Search for Muon to electron conversion at J-PARC

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On behalf of the COMET collaboration

Outline

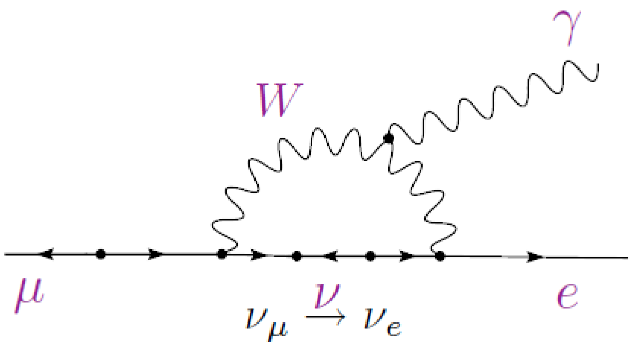
- Physics Motivation
- Design of the COMET Experiment
- Current Status of the COMET Experiment
- Outlook to Future mu-e Conversion Search
- Summary

Charged Lepton Flavor Violation (cLFV)

- Flavor is mostly conserved, only violated by charged weak current:
  - Flavor mixing in quark sector
    - Beta decay
  - Flavor mixing in lepton sector
    - Neutrino oscillation
- No fundamental physics behind flavor conservation. It's actually **natural** to consider favor violation in new physics.
  - FCNC? -> cLFV!
- So far the flavor structure is one of the biggest mystery in the SM
  - Any new phenomena of flavor violation would provide inspiration to new physics.

cLFV as a clean probe to new physics

- cLFV in the SM
  - FCNC in lepton sector is suppressed by neutrino mass and GIM mechanism

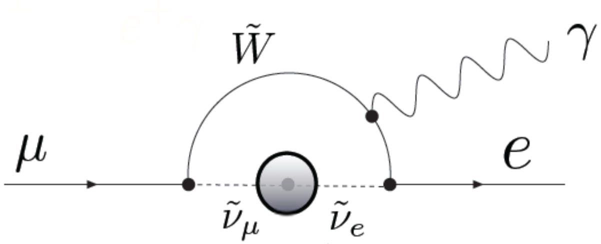


$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 \sim 10^{-54}$$

$* \; Br = \Gamma_{CLFV} / \Gamma_{capture}$

SM background free!
Positive result = new physics!

- cLFV in new physics models
  - Taking SUSY as an example, assuming natural energy scale and mixing angle

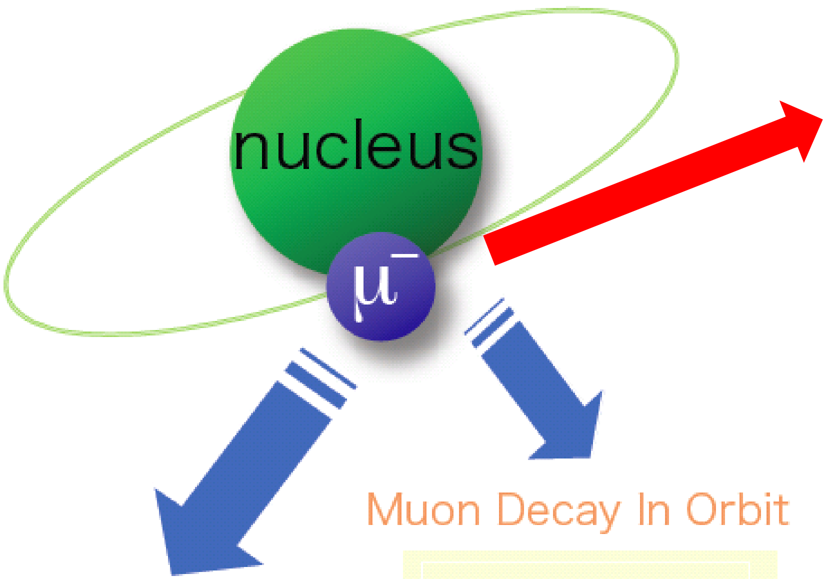


$$Br(\mu \rightarrow e\gamma) = 10^{-11} \times \left(\frac{2\,TeV}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2$$

Reachable with current technology!

$\mu - e$ conversion

1s state in a muonic atom



Muon Decay In Orbit

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

nuclear muon capture

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

$\mu - e$ conversion: neutrinoless muon nuclear capture

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

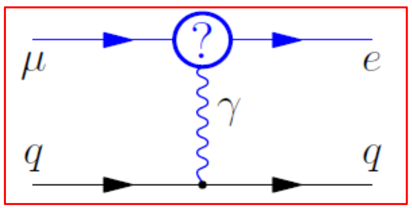
Charged lepton flavor violated

- **Signal signature:**
  - Mono-energetic electron with energy of 105 MeV
- **Background signature:**
  - No accidental background
    - Can utilize high luminosity
  - Beam background can be suppressed by pulsed beam
  - Physics background can be handled with current detector technology

Exloring high energy scale with $\mu - e$ conversion

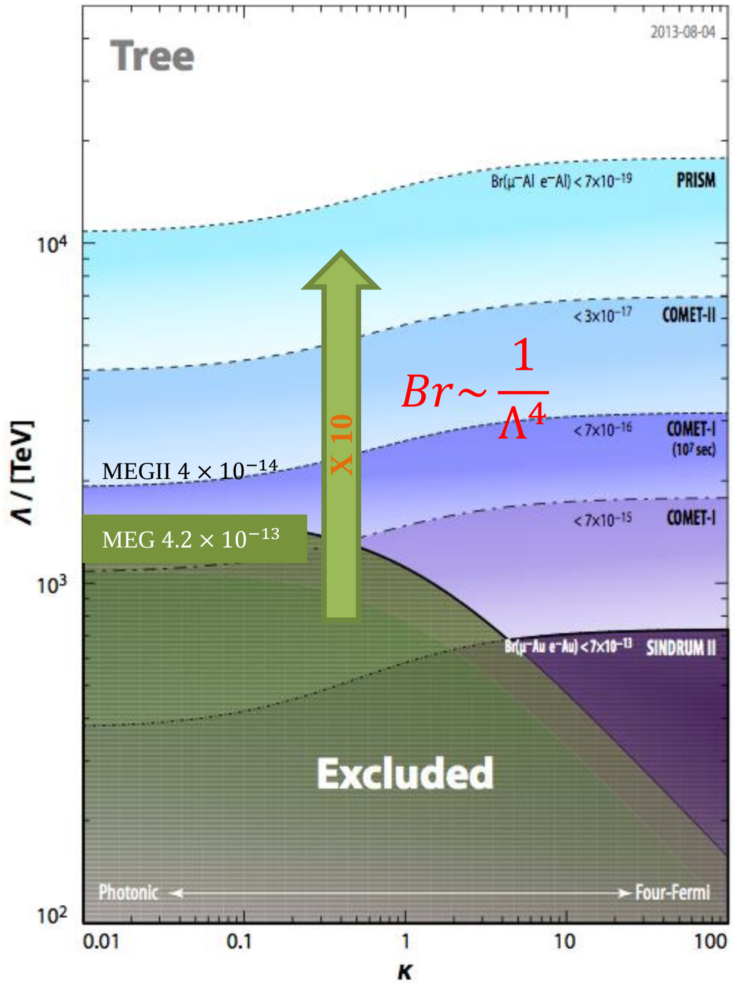
Extend SM in effective field theory with Dim-6 operator: $\mathcal{L} = \mathcal{L}_{SM} + \sum_{n\geq 1} \frac{c_{ij}{}^{4+n}}{\Lambda^n} \mathcal{O}^{4+n}$

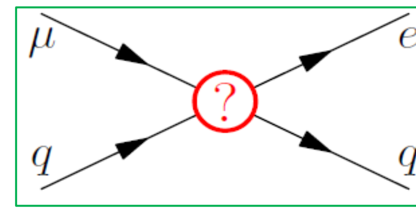
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma_\mu q_L$$



Photonic process
$\kappa \ll 1$

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





Four-Fermi process
$\kappa \gg 1$

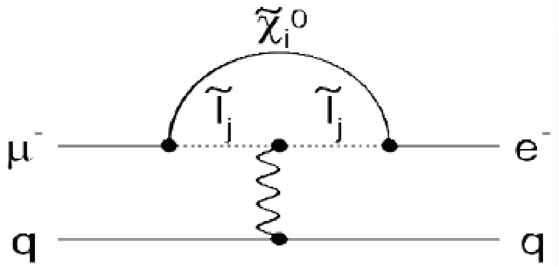
$\mu \to e\gamma$	$\mu - e$
None	Strong

$\mu - e$ conversion can test two different processes.

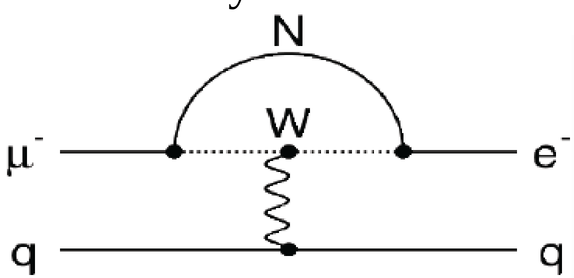
Models for $\mu - e$ conversion

Photonic processes

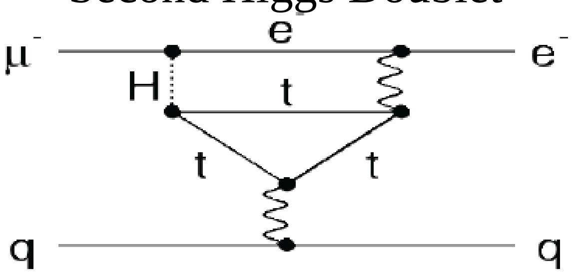
Supersymmetry



Heavy Neutrinos

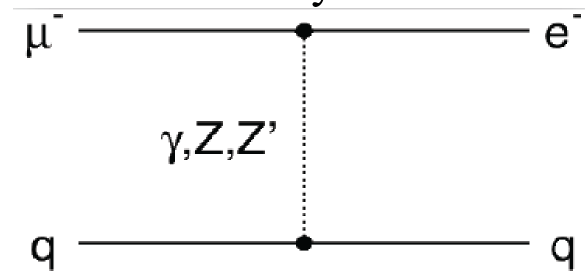


Second Higgs Doublet

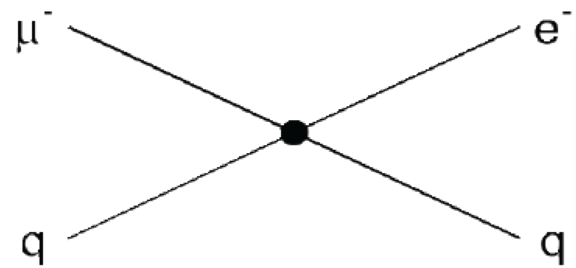


Four-Fermi processes

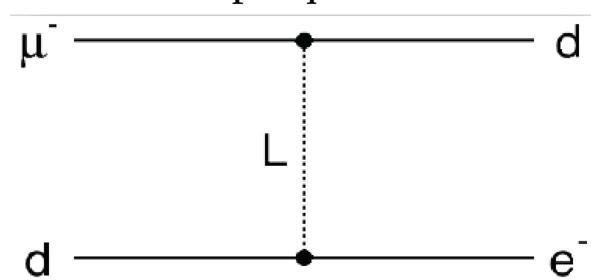
Heavy Z'



