

# Overview of the COMET **Experiment**

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#### Introduction



muon to electron conversion in a muonic atom

$$
\mu^- + N \rightarrow e^- + N
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(Charged Lepton Flavour Violation=CLFV)

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**loutline** 

#### • Physics Motivation of Charged Lepton Flavour Violation

- Muon to electron conversion
- COMET at J-PARC
- COMET Phase-I (under preparation at J-PARC)
- Exotic searches with COMET
- Summary



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## CLFV for New Physics Search



## CLFV in the Standard Model (SM)



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From neutrino oscillation, neutrinos have masses and are mixed in the SM, indicating neutral LFV. How about CLFV ?



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indicating neutral LFV.  $S$  $\frac{1}{2}$  How about CLFV<sup>p</sup>?  $e^{+\gamma} \approx 10^{-54}$  **10<sup>-54</sup>** are mixed in the SM,  $M_{\odot}$  are mixed in the SM, From neutrino oscillation, neutrinos have masses and



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CLFV has a large window for BSM w/o SM backgrounds.



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 $E_{IIRONQON}$  otrotom  $IIRO101(0)$ European strategy update (2019)

5



 $E_{IIRONQON}$  otrotom  $IIRO101(0)$ European strategy update (2019)

(sky blue)

## Present:<br>(sky blue)  $\Lambda \sim \mathcal{O}(10^4) \text{ TeV}$



 $\begin{array}{c}\n\mathsf{OMET}\n\end{array}$ 



 $E_{IIRONQON}$  otrotom  $IIRO101(0)$ European strategy update (2019)

Present:

\n
$$
\Lambda \sim \mathcal{O}(10^4) \text{ TeV}
$$
\n(sky blue)

OM

upcoming experiments aim x10000 improvement

$$
R \propto \frac{1}{\Lambda^4}
$$

5





 $E_{IIRONQON}$  otrotom  $IIRO101(0)$ European strategy update (2019)





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#### $E_{IIRONQON}$  otrotom  $IIRO101(0)$ European strategy update (2019)

operator and the oblique parameters for  $E$  precision tests, respectively. The shown effectively. The shown effectively are shown



compared with the reach the reach in the reach in the collect highthat our present and future colliders can directly reach. CLFV would explore scales way beyond the energies 2



#### Model dependent CLFV Predictions CLFV Predictions (for μ→eγ and µ-e conversion) **1.54 p**

y





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## Muon to Electron Conversion





#### μ→e Conversion in a muonic atom





## μ→e Conversion in a muonic atom

#### 1s state in a muonic atom



#### nuclear muon capture

$$
\mu^- + (A, Z) \to \nu_\mu + (A, Z - 1)
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\mu^- + (A,Z) \rightarrow e^- + (A,Z)
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#### coherent process



(for the case that the final nucleus is the ground state.)

#### Event Signature :

a single mono-energetic electron of 105 MeV



#### μ→e Conversion in a muonic atom  $CR(\mu^-N \to e^-N) \equiv$  $\Gamma(\mu^-N \to e^-N)$  $\Gamma(\mu$ <sup>-</sup>N  $\rightarrow$  all)

#### 1s state in a muonic atom



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### Backgrounds for µ-e conversion

#### intrinsic physics backgrounds

Muon decay in orbit (DIO) Radiative muon capture (RMC) neutrons from muon nuclear capture Protons from muon nuclear capture

beam-related backgrounds

Radiative pion capture (RPC) Beam electrons Muon decay in flights Neutron background Antiproton induced background

cosmic-ray and other backgrounds

Cosmic-ray induced background False tracking







## COMET@J-PARC

#### **COMET**



#### $\bullet$  OMET = COherent Muon to Electron Transition  $\begin{array}{|c|c|c|}\hline \textbf{1} & \text$

#### **COMET PHASE IN GEOMETRY**





**• Proton beam, 8 GeV, 56kW** • 2x10<sup>11</sup> stopped muons/s

#### **COMET PHASE IN GEOMETRY**



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COMET = COherent Muon to Electron Transition

•Single event sensitivity : 1.4x10-17 •90% CL limit : < 3.2x10-17 •x10000 from SINDRUM-II •Total background: 0.32 events •Running time: 2/3 years (2x107sec) • Proton beam, 8 GeV, 56kW • 2x10<sup>11</sup> stopped muons/s

