Staging Approach of the COMET Experiment

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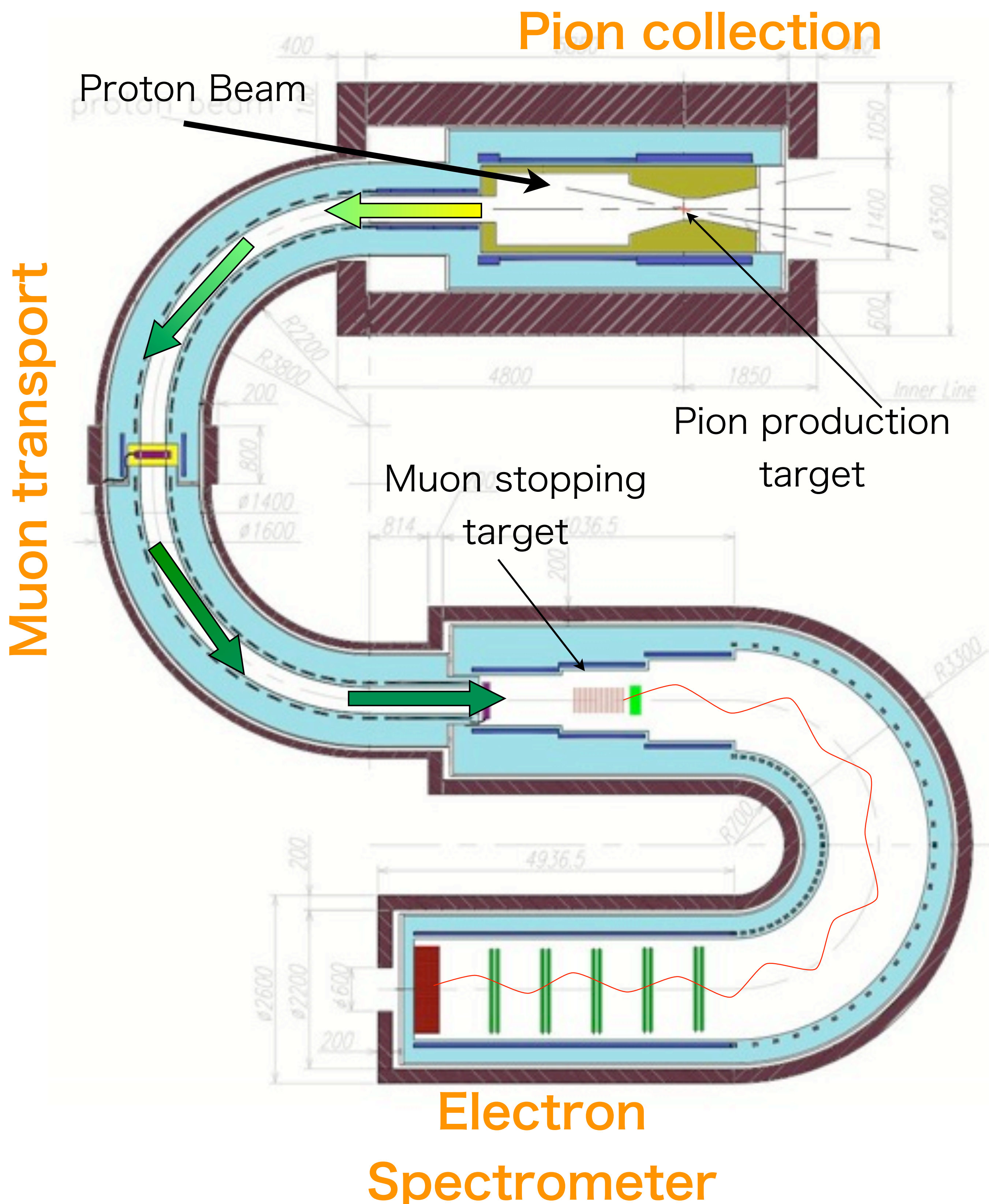
IPNS, KEK

Outline

- Introduction
- COMET Phase-I
  - Beam Study Plan at COMET beam line
  - μ-e conversion search in COMET Phase-I
- Summary

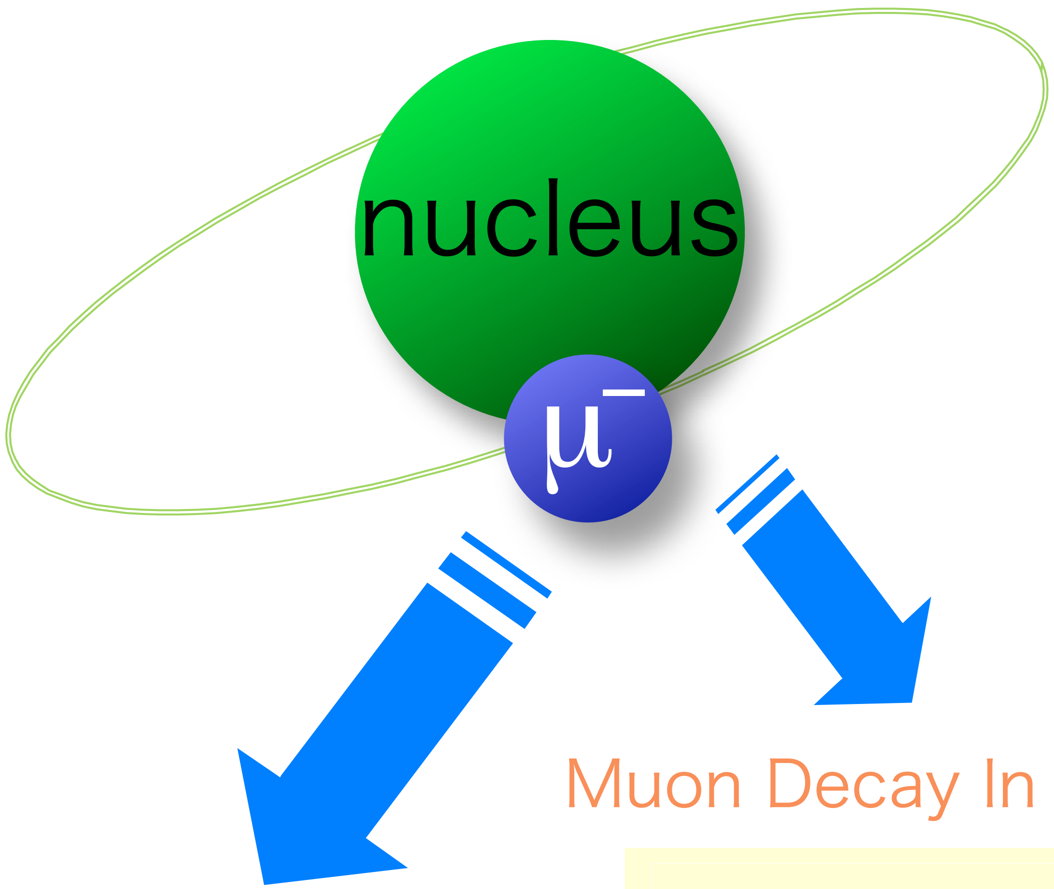
COMET J-PARC E21

- Search for LFV process, μ-e conversion with a sensitivity of 10^{-16}
- J-PARC high- intensity proton beam
  - 8GeV, 7μA
- Innovative apparatus
  - Pion collection
  - Muon Transport
  - Electron Spectrometer



What is mu-e Conversion ?

1s state in a muonic atom



Muon Decay In Orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture (=μ-e conversion)

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

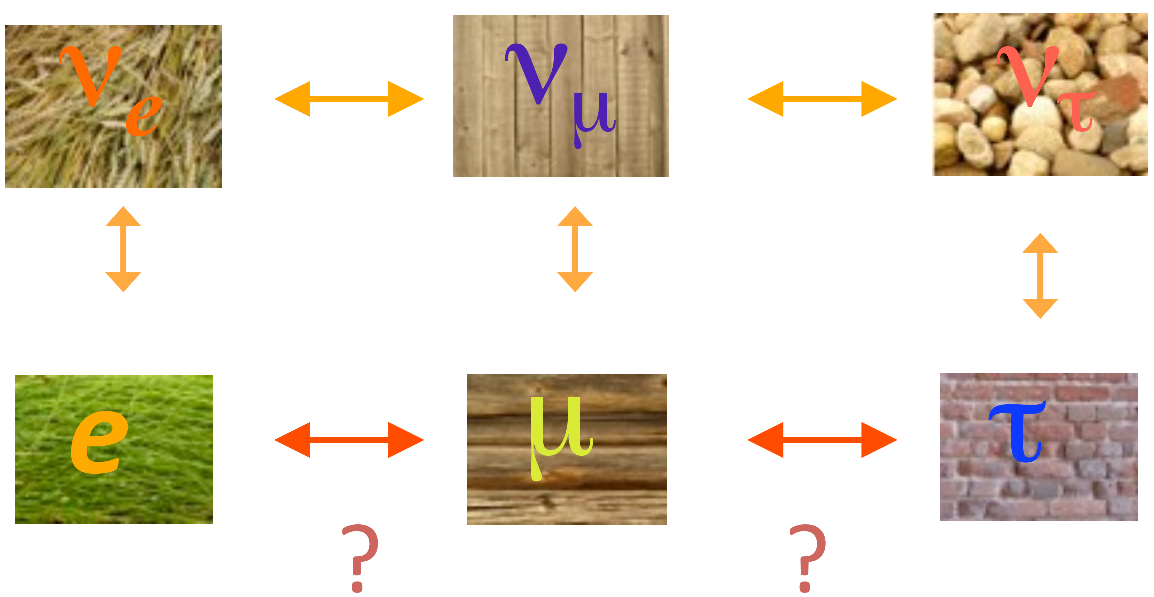
lepton flavours changes by one unit

- $E_{\mu e} \sim m_\mu - B_\mu$
  - B_μ: binding energy of the 1s muonic atom

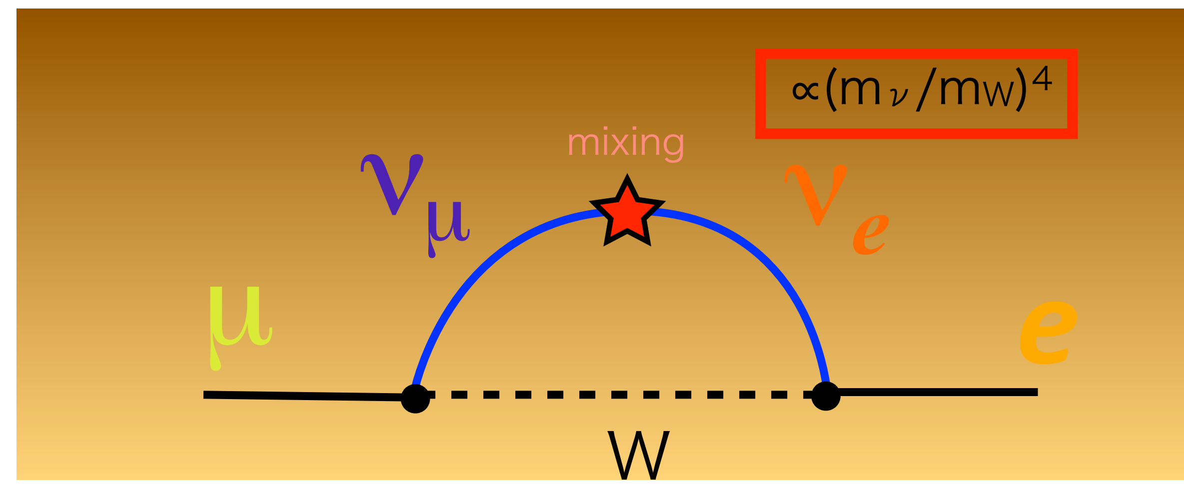
$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Lepton-Flavor Violation in Charged Lepton Sector

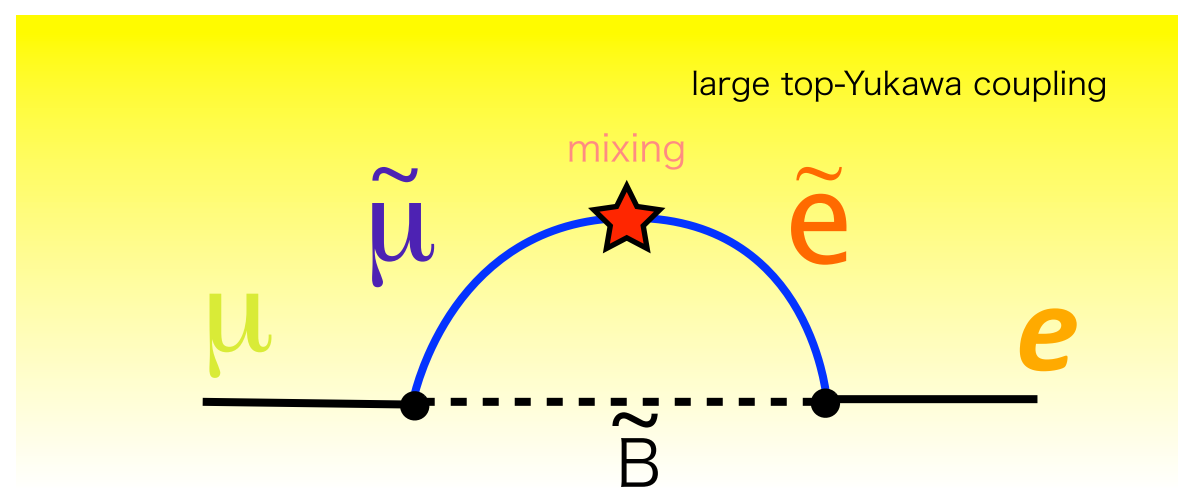
Neutrino Mixing
(confirmed)



Charged Lepton Mixing
(not observed yet)



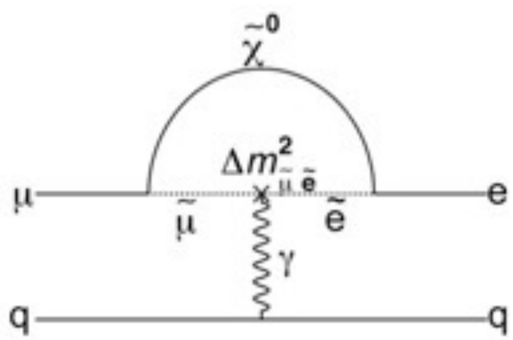
Very Small (10^{-54})



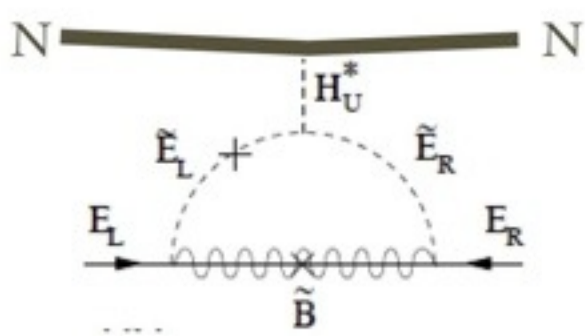
Sensitive to new Physics beyond the Standard Model

Theoretical Models

- SUSY-GUT, SUSY-seesaw (Gauge Mediated process)
    - BR = 10^{-14} = BR($\mu \to e \gamma$) × O(α)
    - $\tau \to l \gamma$

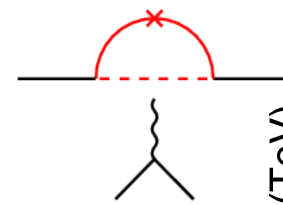


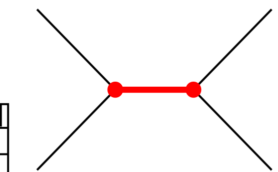
- SUSY-seesaw (Higgs Mediated process)
    - BR = 10^{-12}~10^{-15}
    - $\tau \to l \eta$

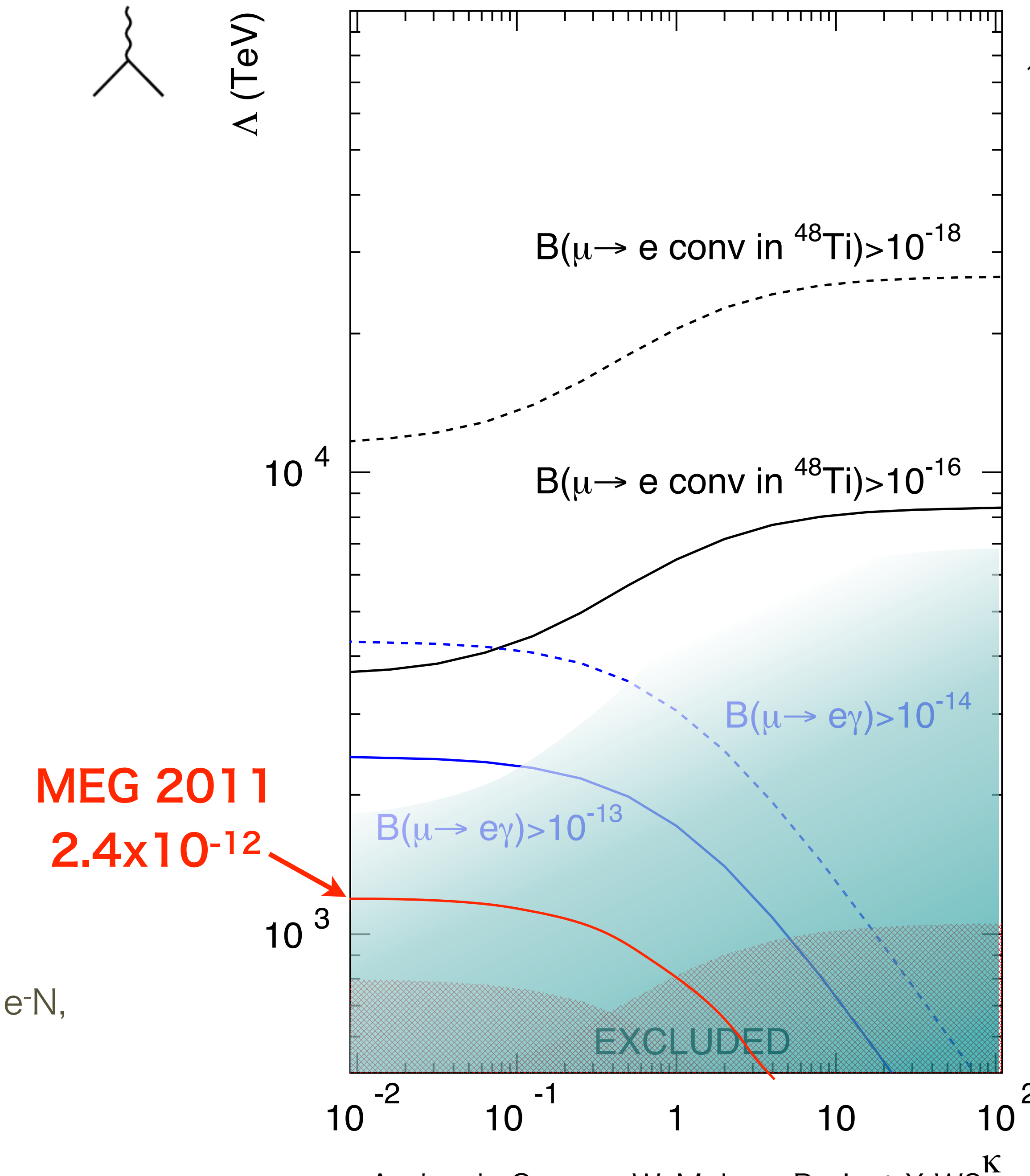


- Doubly Charged Higgs Boson (LRS etc.)
    - Logarithmic enhancement in a loop diagram for $\mu^-N \to e^-N$, not for $\mu \to e\ \gamma$
        - M. Raidal and A. Santamaria, PLB 421 (1998) 250
- and many others

