COMET Experiment and Other Muon CLFV Searches

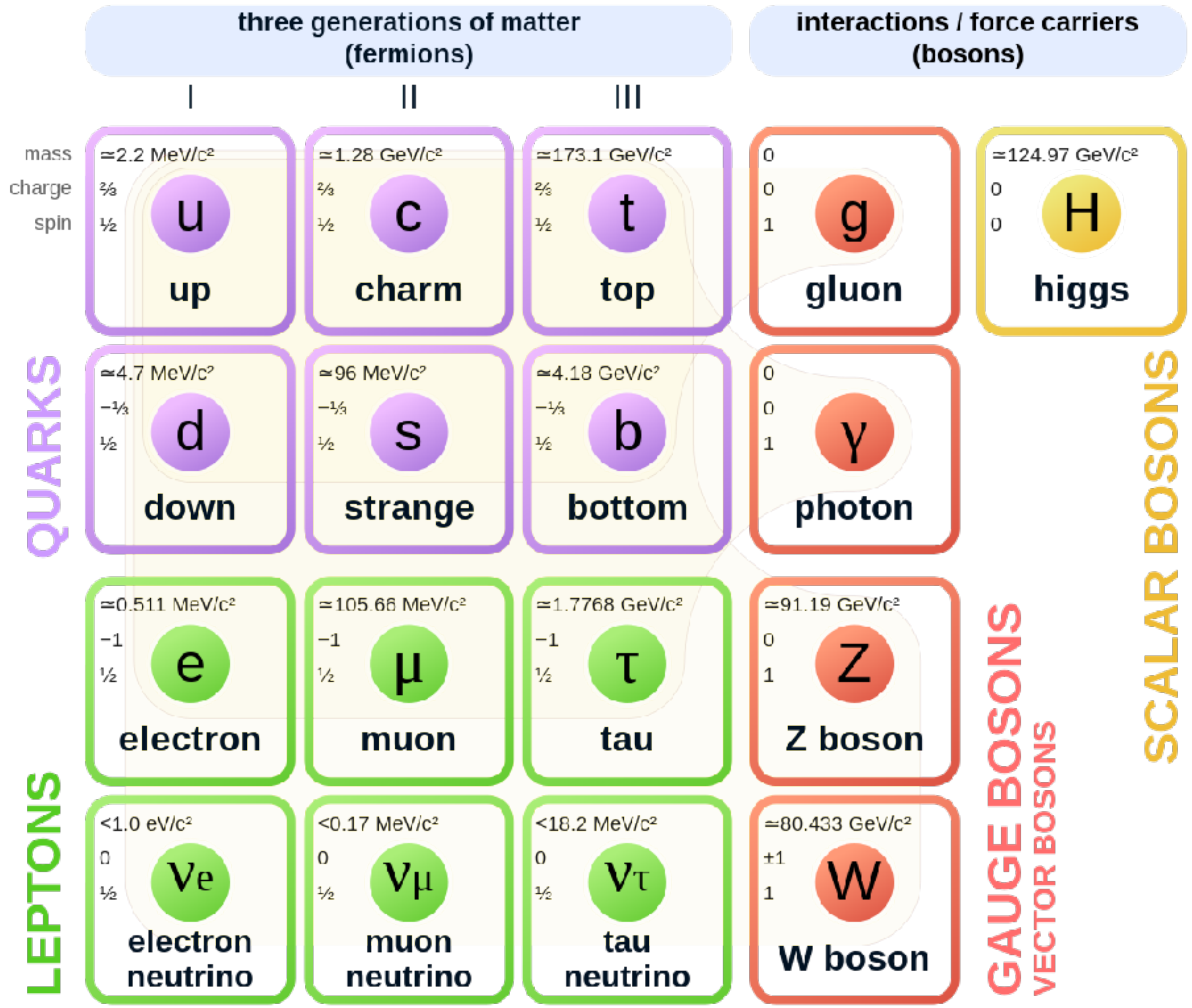
藤井祐樹
モナシュ大学

フレーバー物理研究会2022

2022年11月8日, ホテルニュー八景園

What is CLFV?

Standard Model of Elementary Particles

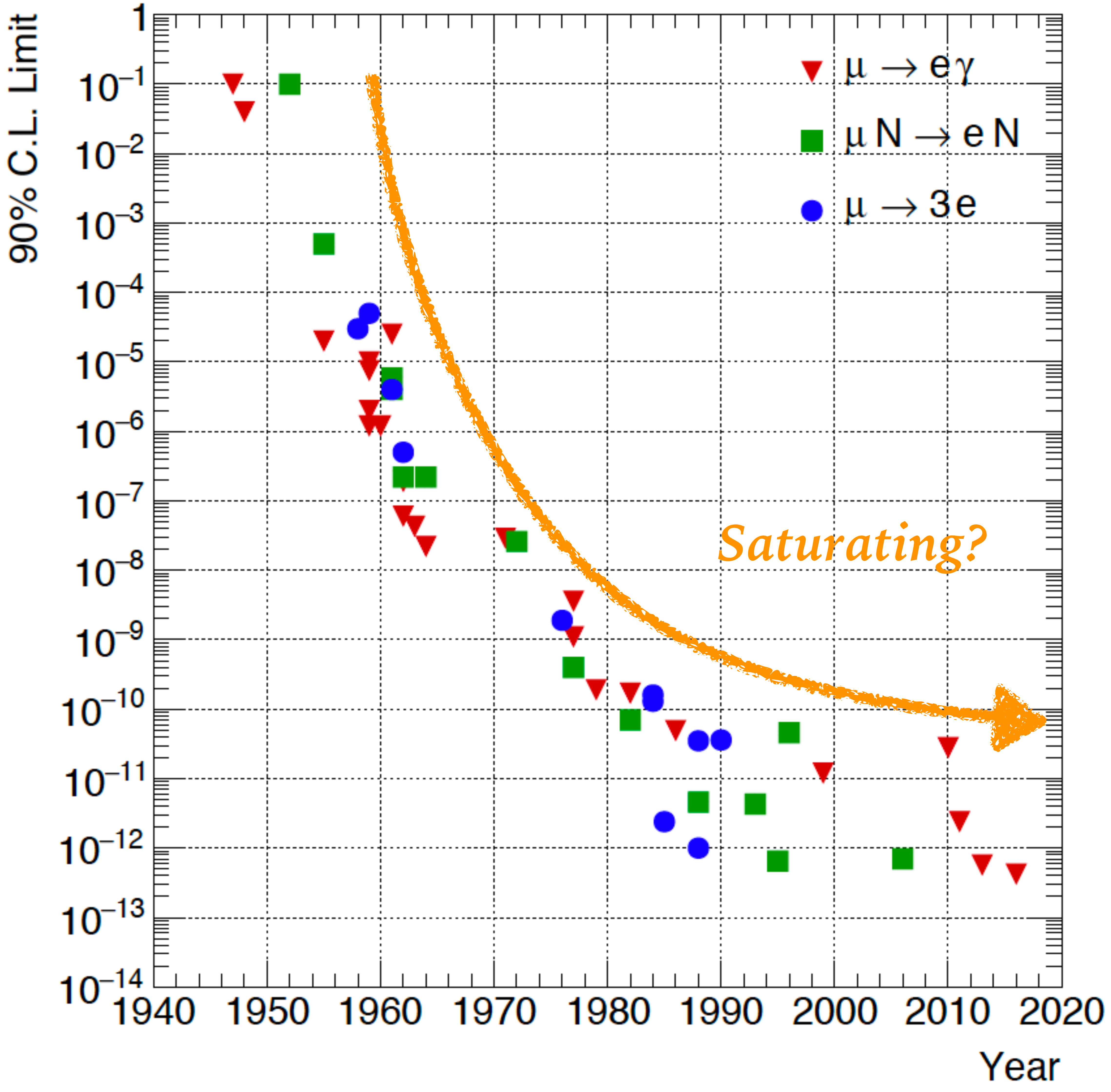


Wikipedia

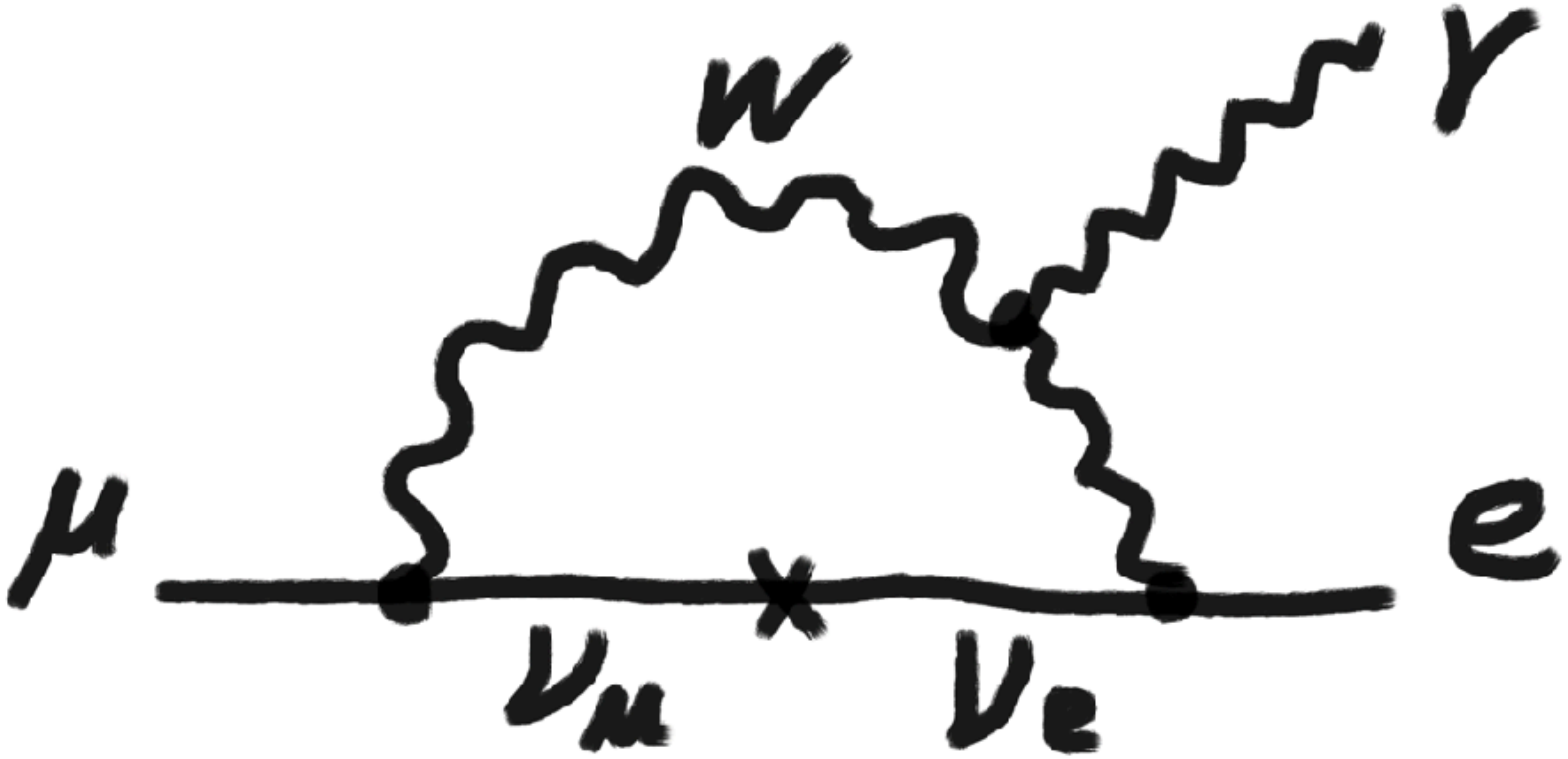
- Modern Particle Physics
  - Based on the beautiful symmetries and conservation laws → eventually broken
  - Forces are nicely unified → but no gravity
  - No dark matters, neutrino masses, *etc*…
- We know
  - Quarks mix (CKM matrix)
  - Neutrinos mix (PMNS matrix)
- So why don't charged leptons mix?
  - Charged Lepton Flavour Violation (CLFV)

CLFV History

- Muons were discovered in 1936 accidentally
  - *"Who ordered that?" — I. I. Rabi*
  - Dawn of the flavour physics
- Current upper limits (for muons = golden channels @90% C.L.)
  - *BR*$(\mu^+ \to e^+e^+e^-)$ **< 1.0 × 10^{-12}** by SINDRUM @PSI, Nucl. Phys. B 299 (**1988**)
  - *CR* $(\mu^- N \to e^- N)|_{Au}$ **< 7.0 × 10^{-13}** by SINDRUM II @PSI, Eur. Phys. J. C 47 (**2006**) 337
  - *BR*$(\mu^+ \to e^+\gamma)$ **< 4.2 × 10^{-13}** by MEG @PSI, Eur. Phys. J. C 76 (**2016**) 434



CLFV Physics



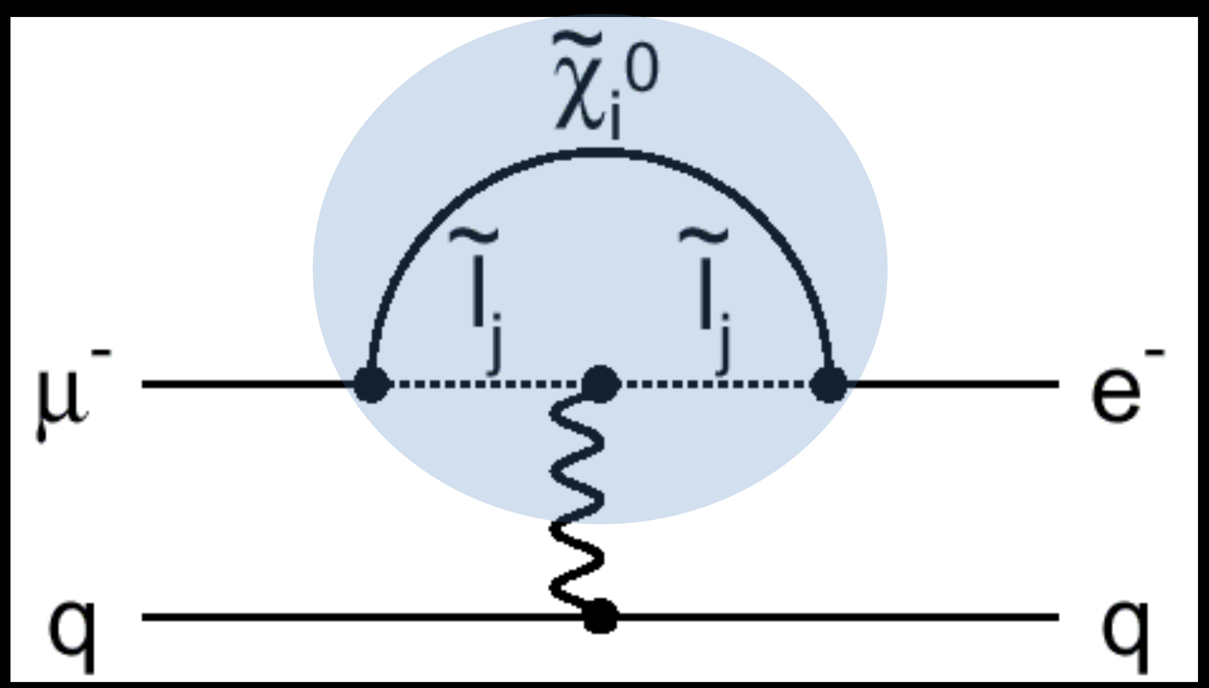
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^{\dagger}_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W} \right|^2 \approx 10^{-54}$$

- No CLFV in the Standard Model
- Massive neutrinos induce CLFV processes via neutrino oscillations
  - Already new physics beyond the Standard Model but completely undetectable
- **Clear sign of the new physics if discovered**

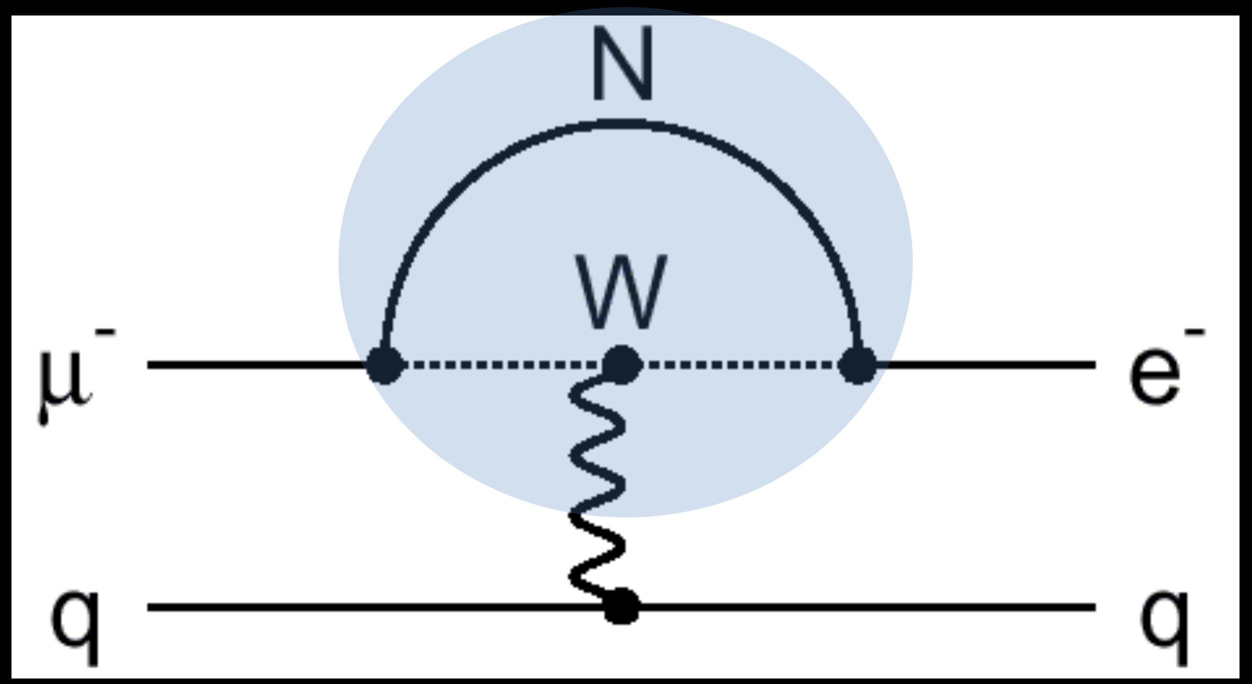
CLFV in BSM

Loops

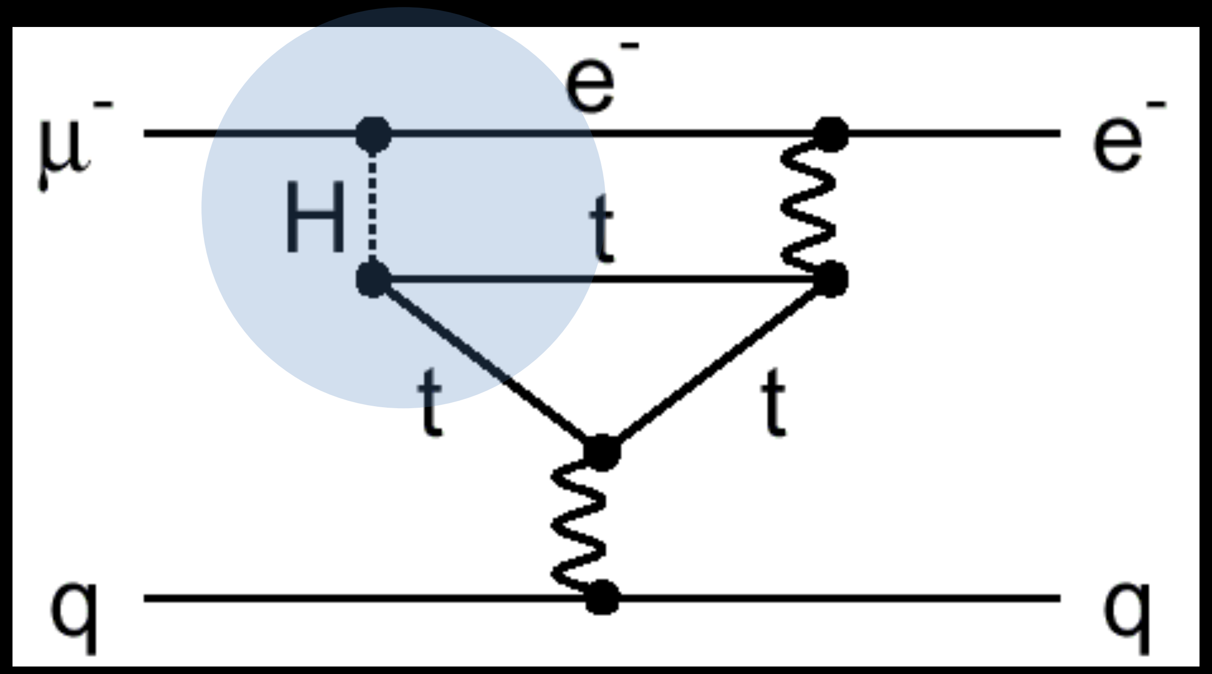
Supersymmetry



Heavy neutrino

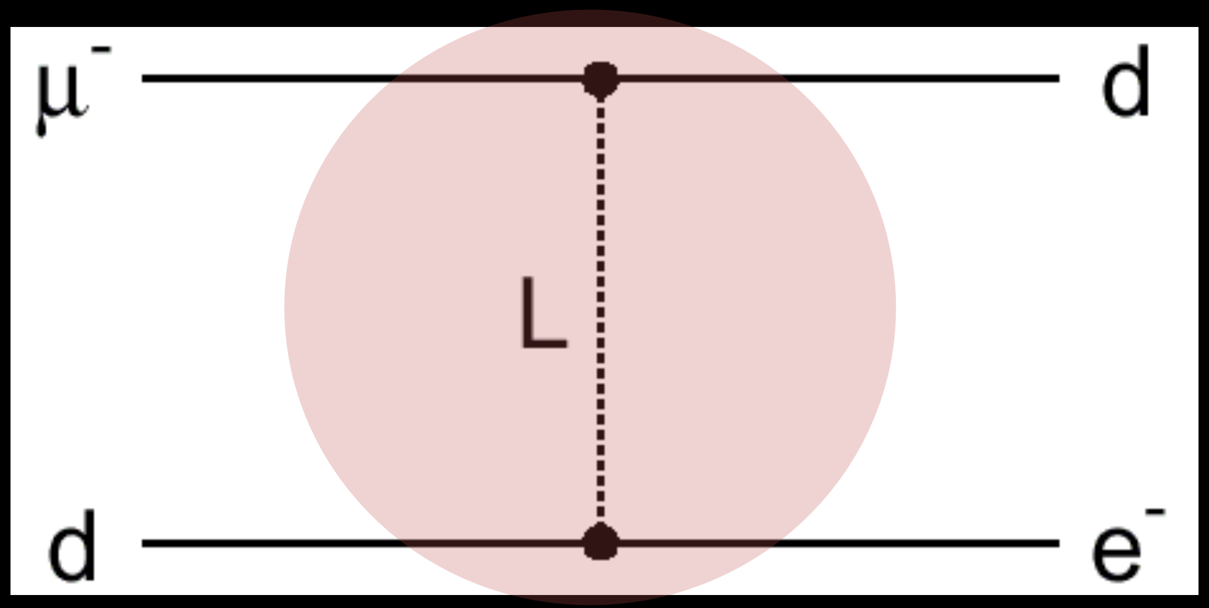


Two Higgs doublet

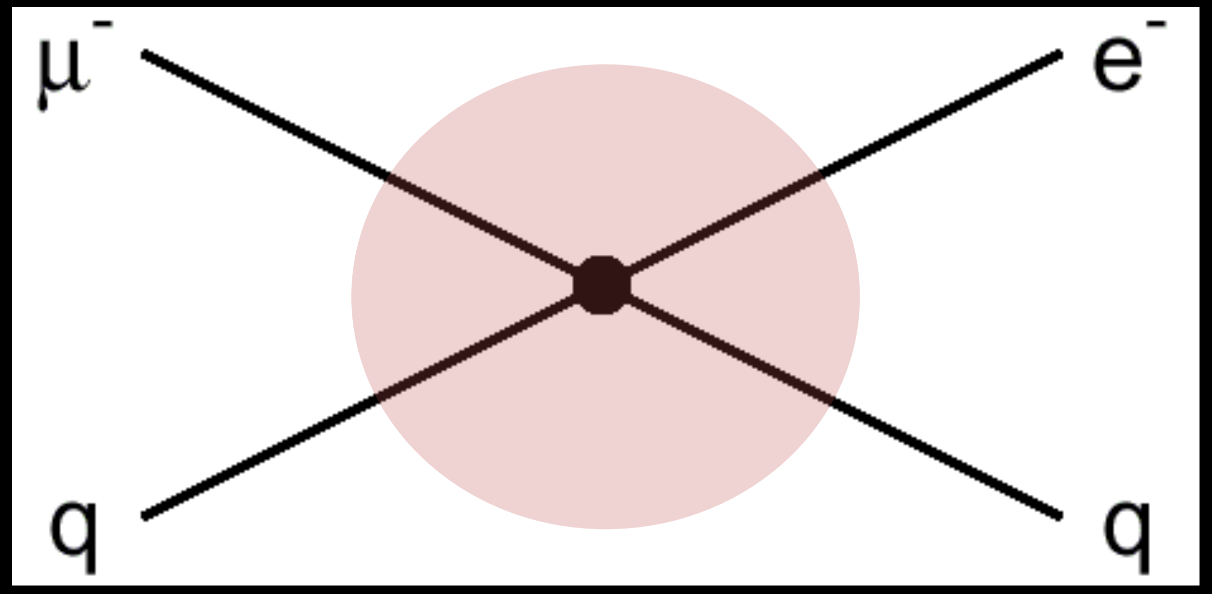


Contact interaction

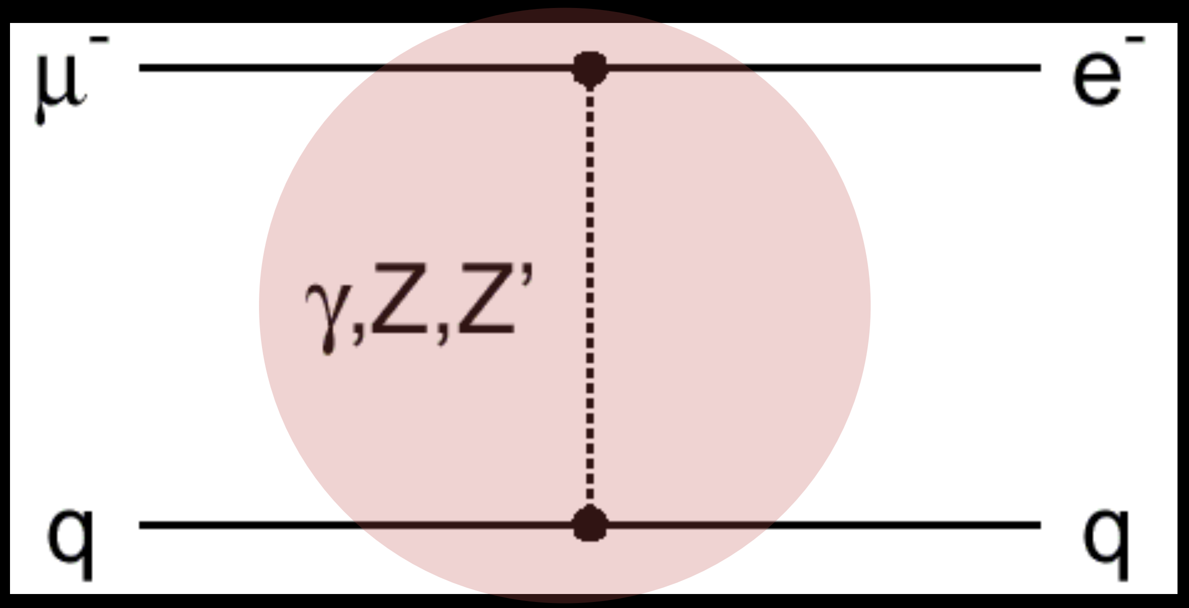
Leptoquarks



Compositeness



New heavy bosons / anomalous coupling



Different interactions generate different processes → complementary searches unveil the BSM structure

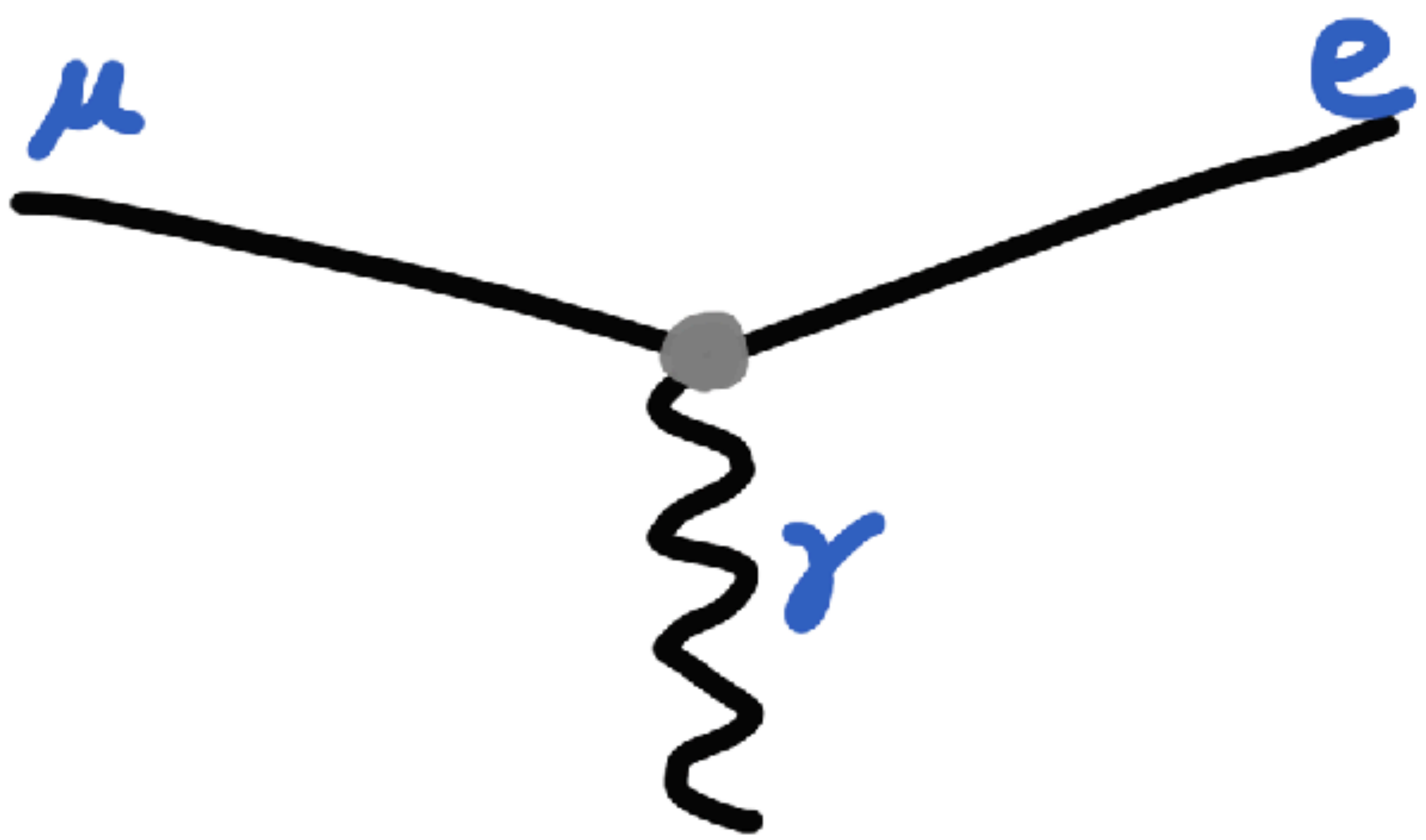
S. Davidson and B Echenard, Rare processes and Precision Frontier kick-off meeting (2020)

CLFV in EFT

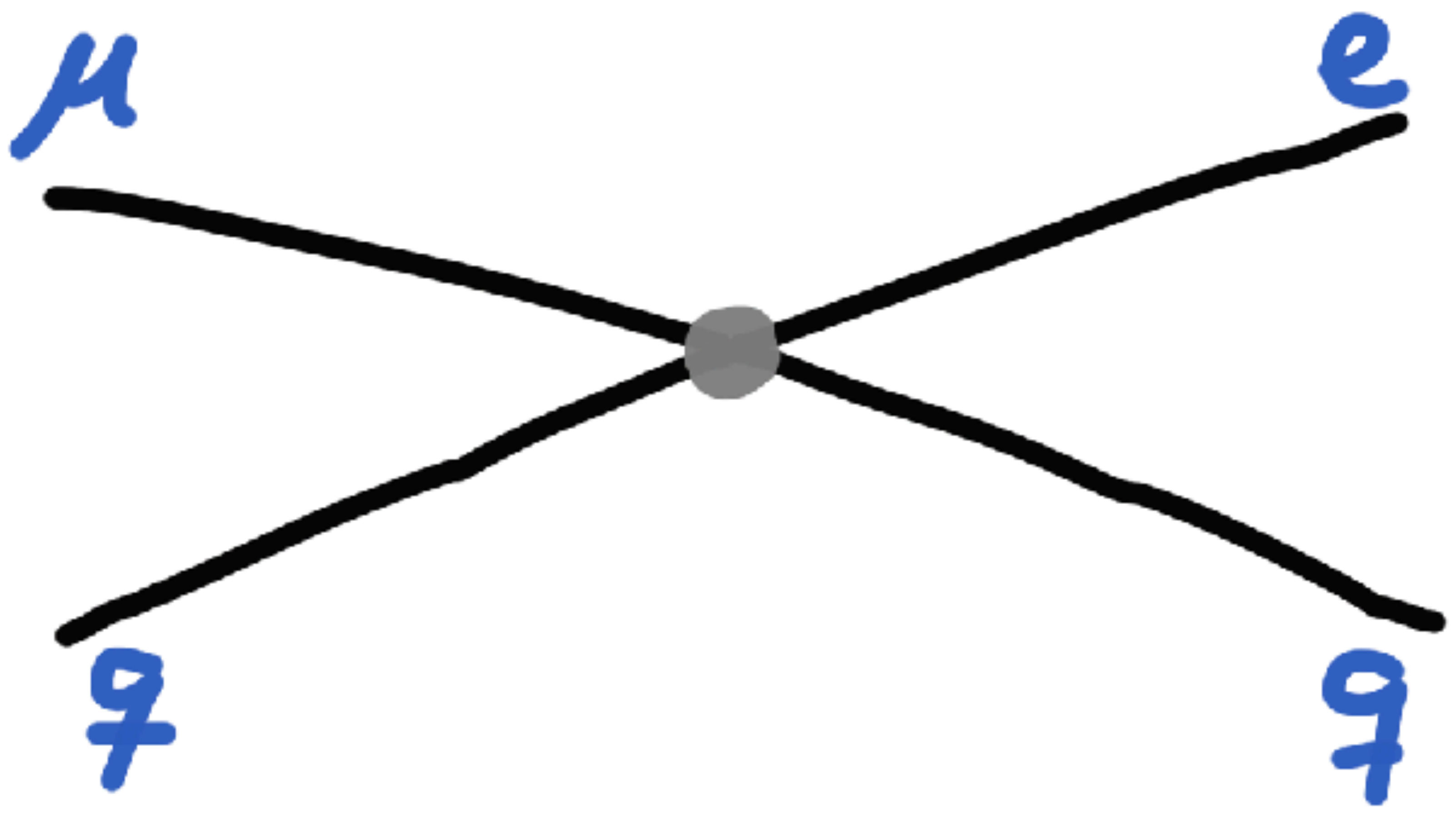
- In a model independent Effective Field Theory (EFT) approach, CLFV related Lagrangian at the new physics scale Λ_{NP}, w/ only **dim-6** operators is written as;

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

Radiative term (loops)

