Pulsed Muon Beam Experiments

Yoshitaka Kuno
Department of Physics,
Osaka University, Japan

August 28th 2019
NuFACT2019,
Daegu, Korea

Introduction

Muon particle physics experiments and Beam time structure

Introduction

Muon particle physics experiments and Beam time structure

Pulsed muon beam

for the experiments of

- delayed measurements ($\mu \rightarrow e$ conversion)
- with storage ring and acceleration (muon g-2)
- with pulsed instruments (laser)

proton synchrotron
(J-PARC, FNAL, RAL)

Introduction

Muon particle physics experiments and Beam time structure

Pulsed muon beam

for the experiments of

- delayed measurements ($\mu \rightarrow e$ conversion)
- with storage ring and acceleration (muon g-2)
- with pulsed instruments (laser)

proton synchrotron
(J-PARC, FNAL, RAL)

DC muon beam

for the experiments of

- coincidence measurements with low instantaneous intensity ($\mu \rightarrow e\gamma$, $\mu \rightarrow eee$)

proton cyclotron
(PSI, TRIUMF, MuSIC)

Introduction: World Map

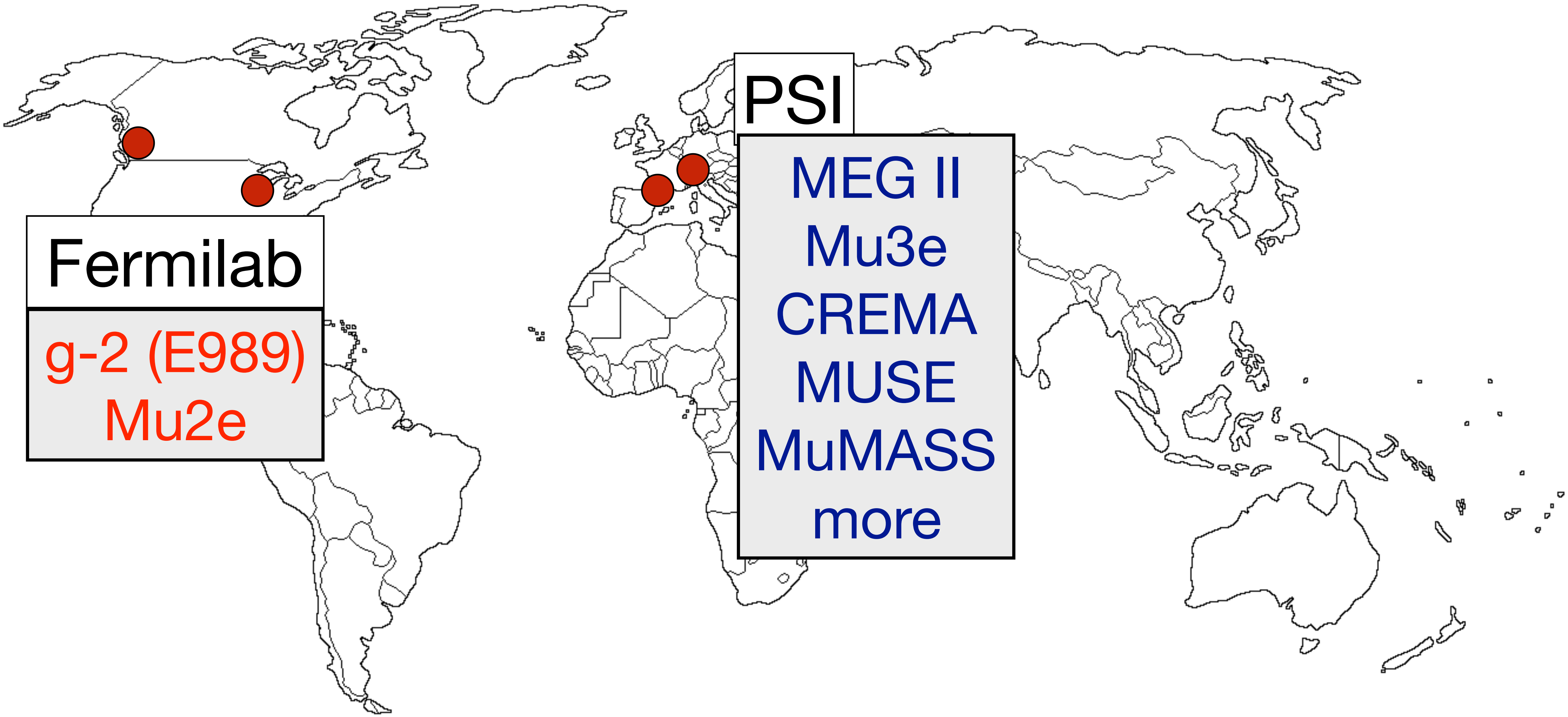
DC muon beam experiments
pulsed muon beam experiments

Introduction: World Map

DC muon beam experiments

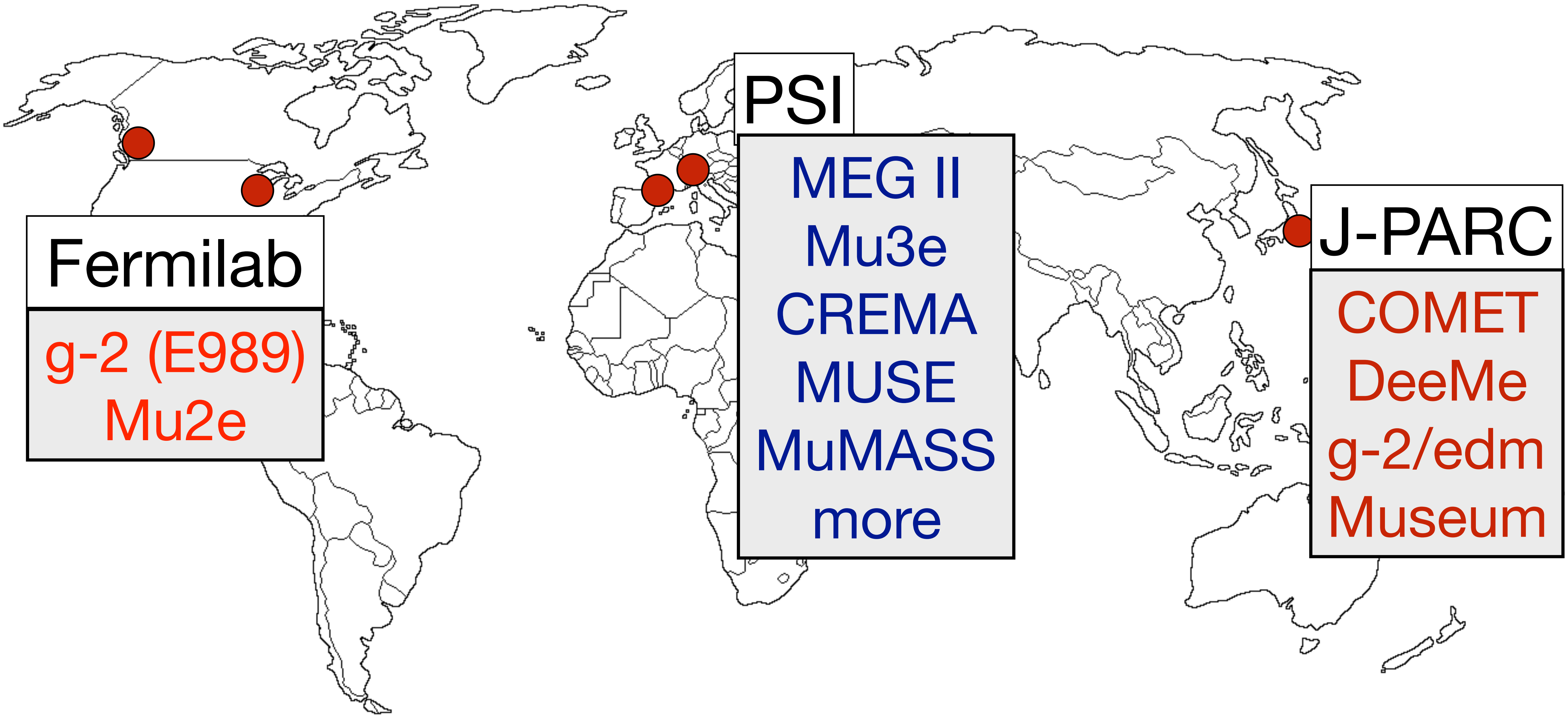
pulsed muon beam experiments

Introduction: World Map



DC muon beam experiments
pulsed muon beam experiments

Introduction: World Map



DC muon beam experiments

pulsed muon beam experiments

Outline

- Charged Lepton Flavour Violation (CLFV) with Muons
  - Physics Motivation
  - $\mu^- \rightarrow e^-$ conversion
  - $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$ (just brief)
- Muon g-2
- Summary

Outline

- Charged Lepton Flavour Violation (CLFV) with Muons
  - Physics Motivation
  - $\mu^- \rightarrow e^-$ conversion
  - $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$ (just brief)
- Muon g-2
- Summary

Details are given in the WG4 sessions.

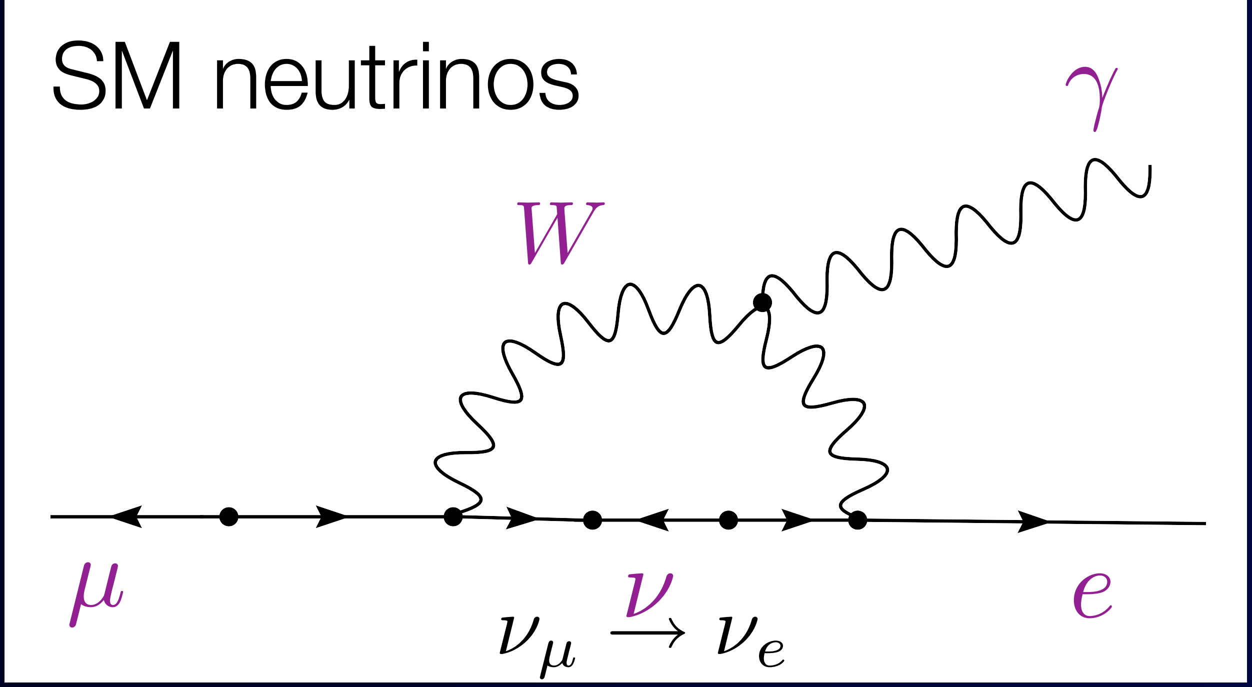
Charged Lepton flavour Violation (CLFV) with Muons

Lepton Mixing in the SM to CLFV

Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.

Lepton Mixing in the SM to CLFV

Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.

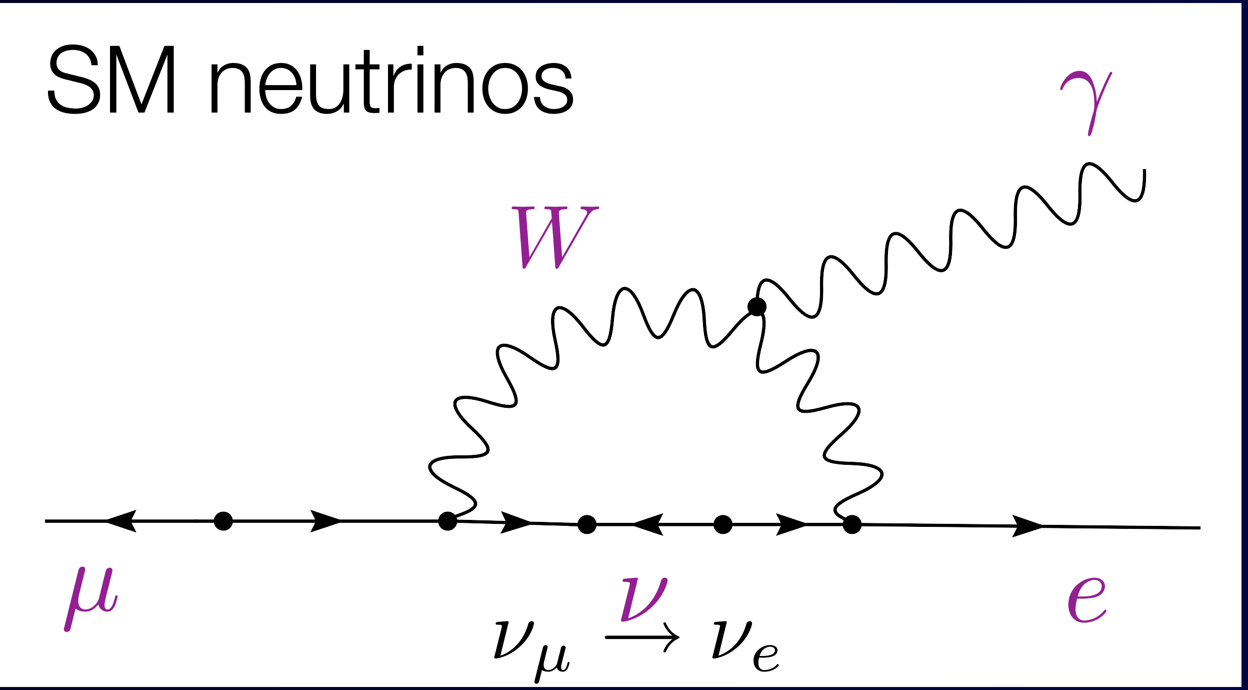


S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

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

Lepton Mixing in the SM to CLFV

Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.



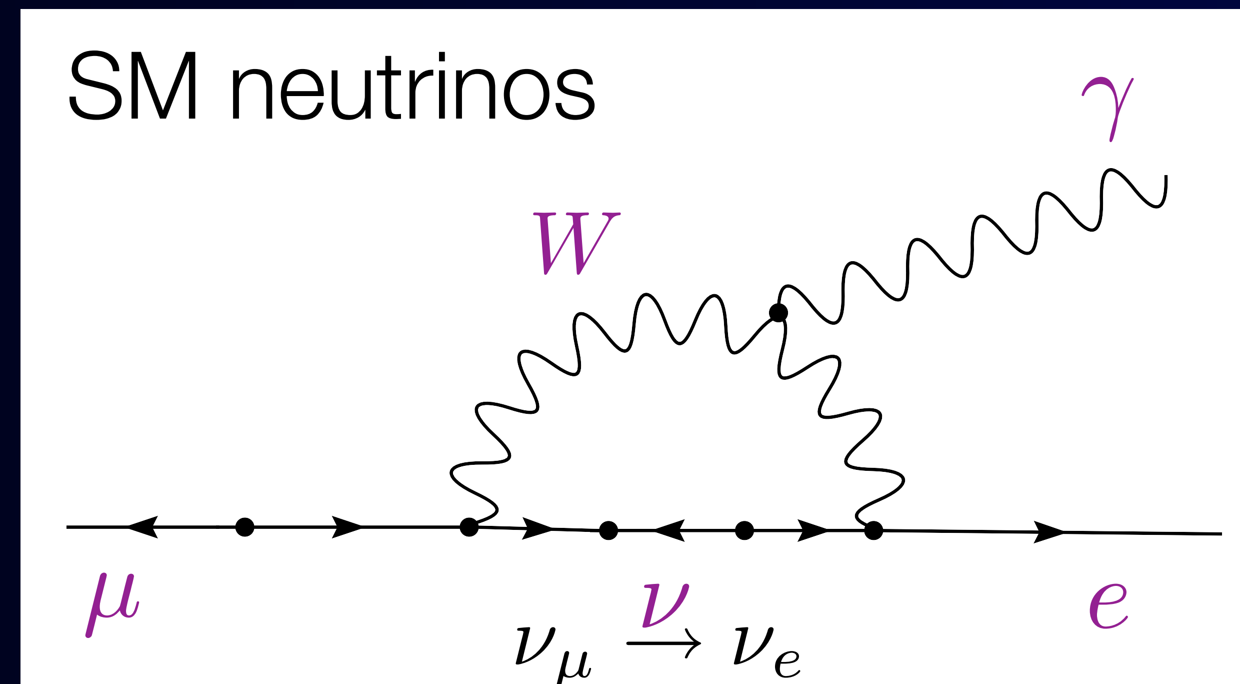
S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

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

BR~O(10^{-54})

Lepton Mixing in the SM to CLFV

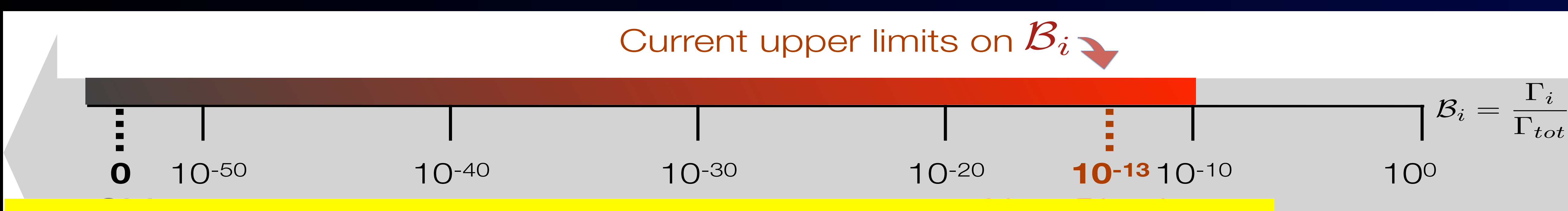
Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.



S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

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

BR~O(10^{-54})



Large window for BSM search without SM backgrounds

New Physics Energy Scale of CLFV Search

Effective Field Theory (EFT) Approach

$$\mathscr{L}_{eff} = \mathscr{L}_{\mathrm{SM}} + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}}$$

Λ is the energy scale of new physics
$C^{(d)}$ is the coupling constant.

New Physics Energy Scale of CLFV Search

Osaka University

Effective Field Theory (EFT) Approach

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}}$$

Λ is the energy scale of new physics
$C^{(d)}$ is the coupling constant.

from BR(μ→eγ)<4.2x10^{-13}

$$\frac{C^6}{\Lambda^2}\mathscr{O}^6 \rightarrow \frac{C^6}{\Lambda^2}\bar{e}_L\sigma^{\rho\nu}\mu_R\Phi F_{\rho\nu}$$

⬇

$$\Lambda \sim \mathscr{O}(10^4)\ \mathrm{TeV}$$

$c.f.\ \Delta m_K, \varepsilon'$

	$\lvert C_a\rvert$ [$\Lambda = 1$ TeV]	Λ (TeV) [$\lvert C_a\rvert = 1$]	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^4	$\mu \to e\gamma$
$C_{\ell e}^{\mu\mu\mu e,e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \to e\gamma$ [1-loop]
$C_{\ell e}^{\mu\tau\tau e,e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \to e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^4	$\mu \to eee$
$C_{\ell\ell,ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \to eee$
$C_{\ell e}^{\mu eee,ee\mu e}$	3.3×10^{-5}	174	$\mu \to eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^4	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{\ell q,\ell d,ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^3	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$
$C_{\ell u,eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^- \mathrm{Au} \to e^- \mathrm{Au}$

F. Feruglio, P. Paradisi and A. Pattori, Eur. Phys. J. C 75 (2015) no.12, 579
G. M. Pruna and A. Signer, JHEP 1410 (2014) 014

New Physics Energy Scale of CLFV Search Future

Future planned CLFV experiments (with muons) expecting improvements by an additional factor of >10,000 or more (will be described later) would probe ….

New Physics Energy Scale of CLFV Search Future

Osaka University

Future planned CLFV experiments (with muons) expecting improvements by an additional factor of >10,000 or more (will be described later) would probe ….

$$\Lambda \sim \mathcal{O}(10^5)\ \text{TeV}$$

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

CLFV would explore scales way beyond the energies that our present and future colliders can directly reach.

It is crucial in establishing where is the next fundamental scale above the electroweak symmetry breaking.

