Overview of the COMET Experiment

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USTC, China, and Osaka University, Japan

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Hefei, China

Introduction

muon to electron conversion in a muonic atom

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

(Charged Lepton Flavour Violation=CLFV)

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outline

- Physics Motivation of Charged Lepton Flavour Violation
- Muon to electron conversion
- COMET at J-PARC
- COMET Phase-I (under preparation at J-PARC)
- Exotic searches with COMET
- Summary

CLFV for New Physics Search

CLFV in the Standard Model (SM)

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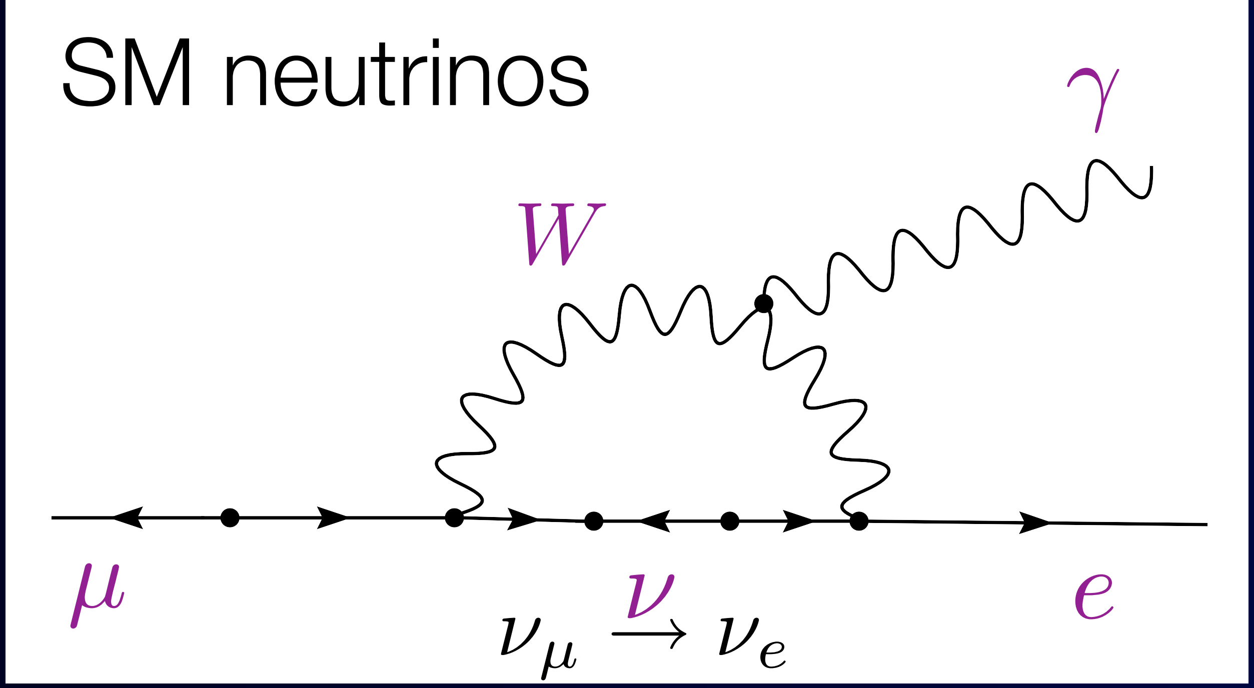

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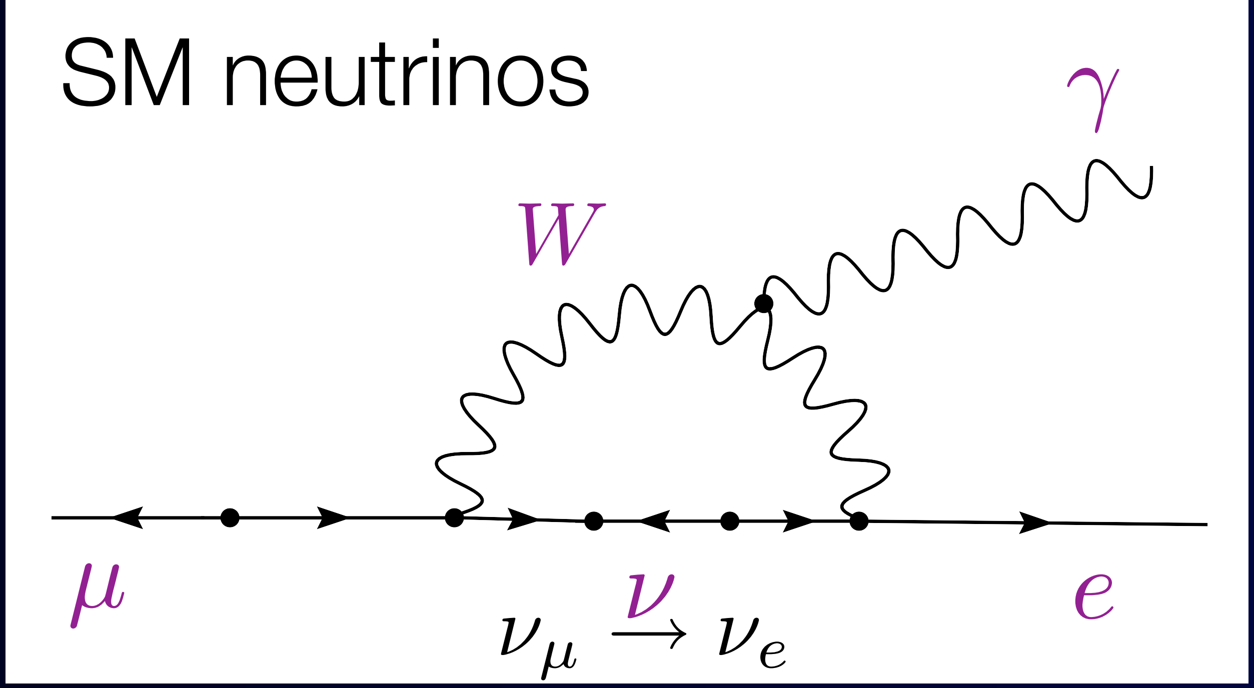

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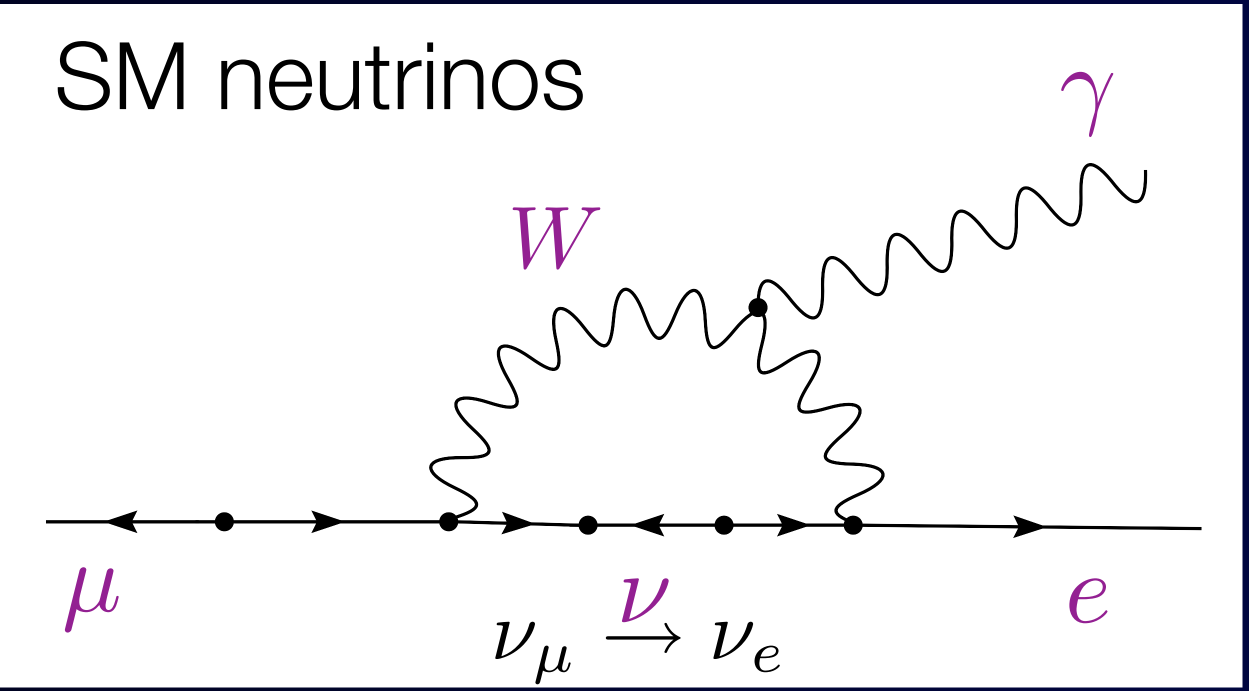

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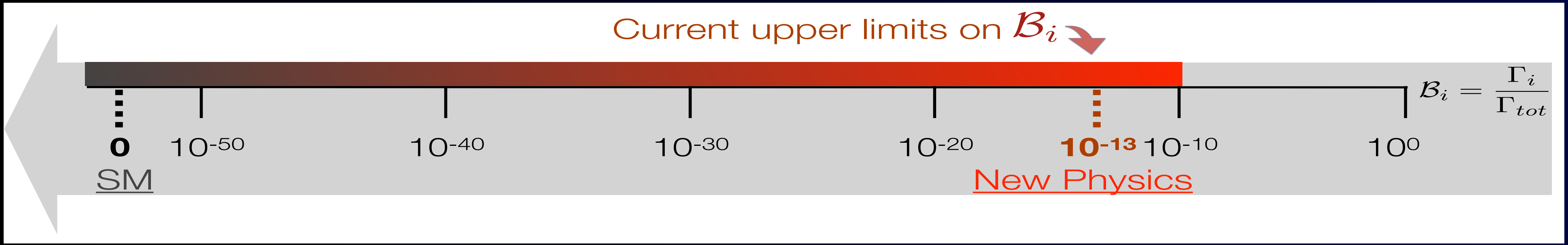

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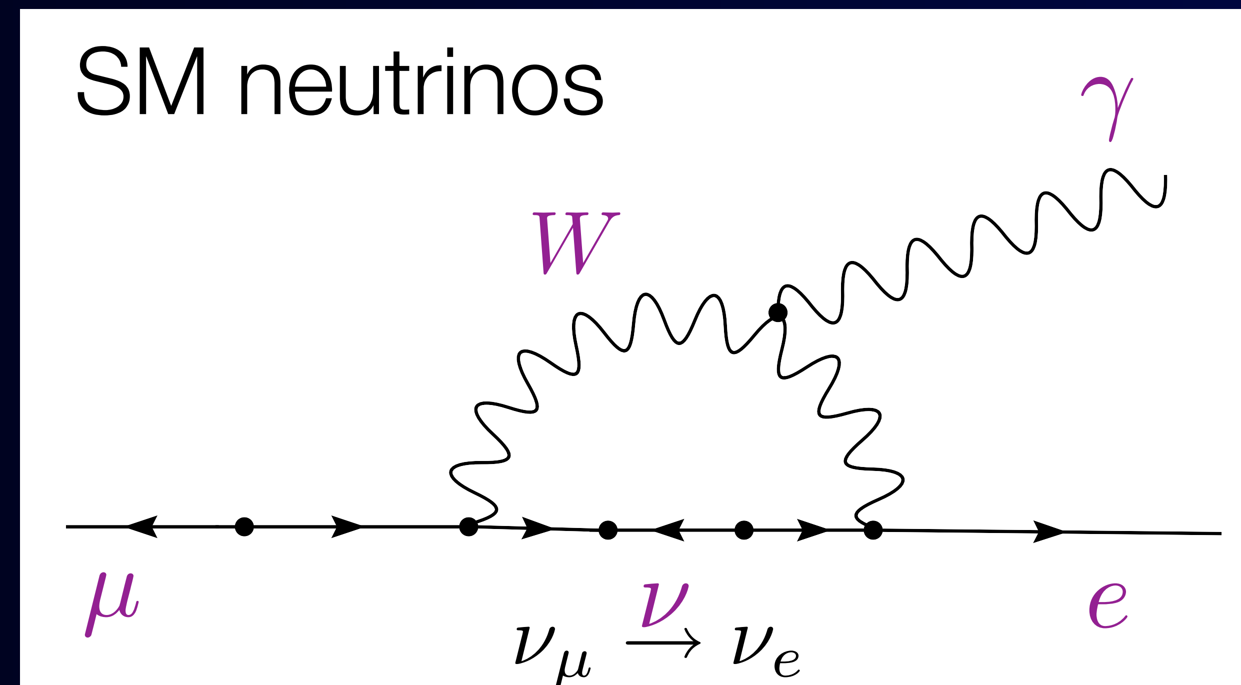

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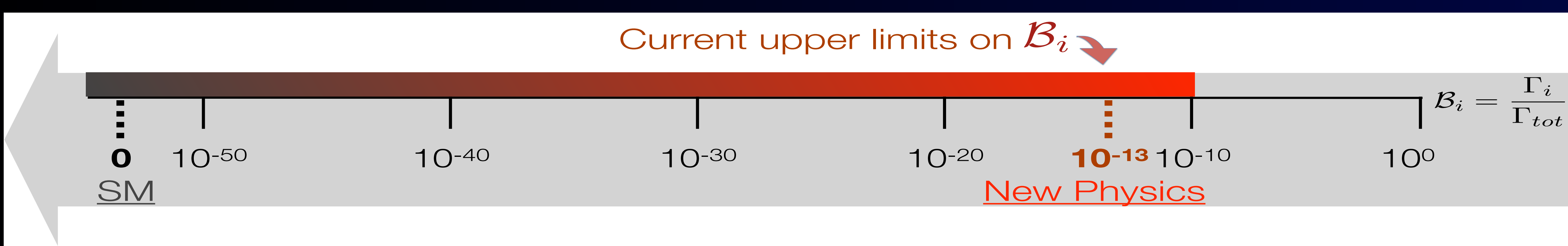

1 CLFV has a large window for BSM w/o SM backgrounds.

Sensitivity to BSM with CLFV

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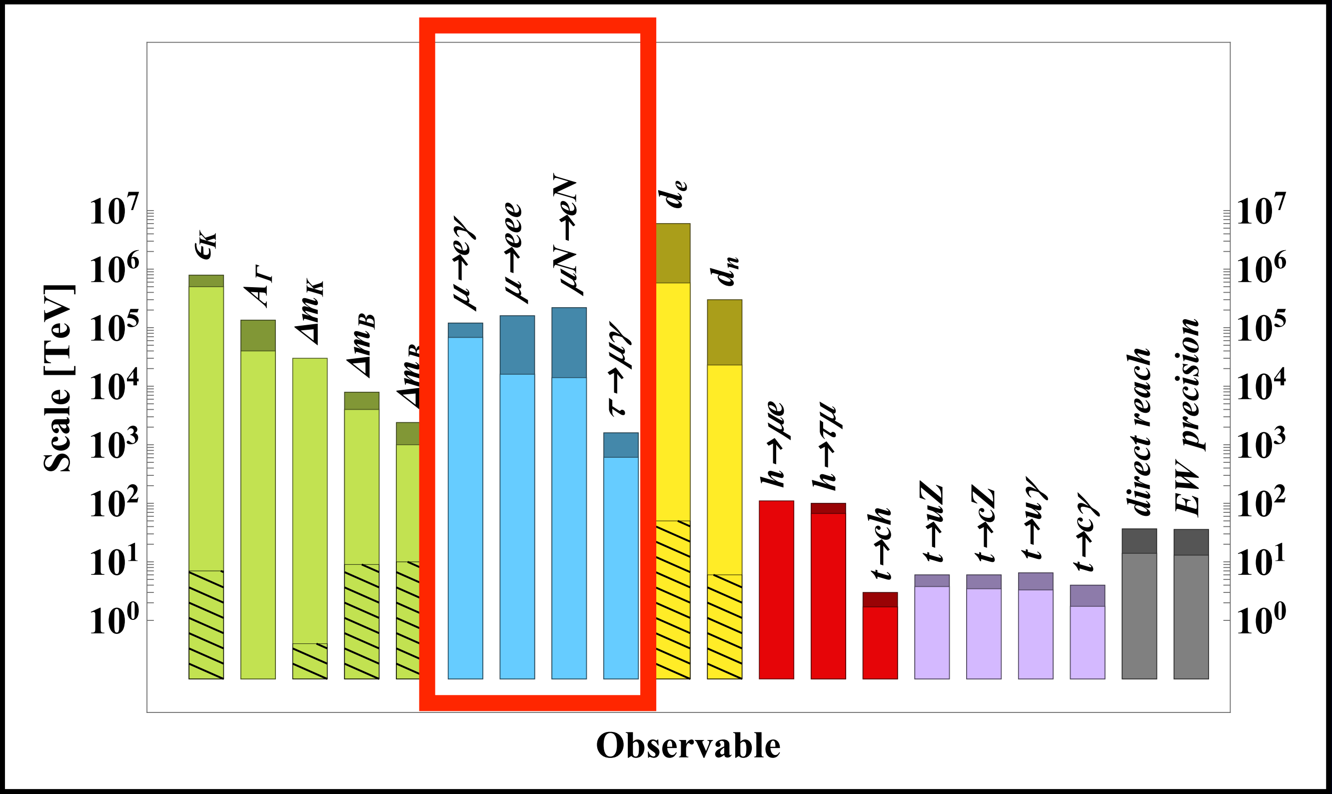

European strategy update (2019)

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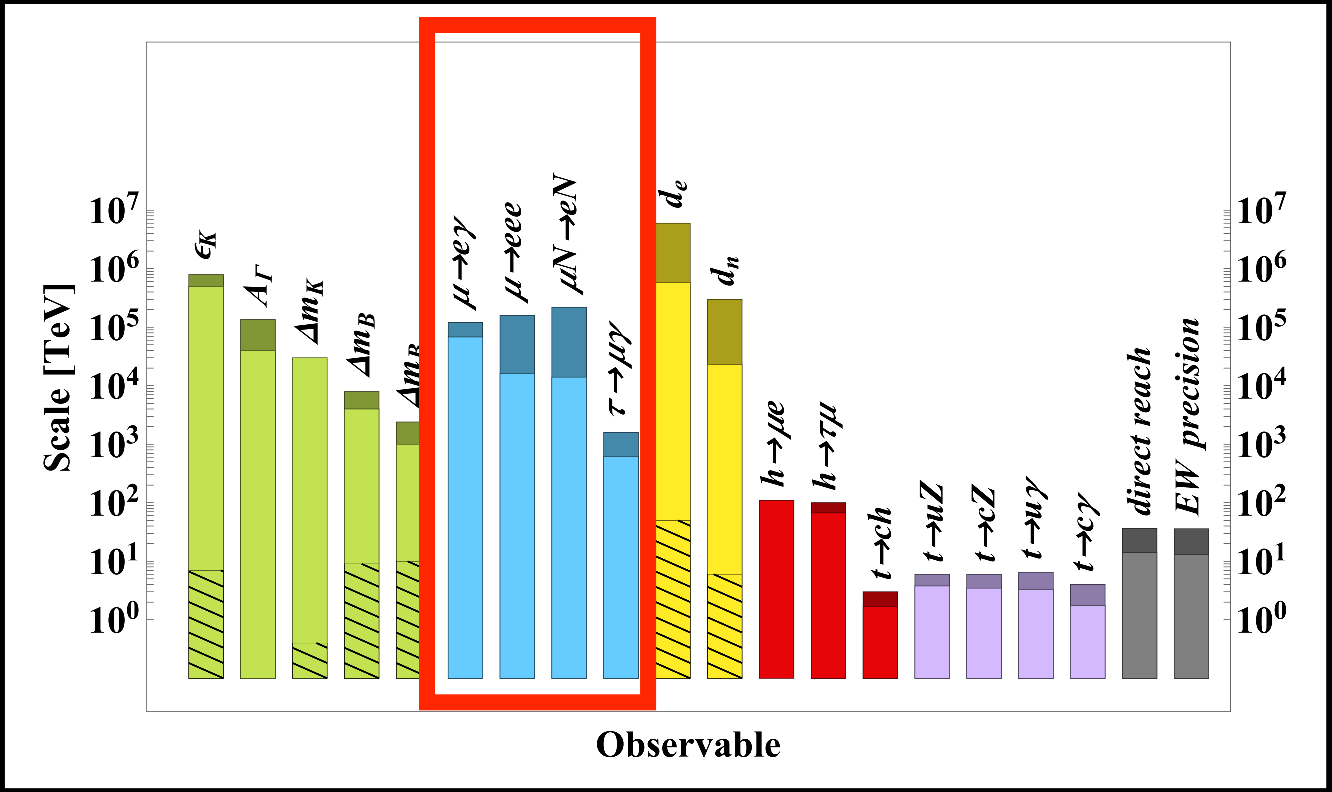

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Present:
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$$\Lambda \sim \mathcal{O}(10^4)\ \text{TeV}$$

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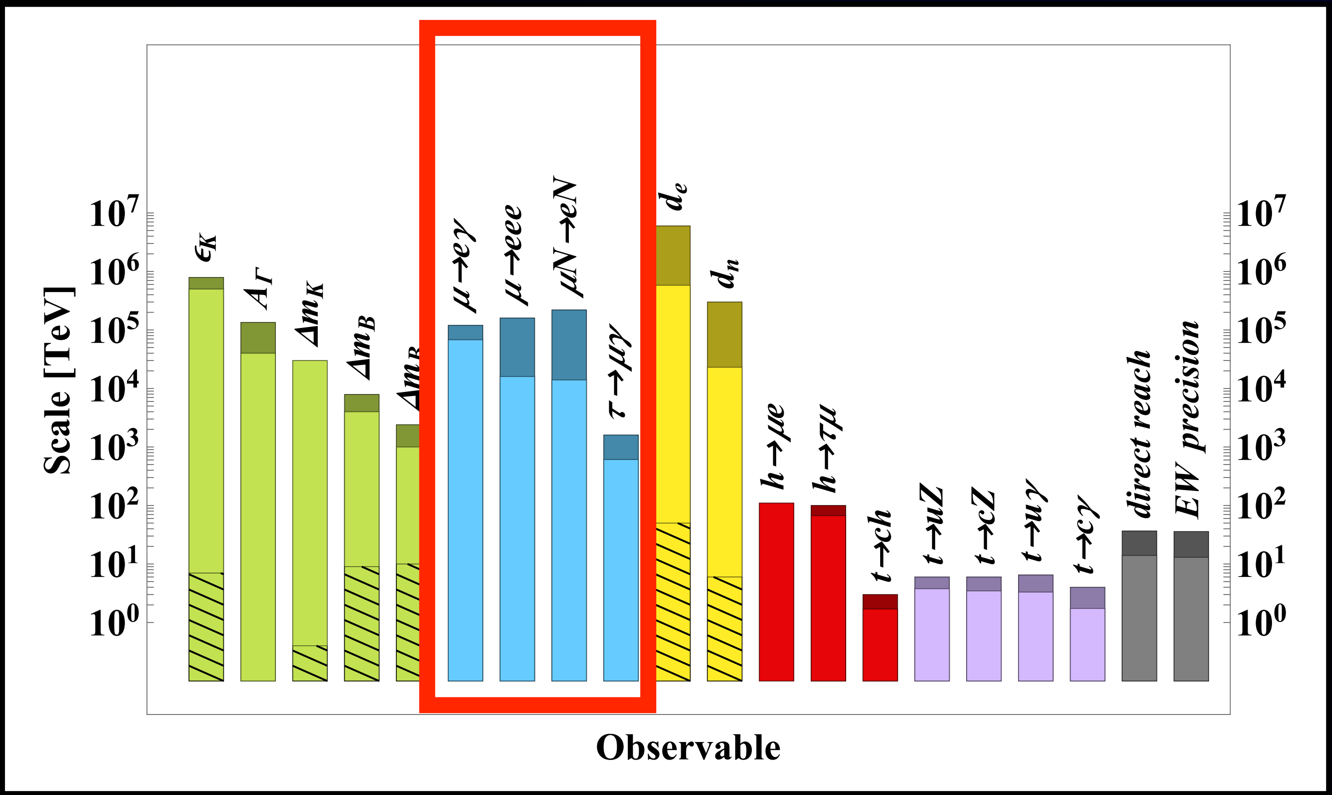

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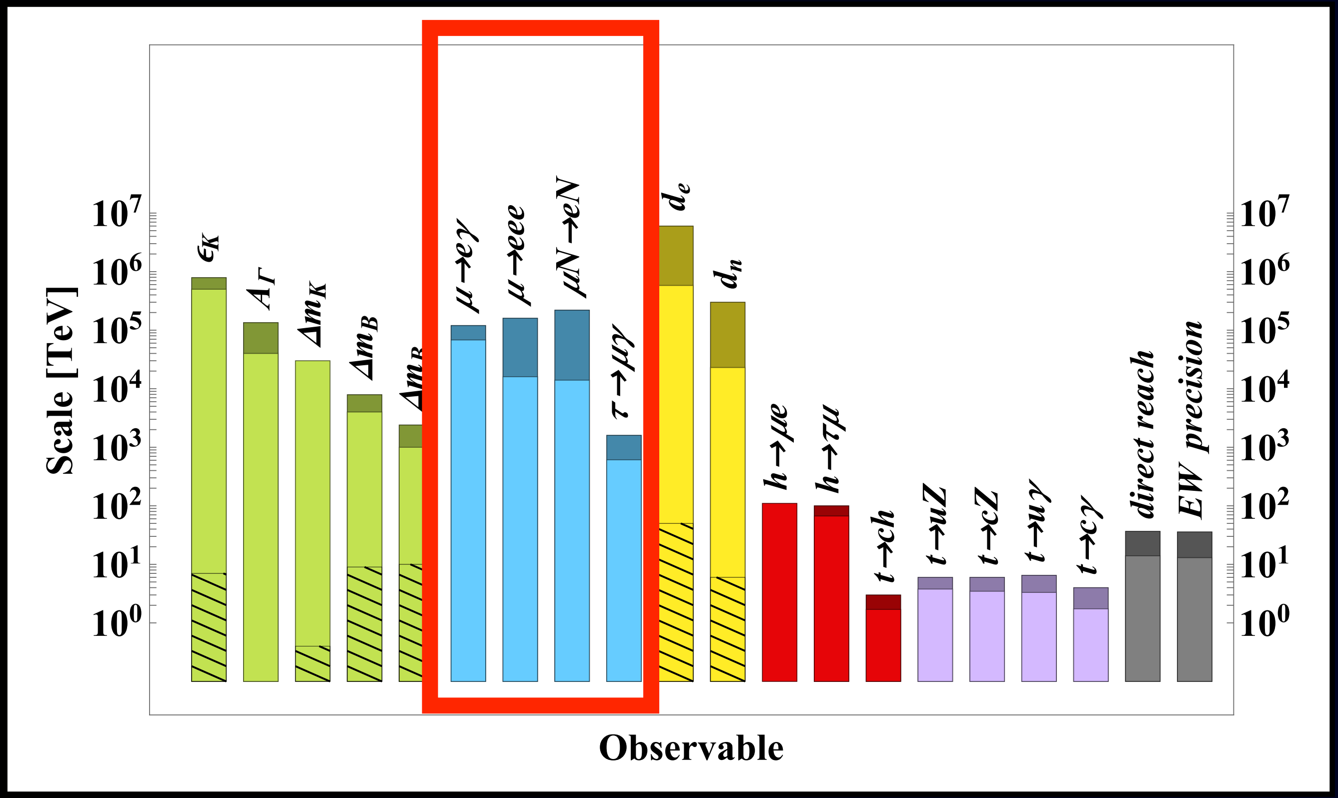

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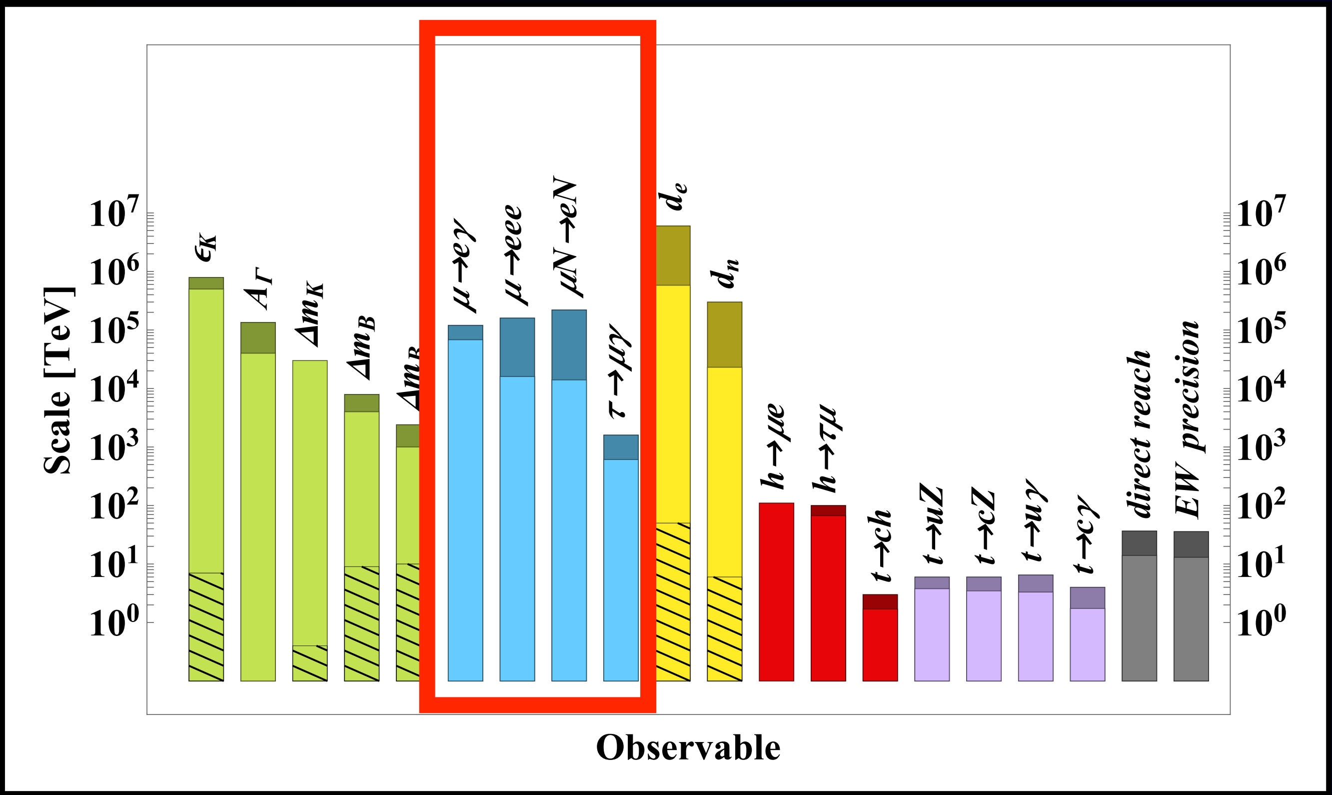

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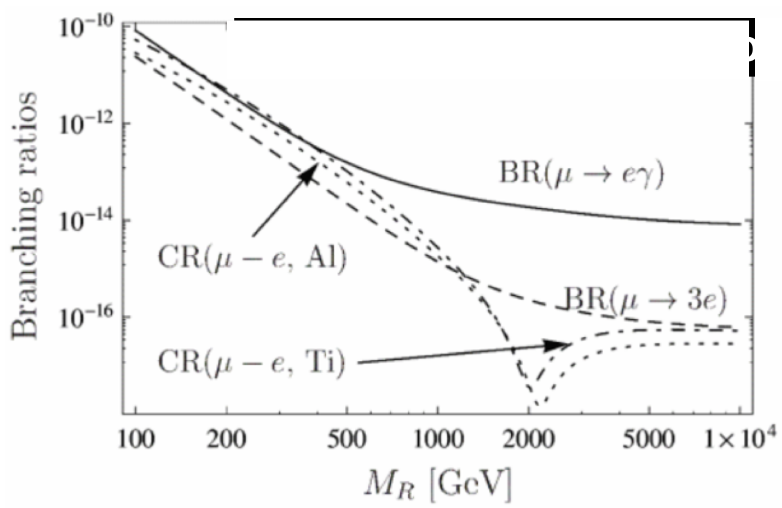
2 CLFV would explore scales way beyond the energies that our present and future colliders can directly reach.