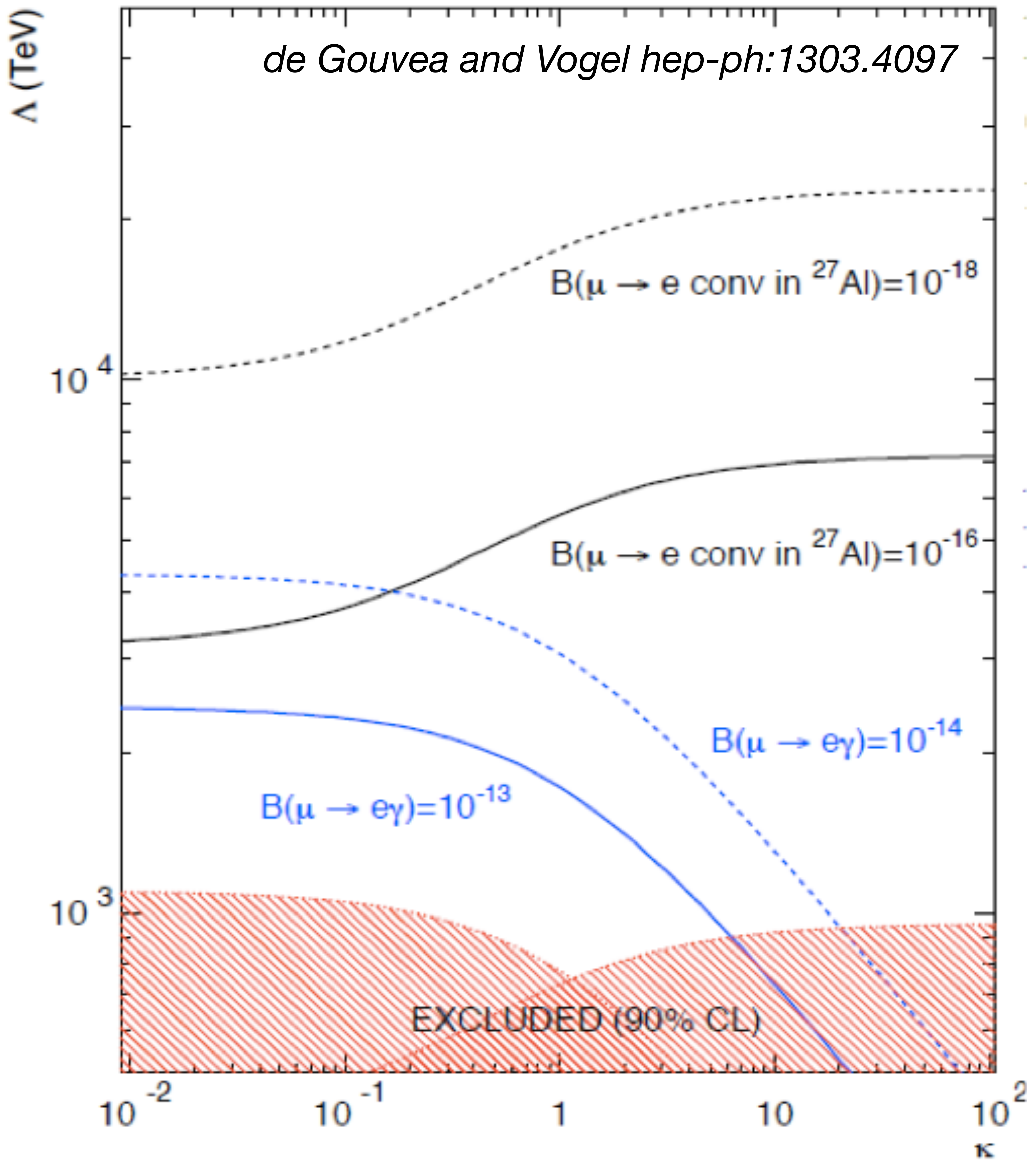


Contact term (tree/box)



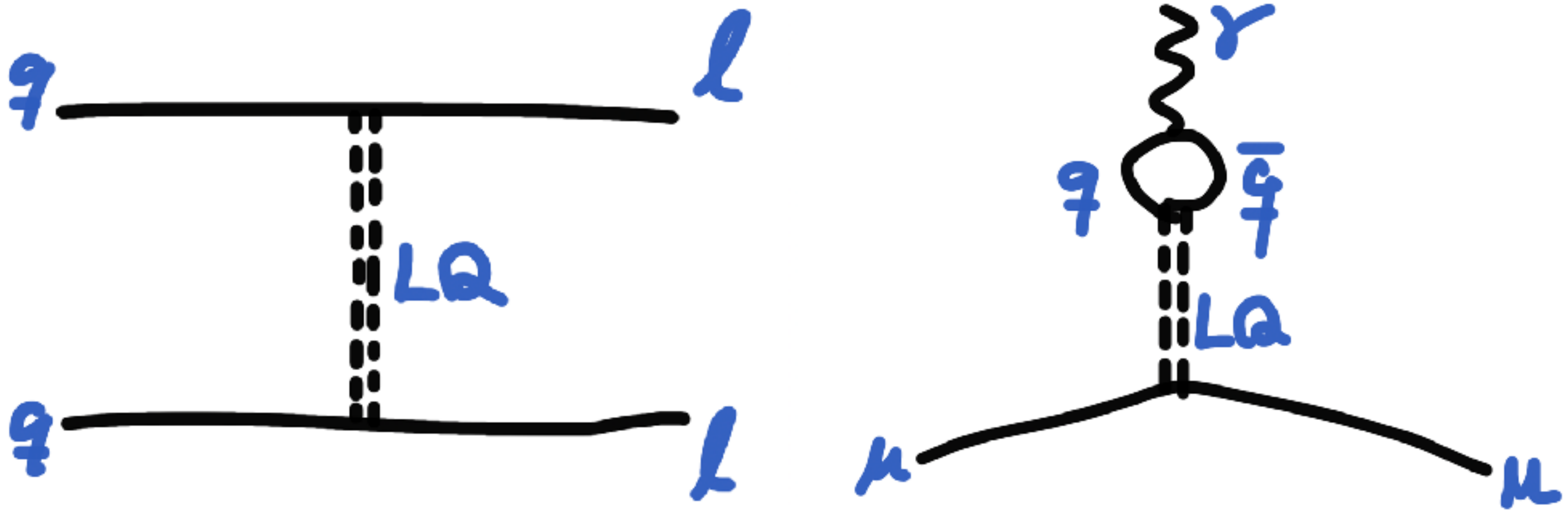
CLFV in EFT

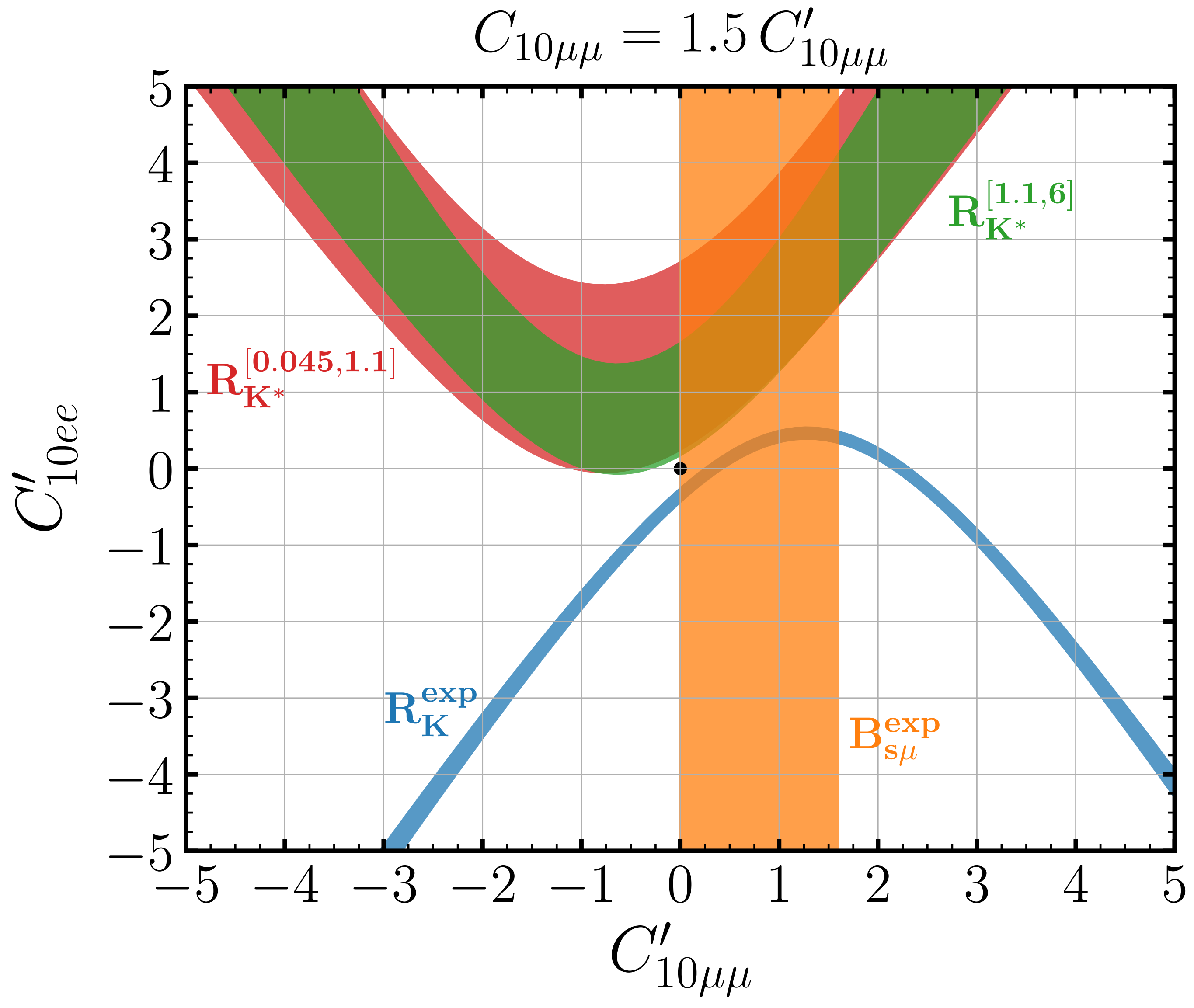
- Searches for CLFV processes indirectly probing Λ_{NP} > 1 PeV
  - ⇔ Ultra large Moon collider, ***14 PeV pp*** (arXiv:2106.02048)
- Complementary searches available with different CLFV modes
- If discovered, $BR(\mu \to e\gamma)/CR(\mu N \to eN)$ will tell us the interaction pattern in NP

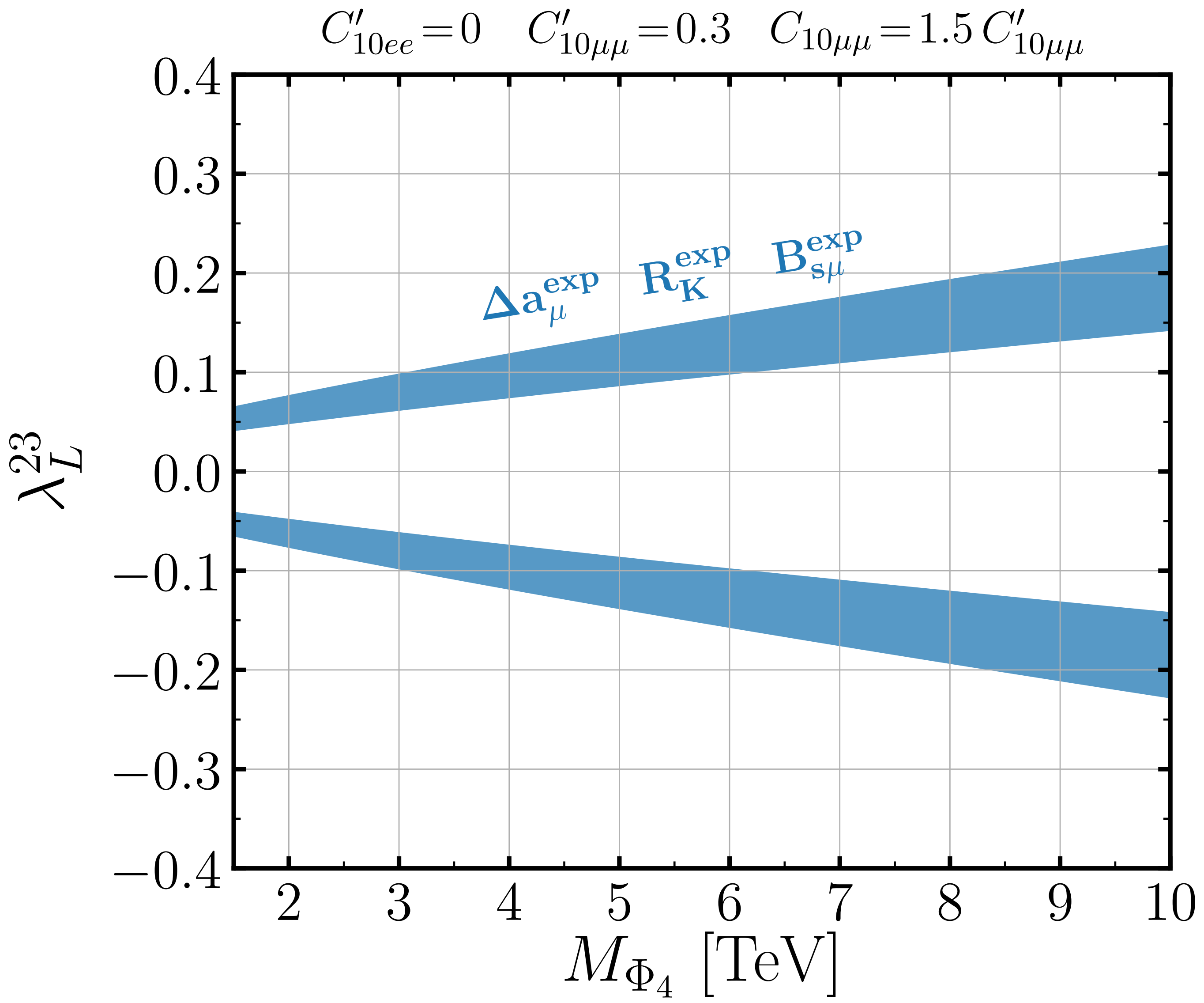


CLFV and Leptoquarks

- LQ can simultaneously explain both;
  - Recent B physics anomalies
  - Long standing g-2 anomaly







Left plot; Scalar LQ, Φ4 satisfies all b

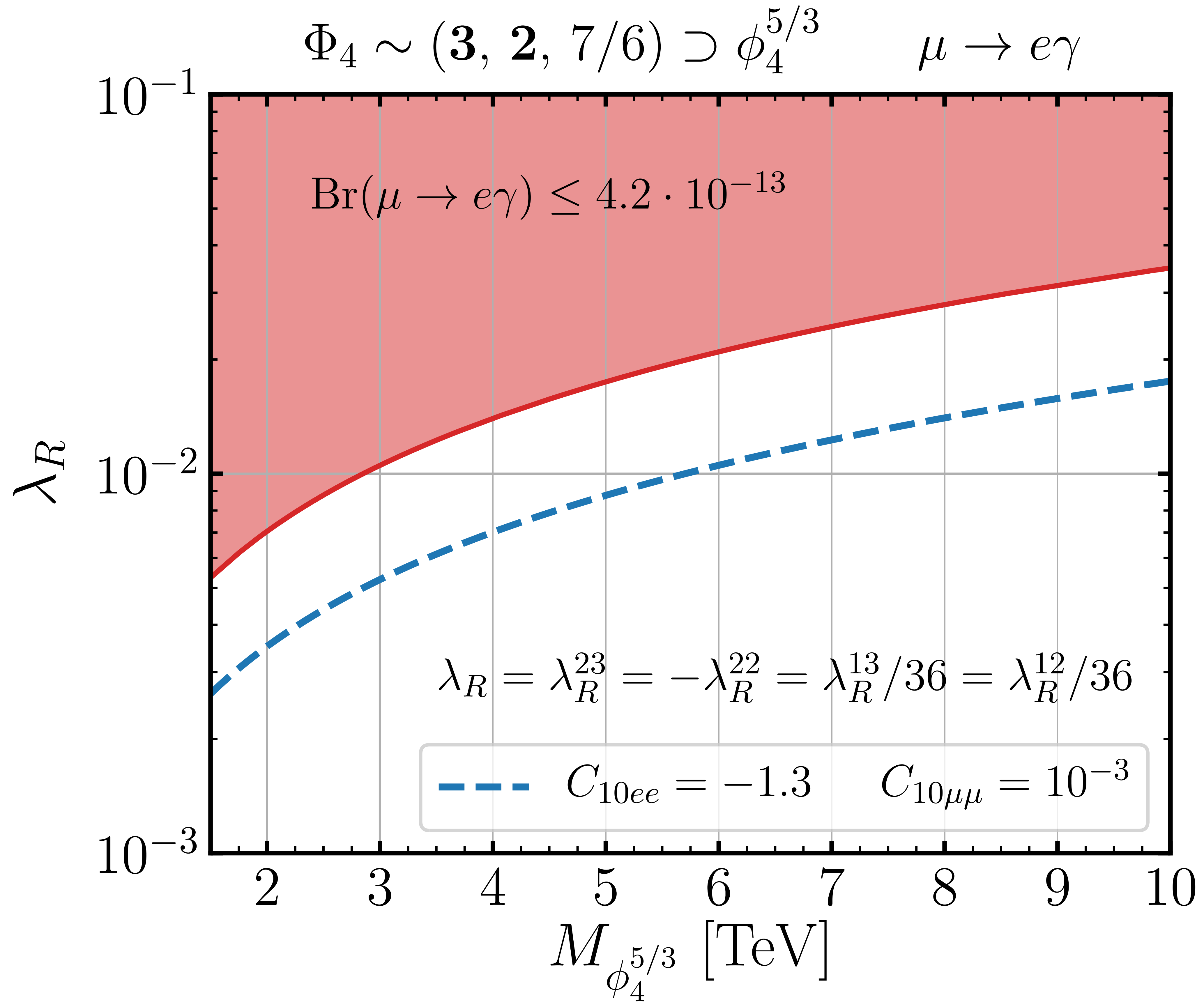
Right plot; Allowed region from g-2 results

anomalies All 1σ band

→ all of them somehow satisfied

P.F. Perez, et.al. arXiv:2104.11229

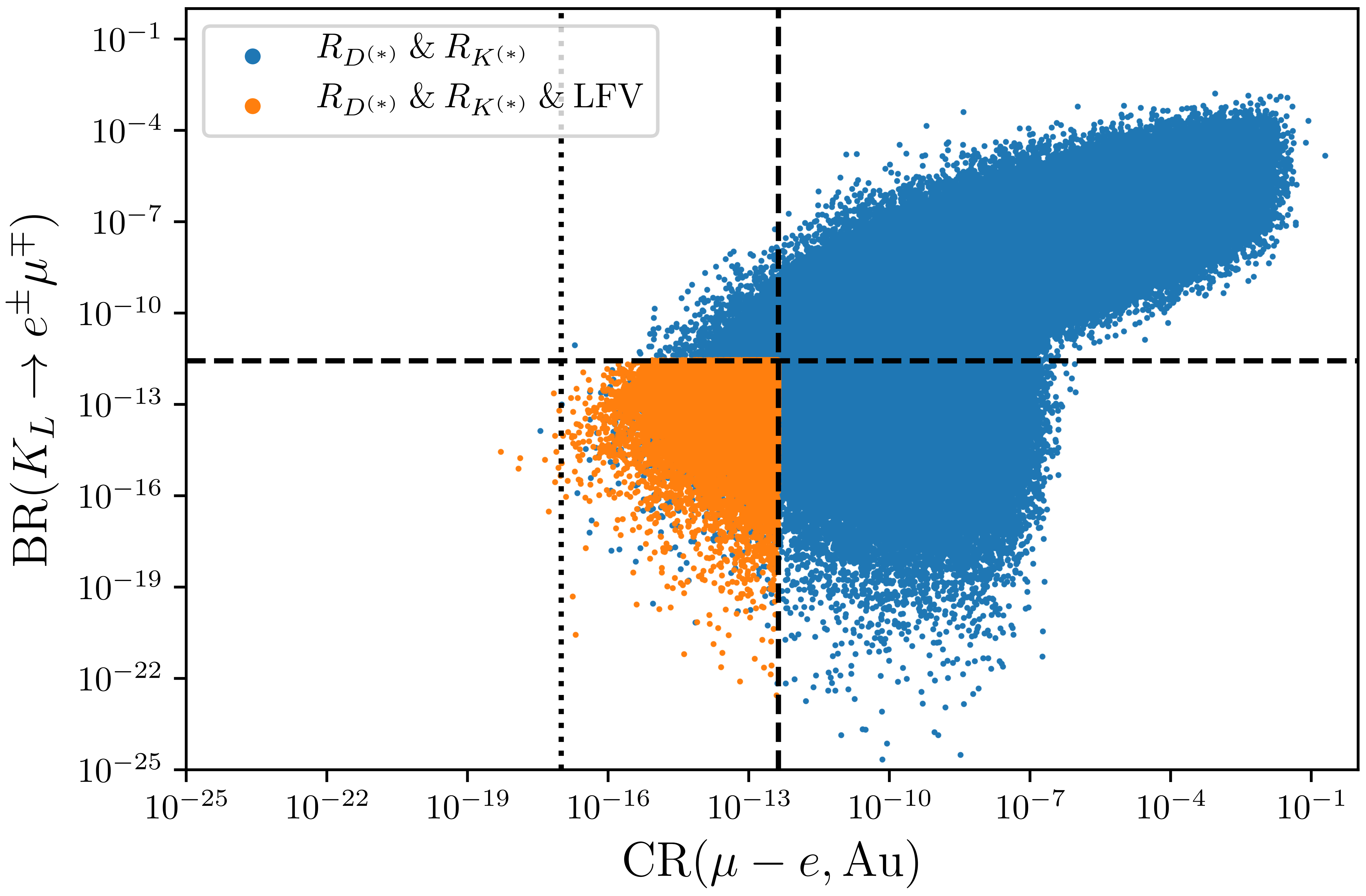
CLFV and Leptoquarks



P.F. Perez, et.al. arXiv:2104.11229

***Scalar LQ** as introduced in the previous page*

C. Hati, et.al. arXiv:1907.05511



Vector LQ

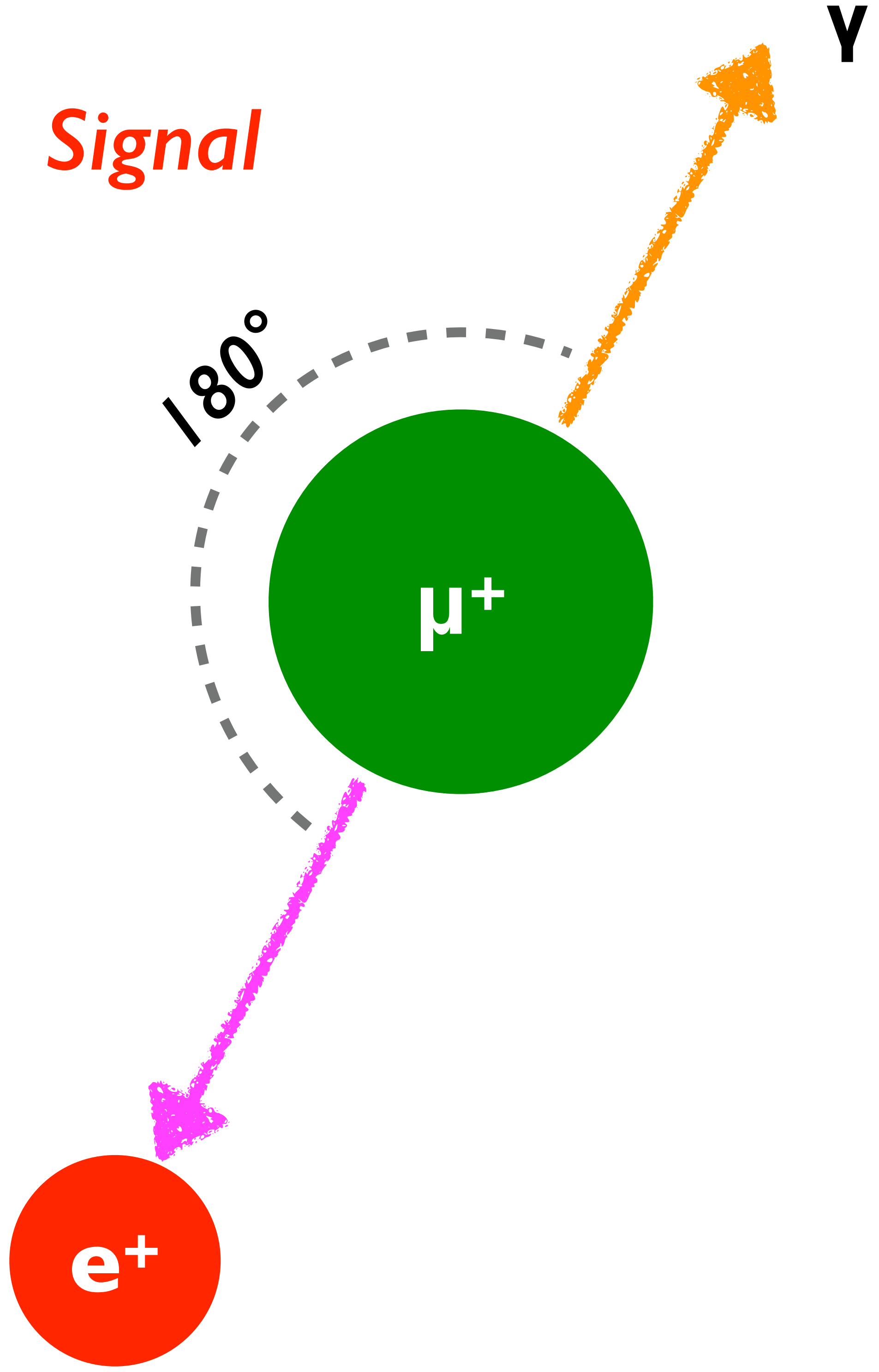
The μ-e conversion rate provides the strong constraint

Searches for $\mu \rightarrow e\gamma$ & $\mu \rightarrow eee$

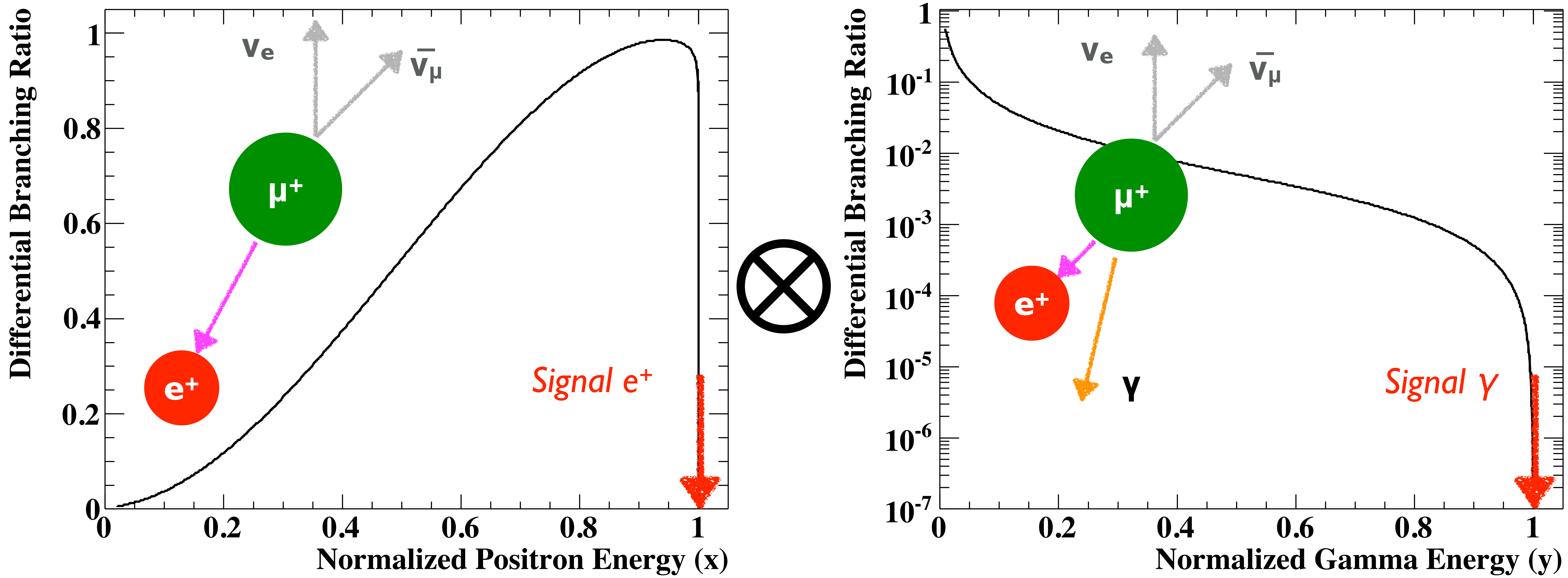
MEG, MEG II, Mu3e

The Kangaroo Sanctuary / Facebook

The μ to e+γ decay

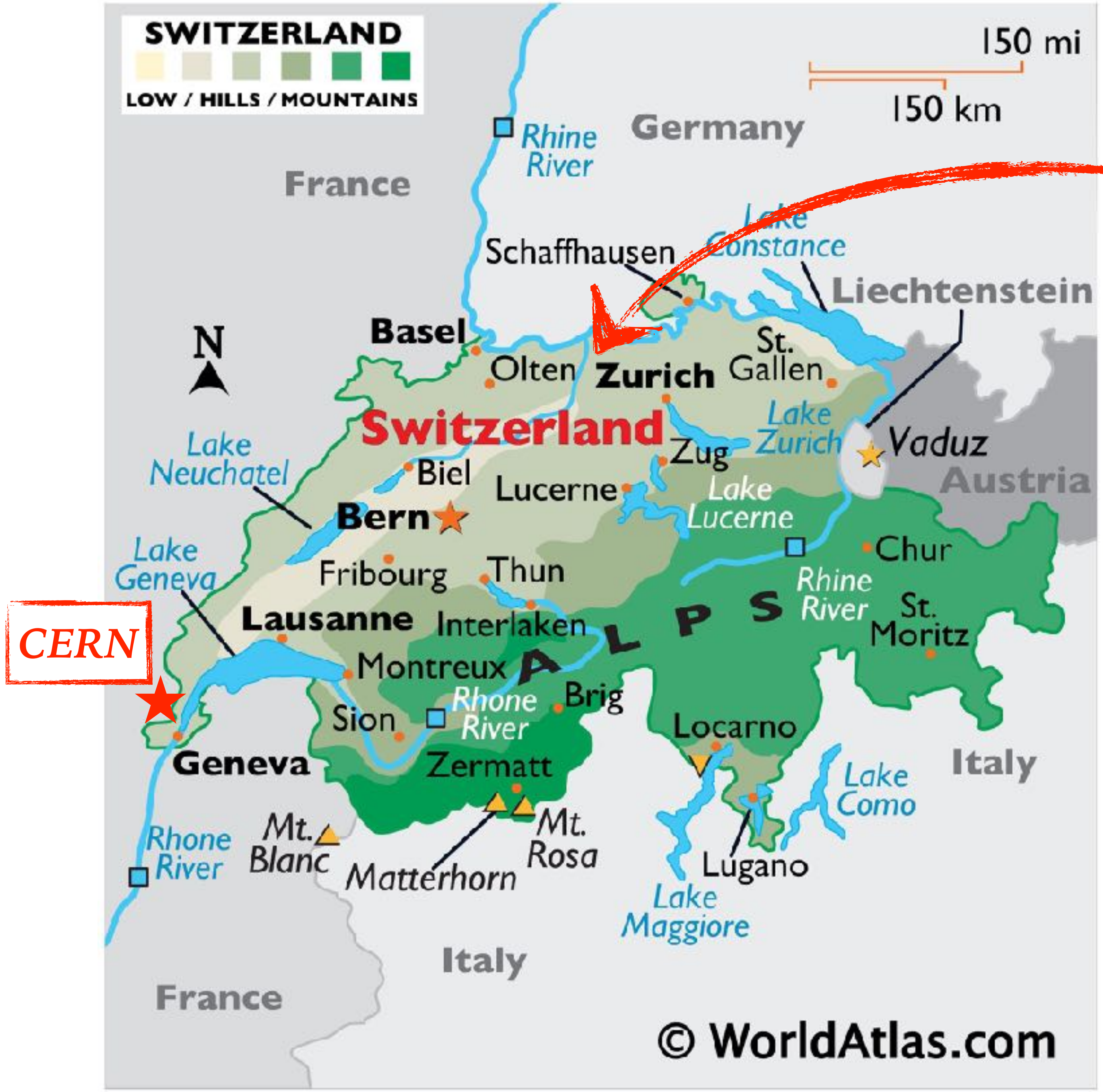


Background



- Combinatorial Backgrounds dominant
  - $R_{BG} \propto L^2$ → <u>lower instantaneous beam luminosity is better</u>
  - **Good DC beam and EXCELLENT detectors** to separate accidental overlaps

Paul Scherrer Institut (PSI)



A CLFV front-runner

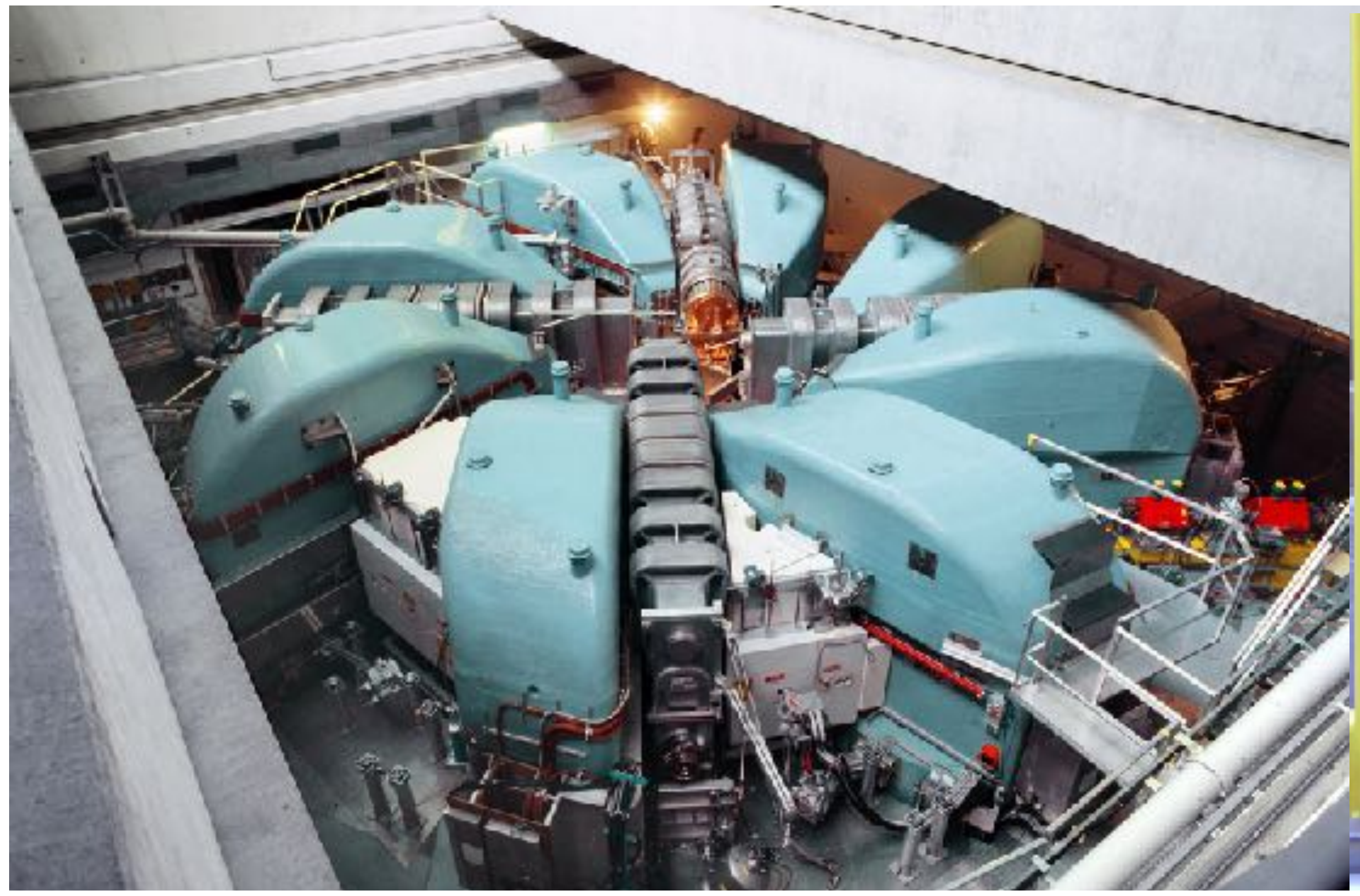
πE5 beam line

1.2MW, 590 MeV proton beam

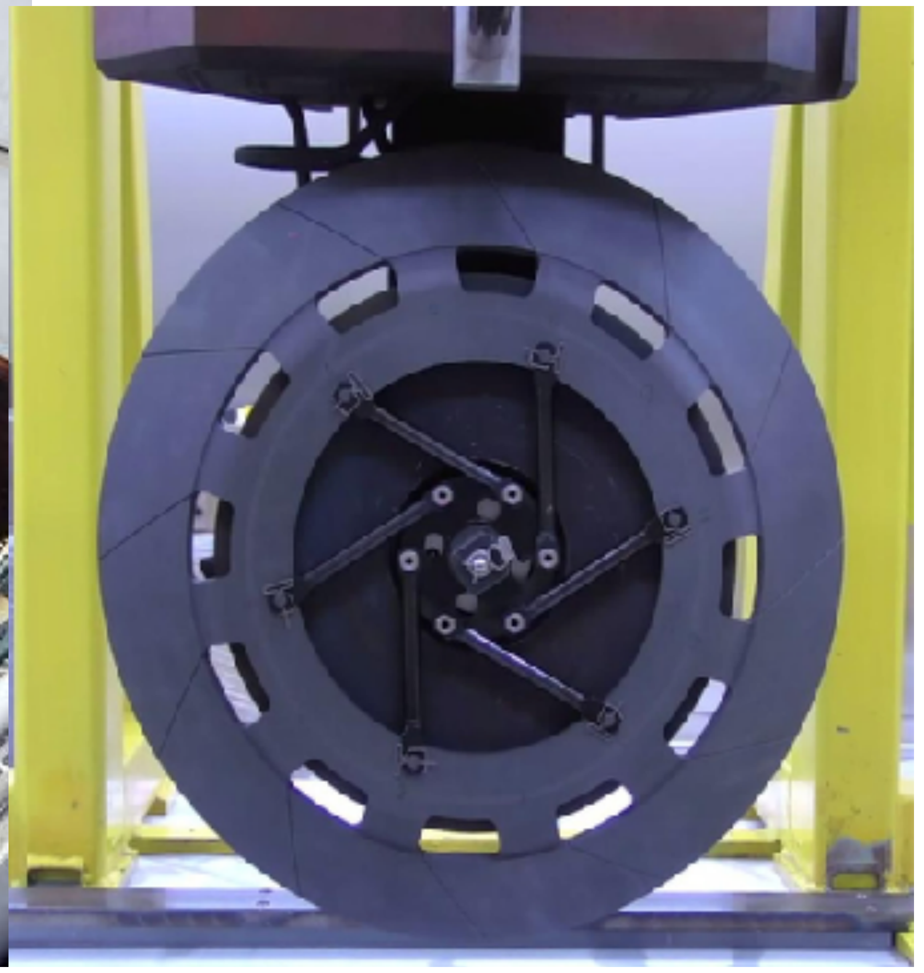
A rotating graphite muon production target (Target E)

