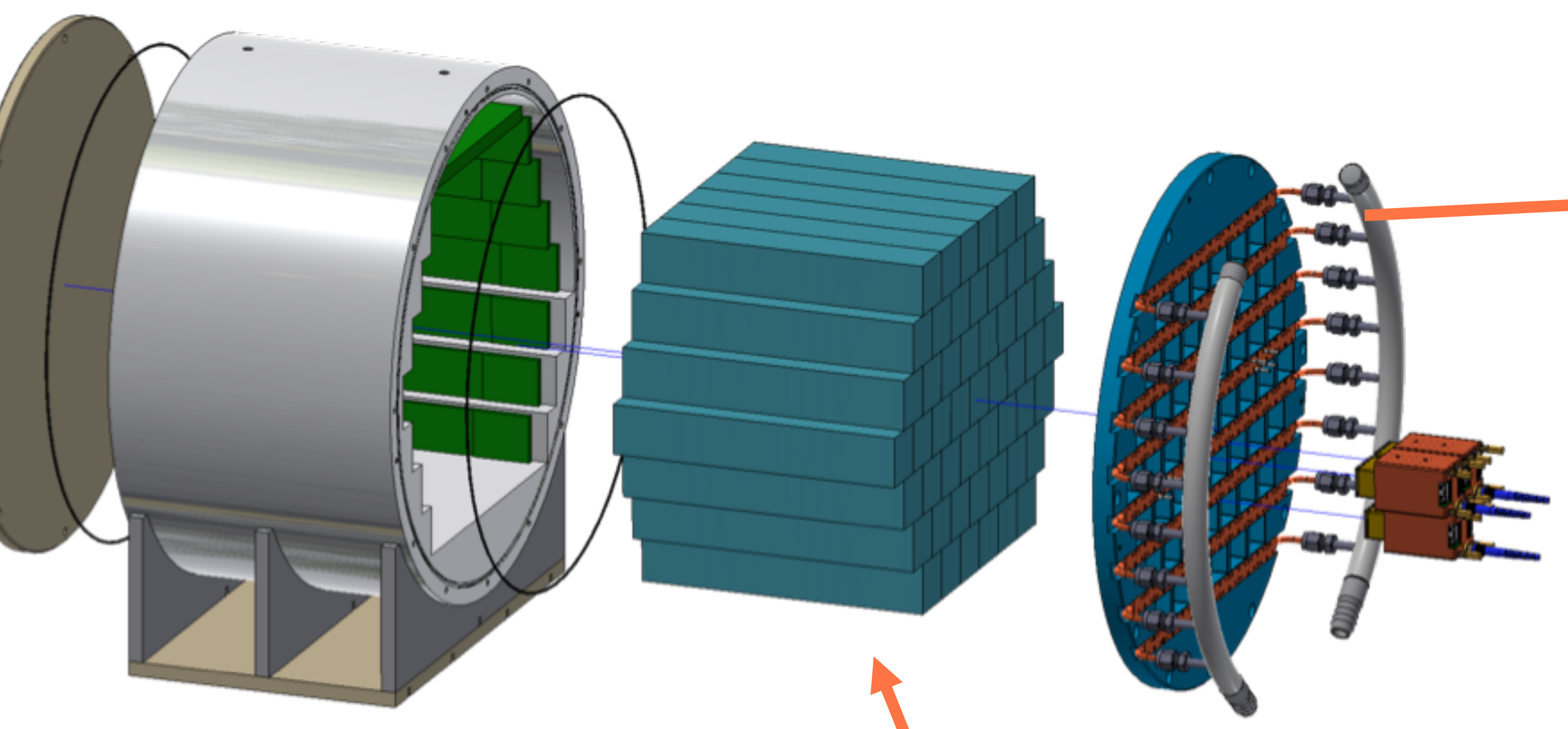


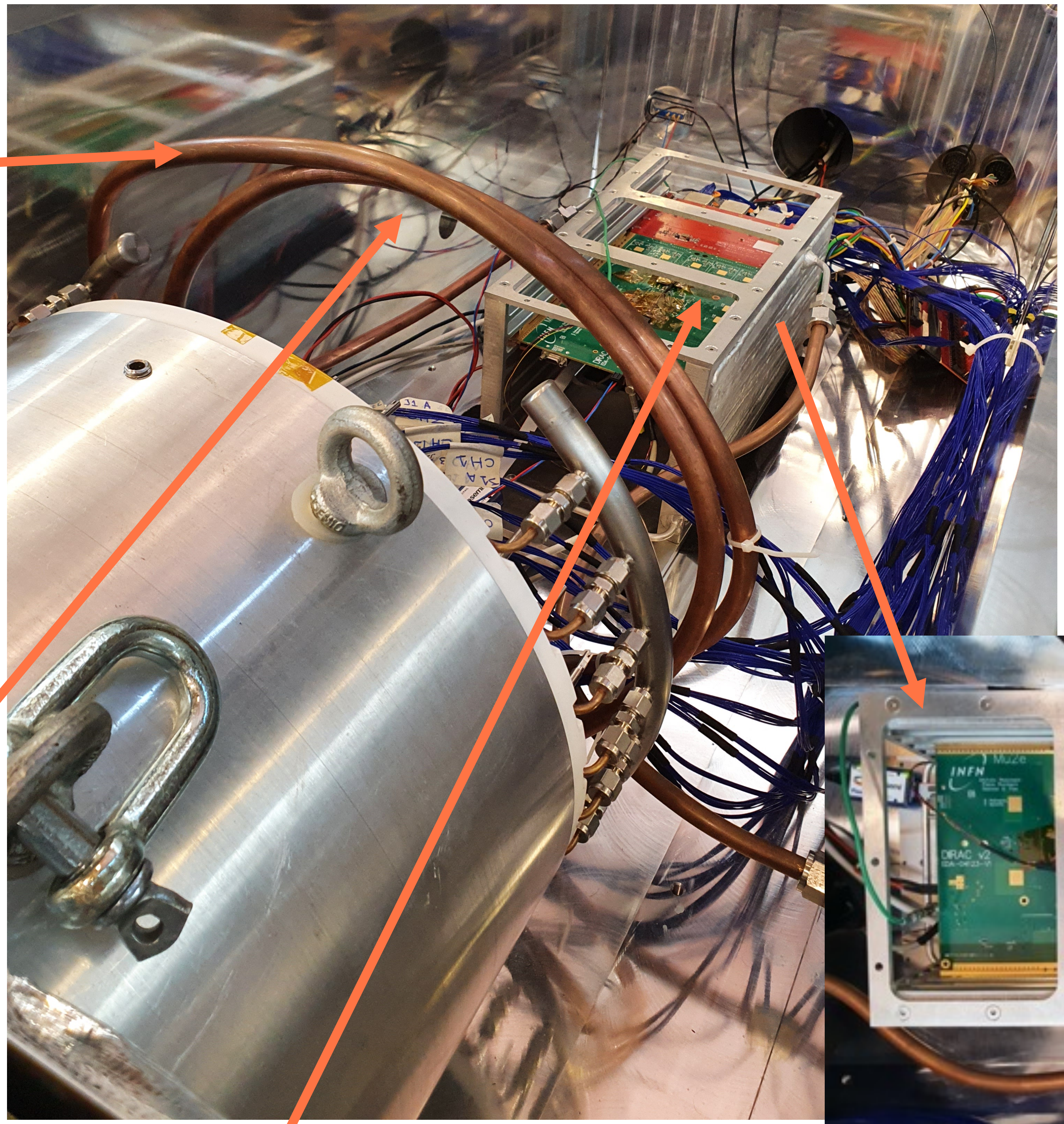


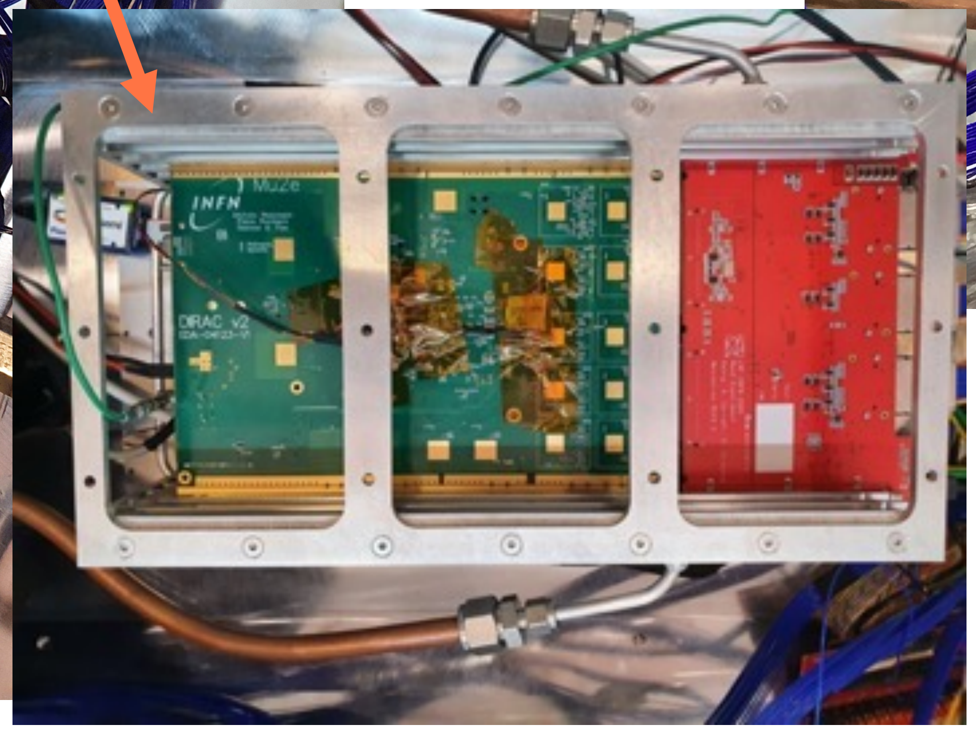


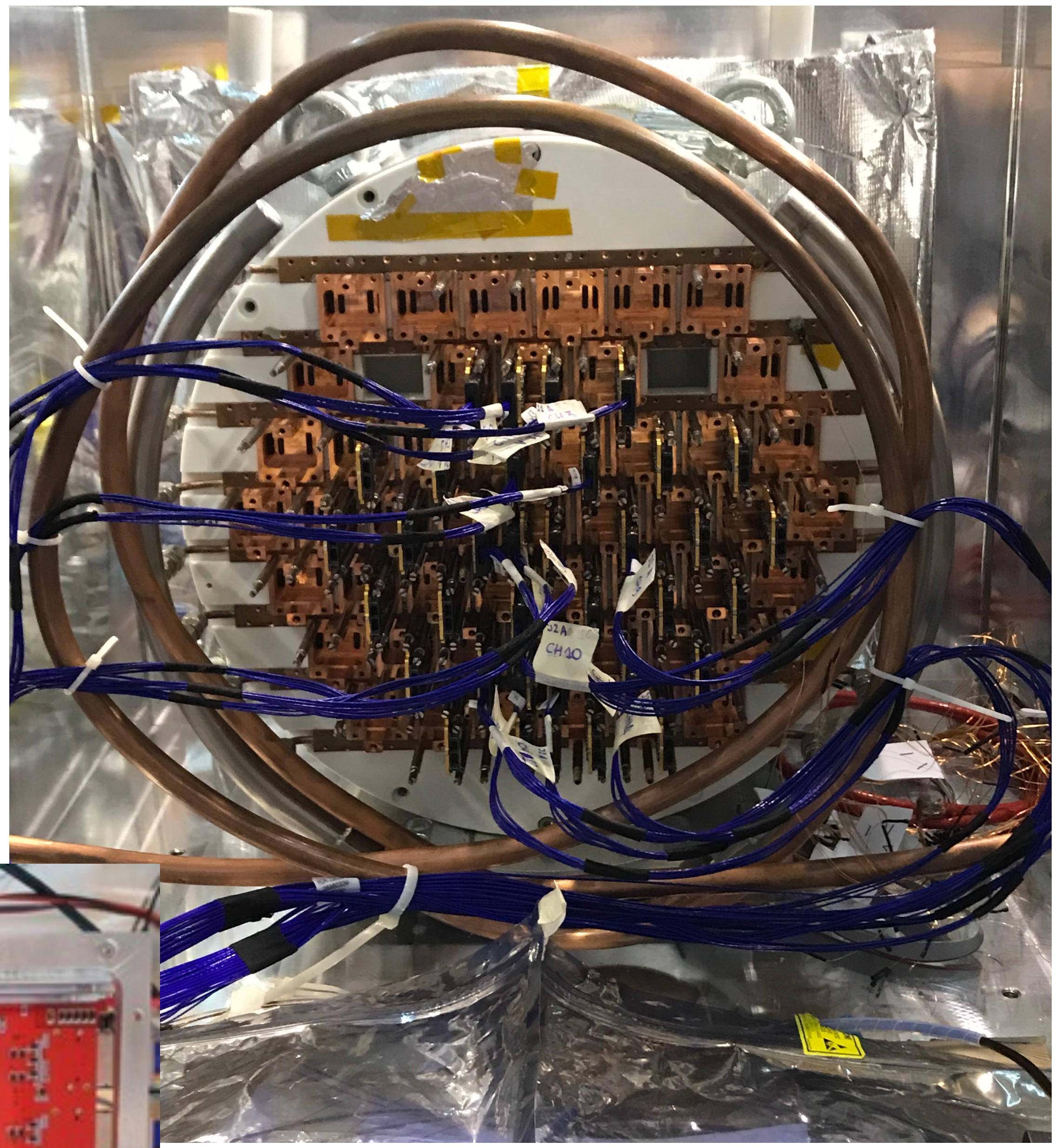


VST with cosmics







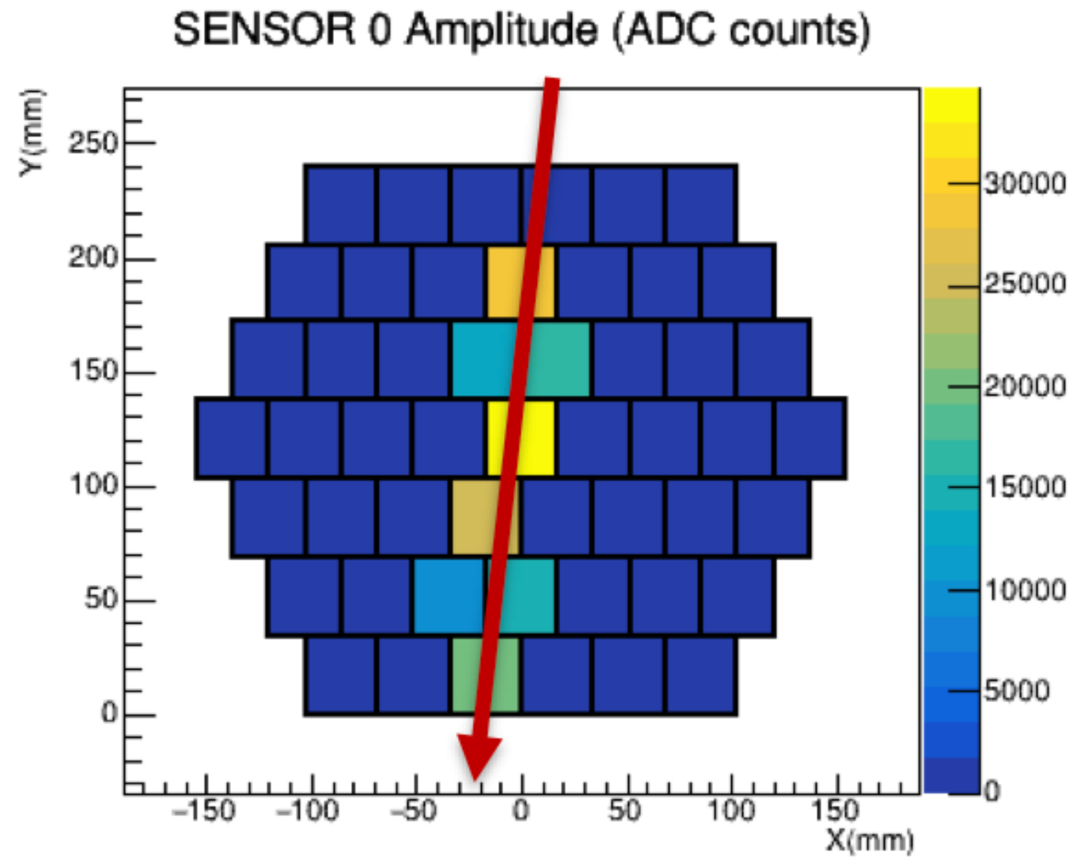


Module-0

- **Large scale prototype** w/51 crystals matrix
- Same cooling system as final Calorimeter
- Same fibre optic laser calibration system as final Calorimeter

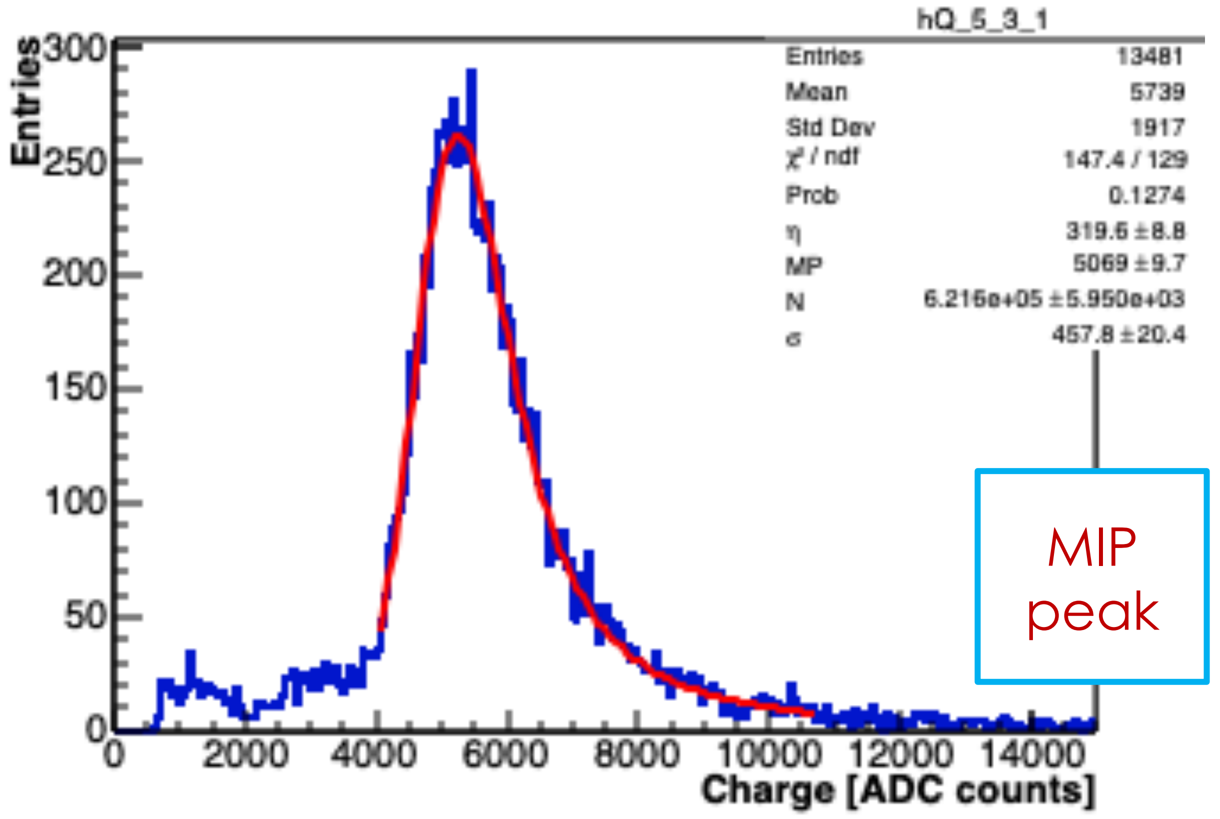
Vertical slice test

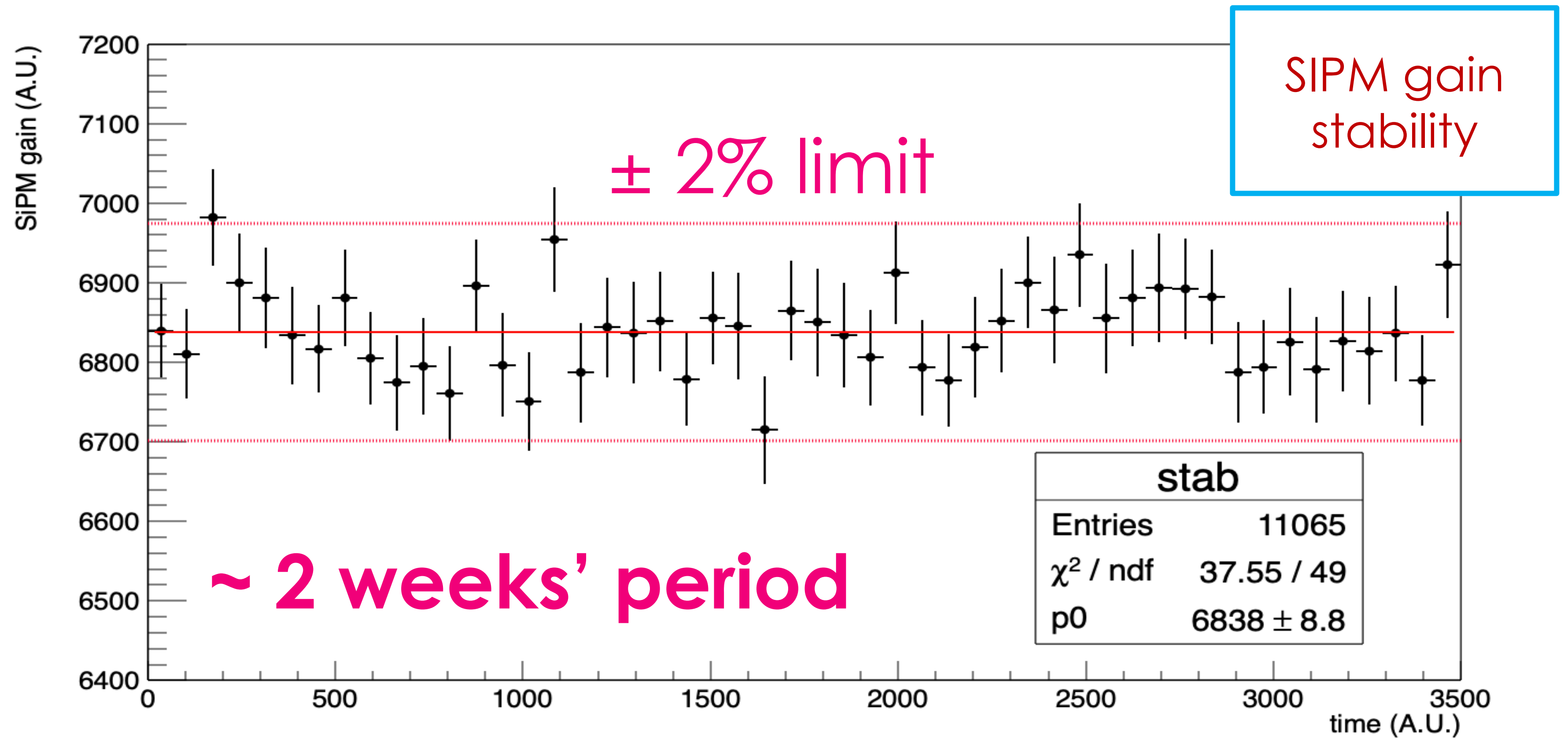
- Final MB and DIRAC versions installed on 1 electronics crate
- Final Mu2e readout chain implemented from FEE to DIRAC digitiser
- Cosmic selector to test whole signal chain with MIPs
- Validation of energy and timing calibration algorithms
- **Tests in vacuum and with cooling system**

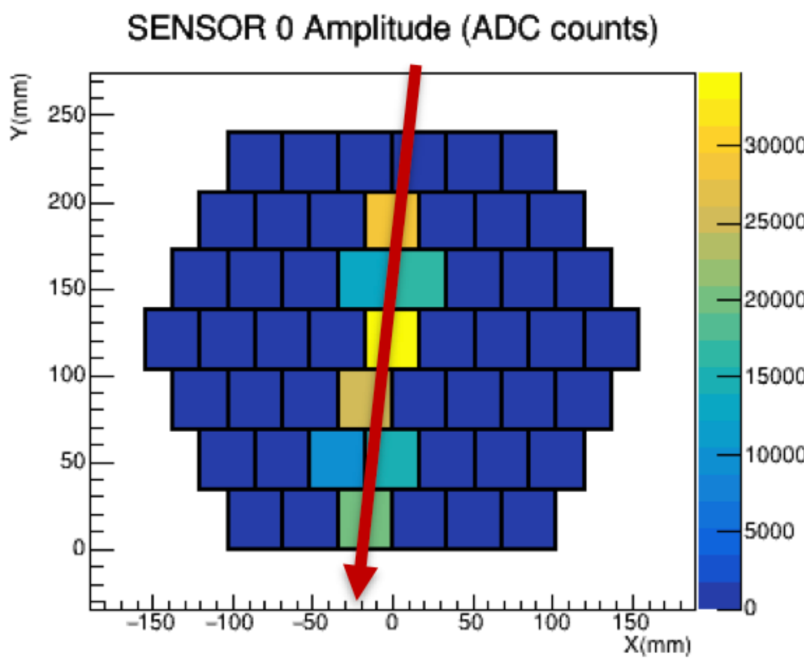


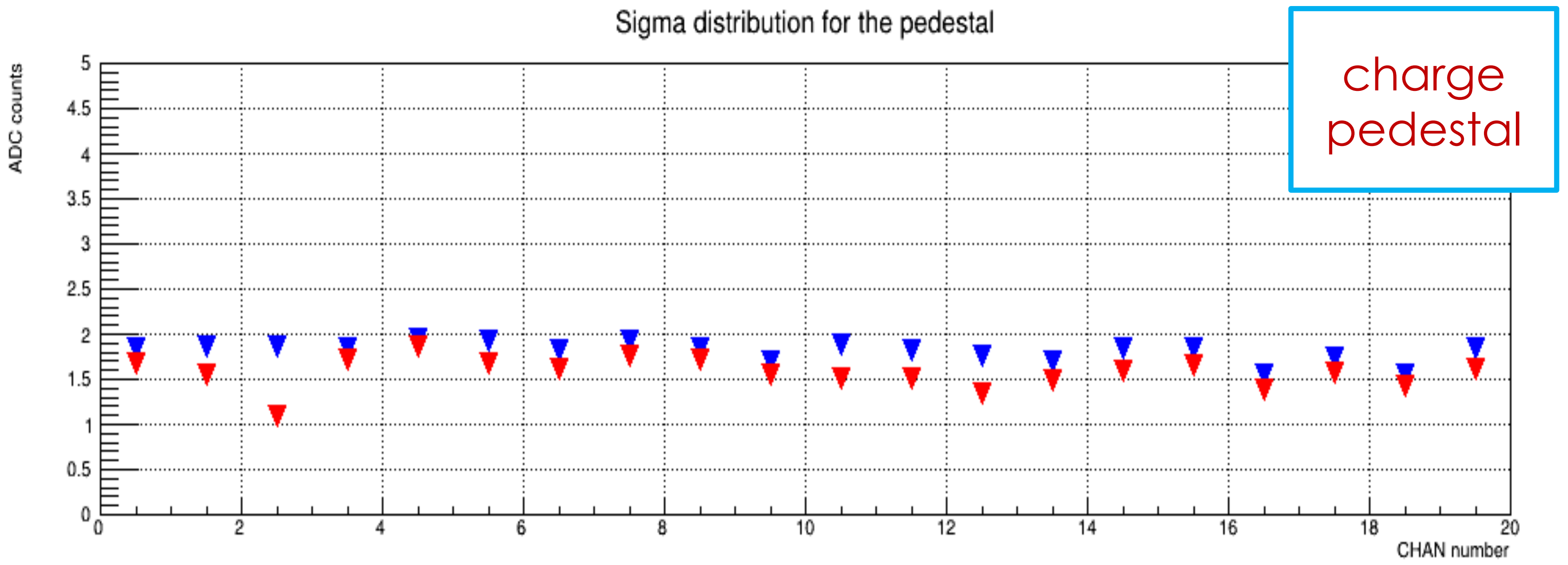
VST with cosmics results overview

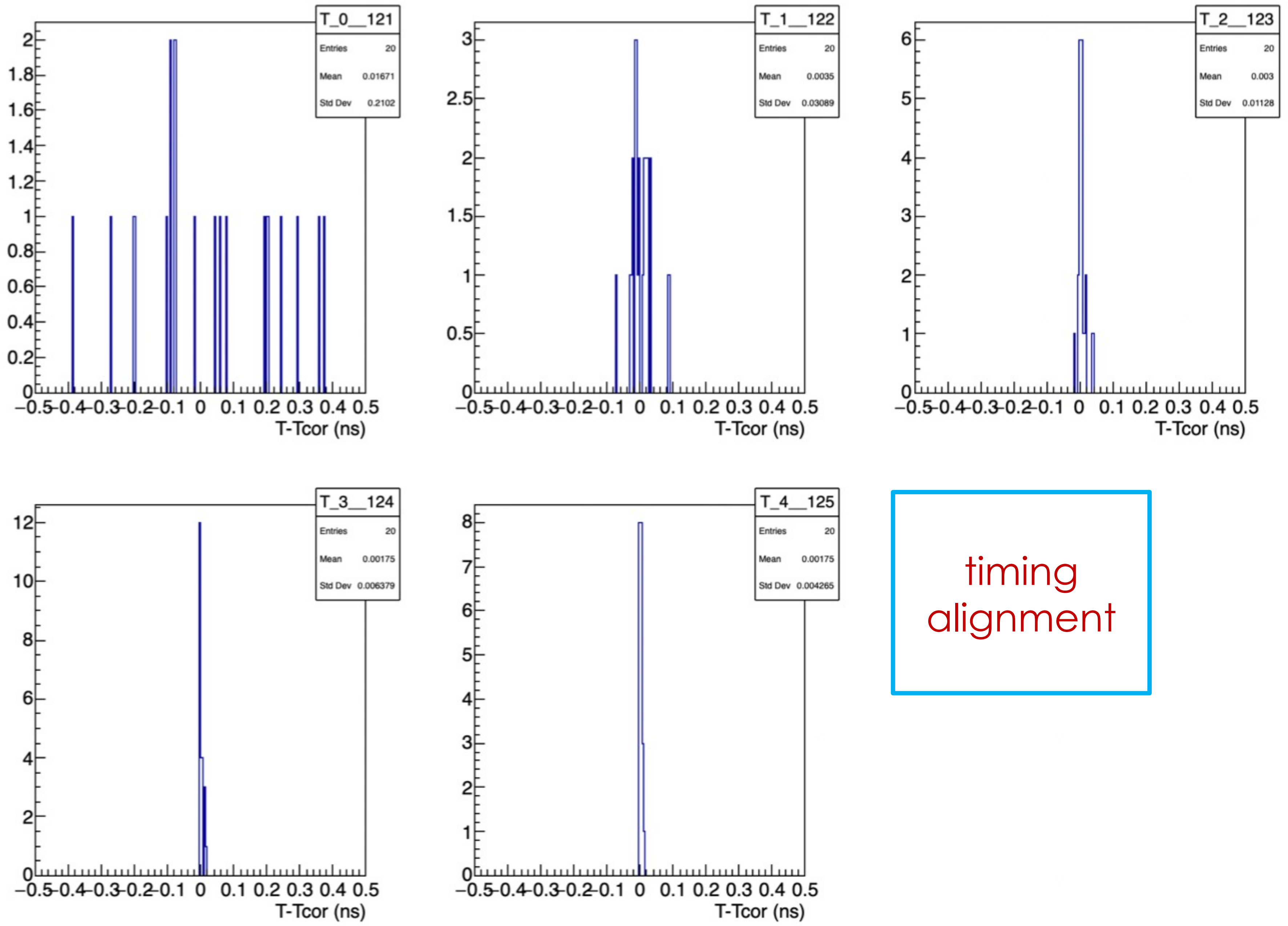
- Module-0 w/ **final readout chain**
- XY (+ YZ slope) **MIP track reconstruction**
- **Energy equalisation** on 21 MeV MIP peak
- NPE (from asymmetry) and **SiPM gain stability** check (+1.6 % /°C for SiPM gain)
- **Equivalent noise** ≈ 200 KeV
- Readout channels **timing offset** correction trough iterative algorithm to a level < 5 ps RMS
- Cell mean **time resolution** w/ MIPs ≈ 210 ps