"Golden" μ→e CLFV Transition Processes

Osaka University

$$\mu^+ \rightarrow e^+\gamma$$

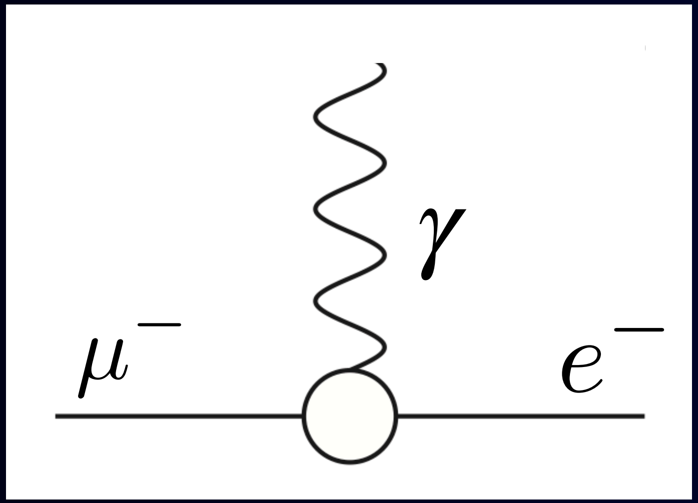
$$\mu^+ \rightarrow e^+e^+e^-$$

$$\mu^-N \rightarrow e^-N$$

"Golden" μ→e CLFV Transition Processes

dipole interaction

$$\mu^+ \to e^+\gamma$$



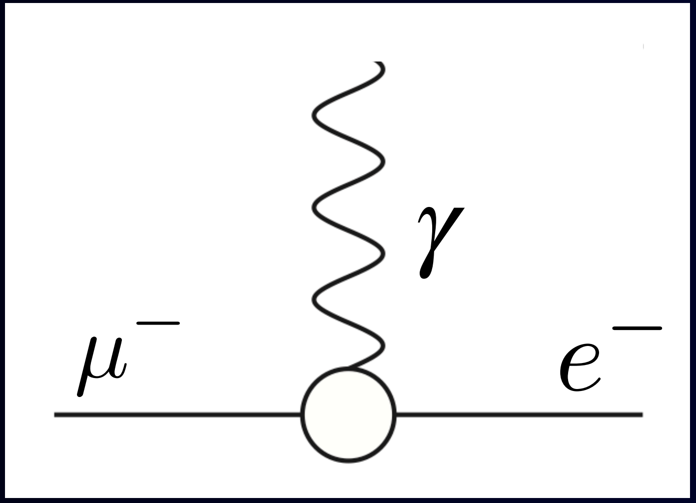
$$\mu^+ \to e^+e^+e^-$$

$$\mu^- N \to e^- N$$

“Golden” μ→e CLFV Transition Processes

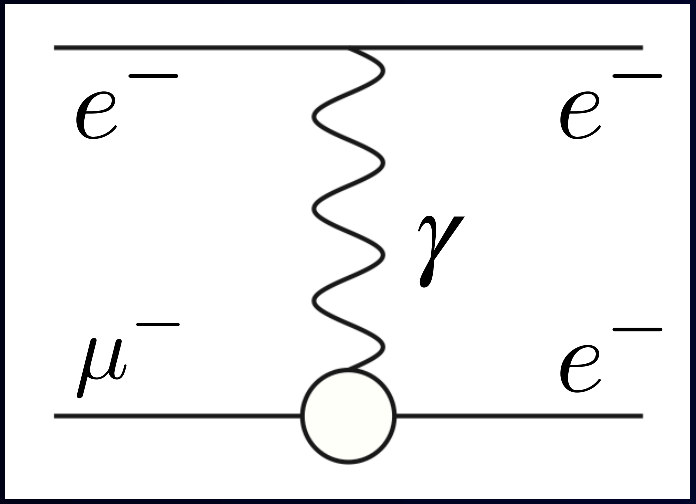
dipole interaction

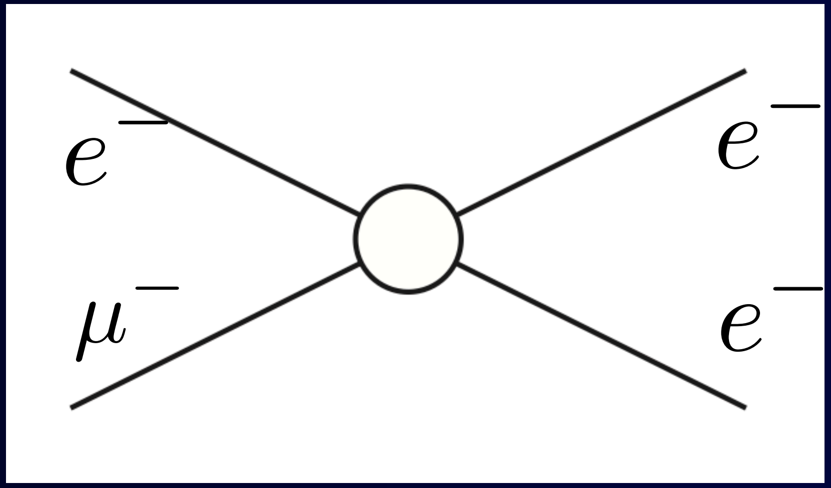
$\mu^+ \rightarrow e^+\gamma$



contact interaction

$\mu^+ \rightarrow e^+e^+e^-$



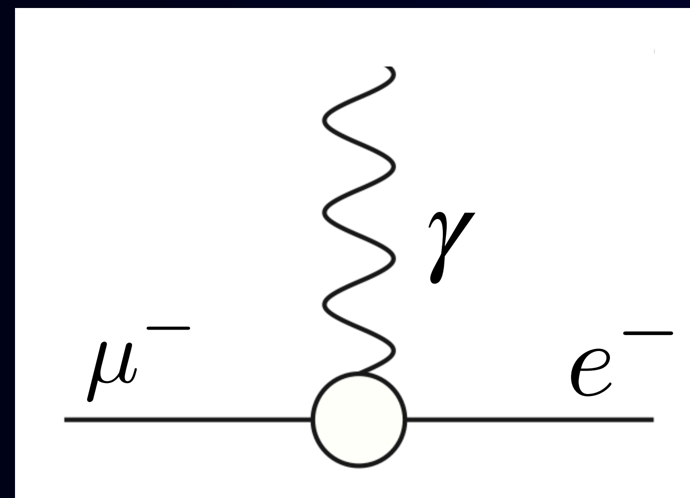


$\mu^-N \rightarrow e^-N$

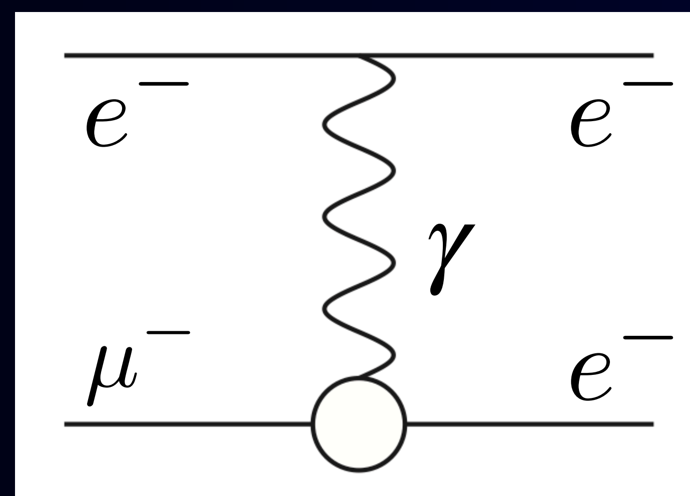
“Golden” μ→e CLFV Transition Processes

dipole interaction

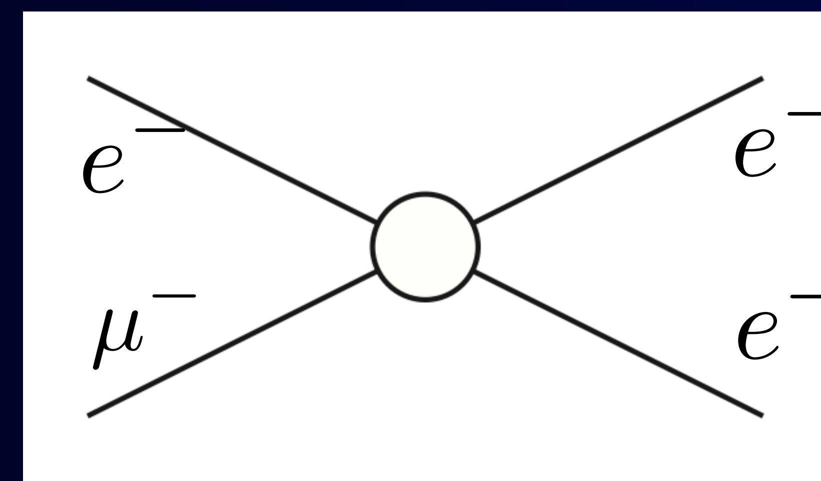
$$\mu^+ \to e^+\gamma$$



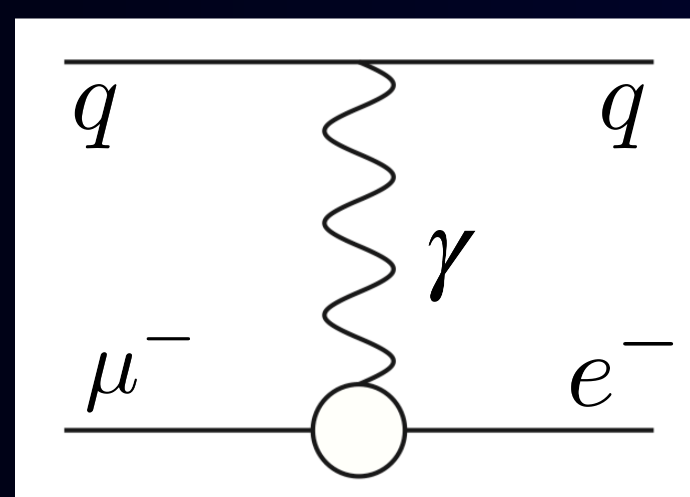
$$\mu^+ \to e^+e^+e^-$$



contact interaction



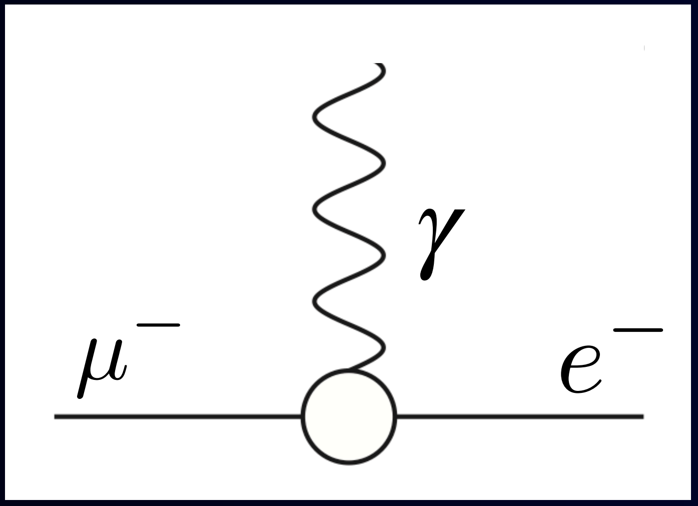
$$\mu^-N \to e^-N$$



“Golden” μ→e CLFV Transition Processes

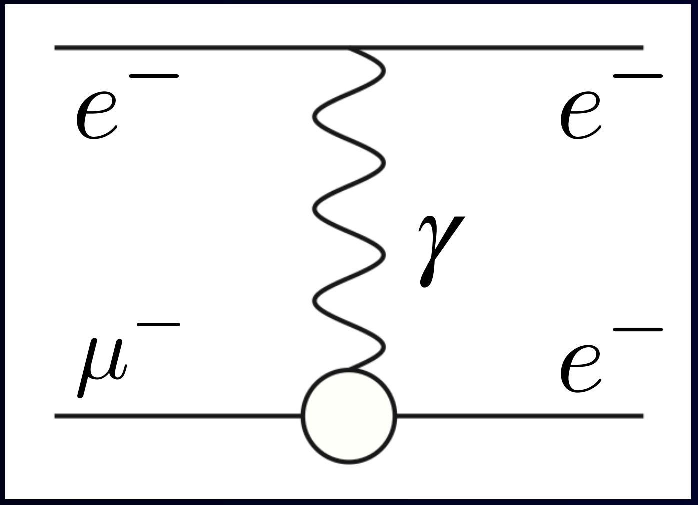
dipole interaction

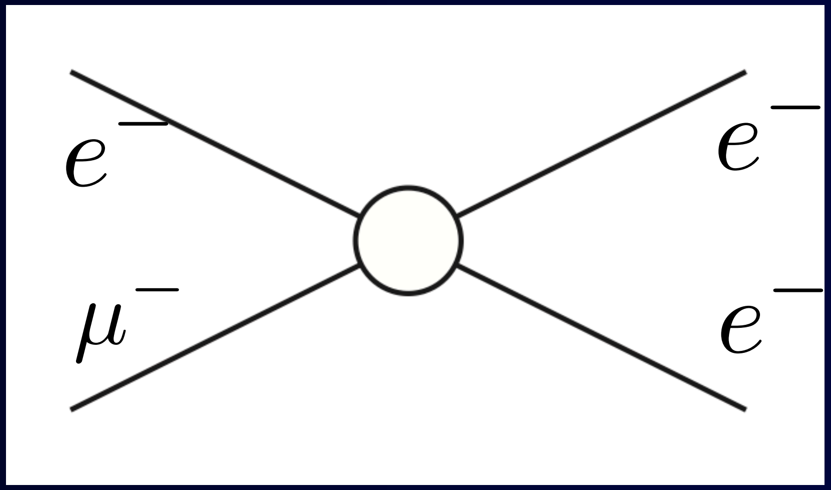
$\mu^+ \to e^+\gamma$



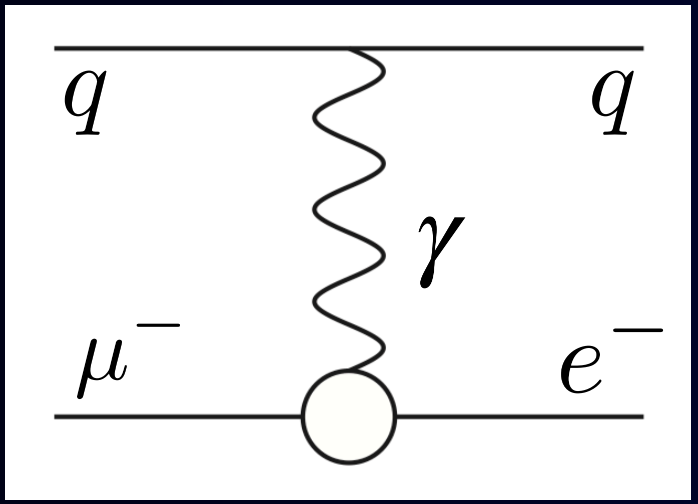
contact interaction

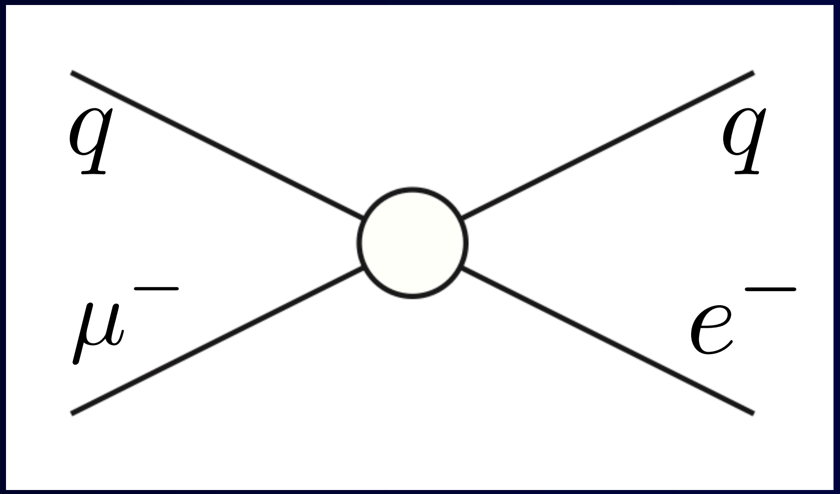
$\mu^+ \to e^+e^+e^-$





$\mu^-N \to e^-N$

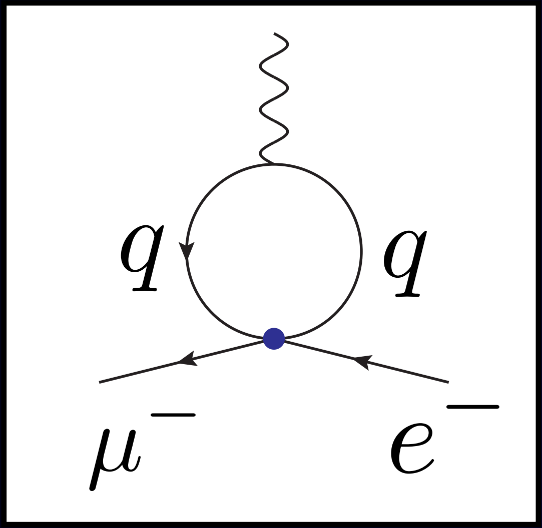


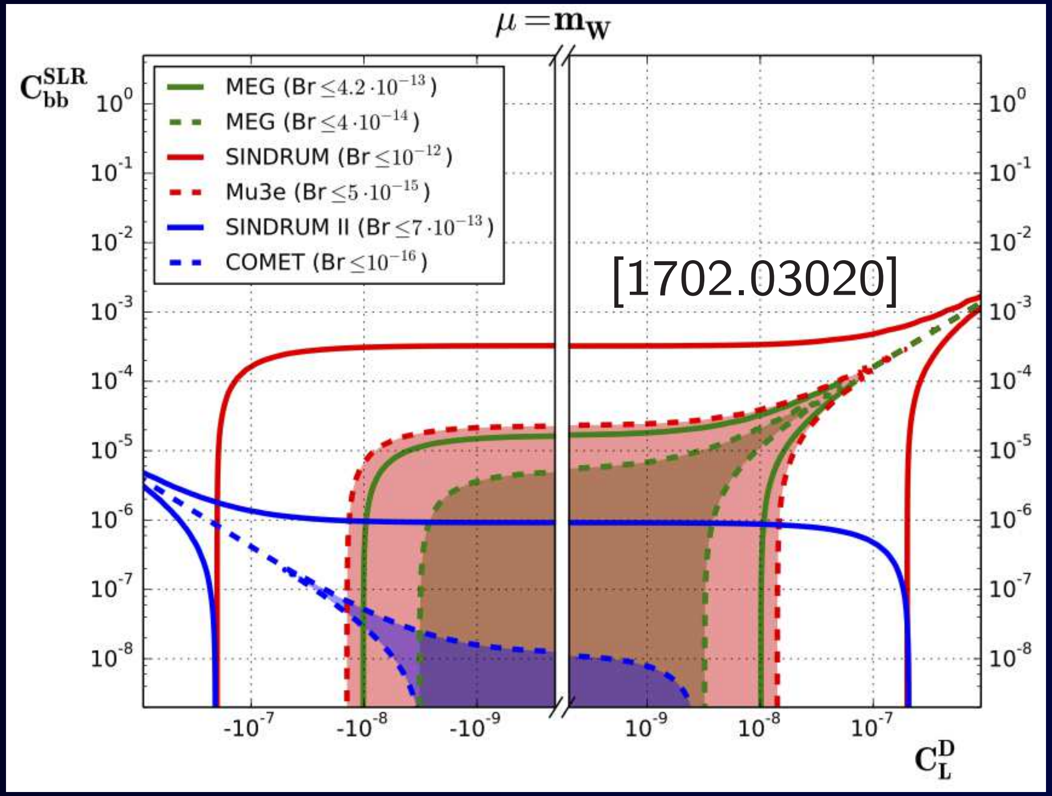


Operator Mixing via RGE

EFT at high physics scale

The operators are mixed in RGE at the experiment scale



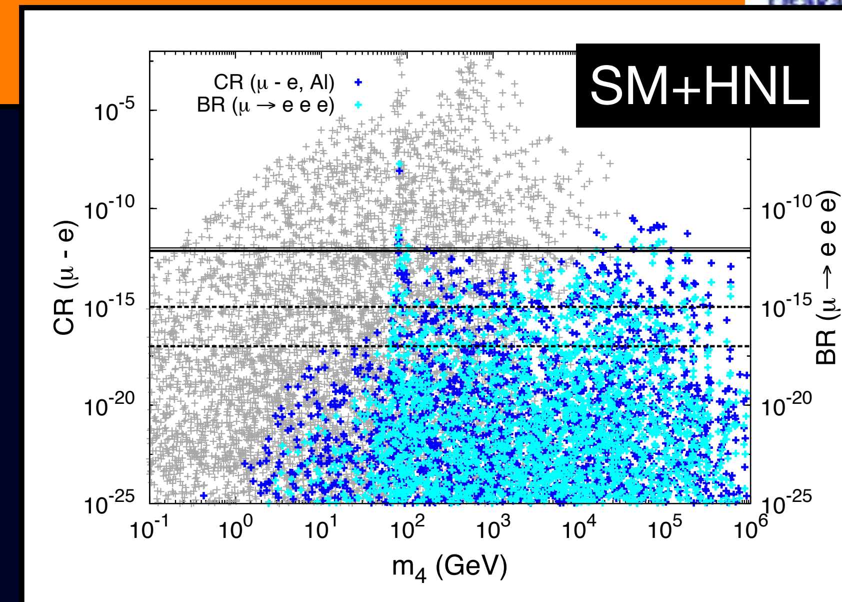


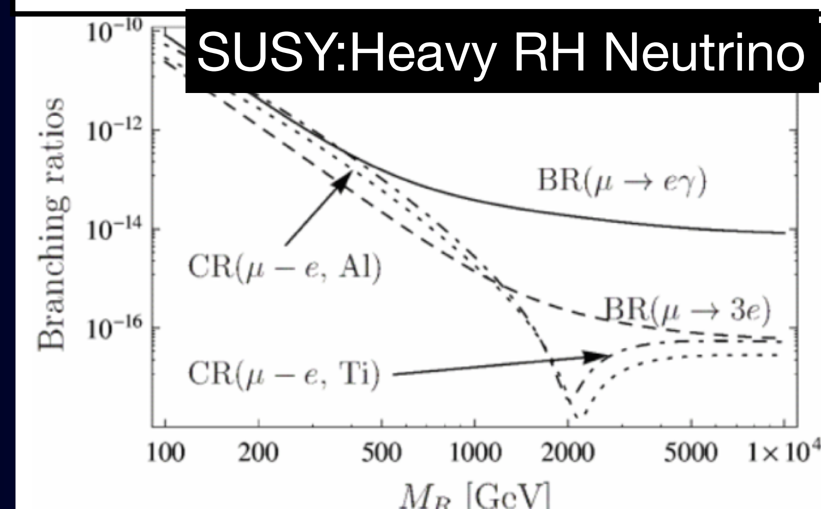
All processes are equally important (complementary).

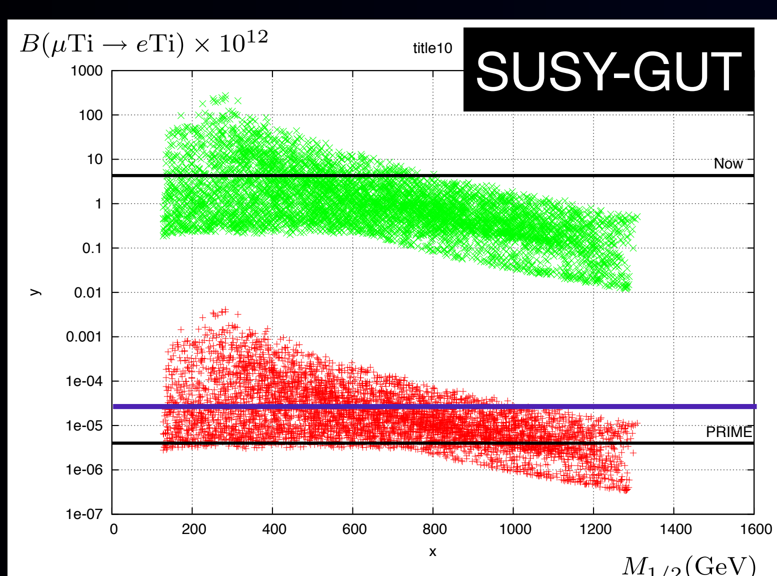
A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, arXiv:1611.03409
A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, JHEP 117 (2017) no.5
S. Davidson, Eur. Phys. J. C76 (2016) 370

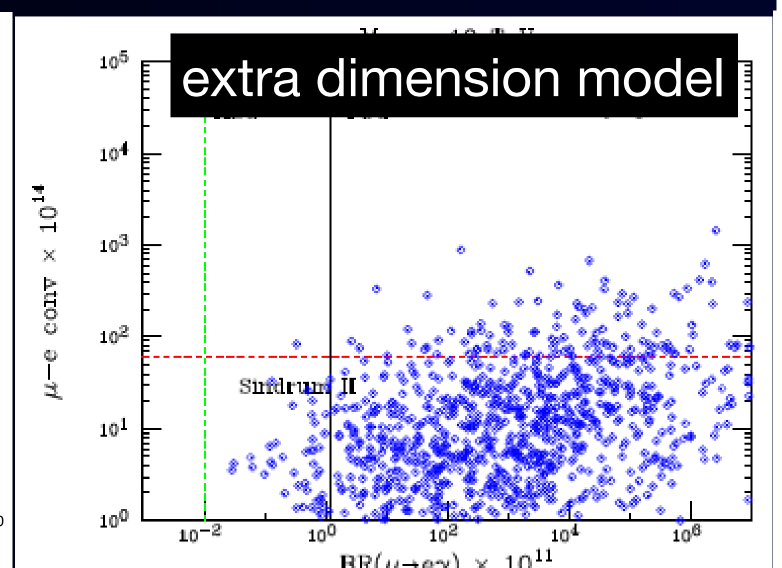
Model dependent CLFV

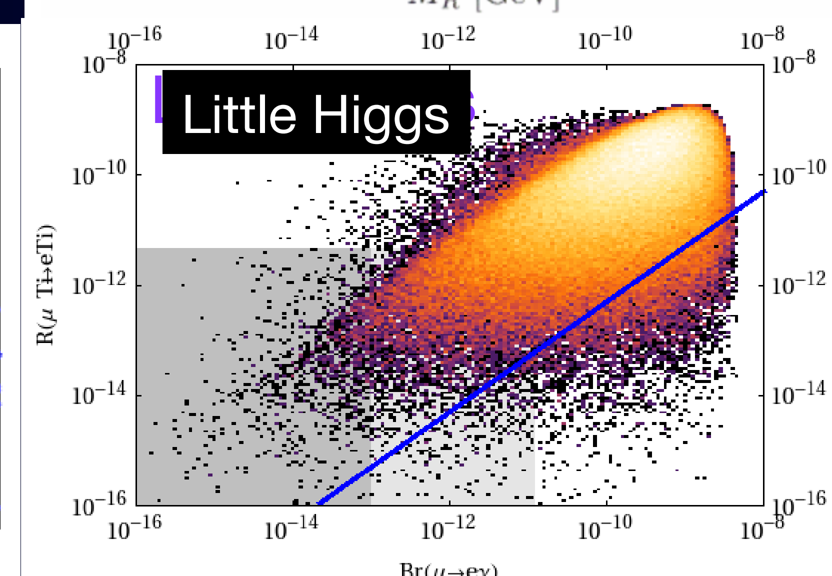
- SM + NHL (neutral heavy lepton)
- large extra dimensions
- extended Higgs sector
- additional vector boson (Z')
- leptoquark
- SUSY-GUT and SUSY seesaw
- R-parity violating SUSY
- low-energy seesaw
- etc. etc.





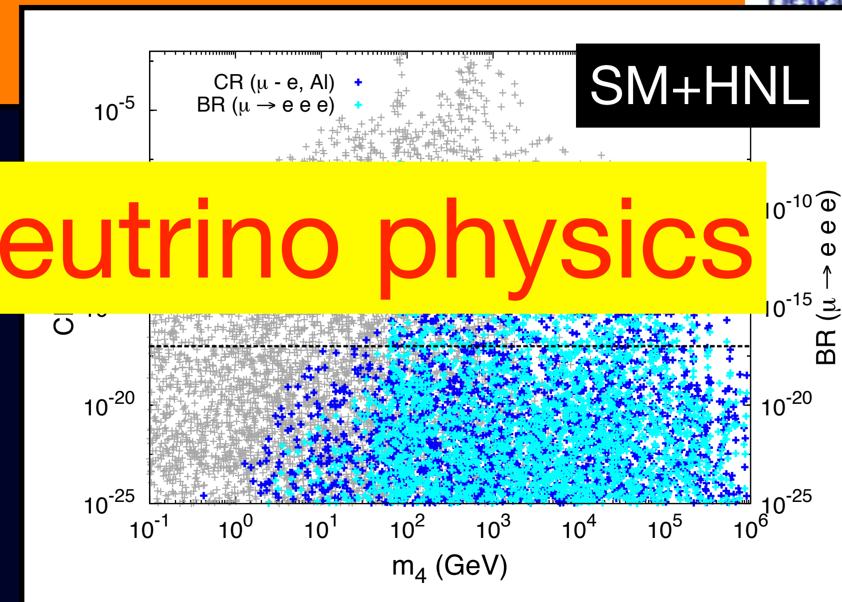




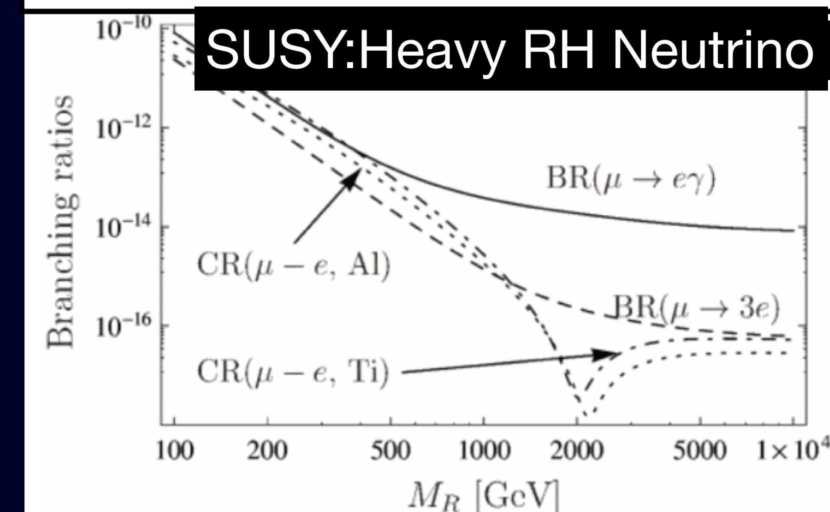


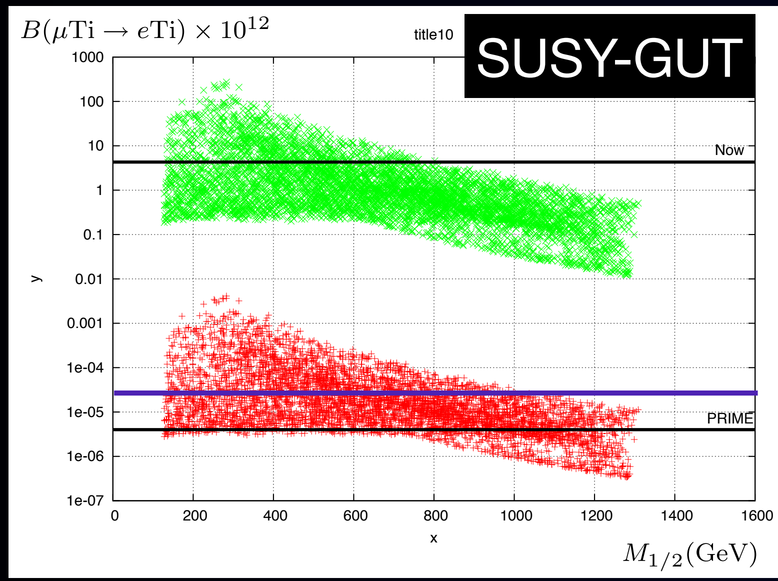
Model dependent CLFV

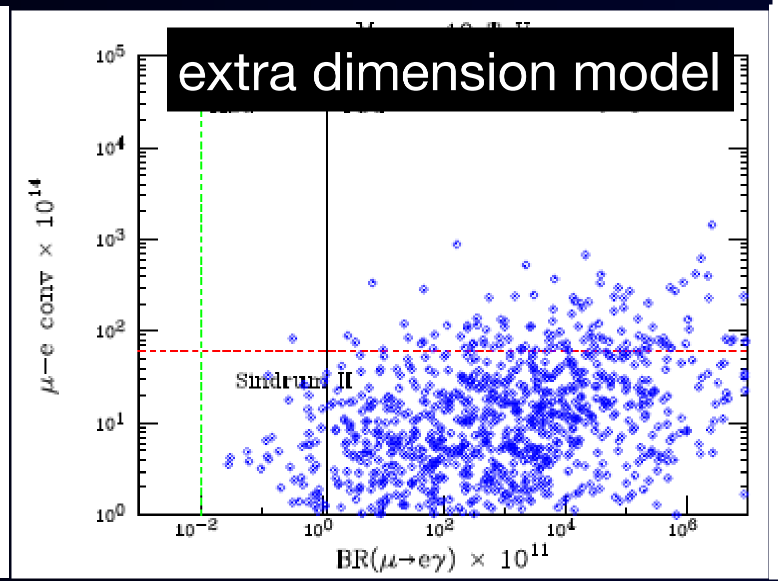
- SM + NHL (neutral heavy lepton)
- large extra dimensions
- extended Higgs sector
- additional vector boson (Z')
- leptoquark
- SUSY-GUT and SUSY seesaw
- R-parity violating SUSY
- low-energy seesaw
- etc. etc.

