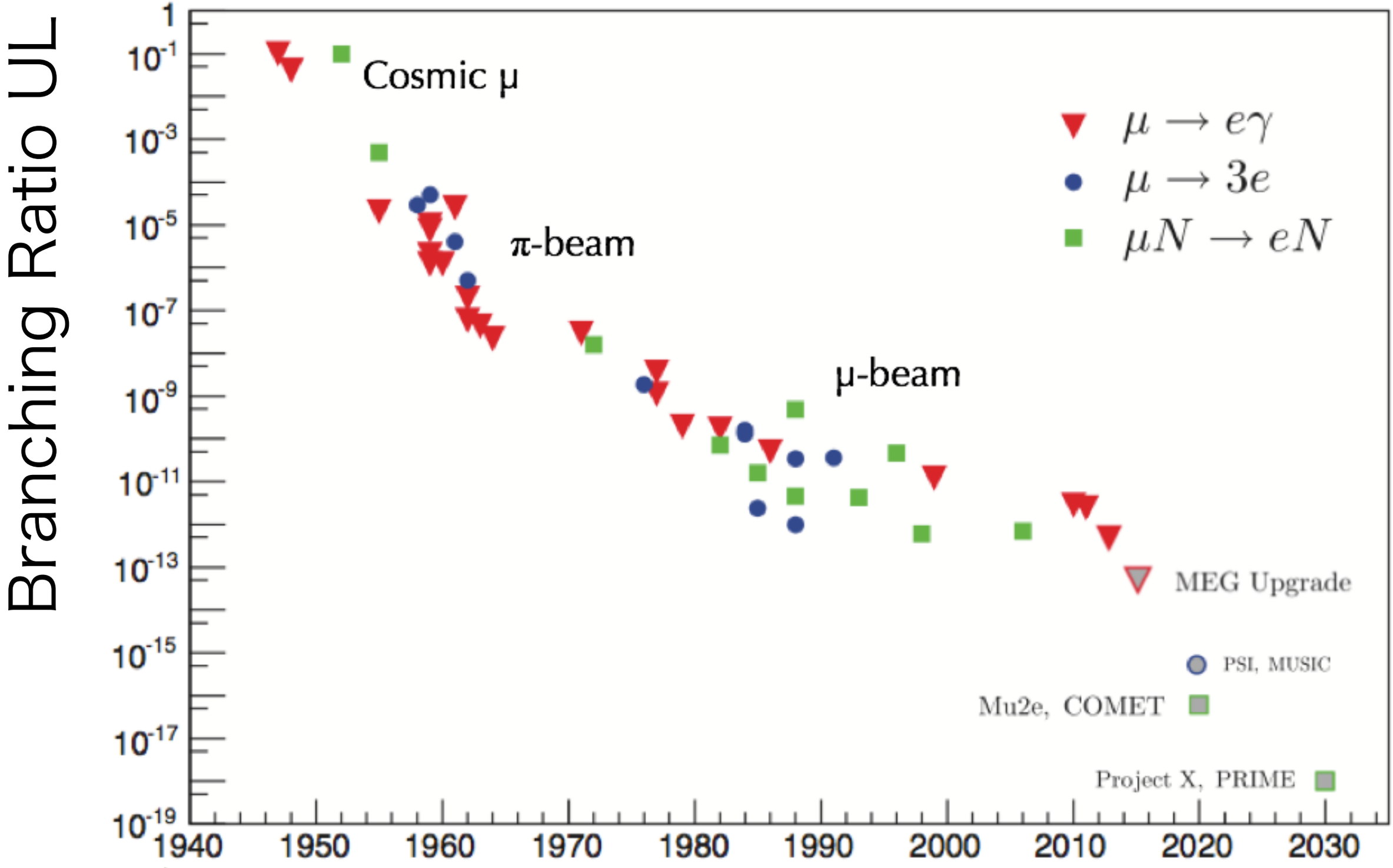
COMET/Mu2e/MEG

Satoshi MIHARA
(KEK-IPNS/J-PARC/Sokendai)

Outline

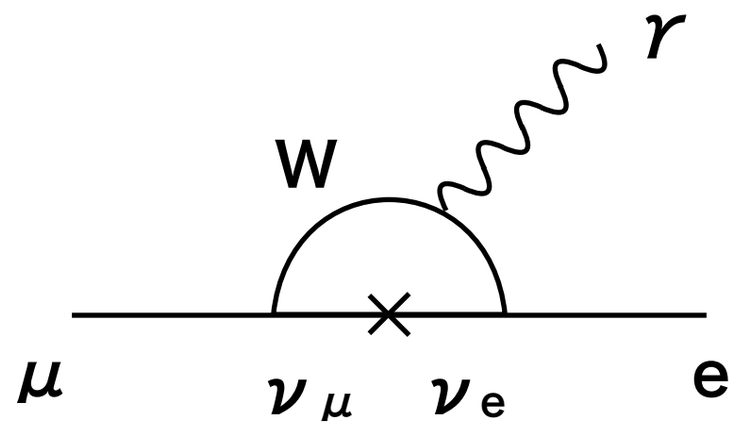
- Introduction
- Muon cLFV experiments
  - MEG & MEG II, COMET, Mu2e
- Summary and Outlook



Bernstein & Cooper

Charged Lepton Flavor Violation

- cLFV rate in the Standard Model with non-zero neutrino mass is too small to be observed in experiments; O(BR) < 10^{-50}



  - No SM Physics Background
    - Observation = clear evidence of NP

- Motivated by many kinds of new physics models BSM

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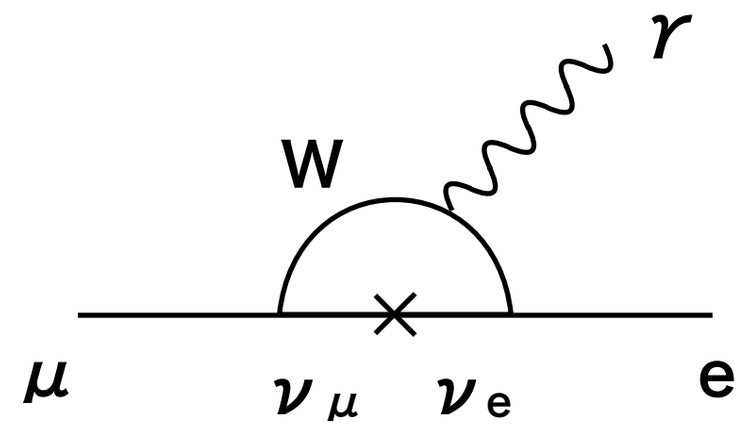

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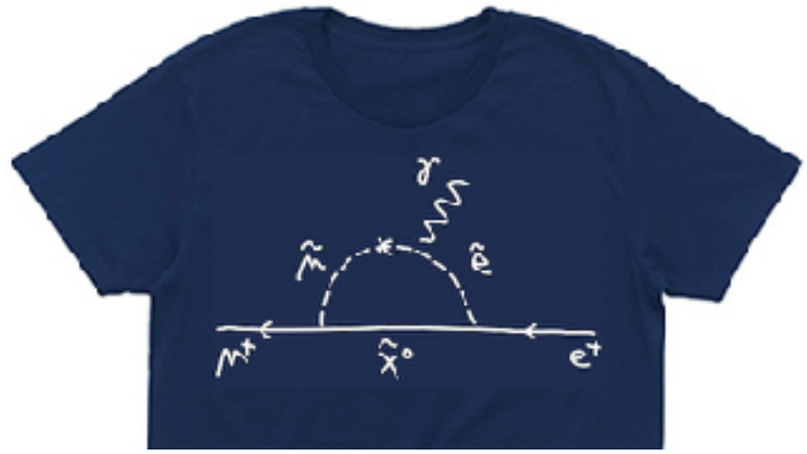

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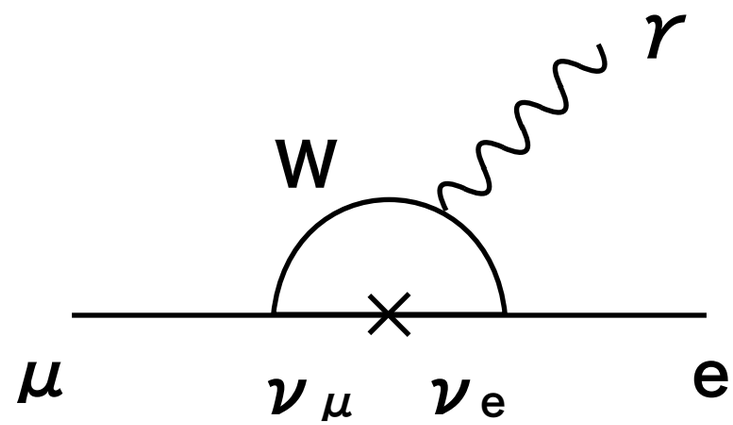

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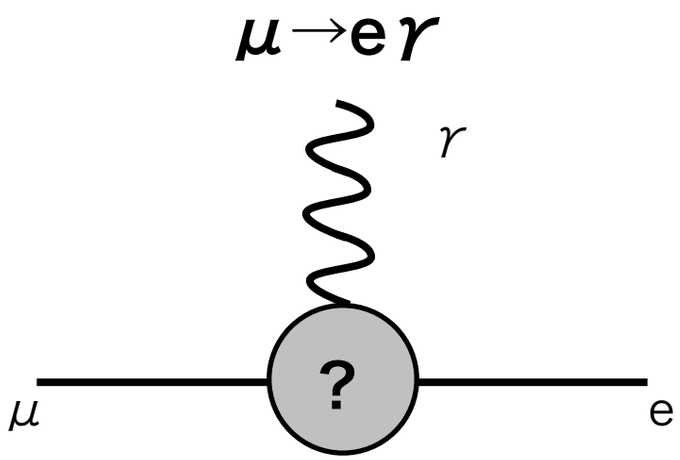

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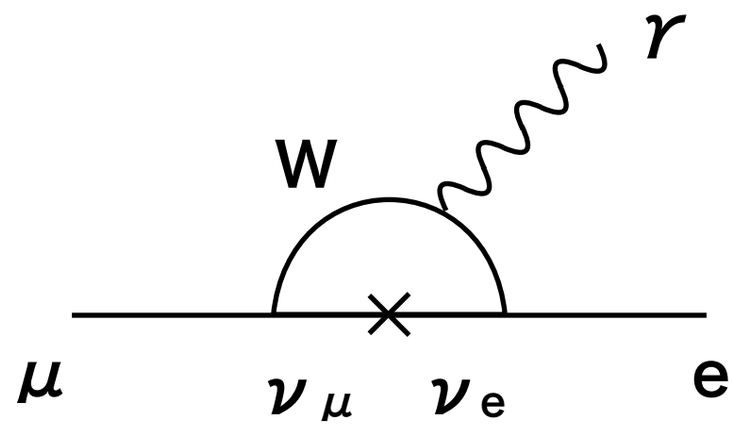

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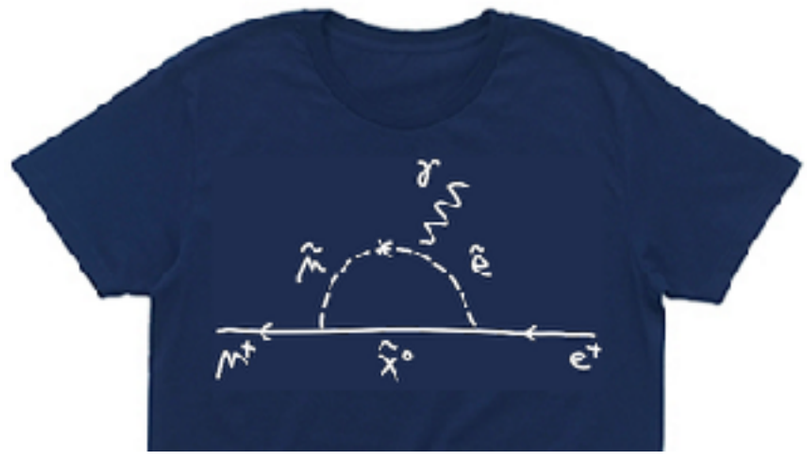

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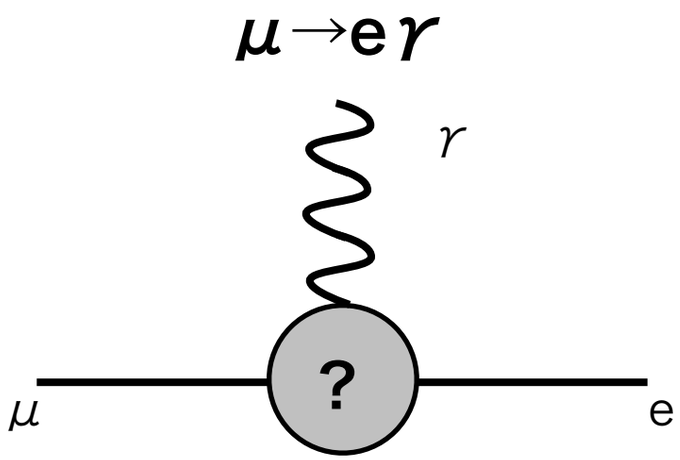

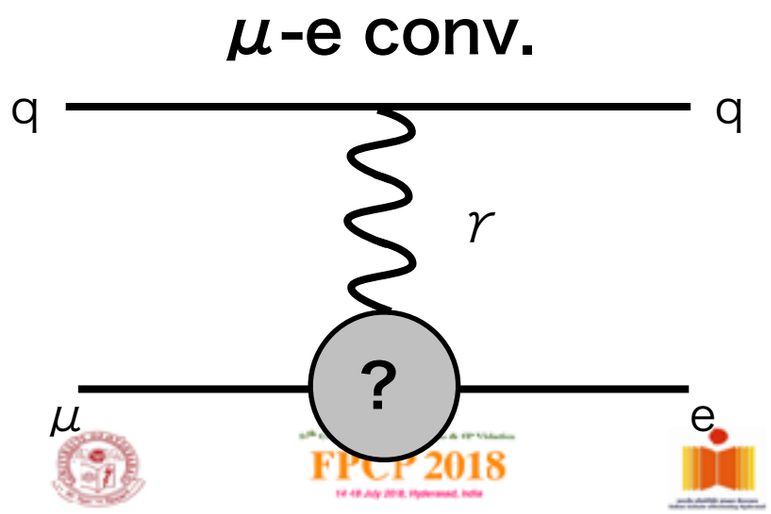

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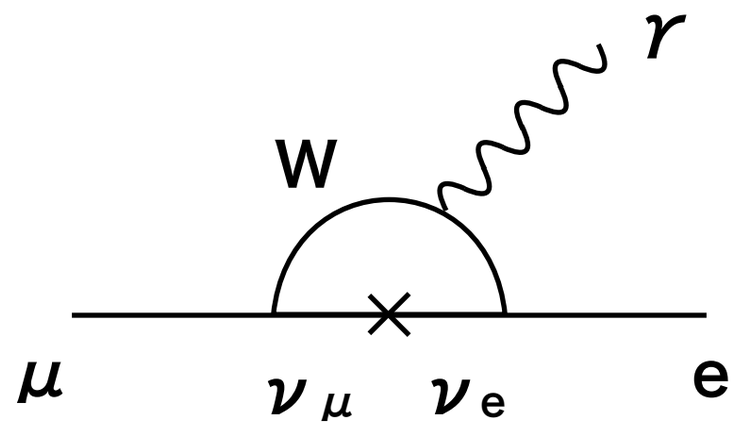

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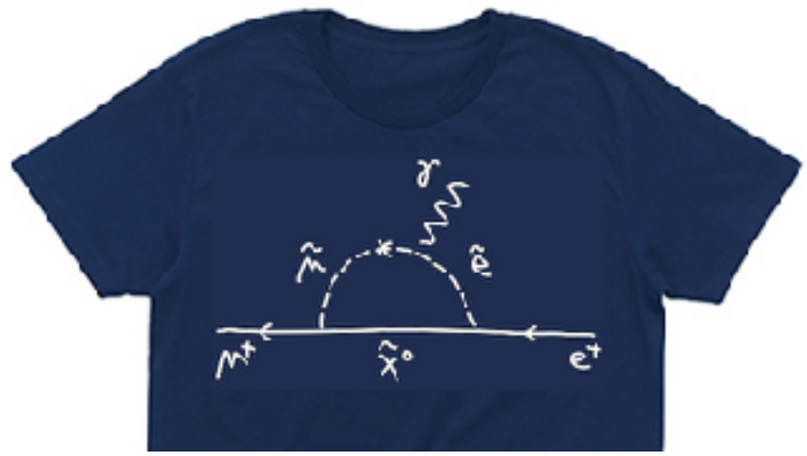

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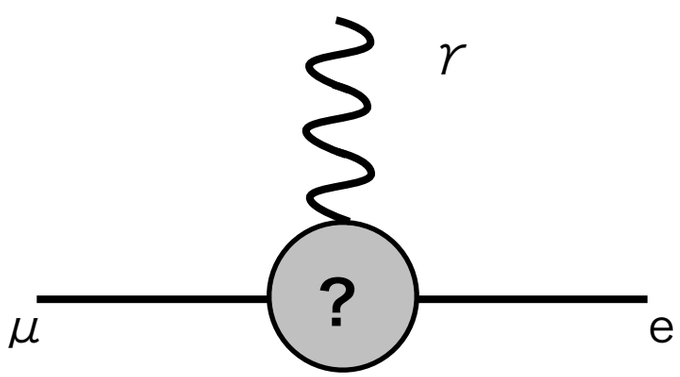
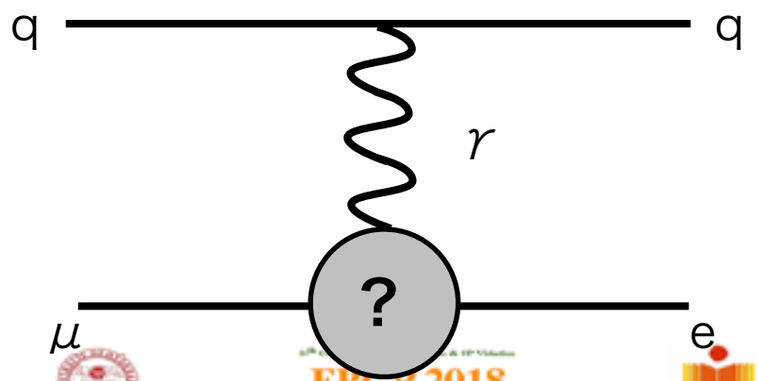
μ→eγ



μ-e conv.