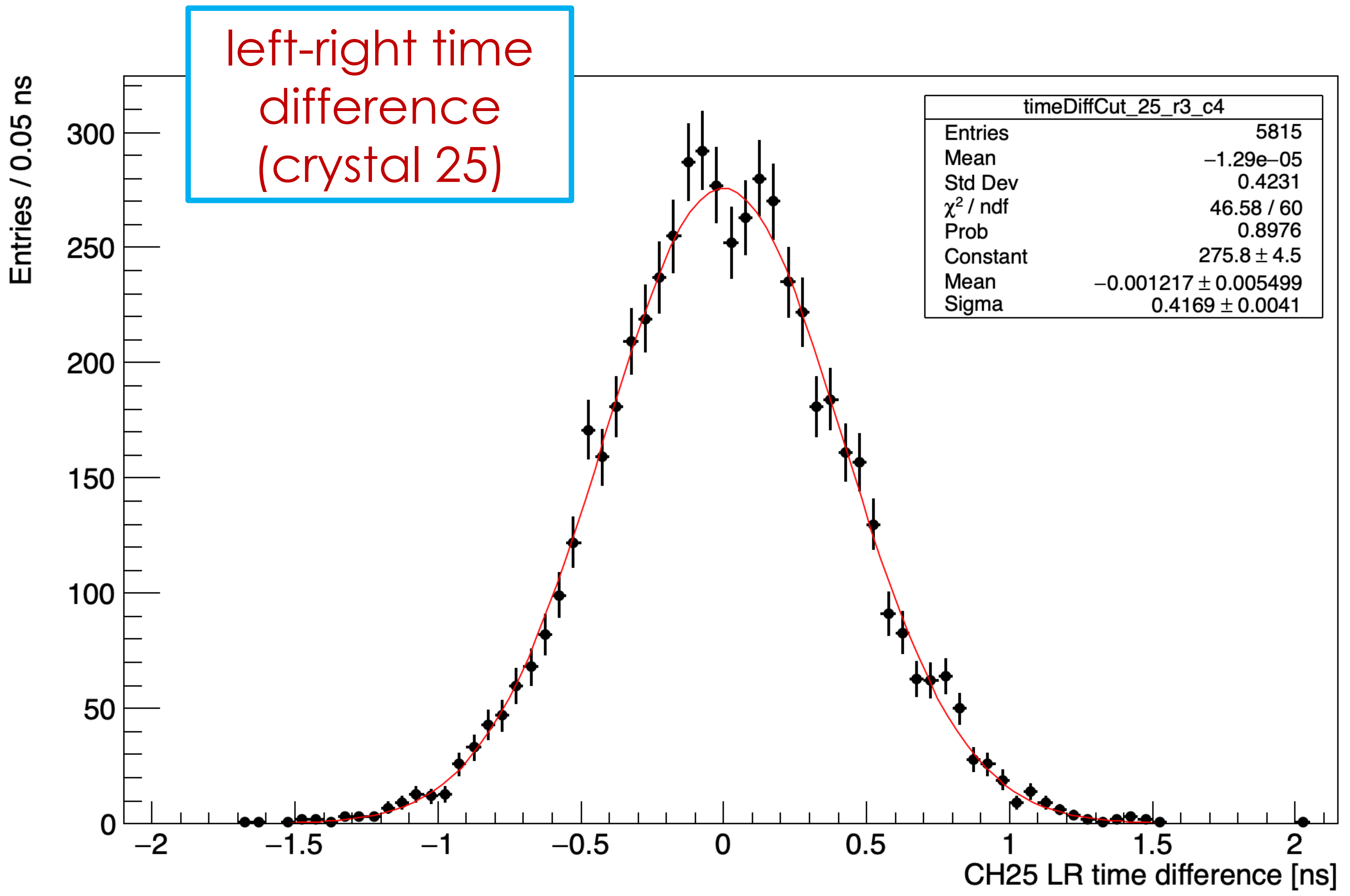


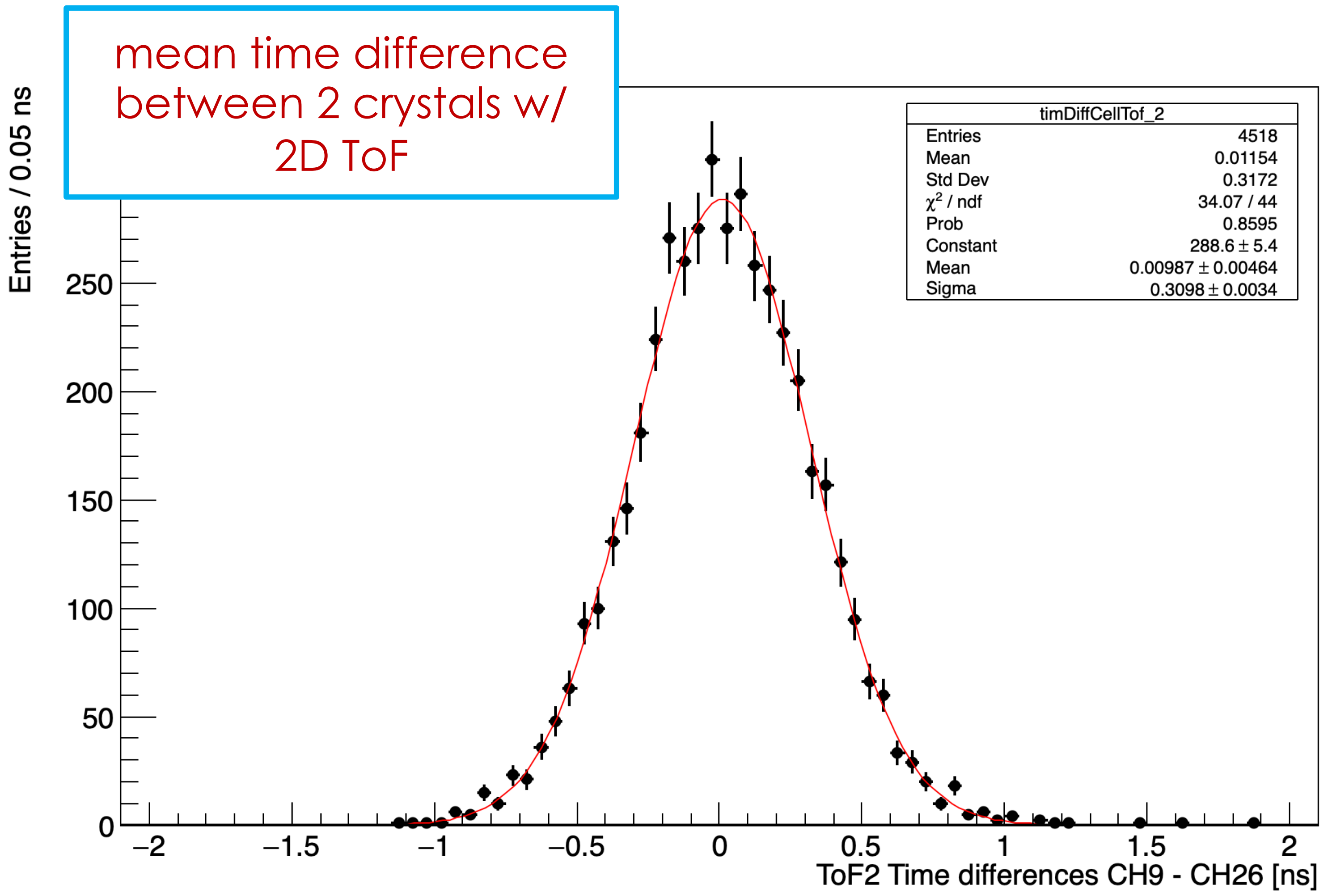




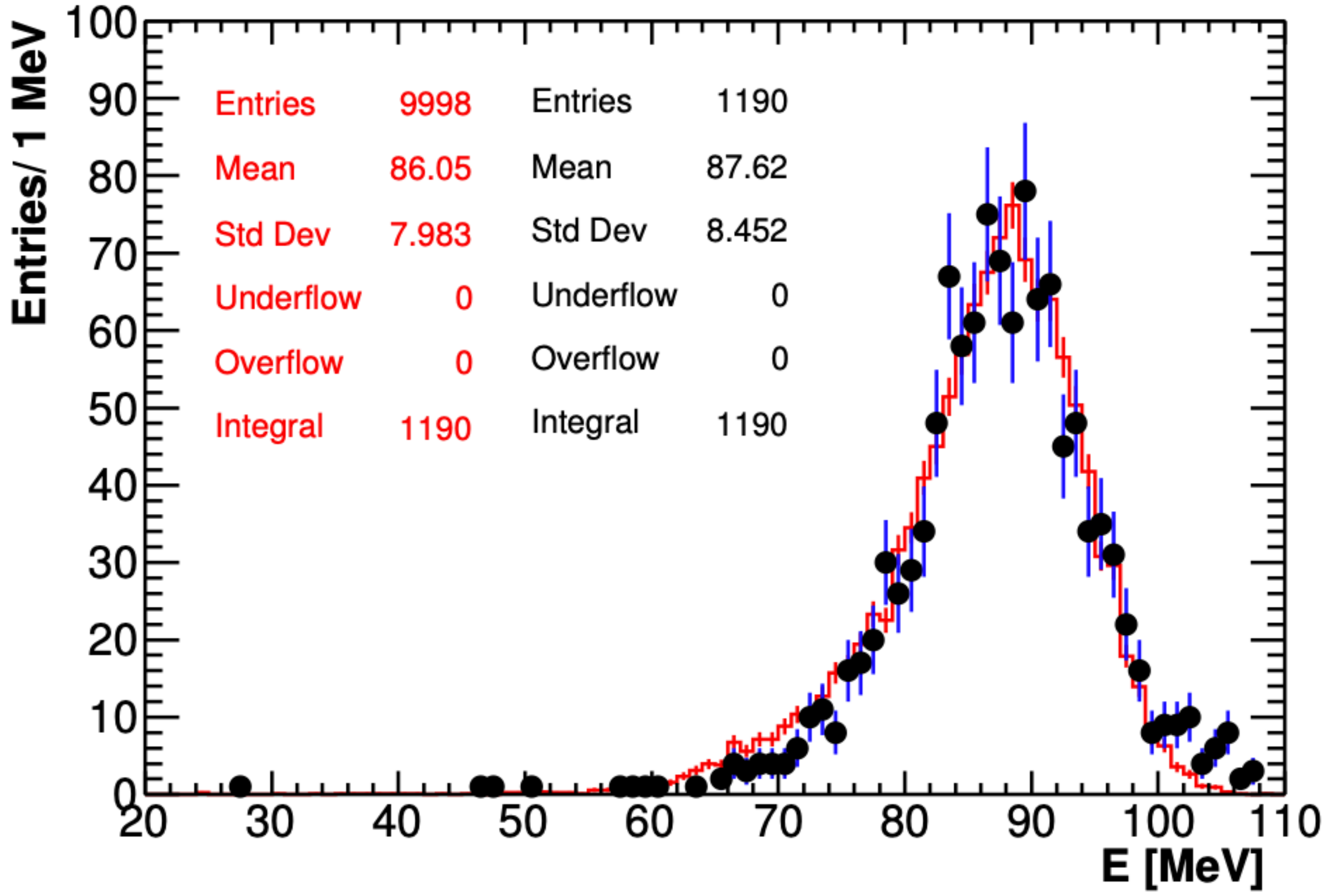


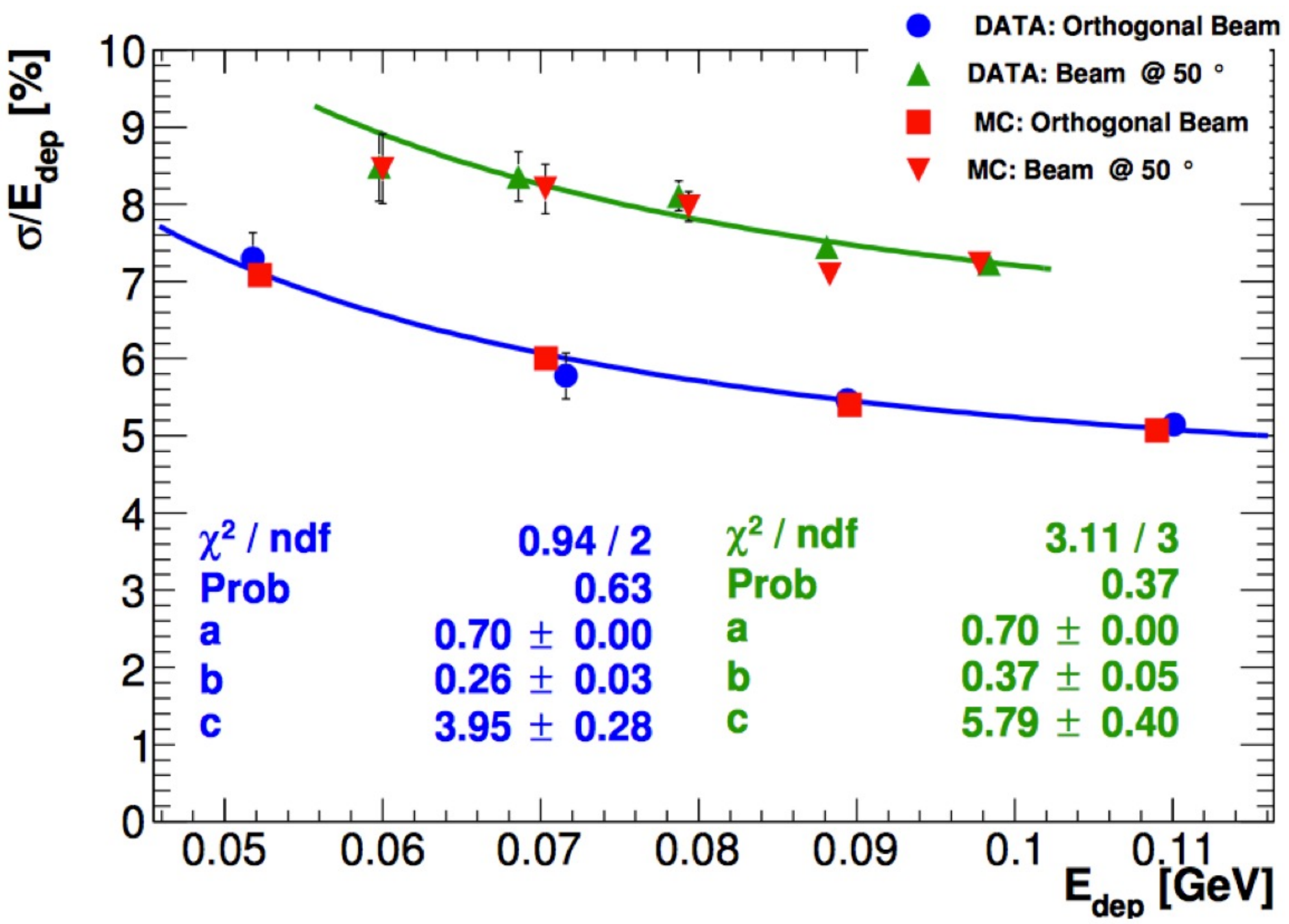






Test beam validation

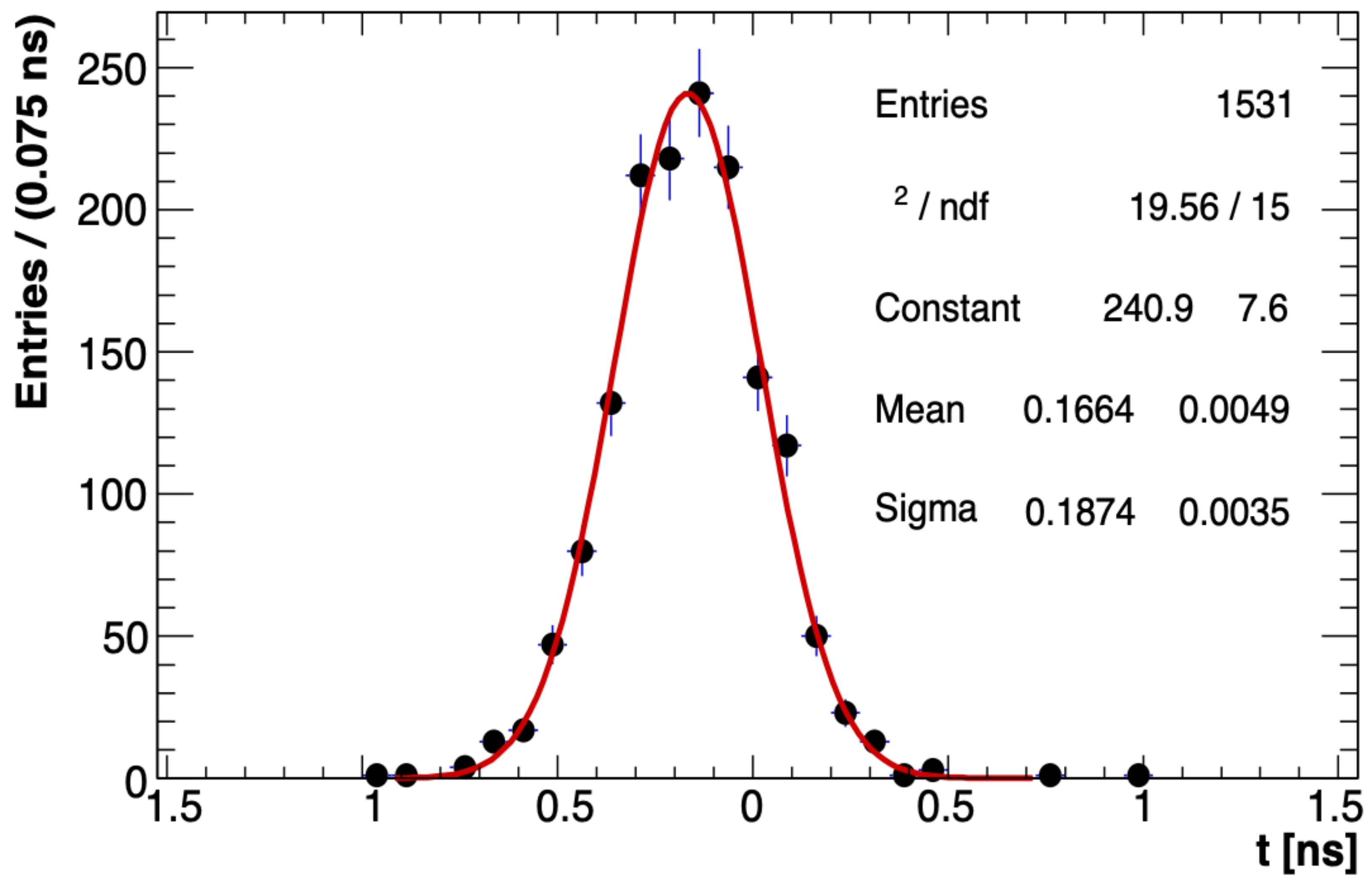


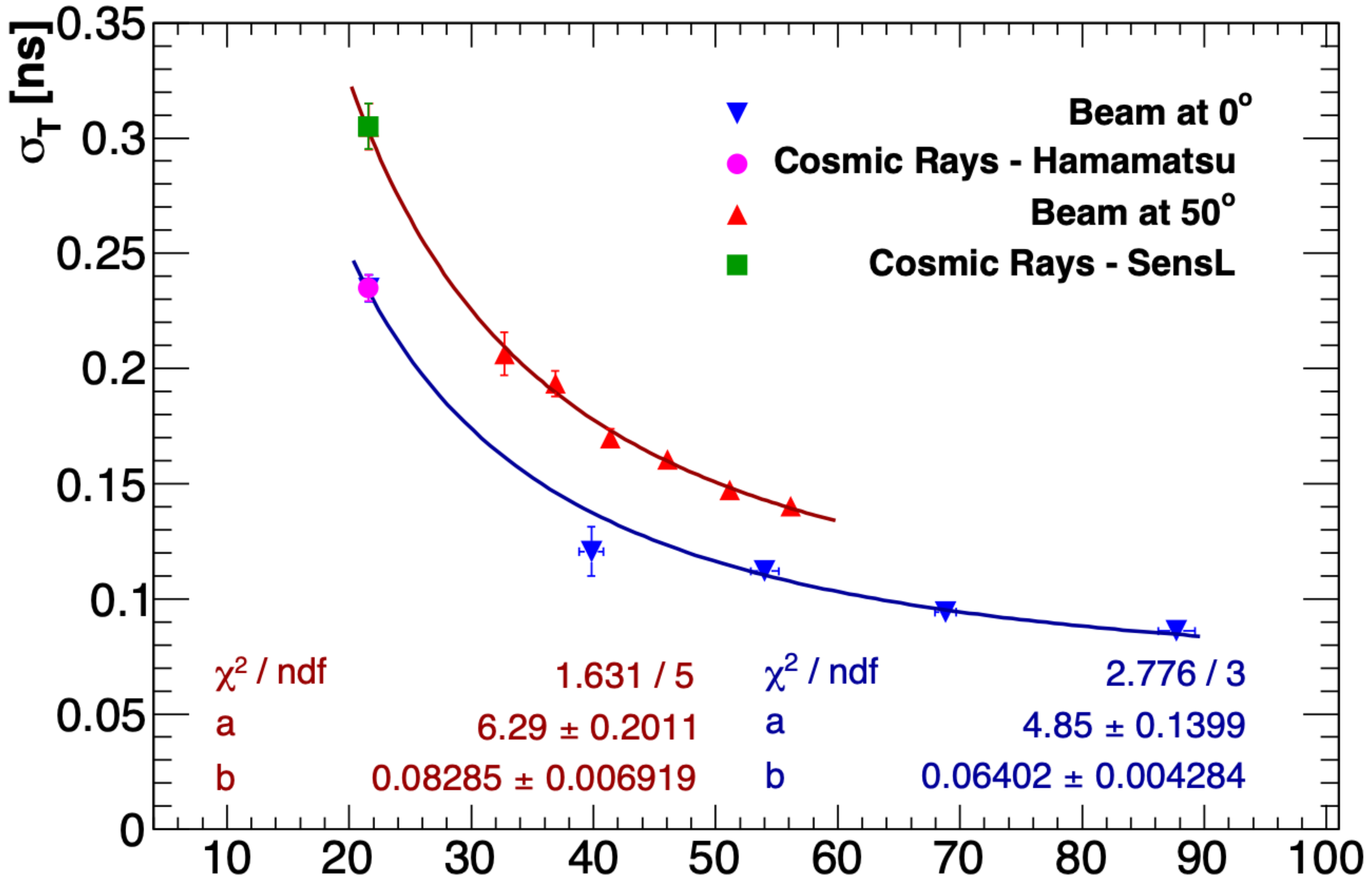


Energy response

- Single particle selection
- MIPs Equalisation & E-scale
- 100 MeV e- beam impinging @ 0° and 50°
- LY/SiPM = 30 pe/MeV
- Great Data-MC agreement

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[GeV]}} \oplus \frac{b}{E[GeV]} \oplus c$$





Time response

- Log-normal fit on leading edge
- 5% CF discrimination
- σ (T1) ~ 130 ps @ Ebeam = 100 MeV

$$\sigma_T = \frac{a}{E[GeV]} \oplus b$$

Conclusions

- ✓ The Mu2e Calorimeter design was fully validated against the harsh operating conditions (B-field, vacuum TID + TNID irradiation)
- ✓ Successful erformance validation w/ 100 MeV e- TB and cosmics VST
- ✓ Production of crystals, SiPMs and FEE completed
- ✓ Production of mechanics almost completed
- ✓ Digital electronics in production as scheduled
- ✓ Downstream calorimter disk assembly in progress at FNAL

Backup

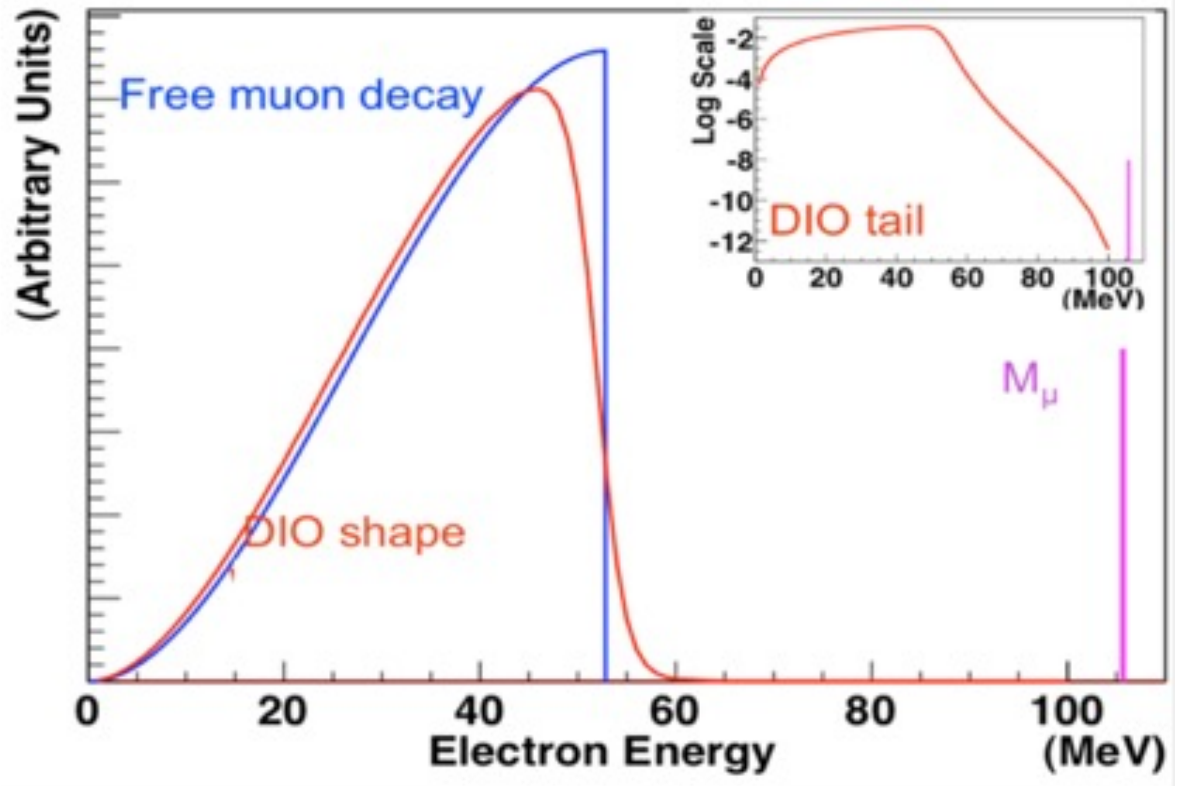
Conclusions

- ✓ The muon conversion experiments (CLFV in general) are excellent tools to look for new physics (BSM)
- ✓ They belong to the Intensity Frontier searches and are complementary to searches @ high-energy colliders while exploring a mass scale not directly accessible
- ✓ The construction of the Mu2e experiment is under way and the commissioning and data taking phase is approaching

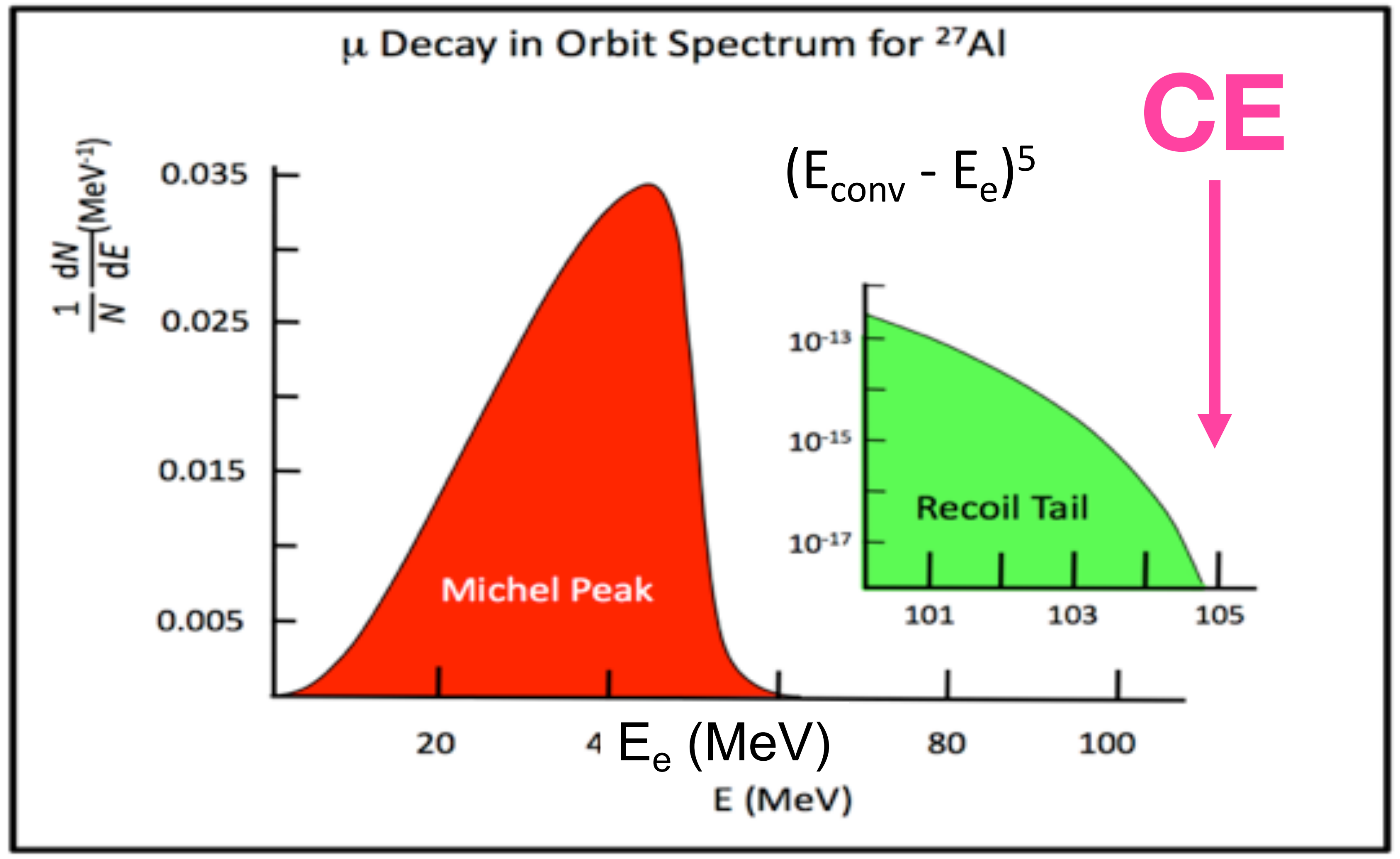
Fermilab

Main backgrounds…

- **Intrinsic** *(scales with μ stopping)*
  - Muon decay in obit (DIO)
  - Radiative μ capture (RMC)



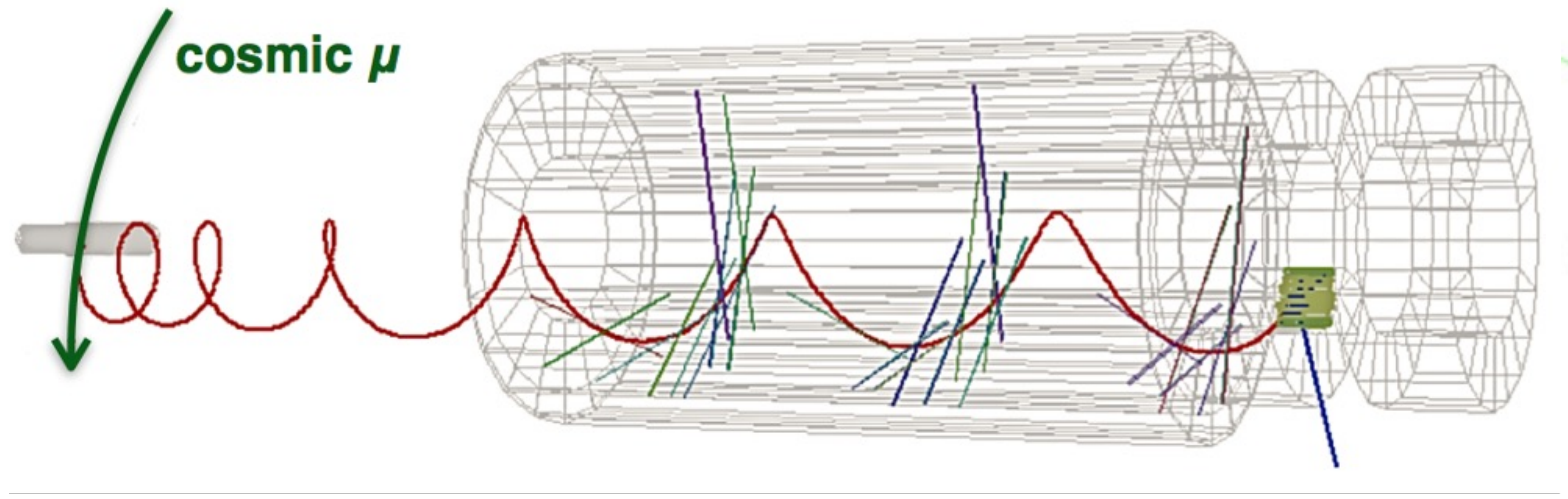
Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2

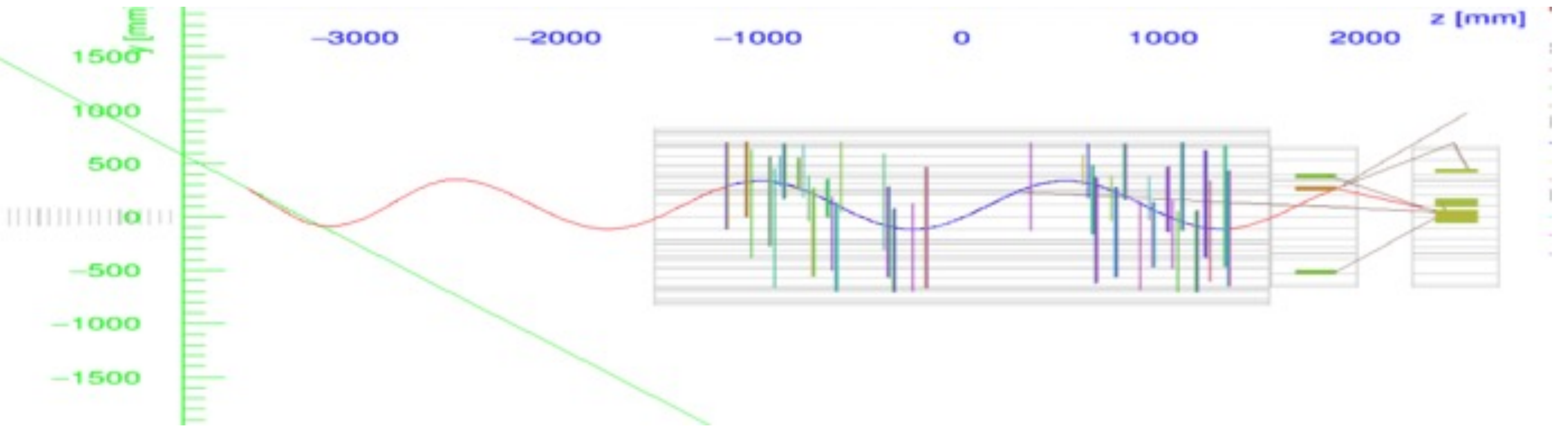


Michel spectrum of e from μ decay gets significantly modified by interaction with the nucleus → presence of a recoil tail with a fast-falling slope close to the μ-e conversion endpoint

- **Late arriving from prompt processes** *(scales with number of late protons)*
  - Radiative π capture
    $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$
    $\pi^- N \rightarrow e^+e^- N'$
  - μ/π decay in flight

- **Cosmic rays** *(1 fake/day)*





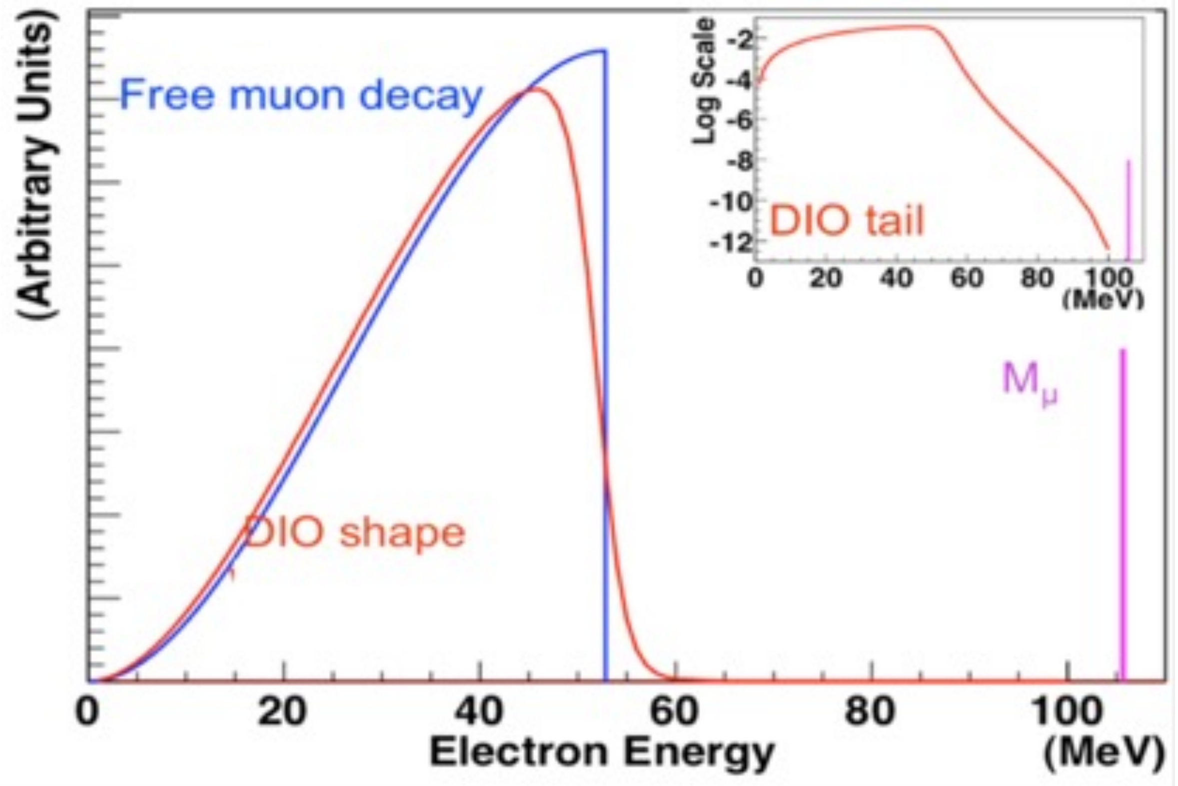
…and solutions

- I ic *(scales with μ stopping)*
  - Muon d bit (DIO)
  - Radiative μ capture (
- L ing from prompt processes *(scales with number of late protons)*
  - Radiative π capt
    $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e$
    $\pi^- N \rightarrow e^+e^- N'$
  - μ/π decay in flight
- **Cosmic ray**
  (1 fake/day)