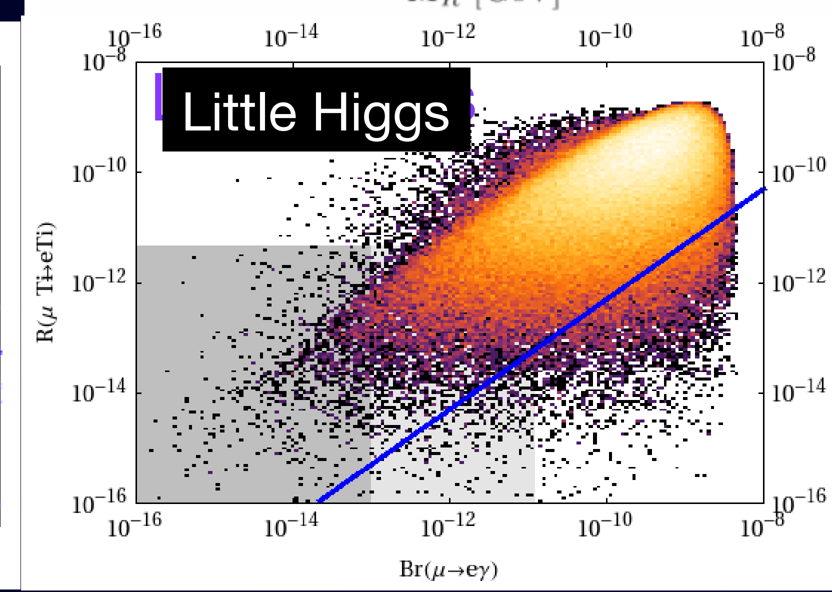


neutrino physics





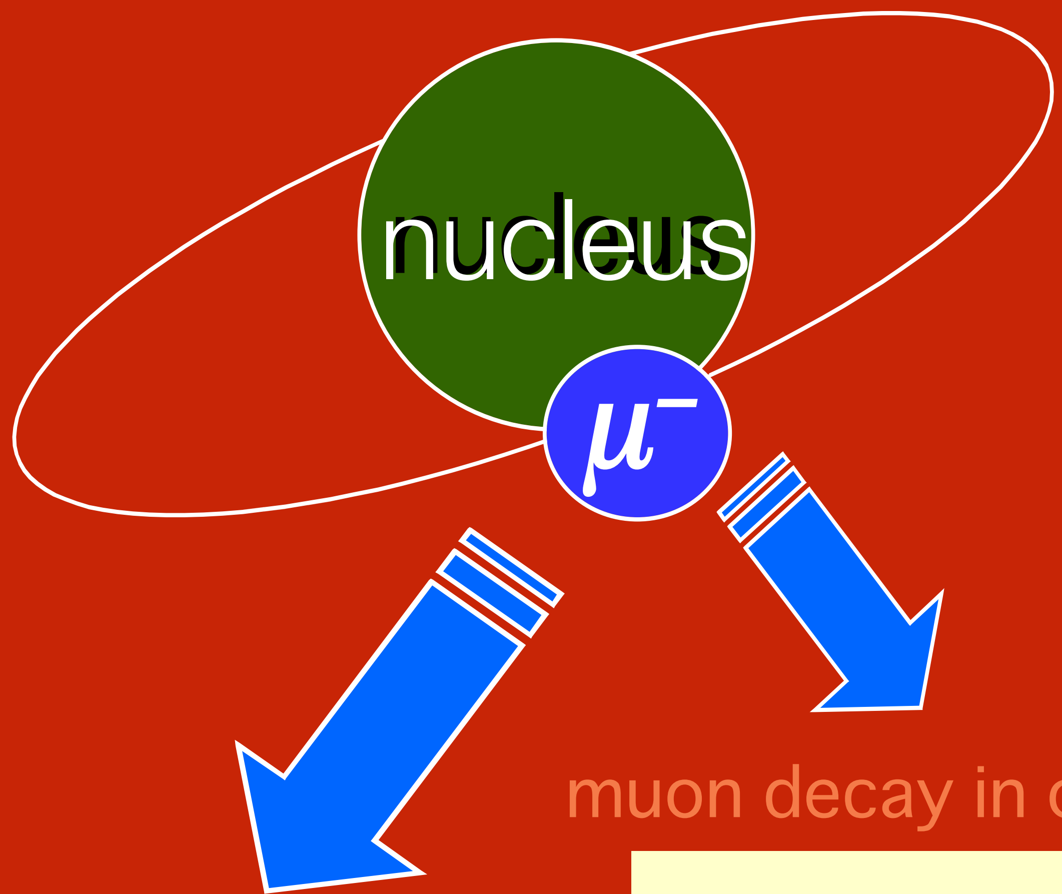





$\mu \rightarrow e$ conversion
in
a muonic atom

What is μ→e Conversion ?

1s state in a muonic atom



muon decay in orbit

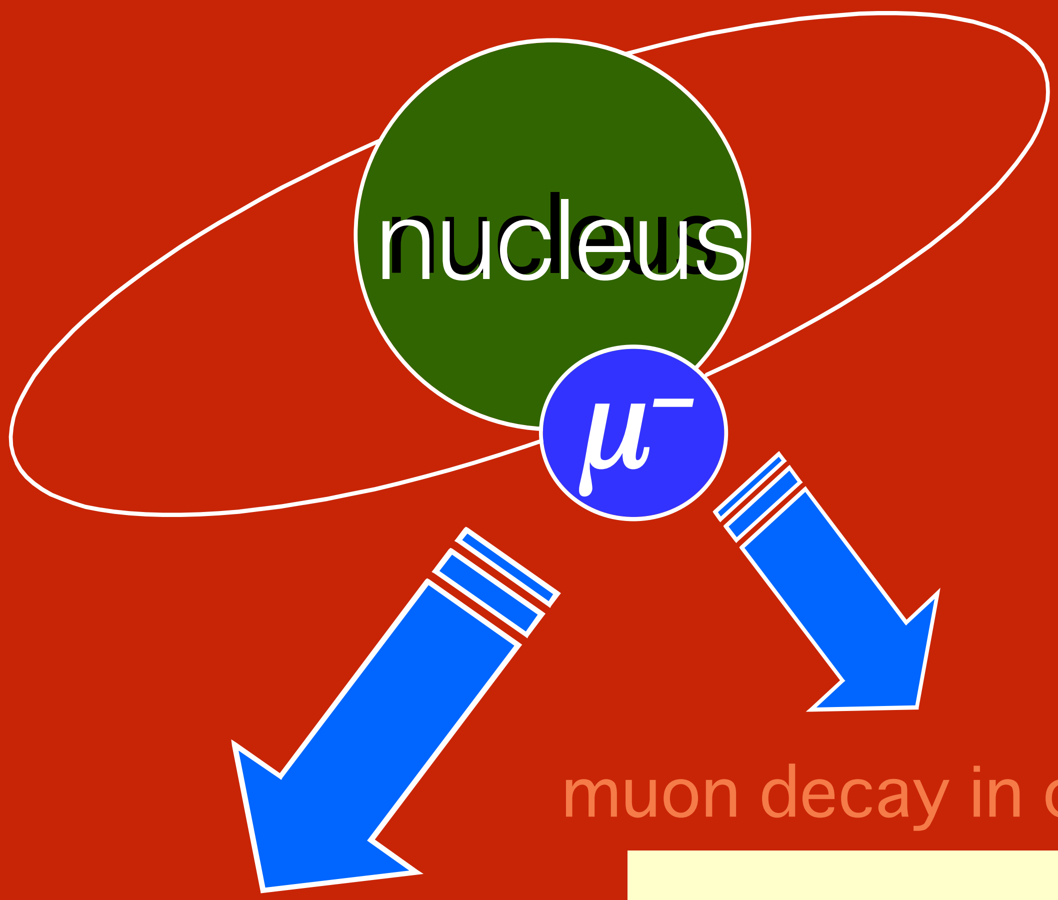
$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

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

What is μ→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

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

coherent process $\propto Z^5$

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

Event Signature :
a single mono-energetic electron of 105 MeV

$$\mathrm{CR}(\mu^-\mathrm{N} \rightarrow e^-\mathrm{N}) \equiv \frac{\Gamma(\mu^-\mathrm{N} \rightarrow e^-\mathrm{N})}{\Gamma(\mu^-\mathrm{N} \rightarrow \mathrm{all})}$$

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

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

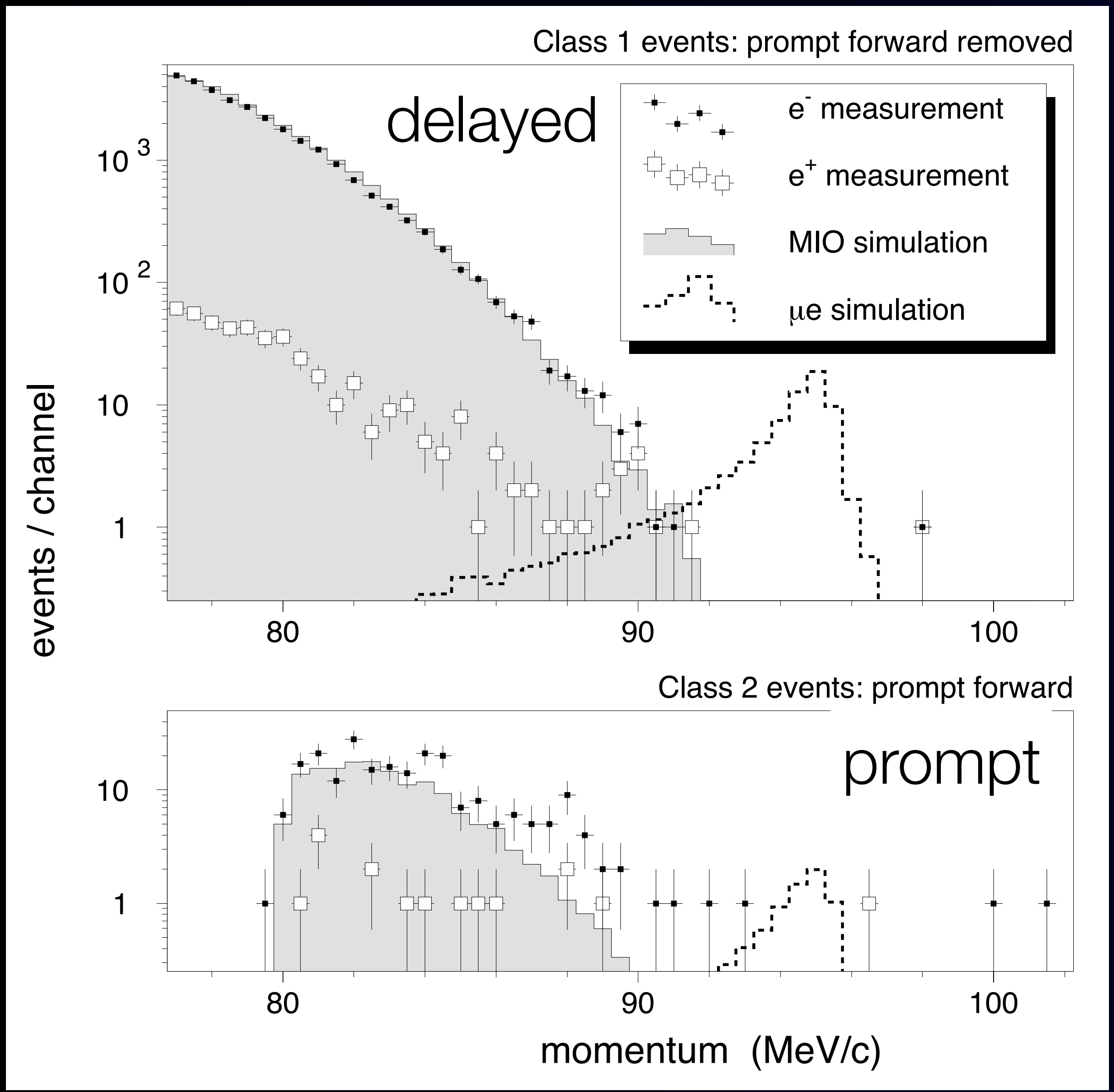
Backgrounds for μ-e conversion

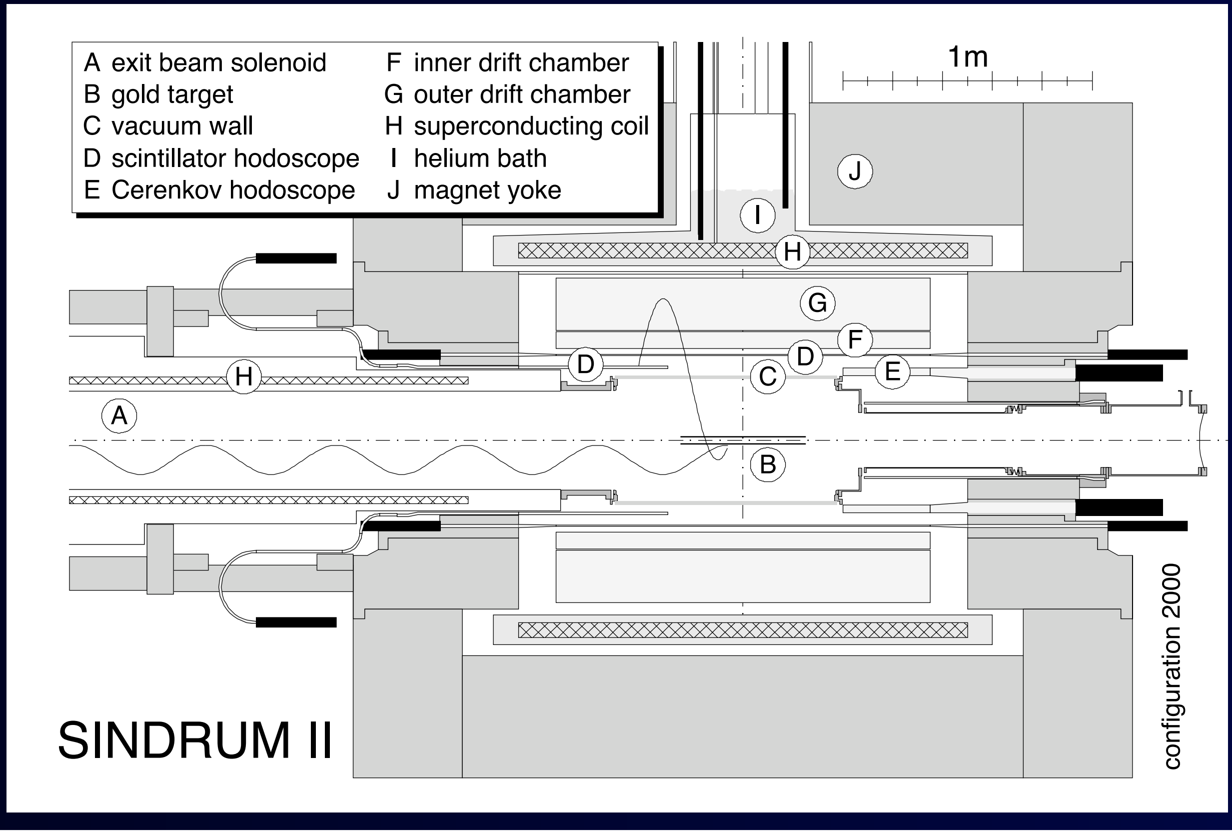
Osaka University

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

Current Limits on μ→e Conversion

SINDRUM-II (PSI)





	Z	S	CR limit
sulfur	16	0	7×10^{-11}
titanium	22	0,5/2,7/2	4.3×10^{-12}
copper	39	3/2	1.6×10^{-8}
gold	79	0,5/2	7×10^{-13}
lead	82	0 (1/2)	4.6×10^{-11}

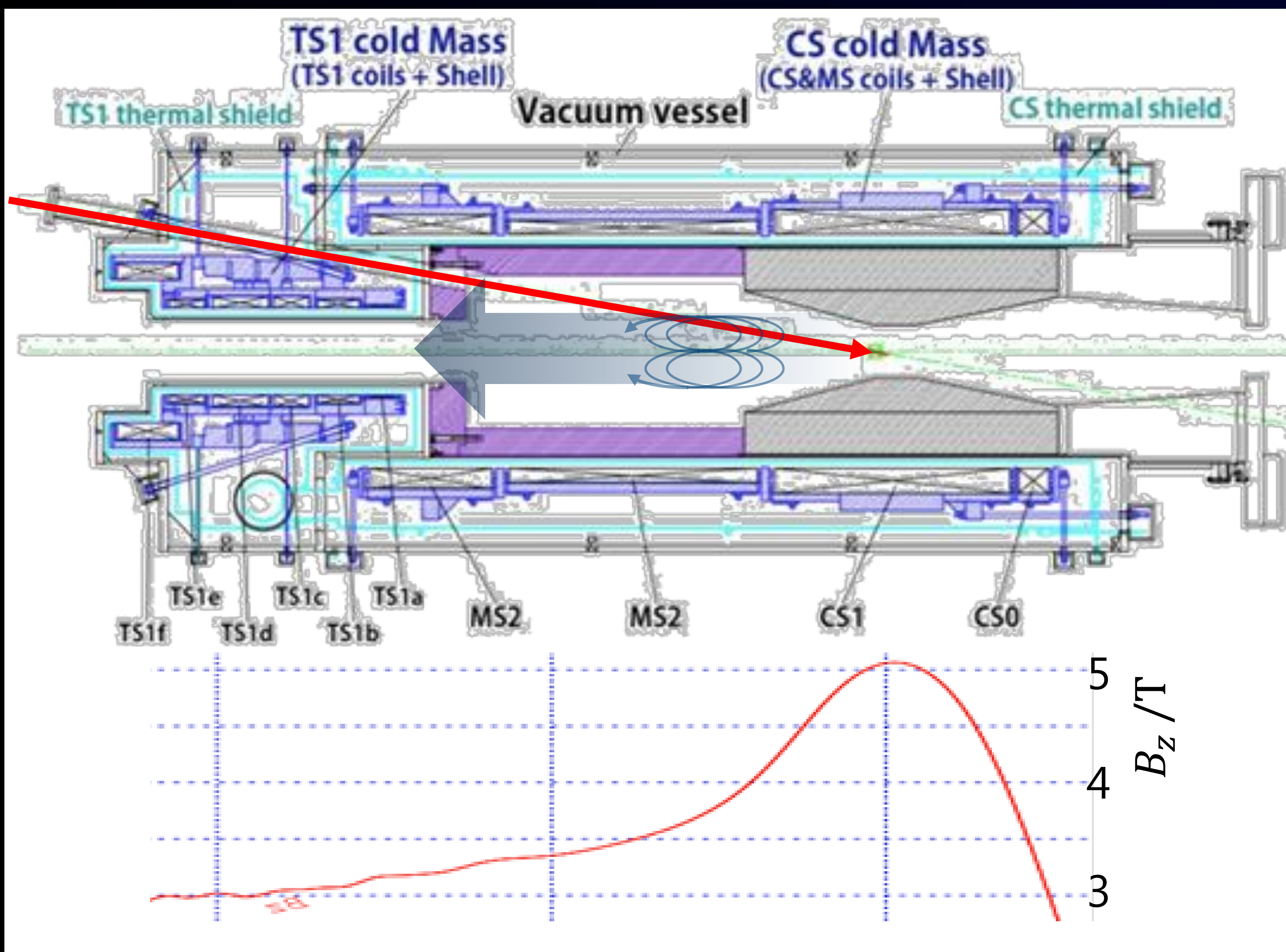
$$B(\mu^- + Au \to e^- + Au) < 7 \times 10^{-13}$$

In order to make a new-generation experiment to search for μ-e conversion …

$$B(\mu N \rightarrow eN) \leq 10^{-16}$$

Highly Intense Muon Source

pion capture in superconducting solenoids



- proton target in a solenoidal field (~5T)
- a long proton target (1.5~2 interaction length) of heavy material)

2×10^{11} μ^-/s
for 56 kW protons

muon yield
>1000 increase

Improvements for Background Rejection

Beam-related backgrounds → Beam pulsing with separation of 1μsec — measured between beam pulses

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

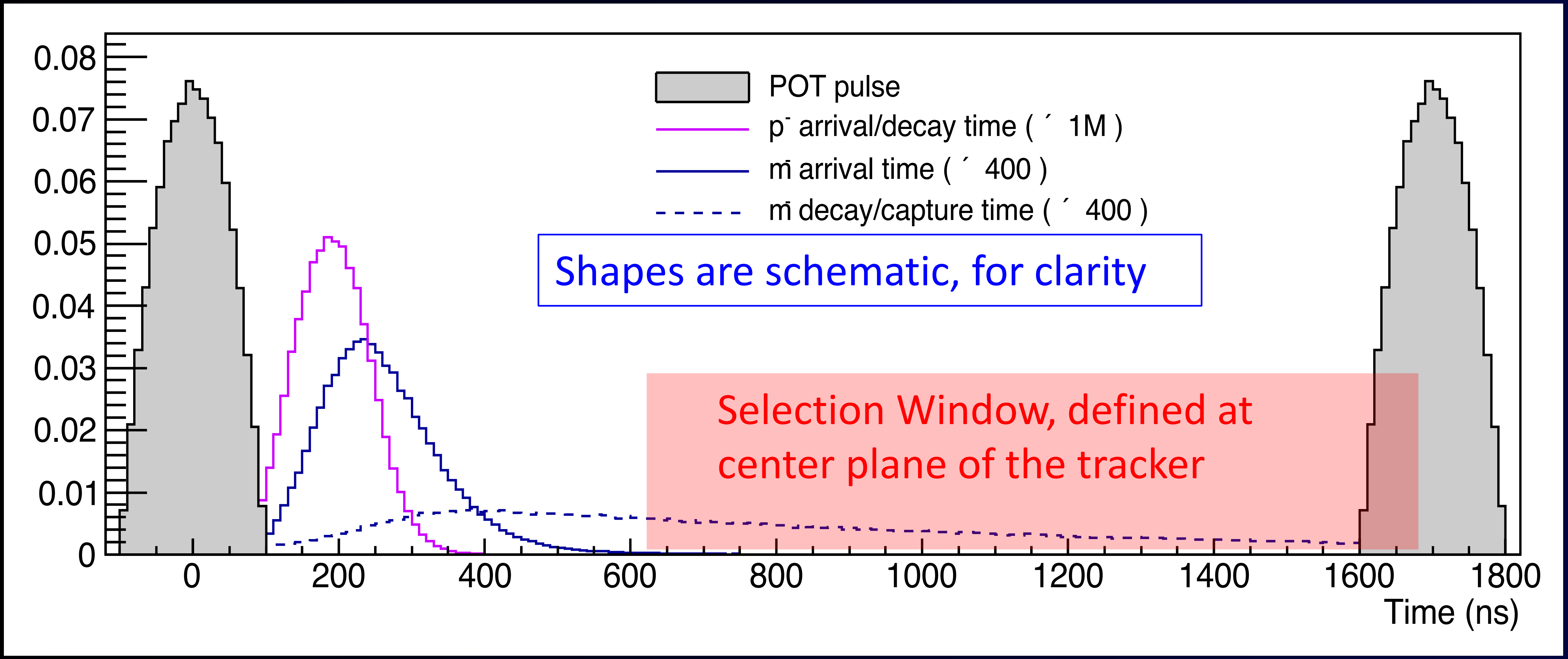
Muon DIO background → low-mass trackers in vacuum & thin target — improve electron energy resolution

Muon DIF background → curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

based on the MELC proposal at Moscow Meson Factory

Pulsed Muon Beam for μ-e conversion

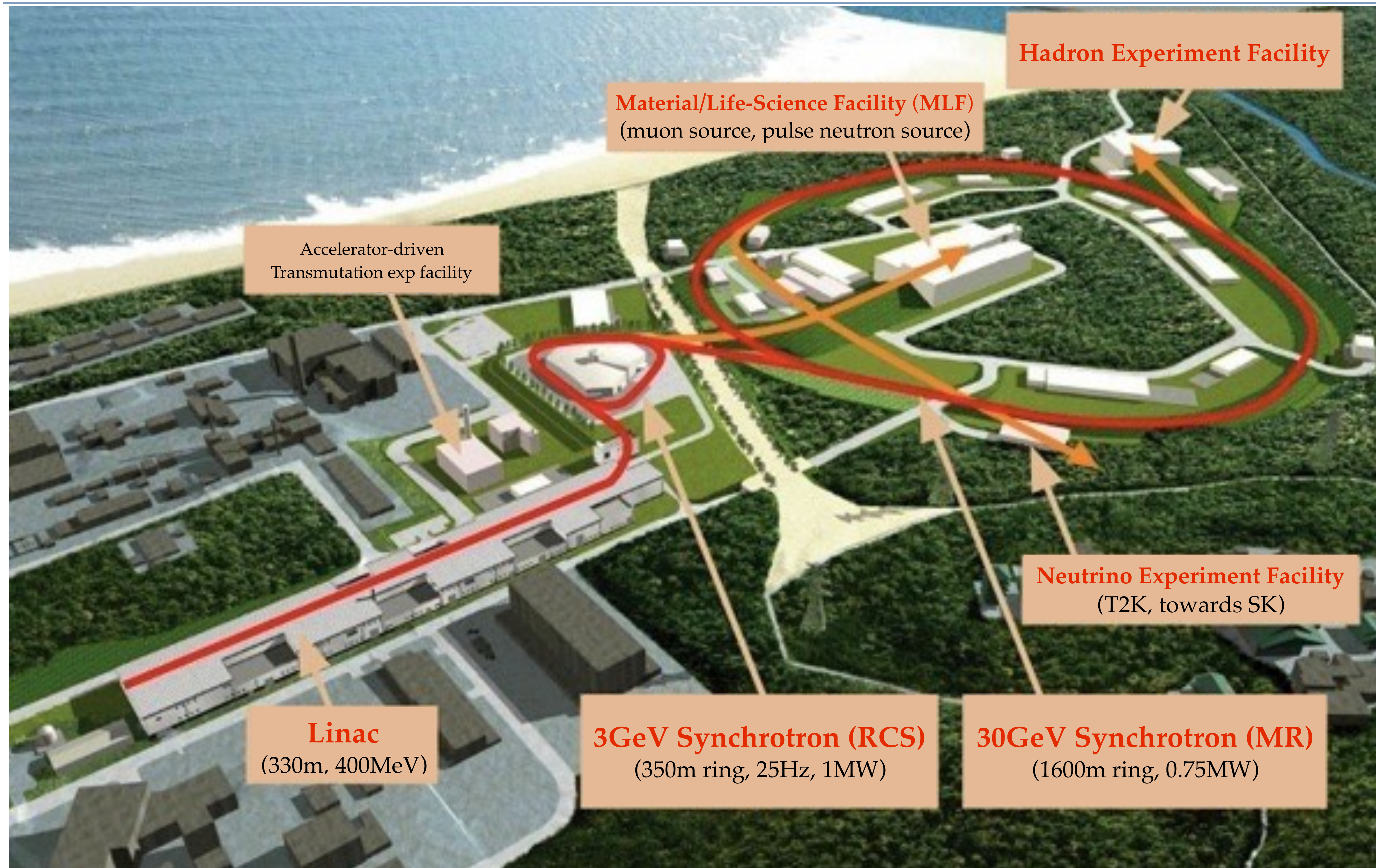
Osaka University



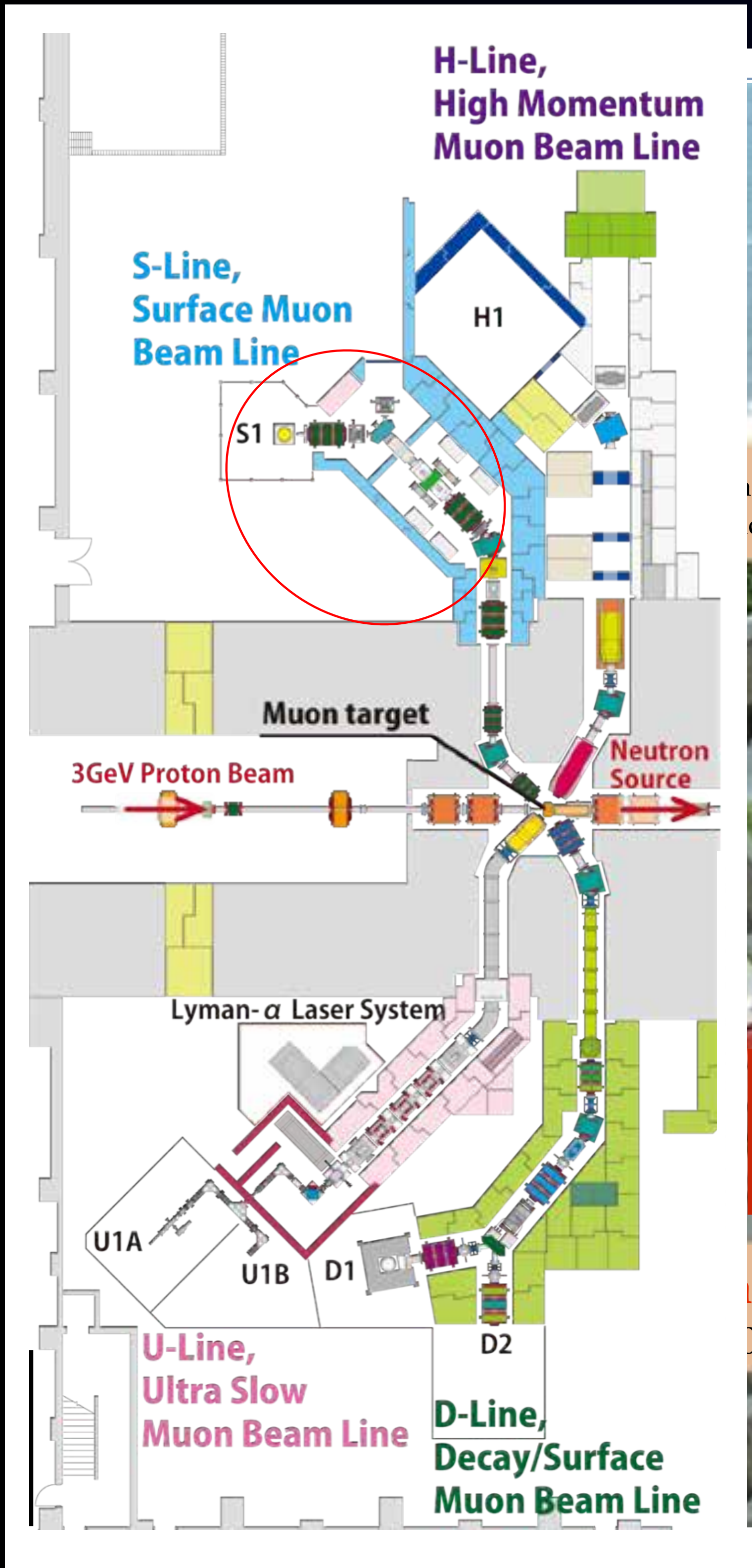
Selection windows turns on late, significantly reducing prompt backgrounds.

