Charged Lepton Flavour Violation: Experimental Activities

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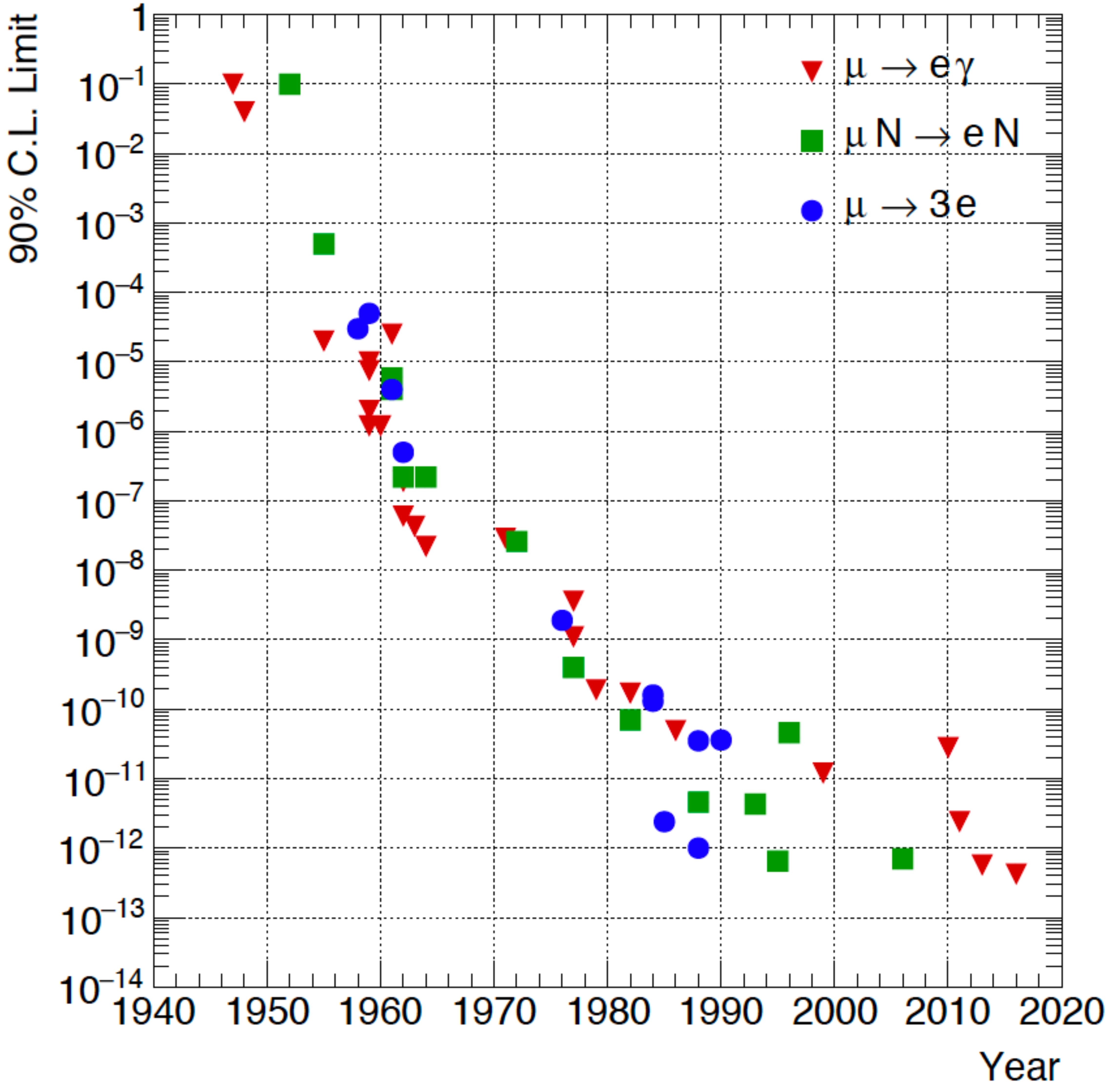
Muon4Future workshop

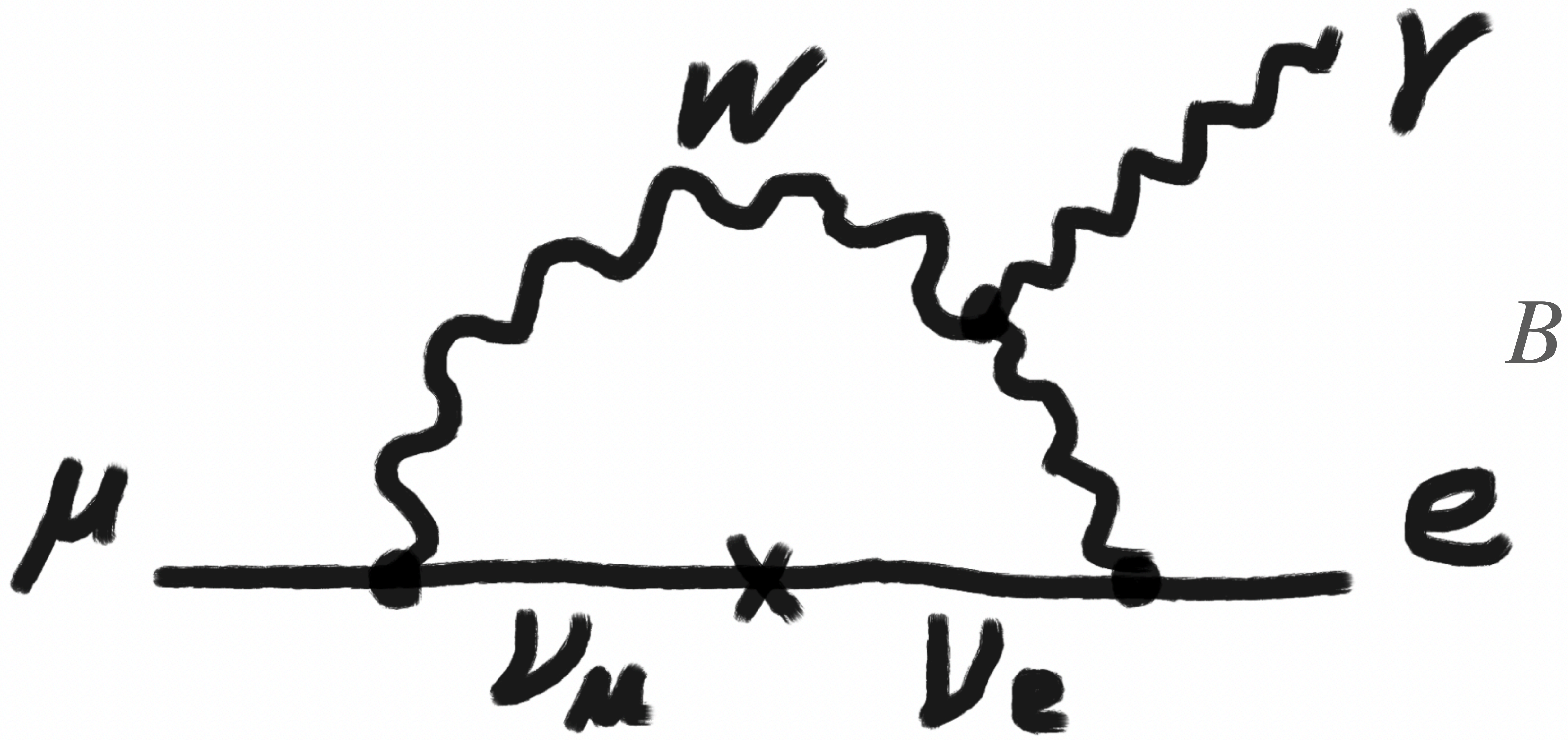
30th May 2023, Venice

Starting from past and present

- **Muon CLFV searches** have quite successful history despite the lack of discovery
  - Highly precise theoretical prediction; **YES** or **NO**
  - Remarkable progress in muon intensity
    - From cosmic-rays to Multi MW beams
  - So many improvements in detector technologies
    - High precision tracking, energy calorimetry, *etc*



Muon Charged Lepton Flavour Violation (CLFV)



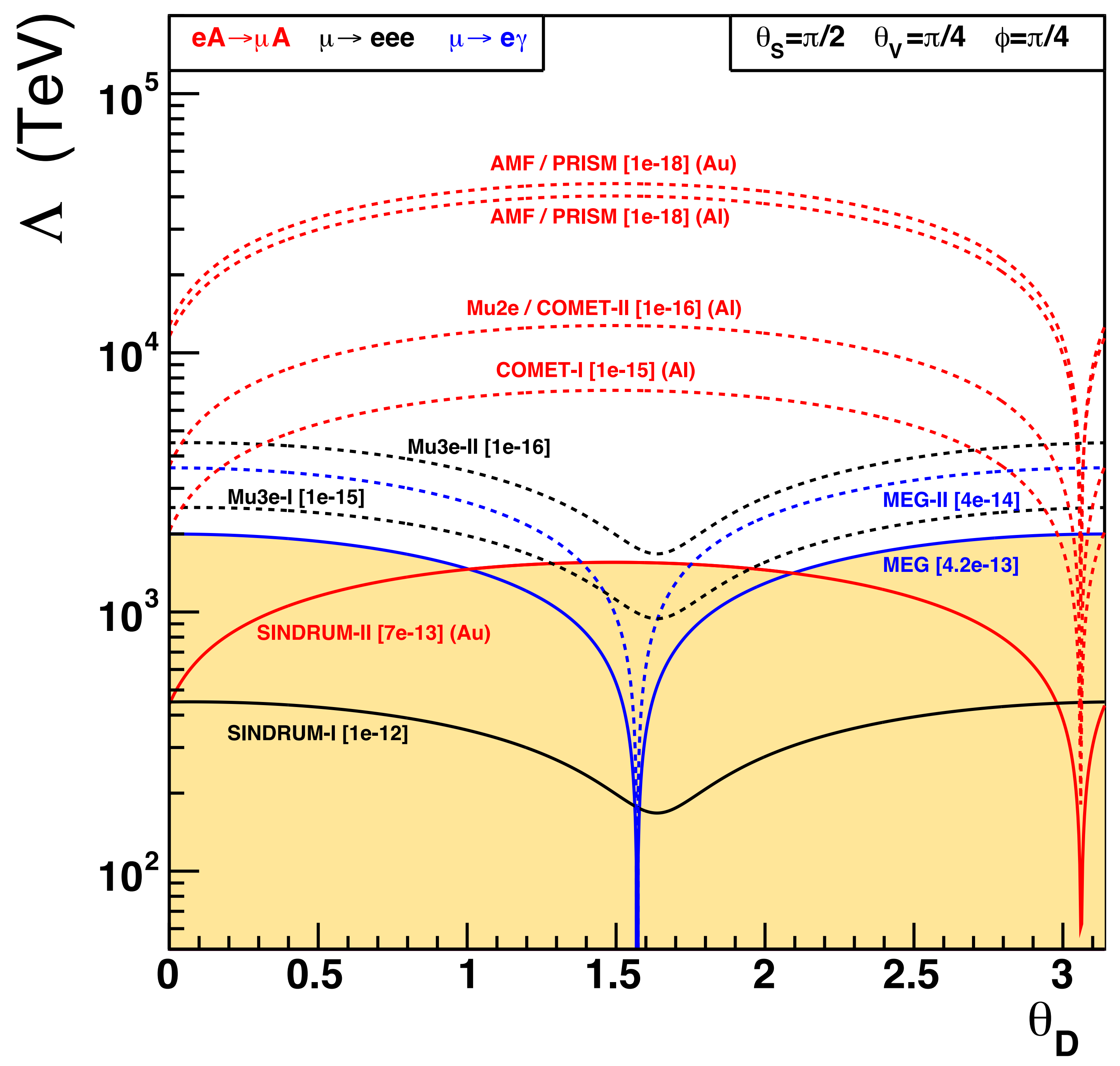
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^{\dagger}_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W} \right|^2 \approx 10^{-54}$$

$$\approx CR(\mu^- N \to e^- N)$$

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

CLFV in EFT

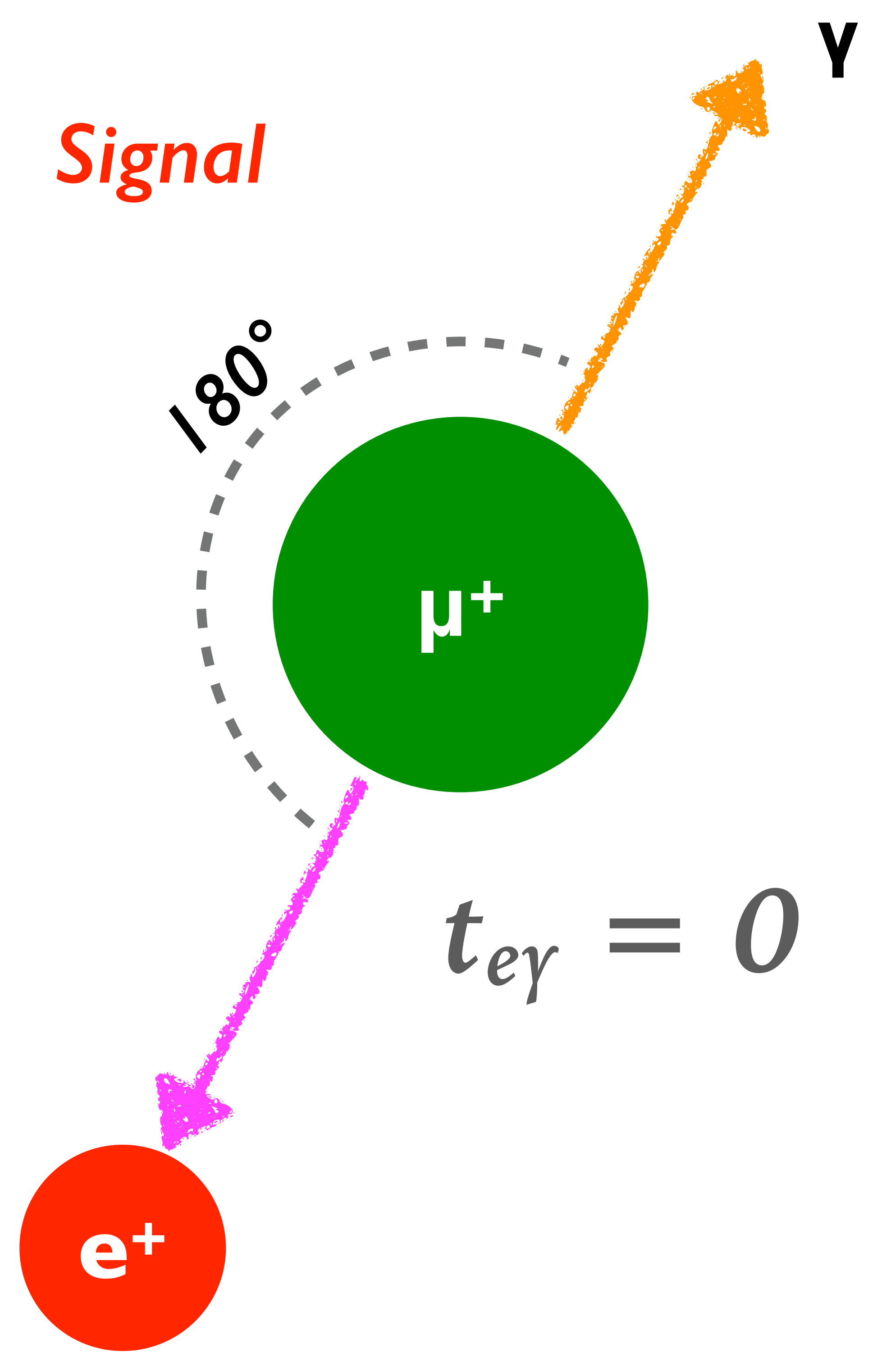
- Searches for CLFV processes indirectly probing Λ_{NP} > *1 PeV* new physics scale
  - ⇔ Ultra large Moon collider, ***14 PeV pp*** (arXiv:2106.02048)
- Complementary searches available with different muon CLFV modes (Muon CLFV golden modes; *μ→eγ*, *μ→eee*, *μN→eN*)



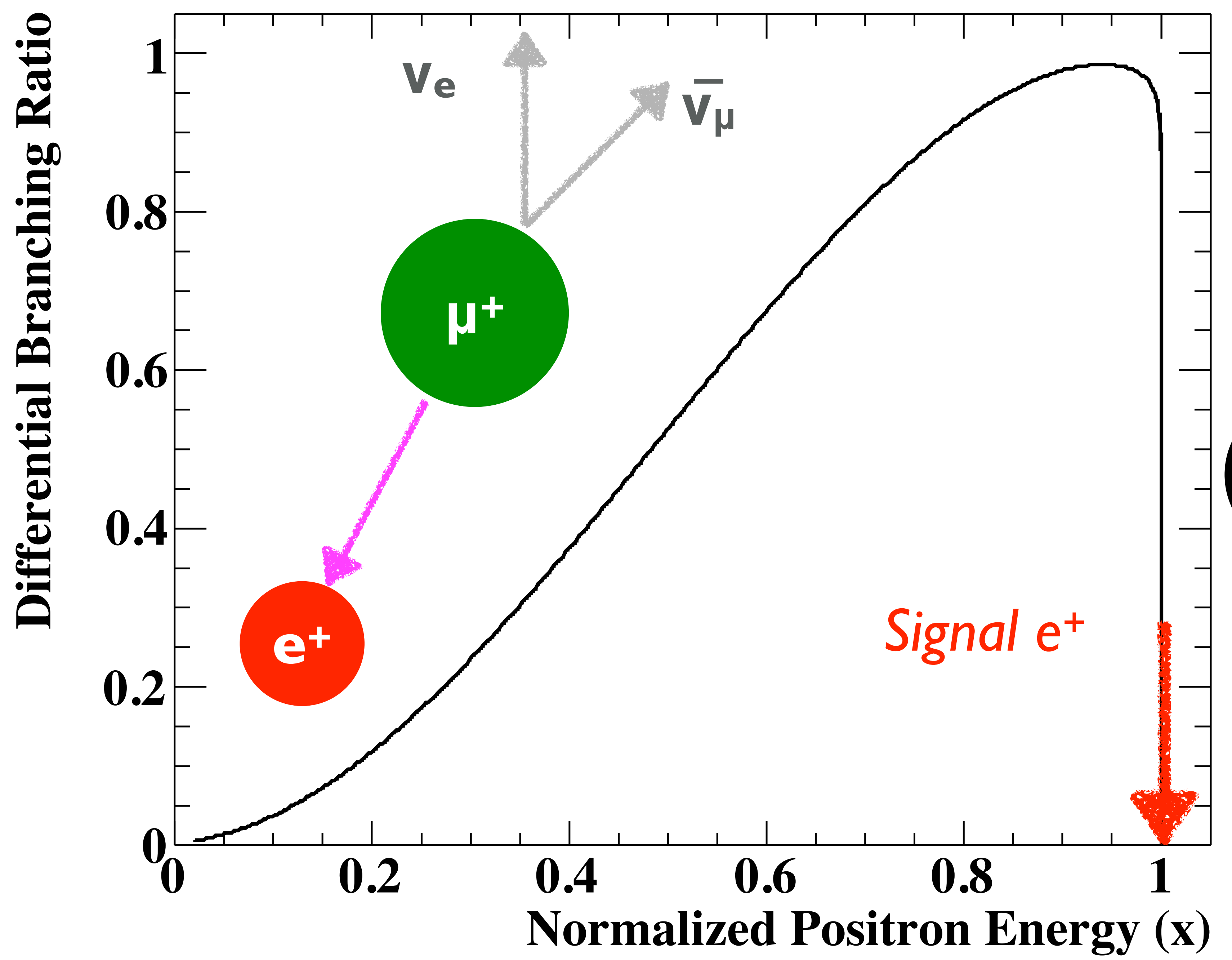
S. Davidson and B Echenard, arXiv:2204.00564

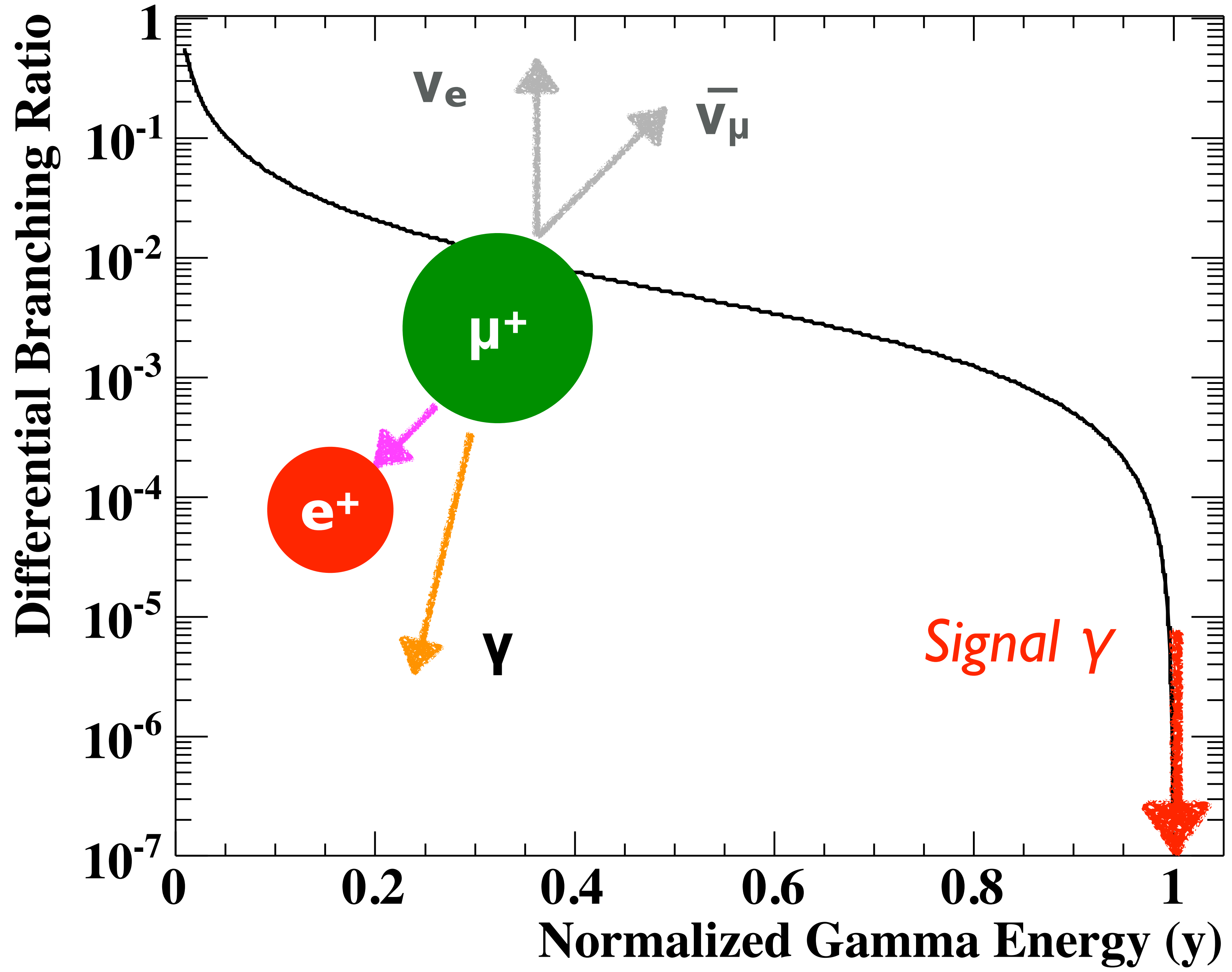
	Current upper limit (90%CL)	Given by	Target 90%CL UL sensitivity	Current Projects
μ→eγ	4.7×10^{-13}	MEG (2016)	6×10^{-14}	MEG II
μ→eee	1.0×10^{-12}	SINDRUM (1988)	$2\times10^{-15}/10^{-16}$	Mu3e/Mu3e p-II
μN→eN	7.0×10^{-13} @Au	SINDRUM II (2006)	$10^{-14}/10^{-17}$	DeeMe/COMET/Mu2e

$\mu^+ \to e^+\gamma$



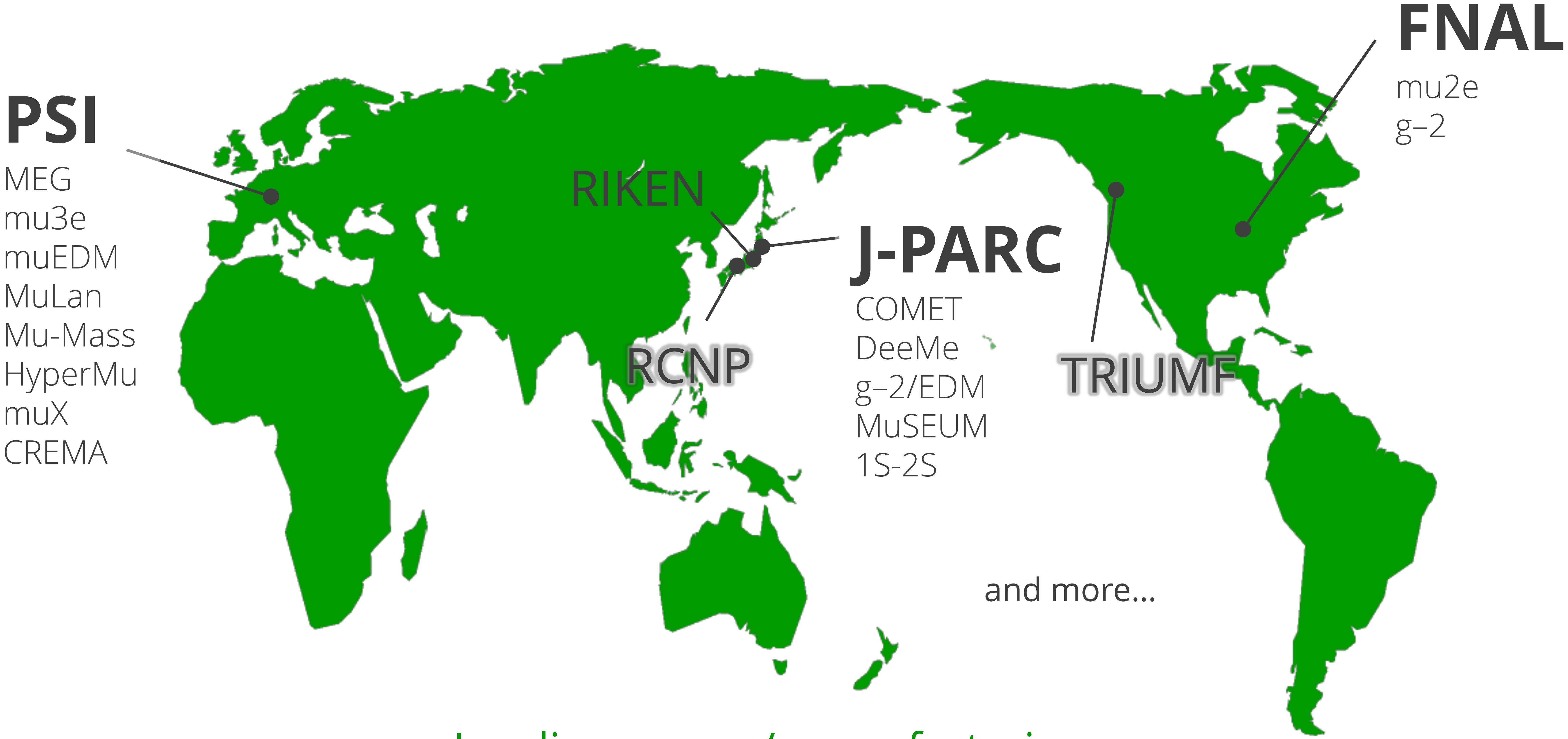
Accidental Background





- Simple kinematics
- Accidental background dominant → DC beam, **high precision measurements**

Muon Sources



Leading meson/muon factories

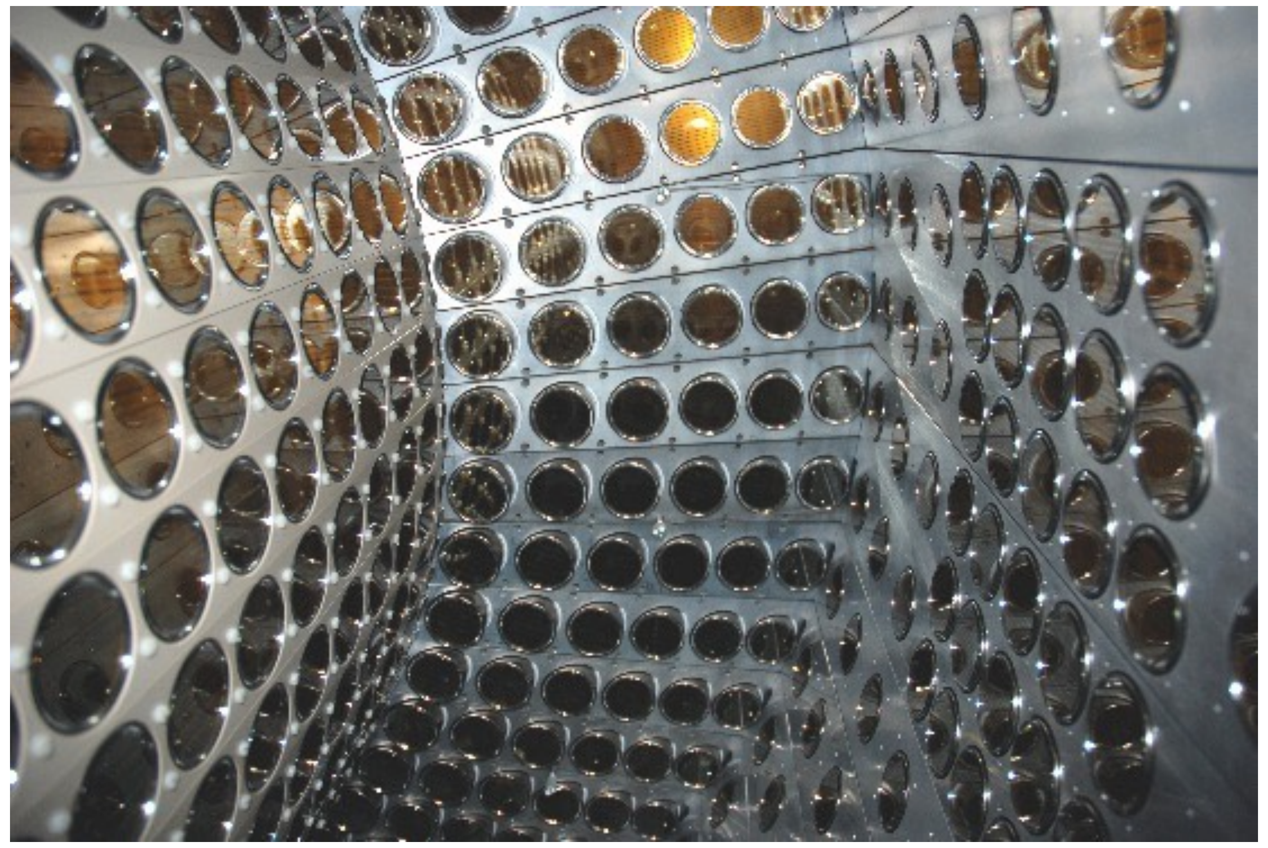
2023/2/2
YUSUKE UCHIYAMA

- High power proton accelerators produce high intensity muons
- Currently DC 10^8 μ/sec available @PSI → J-PARC/FNAL will soon deliver the pulsed muons

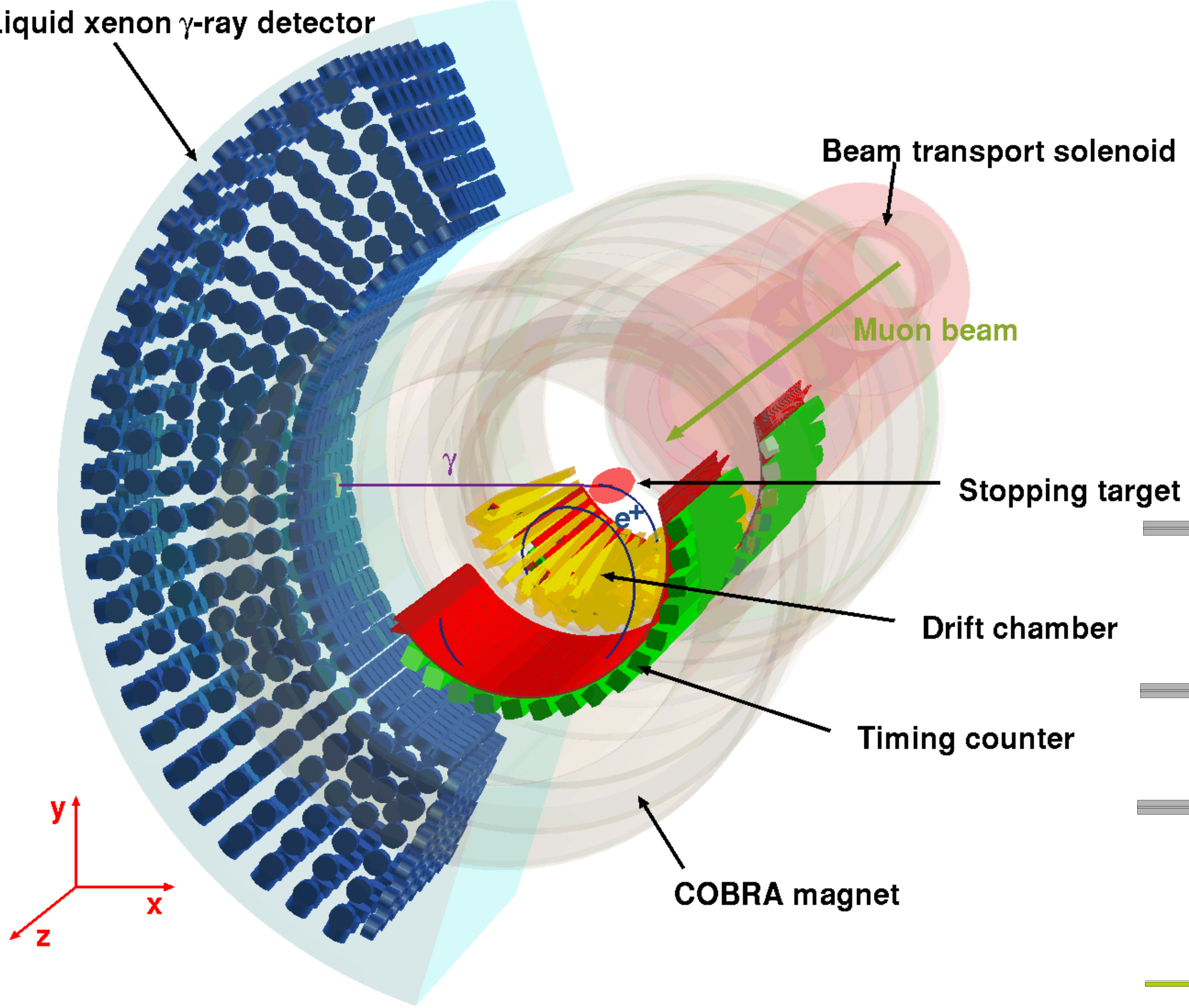
MEG Experiment

- Physics run completed in 2008—2013 using the world's best DC μ beam @PSI πE5
- Two orders better sensitivity than the previous limit ⇔ **Better resolutions**, more muons, larger photon acceptance

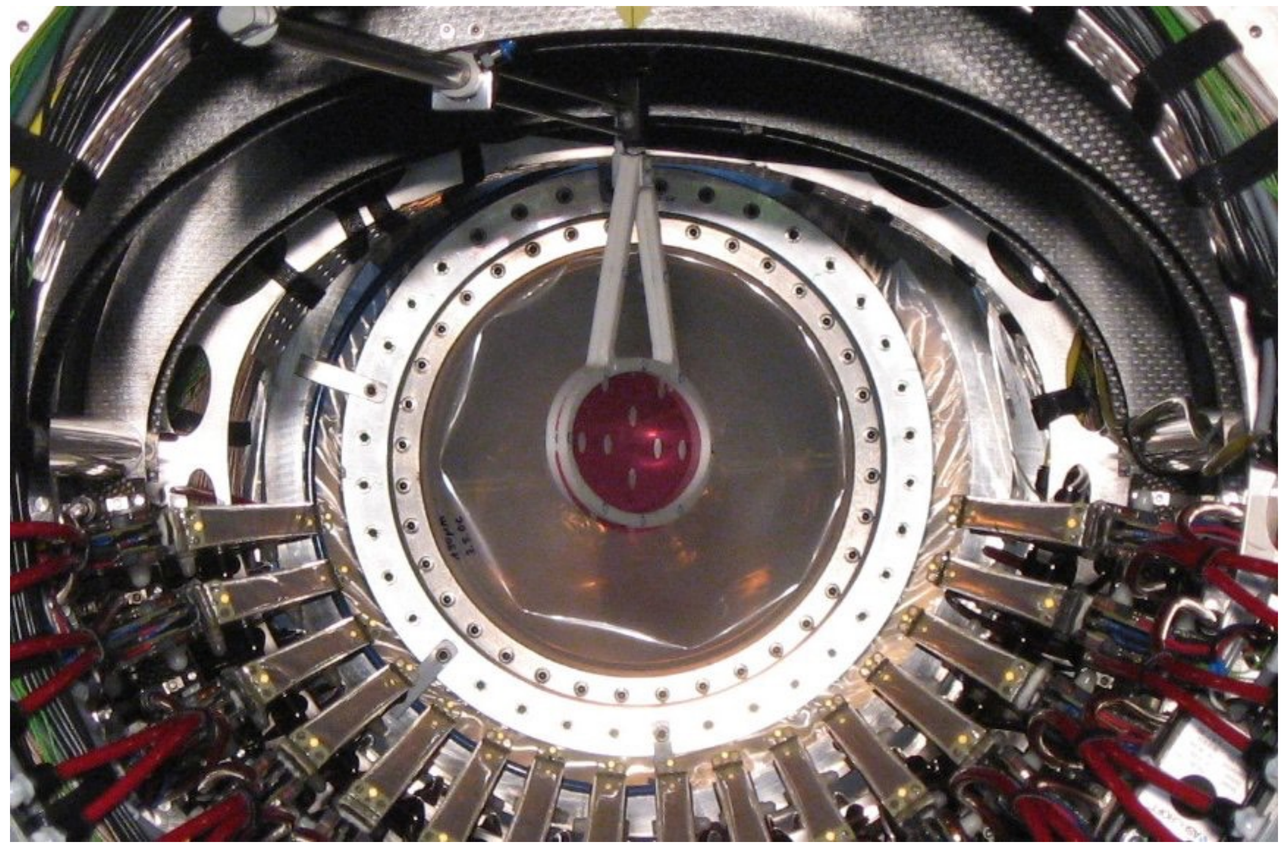
Large liquid xenon gamma calorimeter

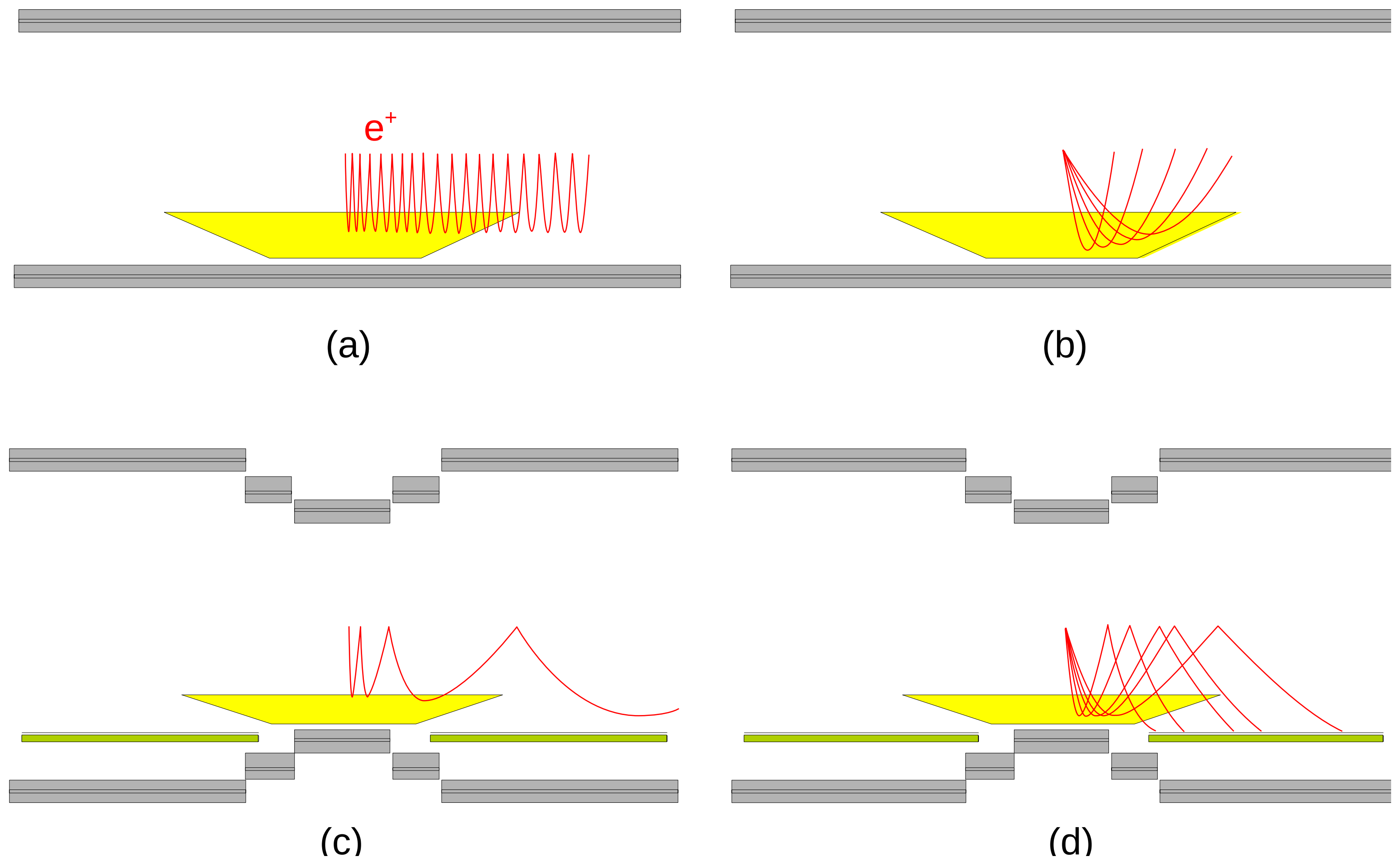


Scintillation timing counter bars



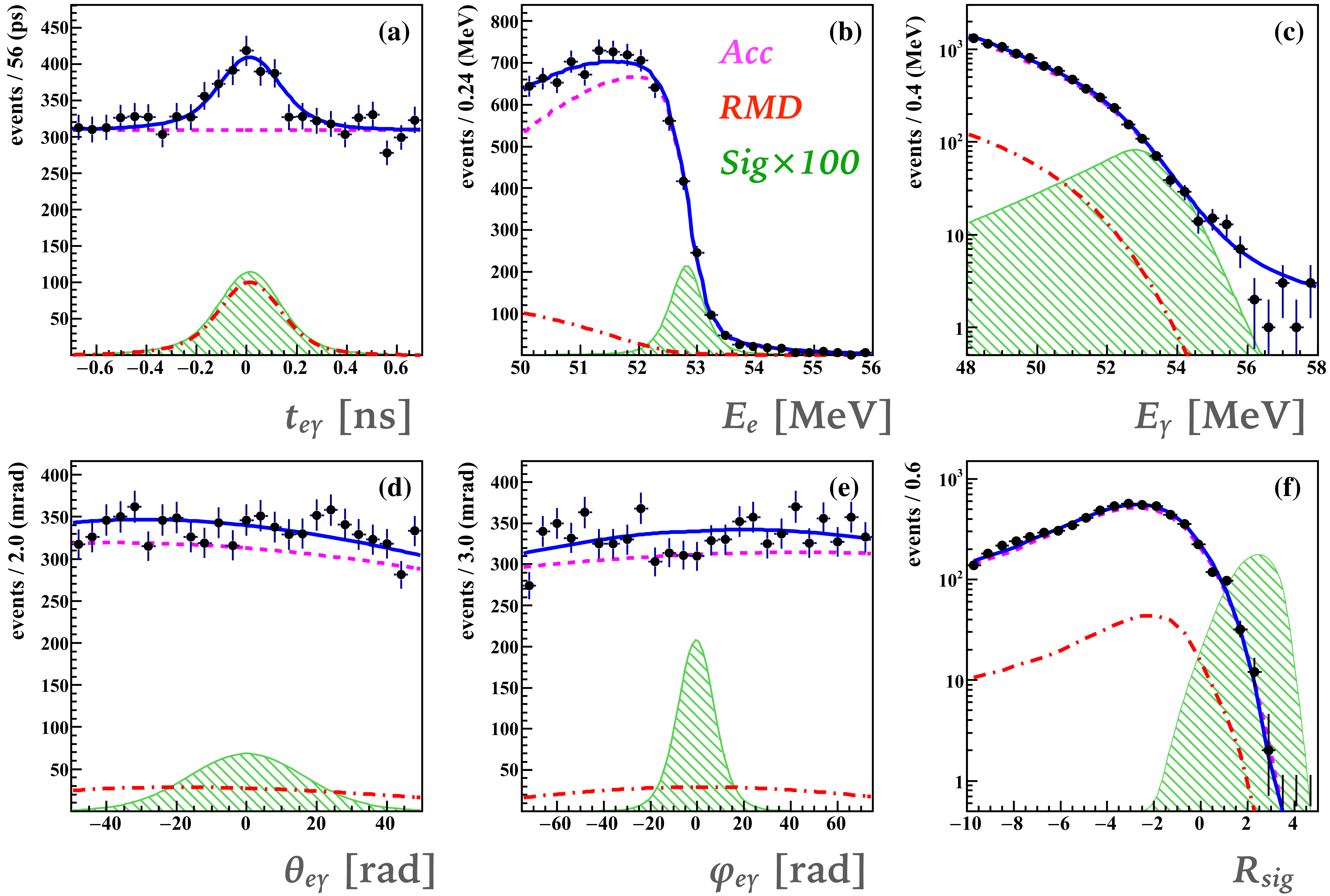
Ultra light drift chamber modules

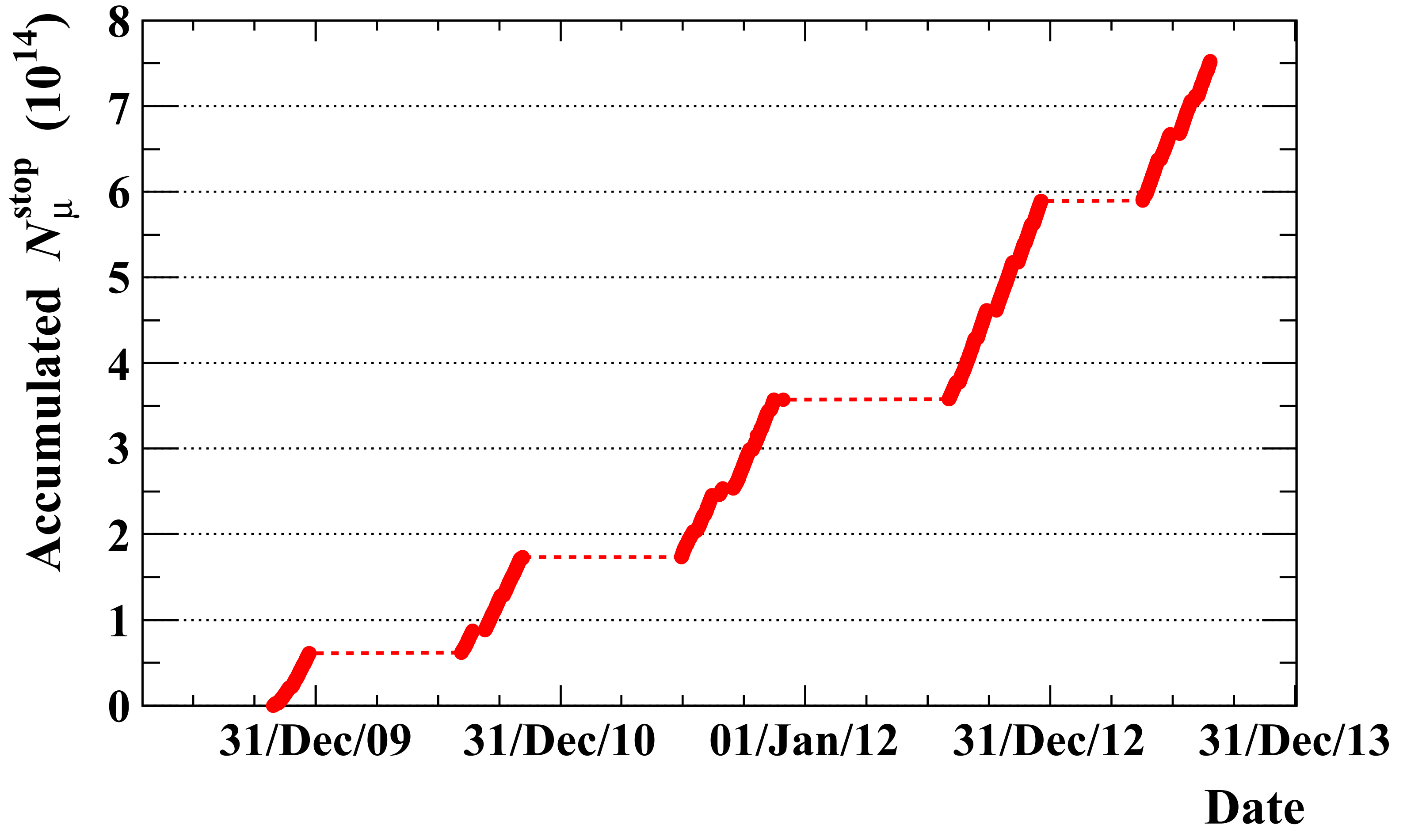




Specially graded magnetic field

MEG Experiment

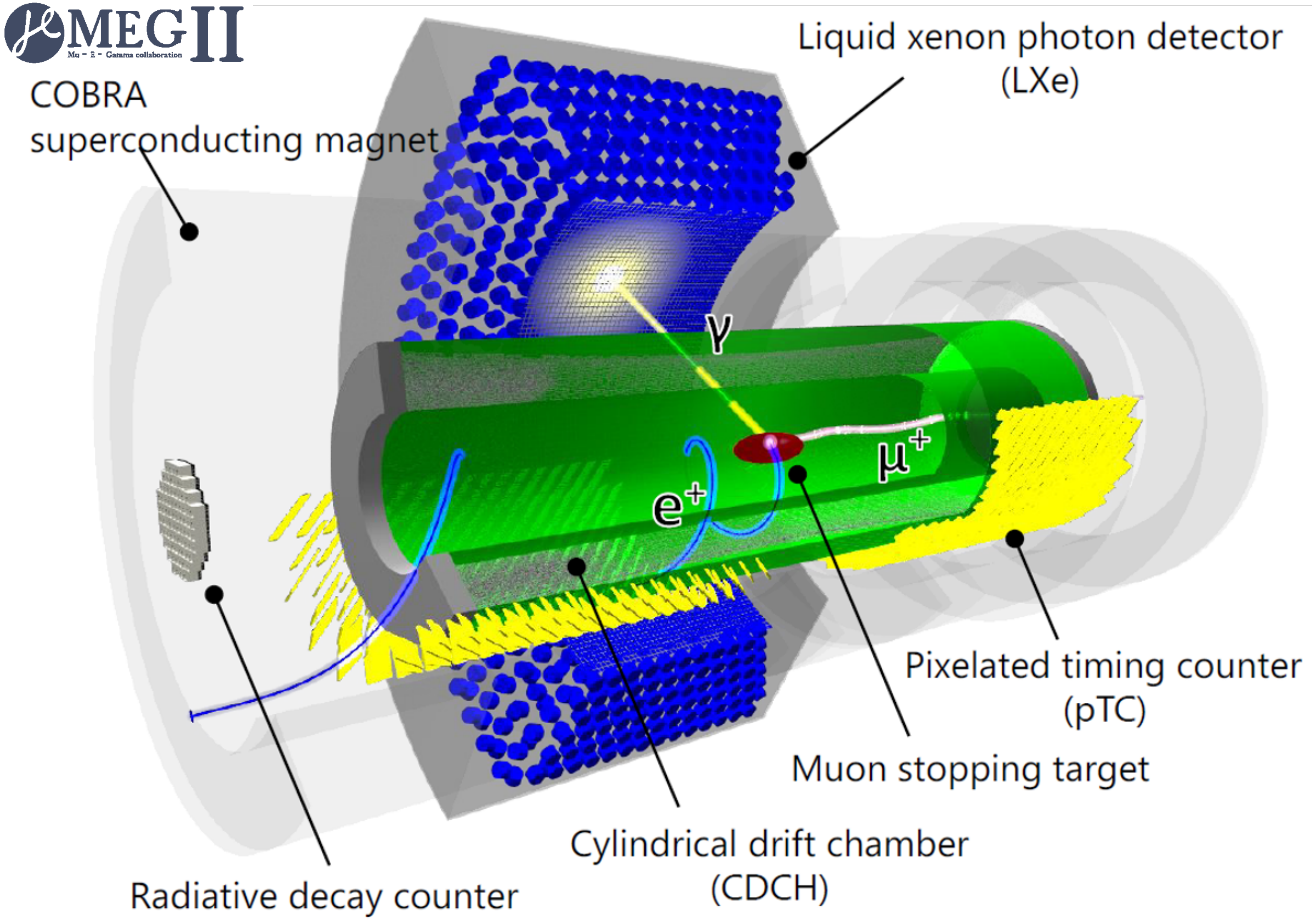


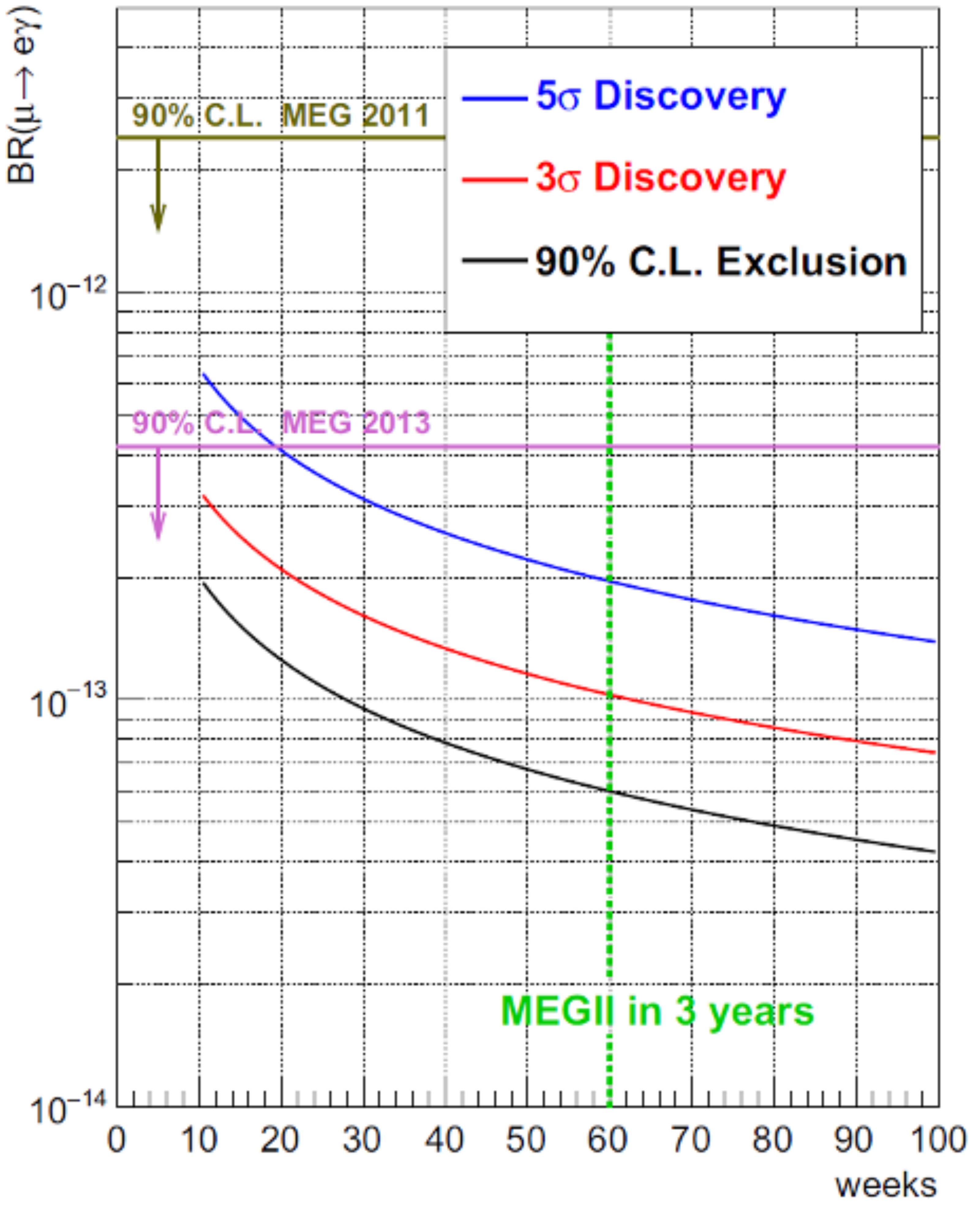


- Final results published in 2016 using the full dataset
- Final results; $BR(\mu\rightarrow e\gamma)<4.2\times10^{-13}$ (90% C.L.), Euro. Phys. J C (2016) 76:434
- Start getting the BG events in the signal region → **time for the upgrade**

