Muon Particle Physics Experiments

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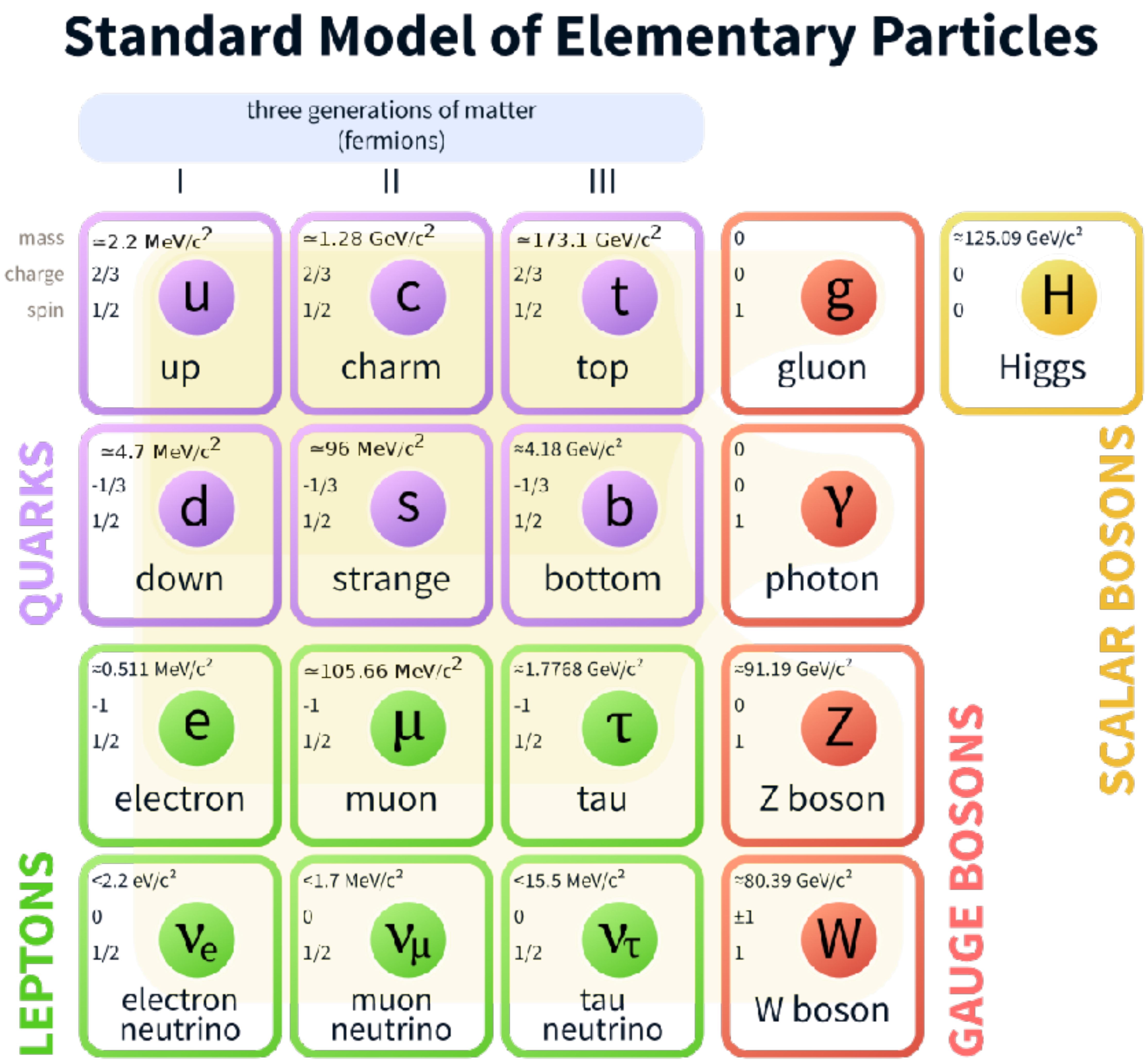
November 4th, 2023
MELODY2023
Chinese Spallation Neutron Source (CSNS),
Dongguan, China

The Standard Model and Muons

Taken from https://en.wikipedia.org/wiki/Elementary_particle.

The Standard Model and Muons



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The Standard Model is considered to be incomplete.

example: origin of flavour
neutrino masses
dark matter,
baryogenesis,
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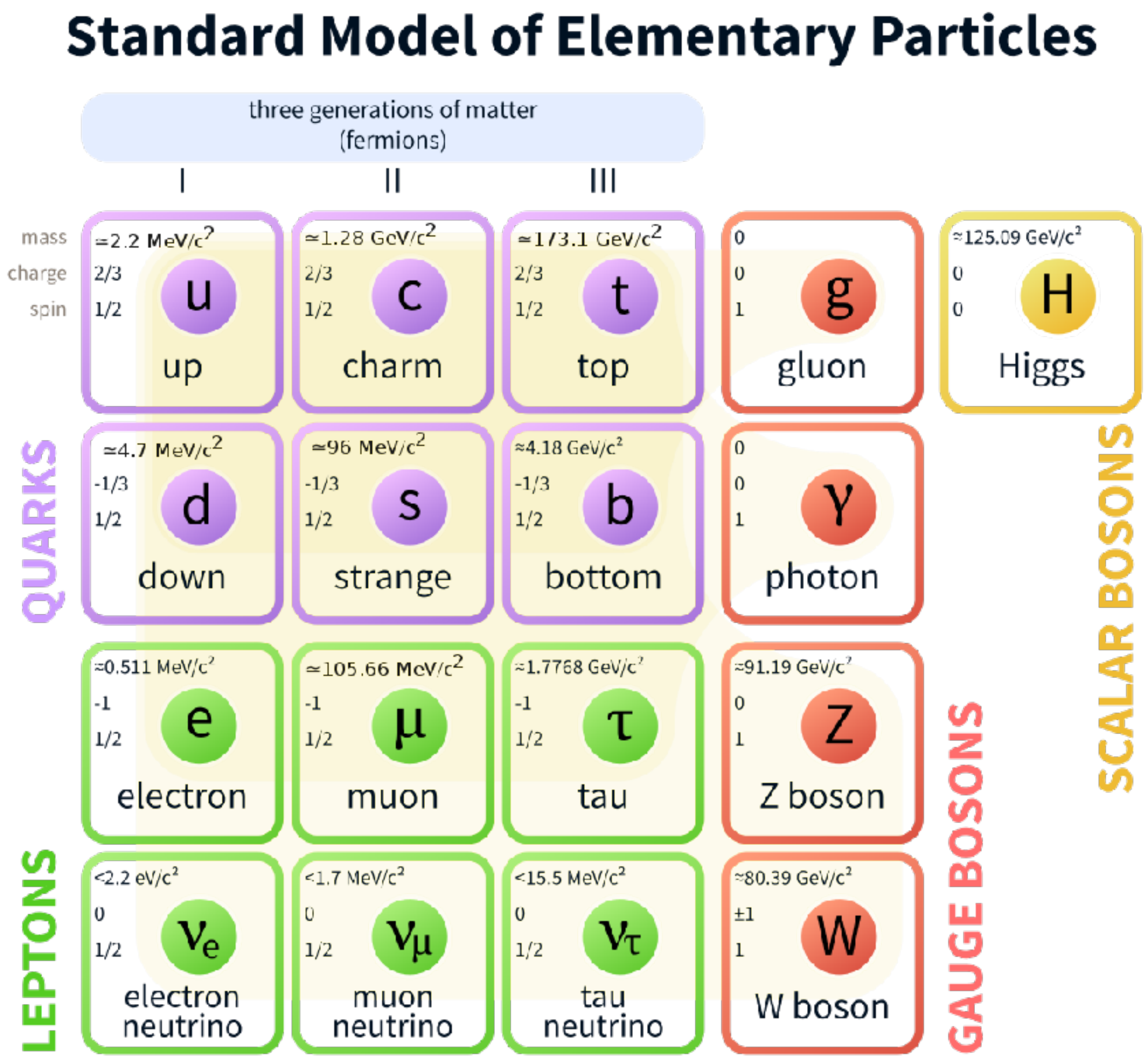
strong CP and more.

The Standard Model and Muons



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New physics beyond the Standard Model (BSM) is needed.

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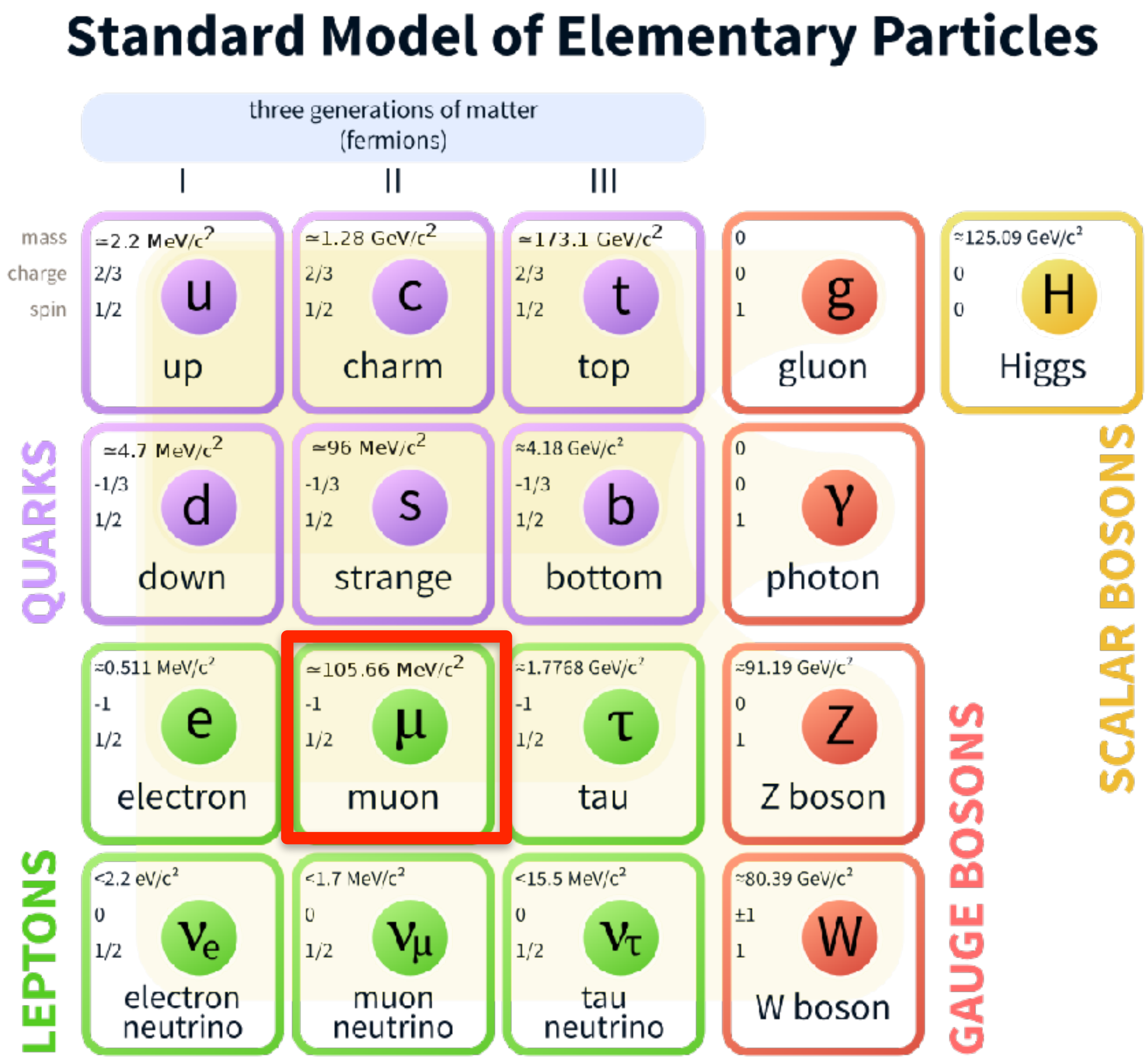

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⇨ Muons

Why Muons ?

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Outline

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- Why New physics needed in Particle Physics ?
- Muon’s dipole moments
- Muon’s charged lepton flavour violation (CLFV)
  - $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, $\mu^- \to e^-$ conversion
  - in the case of discoveries
- Muon’s lepton number violation (LNV) and axion-like particles
  - $\mu^- \to e^+$ conversion, $\mu \to ea$
- Muonium to anti-muonium conversion
- Muon Collider
- Summary

Muon’s Dipole Moments

Muon g-2 and Muon edm

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Muon magnetic dipole moment (g-2)

- Charged, spin=1/2 particles have magnetic dipole moments.
- g=2 for a “pure” Dirac particle, and g>2 due to quantum radiative corrections.
- Deviation of the measurement from the Standard Model prediction indicates new physics beyond the SMl.

$$\vec{\mu} = g\frac{q}{2m}\vec{S} \qquad g = 2(1 + \frac{\alpha}{2\pi} \ldots.)$$

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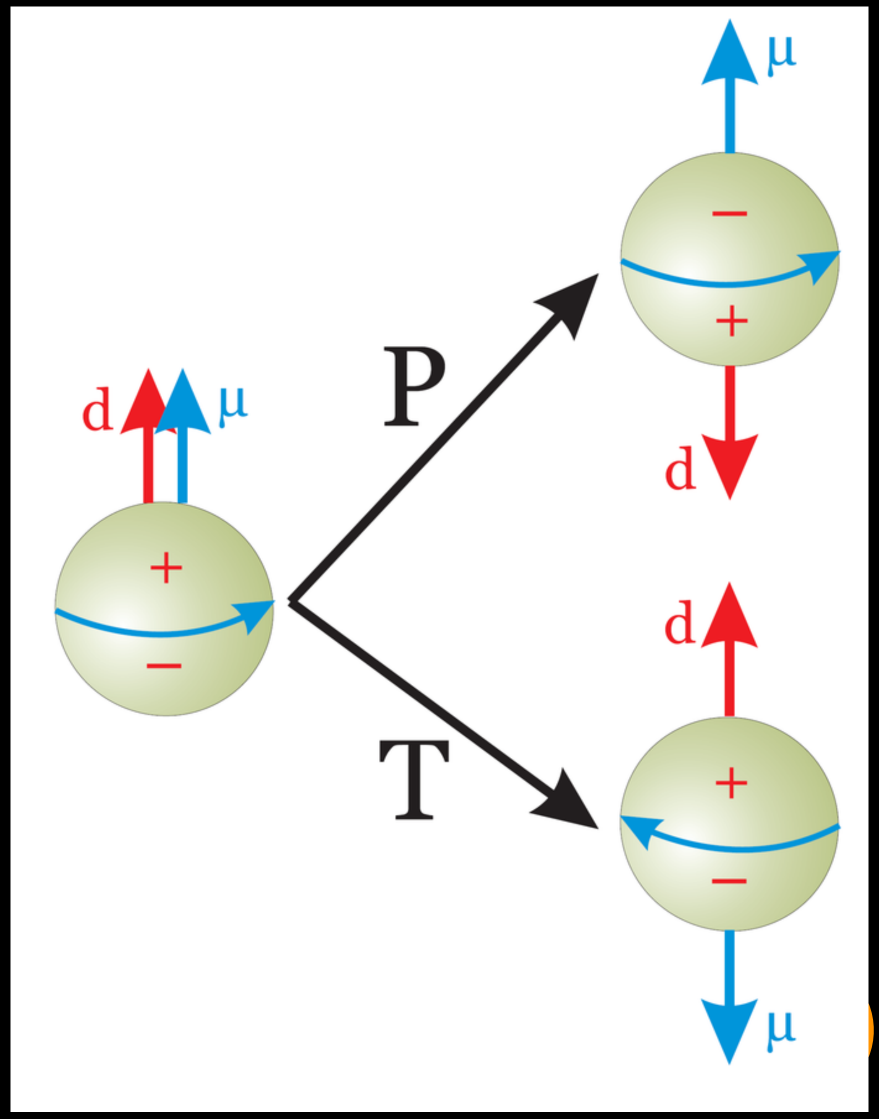
- The current experimental limits $d_\mu < 1.5 \times 10^{-19} e \cdot cm$



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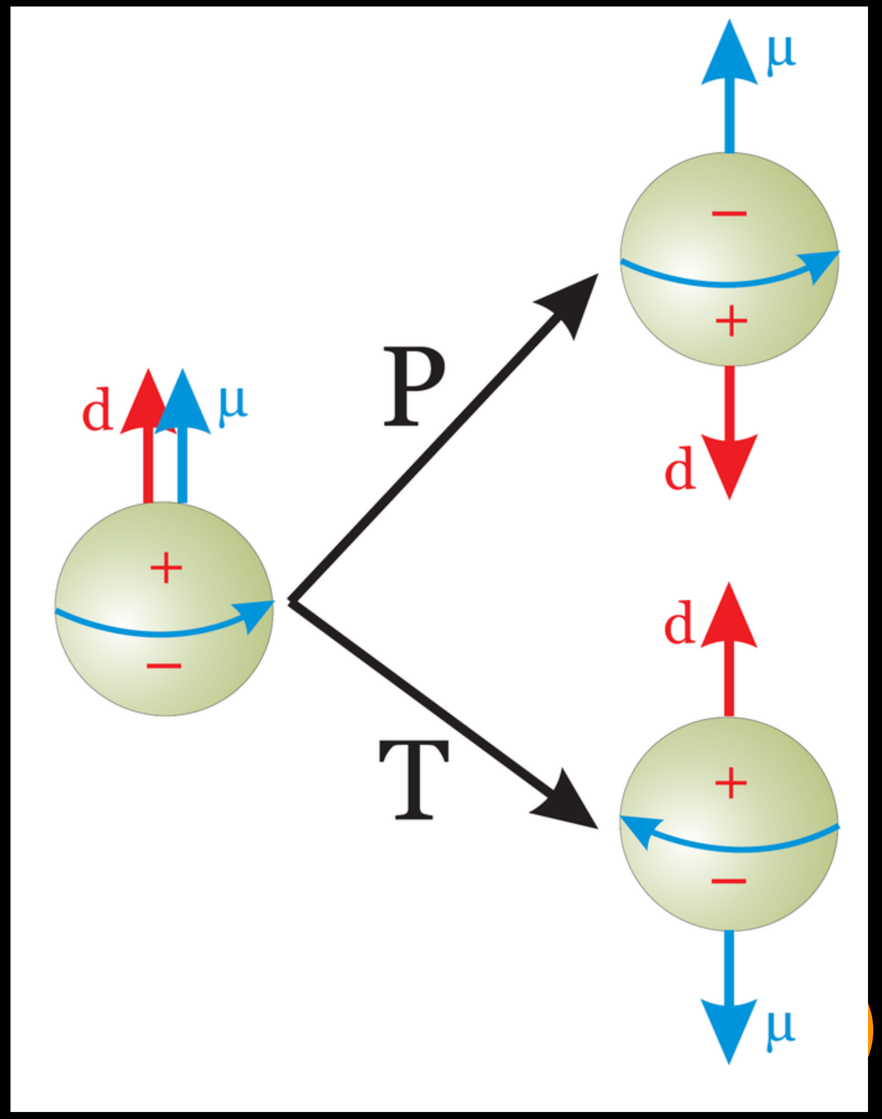

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Charged Lepton Flavor Violation with Muons

Lepton Flavours

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Lepton flavour quantum numbers

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	electron flavour	muon flavour	tau flavour
e generation	1	0	0
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CLFV for BSM search

Two Things you must know on CLFV No.1

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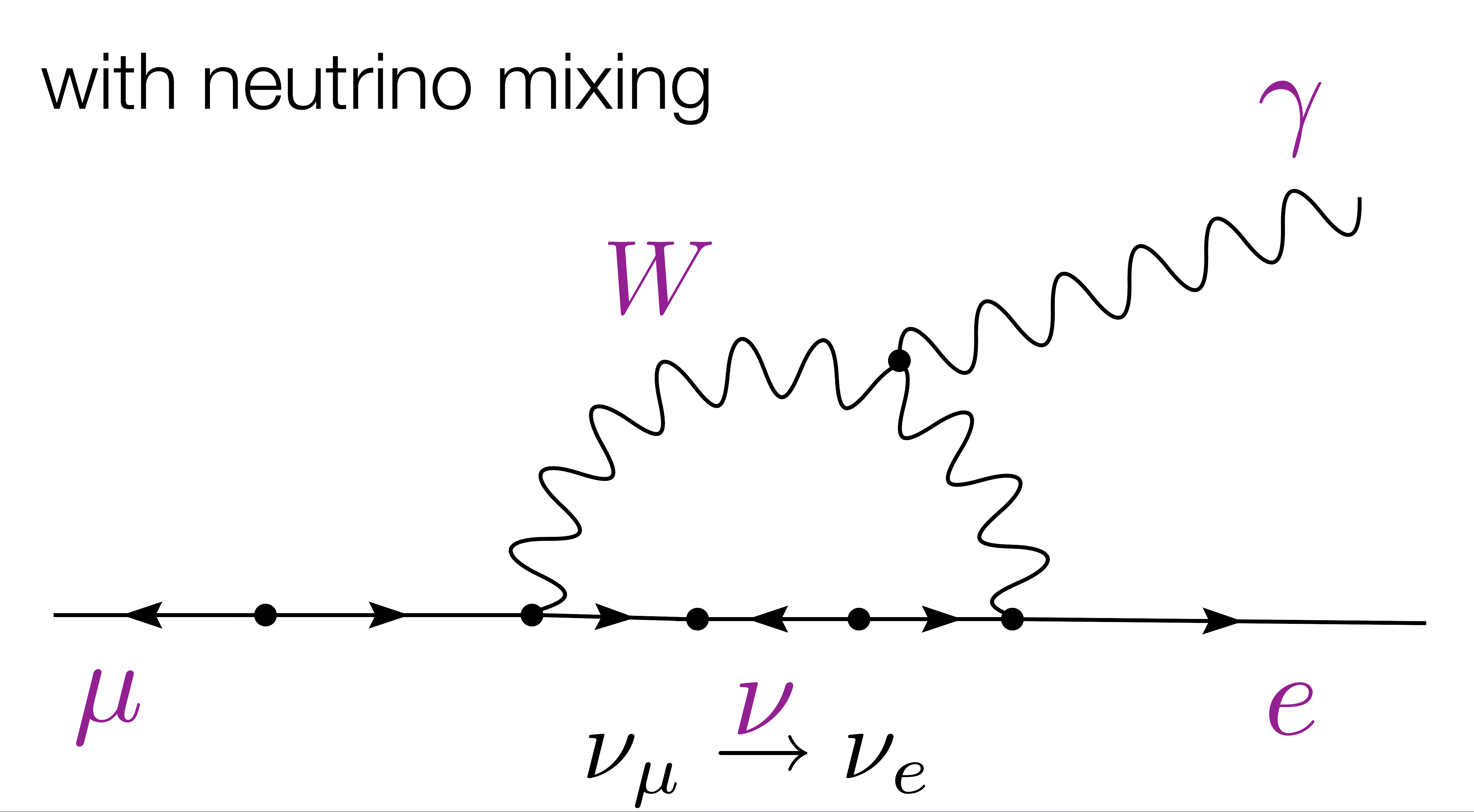
Standard Model Contribution to CLFV



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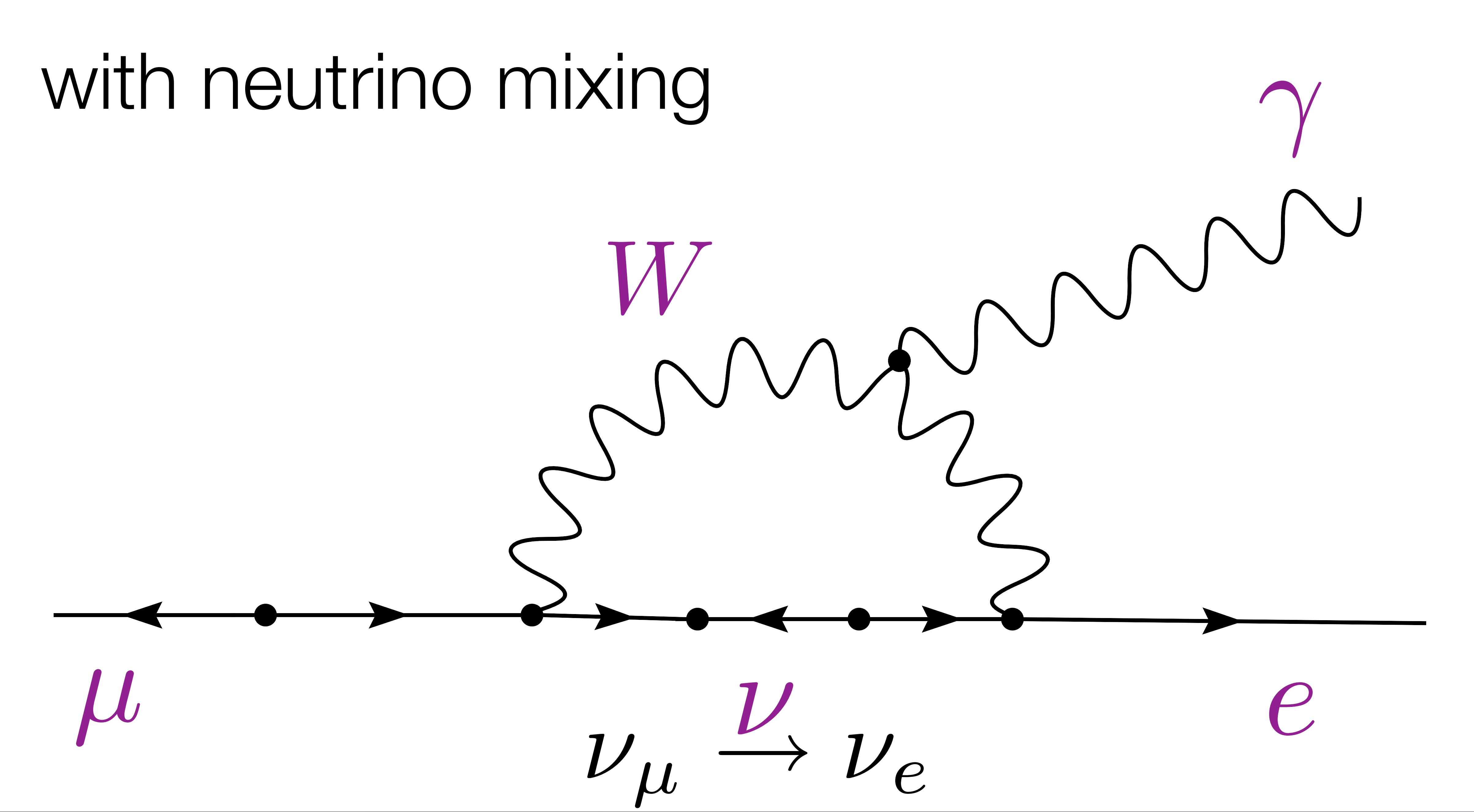

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$

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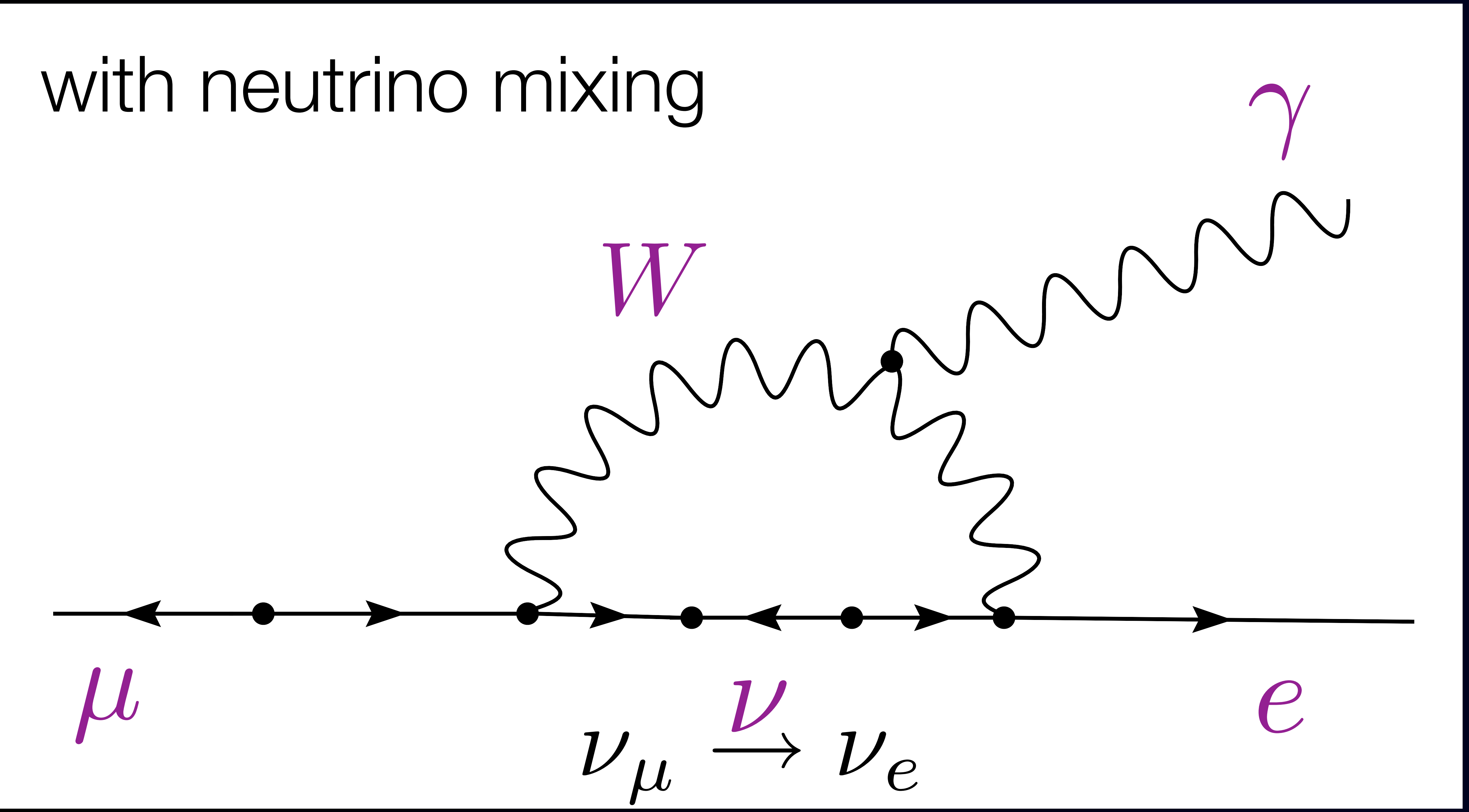

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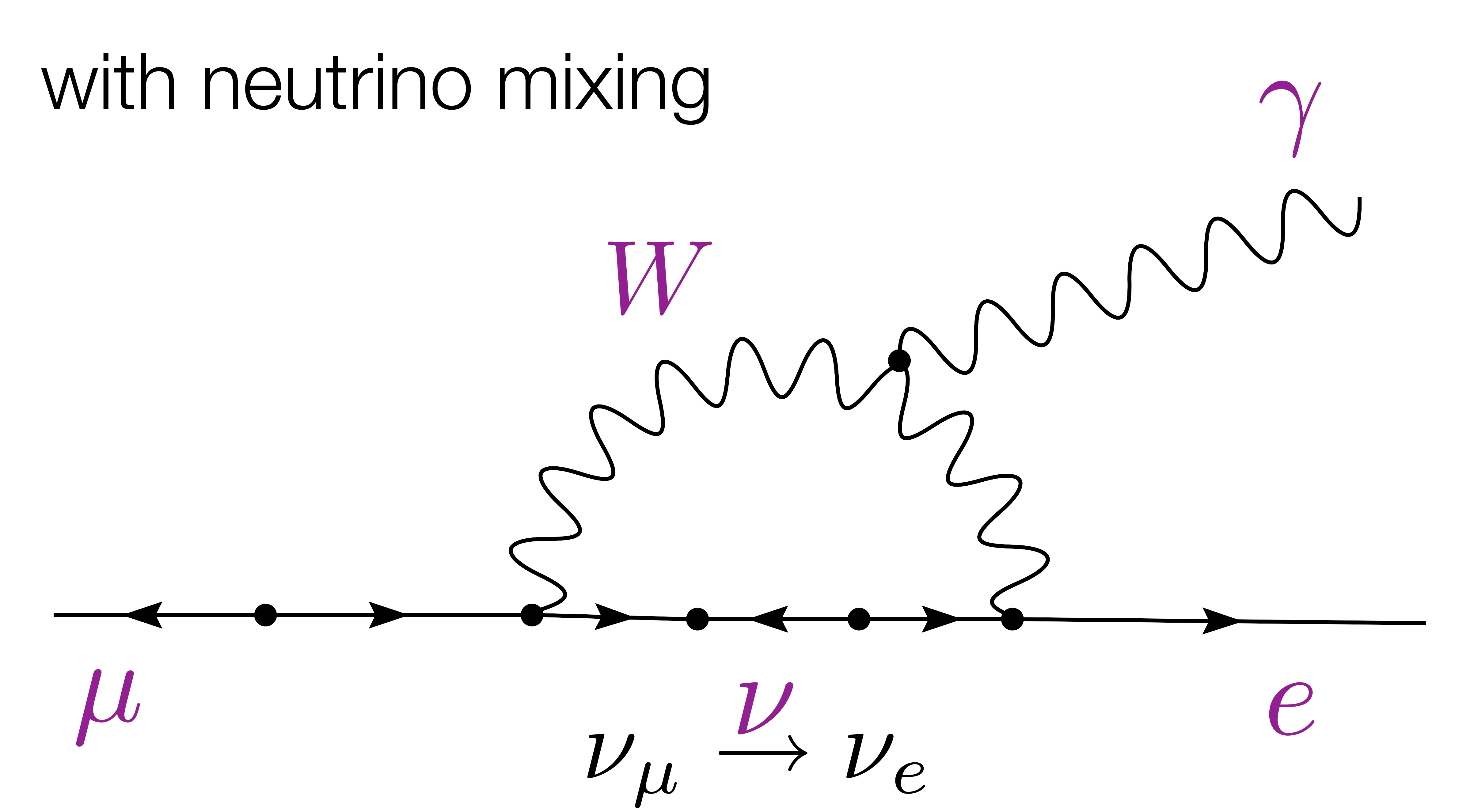

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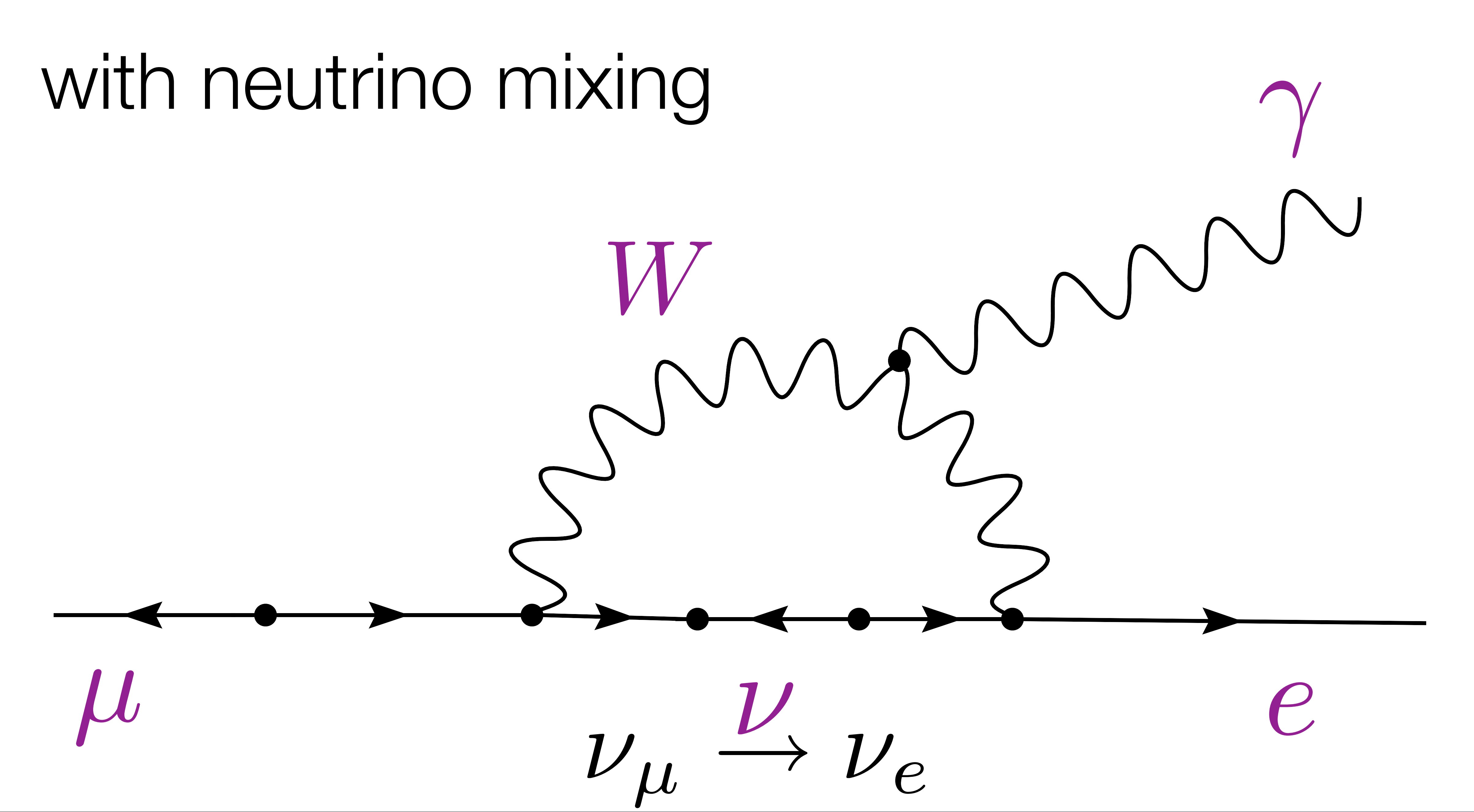

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Searches for CLFV have clear signatures of new physics beyond the Standard Model without the SM backgrounds of massive neutrinos.