Requirements ;
Proton extinction factor during pulses < 10^{-10}

J-PARC (MUSE@MLF)

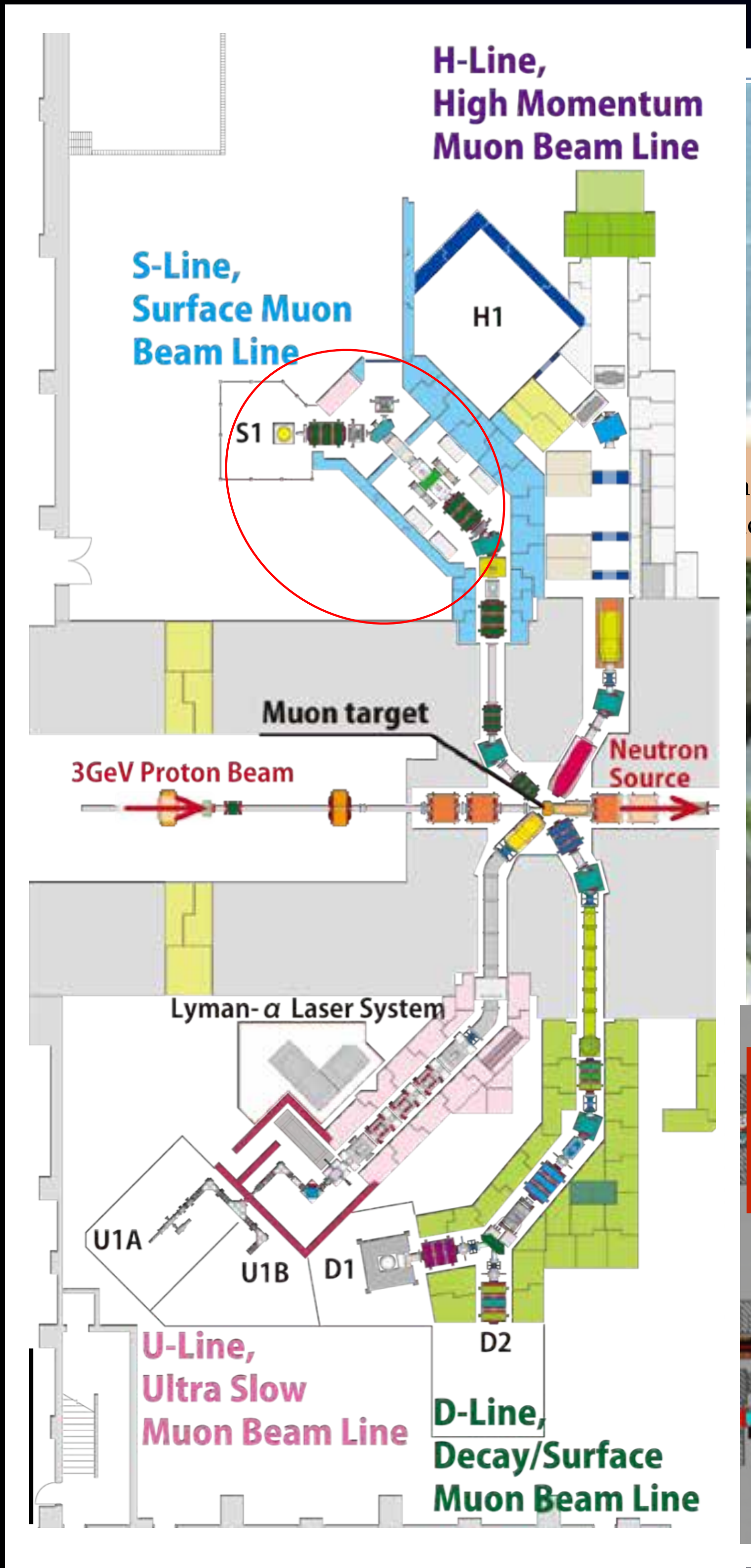


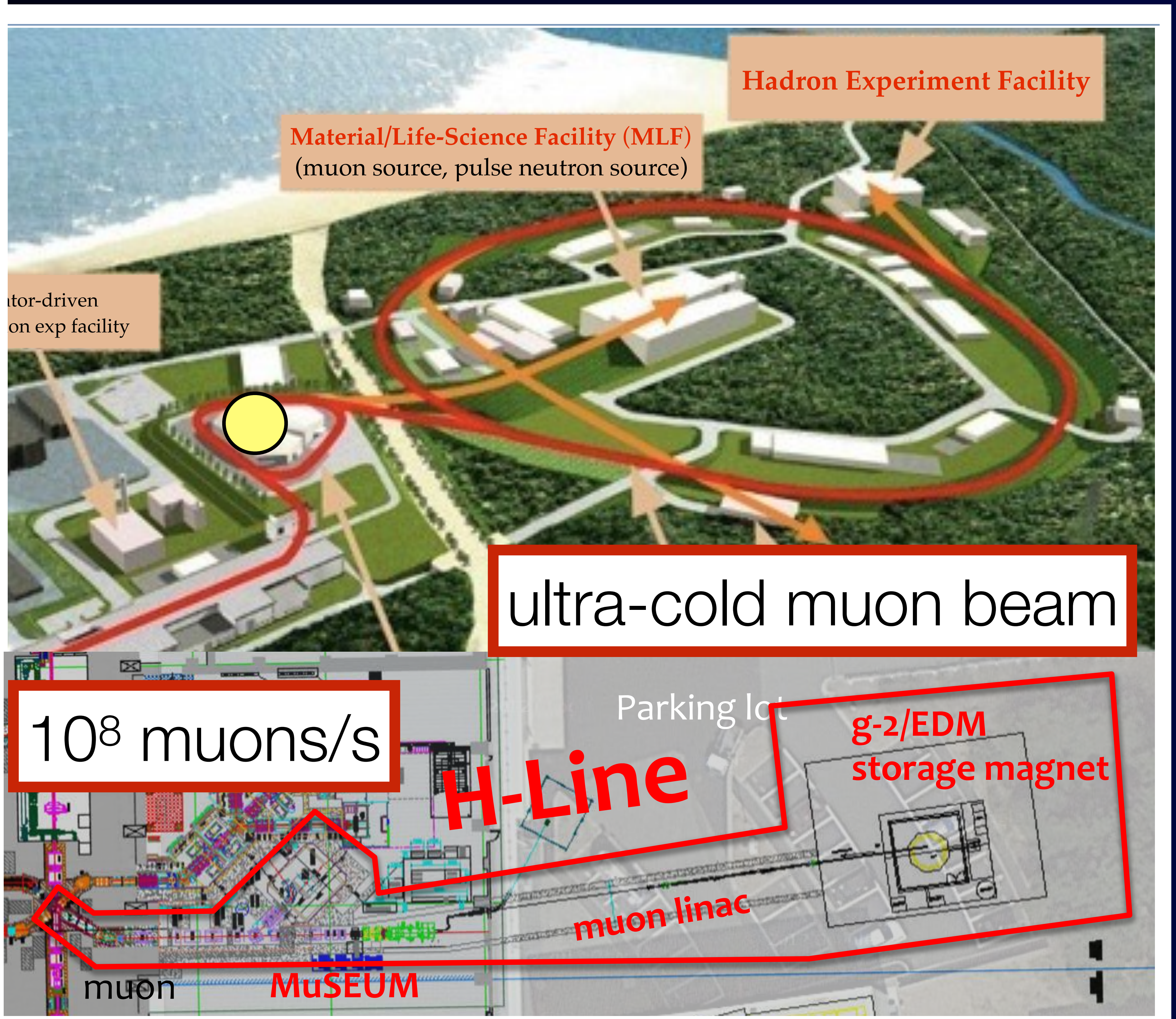
J-PARC (MUSE@MLF)



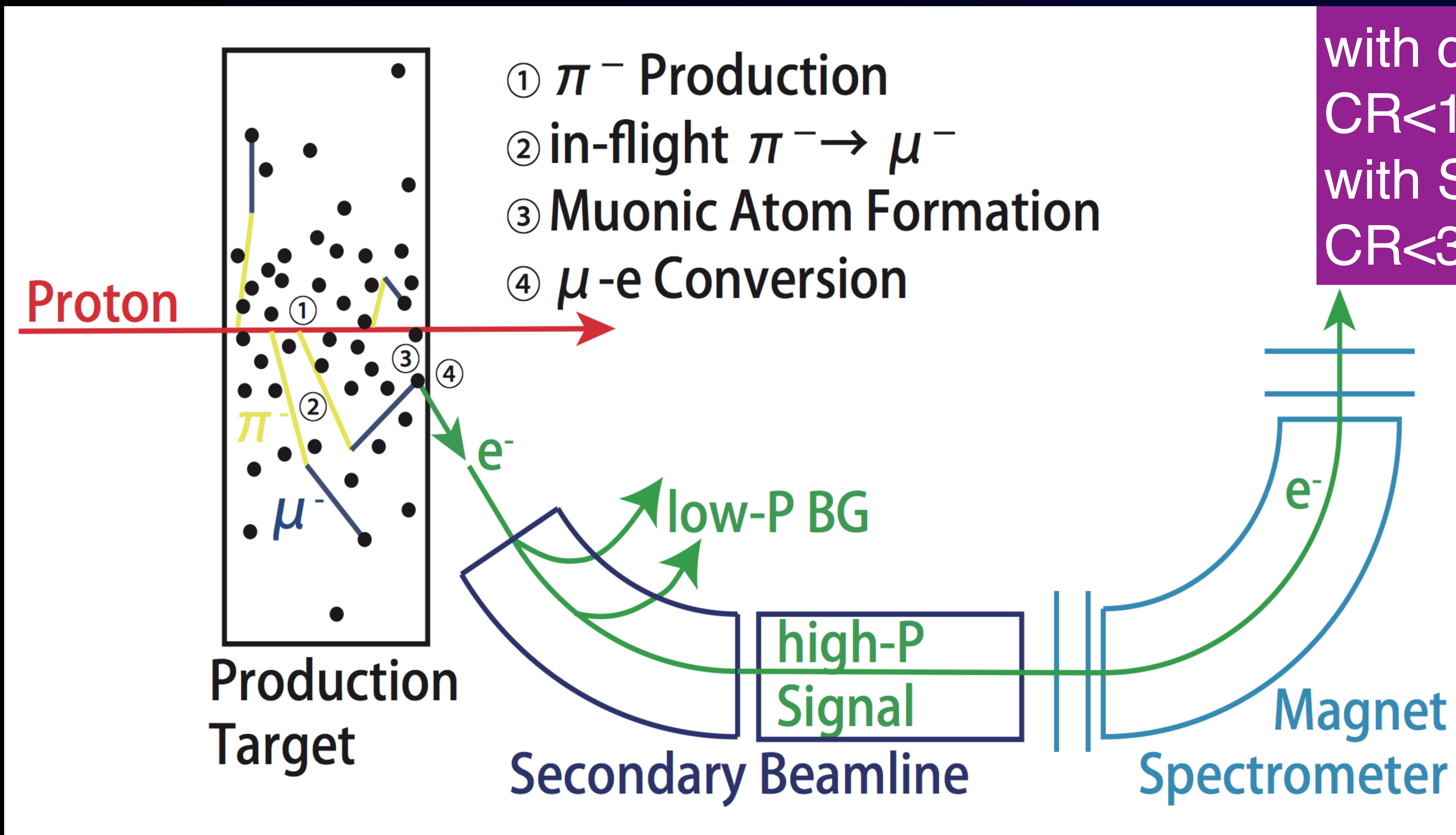
10^8 muons/s

J-PARC (MUSE@MLF)





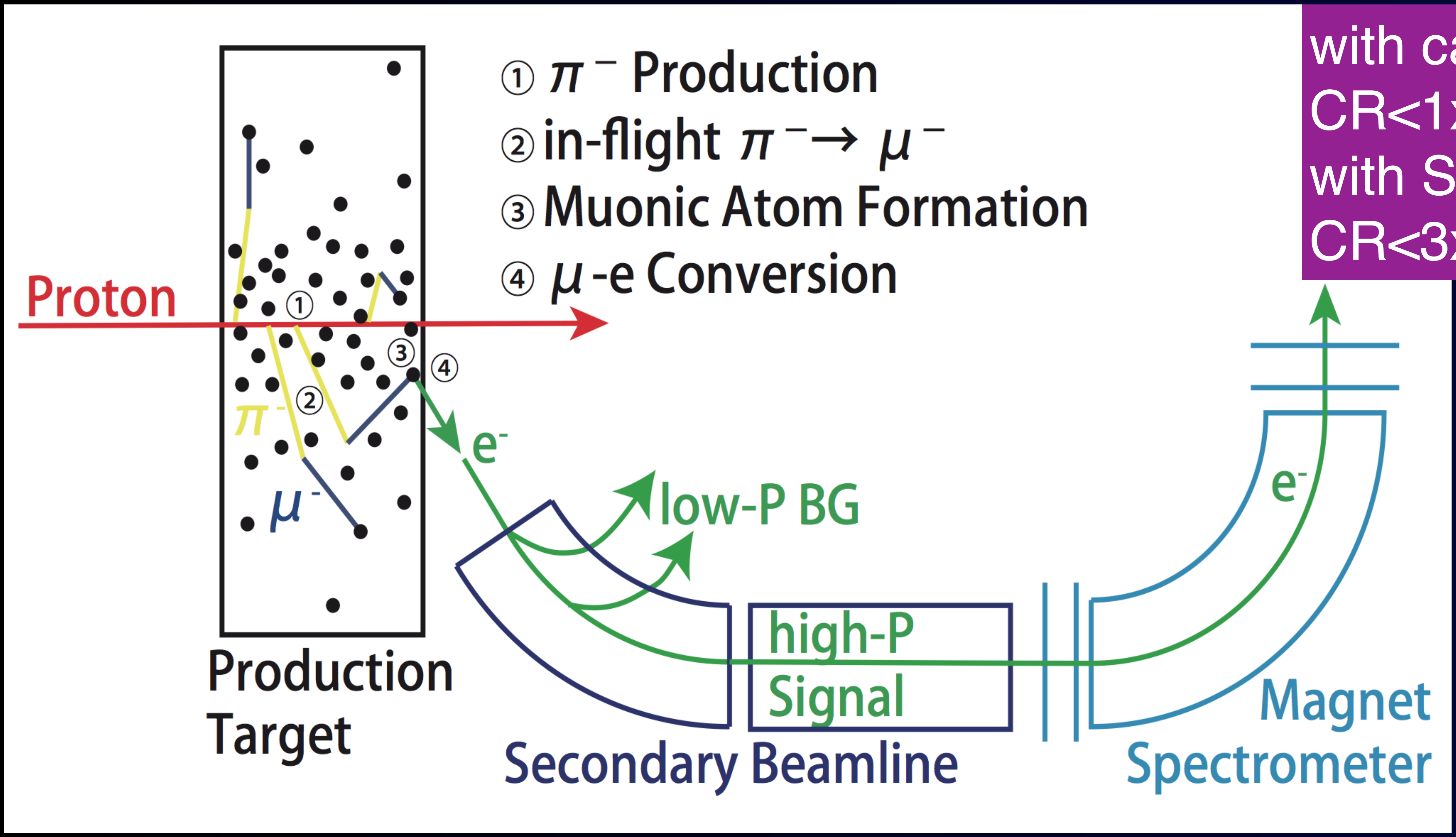
DeeMe at J-PARC MLF



with carbon target
CR<1x10^{-13} (1 year)
with SiC target
CR<3x10^{-14} (1 year)

3 GeV J-PARC RCS protons
- beamline and spectrometer to select 100 MeV e-
- 4 MWPCs with Δp=0.5 MeV

DeeMe at J-PARC MLF

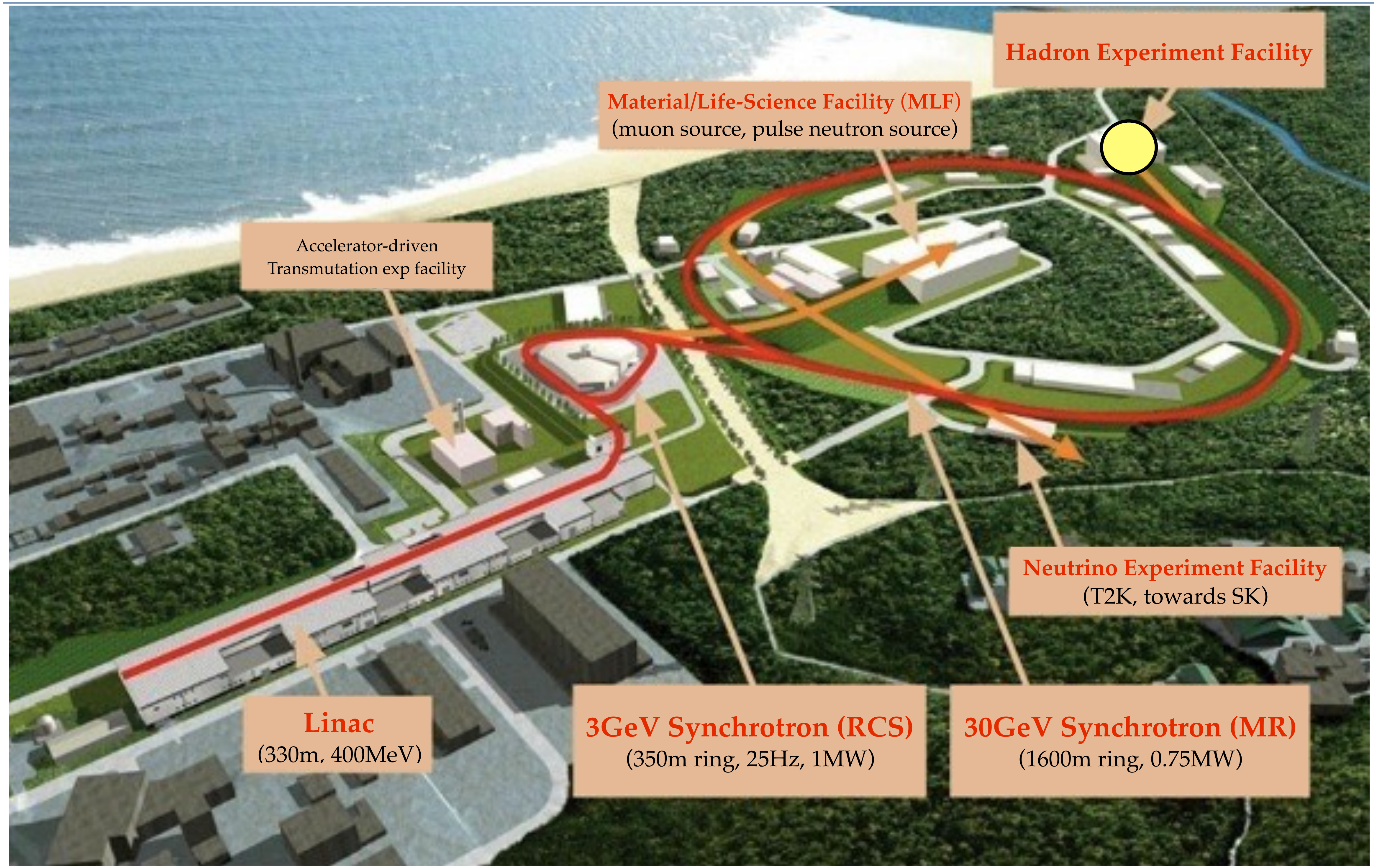


with carbon target
$CR<1\times10^{-13}$ (1 year)
with SiC target
$CR<3\times10^{-14}$ (1 year)

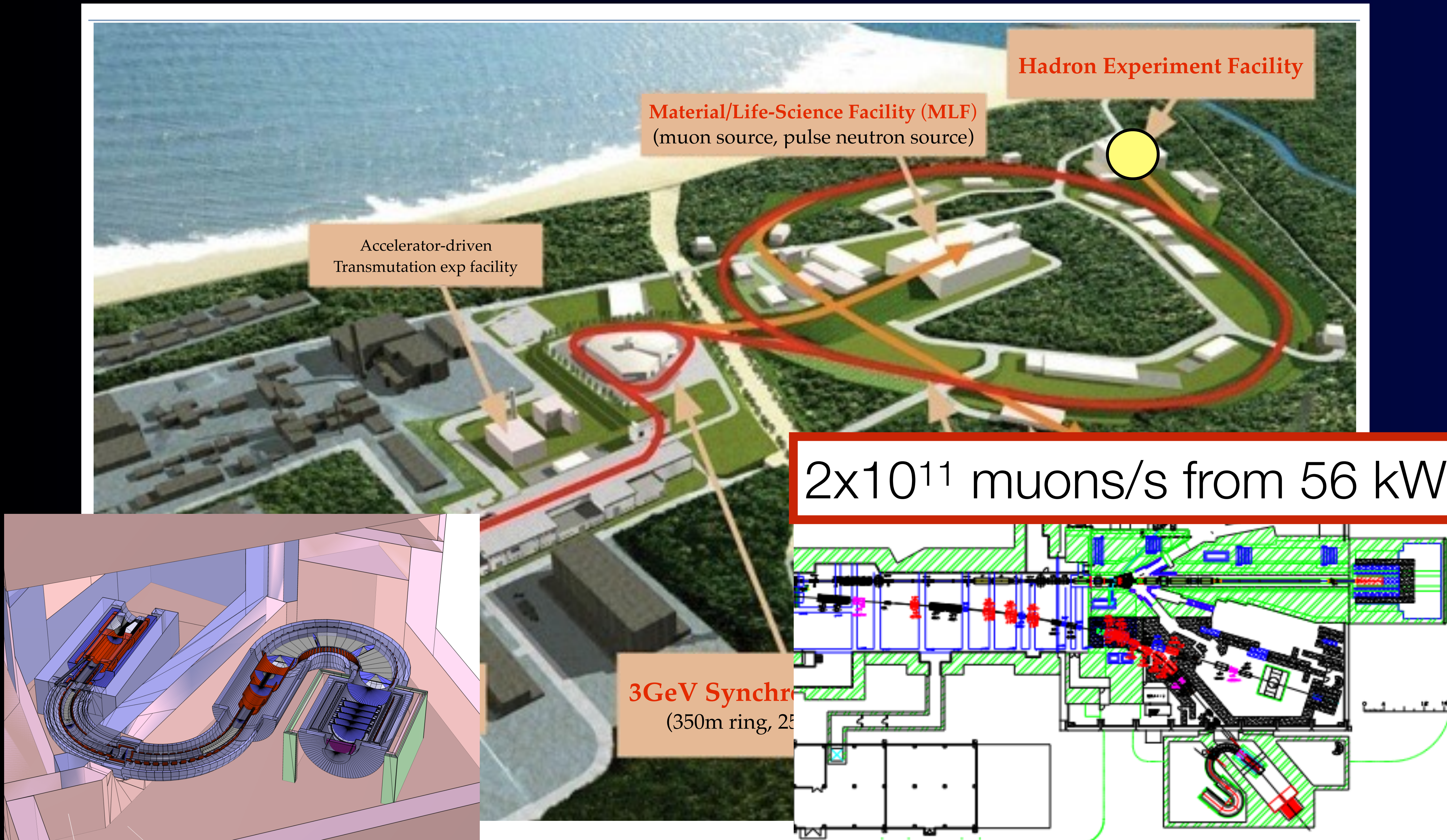
3 GeV J-PARC RCS protons
- beamline and spectrometer to select 100 MeV e
- 4 MWPCs with $\Delta p=0.5$ MeV

N. Teshima on Thursday

J-PARC (COMET@Main Ring)



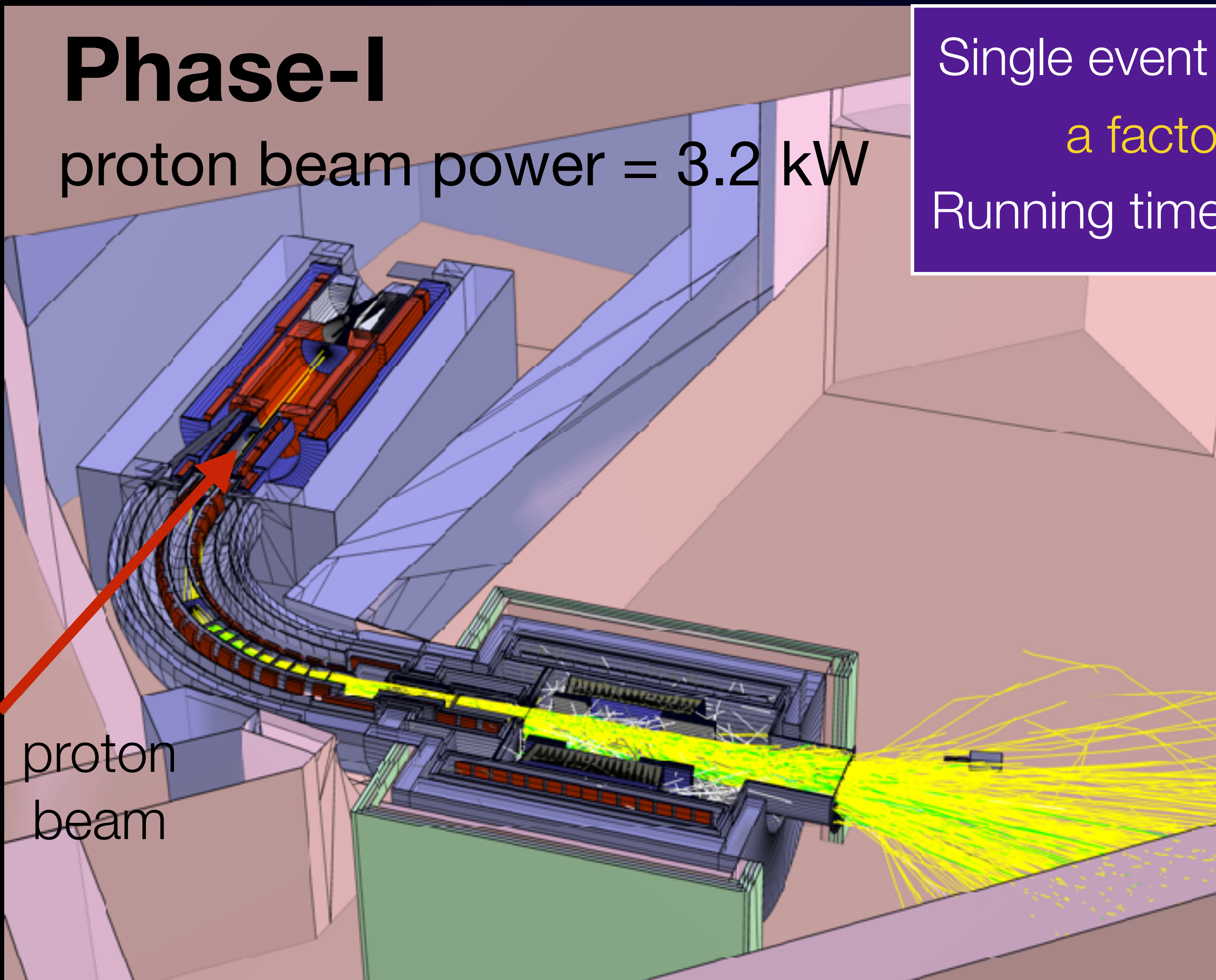
J-PARC (COMET@Main Ring)



