A search for the muon to electron conversion at J-PARC: COMET Experiment

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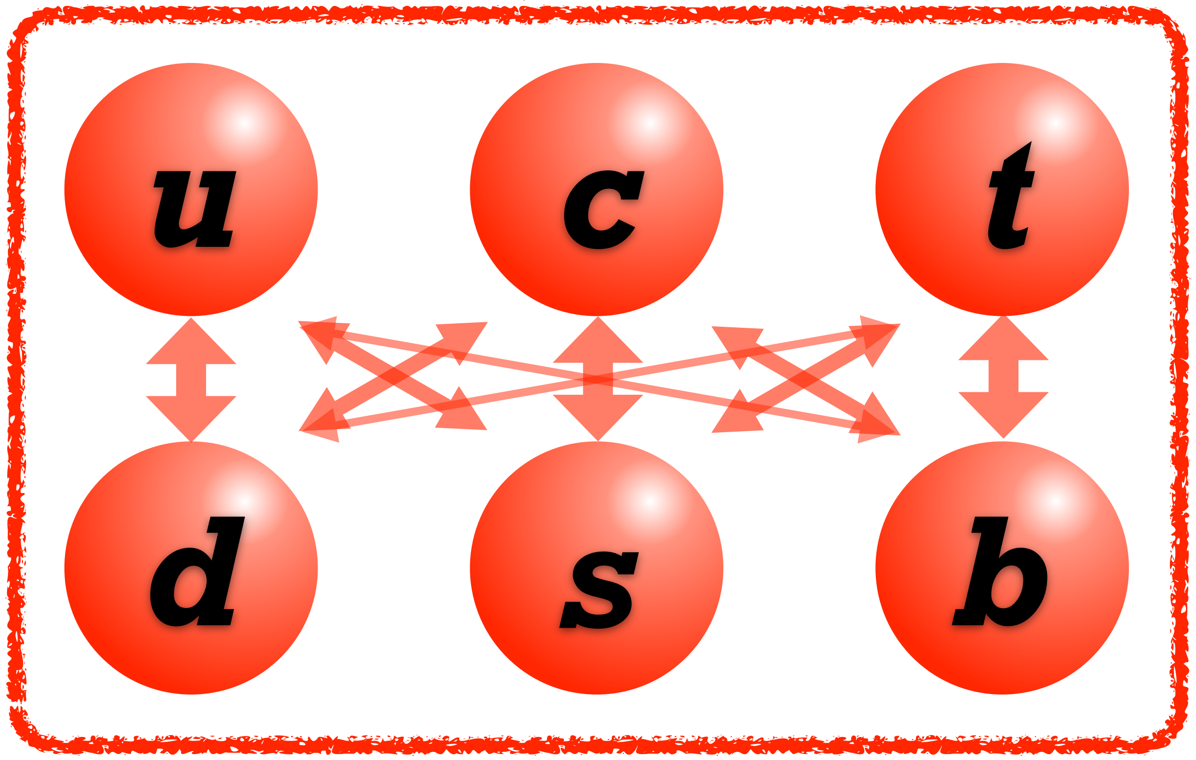
on behalf of the COMET Collaboration
Windows on the Universe, Quy Nhon, Vietnam, 8th August 2018

Outline

- Physics Motivations
- COMET Experiment
- Summary

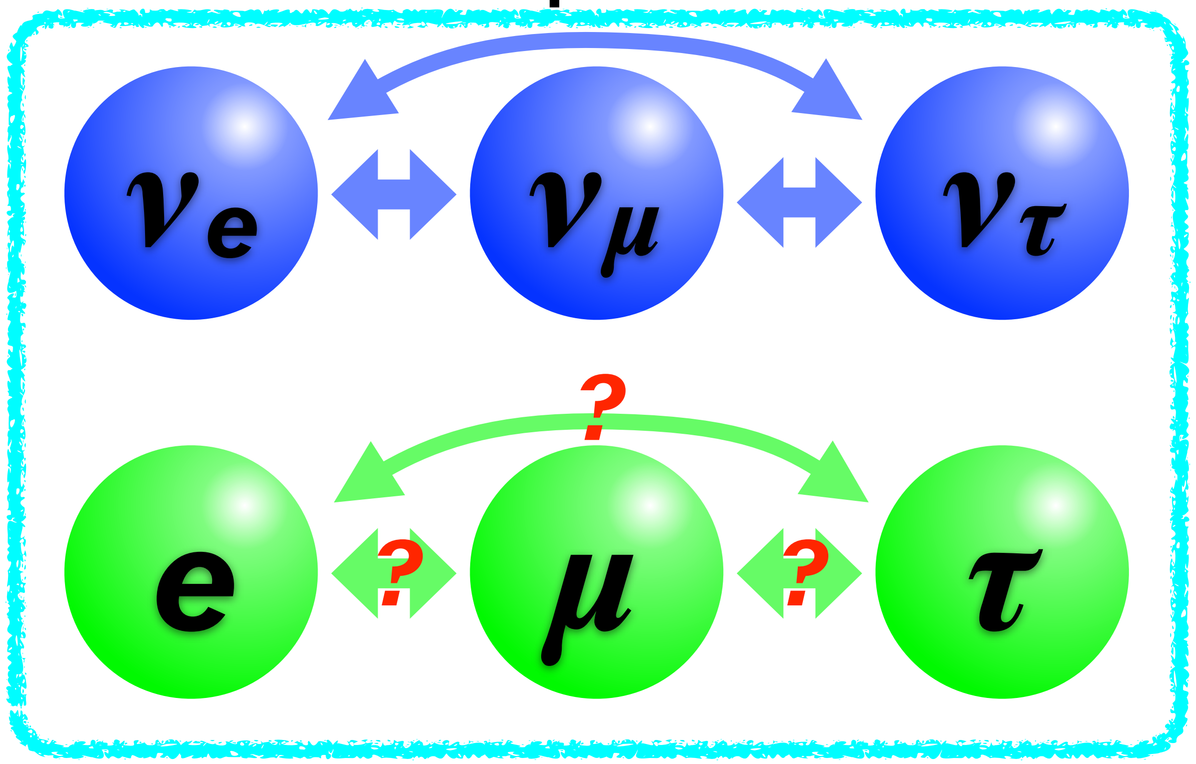
Charged Lepton Flavor Violation
= new physics

Quarks



Flavors are mixed through CKM matrix in the Standard Model,
Already confirmed → Novel Prize in 2008

Leptons



Flavors are mixed through PMNS matrix, Already confirmed (extension of SM) → Novel Prize in 2015

Charged Lepton Flavor Violation
Strongly restricted in the Standard Model,
Not observed so far → Discovery = New Physics

What & Why μ-e conversion?