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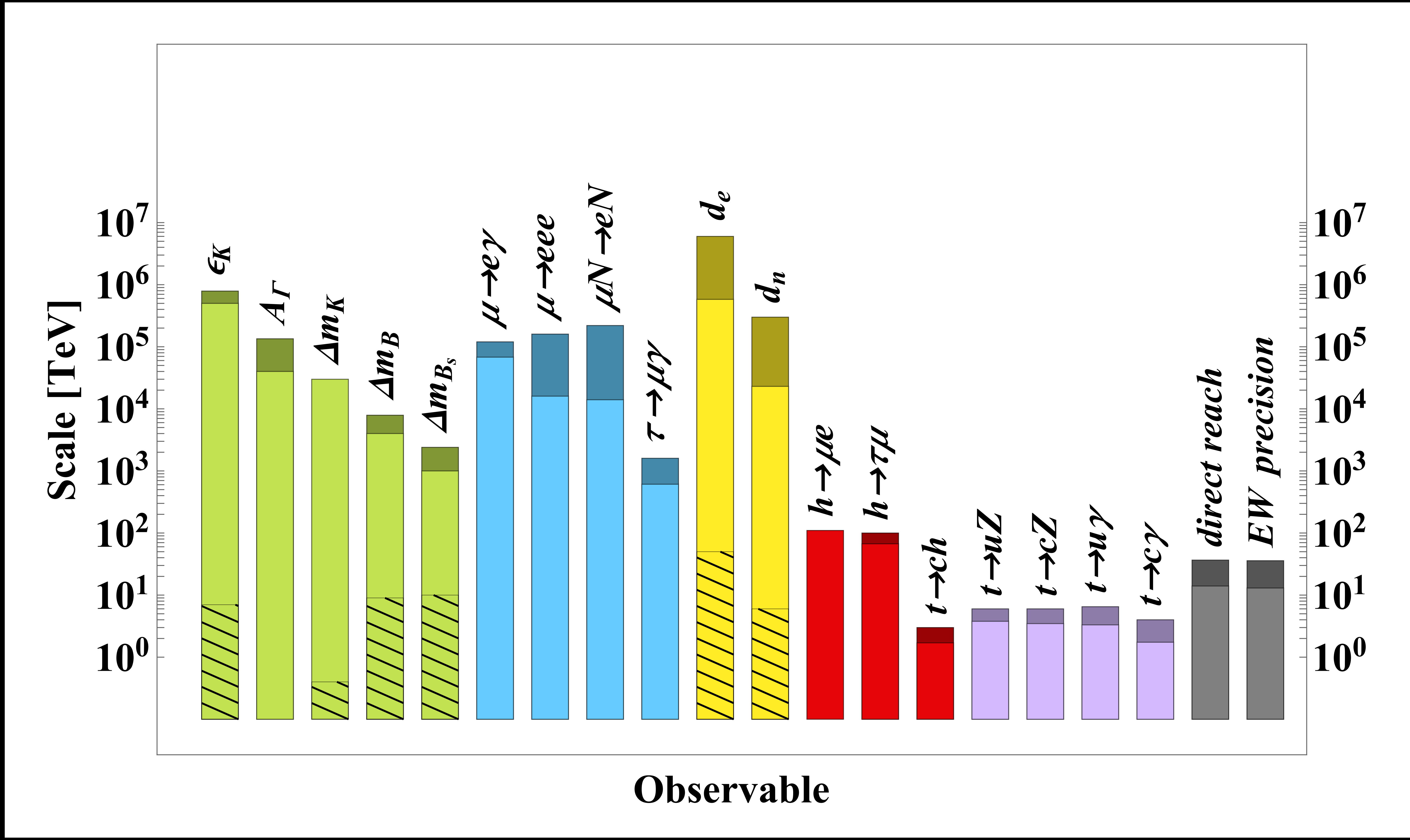

light colour: present

dark colour: future prospect

EPPSU2019 Physics Briefing Book

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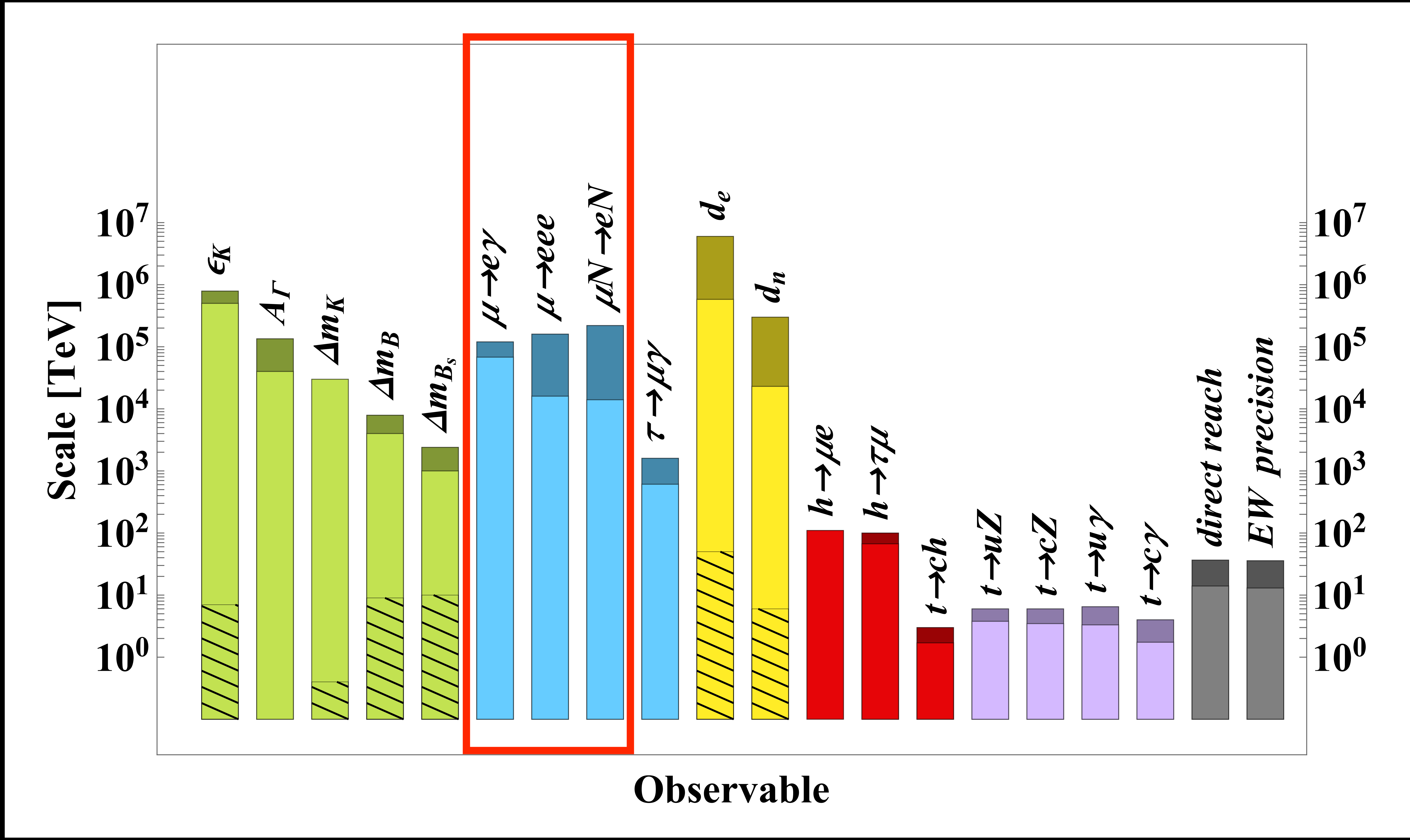

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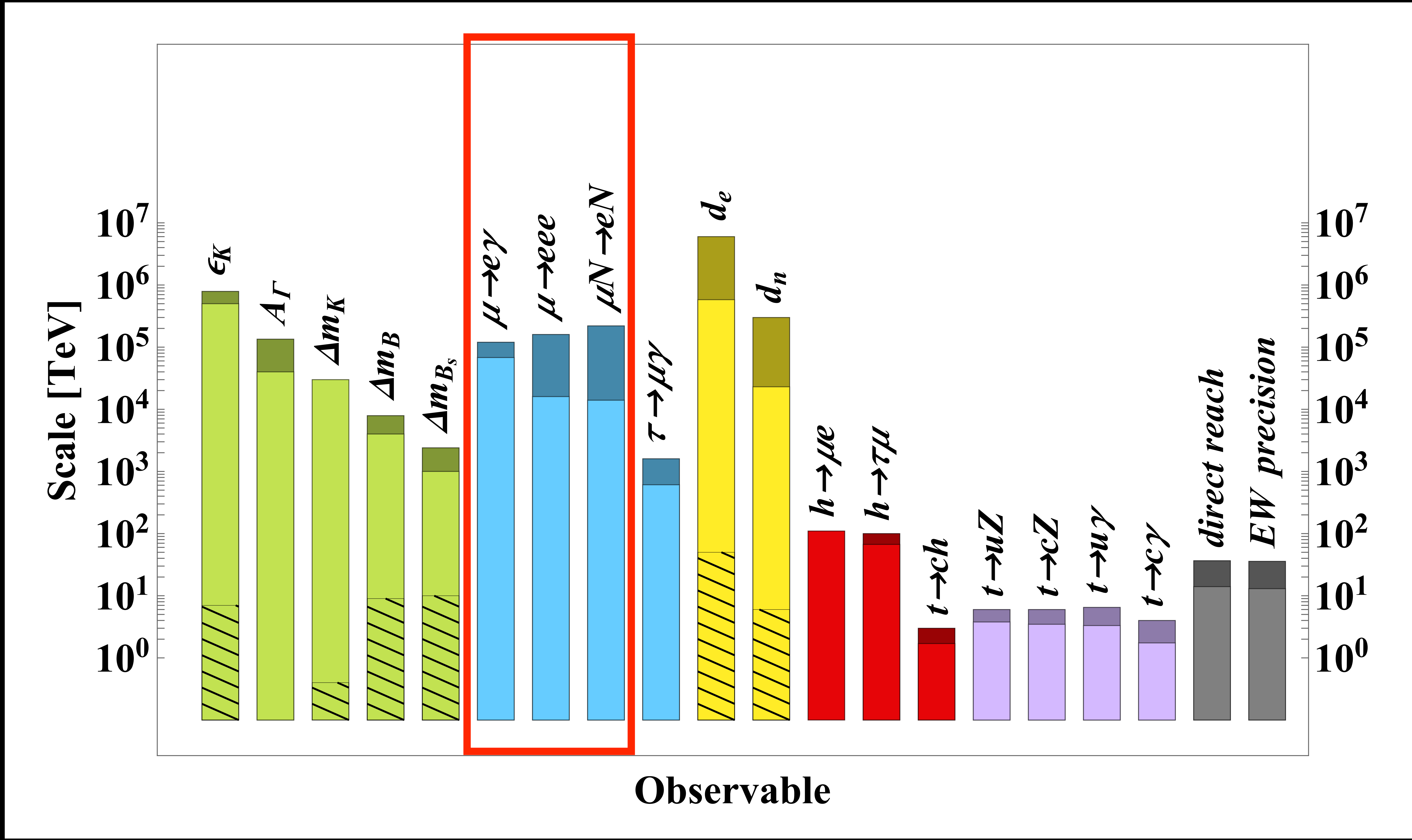

Present CLFV physics scales

Physics scale: $\Lambda = \mathcal{O}(10^3 - 10^4)$ TeV

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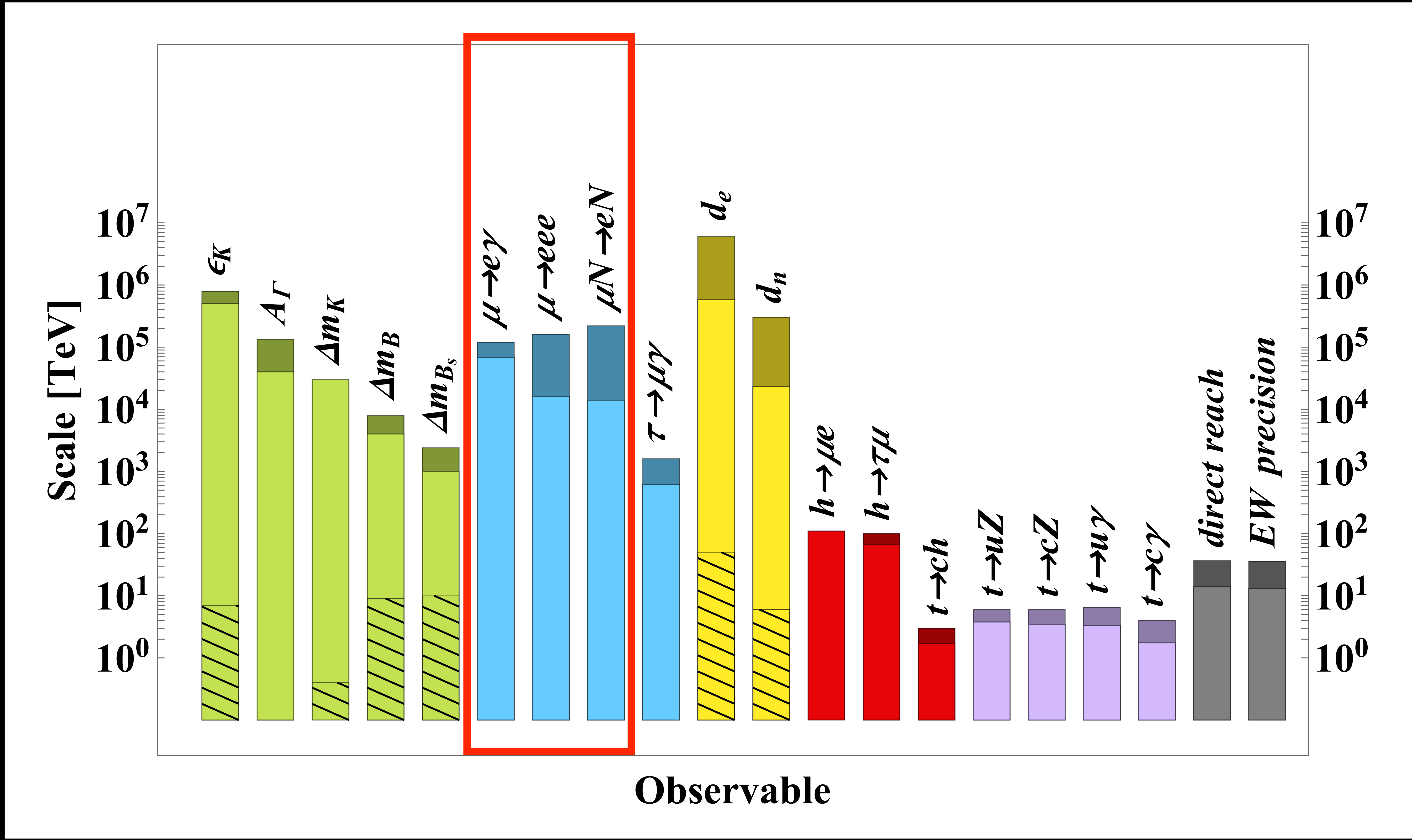

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Prospect from present to future

x10 in physics scale

SM forbidden rate $\propto \dfrac{c^2}{\Lambda^4}$

in dimension 6 operators

↓

x10000 in experimental sensitivity

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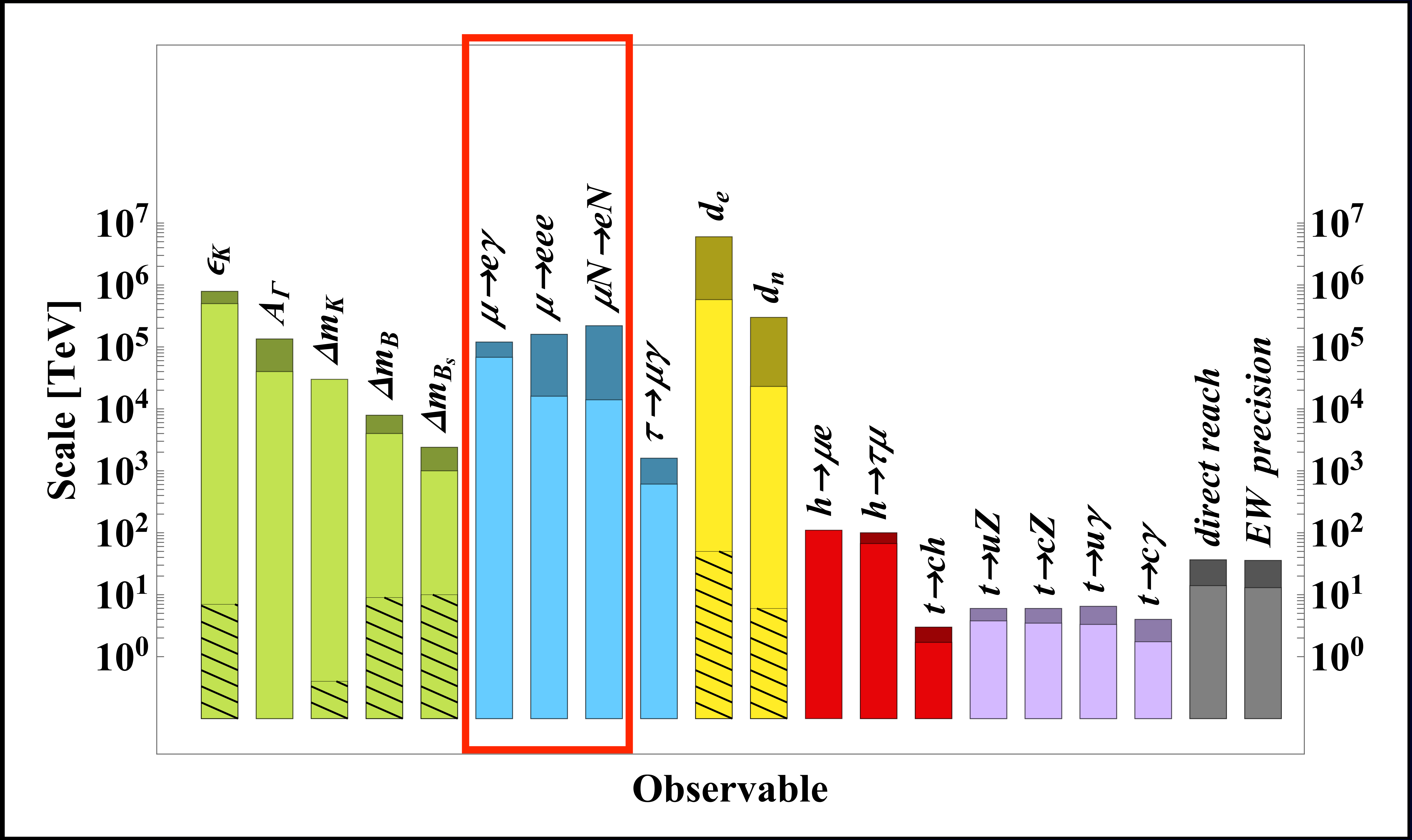

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CLFV probes very high energy scale of new physics.

$\mu \rightarrow e$ CLFV Golden Processes and EFT

$\mu \to e$ CLFV Golden Processes and EFT

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

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

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

$\mu \rightarrow e$ CLFV Golden Processes and EFT

dipole interaction | contact interaction | Effective Field Theory (EFT)

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

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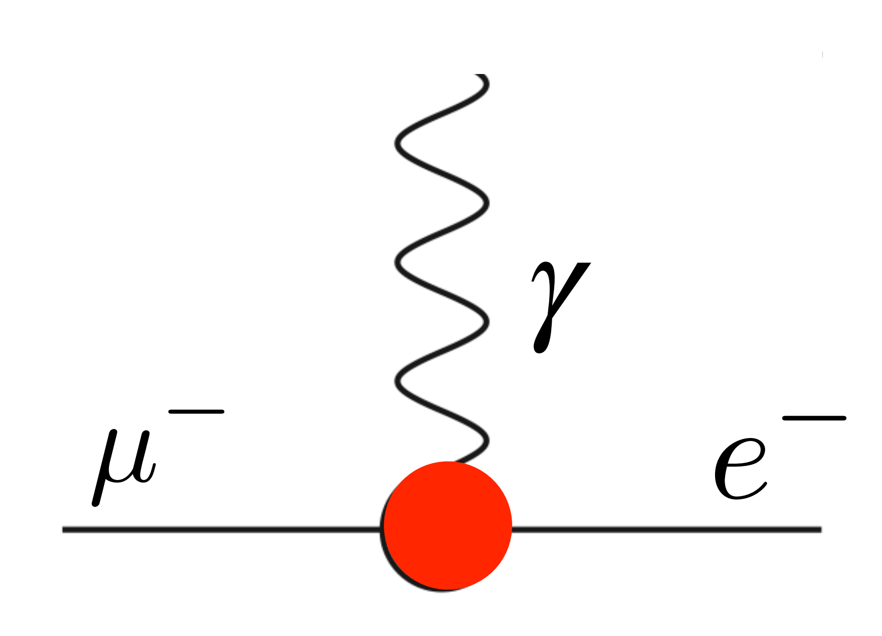
dipole interaction

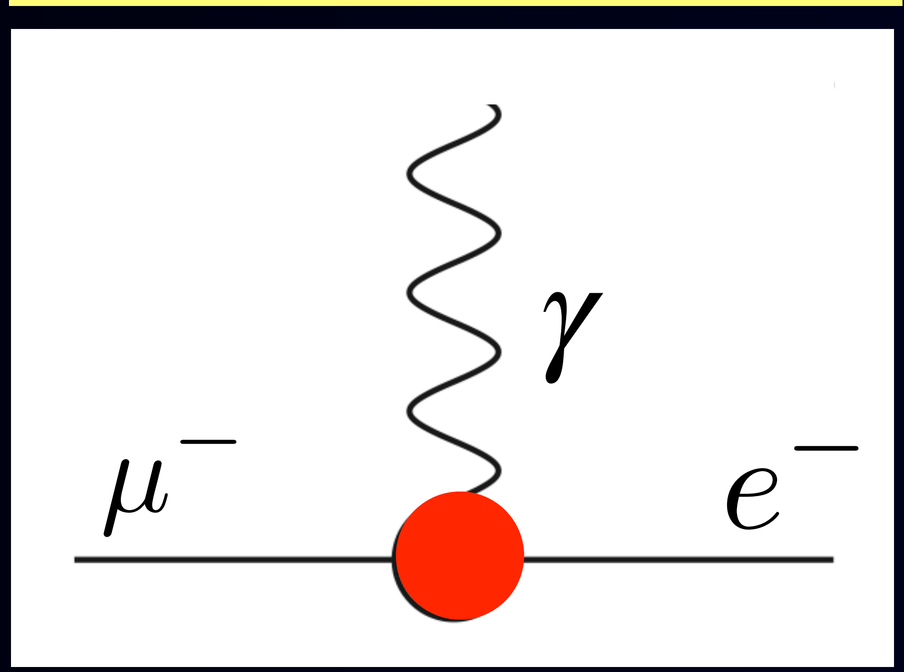
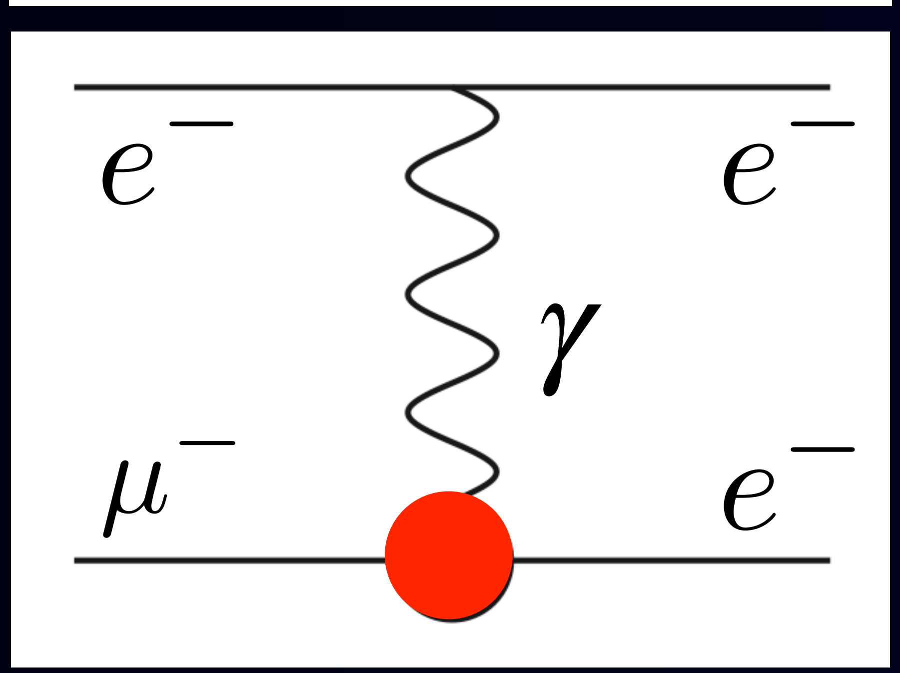
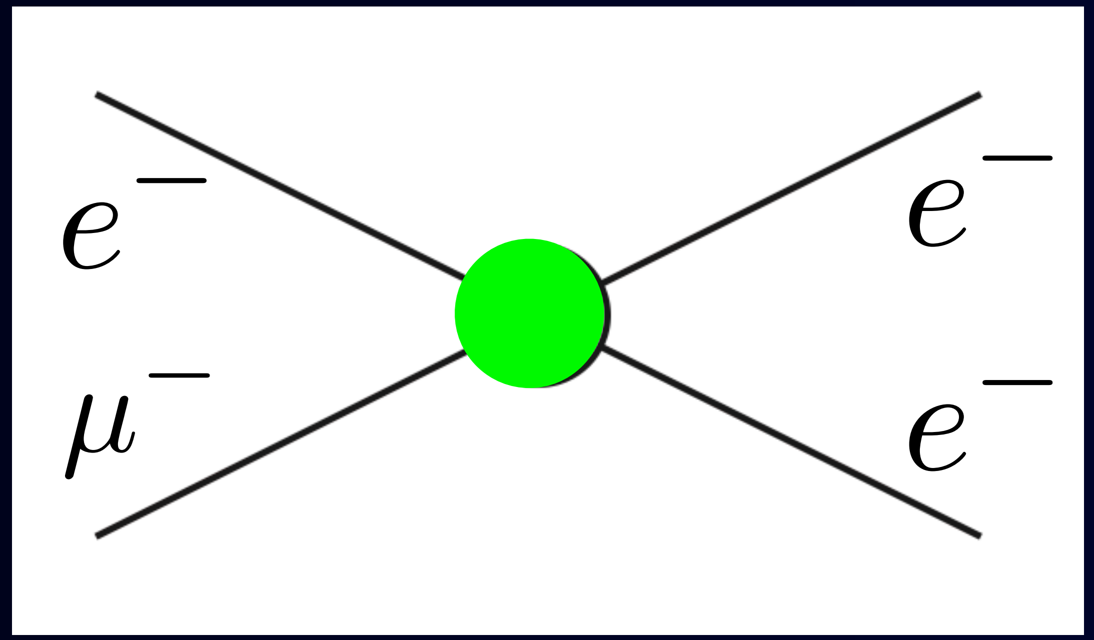


contact interaction

Effective Field Theory (EFT)

- dipole operators (L/R)

$\mu \to e$ CLFV Golden Processes and EFT

	dipole interaction	contact interaction	Effective Field Theory (EFT)
$\mu^+ \to e^+\gamma$			• dipole operators (L/R)
$\mu^+ \to e^+e^+e^-$			• dipole operators (L/R) • 2 scalar contact and 4 vector contact operators
$\mu^-N \to e^-N$			

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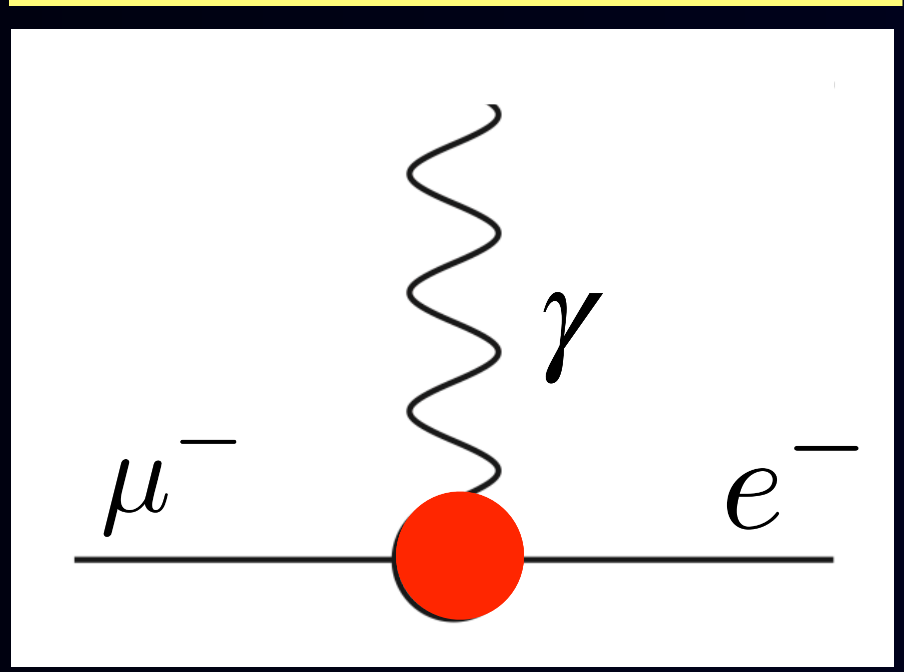
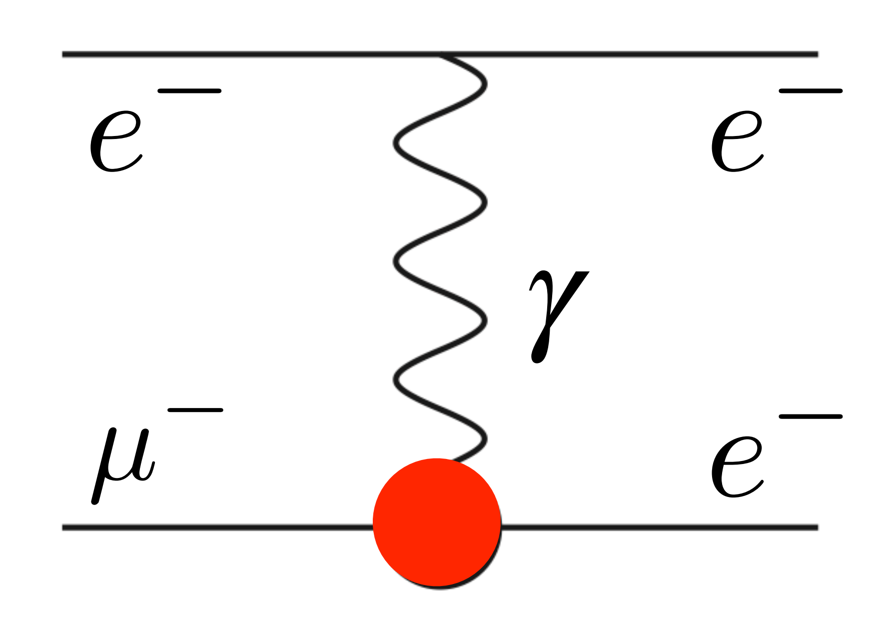
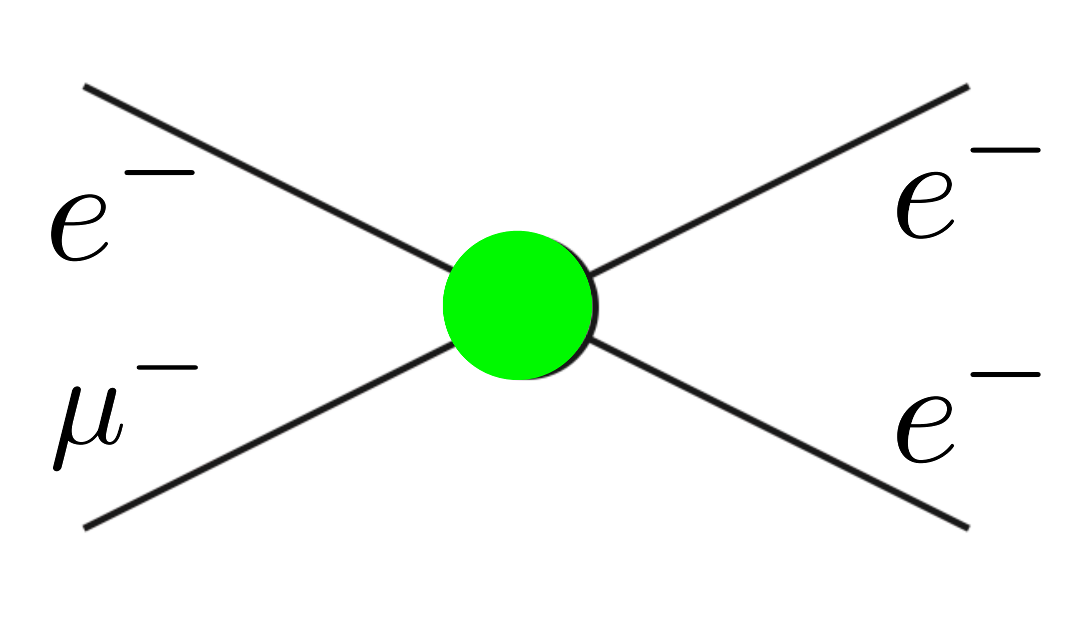
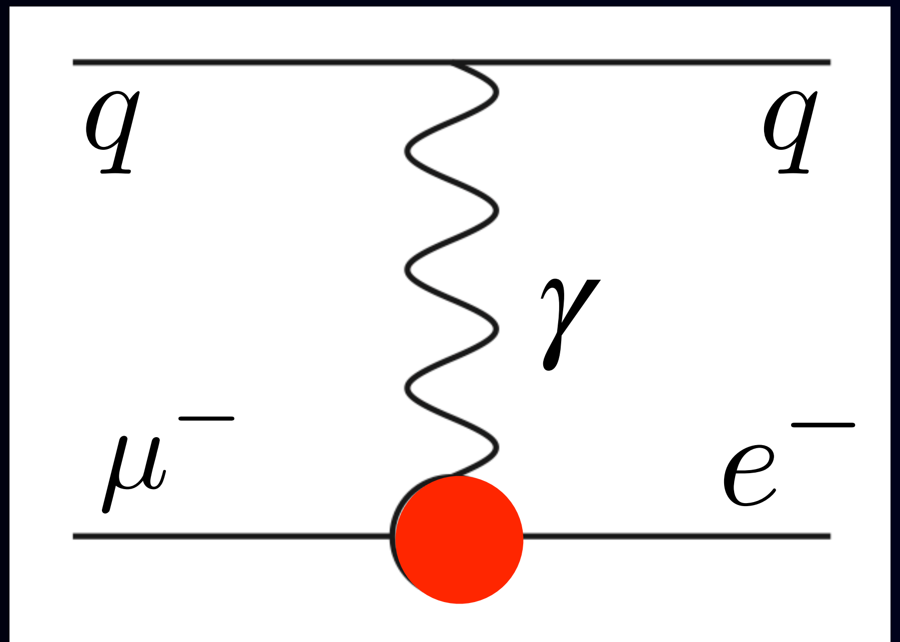
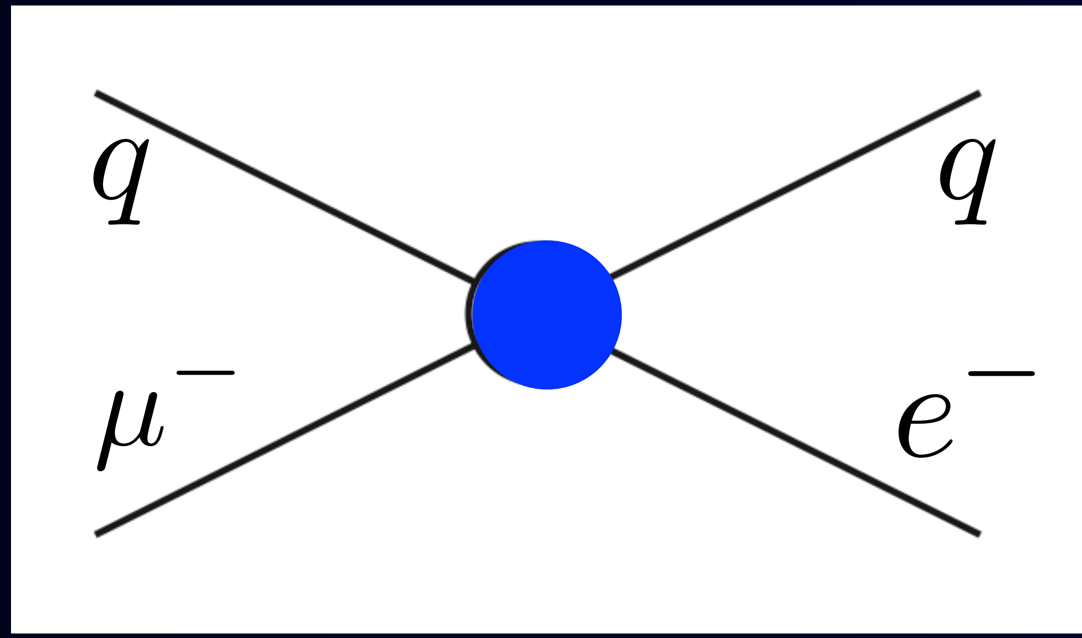
$\mu^+ \to e^+\gamma$			• dipole operators (L/R)
$\mu^+ \to e^+e^+e^-$			• dipole operators (L/R) • 2 scalar contact and 4 vector contact operators
$\mu^-N \to e^-N$			• dipole operators (L/R) • many contact operators • scalar, vector (spin independent) • pseudoscalar, axial vector, tensor (spin dependent)

Present CLFV Upper Limits

from YK, Y. Okada, RMP (2000)

Present CLFV Upper Limits

process	present limit	future
$\tau \to \mu\eta$	$< 6.5 \times 10^{-8}$	$10^{-9} - 10^{-10}$
$\tau \to \mu\gamma$	$< 6.8 \times 10^{-8}$	
$\tau \to \mu\mu\mu$	$< 3.2 \times 10^{-8}$	
$\tau \to eee$	$< 3.6 \times 10^{-8}$	
$K_L \to e\mu$	$< 4.7 \times 10^{-12}$	
$K^+ \to \pi^+ e^- \mu^+$	$< 1.3 \times 10^{-11}$	
$B^0 \to e\mu$	$< 7.8 \times 10^{-8}$	
$B^+ \to K^+ e\mu$	$< 9.1 \times 10^{-8}$	
$Z^0 \to e\mu$	$< 7.5 \times 10^{-7}$	
$Z^0 \to e\tau$	$< 1.2 \times 10^{-5}$	
$Z^0 \to \mu\tau$	$< 9.8 \times 10^{-6}$	
$H^0 \to e\mu$	$< 3.5 \times 10^{-4}$	
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$H^0 \to \mu\tau$	$< 2.5 \times 10^{-3}$	
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	10^{-14} (MEG II)
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$	10^{-16} (Mu3e)
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7.0 \times 10^{-13}$	10^{-17} (COMET, Mu2e)
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}$	$< 3.6 \times 10^{-11}$	10^{-17} (COMET, Mu2e)
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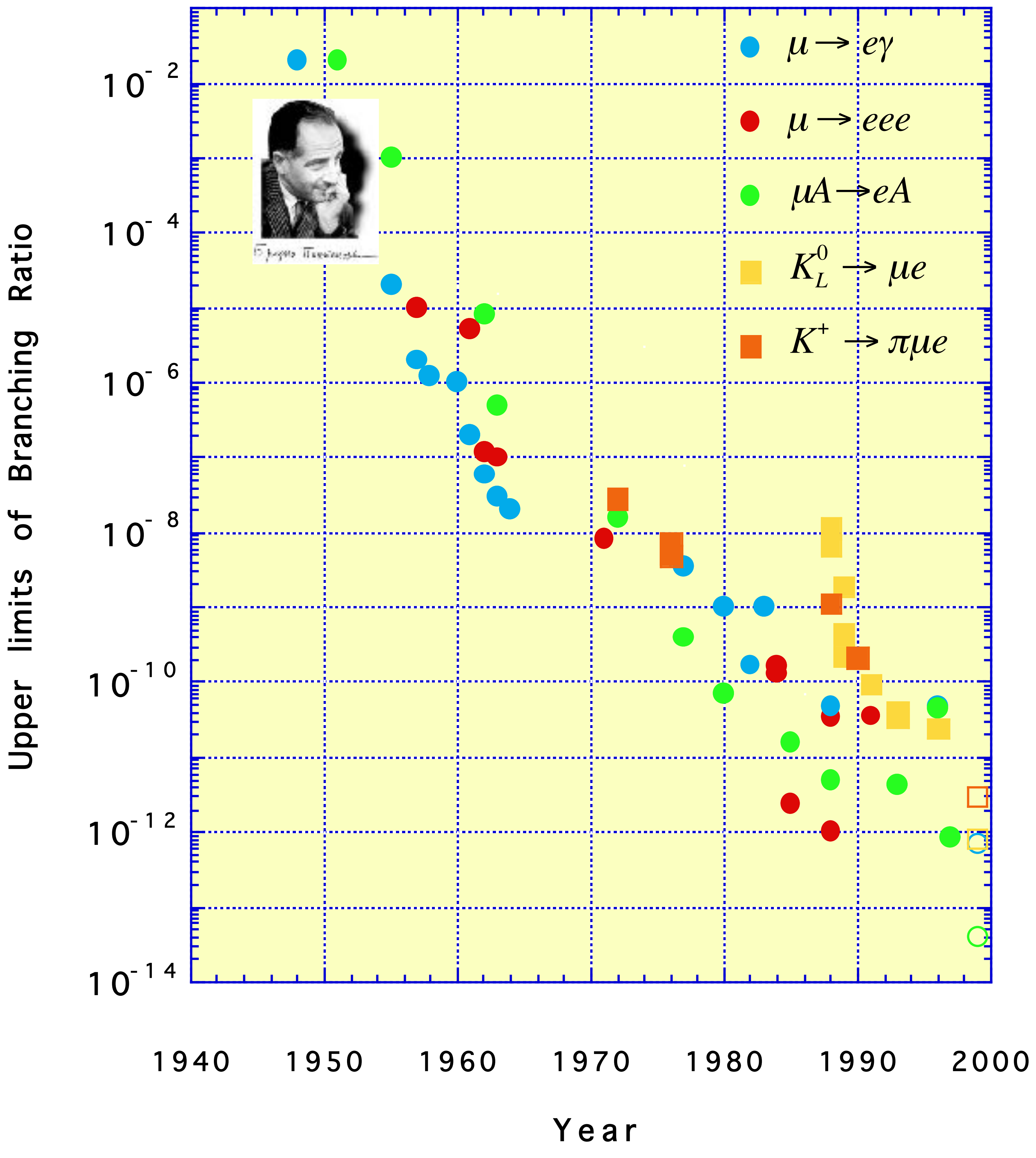

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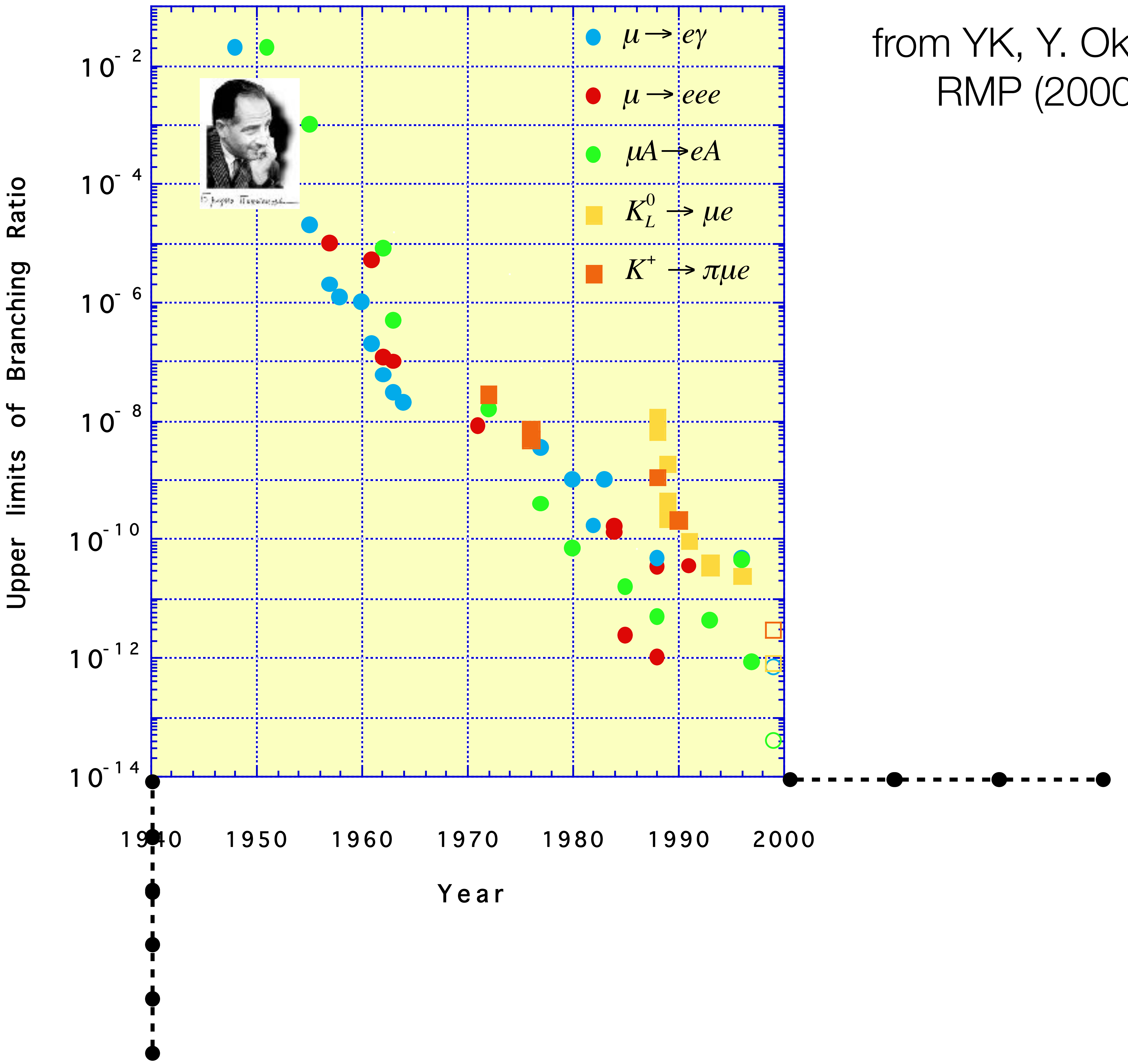