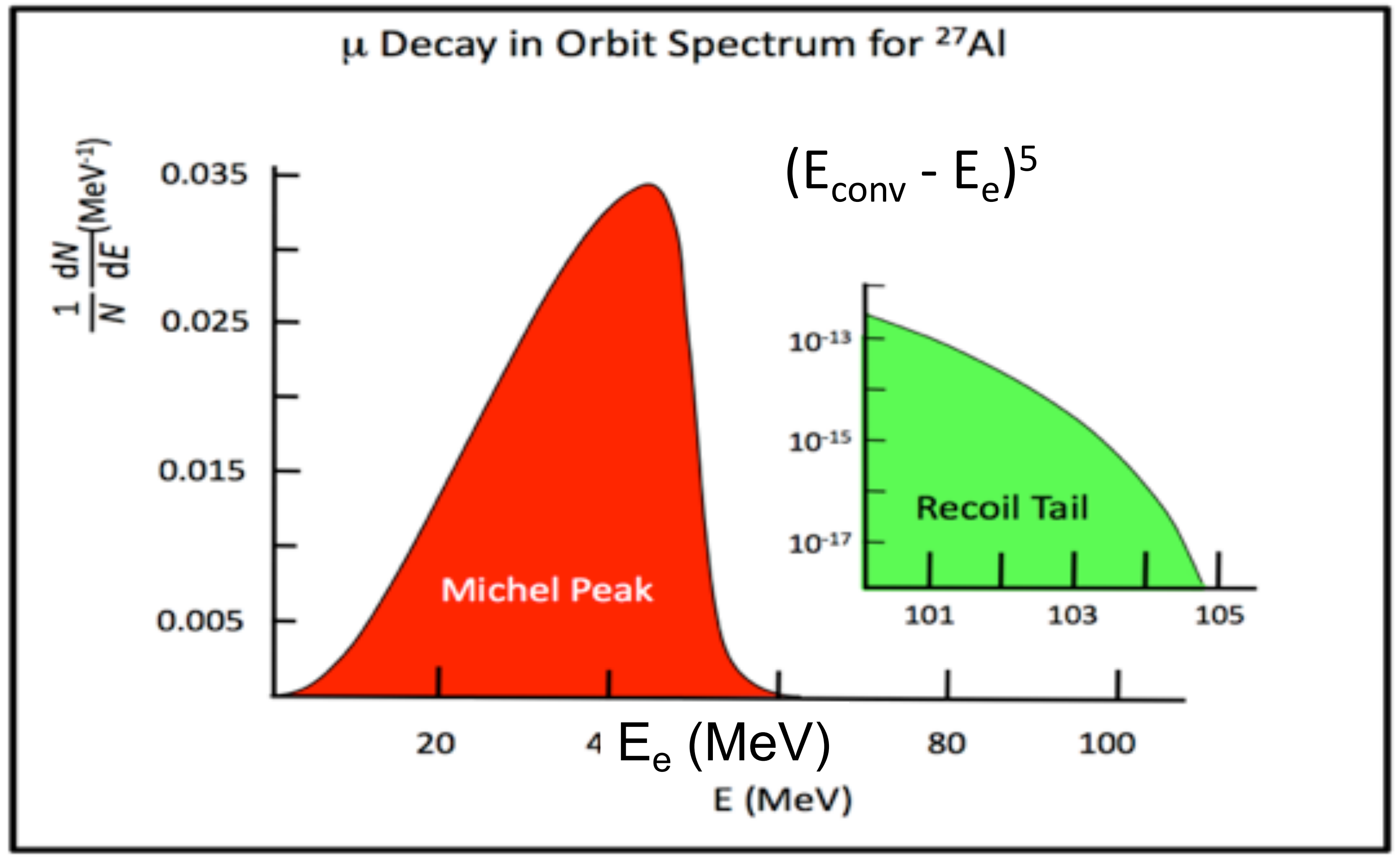
High performance detectors

Pulsed beam

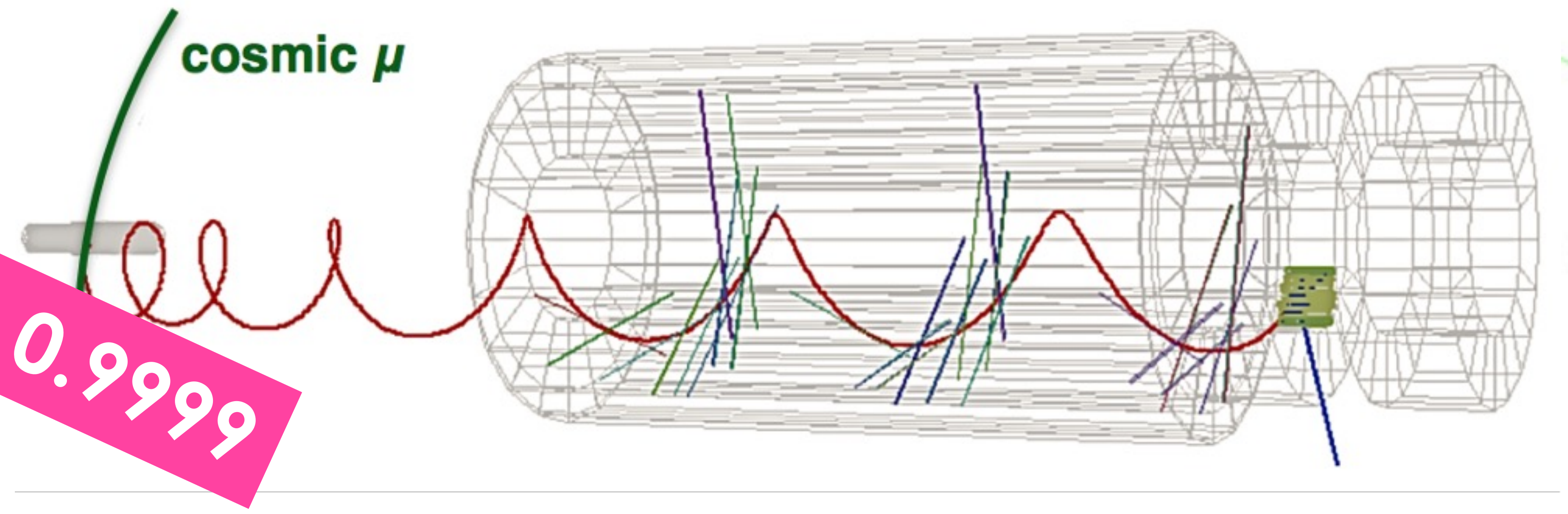
CR veto w/ eff > 0.9999

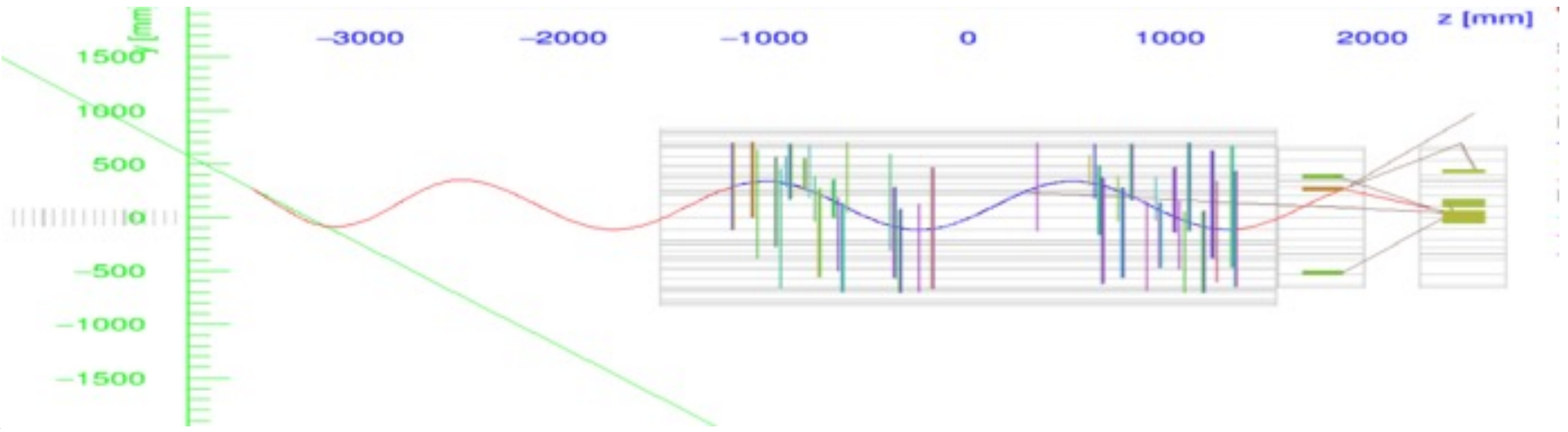


Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2



Michel spectrum of e from μ decay gets significantly modified by interaction with the nucleus → presence of a recoil tail with a fast-falling slope close to the μ-e conversion endpoint



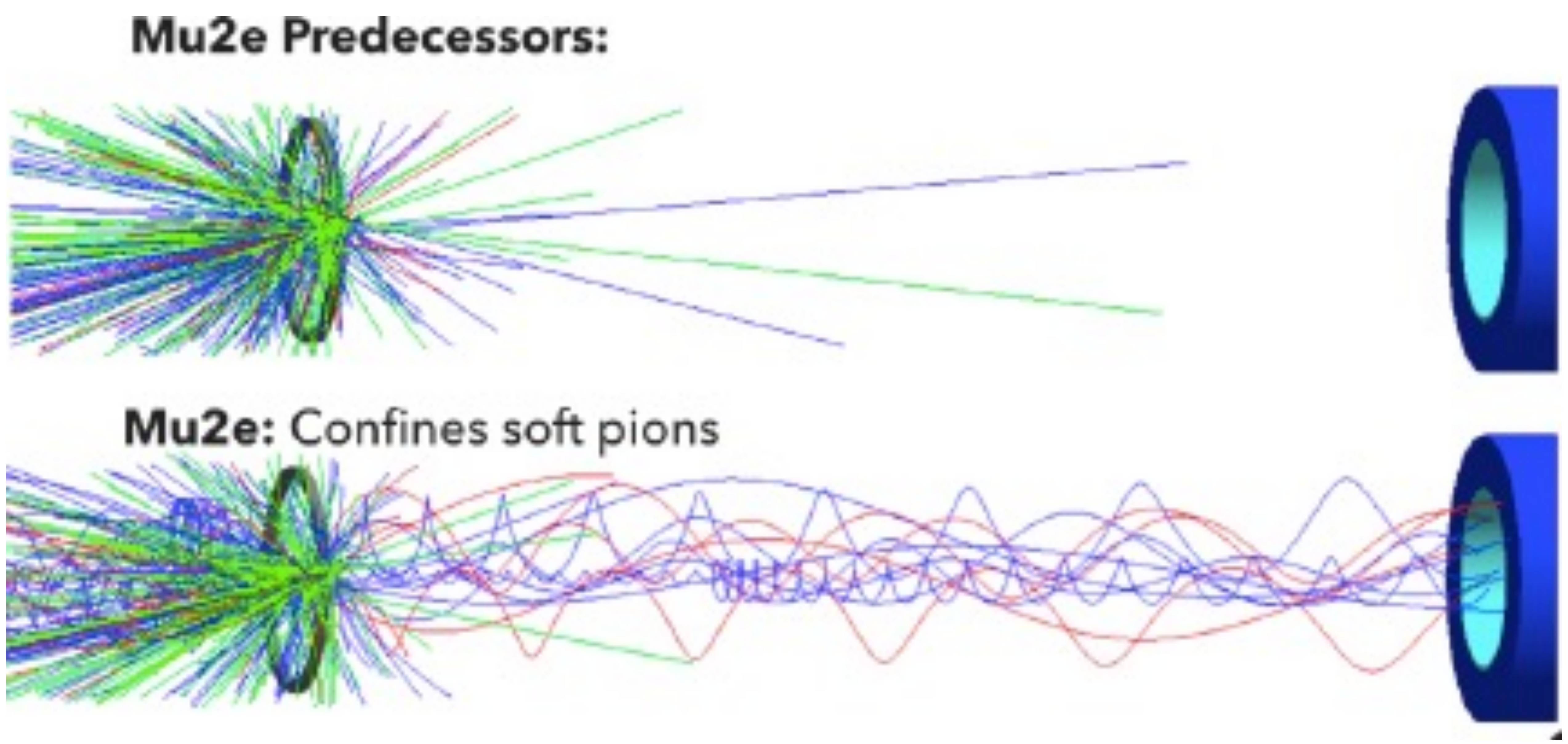


Keys to Mu2e success

- **High intensity pulsed proton beam**
  - Narrow proton pulses (< ± 125 ns)
  - Very few out-of-time protons (extinction < 10^{-10})
  - $3x10^7$ proton/pulse

- **High efficiency in transporting muon to Al target**
  - Need of a sophisticated magnet with gradient fields

- **Excellent detector for 100 MeV electrons**
  → Excellent momentum resolution (< 200 keV core)
  → Calorimeter for PID, triggering and track seeding
  → High Cosmic Ray Veto (CRV) efficiency (>99.99%)
  → Thin anti-proton annihilation window(s)

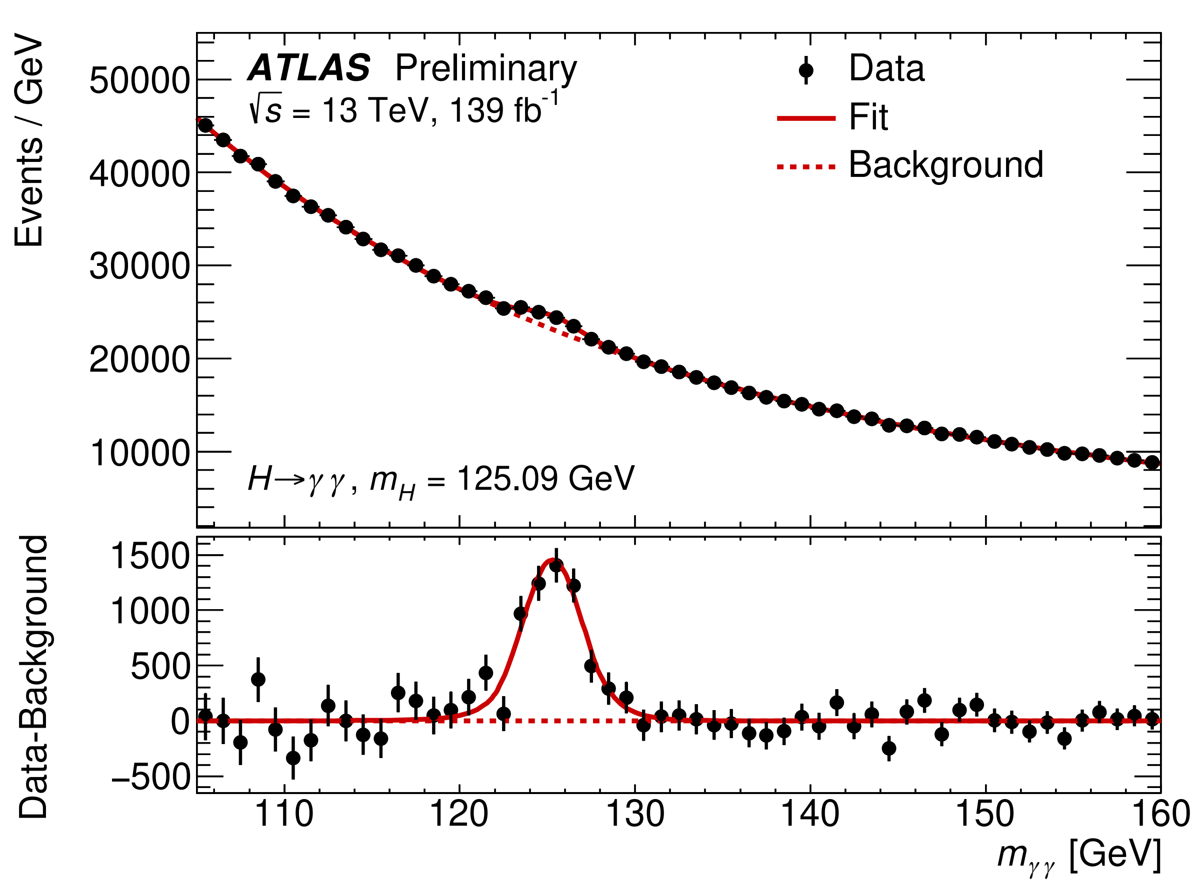


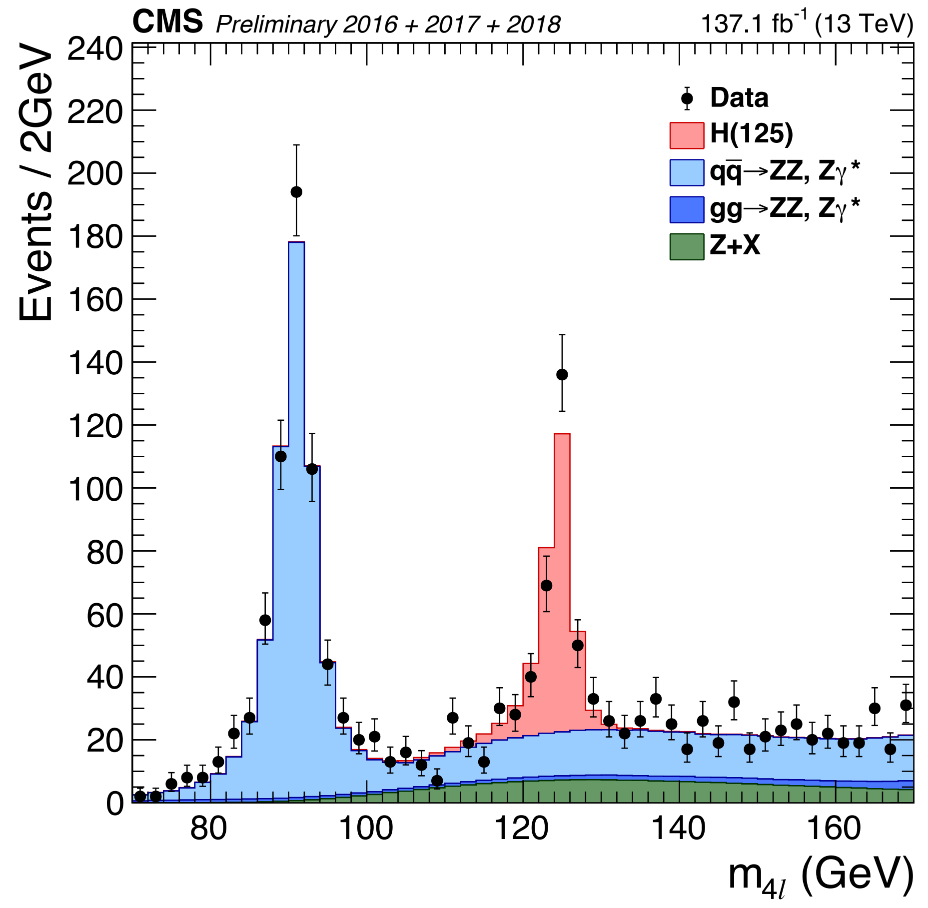
Concept by Lobashev and Djilkibaev
Sov.J.Nucl.Phys. 49, 384 (1989)

Introduction: SM

The Standard Model (SM) represents our better =understanding of particles and forces (besides gravity) and it is very successful at describing a wide range of observations, but it does
not explain yet:

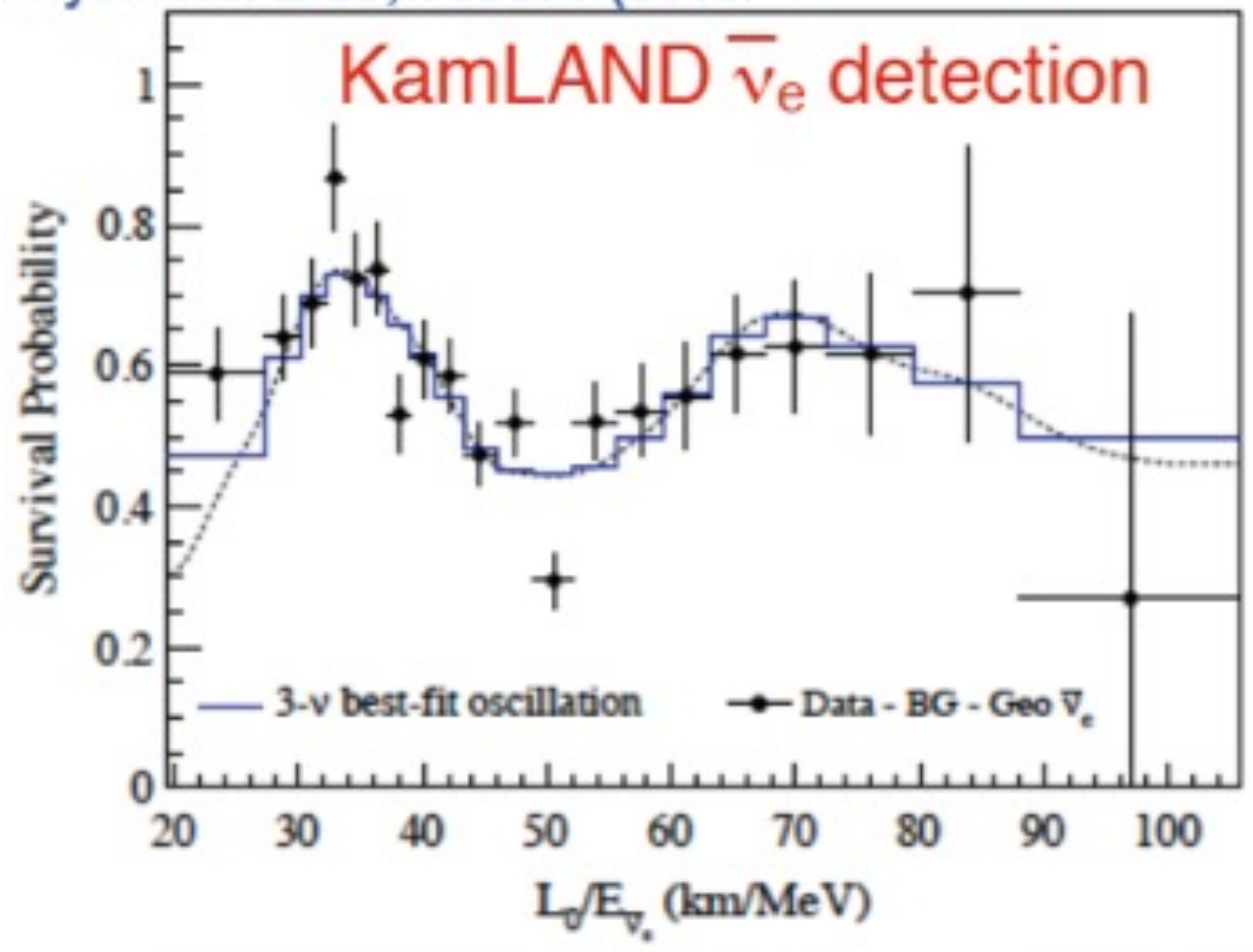
- number of generations
- Pattern of masses
- dark matter / dark energy
- prevalence of matter over antimatter
- …





And it doesn't account for neutrino mixing, which requires massive neutrinos (and which implies lepton number violation).

Phys. Rev. D 88, 033001 (2013)



There should be physics beyond the SM!

Are CLFV processes relevant ?

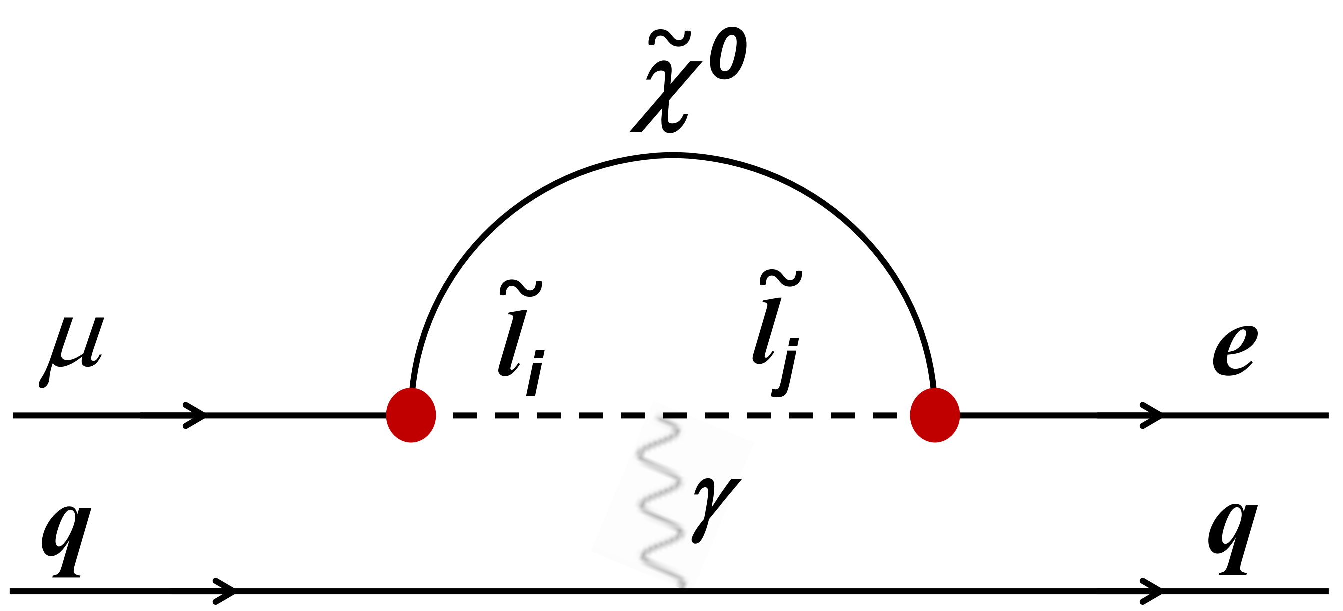
W. Altmannshofer, *et al*, `arXiv:0909.1333 [hep-ph]`

	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.

Specific Example: SUSY

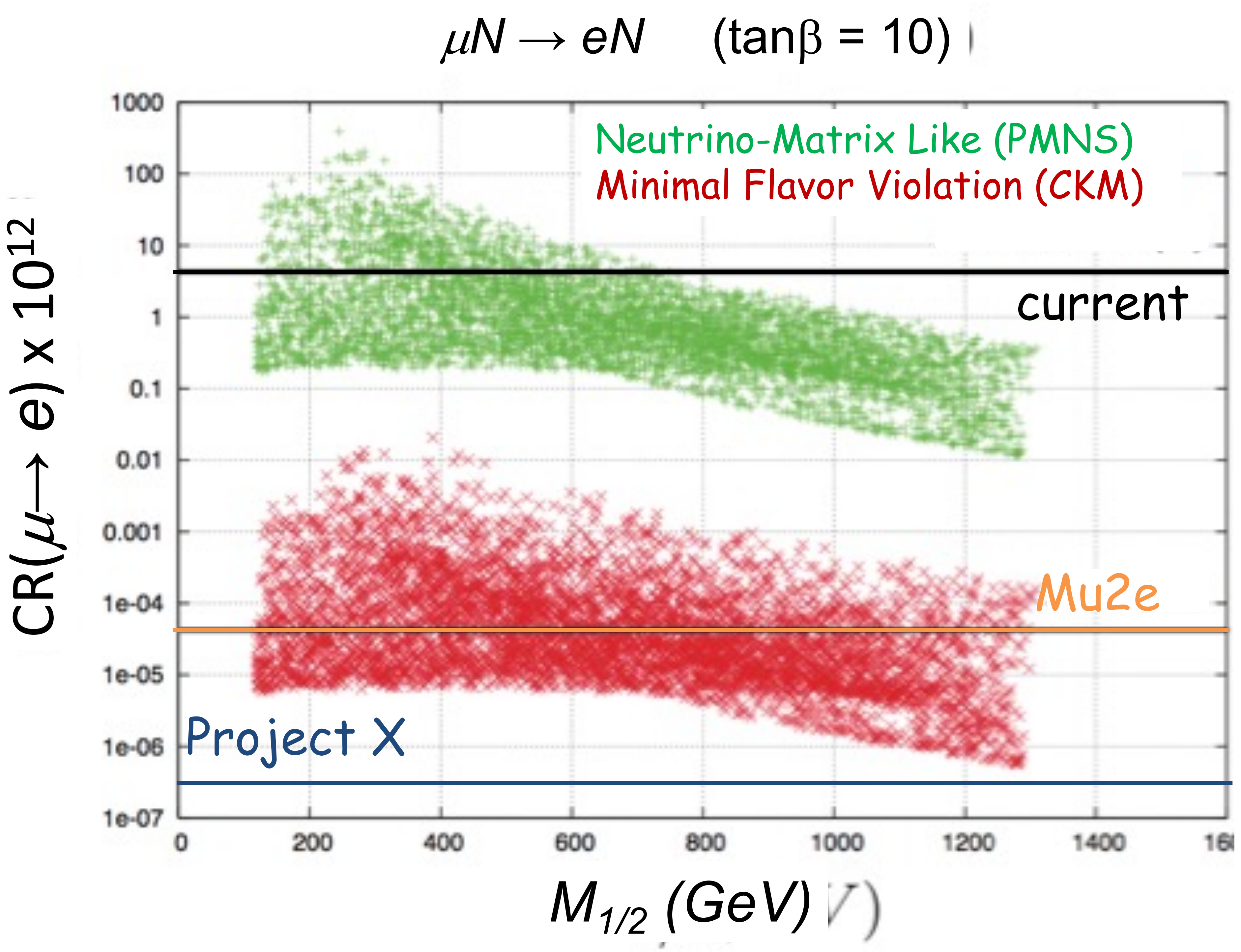
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies O(40) reconstructed signal events with negligible background in Mu2e for many SUSY models.

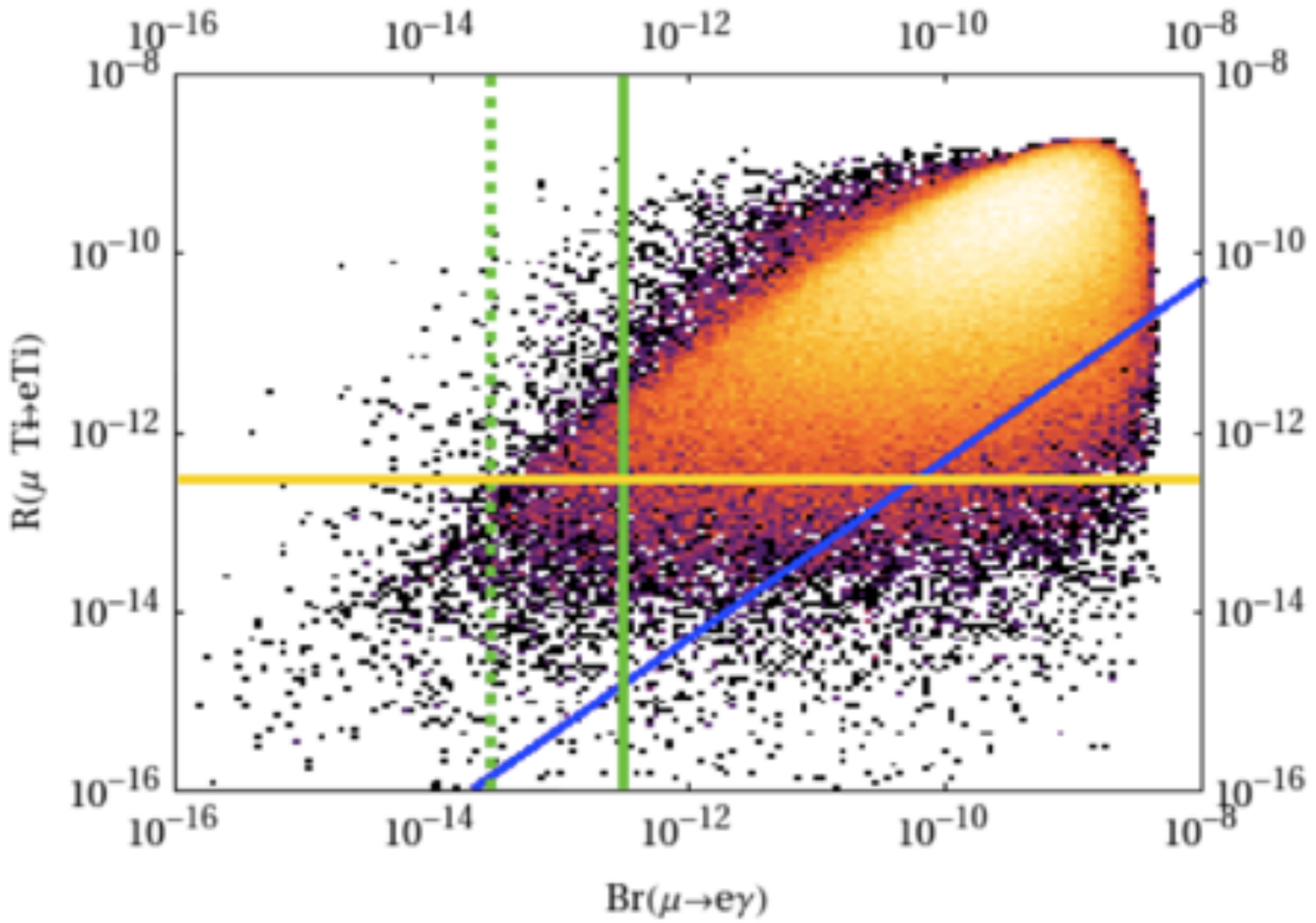
SUSY GUT in an SO(10) framework



L. Calibbi et al., hep-ph/0605139

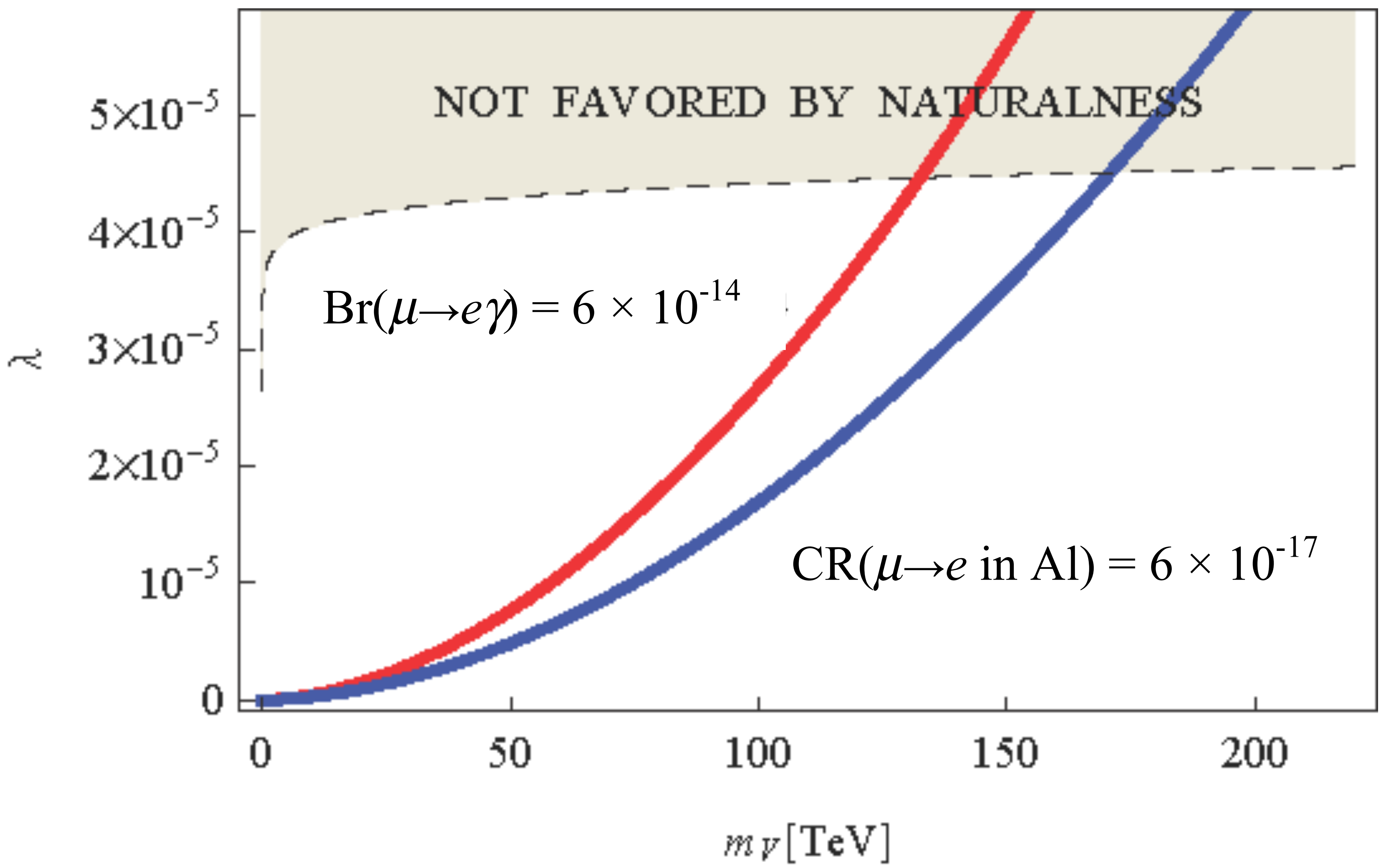
Complementary with the LHC experiments while providing models' discrimination

MU2E vs MEG-upgrade



Littlest Higgs model with T-parity

- Yellow line, limit by SINDRUM-II
- Grenn lines, MEG and MEG-upgrade
- Mu2e covers all parameter space