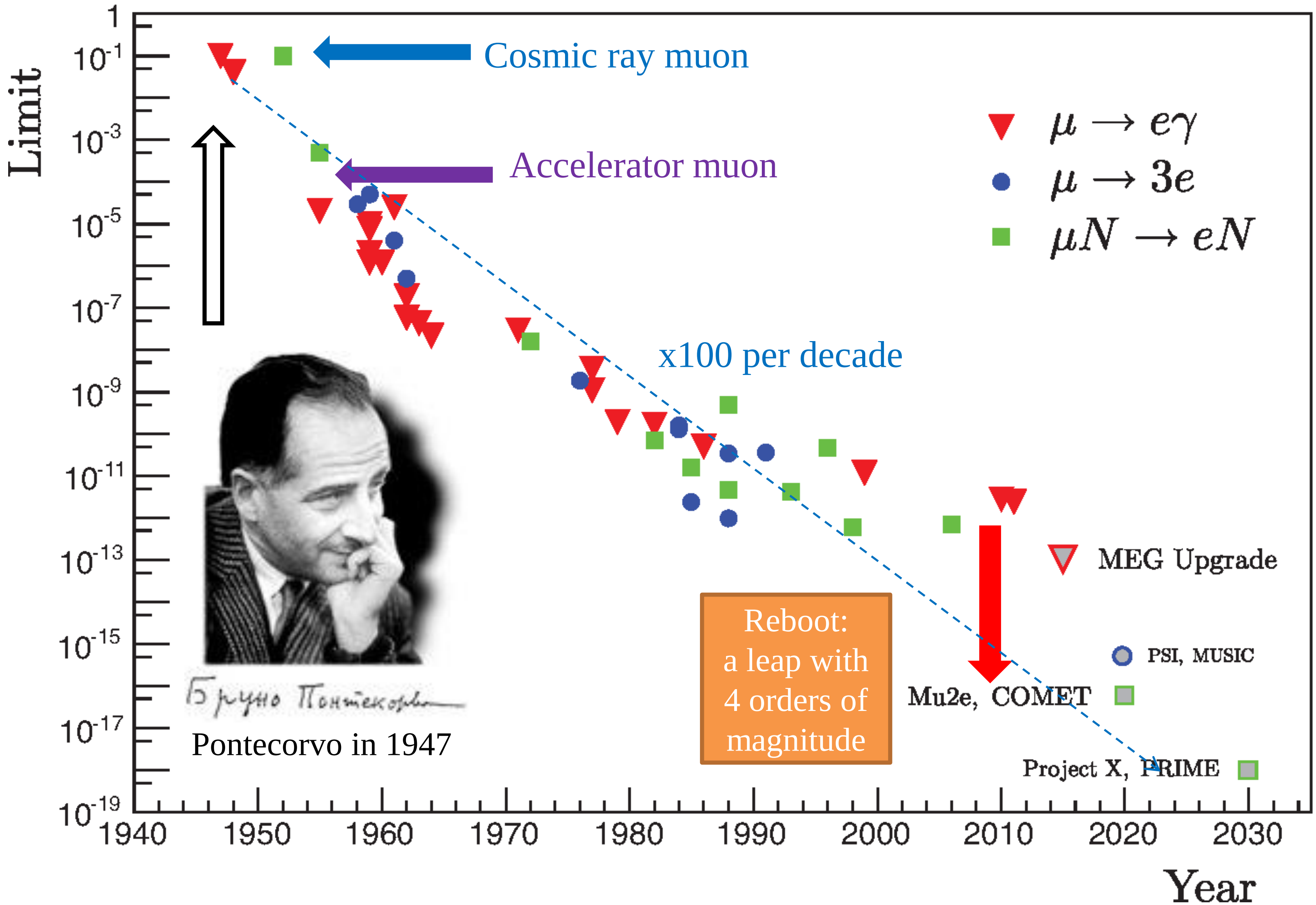
Compositeness



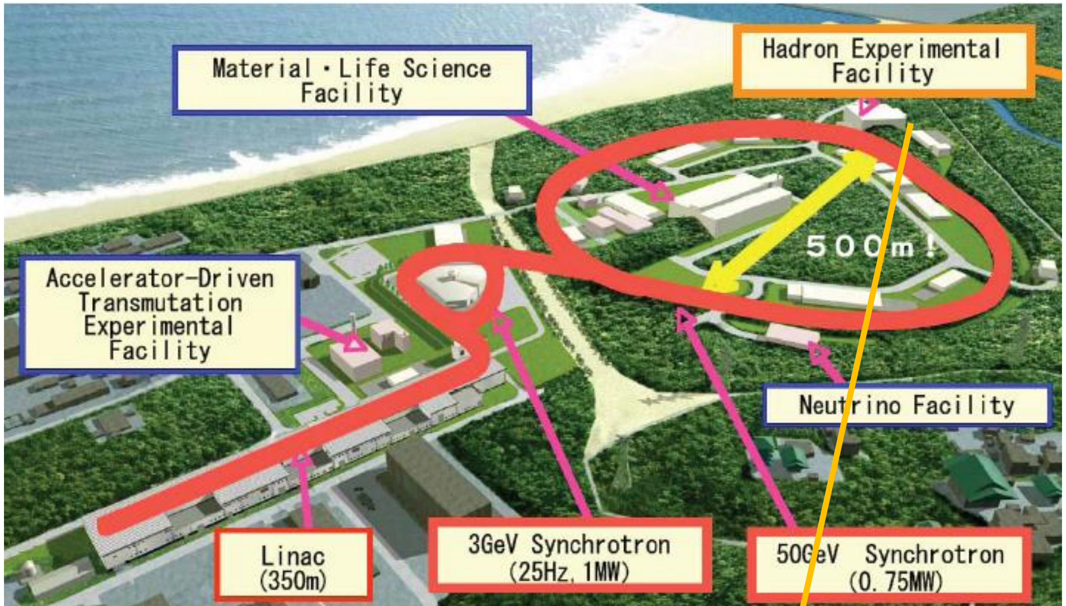
Leptoquarks

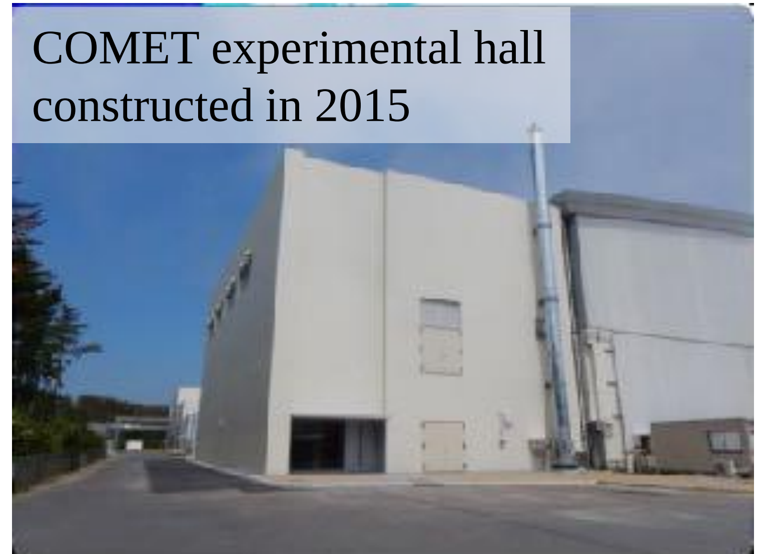


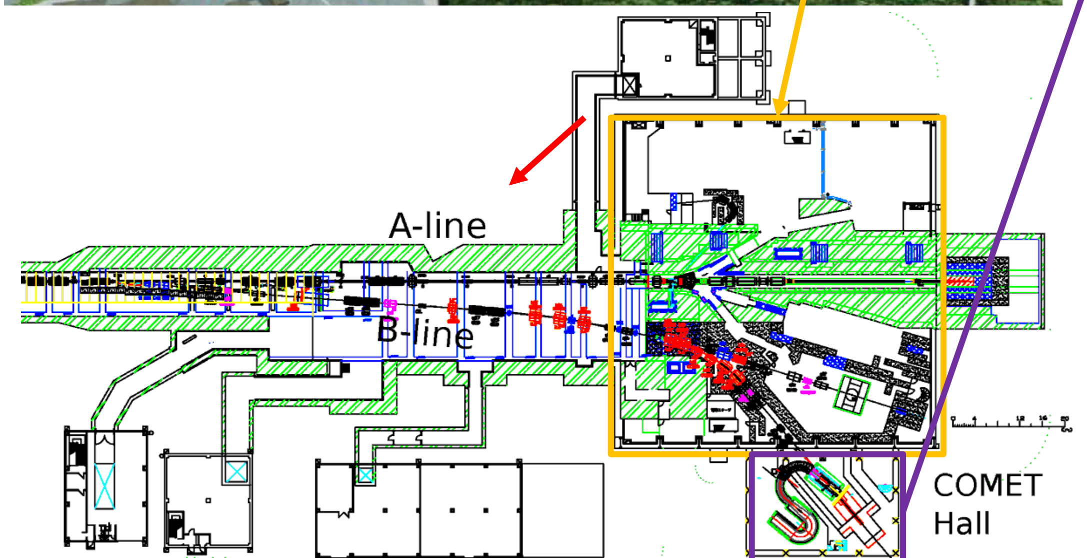
cLFV experiment in the hisotry



COherent Muon Electron Transition (COMET) at J-PARC

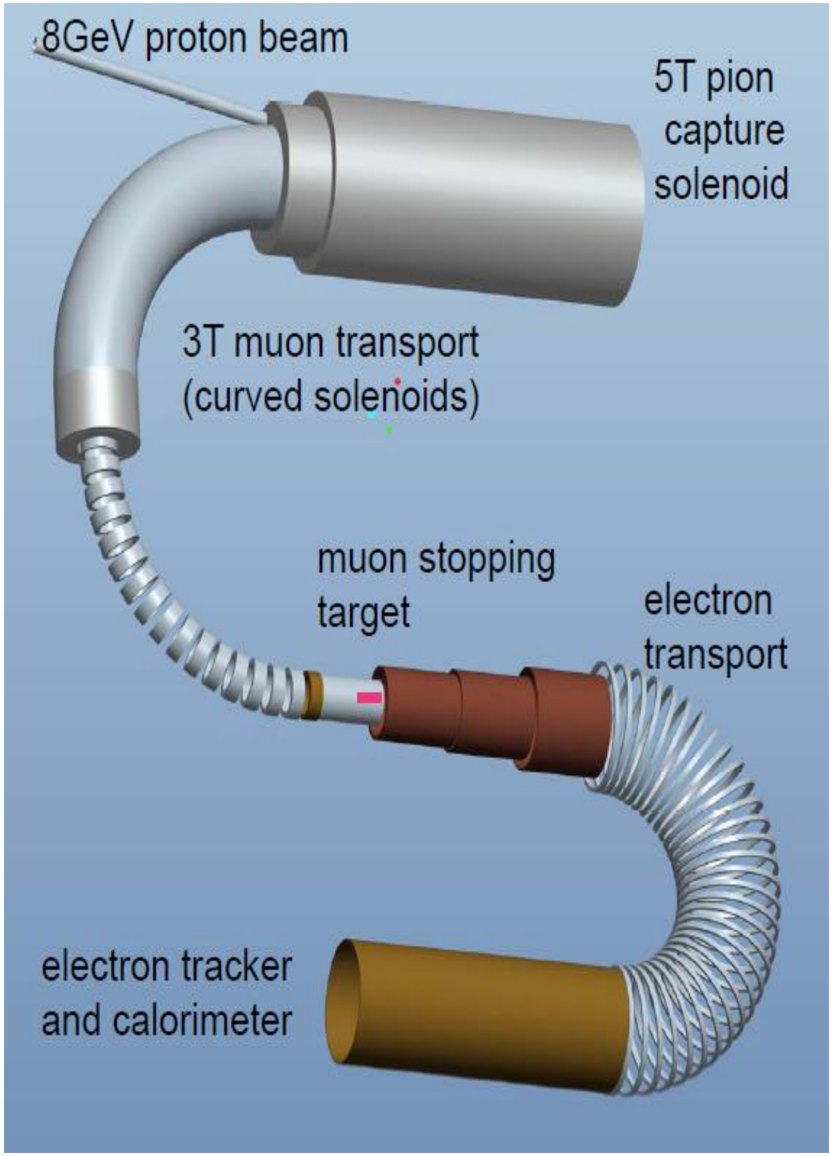






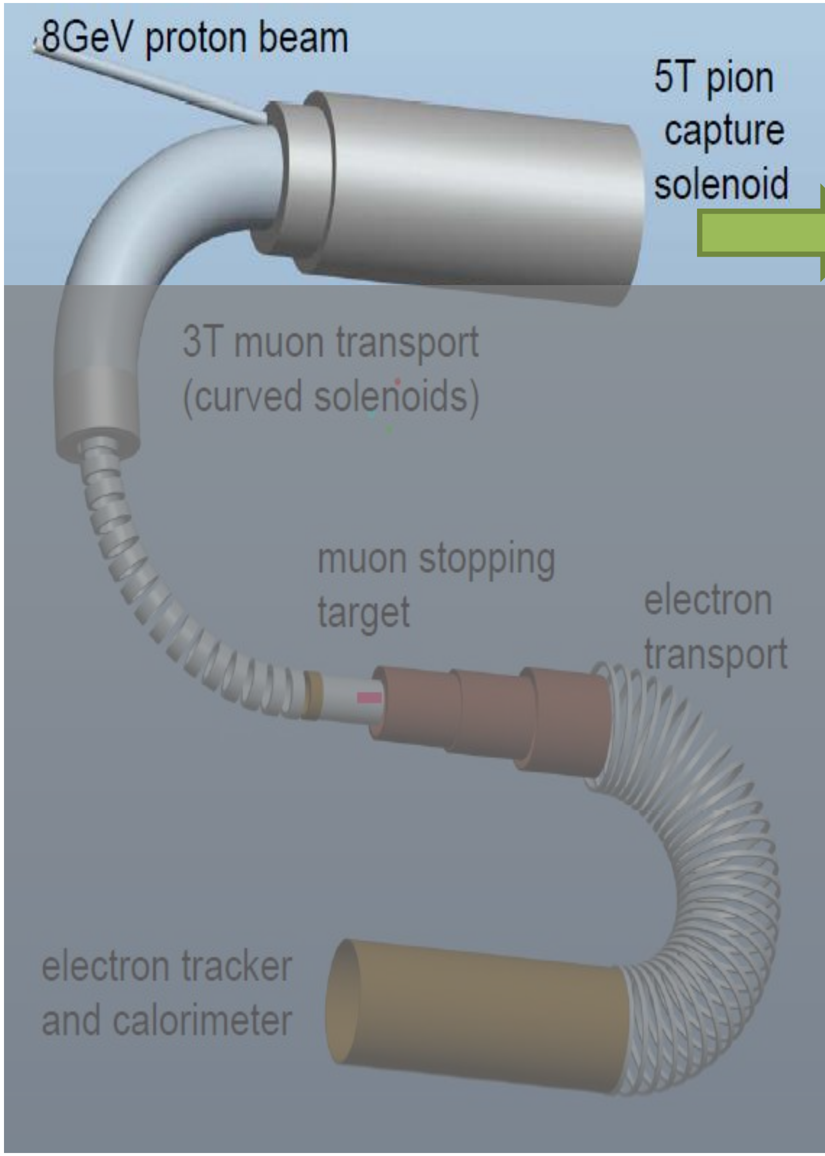
COMET aims at a single event senstivity
(S.E.S) = 2.6×10^{-17}
Current limit given by SINDRUM II experiment at PSI:
7×10^{-13} (90% C.L.)
4 orders of magnitude improvement

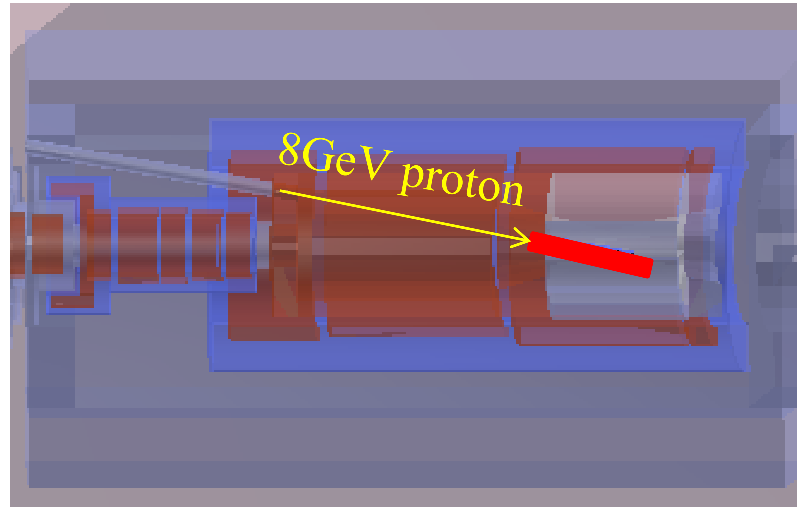
Overview of the COMET experiment



- To achieve 2.6×10^{-17} SES
  - 8 GeV, 56 kW pulsed proton beam
  - One year data taking: aiming to collect 8.5×10^{20} protons on target, yielding 2×10^{18} muons stopped in the stopping target