2x10^{11} muons/s from 56 kW

COMET = COherent Muon to Electron Transition

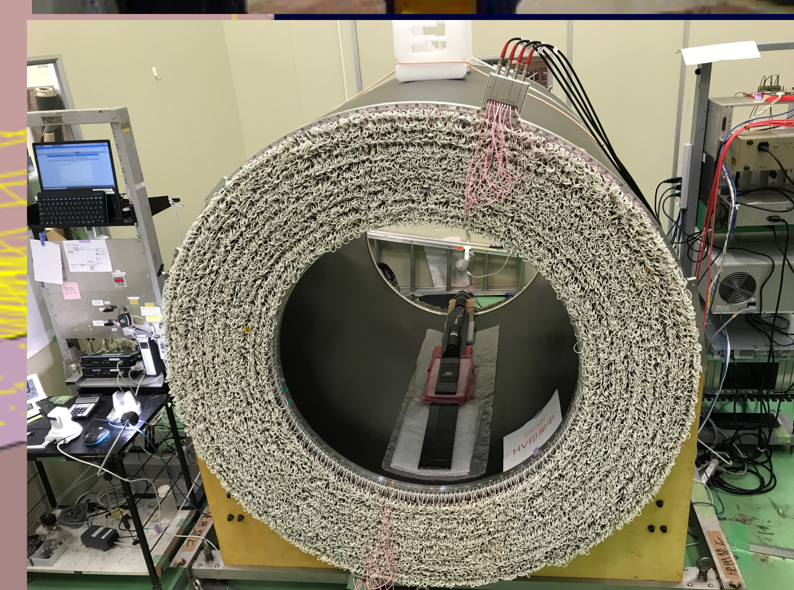
COMET Phase-I : J-PARC E21



Single event sensitivity : 2×10^{-15}

a factor of 100 improvement

Running time: 0.4 years (1.2×10^{7}s)

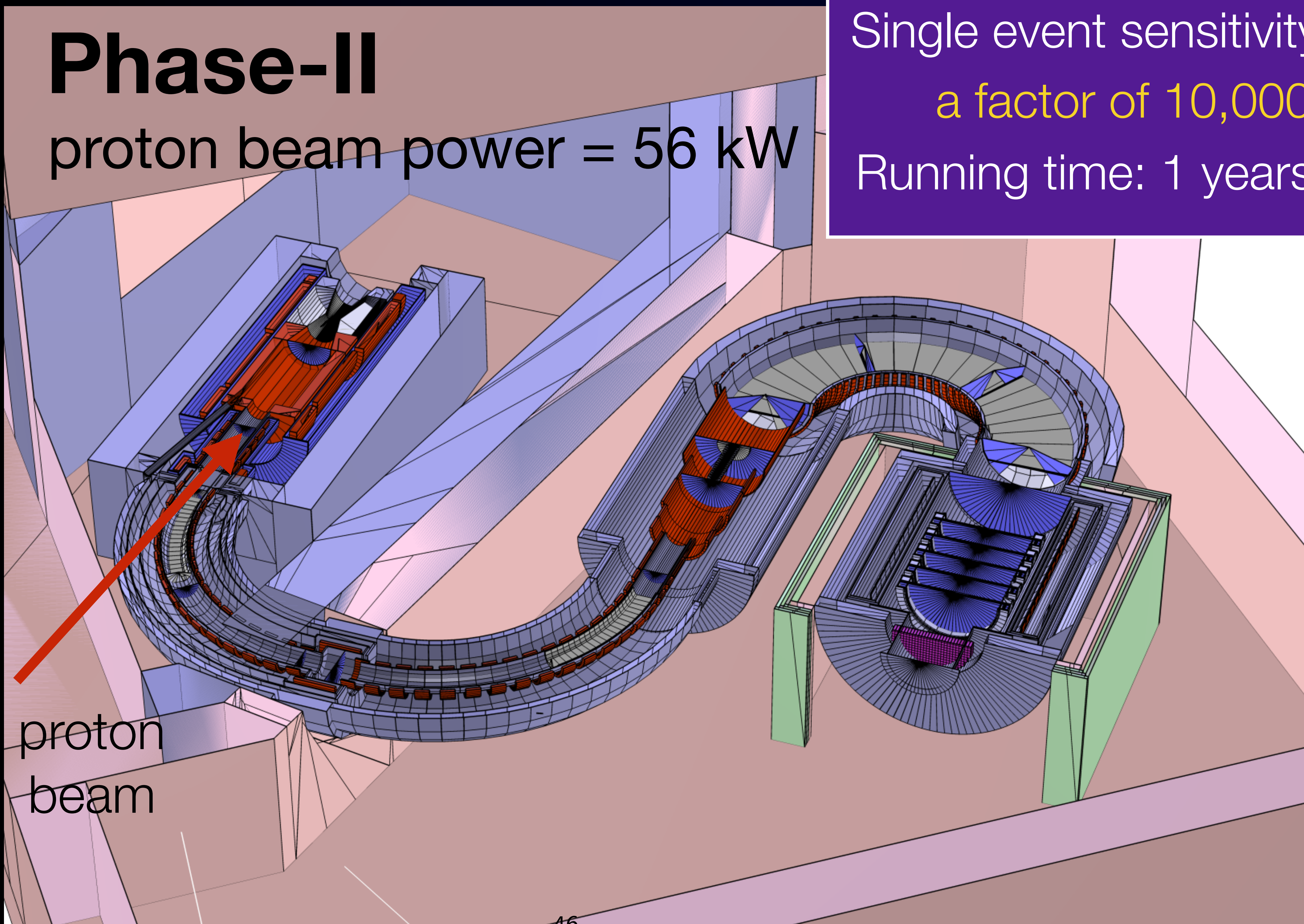


COMET Phase-II : J-PARC E21

Single event sensitivity : 2.6×10^{-17}

a factor of 10,000 improvement

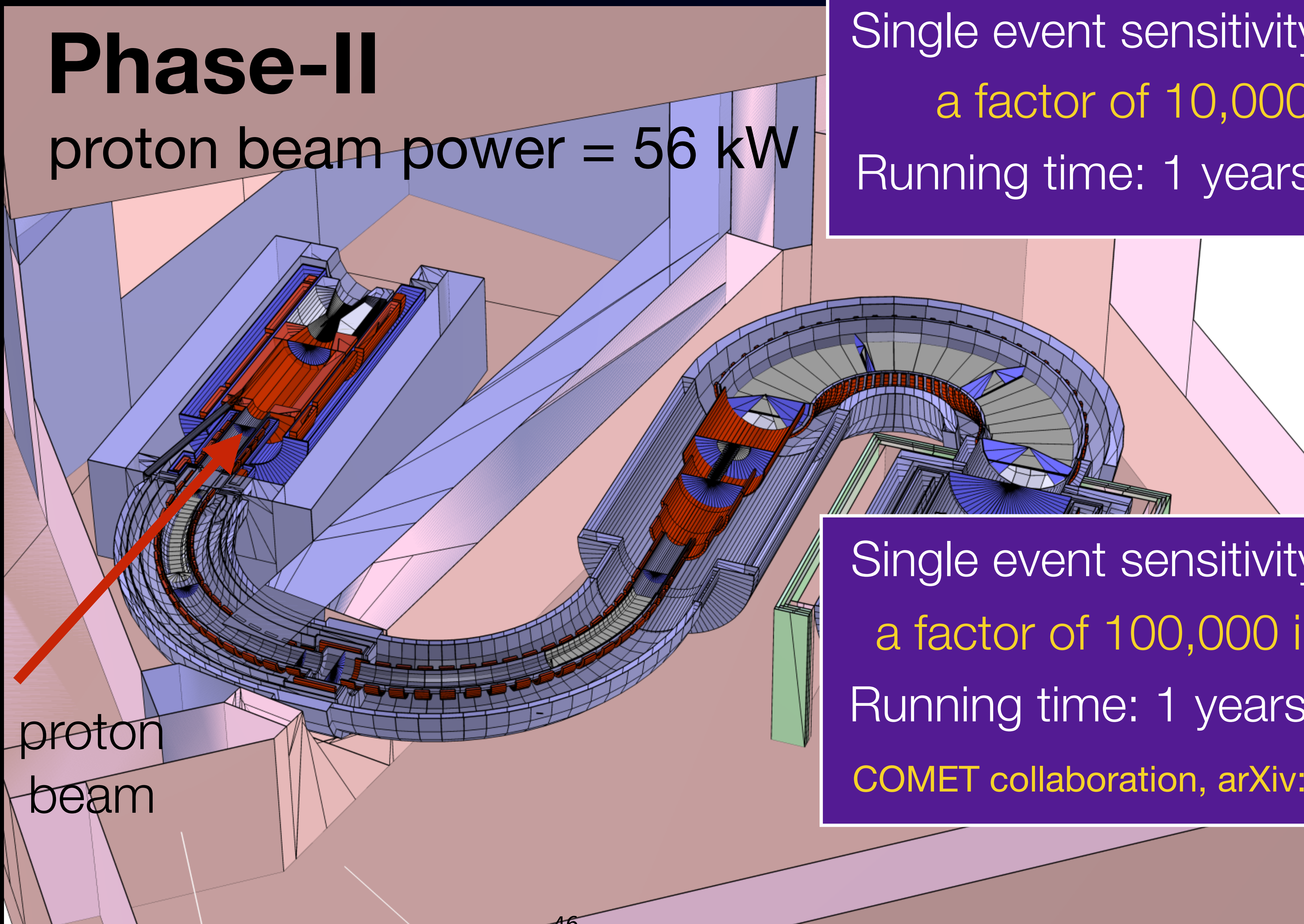
Running time: 1 years (2×10^{7}sec)



COMET Phase-II : J-PARC E21

Phase-II

proton beam power = 56 kW



Single event sensitivity : 2.6×10^{-17}

a factor of 10,000 improvement

Running time: 1 years (2×10^{7}sec)

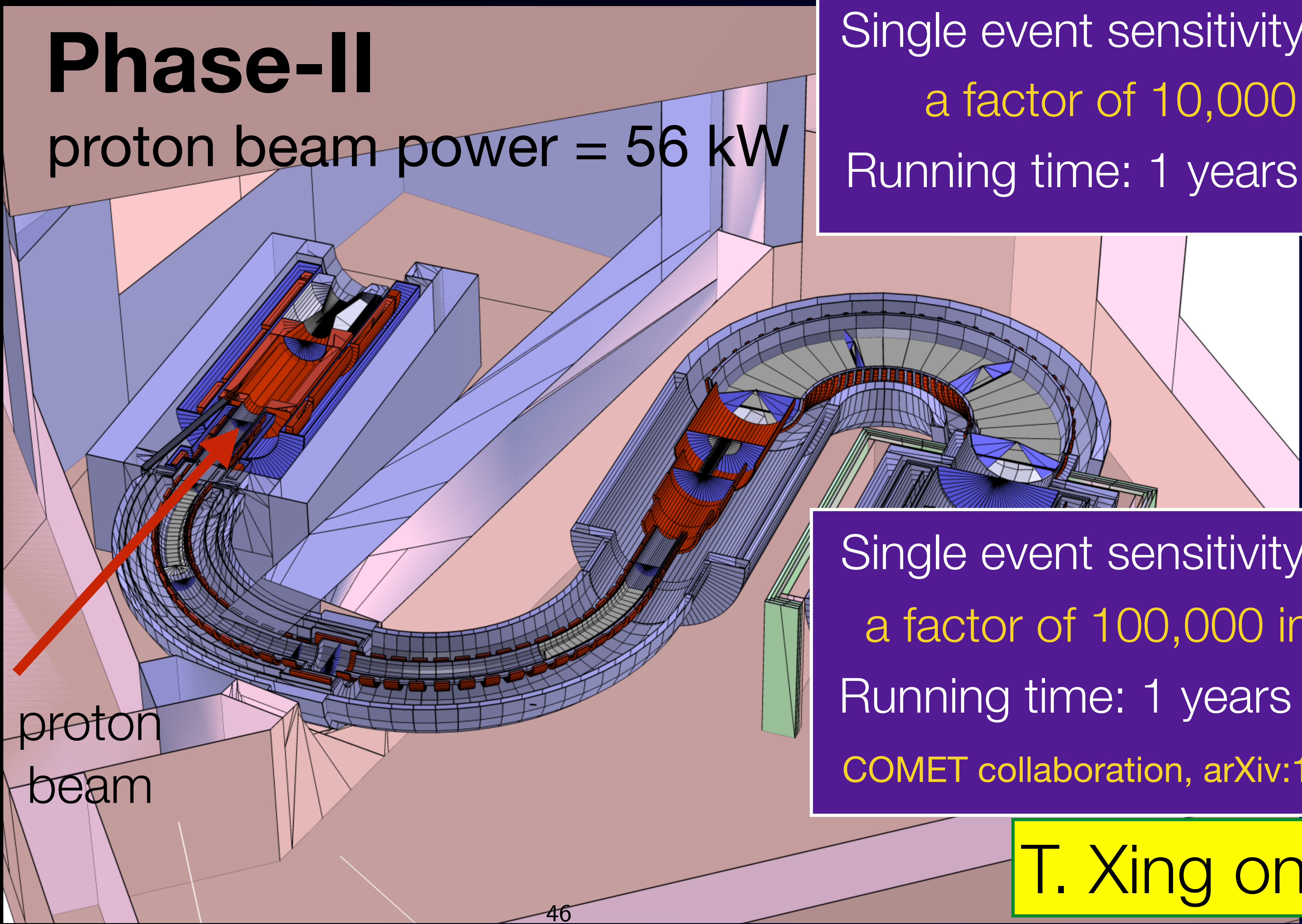
Single event sensitivity : $O(10^{-18})$

a factor of 100,000 improvement

Running time: 1 years (2×10^{7}sec)

COMET collaboration, arXiv:1812.07824, 2018

COMET Phase-II : J-PARC E21



Single event sensitivity : 2.6×10^{-17}

a factor of 10,000 improvement

Running time: 1 years (2×10^{7} sec)

Single event sensitivity : $O(10^{-18})$

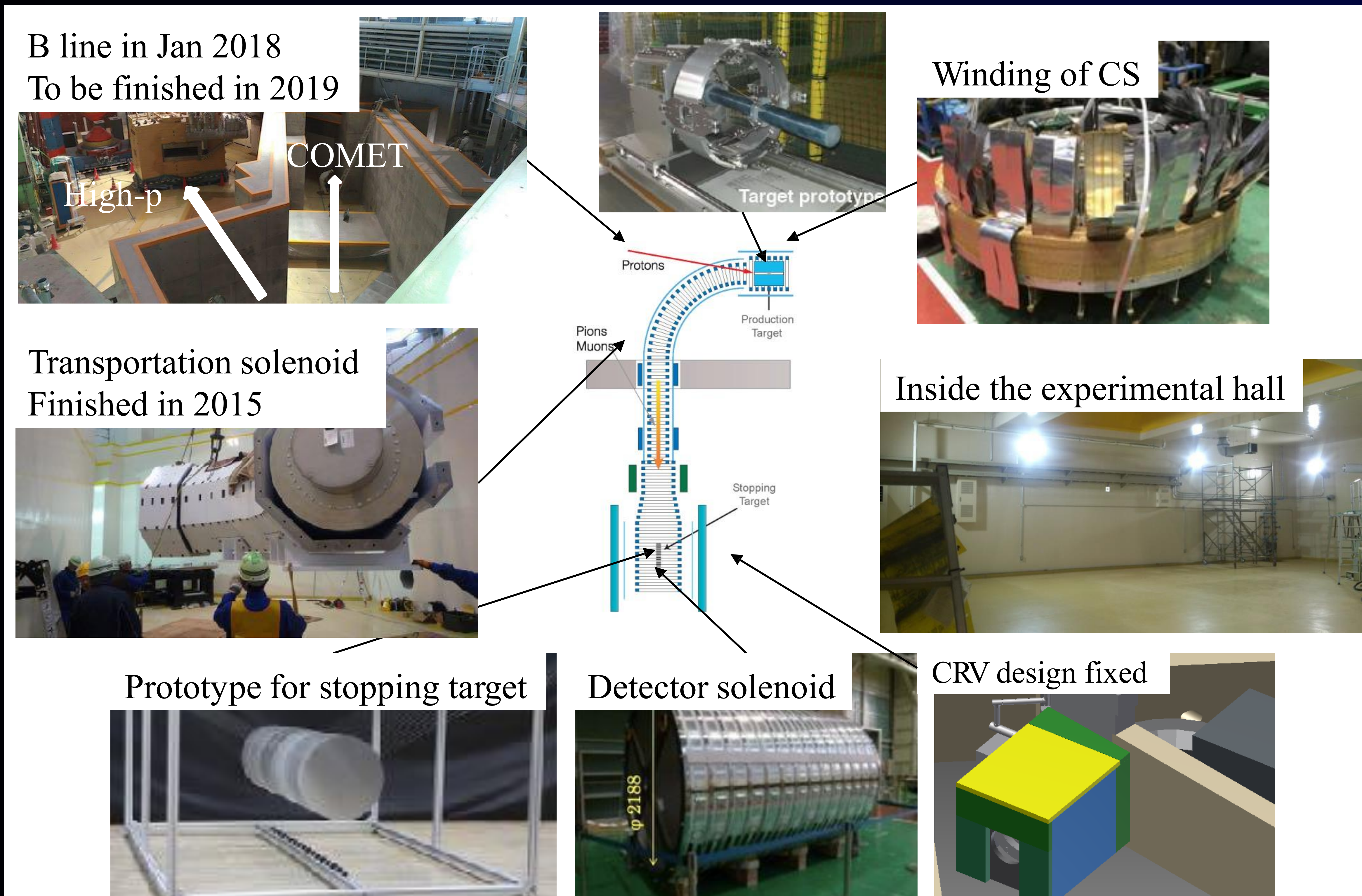
a factor of 100,000 improvement

Running time: 1 years (2×10^{7} sec)

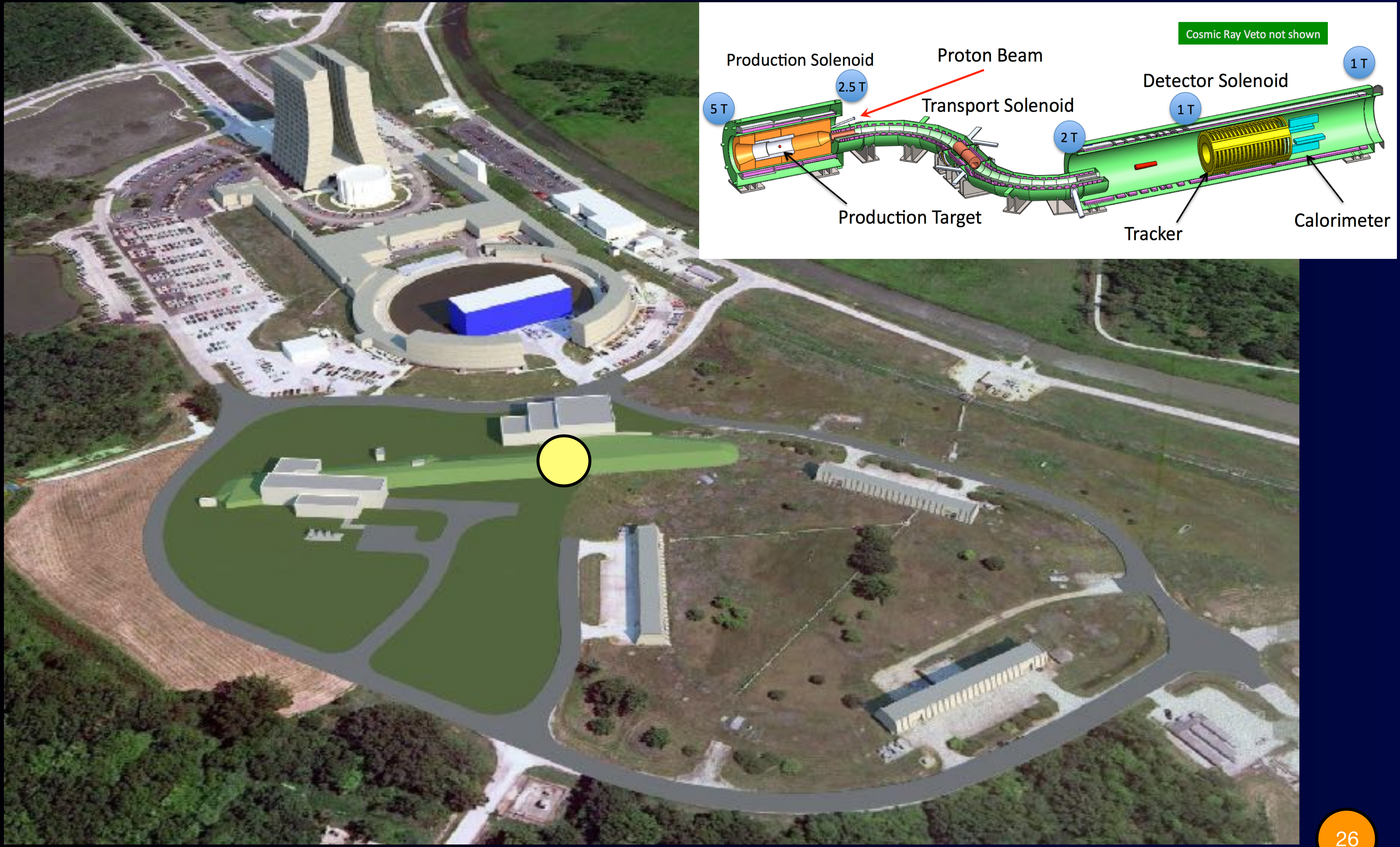
COMET collaboration, arXiv:1812.07824, 2018

T. Xing on Thursday

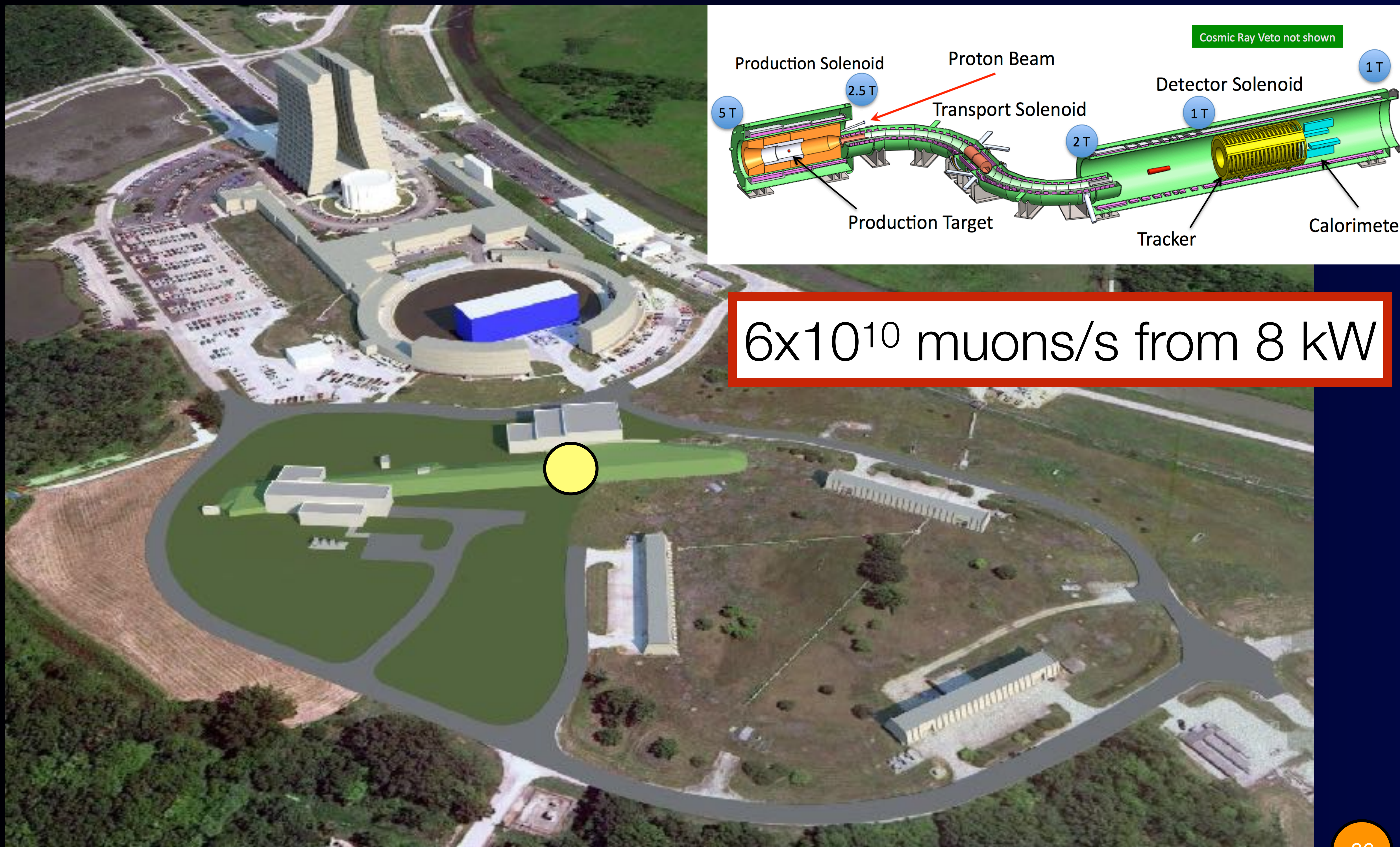
COMET Phase-I : Preparation



Fermilab Muon Campus



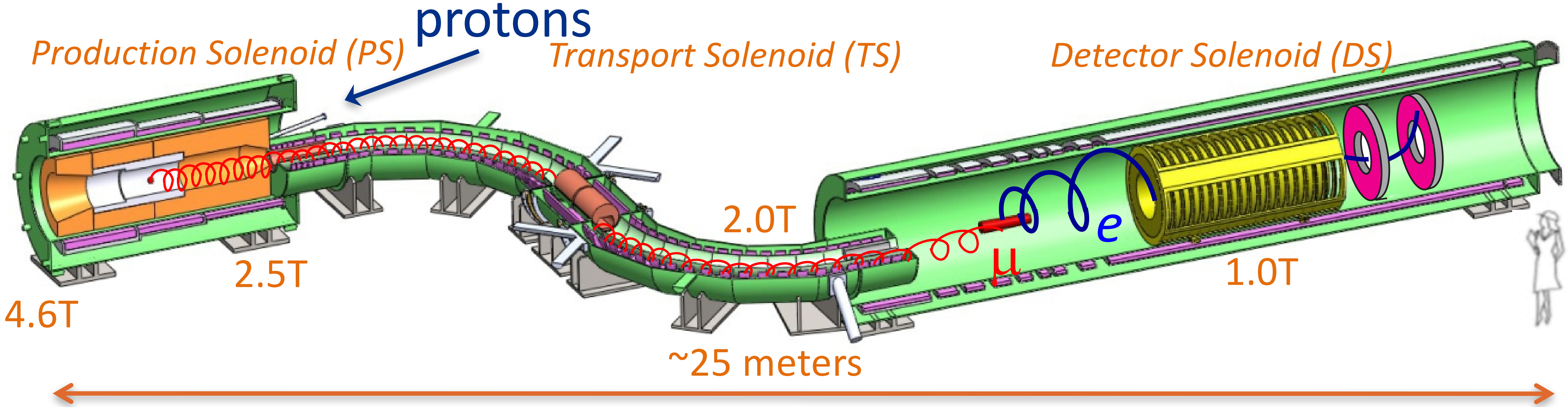
Fermilab Muon Campus



6×10^{10} muons/s from 8 kW

Mu2e at Fermilab

A System of superconducting solenoids and an intense muon beam



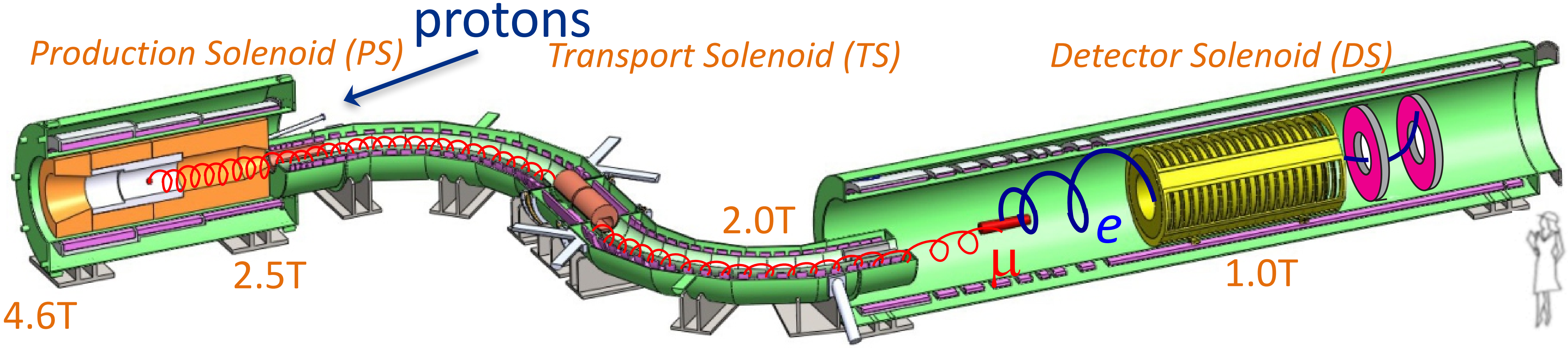
- A search for Charged Lepton Flavor Violation: $\mu N \rightarrow eN$
  - Expected sensitivity of 6×10^{-17} @ 90% CL, x10,000 better than SINDRUM-II
  - Probes effective new physics mass scales up to 10^4 TeV/c^2
  - *Discovery* sensitivity to broad swath of NP parameter space