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$



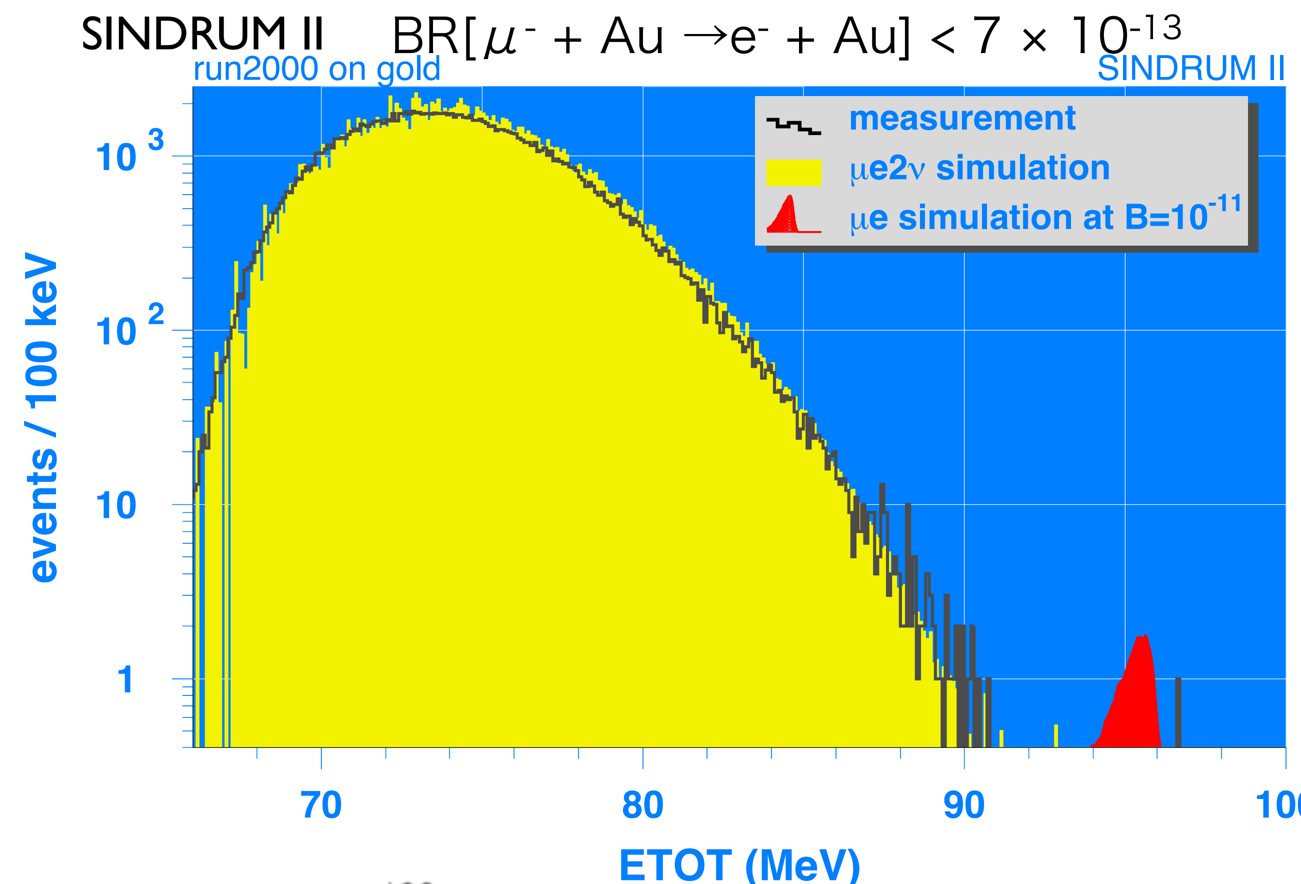




Andre de Gouvea, W. Molzon, Project-X WS (2008)

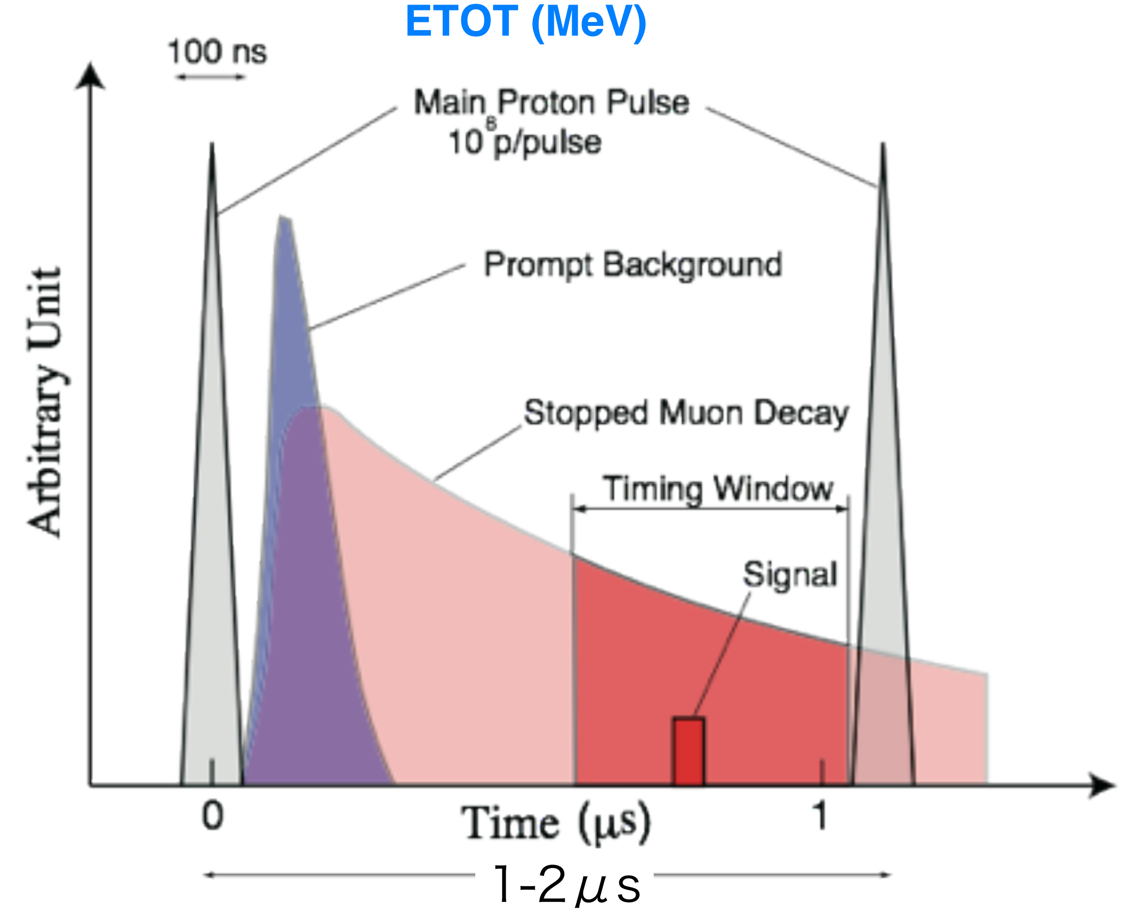
Principle of Measurement

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - $E_{\mu e}(Al) \sim m_\mu - B_\mu$:105 MeV
    - Delayed : ~1 μS



- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - E_e > 102.5 MeV (BR:10^{-14})
    - E_e > 103.5 MeV (BR:10^{-16})

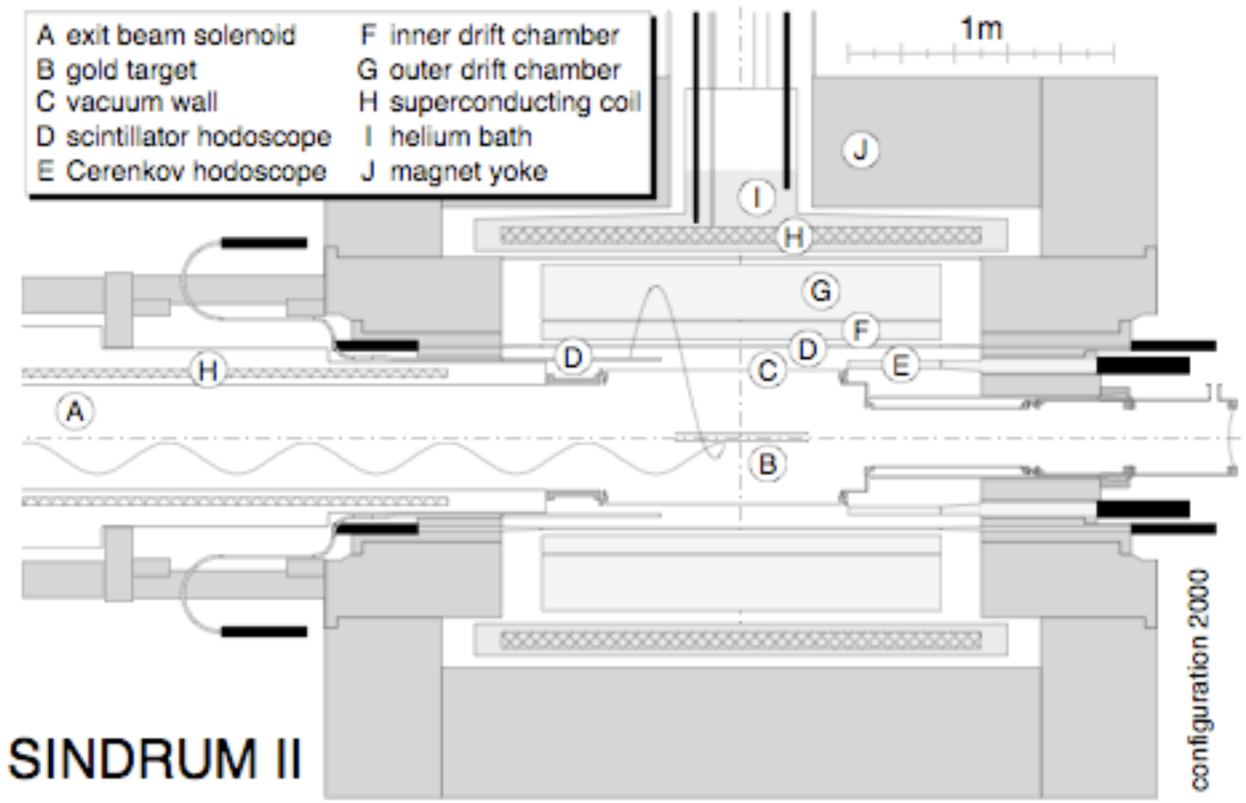
$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

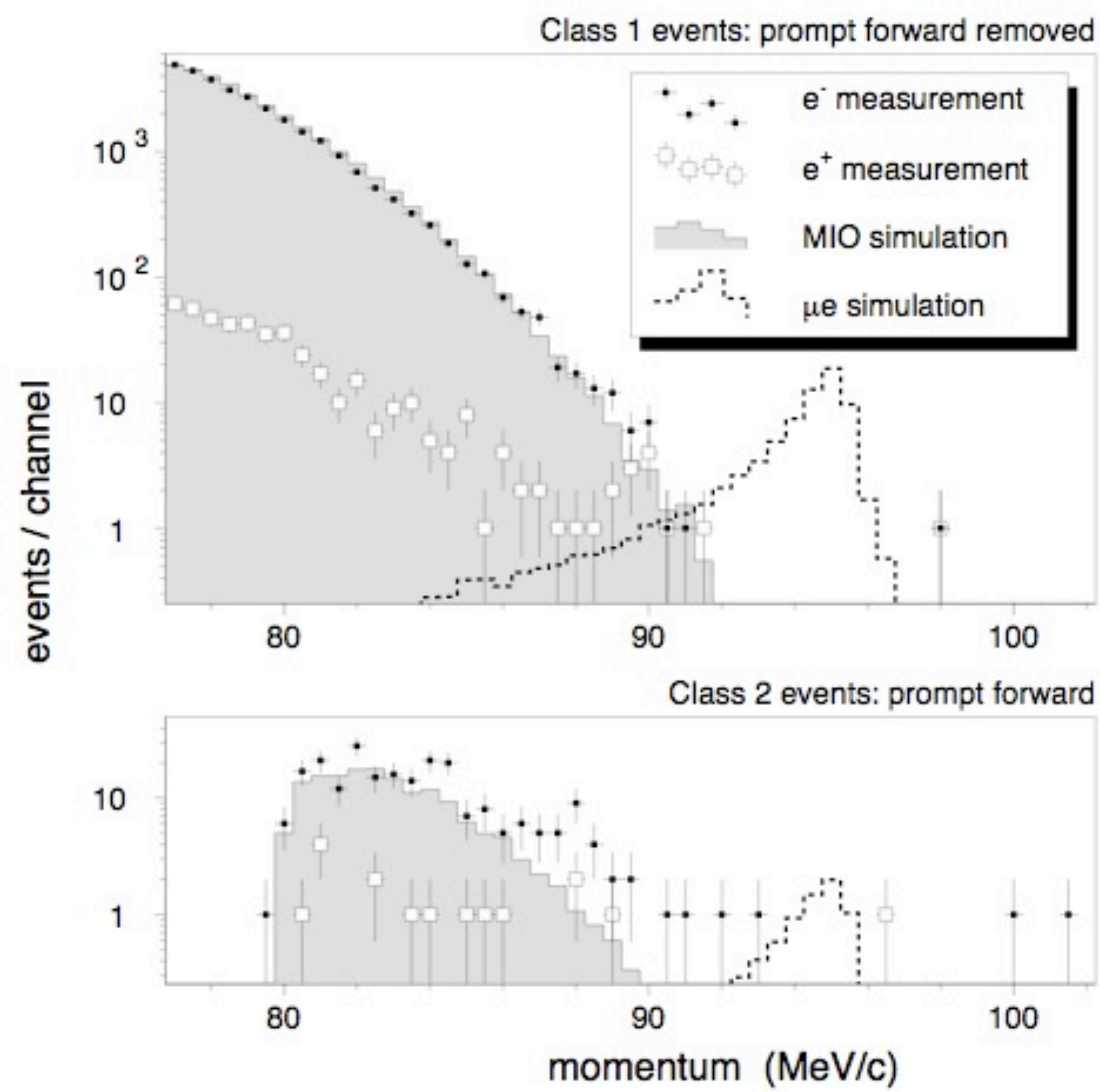


The SINDRUM II Experiment at PSI

Published Results

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$

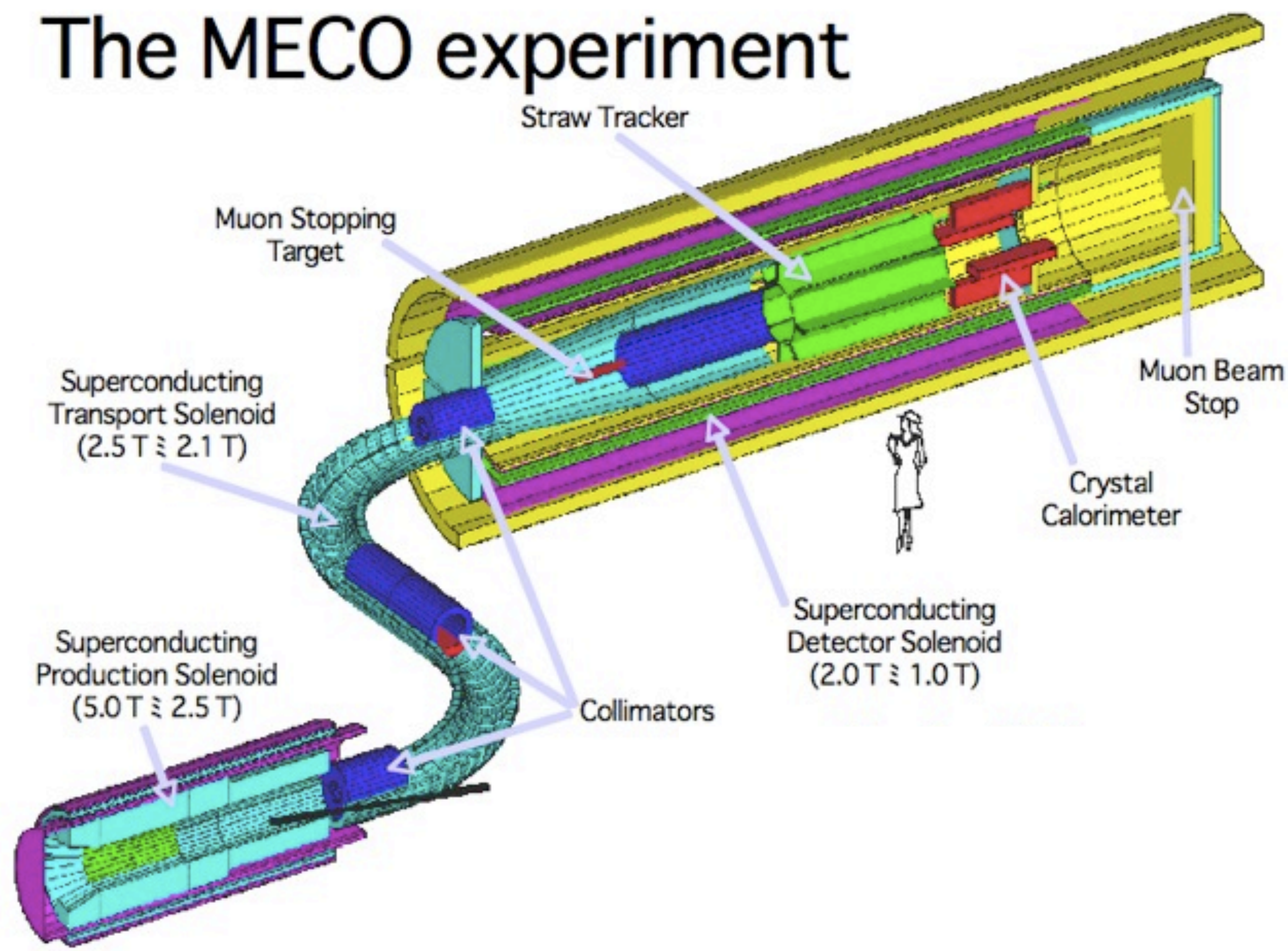


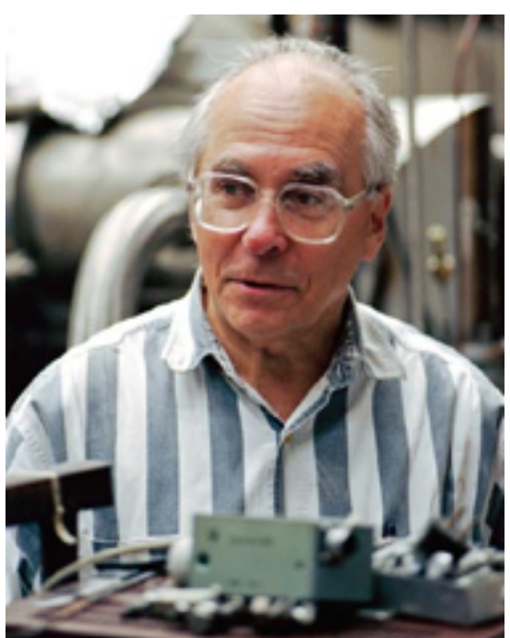


SINDRUM-II used a continuous muon beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed.

