COMET experiment:
— A search for muon-to-electron conversion at J-PARC —

Hajime NISHIGUCHI, KEK
On behalf of the COMET collaboration
CONTENTS

1. COMET overview
   - physics motivation, event signature and backgrounds

2. COMET features
   - experimental principle, muon beam, detectors

3. COMET status & prospects
   - strategy, R&Ds, construction status
1. COMET overview
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Why charged LFV is so attractive?

**Why ? :** Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

**SM + simple ν Oscillation**
- charged LFV is possible
- but extremely rare
  \[ \mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i |U_{\mu i}^* U_{ei}|^2 \frac{m_{\nu_i}^2}{m_W^2} \]
  \[ \mathcal{B}(\mu \to e\gamma) \approx 10^{-50} !!! \]

**beyond SM (SUSY-GUT etc.)**
- charged LFV is largely enhanced
- still rare but observable level
  \[ \mathcal{B}(\mu \to e\gamma) \approx \frac{\alpha^3 \pi \theta_{\text{eff}}}{G_F m^4} \]
  \[ \mathcal{B}(\mu \to e\gamma) = 10^{-15} \sim 10^{-11} !!! \]
Why charged LFV is so attractive?

Why ? : Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

“charged LFV” = “NEW PHYSICS”

TeV-scale New Physics

competitive & complementary to LHC!

$B(\mu \rightarrow e\gamma) \approx 10^{-6}$ !!!

$B(\mu \rightarrow e\gamma) = 10^{-15} \sim 10^{-11}$ !!!
What is the muon-to-electron conversion?

- 1S state in a muonic atom

Muon Decay in Orbit (DIO)

\[ \mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \]

or

Nuclear Muon Capture

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

- If μ-e Conversion is Occurred ...

Neutrino-less Muon Nuclear Capture

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

- Branching Ratio is Determined by

\[ \mathcal{B}(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')} \]
Experimental signature and Backgrounds

**Signal**
- $E_e = m_\mu - B_\mu \sim 105$ MeV
- Coherent Process ($Z_{ini}=Z_{end}$)

**Backgrounds**
- Radiative Muon Capture
- Radiative Pion Capture
- Electrons from Muon DIF
- Muon Decay in Orbit (DIO)
- Cosmic Rays, etc.

**Signal**: Single Mono-Energetic Electron
**Sensitivity**: Limited by Beam Quality
  - Wait until Pion decays
  - Pulsed Beam is the BEST

Hajime NISHIGUCHI (KEK)  COMET Experiment  EPS-HEP2015, 22-29/Jul./2015, Vienna
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Features

- Primary proton beam
- Pion capture solenoid
- Muon transport solenoid
- Muon stopping target
- Electron detectors and solenoid
- Electron transport solenoid
Features

1. Powerful proton source by J-PARC
2. High-eff π-capture system
3. “C-shape” long/bending π/μ transport
4. High reso electron detector with 2ndary “C-shape” transport
1. powerful proton source at J-PARC

- Linac (330m, 400MeV)
- 3GeV Synchrotron (RCS) (350m ring, 25Hz, 1MW)
- 30GeV Synchrotron (MR) (1600m ring, 0.75MW)
- Hadron Experiment Facility
- Neutrino Experiment Facility (T2K, towards SK)
- Material/Life-Science Facility (MLF) (muon source, pulse neutron source)
- Accelerator-driven Transmutation exp facility

Hajime NISHIGUCHI (KEK)
COMET beam-line at J-PARC HD

Hadron Experimental Facility is currently under modification to have more beam lines; **High-\(p\) beam line & the COMET beam line.**

Realized by putting a Lambertson magnet and extending the experimental hall.
Hadron Experimental Facility is currently under modification to have more beam lines; **High-$p$ beam line & the COMET beam line.**

Realized by putting a Lambertson magnet and extending the experimental hall.
2. High efficiency $\pi$-capture system

- Large muon yield by Large Solid Angle
- Powerful Solenoid
- Surround p target

\[ P_T(\text{GeV}/c) = 0.3 \times B(\text{T}) \times \left[ \frac{R(\text{m})}{2} \right] \]

B=5T, R=0.2 \rightarrow P_T=150\text{MeV}/c

- Super-conducting solenoidal magnet
  - 5T
  - 30 cm thick W shield.
- Issue: Heat Load
Demonstration of high-eff. capture solenoid

400MeV 1μA DC proton beam at Osaka Univ. using 3.5T pion capture solenoid and graphite target → 2000μ’s / 6 pA already achieved.
3 “C-shaped” Long/Bending $\pi/\mu$ transport

Utilize C-shape long/bending magnet to reject background particles.

