The COMET Experiment:
Search for Muon to electron conversion at J-PARC

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On behalf of the COMET collaboration

2017/07/26, 9th Workshop on Hadron physics in China and Opportunities Worldwide

Outline

- Motivation
- The COMET Experiment
- The Staged Approach
- Status and Plan
- Summary

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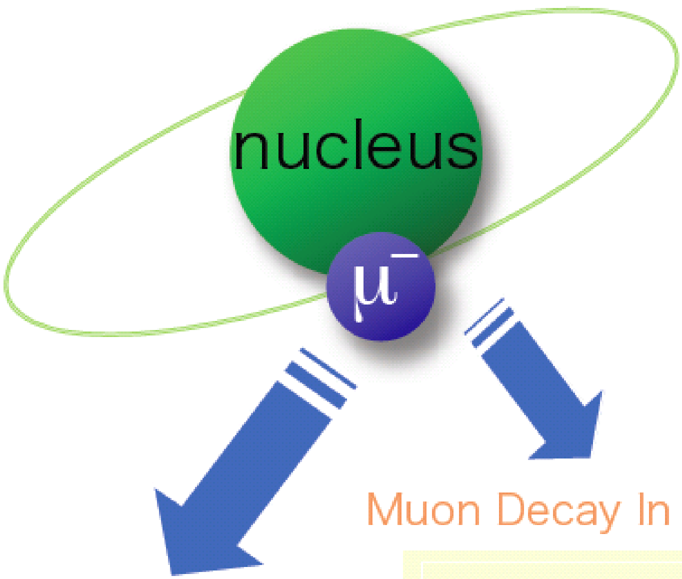
Muon to Electron Conversion

1s state in a muonic atom



Muon Decay In Orbit

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

nuclear muon capture

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

We are searching for:
Neutrino-less muon nuclear capture

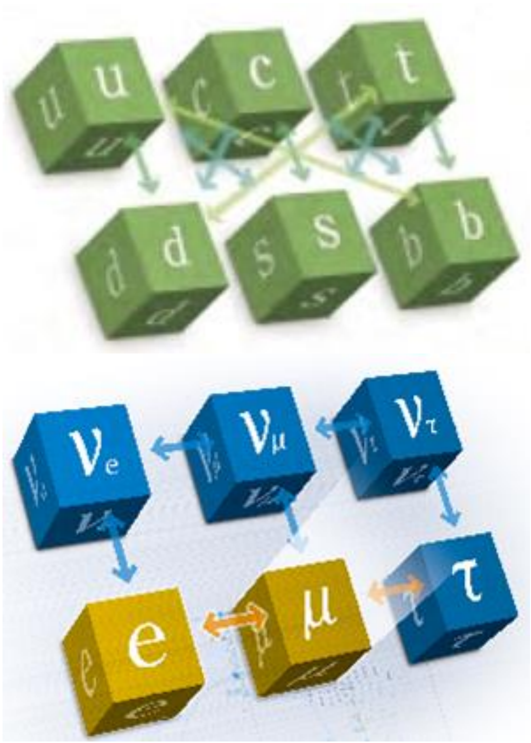
$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

Charged lepton flavor violation (CLFV)

- **Event Signature:**
  - a single mono-energetic electron of 105 MeV
  - Free of accidental background.
    No limit on beam intensity!
- **Backgrounds:**
  - Intrinsic backgrounds,
    ex. muon decay in orbit (DIO), radiative muon capture (RMC)
    Detector Resolution!
  - Beam-related backgrounds,
    ex. radiative pion capture, muon decay in flight, large angle scattering.
    Can be suppressed by pulsed beam!
  - Cosmic rays, false tracking

Why CLFV

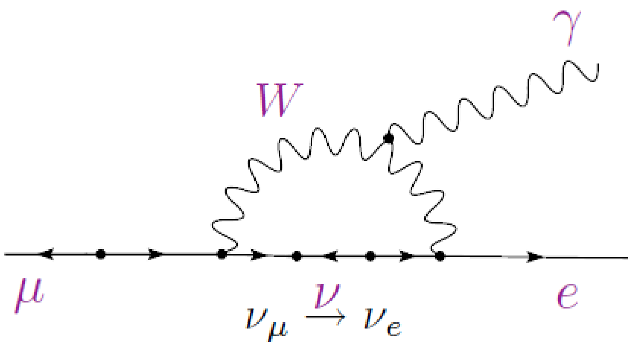
- Flavor is one of the most puzzling aspects of the SM.
  - Why 3 generations? Mass? Mixing?
- We have observed quark mixing and neutrino oscillation, but no charged flavor violation so far.
  - **Will tell us more about the nature of flavor BSM!**



- Quark flavor violation:
  - Characterized by CKM matrix
- Neutral lepton flavor violation:
  - Characterized by PMNS matrix
- Charged lepton flavor violation?
  - Will help to solve flavor puzzle!

CLFV as a Probe to New Physics

- Is CLFV allowed in SM?
  - Through loop diagram with neutrino oscillation, yes. But…

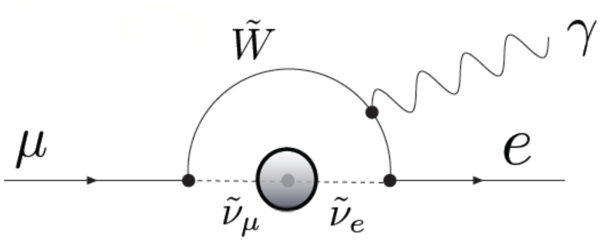


$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 \sim 10^{-54}$$

* *Historically we define:* $Br = \Gamma_{CLFV} / \Gamma_{capture}$

Practically negligible.
Clean probe to NP!

- How about with New Physics?
  - Assuming TeV scale new physics, naturally large coupling constant like SUSY, it may happen just around the corner!



$$Br(\mu \to e\gamma) = 10^{-11} \times \left(\frac{2TeV}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2$$

$10^{-11} \sim 10^{-15}$ level.
Reachable with current technics!

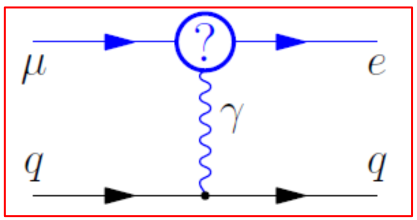
CLFV candidates

- CLFV in τ sector:
  - Studied in B factories: LHCb, BaBar, Belle
  - Will see improvement in Belle II and LHCb
- CLFV in μ sector:
  - Studied at PSI. $\mu \to e\gamma$ is the best result.
  - Will see great improvement in $\mu N \to eN$ at J-PARC and FermiLab
- τ intensity:
  - Current: 2/sec
  - Future: 100/sec
- μ intensity:
  - Current 10^8/sec
  - Future: 10^{11}~10^{12}/sec

Reaction	Current Limit	Future Limit	Location
$\tau \to \mu\gamma$	4.4×10^{-8}	$< 10^{-9}$	Flavor factory
$\tau \to e\gamma$	3.3×10^{-8}	$< 10^{-9}$	Flavor factory
$\tau \to \mu\mu\mu$	2.1×10^{-8}	$< 10^{-9} \sim 10^{-10}$	Flavor factory
$\tau \to eee$	2.7×10^{-8}	$< 10^{-9} \sim 10^{-10}$	Flavor factory
$\tau \to \mu ee$	1.5×10^{-8}	$< 10^{-9} \sim 10^{-10}$	Flavor factory
$\mu \to e\gamma$	4.3×10^{-13}	4×10^{-14}	MEG II
$\mu \to eee$	1×10^{-12}	$10^{-15} \sim 10^{-16}$	mu3e/MuSIC
$\mu N \to eN$ (Au)	7×10^{-13}	$< 10^{-18}$	PRISM/Mu2e II
$\mu N \to eN$ (Al)	$--$	$10^{-15}/10^{-17}$	COMET/Mu2e
$\mu N \to eN$ (Ti)	4.3×10^{-12}	$< 10^{-18}$	PRISM/Mu2e II
$\mu^- N \to e^+ N$ (Al)	4.3×10^{-12}	?	COMET
$\mu^+ e^- \to \mu^- e^+$	8.3×10^{-11}	?	COMET

Model Independent Approach for CLFV

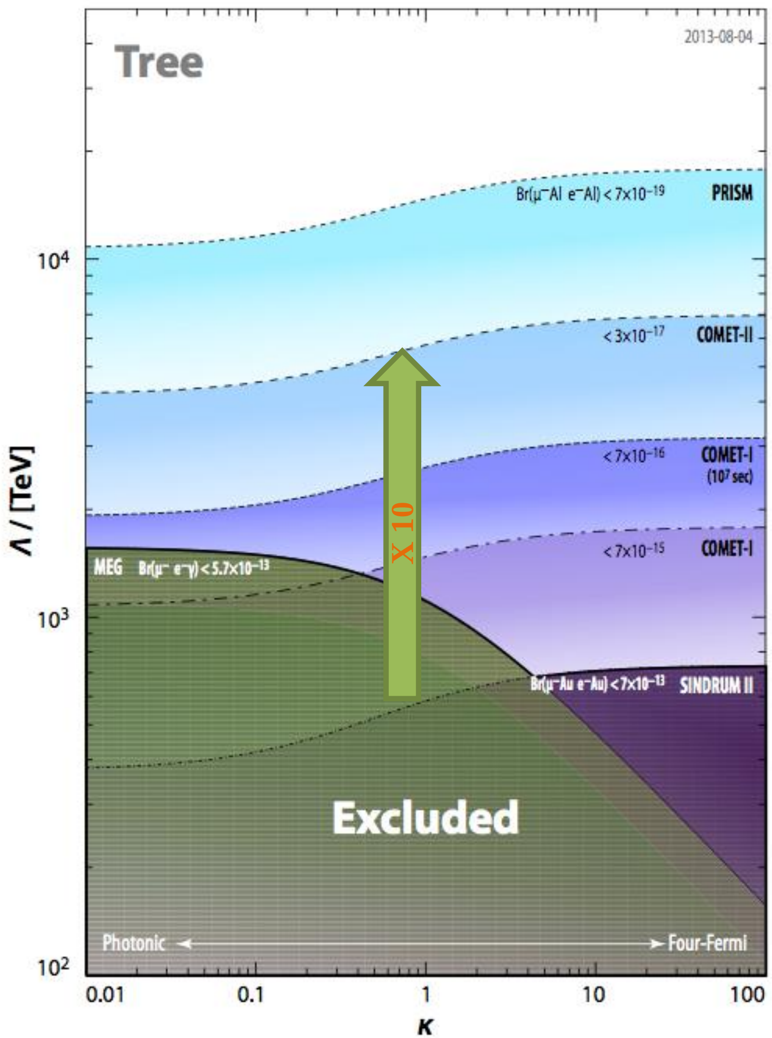
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$

