COMET

Osaka University

Search for Charged Lepton Flavour Violation (CLFV)

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Renconstres de Vietnam - Neutrino
ICISE, Quy Nhon, Vietnam

Outline

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- Physics motivation of charged lepton favour violation (CLFV)
- Muon CLFV experiments
- Muon to electron conversion
  - Mu2e
  - COMET
  - COMET Phase-I
- Summary

Why CLFV?

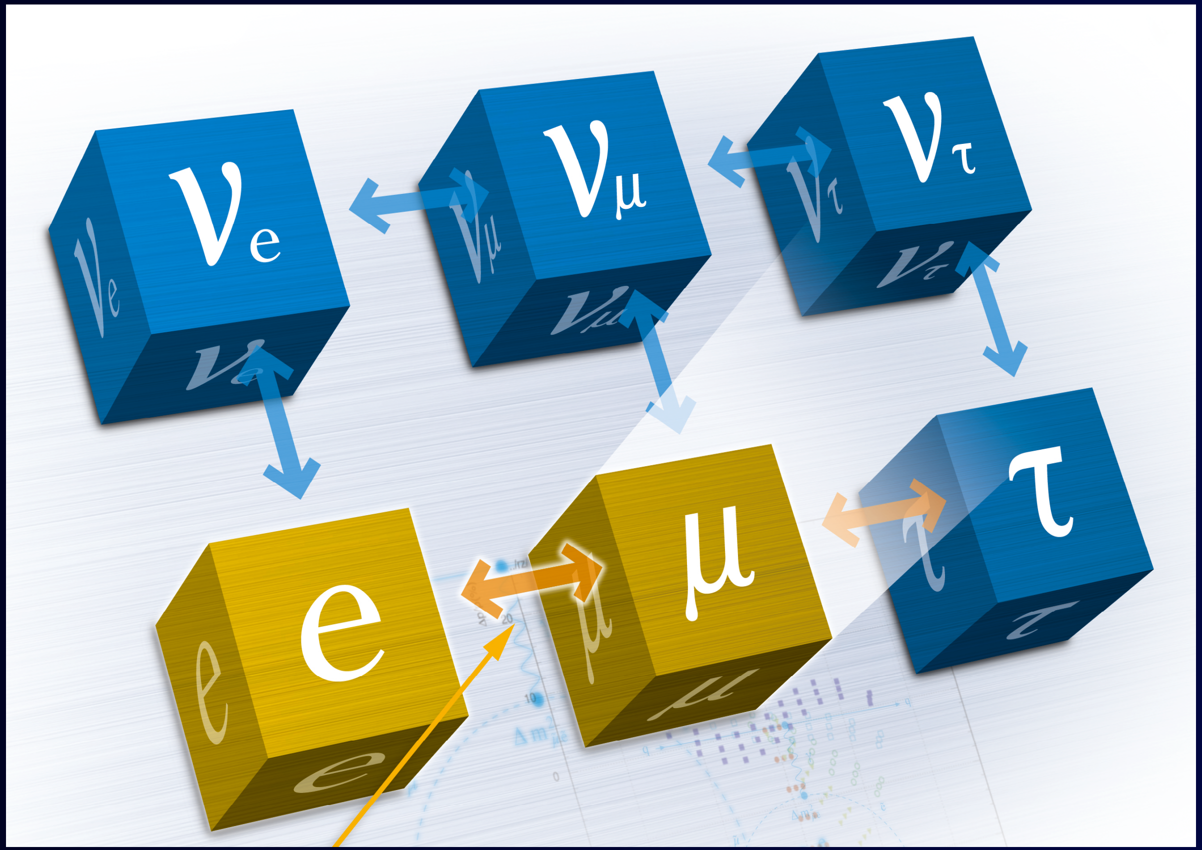
Neutrinos and Charged Leptons

PMNS mixing matrix

$$\nu_\ell = U_{\rm PMNS}\,\nu_i\,, \quad \text{i.e.} \quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

CC current interaction

$$\mathcal{L}_{\rm cc}^{\ell} \sim -\frac{g}{\sqrt{2}} U^{\dagger\, ij}_{\rm PMNS}\, W^{+}_{\mu}\, \bar{\nu}_{Li}\, \gamma^{\mu}\, e_{Lj}\,, \quad U_{\rm PMNS} = R_L^{\ell}\, R_L^{\nu\dagger}$$



no oscillation of charged leptons
but transitions can occur.

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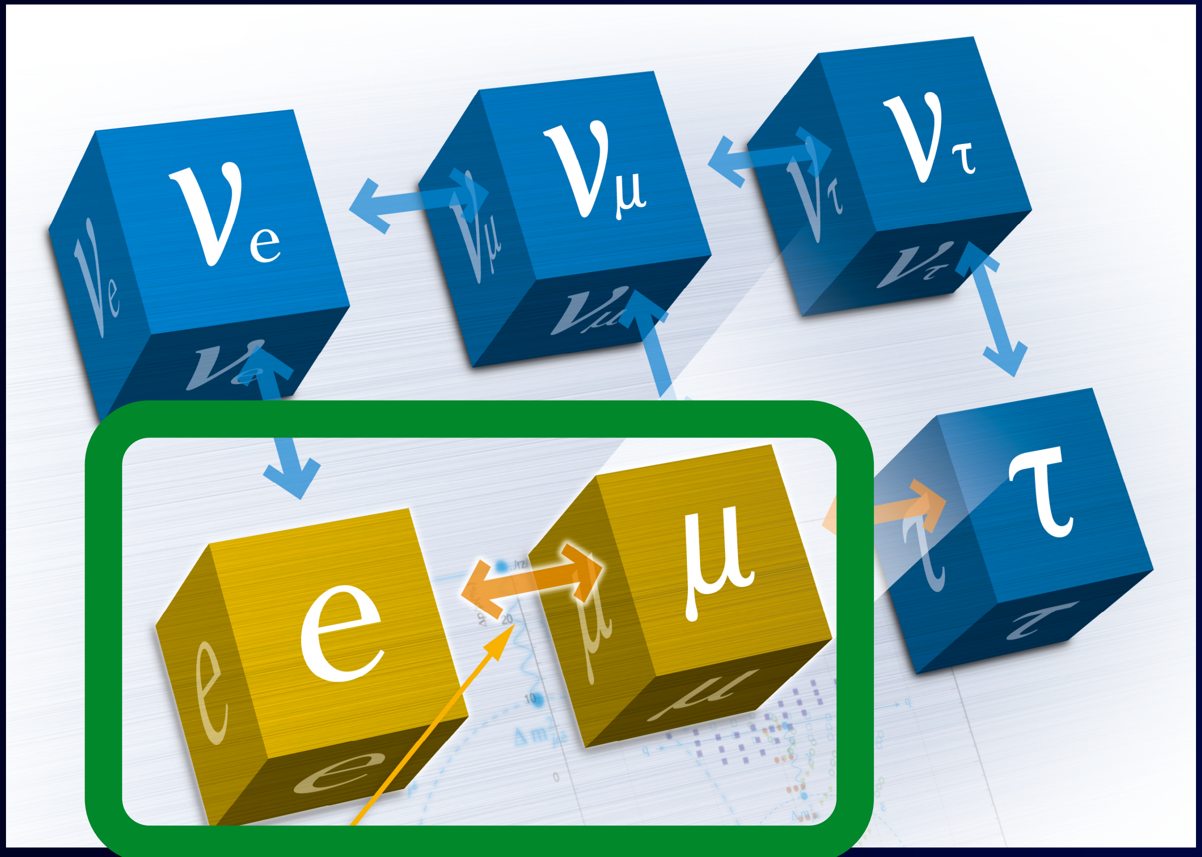

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SM Contribution to CLFV

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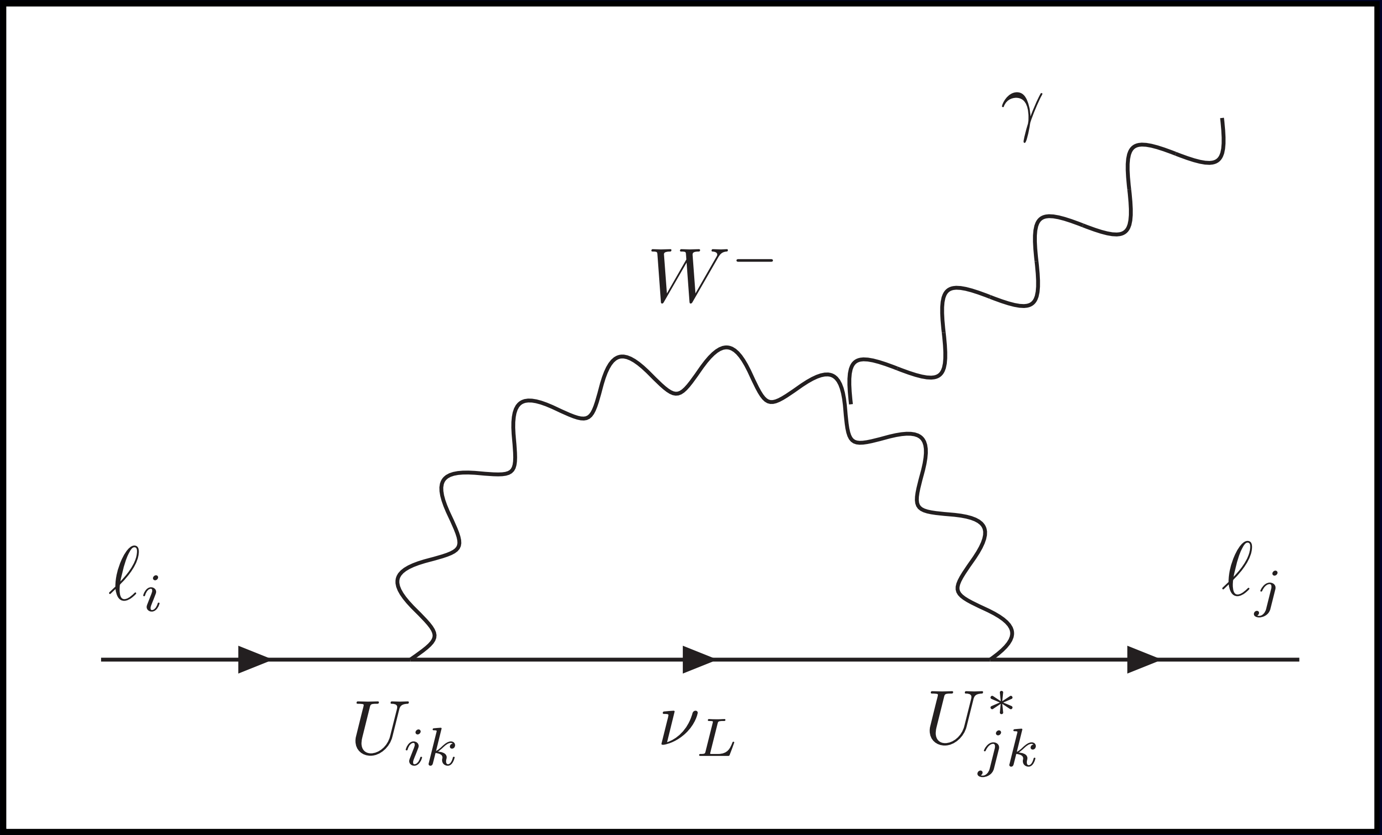
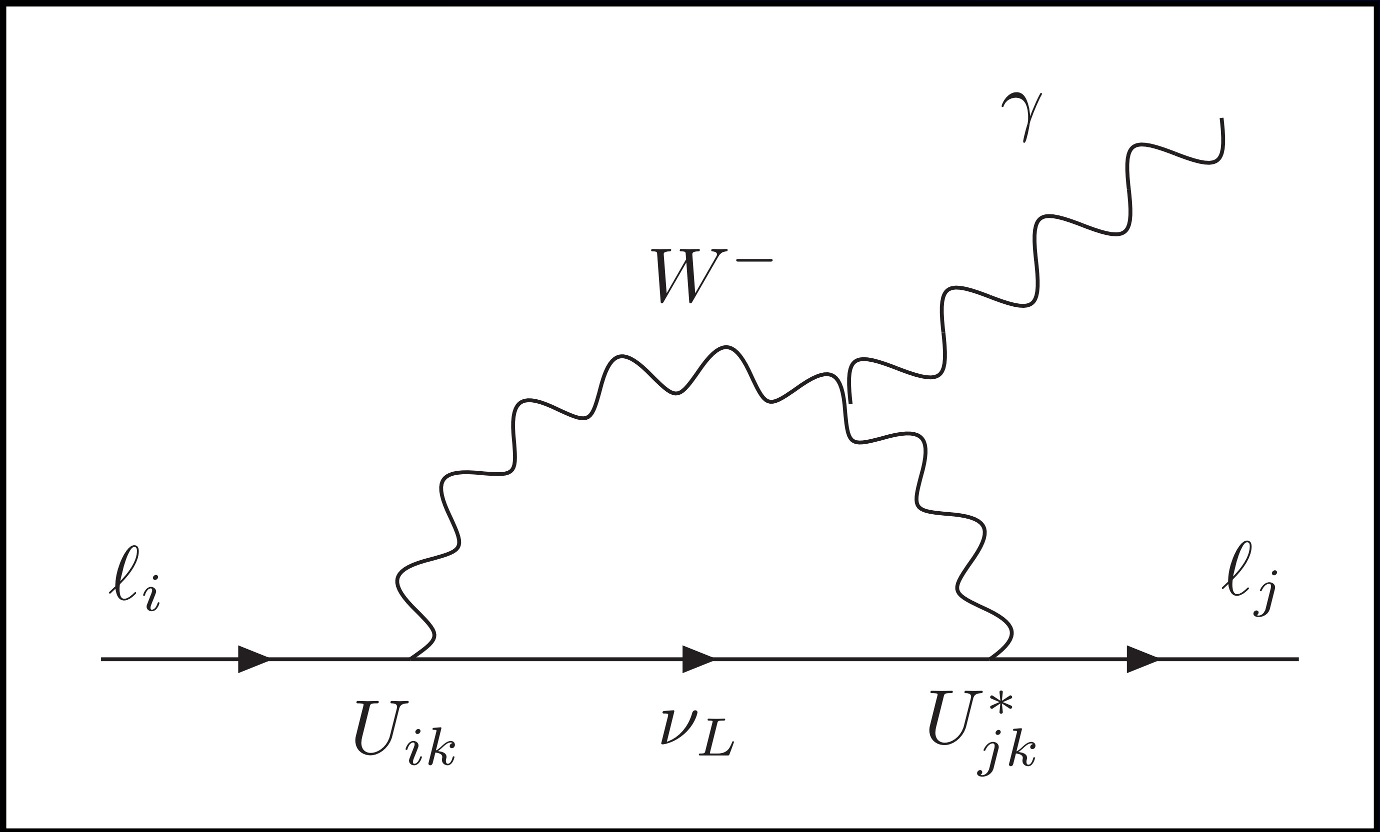


$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu_l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$

SM Contribution to CLFV



BR~O(10^{-54})

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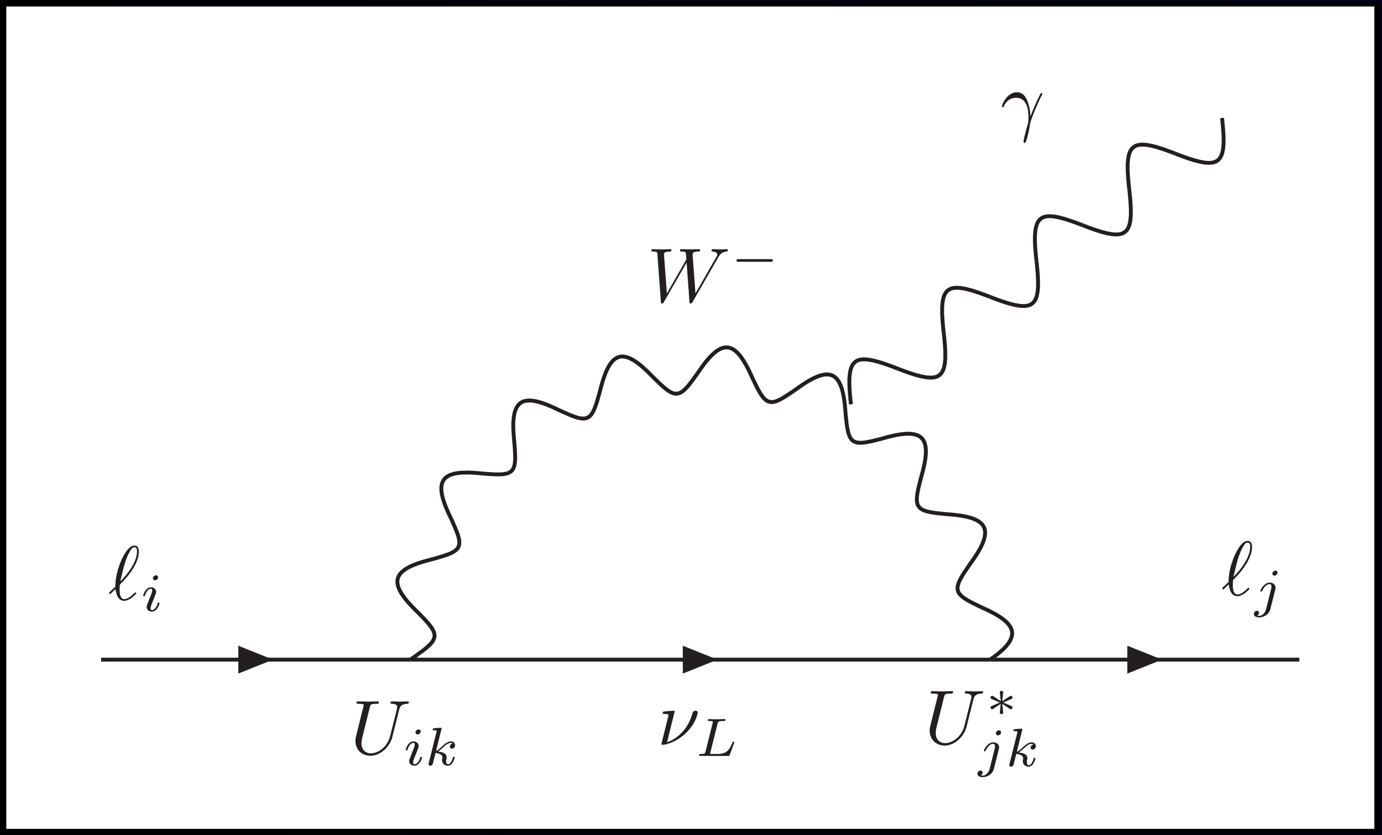

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CLFV provides good opportunities to search for new physics beyond the Standard Model

New Physics Search with CLFV

Effective Lagrangian with New Physics

Effective Lagrangian with New Physics

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{C_{\rm NP}}{\Lambda^2} O_{ij}^{(6)}$$

dimension 6

Λ is the energy scale of new physics （$\sim m_{NP}$)

C_{NP} is the coupling constant.

Effective Lagrangian with New Physics

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C_{NP} is the coupling constant.

New Physics could be….

very high energy scale Λ with not-small C_{NP}

or

very small C_{NP} with not-high energy scale Λ

Effective Lagrangian with New Physics

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ex: Charged lepton flavour violation (CLFV),
μ→eγ (B<4.2×10^{-13} from MEG(2016))

$$\frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)} \rightarrow \frac{C_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu}$$

$$\Lambda > 2 \times 10^5 \text{ TeV} \times (C_{\mu e})^{\frac{1}{2}} \ .$$

$\Lambda > O(10^5)$ TeV with $C_{\mu e} \sim O(1)$

or

$C_{\mu e} \sim O(10^{-9})$ with $\Lambda < O(1)$ TeV

CLFV Rate

Lepton (SM forbidden)

rate

$$|A_{\rm SM} + \varepsilon_{\rm NP}|^2 \sim \cancel{|A_{\rm SM}|^2} + 2Re(\cancel{A_{\rm SM}\varepsilon_{\rm NP}}) + |\varepsilon_{\rm N}|^2$$

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

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Lepton (SM forbidden)

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

Λ ≧x10 —> R≦10^{-4}

Model Dependent CLFV

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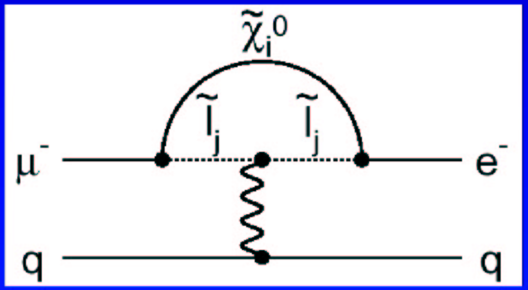
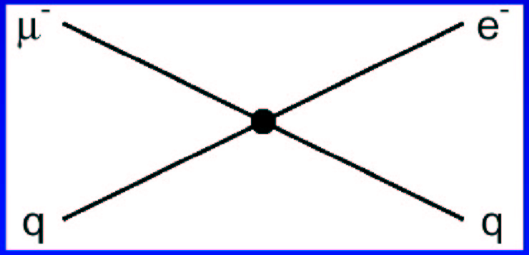
Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}





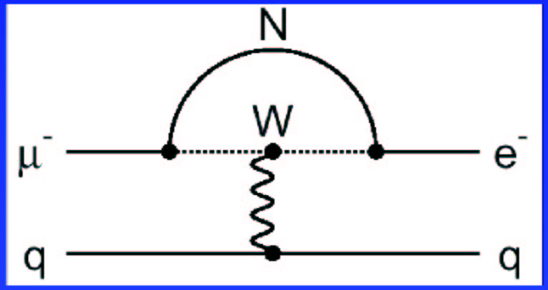
Compositeness

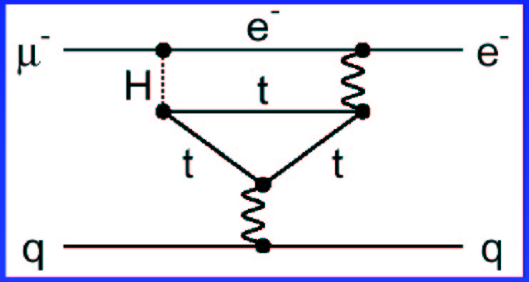
Λ_c = 3000 TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2$ =