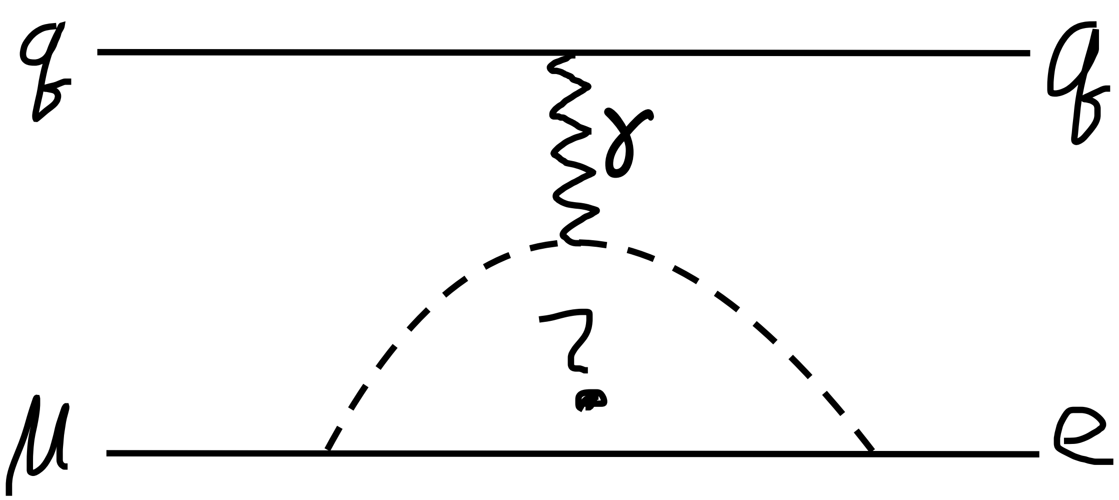


Diagram of μ-e conversion, photonic case

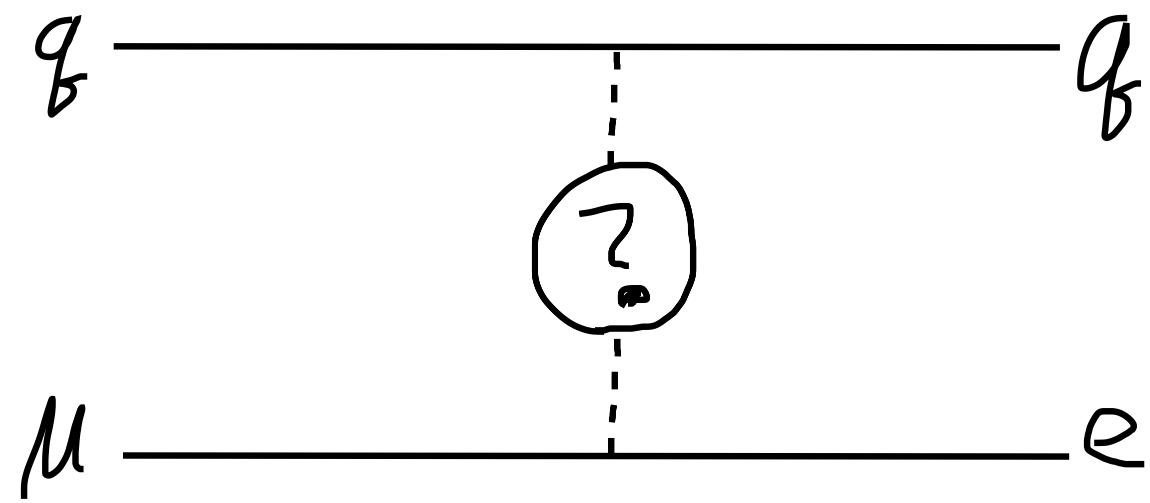
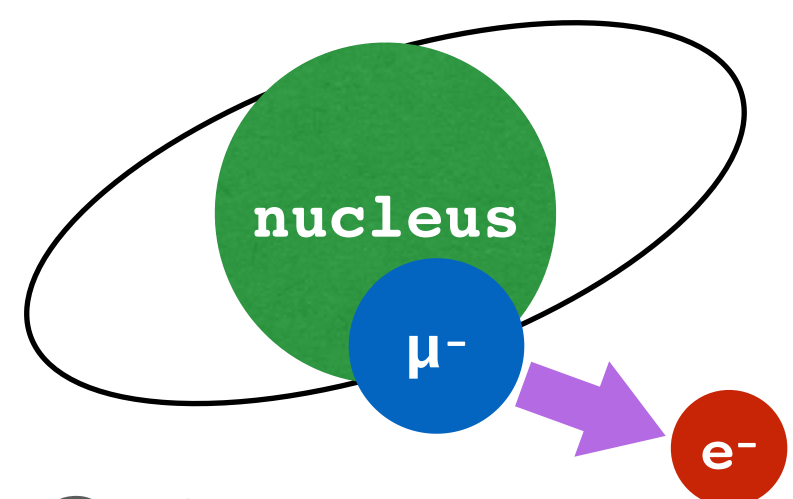
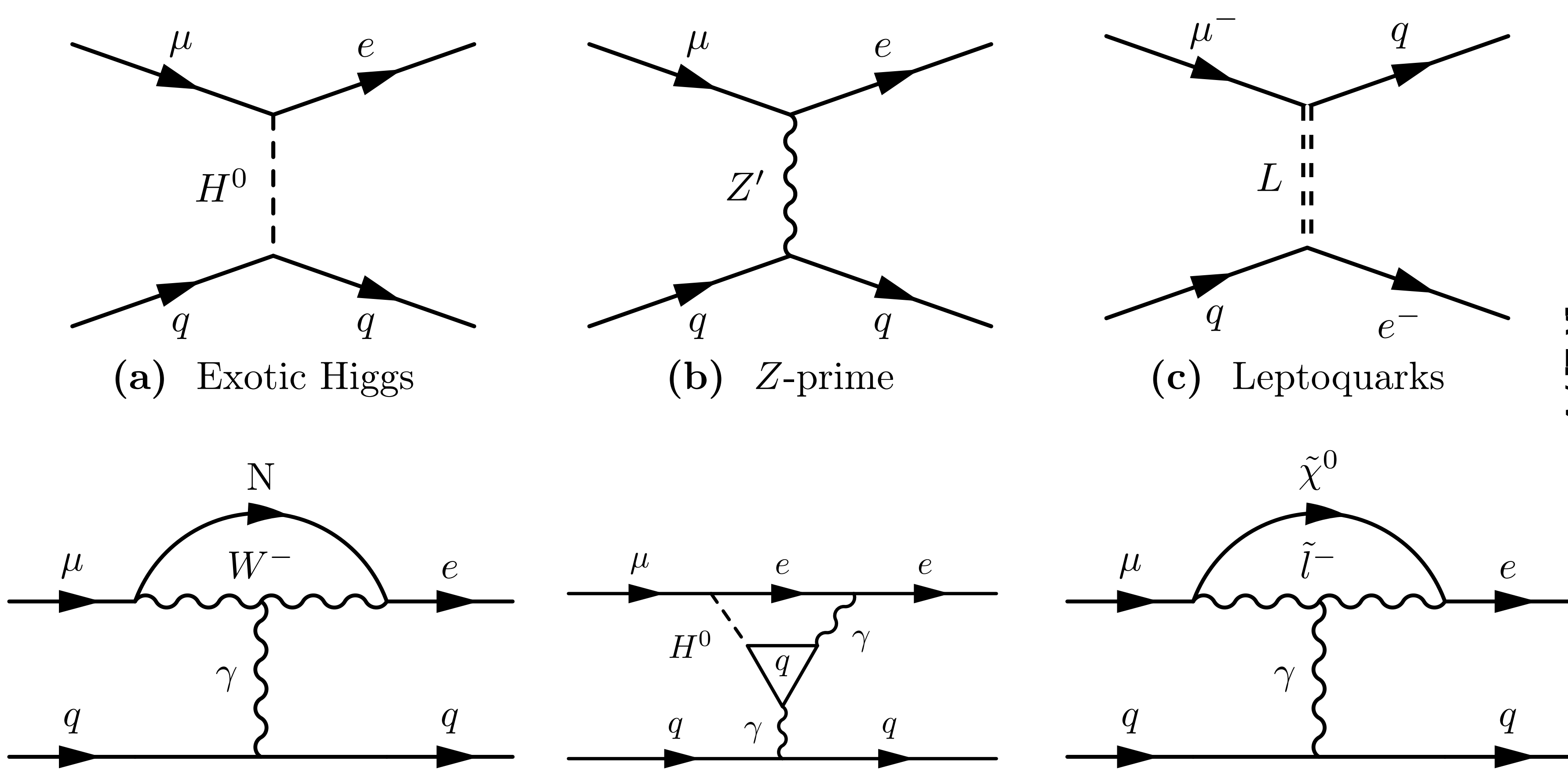


Diagram of μ-e conversion, tree-level case

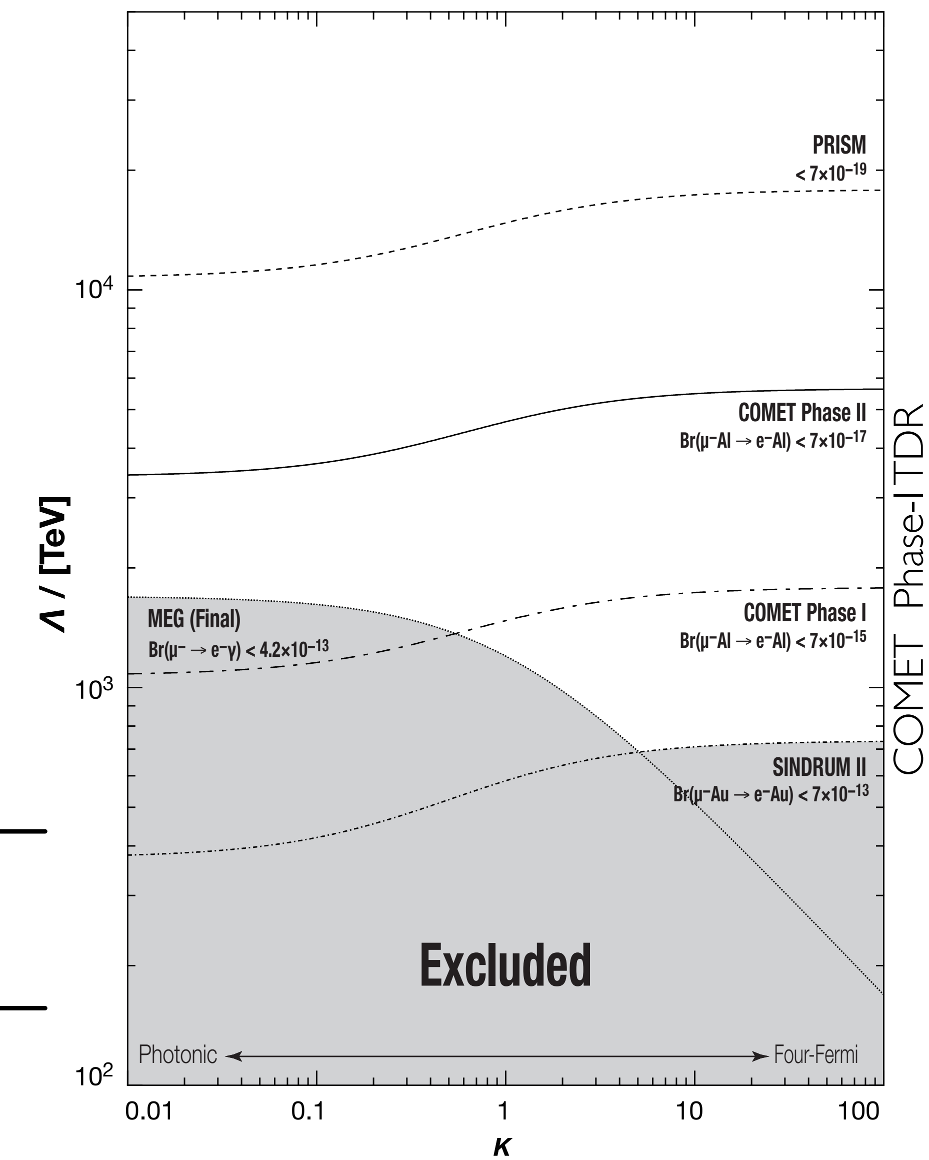
- Muon to electron conversion in nuclei w/o neutrinos
  - ~O(10^{-54}) in SM + ν-oscillation
  - Enhanced in many BSMs
  - **Highly sensitive to New Physics**
- Simple kinematics: **$E_e = M_\mu - B_\mu - E_{recoil} \sim 105$MeV** @Al
- Easy to get high statistics due to its long lifetime (880ns @Al)
- LHC, other CLFV searches, muon g-2, b-physics are complementary
- Current upper limit: **7×10^{-13}** (90% C.L.) by SINDRUM II