- Experiment scope includes
  - Proton Beam line
  - Solenoid systems
  - Detector elements

    (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
  - Experimental hall
  - Commissioning begins in 2022

Mu2e at Fermilab

A System of superconducting solenoids and an intense muon beam



- A search for Charged Lepton Flavor Violation: $\mu N \rightarrow e N$
  - Expected sensitivity of 6×10^{-17} @ 90% CL, x10,000 better than SINDRUM-II
  - Probes effective new physics mass scales up to 10^4 TeV/c^2
  - *Discovery* sensitivity to broad swath of NP parameter space

- Experiment scope includes
  - Proton Beam line
  - Solenoid systems
  - Detector elements

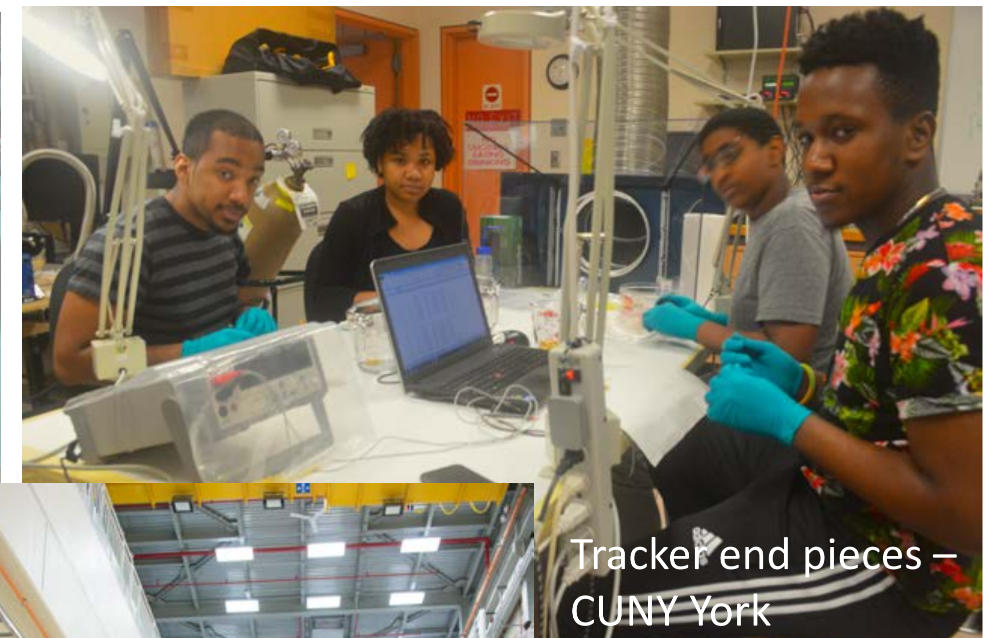
    (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
  - Experimental hall
  - Commissioning begins in 2022

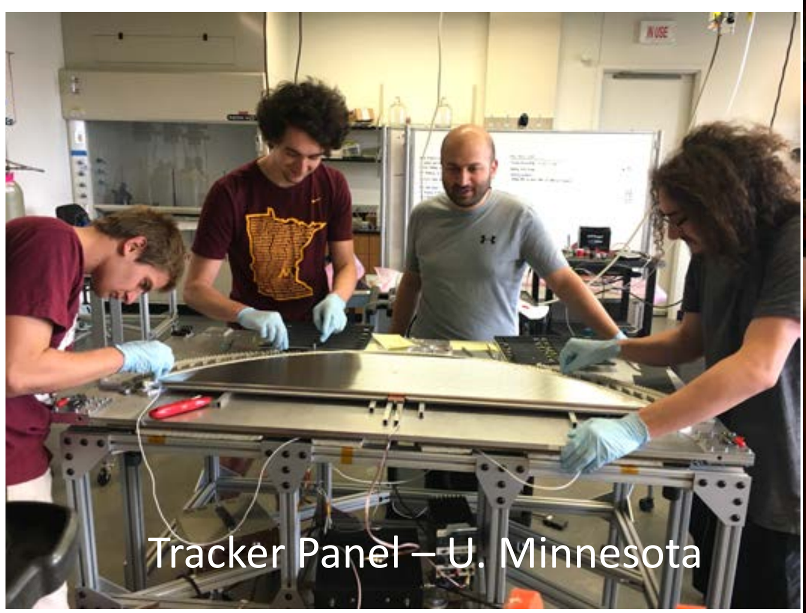
R. Bonvetre on Thursday

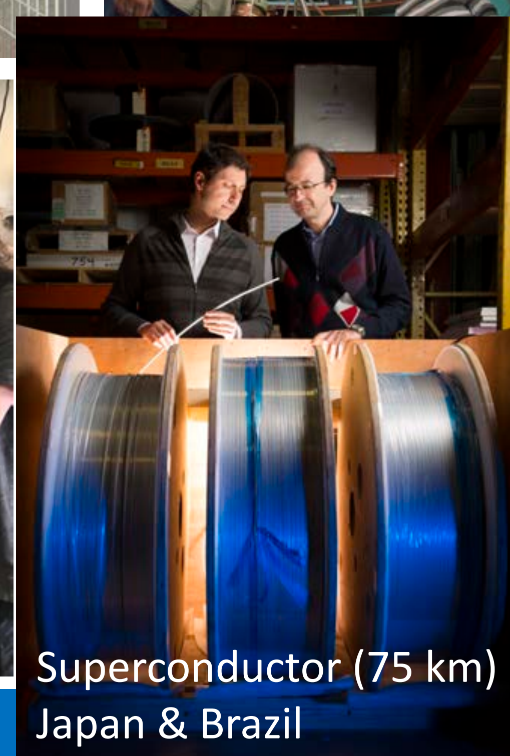
Mu2e at Fermilab


Calorimeter support - Frascati


Magnet testing - Fermilab


Tracker end pieces – CUNY York


Tracker Panel – U. Minnesota


Superconductor (75 km) Japan & Brazil


Mu2e Experimental Hall


Production Target -UK

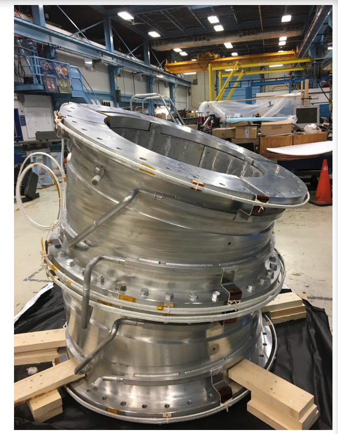

Cosmic Veto – U. Virginia

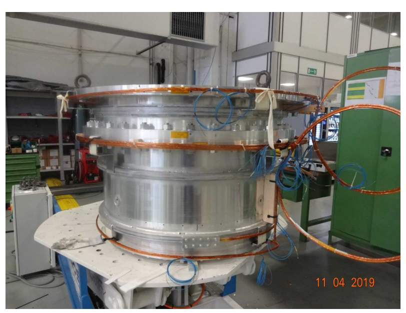
Completed:

- 75 km of superconductor
- 30 km of extruded scintillator
- 25 km of aluminized mylar straws

Mu2e at Fermilab

Transport Solenoid: Testing & assembly in progress!





Production Solenoid - coil windings have begun for the first coil!

Progress across sub-systems:

- 68% of Calorimeter CsI crystals received & tested
- 37% of Cosmic Veto di-counters built & tested
- 75% of pre-production Tracker panels built & tested
- Delivery Ring installed and working
- M4 Beam line installation in progress

Delivery Ring installation complete (in operation for Muon g-2 experiment)

Mu2e-II - a next generation $\mu \rightarrow e$ conversion experiment at FNAL

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

Mu2e-II is an upgrade that will:

- Use ~100 kW of PIP-II protons @800 MeV
- Achieve an order of magnitude improvement in sensitivity
  - probe $R_{\mu e} \sim 10^{-18}$ level,
  - extend Λ_{NP} reach by x2

- EOI Submitted to Fermilab PAC in 2018
- arXiv:1802.02599, Fermilab-FN-1052
- 130 Signatories, 36 Institutions

PAC: "physics case is compelling" "endorse request for R&D funding"

Status: Pursuing high priority R&D. Data taking ~2030 timescale.

Mu2e-II - a next generation $\mu \rightarrow e$ conversion experiment at FNAL

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

Mu2e-II is an upgrade that will:

- Use ~100 kW of PIP-II protons @800 MeV
- Achieve an order of magnitude improvement in sensitivity
  - probe $R_{\mu e} \sim 10^{-18}$ level,
  - extend Λ_{NP} reach by x2

- EOI Submitted to Fermilab PAC in 2018
- arXiv:1802.02599, Fermilab-FN-1052
- 130 Signatories, 36 Institutions

PAC: “physics case is compelling” “end

Status: Pursuing high priority R&D. D

I. Oksuzian on Thursday

If found …

Effective Field Theory for μ→e Conversion

two-lepton and two-nucleon operators and dipole operators

$$
\begin{aligned}
\mathcal{L}_{\mu A\to eA}(\Lambda_{expt}) \;=\; & -\frac{4G_F}{\sqrt{2}}\sum_{N=p,n}\Big[m_\mu\left(C_{DL}\overline{e_R}\sigma^{\alpha\beta}\mu_L F_{\alpha\beta}+C_{DR}\overline{e_L}\sigma^{\alpha\beta}\mu_R F_{\alpha\beta}\right) \\
& +\left(\widetilde{C}^{(NN)}_{SL}\overline{e}P_L\mu+\widetilde{C}^{(NN)}_{SR}\overline{e}P_R\mu\right)\overline{N}N \\
& +\left(\widetilde{C}^{(NN)}_{P,L}\overline{e}P_L\mu+\widetilde{C}^{(NN)}_{P,R}\overline{e}P_R\mu\right)\overline{N}\gamma_5 N \\
& +\left(\widetilde{C}^{(NN)}_{VL}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}^{(NN)}_{VR}\overline{e}\gamma^\alpha P_R\mu\right)\overline{N}\gamma_\alpha N \\
& +\left(\widetilde{C}^{(NN)}_{A,L}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}^{(NN)}_{A,R}\overline{e}\gamma^\alpha P_R\mu\right)\overline{N}\gamma_\alpha\gamma_5 N \\
& +\left(\widetilde{C}^{(NN)}_{Der,L}\overline{e}\gamma^\alpha P_L\mu+\widetilde{C}^{(NN)}_{Der,R}\overline{e}\gamma^\alpha P_R\mu\right) i(\overline{N}\overleftrightarrow{\partial}_\alpha\gamma_5 N) \\
& +\left(\widetilde{C}^{(NN)}_{T,L}\overline{e}\sigma^{\alpha\beta}P_L\mu+\widetilde{C}^{(NN)}_{T,R}\overline{e}\sigma^{\alpha\beta}P_R\mu\right)\overline{N}\sigma_{\alpha\beta}N+h.c.\Big] \quad .
\end{aligned}
$$

dipole

scalar

pseudo-scalar

vector

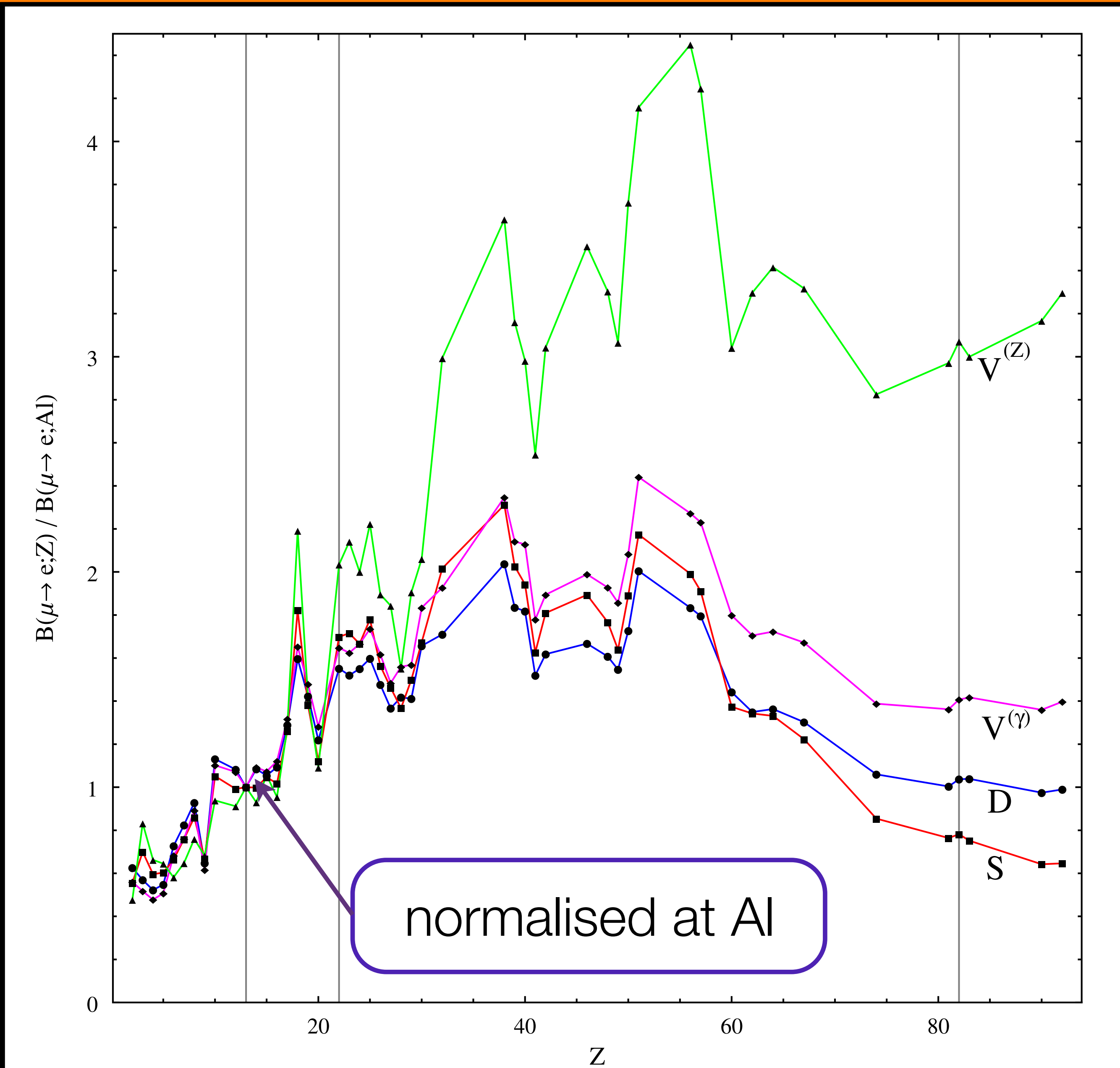
axial-vector

(derivative)

tensor

Discrimination of the interactions by different targets

Osaka University



vector interaction (with Z boson)	with Z penguin
vector interaction (with photon - charge radius)	left-right models
dipole interaction	SUSY-GUT
scalar interaction	SUSY seesaw

R. Kitano, M. Koike and Y. Okada, Phys.Rev. D66 (2002) 096002; D76 (2007) 059902
V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, Phys. Rev. D80 (2009) 013002
S. Davidson, YK, M. Yamanaka, Phys. Lett. B790 (2019) 380-388

Spin Dependent μ-e conversion and Spin Independent μ-e conversion

dipole interaction

vector interaction

scalar interaction

Spin Independent μ-e Conversion (coherent)

Spin Dependent μ-e conversion and Spin Independent μ-e conversion

dipole interaction

vector interaction

scalar interaction

Spin Independent μ-e Conversion (coherent)

Pseudo-scaler interaction

axial vector interaction

tensor interaction

Spin Dependent μ-e Conversion (incoherent)

compare zero-spin and non-zero-spin nuclear targets

V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242

S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109

LNV/CLFV

μ^- to e^+ conversion in muonic atom

$$\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$$

ground or excited final states.

Lepton number violation (LNV) and
Lepton flavour violation (LFV)

signal signature

$$E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - (M(A,Z-2) - M(A,Z))$$

backgrounds

- radiative muon nuclear capture (RMC)
  $\mu^- + N(A,Z) \rightarrow N(A,Z-1) + \nu + \gamma$

$$E_{RMC} = m_\mu - B_\mu - E_{rec} - (M(A,Z-1) - M(A,Z))$$

μ^- to e^+ conversion in muonic atom

$$\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$$ ground or excited final states.

Lepton number violation (LNV) and
Lepton flavour violation (LFV)

signal signature

$$E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - (M(A,Z-2) - M(A,Z))$$

backgrounds

- radiative muon nuclear capture (RMC)
  $\mu^- + N(A,Z) \to N(A,Z-1) + \nu + \gamma$

$$E_{RMC} = m_\mu - B_\mu - E_{rec} - (M(A,Z-1) - M(A,Z))$$

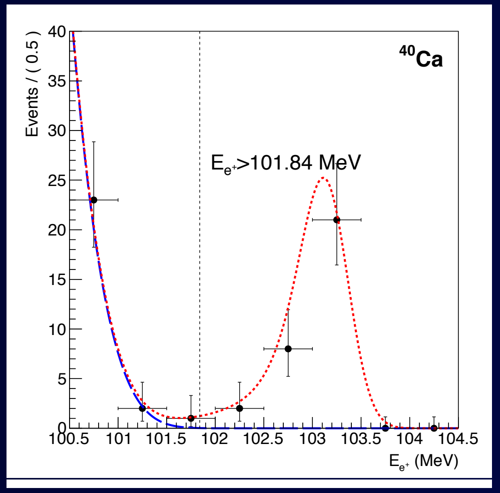
- Current limits :

$$\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca(gs)} \le 1.7 \times 10^{-12}$$

$$\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca(ex)} \le 3.6 \times 10^{-11}$$

J. Kaulard et al. (SINDRUM-II)
Phys. Lett. B422 (1998) 334.

- Future prospects:
  - Mu2e or COMET can improve with proper targets,



T. Geib, A. Merie, K. Zuber, Phys. Lett. B764 (2017) 157-162

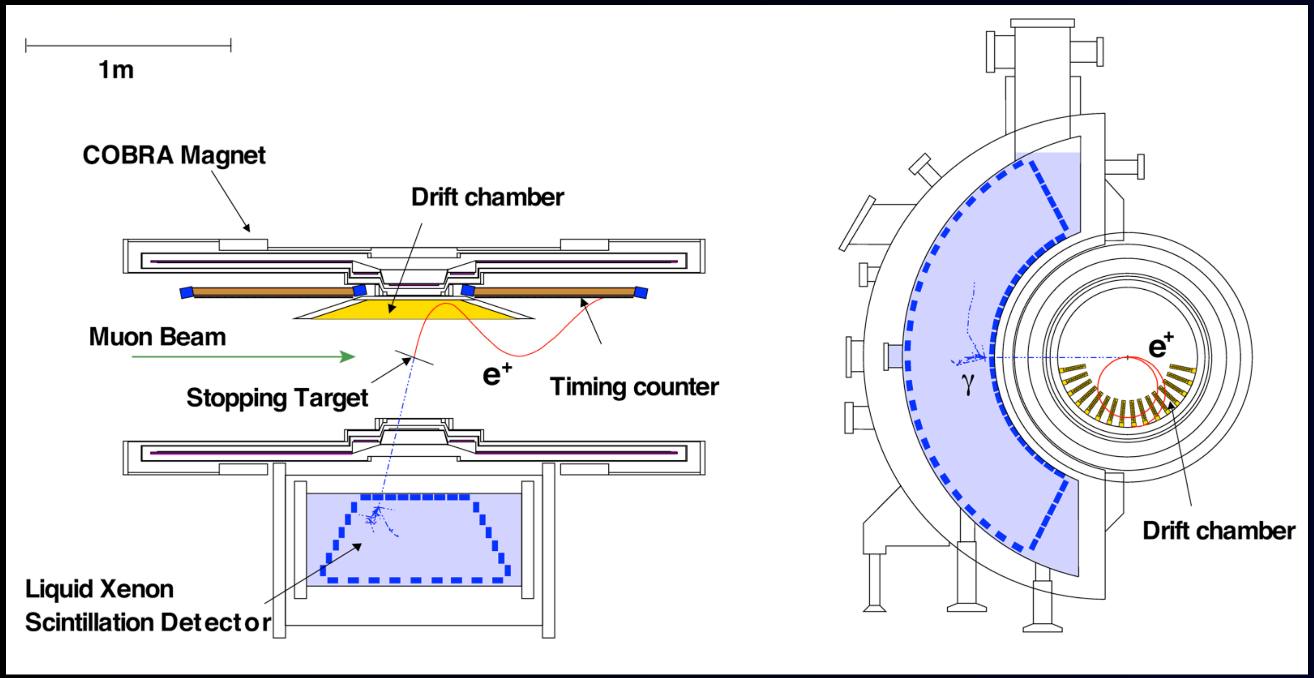
B. Yeo, YK, M. Lee and K. Zuber, Phys. Rev. D96 (2017) 075027

DC muon beam experiments are …

CLFV Decay of Muons : $\mu^+ \to e^+\gamma$

MEG @PSI (2016)

- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI



$$B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

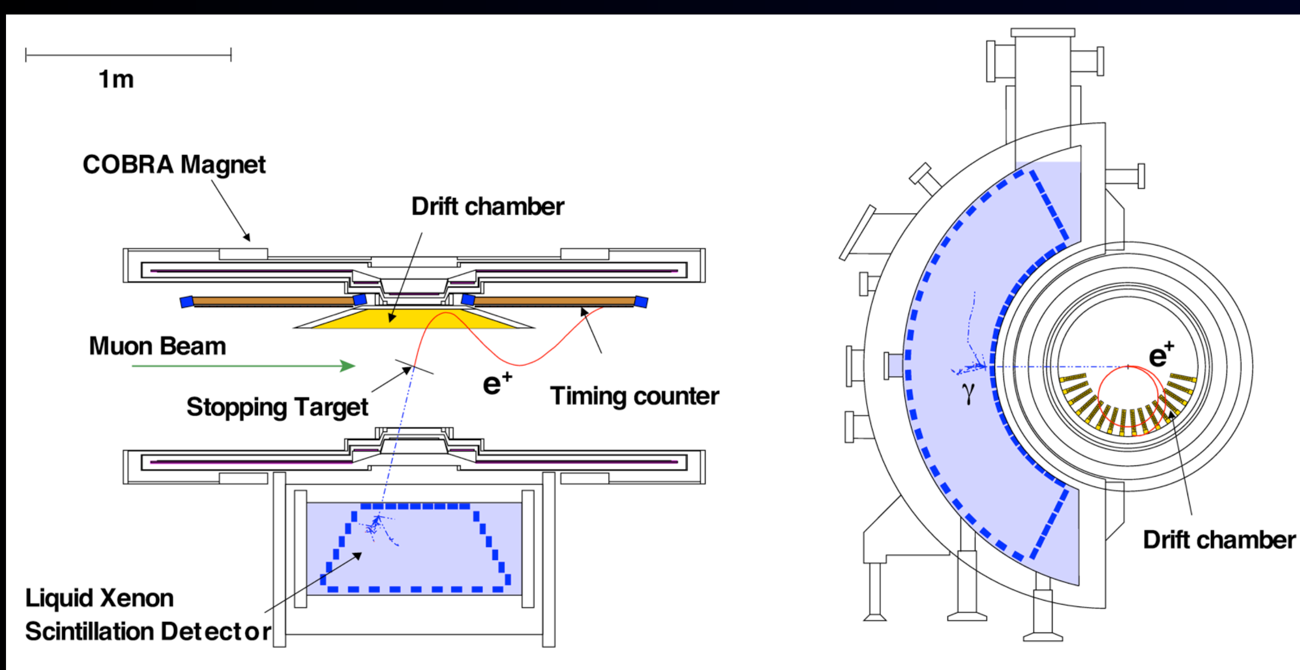
- a factor of 30 improvement

CLFV Decay of Muons : $\mu^+ \to e^+\gamma$

Osaka University

MEG @PSI (2016)

- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI

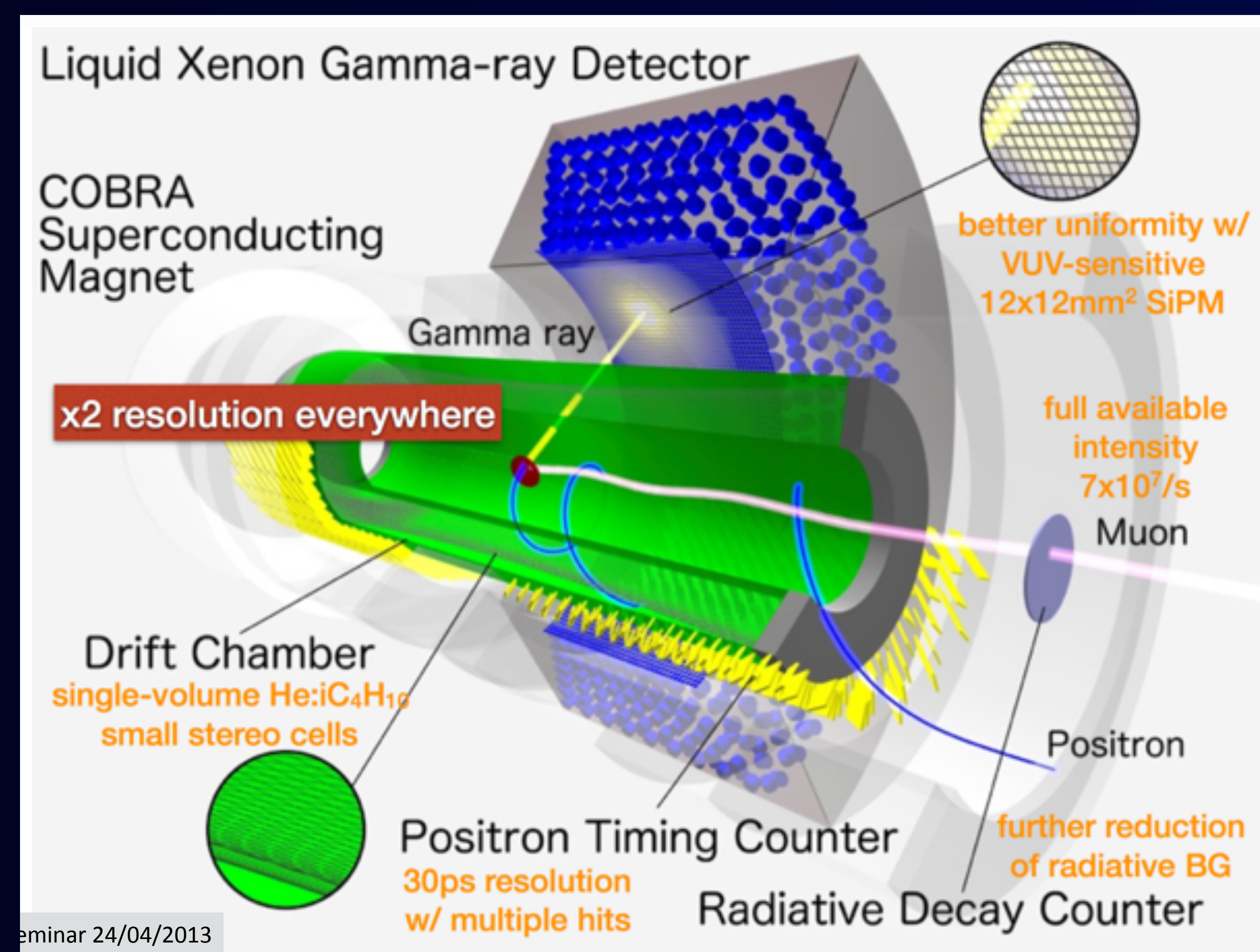


$$B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

- a factor of 30 improvement

MEG II

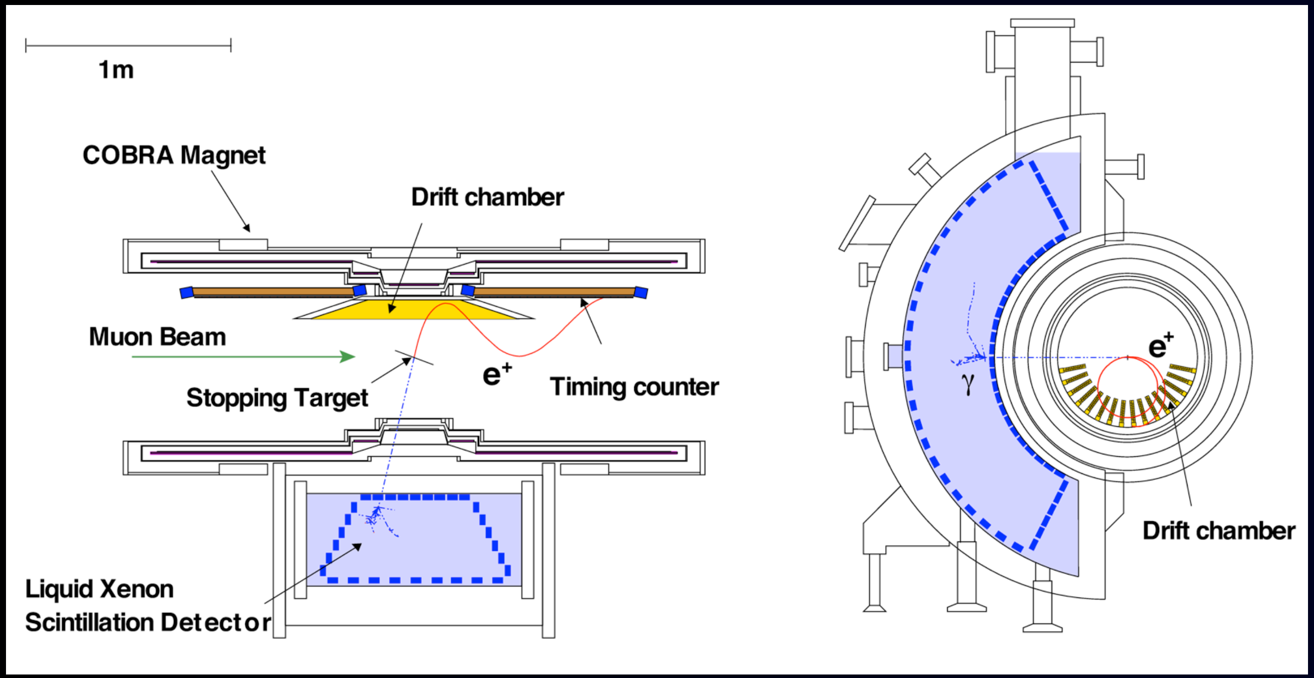
- all detectors upgraded
- full muon beam intensity
- Goal ~ 6×10^{-14} (2020-2023)



