Background Study for COMET Phase-I and II

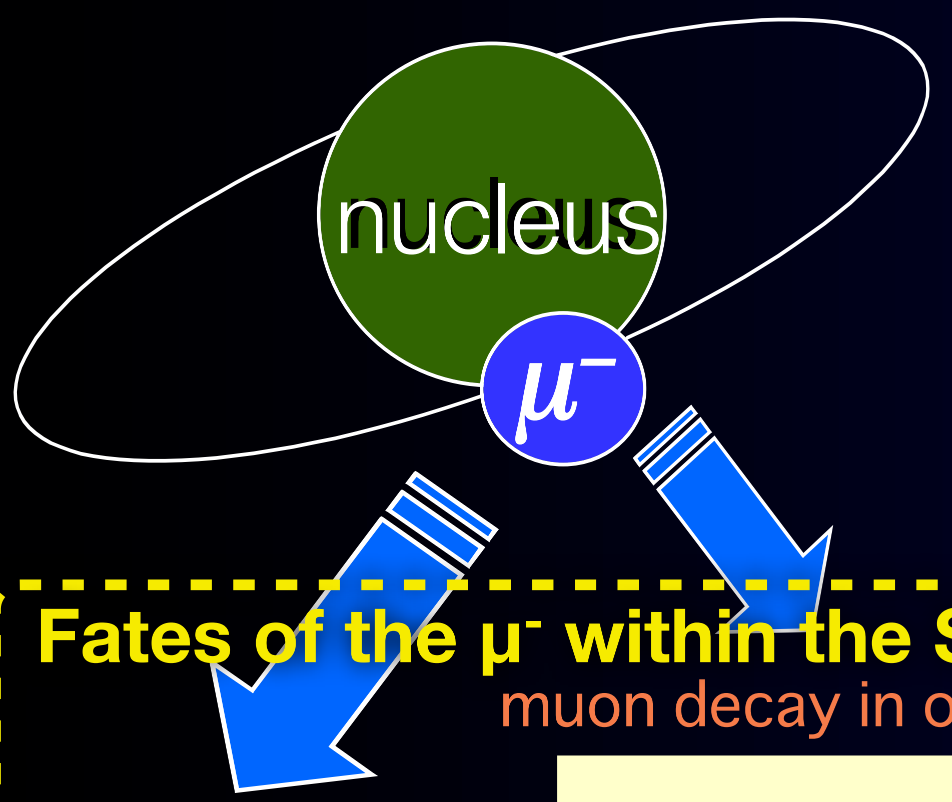
Akira SATO
Department of Physics, Osaka University
on behalf of the COMET collaboration

International Workshop on Neutrino Factories, Super Beams and Beta Beams: NuFact2014
August 25-30, 2014, Glasgow, UK
25+5 min

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

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

nuclear muon capture

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

Beyond the SM

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

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.

BG events for COMET

Intrinsic physics backgrounds — BGs from stopped muons at the stopping target

1	Muon decay in orbit (DIO)	
2	Radiative muon capture (external)	
3	Radiative muon capture (internal)	
4	Neutron emission after after muon capture	
5	Charged particle emission after muon capture	

High p resolution for signal e⁻

* Thin stopping target
* Low mass electron tracker

Beam related prompt/delayed backgrounds

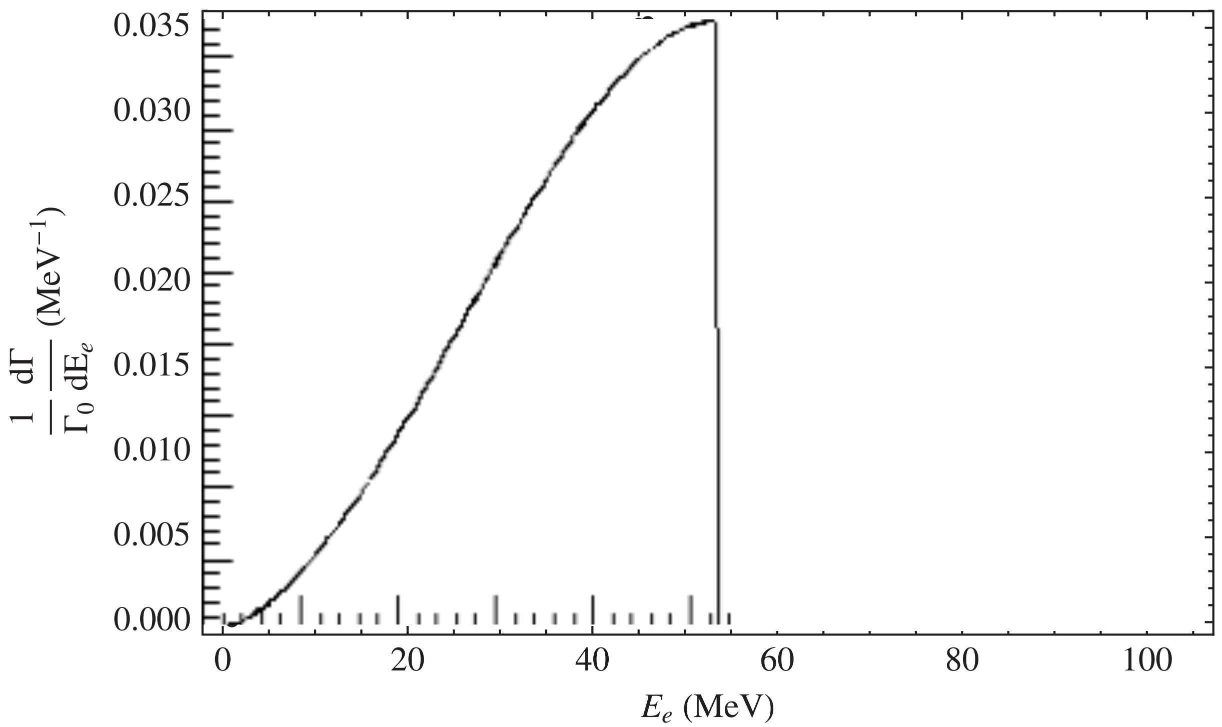
6	Radiative pion capture (external)	$\pi^- + A \to \gamma + A', \gamma \to e^- + e^+$
7	Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$
8	Beam electrons	e^- scattering off a muon stopping target
9	Muon decay in flight	μ^- decays in flight to produce e^-
10	Pion decay in flight	π^- decays in flight to produce e^-
11	Other particles induced backgrounds	Other particles to produce e^-
12	$\bar{p}$ induced backgrounds	$\bar{p}$ hits material to produce e^-

