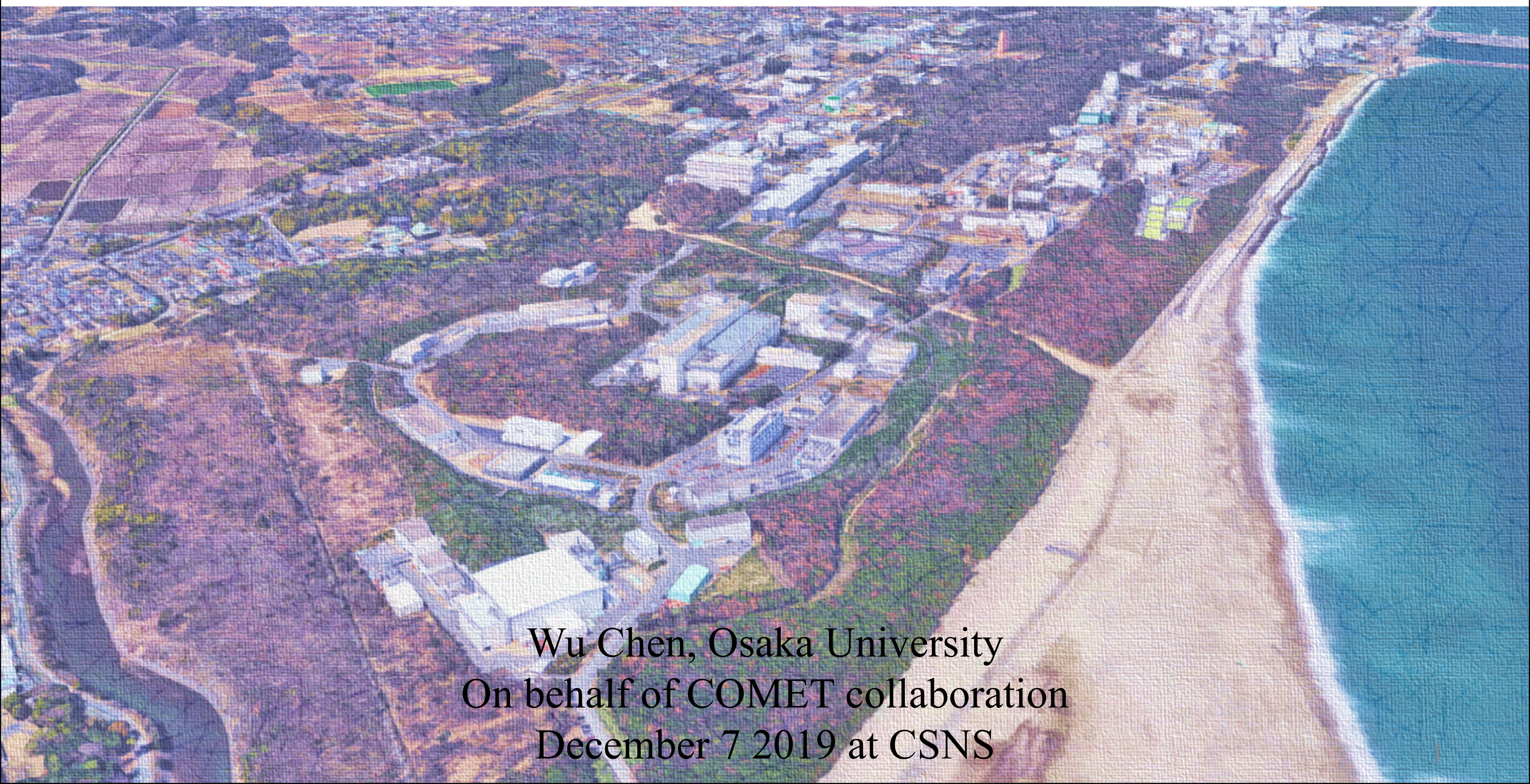
Review of COMET



Wu Chen, Osaka University
On behalf of COMET collaboration
December 7 2019 at CSNS

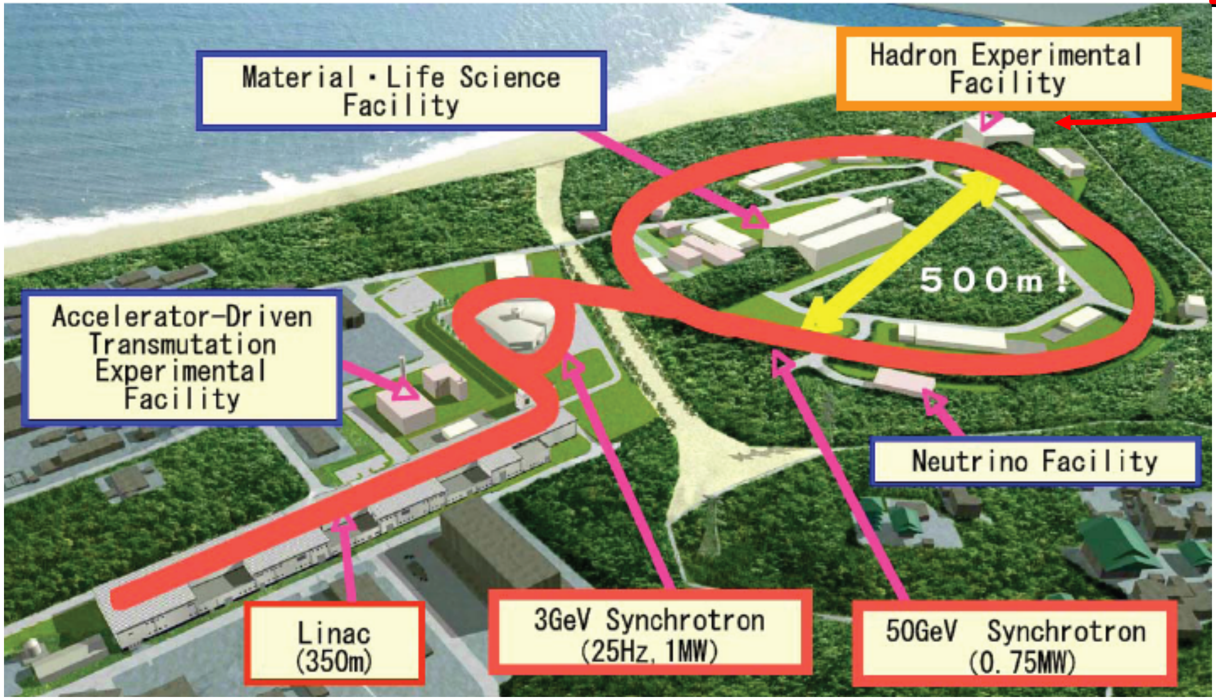
Outline

- About COMET
- Physics Motivation
- Design of the COMET Experiment
- Current Status of the COMET Experiment
- Summary

About COMET

COherent Muon Electron Transition

- Utilizing the proton source from J-PARC main ring, COMET searches for muon to electron conversion process which violates charged lepton flavor conservation.
  - $\mu^- N \rightarrow e^- N$
  - Signal electron is mono-energetic: ~105 MeV



- COMET aims at a single event sensitivity (S.E.S) = 2.6×10^{-17}
  - 4 orders of magnitude improvement!
  - Using slow extraction with 8 GeV proton at 56 kW

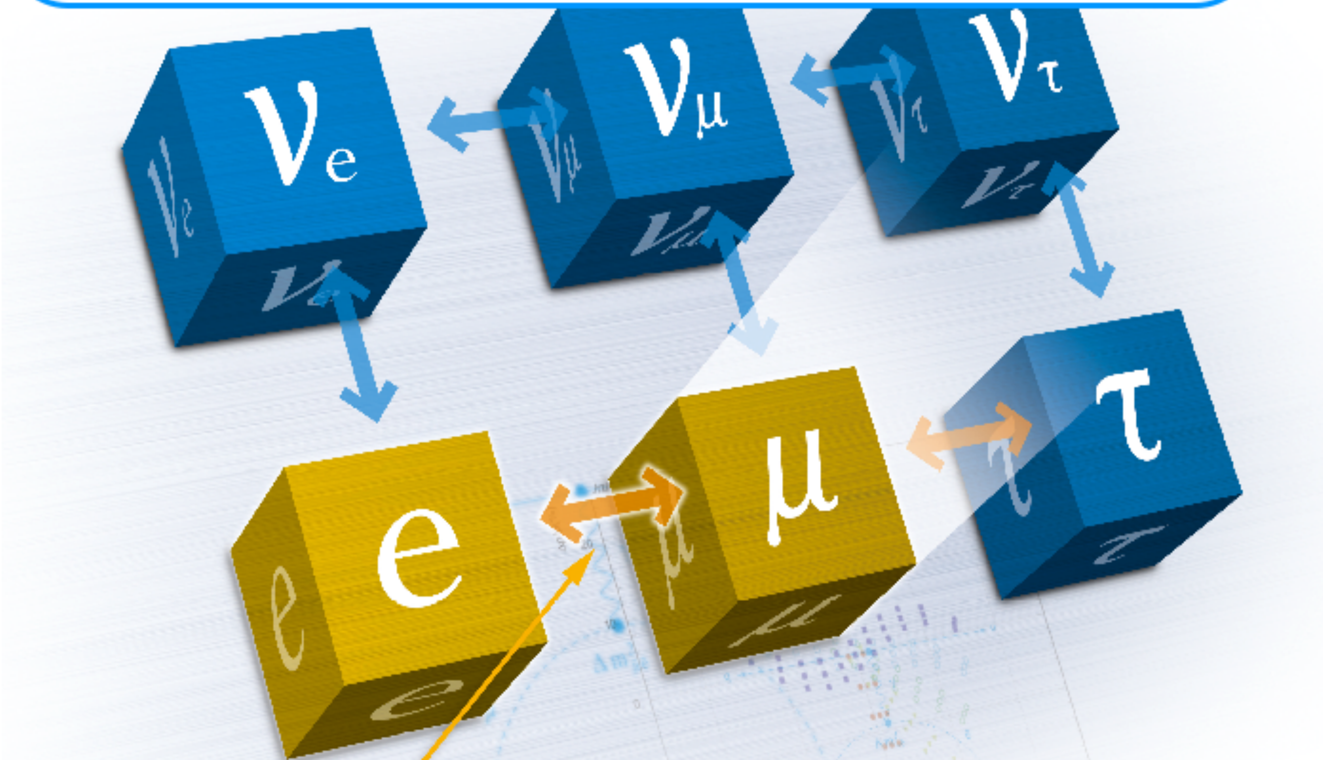
The COMET collaboration

Oct 2018, COMET collaboration meeting in Tbilisi

~200 members,
41 institutes from 17 countries
Still growing!

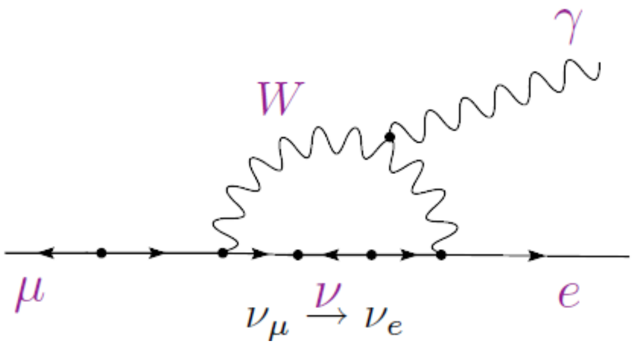
Physics Motivation

Neutrino Flavor Violation is observed !



charged Lepton Flavor Violation !? (cLFV)

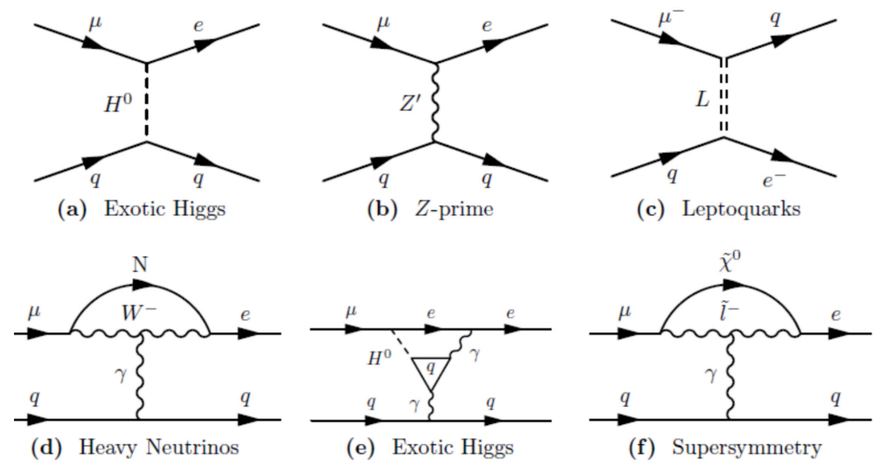
Charged Lepton Flavor Violation



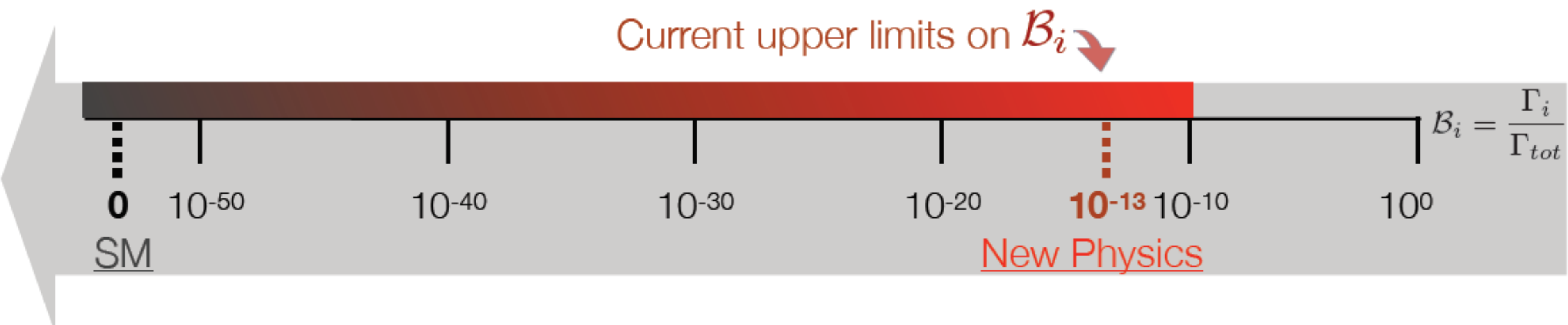
cLFV highly suppressed in SM+m_ν:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W^2} \right|^2 \sim 10^{-54}$$

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340



Yet widely predicted in NP models



Clean field to search for new physics!