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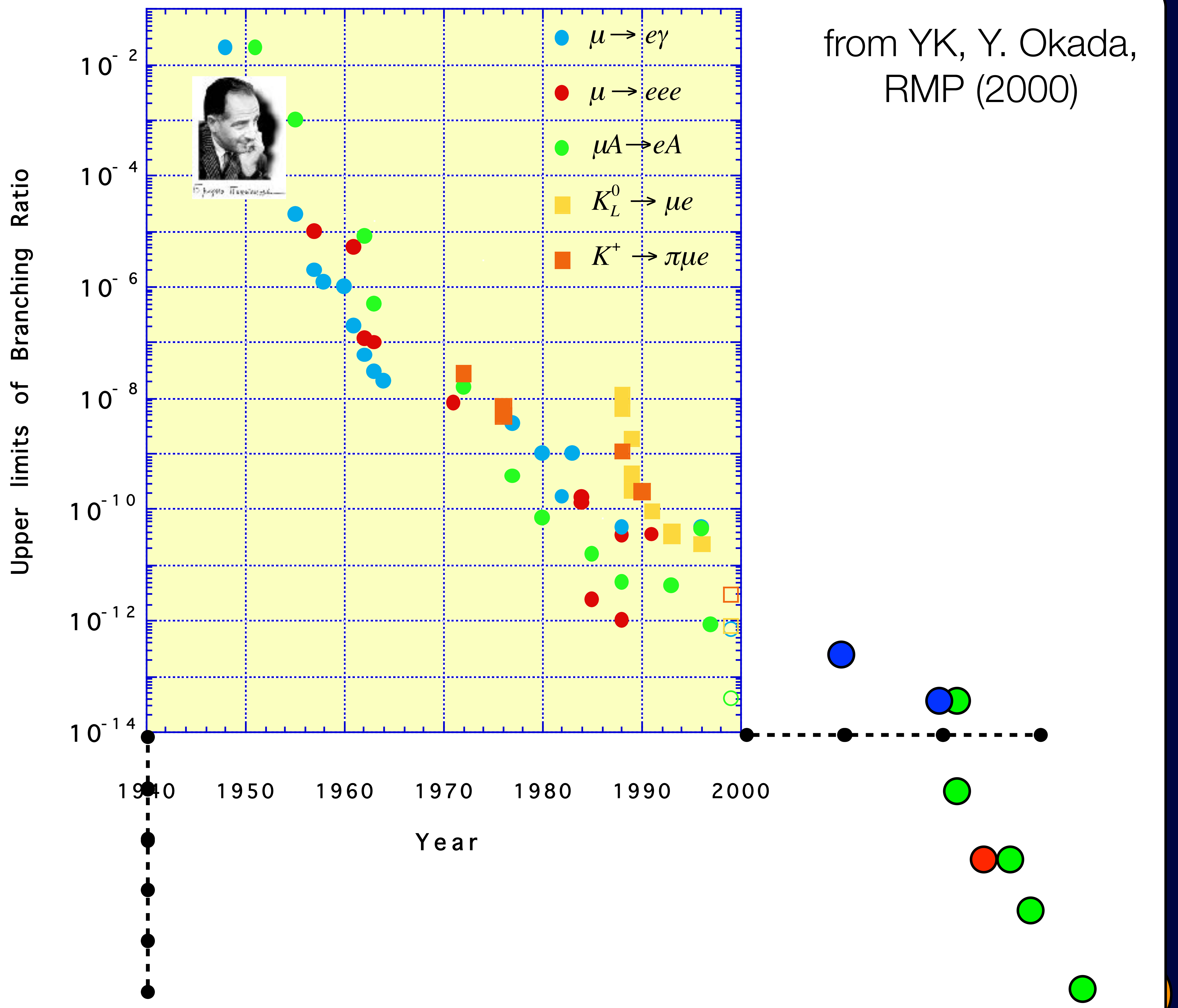
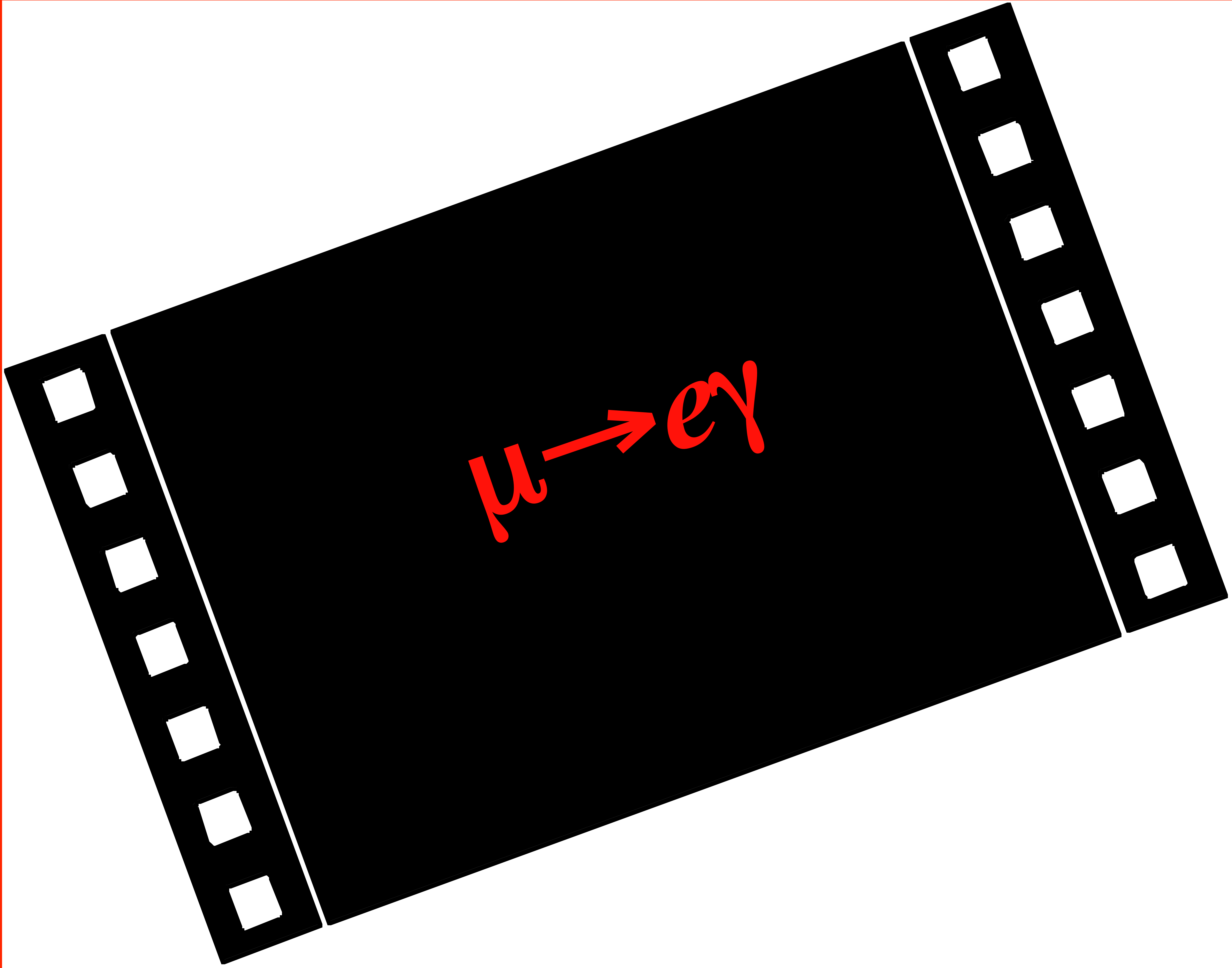
$H^0 \to \mu\tau$	$< 2.5 \times 10^{-3}$	
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	10^{-14} (MEG II)
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$	10^{-16} (Mu3e)
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7.0 \times 10^{-13}$	10^{-17} (COMET, Mu2e)
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}$	$< 3.6 \times 10^{-11}$	10^{-17} (COMET, Mu2e)
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	



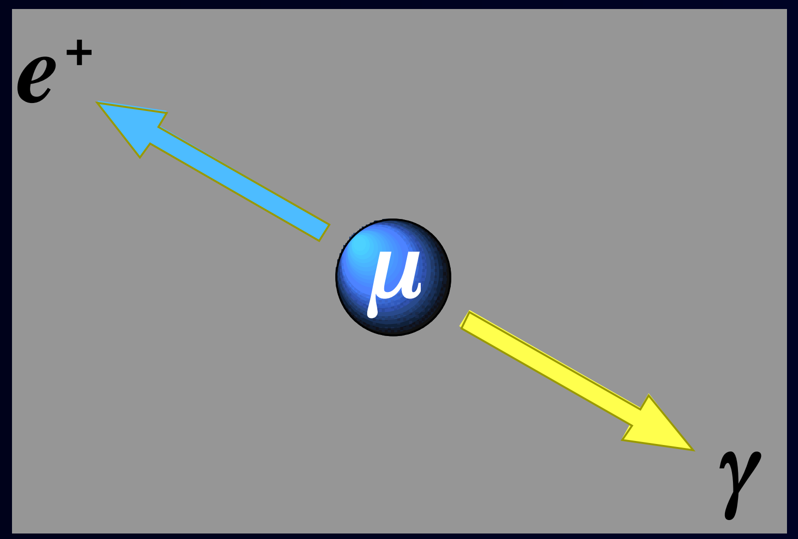
from YK, Y. Okada, RMP (2000)


μ→eγ

$\mu^+ \rightarrow e^+\gamma$: MEG II

$\mu^+ \to e^+\gamma$: MEG II

- Event Signature (μ^+ decay at rest)
  - mono energetic, $m_e = m_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{e\gamma}$=180 degrees
  - time coincidence $\Delta t_{e\gamma}$



- Backgrounds
  - physics background, $\mu^+ \to e^+\nu\bar{\nu}\gamma$
  - accidental background
    - e^+ in $\mu^+ \to e^+\nu\bar{\nu}$ and γ in $\mu^+ \to e^+\nu\bar{\nu}\gamma$
- MEG experiment at PSI
  - $B(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13} \quad (90\,\%\,\mathrm{C.L.})$
- MEG II experiment at PSI
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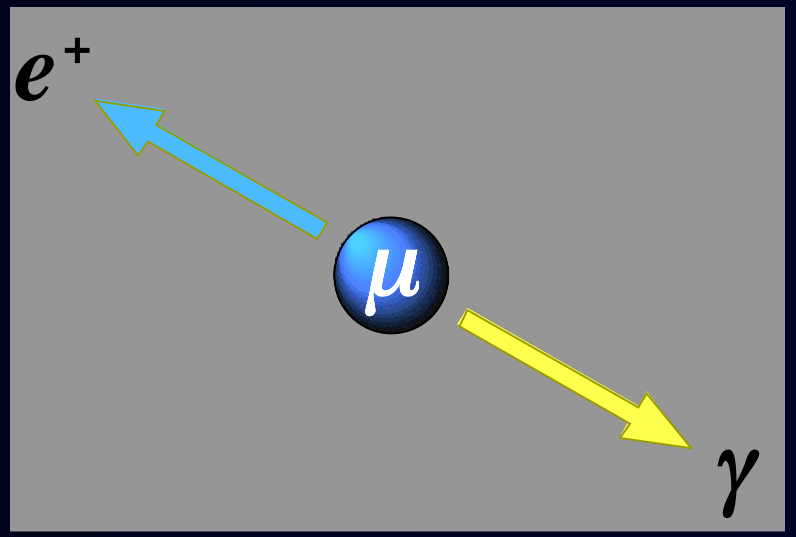
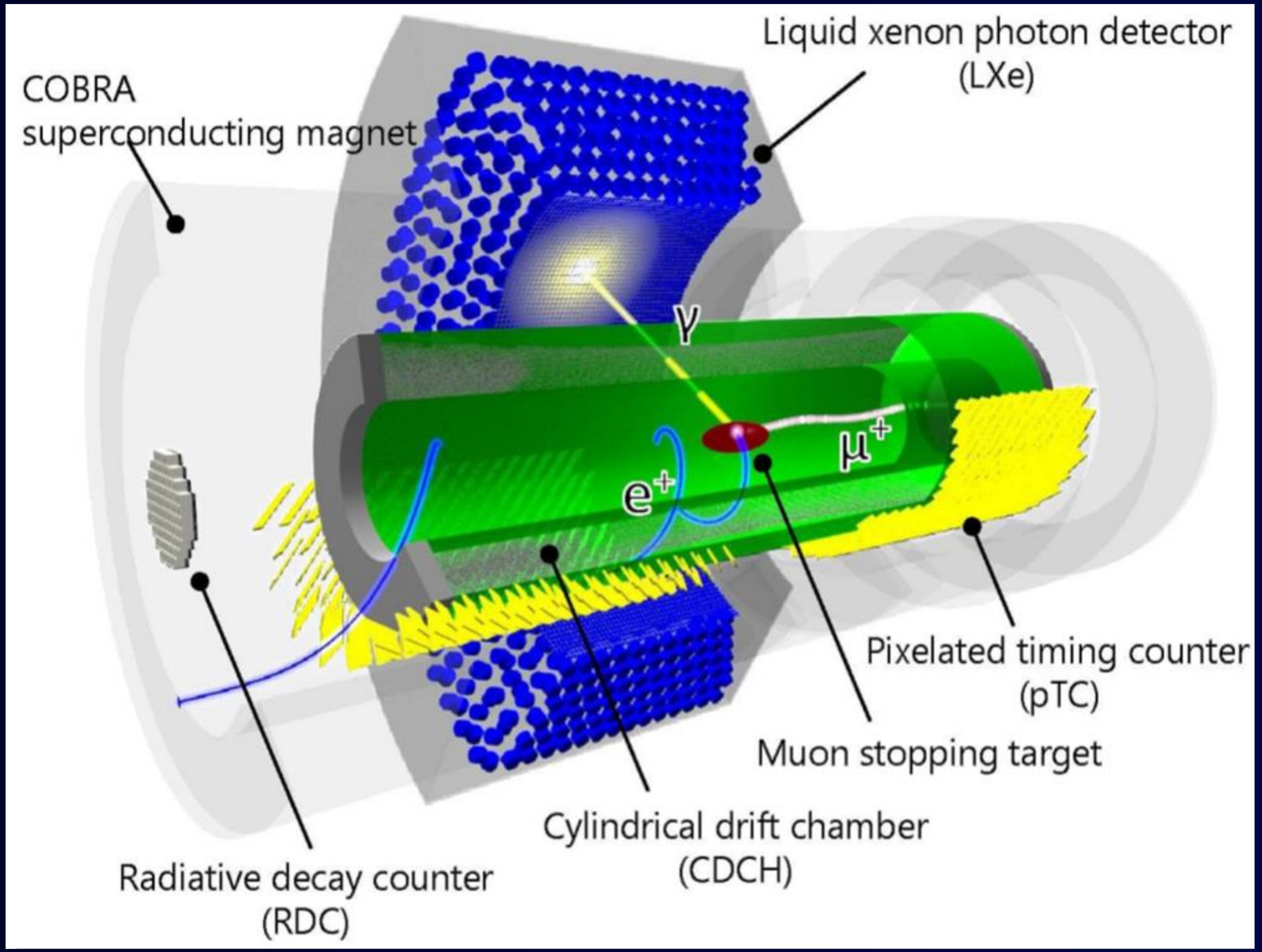


MEG-II



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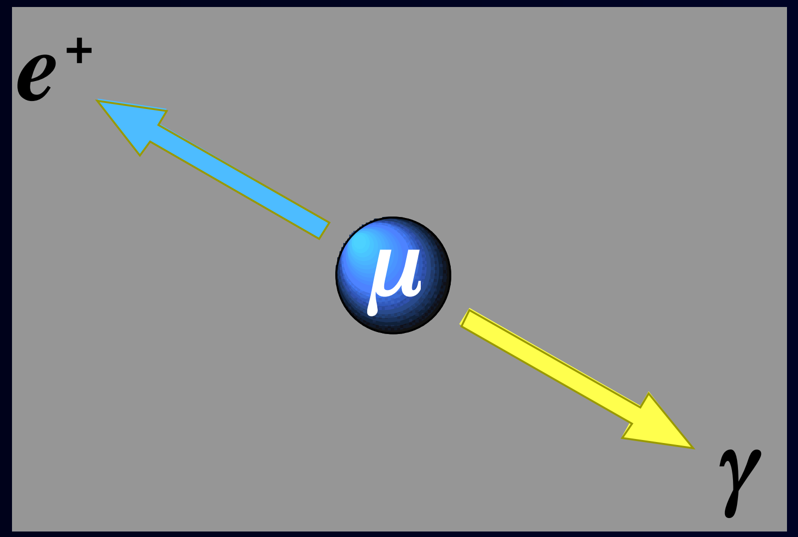
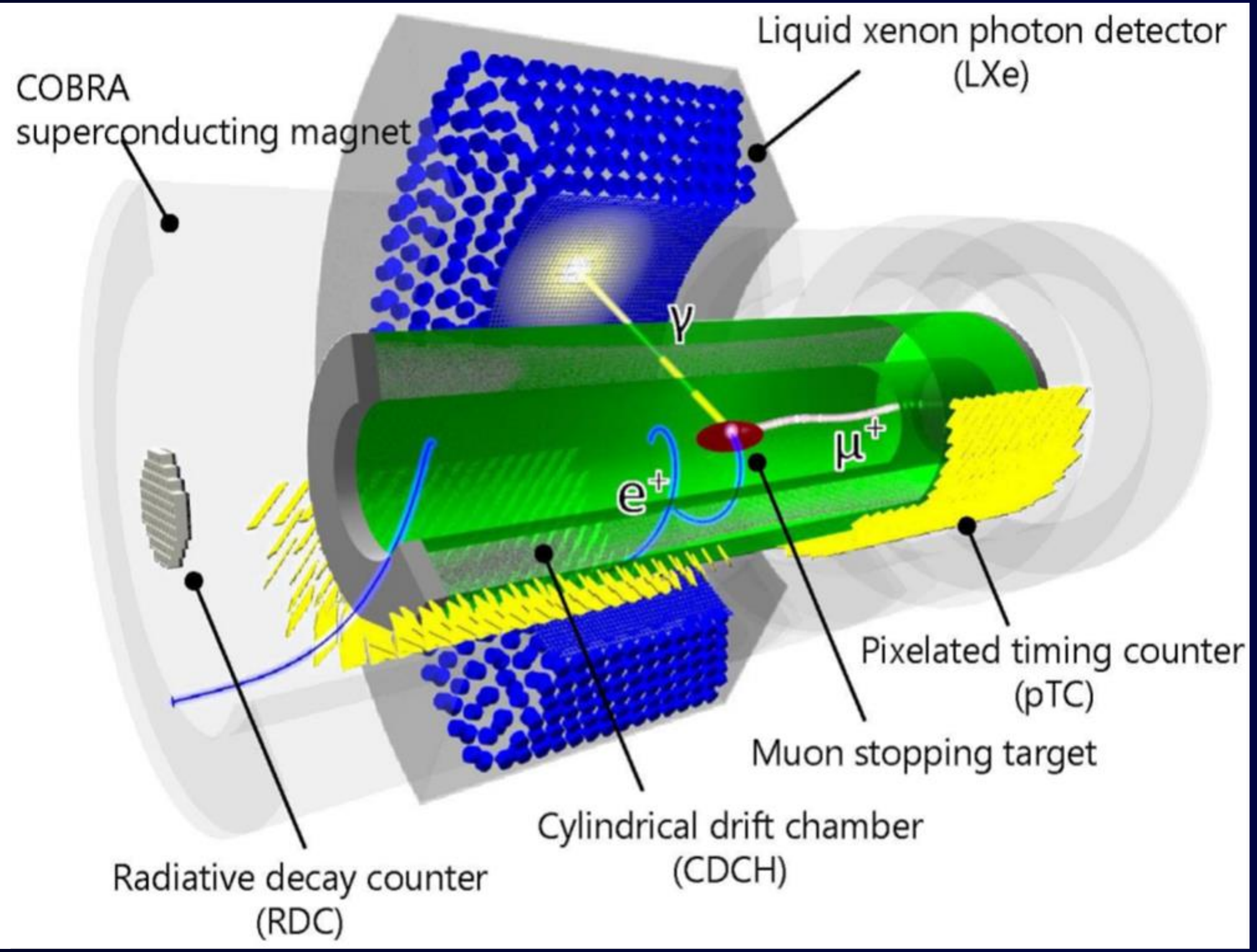