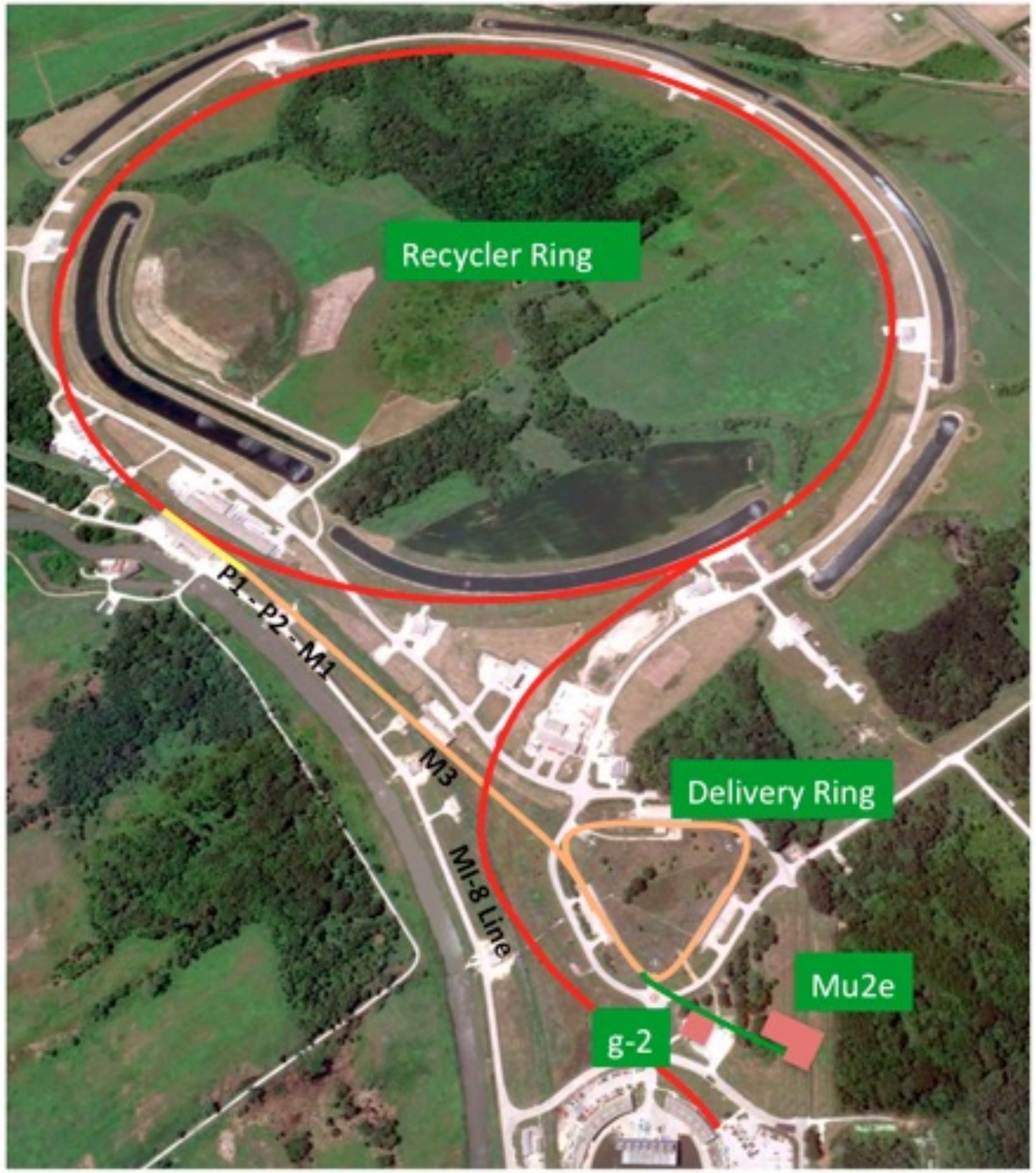


Leptoquarks

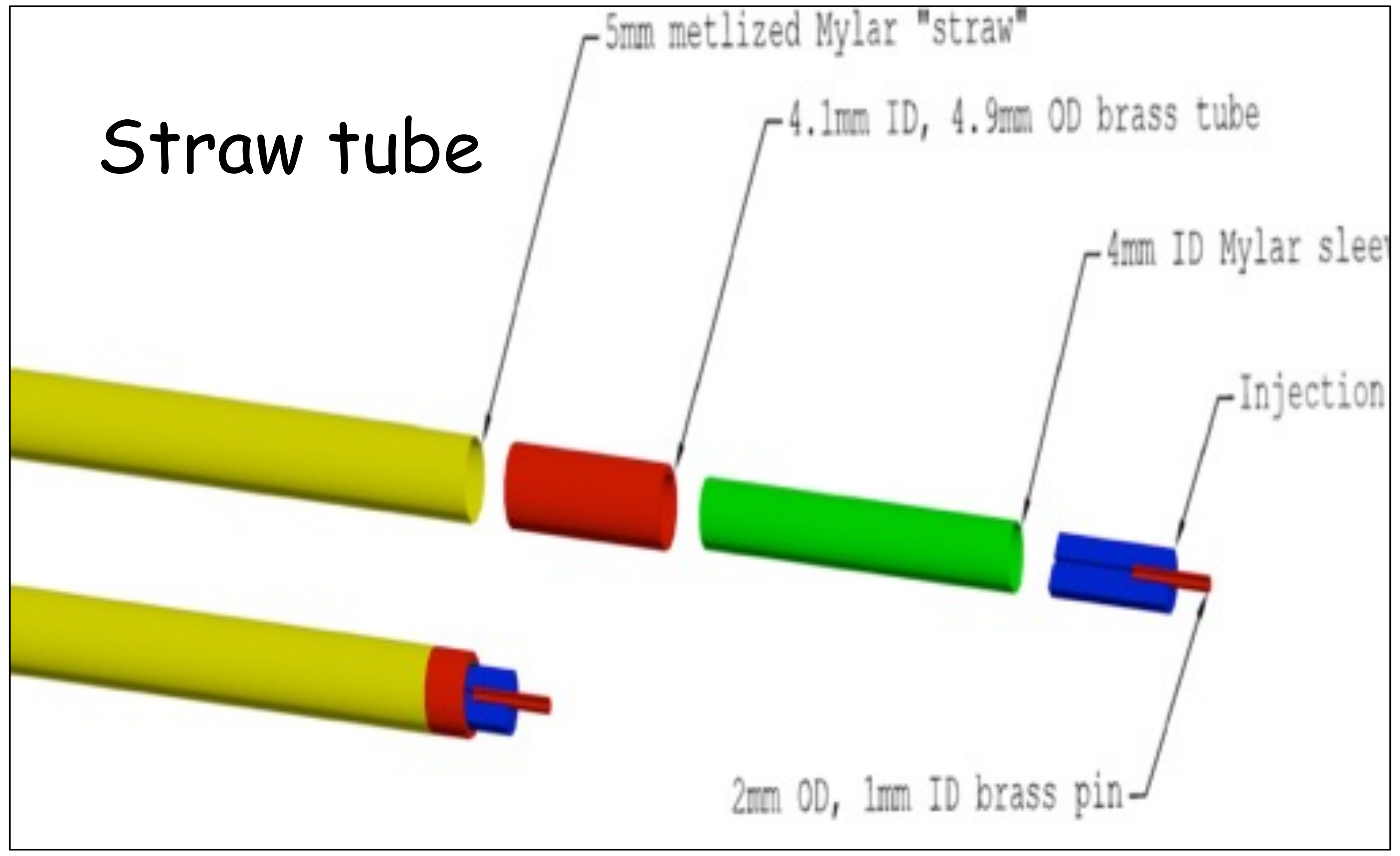
- Red line → MEG-upgrade
- Blue line → MU2E

Accelerator Scheme

- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring
- Batch is re-bunched into 4 bunches
- These are extracted one at a time to the Debuncher/Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure
- **Produces bunches of ~3×10^{7} protons each, separated by 1.7 μs (debuncher ring period)**

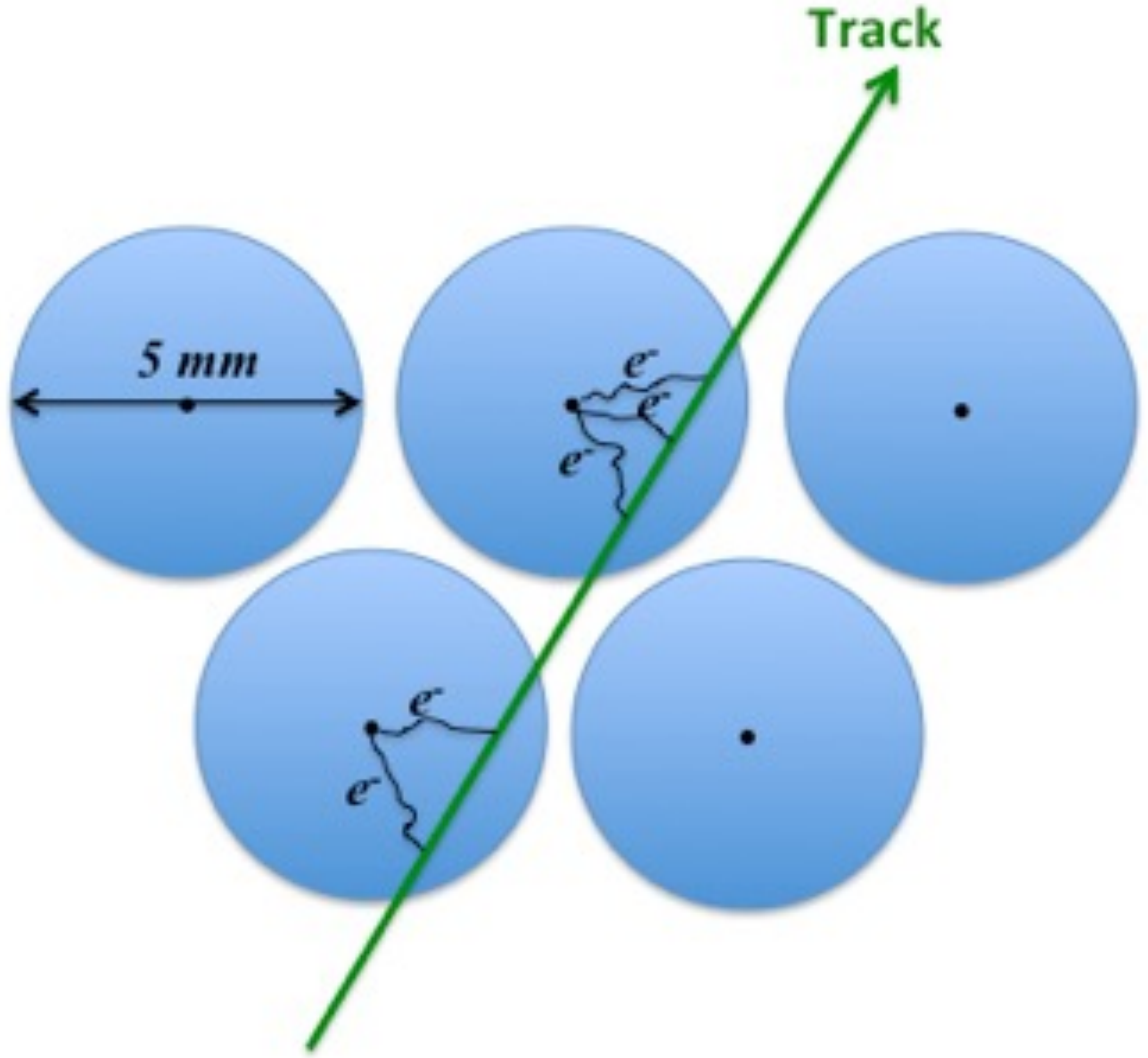


Tracker Design: Thin Straw Tubes - 2



Straw Diameter	5 mm
Straw Length	430 – 1200 mm, 910 mm average
Straw Wall	15 μm Mylar (2×6.25μm plus adhesive)
Straw Metallization	500Å aluminum, inner and outer surface 200Å gold overlaid on inner surface
Gas Volume (straws only)	$4 \cdot 10^8$ mm^3 (0.4 m^3)
Sense wire	25 μm gold-plated tungsten
Drift Gas	Ar:CO_2, 80:20
Gas gain	$3\text{-}5 \cdot 10^4$ (exact value to be set later)
Detector Length	3196 mm (3051 mm active)
Detector Diameter	1620 mm (1400 mm active)

- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm)**



“back on the envelope” resolution

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}} \frac{\sigma_y p_\perp}{(0.3BL^2)} \text{ (m, GeV/c, T)}$$

(P_T example = 100 MeV = 0.1 GeV)

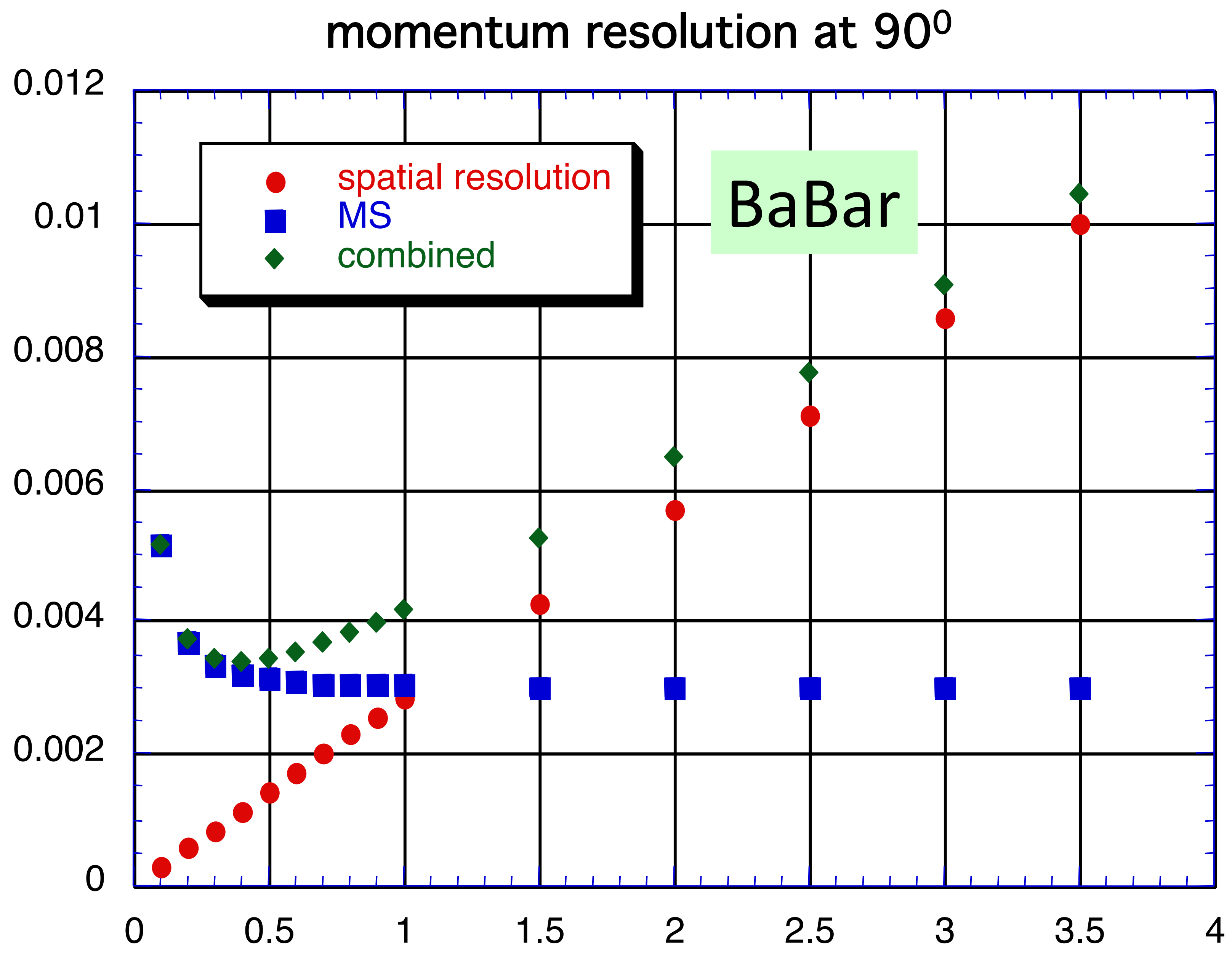
1) SPATIAL RESOLUTION CONTRIBUTION

- **N(hits) per track = 40, B(Field) = 1 T, L = 0.3 x 2π = 2 m, Sy = 200 μm**
- SQRT(720/44) xσ (point) x 0.1 / (0.3 x 1 x 4)

  → 4 x σ(point) x 0.1 x 0.8 = 0.3 x Sy (m) ~ 60 x 10^{-6} = 0.6 x 10^{-4} = 0.06 permil
  → @ 100 MeV → 0.06 x 100 keV = 6 keV

2) MULTIPLE SCATTERING CONTRIBUTION

- Sy (m.s.) = L sin0 x Theta_rms =
- Theta_rms =13 MeV/P(MeV) x SQRT(L(X0))
  → @ 100 MeV and 0.5% X0
  → Theta_rms = 0.13 x SQRT(0.5$10^{-2}$)
  → 0.13 x 0.07 = 0.09
- **Sy (m.s.) = 0.9 cm**
  30 times larger than space resolution
- **σ(p)/p = 0.06 x 30 permil = 0.002**



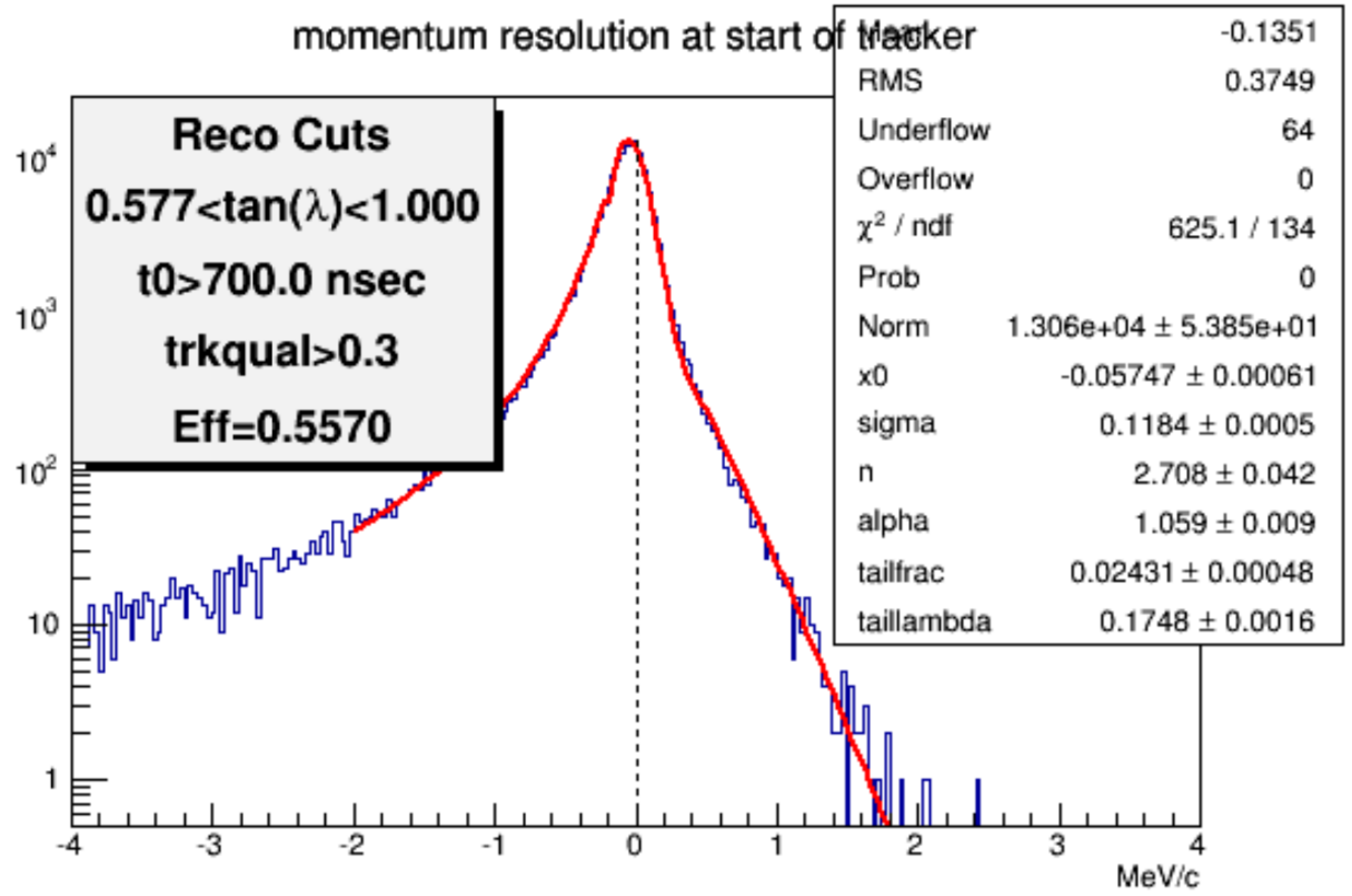
Tracking Performance

Pattern Recognition based on
***BABAR* Kalman Filter algorithm**

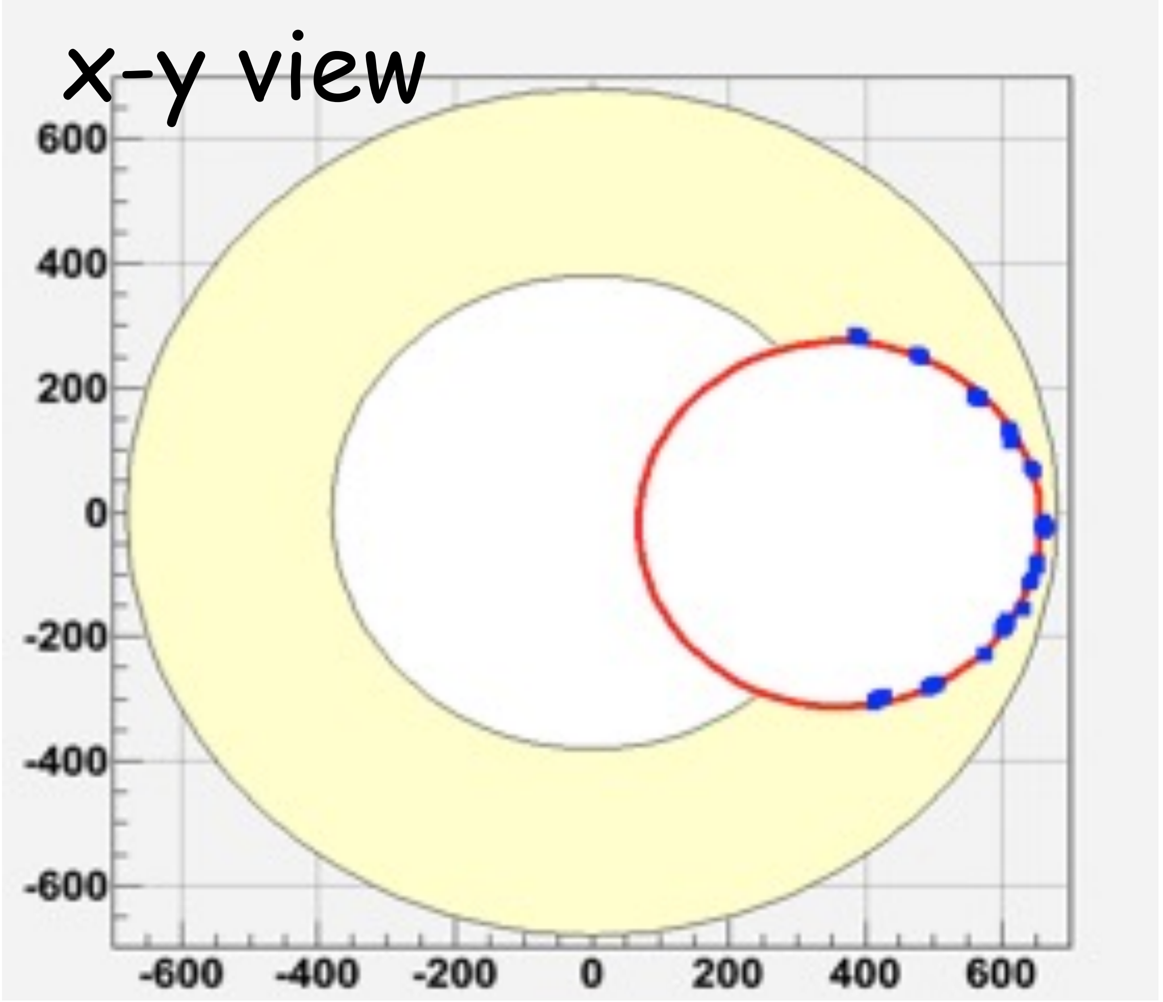
No significant contribution of mis-reconstructed background

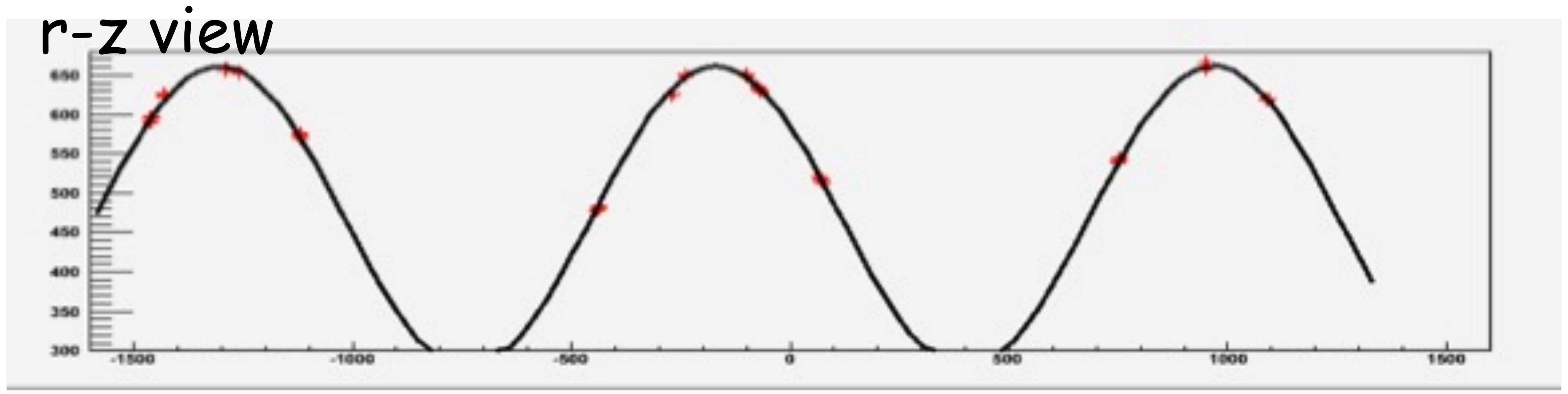
Momentum resolution

core σ~120 keV
tail σ~175 keV (2.5%)



Fit: Crystal Ball + exponential



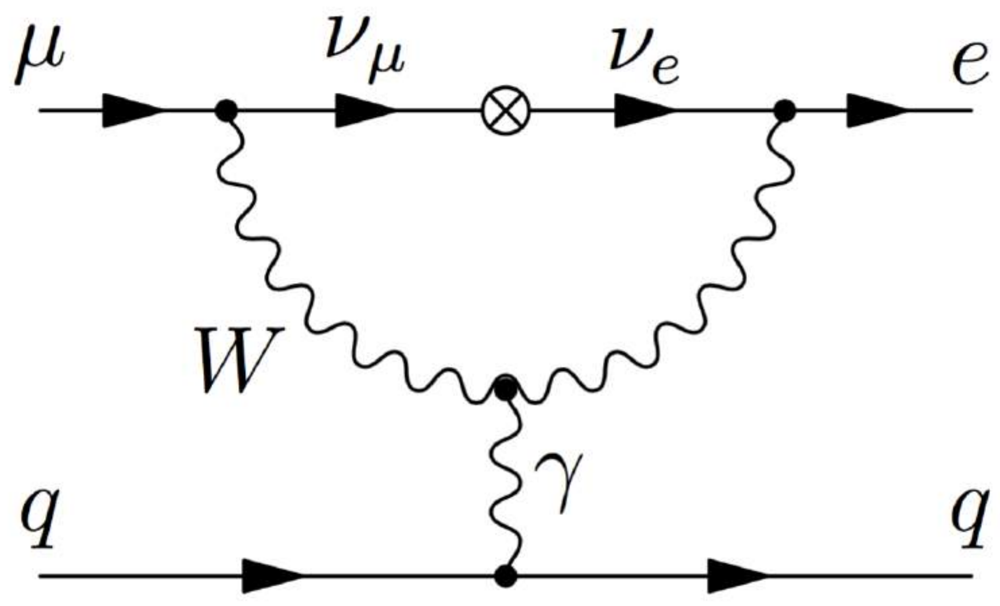


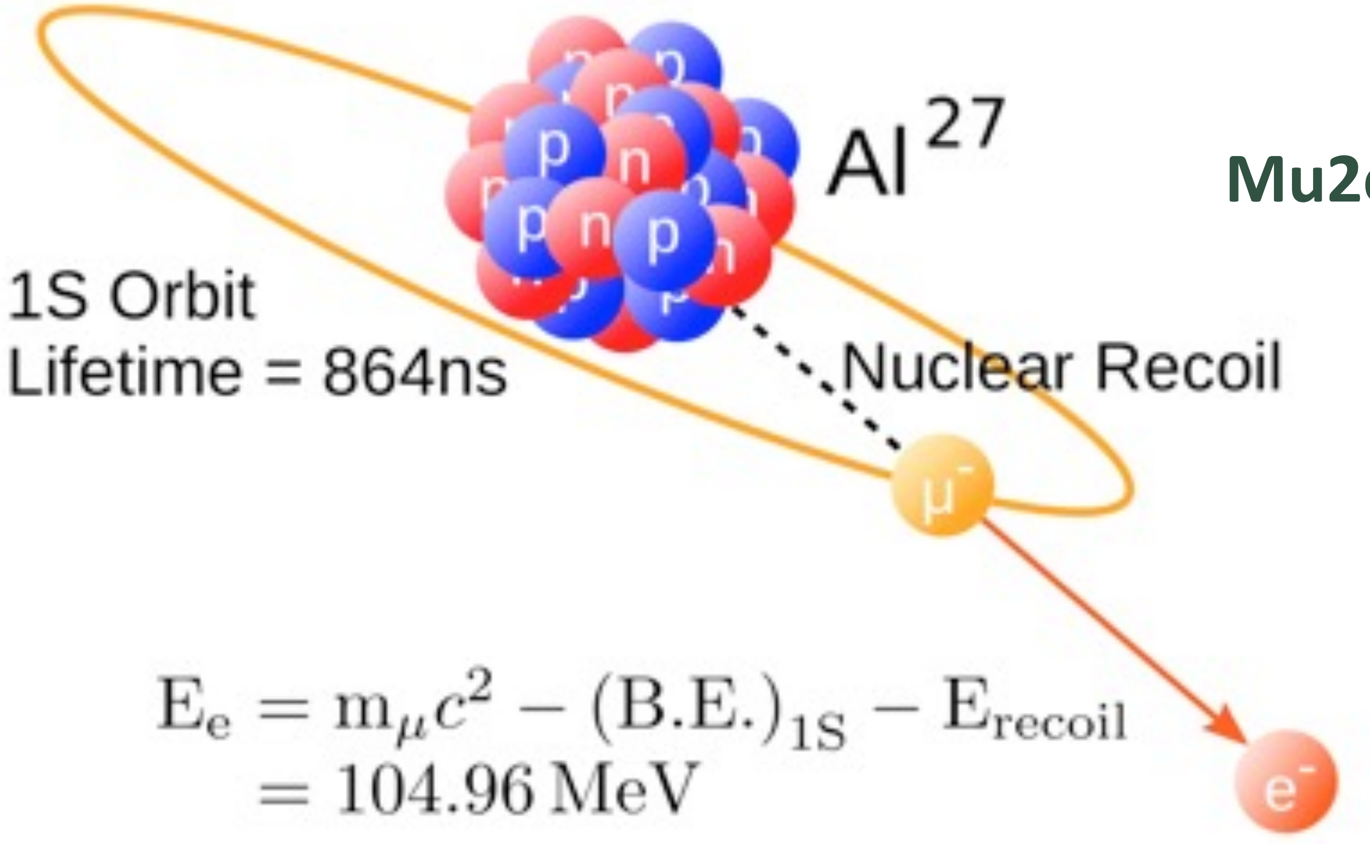
What is the μ-e conversion ?