New Physics Energy Scale of CLFV

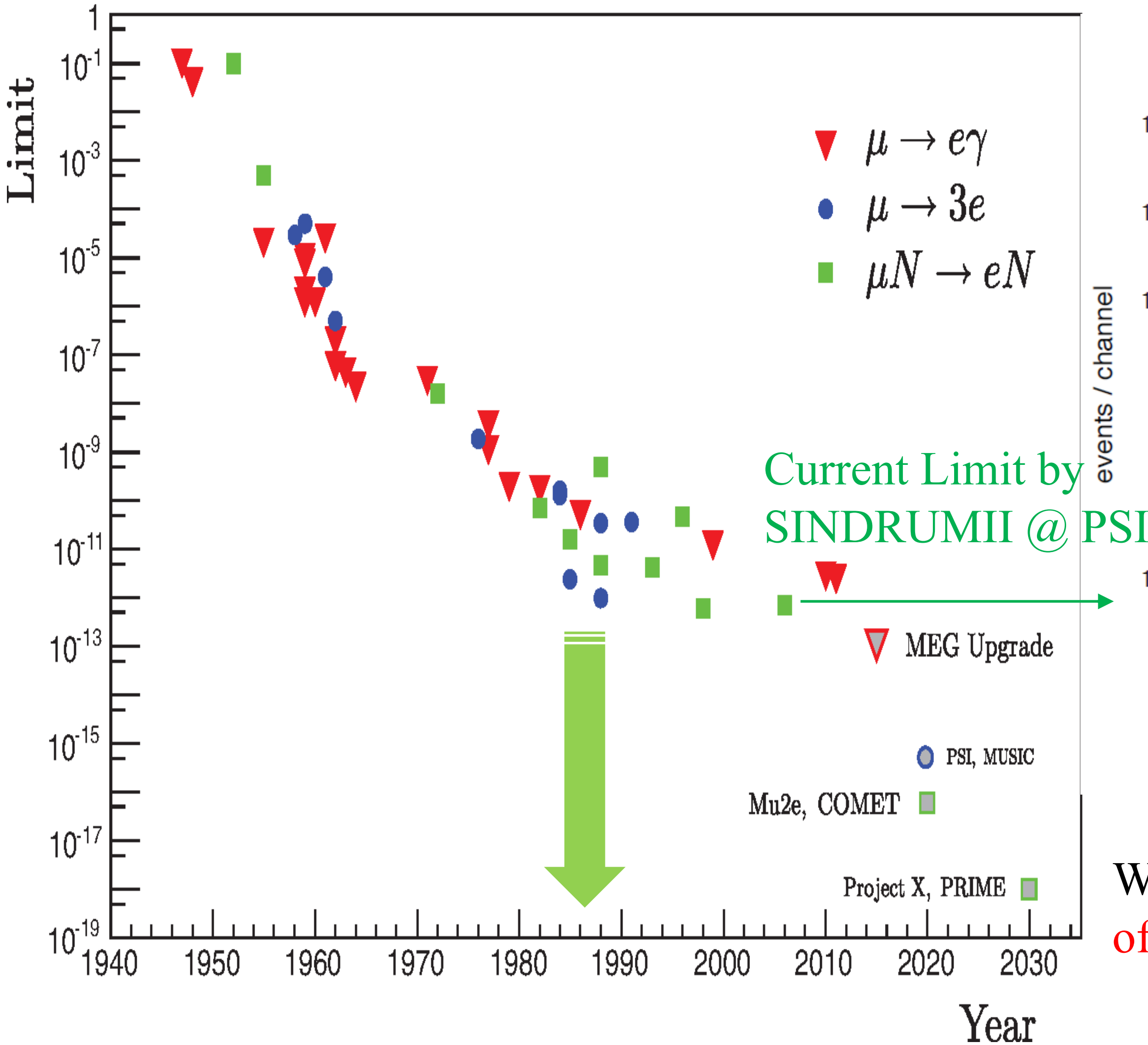
- Effective field theory approach $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n\geq1} \frac{C_{ij}{}^{4+n}}{\Lambda^n} \mathcal{O}^{4+n}$

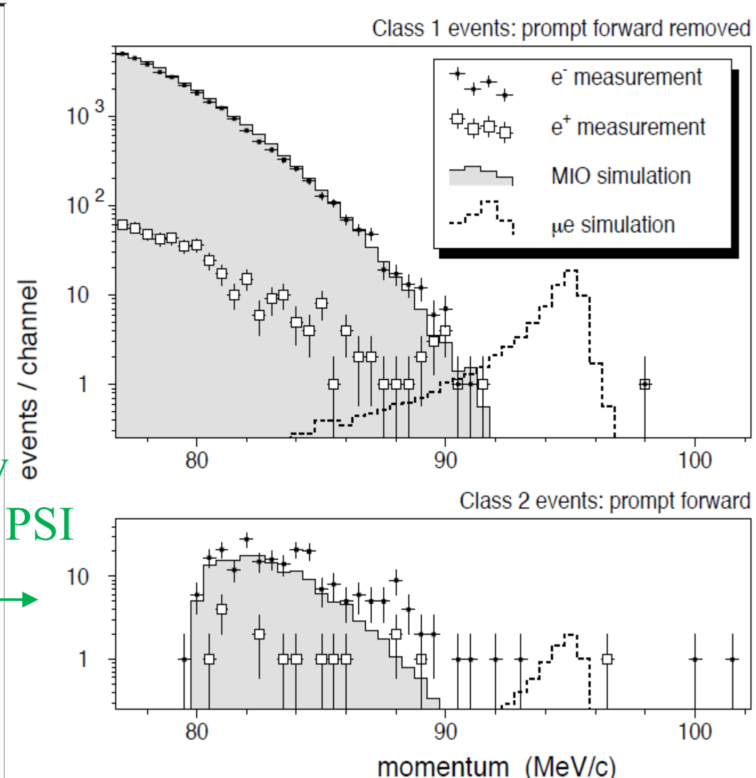
Current Limit	Experiment		$\lvert C_a \rvert$ [$\Lambda = 1$ TeV]	Λ (TeV) [$\lvert C_a \rvert = 1$]	CLFV Process
* 5.7×10^{-13}	*MEG*	$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^4	$\mu \to e\gamma$
Phys. Rev. Lett. **110**(20)		$C_{\ell e}^{\mu\mu\mu e, e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \to e\gamma$ [1-loop]
		$C_{\ell e}^{\mu\tau\tau e, e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \to e\gamma$ [1-loop]
1×10^{-12}	*SINDRUM*	$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^4	$\mu \to eee$
Nucl.Phys. B299 (1988)		$C_{\ell\ell, ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \to eee$
		$C_{\ell e}^{\mu eee, ee\mu e}$	3.3×10^{-5}	174	$\mu \to eee$
7×10^{-13}	*SINDRUMII*	$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^4	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
Eur.Phys.J. C47 (2006)		$C_{\ell q, \ell d, ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
* ***Current limit:*** 4.2×10^{-13}		$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^3	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
Eur.Phys.J. C76 (2016)		$C_{\ell u, eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$

F. Feruglio, P. Paradisi and A. Pattori, Eur. Phys. J. C 75 (2015) no.12, 579
G. M. Pruna and A. Signer, JHEP 1410 (2014) 014

- Given Dim-6 operators (lowest possible order for CLFV), factor 10,000 in precision = factor 10 in energy scale.

Search for Muon to Electron Conversion

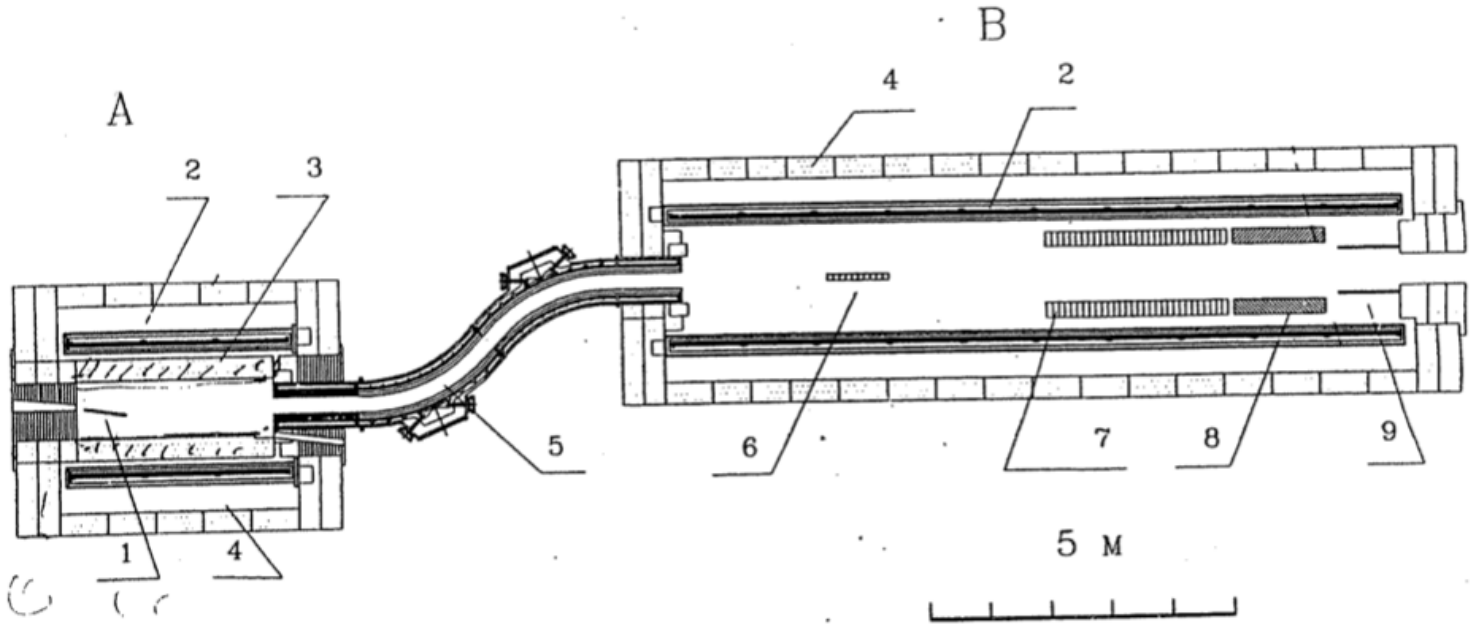




Eur.Phys.J. C47 (2006) 337-346

With a different design, > 4 orders of magnitude improvement is possible!