Other backgrounds

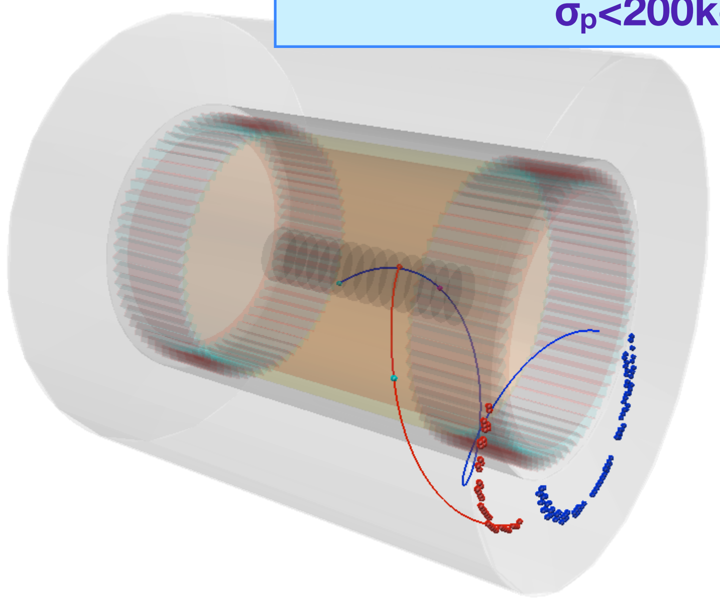
14	Cosmic-ray induced backgrounds	
15	Room neutron induced backgrounds	
16	False tracking	

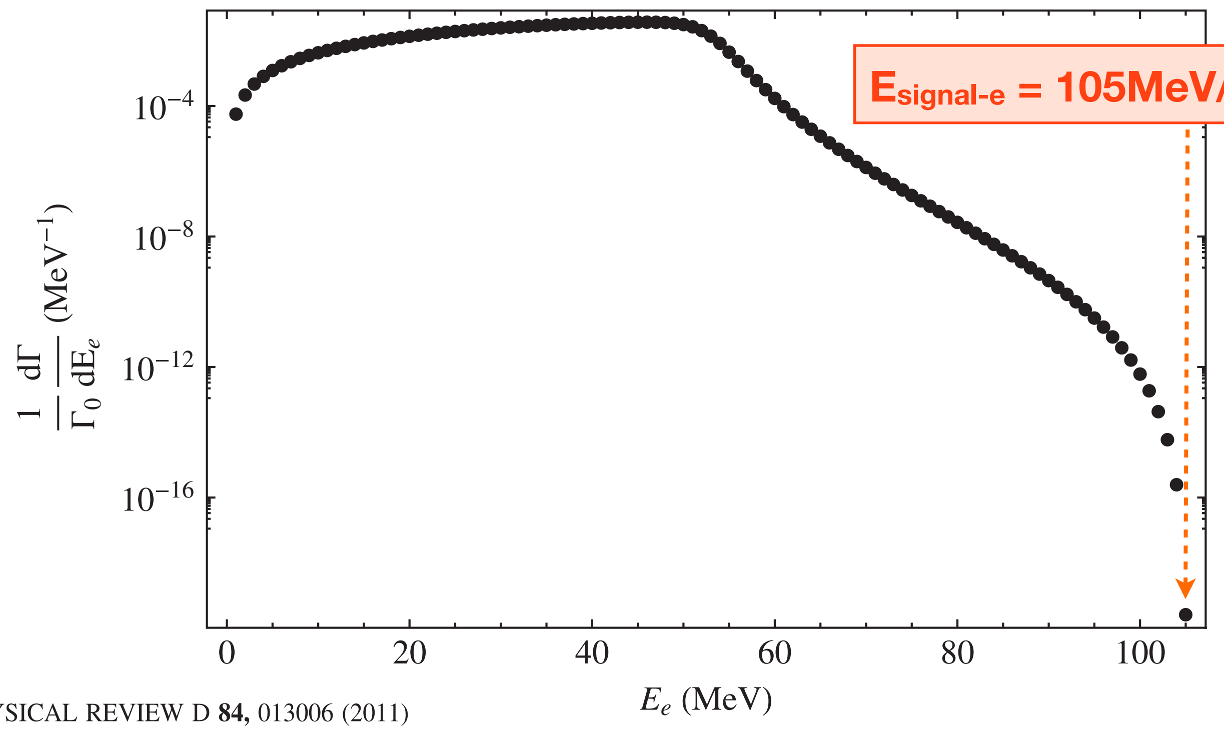
Muon Decay in Orbit (DIO)