μ converts into an electron in the presence of a nucleus

$$\mu^- N \to e^- N$$

- μ-e process is an example of Charged Lepton Flavor Violating (CLFV) process.
- **CLFV processes are forbidden in the Standard Model!**
  - Assuming neutrino oscillation they are allowed **BUT negligible with BR ~ 10^{-50}**
- Many SM extensions enhance the rates to observable values
- **Any observation of a signal will be a clear evidence of New Physics**





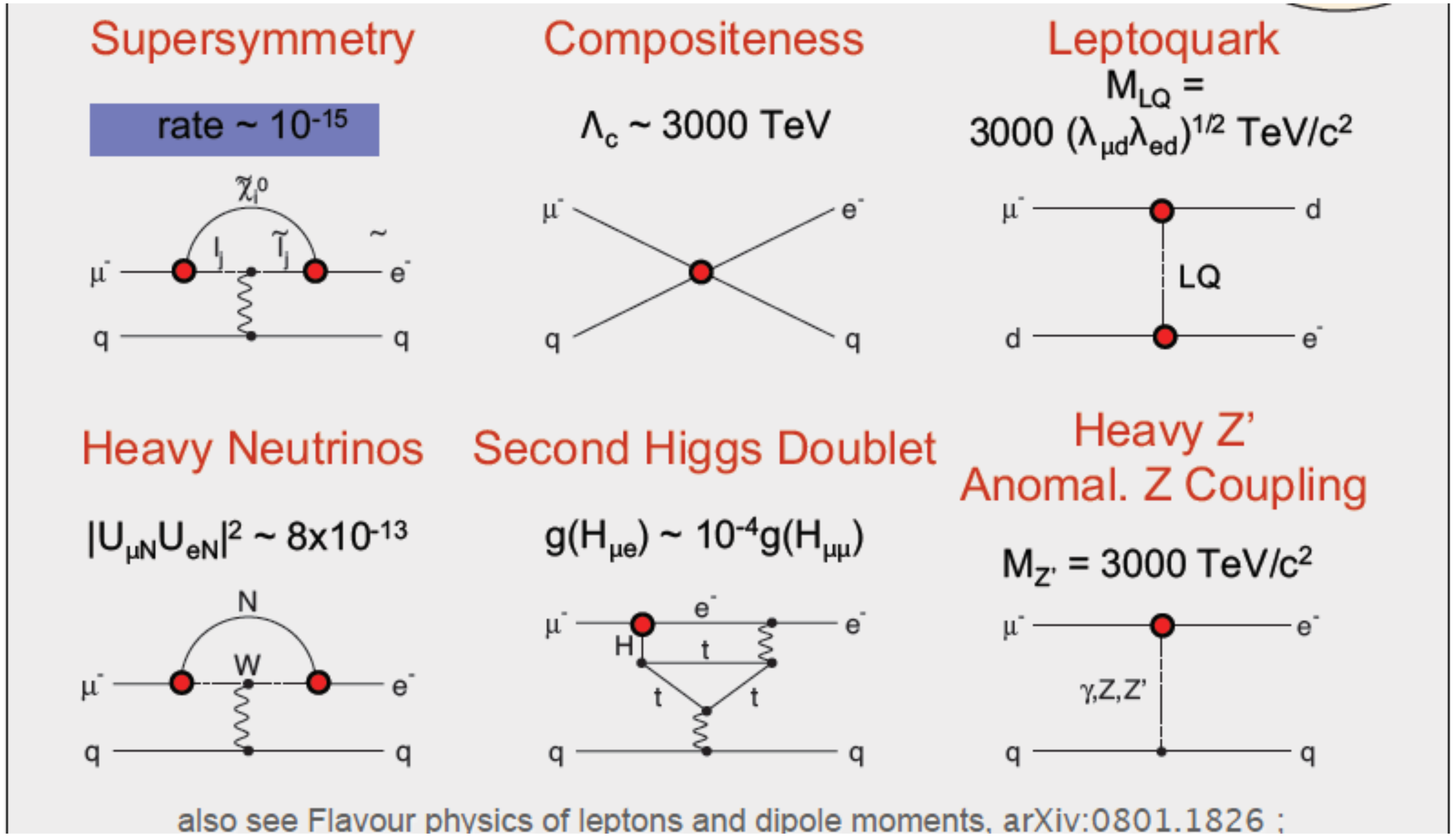
Mu2e measures the rate of μ-e conversion normalized to the μ captures in nuclei:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1))} \leq 8 \times 10^{-17} (@\ 90\%\mathrm{CL})$$

Mu2e physics reach & goal

Sensitivity reach:
10^4 improvement with respect to previous μ to electron conversion experiment (Sindrum-II) by means of 4 handles:

→ Rate (Intensity)
→ Out of Time extinction
→ Delayed gate
→ Resolution



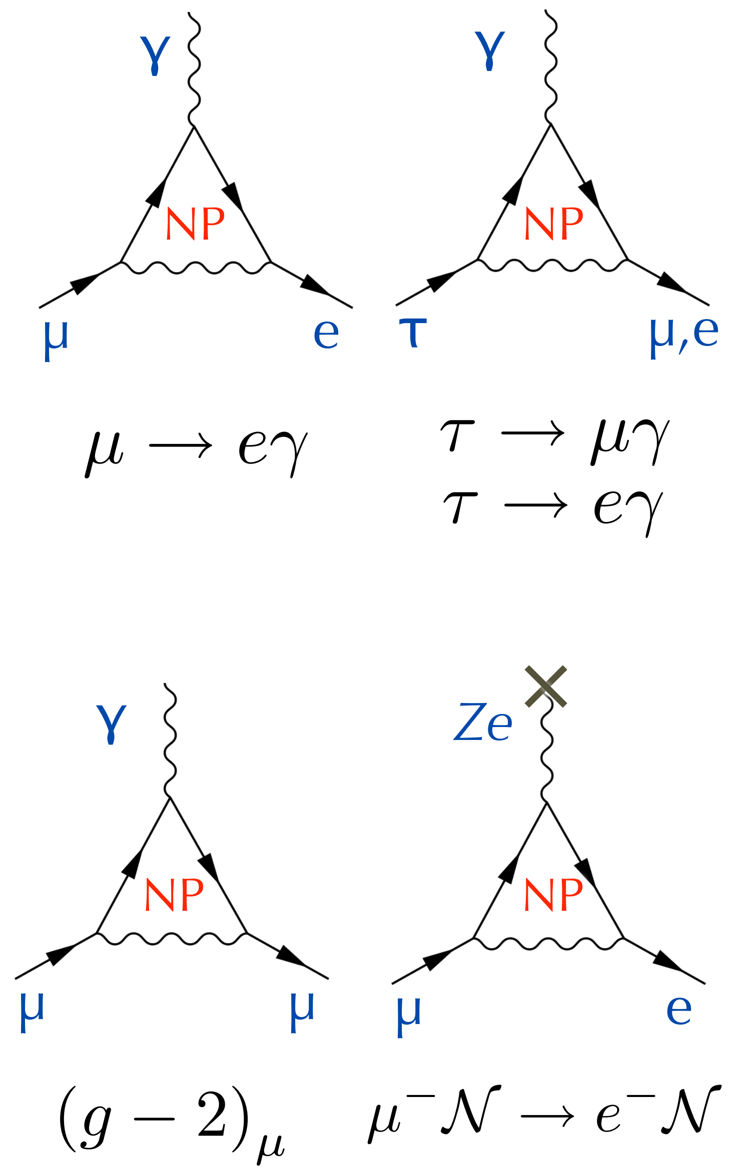
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1))} \leq 8 \times 10^{-17} (@\ 90\%\mathrm{CL})$$

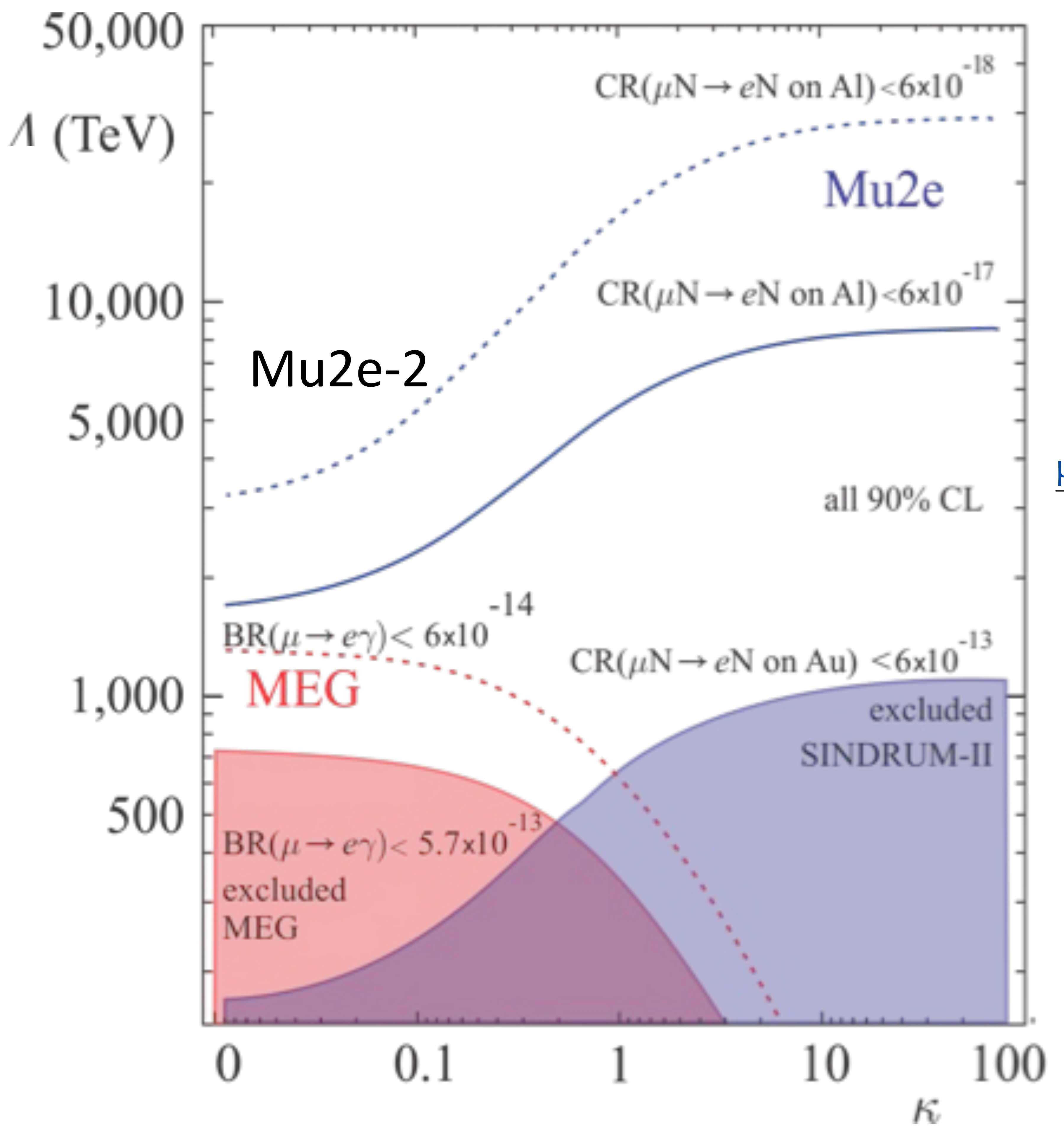
Mu2e vs MEG/MEG upgrade

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

LOOP TERM

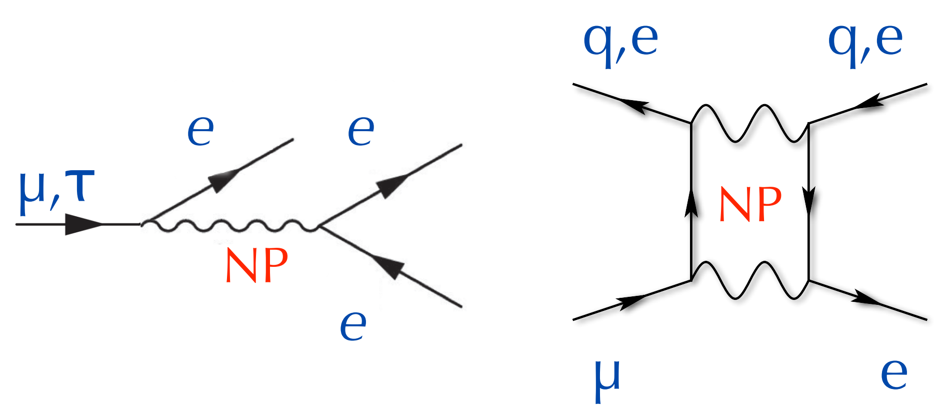
$\kappa \ll 1$





CONTACT TERM

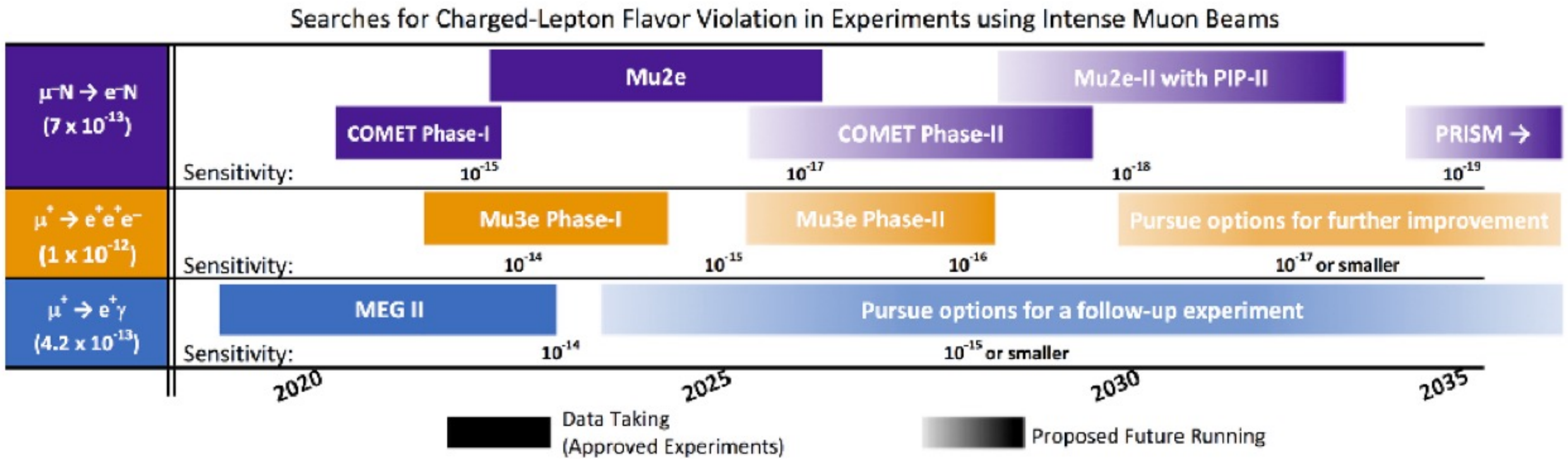
$\kappa \gg 1$



$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

Summary: CLFV search on Muon Sector



Mu2e has a broad discovery sensitivity across all models:

→ Sensitivity to the same physics of MEG but with better mass reach

→ Sensitivity to physics that MEG is not

→ If MEG observes a signal, MU2E does it with improved statistics.

Ratio of the BR allows to pin-down physics model

→ If MEG does not observe a signal, MU2E has still a reach to do so.

In a long run, it can also improve further with PIP-2 at FNAL

- **Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator**

Mu2e sensitivity and rates

- **<u>Design goal: single-event-sensitivity of 3 x 10^{-17}</u>**
  - Requires about **10^{18} stopped muons**
    (as many muons as the earth's sand grains)
  - Requires about **10^{20} protons on target**
  - Requires extremely high suppression of backgrounds
- **Expected limit: $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL**
  - **Factor 10^4 improvement**
- **<u>Discovery sensitivity: $R_{\mu e} > 2 \times 10^{-16}$</u>**
  - Covers broad range of new physics theories

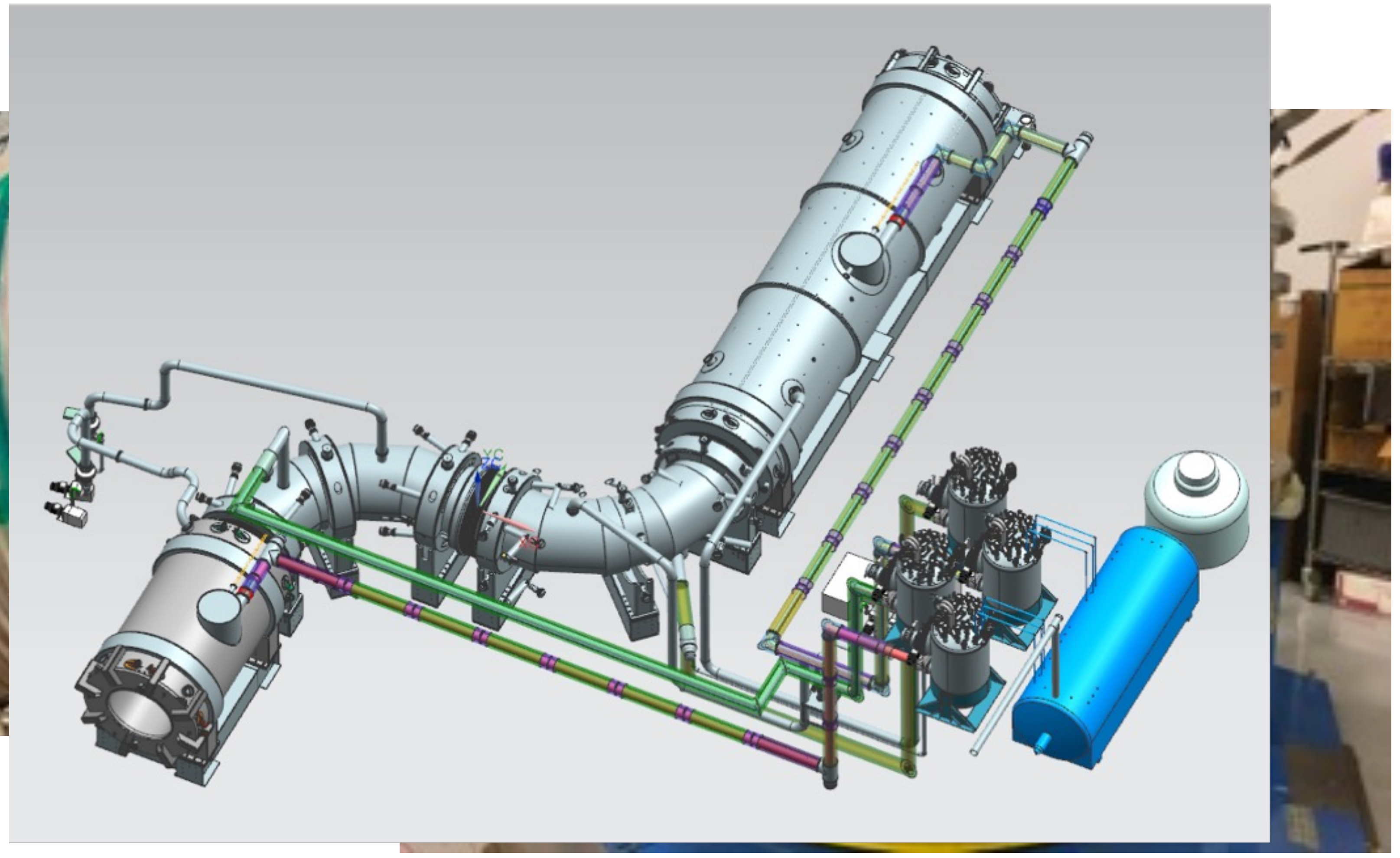
Why Al?

- Determining Z dependence is very important
- Lifetime is *shorter* for high Z -> Decrease in useful search window
- Avoid bkg from radiative muon capture

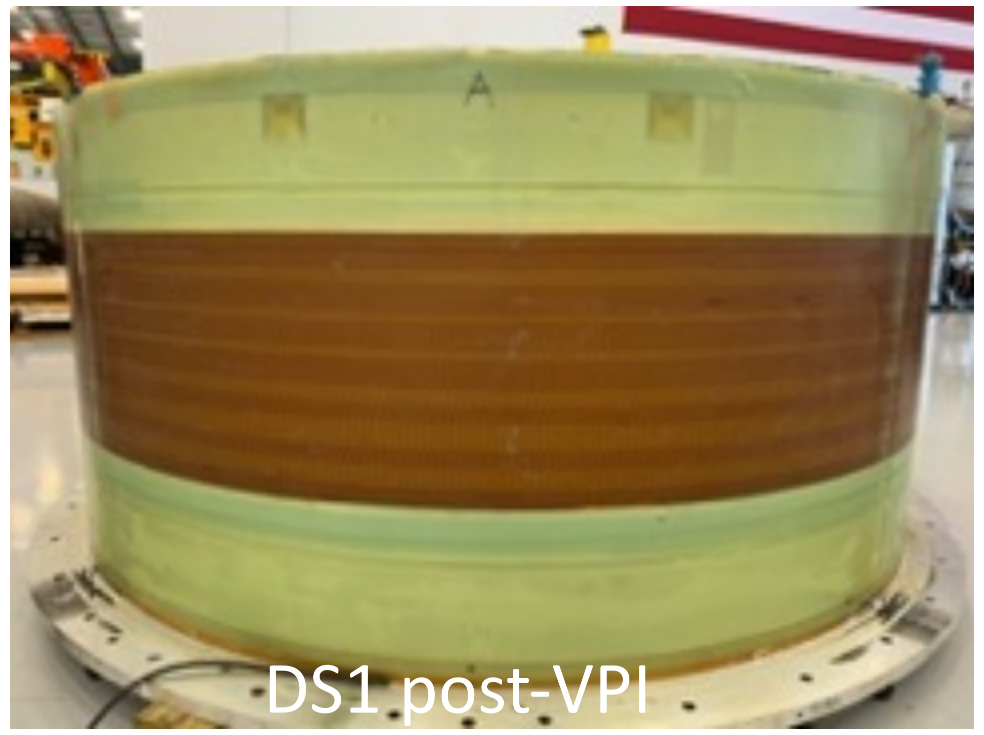
⇒Aluminum is nominal choice for Mu2e

Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

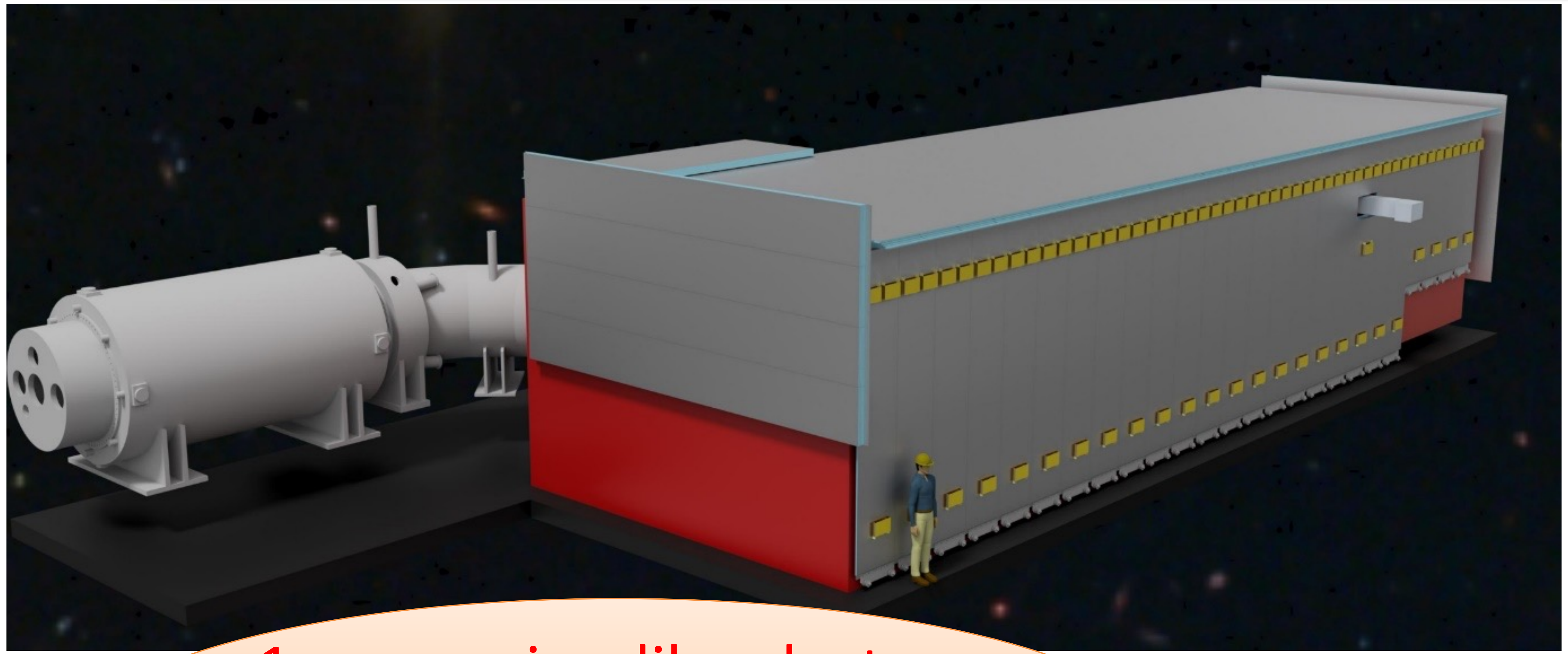
Production and Detector Solenoids



Paes



Cosmic Ray Veto (CRV) system



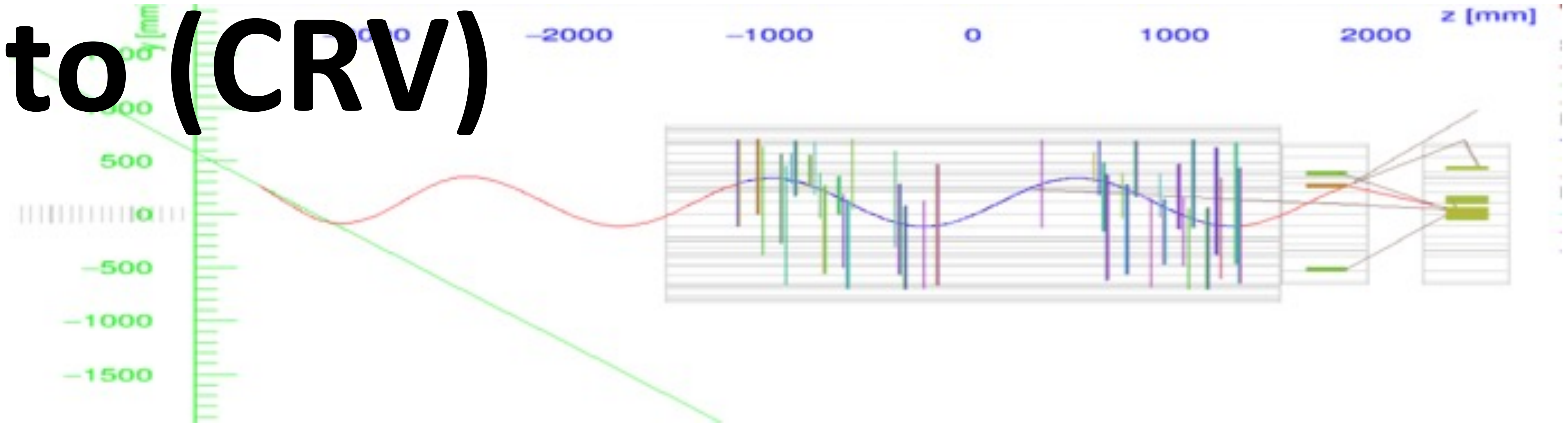
1 conversion-like electron per day is produced by cosmic-ray muons

Details:

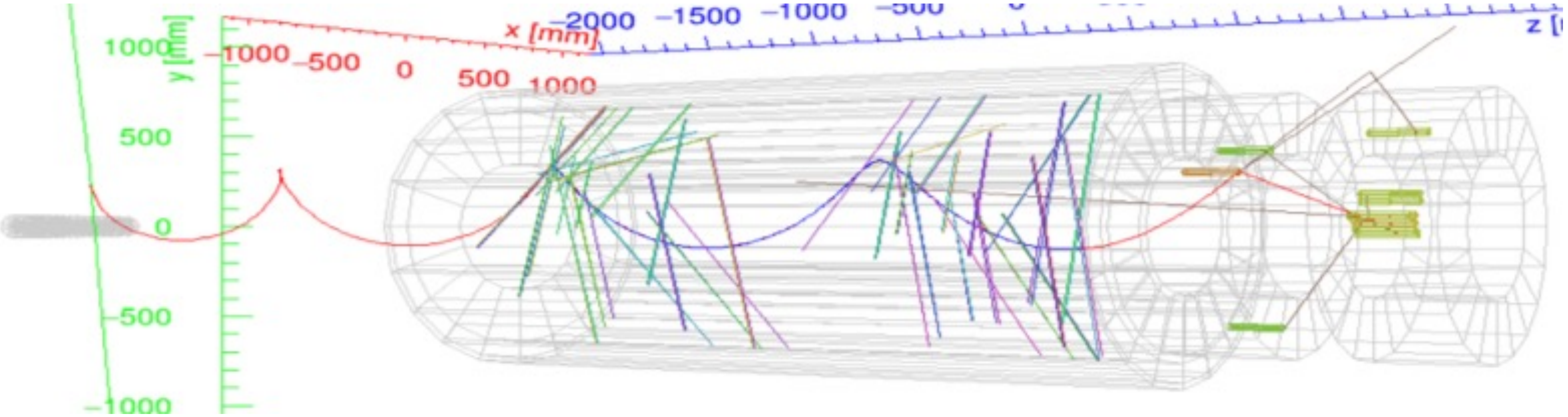
- Area: 335 m^2
- 83 modules; 10 types
- 5,344 counters
- 10,688 fibers
- 19,392 SiPMs
- 4,848 Counter motherboards
- 339 Front-end Boards
- 17 Readout Controllers

- CRV identifies cosmic ray muons that produce conve
- Design driven by need for excellent efficiency, large a background rates, access to electronics, and constrai
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors.
- A track stub in 3/4 layers, localized in time+space produces an Offline-veto

The Cosmic Ray Veto (CRV)

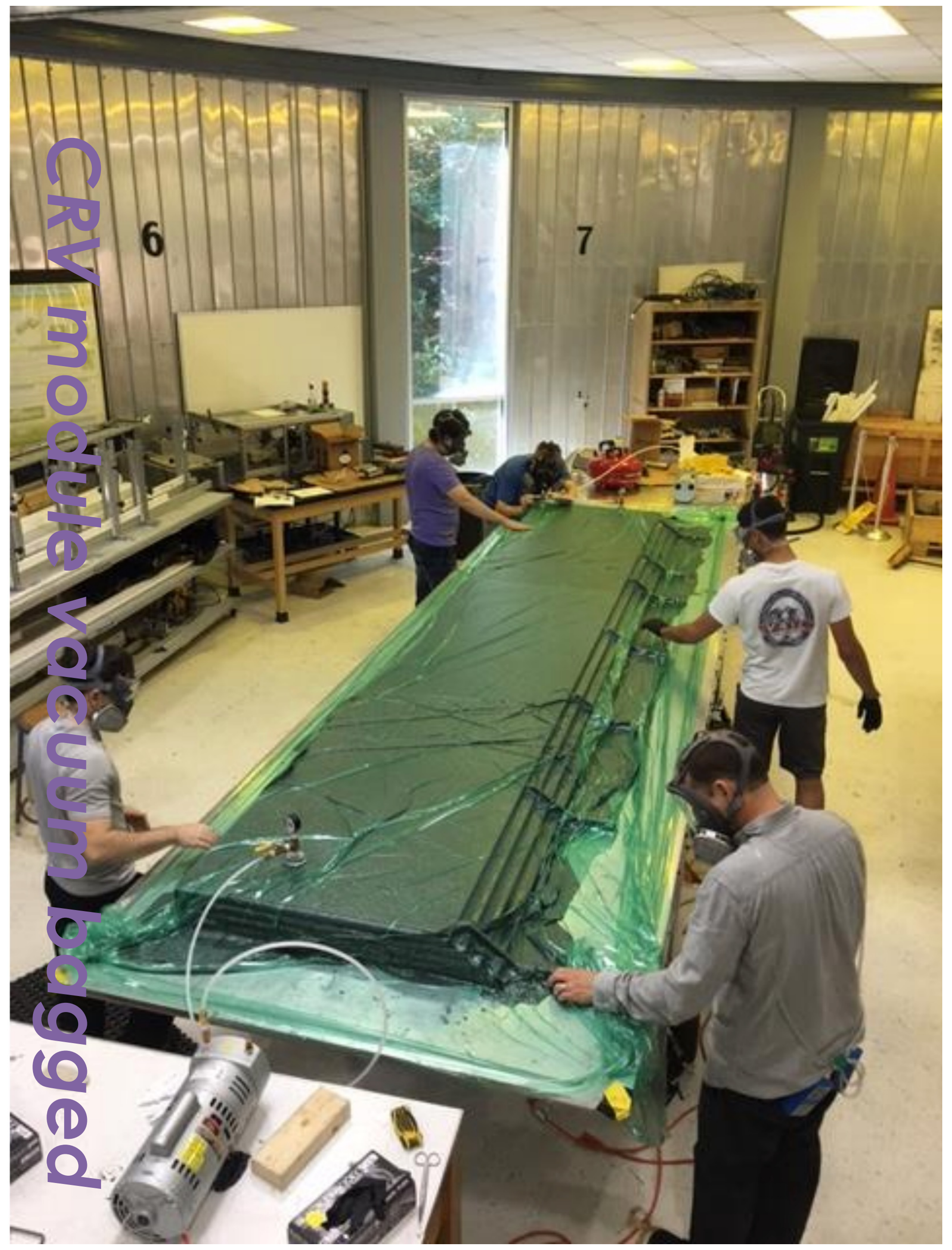


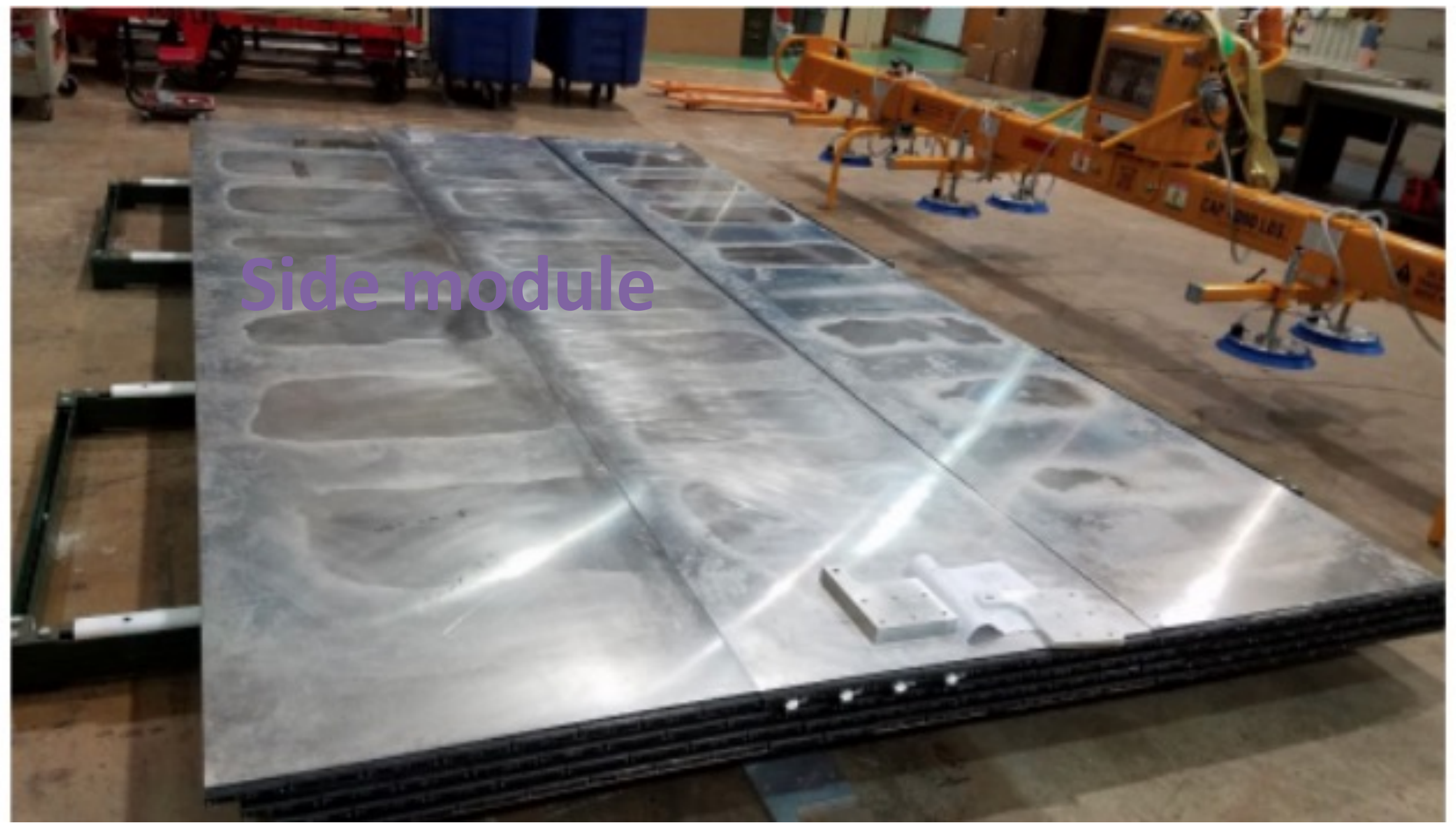
- Cosmic ray muons and interaction products can fake conversion electrons at a rate of ~1 per day



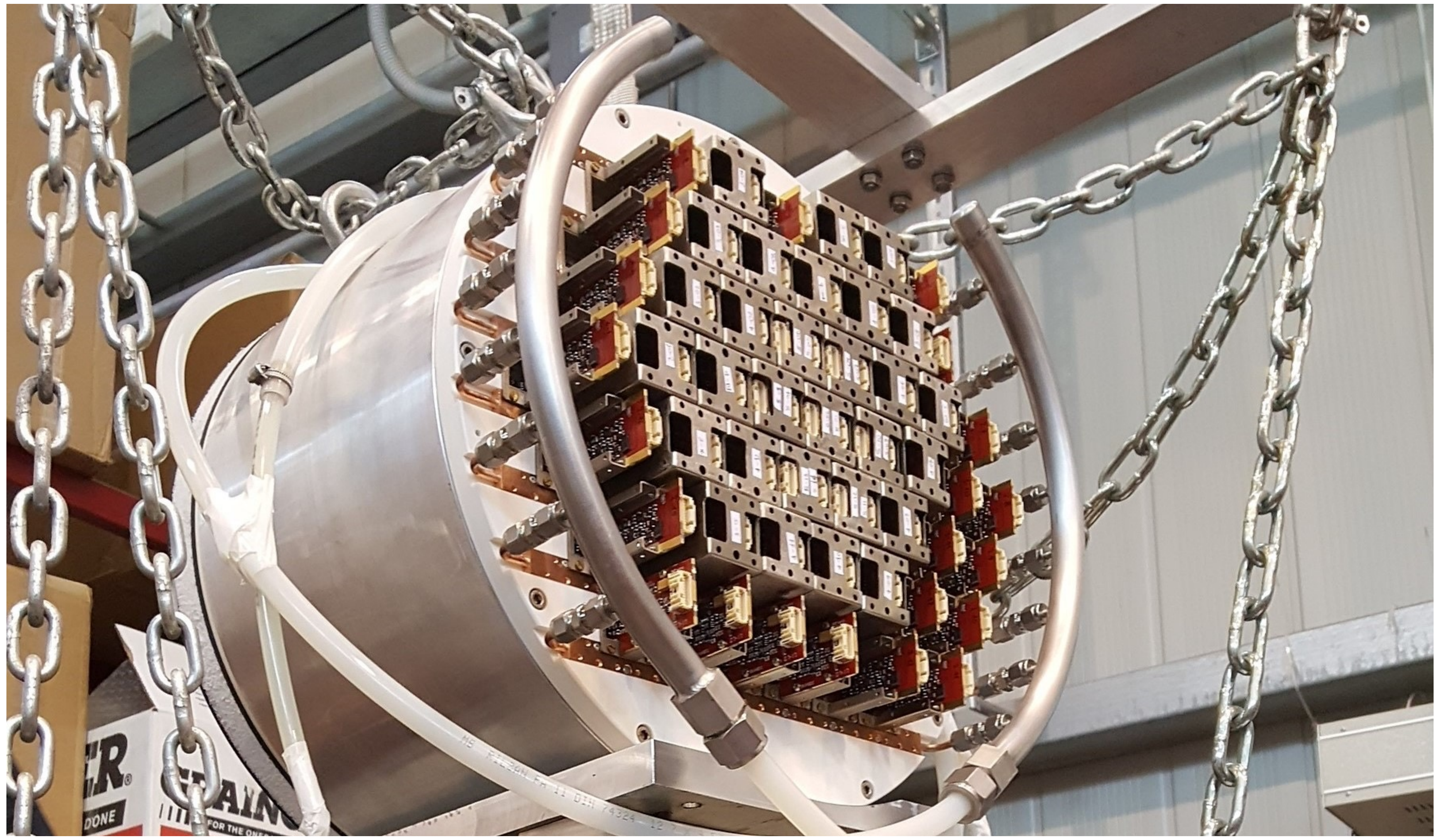
CRV Construction status

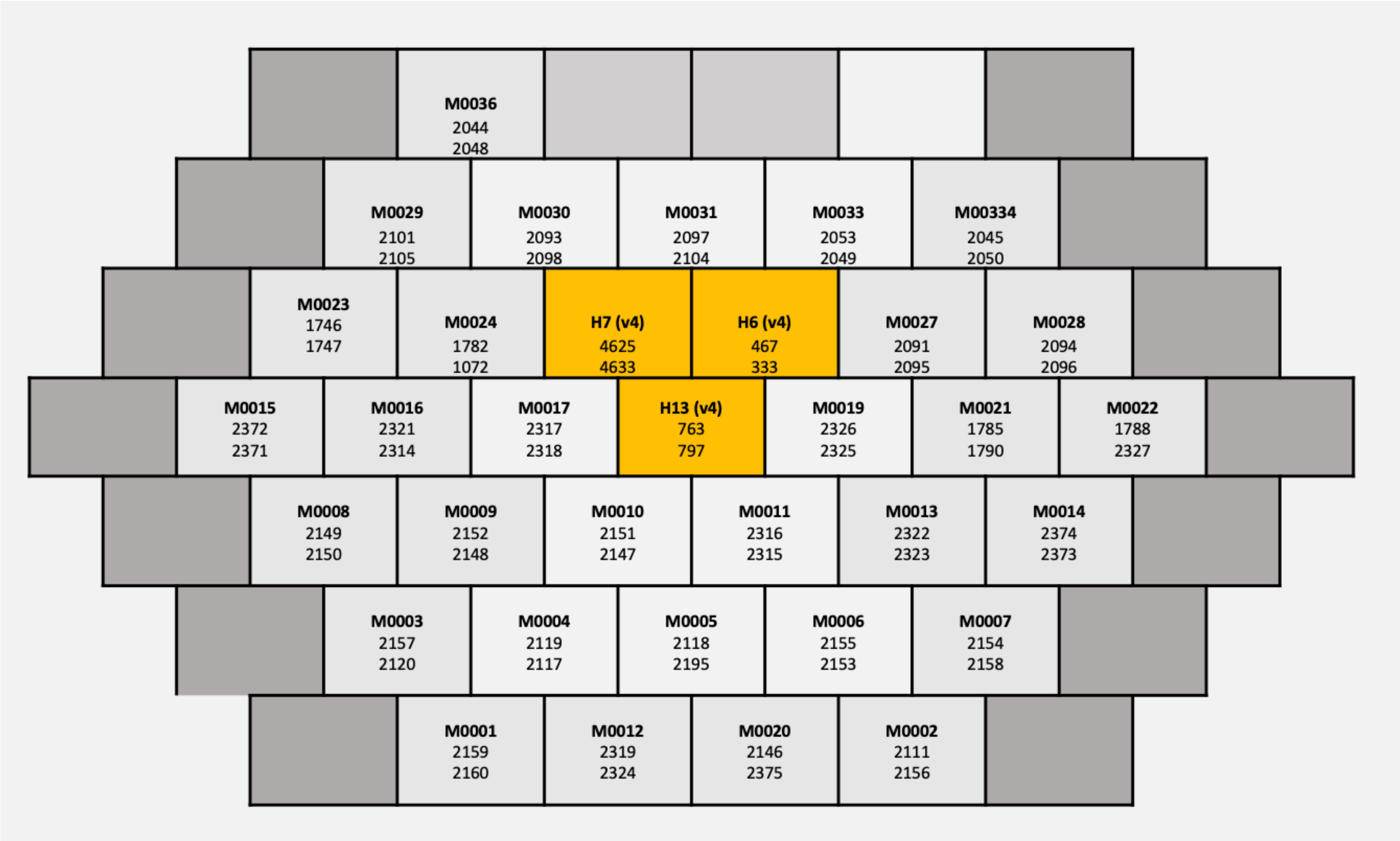
- Prototype tested in Fermilab test beam:
  - LY meets specifications
- SiPMs,FEE produced
- more than half di-counters produced
- more than 30% of modules completed and tested