Design of the COMET Experiment



MELC

The "new idea": MELC

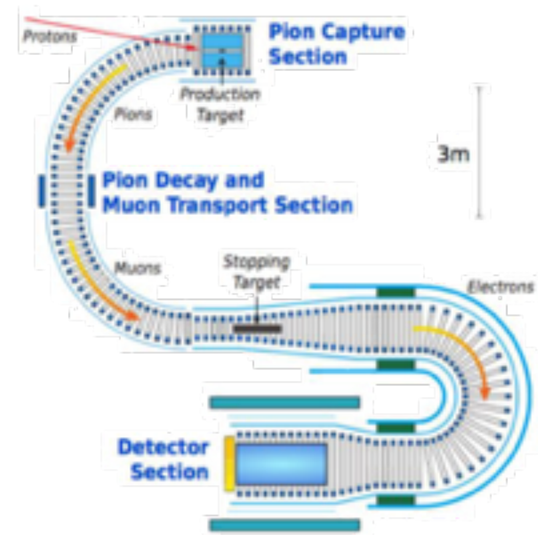
PREPRINT INR – 786/92
NOVEMBER 1992

V.S. Abadjev, B.N. Bakhtin, O.N. Goncharenko, R.M. Djilkibaev,
V.V. Edlichka, V.M. Lobashev, V.I. Parfenov, I.A. Plisco,
V.V. Popov, S.K. Popov, A.L. Proscuryakov, I.V. Sekachev,
A.K. Skasyrskaya, O.B. Sokolova, A.P. Solodukhin,
A.N. Toropin, S.P. Toropov

MELC EXPERIMENT TO SEARCH FOR THE $\mu^- A \to e^- A$ PROCESS

MECO

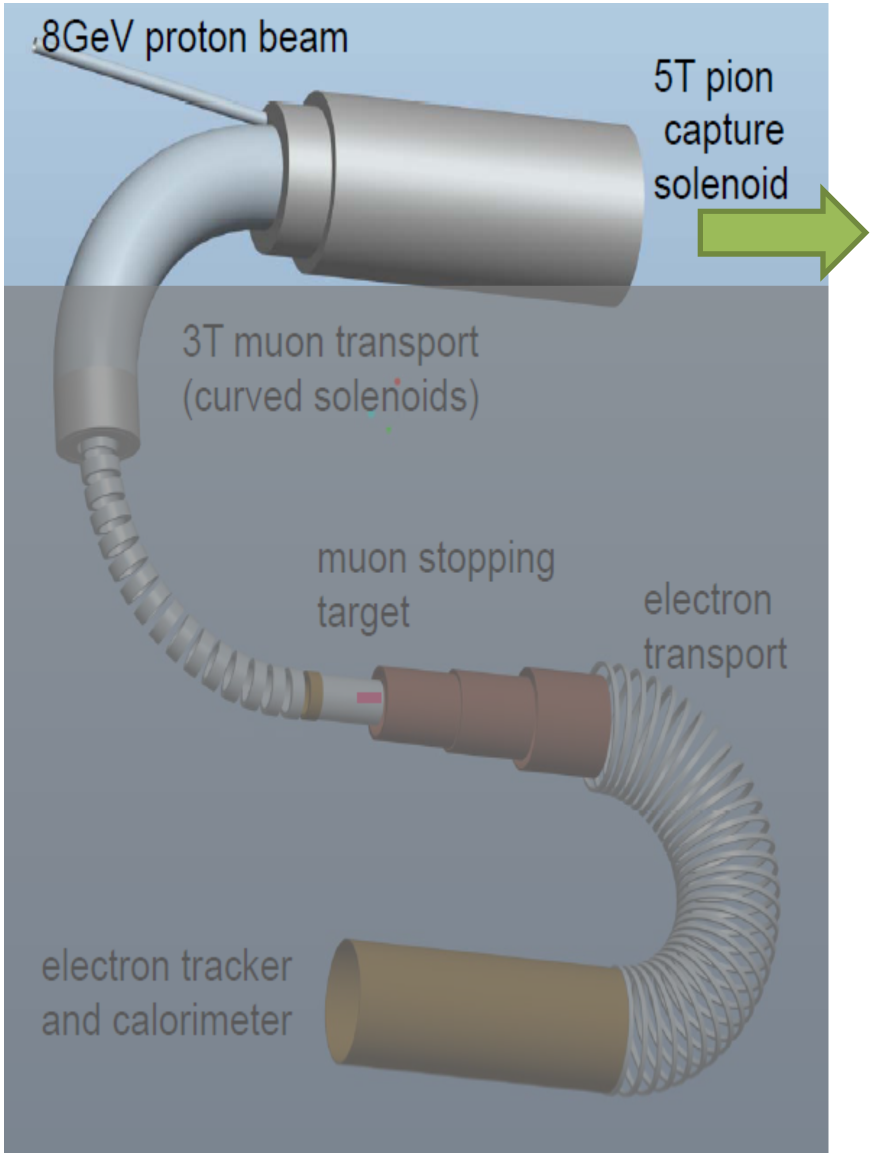
Mu2e

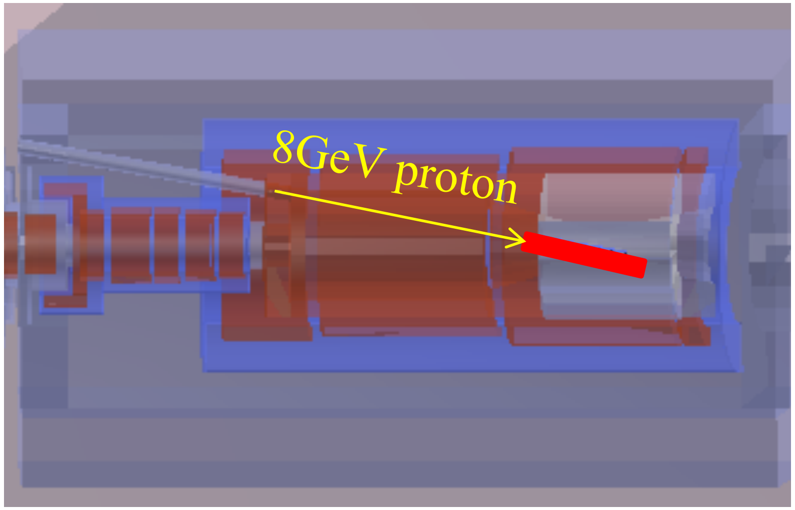


COMET

- Improve the production and capture efficiency
  - Thick target with super conducting solenoid as capture magnet
- Clean muon beam
  - Long beam line with momentum selection
- Search for signal with the special momentum
  - Light detector to provide precise measurement

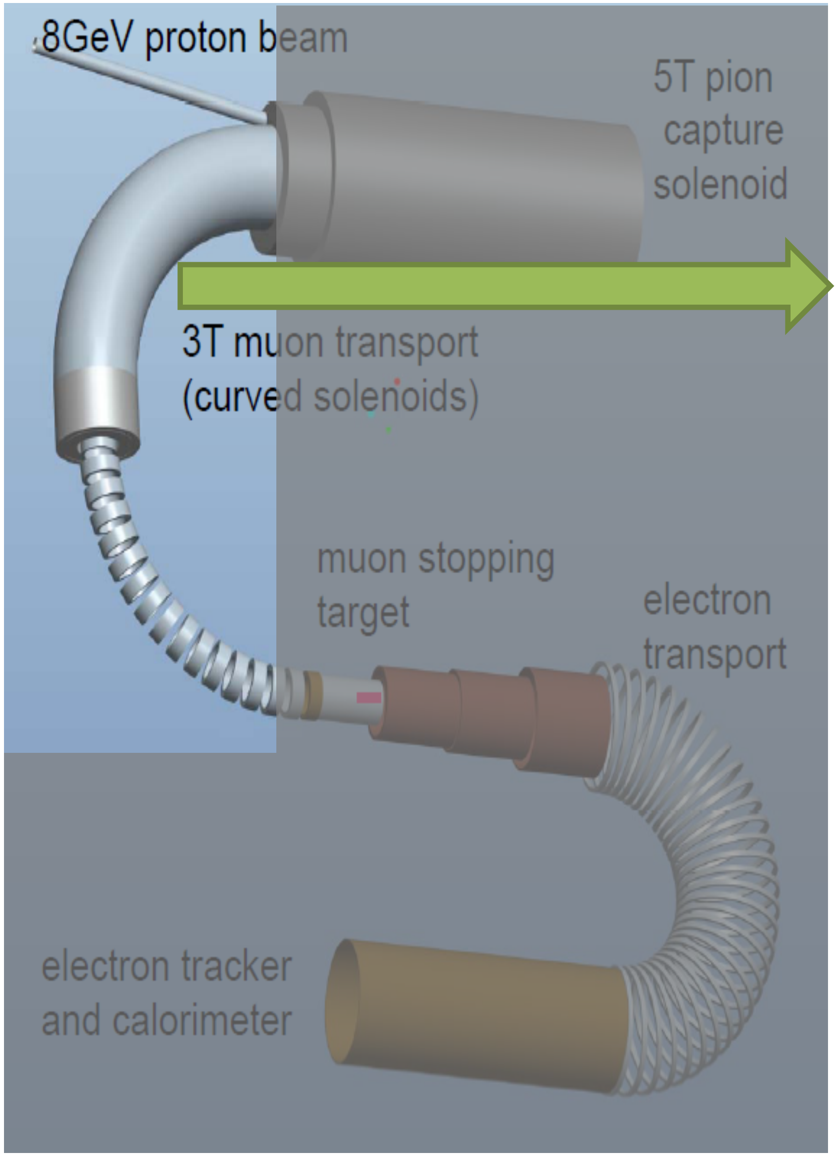
Production target and the capture magnet

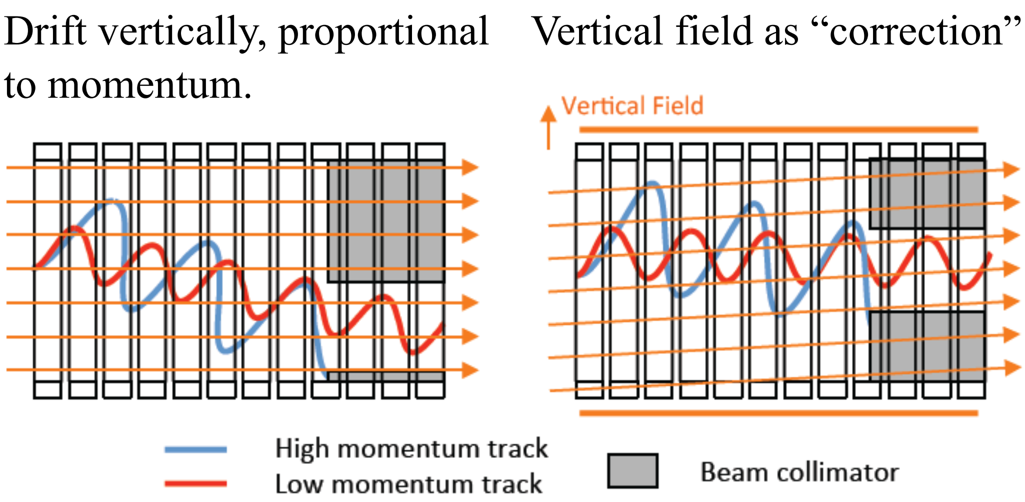




- 8 GeV 56 kW proton beam
- Thick target with 1~2 hadron interaction length
- Powerful capture magnet: 5 T
  - Large inner bore to fit in the shielding
  - Adiabatic decreasing field: focusing and mirroring
- Expected muon yield: 10^{11} muon/sec! (10^{8} @ *PSI*)

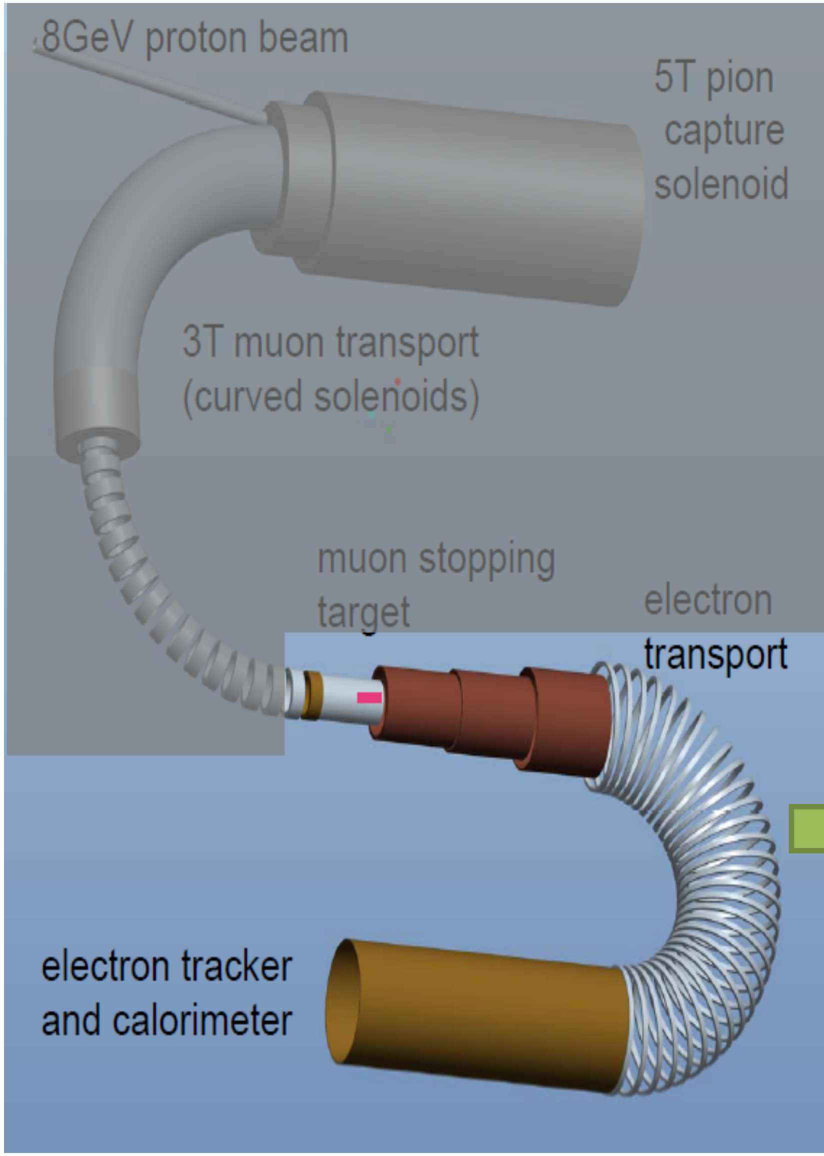
Transportation solenoid



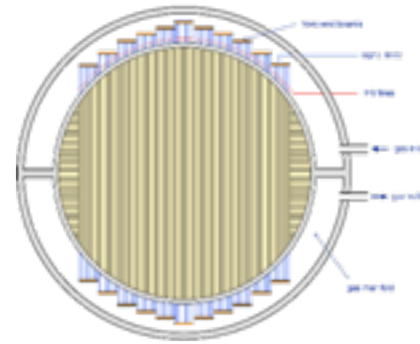


- Use C shape curved solenoid
  - Beam gradually disperses
    - Charge & momentum
  - Dipole field to pull back muon beam
    - Can be used to tune the beam
  - Collimator placed in the end
    - Utilize the separation in 180 degrees