    - 10^{11} muon/sec! (10^{8} @ PSI)
- Requrements:
  - 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 from secondary particles produced by 10^{20} protons
    - Background suppression and radaition hardness

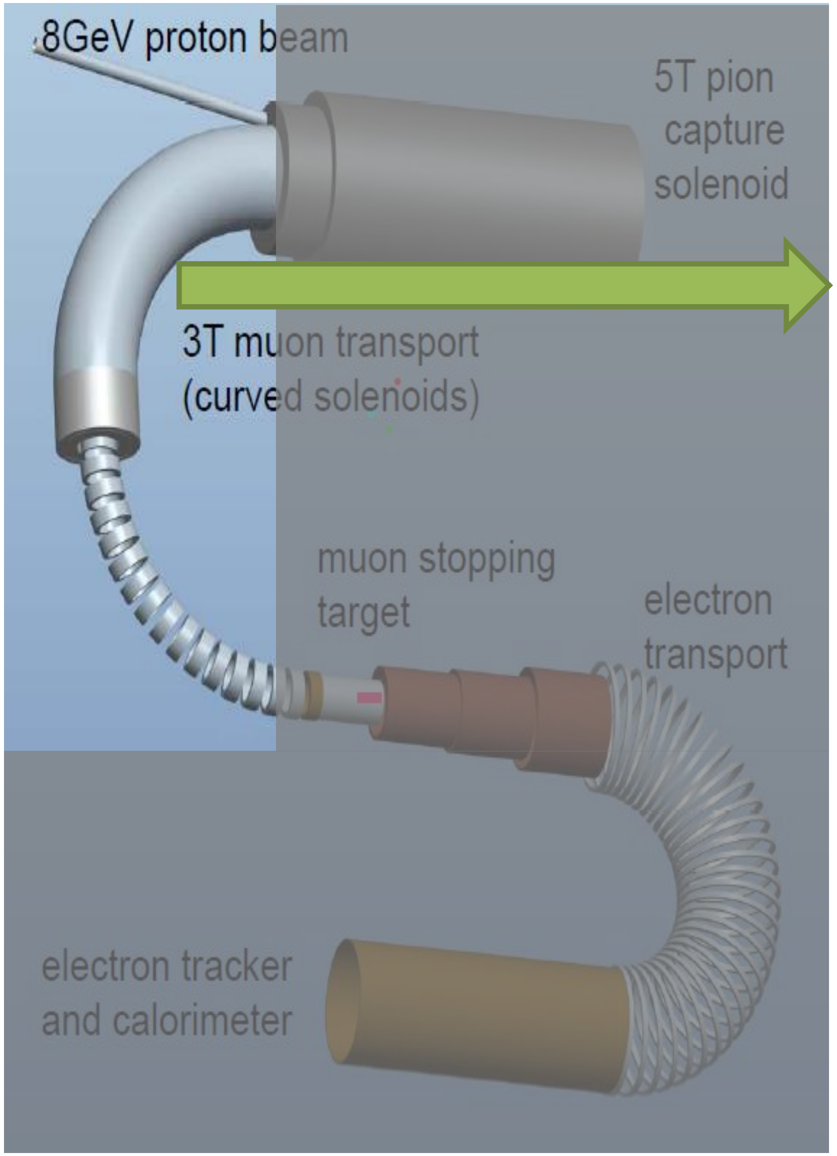
Production target and the capture magnet

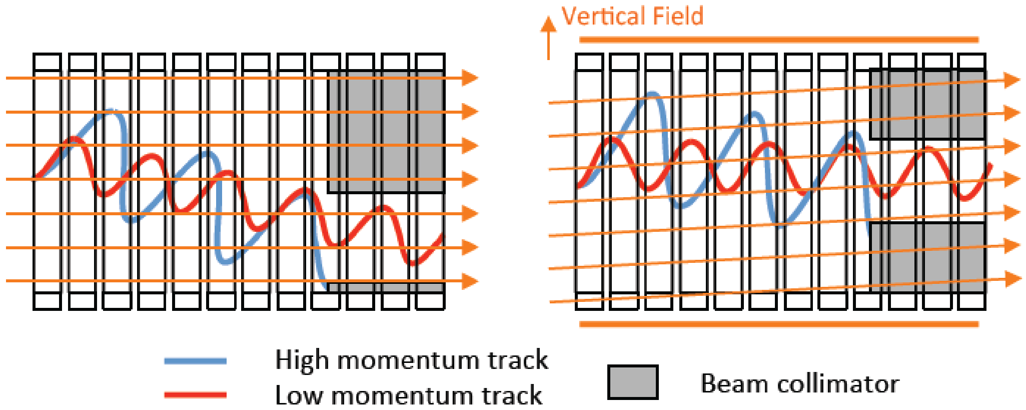




- To improve the production and capture efficiency of muon:
  - Relatively high energy beam: favorable region is 2~8 GeV
  - Thick target with 1~2 hadron interaction length
    - High temperature resistance: W or C
  - Powerful capture magnet: 5 T SCS
    - Large inner bore to fit in the shielding
    - Adiabatic decreasing field: focusing and mirroring