Intensity; $\sim 10^8$ muons/sec (the most intense DC muon beam)

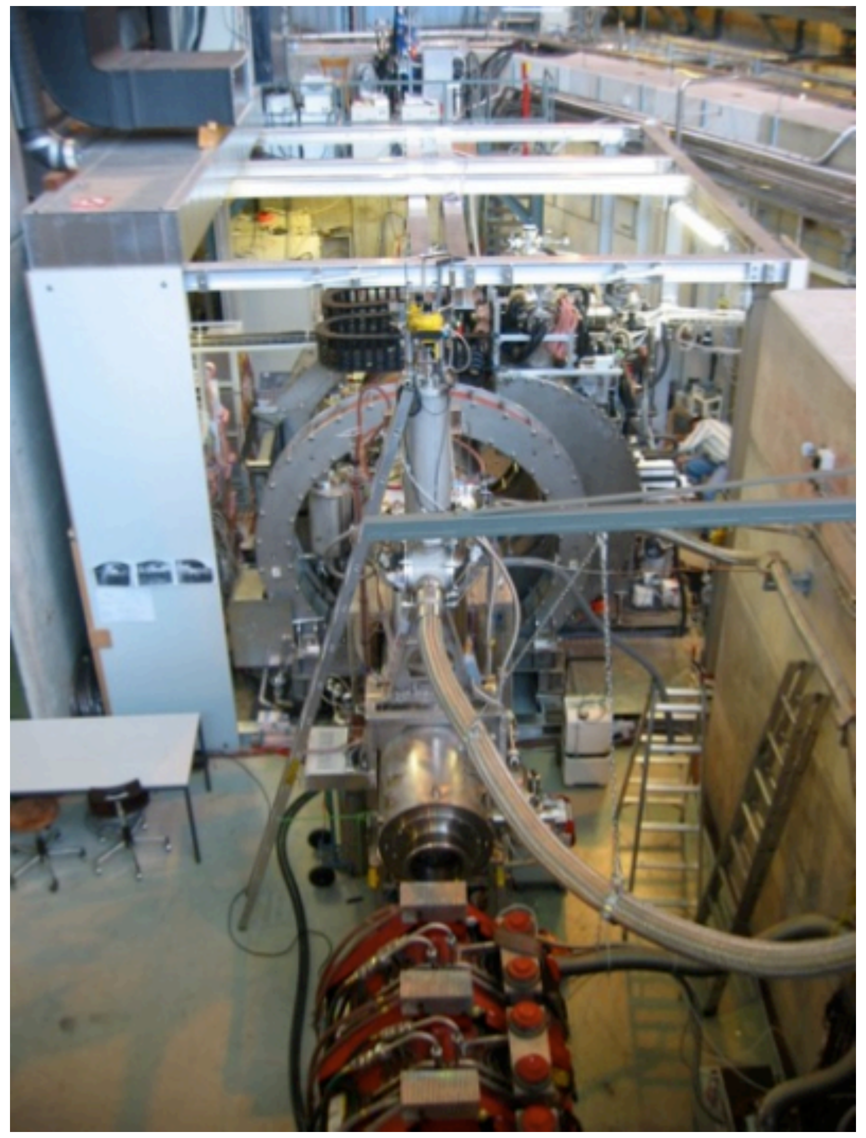
Momentum; 29.8 MeV/c, called "surface" muons

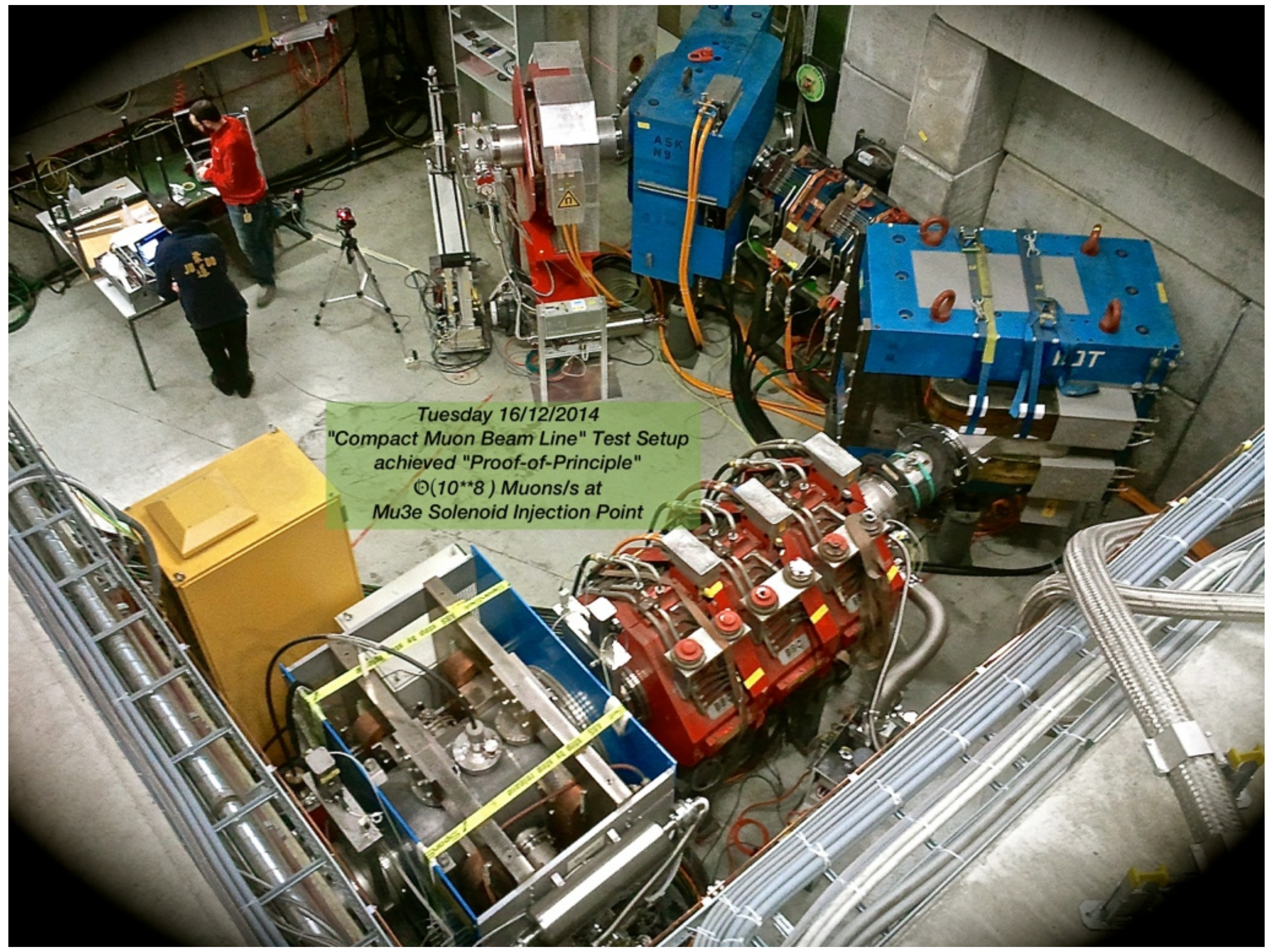


MEG/MEGII Beam Line

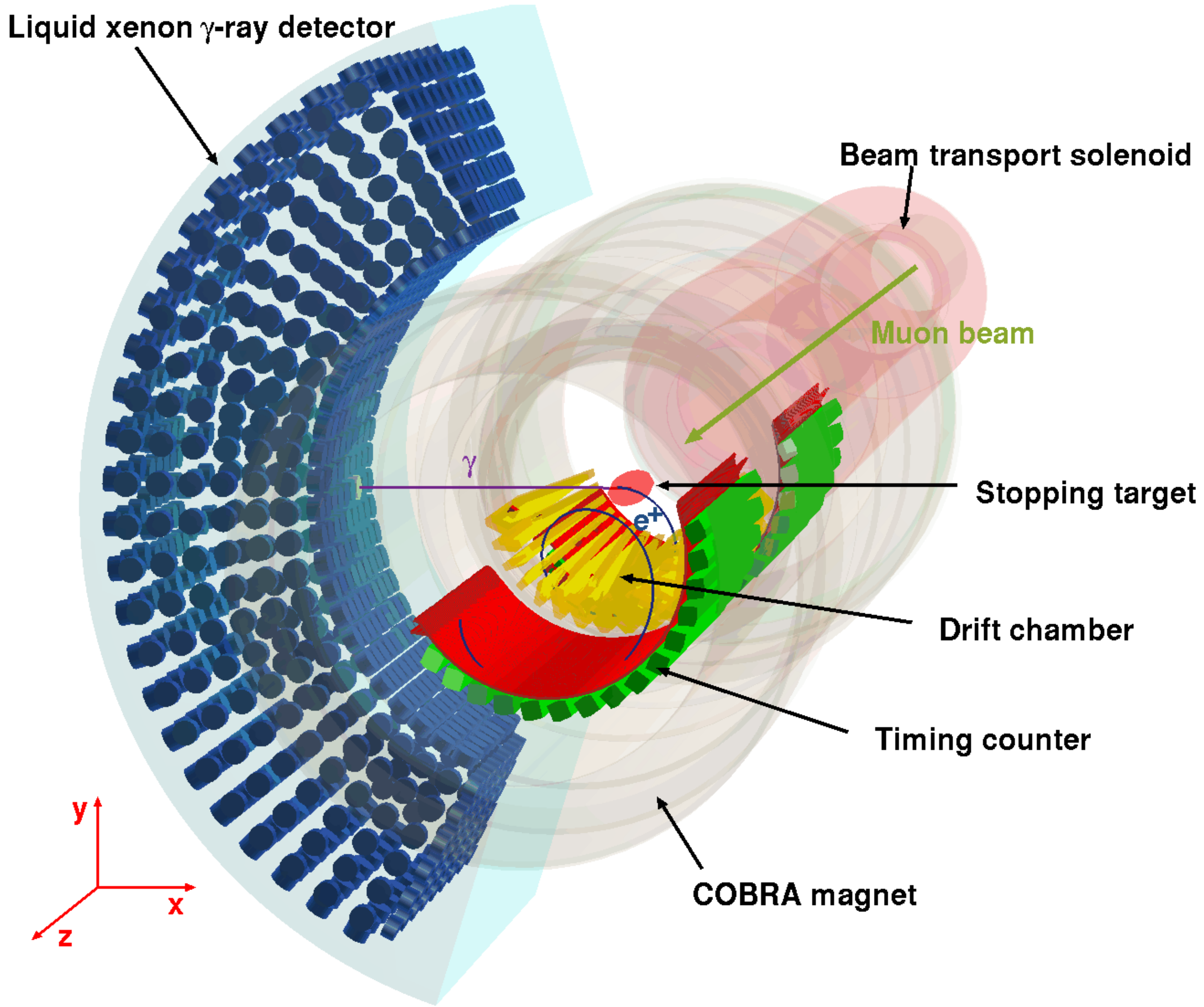


Mu3e Compact Muon Beam Line

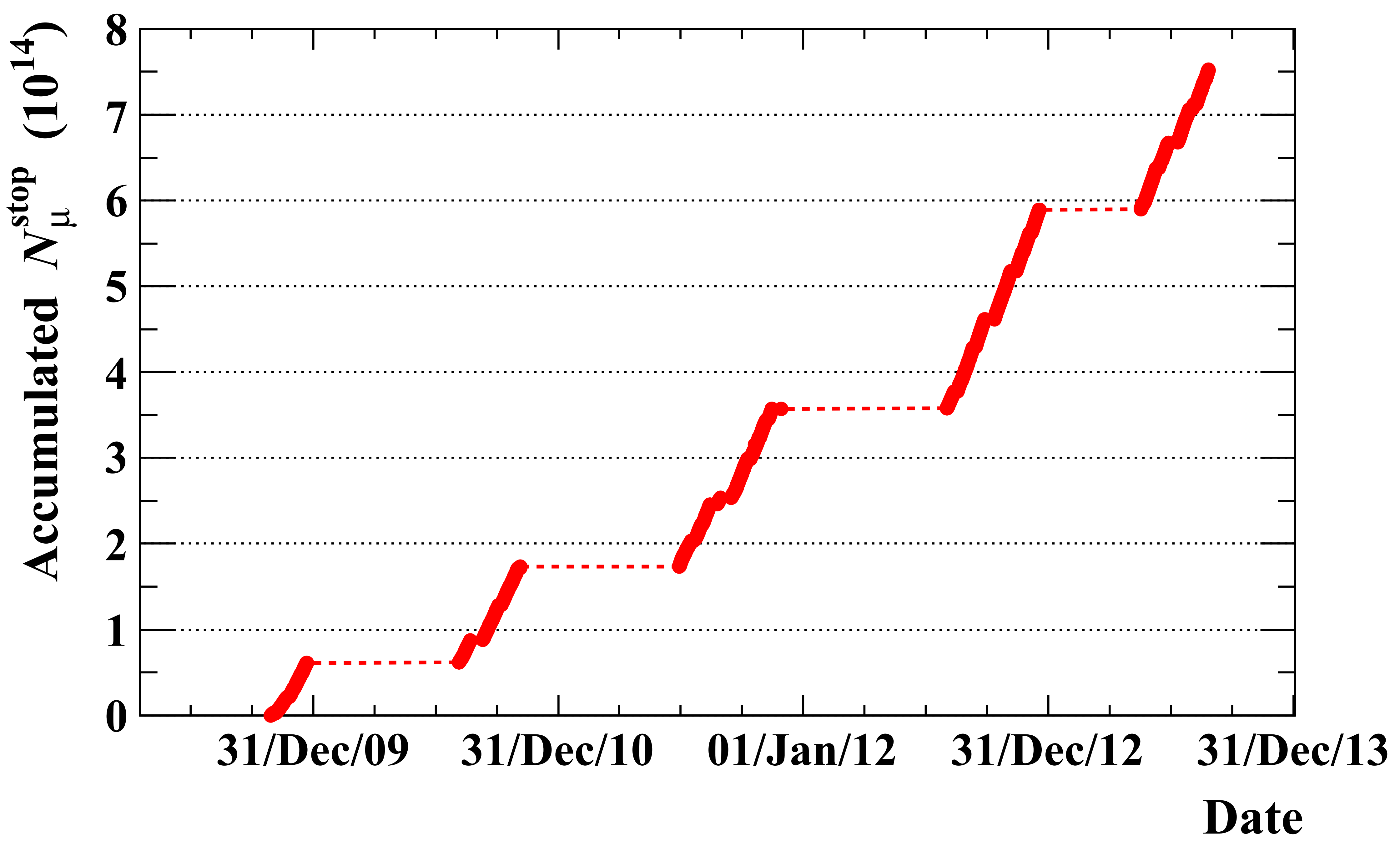




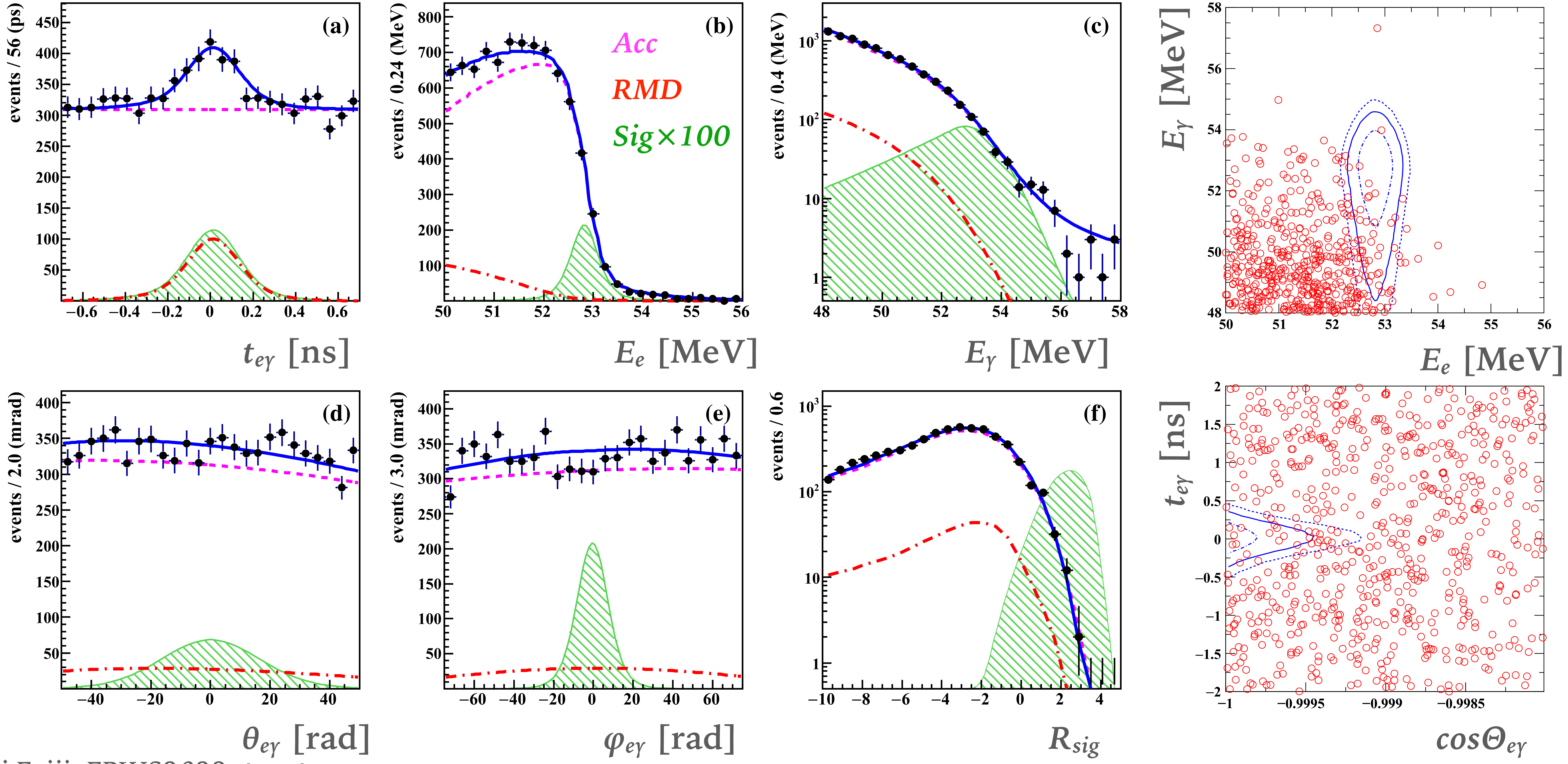
MEG



- Beam intensity: 3×10^7 μ^-/sec
- Aiming sensitivity: 10^{-13} @ 90% C.L.
  - Previous upper limit: 1.2×10^{-11} @ 90% C.L.
  - 100 times better sensitivity
- The physics data taking completed in 2008-2013



MEG



(a)
(b)
(c)
(d)
(e)
(f)
Acc
RMD
Sig×100
events / 56 (ps)
events / 0.24 (MeV)
events / 0.4 (MeV)
events / 2.0 (mrad)
events / 3.0 (mrad)
events / 0.6
$t_{e\gamma}$ [ns]
E_e [MeV]
E_γ [MeV]
$\theta_{e\gamma}$ [rad]
$\varphi_{e\gamma}$ [rad]
R_{sig}
$t_{e\gamma}$ [ns]
$cos\Theta_{e\gamma}$

MEG

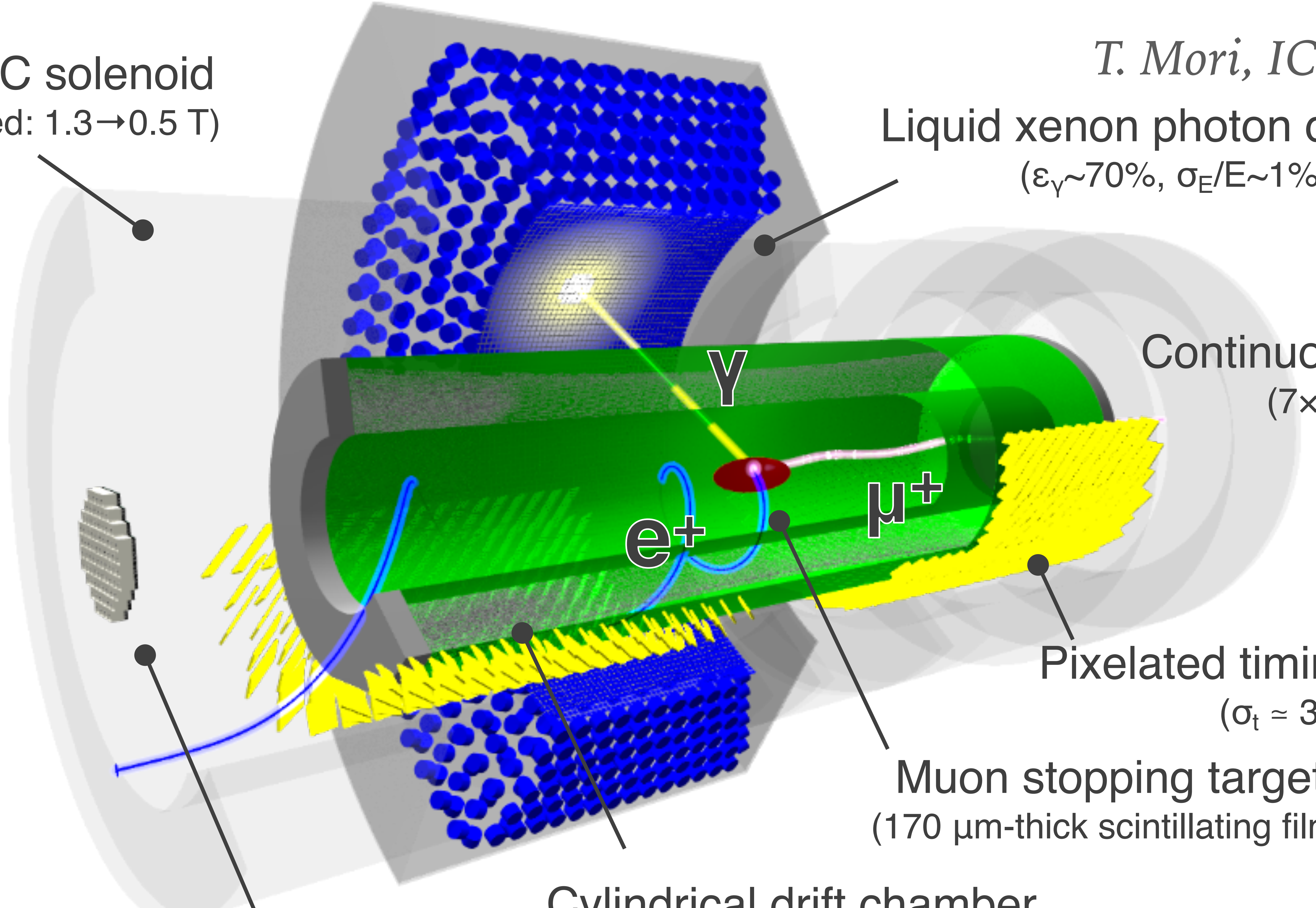
- Sensitivity; **5.3×10^{-13}** @ 90% C.L.
- No signal excess was observed
- Best fit upper limit; **4.2×10^{-13}** @ 90% C.L.
  - $\times30$ improvement from the previous experiment, MEGA
- Sensitivity curve is no longer $\propto 1/N_\mu$ because of the accidental background
  - = The BG influence is getting larger
  - Muon beam is not a bottleneck
  - Time for the major upgrade!

MEG II

×2 **intensity** muon beam
×2 **resolution** everywhere
×2 **efficiency**

Search for $\mu^+ \to e^+\gamma$ down to
6×10^{-14}
(90% C.L. sensitivity)

T. Mori, ICHEP2022

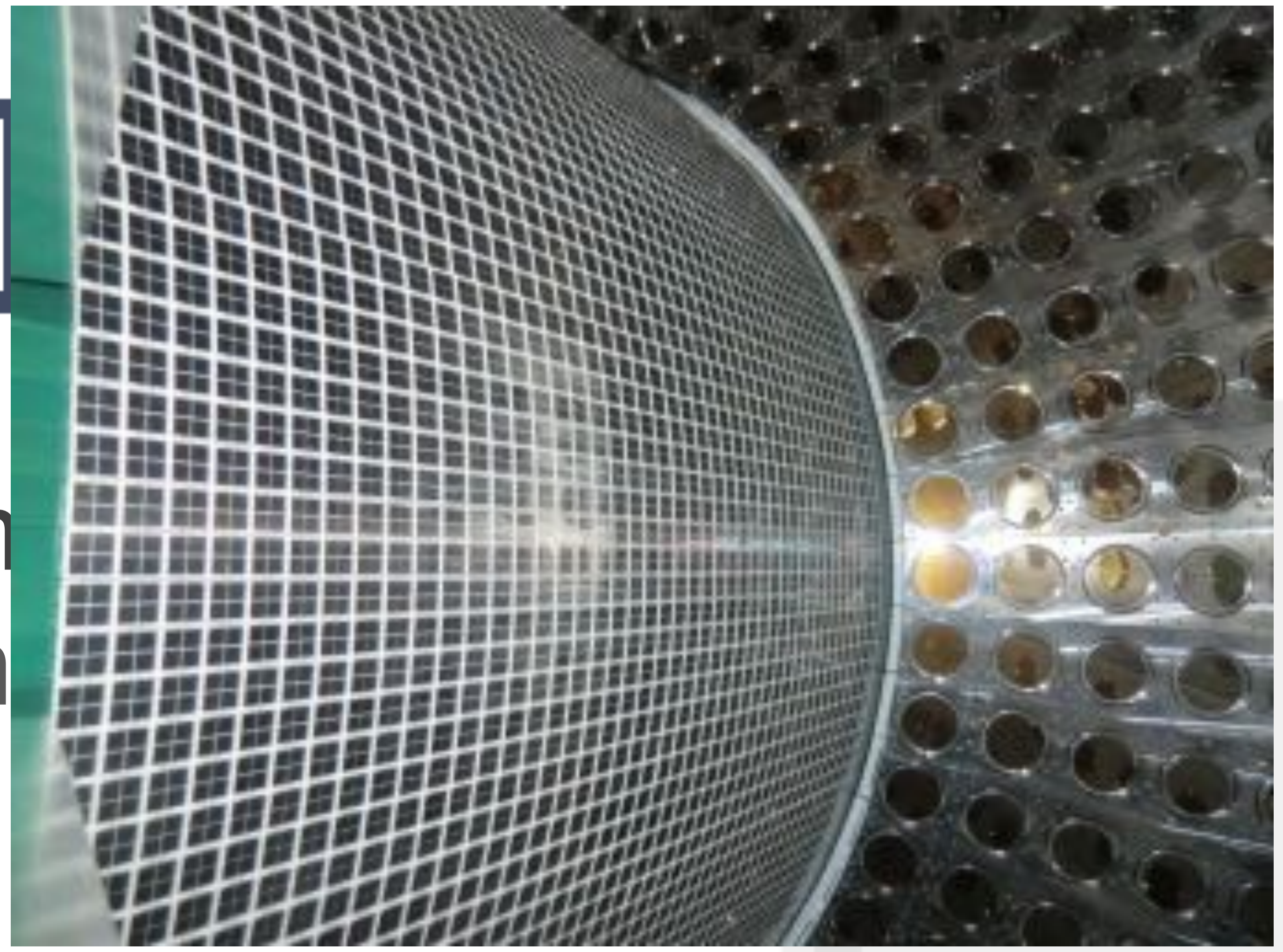


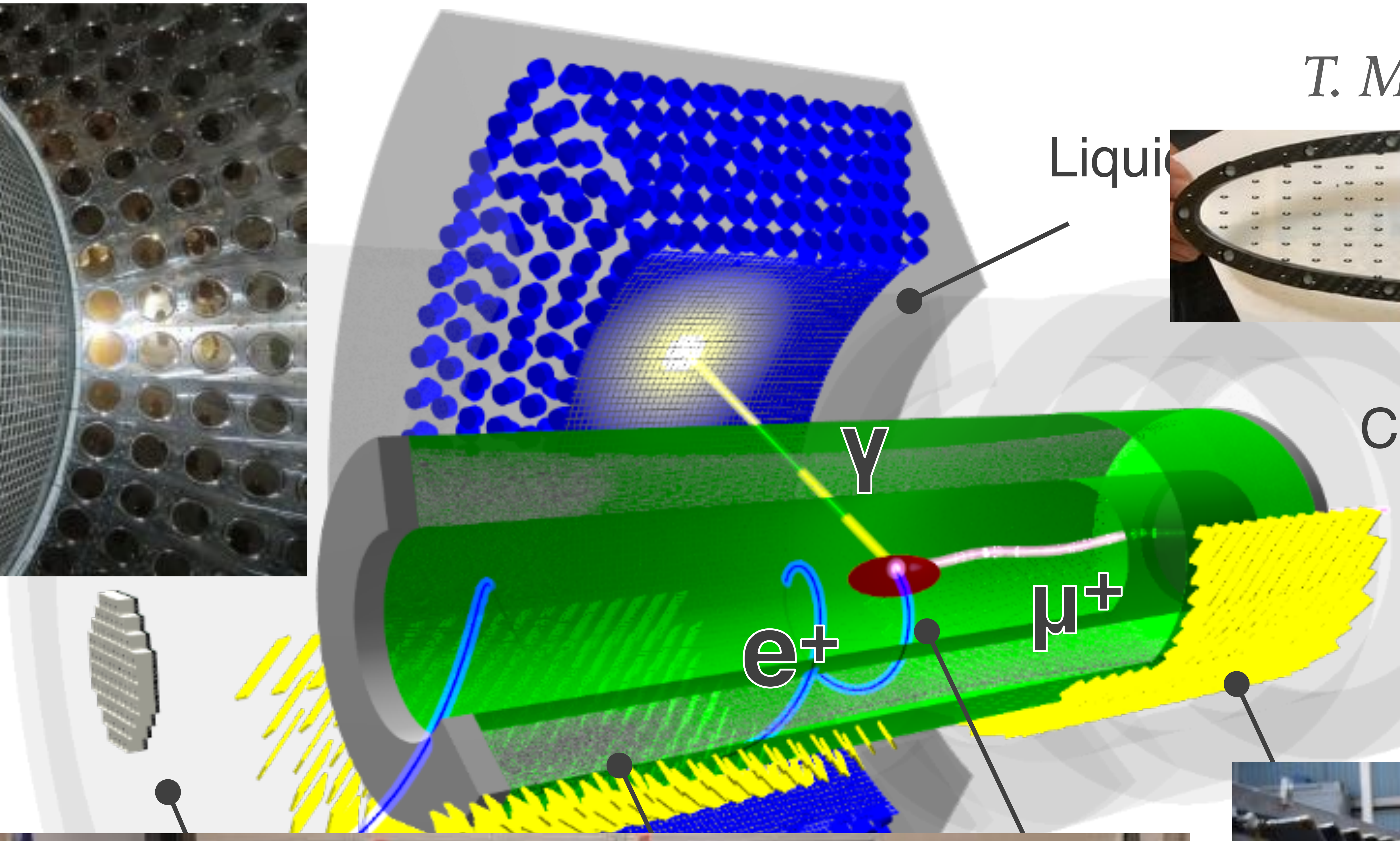
EPJ-C **78** (2018) 380

MEG II

T. Mori, ICHEP2022

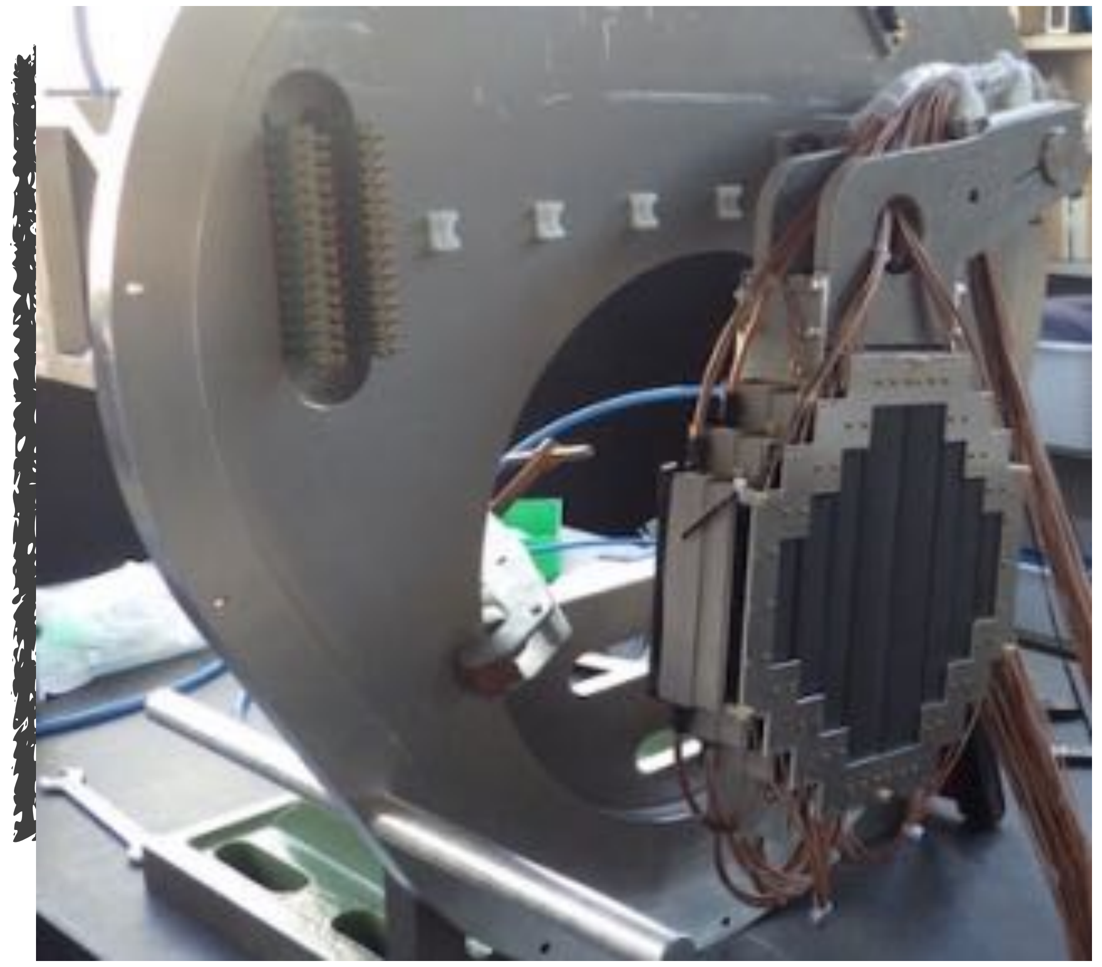
×2 intensity m
×2 resolution
×2 efficiency