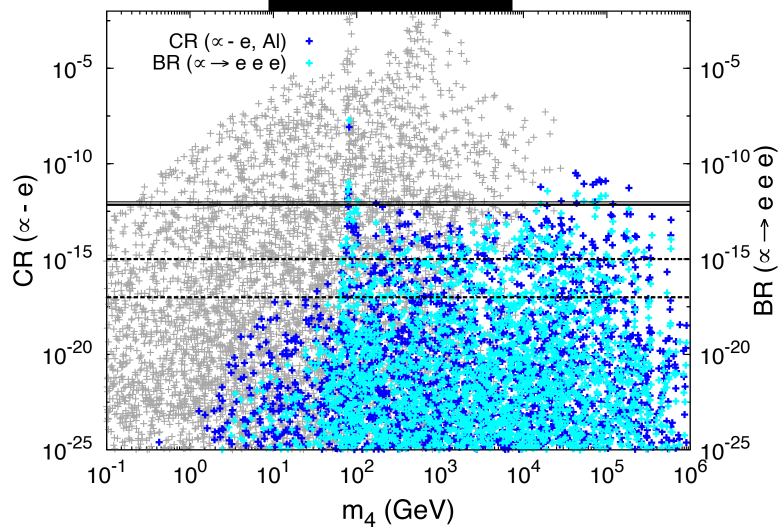
Model dependent CLFV Predictions

COMET experiment aims at BR~O(10^{-18}).

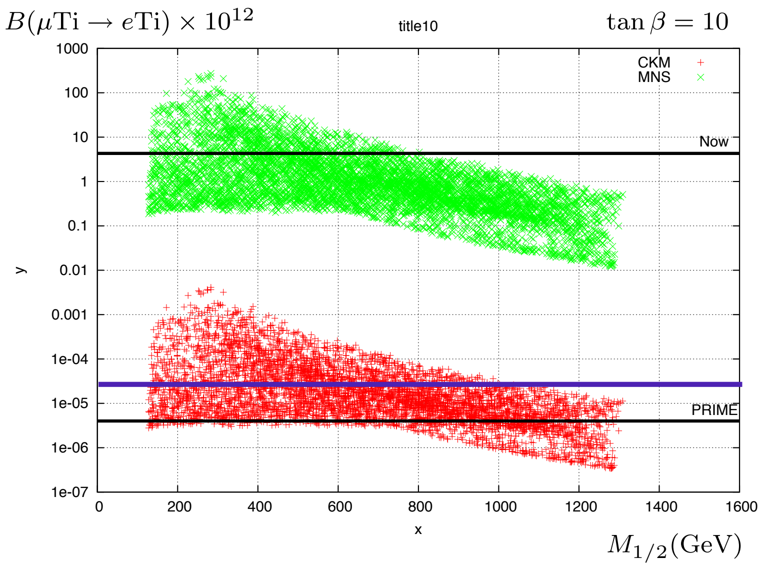
SUSY:Heavy RH Neutrino



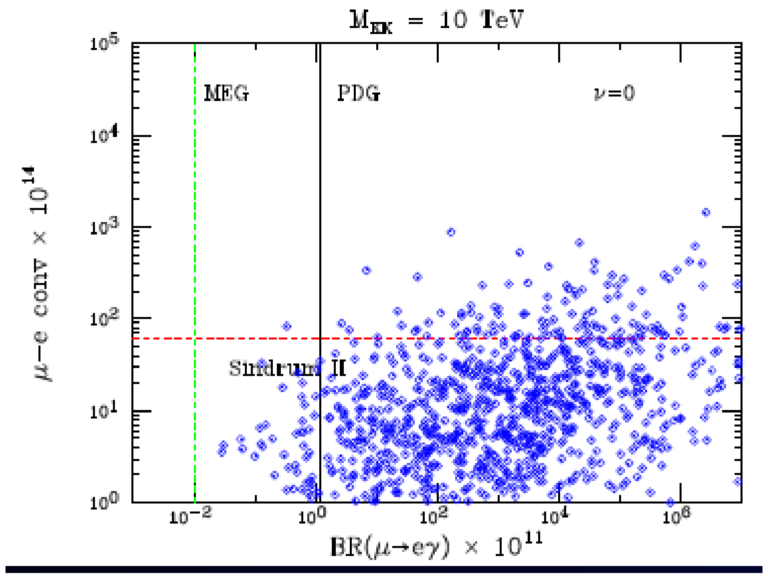
SM+HNL



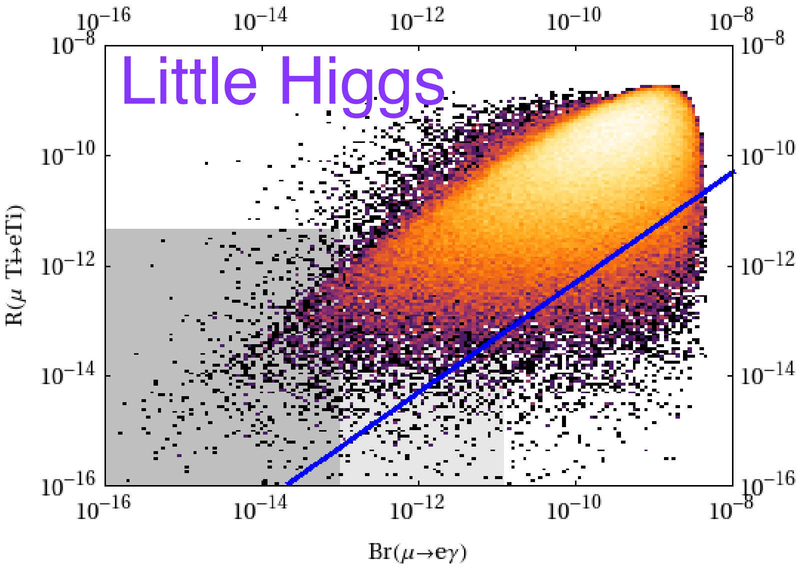
SUSY-GUT



extra dimension model



Little Higgs



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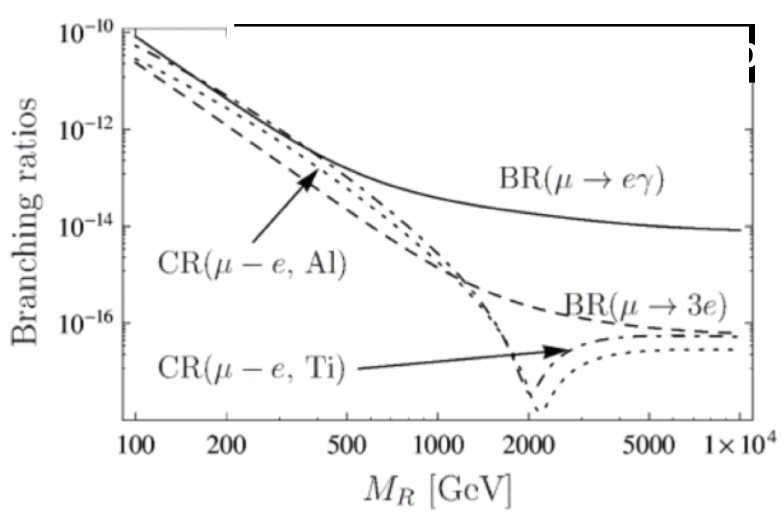

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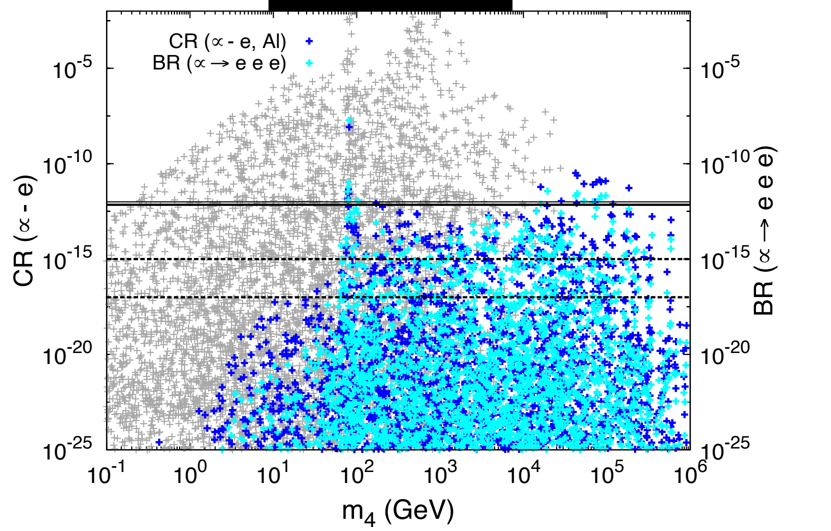

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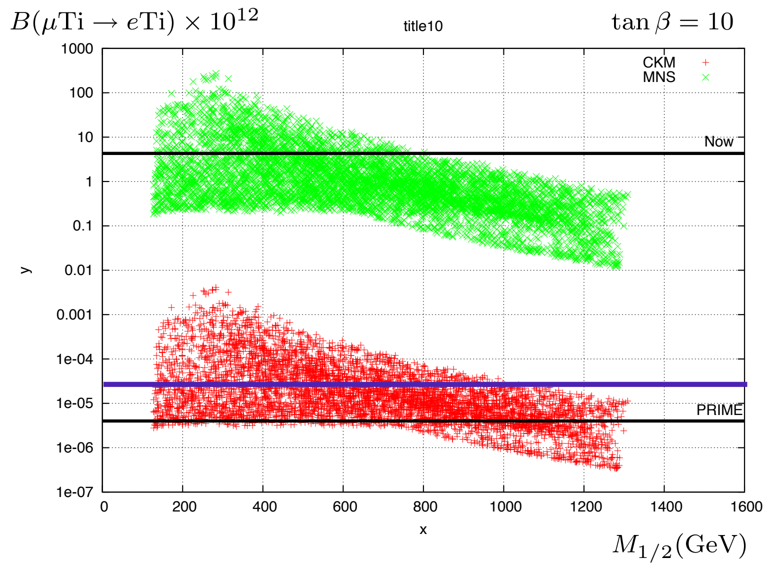

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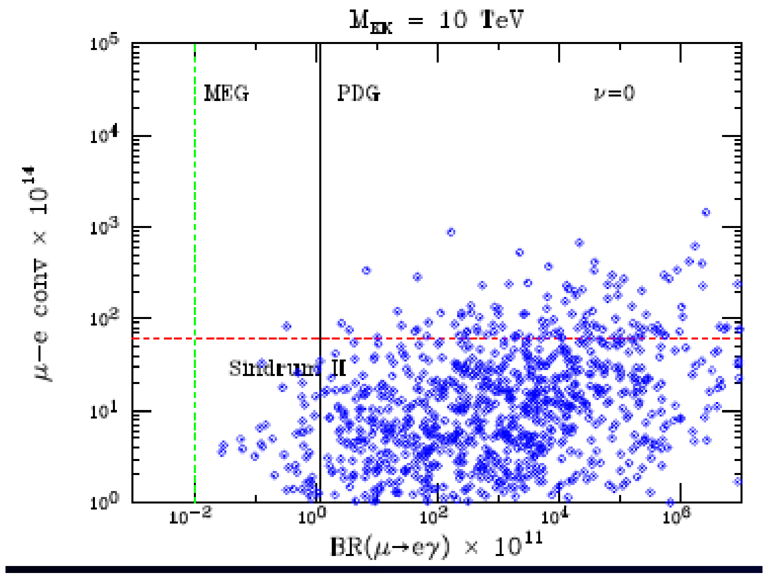

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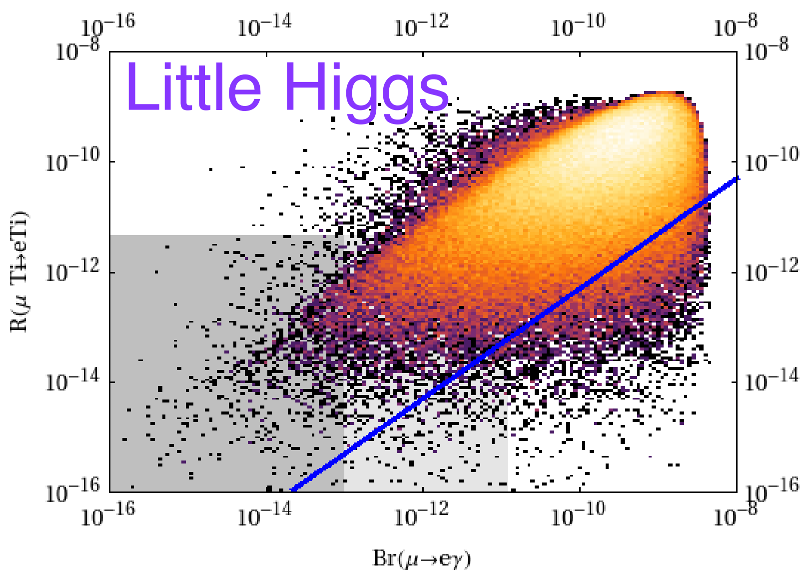

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Muon to Electron Conversion

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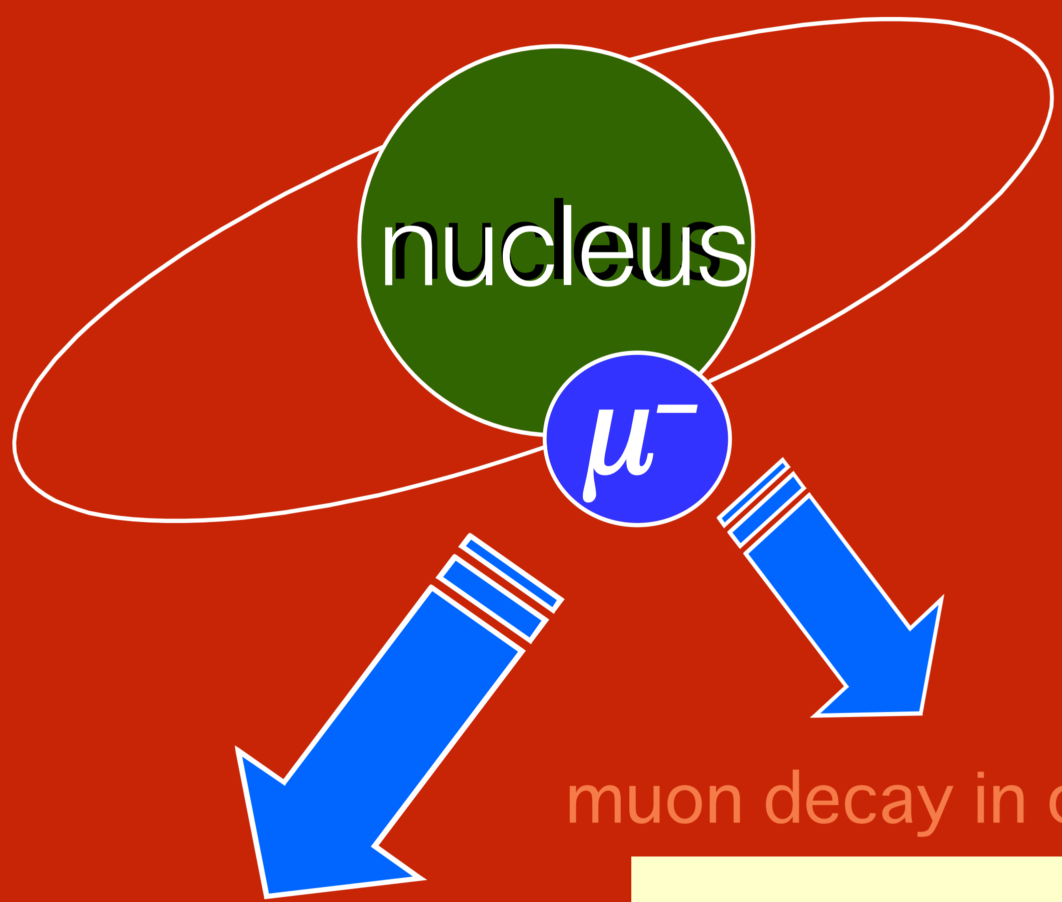

muon decay in orbit

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

nuclear muon capture

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

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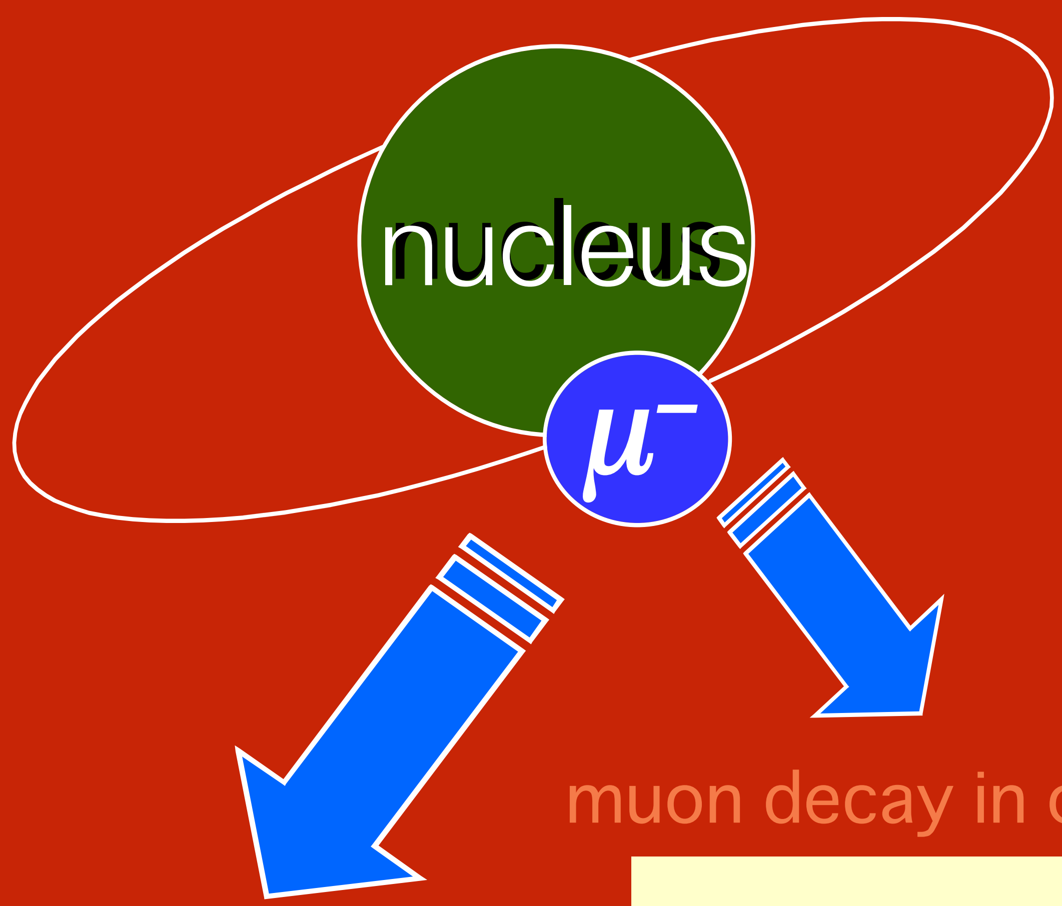

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coherent process $\propto Z^5$

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

Event Signature :

a single mono-energetic electron of 105 MeV

	Z	CR limit
sulphur	16	$<7 \times 10^{-11}$
titanium	22	$<4.3 \times 10^{-12}$
copper	39	$<1.6 \times 10^{-8}$
gold	79	$<7 \times 10^{-13}$
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$$\mathrm{CR}(\mu^- N \to e^- N) \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \mathrm{all})}$$

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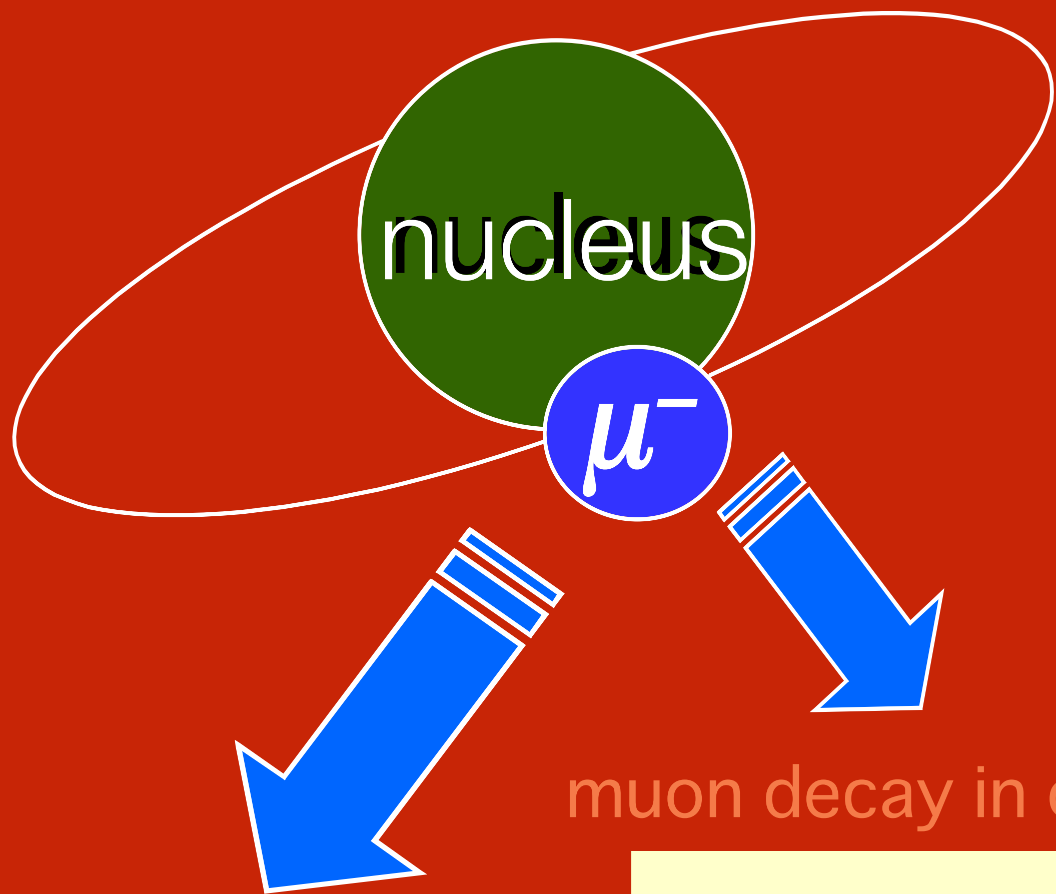

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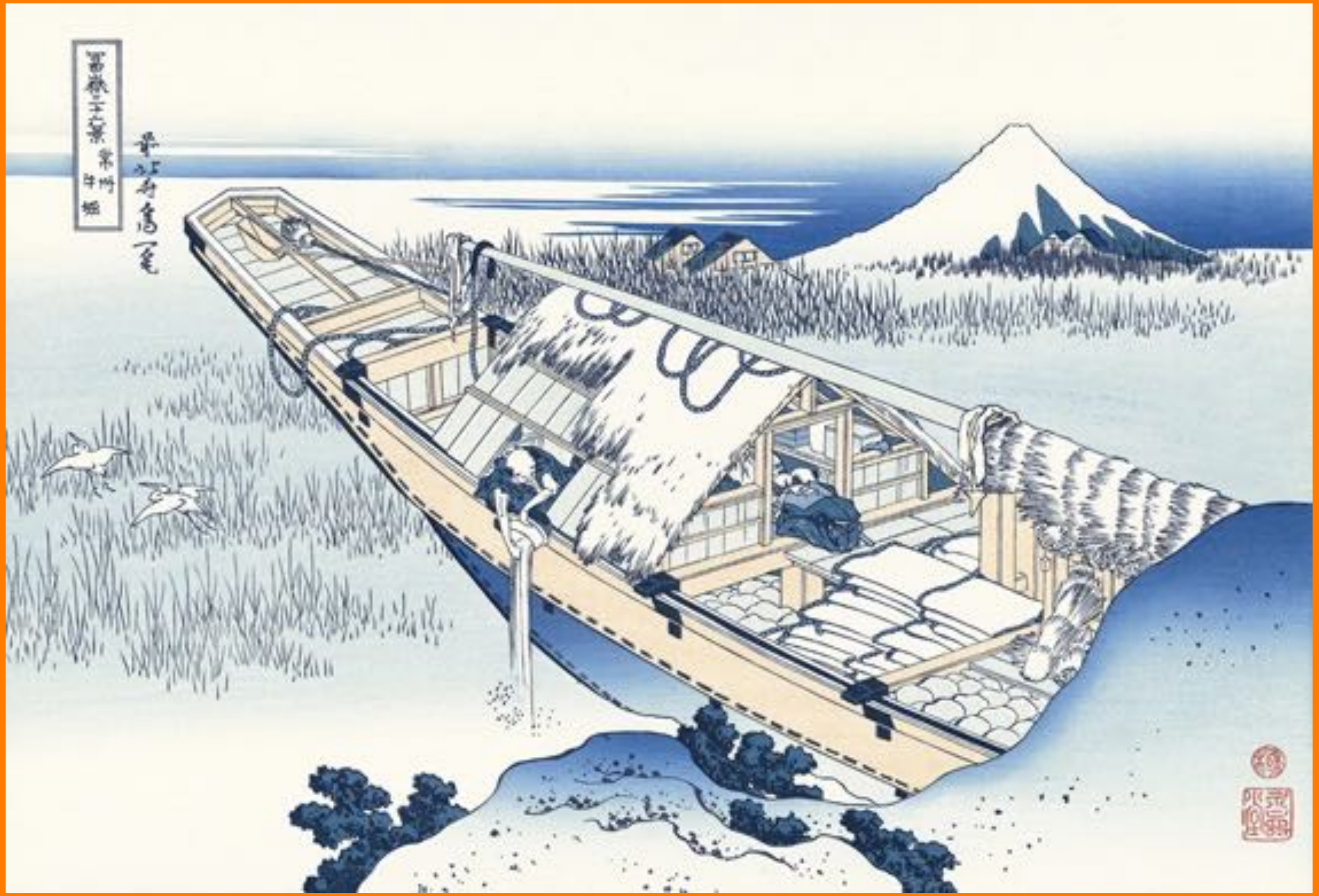
Backgrounds for μ-e conversion

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

COMET@J-PARC



COMET

MET = COherent Muon to Electron Transition

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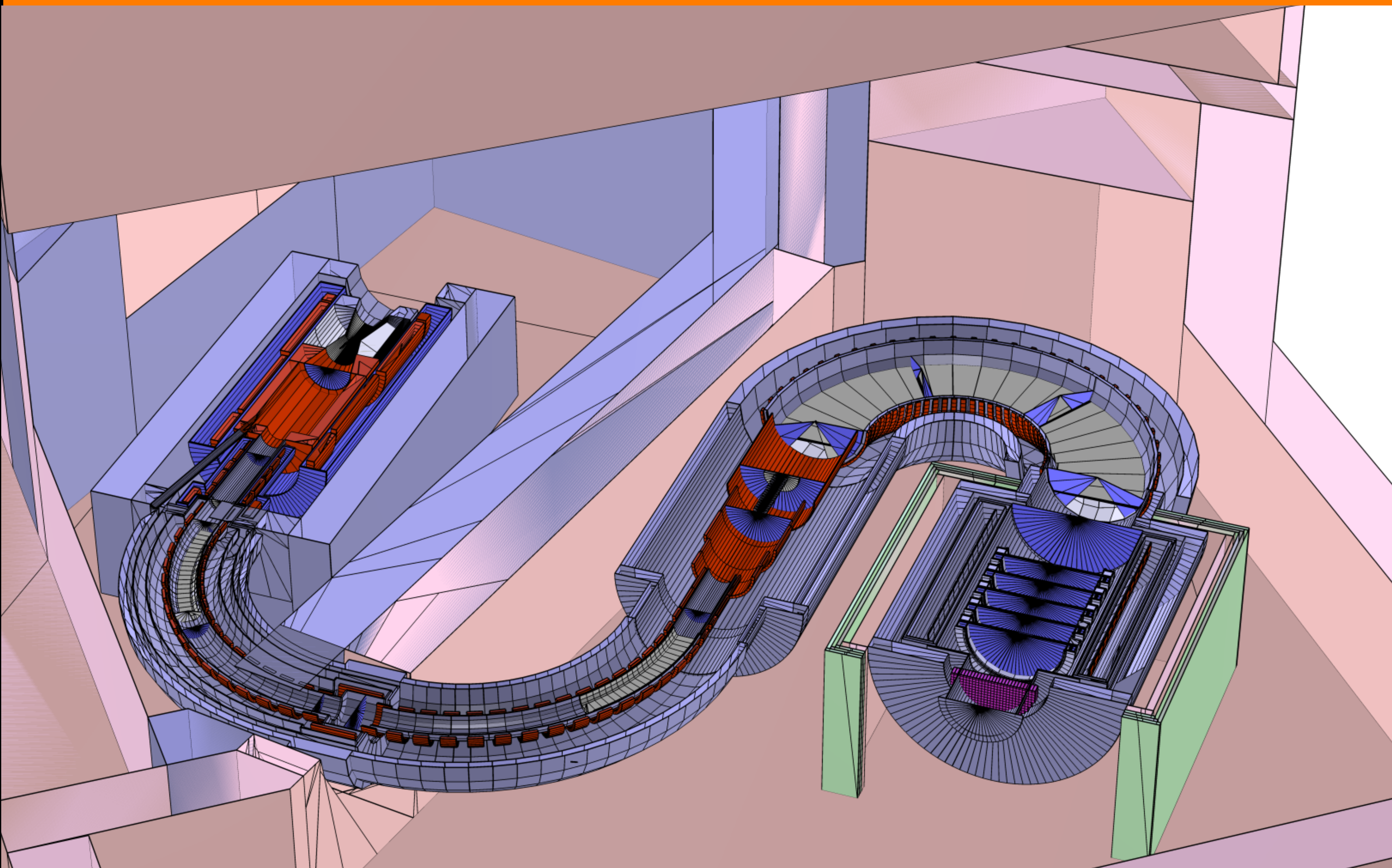