Muon Transport Beamline

- Muons are transported from the capture section to the detector by the muon transport beamline.
- Requirements:
  - Long enough for pions to decay to muons (> 20 meters $\times 10^{-3}$).
  - High transport efficiency ($P \sim 40$ MeV/c).
  - Negative charge selection.
  - Low momentum selection ($P < 75$ MeV/c).
- Straight + curved solenoid transport system is adopted.

Select low-$p$ muons (& reject high-$p$ $\mu$) using C-shaped “transport” solenoid

$B_{\text{max}} = 3.5$T

Select high-$p$ $e^-$ (& reject low-$p$ BGs.) using C-shaped “transport” solenoid

$B_{\text{max}} = 1$T
Secondary-bending for detector system

* Torus drift for rejecting low energy DIO electrons.

\[
D(m) = \frac{1}{0.3 \times B(T)} \times \frac{s}{R} \times \frac{P_L^2 + \frac{1}{2}P_T^2}{P_L}
\]

* Rejection Power : \(~10^{-6}\)

* Good Acceptance for signal electrons (w/o including event selection and trigger acceptance)
  * \(~20\%\)
High resolution electron detector

- to stop muons
- to detect and identify 100 MeV electrons
- to eliminate low-energy beam particles and to transport only ~100 MeV electrons

Hajime NISHIGUCHI (KEK)
Electron Detector (Tracker + Calorimeter)

- Rate $\approx 800$ kHz
- Straw-tube tracker to measure electron mom.
  - 5 stations (super-layers)
  - $\sigma_p < 200$ keV/c
    - 4 planes/ super-layer
    - 5 mm diameter straw-tube with 12 $\mu$m thick Mylar & 70 nm Al.
    - different for phase-I
- should be operational in vacuum
- <200$\mu$m spacial resolution

- Crystal calorimeter for trigger (ECAL)
  - LYSO crystal + APDs
COMET Collaboration

IBS, KAIST (Korea), CC-IN2P3 (France) and Georgian Technical Univ. joined recently

* 179 collaborators (32 institutes, 13 countries), FTE ~30
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Staged approach

Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet.

Detector Section
A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.

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Hajime NISHIGUCHI (KEK)
COMET Experiment
EPS-HEP2015, 22-29 Jul. 2015, Vienna
Staged approach

(Phase-I)

Protons

Production Target

Pions
Muons

Stopping Target

Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet.

Protons

Production Target

Pions

Muons

Detector Section
A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.

(full COMET (phase-II))

5m

EPS-HEP2015, 22-29 Jul. / 2015, Vienna
Goal of COMET phase-I

① Background Study for the full COMET (phase-II)

- direct measurement of potential background sources for the full COMET experiment by using the actual COMET beam line

② Search for μ-e Conversion

- a search for μ-e Conversion at the intermediate sensitivity which would be 100-times better than the present limit (SINDRUM-II)
Background measurement

- Measure almost all particles
- Same detector technology for phase-II
  - SC spectrometer solenoid
  - Straw Tube planner Tracker
  - Crystal Calorimeter
- Particle ID with dE/dx and E/p

Total momentum vs Y for μ at monitor45

Counts / Initial Proton / 2 MeV/c
Search for $\mu^-N \rightarrow e^-N$ by the COMET phase-I

Dedicated CDC-type tracker $\rightarrow$ a large bore CDC in a 1T solenoidal magnet
- all stereo-wire base
- helium-based low mass gas
- with a combination of trig. hodoscope (Cherenkov radiator + plastic scinti.)
Physics Sensitivity for COMET phase-I

- 8 GeV, 3.2 kW proton beam is assumed
- $2.5 \times 10^{12}$ protons/sec
- $< 10^{-9}$ of extinction is supposed, at least
- 110 days ($9.5 \times 10^6$ sec) running time

Expected single event sensitivity

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

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

Upper limit at 90% C.L.

$$B(\mu^-+Al\rightarrow e^-+Al) < 7.0 \times 10^{-15}$$

$\text{cf.}$ present limit $< 7 \times 10^{-13}$ (SINDRUM-II)
Facility Construction

Construction of the COMET building has been already completed. Underground structure, beam line construction is ongoing.
Beam line construction

Main part of pion/muon transport solenoid is already installed
Accelerator-preparation status for COMET

