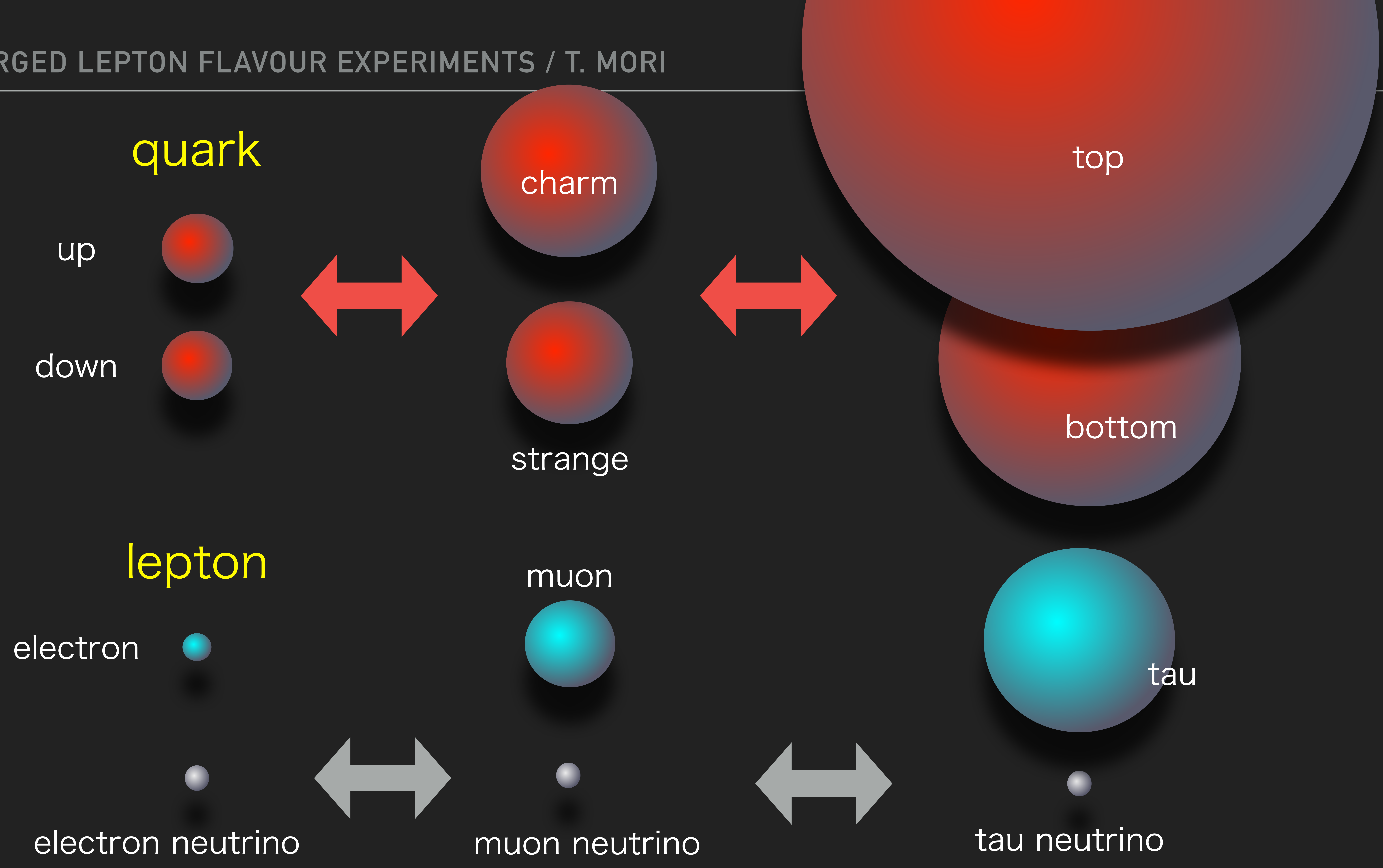
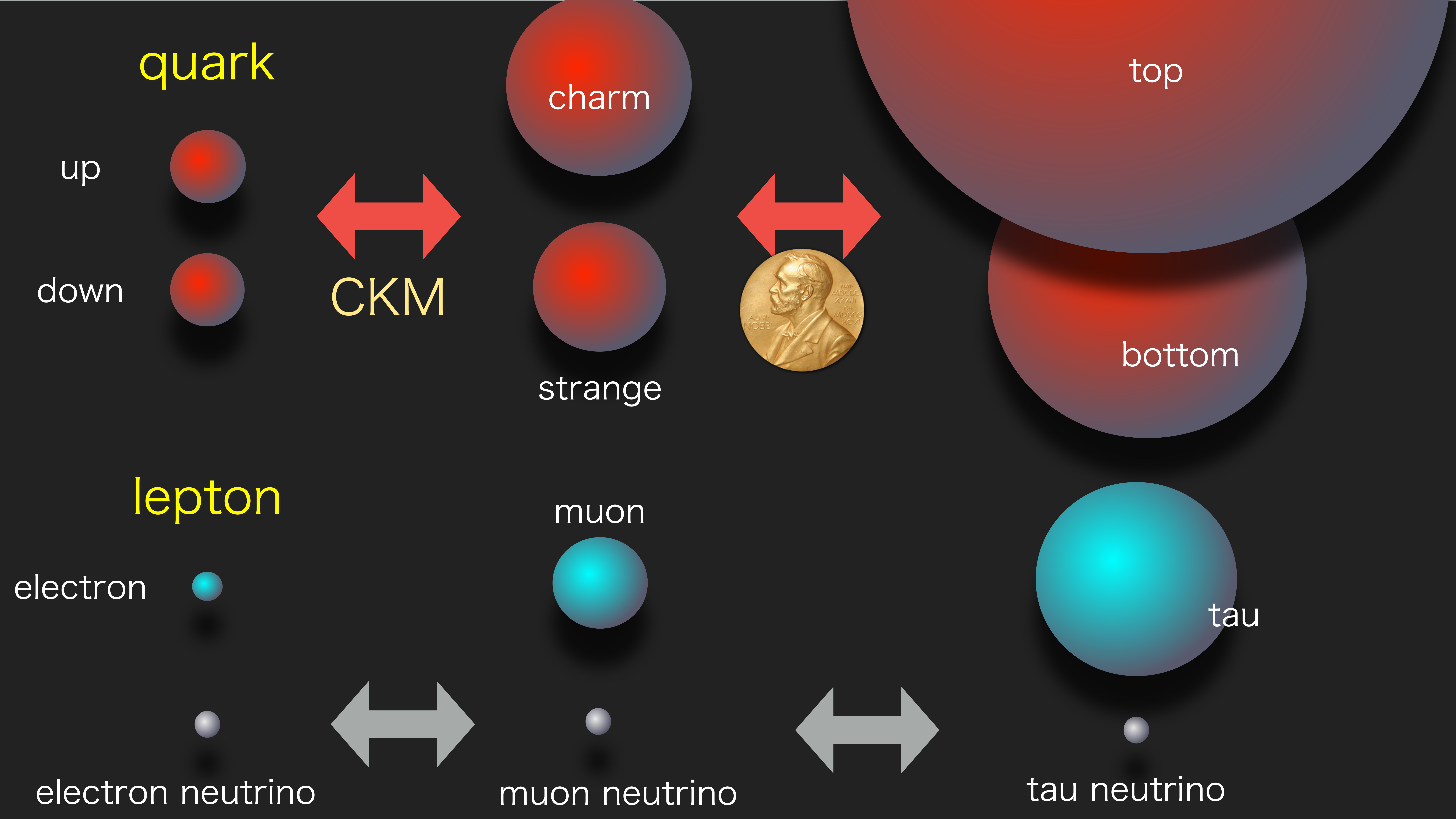
TOSHINORI MORI

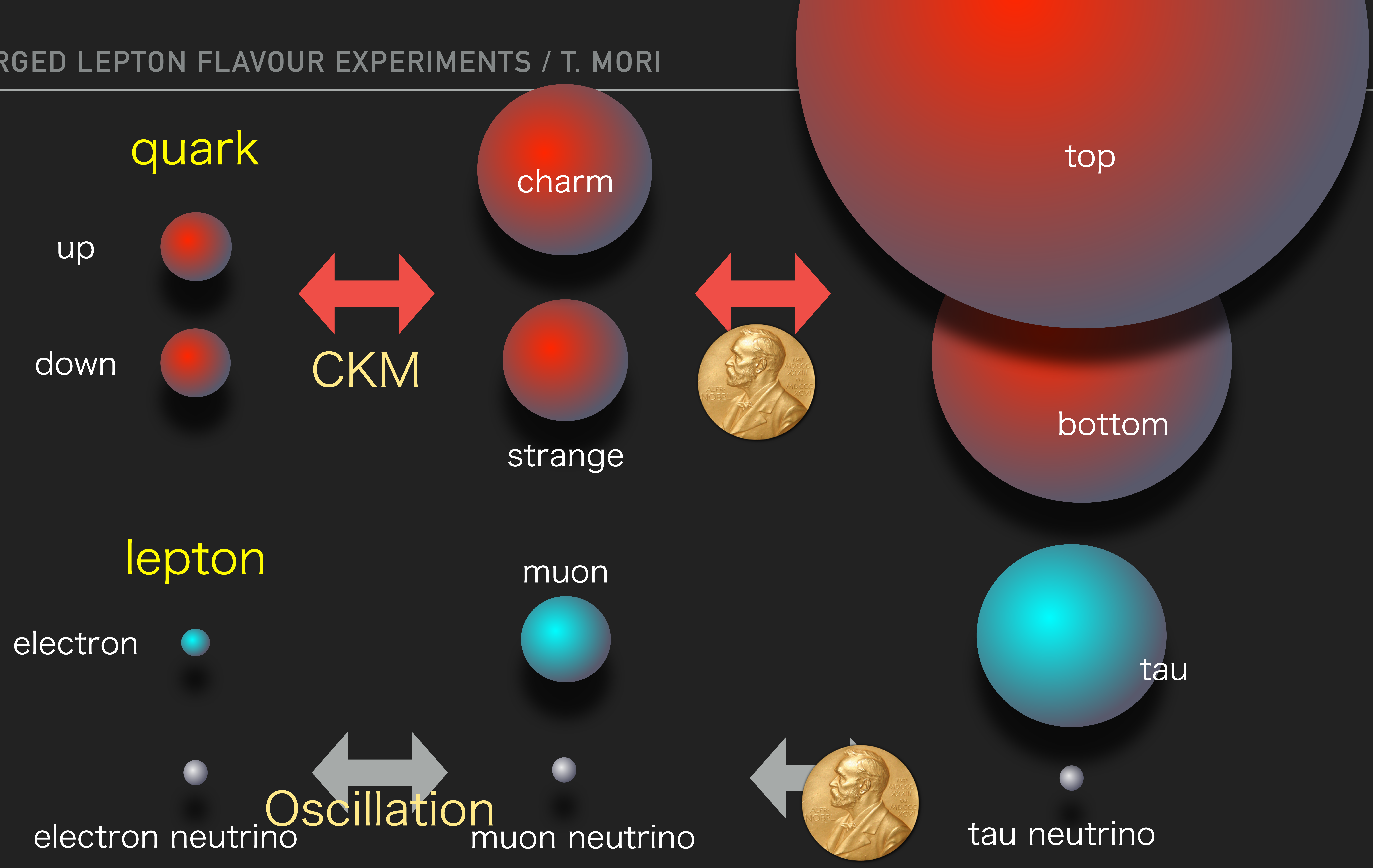
THE UNIVERSITY OF TOKYO

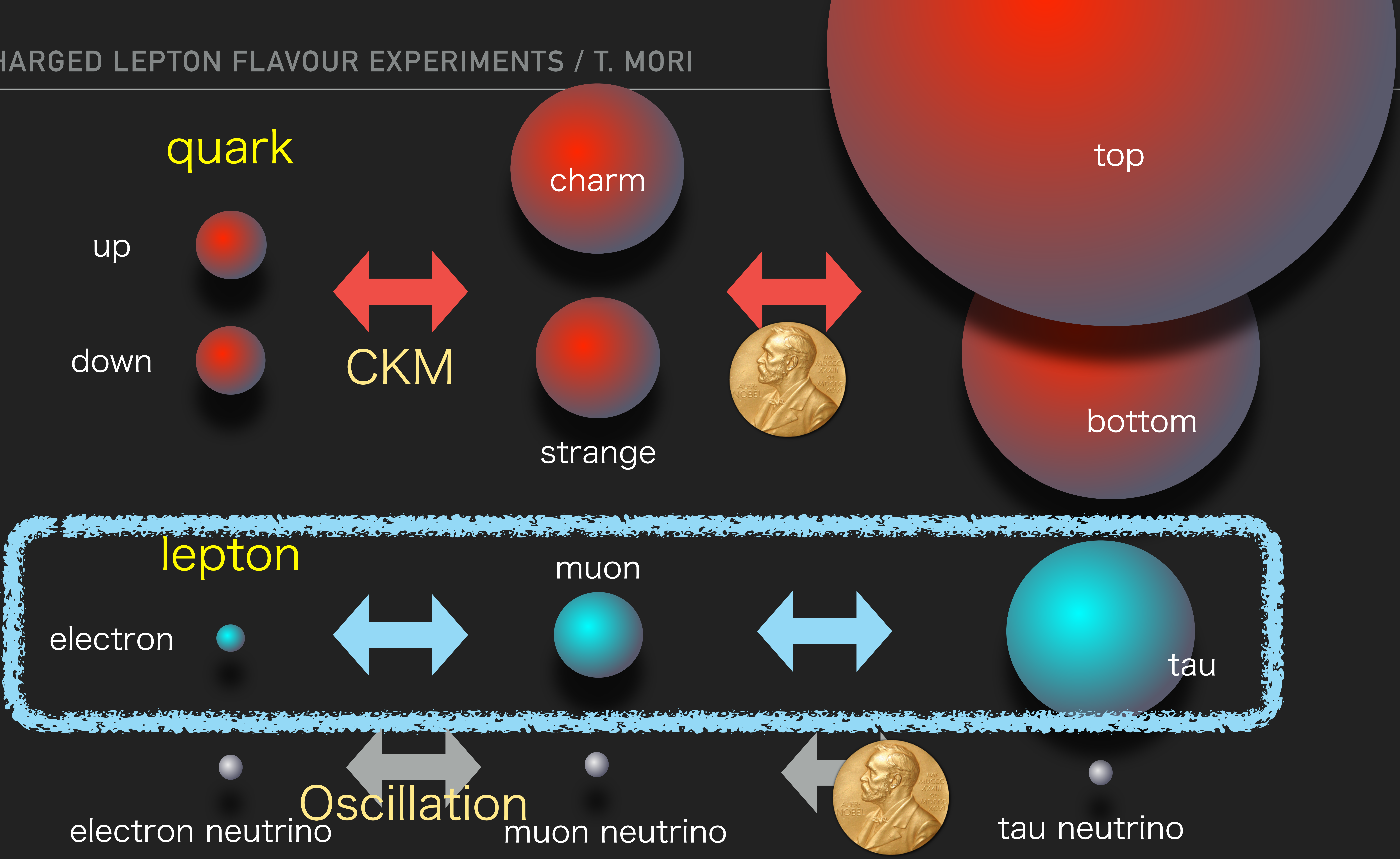
CHARGED LEPTON FLAVOUR EXPERIMENTS

HERE THE FOCUS IS ON <u>“NON-COLLIDER” EXPERIMENTS</u>

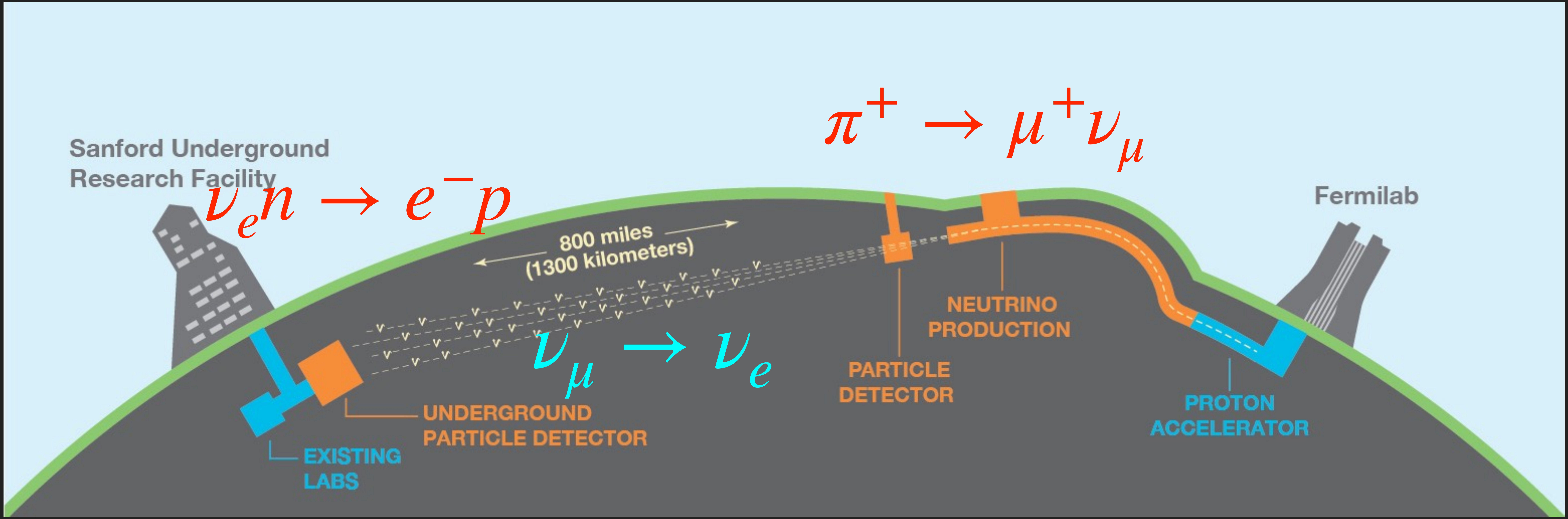

quark
up
down
charm
strange
top
bottom
lepton
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino


quark
up
down
CKM
charm
strange
top
bottom
lepton
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino

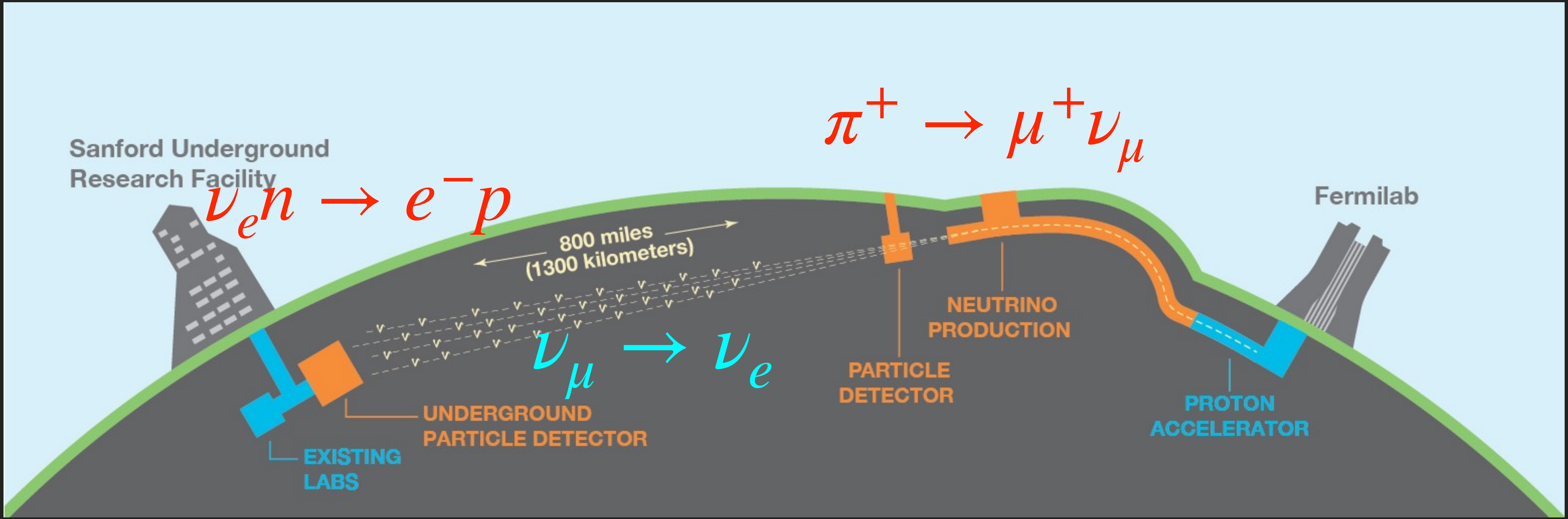

quark
up
down
CKM
charm
strange
top
bottom
lepton
electron
muon
tau
electron neutrino
Oscillation
muon neutrino
tau neutrino


quark
up
down
CKM
charm
strange
top
bottom
lepton
electron
muon
tau
electron neutrino
Oscillation
muon neutrino
tau neutrino

NEUTRINO OSCILLATIONS



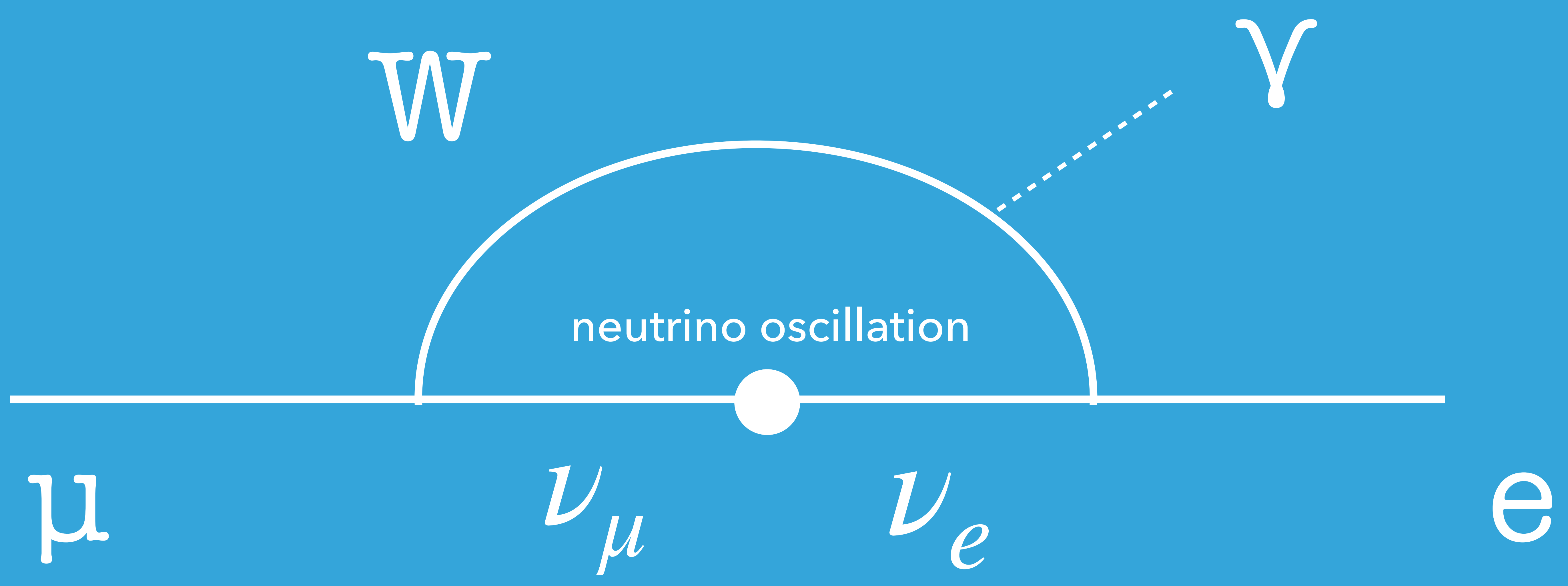
NEUTRINO OSCILLATIONS



$$\pi^+ n \to \mu^+ e^- p$$

CHARGED LEPTON FLAVOR VIOLATION (CLFV)!

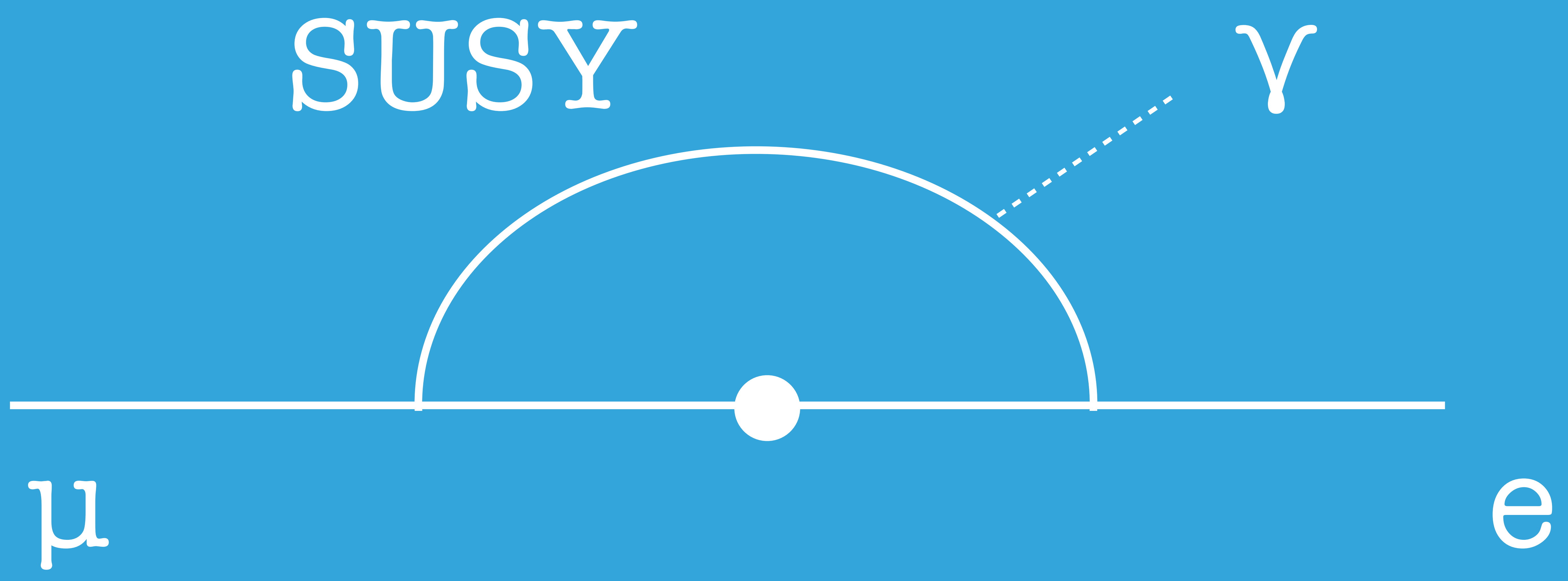
CHARGED LEPTONS SHOULD MIX!



$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-45}$$

The neutrinos are just too light.

TEV SCALE NEW PHYSICS HELP THEM MIX !



$$\left|\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}}\right| \simeq 10^{-12}$$