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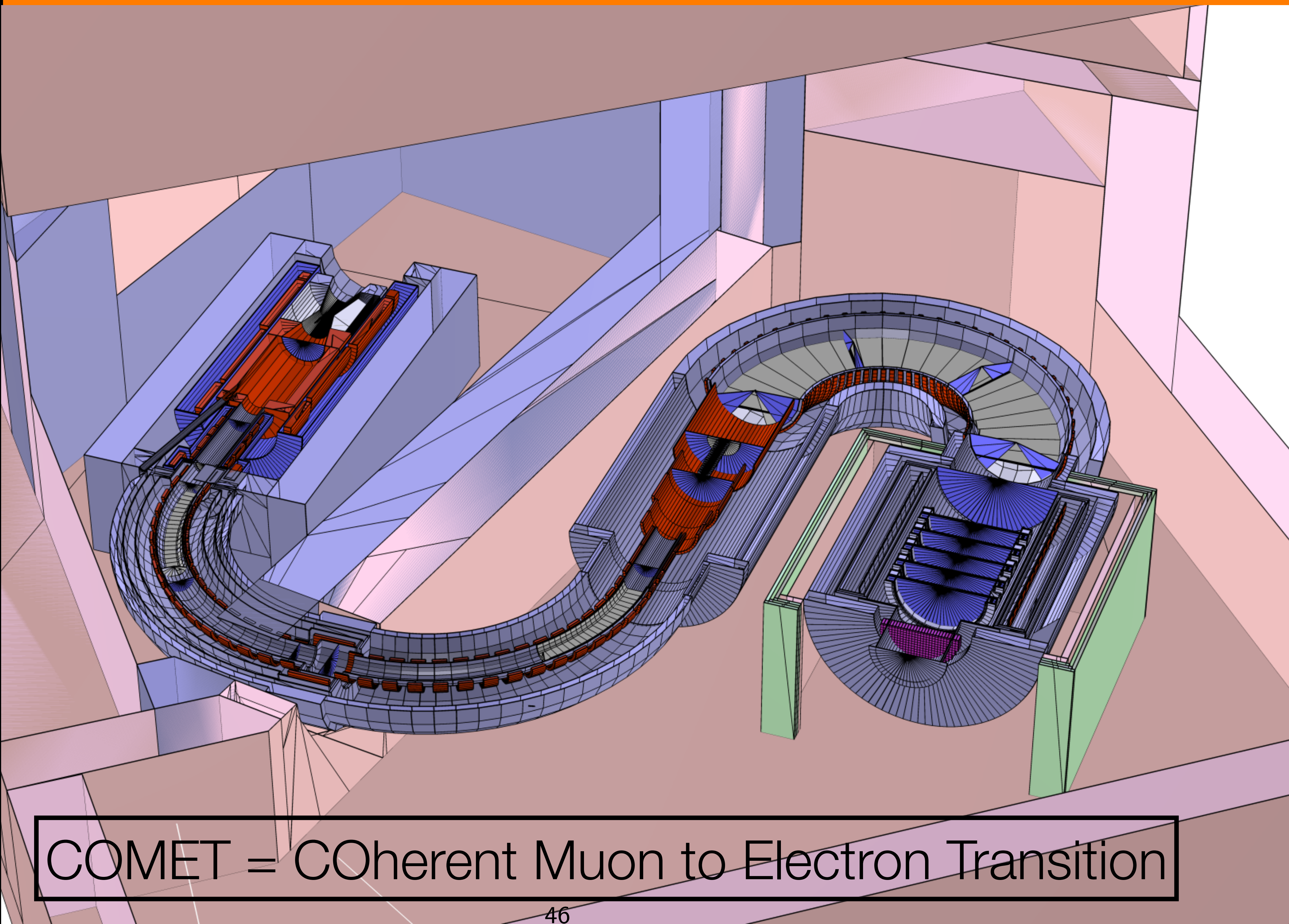
- Proton beam, 8 GeV, 56kW
- 2×10^{11} stopped muons/s



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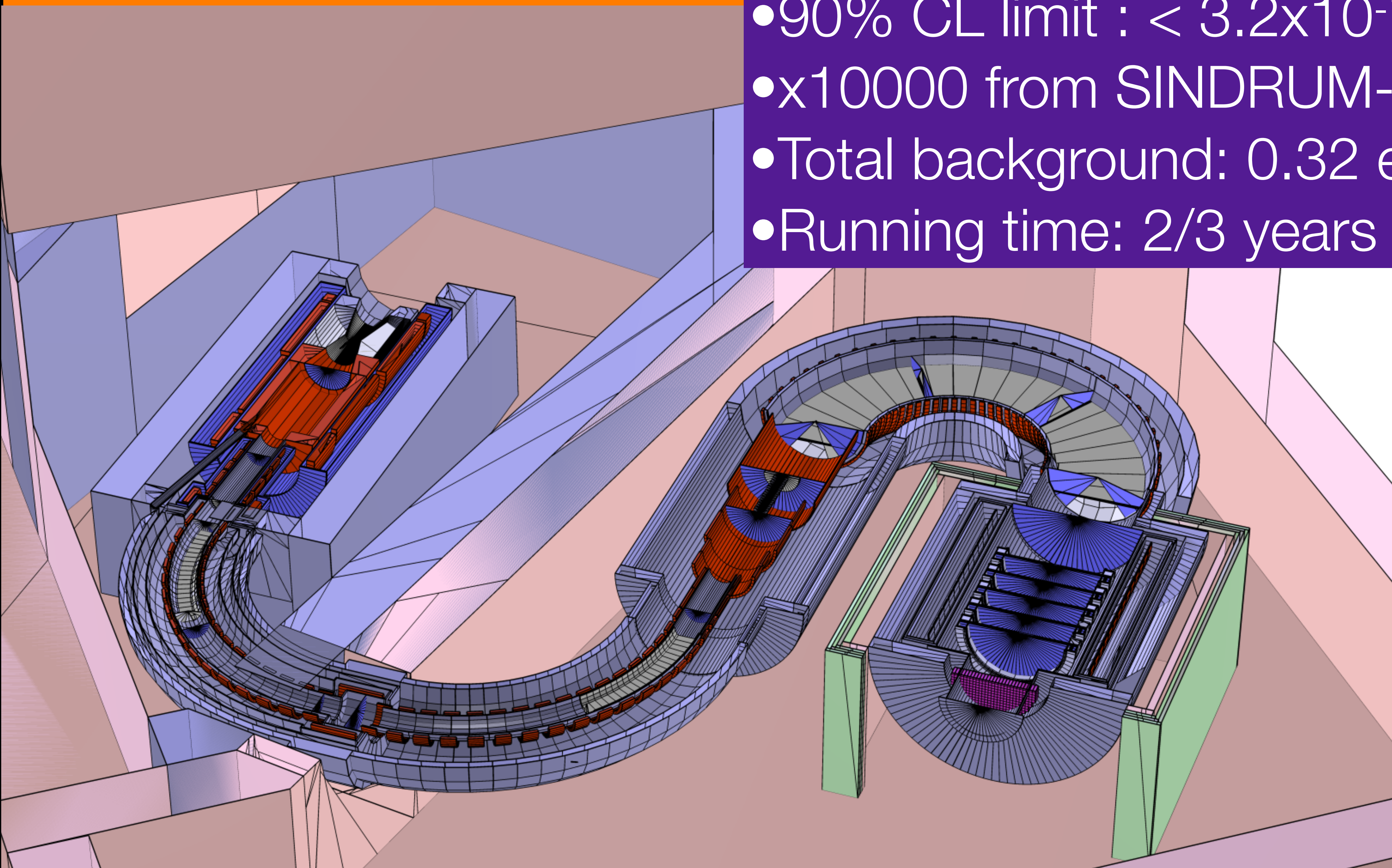
- 90% CL limit : < 3.2×10^{-17}
- x10000 from SINDRUM-II
- Total background: 0.32 events
- Running time: 2/3 years (2×10^{7}sec)



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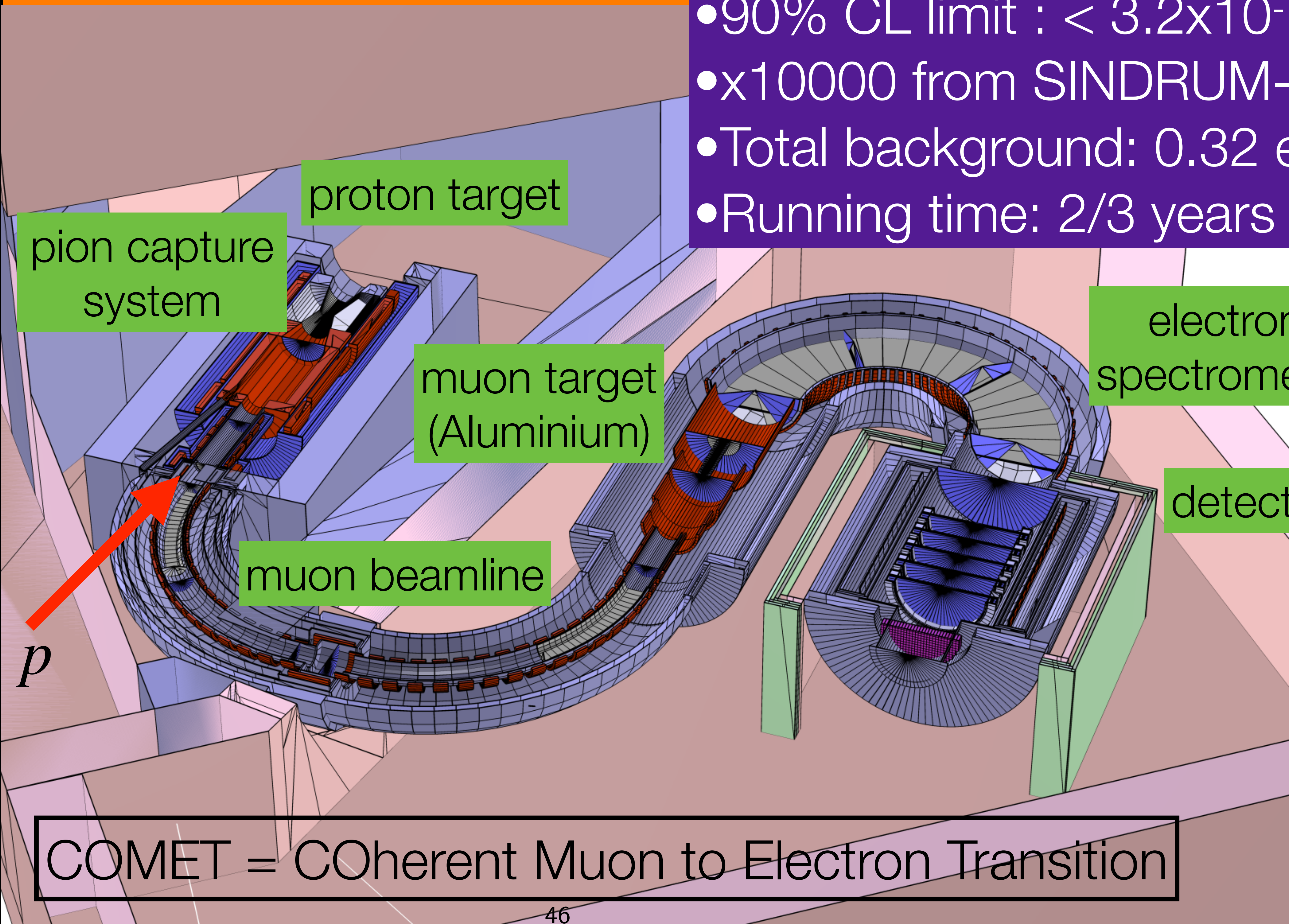

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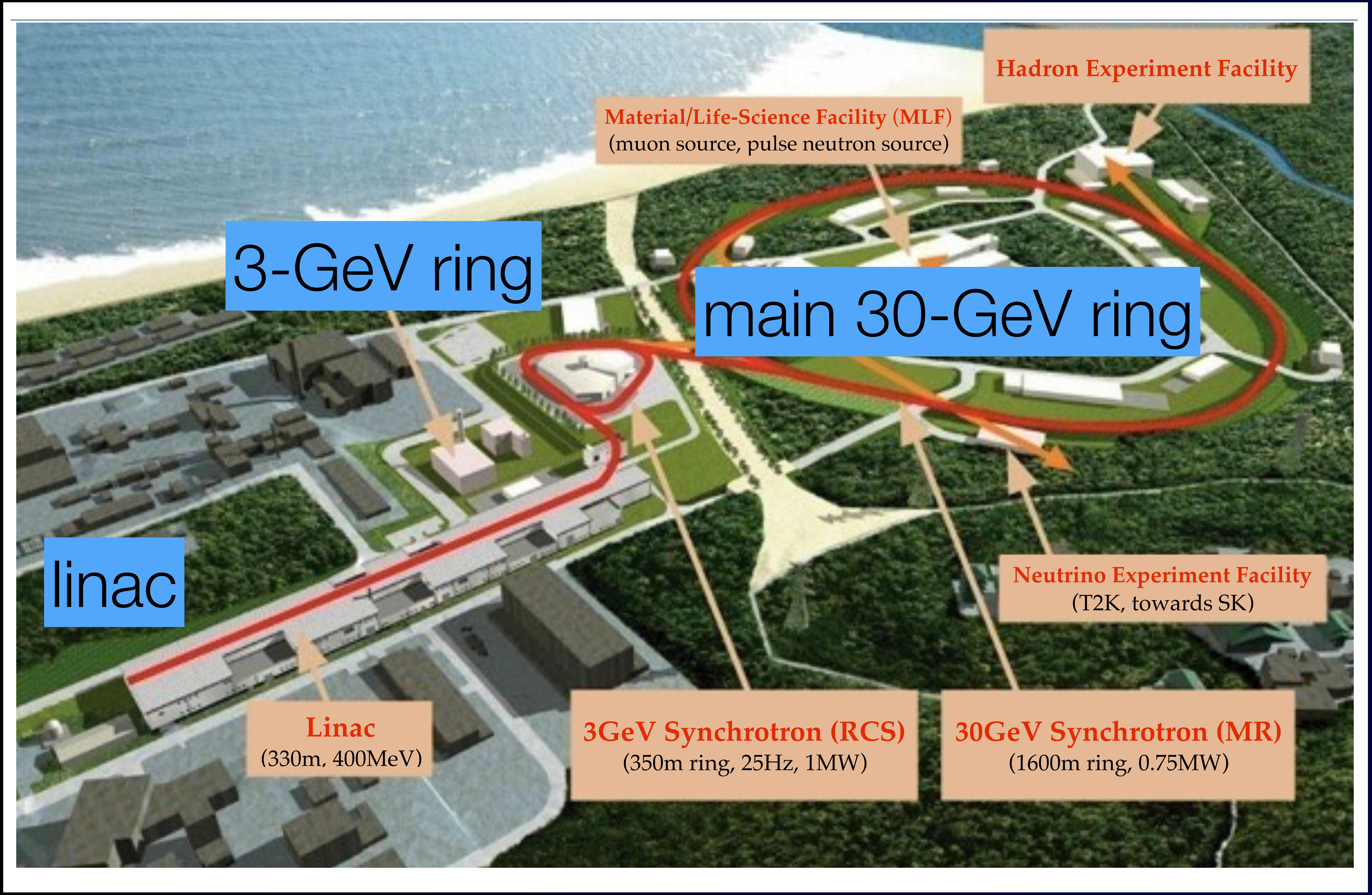
Proton Accelerator
J-PARC



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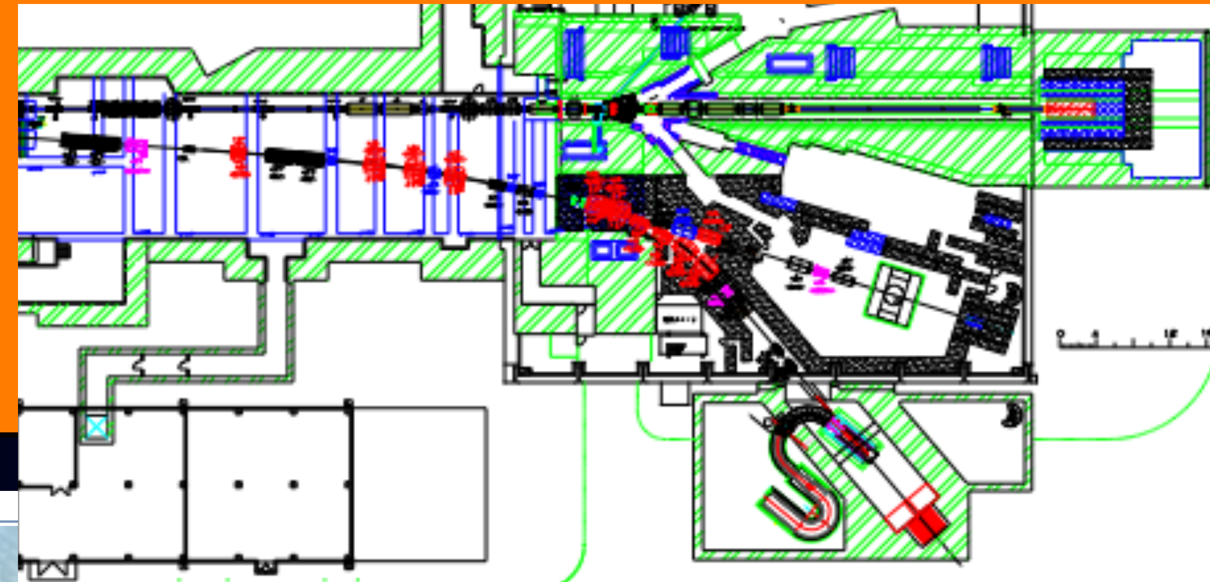

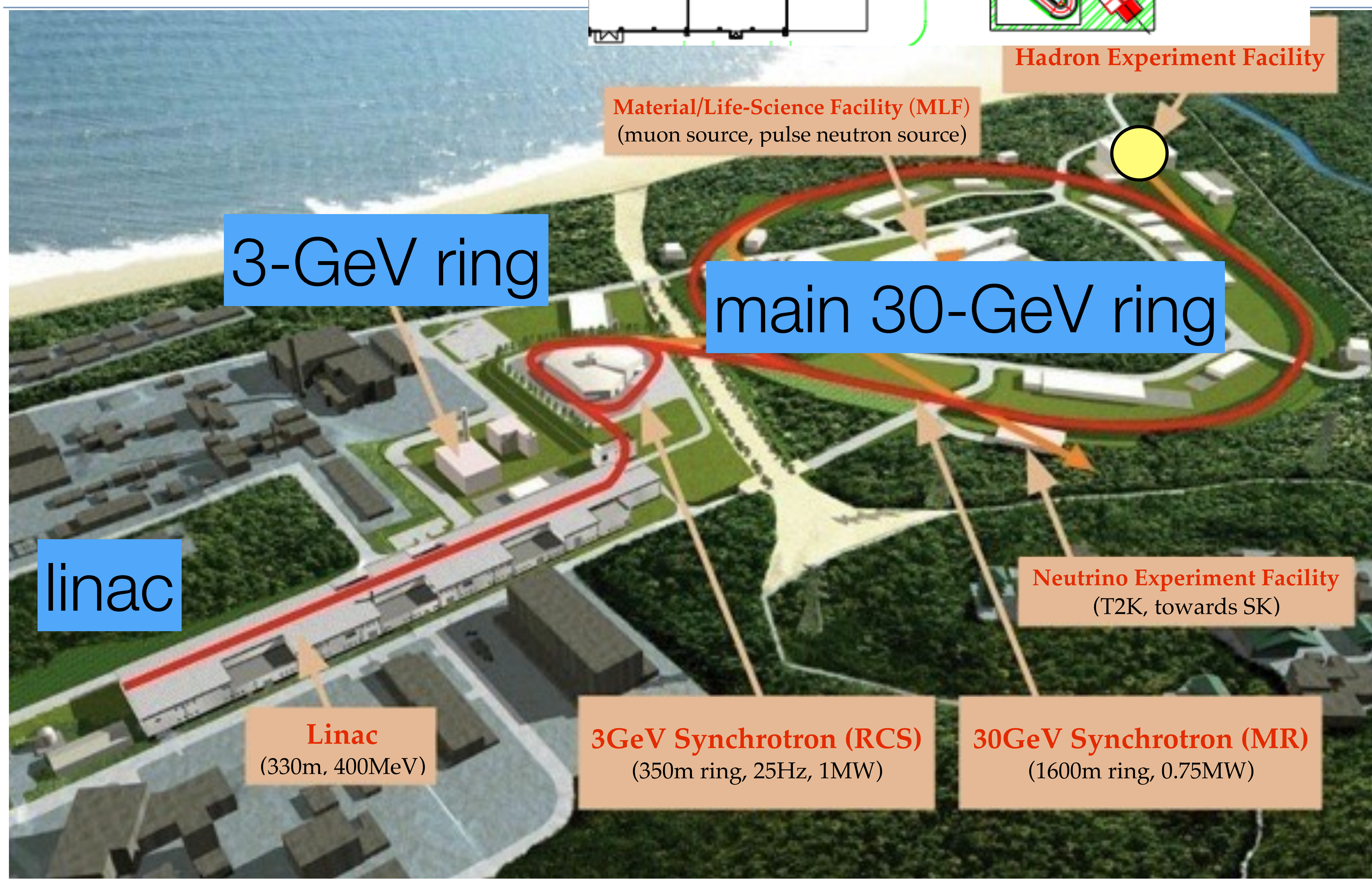

Proton Accelerator
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Improvements for Signal Sensitivity

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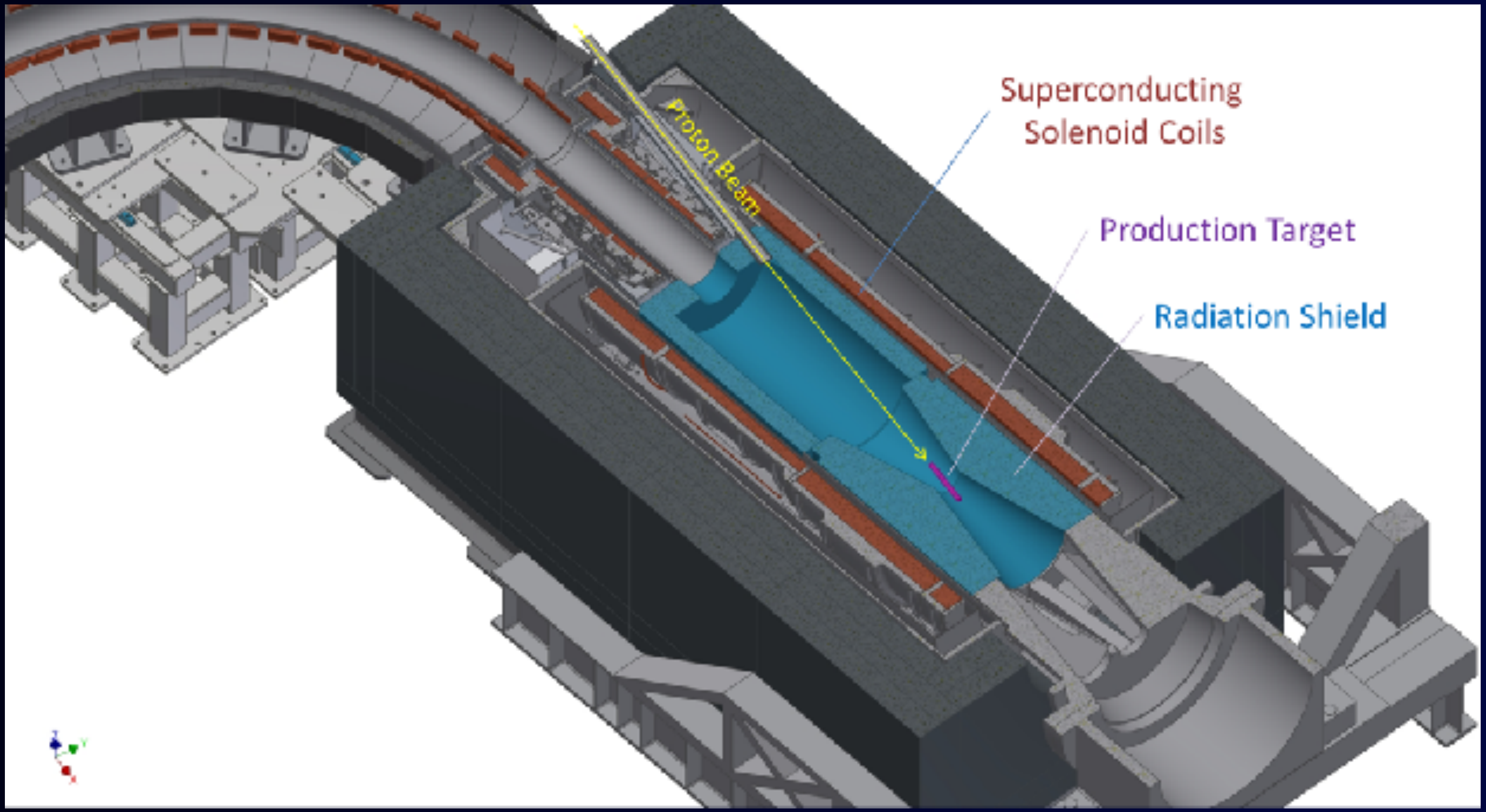
Pion capture and muon transport by high field superconducting solenoid system: 10^{11} μ/s for 50 kW proton beam power



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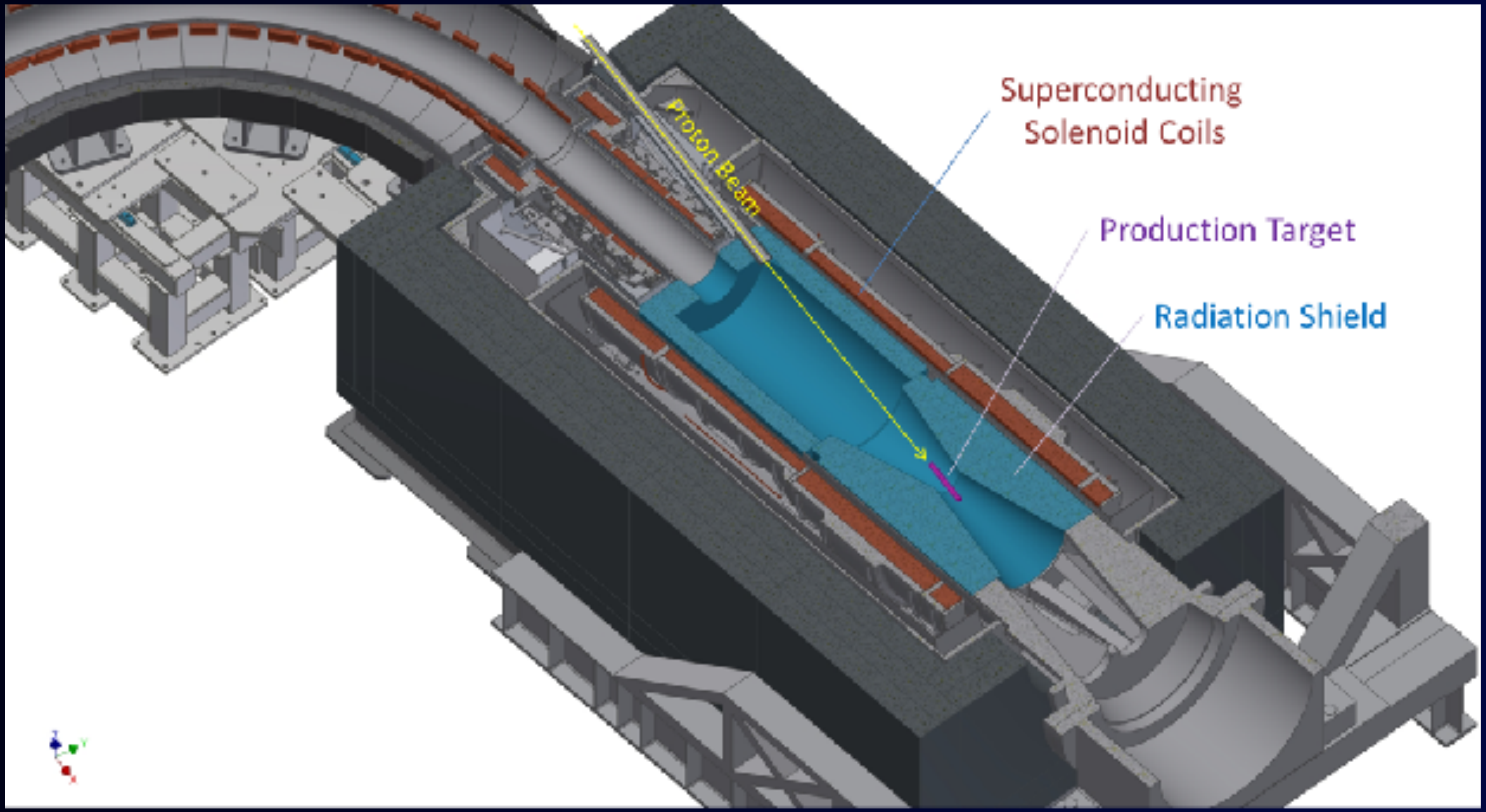