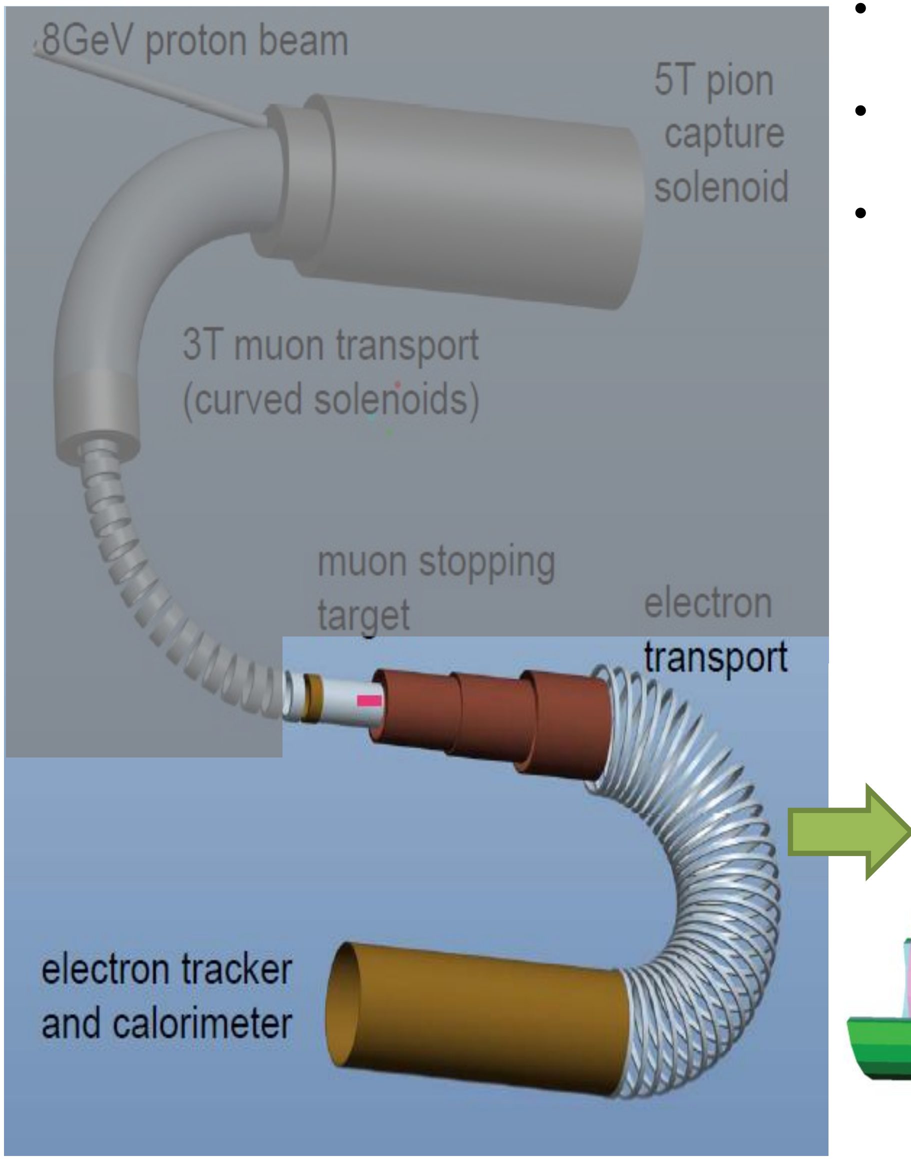
Transportation solenoid



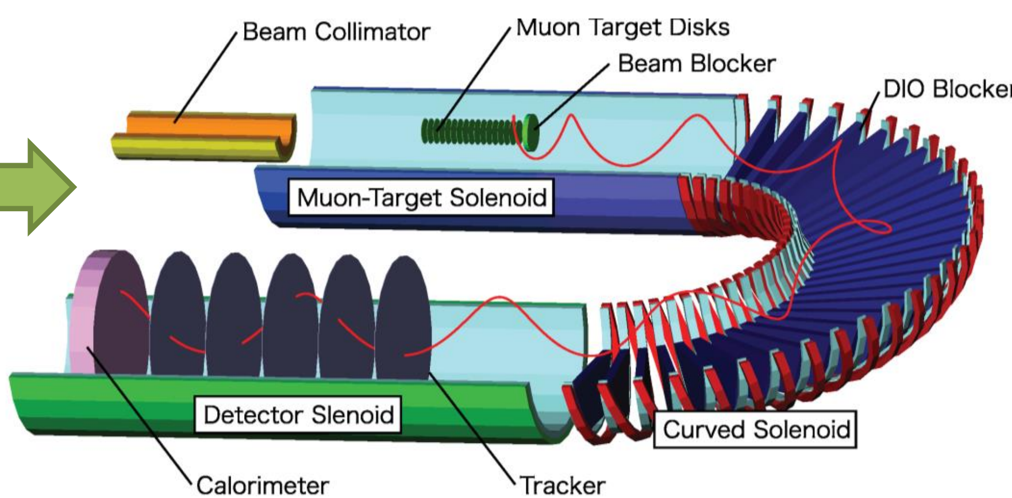


- To improve the purity of the muon beam:
  - Use C shape curved solenoid
    - Charged particles drift vertically. The drift distance is proportional to its momentum.
    - Vertical magnetic field can pull back the wanted particles (~40 MeV μ^-) back to the horizontal plane.
    - Collimator placed in the end can reject unwanted particles.

Stopping target and detector system

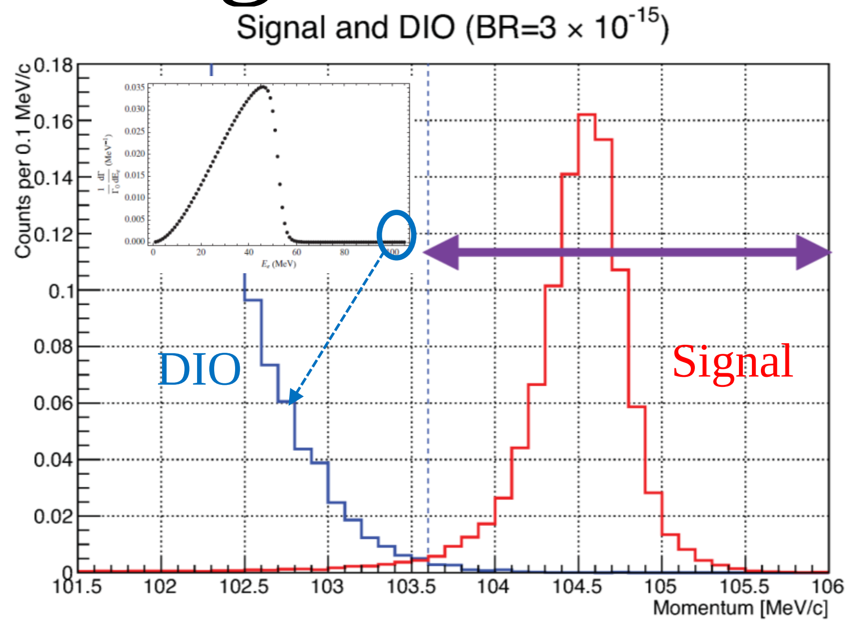


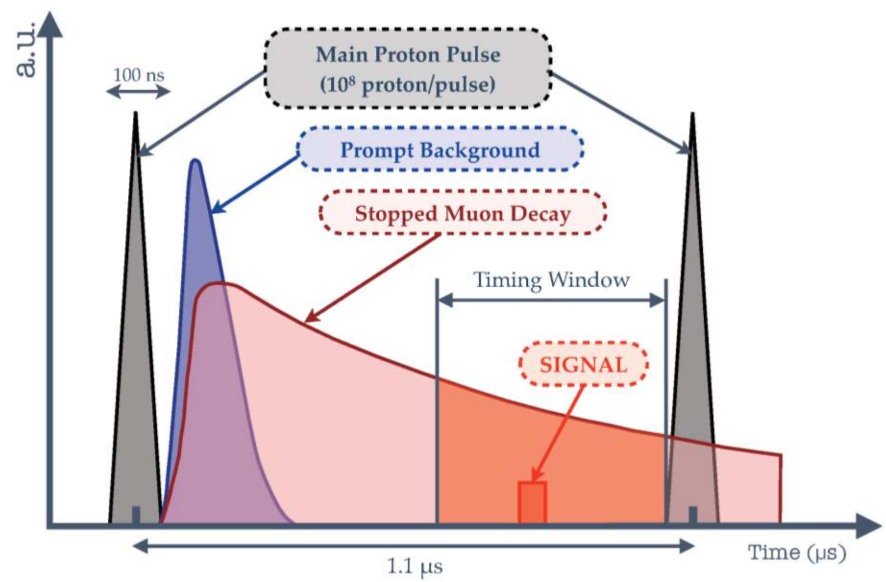
- Stopping target
  - Thin disks of Al (to avoid energy loss)
- Use another C-shape solenoid to select signal electron
  - Clean environment in detector system
- Detector system
  - Straw tube detector with at least 5 stations. 4 planes with different angles per station.
    - High momentum resolution
    - High geometrical acceptance (~50%)
  - Electromagnetic calorimeter
    - Providing trigger, TOF and PID



To control the background

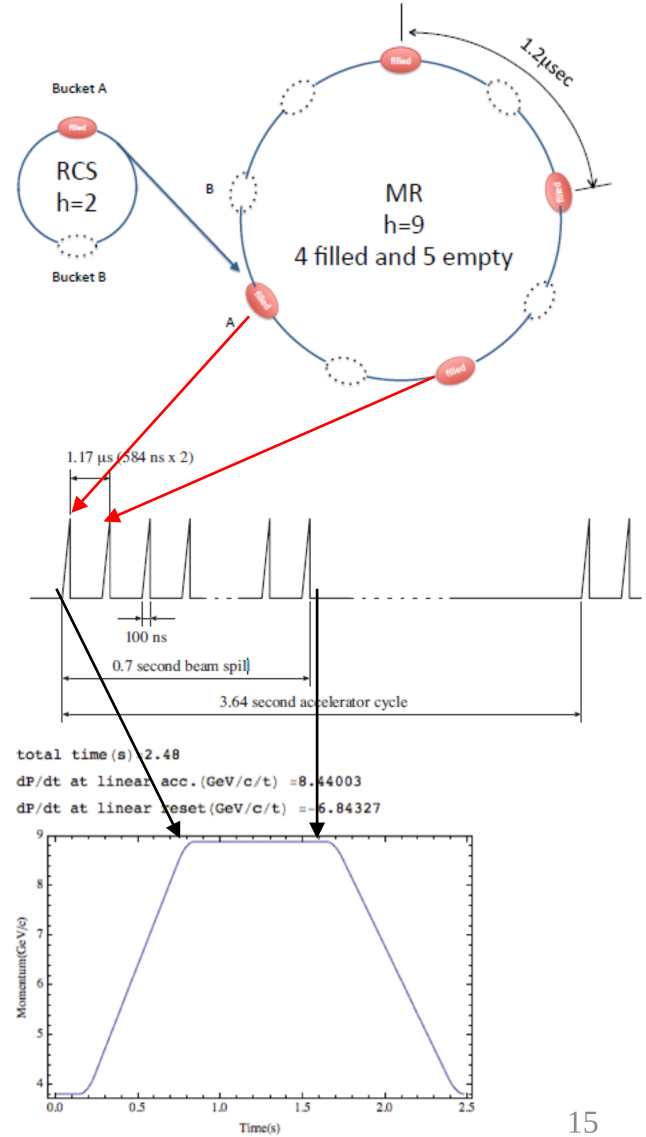
- Intrinsic physics background
  - Mostly from muon decay in orbit (DIO)
    - Calculated by Czarnecki with radiative correction. Branching ratio drops with order-5 function near end point.
    - Momentum resolution required to be better than 200 keV/c
- Beam related background
  - Energetic particles in beam with E>100MeV
    - Mostly prompt. Can be suppressed by a delayed measurement window (~700 ns)
    - Some due to leaked proton. Proton extinction factor required to be $< 10^{-10}$。
- Other background
  - Cosmic ray: cover the system with cosmic ray veto detectors.
  - False tracking: control the tracking quality.