μ-e conversion in BSM



(a) Exotic Higgs (b) Z-prime (c) Leptoquarks
(d) Heavy Neutrinos (e) Exotic Higgs (f) Supersymmetry

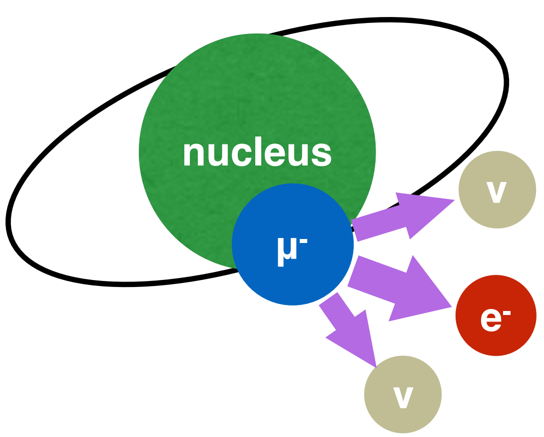


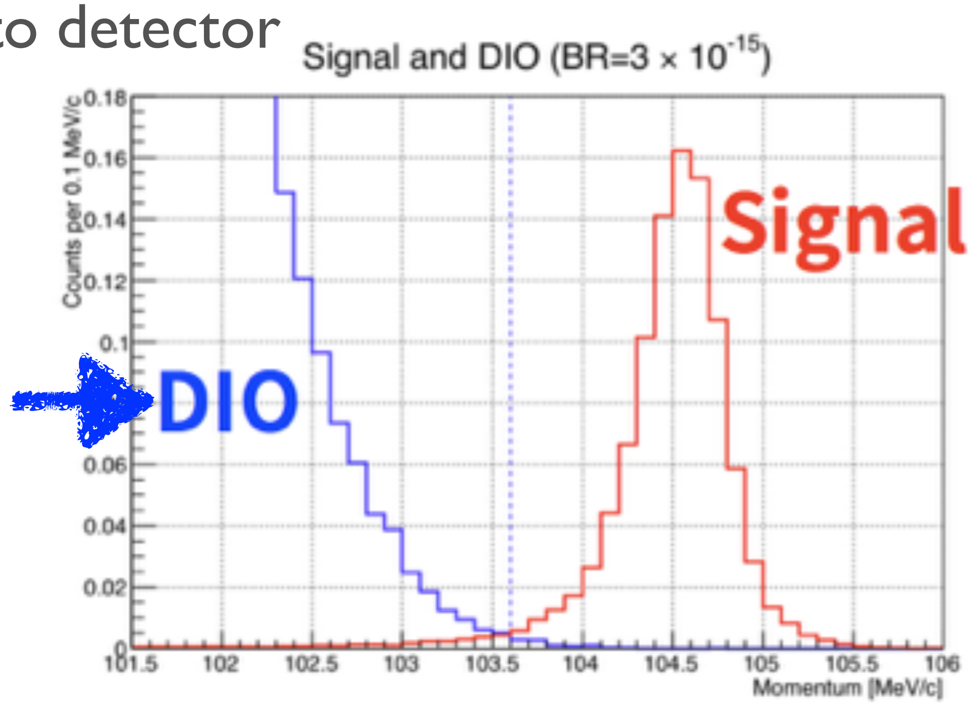
- μ-e conversion appears in many physics models beyond the standard model (BSM)
  - Just requires an additional inter-mediating particle(s) that allow lepton flavor changing
- In most cases, branching ratio(BR) can be detectable
  - BR varies depending on the models and parameters
  - **Detection = Discovery of new physics**
  - **Measurement = Specification of new physics!**

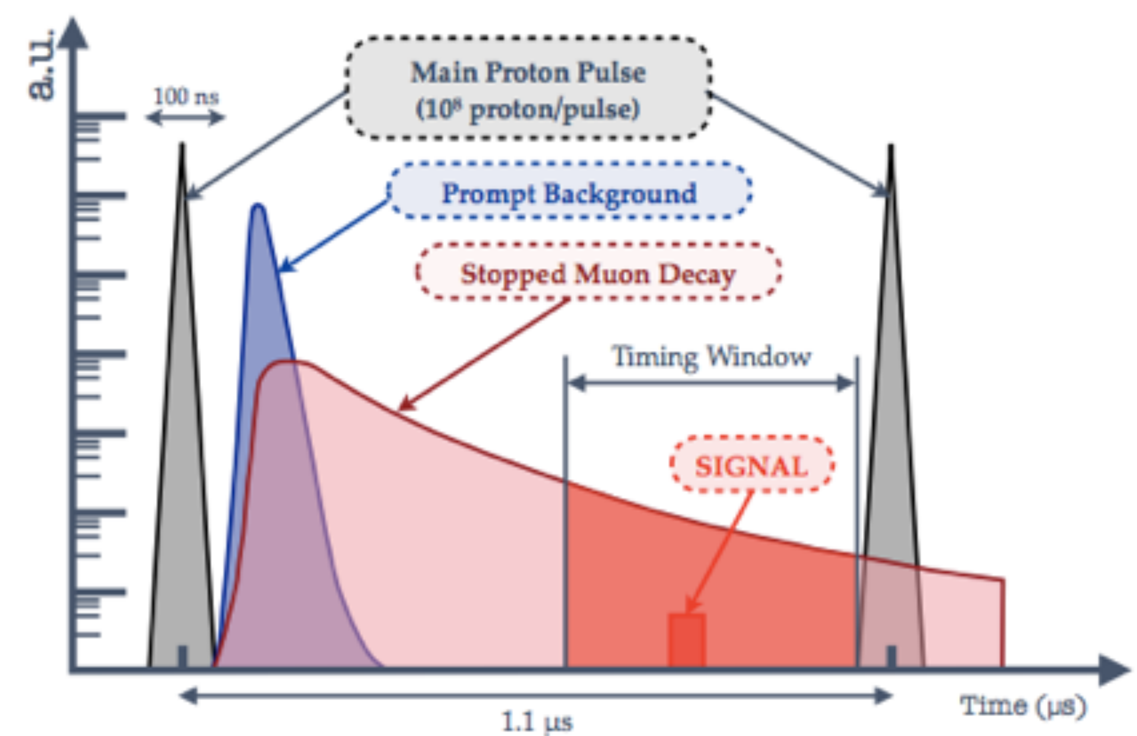
Requirements

- **High statistics**
  - $>10^{18\text{-}20}$ of stopping muons are required
    - ➡ High intensity proton beam & Effective muon production/collection
- **Background suppression**
  - **Intrinsic BG**: Muon DIO (Decay In Orbit)
    - ➡ Good momentum resolution=Less multiple scattering
  - **Beam BG**: Radiative π capture, π/μ decay in flight, Antiproton, Proton leakage, etc.
    - ➡ Pulse beam + off-time measurement, strong pion suppression
    - ➡ Good extinction* factor ($<10^{-10}$)
  - **Other BG**: Cosmic ray
    - ➡ Adding veto detector