BIG PICTURE

GUT

force unification
charge quantization

Flavor violation from
quark Yukawa

SUSY

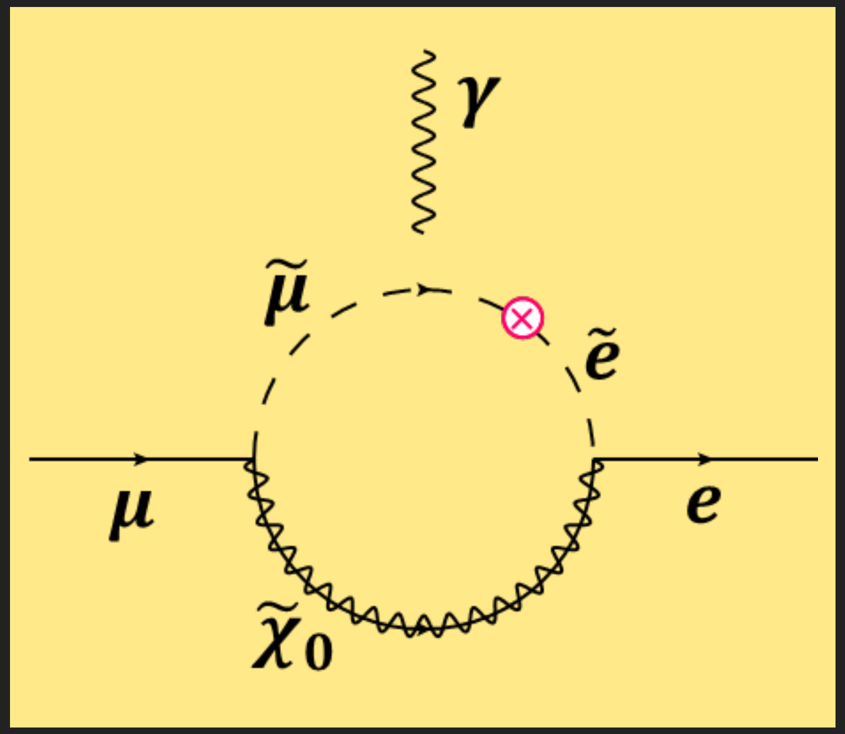
Leptogenesis

seesaw mechanism
neutrino masses

Flavor violation from
neutrino Yukawa

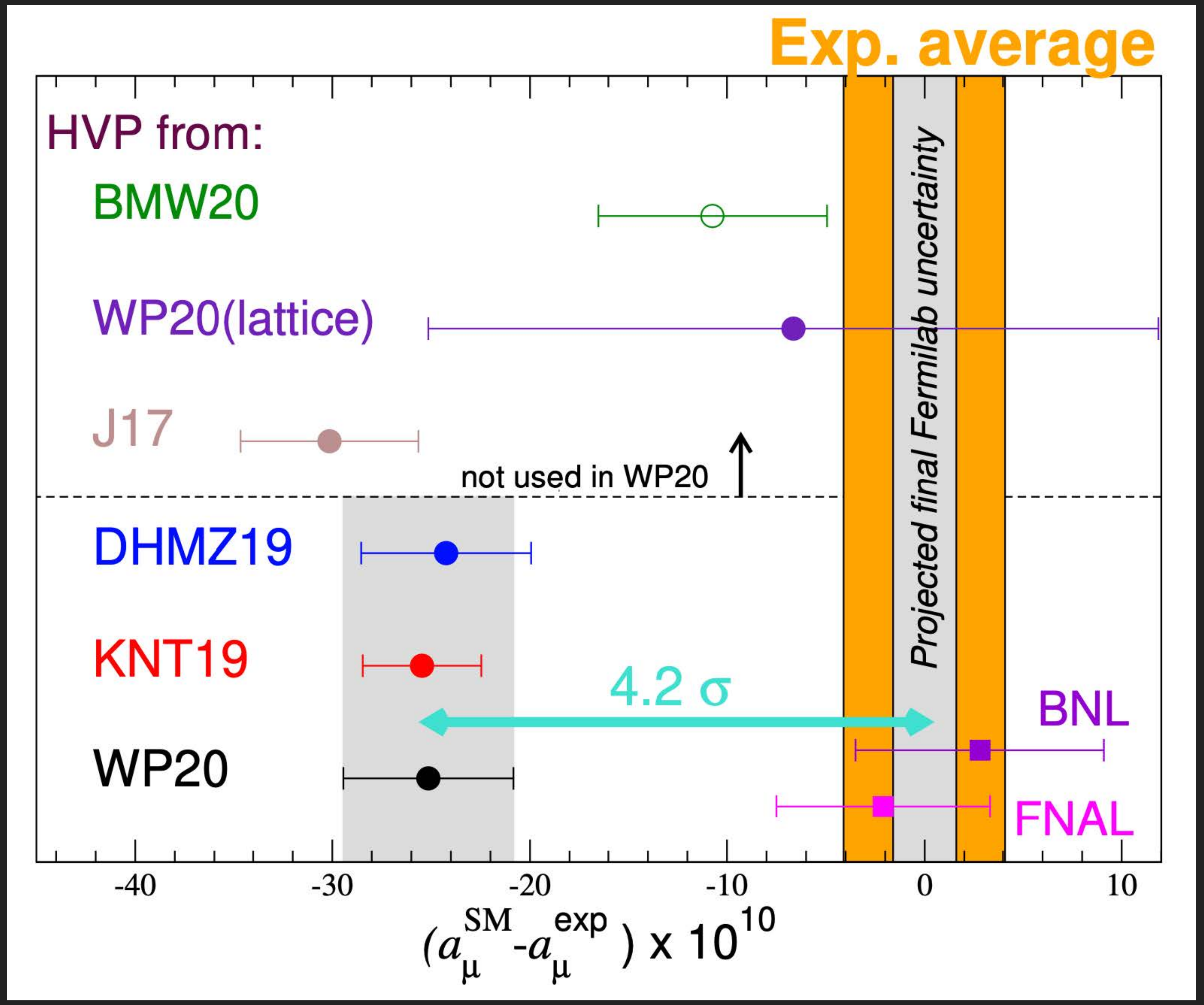
TeV scale physics
Dark Matter

$$\mu \to e\gamma$$

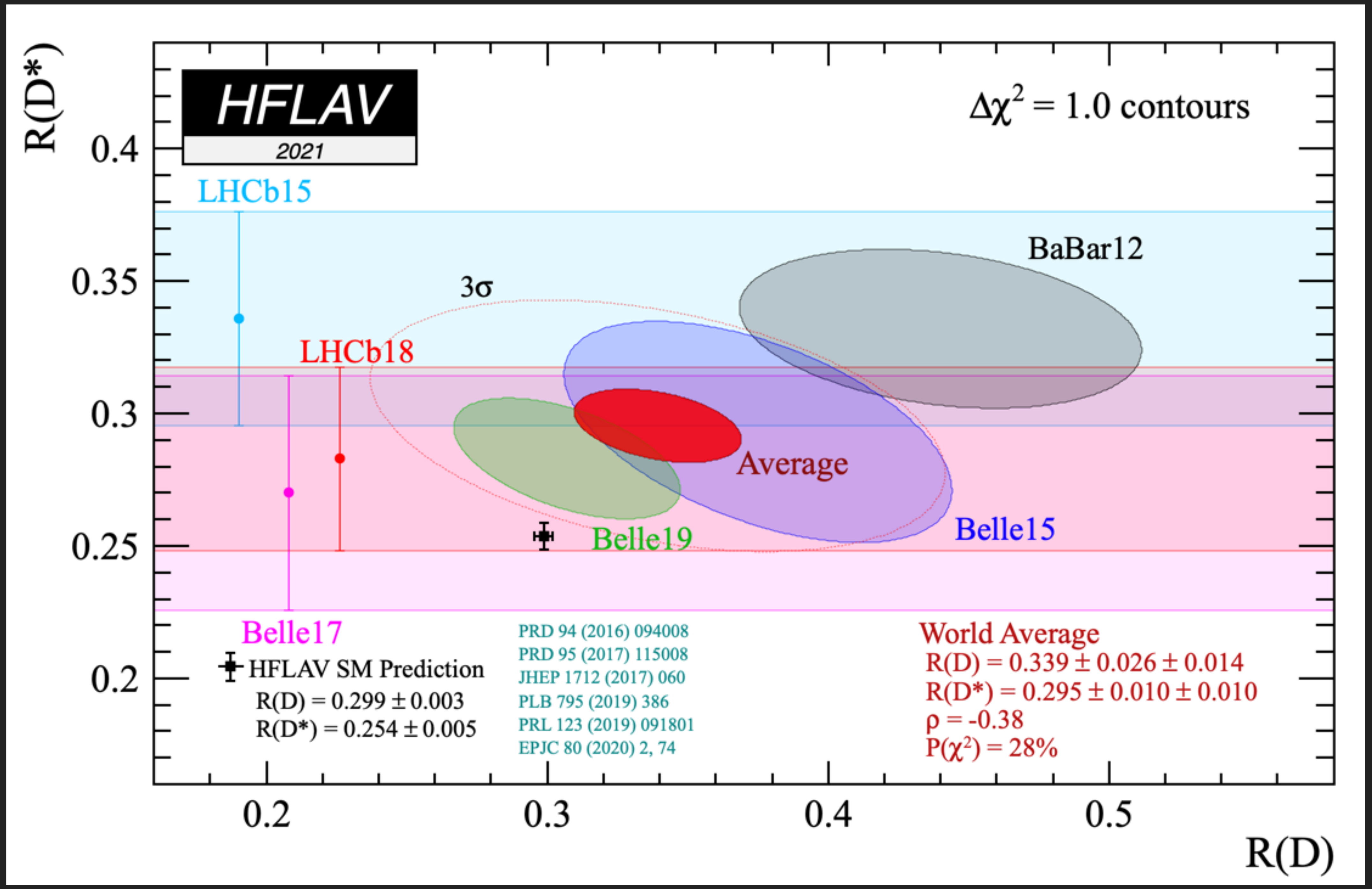


$$\simeq 10^{-12}$$

BOTTOM-UP: POSSIBLE INDICATIONS



muon g-2

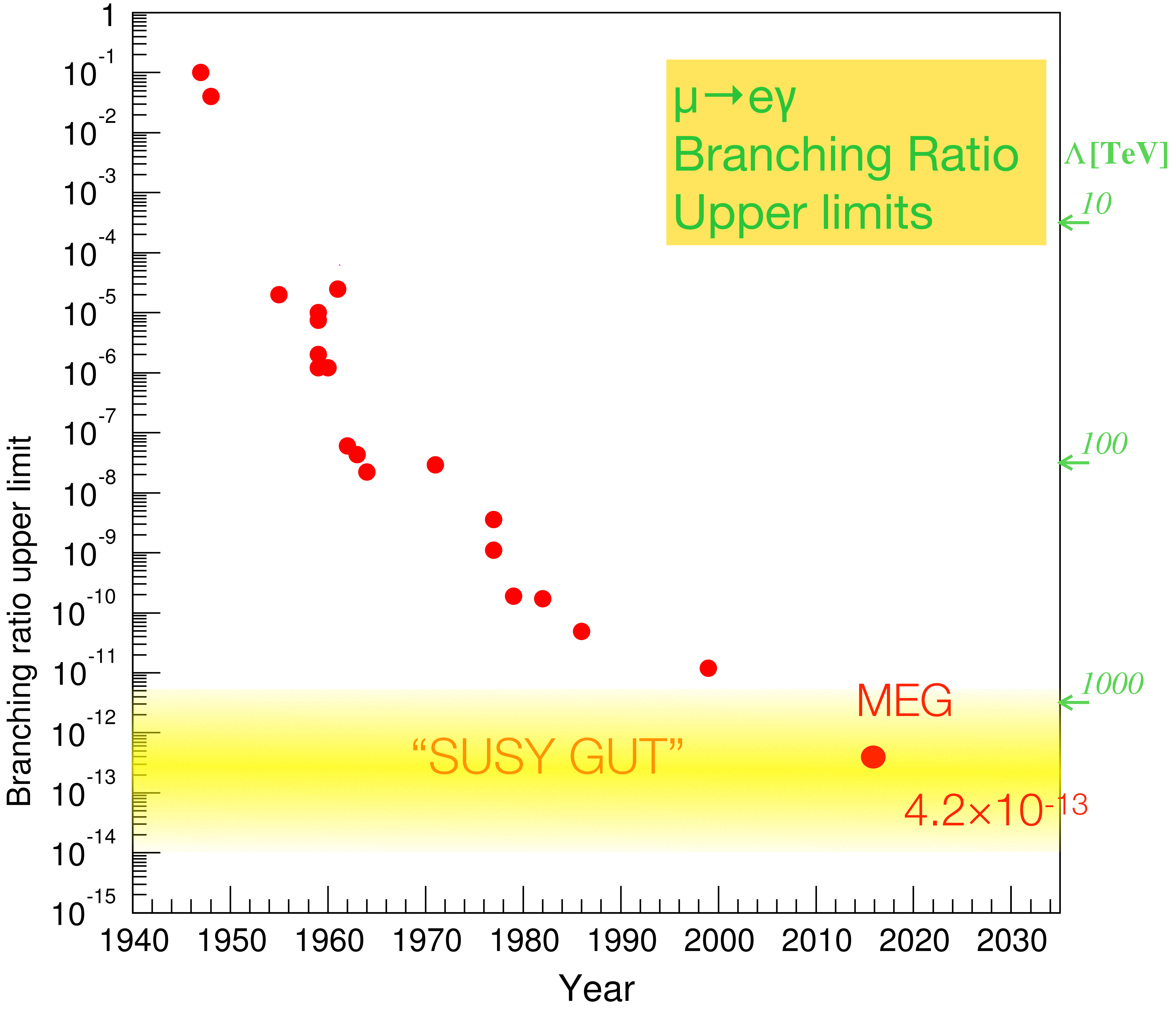


R(D), R(D*)

- Possible indications for lepton flavour anomalies at ~TeV scale

THE CURRENT STATUS:

$$\mu \rightarrow e\gamma$$



the smallest measured
branching ratio
for an elementary particle

RELATED PRESENTATIONS IN PARALLEL SESSIONS

MUON DECAYS & CONVERSIONS

Francesco Renga (MEG II)

Sebastian Dittmeier (Mu3e)

Jian Tang ($M \to \bar{M}$)

MESON DECAYS

Dieter Ries (PIONEER)

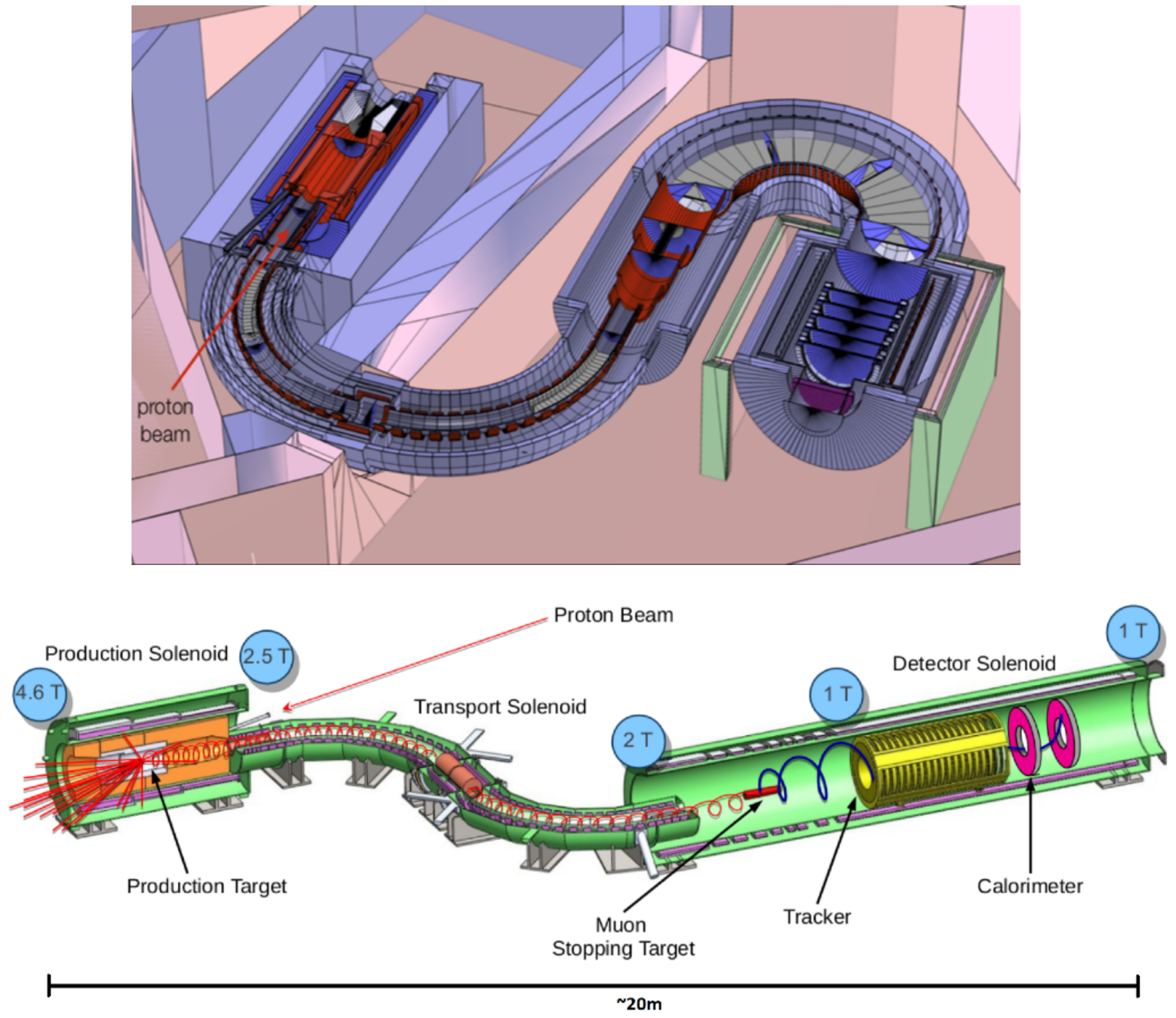
Viacheslav Duk (NA62)

Apologies for any topics that I missed…

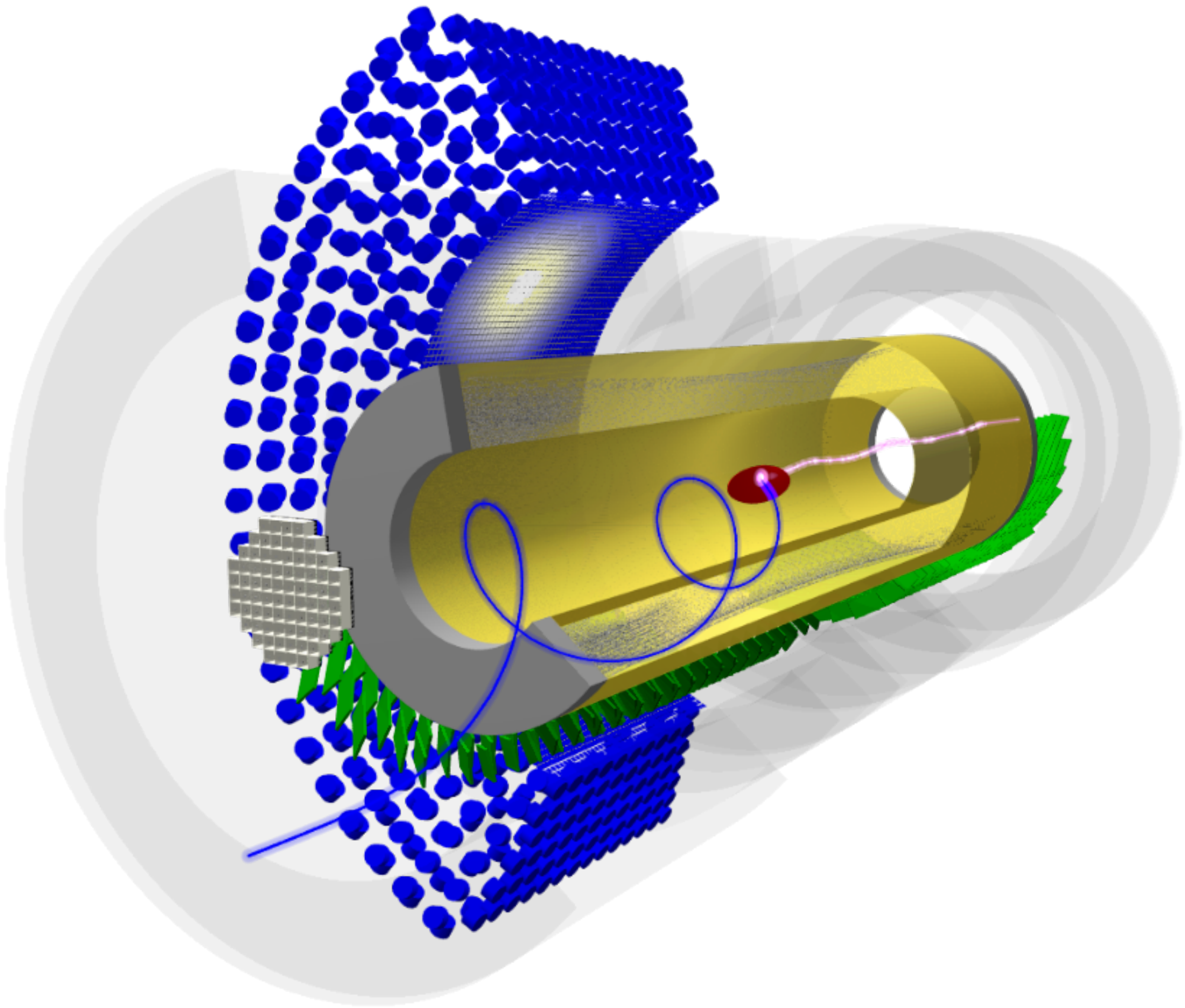
LEPTON-FLAVOUR VIOLATING (LFV) PROCESSES OF MUON

MUON LFV PROCESSES

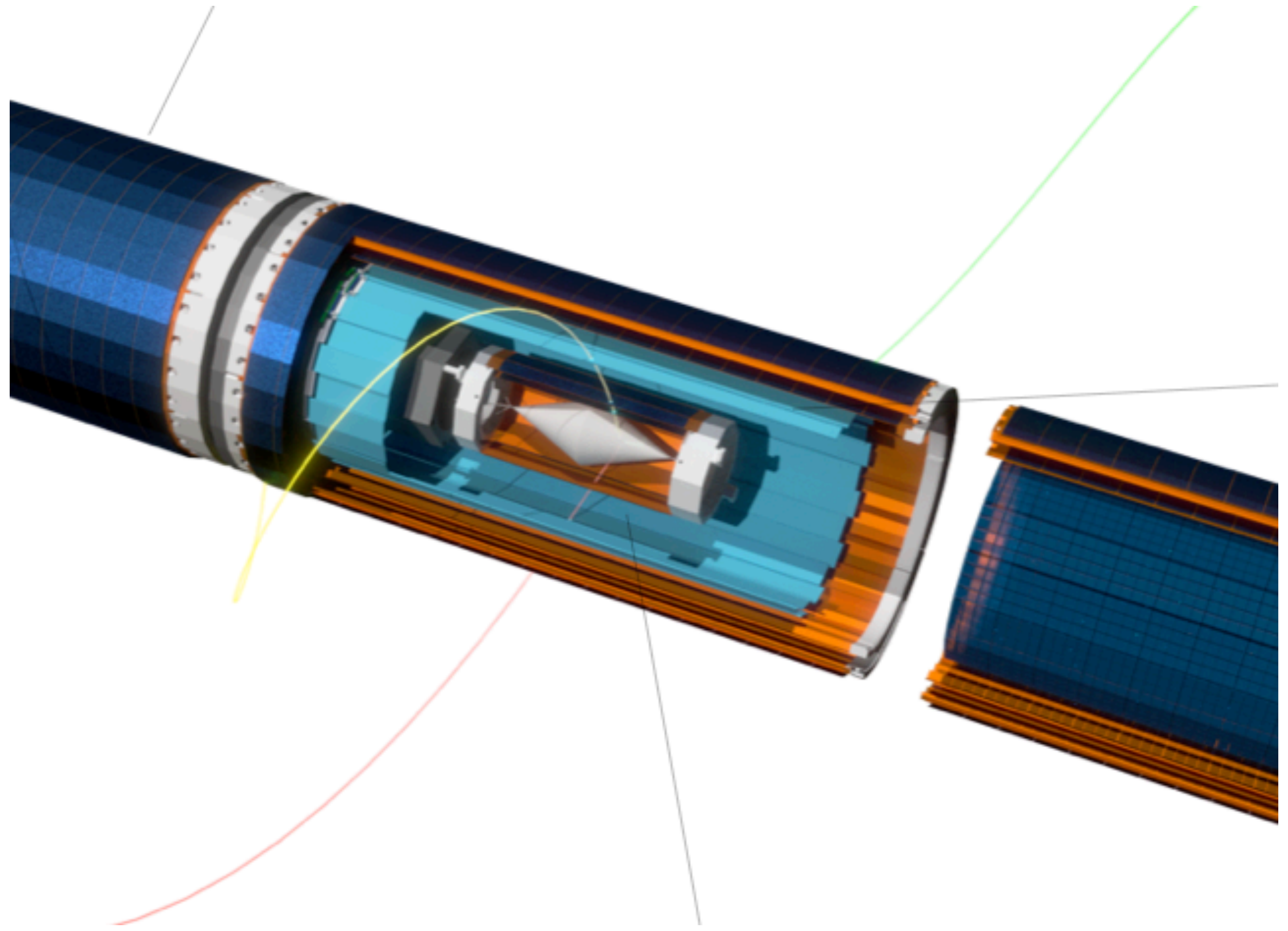
$\mu^- N \to e^- N$



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



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



MUON LFV PROCESSES

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

- signal: monochromatic ~104MeV electron
- BG: beam-related prompt
- pulsed muon beam
- "extinction" of ~10^{-10}
- low mass tracker

$\mu^+ \rightarrow e^+ \gamma$

- signal: 2-body kinematics
- BG: accidental
- DC muon beam
- low mass tracker
- excellent gamma-ray measurement

$\mu^+ \rightarrow e^+ e^- e^+$

- signal: 3-body kinematics
- BG: accidental
- DC muon beam
- low mass tracker

MUON LFV PROCESSES

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

COMET & Mu2e

π capture and π, μ transport by solenoids

prompt

- pulsed muon b
- "extinction" of
- low mass tracker

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

MEG II

gradient field spectrometer & LXe photon detector

- DC muon beam
- excellent gamma-ray measurement

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

Mu3e

low mass pixel tracker based on HV-MAPS

- BG: accidental
- n beam
- s tracker

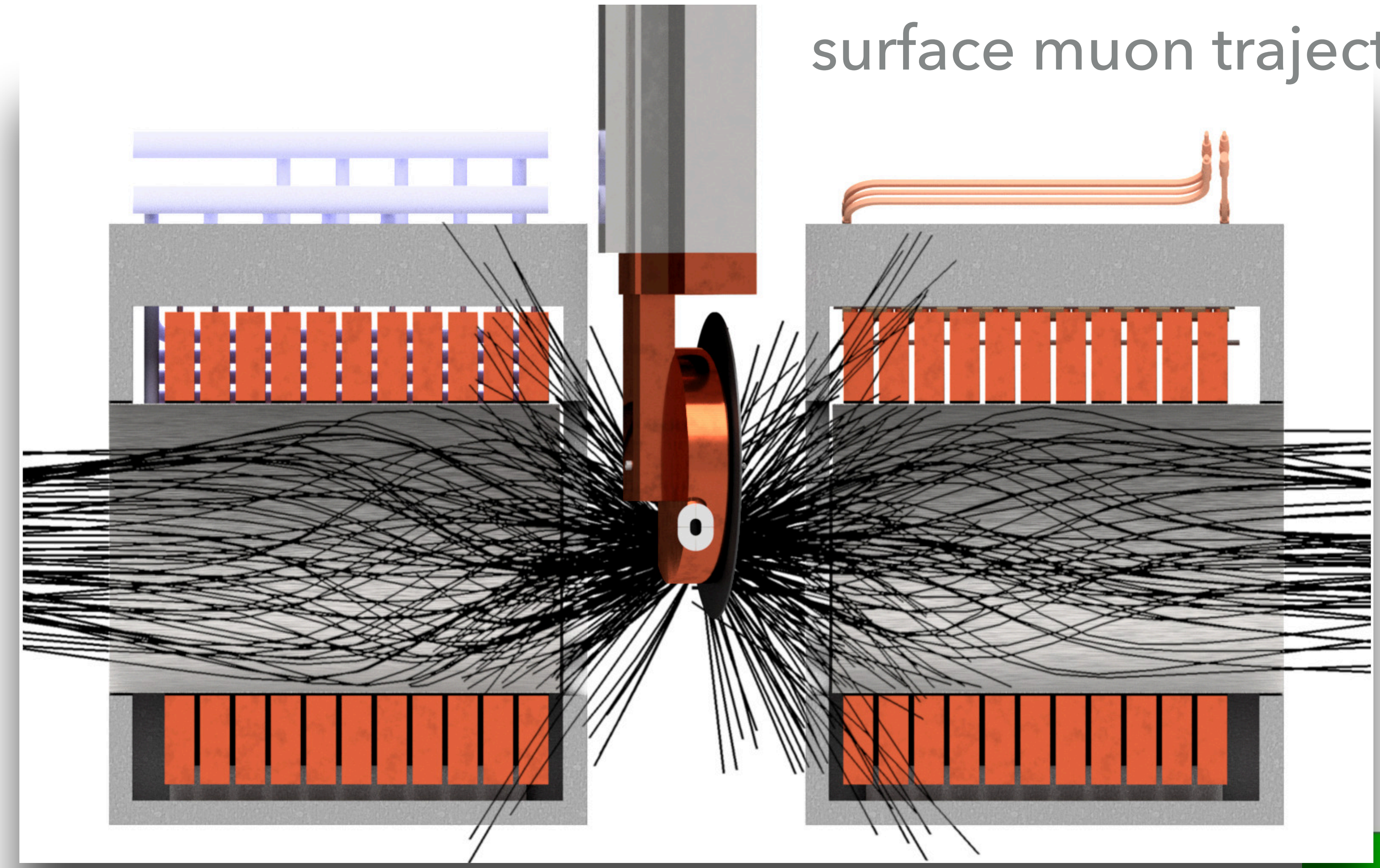
INNOVATIVE EXPERIMENTAL TECHNIQUES ARE DRIVING FORCE

TIMELINE OF MUON CLFV EXPERIMENTS

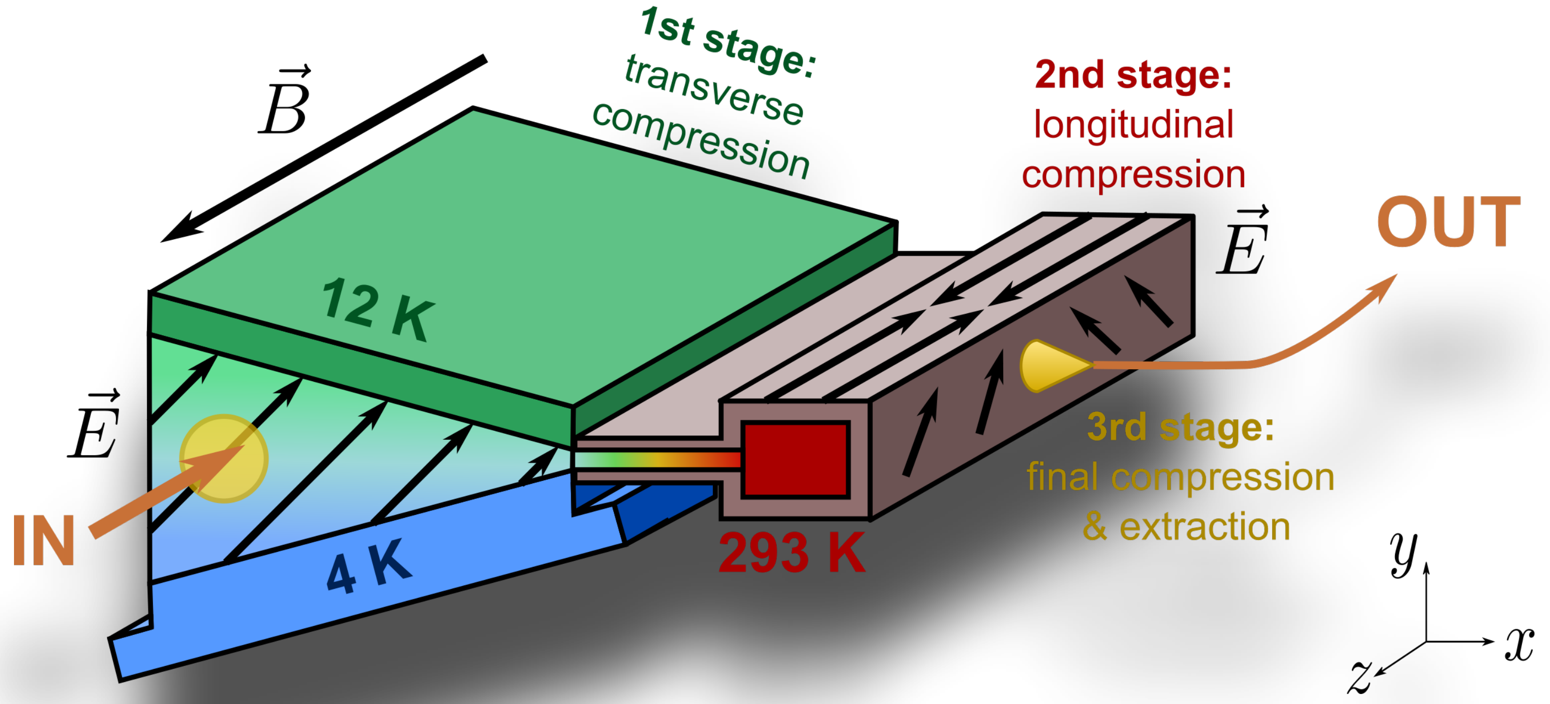
“My Rough Sketch”

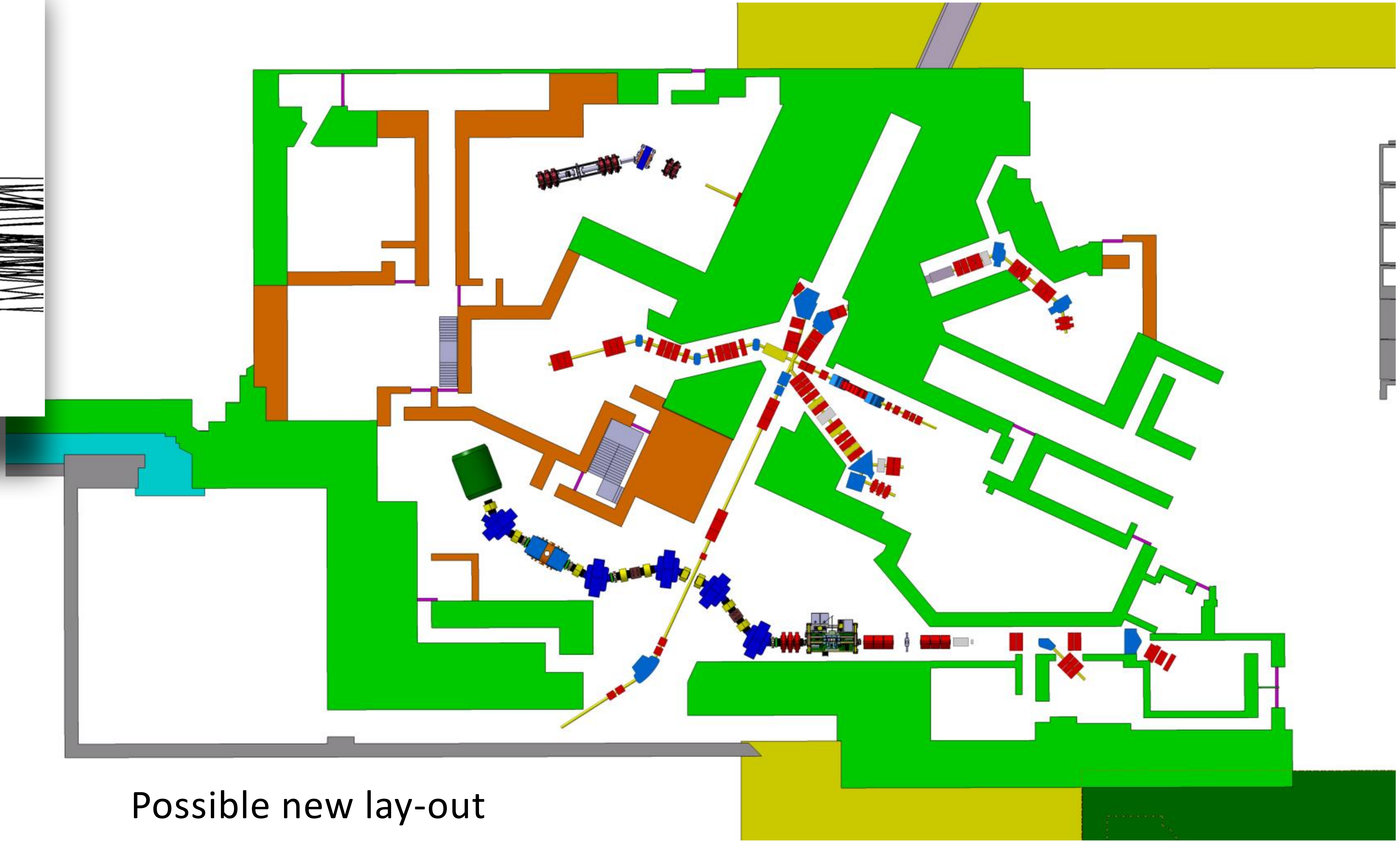
HIMB in WEHA

surface muon trajectories



schematic muCool device





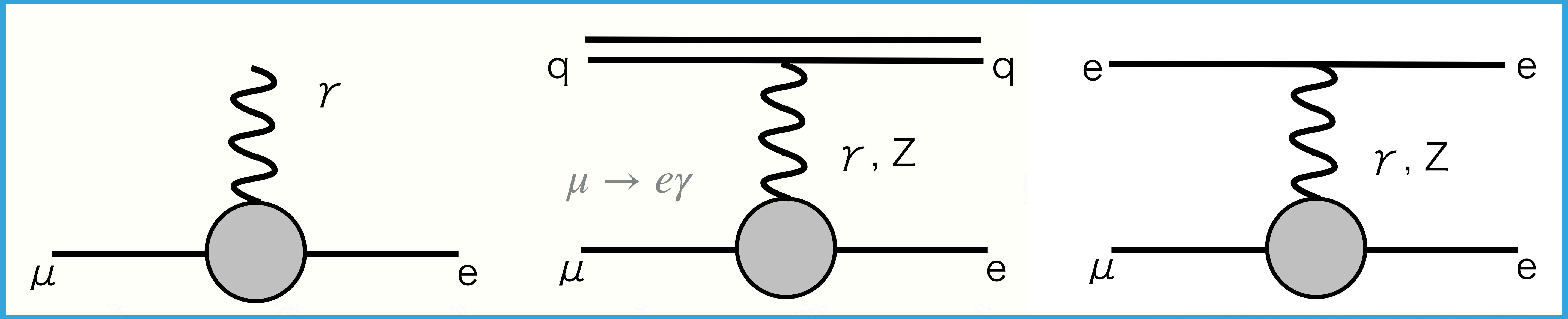
Possible new lay-out

Courtesy: Thomas Rauber

MUON CLFV SENSITIVITY COMPARISONS

$\mu \to e\gamma$ $\mu N \to eN$ $\mu \to 3e$

“dipole” dominant (SUSY)