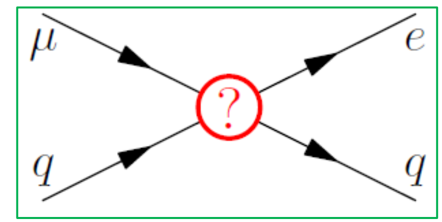


Photonic Process

$\kappa \ll 1$

$\mu \to e\gamma$	$\mu - e$
Strong	Yes





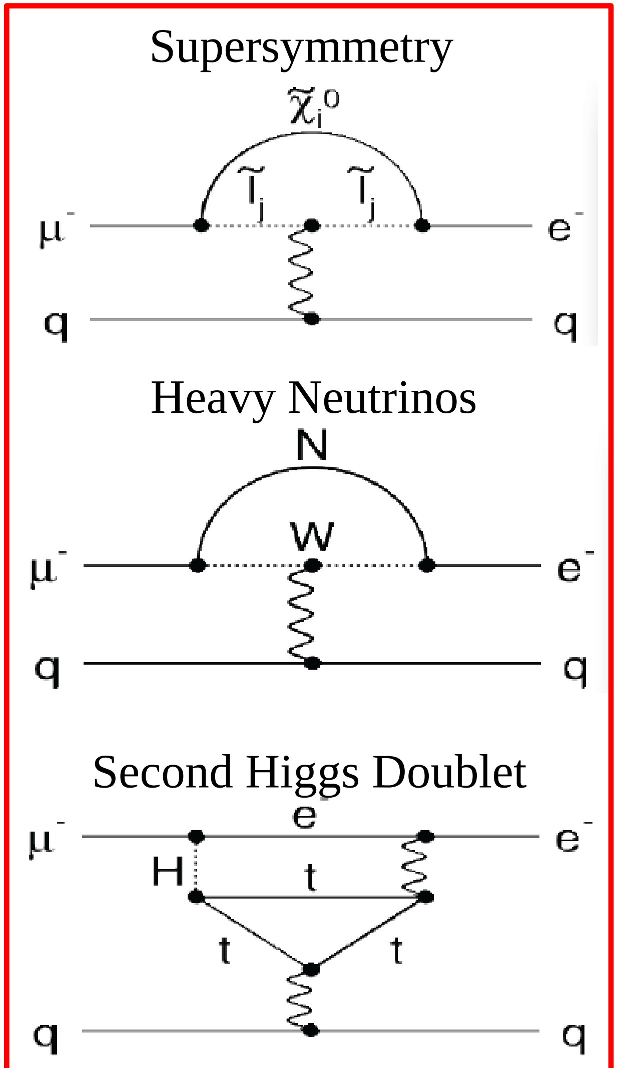
Four-Fermi Process

$\kappa \gg 1$

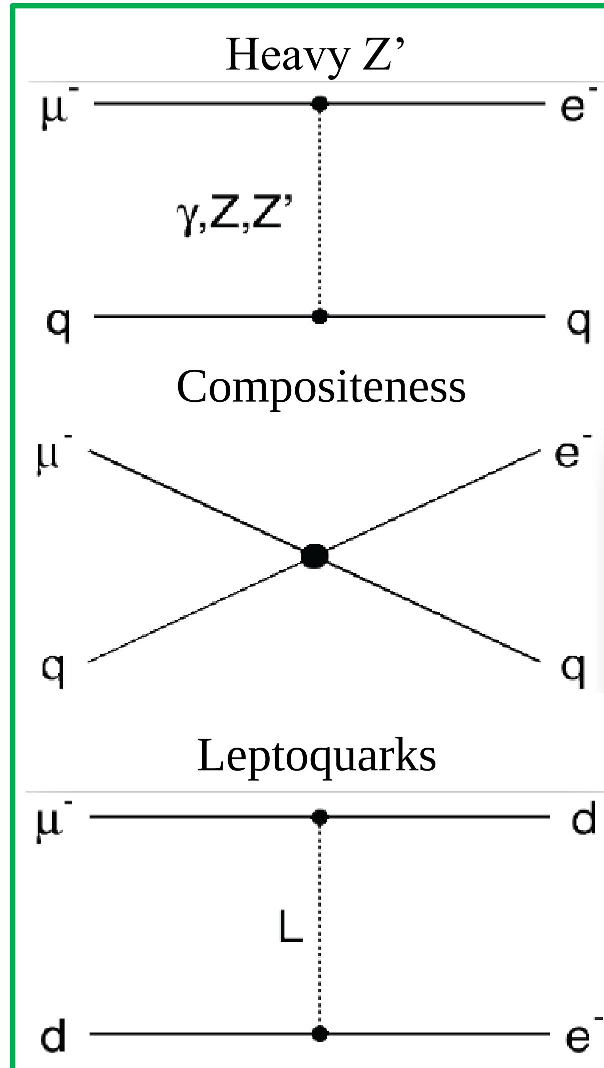
$\mu \to e\gamma$	$\mu - e$
No	Yes

Abundant New Physics Models for Mu-e Conversion

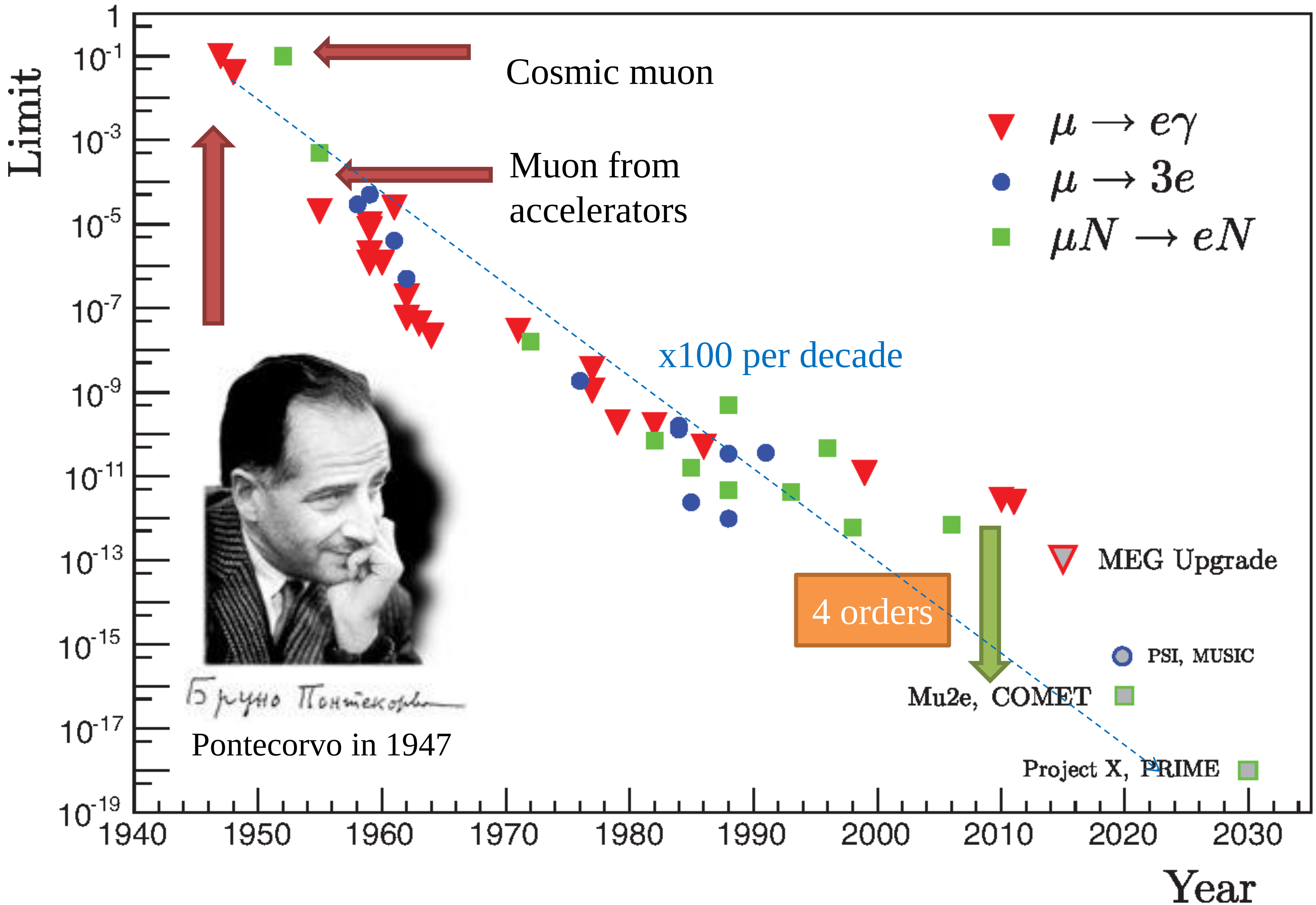
Photonic Processes



Four-Fermi Processes



History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



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COherent Muon Electron Transition (COMET)