MEG II Experiment

Special thanks to Marco Chiappini



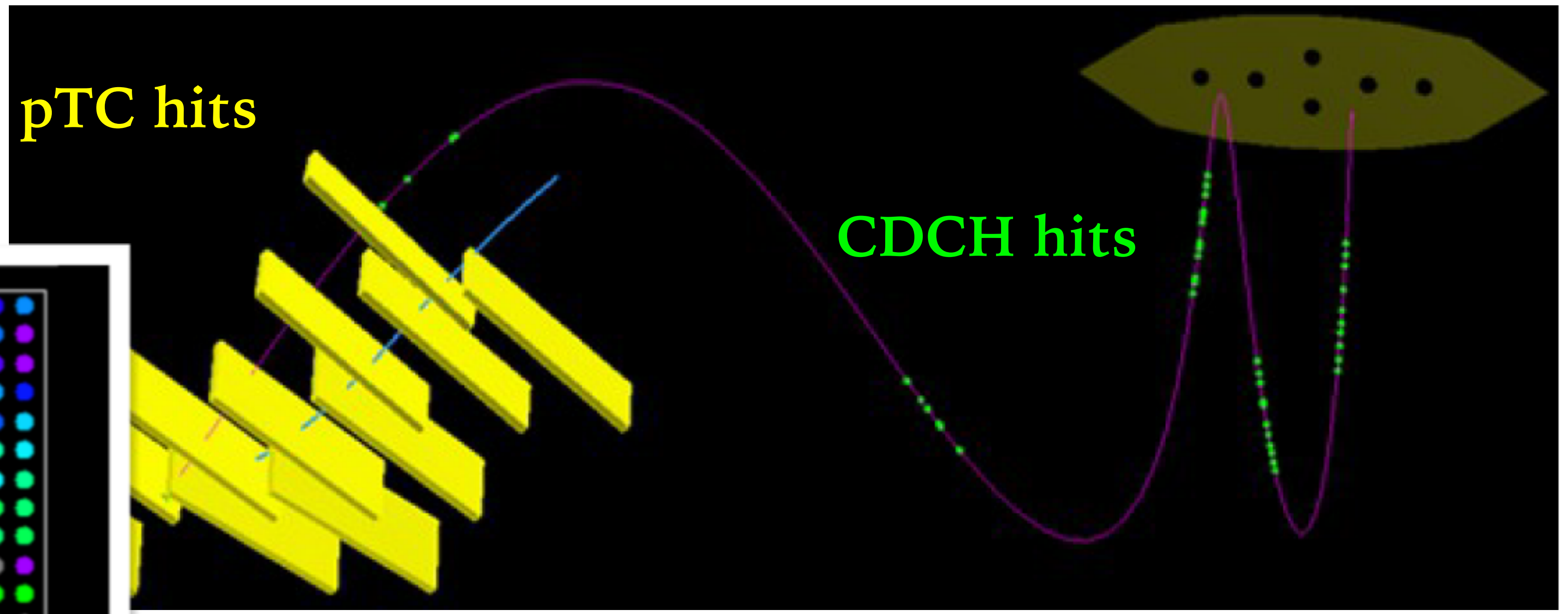


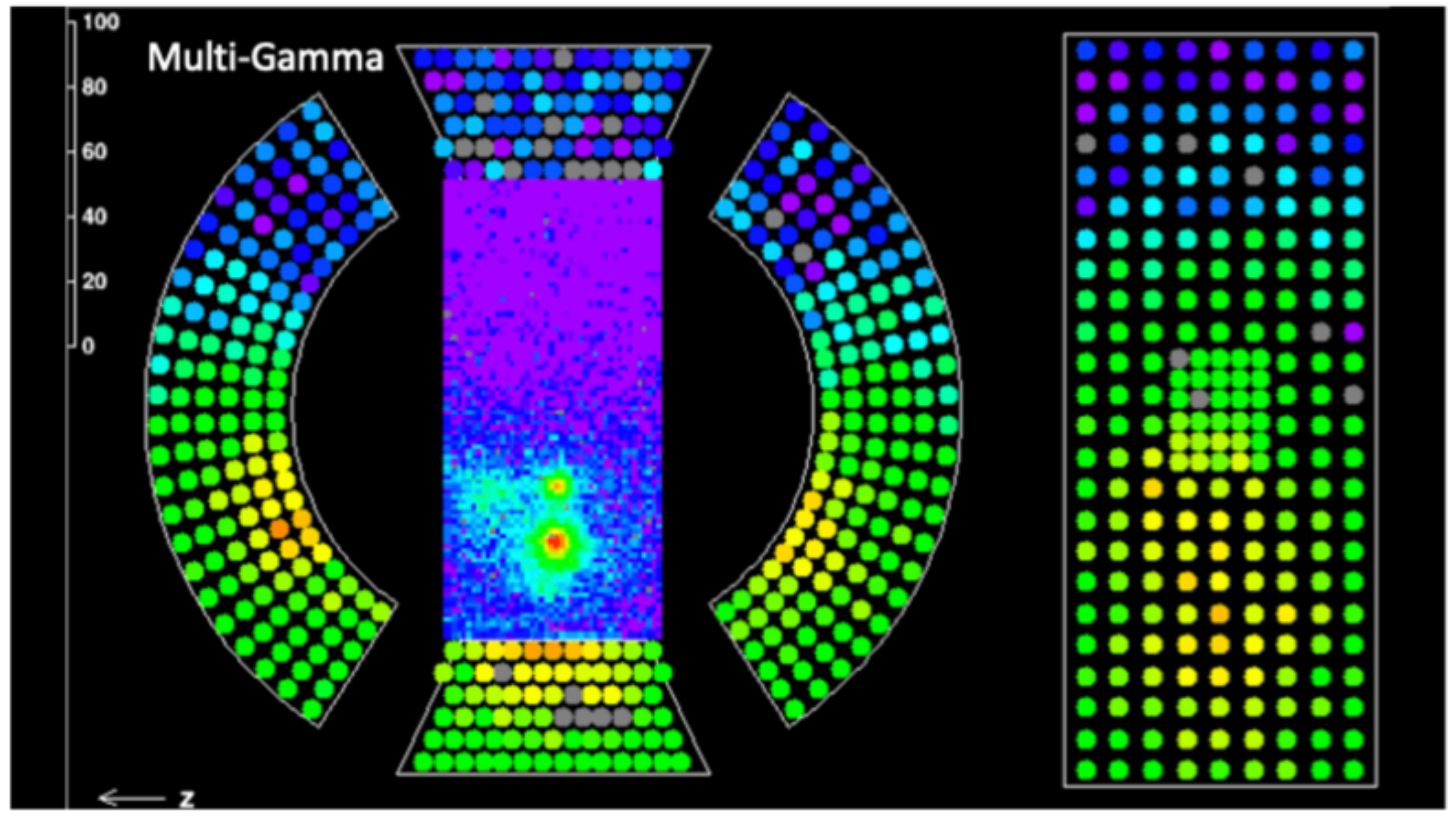
Link to the MEG II design paper

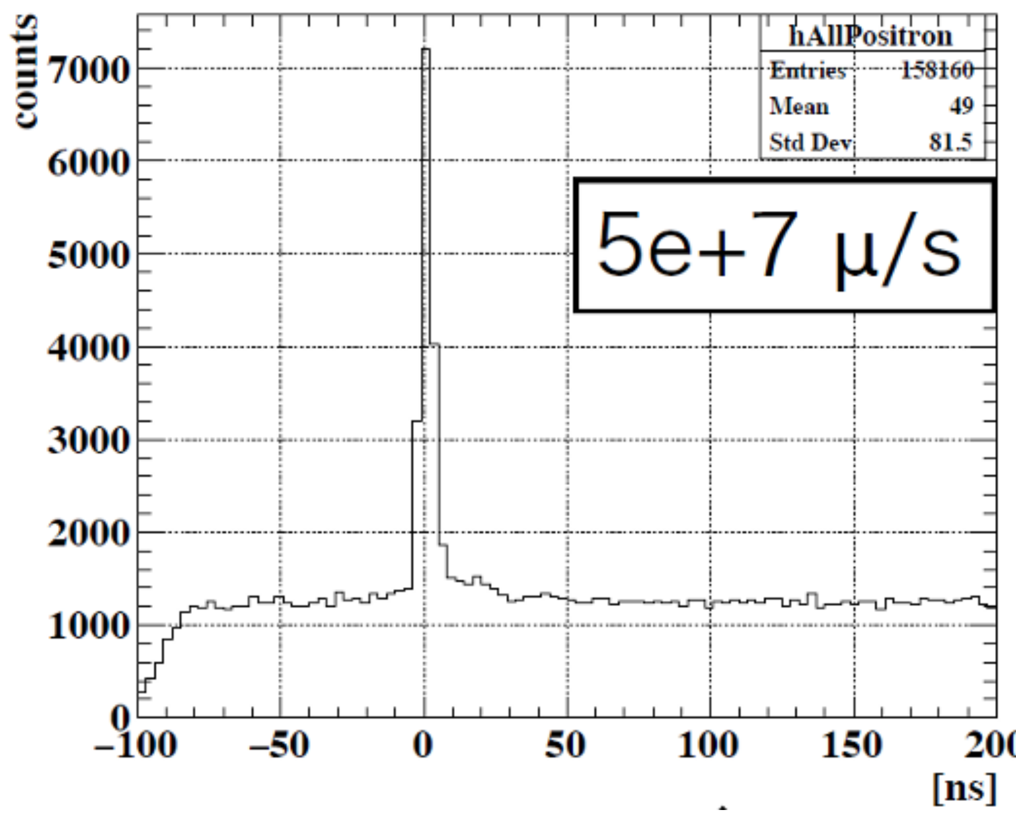
MEG II Experiment

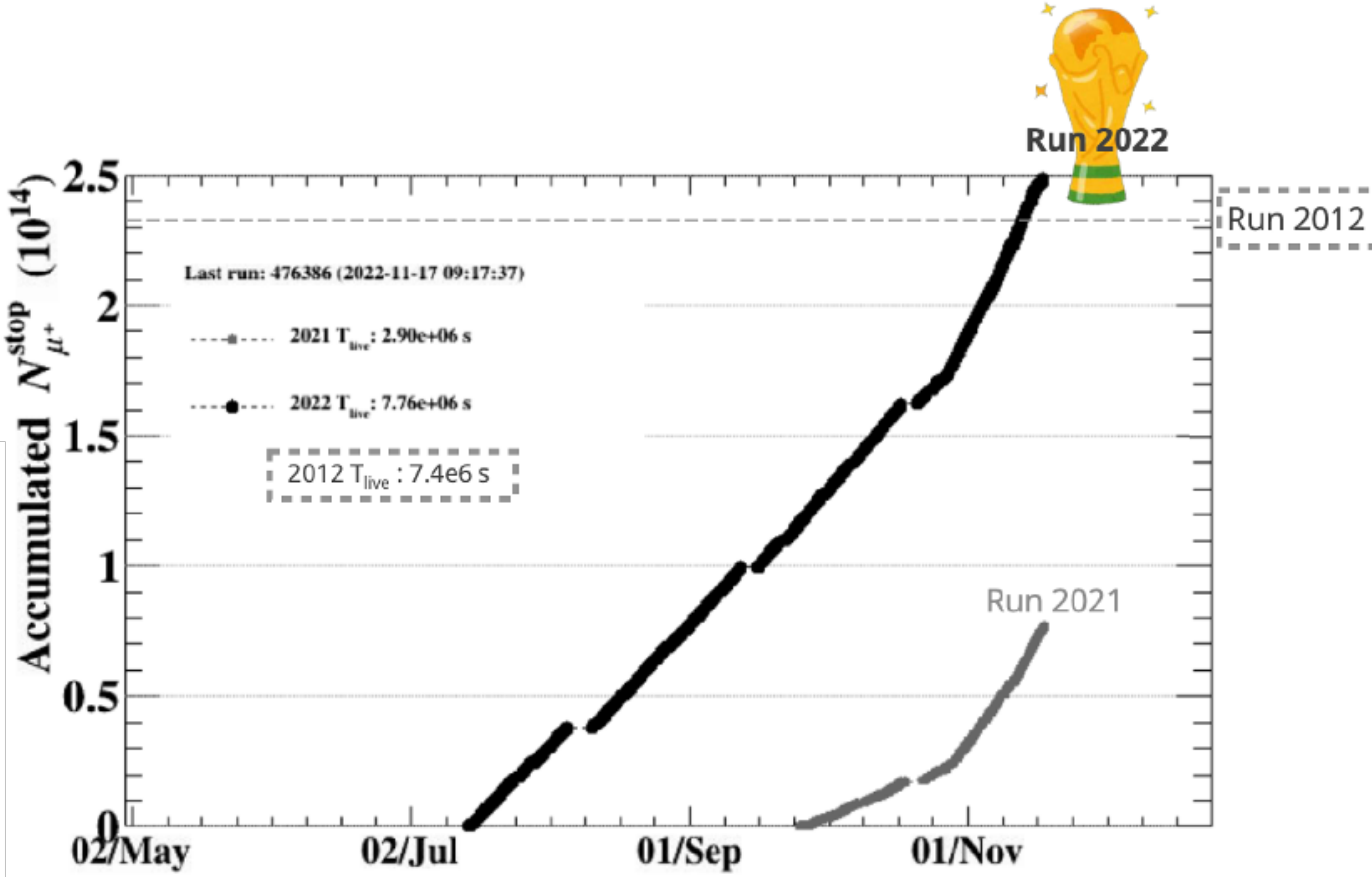
Special thanks to Marco Chiappini

All detectors have much better granularity now !





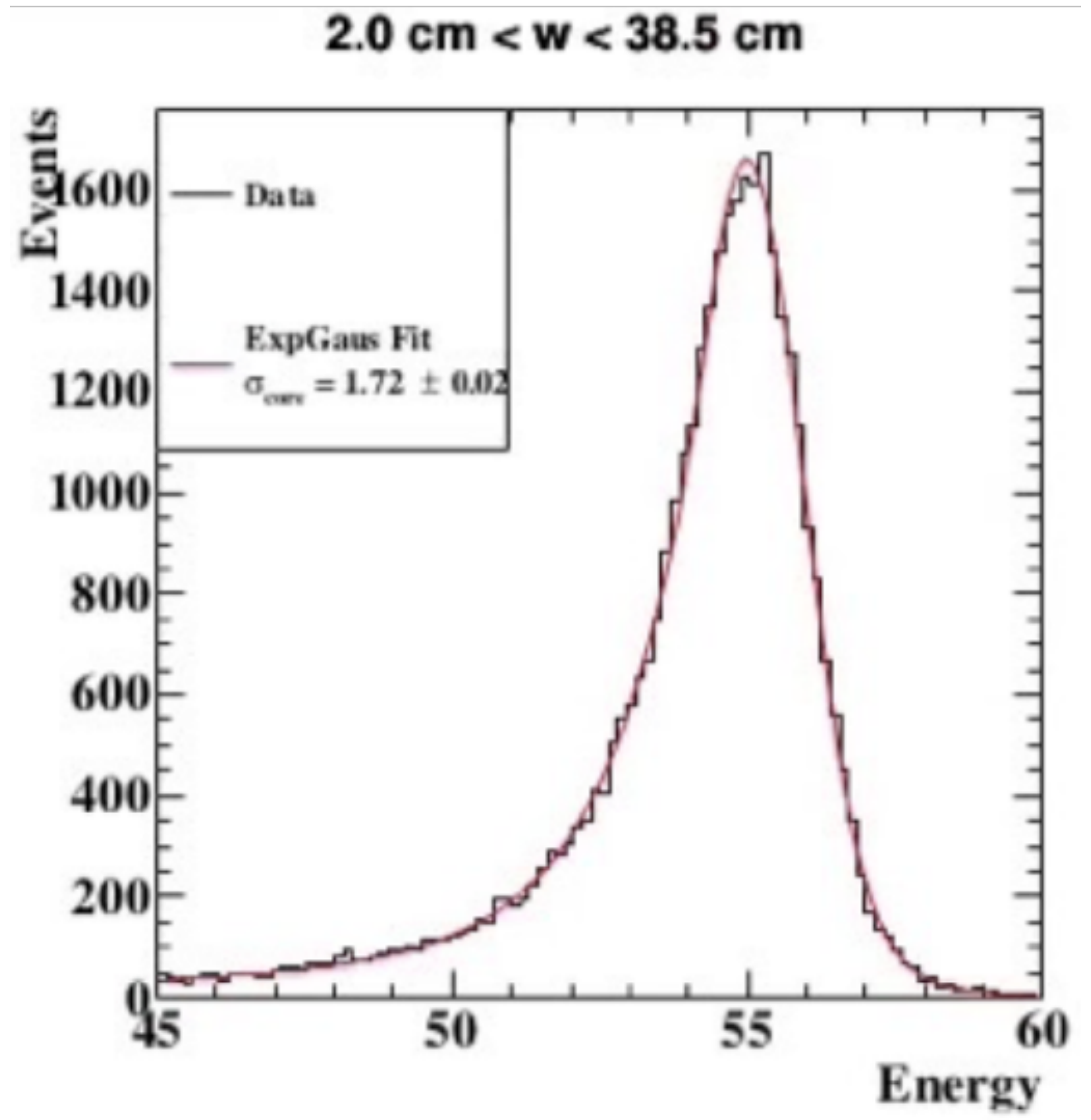


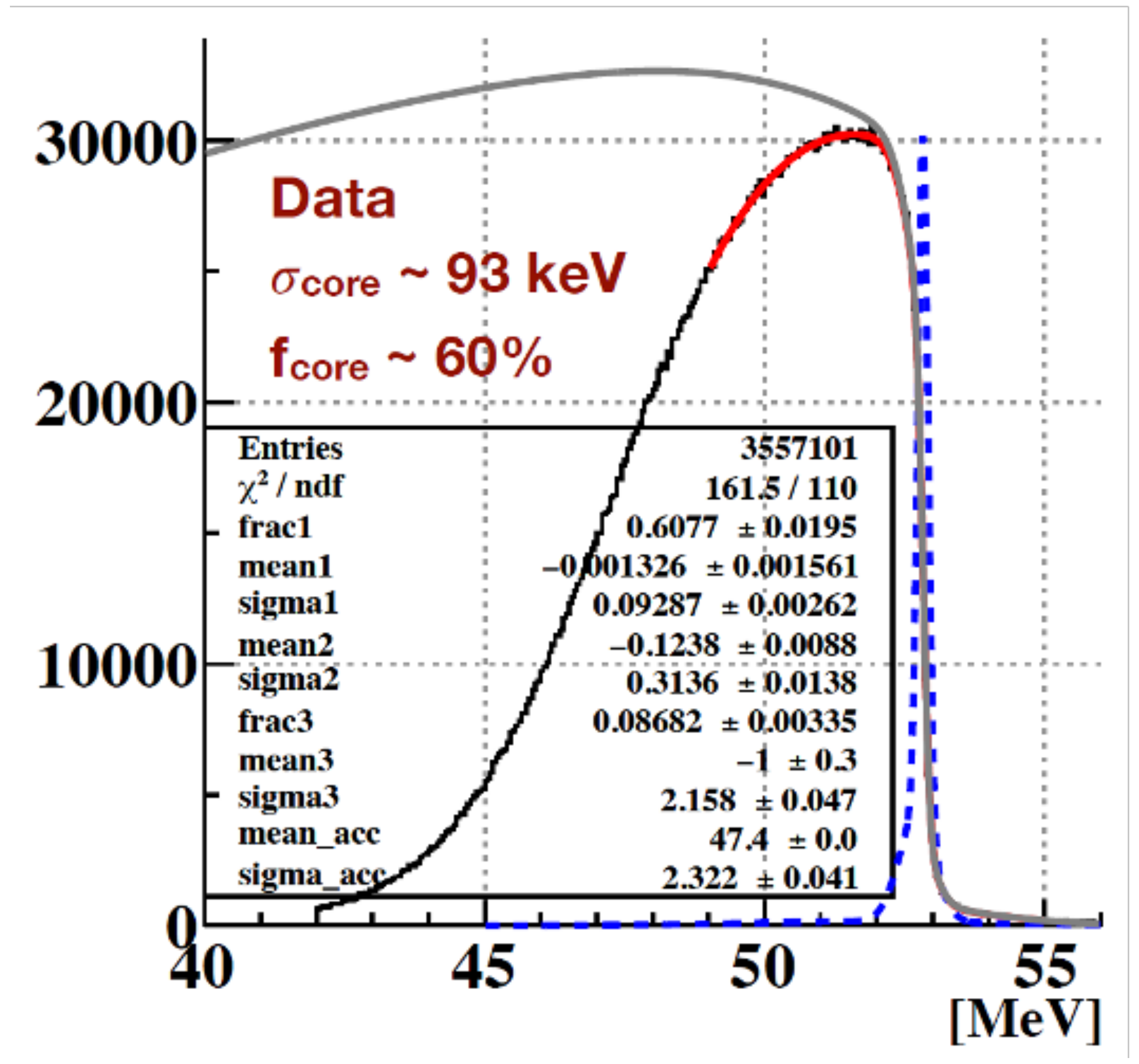


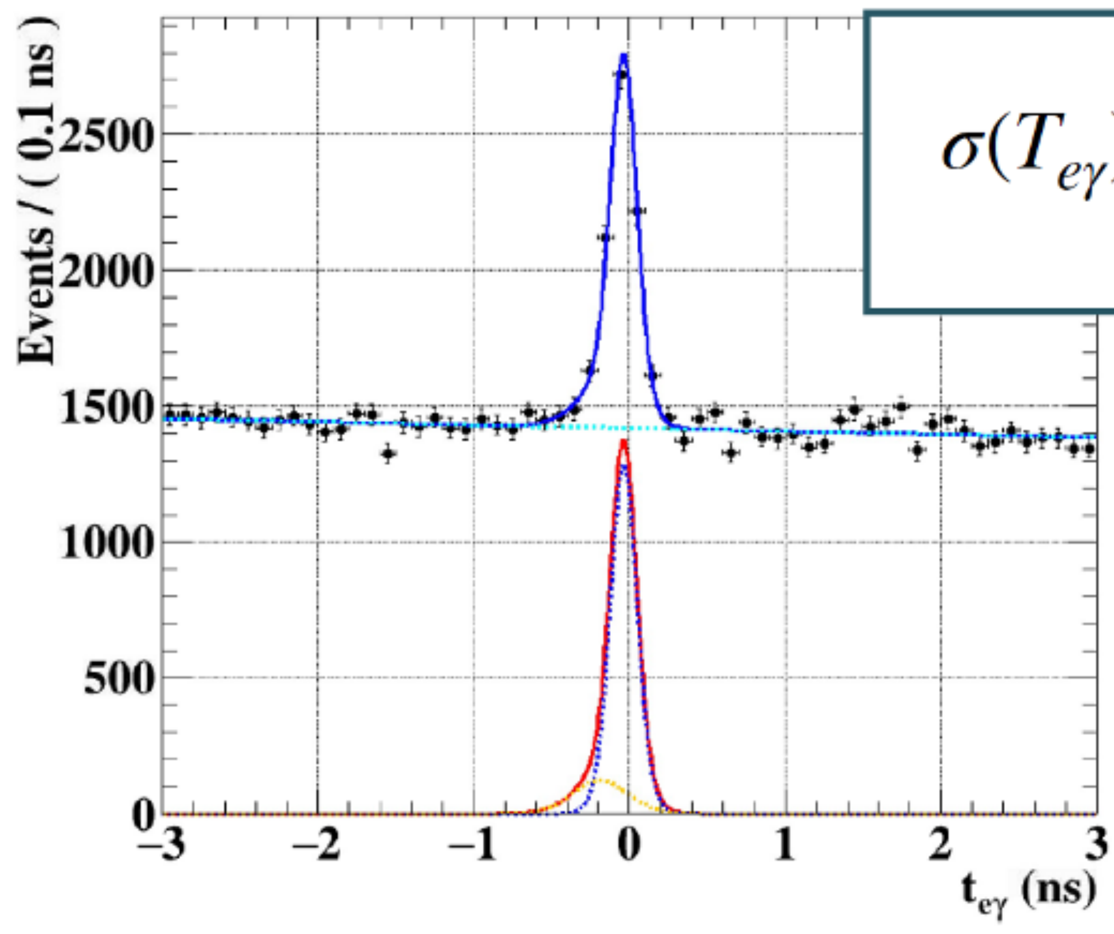
RMD BG peak can be seen in t_{RDC} - t_{LXe}

15% sensitivity improvement at most

MEG II Experiment

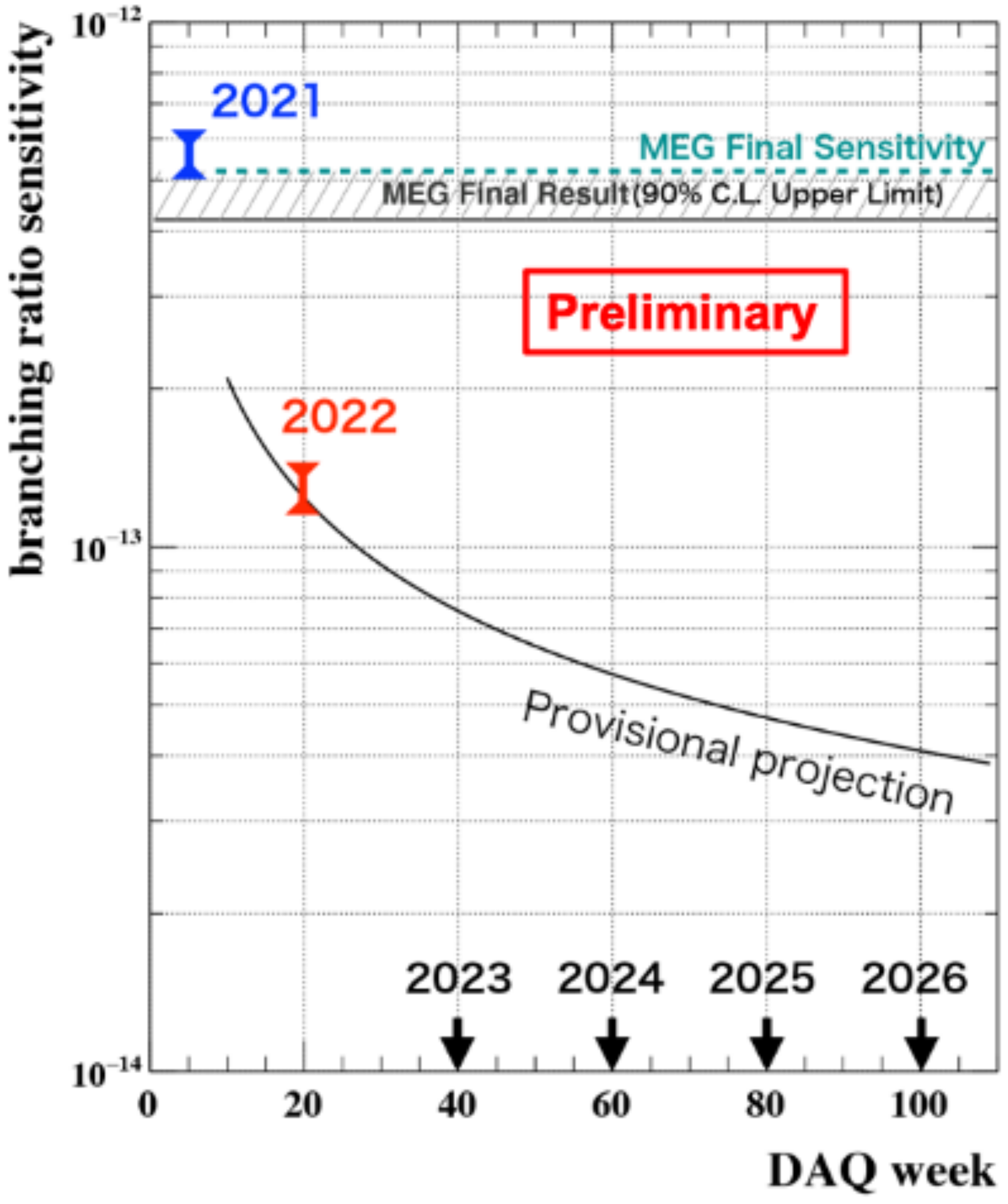






$$\sigma(T_{e\gamma}) = (69 \pm 5) \oplus \frac{105}{\sqrt{n_{TC}}}$$

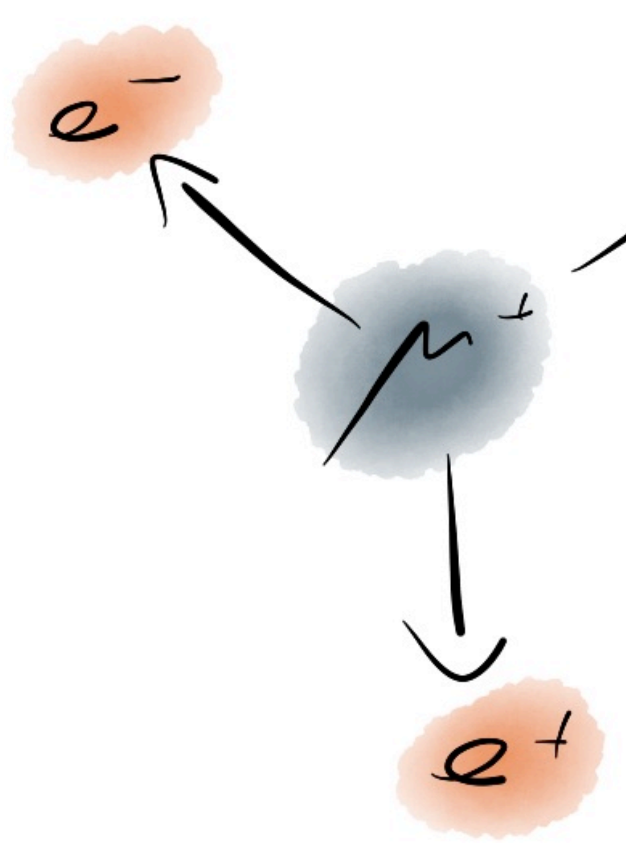
photon positron



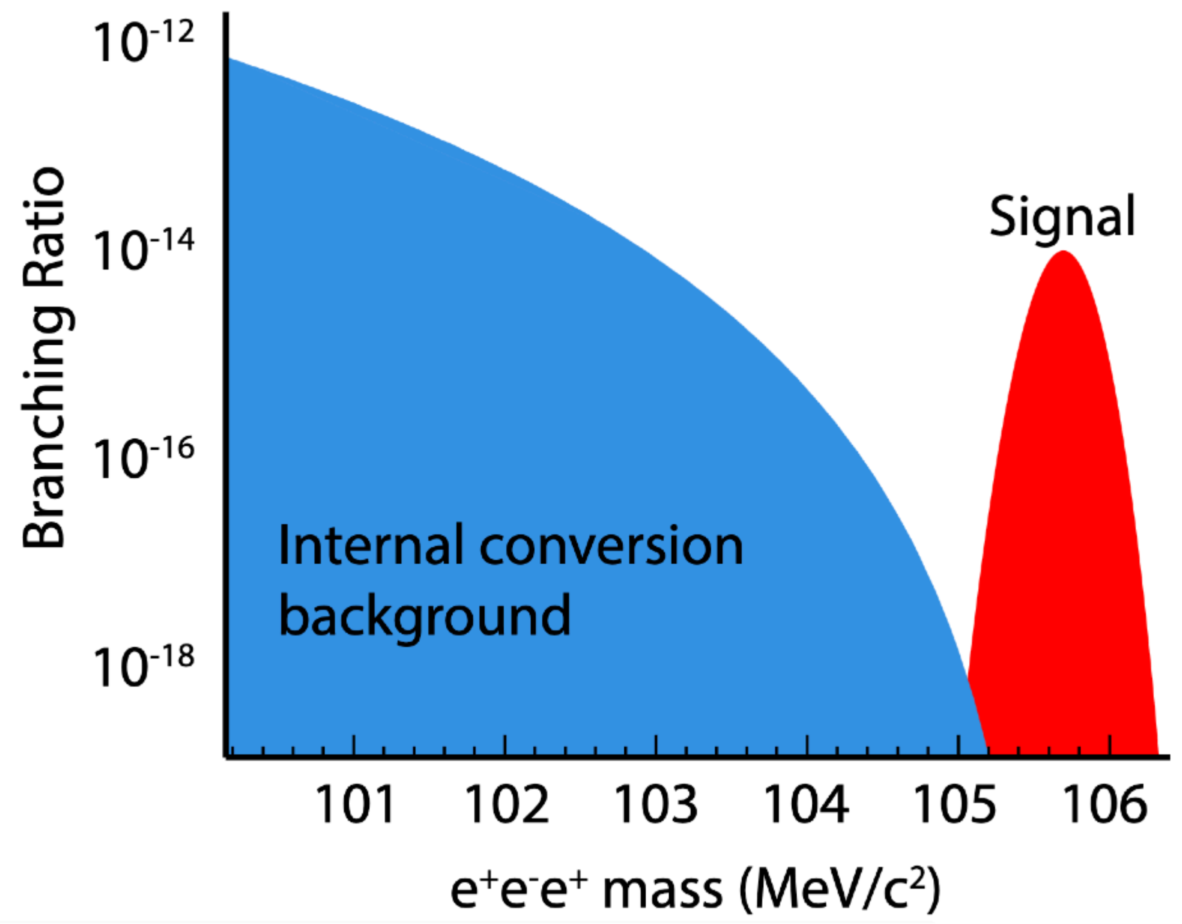
	MEG	MEG II (design)	MEG II (Meas.)
ΔE_e [keV]	380	130	**90**
$\Delta\theta_e$ / $\Delta\varphi_e$ [mrad]	9/9	7.0/5.5	**8/7**
e^+ Eff. [%]	40	70	**65**
ΔE_γ [%] (deep/shallow)	1.7/2.4	1.0/1.1	**1.7/2.0**
Δpos_γ [mm]	5	2.4	**2.5**
γ Eff. [%]	60	70	**60**
$\Delta t_{e\gamma}$ [ps]	120	85	**80**

$\mu^+ \to e^+ e^+ e^-$

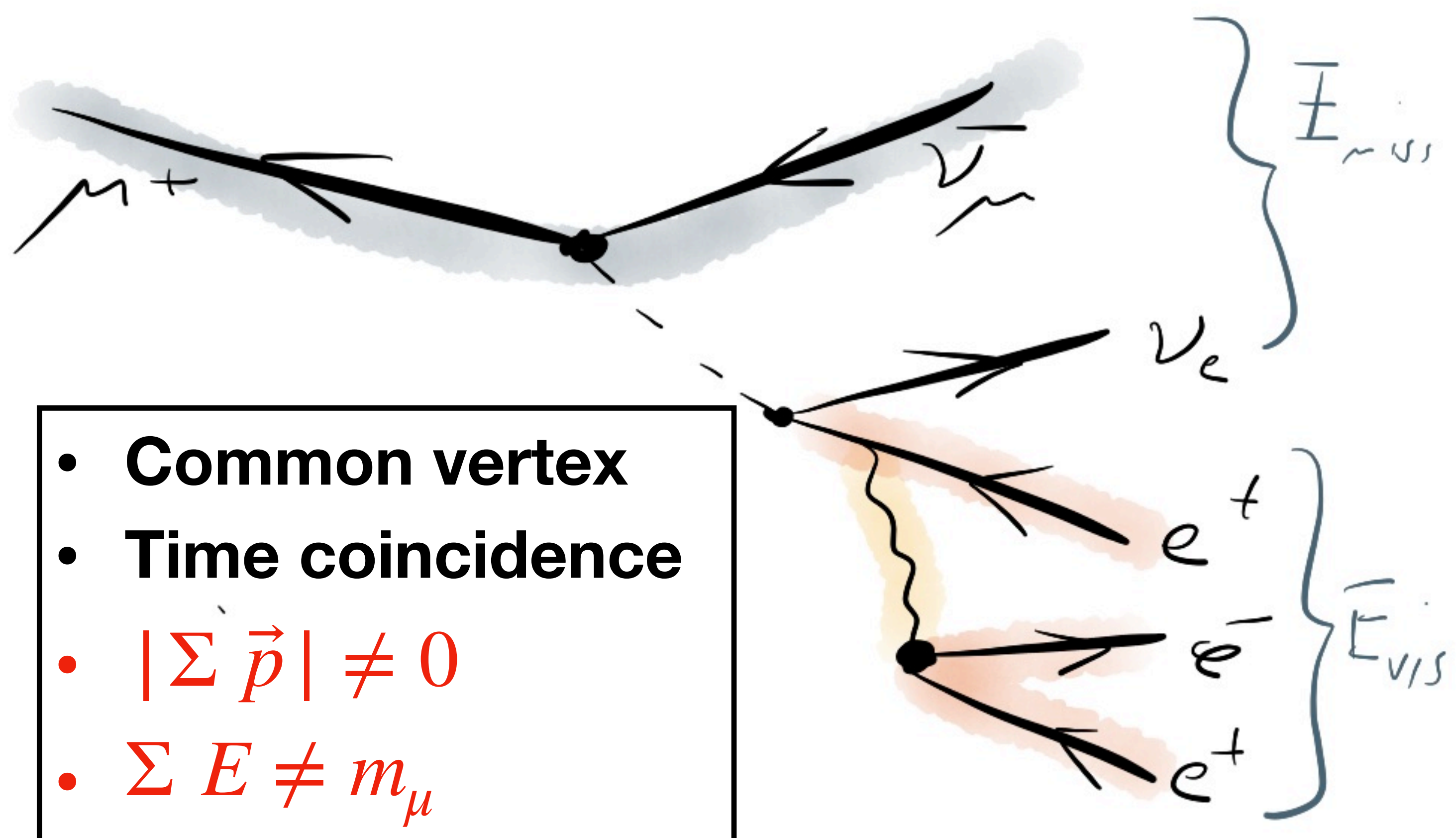
Signal



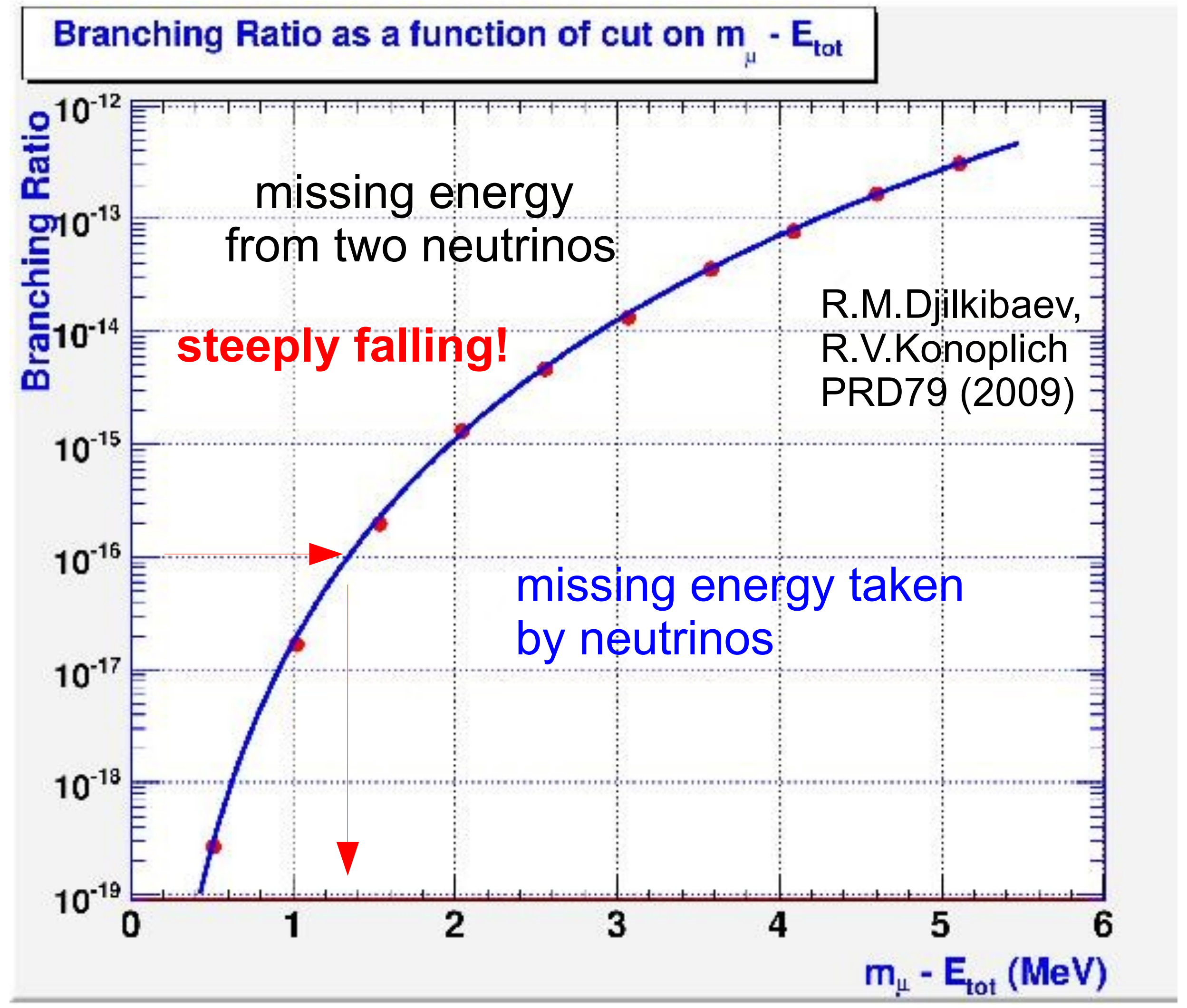
- **Common vertex**
- **Time coincidence**
- $|\Sigma \vec{p}| = 0$
- $\Sigma E = m_\mu$



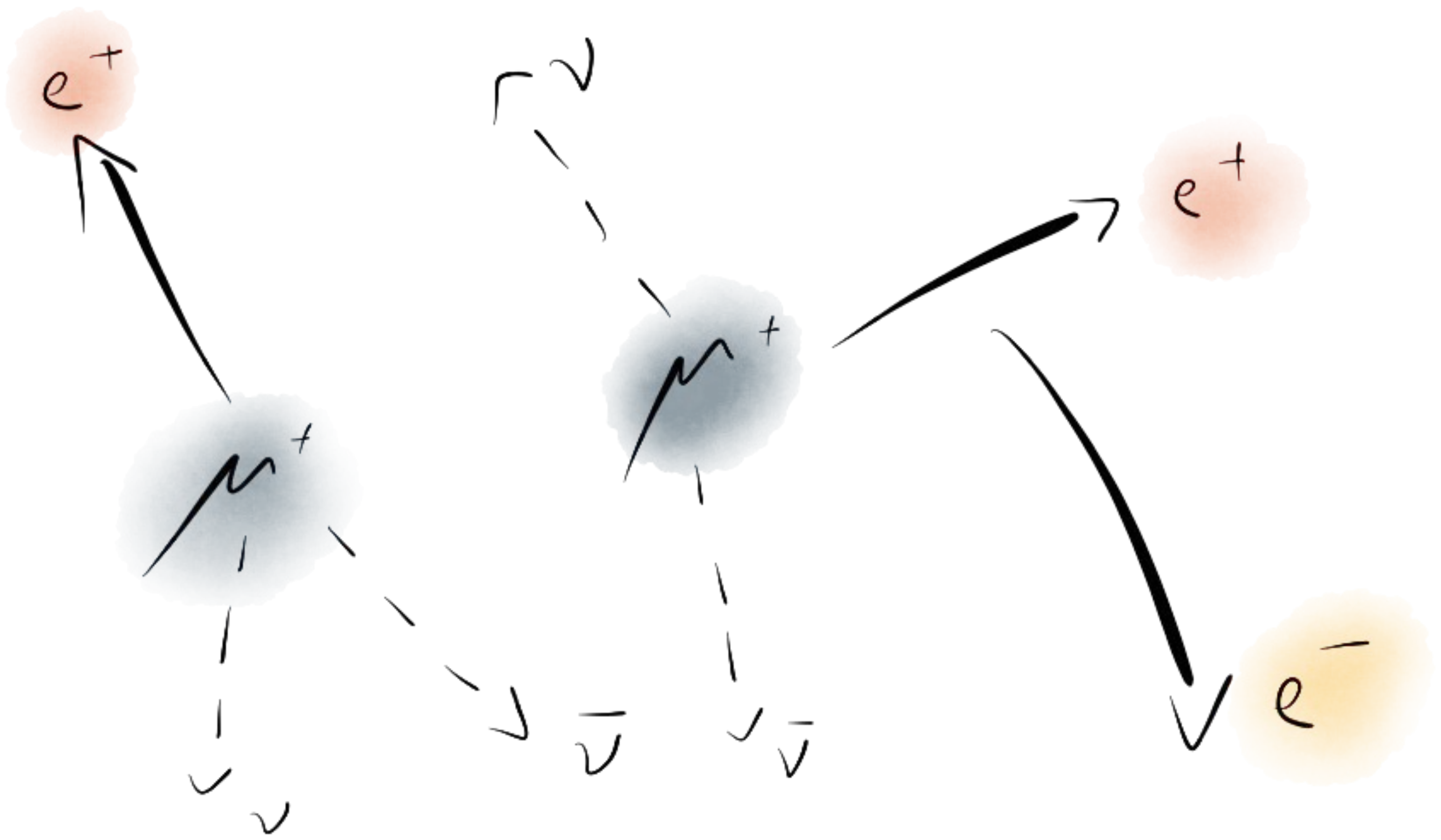
Internal background



- **Common vertex**
- **Time coincidence**
- $|\Sigma \vec{p}| \neq 0$
- $\Sigma E \neq m_\mu$



Combinatorial background



- **No common vertex**
- **No time coincidence**
- $|\Sigma \vec{p}| \neq 0$
- $\Sigma E \neq m_\mu$

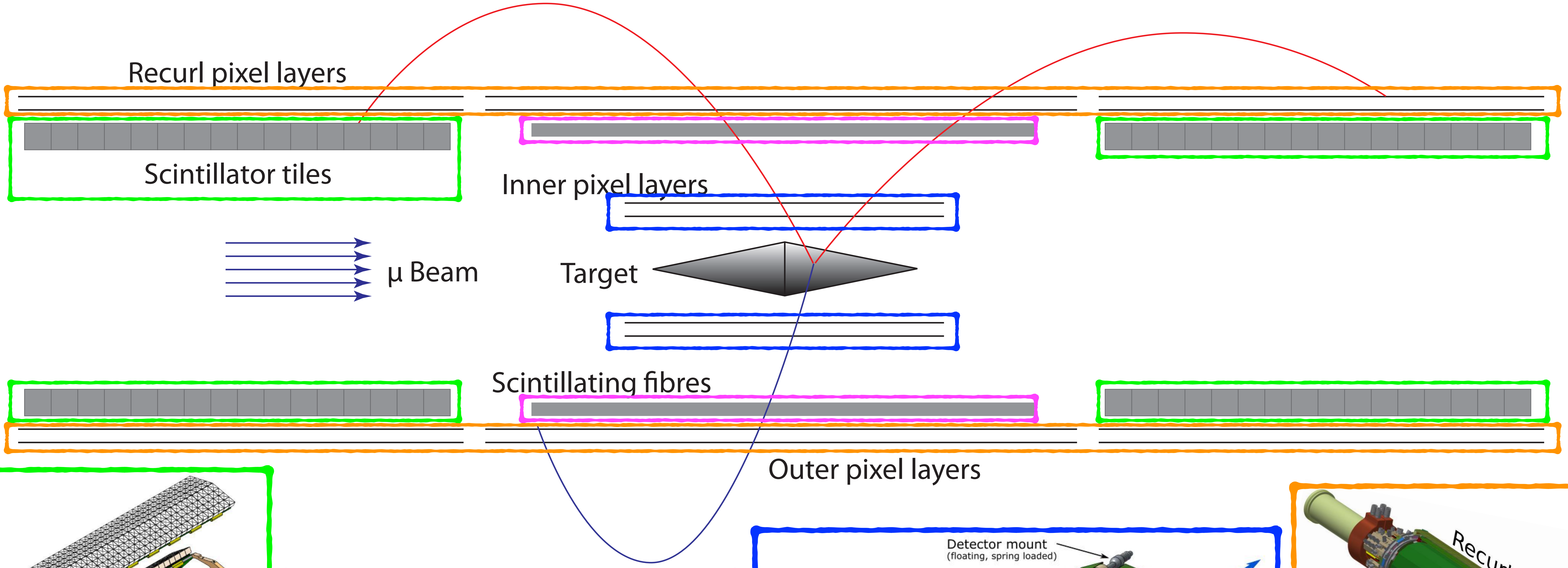
Timing resolution < 100 ps

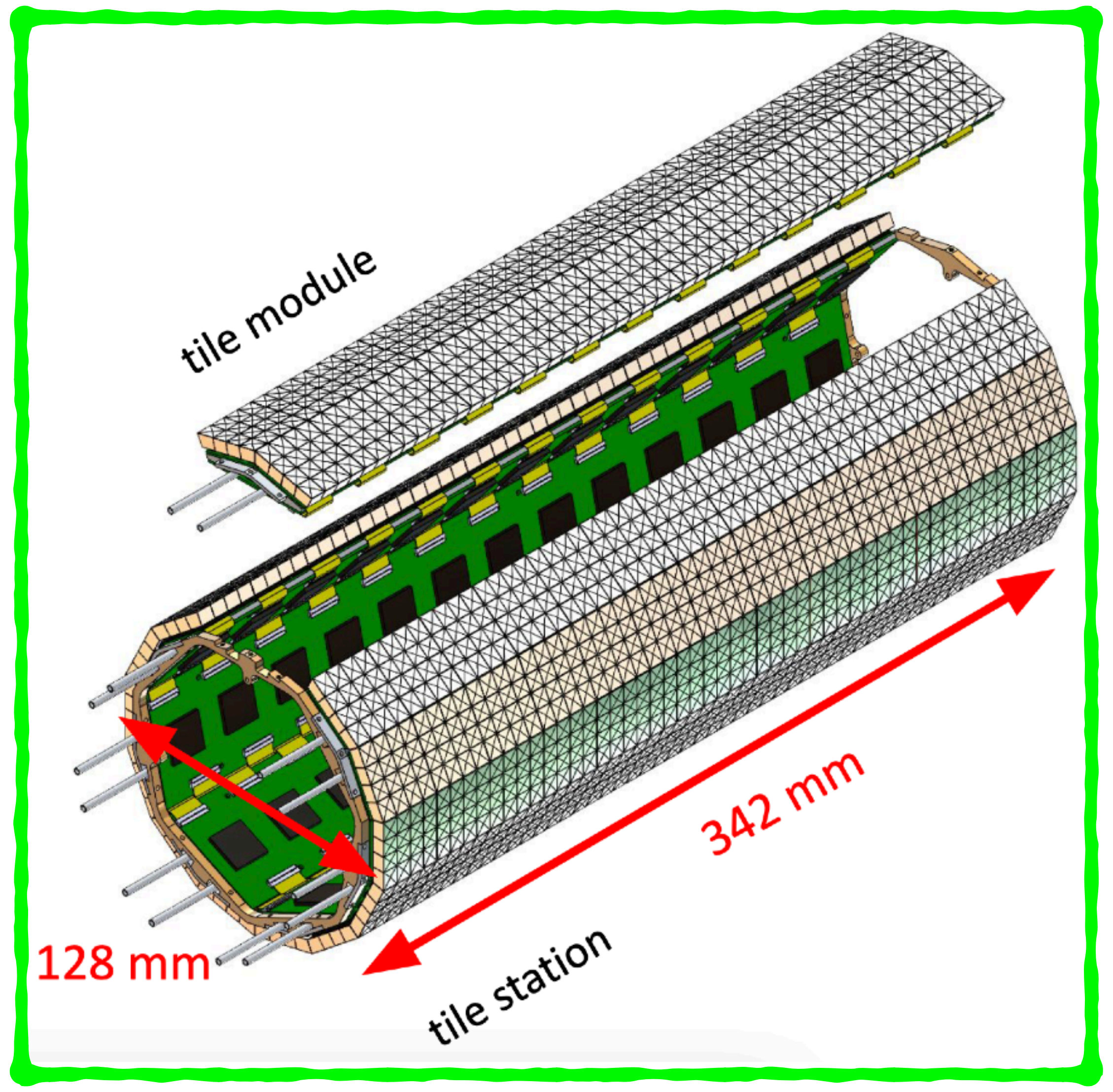
Vertex resolution < 0.5 mm

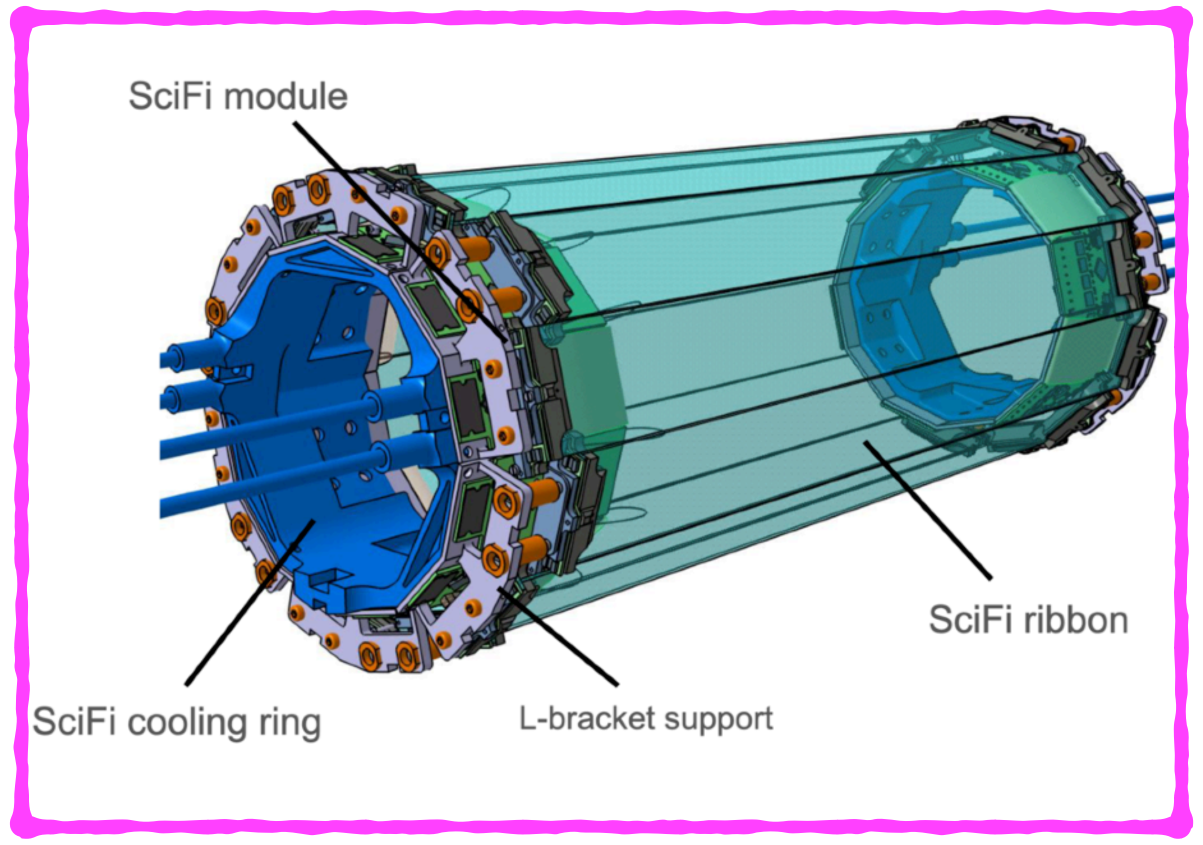
$|\Sigma p|$ *and* ΣE *as precise as* 1 MeV