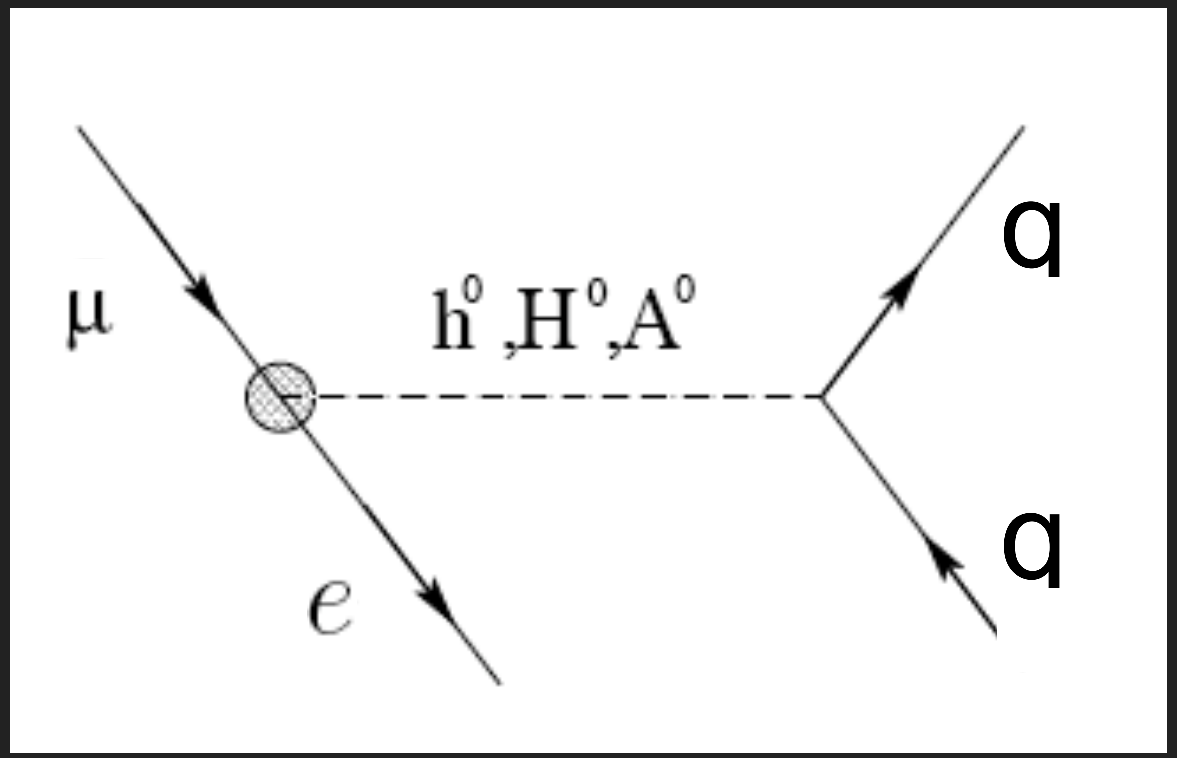
1 : 1/390 : 1/170

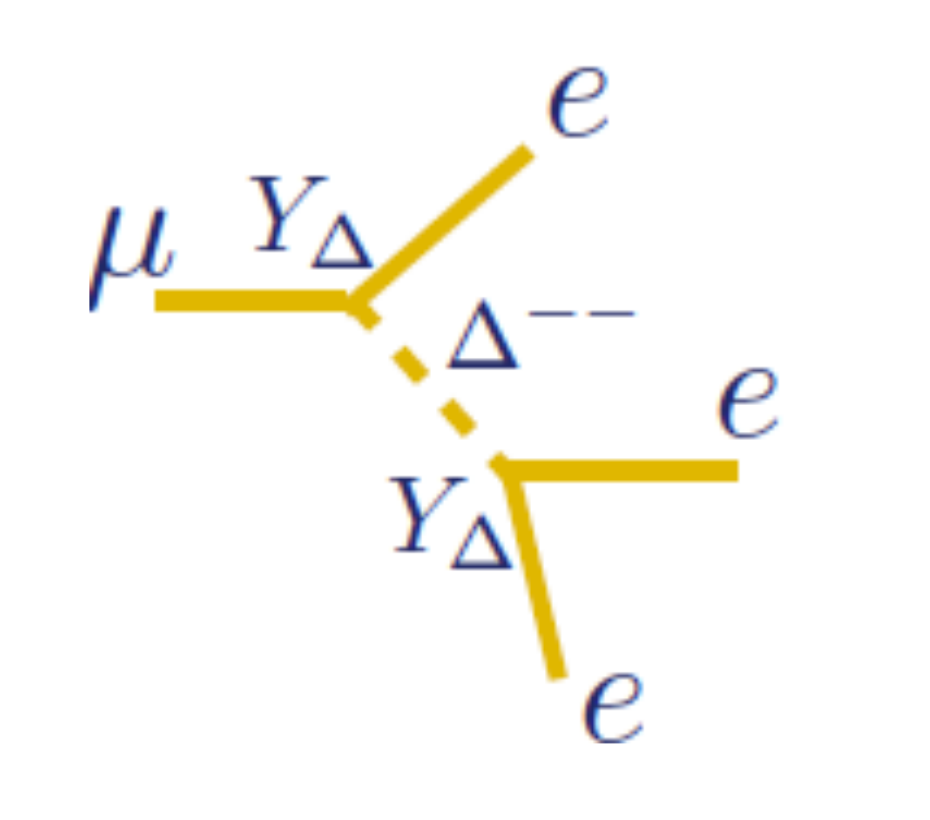
BR = 2×10^{-14} : 5×10^{-17} : 1×10^{-16}

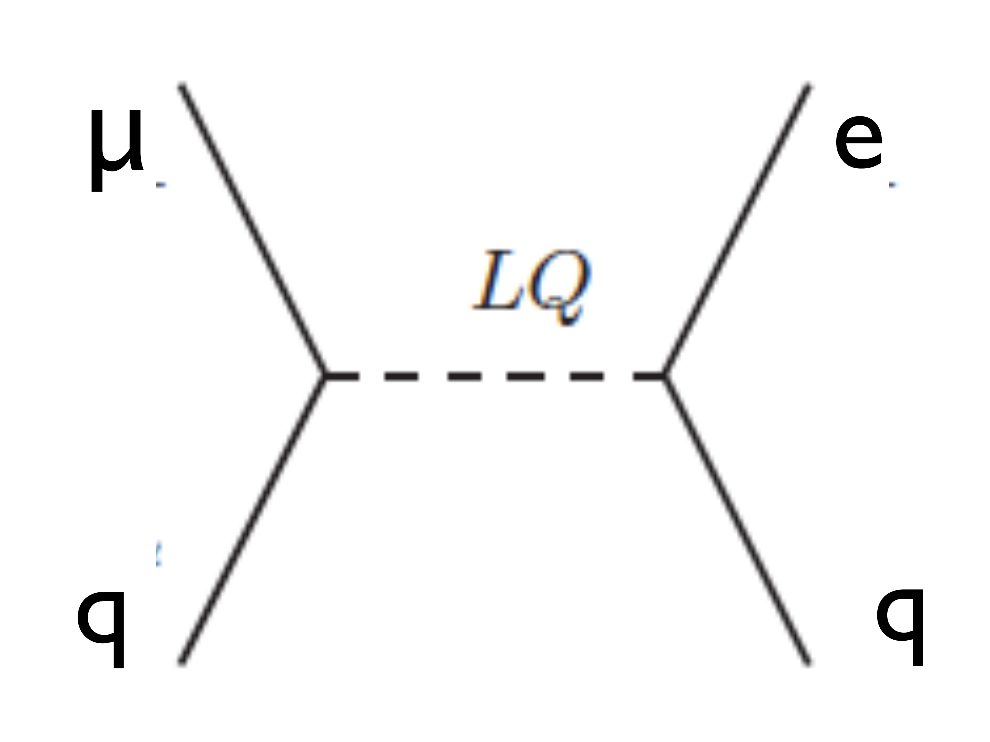
for Al target

NON-DIPOLE CONTRIBUTIONS FROM NEW PHYSICS

- $\mu N \to eN$ and $\mu \to 3e$ can have large contributions from other operators.
- To disentangle the secrets of New Physics, all the three muon CLFV processes should be pursued together.
- Angular distributions of $\mu \to e\gamma$ and $\mu \to 3e$, and atom-dependence of $\mu N \to eN$ can distinguish different new physics scenarios after discoveries.

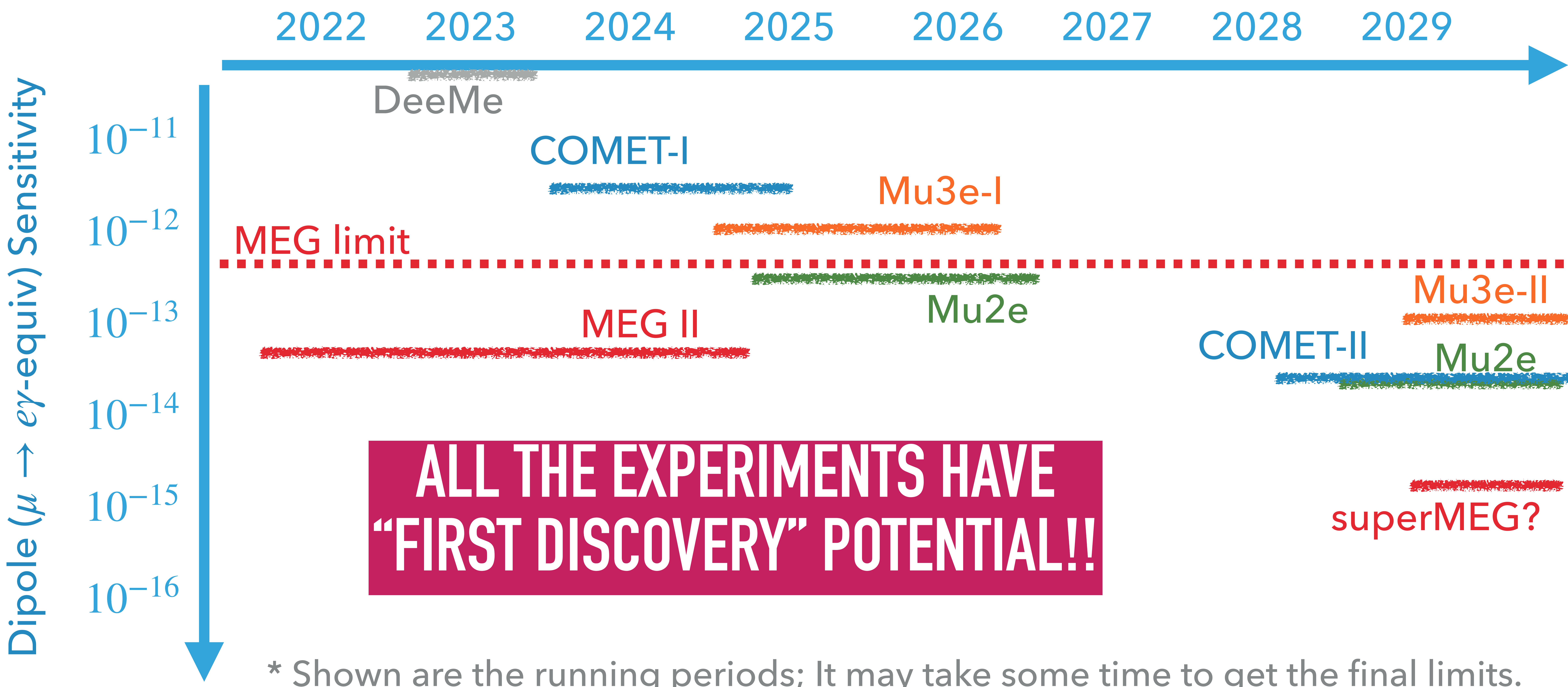






PROSPECTS OF SENSITIVITY IMPROVEMENTS

"My Rough Sketch"



ALL THE EXPERIMENTS HAVE "FIRST DISCOVERY" POTENTIAL!!

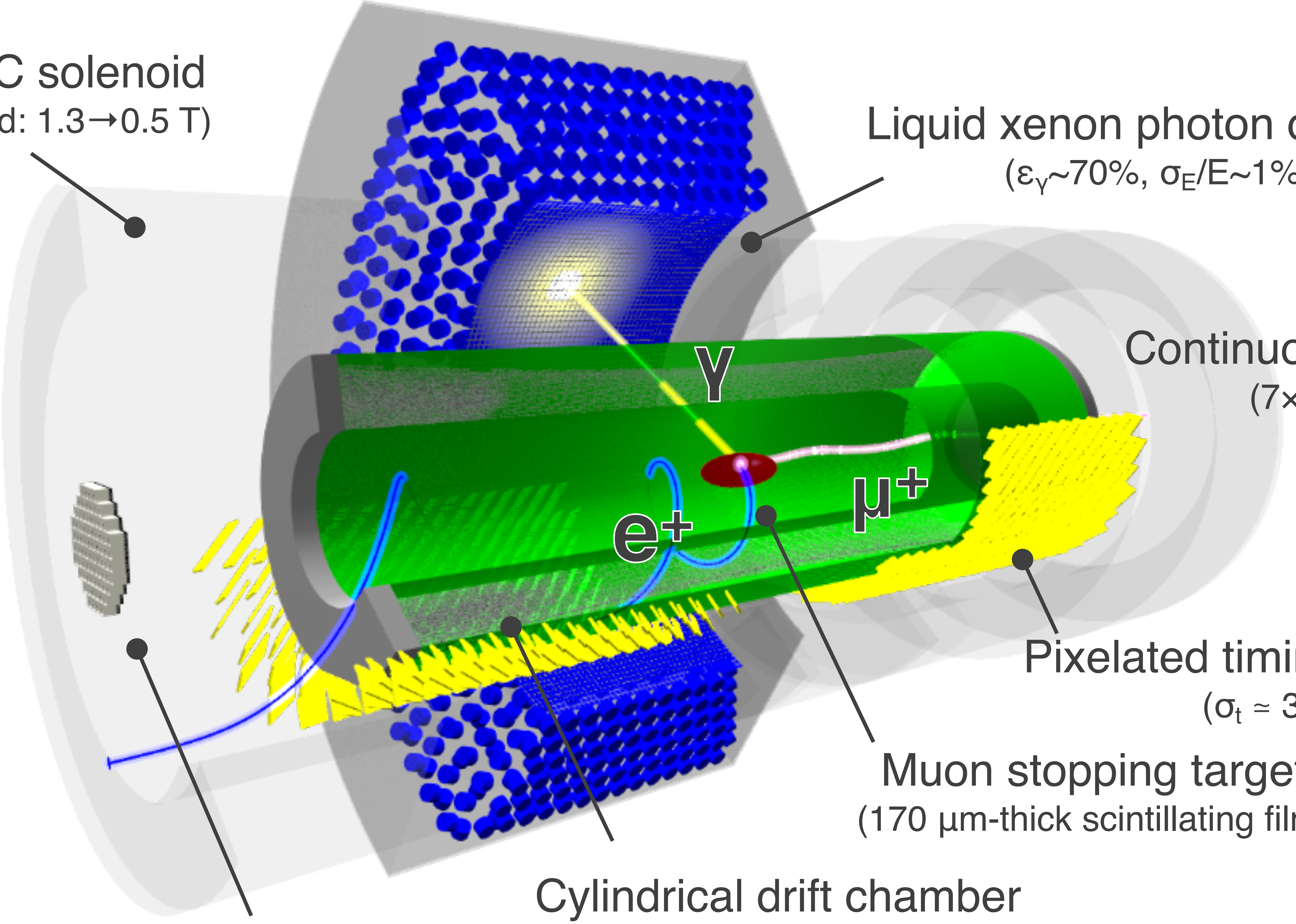
* Shown are the running periods; It may take some time to get the final limits.

MEG II

MEG II – UPGRADE OF MEG

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

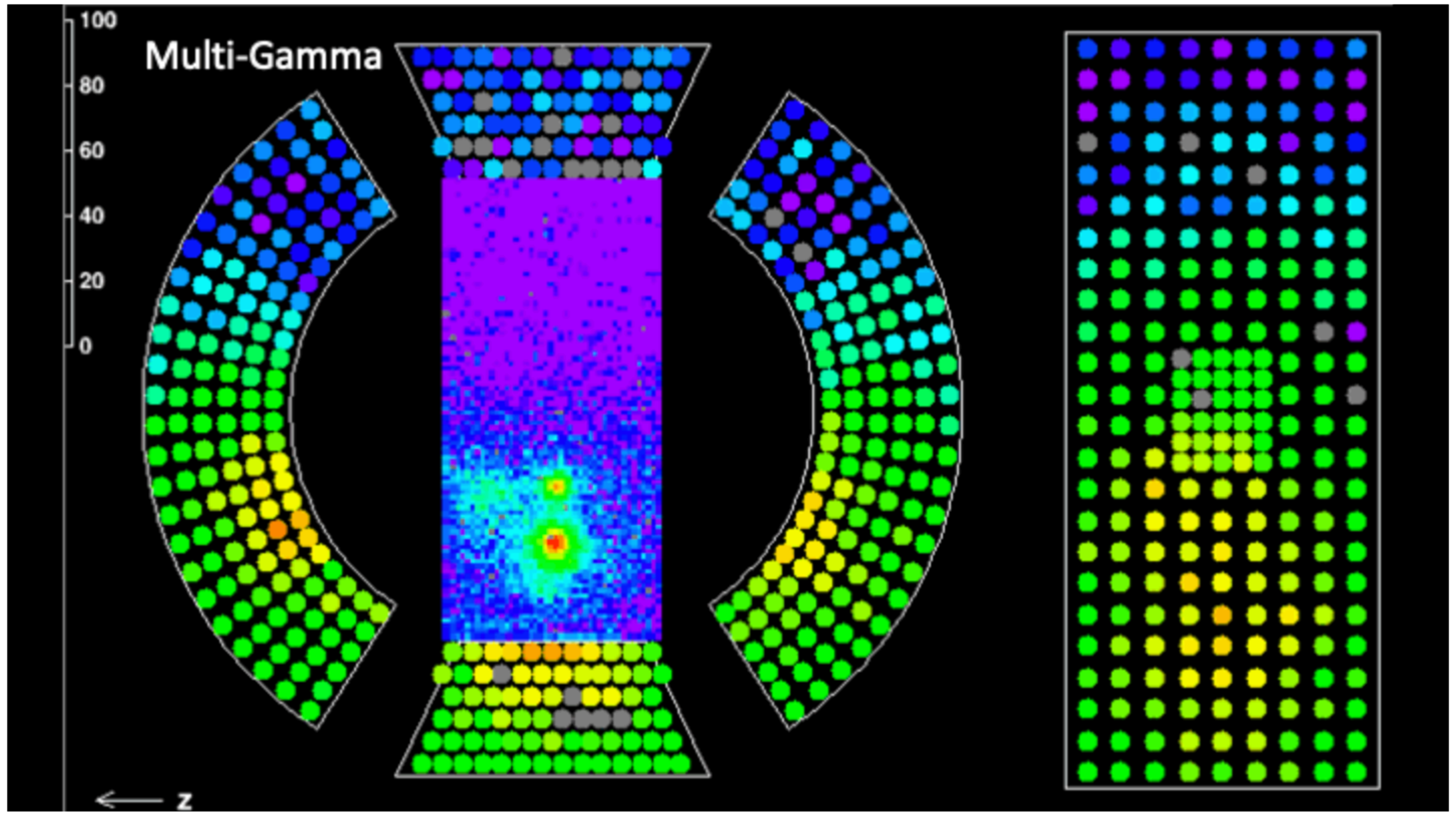
Search for $\mu^+ \to e^+\gamma$ down to 6×10^{-14} (90% C.L. sensitivity)



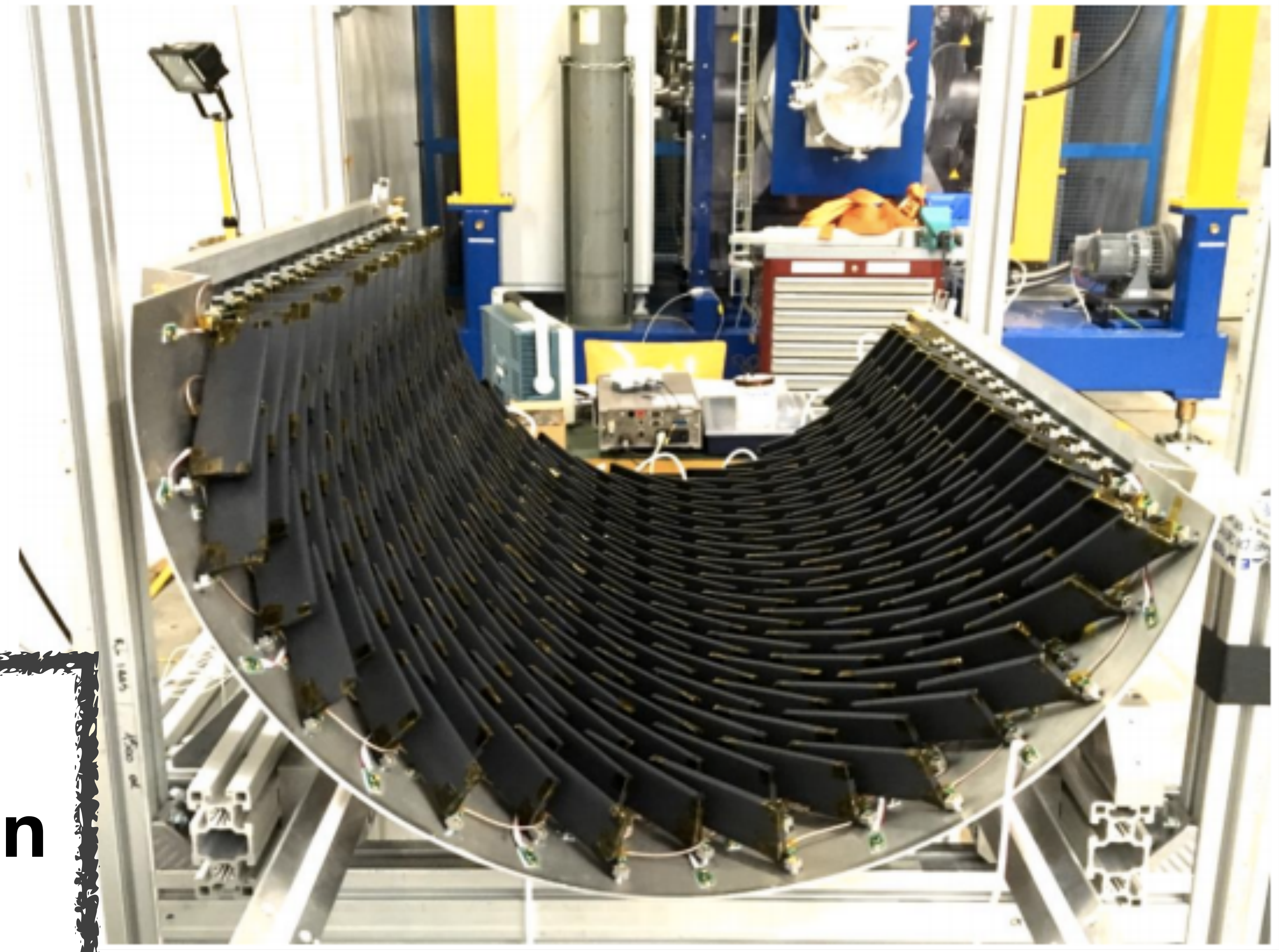
EPJ-C **78** (2018) 380

RECENT HIGHLIGHTS (1)

Liquid Xenon Photon Detector
A recovery procedure for degraded MPPC PDEs during beam time has been established.

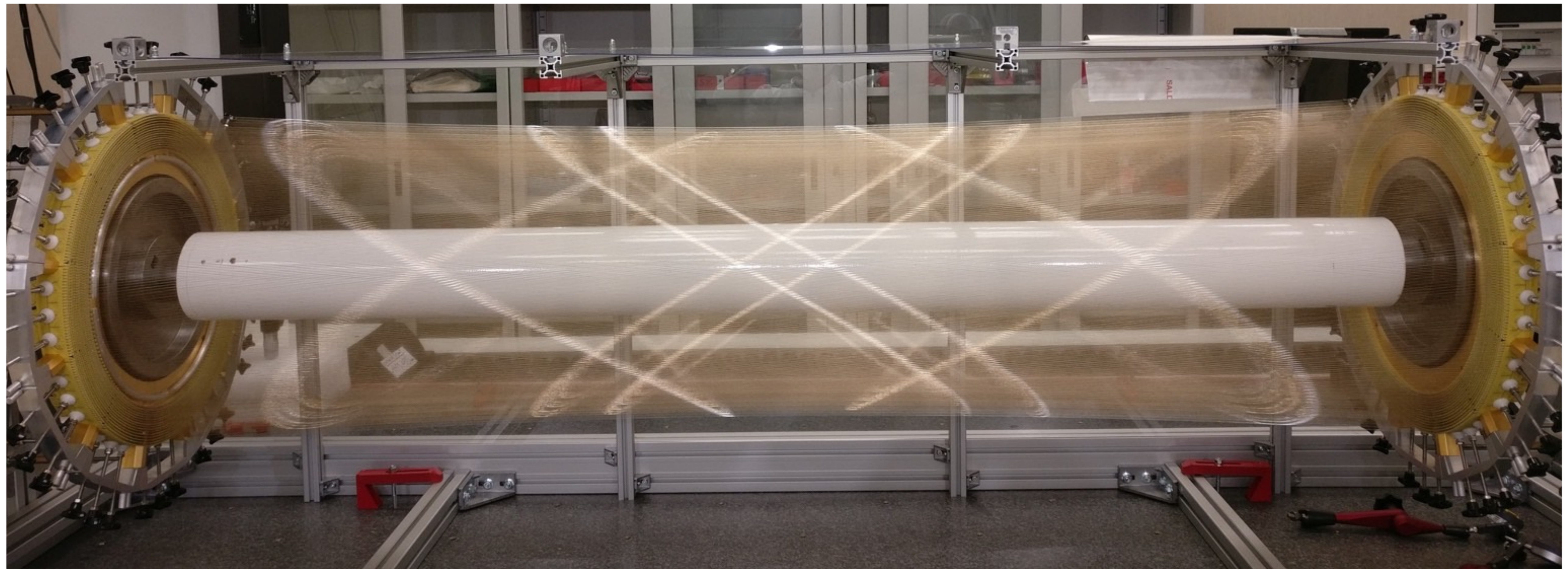


Timing Counter
Stable operation since 2017 - design resolution achieved: σ_T ~ 35 ps



Successful Engineering Run in 2021 w/ full readout of all detectors

Drift Chamber
Stable operation in 2021 - calibration, alignment, & reconstruction algorithm optimization ongoing

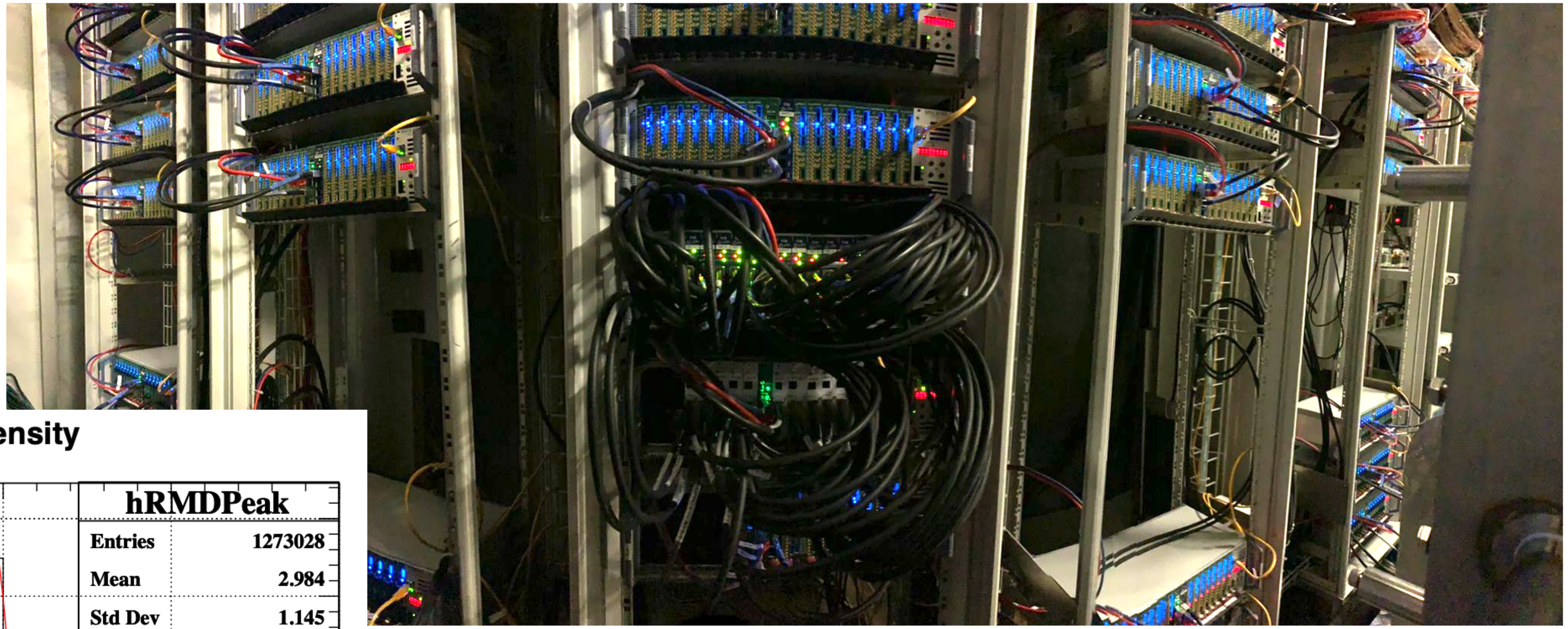


RECENT HIGHLIGHTS (2)

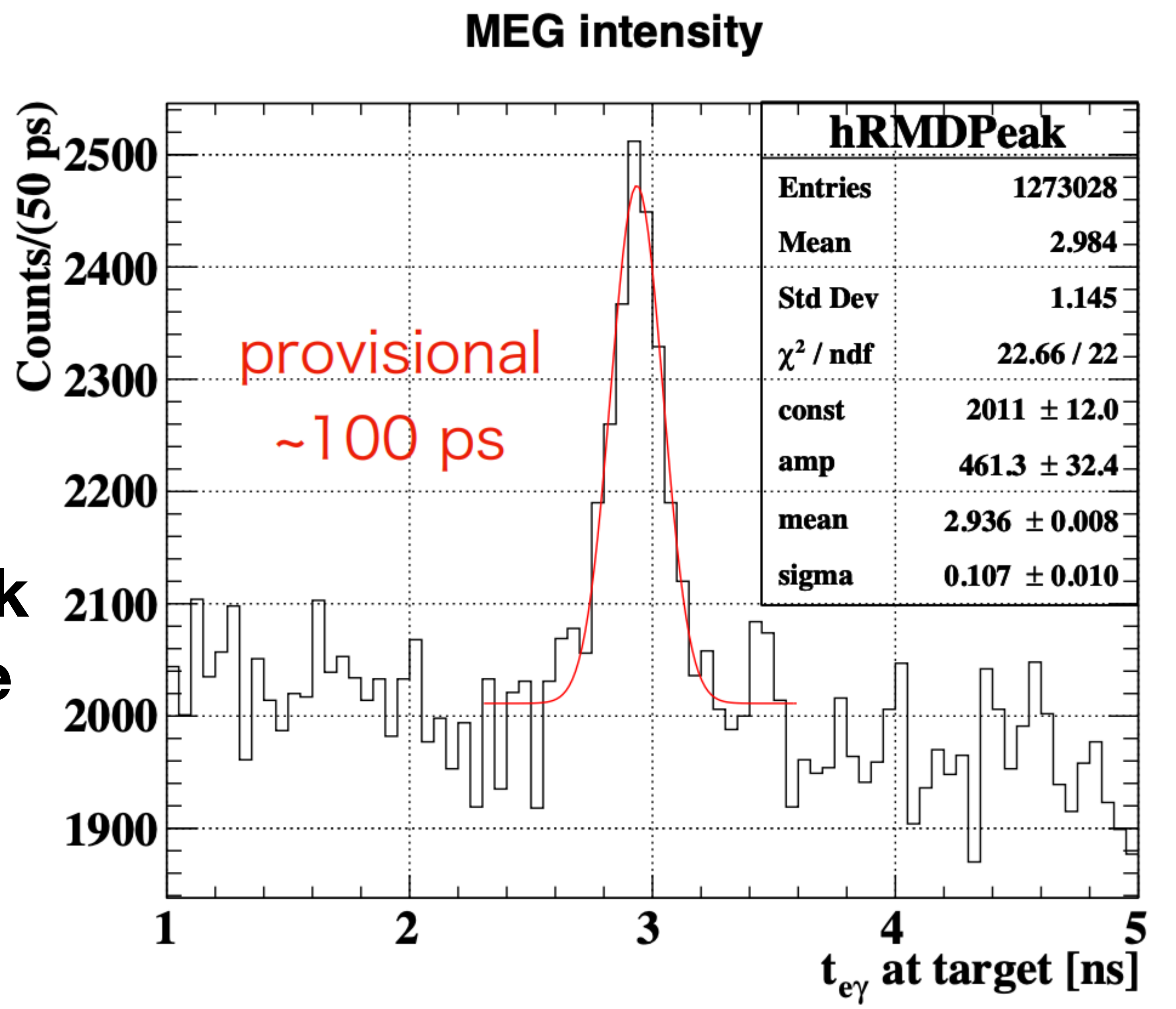
WaveDream DAQ System

Trigger and DAQ integrated in a single, compact system developed for MEG II.