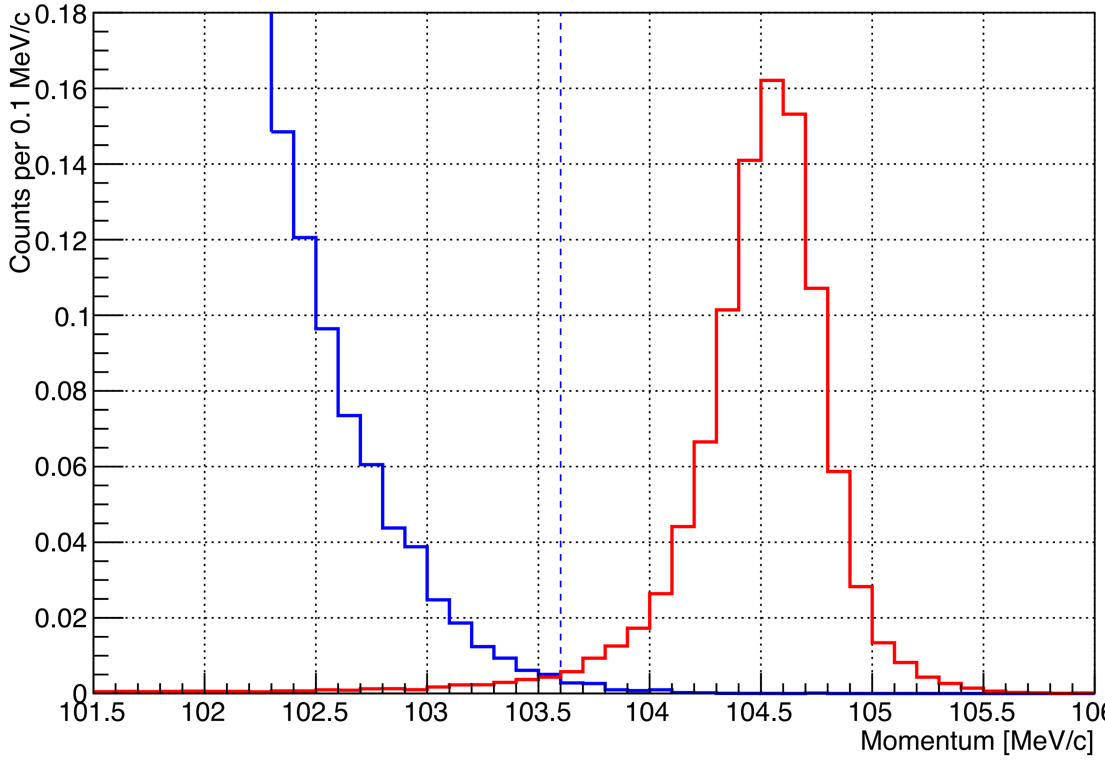
Normal muon decay in a bound state of a muonic atom



COMET Phase-I : CDC He gas based
σ_p<200keV







PHYSICAL REVIEW D **84,** 013006 (2011)

BG events for COMET

BGs from stopped muons at the stopping target

	Intrinsic physics backgrounds
1	Muon decay in orbit (DIO)
2	Radiative muon capture (external)
3	Radiative muon capture (internal)
4	Neutron emission after after muon capture
5	Charged particle emission after muon capture

High p resolution for signal e$^-$

* Thin stopping target
* Low mass electron tracker

	Beam related prompt/delayed backgrounds
6	Radiative pion capture (external)
7	Radiative pion capture (internal)
8	Beam electrons
9	Muon decay in flight
10	Pion decay in flight
11	Other particles induced backgrounds
12	$\overline{p}$ induced backgrounds

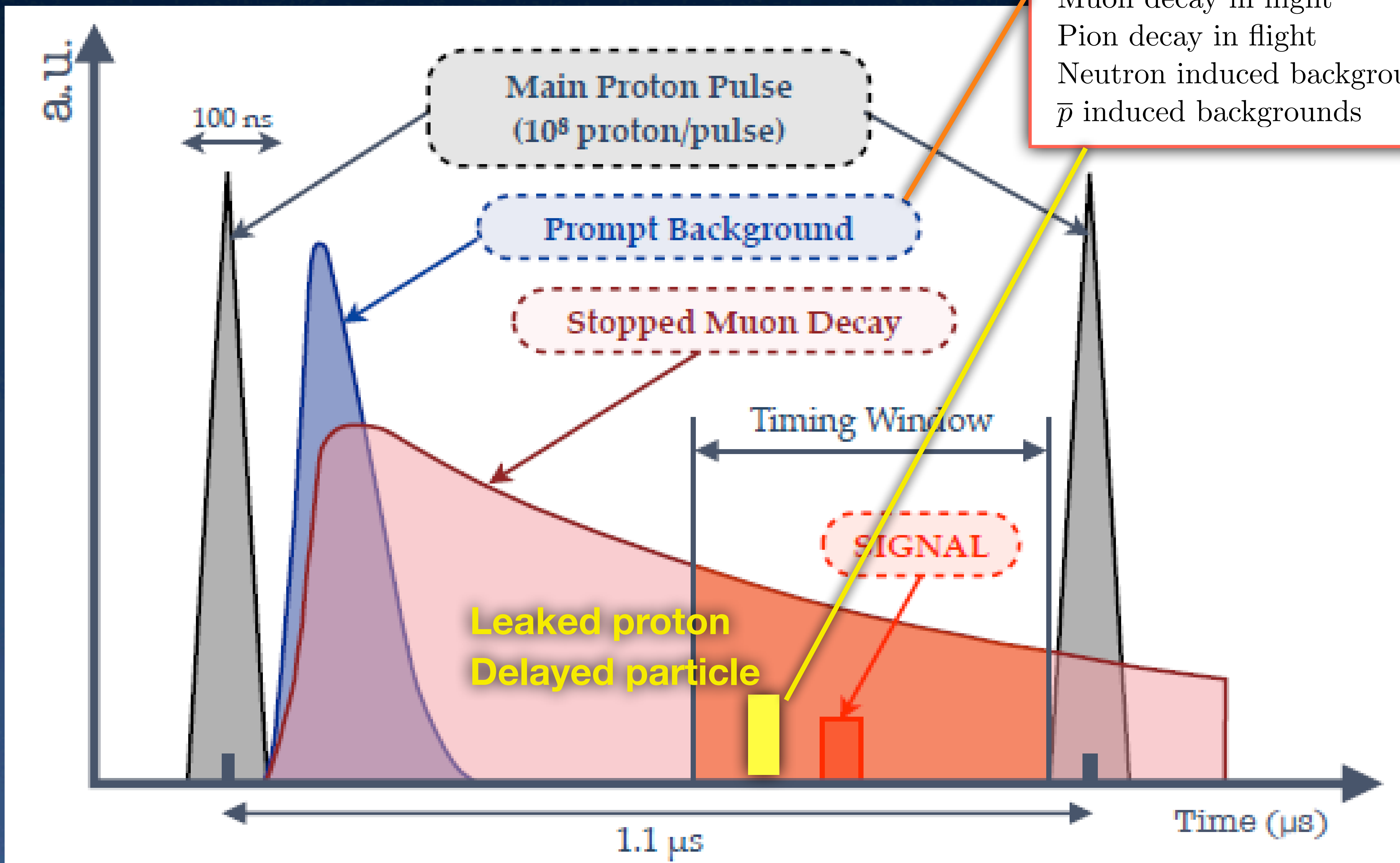
Pulsed muon beam with good quality

* Pulsed proton beam
* Long curved solenoid muon transport
* antiproton absorber

	Other backgrounds
14	Cosmic-ray induced backgrounds
15	Room neutron induced backgrounds
16	False tracking