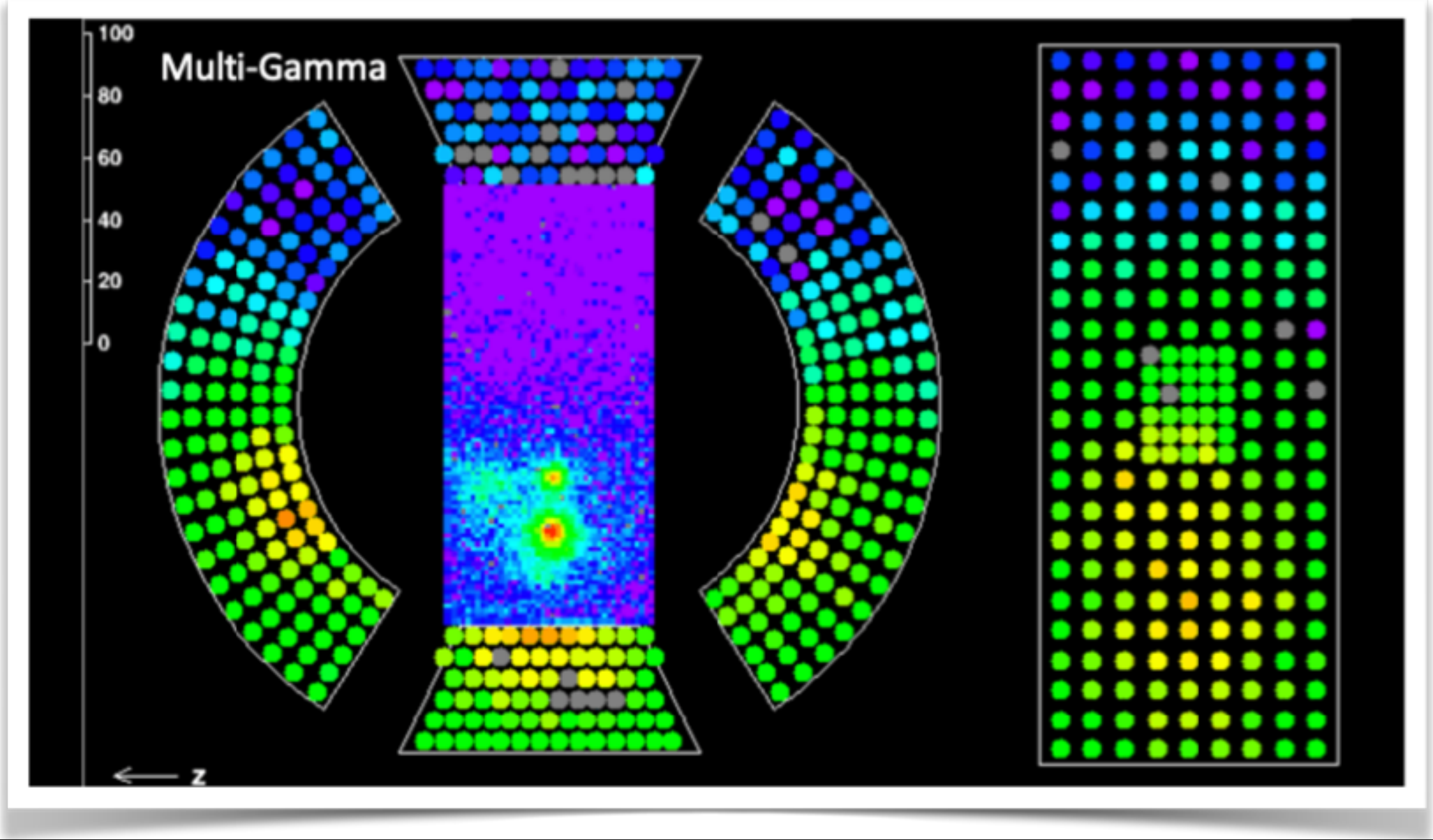
Liqui

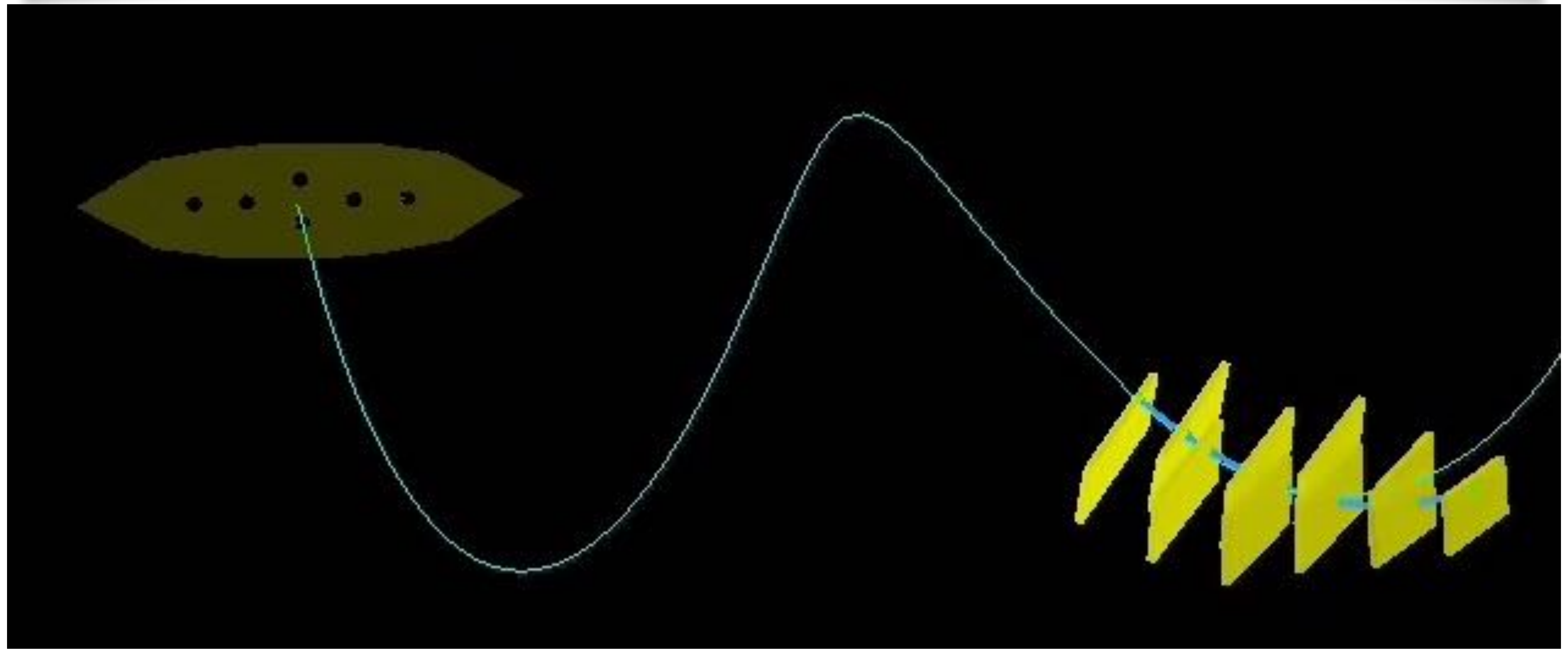
Continuous μ+ beam
($7\times10^{7}\ s^{-1}$)

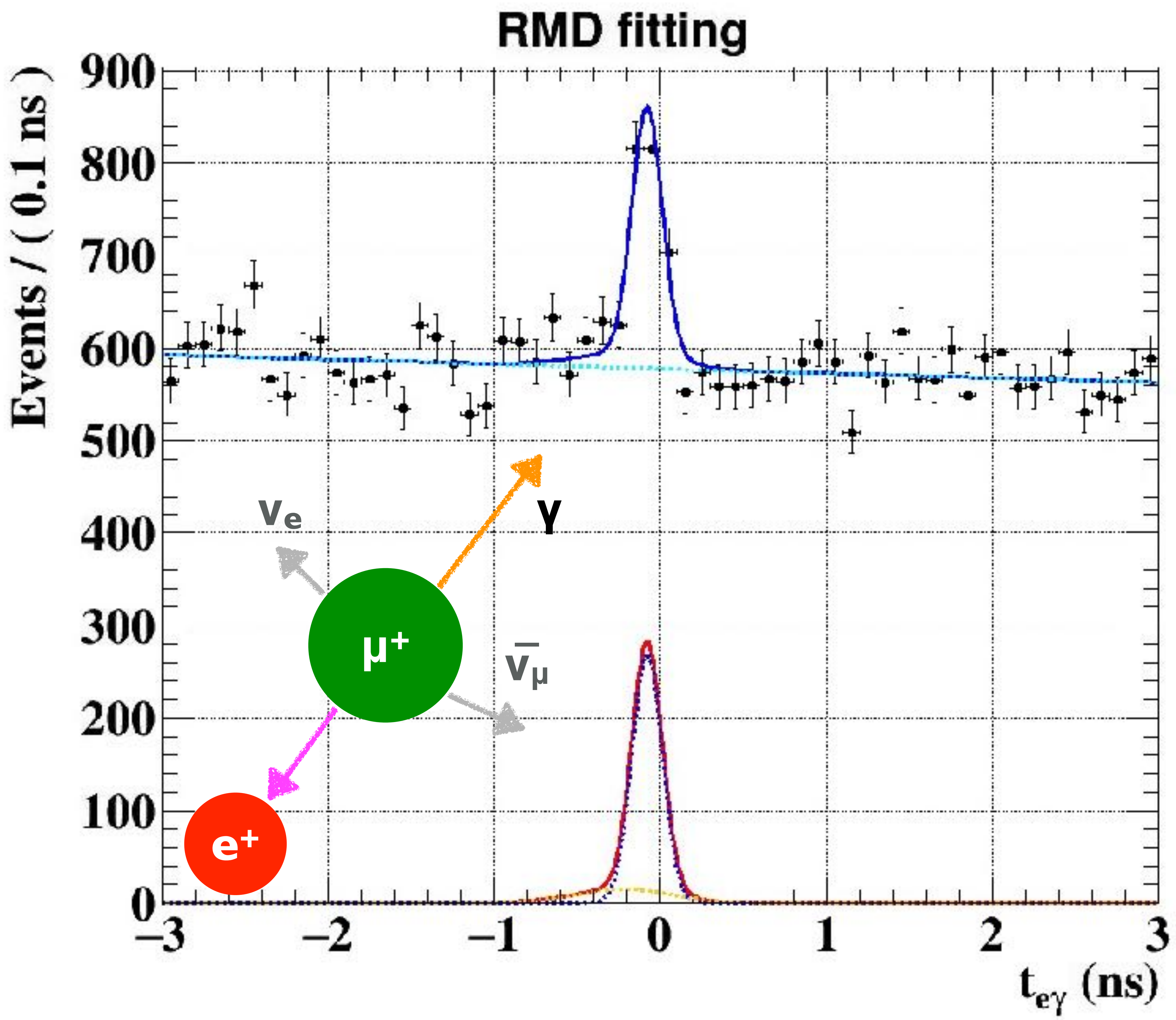


EPJ-C **78** (2018) 380

MEG II





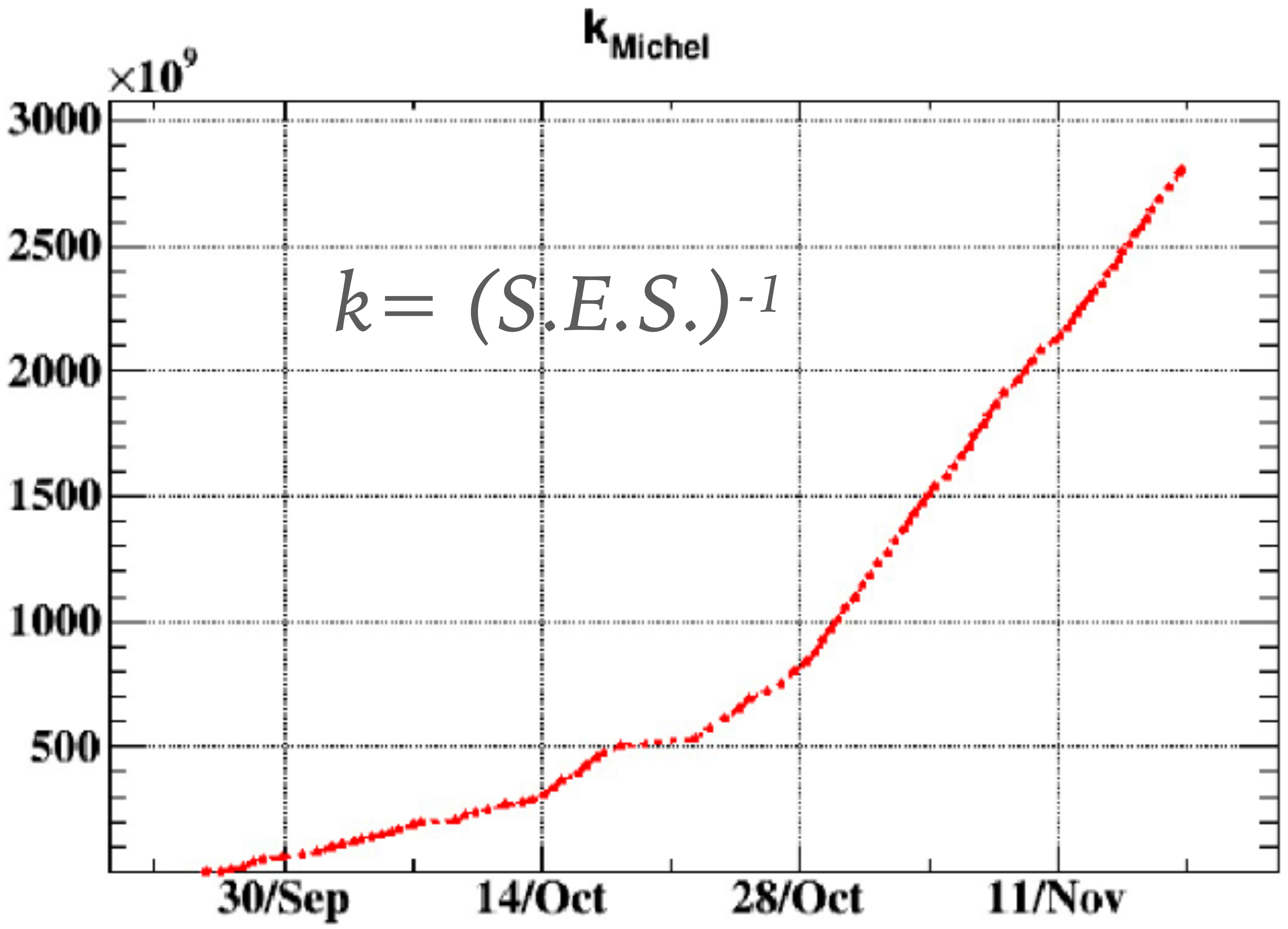


Clear peak in $t_{e\gamma}$ histogram coming from Radiative Muon Decays (RMD)

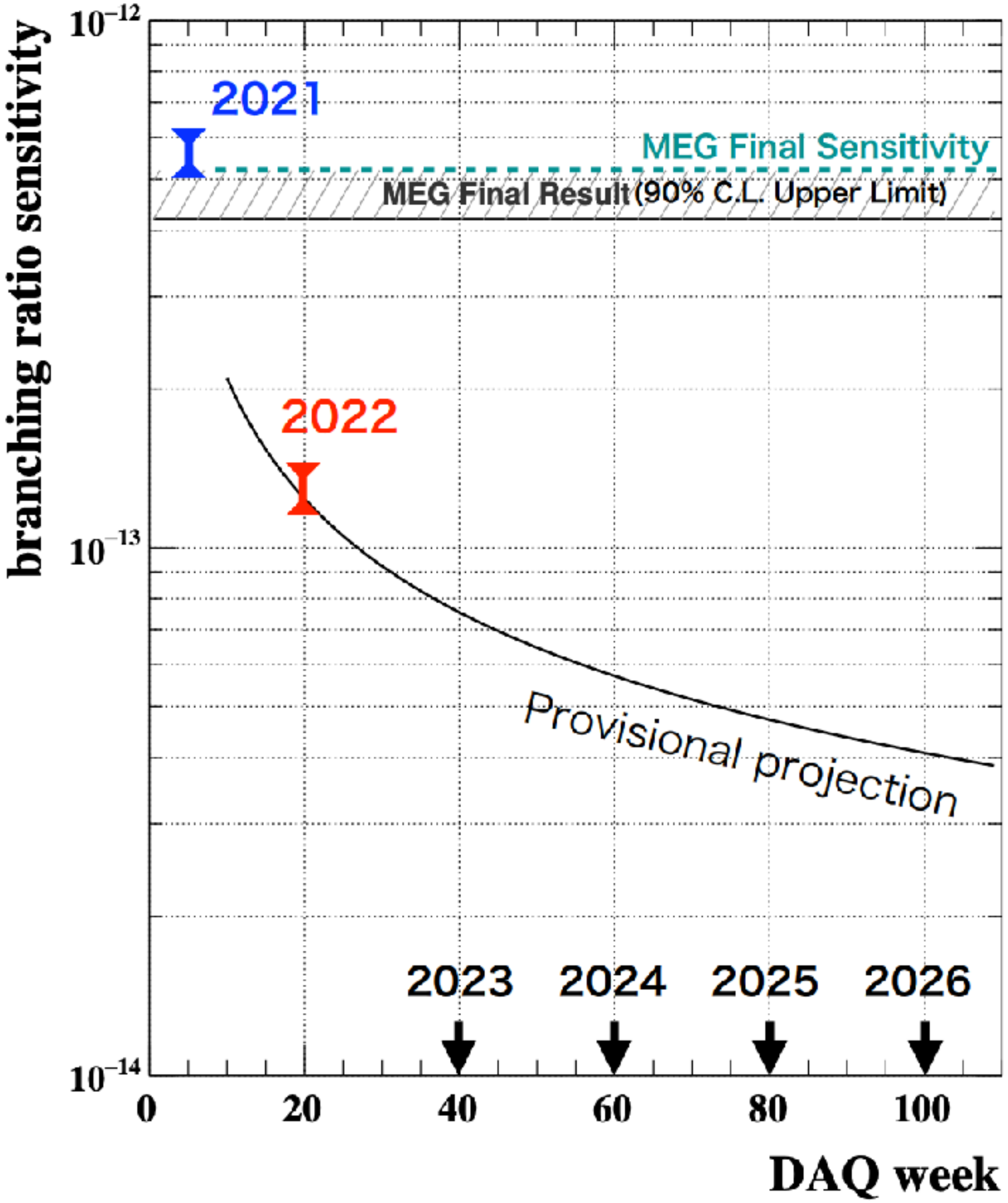
→ Good verification for the $\mu \to e\gamma$ reconstruction

MEG II

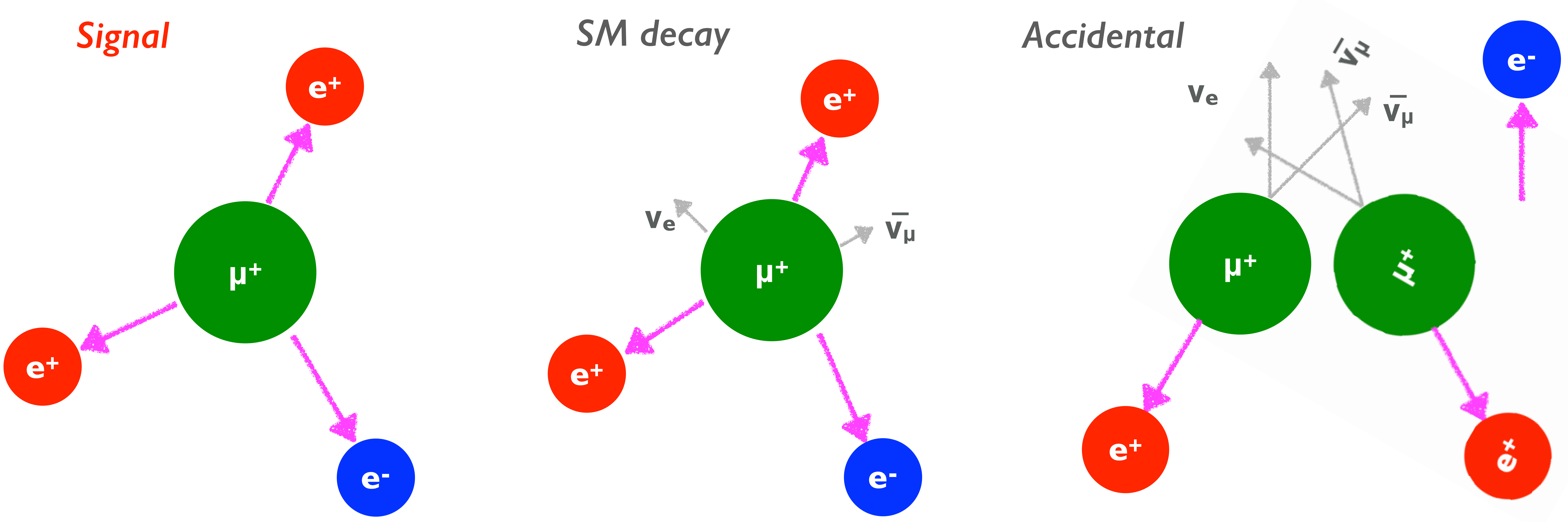
- Reached the sensitivity as good as MEG in one year of data taking
  - Analysis is ongoing, stay tuned!
- One order of magnitude improvement is expected from this year's physics data taking



$k = (S.E.S.)^{-1}$

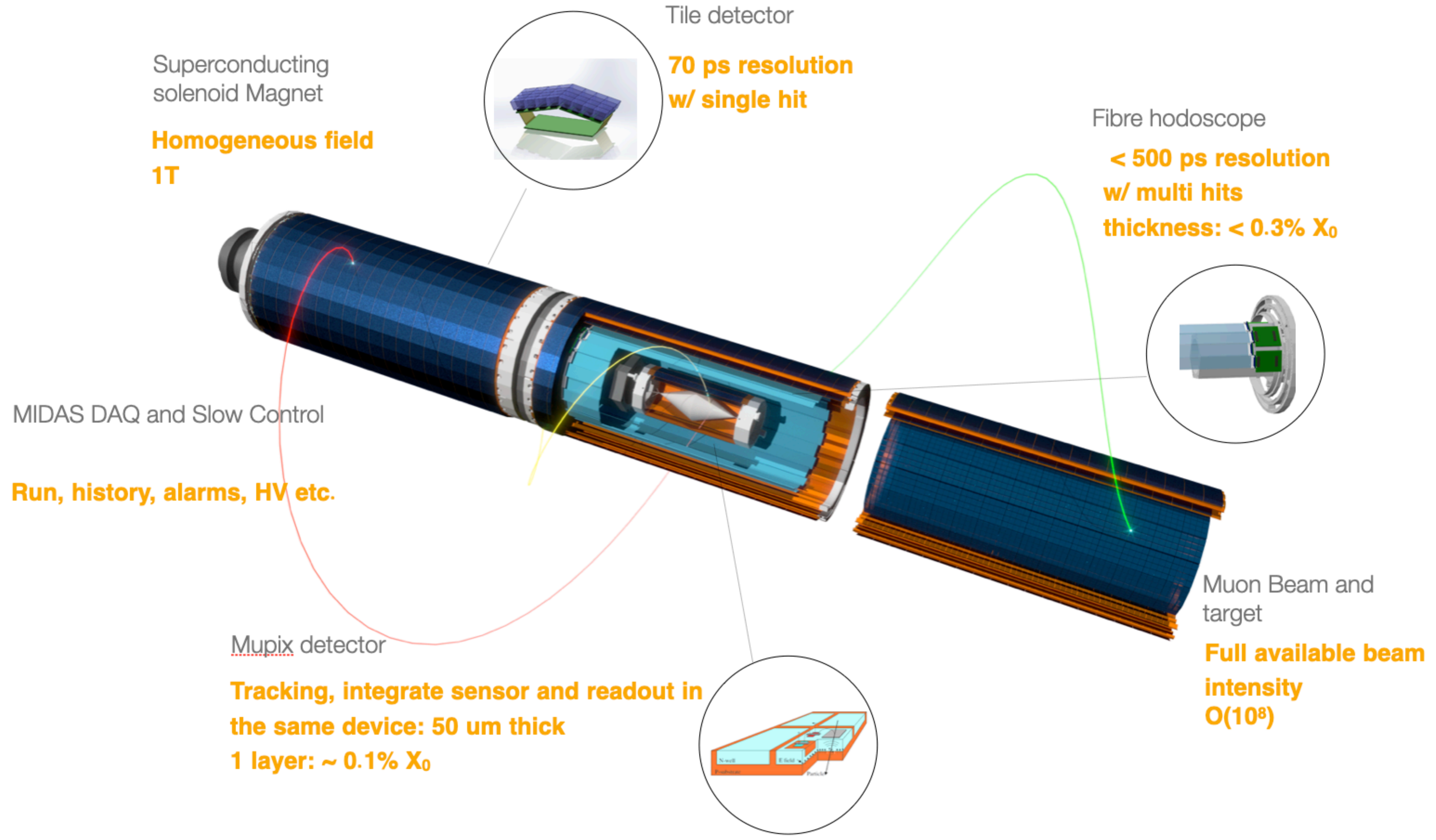


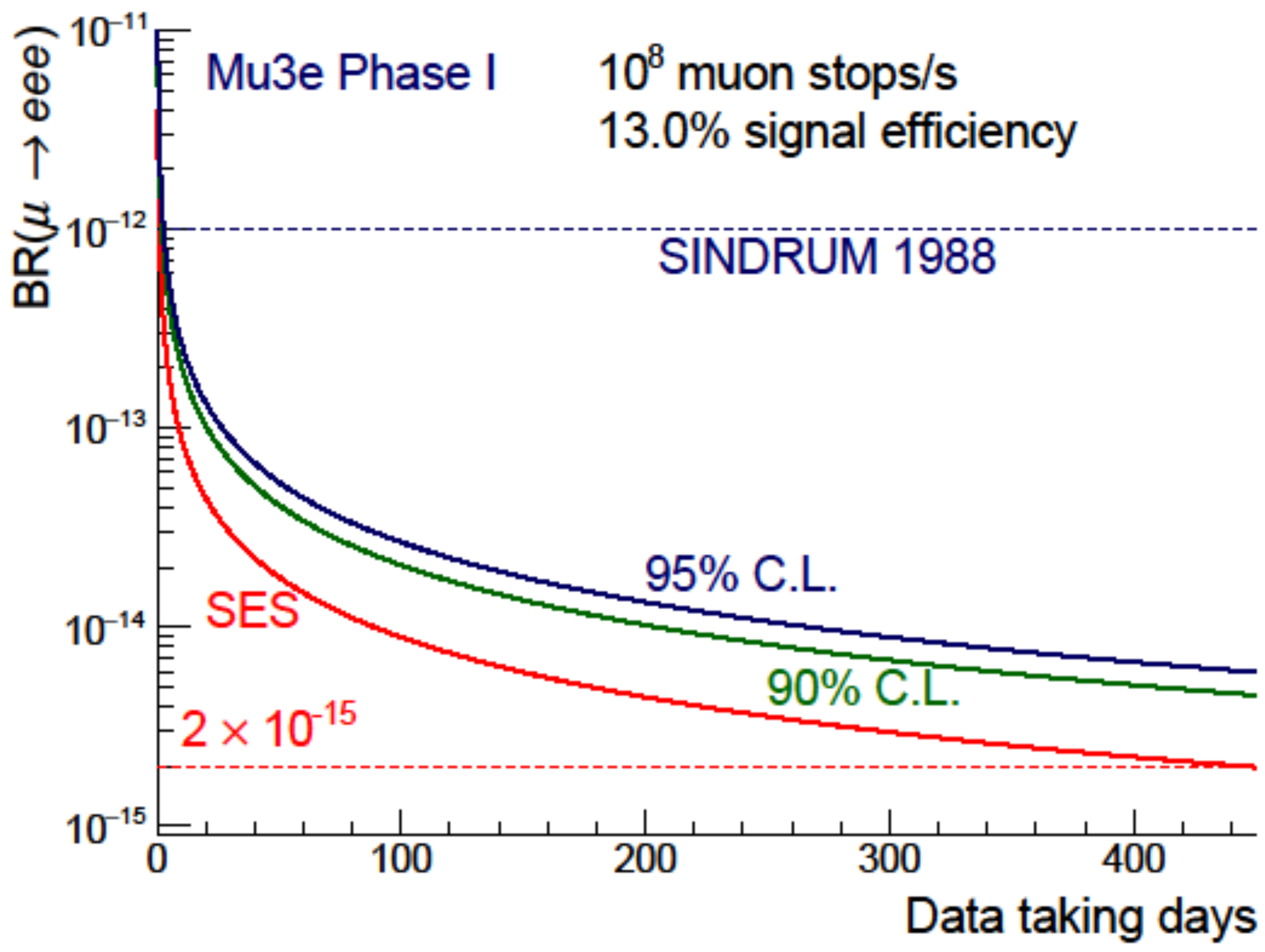
The μ to eee decay



- Accidental background is dominant → DC beam same as MEG/MEG II
  - An excellent vertex reconstruction and momentum resolutions

Mu3e





- ➤ Transitioning from R&D phase to the construction
- ➤ Integration & engineering run in 2023/2024, first physics run expected in 2025

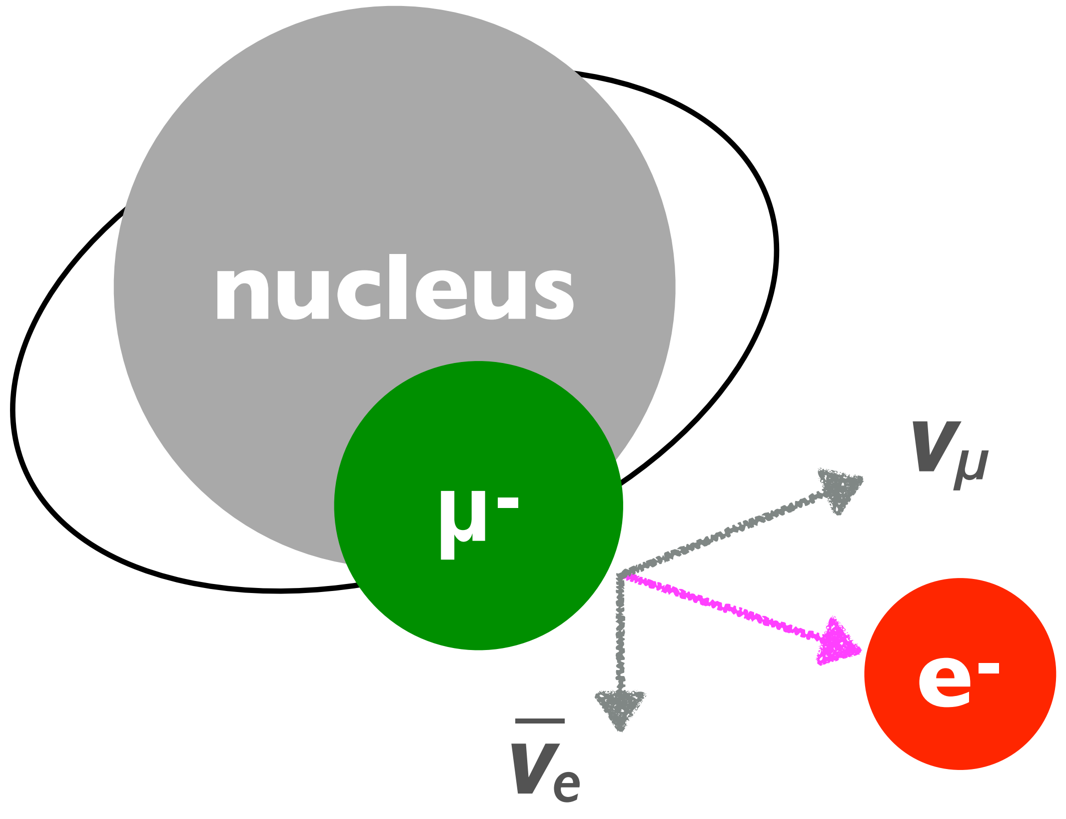
Searches for $\mu N \rightarrow eN$

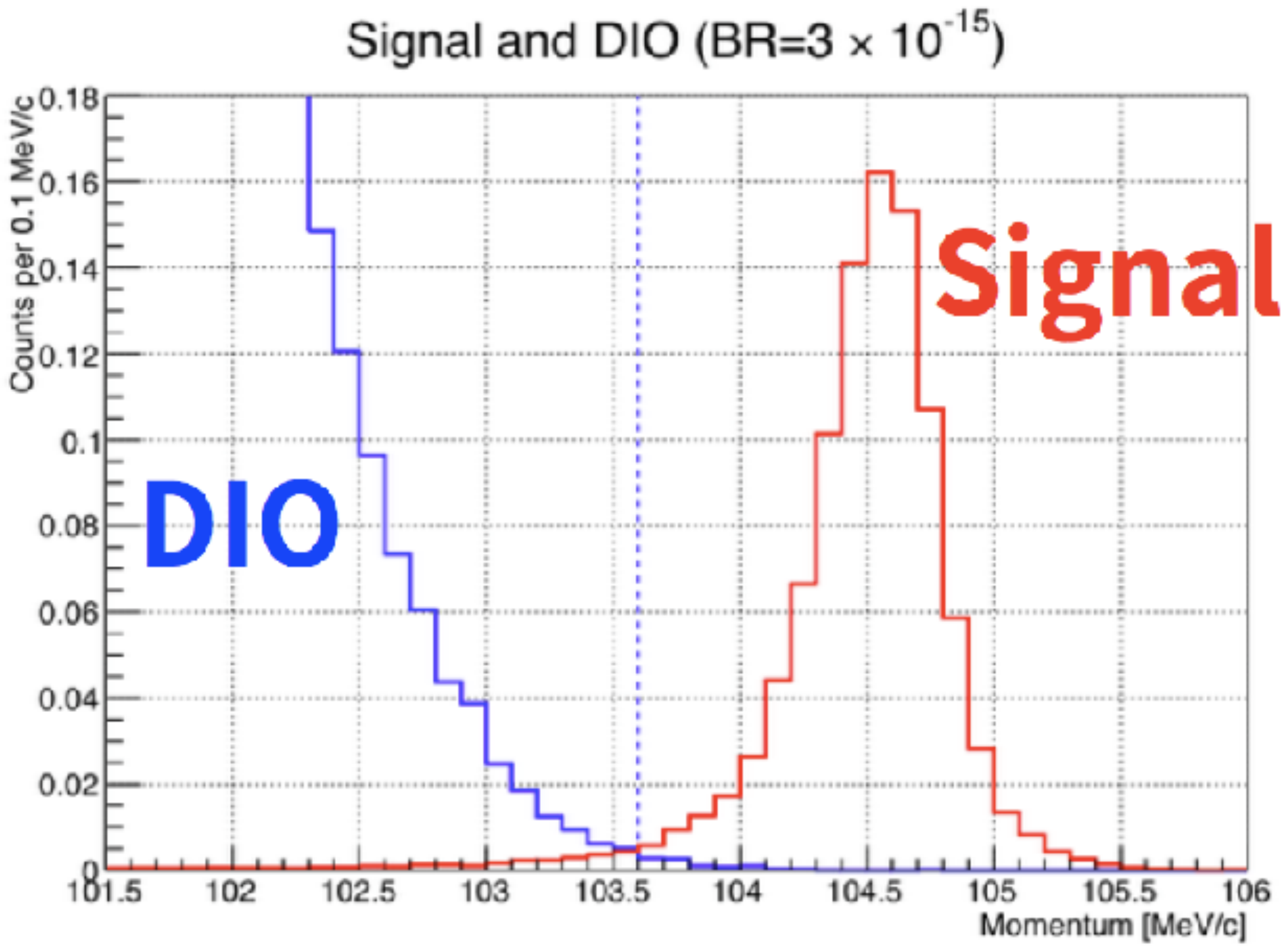
DeeMe, COMET, Mu2e

The Kangaroo Sanctuary / Facebook

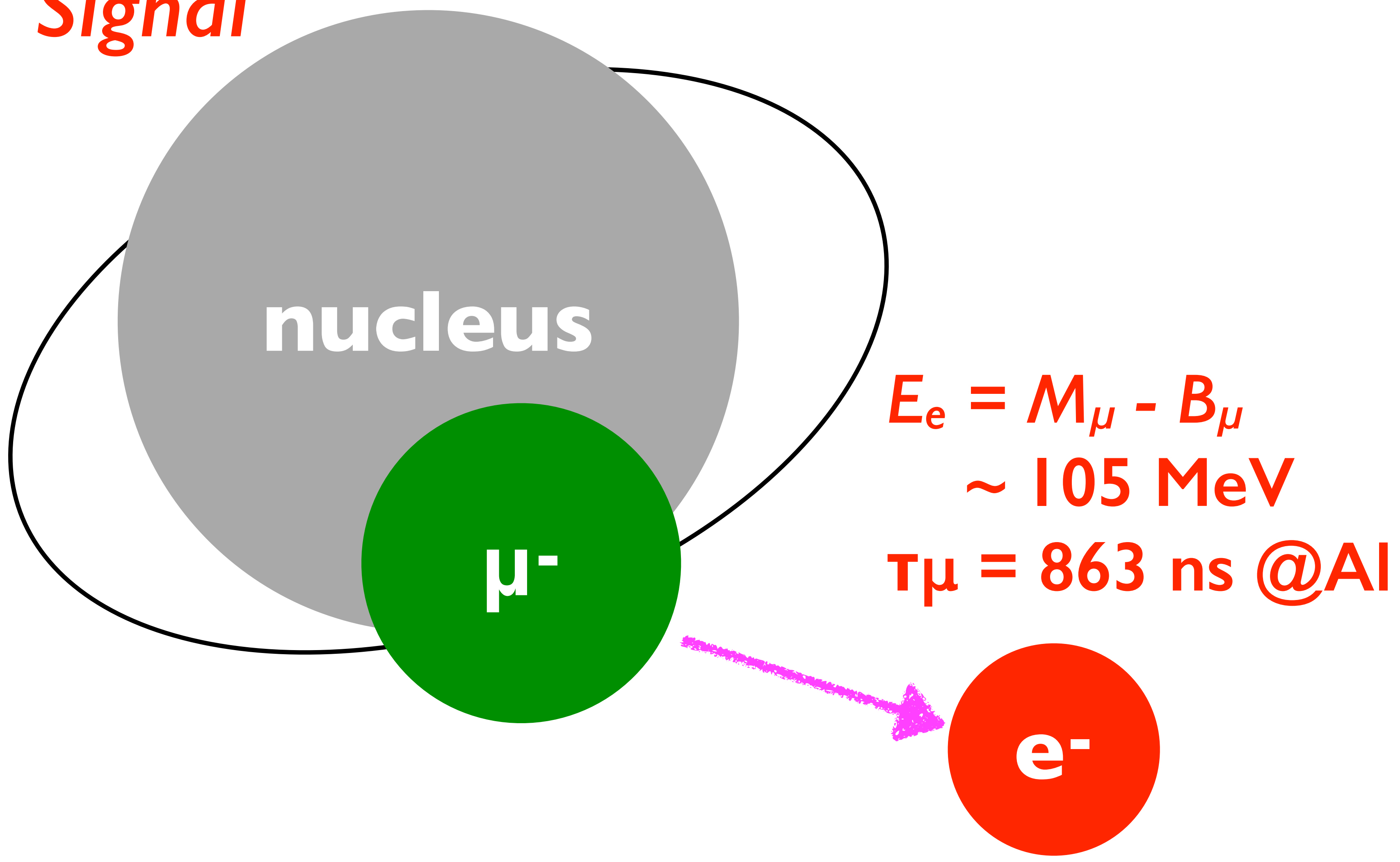
Experimental concept

Decay In Orbit (DIO)