Successful commissioning of $\mu \to e\gamma$ trigger; Physics data equivalent to whole MEG were taken.

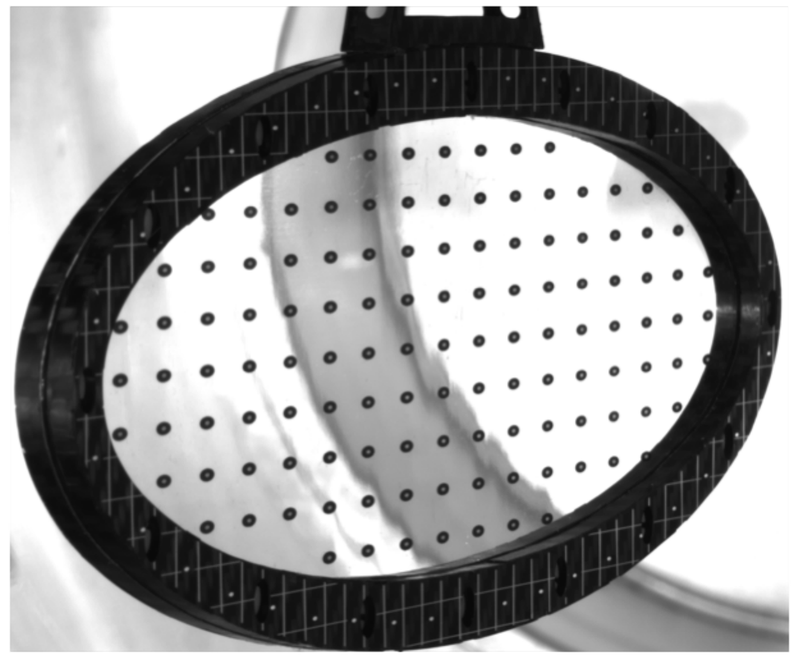


Timing Peak of Radiative Decays



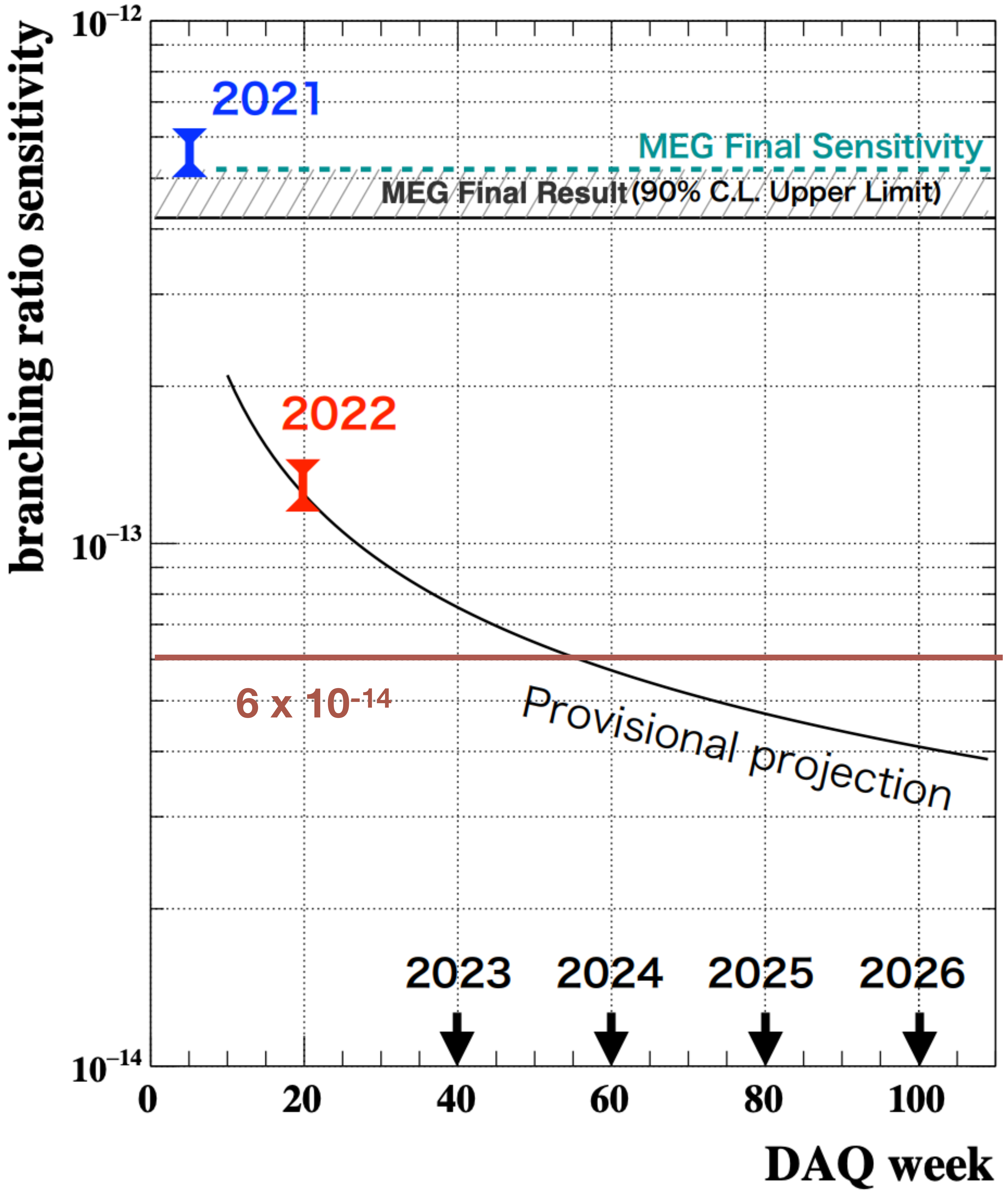
Muon Stopping Target

The target monitoring ensured its position & shape with an accuracy < 100 µm



MEG II IN 2022

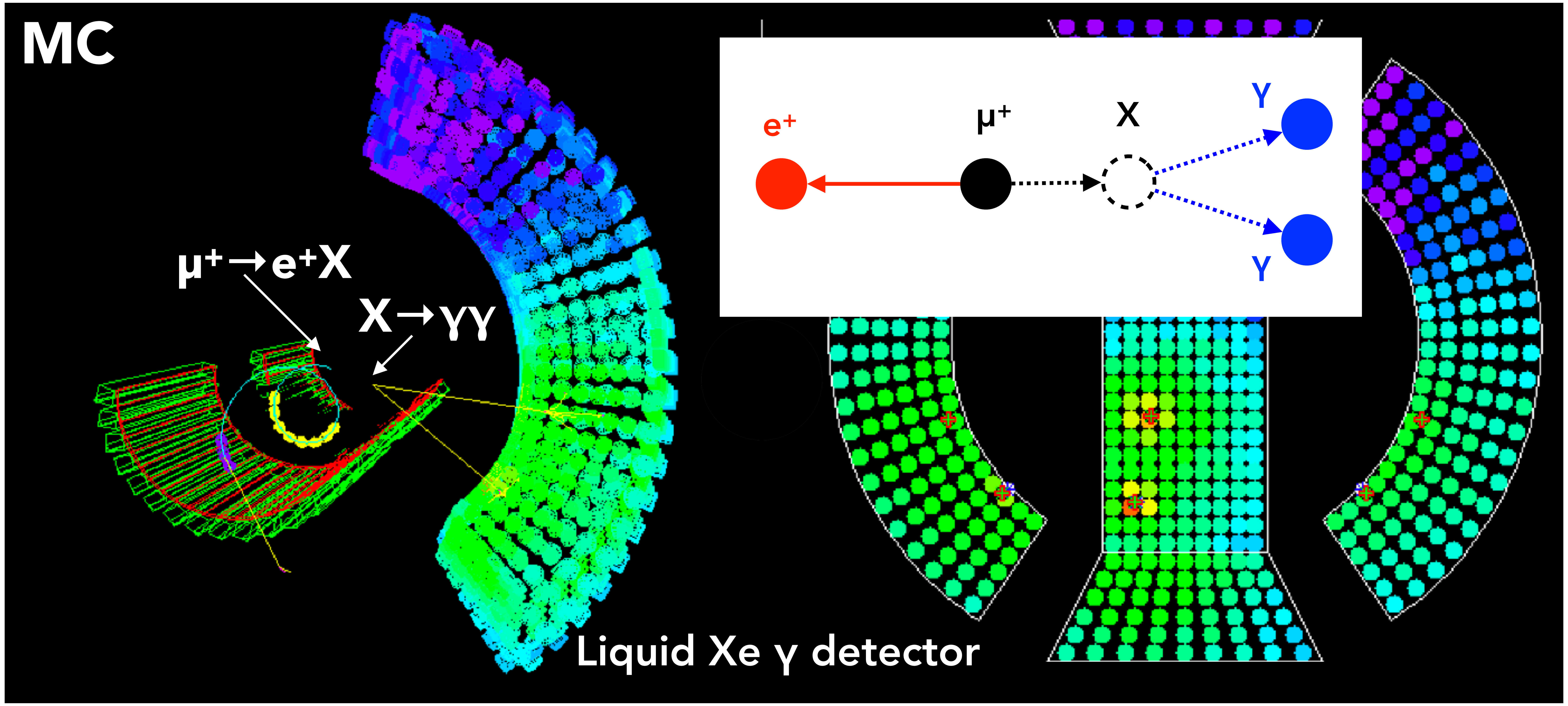
- Stable, long physics data taking to go beyond MEG
  - Expected to be statistics-dominant
  - Evaluation of 2021 data is ongoing
- Starting physics DAQ this week!



GOING BEYOND $\mu \to e\gamma$

- MEG searched for LFV muon decay mediated by a new light particle decaying into two gammas.

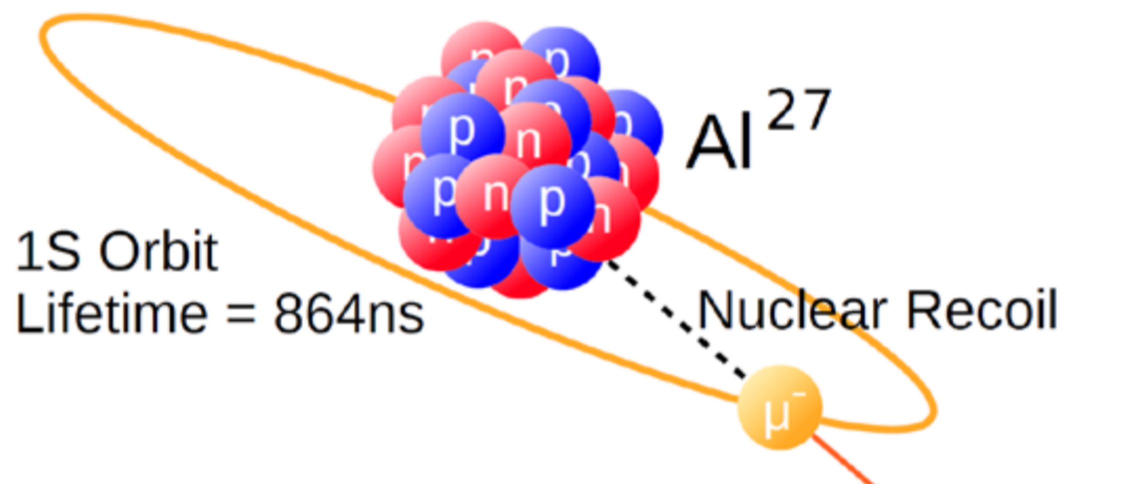
Euro. Phys. J. C80, 858 (2020)



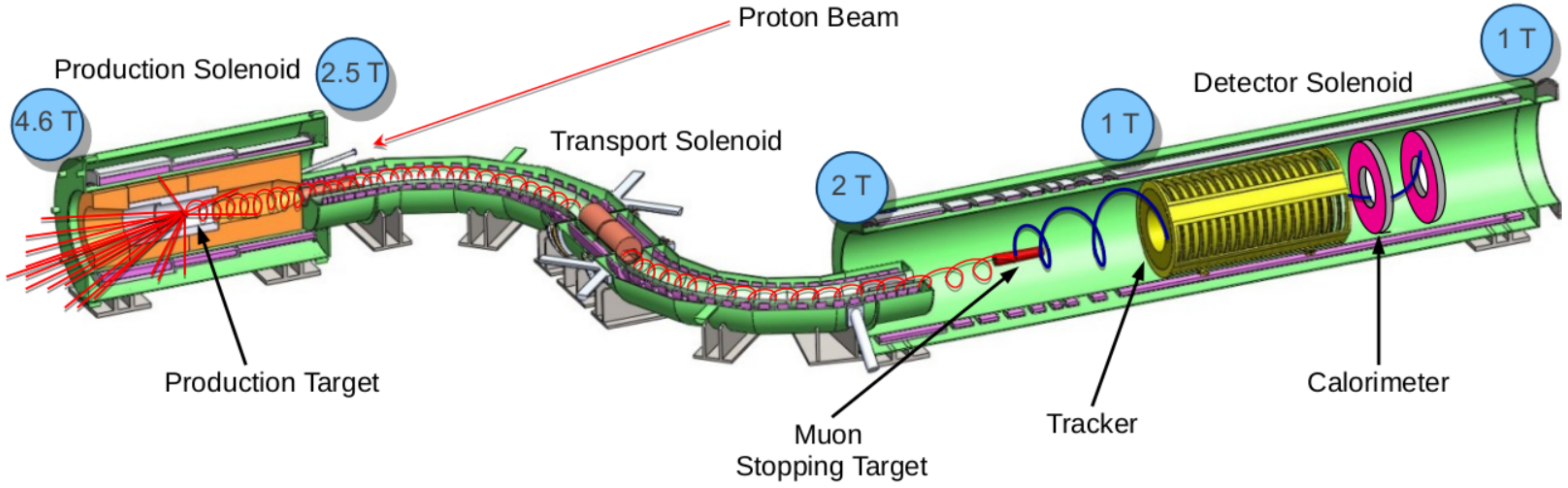
Feasibility studies for $\mu \to e + invisible$ and $\mu \to e\gamma + invisible$ at MEG II are also foreseen

MU2E

MU2E EXPERIMENT



$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil}$$
$$= 104.96\,\text{MeV}$$

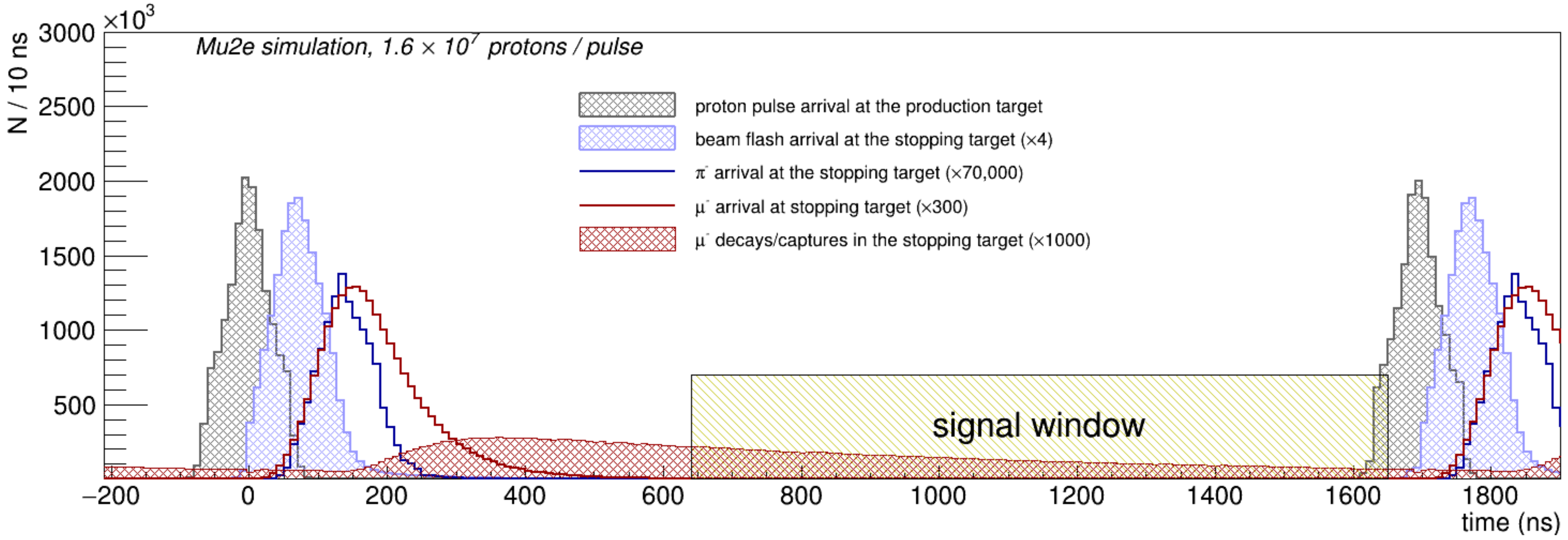


- Production Solenoid
  - pulsed proton beam hits production target
  - pions collected by the graded solenoidal magnetic field
- Transport Solenoid
  - pions decay to muons
  - charge and momentum selection
- Detector Solenoid
  - muons stop in thin Al foils
  - muonic atom decays
  - resulting electrons are detected by a tracker and a calorimeter
  - a cosmic ray veto covers the whole detector solenoid and half the transport solenoid (not shown)

PULSED PROTON BEAM & EXTINCTION

Backgrounds that are prompt with proton-on-target could be significant

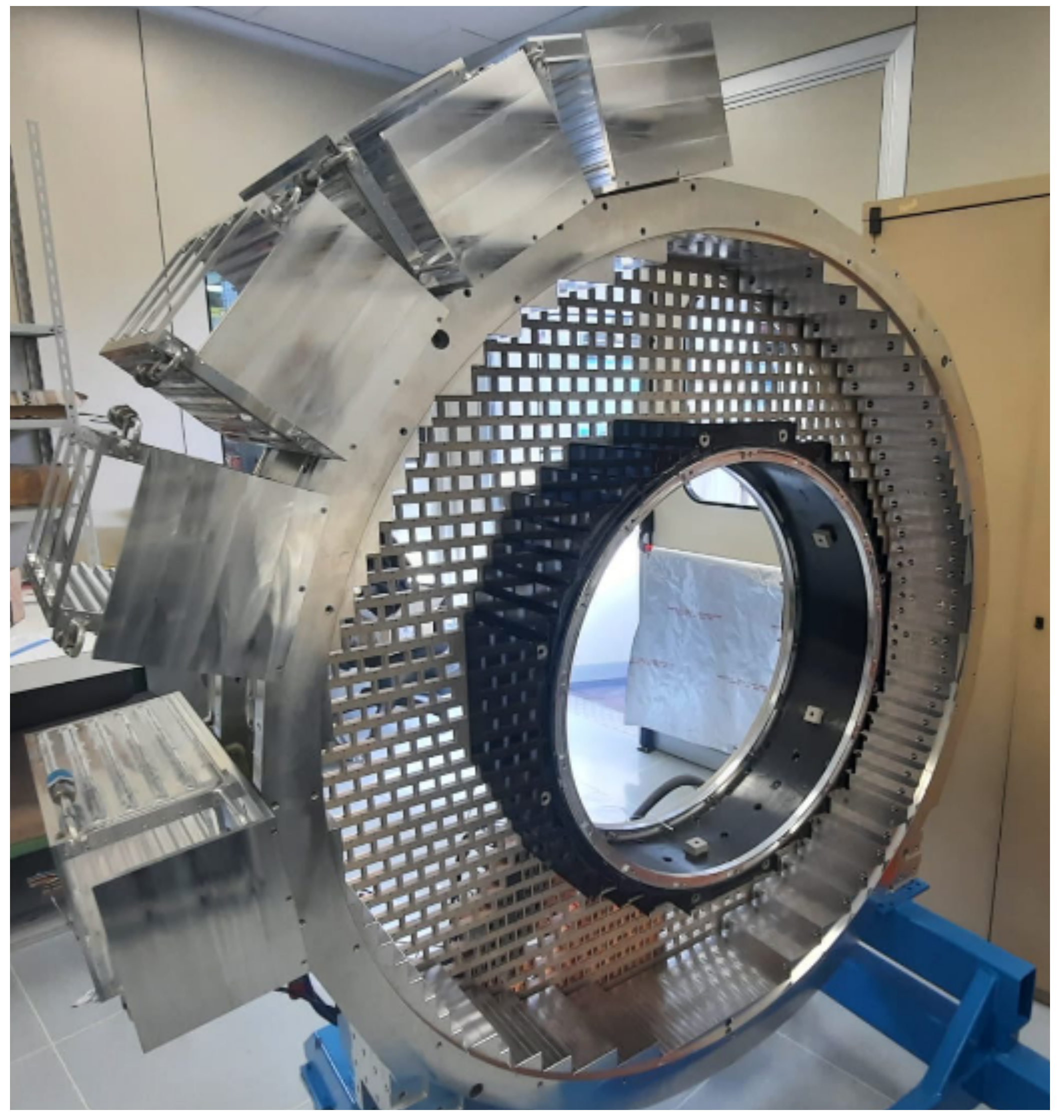
- take advantage of muonic atom's long lifetime and use a pulsed beam to greatly reduce beam-related backgrounds
- we need extinction level (ratio of protons in and out of pulse) to be $< 10^{-10}$



MU2E CURRENT STATUS

tracker all straws produced

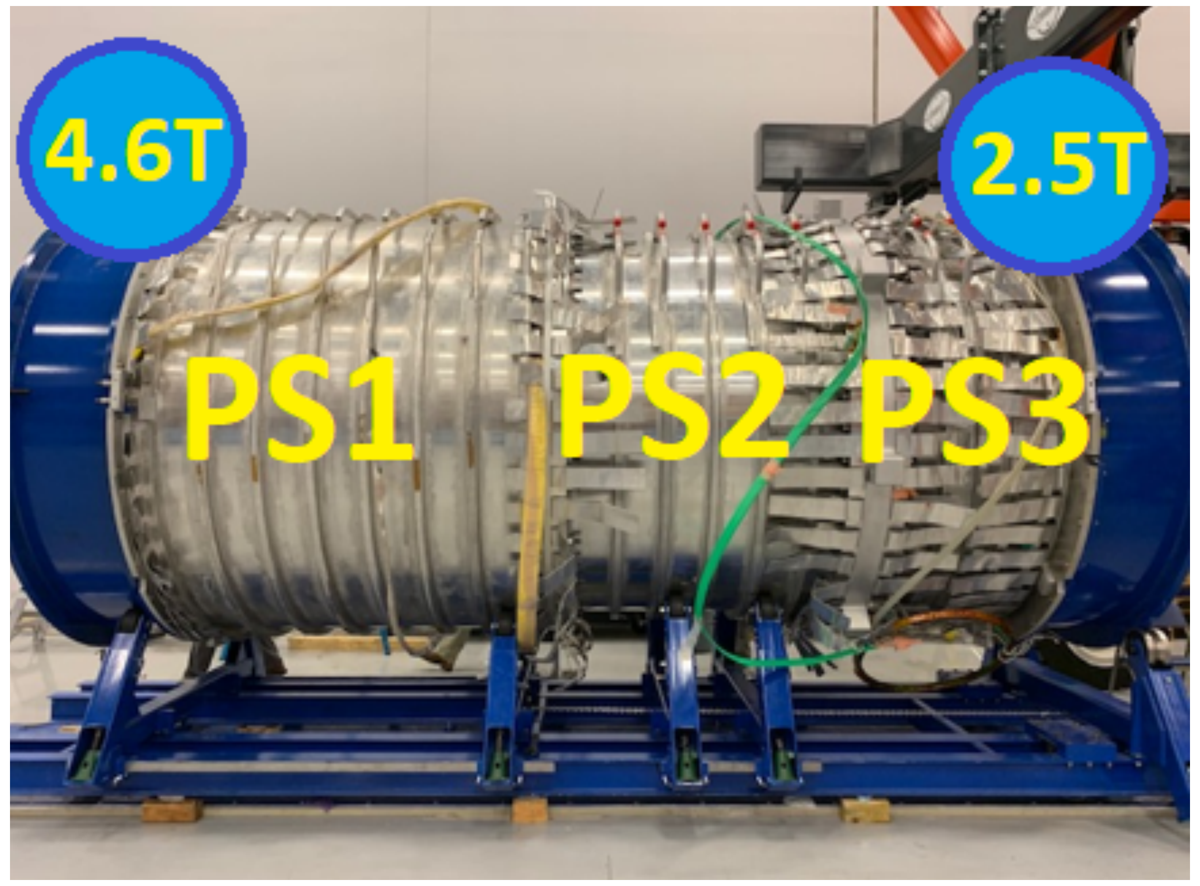
CR veto module assembly

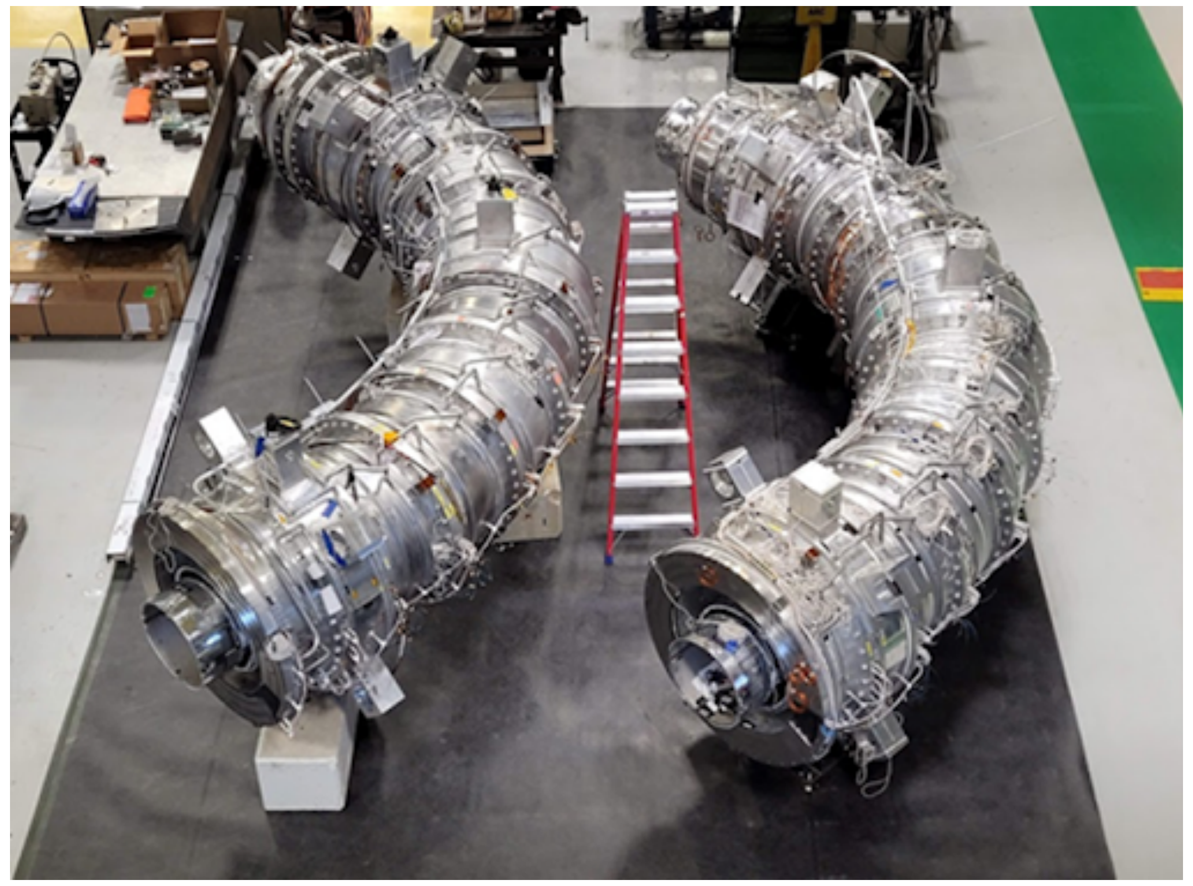


calorimeter all material ready
CR test underway

targets

Production & stopping targets assembled





solenoids all coils for PS & TS and
cold mass for TS are fabricated

MU2E RUN 1 SENSITIVITY

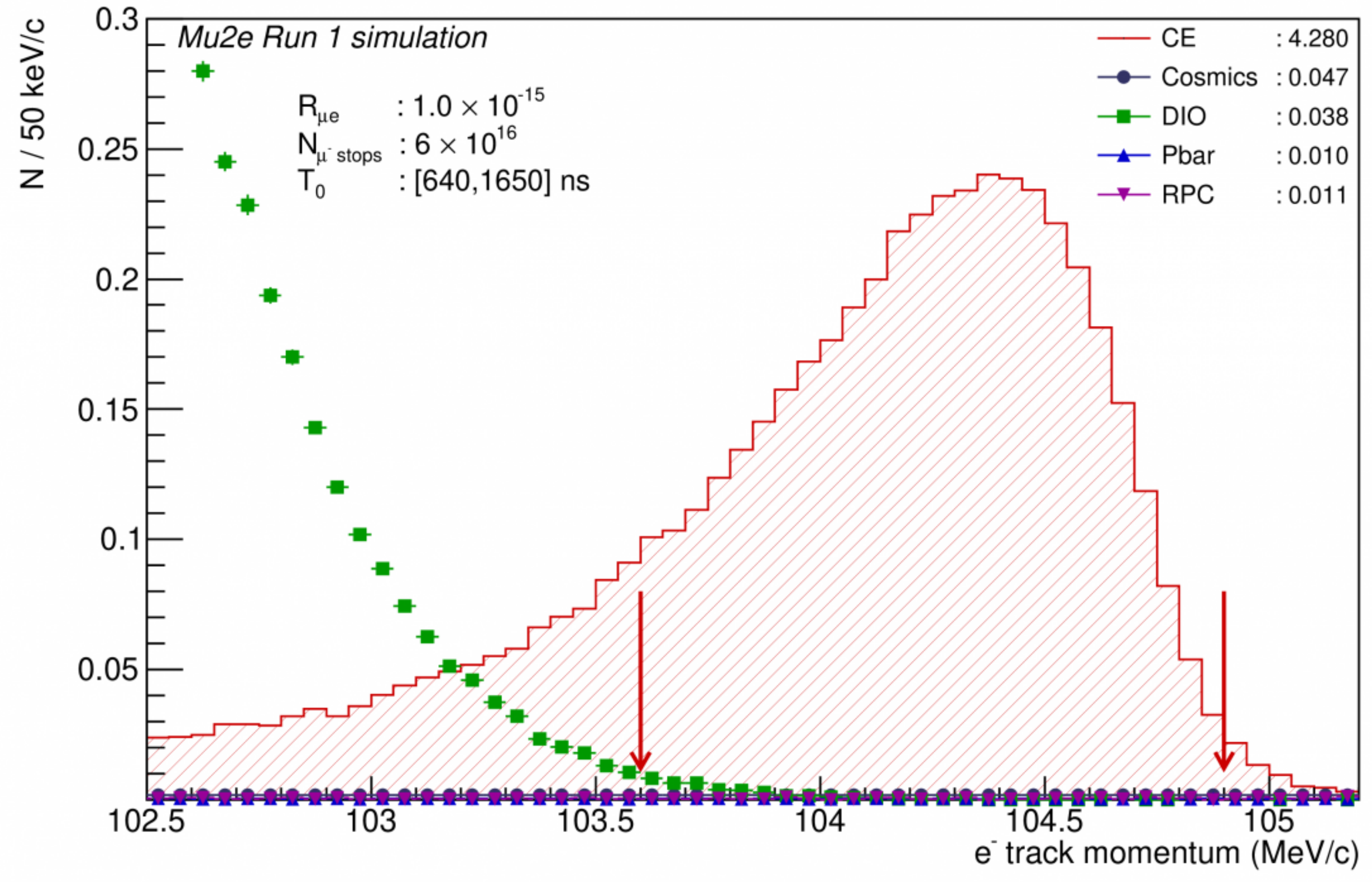
- Detector commissioning through to late 2024
- Take Run 1 data in 2025 and 2026 until LBNF/PIP-II shutdown
  - x1000 improvement over SINDRUM-II
- Resume data collection in 2029 after long shutdown
  - x10000 improvements over SINDRUM-II