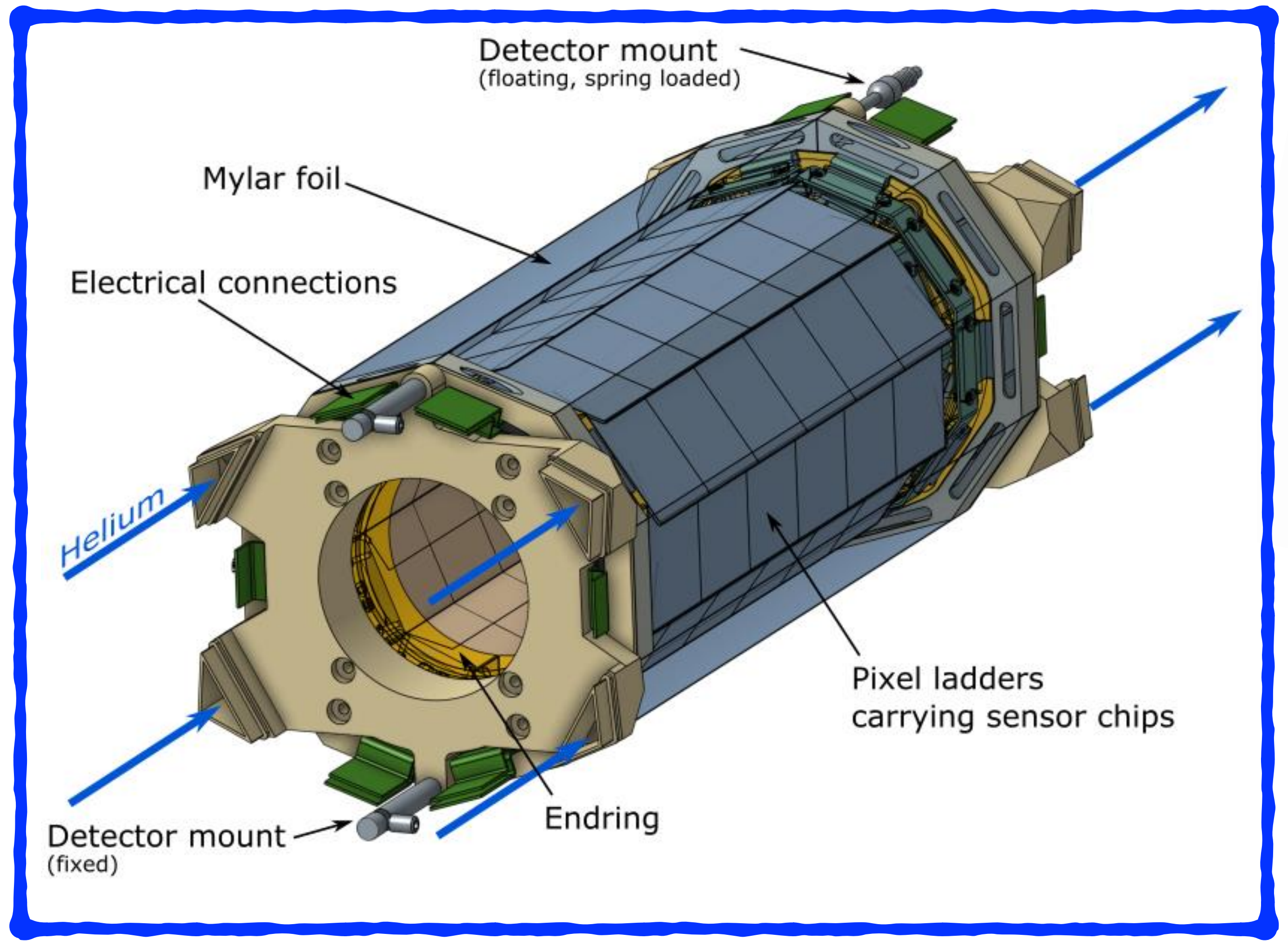
Mu3e Experiment

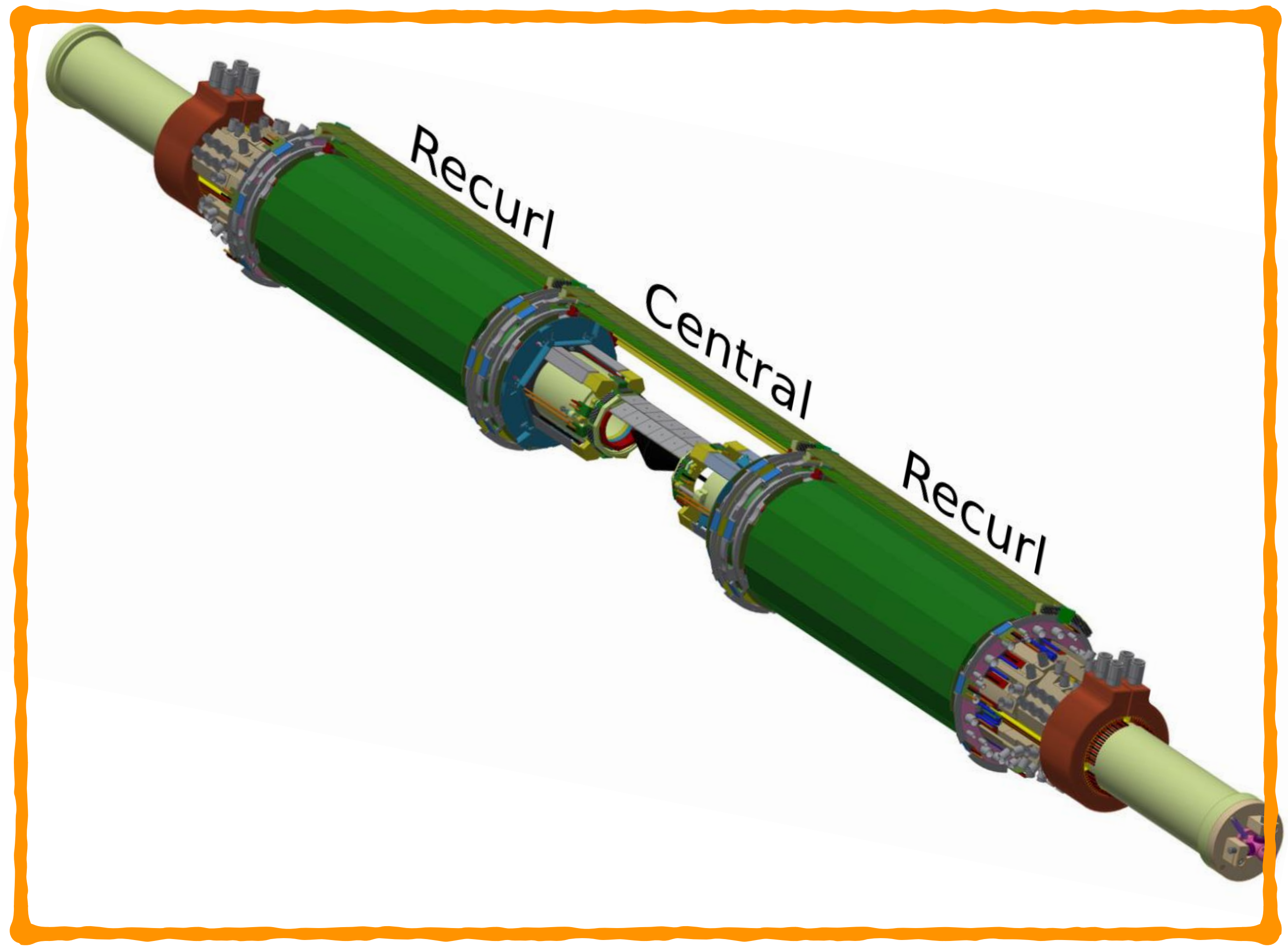
Special thanks to Cristina Martin Perez











Mu3e Experiment

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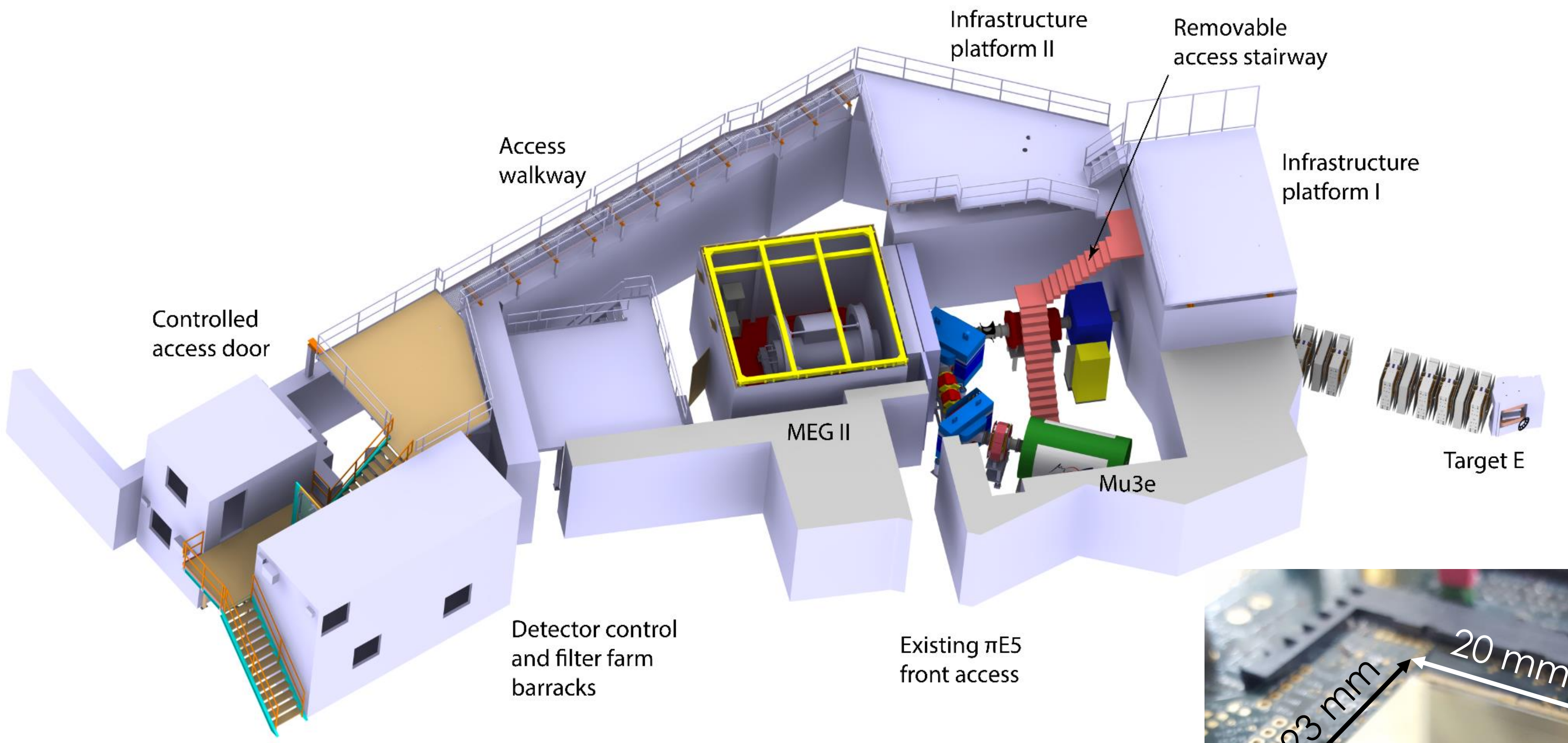
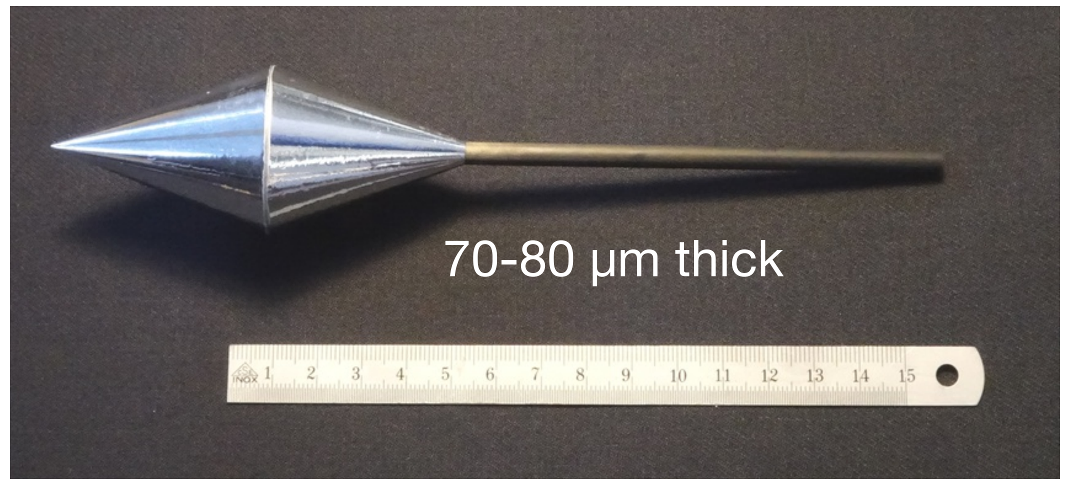
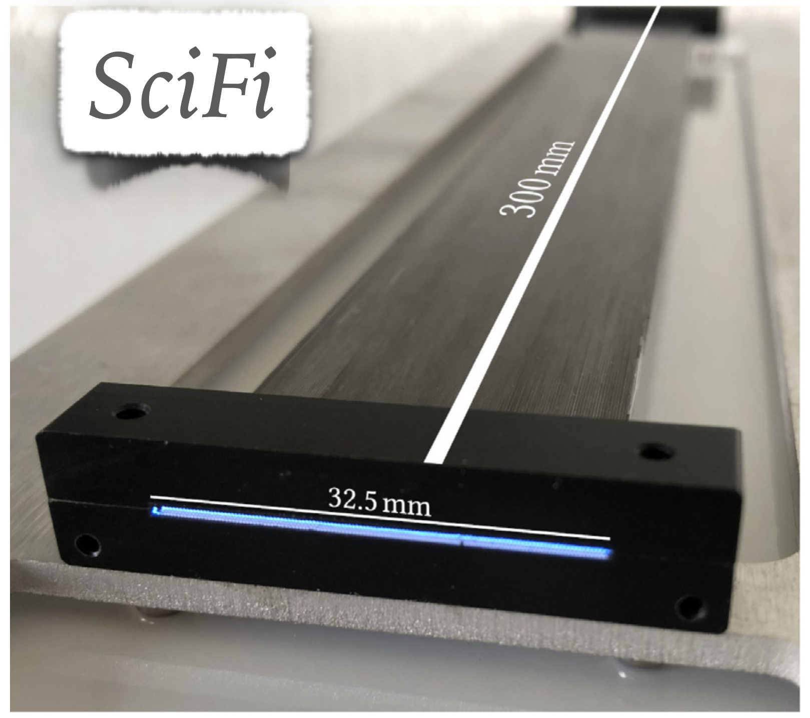
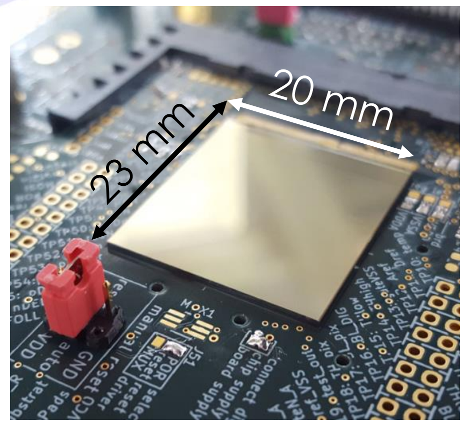
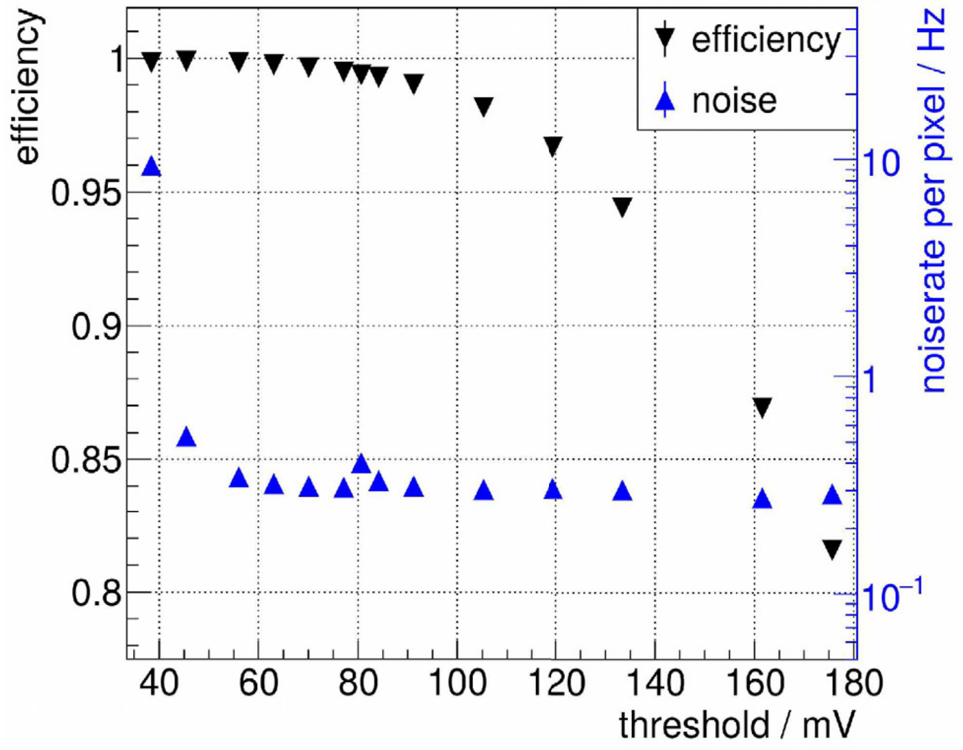


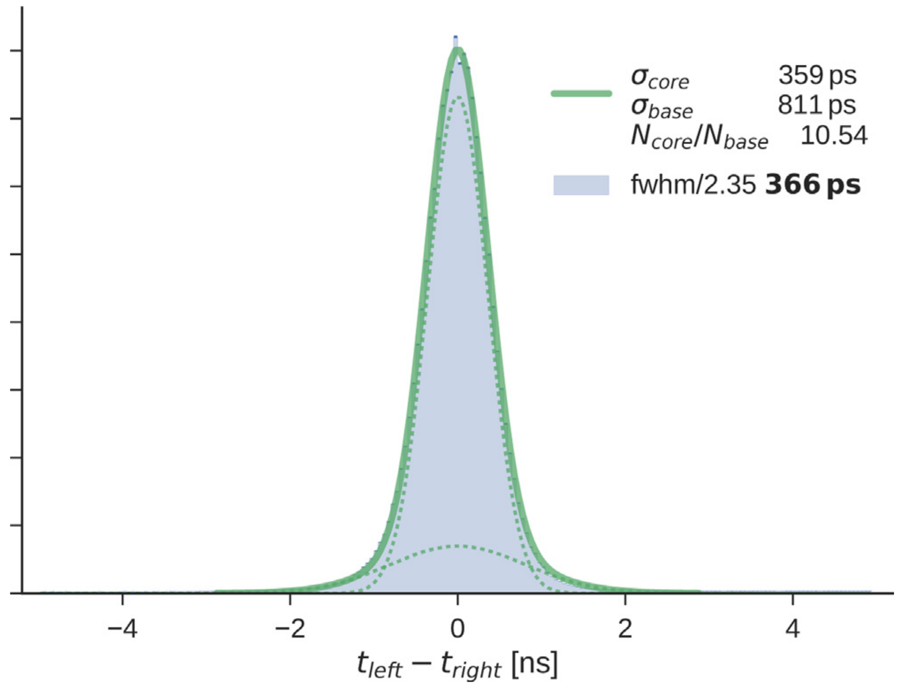


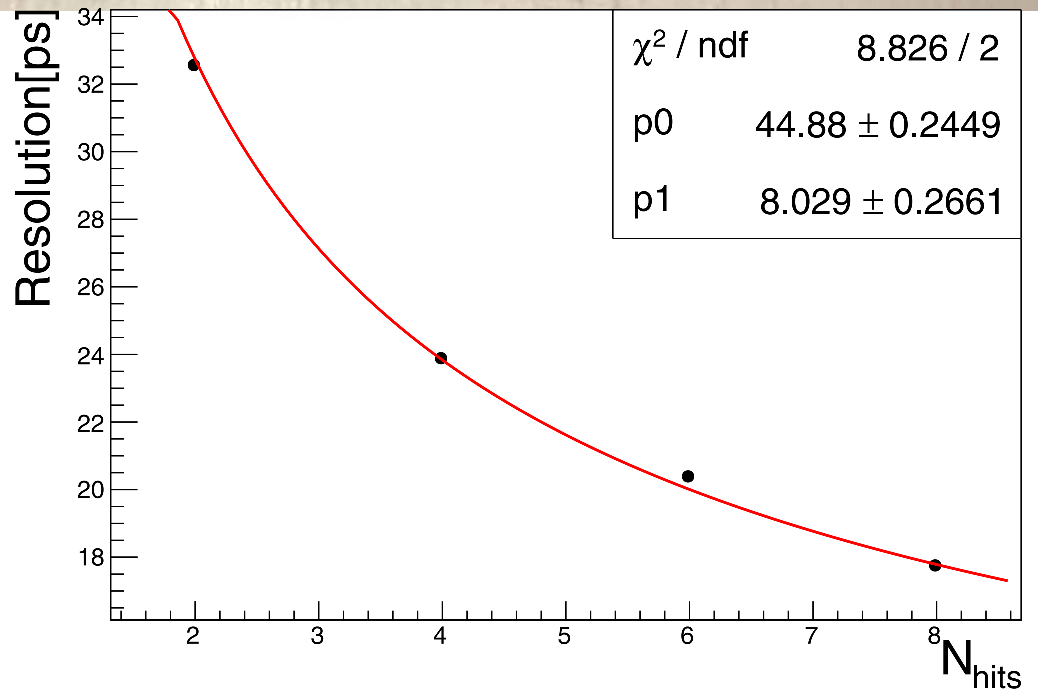


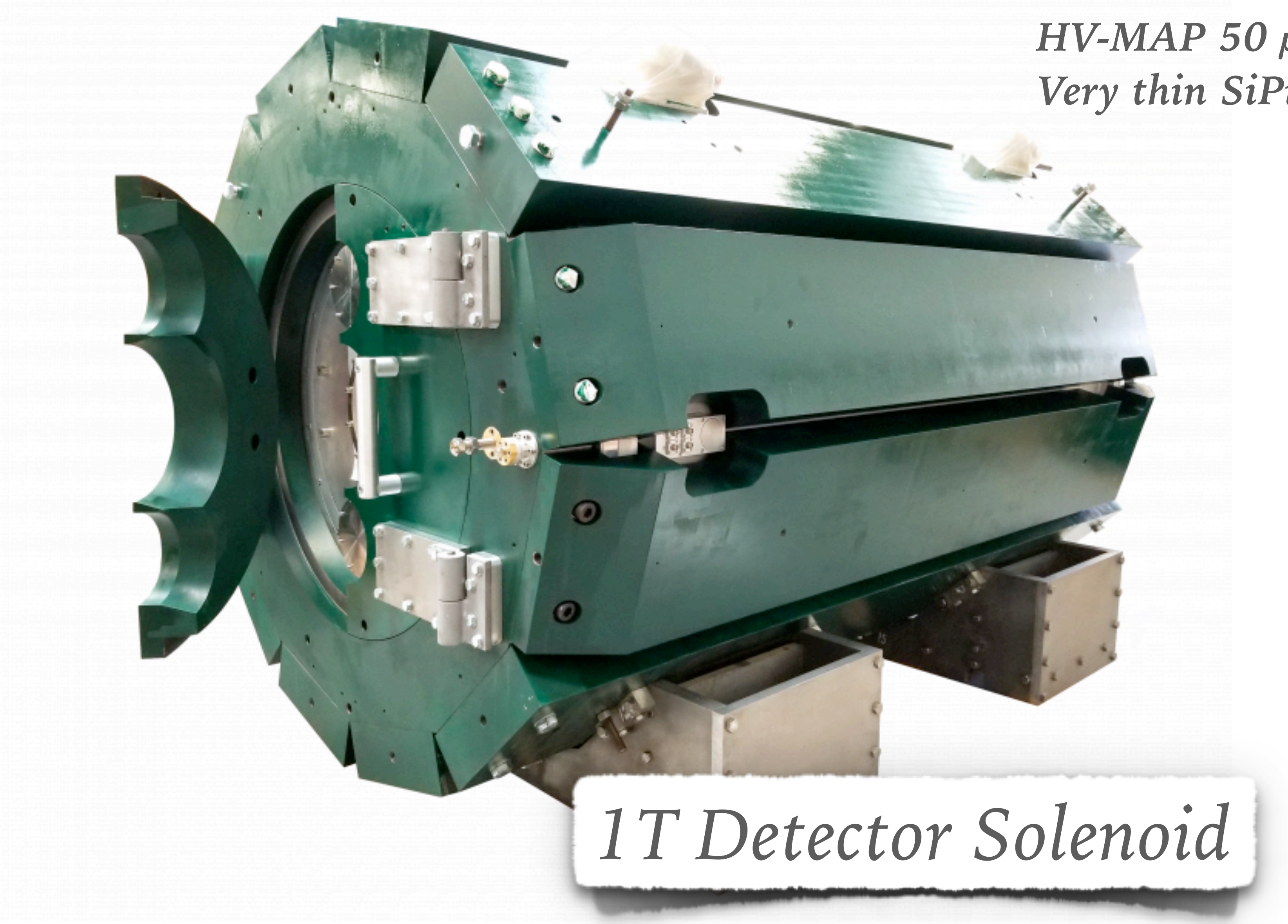


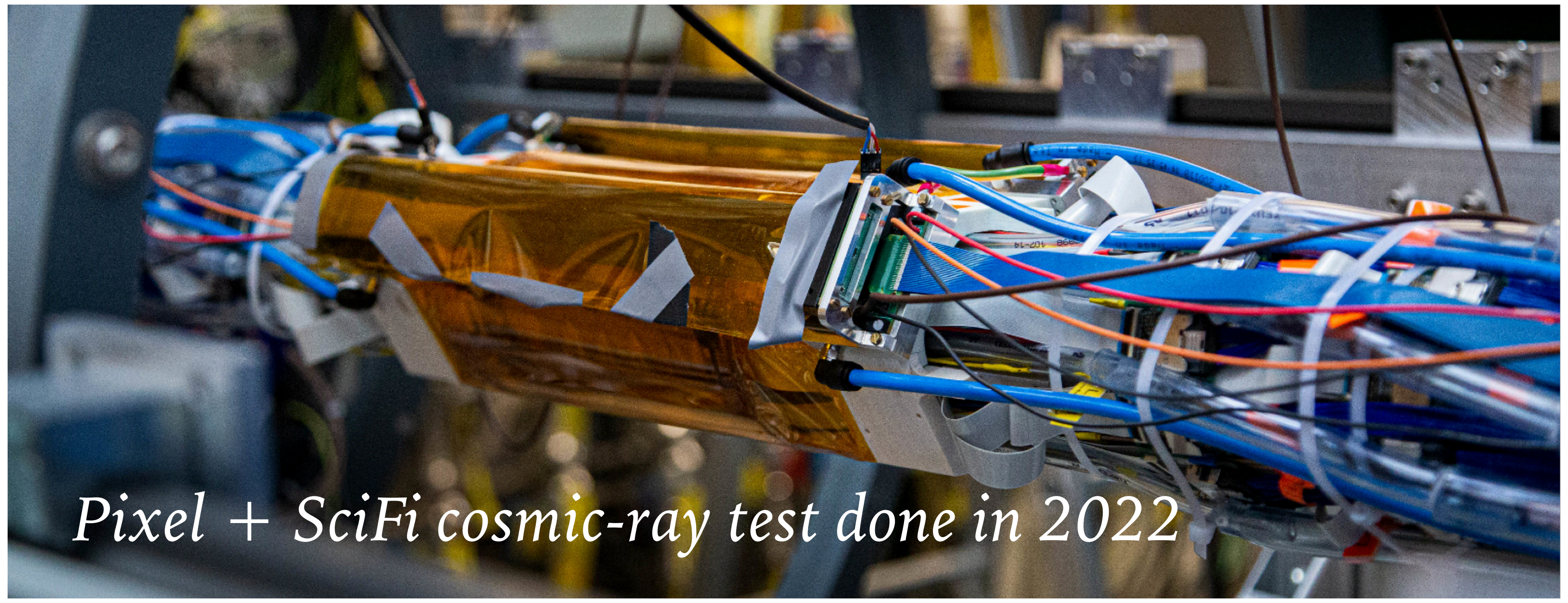
HV-MAP 50 µm
Very thin SiPixel

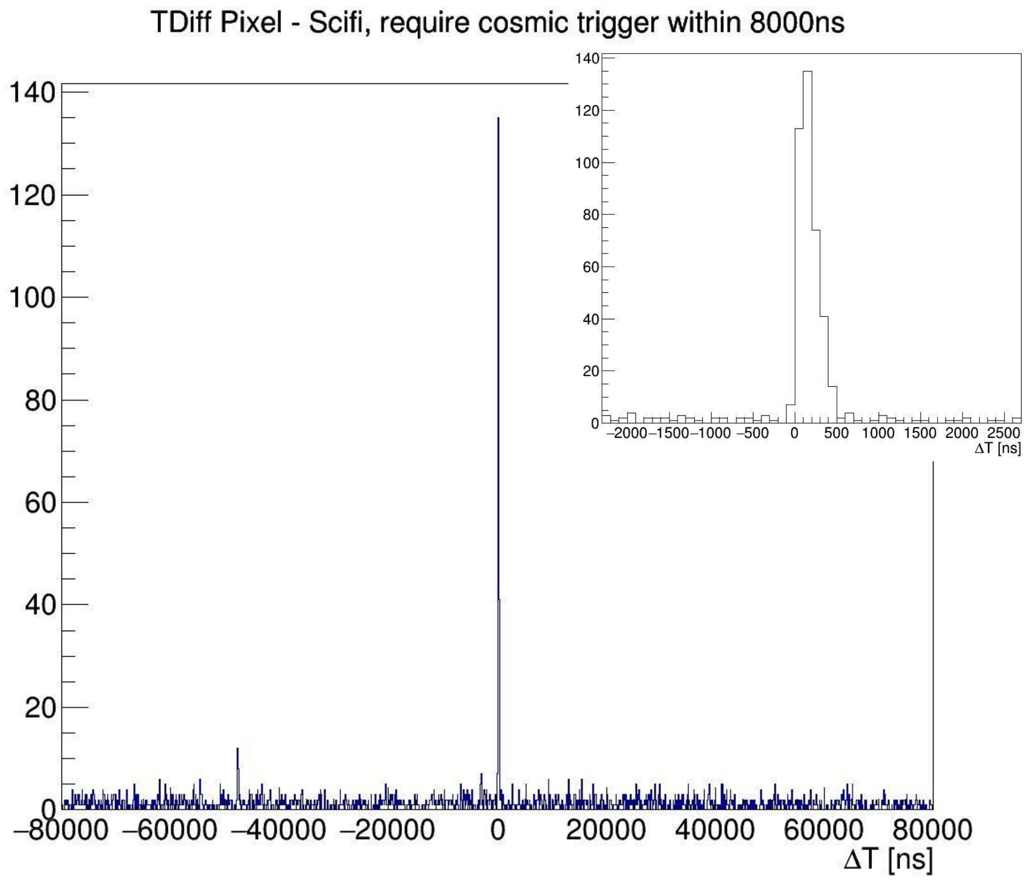






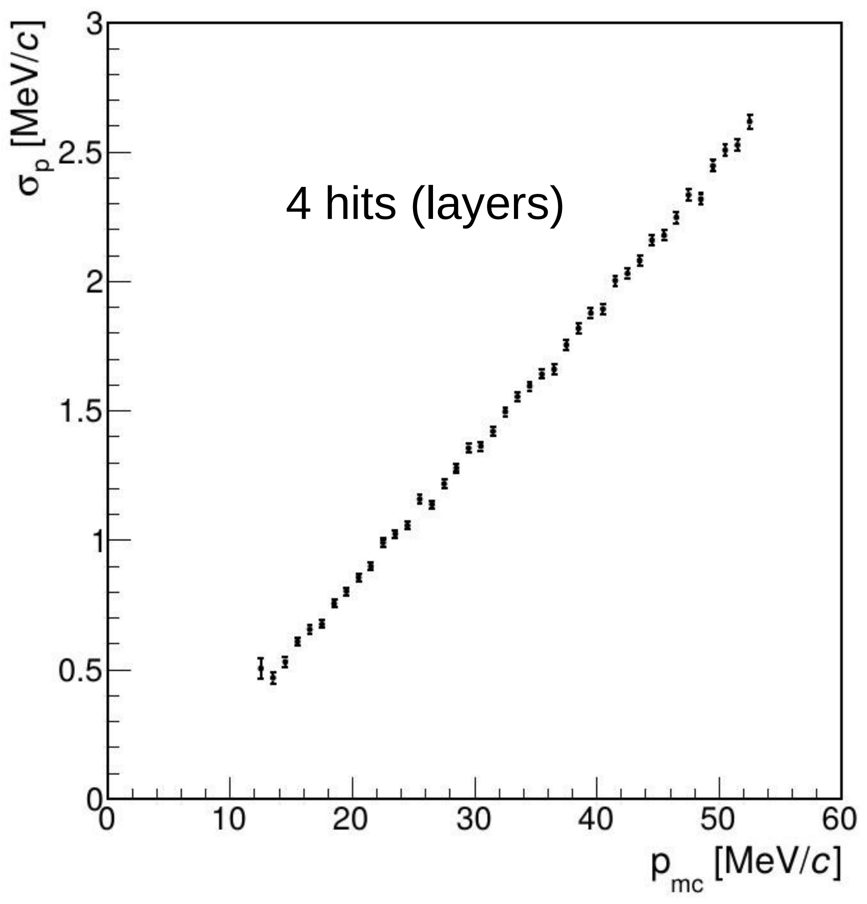


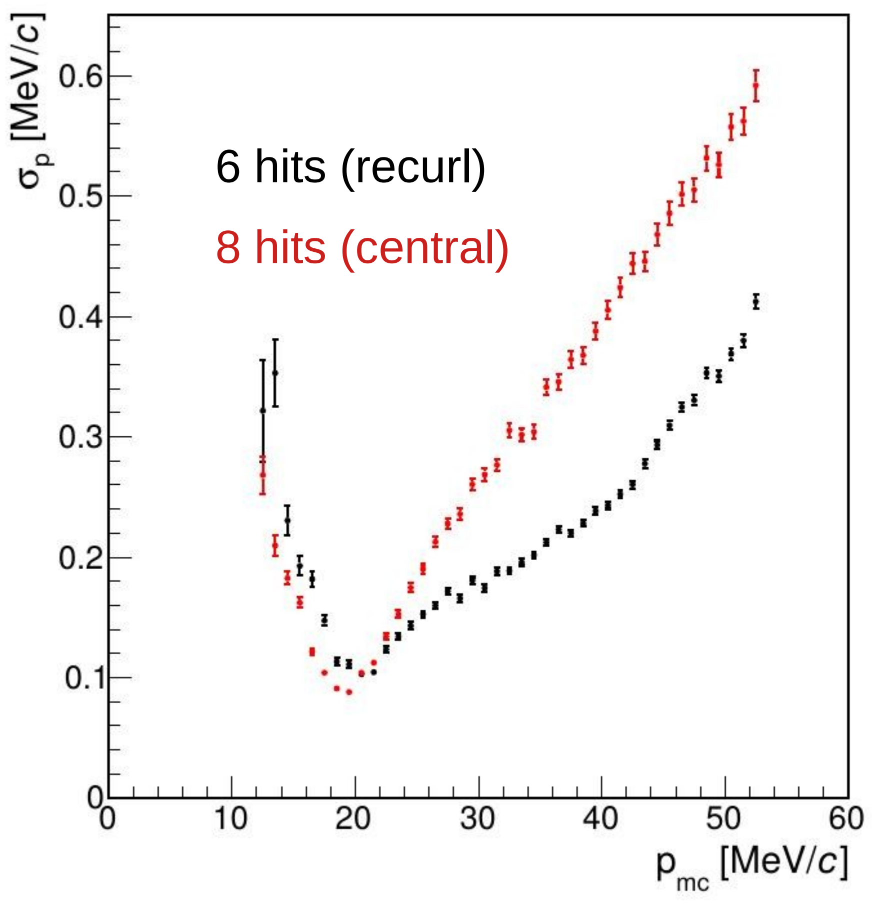


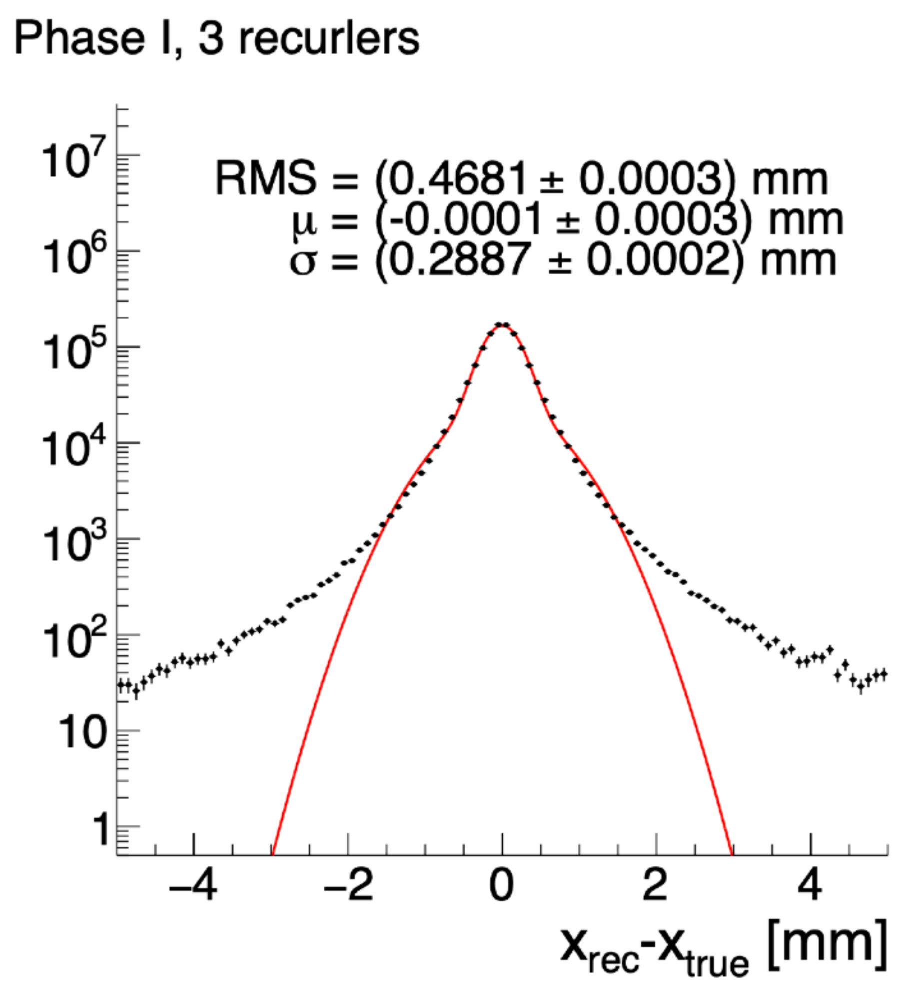


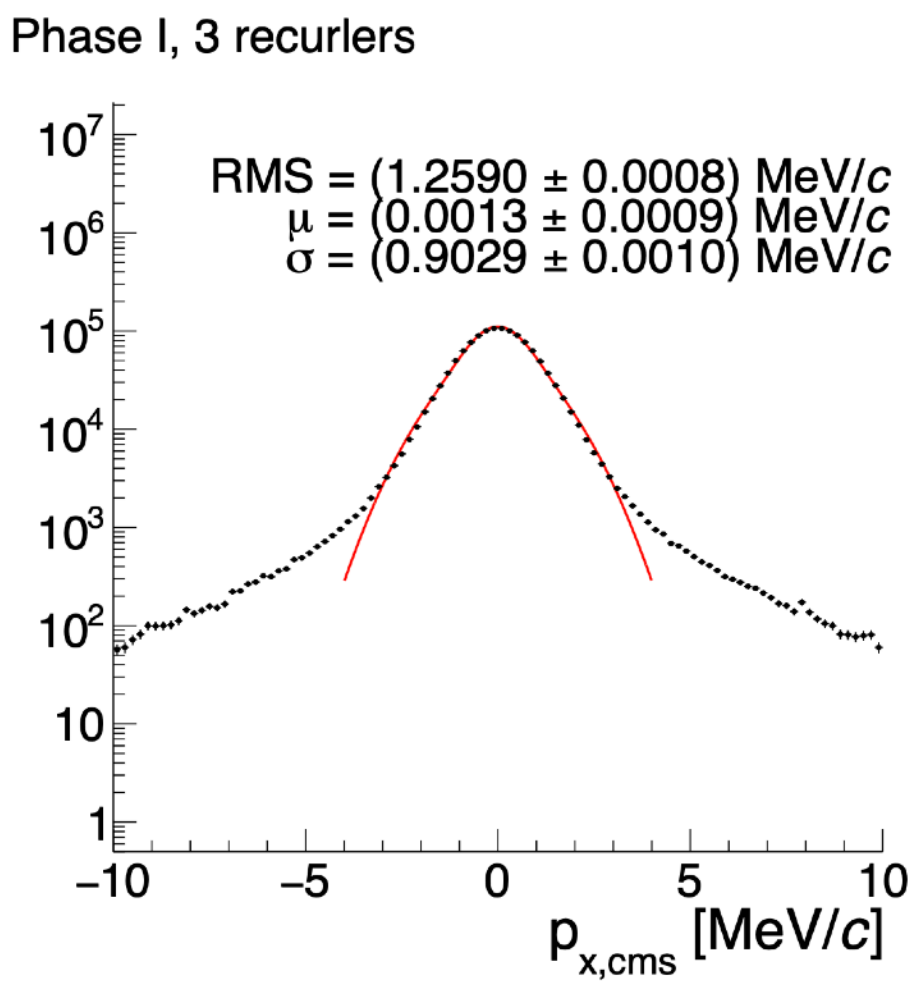
Mu3e Experiment

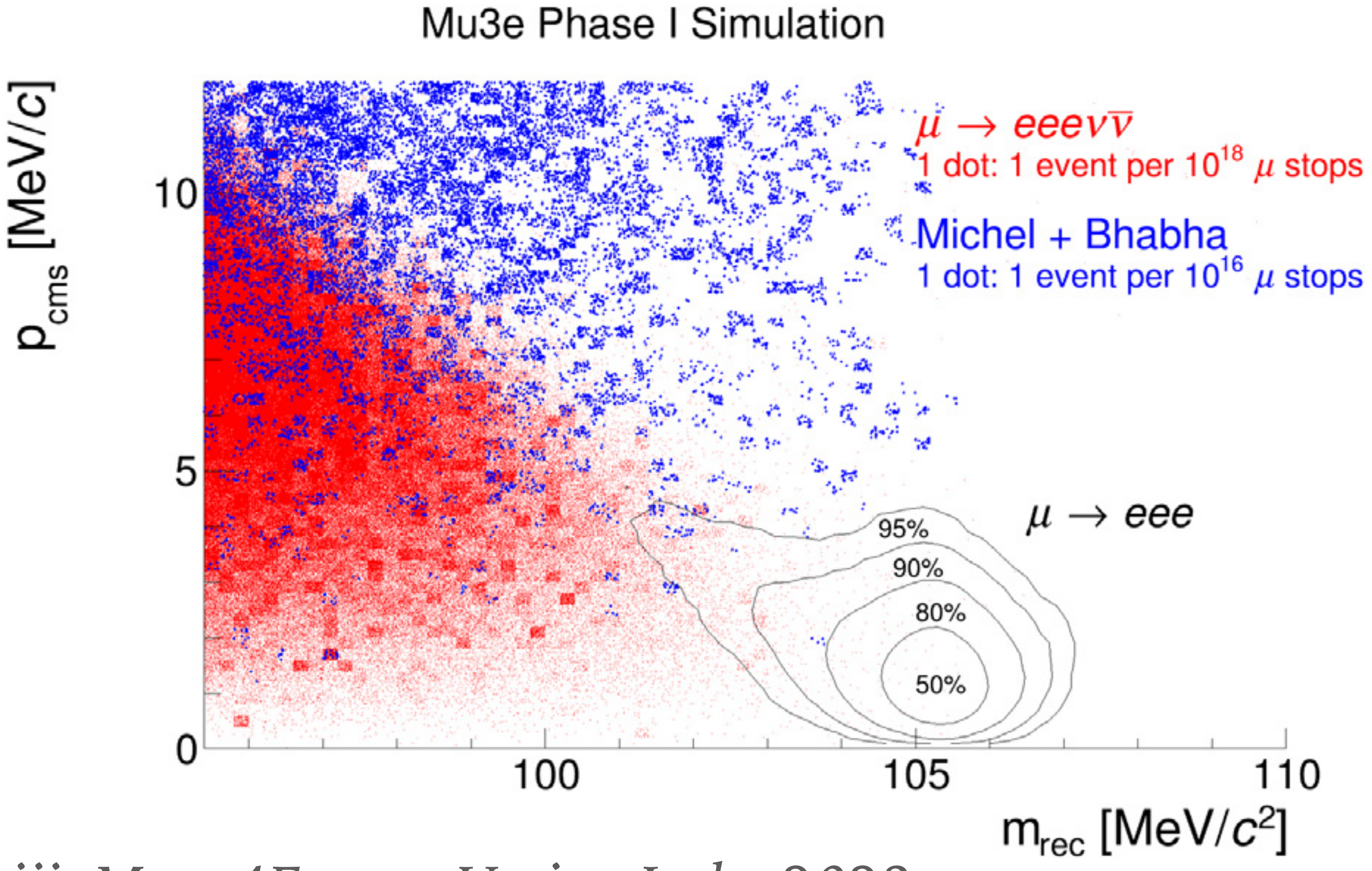
Special thanks to Cristina Martin Perez

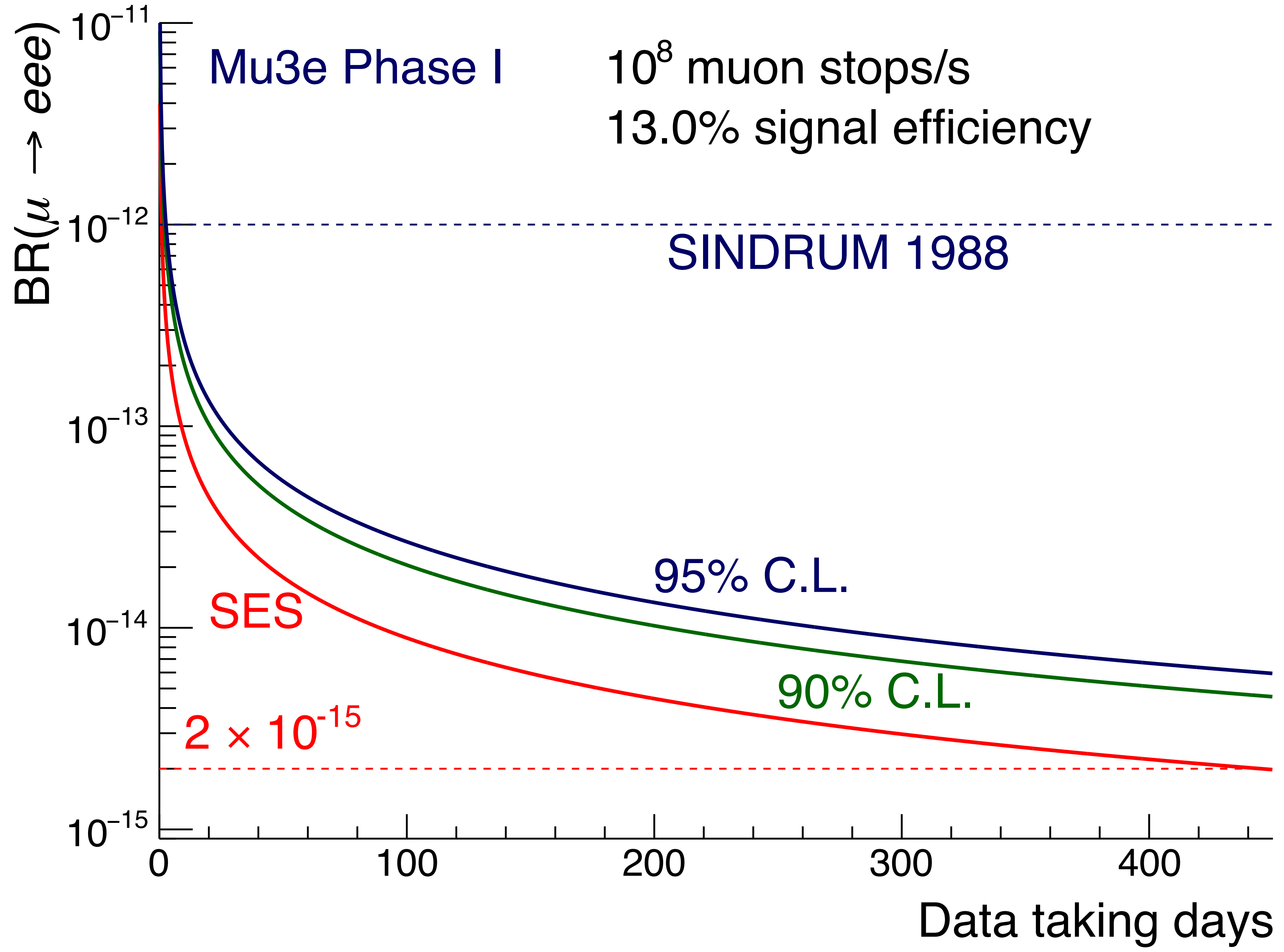












Link to the Mu3e TDR

Mu3e Experiment

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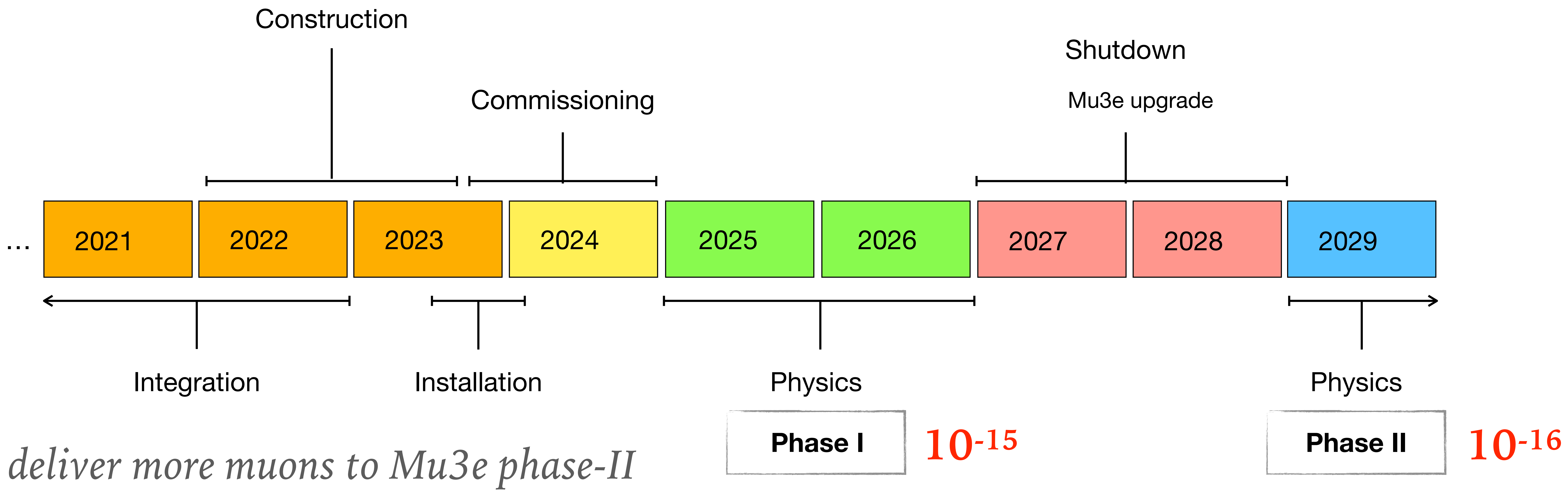
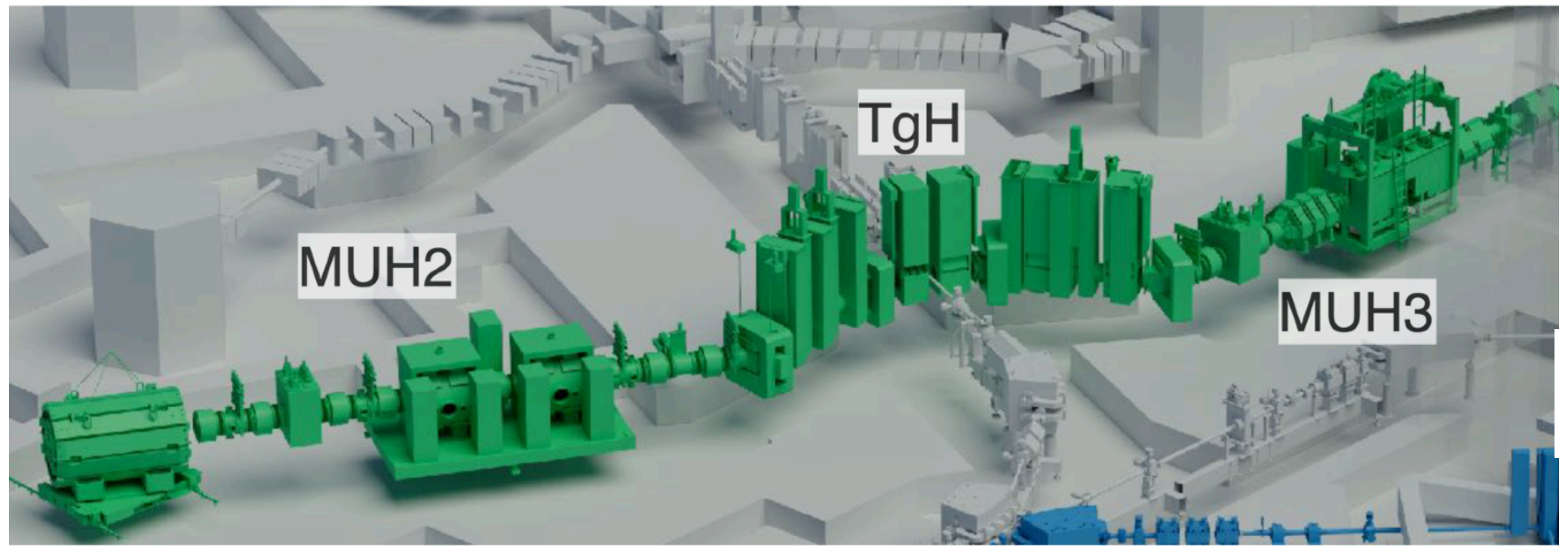
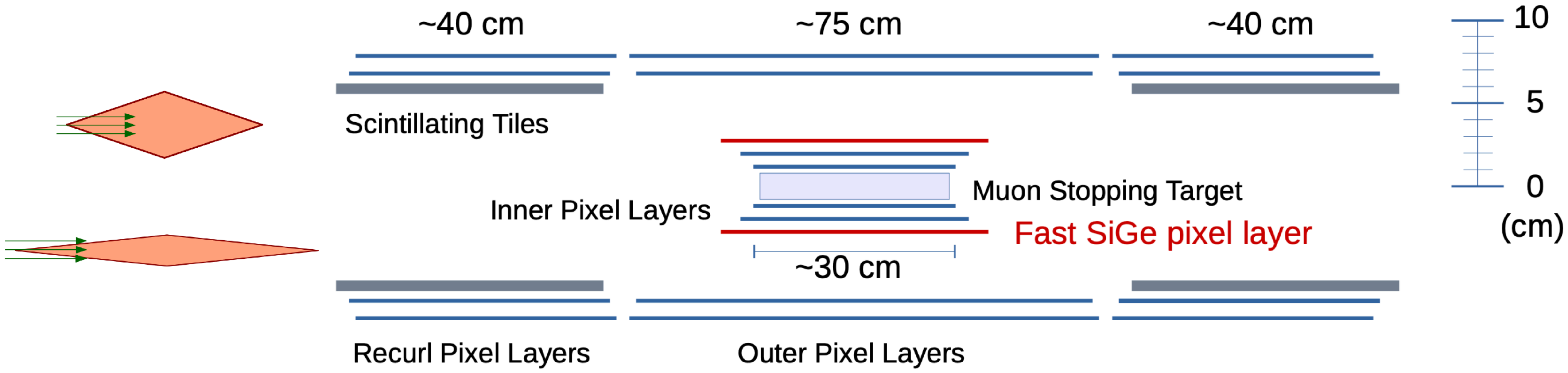


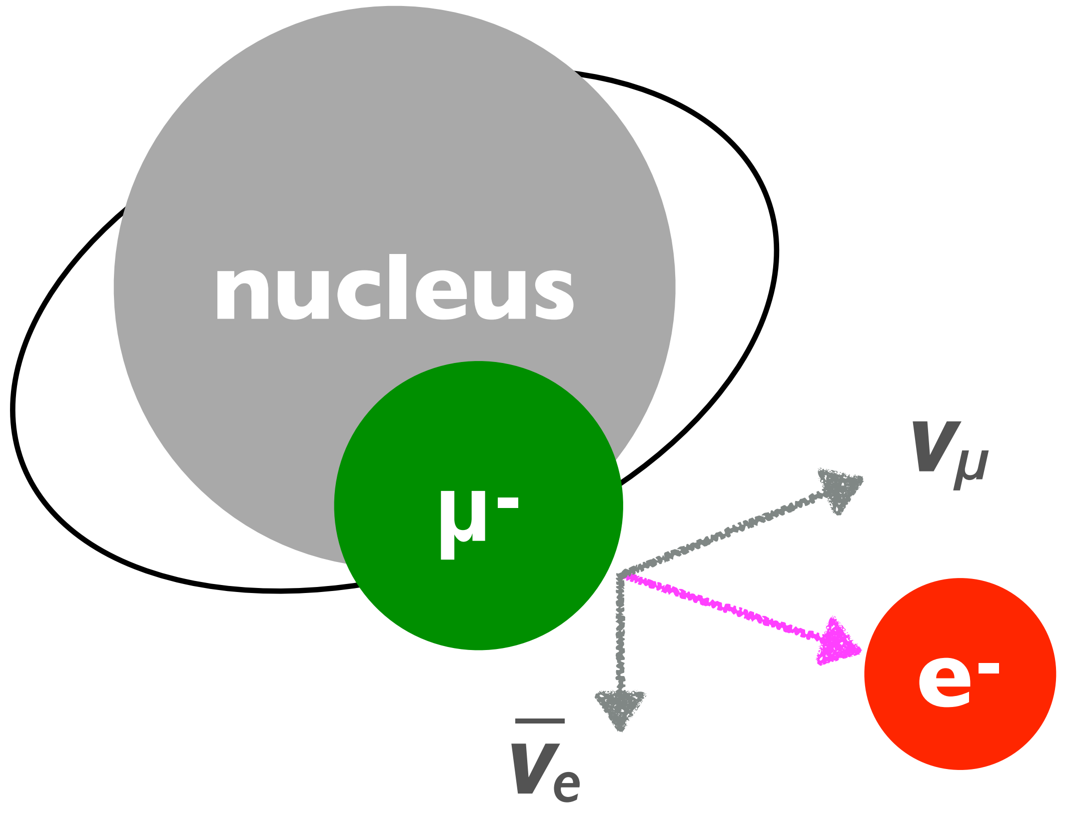
PSI HIMB will deliver more muons to Mu3e phase-II
See A. Papa's talk for more details