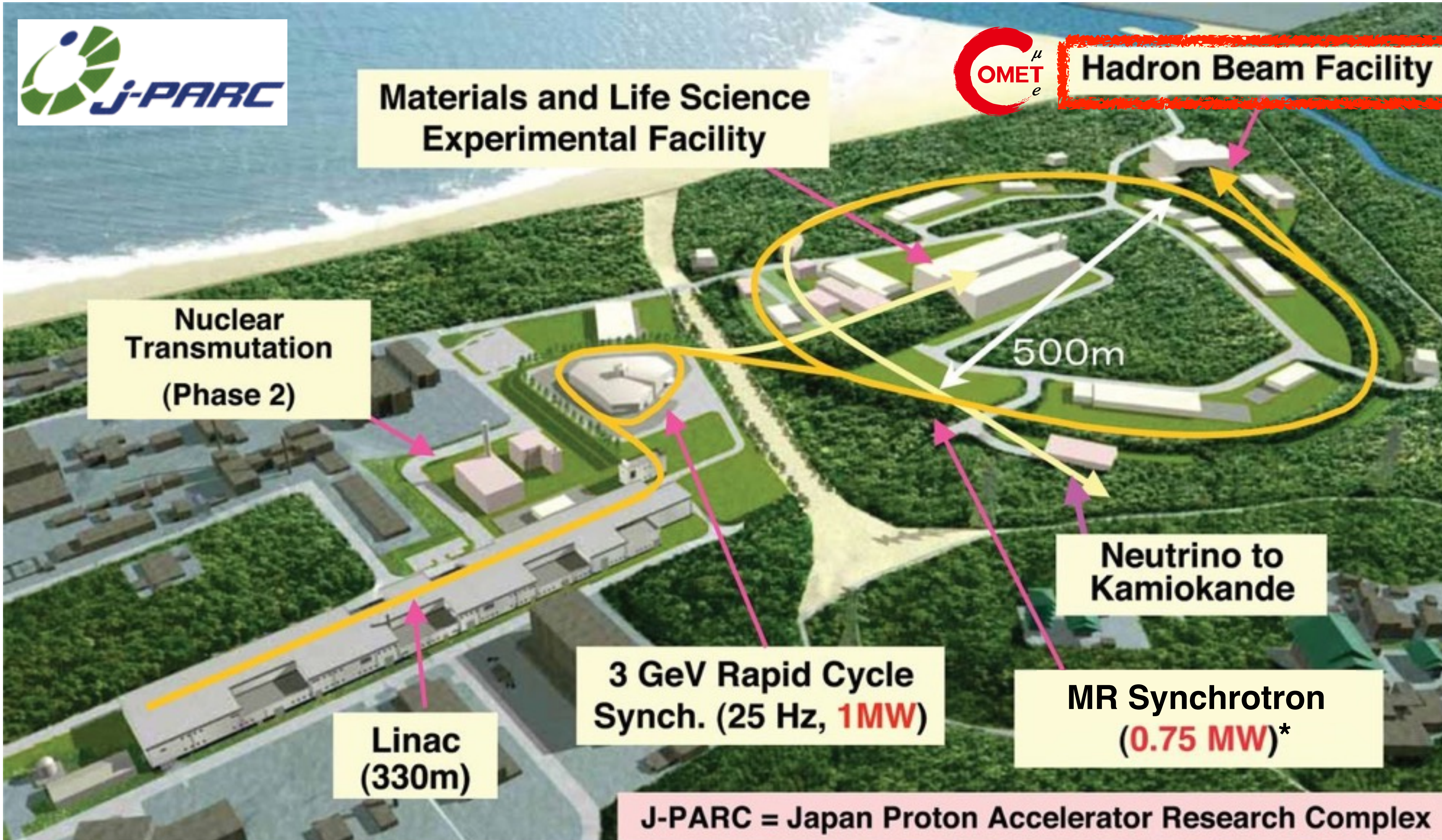
$$\text{*Extinction} = \frac{\text{Number of protons between 2 bunches}}{\text{Number of protons in a bunch}}$$







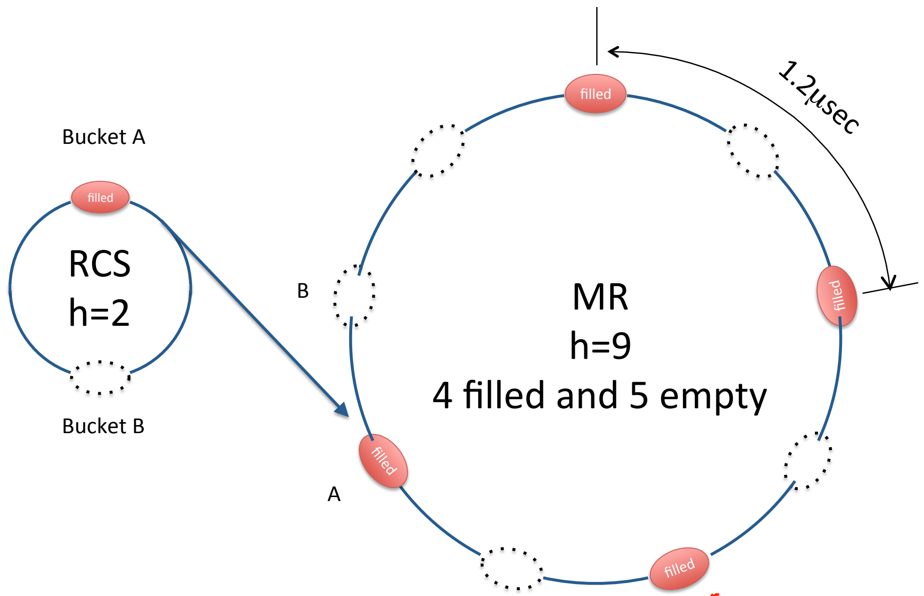
J-PARC

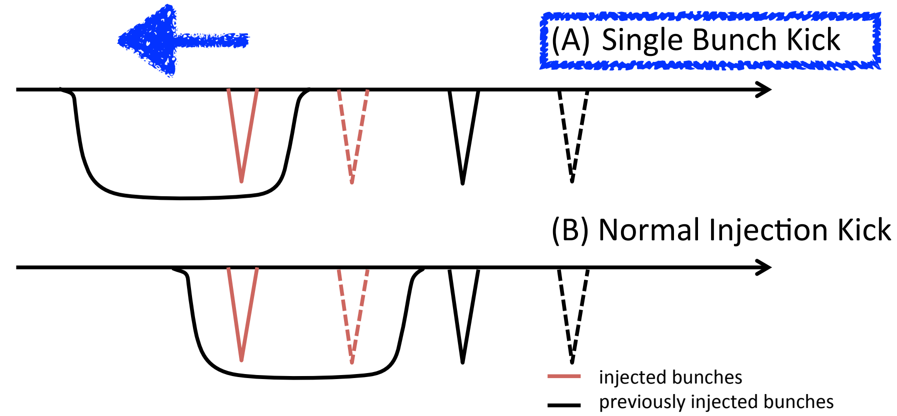


Joint Project between KEK and JAEA

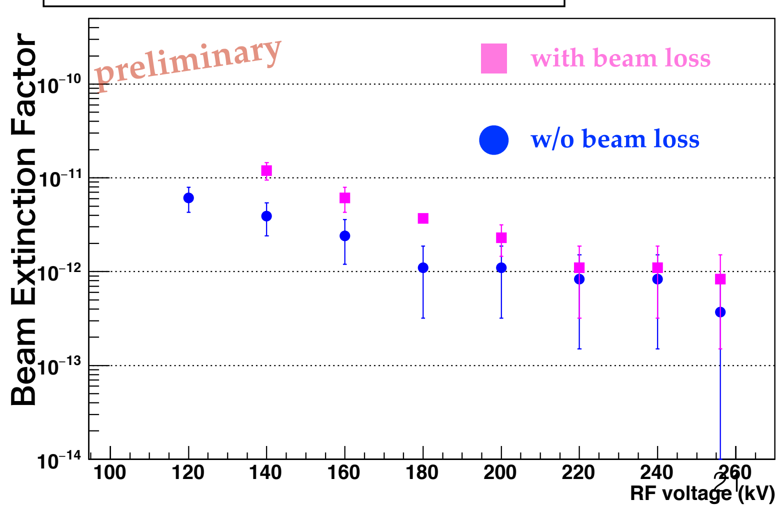
*design value

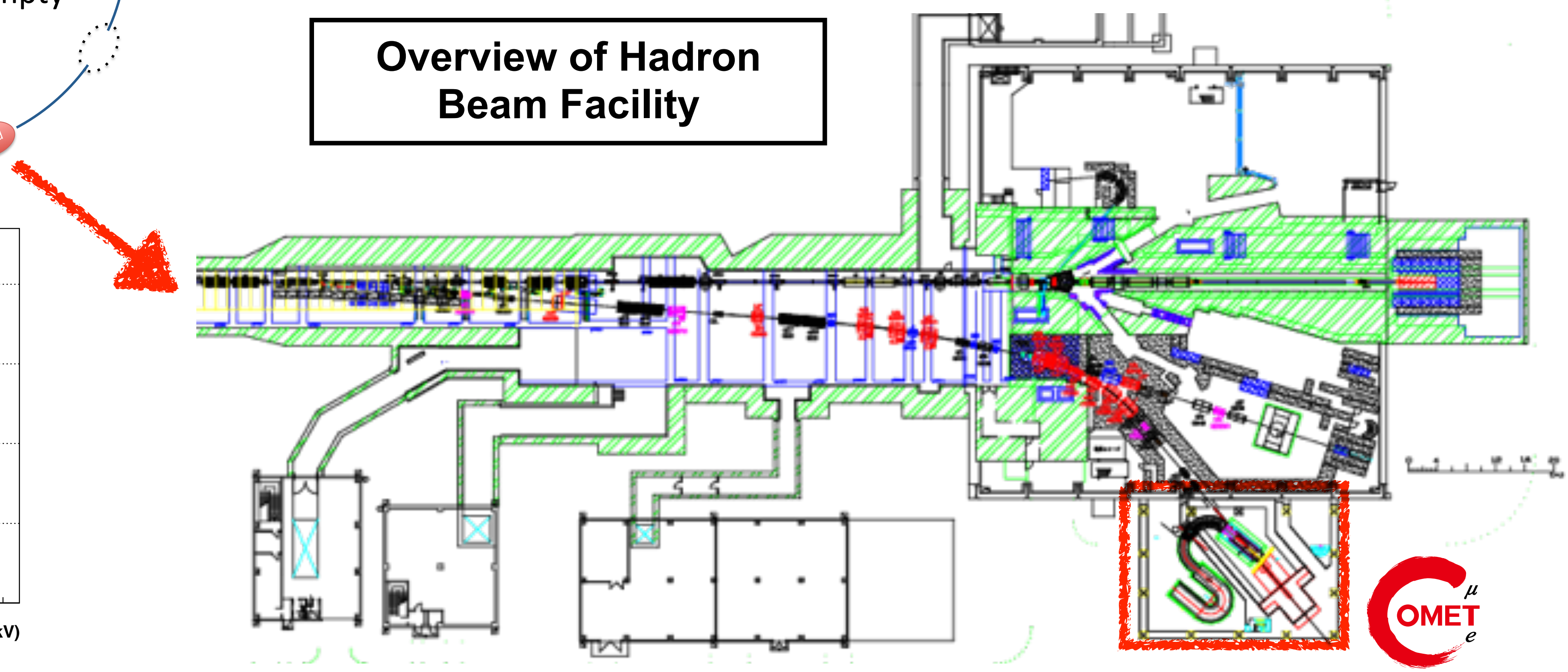
Proton Beam for COMET





Measurement at Abort Line with FX





- Bunched slow extraction with a 3.2(56) kW accelerator operation in Phase-I(Phase-II)
- Pulsed beam with 1.2μs intervals can be realized by emptying one of the two buckets in RCS
- Accelerate protons up to 8GeV in MR → Deliver them to COMET hall @ HD Facility
- Extinction has been recently measured to be $10^{-11\sim-12}$ in FX ($<6\times10^{-11}$ in SX)