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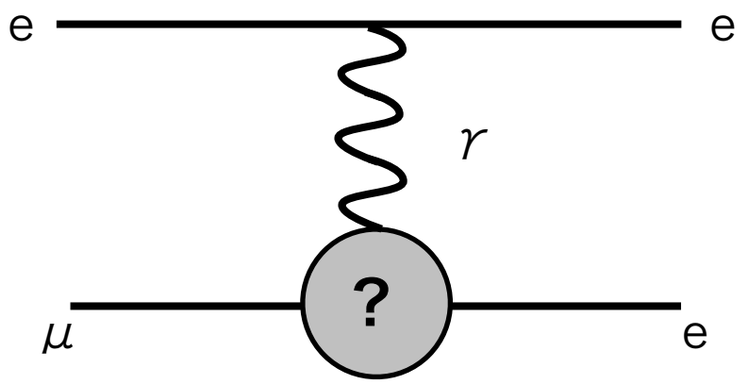

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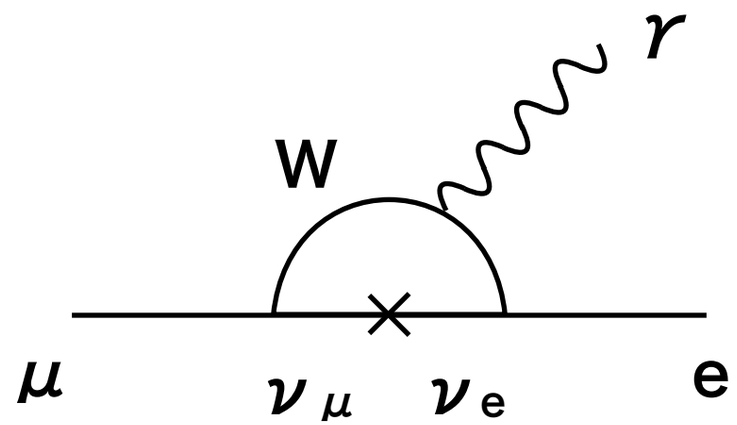

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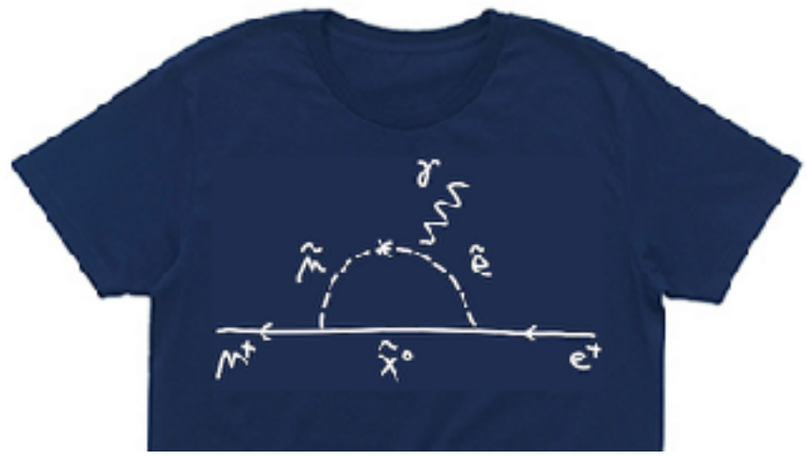

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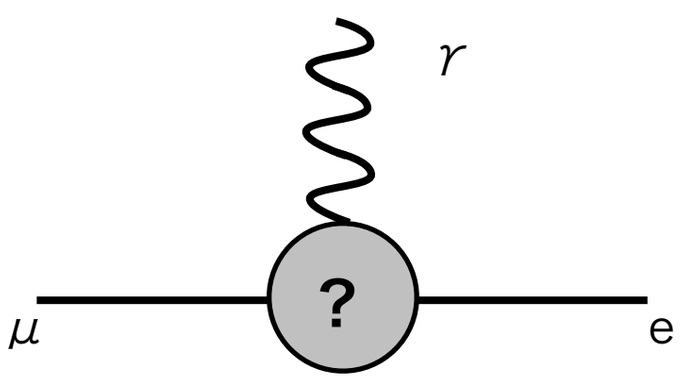

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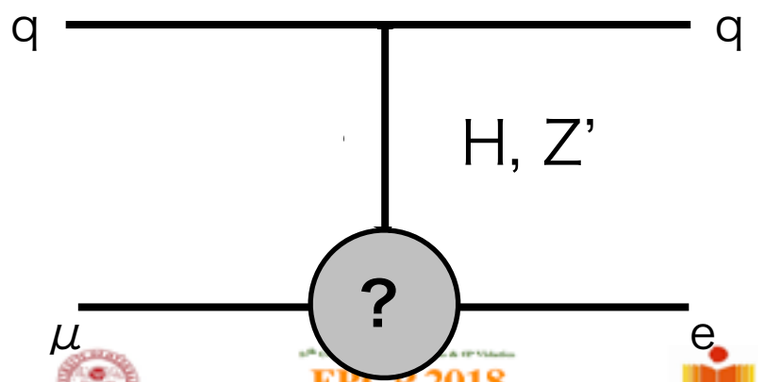

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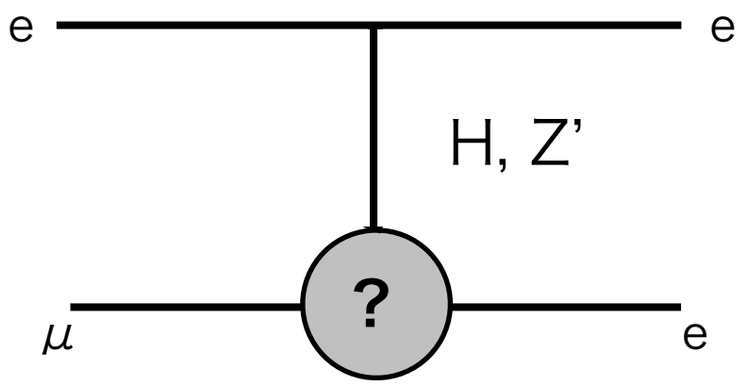

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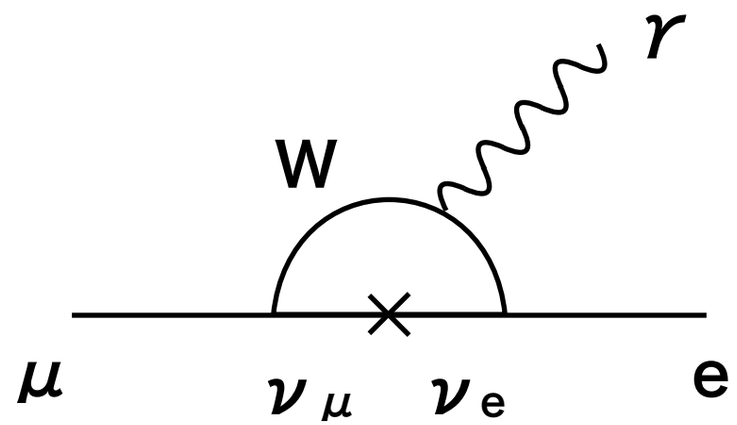

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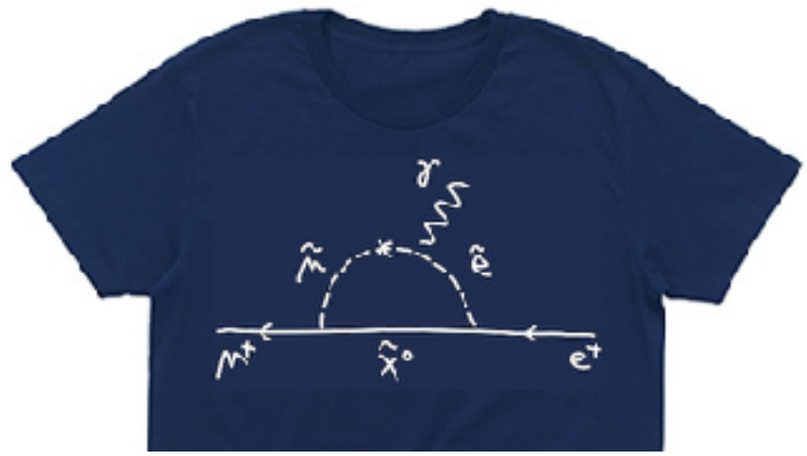

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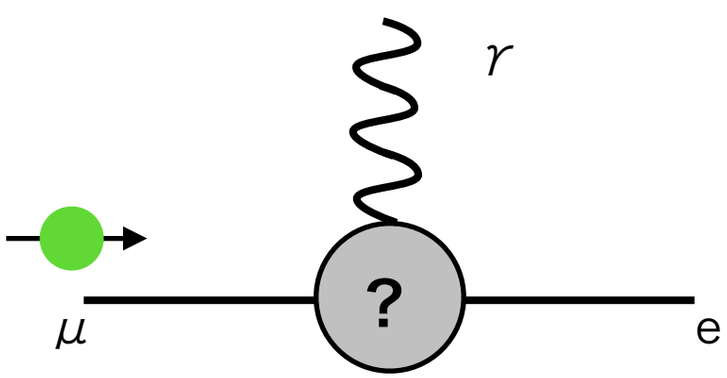

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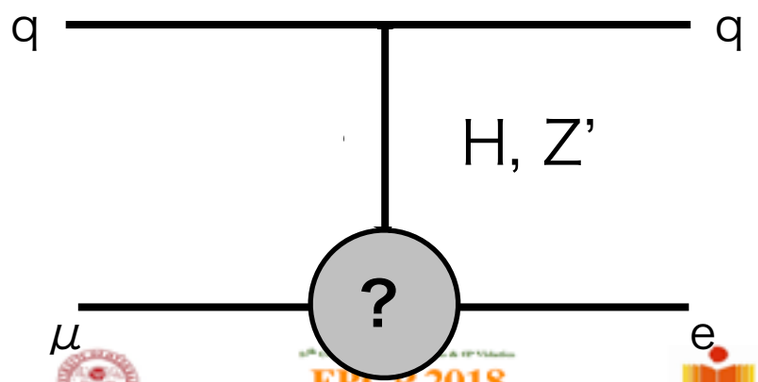

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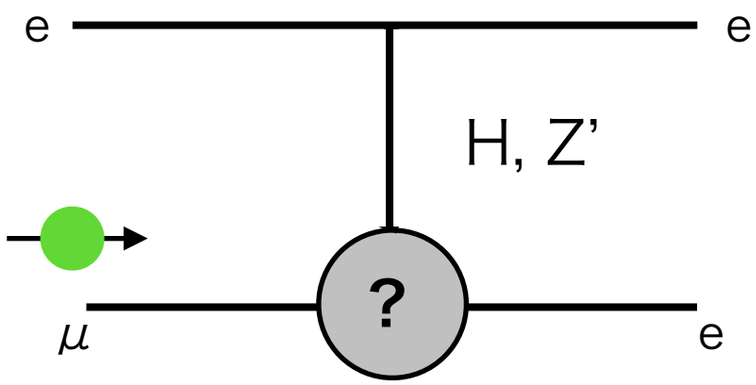
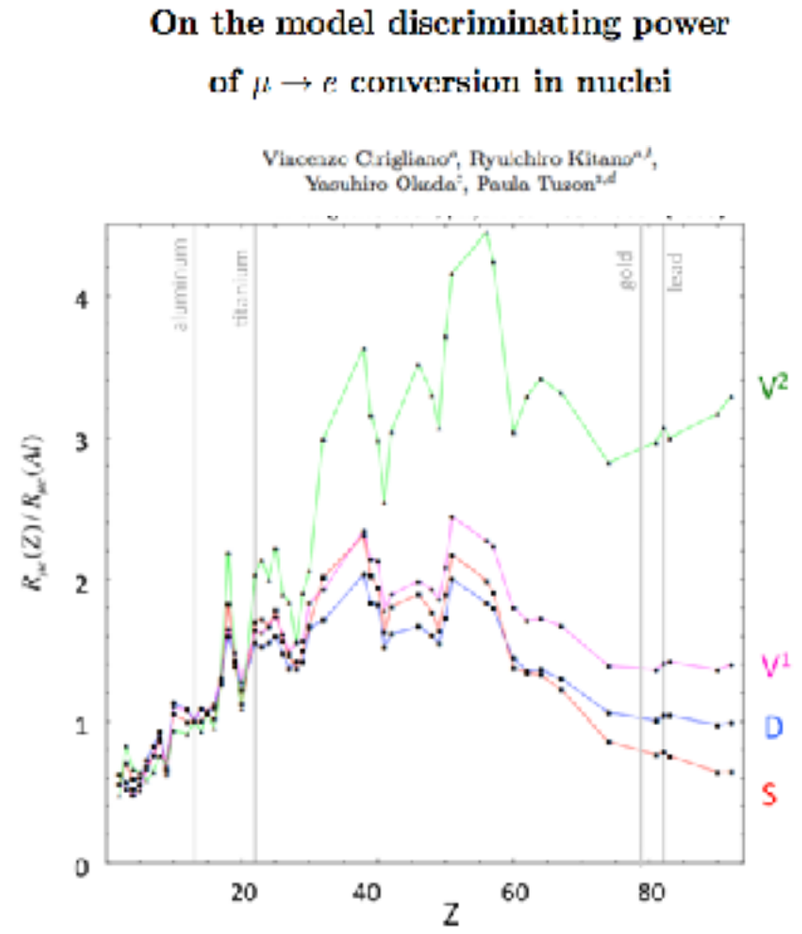


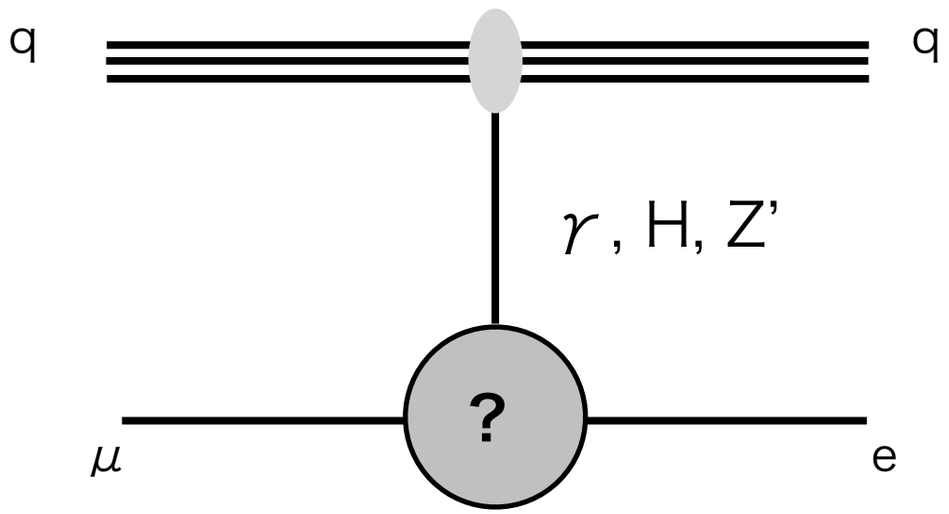
Muon Capture Target Dependence

- Atomic number dependence of the event rate will provide precious information on the type of the force

  - COMET & Mu2e: Al (& Ti in future? & Pb in far future ??)

  - DeeMe: C (& Si)





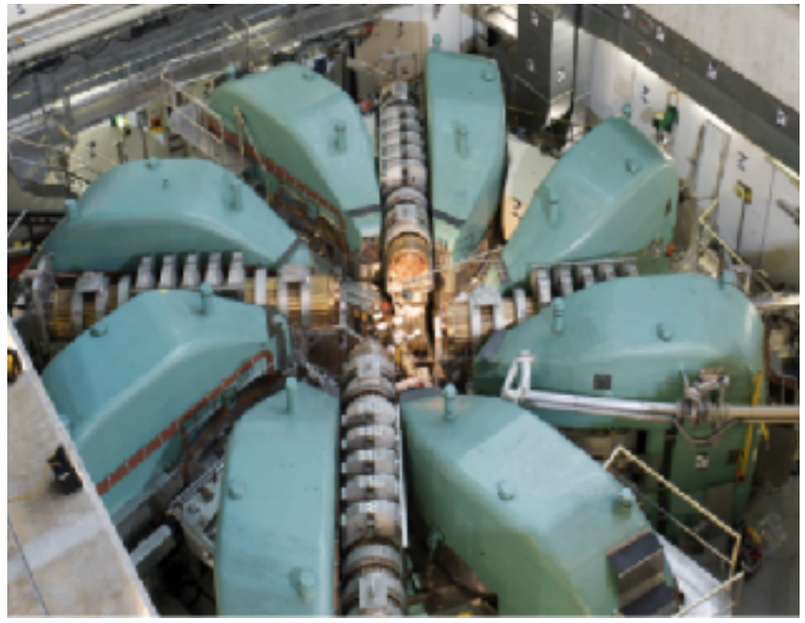
	Al	Ti
lifetime	864 ns	330 ns
time window	0.3	0.2
signal	1	1.5
net	0.3	0.3

MEG & MEG II

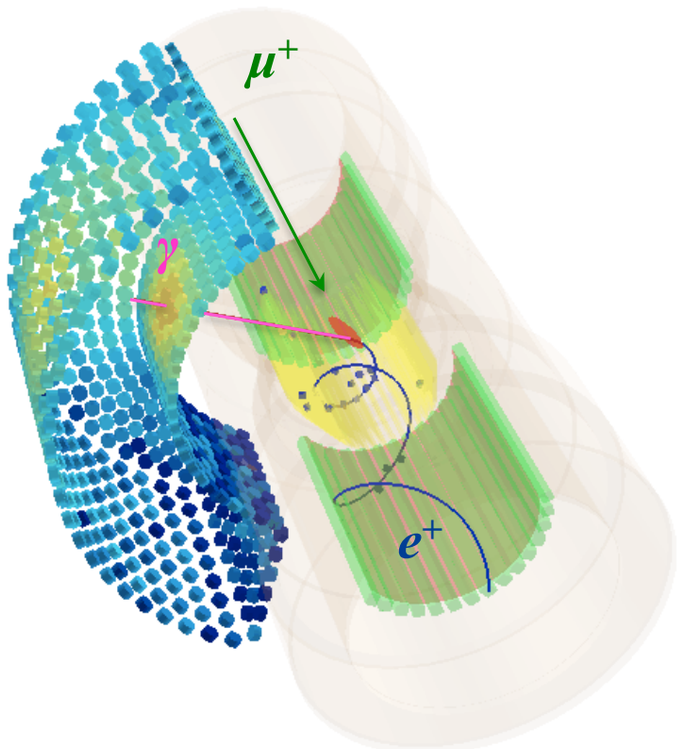
FPCP 2018

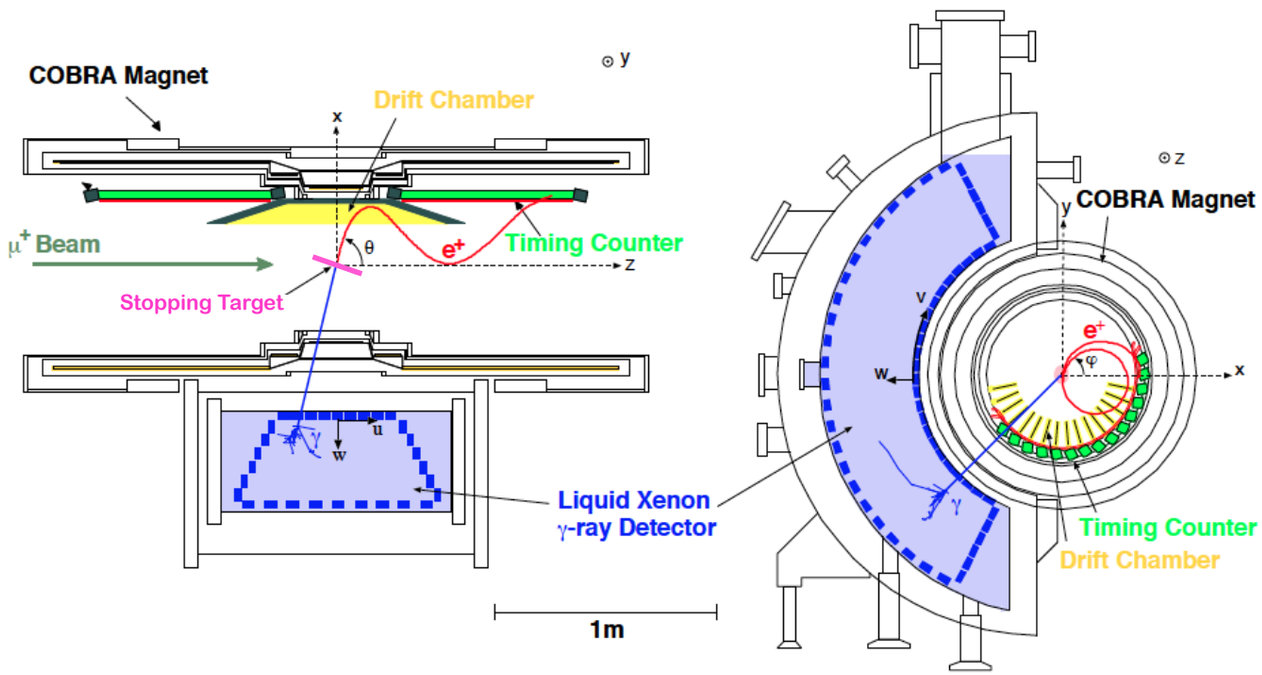
Search for $\mu^+ \to e^+ \gamma$ at Paul Scherrer Institute