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#### **COMET PHASE IN GEOMETRY**

pion capture

system

*p*

electron spectrometer detector muon beamline proton target muon target (Aluminium) •Single event sensitivity : 1.4x10-17 •90% CL limit : < 3.2x10-17 •x10000 from SINDRUM-II •Total background: 0.32 events •Running time: 2/3 years (2x107sec) • Proton beam, 8 GeV, 56kW • 2x10<sup>11</sup> stopped muons/s COMET = COherent Muon to Electron Transition

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#### Proton Accelerator J-PARC





#### Proton Accelerator J-PARC

linac



**Material/Life-Science Facility** (**MLF**) (muon source, pulse neutron source)

#### $\sum_{k=1}^{n}$ TU<del>U</del>VIII main 30-GeV ring

**Neutrino Experiment Facility** (T2K, towards SK)

**Linac** (330m, 400MeV) **3GeV Synchrotron (RCS)** (350m ring, 25Hz, 1MW)

**30GeV Synchrotron (MR)** (1600m ring, 0.75MW)

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#### Improvements for Signal Sensitivity





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Pion capture and muon transport by high field superconducting solenoid system: 10<sup>11</sup>  $\mu$ /s for 50 kW proton beam power





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#### The world's highest muon source

# 1018 muons in total


### Improvements of Background Rejection





### Improvements of Background Rejection

Muon DIO background Low-mass trackers in vacuum & thin target

Beam-related backgrounds



Beam pulsing with separation of 1 μsec improve electron energy resolution

measured between beam pulses

proton extinction = #protons between pulses/#protons in a pulse  $< 10^{-10}$ 

Decay in flight background

Cosmic ray background



eliminate energetic muons (>75 MeV/c)

Cosmic ray active veto system



### Time Structure of Muon Beam





### Time Structure of Muon Beam **Proton Beam Structure of Muc**

(COMET) experiment

Proton Beam for COMET



Aluminum muon target ( muonic atom lifetime of 864 ns is good for this repetition.)



### Time Structure of Muon Beam **Proton Beam Structure of Muc**

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Proton Beam for COMET



### Charge and Momentum Selection in Curved Solenoid with Dipole field



**Charge and Momentum Selection** in Curved Solenoid with Dipole field dipole tield  $j$ unu Mondia Solenoid with Dipole field  $j$ ved Solenoid With Dipol curved solenoid and drifts and dr<br>The curve distribution and drifts dipole field perpendicu to the solenoid field





#### **Charge and Momentum Selection** in Curved Solenoid with Dipole field Charge Terry  $j$ unu Mondia Solenoid with Dipole field  $j$ ved Solenoid With Dipol dipel<del>nye ta legal alg</del>el to the solenoid field Charge and Momentum Selection and Momentum Selepation u and ividitionian boxa<br>ved Solenoid with Dino noid with Dipole fie to the solenoid field





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### Trajectory of Signal Electrons in Curved Solenoid + Dipole Field **Bending the Solenoids Harts**<br>Benefict the Solenoids of Signal Flectrons<br>References Acquatory of Organic Libberond<br>Lin Curved Selengid & Dinele Field momentumthatremainsonaxis.Eg.105MeV/c:



#### simulations

 $n<sub>0</sub>$ dipole no dipole

### -0.08T -0.08T dipole

-0.22T -0.22T dipole



#### Mu2e at Fermilab Transport Solenoid by Graded field. Pions decay to muons.

Pions captured and accelerated towards

Production Solenoid.





 $L$  ,  $L$  , **Sensitivity : <6x10-17 (90% CL)** selection.  $E$ liminates high energy negative particles, positive particl particles and line-of-site neutralistic neutralistic neutralistic neutralistic neutralistic neutralistic neutr<br>Communication in O Run time: 3 years (2x107sec/year) commissioning in 2026 a factor of 10,000 improvement

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#### 6x10<sup>10</sup> muons/s from 8 kW, 8 GeV proton beam **Cosmic Ray Veto not shown Proton Beam** aluminium target **Production Solenoid**  $1T$ **Detector Solenoid**  $2.5^{-}$ **Transport Solenoid**  $5T$  $1<sub>1</sub>$ **Production Target** Calorimeter **Tracker**