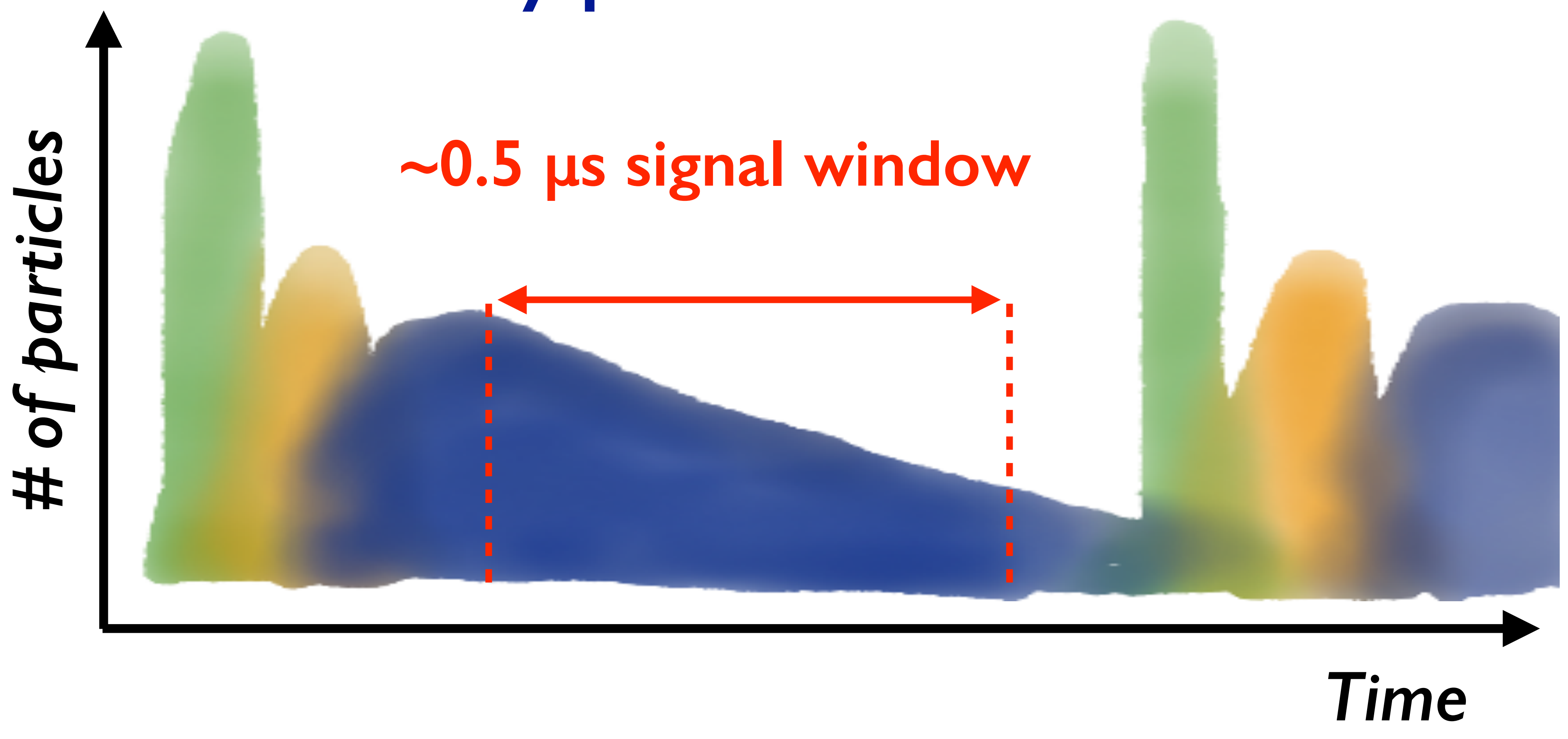




Signal

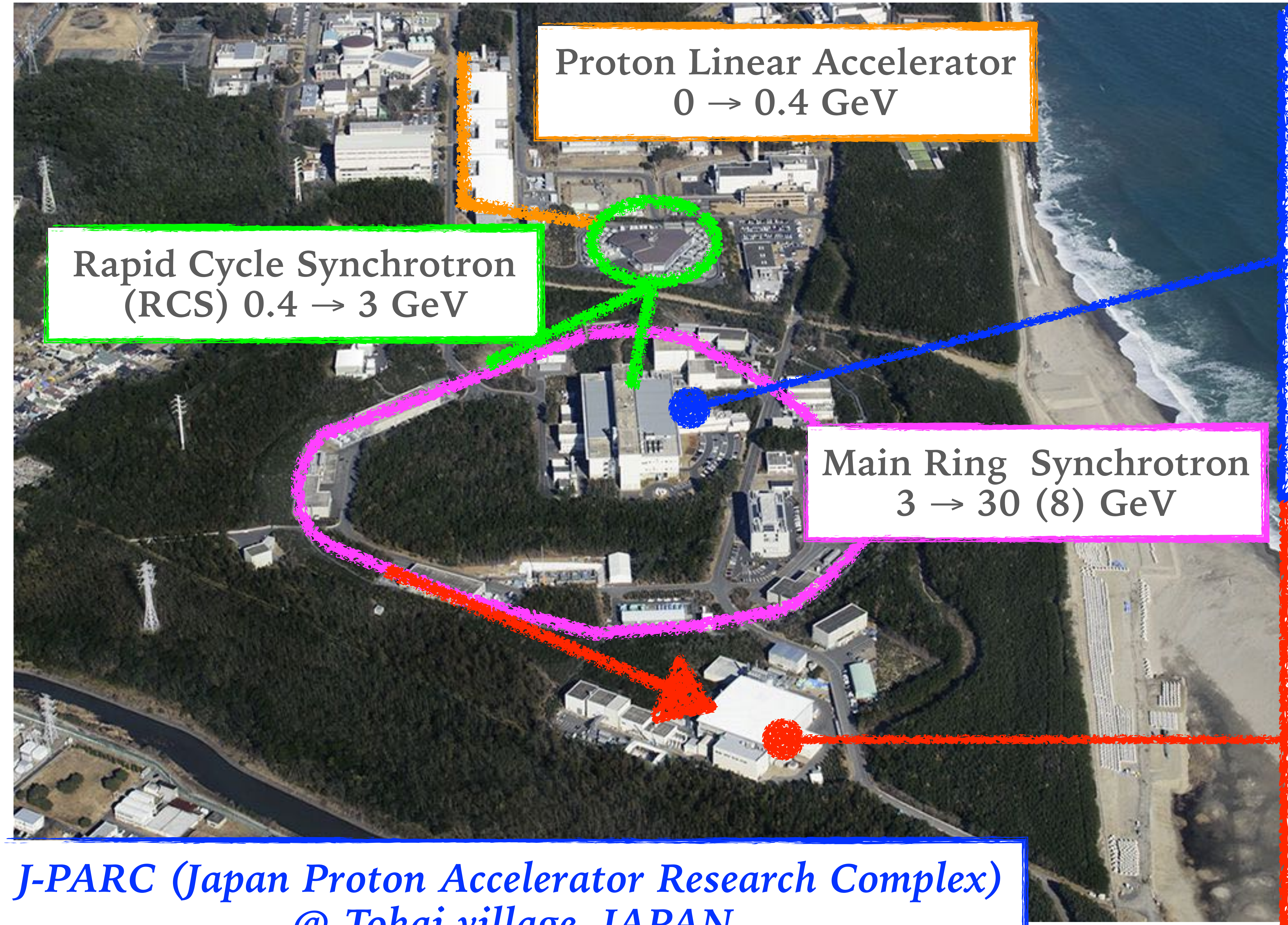


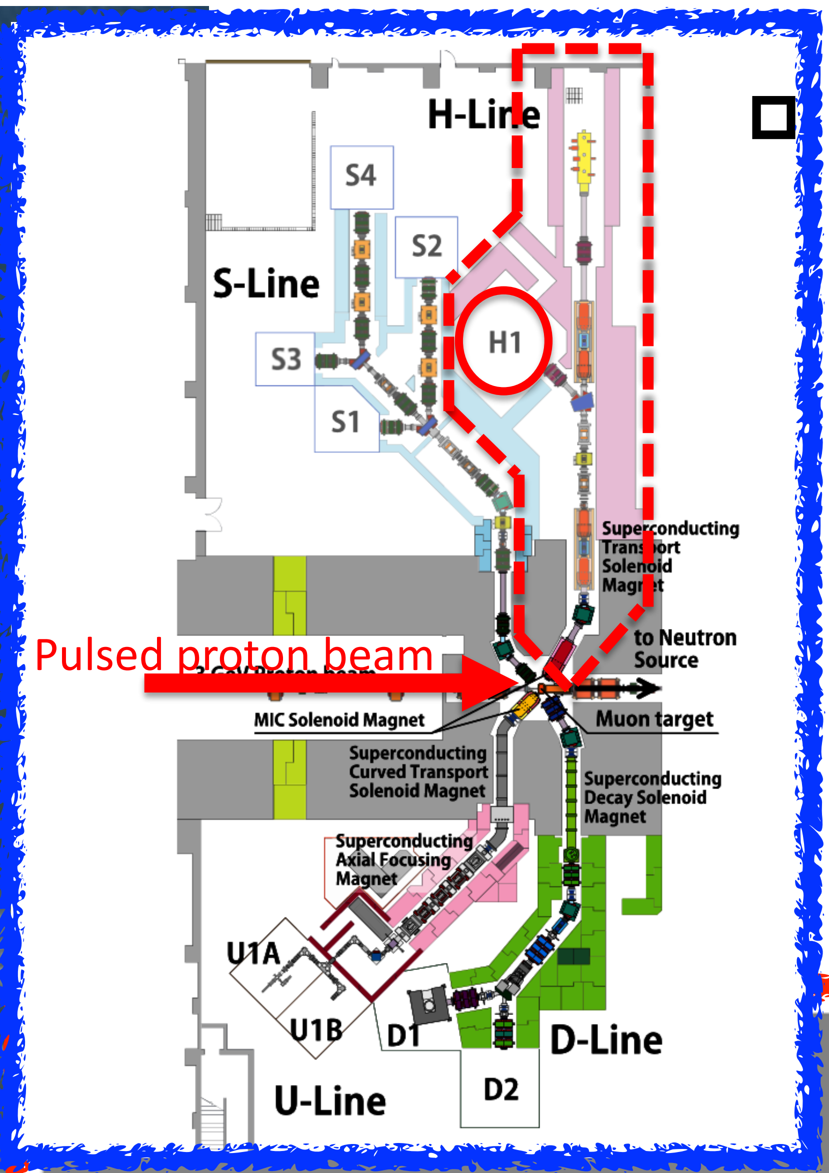
Main beam pulse
Prompt beam induced particles
Muon decay products

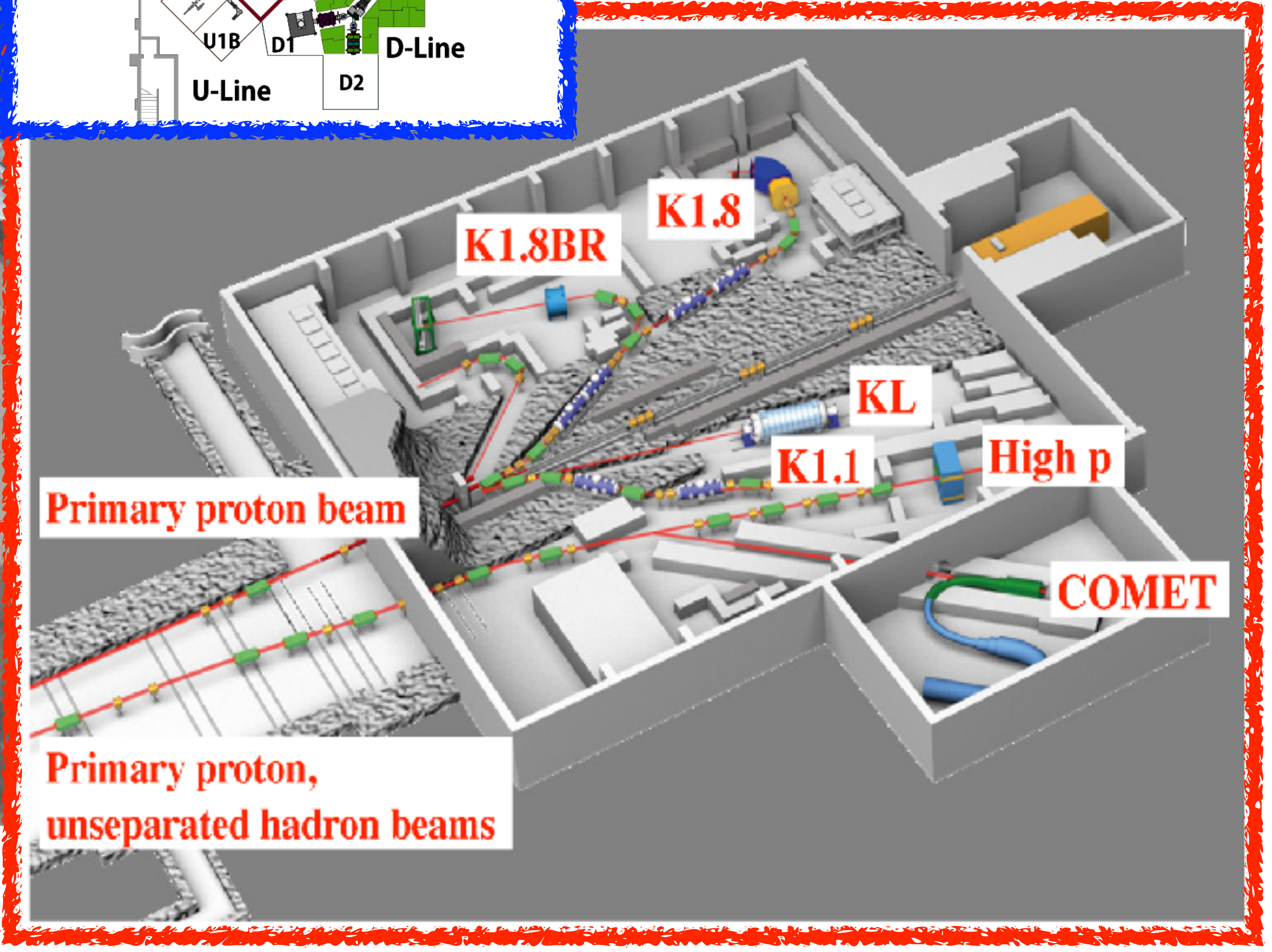


- Single electron with a mono-energy of ~105 MeV
  - No accidental coincidence
  - **sensitivity ∝ beam intensity, more & more muons!**
- Pulsed-beam + delayed time window to sweep out all beam prompt backgrounds

Muons @J-PARC

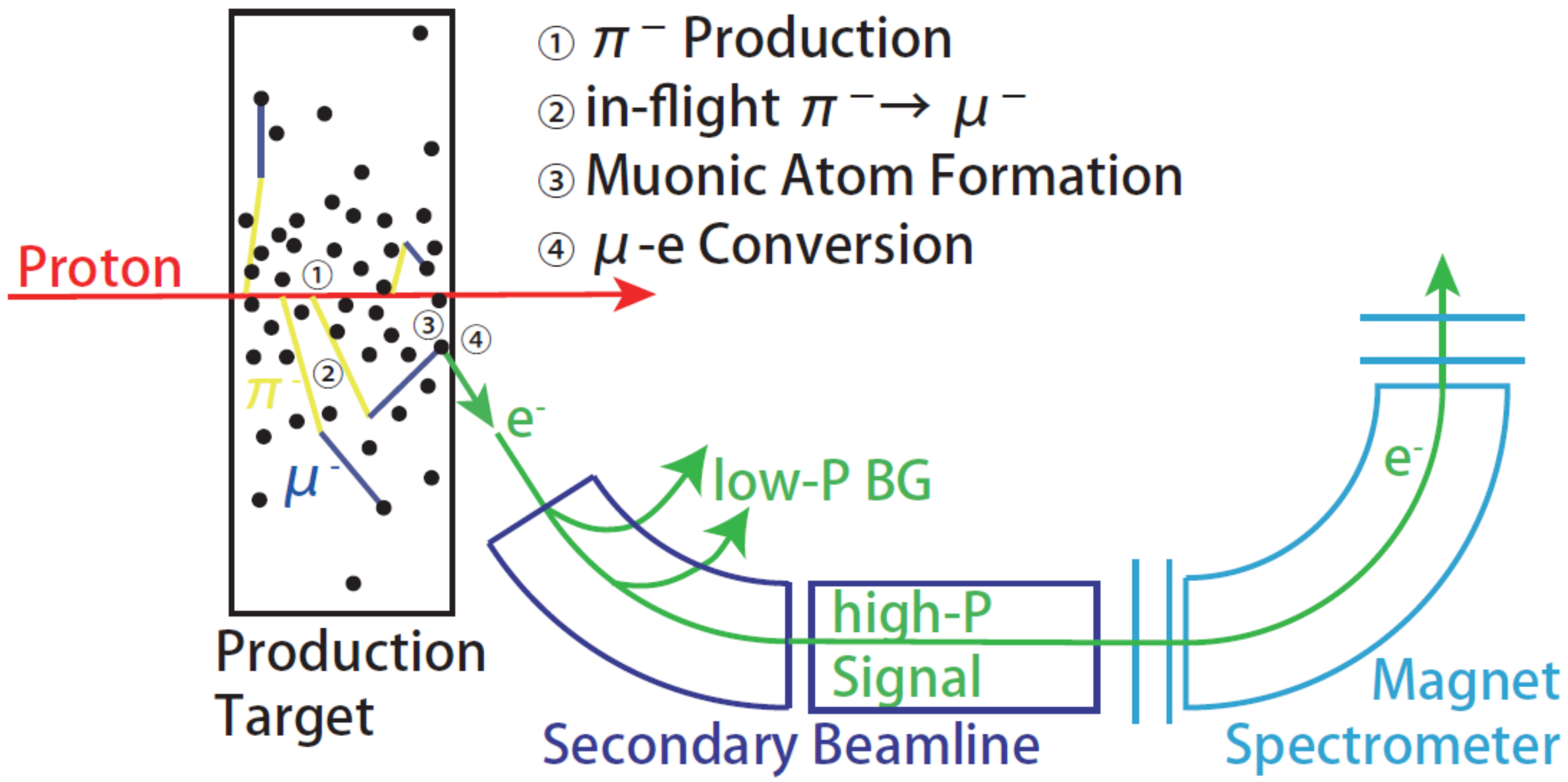


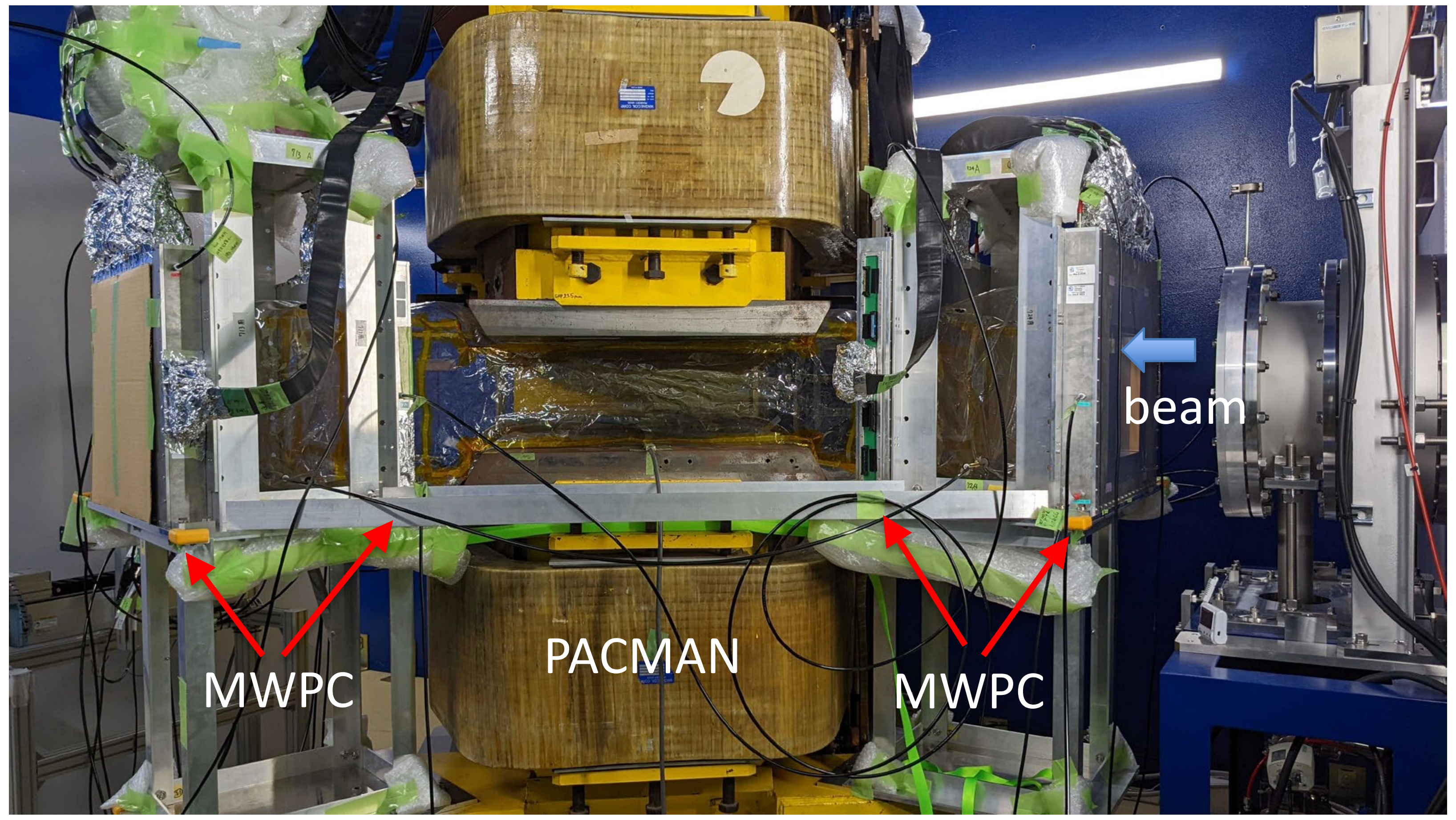


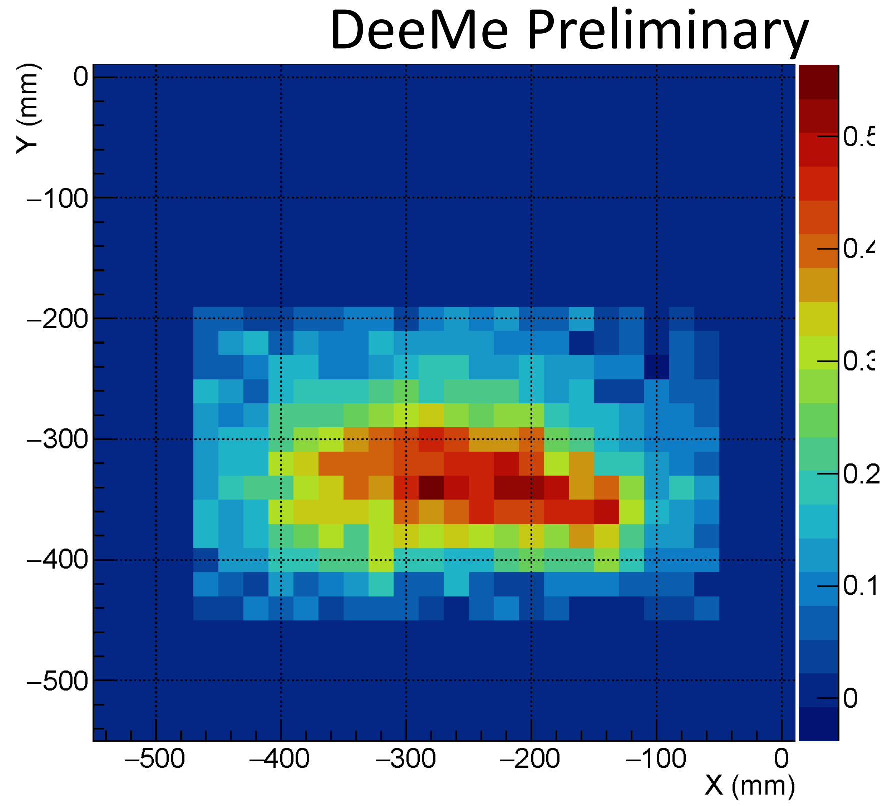


J-PARC (Japan Proton Accelerator Research Complex)
@ Tokai village, JAPAN

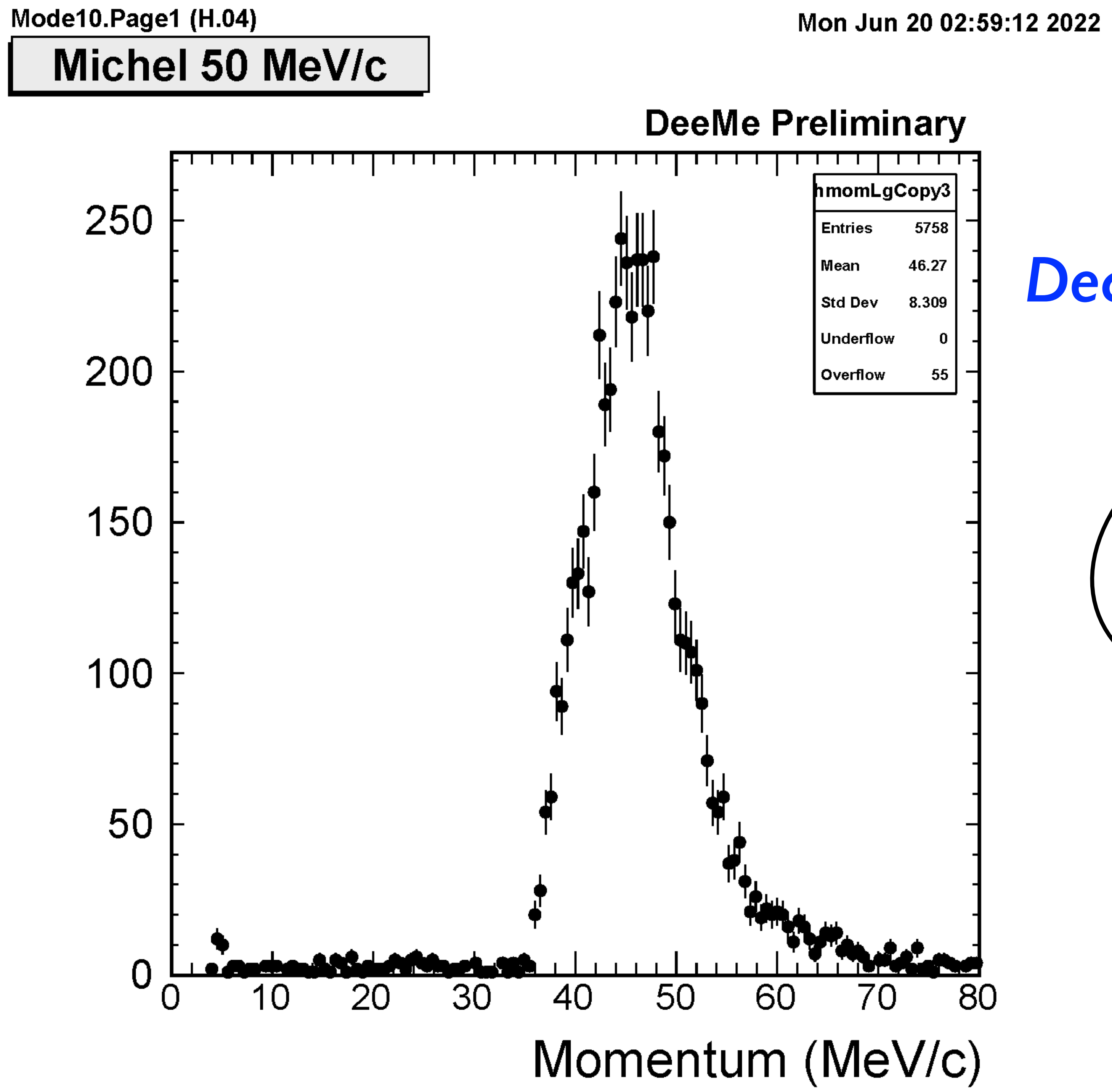
DeeMe @J-PARC MLF

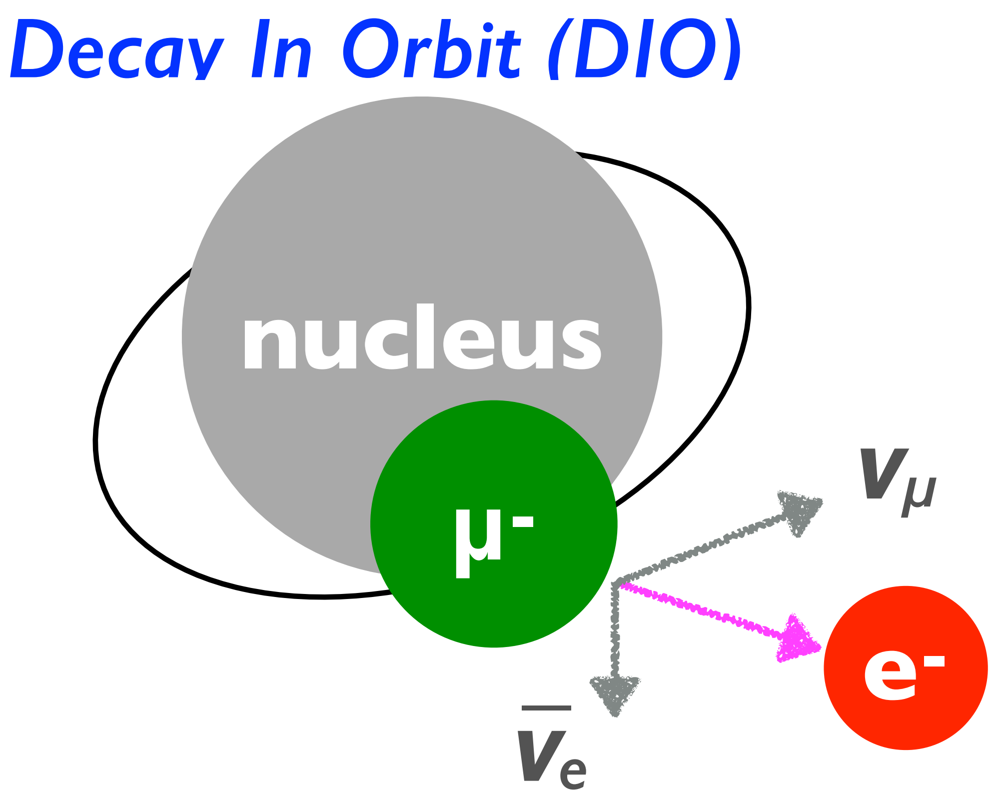






Prompt burst
105 MeV/c electron
beam profile

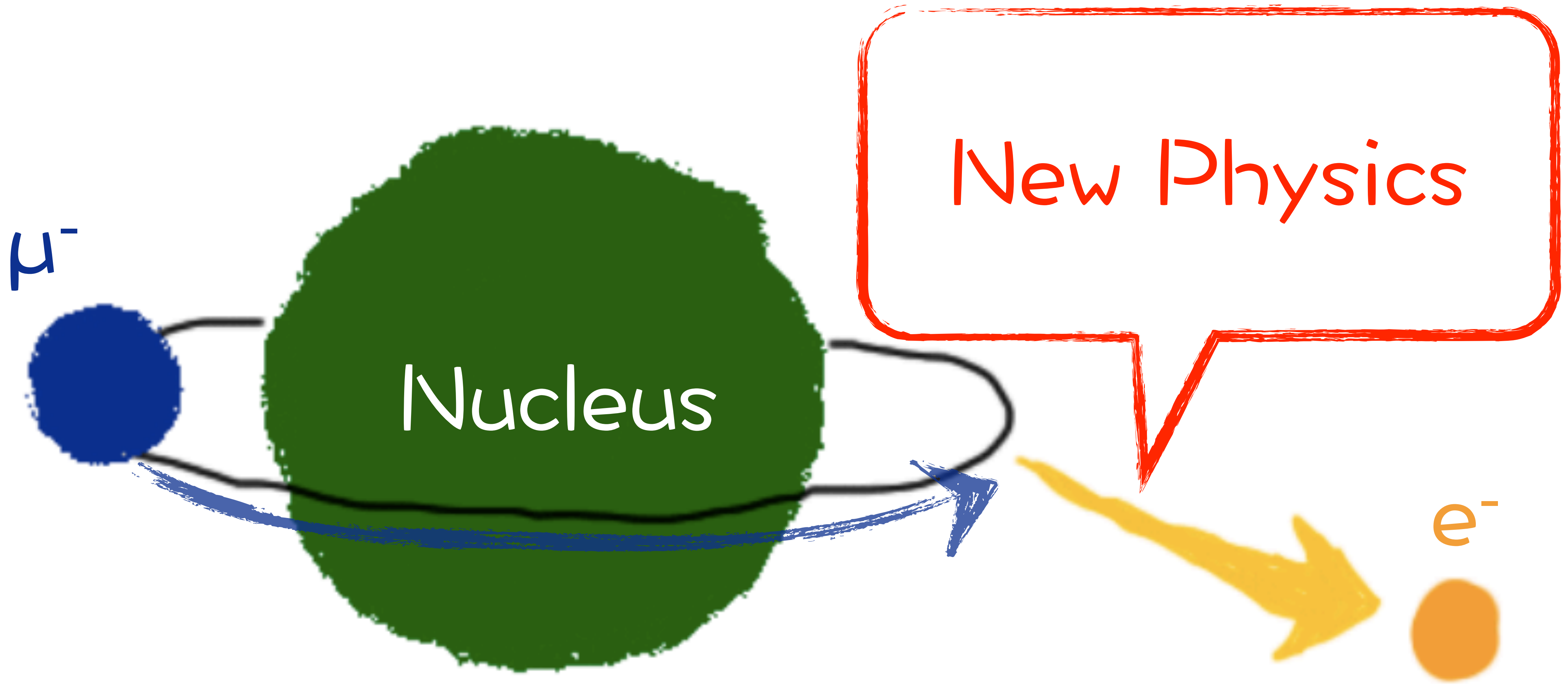


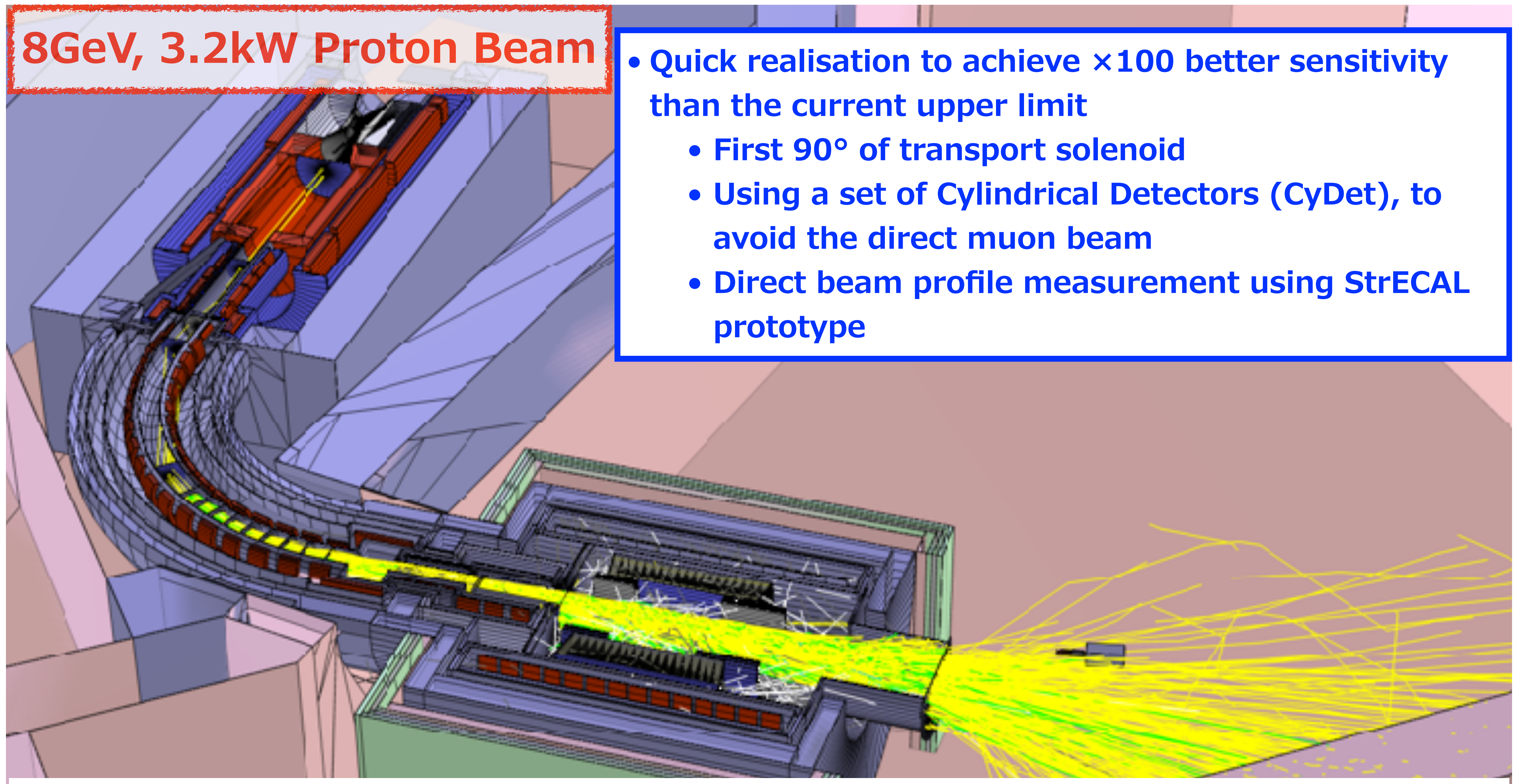


- DIO edge observed in the pilot run
- Physics run is planned in 2023 with an expected sensitivity of 1×10^{-13}