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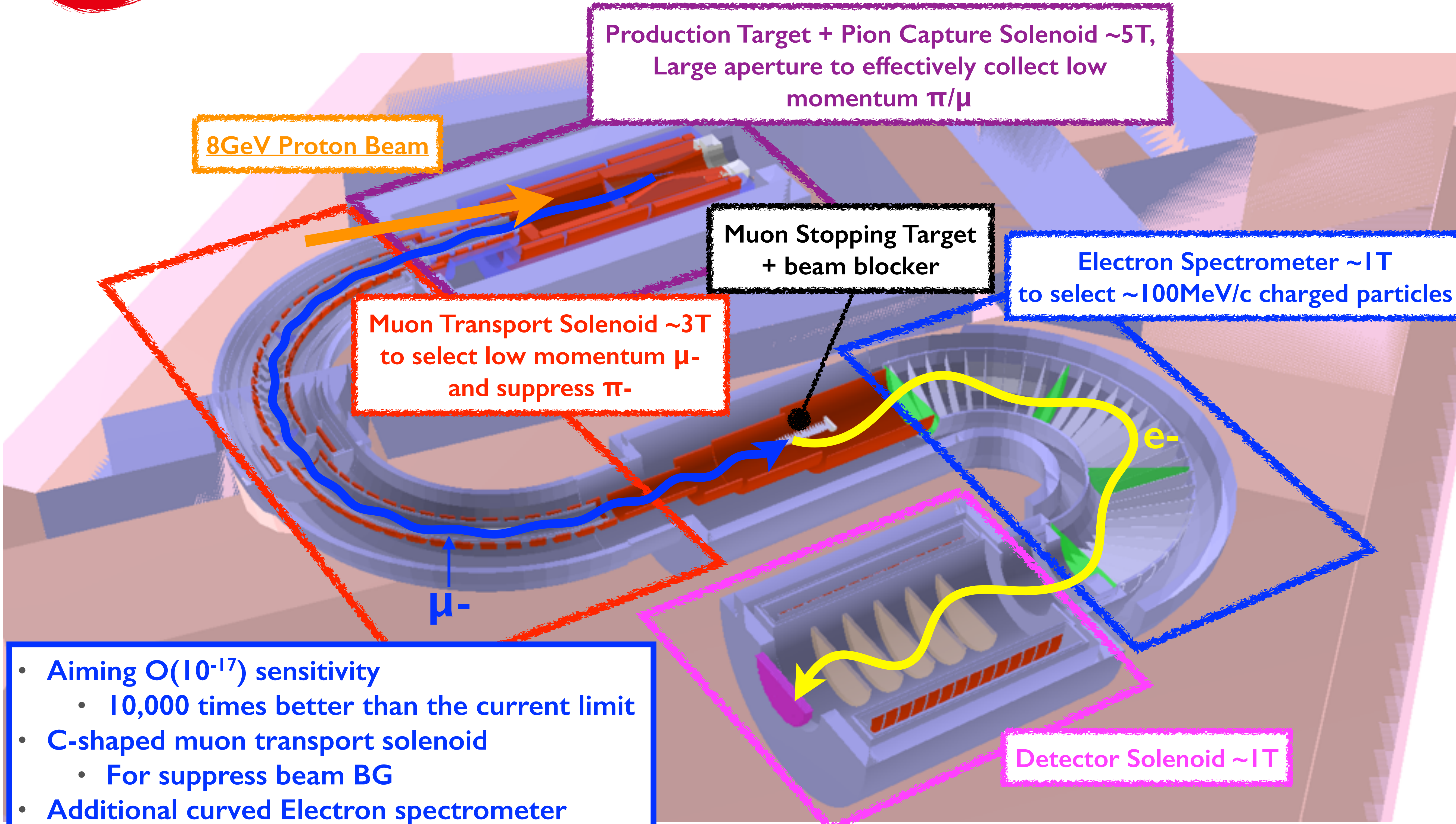
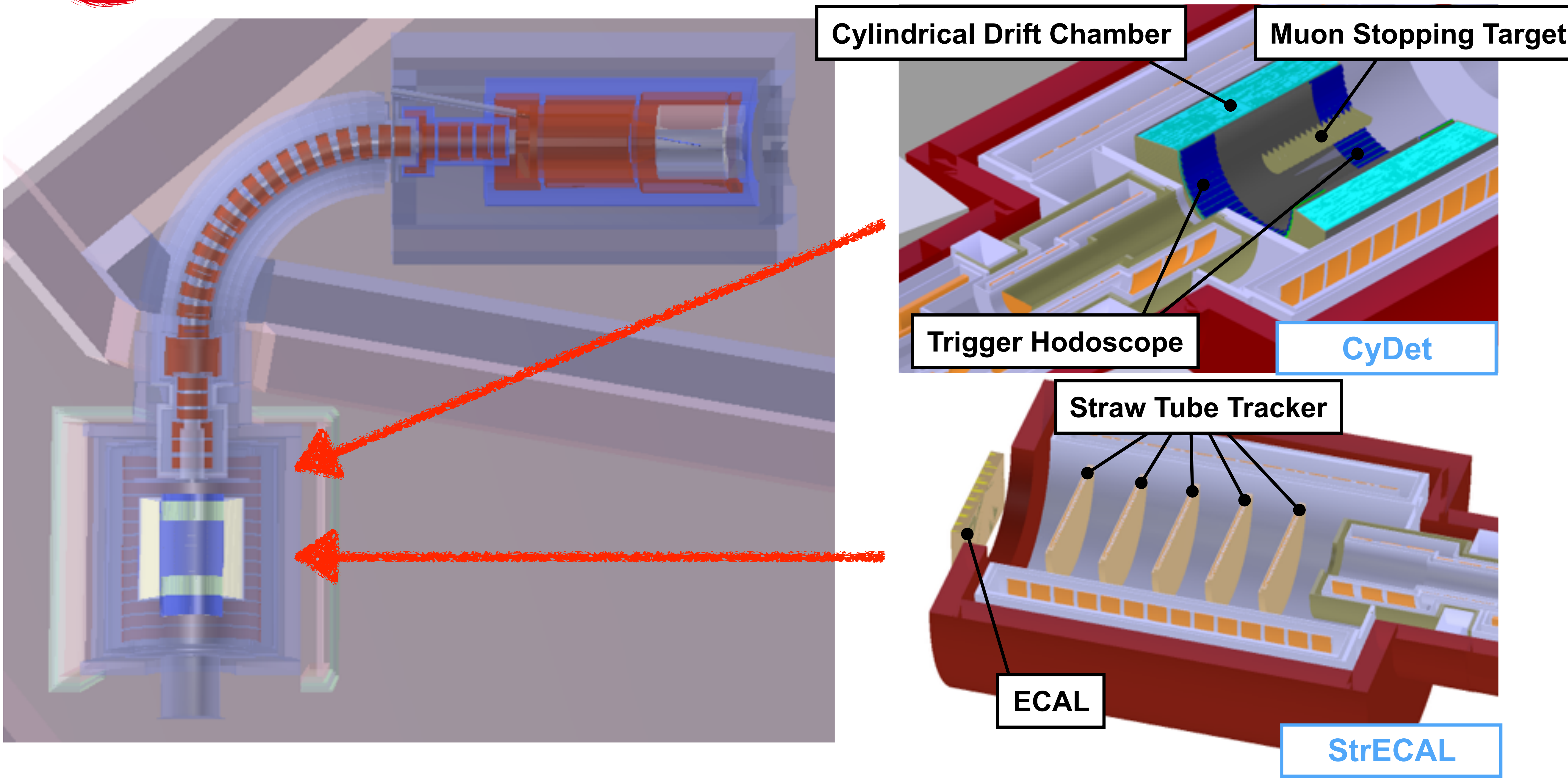
COMET Overview



- Aiming O(10^{-17}) sensitivity
    - 10,000 times better than the current limit
- C-shaped muon transport solenoid
    - For suppress beam BG
- Additional curved Electron spectrometer
    - Suppress DIO+beam BG