The MELC and MECO Proposals

- MELC (Russia) and then MECO (the US)
- To eliminate beam related background, beam pulsing was adopted (with delayed measurement)
- To increase a number of muons available, pion capture with a high solenoidal field was adopted
- For momentum selection, curved solenoid was adopted





Vladimir Lobashev 1934-2011
CERN Courier Vol 51, No 8

Cancelled in 2005

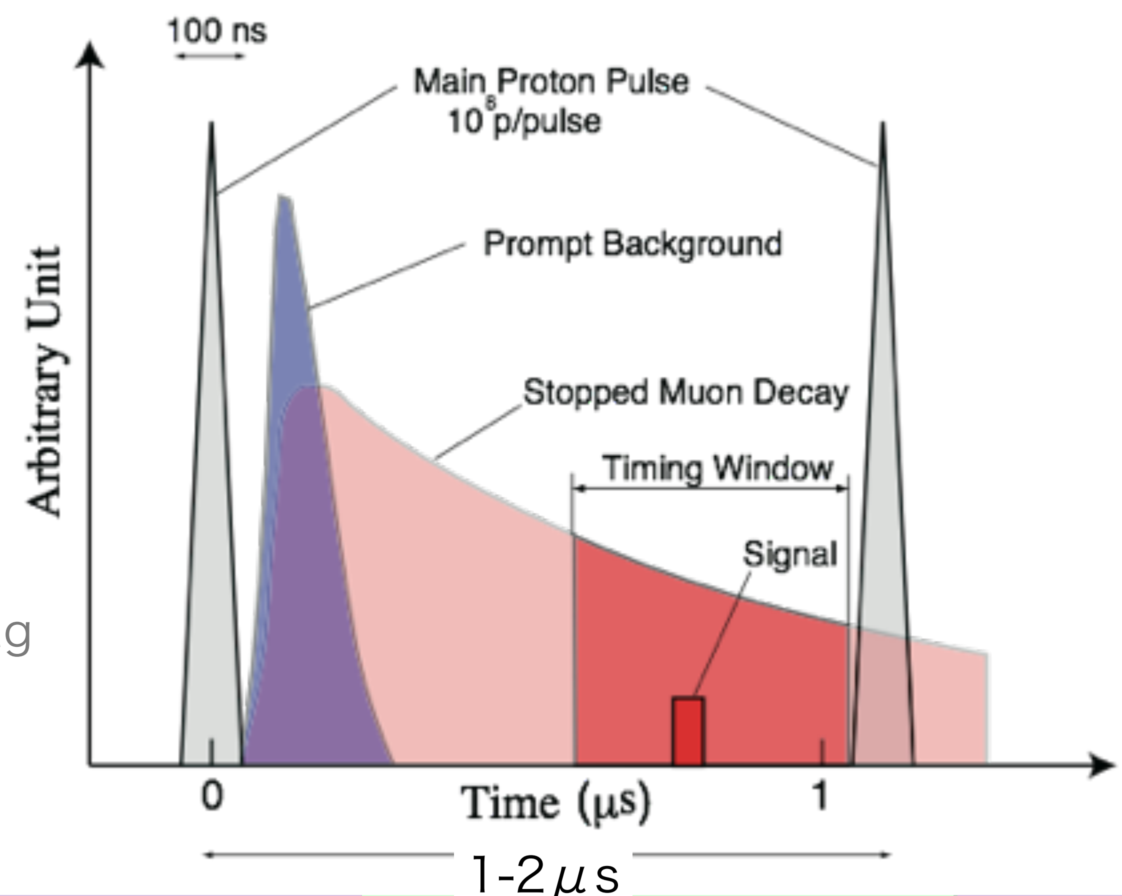
→ mu2e @ Fermilab

Lessons

- Use pulse beam instead of DC beam
    - Blind to prompt background using timing information
- Reduce pion background arriving in a delayed timing
    - Good beam extinction factor
- Sensitive only high-momentum electrons emitted in a delayed timing

Beam Extinction Factor

- COMET Background
  - $\pi^- + (A,Z) \rightarrow (A,Z-1)^*$
  - $(A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
  - $\gamma \rightarrow e^+e^-$
    - Prompt timing
  - Other sources
    - μ^- decay-in-flight, e^- scattering, neutron streaming



N_{bg} = NP x R_{ext} x Y_π/P x A_π x P_γ x A

NP : total # of protons (~10^{21})

R_{ext} : Extinction Ratio (10^{-9})

Y_π/P : π yield per proton (0.015)

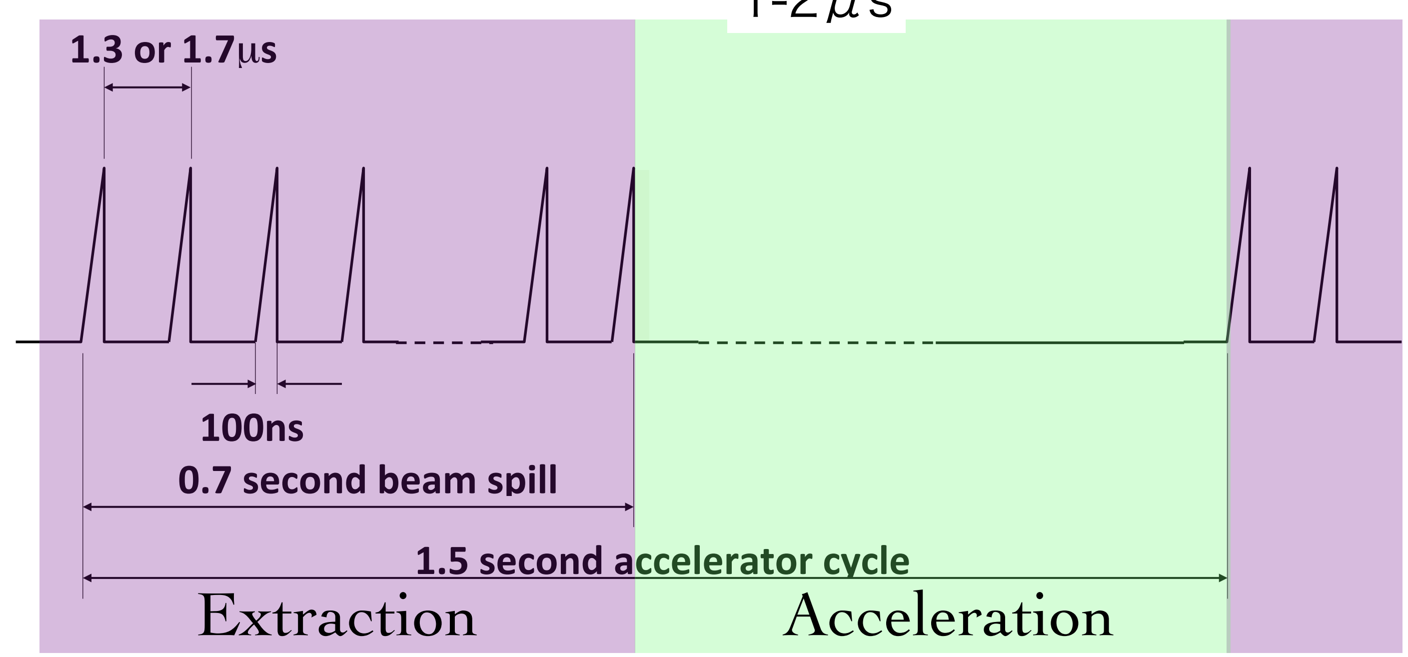
A_π : π acceptance (1.5 x 10^{-6})

P_γ : Probability of γ from π (3.5x10^{-5})

A : detector acceptance (0.18)

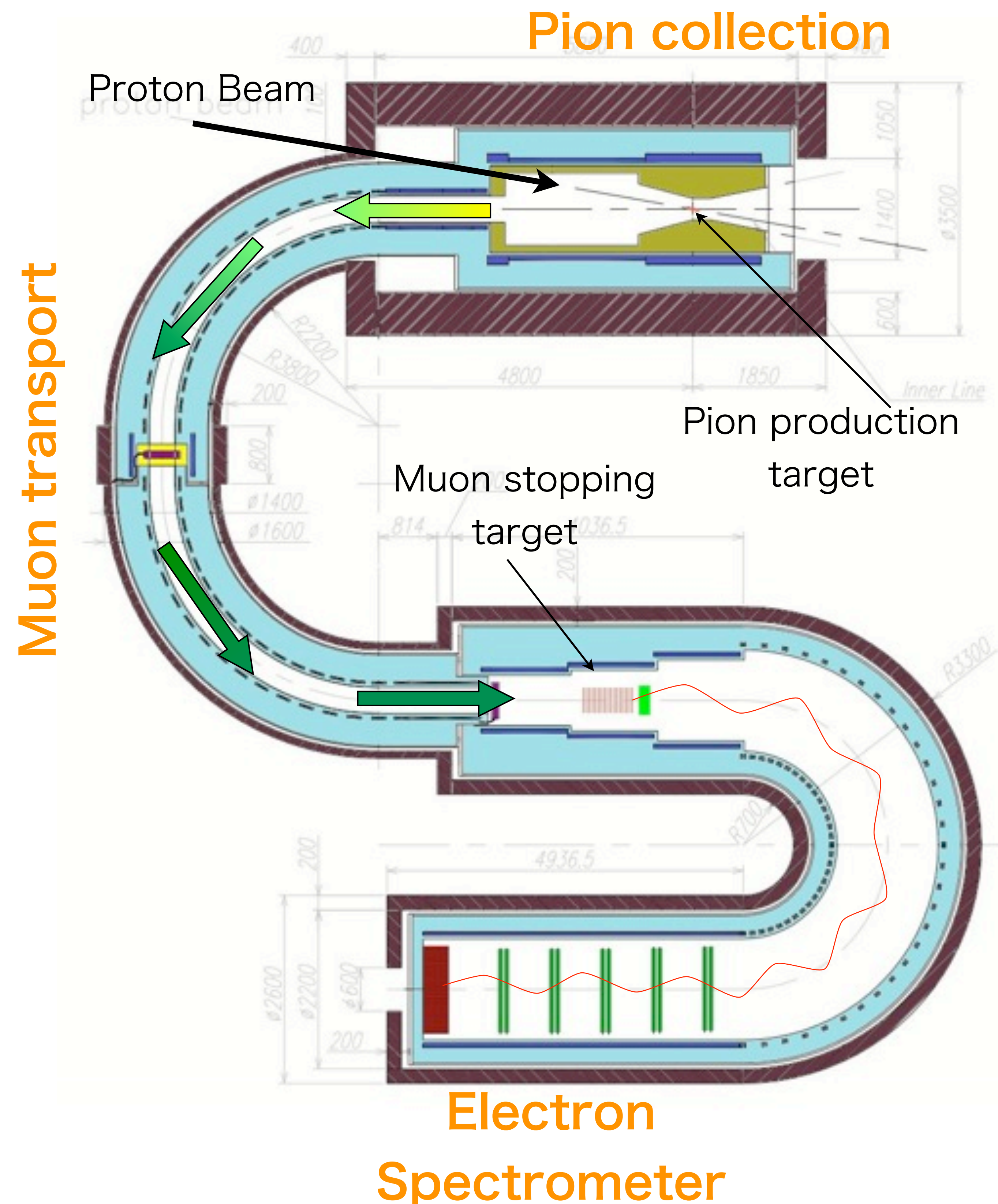
<u>BR=10^{-16}, N_{bg} ~ 0.1 →</u>

<u>Extinction factor < 10^{-9}</u>



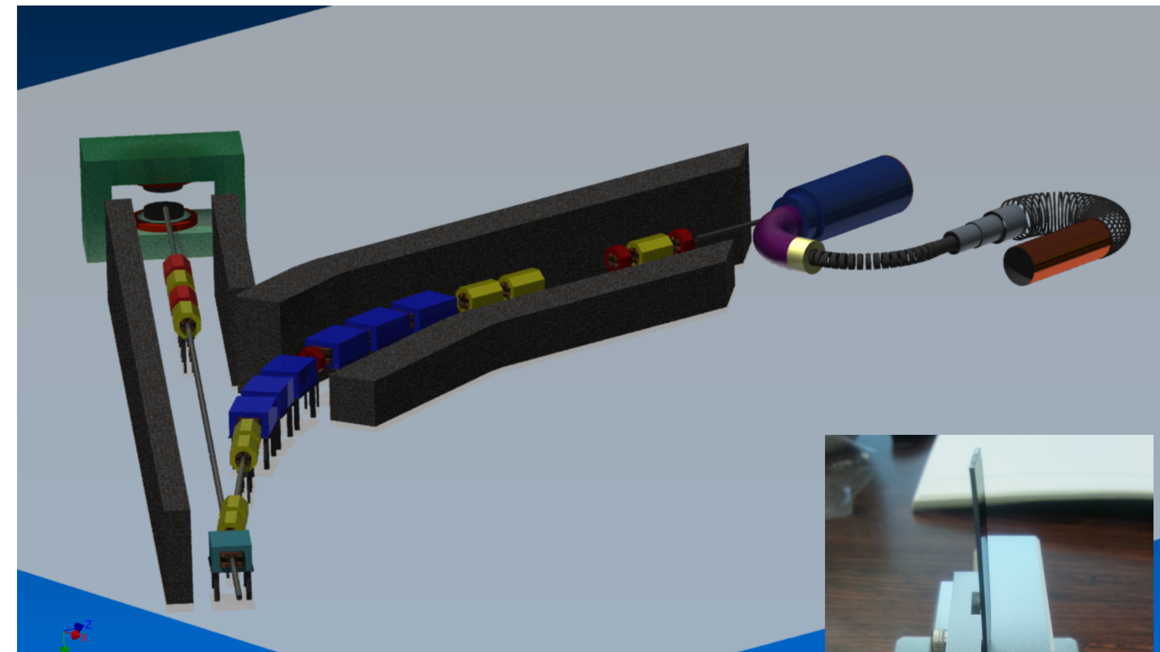
COMET Final Configuration

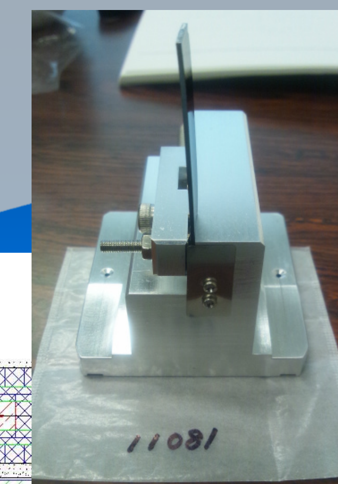
- Pion Collection
    - Collect low momentum (backward) pions
- Muon Transport
    - Momentum selection using a curved solenoid
        - Large acceptance
        - Charge separation using a beam blocker
- Electron Spectrometer
    - Momentum selection
    - Detector in vacuum to suppress multiple scattering effect

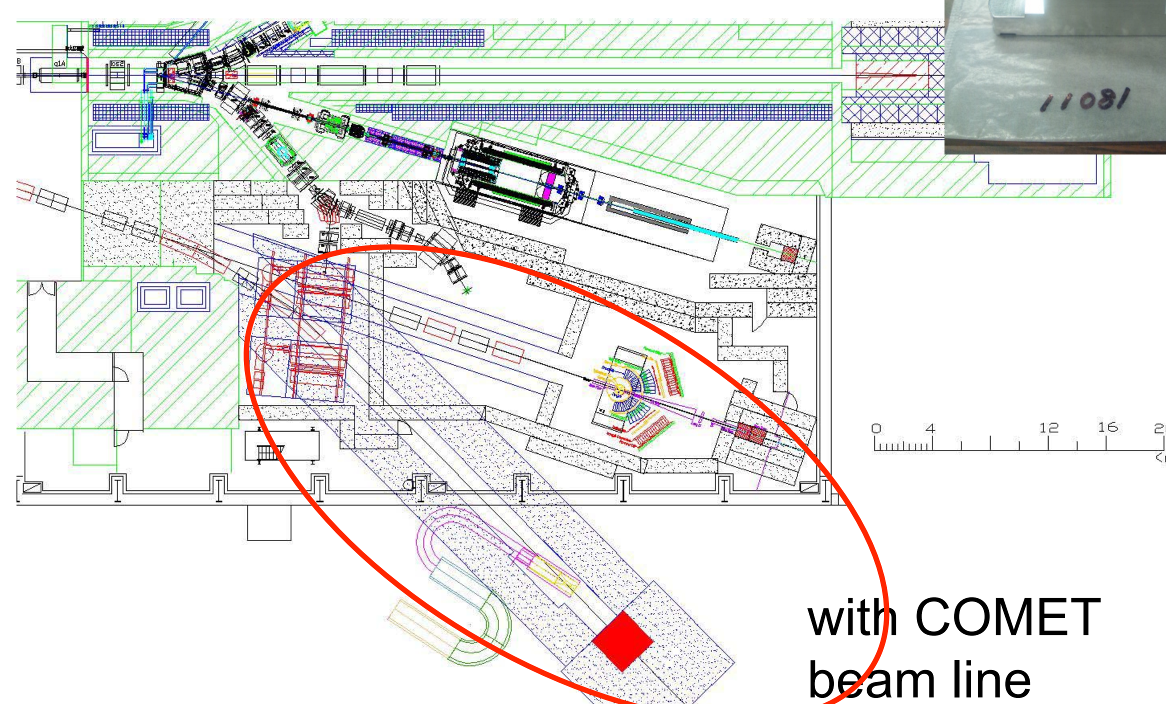


COMET Beam Line

- Proposal of high-p and COMET beam line construction
  - share the upstream
    - branch from A-line; beam stealer for high-p, bending magnet for COMET
  - COMET branch from high-p line
    - no simultaneous usage of two beam lines
    - Switching dipole magnet is enough
  - COMET needs 8 GeV, 7μA (56kW) beam







K. Tanaka Jan/12 PAC Meeting

COMET Phase I

EoI

An Expression of Interest for Phase-I of the COMET Experiment at J-PARC

We hereby express our interest to stage the construction of the COherent Muon to Electron Transition (COMET) experiment that will search for neutrinoless $\mu^- - e^-$ conversions with a single-event sensitivity of 3×10^{-17}. This sensitivity is a factor of 10,000 better than achieved by the SINDRUM-2 experiment which has set the world's best limit for $\mu^- - e^-$ conversions. The COMET experiment was given stage-1 approval by the J-PARC Program Advisory Committee in 2009 and is now J-PARC E21.