8×10^{-13}





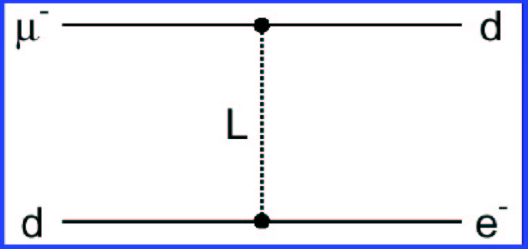
Second Higgs doublet

$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

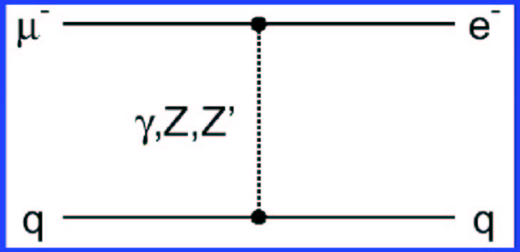
Leptoquarks

M_L =

3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



After W. Marciano

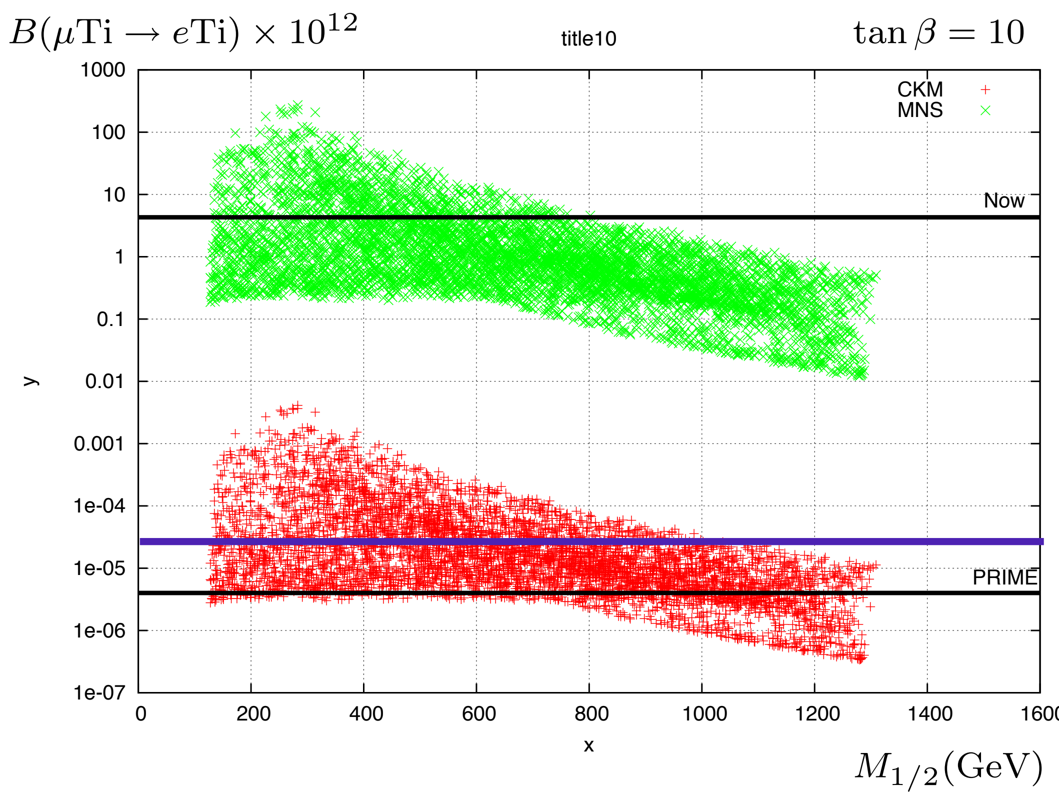


Heavy Z', Anomalous Z coupling

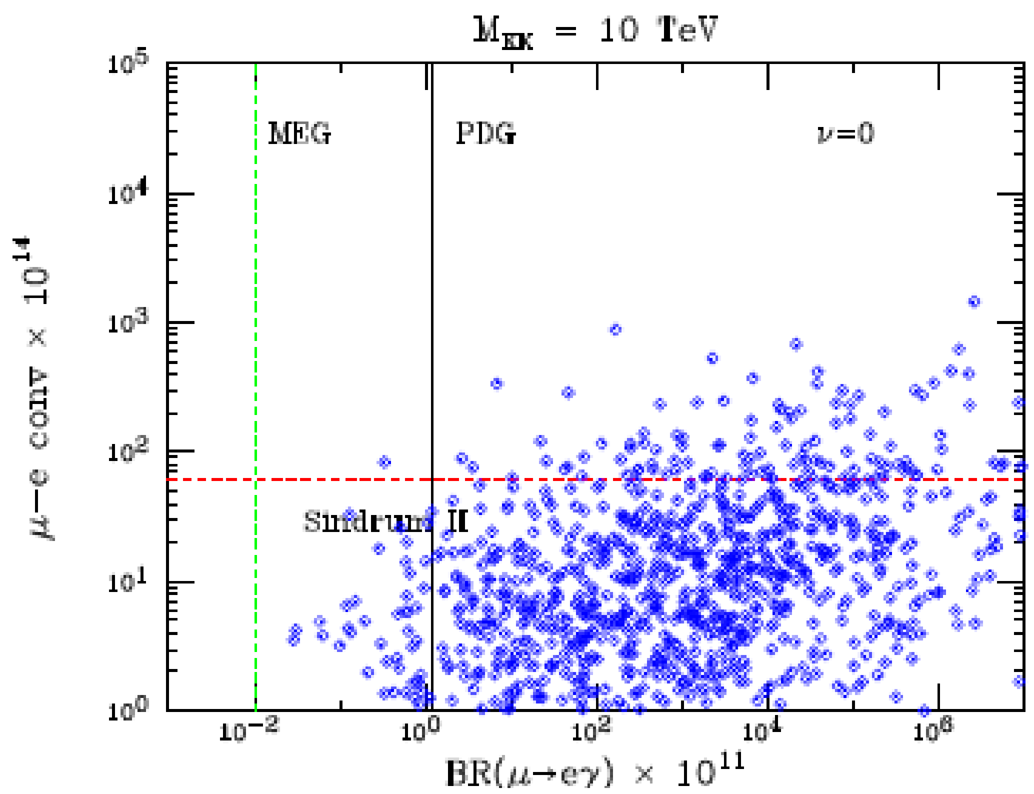
$M_{Z'}$ = 3000 TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

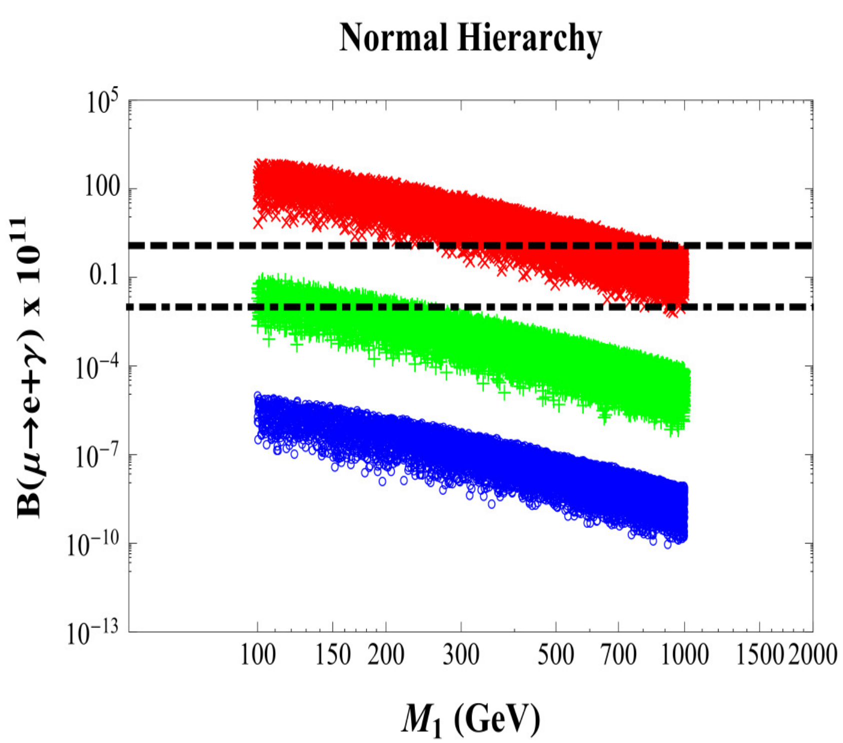
SUSY model



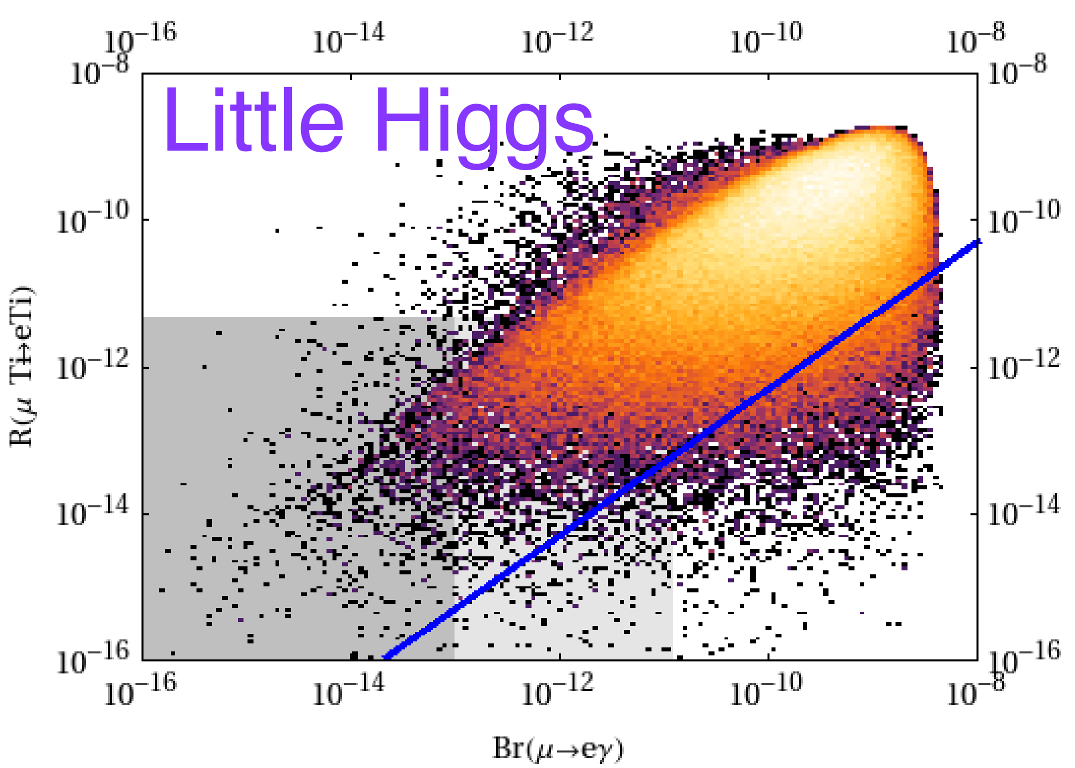
extra dimension model



low-energy seesaw model



little Higgs model



Muon CLFV

Experimental Limits at Present and in the Future

process	present limit	future	
$\mu \to e\gamma$	$<4.2 \times 10^{-13}$	$<10^{-14}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \to eN$ (in Al)	none	$<10^{-16}$	Mu2e / COMET
$\mu N \to eN$ (in Ti)	$<6.1 \times 10^{-13}$	$<10^{-18}$	PRISM
$\tau \to e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB/LHCb

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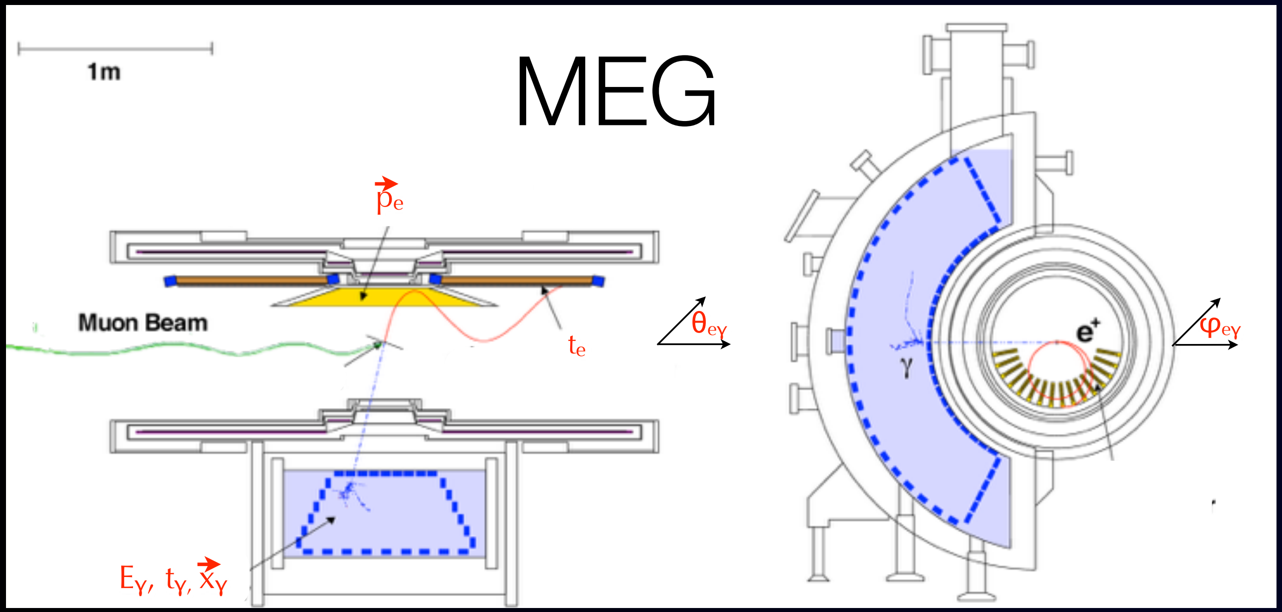
$X10^{-4}$

$\mu \to e\gamma$

- Event Signature
  - $E_e = E_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{\mu e}$=180 (back-to-back)
  - time coincidence
- Backgrounds
  - prompt physics backgrounds
    - radiative muon decay $\mu \to e\nu\nu\gamma$
  - accidental backgrounds



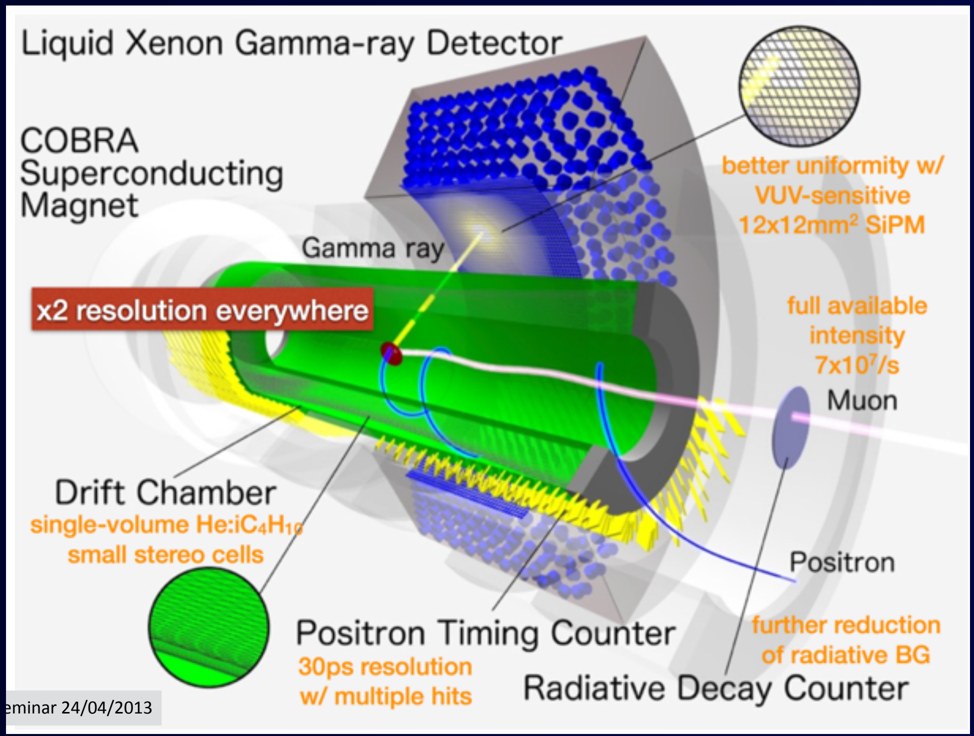
Final MEG result (2016)

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

MEG II

goal ~ 4×10^{-14}

2018-2020

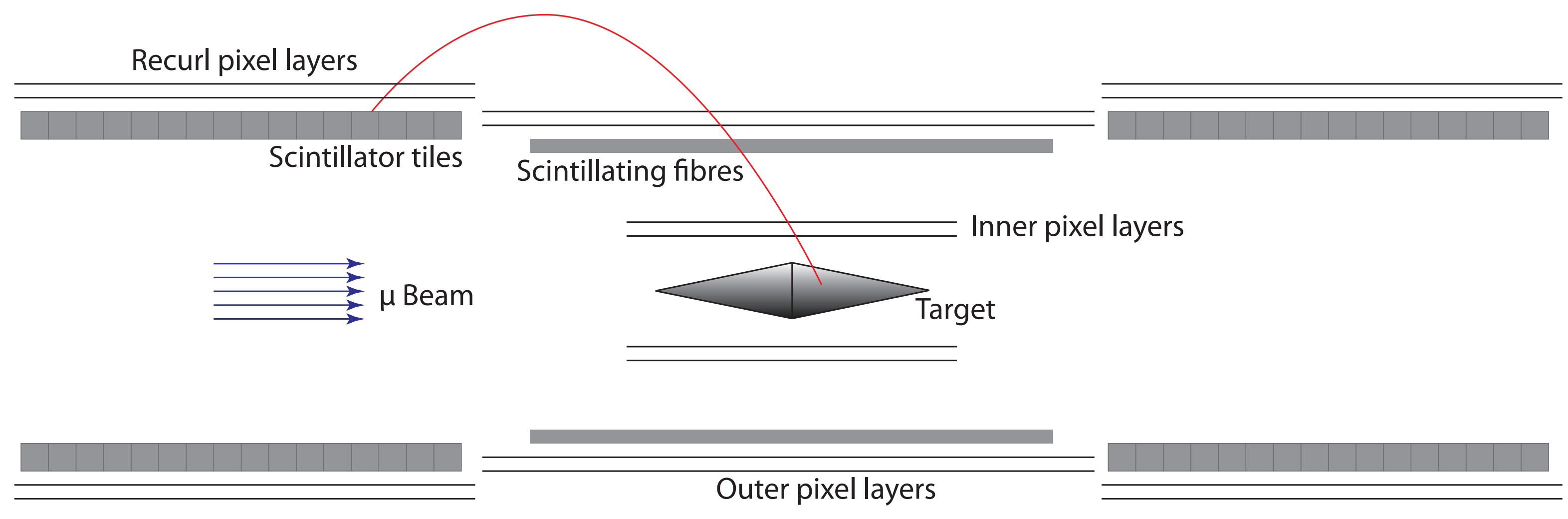


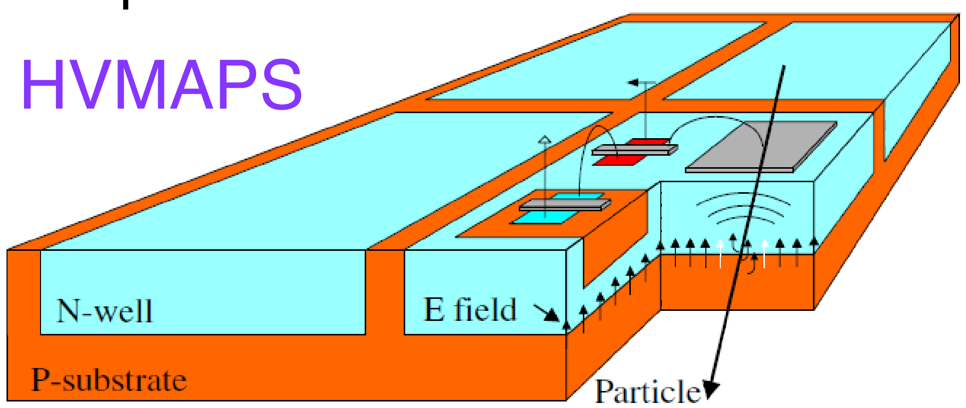
μ→eee

- Event Signature
  - $\Sigma E_e = m_\mu$
  - $\Sigma P_e = 0$ (vector sum)
  - common vertex
  - time coincidence
- Backgrounds
  - physics backgrounds
    - μ→eννee decay
  - accidental backgrounds

Mu3e (@PSI)

- Stage-I (2020 -)
  - $B \sim 10^{-15}$ at πE5
- Stage-2
  - $B < 10^{-16}$ at new muon source





μ^- to e^+ conversion

μ^- to e^+ conversion

$\mu^- + \mathrm{Ti} \rightarrow e^+ + \mathrm{Ca(gs)}$ 1.7×10^{-12}
$\mu^- + \mathrm{Ti} \rightarrow e^+ + \mathrm{Ca(ex)}$ 3.6×10^{-11}

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

Lepton number violation (LNV) and CLFV => CLNLFV

signal signature

$$E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - \Delta_{Z-2}$$

backgrounds

positrons from photon conversion after radiative muon/pion nuclear capture

$\mu^- + \mathrm{Ti} \rightarrow e^+ + \mathrm{Ca(gs)}$	1.7×10^{-12}
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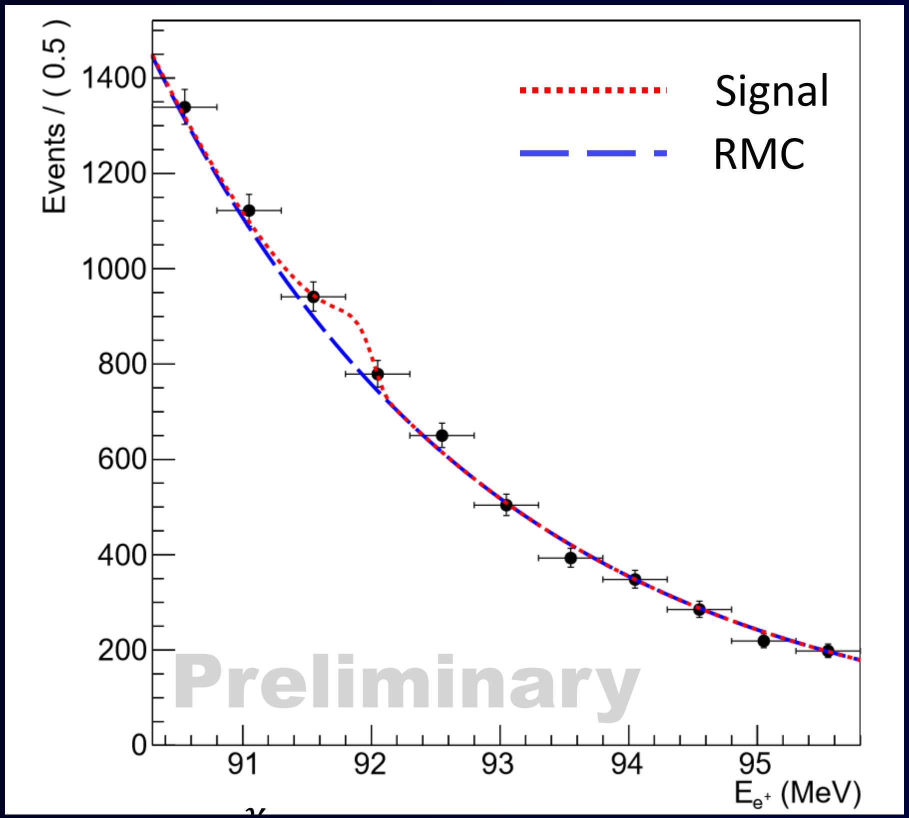
showing that aluminum is not a good target



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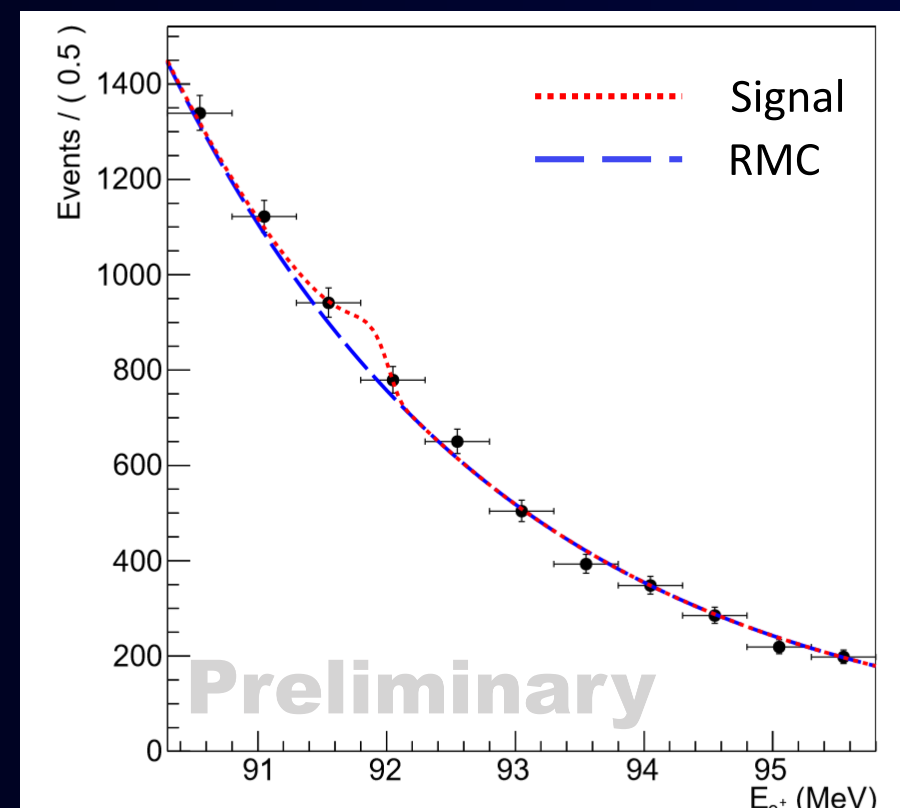

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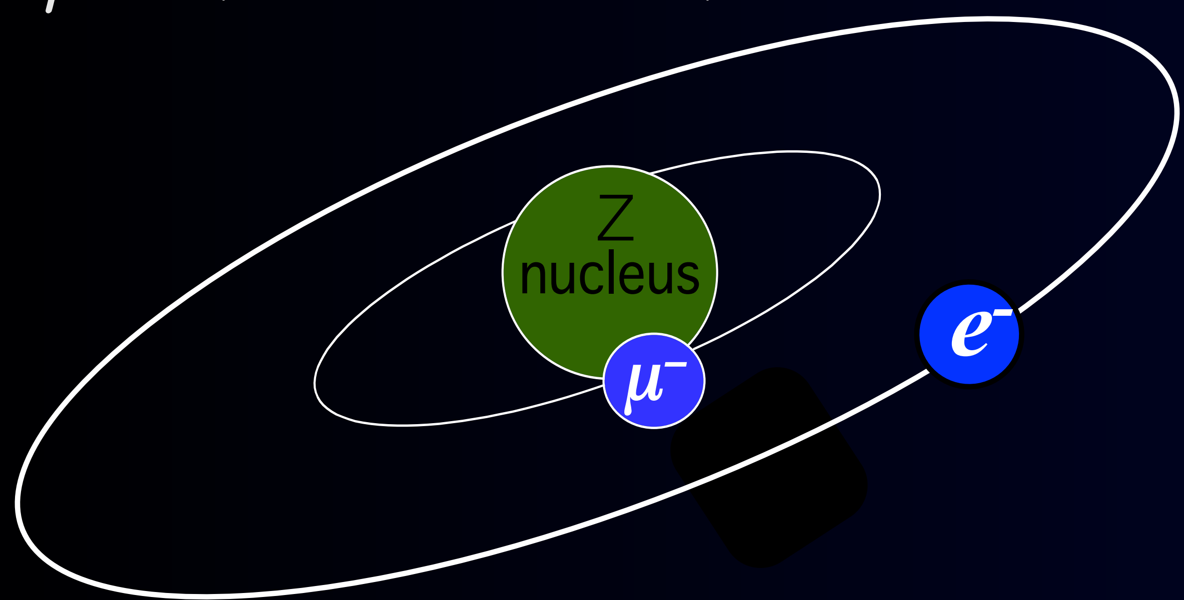
mass relation for target selection

$M(A, Z-1) > M(A, Z-2)$
for $M(A, Z)$

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

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

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



- $\mu^- e^- \to e^- e^-$ has the overwrap of μ^- and e^- which is proportional to Z^3.
- $\mu^- e^- \to e^- e^-$ has two-body final state.