- World's most intense DC muon beam at PSI
- MEG, MEG II (and Mu3e) require
  - Low momentum (surface muon at 29MeV/c)
  - High intensity continuous beam as they observe multi-particles in the final state



PSI Ring Cyclotron
590MeV, 1.4MW





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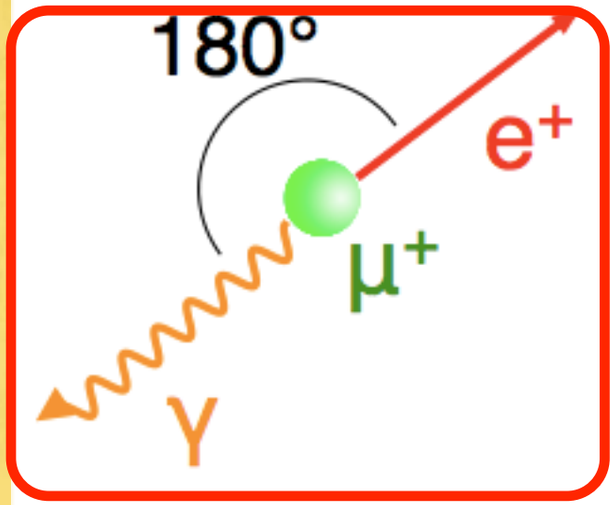
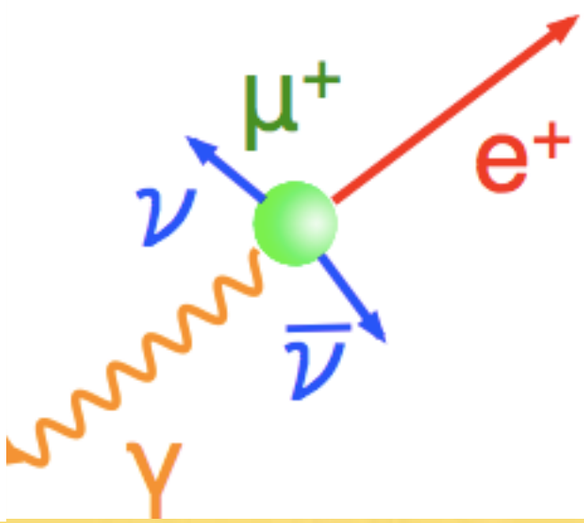
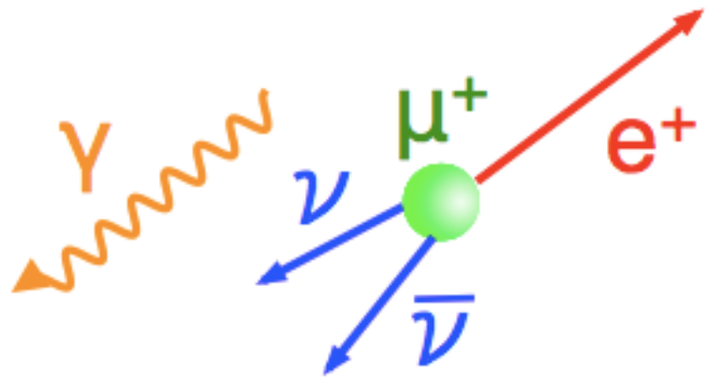
Search for $\mu^+ \to e^+ \gamma$ at Paul Scherrer Institute





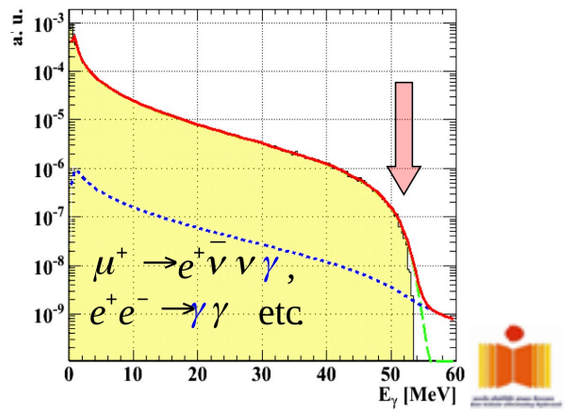


Signal

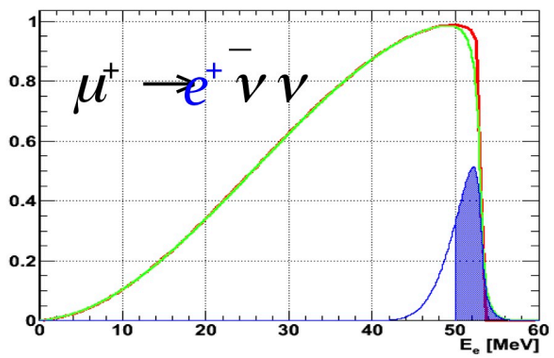
- Eγ = Ee+ = 52.8 MeV
- Back to back
- time coincidence

Background

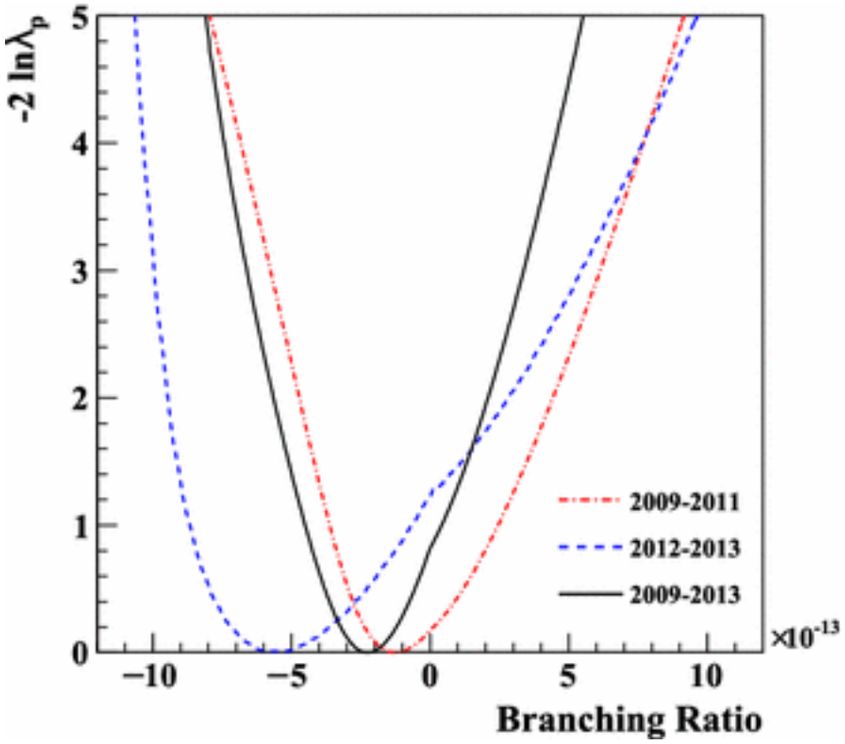
- Radiative muon decay
- Eγ, Ee+ < 52.8 MeV
  - any angle
  - time coincidence

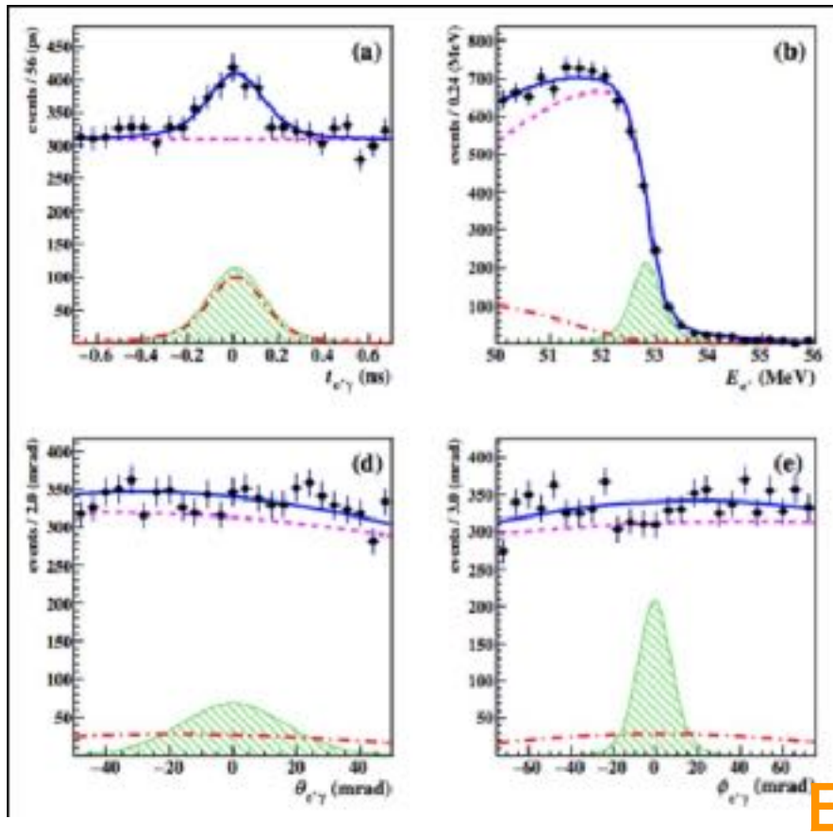


- Accidental
- Eγ, Ee+ < 52.8 MeV
  - any angle
  - flat in time



MEG Result





N_R = 663 ± 59

N_A = 7684 ± 103

No Significant Excess of the Signal

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- Confidence interval calculation by following the Feldman-Cousins approach with the profile-likelihood ratio ordering.

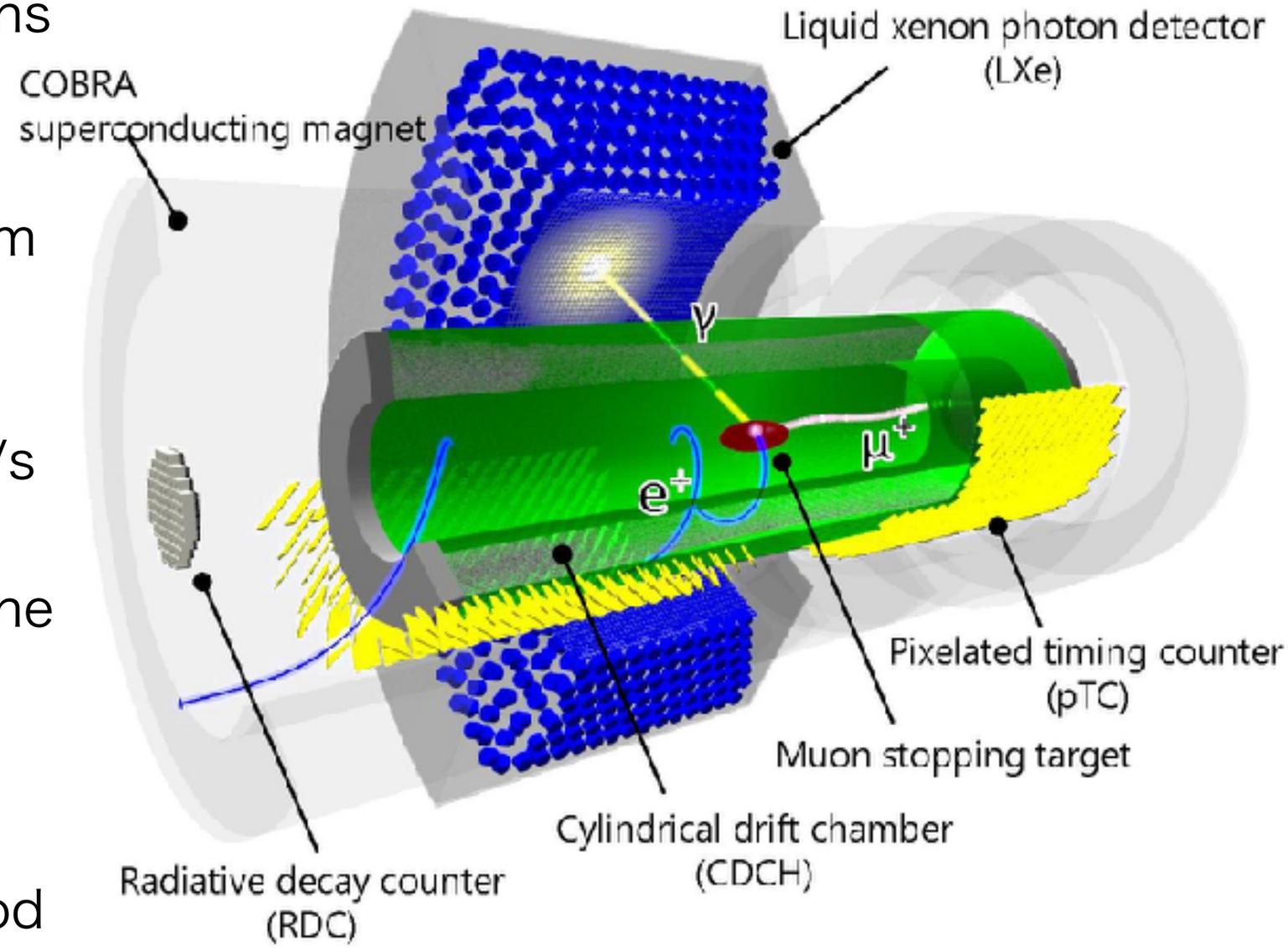
- Profile-likelihood ratios all consistent with a null-signal hypothesis.

$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13} \text{ @ 90\% C.L.}$$

FPCP 2018

Detector Upgrade: MEG II

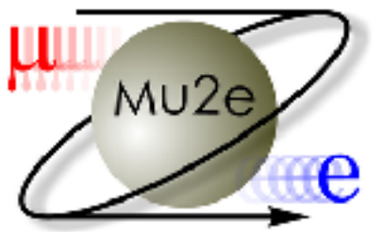
- Twice better resolutions in all components
- Double the muon beam rate
  - 7×10^7 muon stops/s
- New detector to tag the radiative muon decay event
- New calibration method



Target Sensitivity : 6×10^{-14} in 3 years running

COMET & Mu2e

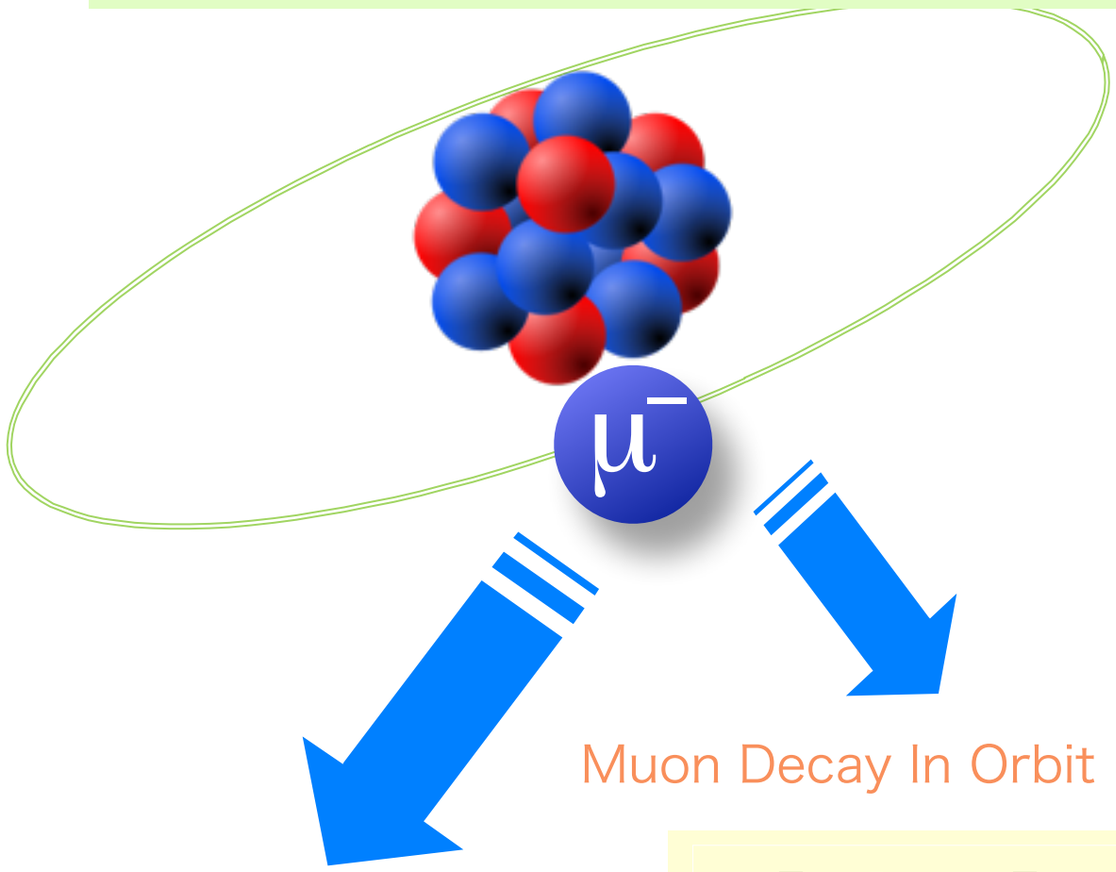
μ-e conversion searches



μ-e Conversion Search

μ-e conversion

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$



- **Atomic capture of μ^-**
  - Decay in orbit (DIO)
    - electron gets recoil energy
  - Capture by nucleus
    - resultant nucleus is different

$\tau_{\mu}^{N} < \tau_{\mu}^{free}$ (τ_{μ}^{Al} = 860 nsec)

Muon Decay In Orbit (39%)

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture (61%)

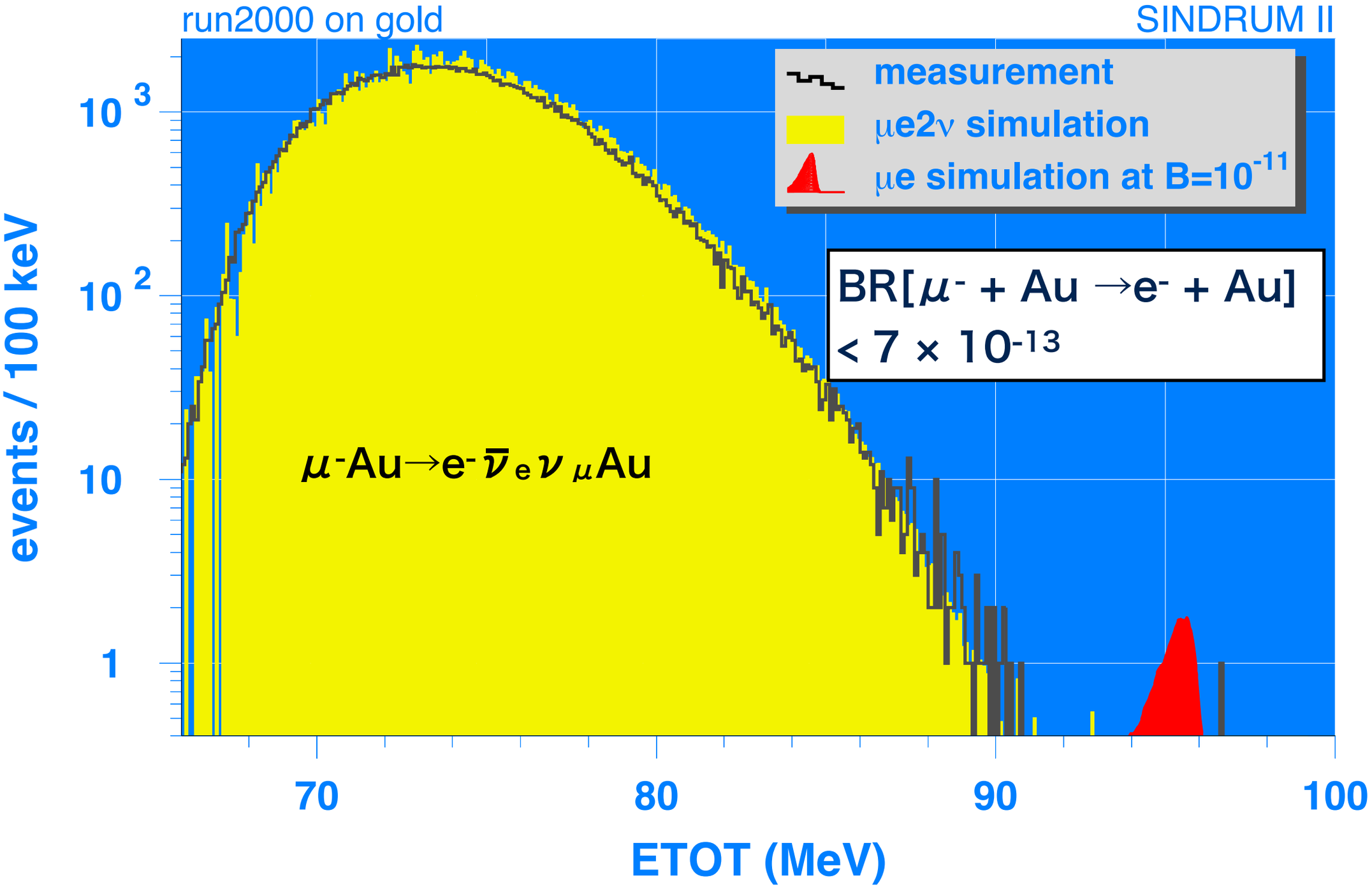
- **μ-e conversion**

$$\mu^- + (A,Z) \rightarrow \nu_{\mu} + (A,Z-1)$$

- $E_{\mu e}(Al) \sim m_{\mu} - B_{\mu} - E_{rec} = 104.97$MeV
  - B_{μ}: binding energy of the 1s muonic atom

