Search for Muon to Electron Conversion in a Muonic Atom

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RCNP, Osaka University

April 20th, 2024

Workshop on Muon Physics at the Intensity and Precision Frontier (MIP2024)

PKU, Beijing, China

Outline

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muon to electron conversion in a muonic atom

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

Charged Lepton Flavour Violation (CLFV)

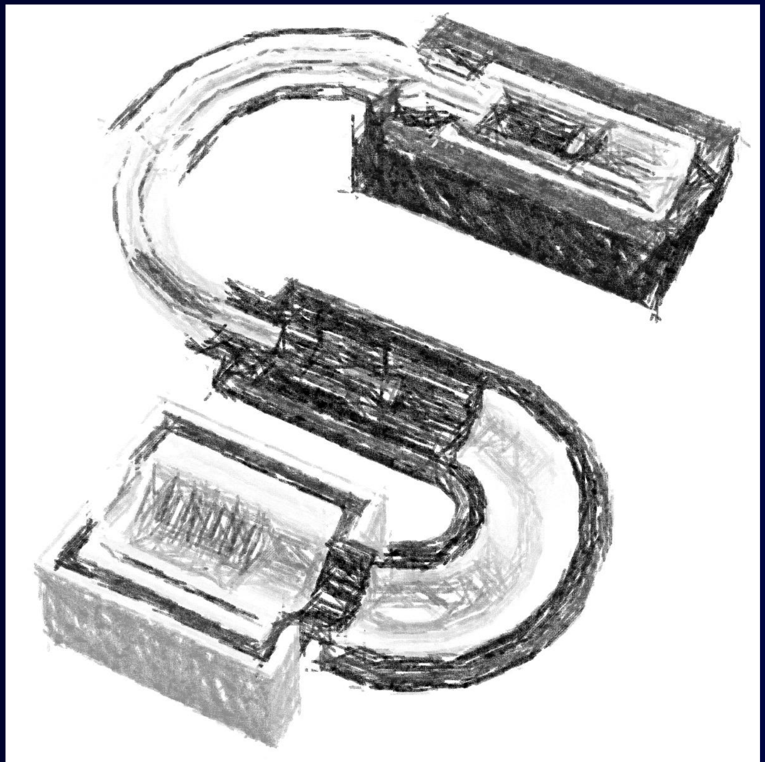
Outline

muon to electron conversion in a muonic atom

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

Charged Lepton Flavour Violation (CLFV)

- Physics Motivation
- Recent Experimental Status (COMET)
- Related Rare Processes
- Future Prospects



Physics and Phenomenology of Charged Lepton Flavour Violation (CLFV)

CLFV in the Standard Model (SM)

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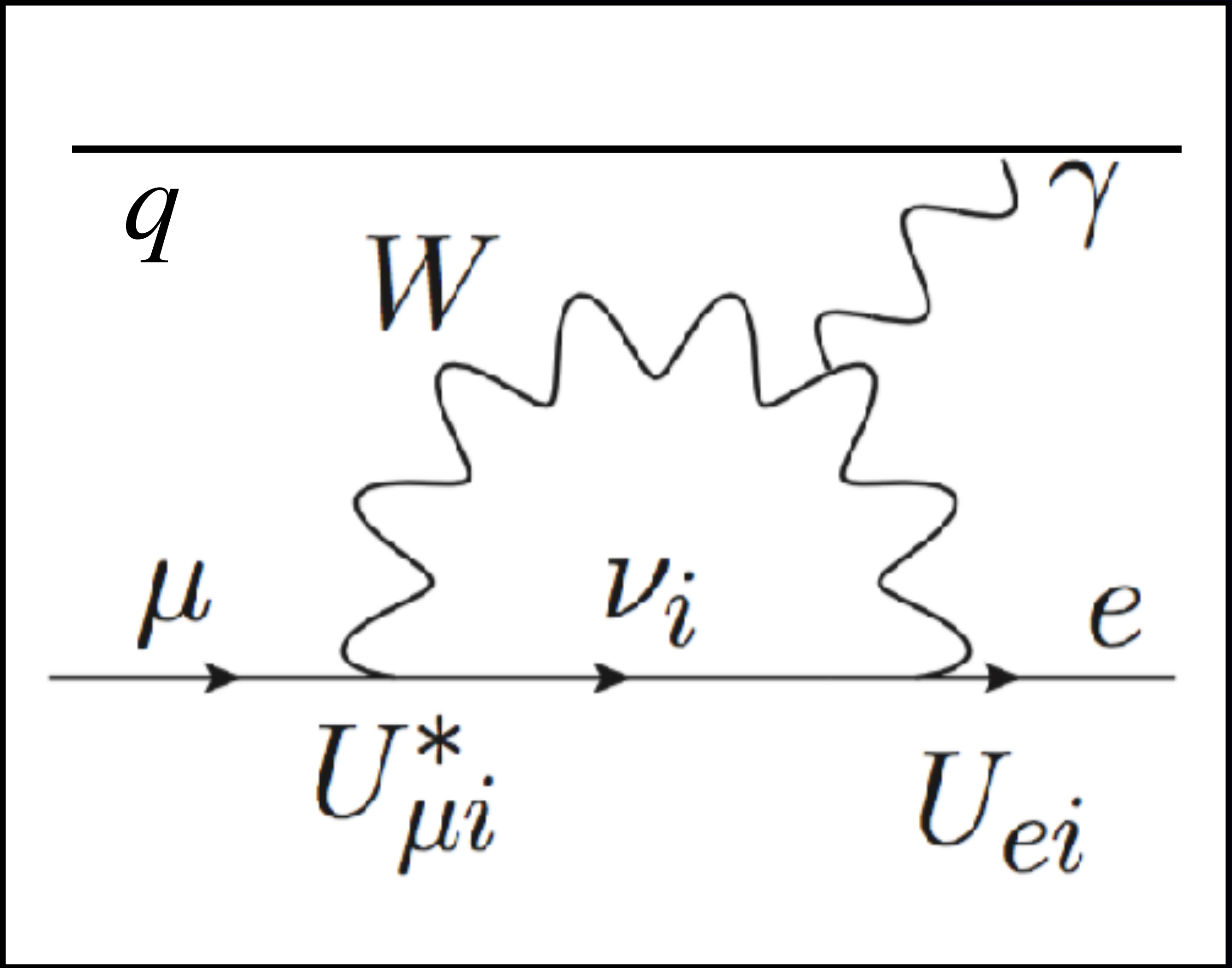
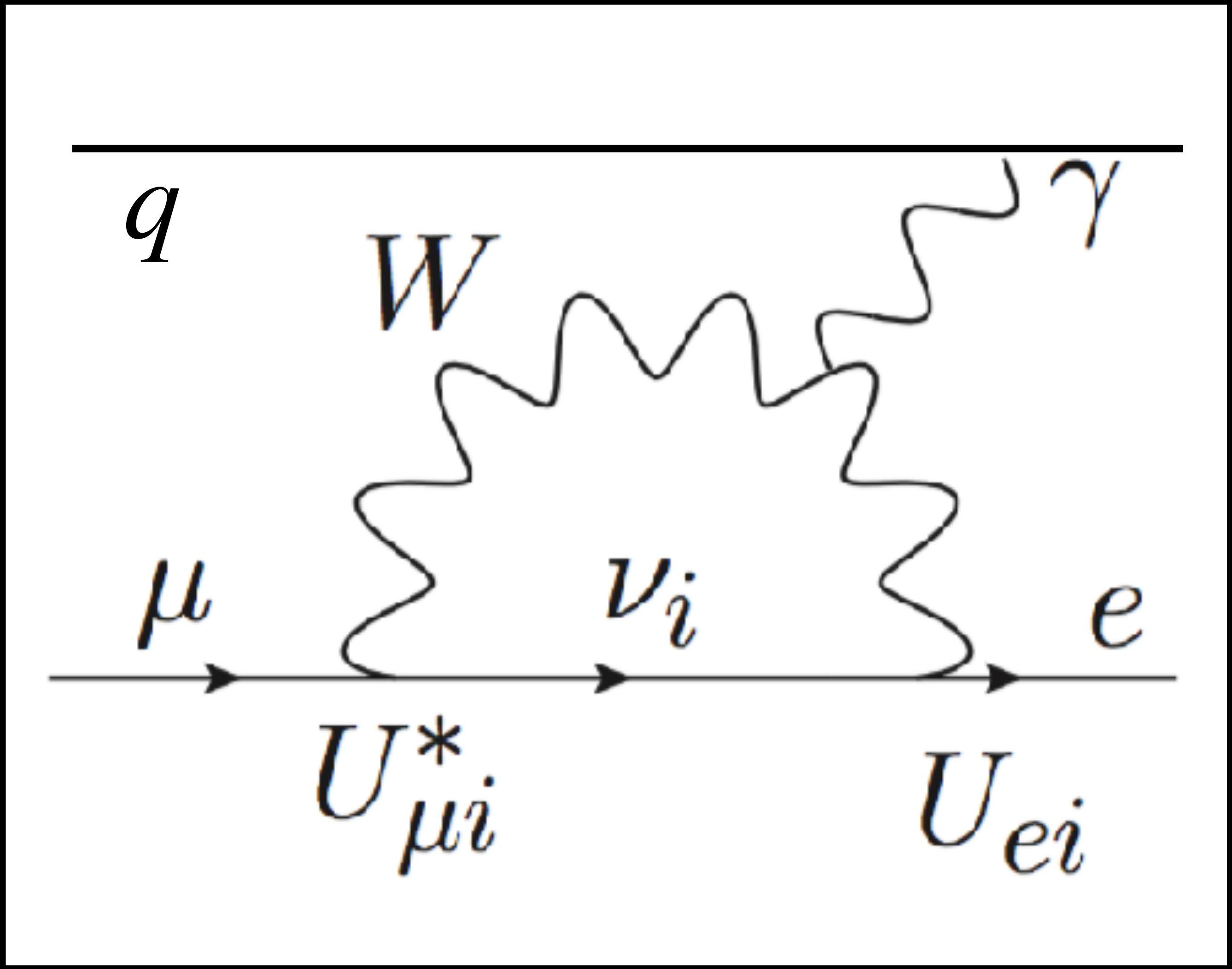


$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2$$

CLFV in the Standard Model (SM)



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BR~O(10^{-54})

$$\left(\left|\frac{\Delta m^2_\nu}{m^2_W}\right|^2 \to 10^{-50}\right)$$

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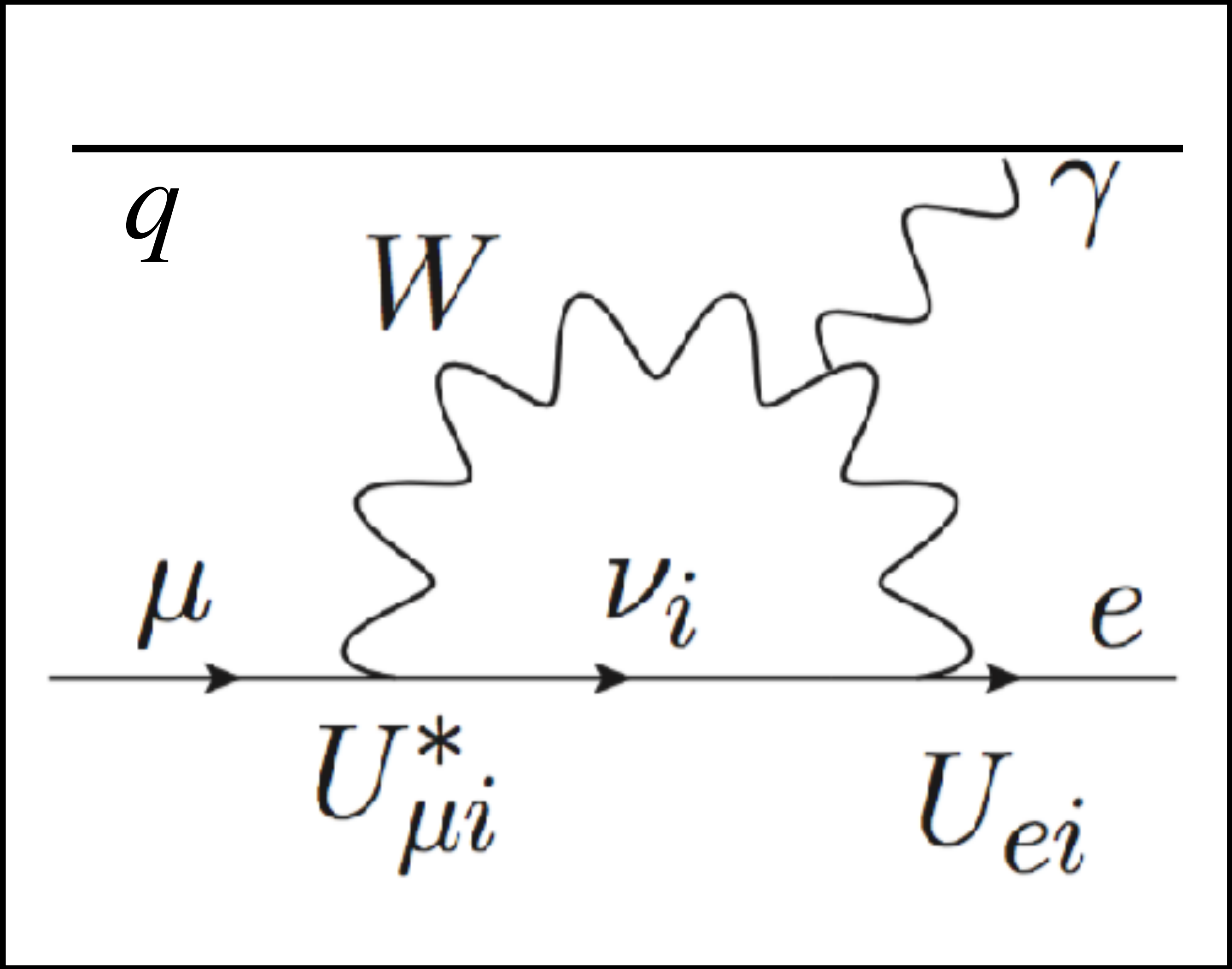

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1 CLFV has clear signature of BSM w/o SM backgrounds.

CLFV Sensitivity to BSM in EFT

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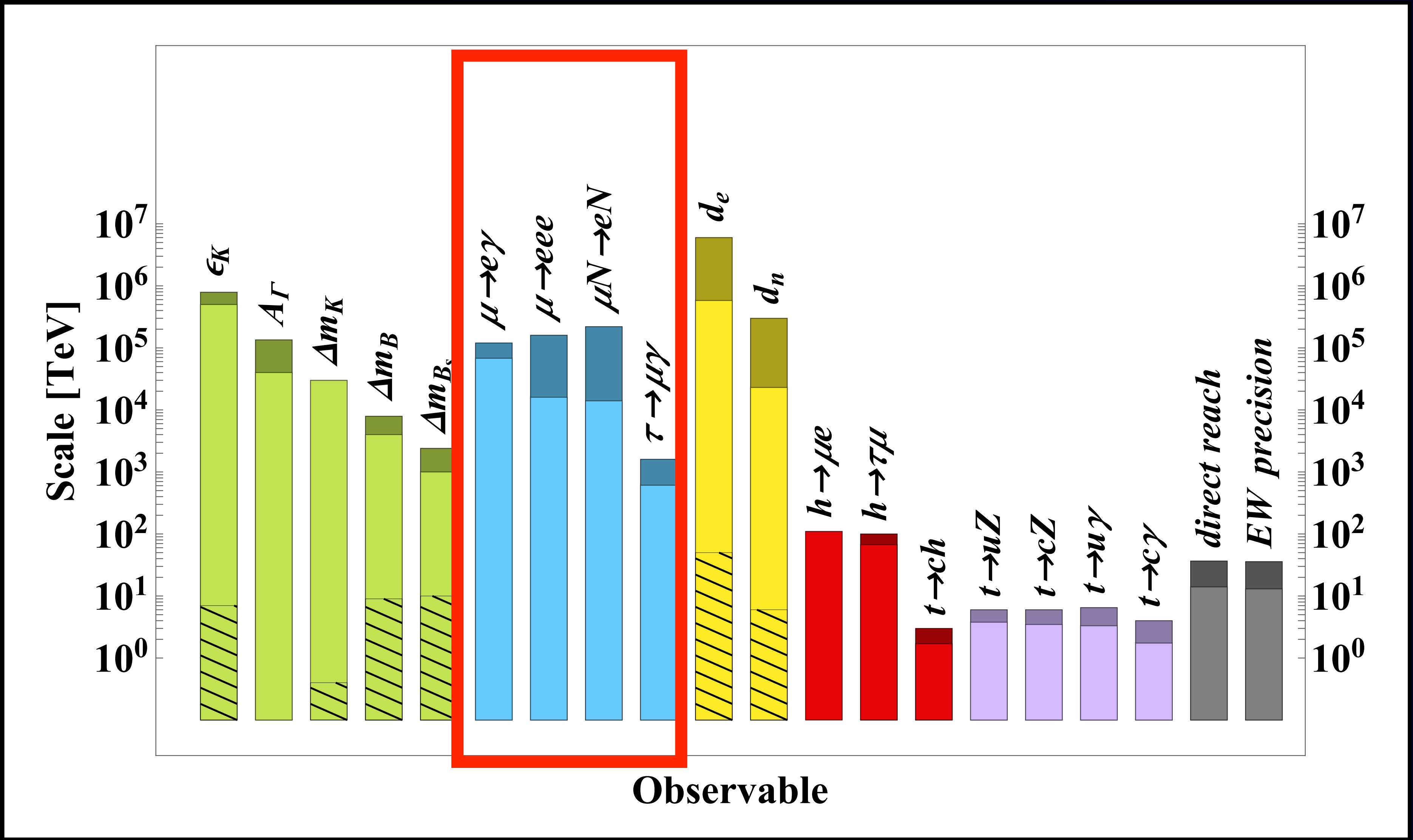
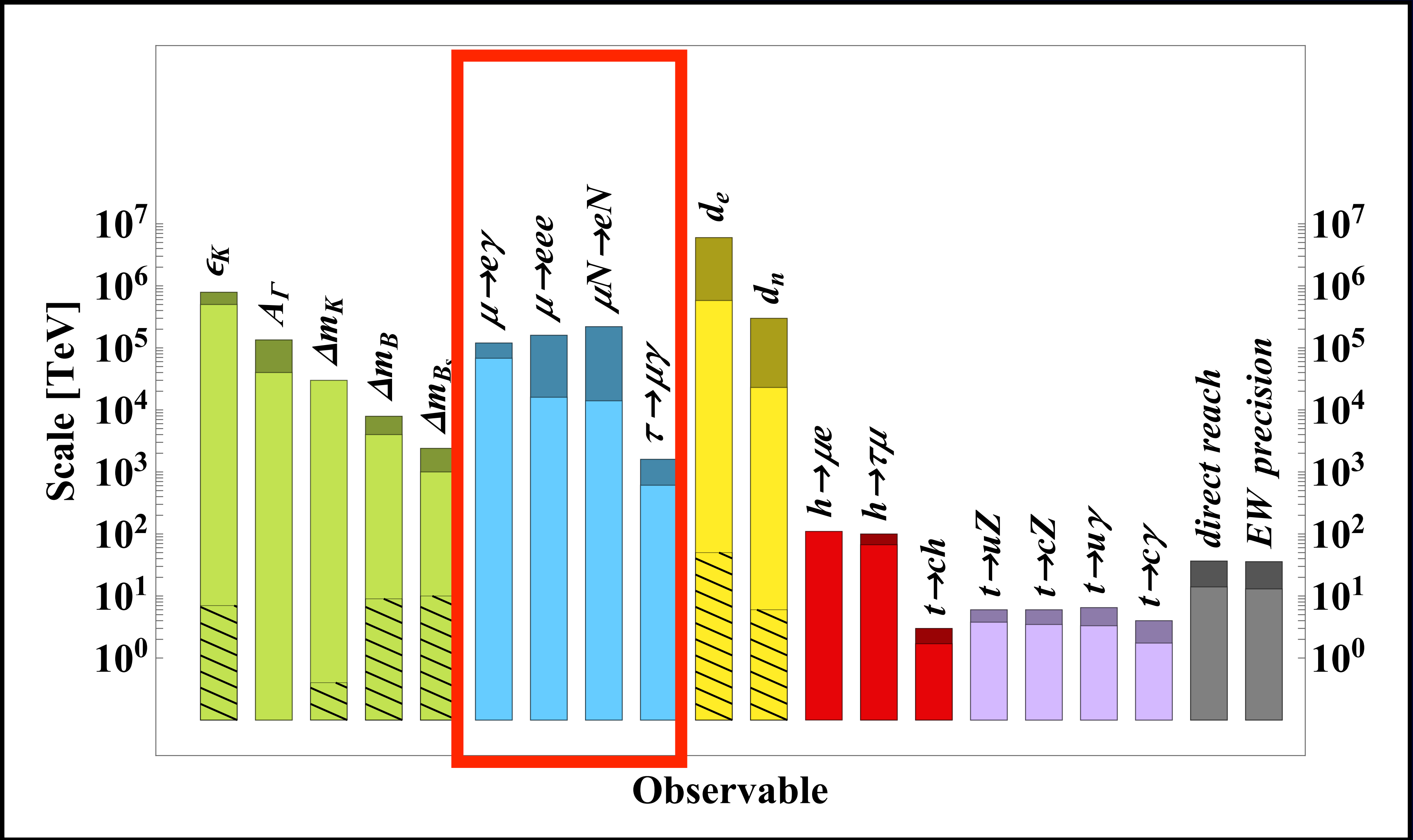


light colour: present, dark colour: future prospect

from European particle Physics Strategy Update (2019)

CLFV Sensitivity to BSM in EFT



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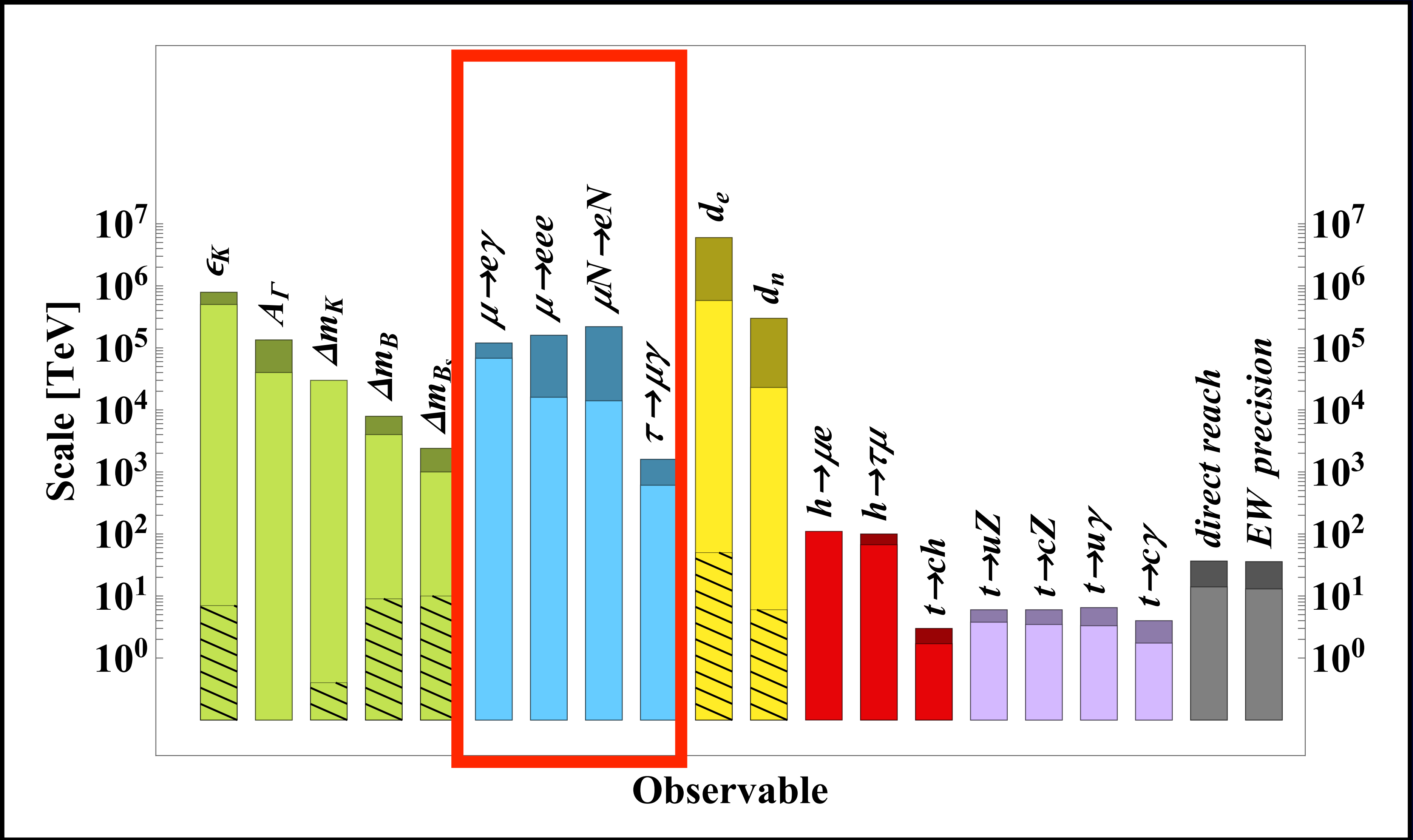
$$\mathscr{L}_{\mathrm{CLFV}} \approx \frac{C}{\Lambda^2} O^{(6)}$$

dimension 6

$$\text{Rate} \propto \frac{C^2}{\Lambda^4}$$

10 times in $\Lambda \rightarrow$ Experimental Improvements: aimed as $\times\, 10^4$

CLFV Sensitivity to BSM in EFT



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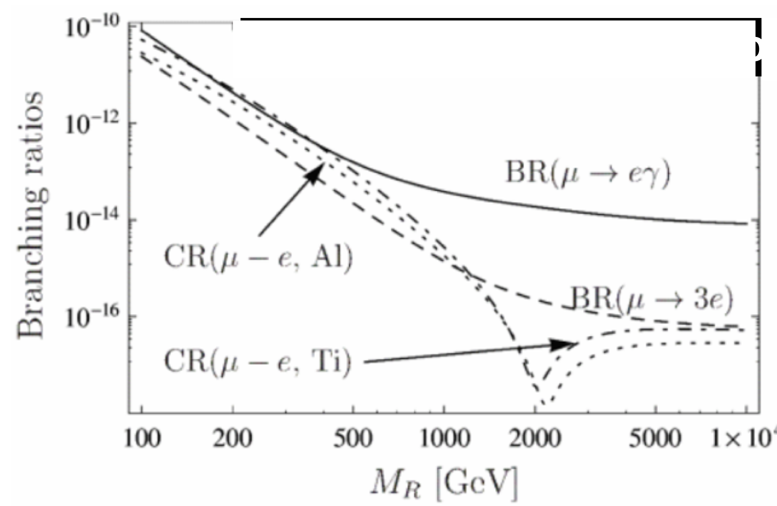
2 CLFV could explore very high energy scale of BSM.

Model Dependent CLFV Predictions

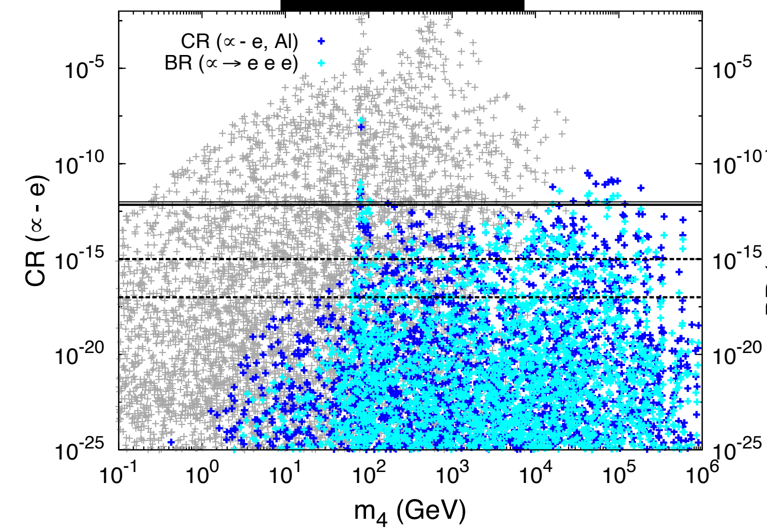
Model Dependent CLFV Predictions

only some examples

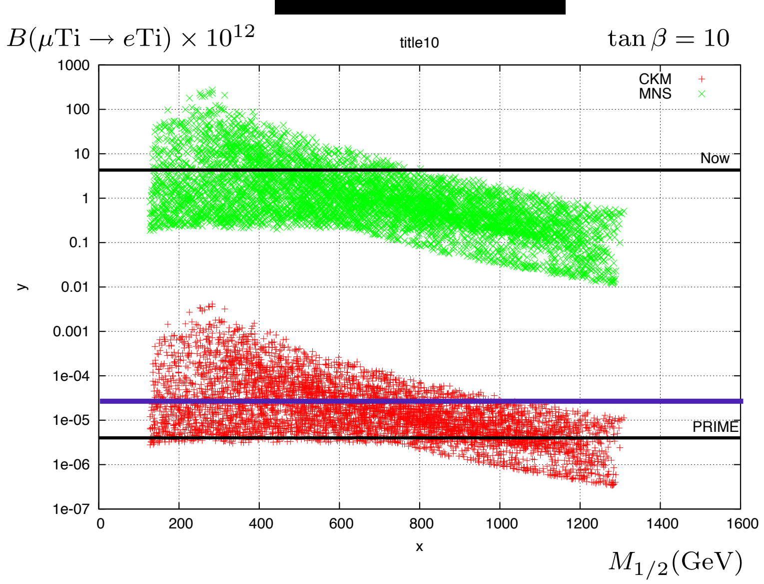
SUSY:Heavy RH Neutrino



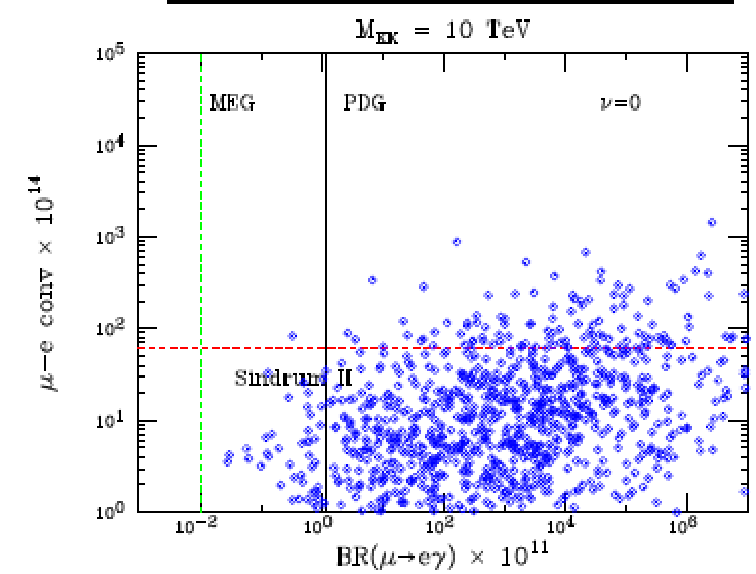
SM+HNL



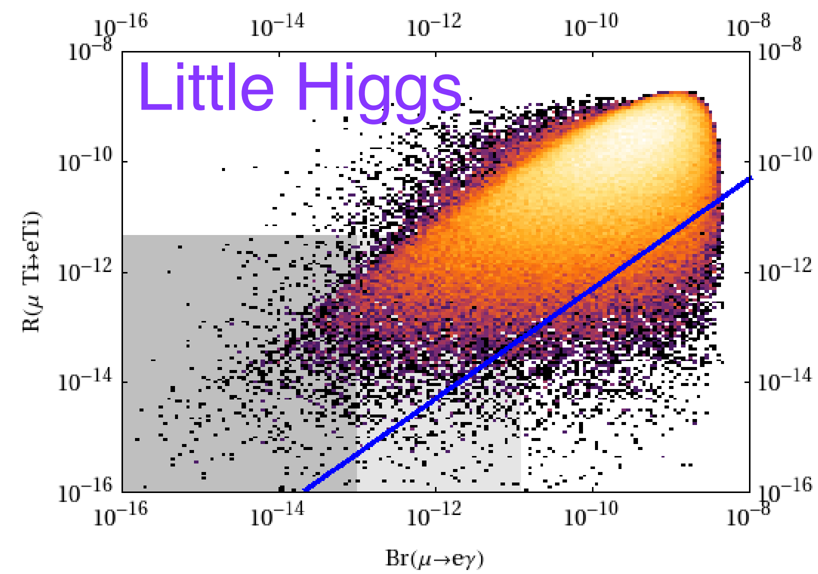
SUSY-GUT



extra dimension model



Little Higgs



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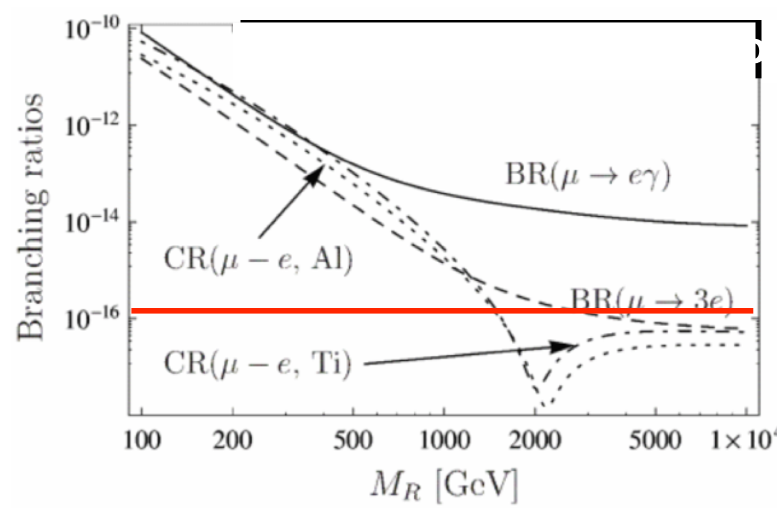

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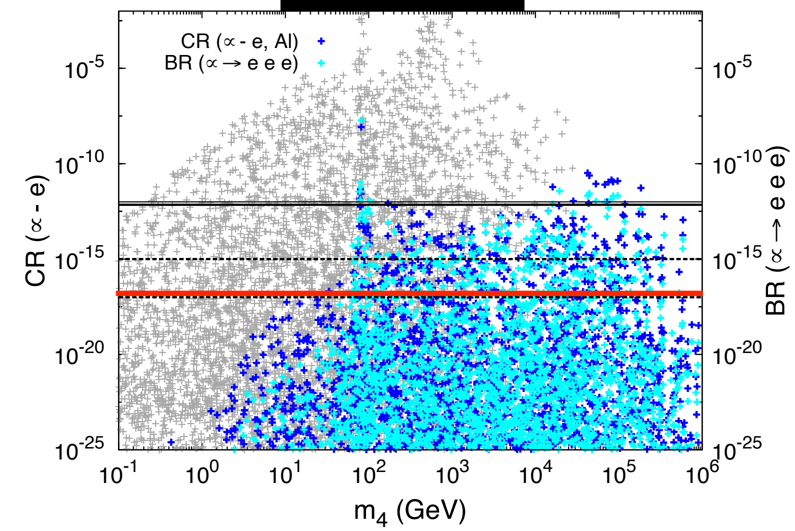

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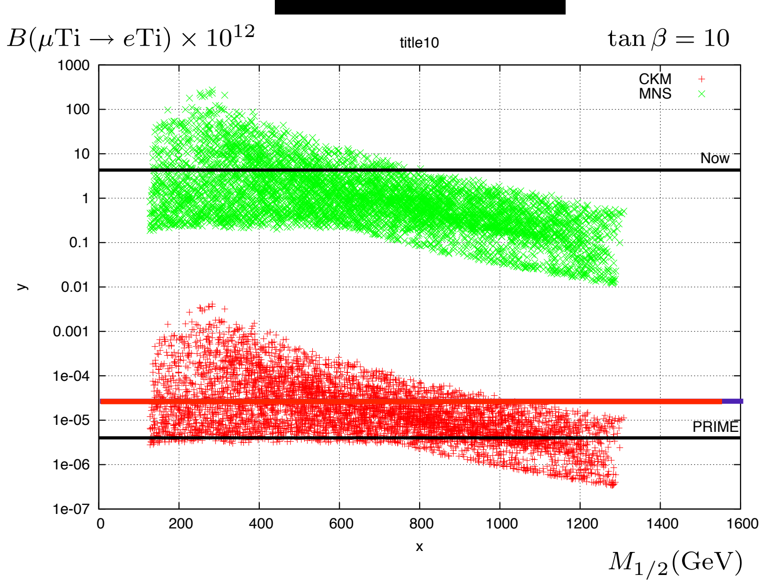

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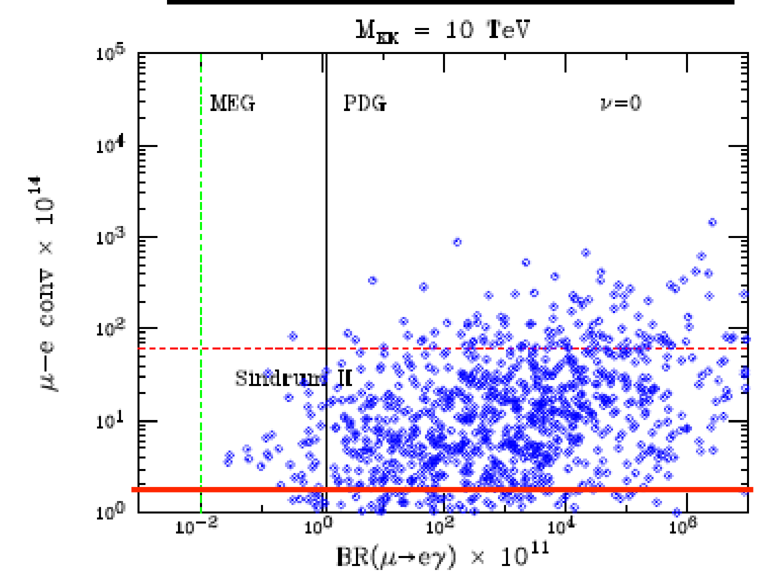

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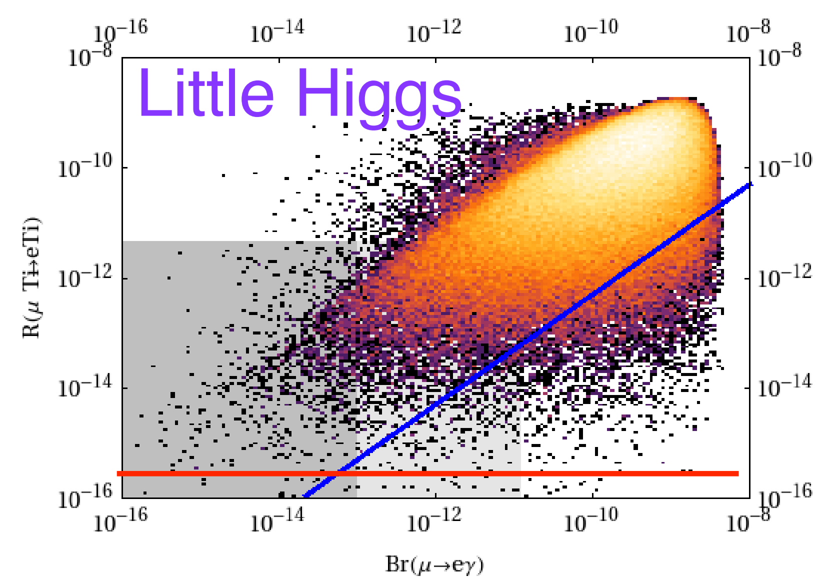

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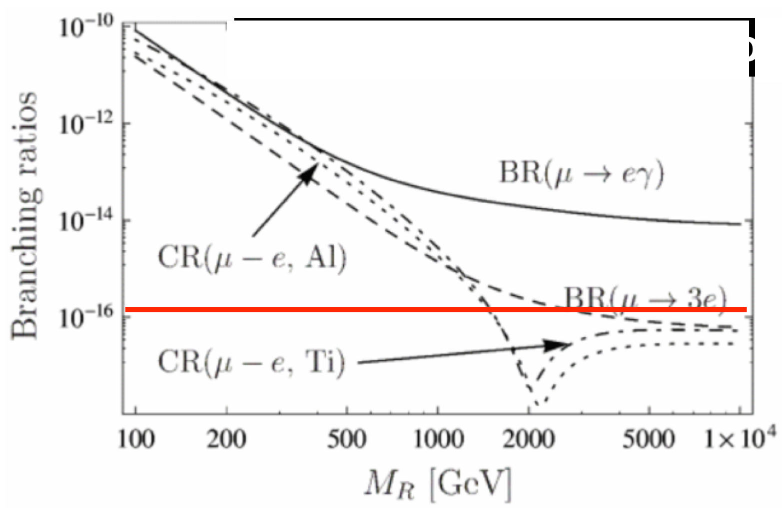