PRL **105,** 121601 (2010) PHYSICAL REVIEW LETTERS week ending 17 SEPTEMBER 2010

New Process for Charged Lepton Flavor Violation Searches: $\mu^- e^- \to e^- e^-$ in a Muonic Atom

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(Received 8 March 2010; published 15 September 2010)

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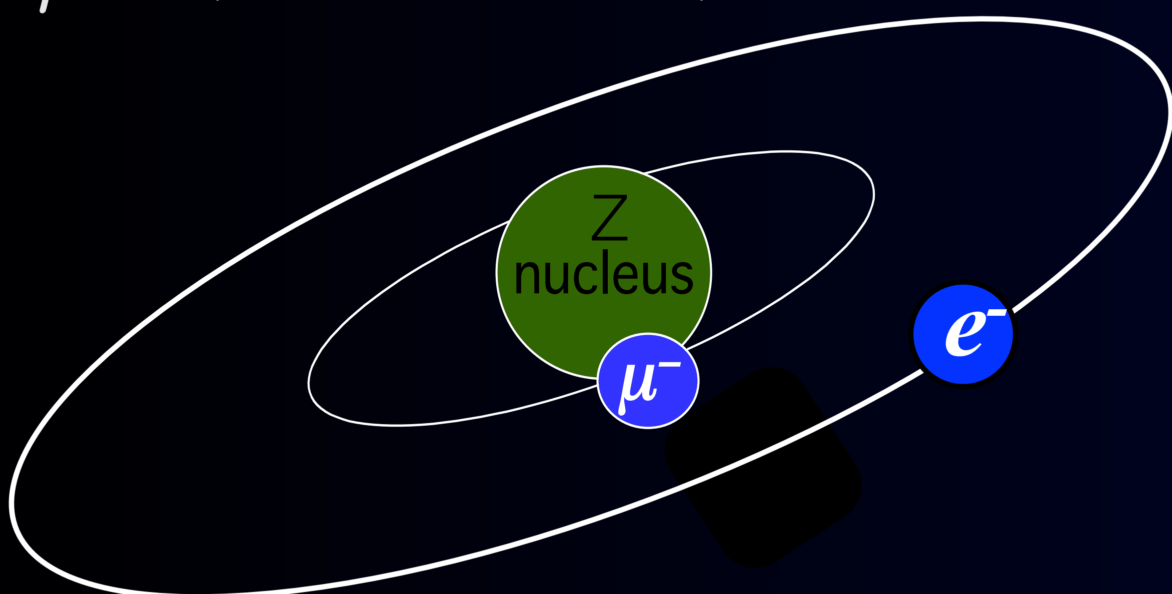

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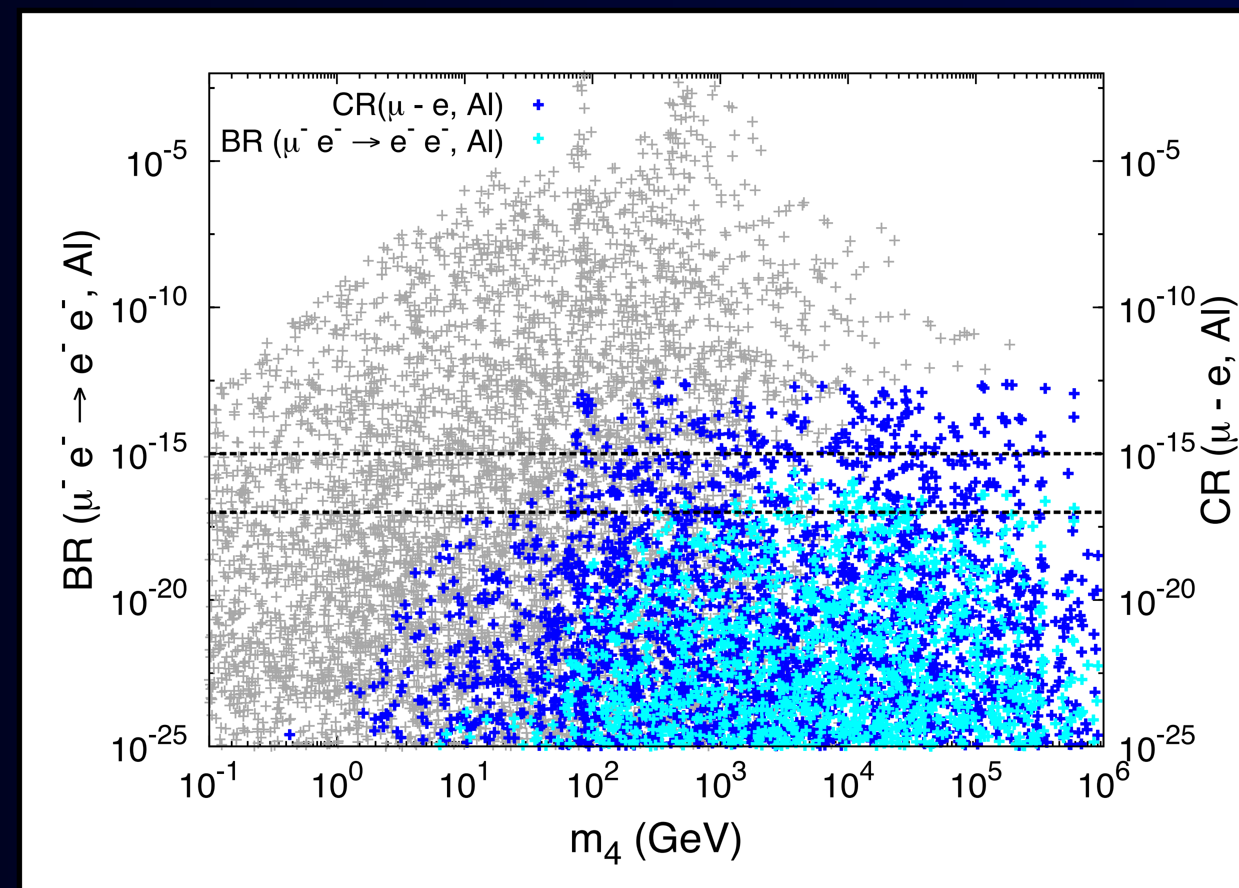

3+1(sterile) model

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Experiments for μ-e conversion

What is Muon to Electron Conversion?

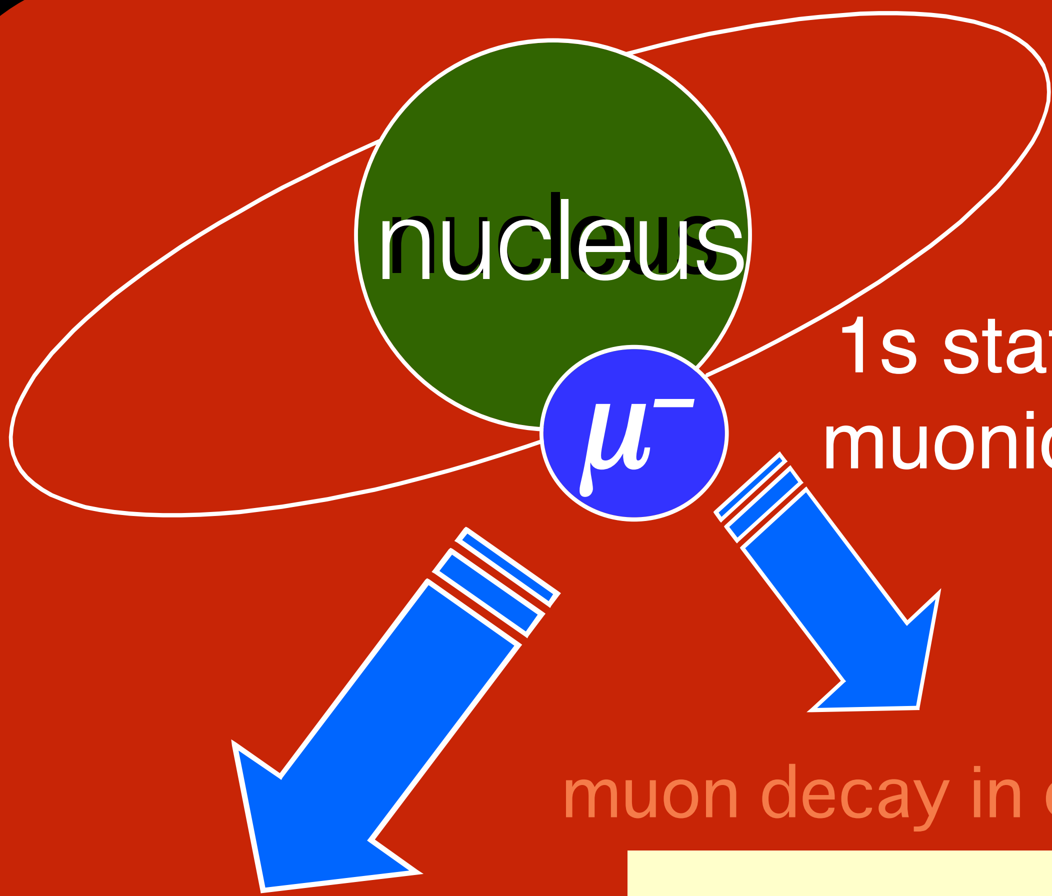
$\mu \to e$ in vacuum

What is Muon to Electron Conversion?

$\mu \rightarrow e$ ~~in vacuum~~ in matter

What is Muon to Electron Conversion?

$\mu \rightarrow e$ ~~in vacuum~~ in matter



1s state in a muonic atom

muon decay in orbit

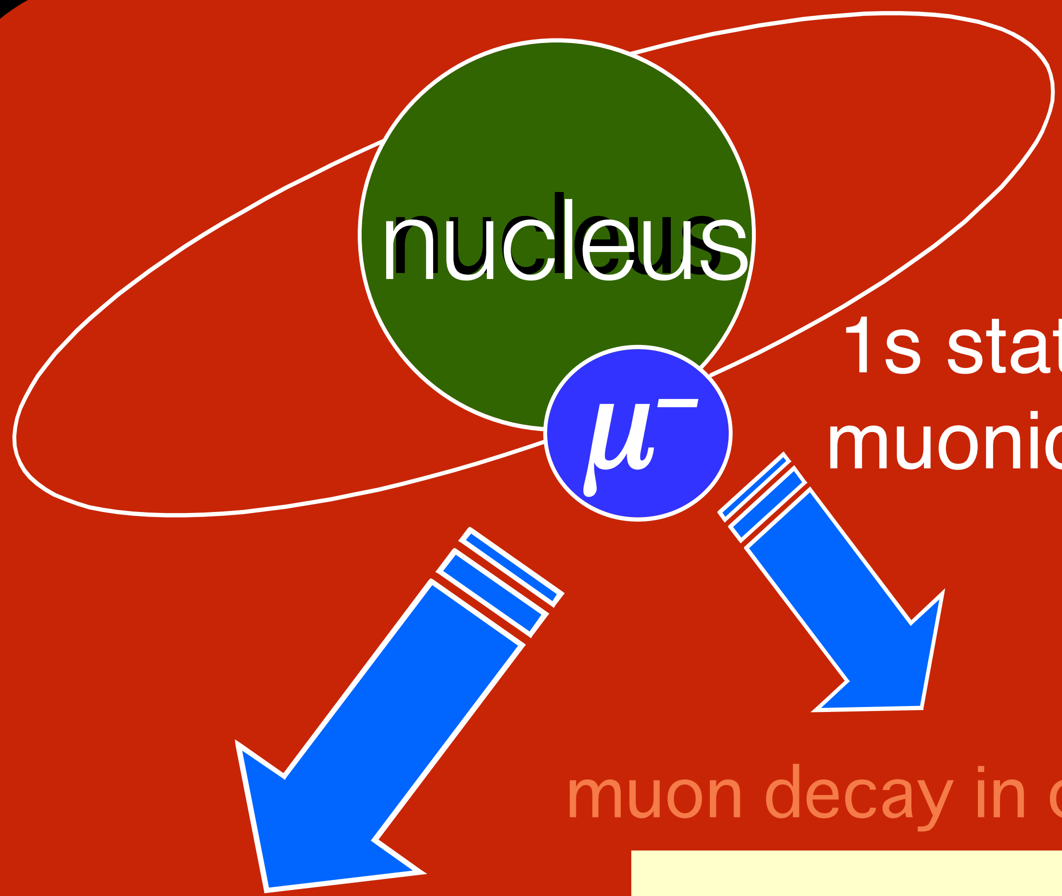
$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

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

What is Muon to Electron Conversion?

$\mu \rightarrow e$ ~~in vacuum~~ in matter



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muon to electron conversion

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

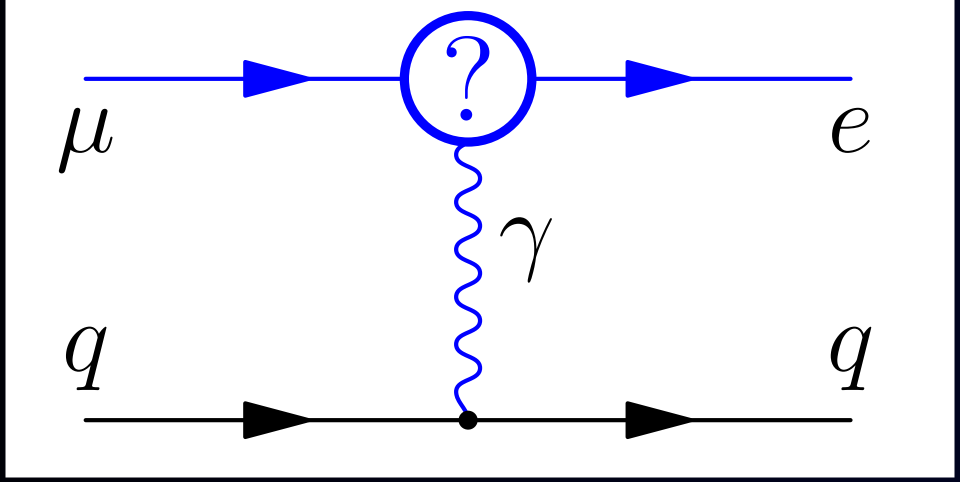
coherent process to the ground state $\propto Z^5$

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

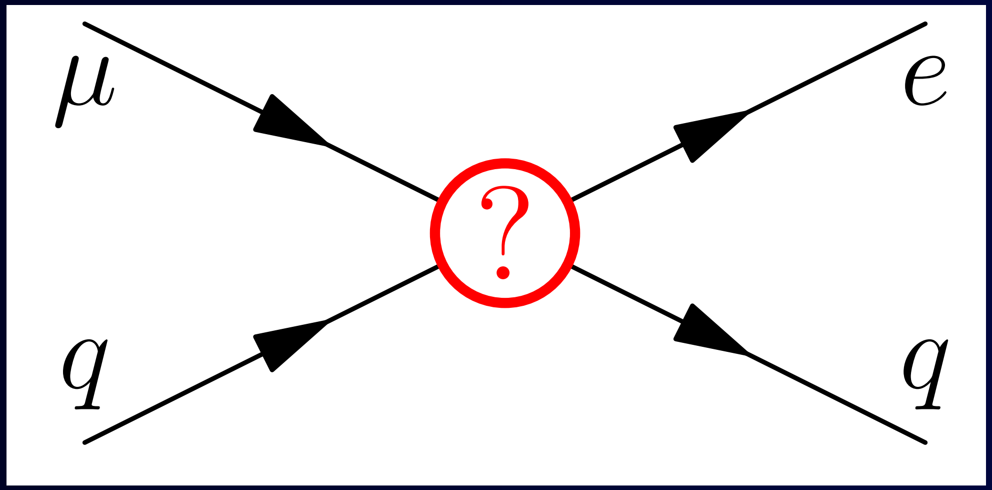
Backgrounds:
(1) physics backgrounds
(2) beam-related backgrounds
(3) cosmic rays, false tracking

Physics Sensitivity Comparison : μ→eγ vs. μ-e conversion

Photonic (dipole) interaction



Contact interaction



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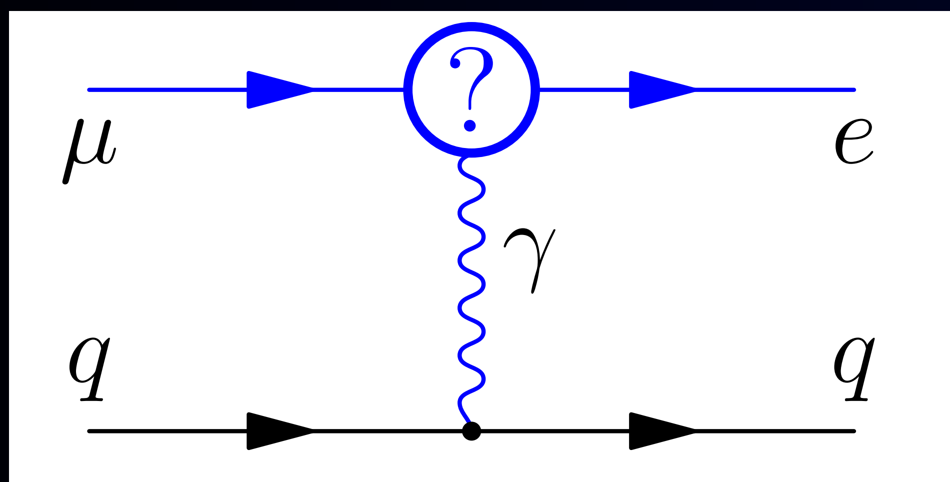

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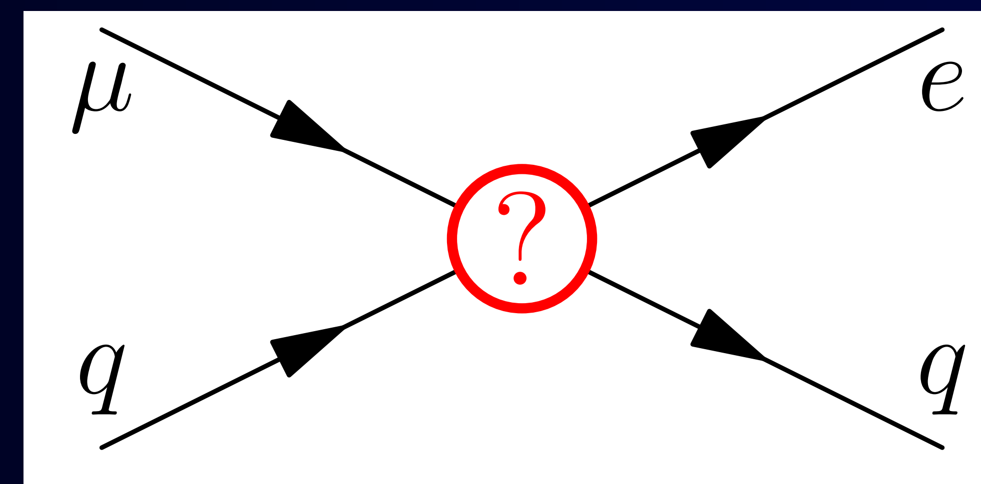
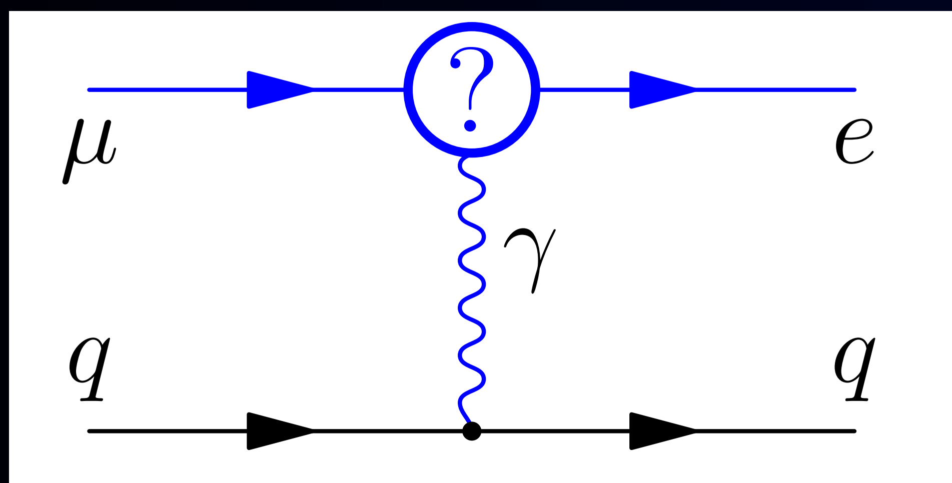


tree levels

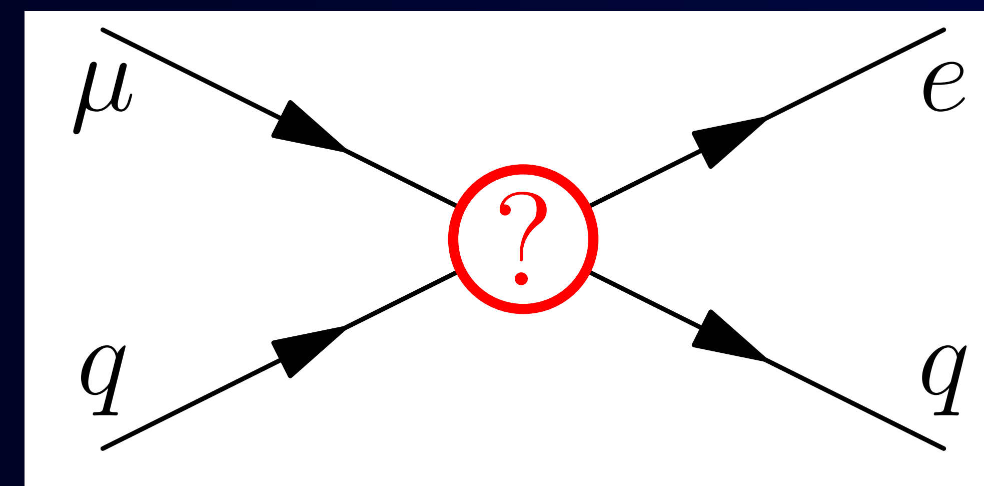
$$L_{\mu N \to eN} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^\mu e_{\rm L})(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})$$