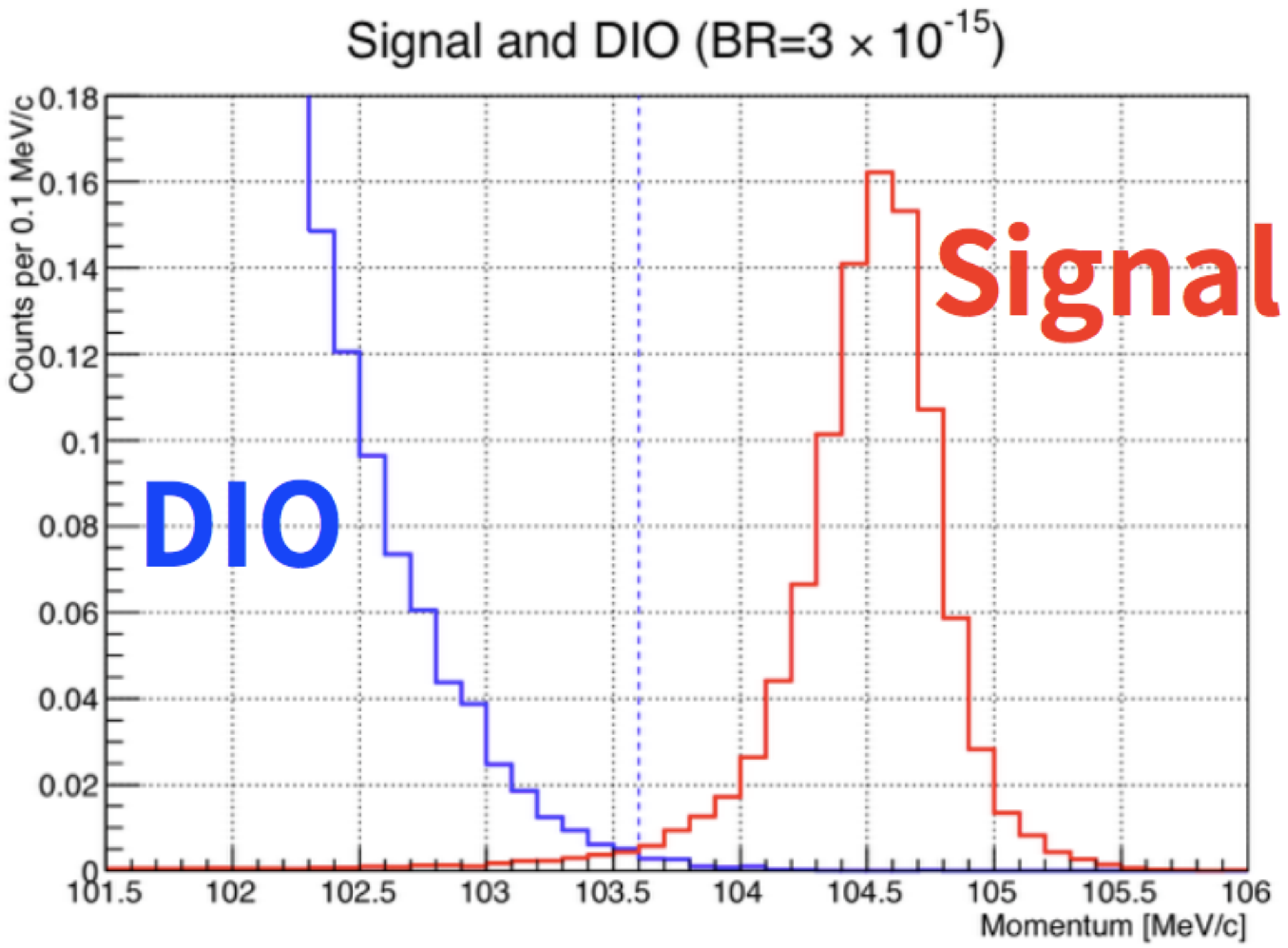




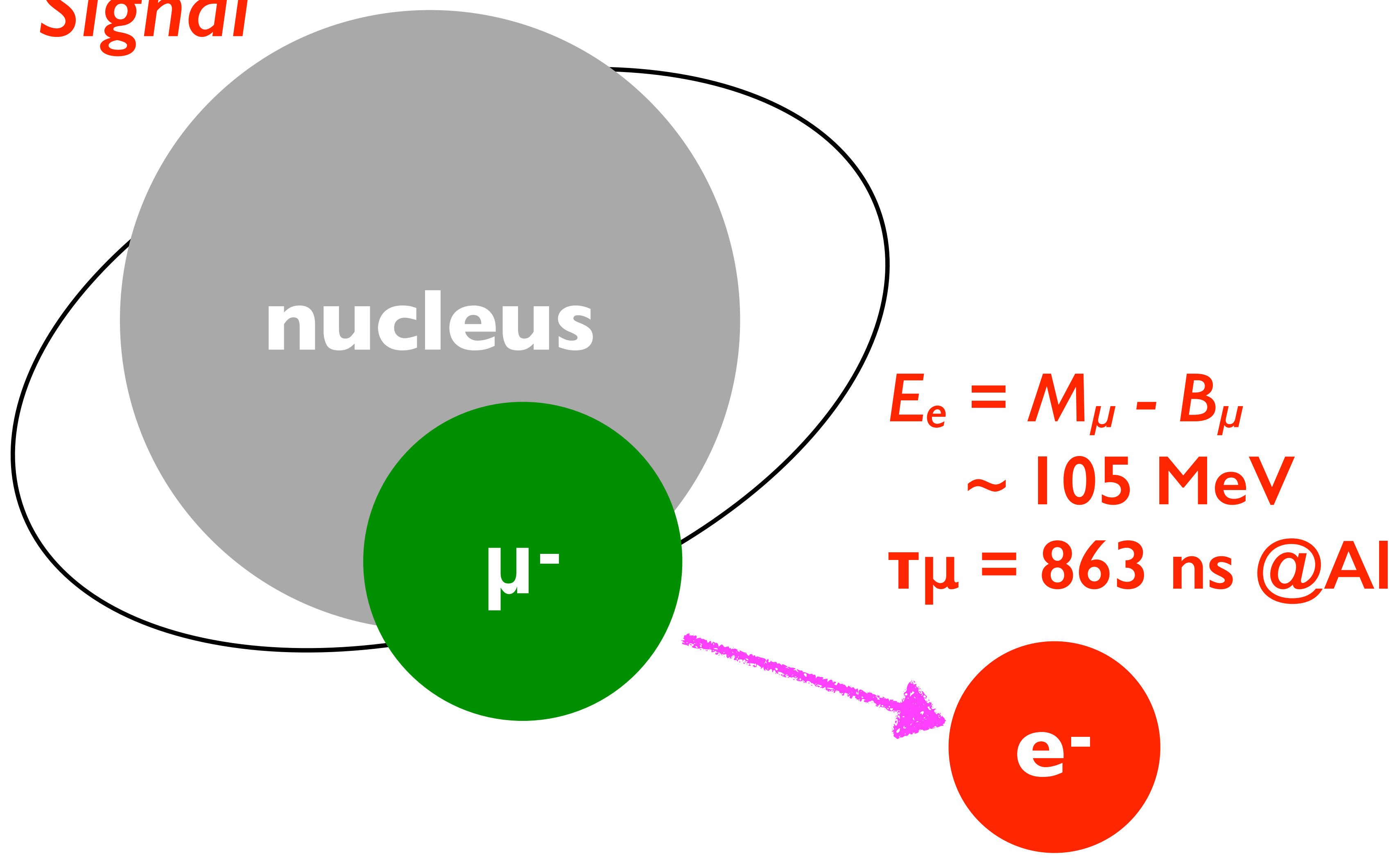
$\mu^- N \rightarrow e^- N$

Decay In Orbit (DIO)

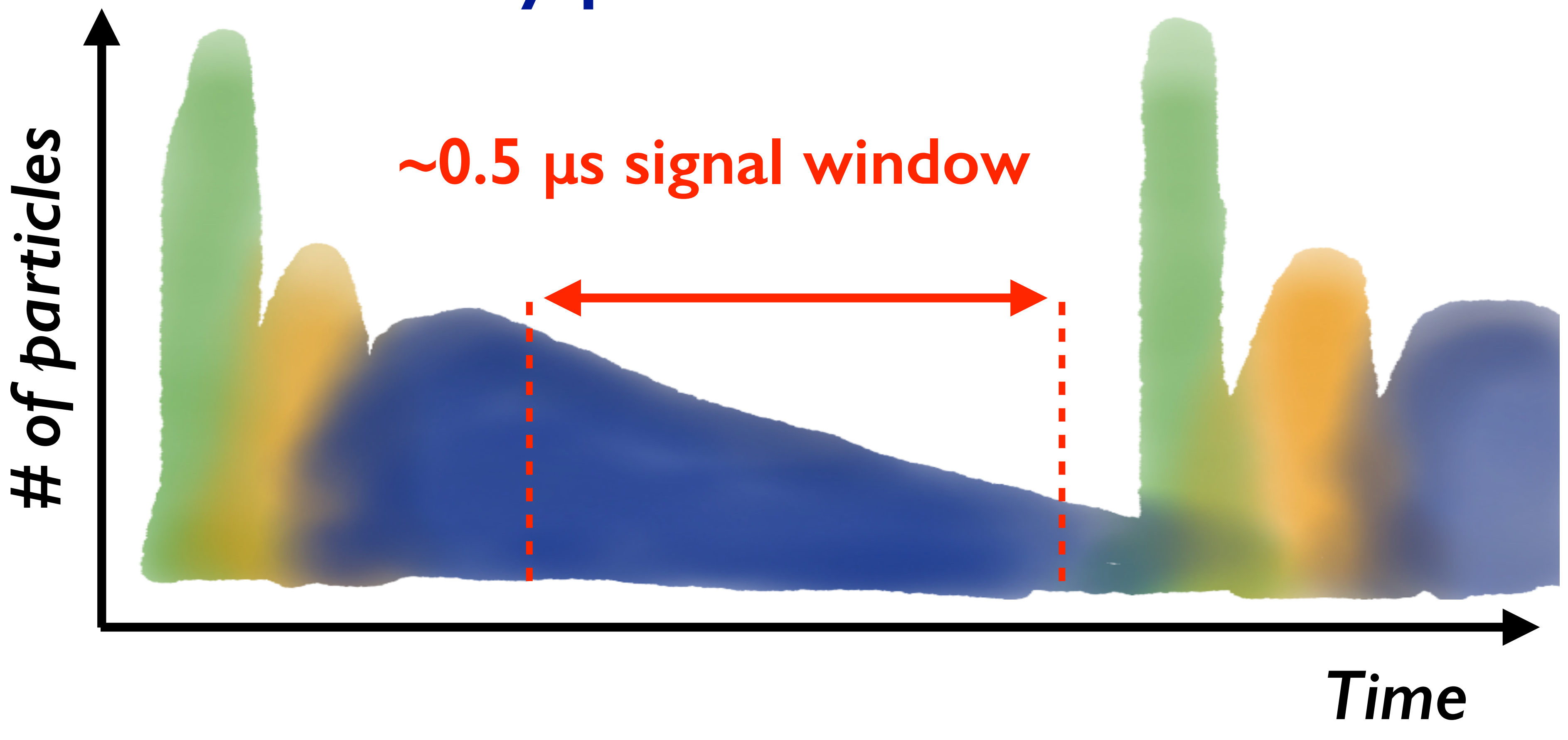




Signal

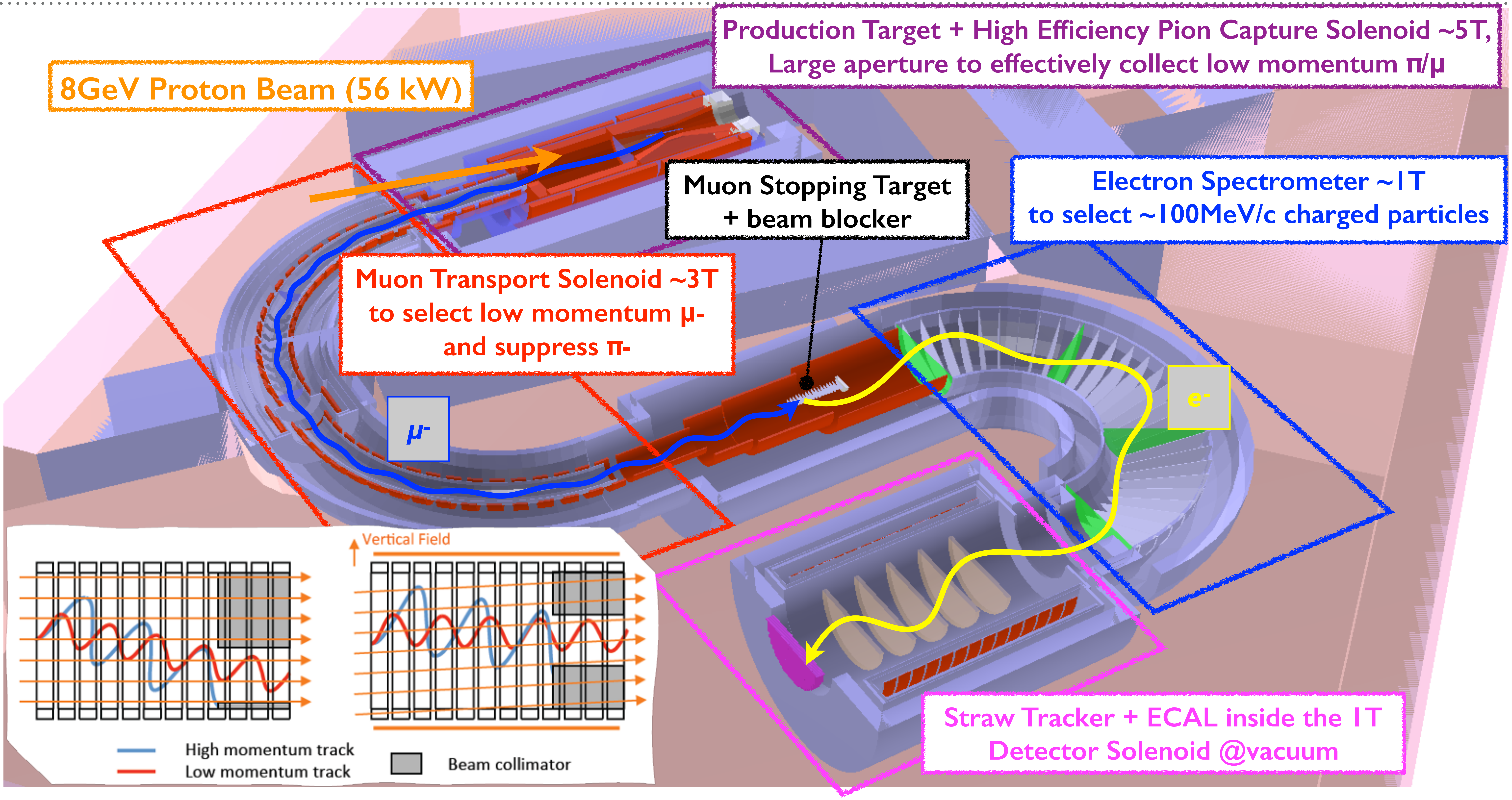


Main beam pulse
Prompt beam induced particles
Muon decay products

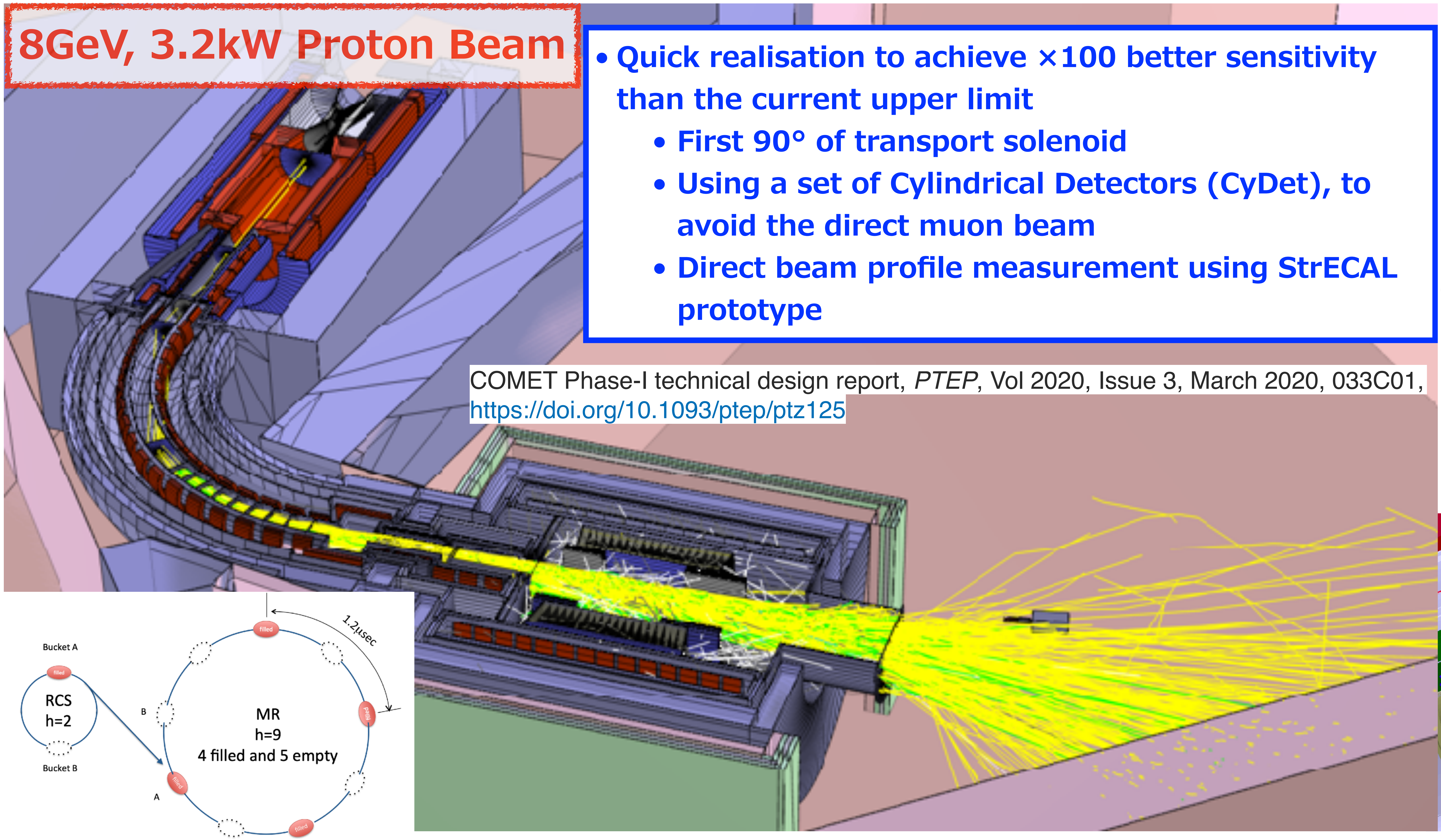


- Single electron with a mono-energy of ~105 MeV
  - No accidental coincidence
  - **sensitivity ∝ beam intensity ➡ more & more muons!**
- Pulsed-beam + delayed time window to sweep out all beam prompt backgrounds

The COMET Experiment



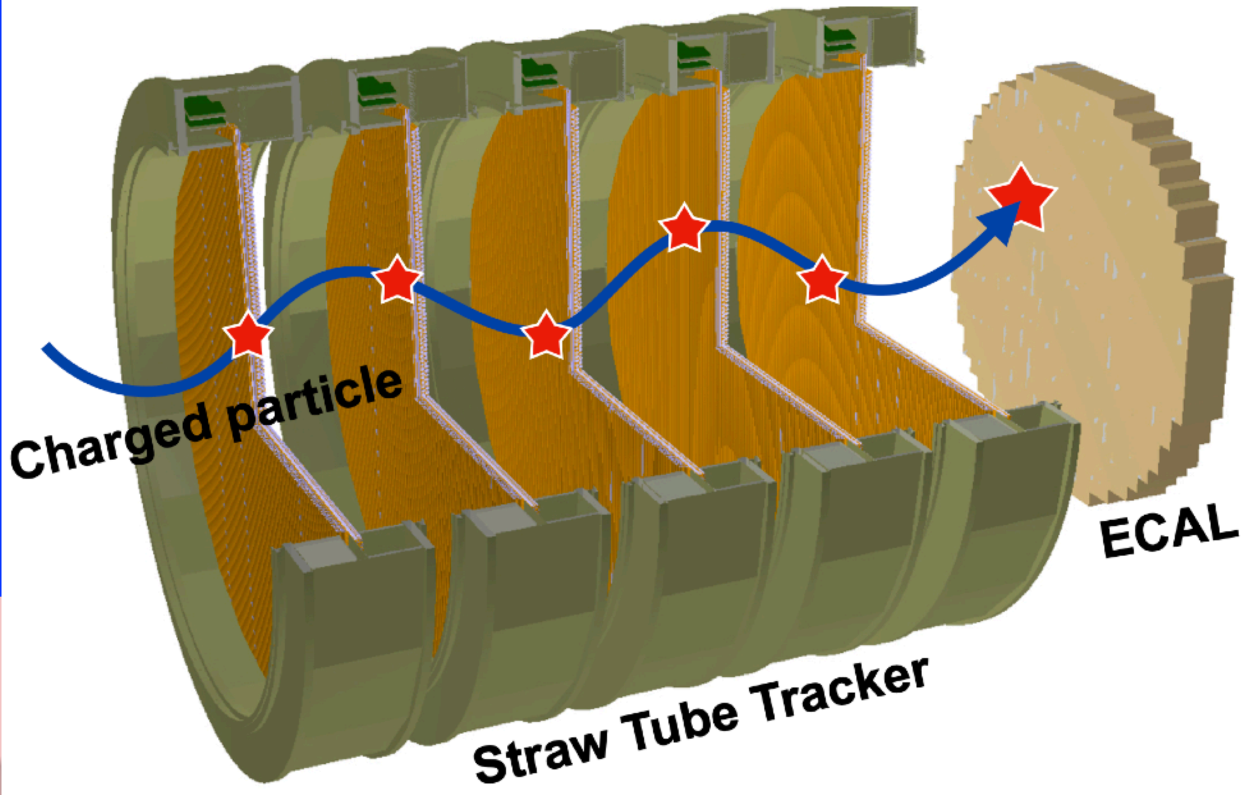
COMET Phase-I



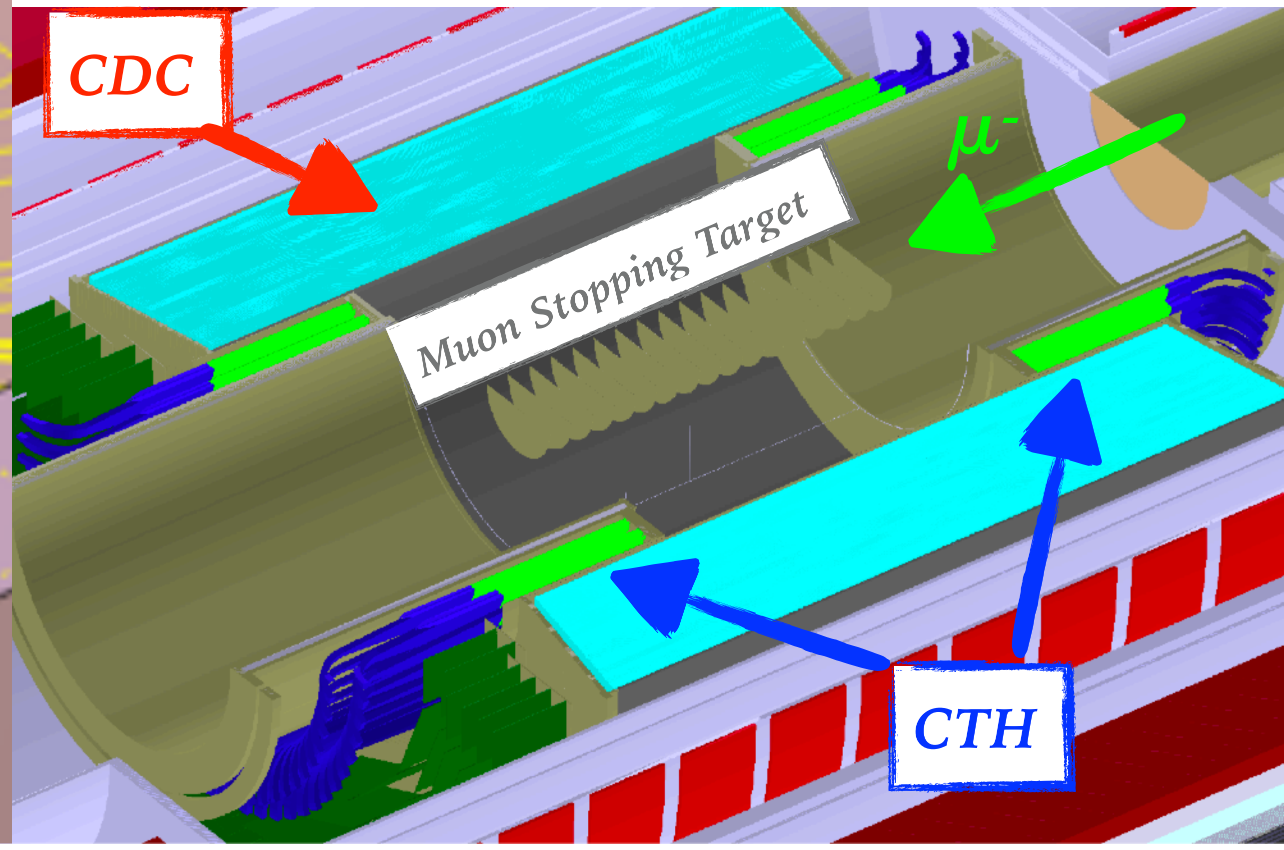
- Quick realisation to achieve ×100 better sensitivity than the current upper limit
  - First 90° of transport solenoid
  - Using a set of Cylindrical Detectors (CyDet), to avoid the direct muon beam
  - Direct beam profile measurement using StrECAL prototype

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

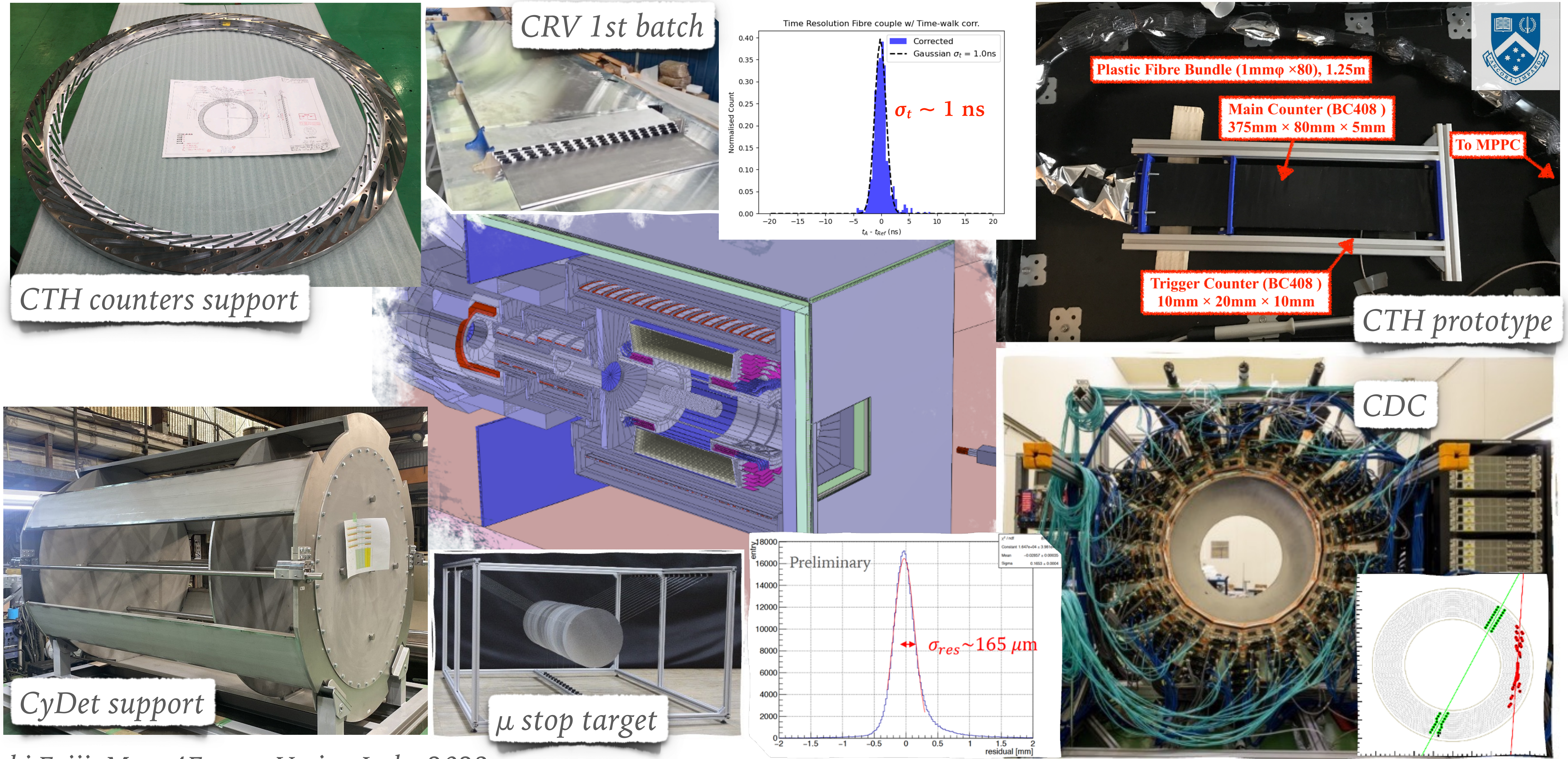
StrECAL for beam measurement



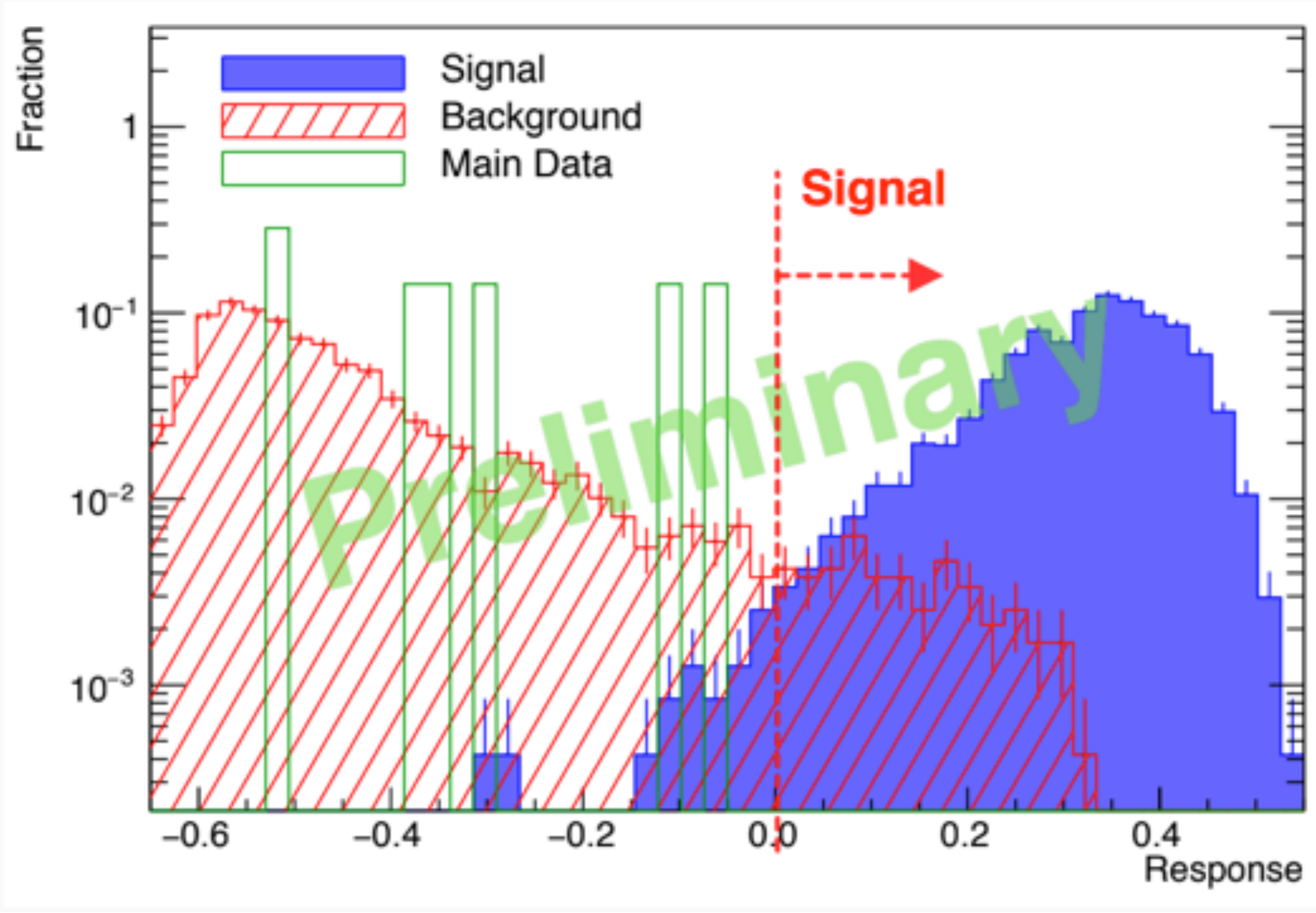
CyDet for Phase-I physics

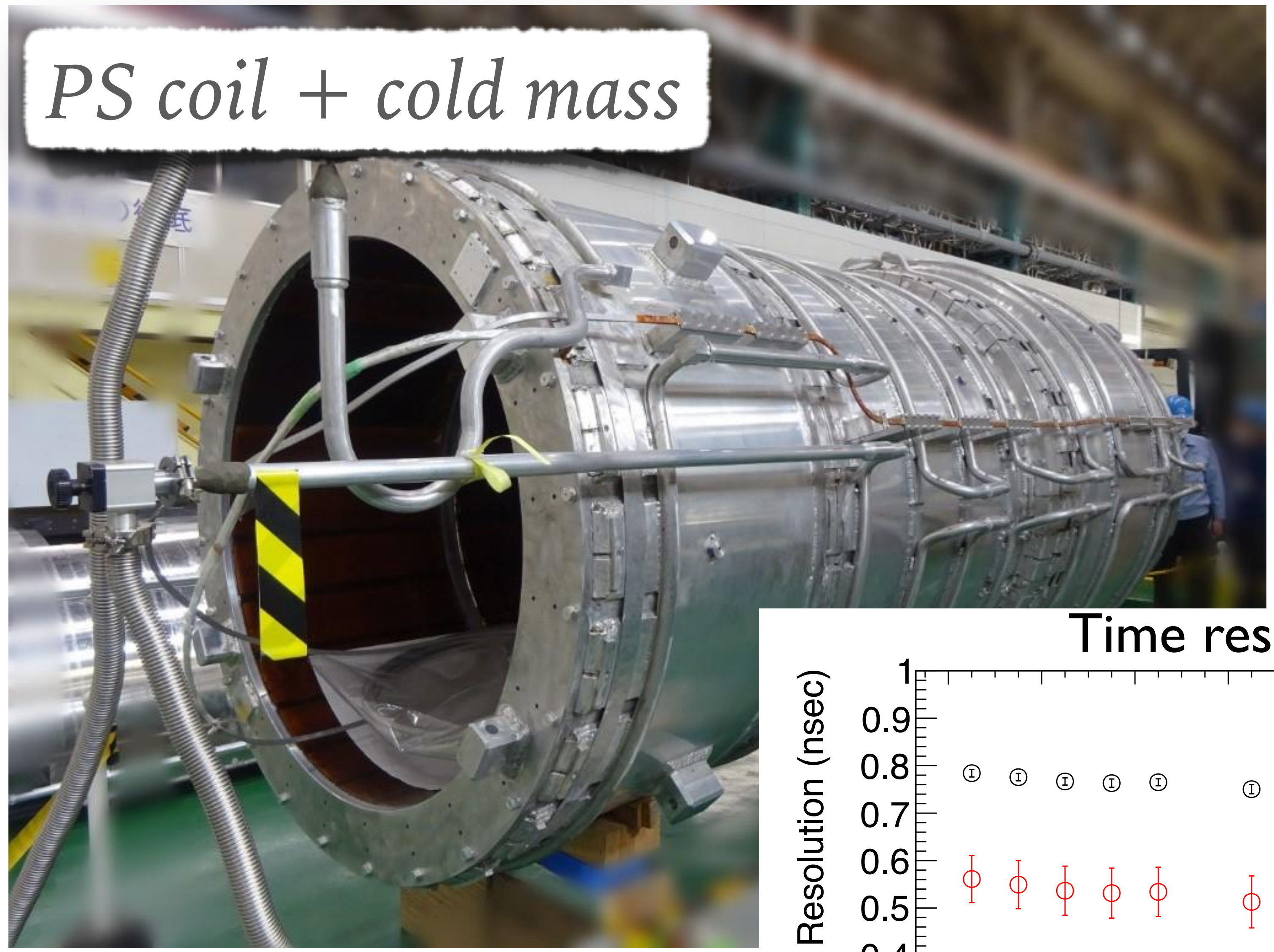


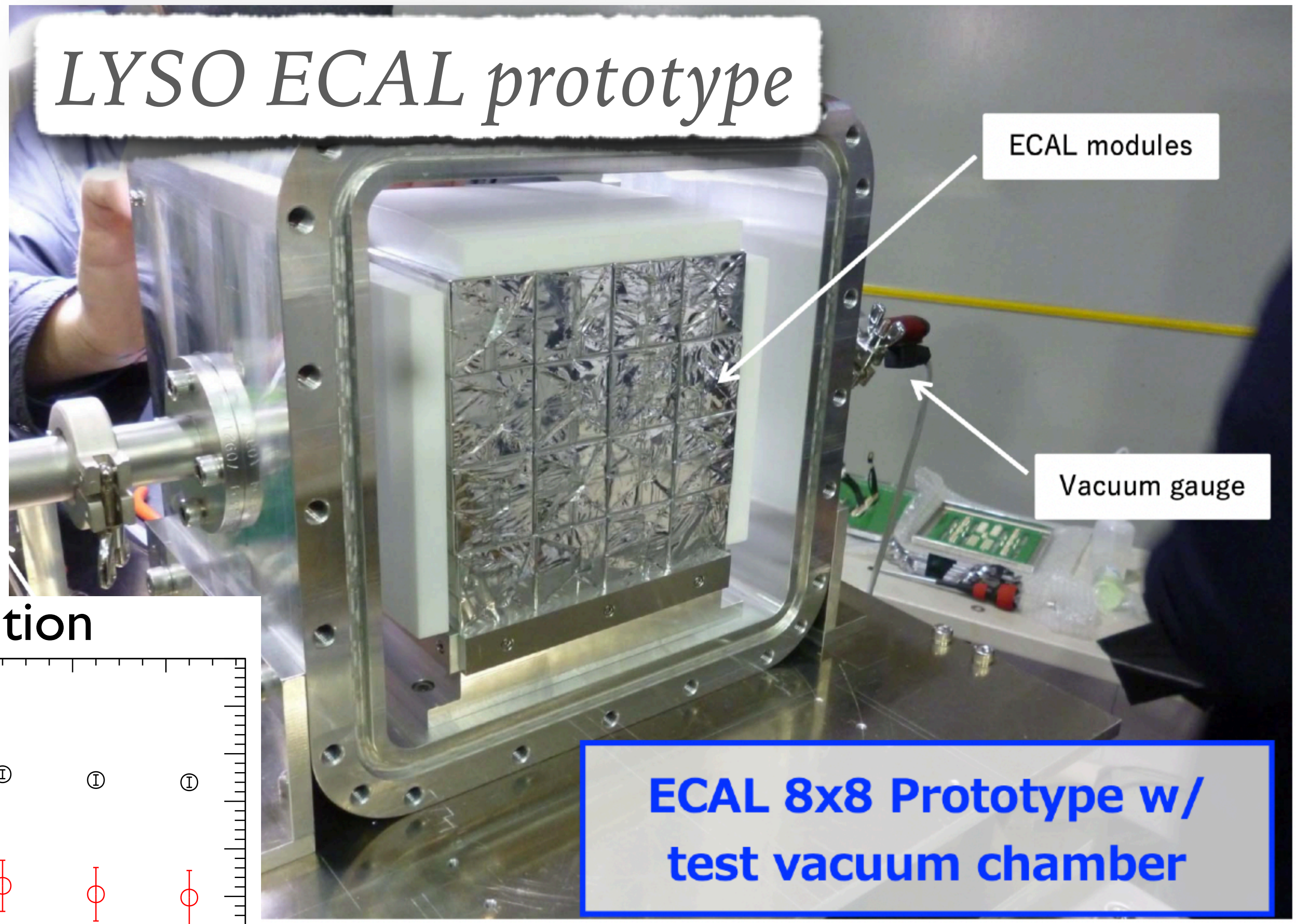
COMET Phase-I CyDet

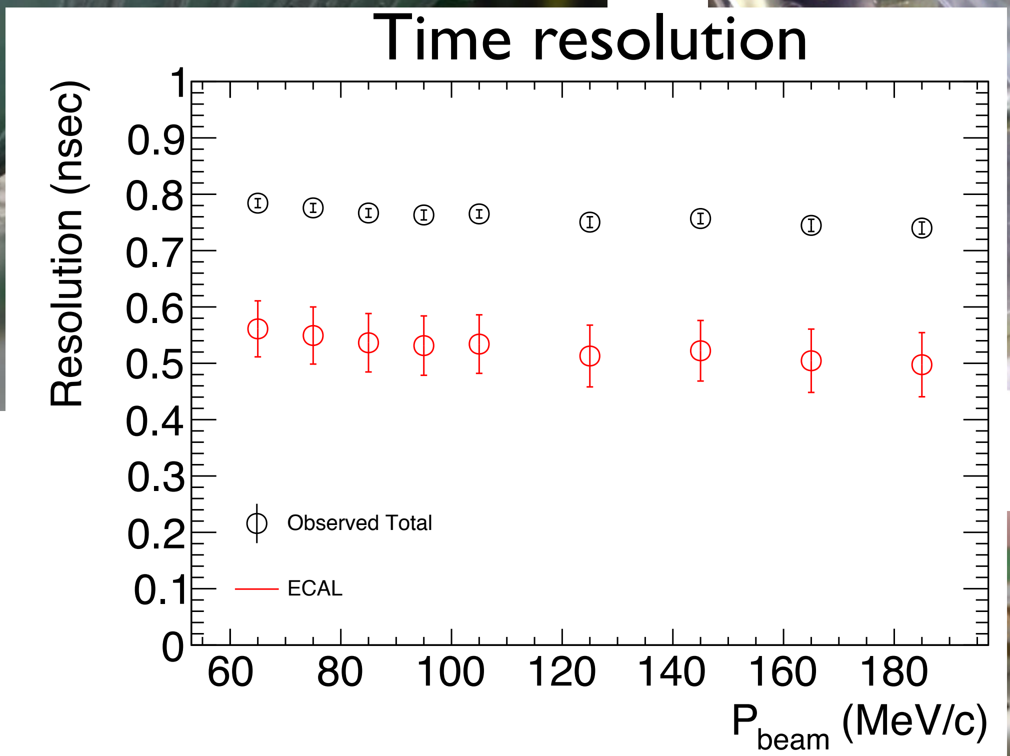


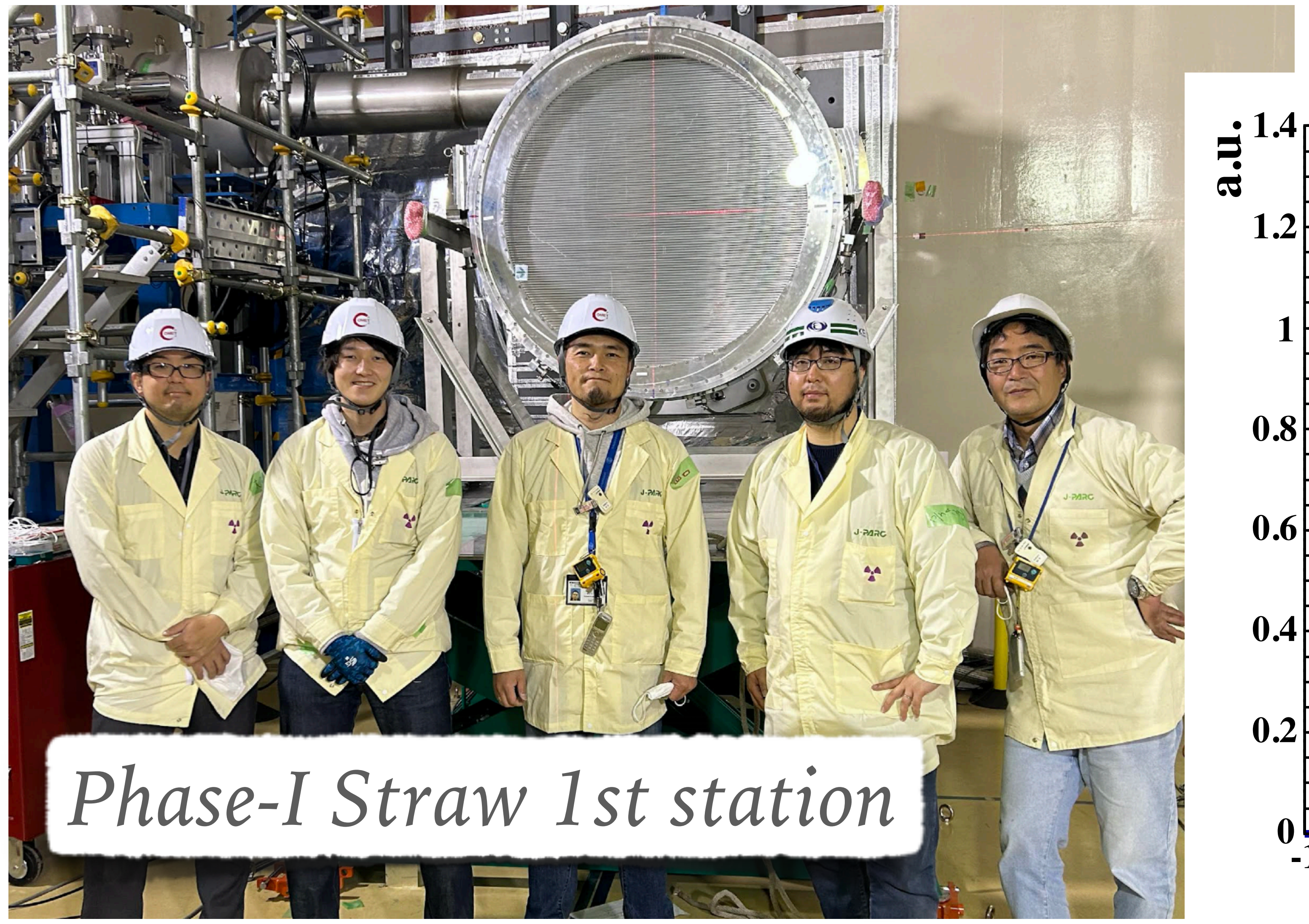
COMET Phase-I Others

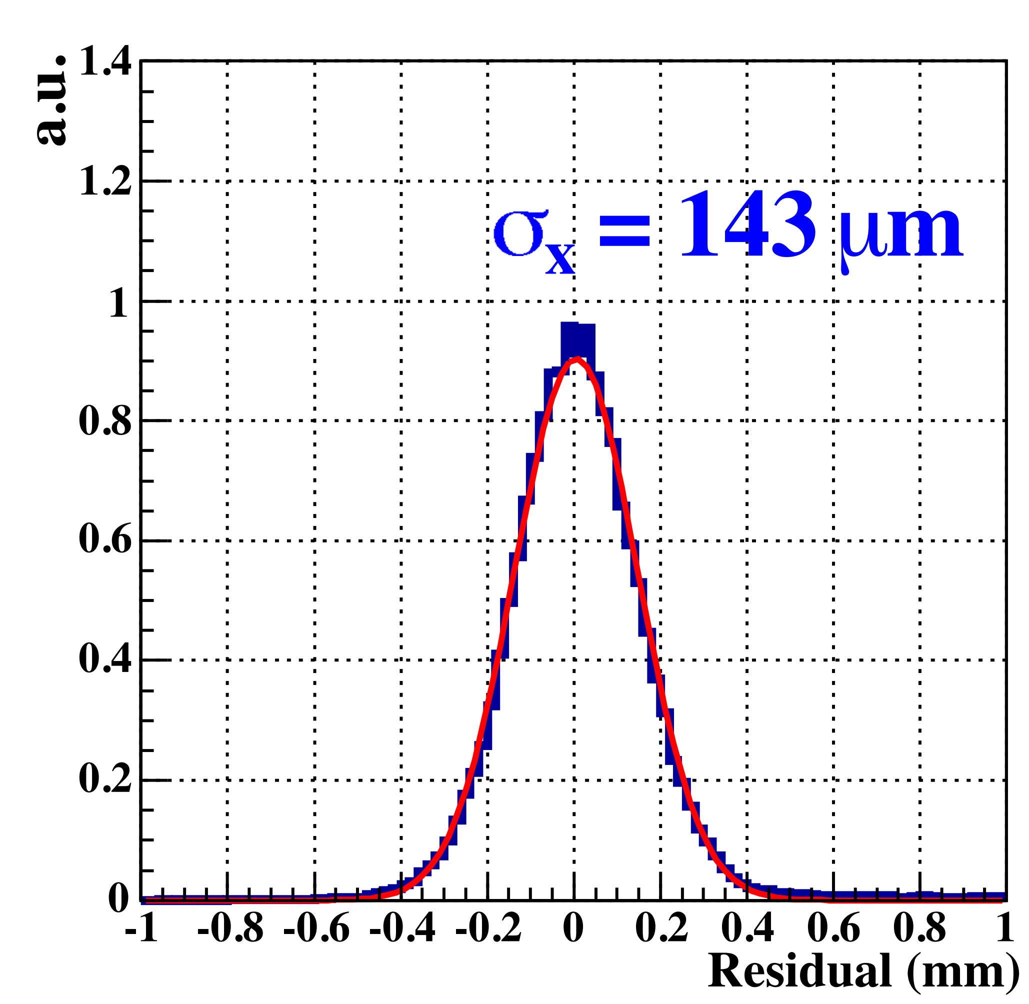


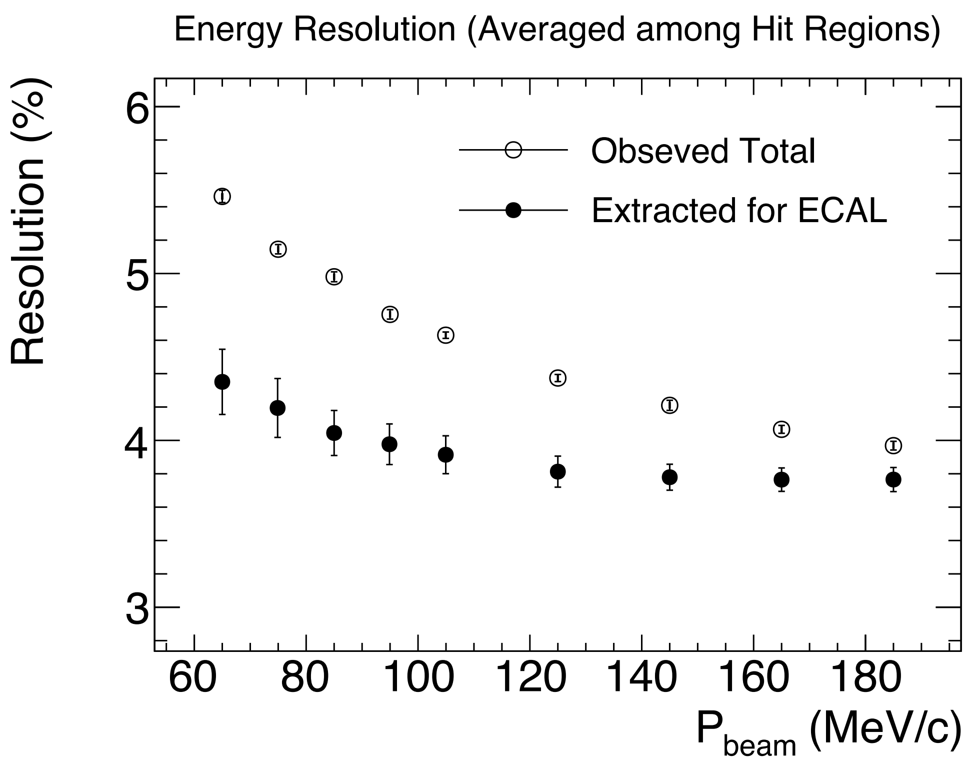


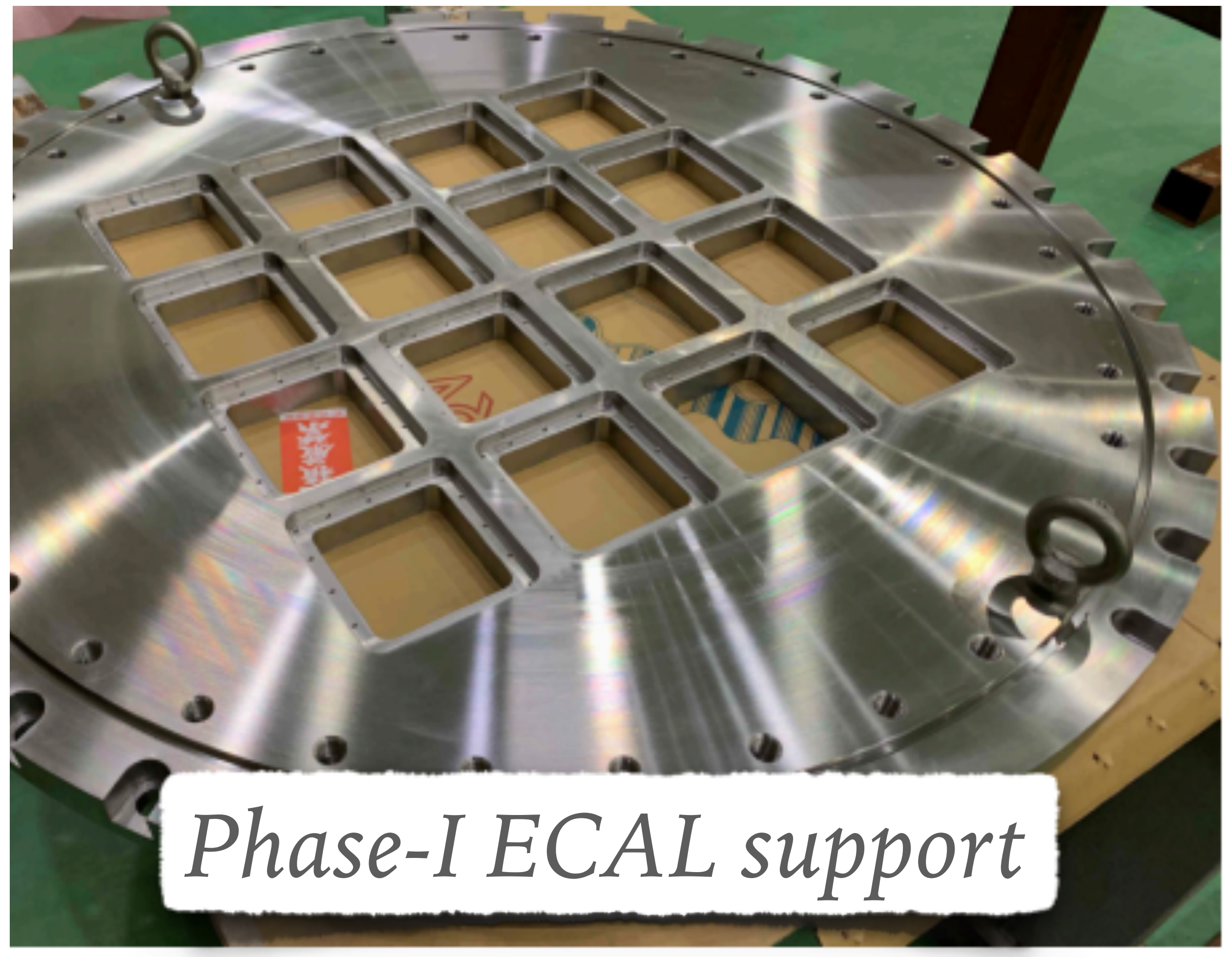












COMET Phase-I

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

Physics data taking will start in 2024/2025

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..