We recently completed a sensitivity estimate for Run 1

- 5σ discovery $R_{\mu\to e} = 1.1 \times 10^{-15}$
- 90% CL $R_{\mu\to e} < 5.9 \times 10^{-16}$
- 1000x better than SINDRUM-II limit
- paper to be submitted to *Universe*

Total background:

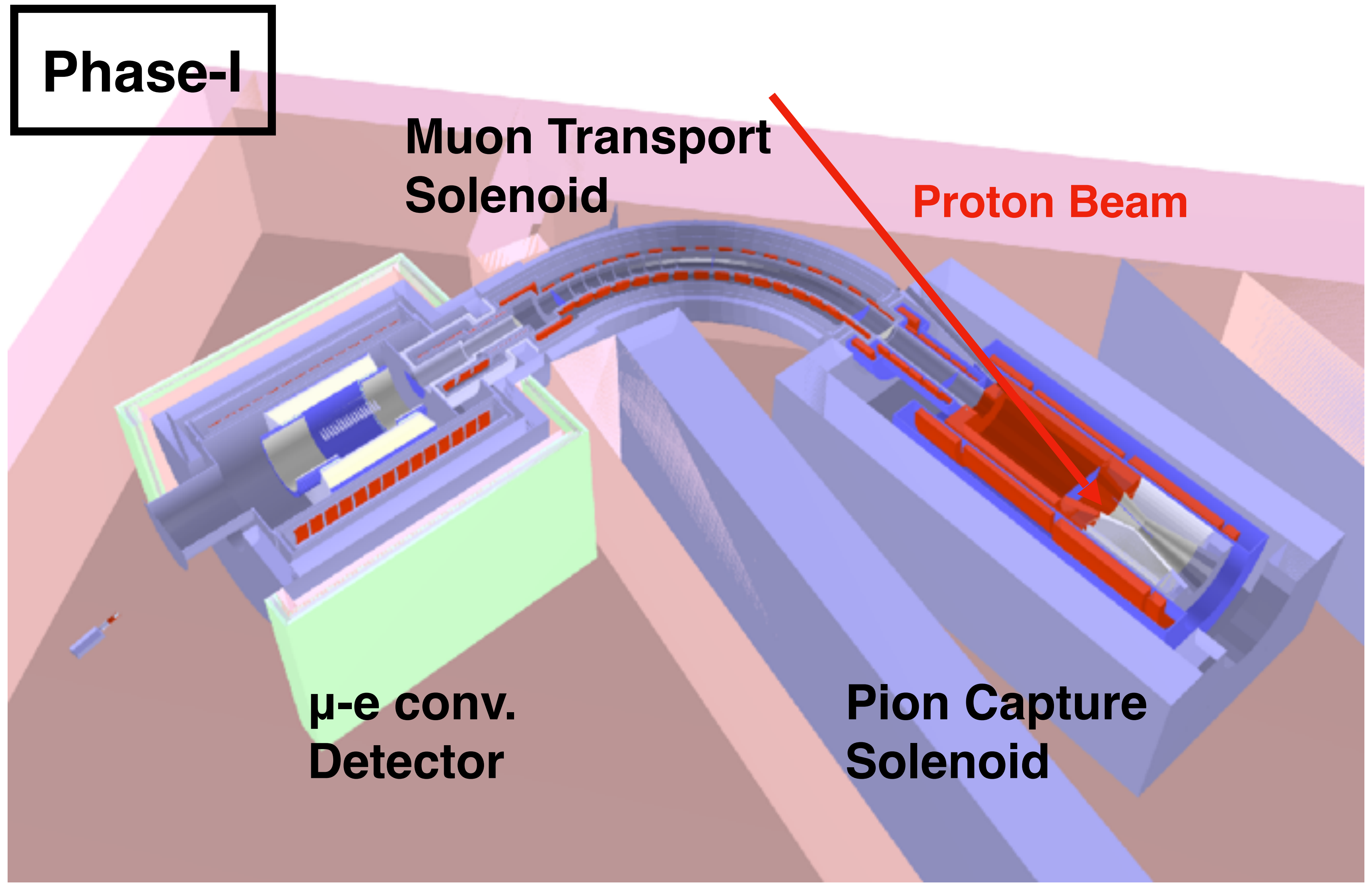
- 0.11 ± 0.03 (stat.+syst.) events
  - cosmics $= 0.05 \pm 0.01$ events
  - DIO $= 0.04 \pm 0.02$ events



Signal and Background PDFs for $R_{\mu\to e} = 10^{-15}$

COMET

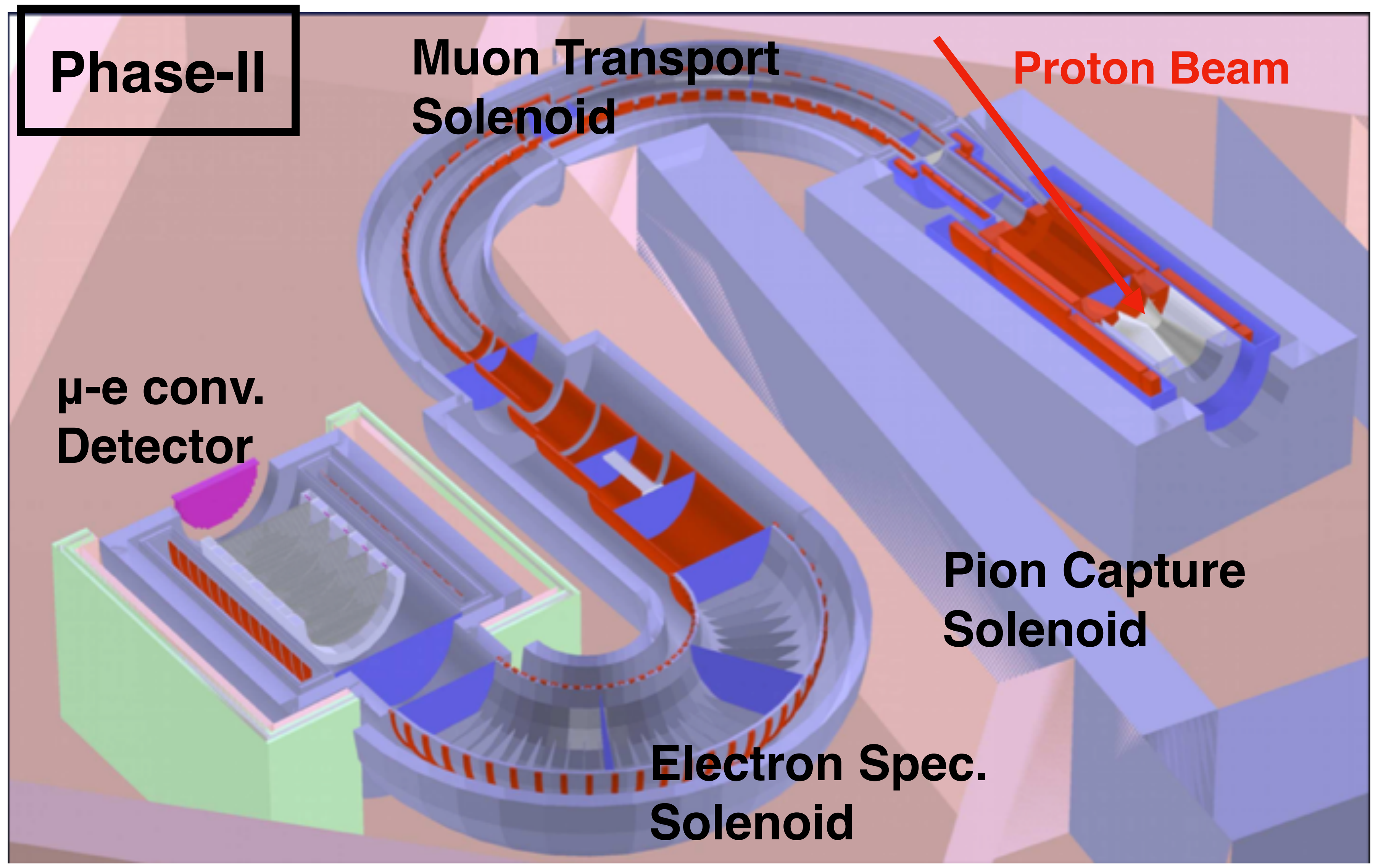
COMET Phase I & II



Target Sensitivity $<10^{-14}$ with 3.2kW beam

- **Proton beam line** construction in progress to be completed in **FY2021**
- **Graphite** as a pion production target
- Pion Capture Solenoid construction is in the 2nd year of multi-year construction contract (FY2020-2022)
- Physics Detector
  - CDC and hodoscope in a solenoid
  - Muon stopping target (Al) at the center of the solenoid

Beam engineering run in FY2022 and physics in FY2023.

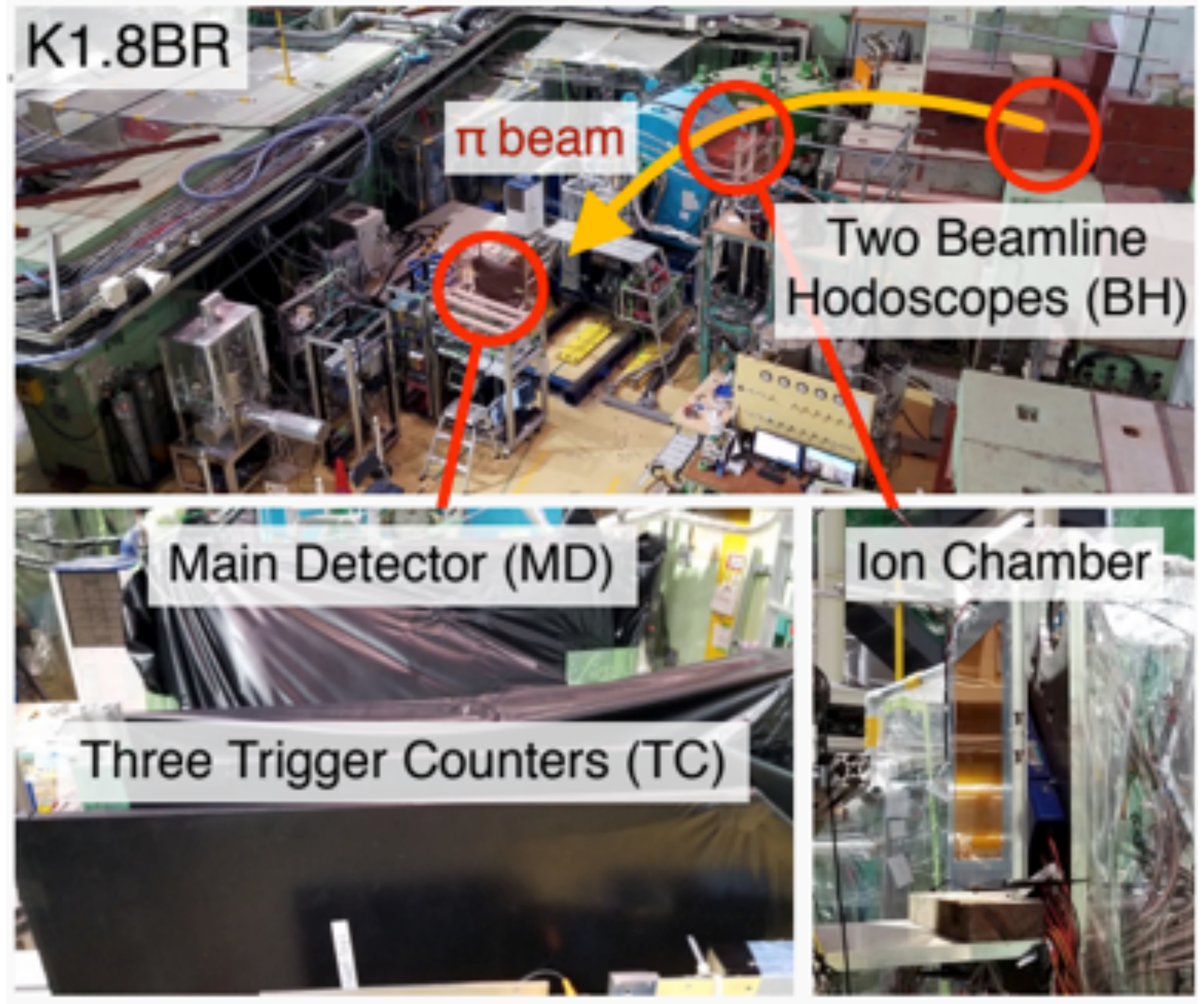


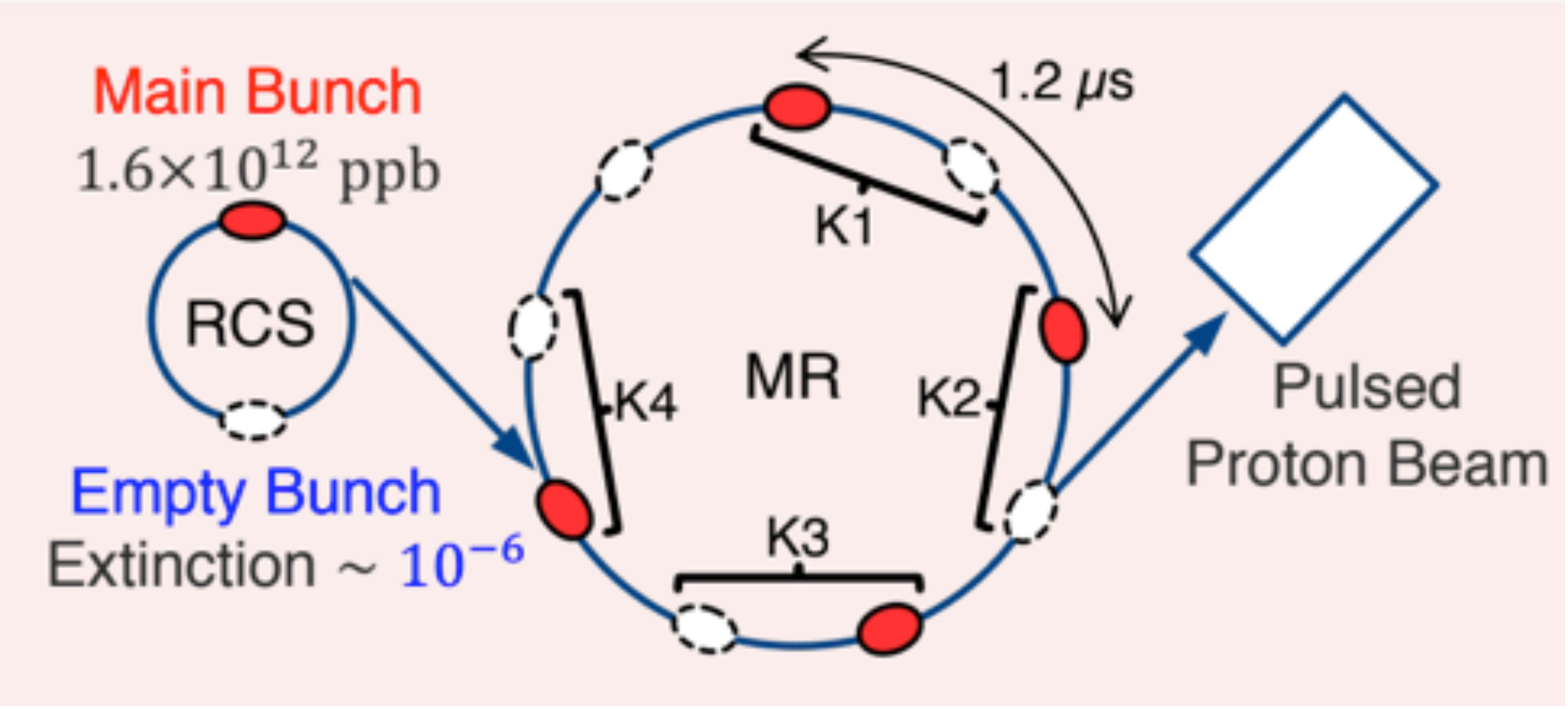
Target Sensitivity $<10^{-16}$ with 56 kW beam

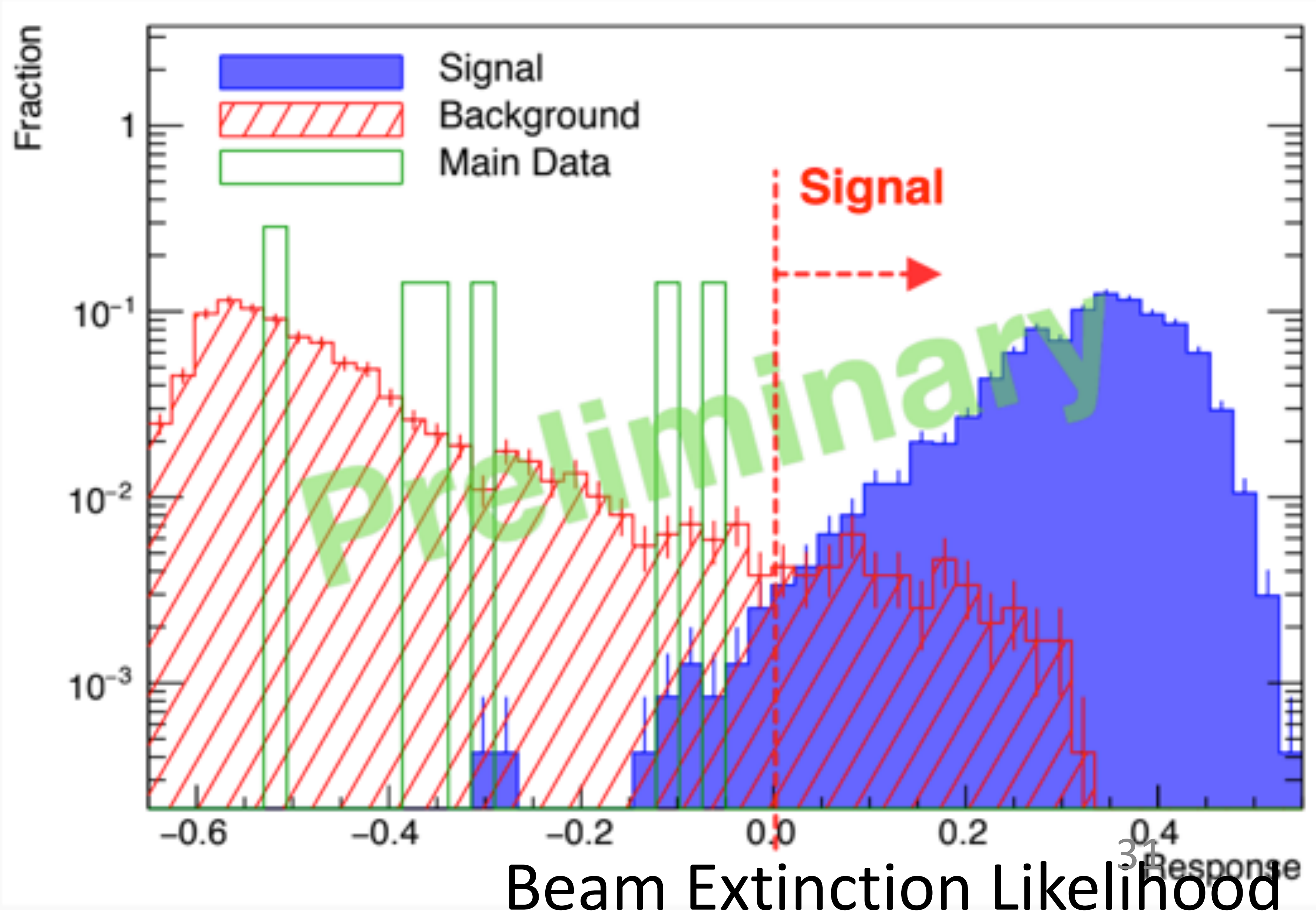
- **Extension of muon transport solenoid** to **cope with higher proton beam power**
  - More efficient beam background suppression
  - Pions decay to muons in longer transport
- **Tungsten alloy** as a pion production target
- **Electron spectrometer solenoid** to suppress the detector counting rate
- Physics detector
  - Straw-tube tracker and LYSO calorimeter
  - Muon stopping target (Al + others) in a gradient magnetic field for the purpose of signal electron collection with a magnetic lens

J-PARC T78 Beam Extinction Measurement

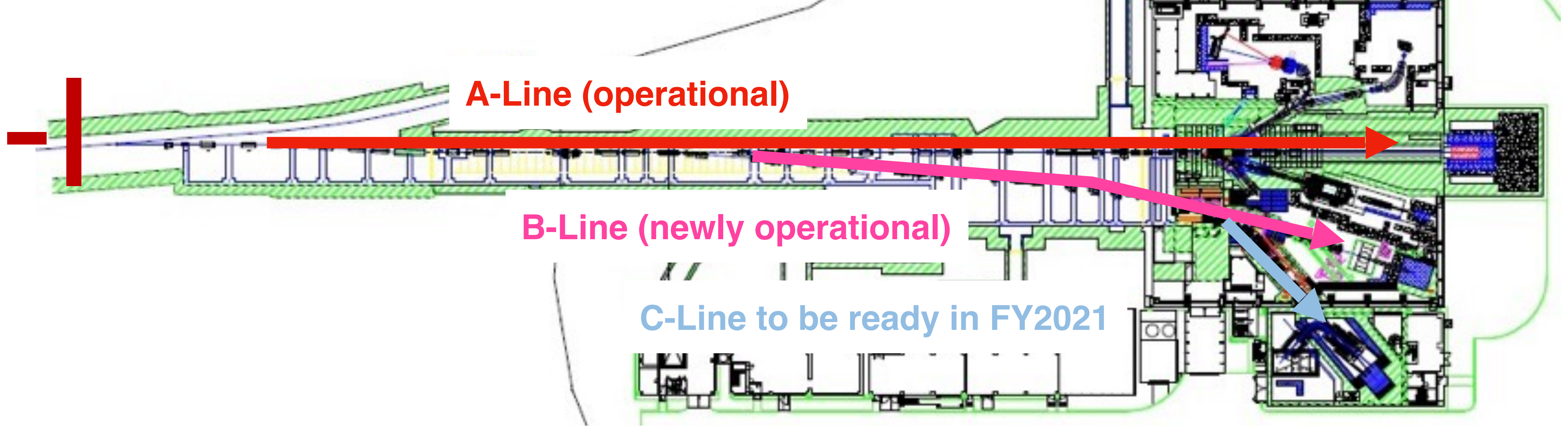
- COMET dedicated beam operation at 8GeV
- Extremely ‘purely’ pulsed proton beam to suppress BG
  - $R_{ext} = \frac{\#\ proton\ in - between\ pulses}{\#\ proton\ in\ a\ puluse} < 10^{-11}$
- R_{ext} measurement with secondary pion beam
- Confirmed 10^{-10} R_{ext}
  - Sufficiently low for Phase-I
  - Further improvement necessary for Pha



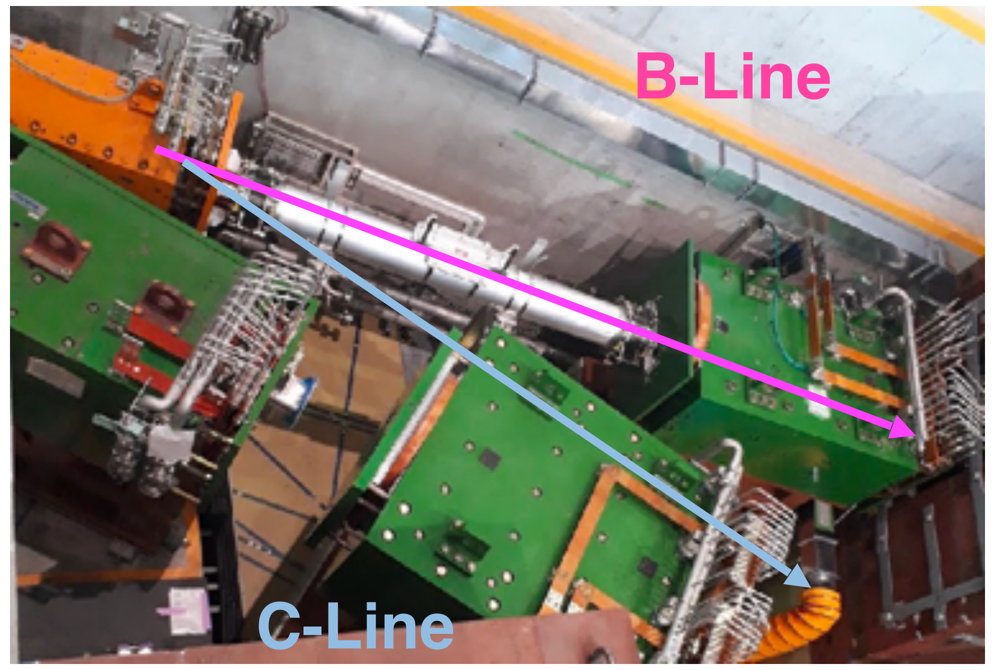


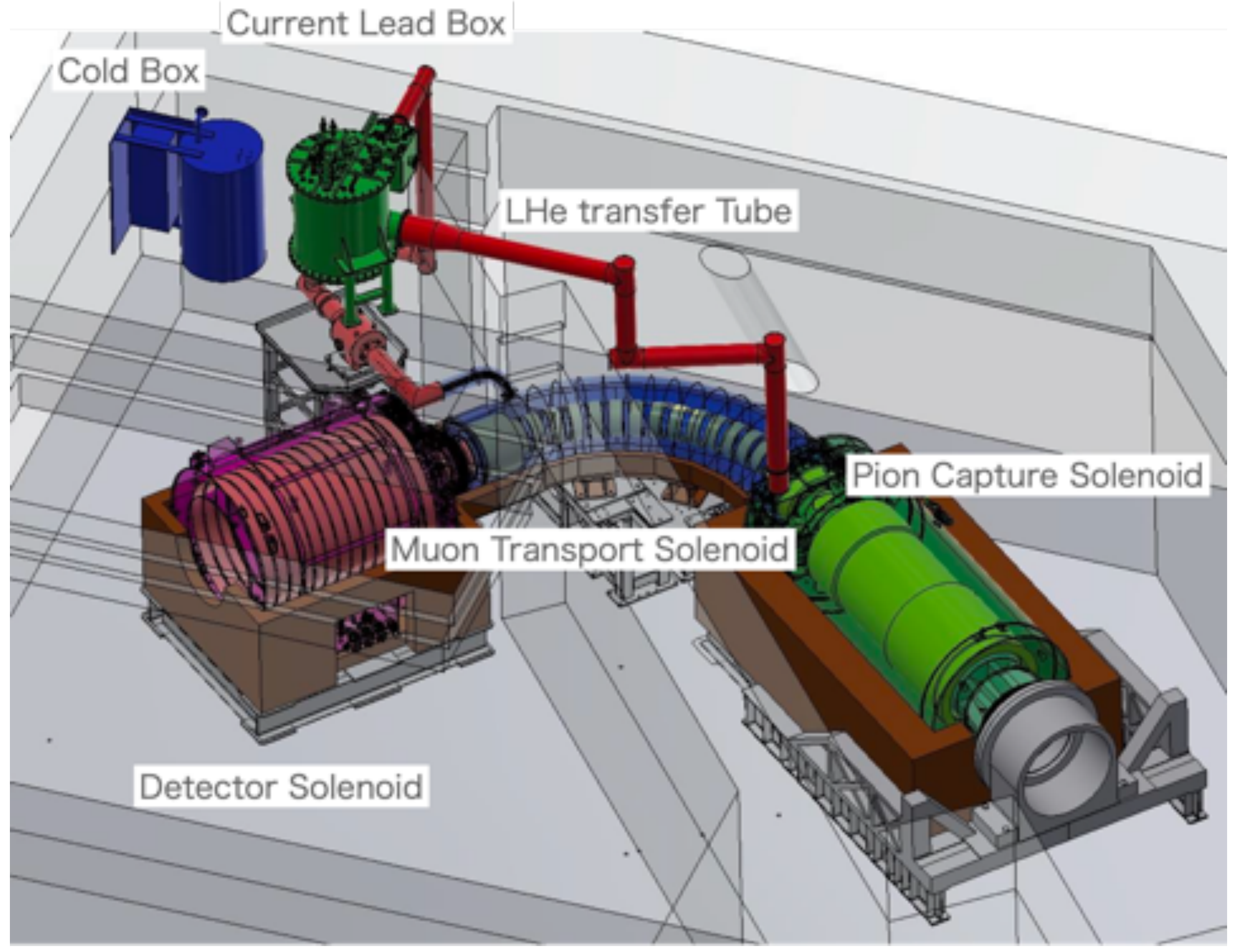


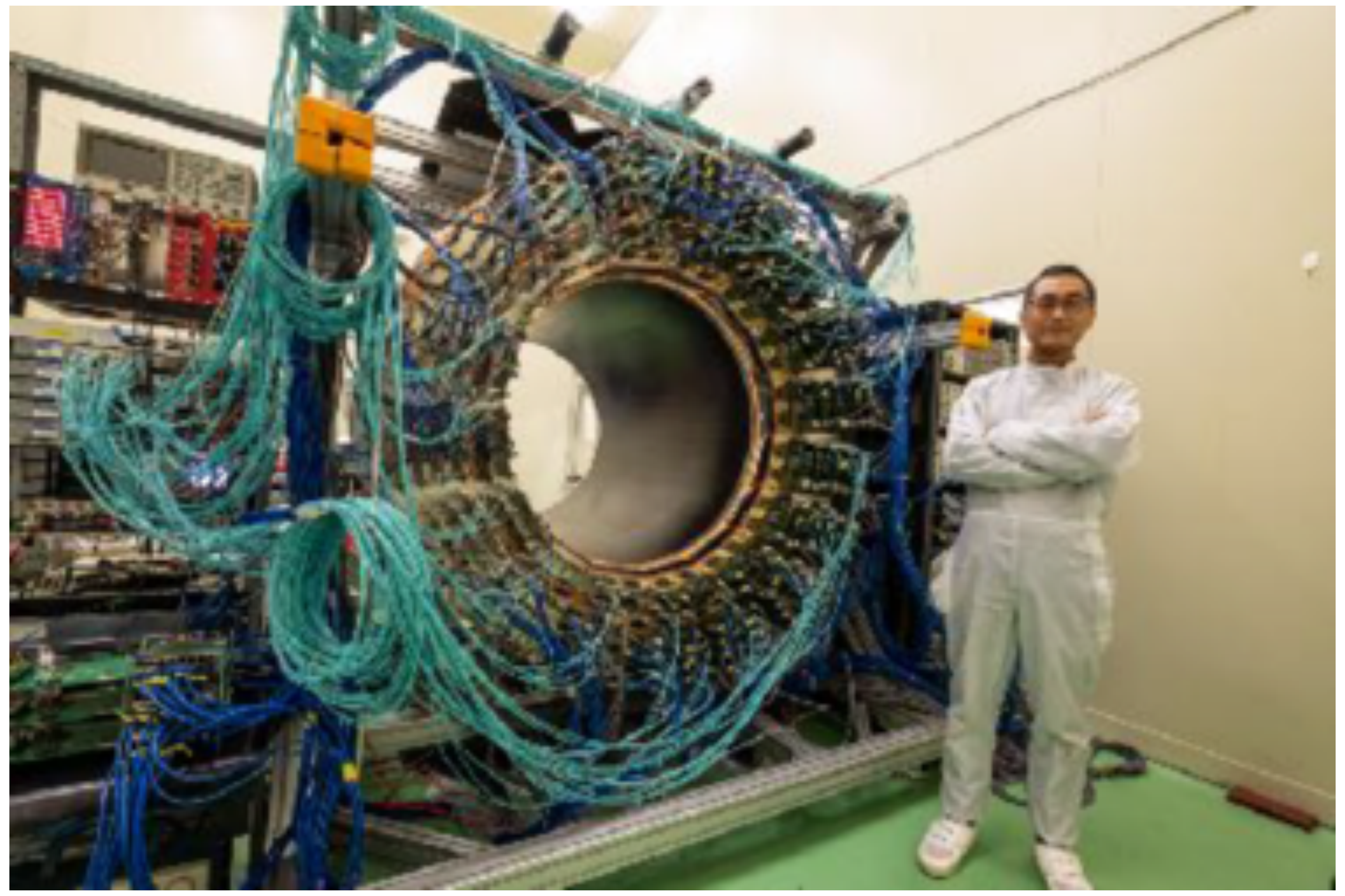
COMET Phase-I



- **Proton transport beamline**
  - **Ready in FY2021**
  - **Beam engineering run** with a thin graphite target **in FY2022**. Proton beam diagnostics & backward pion production (@8GeV) as well as background survey like anti-protons.
- **Solenoid magnet system**
  - **Pion capture solenoid (PCS)** to be **ready in FY2022**
    - Cold mass assembly (FY2020), Cryostat construction (FY2021), and final assembly (FY2022)
  - Cryogenics system to be ready in FY2022 for the engineering run
- Physics detector in preparation by the COMET collaboration toward **Physics run in FY2023-2024**