Physics Sensitivity Comparison : μ→eγ vs. μ-e conversion

Photonic (dipole) interaction



Contact interaction



tree levels

$$L_{\mu N \rightarrow eN} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_{\rm R}\sigma^{\mu\nu}e_{\rm L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_{\rm L}\gamma^\mu e_{\rm L})(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})$$

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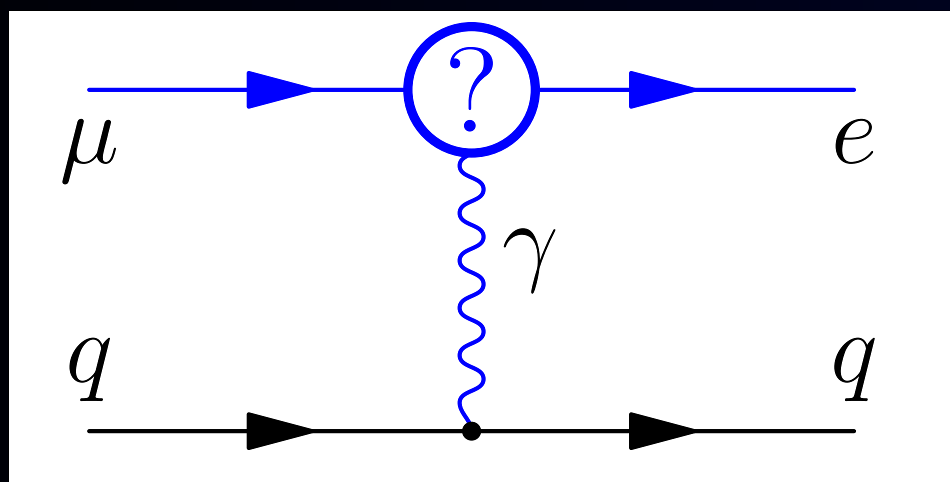

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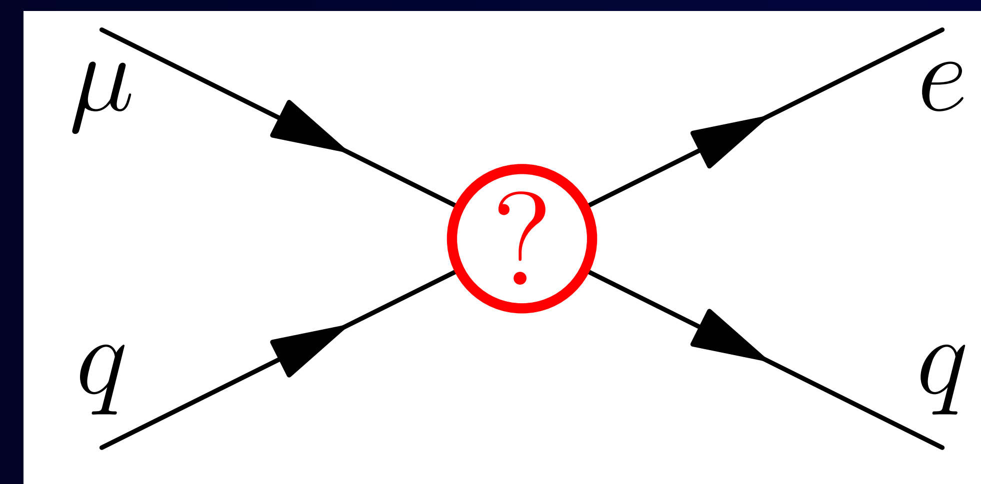

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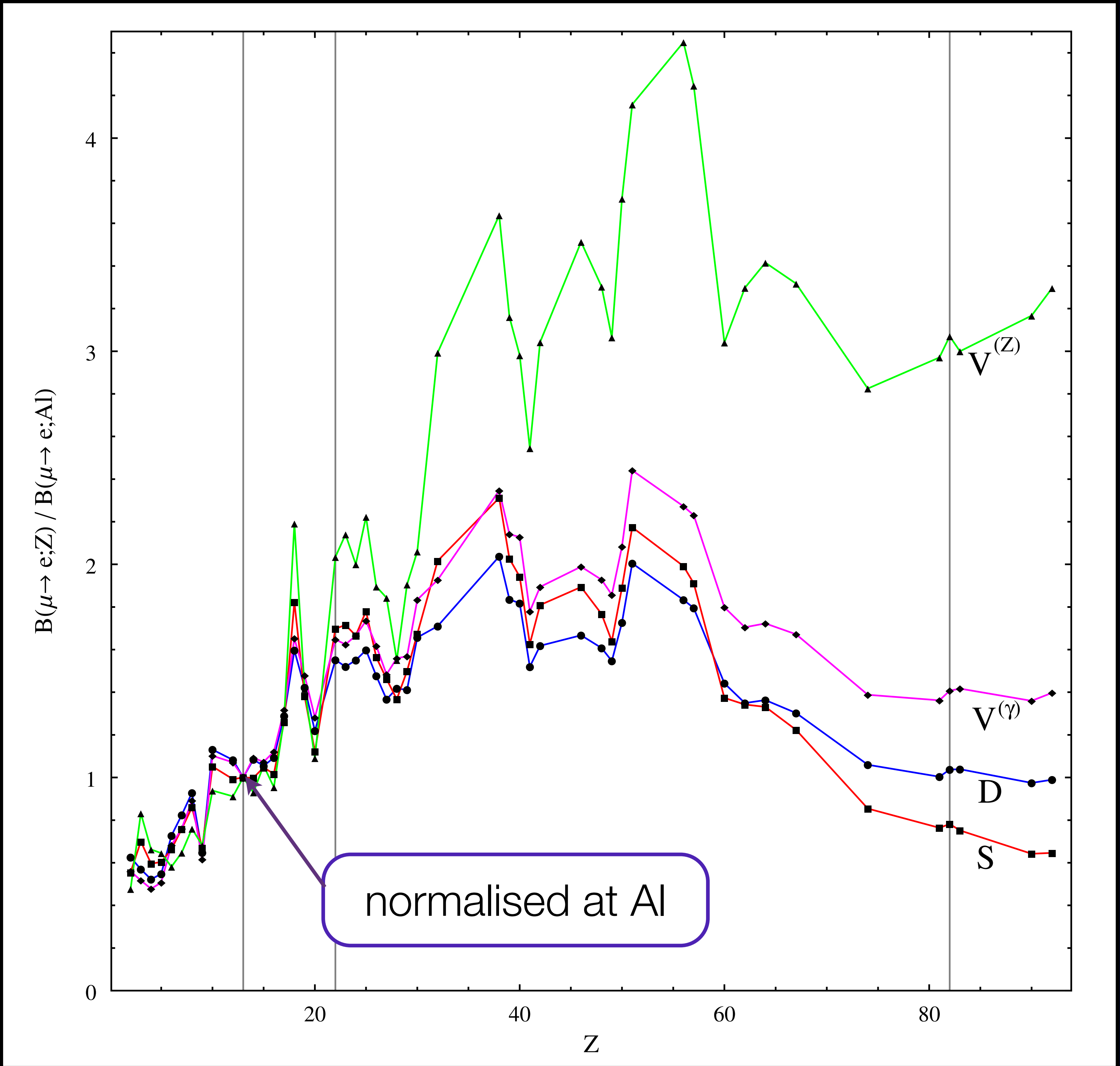
μ-e conversion sensitive to more new physics

μ-e Conversion : Target dependence (discriminating effective interaction)



V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, Phys. Rev. D80, 013002 (2009)

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

CLFV Effective Interactions

CLFV Effective Interactions

Dipole interaction

Contact interaction

dipole interaction

vector interaction

scalar interaction

axial vector interaction

tensor interaction

CLFV Effective Interactions

Dipole interaction

Contact interaction

dipole interaction

vector interaction

scalar interaction

Spin-independent μ-e Conversion (coherent)

axial vector interaction

tensor interaction

Spin-dependent μ-e Conversion (incoherent)

Spin dependent μ-e conversion

Physics Letters B 771 (2017) 242–246

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Spin-dependent $\mu \to e$ conversion

Vincenzo Cirigliano [a], Sacha Davidson [b,*], Yoshitaka Kuno [c]

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[b] IPNL, CNRS/IN2P3, Université Lyon 1, Univ. Lyon, 69622 Villeurbanne, France
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ABSTRACT

The experimental sensitivity to $\mu \to e$ conversion on nuclei is expected to improve by four orders of magnitude in coming years. We consider the impact of $\mu \to e$ flavour-changing tensor and axial-vector four-fermion operators which couple to the spin of nucleons. Such operators, which have not previously been considered, contribute to $\mu \to e$ conversion in three ways: in nuclei with spin they mediate a spin-dependent transition; in all nuclei they contribute to the coherent (A^2-enhanced) spin-independent conversion via finite recoil effects and via loop mixing with dipole, scalar, and vector operators. We estimate the spin-dependent rate in Aluminium (the target of the upcoming COMET and Mu2e experiments), show that the loop effects give the greatest sensitivity to tensor and axial-vector operators involving first-generation quarks, and discuss the complementarity of the spin-dependent and independent contributions to $\mu \to e$ conversion.

Experimental Comparison : $\mu \to e\gamma$ and μ-e Conversion

Experimental Comparison : μ→eγ and μ-e Conversion

	Beam	background	challenge	beam intensity
μ→eγ	continuous beam	accidentals	detector resolution	limited
μ→eee	continuous beam	accidentals	detector resolution	limited
μ-e conversion	pulsed beam	beam-related	beam background	no limitation

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μ-e conversion can go to higher sensitivity

Backgrounds for μ-e conversion

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

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beam-related backgrounds

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

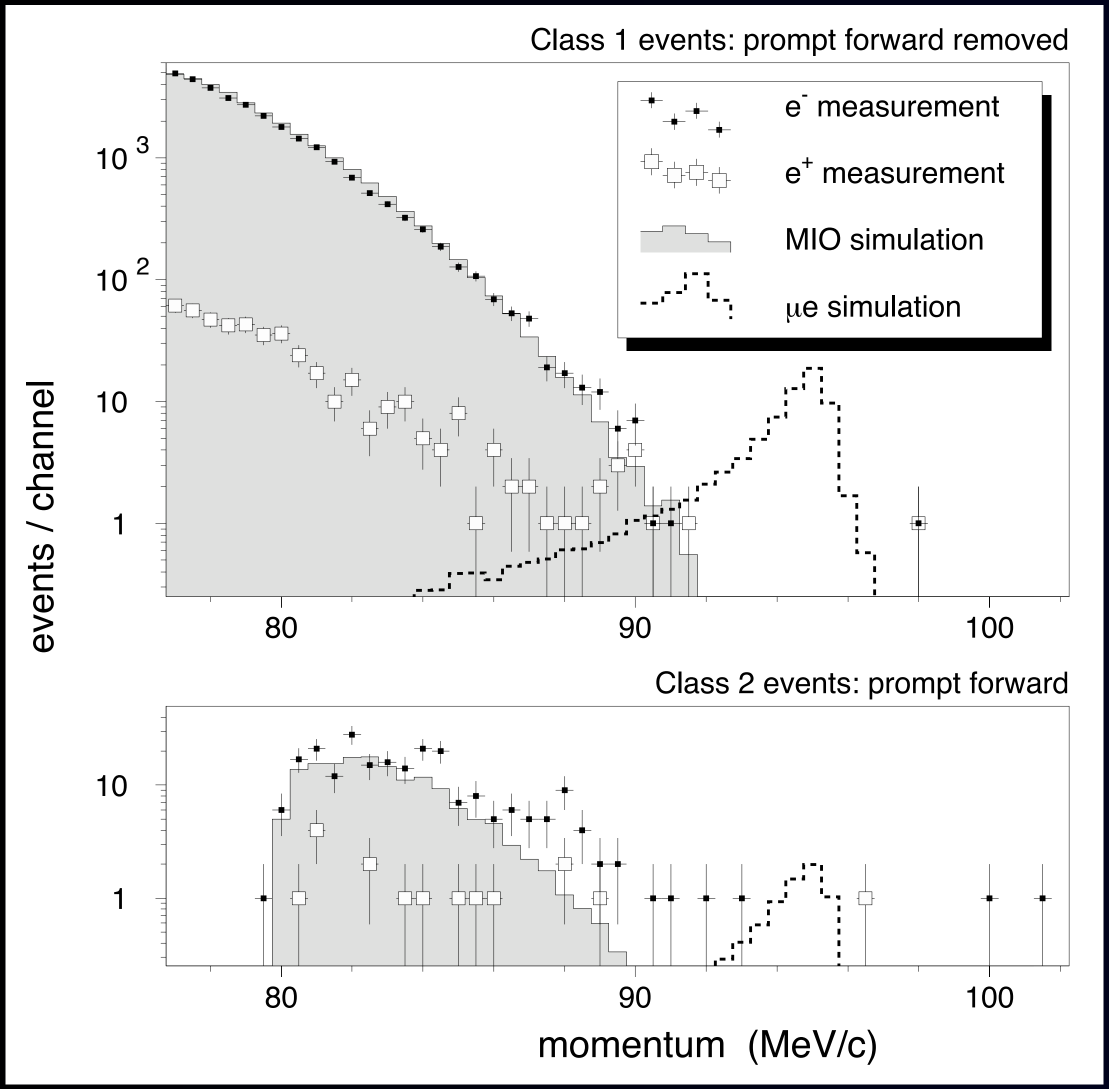
Backgrounds for μ-e conversion

intrinsic physics backgrounds	Muon decay in orbit (DIO) Radiative muon capture (RMC) neutrons from muon nuclear capture Protons from muon nuclear capture
beam-related backgrounds	Radiative pion capture (RPC) Beam electrons Muon decay in flights Neutron background Antiproton induced background
cosmic-ray and other backgrounds	Cosmic-ray induced background False tracking

Previous and Future Measurements for Muon to Electron Conversion

Previous and Future Measurements for Muon to Electron Conversion

SINDRUM-II (PSI)



Published Results (2004)

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

Previous and Future Measurements for Muon to Electron Conversion

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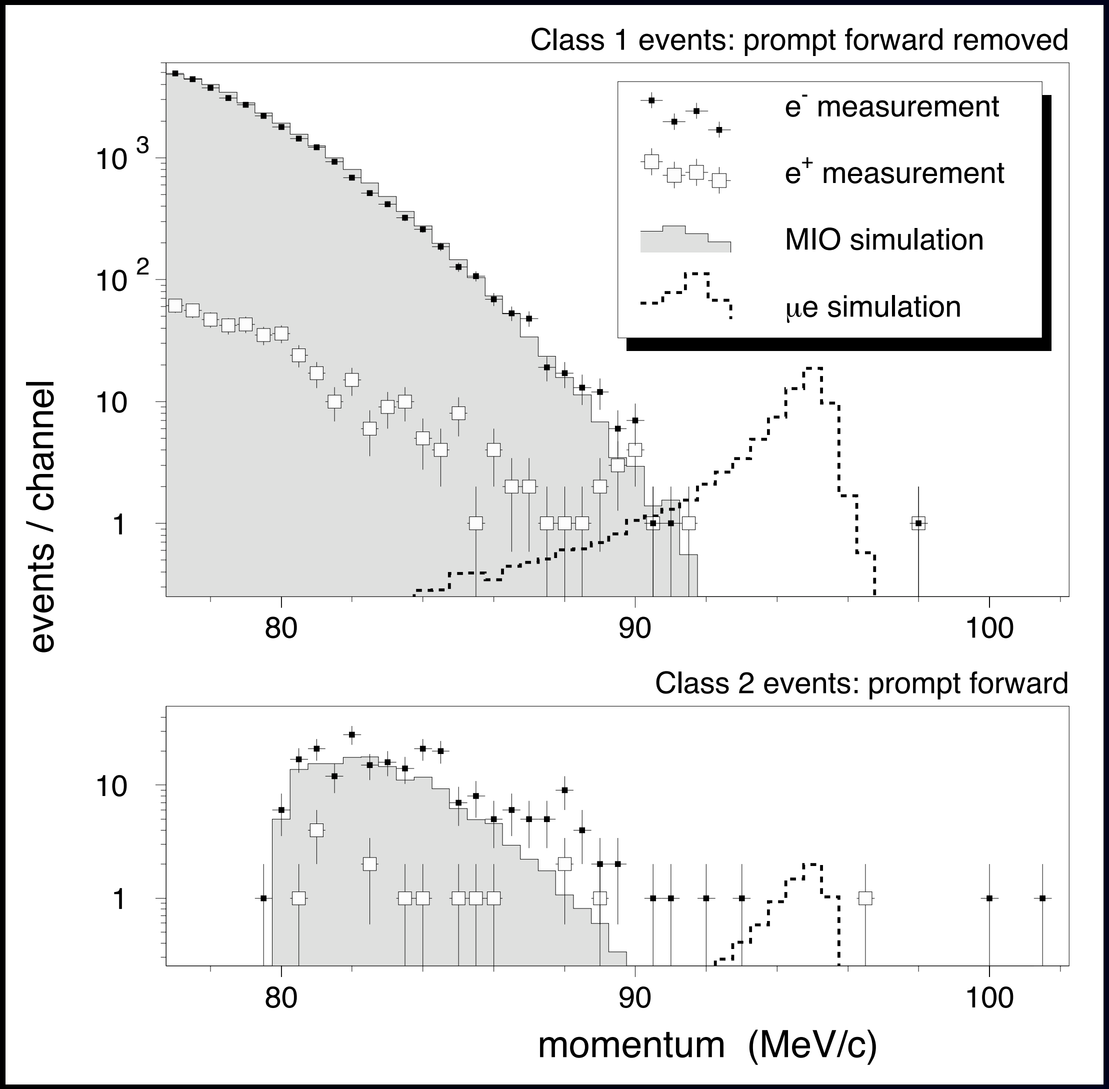

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Future Measurements

A total number of muons is the key for success.

COMET : 10^{18} muons

(past exp. 10^{14} muons)

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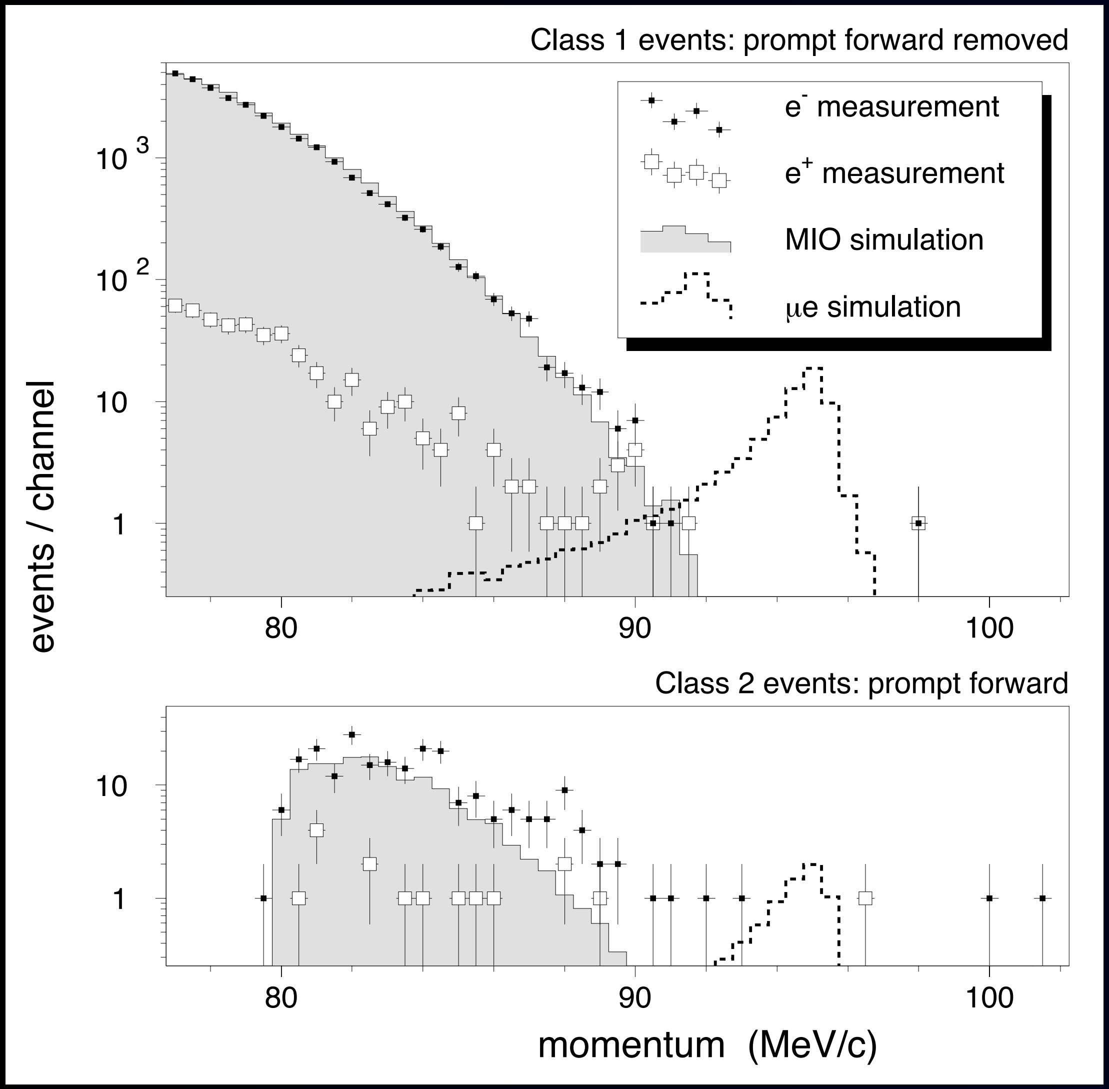

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Future Measurements

A total number of muons is the key for success.