The world's highest muon source

10^{18} muons in total

Improvements of Background Rejection

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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}

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

Time Structure of Muon Beam

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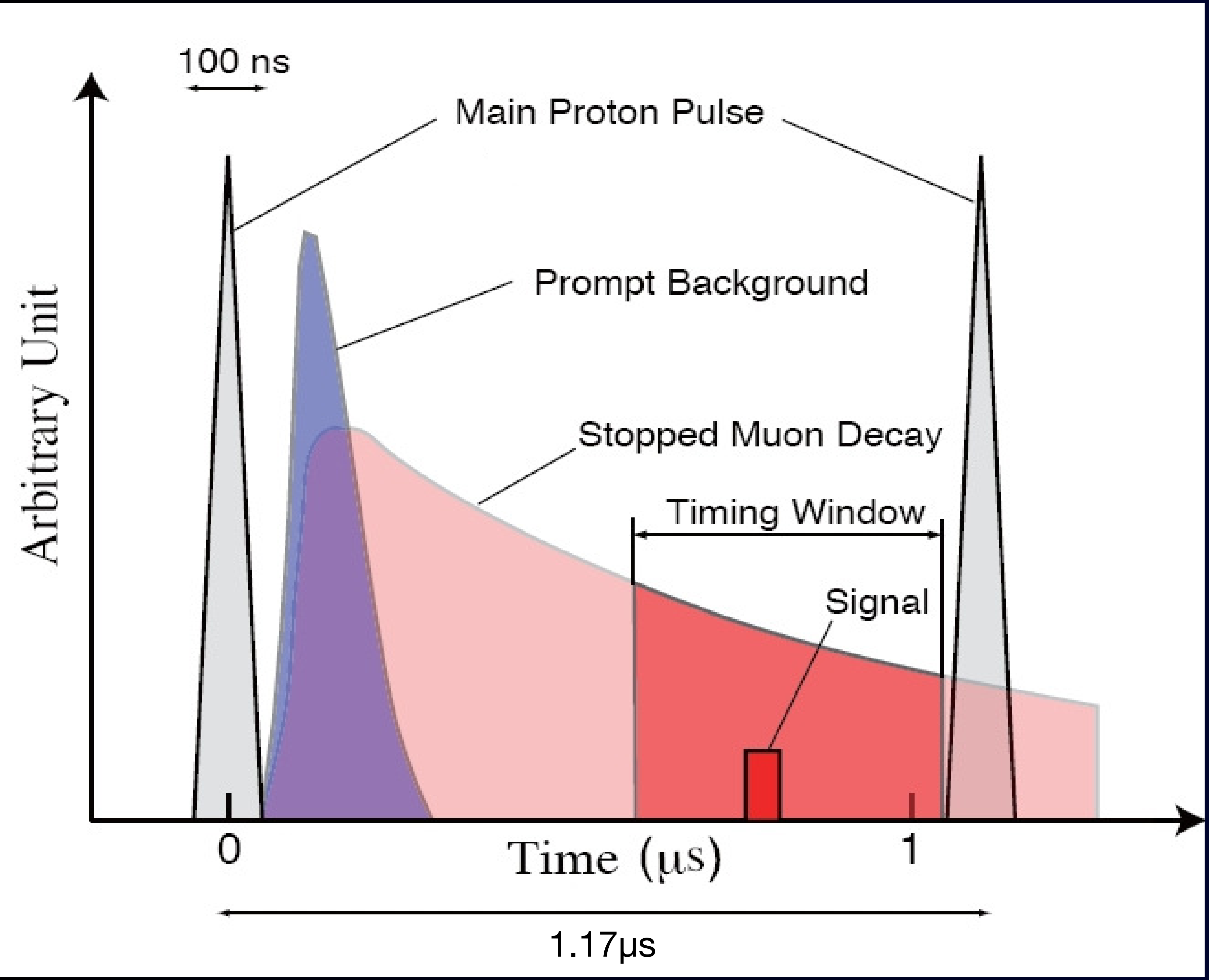

Aluminum muon target (muonic atom lifetime of 864 ns is good for this repetition.)

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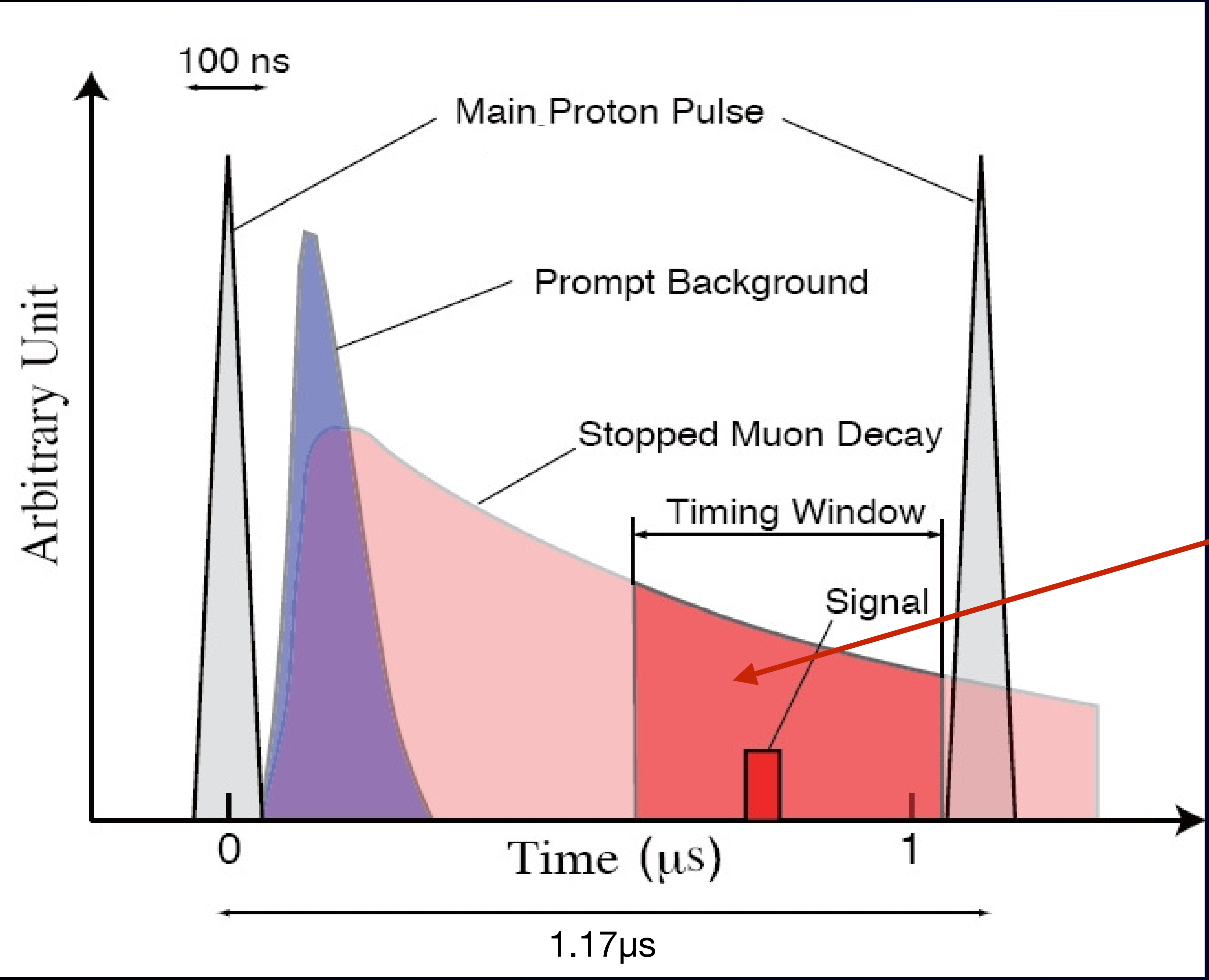

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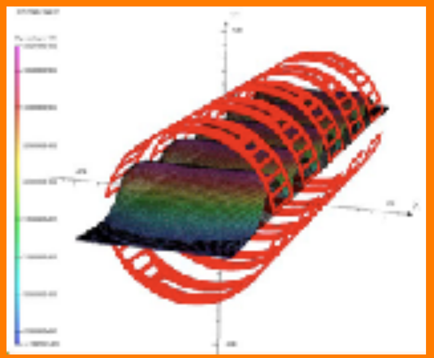
Delayed time window to avoid beam background (from 700 ns to 1.17μs)

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

Charge and Momentum Selection in Curved Solenoid with Dipole field



B_{dipole}

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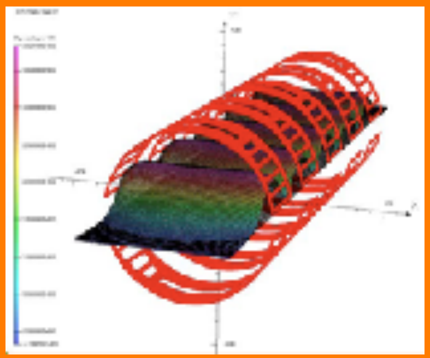

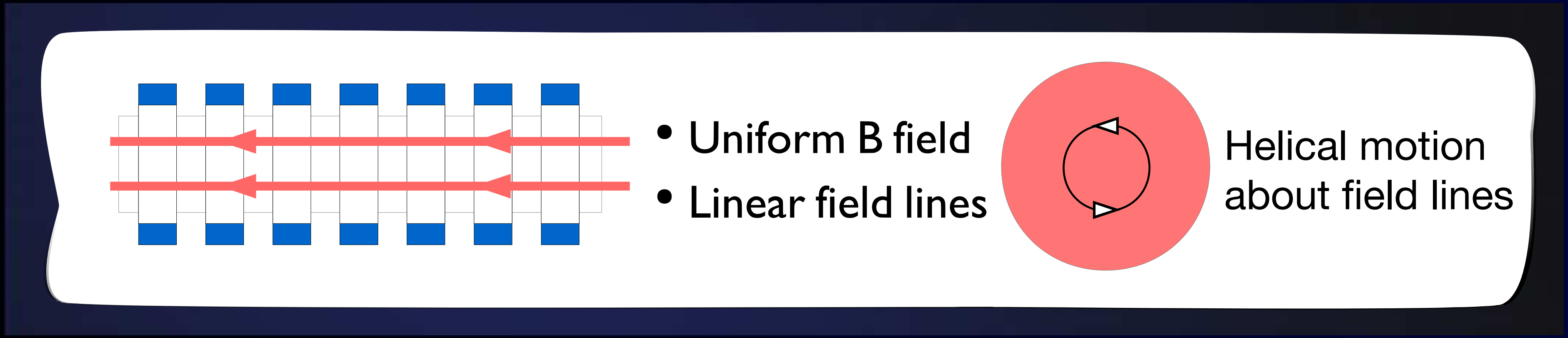

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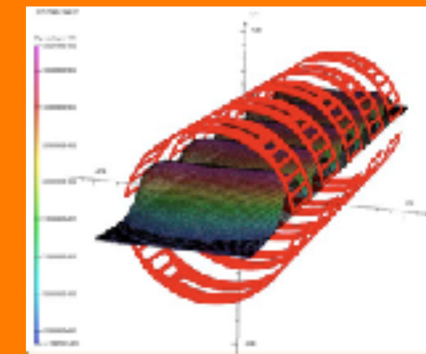
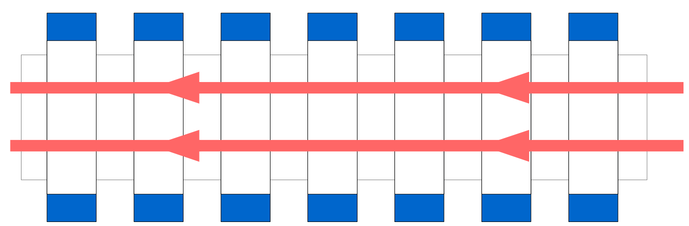
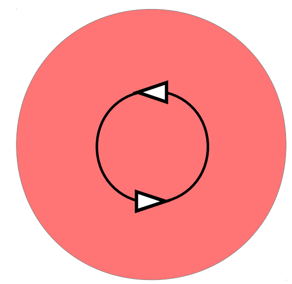
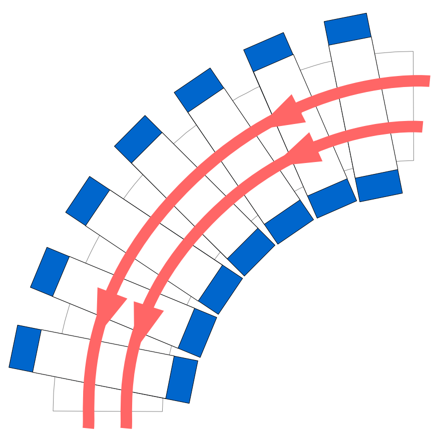




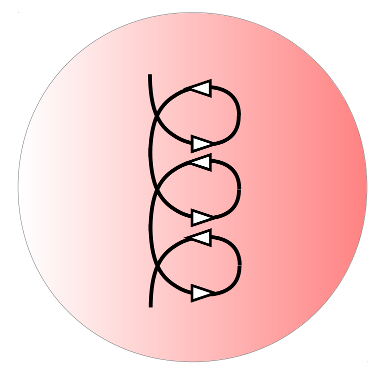
- Uniform B field
- Linear field lines



Helical motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines



Helical motion about a drifting centre

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

B_{dipole}

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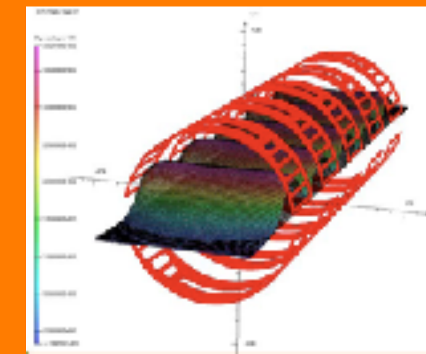

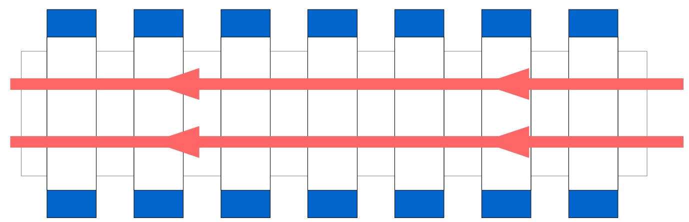

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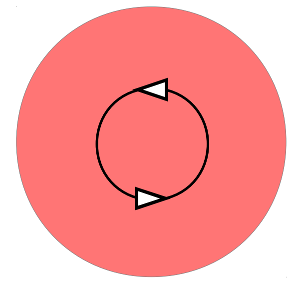

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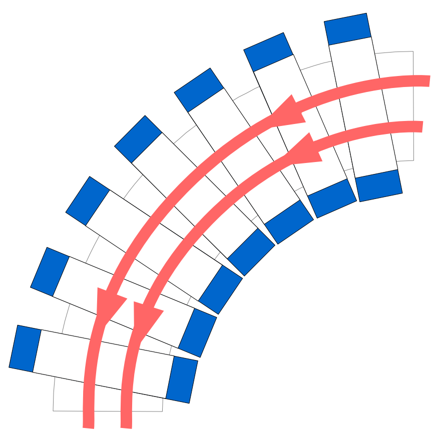

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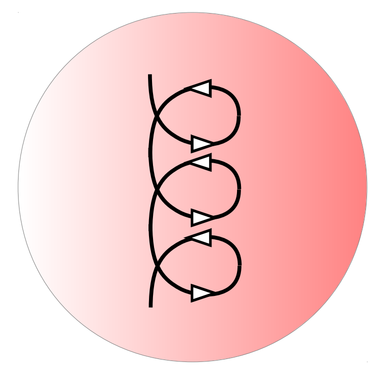

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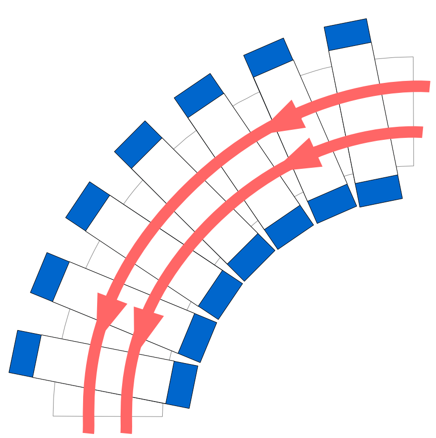
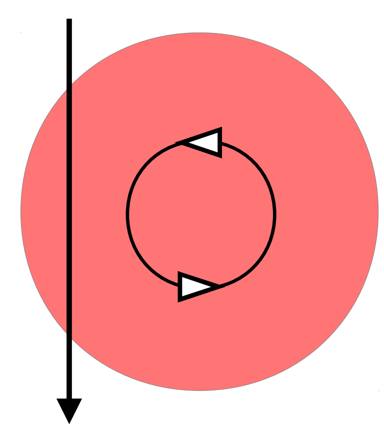


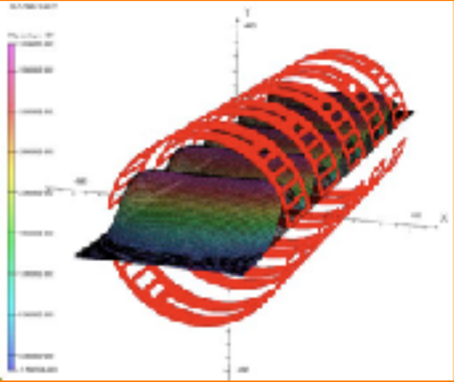
- Radial gradient in magnetic field
- Cylindrical field lines
- dipole field normal to the bending plane

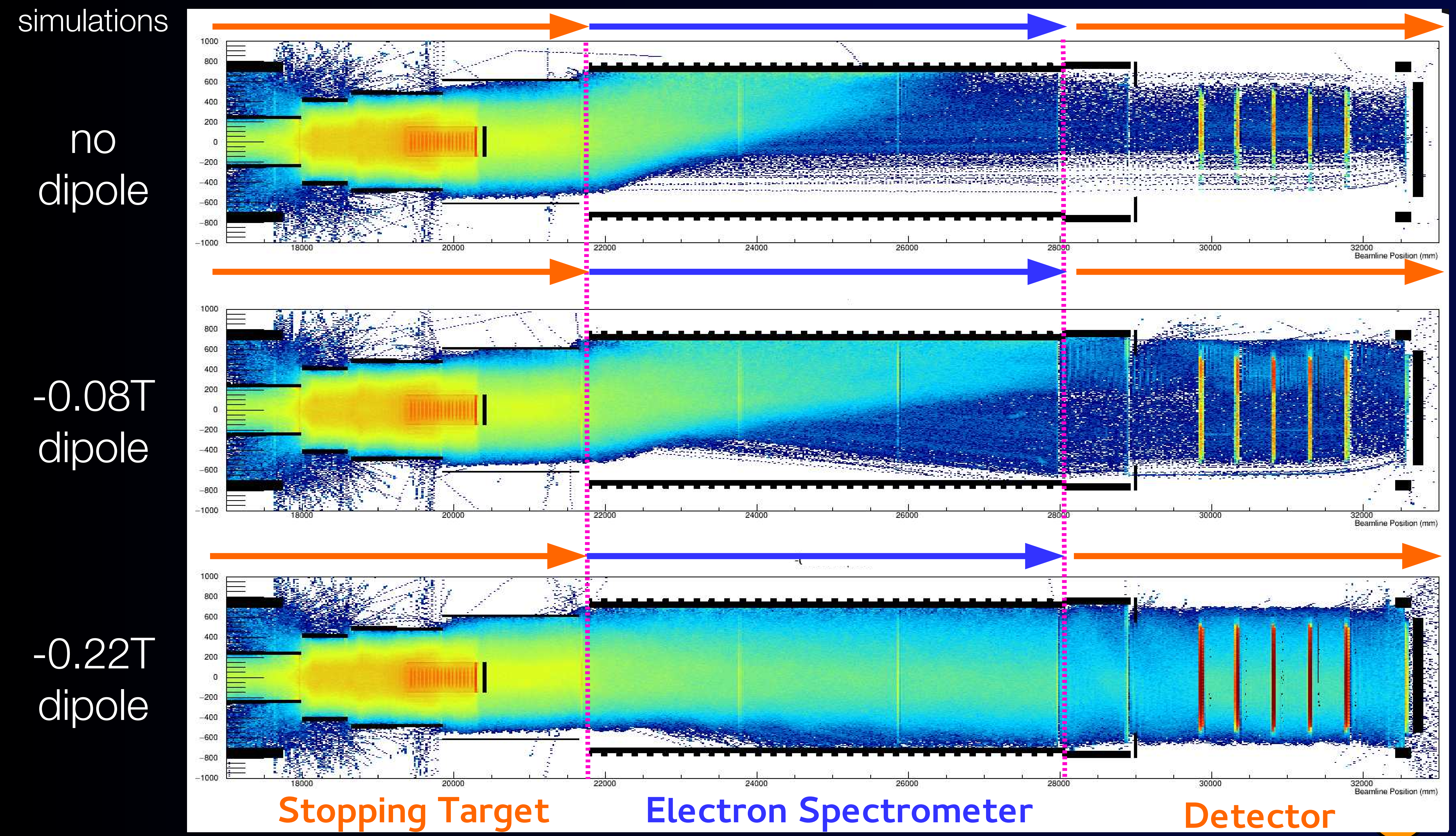


Helical motion of selected momentum p_0 staying in the bending plane

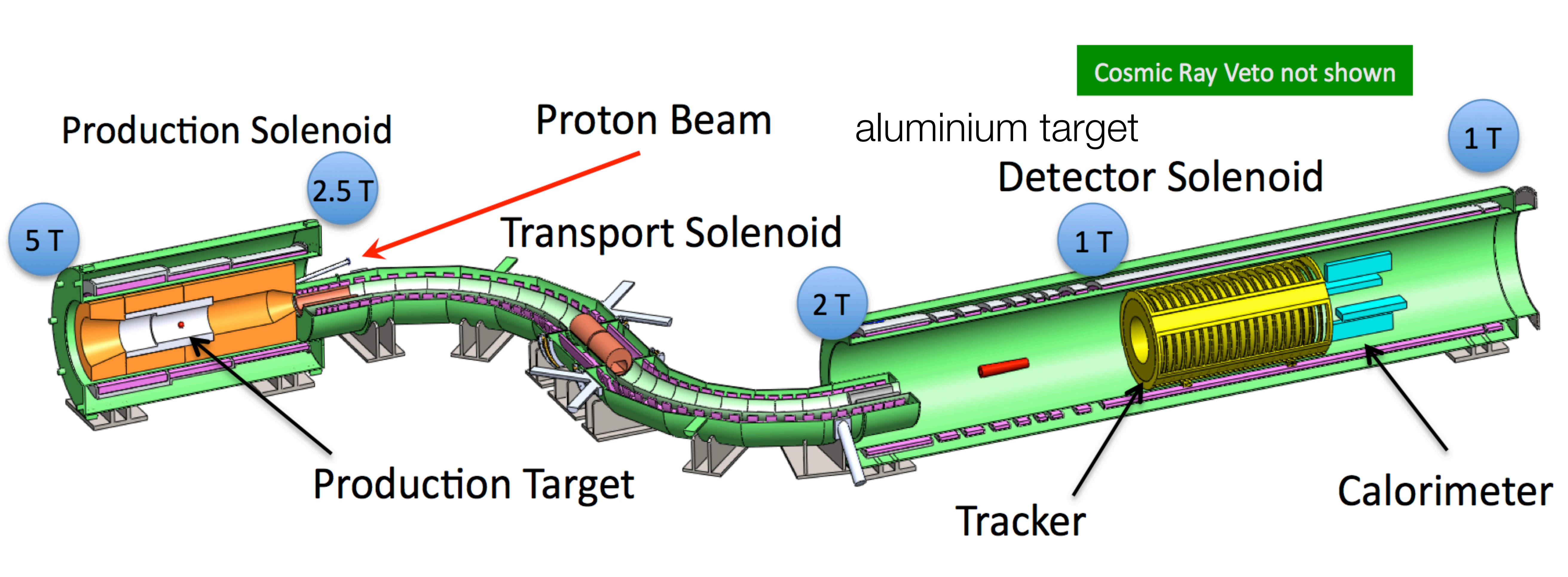
$$B_{\mathrm{dipole}} \propto \frac{p_0}{qR}$$

Trajectory of Signal Electrons in Curved Solenoid + Dipole Field





Mu2e at Fermilab



Sensitivity : <6x10^{-17} (90% CL)

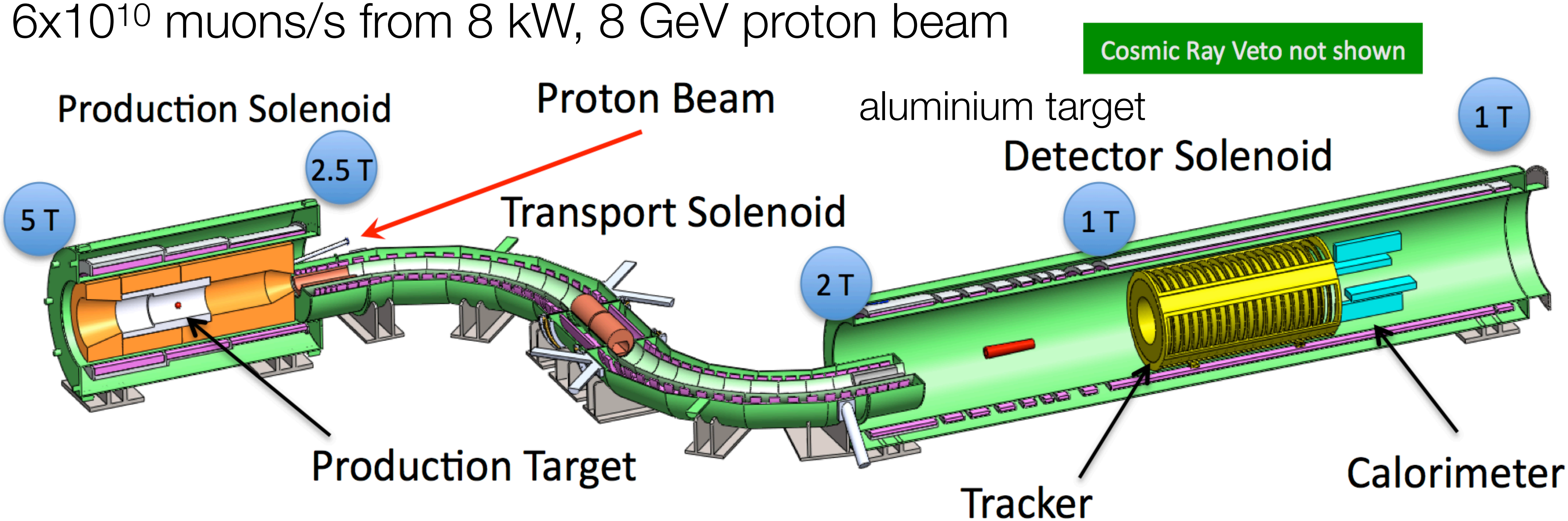
a factor of 10,000 improvement

Run time: 3 years (2x10^{7}sec/year)

commissioning in 2026

Mu2e at Fermilab

6×10^{10} muons/s from 8 kW, 8 GeV proton beam



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a factor of 10,000 improvement

Run time: 3 years (2×10^{7} sec/year)