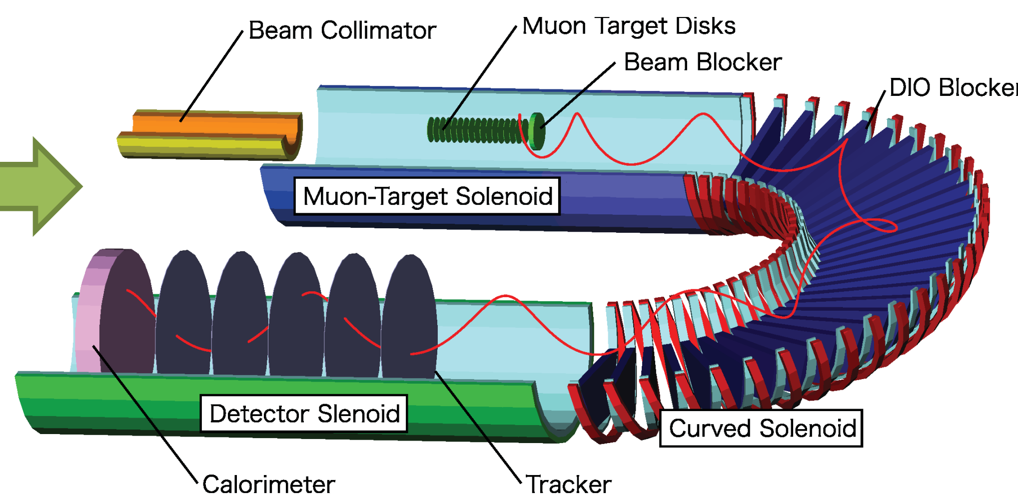
Stopping target and detector system



- Use straw tracker to measure the momentum
  - Really light: put in vacuum, 12 micro meter thin straw

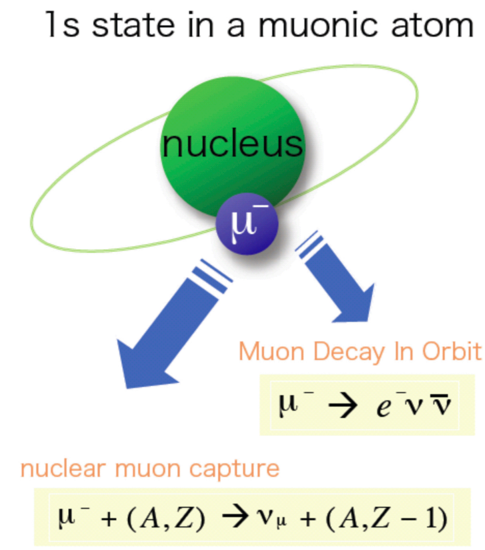


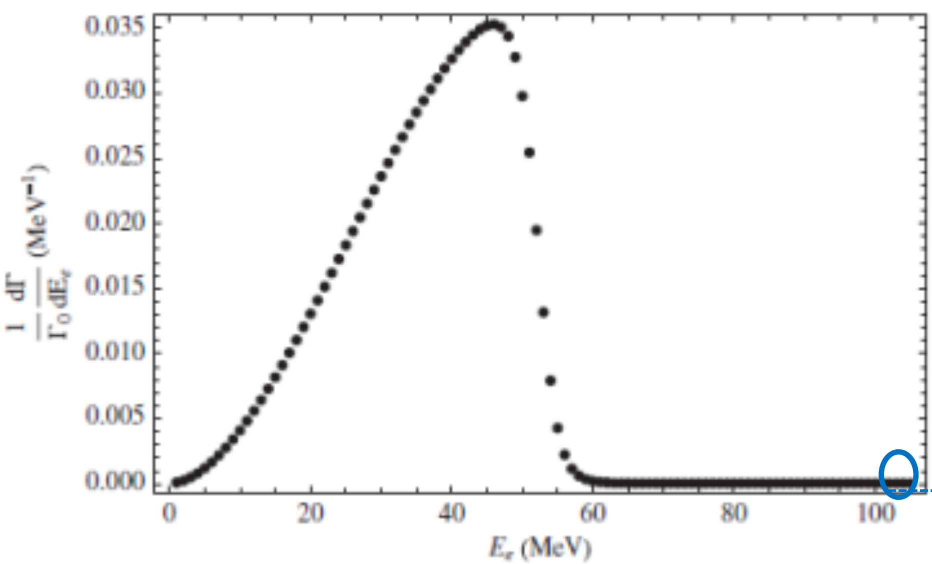
- Electromagnetic calorimeter
  - Providing trigger, TOF and PID

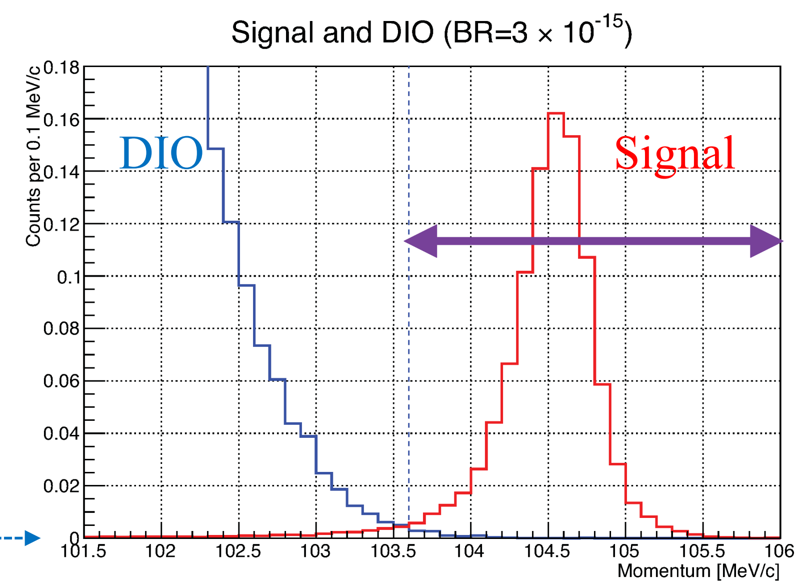


To control the background

- Intrinsic physics background
  - Mostly from muon decay in orbit (DIO)
    - Calculated by Czarnecki with radiative correction. Branching ratio drops with order-5 function near end point.
    - Momentum resolution required to be better than 200 keV/c
      - little false tracking may cause big problems!

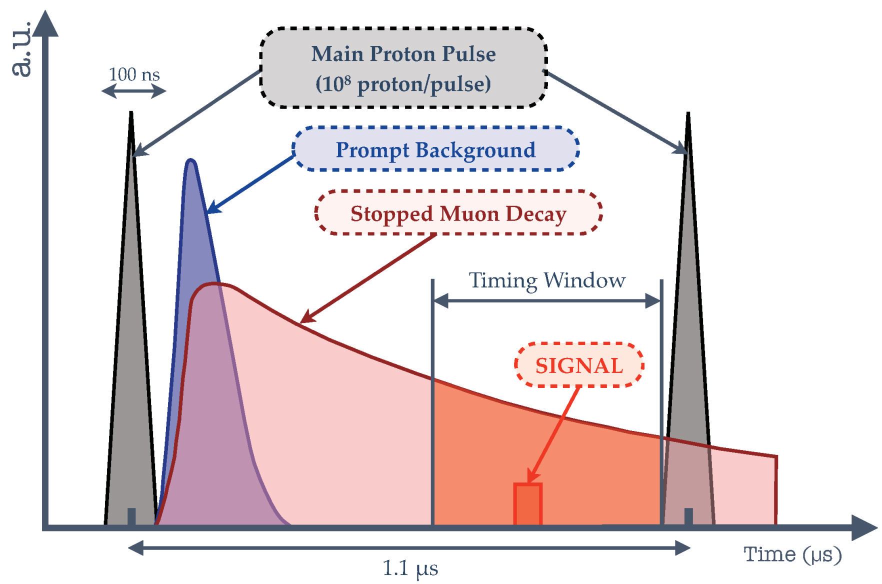






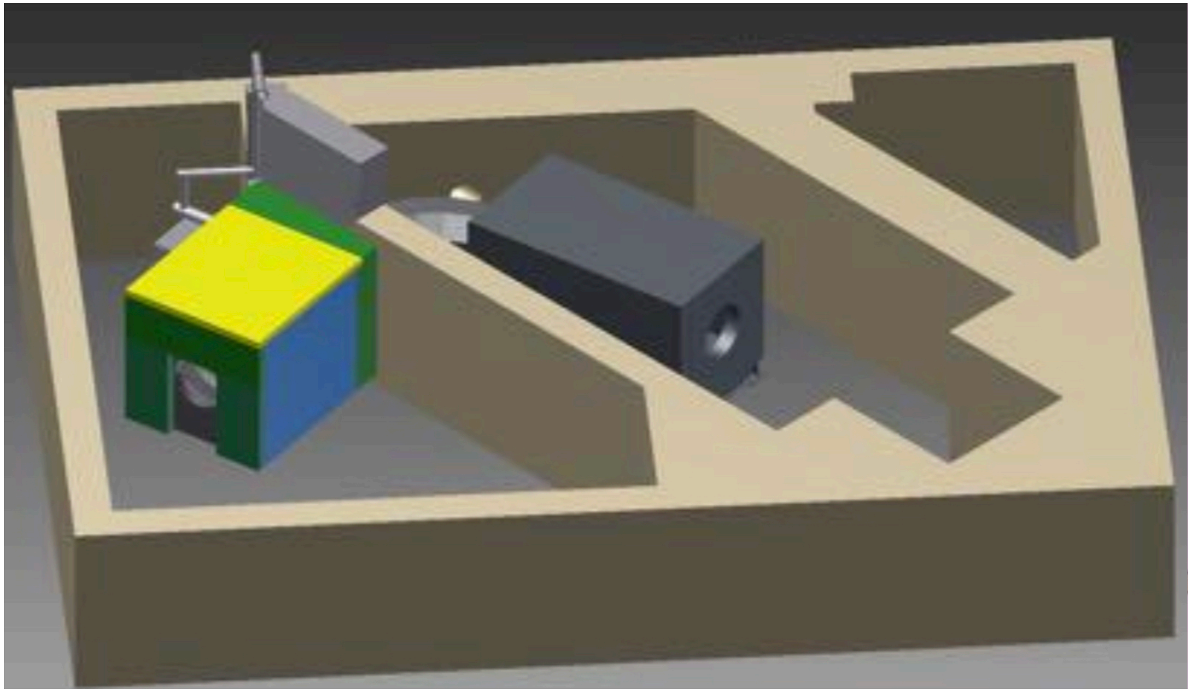
To control the background

- Beam related background
  - Energetic particles in beam with E>100MeV
    - Mostly prompt. Can be suppressed by a delayed measurement window (~700 ns)
      - Raise a requirement to stopping target material: lifetime of muonic atom should be long enough.
      - Decided by pions. Longer beamline can help.
    - Some due to leaked proton. Proton extinction factor required to be $< 10^{-10}$。



To control the background

- Cosmic ray background
  - Cosmic muon may introduce ~105 MeV electrons in detector.
  - Solution: cover the system with cosmic ray veto detectors. Expecting veto efficiency > 99.99%.
  - Radiation level is the challenge towards higher intensity.