COMET Phase-I - Overview -

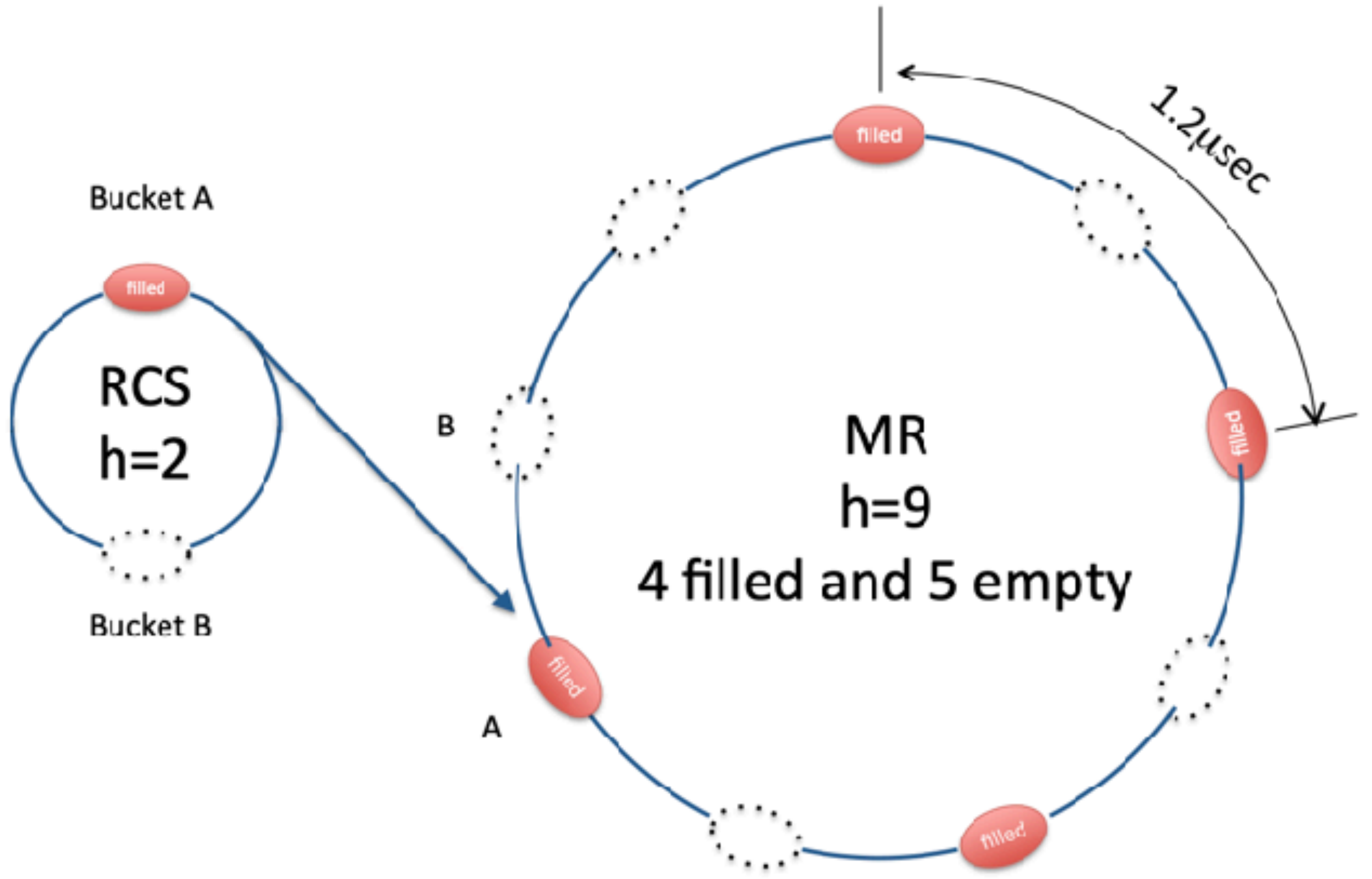
- Searching for a **μ-e conversion** with sensitivity of $O(10^{-15})$
  - Muon beam produced by impinging the 8 GeV proton beam onto the graphite target
  - Requires $\sim 10^{16}$ total stopping muons per 150 days → **10^{9} μ^{-}/sec**
  - So many secondary particles will be expected inside the detectors
- **See Sam Dekkers talk for more details**

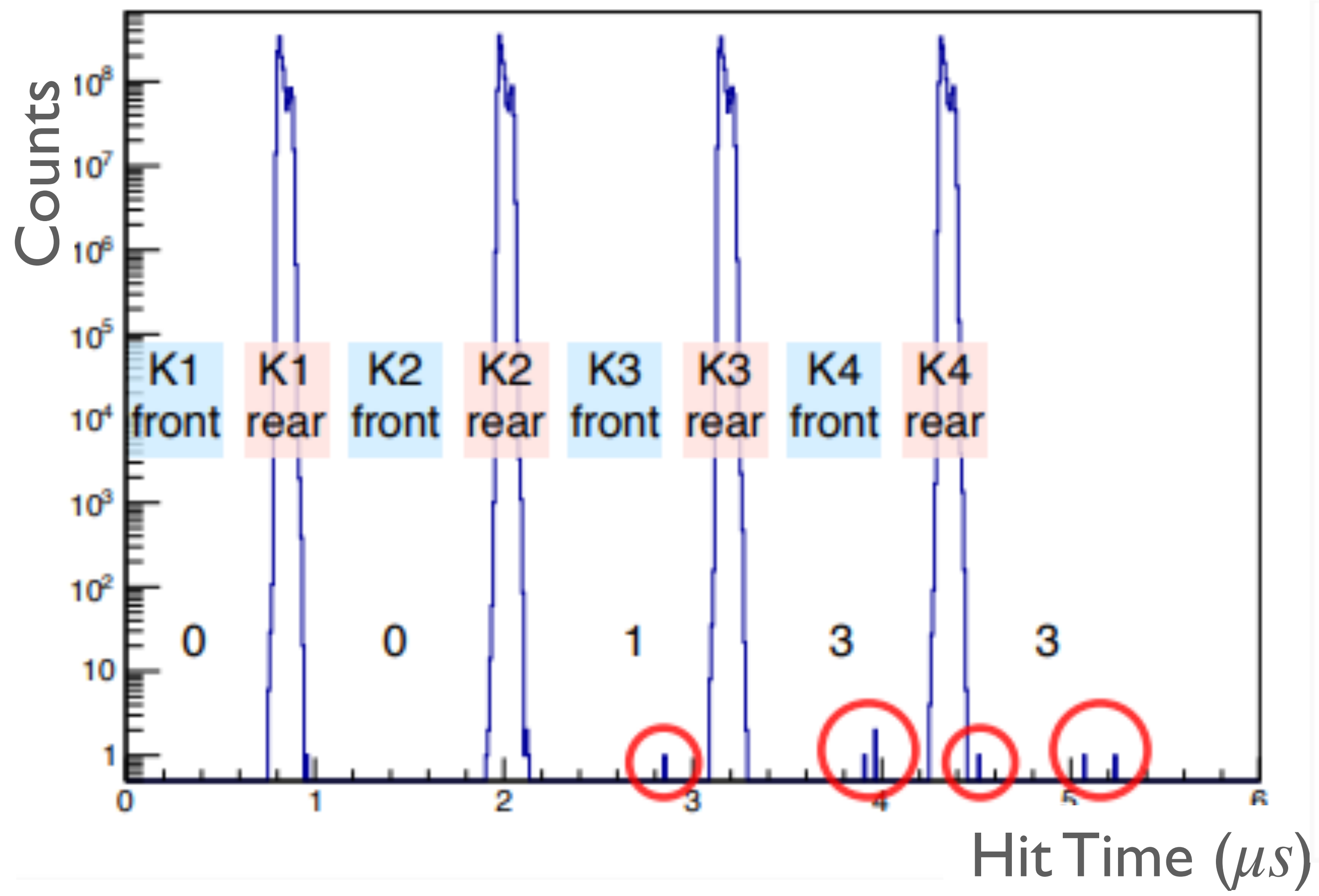


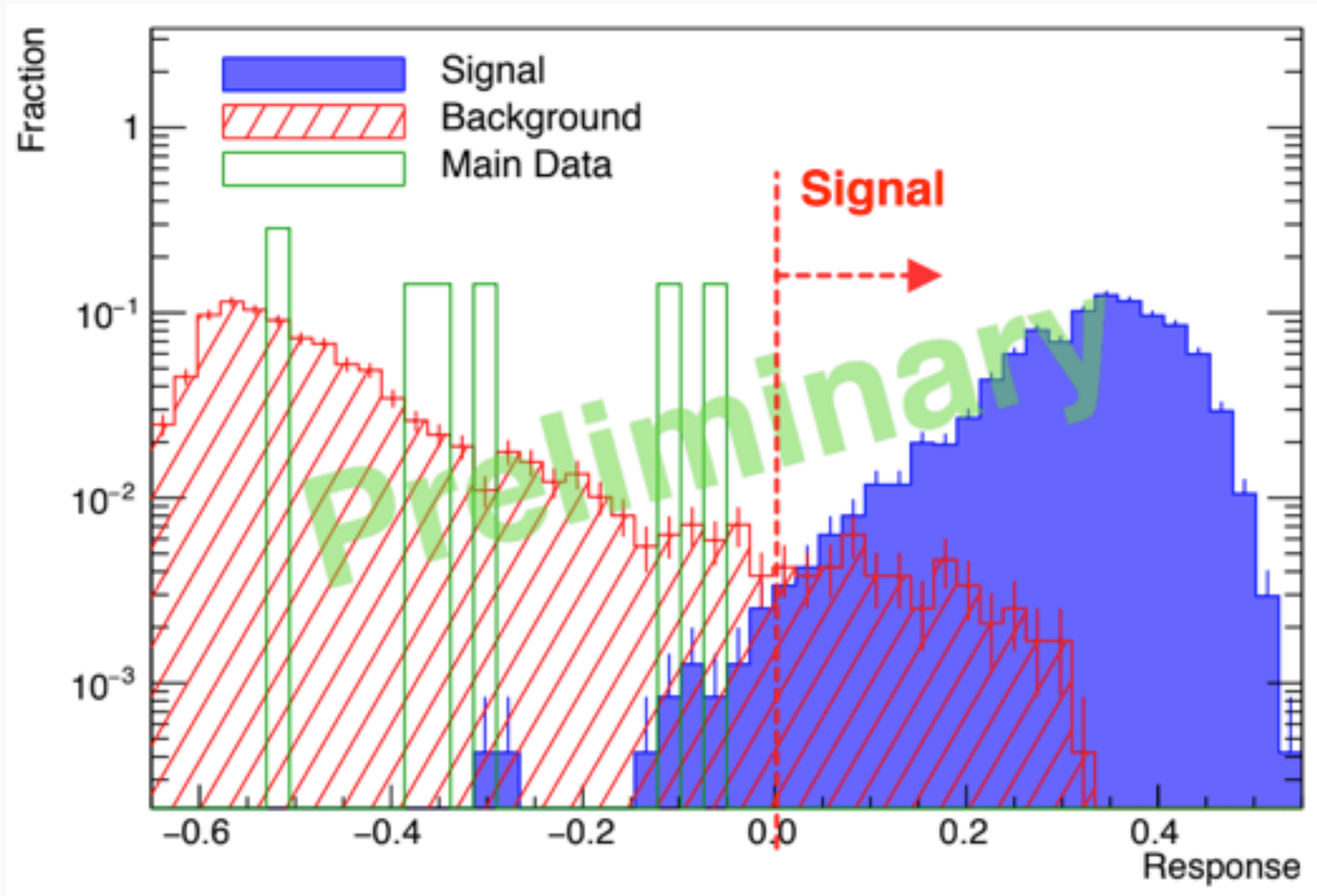


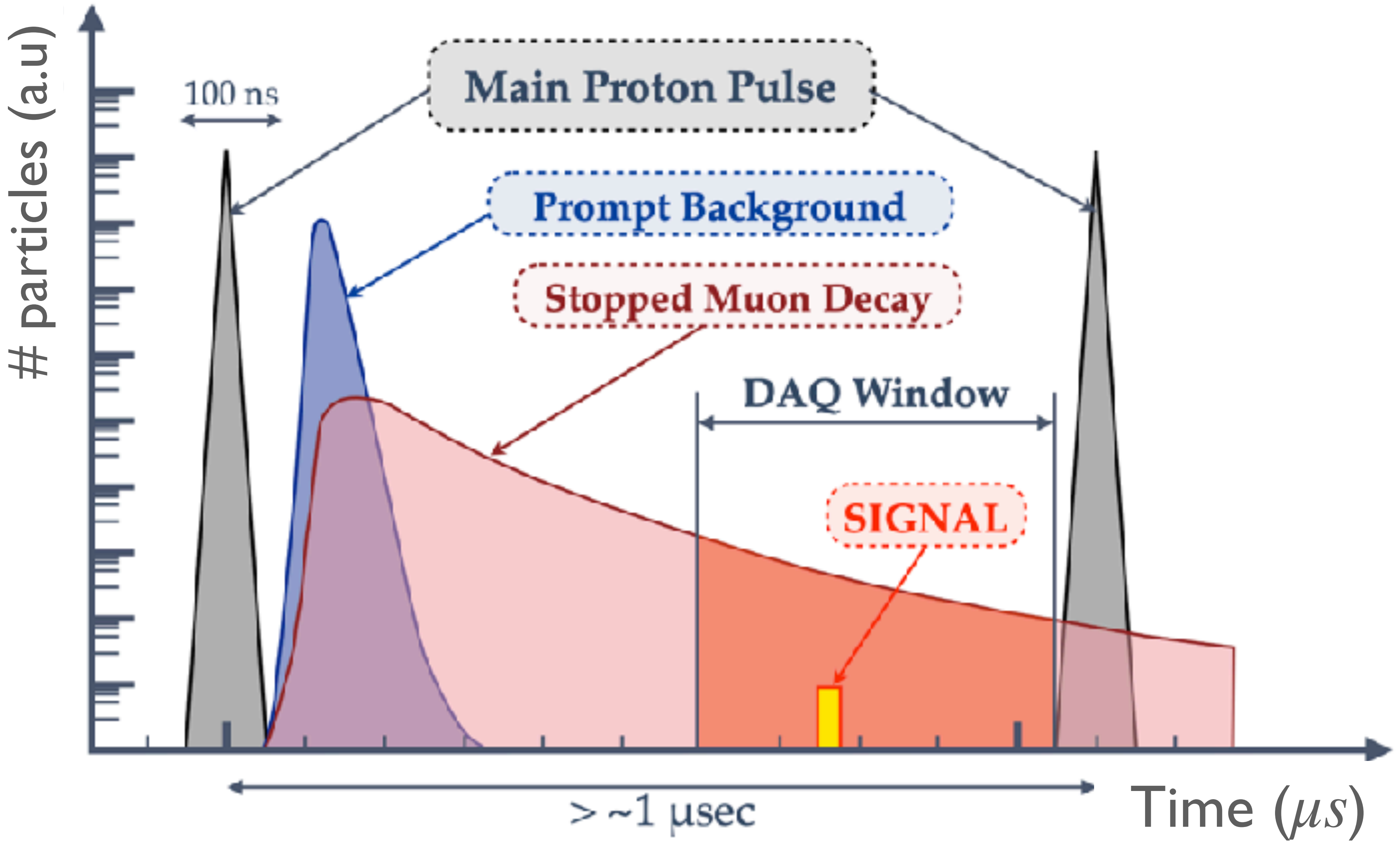
COMET Phase-I technical design report, *PTEP*, Vol 2020, Issue 3, March 2020, 033C01, https://doi.org/10.1093/ptep/ptz125

COMET Phase-I - Proton beam -









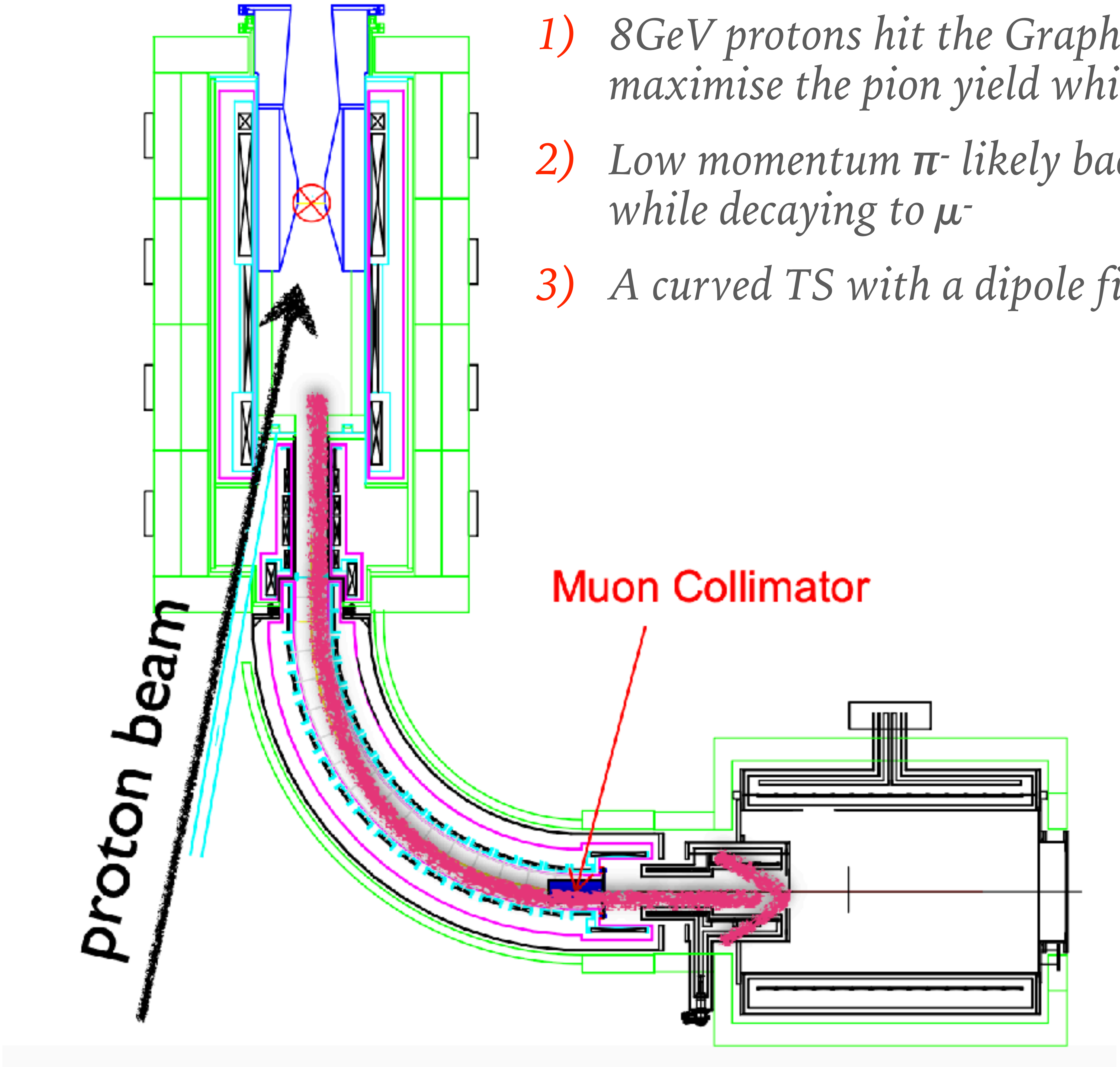
All signals between pulses are "accidental BG" (≠single particle from the beam)

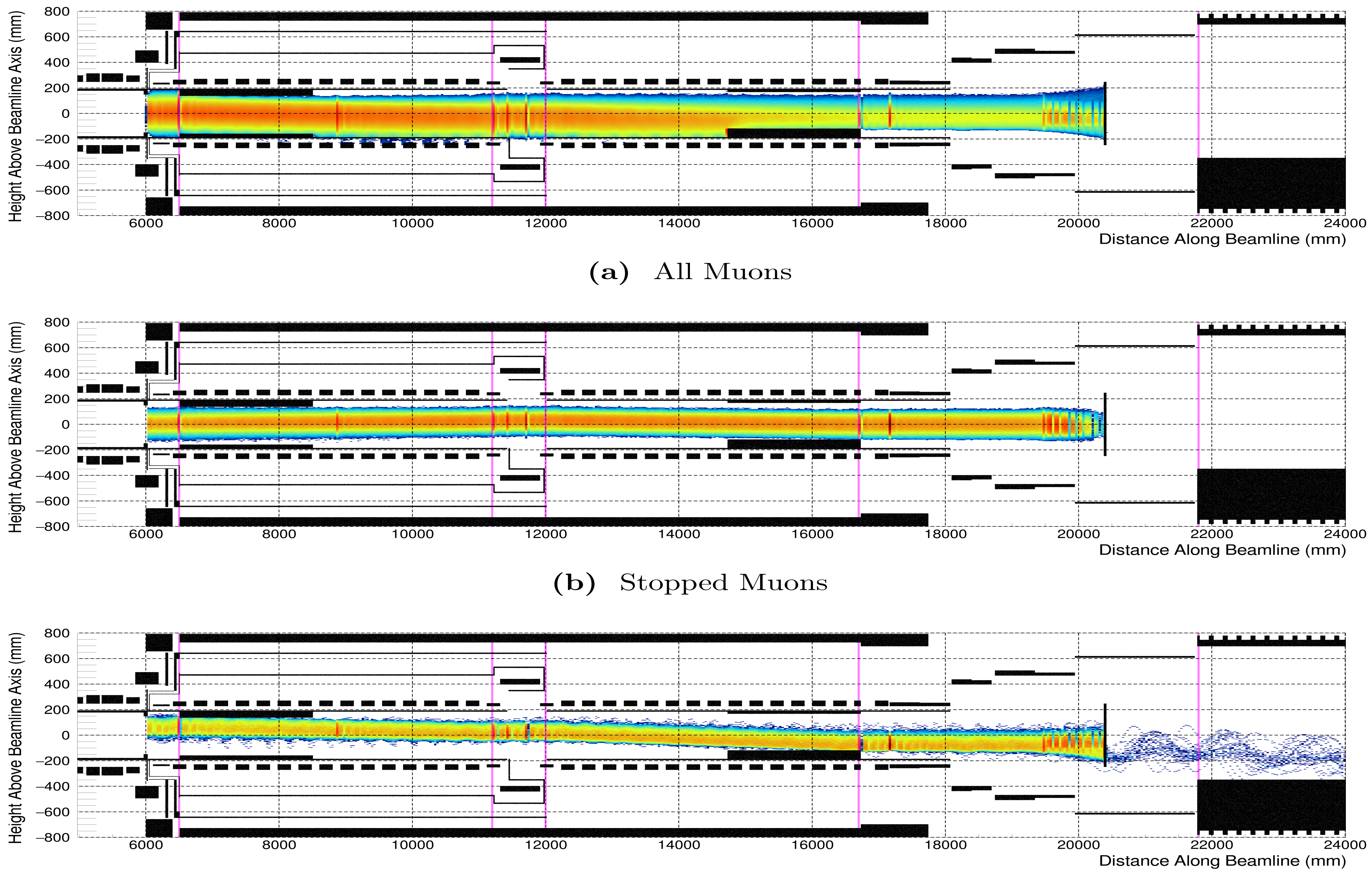
→ $R_{Extinction} < 10^{-11}$

Good enough for Phase-I, more statistics is needed to check this for Phase-II

COMET Phase-I - Muon beam -

1) *8GeV protons hit the Graphite target and produce secondary pions (Energy chosen to maximise the pion yield while preventing anti-protons)*
2) *Low momentum π^- likely back scatter and direct to the muon transportation solenoid (TS) while decaying to μ^-*
3) *A curved TS with a dipole field to select low momentum negative particles*