Beam related BGs

Radiative pion capture (external)
Radiative pion capture (internal)
Beam electrons
Muon decay in flight
Pion decay in flight
Neutron induced backgrounds
$\bar{p}$ induced backgrounds



- Proton extinction level of 10^{-11} has been studied.

Phill's talk on Thursday

BG events for COMET

BGs from stopped muons at the stopping target

Intrinsic physics backgrounds	
1	Muon decay in orbit (DIO)
2	Radiative muon capture (external)
3	Radiative muon capture (internal)
4	Neutron emission after after muon capture
5	Charged particle emission after muon capture

High p resolution for signal e^-

* Thin stopping target
* Low mass electron tracker

Beam related prompt/delayed backgrounds	
6	Radiative pion capture (external)
7	Radiative pion capture (internal)
8	Beam electrons
9	Muon decay in flight
10	Pion decay in flight
11	Other particles induced backgrounds
12	$\bar{p}$ induced backgrounds

Pulsed muon beam with good quality

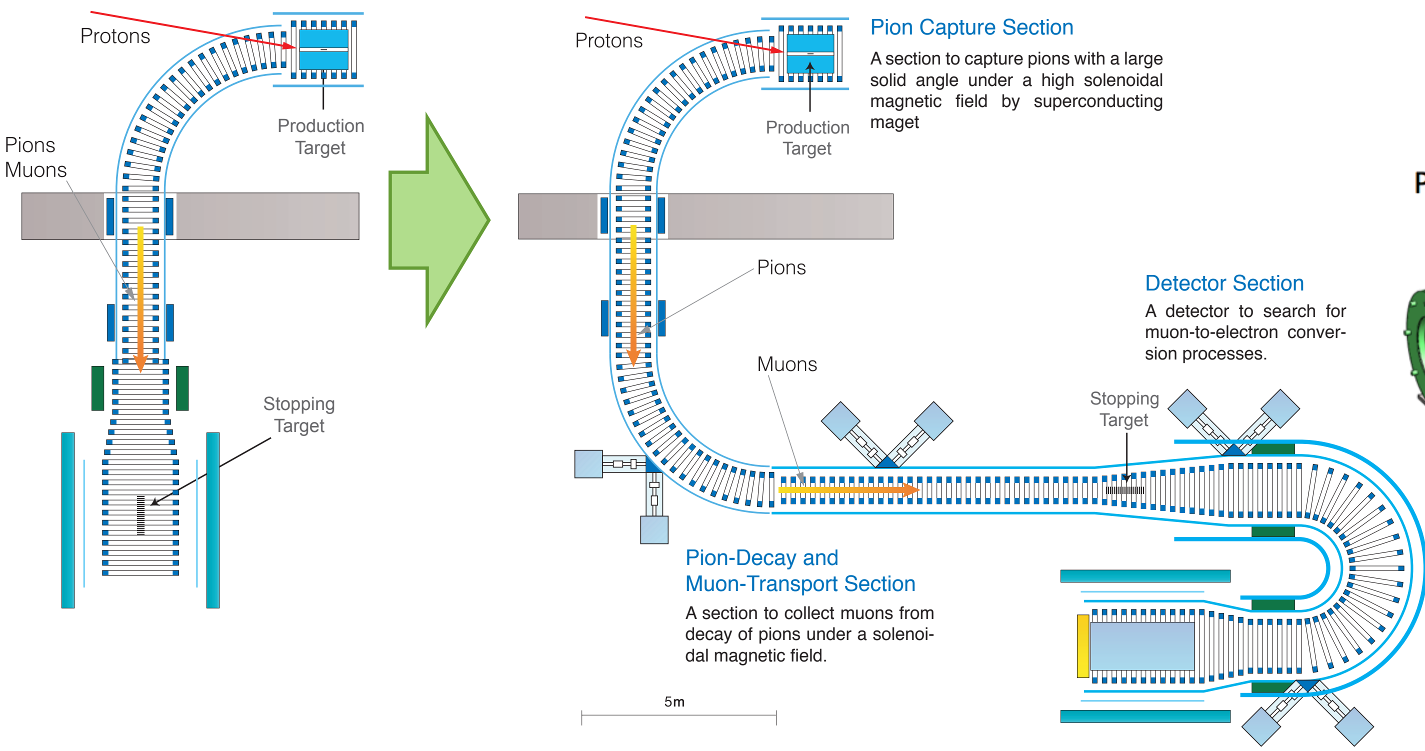
* Pulsed proton beam
* Long curved solenoid muon transport
* antiproton absorber

Other backgrounds	
14	Cosmic-ray induced backgrounds
15	Room neutron induced backgrounds
16	False tracking