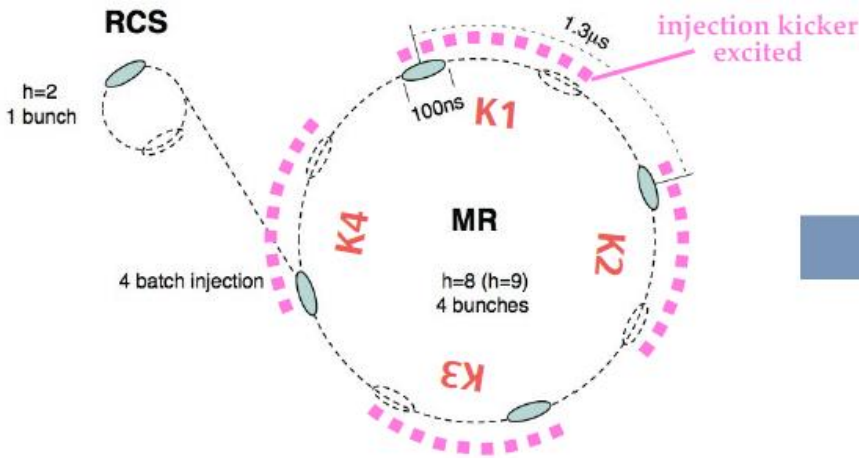
Proton beam at J-PARC

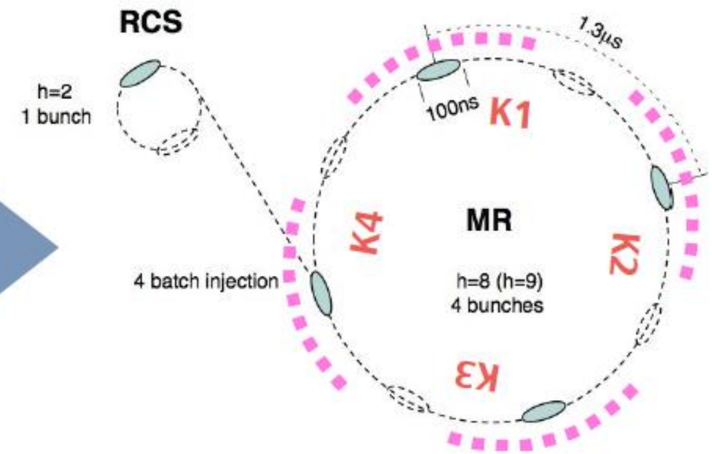
- J-PARC proton pulse after RCS and MR forms pulsed structure with 100 ns pulse width and 585 ns pulse separation.
  - We can form 1.17 us pulse separation by skipping one bucket.
- The operation period of MR is 2.48 second with 0.8 second beam on time. DF = 0.32.
- J-PARC current beam power reached >500 kW. COMET adopts slow extraction (SX) to get 56 kW proton beam.



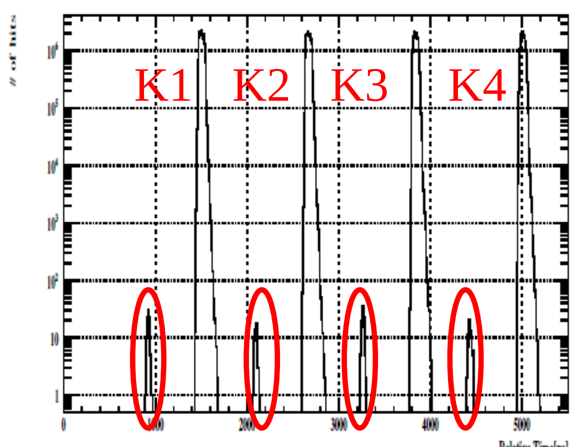
Proton beam at J-PARC

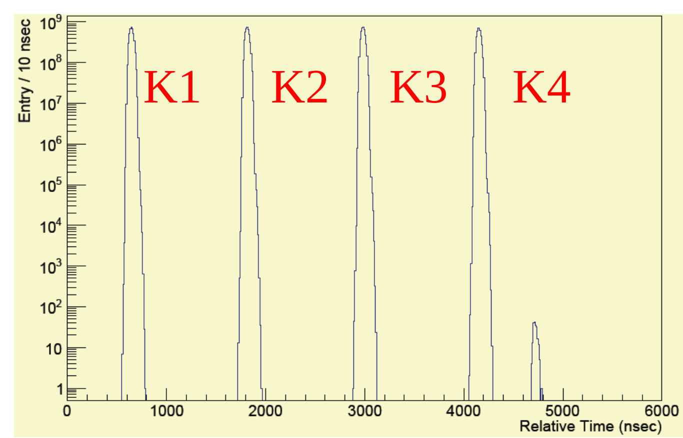
- To make the proton extinction factor $< 10^{-10}$
  - Shift the kicker phase by half period to avoid residual protons in the empty bucket.





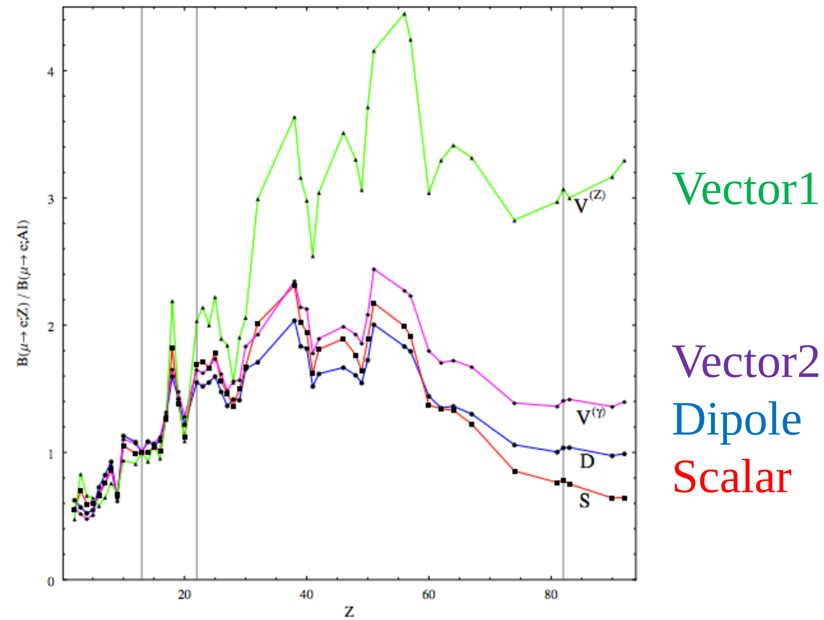
- Tested in early 2018, proton extinction factor $< 6 \times 10^{-11}$



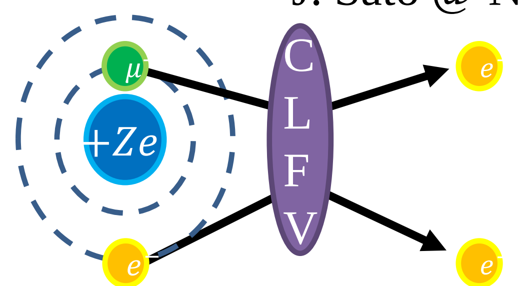


Possible physics output from COMET

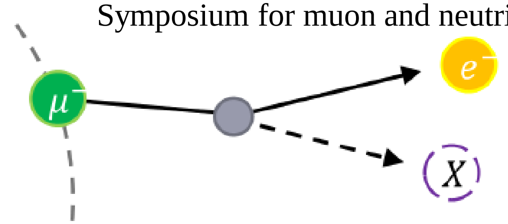
- If signal is found:
  - Direct proof to new physics!
  - Scan the branching ratio with different targets to further study the property of new physics.
- If signal is not found:
  - Strong restriction to the parameter spaces of new physics models.
  - Toward higher sensitivity!
- Beside $\mu - e$ convesion:
  - Precise measurements:
    - Radiative nuclear capture of μ, π. μ decay in orbit.
  - Other cLFV processes:
    - $\mu^- N_Z \to e^+ N_{Z-1}$, $\mu^- e^- \to e^- e^-$, $\mu^- \to e^- X$.



J. Sato @ Nufact18



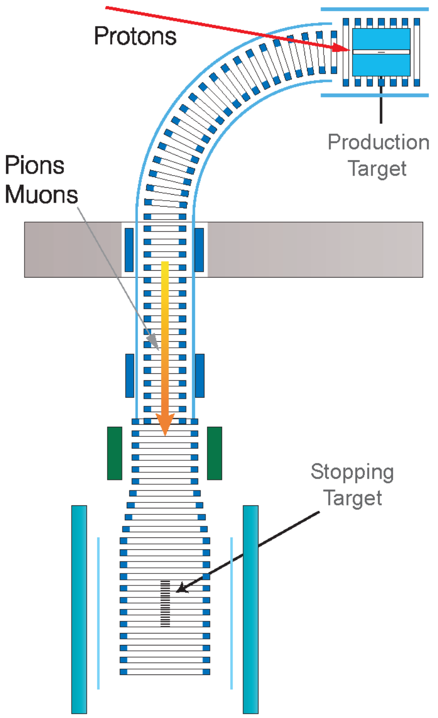
Y. Uesaka @
Symposium for muon and neutrino physics