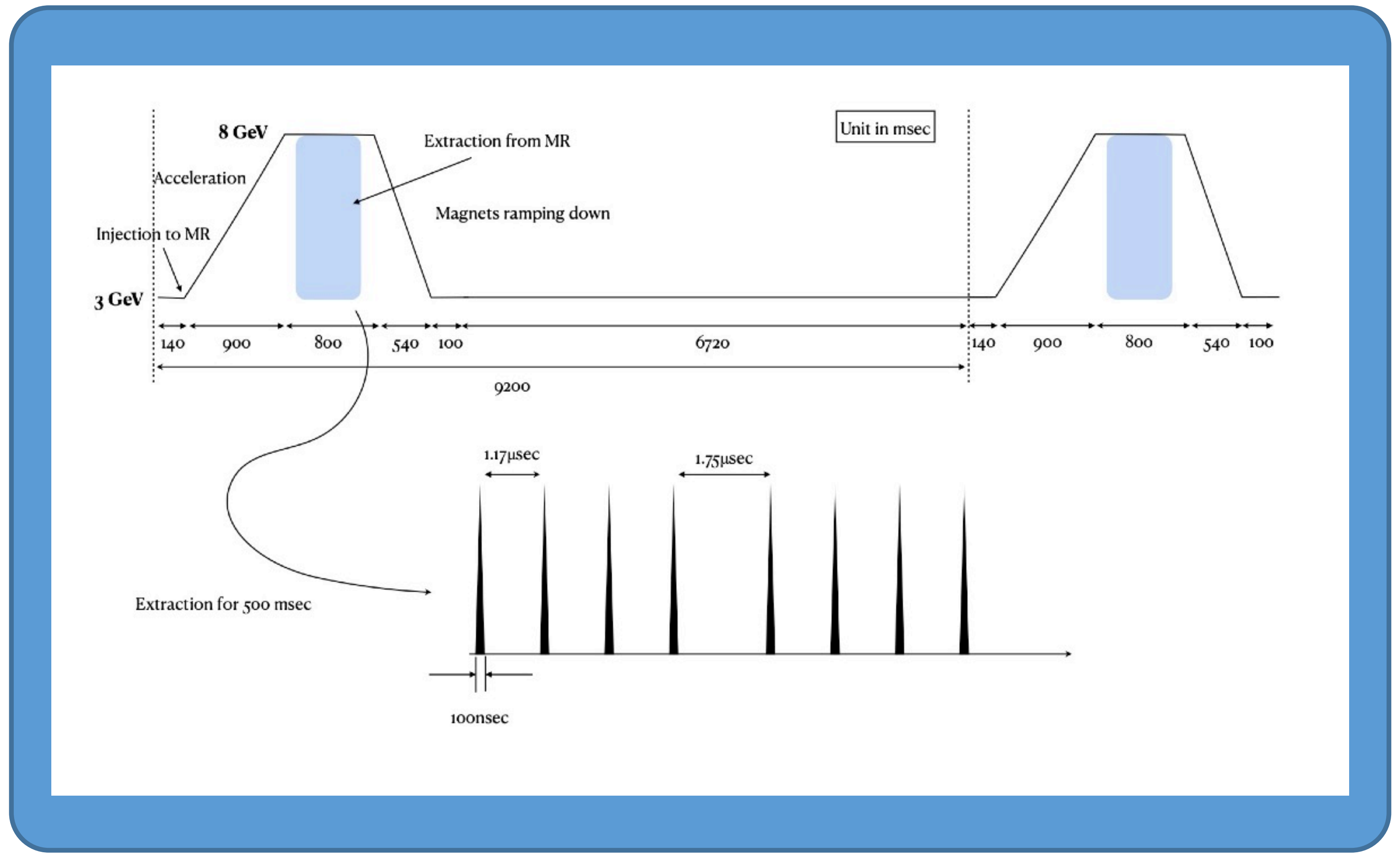




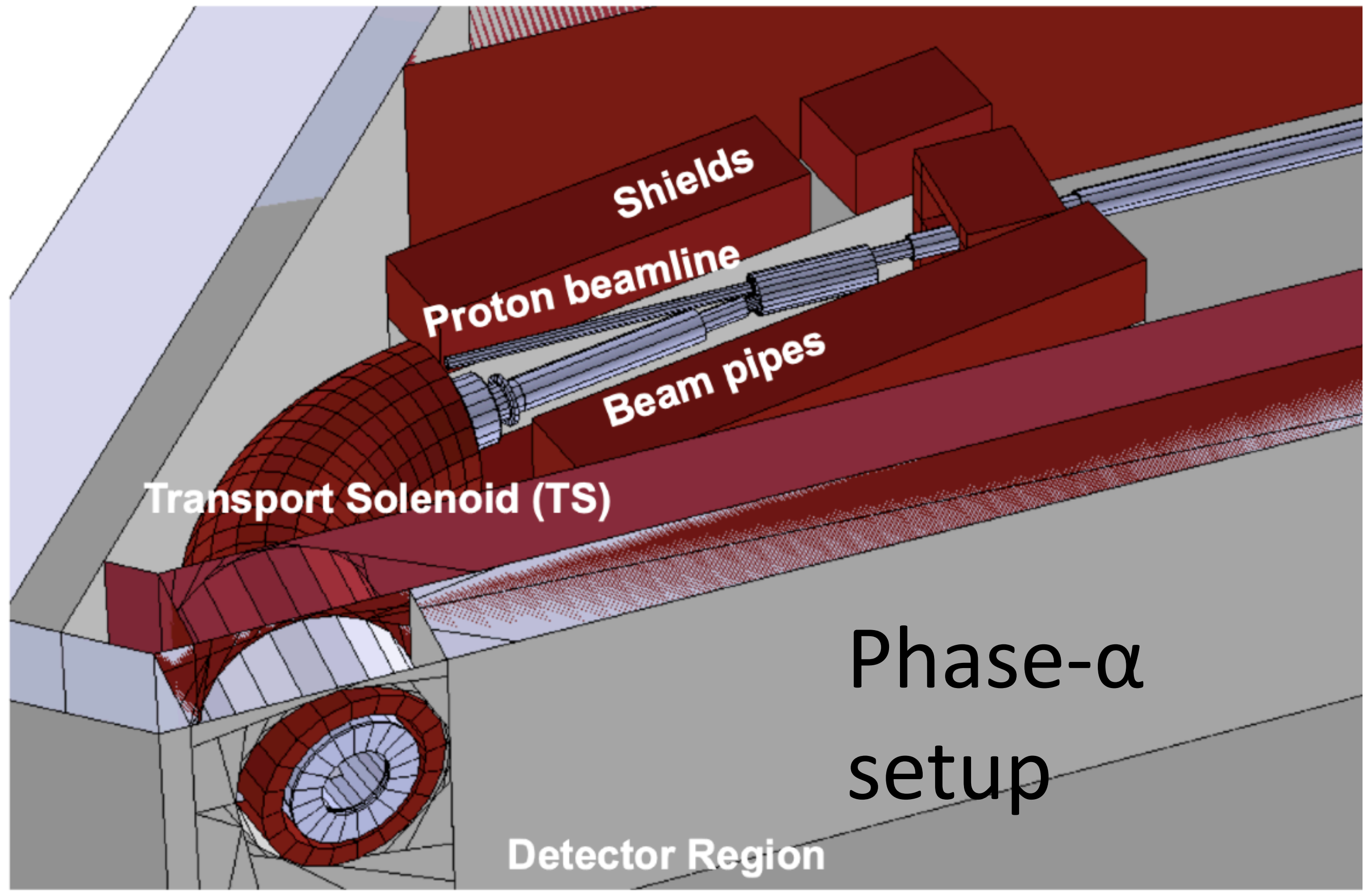


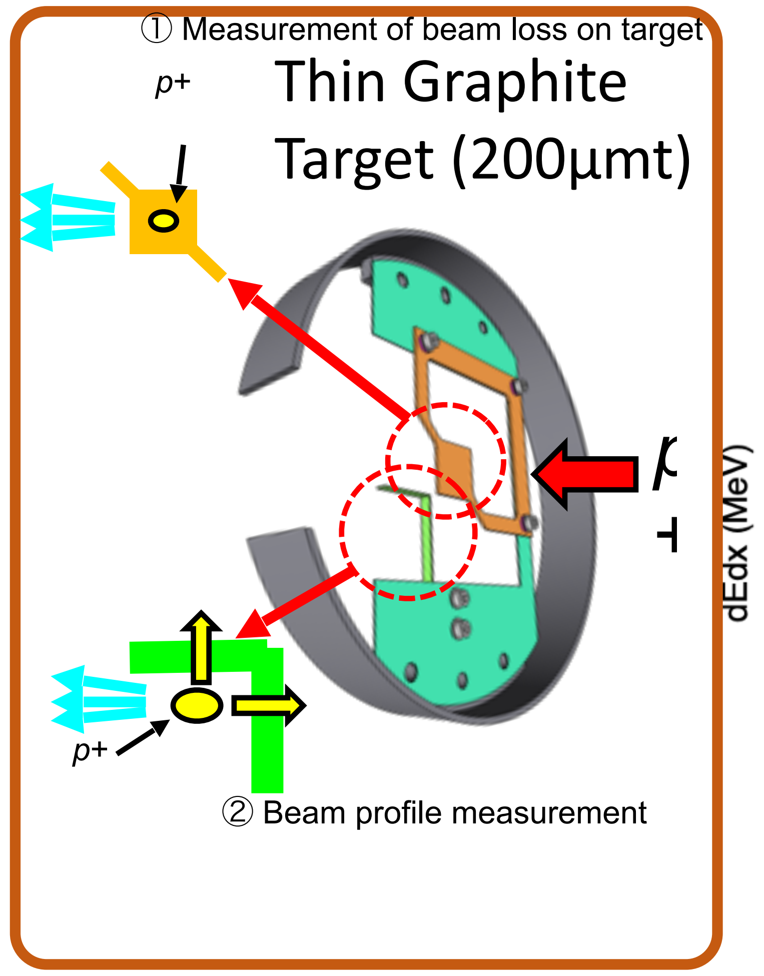
COMET Phase-α: an engineering run before starting physics

- Need **a reliable estimate of the number of muons** reaching the muon stopping target (and **other particles – π±, e±**)
  - No data available of particle (backward) production in the p+A reaction at 8GeV
  - Large ambiguity of **anti-proton** production cross section as it is close to the threshold
- **Proton beam diagnostics w/o PCS**
  - Profile and beam extinction factor
  - Once PCS installed, there is no sufficient space around the pion production target

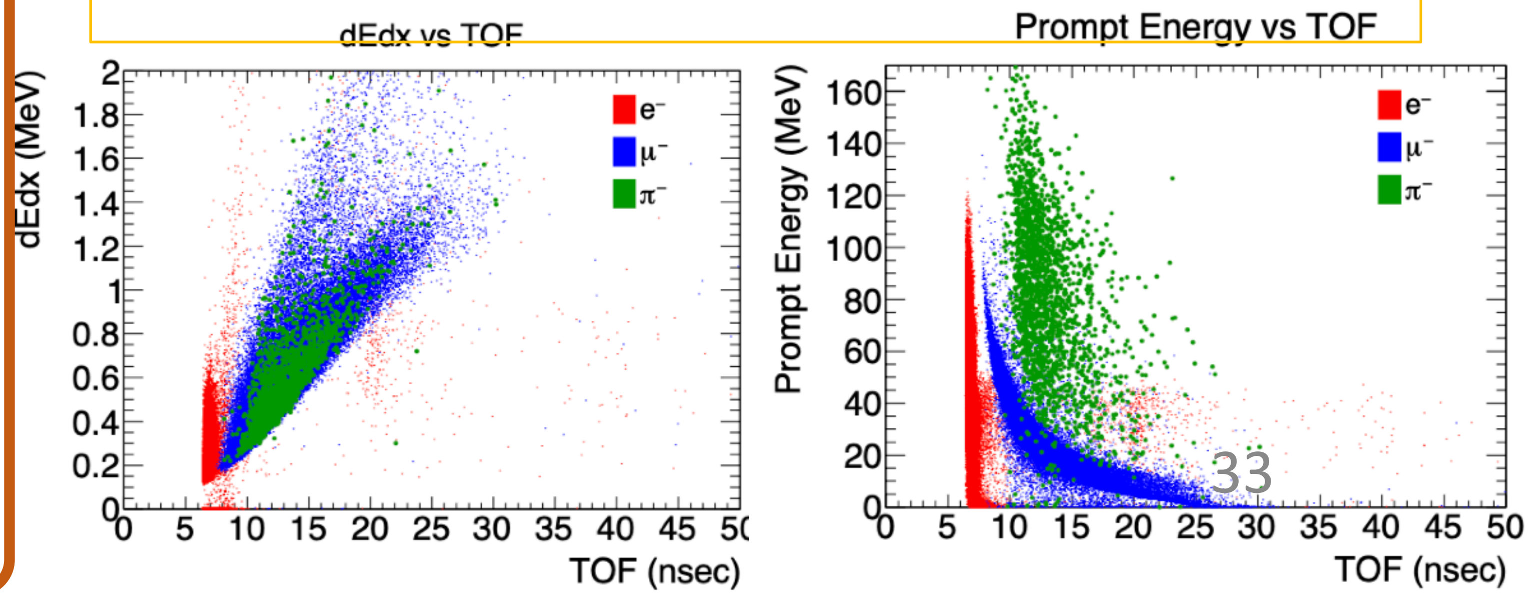


- 300W proton beam
- 9.2 sec acceleration cycle
- 0.8 sec extraction time with 1.17µsec pulse timing structure



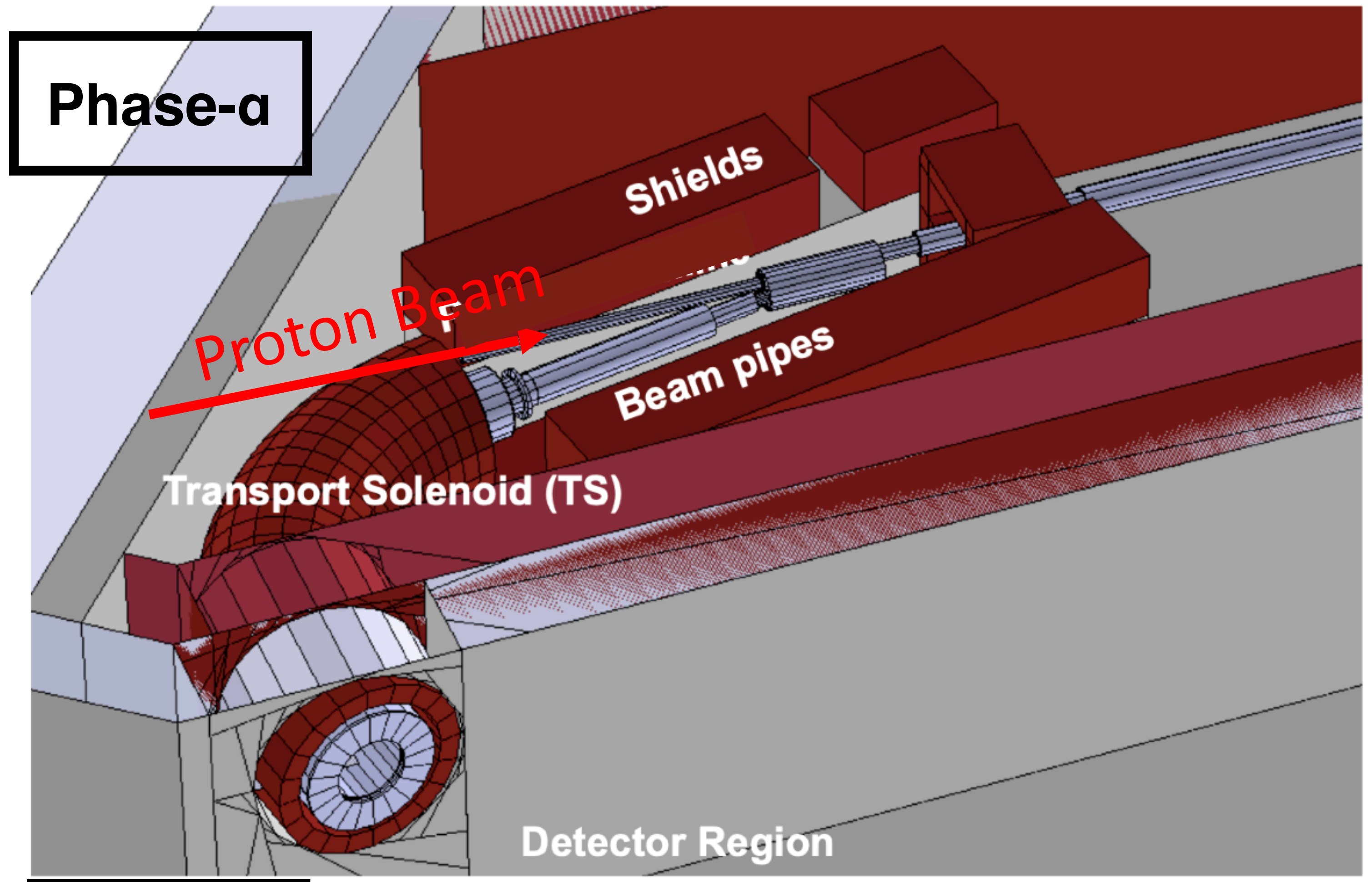


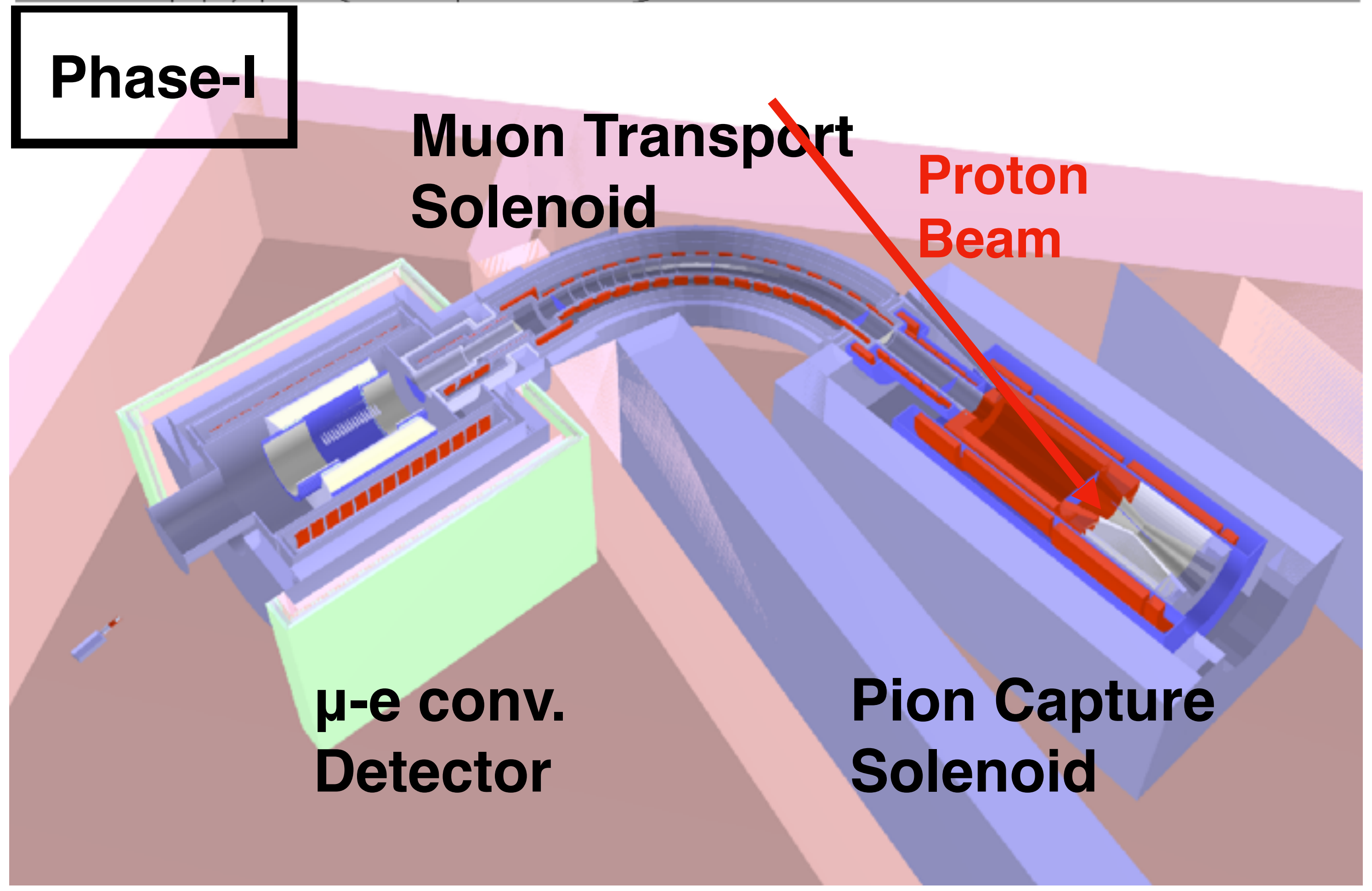
Particle ID performance test with simulated data

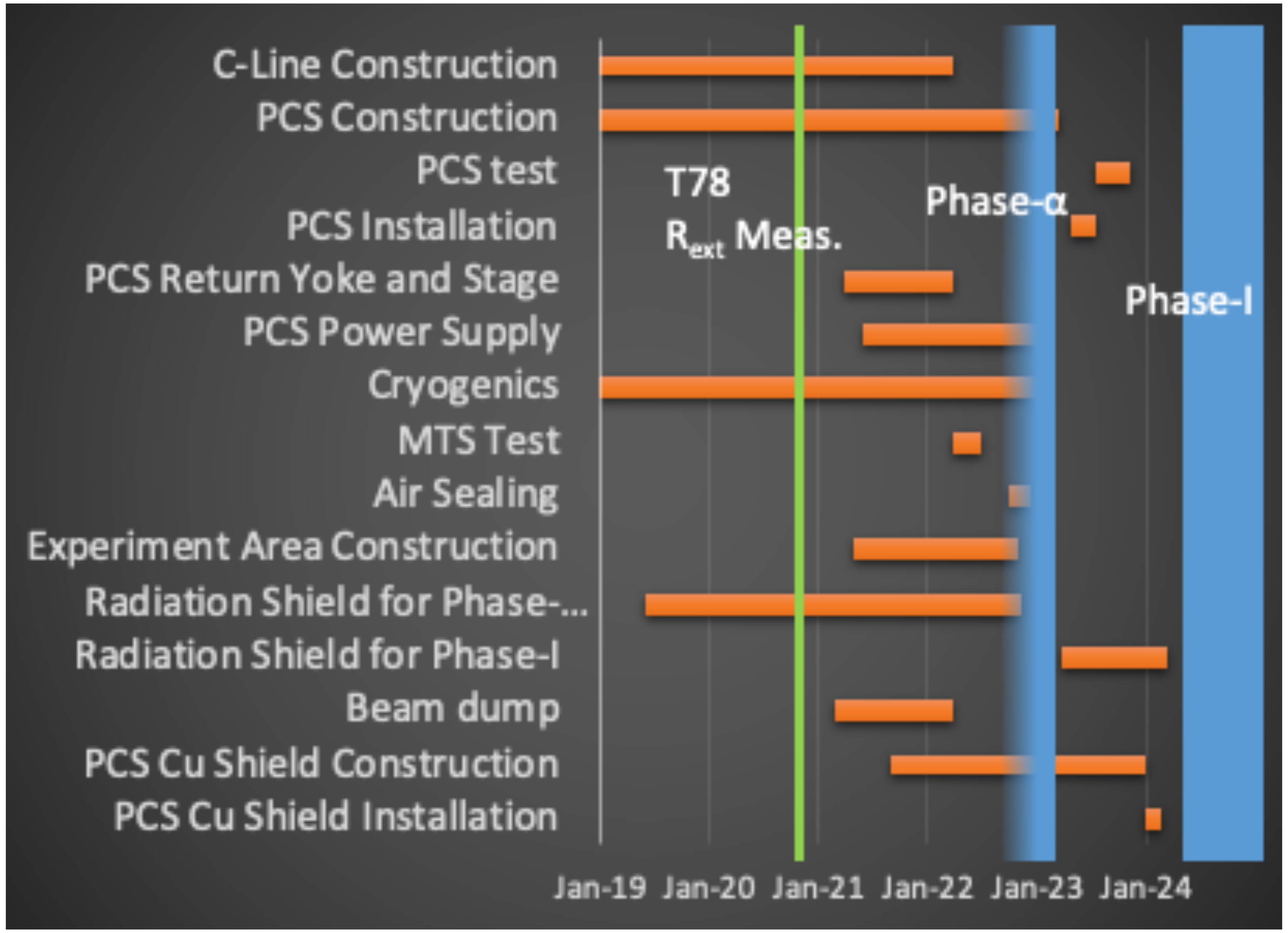


Schedule of Phase-α and Phase-I

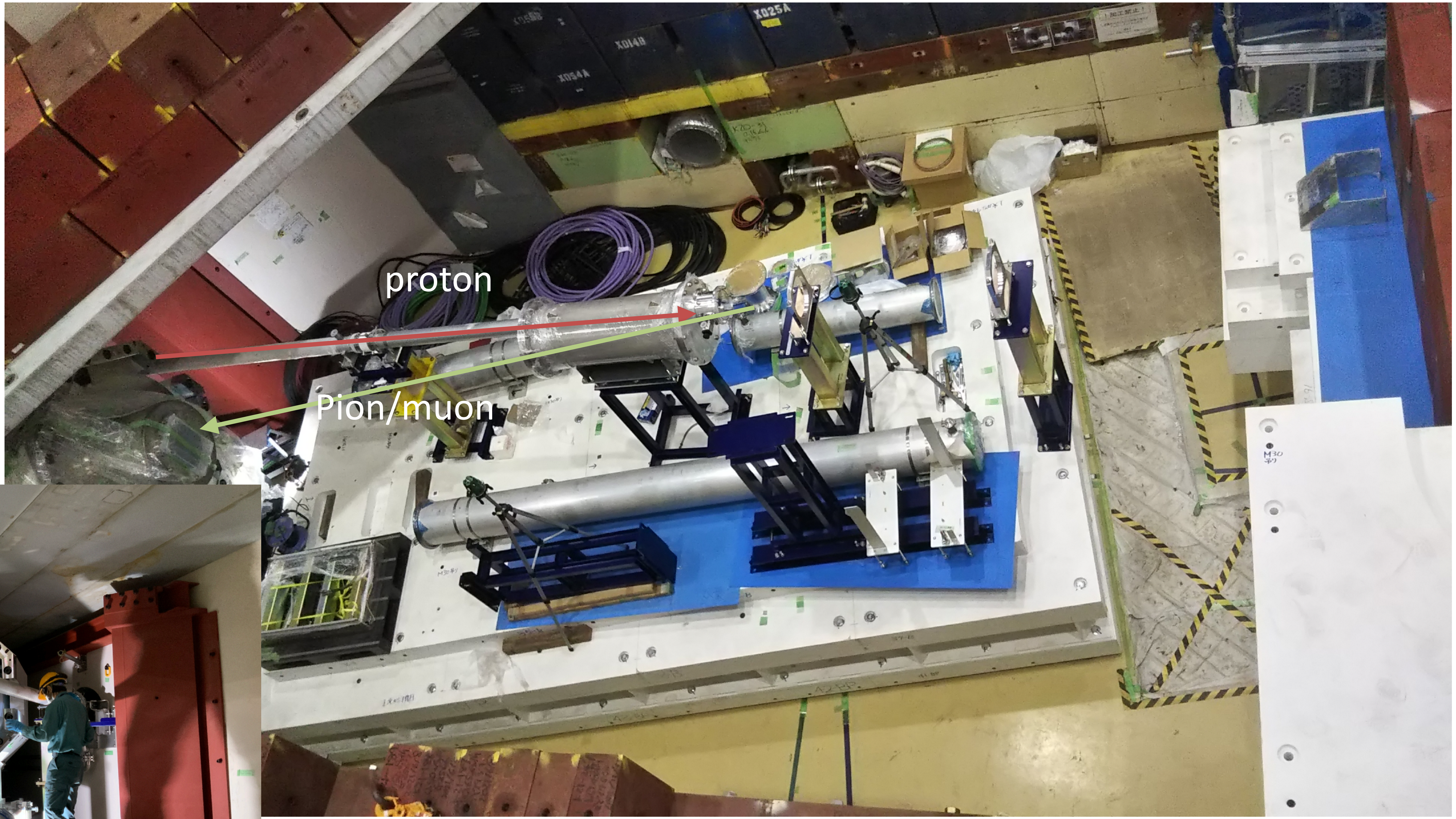
- 8GeV test and R_{ext} measurement in May 2021
- Phase-α Eng. Run in FY2022
- Phase-I Phys. Run in FY2023