MEG-II



MEG II $:B(\mu^+ \to e^+\gamma) < 6 \times 10^{-14}$

- x2 muon beam intensity
- x2 all detector resolution
- x2 efficiency

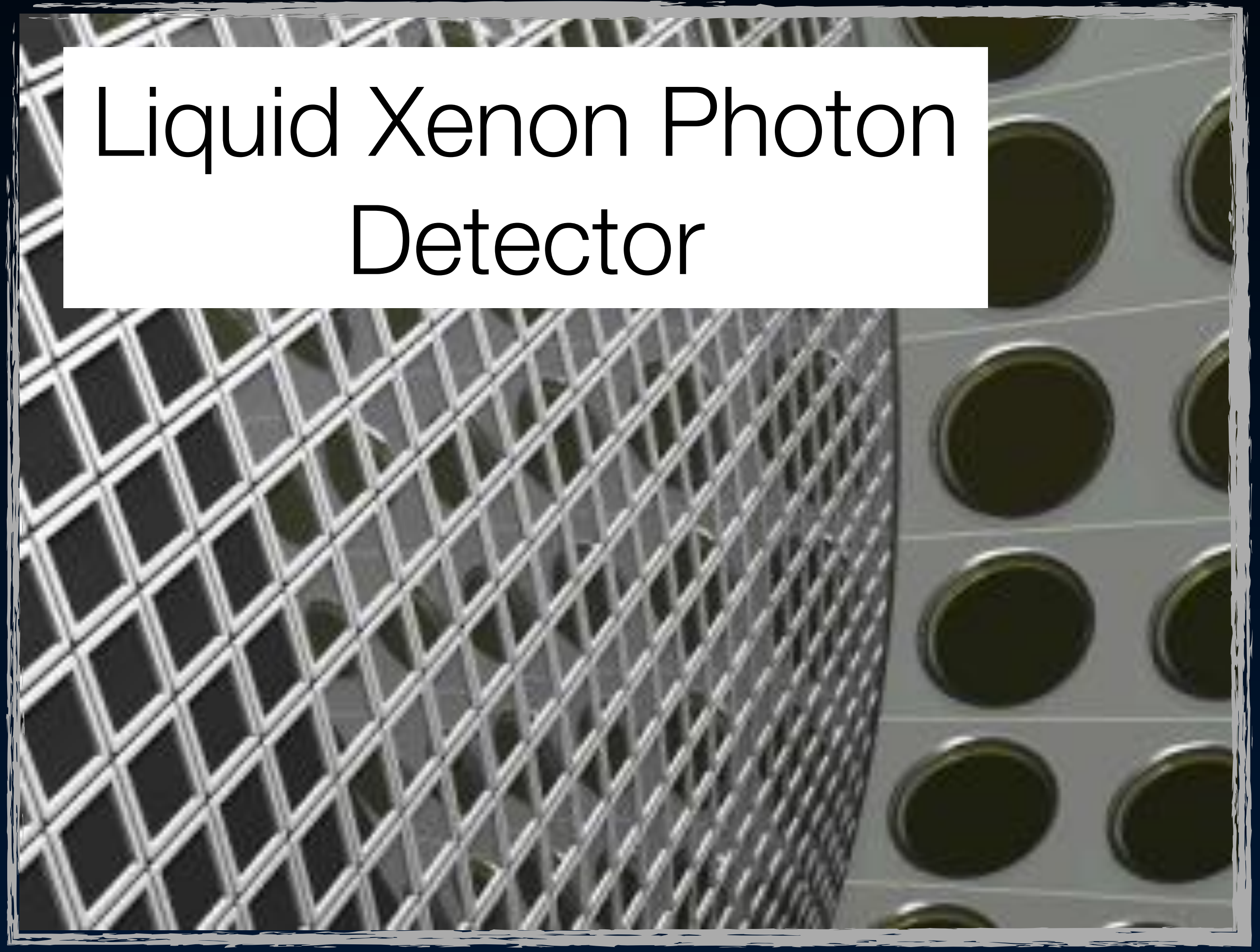
MEG II Detector Upgrade

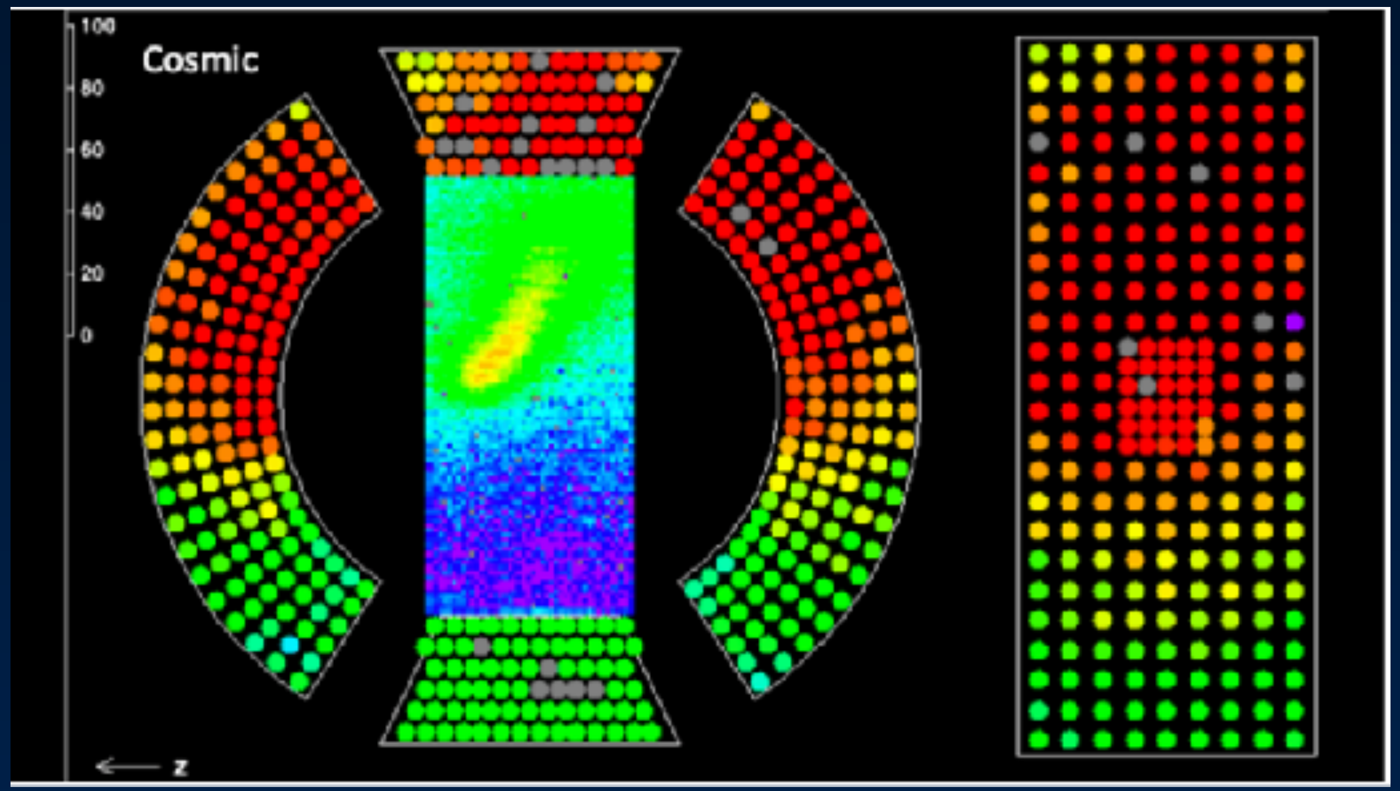
Br<3.1*10^{-13}

Br<3.1*10^{-13}

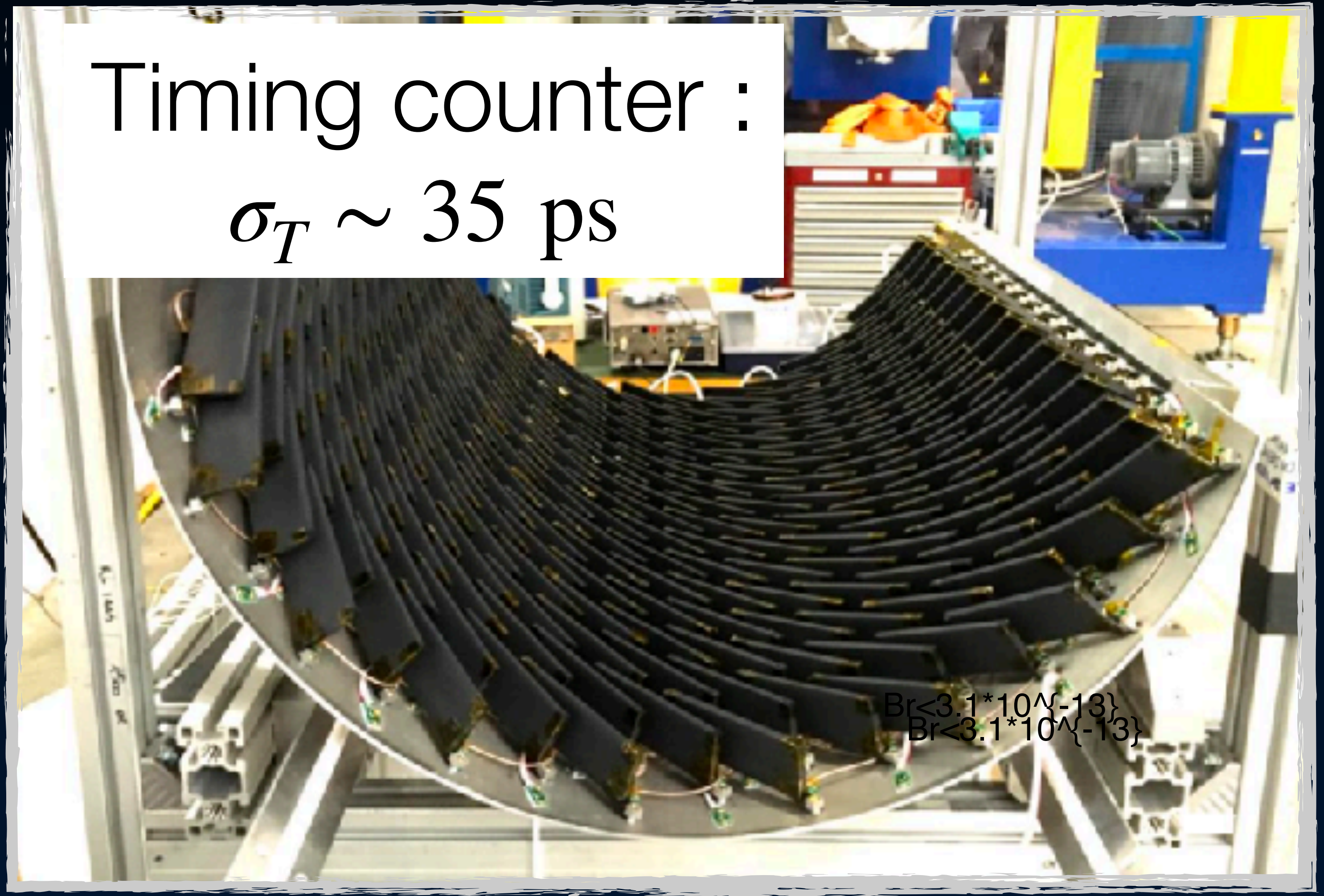
MEG II Detector Upgrade

Liquid Xenon Photon Detector

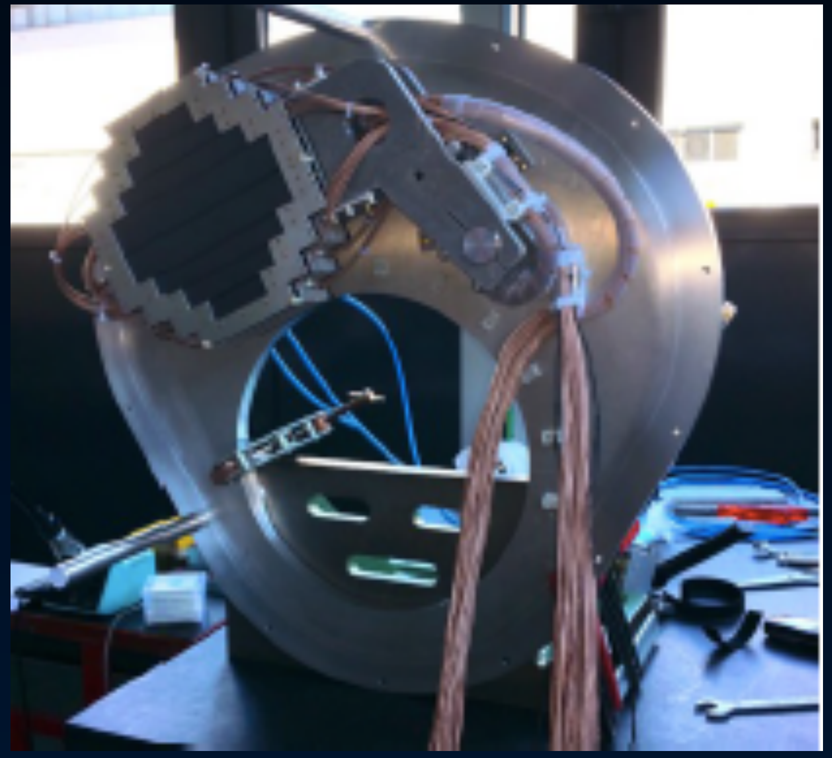




Timing counter : $\sigma_T \sim 35$ ps



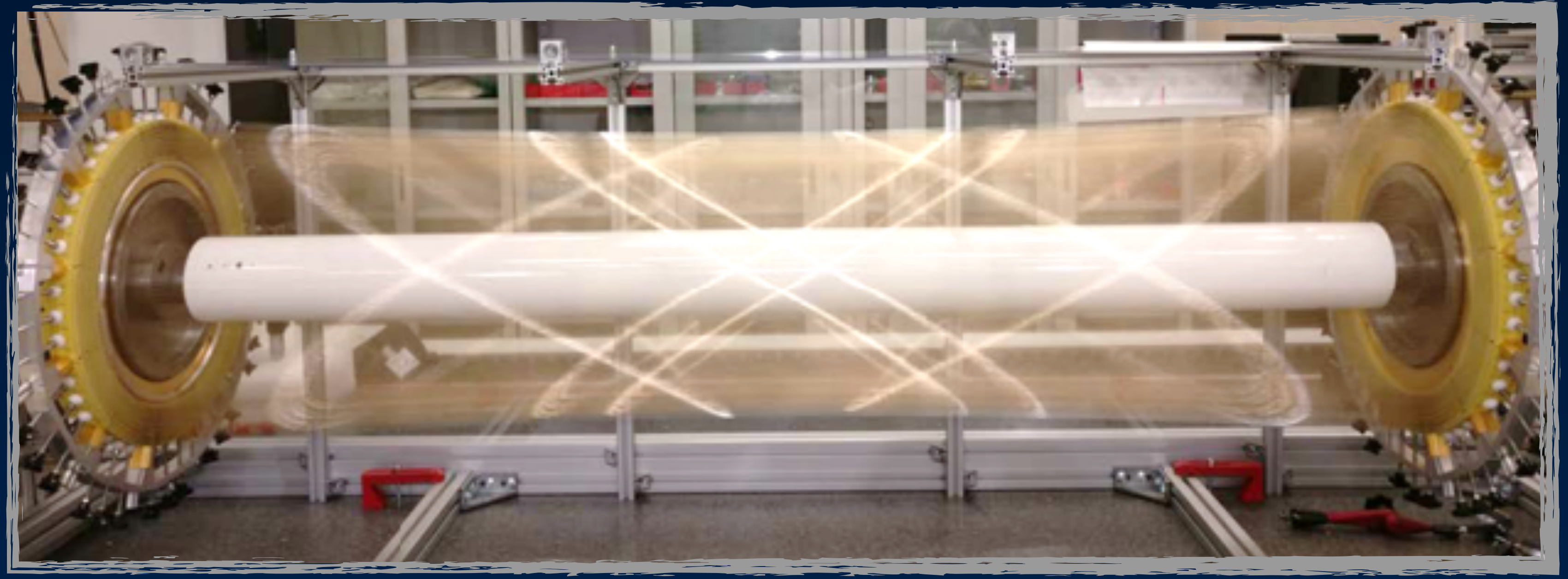
RDC detector



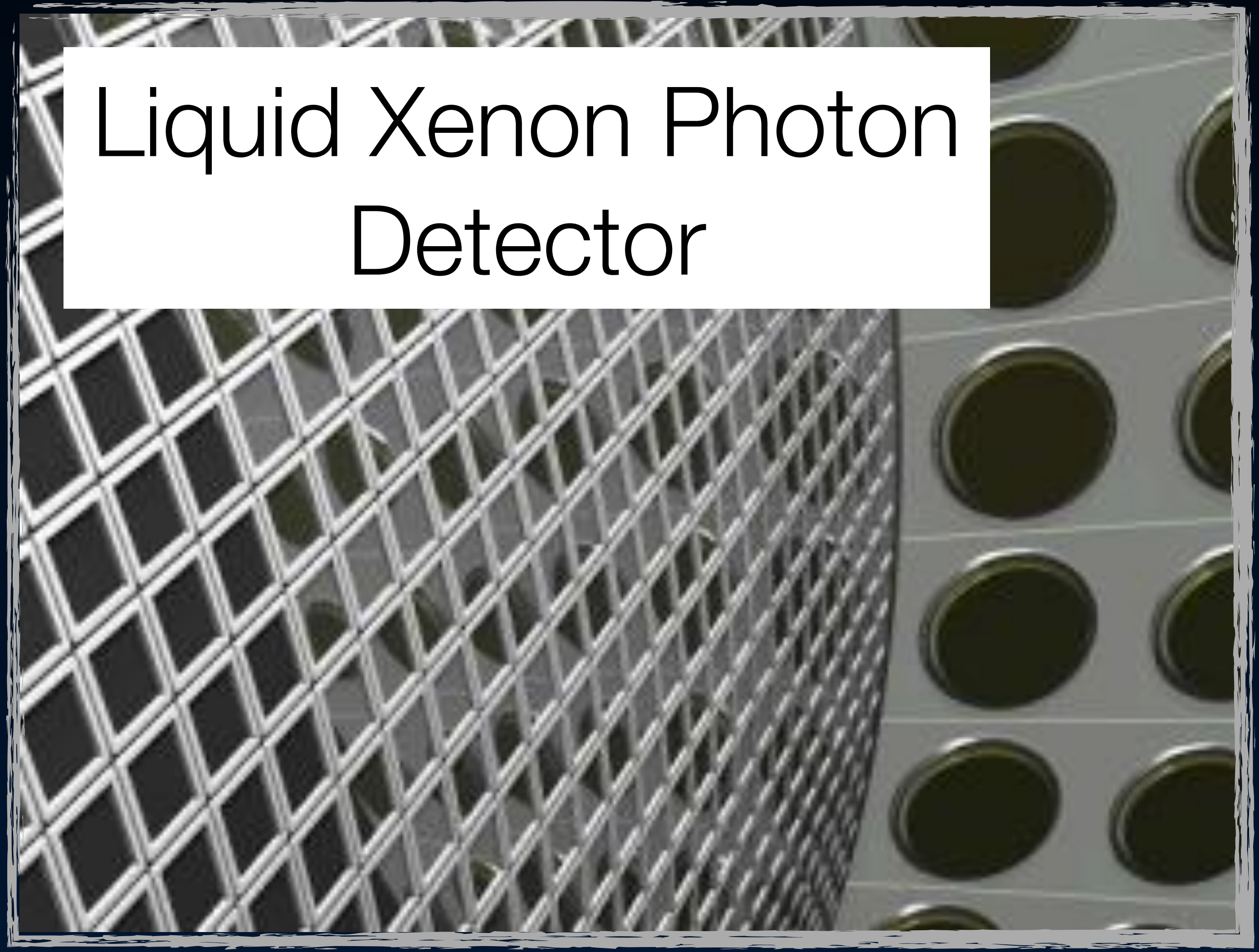
New DAQ/trigger system

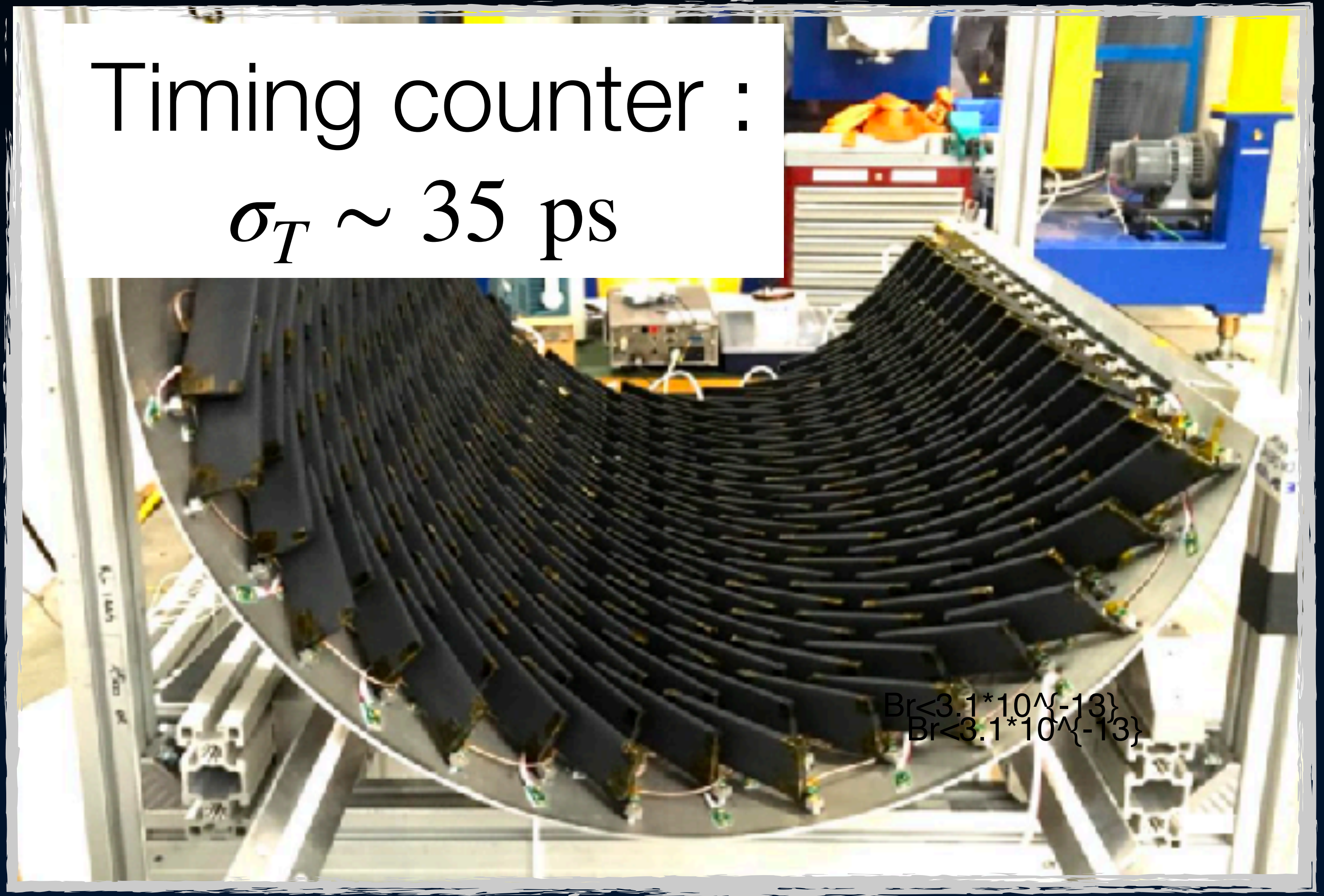
Drift chamber

Cylindrical drift chamber



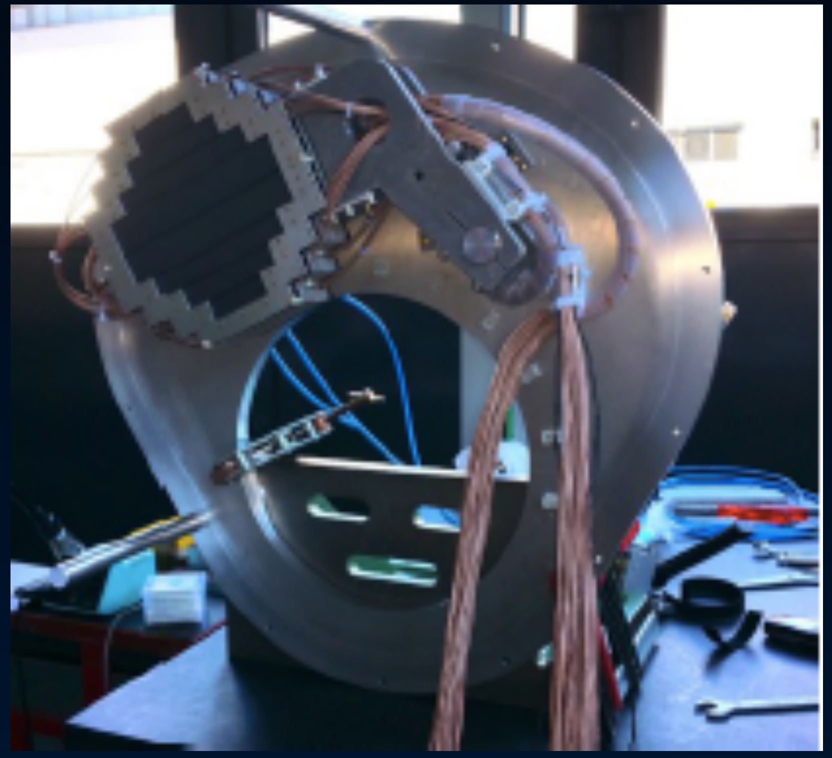
MEG II Detector Upgrade

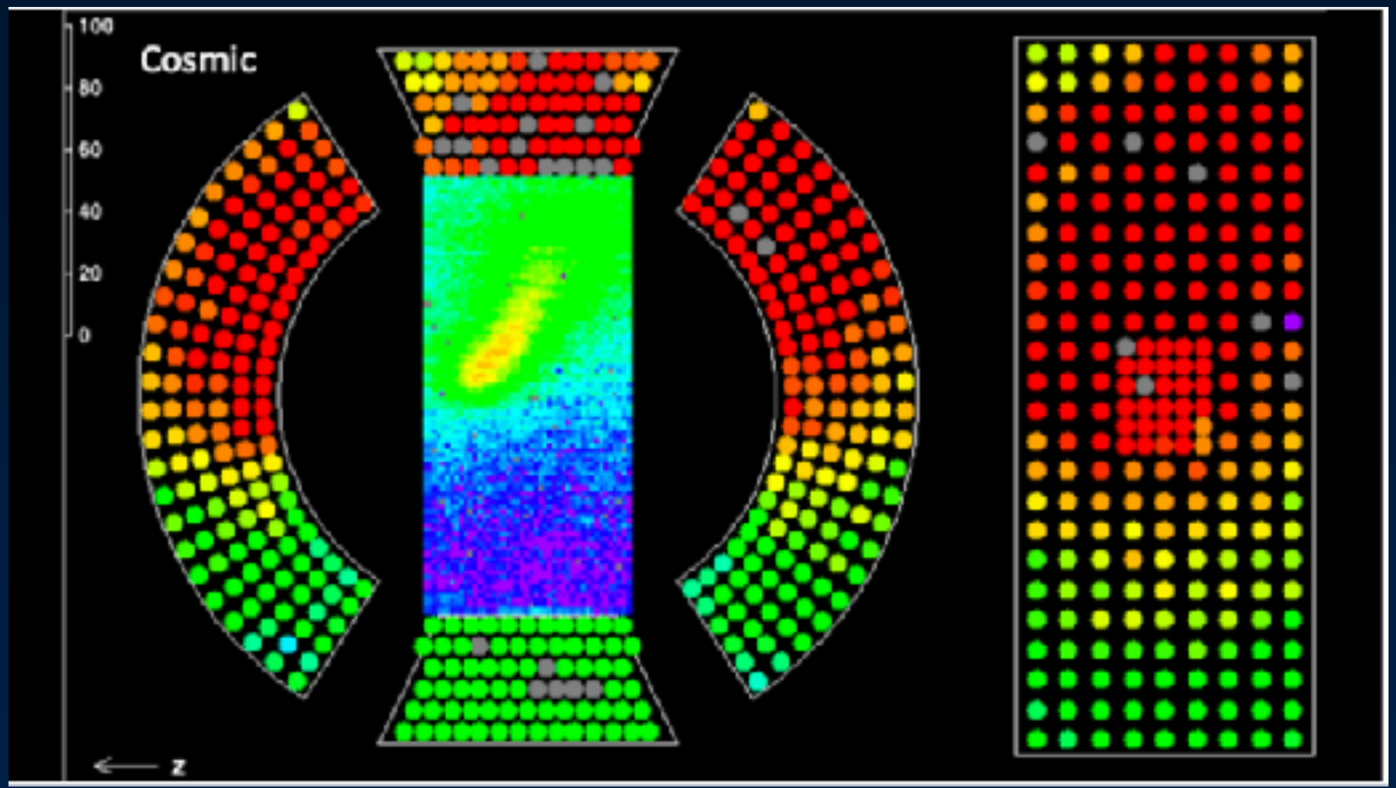




Br<3.1*10^{-13}

RDC detector





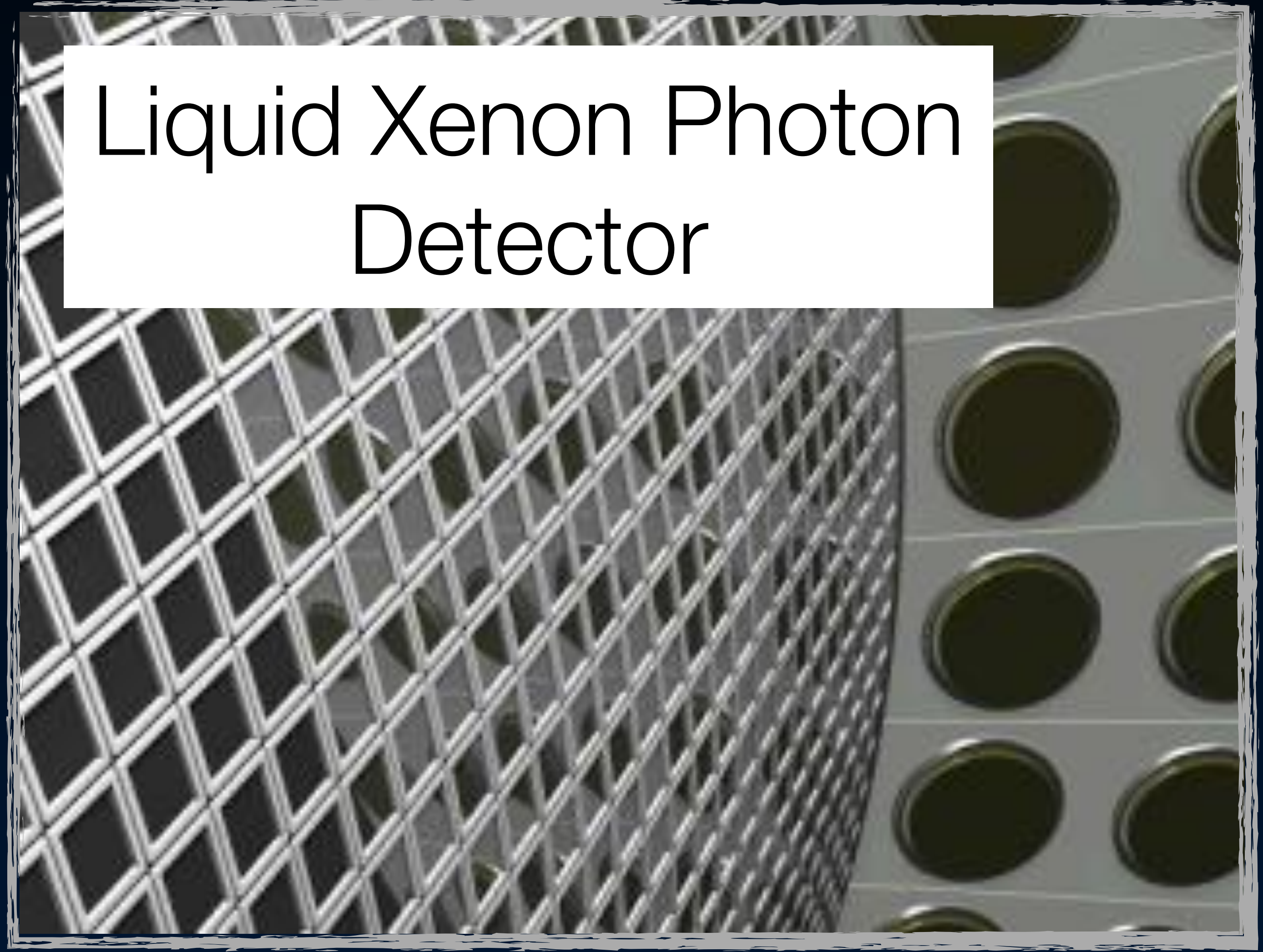
Cylindrical drift chamber

Timeline

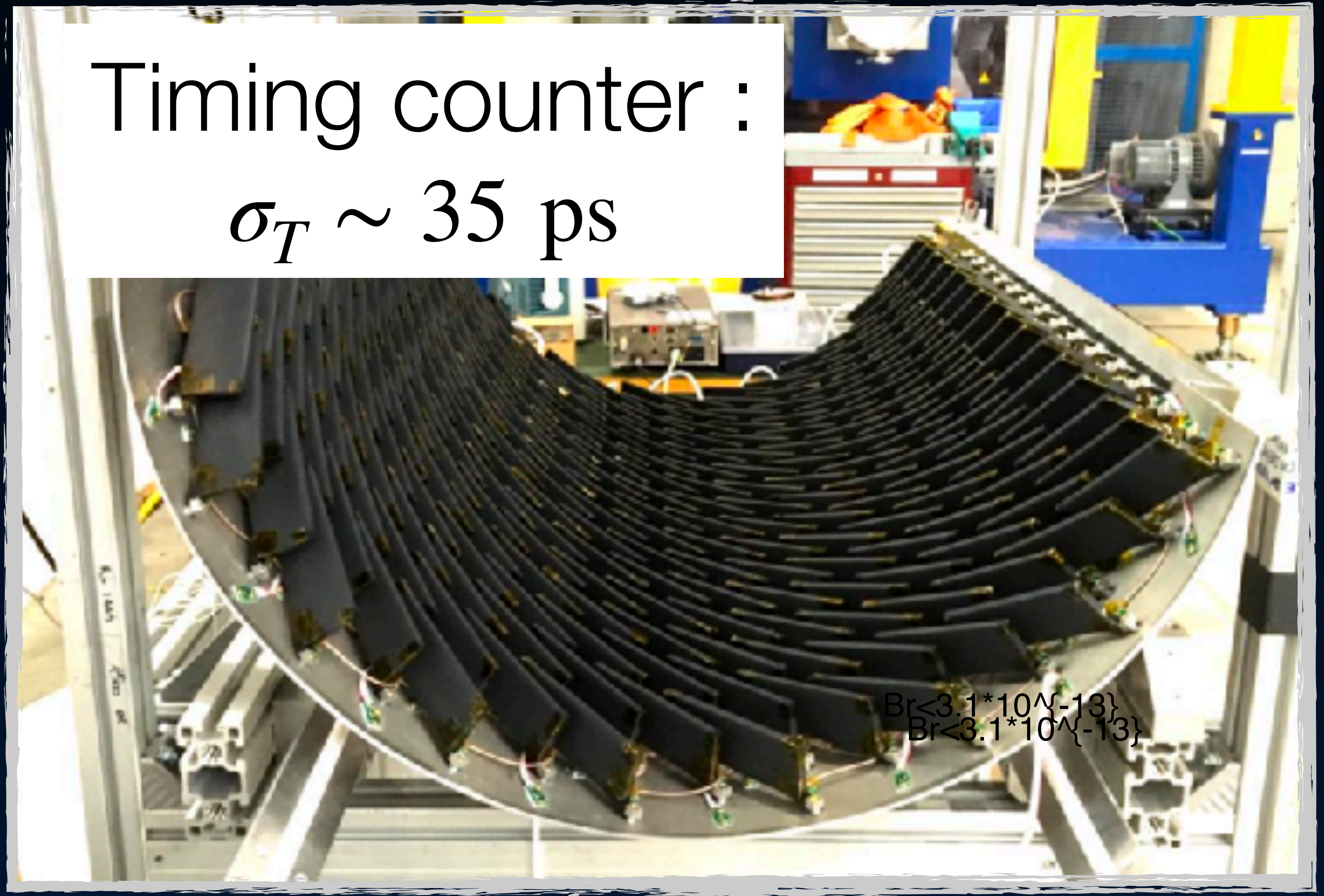
- Physics runs in 2021,2022,2023 - 2025,(2026)
- PSI HIPA accelerator shutdown in 2027-2028

MEG II Detector Upgrade

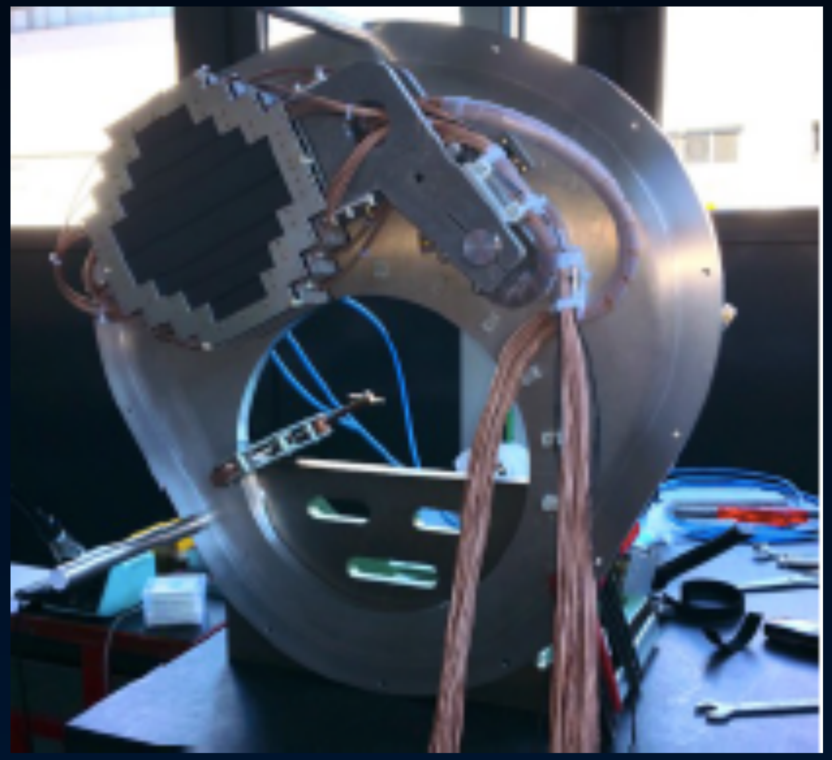
Liquid Xenon Photon Detector



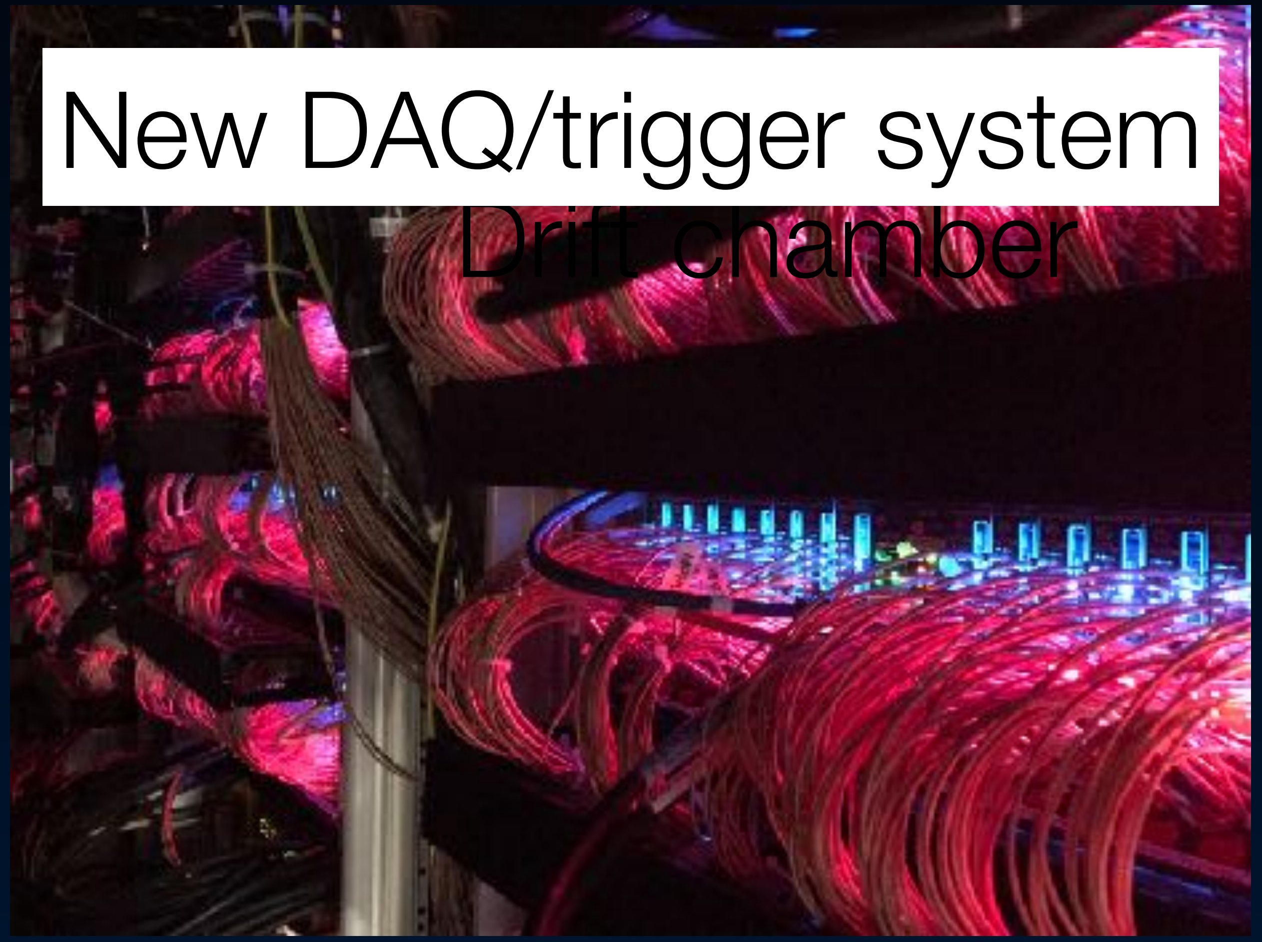
Timing counter : $\sigma_T \sim 35$ ps

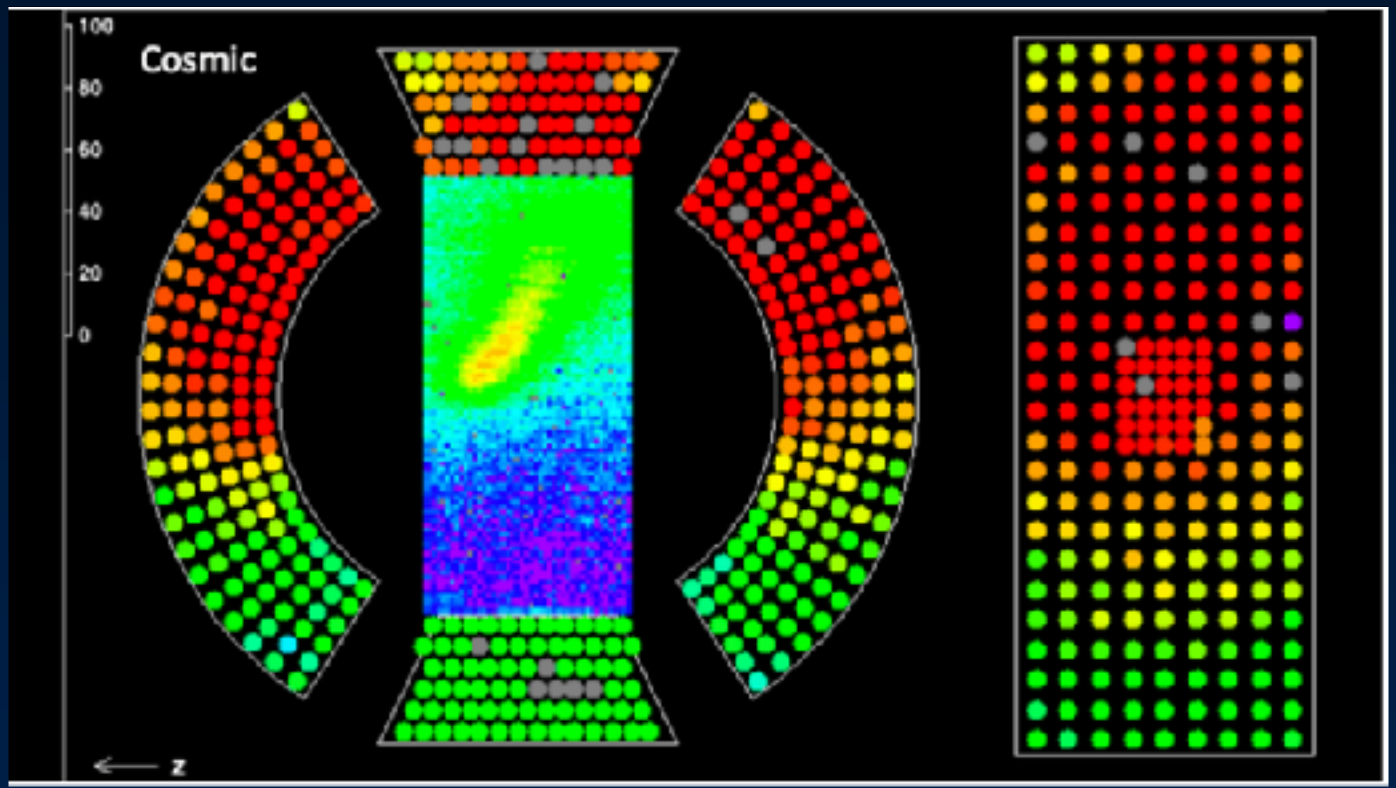


RDC detector



New DAQ/trigger system





Cylindrical drift chamber

Timeline

- Physics runs in 2021,2022,2023 - 2025,(2026)
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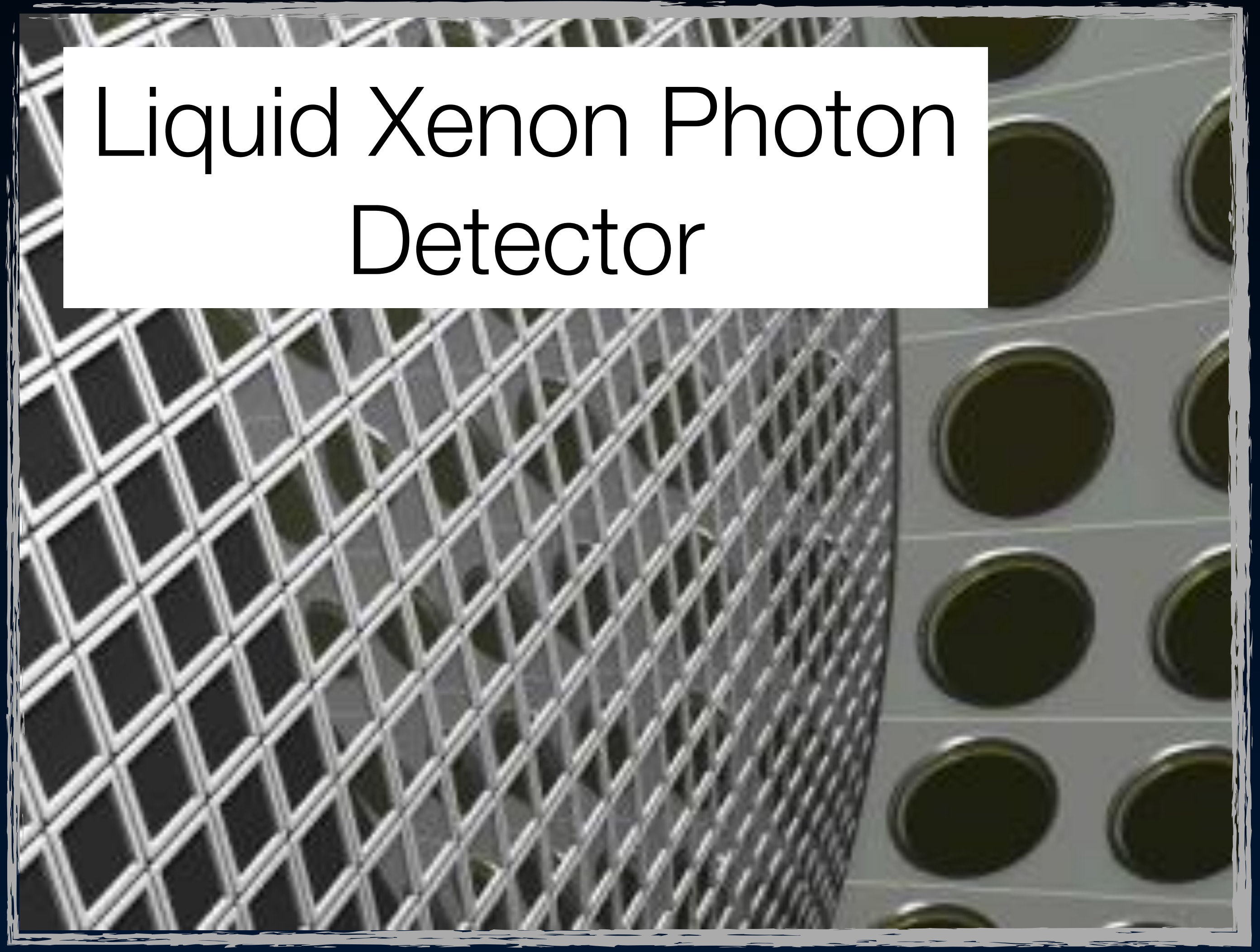
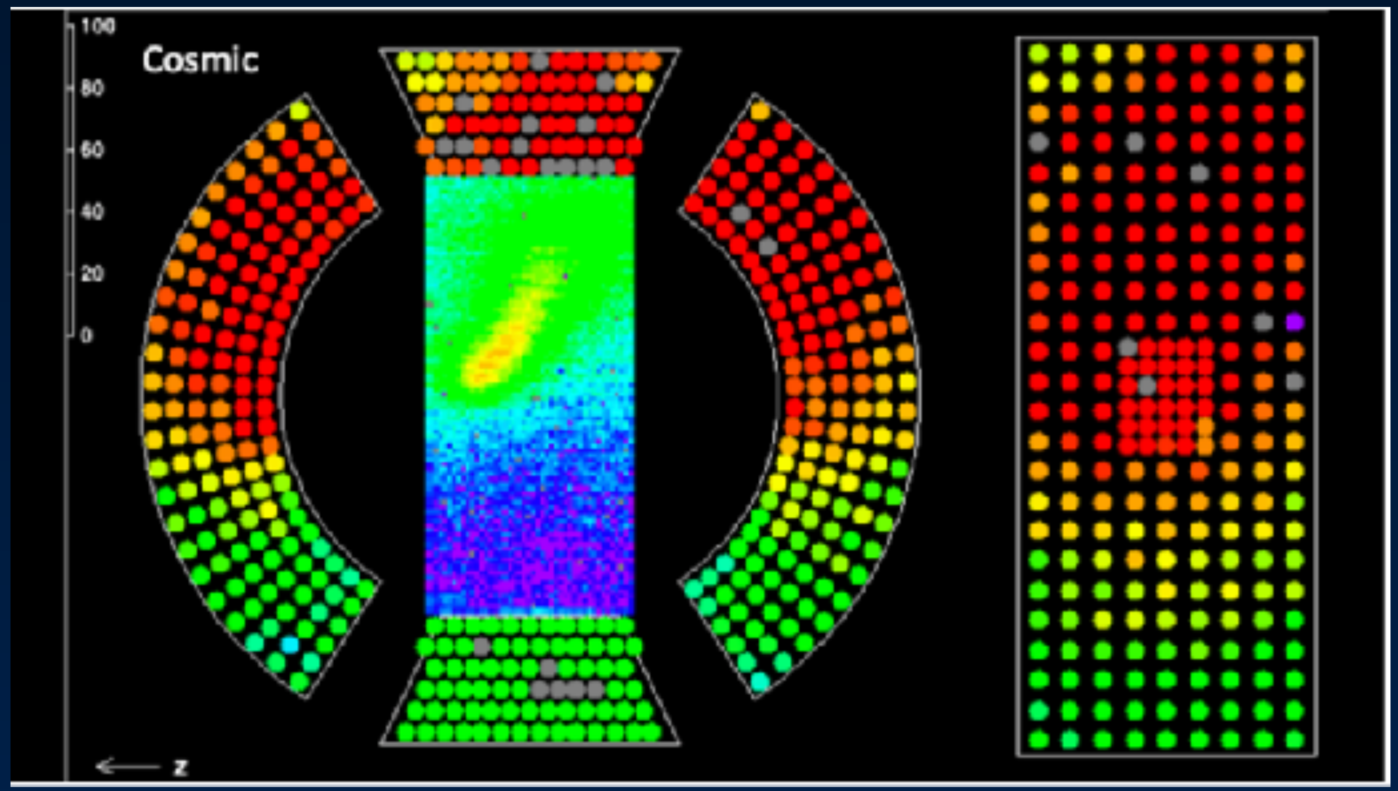
MEG II first result (10.2023): $BR < 7.5 \times 10^{-13}$

MEG II Detector Upgrade

Liquid Xenon Photon Detector





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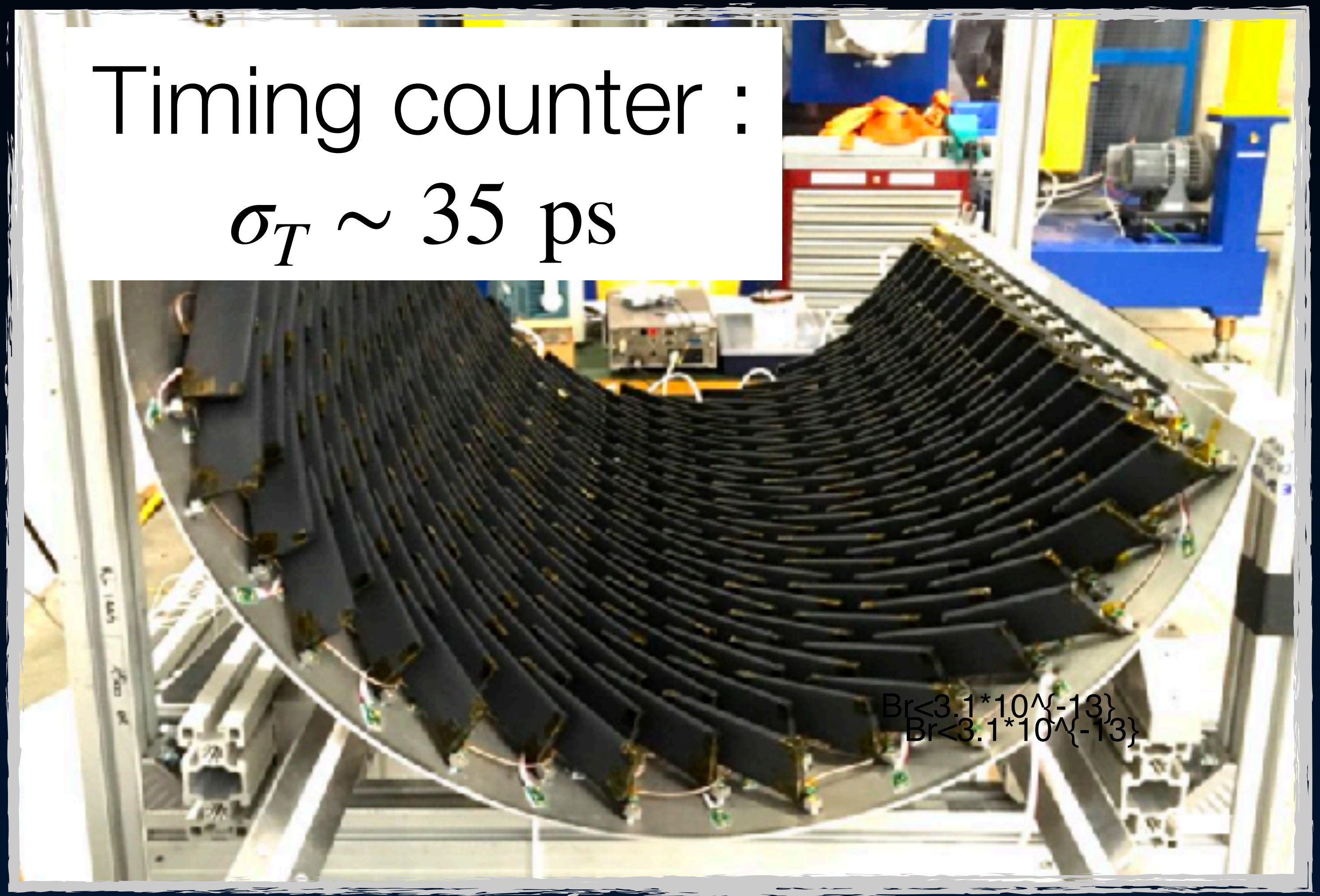

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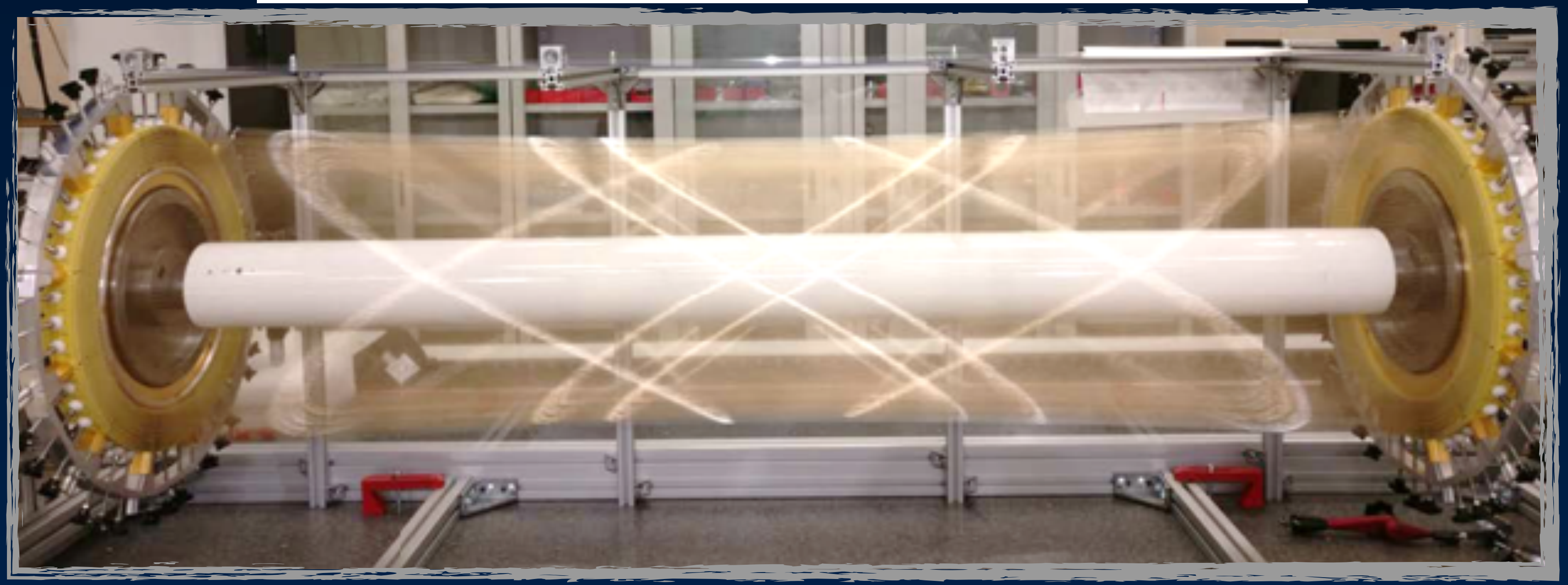
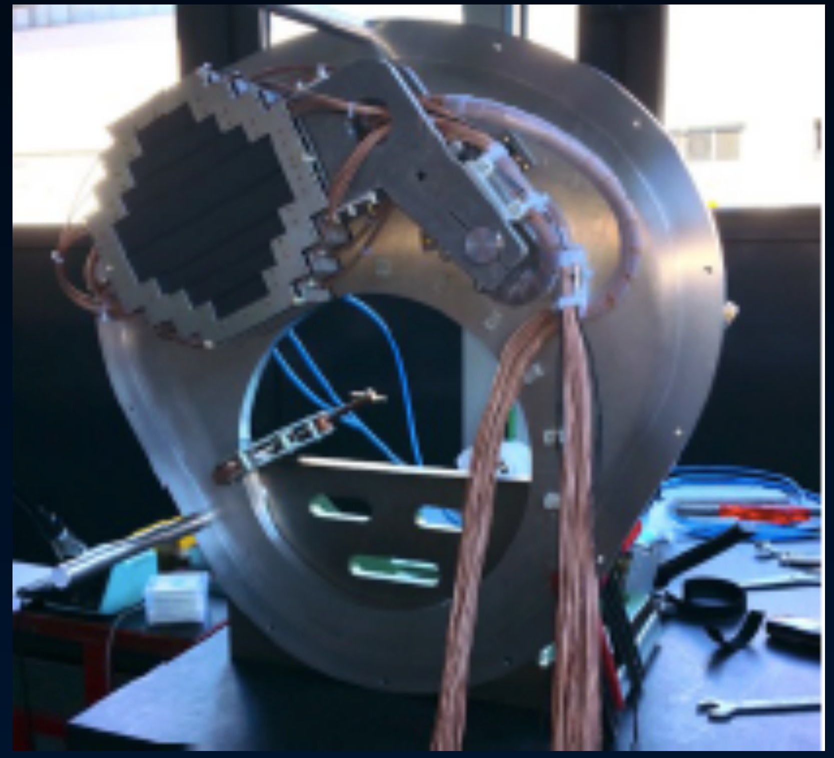


RDC detector



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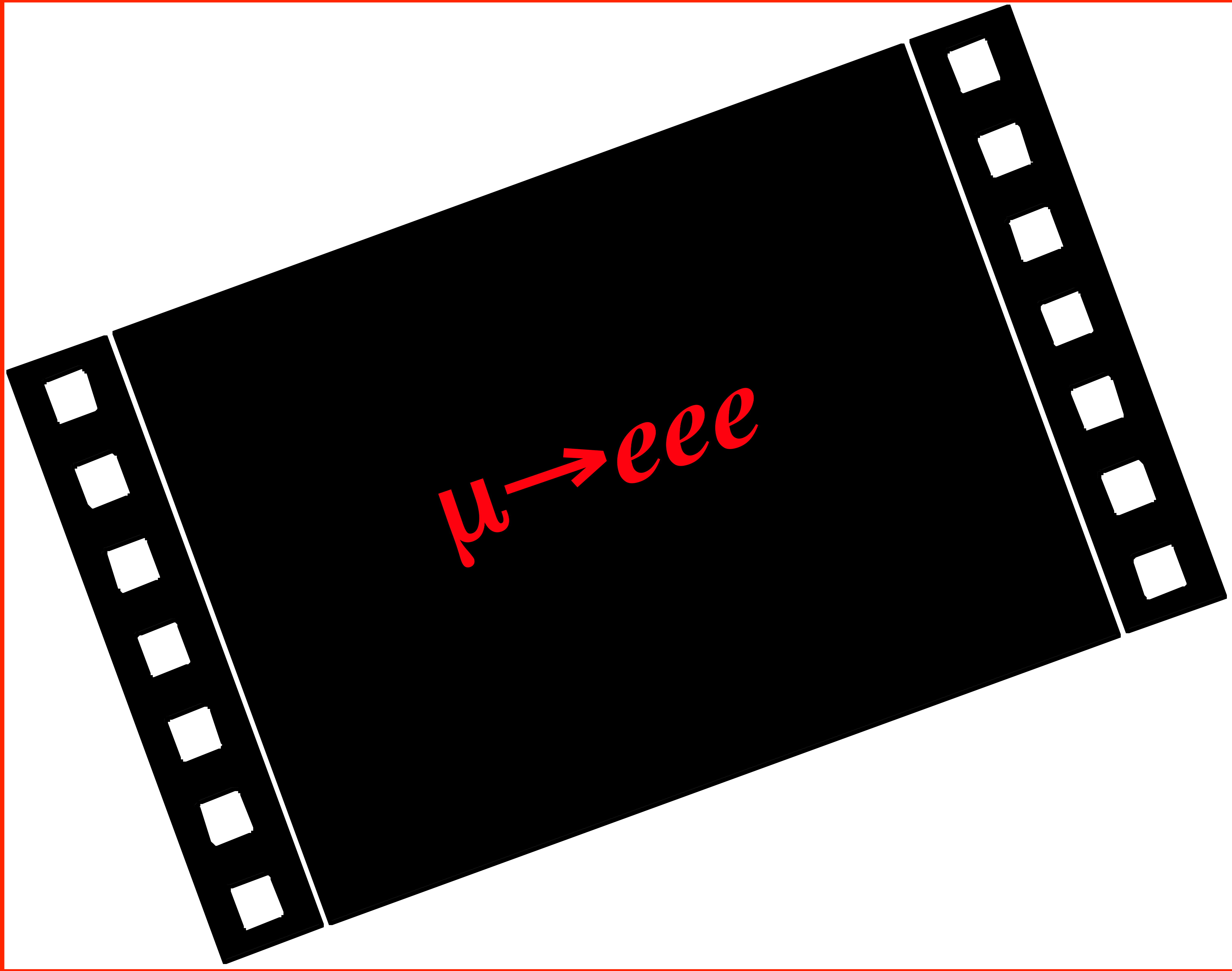
MEG II first result (10.2023): $BR < 7.5 \times 10^{-13}$ combined: $BR < 3.1 \times 10^{-13}$


μ→eee

$\mu^+ \to e^+e^+e^-$: Mu3e

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- Event Signature (μ^+ decay at rest)
  - $\Sigma E_e = m_\mu$ and $\Sigma P_e = 0$ (vector sum)
  - common vertex and time coincidence
- Backgrounds
  - Physics backgrounds, $\mu^+ \to e^+\nu_e\bar{\nu}_\mu e^+e^-$
  - Accidental backgrounds from Michel decays + Bhabha scattering
- Current limits (from SINDRUM at PSI)
  - $B(\mu \to eee) < 1.0 \times 10^{-12}$ (90% C.L.)
- Mu3e at PSI
  - Phase-I: $\mathcal{O}(10^{-15})$ with 10^8 μ/s (πE5)
    - inner pixel detectors, scintillating fibers
  - Phase-II: $\mathcal{O}(10^{-16})$ with 10^9 μ/s (HiMB)