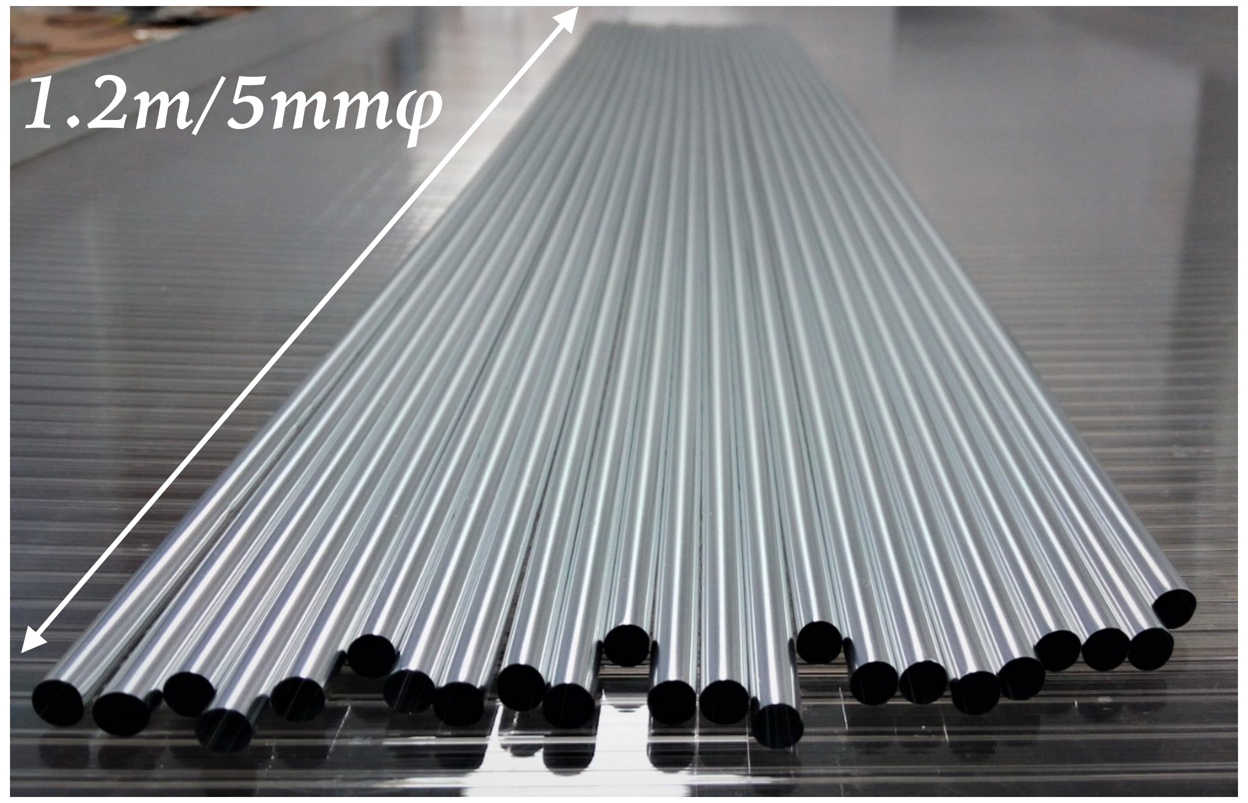
Item	Value	Comment
Acceptance	0.2	Fixed
Trigger/DAQ efficiency	0.8	Subject to change
Track finding efficiency	0.99	SC
Track selection	0.9	SC
Momentum window	0.93	103.6 MeV/c < p < 106.0 MeV/c
Timing window	0.3	700 < t < 1170 ns, SC
Total A_μ	0.04	At least 25% error

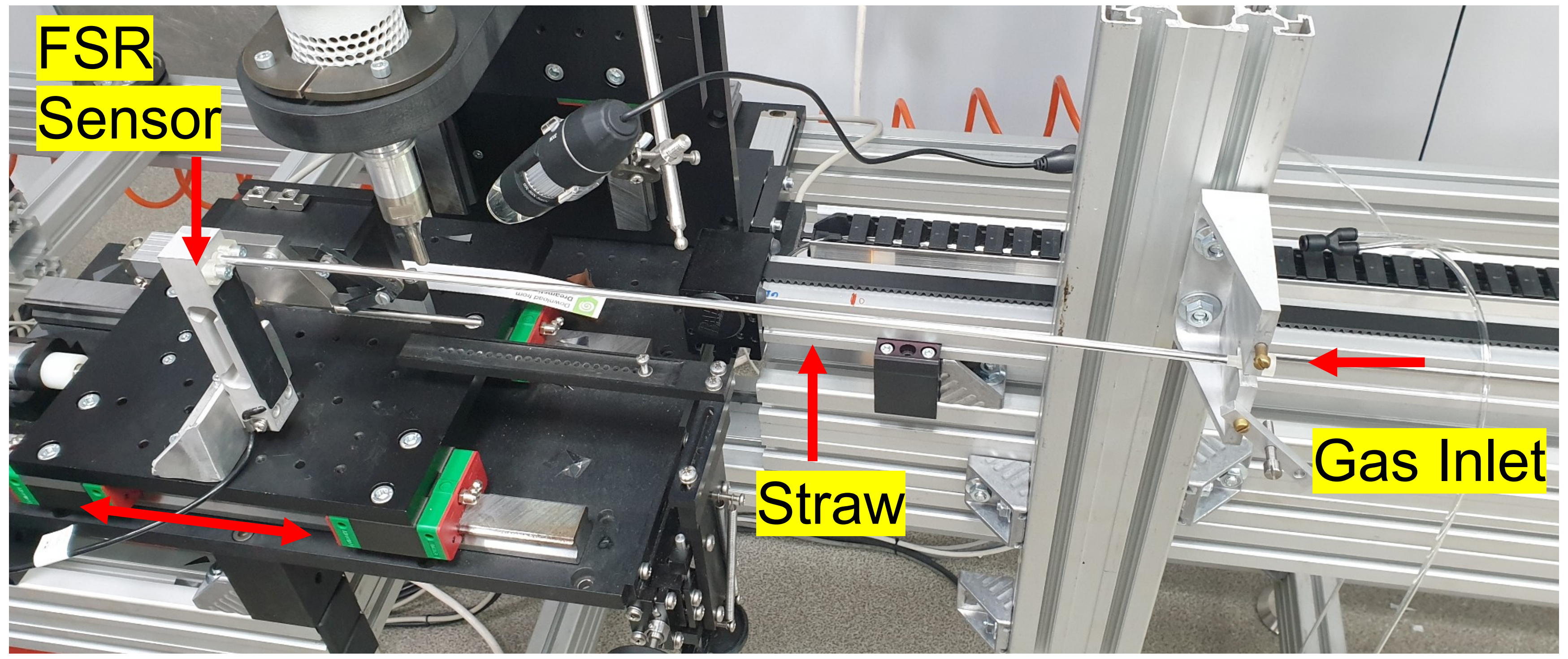
Type	Background	Estimated events
Physics	Muons decay in orbit	0.01
	Radiative muon campture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particles after μ capture	< 0.001
Prompt beam	Beam e^+/e^-, μ/π decay-in-flight, others	Total < 0.0038
	Radiative pion capture	0.0028
Delayed beam	↑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

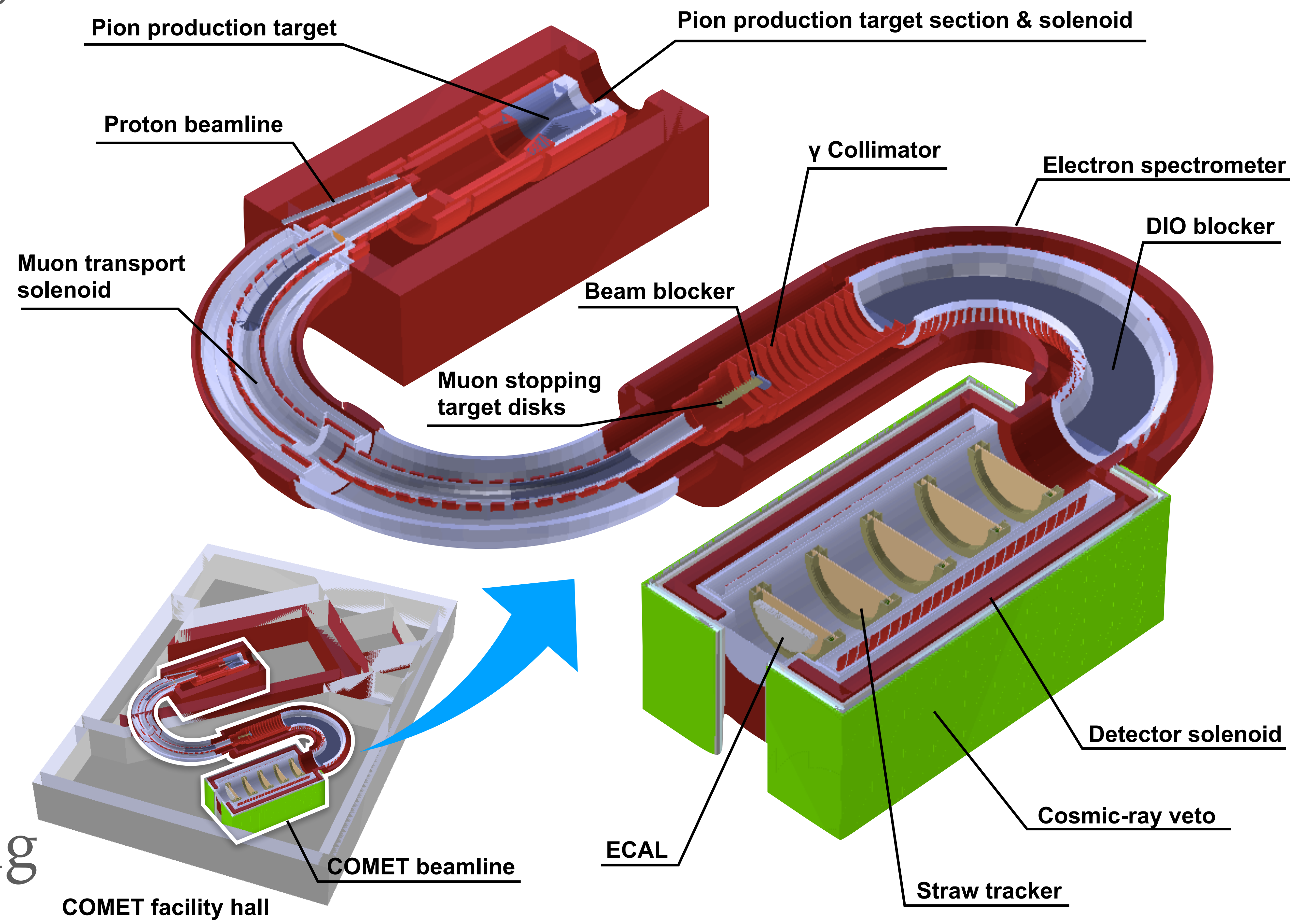
COMET Phase-II

2-3 years after the Phase-I

- New straw tube to reduce the multiple scattering + less pileup hits
  - Reduce the wall thickness from 25 μm to **12** μm and the diameter from 10 mm to **5** mm
  - The prototype tubes have already been produced and being tested





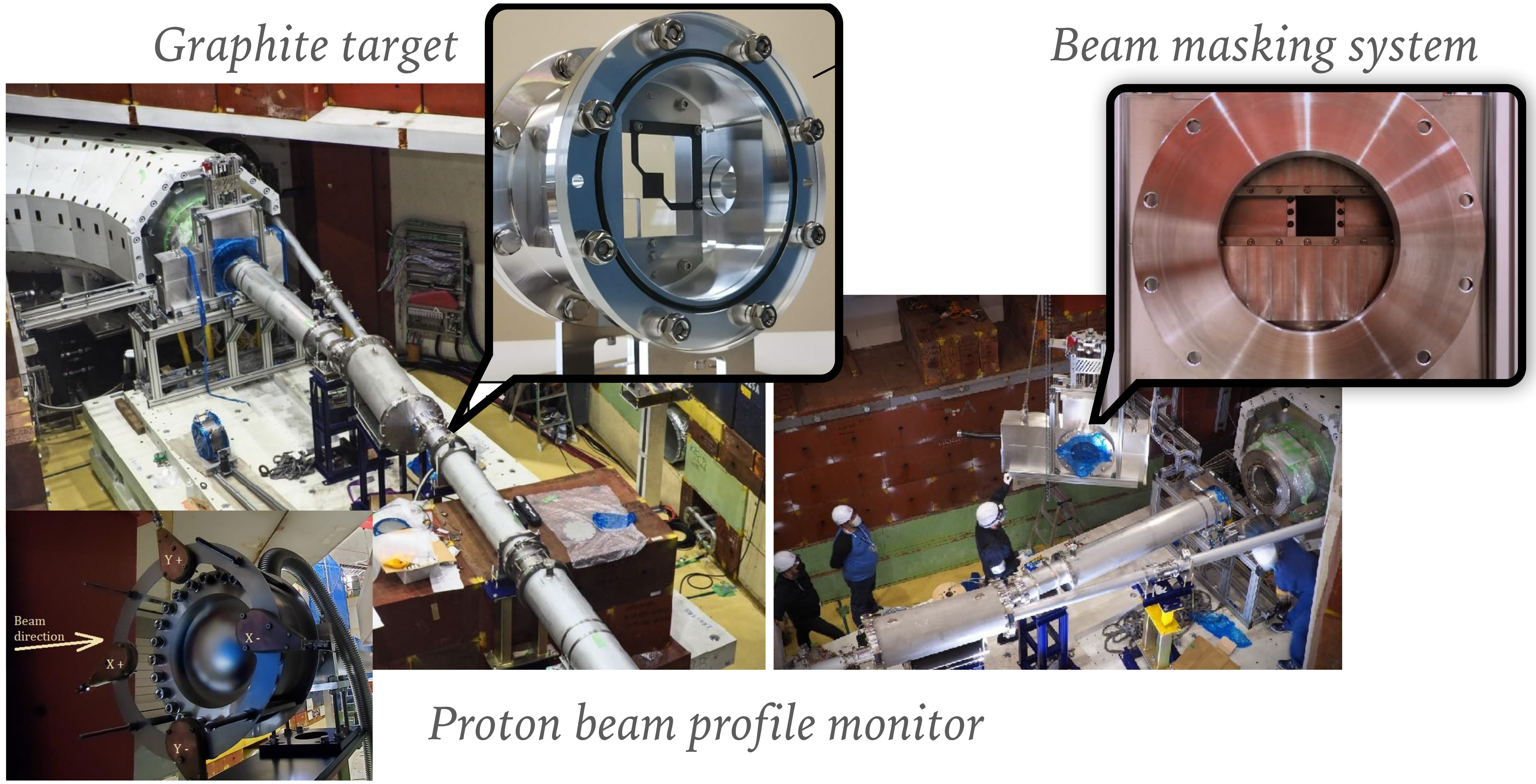


- Simulation studies
  - The simulation study to maximise the sensitivity is ongoing
  - Our current best estimation is **1.4×10^{-17}** in the S.E.S. by optimising the beam-line and the targets (previous estimation was $\sim3\times10^{-17}$)

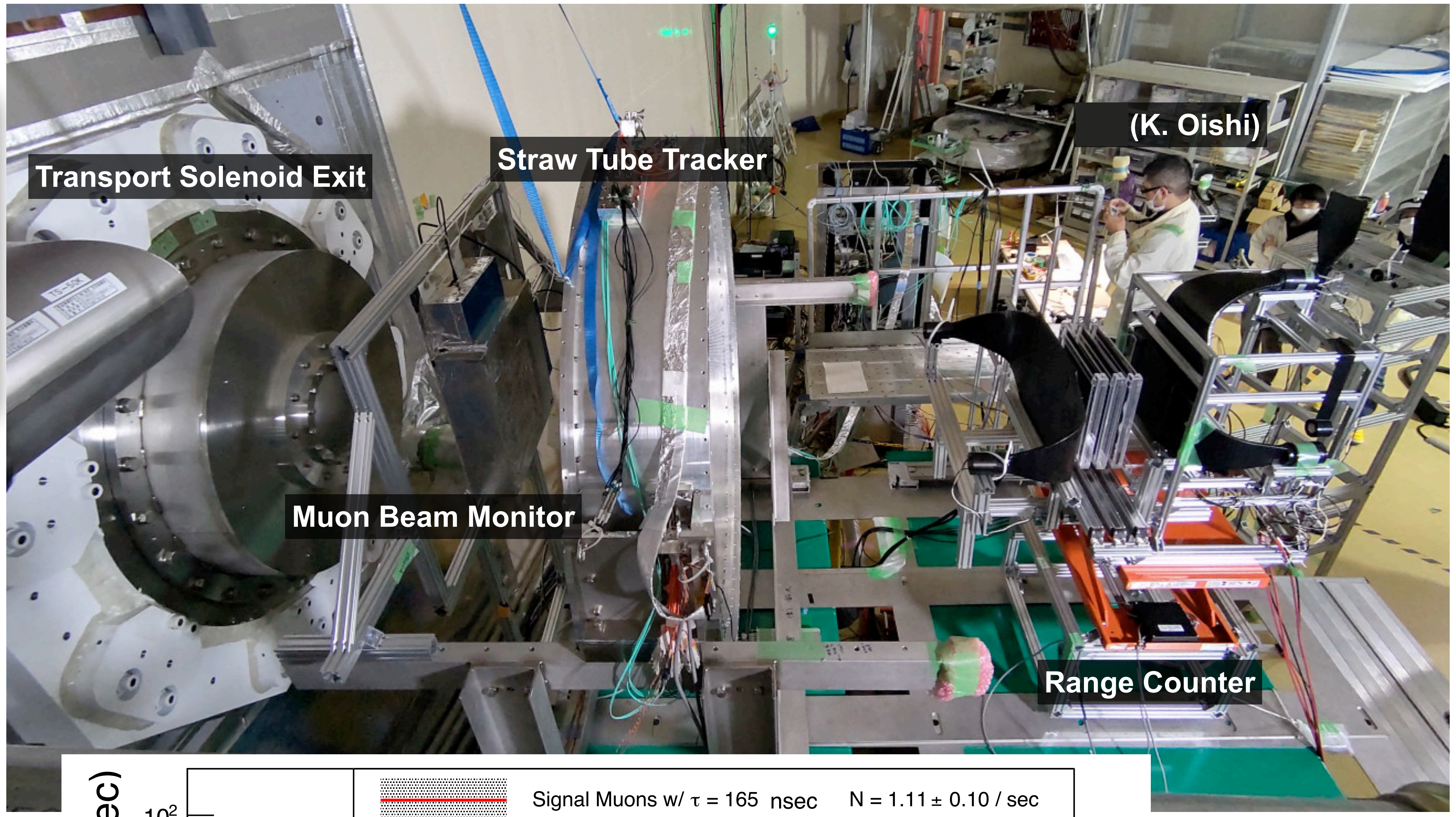
K. Oishi, PhD thesis in 2020

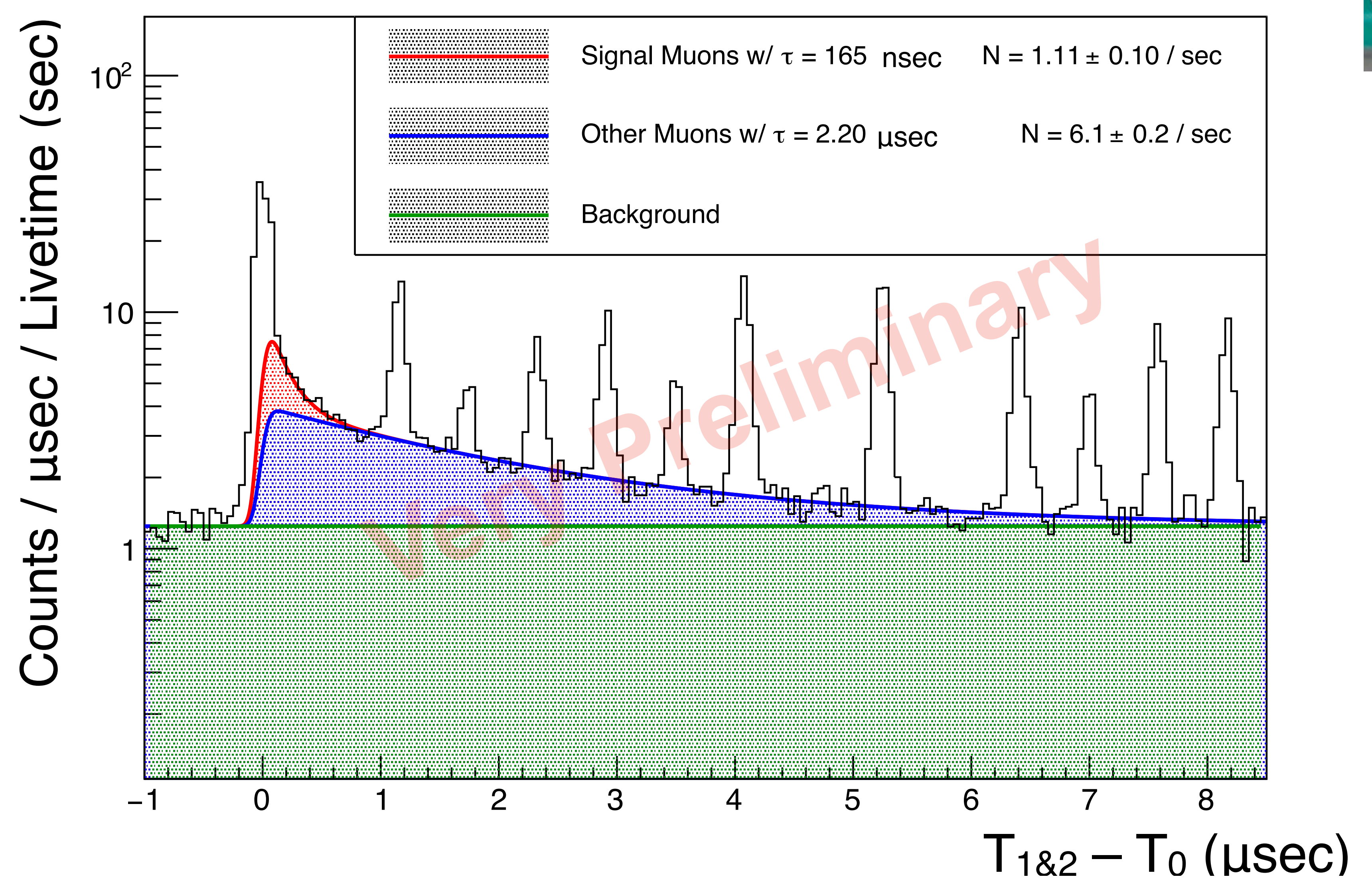
Graphite target

Beam masking system



Proton beam profile monitor

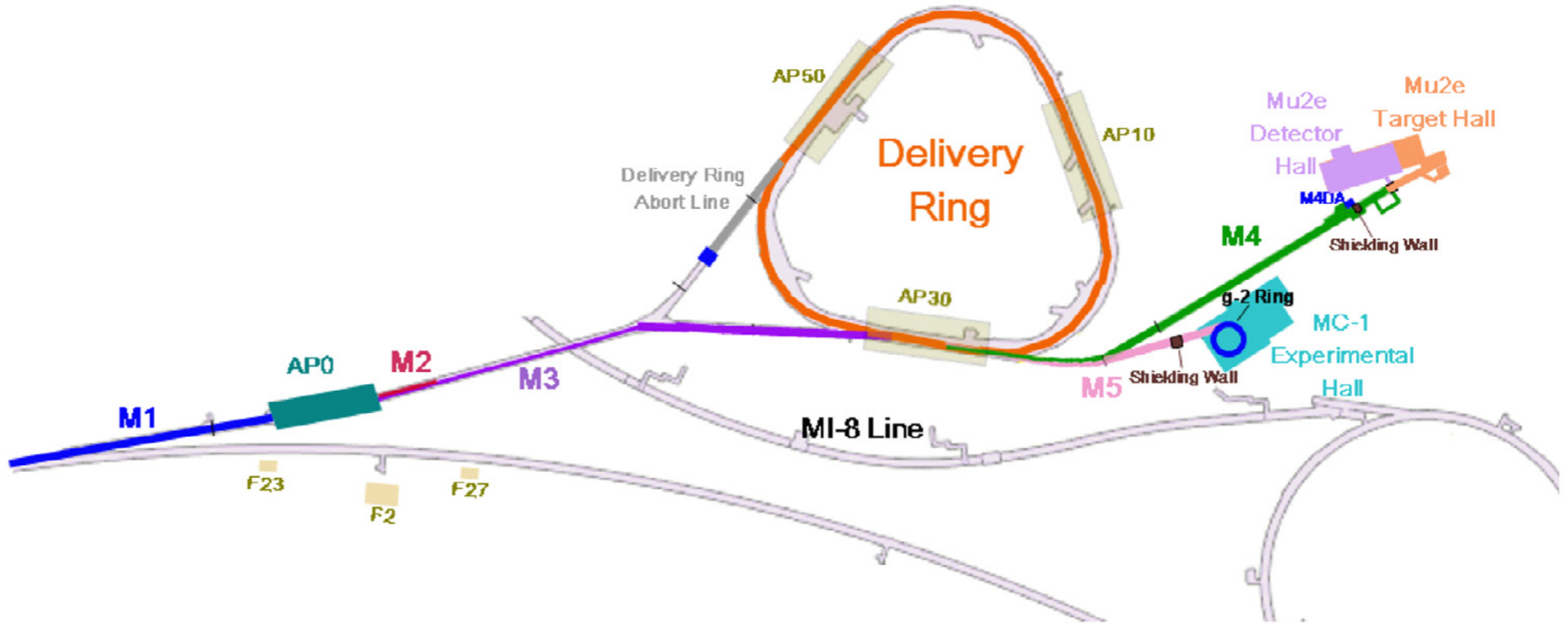


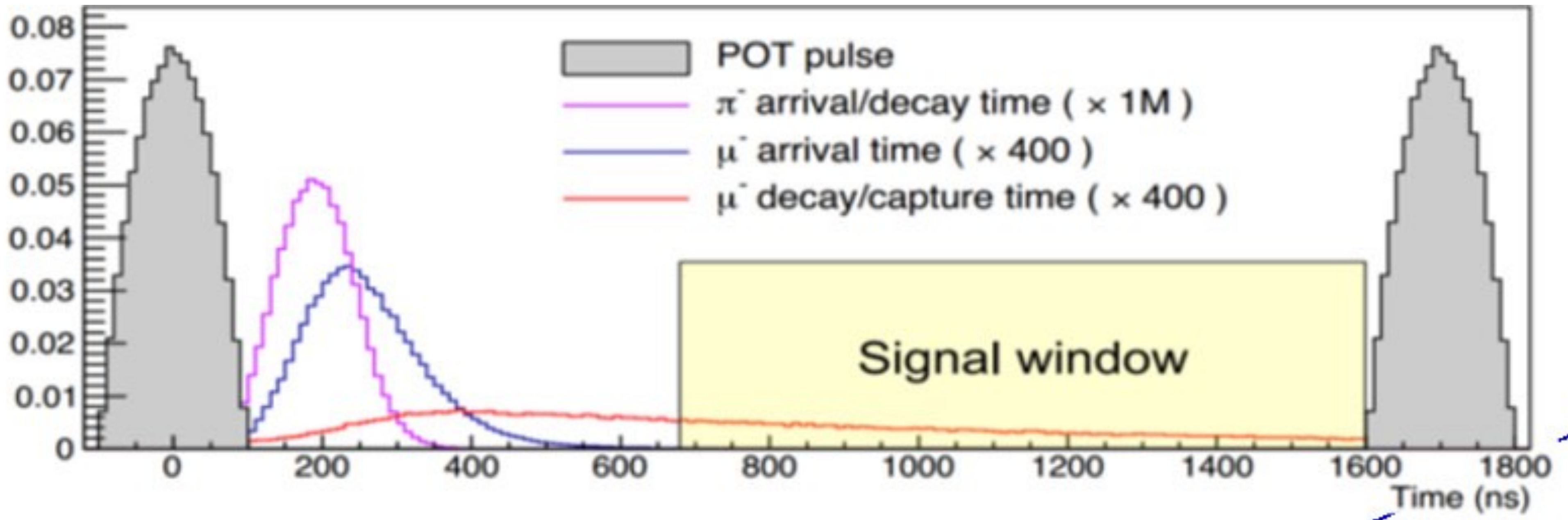


- After C-line completion at J-PARC, muon beam commissioning was performed with a small graphite target & lower beam power
- **The 1st muon beam delivered to the COMET experimental area**

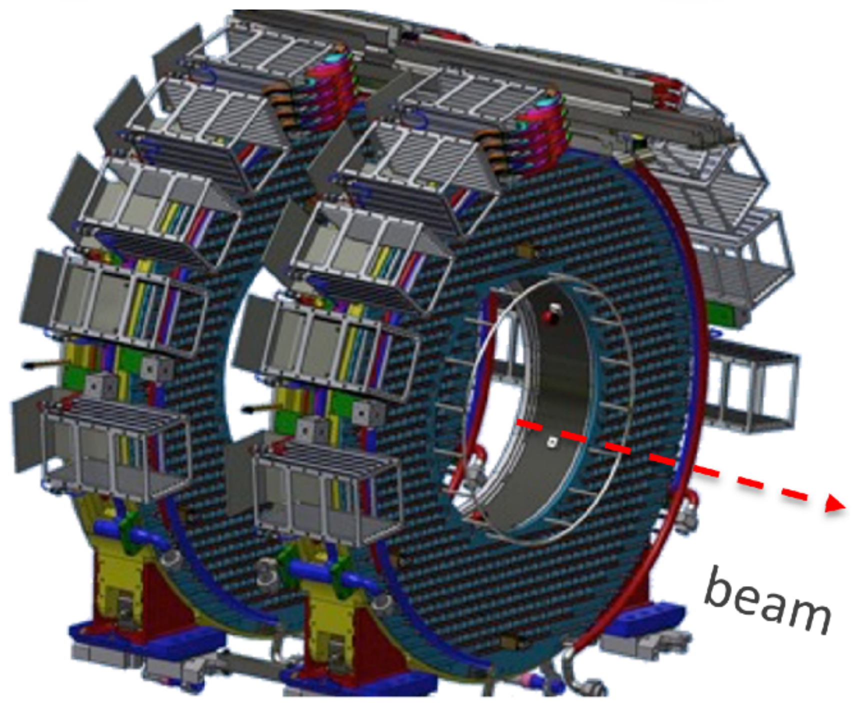
Mu2e Experiment

Special thanks to Pavel Murat

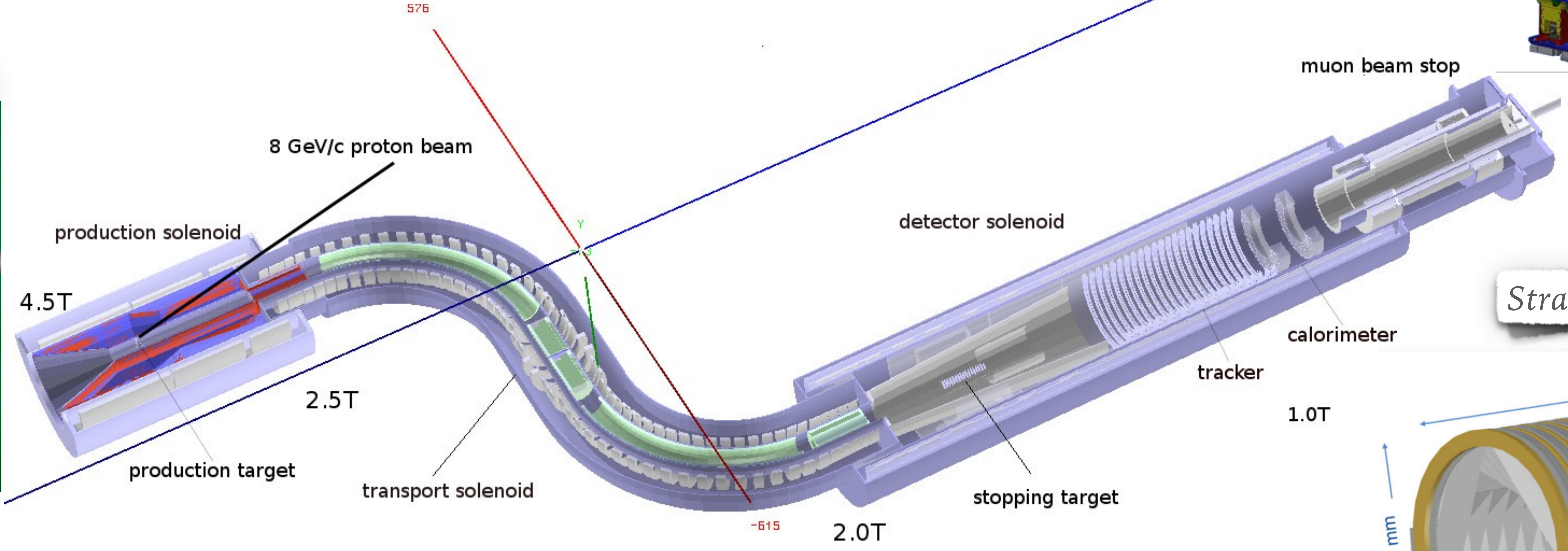




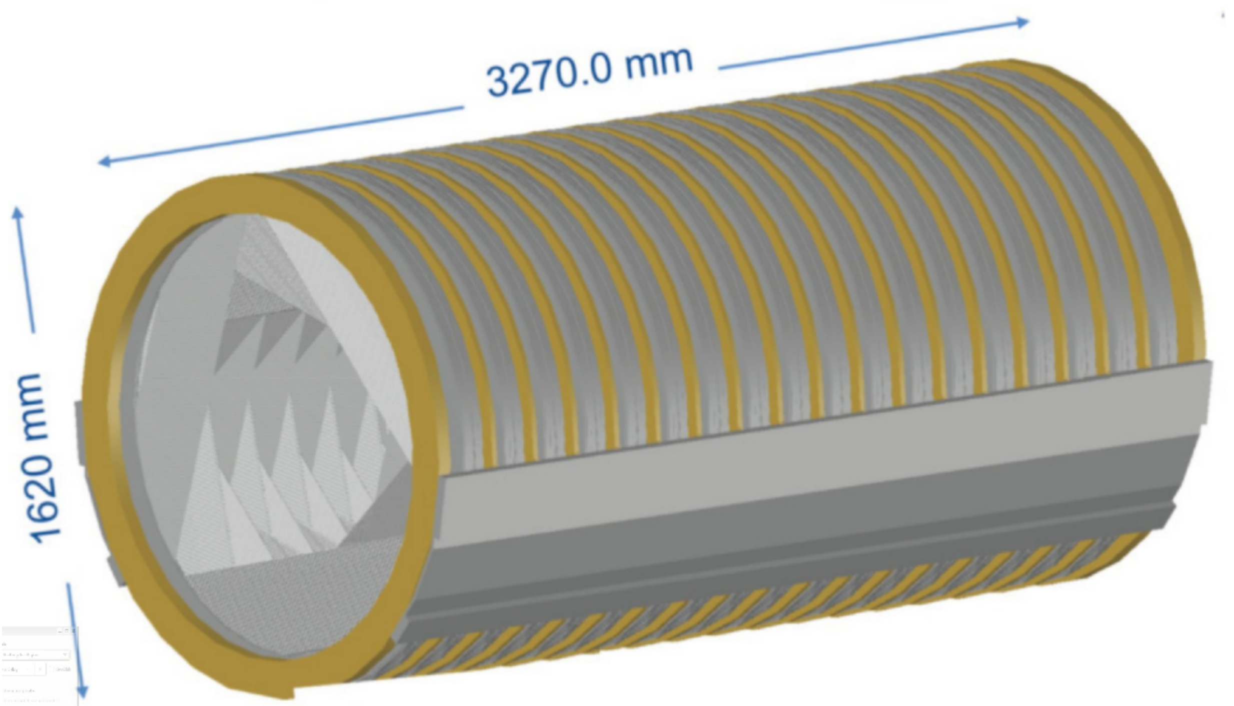
Pure CsI calorimeter



Production target

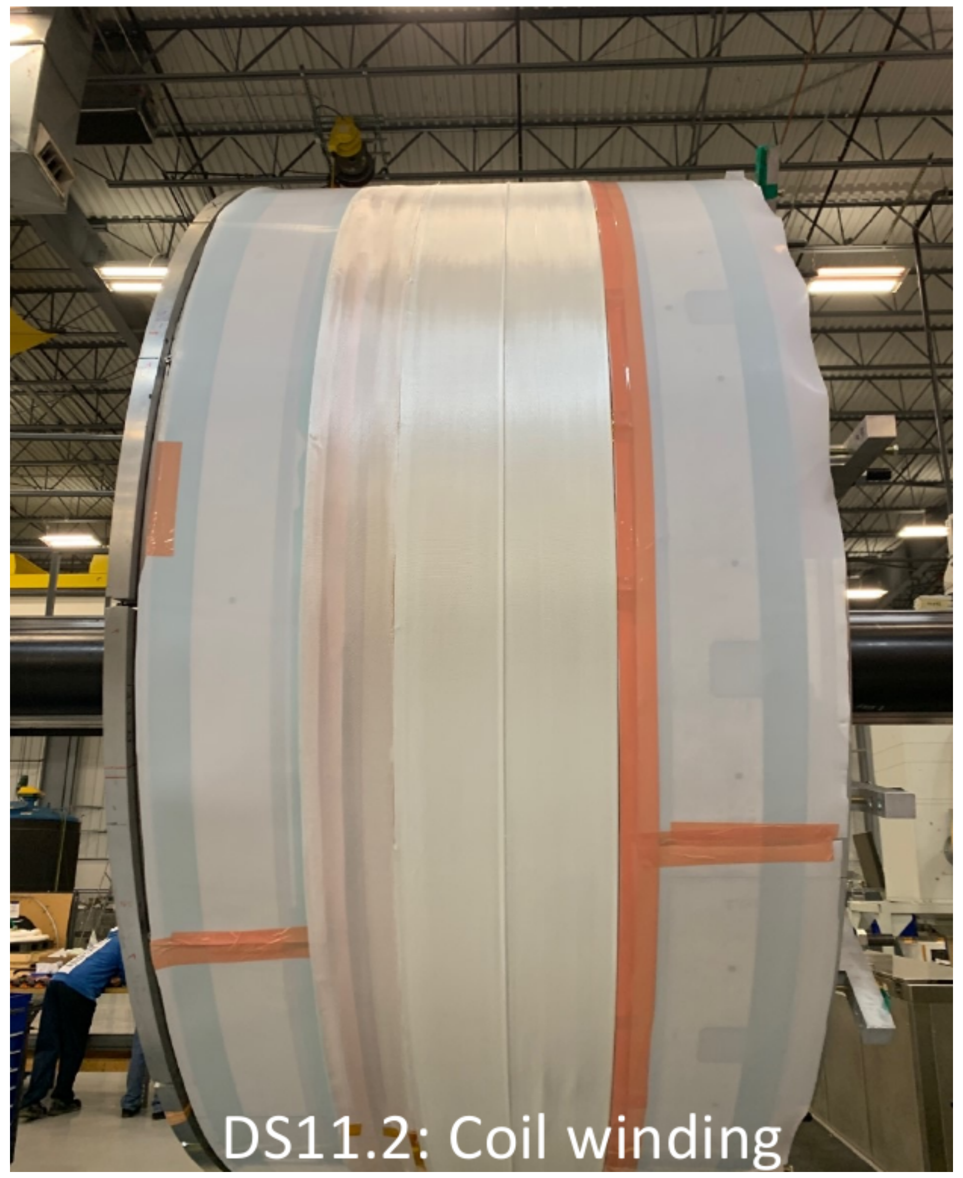


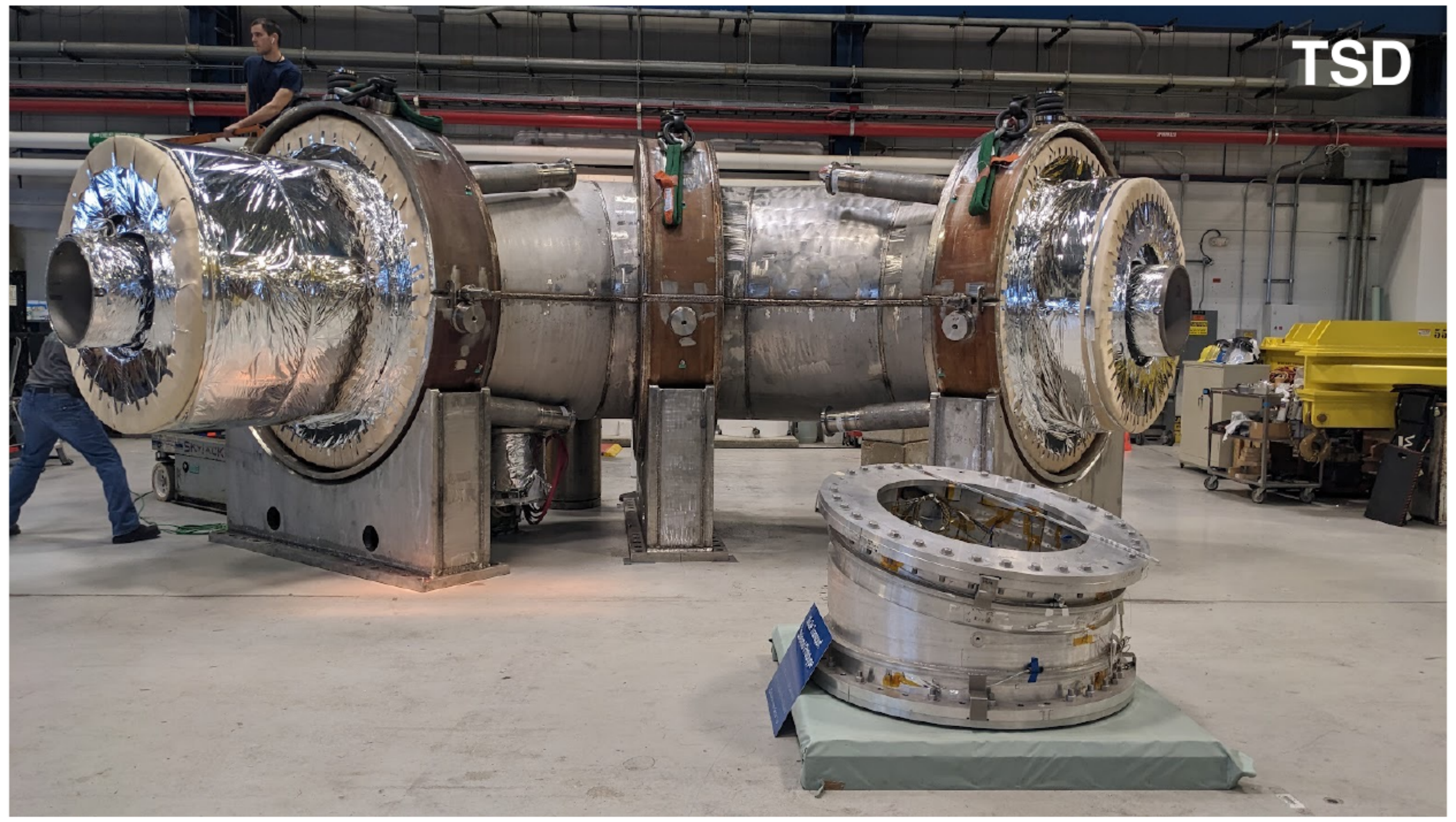
Straw tube trackers



Mu2e Experiment

Special thanks to Pavel Murat



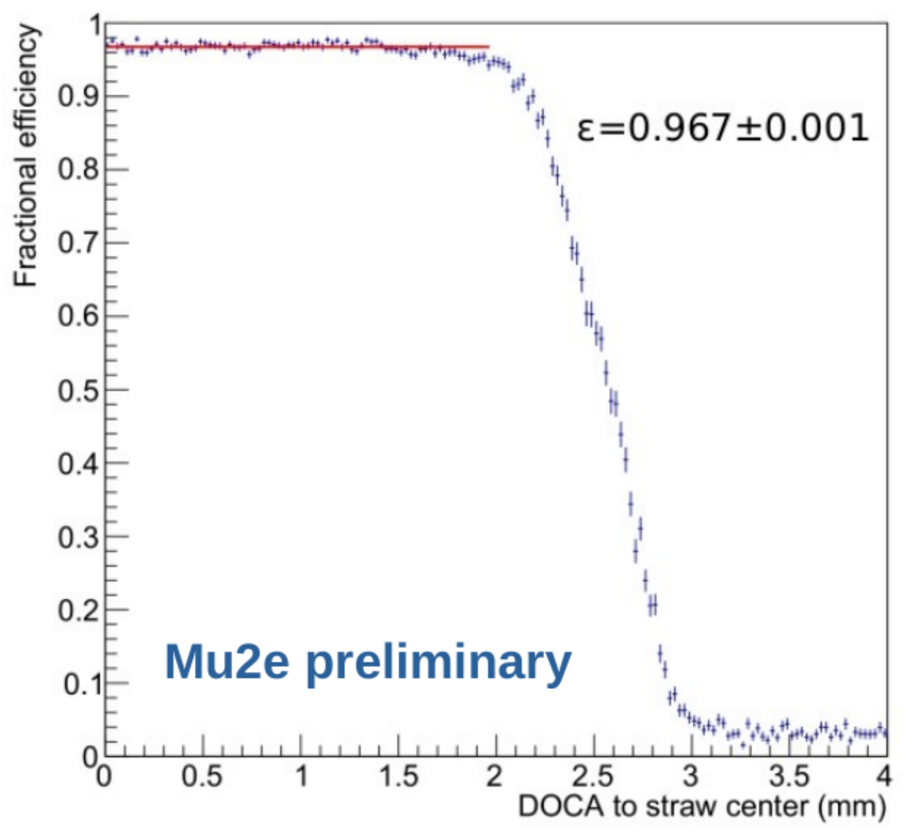


- PS under construction
- DS final coil winding as of two weeks ago
- Both TS are ready for the installation

Mu2e Experiment

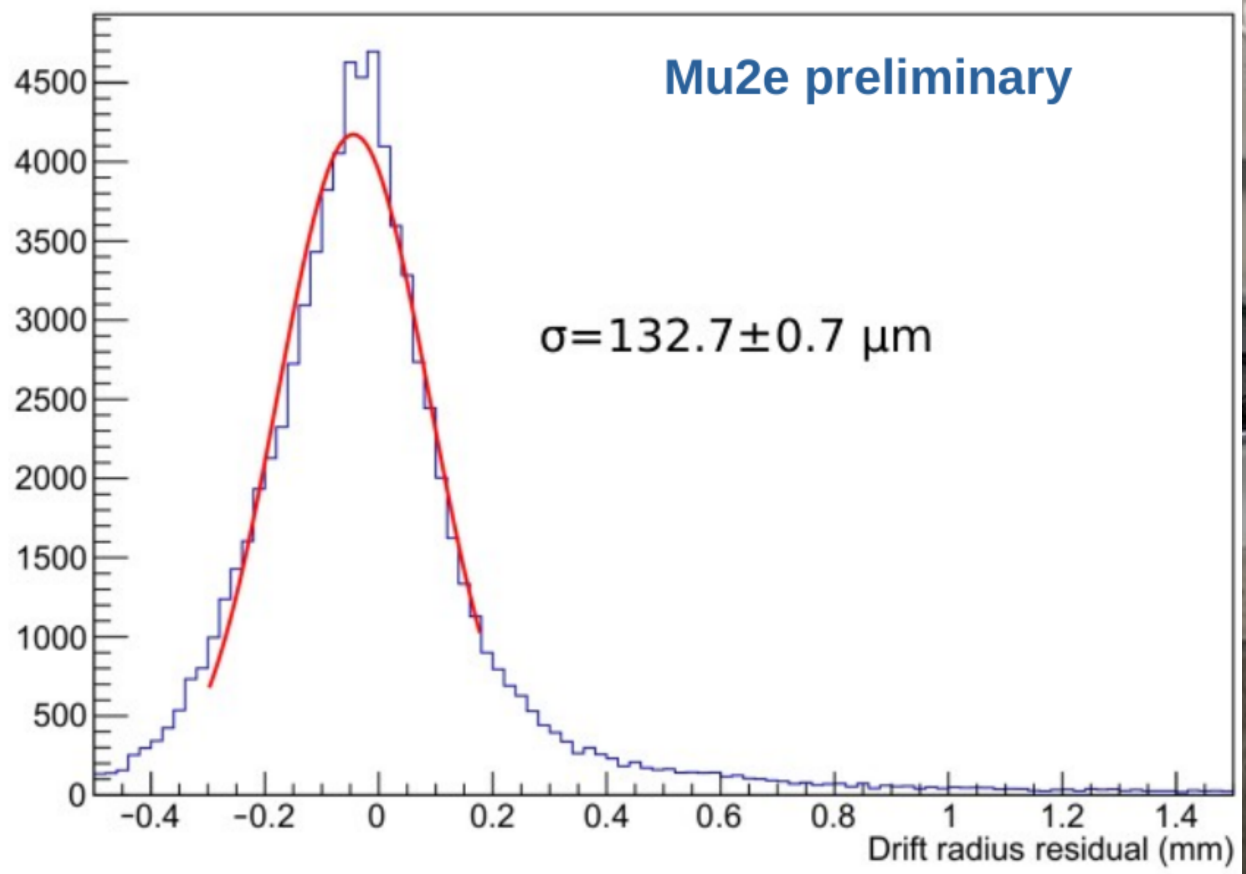
Special thanks to Pavel Murat

Hit efficiency

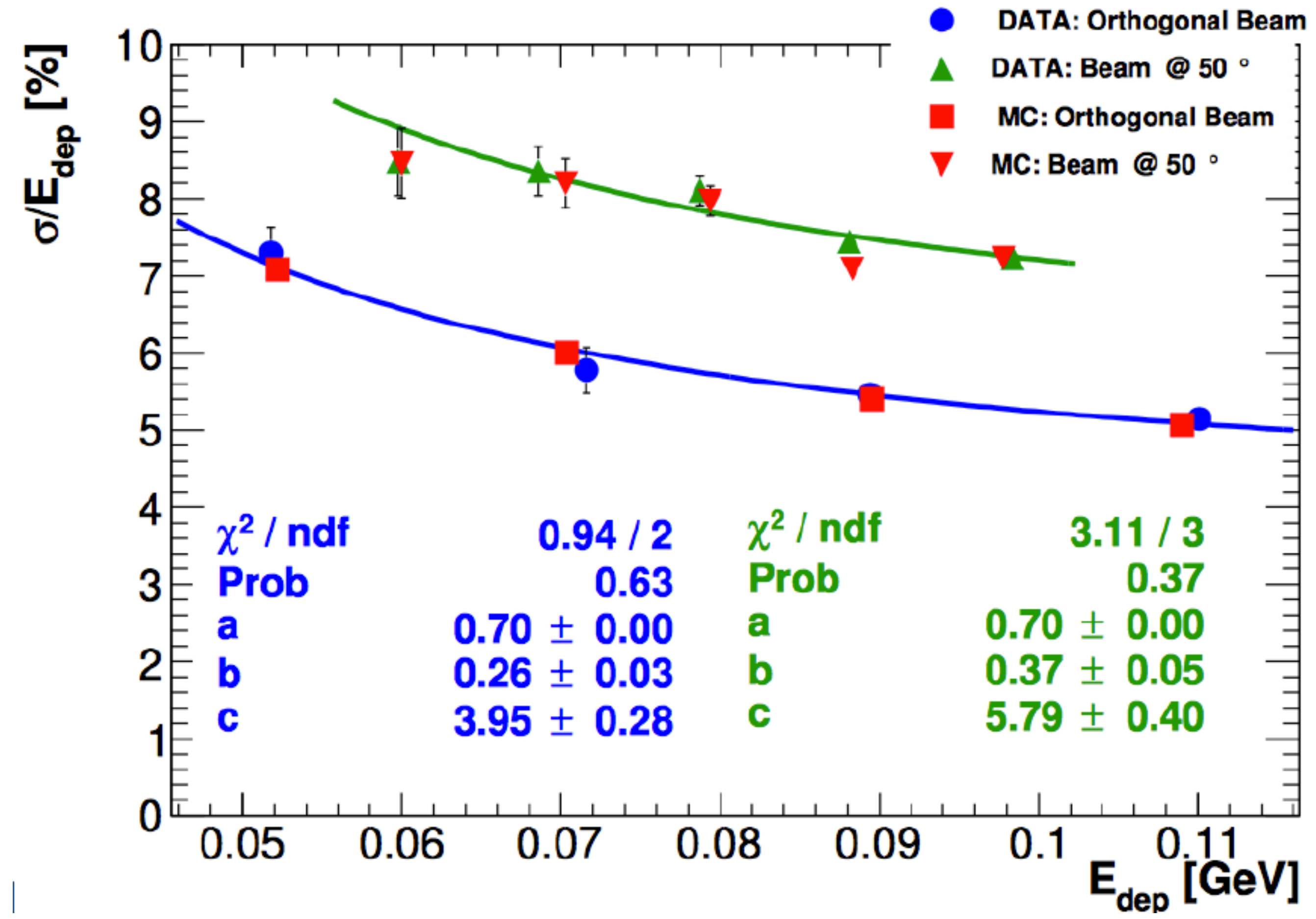


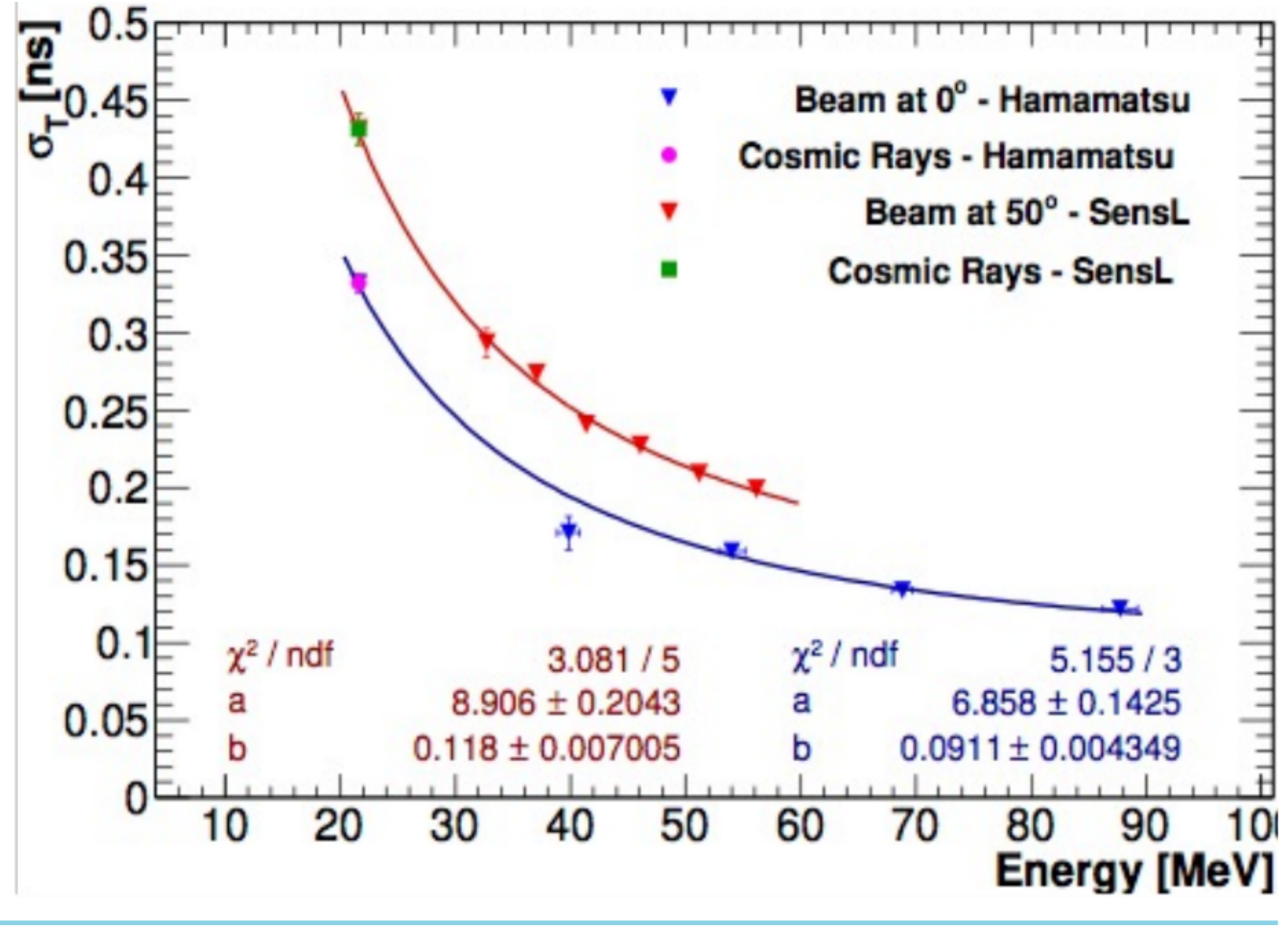
VST straw efficiency

Transverse coordinate resolution



24/36 straw planes have been made





1/2 CsI ECAL assembled

Mu2e Experiment

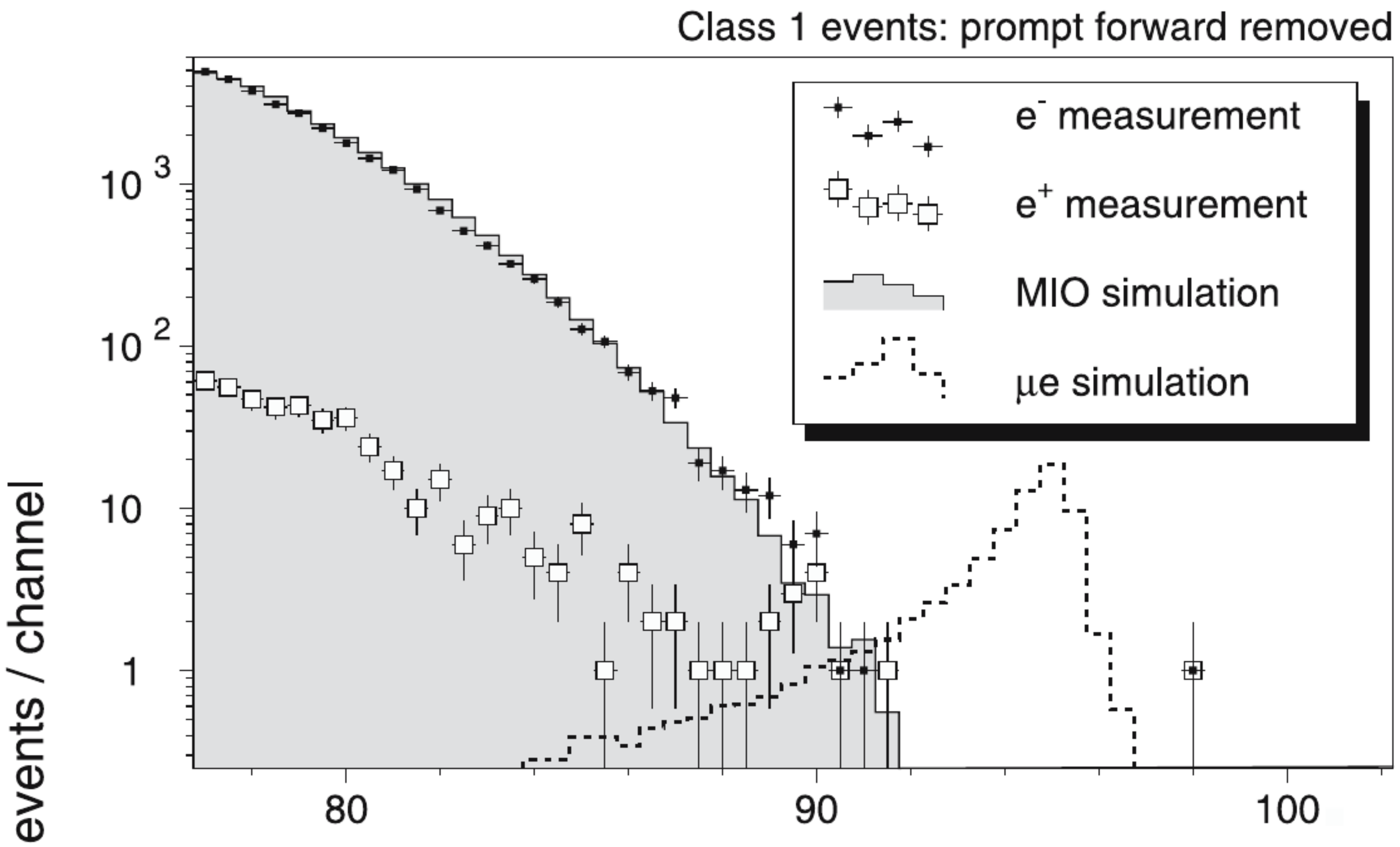
Special thanks to Pavel Murat

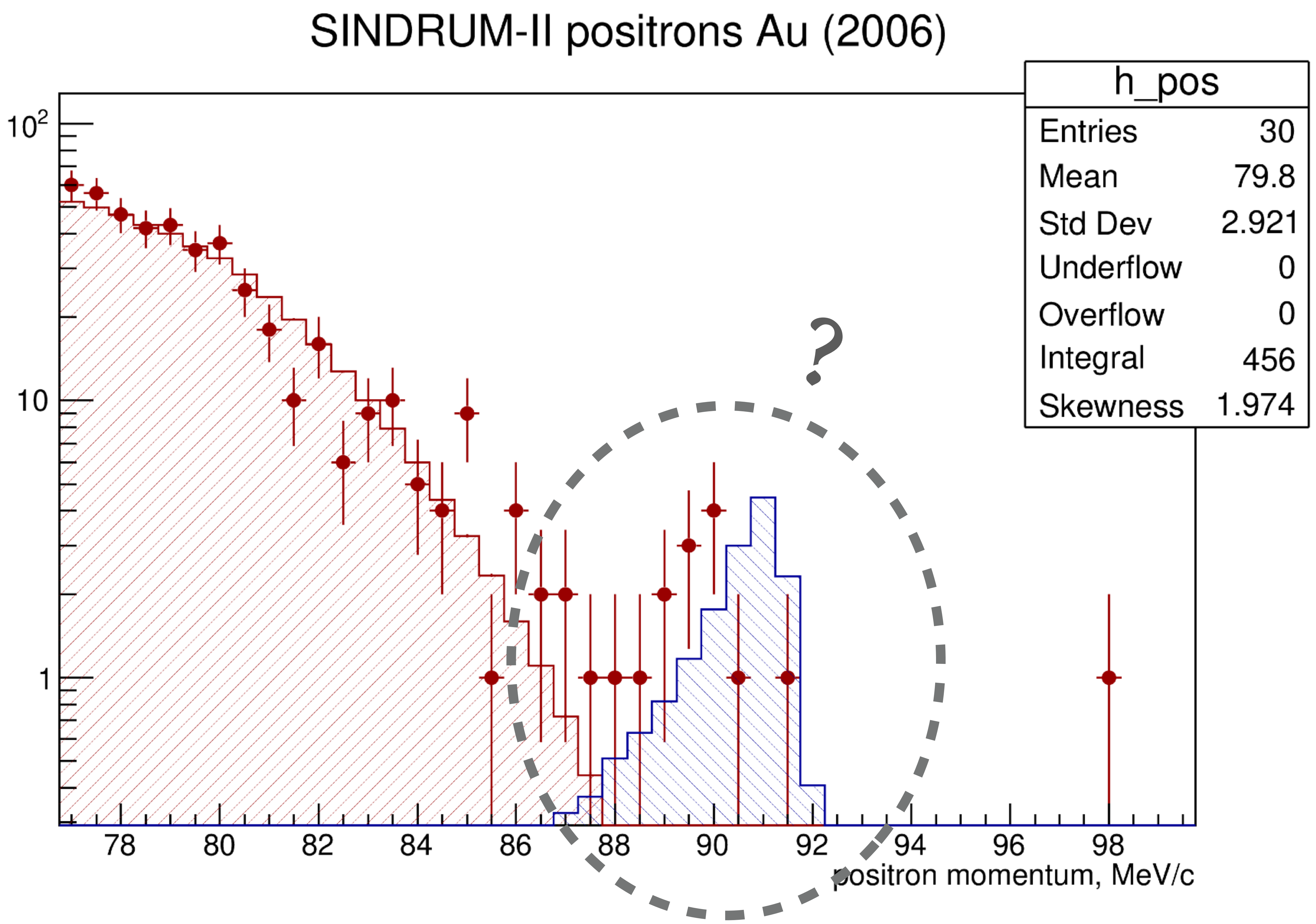
MDPI Universe 2023, 9(1), 54; https://doi.org/10.3390/universe9010054

