Search for μ-e Conversion : COMET at J-PARC

- Staging approach -

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25+5 min

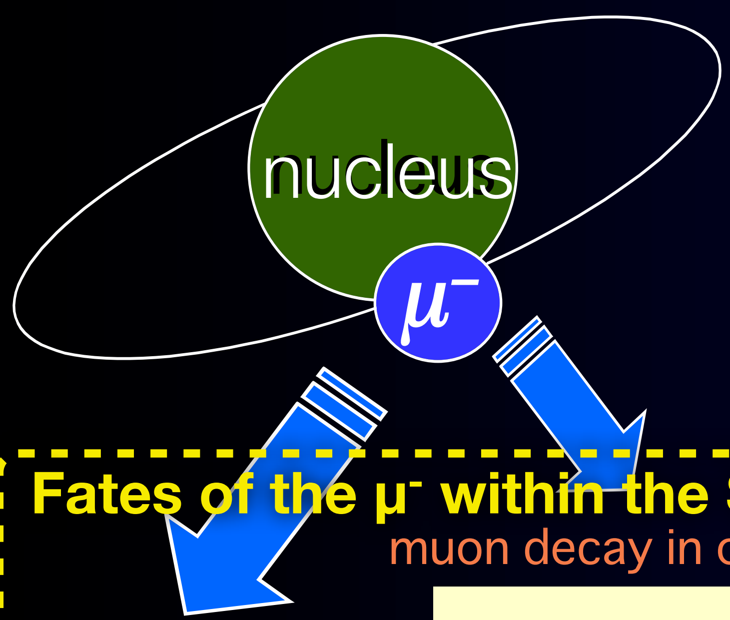
Outline

- Overview of μ-e conversion
- COMET staging approach
- COMET Phase-I
- R&D progress
  - Results of extinction measurement
- Summary

μ-e Conversion Search

- Two experiments are going to start to search for the μ-e conversion process: COMET@J-PARC and Mu2e@FNAL.
- These are stopped muon experiments. When a μ^- in stopped in a material, ...

1s state in a muonic atom



Fates of the μ^- within the SM

muon decay in orbit

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

nuclear muon capture

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

Beyond the SM

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

μ-e conversion

Forbidden by the SM, because
the lepton flavor is changed to μ-flavor to e-flavor.

Event signature :

a single mono-energetic electron of 100MeV

in the SM + ν masses

μ-e conversion can be occur via ν-mixing, but expected rate is well below the experimentally accessible range. Rate ~$O(10^{-54})$

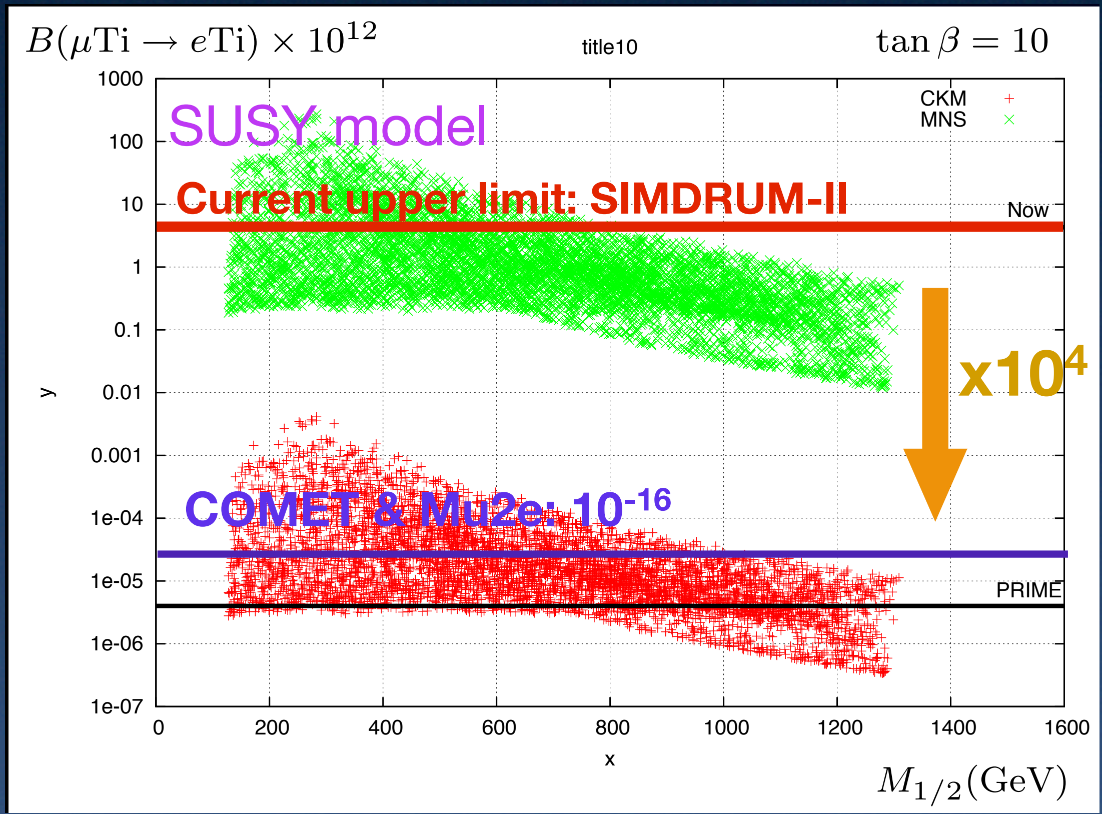
Discovery of the μ-e conversion is a clear evidence of new physics beyond the SM.

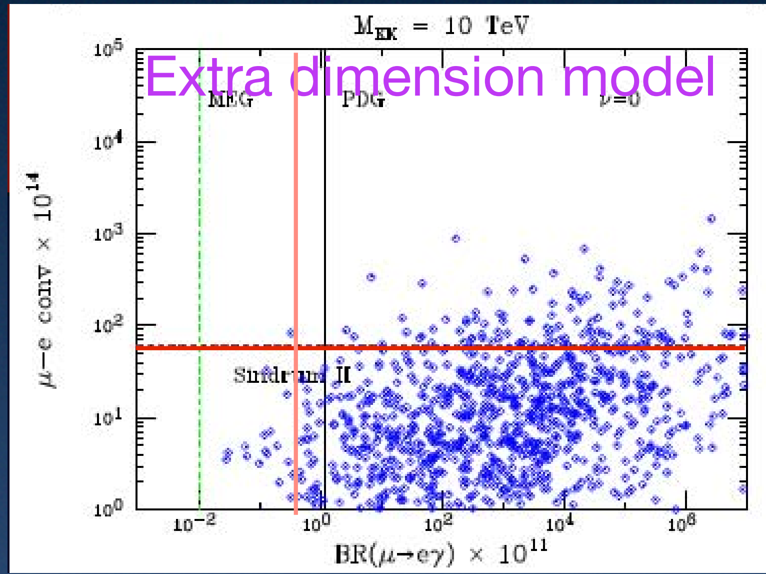
in the SM + new physics

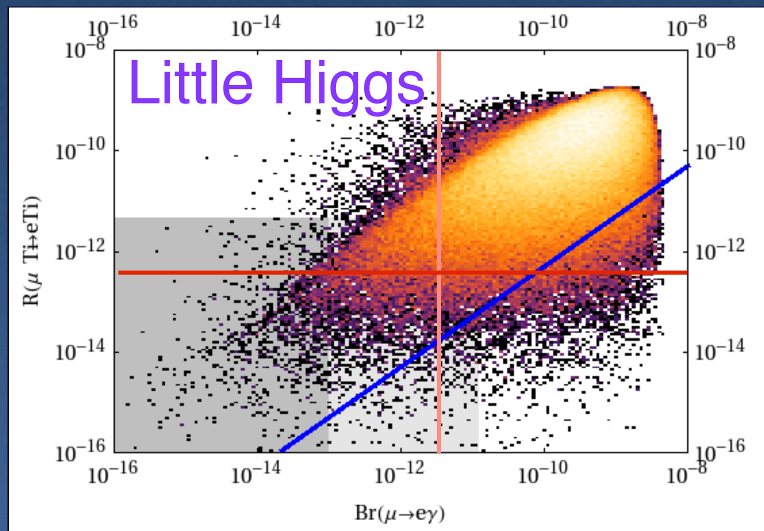
A wide variety of proposed extensions to the SM predict observable μ-e conversion rate.

μ-e Conversion Predictions

- Various beyond the SM models predict sizable **μ**-e conversion.

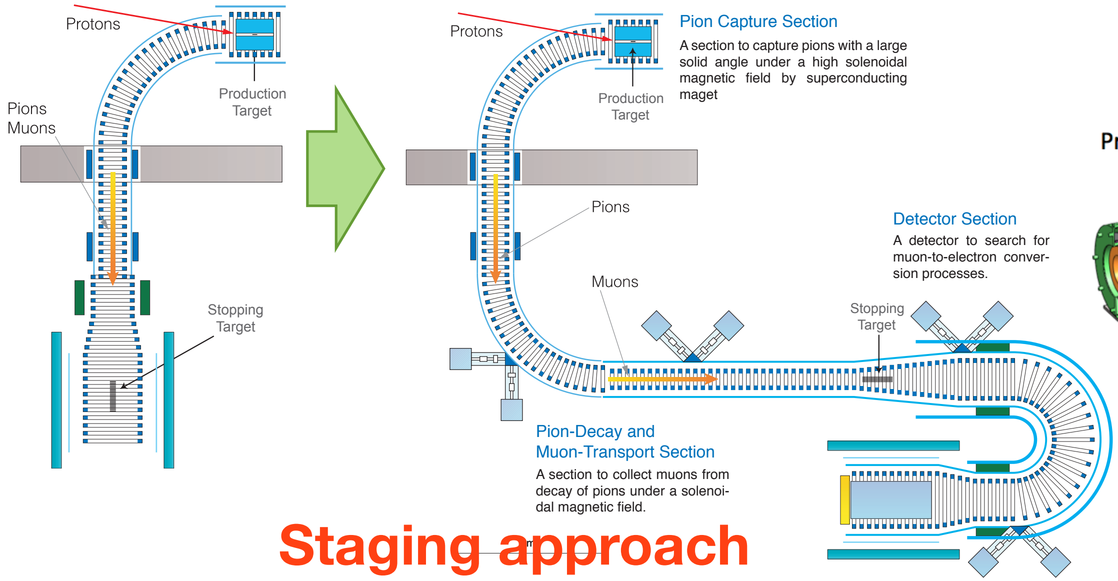


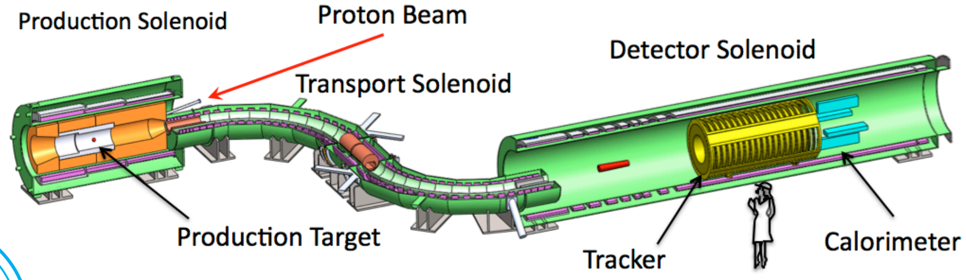




COMET @J-PARC

Mu2e @FNAL





Staging approach

COMET Phase-I :

physics run 2017-

BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL

*8GeV-3.2kW proton beam, 12 days

*90deg. bend solenoid, cylindrical detector

*Background study for the phase2

COMET Phase-II :

physics run 2019-

BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL

*8GeV-56kW proton beam, 2 years

*180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter

Mu2e :

physics run 2019-

BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL

*8GeV-8kW proton beam, 3 years

*2x90deg. S-shape bend solenoid, straw tracker+calorimeter

a factor of 10,000 better sensitivity than the current upper limit (SINDRUM II)

- COMET Phase-I
  - **has a strong endorsement from J-PARC**
    - ”COMET is a high priority component for the J-PARC program.” (KEK/J-PARC-PAC March/2012)
      - The IPNS proposed, as the first priority item in the next 5-year plan, to construct a proton beam line and the 1st half of solenoid magnets for COMET Phase-I. The PAC endorsed the laboratory plan.
    - **Proposal has been submitted to J-PARC PAC (July 2012)**
    - **Construction will be started from 2013.**
- COMET Phase-II
  - **Stage-1 approved by J-PARC PAC in 2009.**

Status of COMET project

- We have submitted a LOI of a staging plan and ap roposal of Phase-I to the J-PARC PAC.
  - **COMET Phase-I: A proposal has been submitted (July 2012)**
    - $B(\mu+Al \rightarrow e+Al) < 7 \times 10^{-15}$ @ 90%CL
      - 8GeV-3.2kW proton beam, 12 days
      - 90deg. bend solenoid, cylindrical detector
    - Background study for the phase2
  - **COMET Phase-II: Stage-1 approved (2009)**
    - $B(\mu+Al \rightarrow e+Al) < 6 \times 10^{-17}$ @ 90%CL
      - 8GeV-56kW proton beam, 2 years
      - 180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter
- After a discussion in the last PAC meeting (16-17, March, 2012), We got a strong recommendation from the J-PARC-PAC.
  - ”COMET is a high priority component for the J-PARC program.” (KEK/J-PARC-PAC March/2012)
  - The IPNS proposed, as the first priority item in the next 5-year plan, to construct a proton beam line and the 1st half of solenoid magnets for COMET Phase-I. The PAC endorsed the laboratory plan.
- **J-PARC plans to submit a budget request to the Ministry of Education, Culture, Sports, Science and Technology, the budget includes 20M-USD(1USD=100JPY) for the COMET-phase1.**
- **The construction will be started from 2013.**