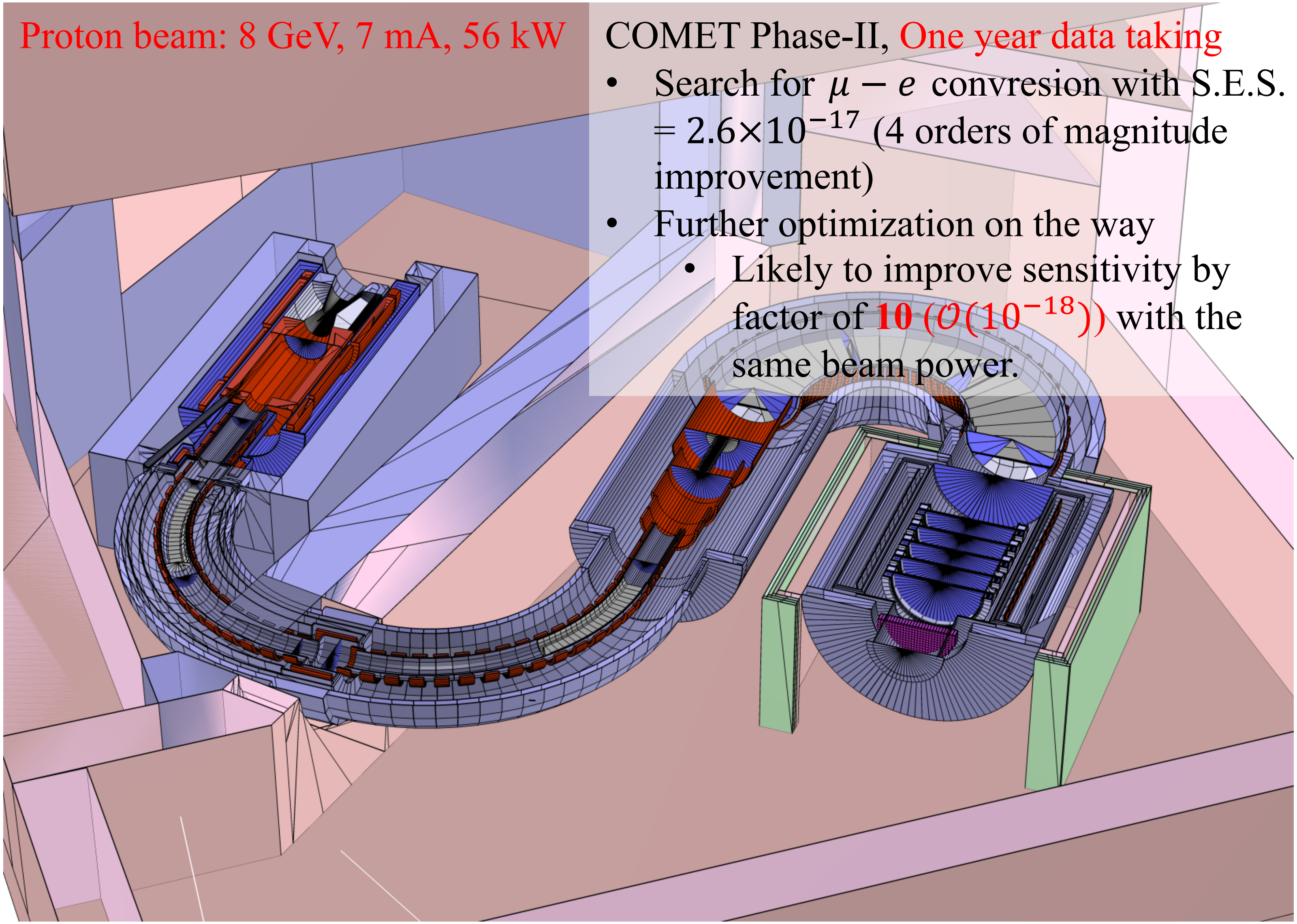


Physics Sensitivity

Proton beam: 8 GeV, 7 mA, 56 kW

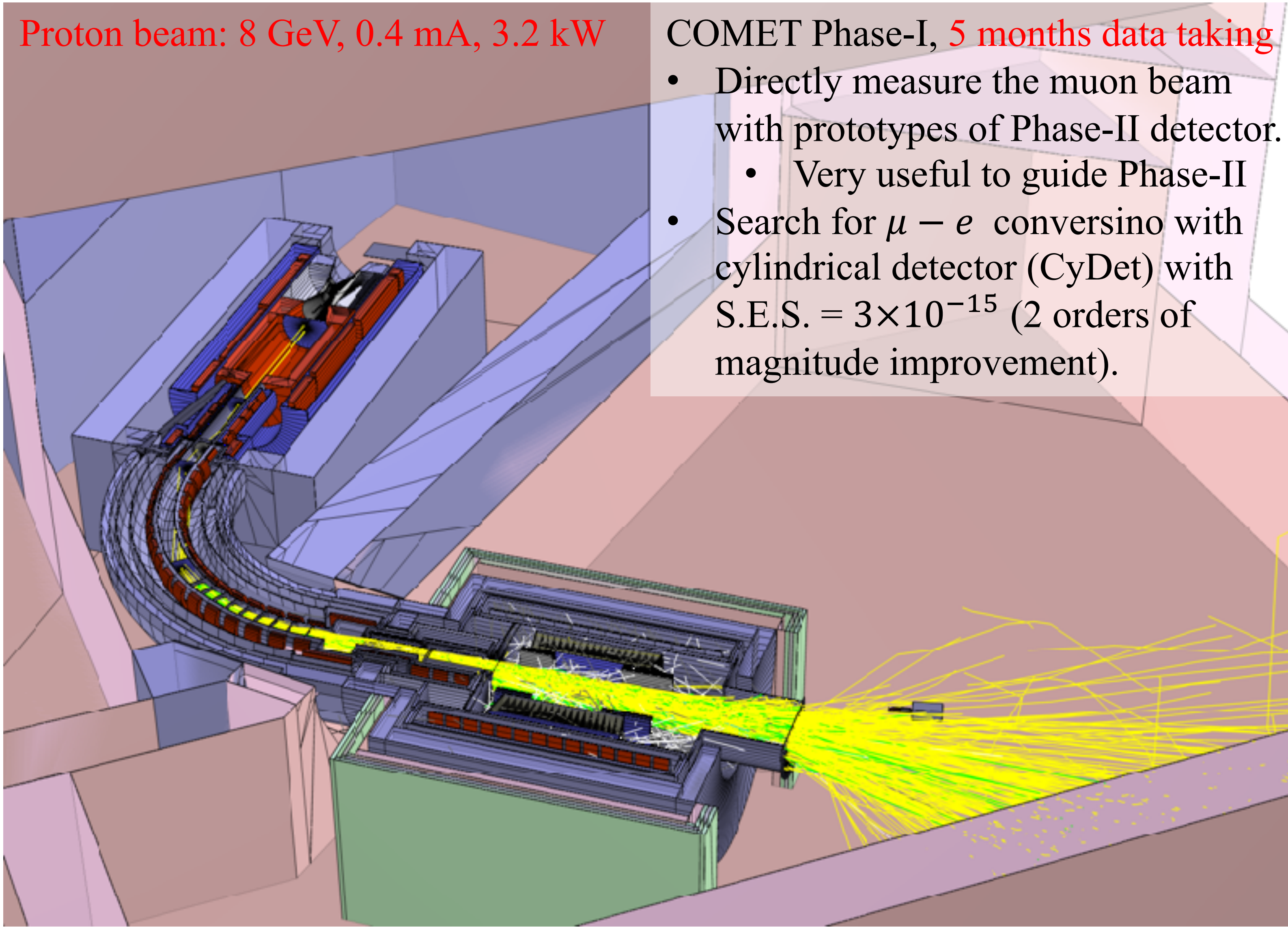
COMET Phase-II, One year data taking

- Search for $\mu - e$ convresion with S.E.S. $= 2.6\times10^{-17}$ (4 orders of magnitude improvement)
- Further optimization on the way
  - Likely to improve sensitivity by factor of **10** ($\mathcal{O}(10^{-18})$) with the same beam power.



Simulation in Geant4 using software framework ICEDUST

Staged plan of COMET



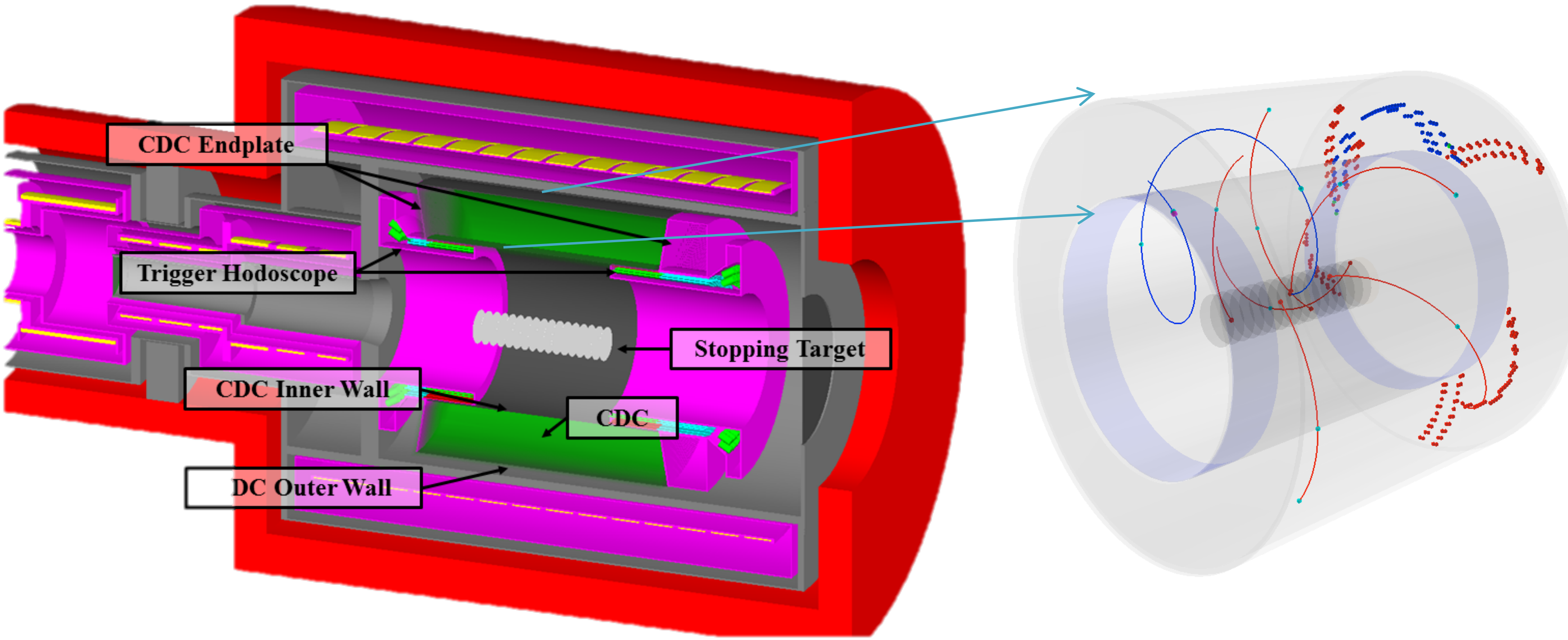
Proton beam: 8 GeV, 0.4 mA, 3.2 kW

COMET Phase-I, 5 months data taking

- Directly measure the muon beam with prototypes of Phase-II detector.
  - Very useful to guide Phase-II
- Search for $\mu - e$ conversino with cylindrical detector (CyDet) with S.E.S. = 3×10^{-15} (2 orders of magnitude improvement).

Simulation in Geant4 using software framework ICEDUST

Cylindrical Detector (CyDet)

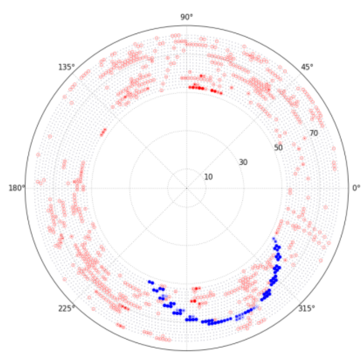


- Specially designed for Phase-I. Consists of:
  - Cylindrical trigger hodoscope (CTH):
    - Two layers: plastic scintillator for t0 and Cerenkov counter for PID.
  - Cylindrical drift chamber (CDC):
    - All stereo layers: z information for tracks with few layers' hits.
    - Helium based gas: minimize multiple scattering.
    - Large inner bore: to avoid beam flash and DIO electrons.