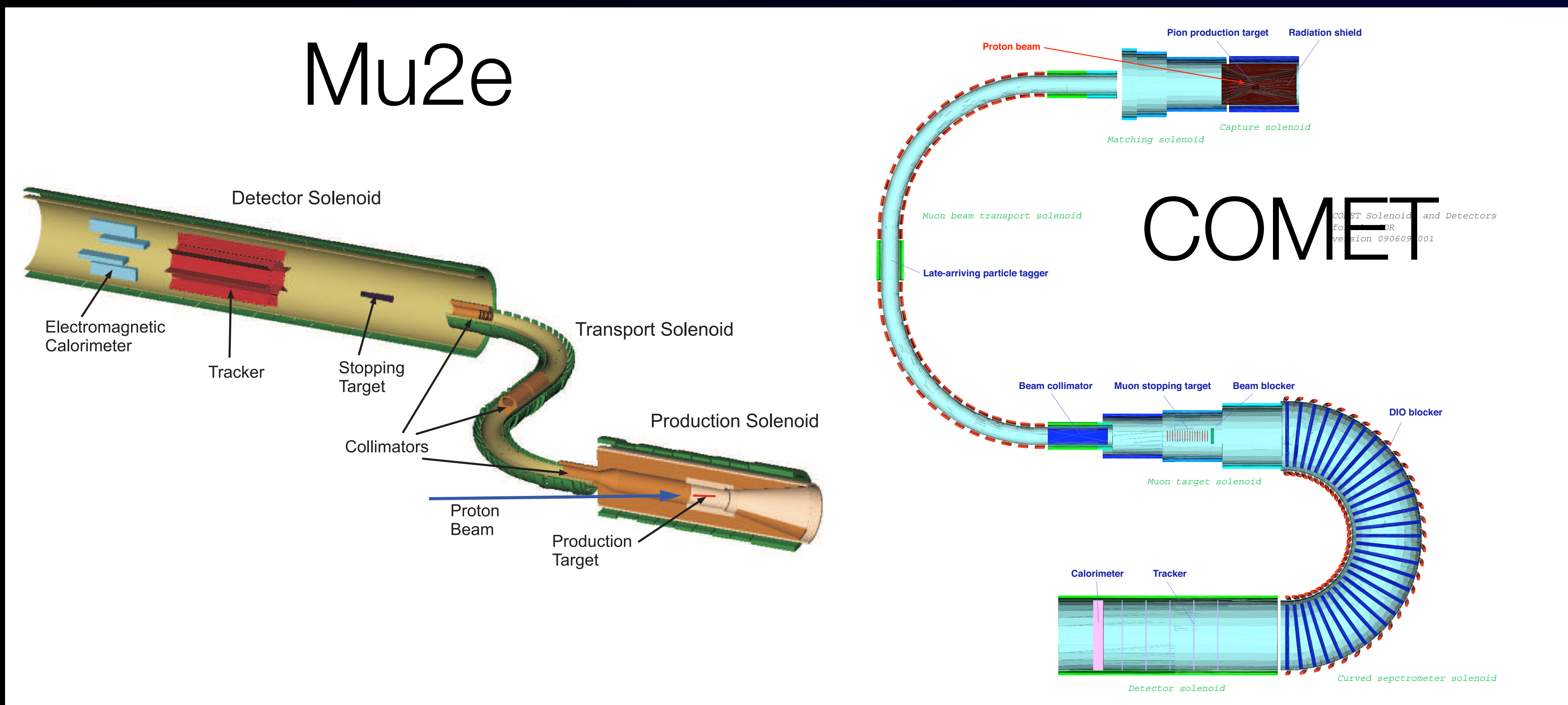
commissioning in 2026

Mu2e-II

- 800 MeV, 100 kW from PIP-II
- aim at $O(10^{-18})$ with 3 years

a factor of 10 from Mu2e

Mu2e vs. COMET

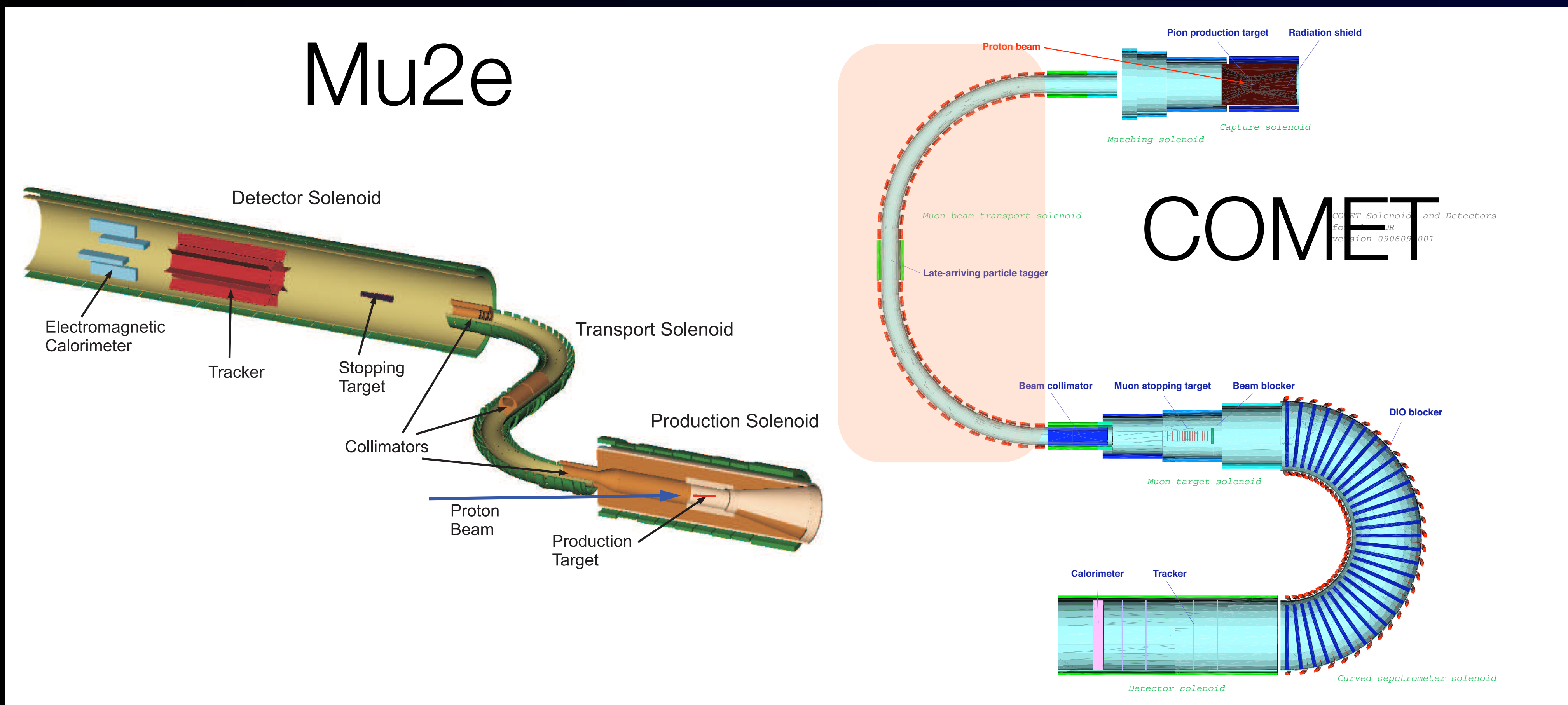


protons	8 kW 3 years	56 kW 1 year
muon beam line	2x 90º bends (opposite direction)	2x 90º bend (same direction)
electron spectrometer	straight solenoid	curved solenoid

Mu2e vs. COMET

Select low momentum muons

eliminate muon decay in flight



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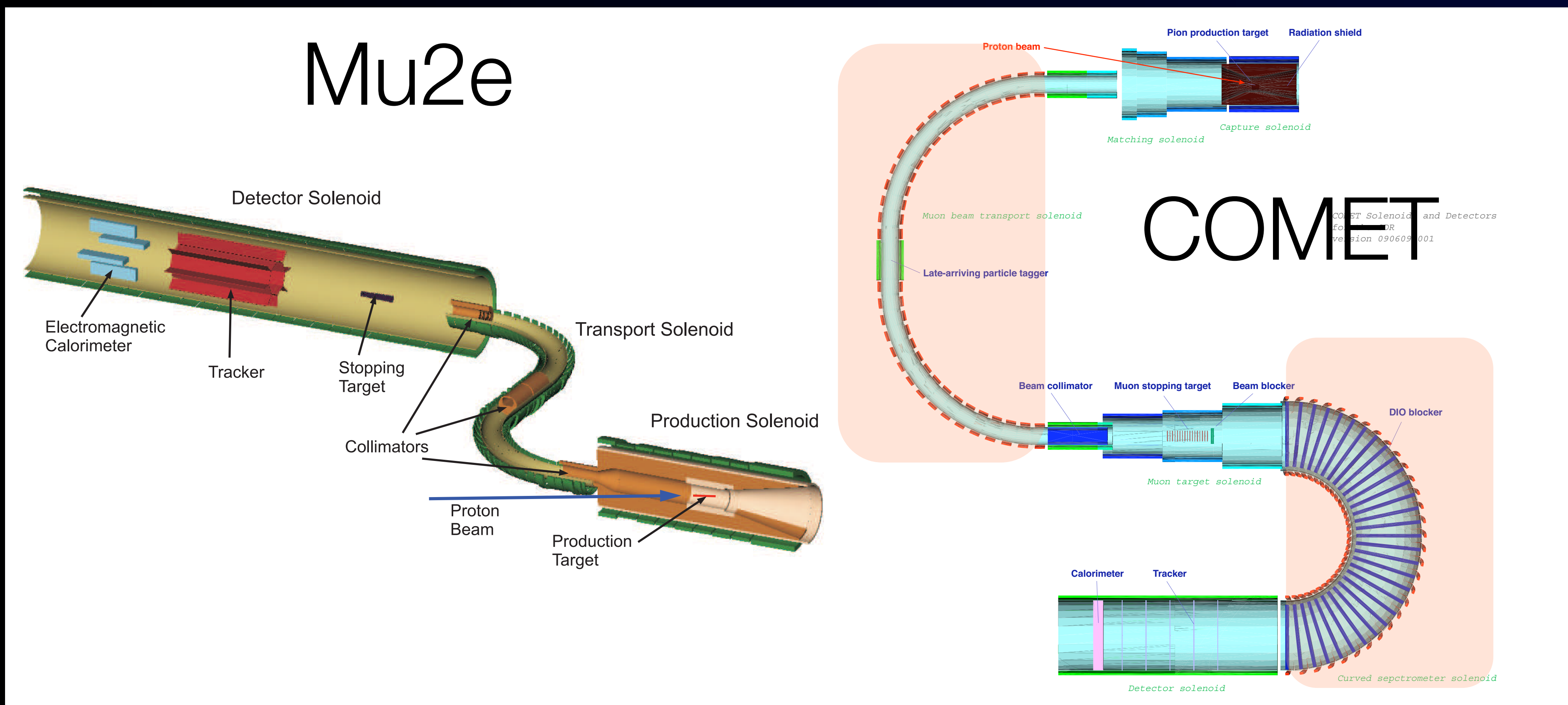

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Select low momentum muons

eliminate muon decay in flight

Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

eliminate low energy events to make the detector quiet.

COMET Collaboration

43 institutes, 17 countries

PI: Y. Kuno

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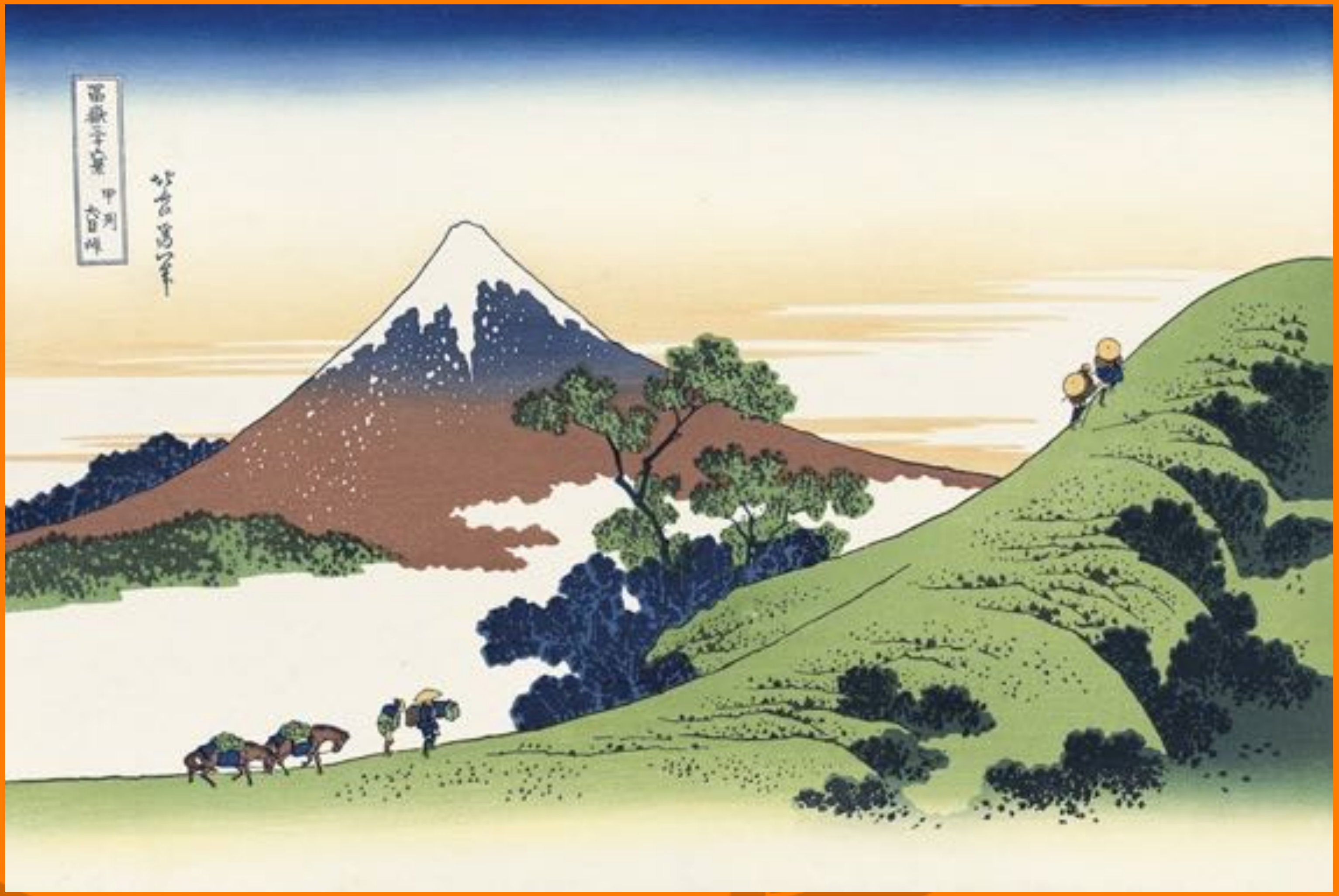
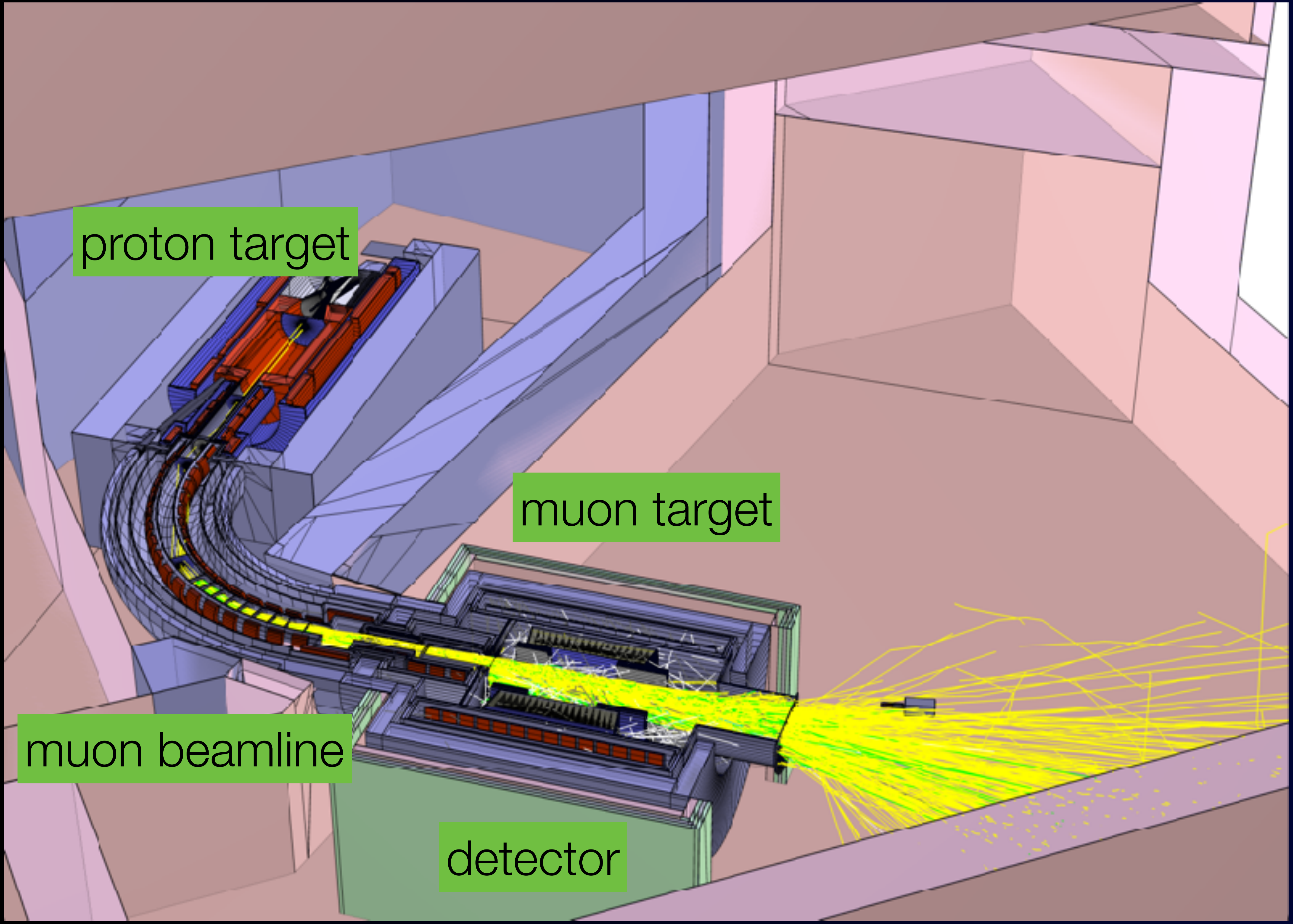
Staged Approach

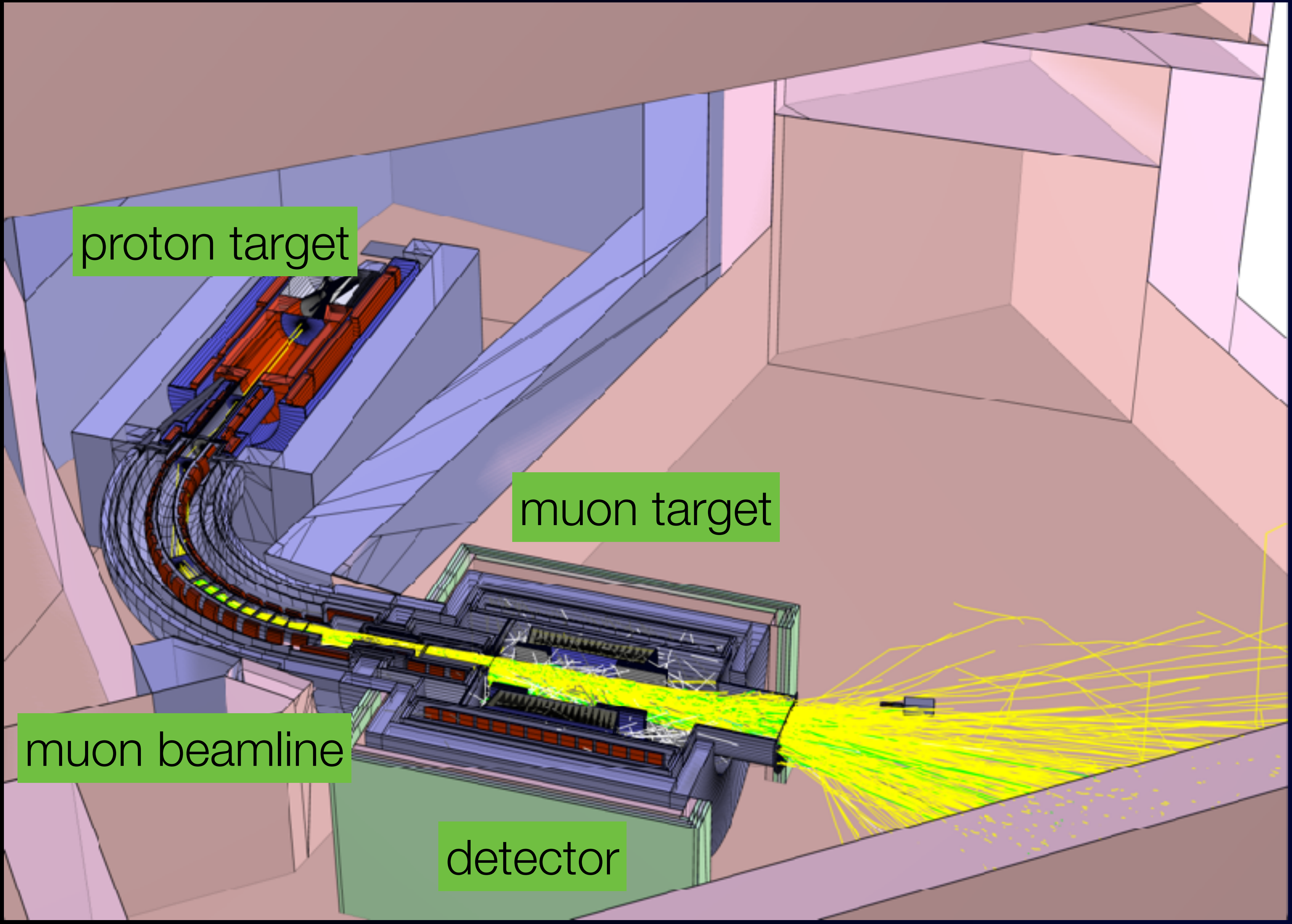


COMET Phase-I (2016 -)



COMET Phase-I (2016 -)

only the first 90 degree curved solenoid + detector solenoid



COMET Phase-I
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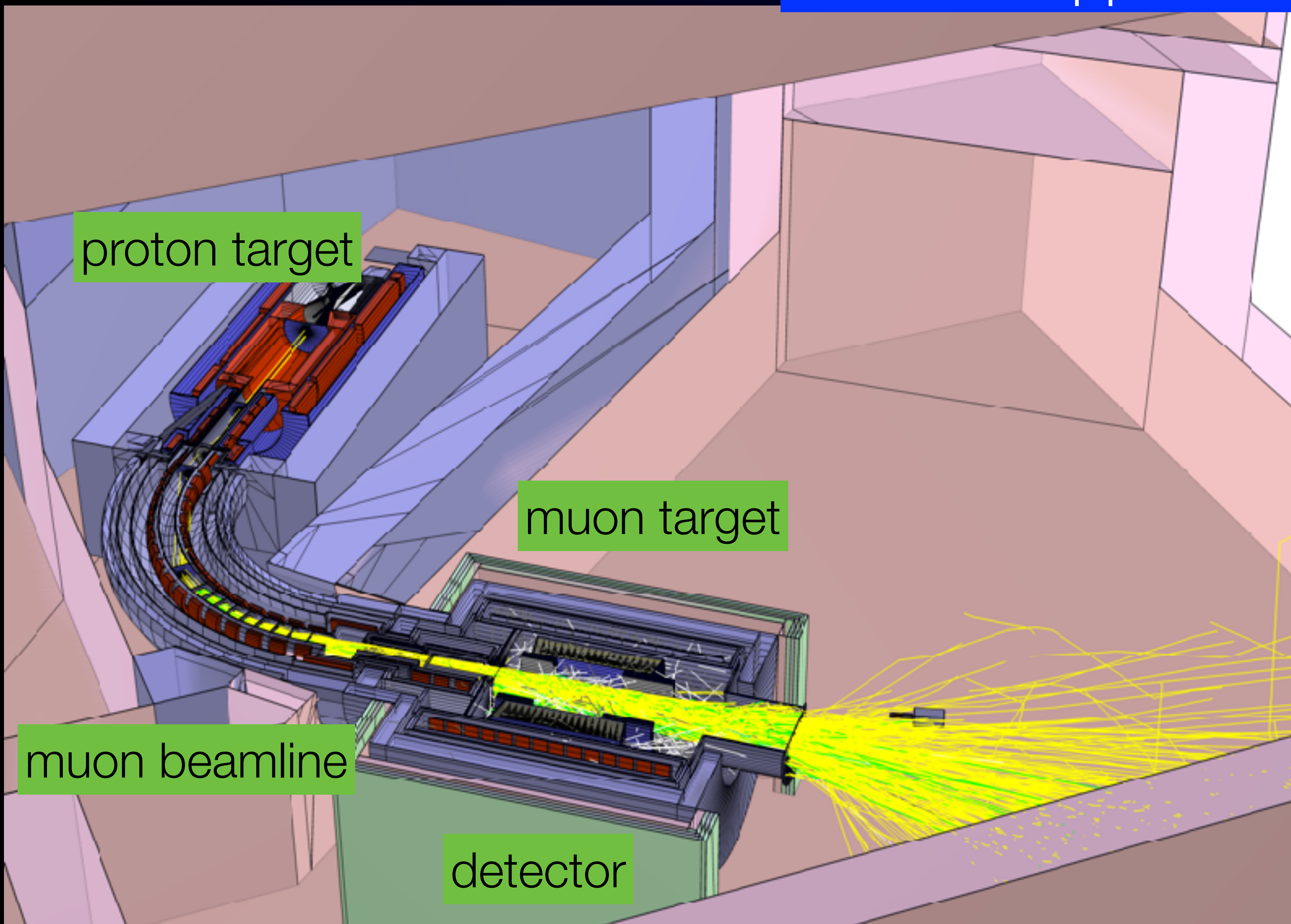
only the first 90 degree
curved solenoid + detector solenoid

- Proton beam, 8 GeV, 3.2kW
- $2x10^9$ stopped muons/s

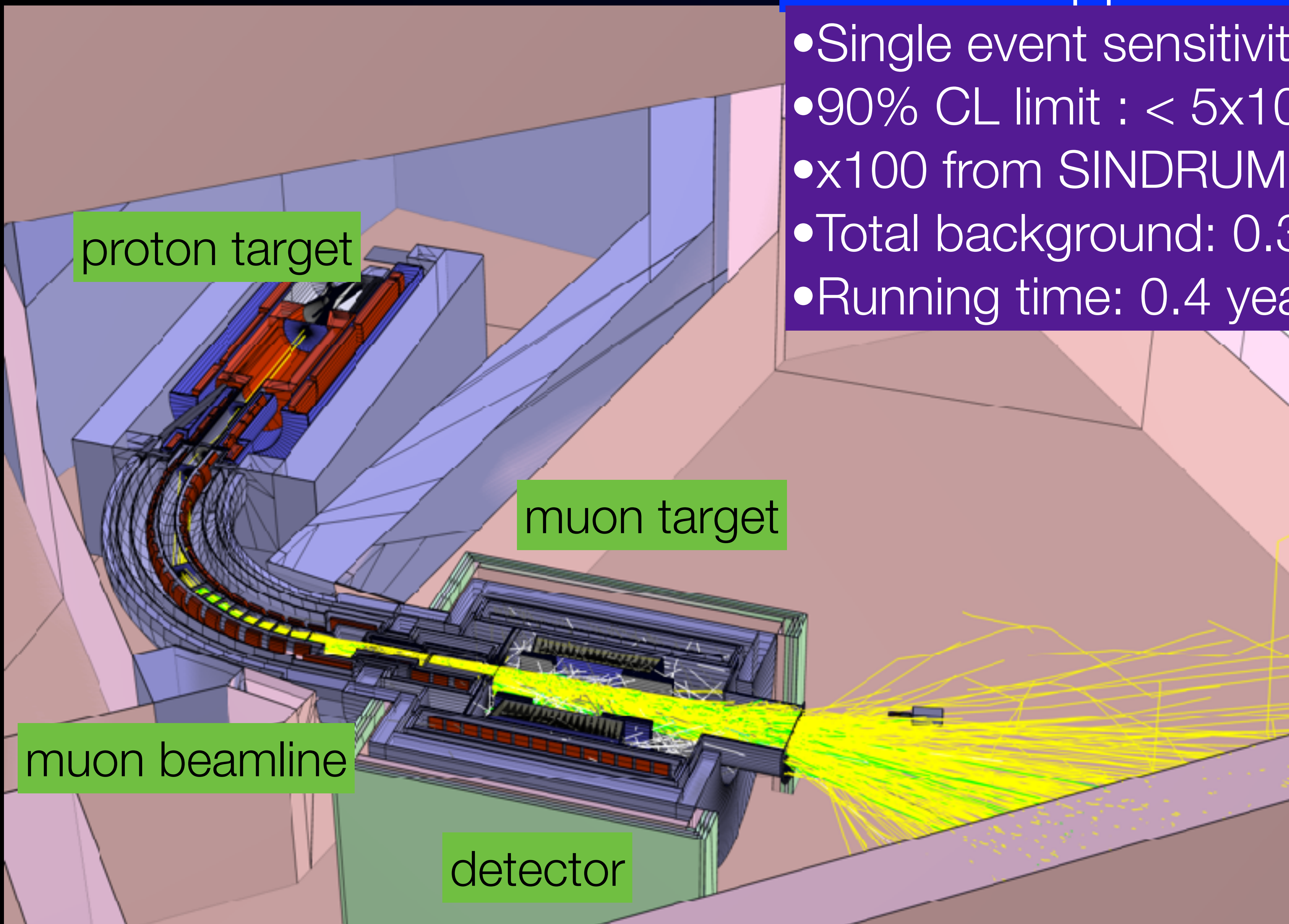


COMET Phase-I (2016 -)

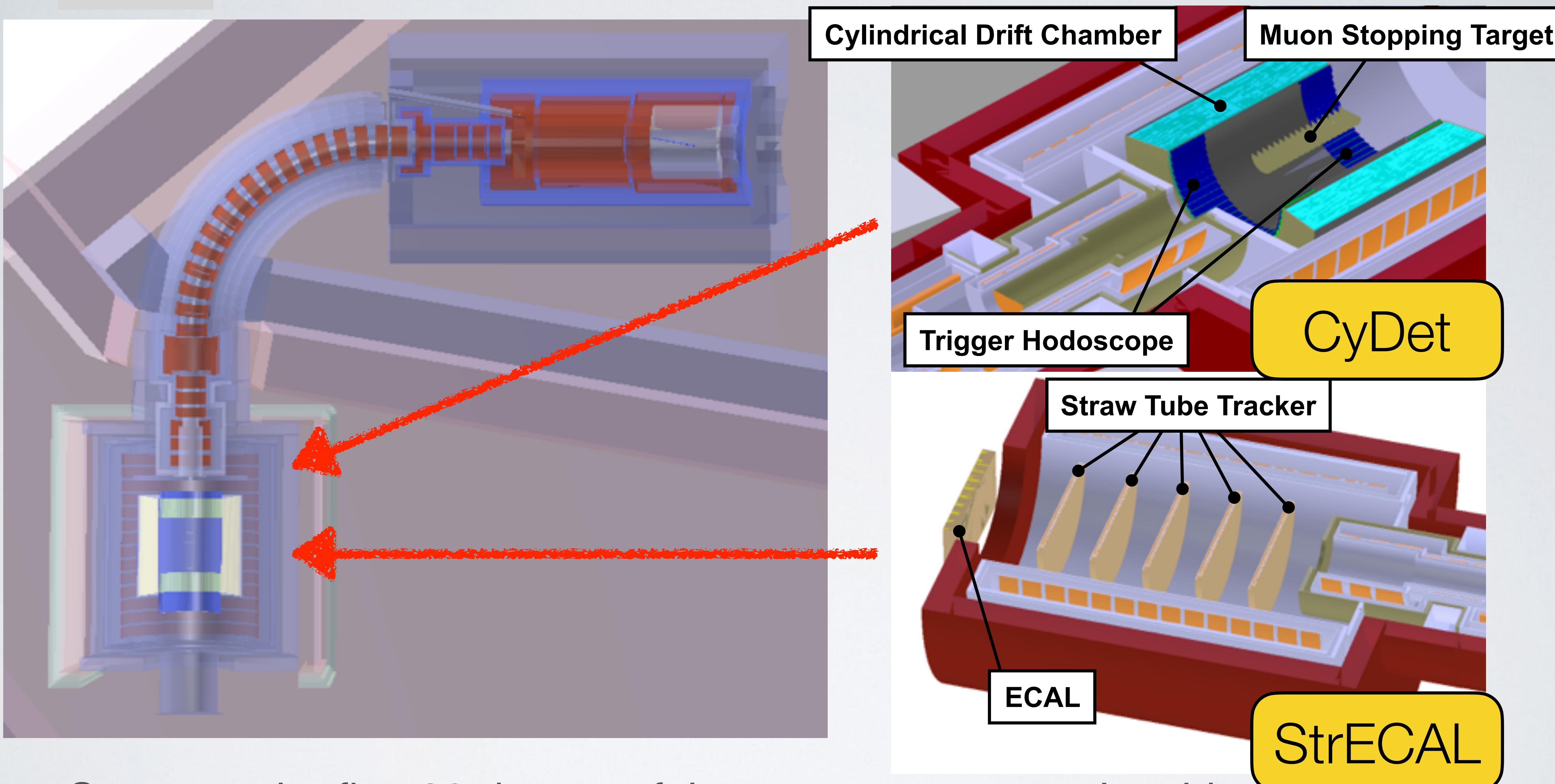
only the first 90 degree curved solenoid + detector solenoid