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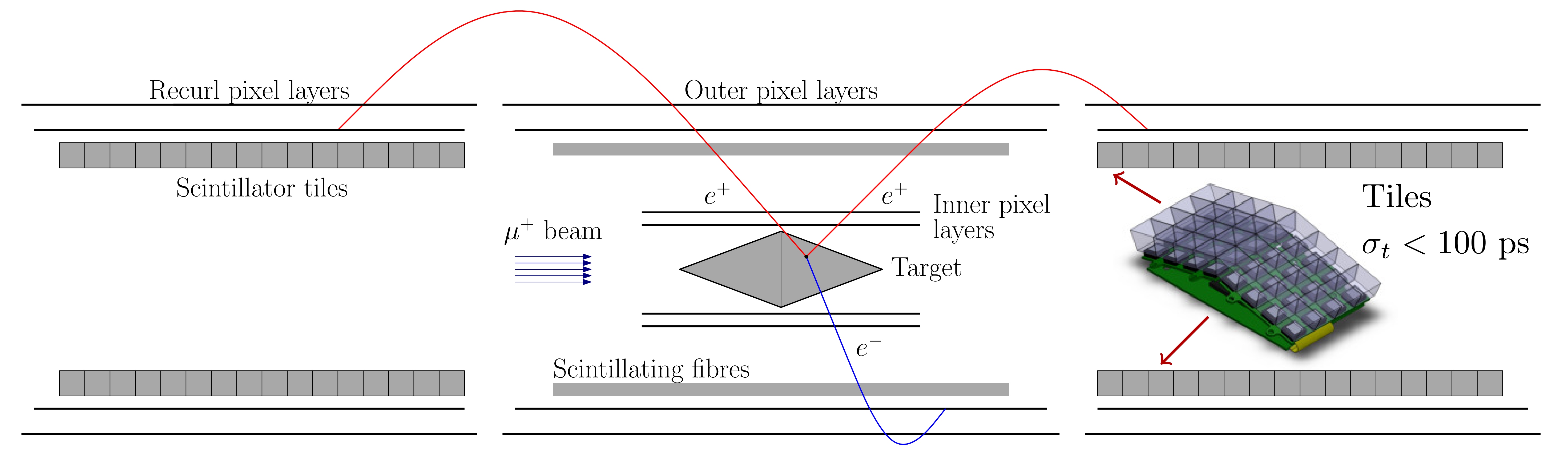

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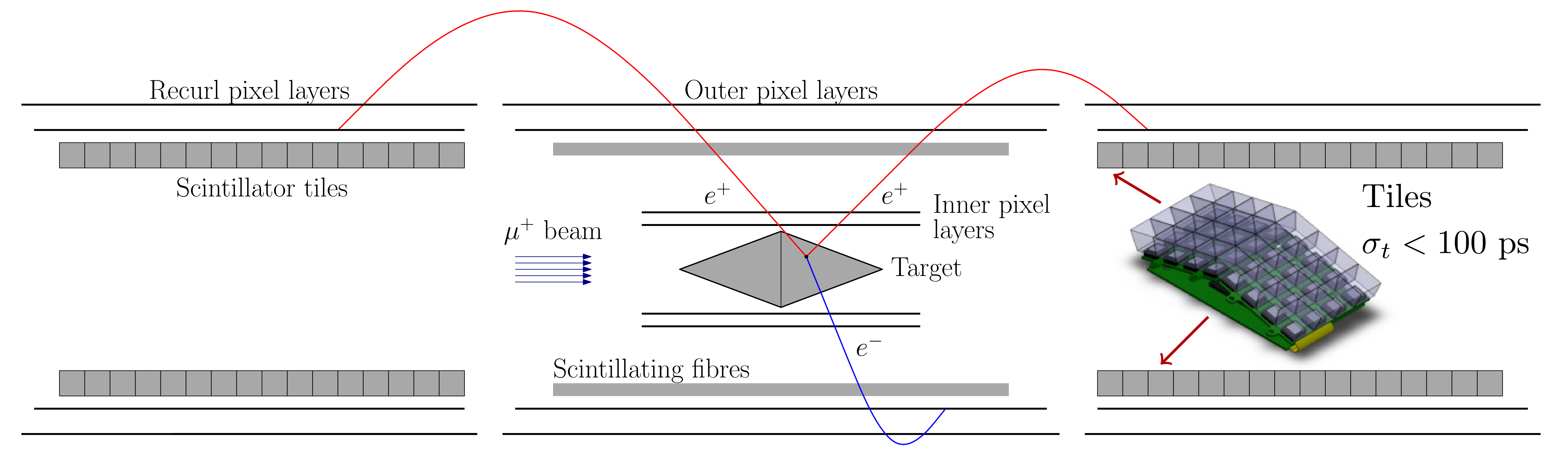

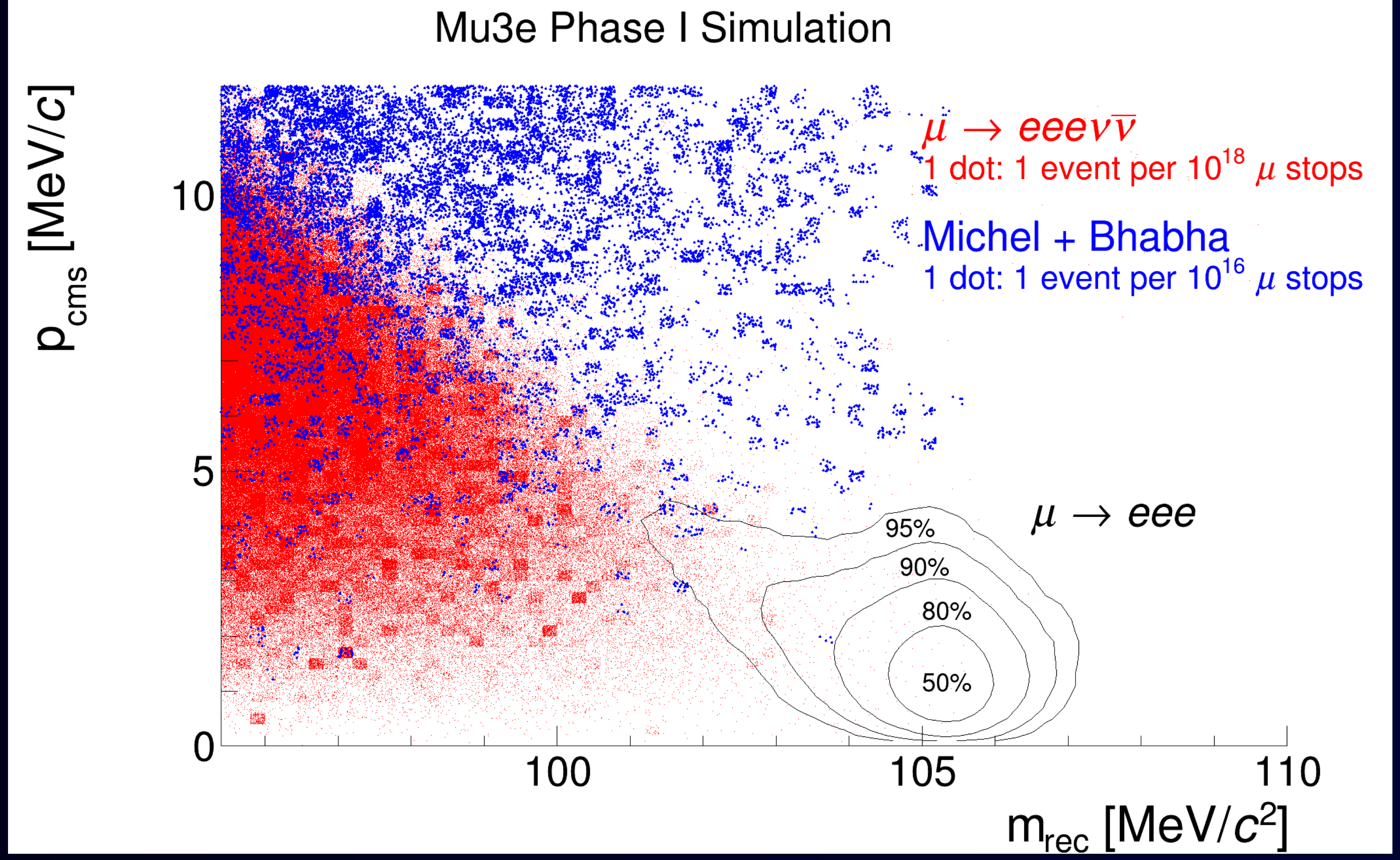

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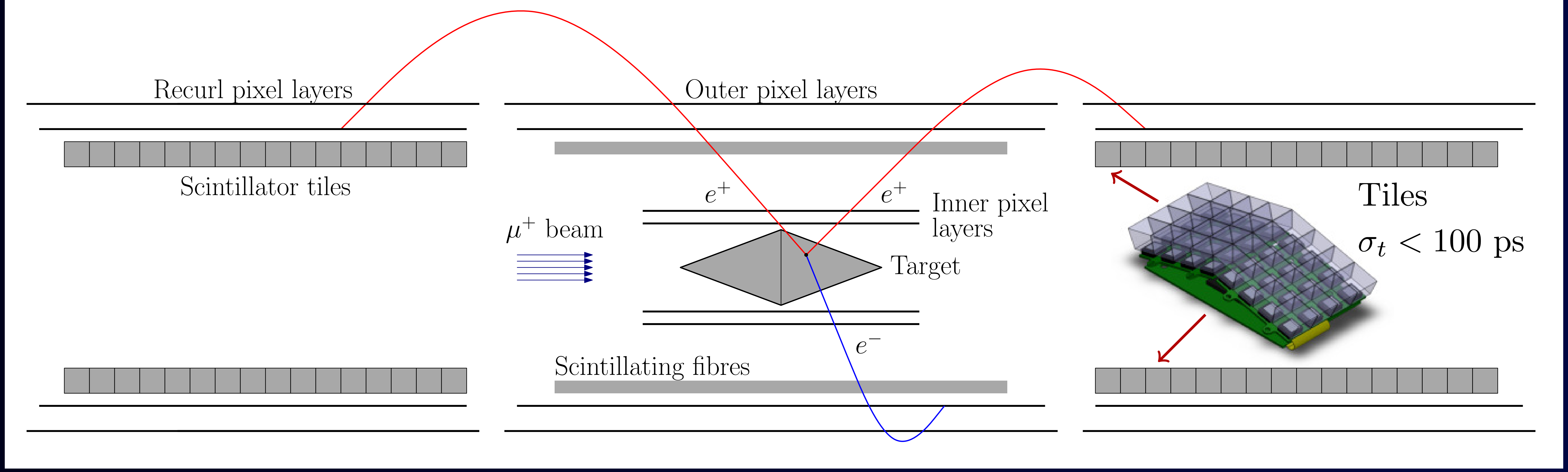

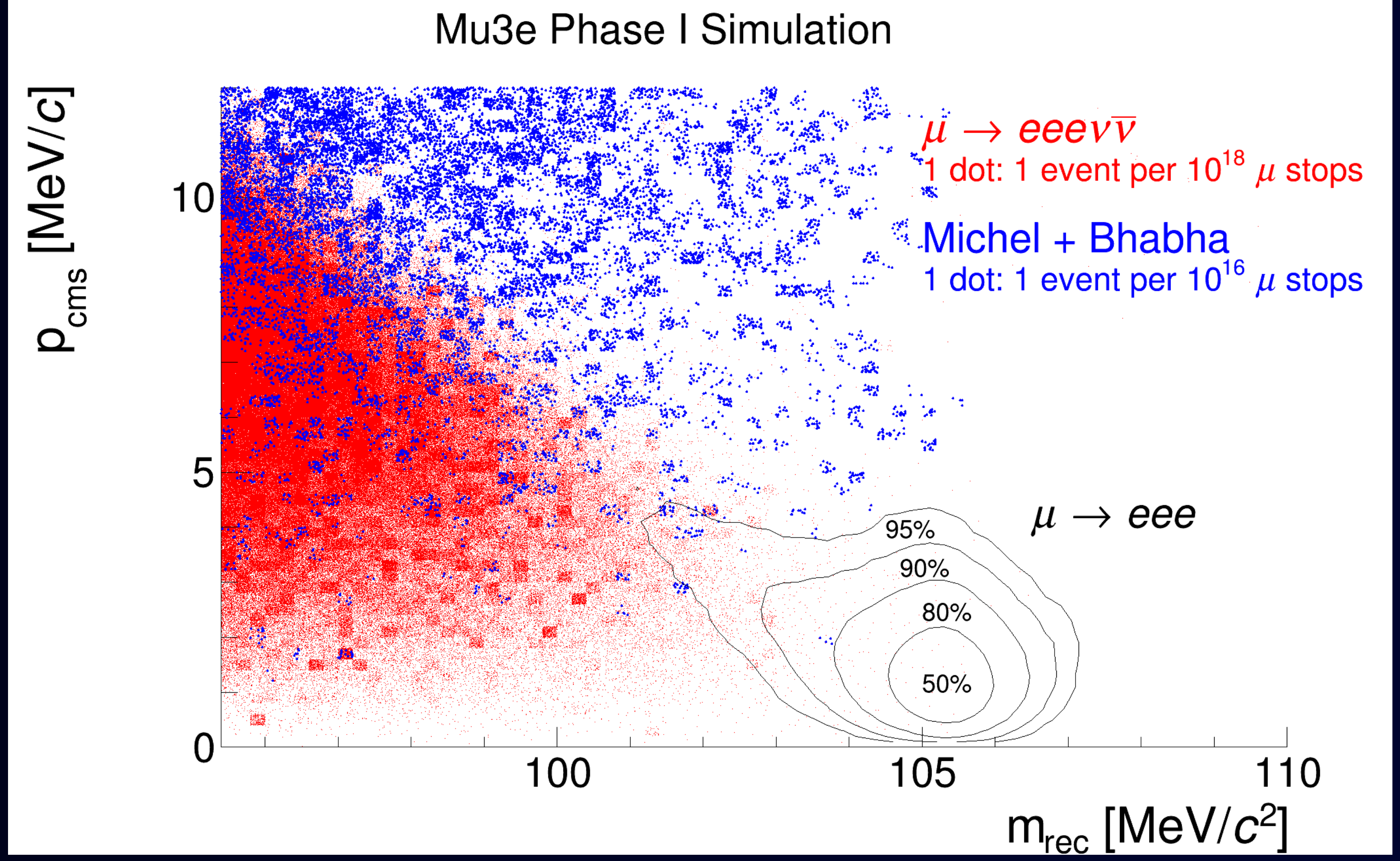

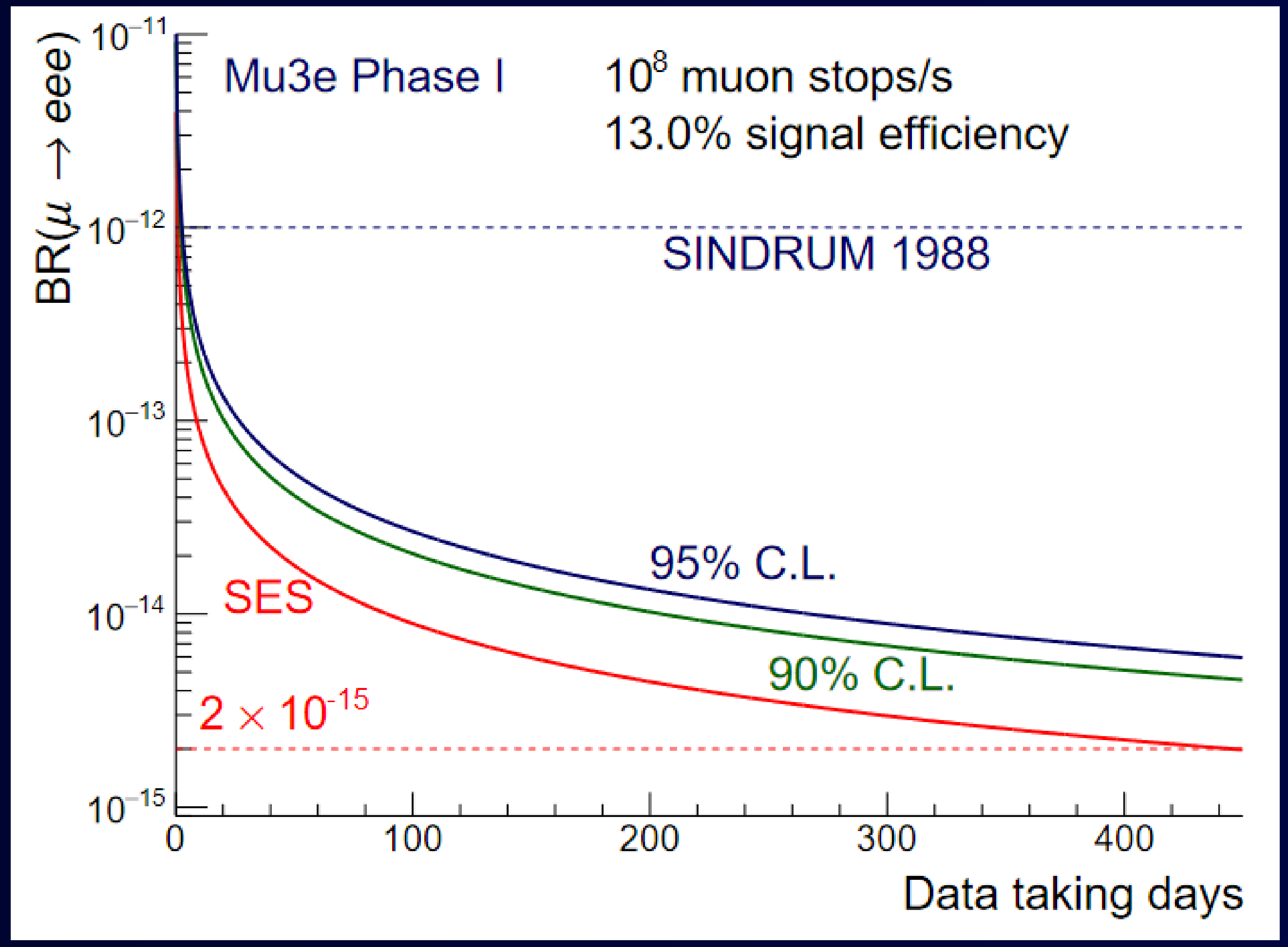

Mu3e Phase-I Preparation Status

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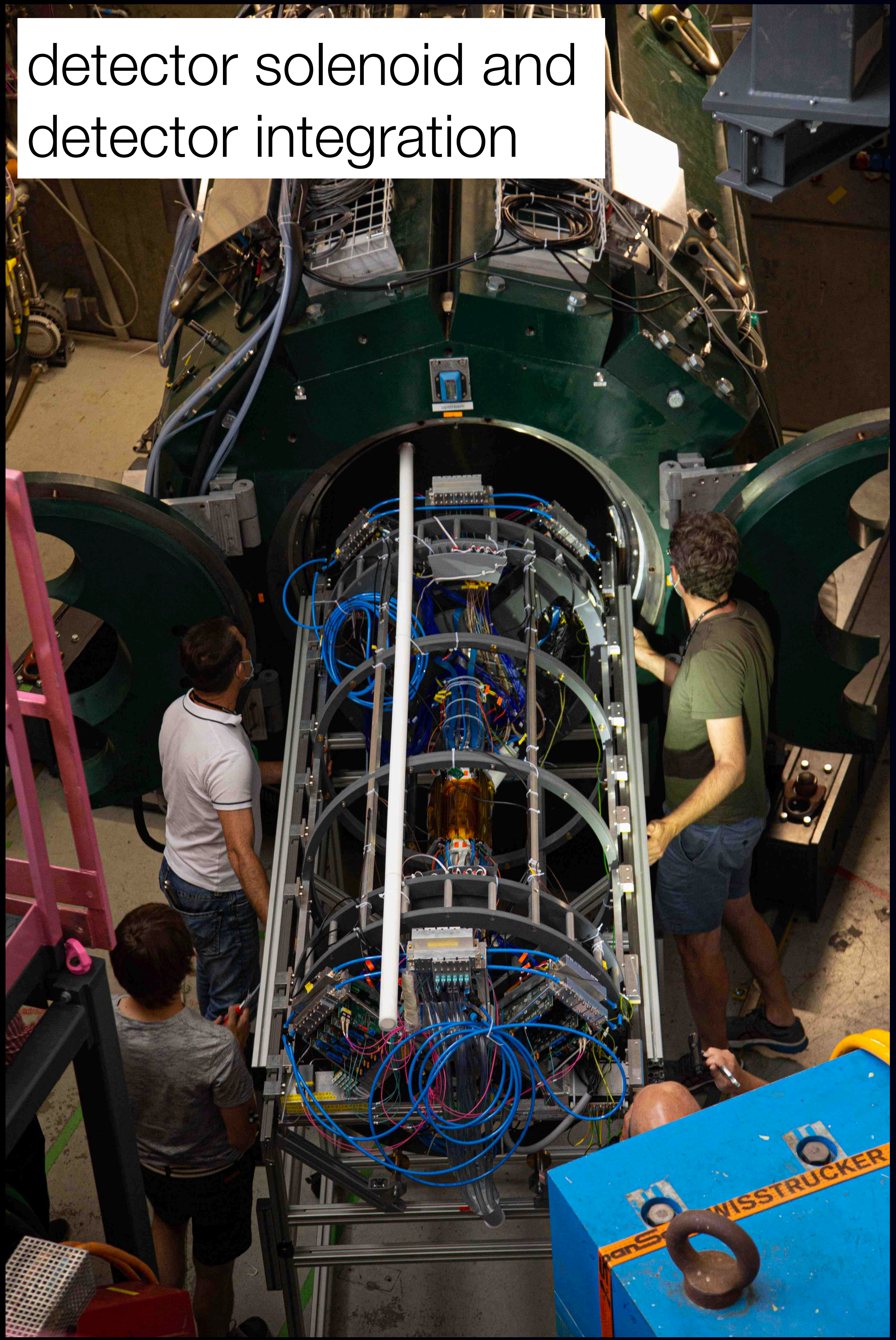

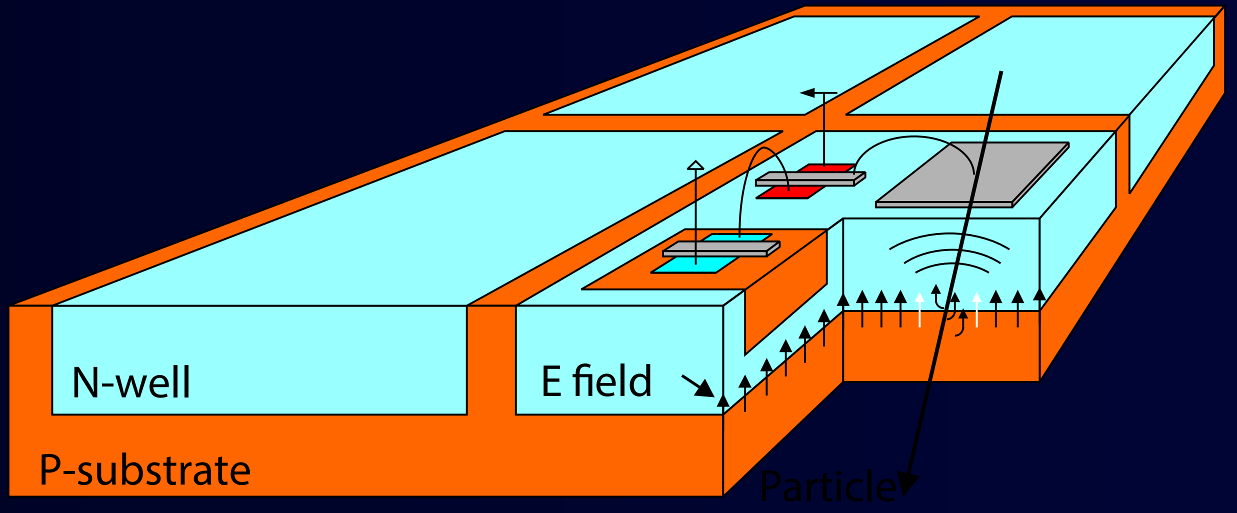

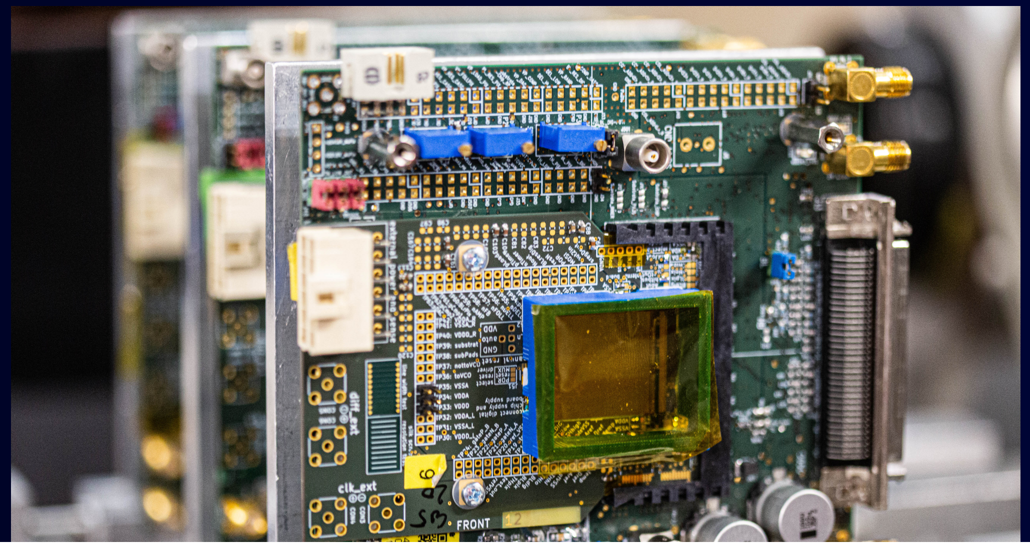

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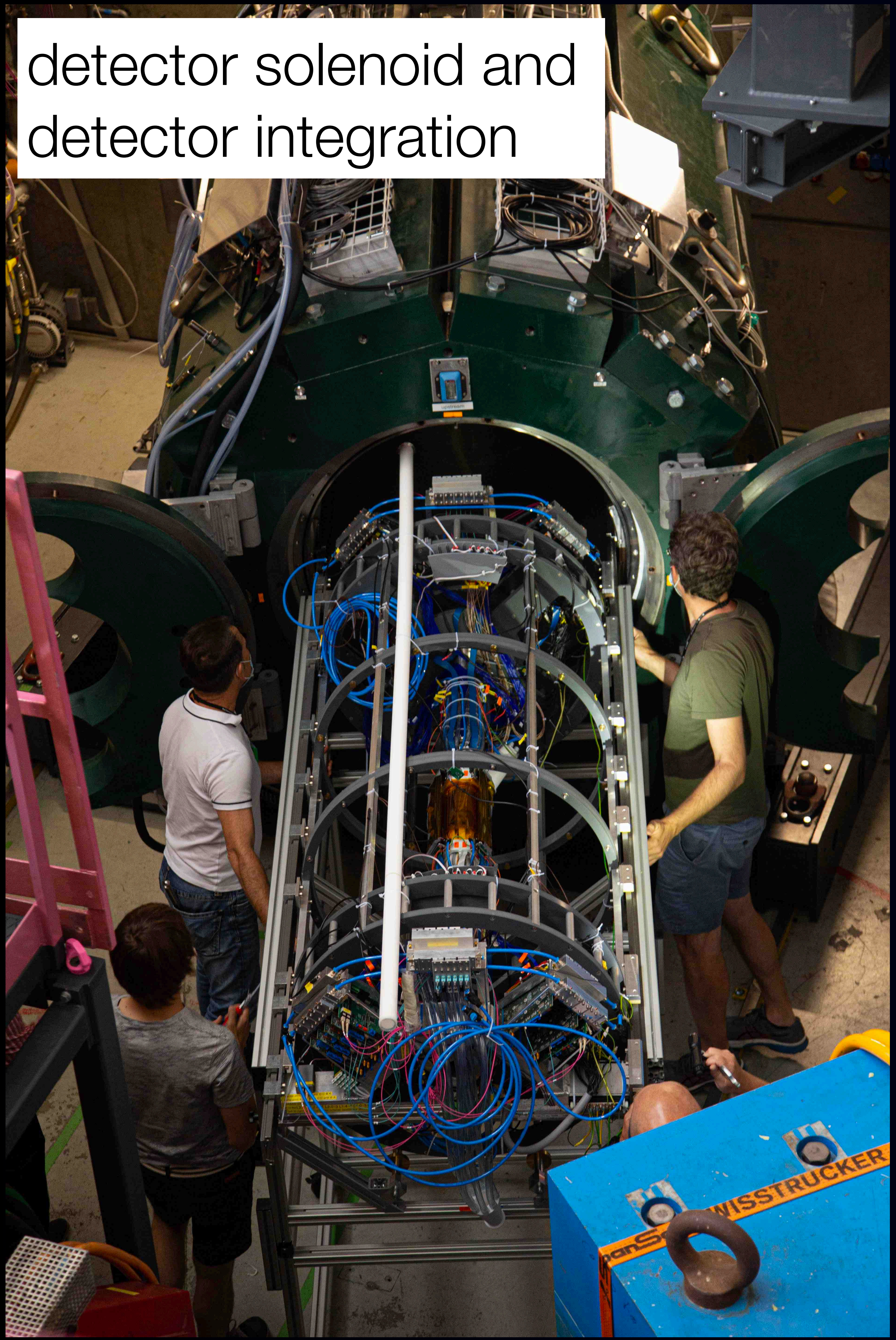
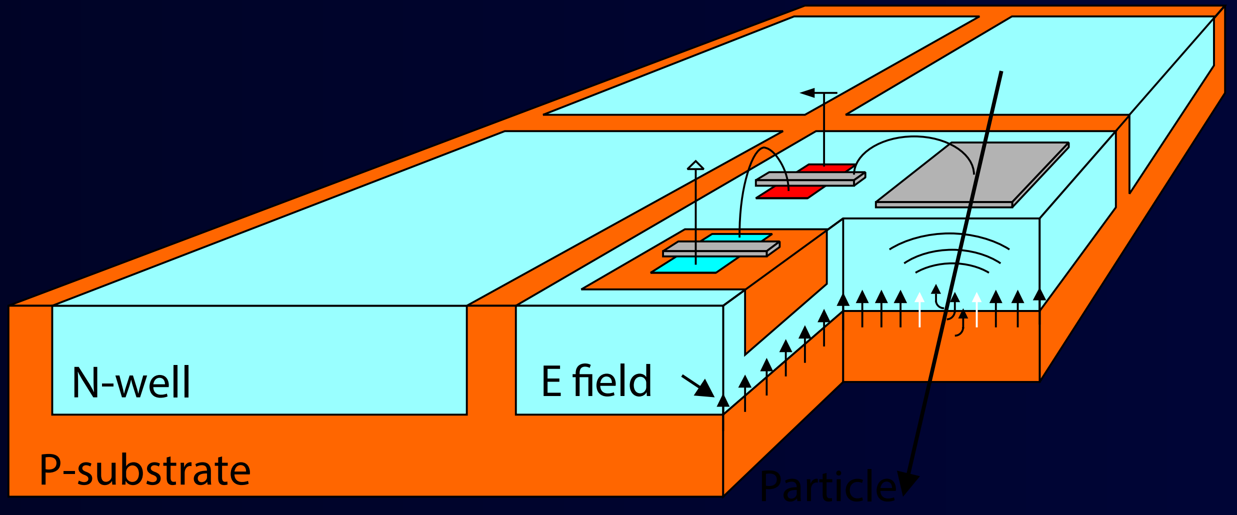
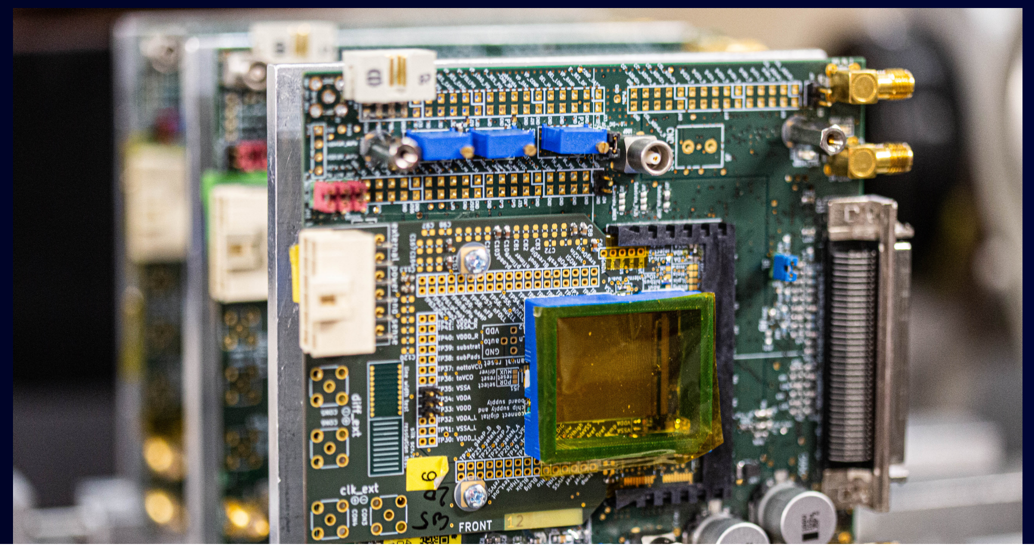


detector solenoid and detector integration

silicon pixel tracker





silicon pixel board (50 µm)

SciFi timing counter

scin. tile counter

Timeline

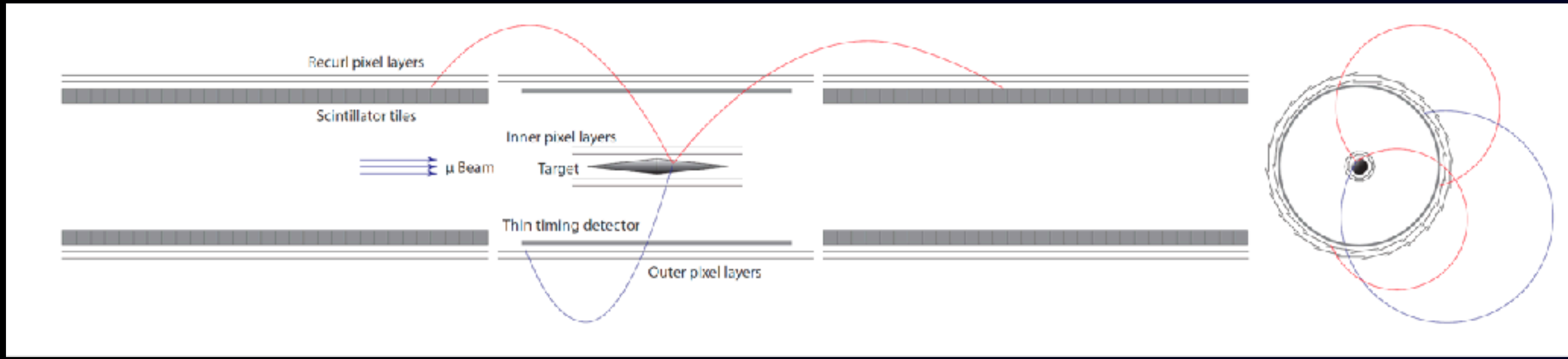
- First detector installation in 2023
- Detector commissioning in 2024/2025
- First data taking in 2025/2026

Mu3e Phase II

Mu3e Phase II

Mu3e Phase II

- Ultimate sensitivity goal of BR < 1×10^{-16}
- muon intensity 2×10^{9}/sec from HiMB
- Upgraded Mu3e detector
  - elongated pixel station for recurl tracks
  - muon target with smaller radius
  - thinner pixel detector
- scheduled after 2029



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- Surface muon (μ^{+}) beam, ~$O(10^{10})$ /s
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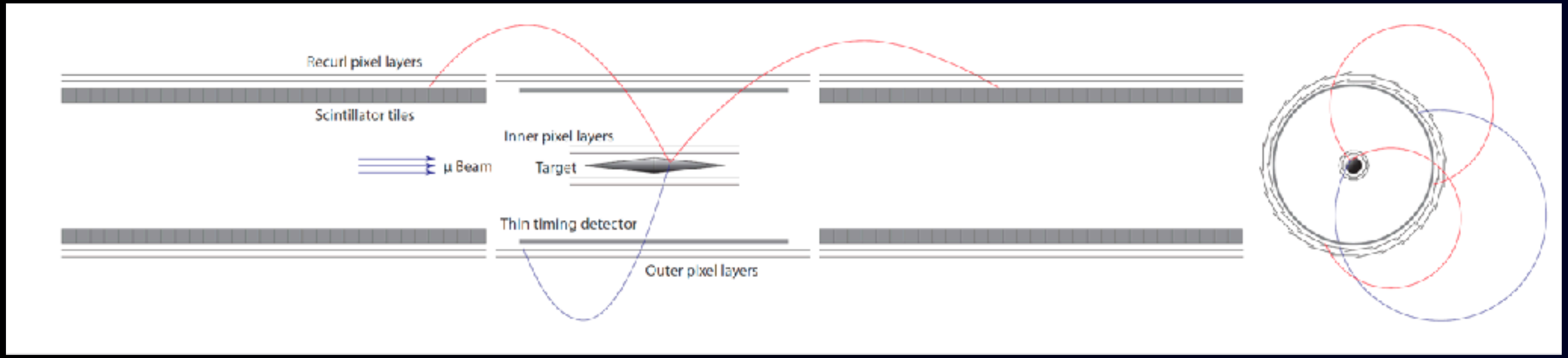

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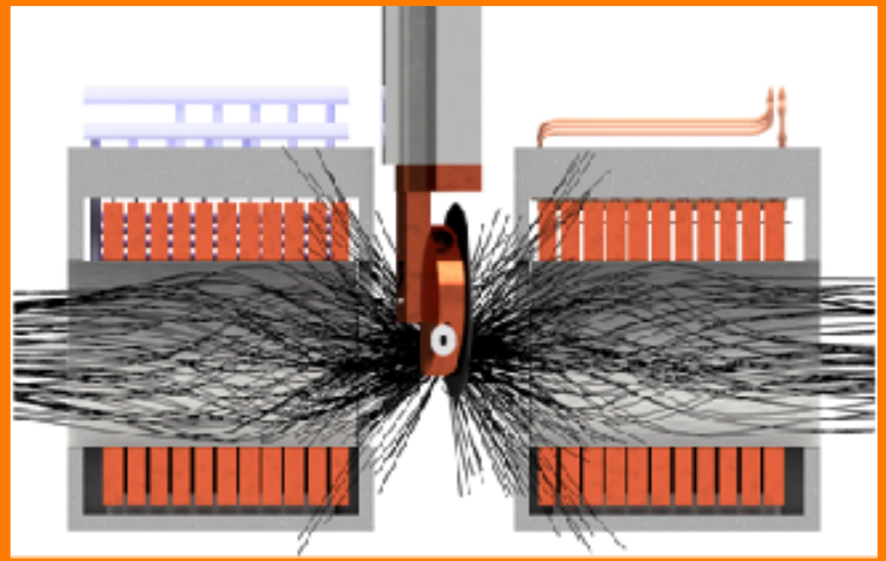

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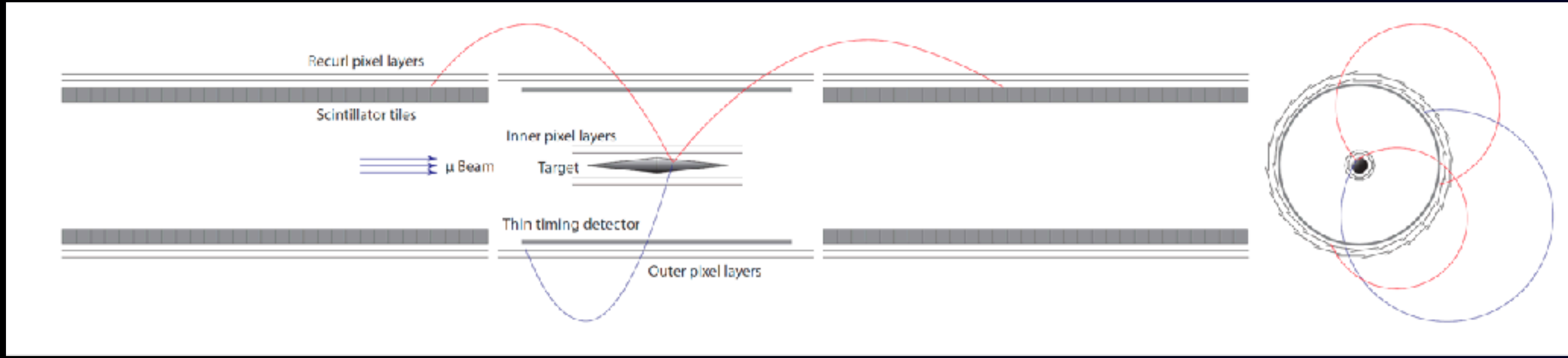