μ-e Conversion

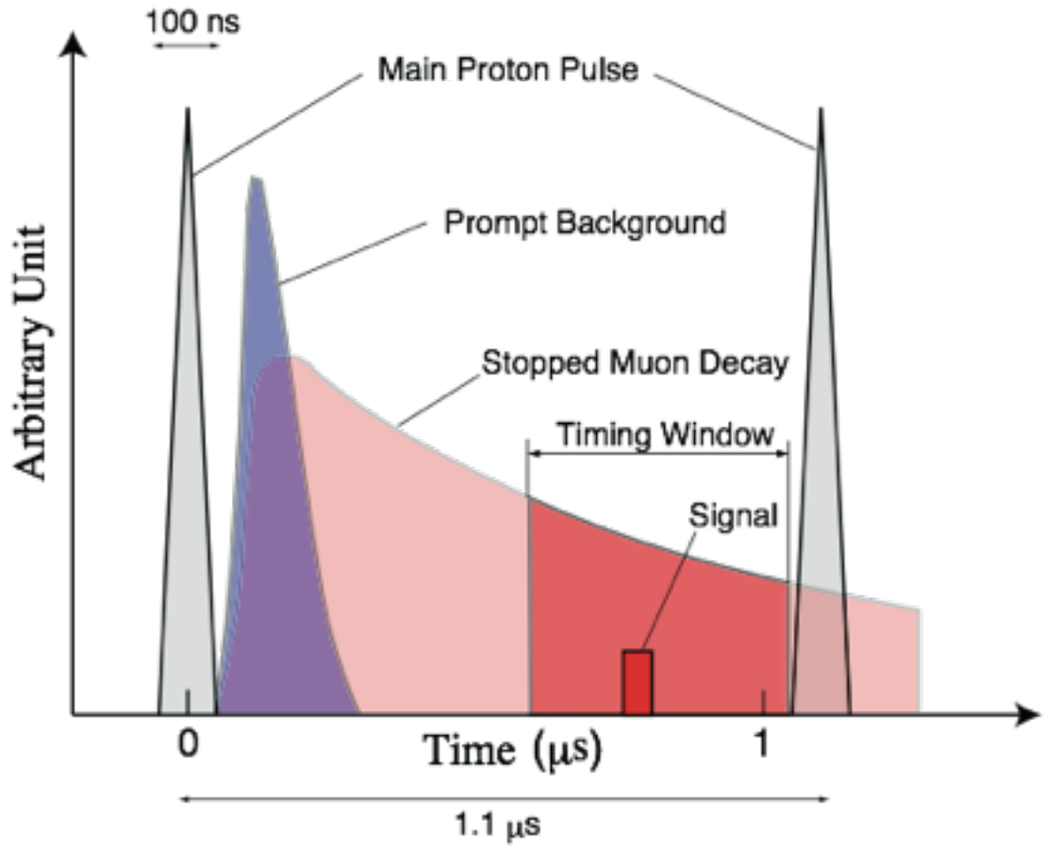
Electron Energy Spectrum



μ-e Conversion

Signal and Background

- Signal
  - Electron from the muon stopping target with a characteristic energy with a delayed timing
- Background
  - Decay in Orbit Electron
  - Radiative muon capture
  - Cosmic-ray
  - and others



Tiny leakage of protons in between consecutive pulses can cause a background through Beam Pion Capture process:

- $\pi^- + (A,Z) \rightarrow (A,Z\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1)$
  $\gamma \rightarrow e^+ e^-$

$$R_{ext} = \frac{\text{Number of protons between pulses}}{\text{Number of protons in a pulse}}$$

J-PARC Facility (KEK/JAEA)

LINAC
400 MeV

Neutrino beam to Kamioka

Rapid Cycle Synchrotron
Energy : 3 GeV
Repetition : 25 Hz
Design Power : 1 MW

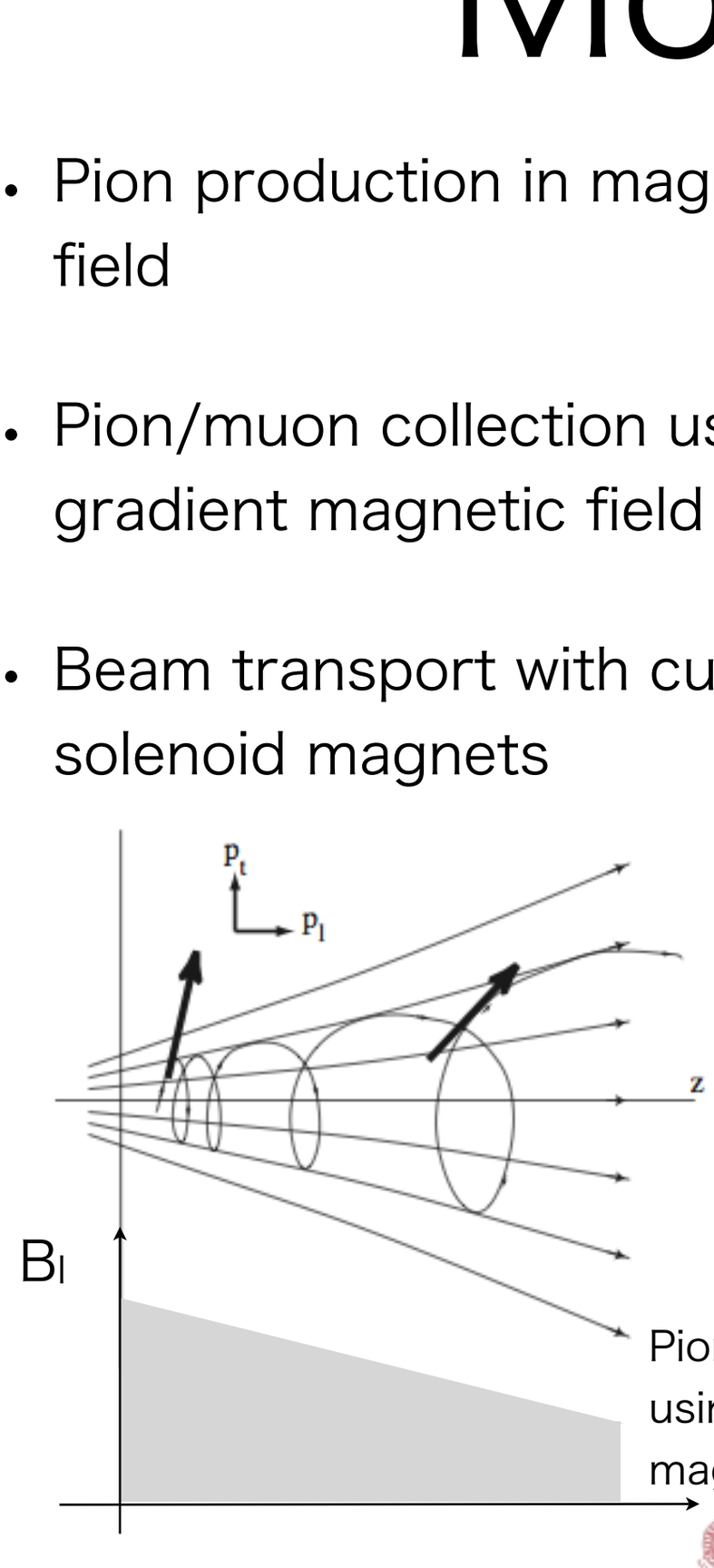
Material and Life Science Facility

Nuclear and Particle Physics Exp. Hall

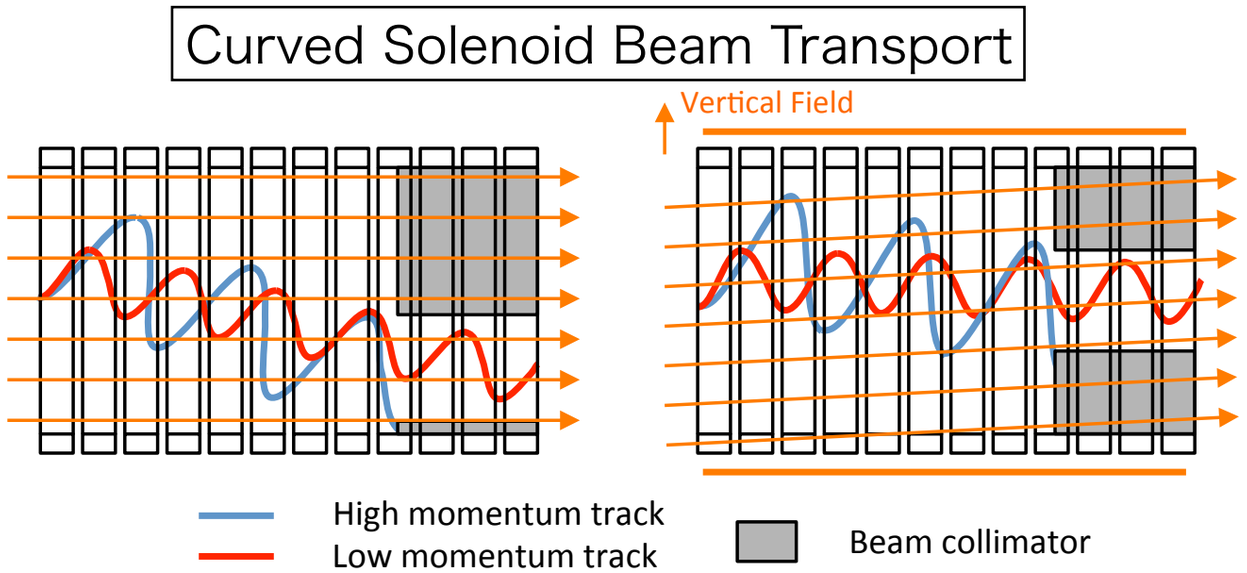
Main Ring
Max Energy : 30 GeV
Design Power for FX : 0.75 MW
Expected Power for SX : > 0.1 MW

More Muons

- Pion production in magnetic field
- Pion/muon collection using gradient magnetic field
- Beam transport with curved solenoid magnets

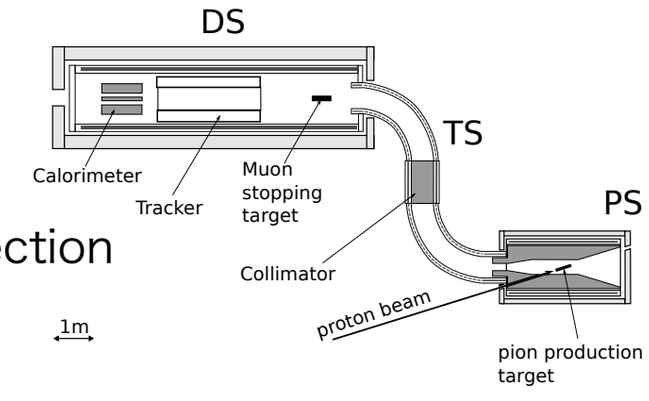


Pion/muon collection using gradient magnetic field

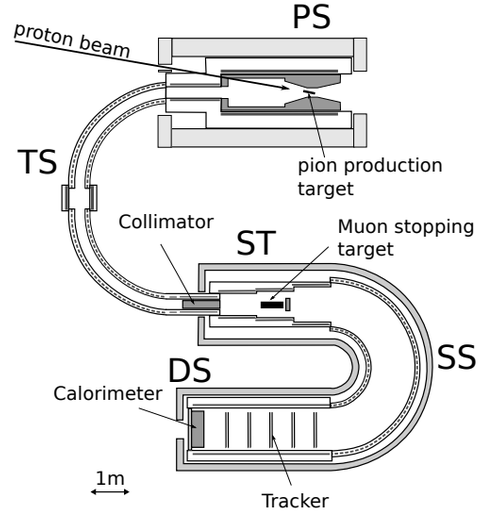


- Momentum and charge separation
- Same scheme used in COMET Phase-II electron spectrometer

Mu2e



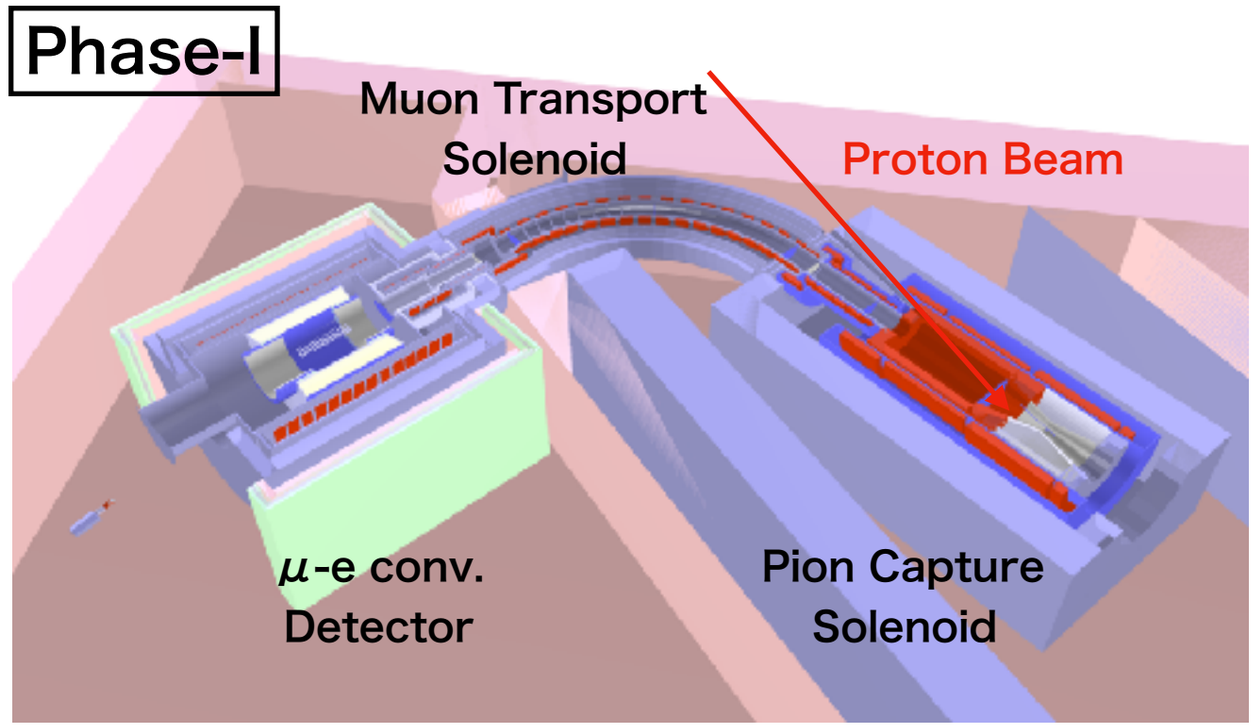
COMET

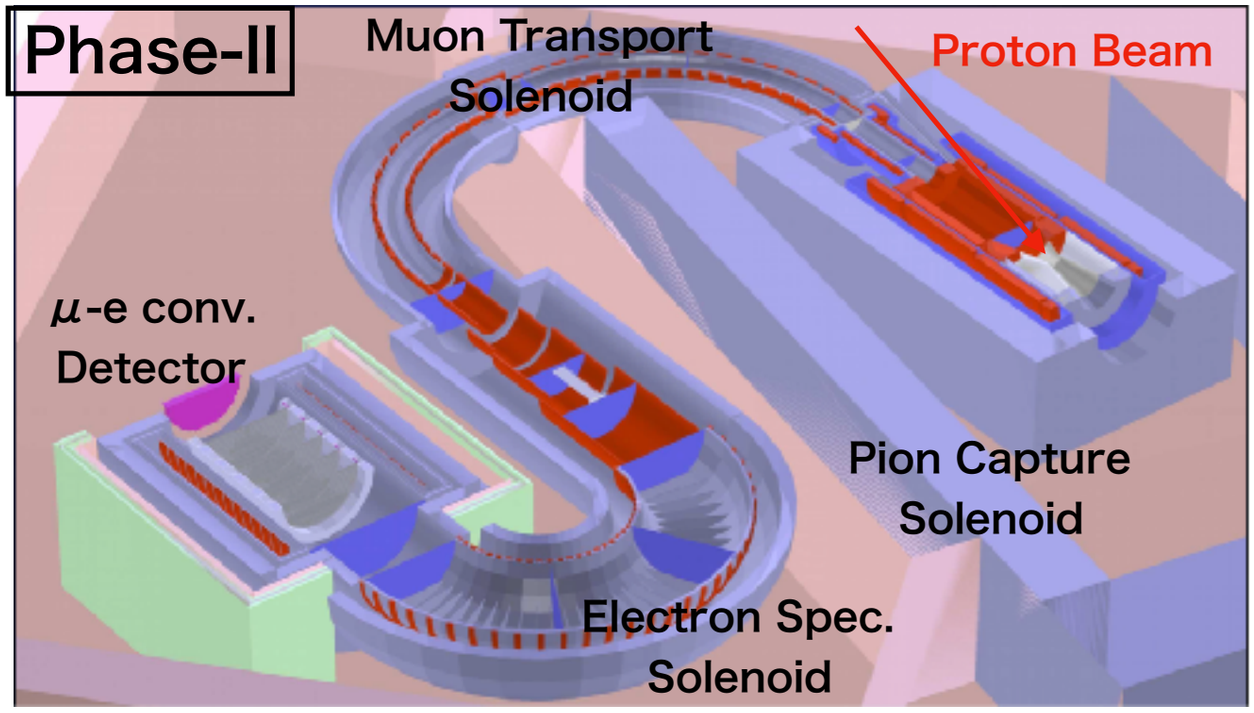


FPCP 2018

COMET at J-PARC

- **Target S.E.S. 2.6×10^{-17}**
- **8GeV Pulsed proton beam at J-PARC**
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- **pion production target in a solenoid magnet**
- **Muon transport & electron momentum analysis using C-shape solenoids**
  - smaller detector hit rate
  - need compensating vertical field
- **Tracker and calorimeter to measure electrons**
- COMET decided to take a staging approach to realize this. The collaboration is making an effort to start physics DAQ as early as possible under this.
  - **Phase-I 8GeV-3.2kW, < 10^{-14}**
  - **Phase-II 8GeV-56kW, < 10^{-16}**