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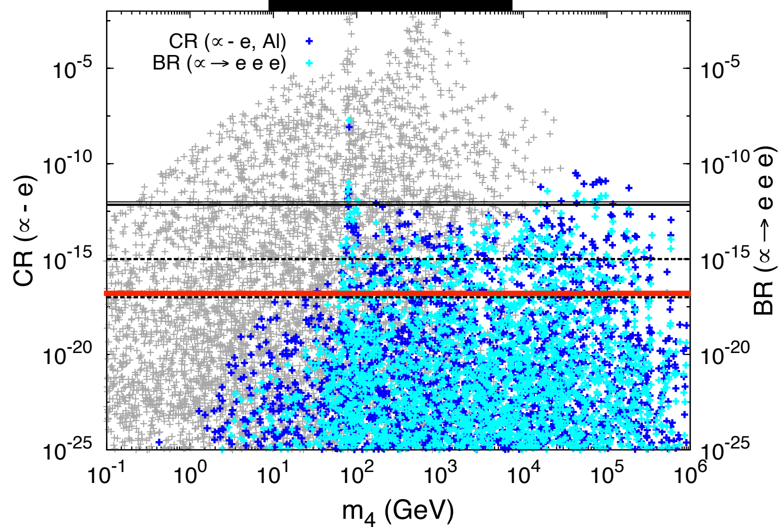

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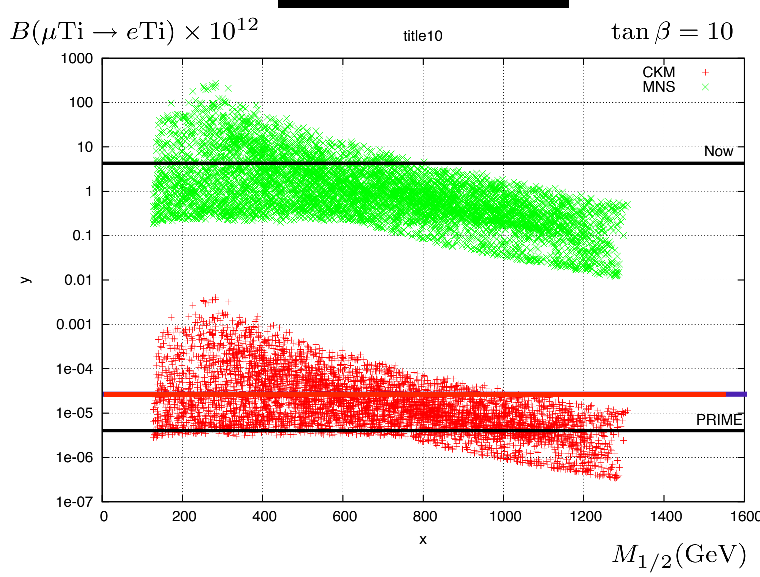

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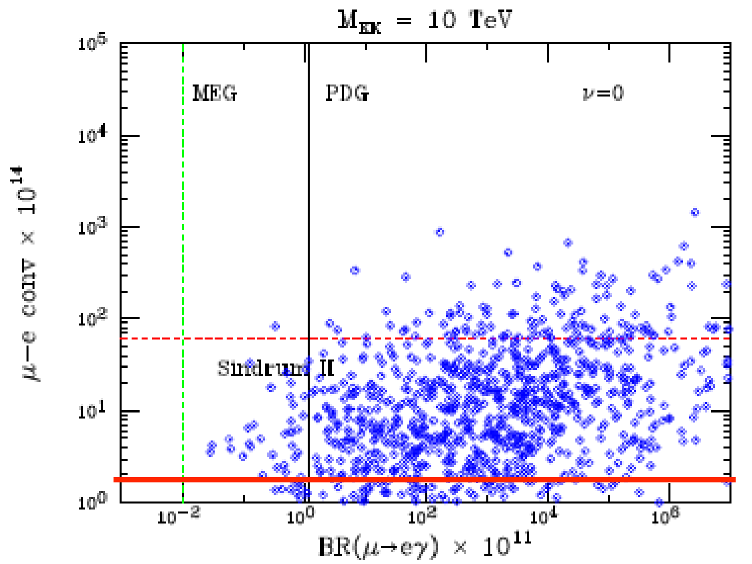

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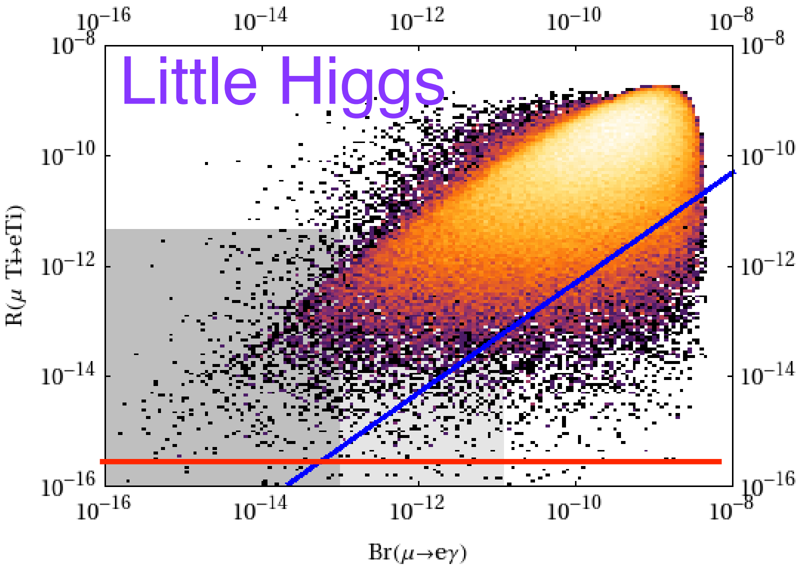
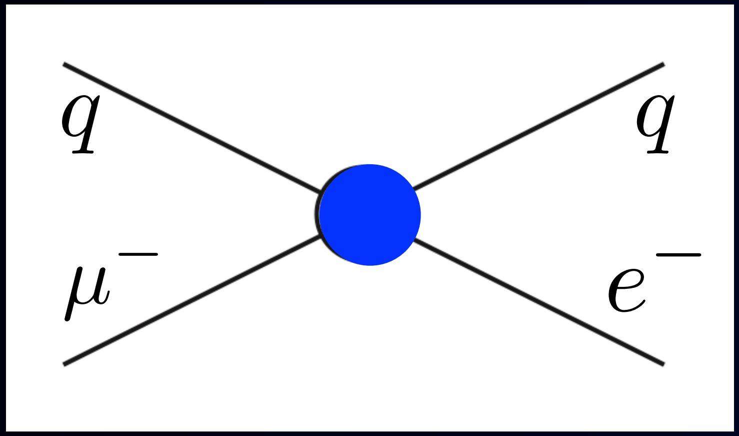


3 Many BSM models predict sizable CLFV rates.

$\mu^- \rightarrow e^-$ Conversion in EFT

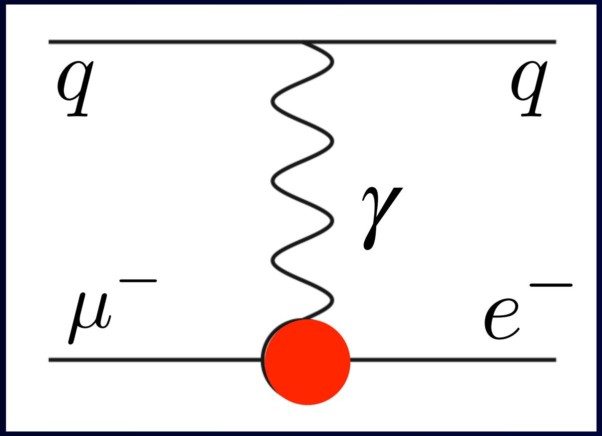
$\mu^- \to e^-$ Conversion in EFT

Contact Interaction



$+$

Photonic Interaction



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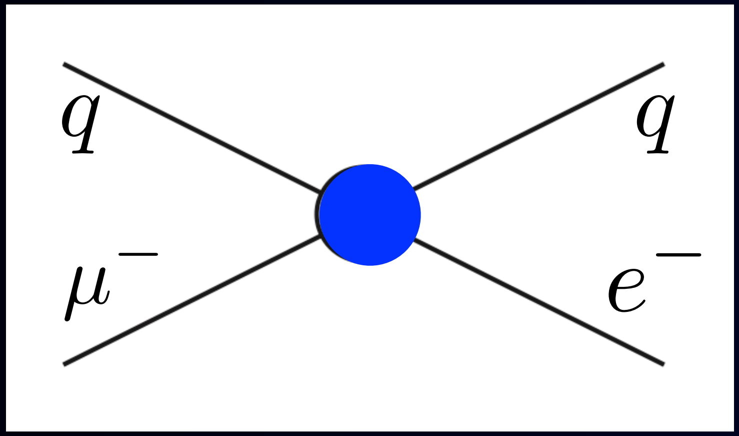

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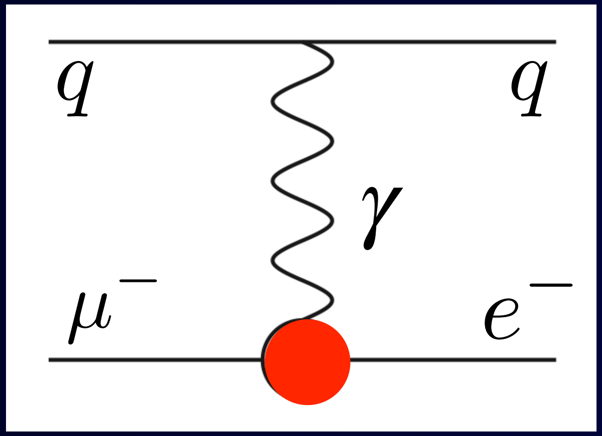


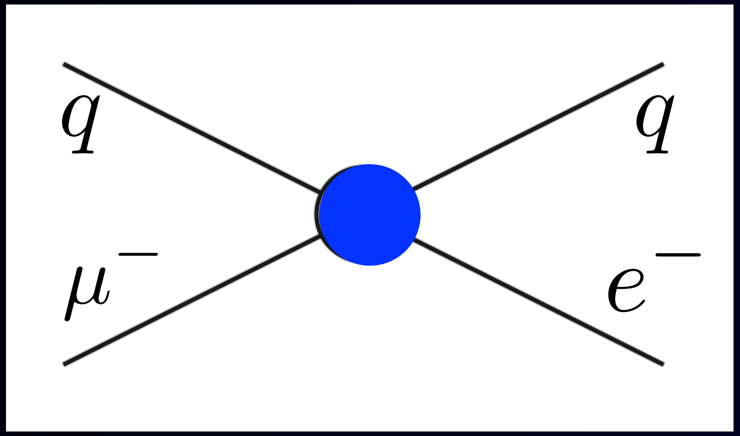
- dipole (L/R) (spin independent)
- di-photons (L/R) $\mu e F F$

S. Davidson, YK, Y. Uesaka, M. Yamanaka, Phys. Rev. D102, 11504 (2020)

$\mu^- \to e^-$ Conversion in EFT

Contact Interaction

analogy to
DM scattering



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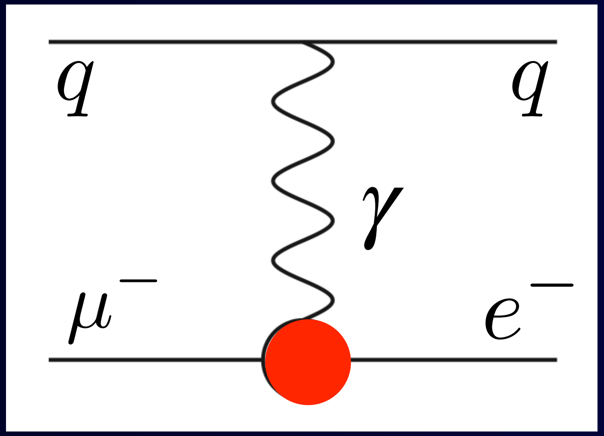

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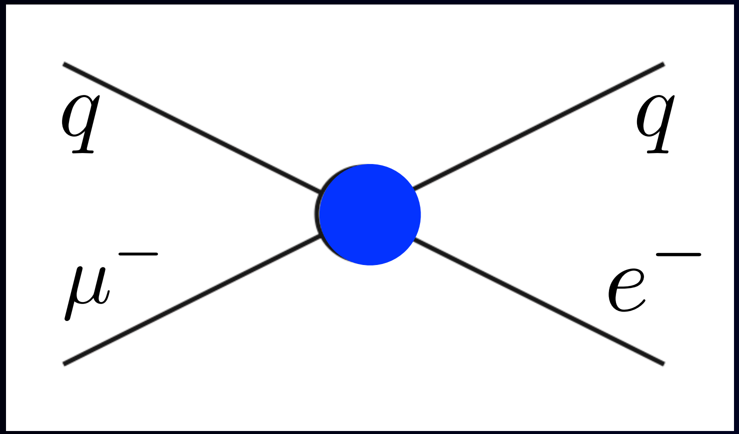

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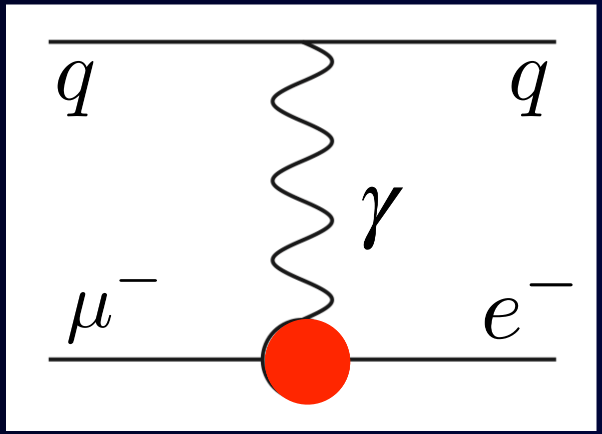

analogy to DM scattering

- scalar (L/R) (spin independent)
- vector (L/R) (spin independent)
- pseudoscalar (L/R) (spin dependent)
- axial vector (L/R) (spin dependent)
- tensor (L/R) (spin dependent)

- dipole (L/R) (spin independent)
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S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109
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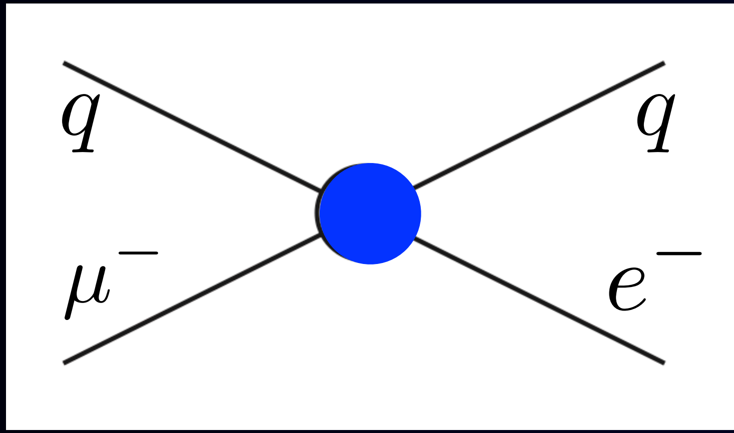

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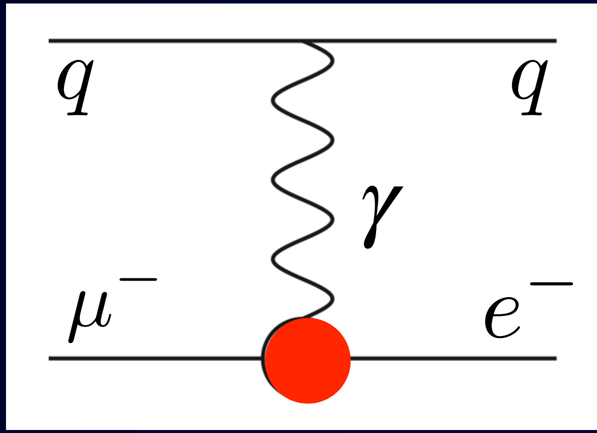

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different for protons and neutrons $\rightarrow$ target dependence

$\mu \to e$ Conversion Rates for Different Target Material

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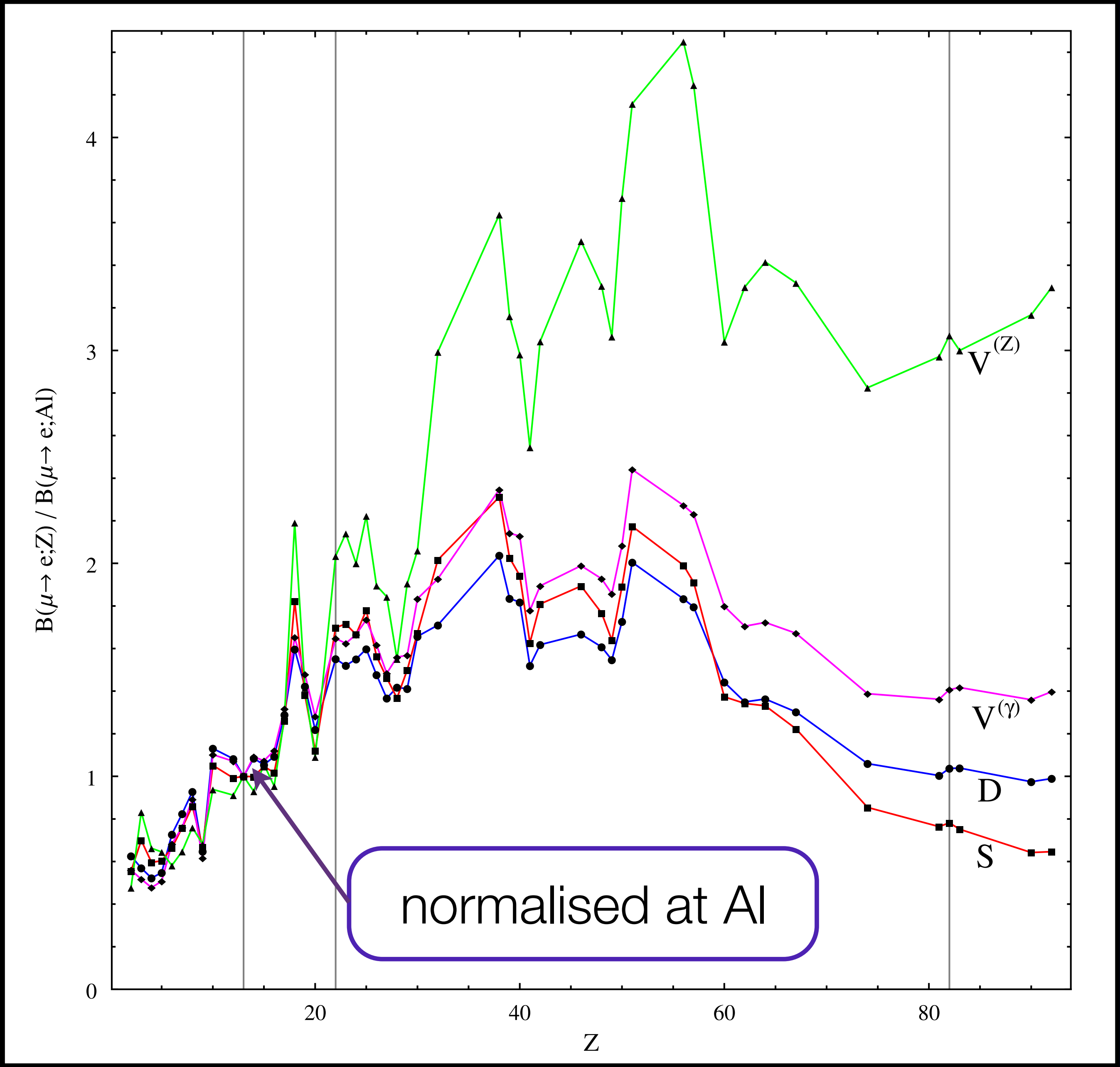

R. Kitano, M. Koike and Y. Okada, Phys.Rev. D66 (2002) 096002; D76 (2007) 059902

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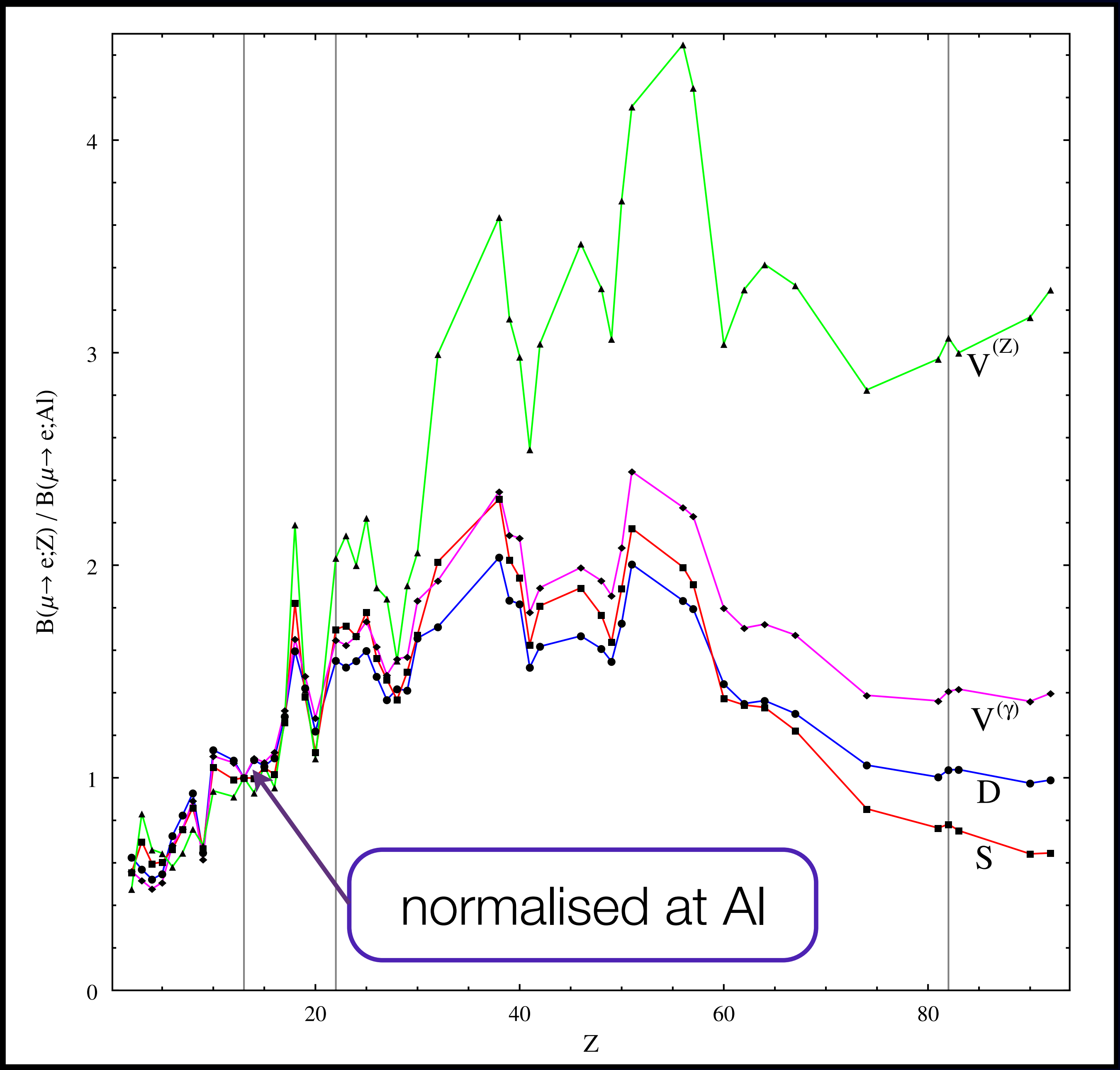
S. Davidson, YK, M. Yamanaka, Phys. Lett. B790 (2019) 380-388

$\mu \to e$ Conversion Rates for Different Target Material

one interaction at a time



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

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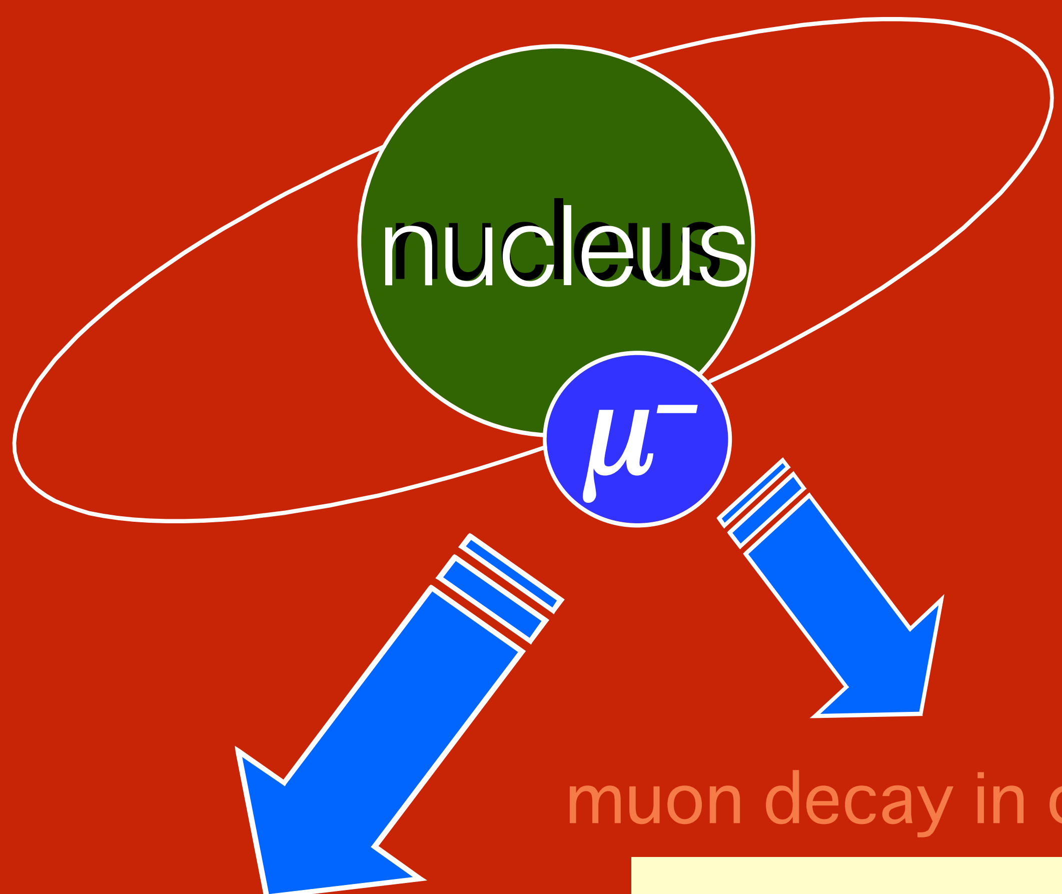
What is $\mu \to e$ conversion ?

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

μ→e Conversion in a muonic atom

1s state in a muonic atom



muon decay in orbit

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

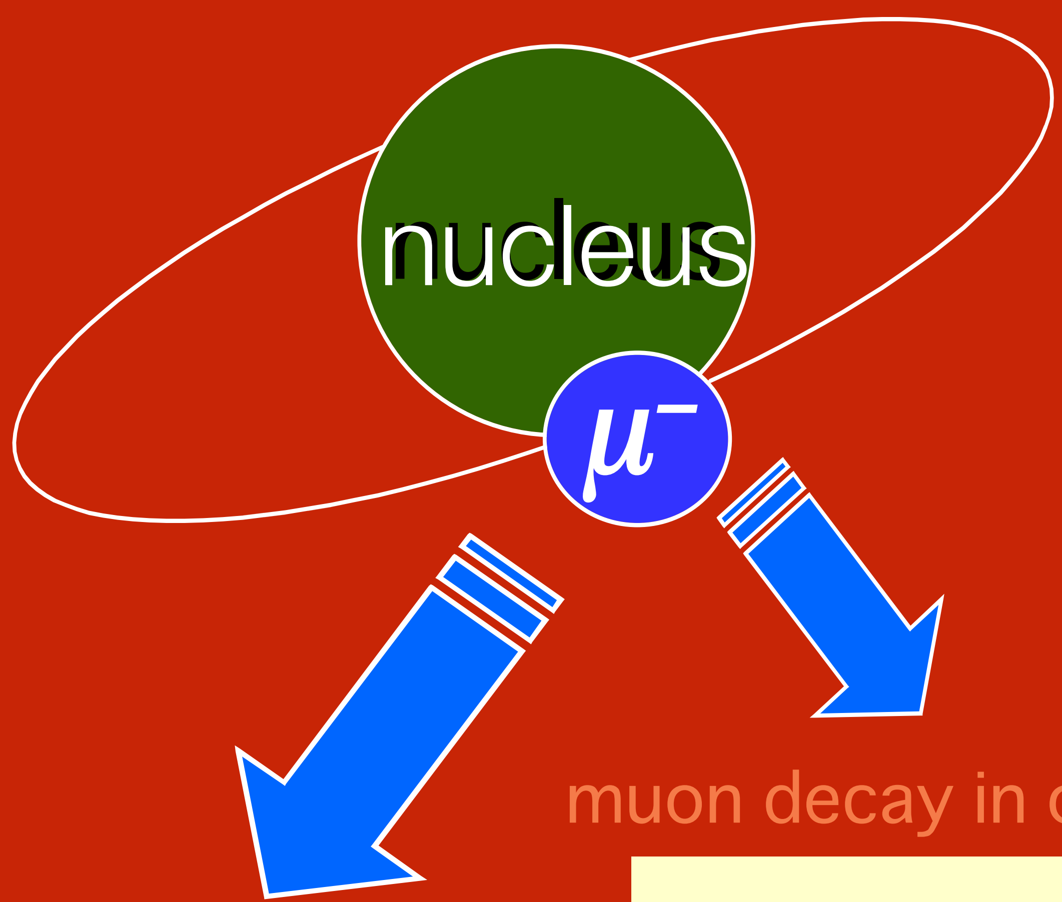
nuclear muon capture

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

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

μ→e Conversion in a muonic atom

1s state in a muonic atom



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nuclear muon capture

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

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

Backgrounds:
(1) physics backgrounds
(2) beam-related backgrounds
(3) cosmic rays, false tracking

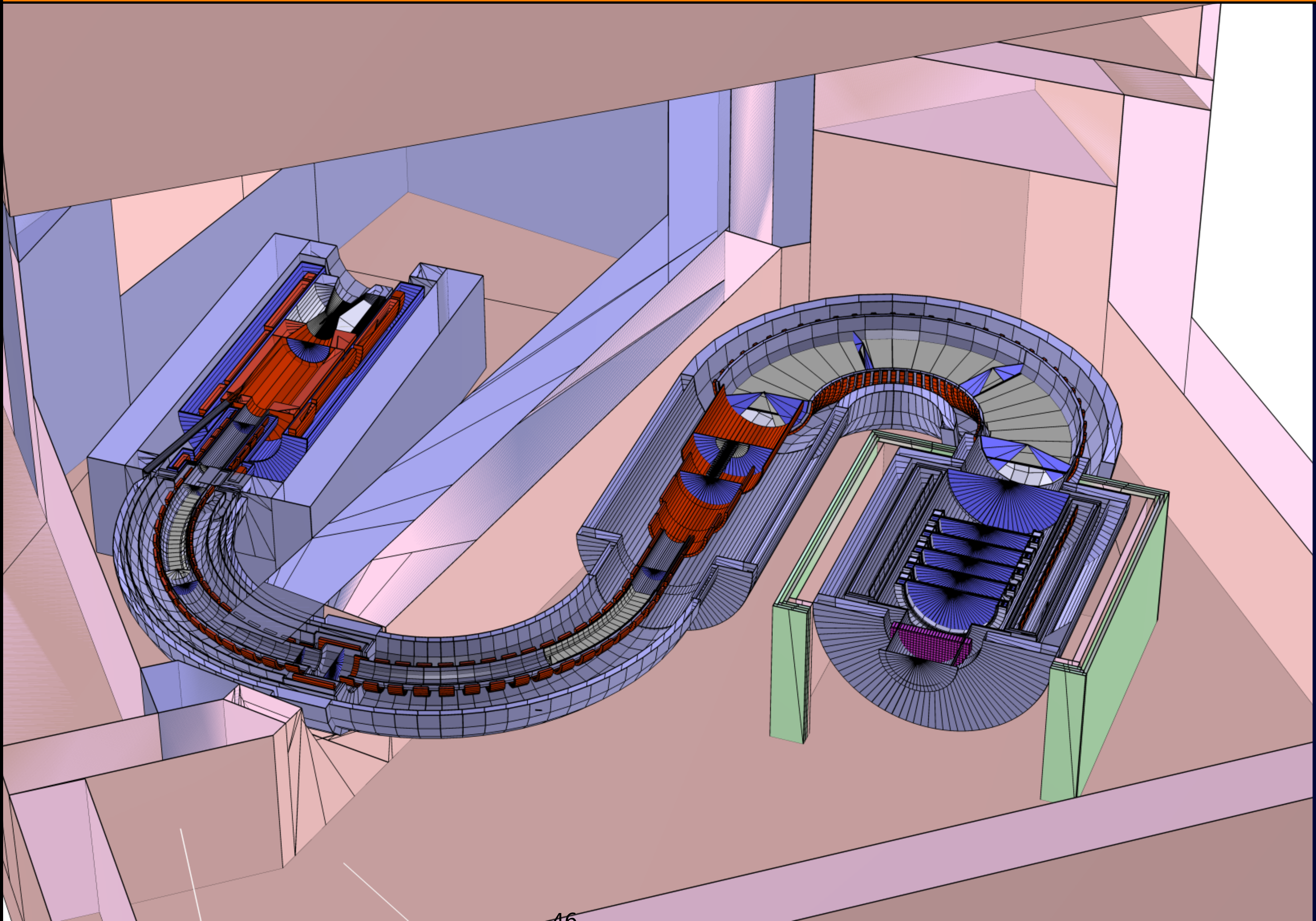
	Z	CR limit
sulfur	16	$<7 \times 10^{-11}$
titanium	22	$<4.3 \times 10^{-12}$
copper	39	$<1.6 \times 10^{-8}$
gold	79	$<7 \times 10^{-13}$
lead	82	$<4.6 \times 10^{-11}$

COMET at J-PARC

COMET=COherent Muon to Electron Transition

COMET

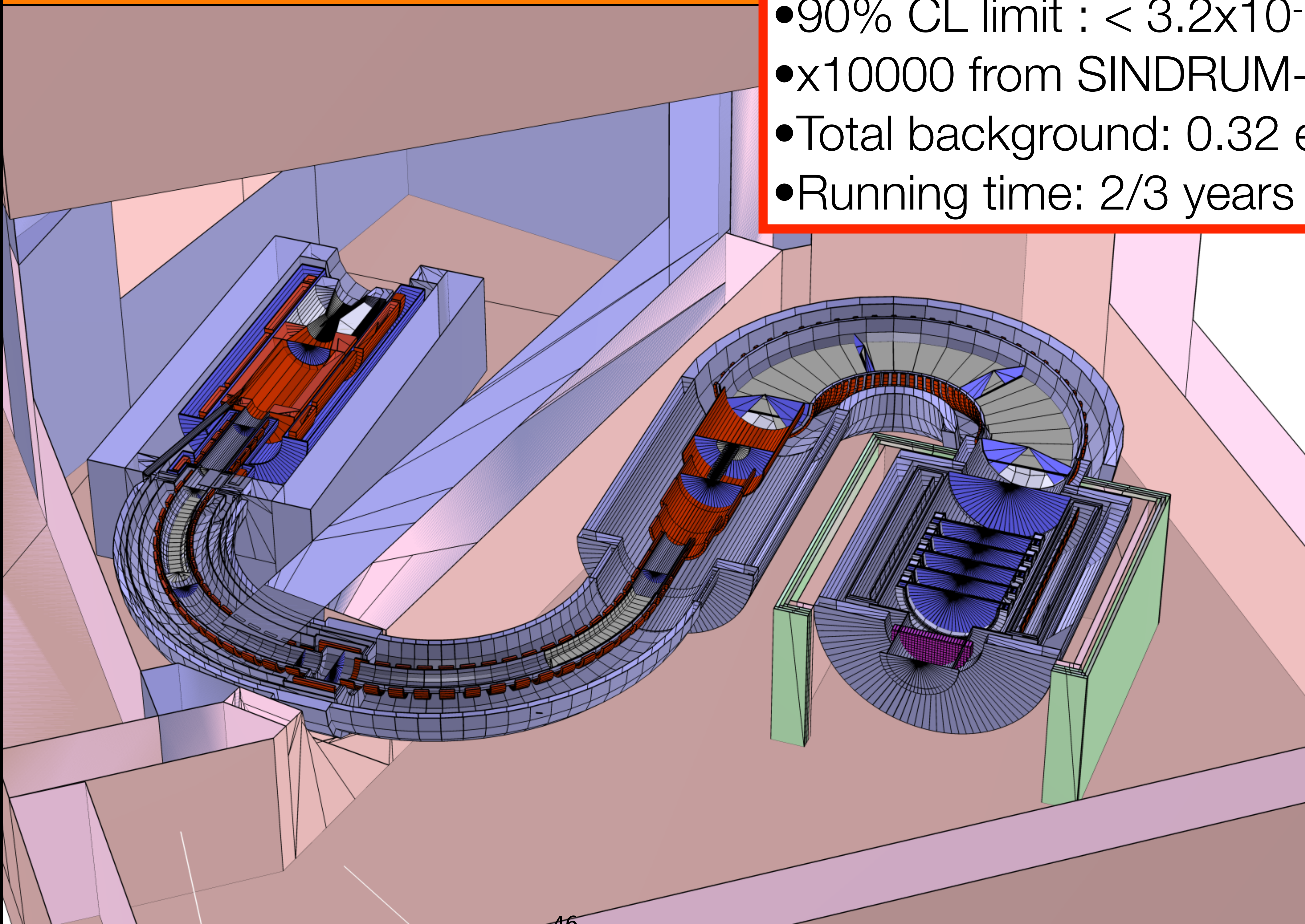
COMET



COMET

- Proton beam, 8 GeV, 56kW
- 5×10^{10} stopped muons/s

- Single event sensitivity : 1.4×10^{-17}
- 90% CL limit : < 3.2×10^{-17}
- x10000 from SINDRUM-II
- Total background: 0.32 events
- Running time: 2/3 years (2×10^{7}sec)



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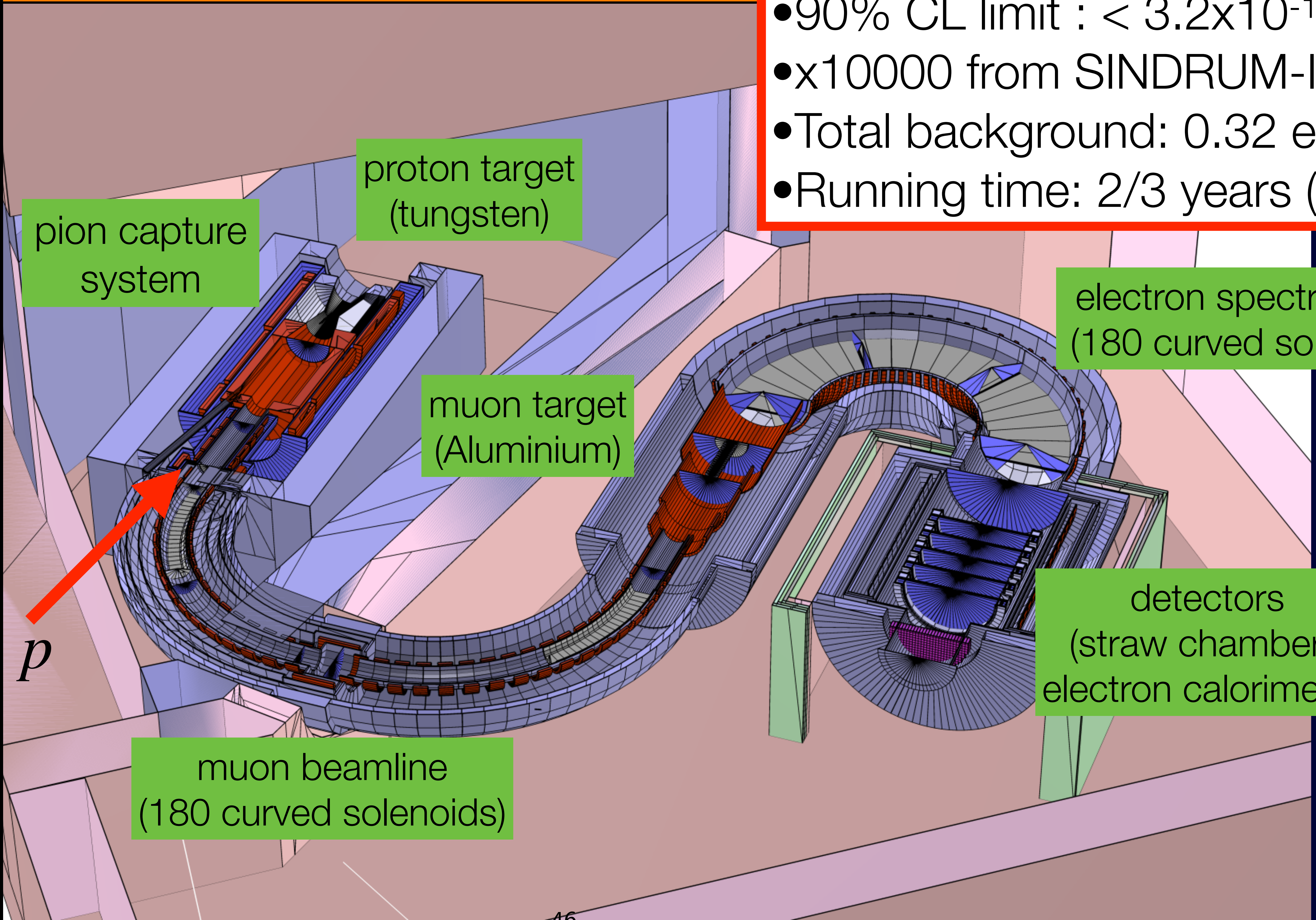
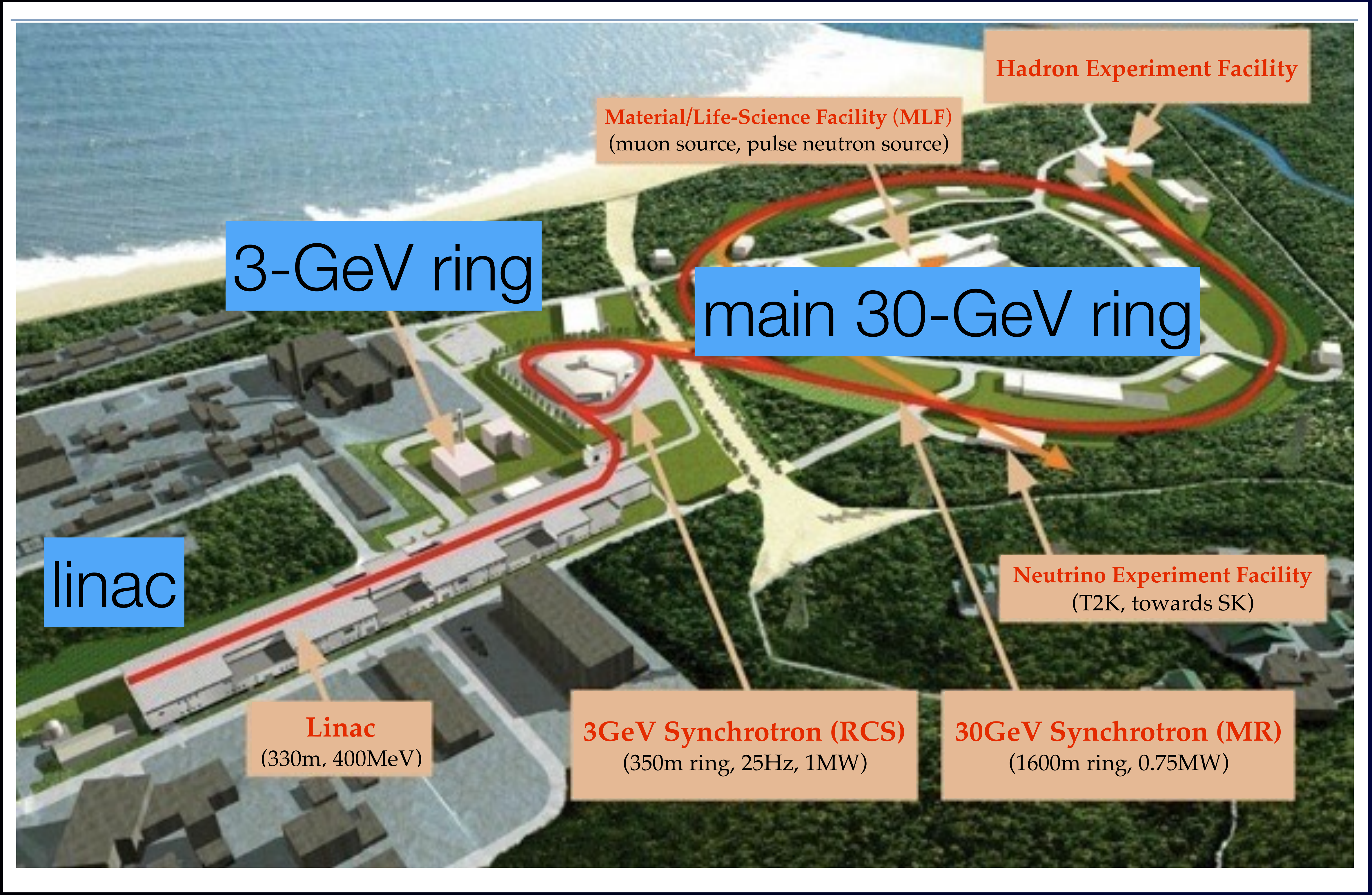