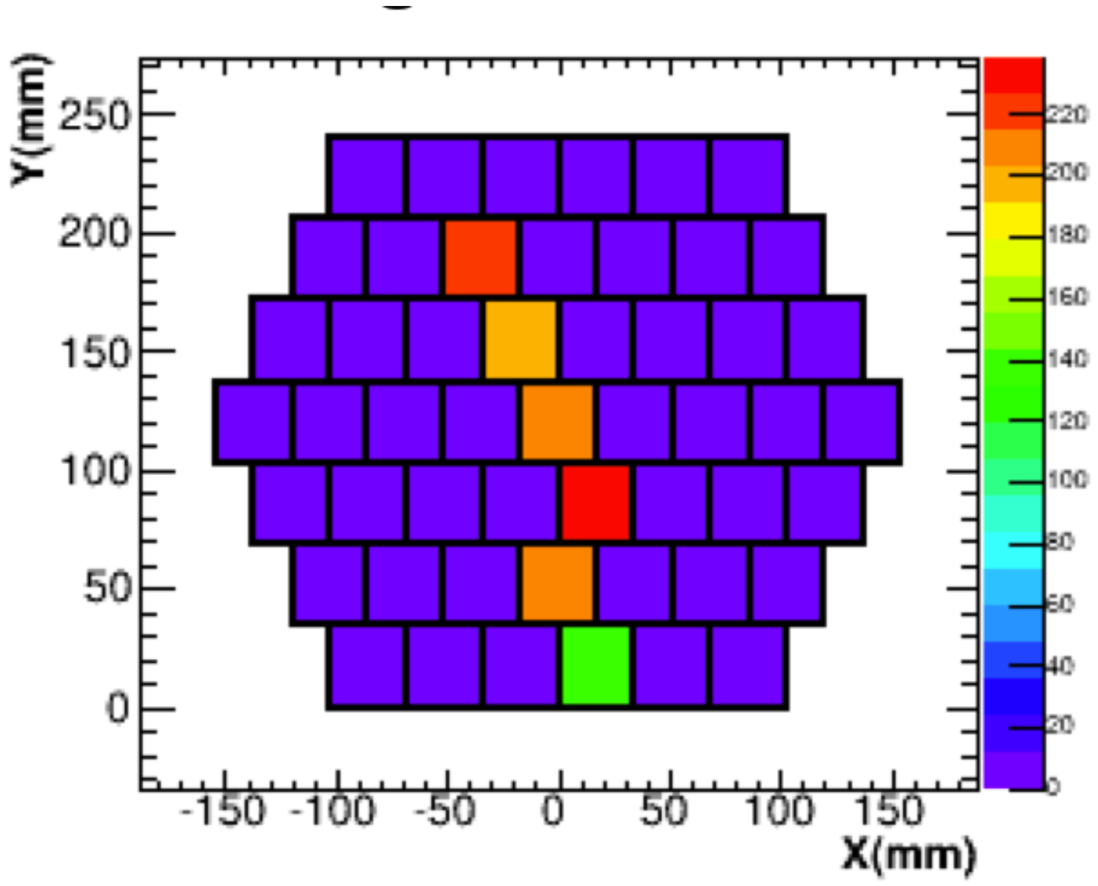




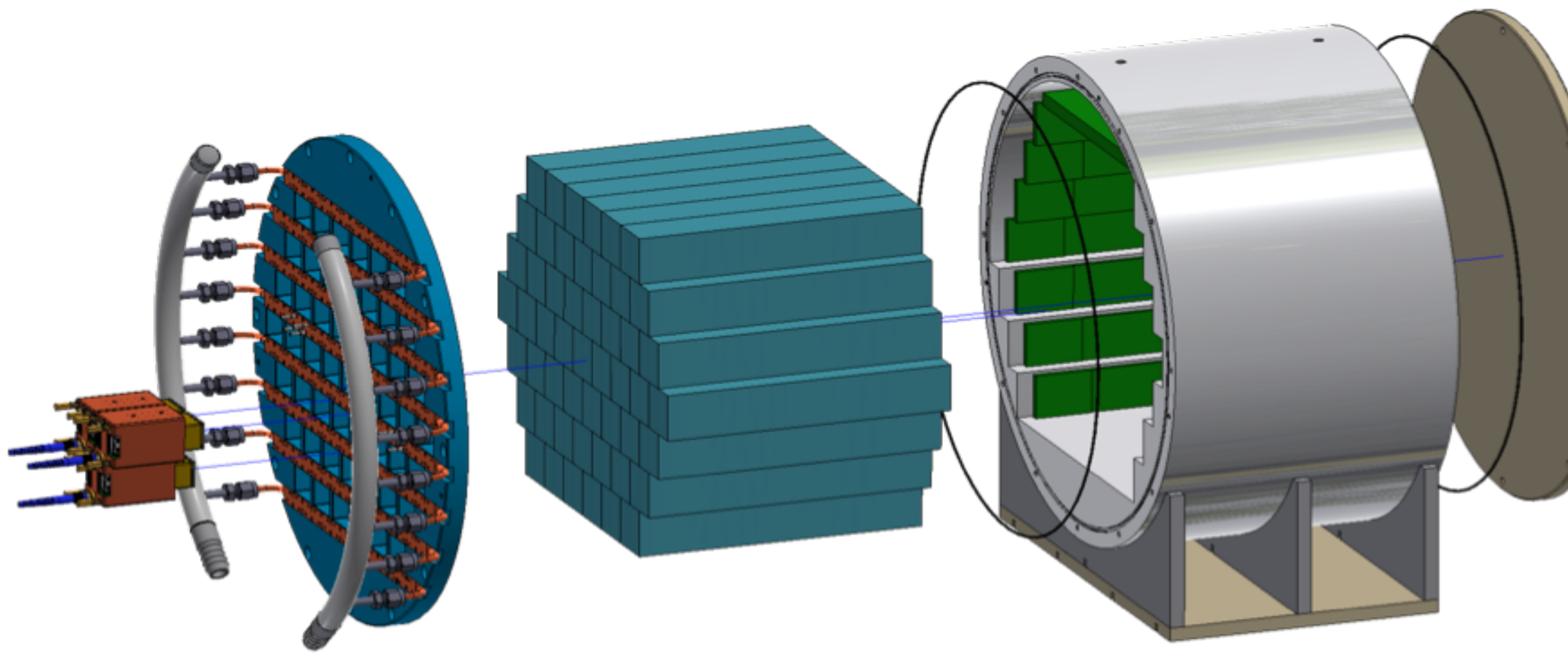
Large scale prototype: Module-0





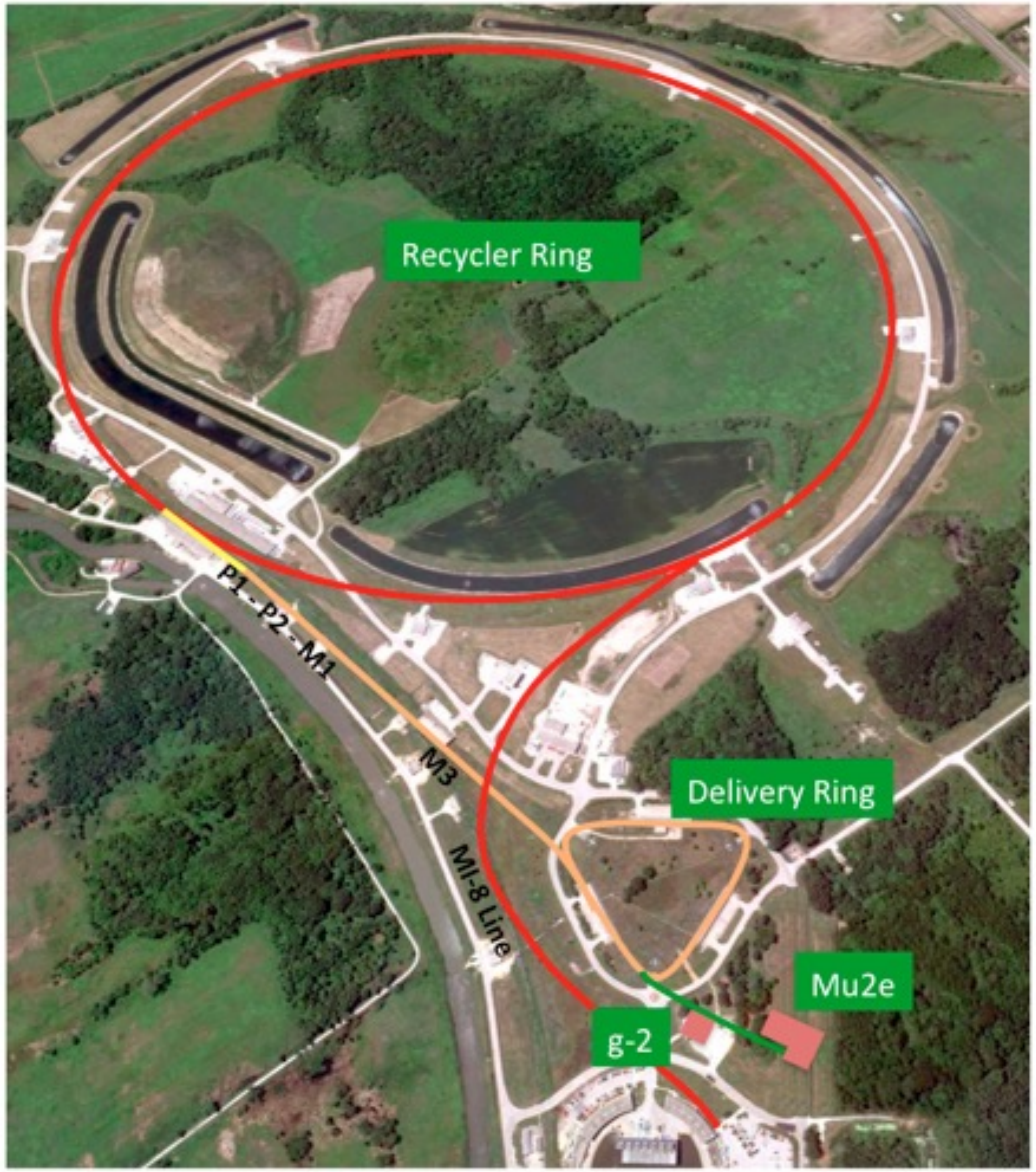


- 51 crystals
- Dual readout
- Final Mu2e SiPM readout
- Cooling system
- Laser calibration system



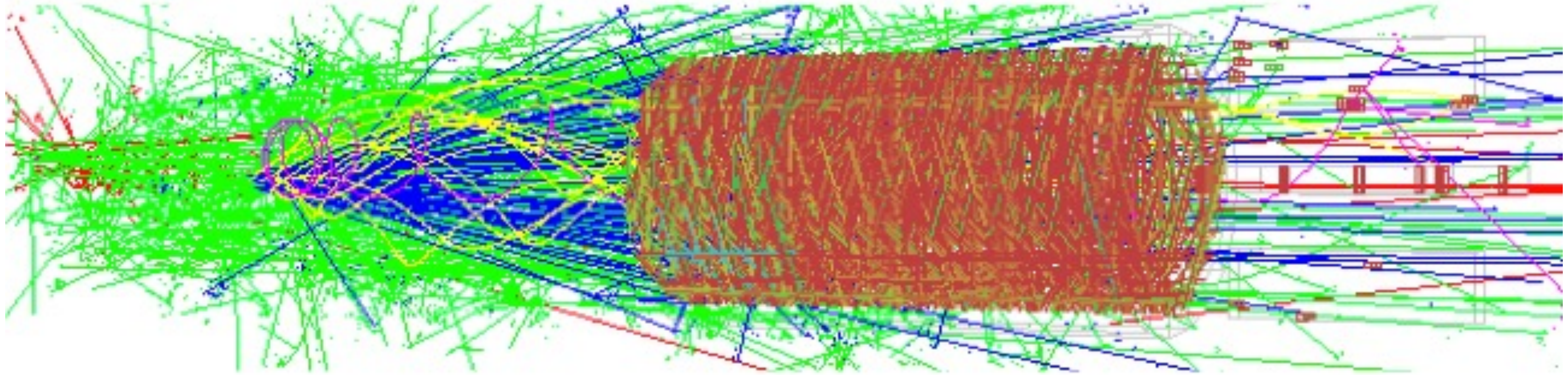
Muon Campus

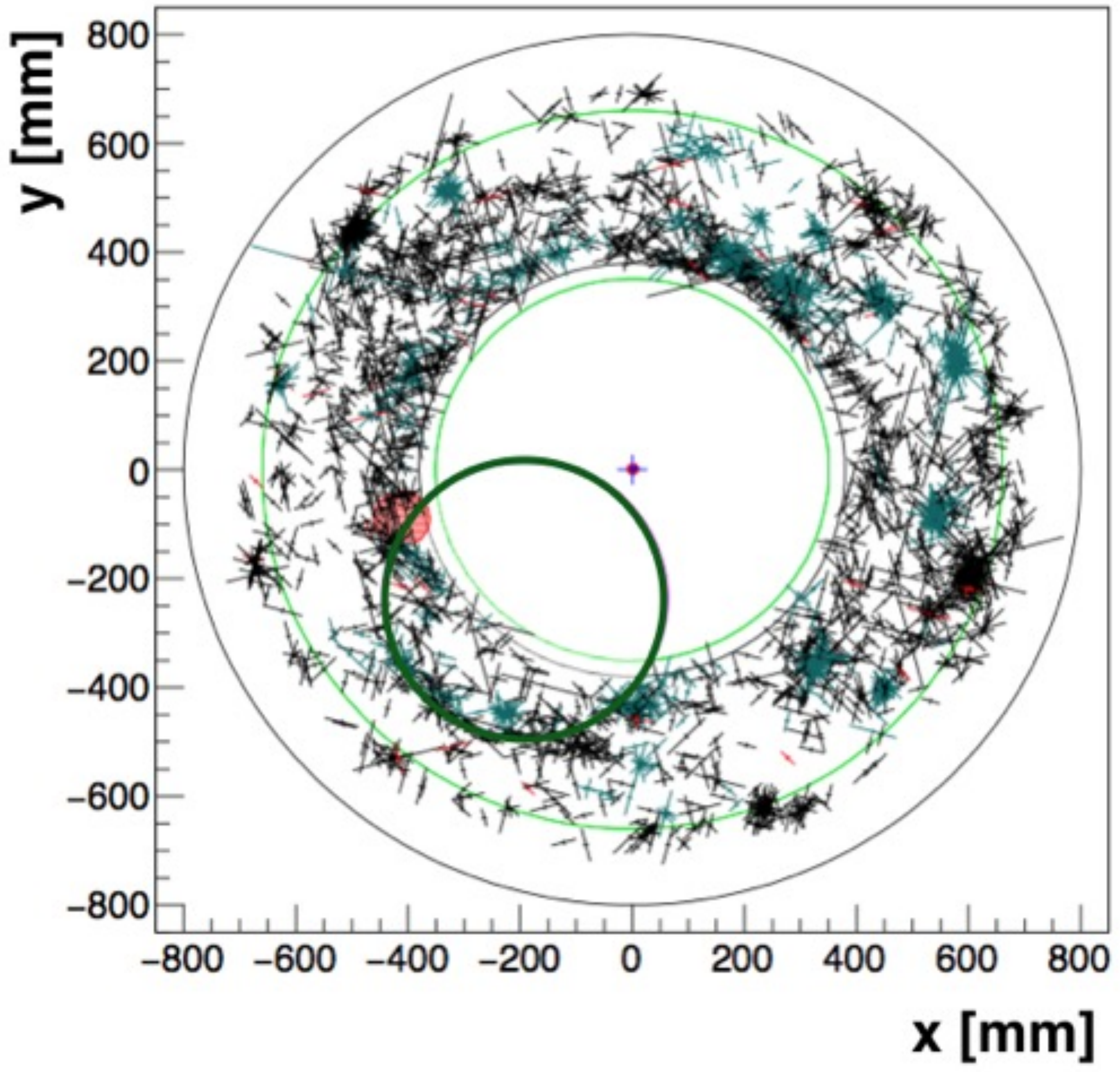
- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring
- Batch is re-bunched into 4 bunches
- These are extracted one at a time to the Debuncher/Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure
- **Produces bunches of ~3×10^{7} protons each, separated by 1.7 μs (debuncher ring period)**



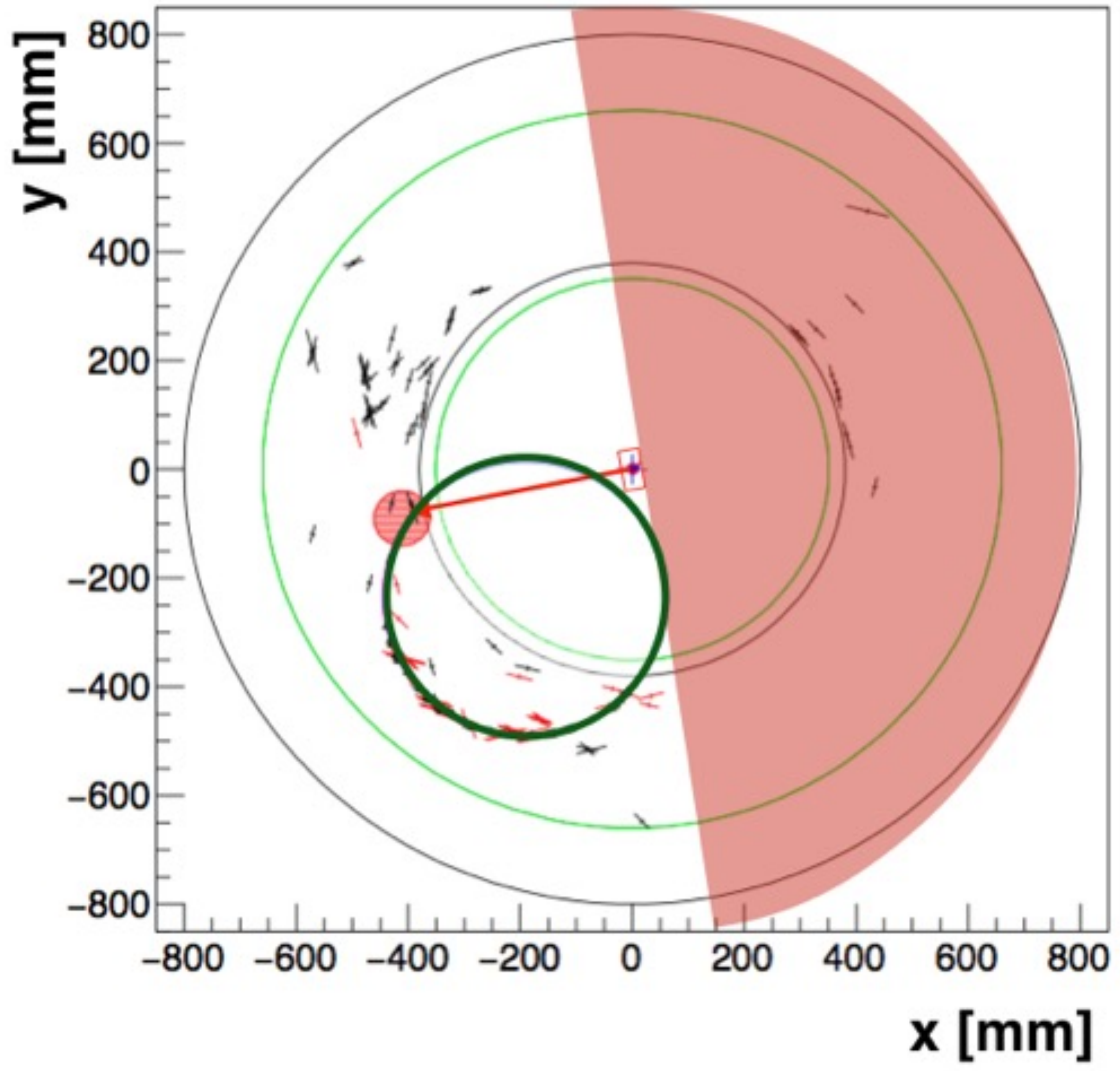
Calorimeter – track seeding idea

500 – 1695 ns window





no selection



calo selection

The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of Calorimeter clusters → simpler pattern recognition

CLFV in the muon sector

- Muon-to-electron conversion is a charged lepton flavor violating process (CLFV)

  similar but complementary to other CLFV processes as μ→ eγ and μ → 3 e.

- μ→ eγ is a CLFV decay searched @ PSI by the MEG (and now MEG-upgrade) experiment. **It is leading the research in this field.**

- Also μ → 3e is an experiment proposed @ PSI. It will be carried out

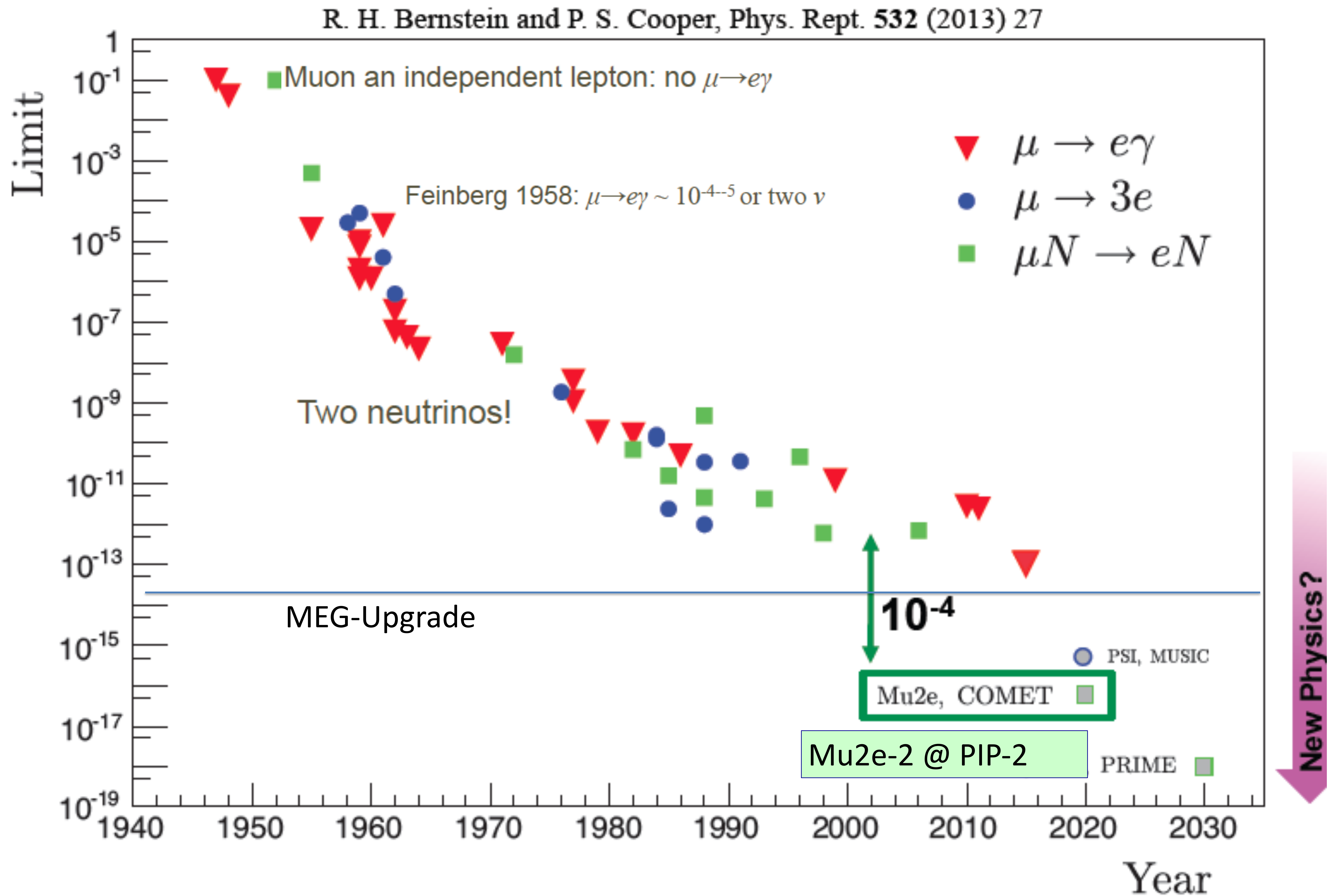
  in two phases with different reaches in sensitivity (10^{-15}, 10^{-16})

- The Mu2e experiment @ FNAL (along with COMET in Japan) searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \rightarrow e^- Al$

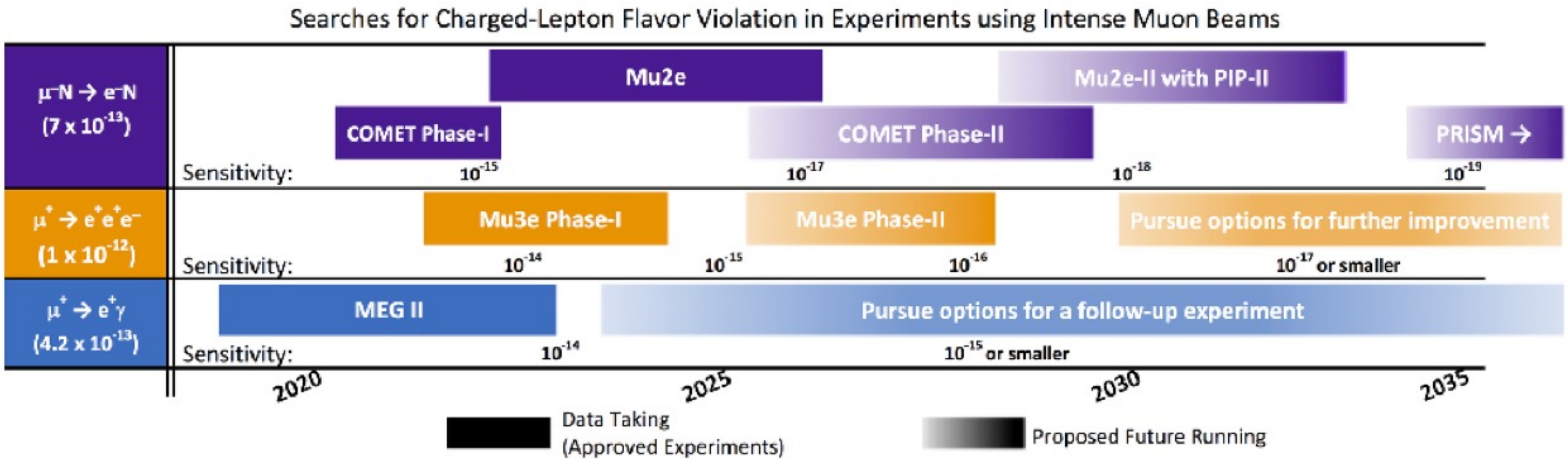
Various NP models allow for it, at levels just beyond current CLFV upper limits.

- SO(10) SUSY
  - L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.*, JHEP **1211**, 40 (2012).
- Scalar leptoquarks
  - J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
- Left-right symmetric model
  - C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

CLFV history



CLFV in the muon sector



Mu2e has a broad discovery sensitivity across all models:

→ Sensitivity to the same physics of MEG but with better mass reach

→ Sensitivity to physics that MEG is not

→ If MEG observes a signal, MU2E does it with improved statistics.

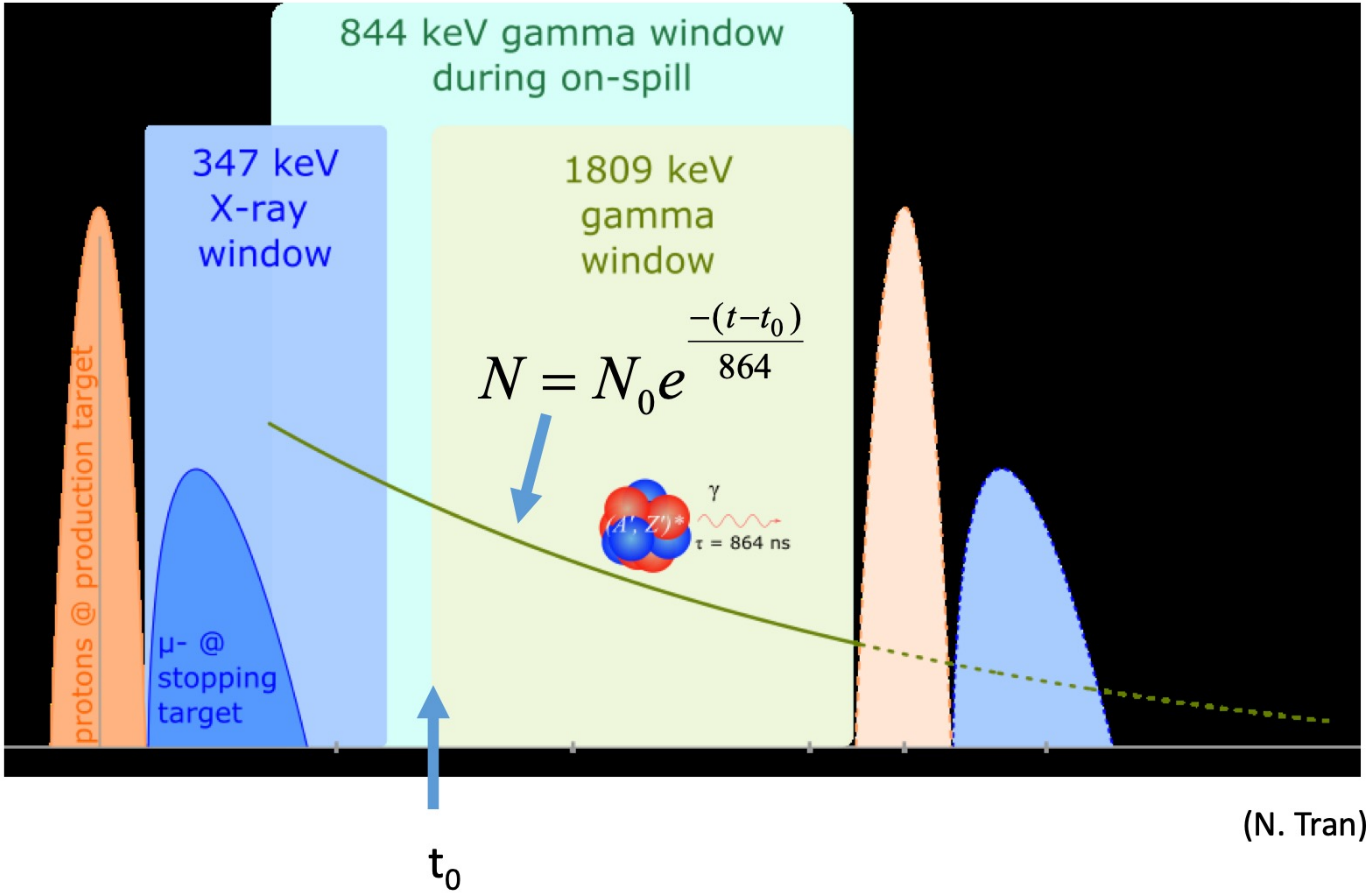
Ratio of the BR allows to pin-down physics model

→ If MEG does not observe a signal, MU2E has still a reach to do so.