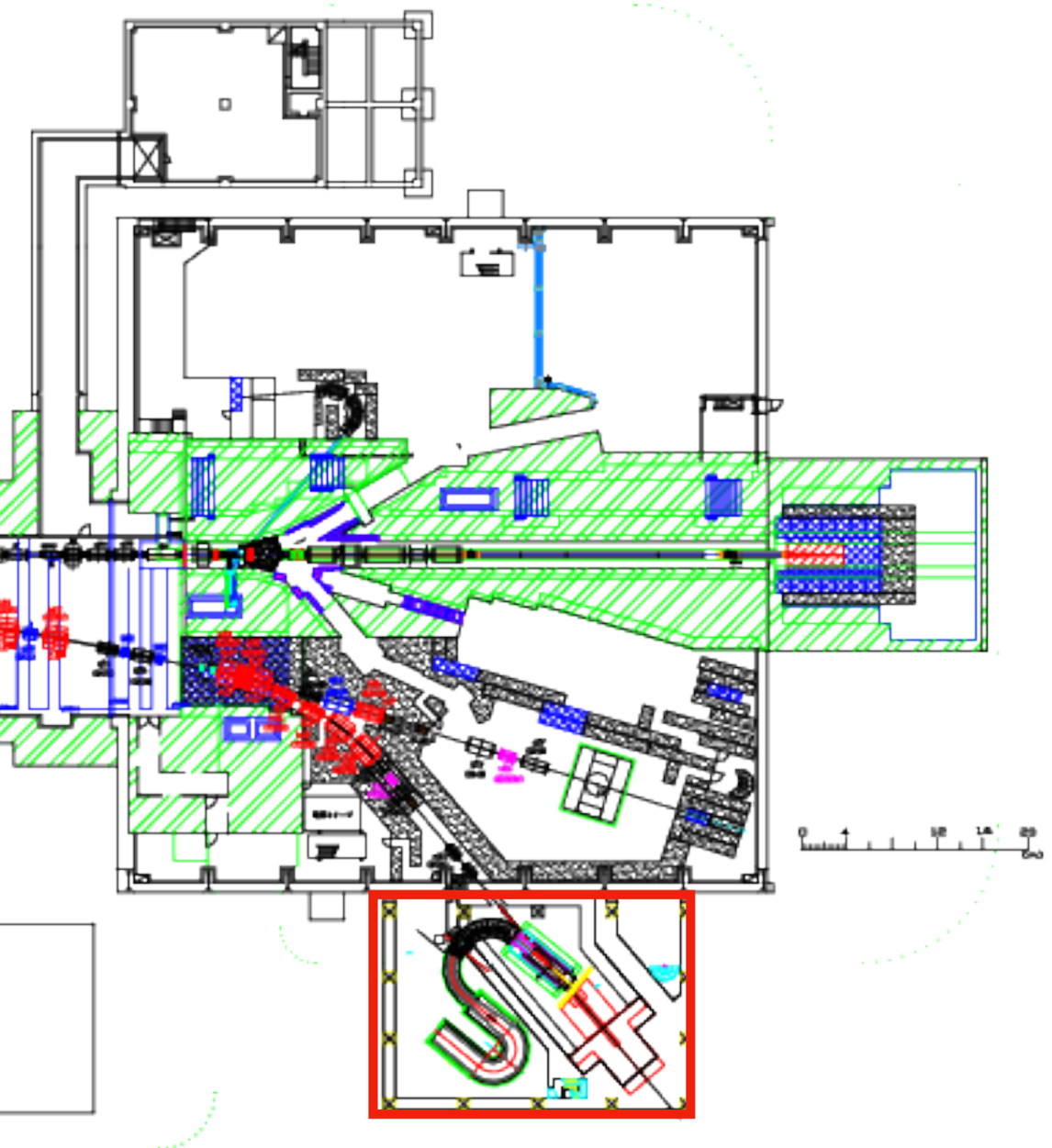




COMET Facility Construction Status

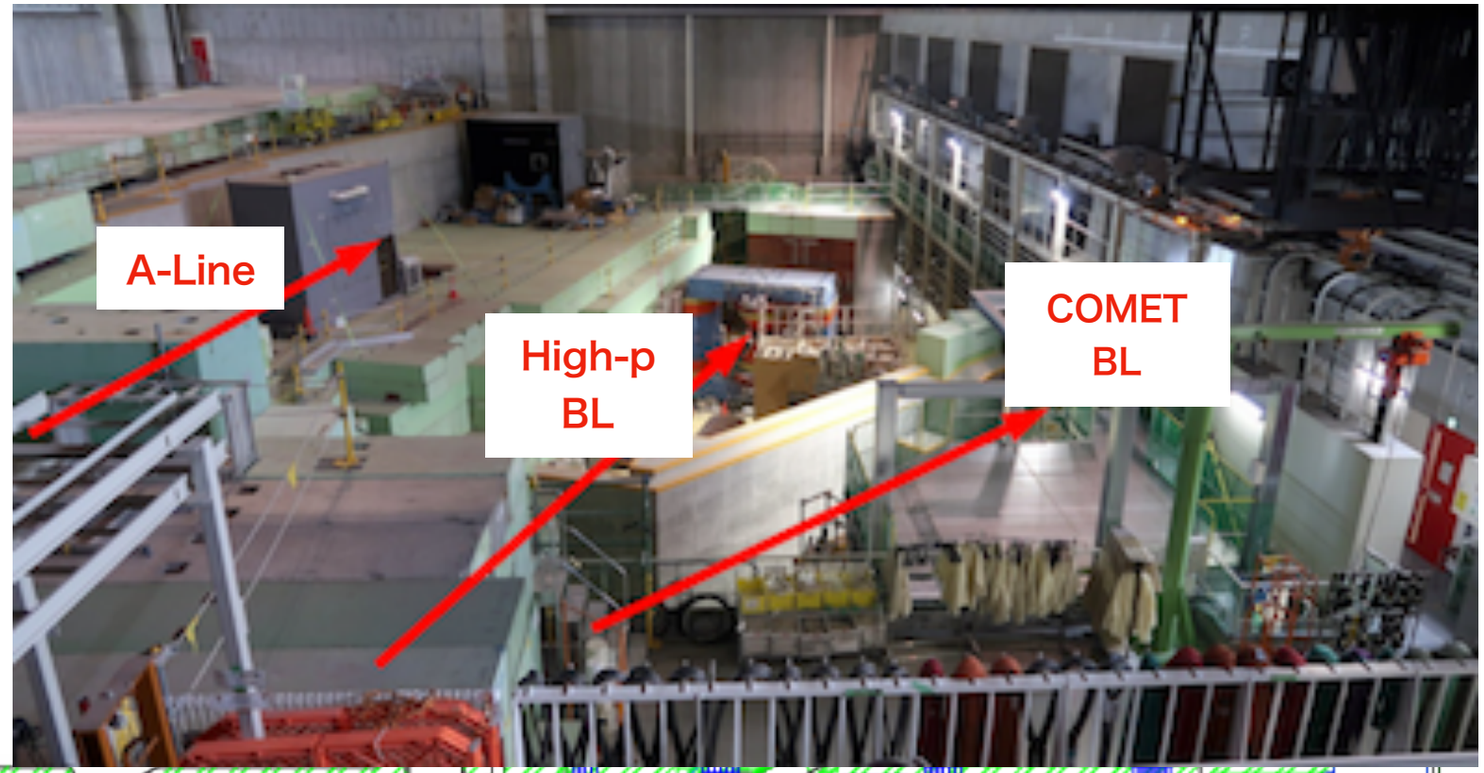
COMET Experiment Hall

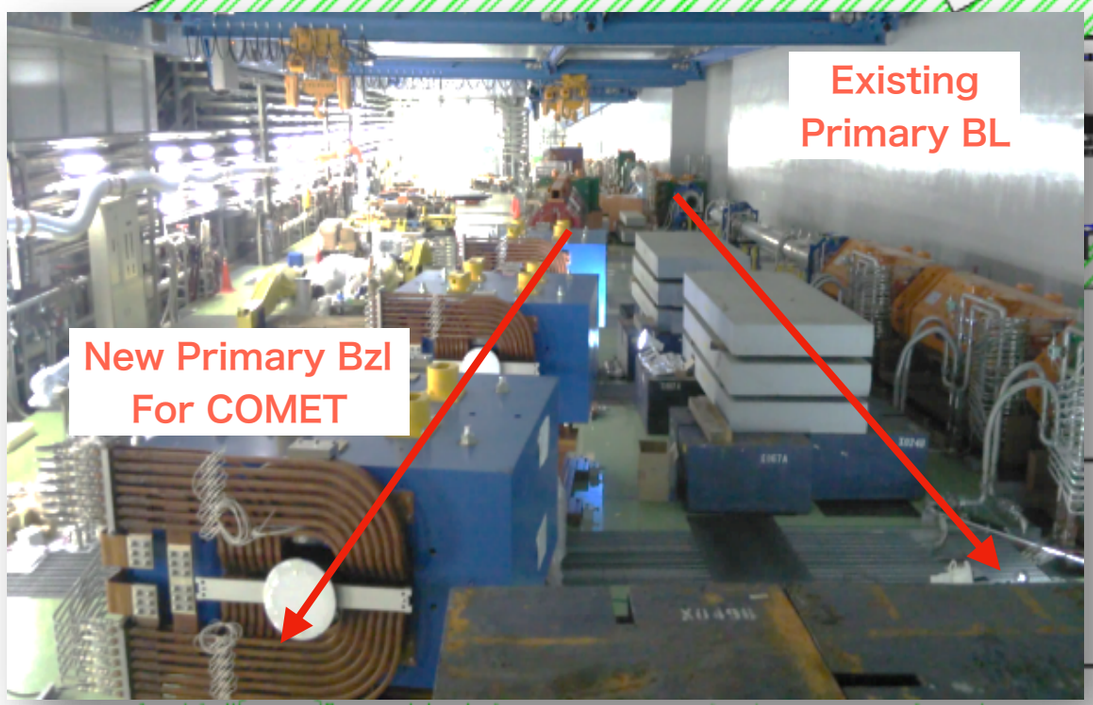
COMET Facility Construction Status

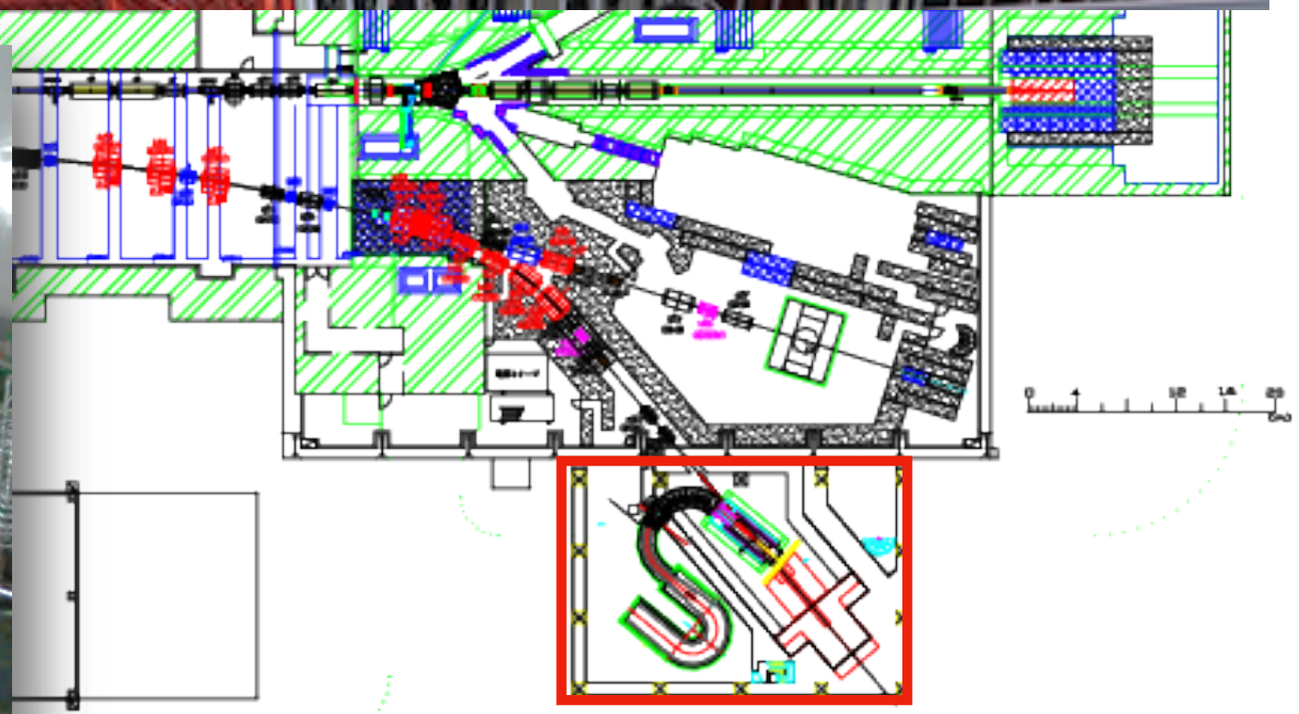


COMET Experiment Hall

COMET Facility Construction Status

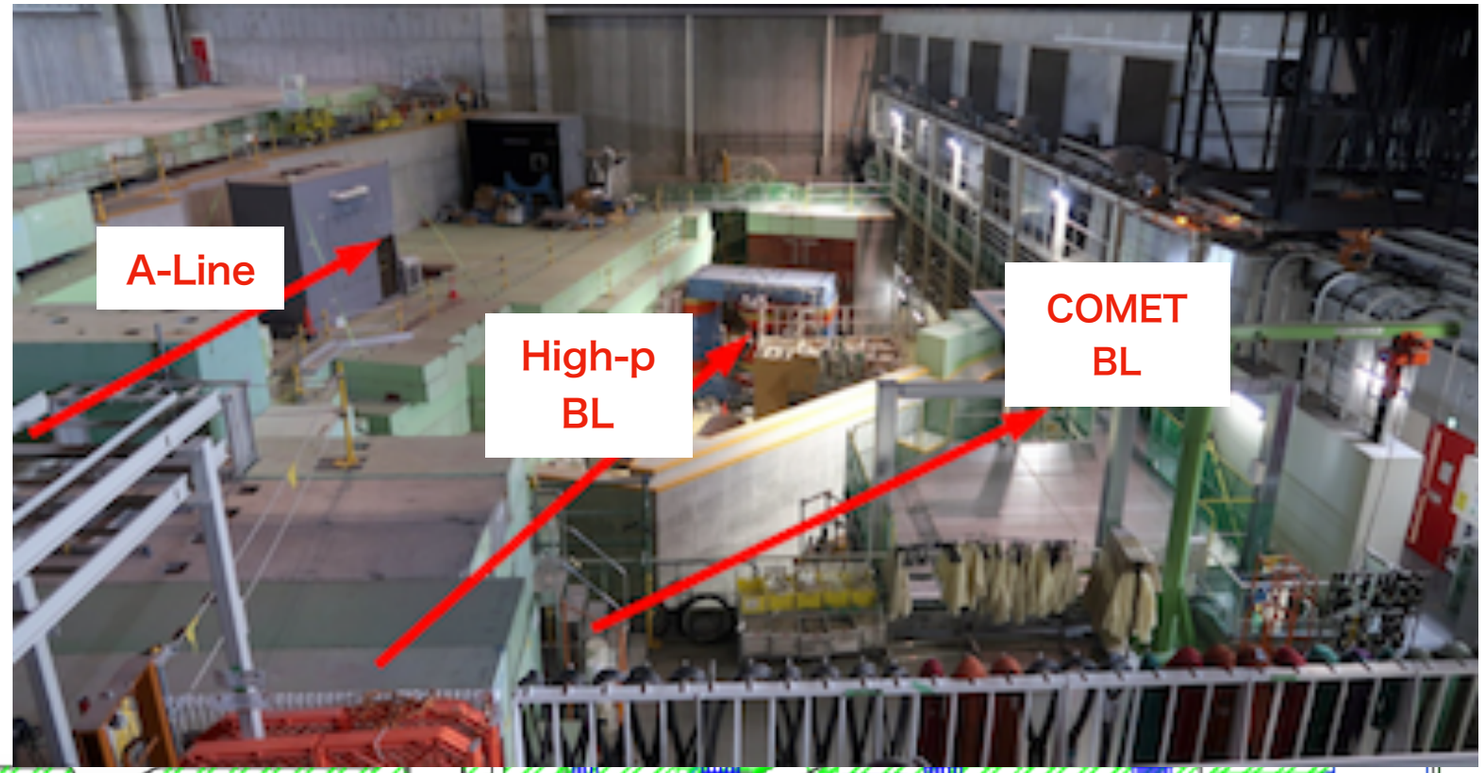


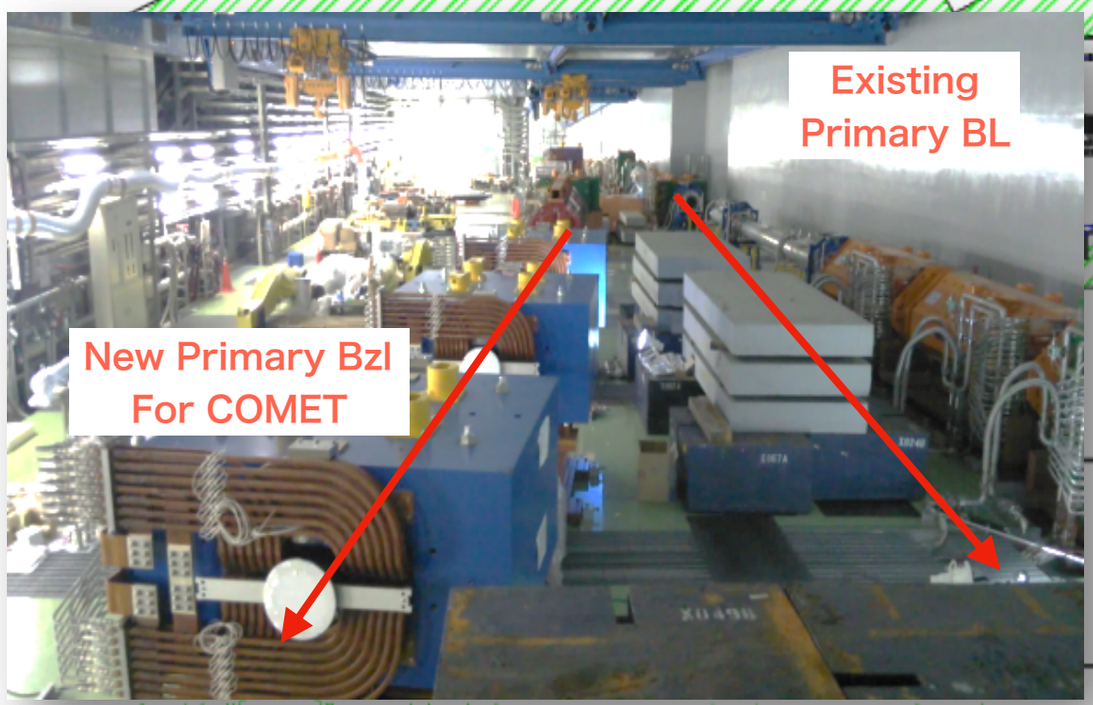


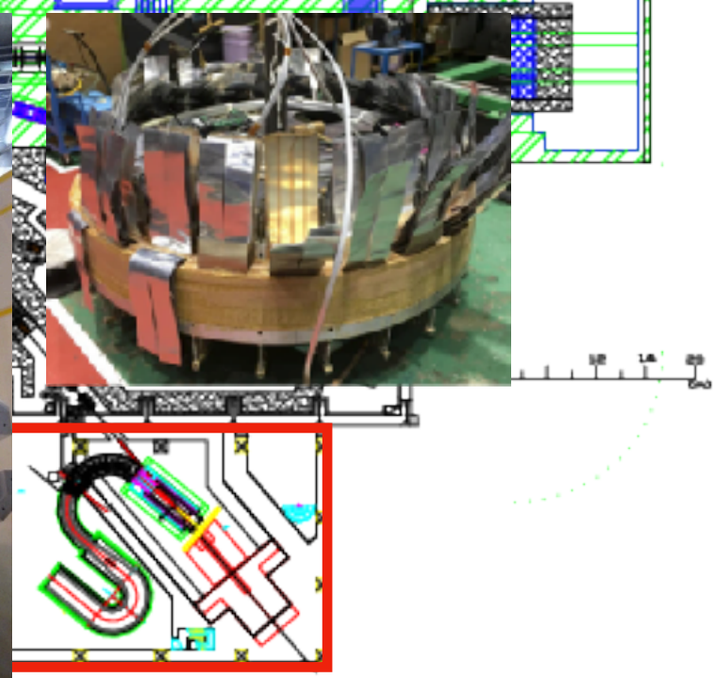


COMET Experiment Hall

COMET Facility Construction Status

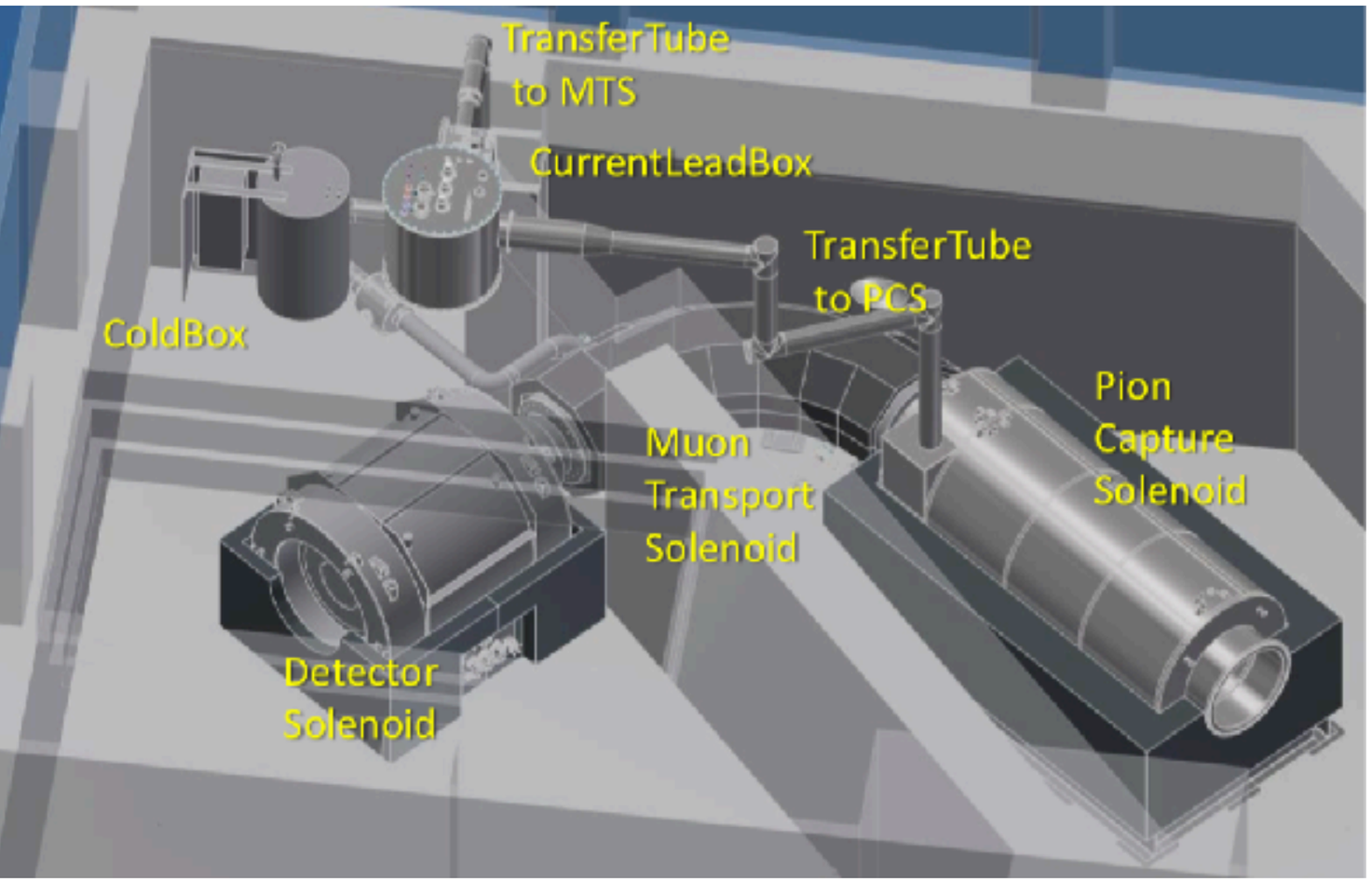


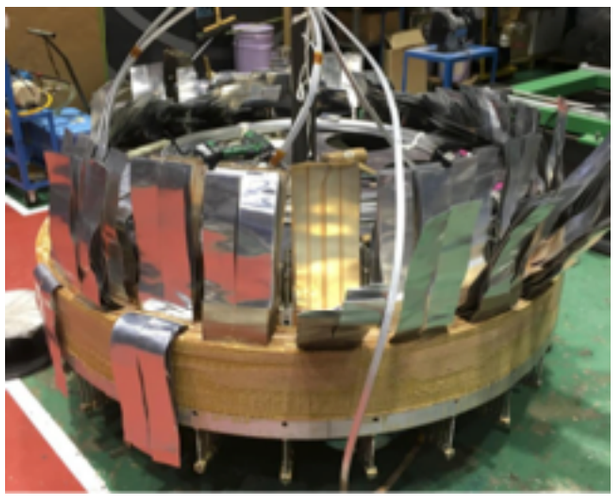


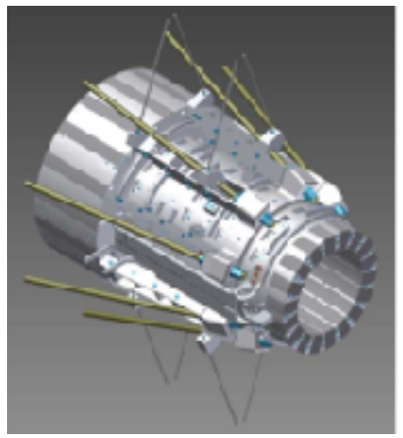


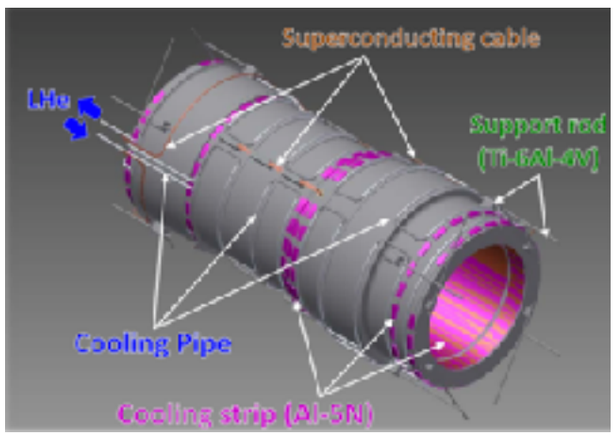
COMET Experiment Hall

Solenoid Magnet System





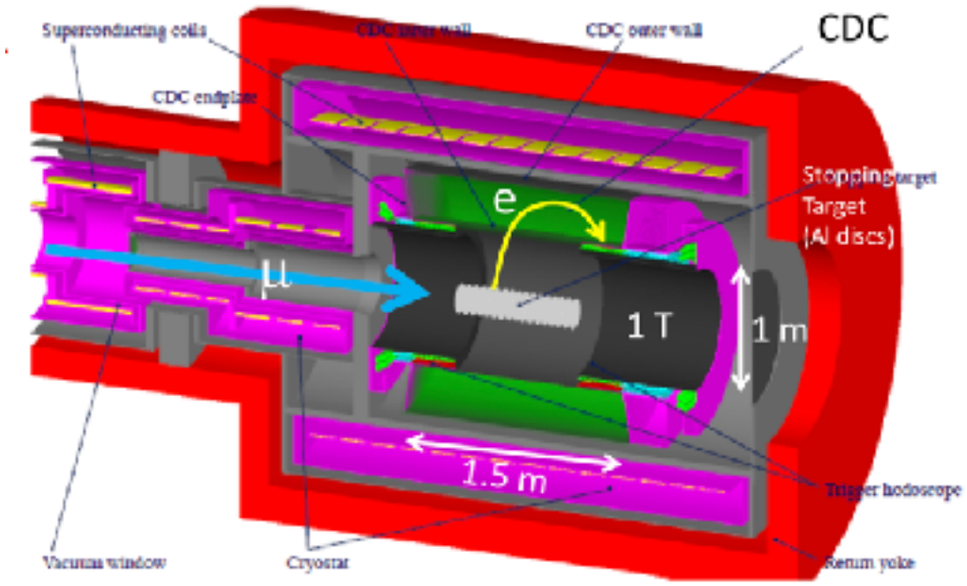


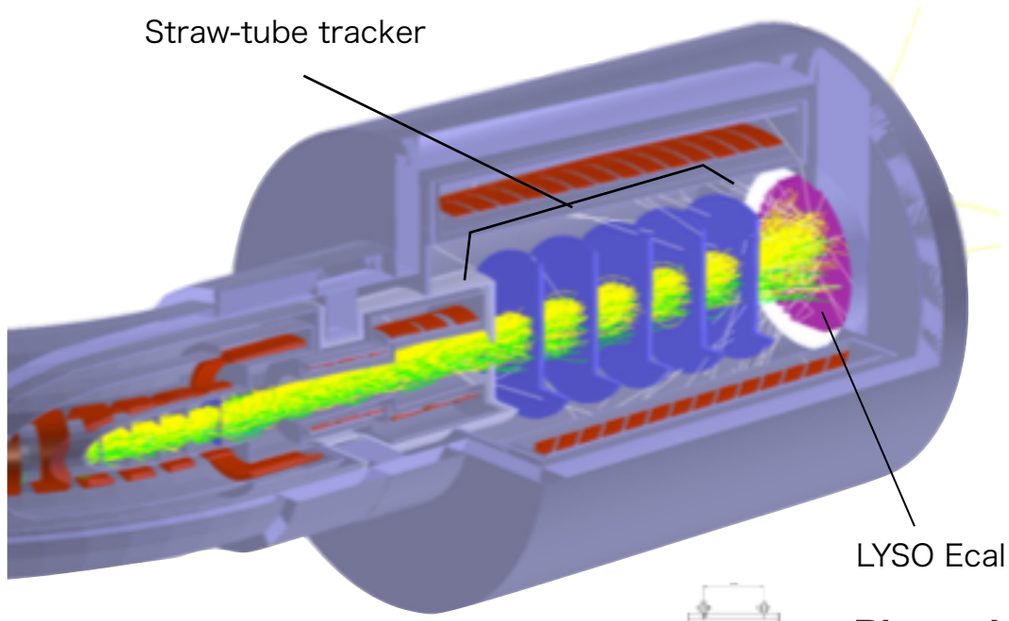


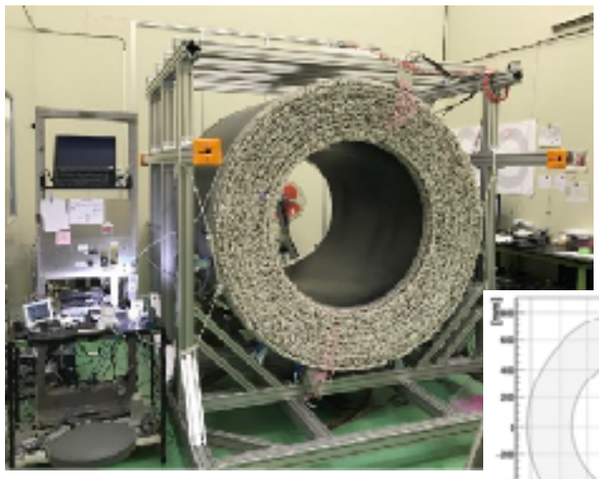