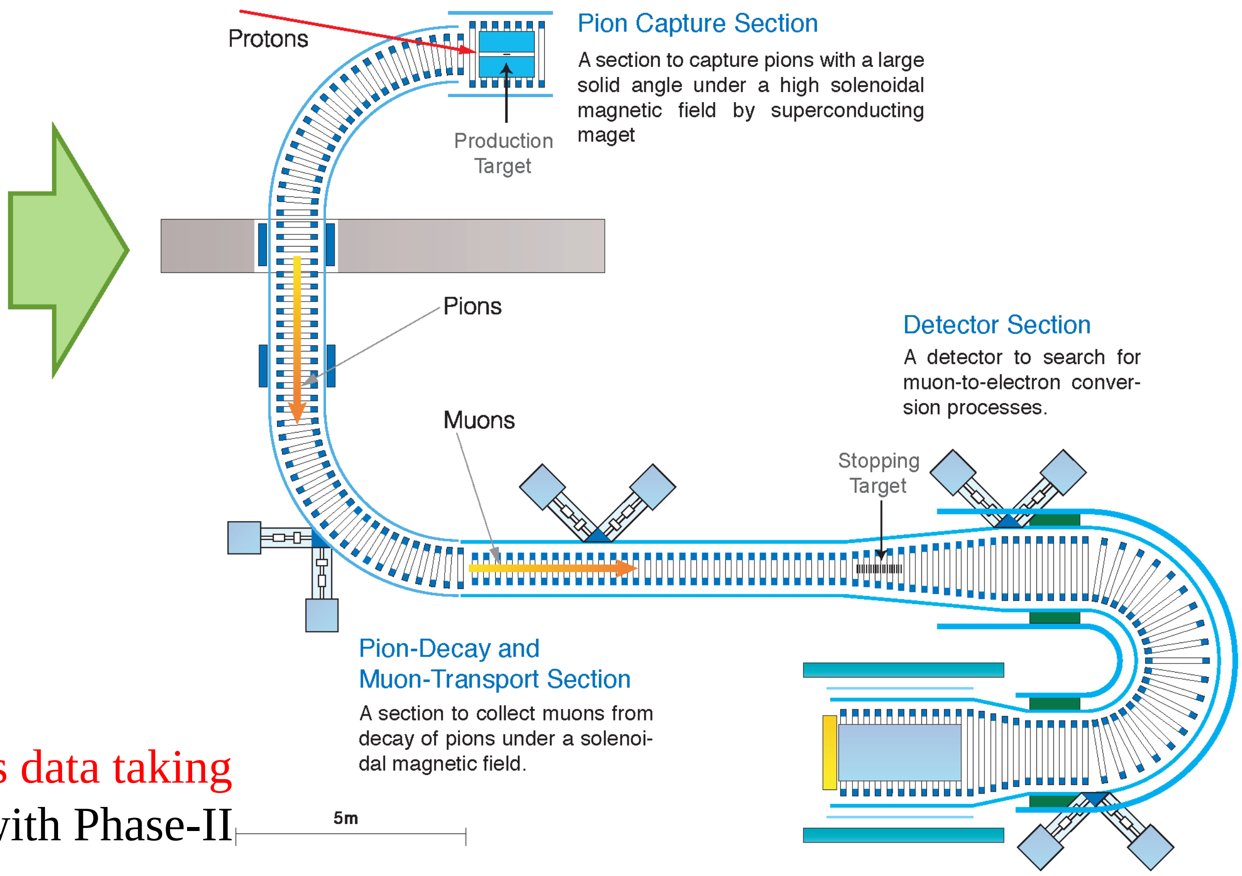


Staged plan of COMET

8GeV, 0.4mA, 3.2 kW

8GeV, 7mA, 56 kW





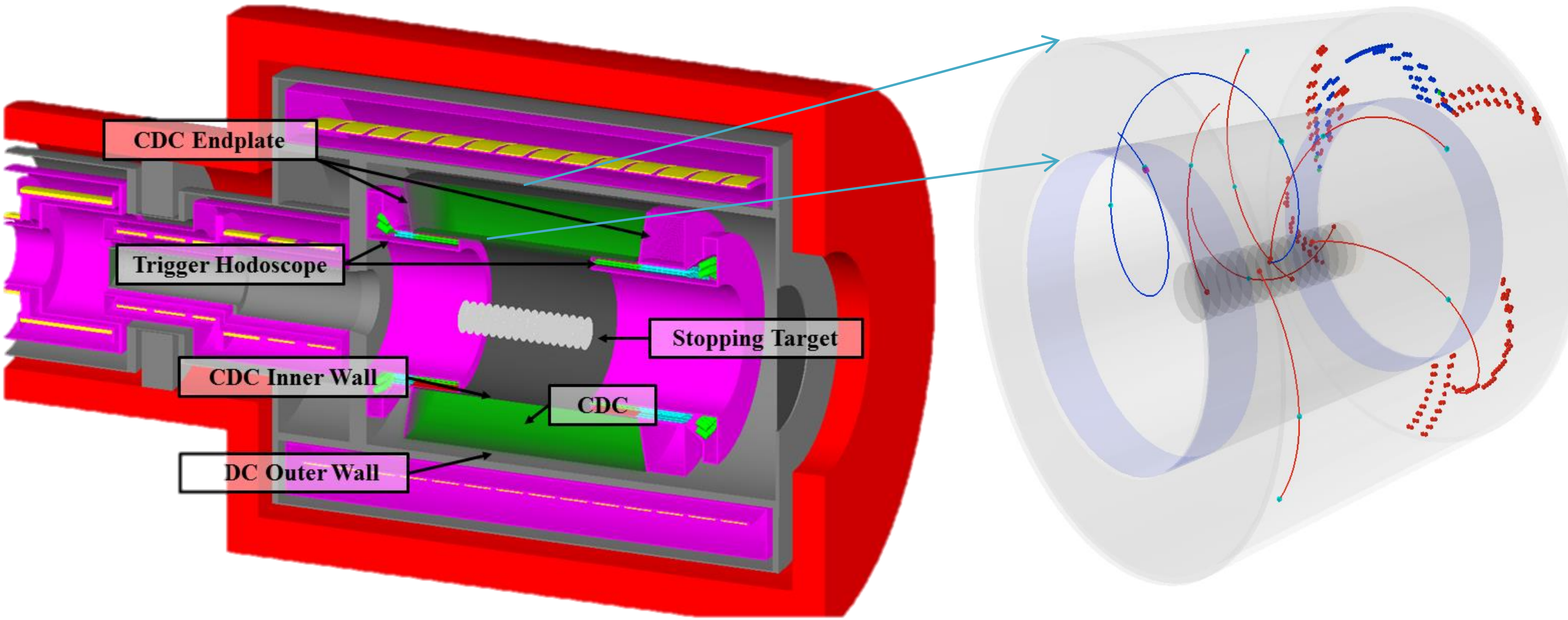
COMET Phase-I, 5 months data taking

- Study the muon beam with Phase-II detectors.
- Search for $\mu - e$ conversino with cylindrical detector (CyDet) with S.E.S. = 3×10^{-15} (2 orders of magnitude improvement).

COMET Phase-II, One year data taking

- Search for $\mu - e$ convresion with S.E.S. = 2.6×10^{-17} (4 orders of magnitude improvement)

Phase-I detector (CyDet)



- Specially designed for Phase-I. Consists of:
  - Cylindrical trigger hodoscope:
    - Two layers: plastic scintillator for t0 and Cerenkov counter for PID.
  - Cylindrical drift chamber:
    - 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.

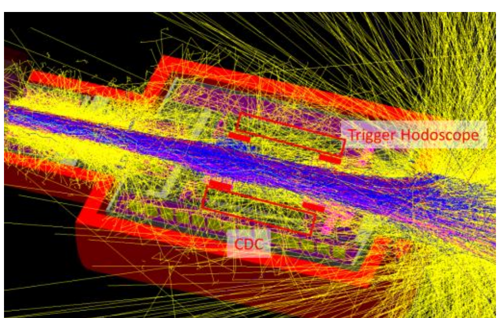
Monte Carlo study of COMET Phase-I

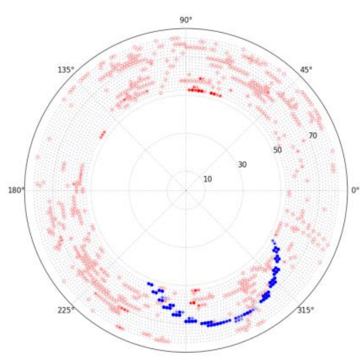
- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies. TDR was published on arXiv last month.
  - Sensitivity:
    - Total acceptance of signal is 0.041
    - Can reach 3×10^{-15} SES in 150 days.
  - Background:
    - With 99.99% CRV total expected 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 (ε_{mom})	0.93
Timing window ($\varepsilon_{\text{time}}$)	0.3
Total	0.041

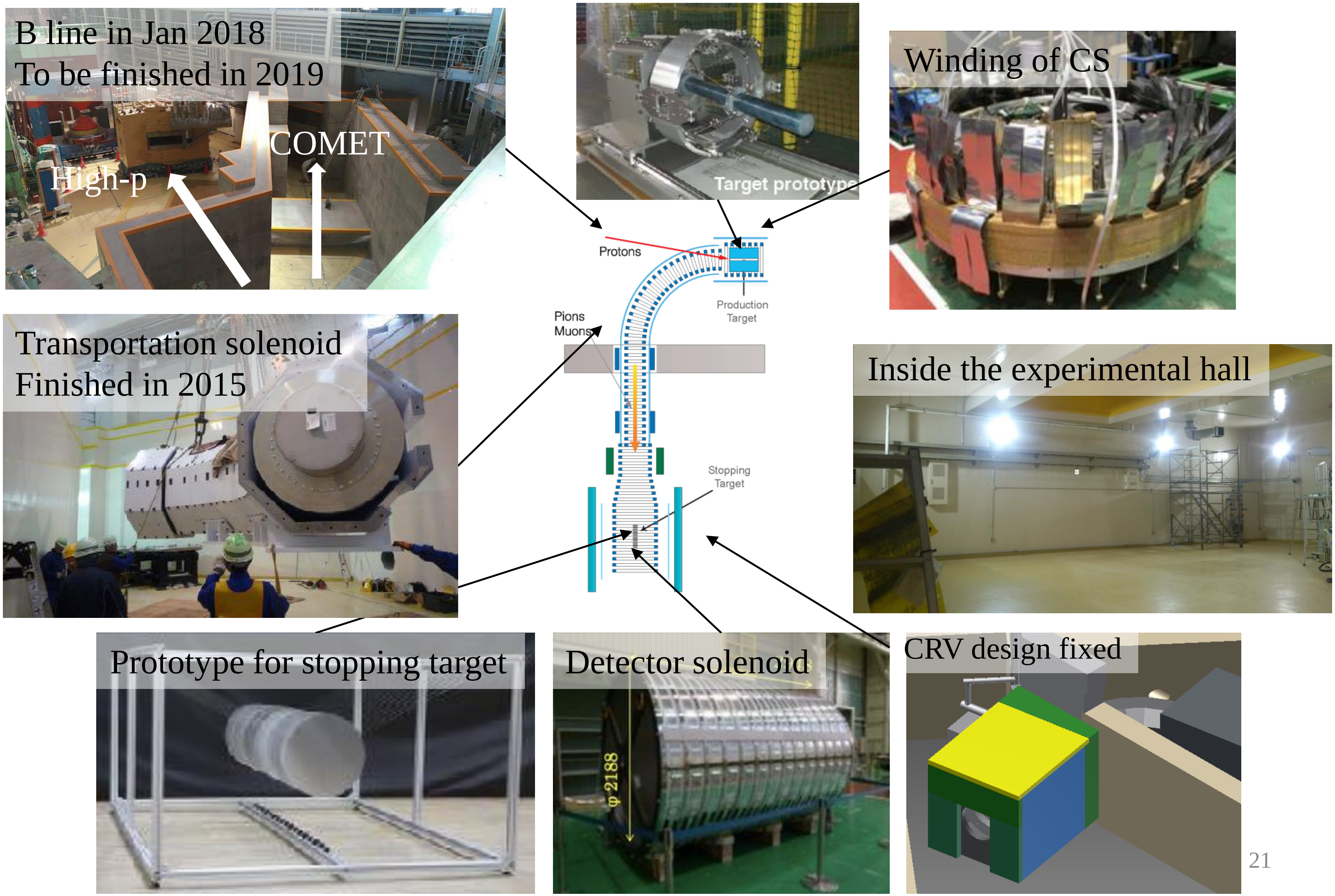
Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	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.