The proposed J-PARC mid-term plan includes the construction of the COMET beamline. This will provide the proton beamline for COMET and part of the muon beamline in the south area of the J-PARC Hadron Experimental Hall. We consider a staged approach for COMET as described below. To realise this staged approach we would like to construct the muon beamline up to the end of the first 90° bend in the muon beamline so that a muon beam can be extracted to the experimental area. We call this "COMET Phase-I". In COMET Phase-I, we will

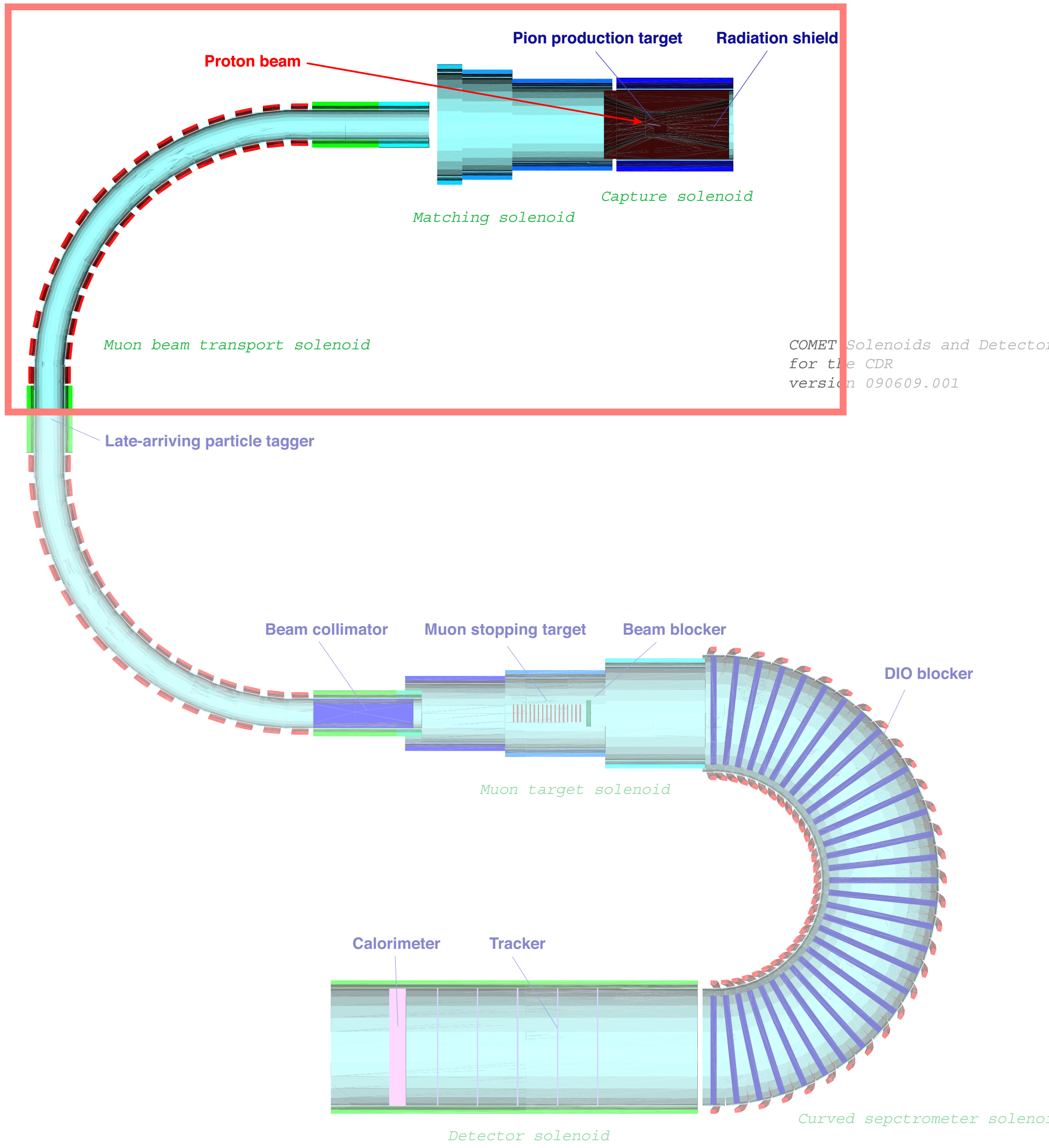
1. make a direct measurement of the proton beam extinction and other potential background sources for the full COMET experiment, using the actual COMET beamline; and
2. carry out a search for $\mu^- - e^-$ conversion with a sensitivity better than achieved by SINDRUM-2.

EoI

- Beam study for COMET
  - Extinction measurement at the actual COMET setup
  - Beam particles and momentum distribution at the end of the 1st 90 degree bend
- μ-e conversion search at intermediate sensitivity: $B(\mu^- + Al \rightarrow e^- + Al) < 7.2 \times 10^{-15}$ at 90% C.L.

COMET Phase-I LoI

- Beam background Study
- μ-e conversion search



Beam Background Study Plan

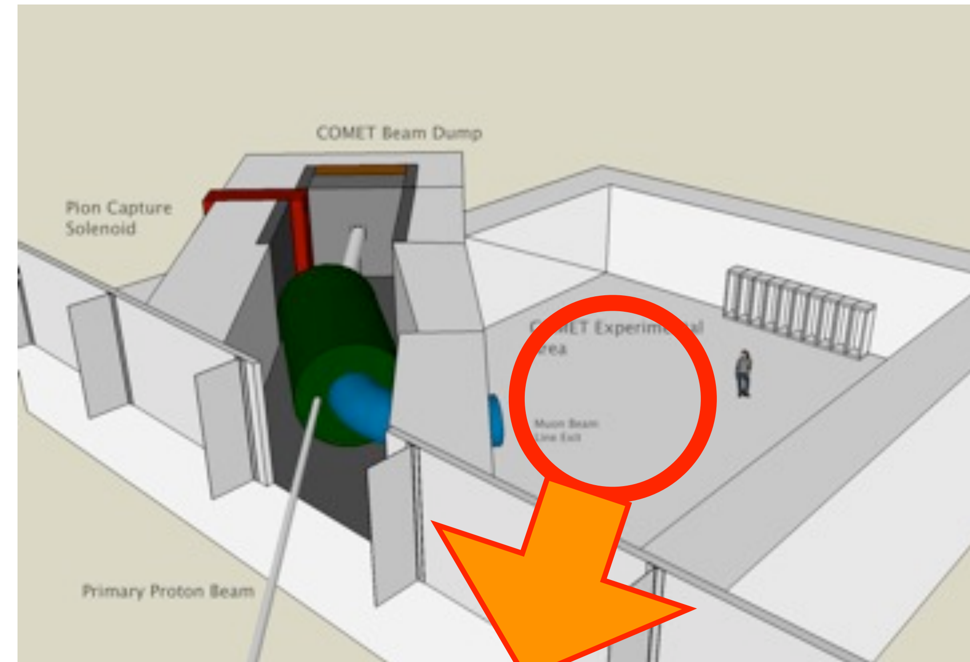
Purpose of the study

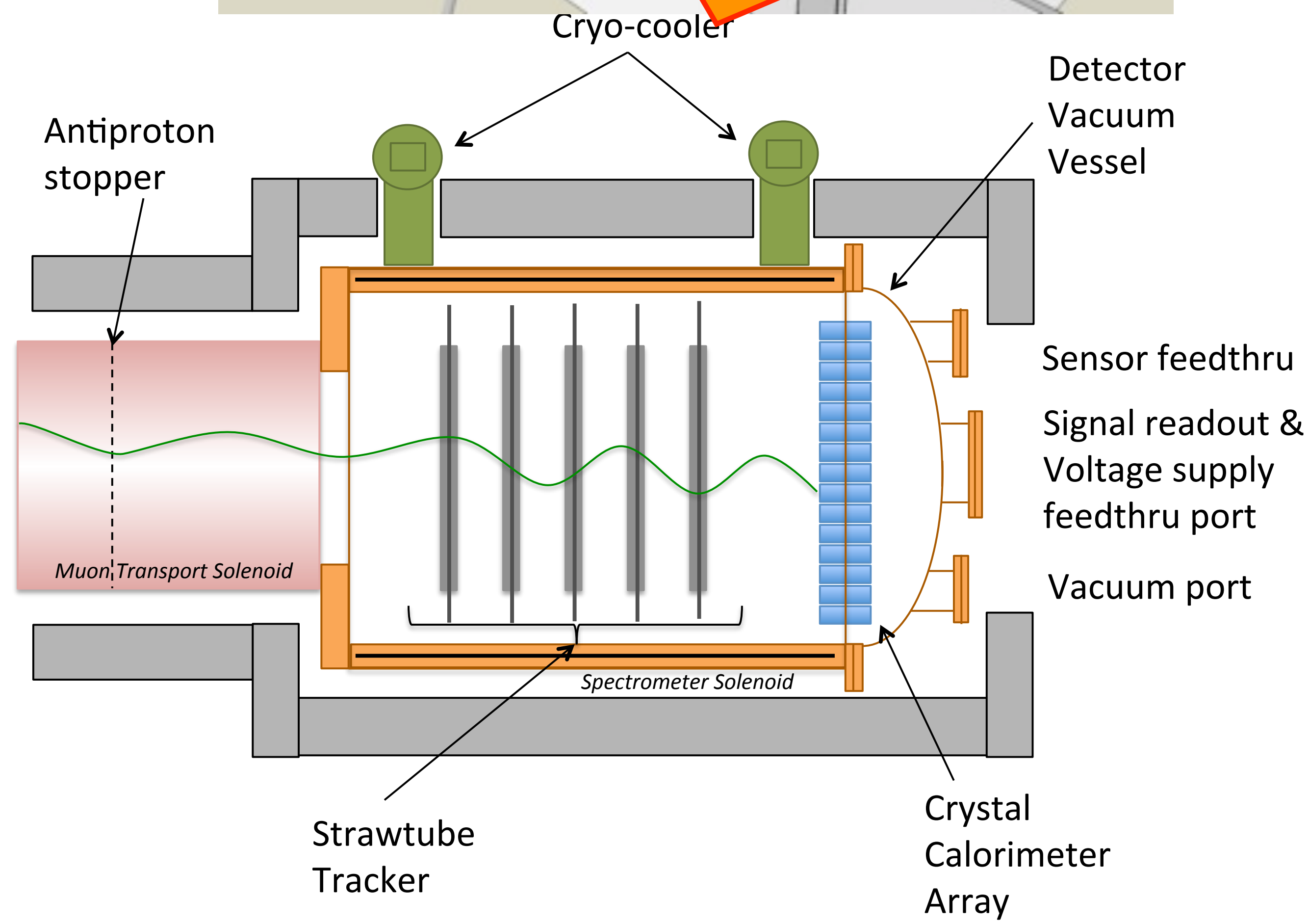
- Verify pion collection using a solenoid magnet surrounding a production target at 8GeV
- Direct measurement of residual dose at the COMET beam line with lower beam power (< 1kW)
- Identify particles contained in the beam and measure their phase space to better understand possible background in COMET
  - No available data of particle production backward at 8 GeV
  - Antiproton and neutron yield
  - Current COMET BG is estimated by extrapolating existing data by 4 orders of magnitude!
- Cosmic-ray associated and room background in the hall as well

Setup

CoCOMET (or COMETino or COMETChen)

- Measure almost all particles
- Same detector technology used in COMET
  - SC spectrometer solenoid
  - Straw tube transverse tracker
  - Crystal calorimeter
- Particle ID with dE/dX and E/p
  - anti-p with event shape
  - γ direction





Particles and Yield

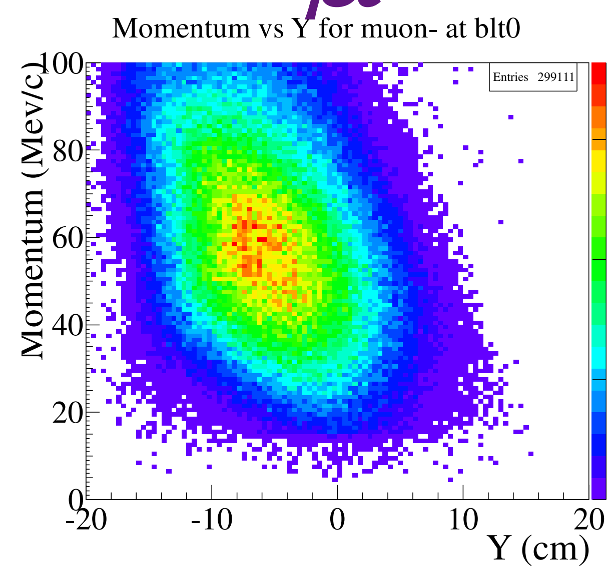
- Beam dispersion

$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + \frac{1}{2}p_T^2}{p_L}$$

  - Collimator to reject high-p particles

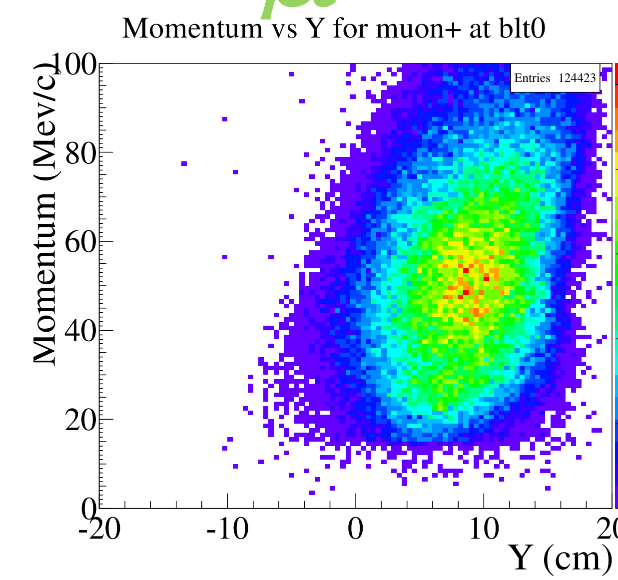
- Positive/negative particles contained in the beam with wide momentum range