- Capture solenoid: Coil winding & cold mass assembly in progress. Cryostat design ongoing
- Transport solenoid: Installed and ready for cryogenic test
- Bridge & detector solenoids: design in progress.
- Cryogenic System: Refrigerator test completed. Helium transfer tube in production

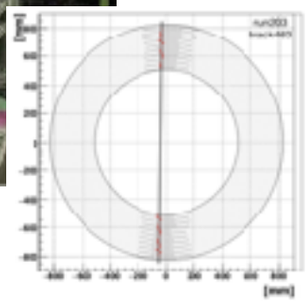
COMET Phase-I Status

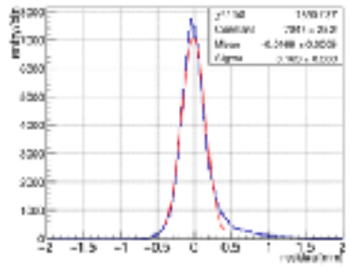
- Physics Detector
  - CDC and trigger counters
  - Optimized for Phase-I physics
- Beam measurement Detector
  - Straw-tube tracker and LYSO Ecal
  - Prototype of Phase-II detector

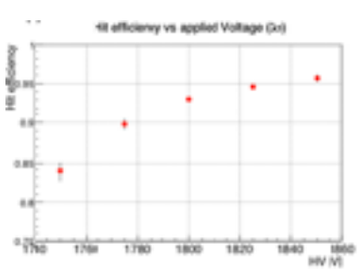


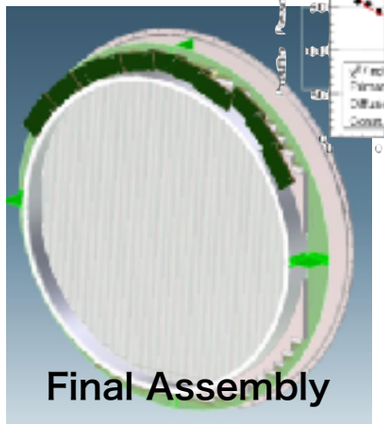


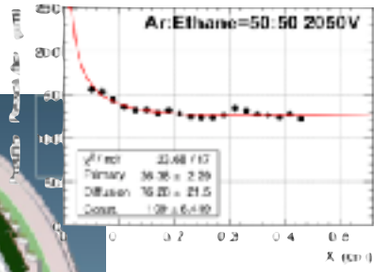




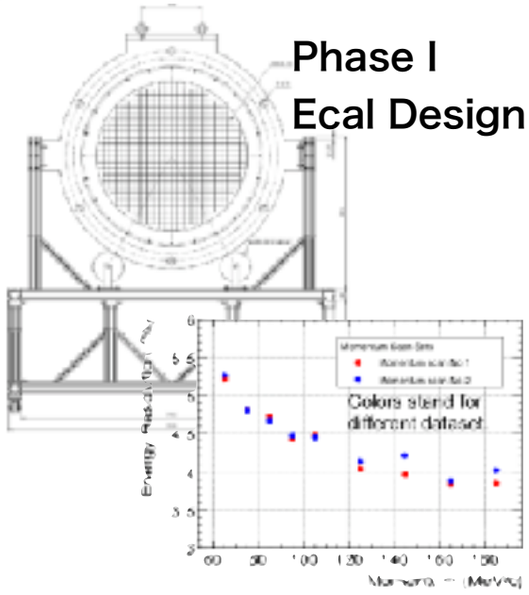








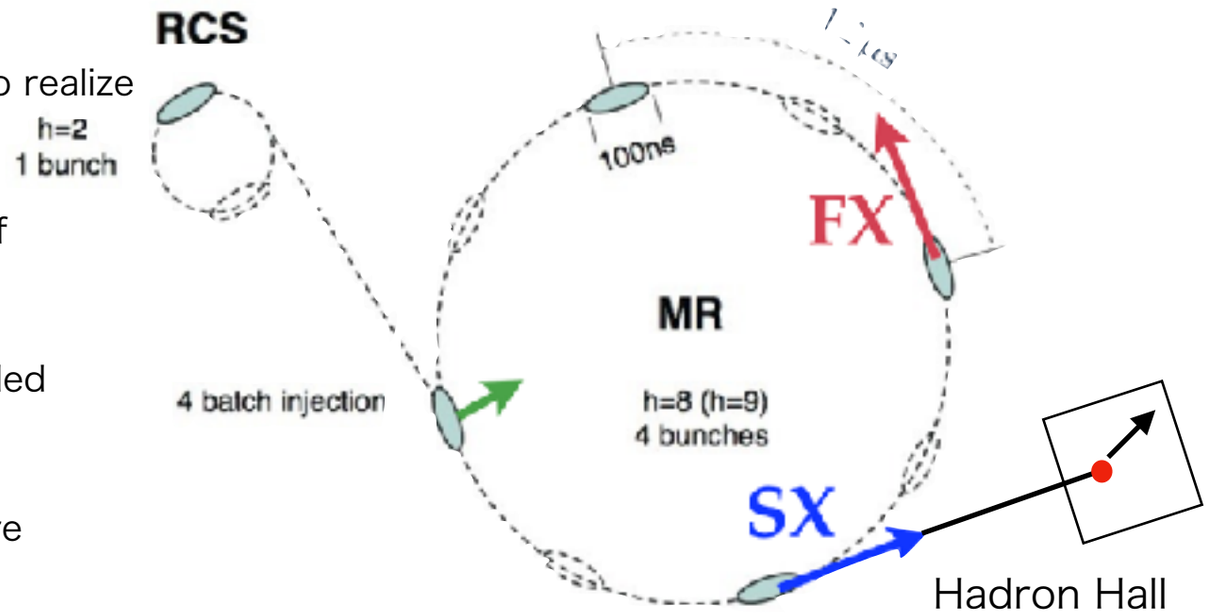
Phase I Ecal Design



FPCP 2018

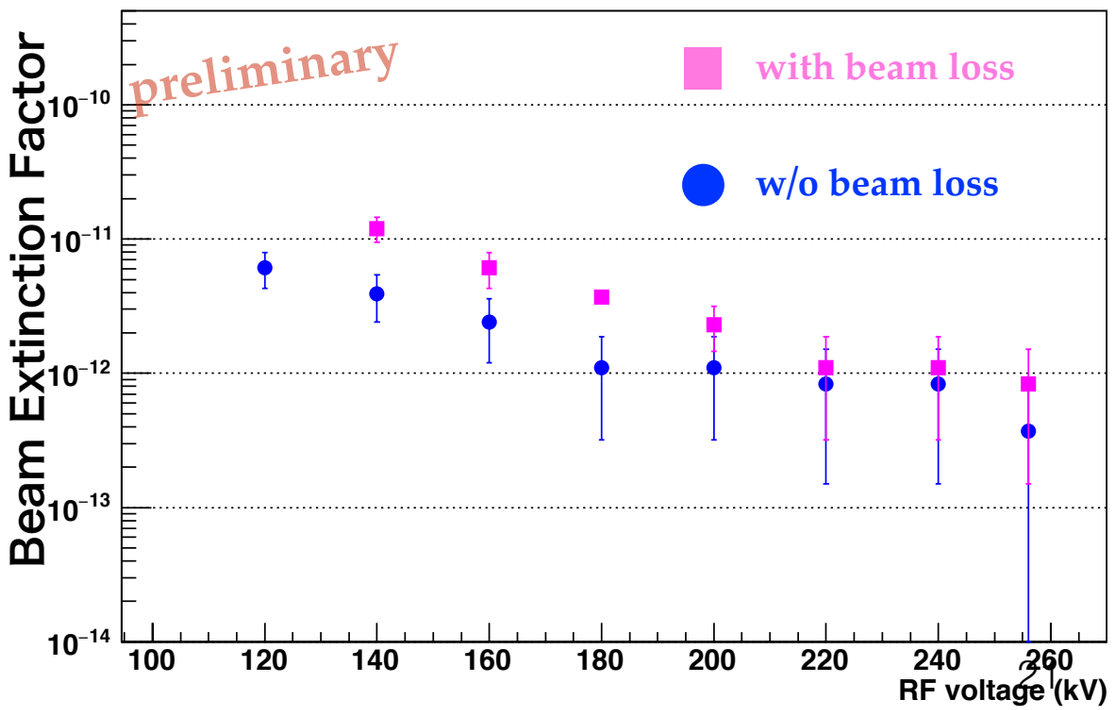
8GeV Acceleration Test and Extinction Factor Measurement