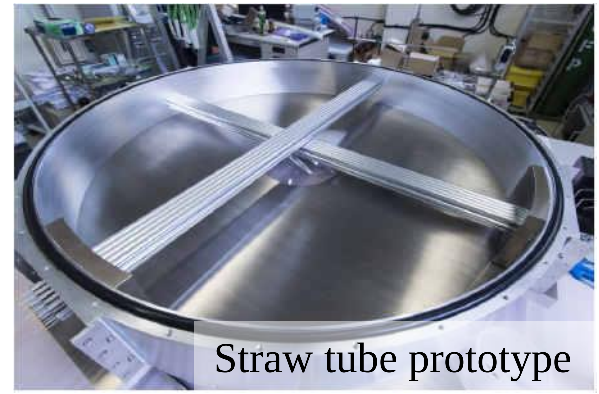


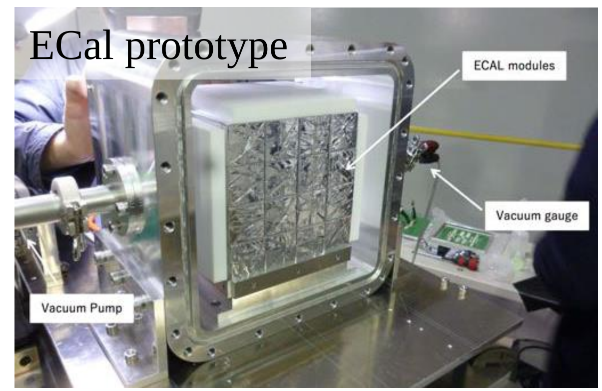
Status of the COMET facility



Status of Phase-II detector (StrEcal)

- Straw tube detector
  - Finished vacuum test with 20 um straw tubes.
  - 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.

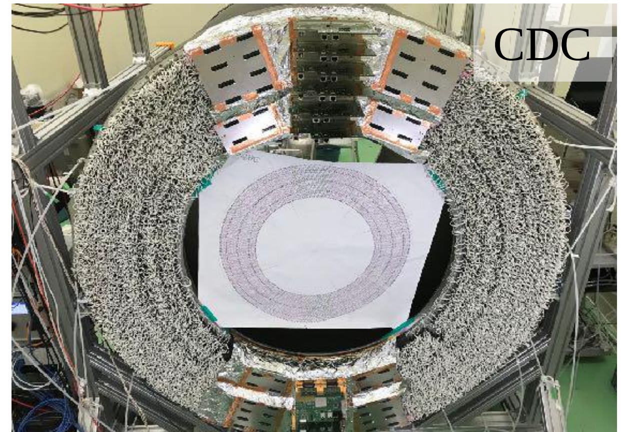

Straw tube prototype

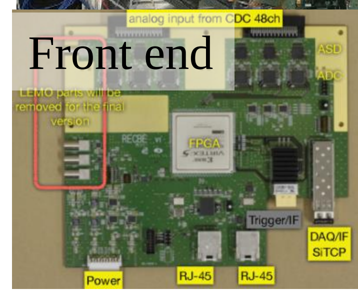
ECal prototype


Front end electronics: ROESTI/EROS

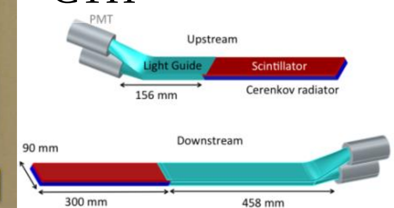
Status of Phase-I detector (CyDet)

- 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.

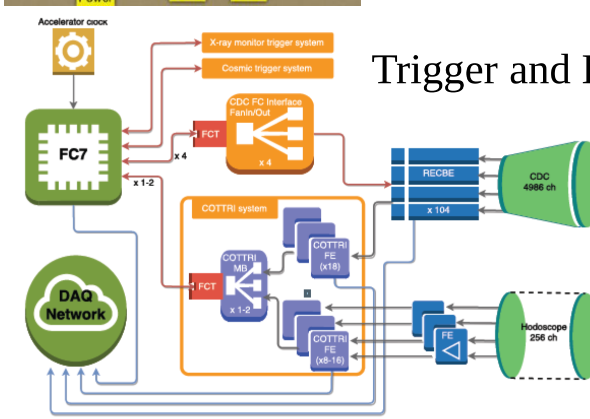




CTH



Trigger and DAQ



The COMET collaboration


Jan 2018, COMET collaboration at Osaka University

~200 members,
41 institutes from 17 countries

 Chinese group: IHEP, Nanjing University, Peking University, Sun Yat-sen University

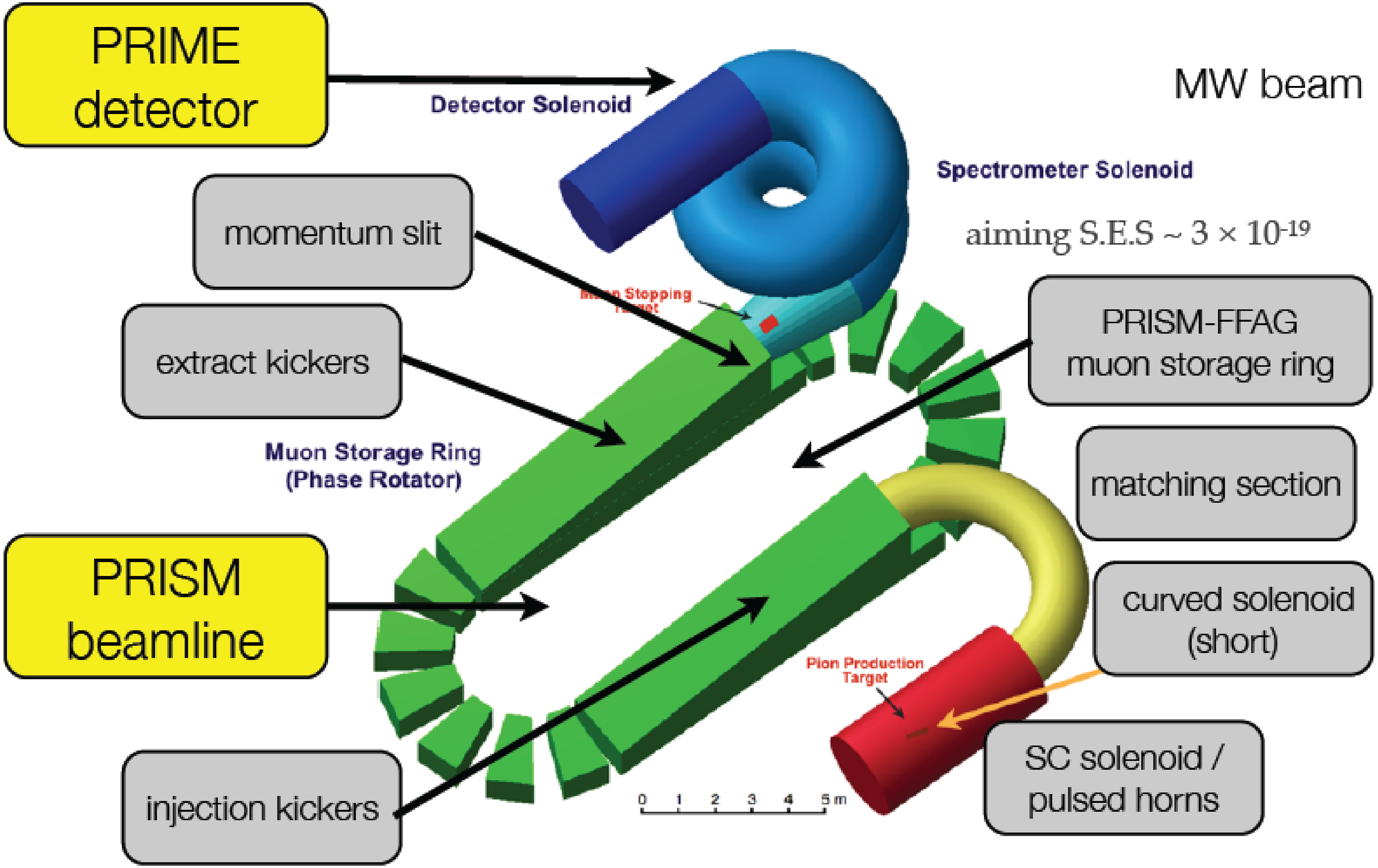
Outlook to future cLFV experiments

- CLFV in tau sector:
  - Belle II and LHCb: 1~2 orders improvement
- CLFV in muon sector:
  - Many-body final state, DC beam
    - $\mu \to e\gamma$: 1 order
    - $\mu \to eee$: 3~4 orders
  - Single-body final state, pulsed beam
    - $\mu N \to eN$: 4~6 orders

- τ intensity:
  - Now 2/sec
  - Expected in future 100/sec
- μ intensity:
  - now 10^8/sec
  - future $10^{11} \sim 10^{12}$/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

$\mu - e$ conversion search in the future: PRISM/PRIME

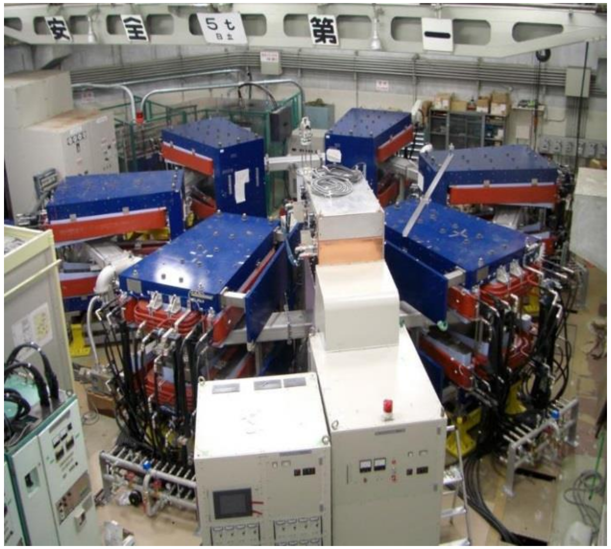


Challenges for PRISM/PRIME

- Proton source
  - MW level, super short pulse (10ns level)
- Capture system
  - Cooling of the target (jet or waterfall)
  - Cooling of the magnet (large inner bore)

Synergy with neutrino factory and muon collider

- Transportation system
  - Longer transportation beamline:
  - FFAG(Fixed Field Alternating gradient) muon storage ring
    - Tested at Osaka University



Summary

- cLFV is an extremely clean probe for new physics probe for new physics. The required FCNC process can be found in many new physics models.
- The simple event signature of $\mu - e$ conversion search makes a 4~6 orders of magnitude improvement in sensitivity possible with the help of high luminosity pusled proton source. Both photonic and four-fermi processes can be tested together.
- COMET at J-PARC aims at S.E.S = 2.6×10^{-17} (4 orders of magnitude improvement) and plans to take data from 2022 for one year.
  - COMET Phase-I will search with S.E.S = 3×10^{-15} (2 orders of magnitude improvement) and directly measure the muon beam.
  - The proton beam and detector systems will be ready by 2019.
- The next phase of$\mu - e$ conversion search (PRISM) is under discussion.