The COMET Collaboration

176 collaborators

33 institutes, 15 countries

The COMET Collaboration

R. Abramishvili[11], G. Adamov[11], R. Akhmetshin[6,31], V. Anishchik[4], M. Aoki[32], Y. Arimoto[18], I. Bagaturia[11], Y. Ban[3], D. Bauer[14], A. Bondar[6,31], Y. Calas[7], S. Canfer[33], Y. Cardenas[7], S. Chen[28], Y. E. Cheung[28], B. Chiladze[35], D. Clarke[33], M. Danilov[15,26], W. Da Silva[23], P. D. Dauncey[14], C. Densham[33], G. Devidze[35], P. Dornan[14], A. Drutskoy[15,26], V. Duginov[16], L. Epshteyn[6,30,31], P. Evtoukhovich[16], S. Fayer[14], G. Fedotovich[6,31], M. Finger[8], M. Finger Jr[8], Y. Fujii[18], Y. Fukao[18], E. Gillies[14], D. Grigoriev[6,30,31], K. Gritsay[16], E. Hamada[18], R. Han[1], K. Hasegawa[18], I. H. Hasim[32], O. Hayashi[32], Z. A. Ibrahim[24], Y. Igarashi[18], F. Ignatov[6,31], M. Iio[18], M. Ikeno[18], K. Ishibashi[22], S. Ishimoto[18], T. Itahashi[32], S. Ito[32], T. Iwami[32], X. S. Jiang[2], P. Jonsson[14], T. Kachelhoffer[7], V. Kalinnikov[16], F. Kapusta[23], H. Katayama[32], K. Kawagoe[22], N. Kazak[5], V. Kazanin[6,31], B. Khazin[6,31], A. Khvedelidze[16,11], T. K. Ki[18], M. Koike[39], G. A. Kozlov[16], B. Krikler[14], A. Kulikov[16], E. Kulish[16], Y. Kuno[32], Y. Kuriyama[21], Y. Kurochkin[5], A. Kurup[14], B. Lagrange[14,21], M. Lancaster[38], M. J. Lee[12], H. B. Li[2], W. G. Li[2], R. P. Litchfield[14,38], T. Loan[29], D. Lomidze[11], I. Lomidze[11], P. Loveridge[33], G. Macharashvili[35], Y. Makida[18], Y. Mao[3], O. Markin[15], Y. Matsumoto[32], A. Melnik[5], T. Mibe[18], S. Mihara[18], F. Mohamad Idris[24], K. A. Mohamed Kamal Azmi[24], A. Moiseenko[16], Y. Mori[21], M. Moritsu[32], E. Motuk[38], Y. Nakai[22], T. Nakamoto[18], Y. Nakazawa[32], J. Nash[14], J. -Y. Nief[7], M. Nioradze[35], H. Nishiguchi[18], T. Numao[36], J. O'Dell[33], T. Ogitsu[18], K. Oishi[22], K. Okamoto[32], T. Okamura[18], C. Omori[18], T. Ota[34], J. Pasternak[14], C. Plostinar[33], V. Ponariadov[45], A. Popov[6,31], V. Rusinov[15,26], B. Sabirov[16], N. Saito[18], H. Sakamoto[32], P. Sarin[13], K. Sasaki[18], A. Sato[32], J. Sato[34], Y. K. Semertzidis[12,17], N. Shigyo[22], D. Shoukavy[5], M. Slunecka[8], D. Stöckinger[37], A. Straessner[37], M. Sugano[18], Y. Takubo[18], M. Tanaka[18], S. Tanaka[22], C. V. Tao[29], E. Tarkovsky[15,26], Y. Tevzadze[35], T. Thanh[29], N. D. Thong[32], J. Tojo[22], M. Tomasek[10], M. Tomizawa[18], N. H. Tran[32], H. Trang[29], I. Trekov[35], N. M. Truong[32], Z. Tsamalaidze[16,11], N. Tsverava[16,35], T. Uchida[18], Y. Uchida[14,32], K. Ueno[18], E. Velicheva[16], A. Volkov[16], V. Vrba[10], W. A. T. Wan Abdullah[24], M. Warren[38], M. Wing[38], M. L. Wong[32], T. S. Wong[32], C. Wu[2,28], H. Yamaguchi[22], A. Yamamoto[18], T. Yamane[32], Y. Yang[22], W. Yao[2], B. K. Yeo[12], H. Yoshida[32], M. Yoshida[18], Y. Yoshii[18], T. Yoshioka[22], Y. Yuan[2], Yu. Yudin[6,31], J. Zhang[2], Y. Zhang[2], K. Zuber[37]

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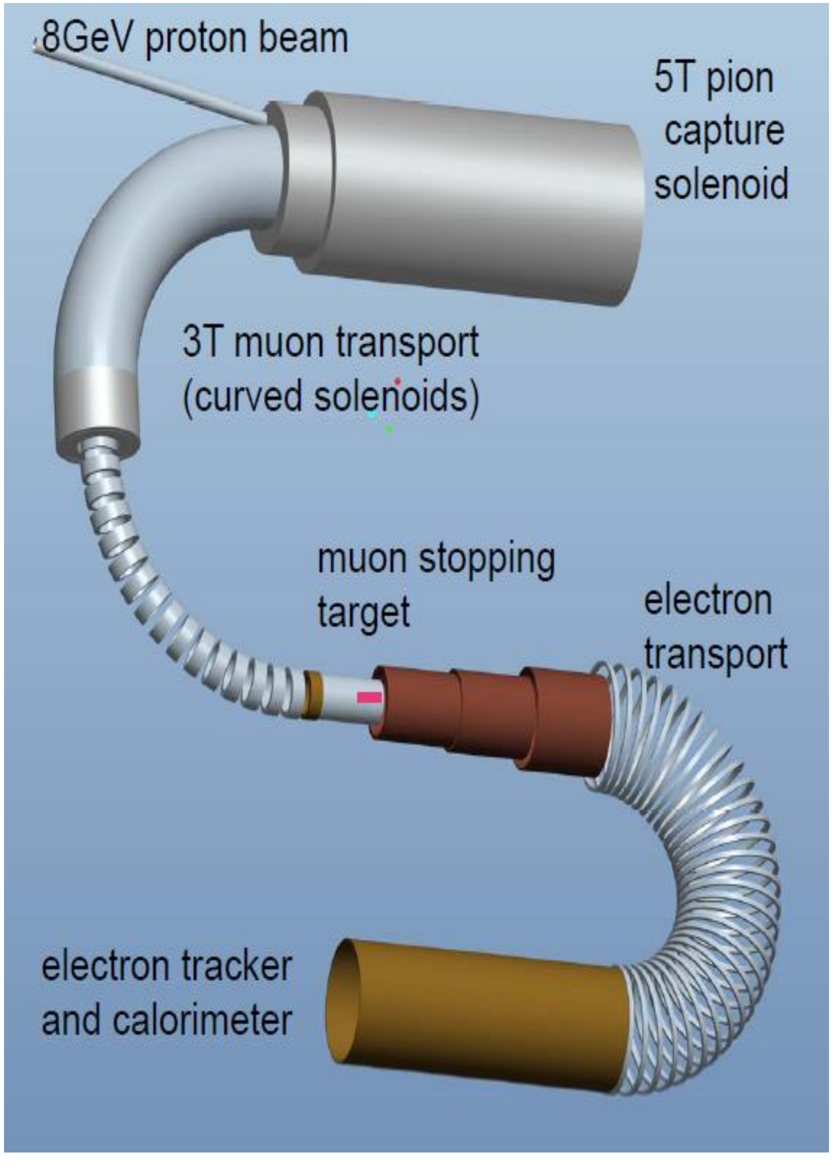
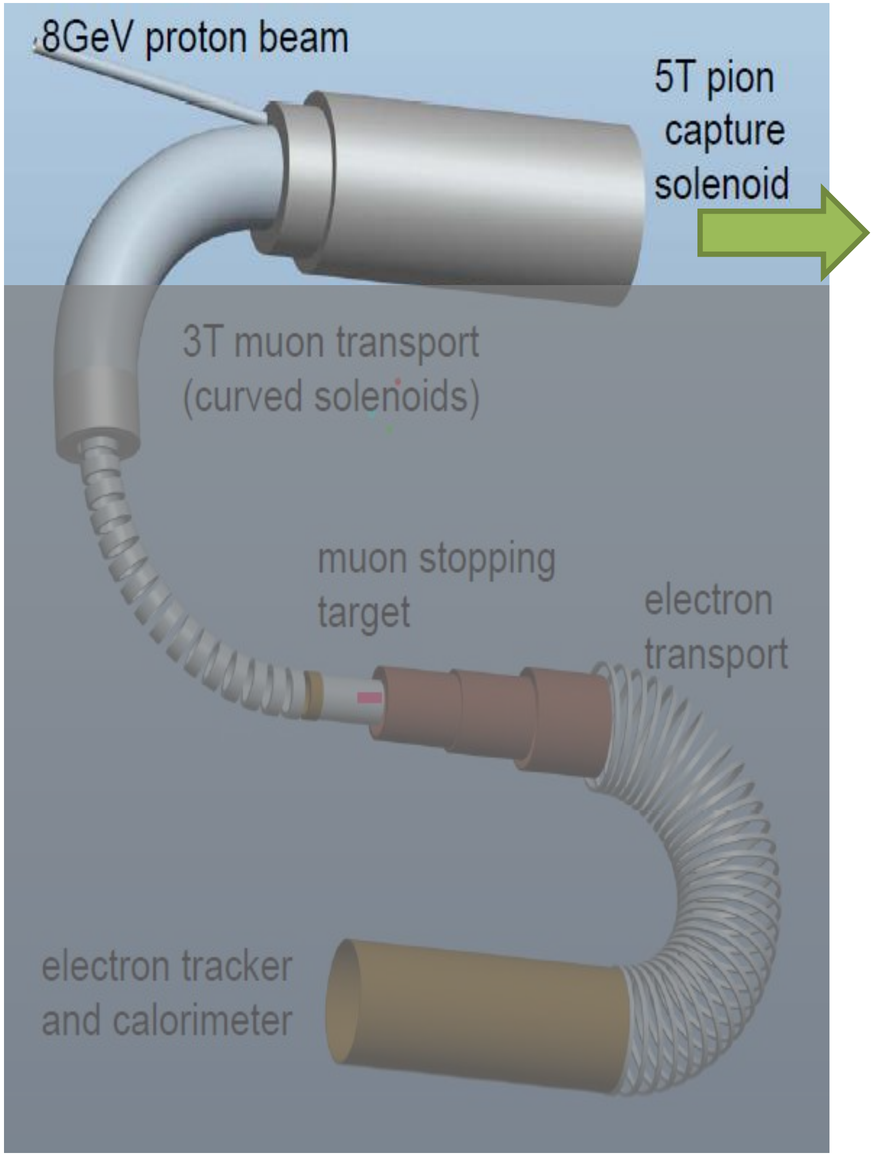
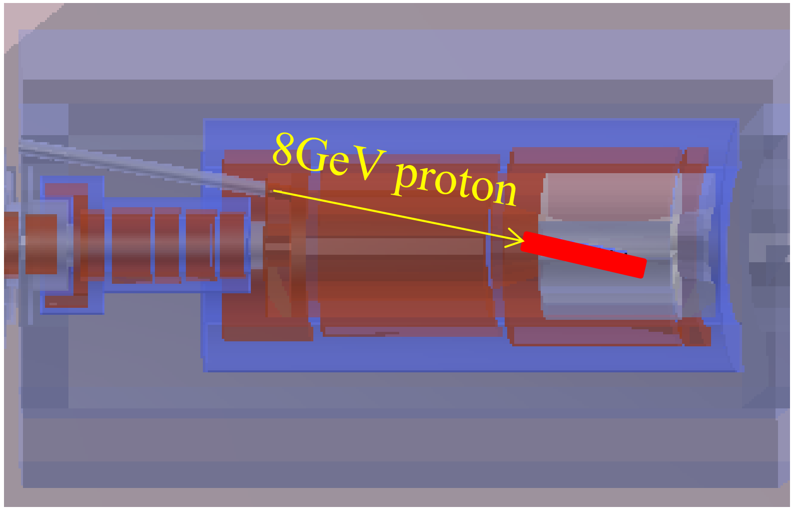
The COMET Experiment



- Single event sensitivity (S.E.S) $= 2.6 \times 10^{-17}$.
  - 8 GeV, 56 kW pulsed proton beam.
  - One year running time: 8.5×10^{20} POT, 2×10^{18} muon stopped in the target.
    10^{11} muon/sec needed!
    $(10^8\ @\ PSI)$
- Most challenging aspects:
  - Produce & capture enough muon.
    - Target, SC solenoid, cooling, ..
  - Get clean muon beam and stop them.
    - Transportation beam line
  - Find the signal from 10^{20} POT
    - Background rejection, signal acceptance, radiation tolerance.