In a long run, it can also improve further with PIP-2 at FNAL

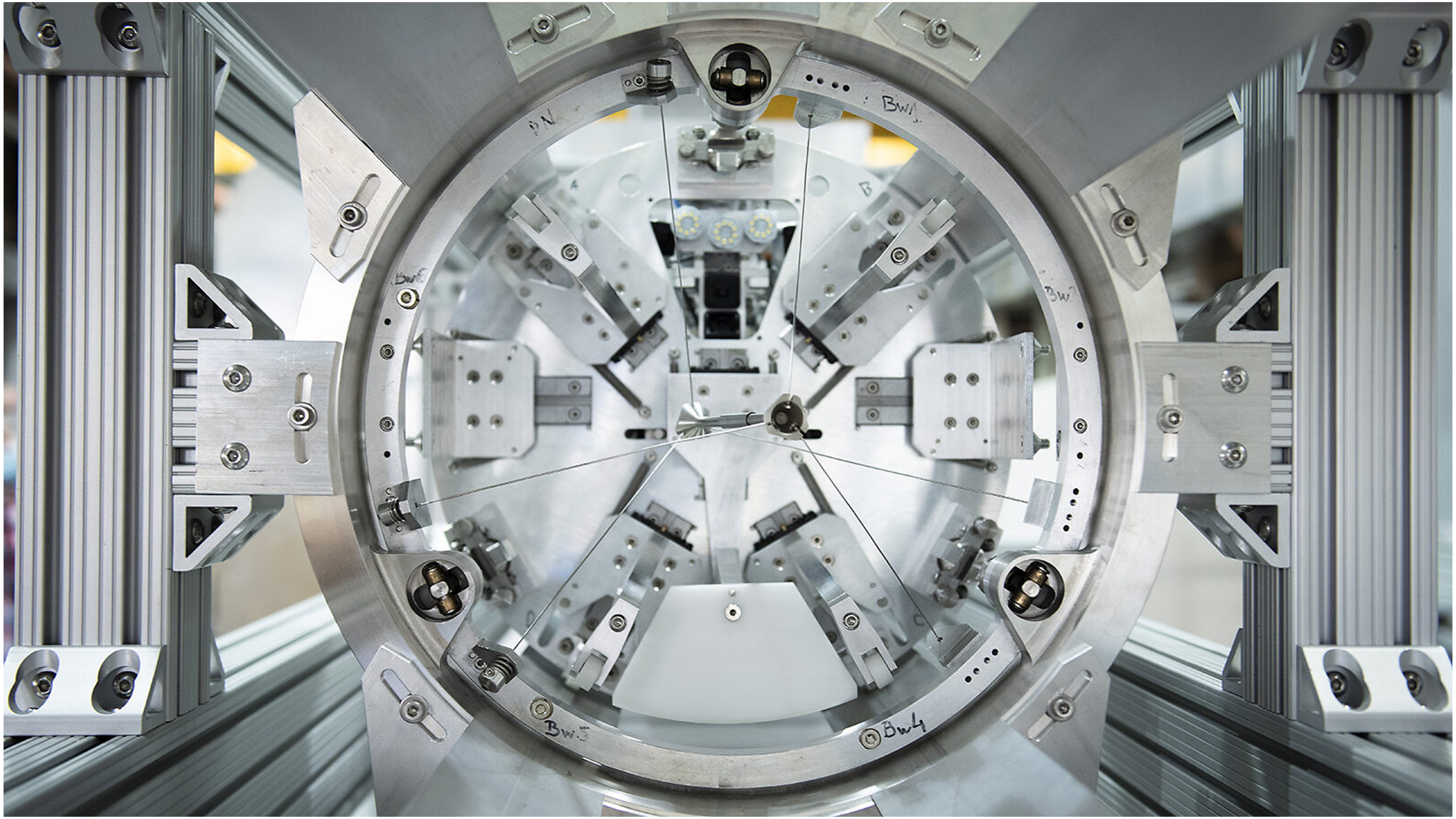
- **Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator**

Normalization



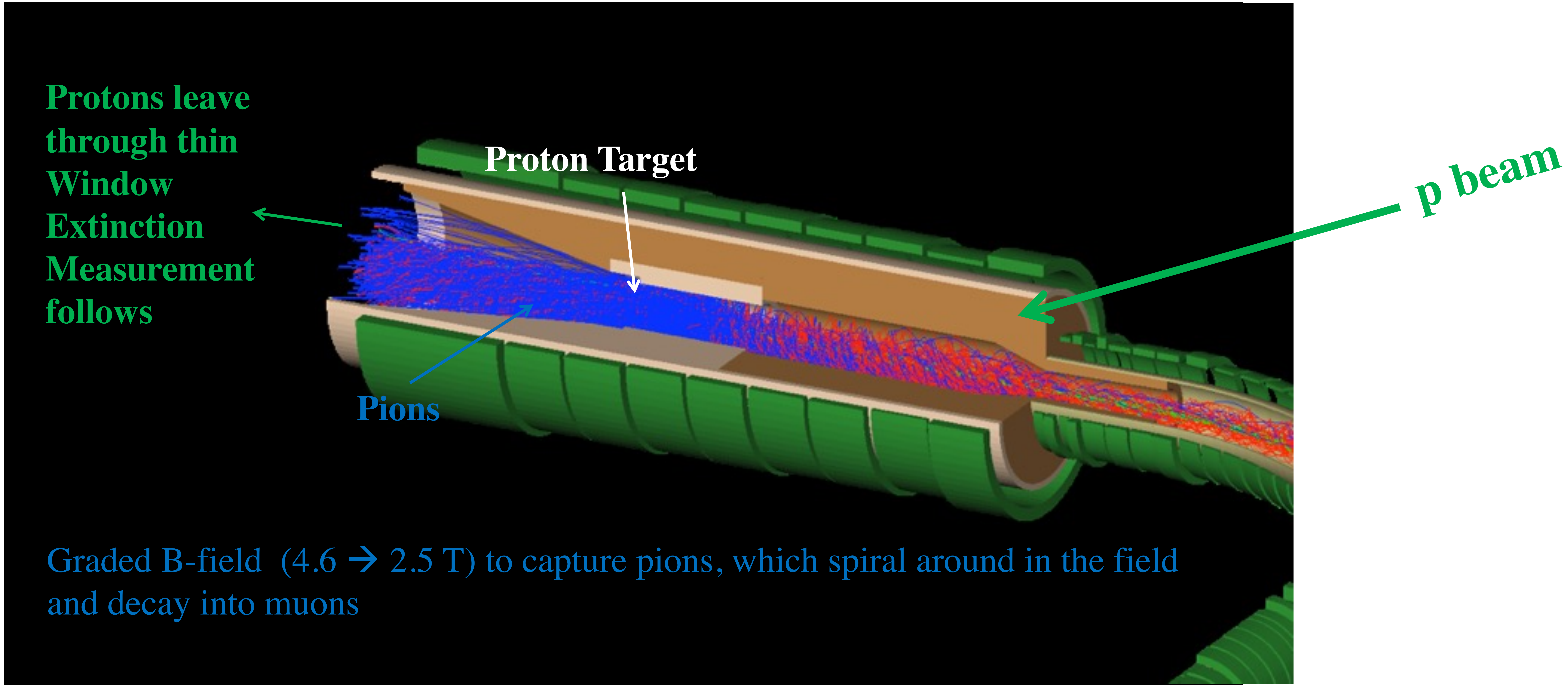
(N. Tran)

Production target detail

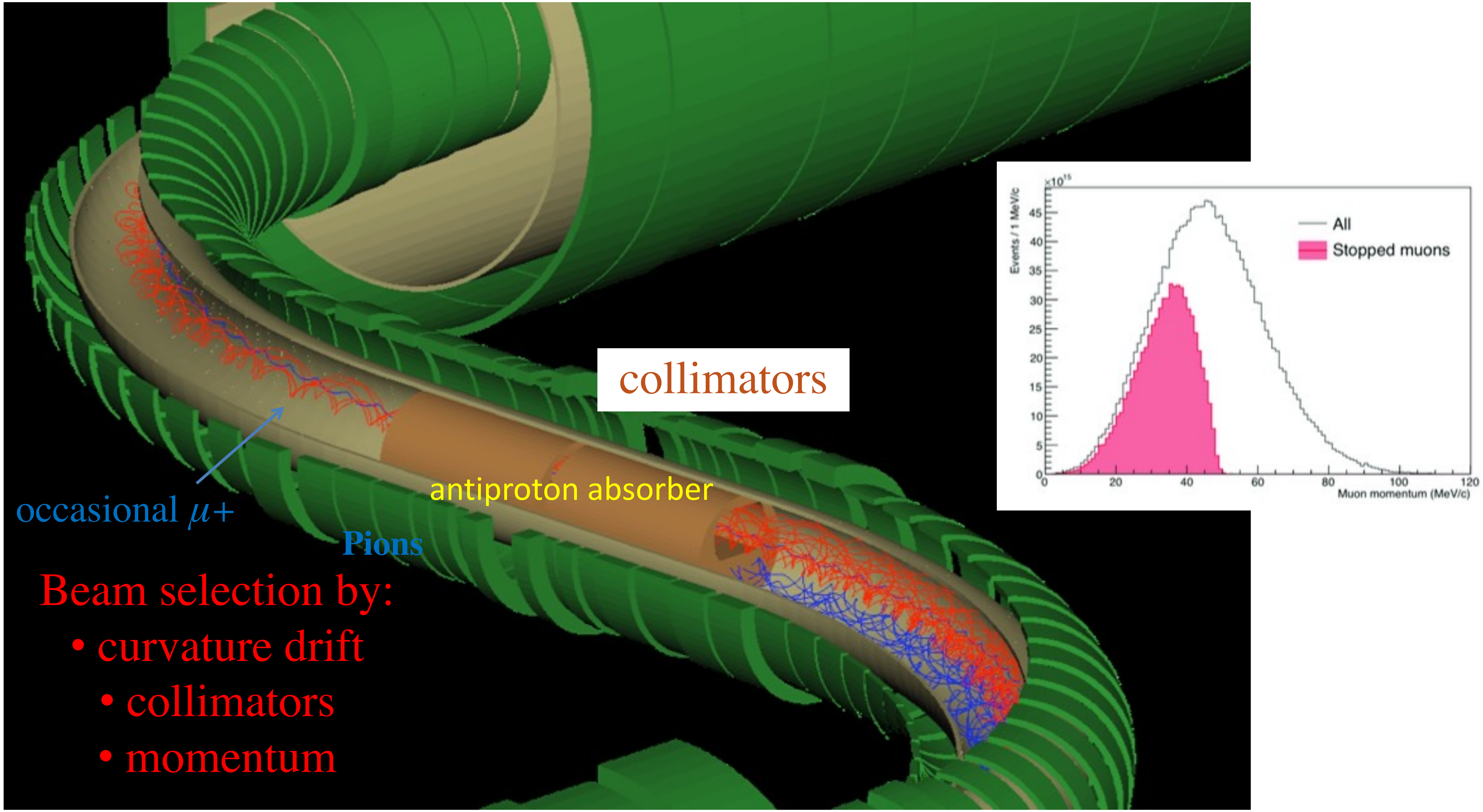


Production solenoid

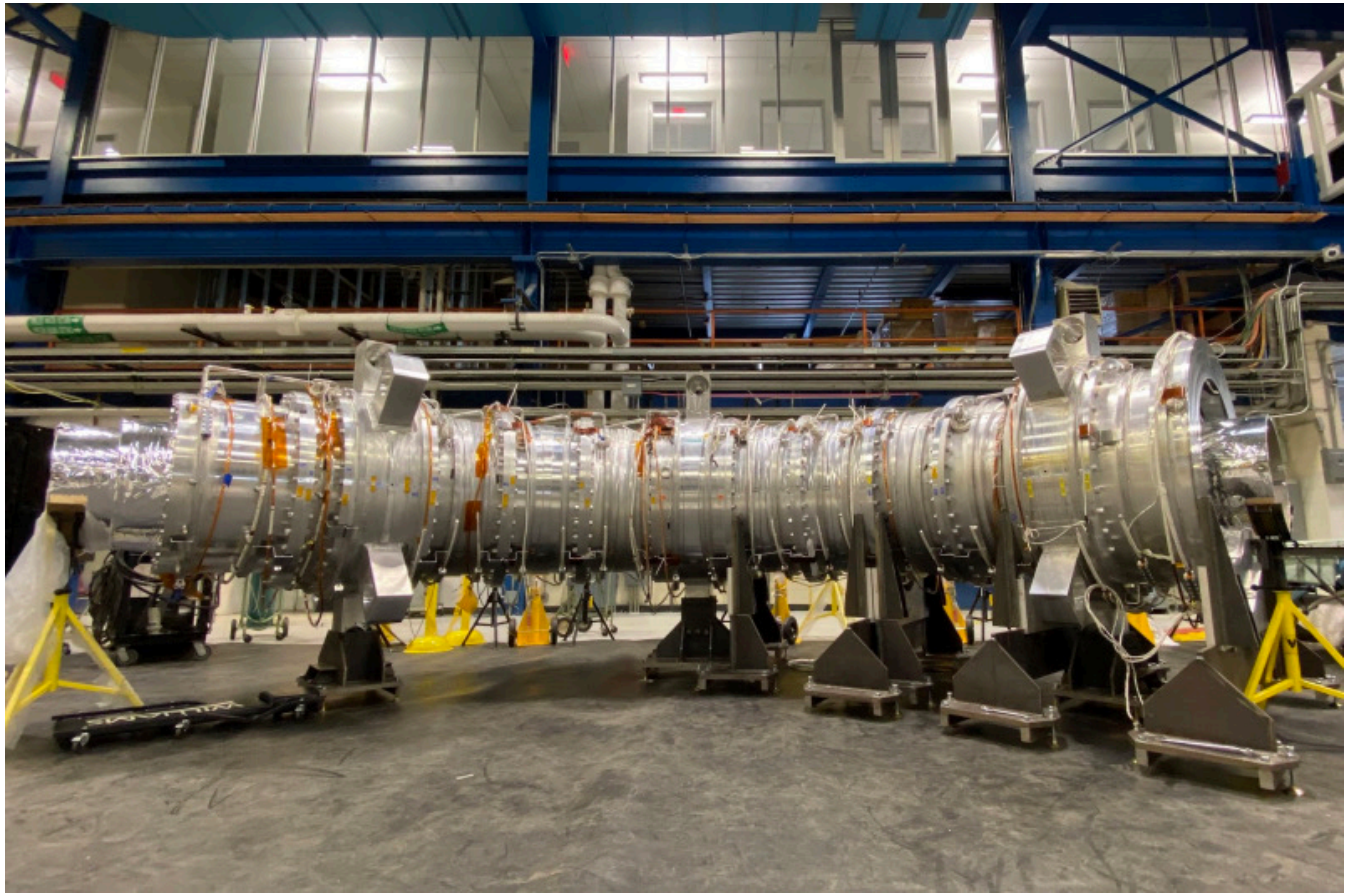
Protons enter opposite to outgoing muons: <u>This is a central idea to remove prompt background</u>



Transport solenoid



Solenoids…



Some perspective…

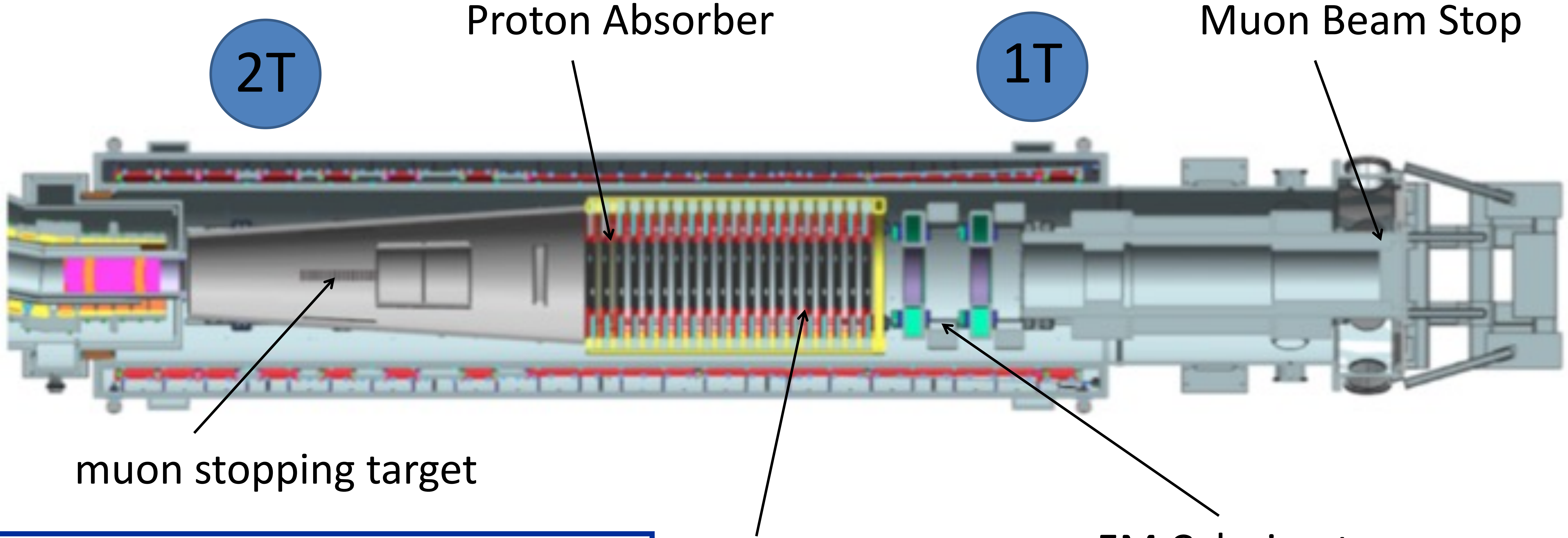
Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

~90% C.L. goal

Single event sensitivity of Mu2e

Detector solenoid

Graded field “reflects” downstream a fraction of conversion electrons emitted upstream



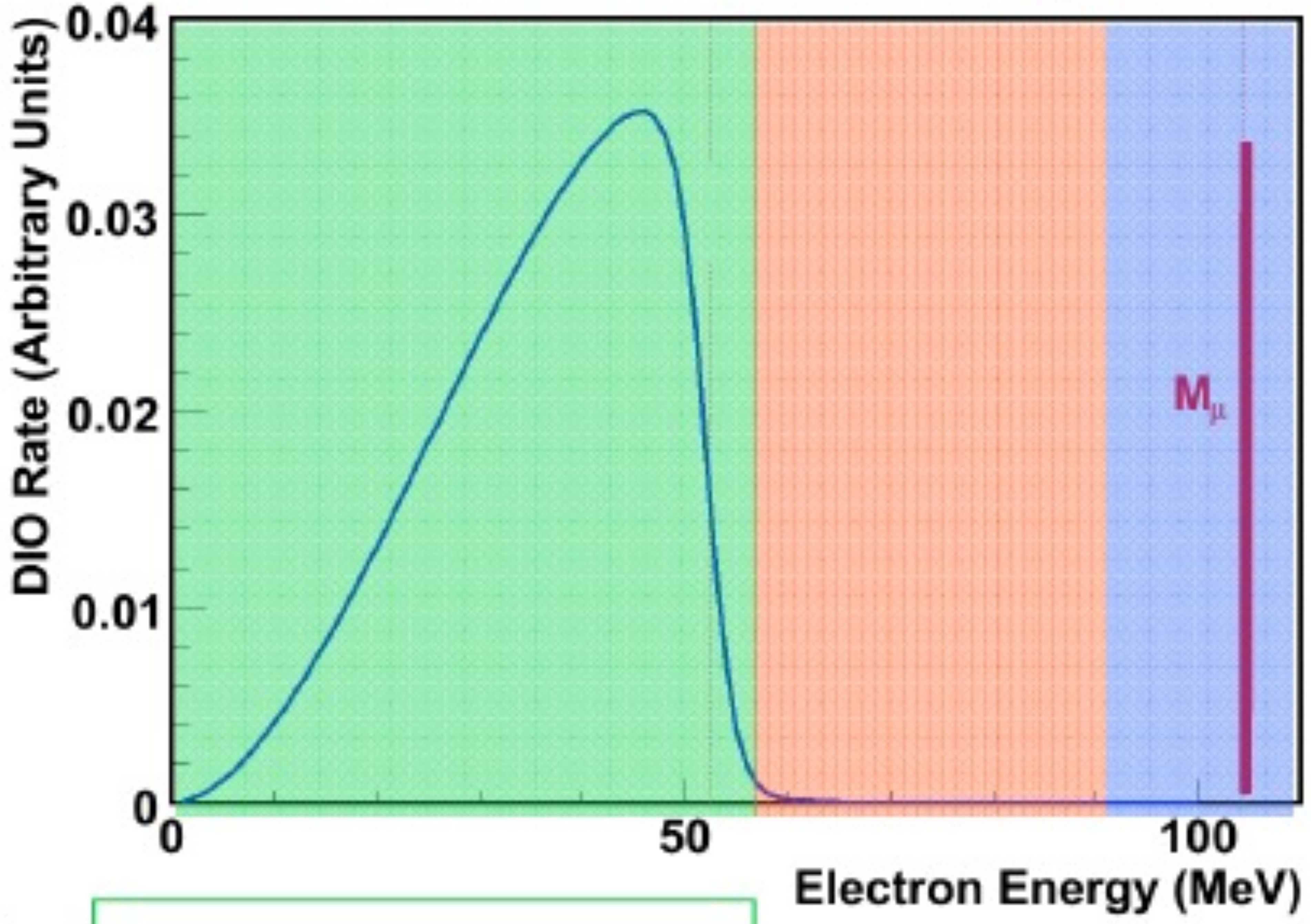
34 Al foils; Aluminum selected mainly for the muon lifetime in capture events (**864 ns)** that matches nicely the prompt separation in the Mu2e beam structure.

For the sensitivity goal → ~ 6 x 10^{17} stopped muons

For 3 year run , 6 x 10^7 sec → 10^{10} stopped muon/sec (10 GHz)

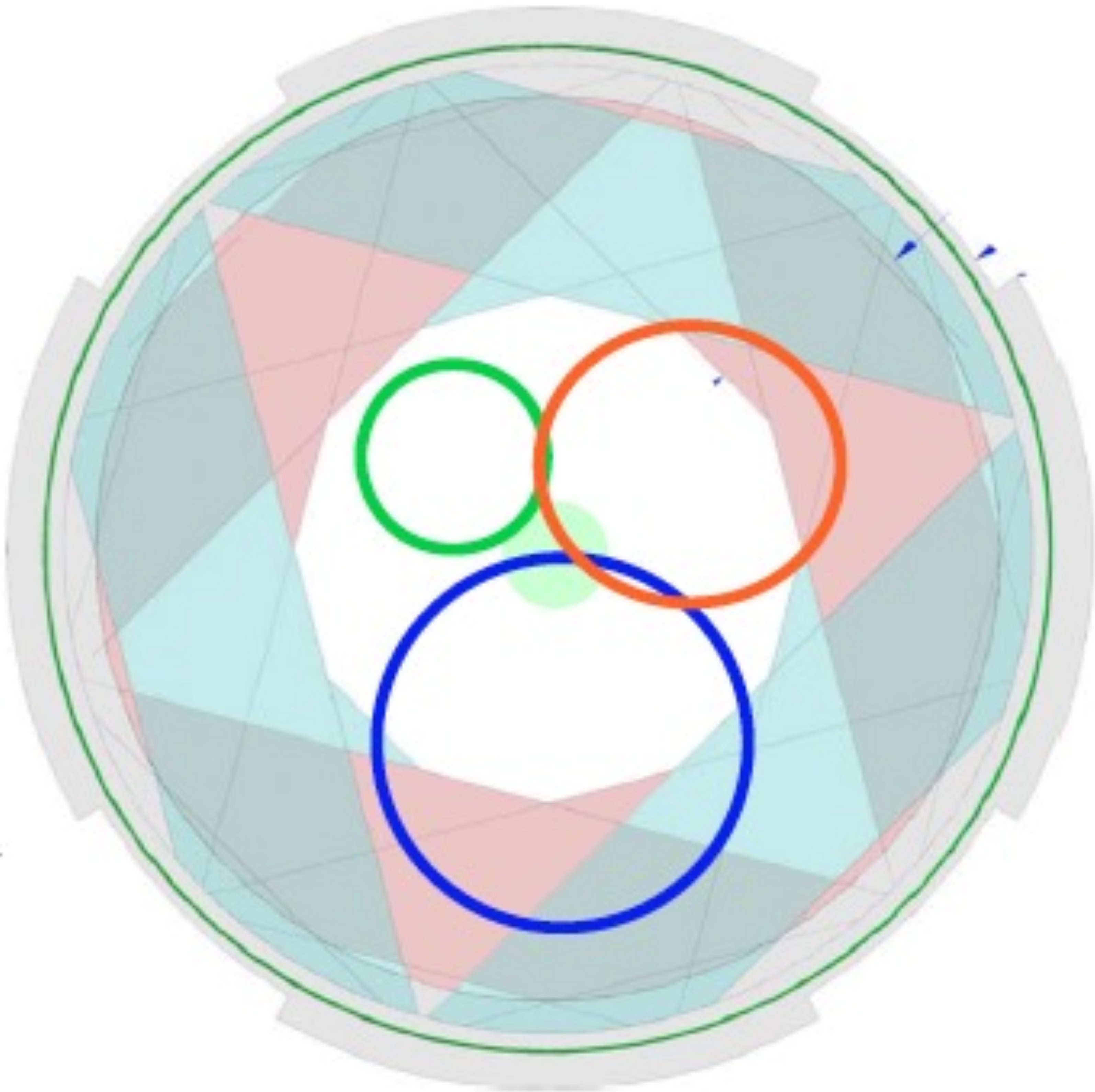
Tracking patterns

reconstructable tracks



no hits in tracker

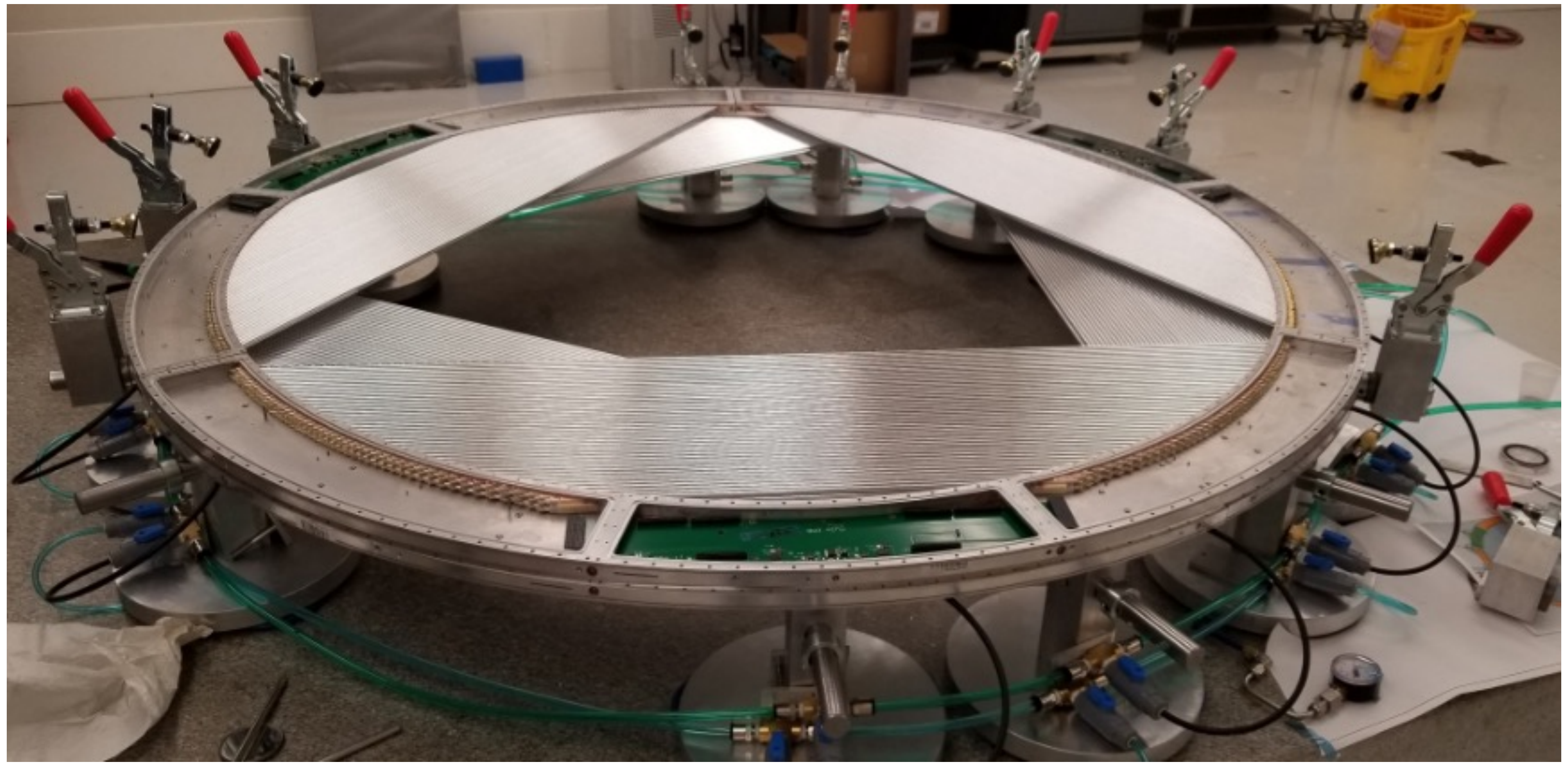
some hits tracker, tracks not reconstructable.



beam's-eye view of the tracker

Tracker readiness

- Panels are produced at U. Minnesota
  - All straw manufactured
  - **>50% of the panels processed**
- Work ongoing to prepare a vertical slice test on a full plane



Mu2e SIPM

- **6 individual 6x6 mm² 50 µm px MPPCs** (Hamamatsu)
- **UV-extended** design matches the CsI 315 nm emission peak (silicone protection layer)
- 30 % PDE @ 300 nm

TNID qualification

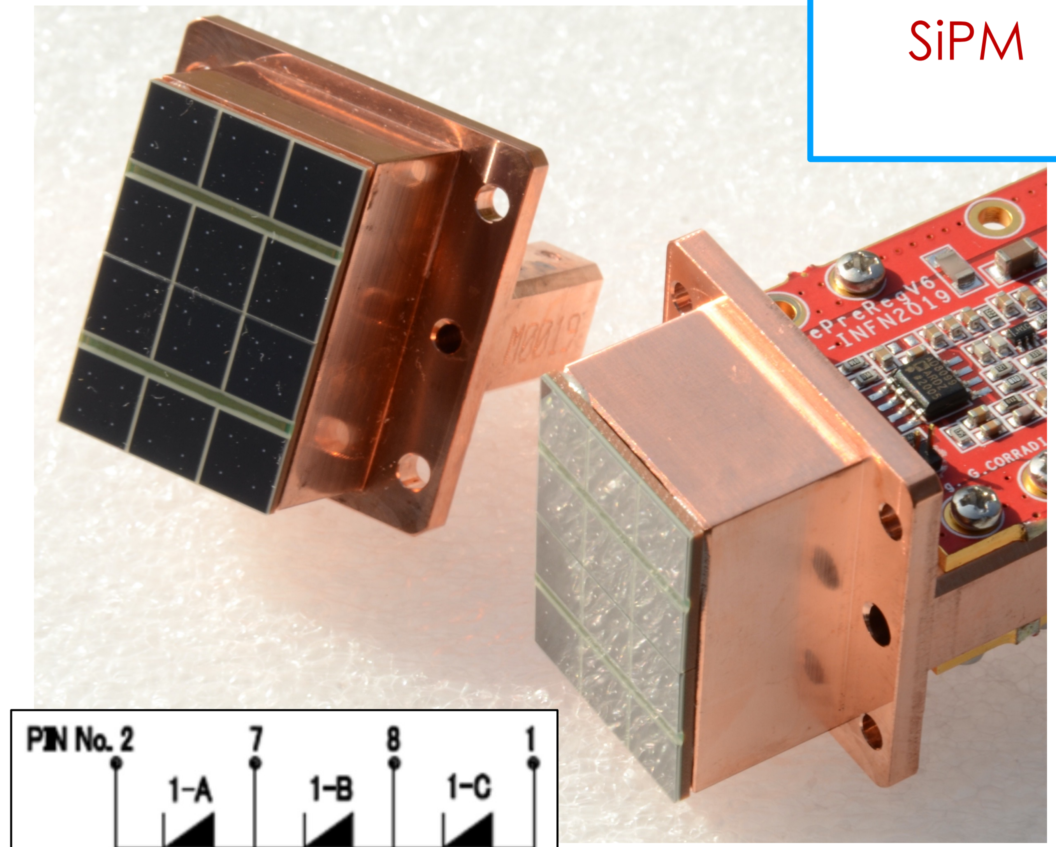
- Neutron irradiation tests @ ENEA-FNG and HZDR
- Required gain drop < 2 after irradiation
- Allowable I_{dark} increase → 2 mA/SiPM limit on FEE linear regulator
- ROU cooling from 0 to -10° C to extend SiPM operation (I_{dark} halves every 10 °C reduction)

QC steps

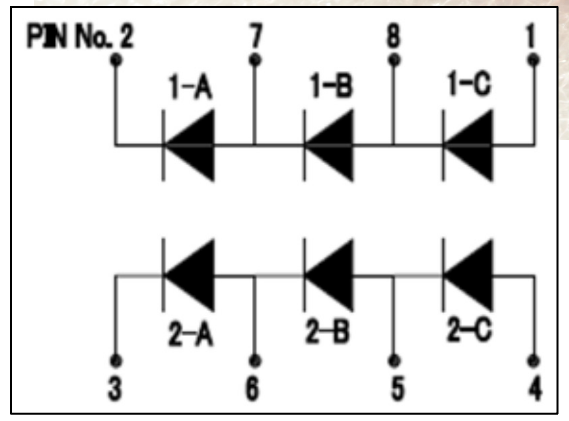
- V_{br}, I_{dark}, gain*PDE measured for each cell
- 5 SiPM/batch underwent 10^{12} n_{1MeV}/cm^2 irradiation test
- QC on all production SiPMs completed in late 2019
- 2 % of out-of-spec components

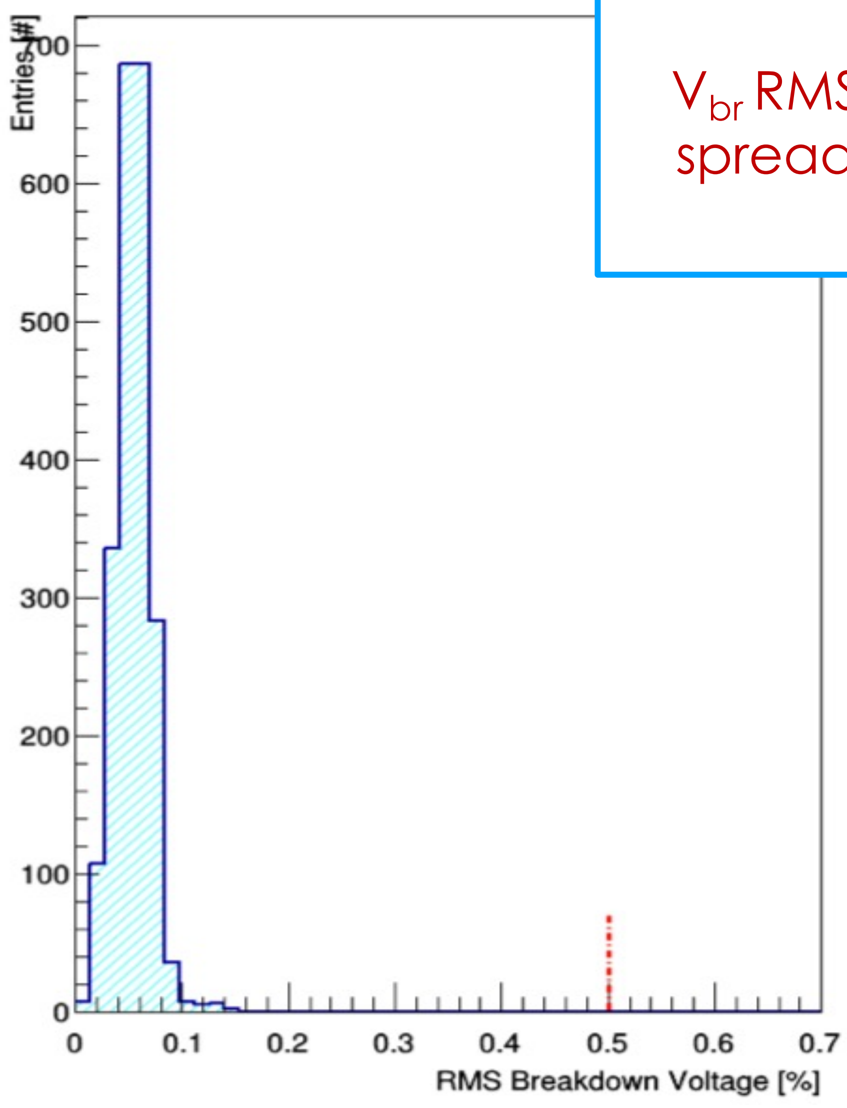
Other requirements

- gain > 10^6 @ V_{ov} = 3 V
- recovery time < 100 ns @ 15 ohm
- Good V_{bd} and I_{dark} matching over 6 cells
- MTTF > 10^6 h @ 20 °C
- Low thermal resistance