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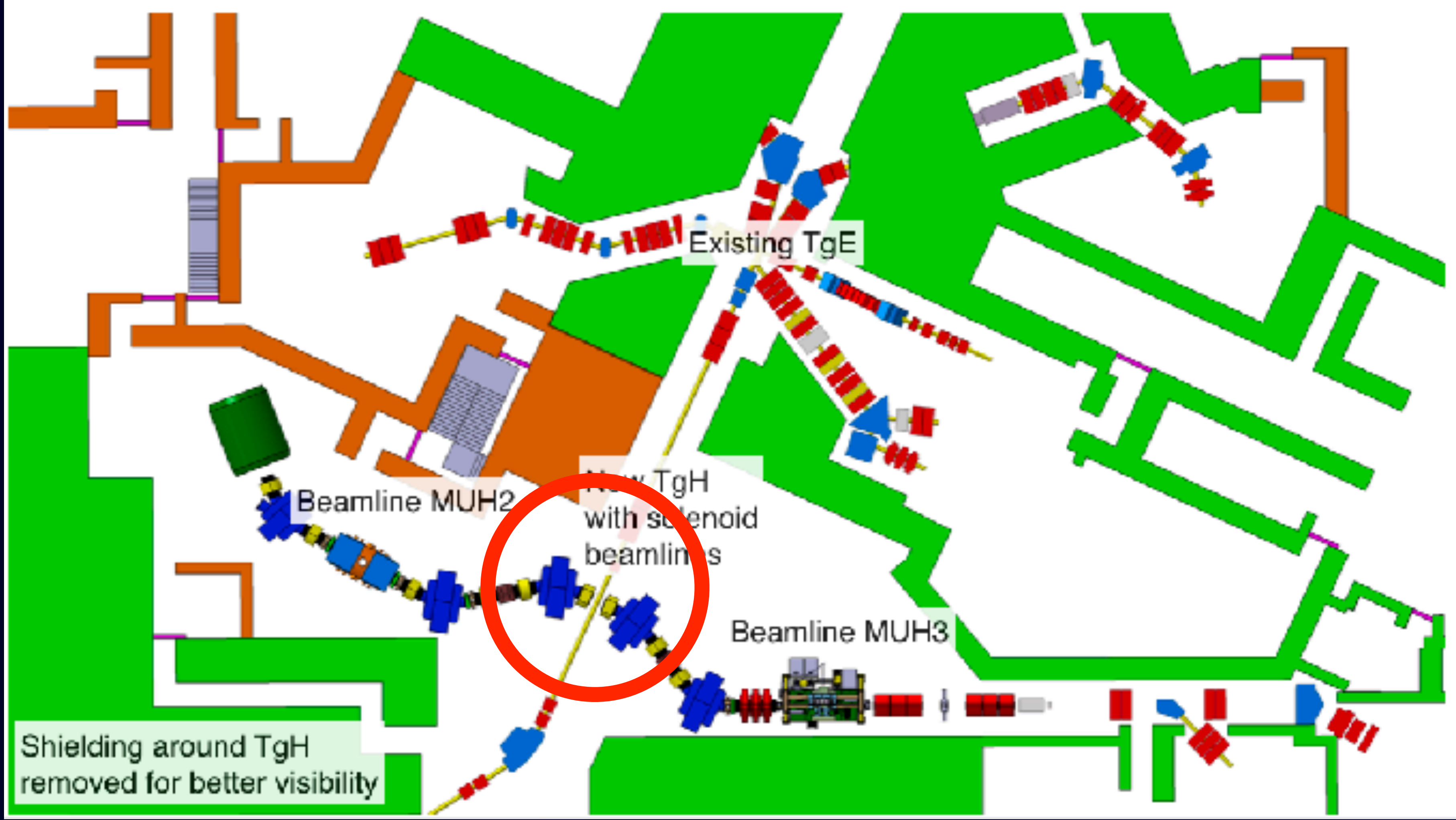
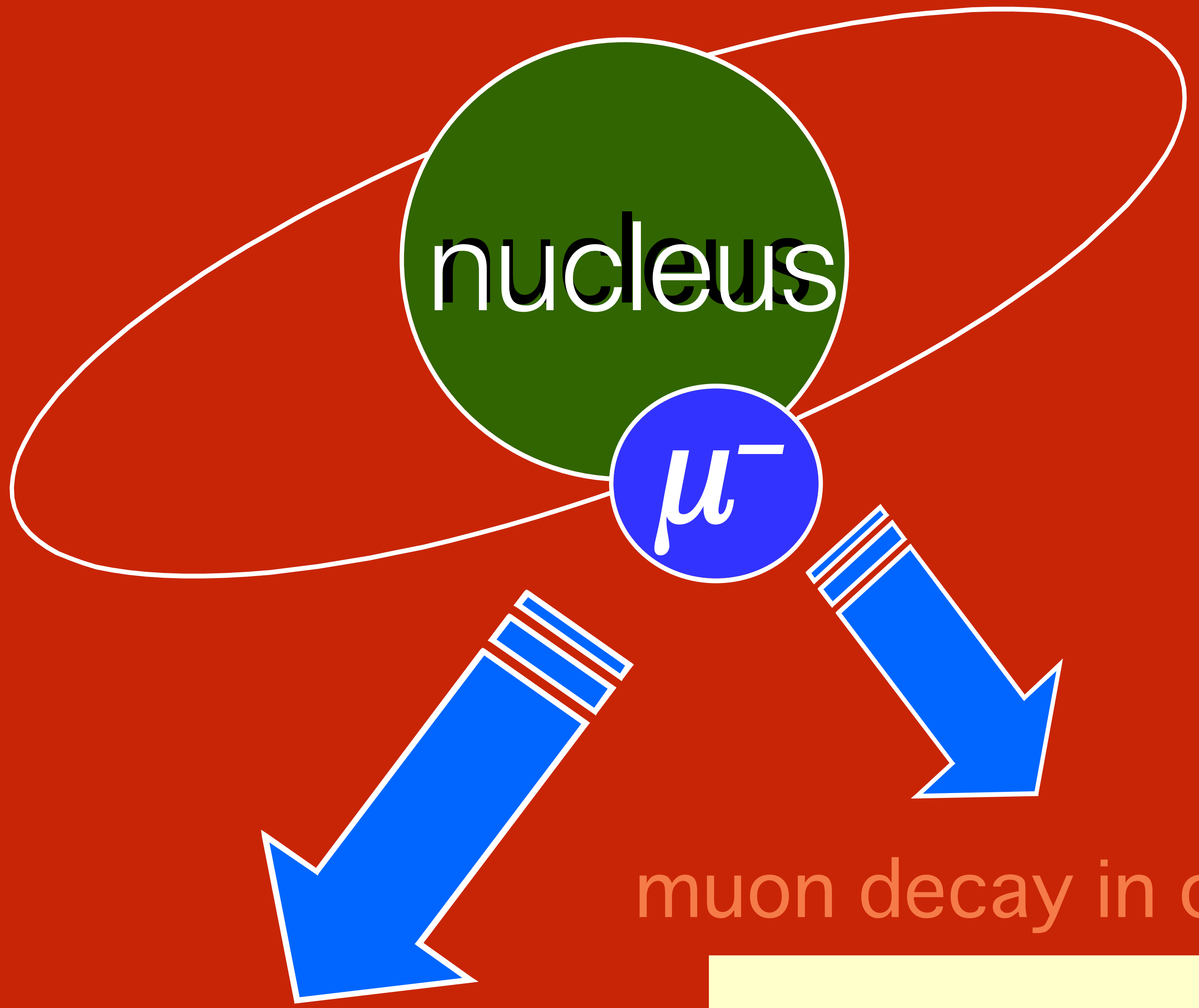



$\mu \rightarrow e$ conversion
in
a muonic atom

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

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

1s state in a muonic atom



muon decay in orbit

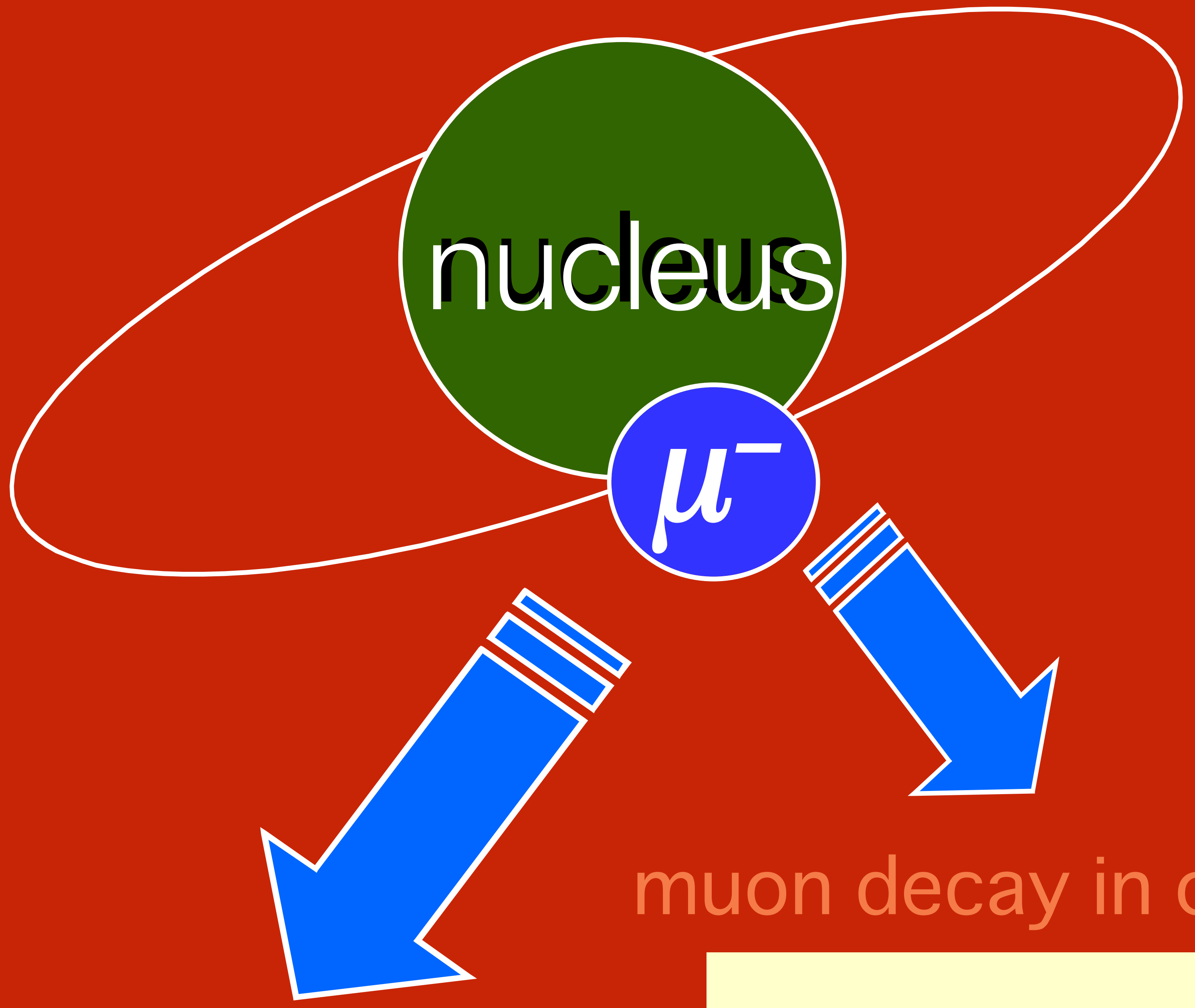
$$\mu^- \to e^- \nu \bar{\nu}$$

nuclear muon capture

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

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

1s state in a muonic atom



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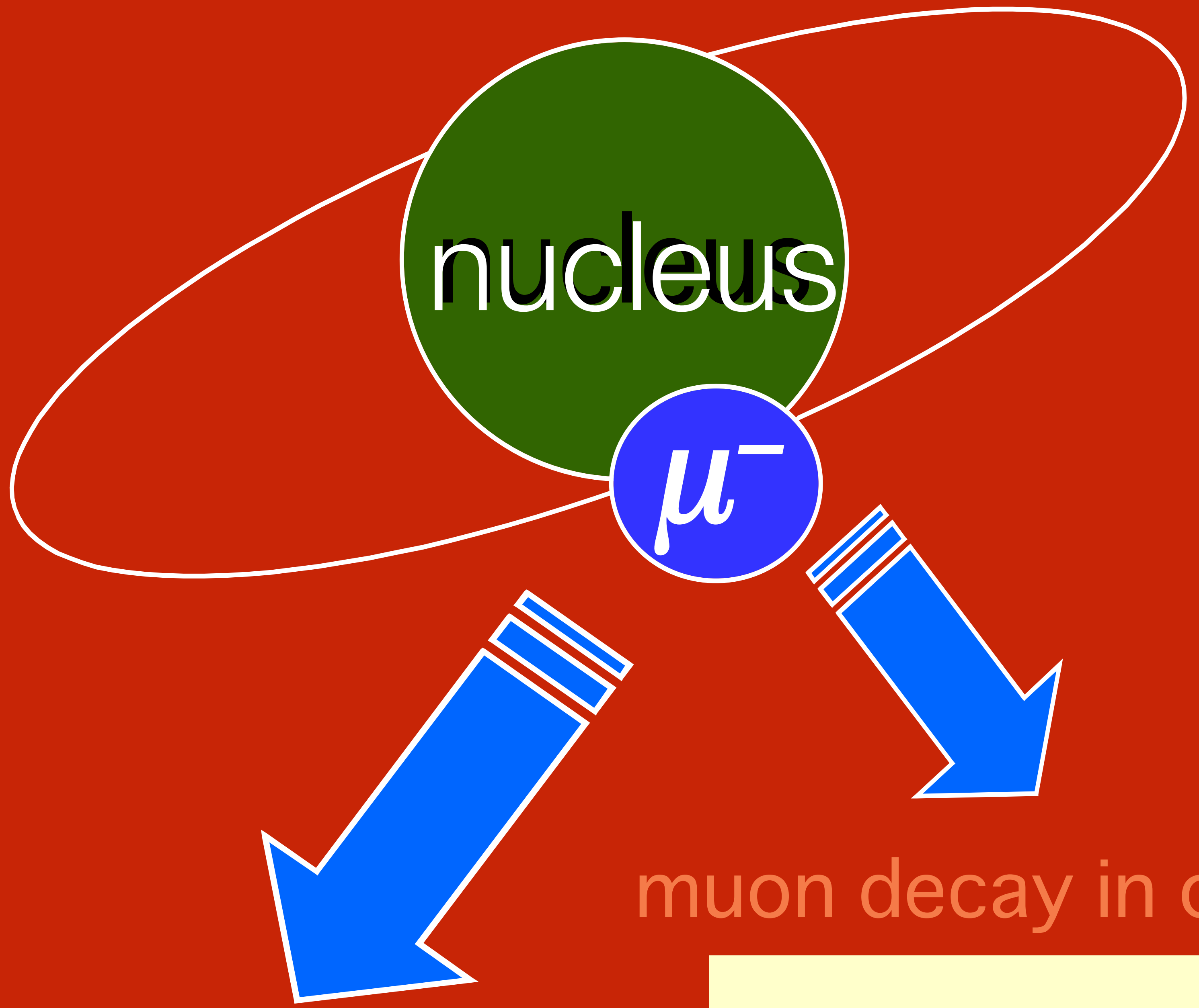

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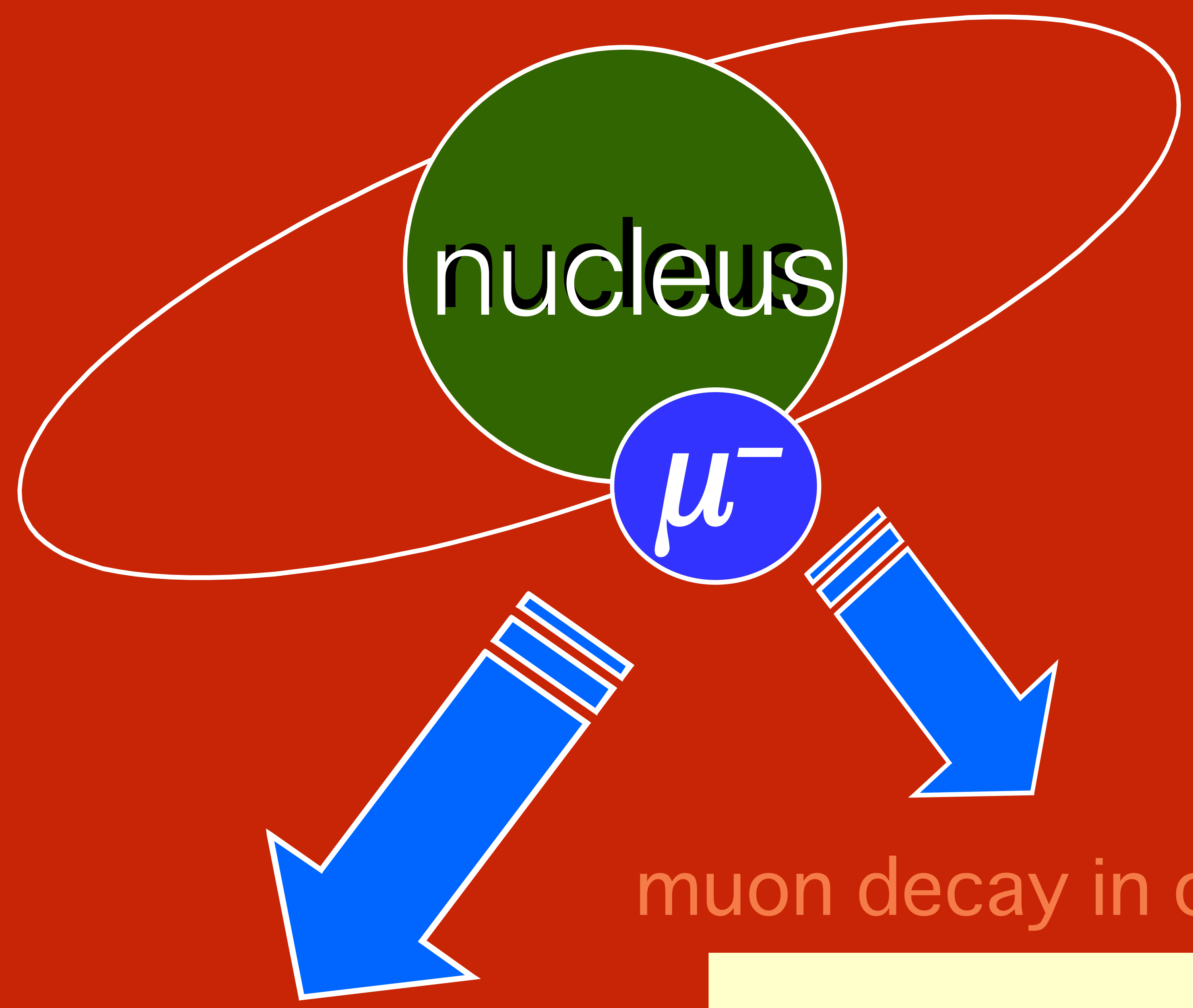
$$\mu^- + (A,Z) \to e^- + (A,Z)$$

coherent process (for transition to ground state) $\propto Z^5$

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

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

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

coherent process (for transition to ground state) $\propto Z^5$

Event Signature :

a mono-energetic electron

(one particle measurement allows higher muon rates.)

$$E_{\mu e} \approx m_\mu - E_{bound\ \mu} - E_{recoil} \approx 105 \text{ MeV}$$

Backgrounds:

(1) physics backgrounds

(2) beam-related backgrounds

(3) cosmic rays, false tracking

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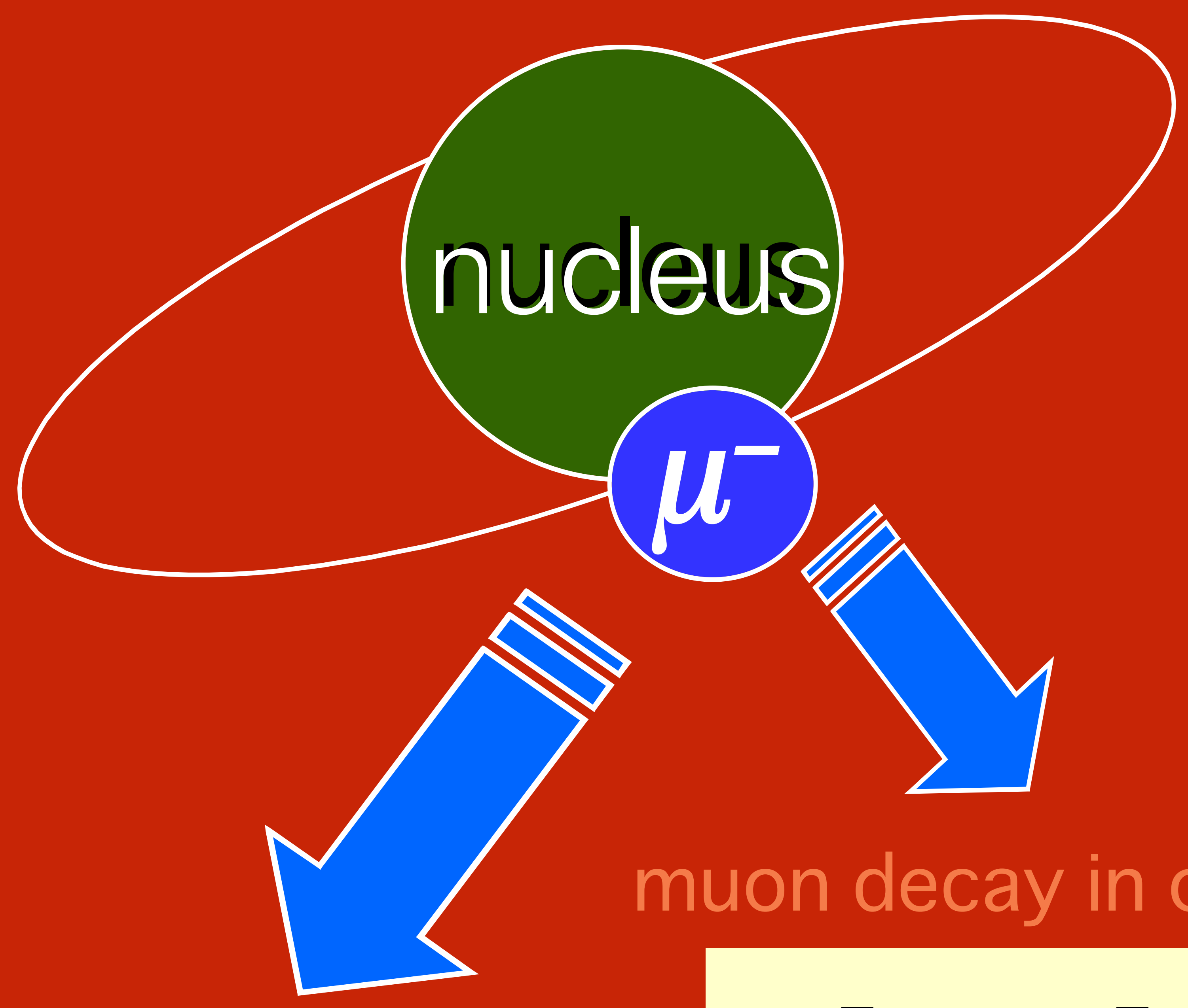

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Backgrounds:

(1) physics backgrounds

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Conversion rate:

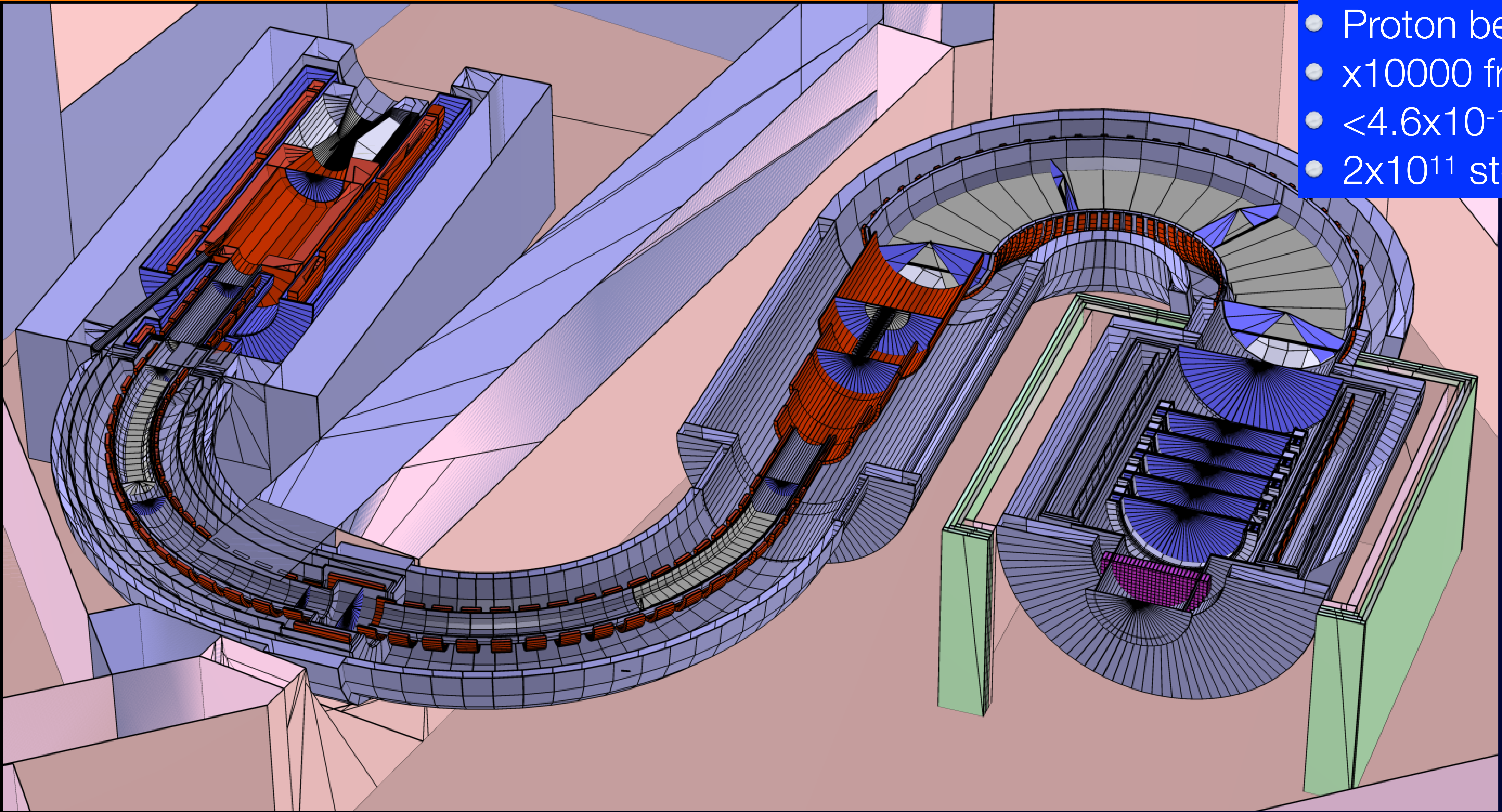
$$\text{CR}(\mu^- \text{N} \to e^- \text{N}) \equiv \frac{\Gamma(\mu^- \text{N} \to e^- \text{N})}{\Gamma(\mu^- \text{N} \to \text{all})}$$

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

COMET at J-PARC

COMET at J-PARC

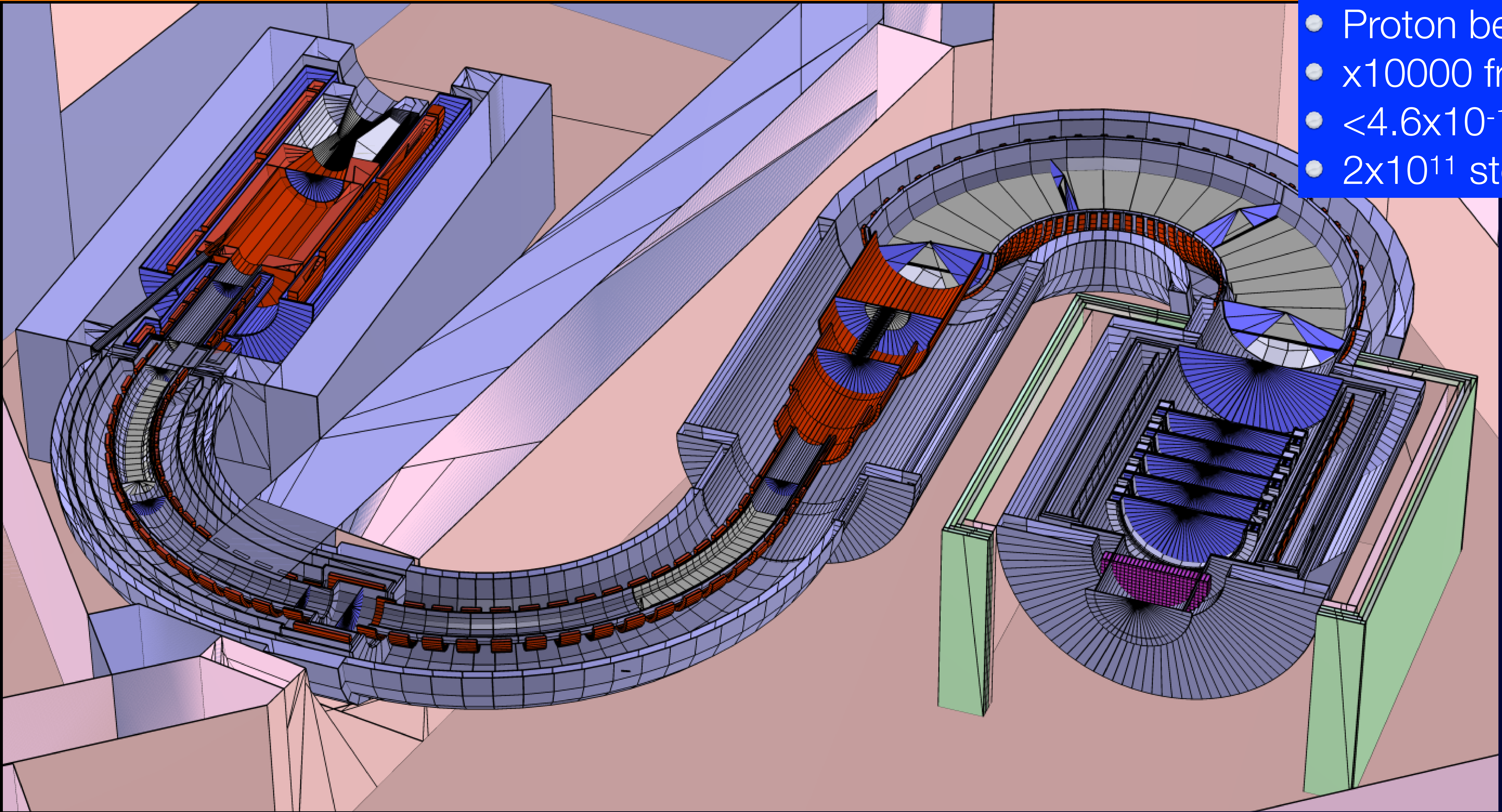
- COMET= COherent Muon to Electron Transition



- Proton beam, 8 GeV, 56 kW
- x10000 from SINDRUM-II
- $<4.6 \times 10^{-17}$ 90% C.L.
- 2×10^{11} stopped muons/s

- COMET= COherent Muon to Electron Transition

COMET at J-PARC



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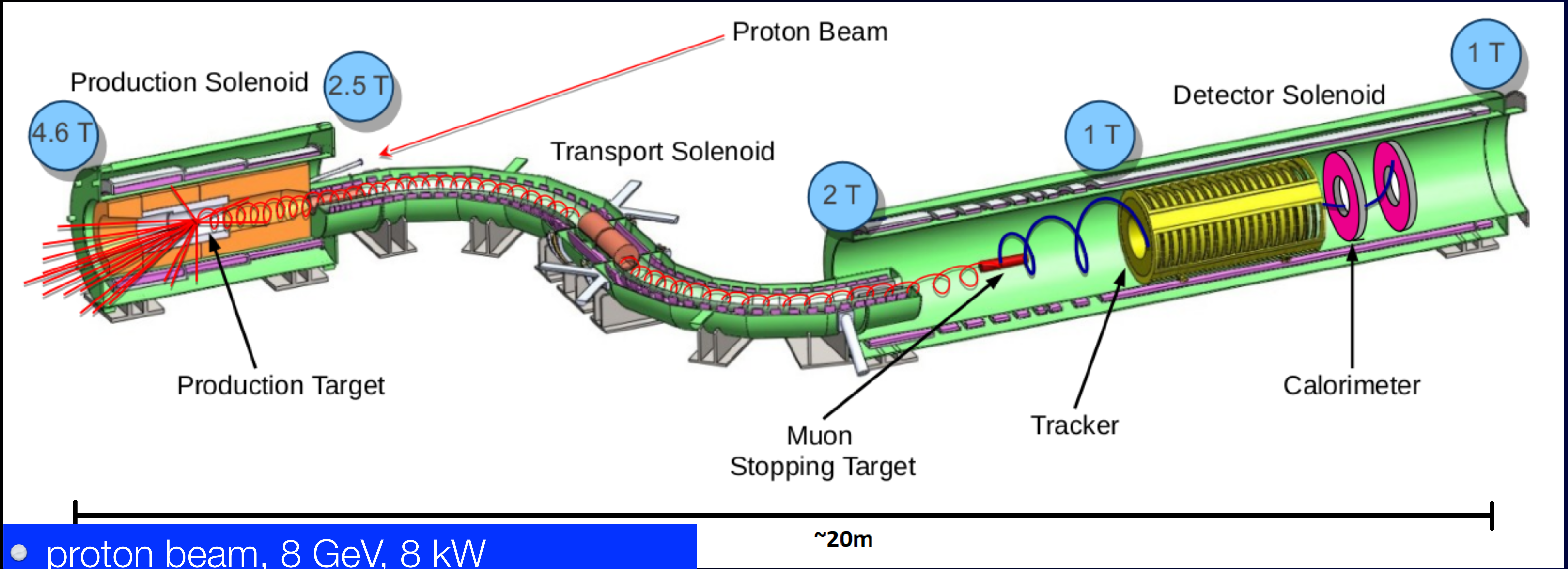
See the talk by Chen Wu

Mu2e at Fermilab

proton beam power = 8 kW

Mu2e at Fermilab



- proton beam, 8 GeV, 8 kW
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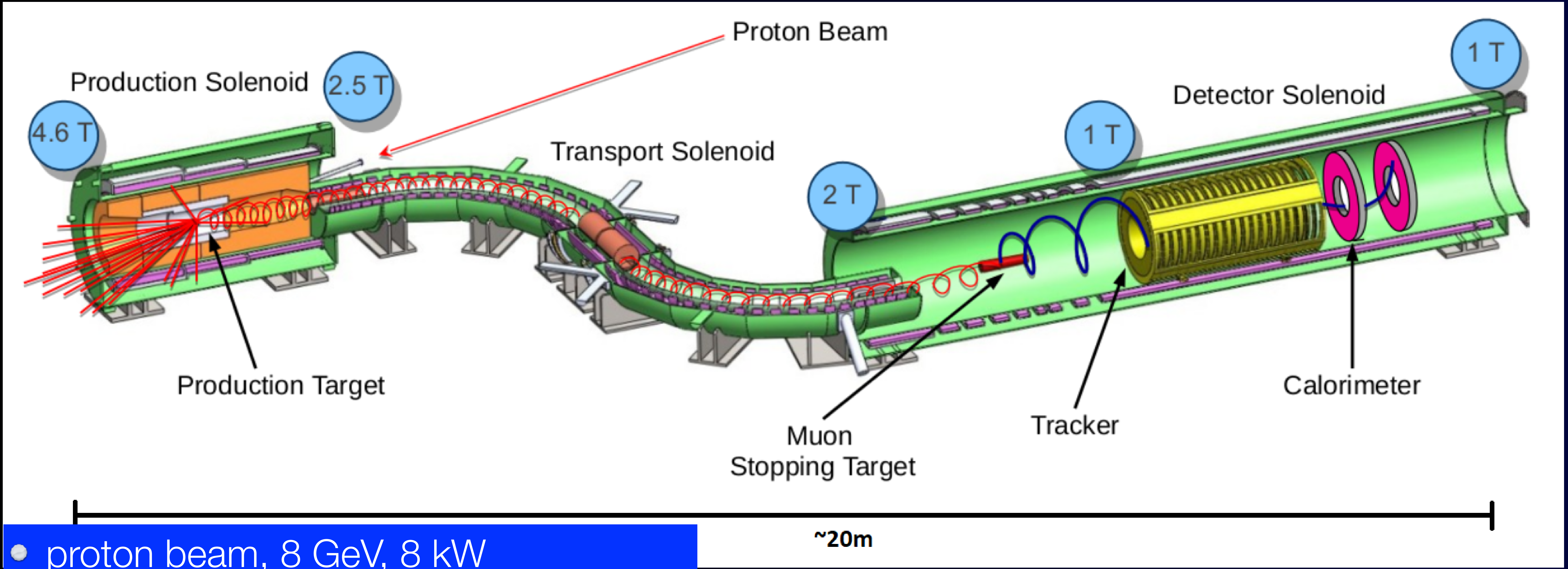
- 0.11 ± 0.03 background events (Run 1)

Mu2e at Fermilab



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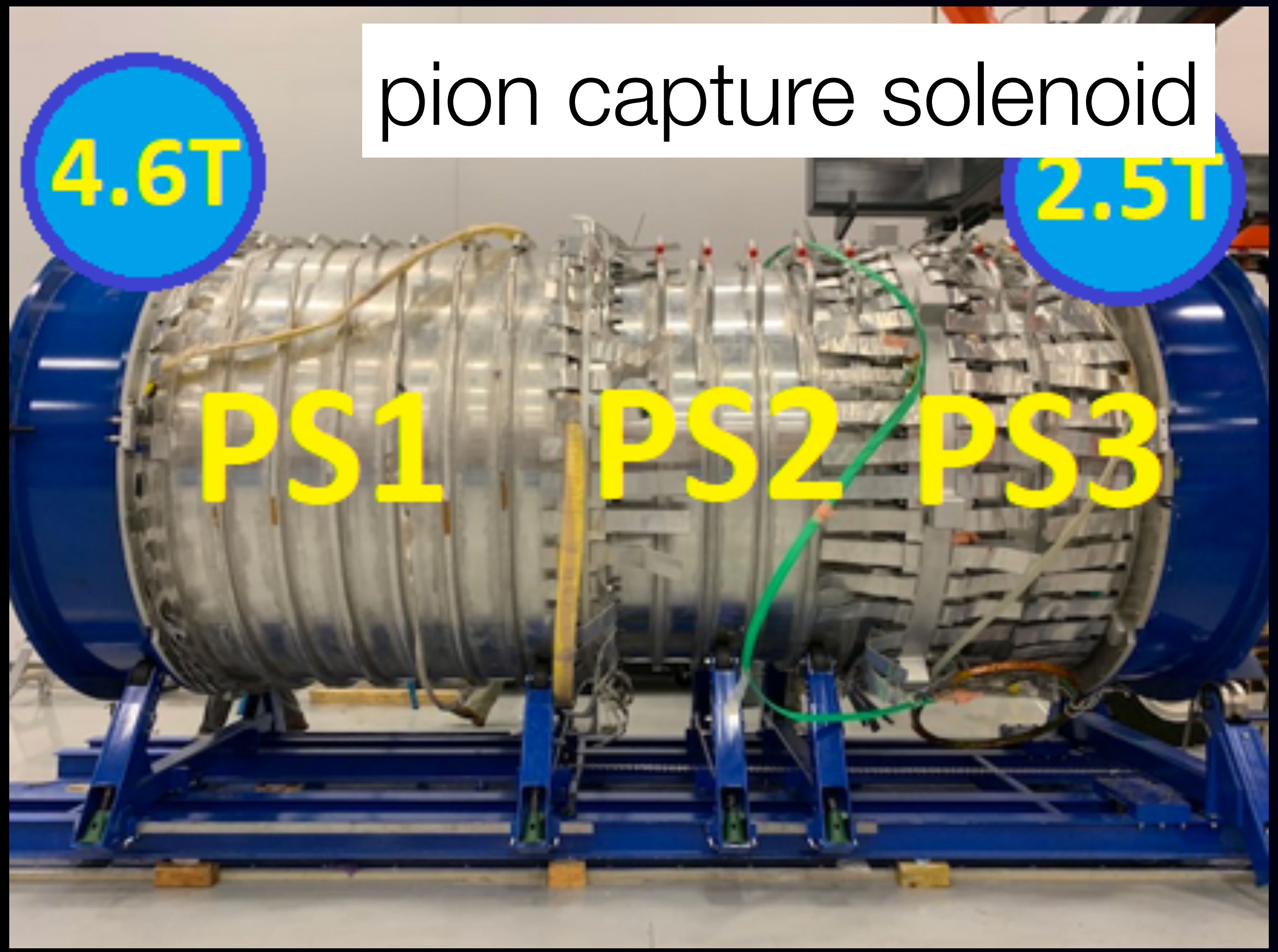
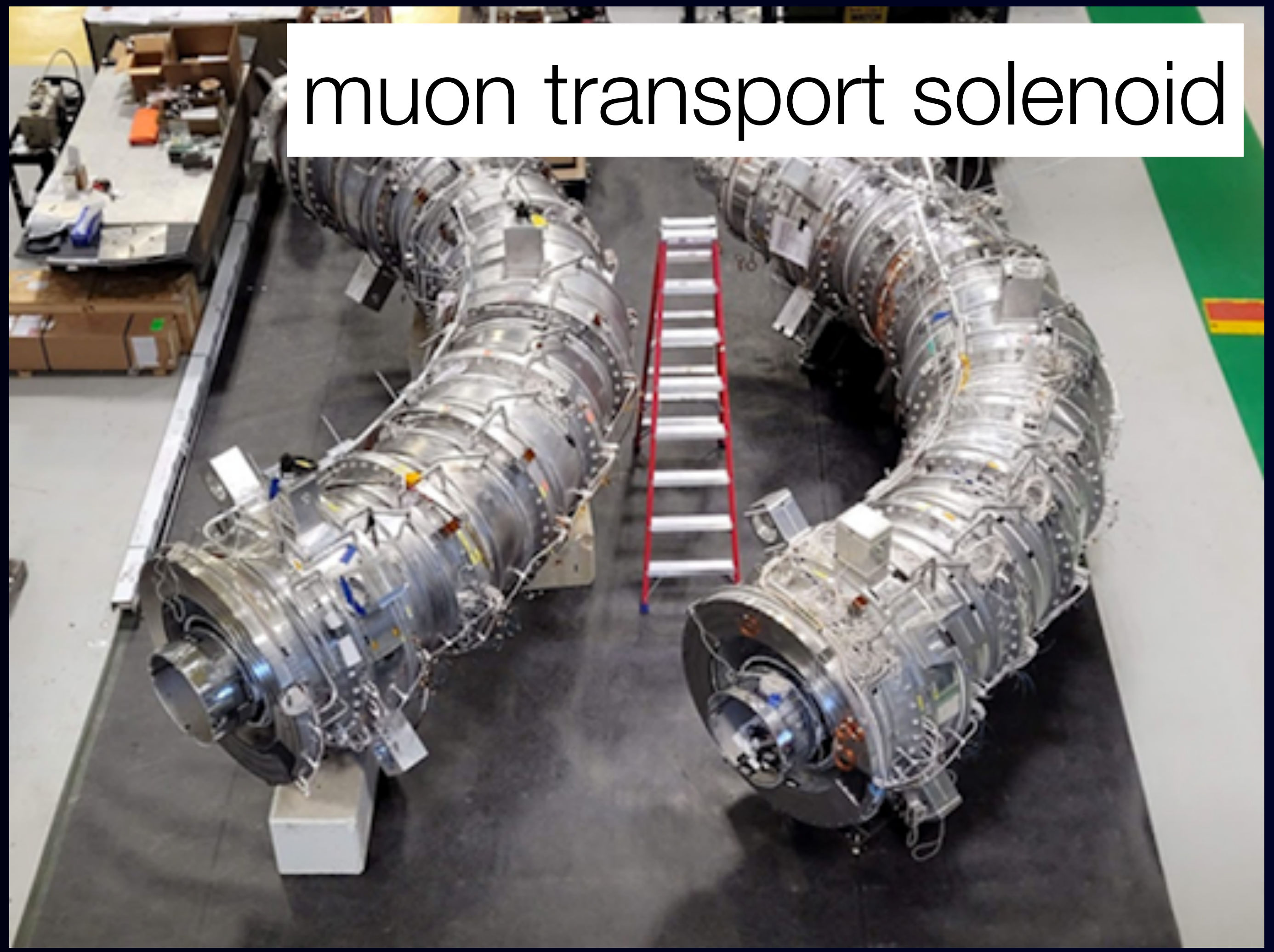
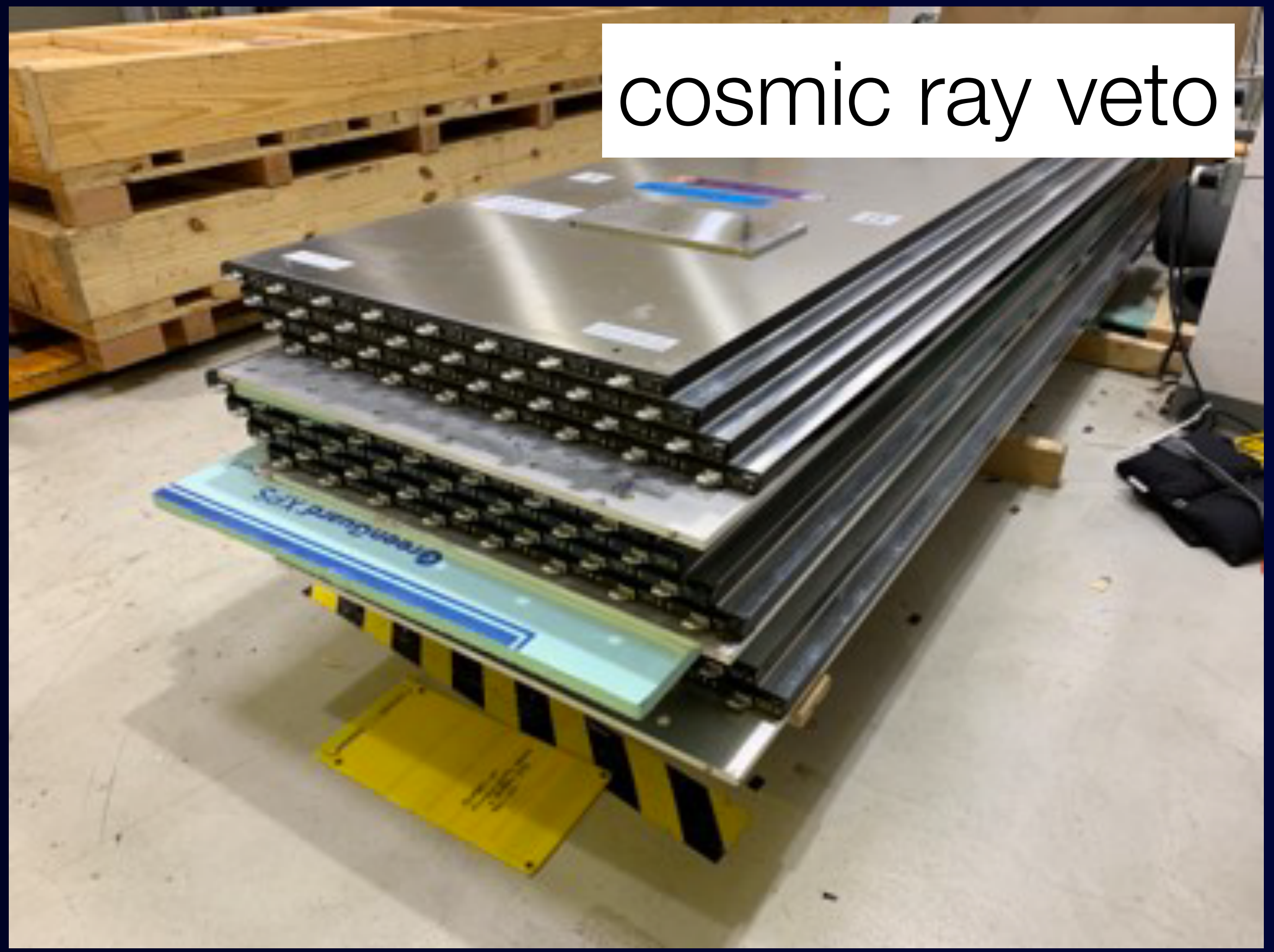
	muon transport	electron transport
Mu2e	s-shape curve	straight
COMET	c-shape curve	c-shape curve