COMET Collaboration

The COMET Collaboration

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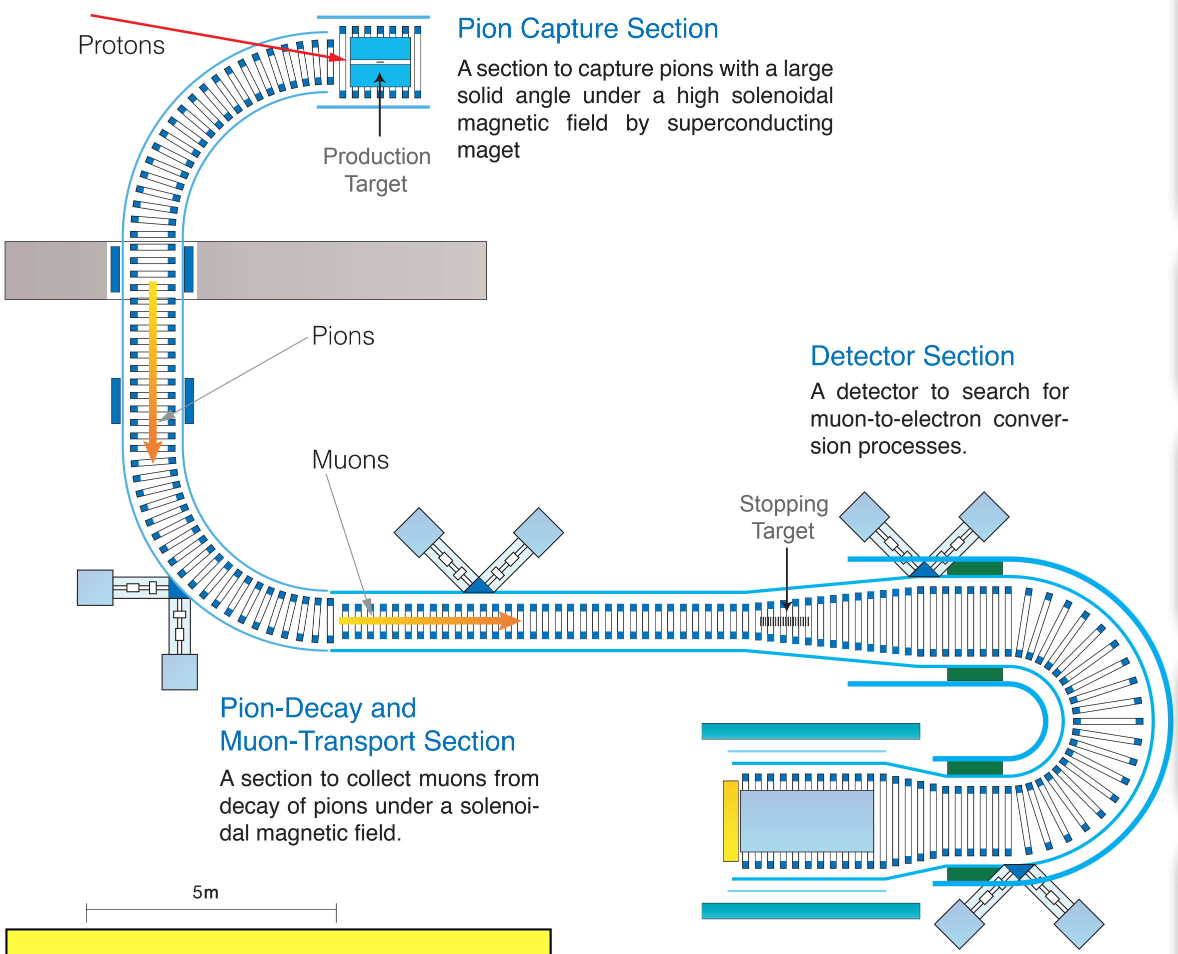
Key Points of COMET(S.E.S 10^{-17})



COMET Phase-II :

physics run 2019-

BR(μ+Al→e+Al)<6×10^{-17} @ 90%CL

*8GeV-56kW proton beam, 2 years

*180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter

Details in a NuFact09 talk by A. Sato

Intense Pulsed Proton Beam
8GeV-56kW (2×10^{7} sec)
width~100ns, separation>1μs
Extinction level < 10^{9} **reduce beam related BG**

Pion Capture Solenoid
5T superconducting **10^{11} μ^{-}/sec**

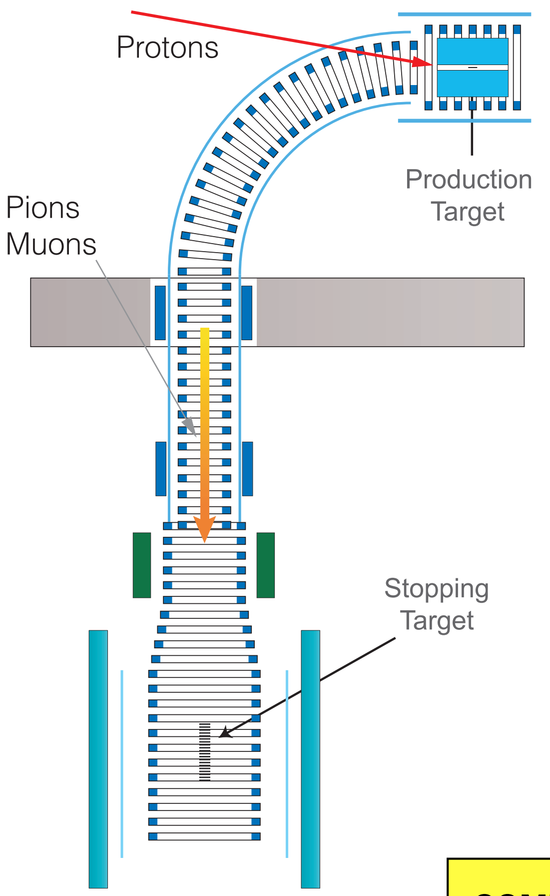
Long Transport Solenoid
L >10m
Curved 180deg Solenoid
eliminate energetic μ (>75 MeV/c) and pions

Thin Stopping Target
Al 200μm x 17
improve e^{-} energy resolution

Electron Spectrometer
Curved Solenoid **reduce detector hit rate**

Low-mass Tracker
Straw chamber in Vacuum
improve e^{-} energy resolution

Key Points of COMET(S.E.S 10^{-17})



COMET Phase-I :

physics run 2017-

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Intense Pulsed Proton Beam
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Thin Stopping Target
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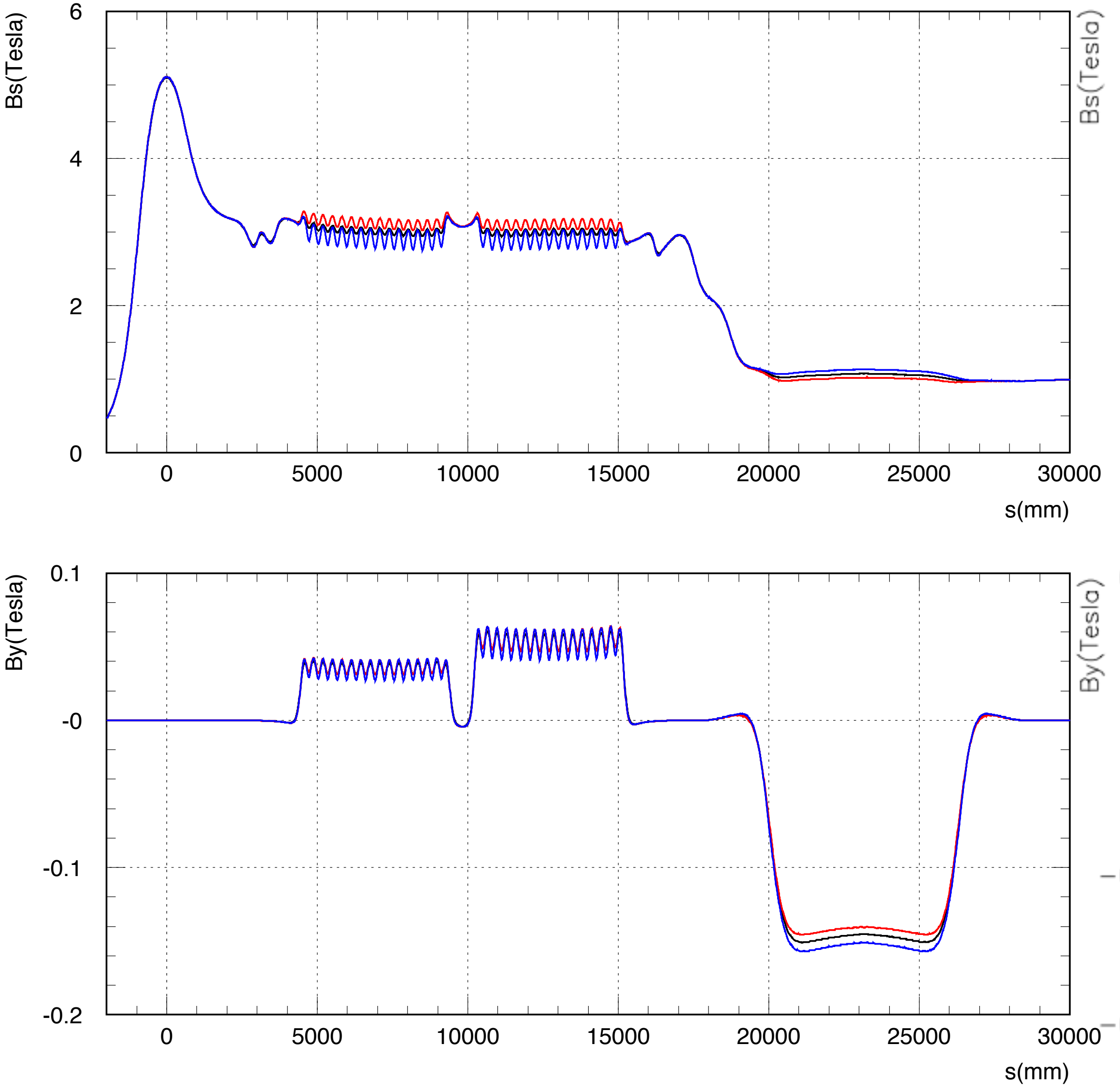
Electron Spectrometer
Curved Solenoid

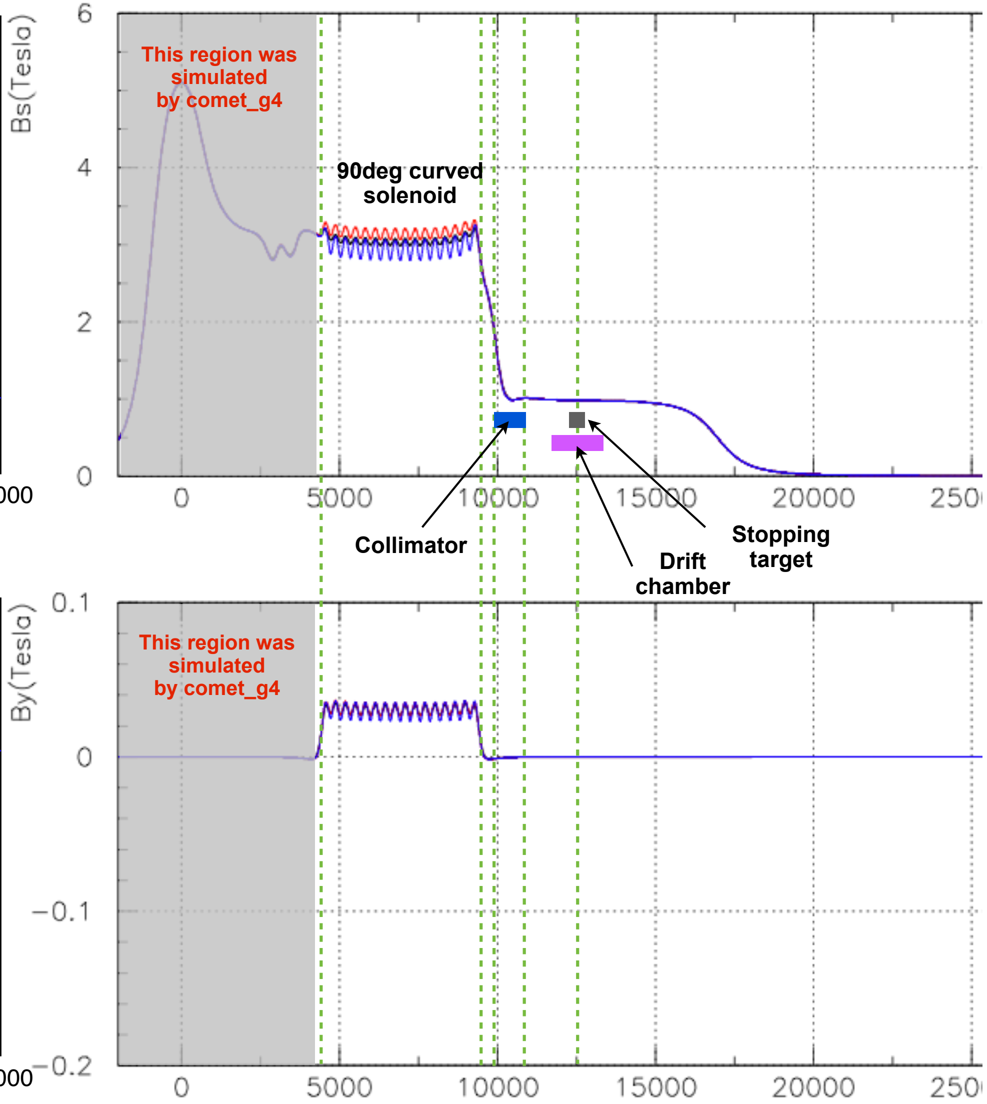
Low-mass Tracker
Cylindrical drift chamber