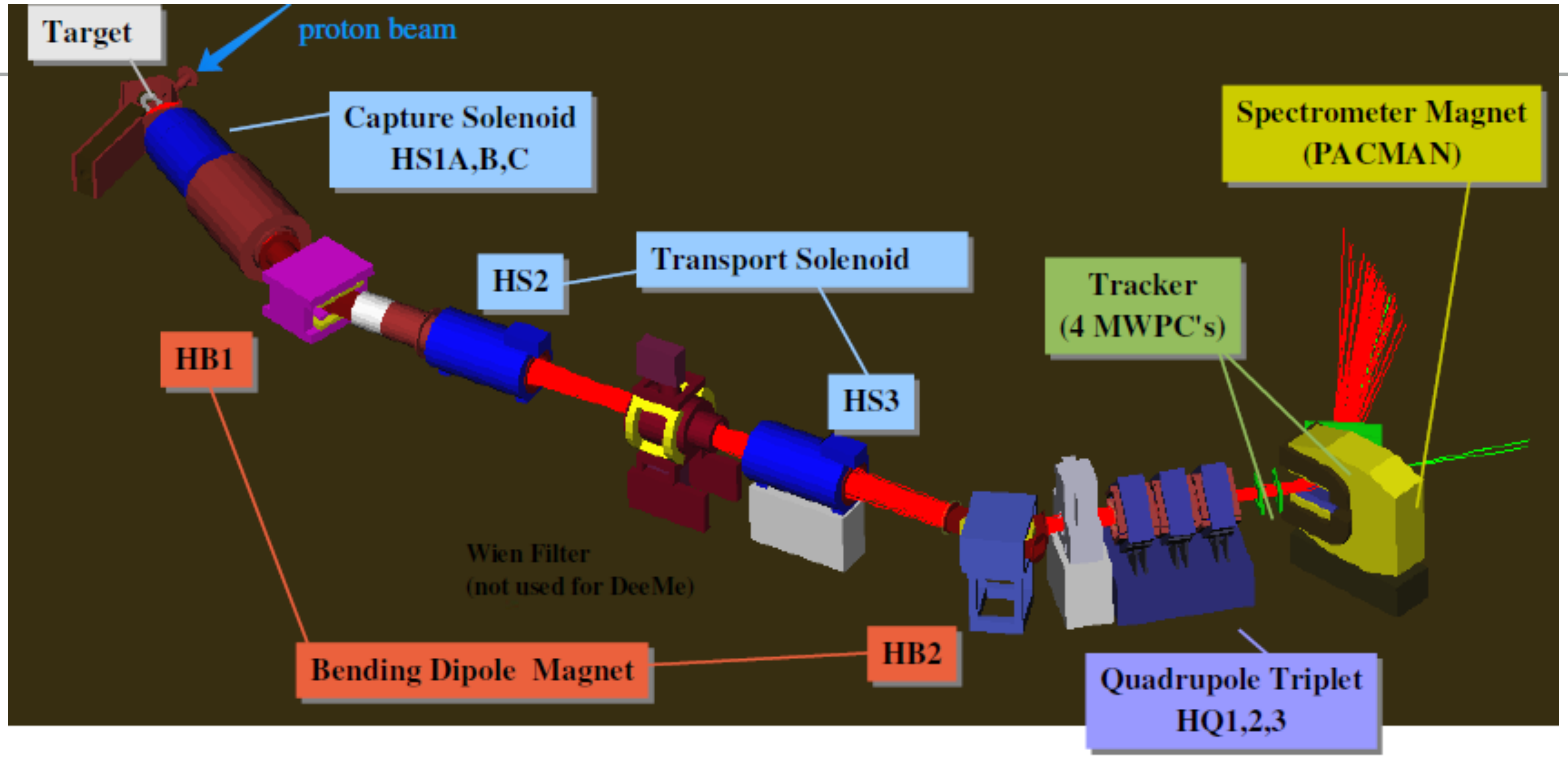


Proton Beamline for COMET Phase-α

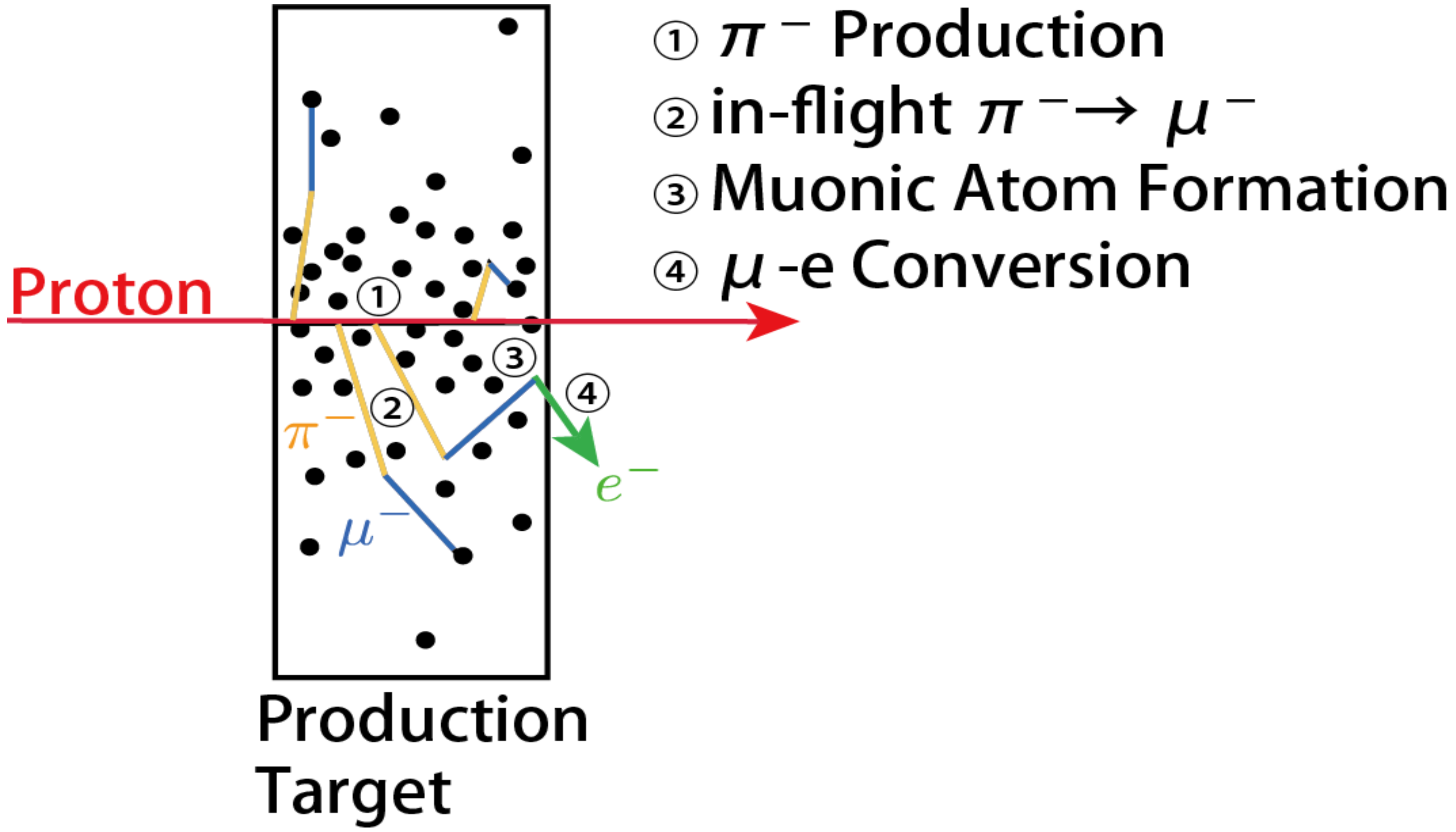


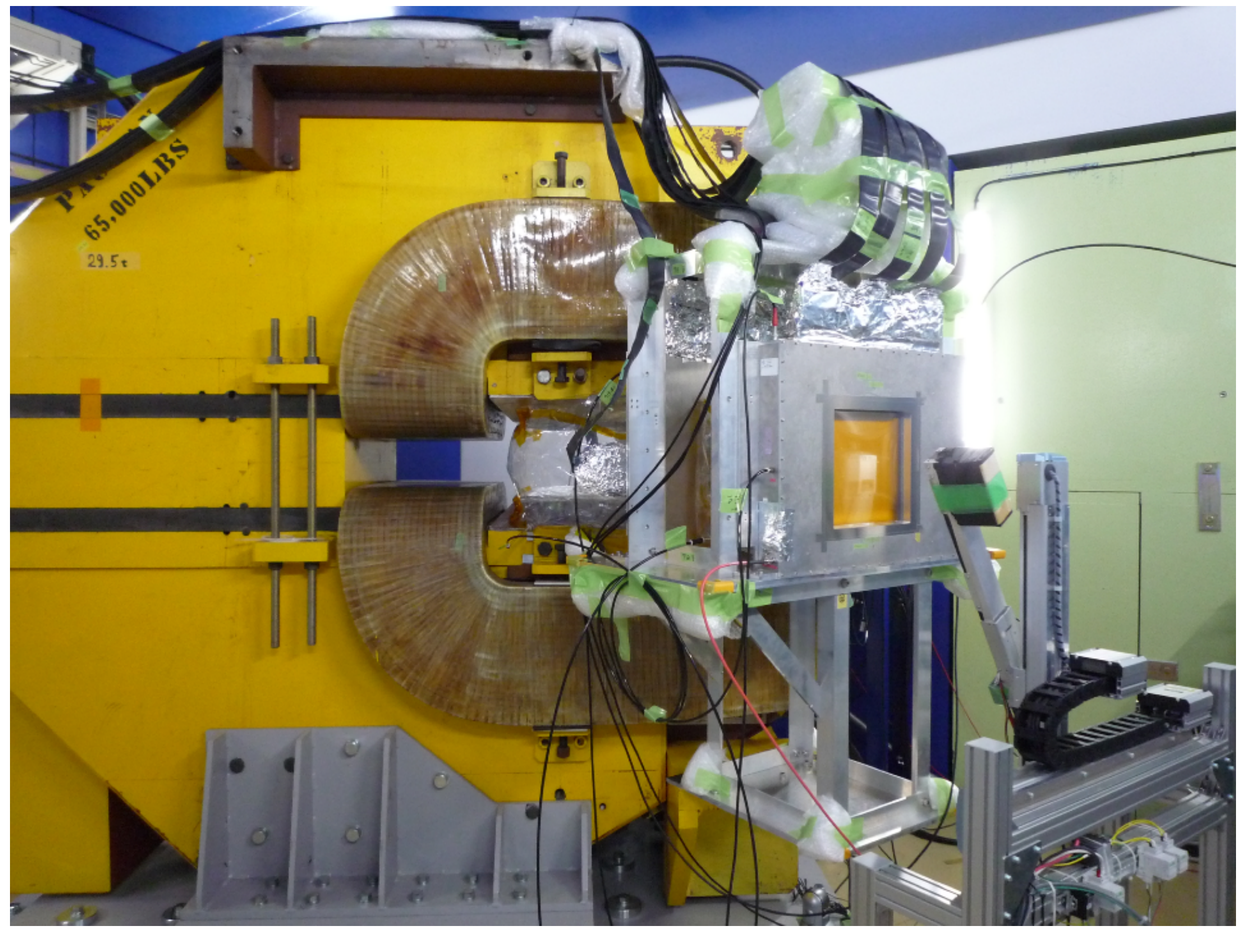
DEEME

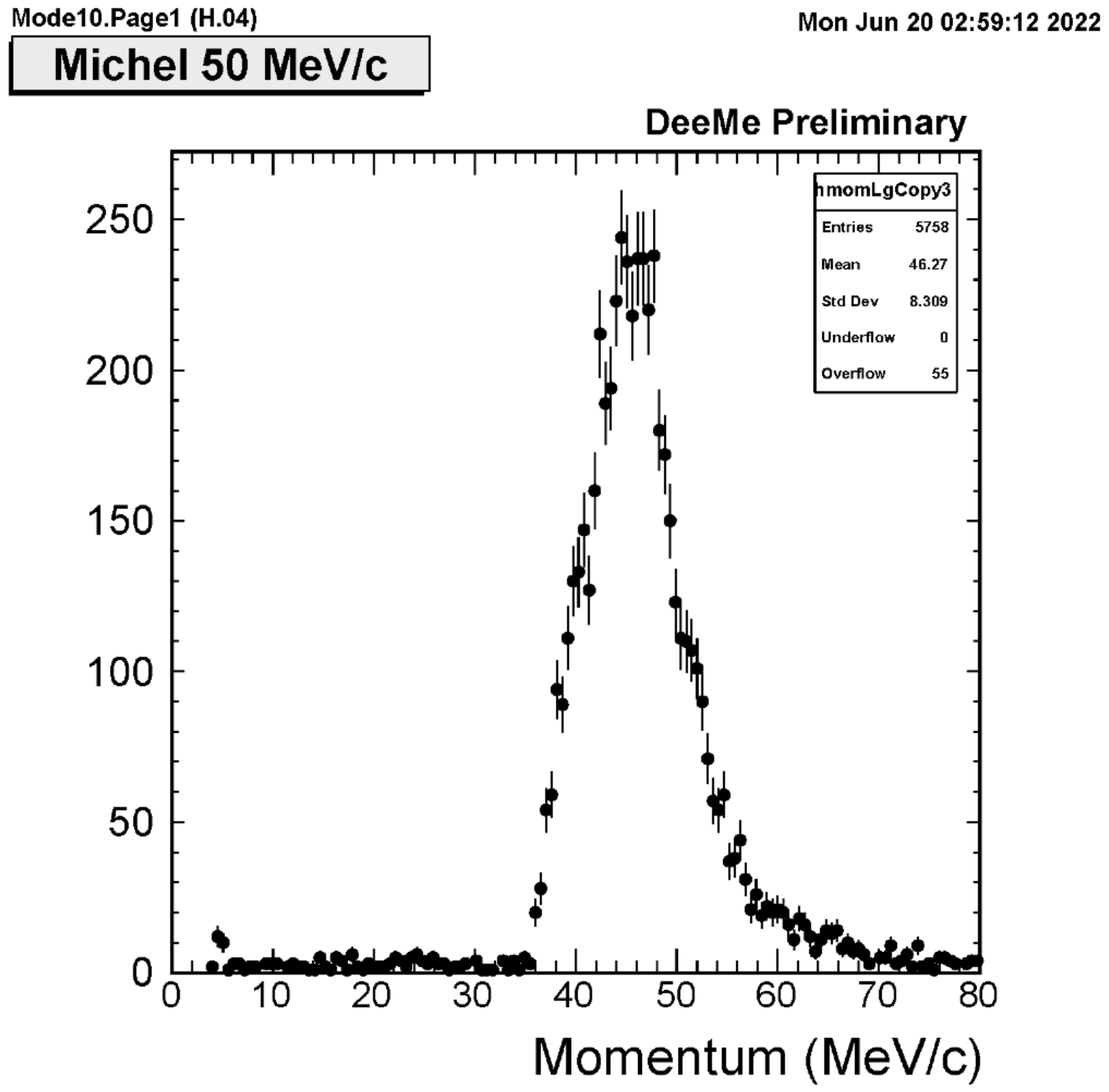
DEEME EXPERIMENT



- Pulsed proton beams from 3 GeV RCS (fast extraction)







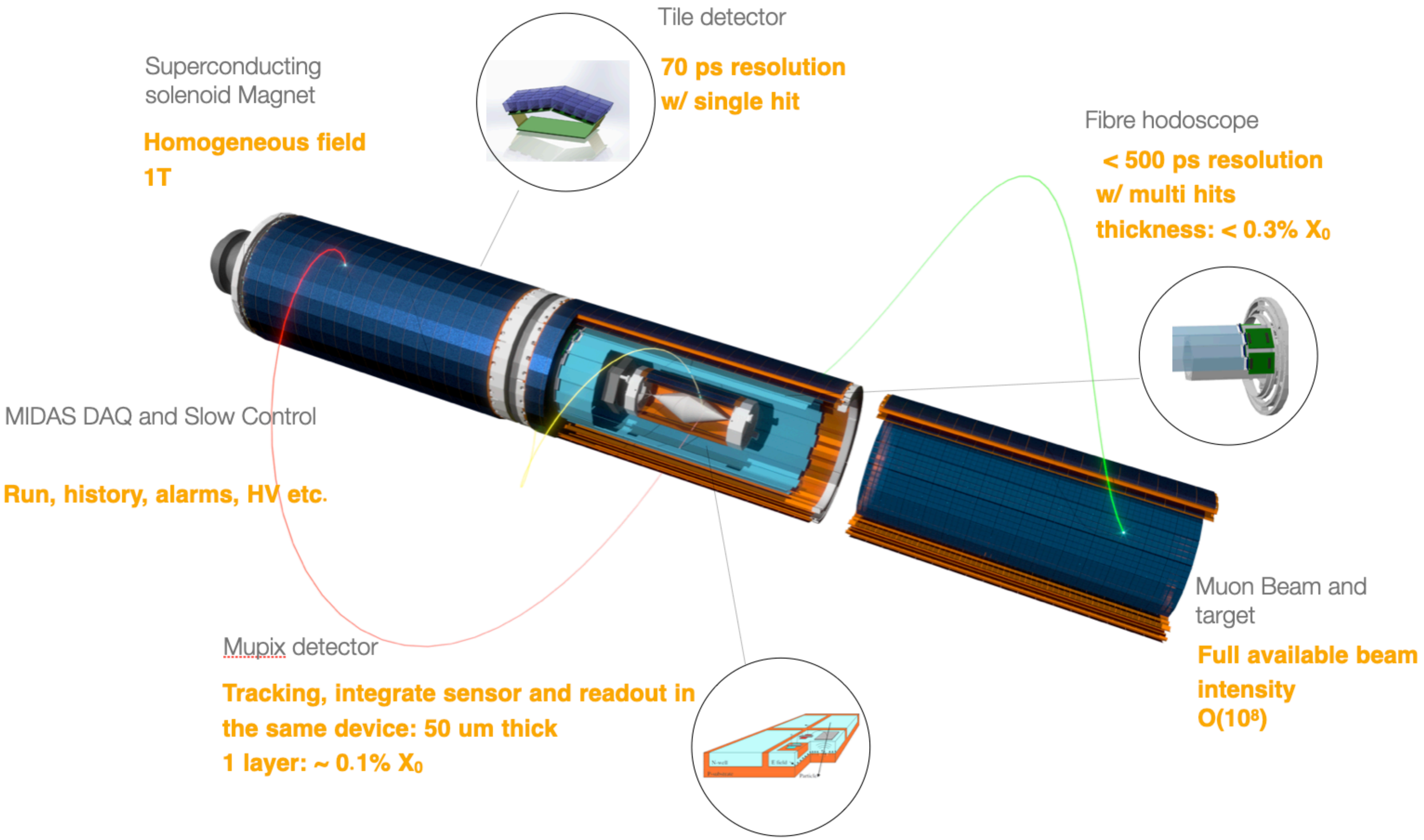
- μ^- production target = stopping target
- SES $\sim 10^{-13}$ (Carbon target, 1 year)

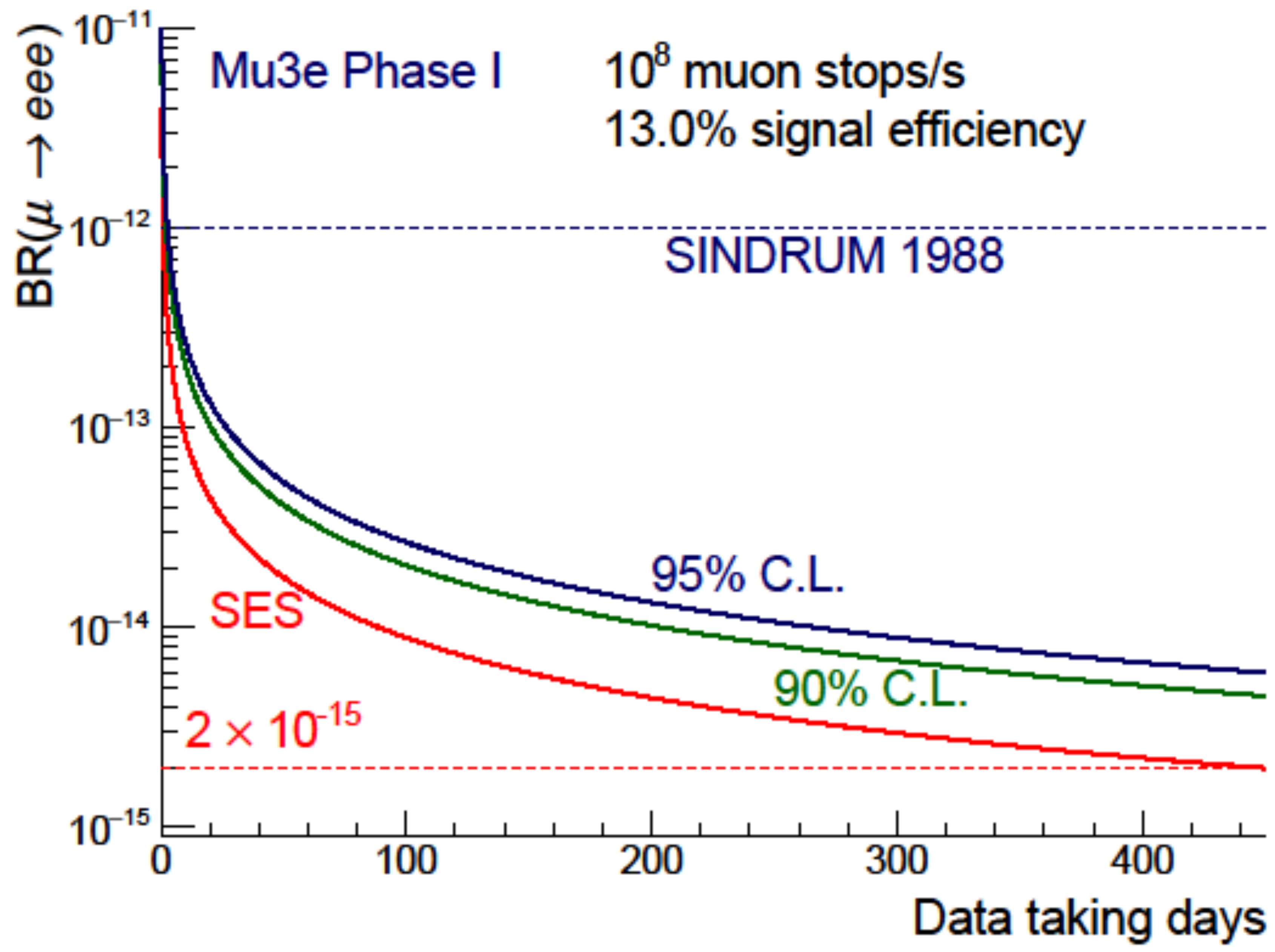
- Detector commissioning in Jun-2022
- Momentum reconstruction successful.
- More beam-time expected later this year (details are not fixed yet).

MU3E

THE MU3E EXPERIMENT

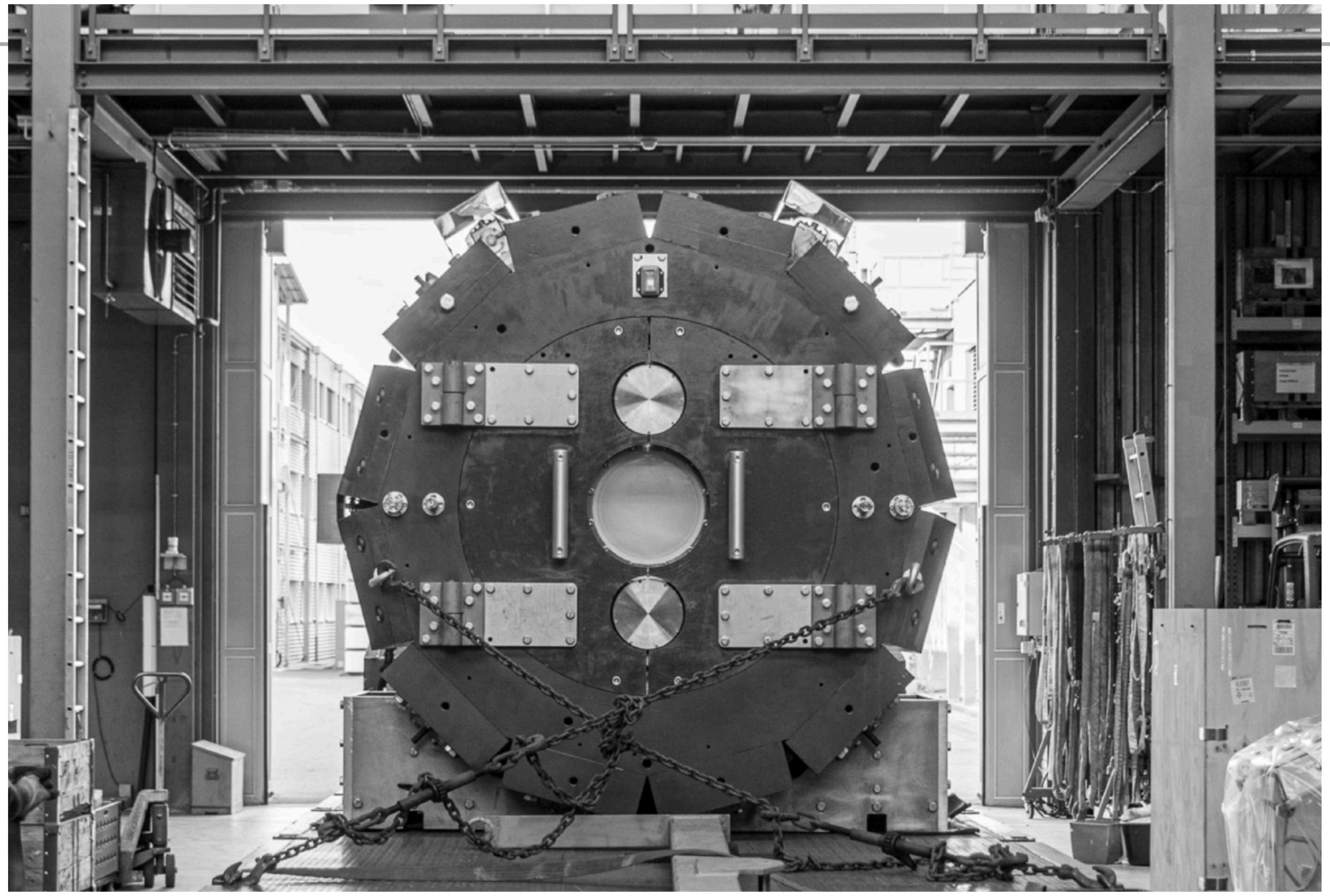
- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit $BR(\mu^+ \to e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)

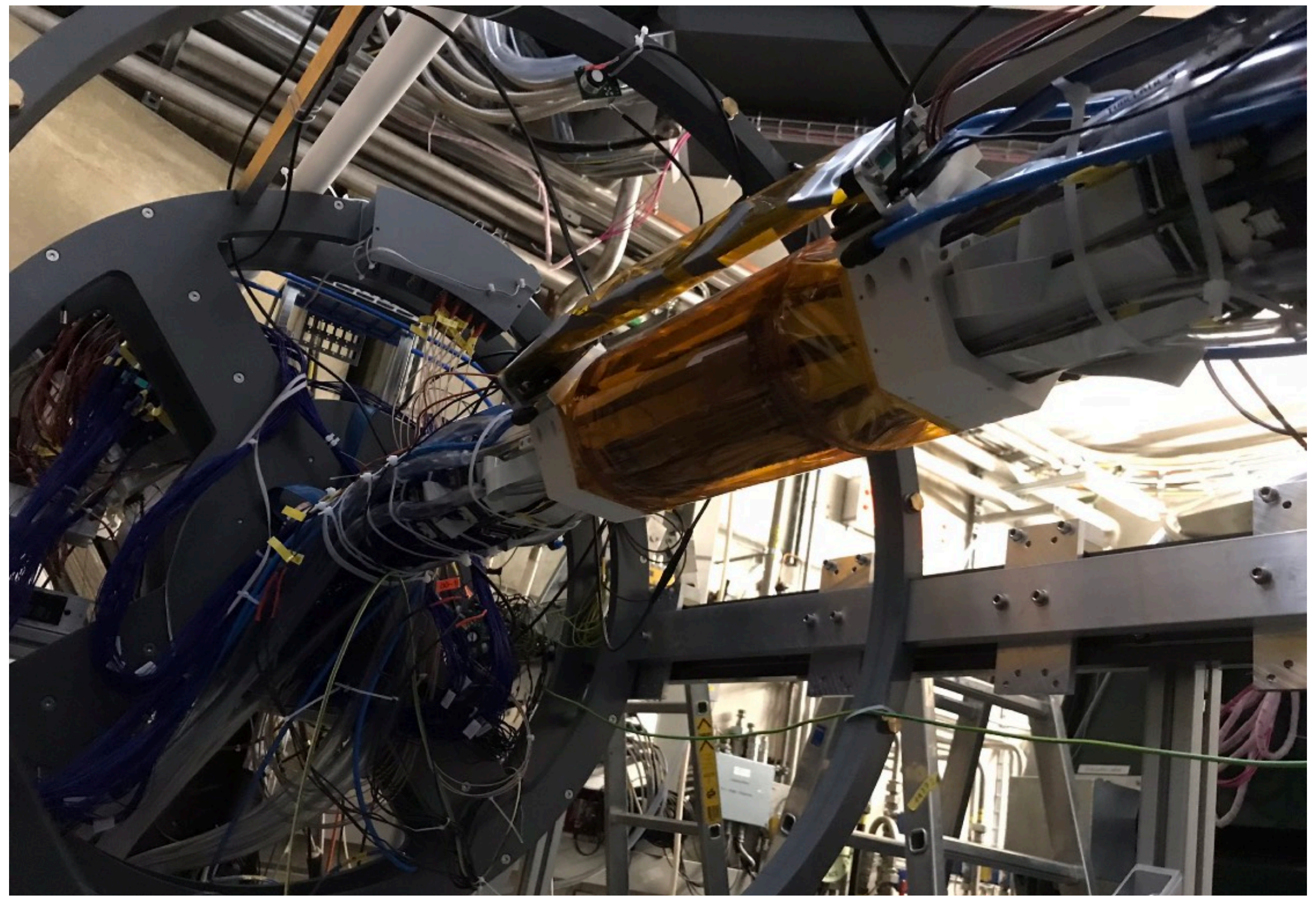




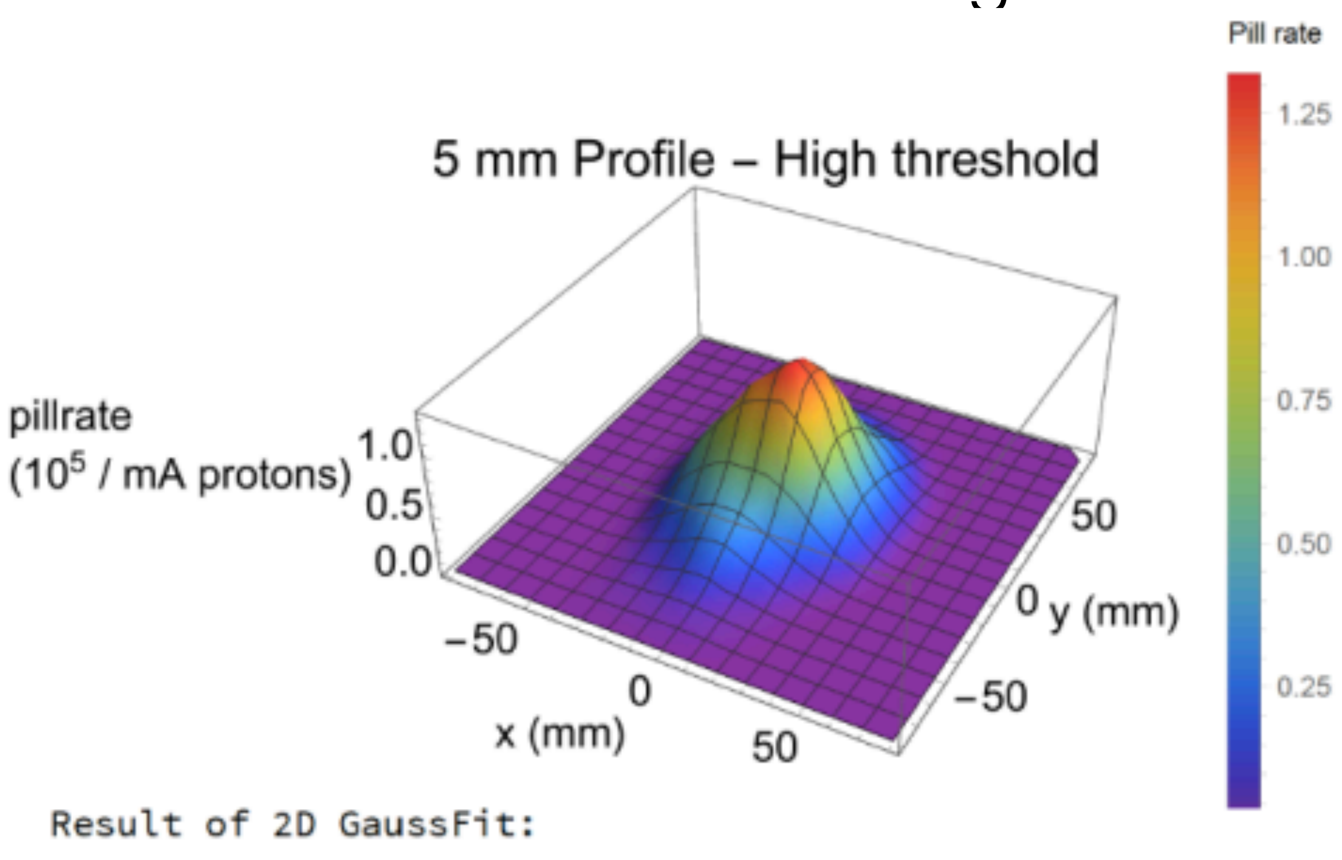
MU3E - LATEST NEWS AND CURRENTS STATUS

- Cosmic Ray Run ongoing outside the experimental area with all sub-detector services
- MuPix mass production: ongoing
- Complete integration run: 2023
- Engineering run: 2024
- First physics run: 2025