μ^-



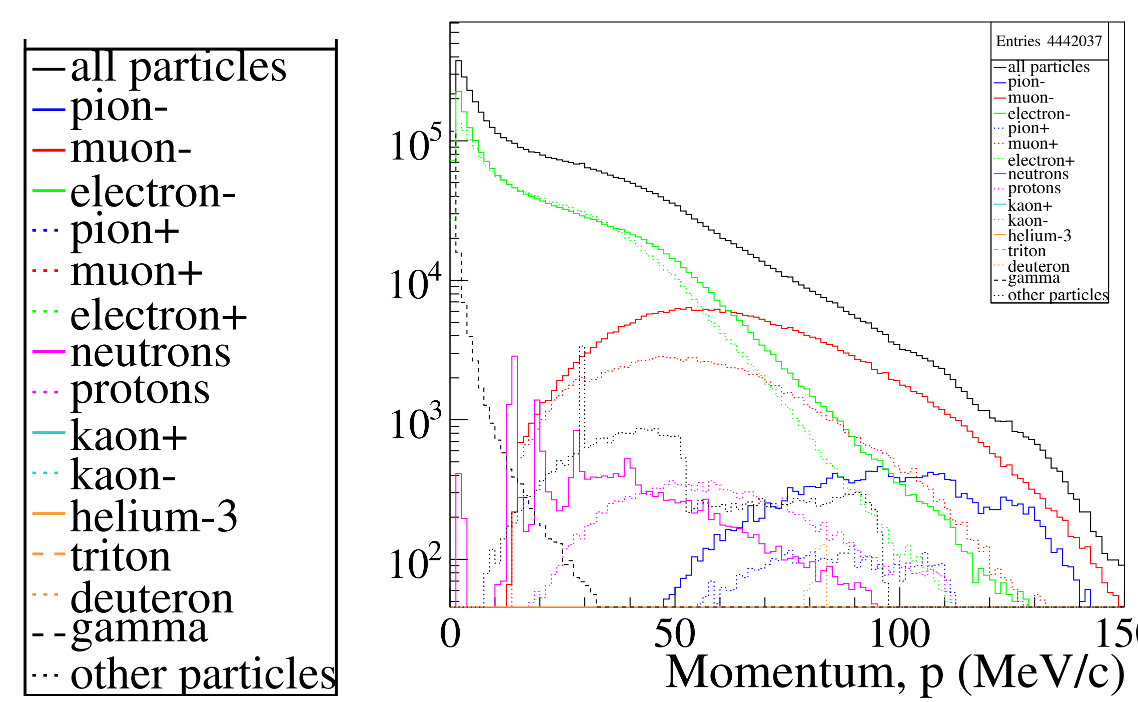
0.0180T, 0.0300T

μ^+



0.0180T, 0.0300T

w/o collimator

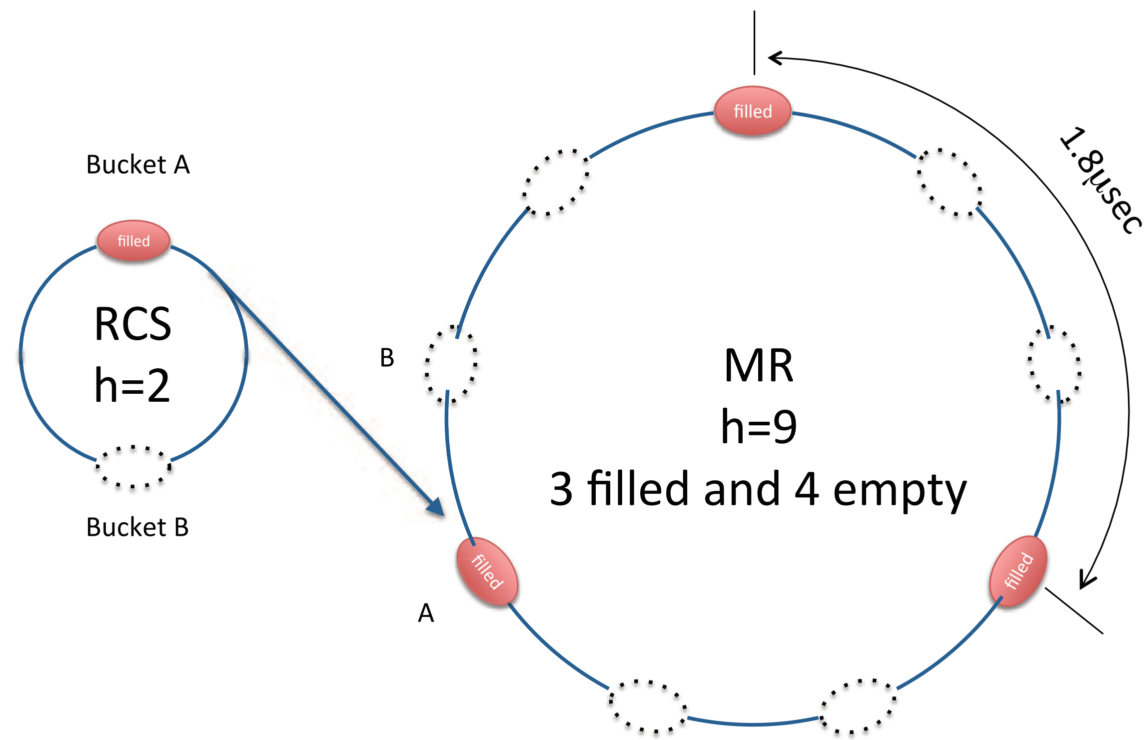


Beam Requirement

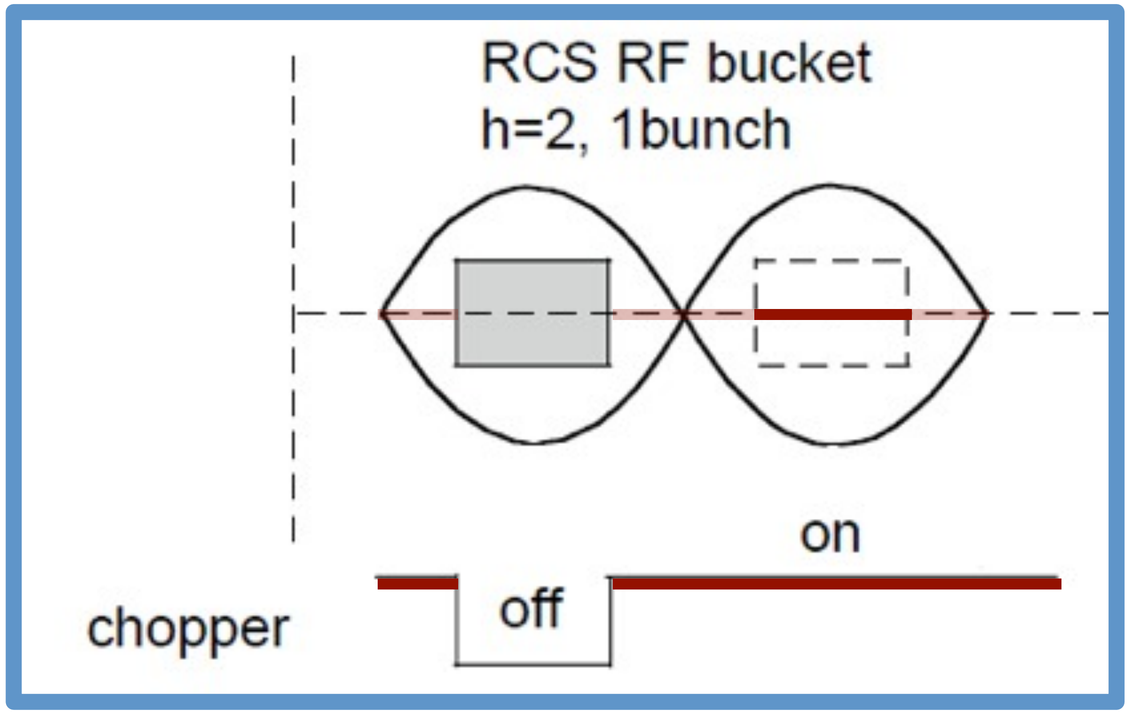
- Continuous (not pulsed) SX beam
- 0.00001kW - 0.1kW beam power for approximately 3 cycles (approx. 3 months)
  - precise estimation in future
- 8GeV beam extraction is necessary for beam study
  - conditioning can be done at 30GeV as long as the beam power is small enough not to produce significant residual dose around the target
- Requesting to the accelerator group for 8GeV beam extraction study before 2016

J-PARC Proton Acceleration for COMET

- RCS: h=2 with one empty bucket
- MR:h=9 with 6(5) empty buckets
- Bunched slow extraction
  - Slow extraction with RF cavity ON

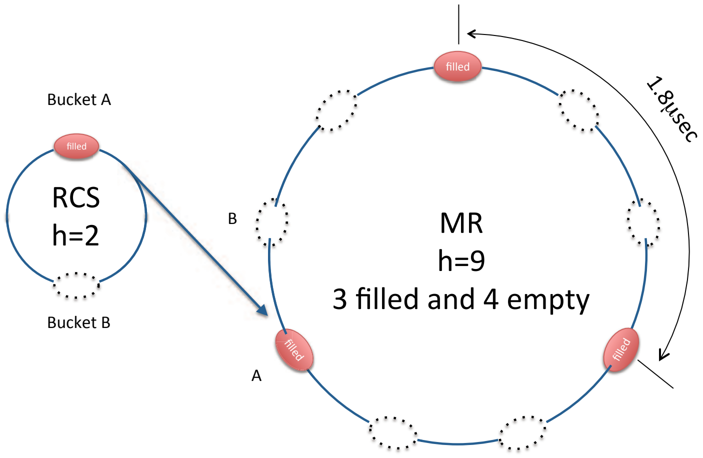


Realization of an empty bucket in RCS by using the chopper in Linac

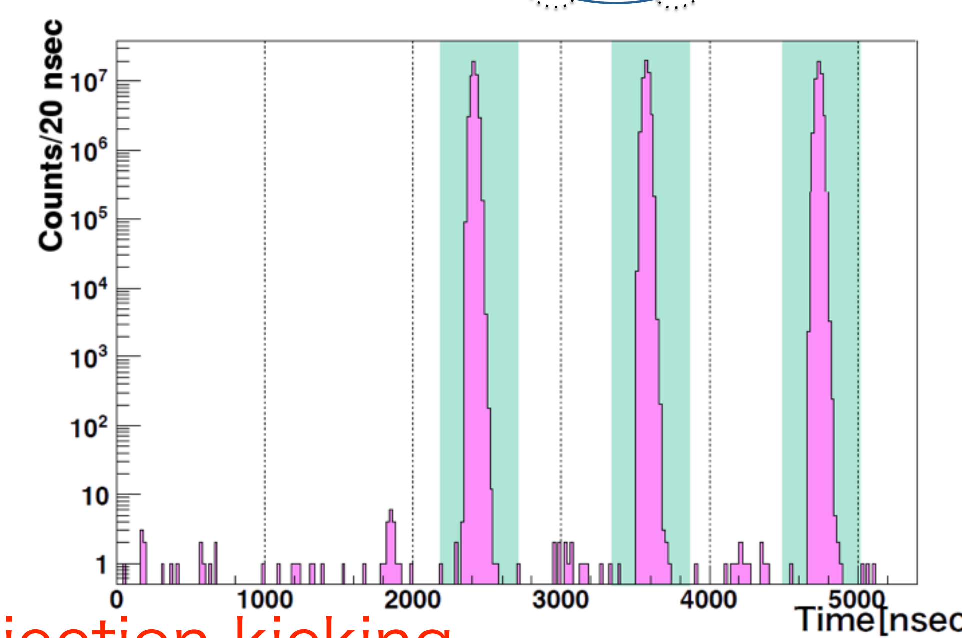


- Simple solution
  - No need of hardware modification
- Heavier heat load in the scraper
- Possible leakage of chopped beam in empty buckets

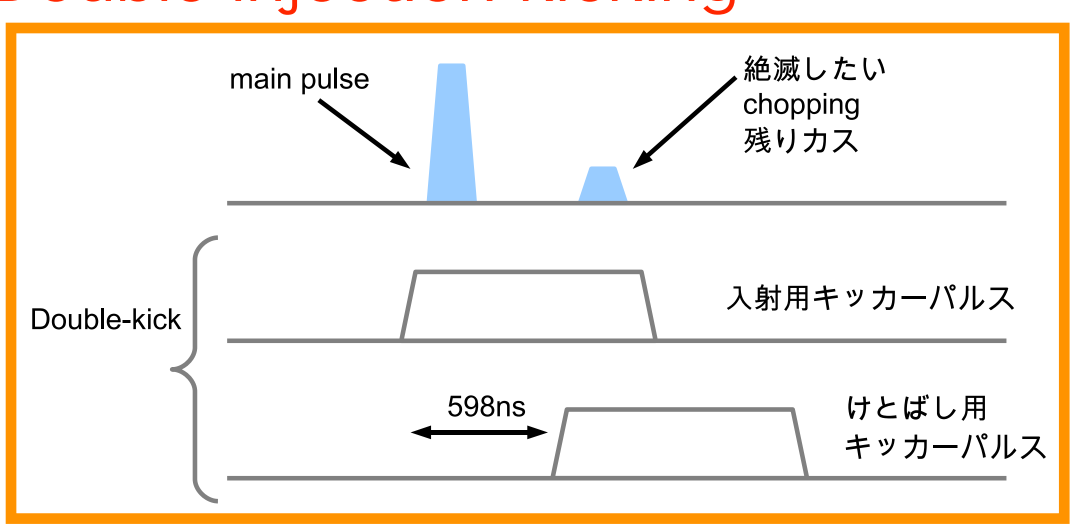
MR Injection for COMET



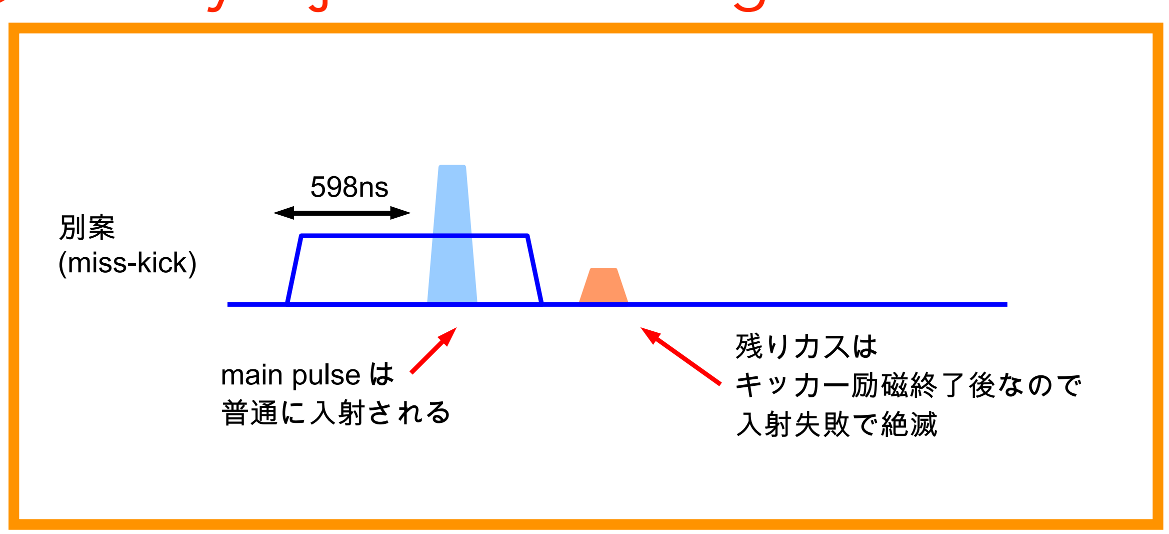
- Preliminary measurement shows 10^{-7} extinction factor
    - Most probably caused by chopper inefficiency
    - Particles must remain in empty buckets at beam injection to MR
    - Once accelerated, difficult to remove
- Remove remaining particles in empty buckets at beam injection to MR



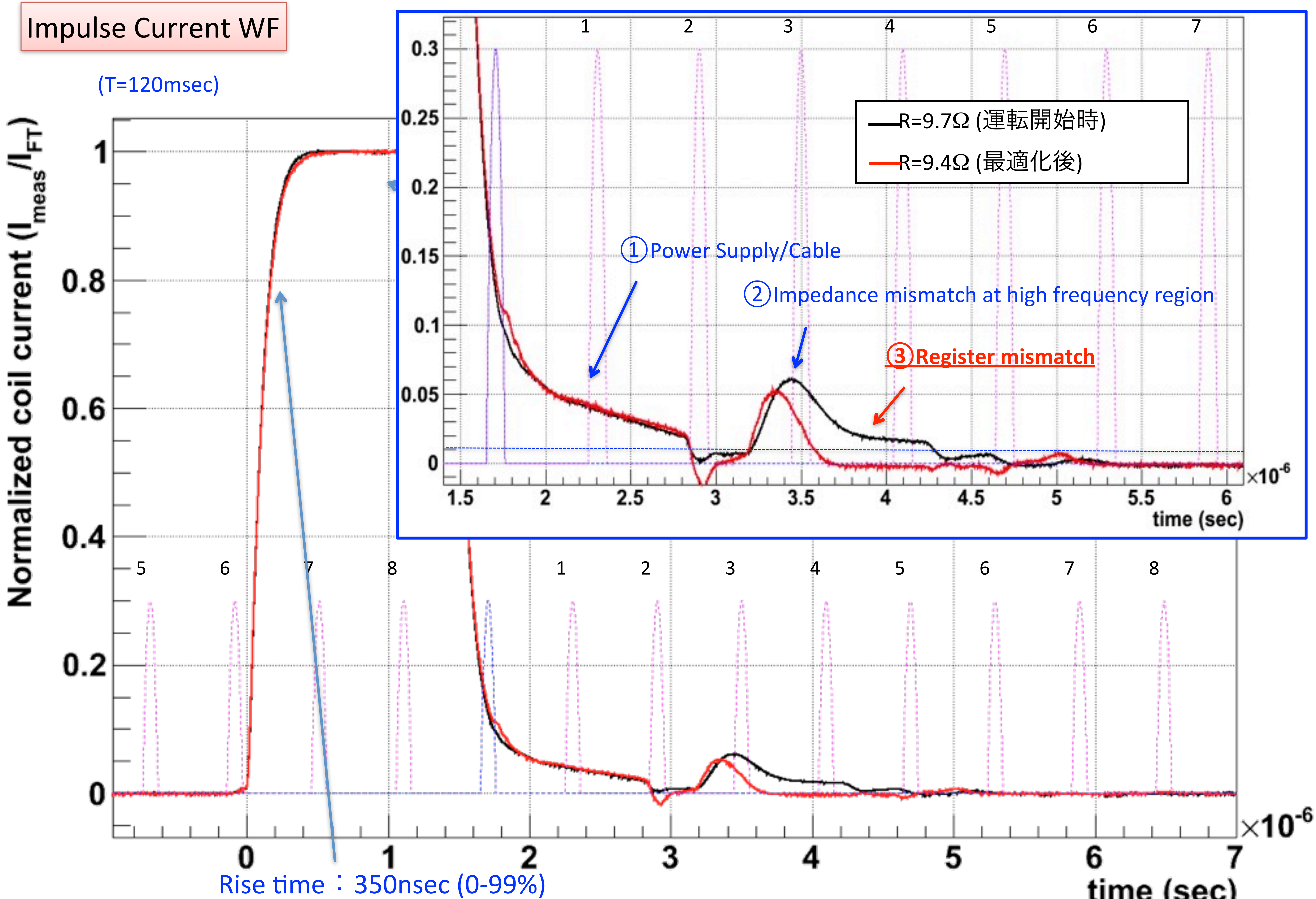
① Double injection kicking



② Early injection kicking



Impulse Current WF



Rise time：350nsec (0-99%)

→ Need to reduce floating capacitance

Sugimoto J-PARC Acc

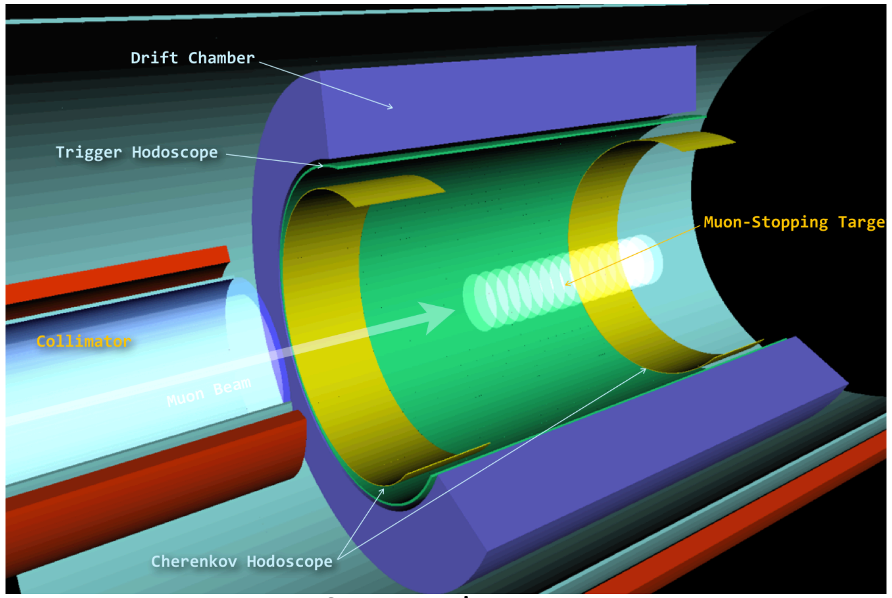
μ-e conversion search in COMET Phase-I

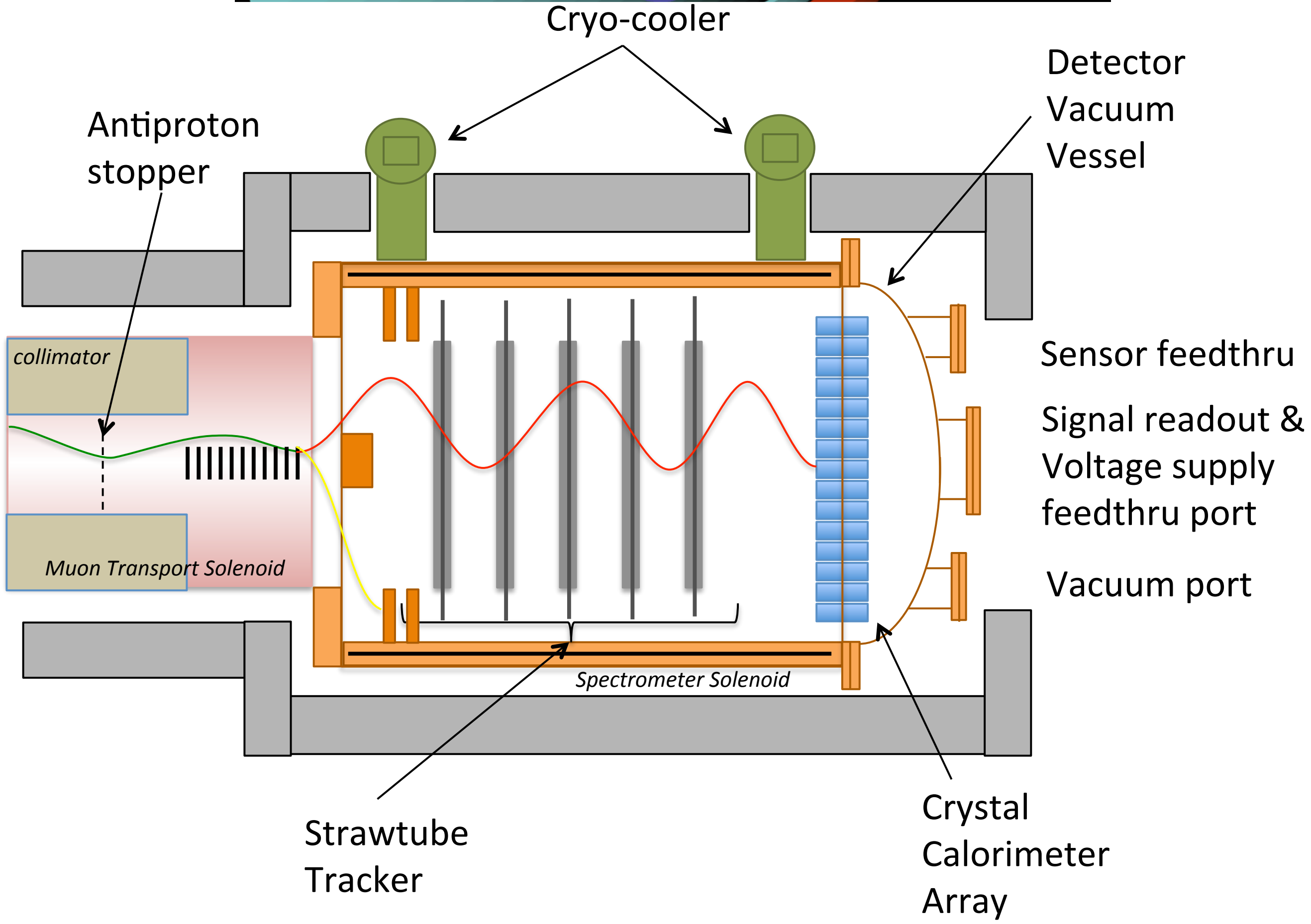
COMET Phase-I Goal

- As an intermediate goal of the COMET experiment
  - gain experience to reach the final goal
- 7×10^{-15} sensitivity (90% C.L. upper limit)
  - better than the current limit by SINDRUM-II (7×10^{-13}) and compatible to MEG sensitivity
- Involve more collaborators