- 8 GeV operation with 3.2kW has been already tested/tuned.
- Extinction studies already involved J-PARC accelerator group.
- Miss kick injection method; Special Thanks to J-PARC Accelerator group
  - Fail injection in purpose to make the completely empty bucket

Obtained best extinction = $O(10^{-12})$ !, Good enough for COMET !!
CDC

General Structure is already completed, Wiring just started, Will complete in December

Wire stringing started in May at the Fuji hall.
Straw Tracker

- Straw Mass Production is ongoing with a strong help from JINR group
- Tracker-stations assembly will be done in 2015-2016

Straw mass production by JINR group

~1.5m

after closed and pumped
ECAL

Event Sample (105 MeV/c runs)

7x7 LYSO Array

Beam Define Counters
Trigger counters
Crystals
Preamps

LYSO is clearer than GSO.
(Amp. gain 1/4 in LYSO runs to compensate light yield difference.)
## Summary of COMET phase-I/II

<table>
<thead>
<tr>
<th></th>
<th>COMET-Phase-I</th>
<th>COMET-Phase-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>experiment starts (*)</td>
<td>in ~2016</td>
<td>in ~2019</td>
</tr>
<tr>
<td>beam power</td>
<td>3.2kW (8GeV,400nA)</td>
<td>56kW (8GeV,7μA)</td>
</tr>
<tr>
<td>running time</td>
<td>9.5 x 10^6 (sec)</td>
<td>2.0 x 10^7 (sec)</td>
</tr>
<tr>
<td># of protons</td>
<td>2.4 x 10^(19)</td>
<td>8.5 x 10^(20)</td>
</tr>
<tr>
<td># of muon stops</td>
<td>1.2 x 10^(16)</td>
<td>2.0 x 10^(18)</td>
</tr>
<tr>
<td>muon rate</td>
<td>5.8 x 10^9</td>
<td>1.0 x 10^(11)</td>
</tr>
<tr>
<td># of muon stops / proton</td>
<td>0.00052</td>
<td>0.00052</td>
</tr>
<tr>
<td># of BG</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td>S.E.S.</td>
<td>3.1 x 10^(-15)</td>
<td>2.6 x 10^(-17)</td>
</tr>
<tr>
<td>U.L. (90%CL.)</td>
<td>7.0 x 10^(-15)</td>
<td>6.0 x 10^(-17)</td>
</tr>
</tbody>
</table>

* including the engineering run
# General Schedule for Phase-I and Phase-II

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>COMET phase-I</td>
<td>construction</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>data taking</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMET phase-II</td>
<td>construction</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>data taking</td>
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</tr>
</tbody>
</table>

**COMET Phase-I**
- **2016~**
- S.E.S. $\sim 3 \times 10^{-15}$
- for $9.5 \times 10^6$ sec
- with 3.2kW proton beam

**COMET Phase-II**
- **2019~**
- S.E.S. $\sim 3 \times 10^{-17}$
- for $2 \times 10^7$ sec
- with 56kW proton beam
Summary

The COMET is a search experiment for $\mu^- N \rightarrow e^- N$ at J-PARC with an excellent sensitivity of $O(-17)$ which is four orders of magnitudes better than the present limit.

The COMET experiment employs the staged approach

- In Phase-I, ‘beam measurement’ and ‘$\mu^- N \rightarrow e^- N$ search with an intermediate sensitivity’.
- Phase-II = ‘Full COMET sensitivity’

Construction for COMET Phase-I beam-line is fully supported by KEK/J-PARC as a first priority project for the J-PARC facility upgrade.

We’re ready for the COMET Experiment phase-I.

Thank you !!!
appendices
Sensitivity for “photonic” and “non-photonic” processes is different.

<table>
<thead>
<tr>
<th></th>
<th>$\mu \rightarrow e\gamma$</th>
<th>$\mu N \rightarrow eN$</th>
</tr>
</thead>
<tbody>
<tr>
<td>photonic (eg. SUSY-base models, etc.)</td>
<td>YES (on-shell)</td>
<td>YES (off-shell)</td>
</tr>
<tr>
<td>non-photonic (eg. Extra-D, Little-Higgs, etc.)</td>
<td>NO</td>
<td>YES !!</td>
</tr>
</tbody>
</table>

eg. SUSY-based case, $B(\mu \rightarrow e\gamma)/B(\mu N \rightarrow eN) \sim O(100)$ (depends on N)
“$\mu \to e\gamma$” vs. “$\mu N \to eN$”