Proton Accelerator
J-PARC



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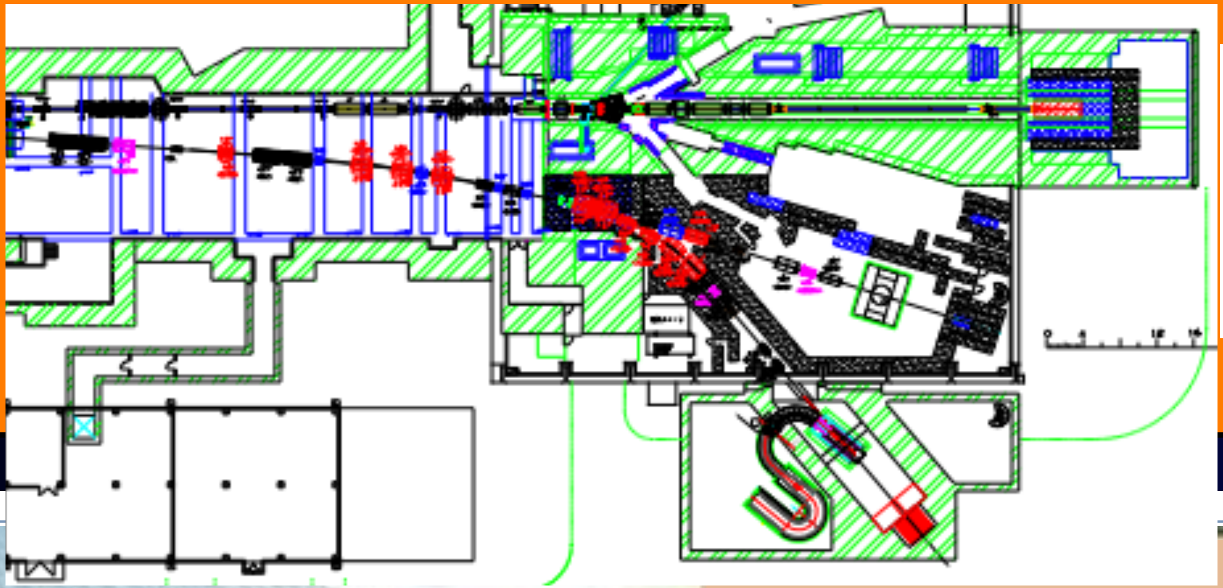
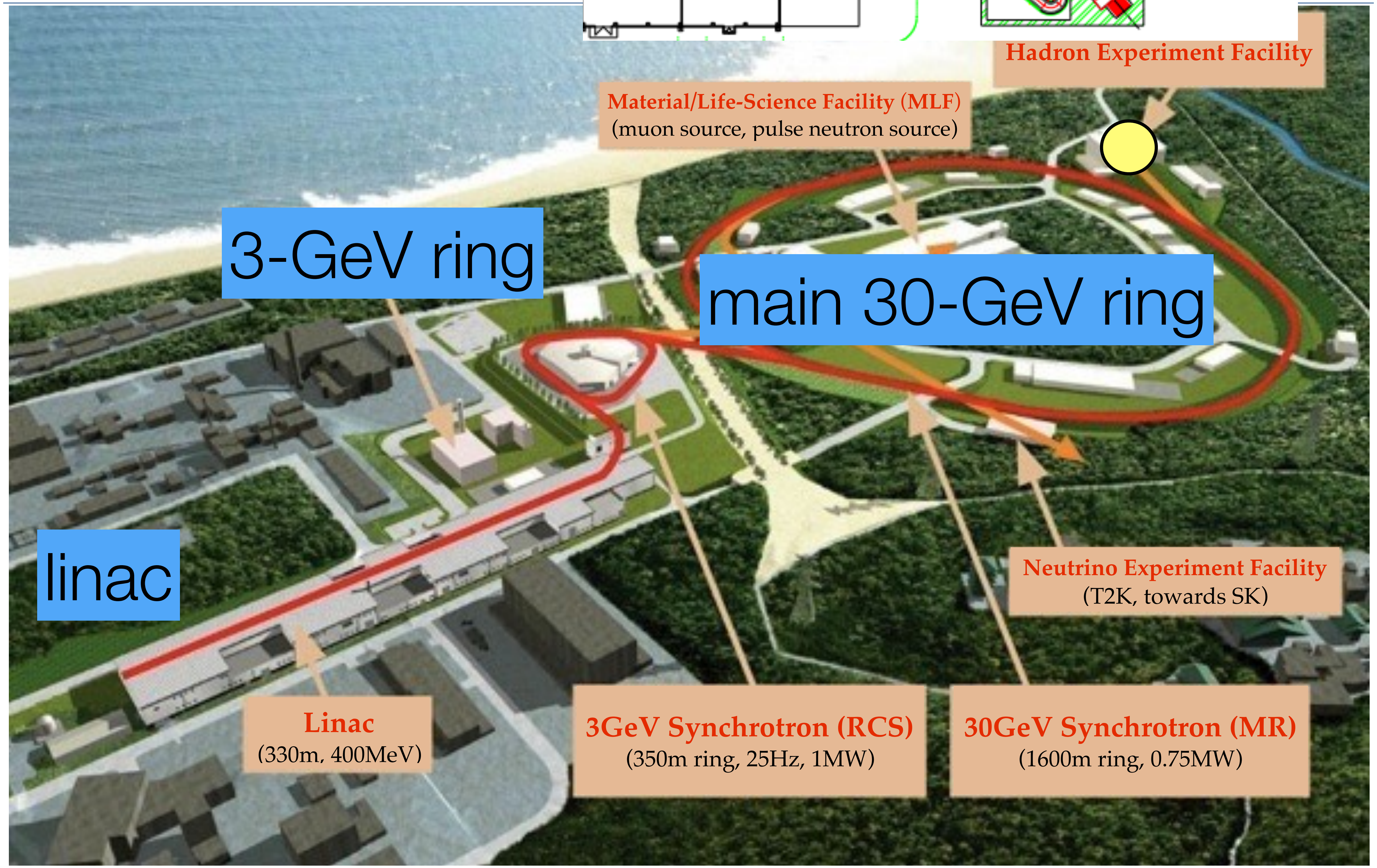




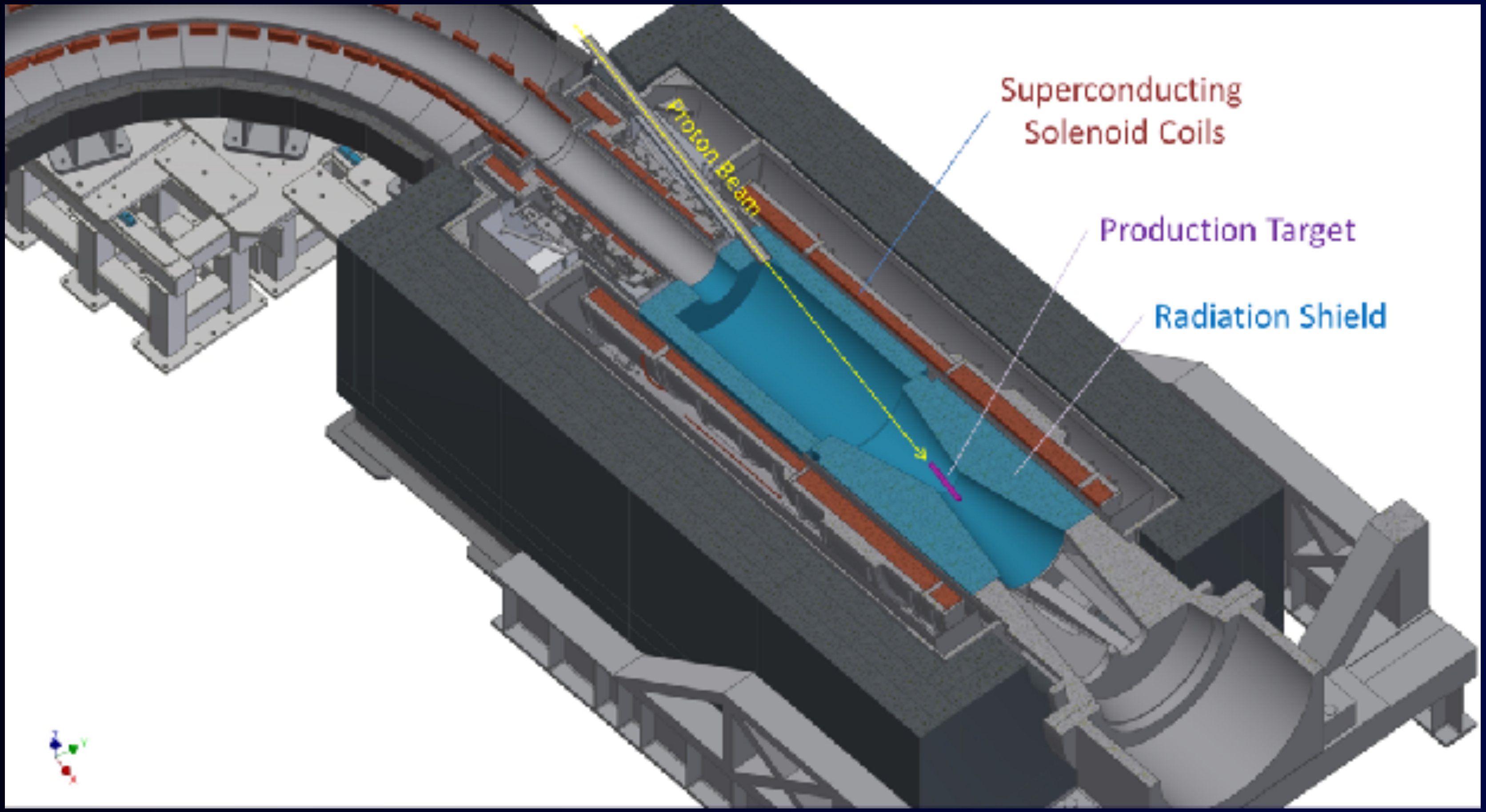
Proton Accelerator J-PARC

Improvements for Signal Sensitivity

Improvements for Signal Sensitivity

Pion Capture System

Pions and muons are captured and transported by high field SC solenoids.



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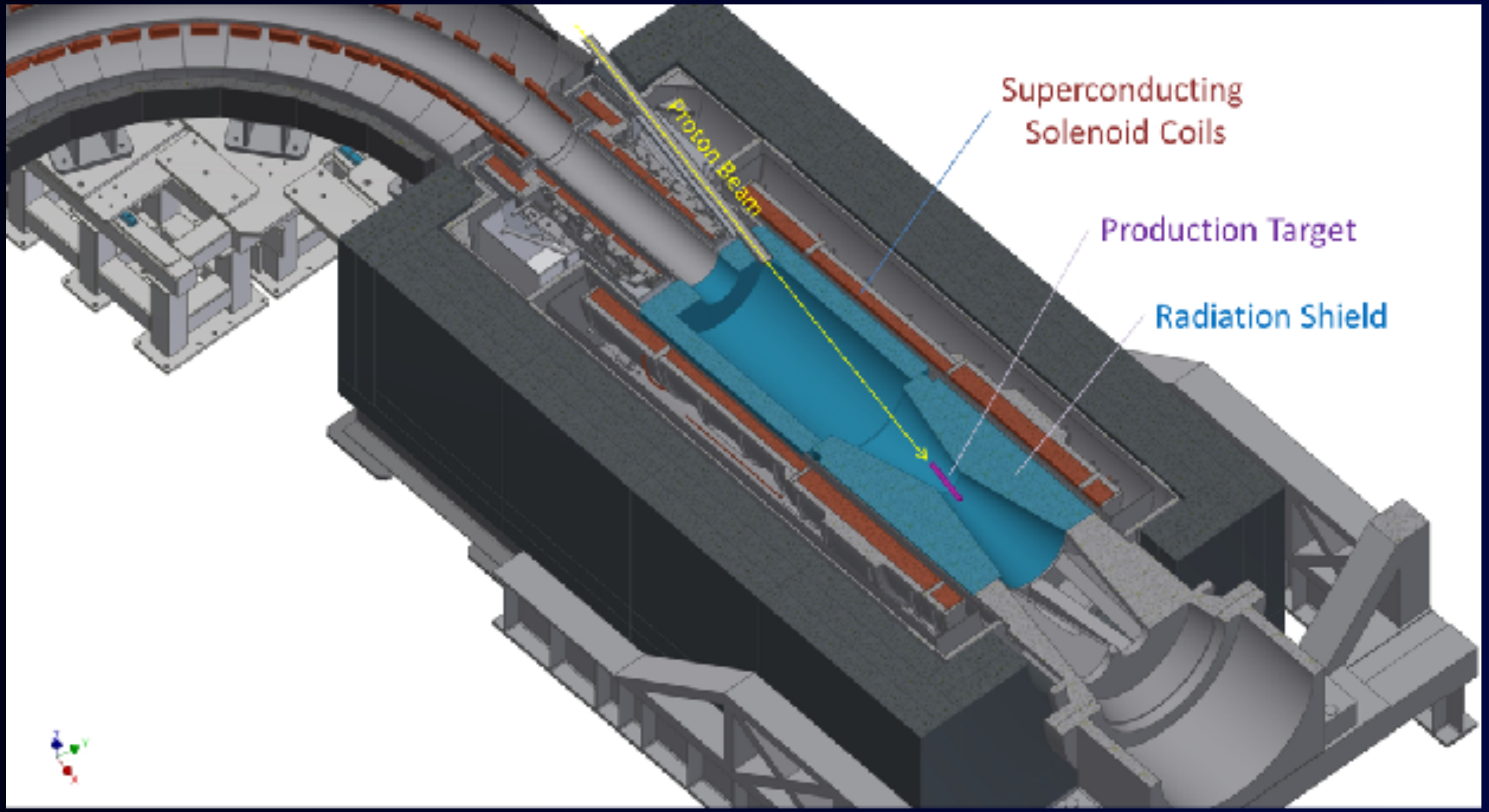

10^{11} μ/s for 50 kW proton beam power or 10^{18} muons in total

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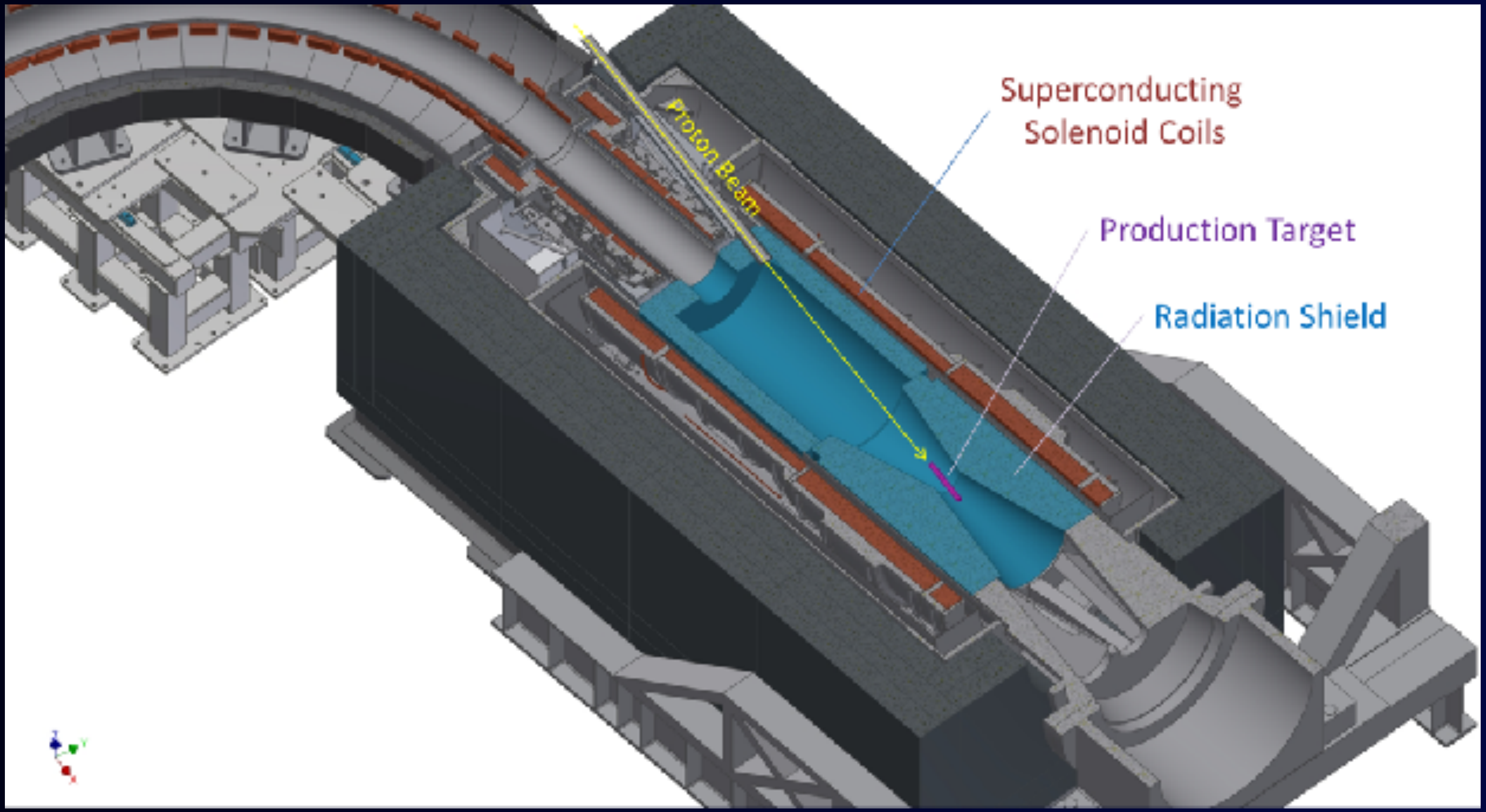
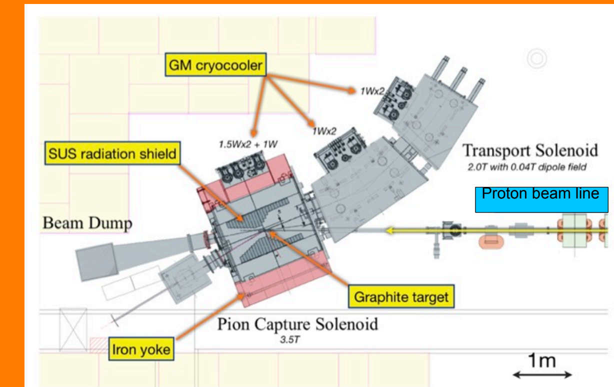


$10^{11}\ \mu$/s for 50 kW proton beam power or 10^{18} muons in total

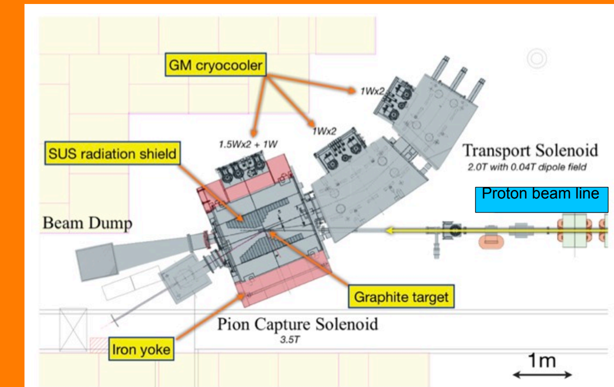
The previous experiment used 10^{14} muons.

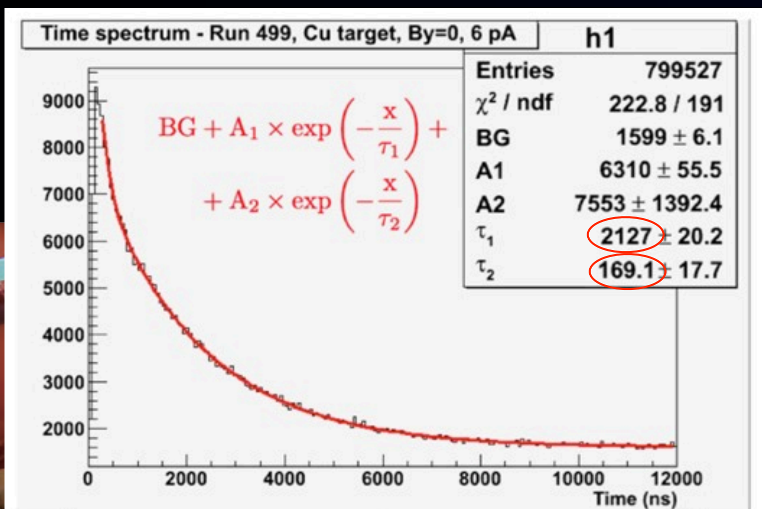
MuSIC at RCNP, Osaka University (2011 -)



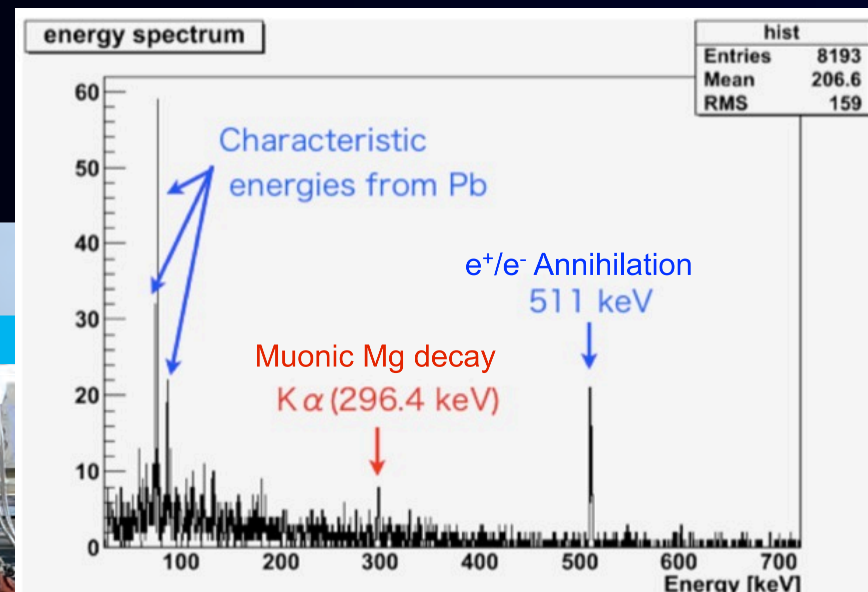
3.5T and graphite proton target

MuSIC at RCNP, Osaka University (2011 -)





	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



MuSIC muon yields

μ^+ : 3×10^8/s with 400W

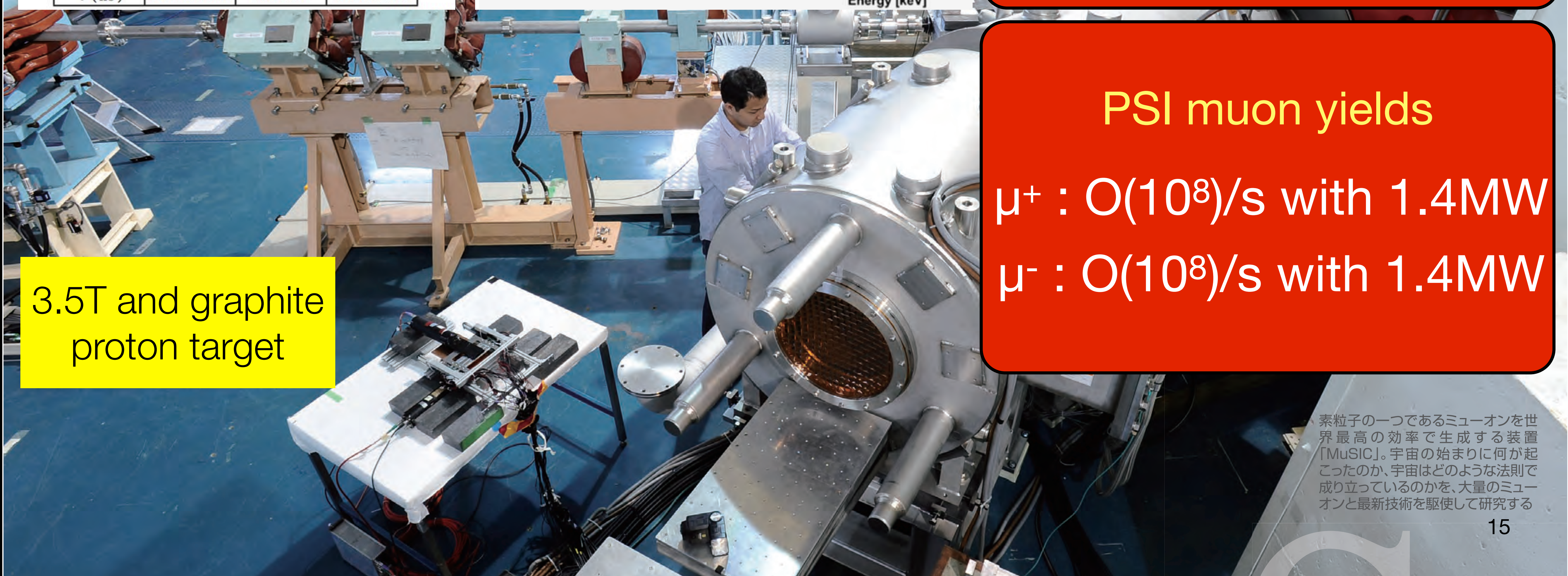
μ^- : 1×10^8/s with 400W

PSI muon yields

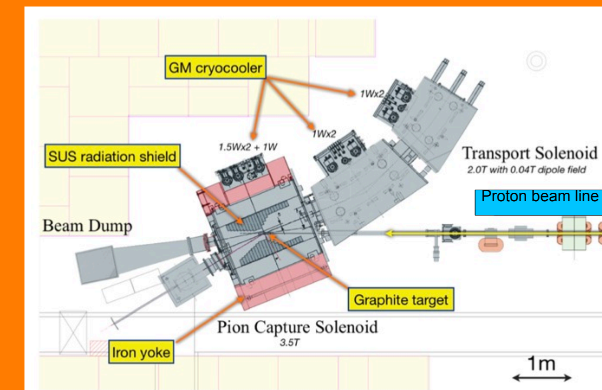
μ^+ : $O(10^8)$/s with 1.4MW

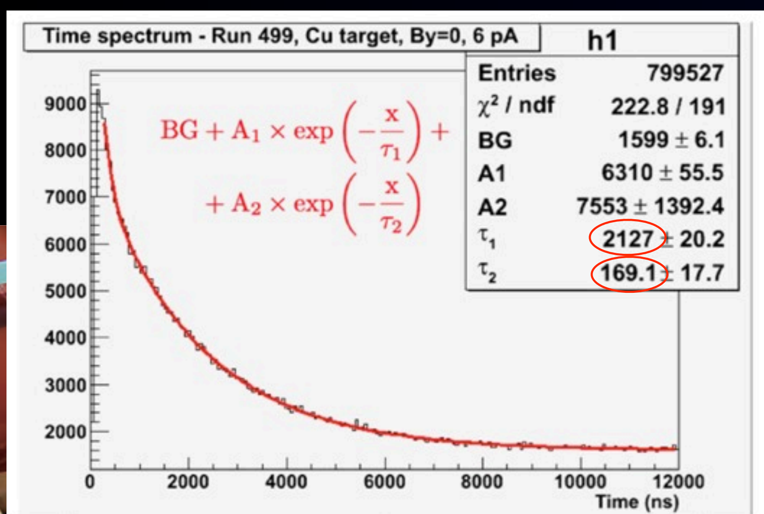
μ^- : $O(10^8)$/s with 1.4MW

3.5T and graphite proton target



MuSIC at RCNP, Osaka University (2011 -)





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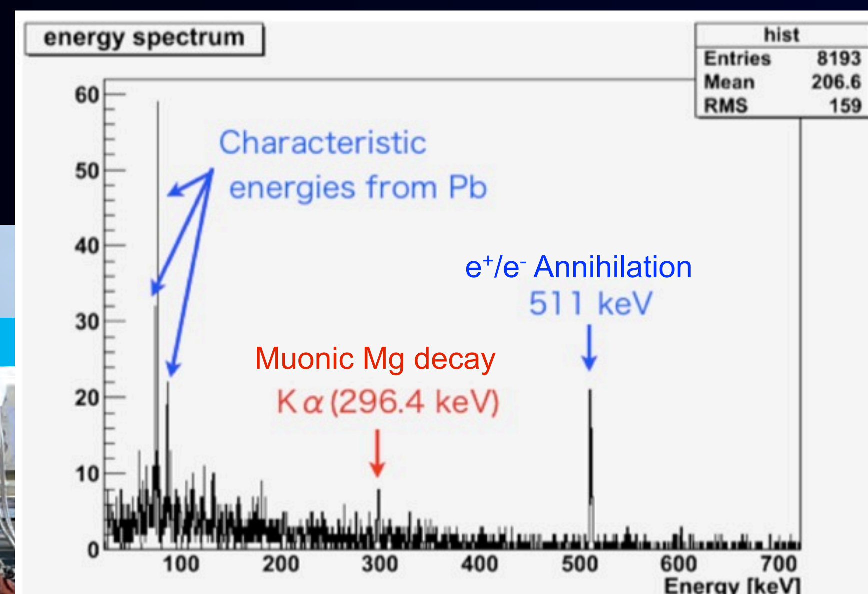

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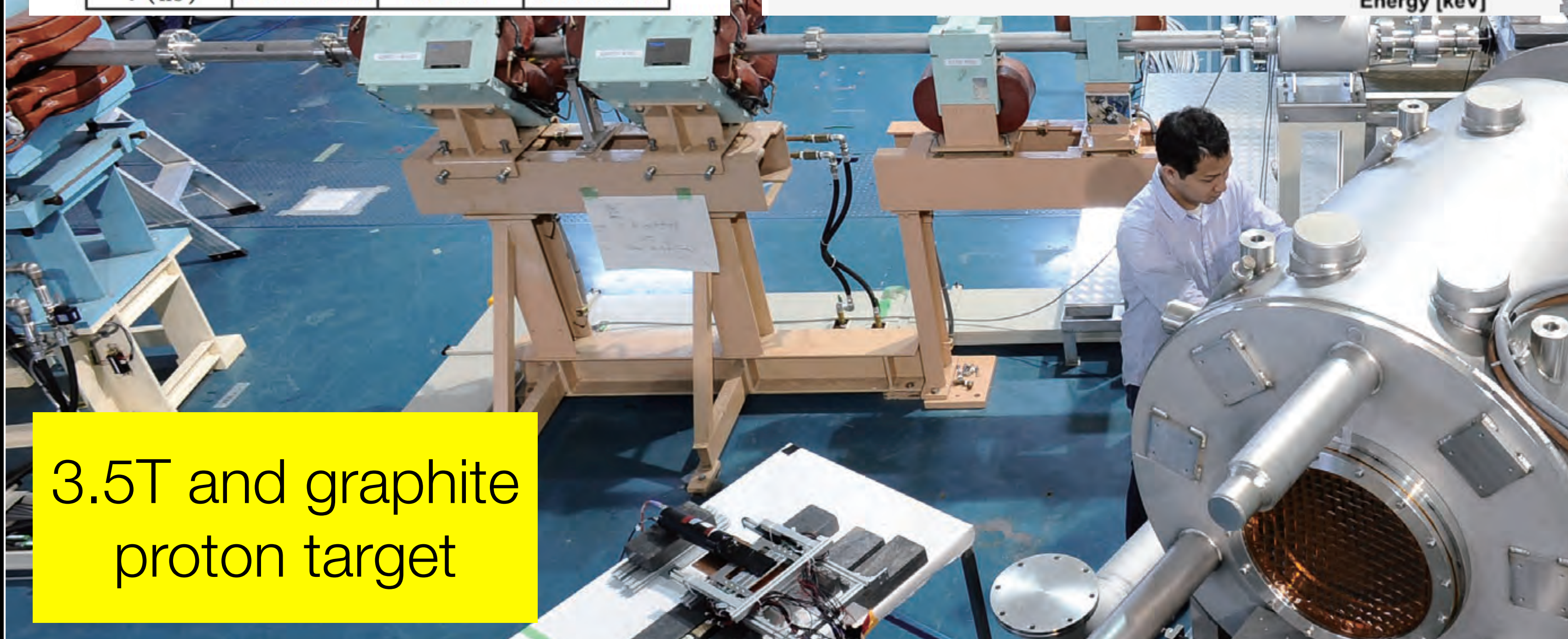


3.5T and graphite proton target

10^{11}/s with 50 kW, possible!