- 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 (1.2×10^7 sec)



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



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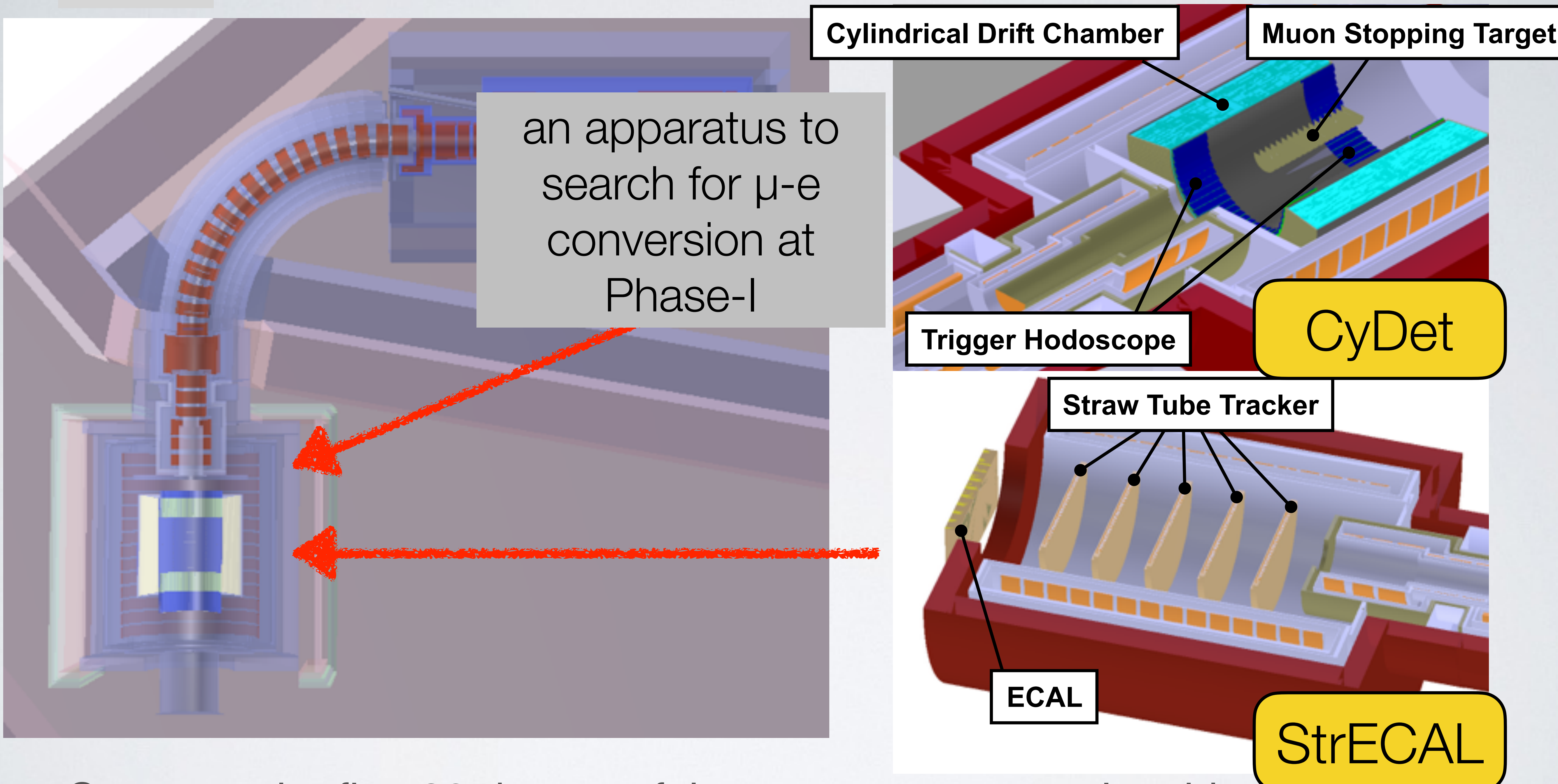

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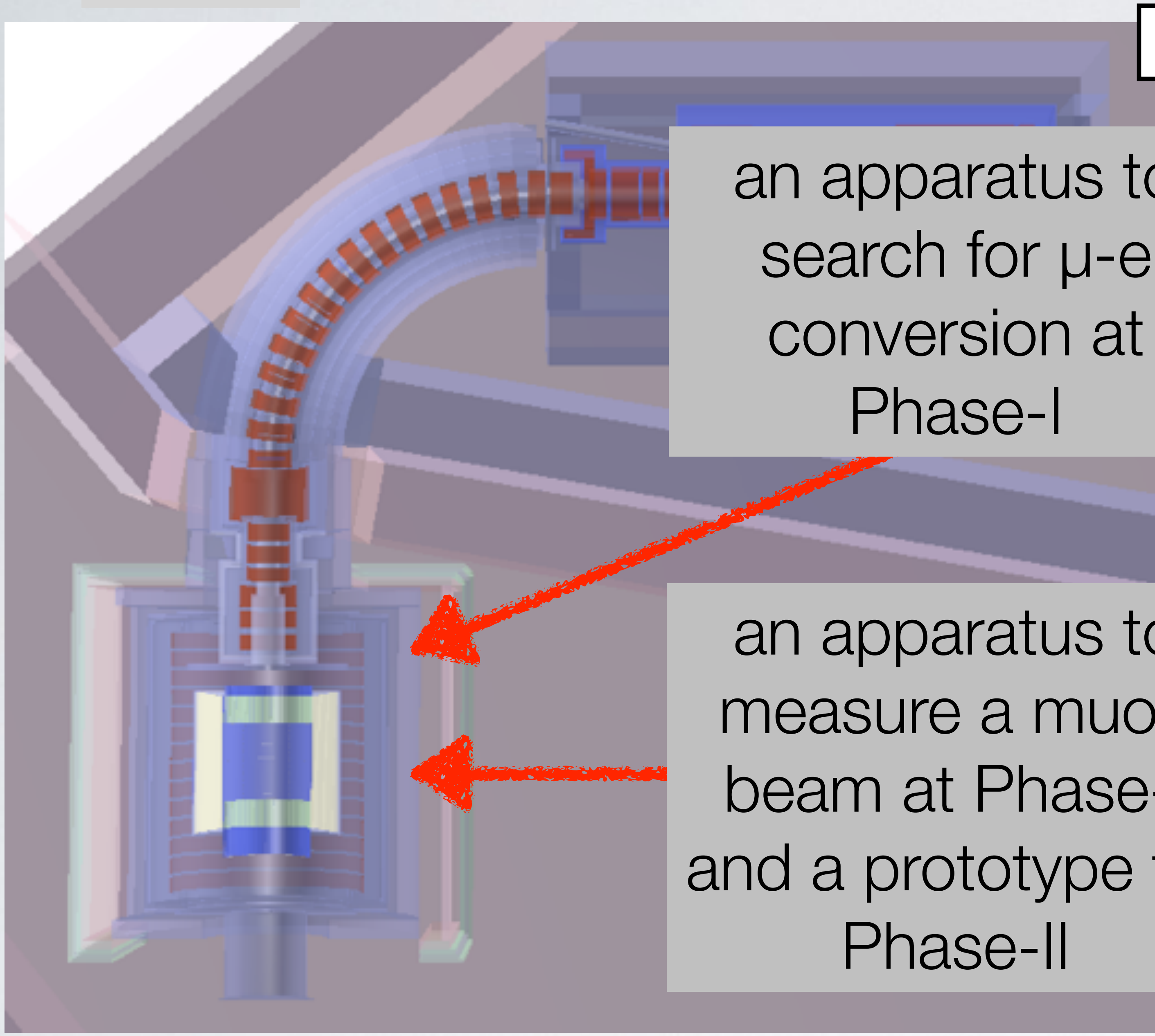
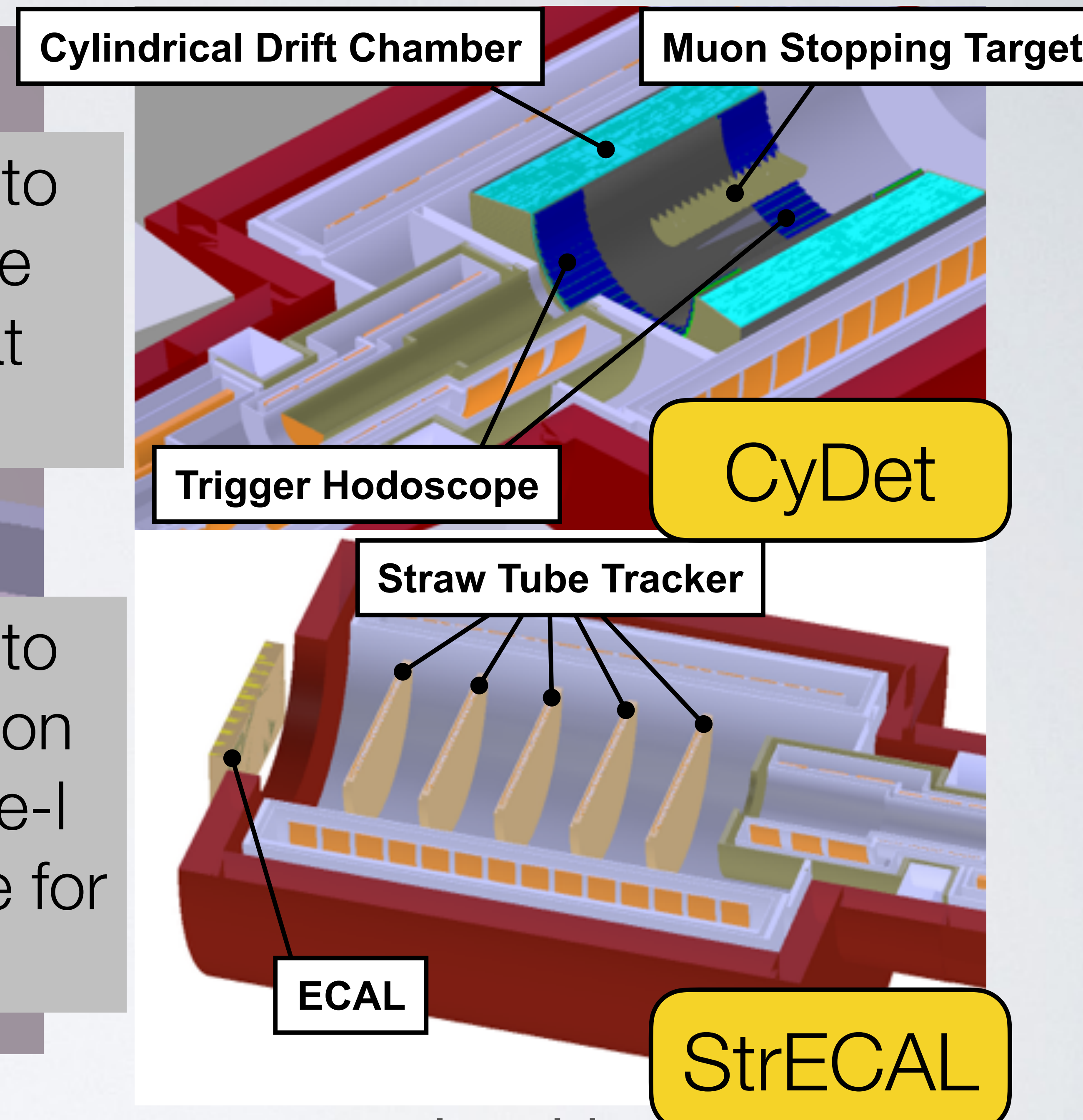


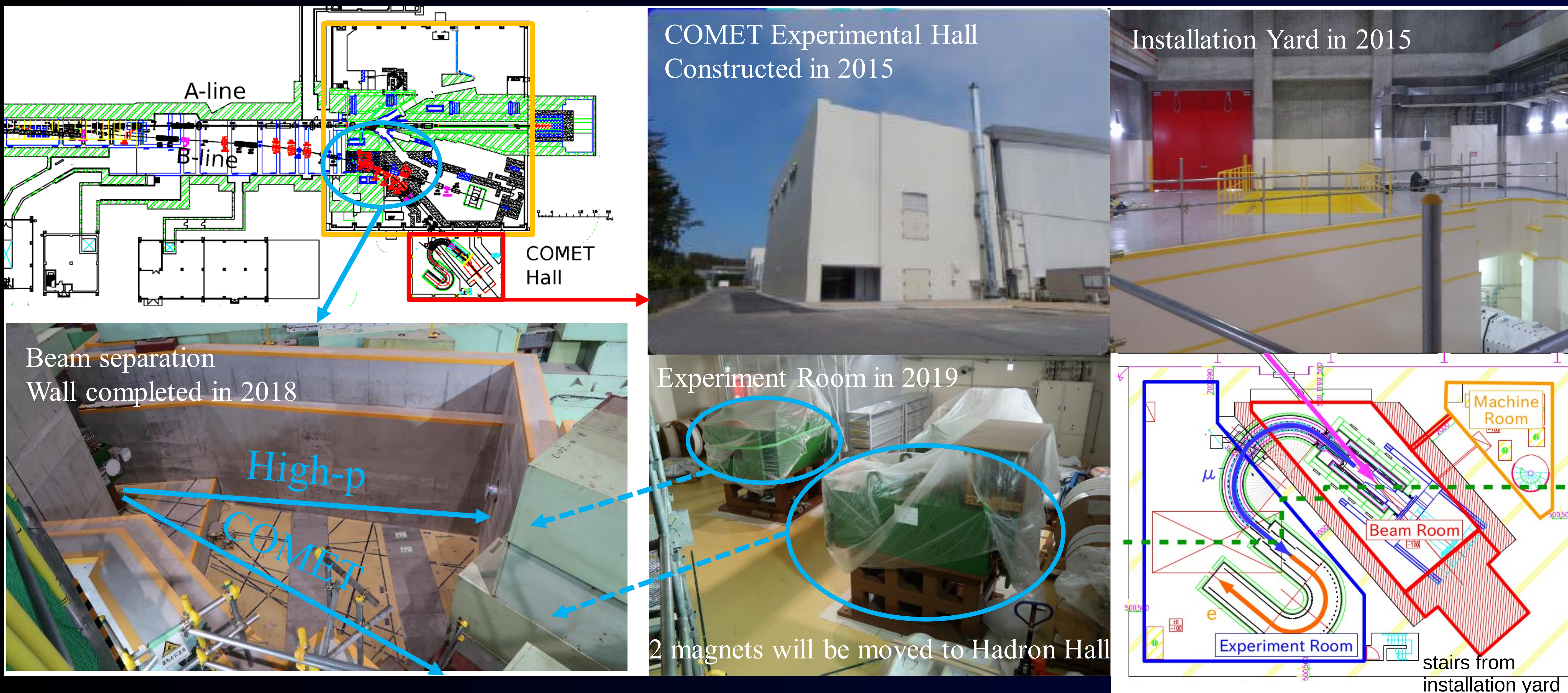
an apparatus to search for μ-e conversion at Phase-I

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



COMET Phase-I Status

COMET Facility at J-PARC



- 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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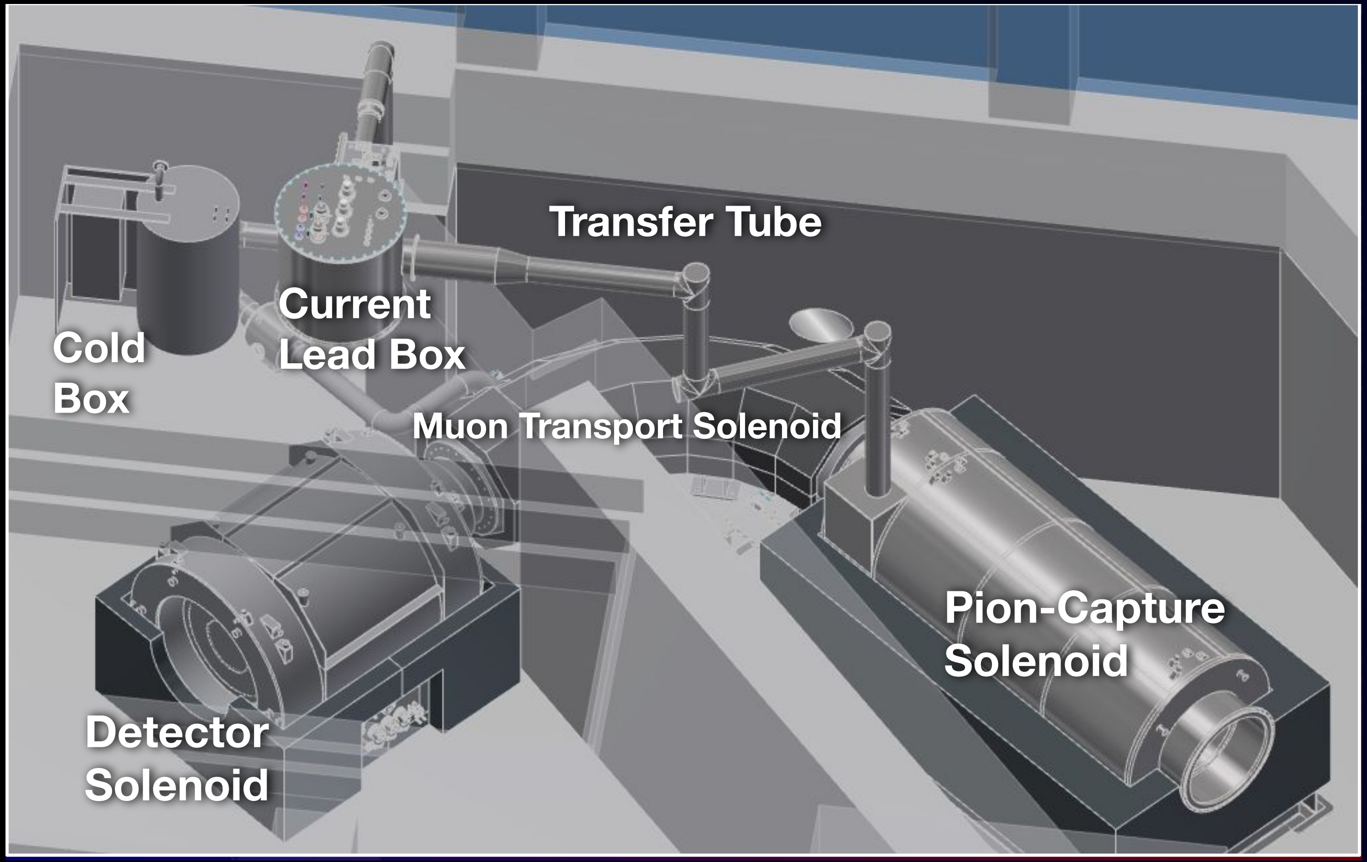

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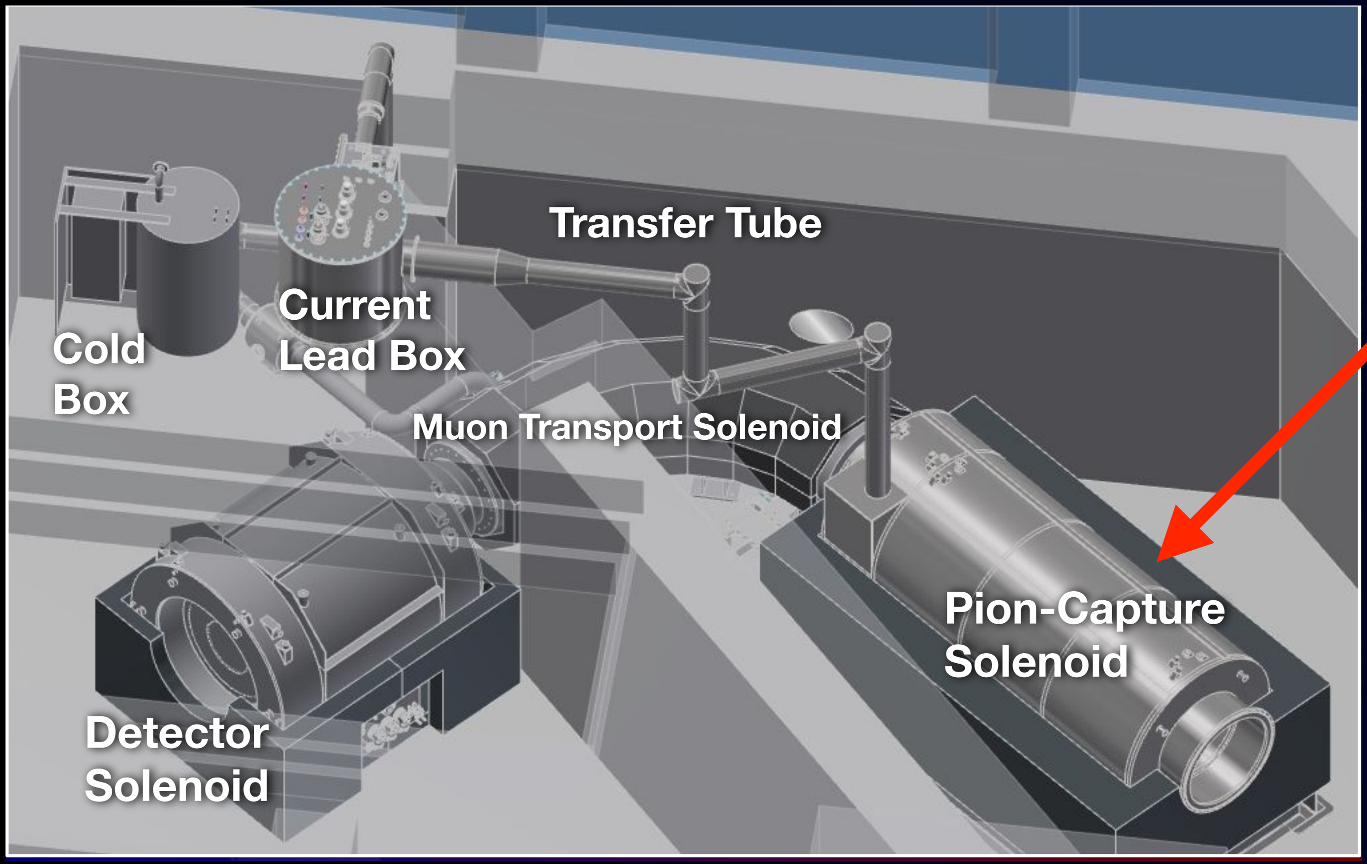

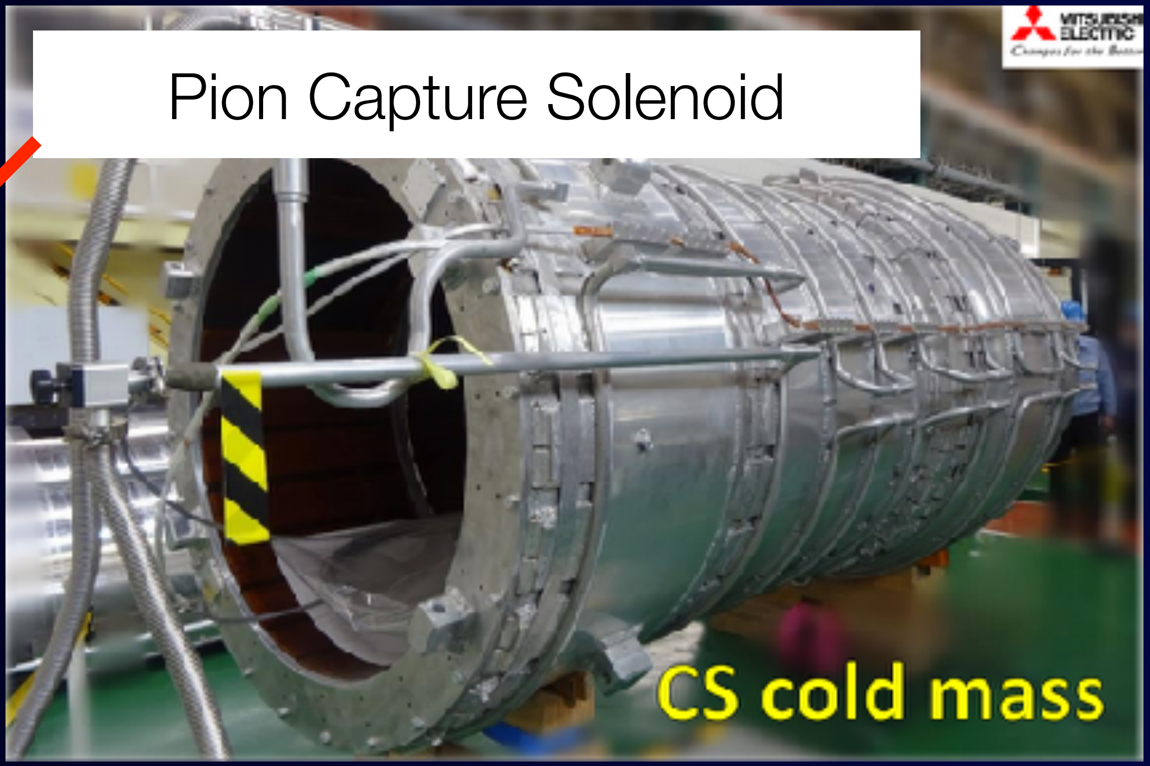

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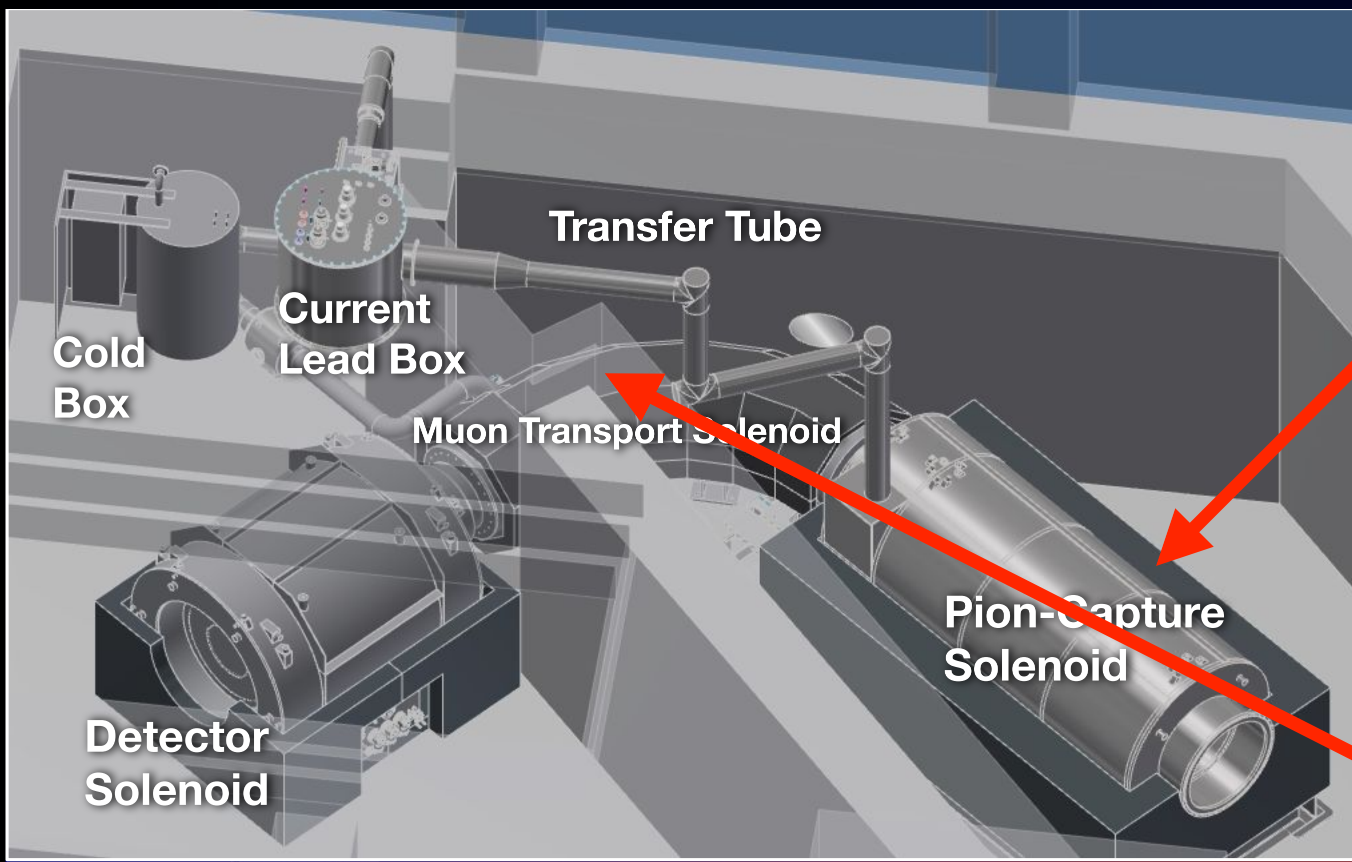