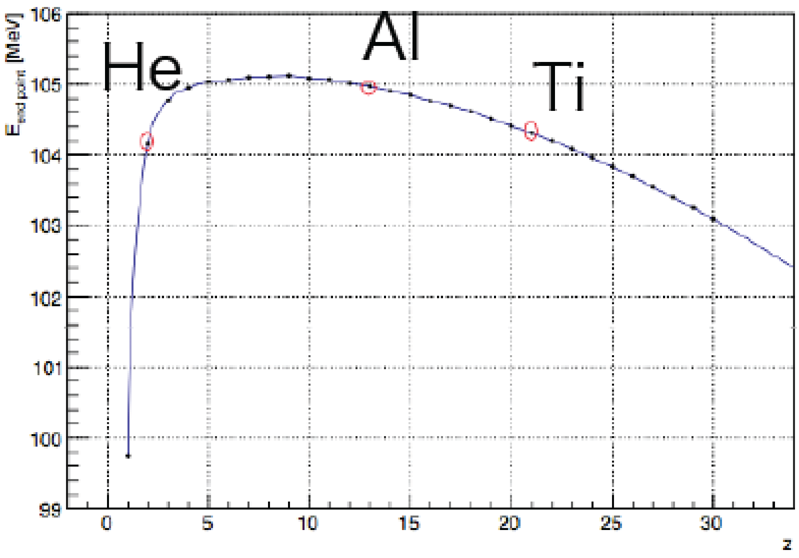
Back up

Selection of the production target

- Stable and strong in high temperature
  - Carbon with 3.2 kW beam power. No cooling system needed.
  - Tungsten with 56 kW beam power. Needs cooling.
  - Jet or waterfall target? (~MW)
- Centralize the production region of pions
  - For the consideration of collection efficiency
  - Dense target with narrow beam preferred.

Selection of the Target Material

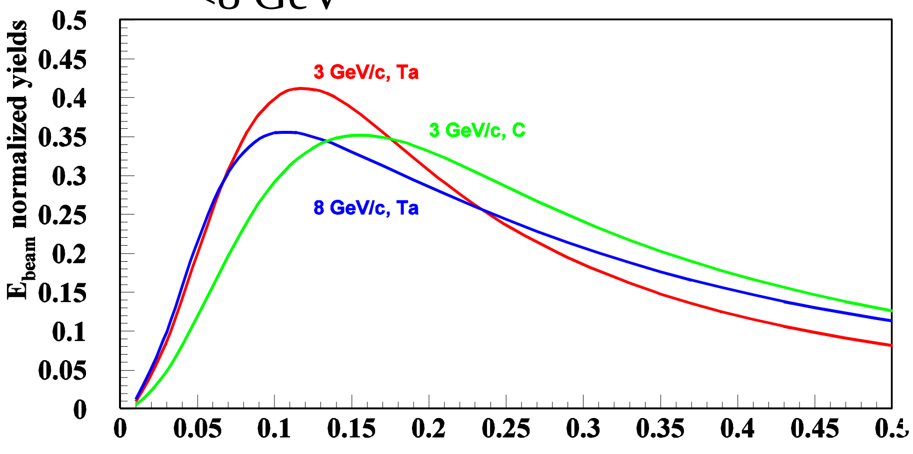
- DIO $E_{endpoing}$ extends to the $E_{\mu\text{-}e}$
    - Recoil energy
    - Muon binding energy
- Select the target material with high $E_{\mu\text{-}e}$ and avoid using the material with larger $E_{endpoint}$ around the target
    - When the target is made of aluminium, we should avoid using materials from Z=5 to Z=12.
    - He (Z=2) is OK to use around the target
- Lifetime of muon in muonic atoms
    - Shorter in larger Z because of the larger nuclear muon capture rate

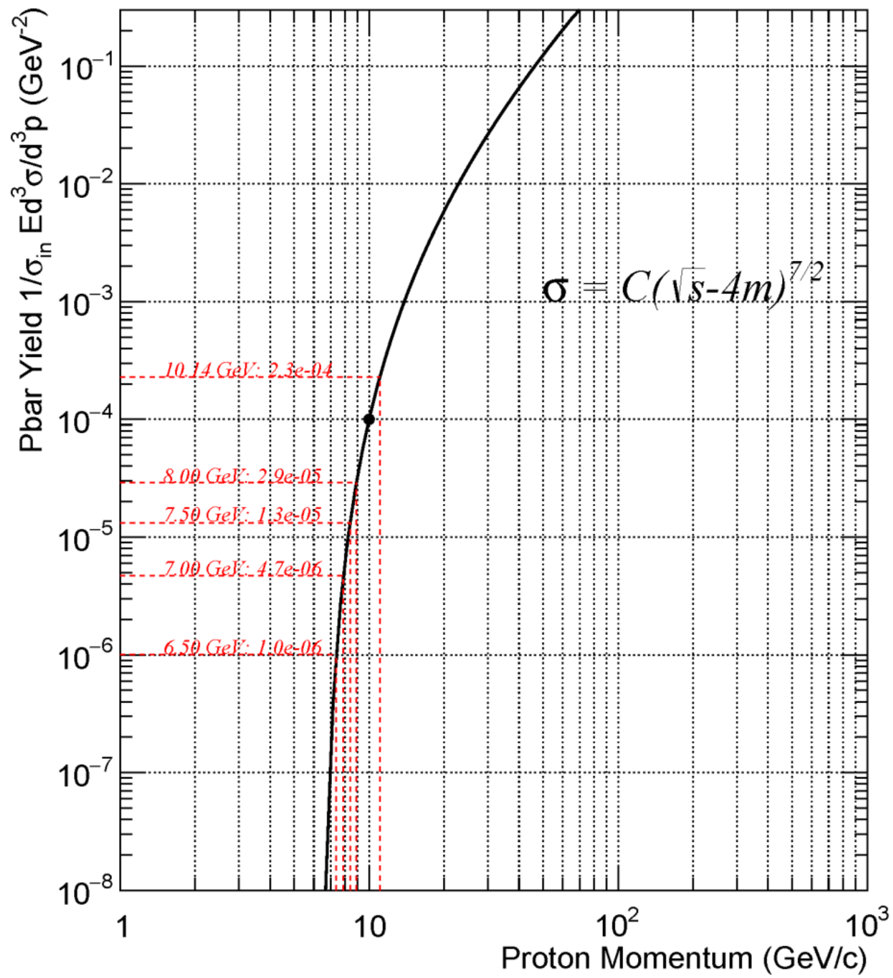


	Al	Ti
lifetime	864 ns	330 ns
time window	0.3	0.2
signal	1	1.5
net	0.3	0.3

Proton energy

- Tries to optimize pion production yield
  - 3 GeV might be better…
  - Highly depends on models.
  - Lack of data for low energy pion.
    - COMET Phase-I!
- Should avoid anti-proton production
  - <8 GeV

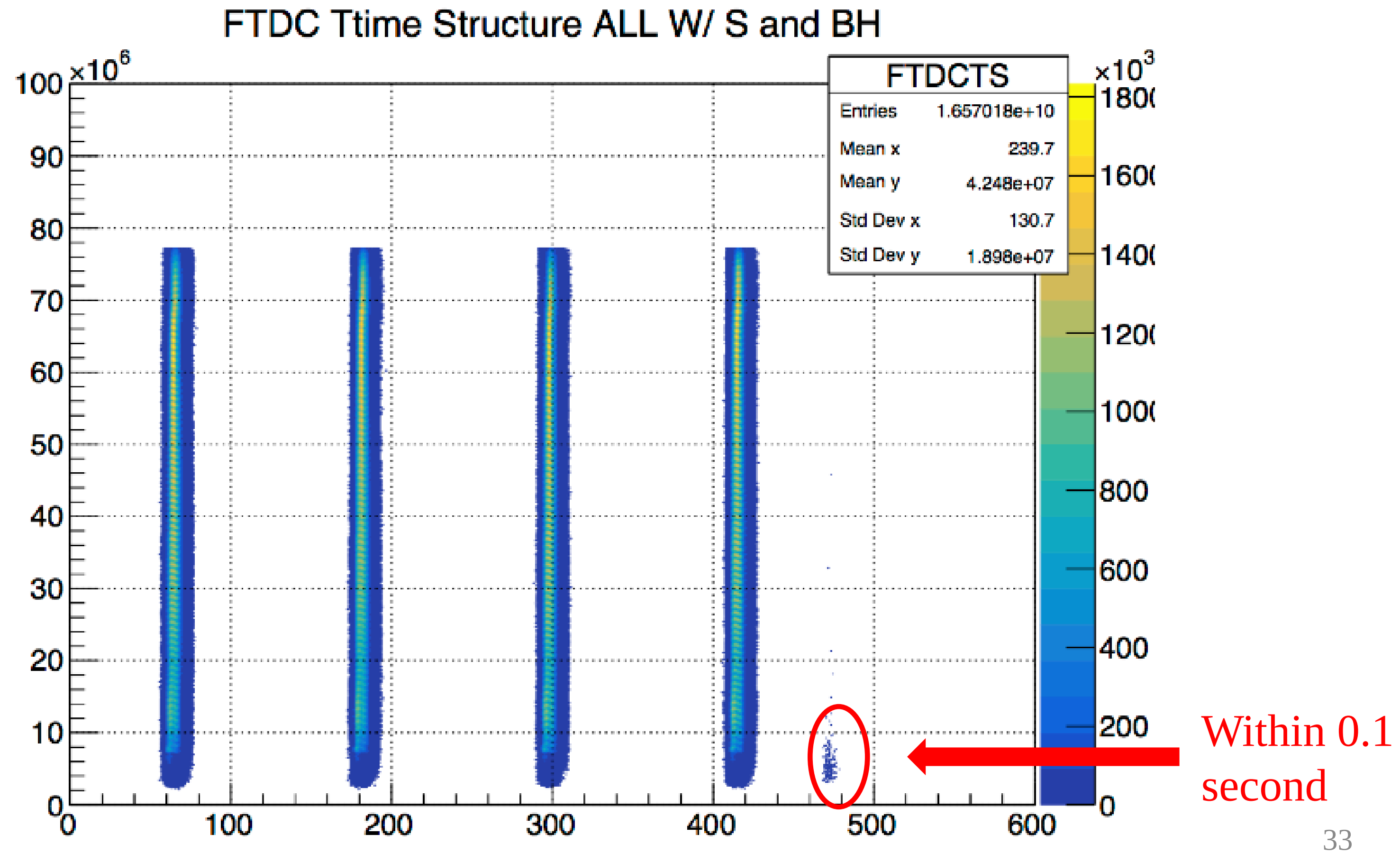




K4 rear end leakage

Found rear end leakage in the test in ealry 2018

- Shadow K4: proton extinction rate $< 10^{-10}$
- Solve from accelerator side: proton extinction rate $\sim 6 \times 10^{-11}$



FFAG

- Time structure to energy str
  - Need narrow pulse: ~10ns