COMET : 10^{18} muons

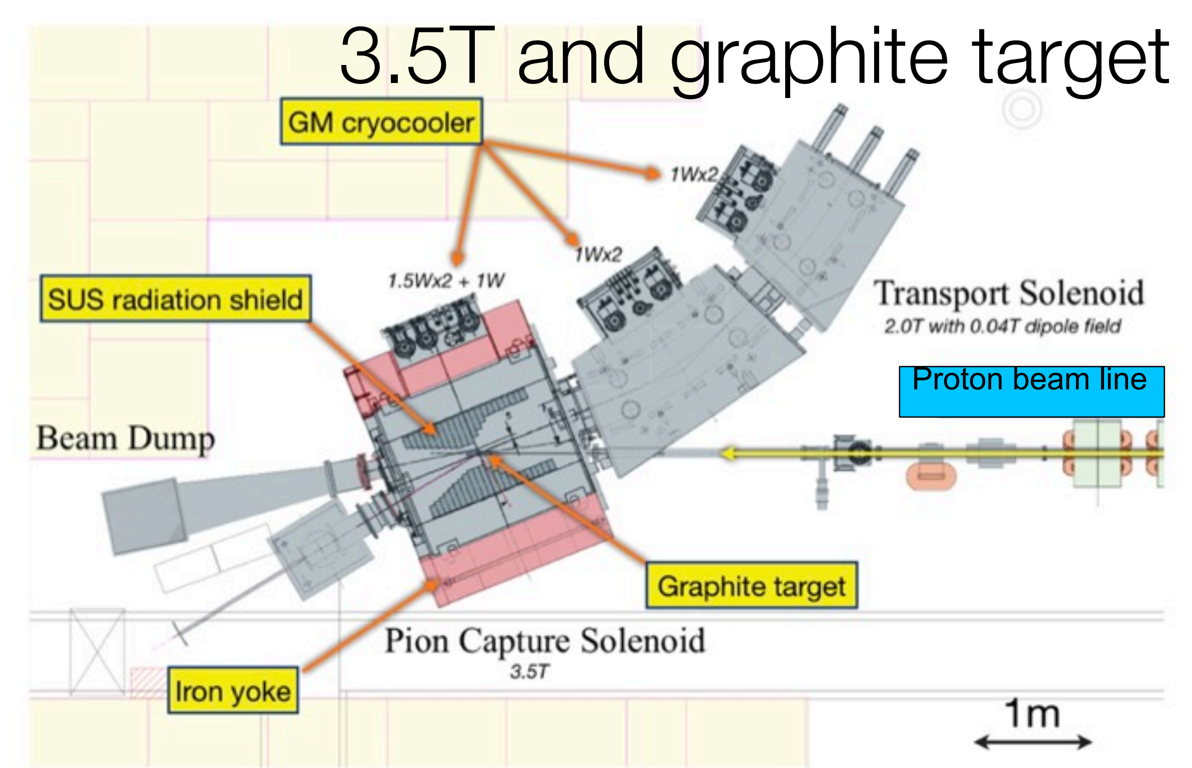
(past exp. 10^{14} muons)

1000 years needed at PSI with intensity of 10^{15} muons/year

MuSIC at RCNP, Osaka University
- Highly Intense Muon Source -

3.5T and graphite target

MuSIC at RCNP, Osaka University - Highly Intense Muon Source -



MuSIC at RCNP, Osaka University
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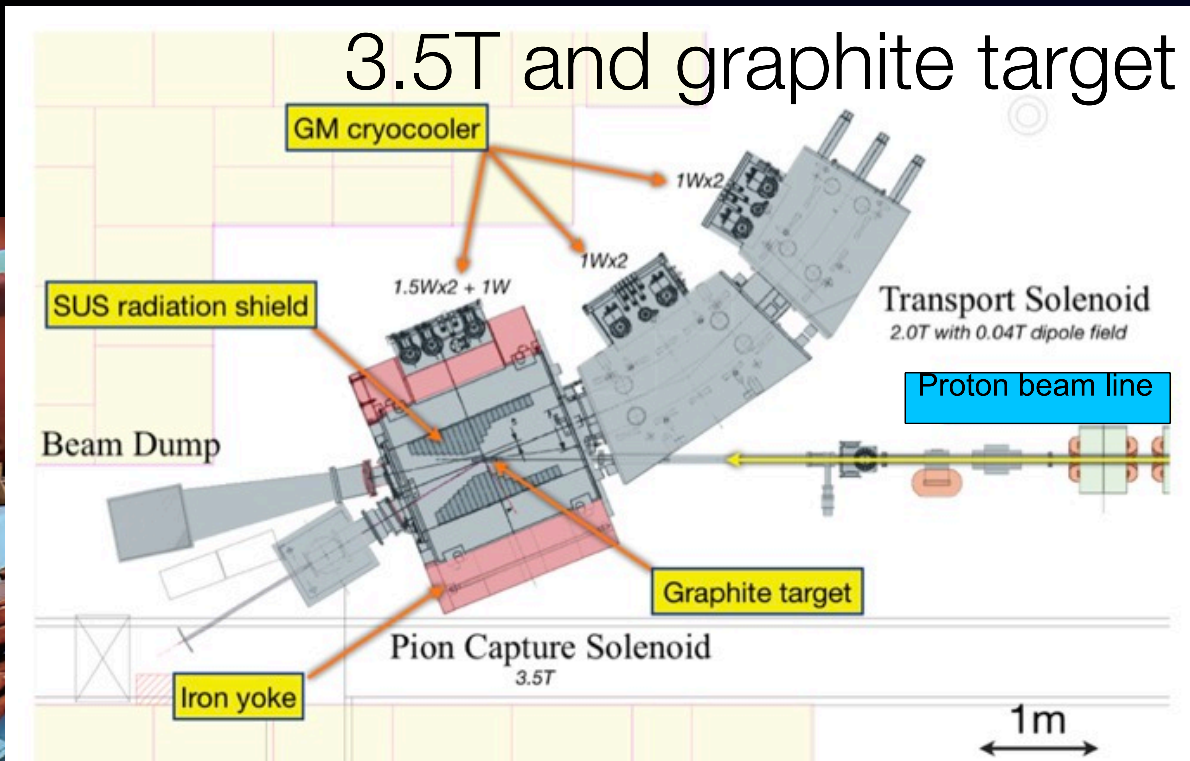

MuSIC at RCNP, Osaka University
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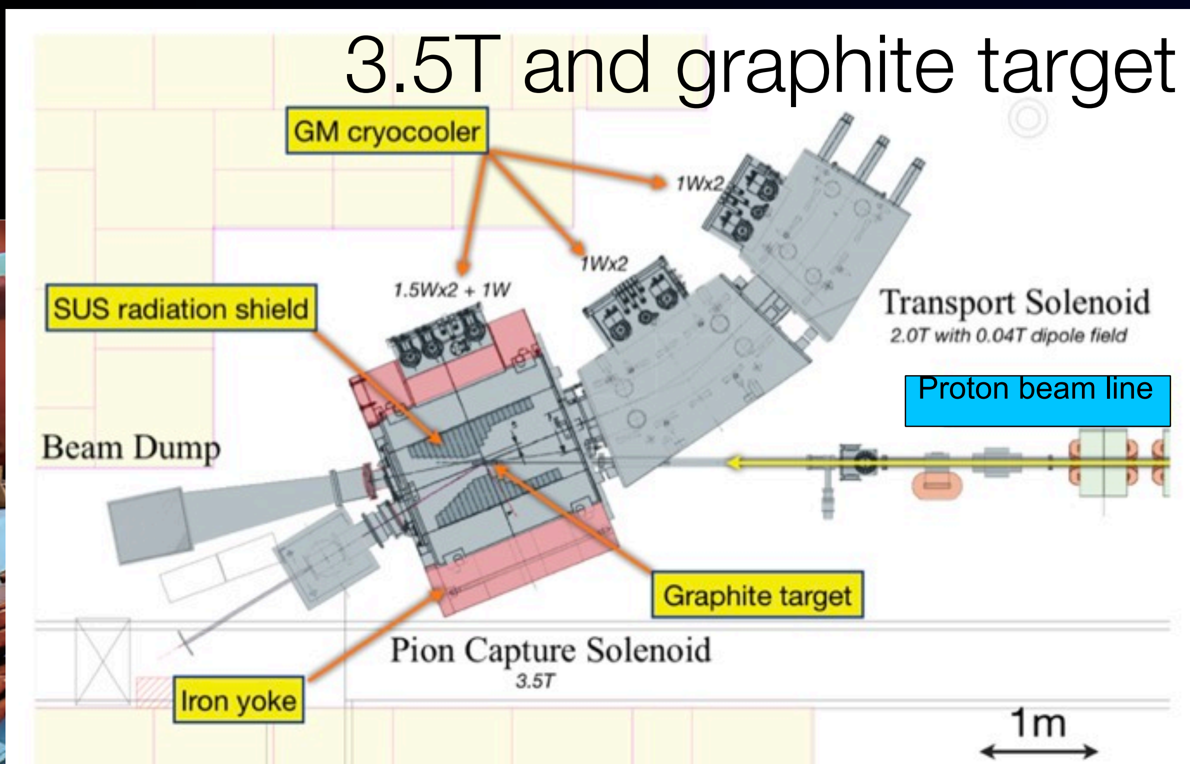
Muon Science Intense Channel (>2011)



MuSIC at RCNP, Osaka University
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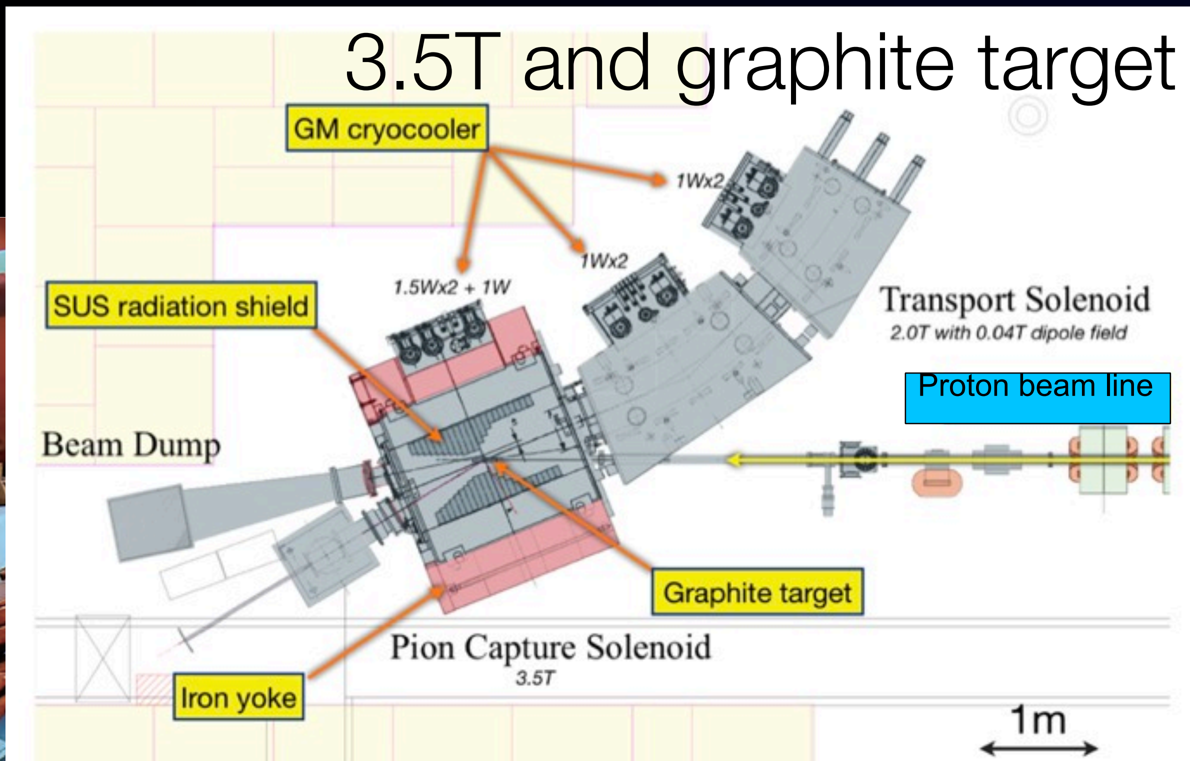
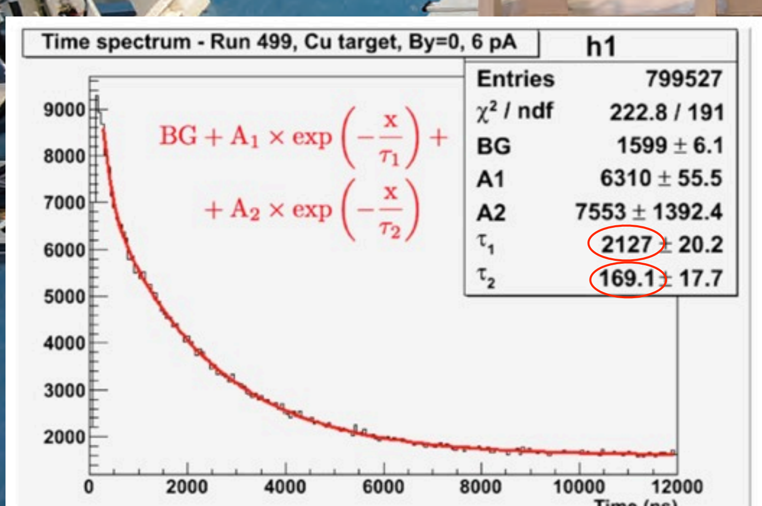
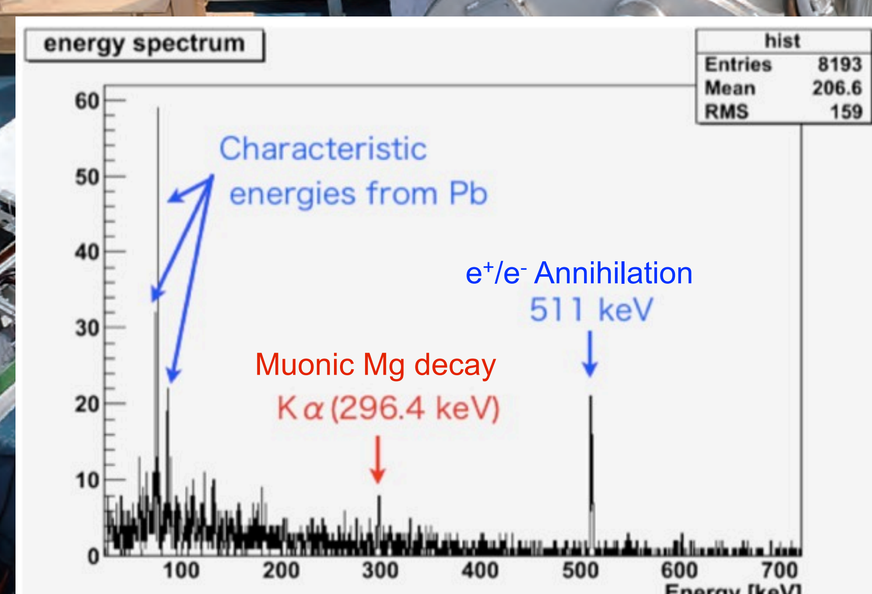




	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



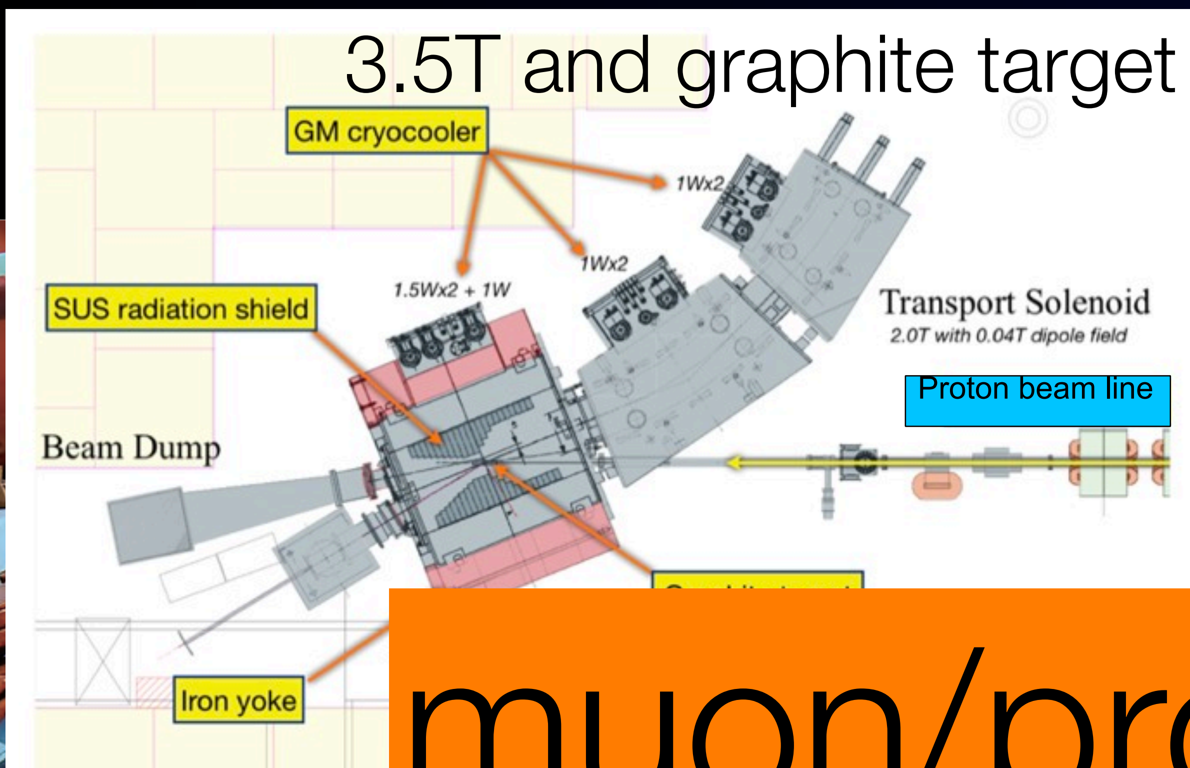
MuSIC muon yields

μ^+ : 3×10^8/s for 400W

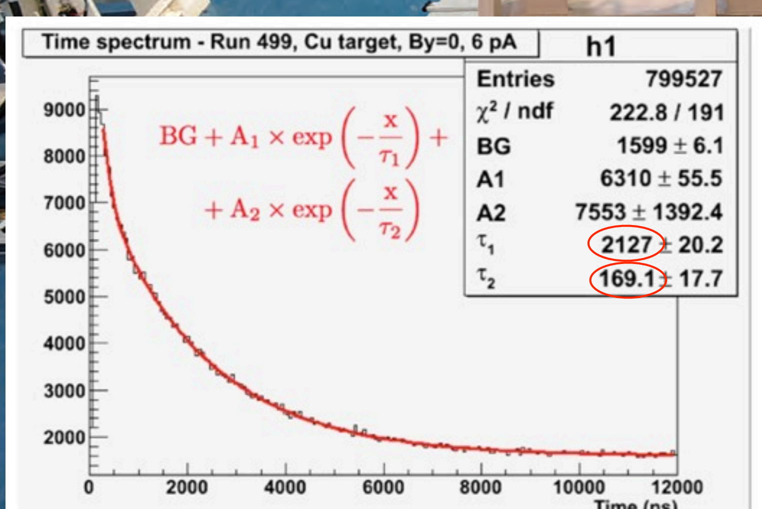
μ^- : 1×10^8/s for 400W

MuSIC at RCNP, Osaka University
- Highly Intense Muon Source -

Muon Science Intense Channel (>2011)



muon/proton~x1000



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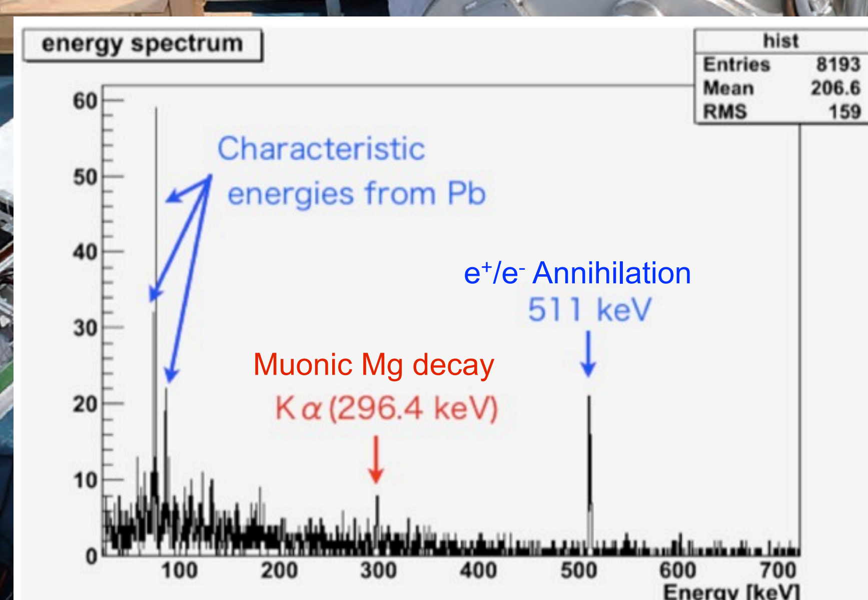

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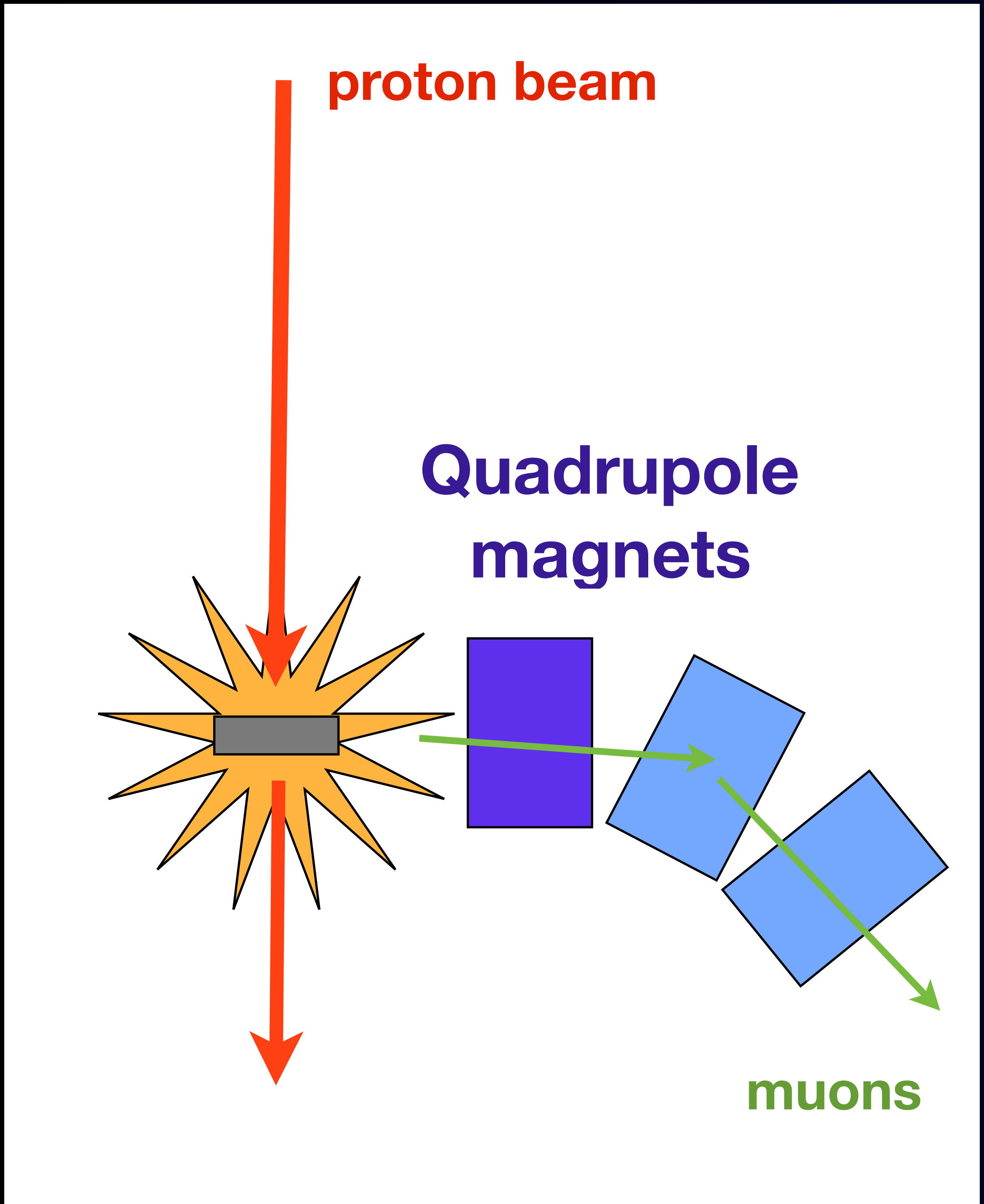
Production and Collection of Pions/Muons in Solenoidal Magnetic Fields