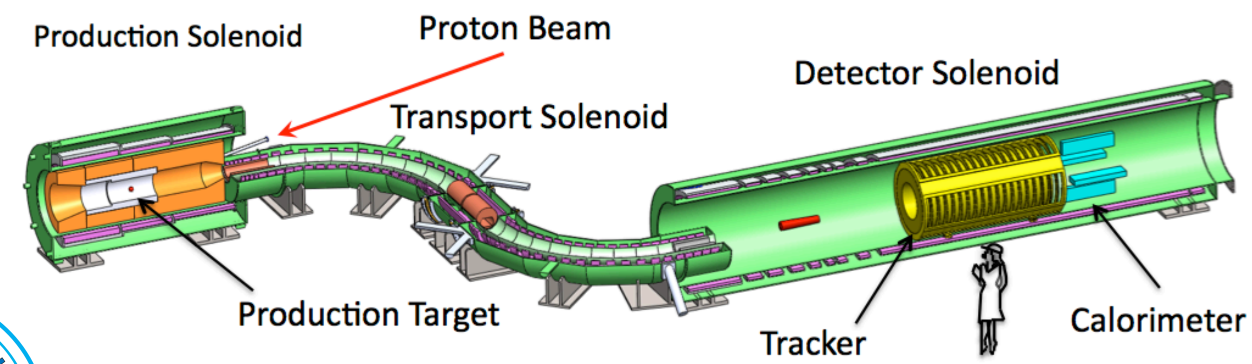
* Cosmic-ray veto
* Neutron shielding

Staging approach in COMET

COMET @J-PARC



Mu2e @FNAL



COMET Phase-I :

physics run 2017-

BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL

*8GeV-3.2kW proton beam, 90 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 :

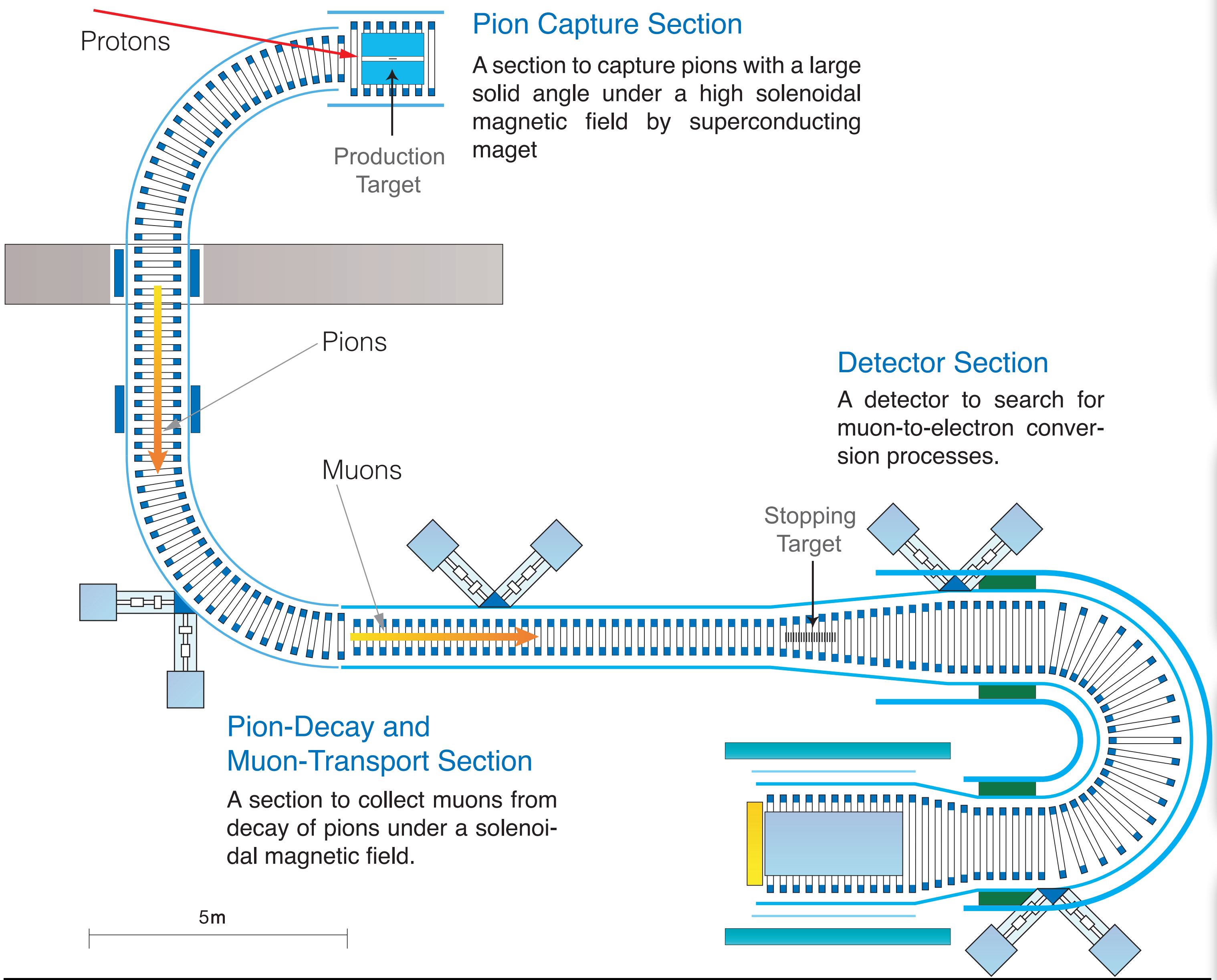
physics run 2019-

BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL

*8GeV-8kW proton beam, 3 years

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

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



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

Intense Pulsed Proton Beam
8GeV-56kW (2x10^{7} sec)
width~100ns, separation>1μs
Extinction level < 10^{9} — **reduce beam related BG**