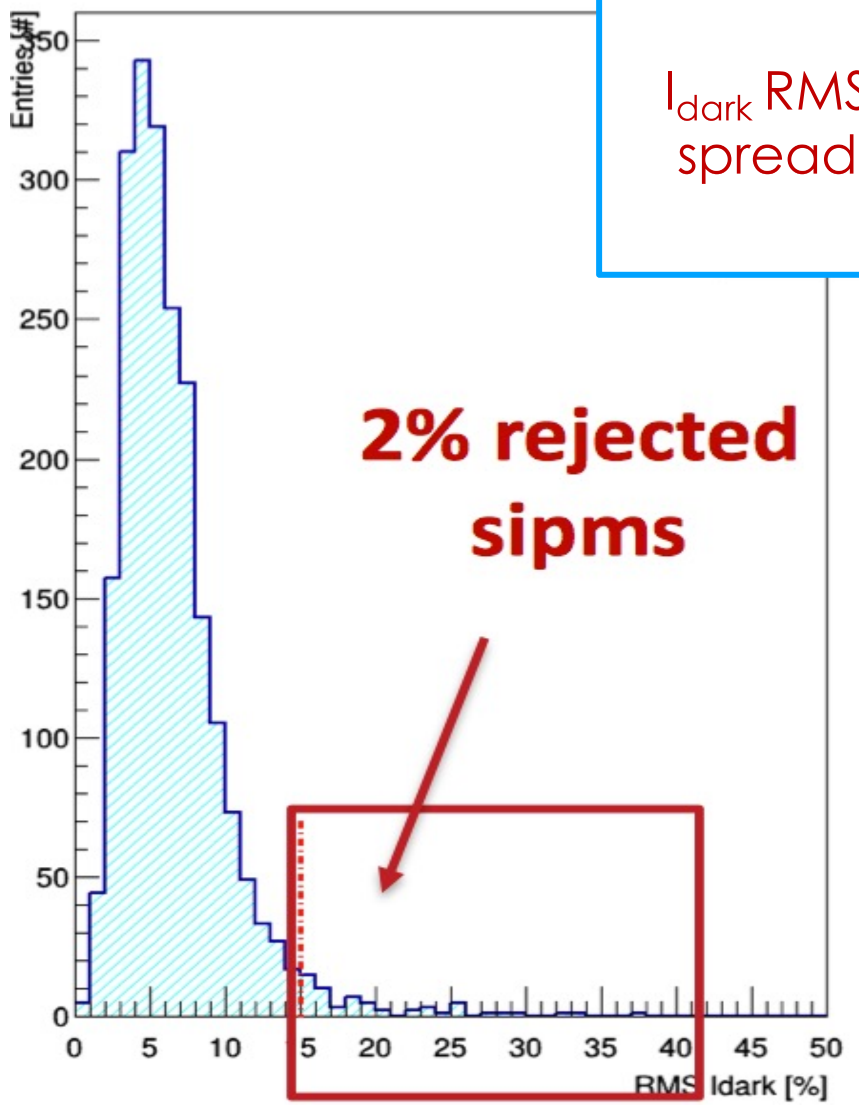


Mu2e SiPM

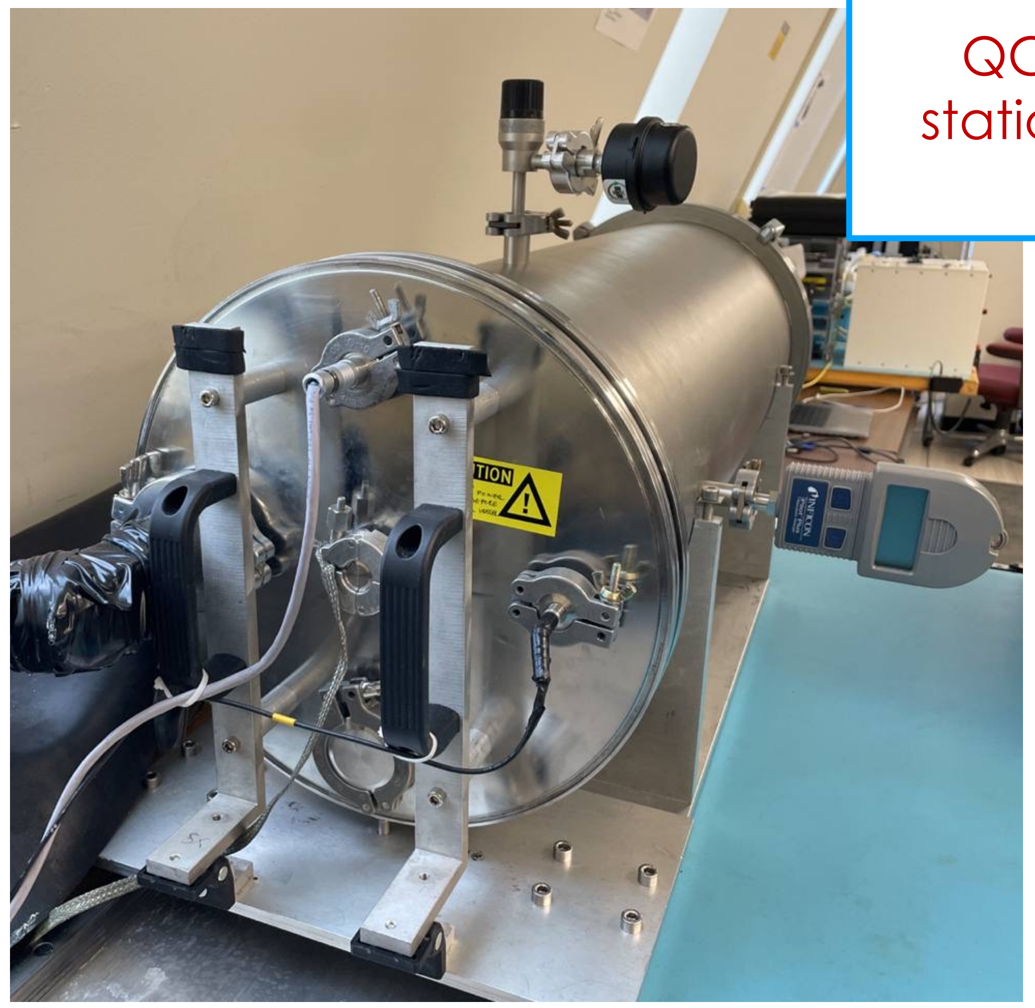




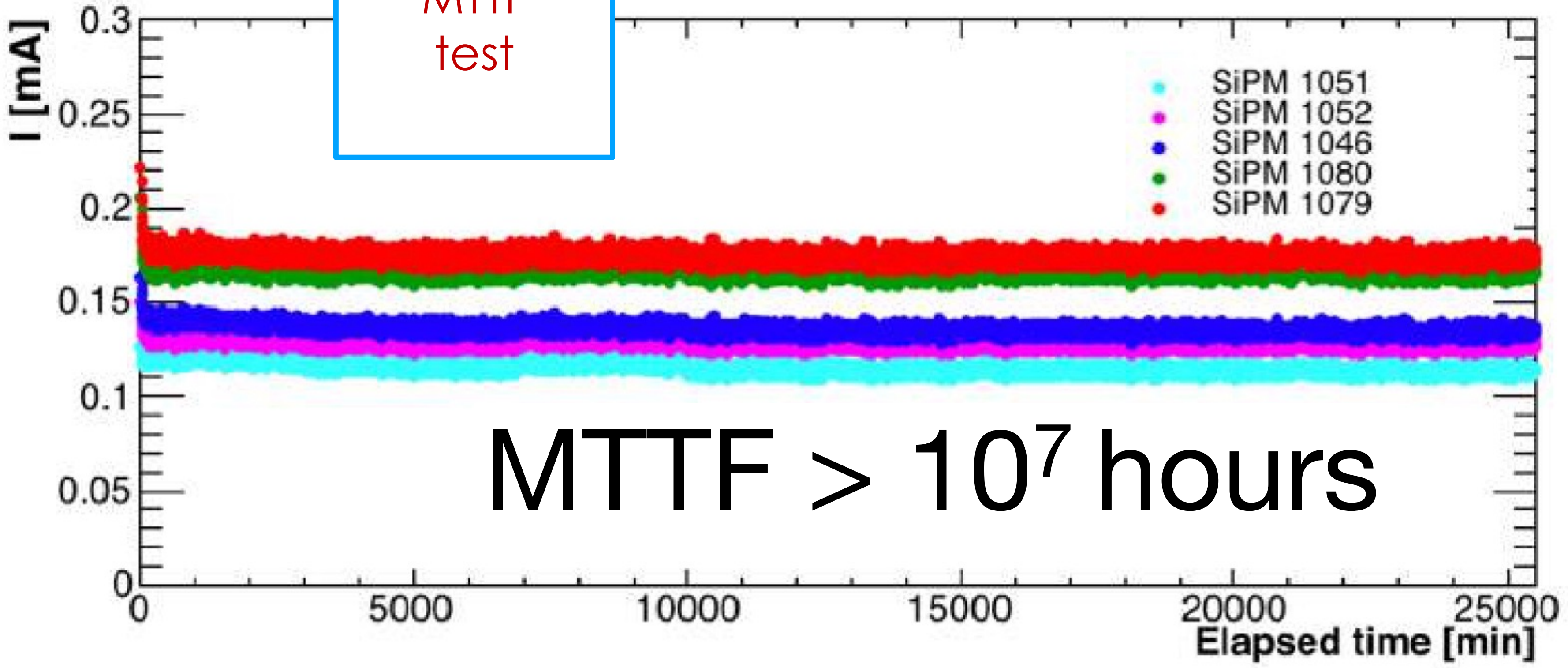
V_{br} RMS spread



I_{dark} RMS spread

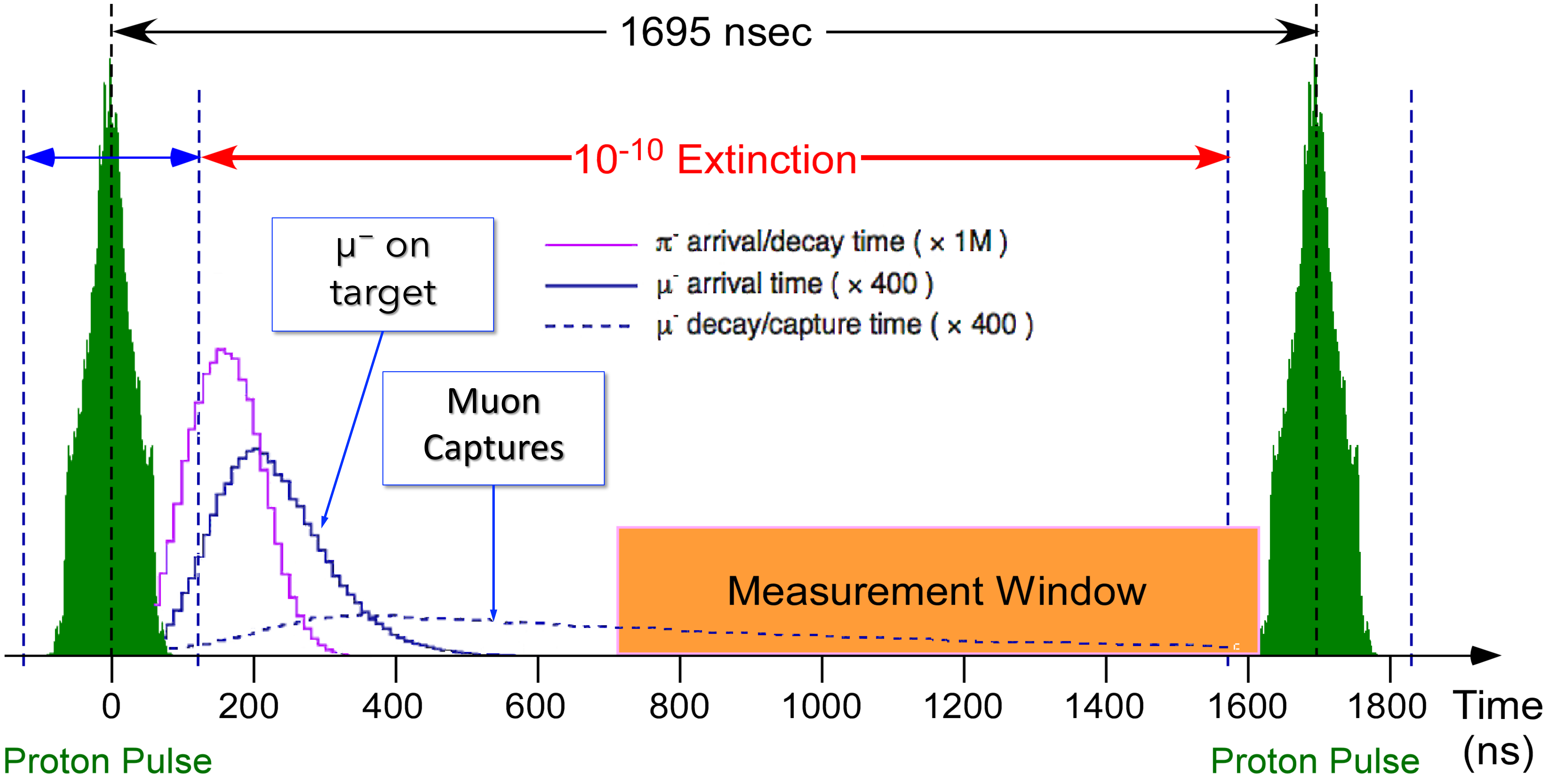


QC station



MTTF test

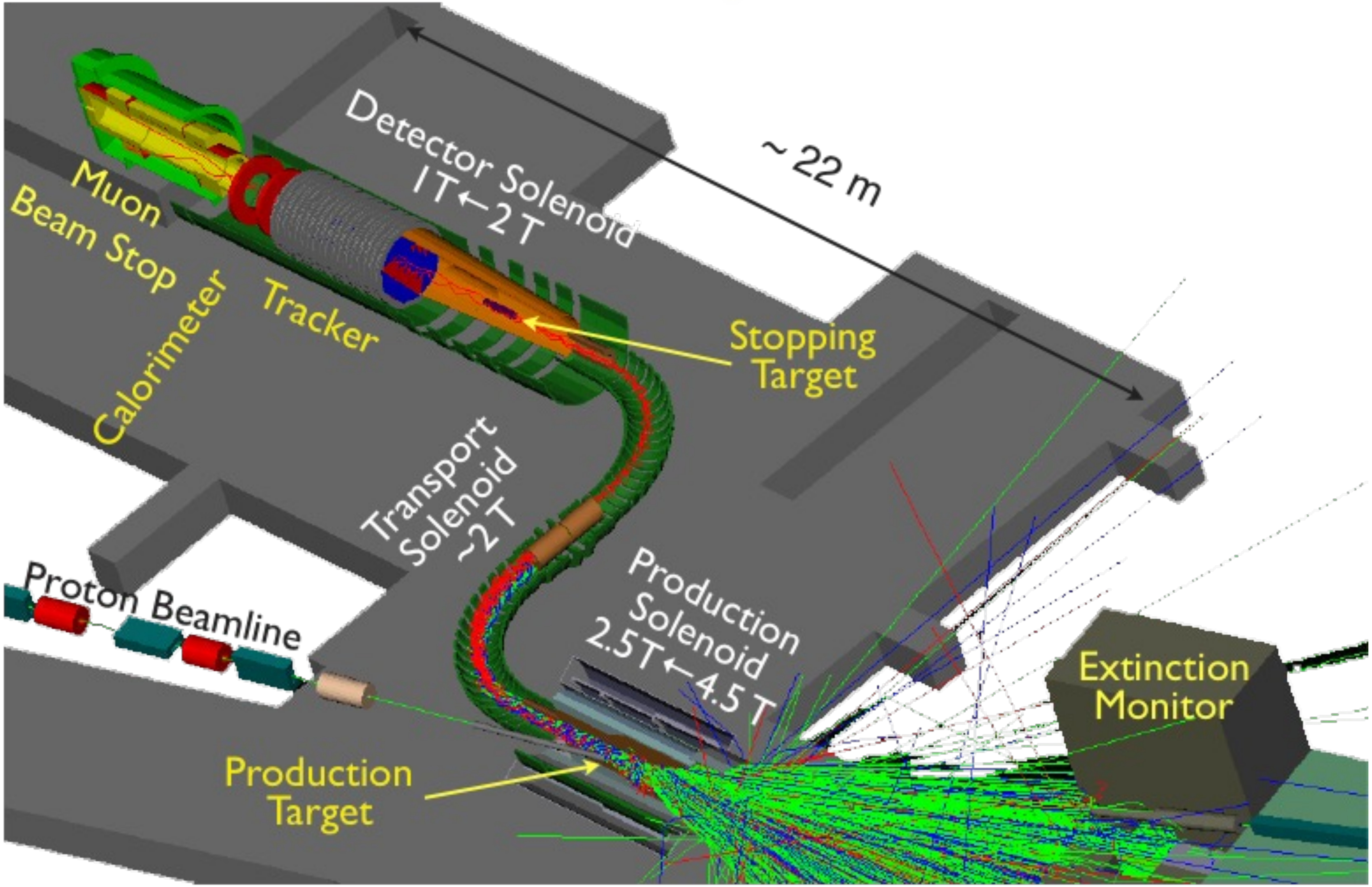
Mu2e beam structure



- Proton bunch → FW ~ 200 ns pulse
- 20,000 muons per bunch (10^{10} μ /second)
- μ reach the stopping target in ~250 ns
- Stopped μ lifetime in 1S Al **~864 ns**

- **Prompt bkg** → protons, unstopped muons, stopped and unstopped pions
- **Late protons noise** → 10^{10} beam extinction needed
- Pions from late p → RPC prompt bkg (t_{pi}^{Al} = 26 ns)
- Mainly **DIO** and **CR** background during observation window

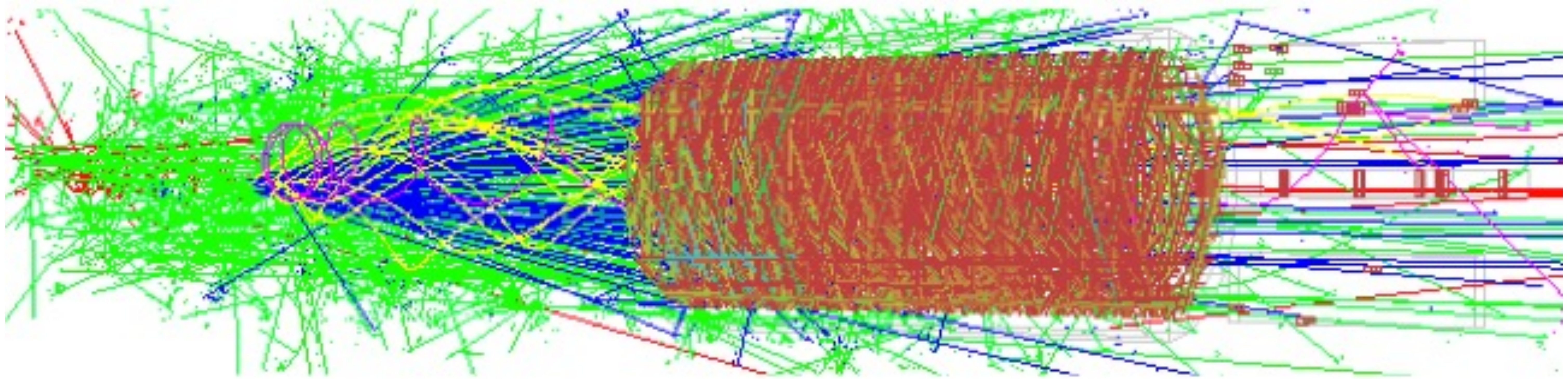
Beam's eye view



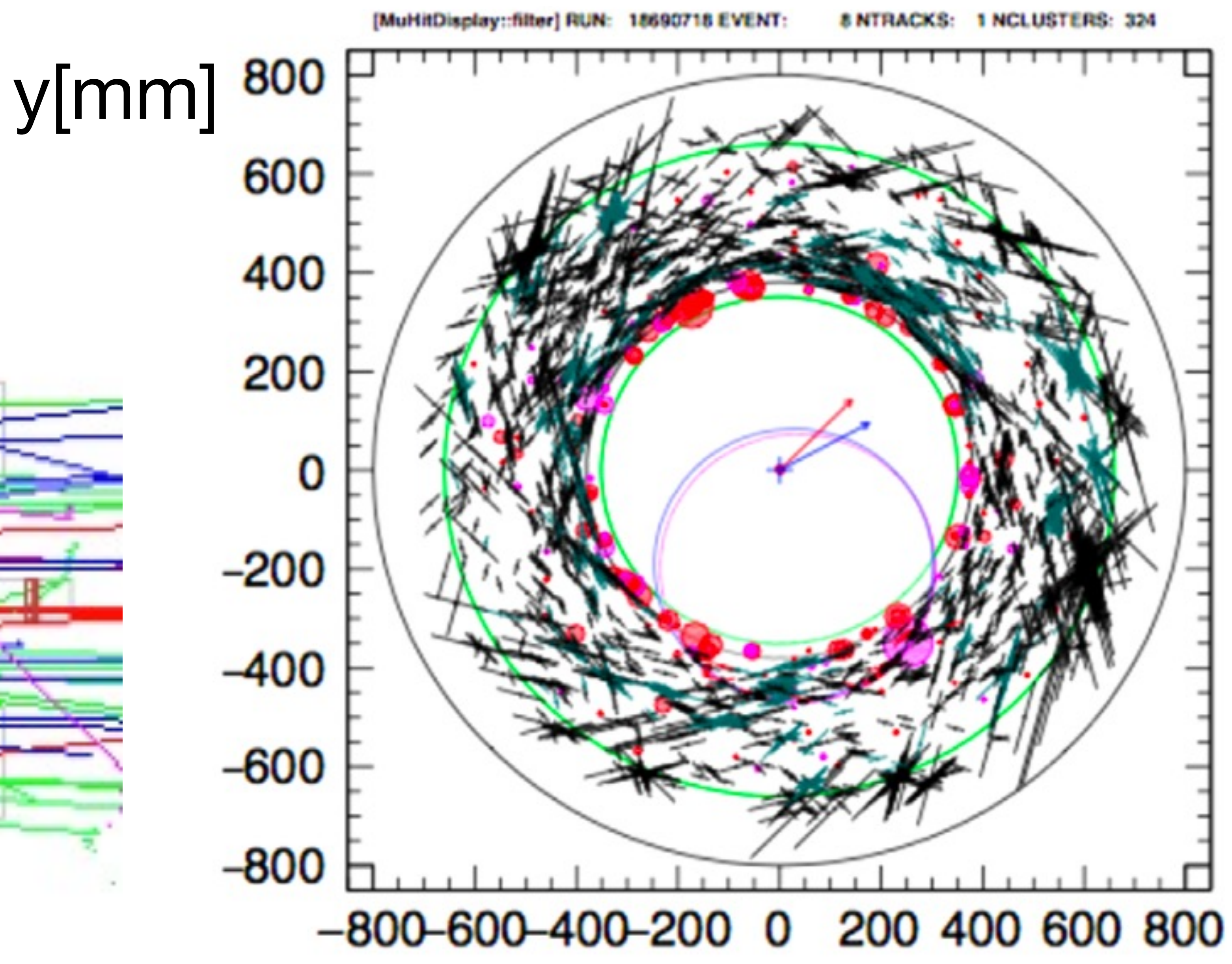
X

Cluster seeding idea

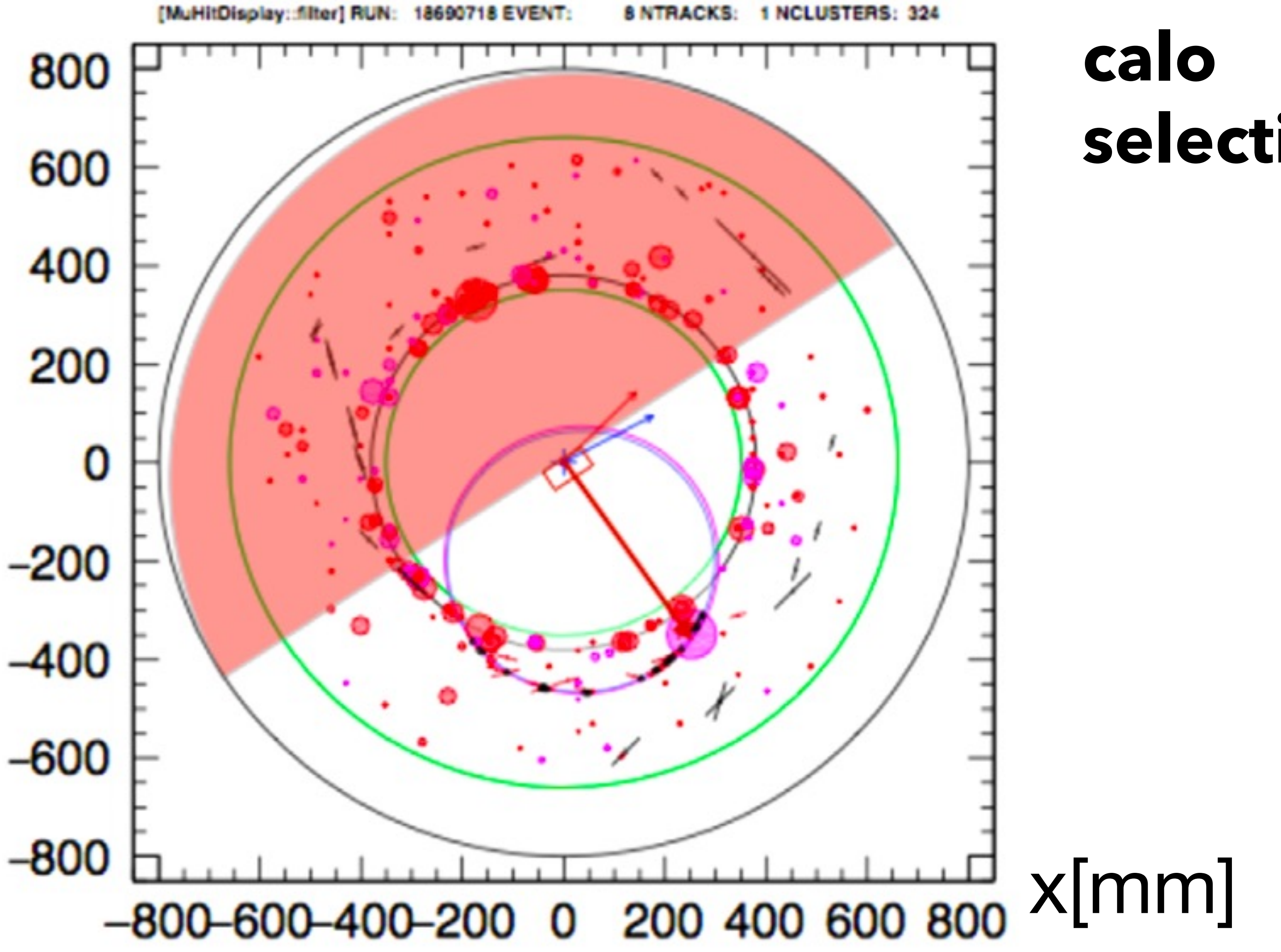
500 – 1695 ns window



The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time (|ΔT| < 50 ns) and azimuthal angle of Calorimeter clusters → simpler pattern recognition

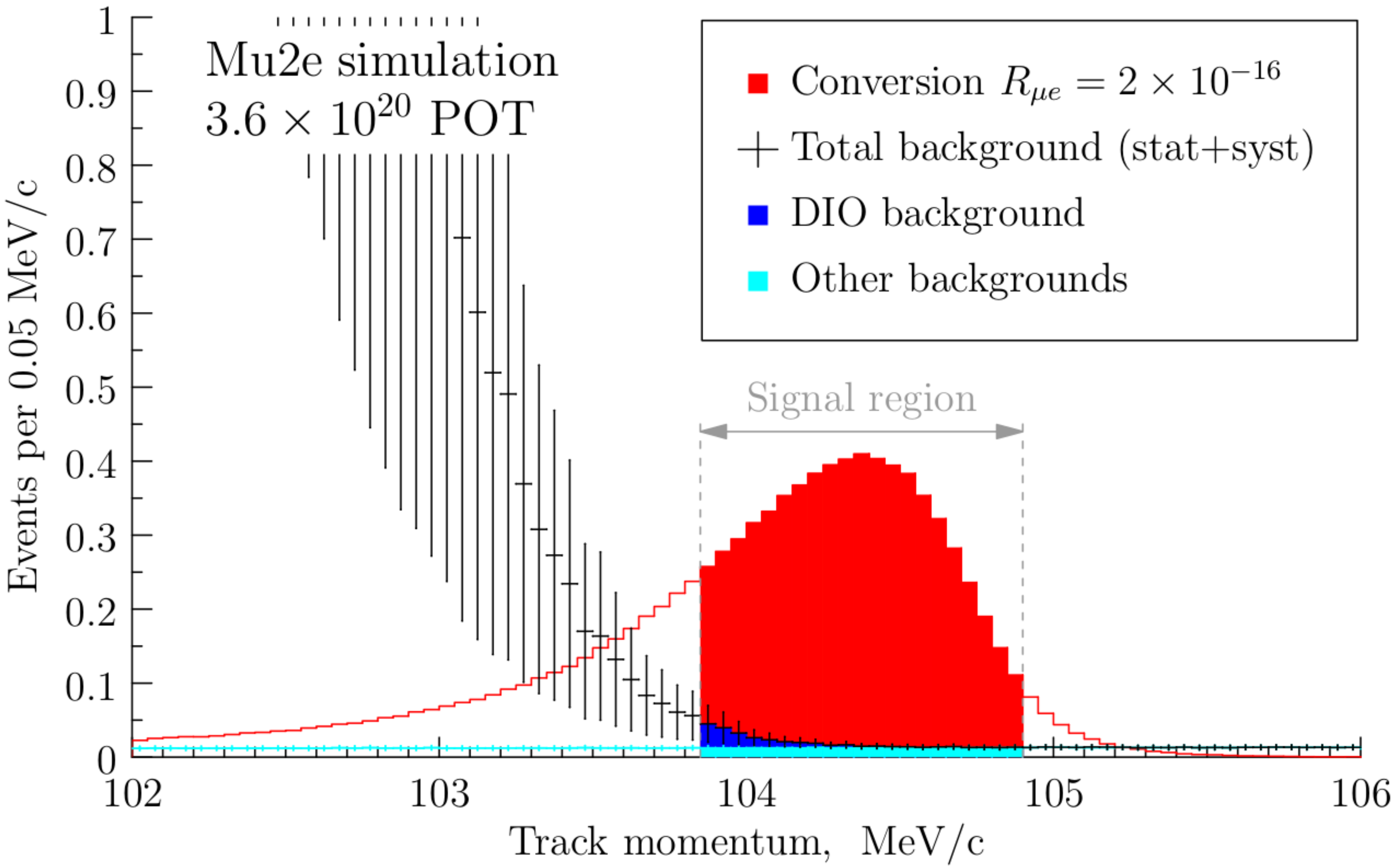


no selection



calo selection

Full simulation for signal extraction



typical SUSY at 10^{-15}: 40 events vs 0.4 backgrounds

Procurement of Crystals and SiPMs

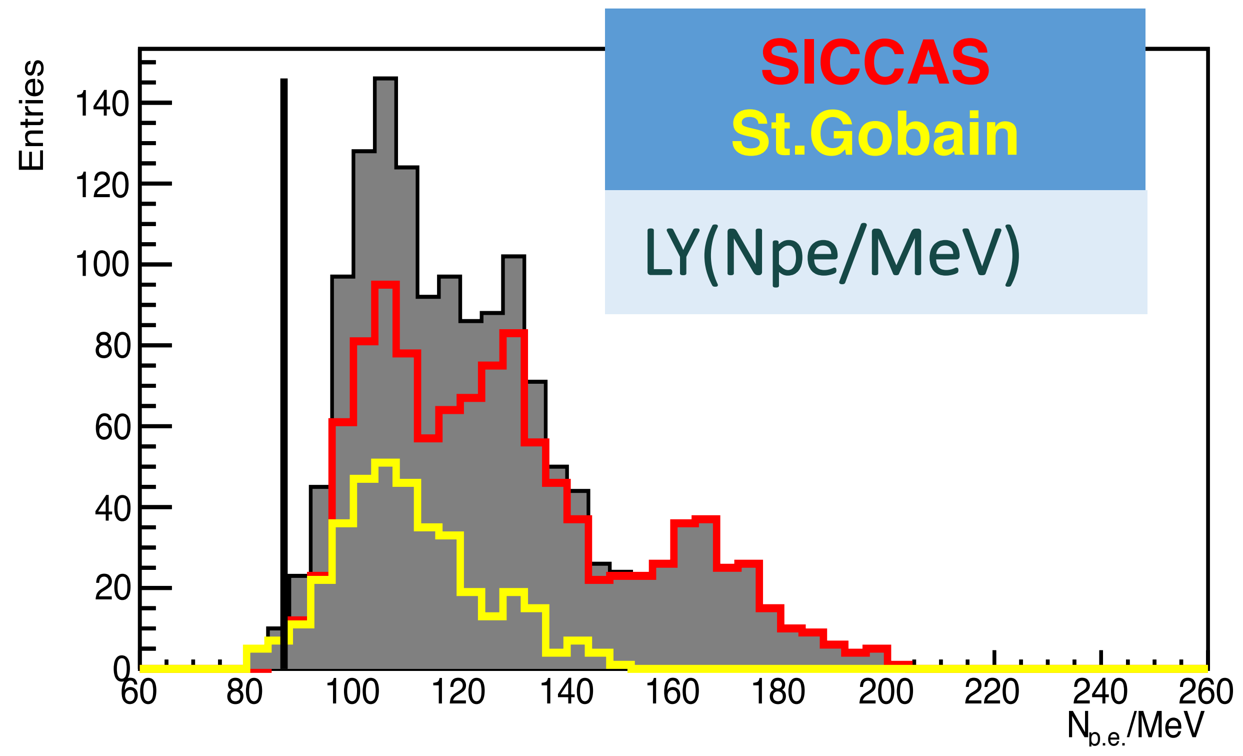
Production Completed

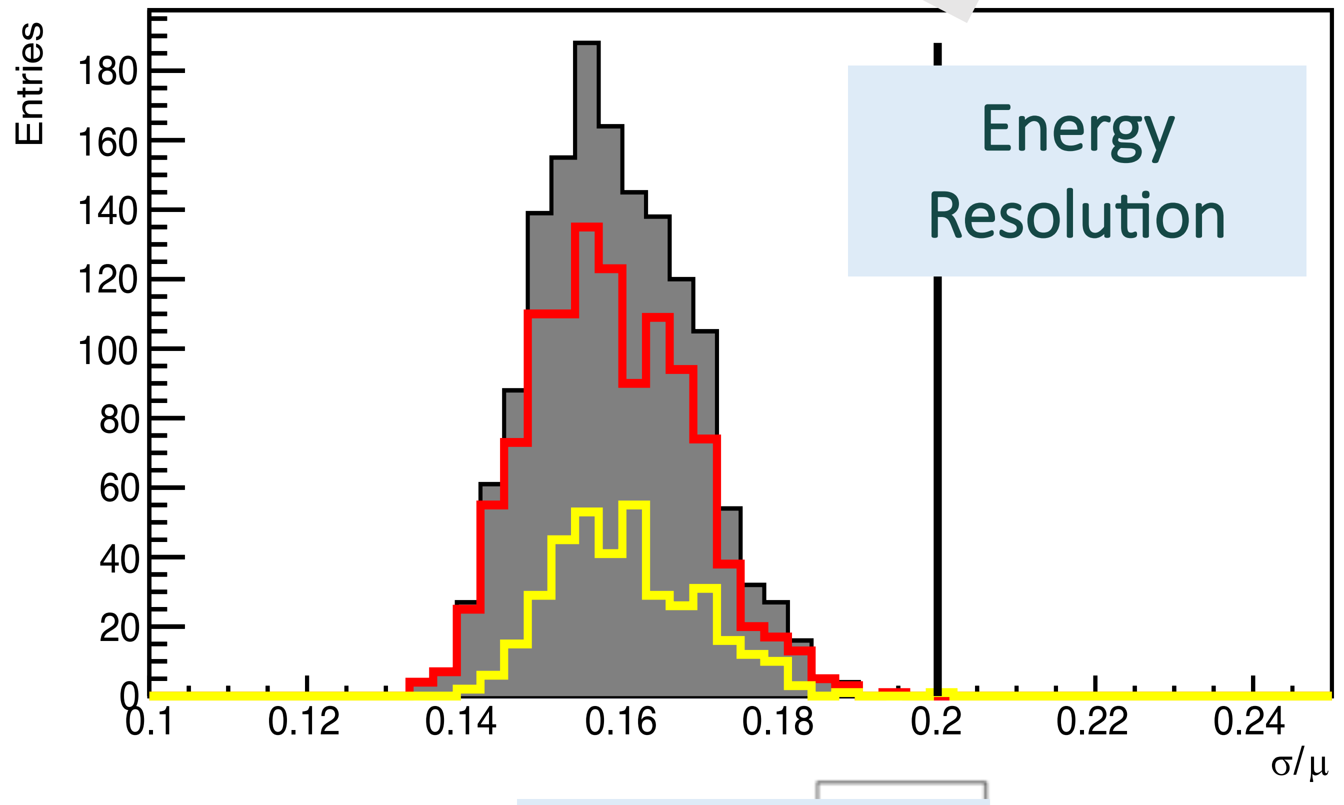
- ❑ Production of 1500 CsI crystals and 4000 Mu2e SiPMs started in 2018
- ❑ ^{22}Na QA test at SIDET (FNAL) + irradiation tests at Caltech, HZDR, FNG, Calliope

Crystals

- ❑ Two producers **(SICCAS, St. Gobain)**
- ❑ QA of optical (**LY, LRU, F/T, RIN)** and mechanical dimensions
  - ✓ St.Gobain failed to match our specs.
  - ✓ Final production back to SICCAS
- ❑ OK with irradiation tests
- ❑ ~8 % had specification failure

Completed end of 2020





SiPMs

- ❑ Producer: **HAMAMATSU**
- ❑ **6 individual 6x6 mm² 50 μm px MPPCs** (Hamamatsu) paralleled series (2/3 C_i)
- ❑ All 6 cells/SiPM tested, measuring

  V_{br}, I_{dark}, Gain x PDE
- ❑ **Irradiation with ~1x10¹² neutrons/cm² and (MTTF)** test on 5 SiPMs/batch

Completed in 2019