<table>
<thead>
<tr>
<th></th>
<th>$\mu \to e\gamma$</th>
<th>$\mu N \to eN$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant B.G.</td>
<td>Accidental</td>
<td>Beam related</td>
</tr>
<tr>
<td>Challenge</td>
<td>Detector Performance</td>
<td>Beam Quality</td>
</tr>
<tr>
<td>Suitable Muon Source</td>
<td>DC Muon Beam</td>
<td>Pulsed Muon Beam</td>
</tr>
<tr>
<td>Beam Intensity</td>
<td>(almost) Limited</td>
<td>No Limitation</td>
</tr>
</tbody>
</table>

$\mu \to e\gamma$ : accidental B.G. $\propto$ (rate)$^2$

MEG (and its upgrade) may be the final experiment

$\mu N \to eN$ : Required Beam is recently / finally achievable

Once we get a required beam, $\mu N \to eN$ experiment might be a next experiment after the MEG.
History of muon LFV search experiment

- Long Tradition on the $\mu \to e\gamma / \mu N \to eN$ Search Experiment
- Started right after the muon discovery
- $\mu \to e\gamma$ has already entered the predicted region !!
- $\mu N \to eN$ is sitting at just in front of the predicted region !!
- NOW VERY VERY ATTRACTIVE !!!!!
Present best limit on $BR(\mu N \rightarrow eN)$

- SINDRUM-II experiment (1989-1993, PSI)
Present best limit on $\mathcal{B}(\mu N \rightarrow eN)$

**SINDRUM-II experiment (1989-1993, PSI)**

- **Results:**
  - $\mathcal{B}(\mu^{-} Ti \rightarrow e^{-} Ti) < 6.1 \times 10^{-13}$ (1993)
  - $\mathcal{B}(\mu^{-} Au \rightarrow e^{-} Au) < 7 \times 10^{-13}$ (2000)

Limited by Significant BG Rate
Linac Chopper at J-PARC

Two Cavities
Proton beam at J-PARC

A pulsed proton beam is needed to reject beam-related prompt BG

Time structure required to be:

- Pulse separation ~ 1\mu s or more (muonic atom lifetime)
- Narrow pulse width ~ 100ns

Pulsed beam from slow extraction.

Fill every other rf buckets with protons and make slow extraction.

Spill length ~ 0.7-3 sec.

Good to be shorter for cosmic-ray backgrounds.
Extinction measurement at J-PARC

**Extinction** = “# of residual proton” / “# of main proton”, should be < $10^{-10}$ !!!

Should be realized with the COMET operation mode;

- 8GeV (56kW), bunched slow extraction

- Abort monitor
  - dynamic R ~ $10^{12}$ counts
- Direct measurement
  - 2010-Dec., @ FX abort line
- Result:
  - Ext. $< \sim O(-7)$

- Beam counter at secondary beam line
- Direct measurement
  - 2010-Oct., @ SX
- Result:
  - Ext. $< 5.4 \times 10^{-7}$
- Consistent with measurement at abort.
Proton beam at J-PARC

RCS
(3GeV, h=2)

598ns

MR
(30GeV, h=9)

RCS
(3GeV, h=2)

1196ns

MR
(30GeV, h=9)

【Normal Operation】

【COMET Operation】
Miss-kick method

- Miss kick injection method; Special Thanks to J-PARC Accelerator group

- By shifting the kicker timing 598ns forward/backward, residual protons are originally not injected into MR.

- Completely empty bucket should be realized!
Miss-kick Demonstration

Miss-kick methode was successfully demonstrated

This was done w/o acceleration...
Test Beam Campaign 2015

Five test-beam experiments are planned in 2015 towards finalising the setups for the COMET phase-I.

**PID demonstrations at PSI**
* PID among $\pi/\mu/e$ beam by waveform difference in LYSO signal
* 28/June-05/July

**Proton emission measur.**
* After muon capture
* AlCap experiment at PSI

**Straw Tracker Test**
* 105MeV $e^-$ beam @ Tohoku Univ
* To be done in late half in 2015
* Performance studies

**CDC performance at Spring8**
* tracker test by $e^-$ beam
* 09-12/July

**StrECAL Test**
* 105MeV $e^-$ beam @ Tohoku Univ
* Integrated test (Straw+ECAL +Trig+FE)
* To be done in beginning of 2016
Front-end Electronics R&D

- Own Front-end electronics is under development
- **ROESTI**: ReadOut Electronics for Straw Tube Instrument
- power consumption
- # of feedthrough
- space limitation
- pile-up elimination (WF)
- picking up a small charge / timing resolution, etc.