Beam commissioning **2022**



$2.49e10^8$ mu/s @2.4 mA

OTHER MUON EXPERIMENT

MUON FACILITY IN CHINA FOR MUONIUM TRANSITION

Basic concept:

The coincidence of **spectrometer**, **MCP**, **and** **calorimeter.**

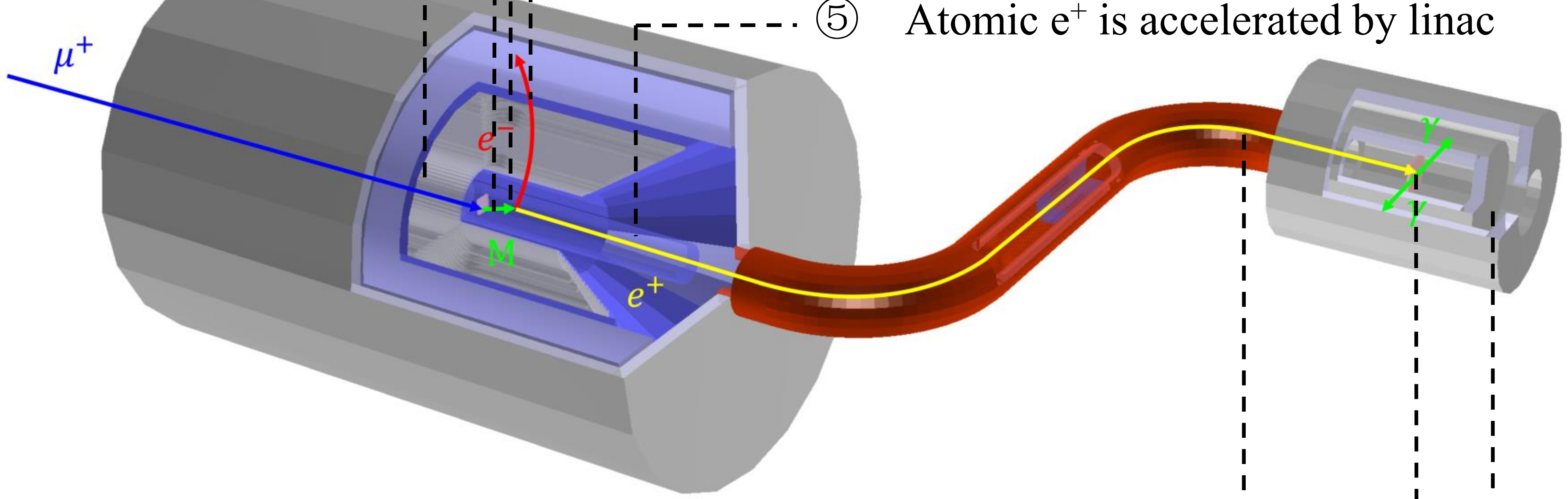
① Surface muon → Muonium

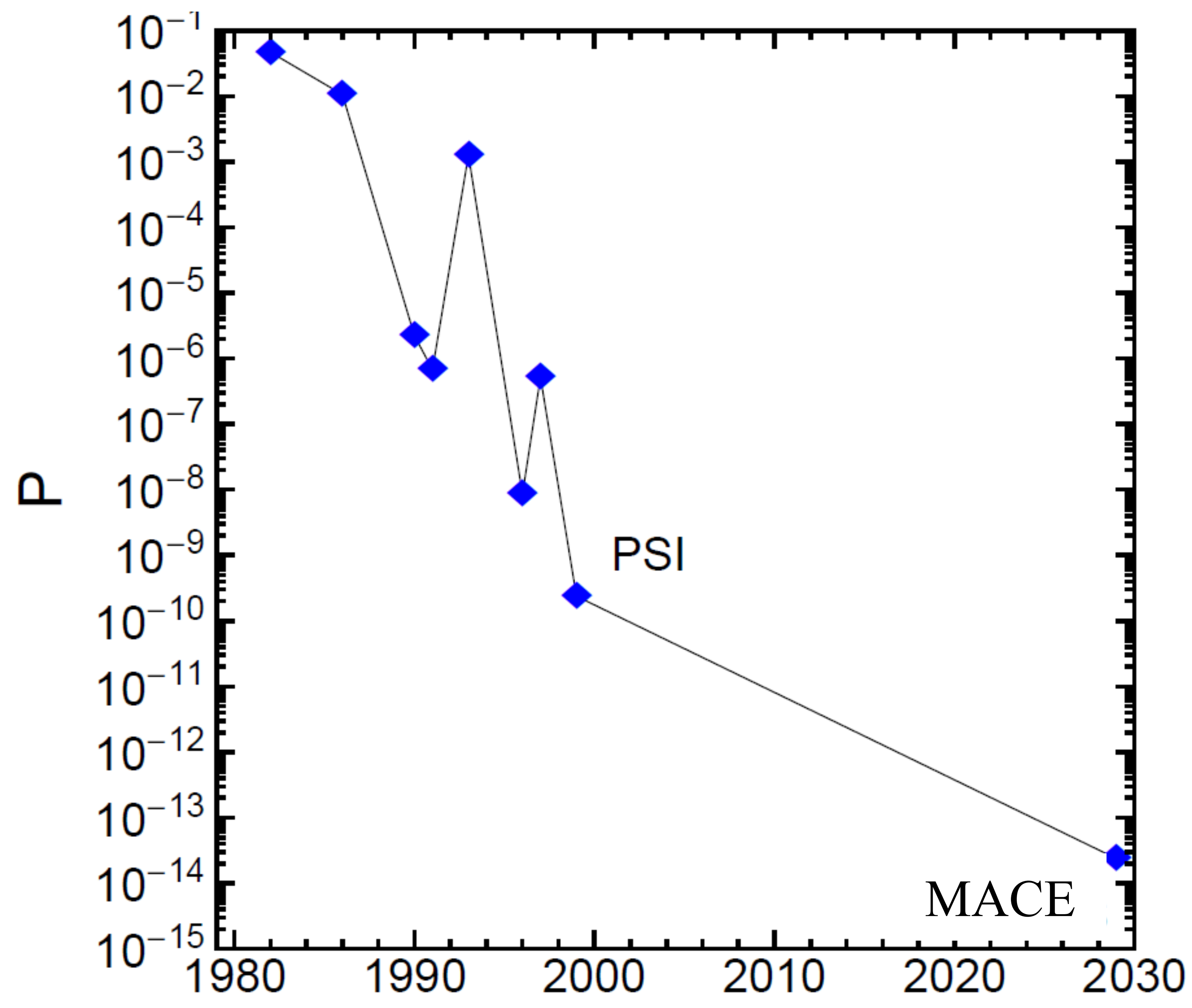
② Muonium emission to vacuum

③ M converts to $\bar{\mathrm{M}}$ and decay

④ Spectrometer detects the Michel e^-

⑤ Atomic e^+ is accelerated by linac



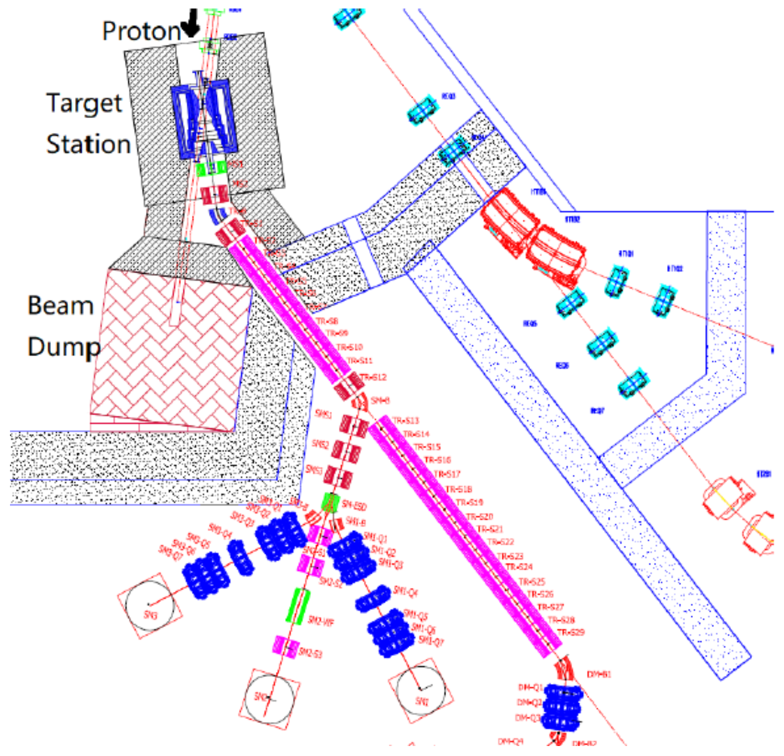


- Spectrometer: identifies Michel e^-.
- Vertex coincidence: Michel e^- track and e^+ transverse position projection.
- Calorimeter: identifies atomic e^+.

⑥ Transport atomic e^+ to MCP

⑦ MCP measure the transverse position

⑧ Calorimeter detect the e^+ annihilation



a proposal to build first muon beam line for physics studies in China (YGA bay area)

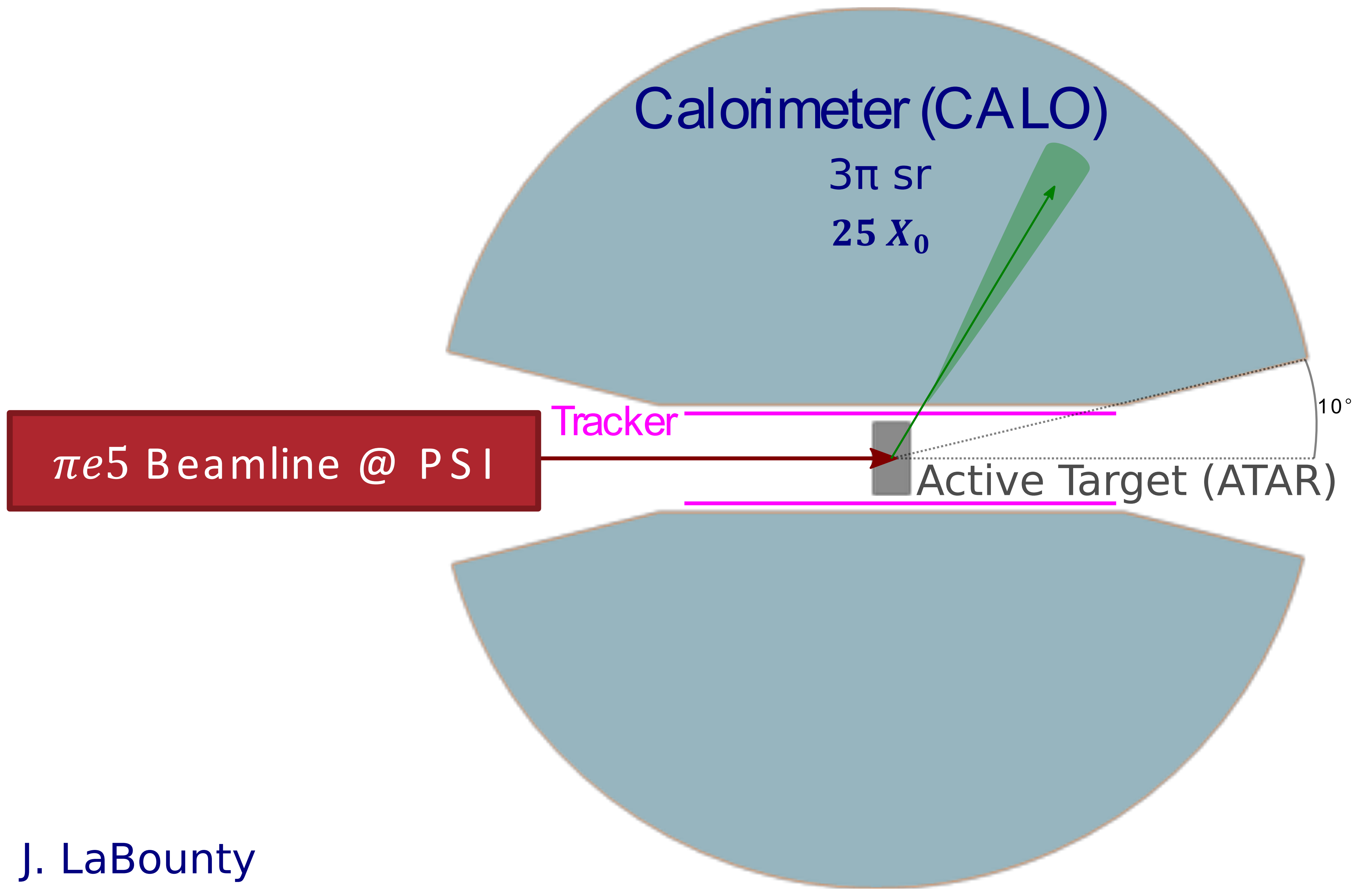
MESON DECAY EXPERIMENTS

PIONEER EXPERIMENT AT PSI

a stringent test of lepton universality

$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

$$= (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad \text{(SM)}$$
$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(exp.)}$$



Goals:

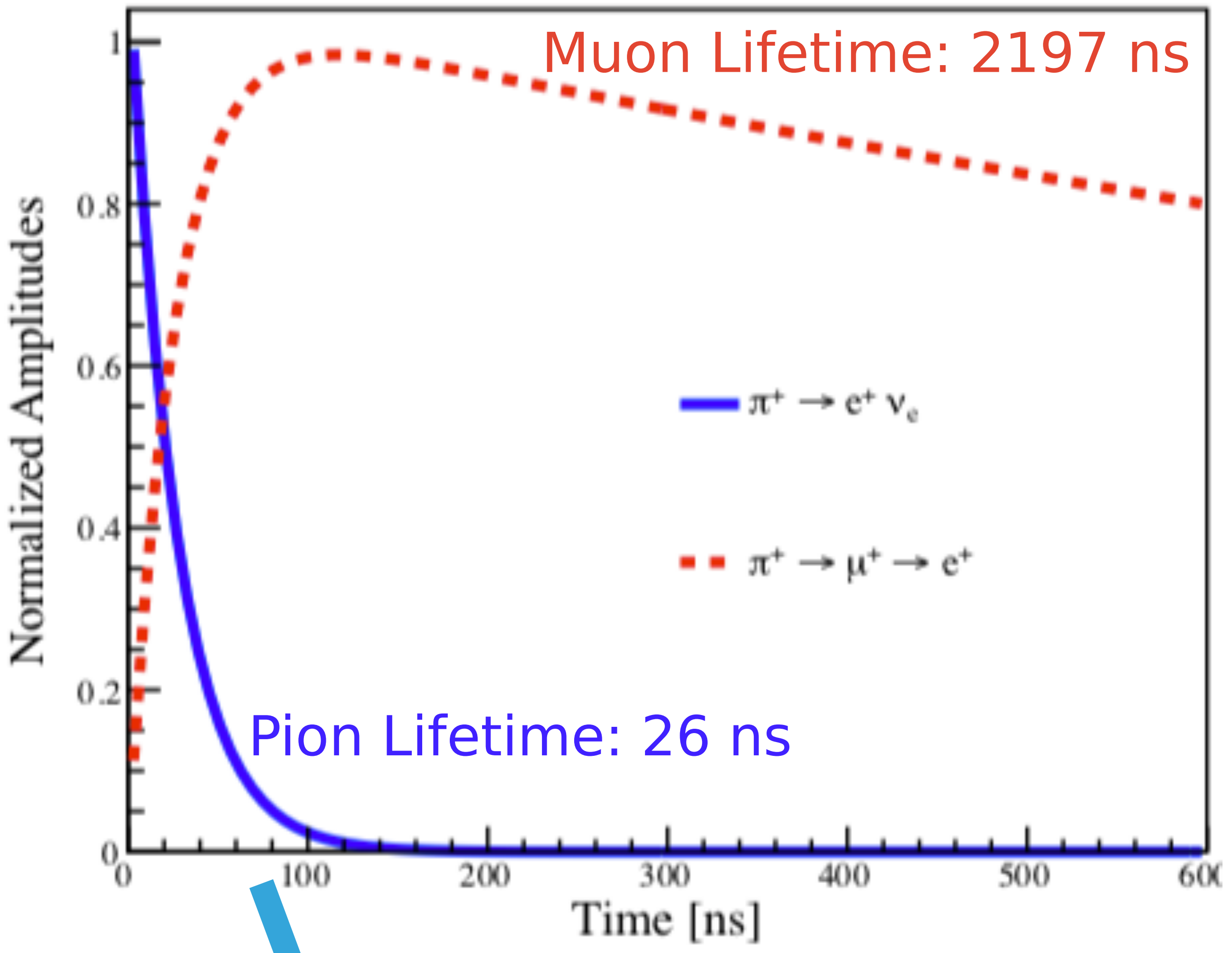
- measure R^{μ} to 0.01 % relative precision (Phase I)
- measure BR($\pi^+ \to \pi^0 e^+ \nu$) to 0.2 % (Phase II)
- measure BR($\pi^+ \to \pi^0 e^+ \nu$) to 0.06 % (Phase III)

Needs high intensity π^+ beam (Phase 1: $3 \times 10^5\,\text{s}^{-1}$, Phases II/III: $2 \times 10^7\,\text{s}^{-1}$)

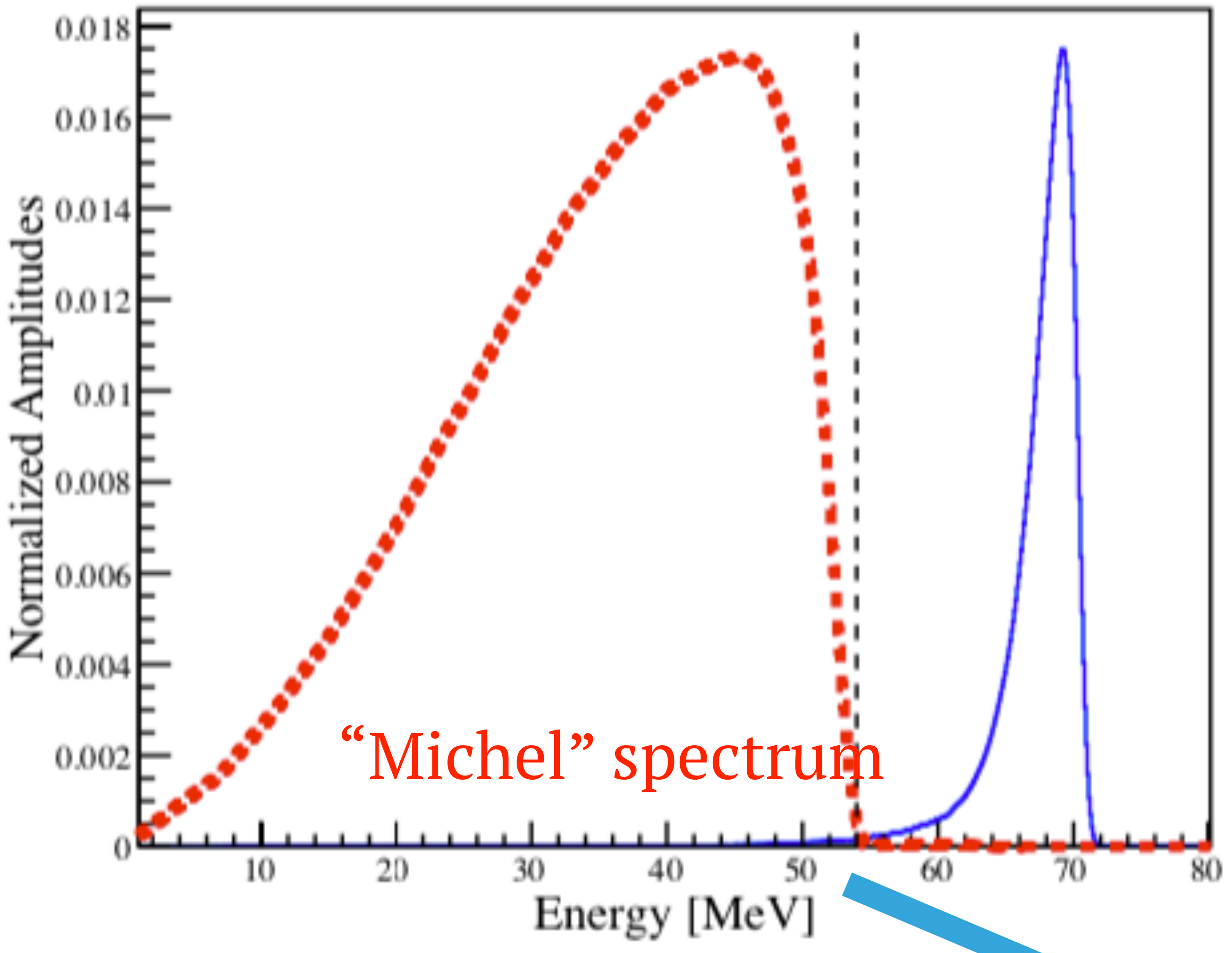
Phase I approved to run at PSI
(Proposal: https://arxiv.org/abs/2203.01981)

PIONEER ESSENTIALS

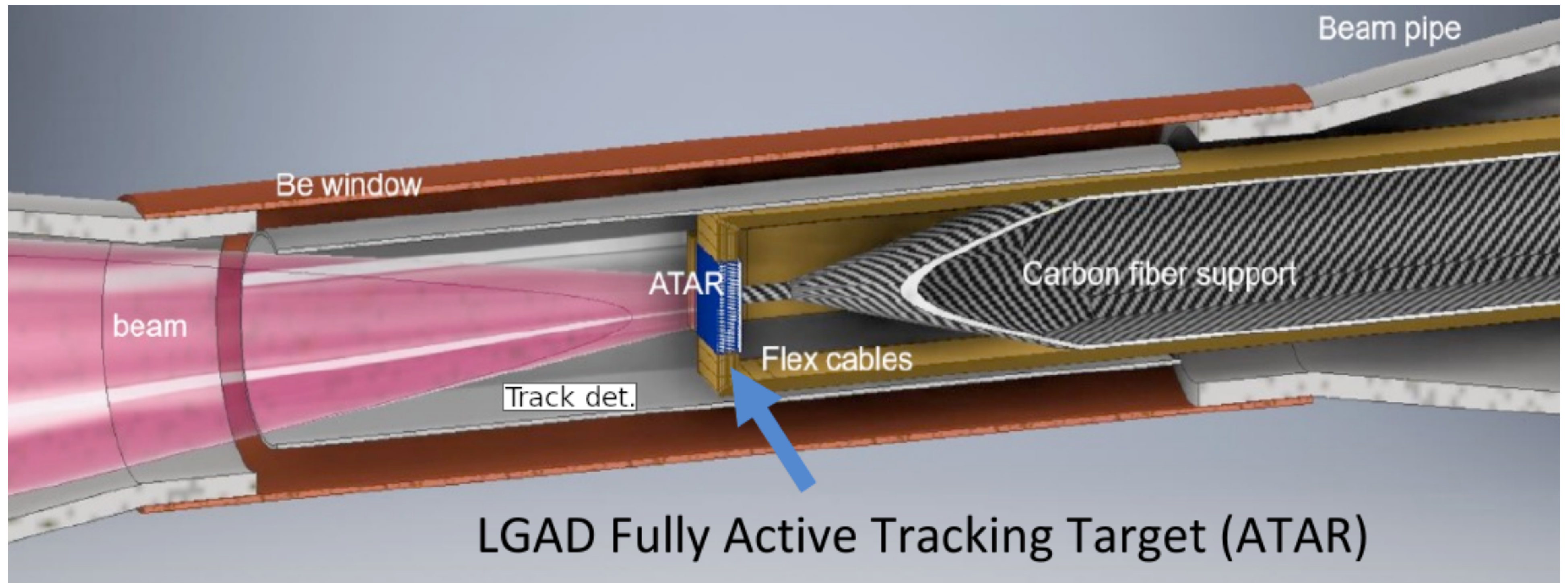
$25X_0$, 3π sr, fast and uniform, high precision calorimeter

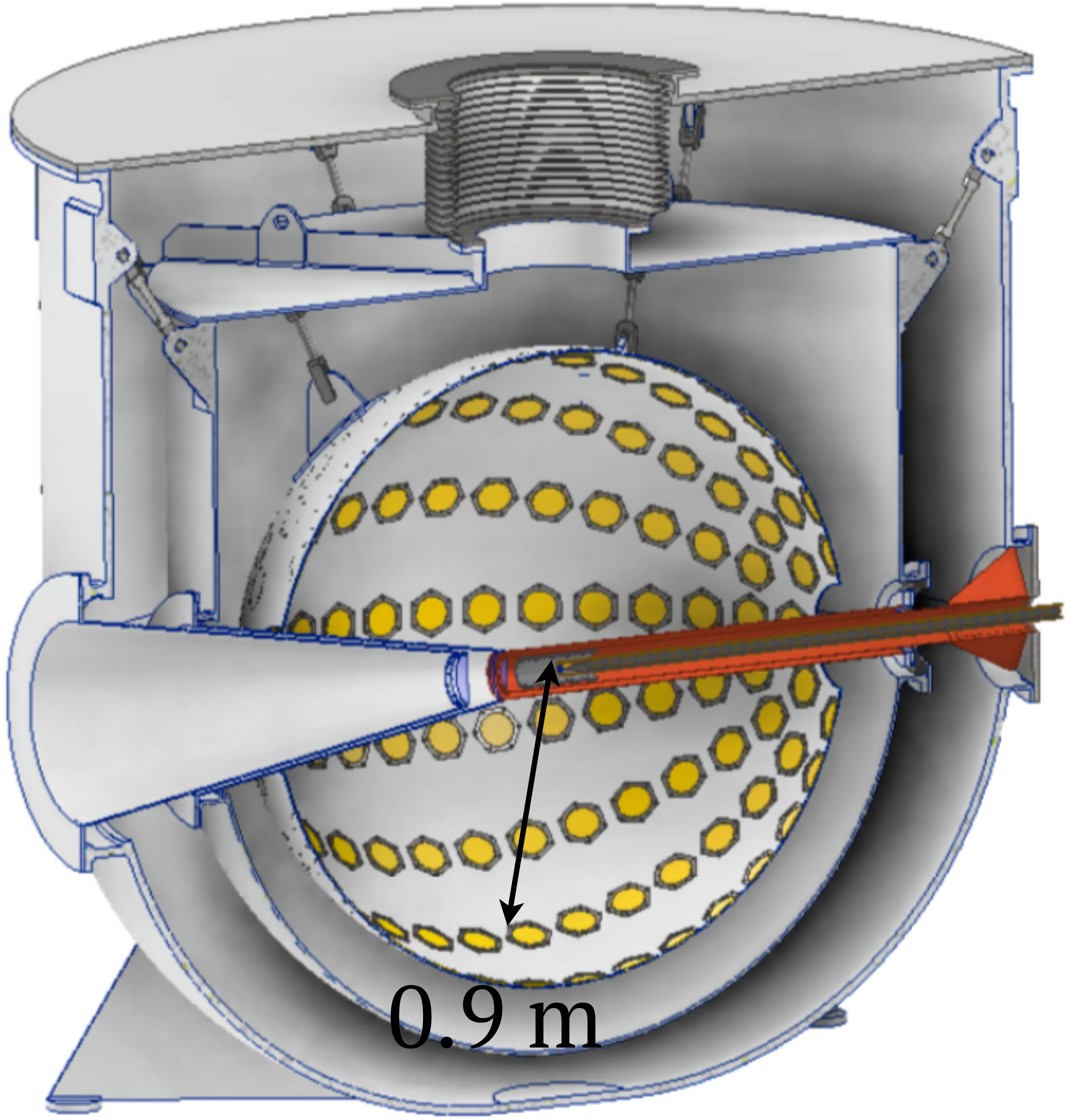


Time spectrum



e^+ energy spectrum





liquid xenon

NA62 SEARCH FOR LEPTON FLAVOUR VIOLATION

Decay mode	Previous UL on BR (90% CL)	NA62 UL on BR (90% CL)	improvement
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	Factor of 2 (partial dataset)
$K^+ \rightarrow \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	Factor of 12
$K^+ \rightarrow \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	Factor of 12
$K^+ \rightarrow \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	Factor of 8
$\pi^0 \rightarrow \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	Factor of 13
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	-	8.5×10^{-10}	First search
$K^+ \rightarrow \mu^- \nu e^+ e^+$	2.1×10^{-8}	8.1×10^{-11}	Factor of 250

ECN3 hall at CERN

CONCLUSION

- A significant progress (discoveries!) is foreseen in the coming decade.
  - All muon CLFV experiments are scheduled to take data.
  - Essential to <u>search all muon CLFV processes</u> for identification of new physics.
  - The MEG experiment takes the lead by starting physics run this week.
- Upgrades of muon production facilities (HIMB@PSI, PIP-II@FNAL) will keep the momentum going further into the future.
  - Higher-sensitivity experiments to measure <u>angular distributions</u> of $\mu \to e\gamma$ and $\mu \to 3e$, and <u>atom-dependence</u> of $\mu N \to eN$ are indispensable to untangle new physics after discovery.
- Highly sensitive CLF studies are planned for pion and kaon decays.