Magnetic Fields

COMET Phase-II



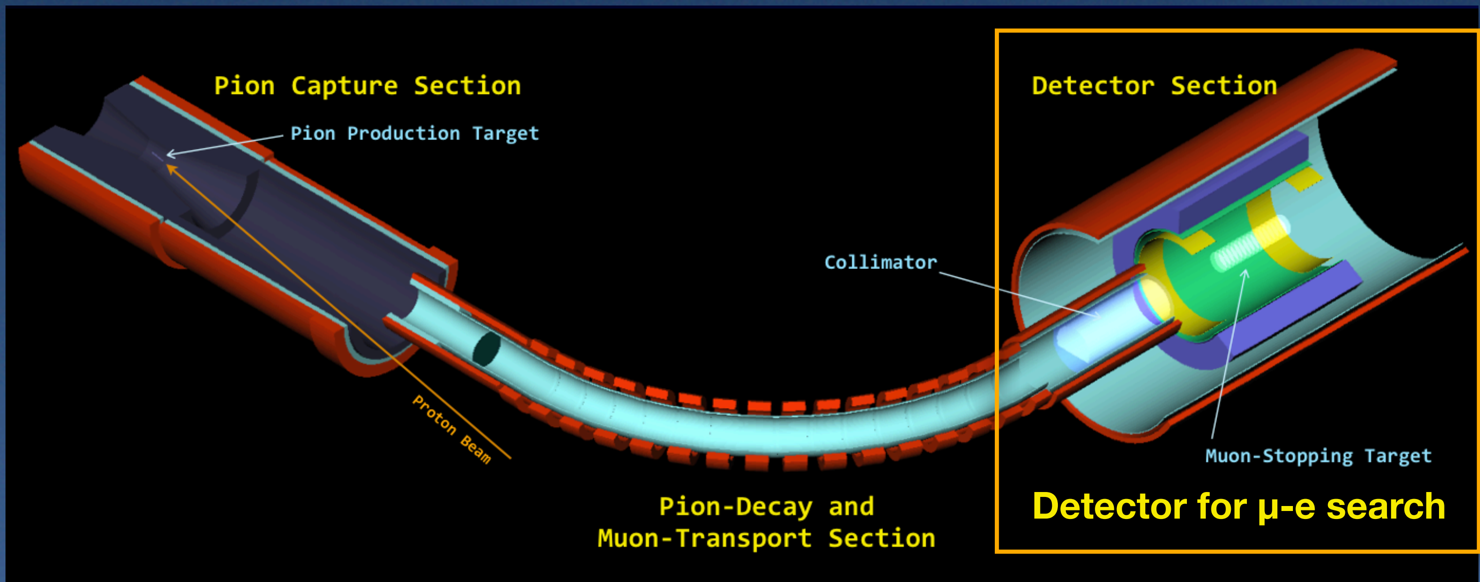
COMET Phase-I

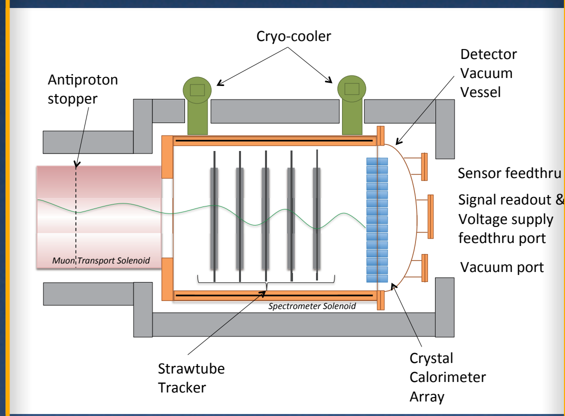


COMET Phase-I Overview

Goal of COMET Phase-I

- **Background Study for COMET Phase-II**
  - direct measurement of potential background sources for the full COMET experiment by using the actual COMET beamline constructed at Phase-I
- **Search for μ-e conversion**
  - a search for $\mu^- - e^-$ conversion at intermediate sensitivity which would be more than 100 times better than the SINDRUM-II limit



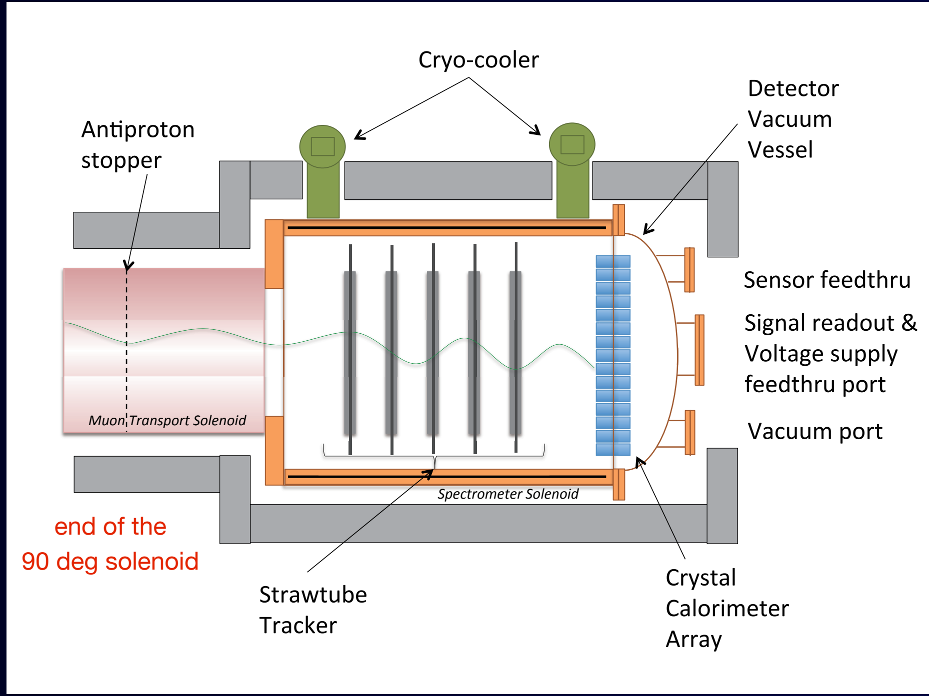


Detector for BG study

Background Study

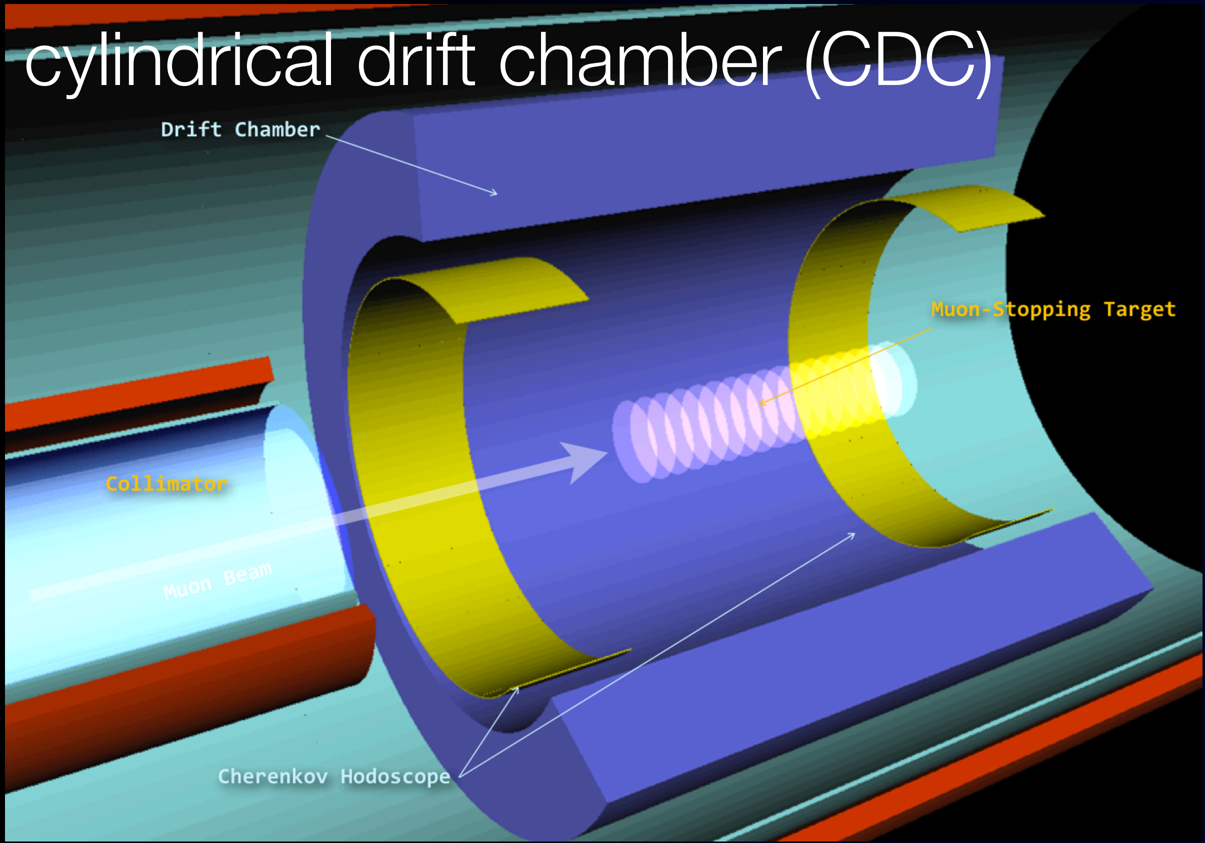
- measure almost all background schematic layout
- sources
  - muons, pions, electrons, neutrons, antiprotons, photons
- same detector technology used in COMET Phase-II
  - SC spectrometer solenoid
  - straw tube transverse tracker
  - crystal calorimeter
- particle ID with dE/dX and E/P

schematic layout



aim to know the known BG &
aim to know the unknown BG

Search for μ-e conversion at Intermediate Sensitivity (CDC case)



Design Philosophy
by keeping an open end in a solenoid geometry, beam particles continue downstream and escape the detector.

- CDC design is based on Belle II CDC (small cell part)
- Design difference (from LOI)
  - He:C_2H_6 (=50:50) gas
  - trigger counters at the both ends (smaller acceptance)
  - no proton absorber
- CDC hit rates
  - 40 kHz/wire at the innermost layer by proton emission from muon capture (0.15 per capture)
- CDC trigger rate
  - 270 Hz from DIO

S.E.S. for COMET Phase-I

- Single event sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- N_μ is a number of stopping muons in the muon stopping target. It is $8.7\text{x}10^{15}$ muons.
- $5.8\text{x}10^9$ stopped μ/s with 3 kW proton beam power, with $1.5\text{x}10^6$ sec running.
- f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
- A_e is the detector acceptance, which is 0.06.

Event selection	Value	Comments
Geometrical acceptance	0.24	tracking efficiency included
Momentum selection	0.74	104.1 MeV/c < P_e <106 MeV/c
Timing selection	0.39	same as COMET
Trigger and DAQ	0.9	same as COMET
Total	0.06	

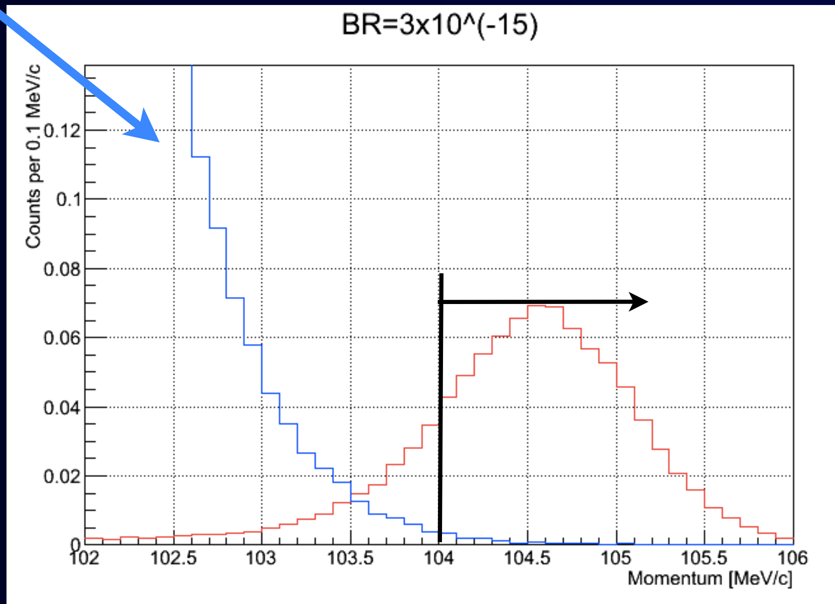
$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15}$$

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

Backgrounds for COMET Phase-I

Background	estimated events
Muon decay in orbit	0.01
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.0096*
Beam electrons Muon decay in flight Pion decay in flight	< 0.00048*
Neutron induced background	~ 0*
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Electrons from cosmic ray muons	< 0.0002
Total	0.03

DIO



with proton extinction factor of 3×10^{-11}

Expected BG events are about 0.03 at S.E.S. of 3×10^{-15}.