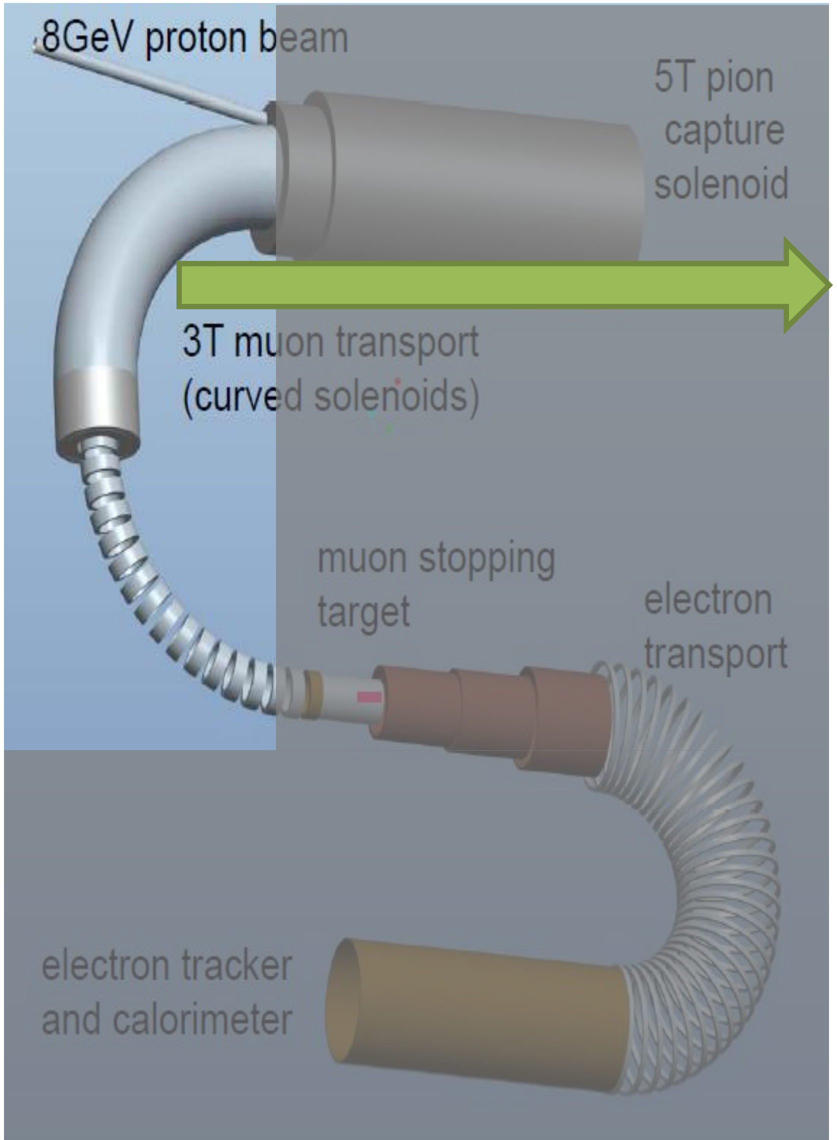
Pion Production & Capture

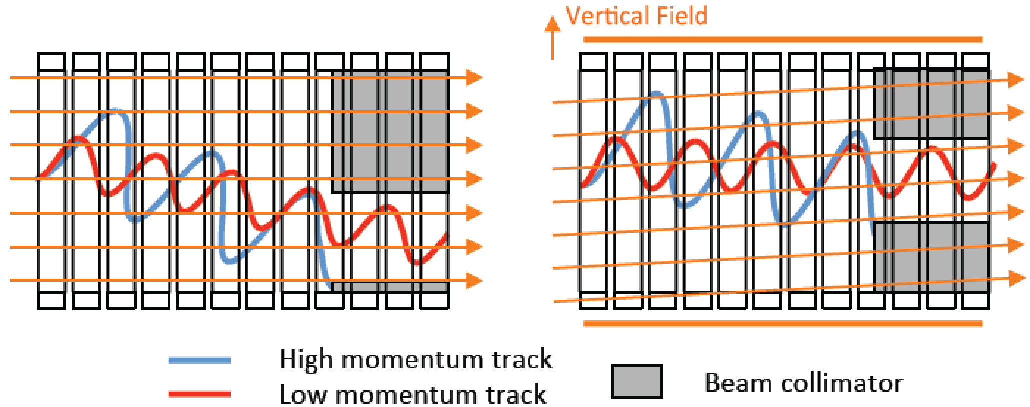




- To get 1000 times more muons per second:
  - High E proton: 2~8 GeV preferred
  - A long target instead with $L = 1 \sim 2 \times L_{Radi}$
    - High T! Tungsten (graphite).
  - 5 T capture solenoid
    - Superconducting: cooling!
    - Adiabatically decreasing: larger acceptance.

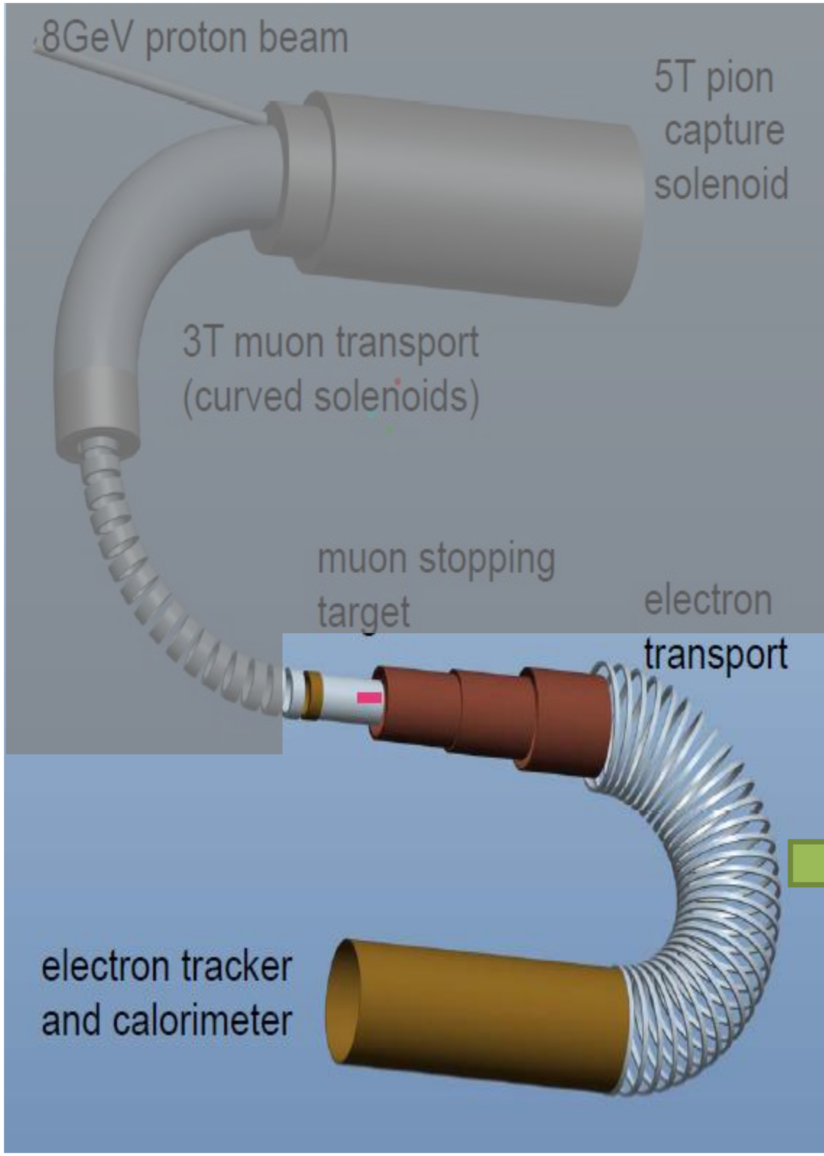
Muon Transport



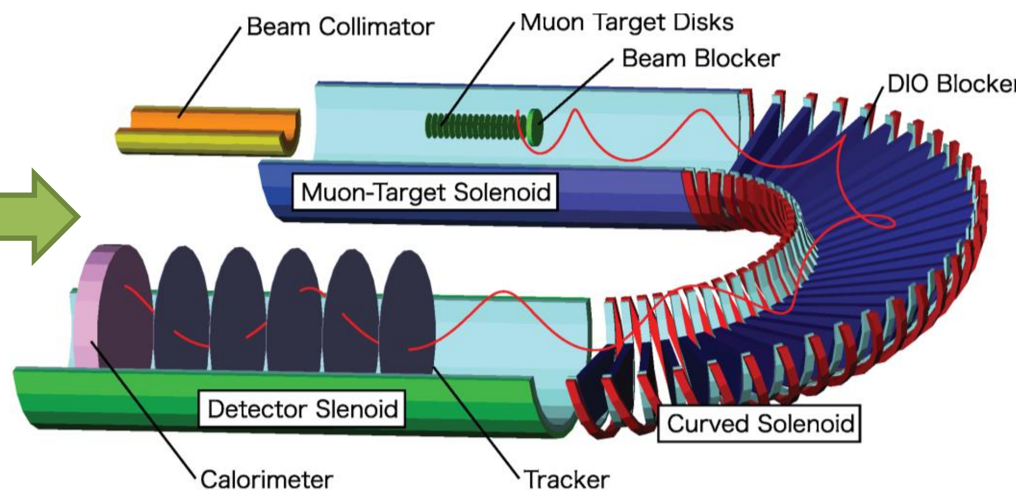


- To get pure muon beam:
  - C shape bending solenoid is used
    - Charged particle will drift vertically. Direction decided by charge. Distance decided by momentum.
    - Vertical Field will make tracks with preferred charge & momenta (~40 MeV μ^-) stay on the beam line.
    - Collimator in the end will remove unwanted beam particles.