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

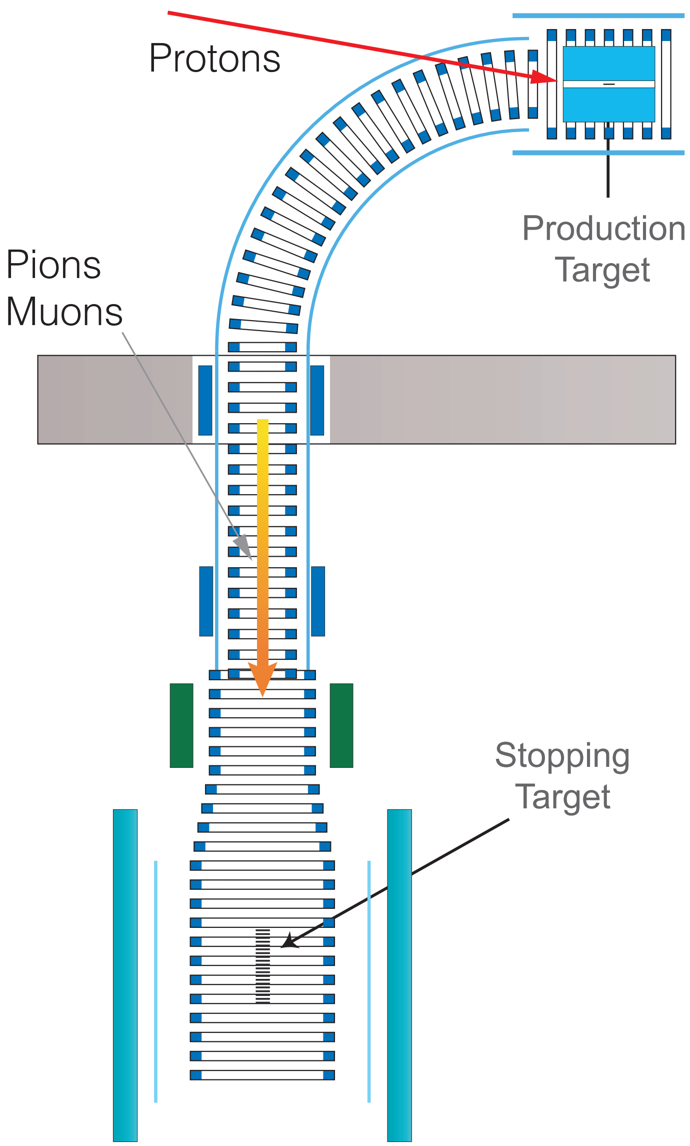
Long Transport Solenoid
L ~10m
Curved 180deg Solenoid — **eliminate energetic μ (>75 MeV/c) and pions**

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 Phase-I (S.E.S 10^{-15})



Proton beam intensity in limited by the CDC hit rate.

Beam quality is worse than Phase-II. Makes higher BG rates.

Intense Pulsed Proton Beam
8GeV-3.2kW (90 days)
width~100ns, separation>1μs
Extinction level < 10^9 reduce beam related BG

Pion Capture Solenoid
5T superconducting 1.7×10^9 μ^-/sec

Long Transport Solenoid
L ~5m
Curved 90deg Solenoid
eliminate energetic μ (>75 MeV/c) and pions

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

Electron Spectrometer
Curved Solenoid

Low-mass Tracker
Cylindrical drift chamber

COMET Phase-I : physics run 2017-
- **BR(μ+Al→e+Al)<7×10^{-15} @ 90%CL**
  - *8GeV-3.2kW proton beam, 90 days
  - *90deg. bend solenoid, cylindrical detector
- **Beam & Background study for the phase-II**

The sensitivity is limited by the BG rates.

COMET Phase-I

BG events for COMET Phase-I

of events for S.E.S. of 3.1×10^{-15}

Intrinsic physics backgrounds

1	Muon decay in orbit (DIO)	Bound muons decay in a muonic atom	0.01
2	Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A' + \gamma$, followed by $\gamma \to e^- + e^+$	5.6×10^{-4}
3	Radiative muon capture (internal)	$\mu^- + A \to \nu_\mu + e^+ + e^- + A'$,	
4	Neutron emission after after muon capture	$\mu^- + A \to \nu_\mu + A' + n$, and neutrons produce e^-	< 0.001
5	Charged particle emission after muon capture	$\mu^- + A \to \nu_\mu + A' + p$ (or d or α), followed by charged particles produce e^-	< 0.001

Beam related prompt/delayed backgrounds *with proton extinction factor* *3×10^{-11}*

6	Radiative pion capture (external)	$\pi^- + A \to \gamma + A'$, $\gamma \to e^- + e^+$	4.24×10^{-4}
7	Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$	
8	Beam electrons	e^- scattering off a muon stopping target	7.1×10^{-4}
9	Muon decay in flight	μ^- decays in flight to produce e^-	$\leqq 1.7 \times 10^{-4}$
10	Pion decay in flight	π^- decays in flight to produce e^-	$\leqq 2.0 \times 10^{-3}$
11	Other particles induced backgrounds	Other particles to produce e^-	$\leqq 2.4 \times 10^{-6}$
12	$\bar{p}$ induced backgrounds	$\bar{p}$ hits material to produce e^-	0.007

Other backgrounds

14	Cosmic-ray induced backgrounds		< 0.0001
15	Room neutron induced backgrounds		$< 4 \times 10^{-10}$
16	False tracking		-
Total			**0.019**

COMET Phase-II

Sensitivity of COMET Phase-II

Single event sensitivity

$$= (N_p \cdot N^{stop}_{\mu/p} \cdot f_{cap} \cdot A_{\mu\text{-}e})^{-1}$$

$= 2.6 \times 10^{-17}$

→ 90% C.L. upper limit

$= 6.0 \times 10^{-17}$

→ Events per 1×10^{-16} BR

= 3.8

Total number of protons: N_p	**8.5×10^{20}**	
Proton kinetic energy	8	[GeV]
Harmonics of MR	8	
Bunch time spacing	657	[nsec]
Number of RF bunches filled with protons per spill	4	
Time between adjacent filled bunches	1314	[nsec]
Number of protons in each RF bunch	1.6×10^{13}	
Cycle time of MR (=spill period)	1.47	[sec]
Flat top for the slow extraction	0.7	[sec]
Number slow-extracted pulse in a spill	5.3×10^{5}	[pulses/spill]
Number of Protons in each slow-extracted pulse	1.2×10^{8}	
Average beam current	7.0	[μA]
Average beam power	56	[kW]
Average proton intensity	4.4×10^{13}	[protons/sec]
Total running time	2.0×10^{7}	[sec]
Running time per year	1.0×10^{7}	[sec/year]
Number of stopped muons per proton: $N^{stop}_{\mu/p}$	**0.0023**	[muons/proton]
Rate of muons per proton transported to the target	0.0035	[muons/proton]
Muon stopped acceptance	0.66	
Number of stopped muons: $N^{stop}_{\mu/year}$	1.0×10^{18}	[muons/year]
Total number of stopped muons: N^{stop}_{μ}	2.0×10^{18}	
Fraction of captured muon: f_{cap}	**0.61**	
Net acceptance: $A_{\mu\text{-}e}$	**0.031**	
Geometrical acceptance, fitting and selection criteria	0.09	
Solid angle with mirroring acceptance	*(0.73)*	
Muon beam stop acceptance	*(0.57)*	
Curved solenoid acceptance	*(0.47)*	
Track reconstruction efficiency	*(0.88)*	
Track quality cut efficiency	*(0.89)*	
Transverse momentum cut efficiency	*(0.83)*	
E/p cut efficiency	*(0.99)*	
Helix pitch cut efficiency	*(0.99)*	
Momentum selection efficiency	*(0.72)*	
Timing window selection efficiency	0.39	
Trigger acceptance and DAQ live efficiency	0.90	