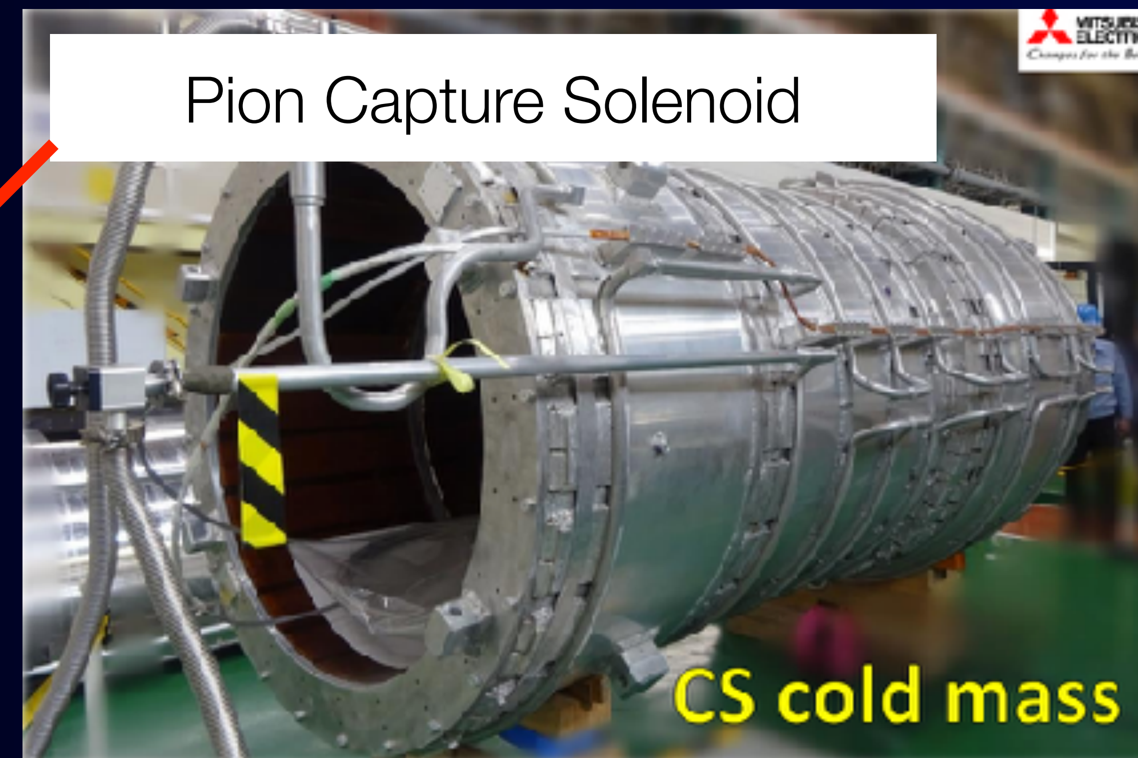

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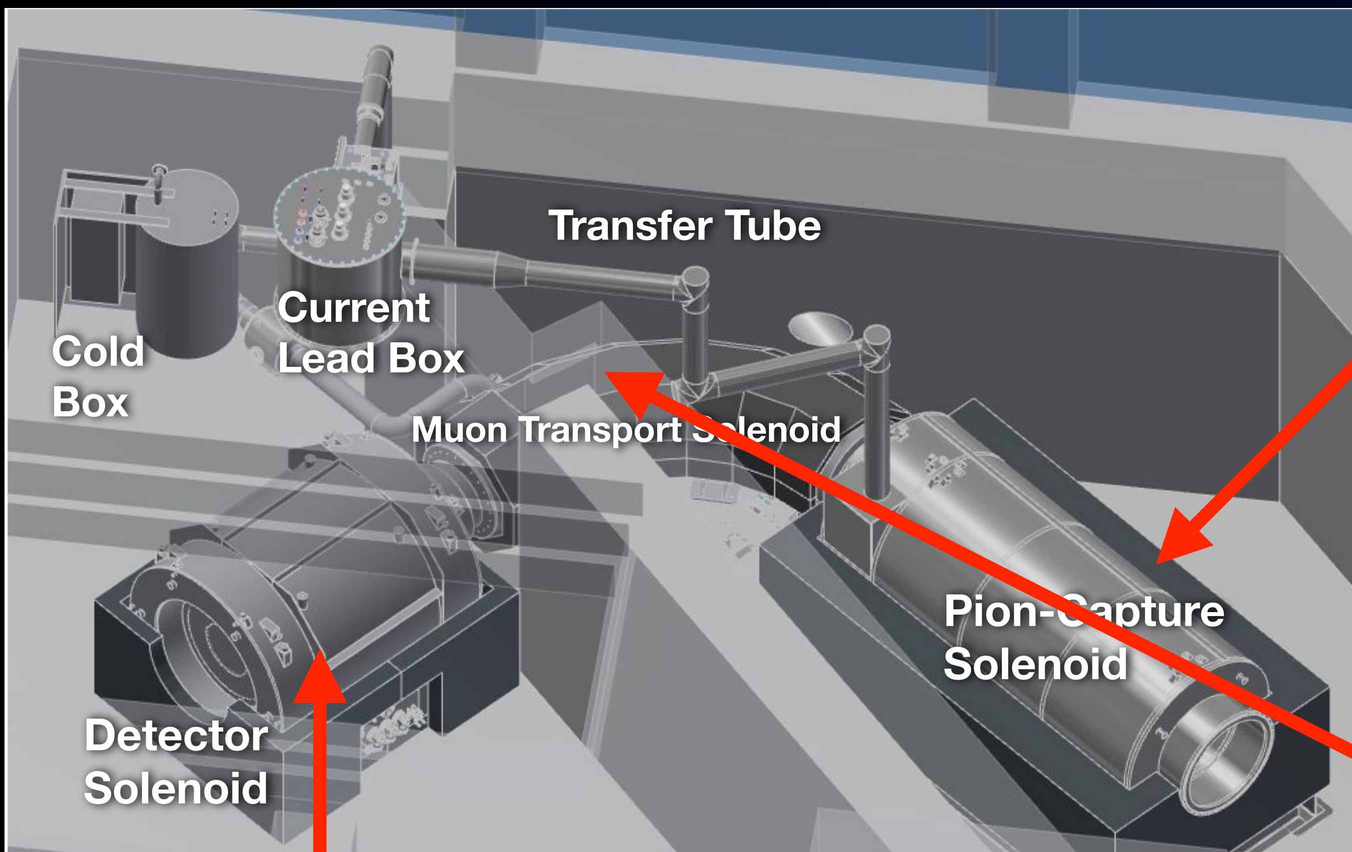
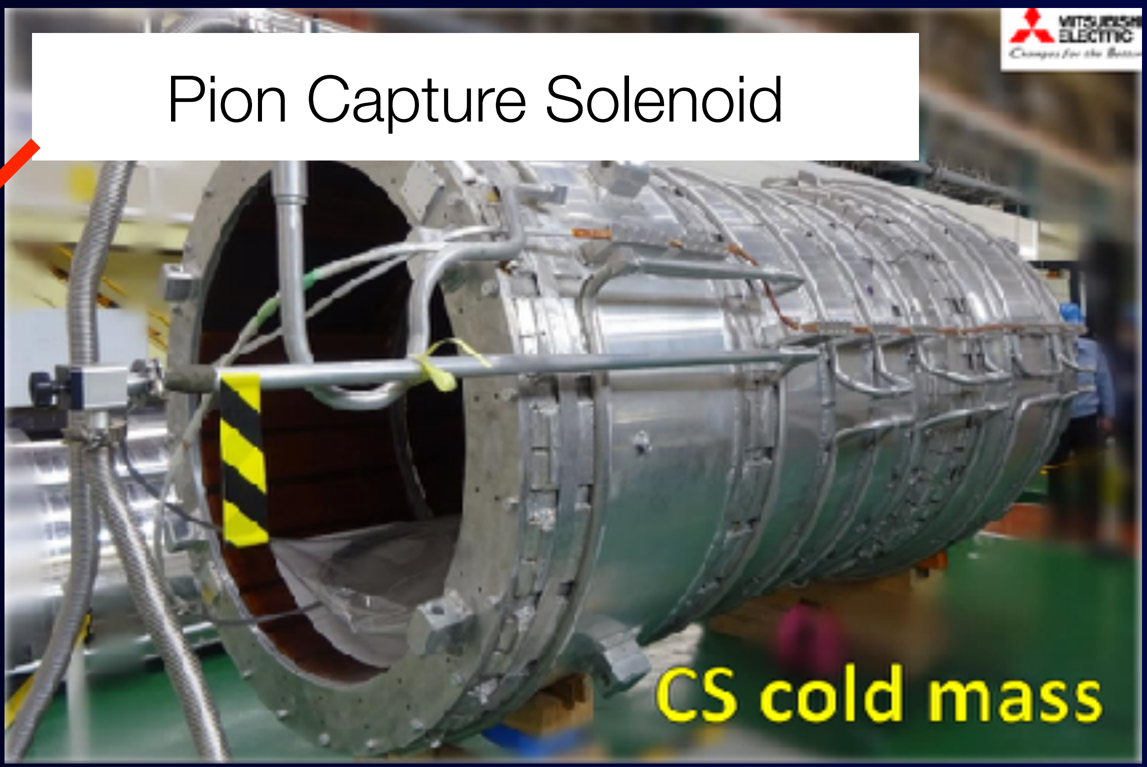
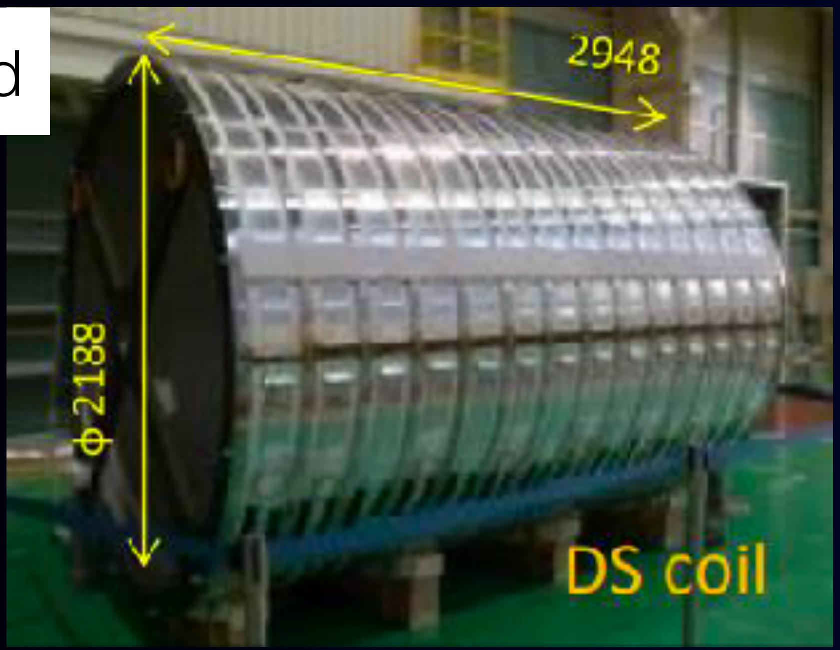




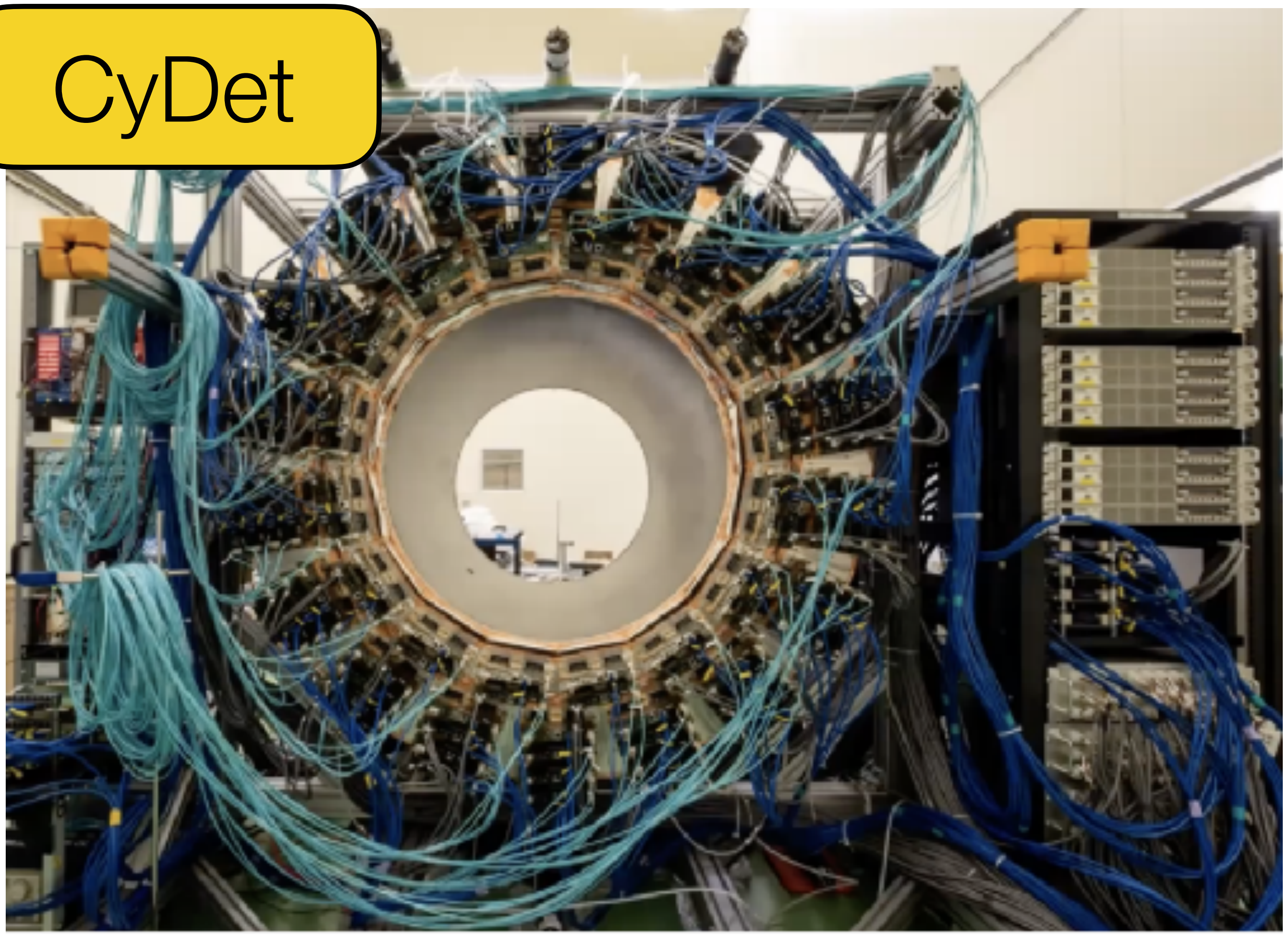
Detector Solenoid



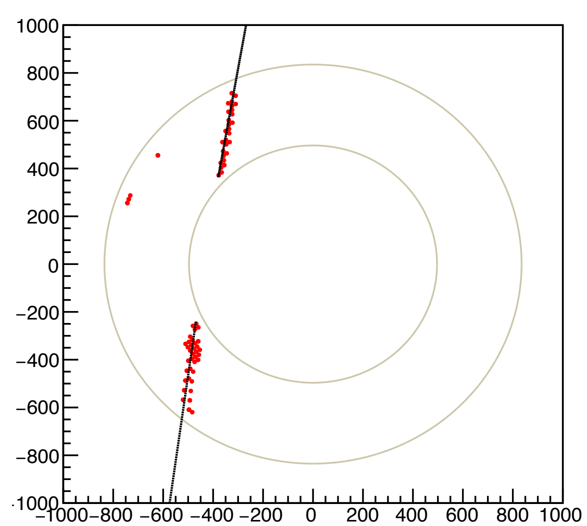
Construction of CyDet and StrECAL

Construction of CyDet and StrECAL

CyDet



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



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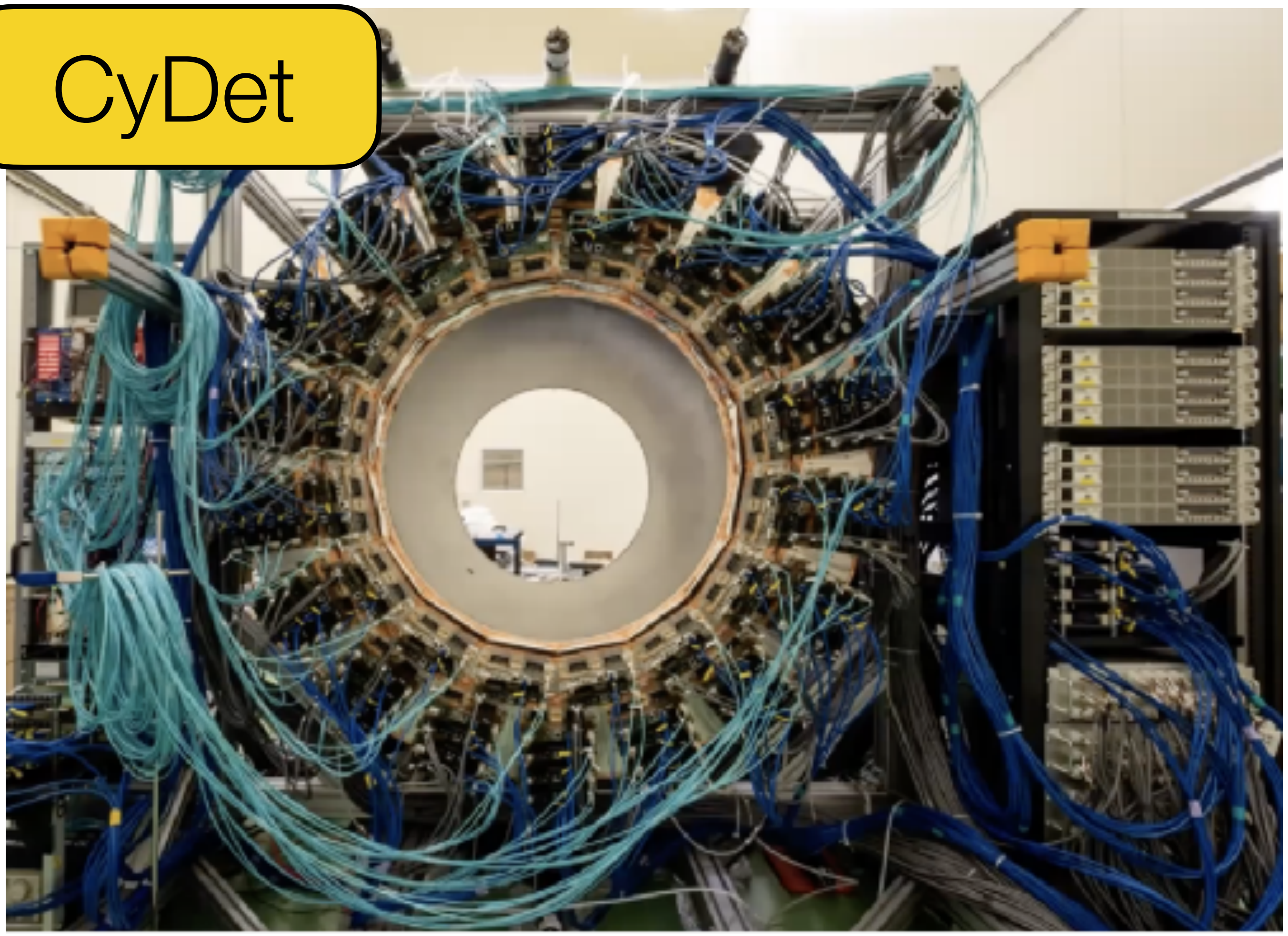
CyDet



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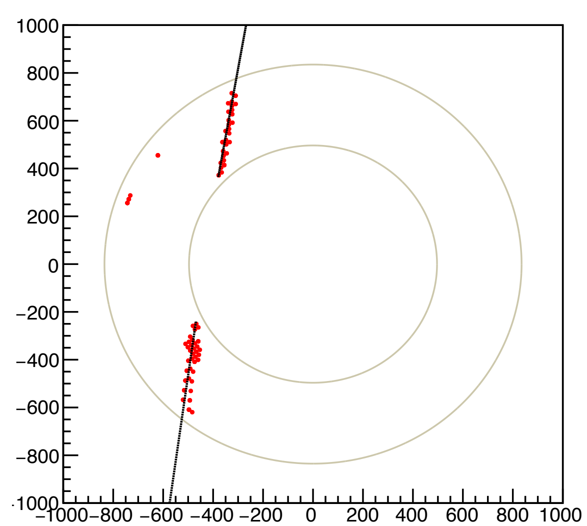
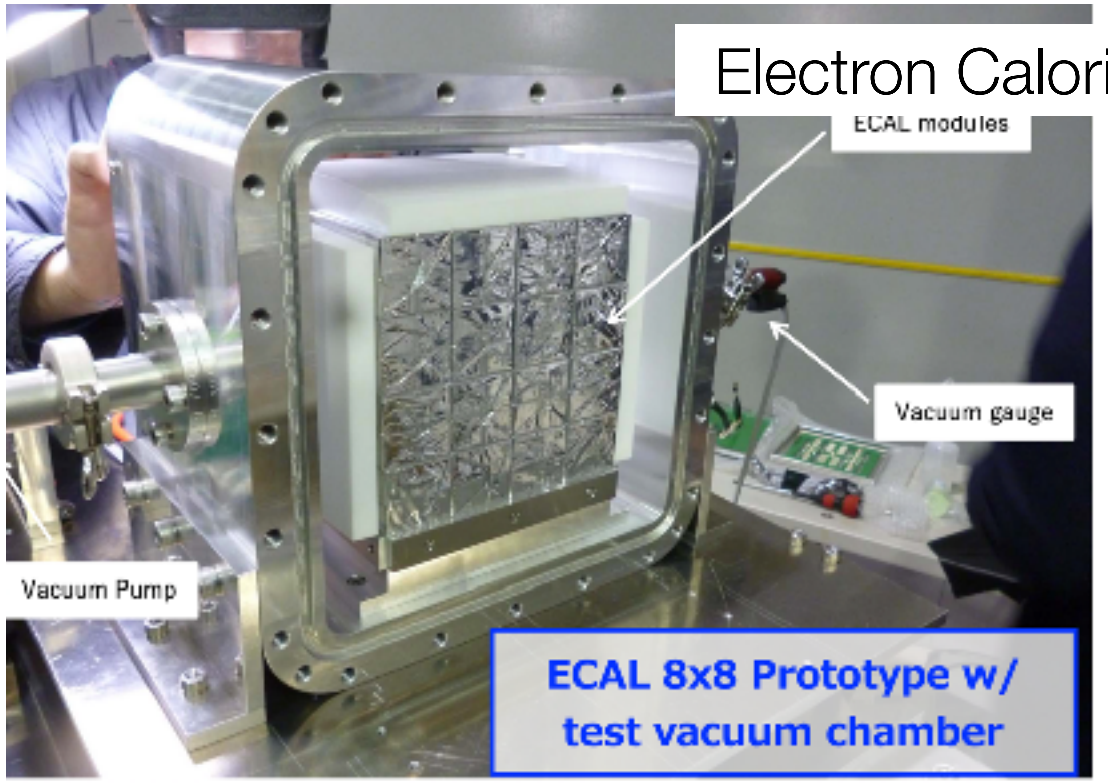


StrECAL



COMET Phase α (2023)

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COMET proton beam commissioning

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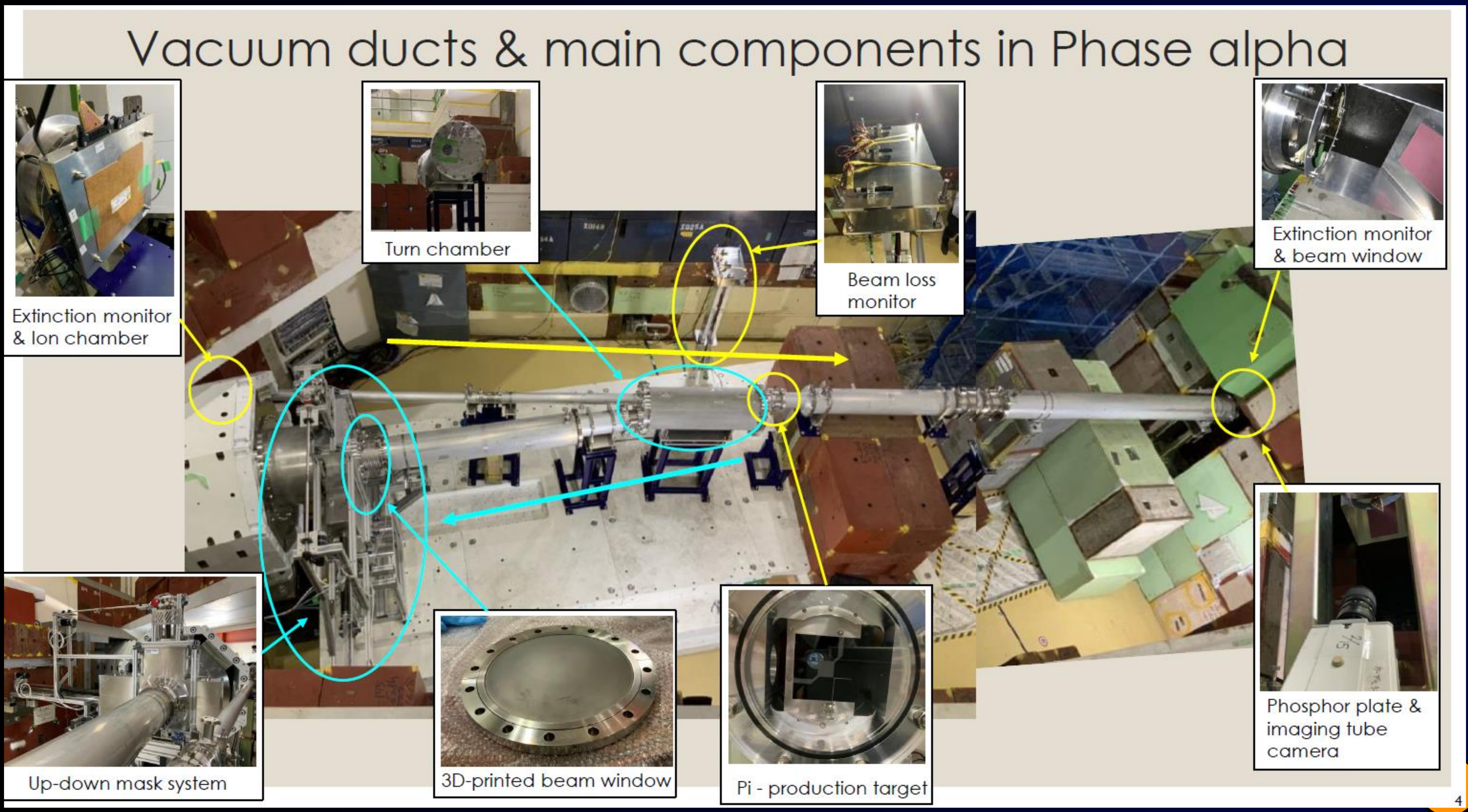

COMET Phase α (2023)

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

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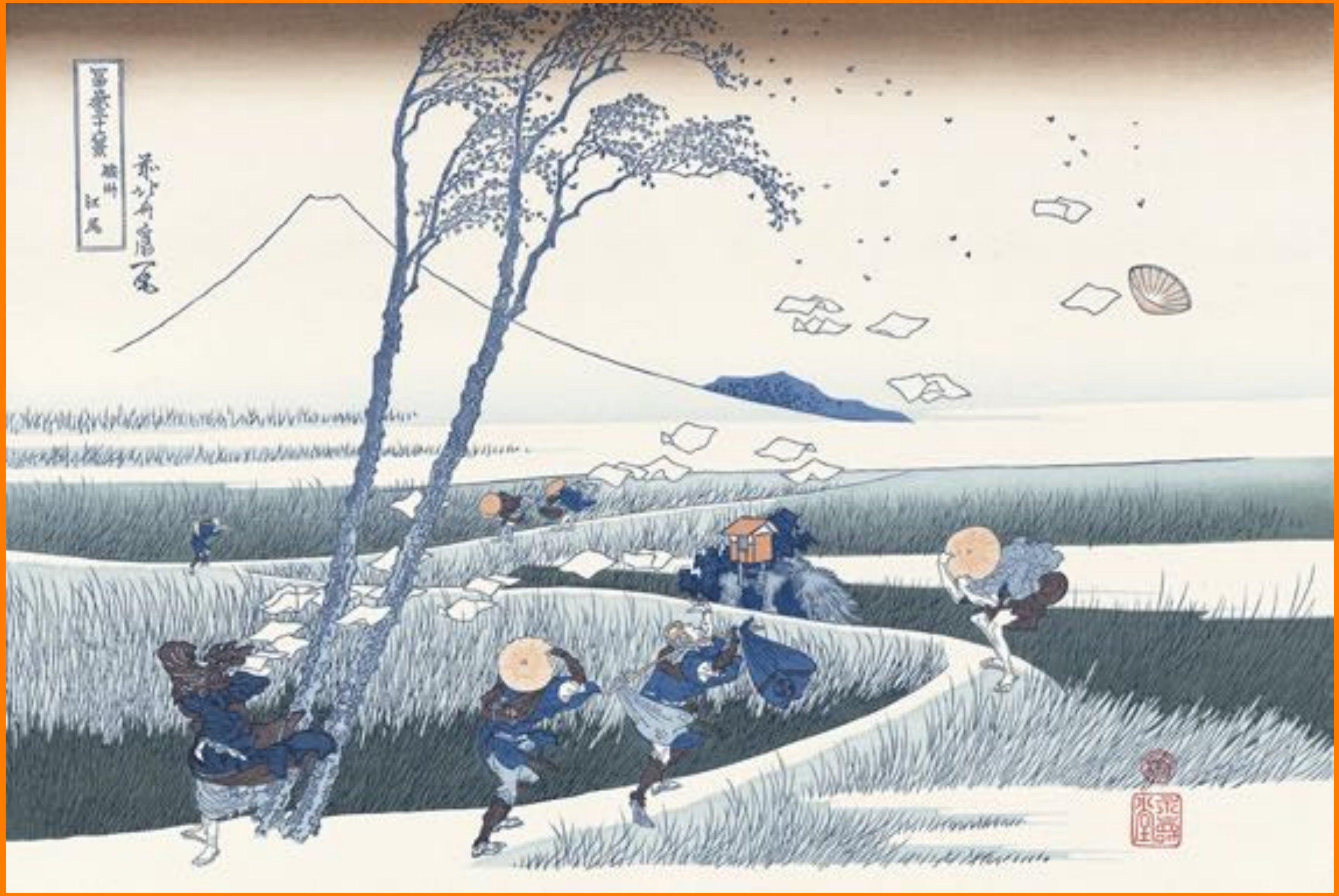
COMET Phase-I is planned to start in JFY2025.