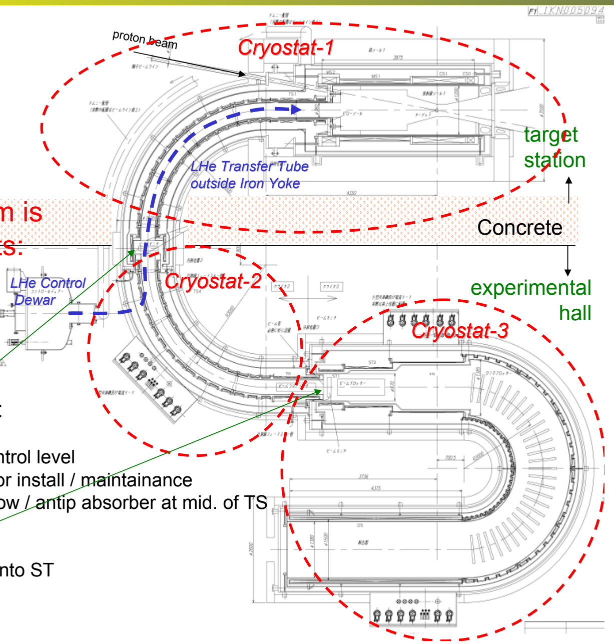
R&D for COMET

R&Ds

COMET Magnet Design

The magnet system is separated in 3 parts:

Cryostat-1: CS+UpstreamTS
Cryostat-2: DownstreamTS
Cryostat-3: ST+SS+DS



Purpose of separation:

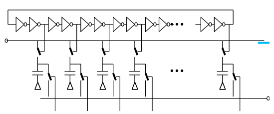
- At concrete wall
  - Different radiation control level
  - Movable Cryostat-2 for install / maintainance
  - Vac. separation window / antip absorber at mid. of TS
  - Beam monitors
- At stopping target
  - inject electron beam into ST
  - Muon beam monitor

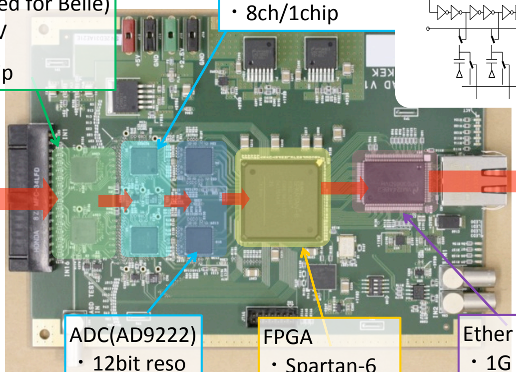
ROESTI Prototype I

- Specifications

Front-end:ASD
(Developed for Belle)
- 1pC → 1V
- 8ch/1chip

Analog Memory (Wave Form Sampling): DRS4
- 1024 Switching capacitor array
- 0.7-5 GSPS
- 8ch/1chip



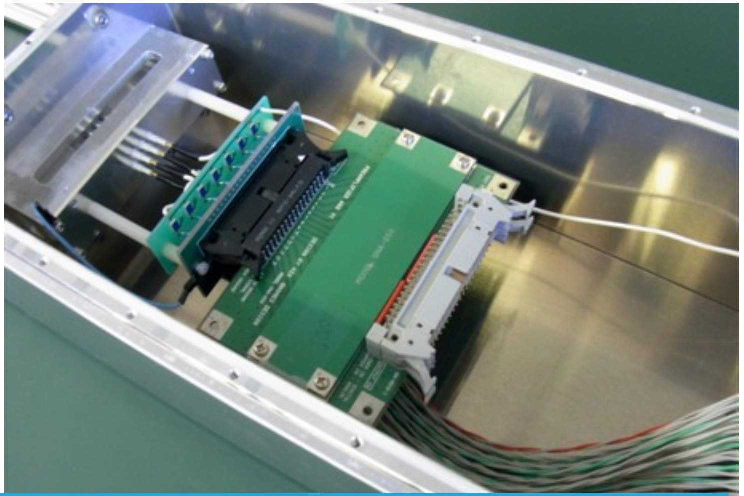


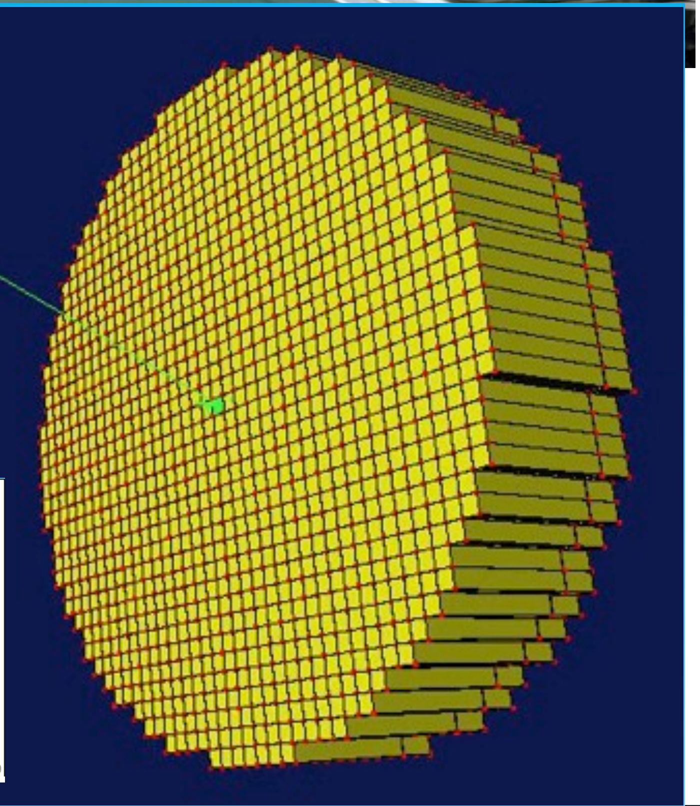
16ch/board

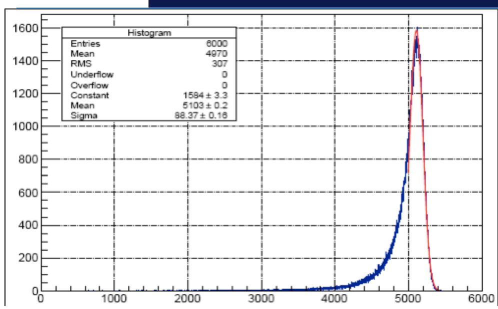
ADC(AD9222)
- 12bit reso
- 8ch/1chip

FPGA
- Spartan-6
(LX100-2fgg676)

Ether Net
- 1G bit/sec
- SiTCP



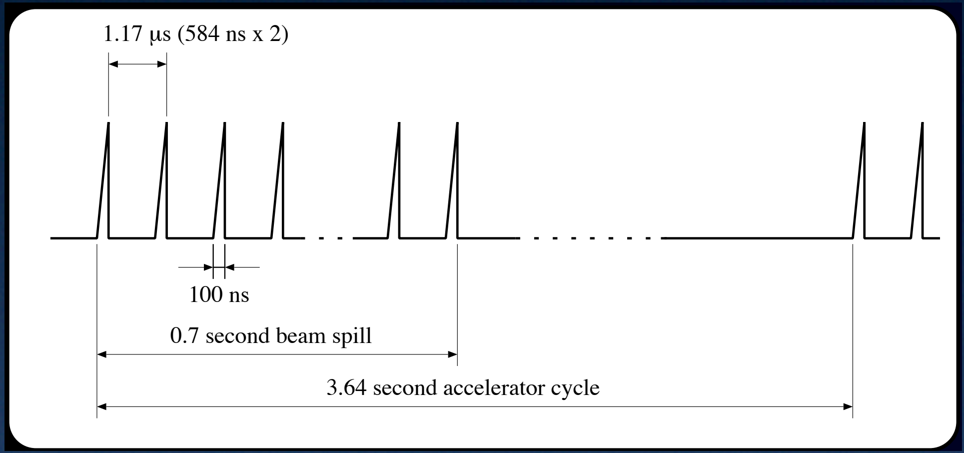


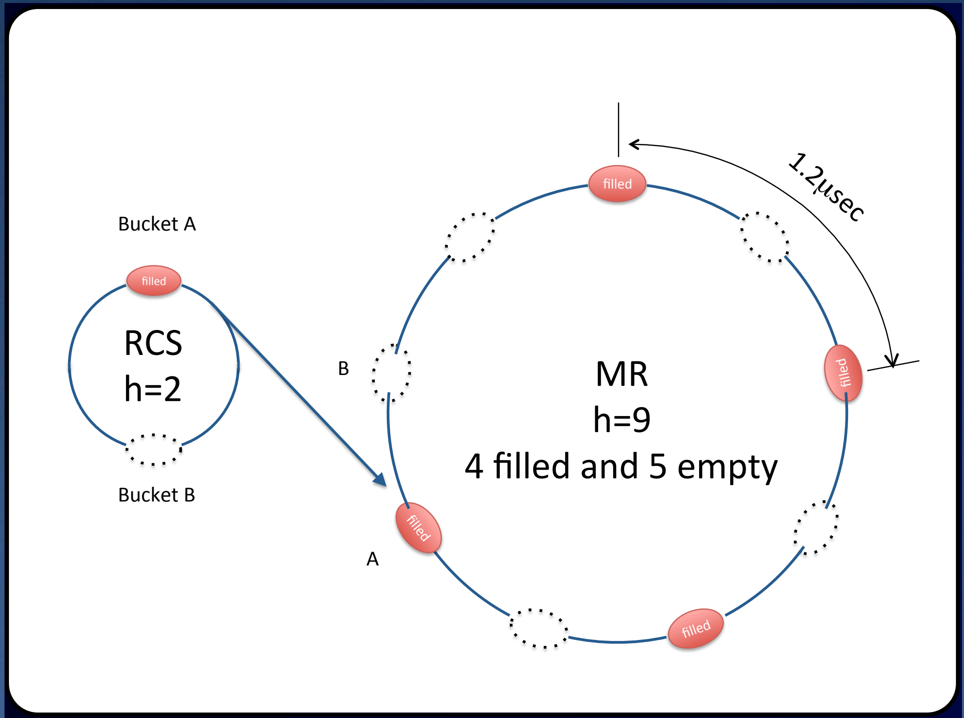


Extinction Measurements at J-PARC MR

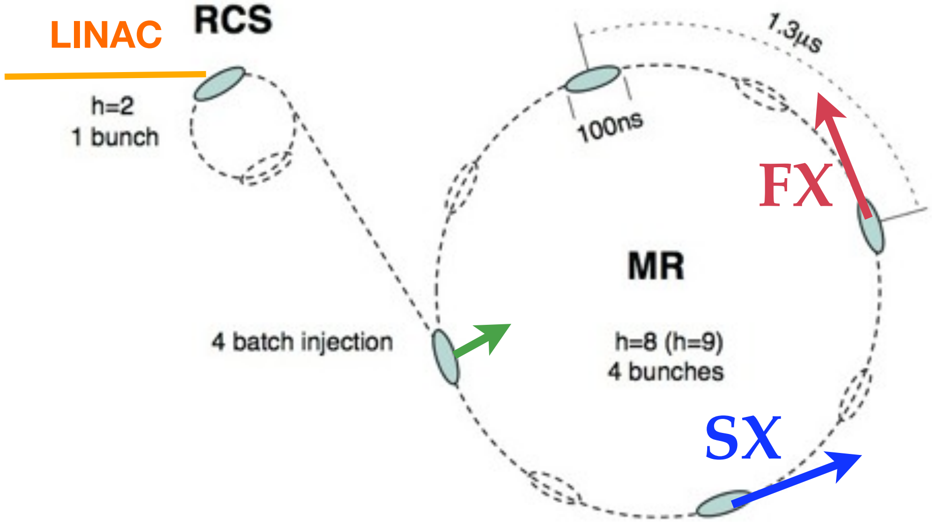
Pulsed Proton Beam at J-PARC

- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams:
  - Pulse separation is ~ 1 μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)
- Pulsed beam from slow extraction.
  - fill every other RF buckets with protons and make slow extraction applying the RF.
  - spill length (flat top) ~ 0.7
- Extinction level is very important!

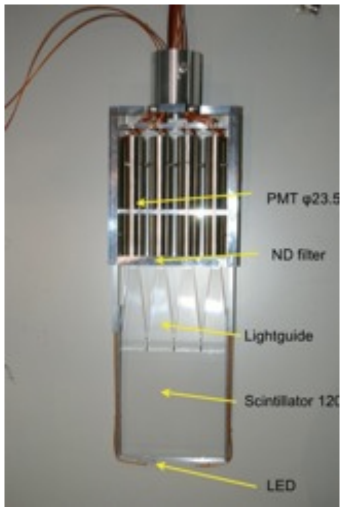




Available Two Measurements



- **FX** : Fast Extraction for Neutrino beam
  - Abort monitor is installed in front of the beam dump to measure extinction
- **SX** : Slow Extraction for Hadron hall
  - By measuring the secondary beam, extinction at hadron hall is measured

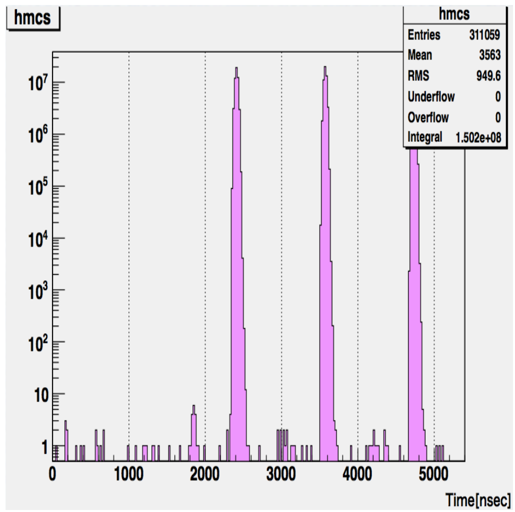


- Last measurement
  - 2010-Dec., @ FX abort line
  - Result:

    Ext. <~ *O*(-7)
- In addition, **double kick injection** method was demonstrated to achieve the required extinction level.