from COMET Phase-I TDR 15 Jan 2014 and COMET CDR

BG events for COMET Phase-I and II

			Phase-I	Phase-II	
Intrinsic physics backgrounds			S.E.S. = 3.1×10^{-15}	2.6×10^{-17}	
1	Muon decay in orbit (DIO)	Bound muons decay in a muonic atom	0.01	0.15	
2	Radiative muon capture (external)	$\mu^- + A \to \nu_\mu + A' + \gamma$, followed by $\gamma \to e^- + e^+$	5.6×10^{-4}	< 0.001	
3	Radiative muon capture (internal)	$\mu^- + A \to \nu_\mu + e^+ + e^- + A'$,			
4	Neutron emission after after muon capture	$\mu^- + A \to \nu_\mu + A' + n$, and neutrons produce e^-	< 0.001	< 0.001	
5	Charged particle emission after muon capture	$\mu^- + A \to \nu_\mu + A' + p$ (or d or α), followed by charged particles produce e^-	< 0.001	< 0.001	
Beam related prompt/delayed backgrounds		with proton extinction factor	*3×10^{-11}*	*1×10^{-9}*	*3×10^{-11}*
6	Radiative pion capture (external)	$\pi^- + A \to \gamma + A'$, $\gamma \to e^- + e^+$	4.24×10^{-4}	0.052	/33 (rows 6–12)
7	Radiative pion capture (internal)	$\pi^- + A \to e^+ + e^- + A'$			
8	Beam electrons	e^- scattering off a muon stopping target	7.1×10^{-4}	< 0.1	
9	Muon decay in flight	μ^- decays in flight to produce e^-	≦ 1.7×10^{-4}	< 0.0002	
10	Pion decay in flight	π^- decays in flight to produce e^-	≦ 2.0×10^{-3}	< 0.0001	
11	Other particles induced backgrounds	Other particles to produce e^-	≦ 2.4×10^{-6}	-	
12	$\bar{p}$ induced backgrounds	$\bar{p}$ hits material to produce e^-	0.007	0.007	
			sub-total : 0.01	0.16	0.005
Other backgrounds					
14	Cosmic-ray induced backgrounds		< 0.0001	0.004	
15	Room neutron induced backgrounds		< 4×10^{-10}	0.024	
16	False tracking		-	-	
Total			**0.019**	**0.34**	**0.19**

BG events for COMET Phase-I and II

			Phase-I	Phase-II	
Intrinsic physics backgrounds			S.E.S. = 3.1×10^{-15}	2.6×10^{-17}	
1	Muon decay in orbit (DIO)				
2	Radiative muon capture (external)				
3	Radiative muon capture (internal)	$\mu^- + A \rightarrow \nu_\mu + e^+ + e^- + A'$,			
4	Neutron emission after after muon capture				
5	Charged particle emission after muon capture				
Beam related prompt/delayed backgrounds		with proton extinction factor	*3×10^{-11}*	*1×10^{-9}*	*3×10^{-11}*
6	Radiative pion capture (external)				
7	Radiative pion capture (internal)				
8	Beam electrons				
9	Muon decay in flight				*/33*
10	Pion decay in flight				
11	Other particles induced backgrounds	Other particles to produce e^-	≦ 2.4×10^{-6}	-	
12	$\bar{p}$ induced backgrounds	$\bar{p}$ hits material to produce e^-	0.007	0.007	
Other backgrounds					
14	Cosmic-ray induced backgrounds		< 0.0001	0.004	
15	Room neutron induced backgrounds		$< 4 \times 10^{-10}$	0.024	
16	False tracking		-	-	
Total			**0.019**	**0.34**	**0.19**

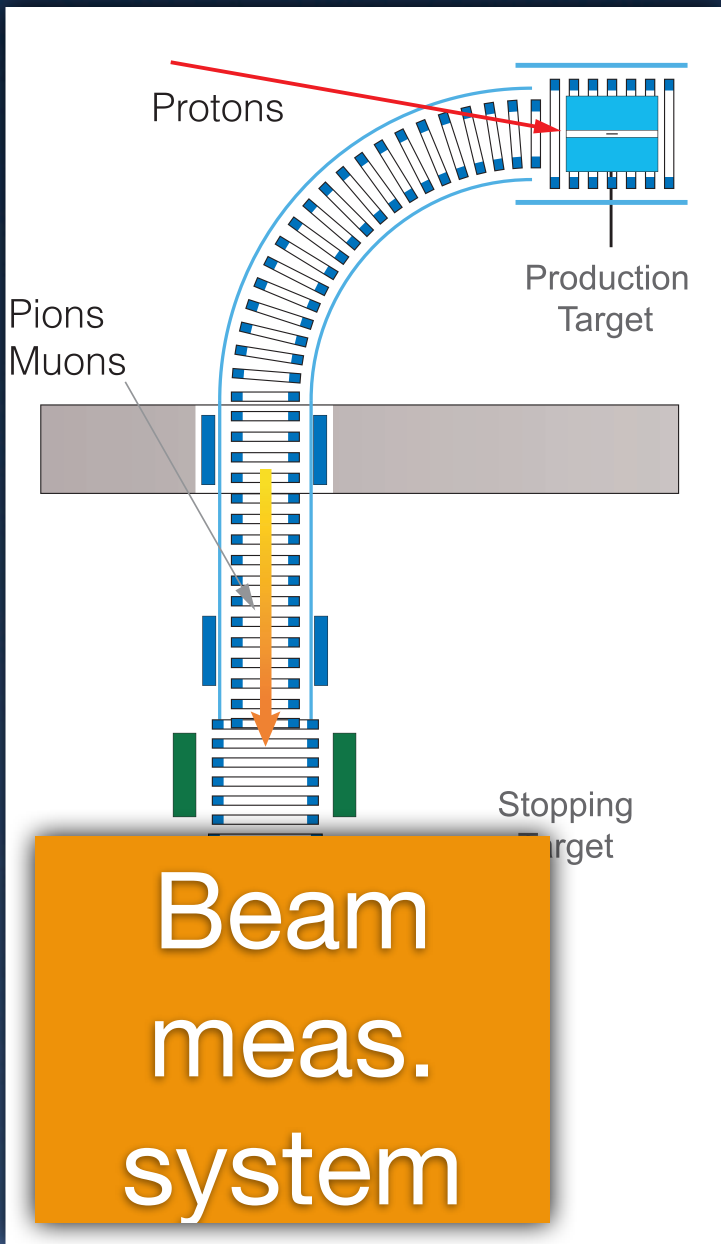
DIO spectrum will be measured in Phase-I.