Monte Carlo study of COMET Phase-I

- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies. TDR was accepted by PTEP.
  - Sensitivity:
    - Total acceptance of signal is 0.041
    - Can reach 3×10^{-15} SES in 150 days.
  - Background:
    - With 99.99% CRV total expected background is 0.032
  - Trigger rate:
    - Average trigger rate ~10kHz (after trigger with drift chamber hits)

Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window ($\varepsilon_{\mathrm{mom}}$)	0.93
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3
Total	0.041



Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

Other Physics Topics on COMET

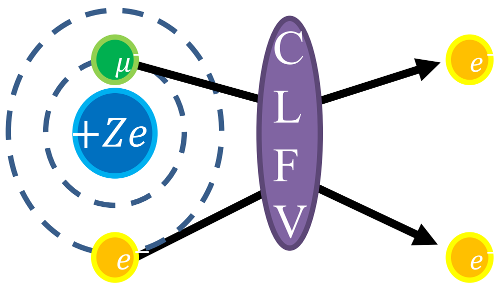
- $\mu^- N_z \rightarrow e^+ N_{Z-1}$: Lepton number violation (LNV)
  - Current limits: $\mu^-\ Ti \rightarrow e^+\ Ca(gs) \leq 1.7 \times 10^{-12}$
    $\mu^-\ Ti \rightarrow e^+\ Ca(ex) \leq 3.6 \times 10^{-12}$
  - Can improve with a proper target

Phys. Lett. B422 (1998)

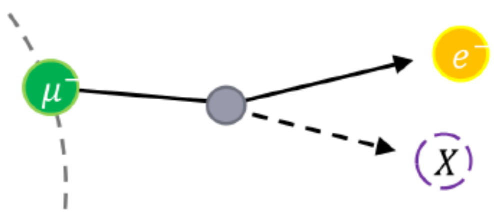
Phys. Lett. B764 (2017)
Phys. Rev. D96 (2017)

- $\mu^- e^- \rightarrow e^- e^-$: μ^- and e^- overlap proportional to Z^3

Phys. Rev. Lett. 105 (2010)
Phys. Rev. D93 (2016) 076006
Phys. Rev. D97 (2018) 015017

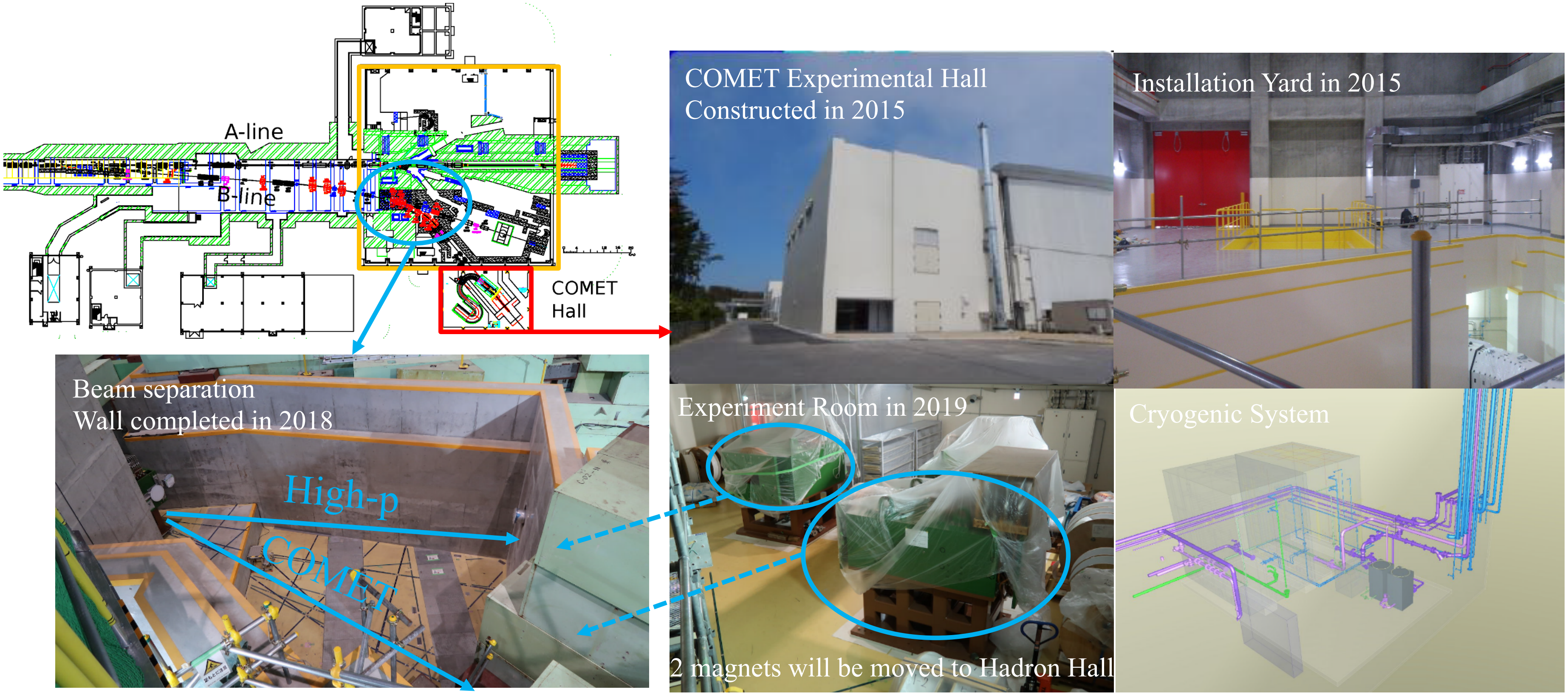


- $\mu^- \rightarrow e^- X$: X can be a new light boson, axion, etc.
  - feasibility being studied in COMET



Current Status of the COMET Experiment

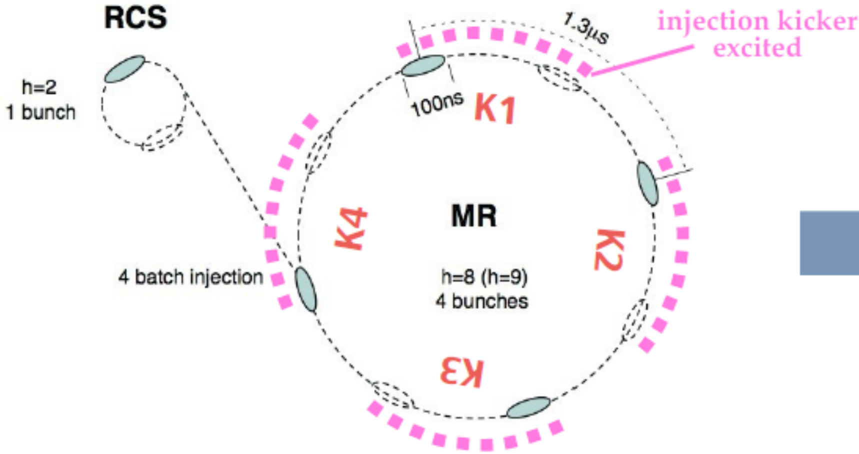
COMET Facility

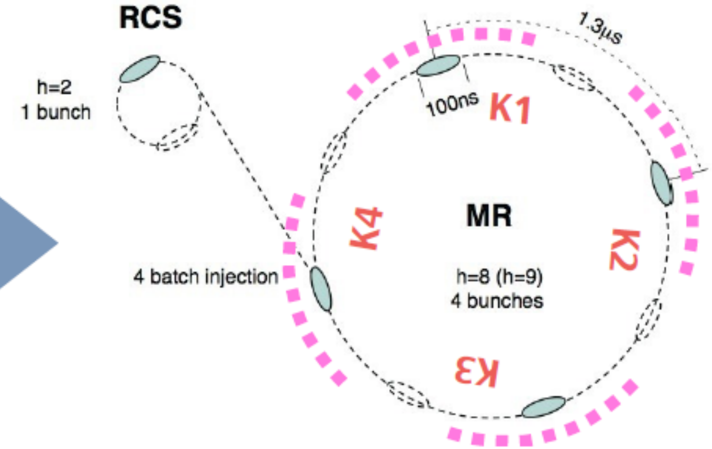


- Experimental Hall building completed
- Cryogenic system under construction
- Proton beamline will be ready this year
  - Shield wall & power station completed. 2 more magnets to be located soon.

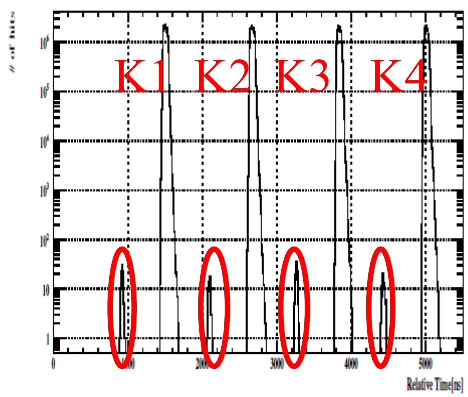
Proton beam from J-PARC MR

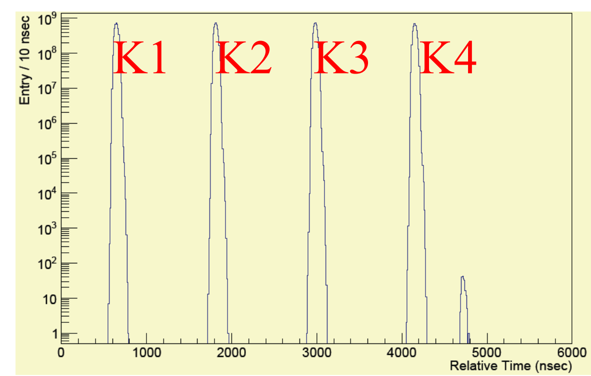
- To make the proton extinction factor $< 10^{-10}$
  - Shift the kicker phase by half period to avoid residual protons in the empty bucket.





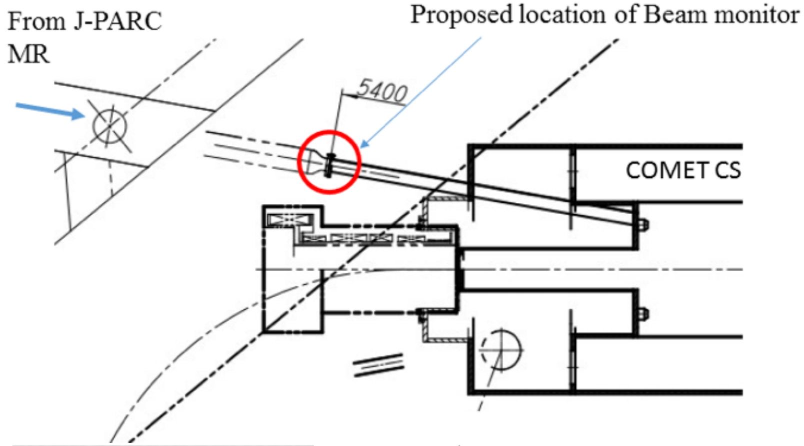
- Tested SX in early 2018, proton extinction factor $< 6\times10^{-11}$

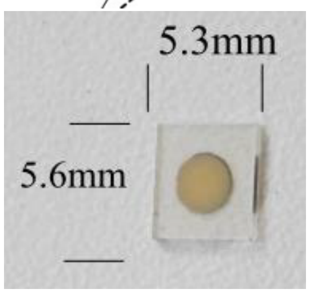


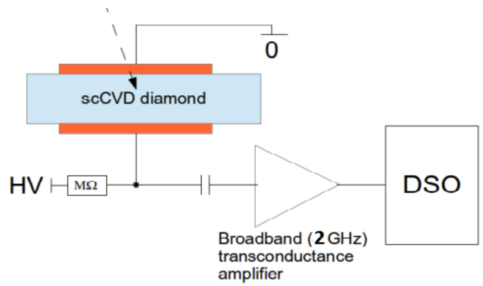


**The rear end small peak is solved this year!*

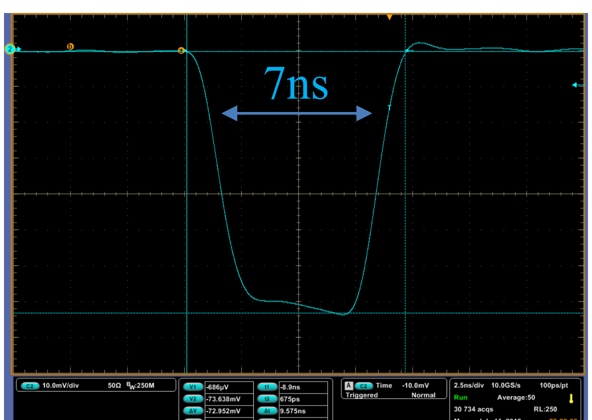
Proton Beam Monitor

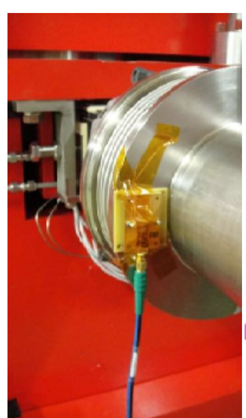


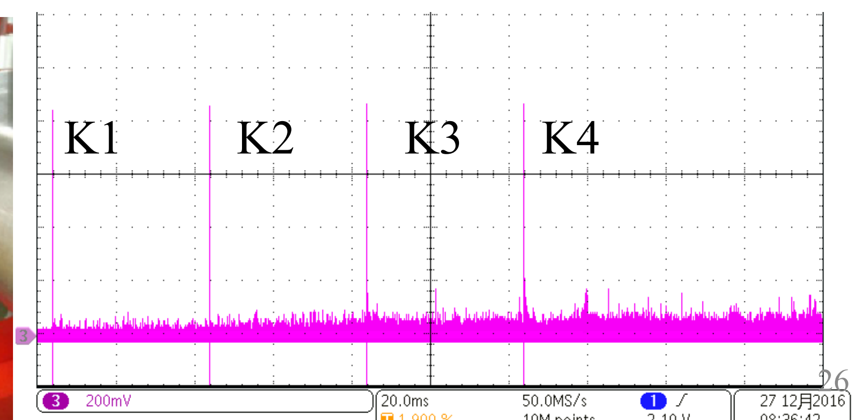




- Measure the proton beam profile and monitor extinction
  - First attempt to get real time profile for such intense beam!
- **Diamond semiconductor**
  - High radiation tolerance
  - Simple geometry
  - Fast response
- Tested at J-PARC main ring
  - Excellent timing response
- Considering backup plans:
  - Gallium Nitride
  - TiO2 nanotube arrays