Proposed Setup

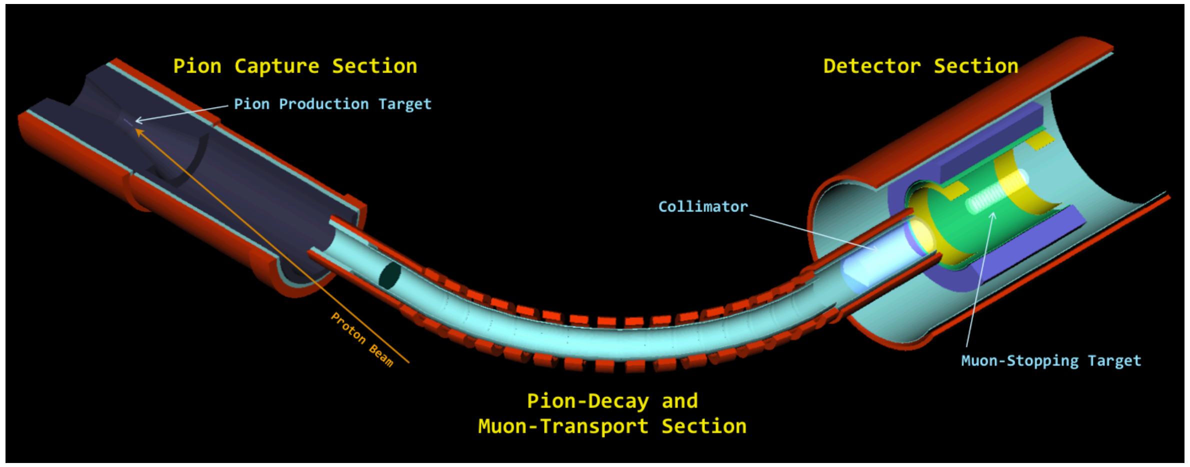
- Cylindrical detector
- Transverse tracker detector

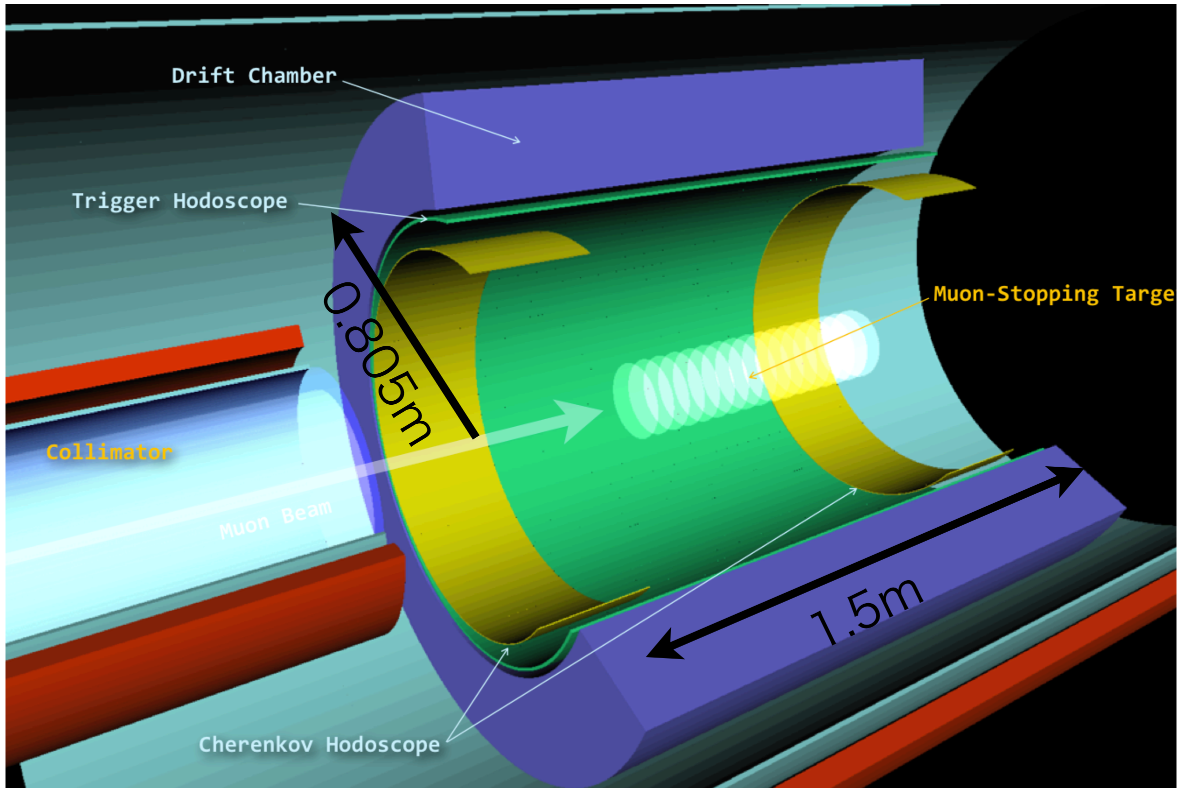




Cylindrical Detector

- Collimator of 200 mm diam. at the end of 90 degree bend
  - determine a beam size
  - eliminate high-p particles
- Beam particles not stopped on the target will escape from the detector
- Optimization of detector configuration
  - p_t threshold > 70MeV/c
  - trigger counter (5mm thick) as a proton absorber

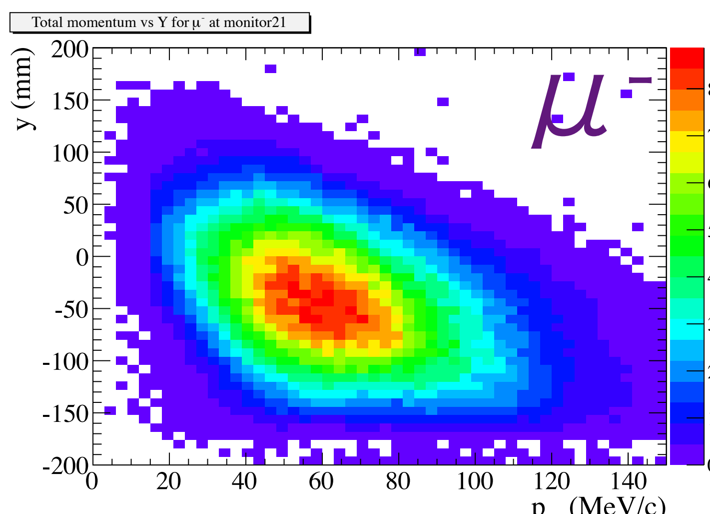




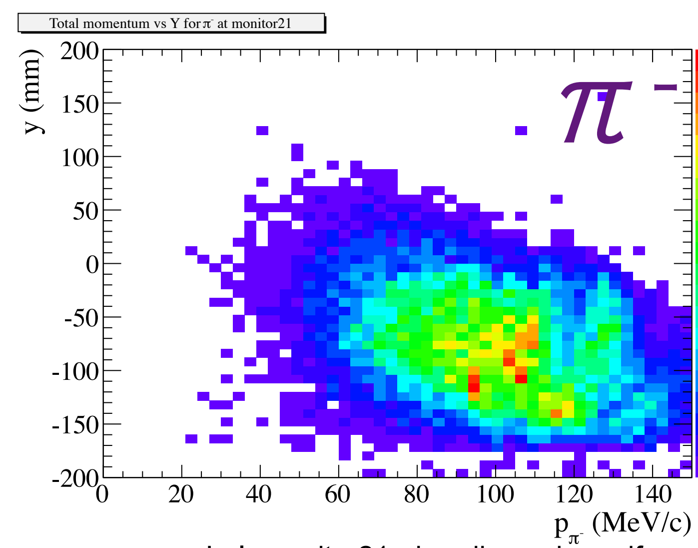
Beam Simulation

- MARS(production) & g4beamline (simulation)
- Tosca (B field)

before collimation

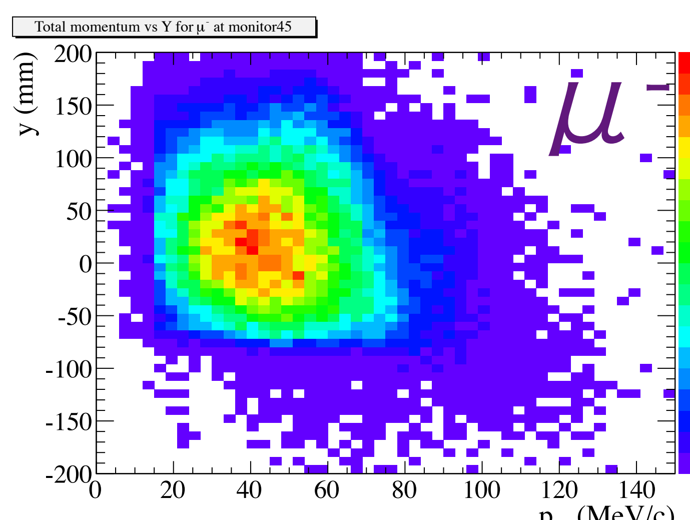


LoI_monitor21-mu_n-dispersion.pdf

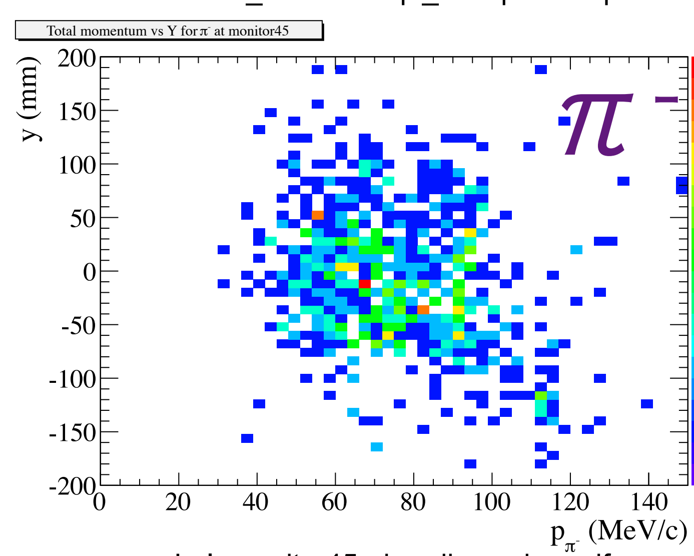


LoI_monitor21-pi_n-dispersion.pdf

after collimation

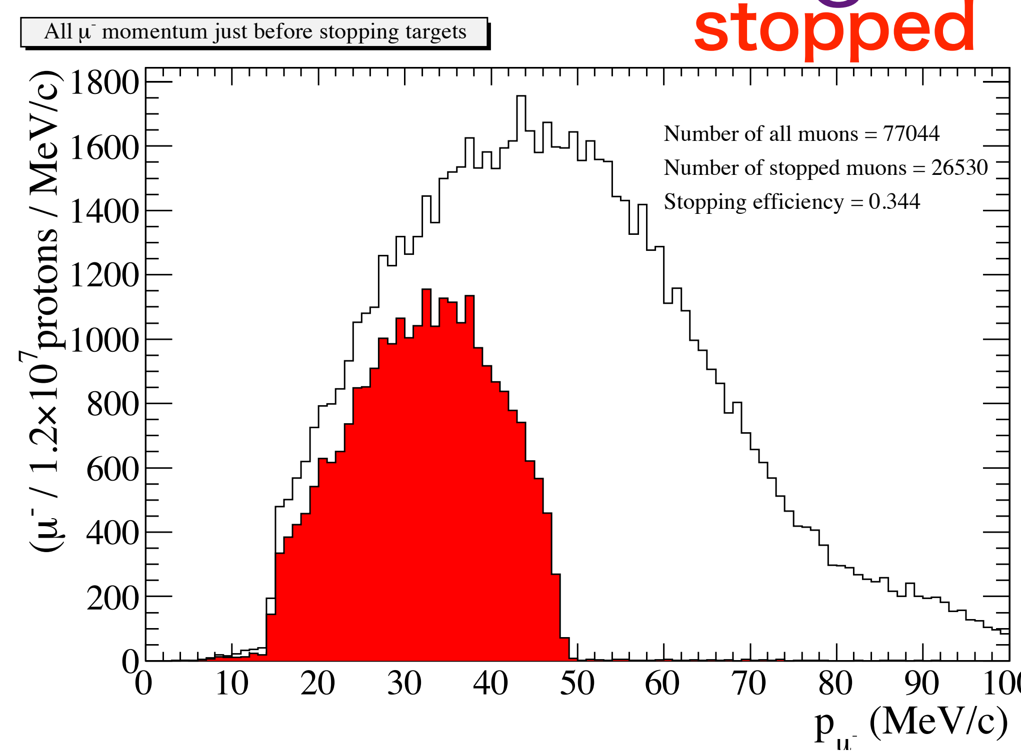


LoI_monitor45-mu_n-dispersion.pdf

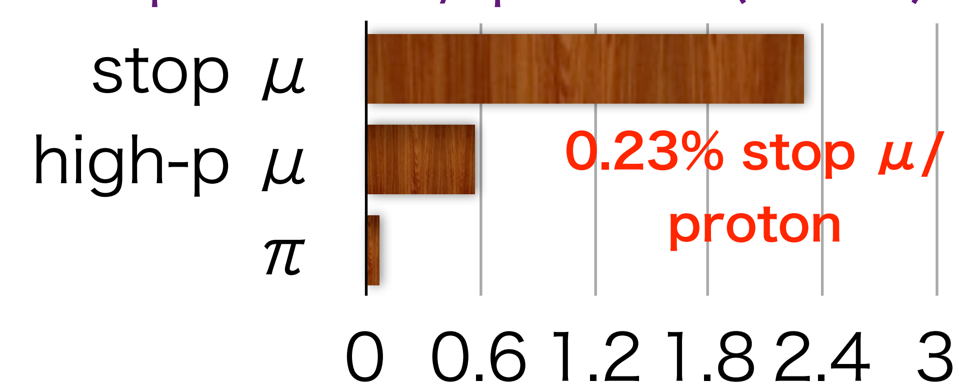


LoI_monitor45-pi_n-dispersion.pdf

μ^- on the target

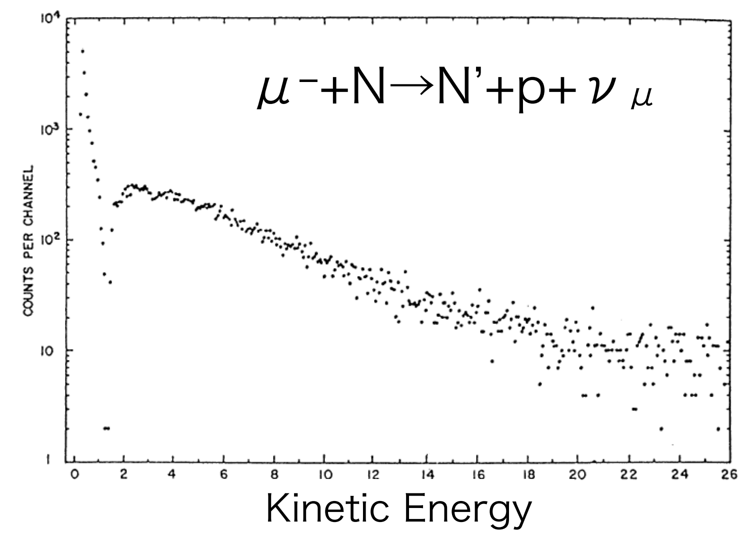


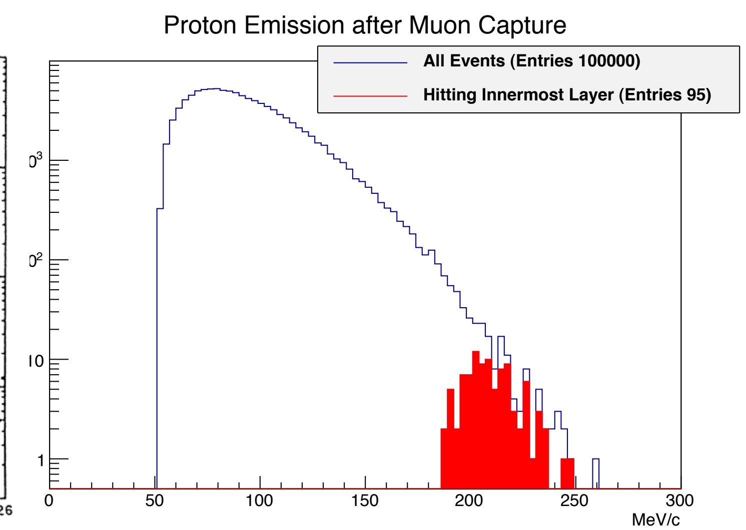
# of particles / proton (x10^{-3})



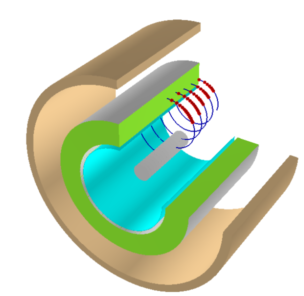
Expected Performance

- Detector hit rate
  - Proton emission after muon capture
    - peak at 70MeV/c and extends to > 200MeV/c
    - 15% of muon capture (for Si, no data for Al)
    - Trigger counter as a proton absorber
  - DIO e^-
  - e^+e^- from high-E γ conversion
- Momentum resolution