Detector System

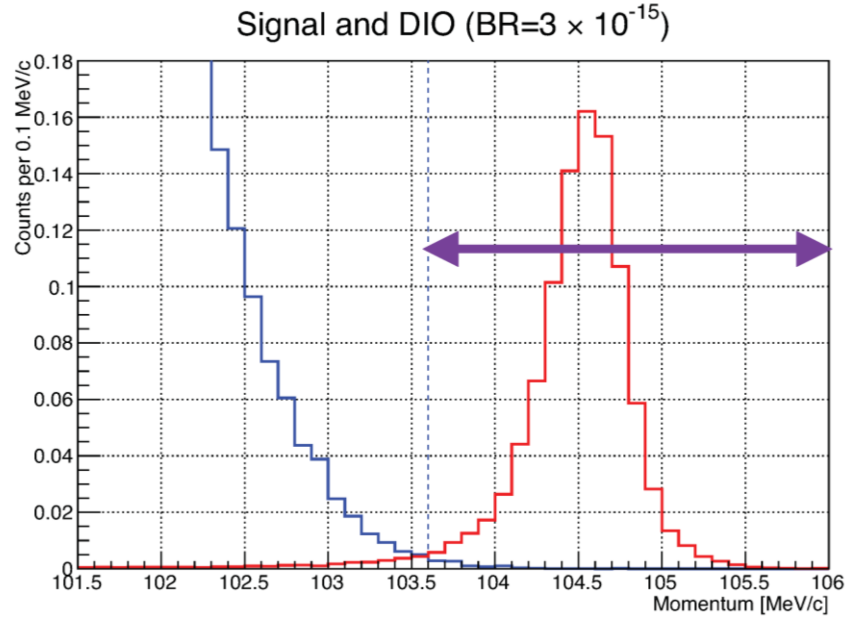


- Low energy muons stopped in the stopping target.
- Beam particle and secondaries from the target will be selected by another C shape solenoid.
- A detector system with high resolution & acceptance is placed after it.
  - Straw tracker consists of >5 stations, each with 4 layers of straw tubes.
  - Energy calorimeter is a plane of crystals

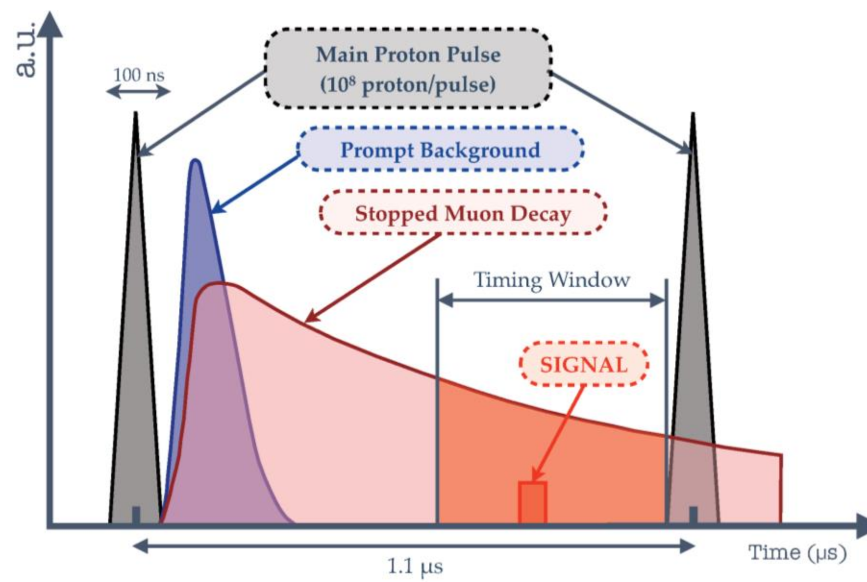


Background

- physics backgrounds
  - muon decay in orbit (DIO)
    Detector Resolution should be very good @ 100 MeV.
    Light, precise, large acceptance:
  - Straw tube tracker or drift chamber

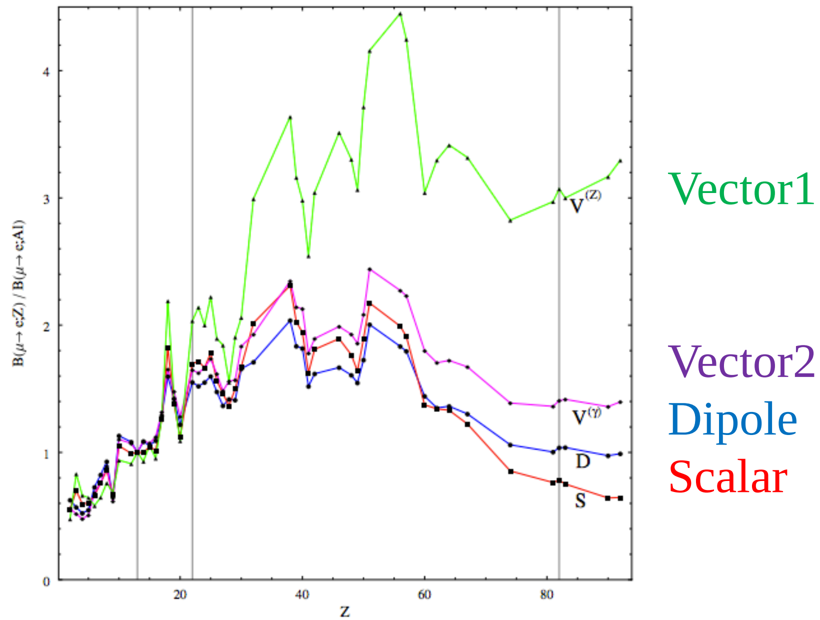


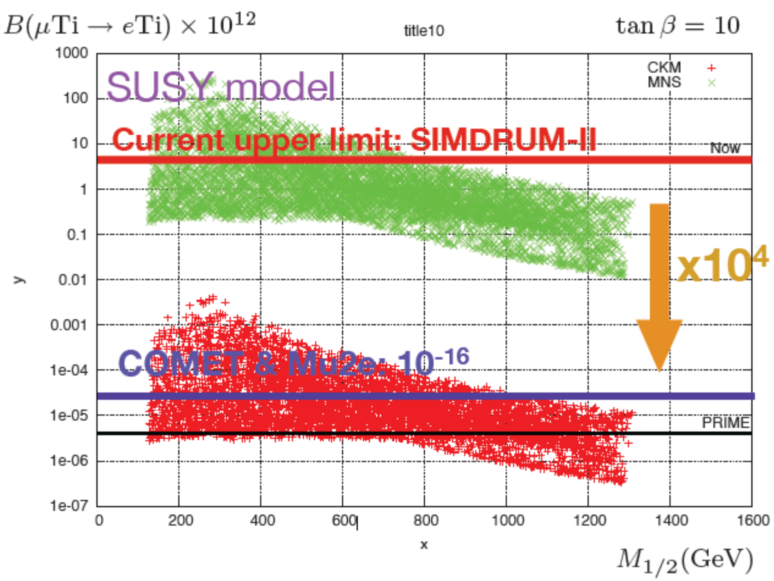
- beam-related backgrounds
  - High energy particles in the beam
    Very good pulse structure: separation ~muon lifetime and much larger than prompt peak delay ~100 ns; proton leakage <10^{-9}.
  - All available on proton synchrotron !
- cosmic rays, false tracking
  - Cosmic ray veto counter.



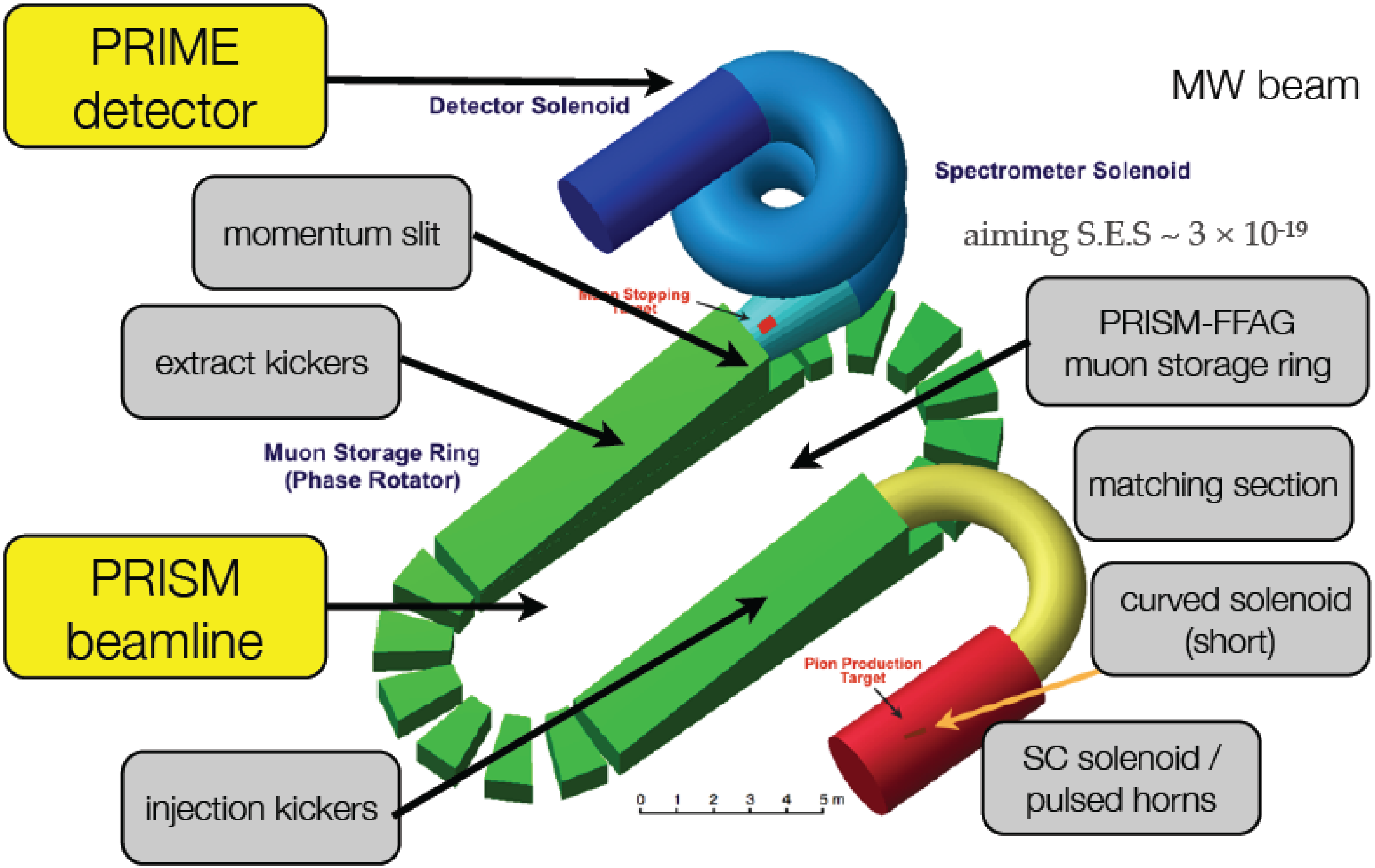
Prospects of COMET

- If mu-e conversion signal is found:
  - Try with different target to scan the property of NP!
- If mu-e conversion signal is not found:
  - Exclude a large area of NP!
  - Move towards PRISM!
- Besides the signal:
  - Beam measurements:
    - better understanding of hadron physics of backward pion yield.
  - muon capture measurements: DIO, Radiative pion/muon capture
    - Better understanding of nuclear structure with Q~100MeV.
    - Any interesting topics?
  - Background measurements:
  - Other CLFV channels: $\mu^- N \rightarrow e^+ N$, $\mu^+ e^- \rightarrow \mu^- e^+$, etc.