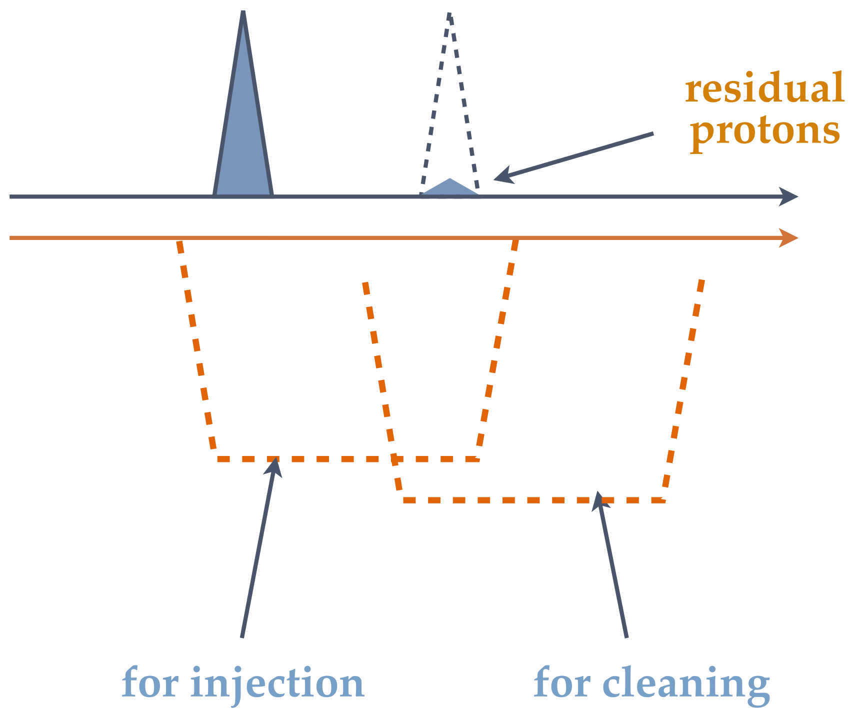
- Last measurement
  - 2010-Oct., @ SX
  - Result:

    Ext. < 5.4×10^{-7}
- w/o any treatment to improve extinction
- Consistent with measurement at abort.



Injection from RCS to the MR

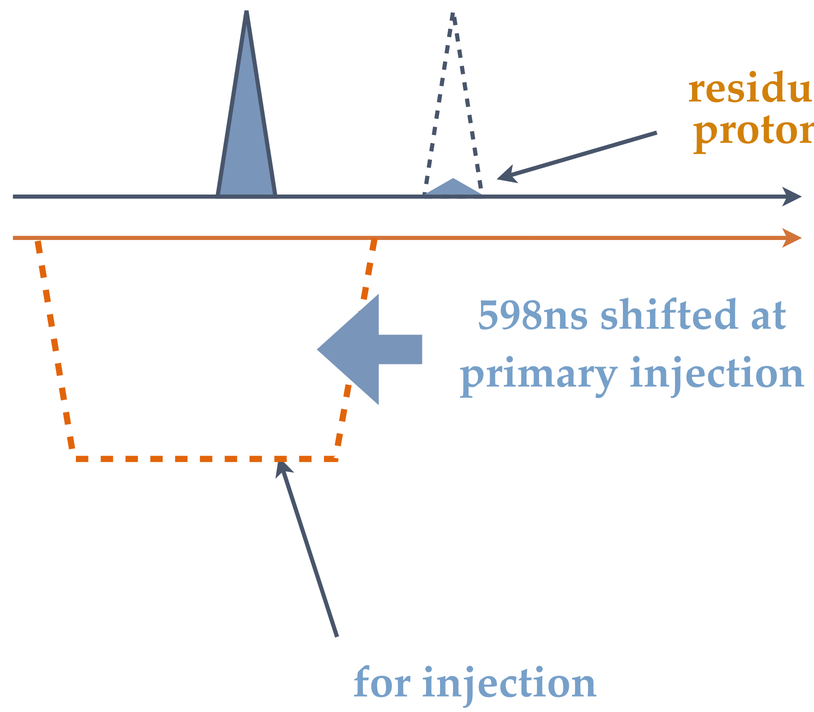
- Double kick injection



- Residual protons are swept away by the secondary kicking which is shifted by 1/2 phase (598ns).
- Not realistic, Need big modification on accelerator (RCS kicker, Injector for MR)

New

- Single bunch kick injection



- By shifting the kicker timing 598ns forward/backward, residual protons are originally not injected into MR.
- Completely empty bucket should be realized !

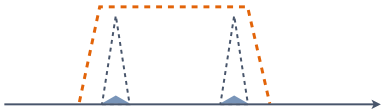
Results

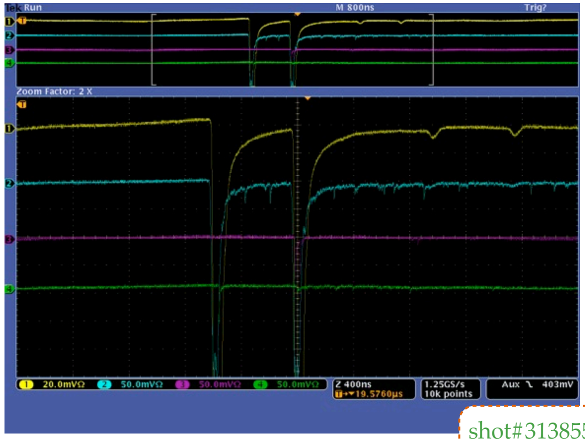
All beam chopped at LINAC

with filled buckets

Double bunch kick

- "all chop", w/o kicker-timing shift



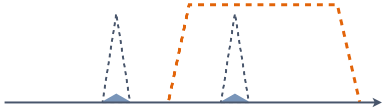


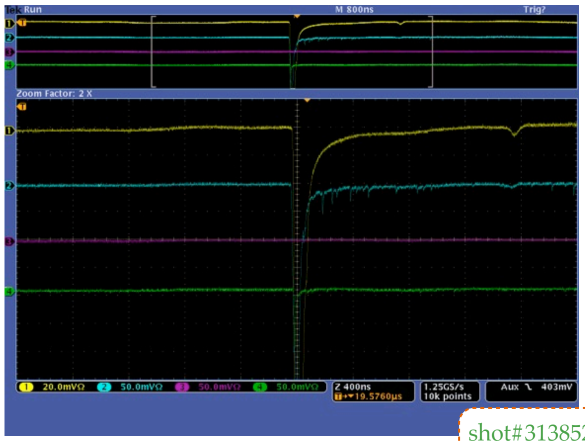
shot#313855

(!) macro pulse width is 0.5ms, thus number of residual protons are 5 times more than before.

Single bunch kick

- all chop, kicker shifted by 1/2 backward





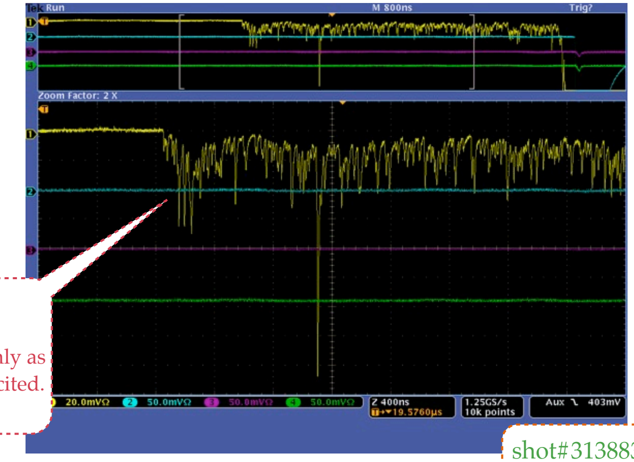
shot#313852

proton leakage after acceleration

1.7×10^{10} proton, Kicker timing is shifted by 1.8μsec (≈1.5 phase)

RF=16kV

many proton leakage



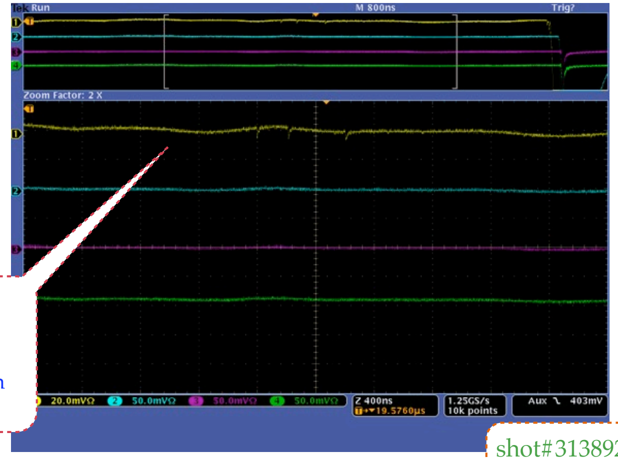
Residuals are distributed uniformly as long as kicker is excited.

shot#313883

Kicker timing is shifted by 1.8μsec (≈1.5 phase)

RF=260kV

only 3 protons observed

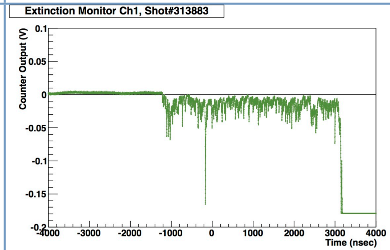
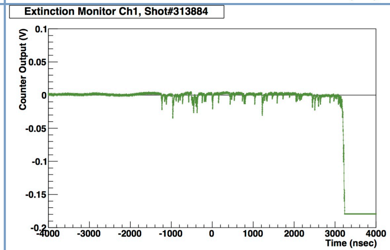
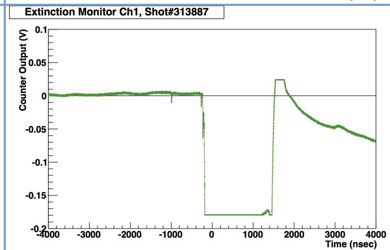
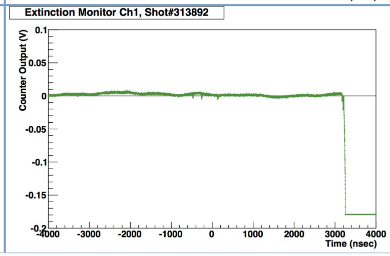


Three protons are remained.
Limit of Extinction

shot#313892

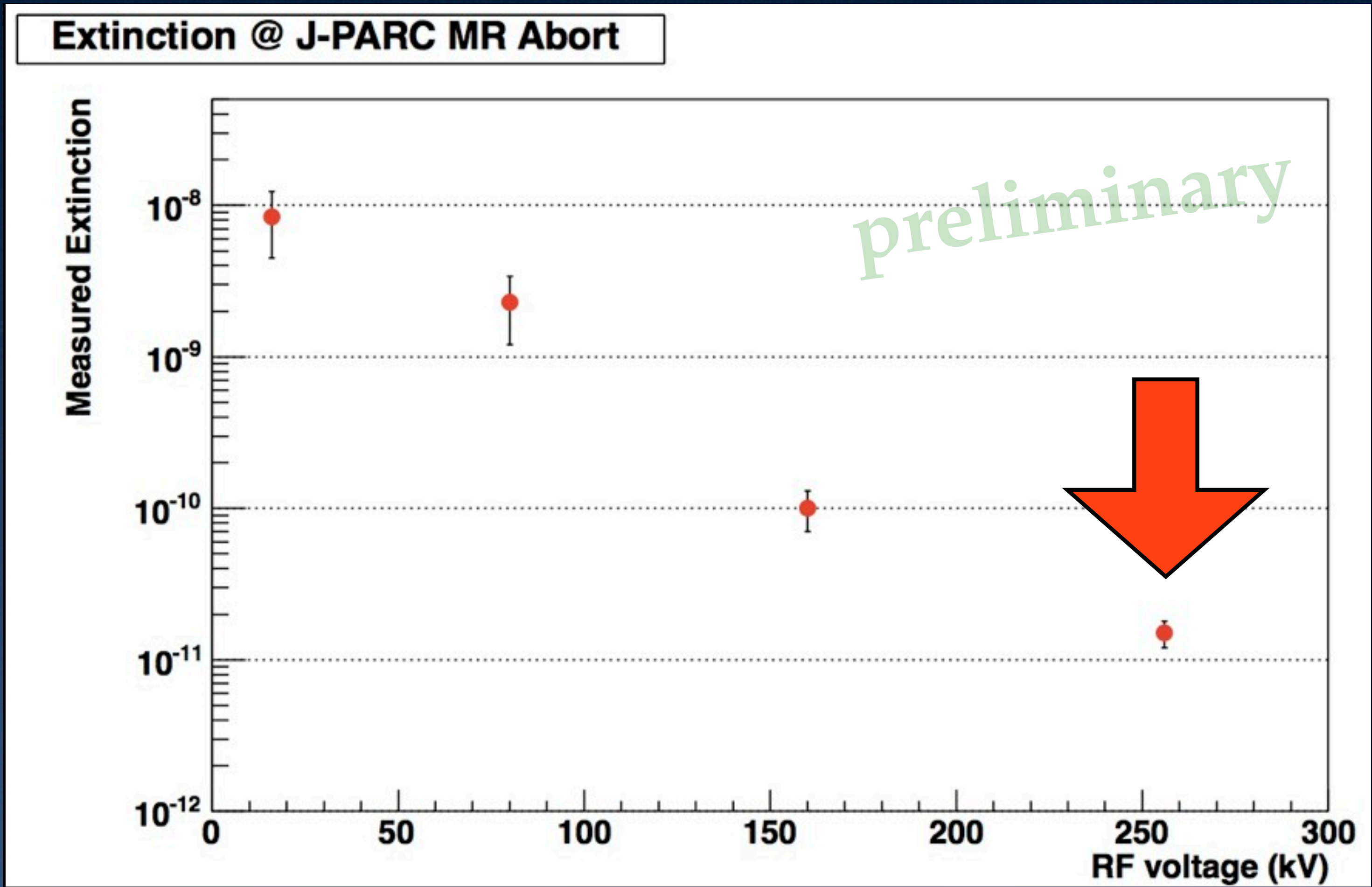
Single bunch kick

Results of Extinction Measurement

Beam Condition	Tuned Intensity	Abort Monitor Output	# of Residual Protons (between bunches)	Extinction
shot# 313883 macro pulse 0.1ms, chop width 25ns, thinner 3/32, kicker delayed 1.8μs, RF 16kV	1.7×10^{10} protons		142.3±19	**8.4×10^{-9}**
shot# 313884 macro pulse 0.1ms, chop width 25ns, thinner 3/32, kicker delayed 1.8μs, RF 80kV	1.7×10^{10} protons		38.8±21	**2.3×10^{-9}**
shot# 313887 macro pulse 0.1ms, chop width 25ns, thinner 32/32, kicker delayed 0.6μs, RF 160kV	1.0×10^{11} protons		10±0.3	**1.0×10^{-10}**
shot# 313892 macro pulse 0.1ms, chop width 25ns, thinner 32/32, kicker delayed 1.8μs, RF 256kV	1.0×10^{11} protons		1.5±0.3	**1.5×10^{-11}**