Production and Collection of Pions/Muons in Solenoidal Magnetic Fields

Conventional muon beam source



Production and Collection of Pions/Muons in Solenoidal Magnetic Fields

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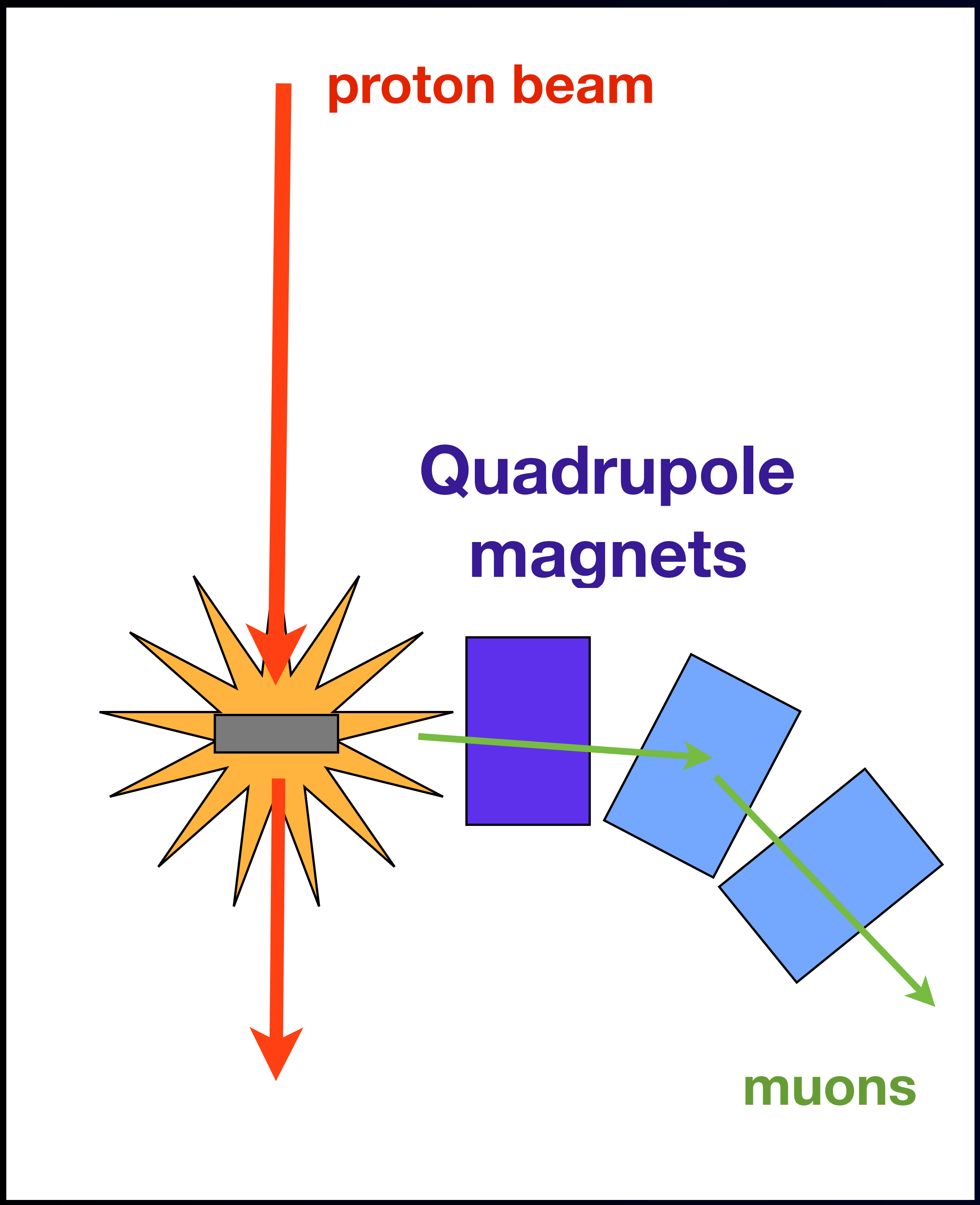
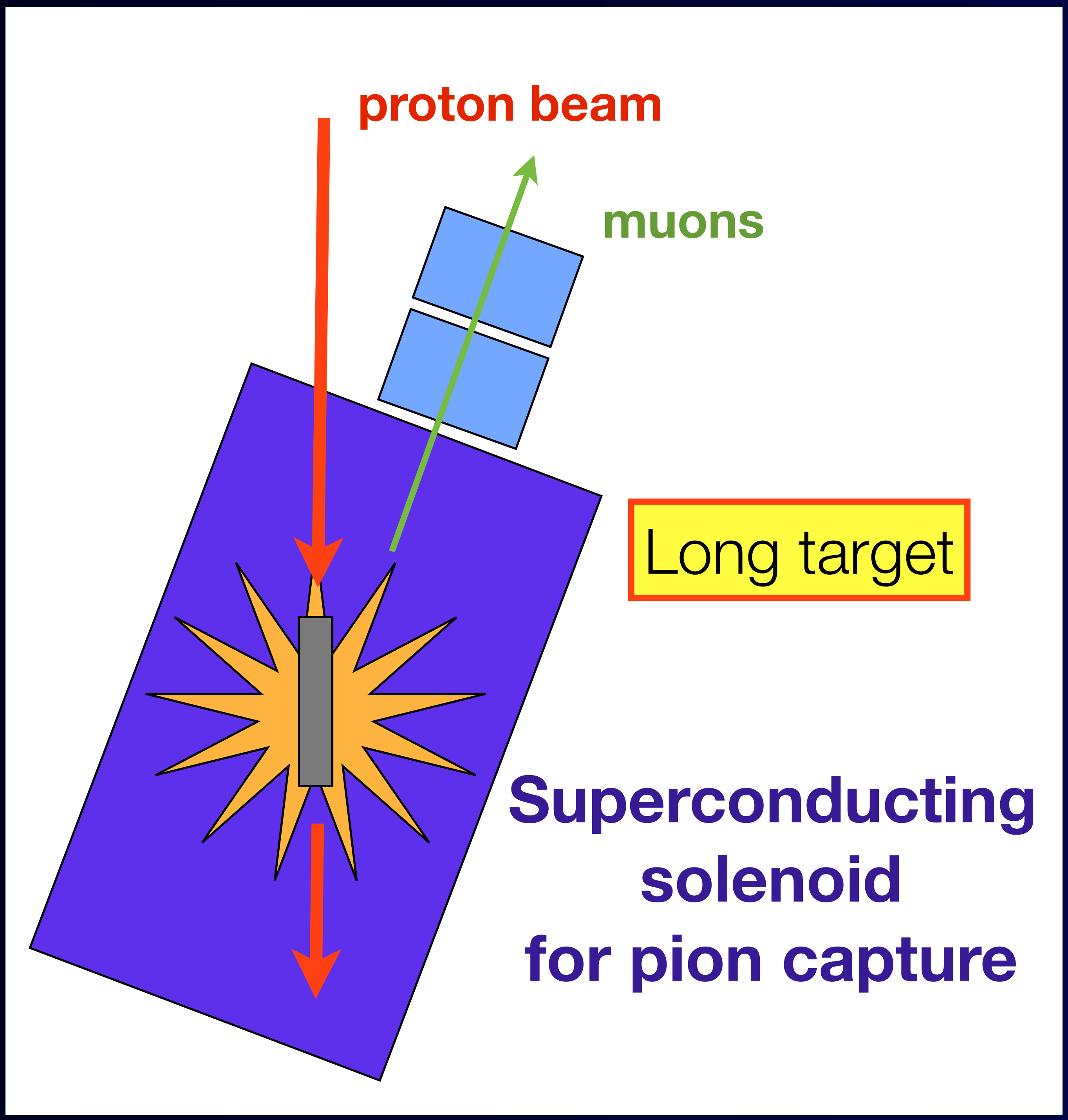


New muon beam sources



Article on the MuSIC facility…

March, 2017, Editors Suggestions

Edittors Suggestions

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 030101 (2017)

Delivering the world's most intense muon beam

S. Cook,[1] R. D'Arcy,[1] A. Edmonds,[1] M. Fukuda,[2] K. Hatanaka,[2] Y. Hino,[3] Y. Kuno,[3] M. Lancaster,[1] Y. Mori,[4] T. Ogitsu,[5] H. Sakamoto,[3] A. Sato,[3] N. H. Tran,[3] N. M. Truong,[3] M. Wing,[1,*] A. Yamamoto,[5] and M. Yoshida[5]

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[2]*Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan*
[3]*Department of Physics, Graduate School of Science, Osaka University, Osaka 569-0043, Japan*
[4]*Kyoto University Reactor Research Institute (KURRI), Kyoto 590-0494, Japan*
[5]*High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

(Received 25 October 2016; published 15 March 2017)

A new muon beam line, the muon science innovative channel, was set up at the Research Center for Nuclear Physics, Osaka University, in Osaka, Japan, using the 392 MeV proton beam impinging on a target. The production of an intense muon beam relies on the efficient capture of pions, which subsequently decay to muons, using a novel superconducting solenoid magnet system. After the pion-capture solenoid, the first 36° of the curved muon transport line was commissioned and the muon flux was measured. In order to detect muons, a target of either copper or magnesium was placed to stop muons at the end of the muon

Improvements for Background Rejection

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Beam-related backgrounds → Beam pulsing with separation of 1μsec

measured between beam pulses

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

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improve electron energy resolution

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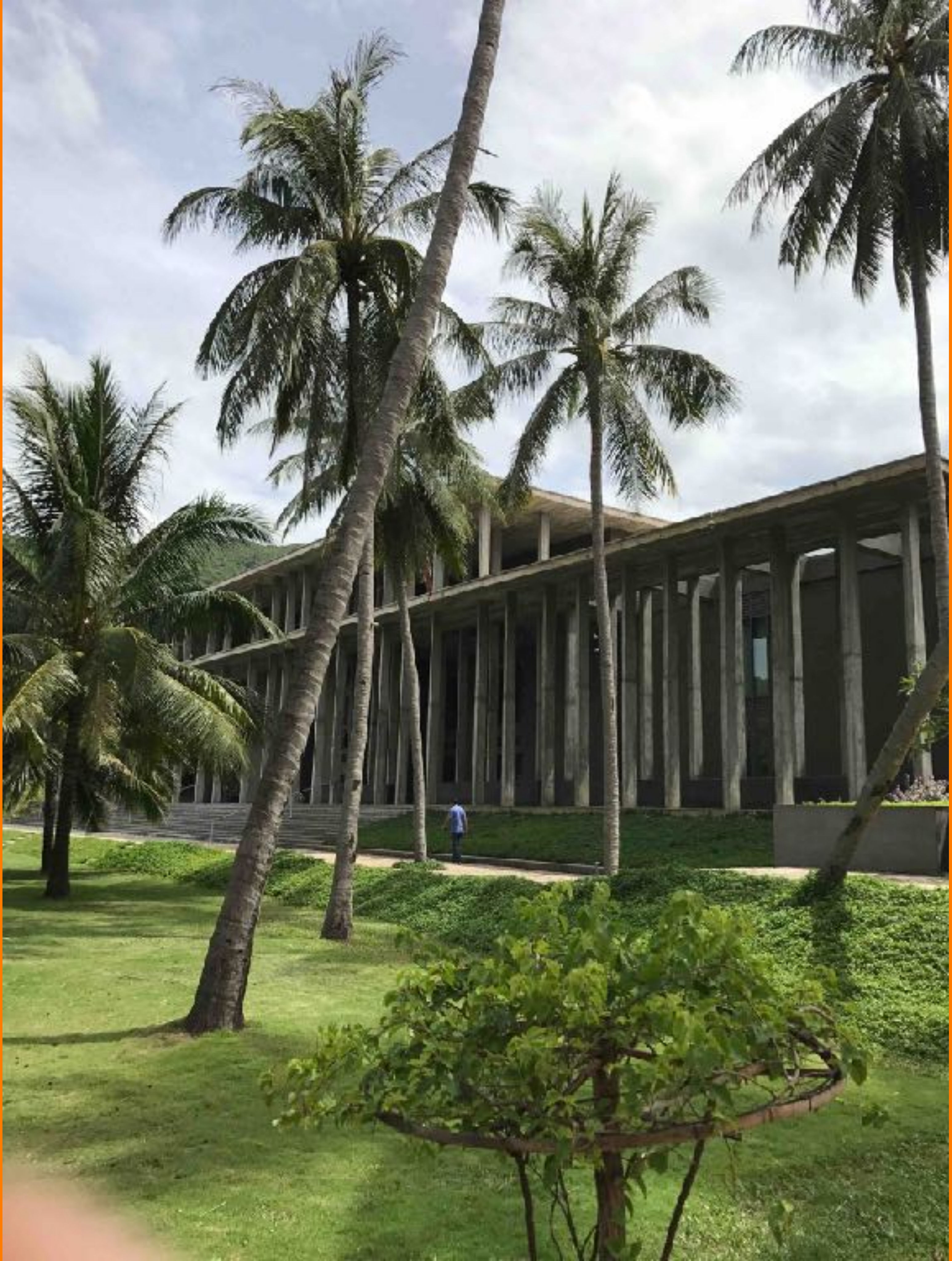
based on the MELC proposal at Moscow Meson Factory

Experiments
for μ-e conversion



Mu2e at Fermilab

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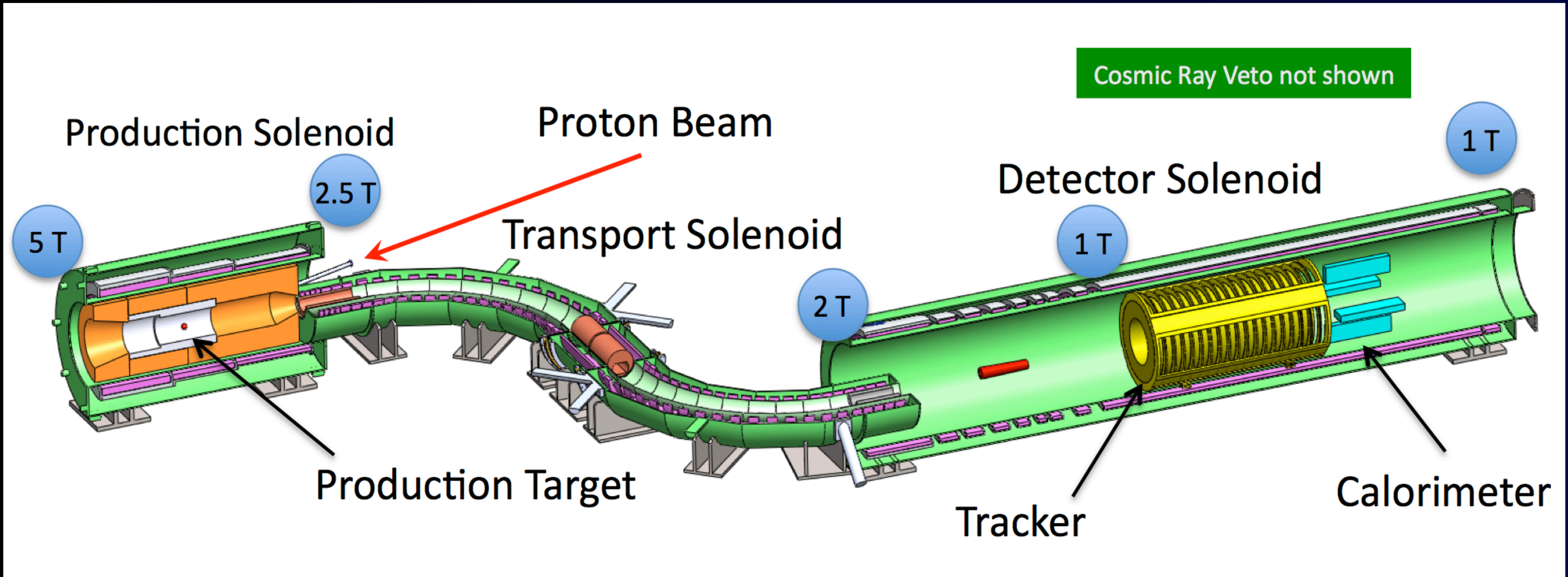
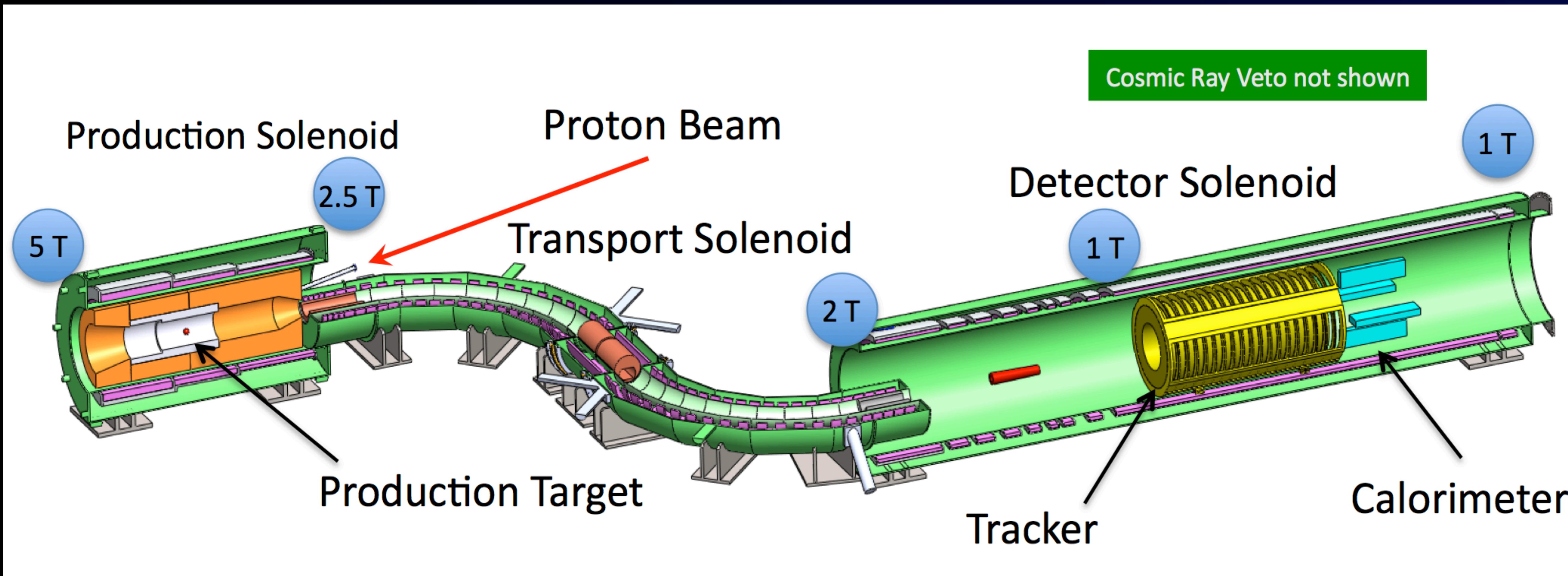


Mu2e at Fermilab



Single-event sensitivity : $(2.5\pm0.3)\times10^{-17}$

Total background : (0.36 ± 0.10) events

Expected limits : $< 6\times10^{-17}$ @90%C.L.

Running time: 3 years (2×10^{7}sec/year)

proton beam power = 8 kW

COMET at J-PARC: E21

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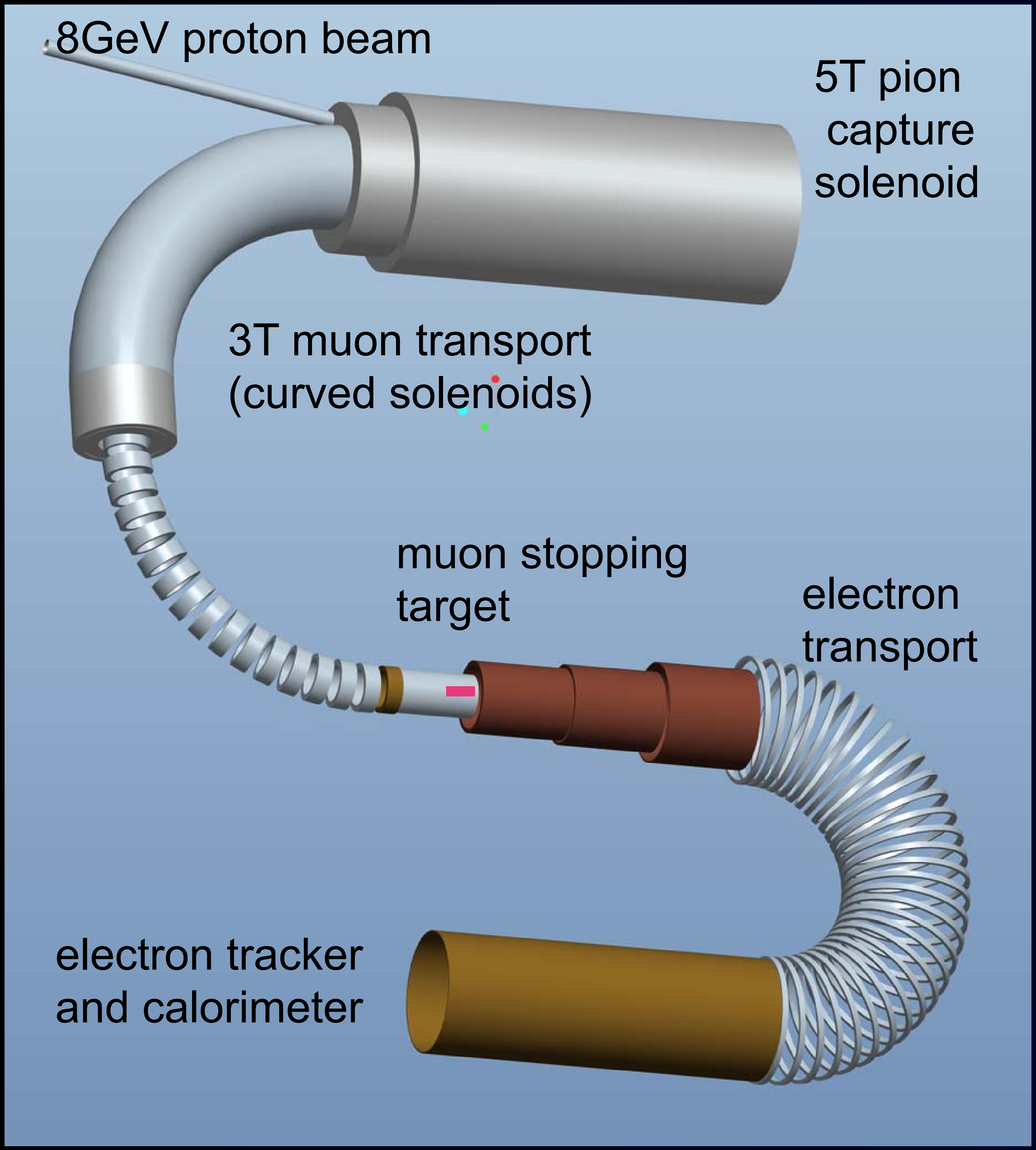