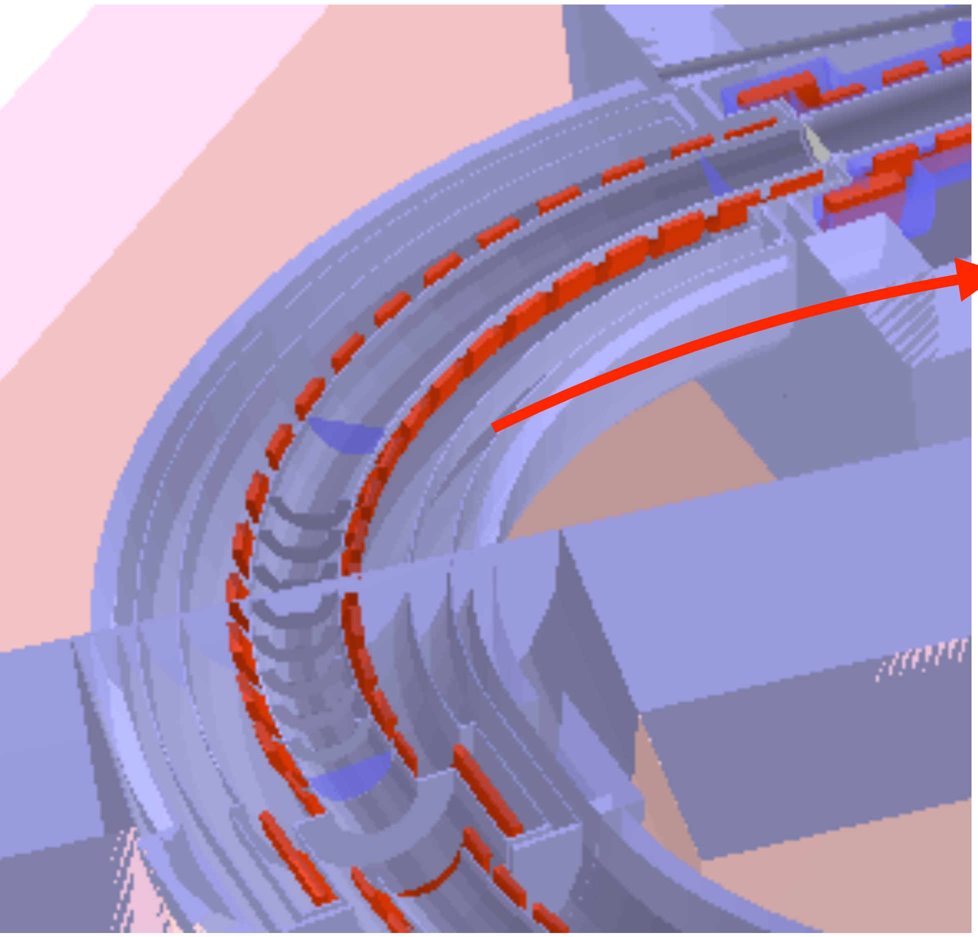
COMET Phase-I

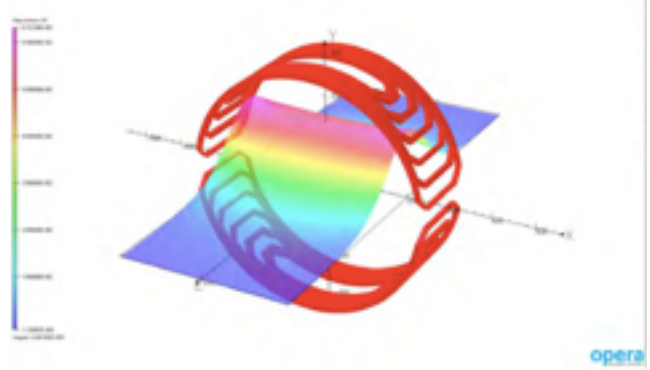


- Construct the first 90° of the muon transport solenoid
- Perform the μ-e conversion search with a sensitivity of 10^{-15} using **CyDet**
- Measure the beam directly using **StrECAL** as a Phase-II prototype detector

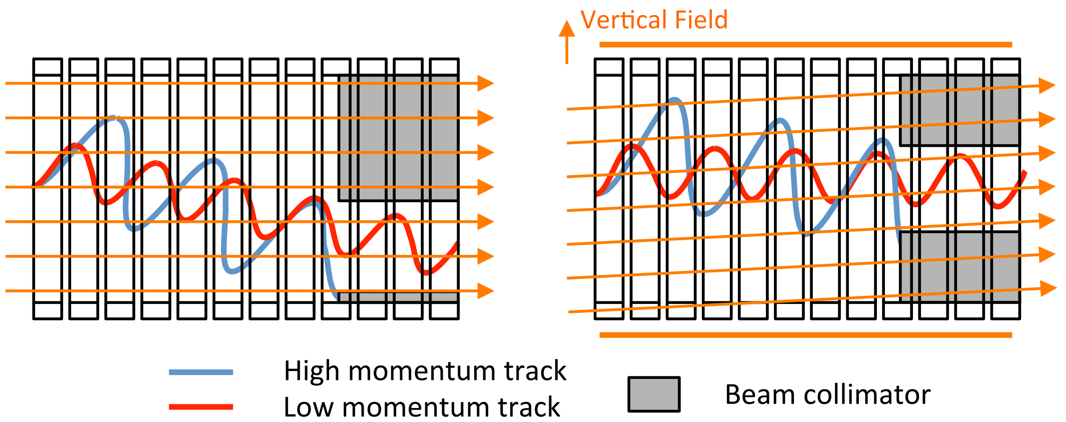
Muon Beam/Target

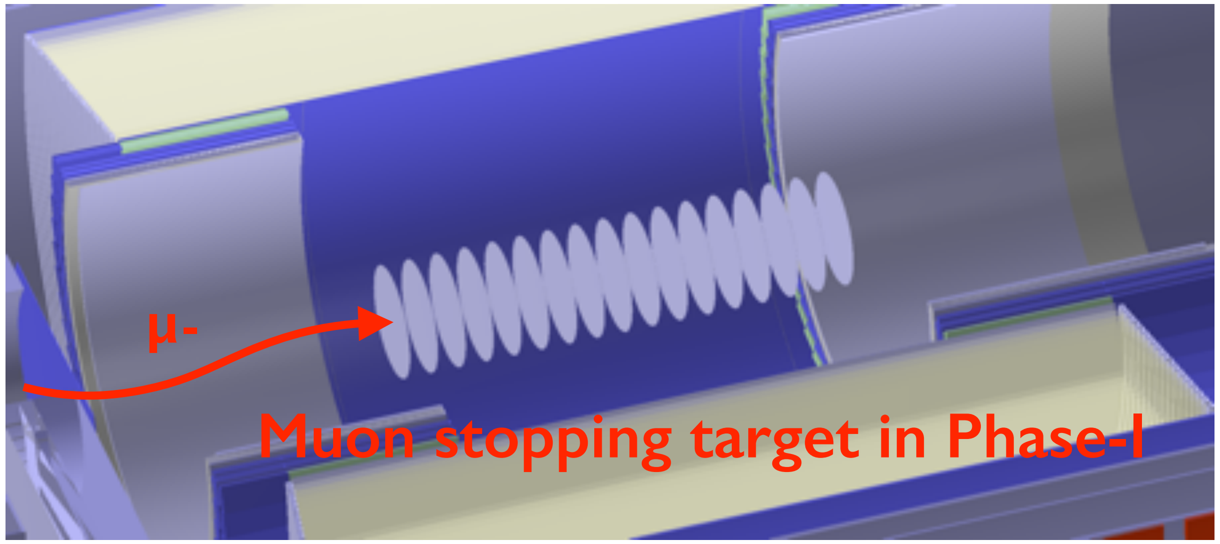
- Muon transported in a curved solenoid w/ a dipole field
  - Reduce pions which can produce high momentum secondaries
  - Momentum/charge selection
- Muons stopped inside the series of 200μm thin aluminum disks
  - Stopping rates are ~5×10^{-4} (1.6×10^{-3}) / POT(=a Proton On Target) in Phase-I (Phase-II)