CLFV Decay of Muons : μ⁺→e⁺γ

MEG @PSI (2016)

- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI

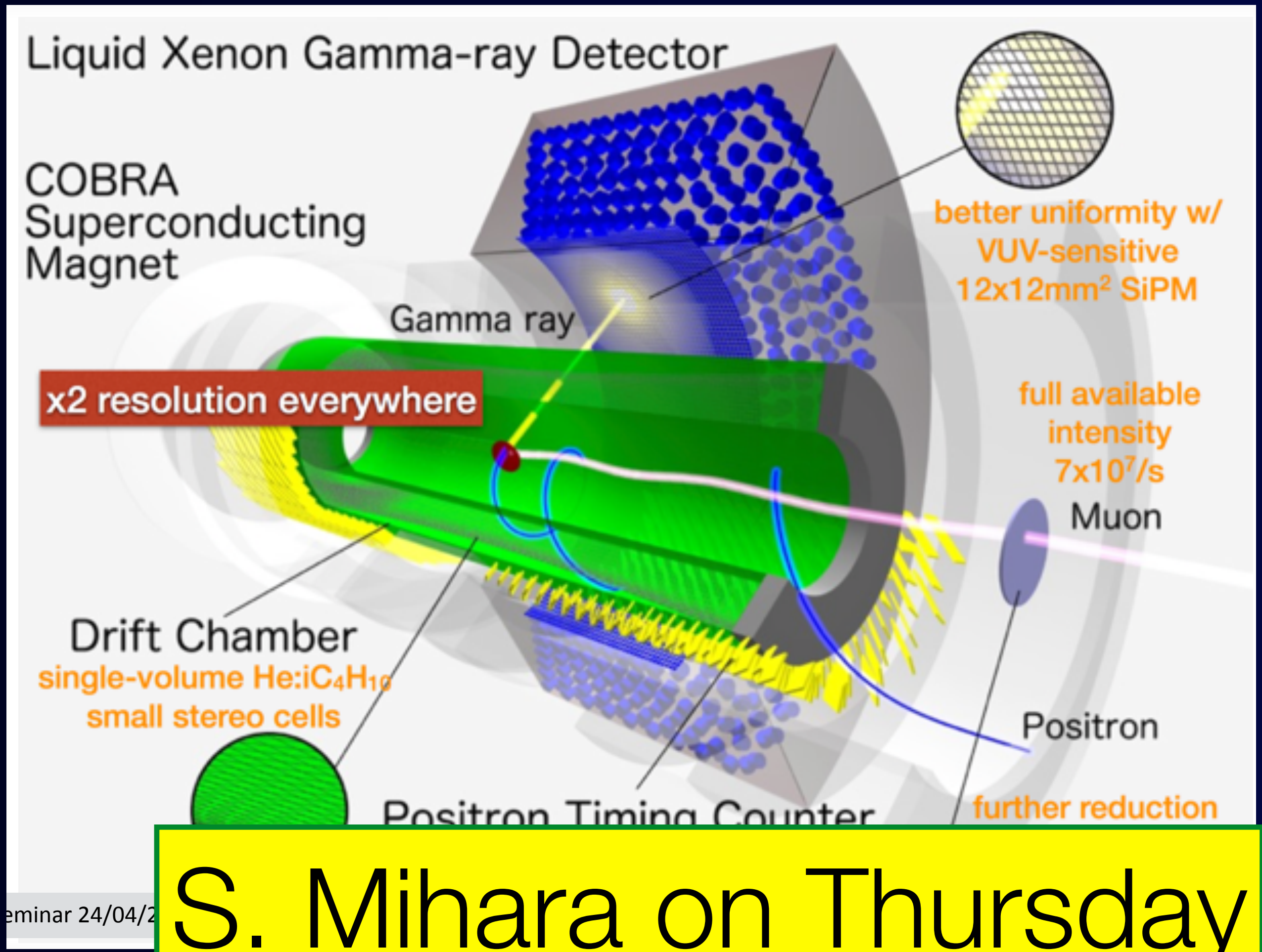


$$B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

- a factor of 30 improvement

MEG II

- all detectors upgraded
- full muon beam intensity
- Goal ~ 6×10^{-14} (2020-2023)



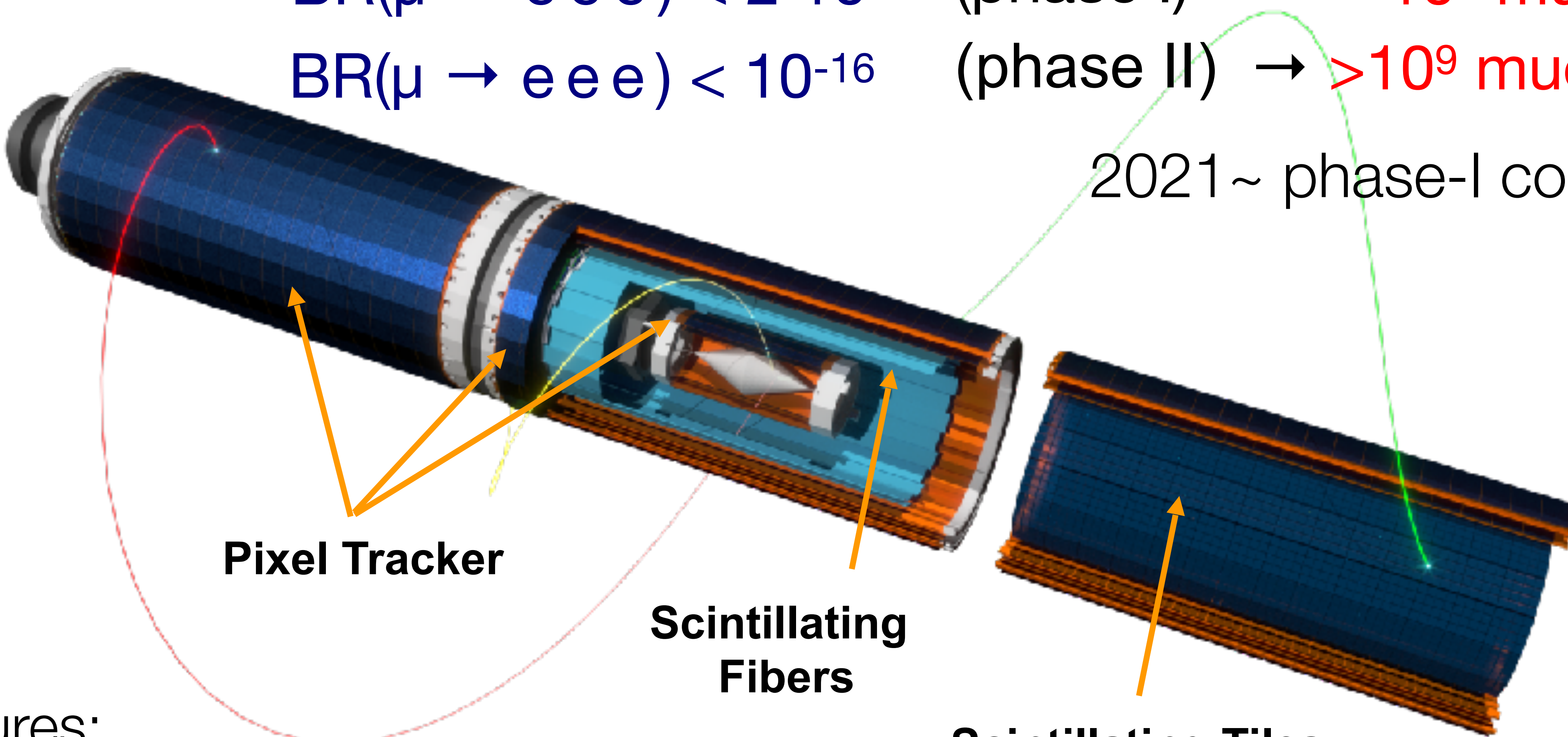
S. Mihara on Thursday

Mu3e at PSI

$BR(\mu \to eee) < 2 \cdot 10^{-15}$ (phase I) → 10^8 muons/s (PiE5)

$BR(\mu \to eee) < 10^{-16}$ (phase II) → $>10^9$ muons/s (HiMB)

2021~ phase-I commissioning



Features:

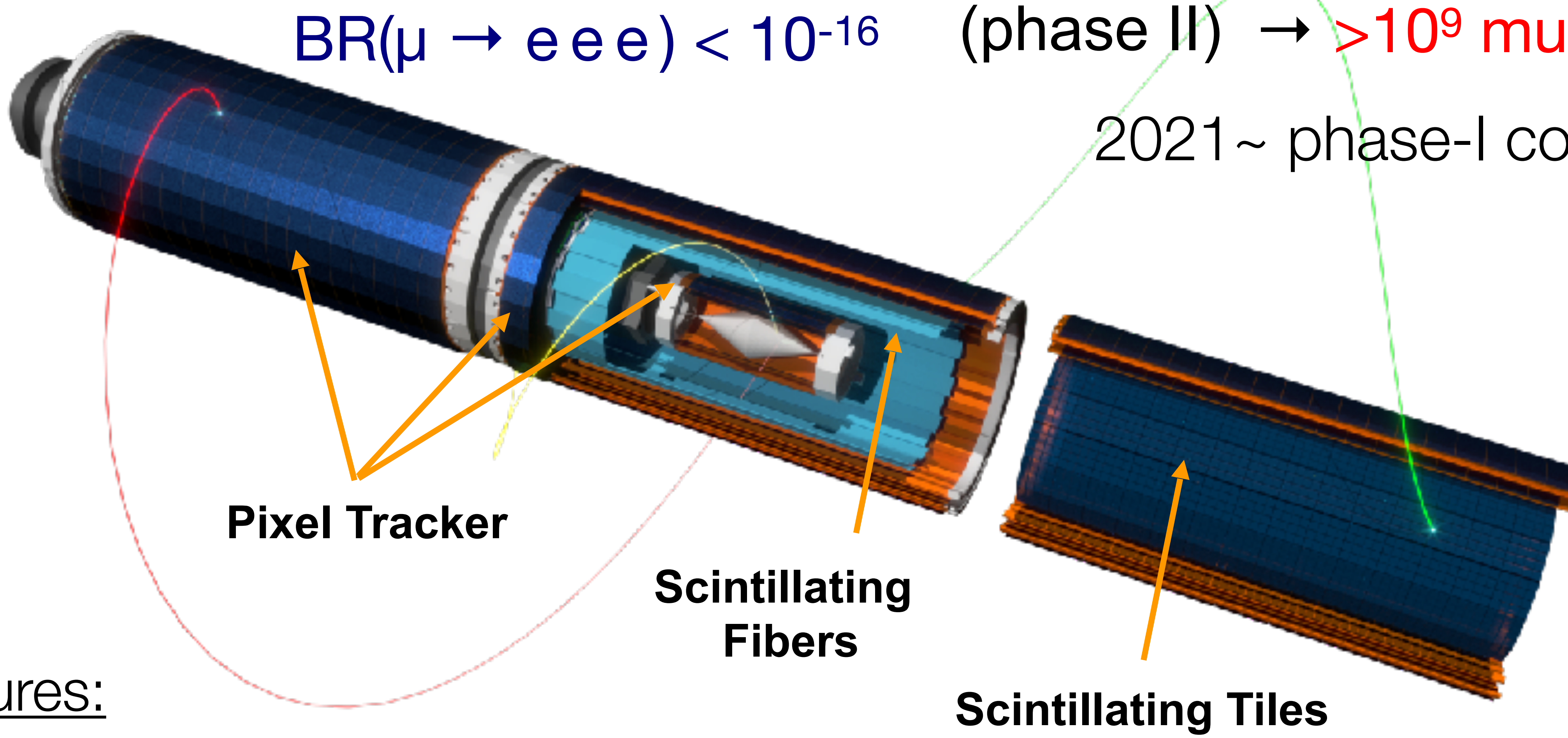
- surface muons (p=29 MeV/c, DC) stopped on target at high rate: 10^8 - 10^9 /s
- ultra thin silicon pixel detector (HV-MAPS) with 1 per mill radiation length / layer
- high precision tracking using recurling tracks in strong magnetic field
- fast timing detectors (scintillating fibers & tiles)
- helium gas cooling

Mu3e at PSI

BR($\mu \rightarrow e\,e\,e$) < $2 \cdot 10^{-15}$ (phase I) → 10^{8} muons/s (PiE5)

BR($\mu \rightarrow e\,e\,e$) < 10^{-16} (phase II) → >10^{9} muons/s (HiMB)

2021~ phase-I commissioning



Features:

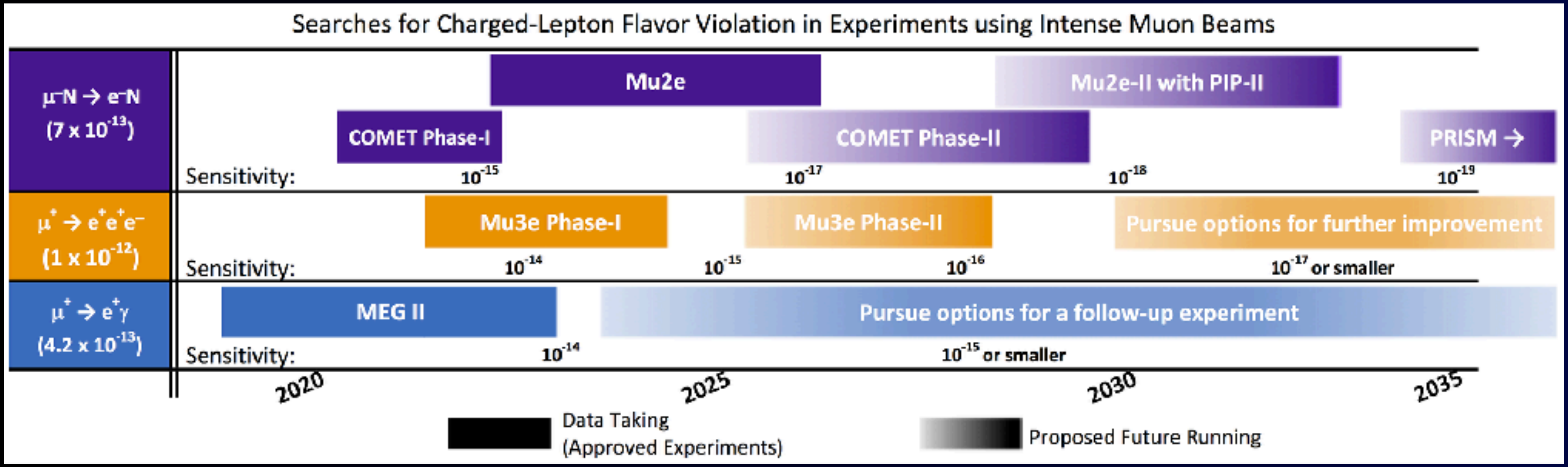
- surface muons (p=29 MeV/c, DC) stopped on target at high rate: 10^{8} - 10^{9} /s
- ultra thin silicon pixel detector (HV-MAPS) with 1 per mill radiation length / layer
- high precision tracking using recurling tracks in strong magnetic field
- fast timing detectors (scintillating fibers & ti
- helium gas cooling

S. Dittmeier on Thursday

Schedule of “golden” μ→e Transition processes in 2025 and beyond

Osaka University

Timeline submitted to EPPSU 2020



Improvement : > 10,000

COMET, MEG, Mu3e, Mu2e, arXiv:1812.06540

Muon g-2

Muon g-2 : Spin precession

Under a magnetic field

Spin vector precession

$$\omega_S = \frac{eB}{m_\mu \gamma}[1 + \frac{(g-2)}{2}\gamma]$$

Momentum vector motion

$$\omega_C = \frac{eB}{m_\mu \gamma}$$

Muon g-2 : Spin precession

Francis Farley, Hans Sens, Georges Charpak, Theo Muller, Anton with the 6-meter g-2 magnet

Under a magnetic field

Spin vector precession

$$\omega_S = \frac{eB}{m_\mu \gamma}\left[1 + \frac{(g-2)}{2}\gamma\right]$$

Momentum vector motion

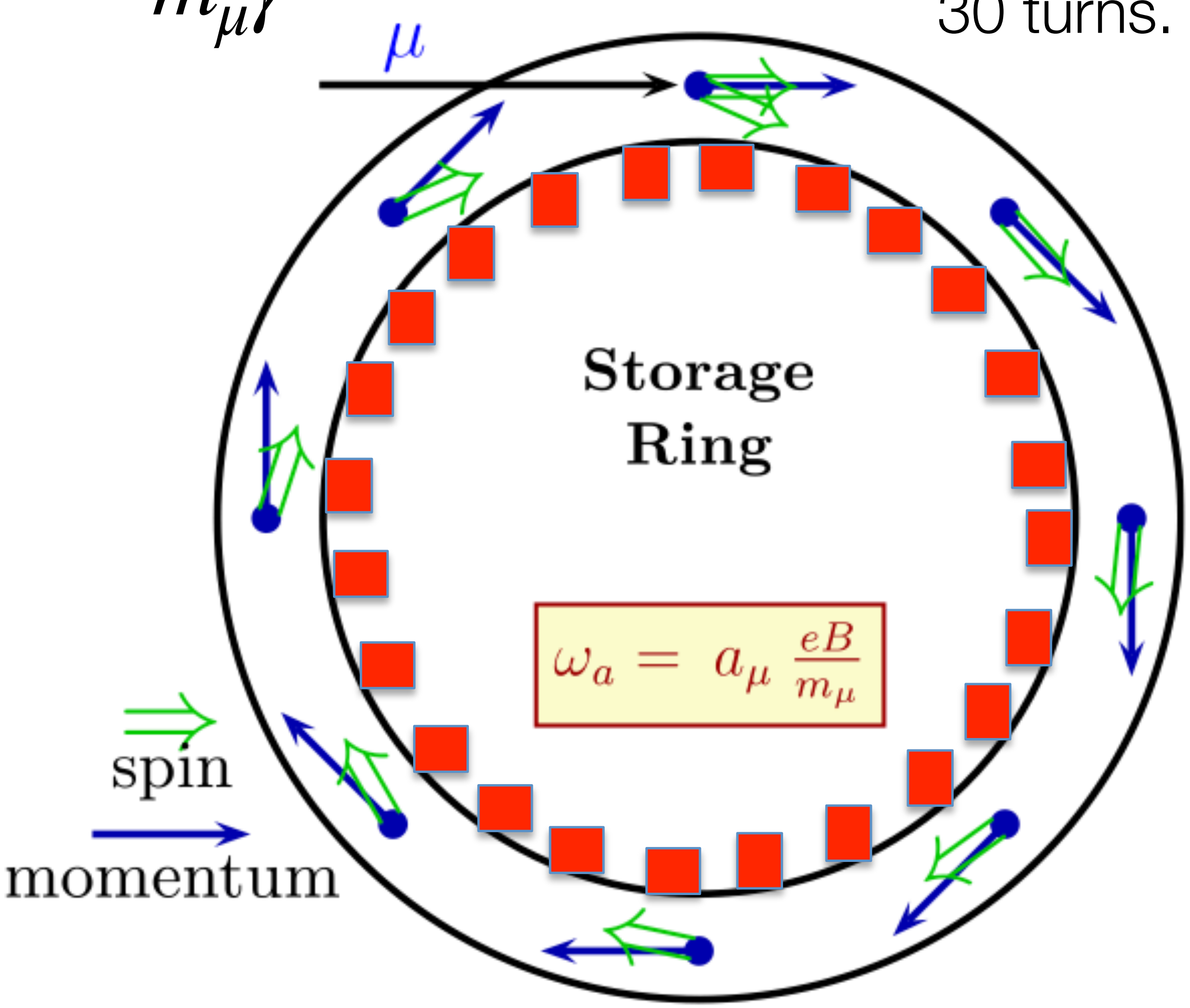
$$\omega_C = \frac{eB}{m_\mu \gamma}$$

At the BNL experiment, spin precesses around momentum once every 30 turns.

Spin precession with respect to the momentum vector

$$\omega_S - \omega_C = \omega_a = \frac{a_\mu eB}{m_\mu}$$

$$a_\mu = \frac{1}{2}(g-2)$$



Muon g-2

$$\omega_a$$

$$\omega_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

ZERO

ZERO

FNAL/BNL approach : effect of focussing E-field cancelled by using "magic" 3.09 GeV momenta muons.

J-PARC approach : 300 MeV beam with v. low transverse momenta requiring no E-field to focus.

Muon g-2

ω_a

$$\omega_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

ZERO

ZERO

FNAL/BNL approach : effect of focussing E-field cancelled by using "magic" 3.09 GeV momenta muons.

J-PARC approach : 300 MeV beam with v. low transverse momenta requiring no E-field to focus.

ω_p

B is measured using NNR in terms of the proton Larmor frequency

Muon g-2

ω_a

$$\omega_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

ZERO **ZERO**

FNAL/BNL approach : effect of focussing E-field cancelled by using “magic” 3.09 GeV momenta muons.

J-PARC approach : 300 MeV beam with v. low transverse momenta requiring no E-field to focus.