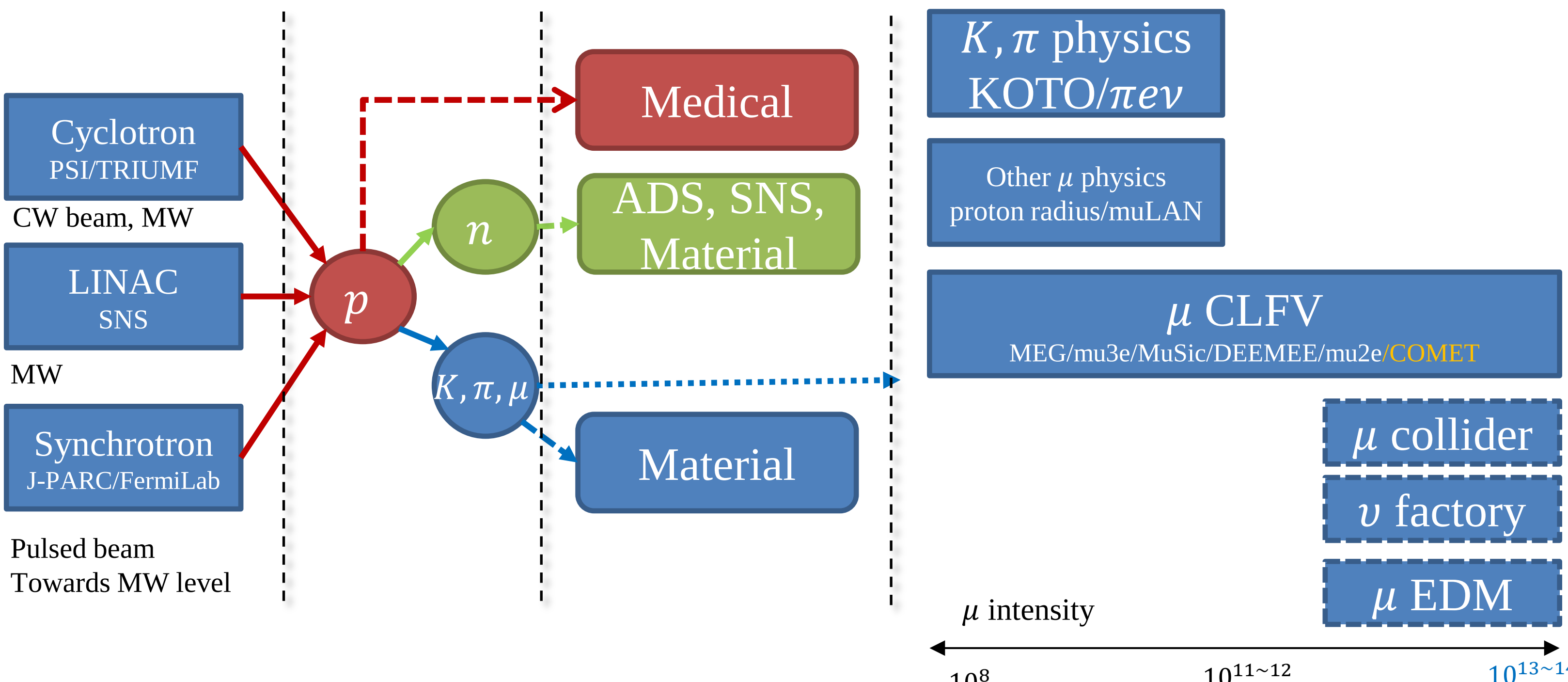


PRISM/PRIME Experiment

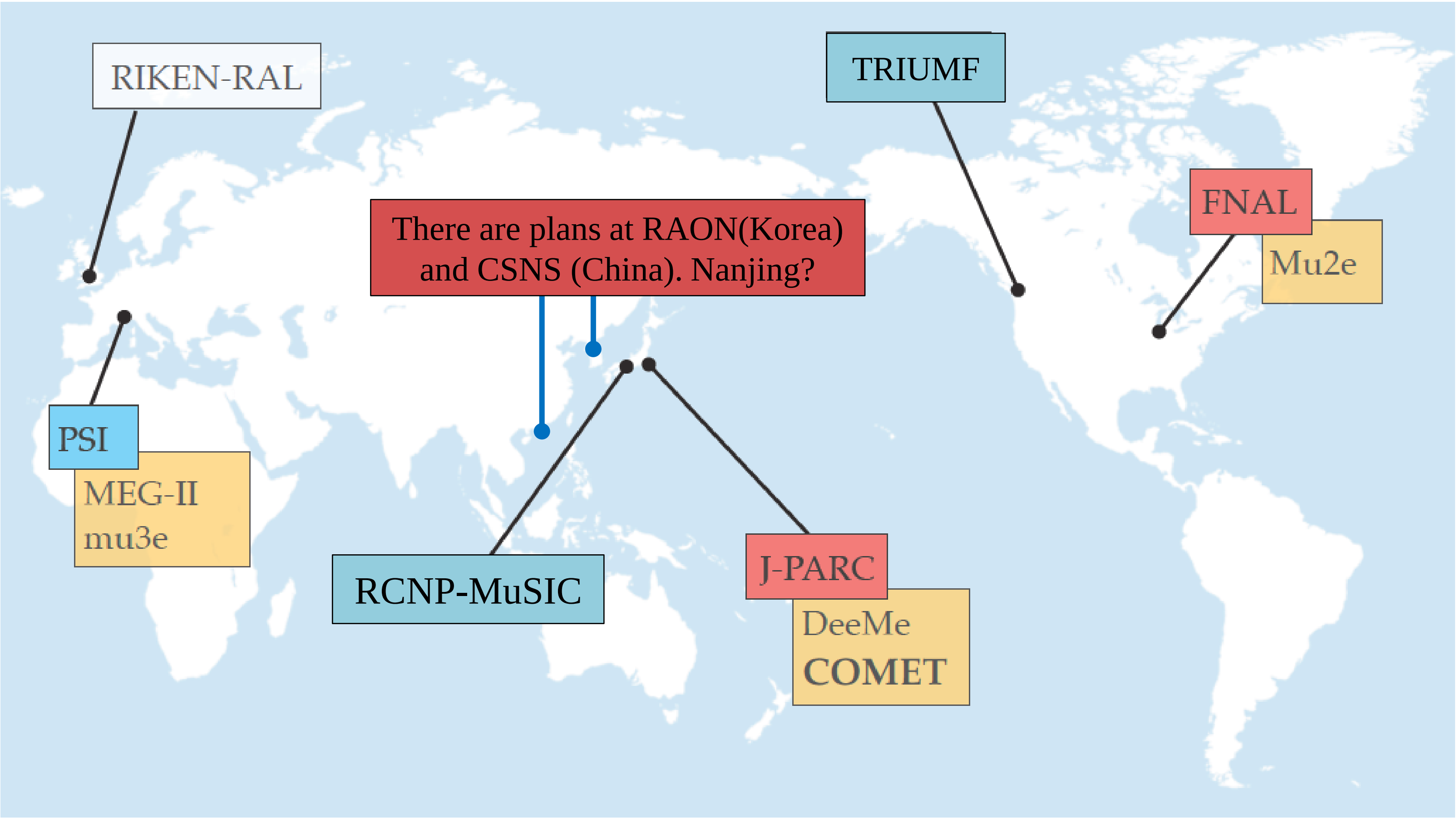


Cooperation With Others

- It's challenging to achieve the ambitious sensitivity of CLFV search. But the requirements are common thus the experience can be shared among a large variety of experiments.
  - Intensive & stable proton beam with specified structure.
  - Handling thick target with high beam power.
  - Obtain intensive and pure muon beam.
  - Operation of magnet in high radiation level.
  - High precision measurement in high radiation level.



Muon Sources Worldwide



DC Muon Beam — suitable for "coincidence" experiments

Pulsed Muon Beam — suitable for "**μ-e conversion**" experiments

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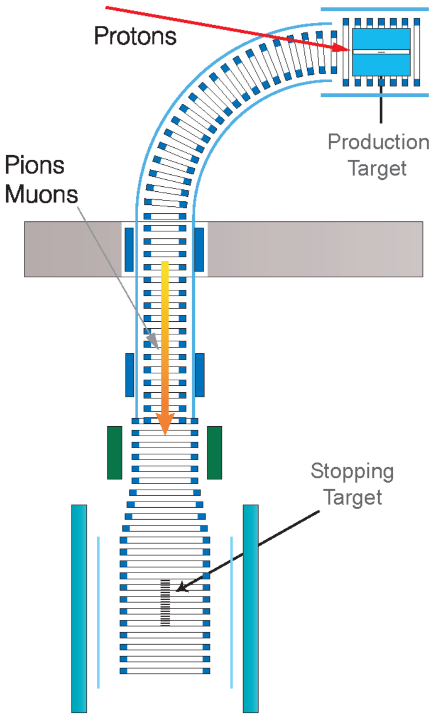
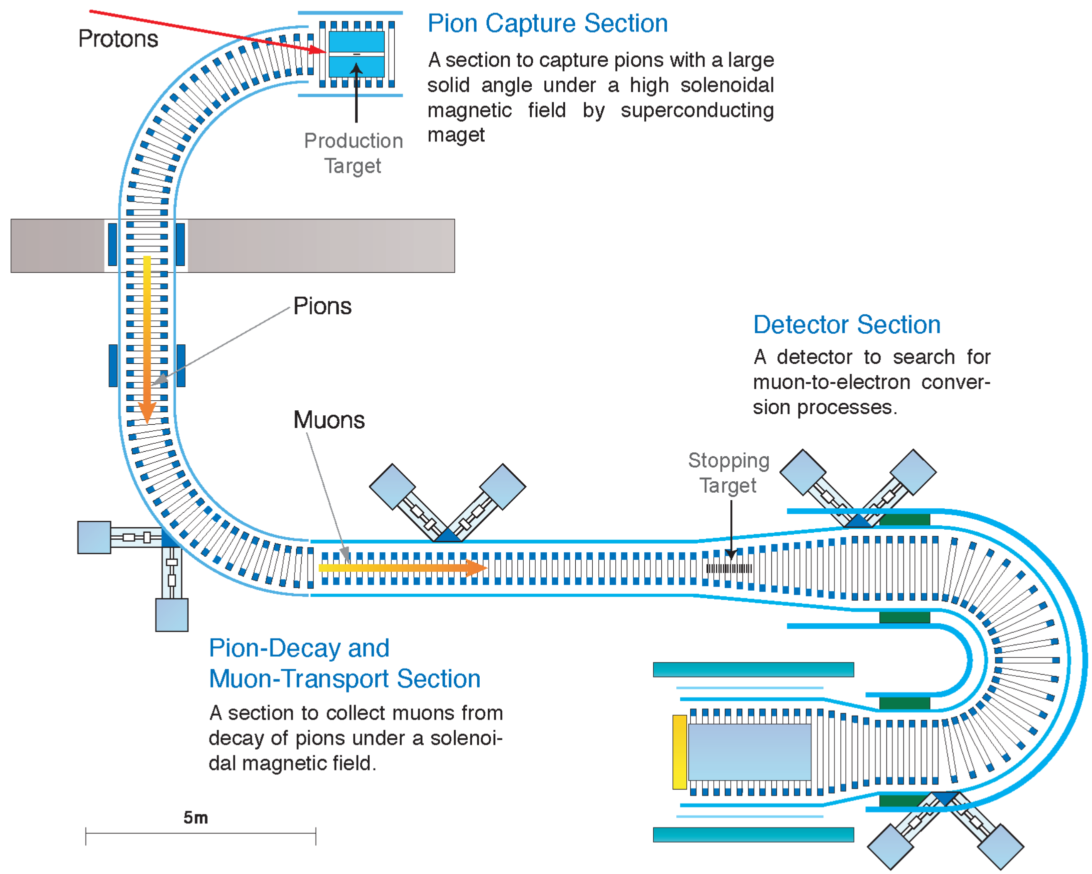
Staged Plan of COMET