Improvements of Background Rejection

Improvements of Background Rejection

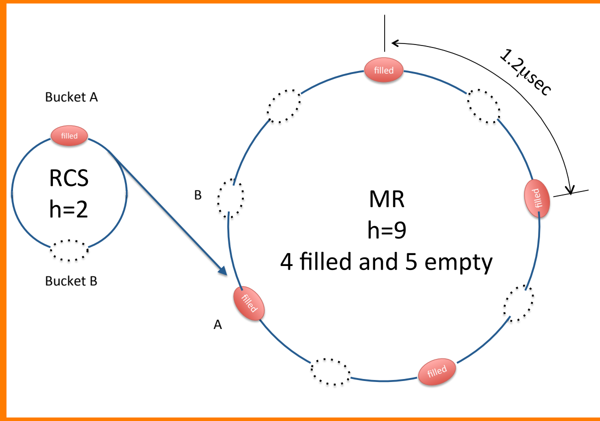
Background	Solution	Notes
Muon DIO background	Low-mass trackers in vacuum & thin target	improve electron energy resolution
Beam-related backgrounds	Beam pulsing with separation of 1μsec	measured between beam pulses

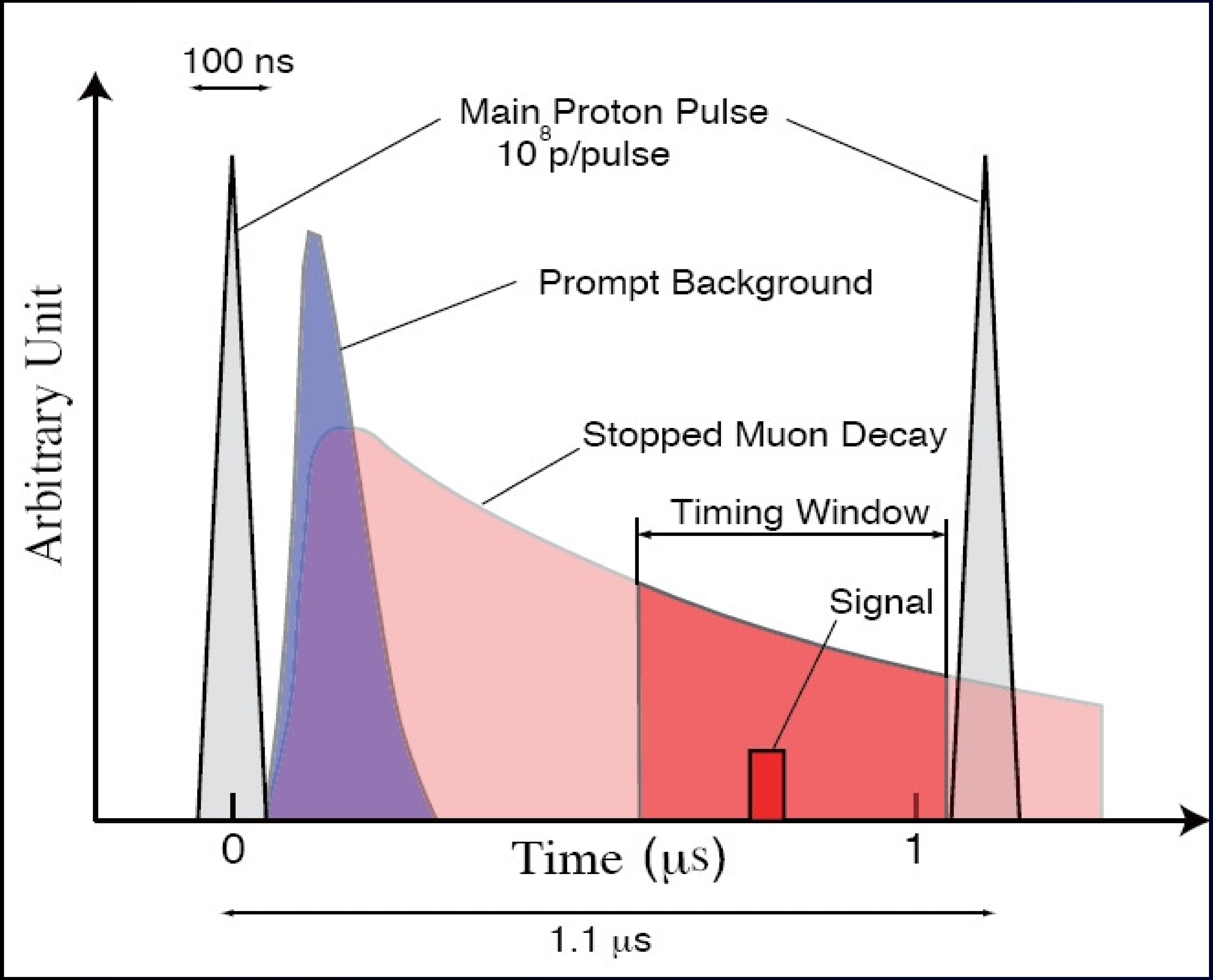
proton extinction = #protons between pulses/#protons in a pulse < 10^{-10}

Background	Solution	Notes
Decay in flight background	Curved solenoids for momentum selection	eliminate energetic muons (>75 MeV/c)
Cosmic ray background	Cosmic ray active veto system	

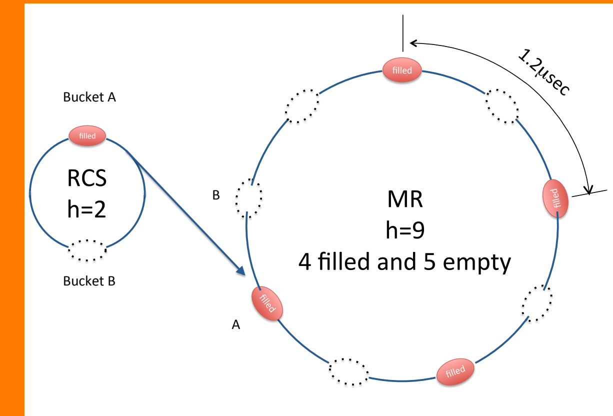
Pulsed Proton Beam Time Structure at J-PARC

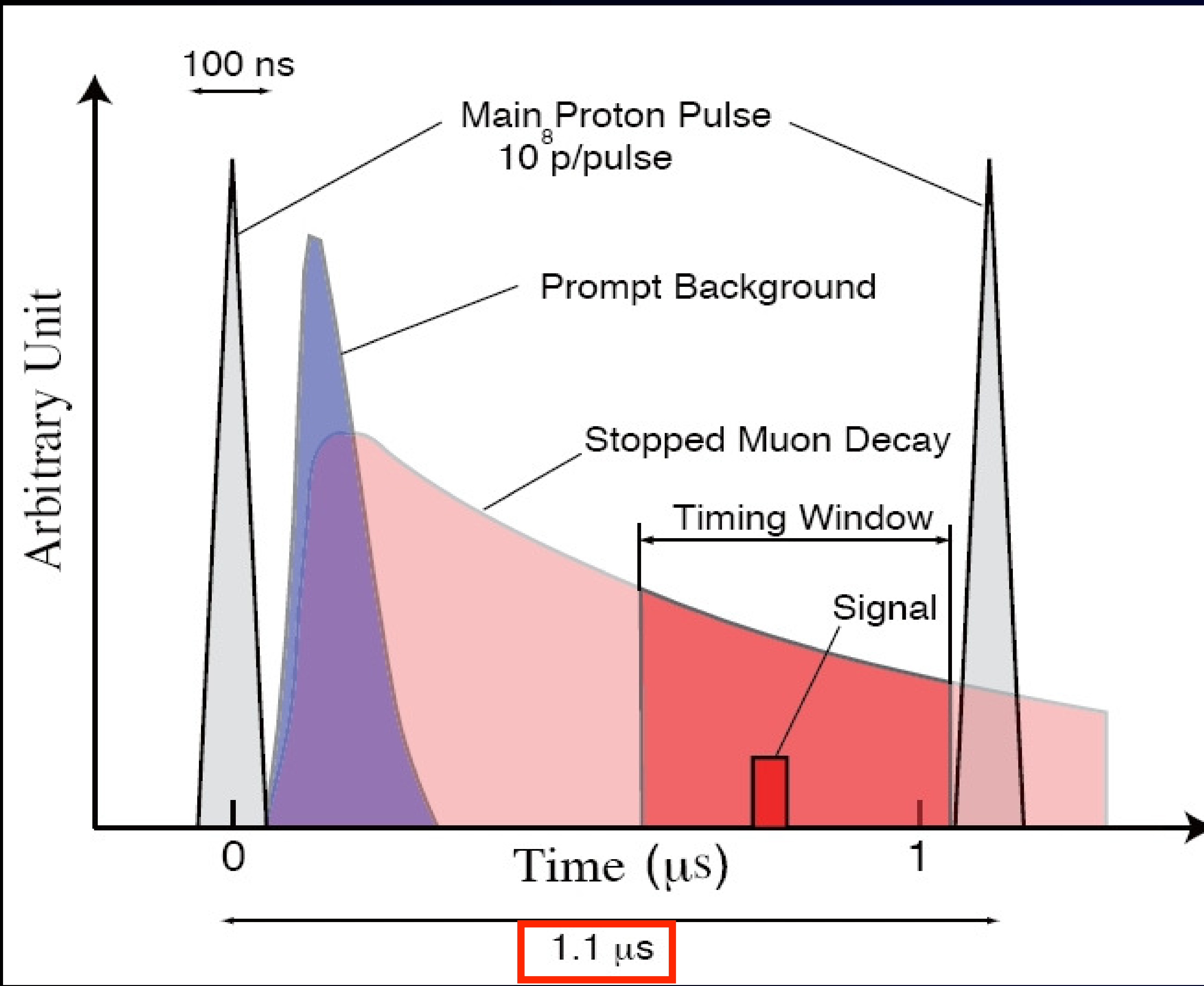
Pulsed Proton Beam Time Structure at J-PARC





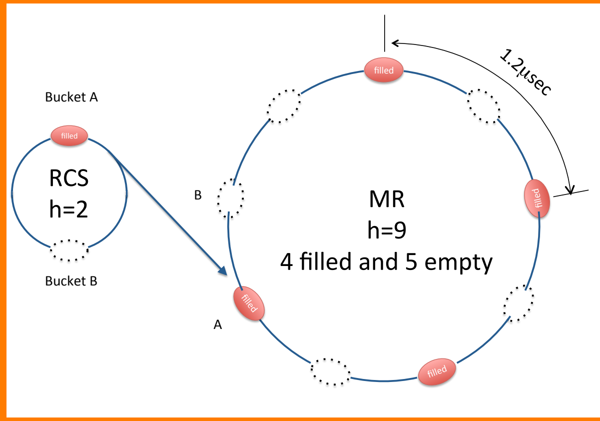
Pulsed Proton Beam Time Structure at J-PARC

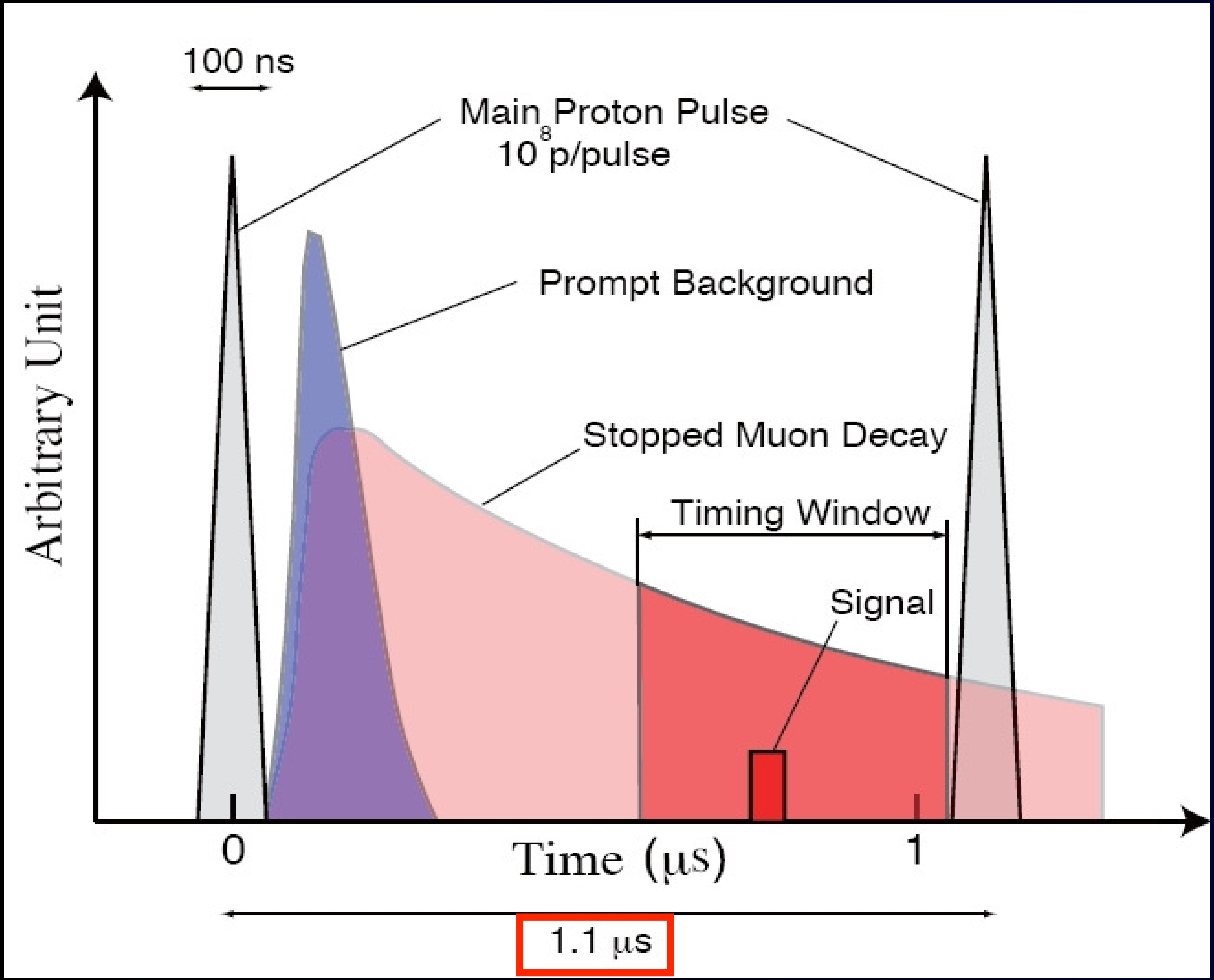




Bunched slow extraction with every other RF bunch filled by protons.

Pulsed Proton Beam Time Structure at J-PARC

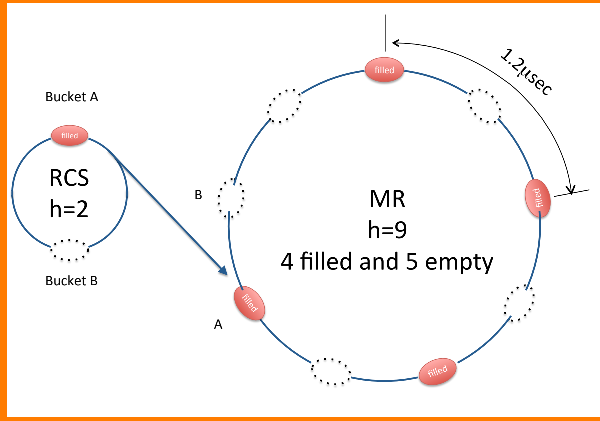


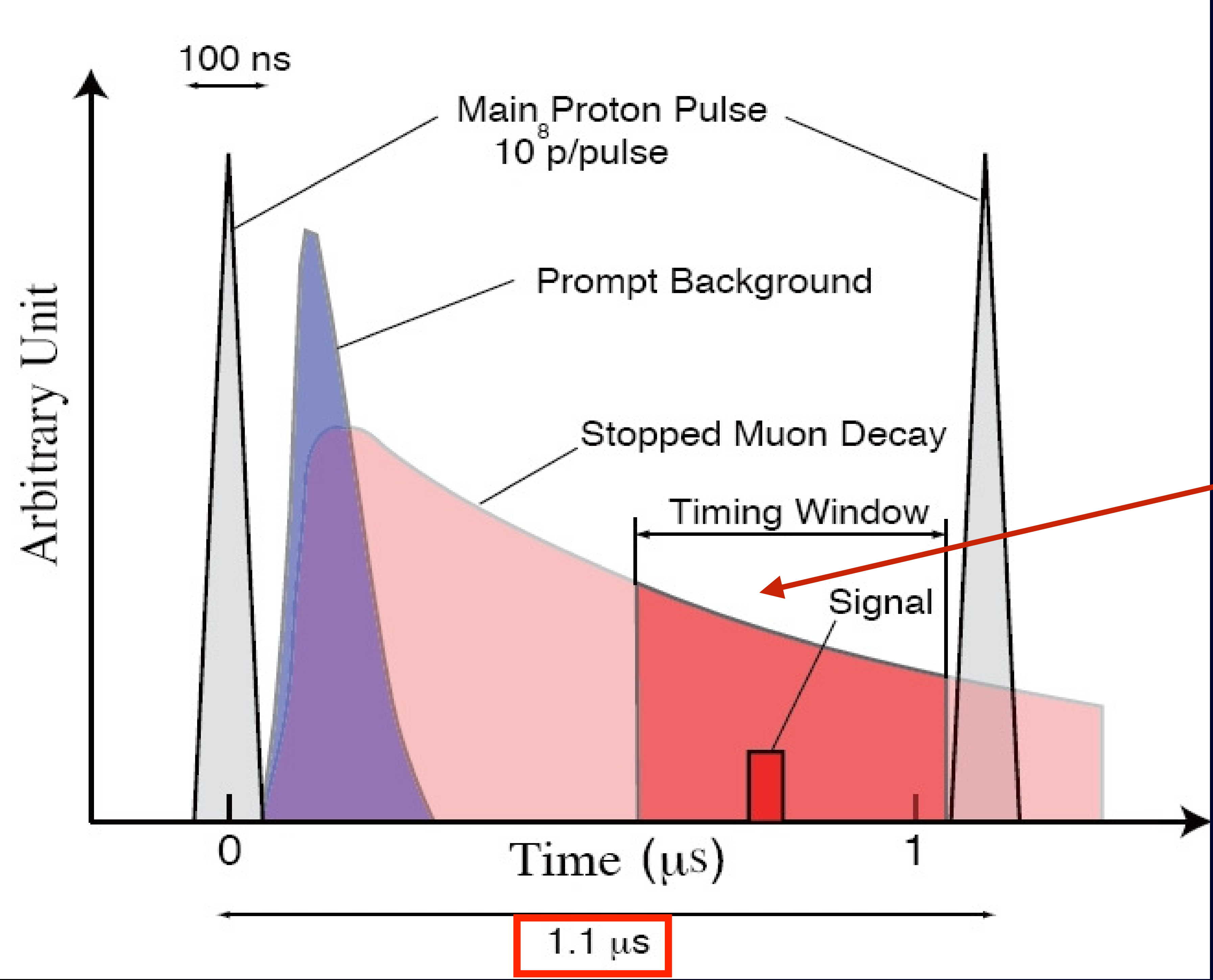


Aluminum muon target (muonic atom lifetime of 864 ns is good for 1.1μs repetition.)

Bunched slow extraction with every other RF bunch filled by protons.

Pulsed Proton Beam Time Structure at J-PARC



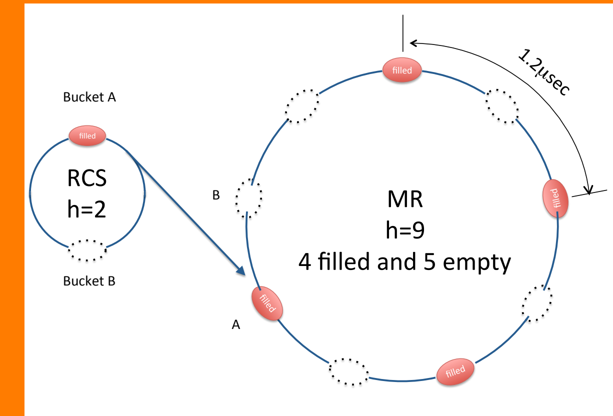


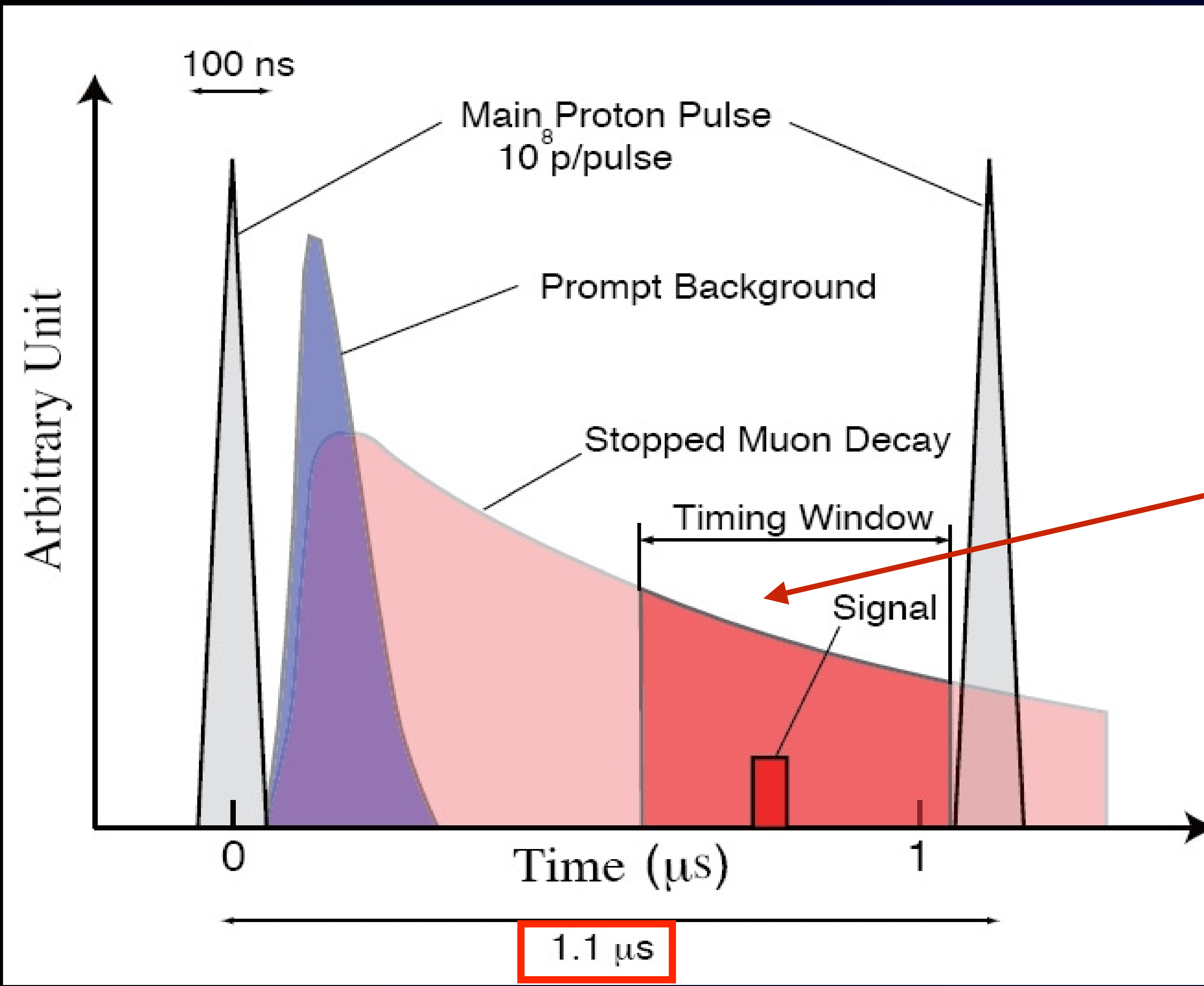
Aluminum muon target (muonic atom lifetime of 864 ns is good for 1.1μs repetition.)

Delayed time window to avoid beam background , like pions.
(from 700 ns to 1.1μs)

Bunched slow extraction with every other RF bunch filled by protons.

Pulsed Proton Beam Time Structure at J-PARC





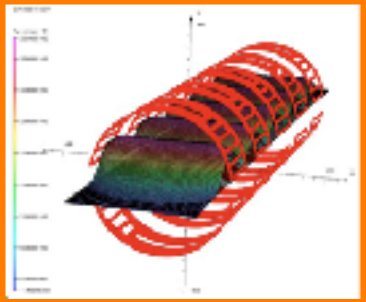
Aluminum muon target (muonic atom lifetime of 864 ns is good for 1.1μs repetition.)

Delayed time window to avoid beam background , like pions.
(from 700 ns to 1.1μs)

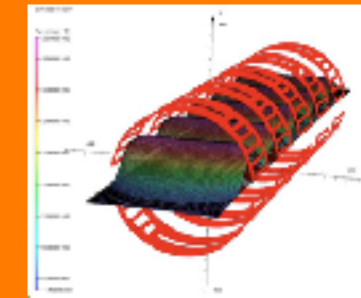
Proton extinction factor (proton leakage between pulses) ~ 10^{-10}

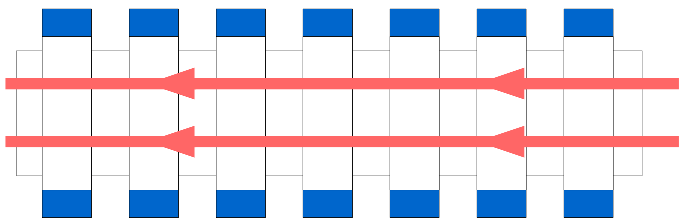
Bunched slow extraction with every other RF bunch filled by protons.

Curved Solenoids with Dipole field in COMET

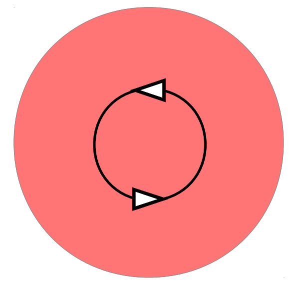


Curved Solenoids with Dipole field in COMET



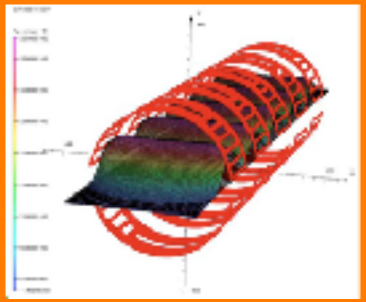


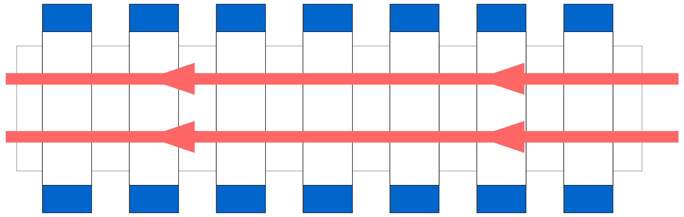
- Uniform B field
- Linear field lines



Helical motion about field lines

Curved Solenoids with Dipole field in COMET





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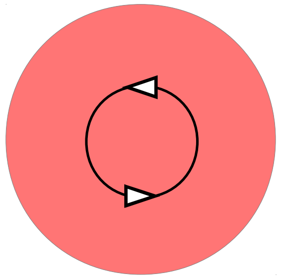
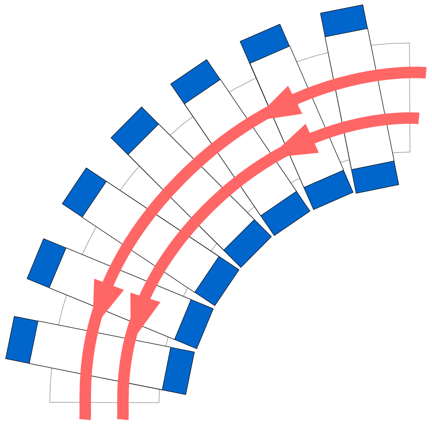
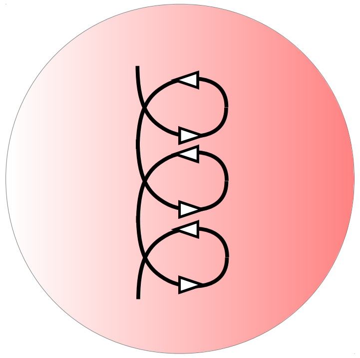


Helical motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines

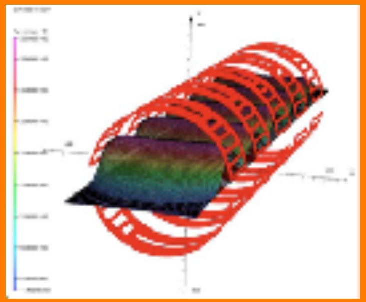


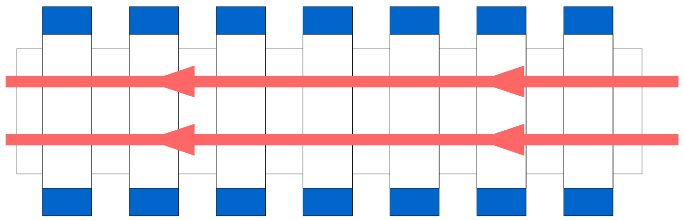
Helical motion about a drifting centre

$$D_{\mathrm{drift}} \propto \frac{p}{qB}\frac{s}{R}$$

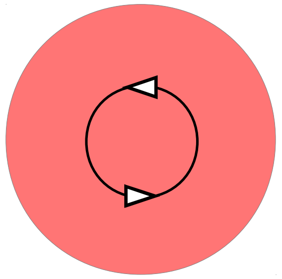
$$\begin{aligned} D &= \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2+\frac{1}{2}p_T^2}{p_L}, \\ &= \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p}{2}\left(\cos\theta+\frac{1}{\cos\theta}\right) \end{aligned}$$

Curved Solenoids with Dipole field in COMET

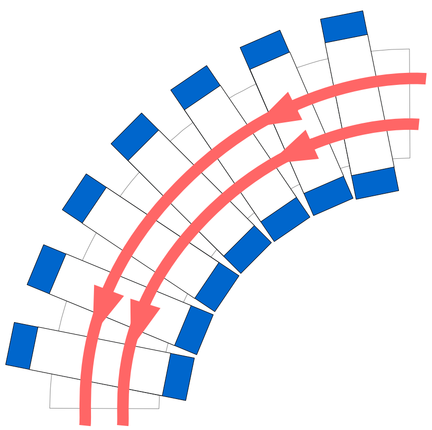




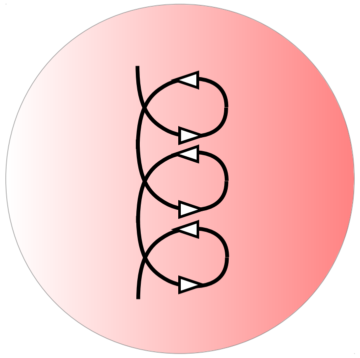
- Uniform B field
- Linear field lines



Helical motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines



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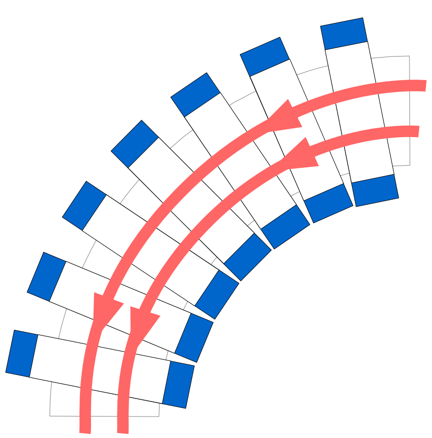
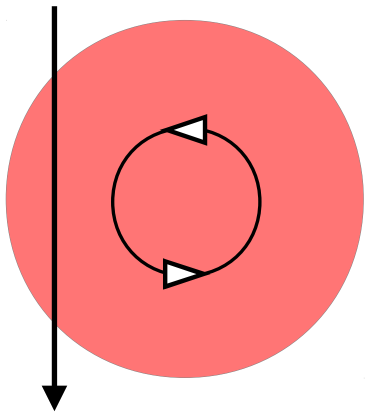


- Radial gradient in magnetic field
- Cylindrical field lines
- dipole field normal to the bending plane

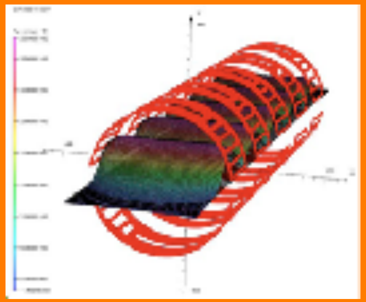


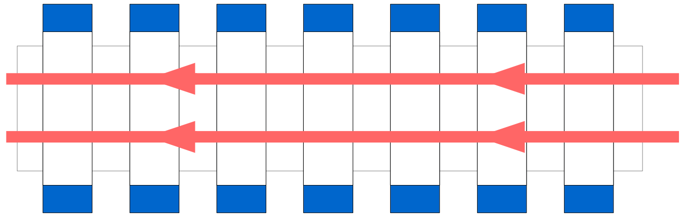
Helical motion of selected momentum p_0 staying in the bending plane

$$\mathrm{B}_{\mathrm{dipole}} \propto \frac{p_0}{qR}$$

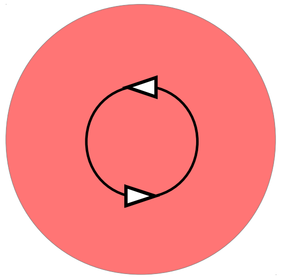
$$B_{\mathrm{comp}} = \frac{1}{qR}\frac{p_0}{2}\left(\cos\theta_0 + \frac{1}{\cos\theta_0}\right)$$

Curved Solenoids with Dipole field in COMET

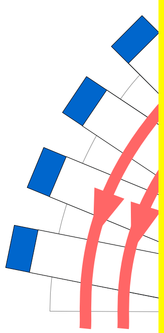




- Uniform B field
- Linear field lines



Helical motion about field lines

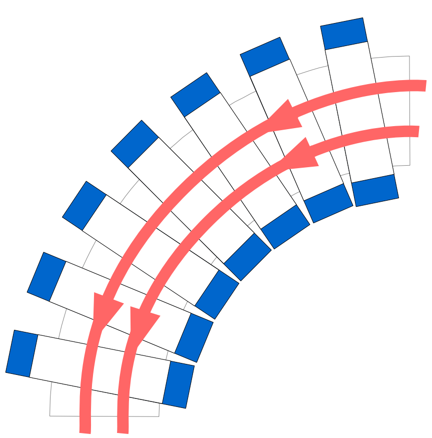


$\frac{1}{2}p_T^2$,

$\cos\theta + \frac{1}{\cos\theta})$

Advantages:

- The second curved solenoid with opposite bending is not needed.
- The diameter of curved solenoids gets smaller.
- Muon beam is momentum-dispersive at the end.



- Radial gradient in magnetic field
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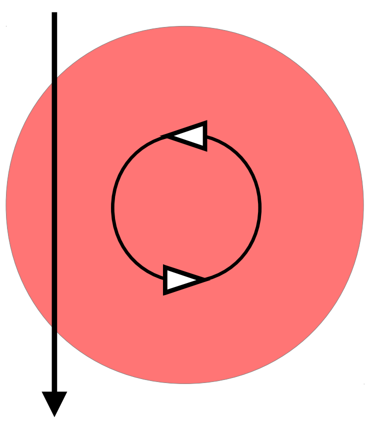

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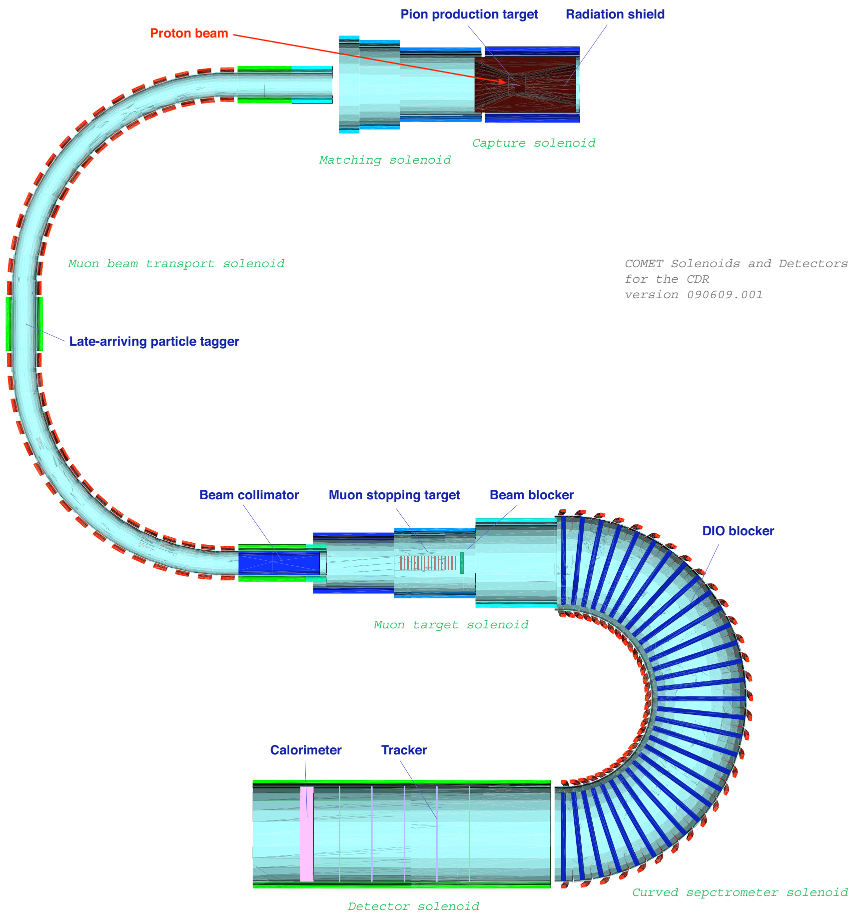
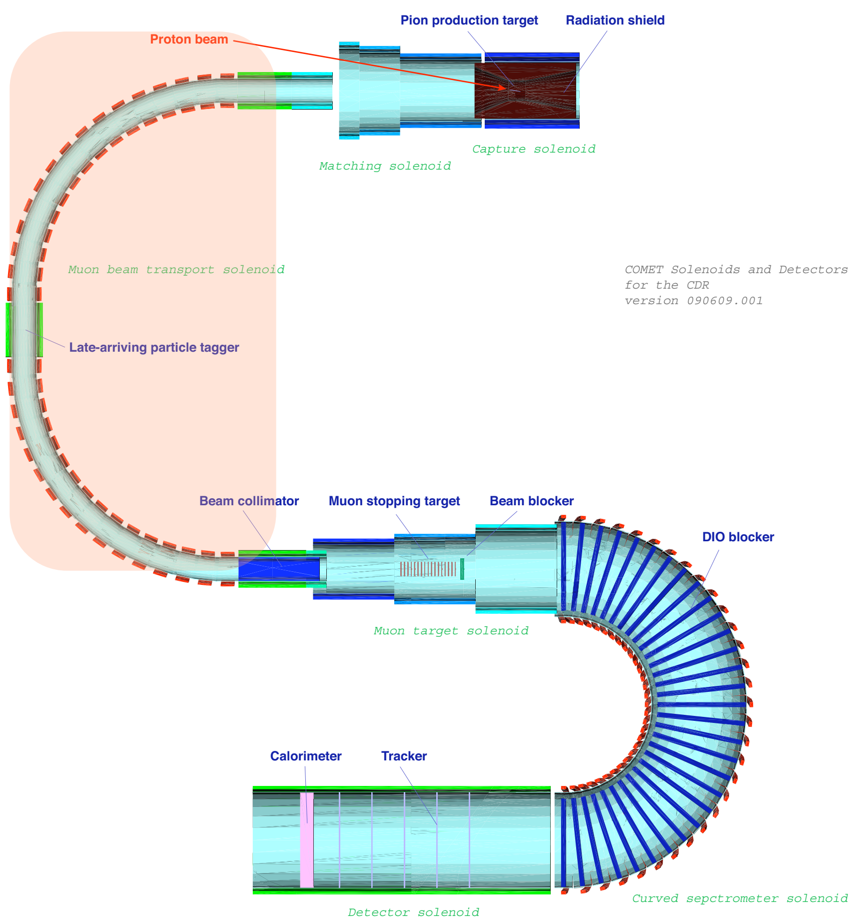
COMET Features

COMET Features



muon beam line	2x 90° bend (same direction)
electron spectrometer	180° bend curved solenoids

COMET Features



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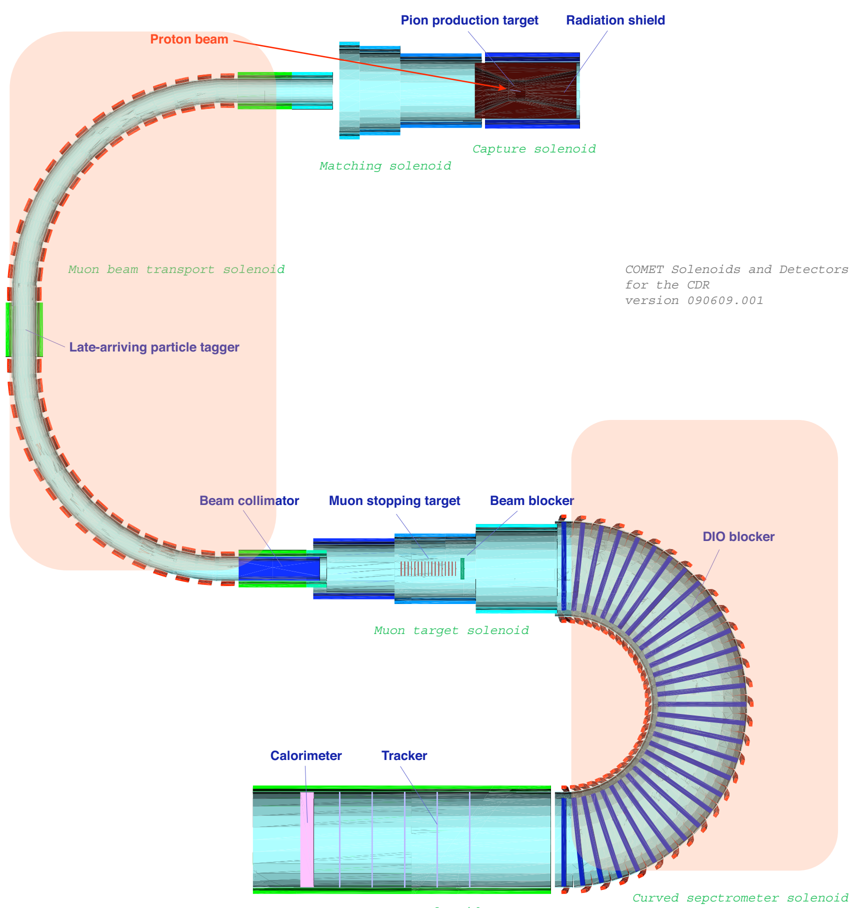
electron spectrometer	180° bend curved solenoids

Selection of low momentum muons

- eliminate high energy electrons from muon decays in flight

momentum selection capability is proportional to bending angle

COMET Features



muon beam line	2x 90° bend (same direction)
electron spectrometer	180° bend curved solenoids

Selection of low momentum muons

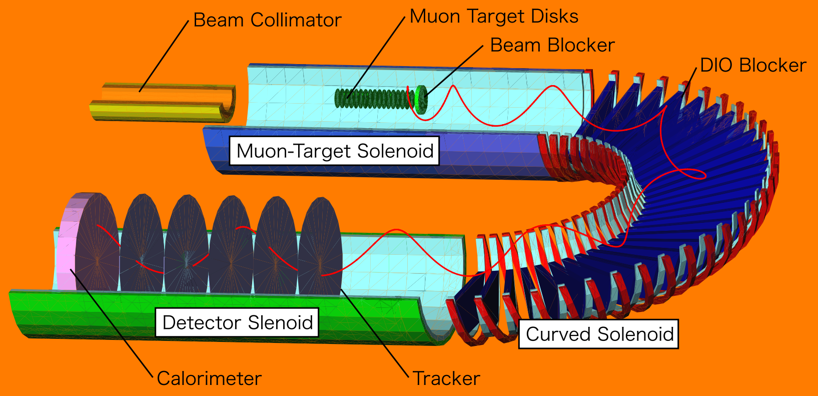
- eliminate high energy electrons from muon decays in flight

momentum selection capability is proportional to bending angle

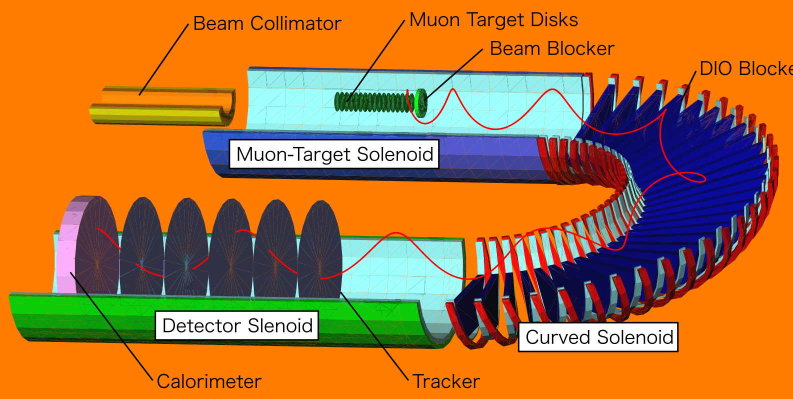
Selection of 105 MeV signal electrons

- eliminate neutrons and gamma-rays from muon target
- eliminate protons from muon target
- eliminate low energy DIO electrons from muon decays from muon target