Exotic Search with COMET



Search for $\mu \rightarrow ea$

Search for $\mu \to ea$

$\mu \to ea$

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

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

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$$\mathscr{L}_{alp} = \sum_{i,j} \frac{\partial_\mu a}{2f_a} \bar{\ell}_i \gamma^\mu [C^V_{i,j} + C^A_{i,j}] \gamma^5 \ell_j$$

$$\Gamma(\ell_i \to \ell_j a) = \frac{1}{16\pi} \frac{{m_{\ell_i}}^2}{F^2_{ij}} \left(1 - \frac{m_a^2}{m^2_{\ell_i}}\right)^2$$

$$\propto 1/f_a^2$$

$$F_{ij} = \frac{2f_a}{\sqrt{{C^V_{ij}}^2 + {C^A_{ij}}^2}}$$

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

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

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

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

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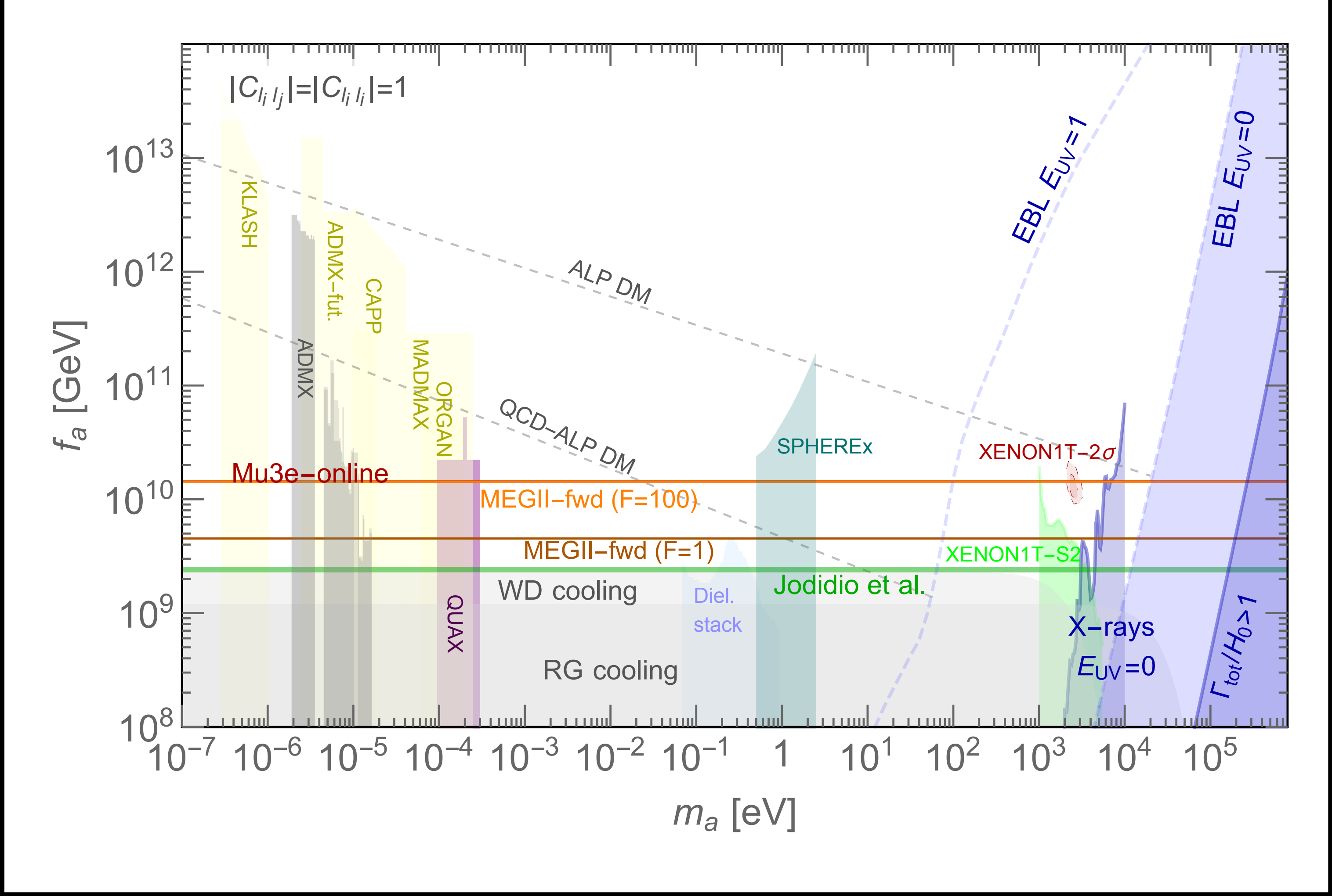

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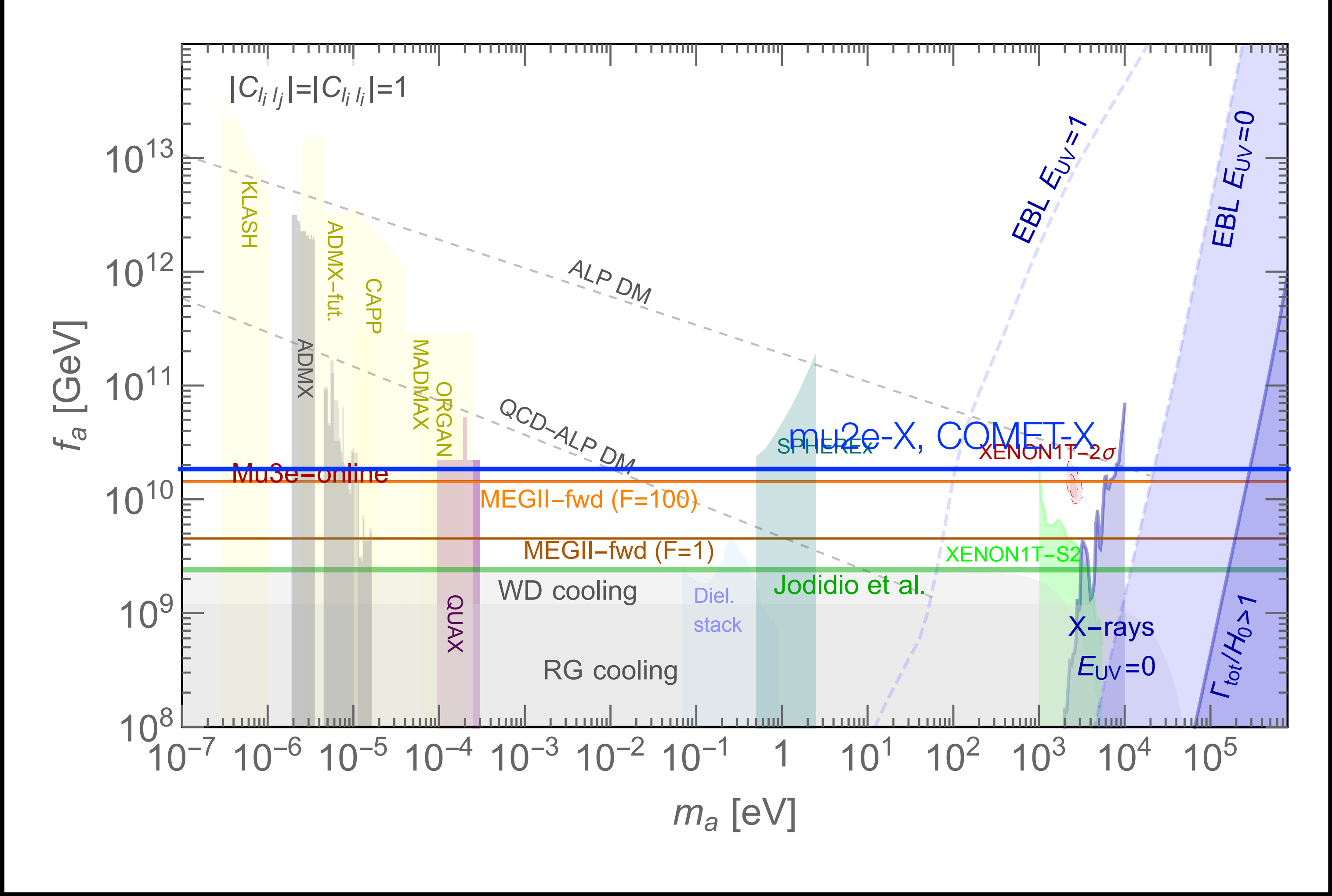

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Bound $\mu^- \to e^- a$ in a muonic atom

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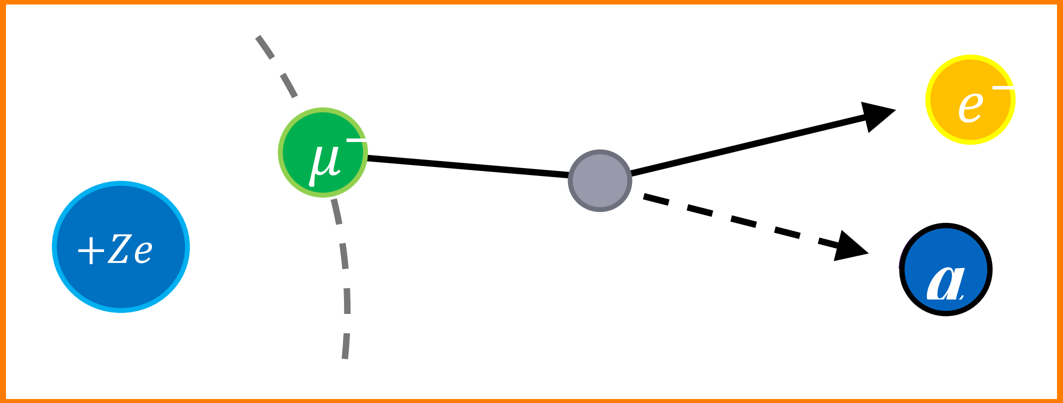

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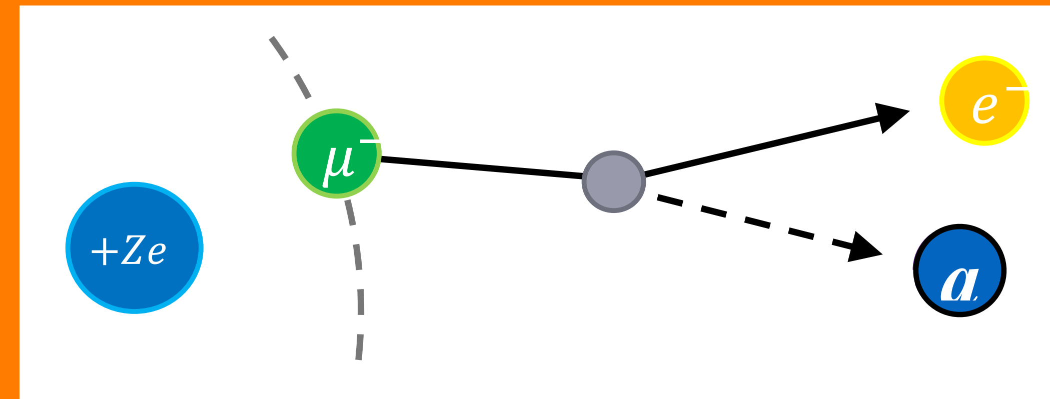
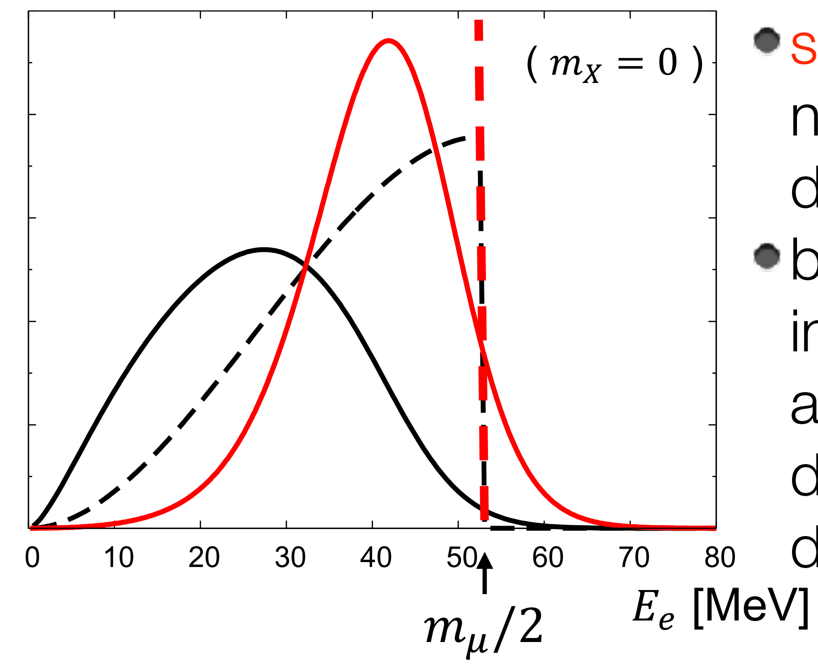
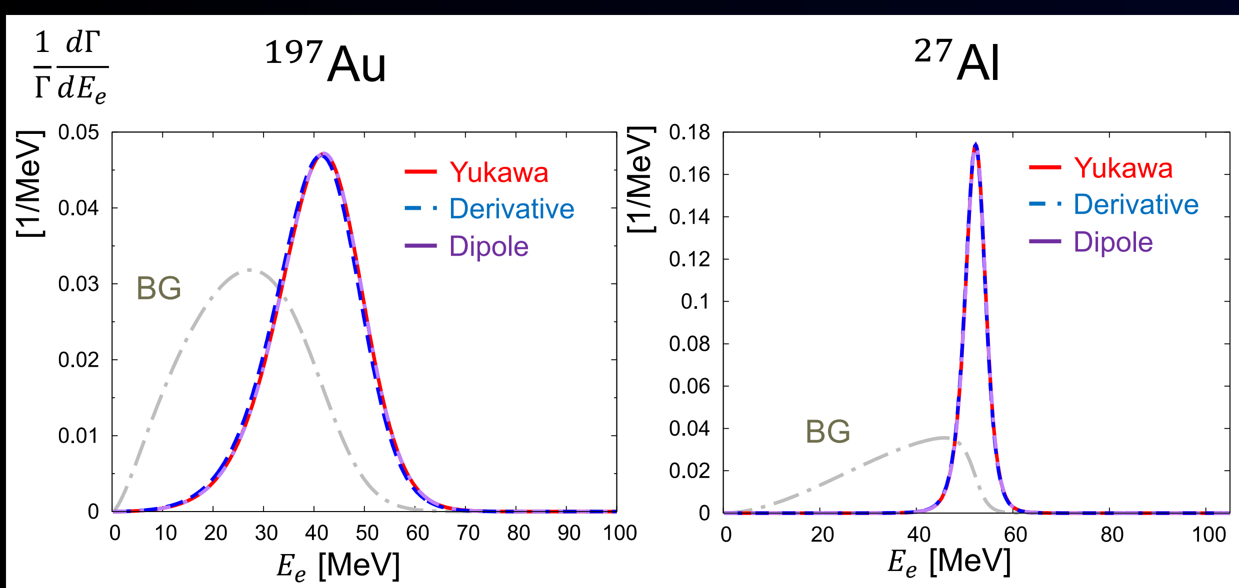




- signals in red, normal muon decays in black
- bound μ- decay in solid lines and free μ+ decays in dashed lines



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

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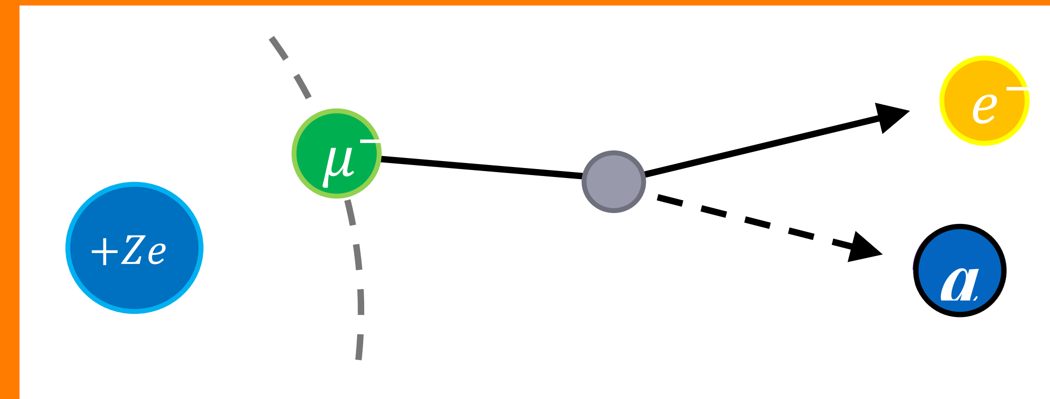

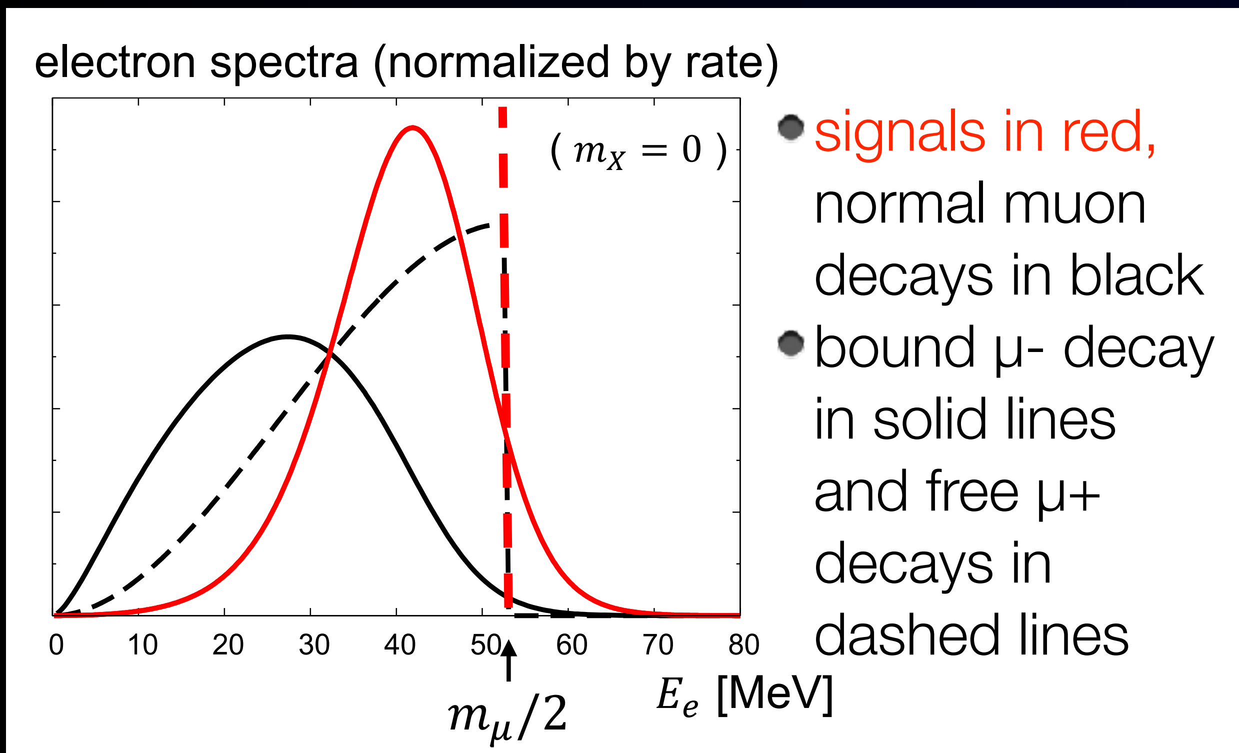

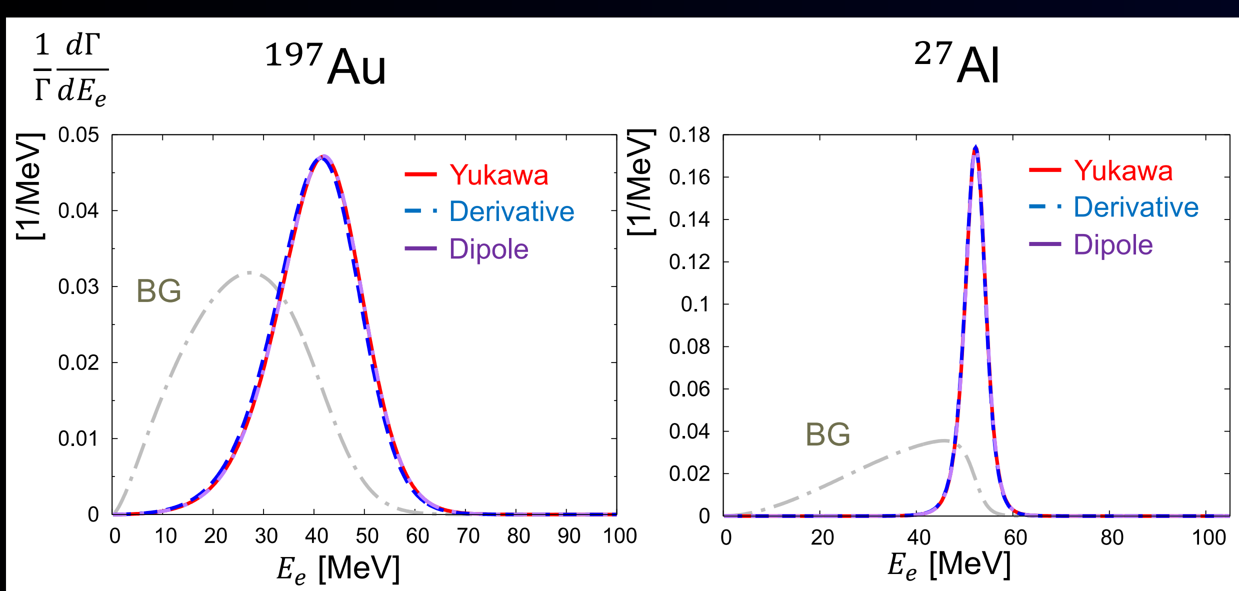

- Advantage
  - For $m_X \sim 0$, a signal peak is not on Michel edge.
  - Spectrum depends on Z of a target, systematic control, possible.
- Disadvantage
  - Not mono-energetic.

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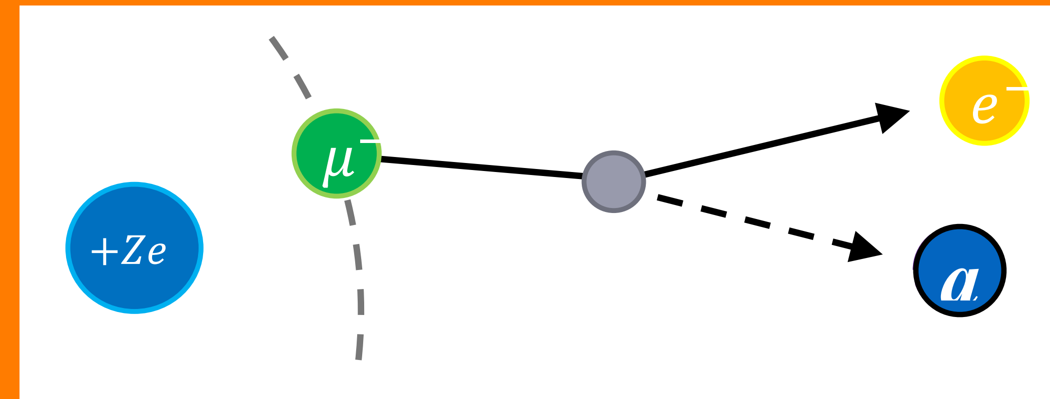

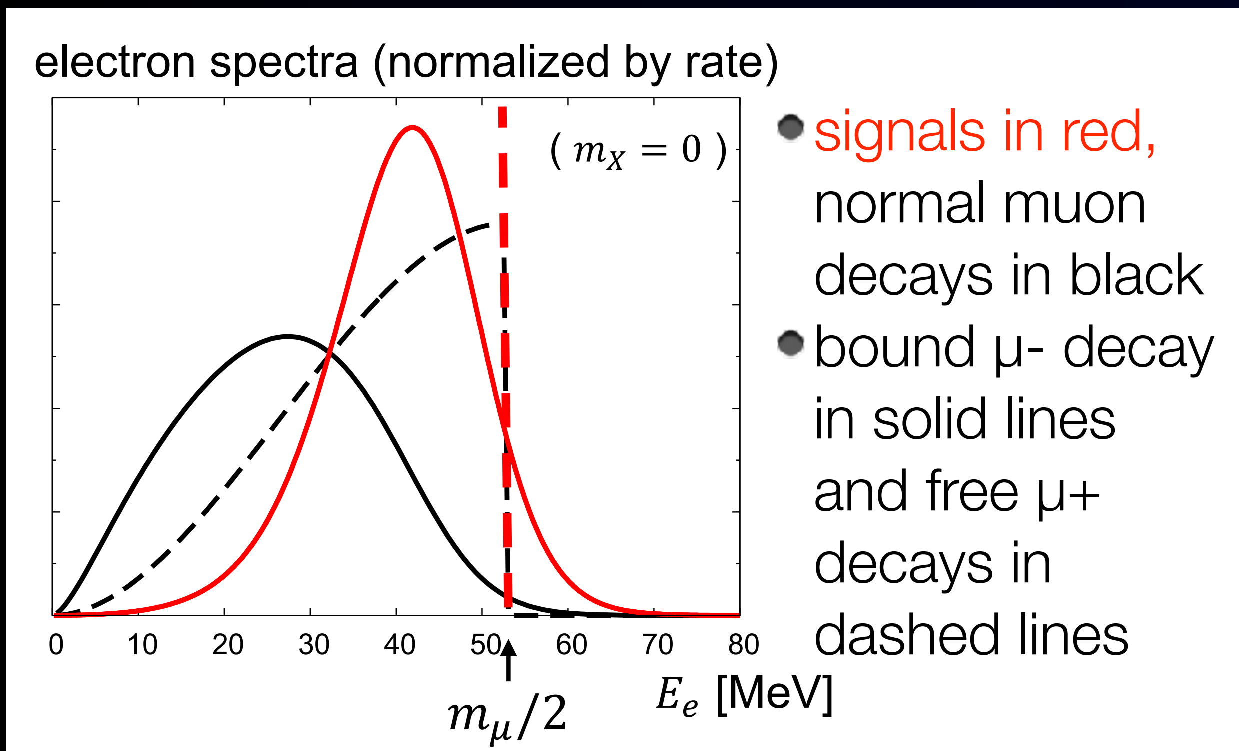

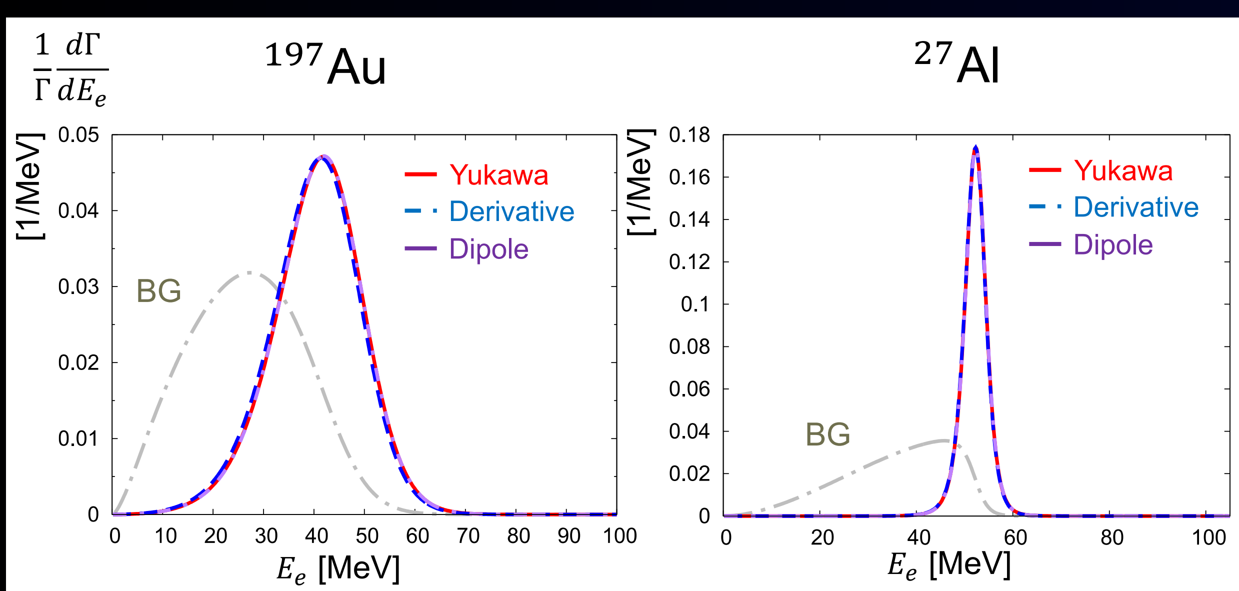

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- Preliminary COMET study was made.
- Phase-I, $B(\mu^- \to e^- a) < O(10^{-5})$
- Phase-II, $B(\mu^- \to e^- a) < O(10^{-(8-9)})$
  - $f_a > 10^{10-11}$ GeV

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

Conclusion

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- $\mu \to e$ conversion in a muonic atom has a unique discovery potential for BSM.
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