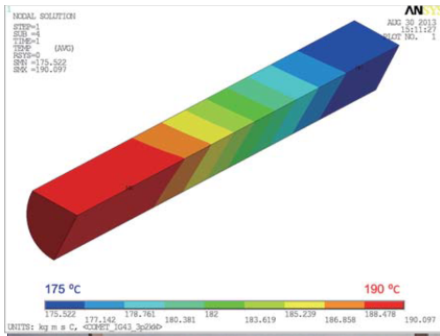


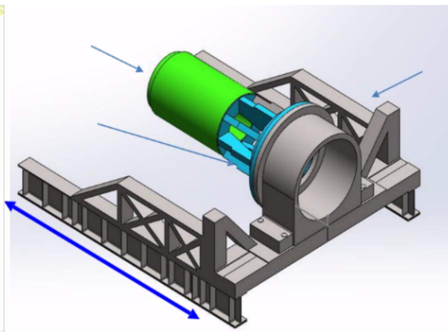


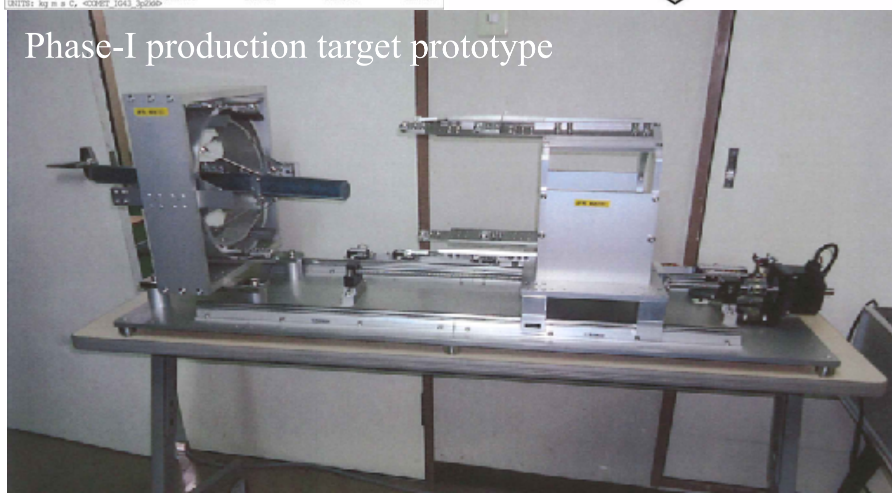


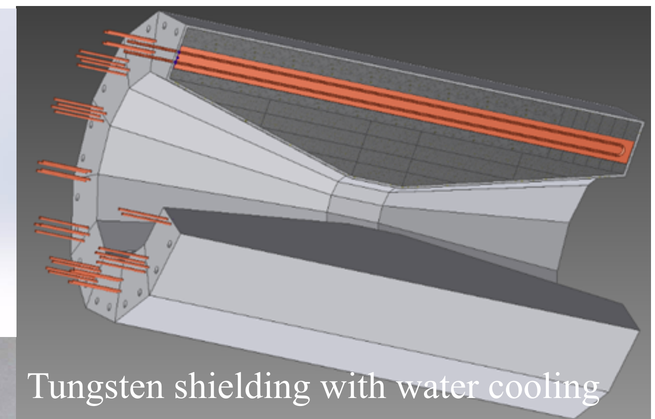
Production Target System

- Phase-I graphite target (IG-43) can be cooled by radiation with 3.2 kW beam.
- Remote handling and cask design of target is in progress.
- Shielding blocked with water cooling is being designed.

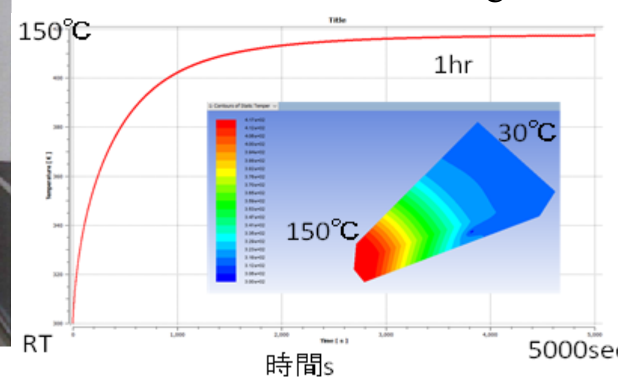




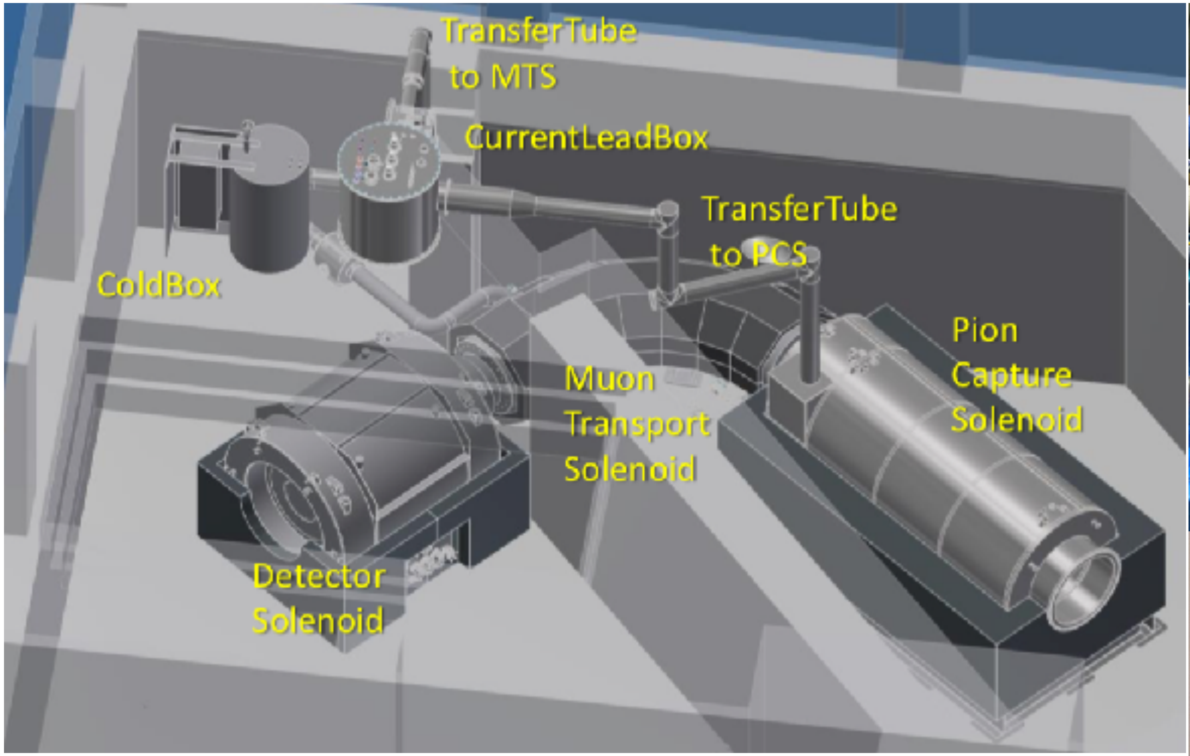

Phase-I production target prototype

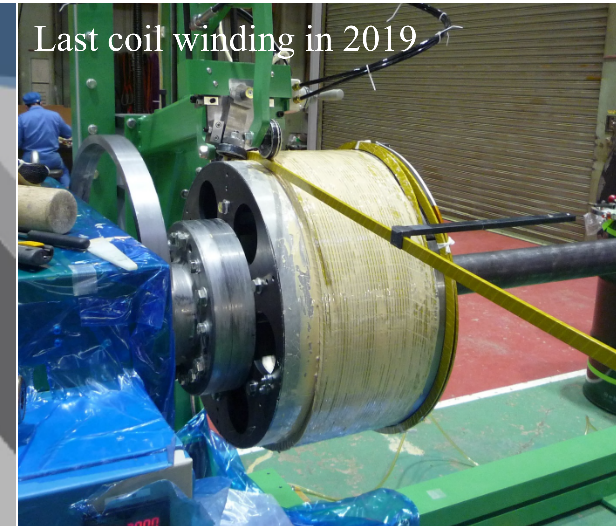

Tungsten shielding with water cooling

27 °C 3 m/s inlet water is enough to cool the block



Solenoids

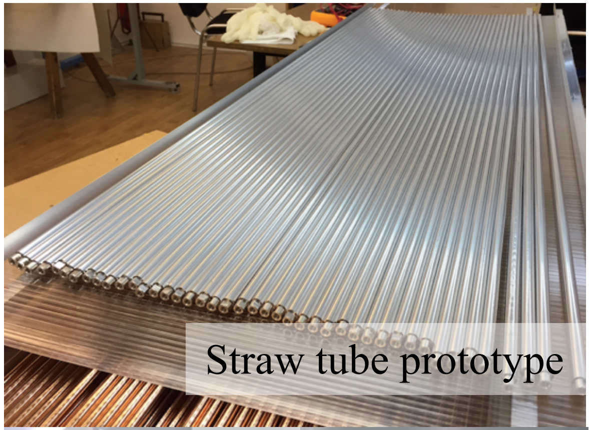


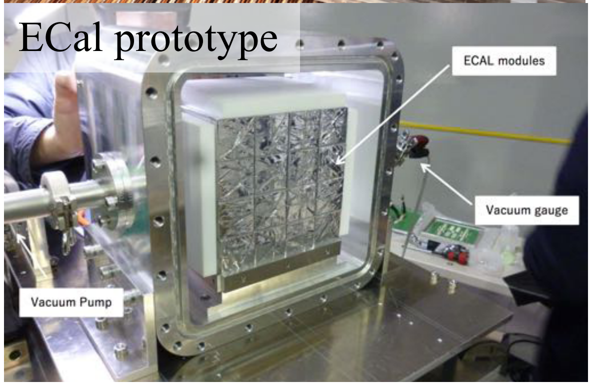


- Capture solenoid
  - Last coil under winding.
- Transport solenoid
  - Installed and ready for cryogenic test.
- Bridge & detector solenoid
  - DS coil and cryostat ready. BS coil delivered.
- Cryogenic system:
  - Refrigerator test completed.
  - Helium transfer tube in production.

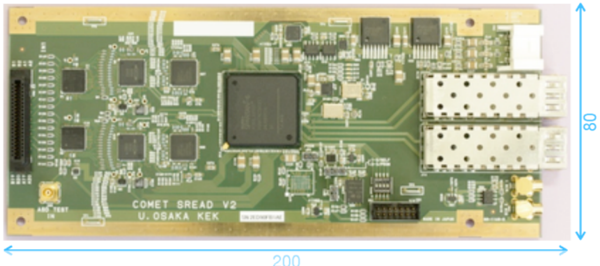
StrEcal

- Straw tube detector
  - Finished vacuum test with 20 um straw tubes.
  - Mass production for Phase-I finished.
  - Tested with 100 MeV electron beam. 150 um spatial resolution achieved.
- Electromagnetic calorimeter
  - Tested GSO and LYSO. Preliminary resolutions are 5.7% and 4.6% for each. LYSO chosen as final option.
- Front end electronics
  - Finished designing (ROESTI/EROS) based on DRS4 with GHz sampling rate.
  - Radiation tests results published.


Straw tube prototype



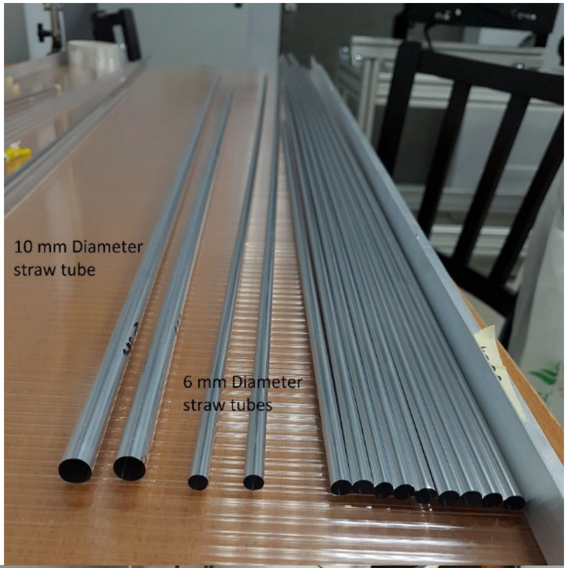
ECal prototype

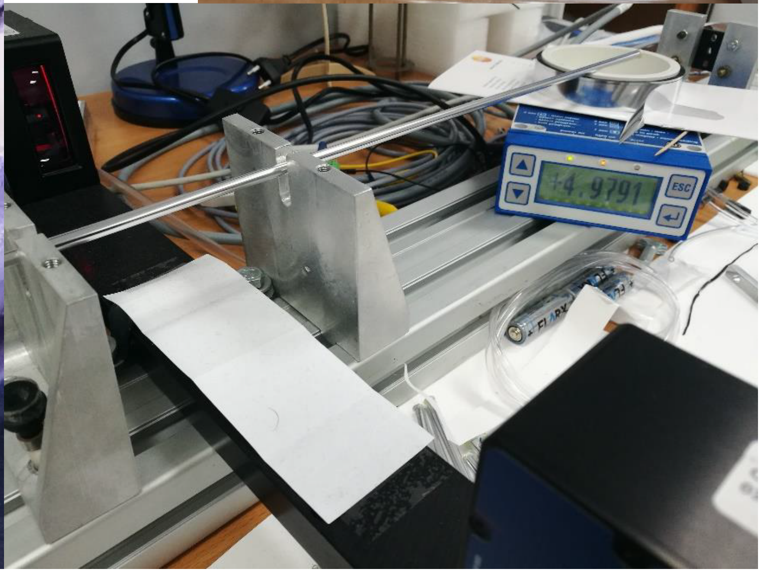


Front end electronics: ROESTI/EROS

R&D of straw for Phase-II

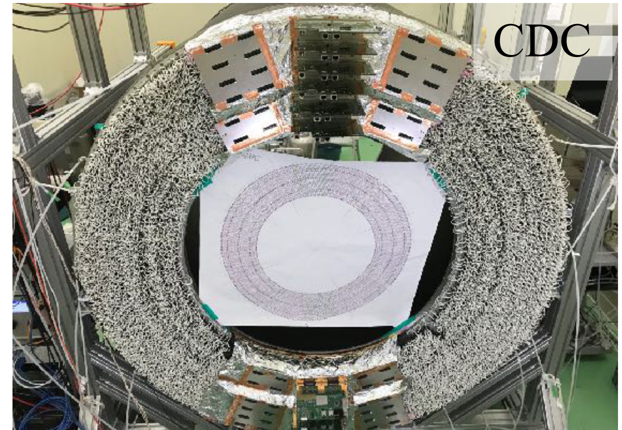
- 12 micro meter thin straw produced for Phase-II!
- Diameter 5 mm
  - 1 bar overpressure straw tube diameter measurement shows 0.1 um accuracy.
- Over pressurization test holding more then 4 bar