Electron Spectrometer in COMET Phase-II



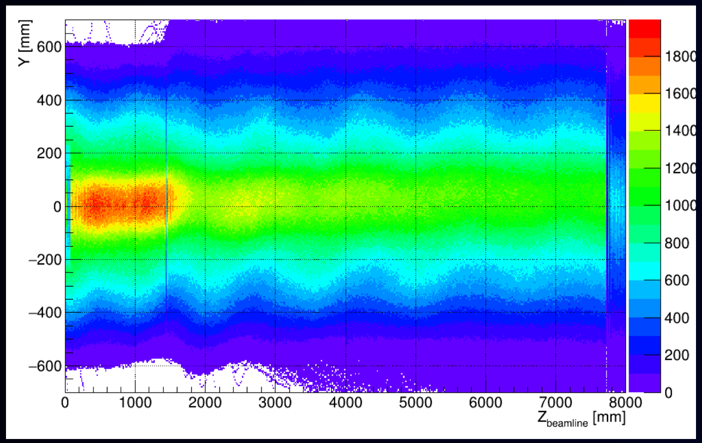
Electron Spectrometer in COMET Phase-II

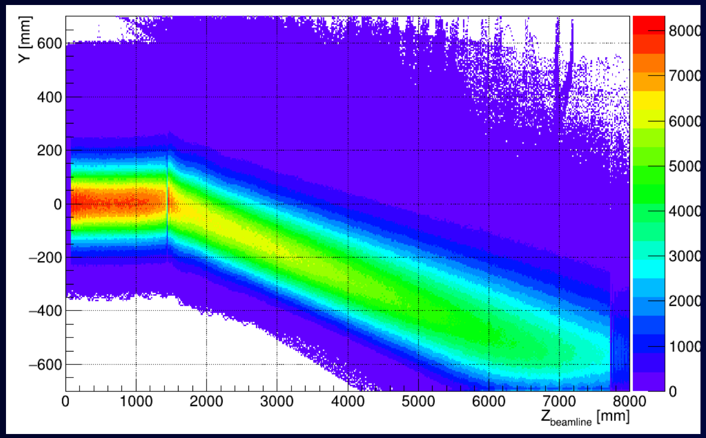


105 MeV/c signal electrons

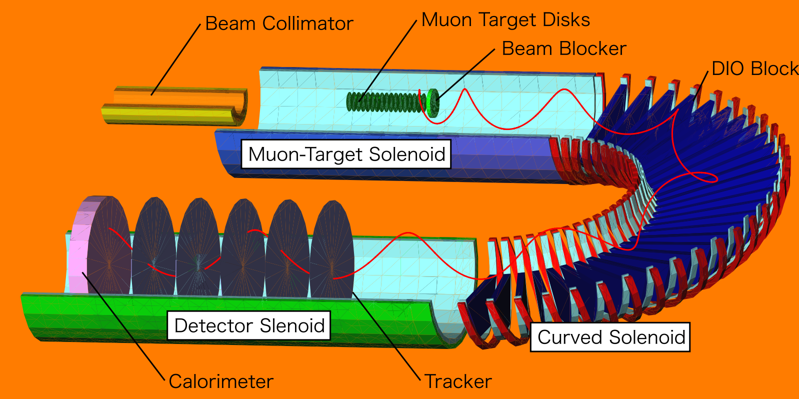
52 MeV/c DIO electrons

B_{dipole}=-0.22T





Electron Spectrometer in COMET Phase-II



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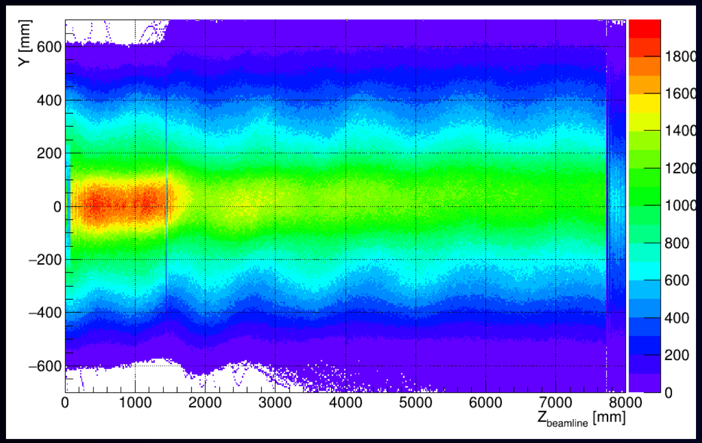
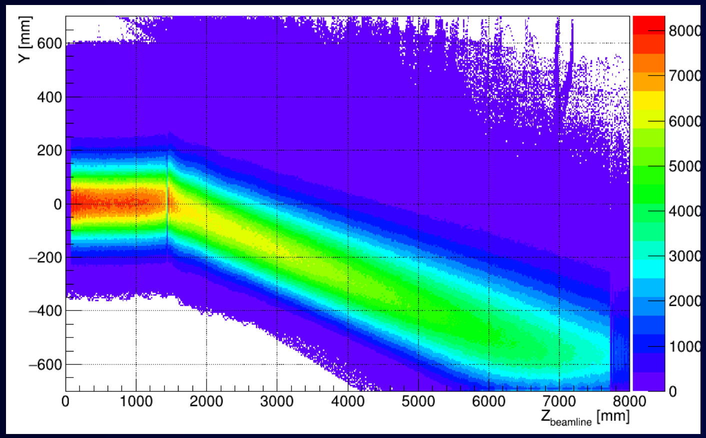
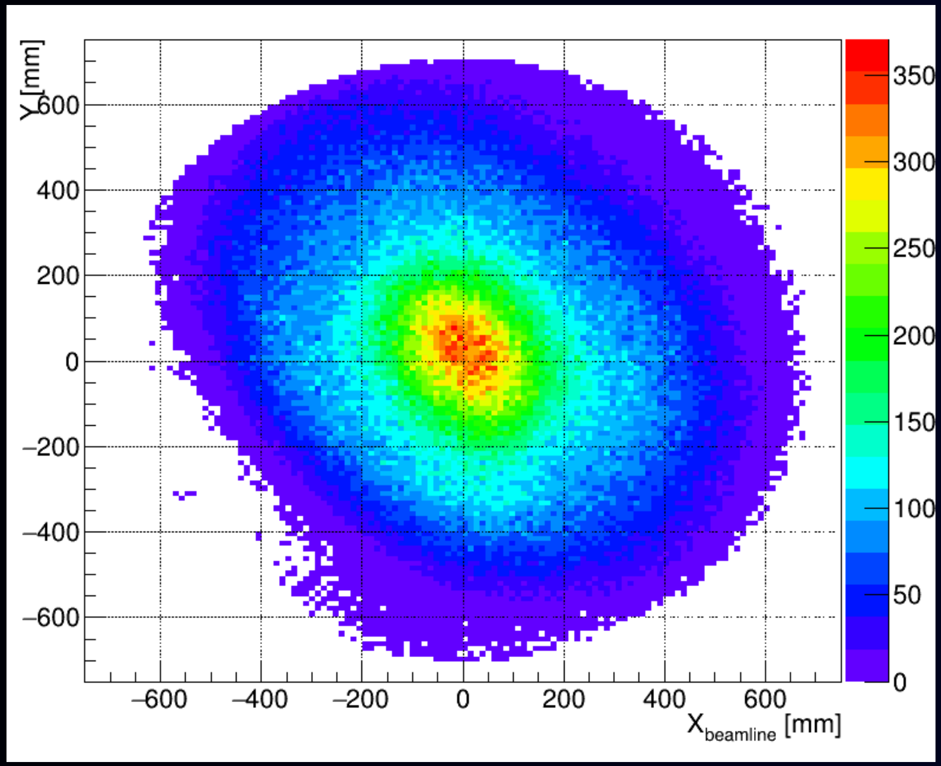




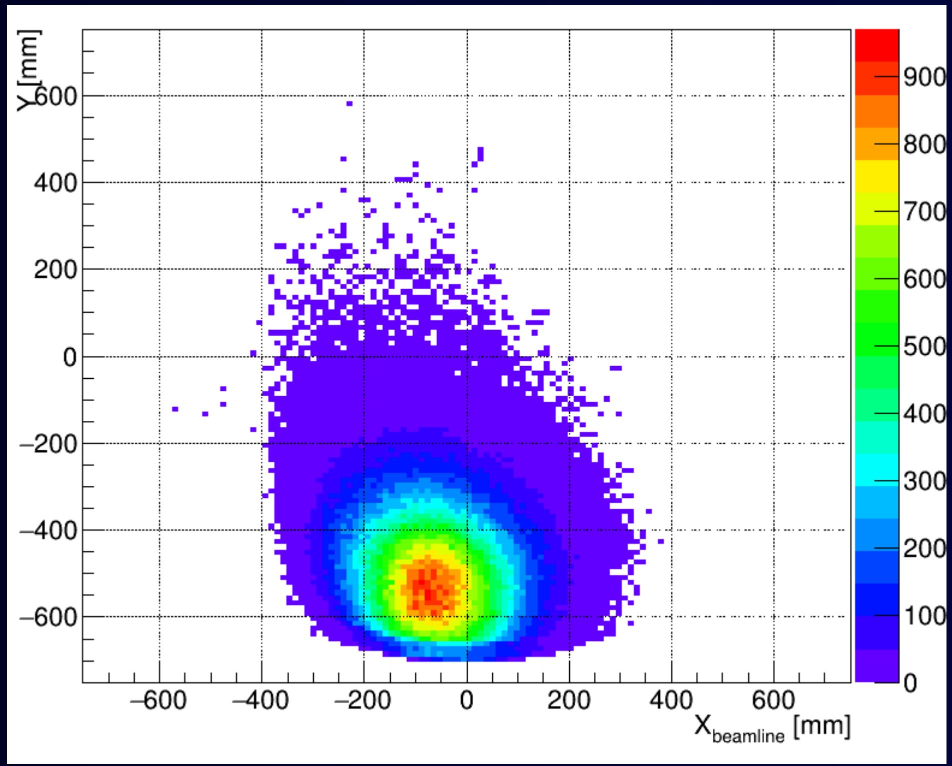
at the end of the electron spectrometer

vertical



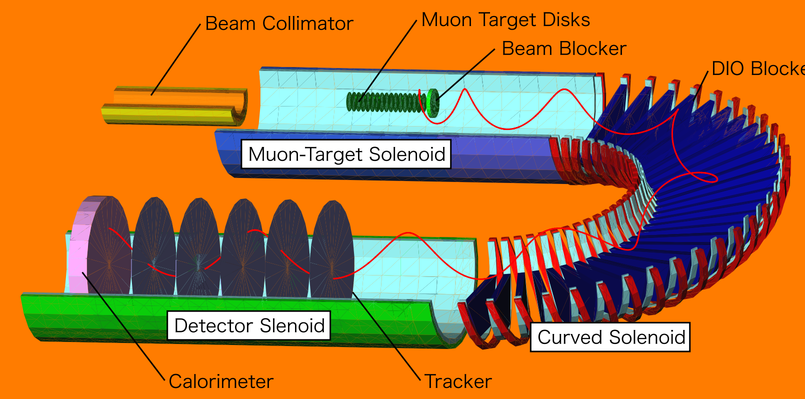
horizontal

vertical



horizontal

Electron Spectrometer in COMET Phase-II



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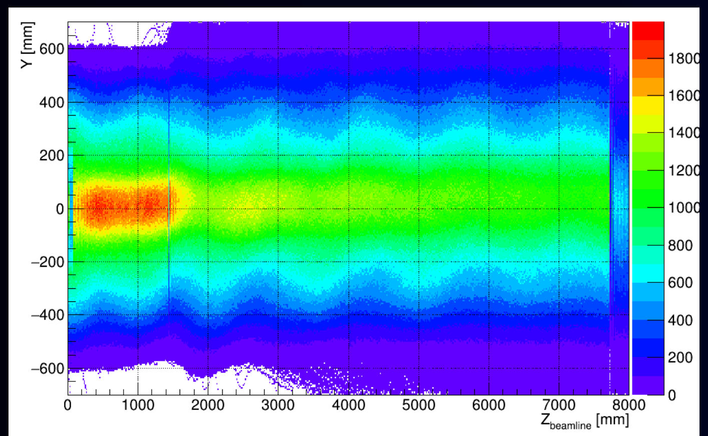
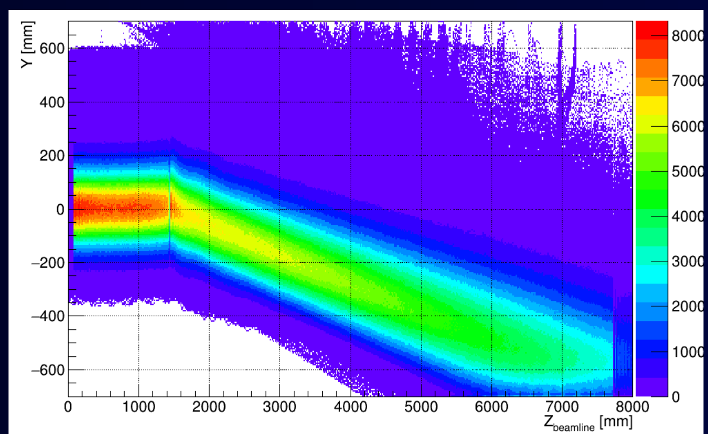
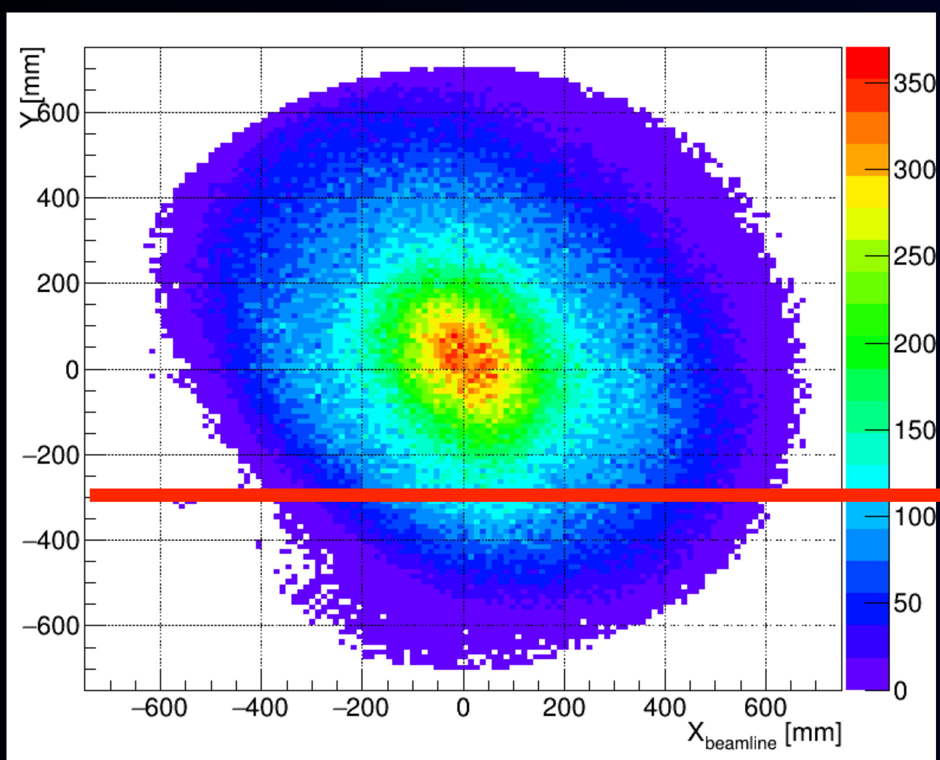




at the end of the electron spectrometer

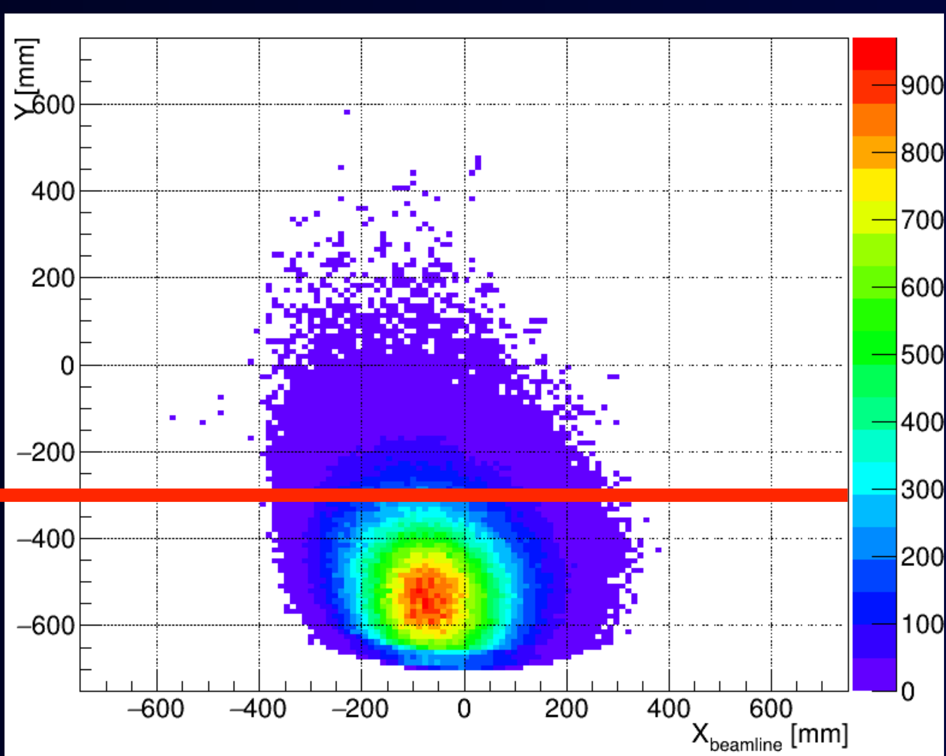
vertical



horizontal

removed

vertical



horizontal

COMET Collaboration

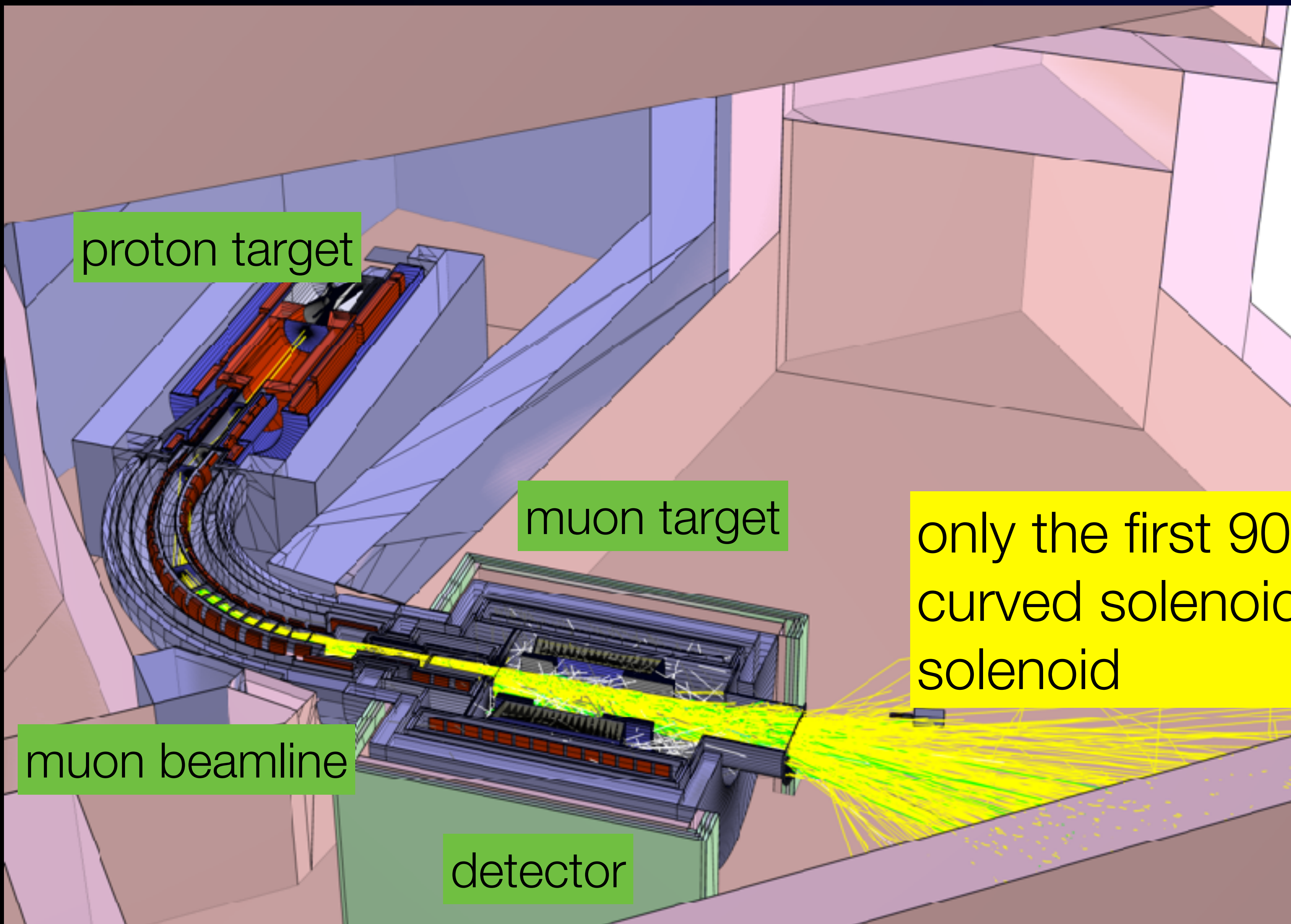
COMET Collaboration

43 institutes, 17 countries

COMET Staged Approach

COMET Phase-I
(2016 -)

COMET Phase-I (2016 -)

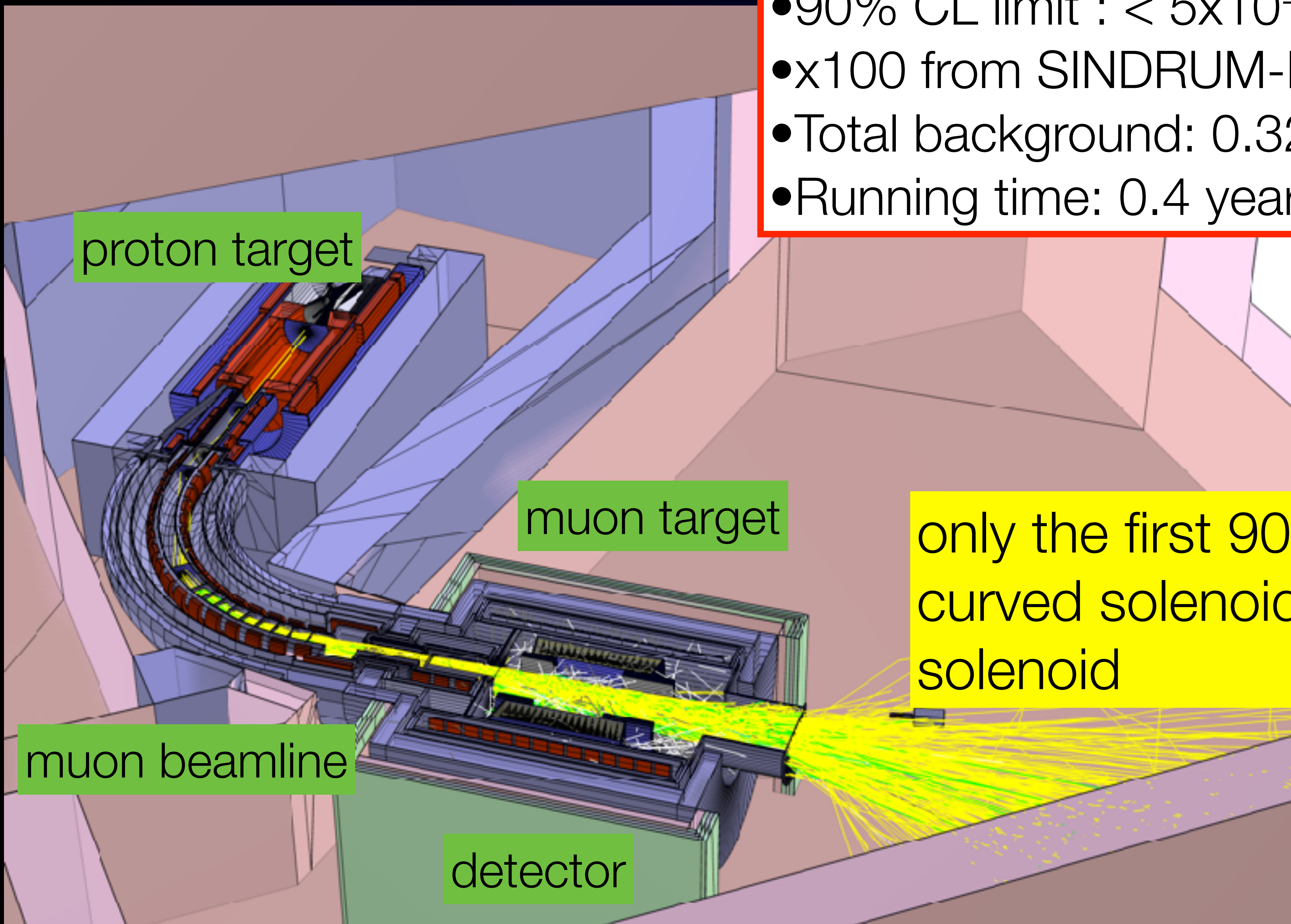


only the first 90 degree curved solenoid + detector solenoid

COMET Phase-I (2016 -)

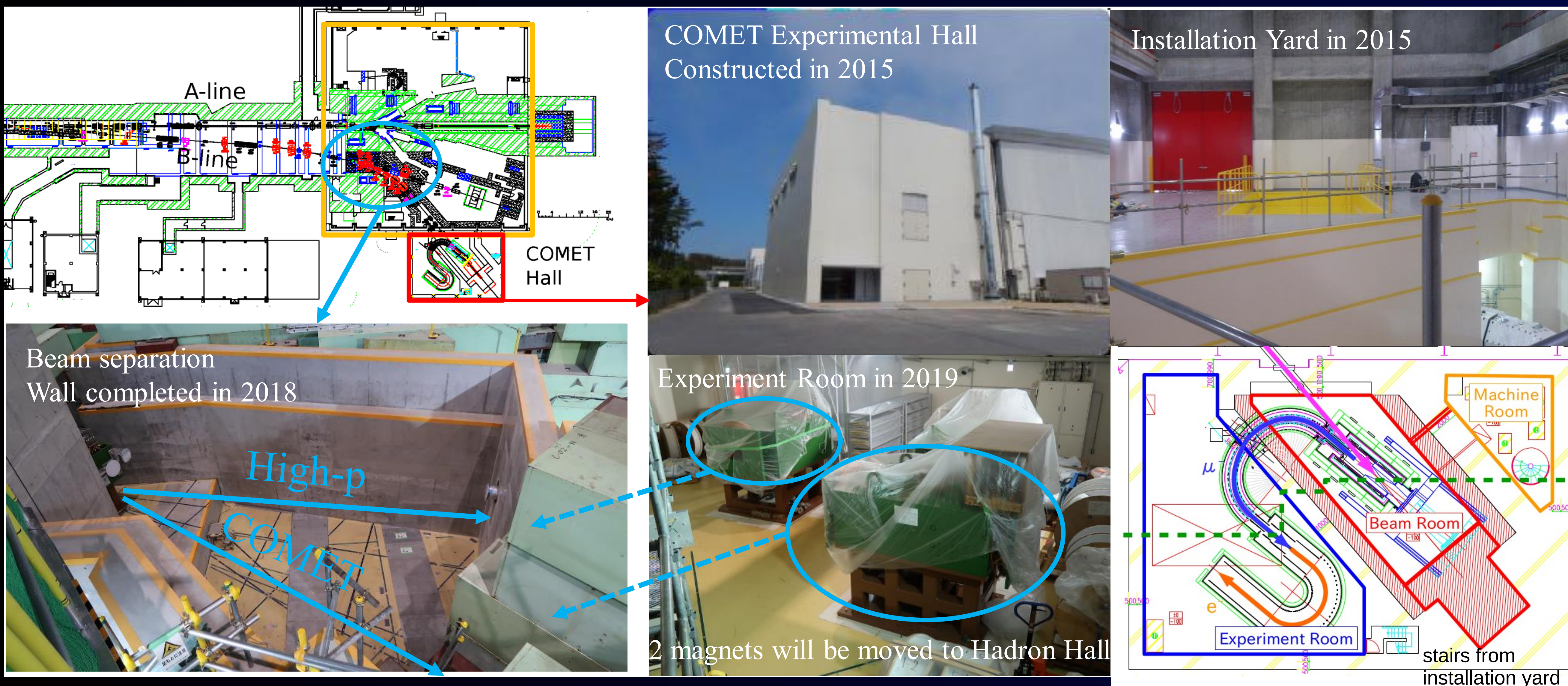
- Proton beam, 8 GeV, 3.2kW
- 2×10^9 stopped muons/s

- Single event sensitivity : 2×10^{-15}
- 90% CL limit : < 5×10^{-15}
- x100 from SINDRUM-II
- Total background: 0.32 events
- Running time: 0.4 years (1.2×10^7sec)



only the first 90 degree curved solenoid + detector solenoid

COMET Facility at J-PARC



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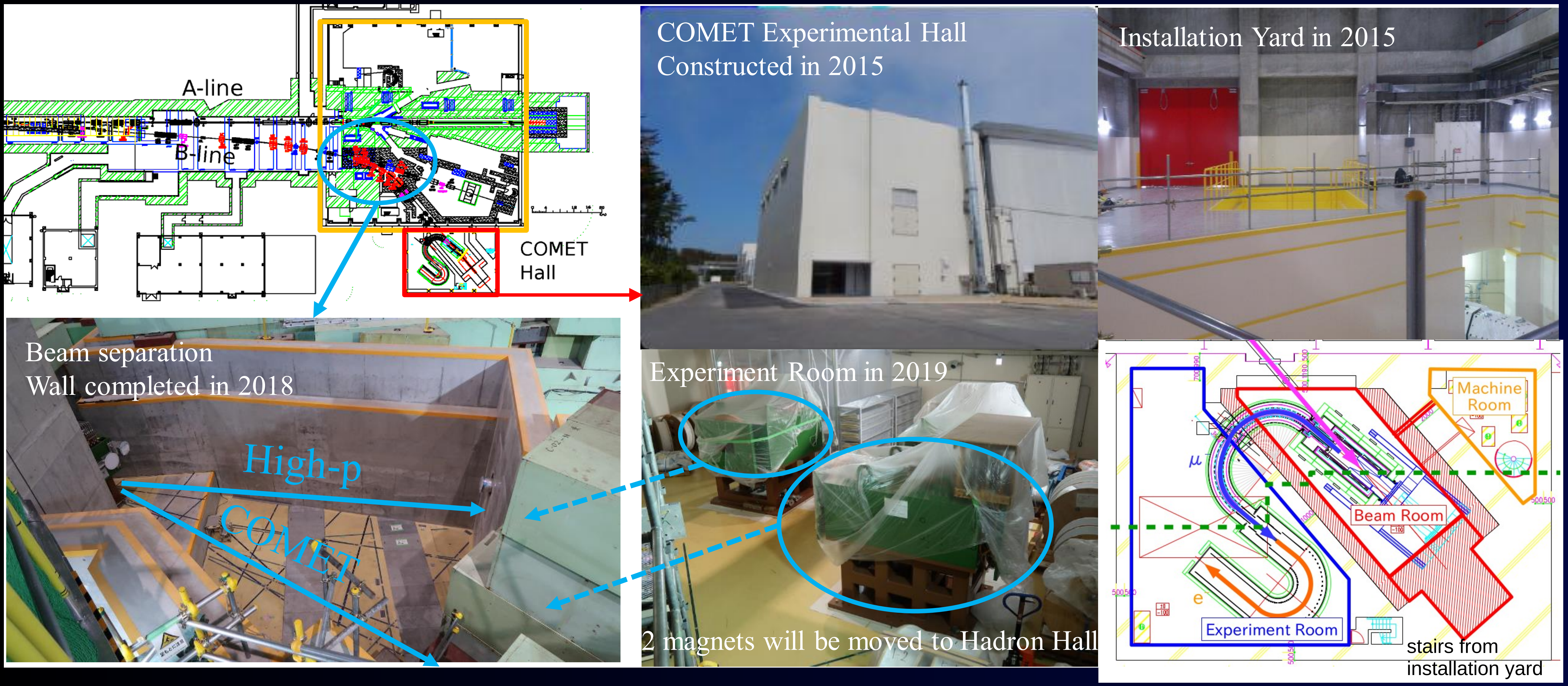

- COMET experimental hall building, completed in 2015
- Cryogenic system, completed in 2021
- New proton C line, completed in 2022

COMET Phase-I : Superconducting Solenoid Construction

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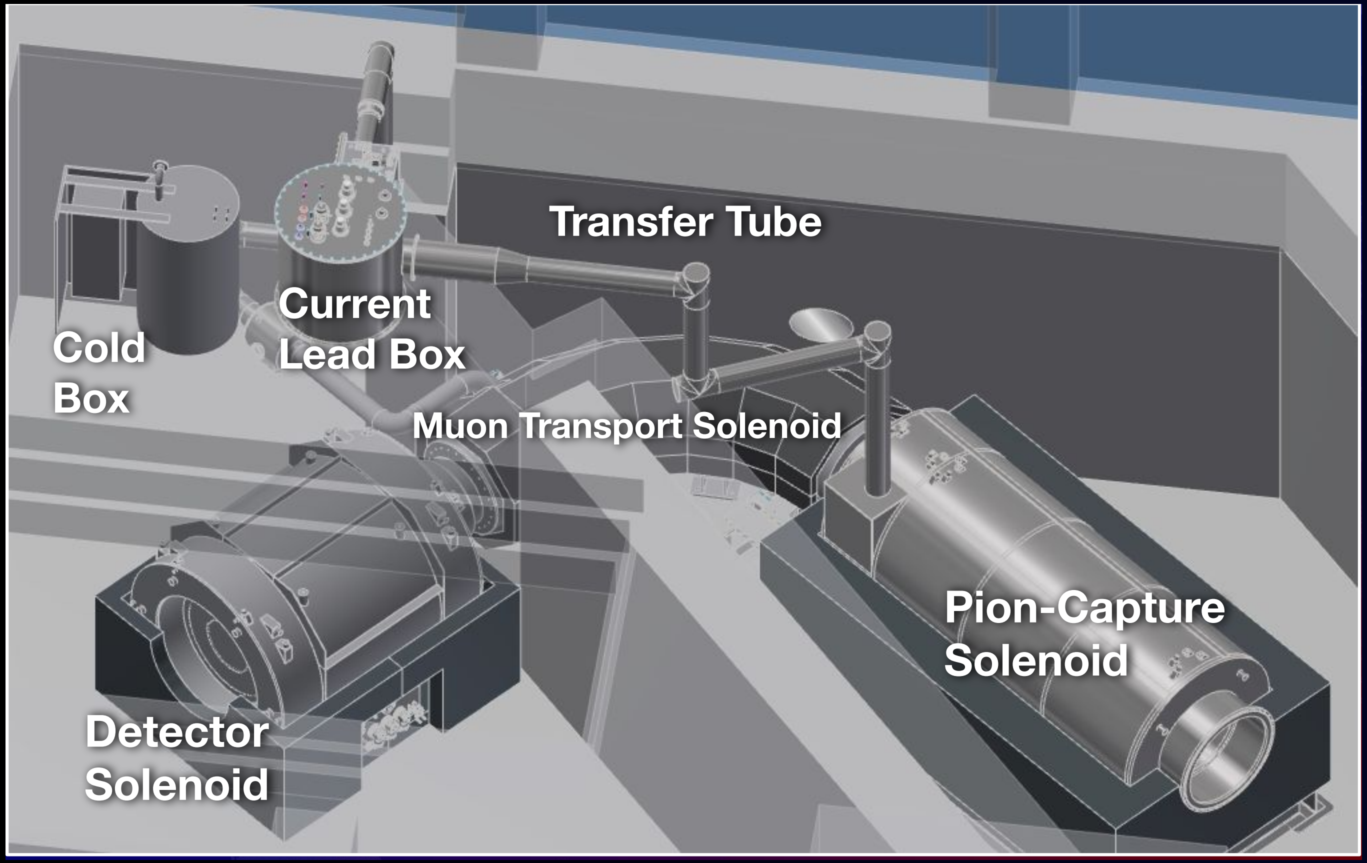

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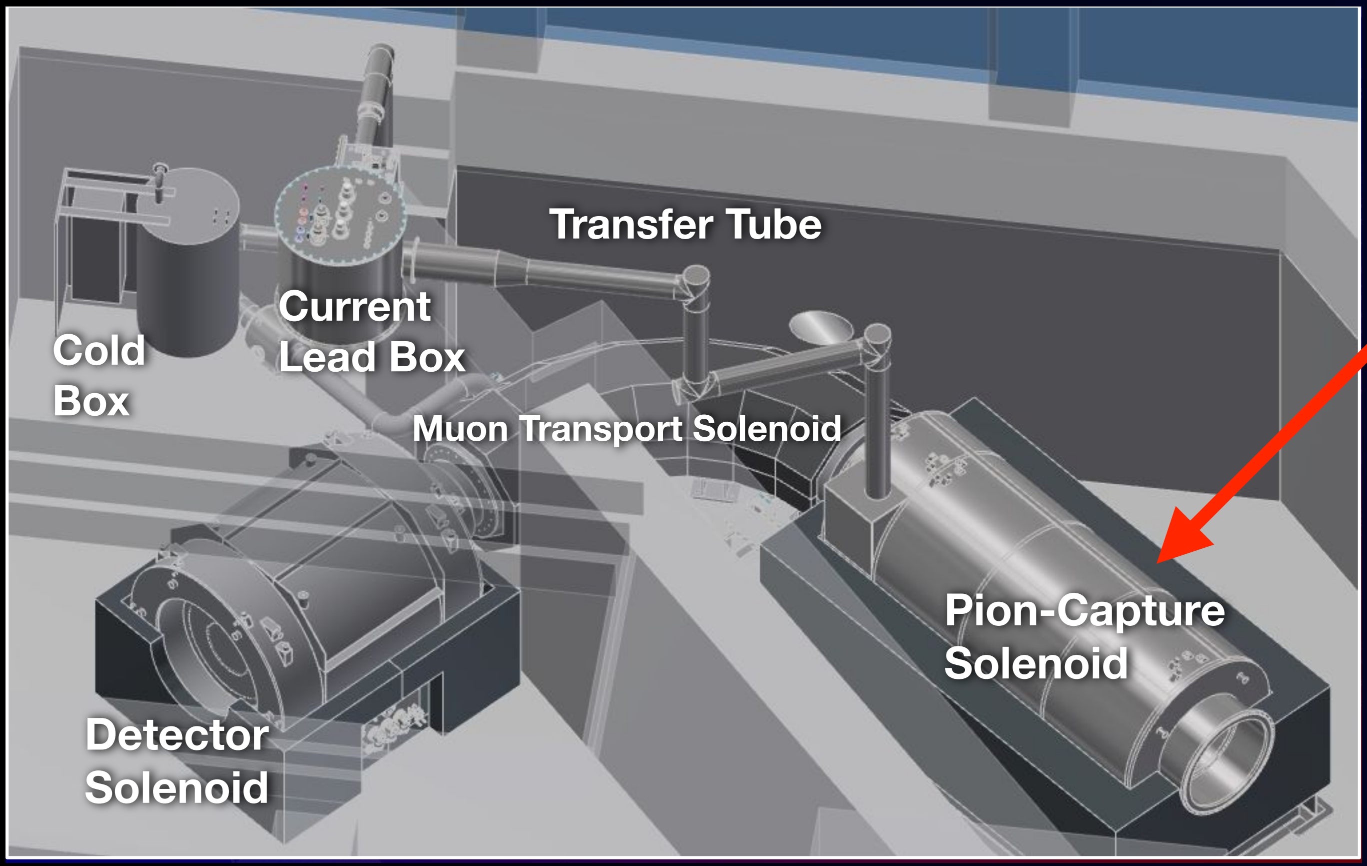