Physics sensitivity : $(1.0\text{-}2.6)\times10^{-17}$

Total background : 0.32 events

Expected limits : $< 6\times10^{-17}$@90%CL

Running time: 1 years (2×10^{7}sec)

proton beam power = 56 kW

COMET = COherent Muon to Electron Transition

COMET

Osaka University

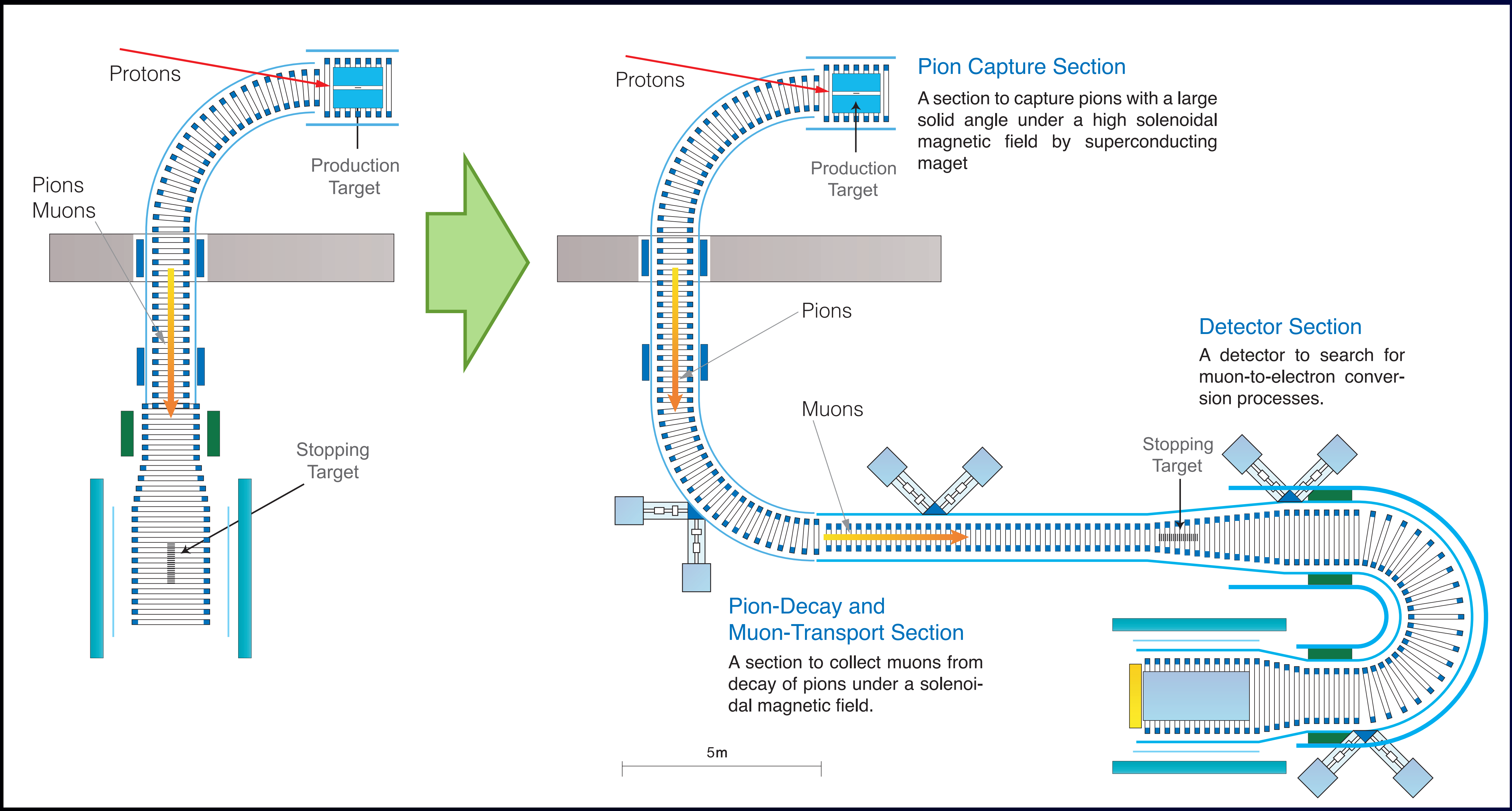
COMET Phase-I

COMET Staged Approach (2012~)

COMET Staged Approach (2012~)

COMET Phase-I

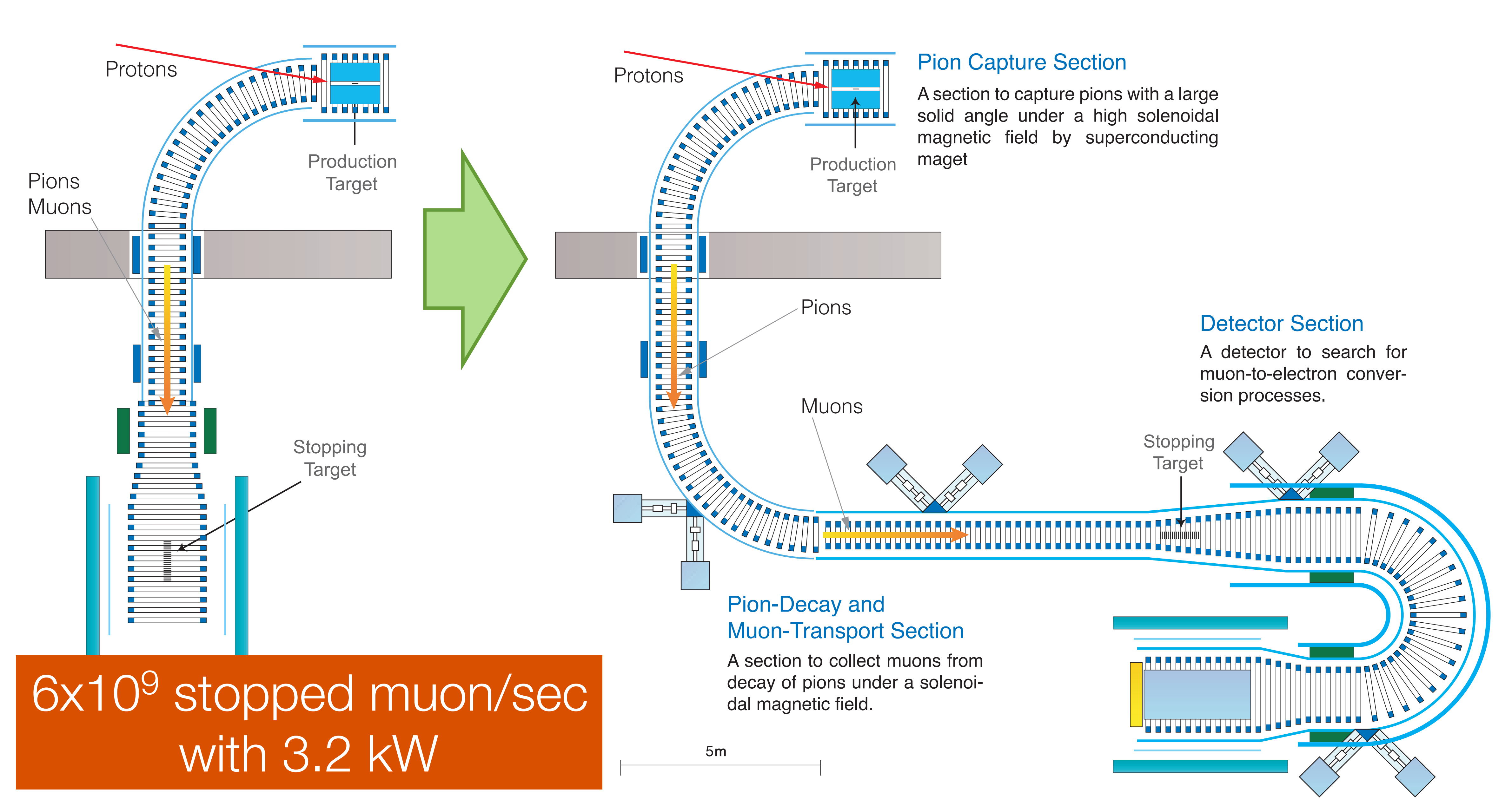
COMET Phase-II



COMET Staged Approach (2012~)

COMET Phase-I

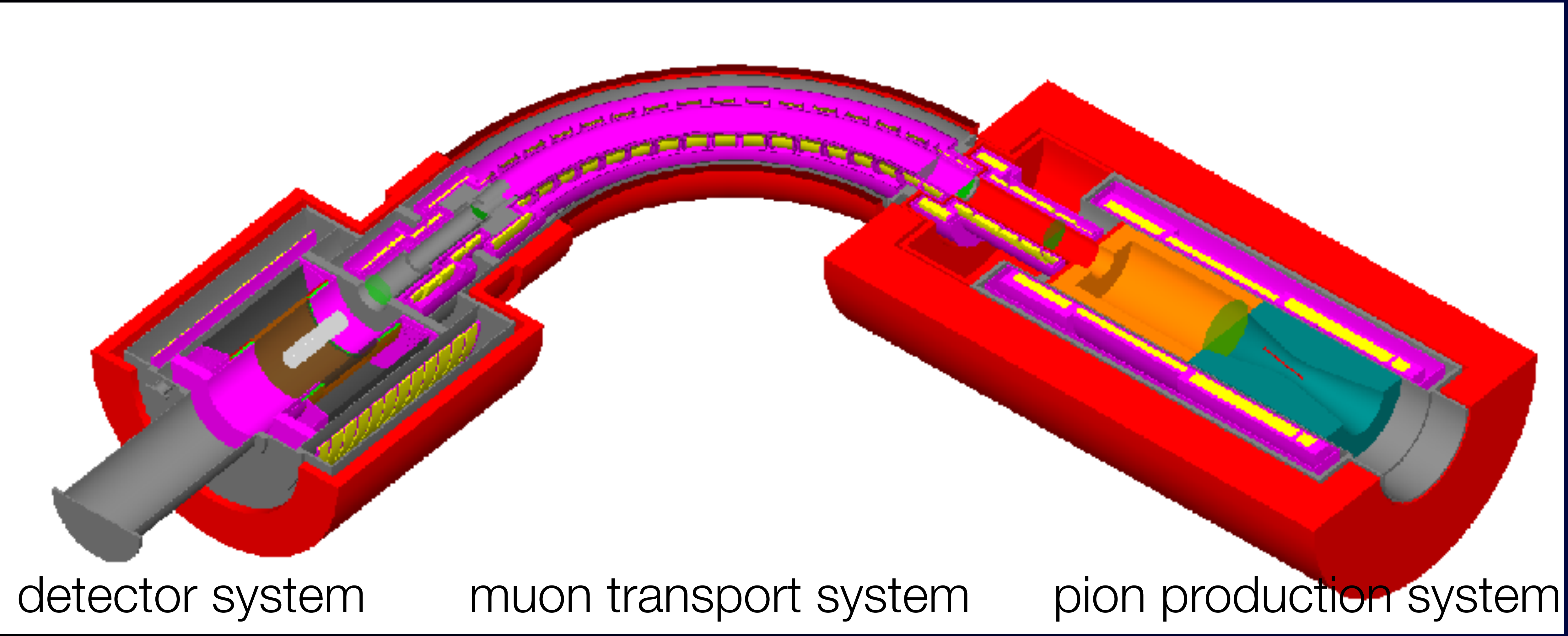
COMET Phase-II



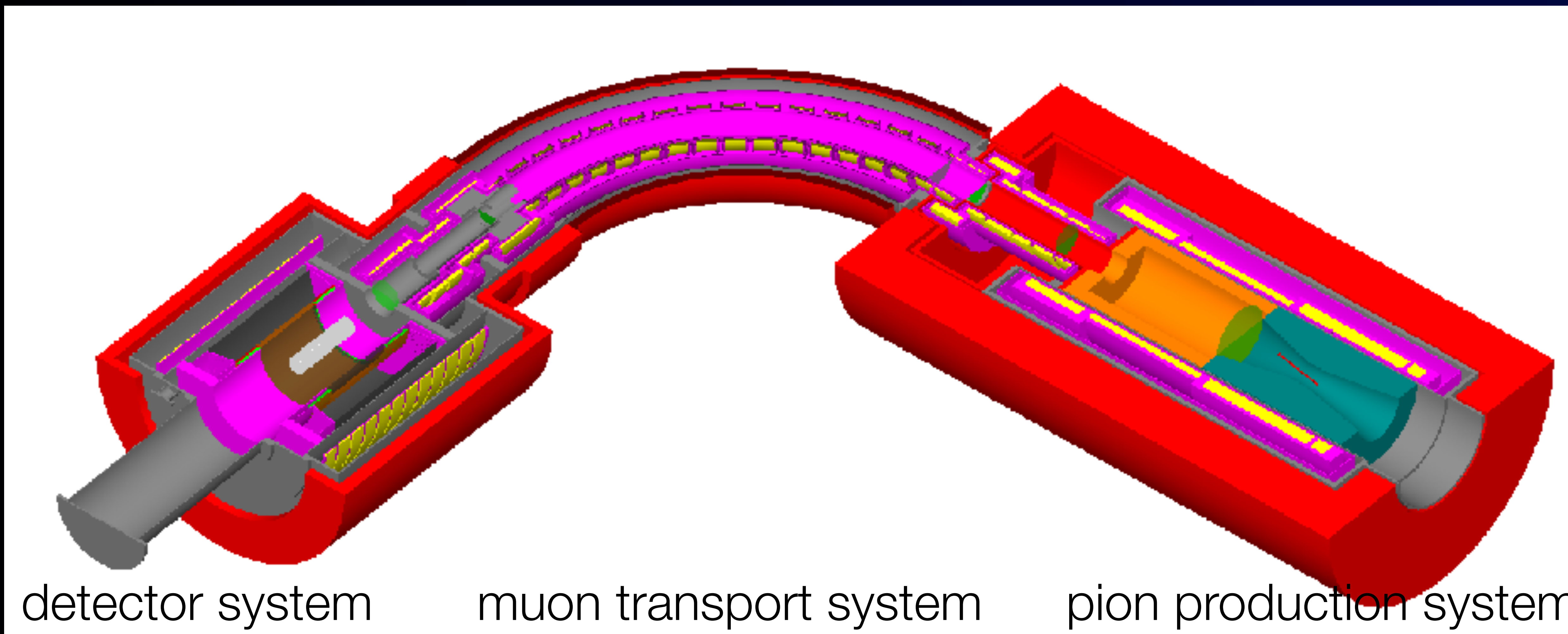
6×10^9 stopped muon/sec with 3.2 kW

COMET Phase-I

COMET Phase-I



COMET Phase-I



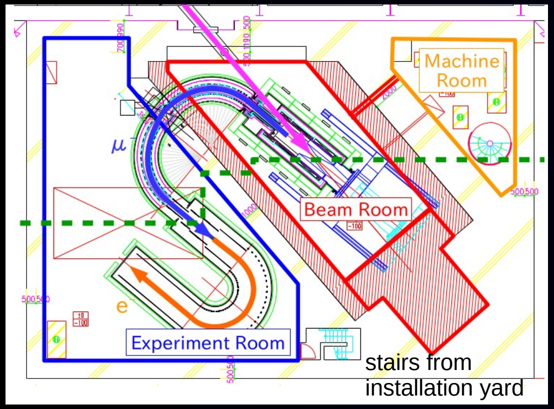
Single-event sensitivity : 3×10^{-15}

Total background : 0.2 events

Expected limits : < 6×10^{-15} @90%CL

Running time: 150 days

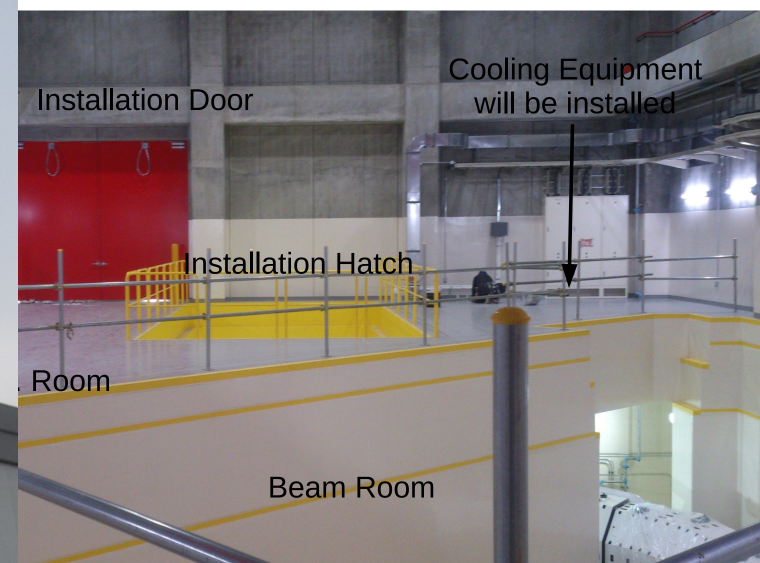
New COMET Building at J-PARC



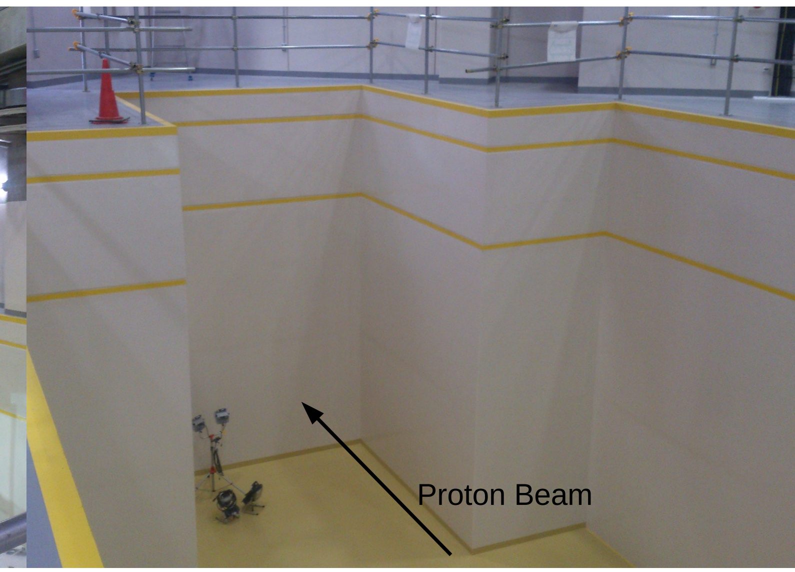
New COMET Building at J-PARC

New COMET Building at J-PARC

Installation Yard

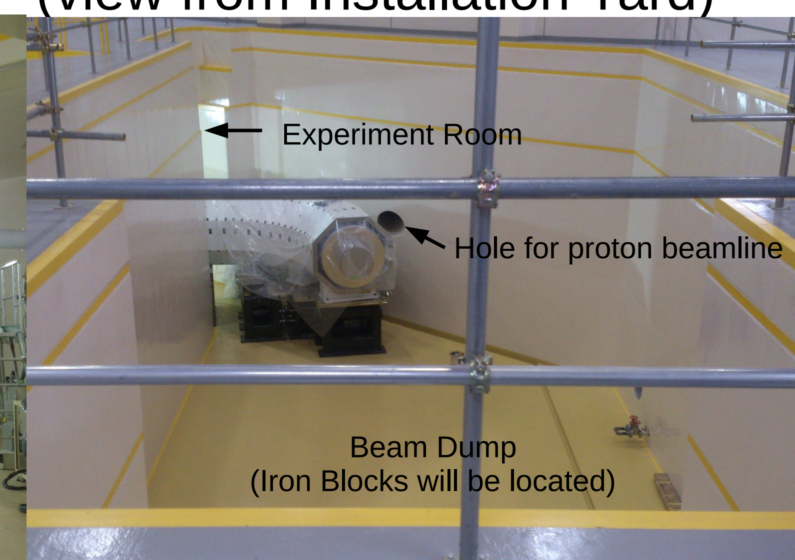


Beam Room



Experiment Room (View from Door)

Beam Room (view from Installation Yard)



Curved Solenoids for Muon Transport Completed and Delivered!

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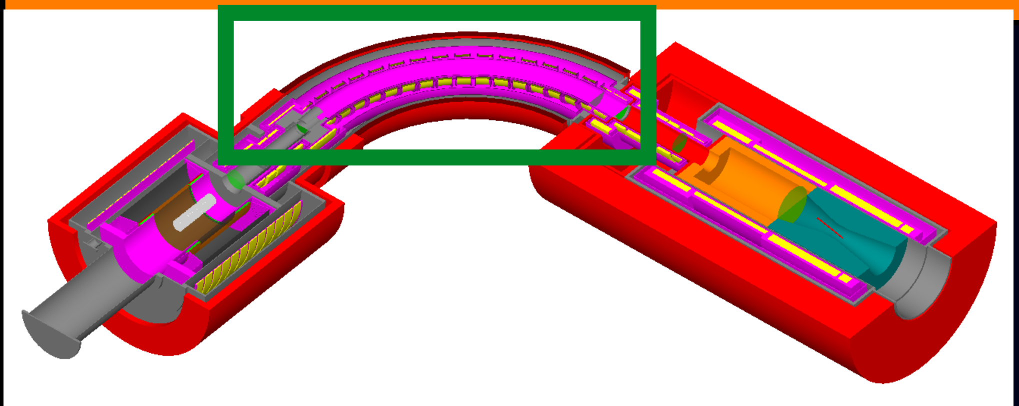