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

- Mu2e Run-1 (**2025**) expected sensitivity assuming 6×10^{16} stopped muons on the proton target
- Upper limit sensitivity is **6.2×10^{-16}** @90% C.L. and 5 σ discovery potential with N_{sig}=**5**
- An order improvement expected in Run-2, **See more details in G. Pezzullo's talk**

$\mu^- N \rightarrow e^+ N'$ *Special thanks to Pavel Murat*

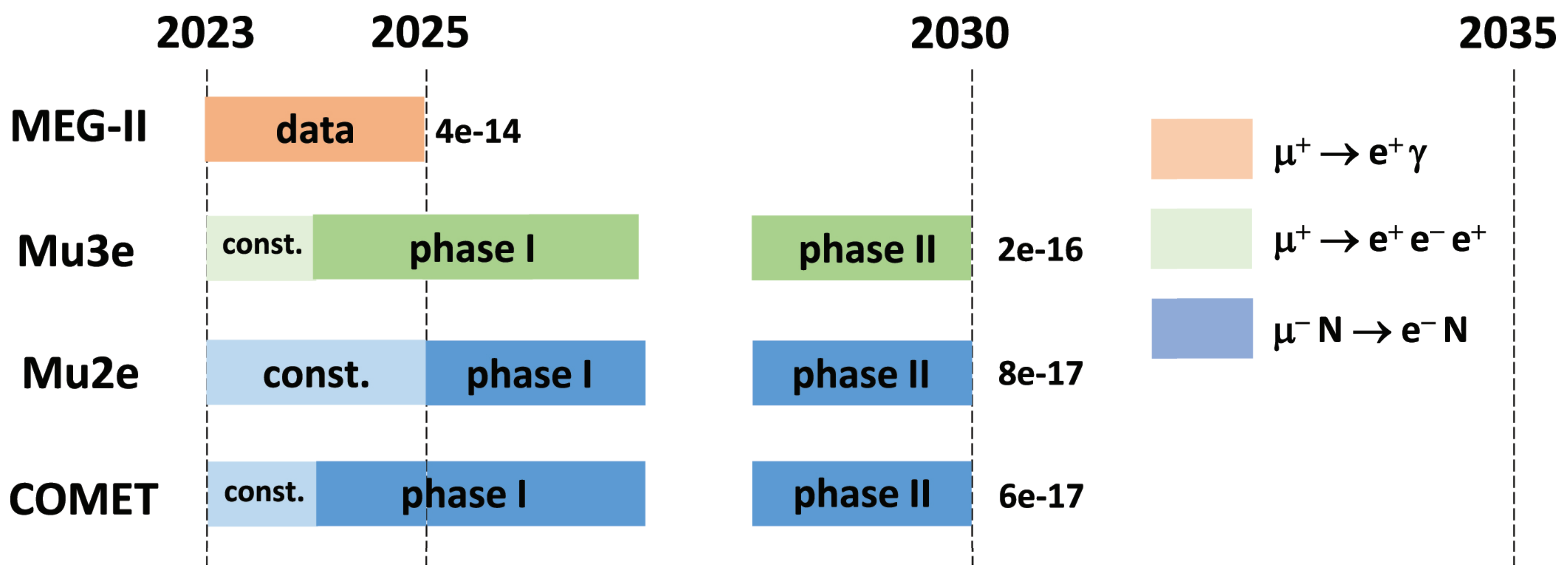




- ➤ No detailed information from SINDRUM-II collaboration
- ➤ Details described in arXiv:2009.00214 (M. MacKenzie and P. Murat)
- ➤ **COMET/Mu2e will be able to investigate this with much better sensitivity**

Summary

- The CLFV processes are powerful probes to search for the new physics beyond the standard model
  - Already got into the high energy region above 1 TeV indirectly
  - There are more muons to further investigate the BSM with CLFV processes @ PSI, J-PARC and Fermilab
  - Many ongoing activities in CLFV searches and results coming up in the next few years from **MEG 2, Mu3e, DeeMe, COMET and Mu2e.** *Stay tuned!*
- More details can be found in *New Frontiers in Lepton Flavor* in Pisa, May 2023
- My perspectives; Muons are there thanks for the accelerator ppl's efforts, more challenges are foreseen in managing the higher rate environment, the background suppression/understanding are the **most** important keys in CLFV



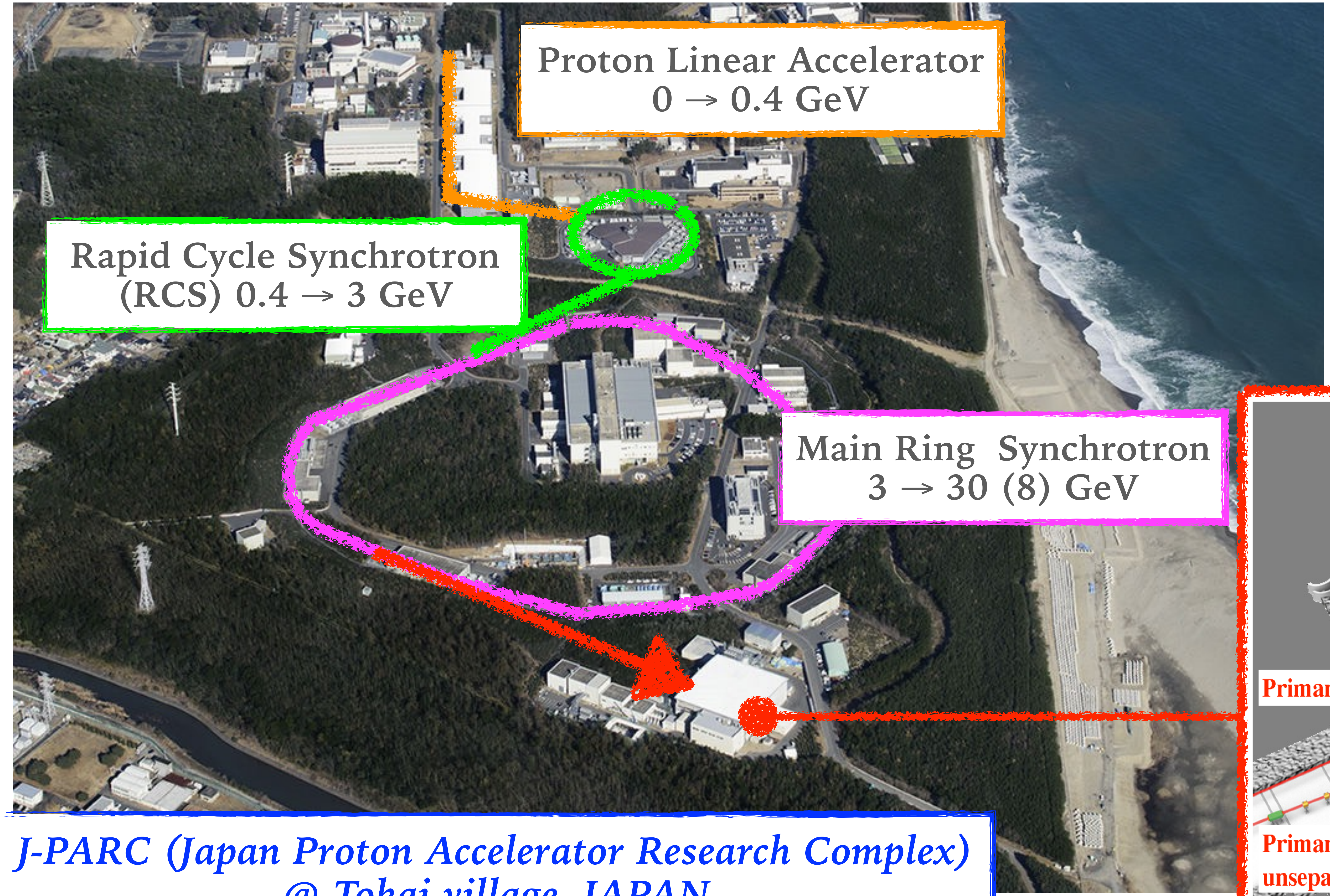
Thank you! / Grazie!

p.s. abstract submission for NuFact2023 is due on 3rd of June

https://indico.cern.ch/event/1216905/

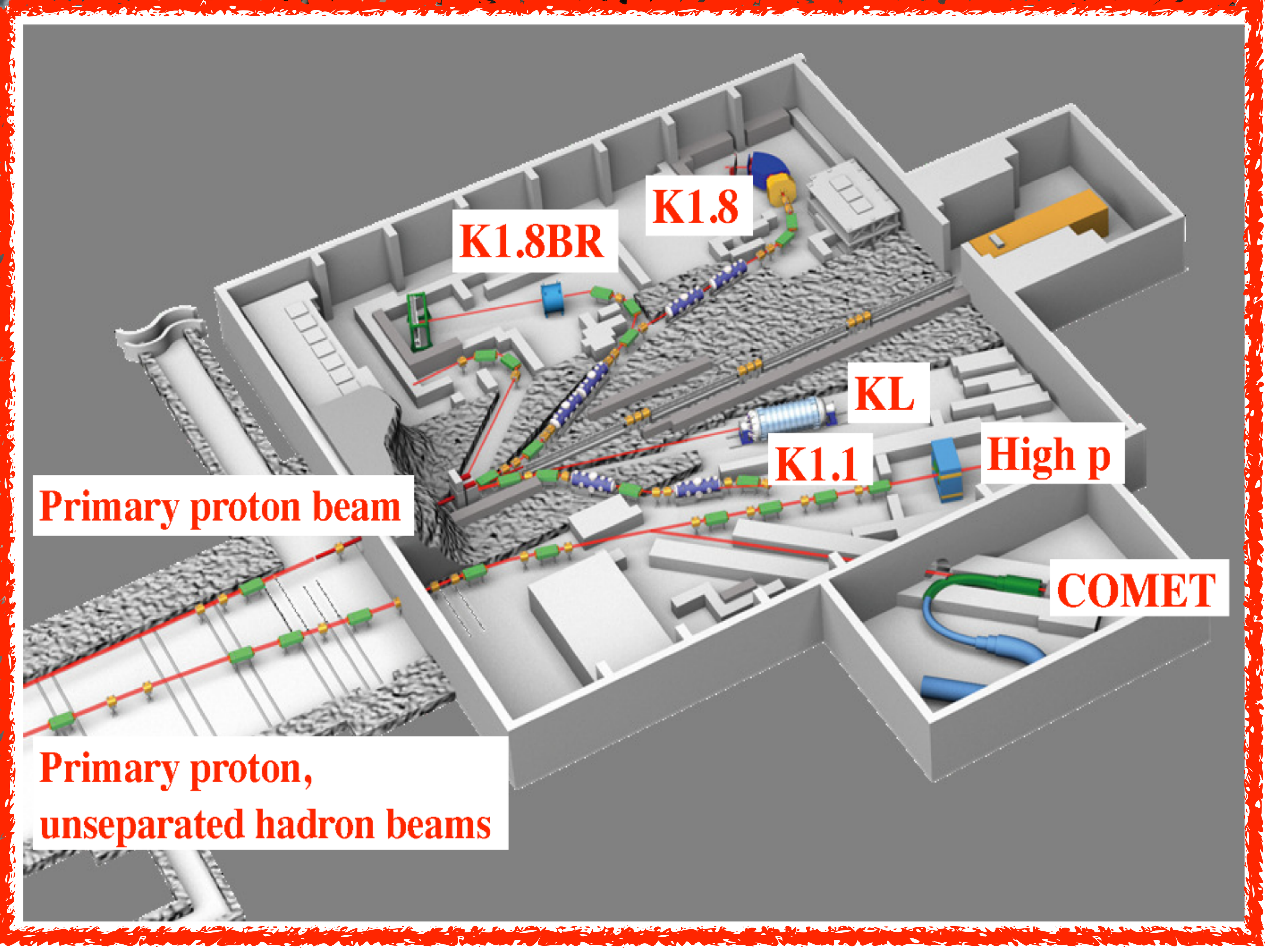
BACKUP SLIDES

COMET Experiment @J-PARC

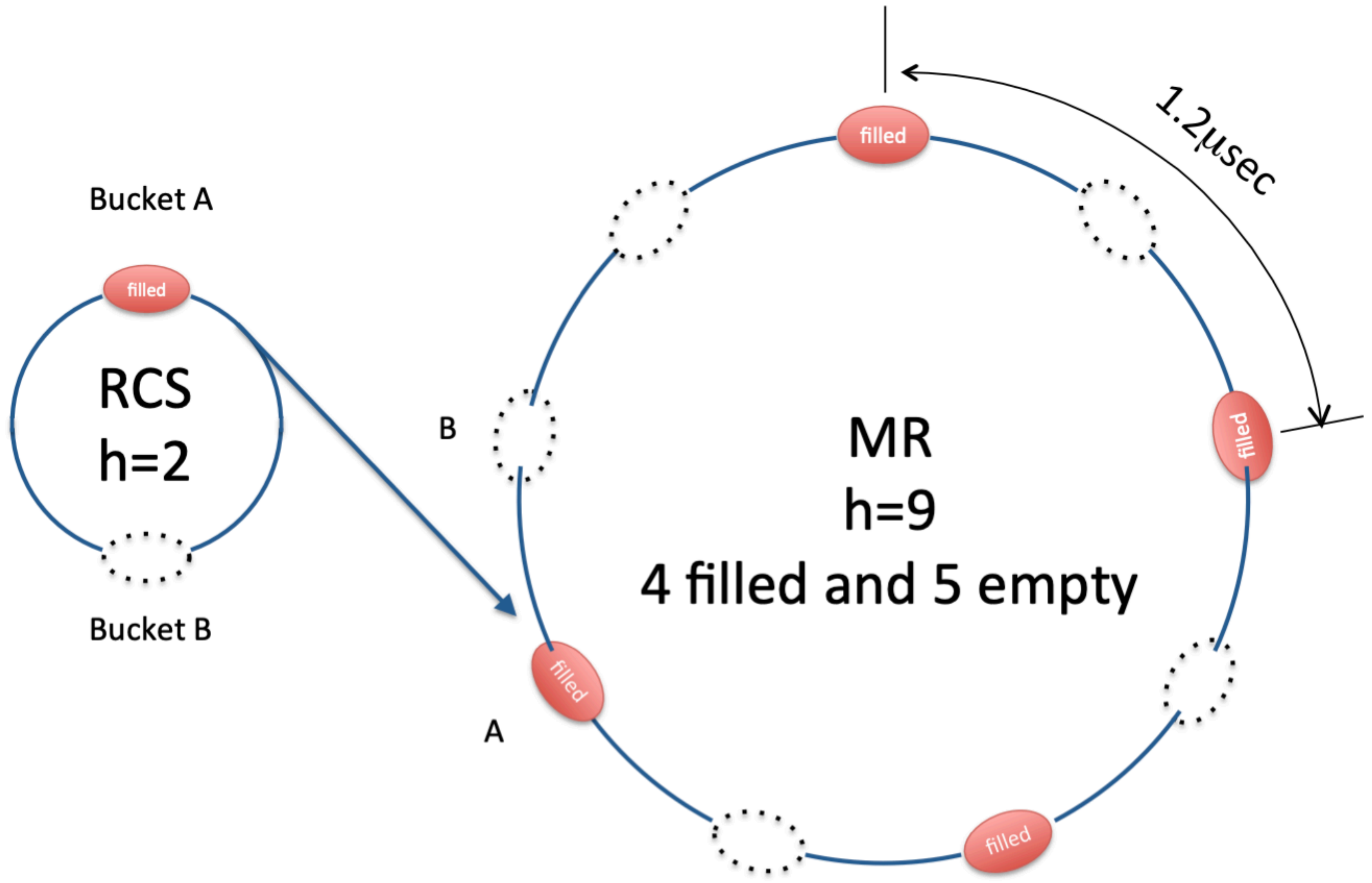


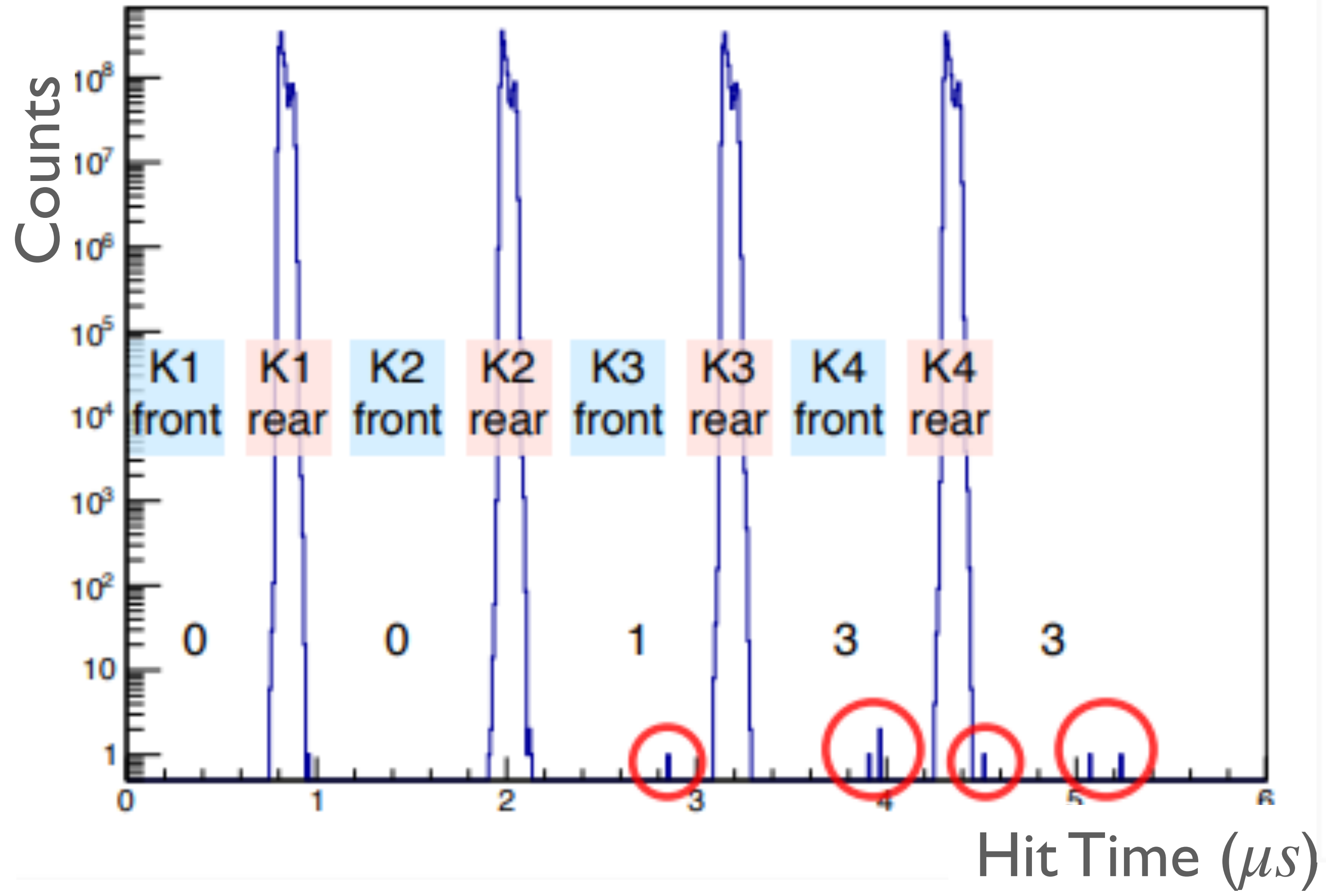
J-PARC (Japan Proton Accelerator Research Complex)
@ Tokai village, JAPAN

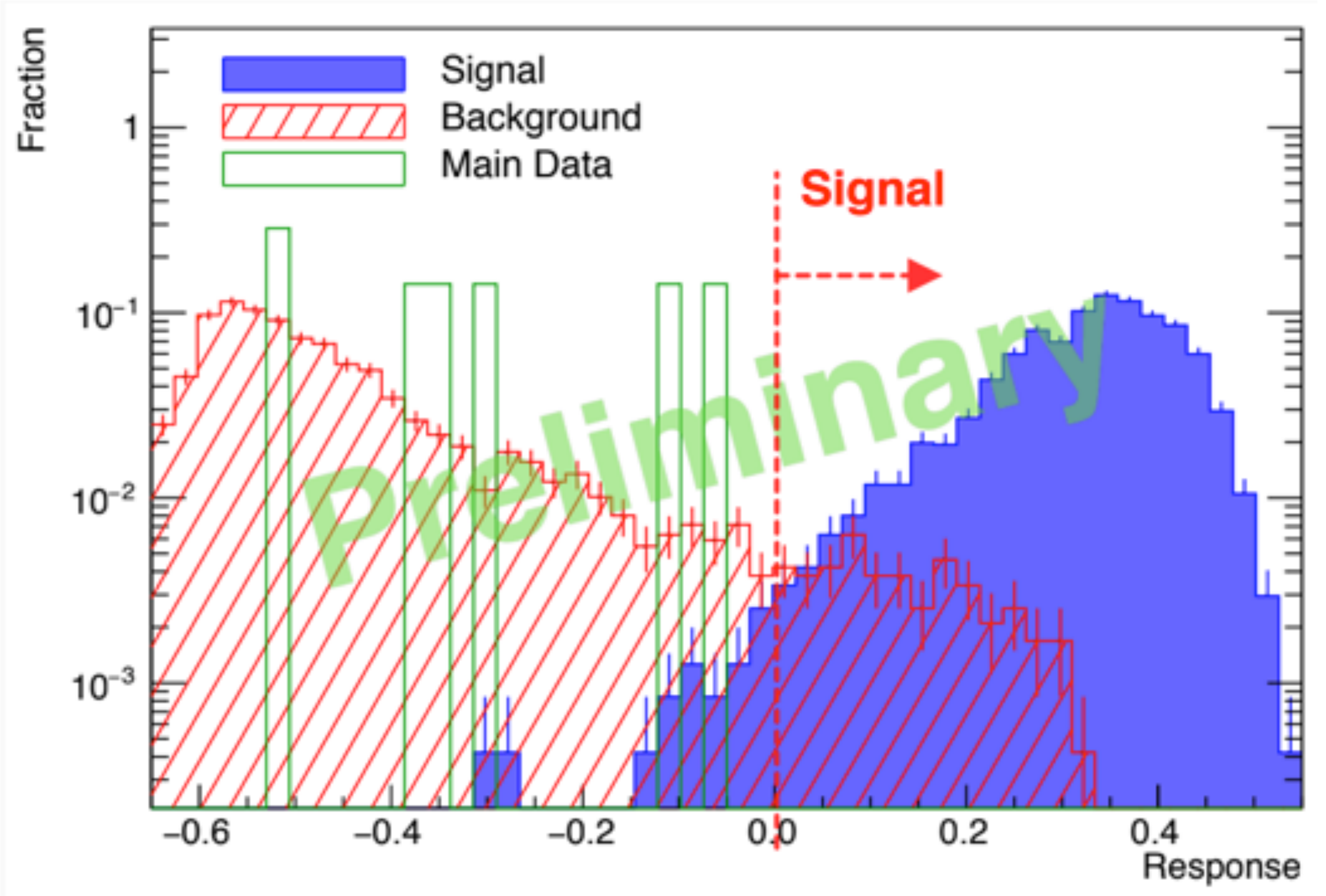
>200 researchers

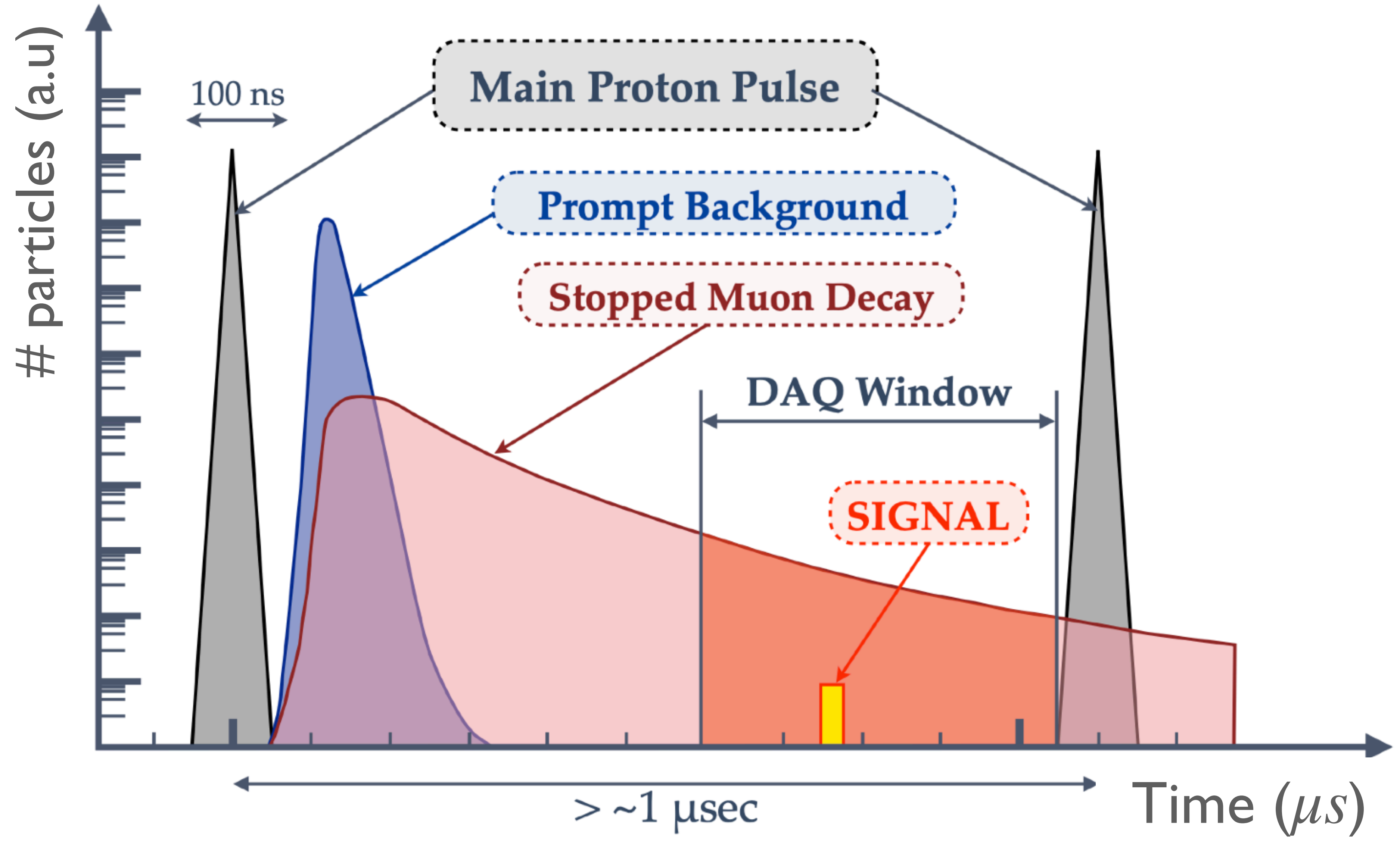


COMET Phase-I ~Proton beam~









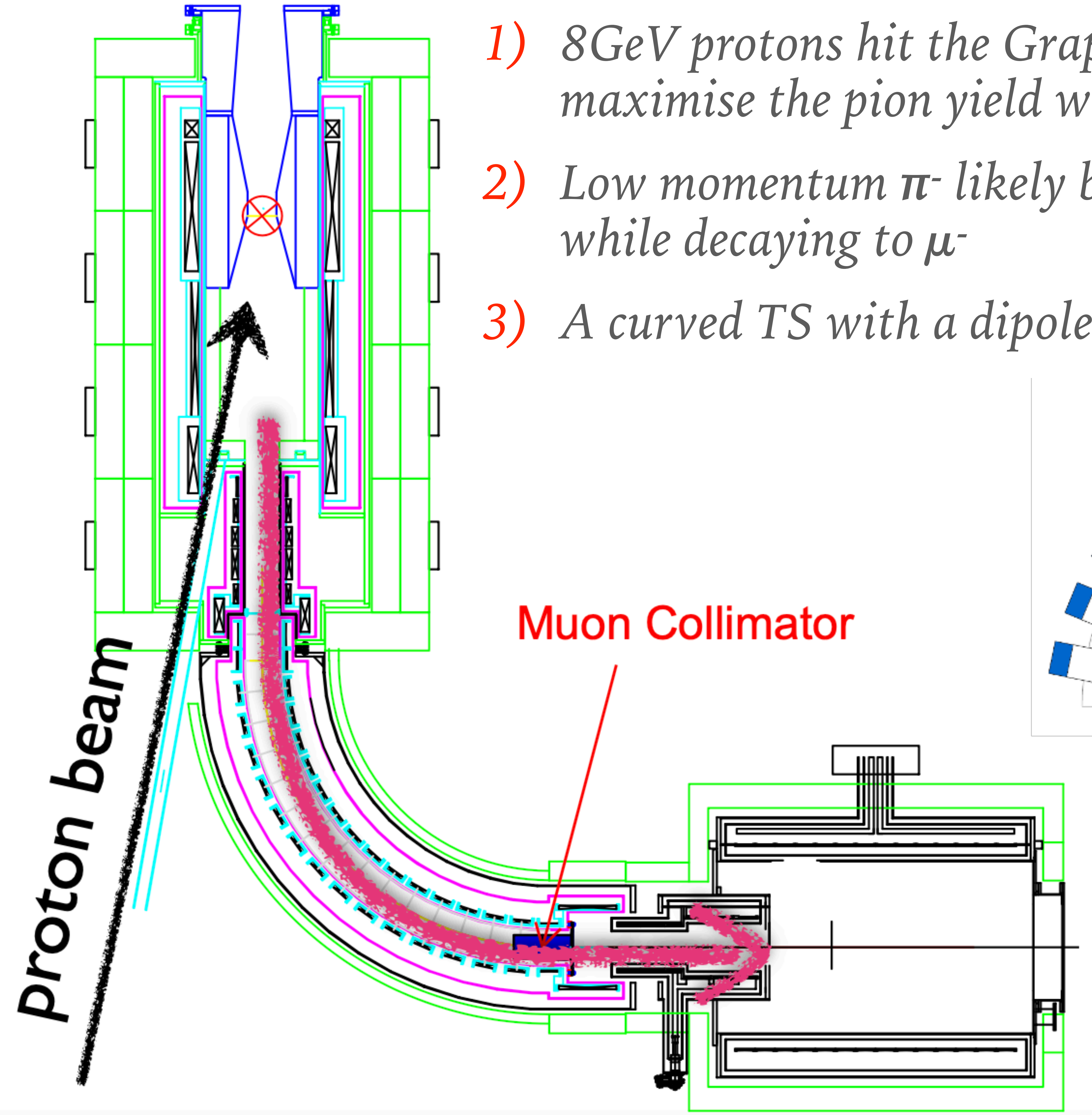
Bunched-slow extraction @8GeV has been well studied at J-PARC hadron hall and high quality bunched beam was obtained

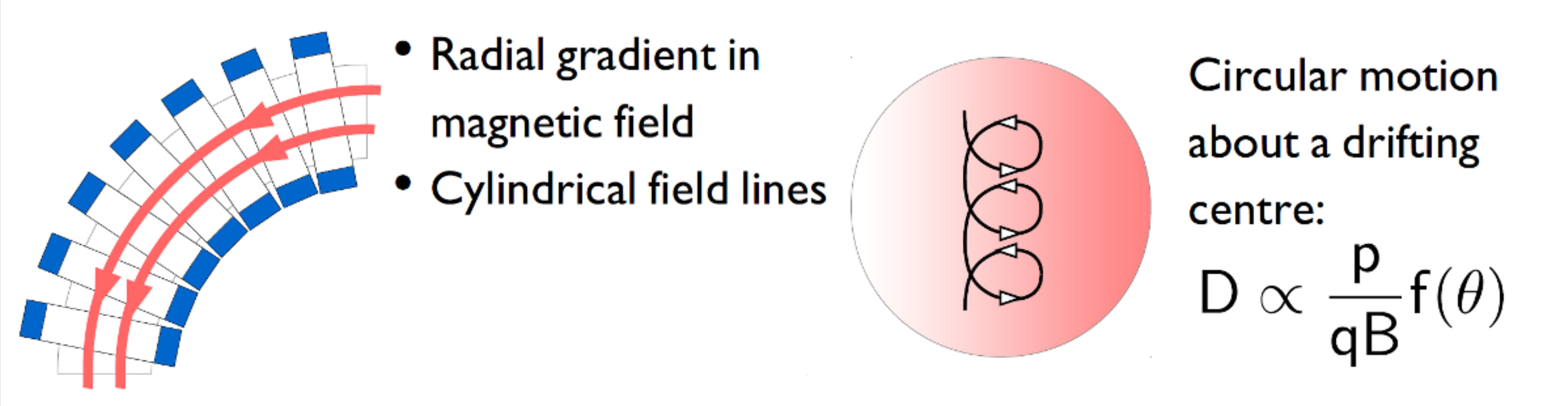
All events between pulses are most probably "accidental BG" (≠single particle from the beam)

→ $R_{Extinction} < 10^{-11}$ (K. Noguchi *et.al.* NuFact2021)

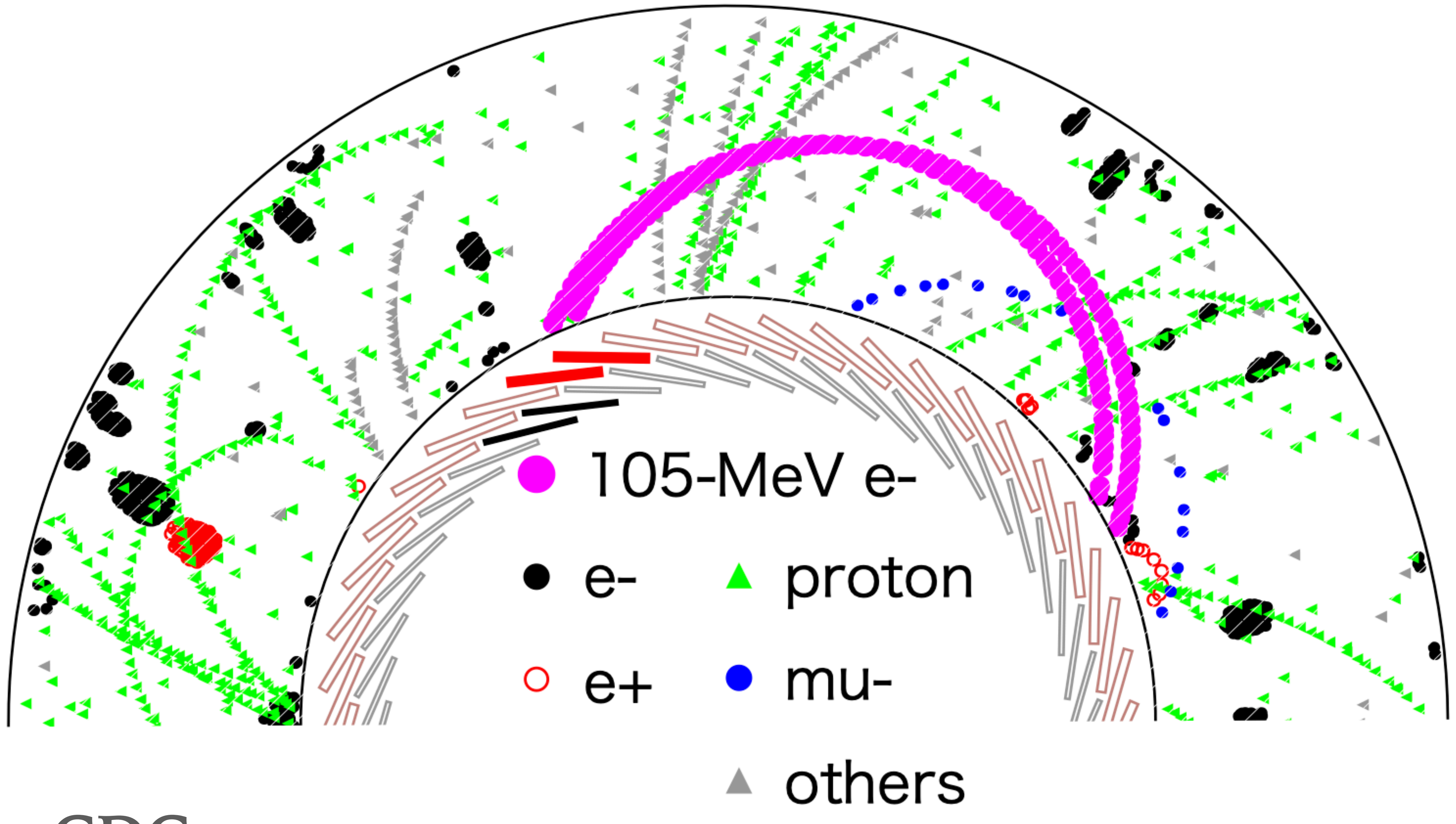
COMET Phase-I ~Muon beam~

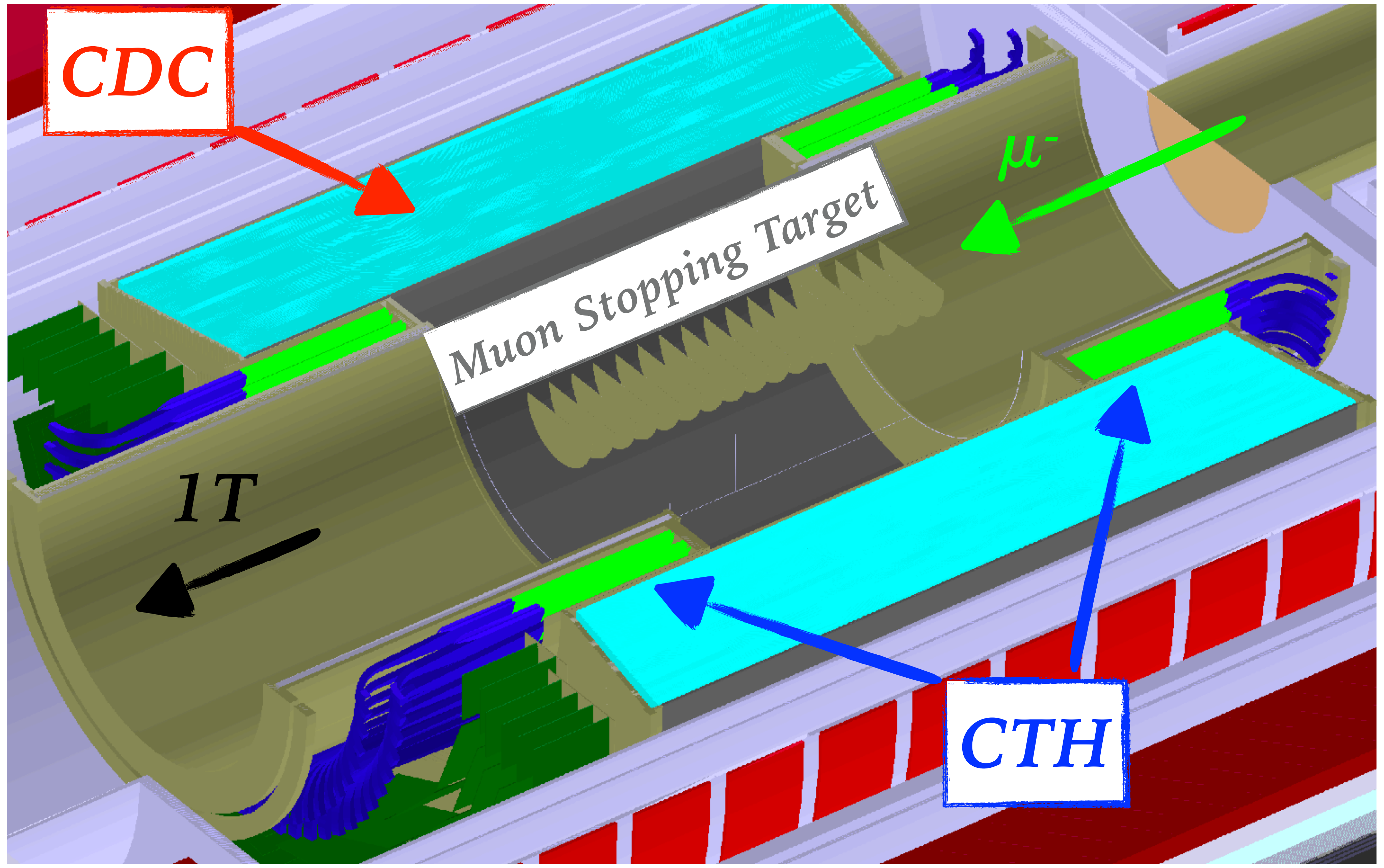
1) *8GeV protons hit the Graphite target and produce secondary pions (Energy chosen to maximise the pion yield while preventing anti-protons)*
2) *Low momentum π^- likely back scatter and direct to the muon transportation solenoid (TS) while decaying to μ^-*
3) *A curved TS with a dipole field to select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





COMET Phase-I ~CyDet~

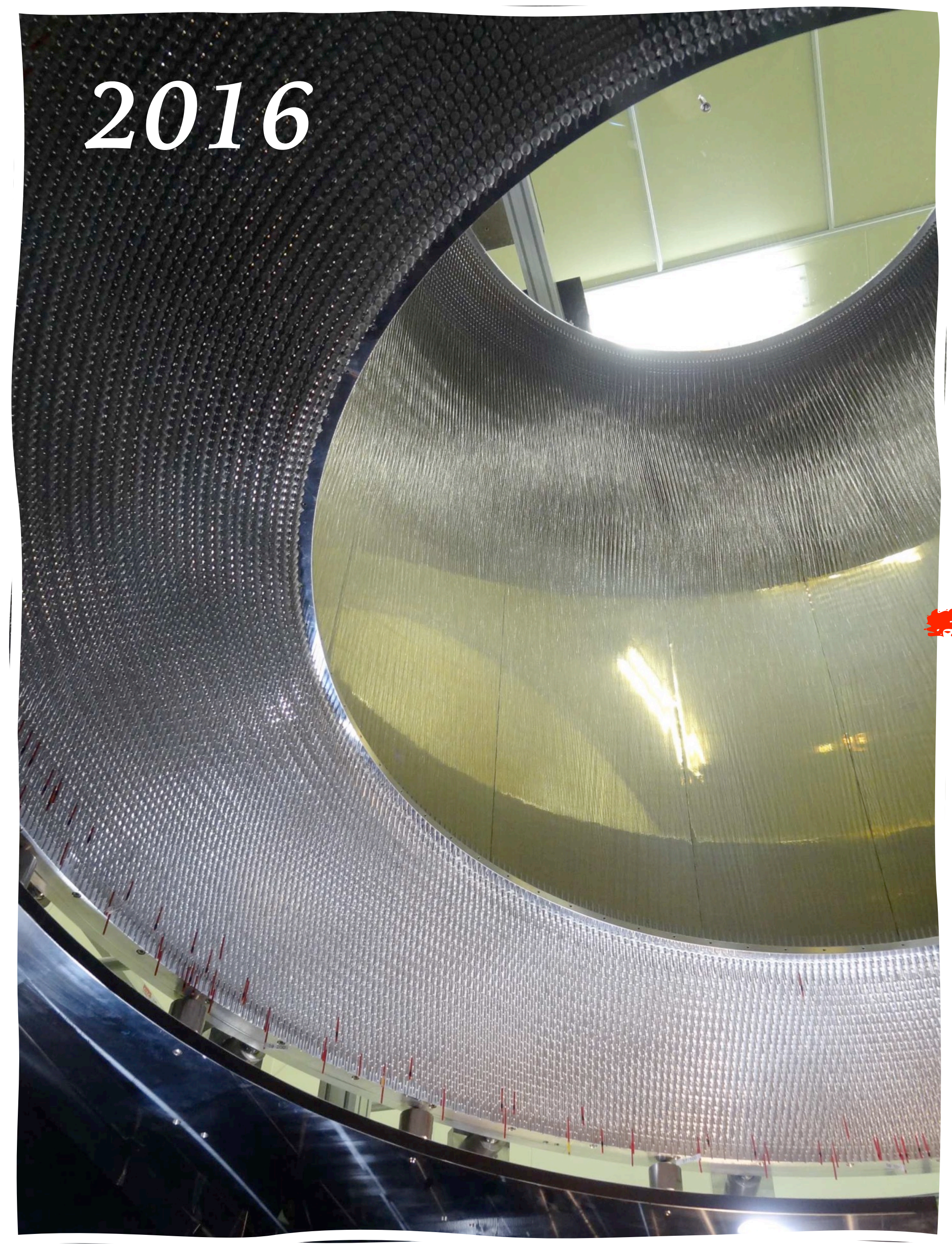


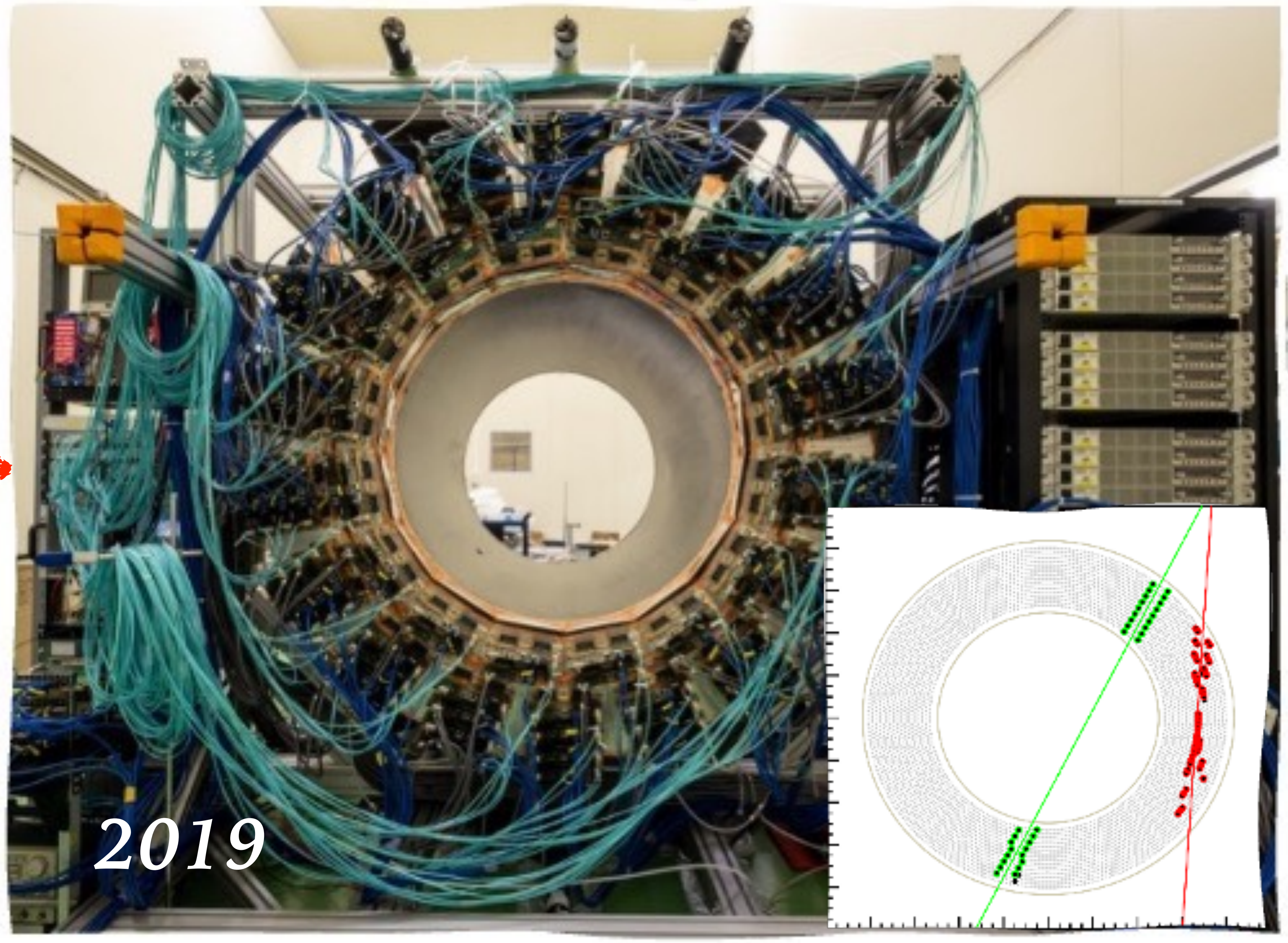


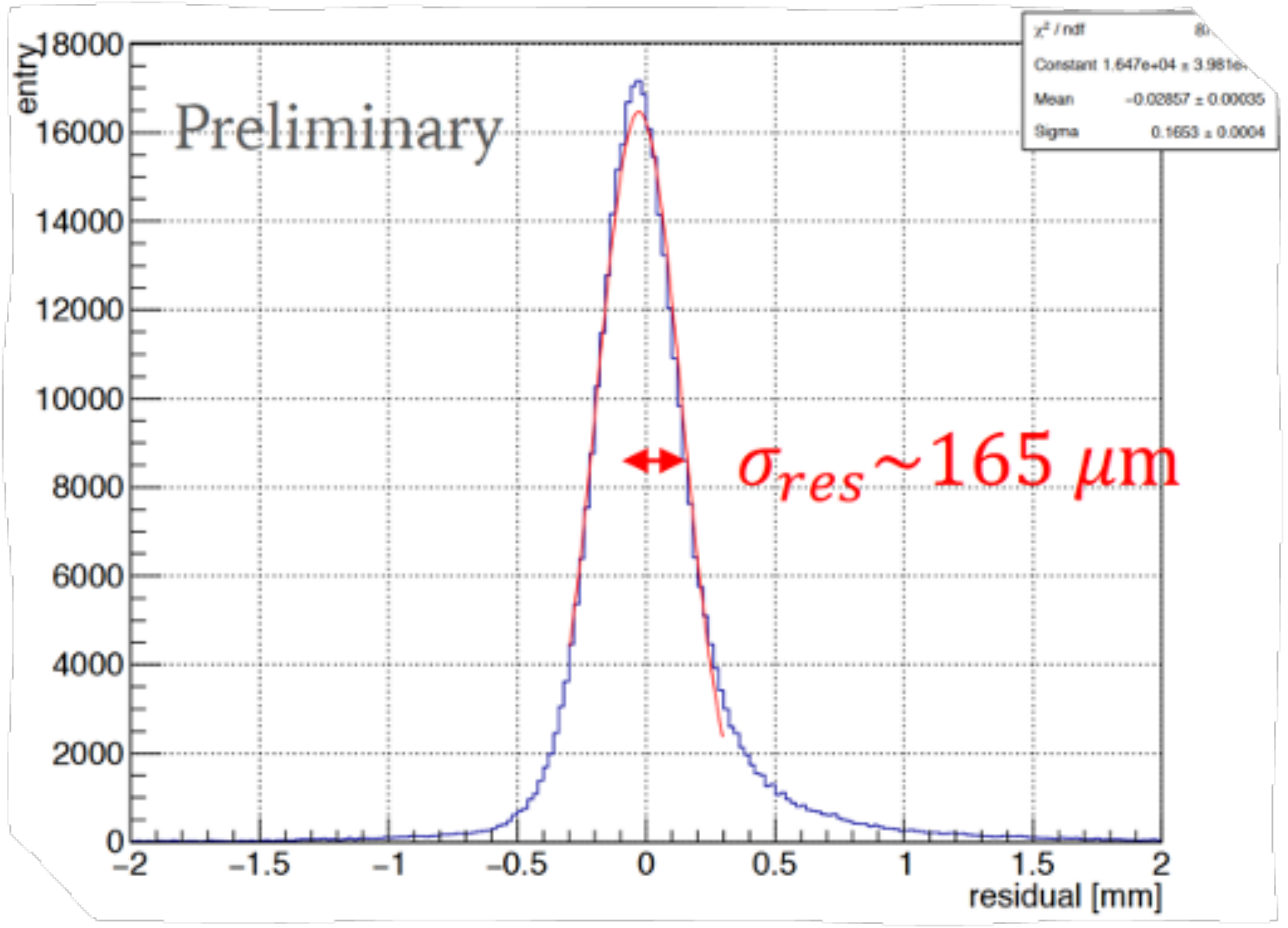
- CDC
  - ~5,000 wires, 20 stereo layers for momentum measurement, He:iC_5H_{10}=90:10, typical drift time <400ns
  - Signal electrons' trajectories fully contained inside the volume
- CTH
  - 2 layers of 64 segmented plastic scintillator rings at both ends of CDC for the timing measurement
  - Suppress accidental events and low momentum particles by taking four-fold coincidence