- **8GeV acceleration and extraction to the abort line (FX) and Hadron Hall (SX)**
  - 4 bunches out of 9 bunches are filled with protons to realize the COMET beam time structure
    - Same number of protons per bunch with that of Phase-I beam
  - Injection kicker timing is shifted to kick in only the filled bunch
  - SX with RF HV on to keep the bunched time structure

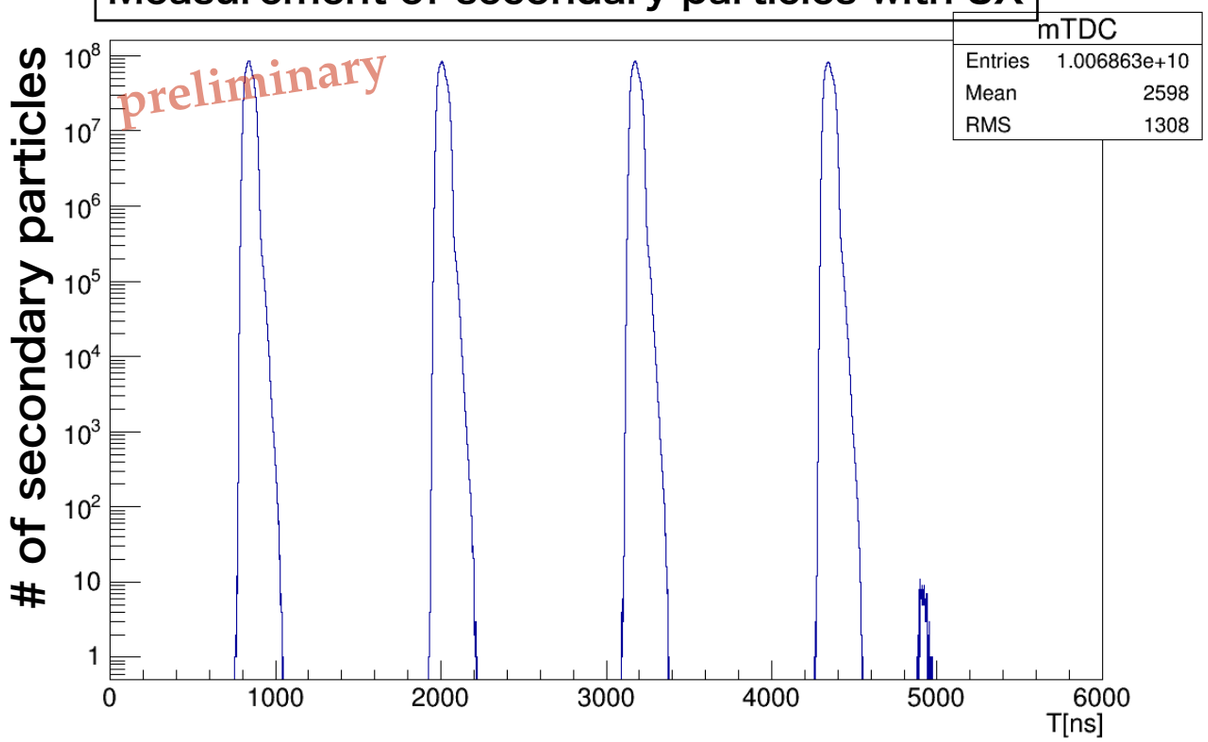


- **R_{ext} = $10^{-11\sim-12}$ in FX and < 6×10^{-11} in SX, possible to improve even further with more accelerator study time in future**

Measurement at Abort Line with FX



Measurement of secondary particles with SX

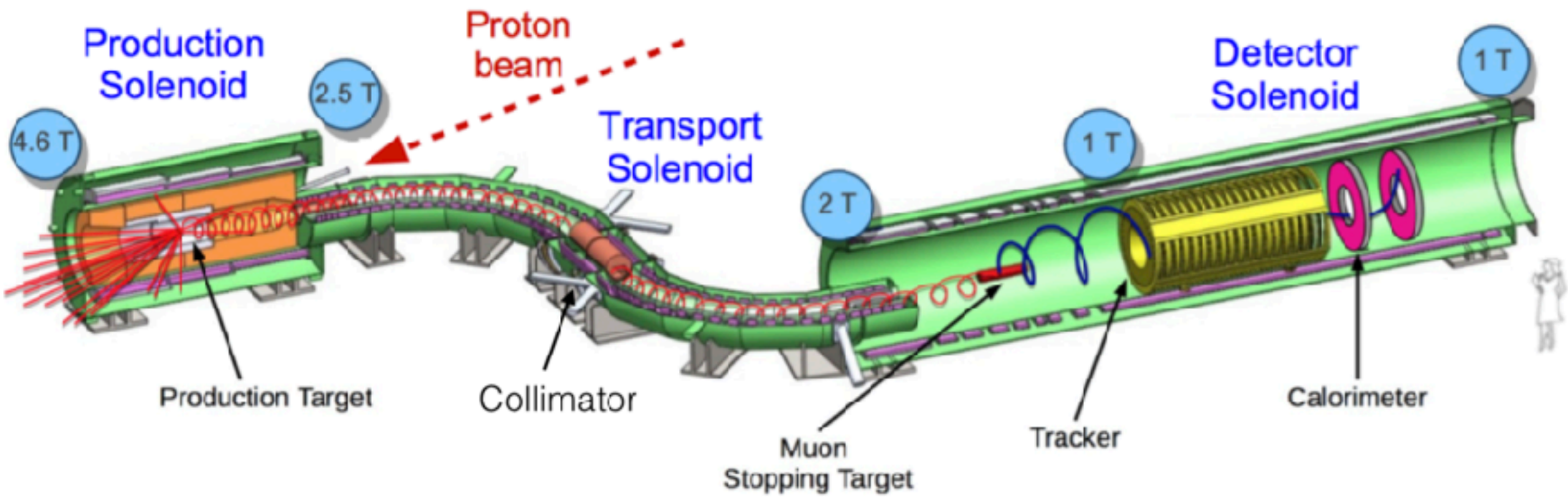


Mu2e at FNAL

- 8GeV protons from FNAL accelerator complex
- Re-bunching in the Delivery Ring
- Injected onto the tungsten target located in Capture Solenoid magnet
- Single event sensitivity: 3×10^{-17}
- DAQ starts in 2022, 1 yr commissions and 3 yrs running.

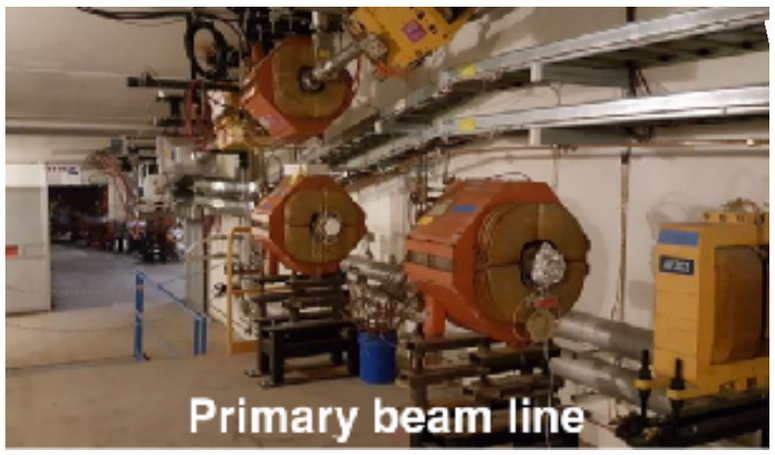
Mu2e Experimental Setup

- Production solenoid with a production target inside
    - Collects backward π/μ and “reflects” forward slow π/μ
- S-shape transport solenoid with a collimator at the middle
    - Selects low-momentum negatively charged μ
- Detector solenoid with Tracker and Calorimeter inside
- Muon capture on Al target. Measure momentum in Tracker and energy in ECAL

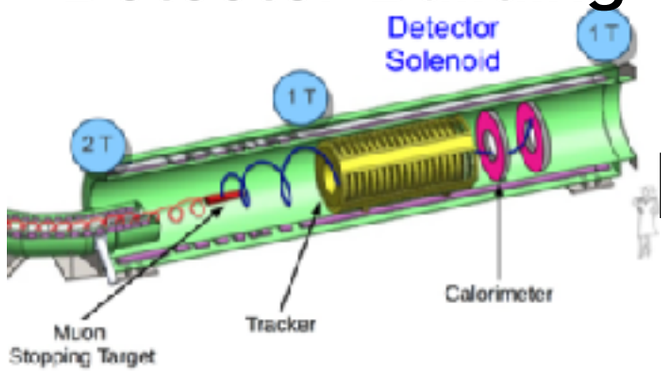


Mu2e Status

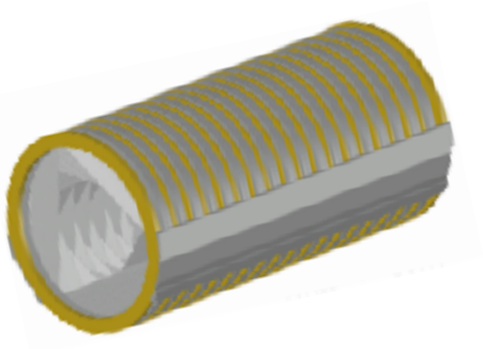
Facility Construction



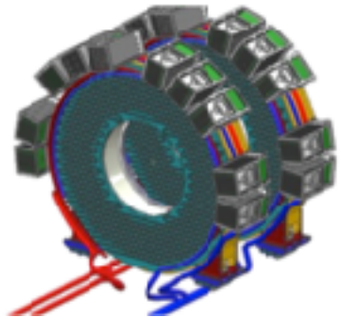
Detector Building



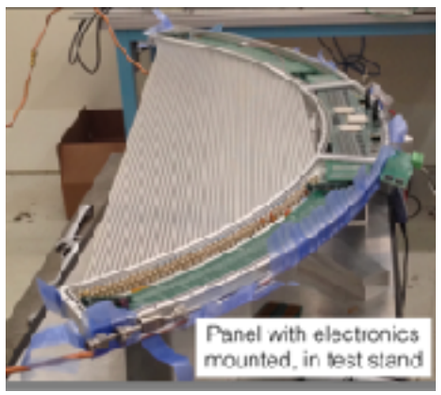
Straw Tube Tracker

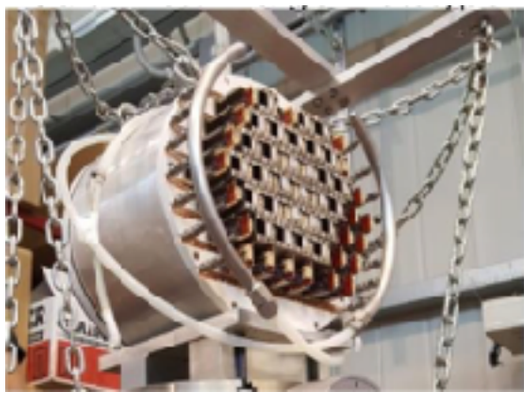


CsI Calorimeter



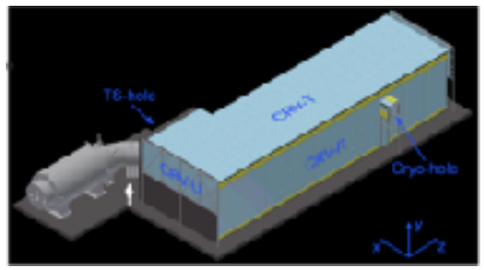
2 disks, each disk contains 674 undoped CsI crystals of $20 \times 3.4 \times 3.4 cm^3$



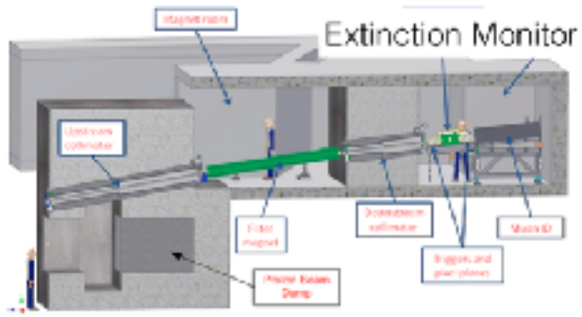


Other essential components

Target remote handling



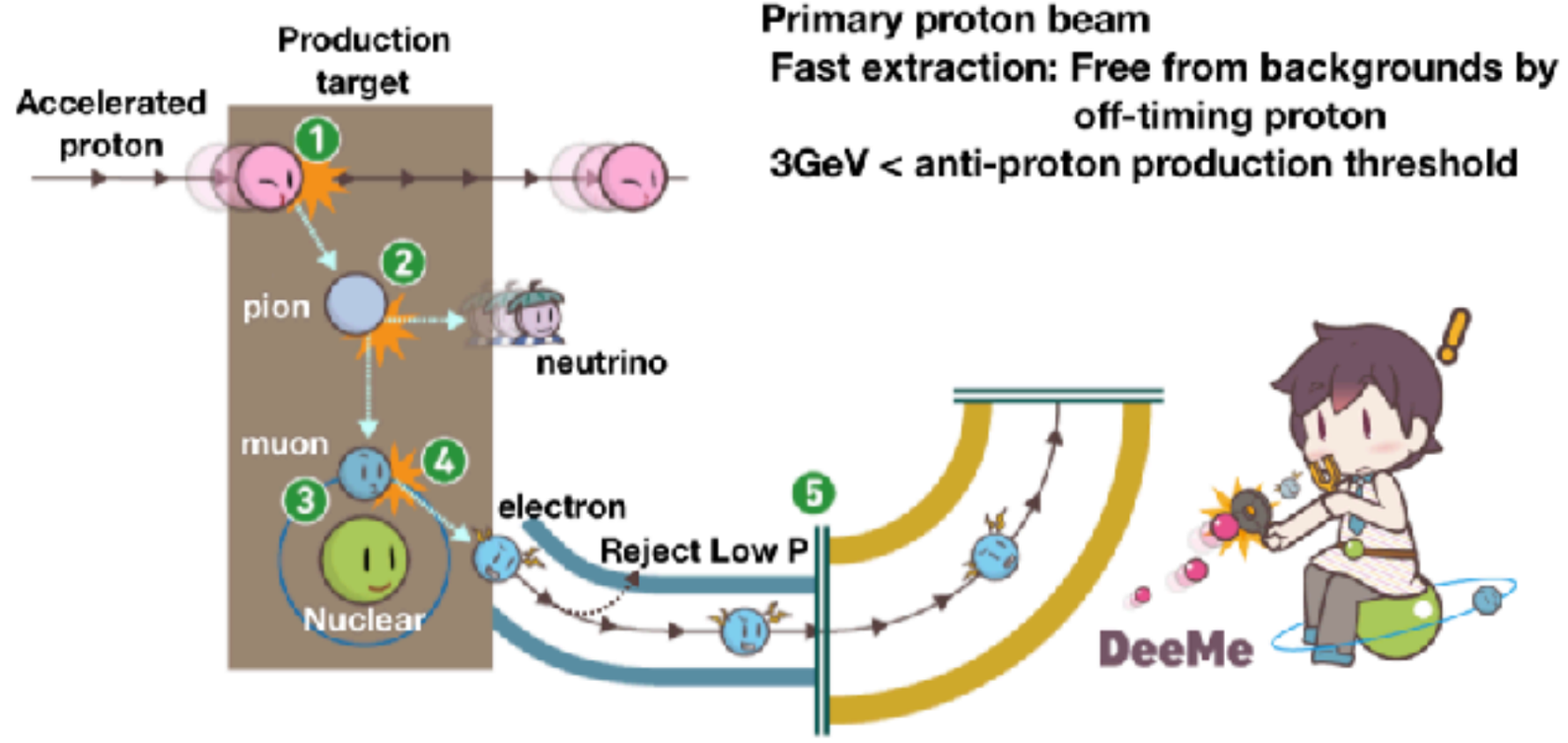
CR Veto



Extinction monitor

Yet Another μ-e Conversion Search at J-PARC

Design of DeeMe



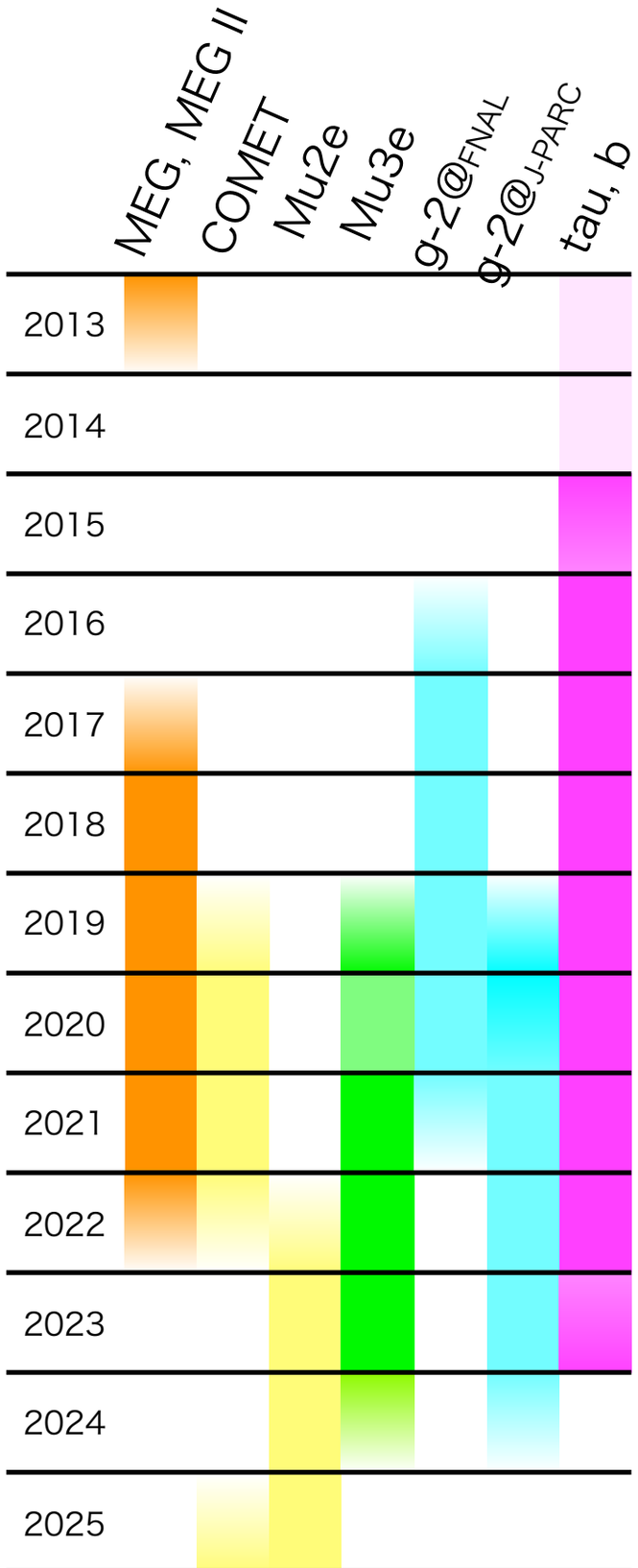
Primary proton beam
Fast extraction: Free from backgrounds by off-timing proton
3GeV < anti-proton production threshold

1. Pion production by accelerated proton hits on target
2. $\pi^- \rightarrow \mu^- + \nu_\mu$
3. μ^- trapped by a nuclear. Muonic atom formation
4. Particles emitted from muonic atom
5. Extract electron via secondary beam line and measure the momentum

H. Natori

ICHEP 2018, 2018/July/07 @ COEX, Seoul 6

Summary and Outlook



- Muon cLFV search is a unique tool to investigate BSM in a complementary way to High-Energy Frontier Experiment