Transport solenoid performs sign and momentum Sensitivity : <6x10-17 (90% CL) selection.  $E$ liminates high energy negative particles, positive particl particles and line-of-site neutralistic neutralistic neutralistic neutralistic neutralistic neutralistic neutr<br>Communication in O Run time: 3 years (2x107sec/year) commissioning in 2026 a factor of 10,000 improvement |  $\bullet$ 800 MeV, 100 kW from PIP-II

### Mu2e-II

 $\sim$  Fermion – Fermilab Snowmass Package Snowmass P •aim at O(10-18) with 3 years a factor of 10 from Mu2e



### Mu2e vs. COMET

beam line

electron



(same direction)

(opposite direction)

spectrometer straight solenoid curved solenoid



### Mu2e vs. COMET



Detector solenoid Curved sepctrometer solenoid protons | 8 kW 3 years | 56 kW 1 year muon beam line 2x 90º bends (opposite direction) 2x 90º bend (same direction) electron spectrometer straight solenoid curved solenoid

Select low momentum muons

eliminate muon decay in flight

### Mu2e vs. COMET





Select low momentum muons

eliminate muon decay in flight

Selection of 100 MeV electrons

eliminate protons uclear muon apture.

19 inate low y events to the detector quiet.



**Proton beam**

**Pion production target Radiation shield**

## **COMET Collaboration** PV I ation COMET Collaboration Increasing...

New members are





## **COMET Collaboration** PV I ation COMET Collaboration Increasing...

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### Staged Approach







### only the first 90 degree curved solenoid + detector solenoid



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only the first 90 degree curved solenoid + detector solenoid

• Proton beam, 8 GeV, 3.2kW • 2x10<sup>9</sup> stopped muons/s



only the first 90 degree curved solenoid + detector solenoid

• Proton beam, 8 GeV, 3.2kW • 2x10<sup>9</sup> stopped muons/s **•Single event sensitivity : 2x10-15** •90% CL limit : < 5x10-15 •x100 from SINDRUM-II •Total background: 0.32 events •Running time: 0.4 years (1.2x107sec)

muon target

detector

muon beamline

proton target

### Two Detectors, CyDet and StrECAL , for COMET Phase-I **COMET Phase-I**





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### Two Detectors, CyDet and StrECAL , for COMET Phase-I







### COMET Phase-I Status



## COMET Facility at J-PARC COMET Facility at I-PARC



- Experimental Hall building completed • COMET experimental hall building, completed in 2015
- Cryogenic system, completed in • Cryogenic system, completed in 2021
- New proton C line, completed in 2022

 $\mathbf O$ 

### COMET Phase-I : Superconducting Solenoid Construction







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#### Muon Transport Solenoid





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# **ELECTRO** Pion Capture Solenoid **CS cold mass**

### Muon Transport Solenoid



### Construction of CyDet and StrECAL

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### Construction of CyDet and StrECAL



Standard setup: RECBE Suppressed/Raw mode  $CDC HV = 1800 V$ Threshold =  $3500$  mV <- a little high Trigger rate  $\sim$  33 Hz

Event 4 RO side



−400 −200 constructed at 0 CDC readouts 400 Osaka University. 800 1000 C<sup>®</sup>C constructed at

−800

IHLP, China.

 $X$  [mm] <sup>−</sup>1000−<sup>800</sup> <sup>−</sup><sup>600</sup> <sup>−</sup><sup>400</sup> <sup>−</sup><sup>200</sup> <sup>0</sup> <sup>200</sup> <sup>400</sup> <sup>600</sup> <sup>800</sup> <sup>1000</sup> <sup>−</sup><sup>1000</sup>







### Construction of CyDet and StrECAL





### COMET Phase *α* (2023)




### COMET Phase *α* (2023)

#### COMET proton beam commissioning

#### COMET Phase *α* (2023)  $\alpha$  (2023)



## COMET proton beam commissioning

#### Vacuum ducts & main components in Phase alpha





### COMET Phase *α* (2023)



# COMET Phase *α* (2023) COMET Phase α





### Observation of the first muon beam on February 11th, 2023

# COMET Phase *α* (2023) COMET Phase α





### Observation of the first muon beam on February 11th, 2023

### COMET Phase-I is planned to start in JFY2025.



## 100年6月 凉  $\begin{picture}(120,15) \put(0,0){\vector(1,0){30}} \put(15,0){\vector(1,0){30}} \put(15,0){\vector($ **SED** plengangydologistikonomialna virokonomial **SERBERBERG DEVENDENTIBULARING CONTROL** U Marini.