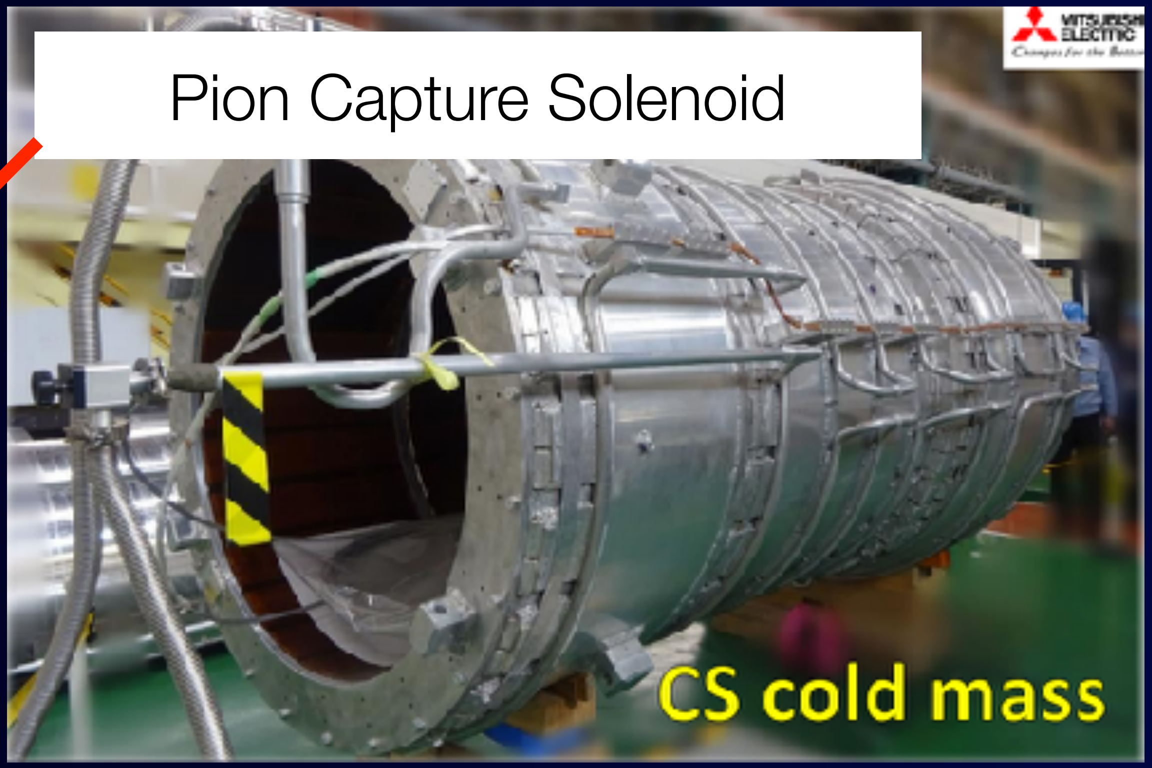

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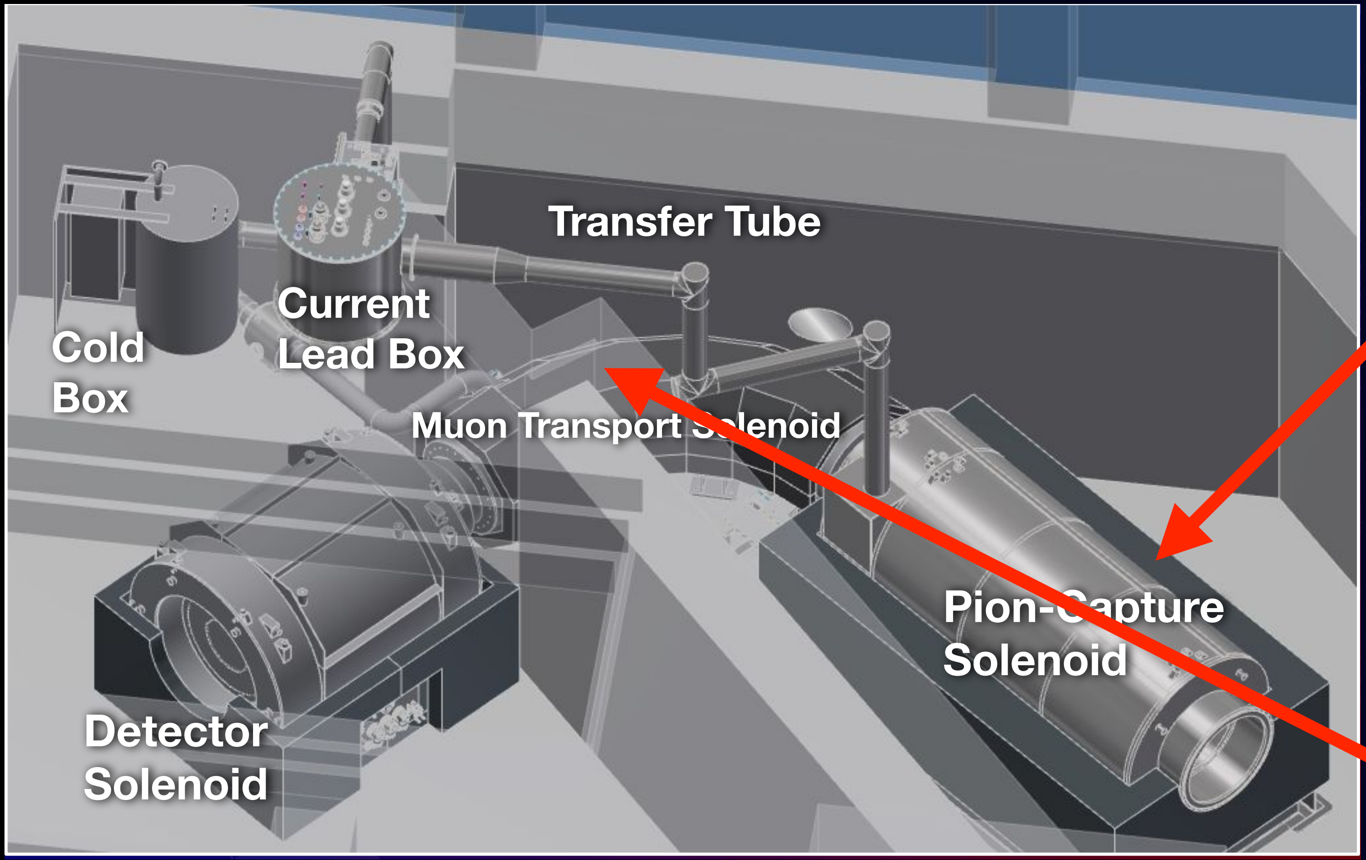

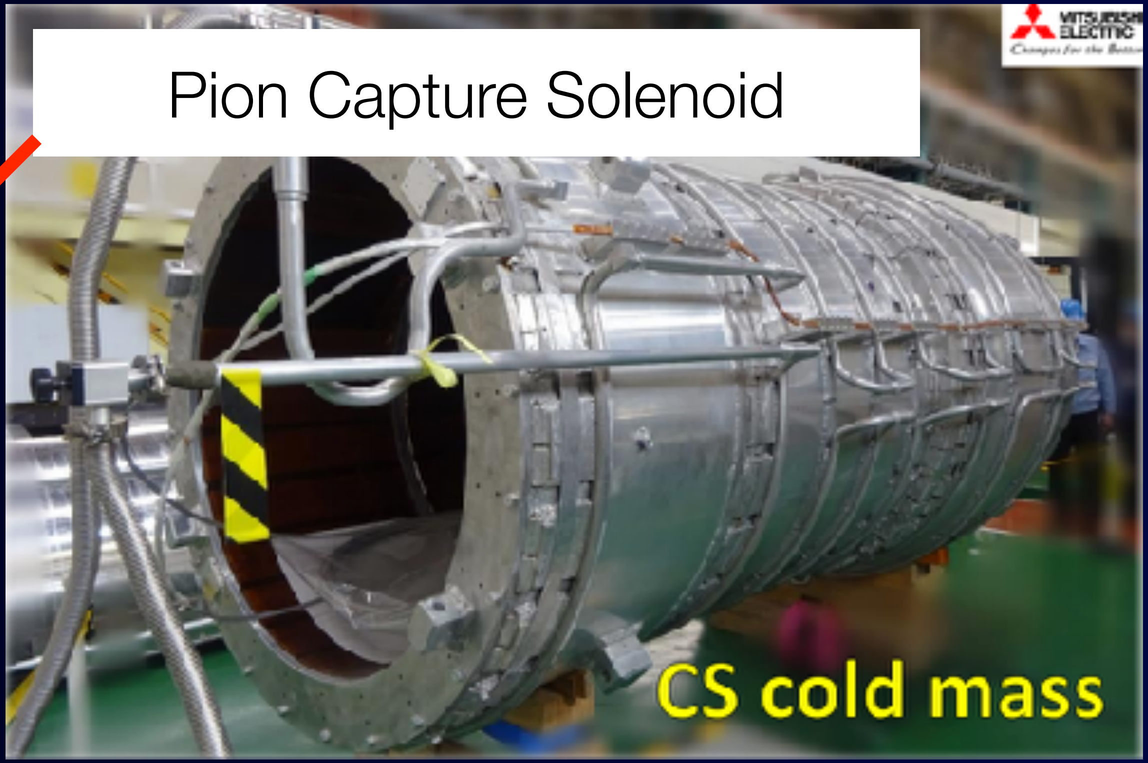

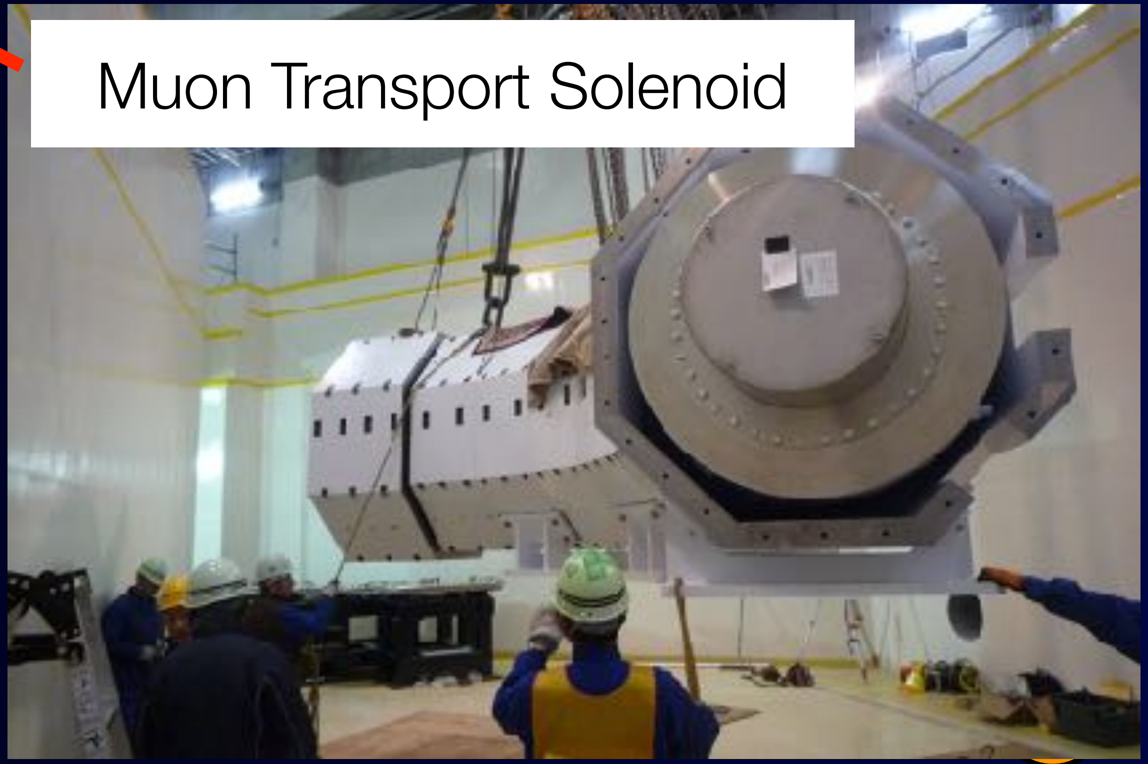

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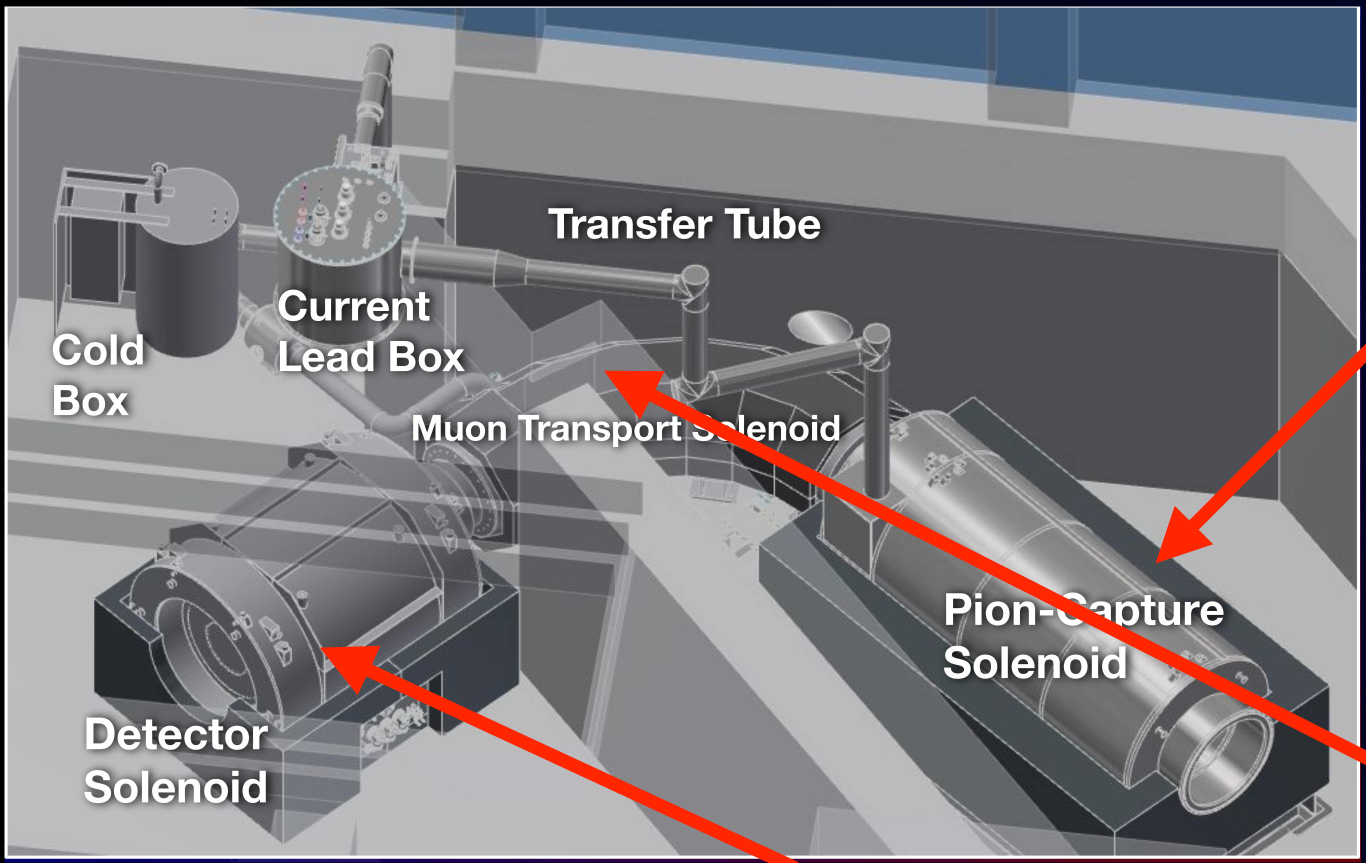
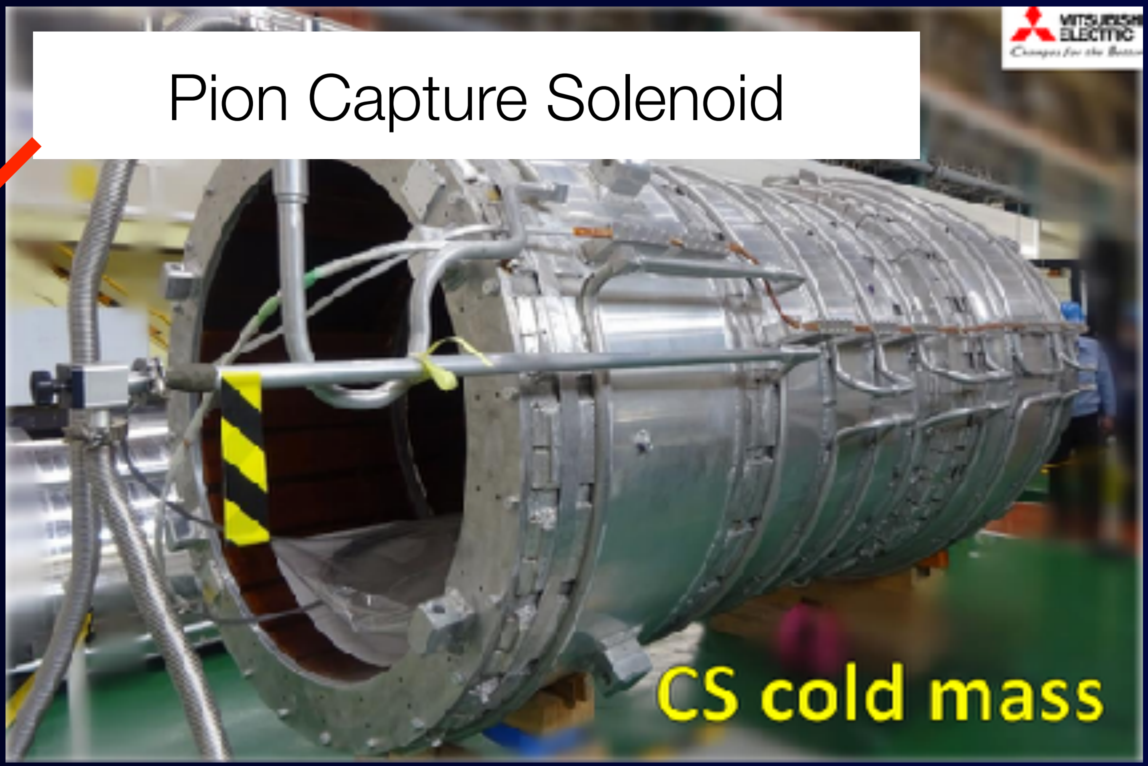
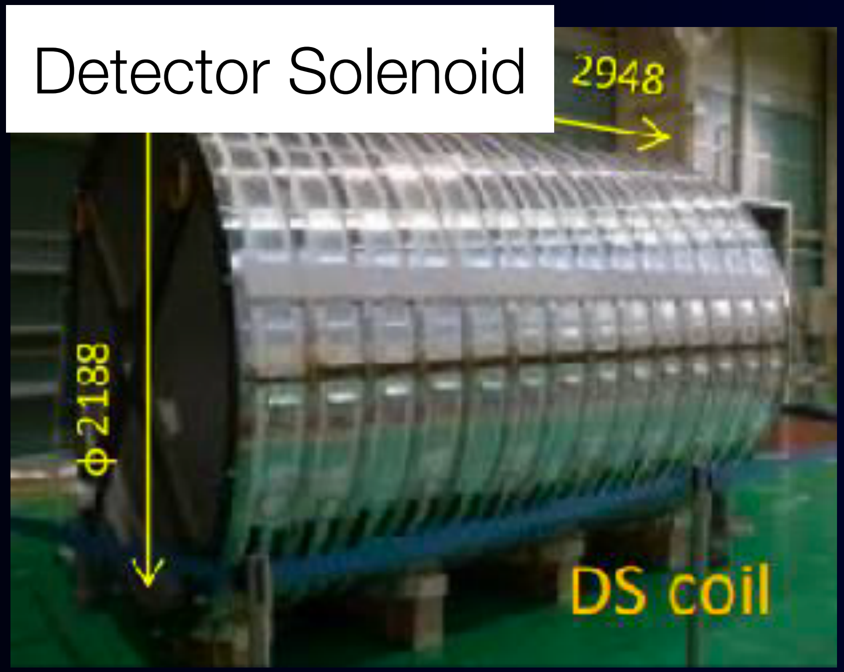
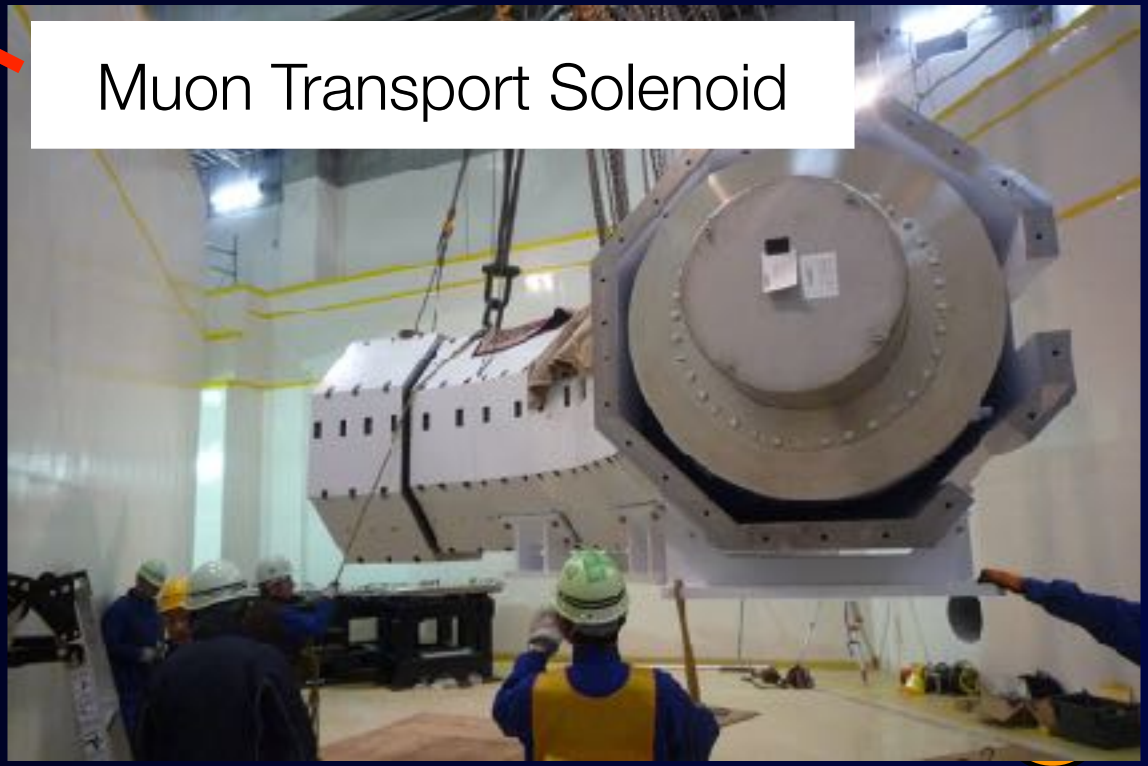


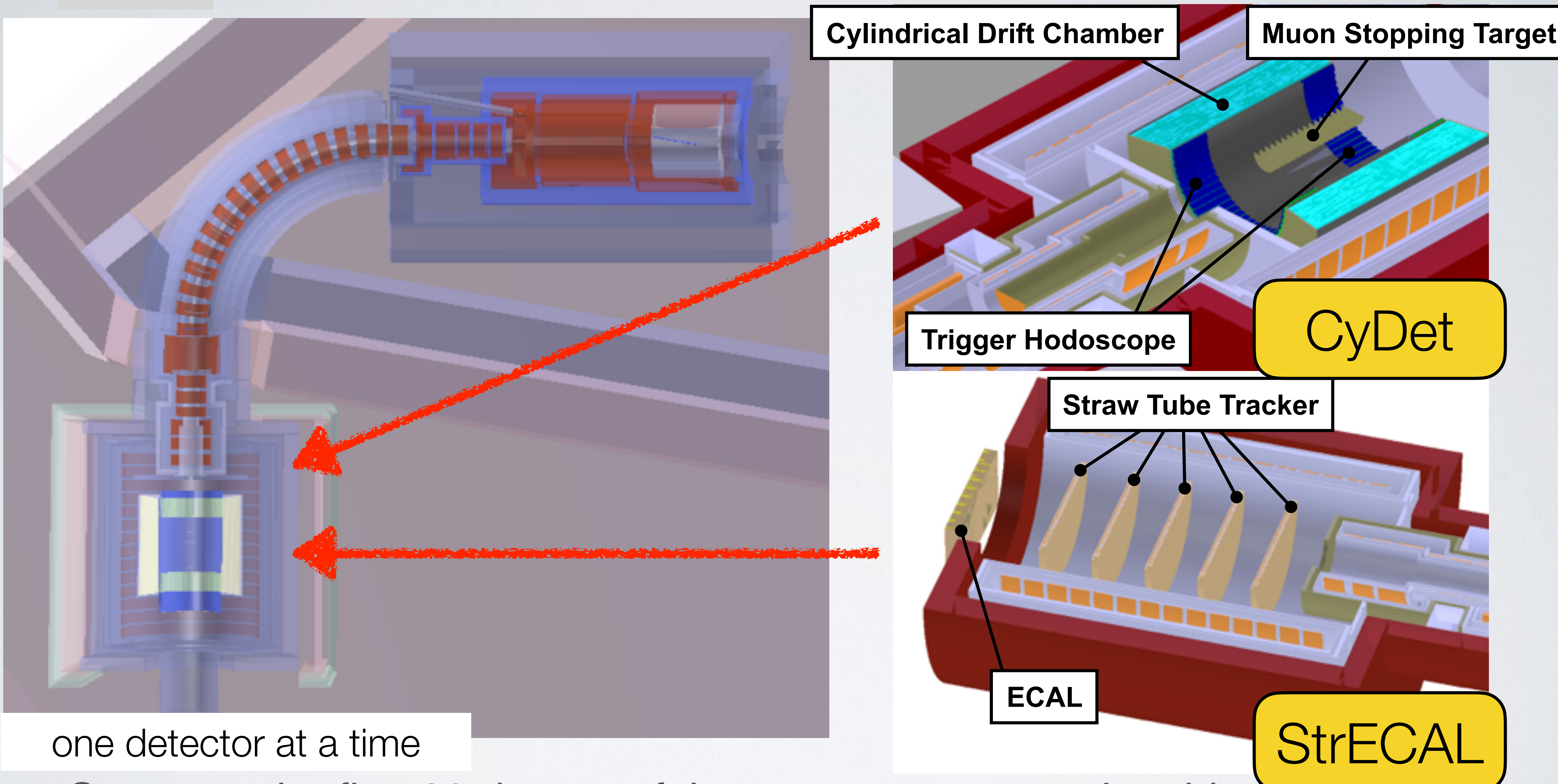






- PCS completed and commissioning will be made n 2025.
- MTS excitation complete in 2023.
- DS assembly will be complete in 2024.

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



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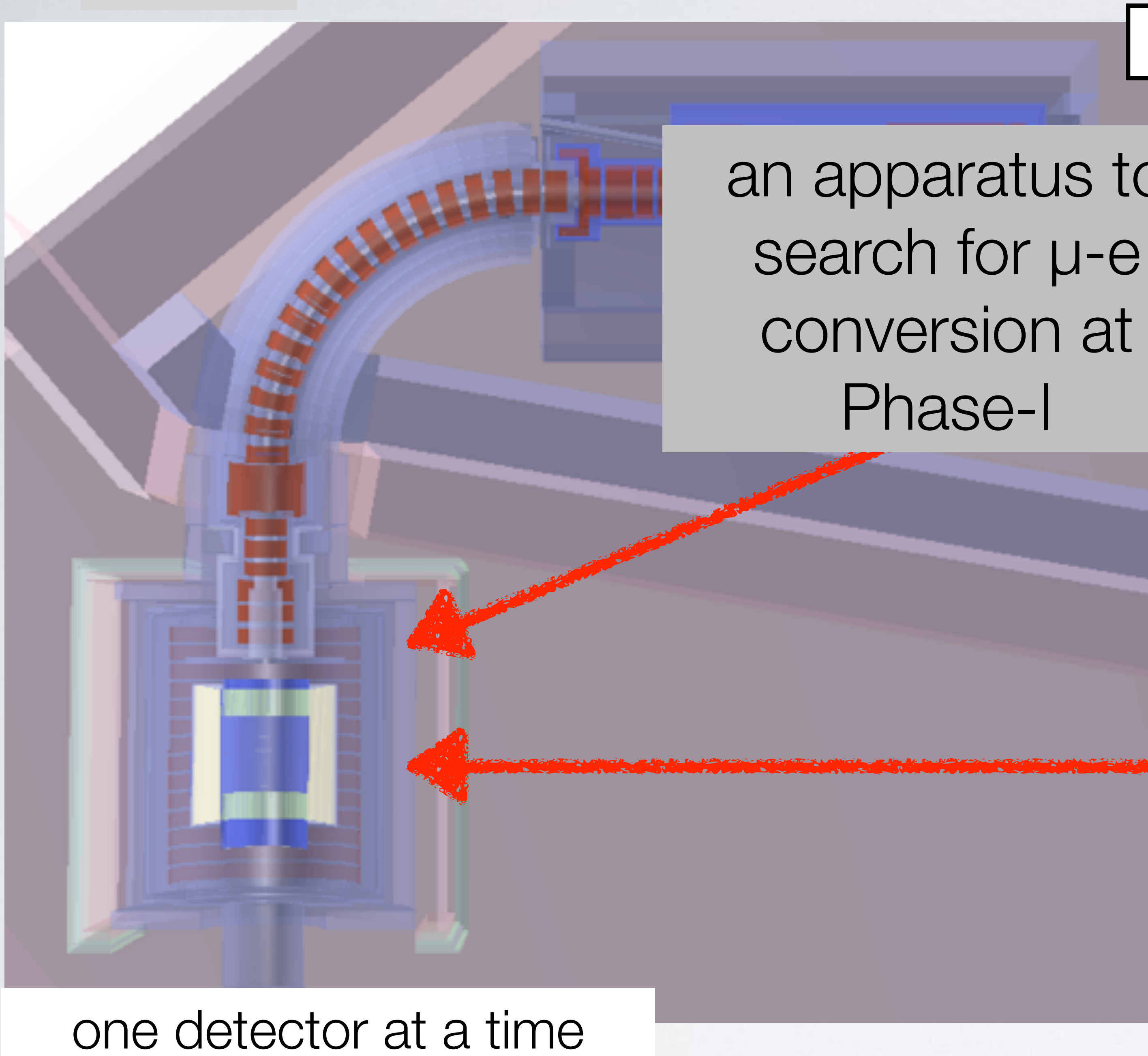

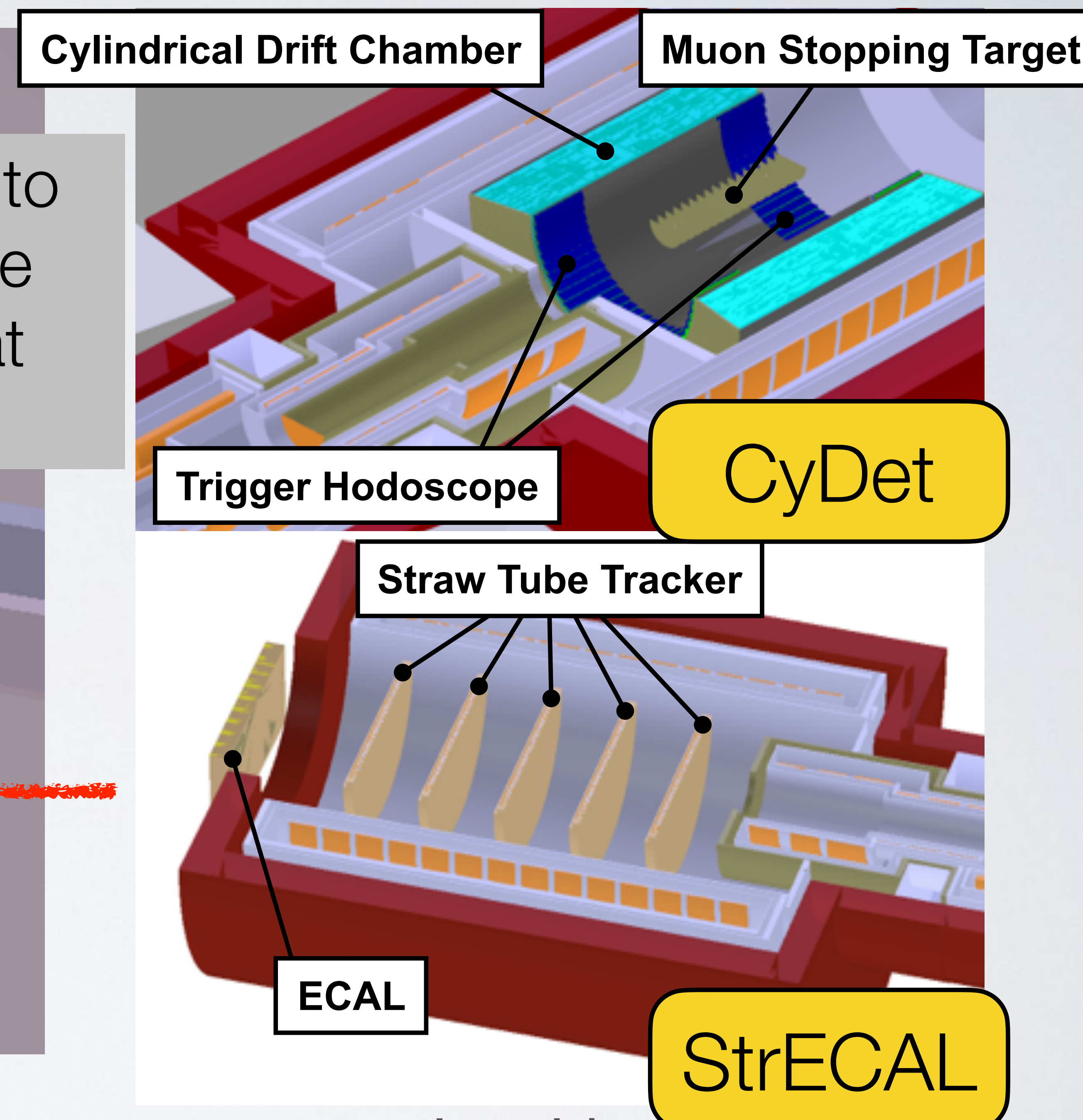

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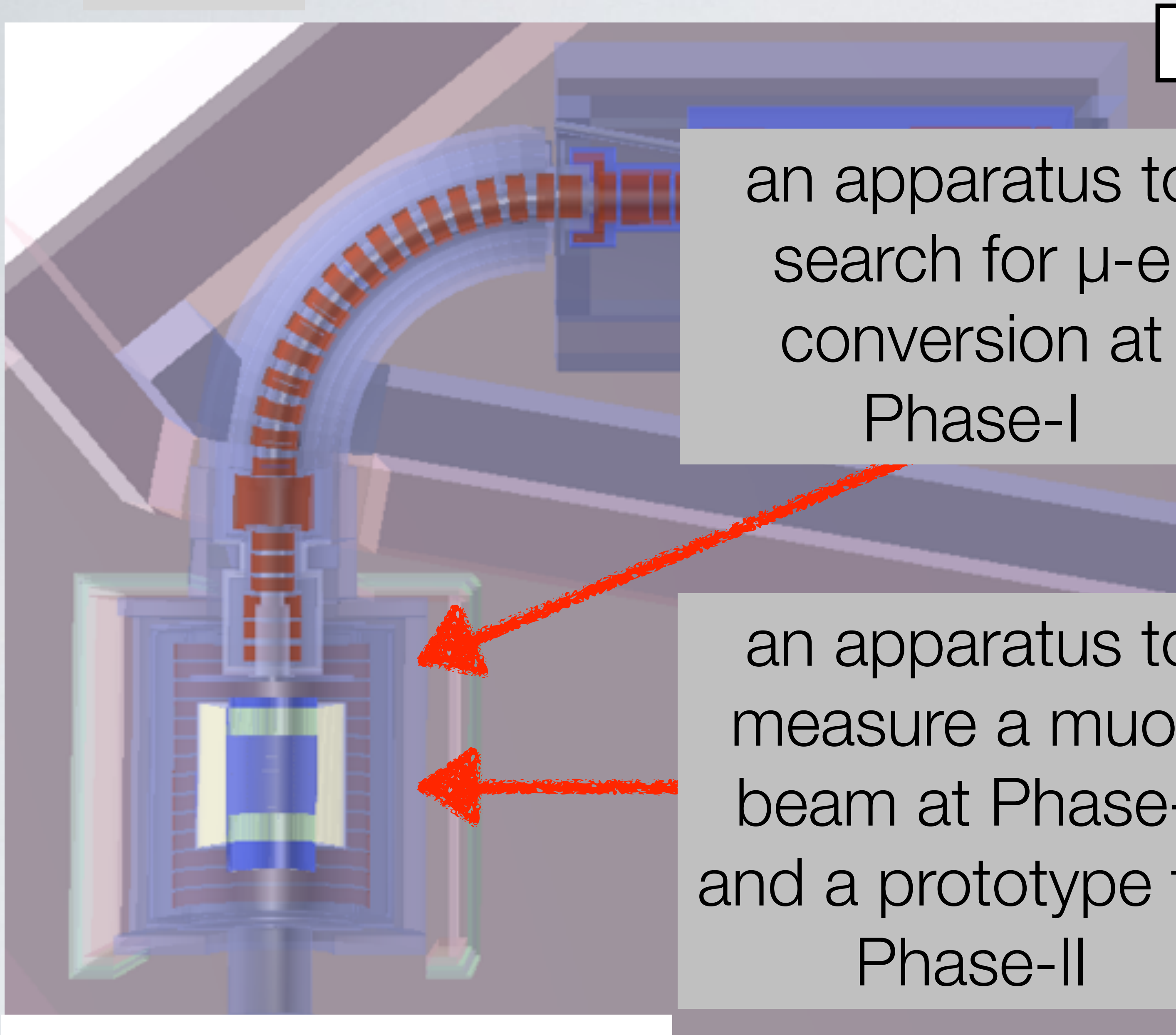
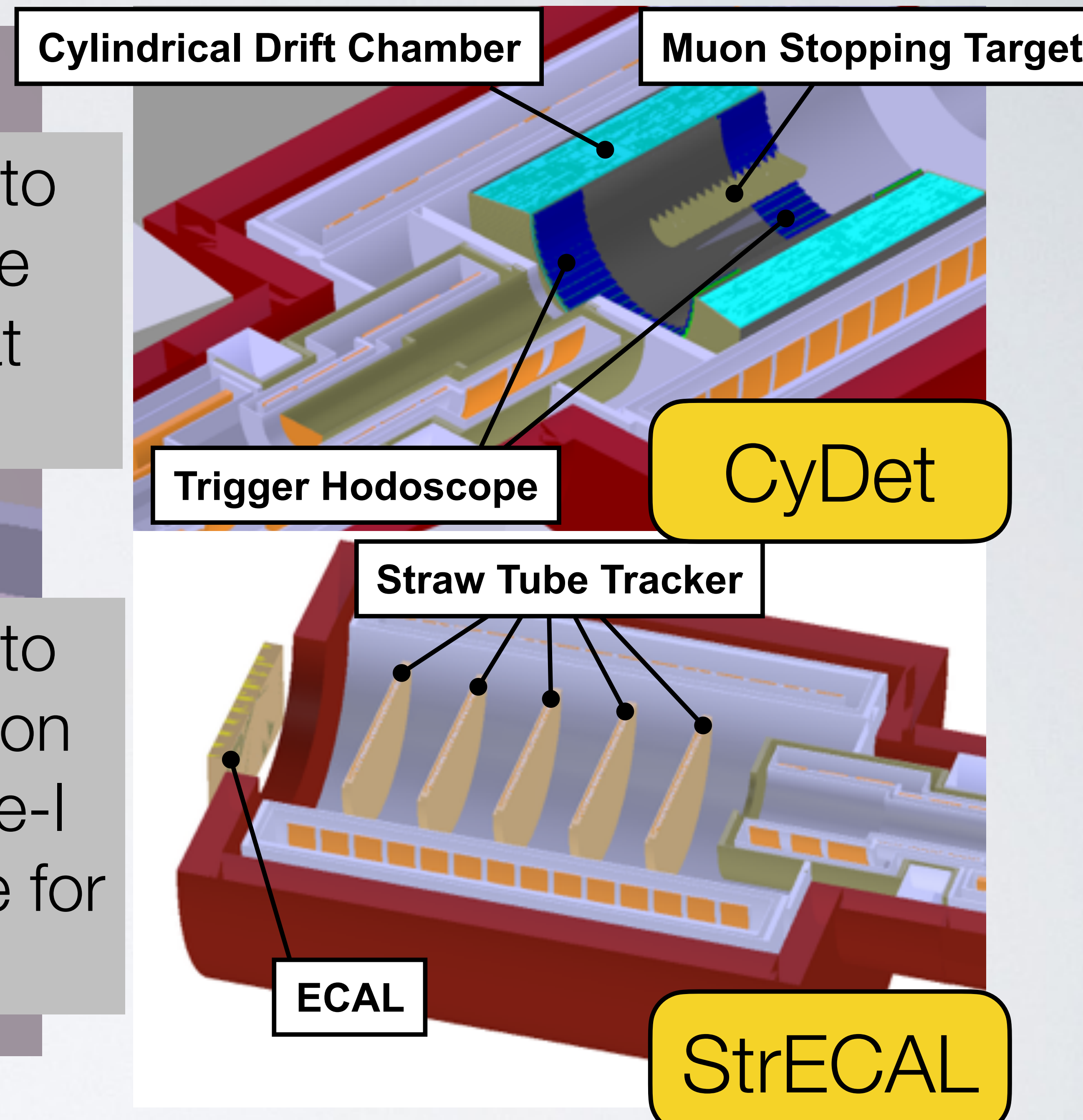


an apparatus to search for μ-e conversion at Phase-I

an apparatus to measure a muon beam at Phase-I and a prototype for Phase-II

one detector at a time



Construction of CyDet and StrECAL

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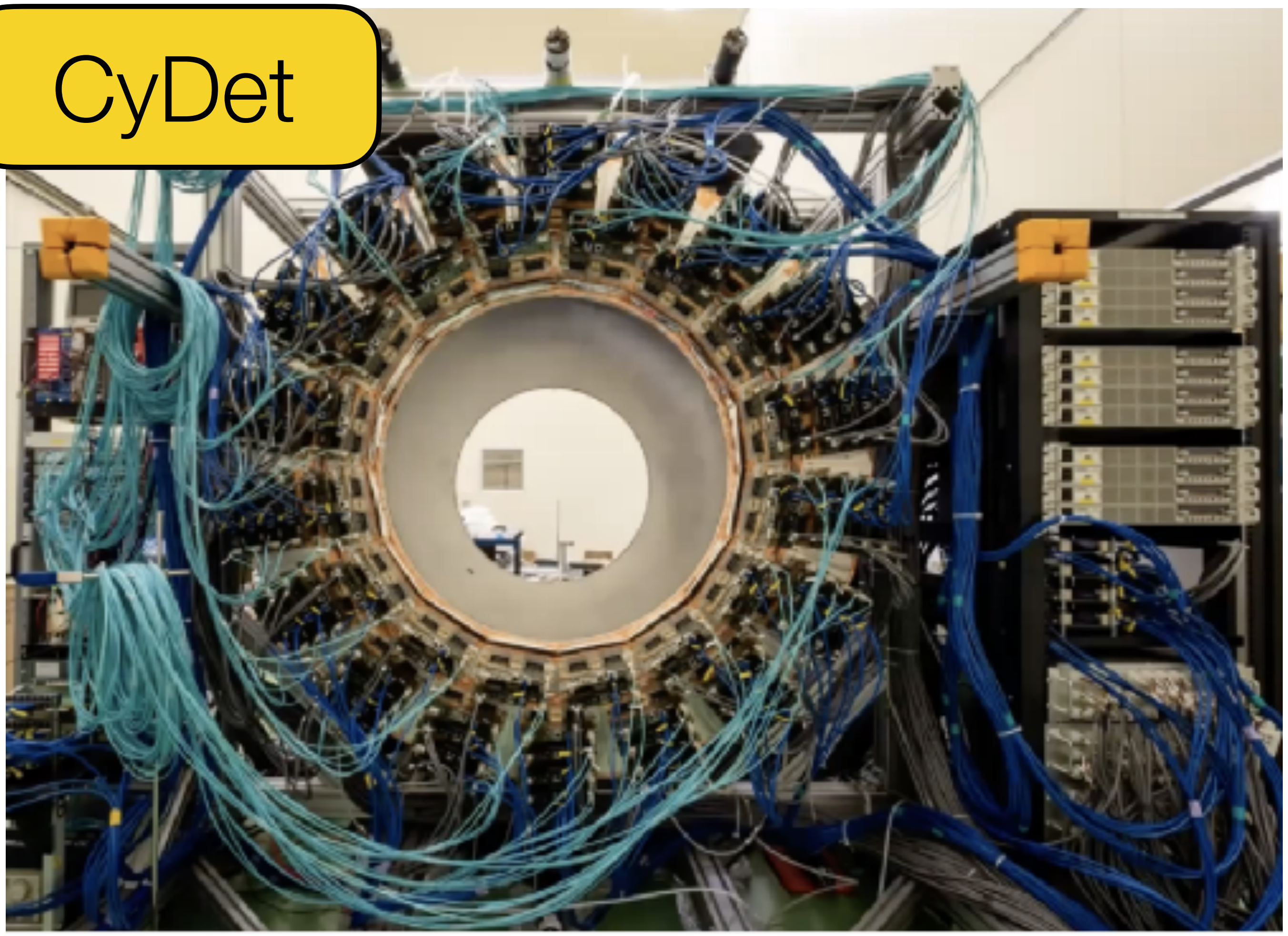
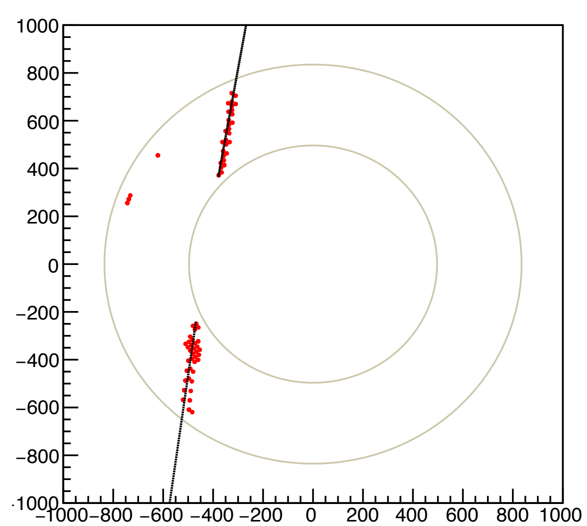
CyDet

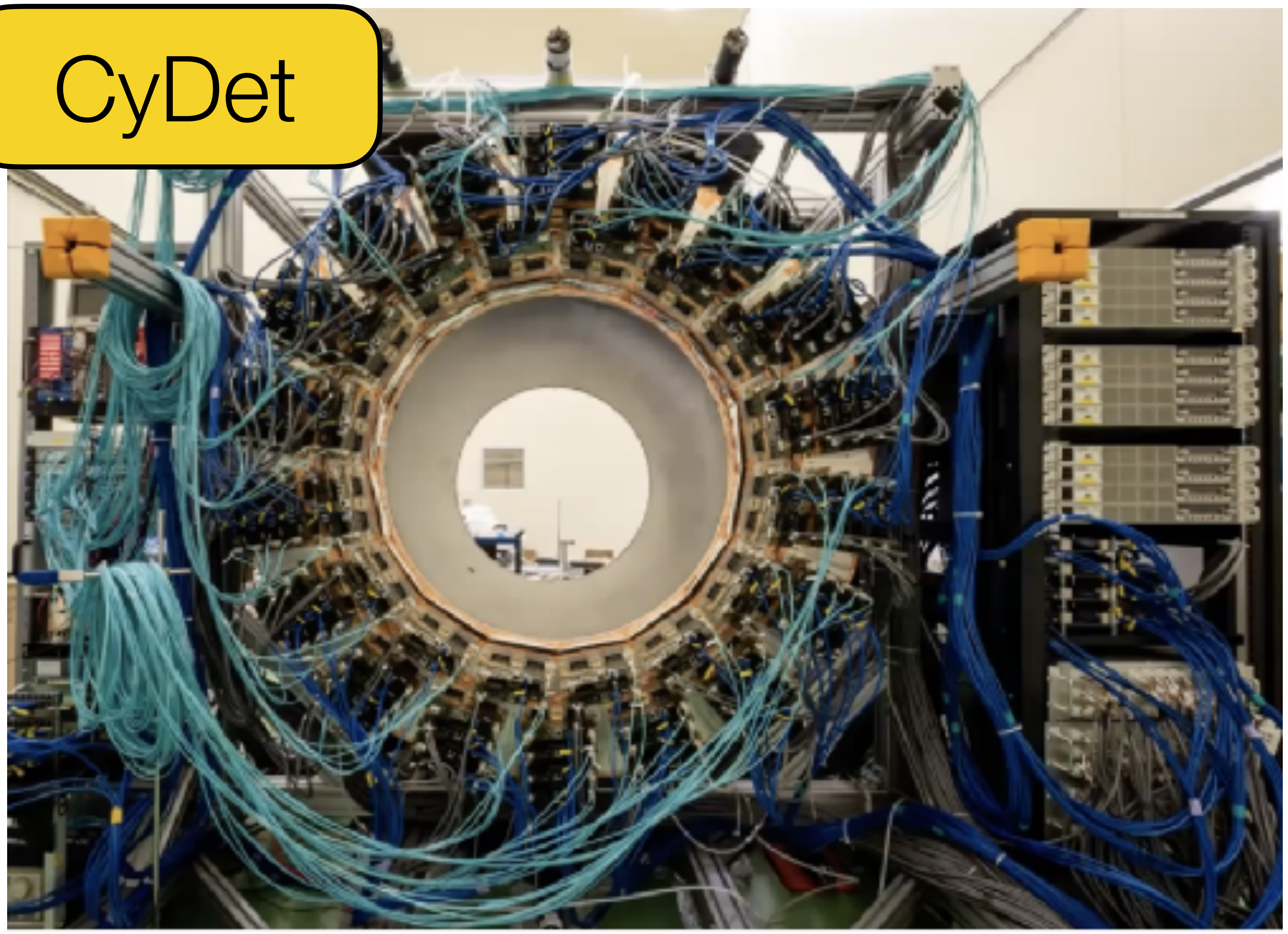


- CDC constructed at Osaka University.
- CDC readouts constructed at IHEP, China.