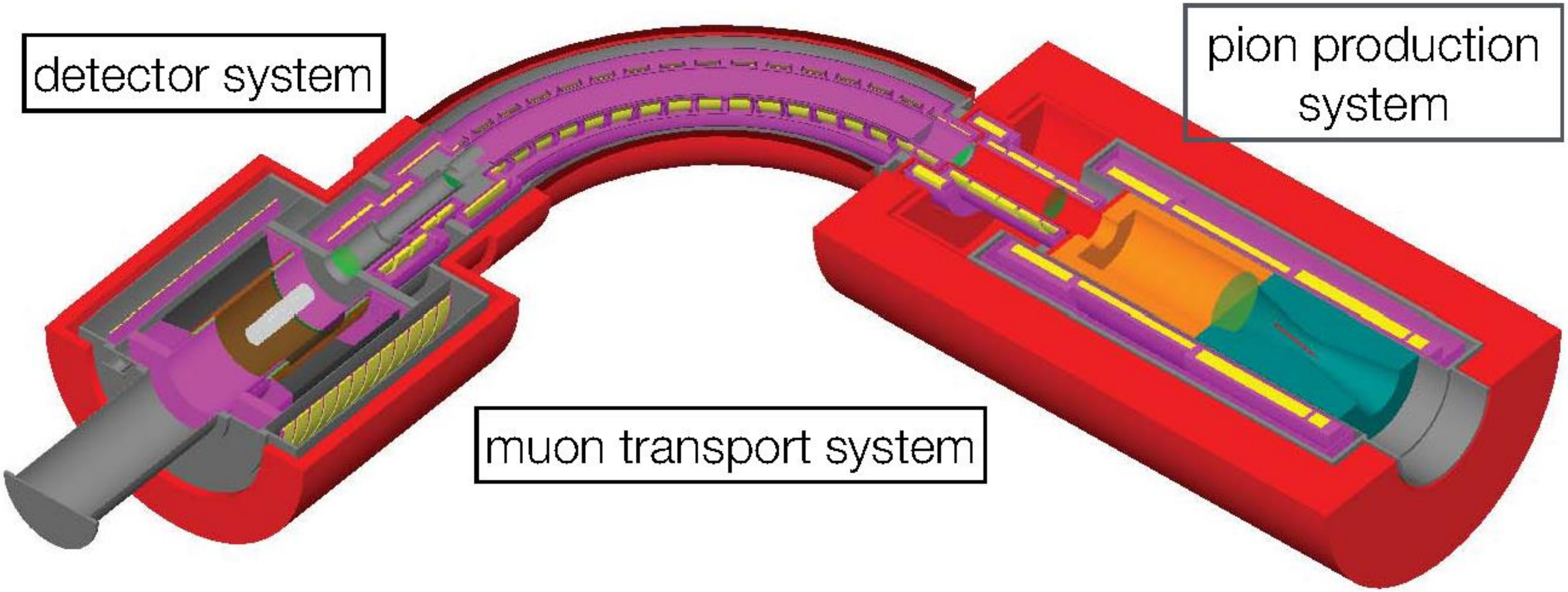
COMET Phase-I
Start from 2019

COMET Phase-II
Start from 2022

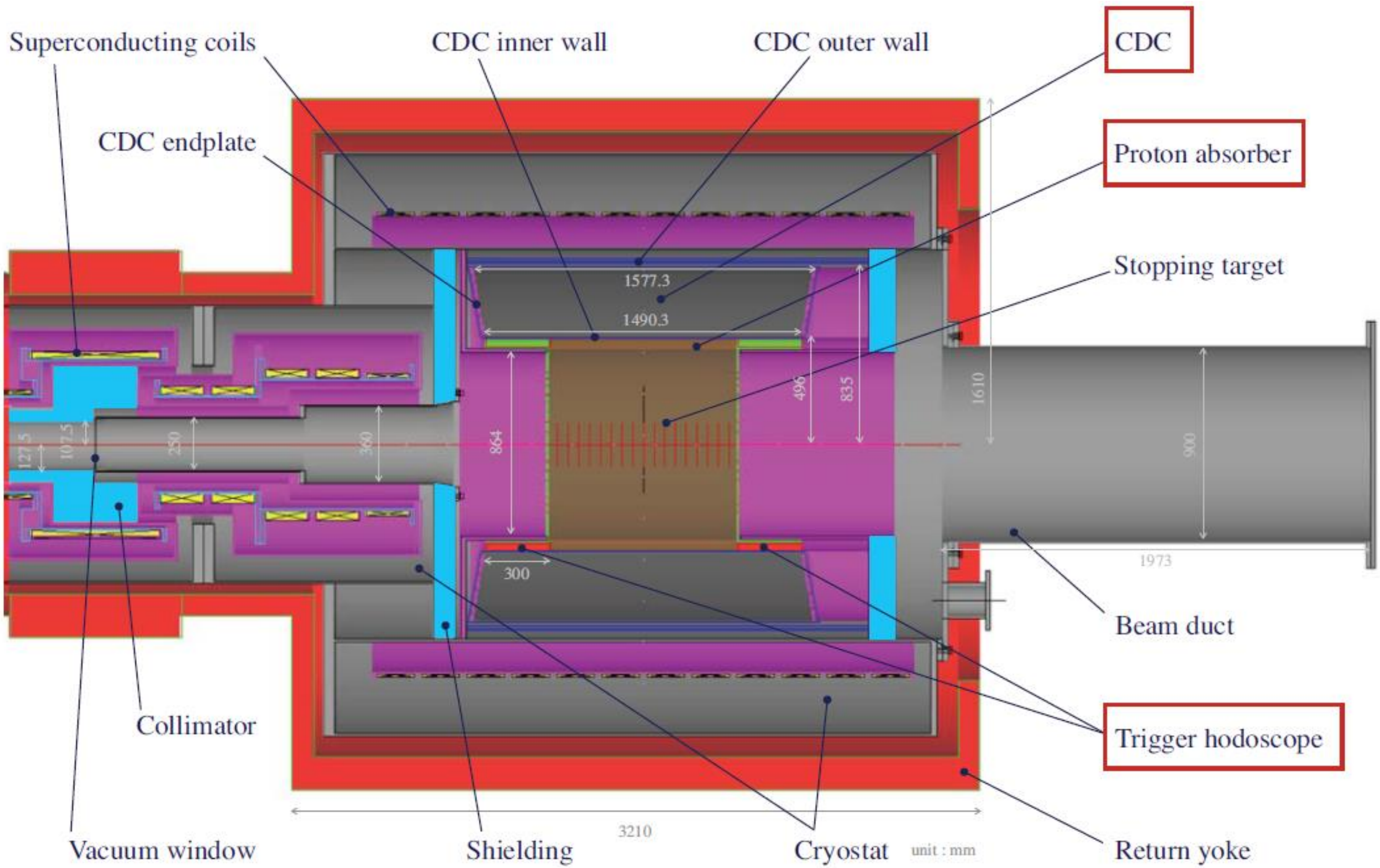
COMET Phase-I

The COMET Phase-I is designed to conduct the following tasks:

- Background study for COMET Phase-II:
    - A direct measurement of potential background sources for the full COMET experiment by using the actual COMET beamline is important before we finalize the COMET Phase-II design. Will use Phase-II detectors.
- Search for mu-e conversion:
    - With an intermediate sensitivity 3×10^{-15}, which is still 100 times better than current limit. Will use new detector dedicated for Phase-I: Cylindrical Detector.



Cylindrical Detector (CyDet) for COMET Phase-I



Signal Sensitivity and Background in COMET Phase-I

1. The fact of COMET beam witin about $1.26 \times 10^7 sec$ (146 days).

total protons	3.2×10^{19}
muon efficiency	0.00047
Number of stopped muons	1.5×10^{16}

2. Considering that the capture ratio in Al is 0.61 and the detector acceptance is 0.041, the fraction of $\mu - e$ conversion to the ground state in the final state of $f_{gnd} = 0.9$, we can achieve:

$S.E.S. = 3.1 \times 10^{-15}$

$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} (90\% C.L.)$

100 times better than the current limit!

Expected background events are about 0.032

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.

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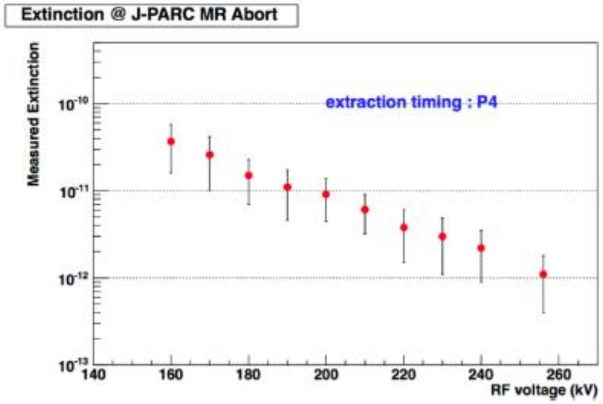
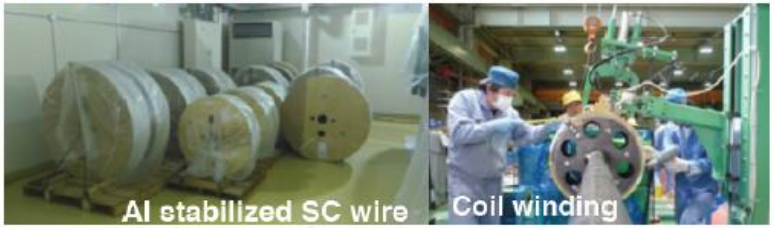
Status of COMET Beamline

1. Proton extinction factor measured to be $\sim O(10^{-11})$.



2. Diamond detector has been studied to measure the beam profile/extinction in front of the capture solenoid.
3. Prototype of graphite target for Phase-I has been developed.