COMET Phase-I ~CDC~

- ➤ All stereo-angle wire cylindrical drift chamber to measure the momentum of incoming charged particle
- ➤ Following the wiring completion in 2016, the full channels readout tested in 2019 → almost ready for the installation



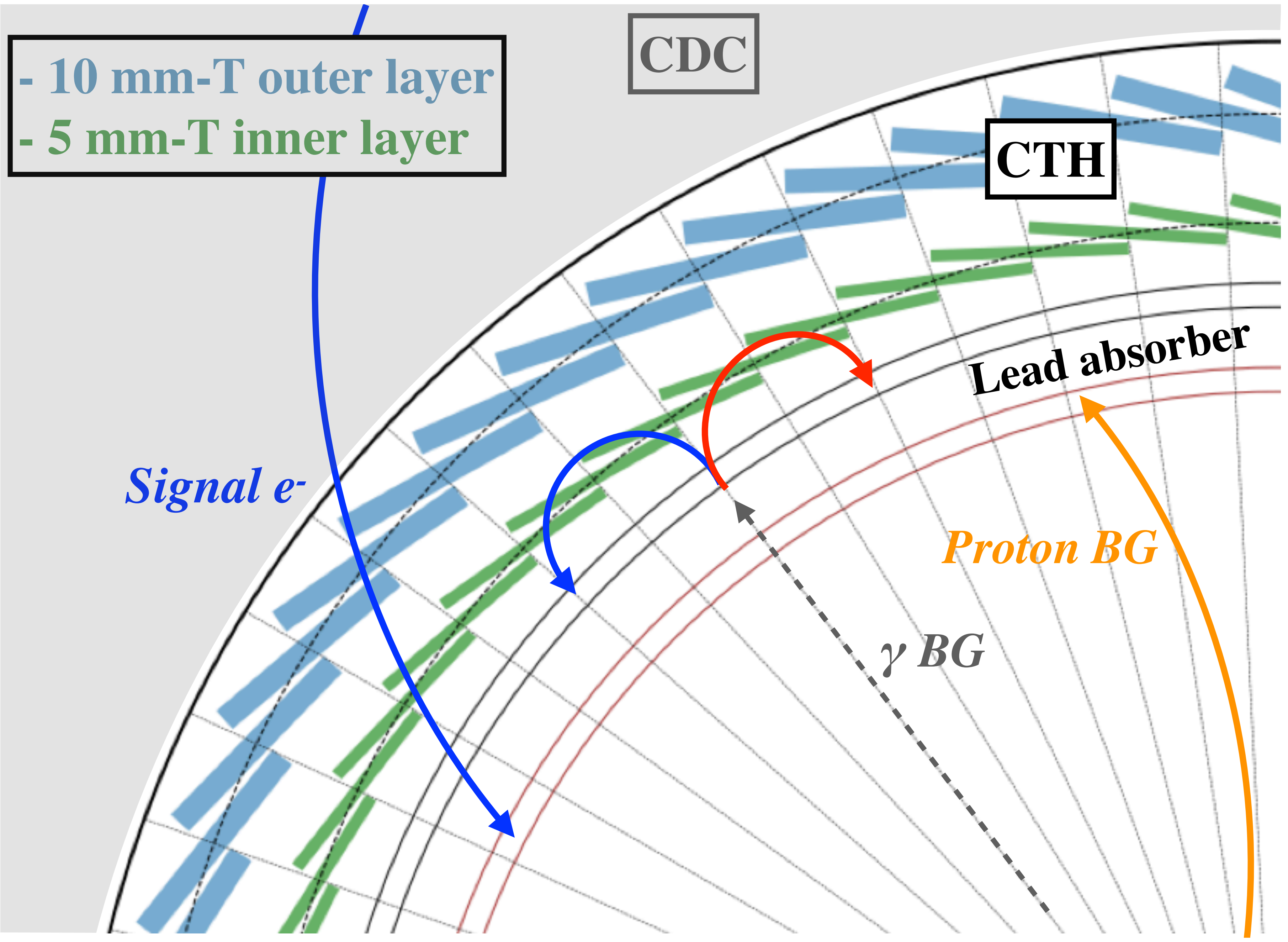




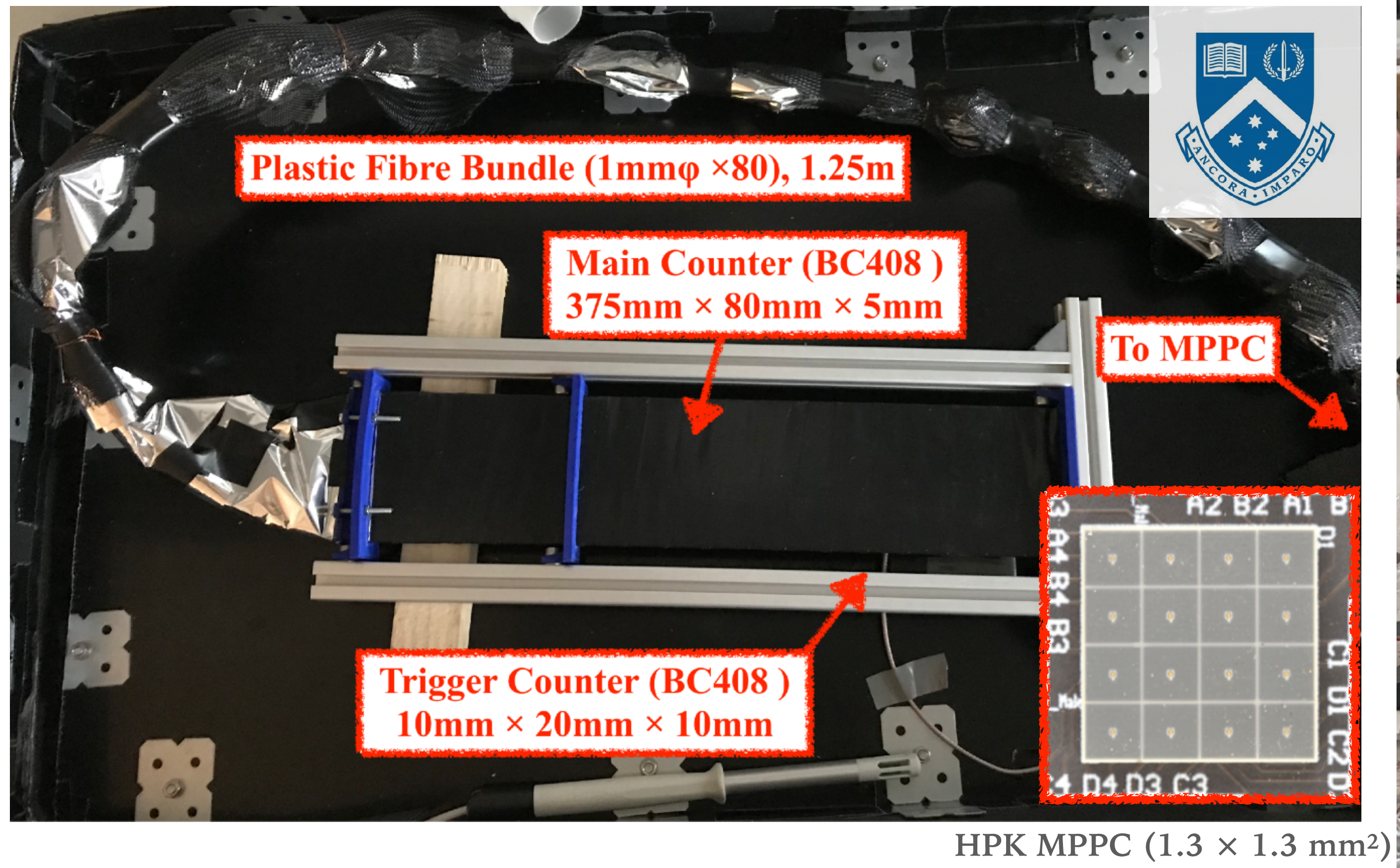
C. Wu, *et.al.* DOI:10.1016/j.nima.2021.165756

COMET Phase-I ~CTH~

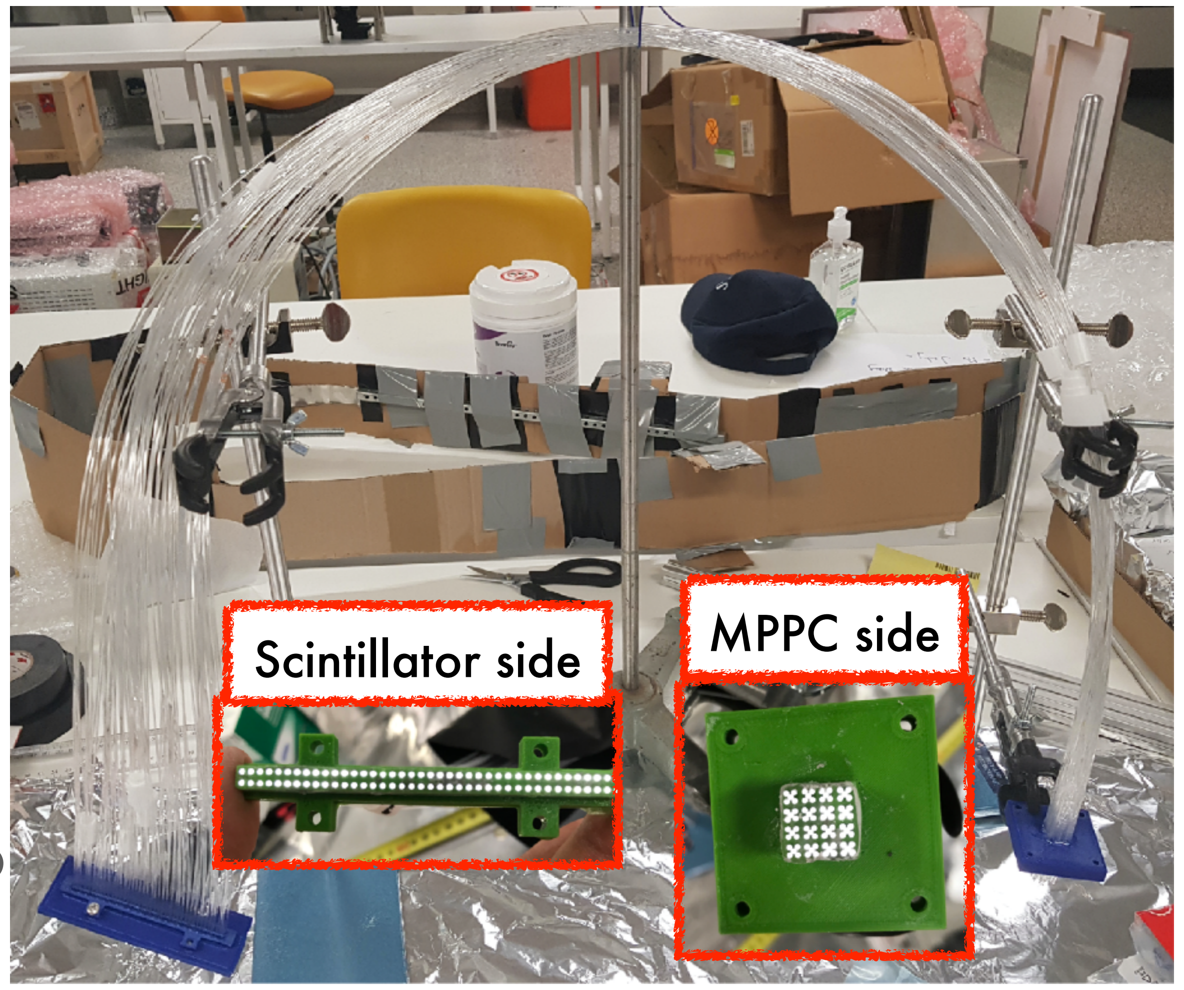
- Four fold coincidence for better timing determination & less accidental events ⇔ the rate of e+/e- <10MeV is as high as 1-10 MHz
  - After 4-fold coincidence, the rate become less than 100 kHz (based on simulation studies)
  - Photon extraction with fibre bundles to use inexpensive commercial SiPMs



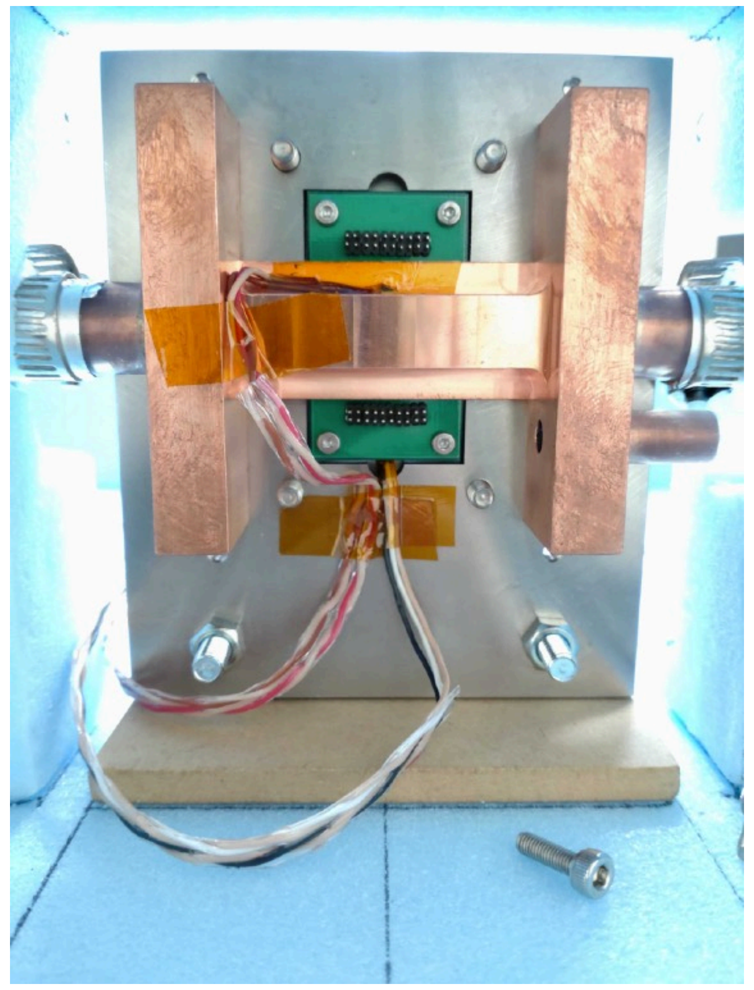
Y. Fujii, *et.al.* DOI:10.5281/zenodo.6781368



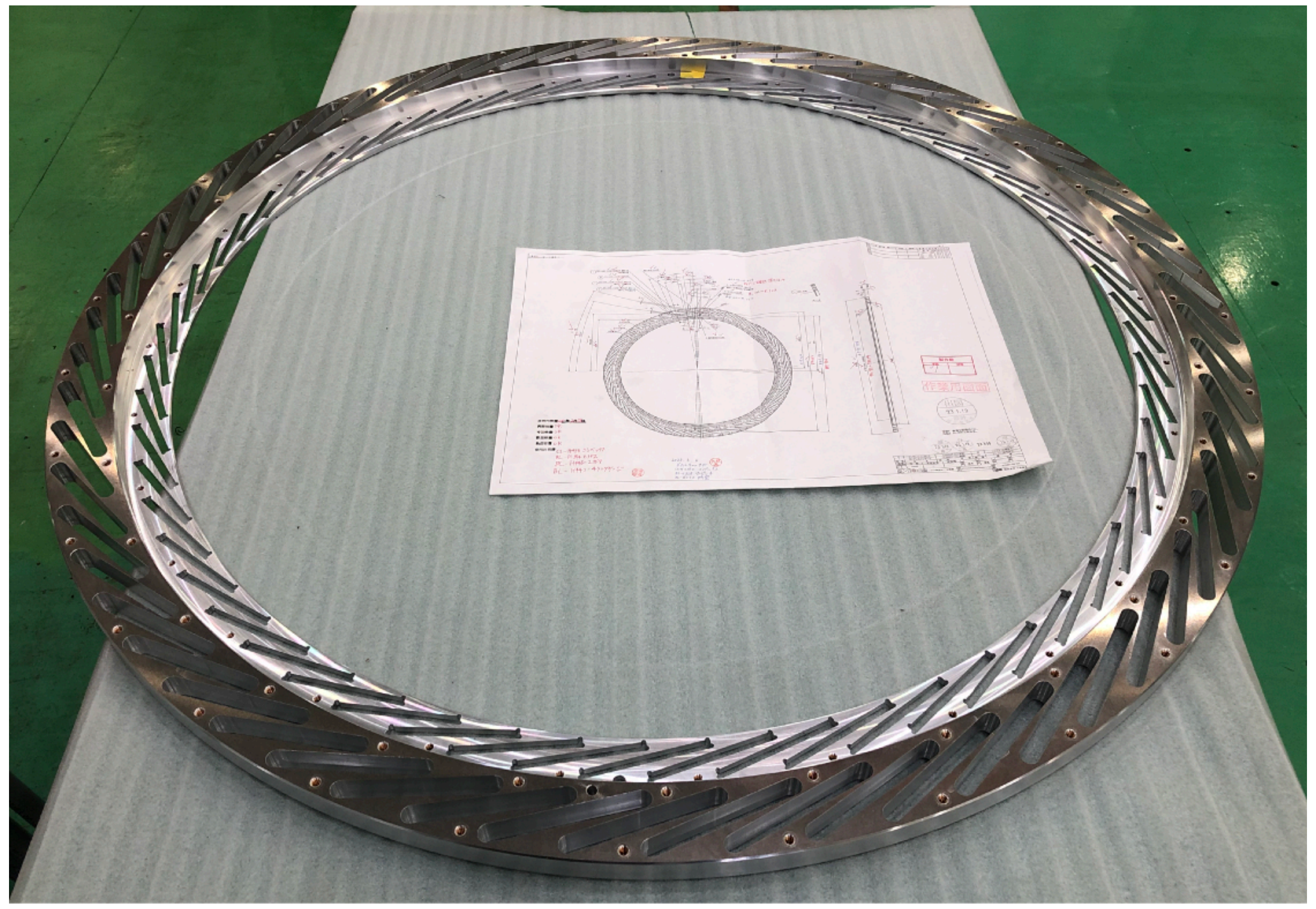
CTH counter + fibre prototype constructed and tested @Monash



Fibre bundle prototype

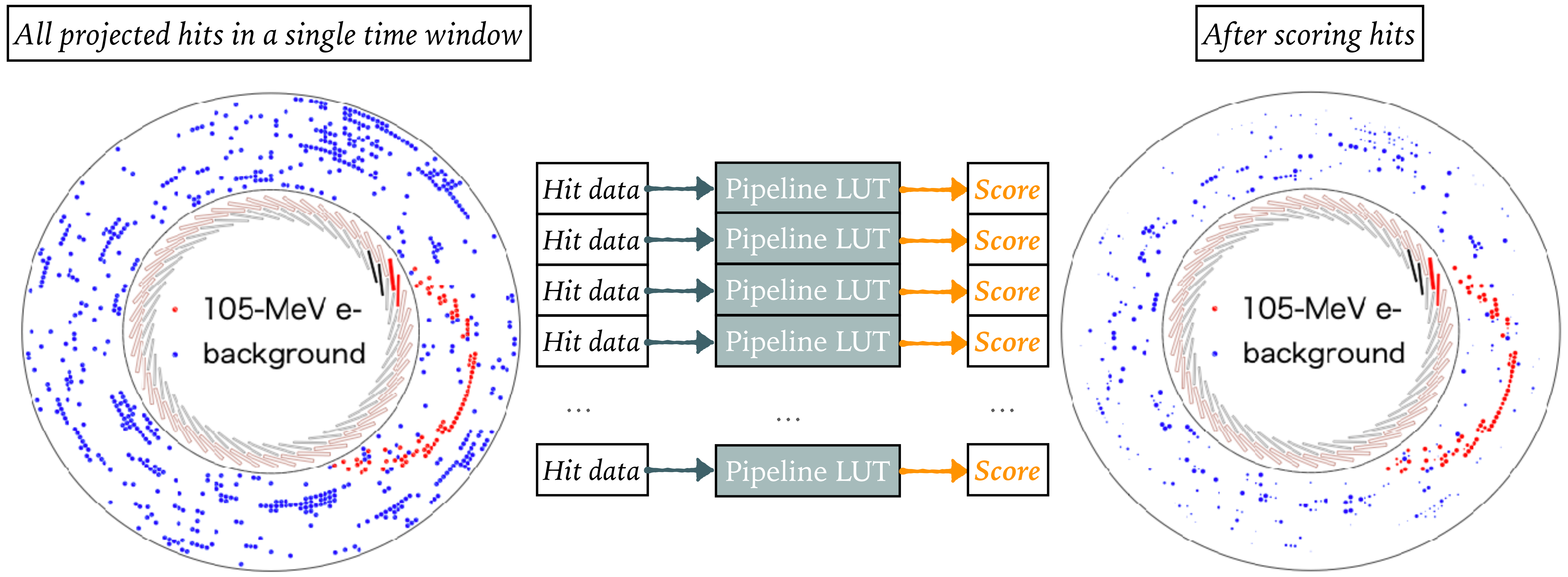


MPPC cooling system to achieve ~ -40°C

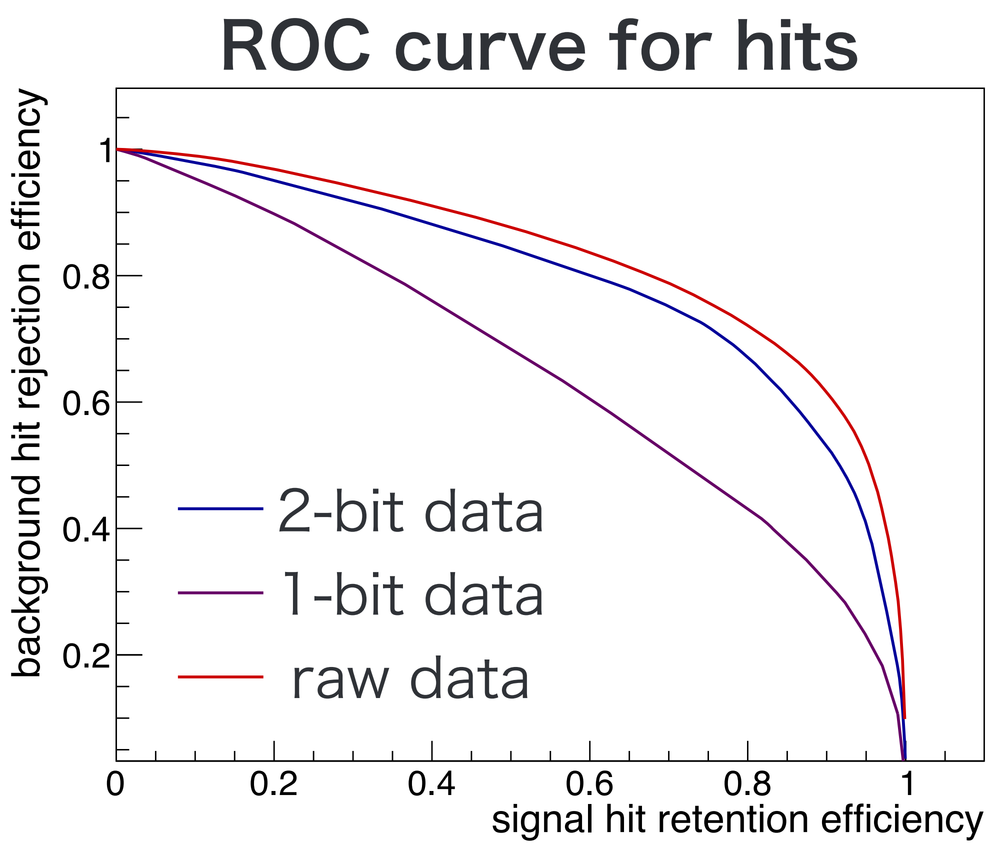


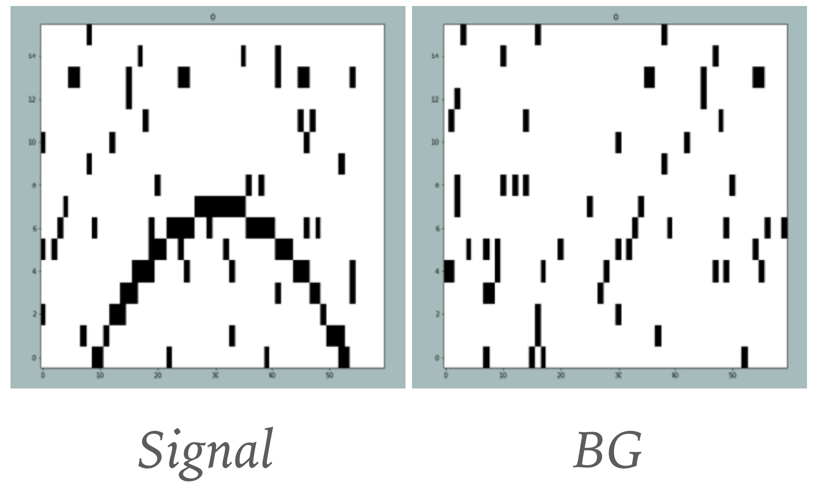
CTH Counter supporting structure

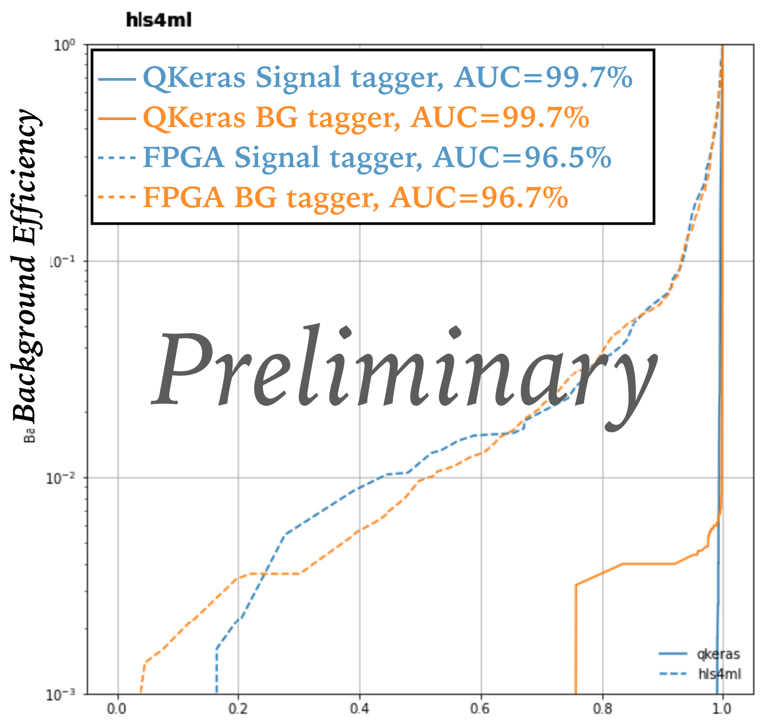
COMET Phase-I ~CyDet trigger~



Y. Nakazawa's PhD thesis

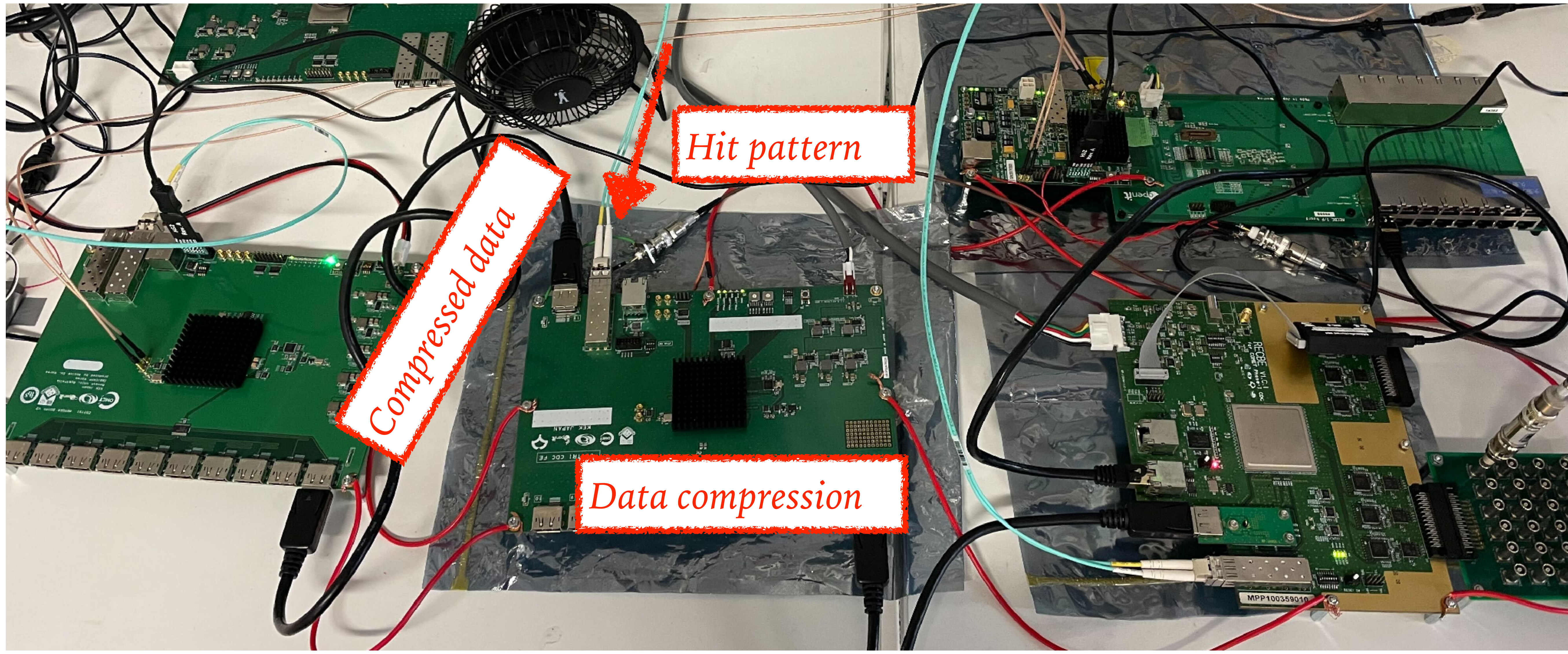






Using mock data and real FPGA boards, 120 ns latency achieved without losing too many signals

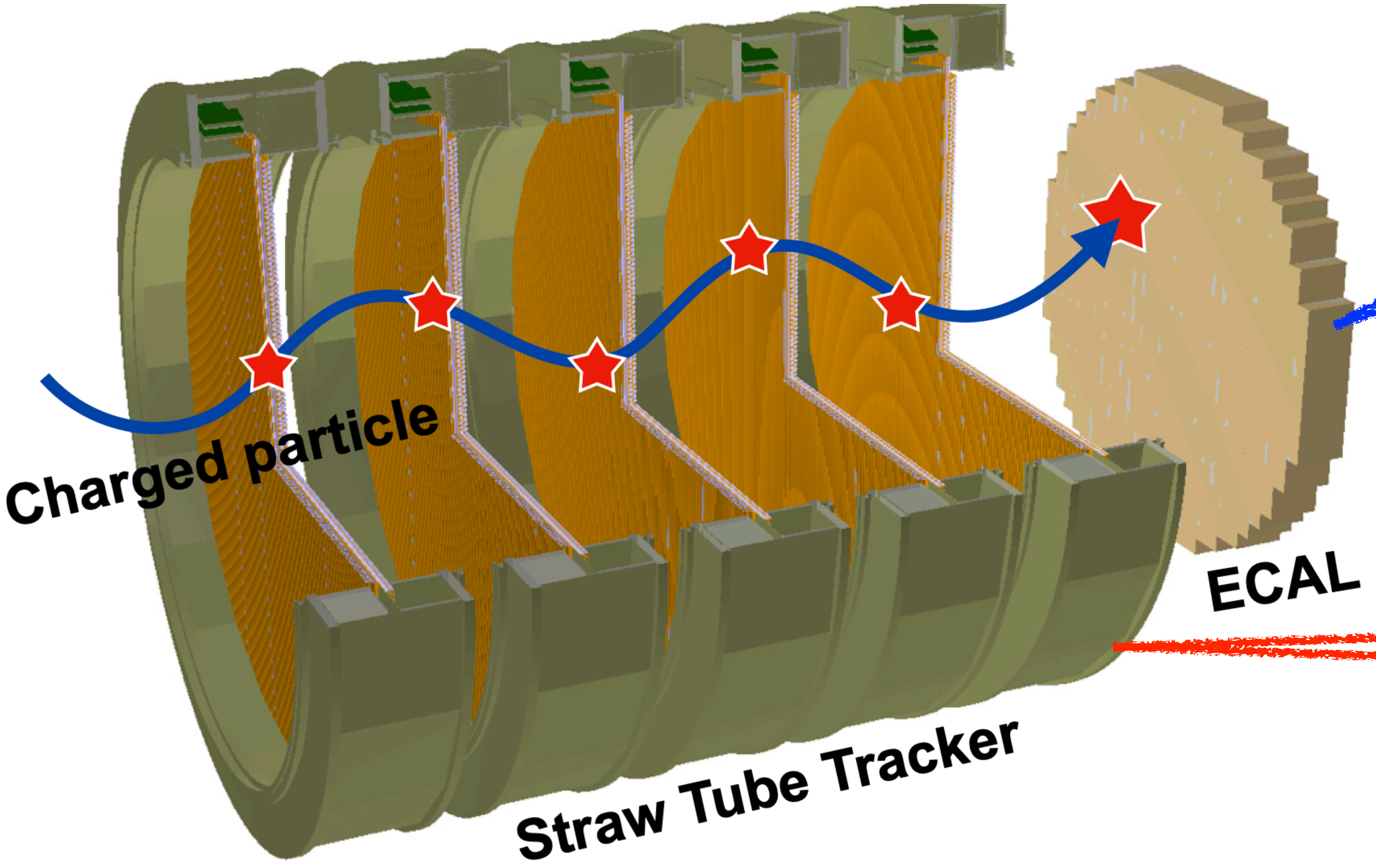
- Further trigger rate suppression by using the CDC hit information @FPGA level to achieve the trigger rate less than 13 kHz with the maximum signal efficiency
  - Many BG hits deposit larger energy than signal ones without helix pattern contained inside the CDC
  - GBDT for hit classification to reduce the BG-like hits
  - Neural network based event classification trigger is being developed for further BG trigger suppression



Y. Fujii, M. Miyataki et.al. NuFact 2023

COMET Phase-I ~StrECAL~

Direct beam measurement with Phase-II prototype detectors



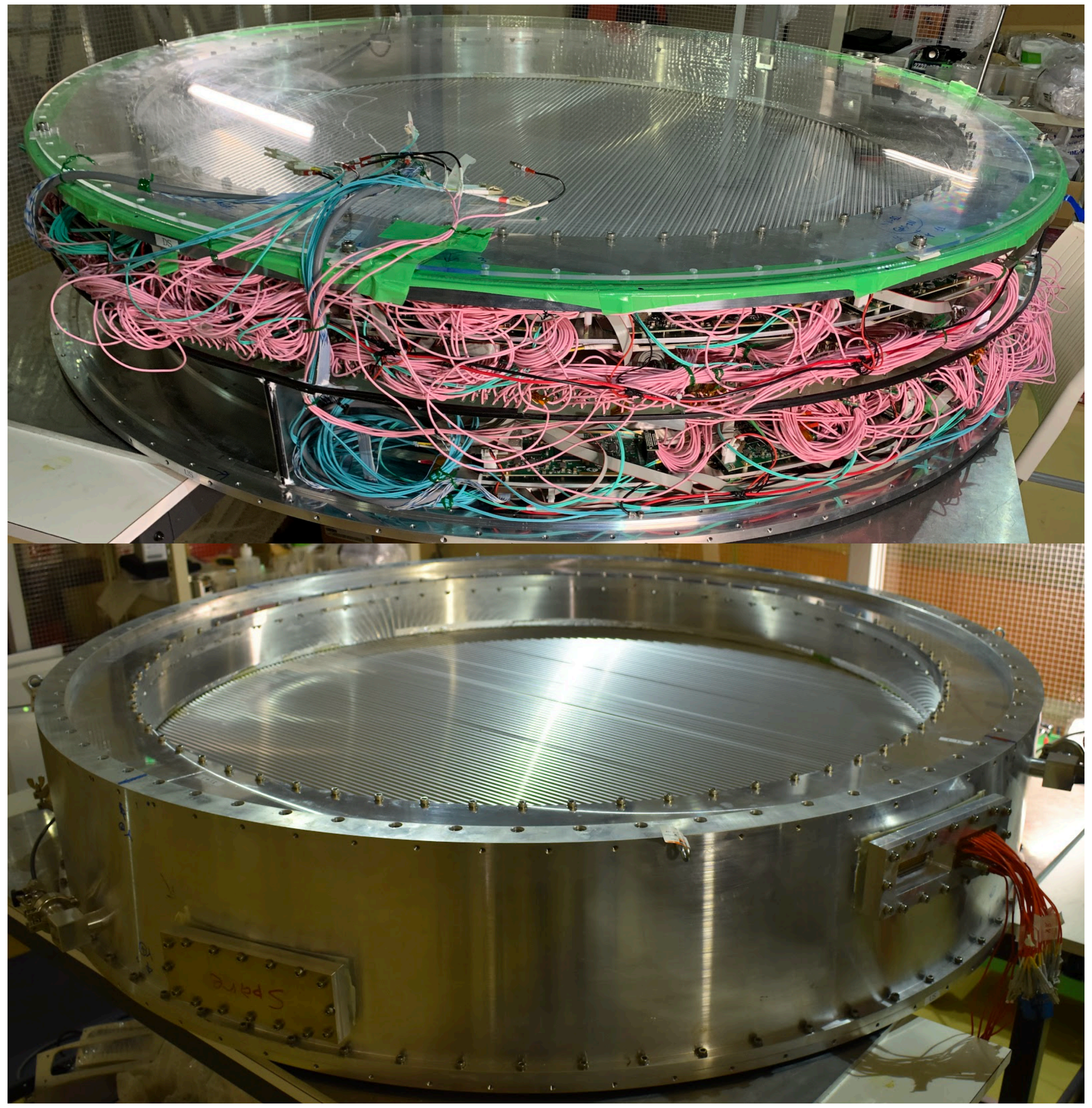
LYSO crystals
- Full energy absorption
- Fast time response

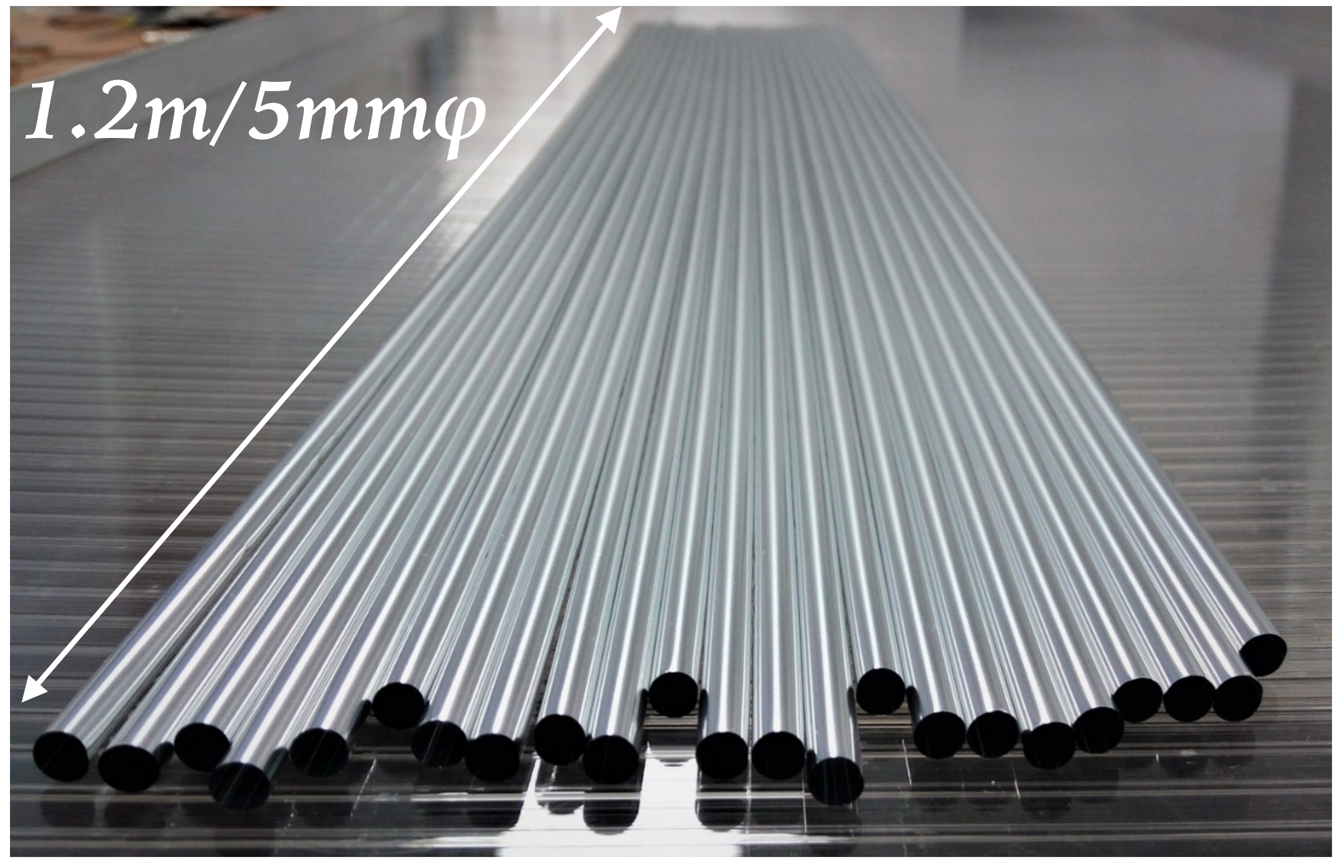
APD readout (space & radiation tolerance)

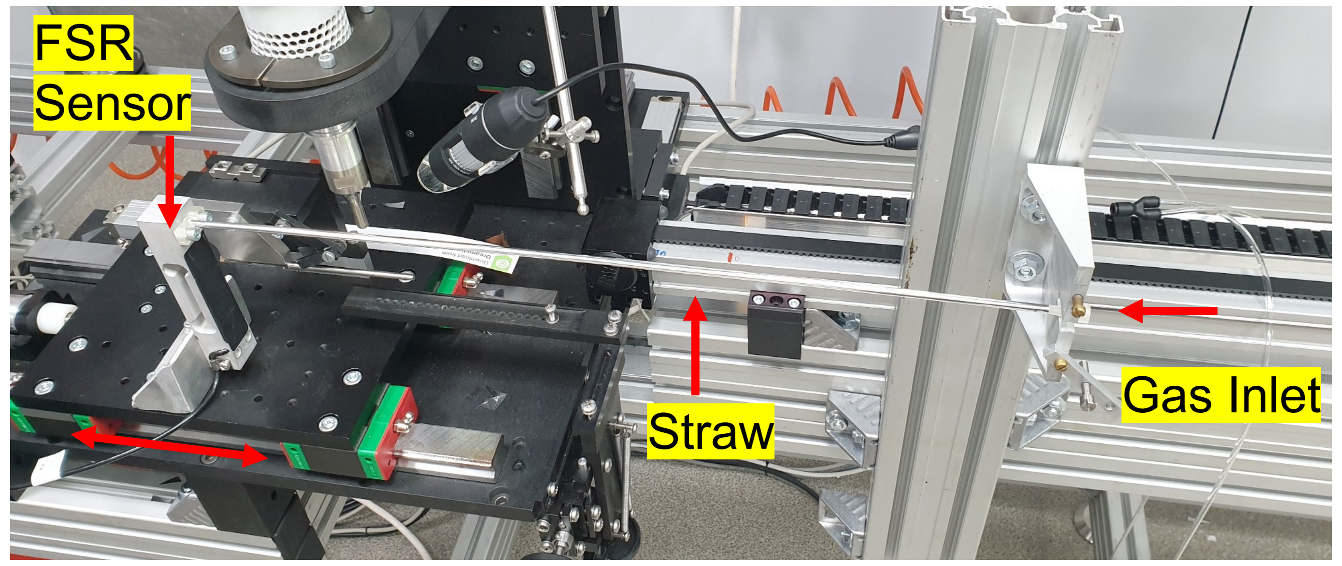
5 or more Straw stations
- Each station consists of 2 horizontal and 2 vertical layers
- Vacuum tight ultra thin straw tubes

COMET Phase-I ~Straw Tracker~

- The 1st full channel straw station constructed for COMET Phase-α/Phase-I beam measurements
  - Made of Aluminised mylar 20μmT, 10mmφ tolerate the 1 atm pressure difference, filled with Ar:Ethane 50:50
  - Expected $\sigma_p \sim 180$ keV/c
- Besides, 12μmT, 5mmφ straws have been developed and being tested, $\sigma_p \sim 150$ keV/c essential to achieve the aiming sensitivity in Phase-II

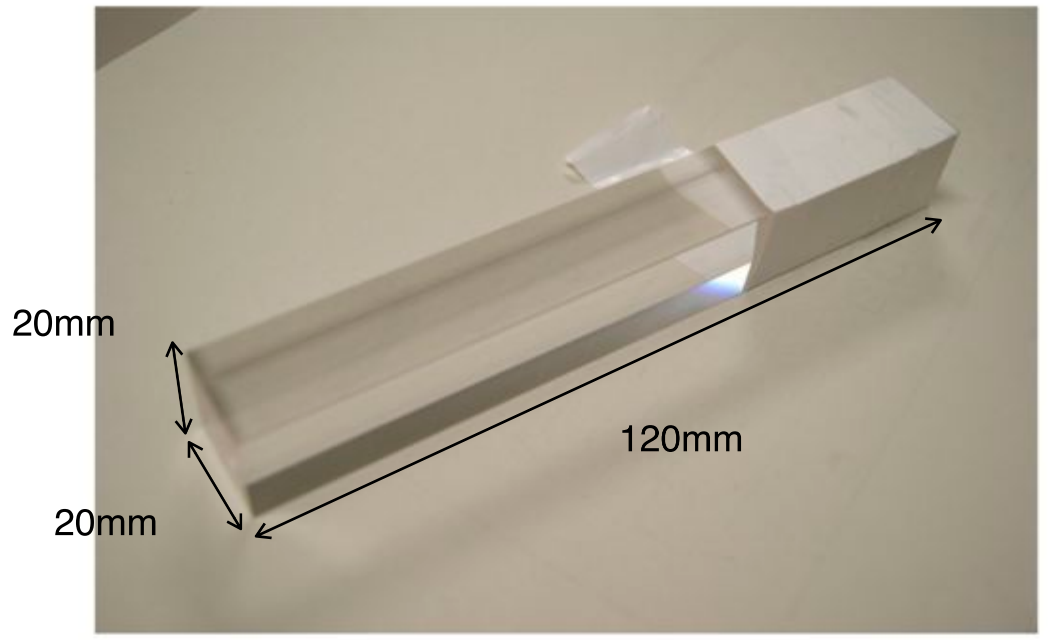


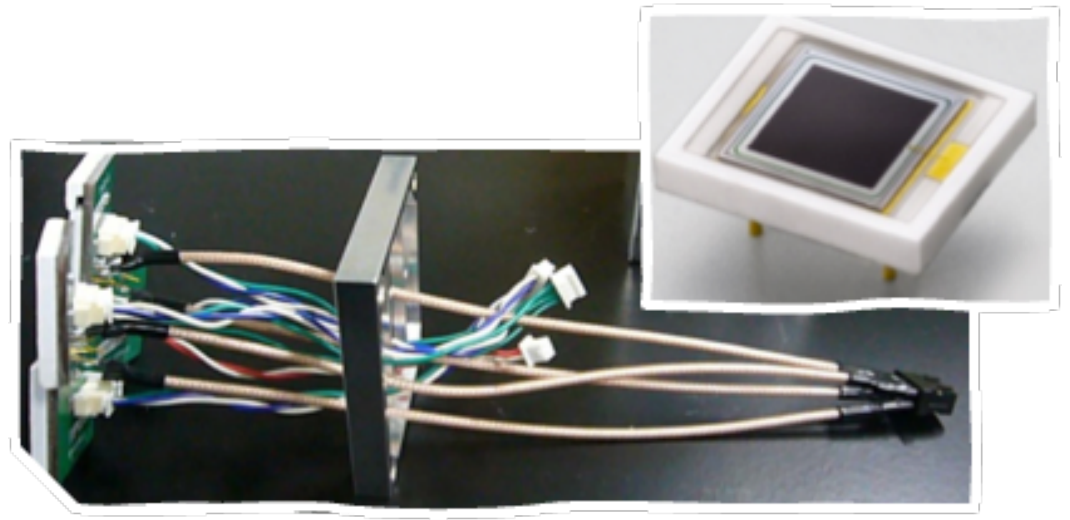


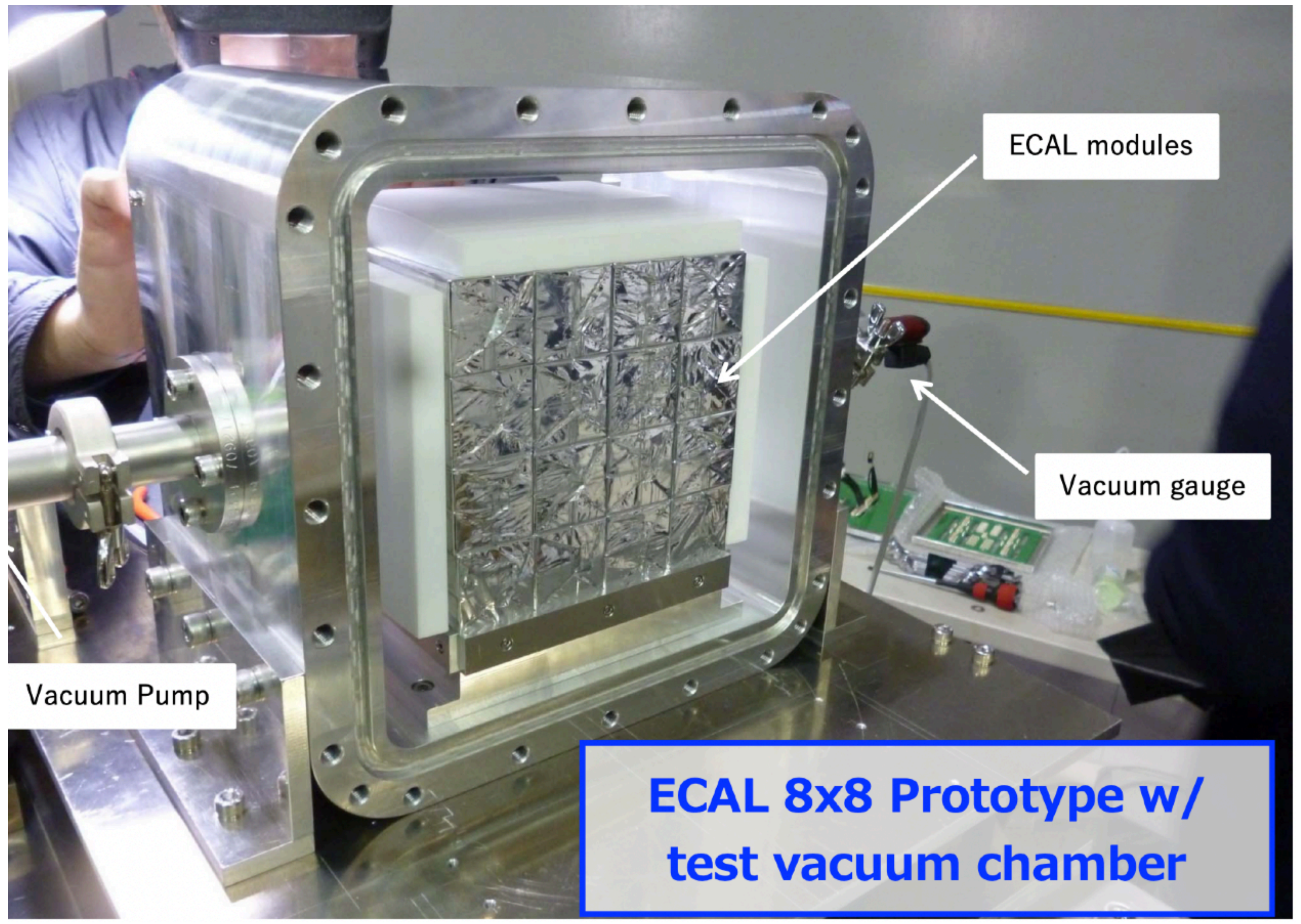


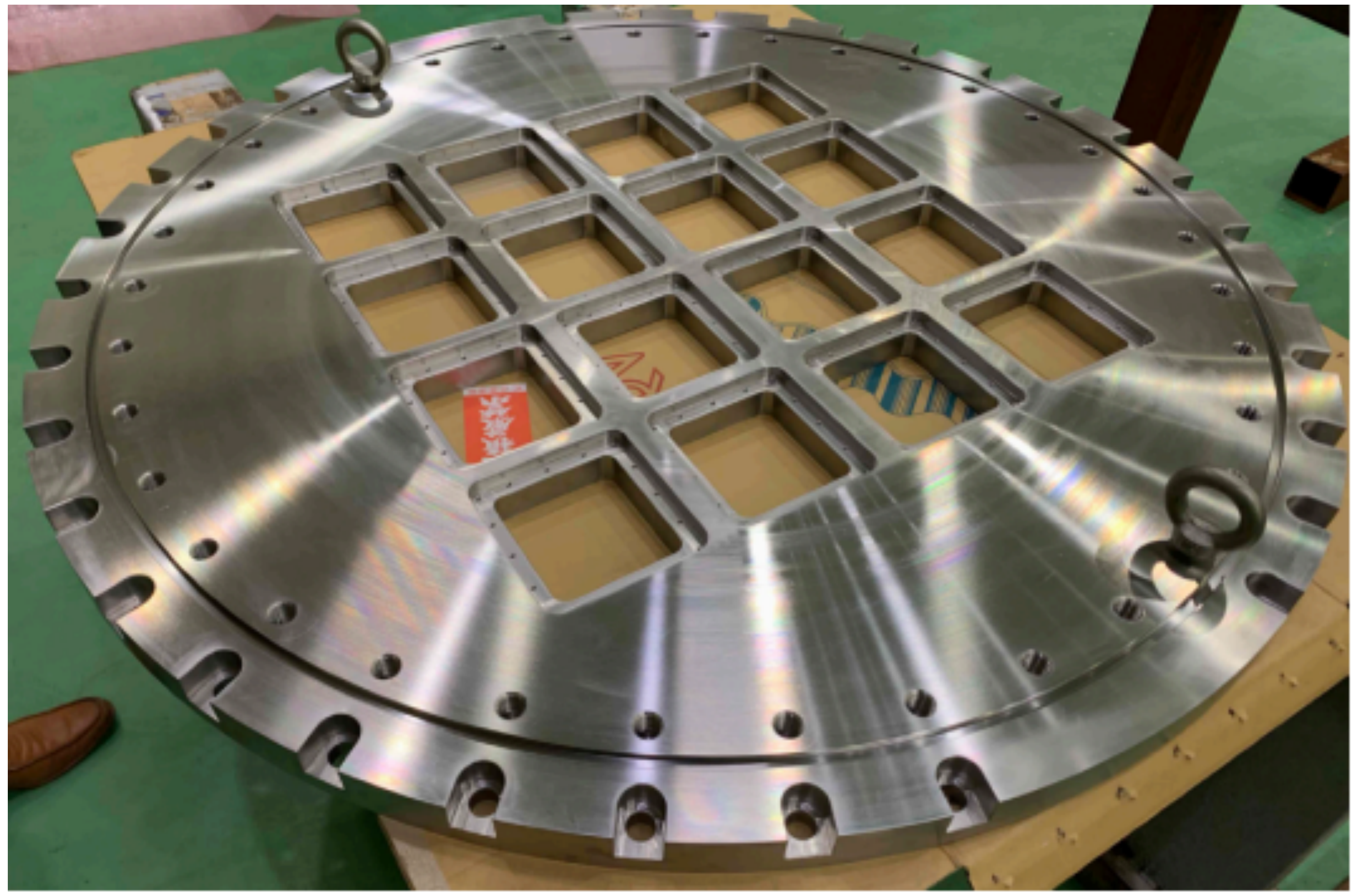
COMET Phase-I ~Electron Calorimeter~

- Measure the electron arrival time with good energy resolution
- Energy resolution better than 5% @100 MeV e^-, $\sigma_t \sim 0.5$ ns, $\sigma_{X/Y} \sim$ 6mm, all validated in the test beam measurement
- 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 with smaller gaps