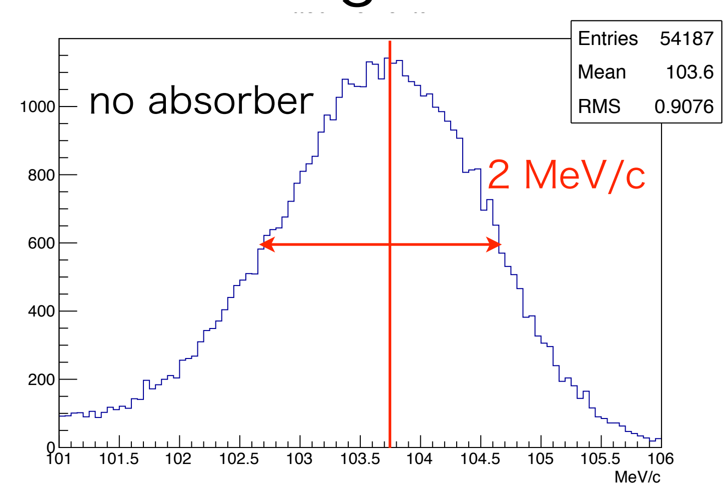


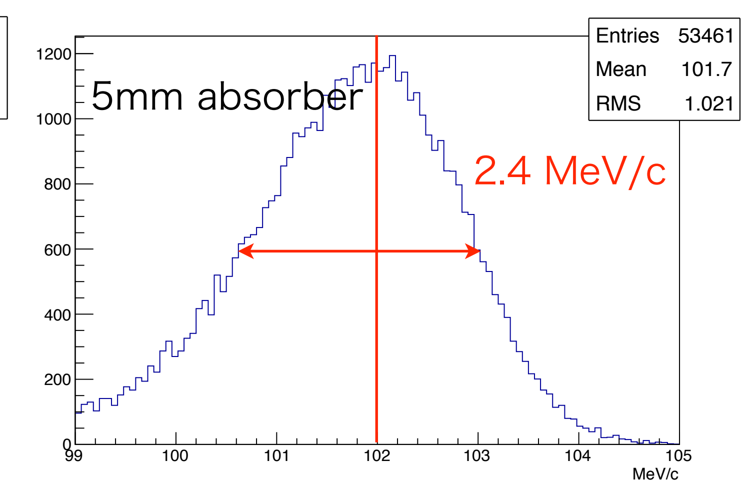


530kHz in the 1st layer of DC (530k/345=1.5kHz/ch) for 5.8×10^9 muon stops



Signal Electron 105MeV/c



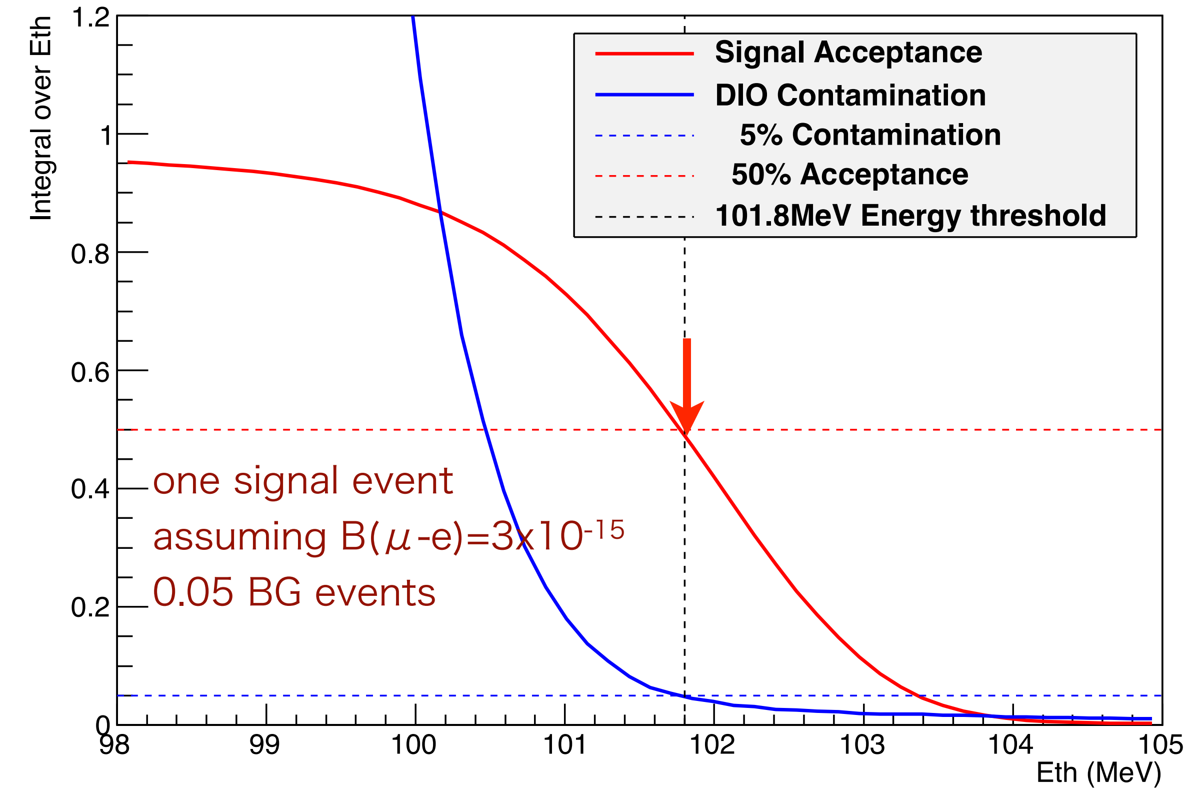


Sensitivity and BG

- **8GeV, 3.2kW proton beam**
  - 2.5×10^{12} proton/sec
- 12 days (10^6 sec) running time
- Single event sensitivity

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

  - $B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = 3.1 \times 10^{-15}$
- Upper limit at 90% C.L.
  - $B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) < 7.2 \times 10^{-15}$



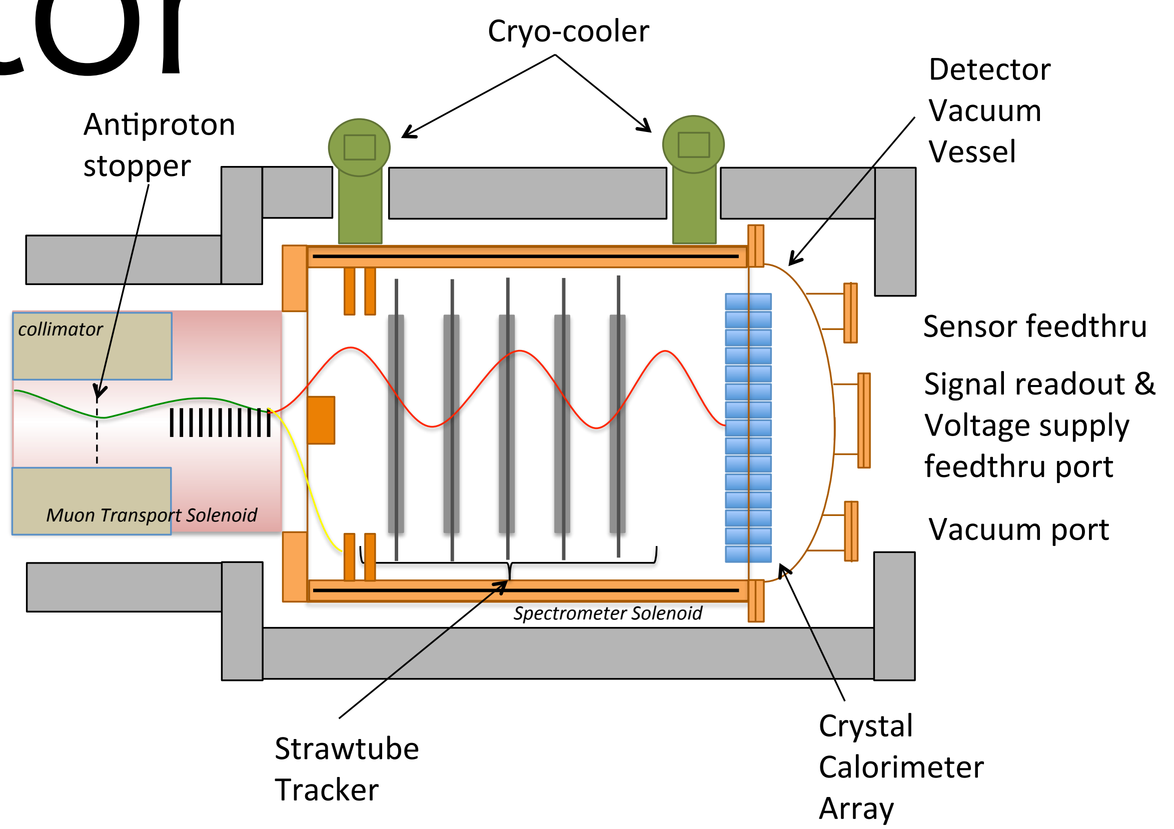
Selection	Value	Comments
Geometrical Acc	0.53	tracking eff. included
momentum	0.50	p_e>101.9MeV/c
Timing	0.39	same as COMET
Trigger and DAQ	0.9	same as COMET
Total	0.09	

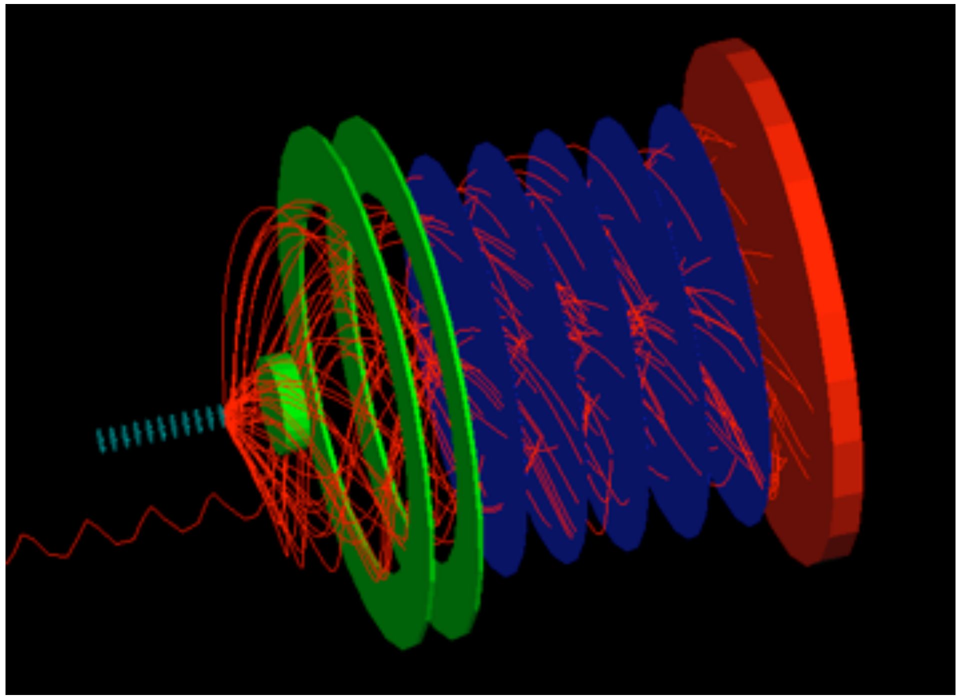
Background	estimated events
Muon decay in orbit	0.05
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.024
Beam electrons	< 01
Muon decay in flight	0.0004
Pion decay in flight	< 0.0001
Neutron induced background	0.024
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Cosmic ray muons	0.0001
Electrons from cosmic ray muons	0.0001
Total	0.11

supposing beam extinction factor of 10^{-9}

Transverse Tracking Detector

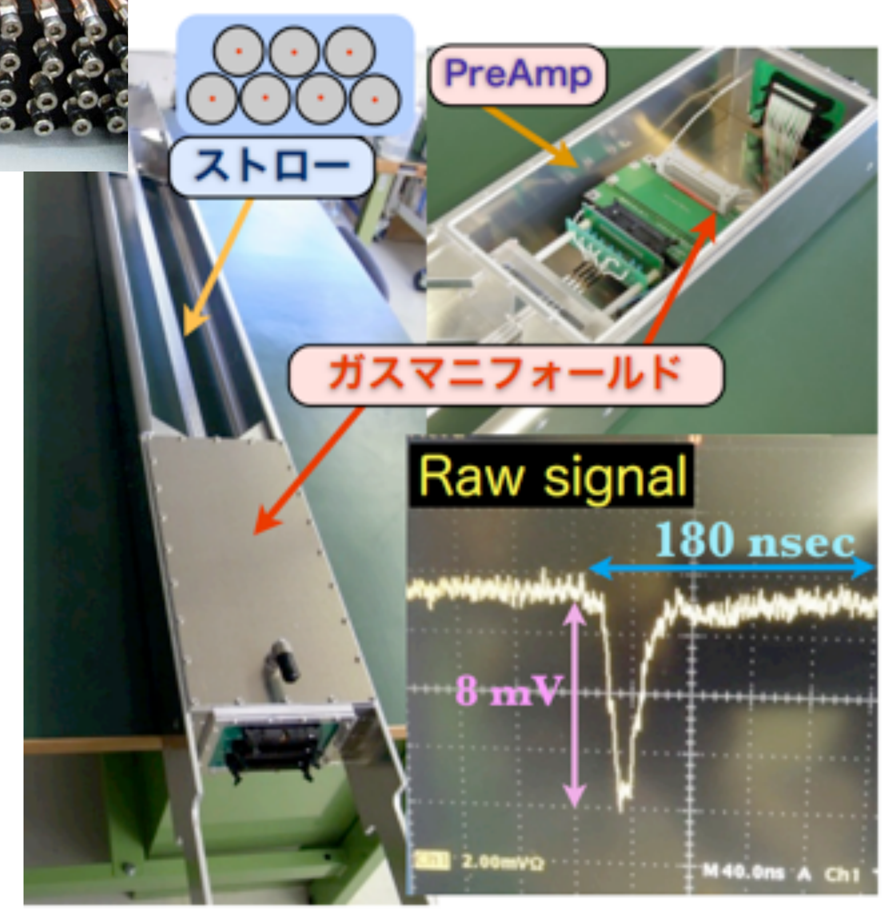
- Reuse the detector for beam study
  - Beam collimator
  - Beam blocker
  - High-p wedges
  - proton degrader
    - Signal electron momentum spread 200MeV/c (FWHM)
- Geometrical acceptance smaller than the cylindrical detector: 22.5% and more beam related background
  - lower sensitivity
- 80 kHz/ch detector hit rate in the 1st layer expected for 5x10^9 muon stops/sec
- Momentum resolution expected as good as COMET (1% in sigma)
- Sensitivity and BG calculation in progress





Detector R&D

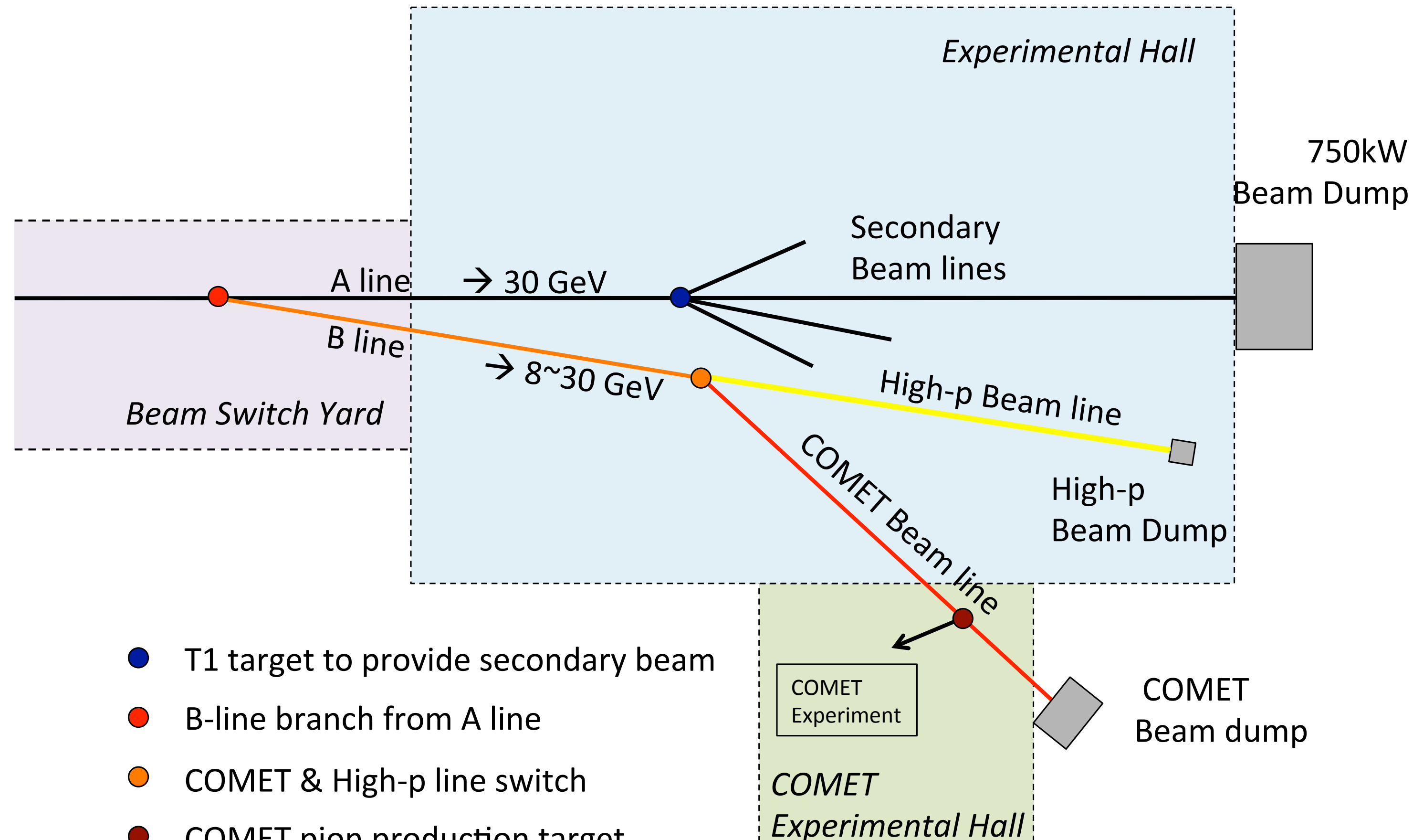
- Muon profile monitor
- Straw tube tracker
- Electron calorimeter