4. The coil winding for capture solenoid is almost done.



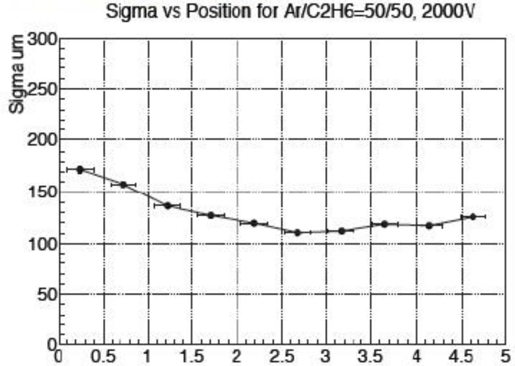
5. Muon transportation solenoid has been constructed.
6. 14 coils of the detector solenoid has been assembled.

Status of COMET Facility

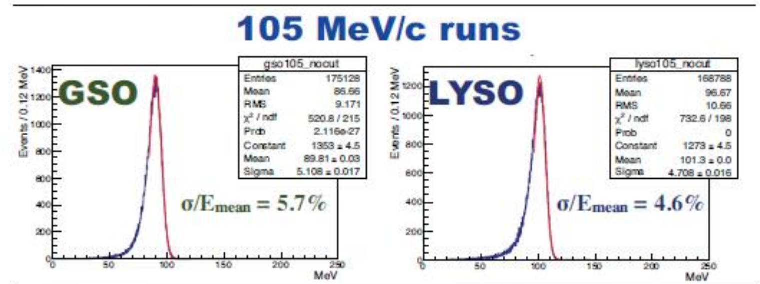
Status of COMET Phase-I Detectors

1. Straw assembly prototype with 20 micron straws.

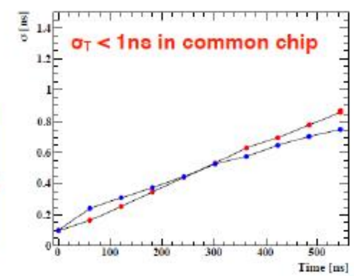
2. Operation in vacuum performed in success
3. Beam test with 105MeV/c electron was done: σ_X 150um



4. GSO and LYSO crystal test has been conducted and LYSO was chosen for higher yield and faster time response.

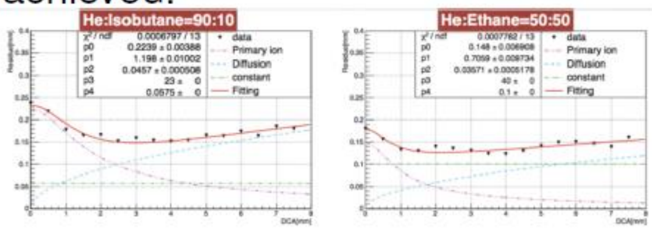


5. The front end board (ROESTI/EROS) has been developed. ROESTI V3 tests show good time resolution (<1ns).

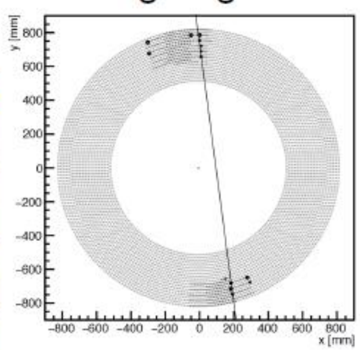


Status of COMET Phase-I Detectors

1. Beam tests and cosmic ray tests with prototypes have been conducted. Good spatial resolution and efficiency (150 um, 99%) have been achieved.

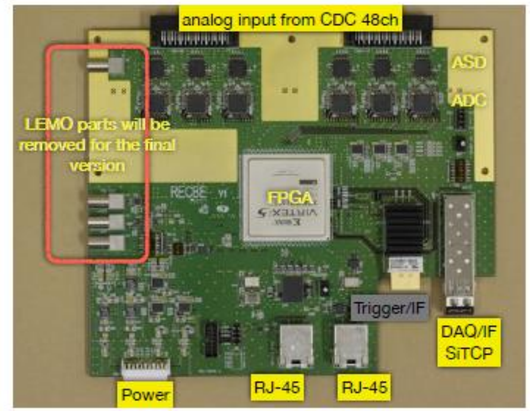


2. CDC construction completed in June 2016. Cosmic ray test is on going.



3. Beam tests for CTH prototype has been conducted. 1ns time resolution obtained.

4. Front end boards have been produced and mass test finished last year.



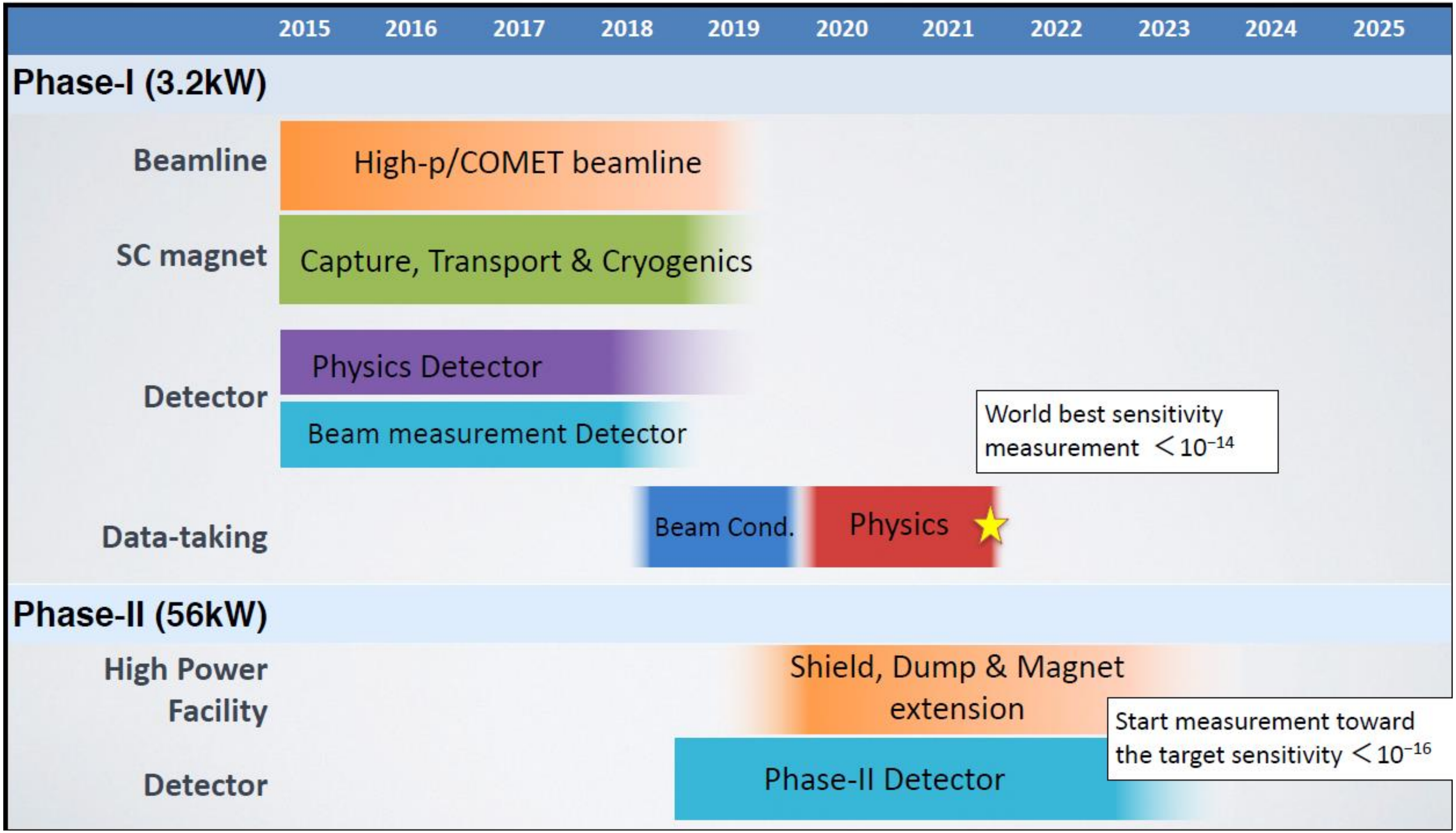
5. Trigger scheme using FC7-FCT with frontend trigger system has been studied.

6. Software framework (ICEDUST) finished last year. Full MC study indicates that the pre-trigger rate estimated as $\sim O(10)kHz$, and momentum resolution is appreciated ($\sim 170keV/c$).

Contributions from China

- The Chinese group in COMET includes IHEP, PKU and NJU. Contributions from this group includes:
  - The electronics of CyDet were produced and tested group in 2014~2015. Will be mounted this year.
  - Leading the tracking development (two independent groups).
  - Contributing to the software framework development.
  - Took charge of the muon beam optimization, stopping target optimization, and CyDet parameter optimization.
  - Contributing to the design of CRV system.
  - Contributing to the calculation of magnetic field.
  - Joining the preparation of analysis framework.
  - Joined CyDet prototype tests and lead the analysis.
  - Participated in the construction of CyDet.
  - Participating the cosmic ray test and radiation test for CyDet.

Timeline



2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Phase-I (3.2kW)
Beamline
High-p/COMET beamline
SC magnet
Capture, Transport & Cryogenics
Detector
Physics Detector
Beam measurement Detector
World best sensitivity measurement $< 10^{-14}$
Data-taking
Beam Cond.
Physics
Phase-II (56kW)
High Power Facility
Shield, Dump & Magnet extension
Start measurement toward the target sensitivity $< 10^{-16}$
Detector
Phase-II Detector

Outline

- Motivation
- The COMET Experiment
- Status and Plan
- Summary

Summary

- The CLFV process is a good probe to new phsycis beyond the Standard Model.
- With a new generation of muon beam being available soon, the prospect of searching for muon to electron conversion is very attractive.
- COMET at J-PARC aims at a search for muon to electron conversion with signal sensitivity S.E.S = 2.6×10^{-17} (10,000 times better than current limit) from 2022 with 1 year beam time.
- Staged plan for COMET has been approved and COMET Phase-I is expected to take data from 2019 with ~150 days beam time. It will carry out a background study for Phase-II together with a direct search for muon to electron conversion with signal sensitivity S.E.S = 3×10^{-17} (100 times better than current limit).
- R&D and construction are in good shape.

Acknowledgement

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Thank you!