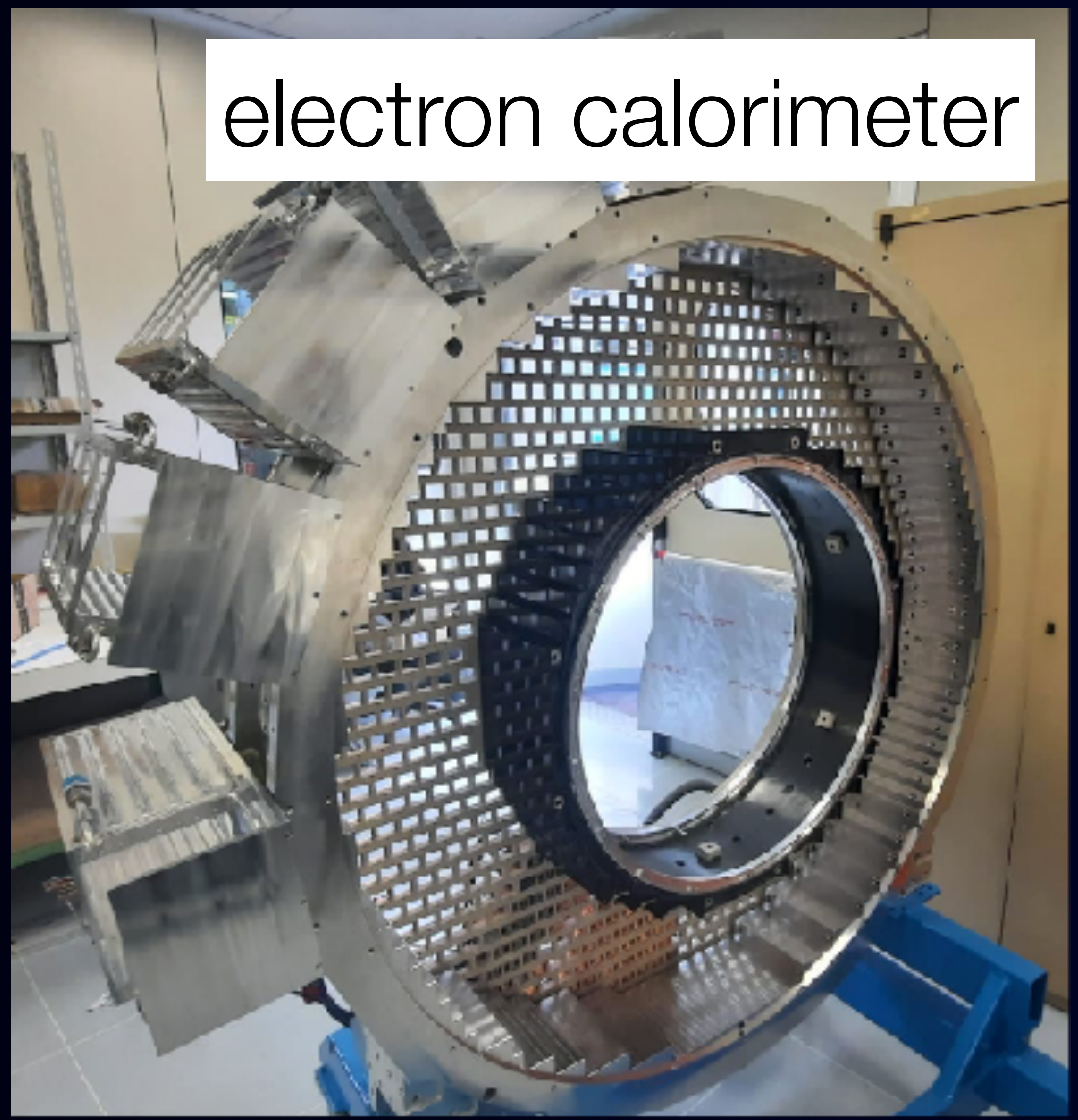
Mu2e at Fermilab

Mu2e at Fermilab









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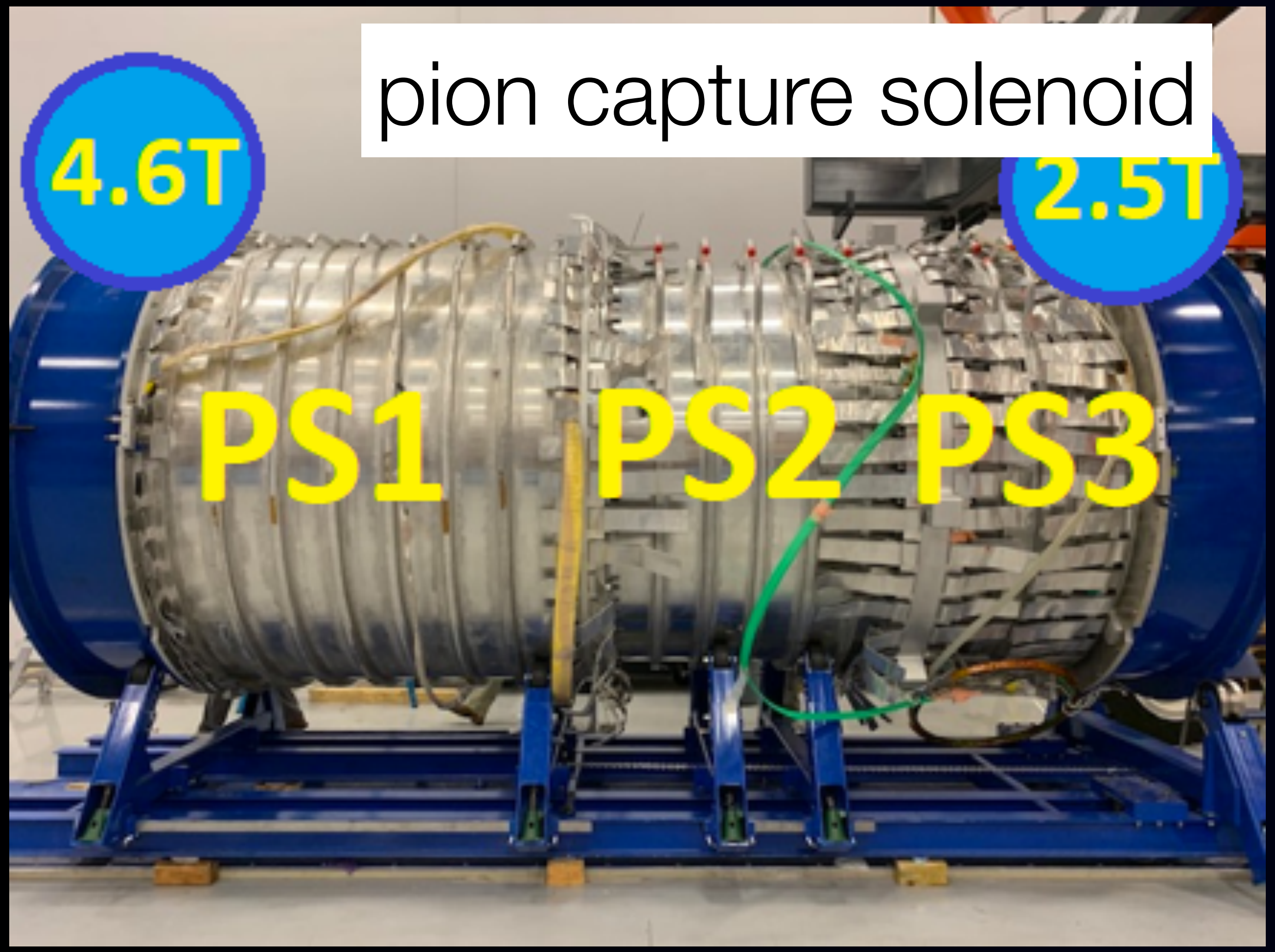
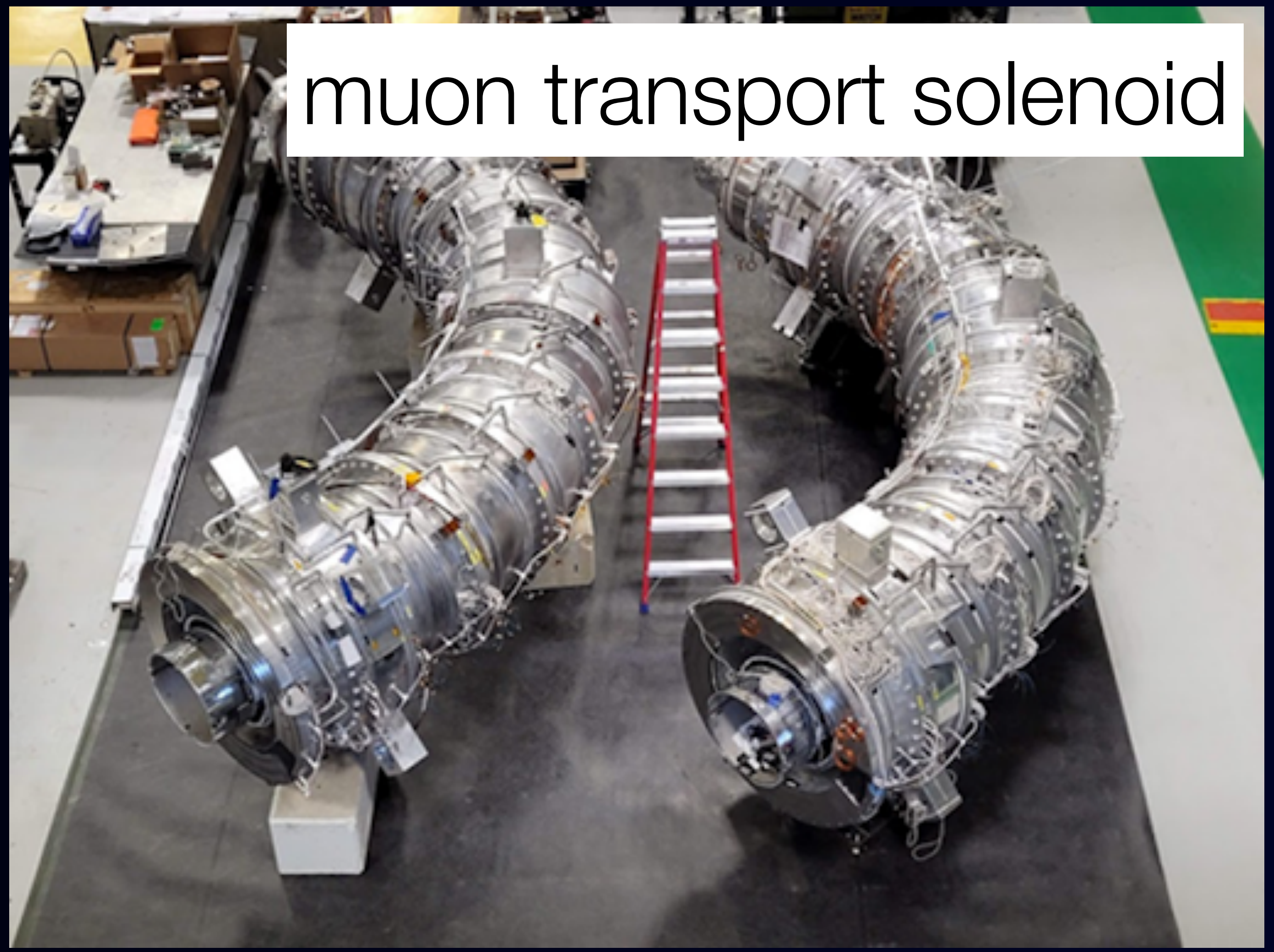
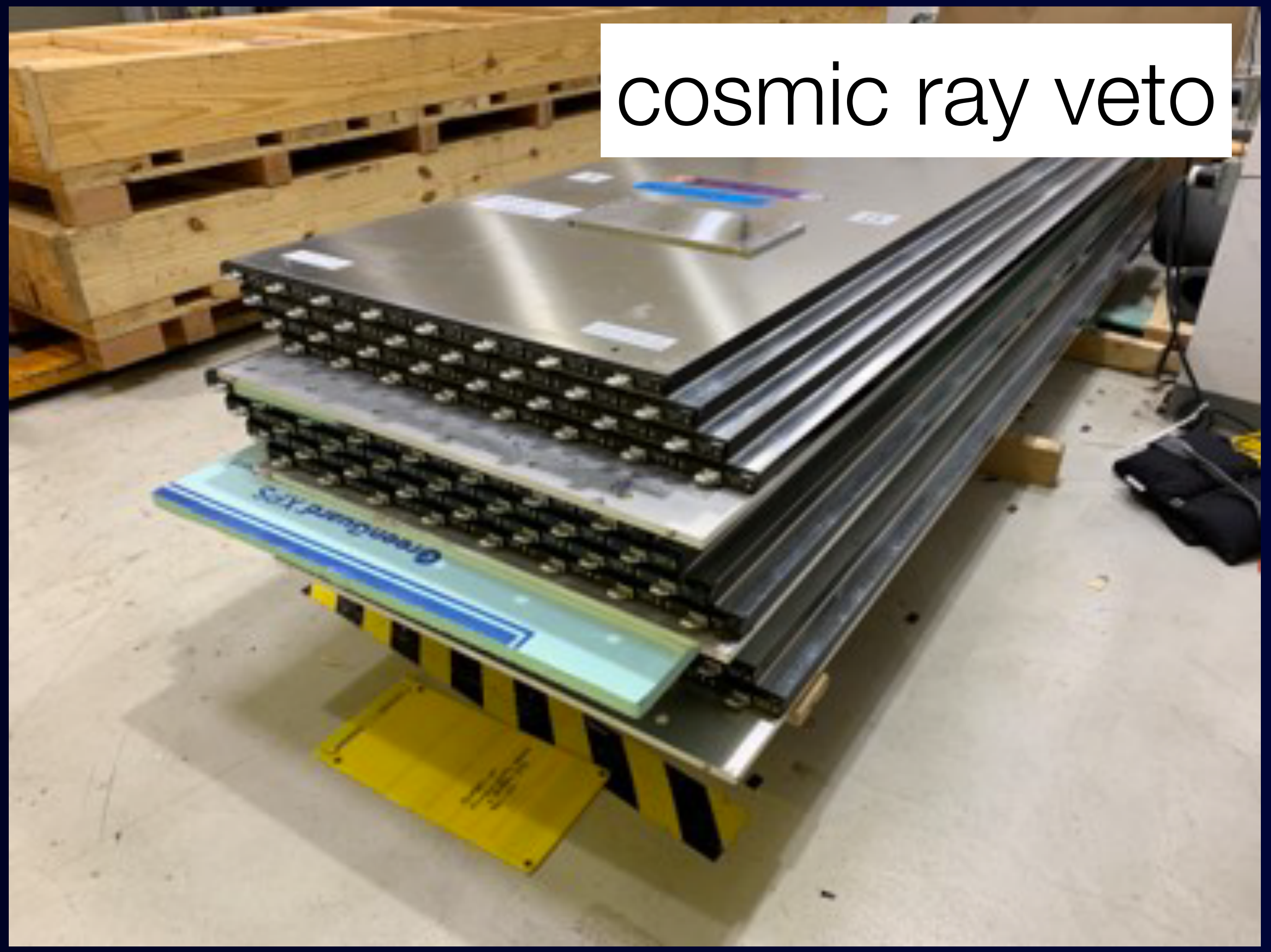
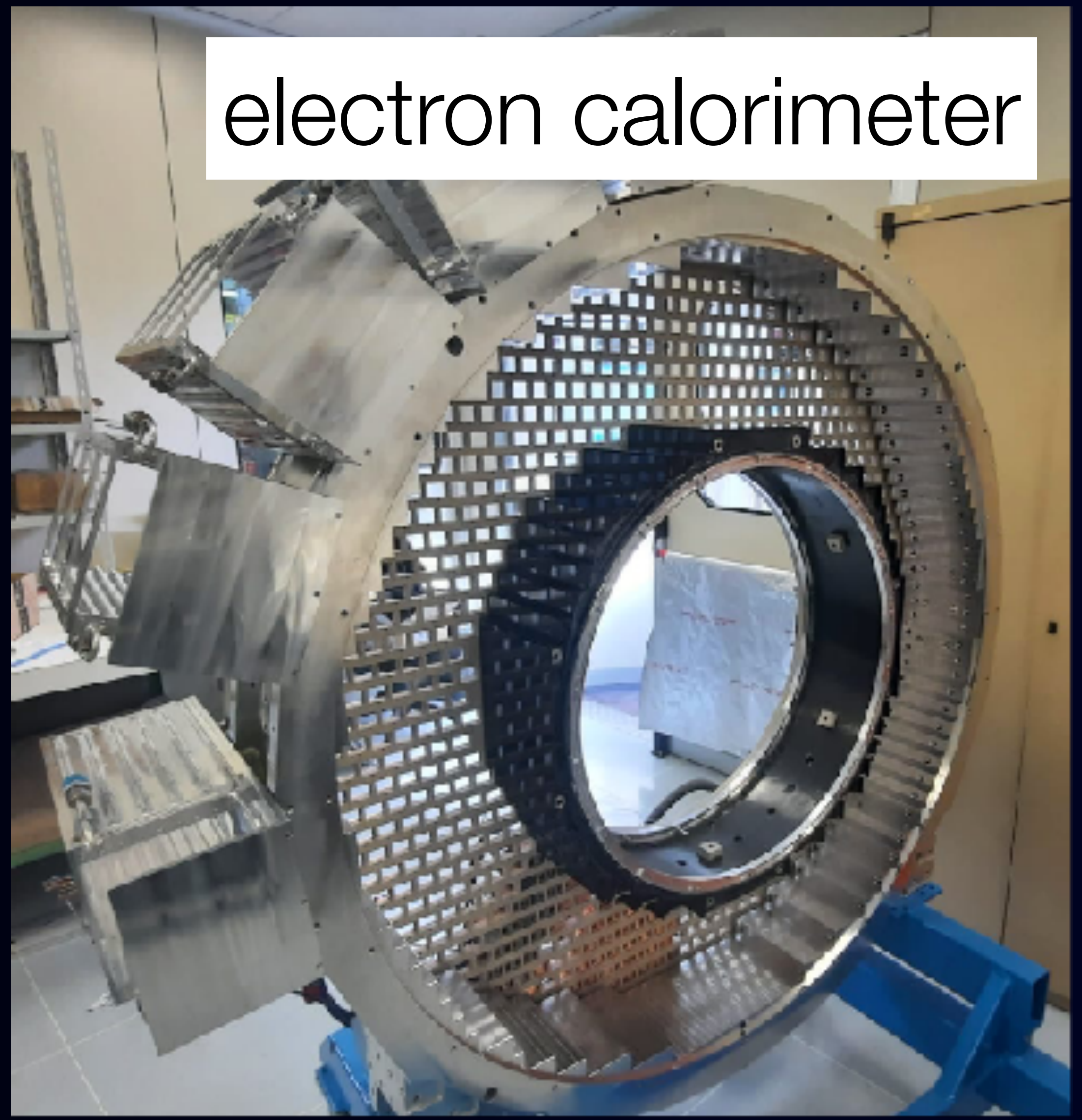








Timeline

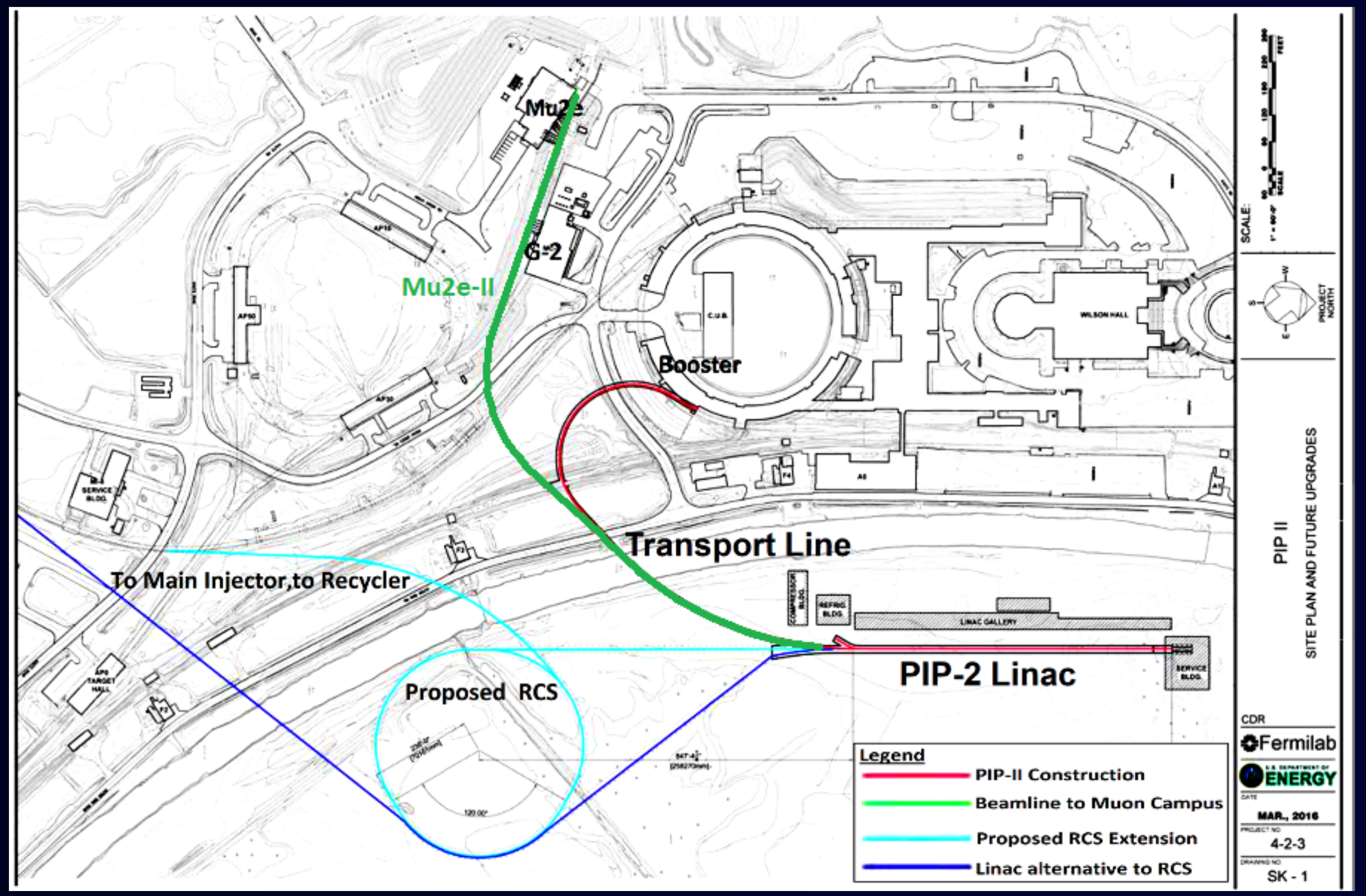
- Detector commissioning from 2024
- Run 1 data taking in 2026 until LBNF/PIP-II shutdown (x1000 improvements)
- Run 2 data taking from 2029 after the shutdown

Mu2e-II and AMF at Fermilab

Mu2e-II and AMF at Fermilab

Mu2e-II

- 800 MeV, 100 kW from PIP-II Linac
- 5 years running (5.5×10^{19} stopped μs)
- Goal: $<6.4 \times 10^{-18}$ at 90% CL limit
    - x10 from Mu2e
    - 0.47 background events
- Detector refinements for Mu2e-II
    - proton target, tracker, calorimeter (BaF_2), cosmic ray veto
- Timeline ~ 2030s decade



PIP-II Project

Mu2e-II and AMF at Fermilab

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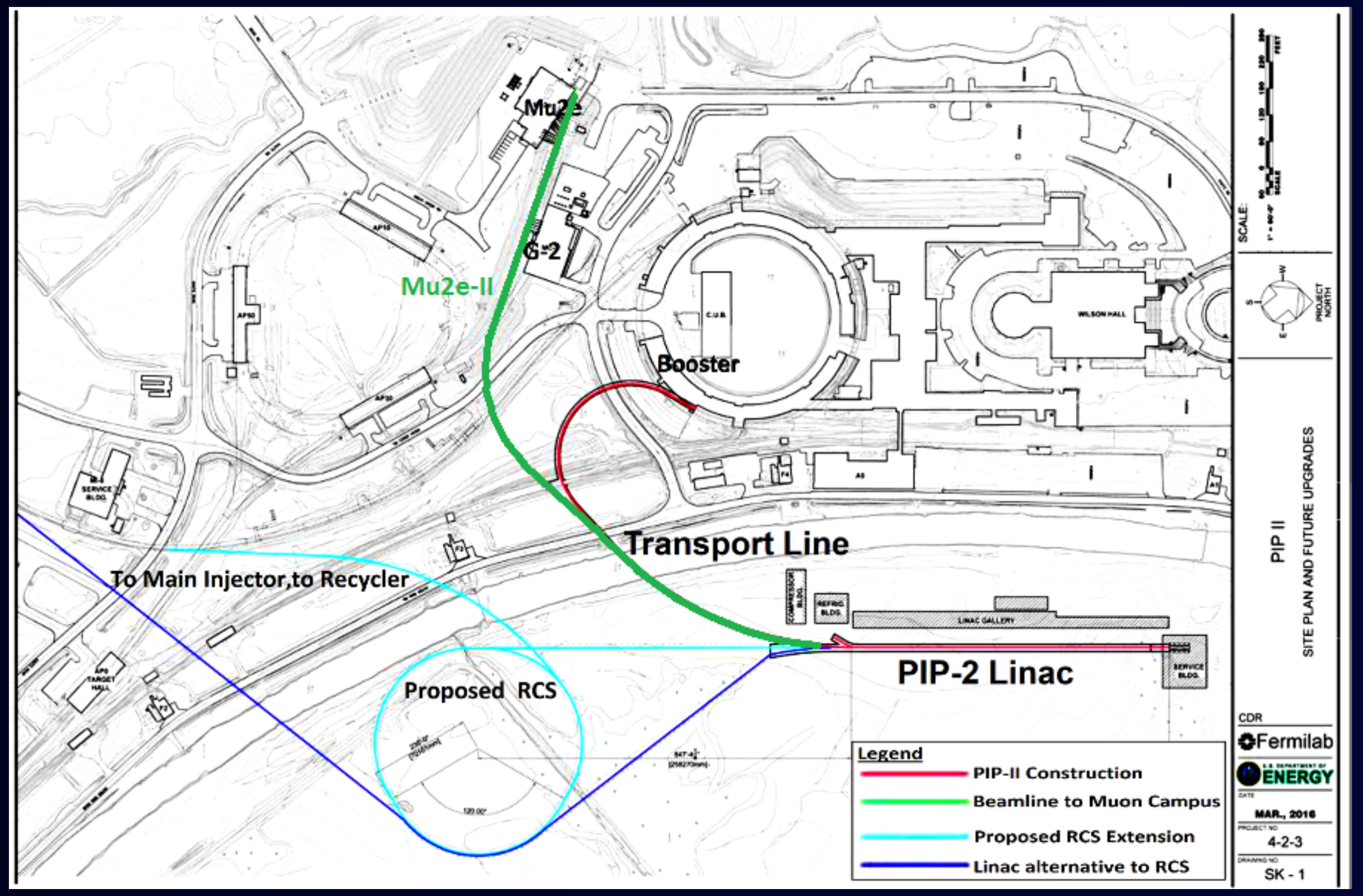
AMF (Advanced Muon Facility)

- >1 MW beam from PIP-II Linac
- aiming at searches for three muon CFLV processes
- muon storage ring (FFA) for $\mu \to e$ conversion (Enigma@AMF)
- ~2040

PIP-II Project



$\mu^- \to e^-$ Conversion at <O(10^{-19}) with Muon Storage Ring

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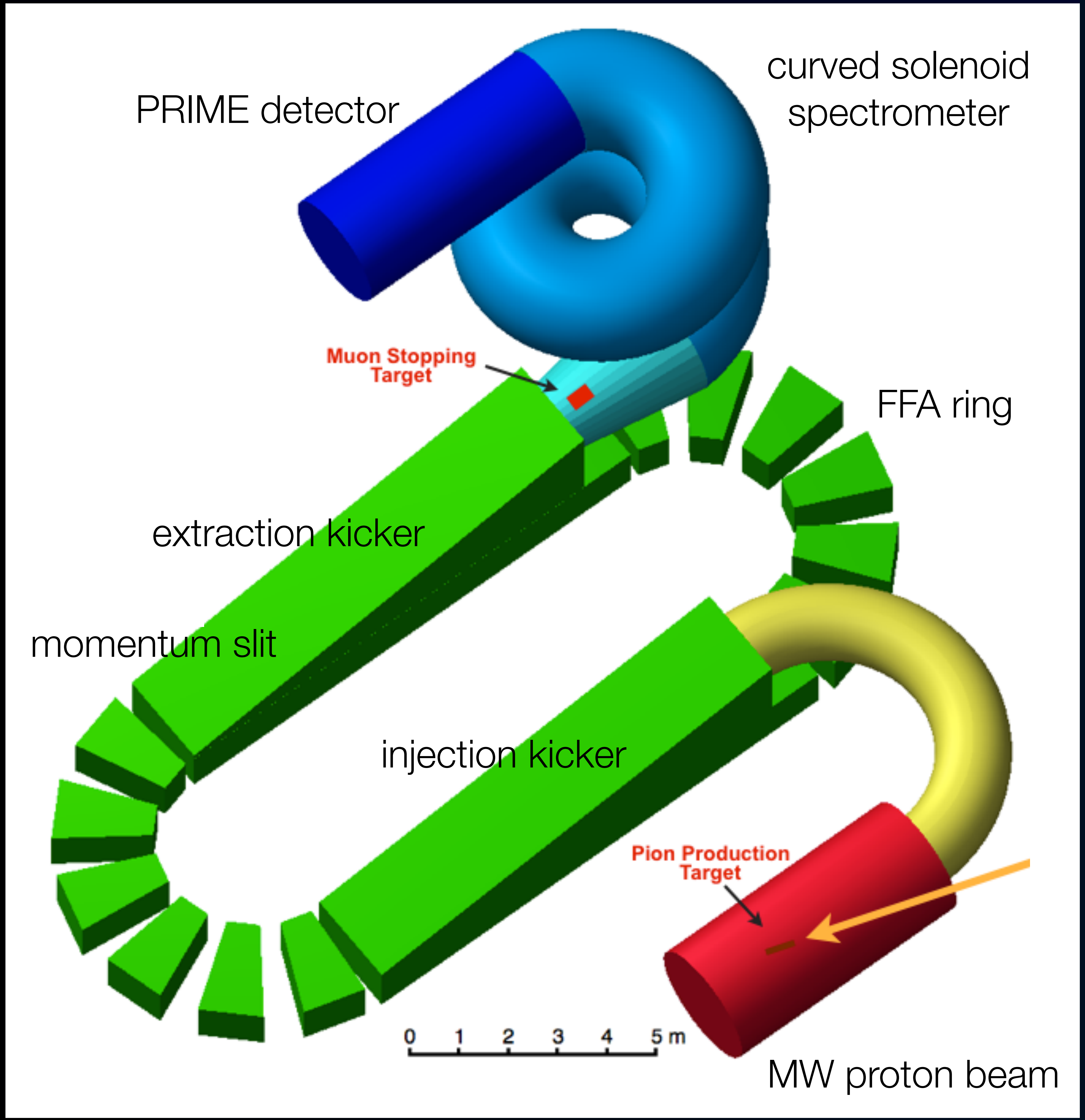
PRISM



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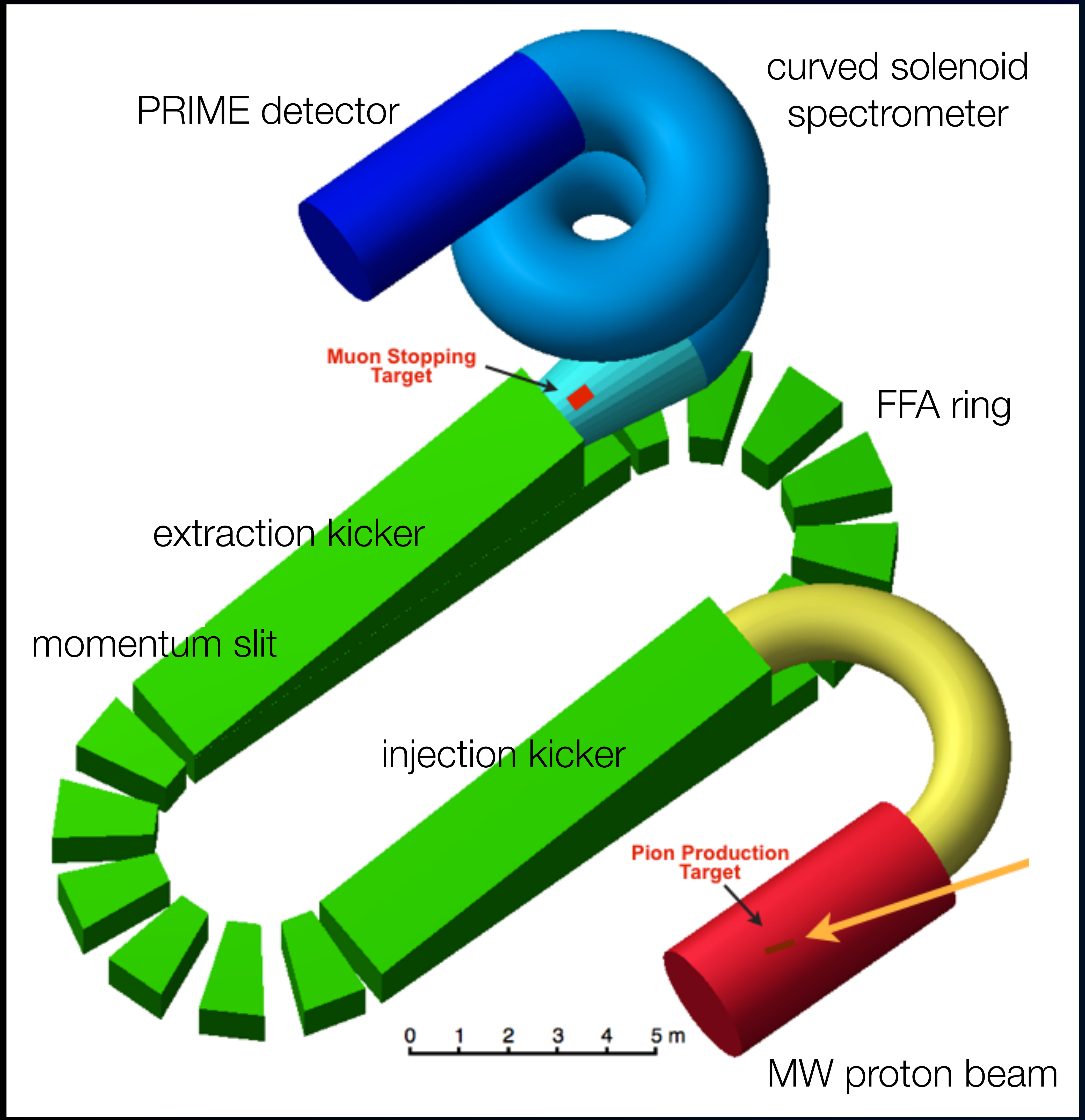

- Advantage of muon storage ring for $\mu \rightarrow e$ conversion
  - Removal of pions in a muon beam
    - long flight length in a ring to eliminate pions (pion reduction of 10^{-20} for 5 turns, 30 m circumference)
    - High-Z muon targets can be used
  - Phase rotation to narrow beam energy spread
    - accelerate slow muons and decelerate fast muons
    - thinner muon target for better signal acceptance

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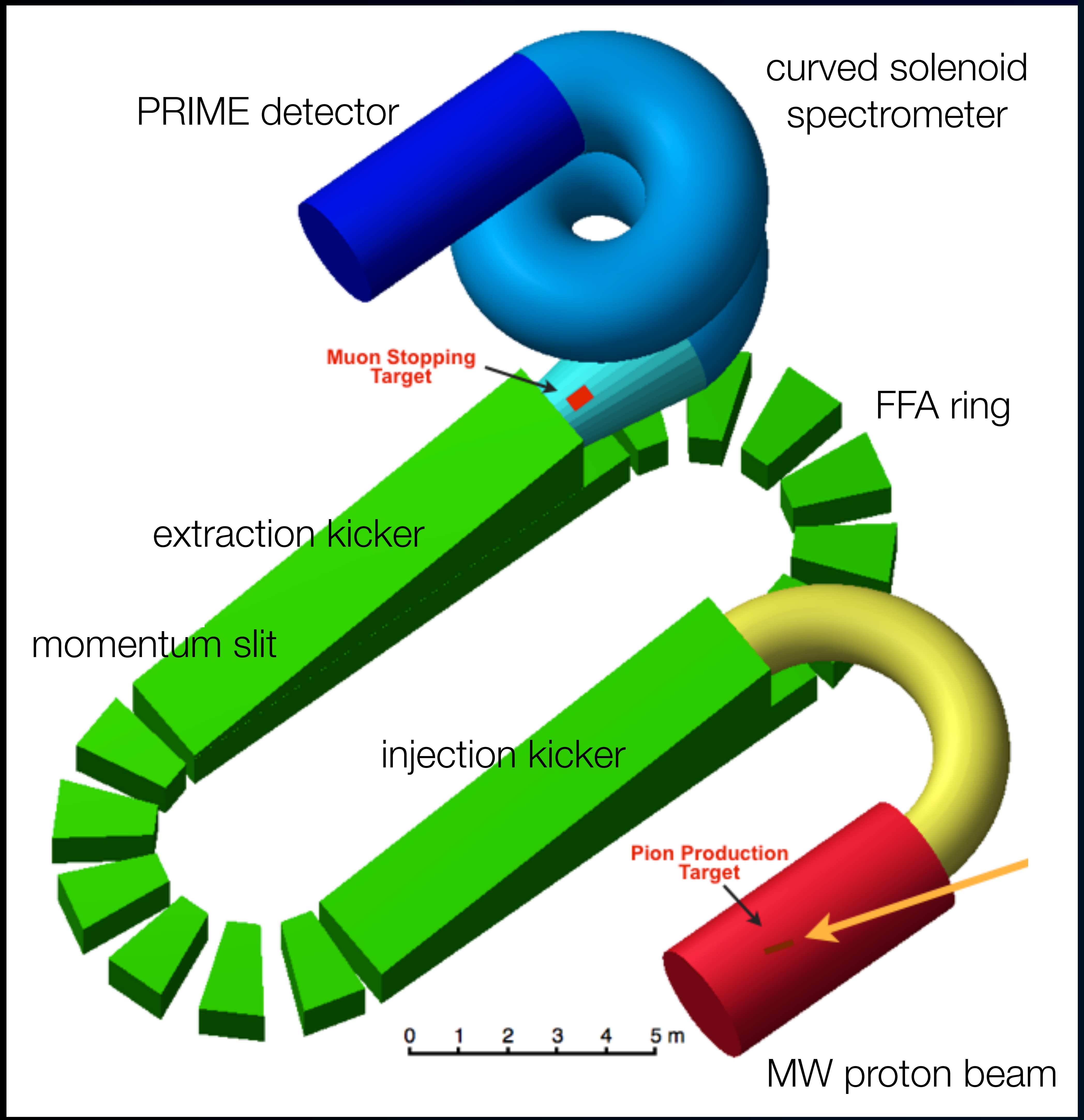