(Estimated error is **very preliminary**, need DCCT calibration and systematics estimation)

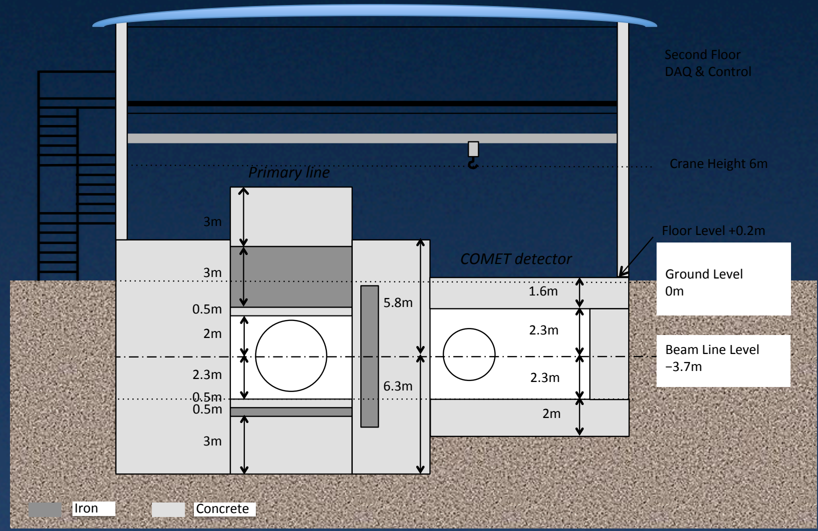
Results of Extinction Measurement (June, 2012)

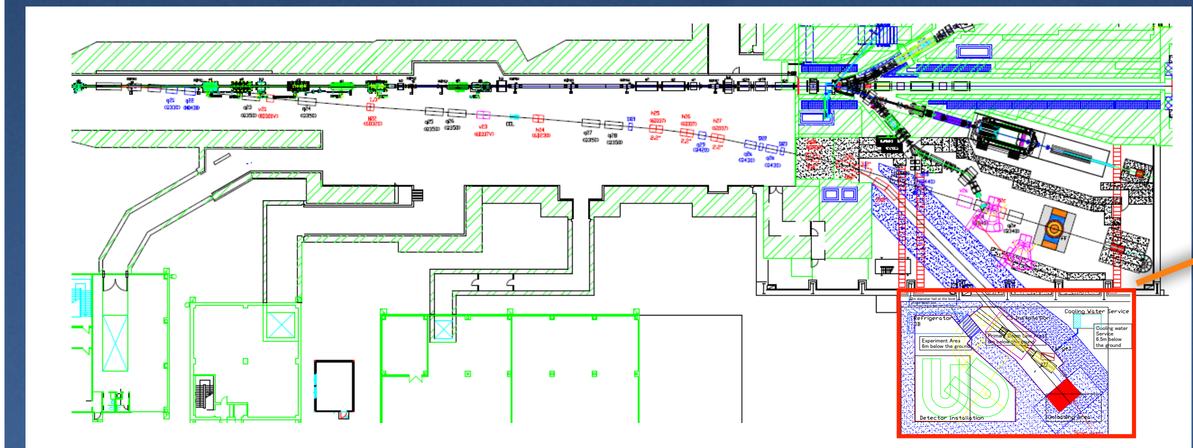


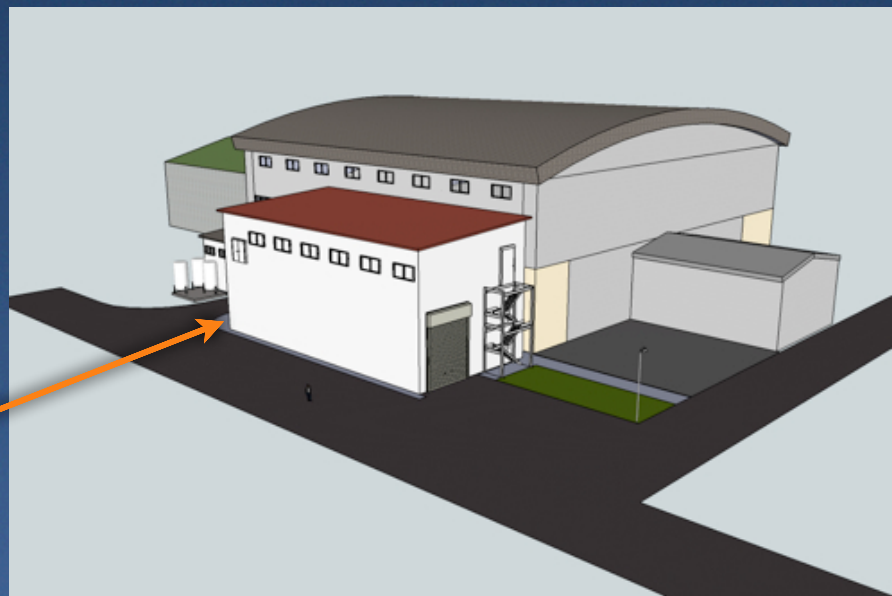
- proton extinction factor of 1.5 x10^{-11} has been achieved.
  - at MR abort line after acceleration up to 30GeV.
- Next step: measurements at SX line.

Facility Construction

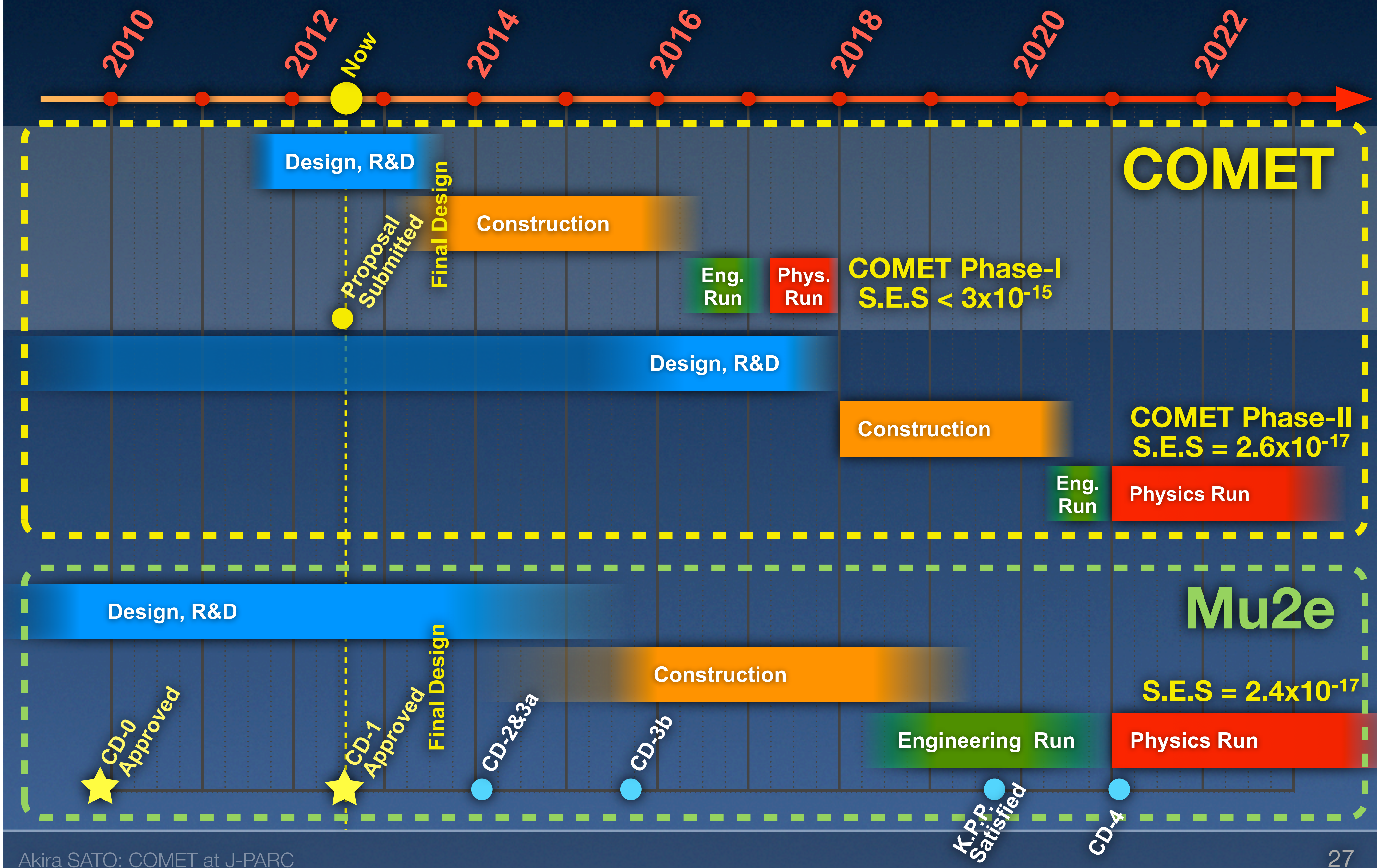
- Design work is in progress
  - Primary proton beam area, and beam line
  - Experimental area
- Ground floor for service/power supply/refrigerator
- Compressor will be installed in a separate building







Schedule of COMET and Mu2e

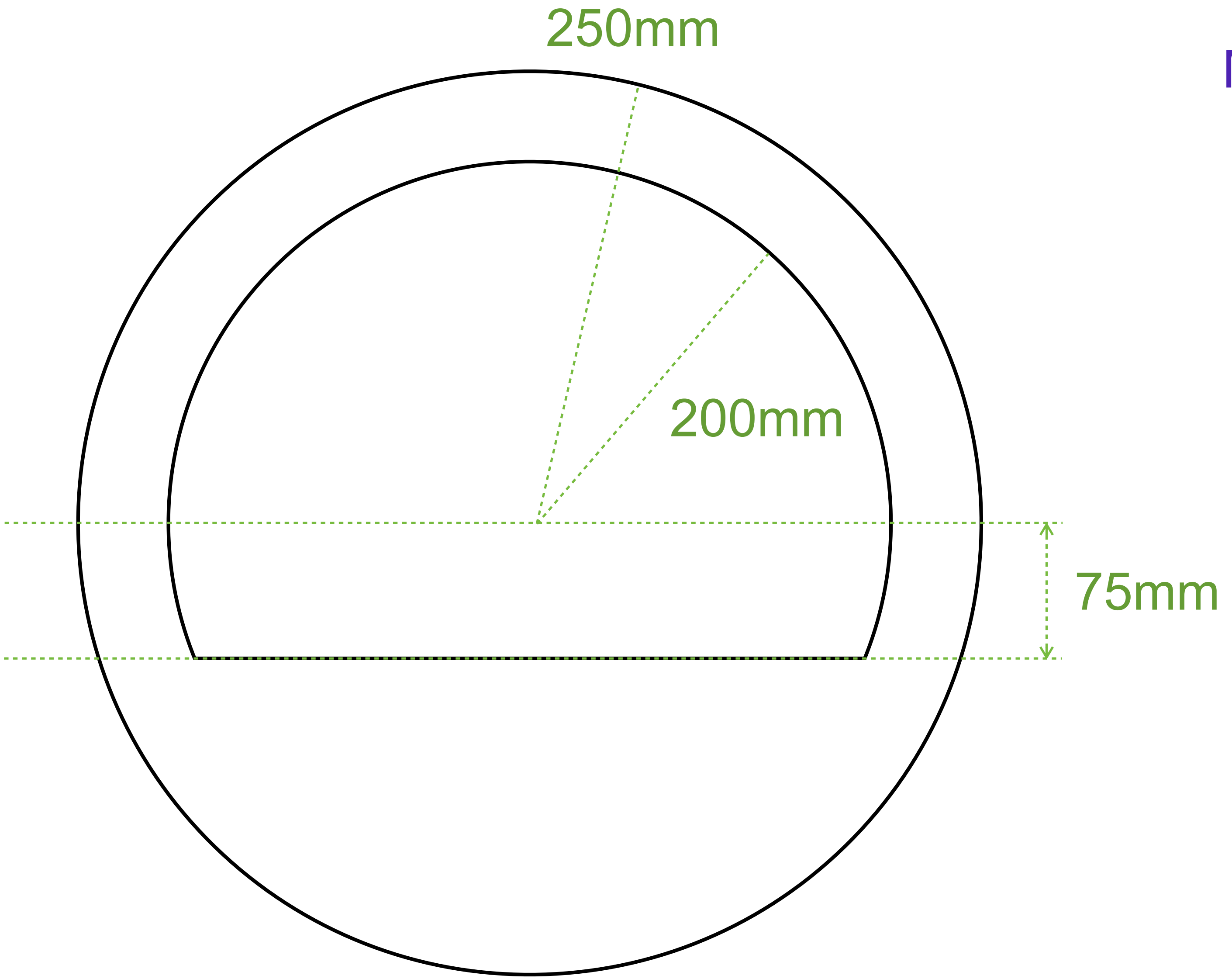


Summary

- COMET is preparing the staging approach for the μ-e conversion search at J-PARC with strong endorsements and supports from KEK/J-PARC.
  - COMET Phase-I: Construction start from 2013
    - $B(\mu+Al \rightarrow e+Al) < 7\times10^{-15}$ @ 90%CL
      - 8GeV-3.2kW proton beam, 12 days
      - 90deg. bend solenoid, cylindrical detector
    - Background study for the phase2
      - transverse tracker+calorimeter
  - COMET Phase-II: Stage-1 approved (2009)
    - $B(\mu+Al \rightarrow e+Al) < 6\times10^{-17}$ @ 90%CL
      - 8GeV-56kW proton beam, 2 years
      - 180deg. bend solenoid, bend spectrometer, transverse tracker +calorimeter