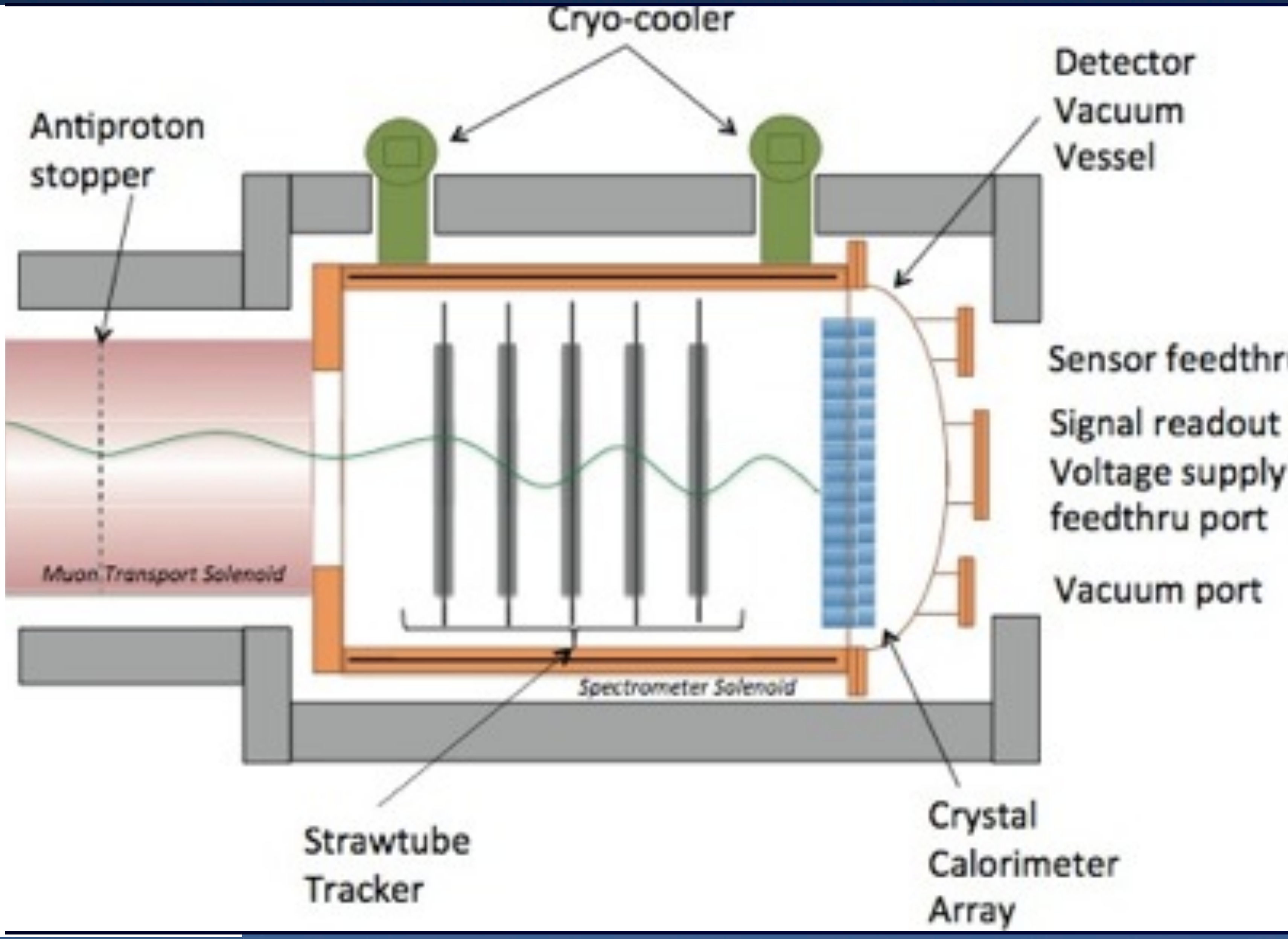
Particles emitted from μ capture in Al will be measured in AlCap.

Beam from the solenoid will be measured in Phase-I.

Beam measurements at Phase-I

- Beam at the end of 90deg solenoid will be measured in COMET Phase-I.
  - yield and energy for pion, muon, antiproton ...





Summary

- Characteristic of the muon beam is very important for μ-e conversion experiments.
- BGs were estimated for COMET Phase-I and re-estimation towards a new TDR is in progress.
- Better understanding of the beam and backgroung source is crucial for the sensitivity of $\sim 10^{-17}$ at the Phase-II.
- One of the important task for the COMET Phase-I is beam measurements. We will re-optimize the beamline of the Phase-II (another 90deg of the bend solenoid and collimators ...)