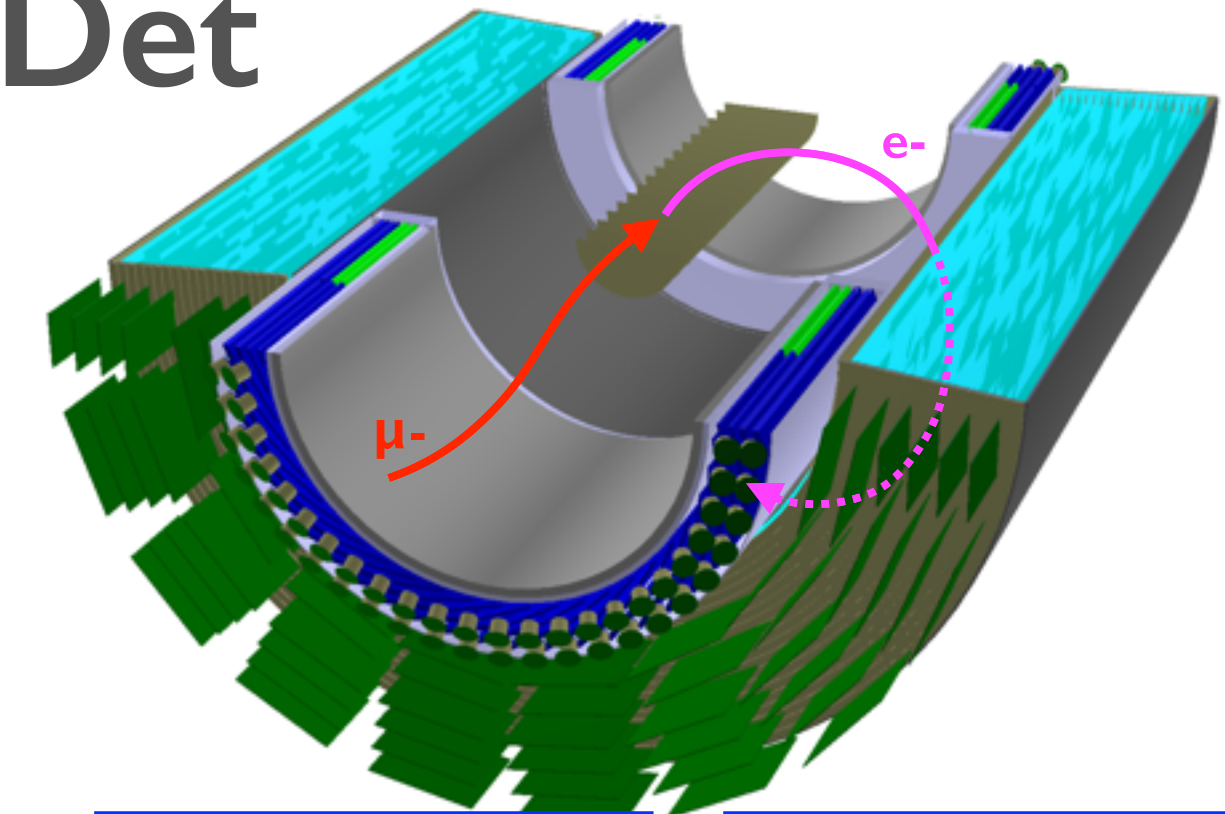


Saddle type coil is put outside of each solenoid coil to generate dipole field



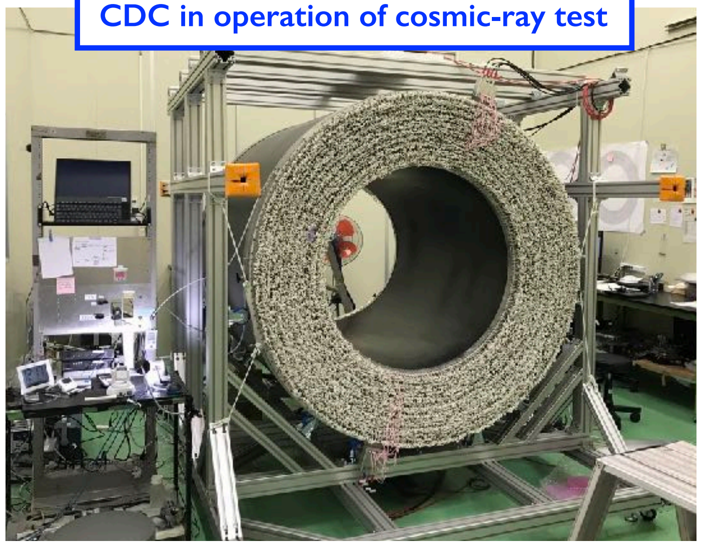


CyDet

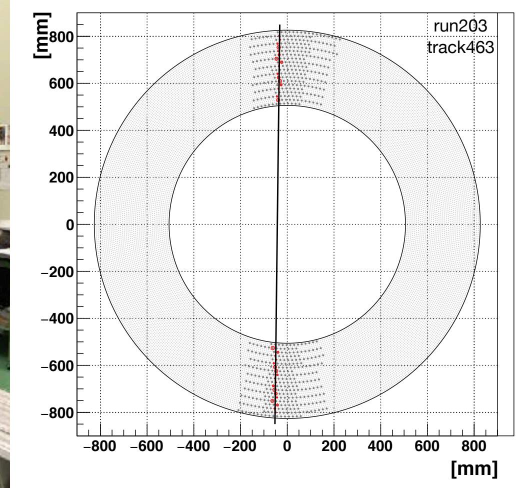


- Cylindrical Drift Chamber (CDC)
  - Main tracker for Phase-I physics measurement
    - All stereo wires to reconstruct 3D trajectories
    - 20layers with ~5k/15k sense/field wires
    - Gas mixture, He:iC_4H_{10}=90:10
    - **σ_p ~ 200 keV/c** @105MeV/c, is required
  - Detector has been constructed & performance study with cosmic-rays is ongoing
- Cherenkov Trigger Hodoscope (CTH)
  - Each module consists of an acrylic Cherenkov radiator and a plastic scintillator
  - 48 modules arranged both up/downstream
  - Require 4 hits coincidence to suppress the accidental trigger due to γ rays
  - **Better than 1ns time resolution** is already obtained