Backup Slides

Collimator

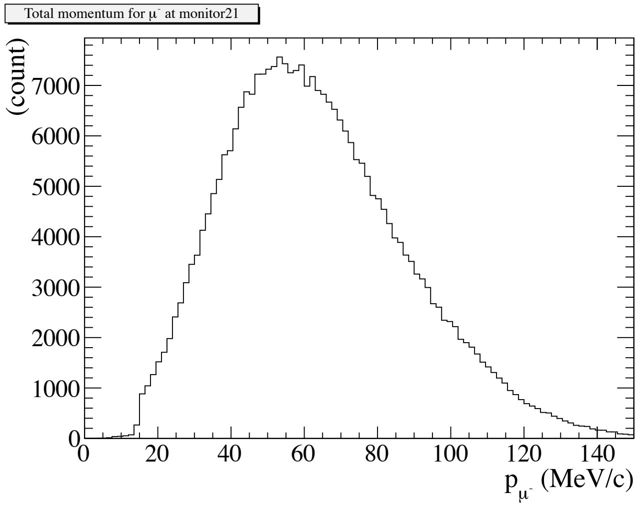


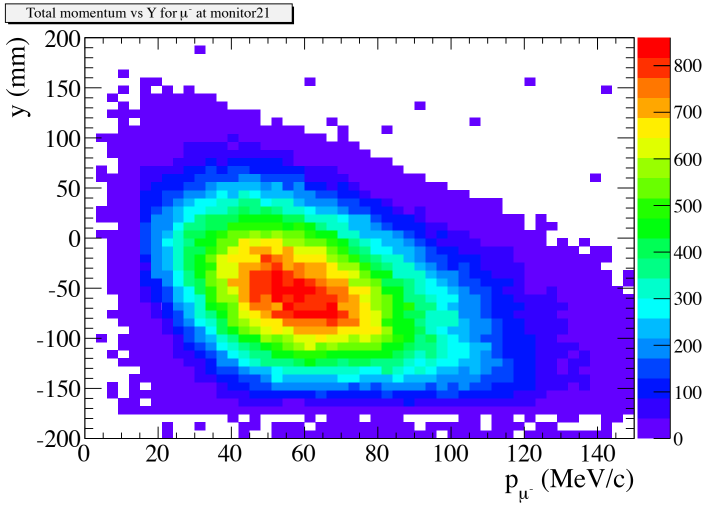
Material : Tungsten

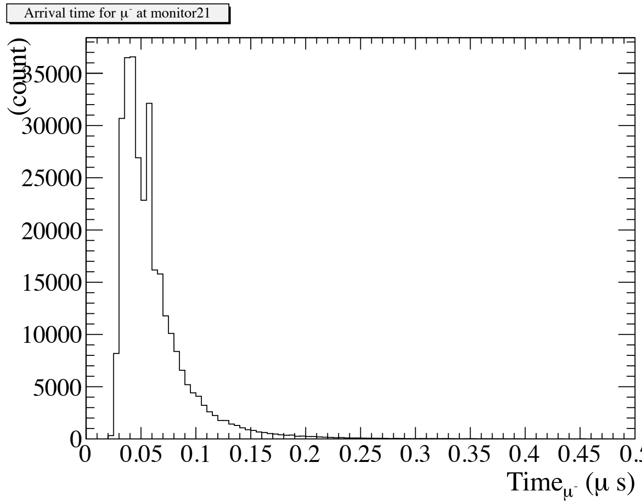
Length = 1000mm

Muons before/after the collimeter

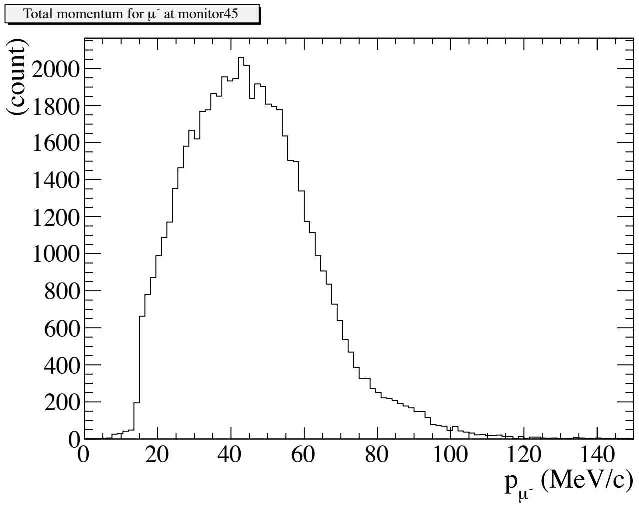
monitor21: before the collimator

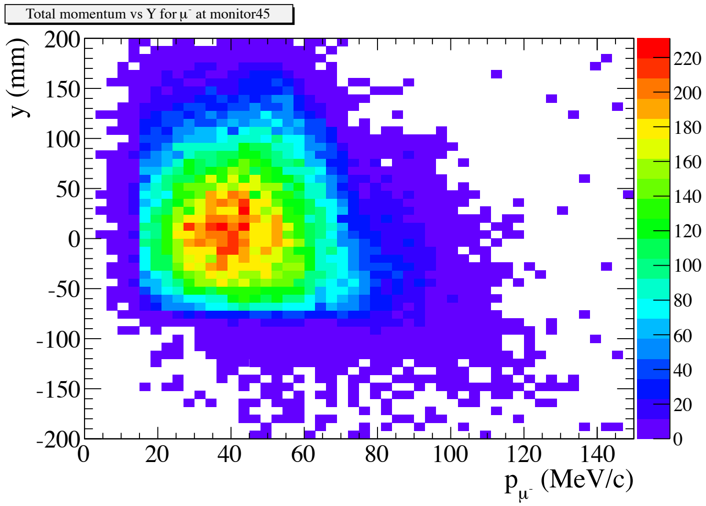


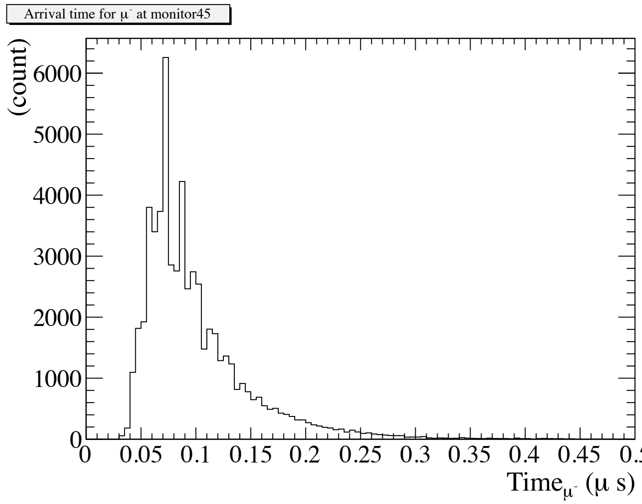




monitor45: after the collimator (before the stopping target)

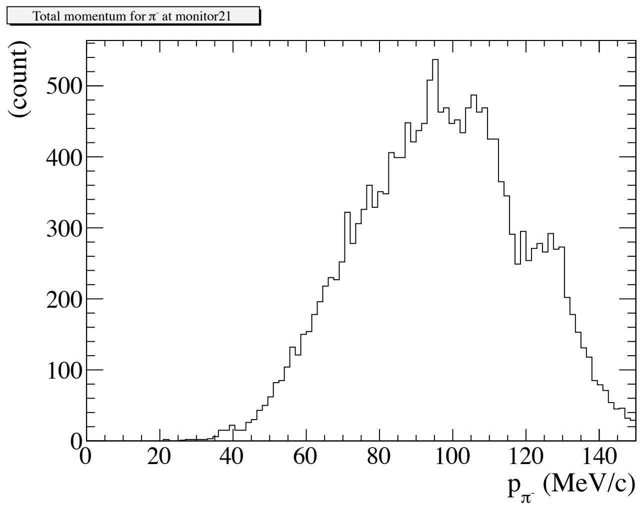


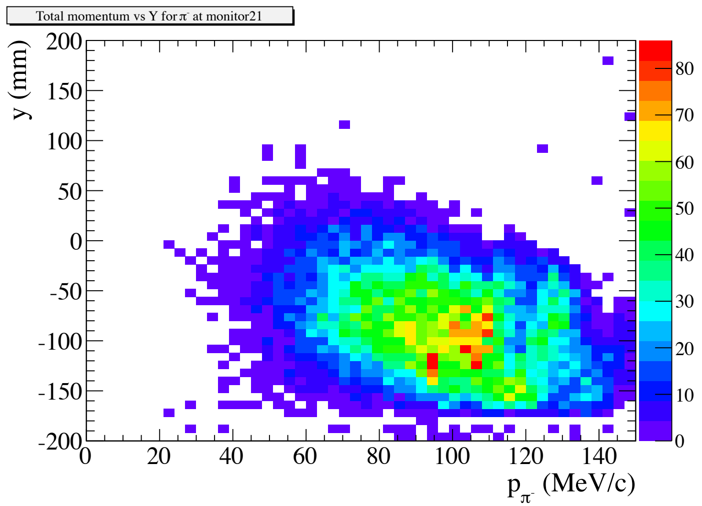


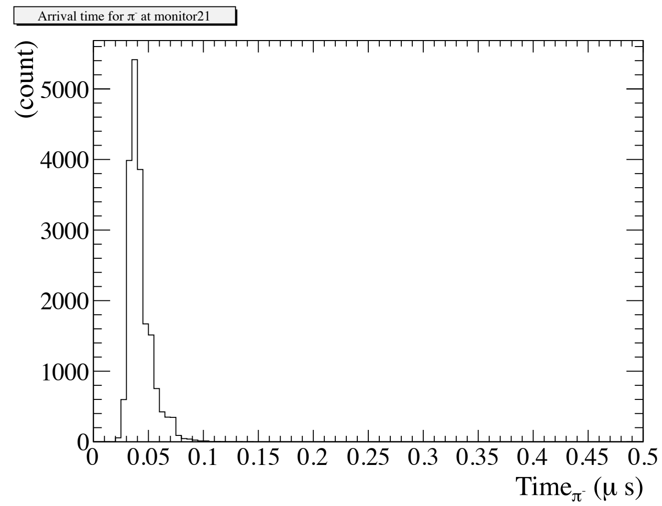


Pions before/after the collimeter

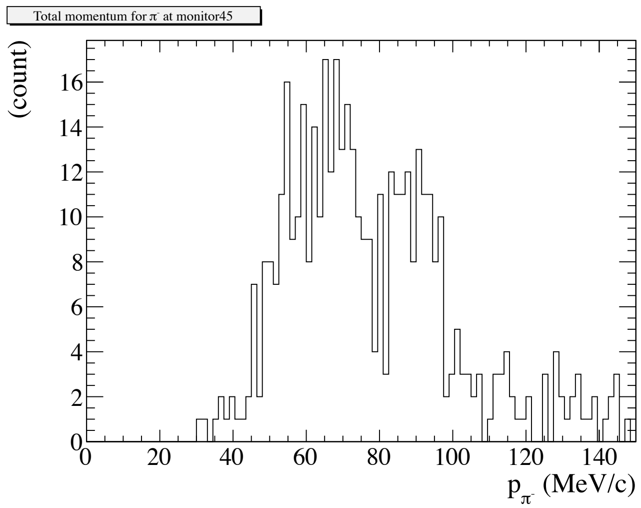
monitor21: before the collimator

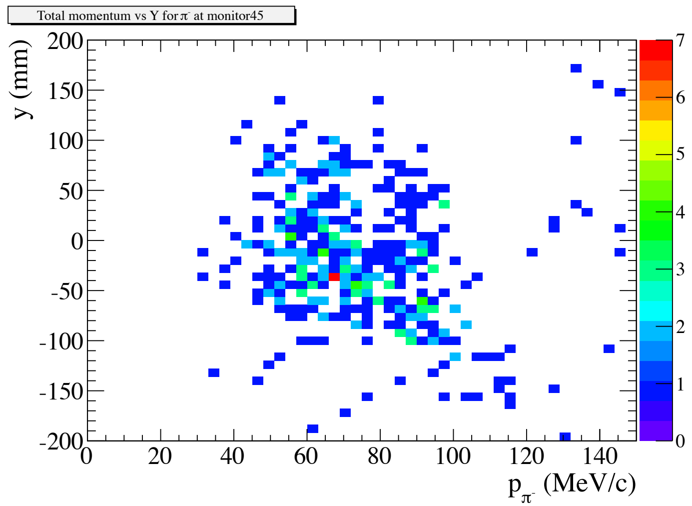


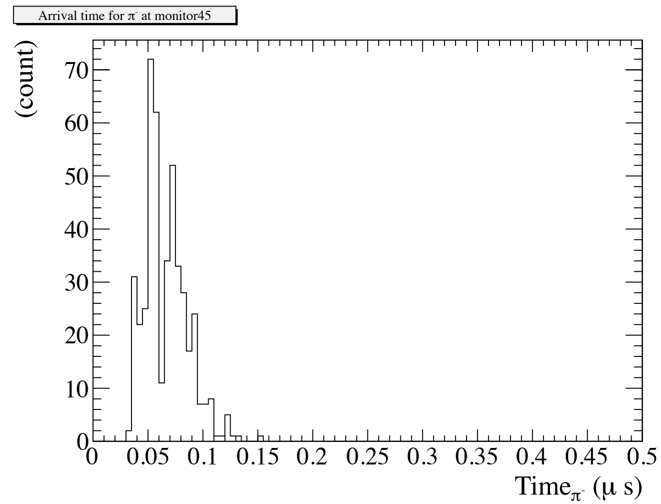




monitor45: after the collimator (before the stopping target)