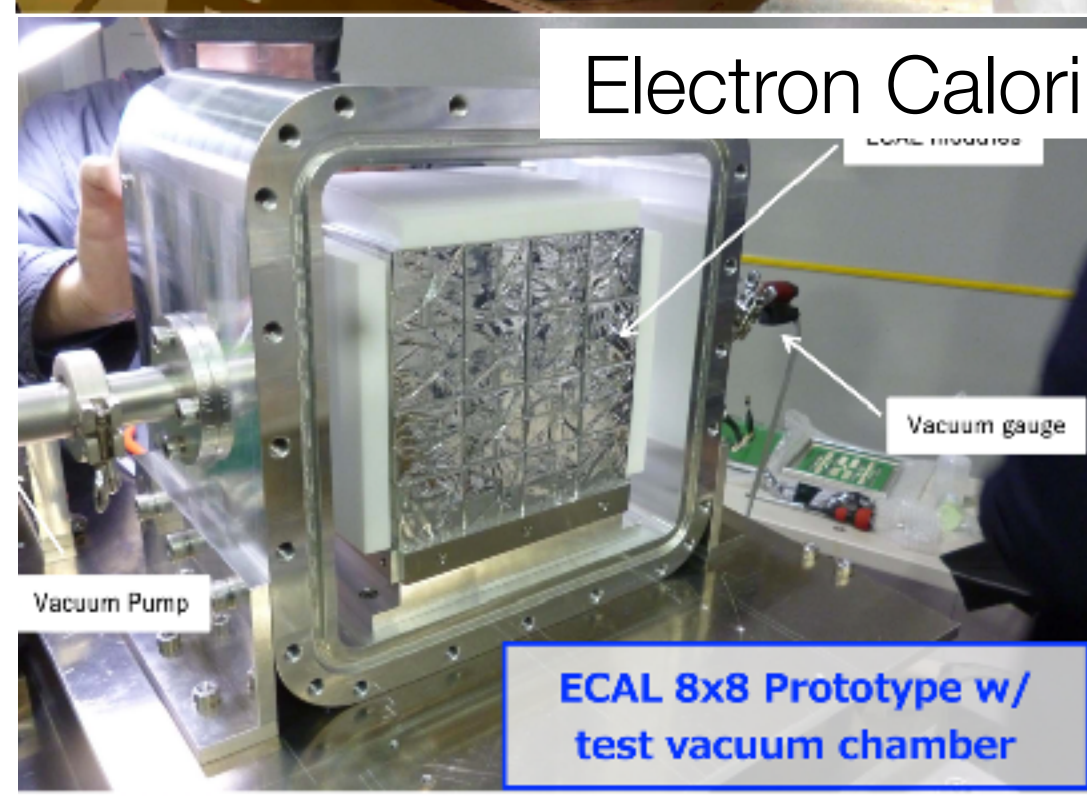


Construction of CyDet and StrECAL

CyDet



StrECAL



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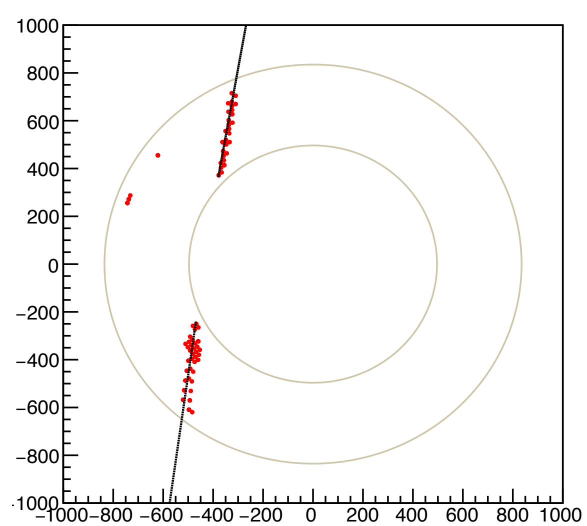
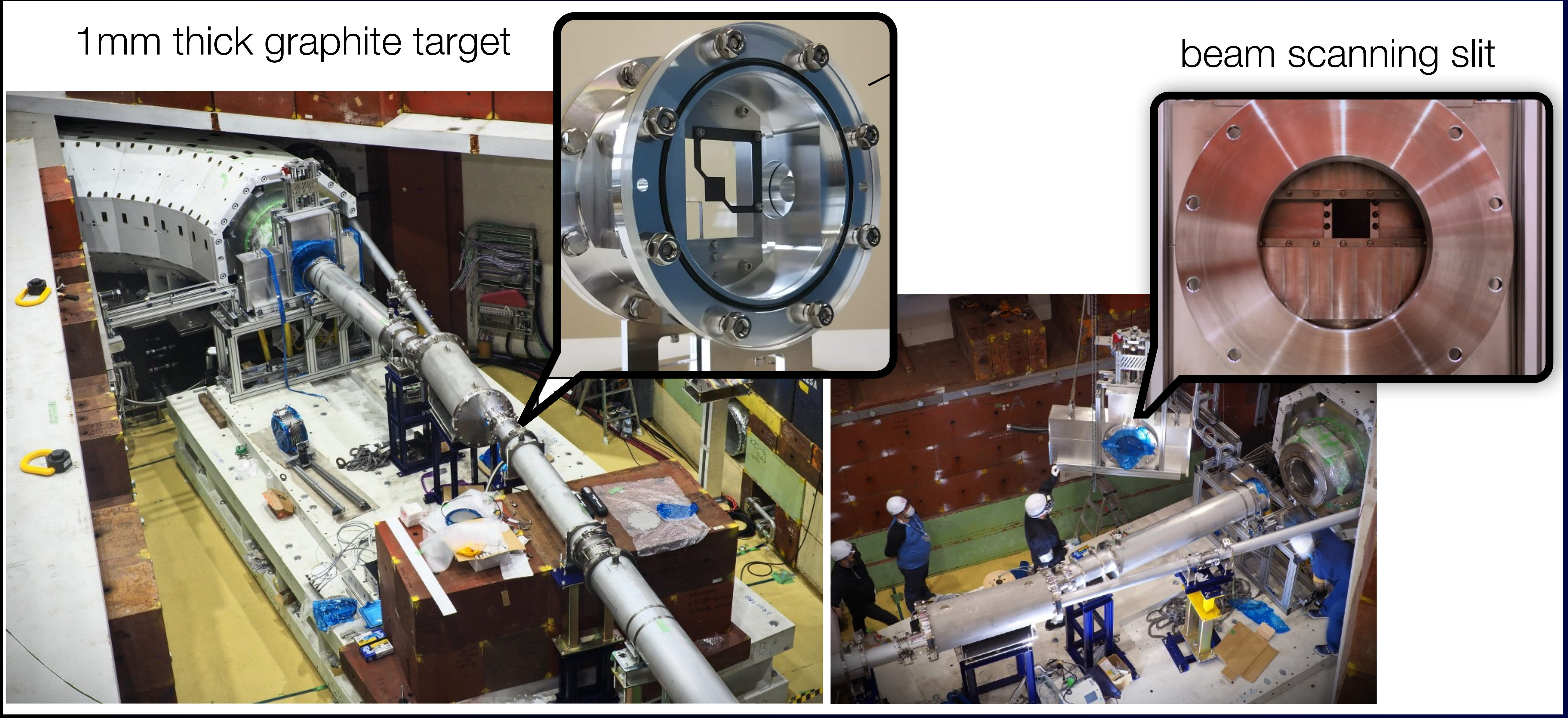


COMET Phase-α (Engineering Run)

COMET Phase α (2023) Proton Beam Area

COMET Phase α (2023)
Proton Beam Area

Beam commissioning: 0.26 kW beam power
Proton bunch time structure was the same as COMET Phase-I.



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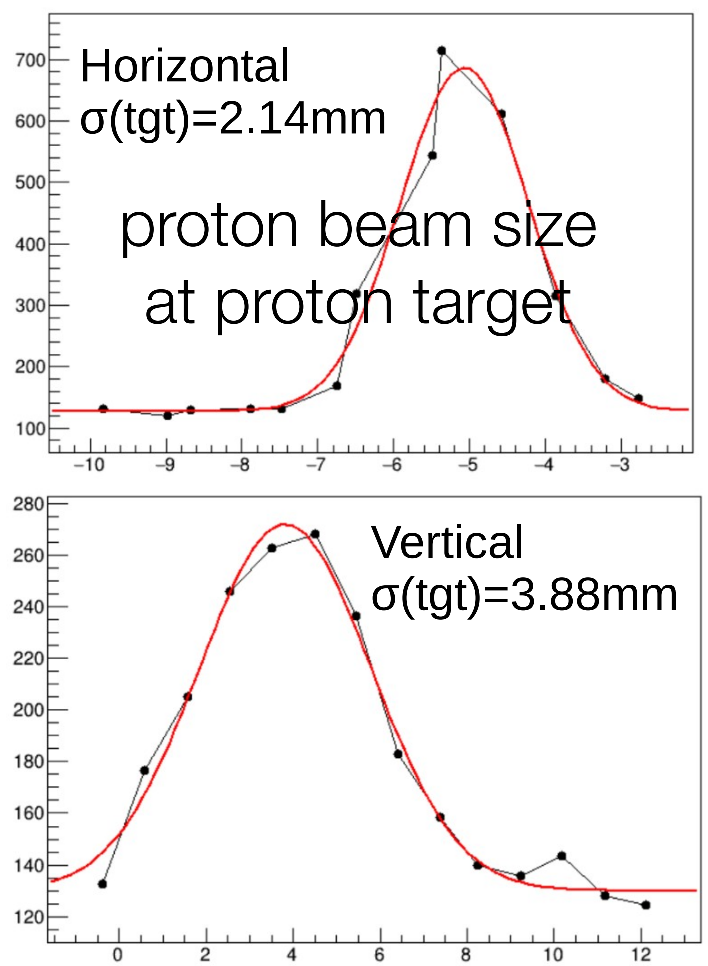
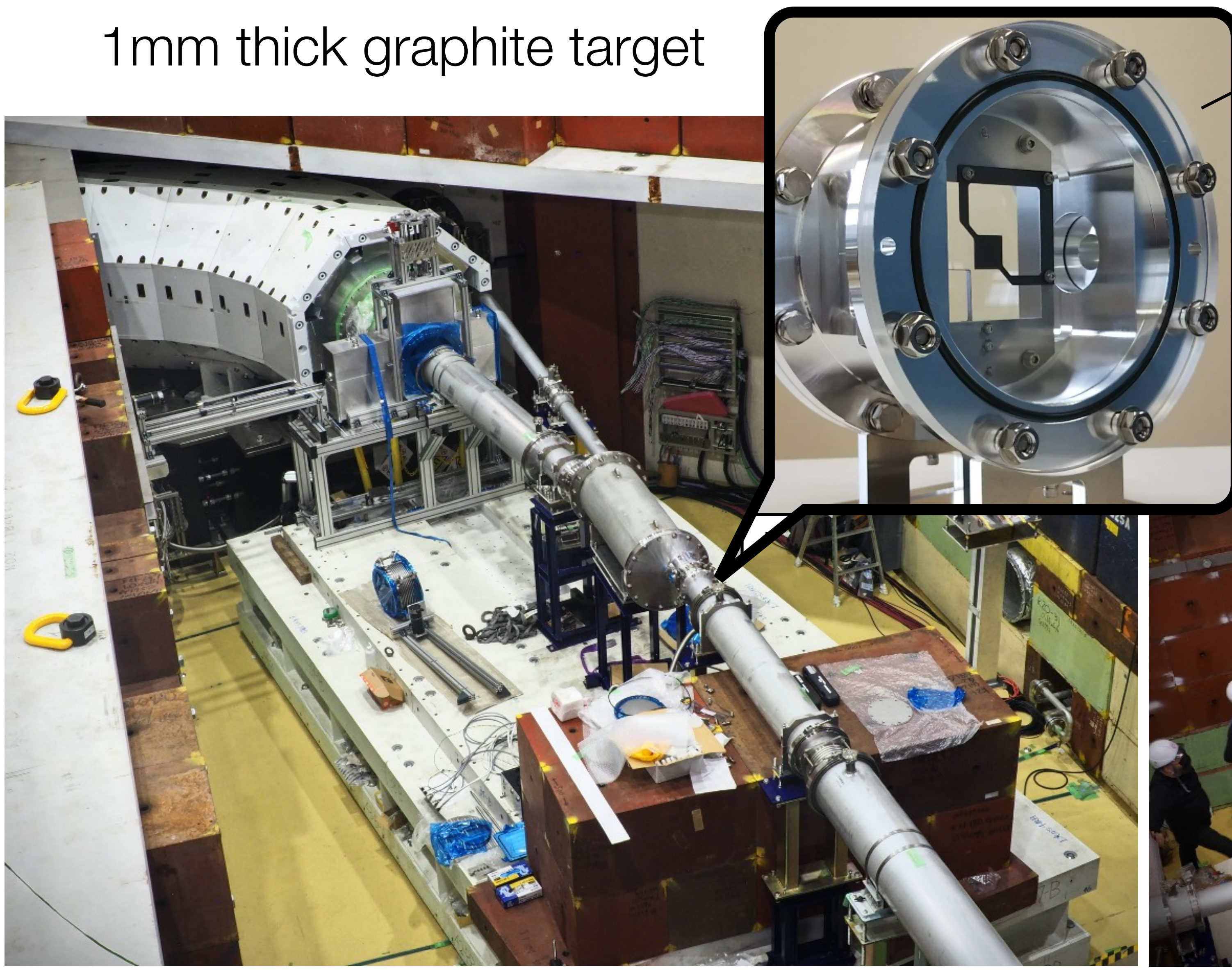
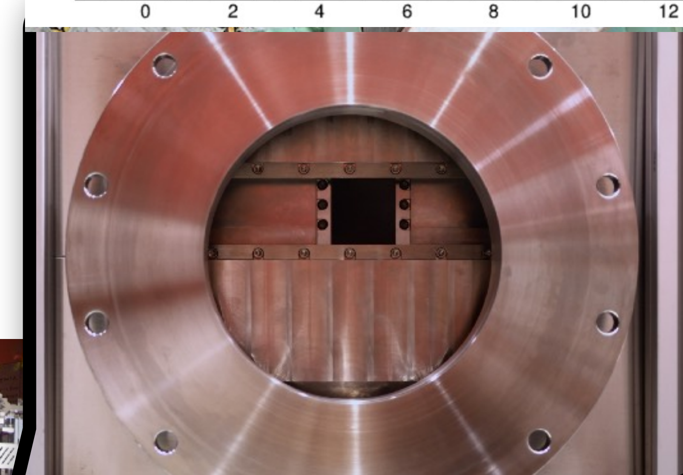
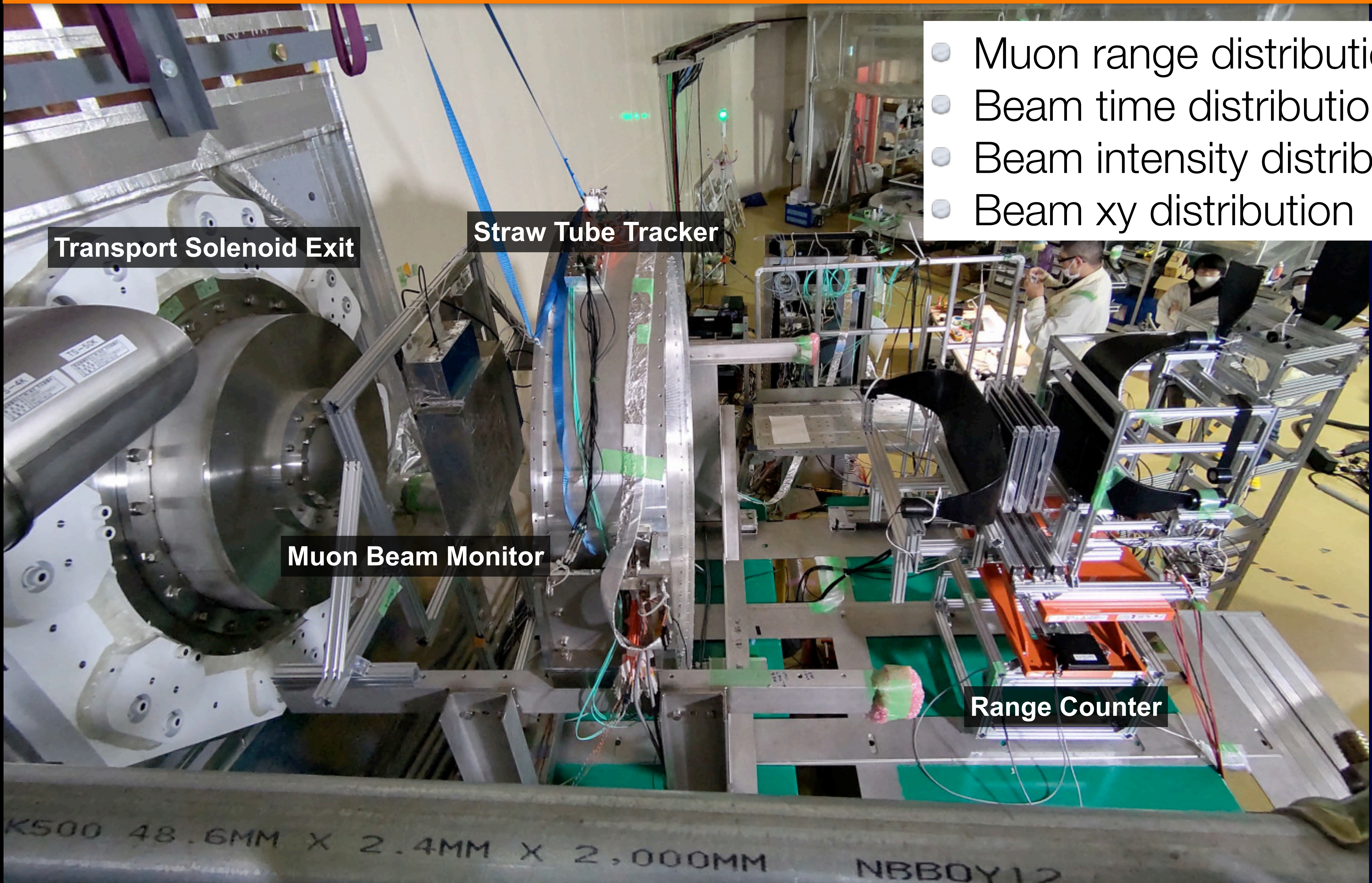


1mm thick graphite target





COMET Phase α (2023) Experimental Area



- Muon range distribution
- Beam time distribution
- Beam intensity distribution
- Beam xy distribution

COMET Phase α (2023)
First Muon Beam at COMET !

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

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Upcoming schedule:

The engineering run is expected to start with a reduced beam intensity in late 2026 (or 2027), and gradually ramping up to its designed intensity thereafter.

Related Rare Physics Phenomena

$\mu^- \to e^+$ conversion in muonic atom

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

$\mu^- \rightarrow e^+$ conversion in muonic atom

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- Lepton number violation (LNV) and CLFV
- Sensitive to short ranged TeV LNV Physics

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Event Signature :

a single mono-energetic positron (when the final nucleus is the ground state.)

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Backgrounds:

radiative muon nuclear capture (RMC)

$$\mu^- + N(A,Z) \to N(A,Z-1) + \nu + \gamma$$

$$: \gamma \to e^- e^+$$

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Current limits

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

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

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- Similar sensitivity to $\mu^- \to e^-$ conversion.

T.S. Wong, Ph.D. thesis (Osaka Univ.), 2020

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- measurement of RMC by CDC

D. Pietres, Ph.D. thesis (Osaka Univ.), 2023

Bound $\mu^- \rightarrow e^- a$ in a muonic atom

Bound $\mu^- \to e^- a$ in a muonic atom

$$\mu \to ea$$

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

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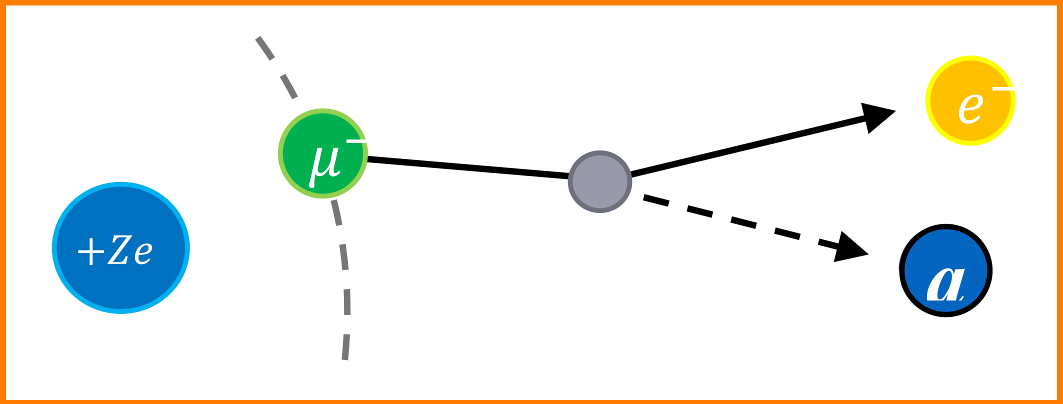

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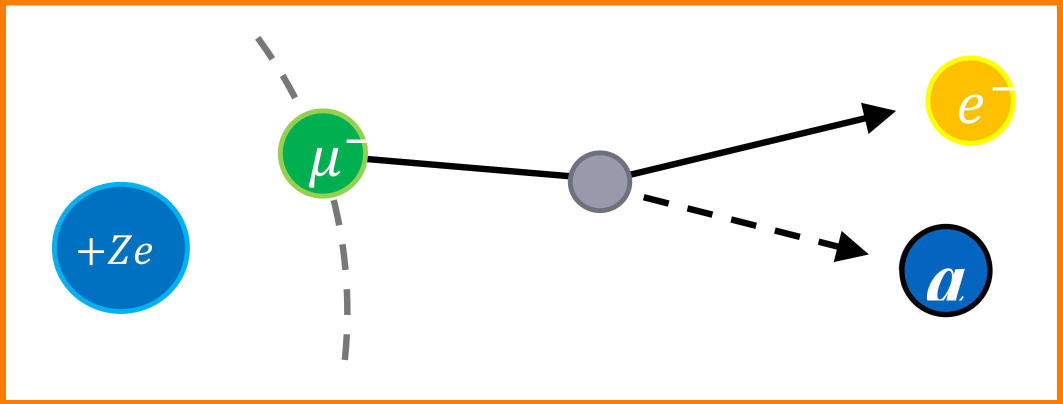

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  - different muon targets
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  - Not mono-energetic.

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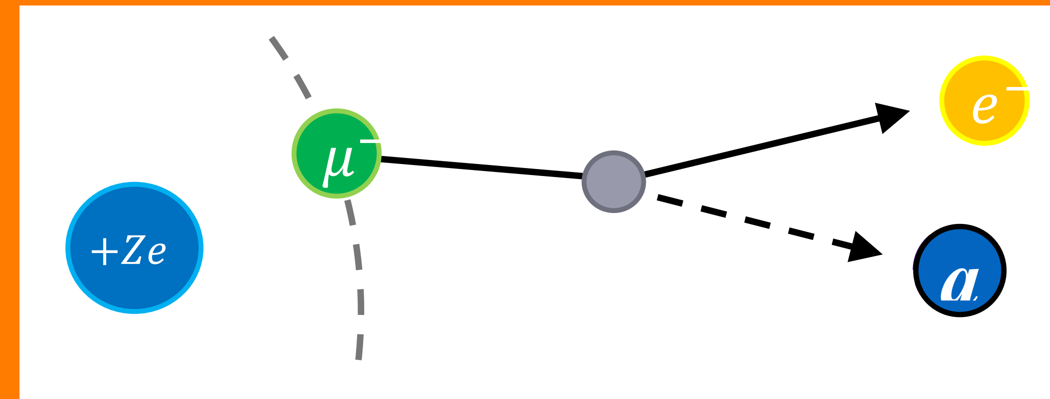

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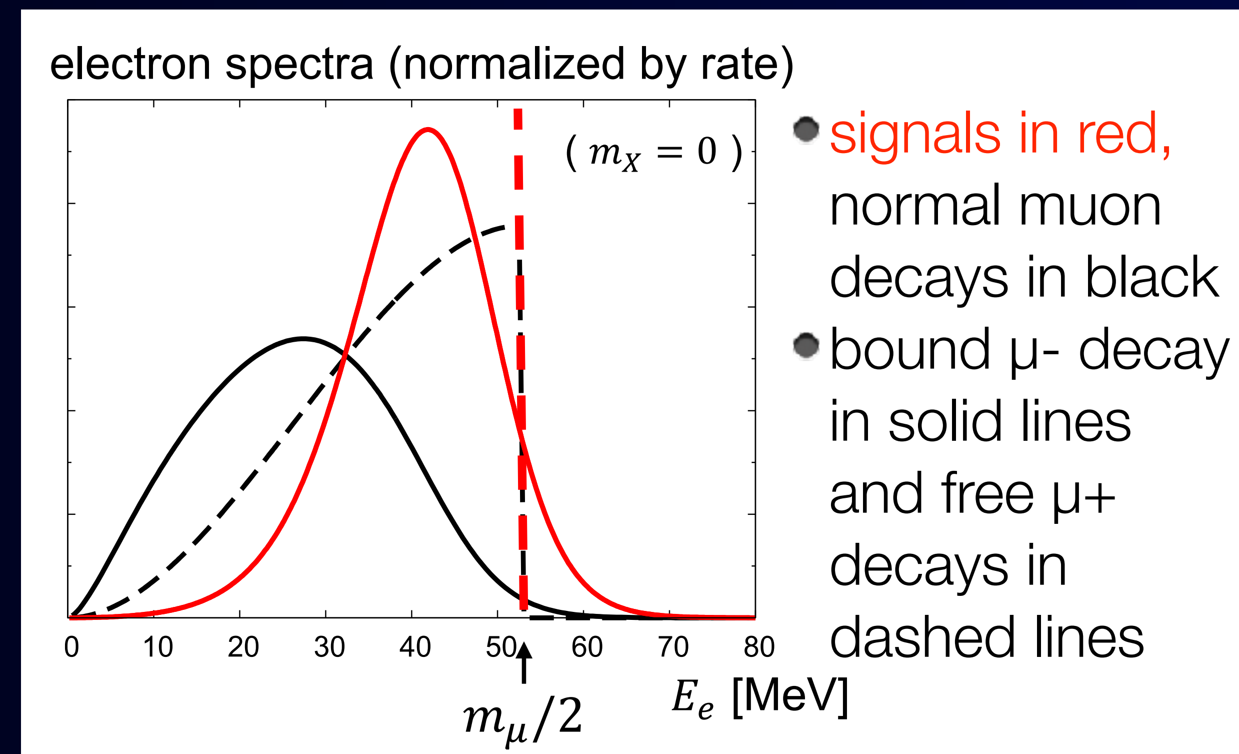

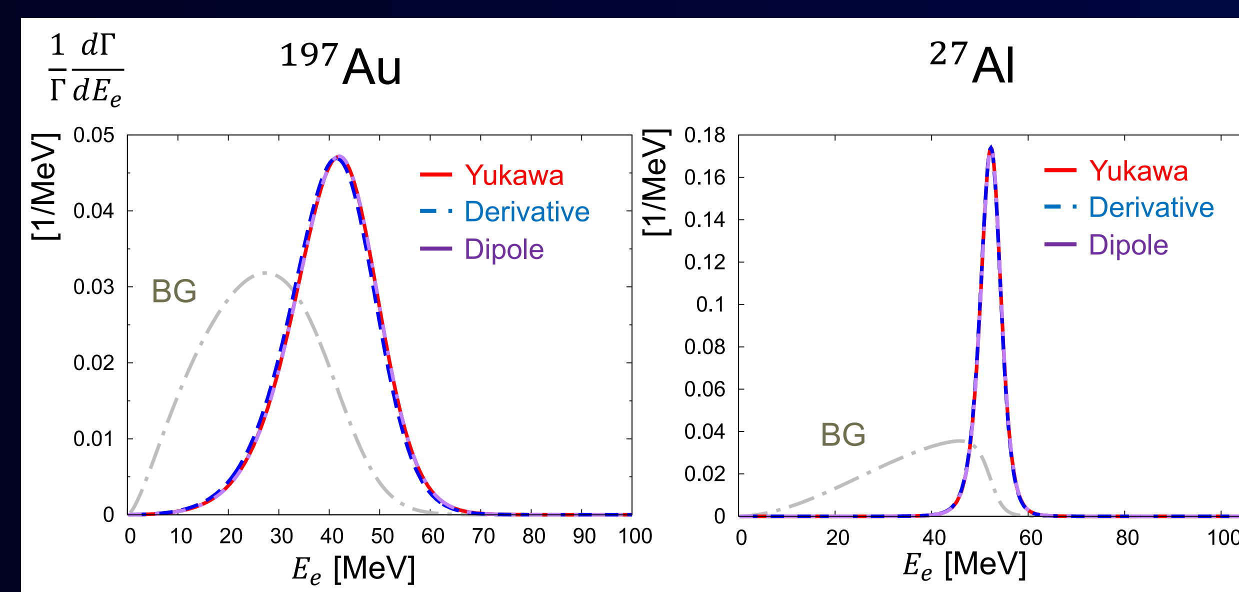

Y. Uesaka, Phys. Rev. D102, 095007 (2020)

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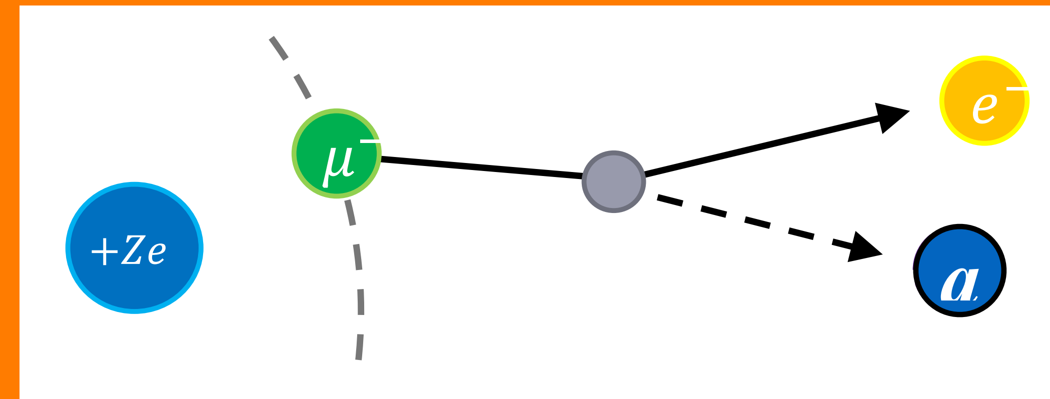

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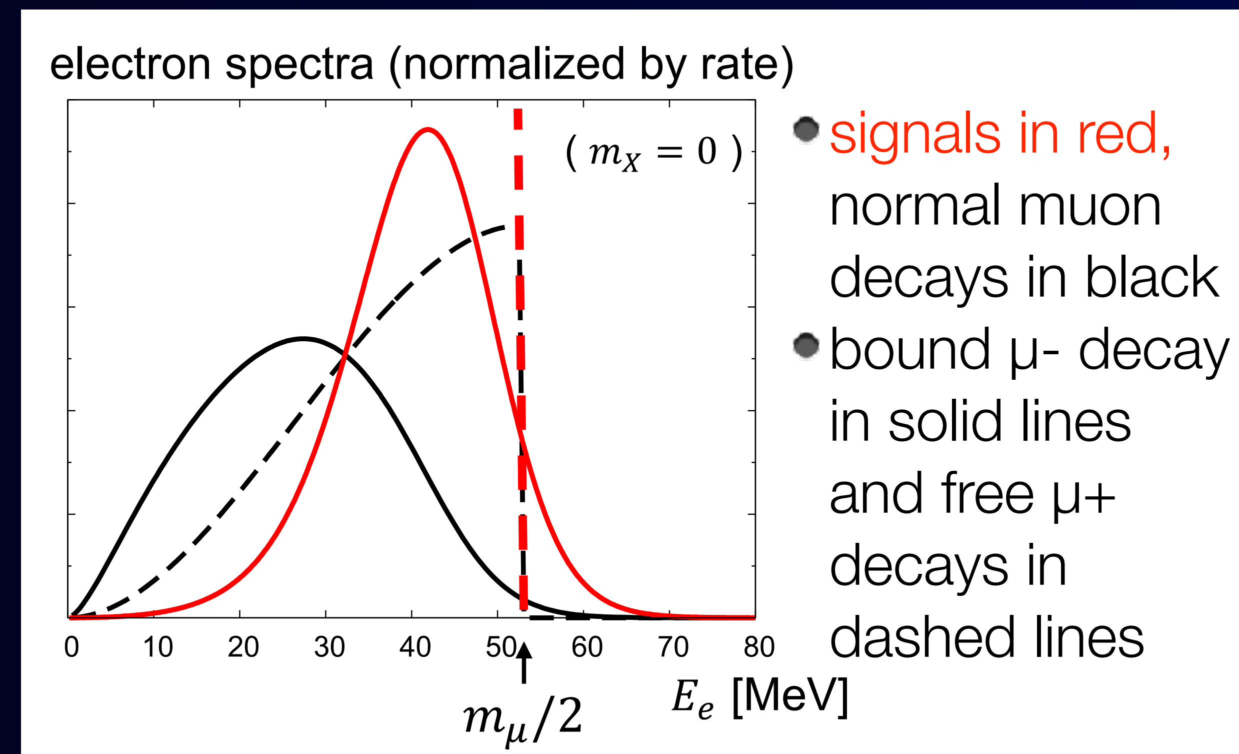
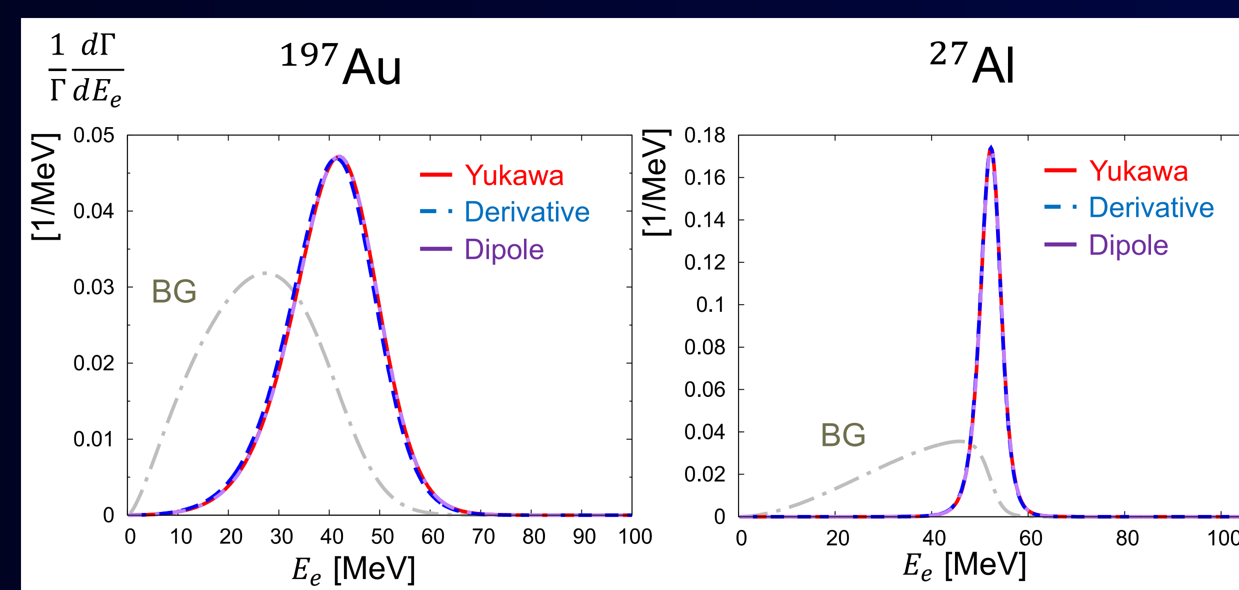
- COMET Phase-II :
  - $B < O(10^{-9})$ $f_a > 10^{10-11}$ GeV