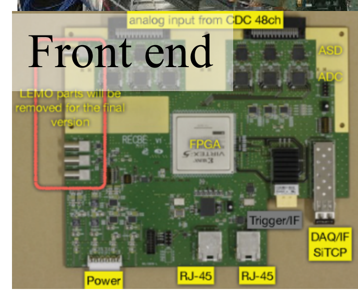


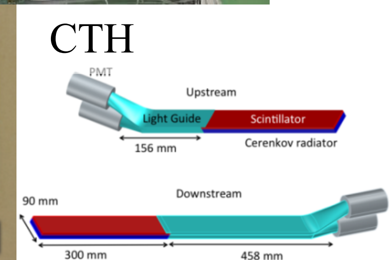


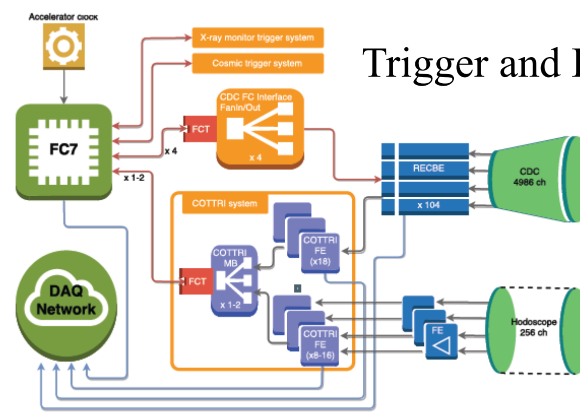
CyDet

- Cylindrical Drift chamber (CDC)
  - Prototype tests finished in 2015. 150 um spatial resolution and 99% hit efficiency were achieved.
  - Construction of the chamber was finished in 2016.
  - Cosmic ray test is under data taking phase.
- Front end electronics
  - Based on RECBE boards from BELLE-II
  - Finished the production and mass tests of 108 boards.
  - Radiation tests are published / to be published.
- Trigger system
  - Cylindrical trigger hodoscope (CTH) under mechanical design.
  - Trigger logic and trigger board design finished. Communication tests with FCT-FC7 trigger system is on going.

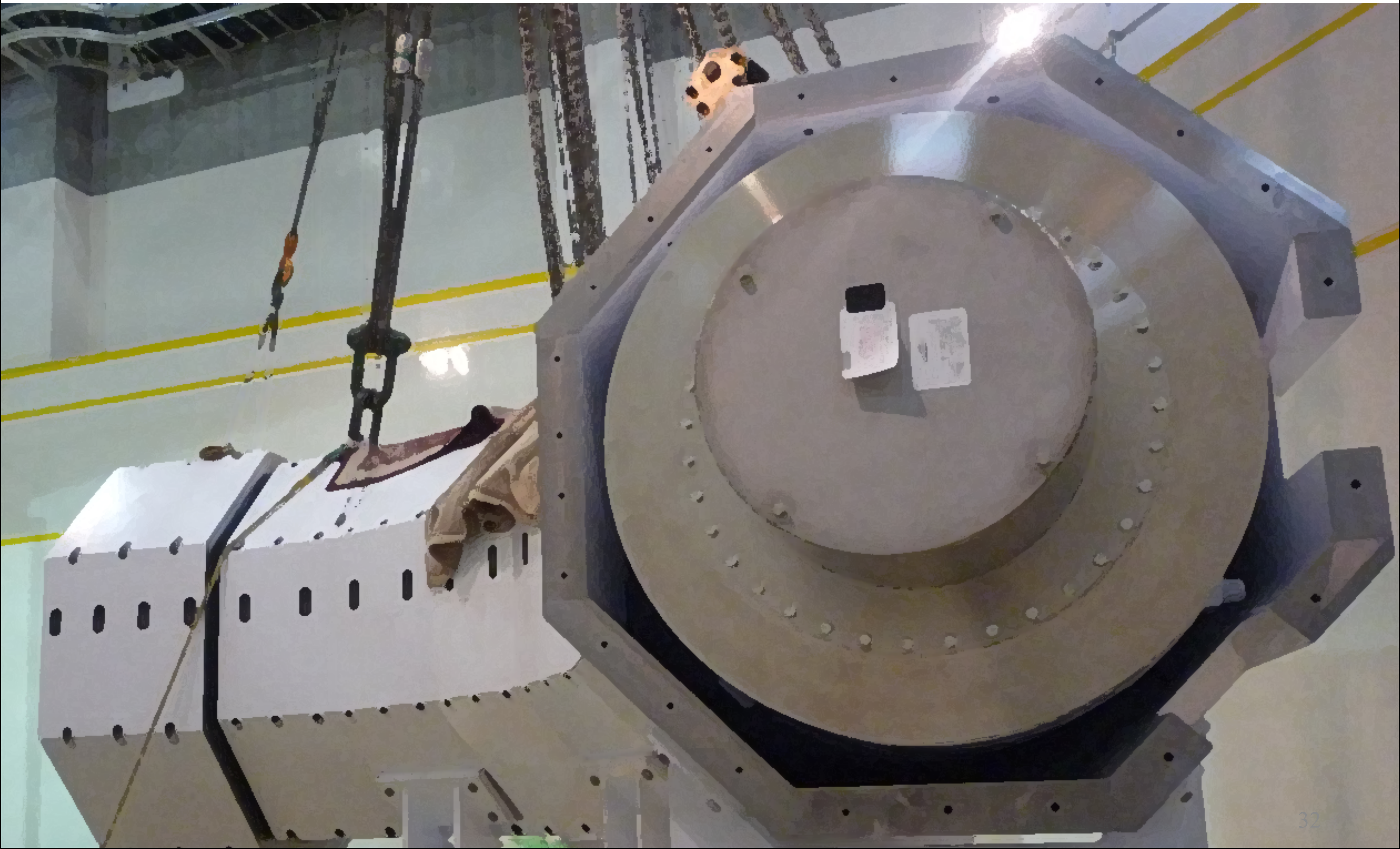






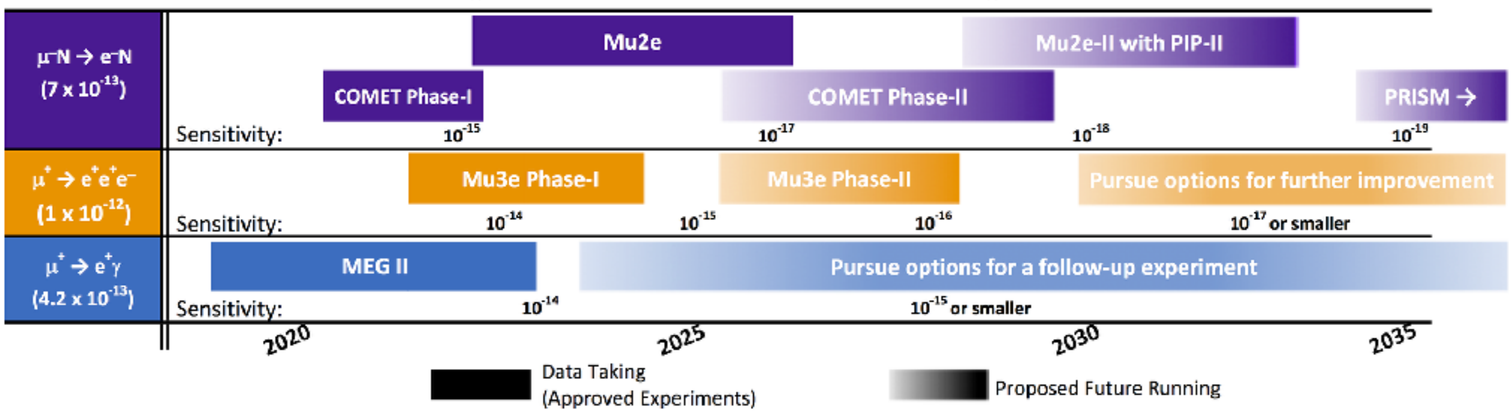


Summary



- COMET is an experiment at J-PARC searching for muon to electron process.
  - Aims at S.E.S = 2.6×10^{-17} (4 orders of magnitude improvement) with 1 year beam time using 56 kW 8 GeV proton beam.
  - With the same beam power, **10** times better sensitivity ($\mathcal{O}(10^{-18})$) is likely and optimization is on the way.
- COMET will be carried out in two phases and Phase-I is under construction.
  - Aims at S.E.S = 3×10^{-15} (2 orders of magnitude improvement) with 150 days beam time using 3.2 kW 8 GeV proton beam.
  - Will directly measure the muon beam.
- COMET Phase-II R&D study is on going and will be adjusted based on Phase-I result.

Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams



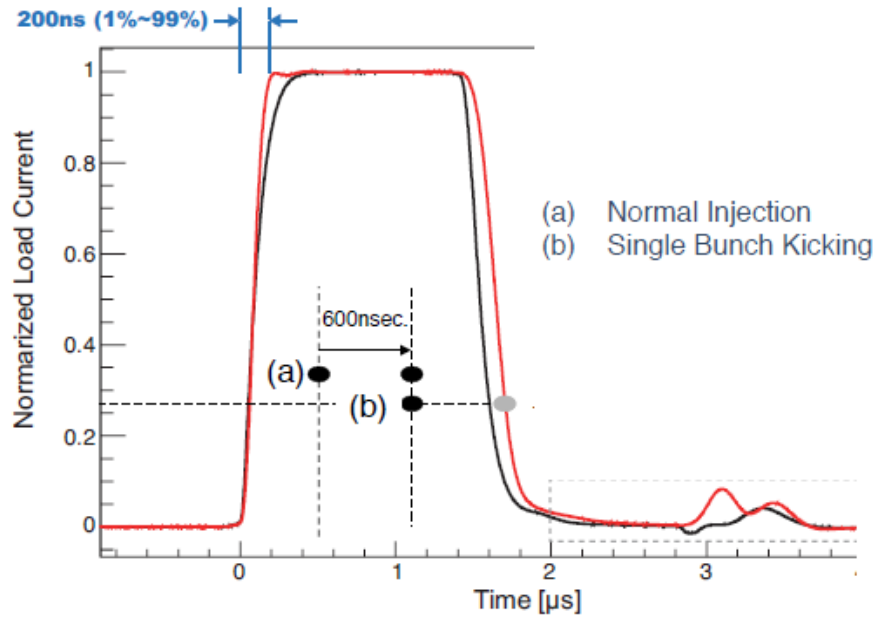
Thank You!

Backup slides

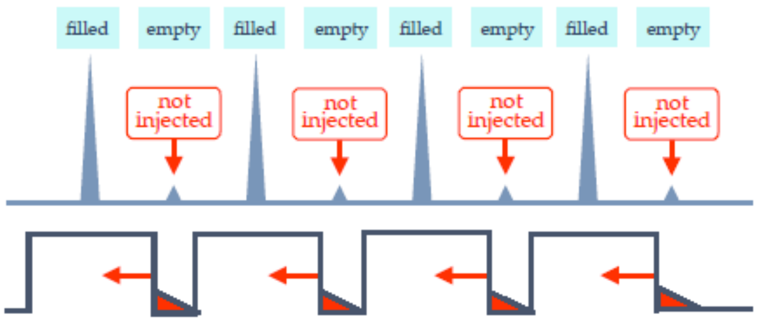
"What does cause K4_rear Mystery" ???

- **Most suspicious assumption:**
  - **Tail of Kicker Excitation ?**
  - **Injection Kicker filed has a small but a certain trailing component**
  - Shift for "Single Bunch Kicking" is half a excitation duration (= 600 nsec)
  - Shift of 600 nsec might be not long enough

    → Can cause imperfect extinction



- **Why only K4_rears shows a Mystery ?**
  - Every injection batch has a following injection immediately except for K4
  - Kicker excitation can extinct the residual protons in the prior batch



- **Can be tested quickly just shit the kicker timing little more**
- **Following kicker excitation might have a finite effect…**
- **Let's test it by FX !!**