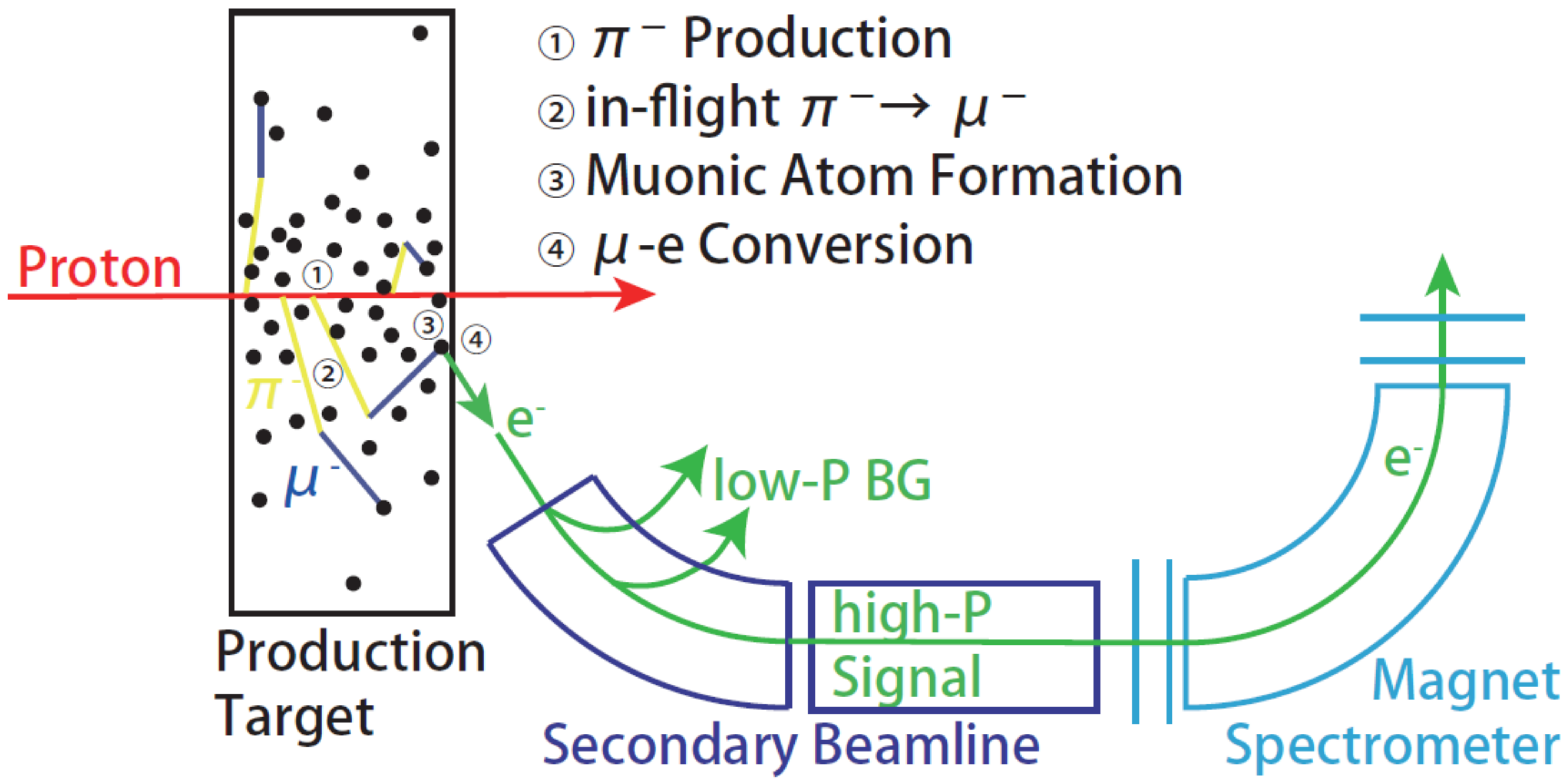


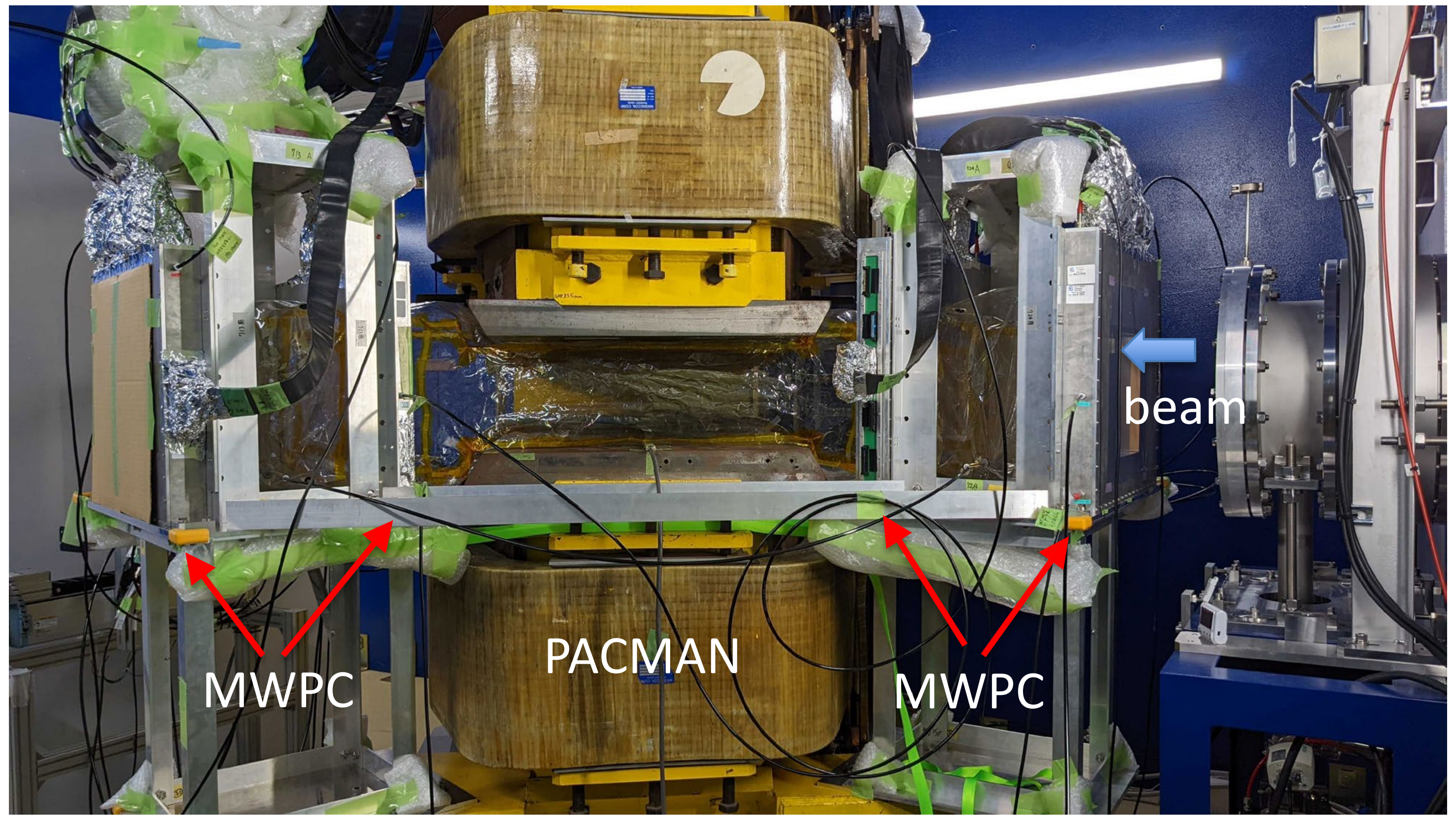


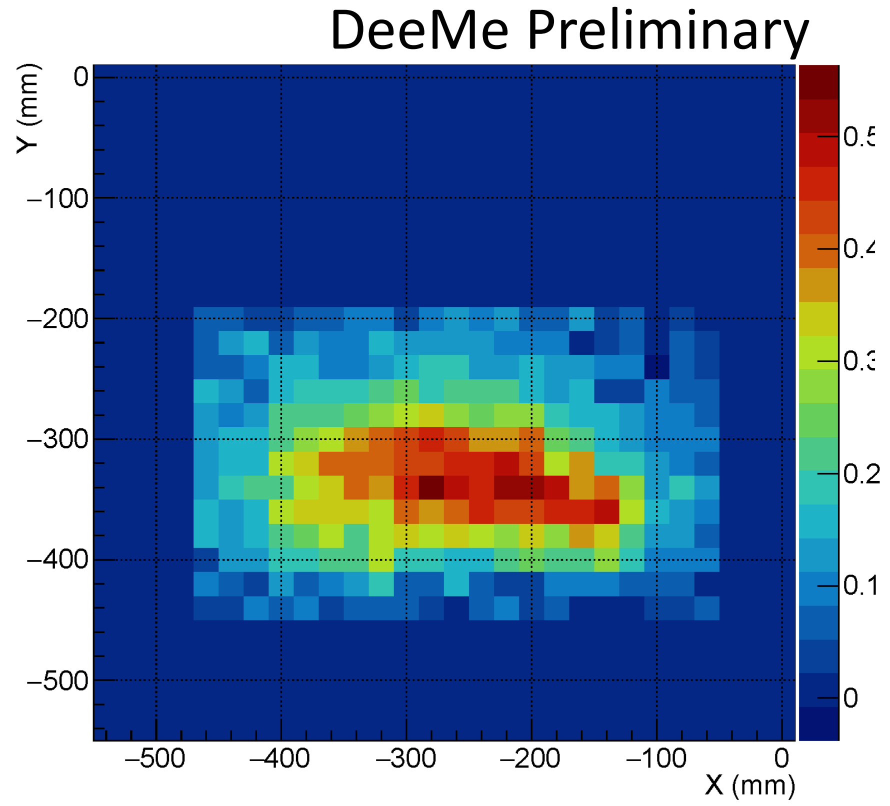




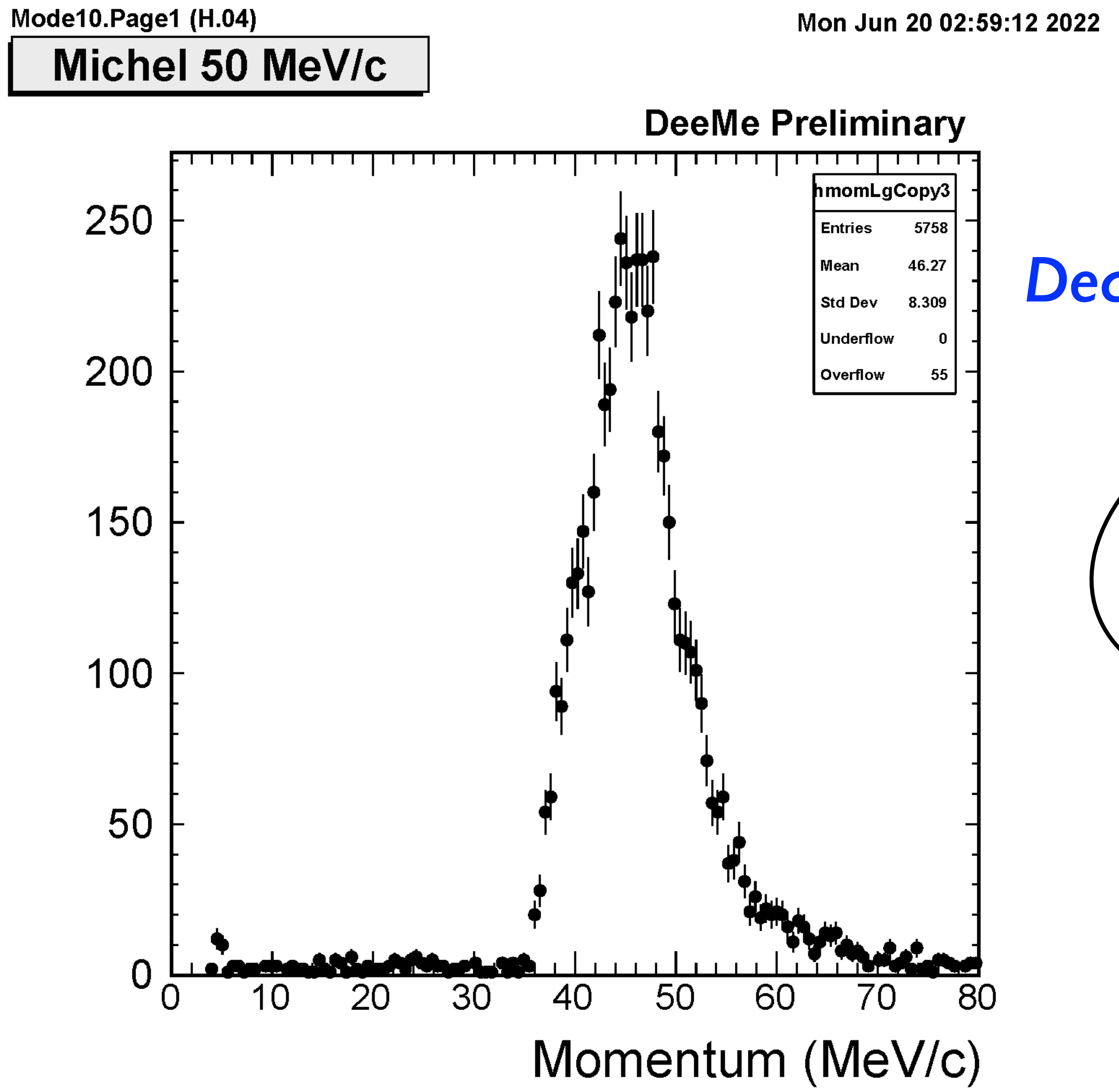
DeeMe @J-PARC MLF

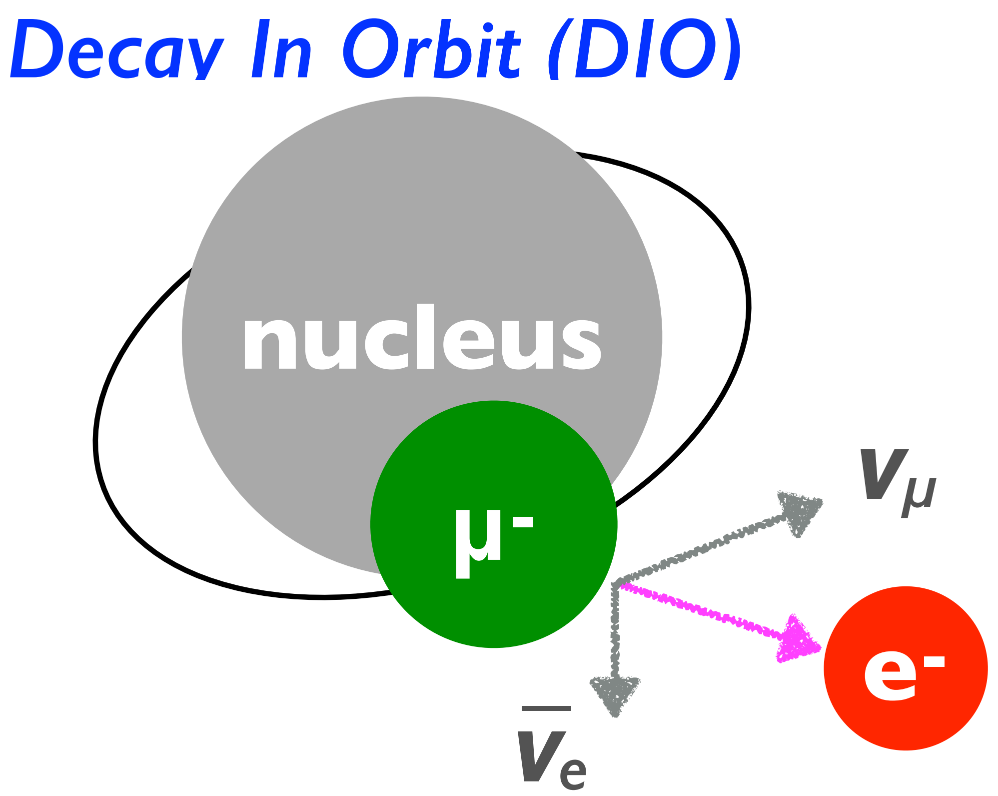






Prompt burst
105 MeV/c electron
beam profile





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

COMET Phase-I ~Expected Sensitivity~

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

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..

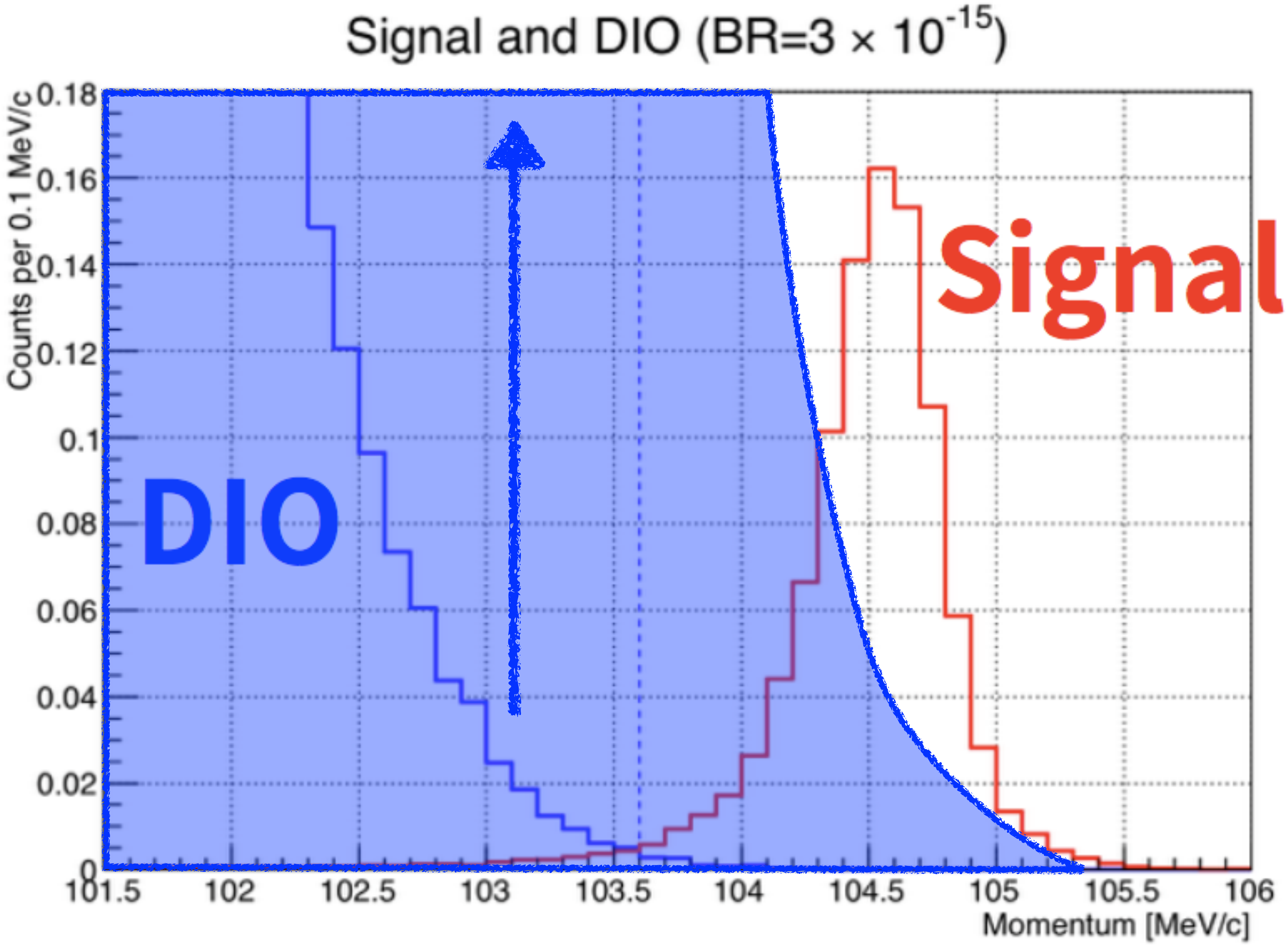
Item	Value	Comment
Acceptance	0.2	Fixed
Trigger/DAQ efficiency	0.8	Subject to change
Track finding efficiency	0.99	SC
Track selection	0.9	SC
Momentum window	0.93	103.6 MeV/c < p < 106.0 MeV/c
Timing window	0.3	700 < t < 1170 ns, SC
Total	0.04	At least 25% error

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 ~Concept~



×100 Sensitivity means ×100 background particles

- DIO background suppression is essential
  - Better momentum resolution ≒ less materials
  - Higher pile-up situation

Smaller diameter straw-tubes with thinner wall

Additional electron spectrometer to reduce lower momentum DIOs

COMET Phase-II ~Sensitivity~

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

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..

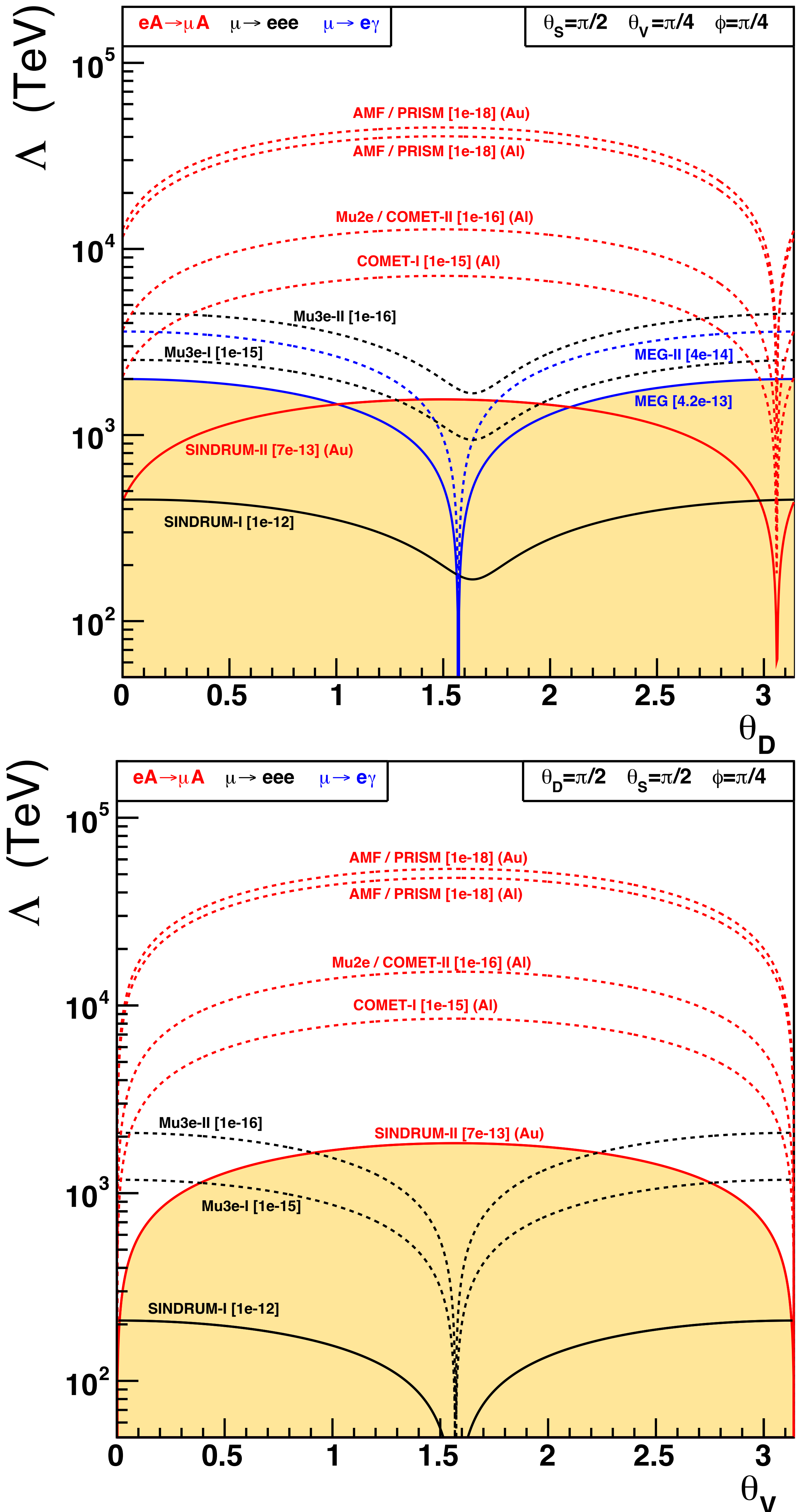
Item	Value in P-I	Value in P-II	Comment
Acceptance	0.2	**0.18**	Fixed
Trigger/DAQ efficiency	0.8	**0.87**	Subject to change
Track reconstruction efficiency	0.99	**0.77**	SC
Track selection	0.9	**0.94**	SC
Momentum window	0.93	**0.62**	104.2 MeV/c < p < 105.5 MeV/c
Timing window	0.3	**0.49**	600 < t 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

K. Oishi, PhD thesis in 2020

CLFV in EFT

- Searches for CLFV processes indirectly probing ***Λ_{NP} > 1 PeV*** new physics scale
  - ⇔ Ultra large Moon collider, ***14 PeV pp*** (arXiv:2106.02048)
- Complementary searches available with different muon CLFV modes (Muon CLFV golden modes; $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$)

	Current upper limit (90%CL)	Given by	Target 90%CL UL sensitivity	Projects
μ→eγ	4.7×10^{-13}	MEG	**6×10^{-14}**	**MEG II**
μ→eee	1.0×10^{-12}	SINDRUM	**$2\times10^{-15}/10^{-16}$**	**Mu3e/Mu3e p-II**
μN→eN	7.0×10^{-13} @Au	SINDRUM II	**$10^{-14}/10^{-17}$**	**DeeMe/COMET/ Mu2e**

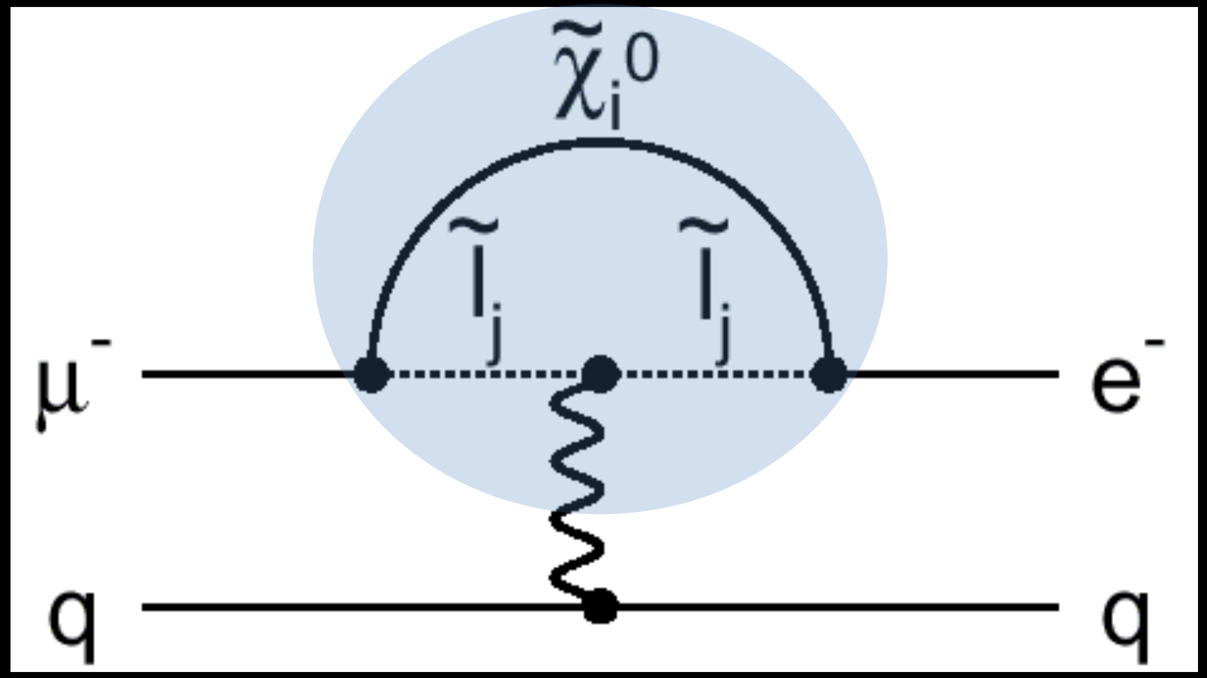


S. Davidson and B Echenard, arXiv:2204.00564

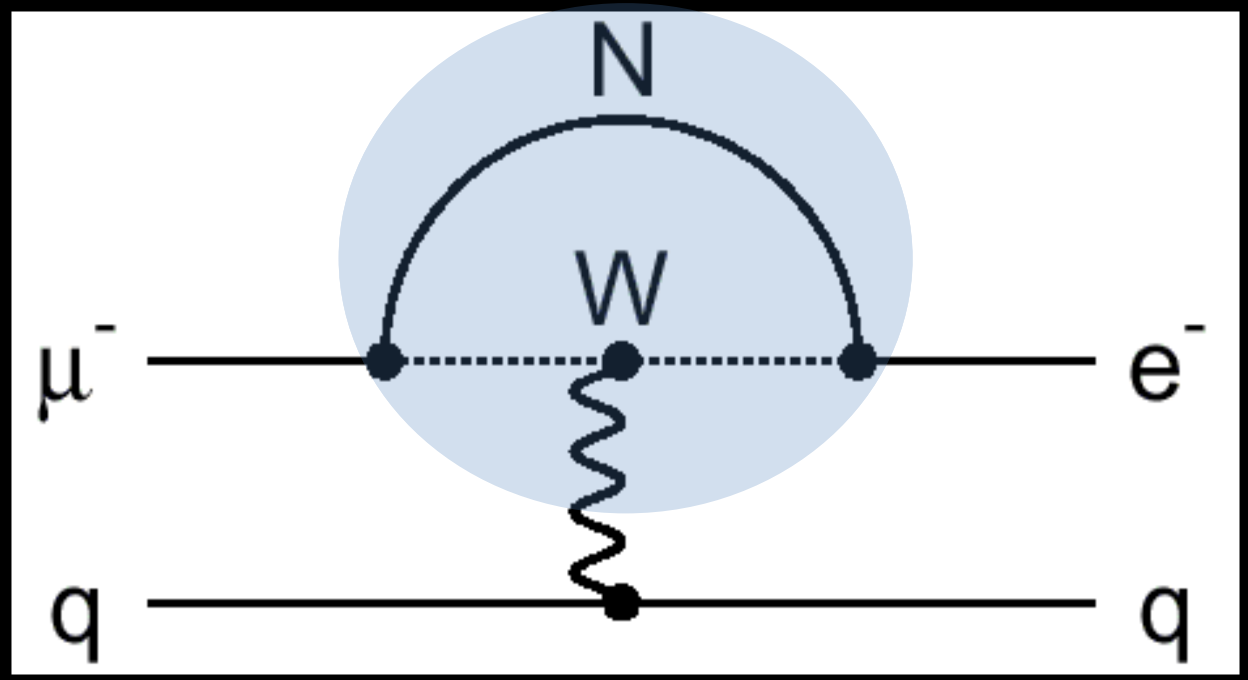
μ-e conversion in BSM

Loops

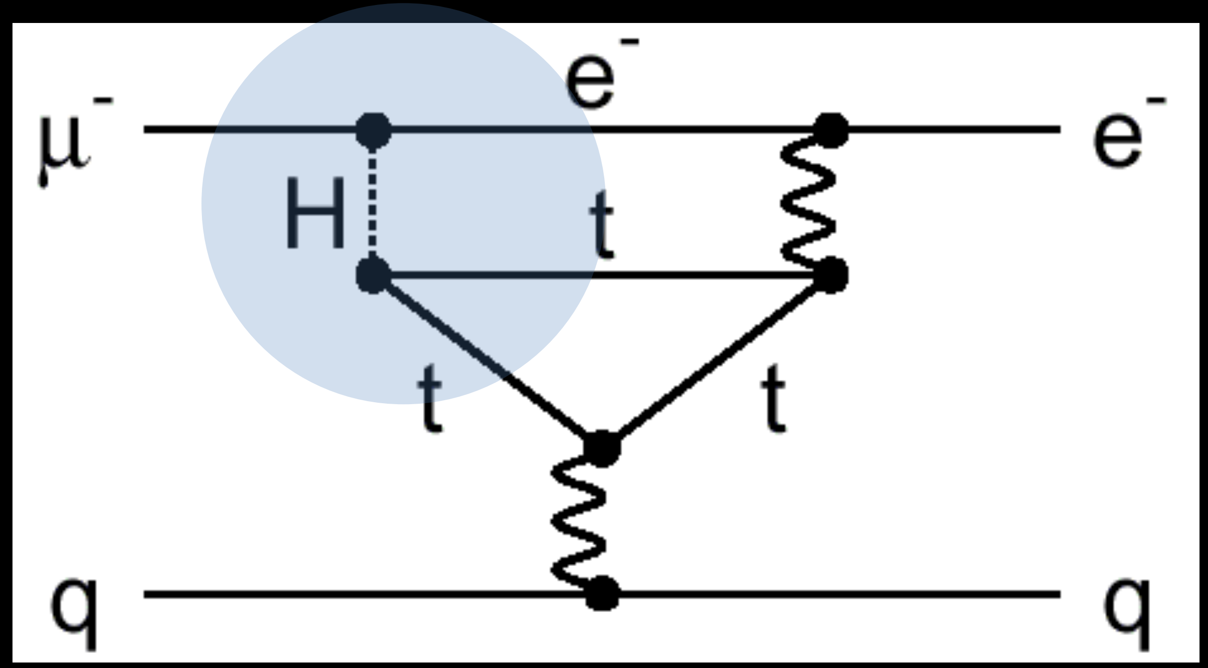
Supersymmetry



Heavy neutrino

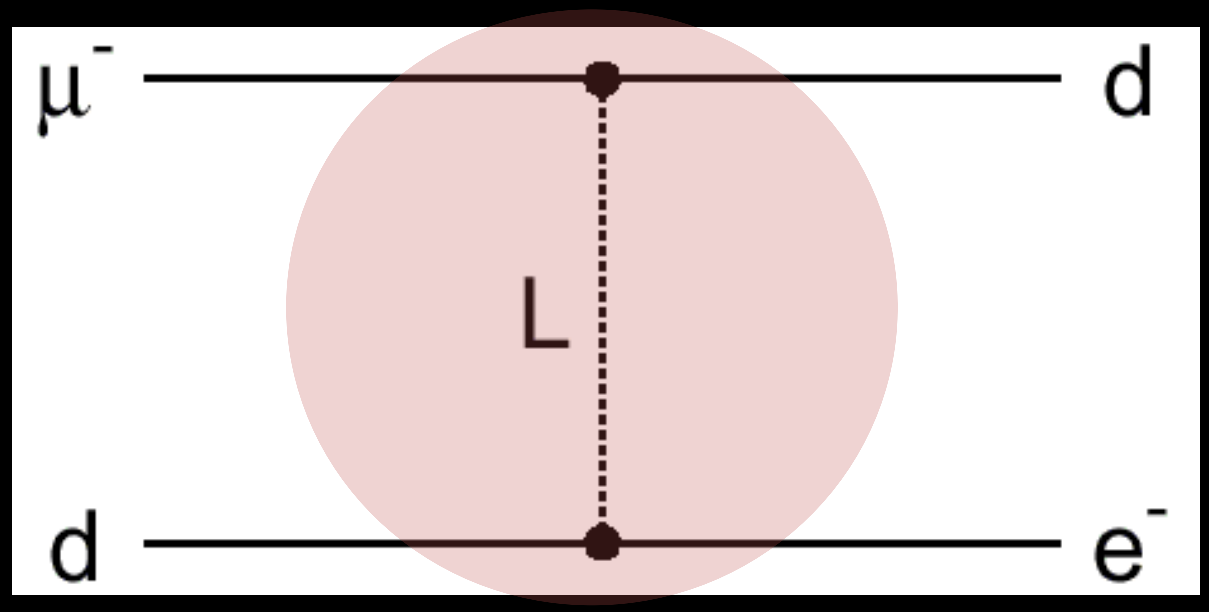


Two Higgs doublet

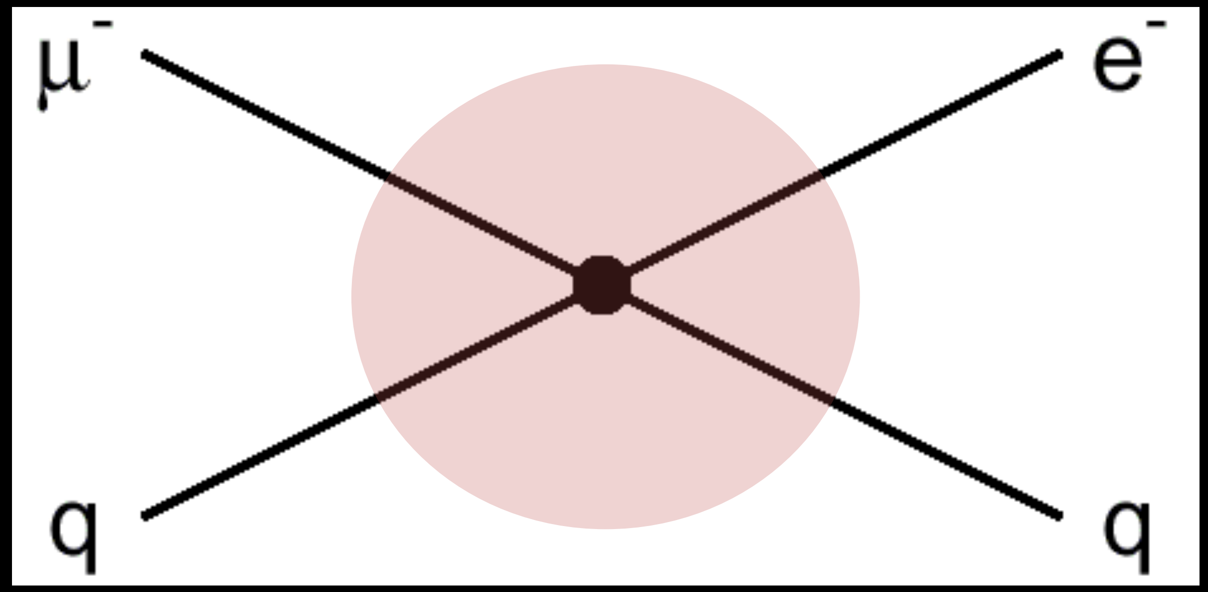


Contact interaction

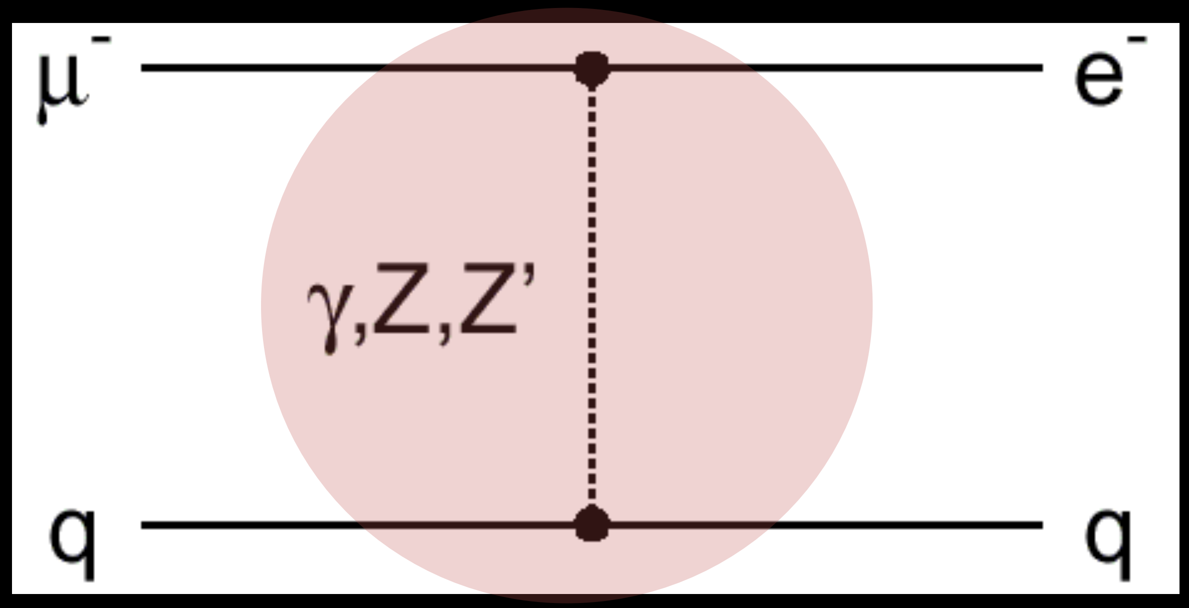
Leptoquarks



Compositeness



New heavy bosons / anomalous coupling

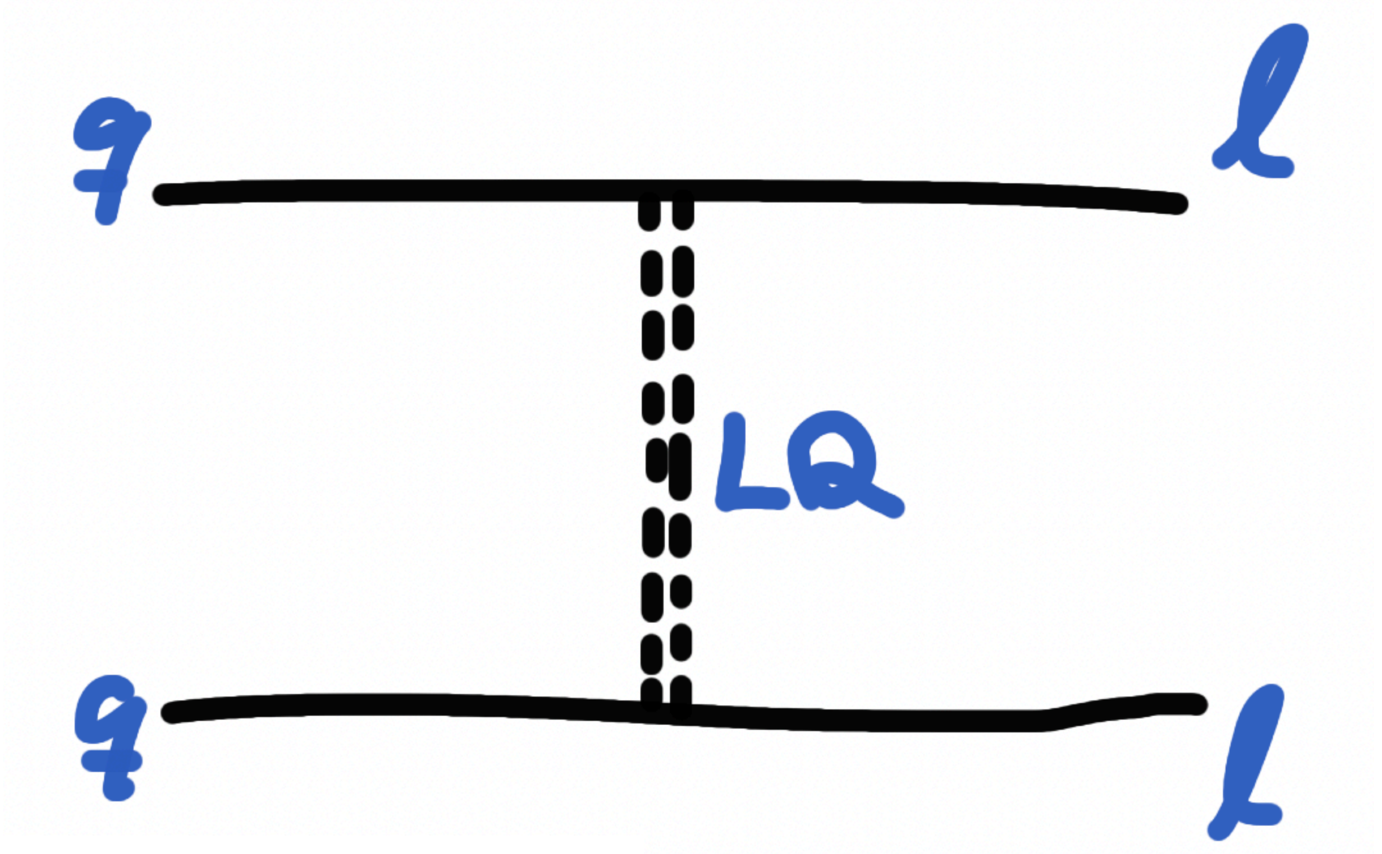


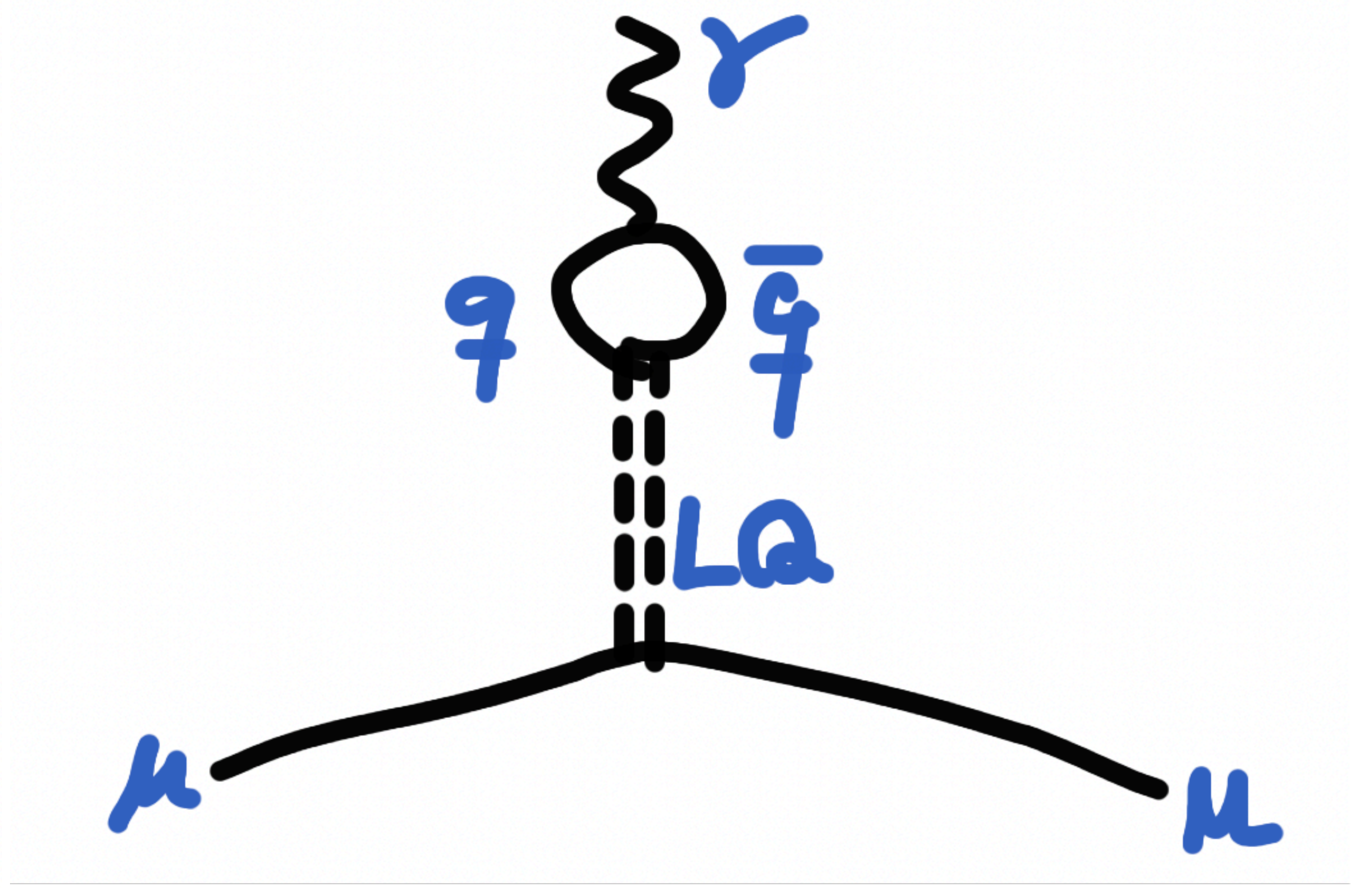
Different interactions generate different processes → complementary searches unveil the BSM structure

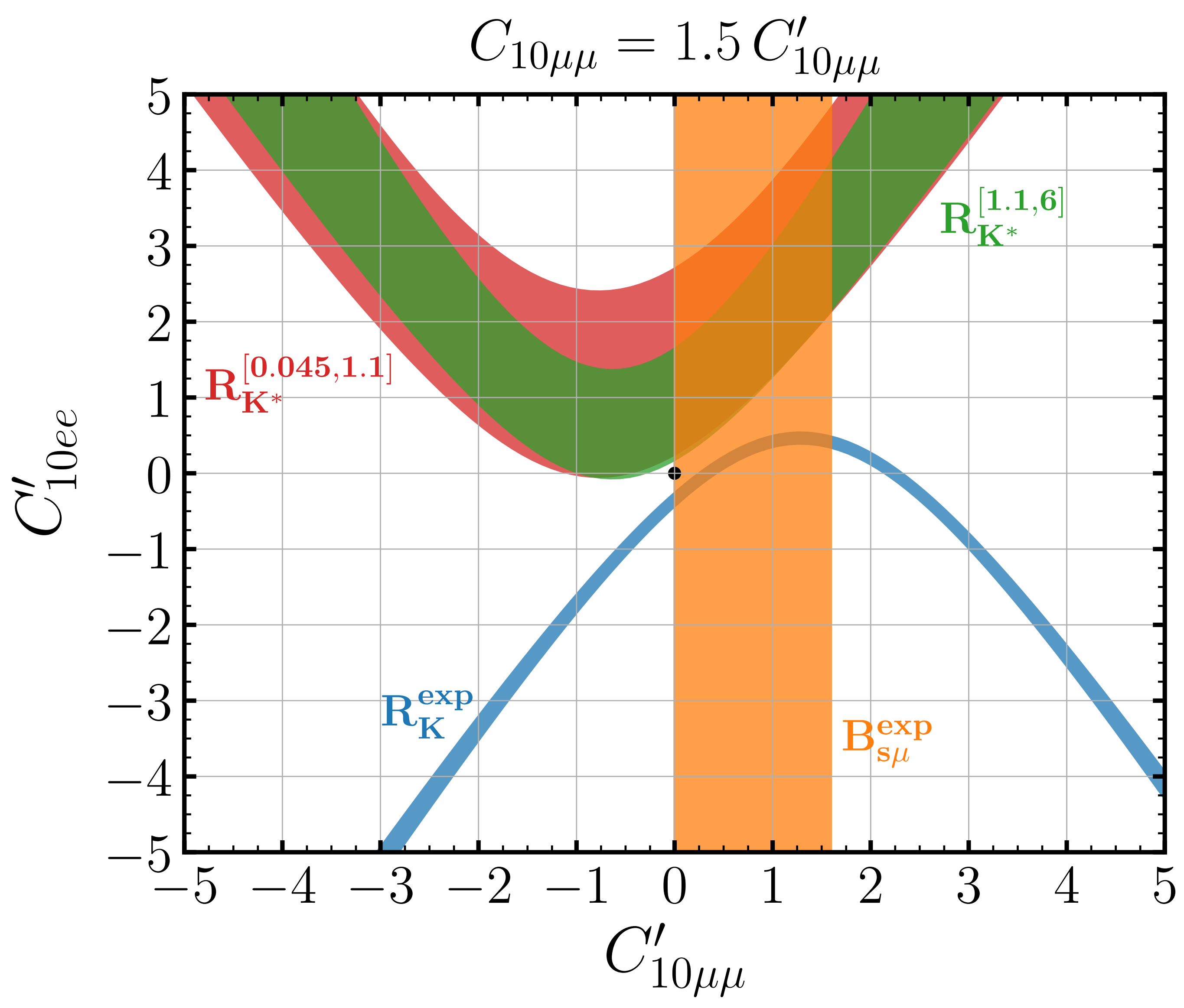
S. Davidson and B Echenard, Rare processes and Precision Frontier kick-off meeting (2020)

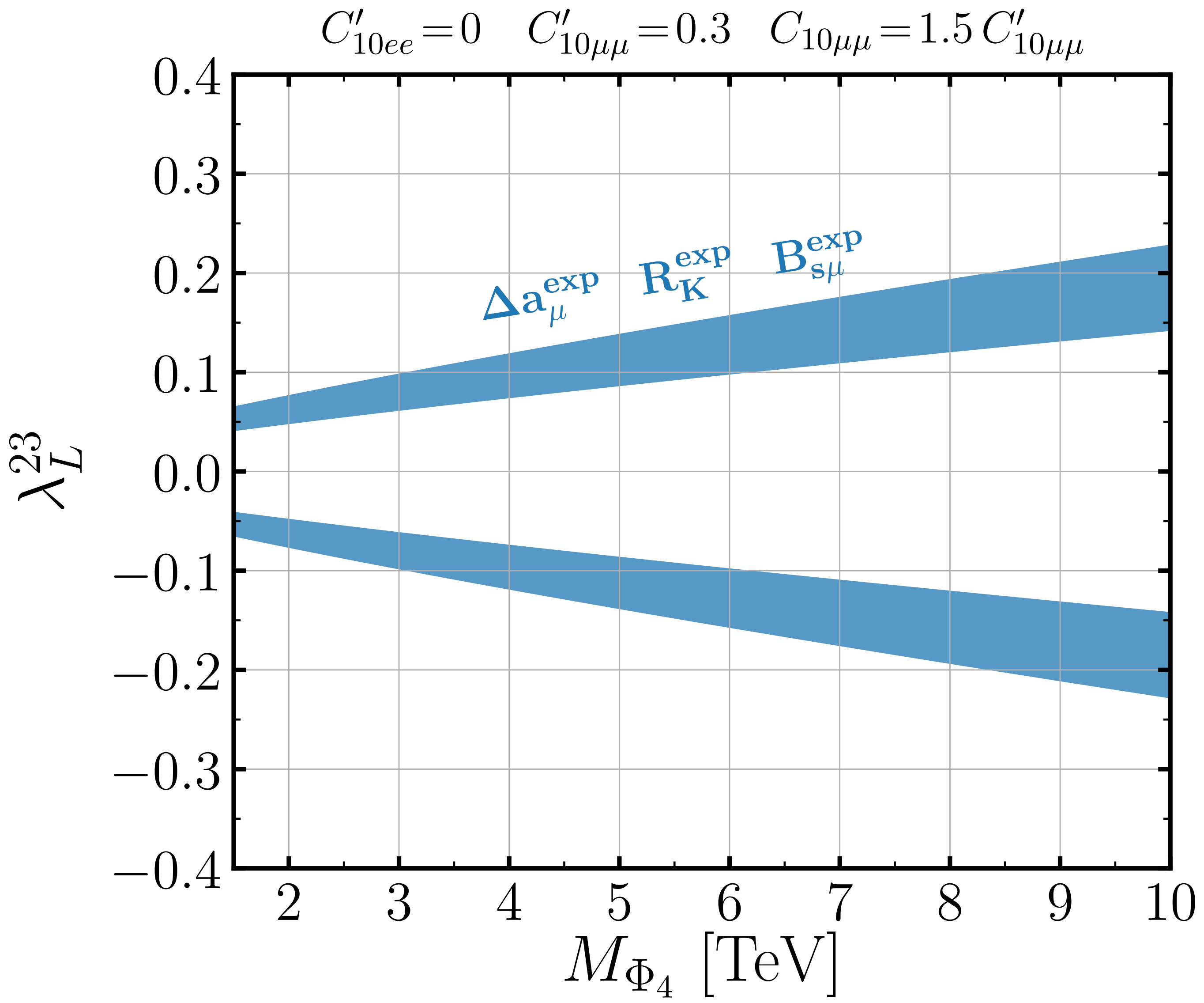
CLFV and Leptoquarks

- 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