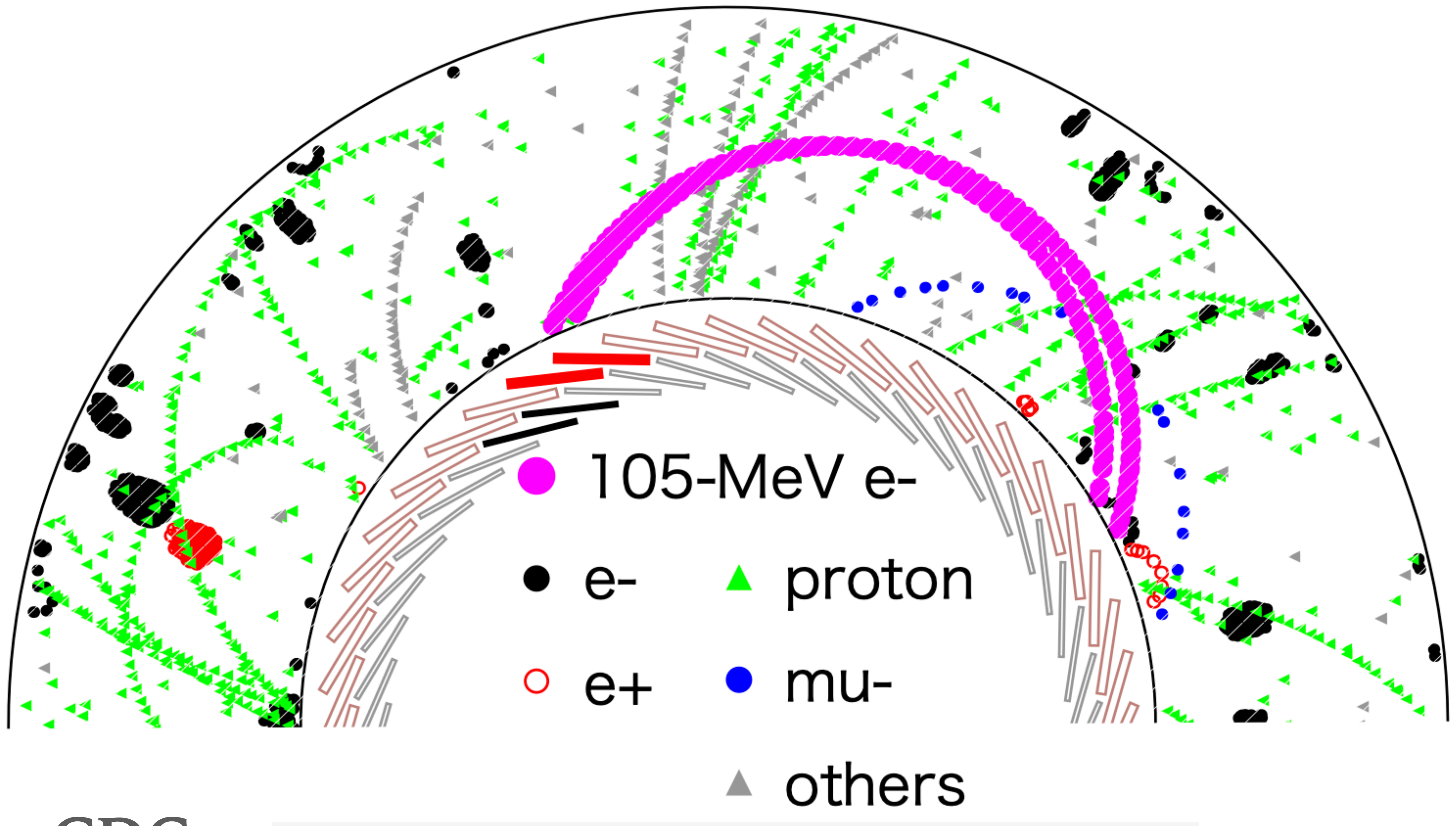


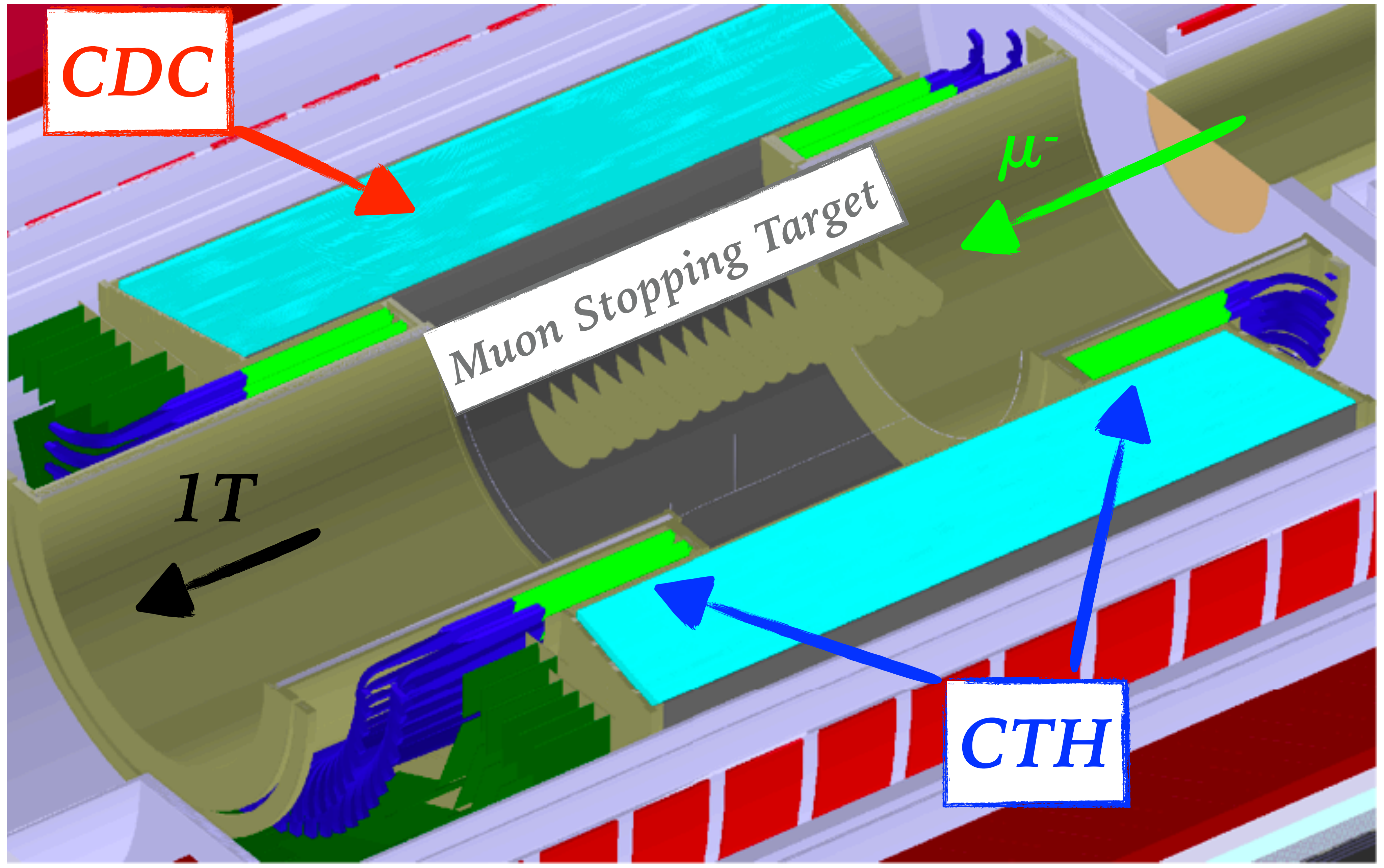
(a) All Muons

(b) Stopped Muons

(c) Muons with $p > 70$ MeV/c around the stopping target

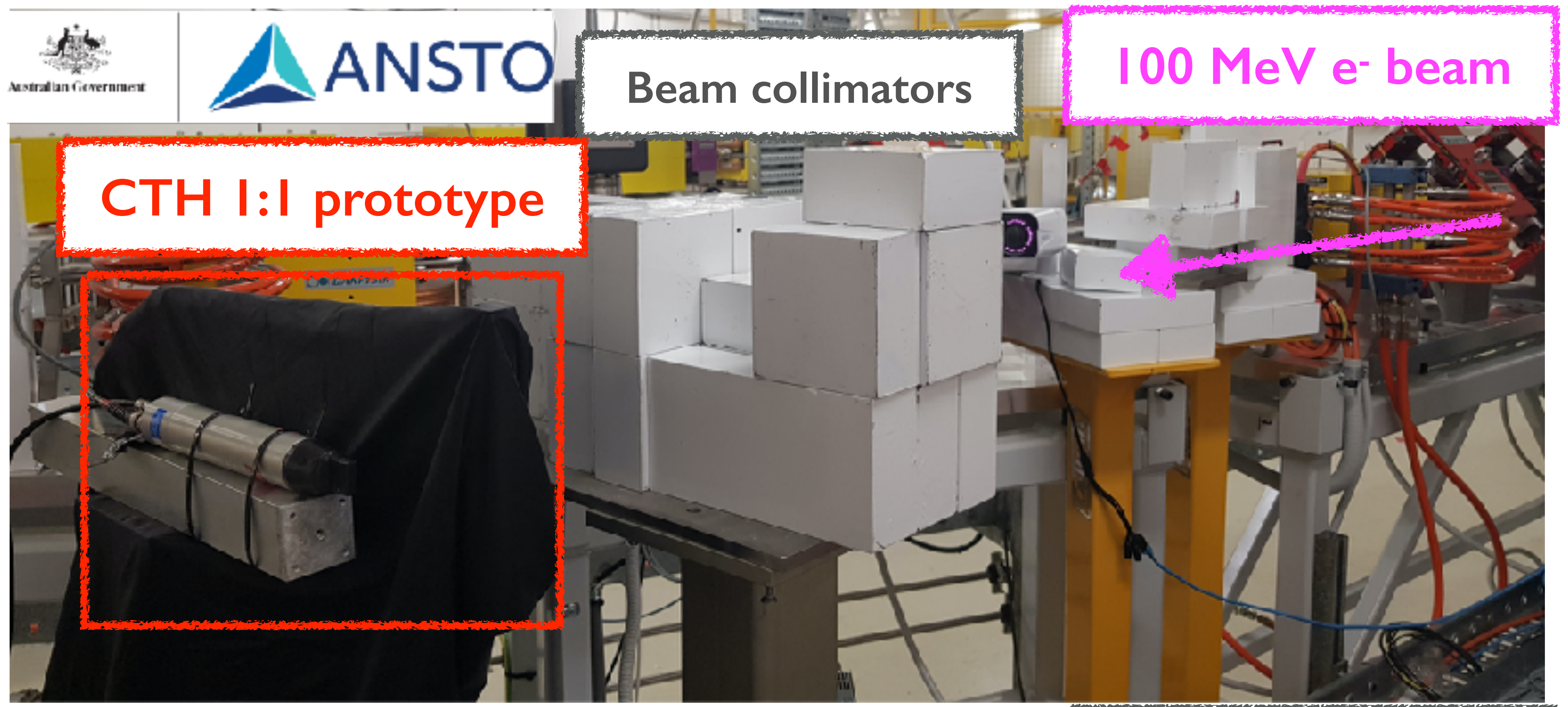
COMET Phase-I - CyDet -

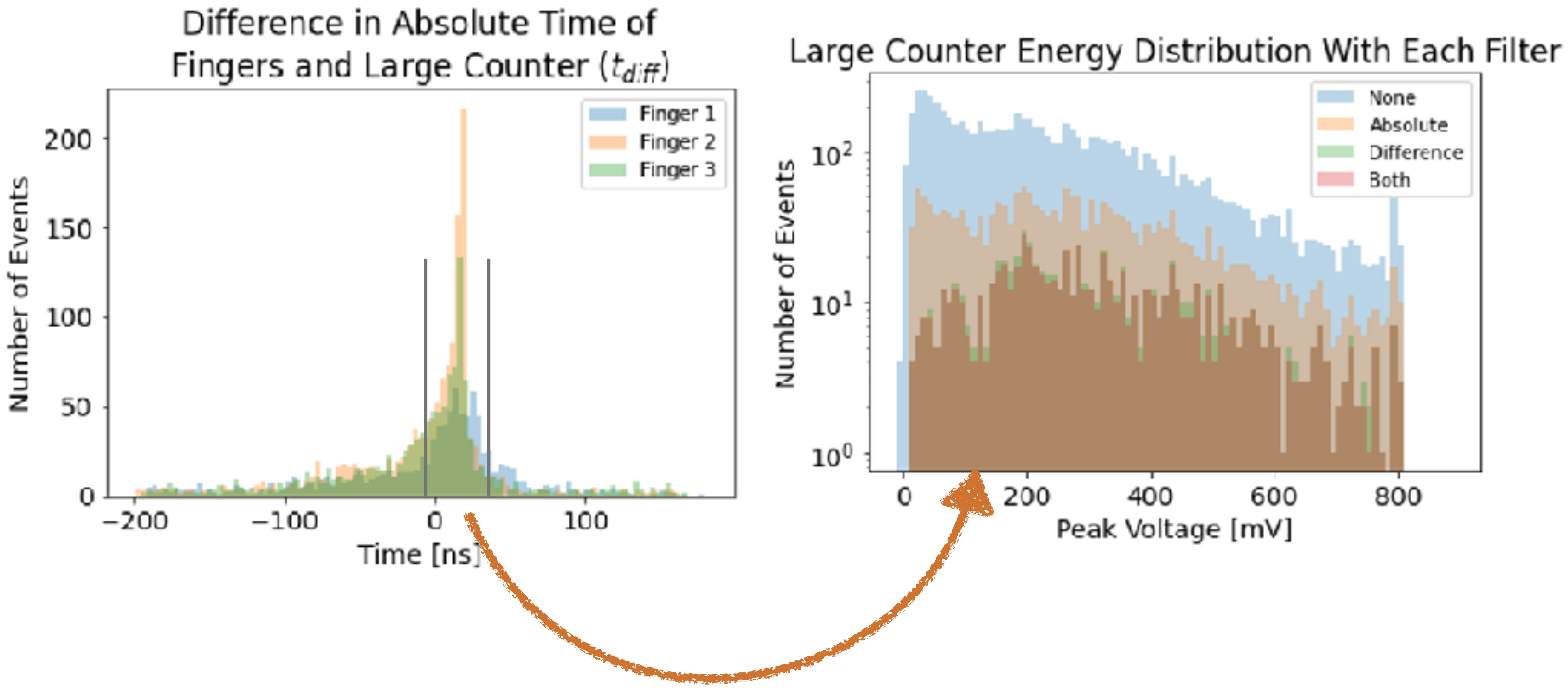




- CDC C. Wu, *et.al.* DOI:10.1016/j.nima.2021.165756
  - ~5,000 wires, 20 stereo layers for momentum measurement, He:iC_5H_{10}=90:10, typical drift time <400ns
  - Signal electrons' trajectories fully contained inside the volume
- CTH Y. Fujii, *et.al.* DOI:10.5281/zenodo.6781368
  - 2 layers of 64 segmented plastic scintillator rings at both ends of CDC for the timing measurement
  - Suppress accidental events and low momentum particles by taking four-fold coincidence

COMET Phase-I – Monash Activities –

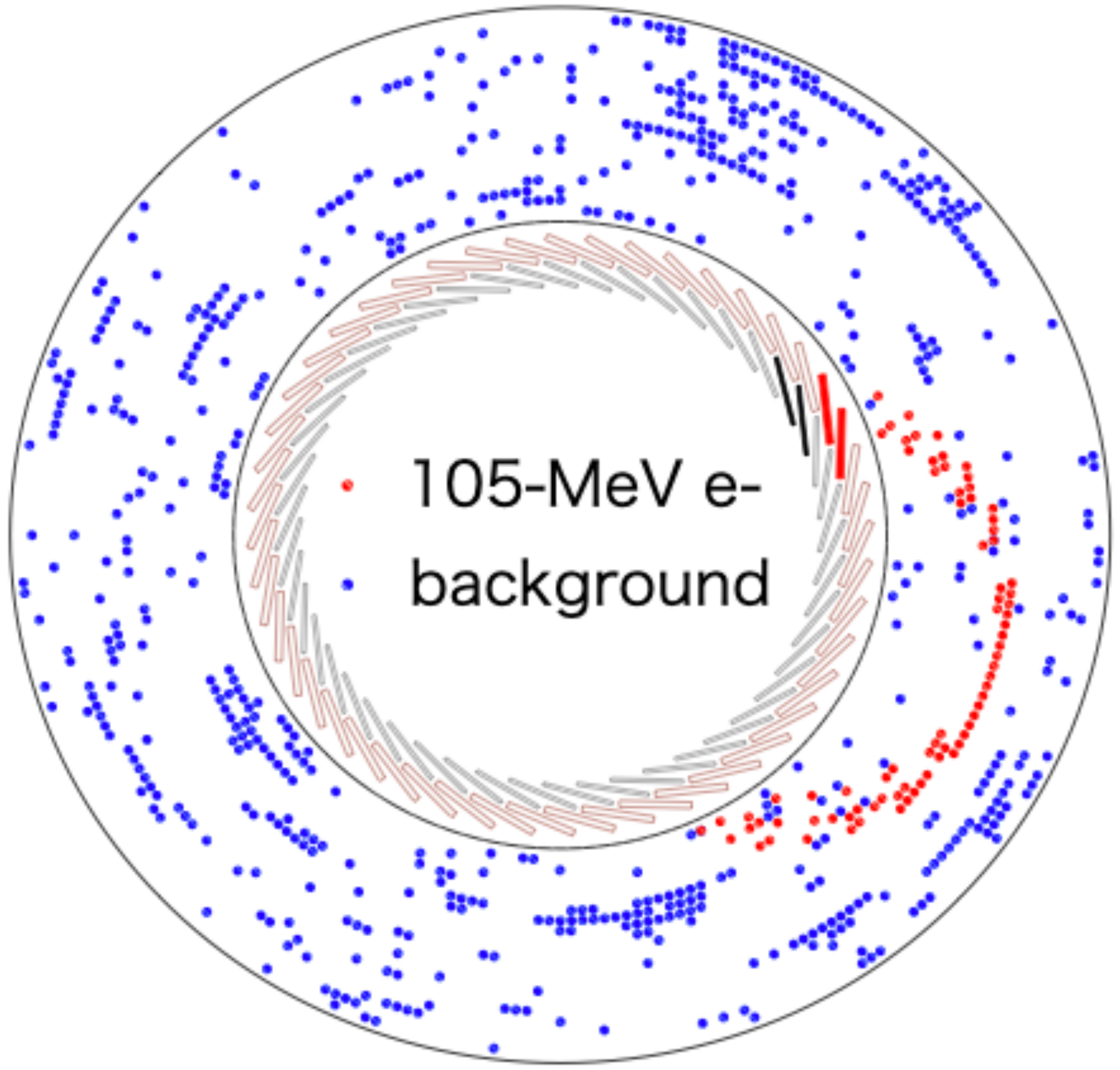


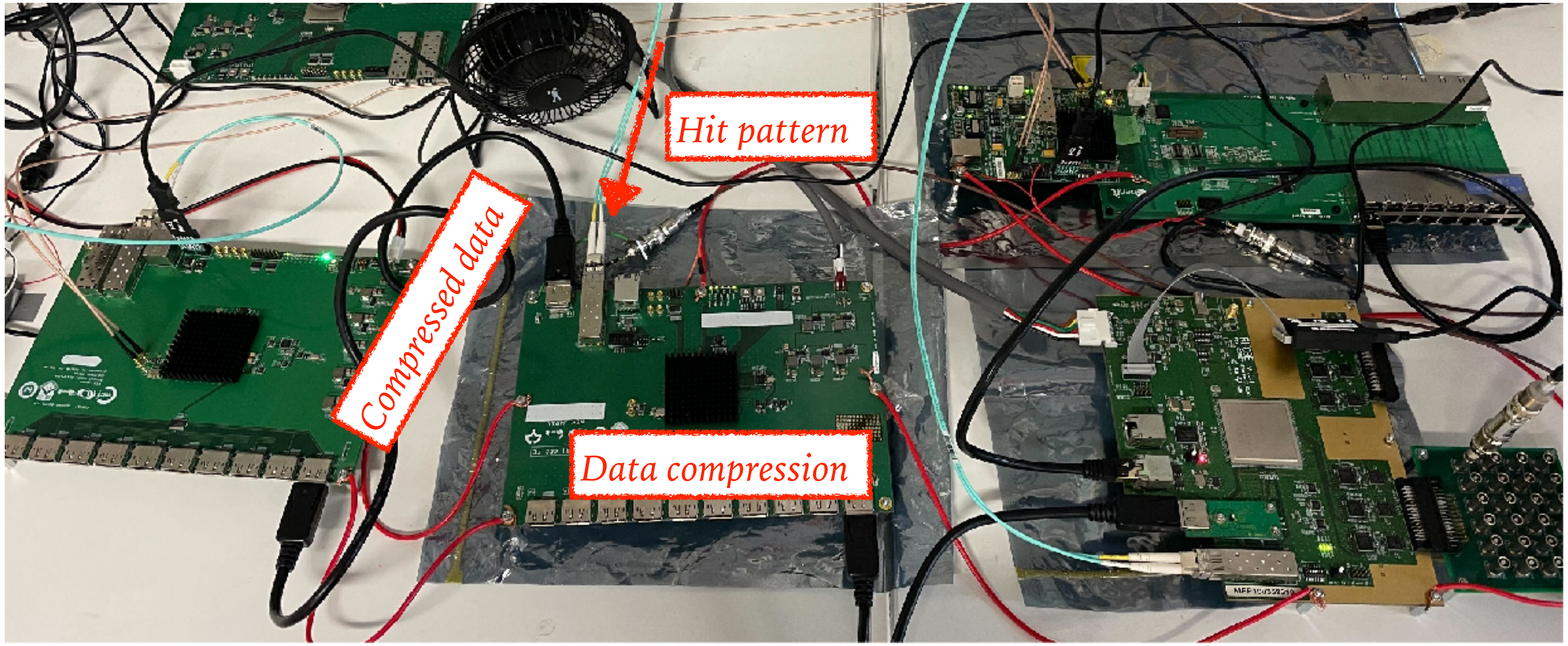


COMET Phase-I - Monash Activities -

- Even though a four fold coincidence in CTH significantly suppress the trigger rate, an expected rate is still as high as 100 kHz → 10 times more suppression is required from DAQ side
  - Mostly from 10-50 MeV/c electrons/positrons induced by gamma-rays → no trajectories in CDC
  - Some intelligent trigger can solve this issue collaborating with students @ Osaka group

Before BDT





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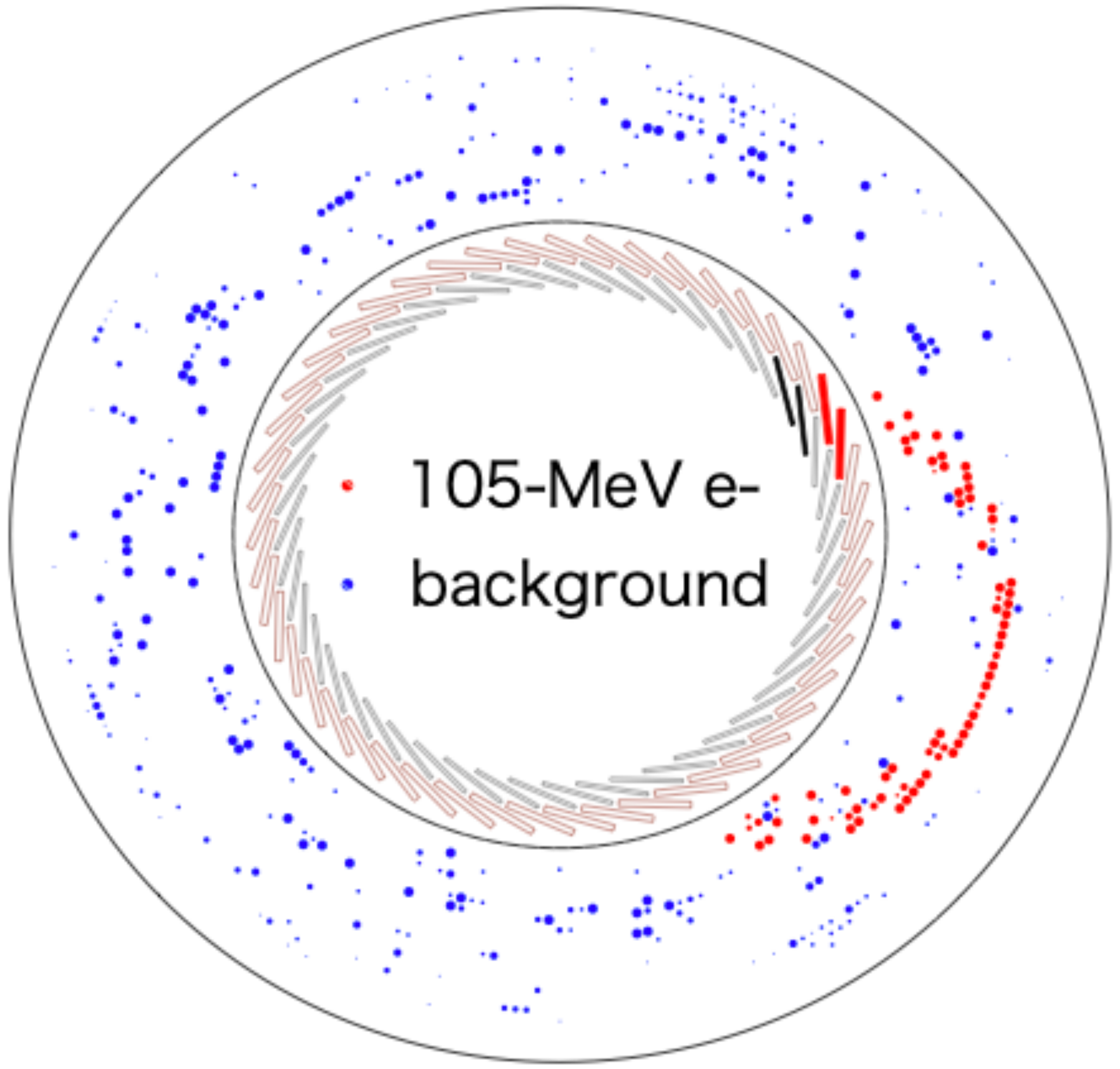
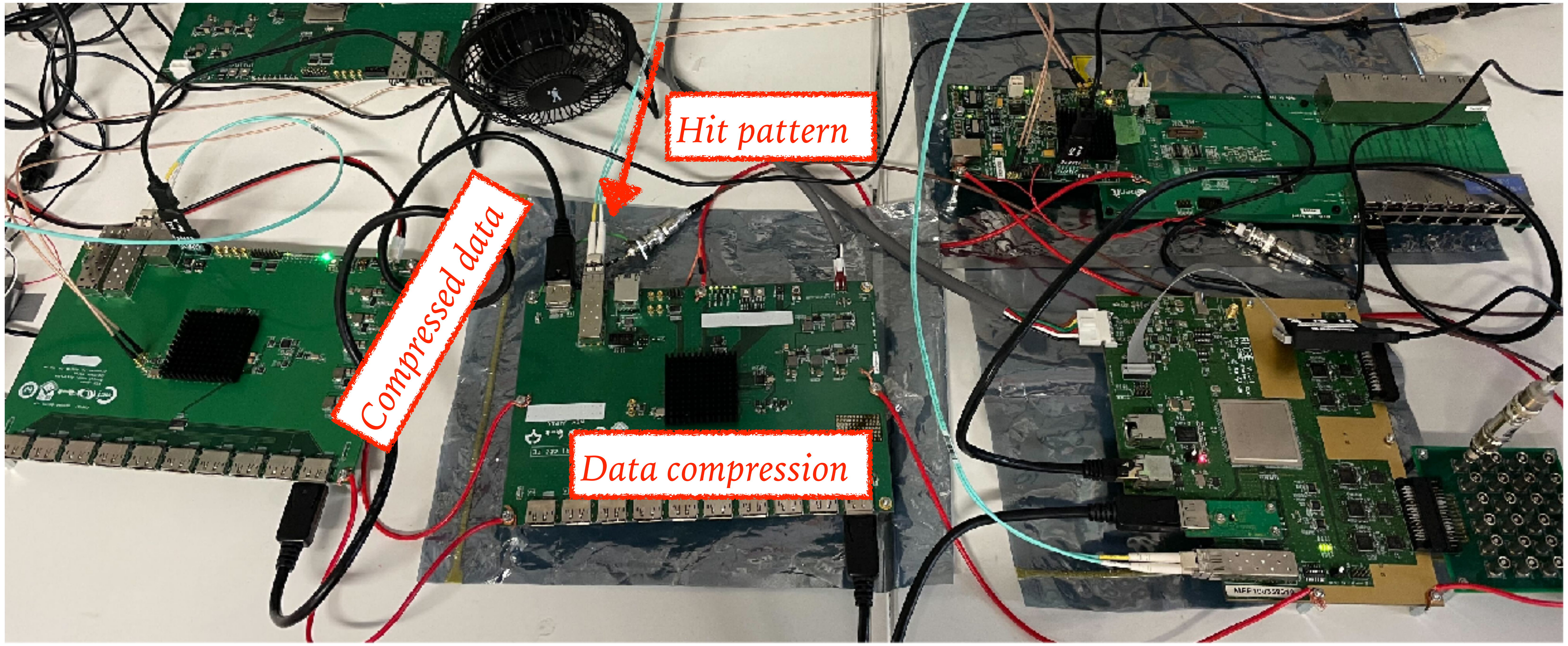
After BDT





COMET Phase-I - Expected Sensitivity -

$$\mathcal{B}(\mu^- N \to e^- N)|_{Al} = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu-e}} = 3.0 \times 10^{-15}$$

N_μ : #of stopped μ^-, 1.5×10^{16}, exp. @ 150 days,

f_{cap} : fraction of stopped μ^- captured, 0.61, theory,

f_{gnd} : fraction of μ^- bound to ground state, 0.9 theory,

A_μ : acceptance of μ-e signal, 0.041, exp..

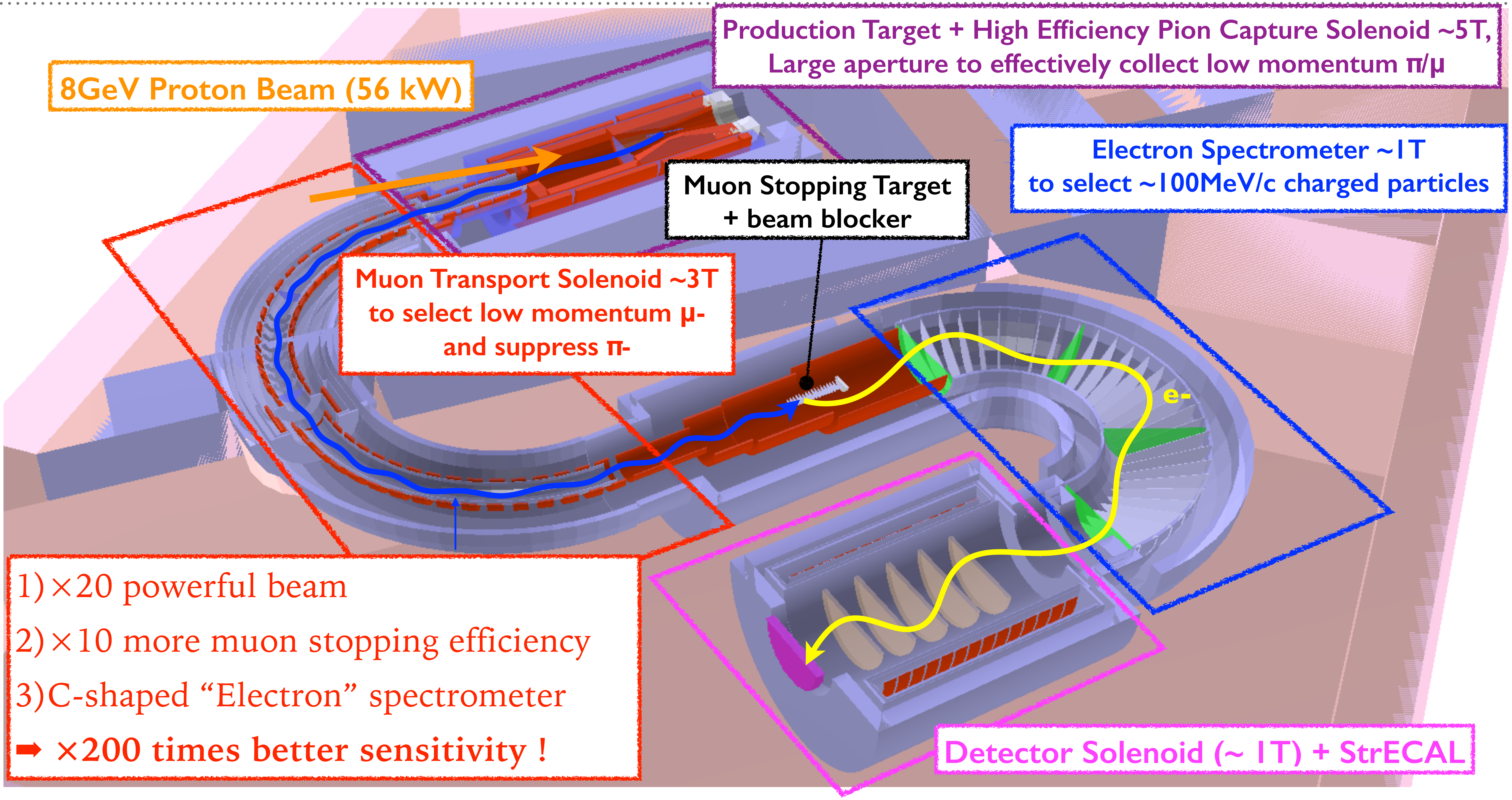
Item	Value	Comment
Acceptance	0.2	Fixed
Trigger/DAQ efficiency	0.8	Subject to change
Track finding efficiency	0.99	SC
Track selection	0.9	SC
Momentum window	0.93	103.6 MeV/c < p < 106.0 MeV/c
Timing window	0.3	700 < t < 1170 ns, SC
Total	0.04	At least 25% error

COMET Phase-I - Background -

Type	Background	Estimated events
Physics	Muons decay in orbit	0.01
	Radiative muon campture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt beam	Beam electrons, μ/π decay-in-flight, others	Total < 0.0038
	Radiative pion capture	0.0028
Delayed beam	↑ from delayed proton beam	Negligible
	Antiproton induced background	0.0012
Others	Cosmic rays (computationally limited)	< 0.01
Total		**< 0.032**

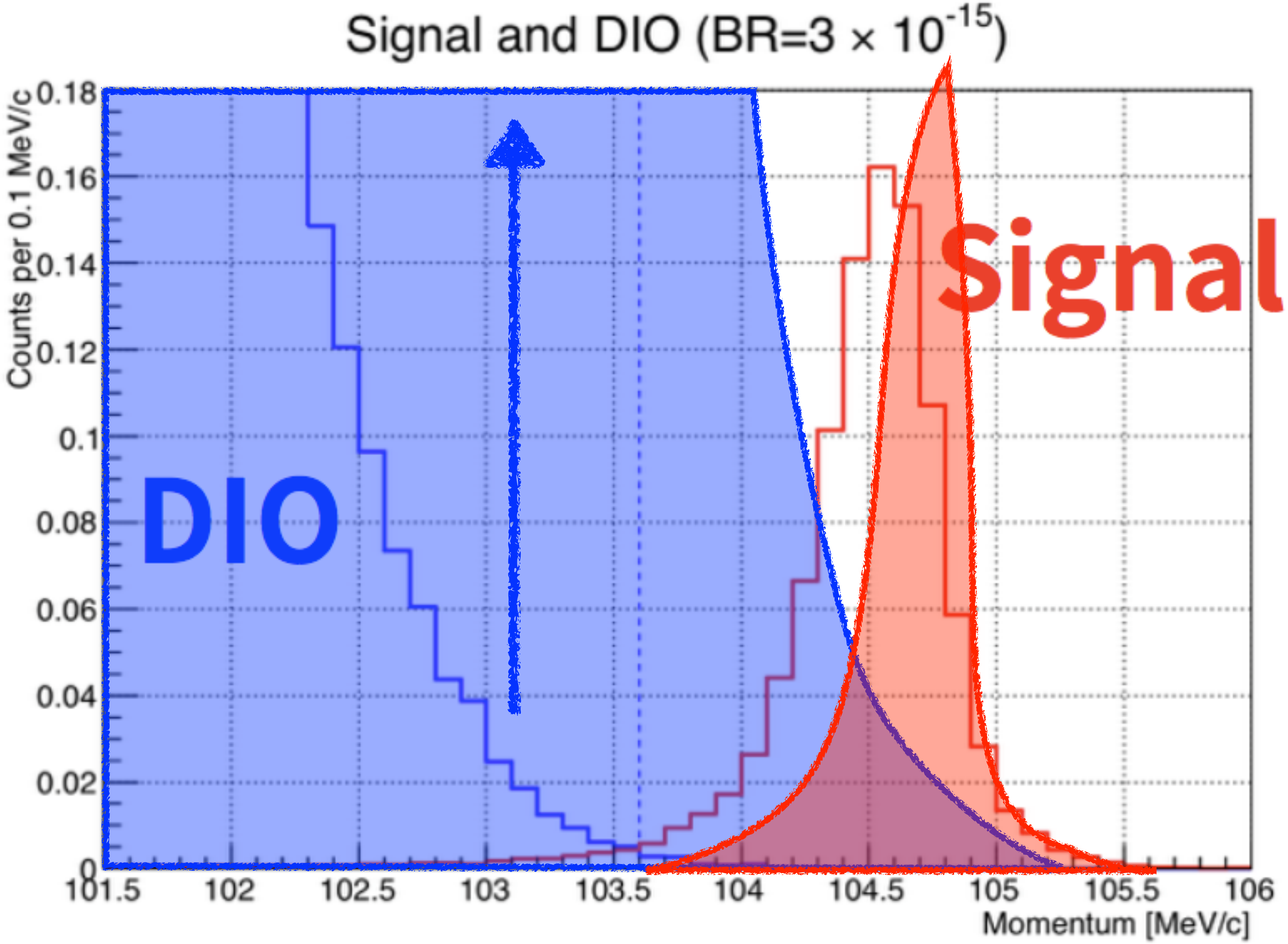
➡ ***COMET Phase-I is almost BG free**, sensitivity is only limited by the cost of radiation shielding and detector's rate capabilities!*

COMET Phase-II



1) ×20 powerful beam
2) ×10 more muon stopping efficiency
3) C-shaped "Electron" spectrometer
➡ **×200 times better sensitivity !**

COMET Phase-II – Concept –



×100 Sensitivity means ×100 BG

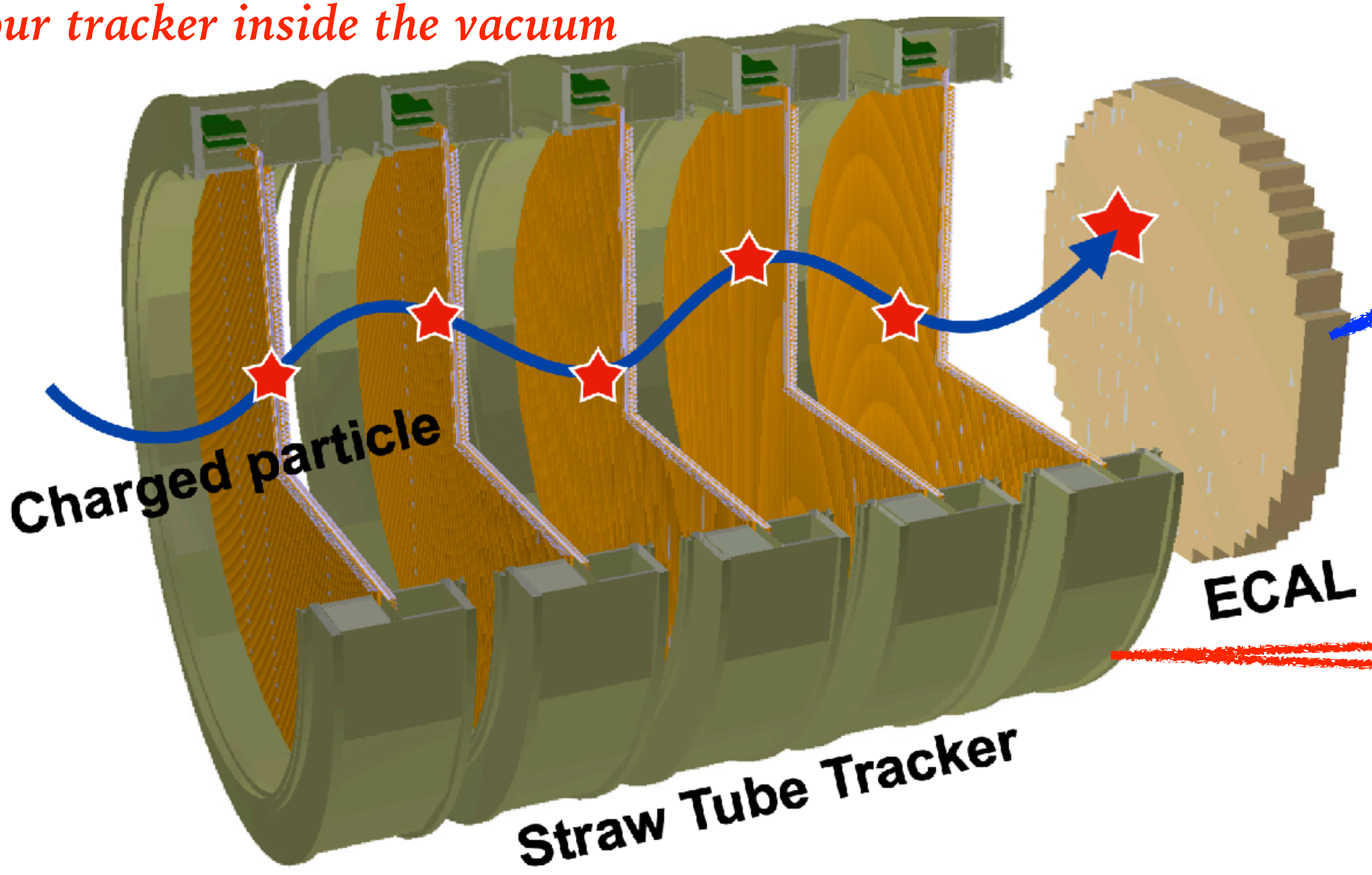
➡ *DIO BG will become dominant if we do nothing in Phase-II*

➡ *Make a signal peak sharper = better momentum resolution and less materials*

COMET Phase-II - Detectors -

A simple solution:

Put our tracker inside the vacuum



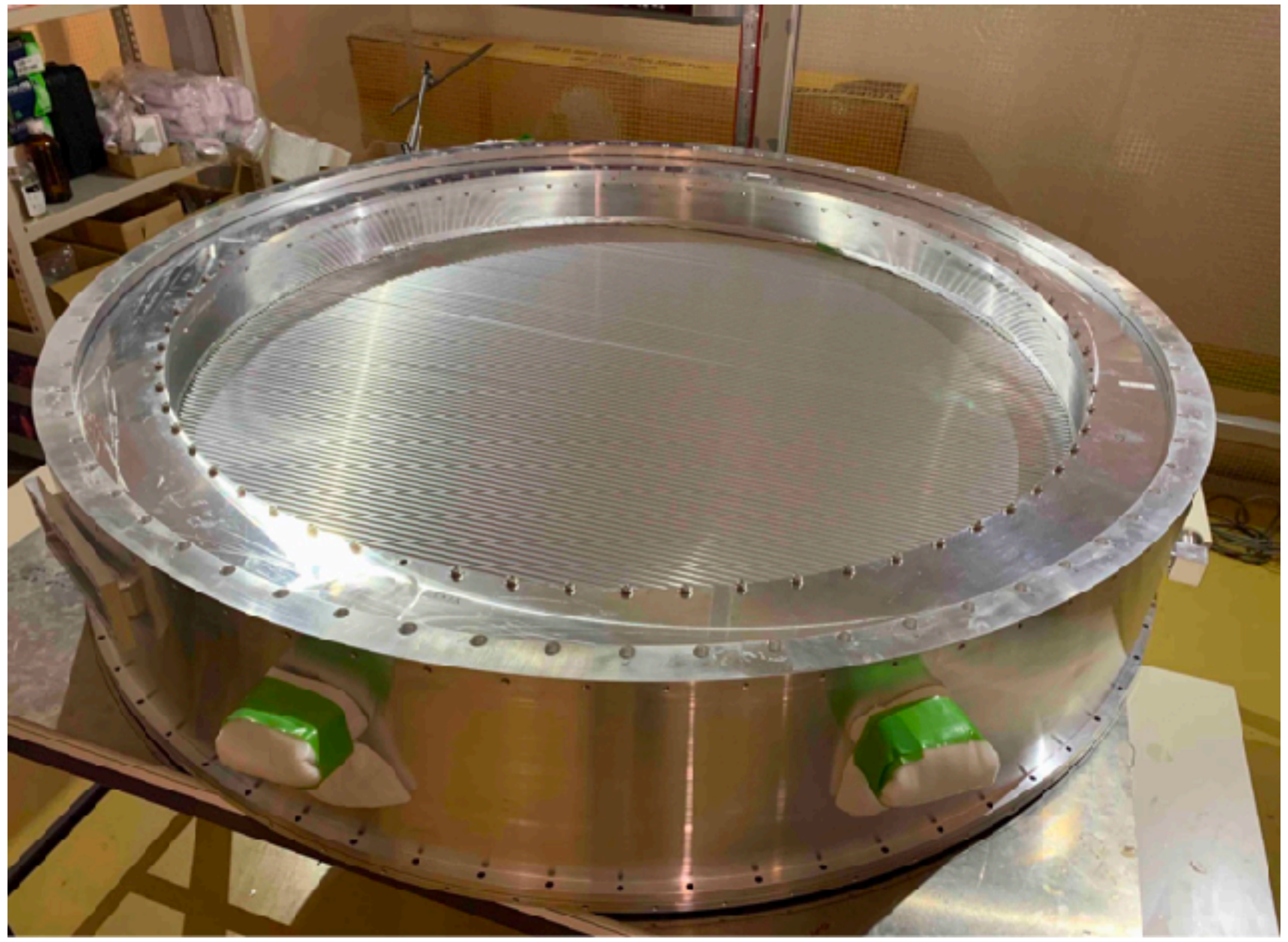
LYSO crystals
- Full absorption length
- Fast time response for pileup tolerance