- MEG limit: Br($\mu \rightarrow e\gamma$) < 4.2x10^{-13}
  - MEG II engineering run, followed by physics DAQ

- COMET and Mu2e in 2019-202x

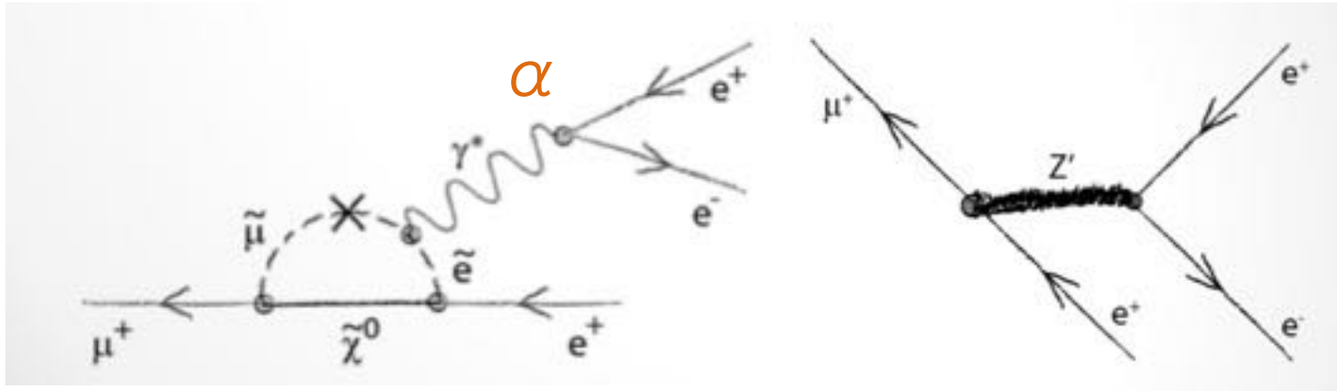
- More tau data from Belle II

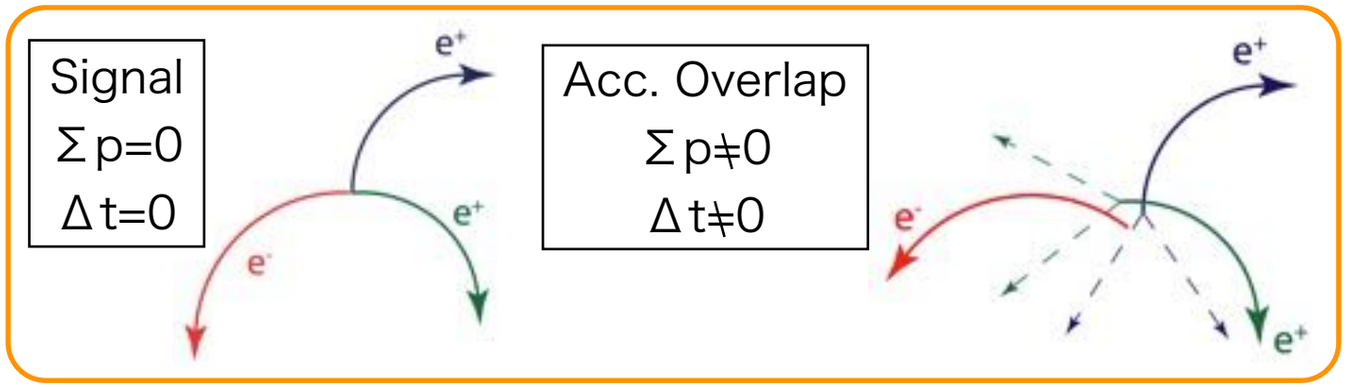
Mu3e

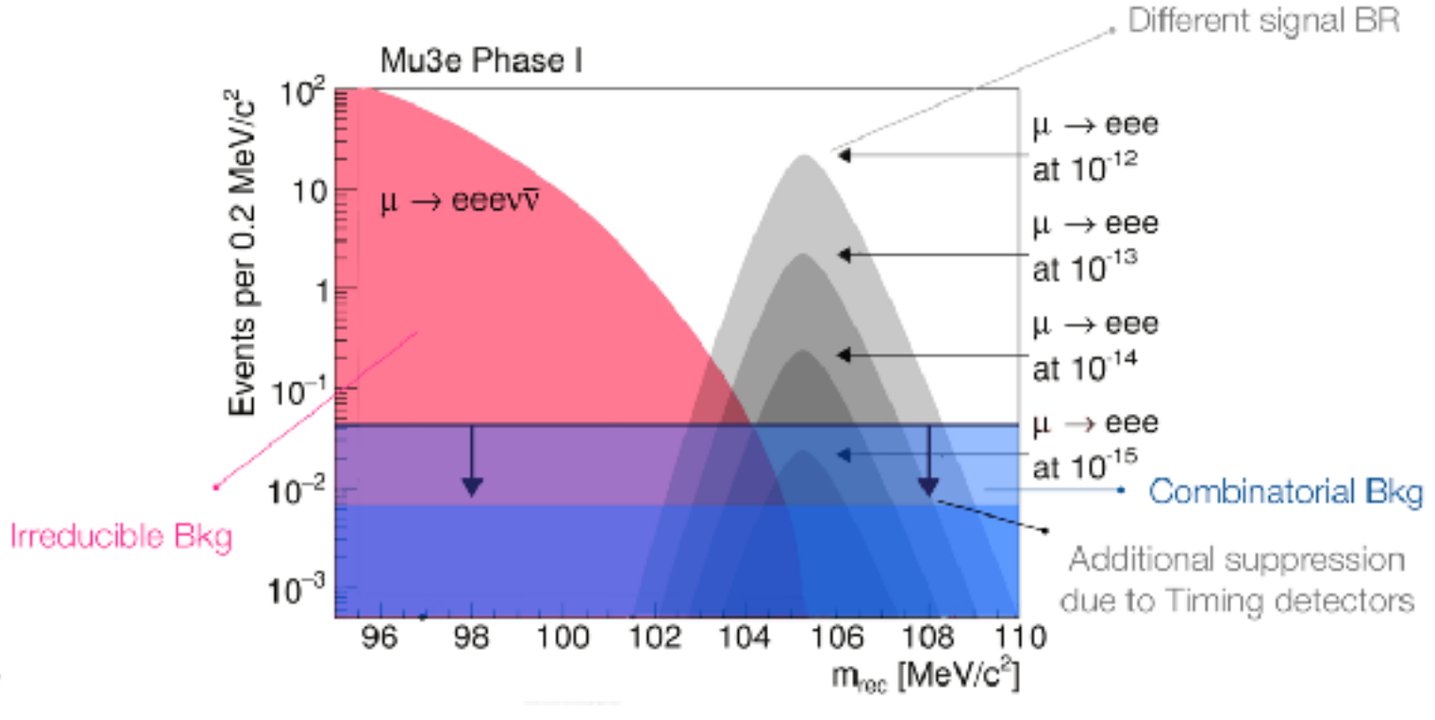
FPCP 2018

$\mu \rightarrow$eee Search using DC Muon Beam

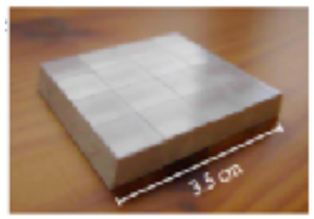
- Another channel sensitive to cLFV with DC muon beam
  - 1.0x10^{-12} (90% C.L.) by SINDRUM
  - **Goal : 10^{-16} in 2 steps**
- Measure all electron tracks with extreme precision
- Background source
  - $\mu^+ \rightarrow e^+ \underline{e}^+ e^- \nu\ \nu$
  - Accidental overlap
- Beamline is shared with MEG



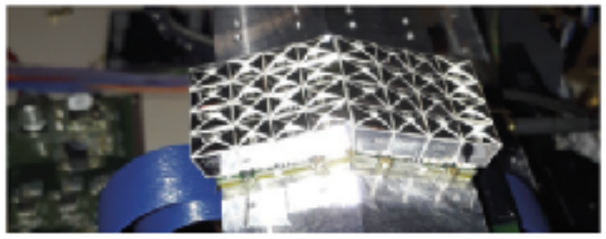


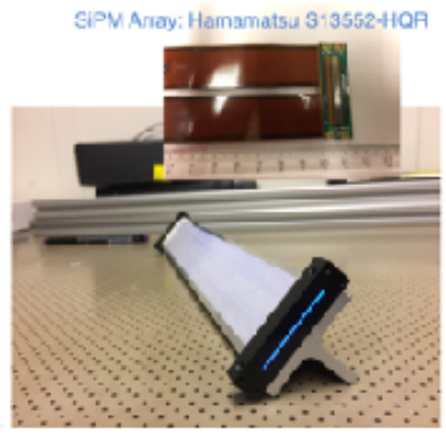


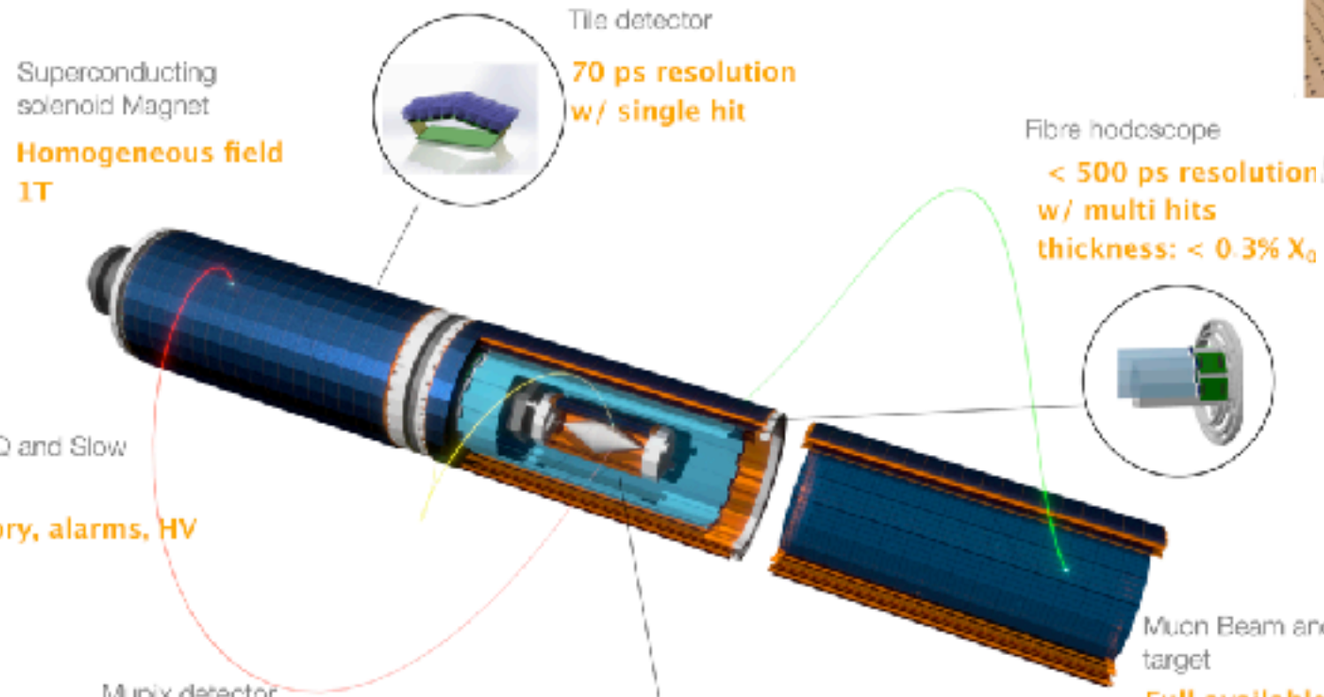
Detector Preparation



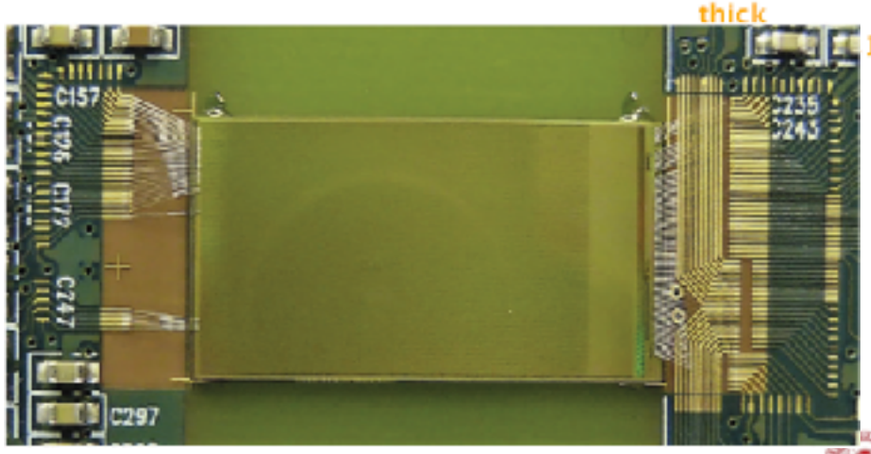
Tile detector prototype
Good enough σ_t





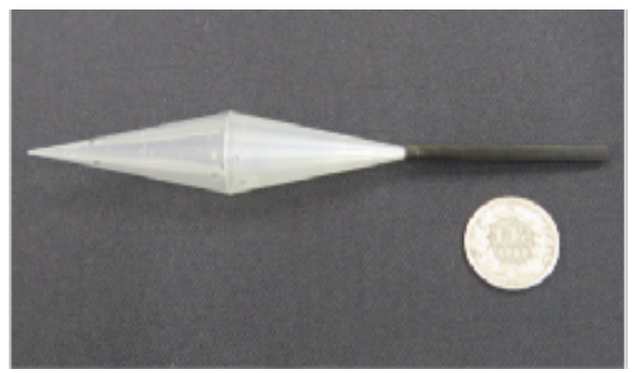


Fiber hodoscope prototype
Good enough σ_t



1st large-area prototype
MuPix8 is being tested
MuPix9 & MuPix10 follow

Target prototype



Tau cLFV

New Physics Searches with τ Leptons

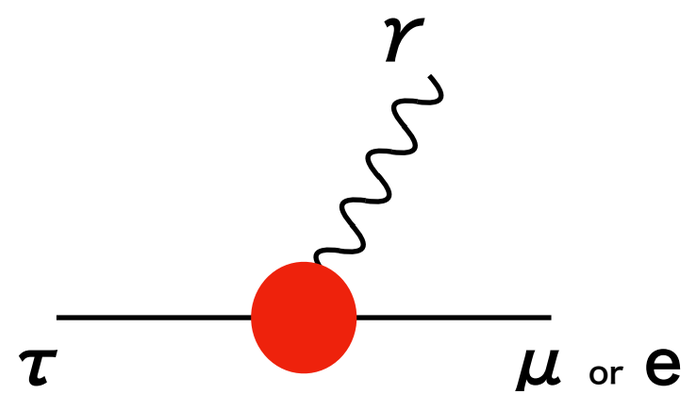
- Same physics motivation with muon cLFV searches

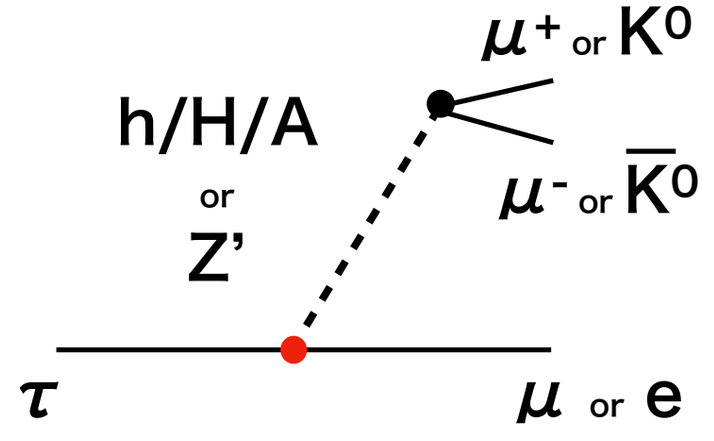
- m_τ heavier than m_μ

  - Different, perhaps larger, coupling expected to new physics

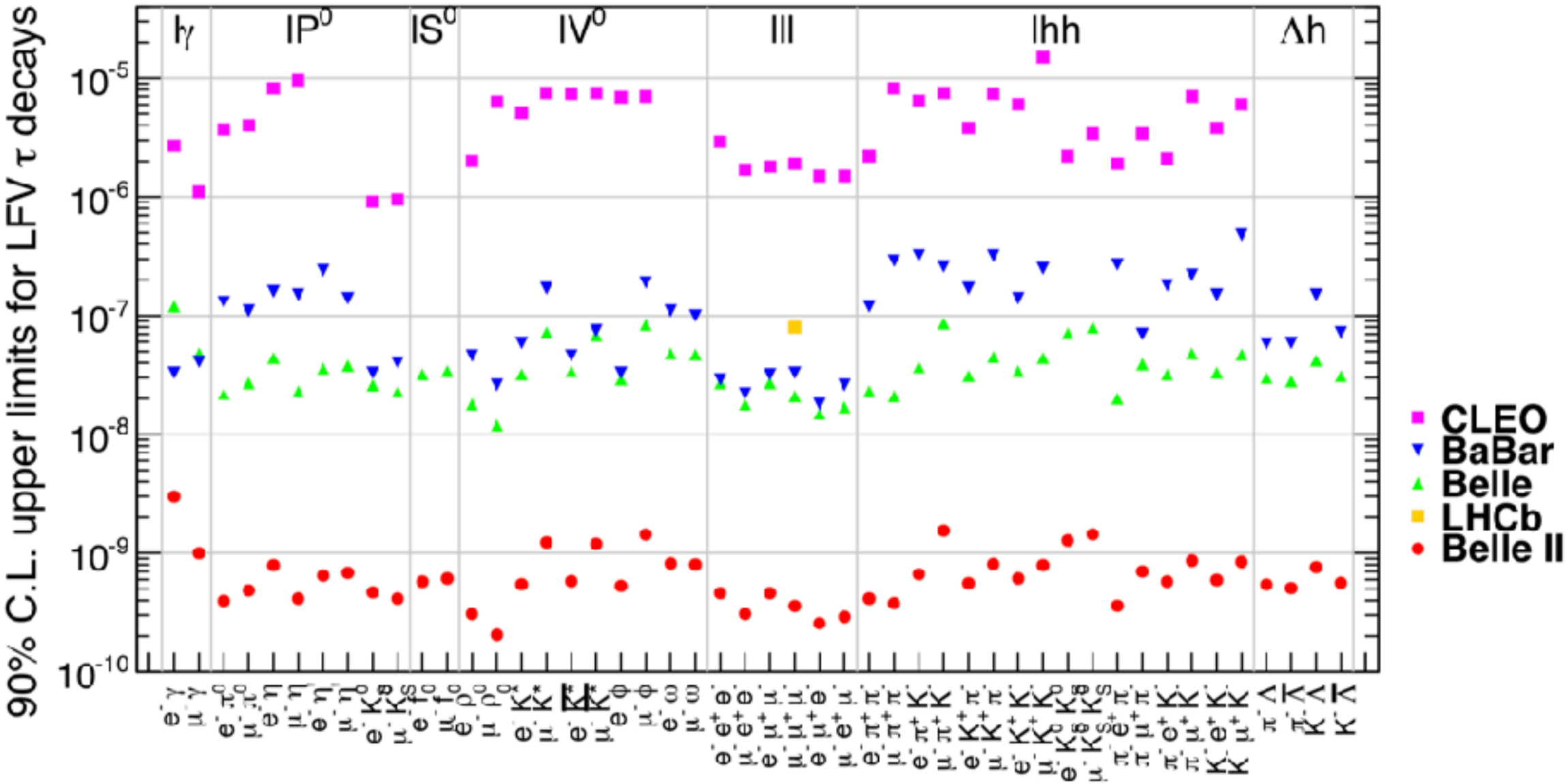
  - More final state types

- Large τ statistics in collider experiments including LHCb





τ LFV searches summary and prospects



Y. Kwon WIN2017