## Exotic Search with COMET



## Search for *μ* → *ea*





### Search for *μ* → *ea*



 $a$  is a light, invisible, neutral particle with LFV coupling to leptons.

- : axion like particle (ALP)
- : Neutral Heavy Lepton (NHL)
- : light flavour violating Z'



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\mathcal{L}_{alp} = \sum_{i,j} \frac{\partial_{\mu} a}{2f_a} \overline{\mathcal{E}}_i \gamma^{\mu} [C_{i,j}^V + C_{i,j}^A] \gamma^5 \mathcal{E}_j
$$
  

$$
\Gamma(\mathcal{E}_i \to \mathcal{E}_j a) = \frac{1}{16\pi} \frac{m_{\mathcal{E}_i}^2}{F_{ij}^2} \left(1 - \frac{m_a^2}{m_{\mathcal{E}_i}^2}\right)^2
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$$

- Jodidio et al. (TRIUMF) 1986
	- polarised muons
	- $BR(\mu^+ \to e^+a) < 2.6 \times 10^{-6}$
	- $F_{e\mu}$  > 5.5 × 10<sup>9</sup> GeV
- TWIST (TRIUMF) 2014
	- Michel parameters
	- $BR(\mu^+ \to e^+a) < 5.8 \times 10^{-5}$
	- $F_{e\mu} > 1.2 \times 10^9 \,\text{GeV}$
- Crystal Box (LAMPF) 1988
	- Nal(TI) crystals
	- $BR(\mu^+ \to e^+ a \gamma) < 1.1 \times 10^{-9}$
	- $F_{e\mu} > 9.8 \times 10^8$  GeV
- MEG-II fwd (PSI), planned
	- polarized muons
	- BR( $\mu^+ \to e^+ a$ ) < 10<sup>-7</sup>
	- $\sqrt{F_{eu}} > 10^9 10^{10} \text{ GeV}$
- Mu3e-online (PSI), planned
	- 25  $< m_a < 90$  MeV
	- $BR(\mu^+ \to e^+ a) < 10^{-8}$
	- $F_{e\mu} > 10^{10} \text{ GeV}$



## Search for  $\mu^+ \rightarrow e^+a$  with COMET/Mu2e





## Search for  $\mu^+ \rightarrow e^+a$  with COMET/Mu2e

- COMET and Mu2e will use beam for detector *μ*+/*π*<sup>+</sup> responce calibration runs.
- •These data set will be larger than the existing data by orders of magnitude.
	- $\bullet \mu^{+} : 3 \times 10^{13}$
	- $\bullet \pi^{+} : 2 \times 10^{12}$
- •It was pointed out that searches for  $\mu^+ \rightarrow e^+ a$  and  $\pi^+ \rightarrow e^+a$  can be made.

R.J. Hill, R. Plestid, and J. Zupan, ArXiv 2310.00043, September 2023 L. Calibbi, D. Redigolo, R. Zieglerand J. Zupan, JHEP09 (2021) 173



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#### electron spectra (normalized by rate)





Y. Uesaka, Phys. Rev. D102, 095007 (2020)

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#### Advantage

- For  $m_X \thicksim 0$ , a signal peak is not on Michel edge.  $\blacksquare$  Sasakawa Scientific Research Grant from The  $\blacksquare$ 
	- Spectrum depends on Z of a target, systematic control, possible.
- Disadvantage  $\bullet$ 
	- Not mono-energetic.

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- · Disadvantage
	- Not mono-energetic.
- Preliminary COMET study was made.
- Phase-I,  $B(\mu^{-} \to e^{-}a) < O(10^{-5})$
- Phase-II,  $B(\mu^- \to e^- a) < O(10^{-(8-9)})$ 
	- $f_a > 10^{10-11}$  GeV

33 T. Xing, C. Wu, H. Miao, H.B. Li, W. Li, Y. Yuan, Y. Zhang, Chine. Physics C, 47 (2023) 013108

### **Conclusion**



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- $\bullet \mu \rightarrow e$  conversion in a muonic atom has a unique discovery potential for BSM.
- Current limits probe BSM at 10<sup>4</sup> TeV, and the upcoming experiment will do at 105 TeV.
- COMET Phase-I is aiming at a 100 times improvement over the current limit (i.e. S.E. sensitivity of 3x10-15), whilst COMET Phase-II aims at a factor of 10,000 or more.
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my dog, IKU