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





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

PRISM/PRIME

$$B(\mu N \to eN) \sim 10^{-19}$$

with a factor of 1000,000 improvement

Requirements of Muon Beam for New $\mu \to e$ Conversion

Requirements of Muon Beam for New $\mu \rightarrow e$ Conversion

No pions → long muon beam-line

long beam flight length (~100m)

allowing high-Z muon target

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PRISM

COMET

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Better beam → **narrow muon beam spread**

improvement of resolution of electron detection

allowing a thinner muon target

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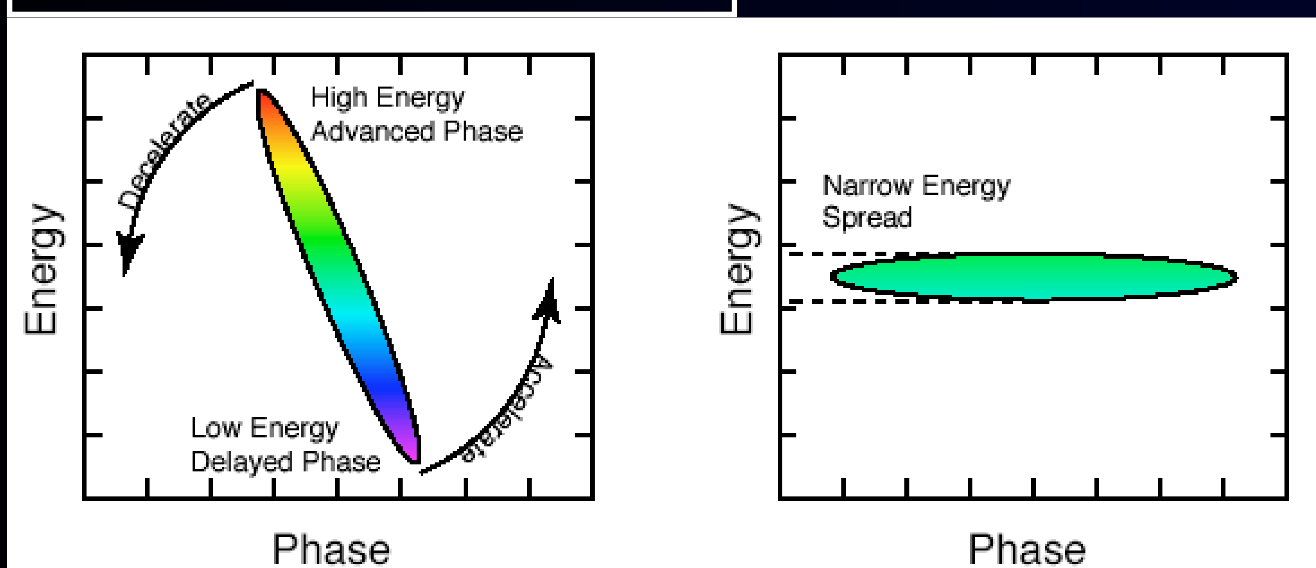
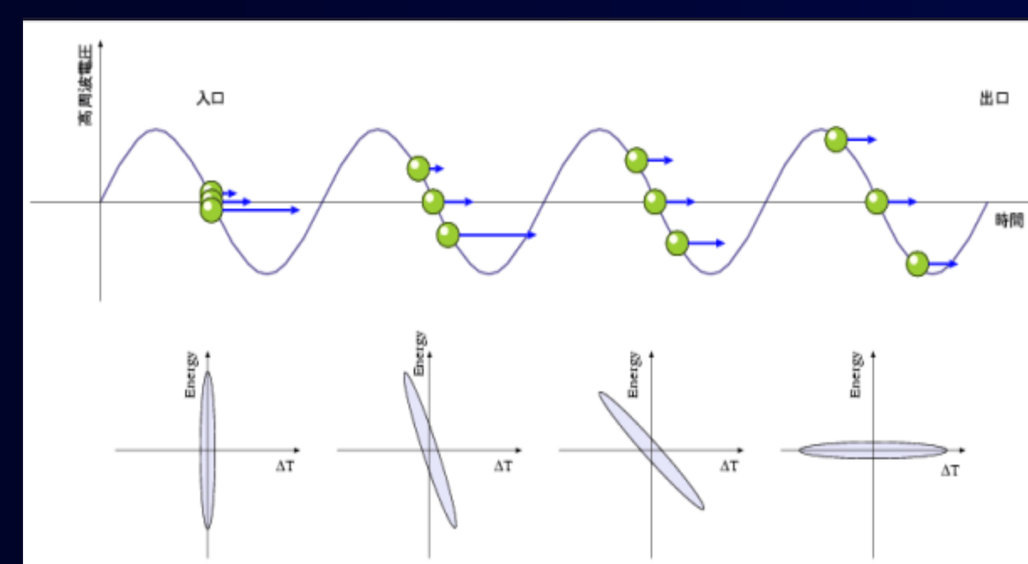
Phase rotation





PRISM/PRIME (2003)

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PRISM=Phase Rotated Intense Slow Muon source

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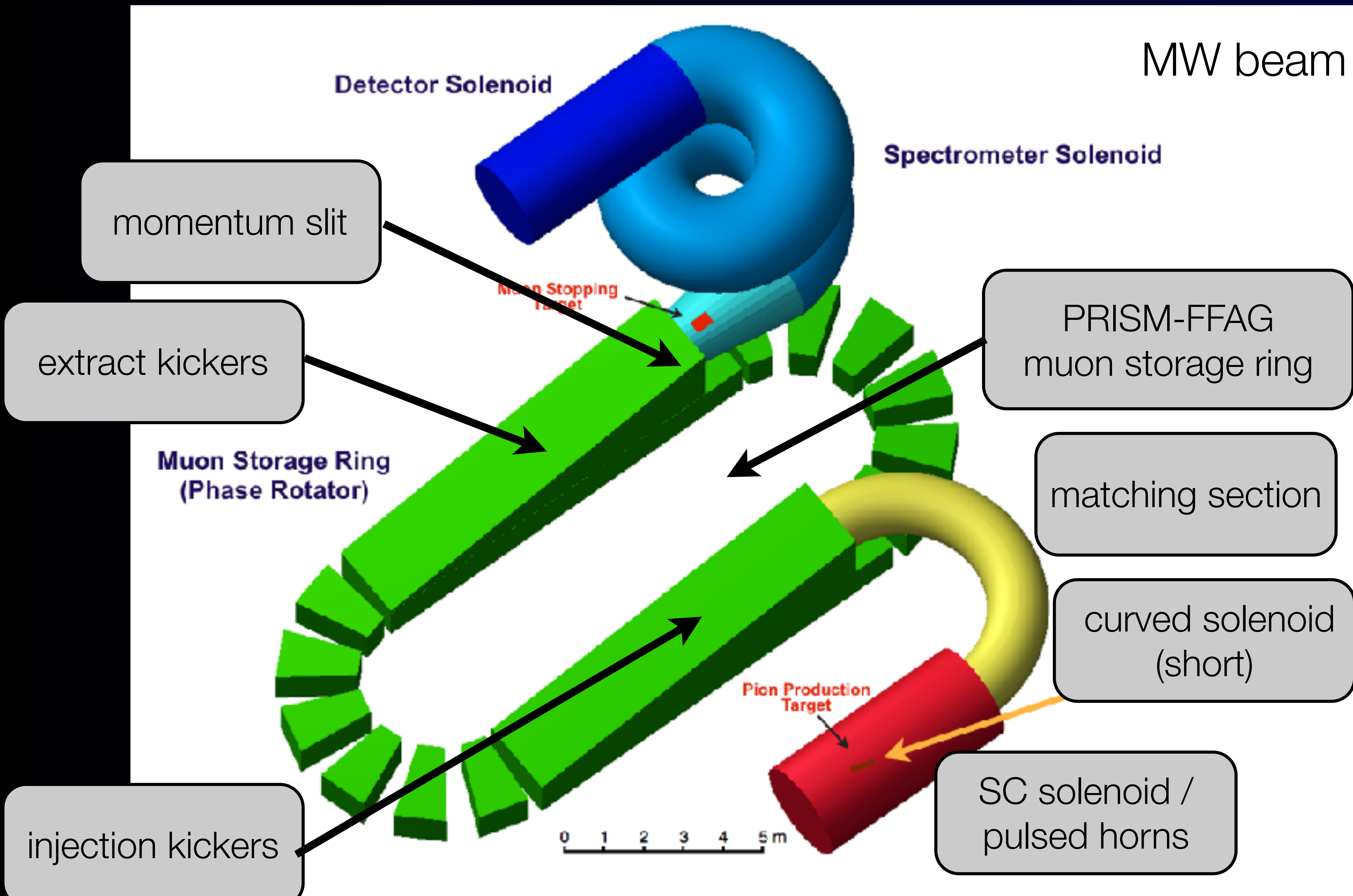

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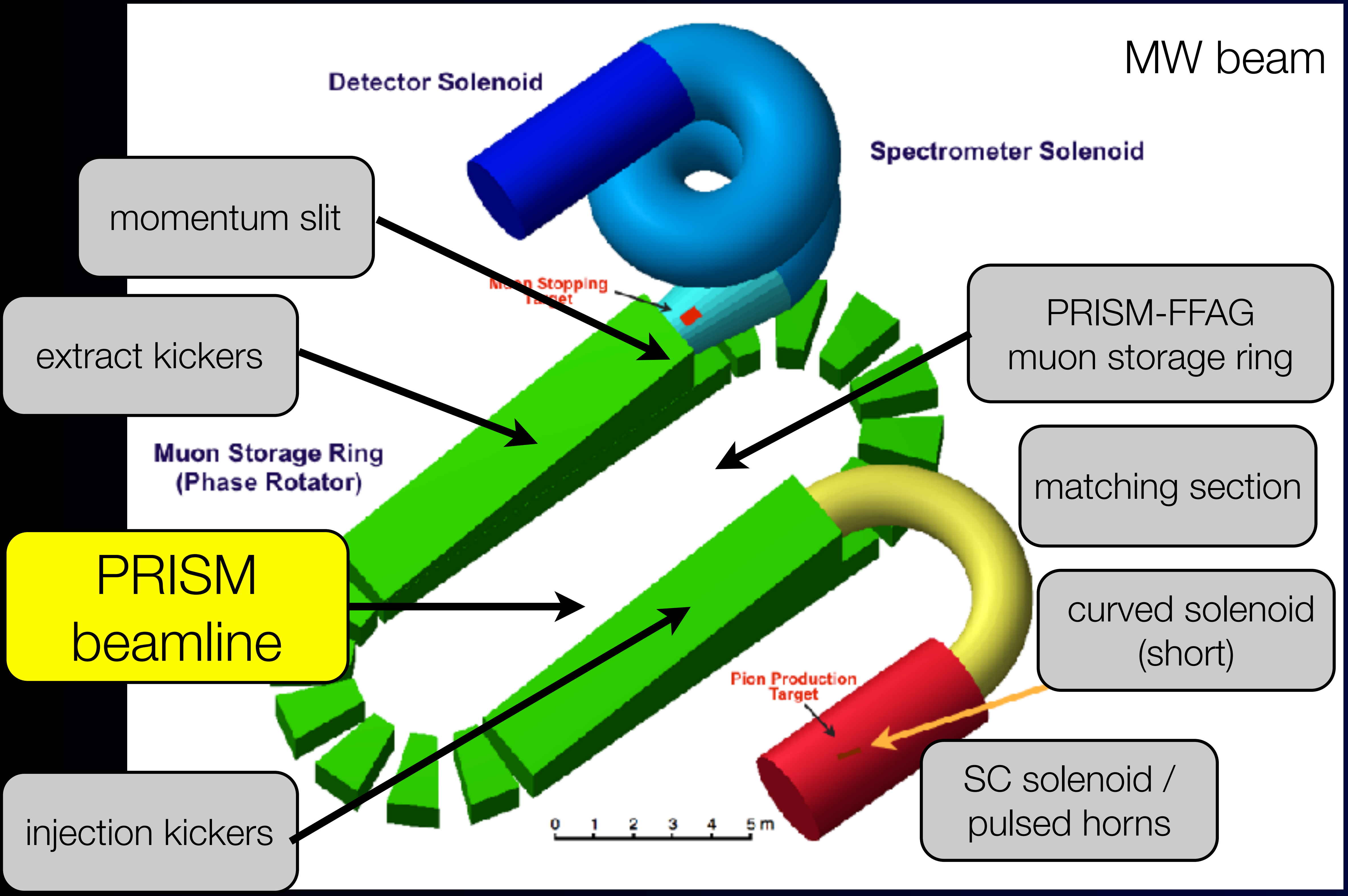

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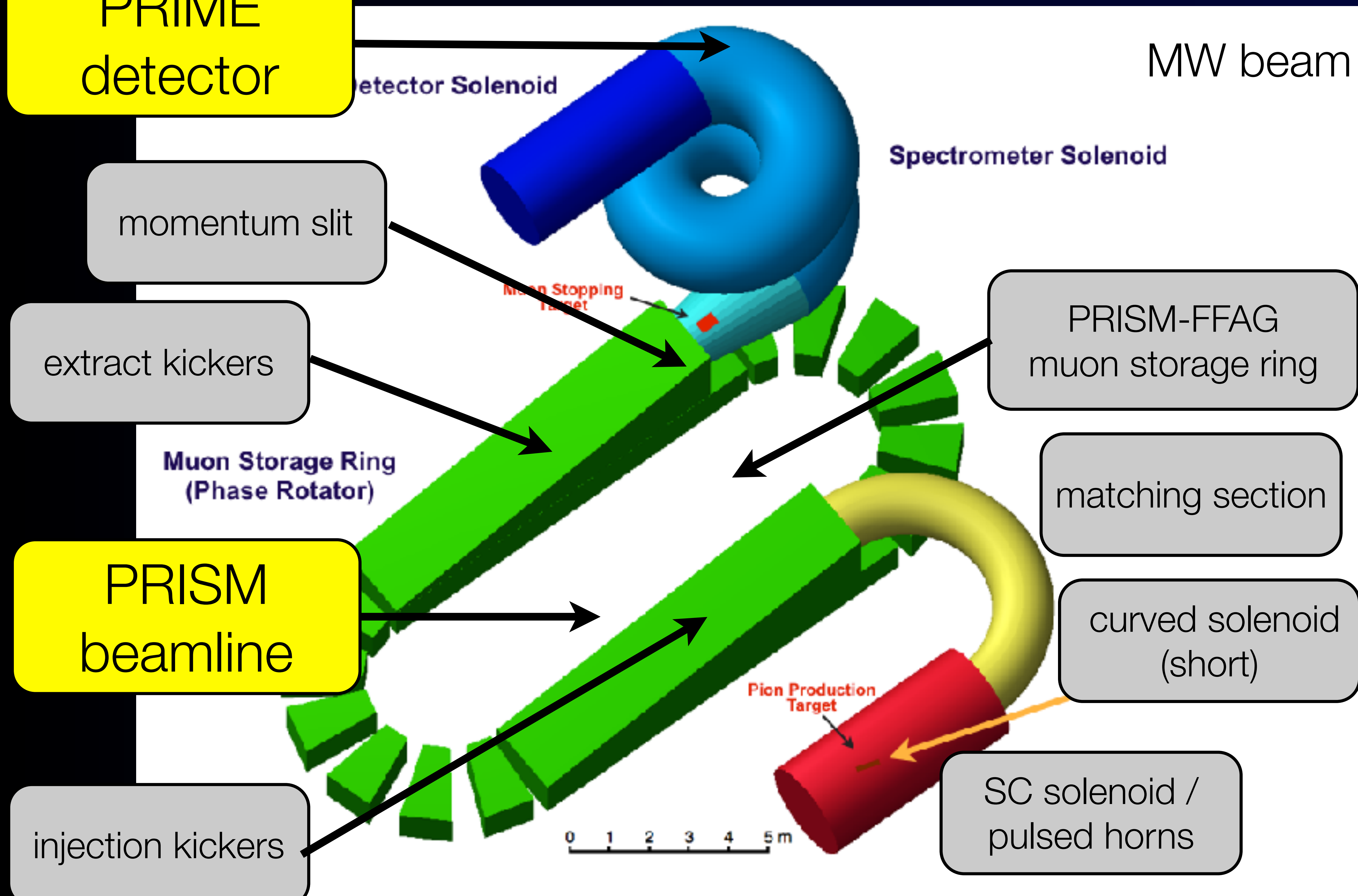

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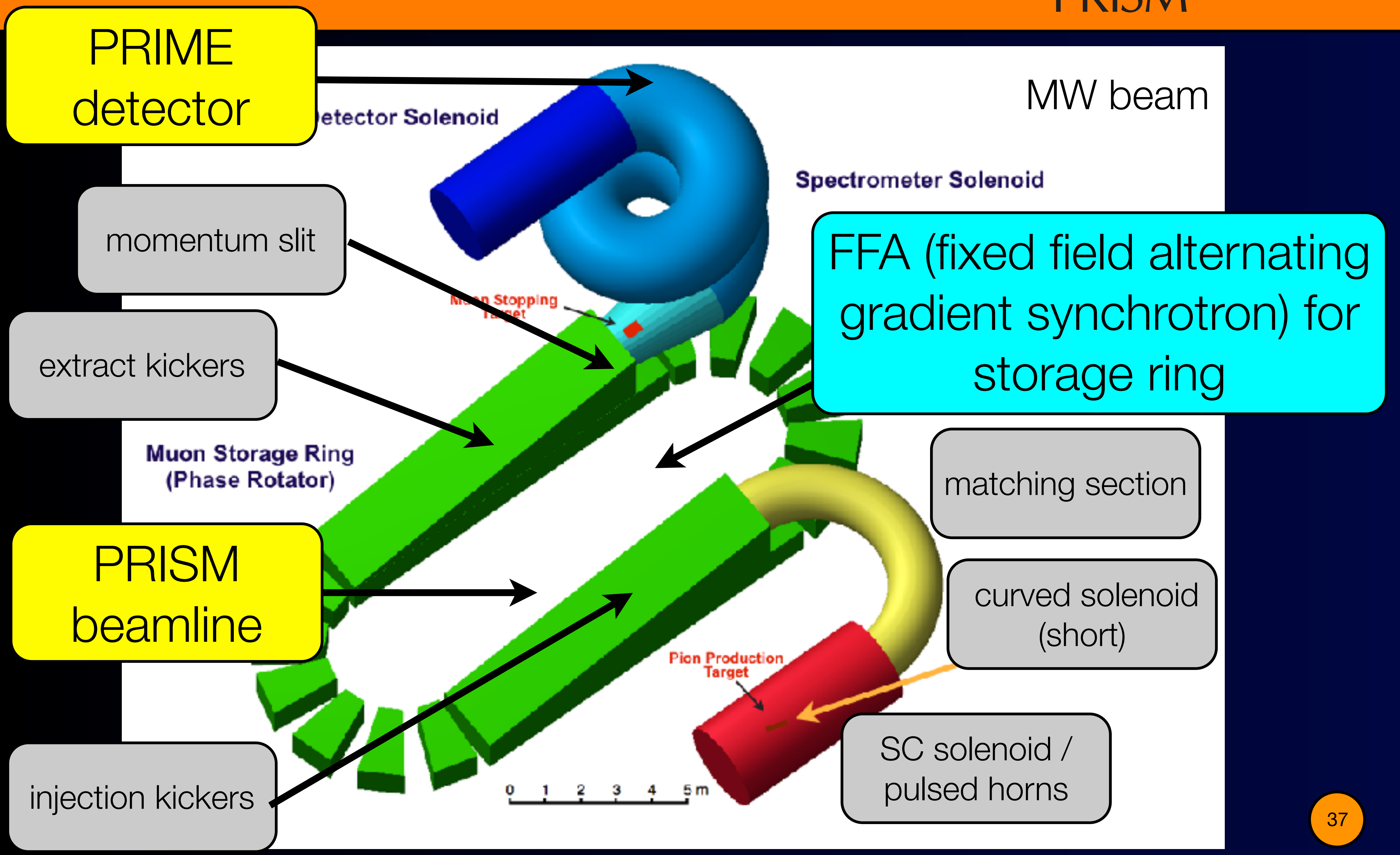

PRISM FFA Phase Rotation at Osaka University (2003 - 2007)

Phase rotation at the PRISM FFA ring with α rays successfully demonstrated at Osaka University (2007)

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T. Nakanishi, Ms.thesis (2008)

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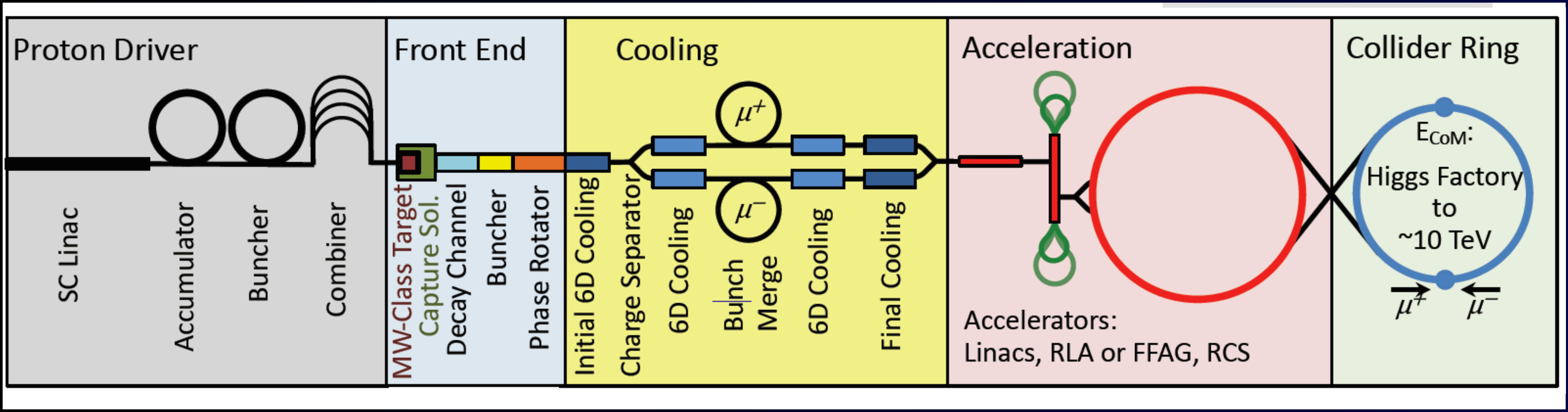
Synergy with Muon Collider R&D

Muon Acceleration Program (US)



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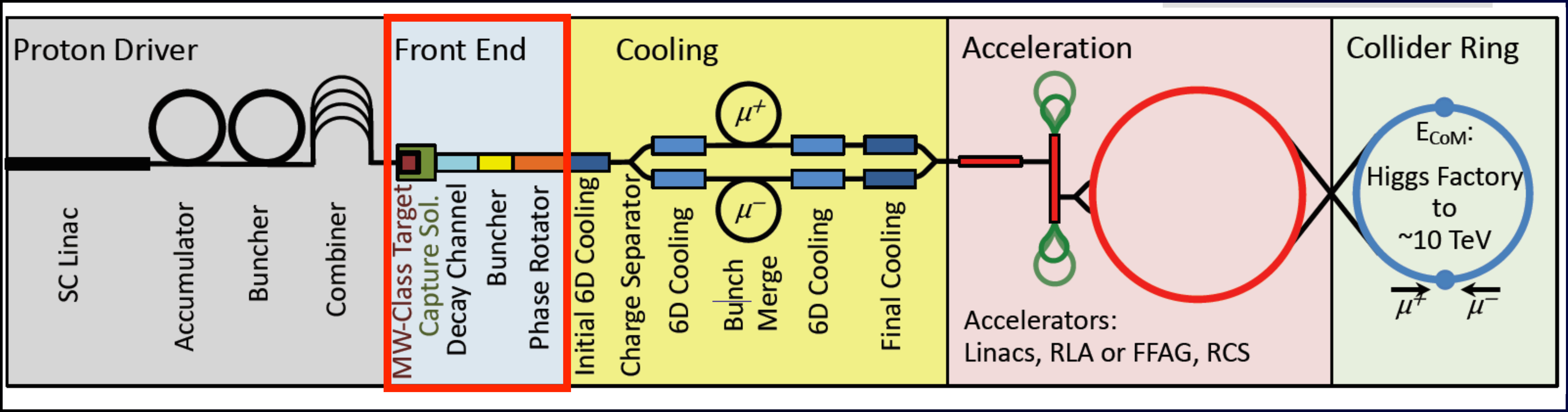

Pion capture solenoids
Phase Rotator

Synergy with Muon Collider R&D

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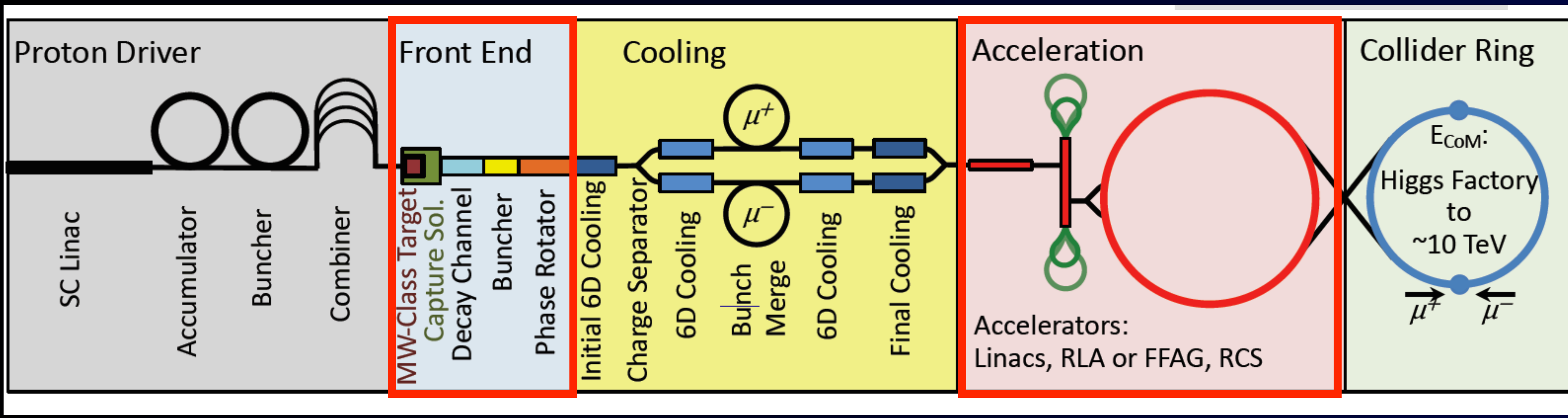

Pion capture solenoids
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FFA accelerator
(at arc)

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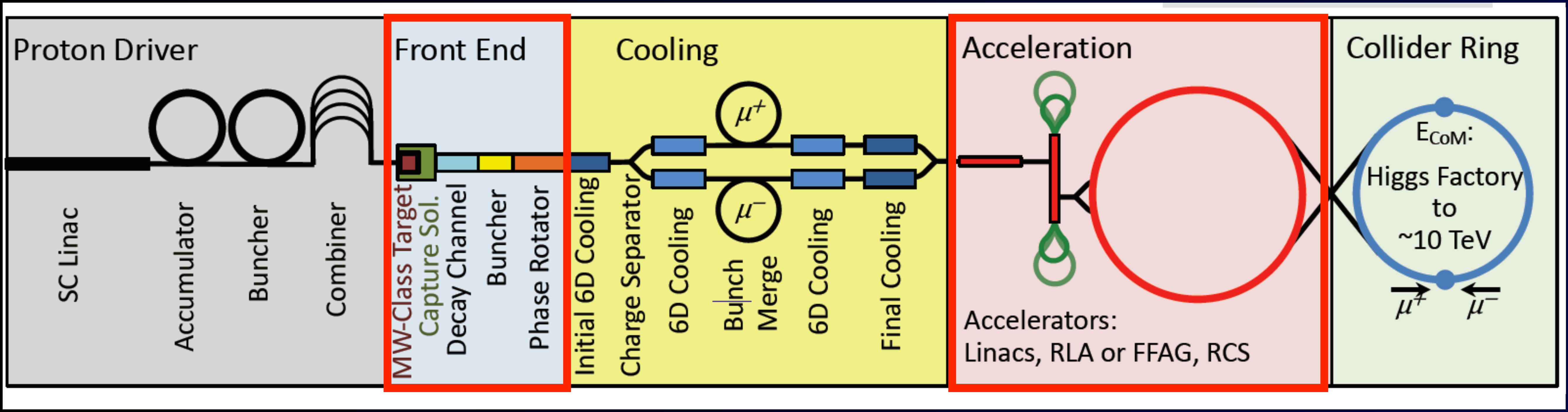

Pion capture solenoids
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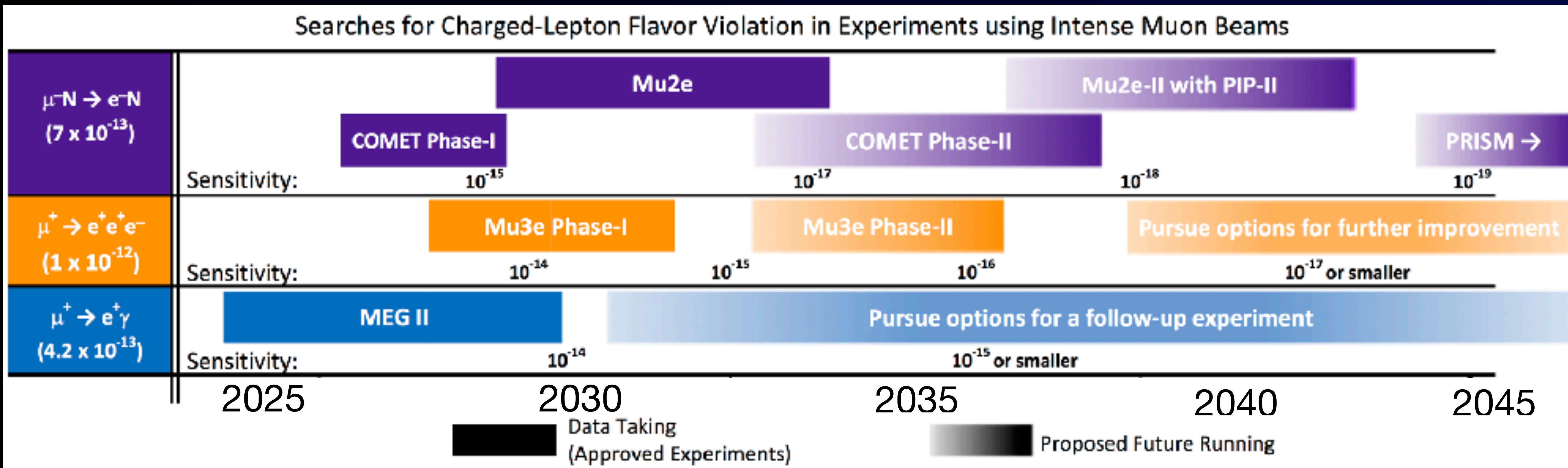
Developments of Highly intense muon sources would have strong synergy with muon collider R&D

“My” Wishful Timeline of Muon CLFV



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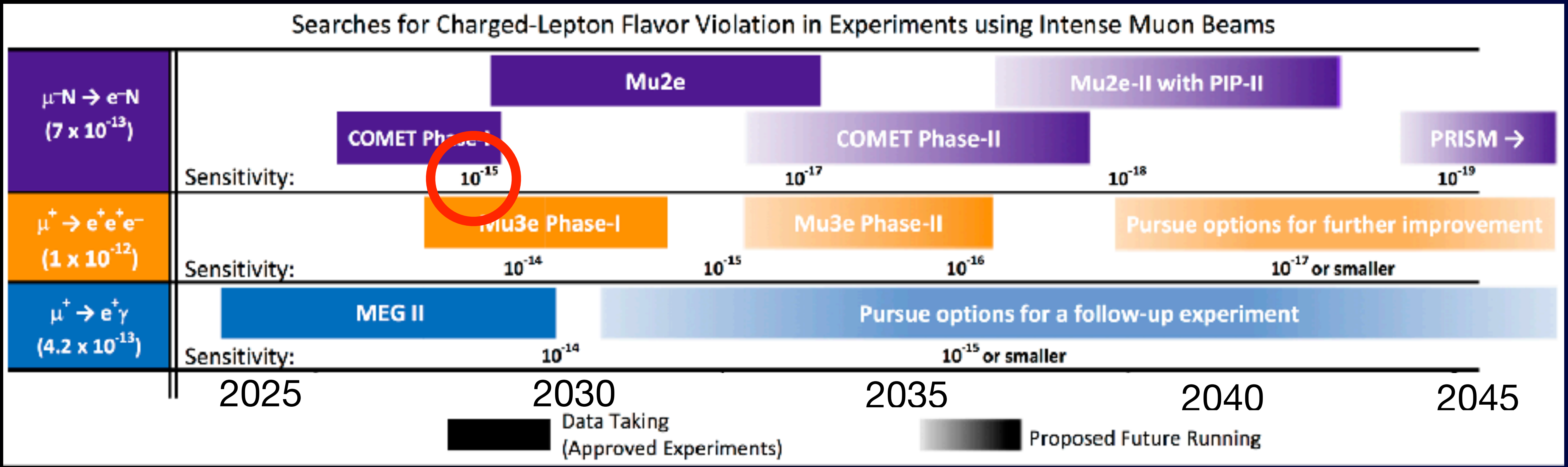

COMET Phase-I

$\times\, 100$

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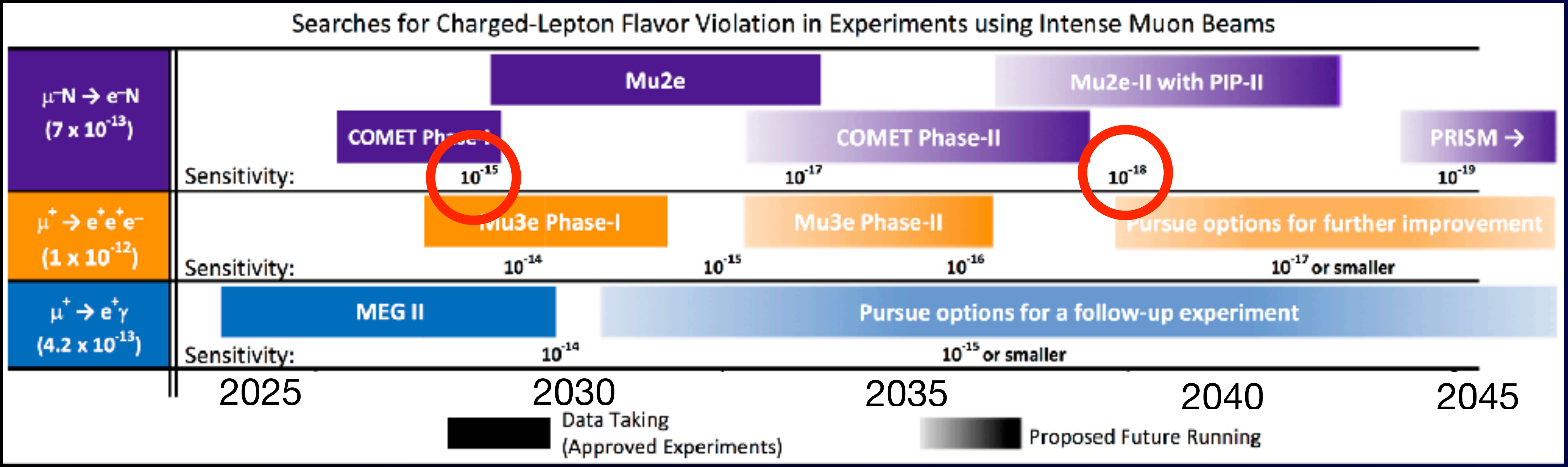

COMET Phase-I

$\times\, 100$

COMET Phase-II

$\times\, 10{,}000$

$-\ \times\, 100{,}000$

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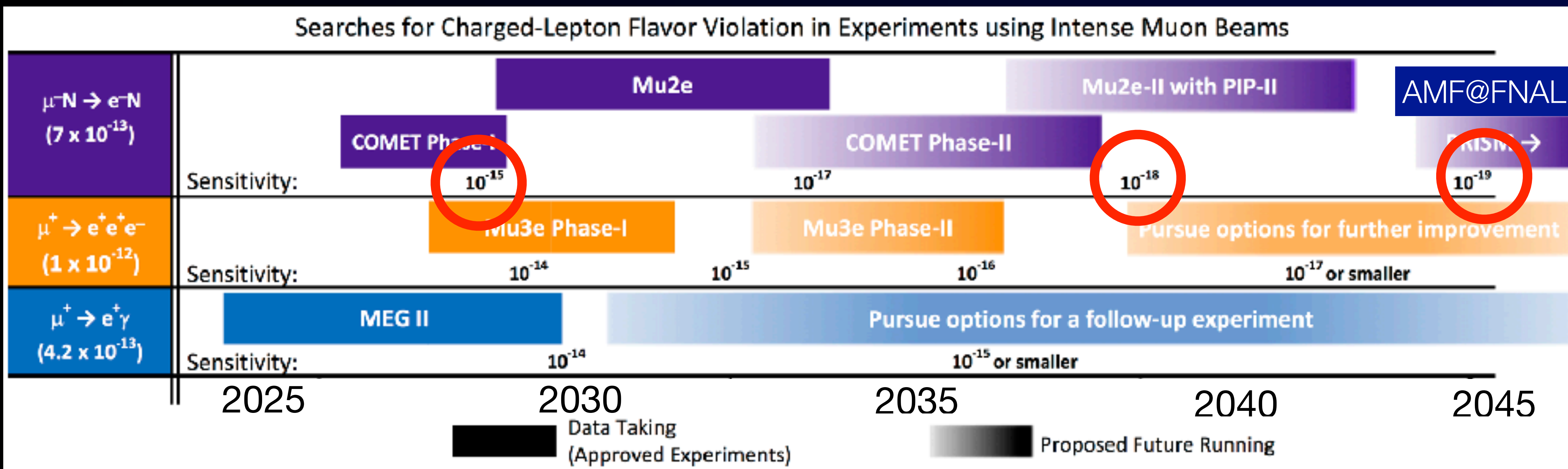

COMET Phase-I	COMET Phase-II	PRISM
$\times 100$	$\times 10{,}000 - \times 100{,}000$	$\times 1{,}000{,}000$

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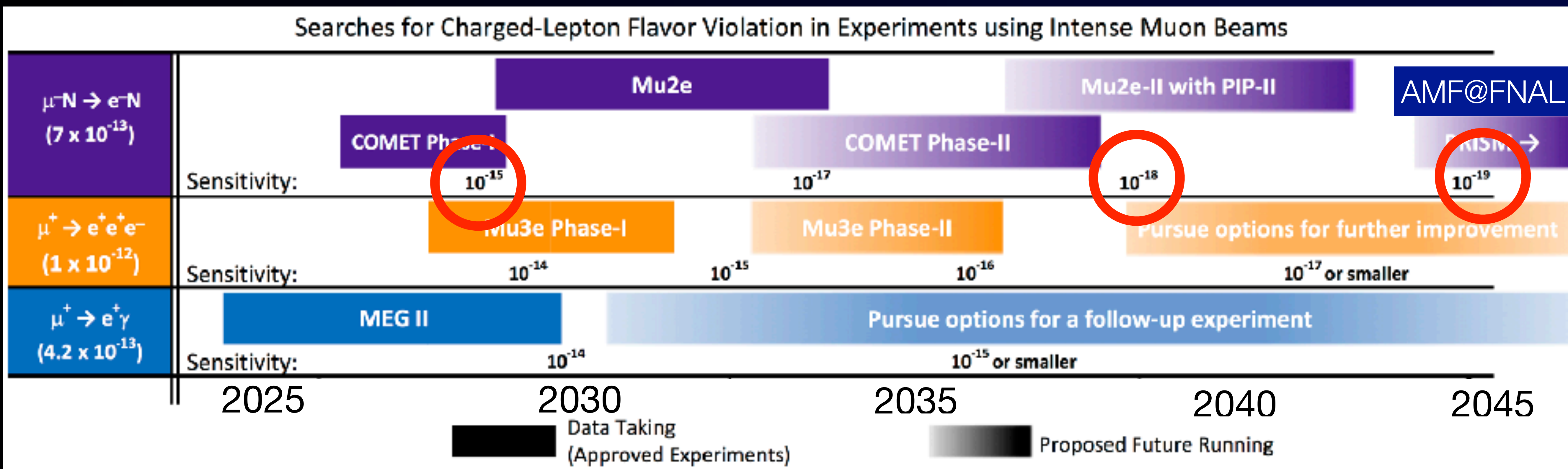

COMET Phase-I

$\times$ 100

COMET Phase-II

$\times$ 10,000

– $\times$ 100,000

PRISM

$\times$ 1,000,000

modified from the muon CLFV white paper for the 2020 update of European Strategy of Particle Physics

Summary

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- CLFV serves as a crucial probe to search for BSM.
- $\mu \rightarrow e$ conversion is one of the most important muon CLFV processes.
- The latest experimental developments (like COMET) together with related physics topics are presented, mentioning future technical advancement (PRISM).
- It is hoped that exploration of CLFV will make implications in particle physics.

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my dog, IKU

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谢谢

Backup