ω_p B is measured using NNR in terms of the proton Larmor frequency

$$\frac{g-2}{2} = a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

3ppb 22ppb 0.26ppt

Muon g-2 Prediction

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

$$a_\mu^{\rm SM} = 116591820.5(35.6) \times 10^{-11}$$

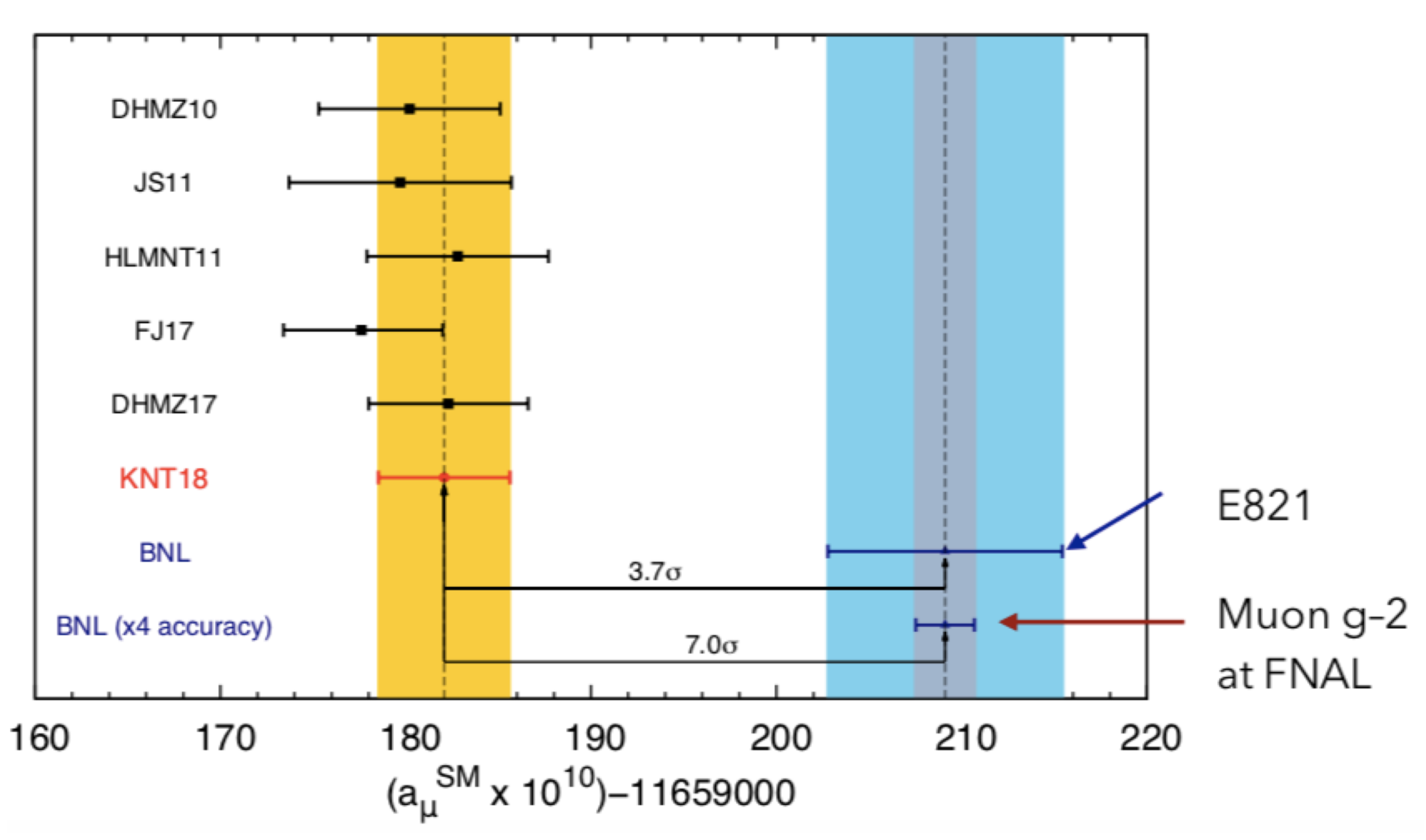
Muon g-2 Prediction

Osaka University

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

$$a_\mu^{\mathrm{SM}} = 116591820.5(35.6) \times 10^{-11}$$

$$a_\mu^{\exp} = 116595208.9(63) \times 10^{-11}$$ BNL E821



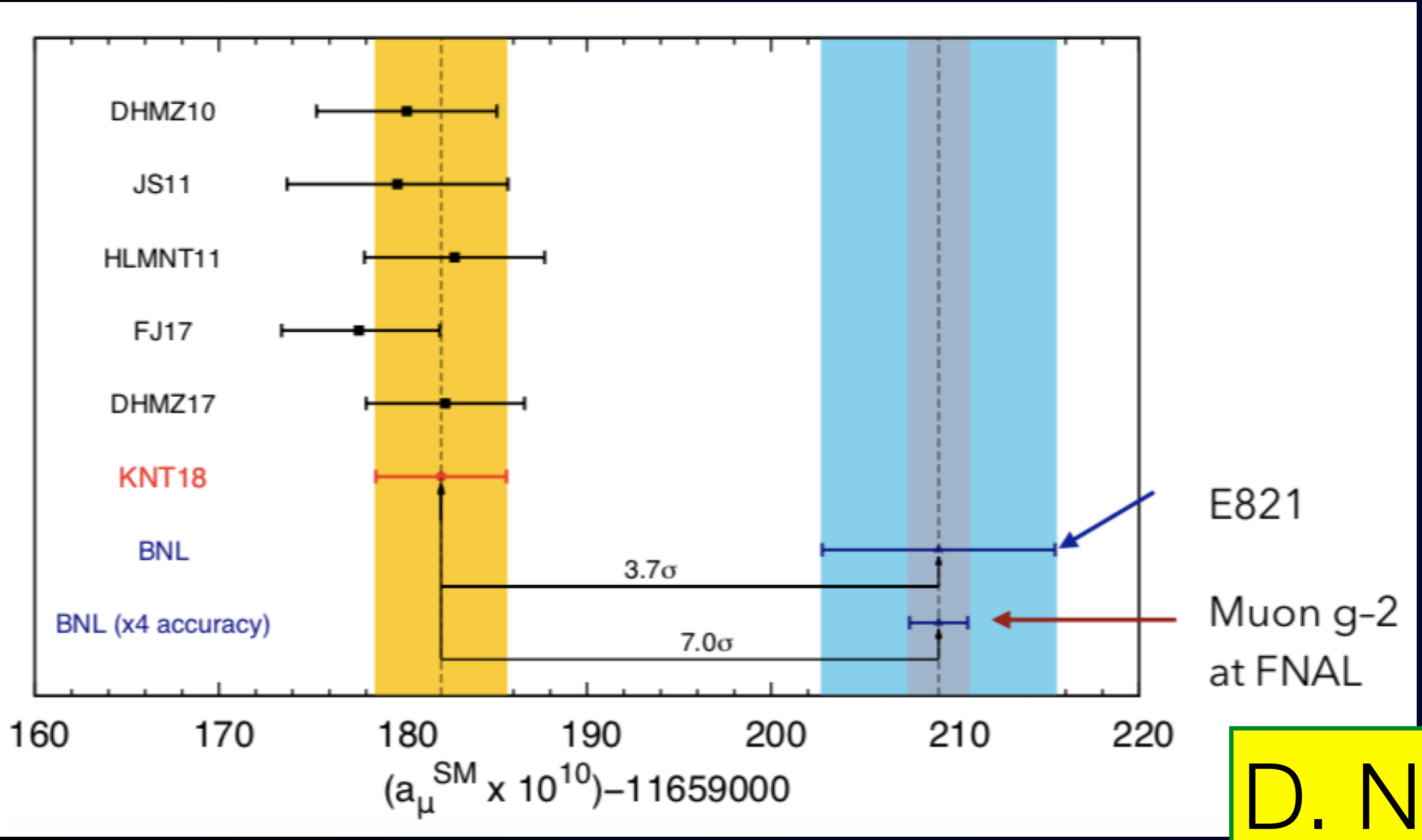
3.7σ deviation from the SM expectation

Muon g-2 Prediction

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

$$a_\mu^{\rm SM} = 116591820.5(35.6) \times 10^{-11}$$

$$a_\mu^{\rm exp} = 116595208.9(63) \times 10^{-11}$$ BNL E821



3.7σ deviation from the SM expectation

D. Nomura on Tuesday

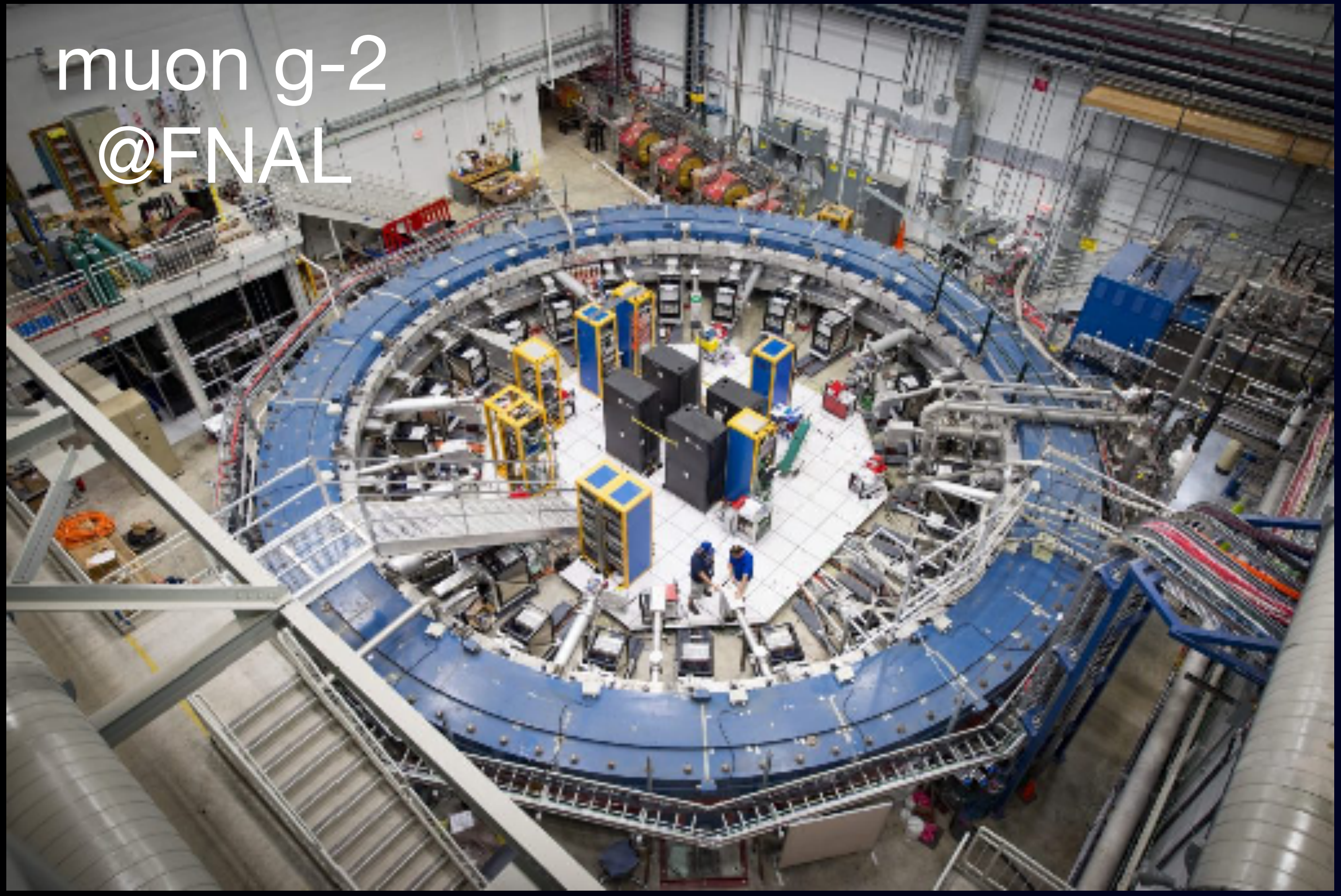
Muon g-2 (E989) at FNAL

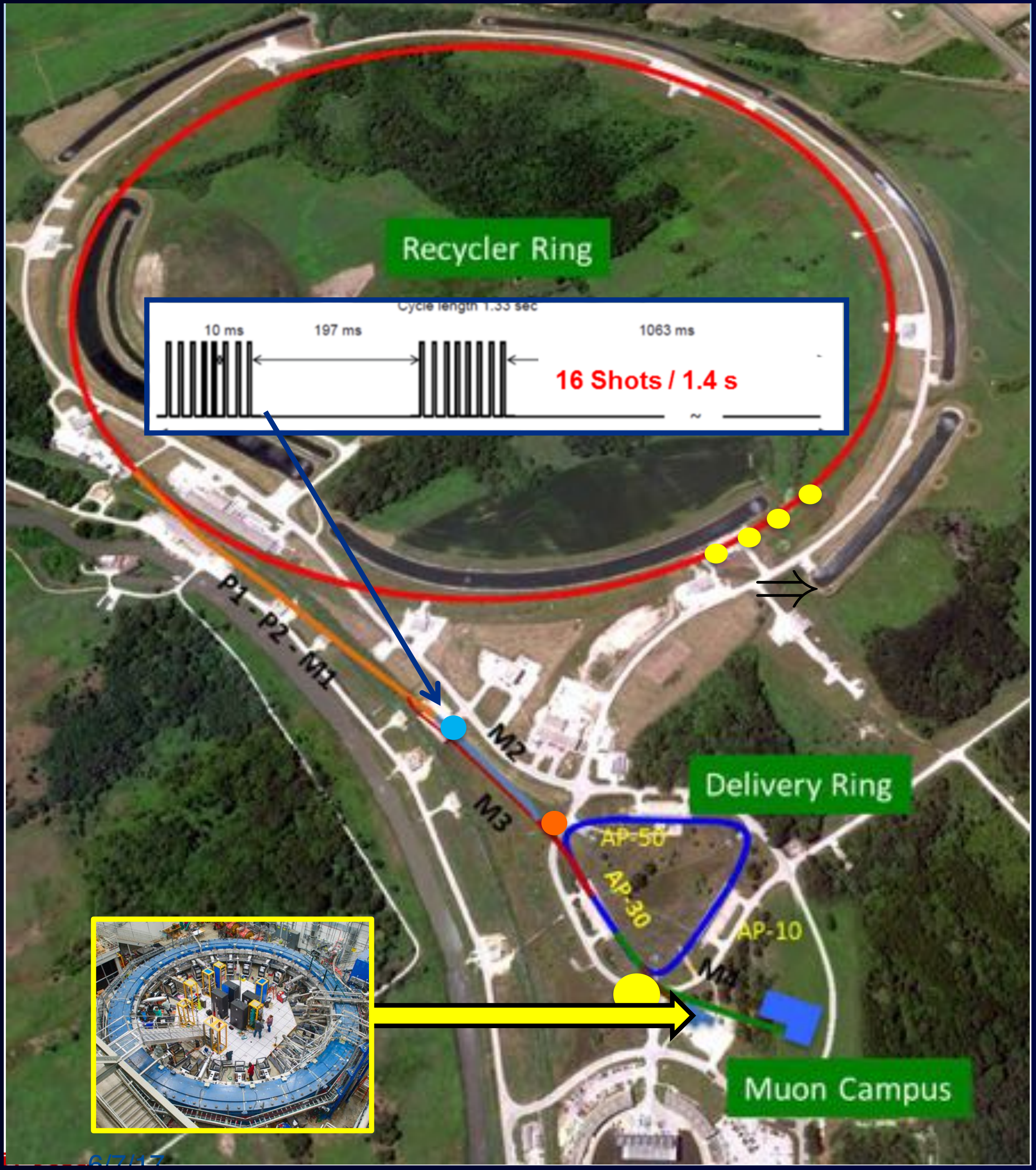
- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year

Muon g-2 (E989) at FNAL

Osaka University

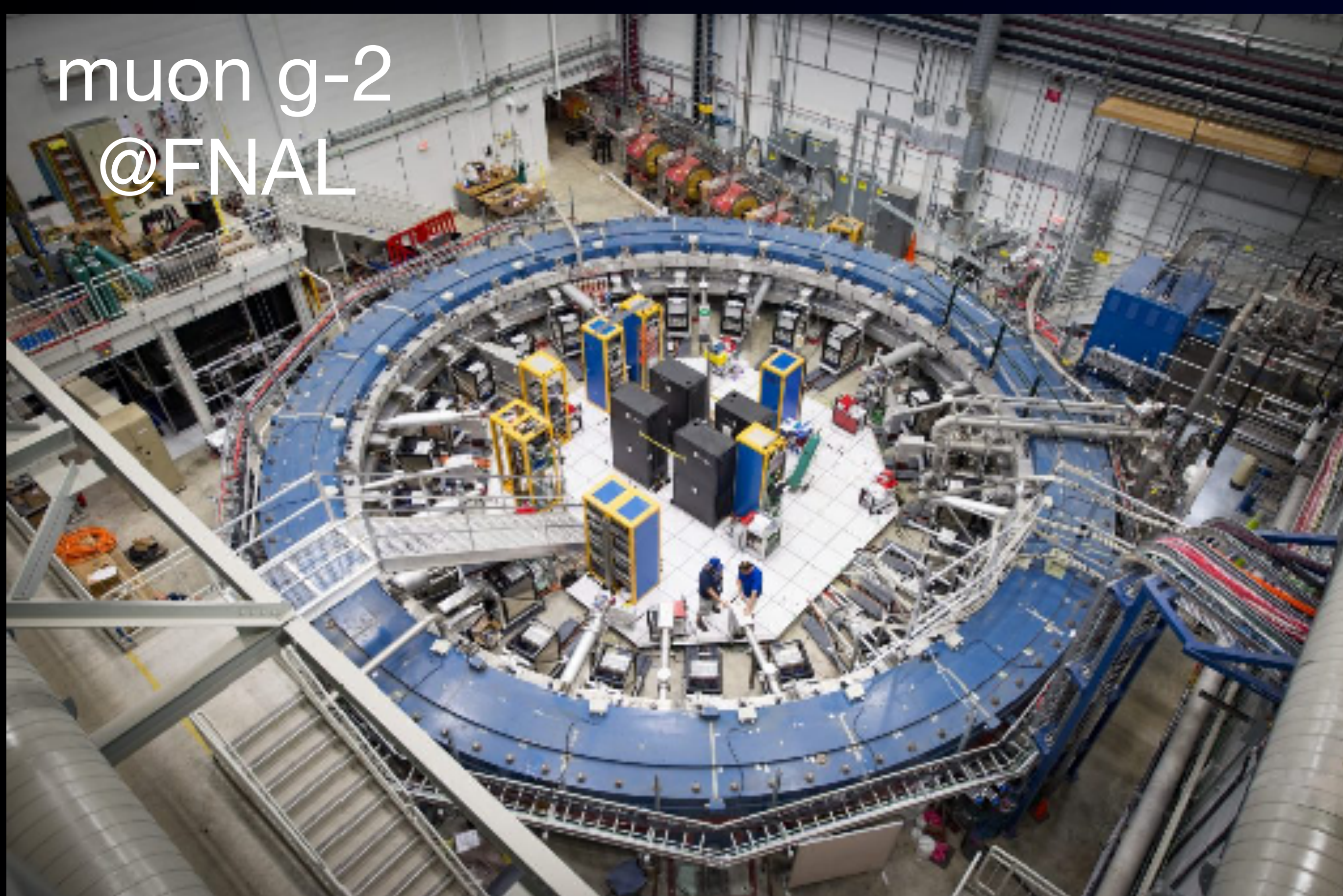
- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year

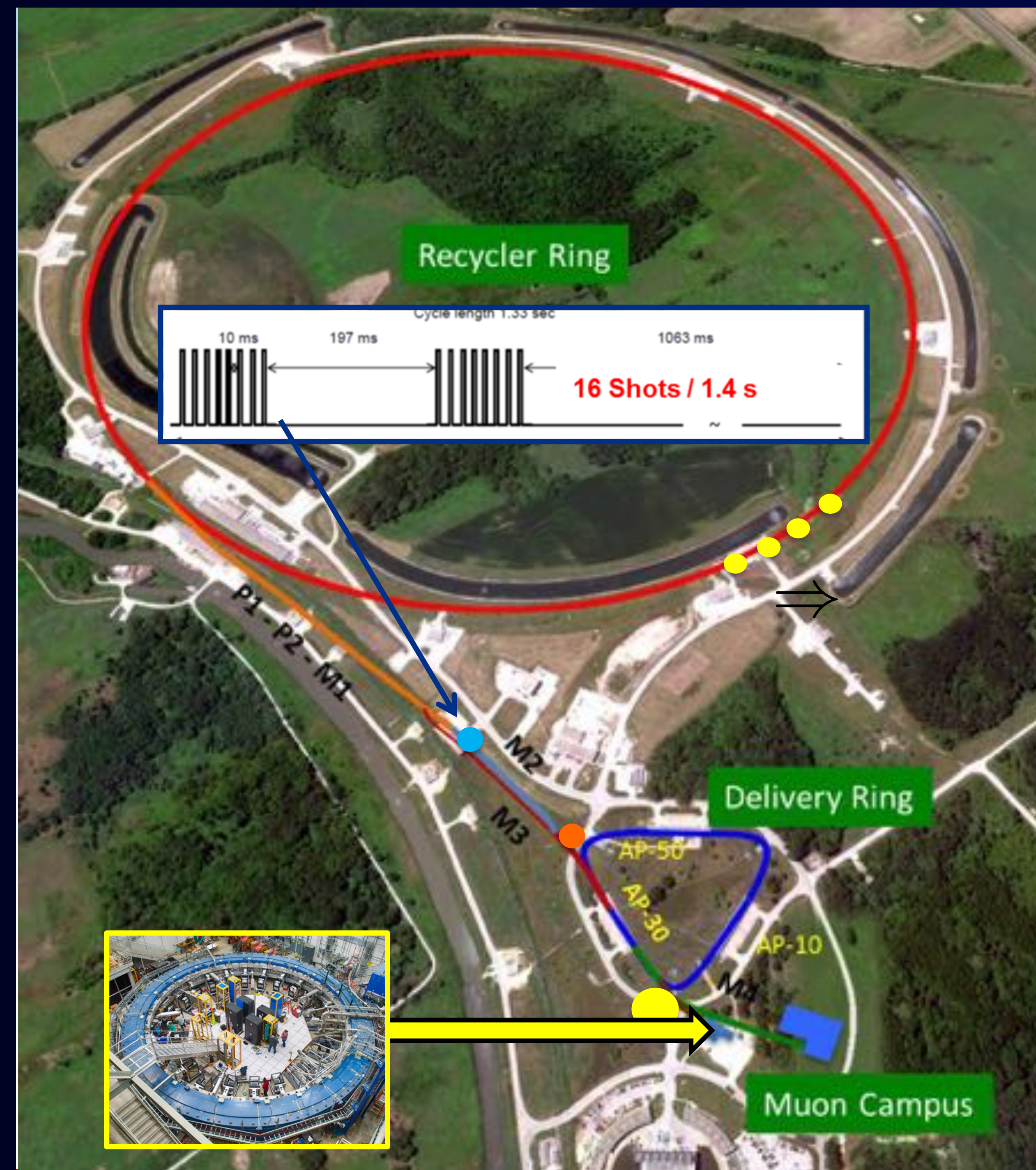




Muon g-2 (E989) at FNAL

- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year

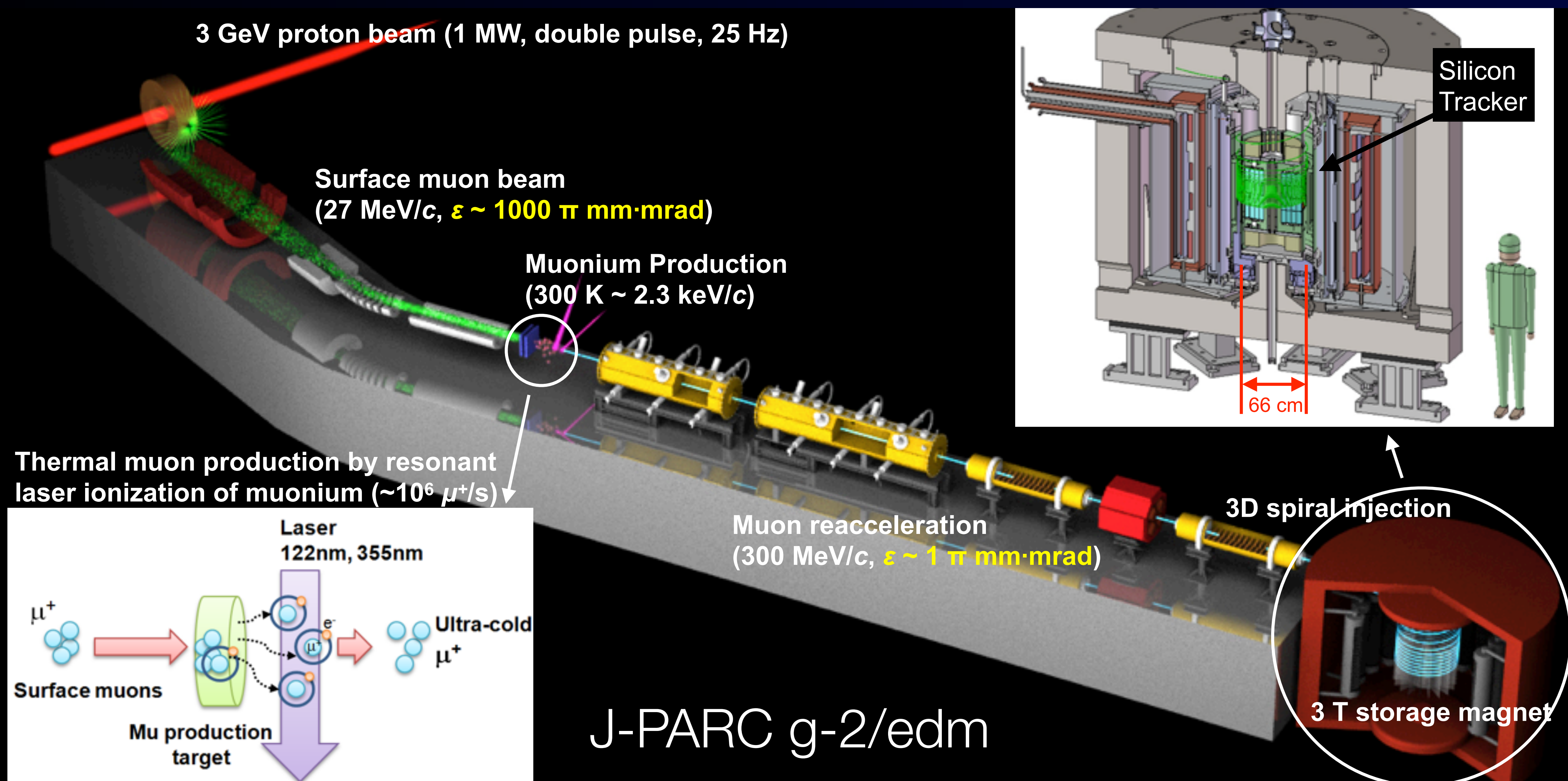




S. Corrodi on Tuesday

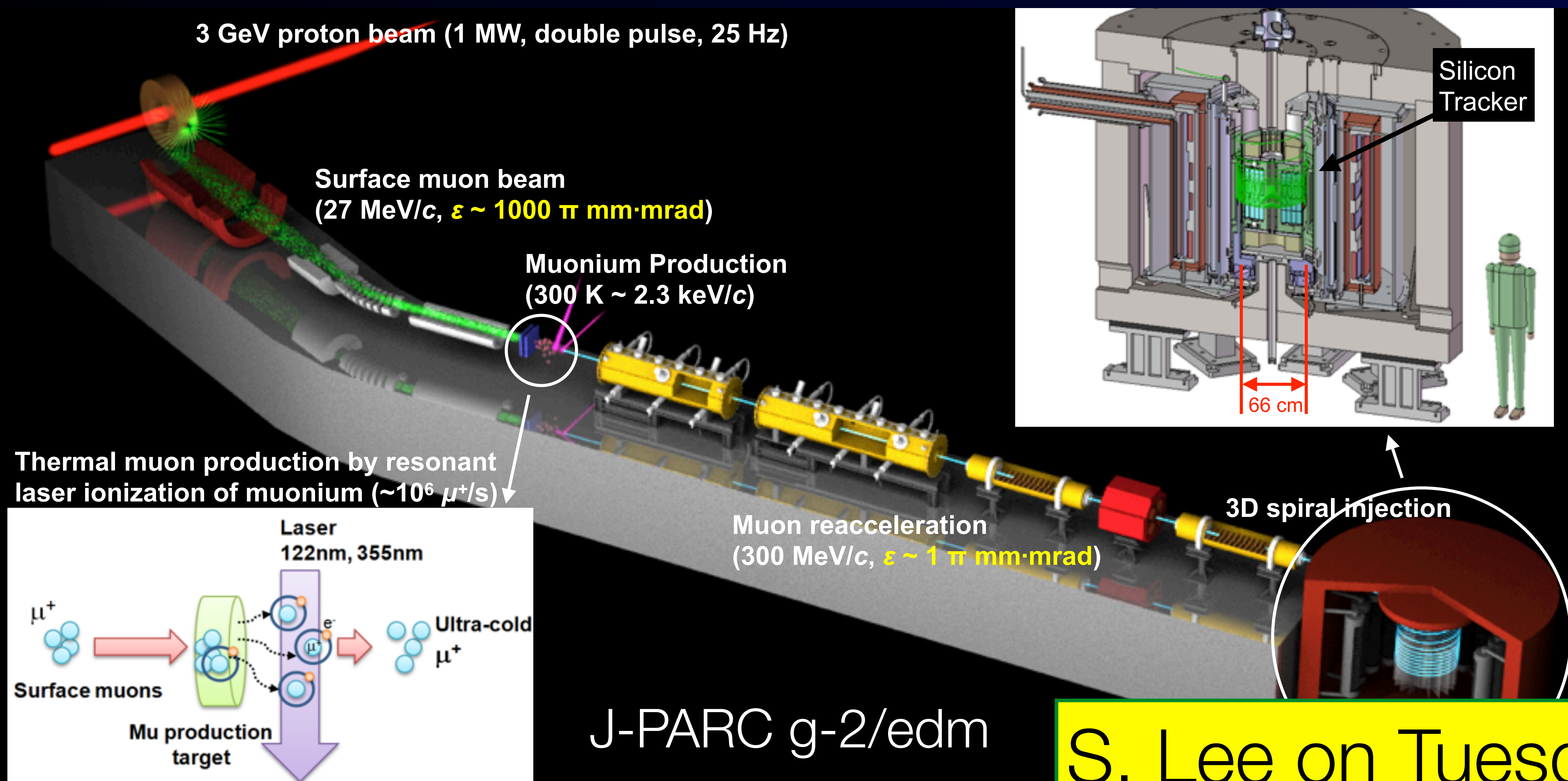
J-PARC g-2/edm

- new technique : slow muons from laser ionization of muonium.
- aim at 0.45 ppm
- different systematics



J-PARC g-2/edm

- new technique : slow muons from laser ionization of muonium.
- aim at 0.45 ppm
- different systematics



S. Lee on Tuesday

Muon g-2 Anomaly and Muon CLFV

Osaka University

muon g-2 anomaly

flavour conserving component of the BSM dipole operator

muon CLFV ($\mu \rightarrow e\gamma$ etc.)

flavour violating component of the BSM dipole operator

Muon g-2 Anomaly and Muon CLFV

Osaka University

muon g-2 anomaly

flavour conserving component of the BSM dipole operator

muon CLFV ($\mu \rightarrow e\gamma$ etc.)

flavour violating component of the BSM dipole operator

If the Muon g-2 anomaly is confirmed, it will establish the presence of a BSM muon interaction which may induce sizable effects of muon CLFV.

M. Lindner, M. Platscher, and F.S. Queiroz, arXiv:161006587

Summary

- Physics prospects with muons are rich.
- Study of charged leptons has sensitivity to BSM physics extending and complementing the reach of the LHC with a significant synergy with the neutrino program.
- Many projects will have their first results/start data taking in the next 2-3 years.

Summary

- Physics prospects with muons are rich.
- Study of charged leptons has sensitivity to BSM physics extending and complementing the reach of the LHC with a significant synergy with the neutrino program.
- Many projects will have their first results/start data taking in the next 2-3 years.

my dog, IKU