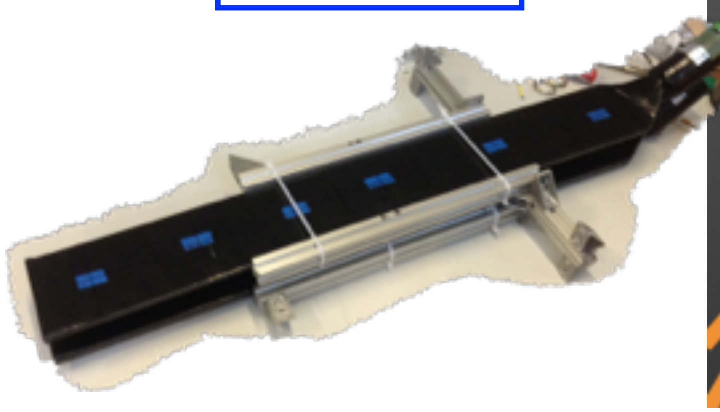
CDC in operation of cosmic-ray test

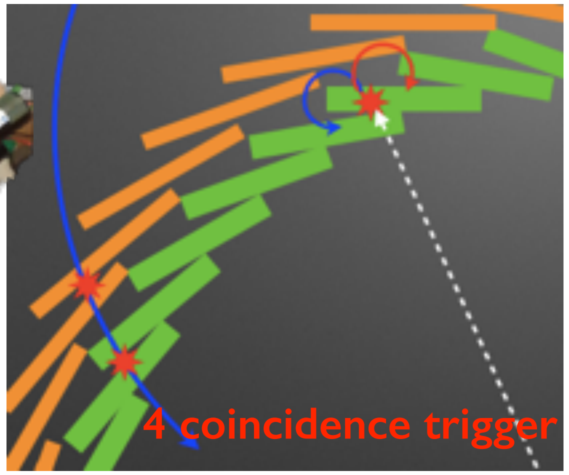


An example of cosmic-ray event

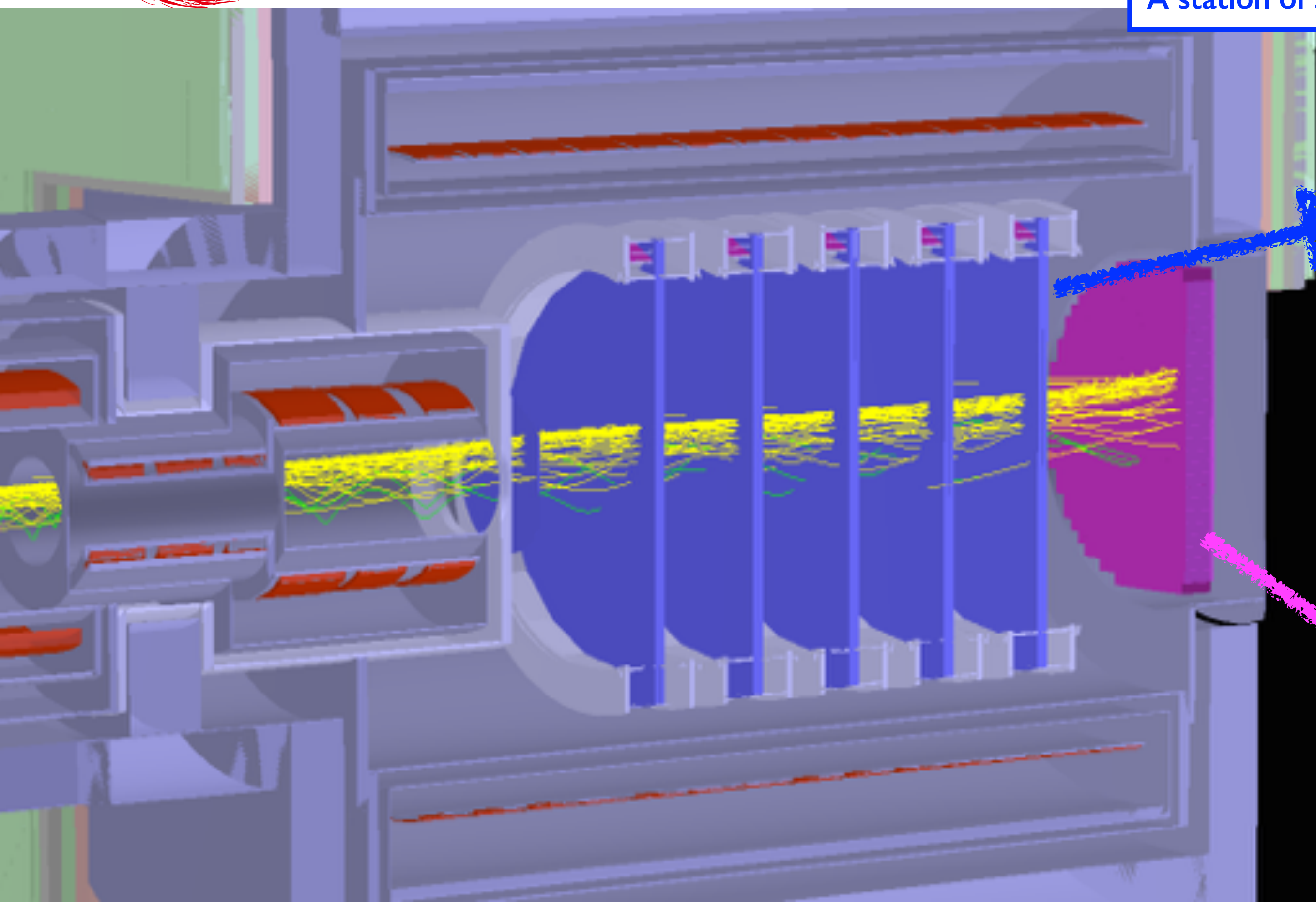


CTH Prototype

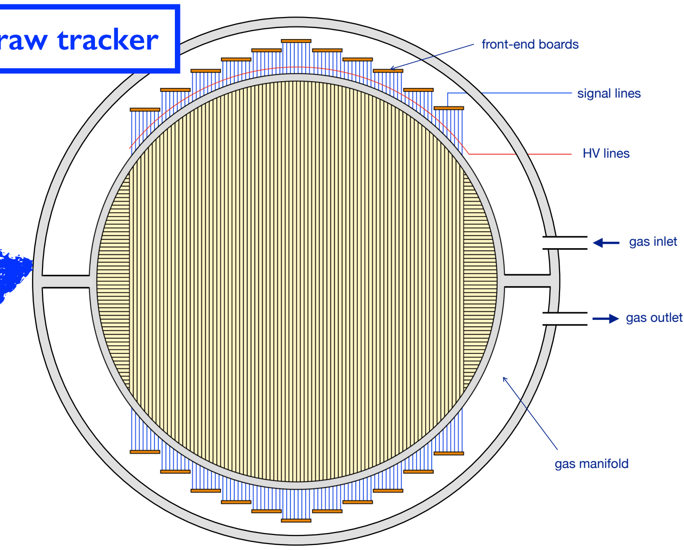


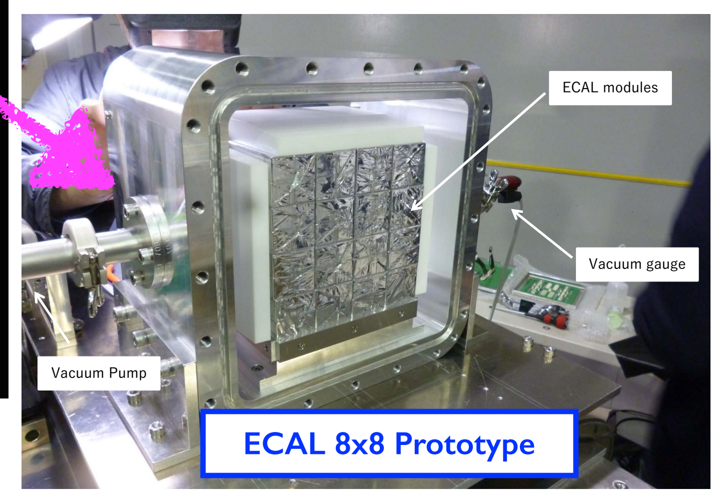


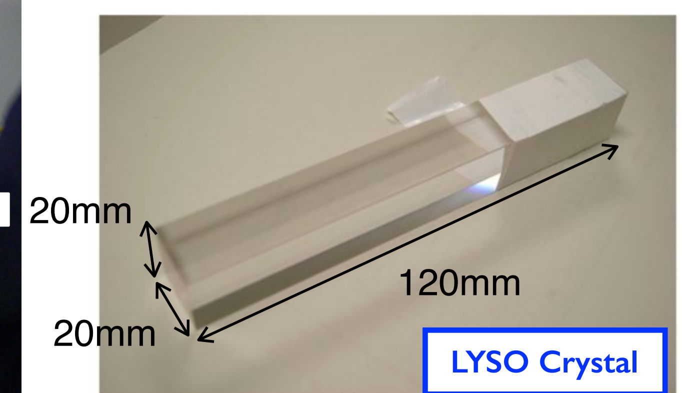
StrECAL



A station of straw tracker







- StrawTracker
  - **20/12µm** thin straw tubes with diameters of 10/5mm, operational in vacuum, for Phase-I/II
  - Precise position/momentum measurement (σ_x<200µm, σ_p=150-200keV/c @105MeV/c e-)
  - Mass production of phase-I Straw tubes was completed, ready for the detector construction!
- ECAL
  - Array of 2,000 LYSO crystals
  - Fast decay time (~40ns), good energy resolution (<5% @105MeV/c e-), High density (7.2g/cm^3)
  - Performance study is almost completed, start purchasing the crystals

Phase-I Single Event Sensitivity

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

$103.6 < p_e < 106.0$ MeV/c

$700 < t_e < 1170$ ns

$$B(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}},$$

- N_μ: Number of muons stopped inside targets
- f_{cap}: Fraction of muons to be captured by Al target = 0.61
- f_{gnd}: Fraction of μ-e conversion to the ground state = 0.9

- 3×10^{-15} S.E.S. is achievable within ~150 days of DAQ time
  - Corresponding to $N_\mu = 1.5\times10^{16}$ ($=3\times10^{19}$ POT)

Phase-I Backgrounds

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.

Due to incident protons arriving between the main proton bunches (Prompt Beam)

Due to particles delayed inside capture/transport solenoids (Delayed Beam)

- Normalized to a 3×10^{-15} of S.E.S., assuming extinction factor=3×10^{-11}
- Background is almost negligible
- <u>To be measured directly in Phase-I beam measurement</u>

COMET Phase-II

- In comparison with Phase-I…
  - Beam power: 3.2kW →**56kW** (×18)
    - ➡ Longer muon transportation enables to use more powerful proton beam
  - Muon stopping rate (per POT): 5×10^{-4} → $\mathbf{1.6\times10^{-3}}$ (×3)
    - ➡ Replacement of production target from Graphite to Tungsten, longer transportation solenoid
  - Total signal acceptance: 0.04 →**0.06** (×1.5)
    - ➡ Larger detector acceptance (covers the most of forward direction)
  - Momentum resolution will be improved: ~200keV/c →**160-180keV/c** (~10%)
    - ➡ Less materials in tracker: CDC→thin straw tube tracker in vacuum

Phase-II Sensitivity & Backgrounds

Type	Source	Background Rate per μ^- stop	per POT	per second	Total Events
Intrinsic	DIO	6.20×10^{-20}	9.92×10^{-23}	4.31×10^{-9}	0.068
	RMC	3.73×10^{-31}	6.01×10^{-34}	2.61×10^{-20}	4.10×10^{-13}
Delayed	RPC	–	1.73×10^{-27}	7.51×10^{-14}	1.18×10^{-6}
	Beam	–	1.47×10^{-24}	6.39×10^{-11}	1.00×10^{-3}
	Stopped $\bar{p}$	–	4.34×10^{-22}	1.89×10^{-8}	0.296
	π^- from $\bar{p}$	–	1.95×10^{-30}	8.49×10^{-17}	1.33×10^{-9}
Prompt	RPC	–	1.82×10^{-24}	7.91×10^{-11}	1.24×10^{-3}
	Beam	–	2.80×10^{-24}	1.22×10^{-10}	1.91×10^{-3}
	π^- from $\bar{p}$	–	3.56×10^{-29}	1.55×10^{-15}	2.43×10^{-8}
Cosmics		–	–	1.87×10^{-8}	0.294
Total		–	–	4.22×10^{-8}	0.662

← DIO in signal region

← Electron from Radiative Muon Capture

← Anti-proton rate is estimated conservatively

← Electron rate from cosmic-rays is estimated conservatively

- Assuming 0.5year of DAQ time (20% longer than in Phase-I)
  - Total statistical improvement is calculated to be **100**!
  - 3×10^{-17} S.E.S. is achievable in 0.5year, or 2.7×10^{-17} in 200days
- Nevertheless, BG rate will be low enough based on the simulation study

Summary

- CLFV processes are predicted by many BSMs while they're strongly suppressed in the Standard Model
- COMET aims to search for μ-e conversion with unprecedented S.E.S. of 3×10^{-15} ($<10^{-16}$) in Phase-I (Phase-II) @J-PARC
  - **There is a huge discovery potential**
- Phase-I experiment has been already approved by J-PARC PAC
  - All detectors are being prepared on schedule
  - Facility/beam-line are under construction in parallel
- Detector will be ready in 2019 for Phase-I, start soon after completing the beam-line construction
- Phase-II will follow Phase-I to reach **100** times better sensitivity than in Phase-I
  - Almost all R&Ds for Phase-II will be completed in Phase-I
- Further information can be found at http://comet.kek.jp/Introduction.html

➡ **Stay tuned!**

Backup