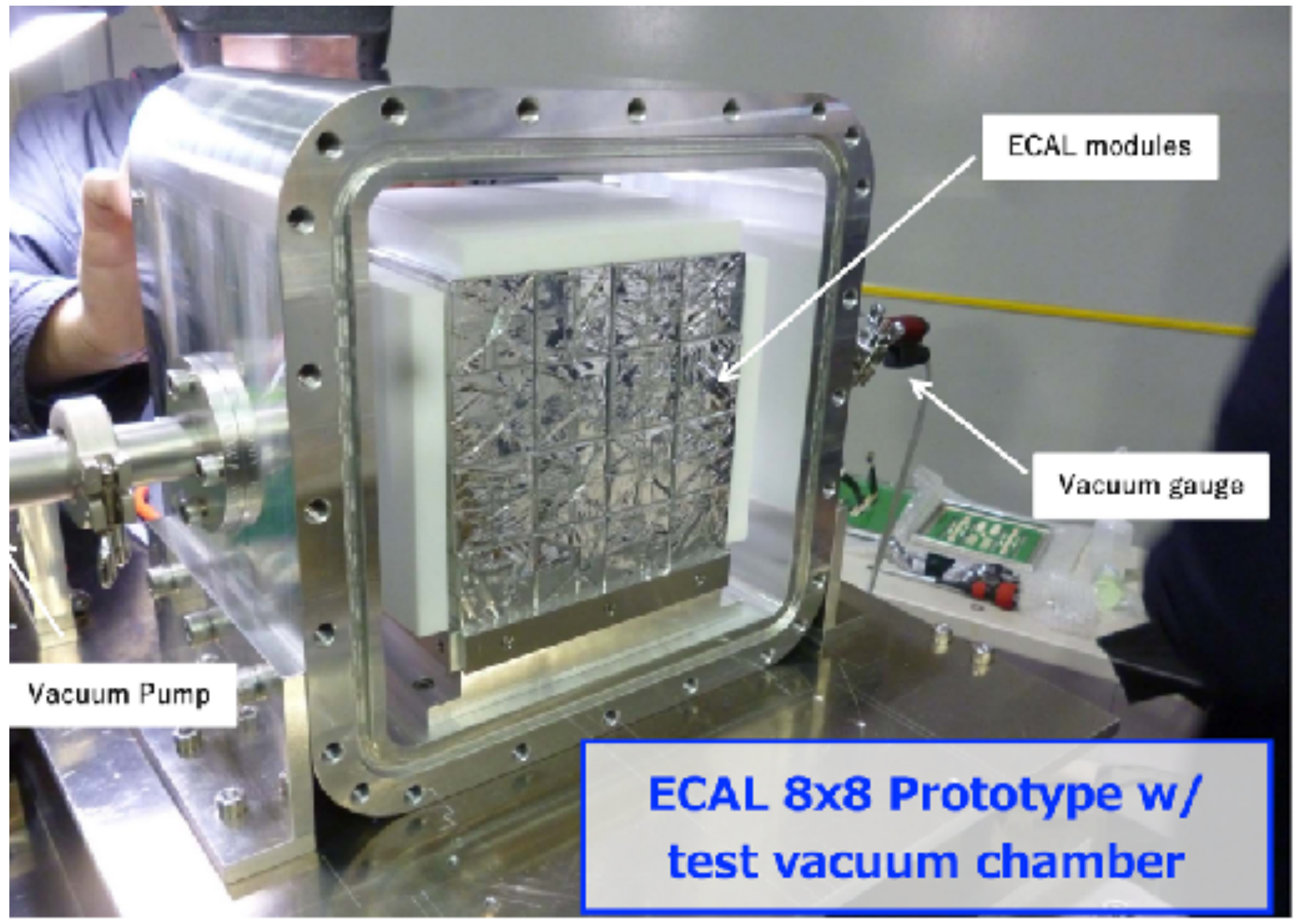
APD readout (space & radiation tolerance)

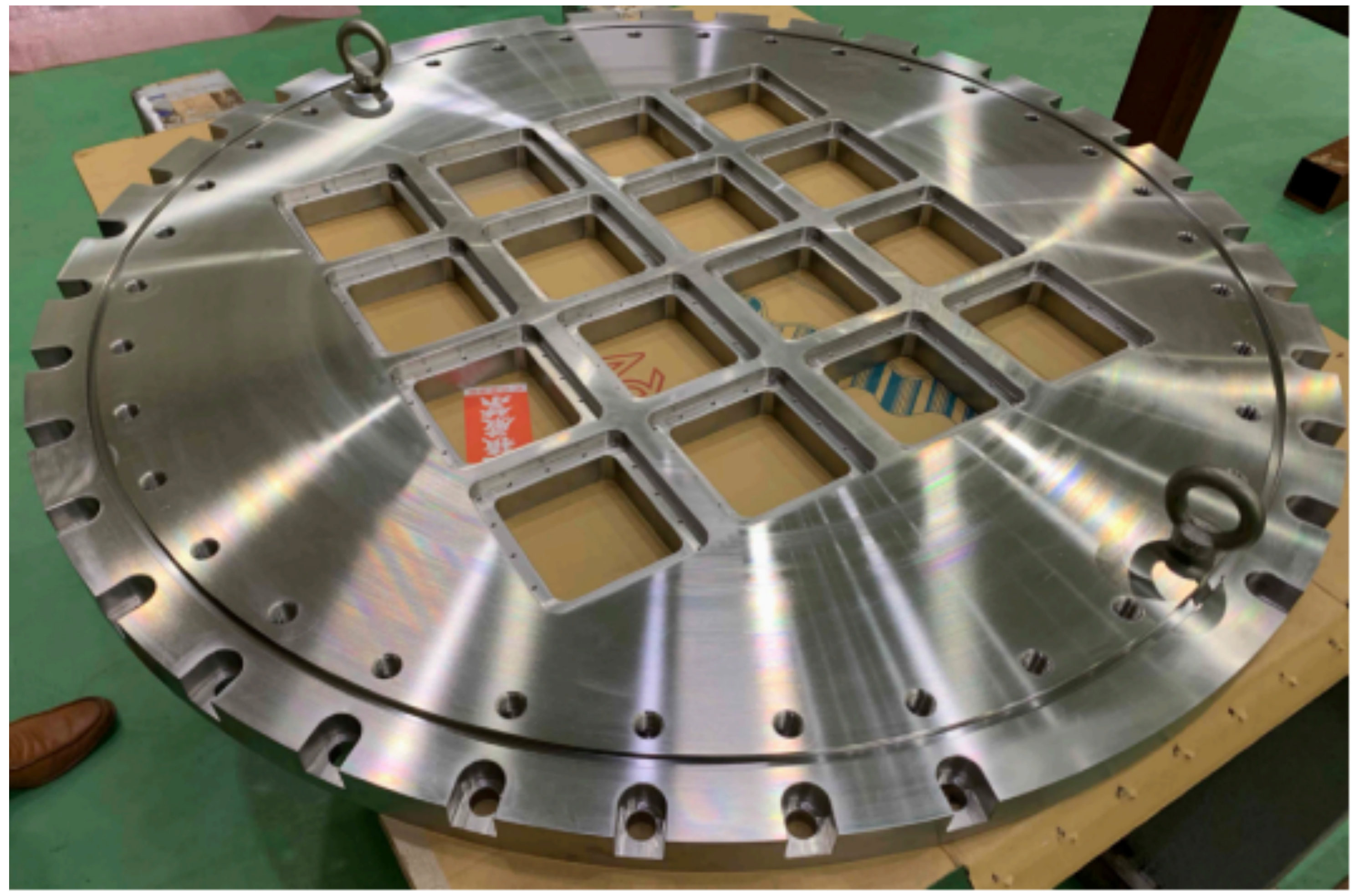
5 or more Straw stations
- A station consists of 2 horizontal and 2 vertical layers
- A straw is designed to be vacuum tight

COMET Phase-II - Detectors -

- Straw + ECAL prototype will be used in the Phase-I beam measurement
- A 20 μm thick, 10mmφ straw tube for the Phase-I beam measurement ($Ar:C_2H_6$ or $Ar:CO_2$), expected σ_p ~180 keV/c
  - 12.5 μmT, 5mmφ for Phase-II straw being developed, expected σ_p ~150 keV/c
- LYSO 64 × 16 modules to be installed in the Phase-I
  - In Phase-II it'll be scaled up to 5,000 for ~1.5 mφ coverage







COMET Phase-II - Sensitivity -

$$\mathscr{B}(\mu^- N \to e^- N)|_{Al} = \frac{1}{N_\mu \cdot f_{cap} \cdot f_{gnd} \cdot A_{\mu-e}} = 1.4 \times 10^{-17}$$

N_μ : #of stopped μ^-, **3.3×10^{18}**, exp. @ 230 days,

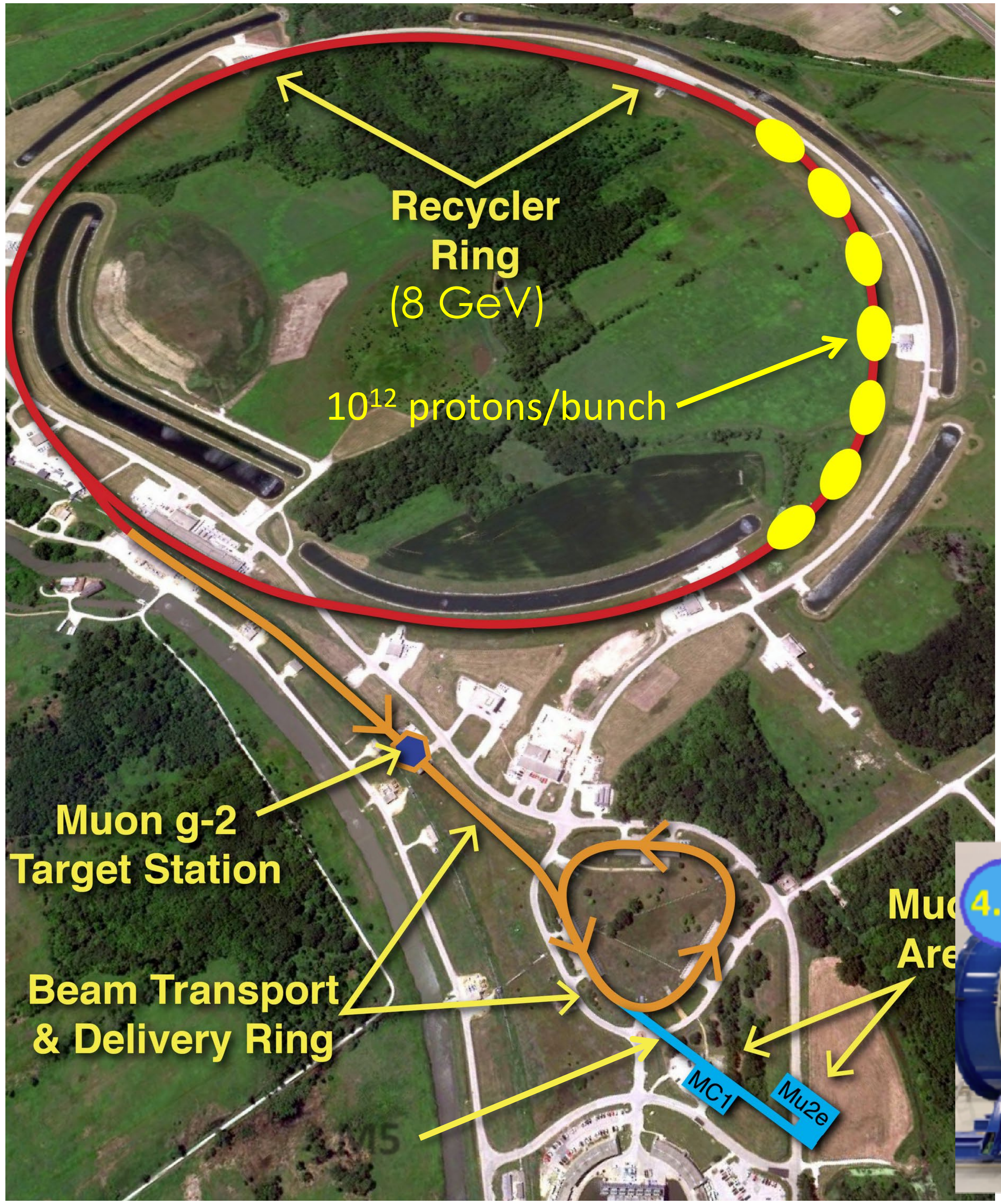
f_{cap} : fraction of stopped μ^- captured, 0.61, theory,

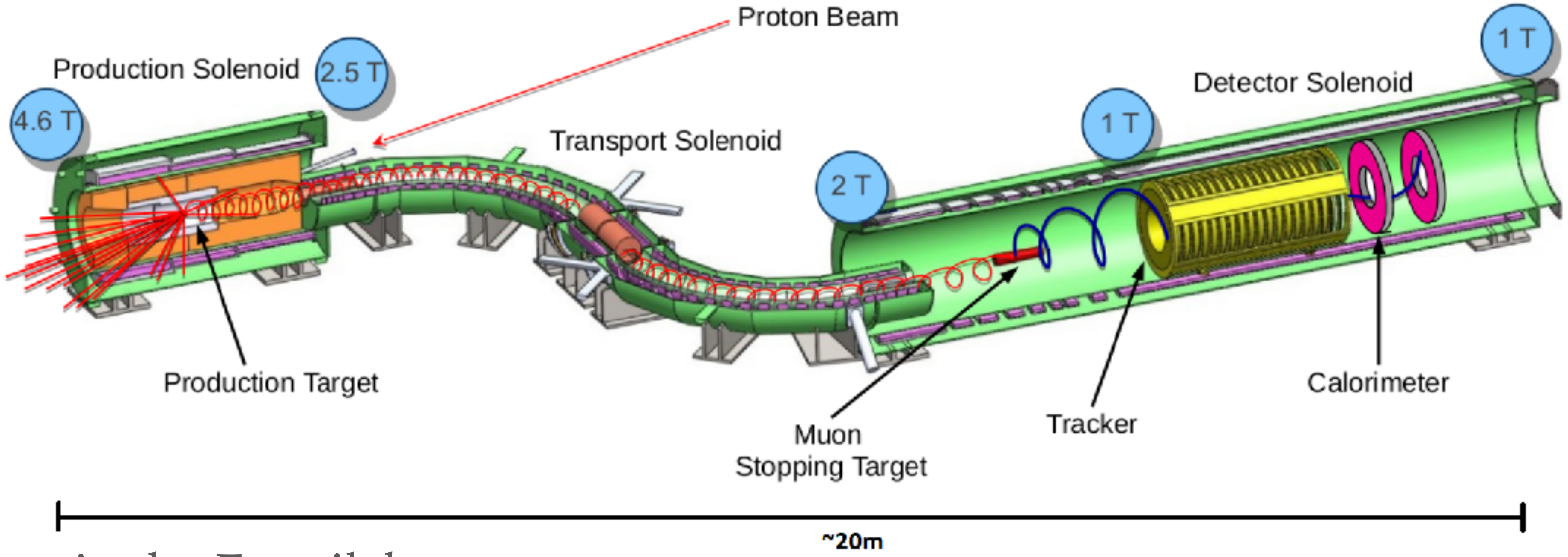
f_{gnd} : fraction of μ^- bound to ground state, 0.9 theory,

A_μ : acceptance of μ-e signal, **0.036**, exp..

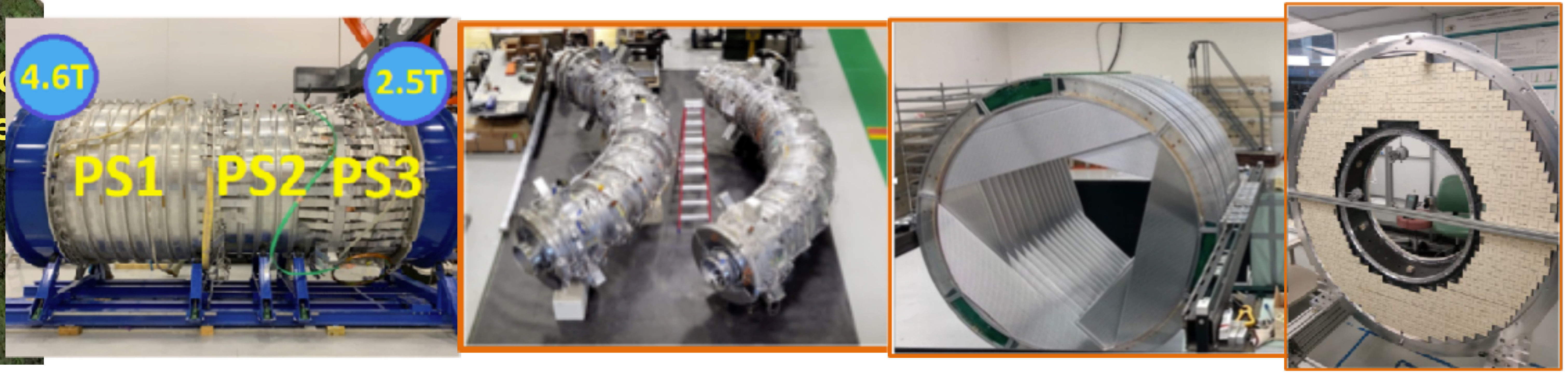
Item	Value in P-I	Value in P-II	Comment
Acceptance	0.2	**0.18**	Fixed
Trigger/DAQ efficiency	0.8	**0.87**	Subject to change
Track reconstruction efficiency	0.99	**0.77**	SC
Track selection	0.9	**0.94**	SC
Momentum window	0.93	**0.62**	104.2 MeV/c < p < 105.5 MeV/c
Timing window	0.3	**0.49**	600 < t < 1170 ns, SC
Total	0.04	**0.034**	At least 25% error

Mu2e

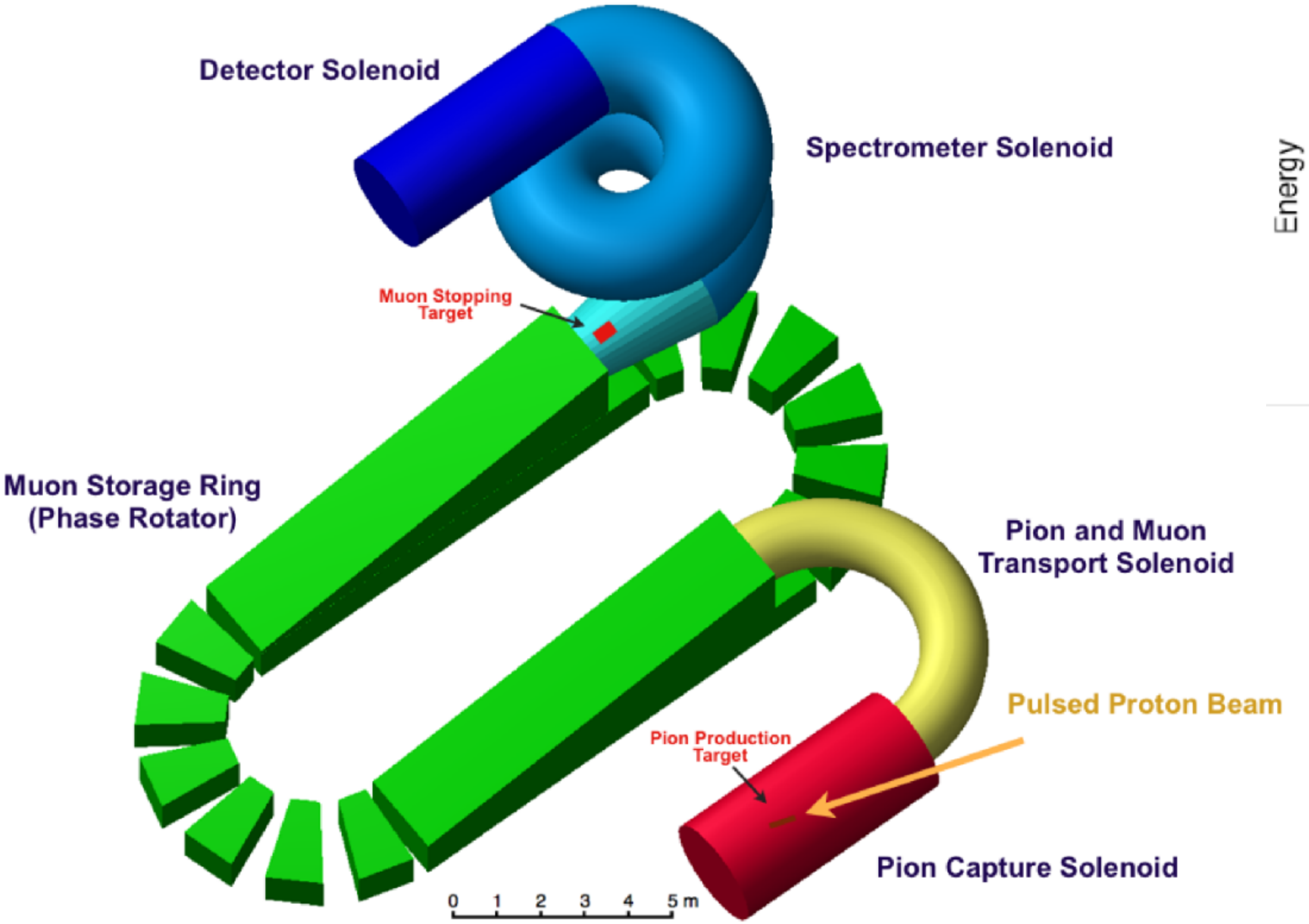


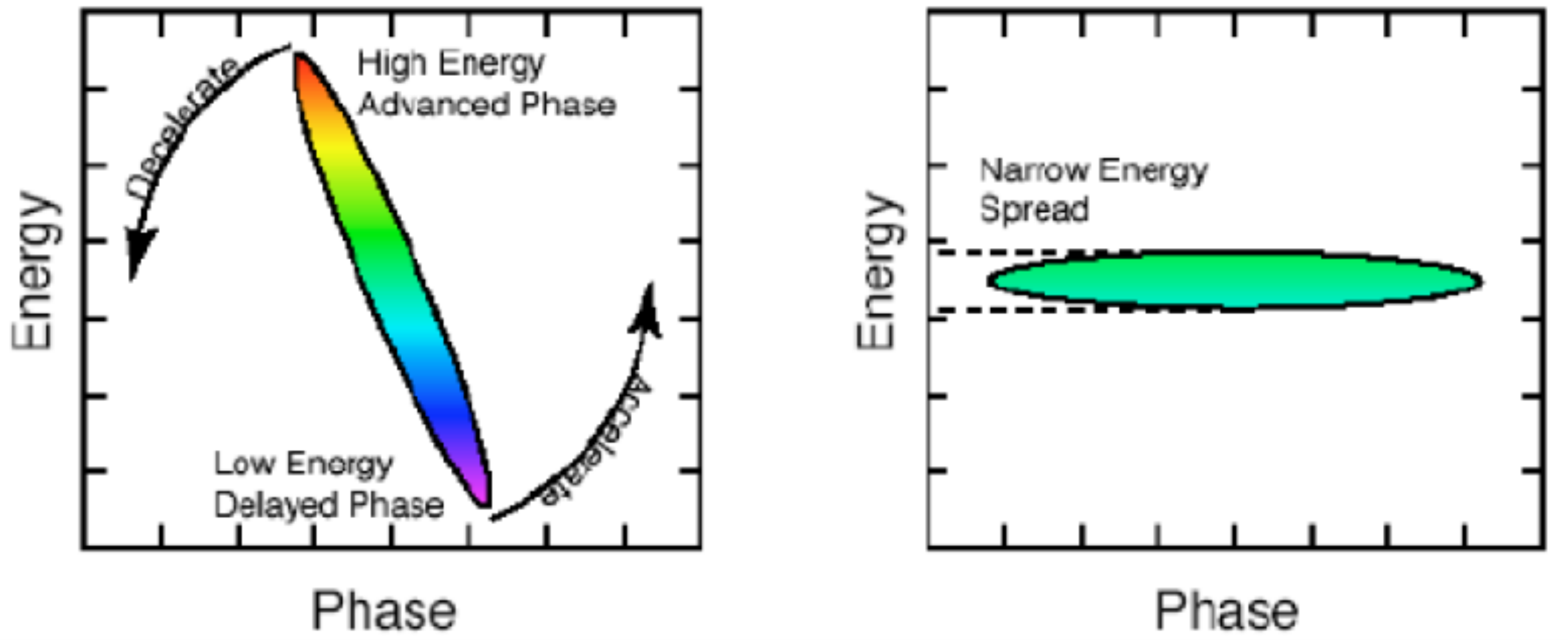


- At the Fermilab muon campus
- Aiming 10^{-17} level sensitivity without staging
- Construction is in progress and will take physics data in 2025/2026



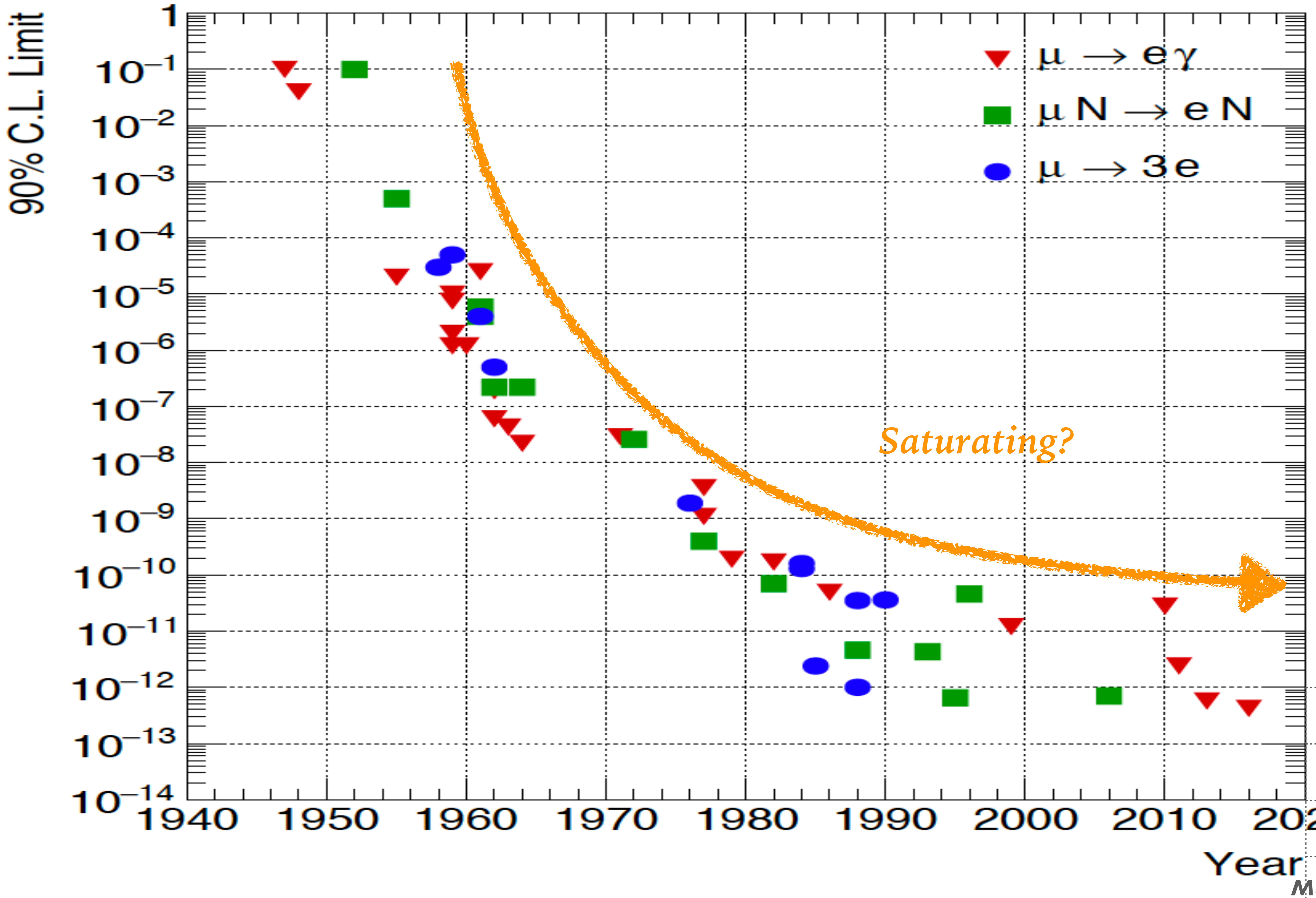
PRISM / PRIME



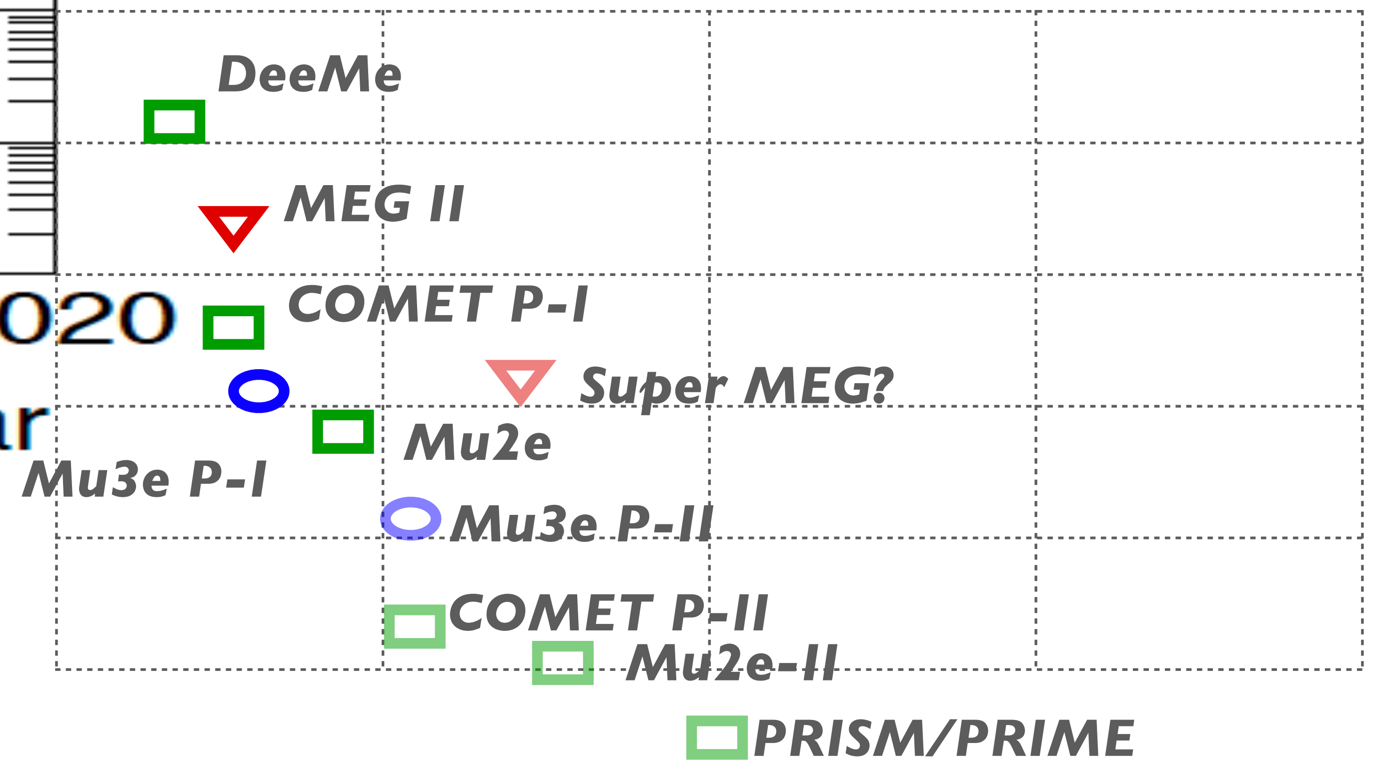


- Muon storage & phase rotation ring using a Fixed Field Alternating Gradient (FFAG) ring
- Significantly reduce the beam induced background
- Pure low momentum muons enable to explore high-Z target materials, **10^{-18}** or even higher sensitivity

Future Prospects (from my optimistic view)



Of course NO!



Summary & Prospects

- CLFV searches are strong new physics probes and strongly related to other heavy flavour physics
- Many results from muon CLFV searches are expected to come
  - We are entering the "new-physics-exploring" region now
- And…

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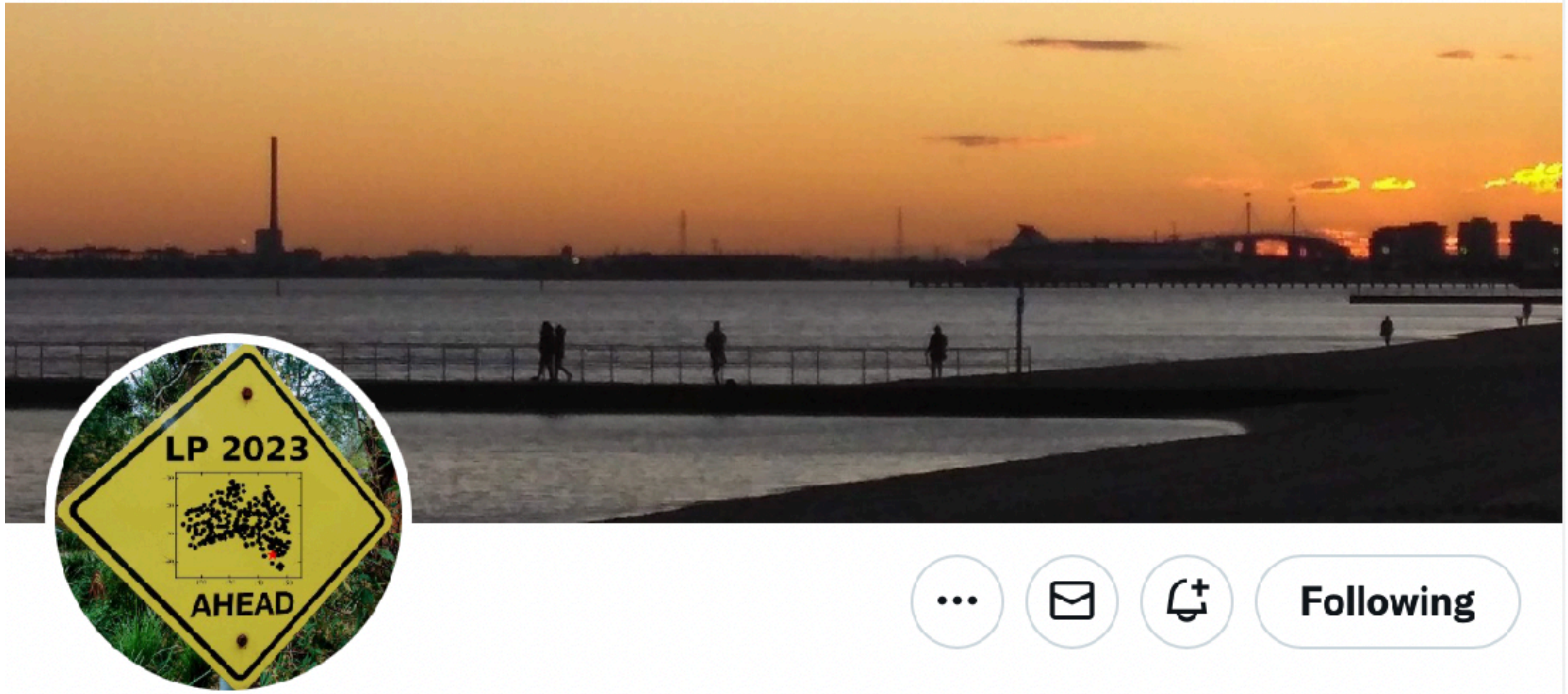

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