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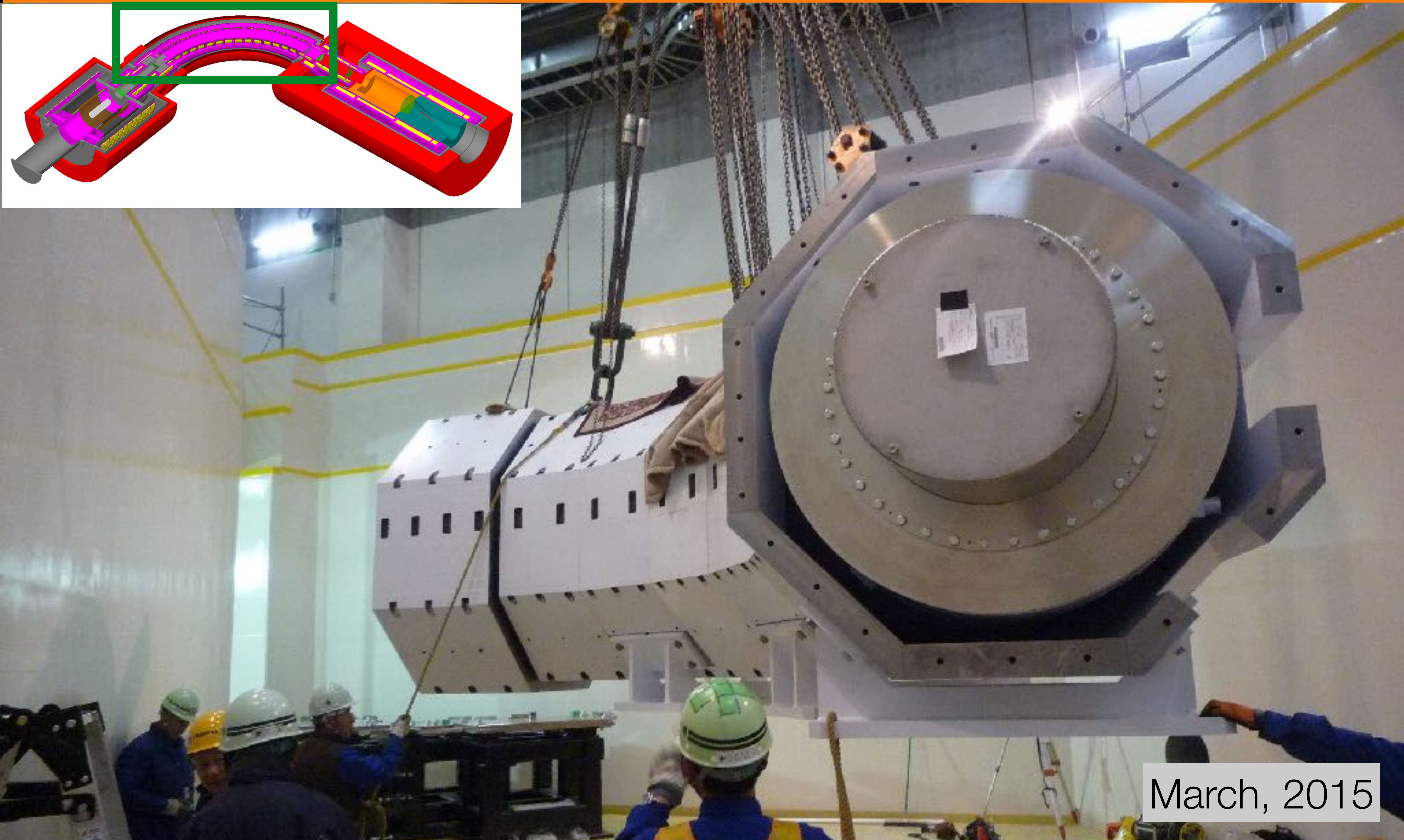
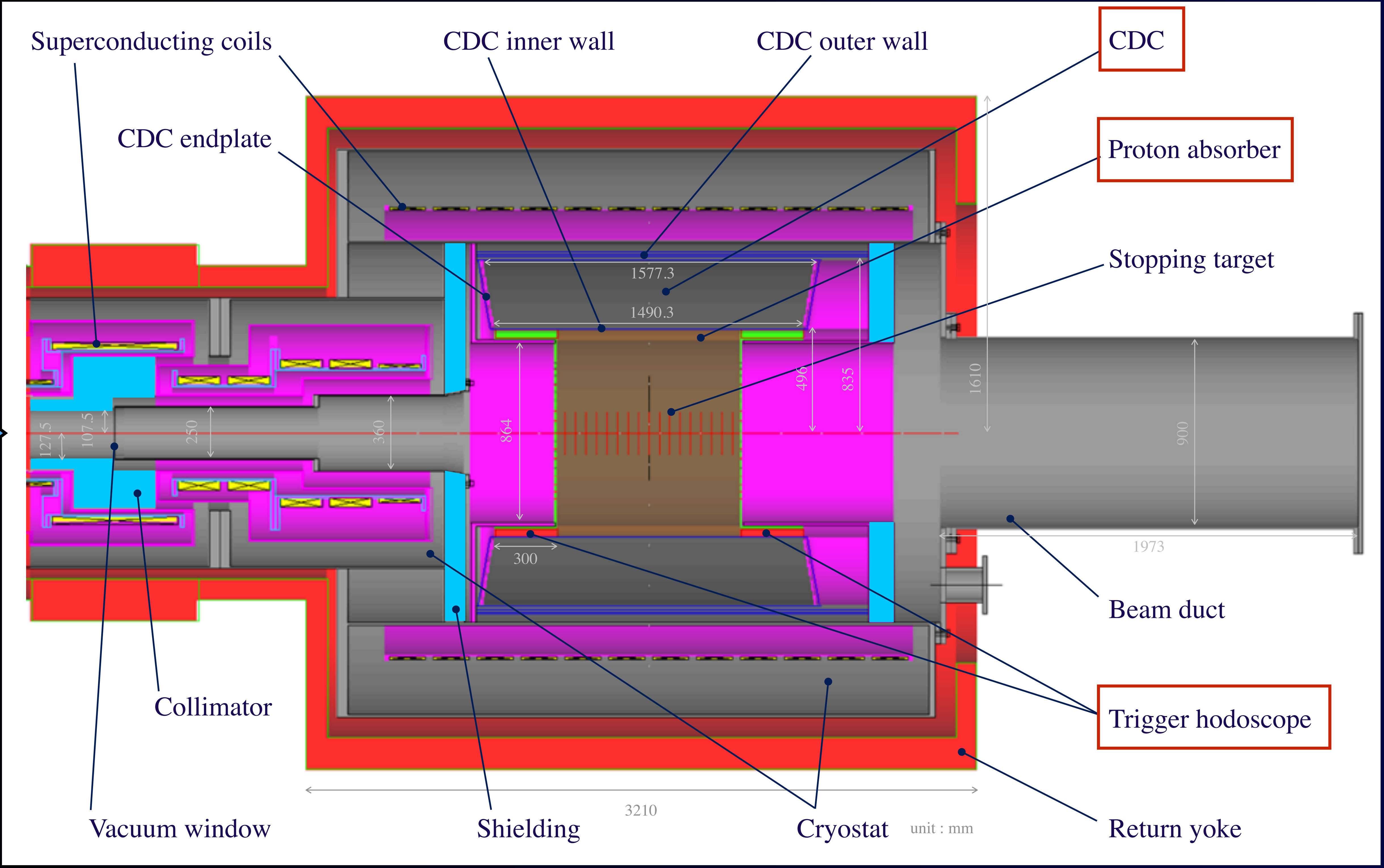


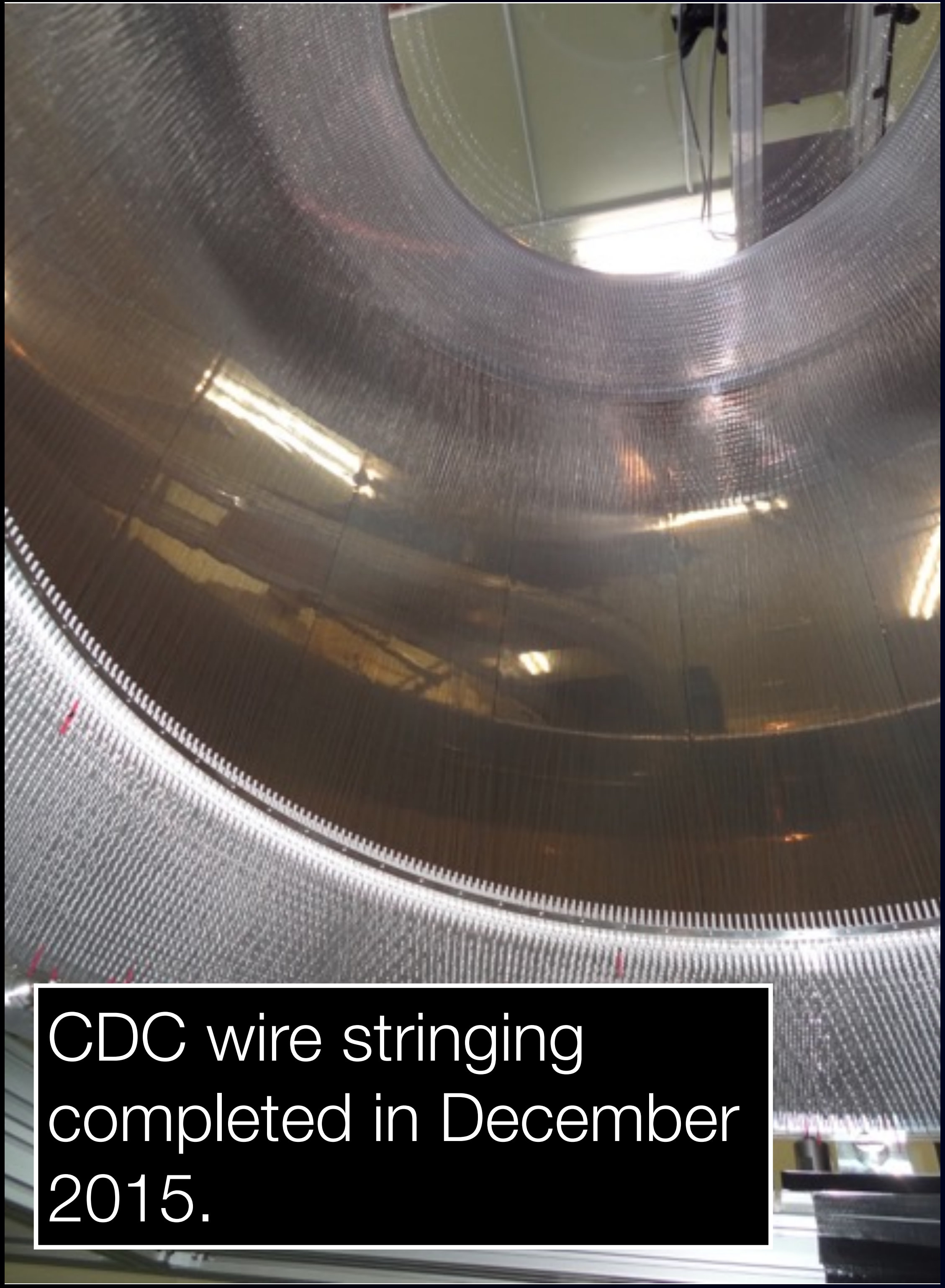
March, 2015

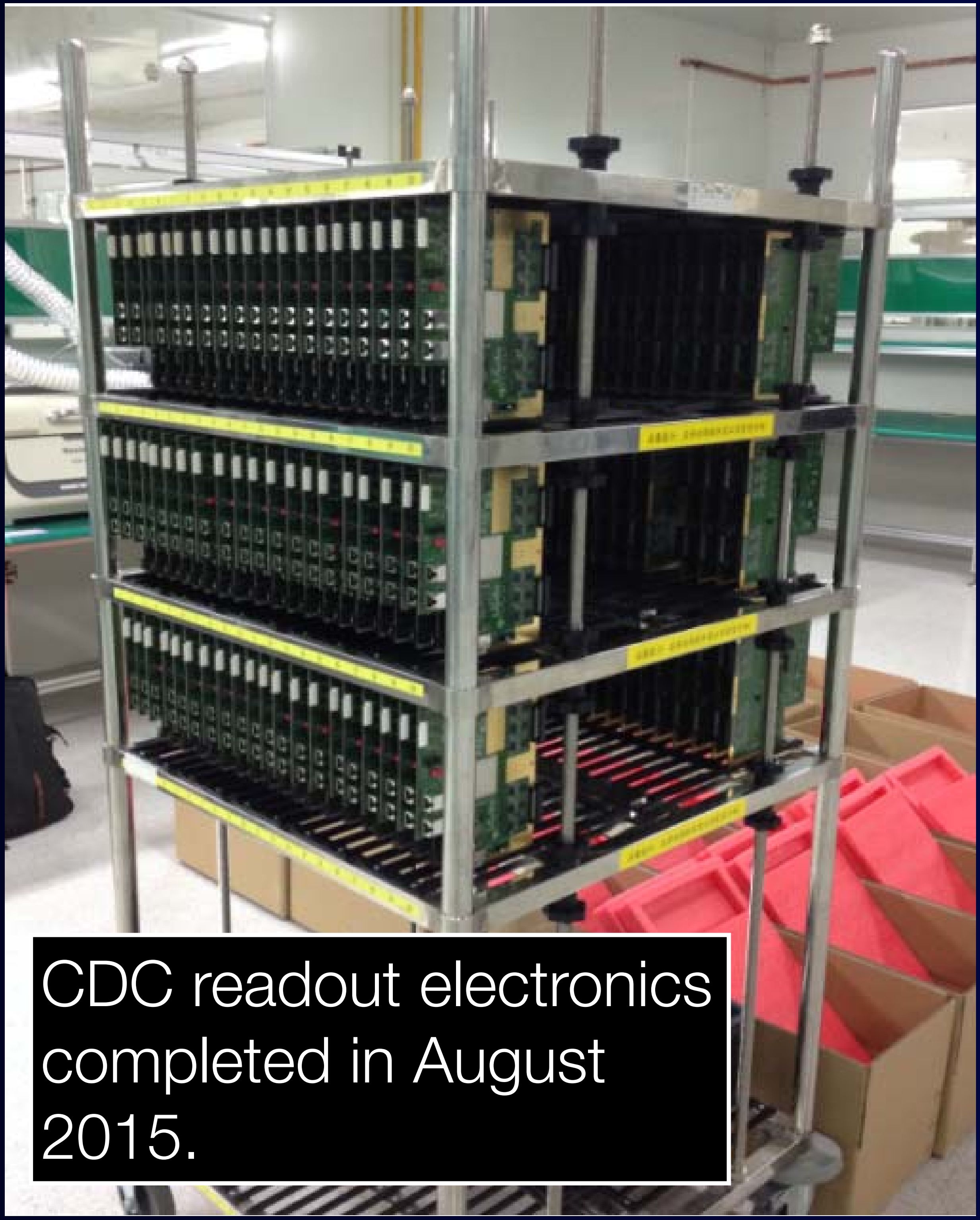
CyDet (Cylindrical Detector)

muon



CDC Construction completed!





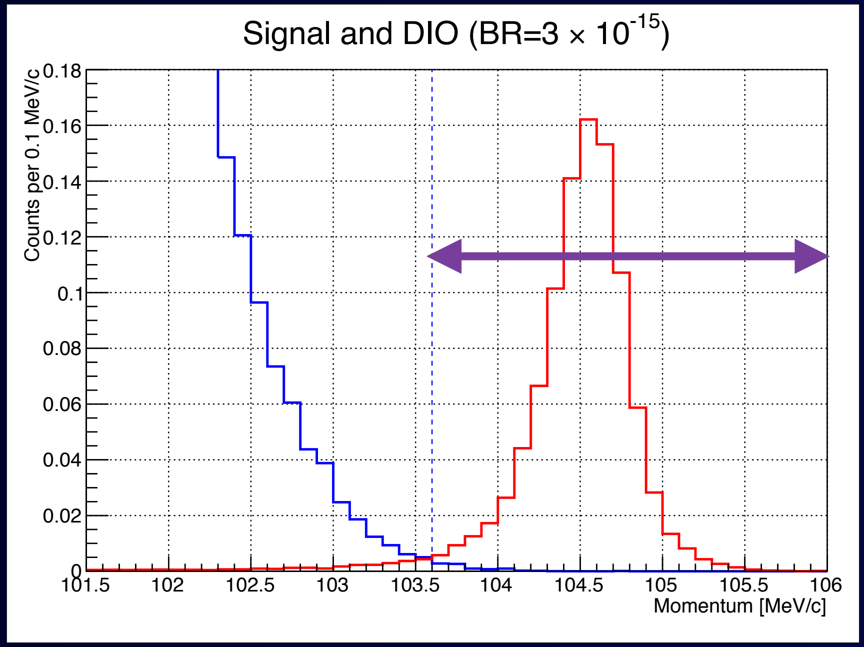
COMET Phase-I Signal Sensitivity

Osaka University

Signal Acceptance

Table 28: *Breakdown of the $\mu^- N \to e^- N$ conversion signal acceptance.*

Event selection	Value	Comments
Geometrical acceptance	0.37	
Track quality cuts	0.66	
Momentum selection	0.93	103.6 MeV/c < P_e <106.0 MeV/c
Timing window	0.3	700 ns < t < 1100 ns
Trigger efficiency	0.8	
DAQ efficiency	0.8	
Track reconstruction efficiency	0.8	
Total	0.043	



Signal Sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

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

$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

Muon intensity

With 0.4 μA, a running time of about 150 days is needed.

COMET Phase-I Signal Sensitivity

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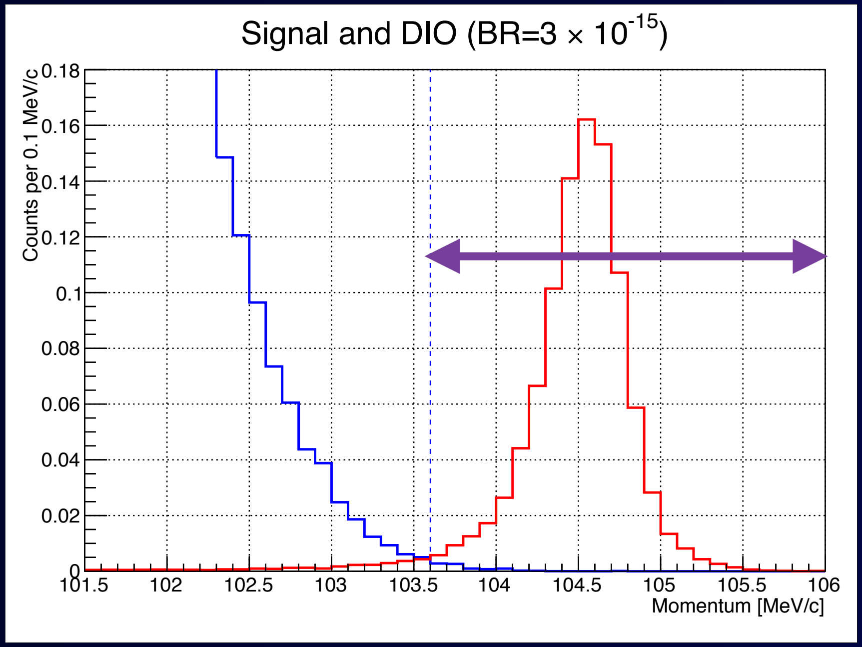

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$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- $f_{cap} = 0.6$
- $A_e = 0.043$
- $N_\mu = 1.23 \times 10^{16}$ muons

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

$$B(\mu^- + Al \rightarrow e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

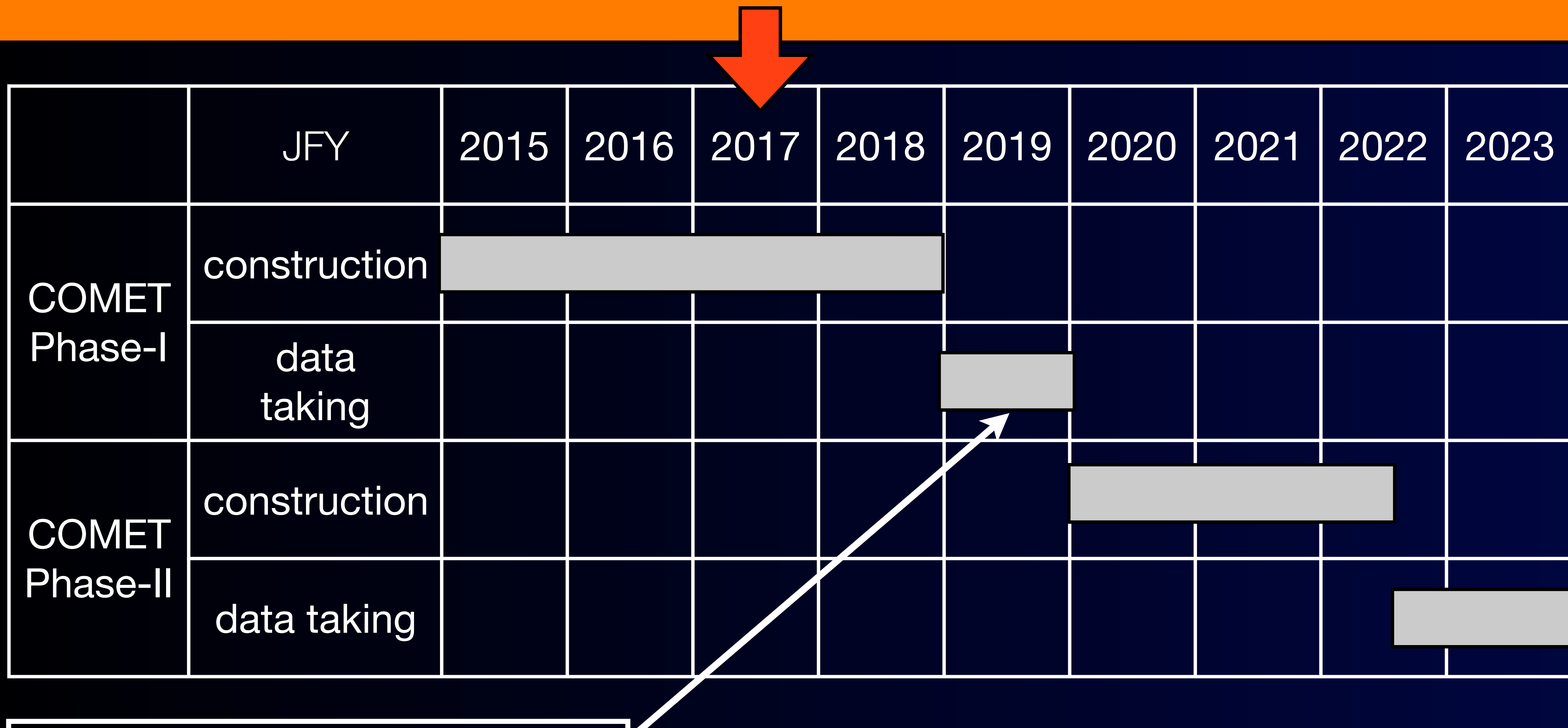
Muon intensity

With 0.4 μA, a running time of about 150 days is needed.

Tentative Schedule of COMET Phase-I and Phase-II

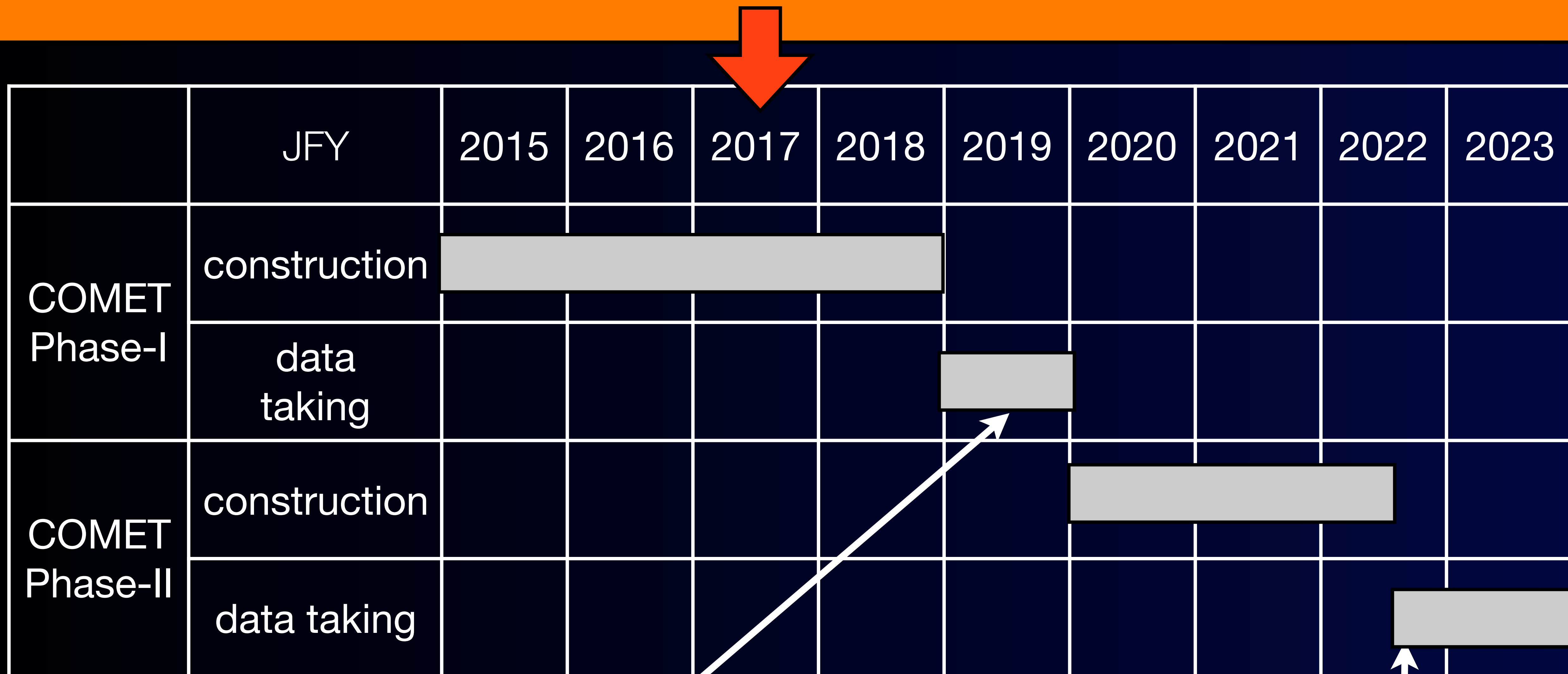
	JFY	2015	2016	2017	2018	2019	2020	2021	2022	2023
COMET Phase-I	construction									
	data taking									
COMET Phase-II	construction									
	data taking									

Tentative Schedule of COMET Phase-I and Phase-II



COMET Phase-I :
2019 ~
S.E.S. ~ 3×10^{-15}
(for 150 days
with 3.2 kW proton beam)

Tentative Schedule of COMET Phase-I and Phase-II



COMET Phase-I :
2019 ~
S.E.S. ~ 3×10^{-15}
(for 150 days
with 3.2 kW proton beam)

COMET Phase-II :
2022 ~
S.E.S. ~ $(1.0\text{-}2.6) \times 10^{-17}$
(for 2×10^{7} sec
with 56 kW proton beam)

Summary

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- Charged lepton flavor violation (CLFV) would provide the best opportunity to search for new physics beyond the SM.
- Next generation experiments for CLFV with muons are coming.
  - MEG II for $\mu \rightarrow e \gamma$
  - Mu3e for $\mu \rightarrow eee$
  - COMET and Mu2e for muon to electron conversion.
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my dog, IKU

Backup