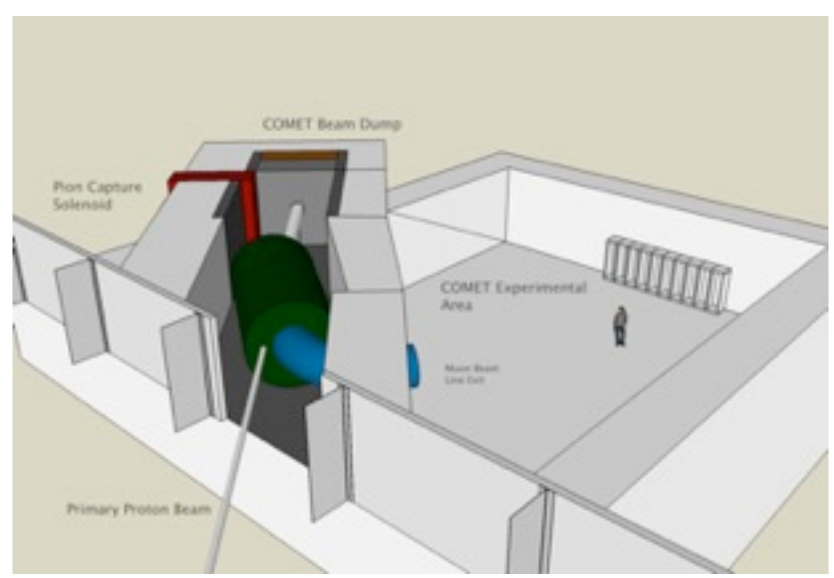


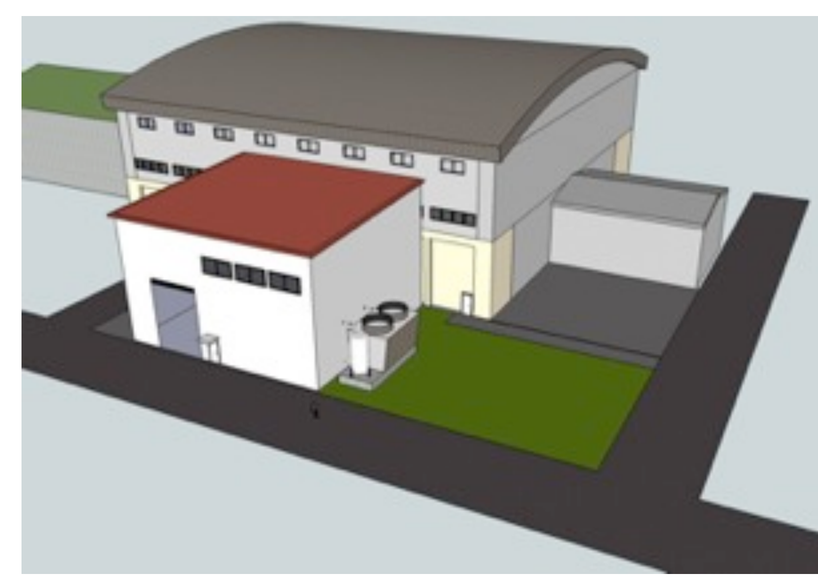
Calorimeter electronics group ← → Calorimeter simulation group

Facilities

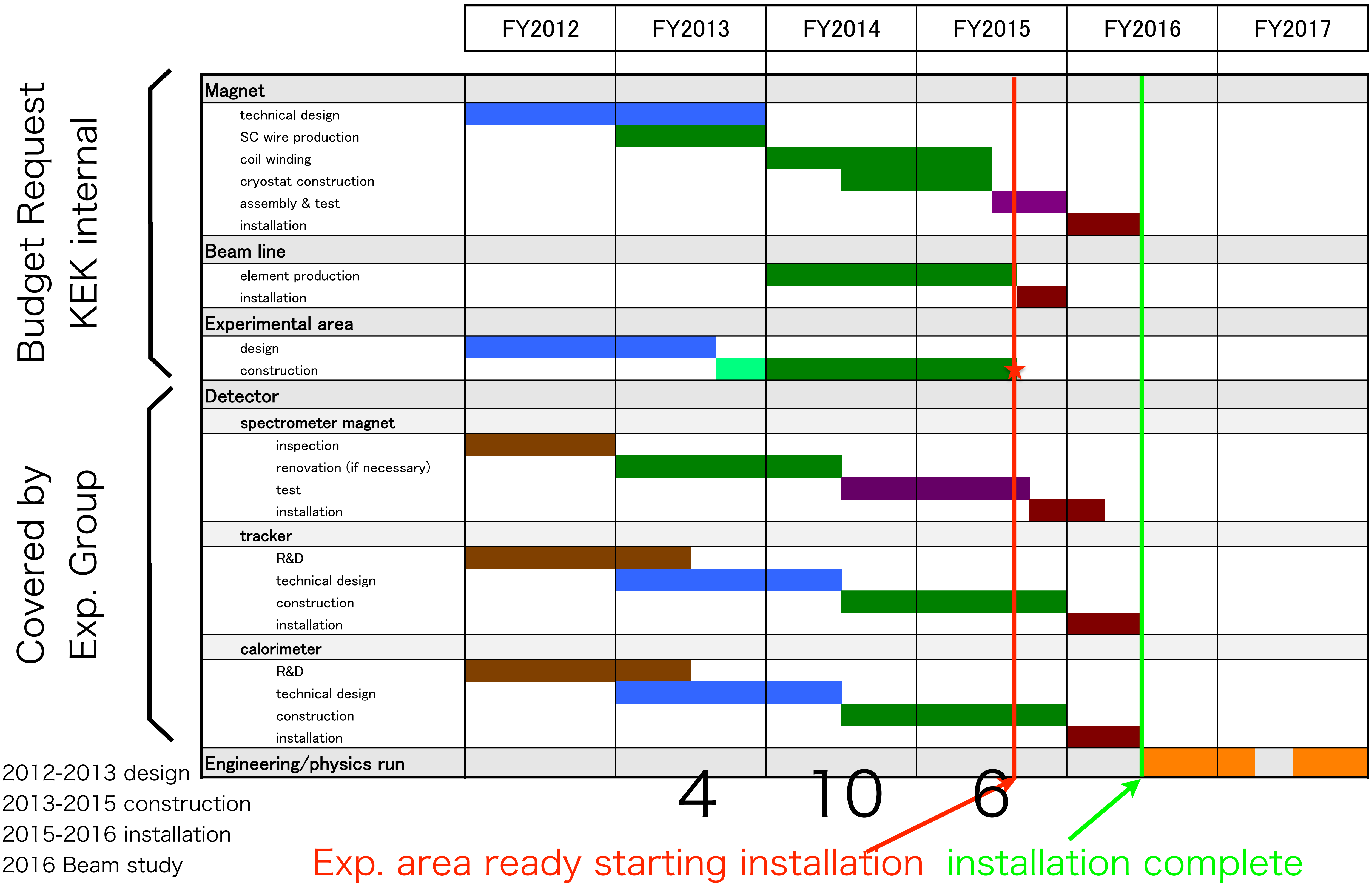
- Building construction in 2013-2015
- High-p beam line installation in 2015 followed by COMET beam line installation in 2016
- Detector installation can be started when the building construction completes







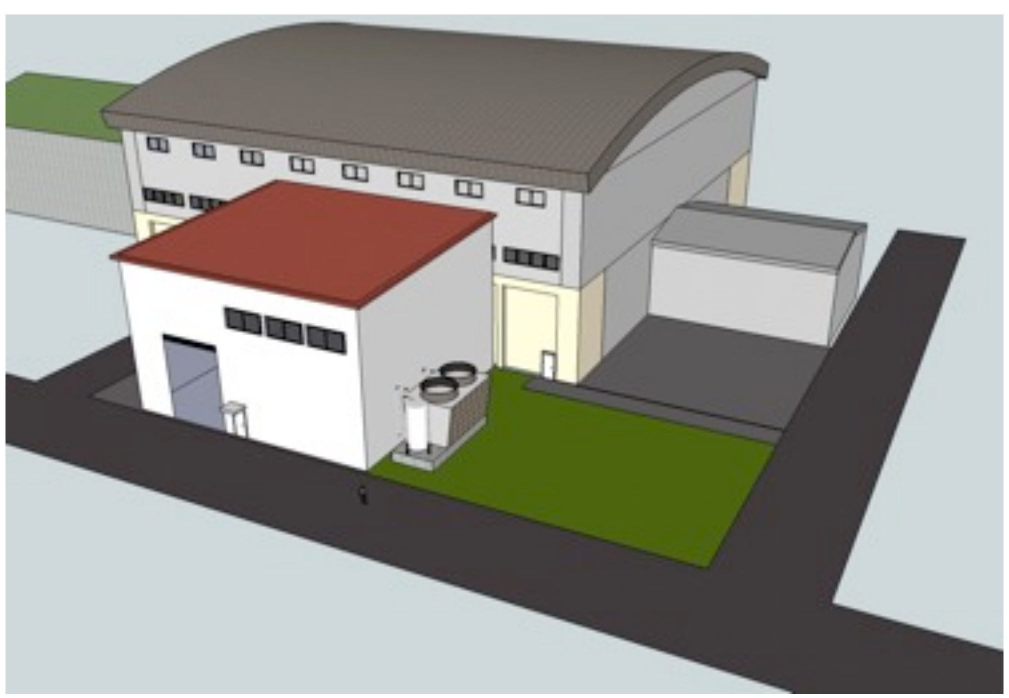
Schedule



2012-2013 design
2013-2015 construction
2015-2016 installation
2016 Beam study
2017 Engineering/physics run

Cost Estimate

- Based on
  - KEK facility department cost estimate
  - Toshiba design
- Budget request 20 Oku JPY includes building, beam line, magnet (up to 1st 90° bend)
- Expect support from J-PARC project budget
- Detector construction by the experiment group by external funding



1 Oku JPY = 1 M €

		Budget request	KEK internal	External funding	Optional	Future funding	Comments
Building		8.0					
Beam dump		1.0	0.5				
SC magnet		8.0					to first 90^o bend
						20.0	remaining beam line
	W shield					2.0	for higher power
Power supply					2.0		if purchased
			0.5				installation
						2.5	for upgrade
refrig-erator					2.0		if constructed
			0.5				installation
Beam line	magnet		0.5				installation
						5.0	for higher power
	piping	0.3	0.3				
	cabling	0.6	0.6				
	vacuum	0.6	0.6				
Radiation shielding	NP-hall	1.5					for 3 kW operation
						6.5	for high power
Safety			0.5				
π target				0.8			experimental group
Detector	magnet		0.5	0.5			for Phase-I
	μ target			0.1			experimental group
	μ monitor			1.5			experimental group
	tracker			1.1			experimental group
	ECAL			1.6			experimental group
	CR veto			5.7			experimental group
	DAQ			0.5			experimental group
Total		20.0	4.5	11.8	4.0	36.0	72.3+4.0

Building 9.5 Oku

Magnet 9 Oku

Beam Line 6.3 Oku

Detector 11.5 Oku

Budget request 20 Oku

J-PARC project budget 4.5 Oku

experiment group 11.8 Oku

COMET Phase-I Proto-collaboration

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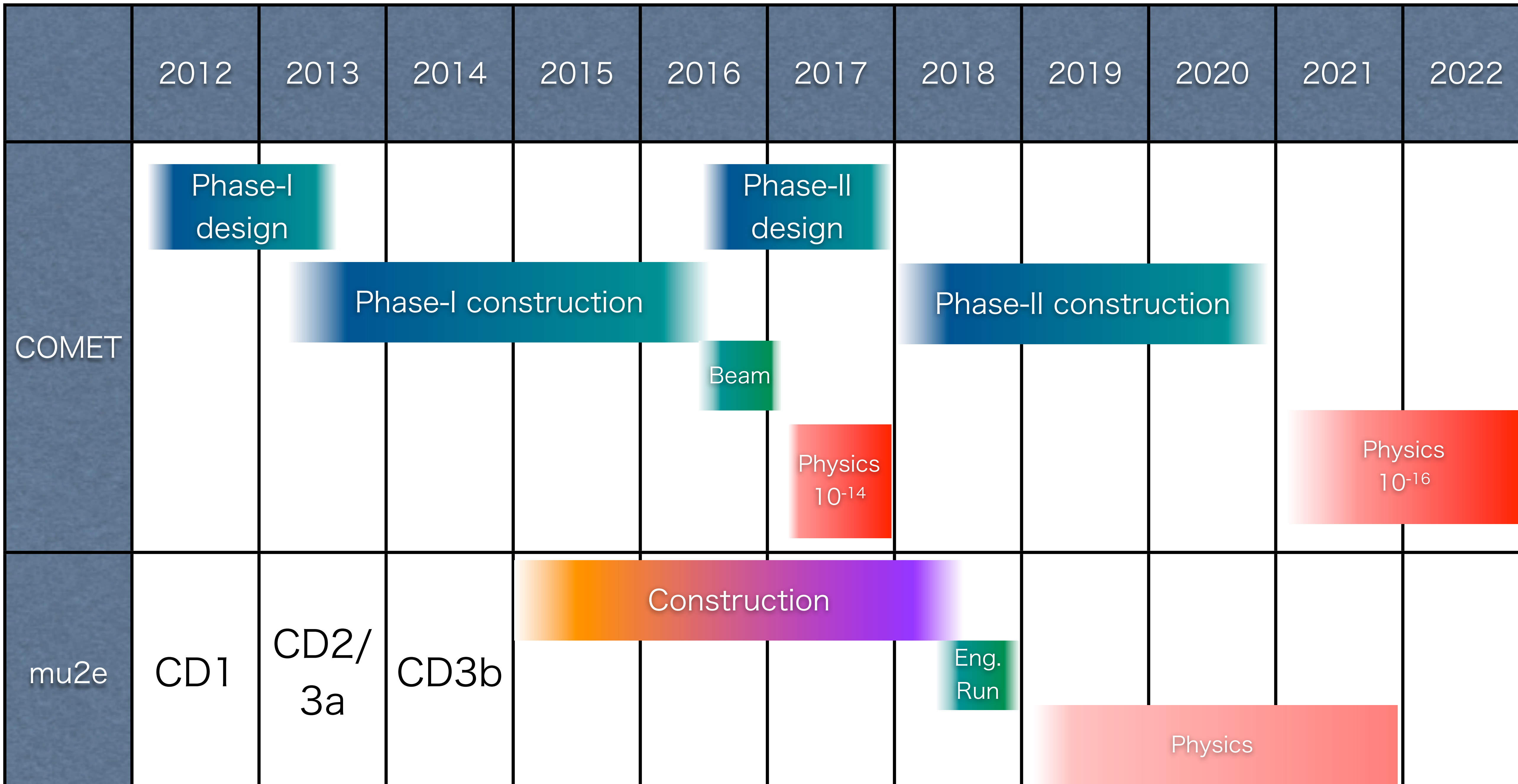
TRIUMF, Canada

- 107 collaborators
- 25 institutes
- 11 countries

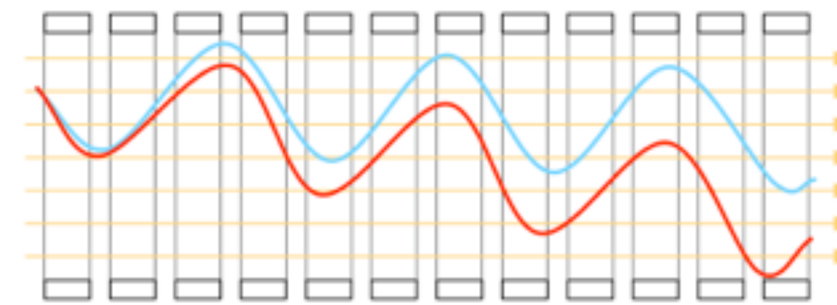
Summary

- COMET Staging Plan
- Phase-I
    - Experimental area and beam line construction up to the end of the 1st 90 degree bend
    - Beam background study with an actual setup
        - better understanding of background
    - μ-e conversion search with an intermediate sensitivity
        - step to the final goal 10^{-16}
        - Sensitivity of 7×10^{-15} (90% C.L. upper limit) foreseen
    - Start running 2016 (if funding starts in 2013)
- Phase-II
    - Beam line upgrade/Spectrometer upgrade/50kW accelerator power

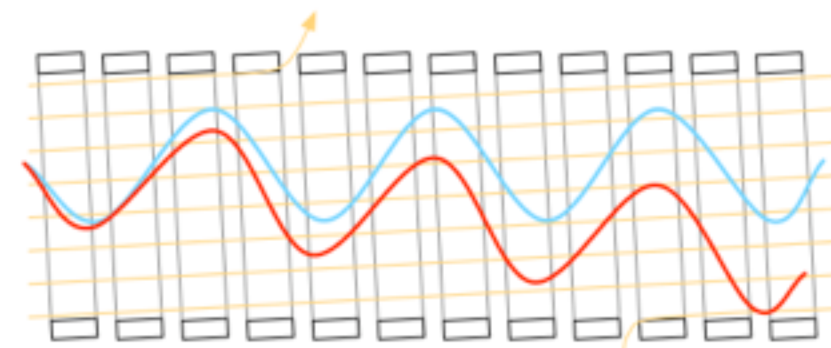
COMET vs mu2e



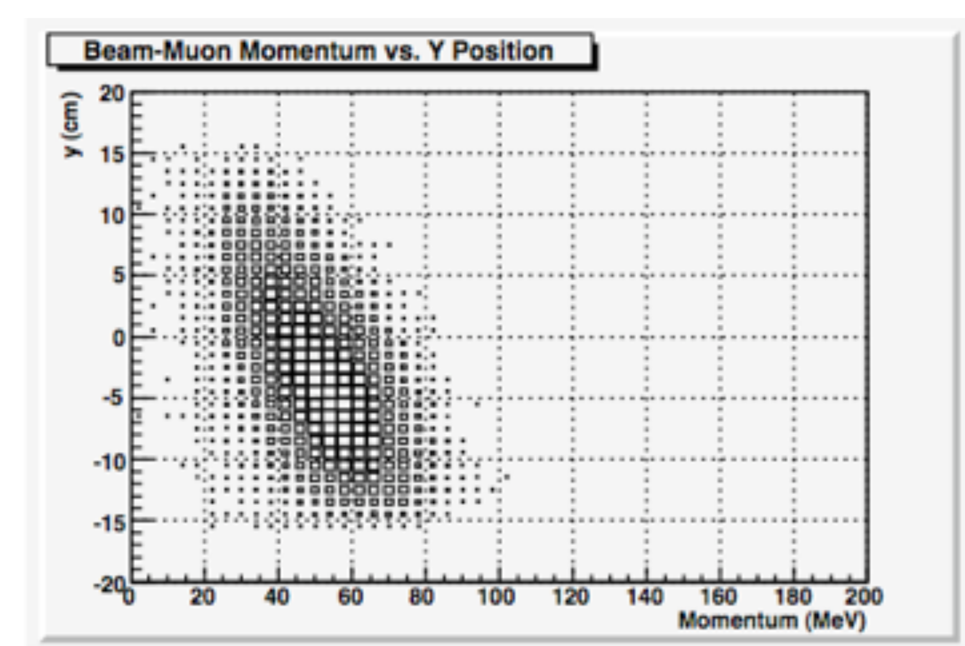
High-p Suppression



- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by



  - This effect can be used for charge and momentum selection.



$\delta p / \delta x$ = 1 MeV/c/cm

- This drift can be compensated by an auxiliary field parallel to the drift direction

Extinction Measurement Result

- Normal beam injection to MR
- Integration over 20 minutes
- Extinction level at $(5.4 \pm 0.6) \times 10^{-7}$