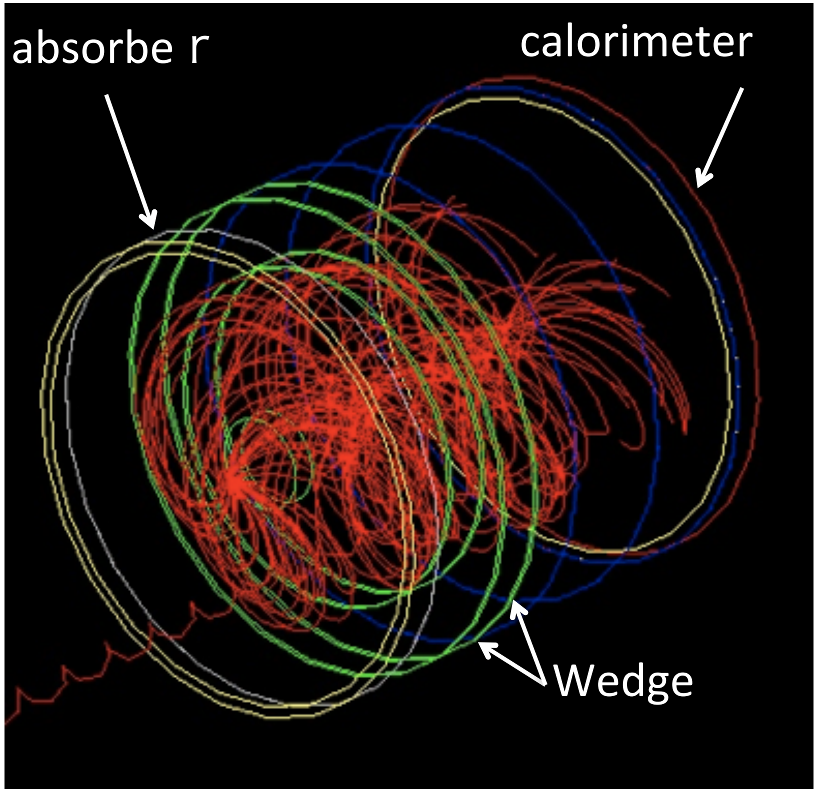


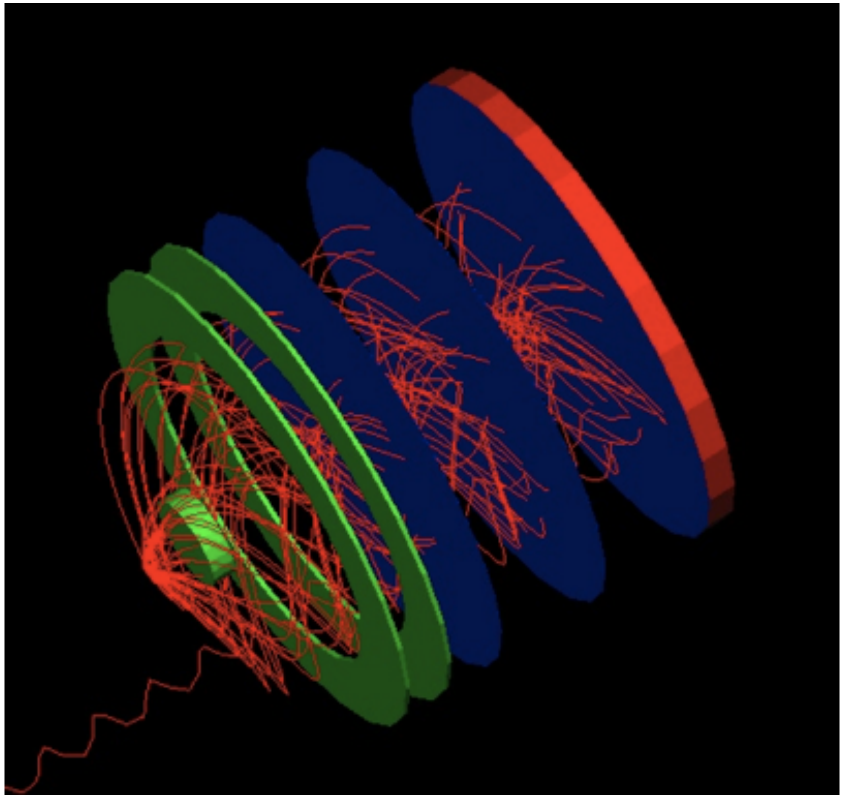




Configuration

- Muon stopping target : 11 points along the beam
- Proton degrader; 500 um, polystyrene
- Cu Beam Blocker; 200 mm radius, 100mm length
- Two Proton stopping wedges made of Cu, 20 mm thick
- 3 planes of virtual detectors and calorimeter





Key Points of COMET

COMET Phase-I / Phase-II and Mu2e

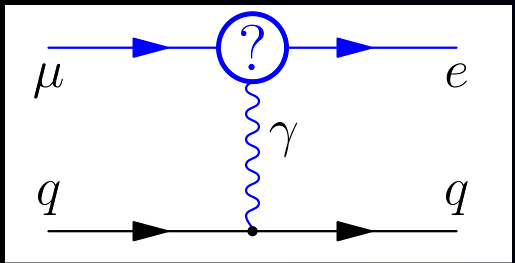
	S.E. sensitivity	BG events at aimed sensitivity	running time (sec)	Year	Comments
COMET Phase-I	3×10^{-15}	0.03	1.5×10^{6}	~2016	Proposal (2012)
COMET Phase-II	3×10^{-17}	0.34	2×10^{7}	~2019	CDR (2009)
Mu2e	3×10^{-17}	0.4	3x (2×10^{7})	~2019	J. Miller's talk at SSP2012

Physics Sensitivity: μ→eγ vs. μ-e conversion

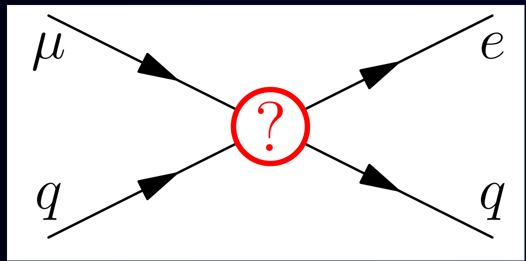
constructive

$$L_{\rm CLFV} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^\mu e_{\rm L})(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})$$

Photonic (dipole) interaction



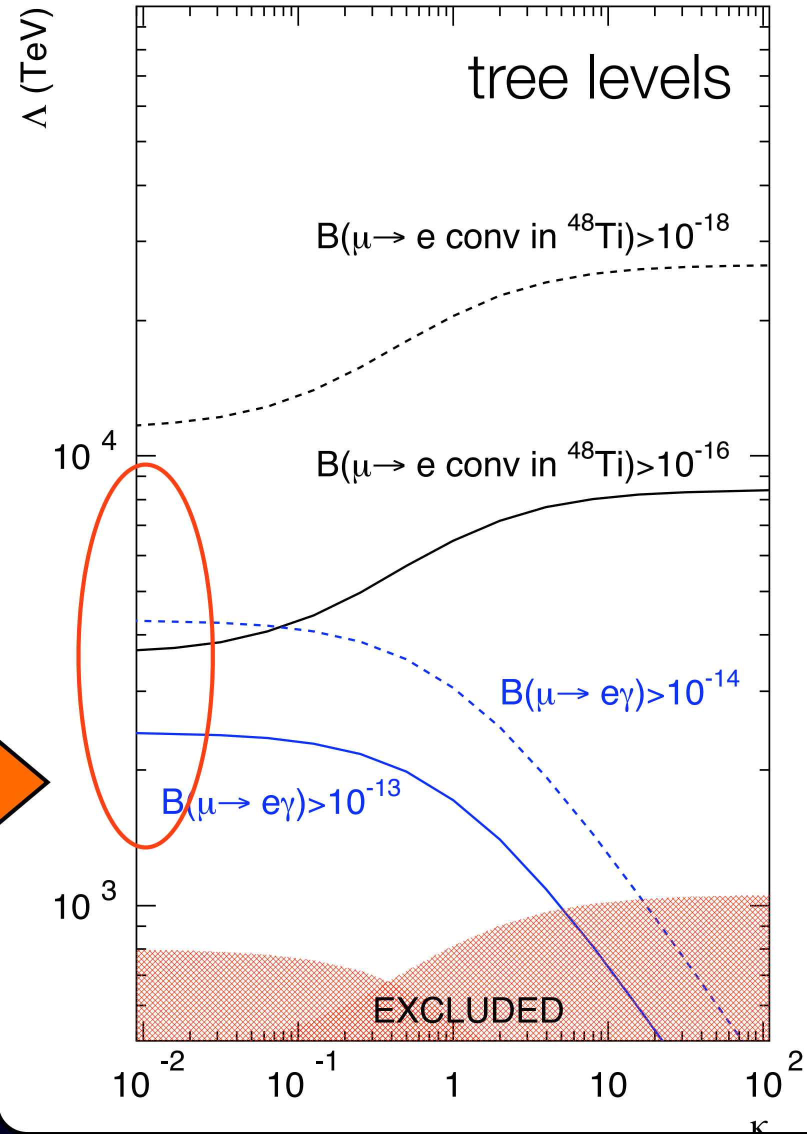
Contact interaction



if photonic contribution dominates,

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z) \sim \frac{B(A,Z)}{428}$$

- for aluminum, about 1/390~0.003
- for titanium, about 1/230



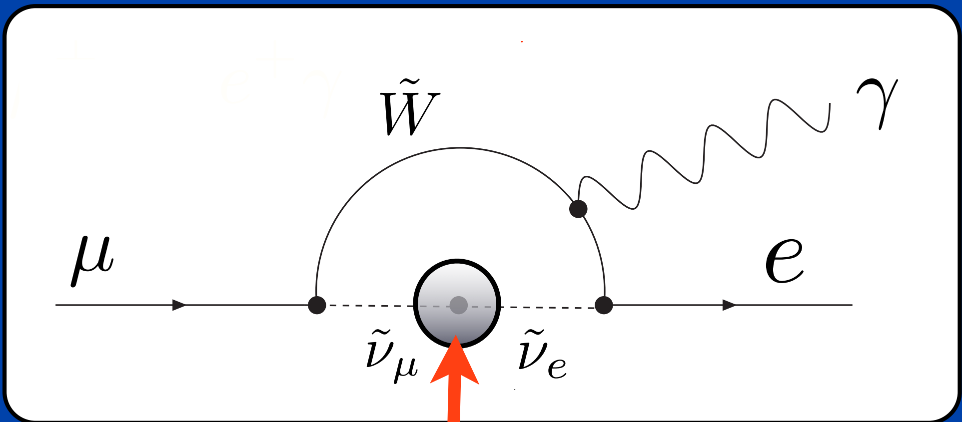
Example: Sensitivity to Energy Scale of NP
Loop contribution in SUSY models

- For loop diagrams,

$$\mathrm{BR}(\mu \to e\gamma) = 1 \times 10^{-11} \times \left(\frac{2\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2$$

$$y = \frac{g^2}{16\pi^2}\theta_{\mu e}$$

> sensitive to TeV energy scale with reasonable mixing



example diagram for SUSY (~TeV)

Physics at about 10^{16} GeV

slepton mixing (from RGE)

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln\frac{M_{GUT}}{M_{R_s}}$$

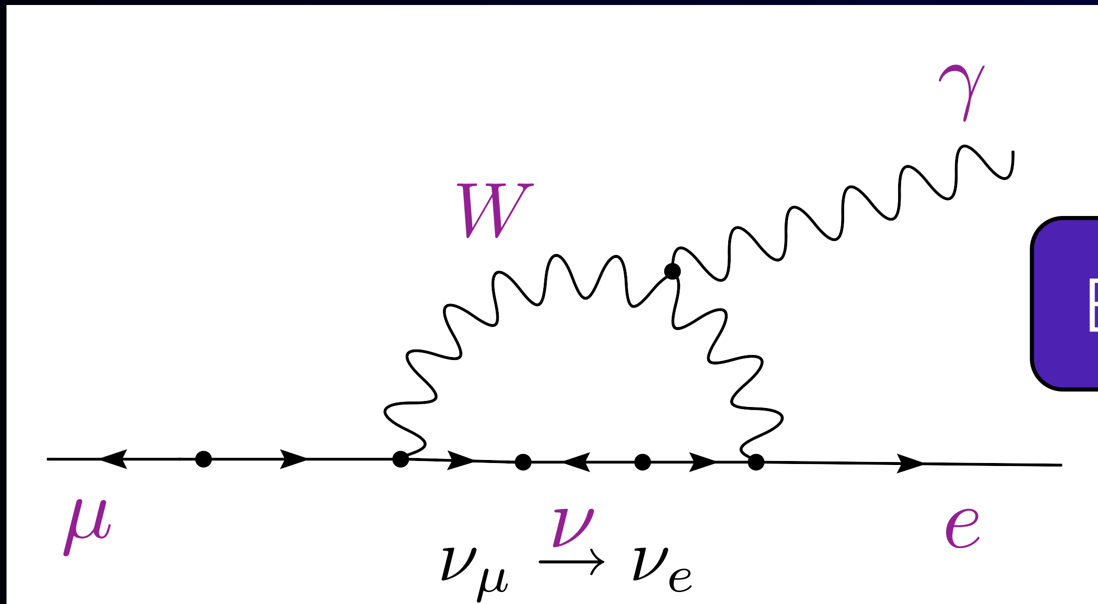
SUSY-GUT model

$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_\tau^2 U_{31} U_{32} \ln\frac{M_{GUT}}{M_R}$$

SUSY neutrino seesaw model

CLFV in the SM with Massive ν

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_l (V_{MNS})^*_{\mu l} (V_{MNS})_{el} \frac{m^2_{\nu_l}}{M^2_W} \right|^2$$



BR~O(10^{-54})