Pre-amplification → Pulse shaping, discrimination is done by ASD and Waveform digitization is done by DRS4, controlled by FPGA-based local bus control system on the board.
ROESTI prototype

* Two prototypings were done, and ver.3 is under development which will be the final prototype.
Funding for Phase-I

Almost secured...

Proton beam-line supplemental-budget-JFY2012

Detector (CDC+trig.+elec.) + Solenoid Grant-in-Aid JFY2013-17
Detector (Straw+ECAL+elec.)
Partially secured by another Grant-in-Aid.
Remaining cost would be covered by efforts from other countries, eg. UK, JINR, etc.

COMET building suppl-bdg.-JFY12 / project bdg.
## Background list for Phase-I

### Intrinsic physics backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Equation/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Muon decay in orbit (DIO)</td>
<td>Bound muons decay in a muonic atom $\mu^- + A \rightarrow \nu_\mu + A' + \gamma$, followed by $\gamma \rightarrow e^- + e^+$.</td>
</tr>
<tr>
<td>2</td>
<td>Radiative muon capture (external)</td>
<td>$\mu^- + A \rightarrow \nu_\mu + e^+ + e^- + A'$, followed by neutrons producing $e^-$.</td>
</tr>
<tr>
<td>3</td>
<td>Radiative muon capture (internal)</td>
<td>$\mu^- + A \rightarrow \nu_\mu + A' + n$, and neutrons producing $e^-$.</td>
</tr>
<tr>
<td>4</td>
<td>Neutron emission after after muon capture</td>
<td>$\mu^- + A \rightarrow \nu_\mu + A' + p$ (or d or $\alpha$), followed by charged particles producing $e^-$.</td>
</tr>
<tr>
<td>5</td>
<td>Charged particle emission after muon capture</td>
<td></td>
</tr>
</tbody>
</table>

### Beam related prompt/delayed backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Equation/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Radiative pion capture (external)</td>
<td>$\pi^- + A \rightarrow \gamma + A'$, $\gamma \rightarrow e^- + e^+$.</td>
</tr>
<tr>
<td>7</td>
<td>Radiative pion capture (internal)</td>
<td>$\pi^- + A \rightarrow e^+ + e^- + A'$.</td>
</tr>
<tr>
<td>8</td>
<td>Beam electrons</td>
<td>$e^-$ scattering off a muon stopping target.</td>
</tr>
<tr>
<td>9</td>
<td>Muon decay in flight</td>
<td>$\mu^-$ decays in flight to produce $e^-$.</td>
</tr>
<tr>
<td>10</td>
<td>Pion decay in flight</td>
<td>$\pi^-$ decays in flight to produce $e^-$.</td>
</tr>
<tr>
<td>11</td>
<td>Neutron induced backgrounds</td>
<td>Neutrons hit material to produce $e^-$.</td>
</tr>
<tr>
<td>12</td>
<td>$\bar{p}$ induced backgrounds</td>
<td>$\bar{p}$ hits material to produce $e^-$.</td>
</tr>
</tbody>
</table>

### Other backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Cosmic-ray induced backgrounds</td>
</tr>
<tr>
<td>15</td>
<td>Room neutron induced backgrounds</td>
</tr>
<tr>
<td>16</td>
<td>False tracking</td>
</tr>
</tbody>
</table>
Table 26: Summary of the estimated background events for a single-event sensitivity of $3 \times 10^{-15}$ with a proton extinction factor of $3 \times 10^{-11}$.

<table>
<thead>
<tr>
<th>Type</th>
<th>Background</th>
<th>Estimated events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics</td>
<td>Muon decay in orbit</td>
<td>0.01</td>
</tr>
<tr>
<td>Physics</td>
<td>Radiative muon capture</td>
<td>$5.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Physics</td>
<td>Neutron emission after muon capture</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Physics</td>
<td>Charged particle emission after muon capture</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Beam electrons (prompt)</td>
<td>$7.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Muon decay in flight (prompt)</td>
<td>$\leq 1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Pion decay in flight (prompt)</td>
<td>$\leq 2.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Other beam particles</td>
<td>$\leq 2.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>Radiative pion capture(prompt)</td>
<td>$4.24 \times 10^{-4}$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Beam electrons (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Muon decay in flight (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Pion decay in flight (delayed)</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Radiative pion capture (delayed)</td>
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<tr>
<td>Delayed Beam</td>
<td>Anti-proton induced backgrounds</td>
<td>0.007</td>
</tr>
<tr>
<td>Others</td>
<td>Electrons from cosmic ray muons</td>
<td>$&lt; 0.0001$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.019</td>
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