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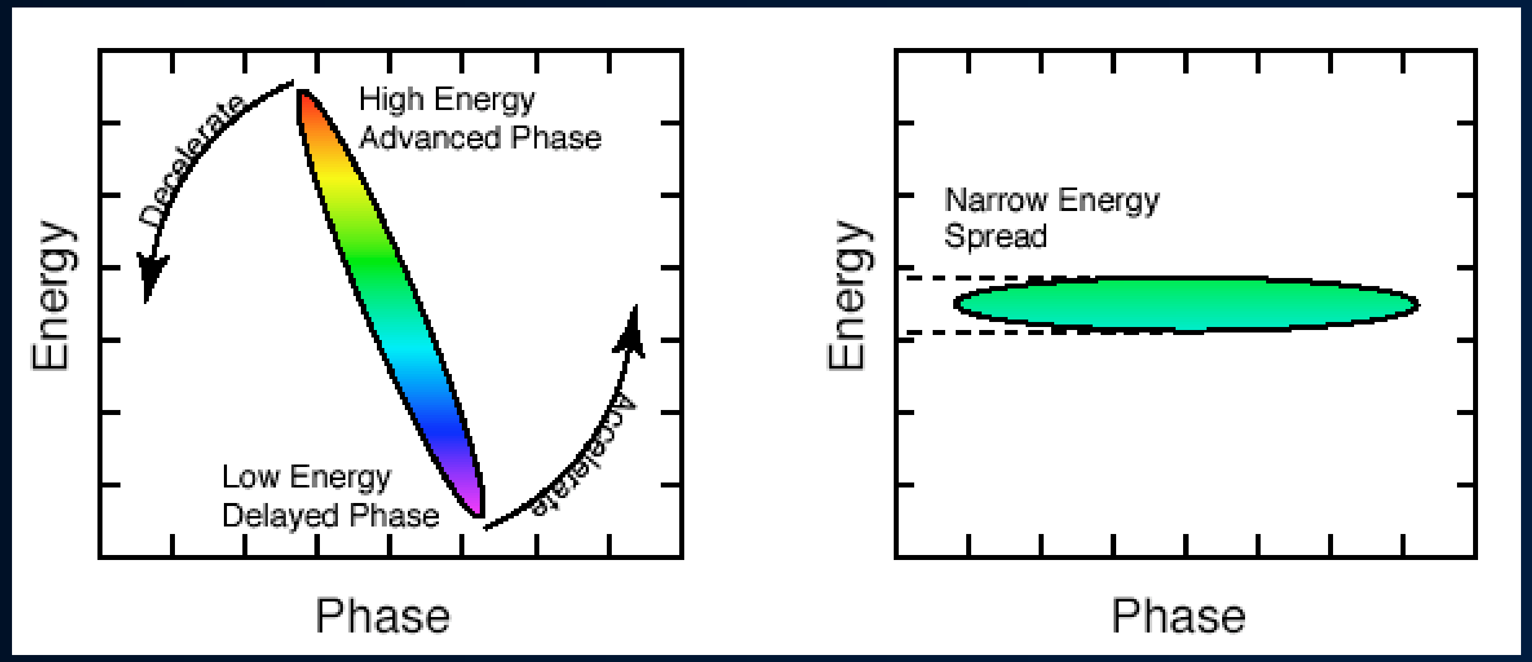
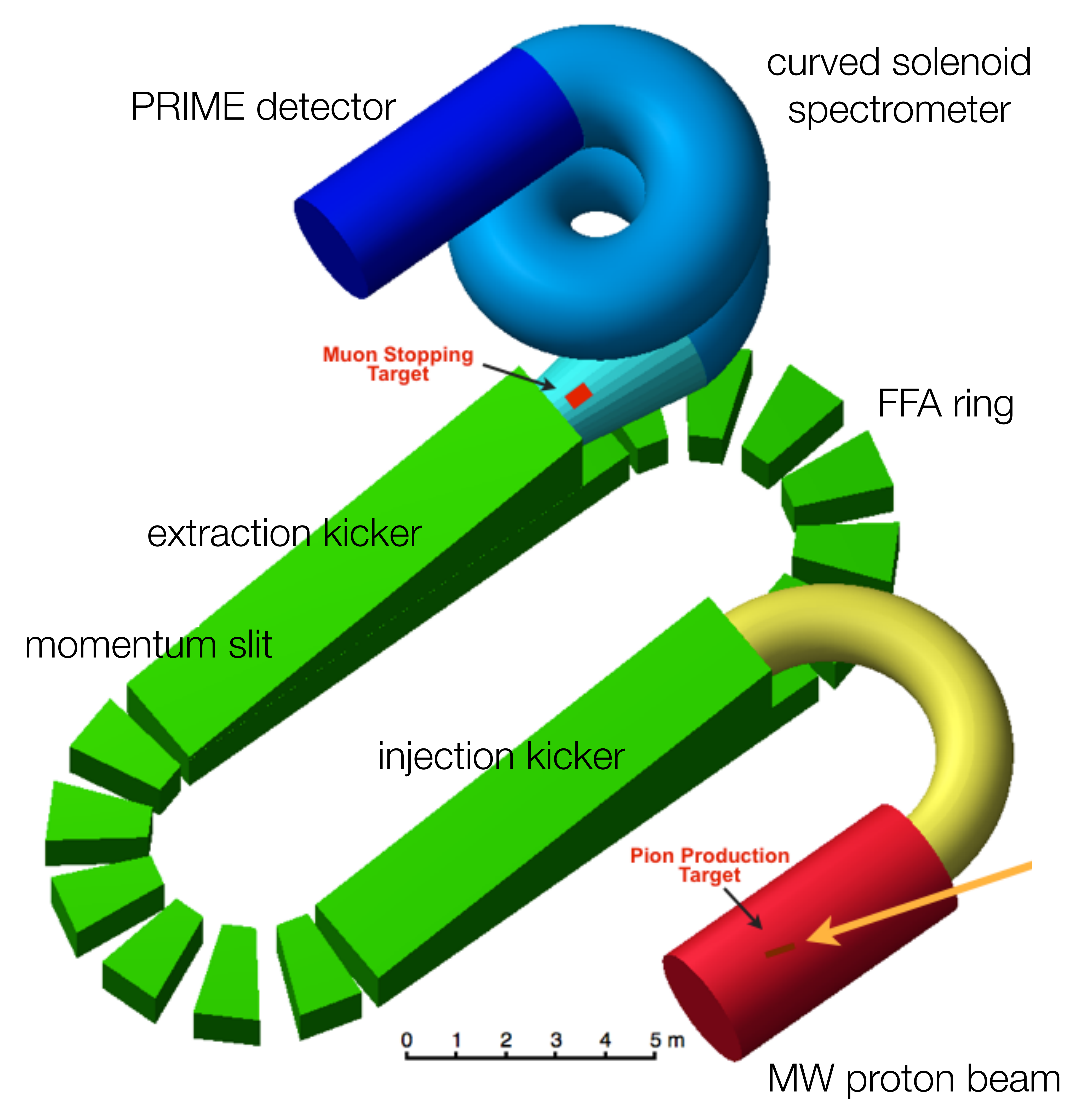


principle of phase rotation

$\mu^- \rightarrow e^-$ Conversion at <O(10^{-19}) with Muon Storage Ring

PRISM

COMET



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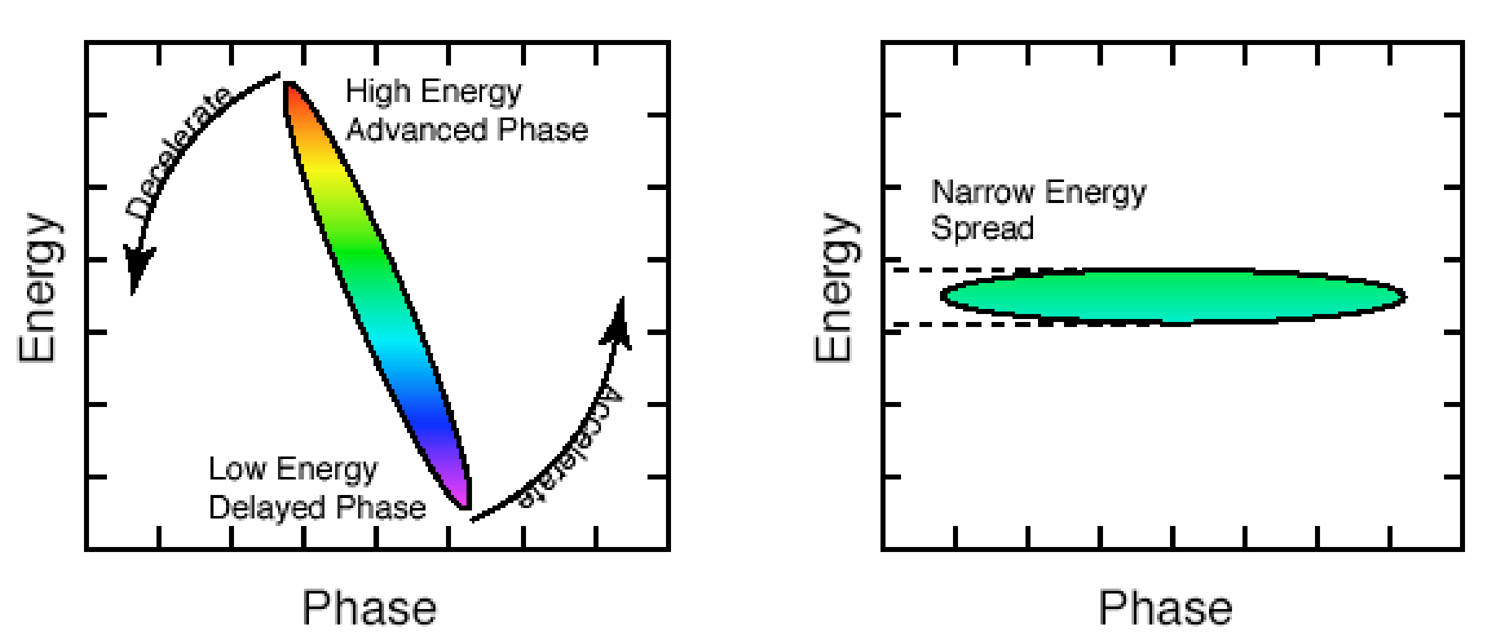

principle of phase rotation

- Future Prospects (2040~)
  - Enigma@AMF or PRISM@J-PARC

PRISM R&D at Osaka (2003-2007)

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Fixed Field Alternating Gradient Synchrotron (FFA)

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- High field RF development
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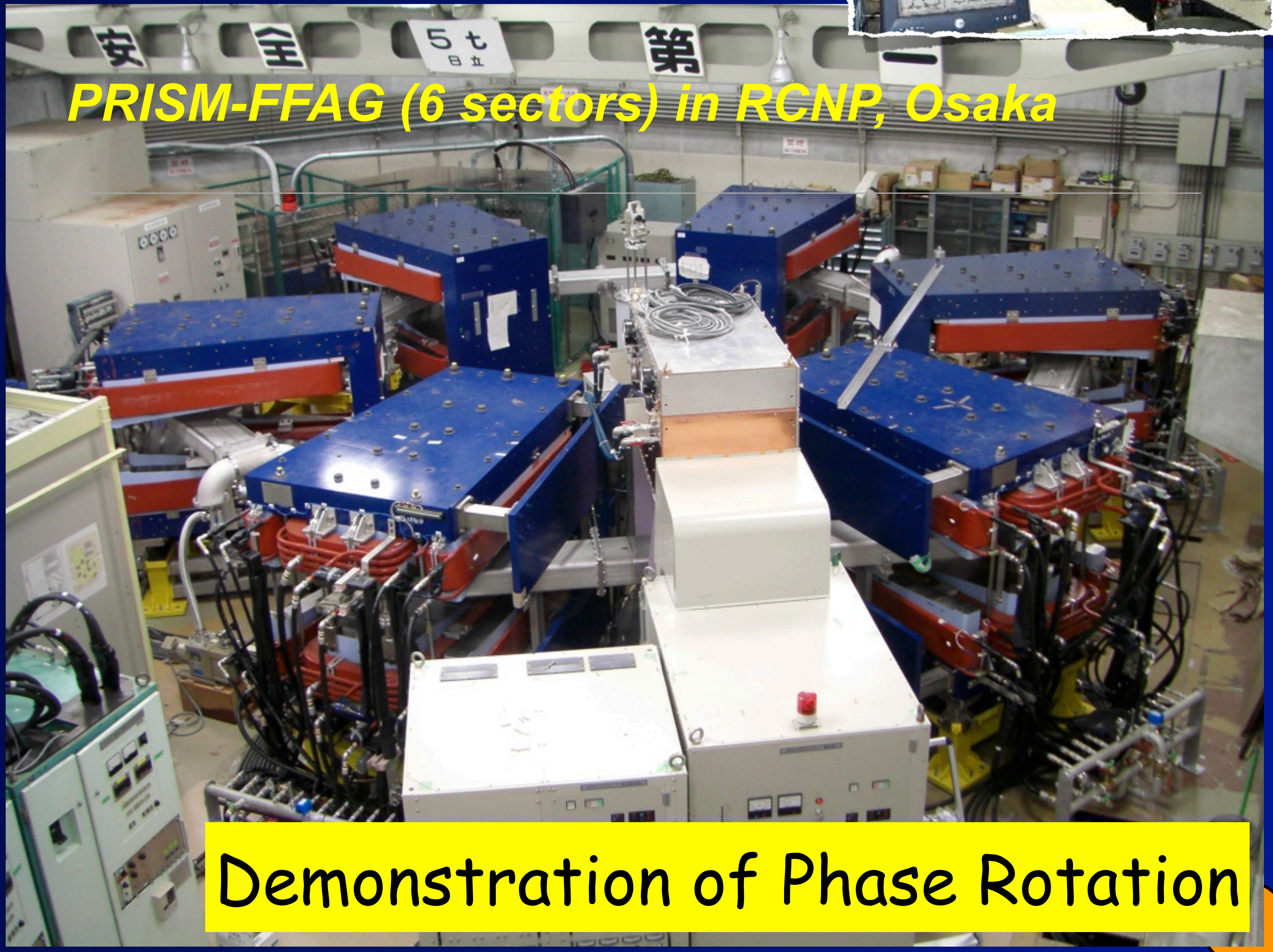
$$B(r) \propto (\frac{r}{r_0})^5$$

2003 - 2007 at Osaka University



Global Timeline of Muon CLFV

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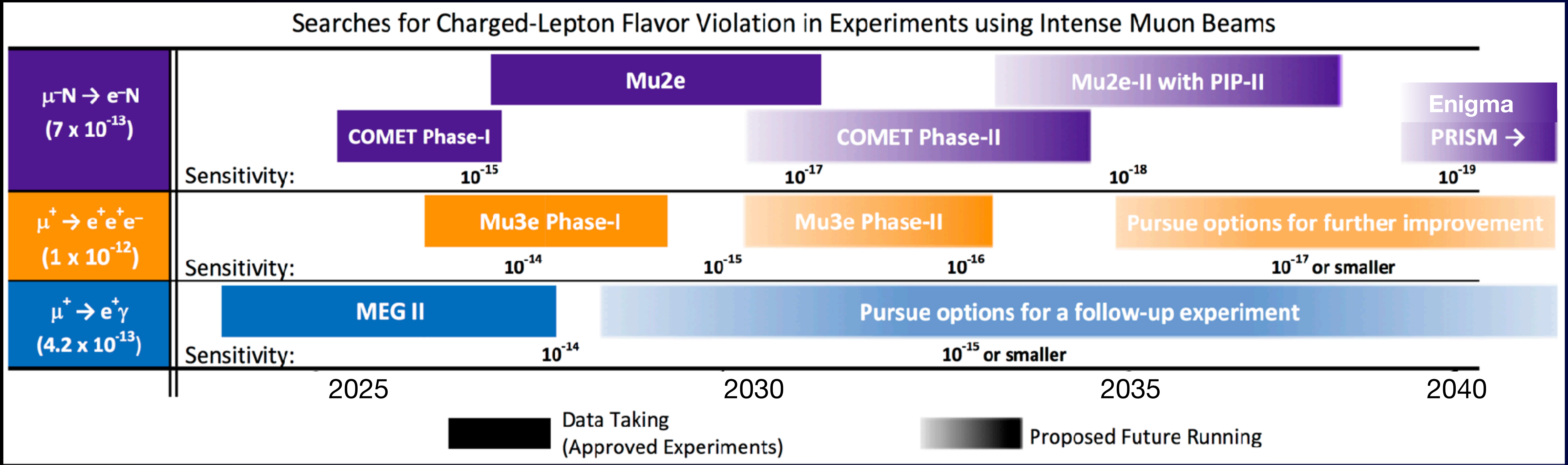

modified from the muon CLFV white paper for the EPPSU2019 by YK

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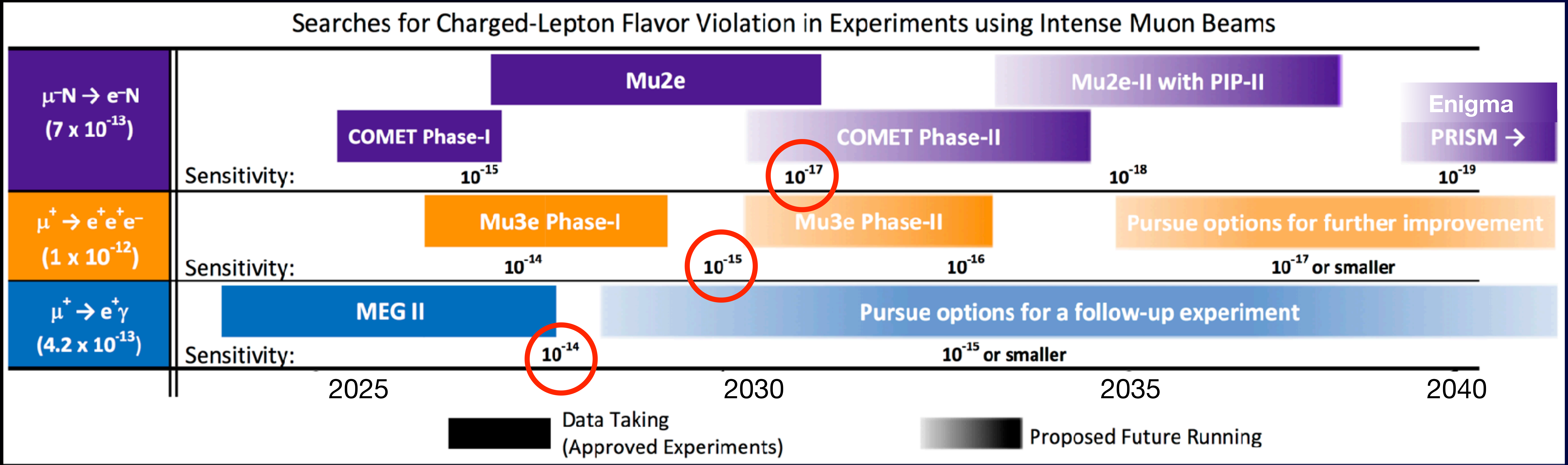

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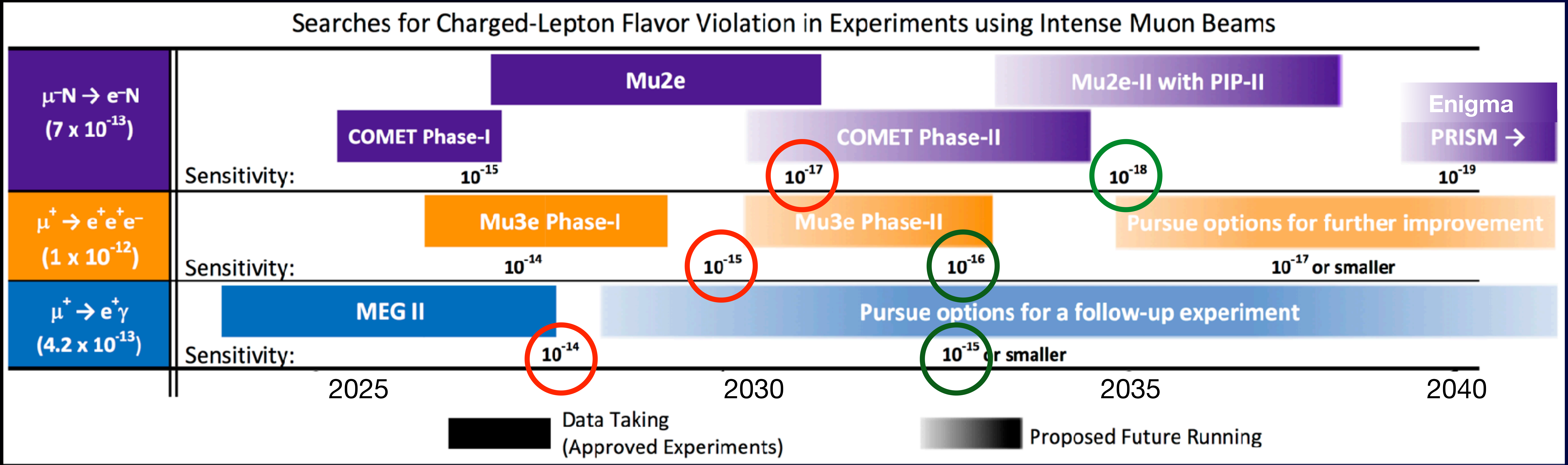

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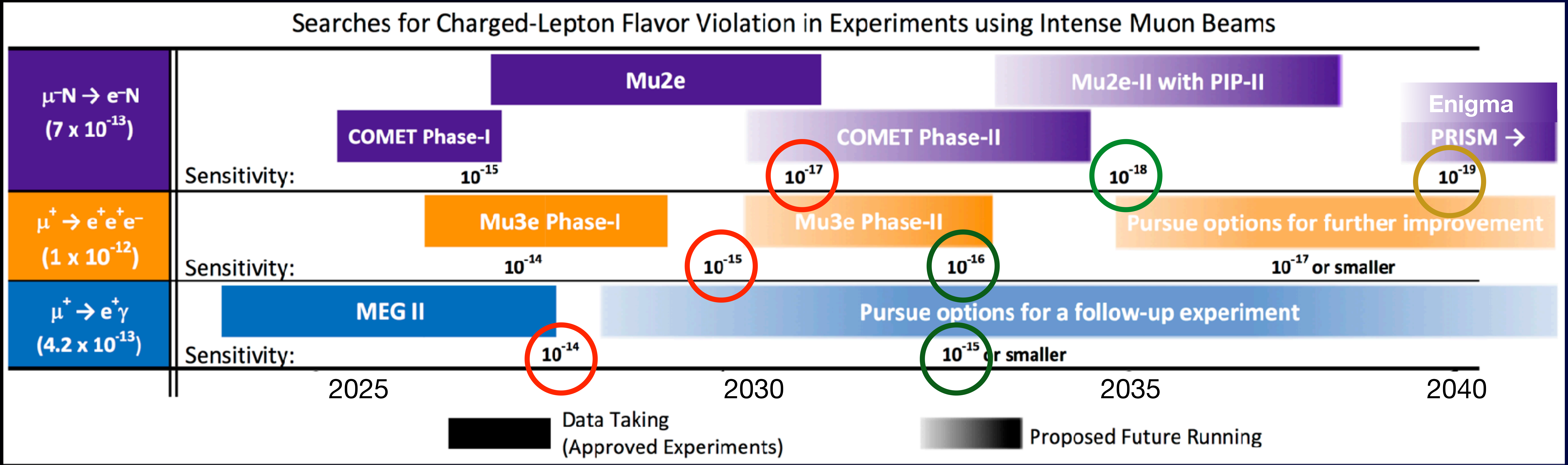

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In Case of Muon CLFV Discovery…

CLFV is an indirect search but,

In Case of Muon CLFV Discovery…

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

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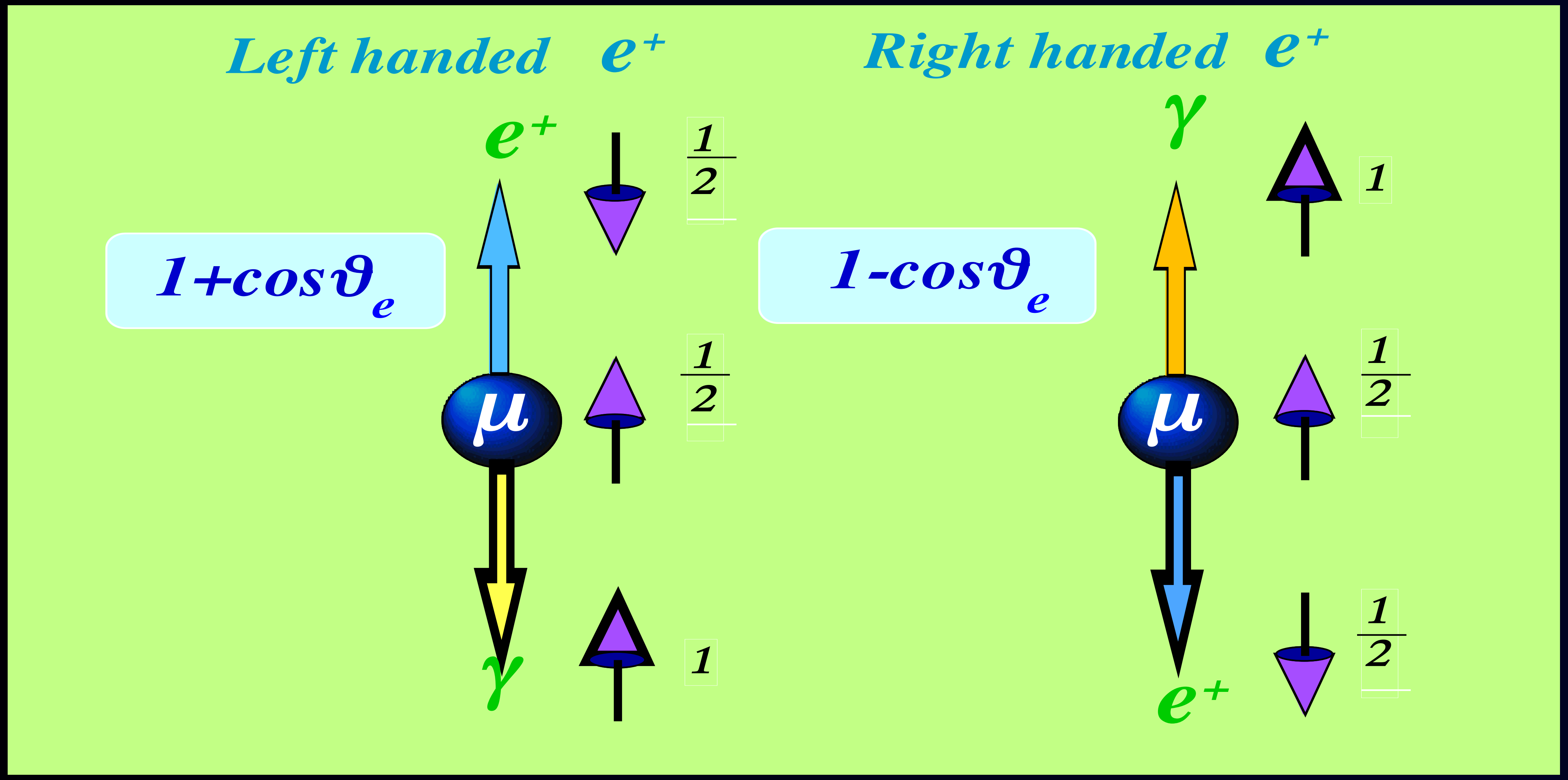
Angular distribution of polarized $\mu^+ \to e^+\gamma$ Decay



- discriminate models by chirality of positrons.
- surface muon beam is 100% polarized.
- polarized muon decays can be used to suppress backgrounds.

B.W. Lee, et al., Phys. ReV. Lett. 38 (1977) 937
YK, Y. Okada, Phys. Rev. Lett. 77 (1996) 434
YK. A. Maki and Y. Okada, Phys.Rev.D 55 (1997) 2517

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

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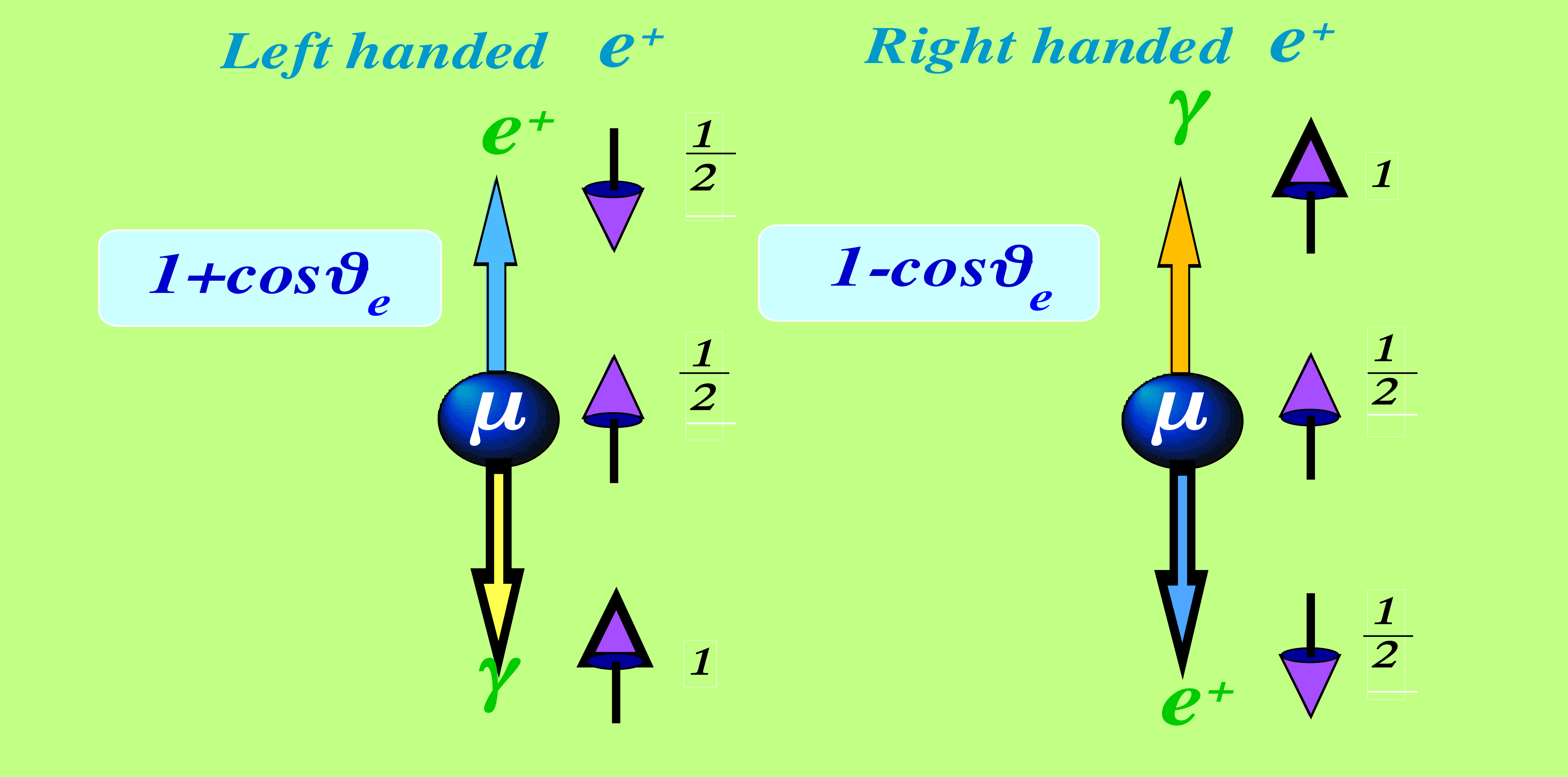

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$\mu^+ \to e^+e^+e^-$ Decay

- Dalitz distribution of 3 body decay may be measured for model discrimination and correct rate estimation.

Model Discrimination in $\mu \to e$ conversion

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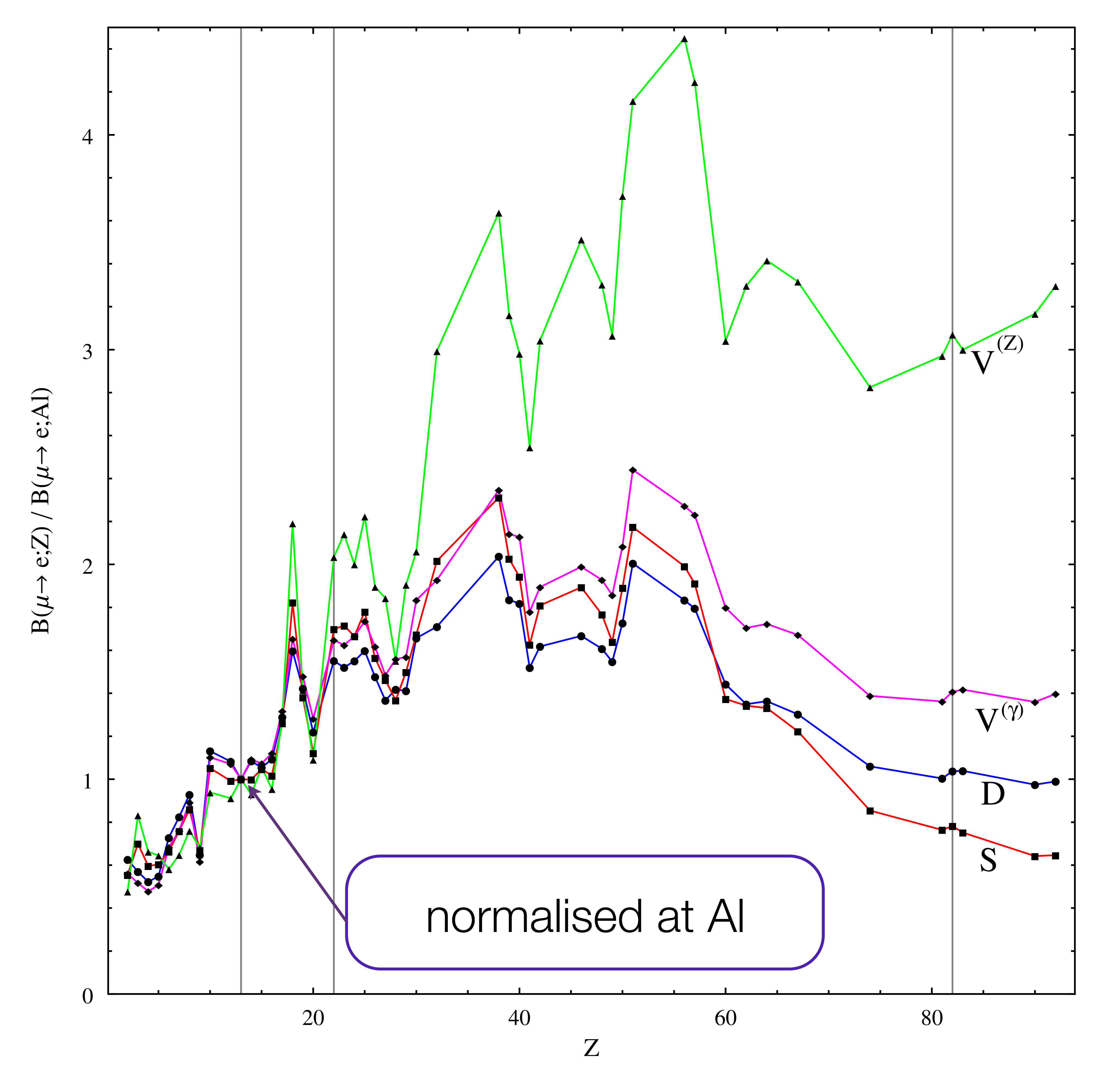
Muon Target Dependence for $\mu \to e$ conversion



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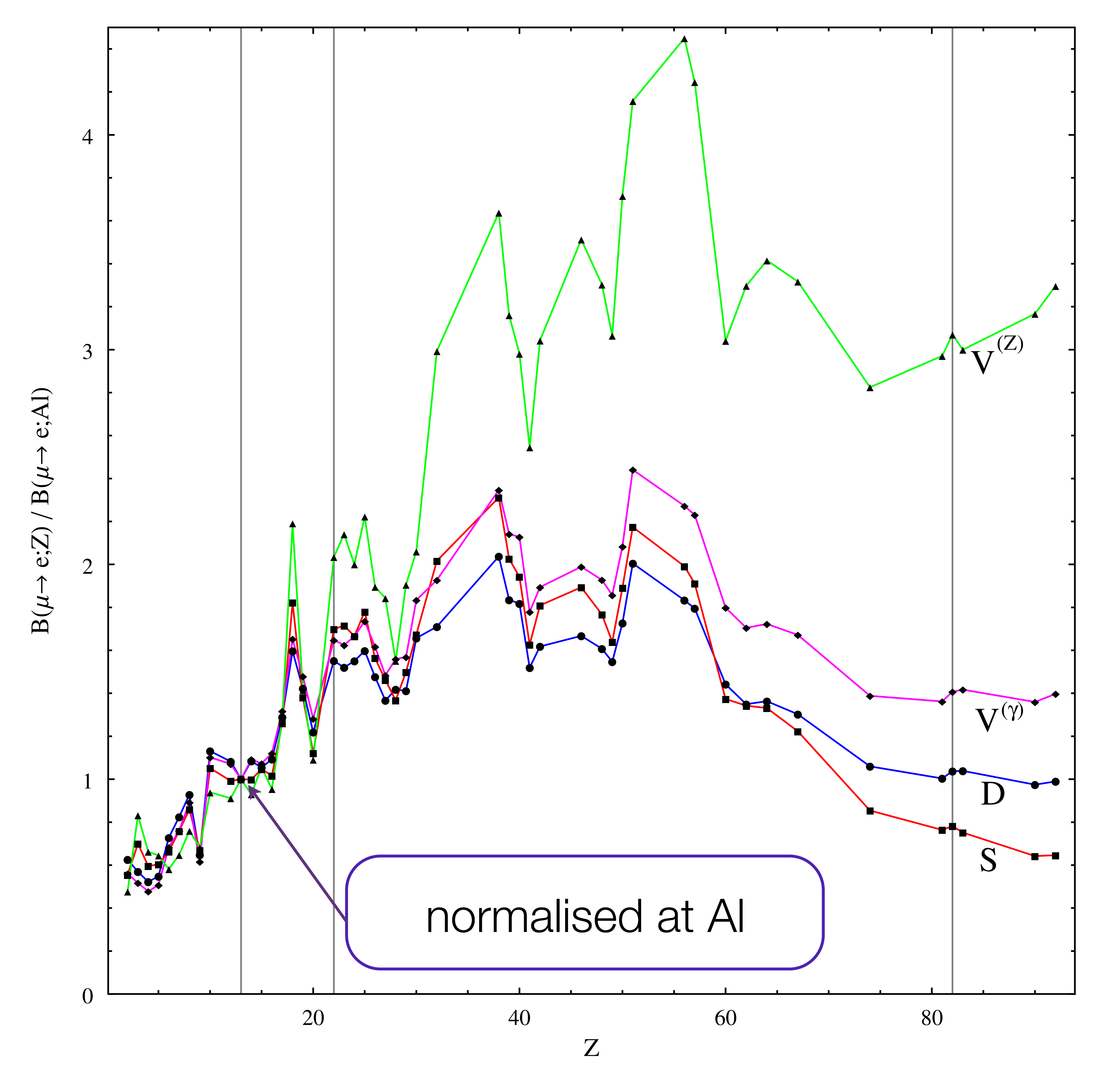

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vector interacton (charge radius)	
dipole interaction	SUSY GUT, SUSY seesaw
scalar interaction	RPV SUSY, Leptoquark

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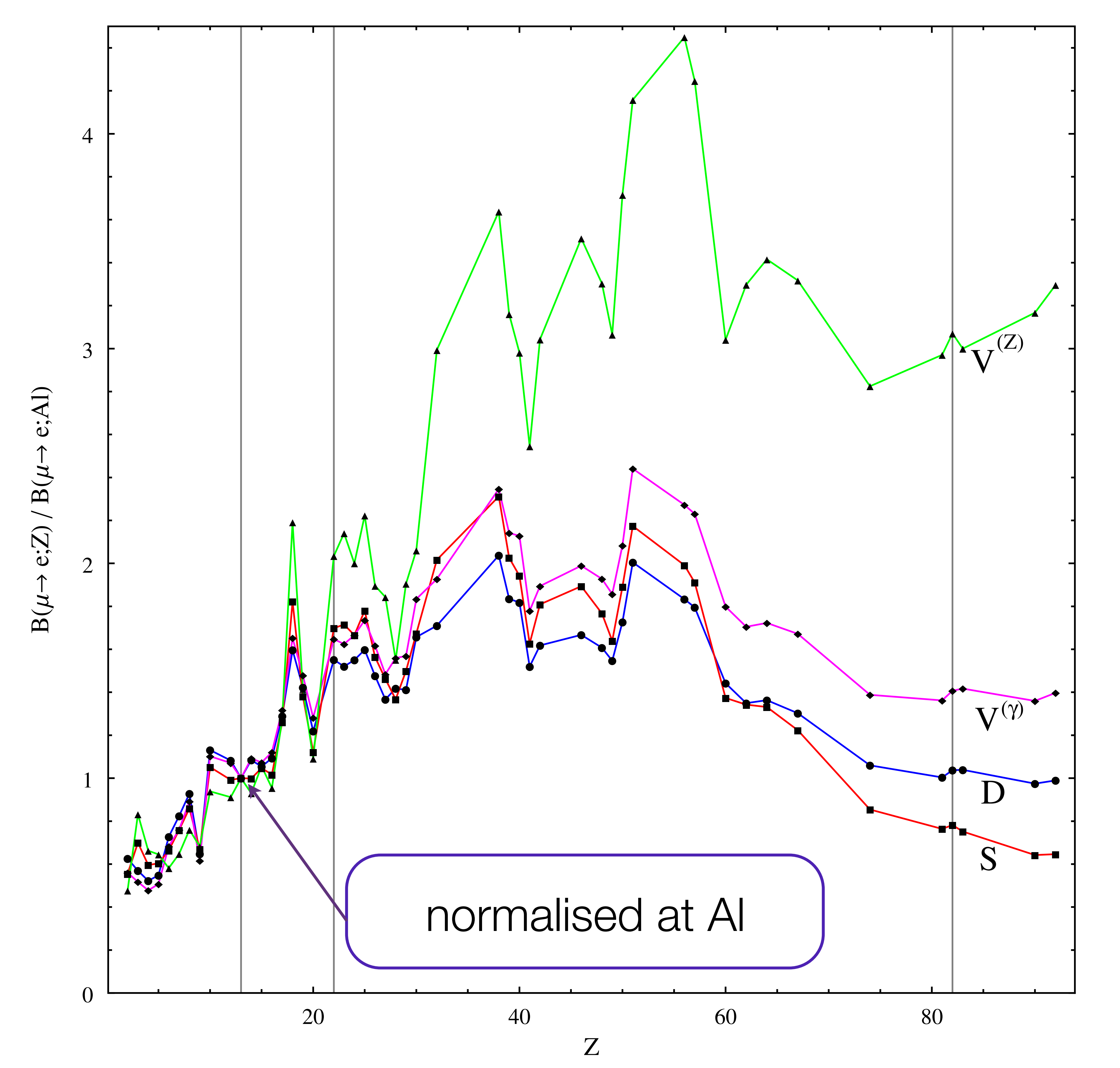
Muon Target Dependence for $\mu \to e$ conversion

single operator analysis



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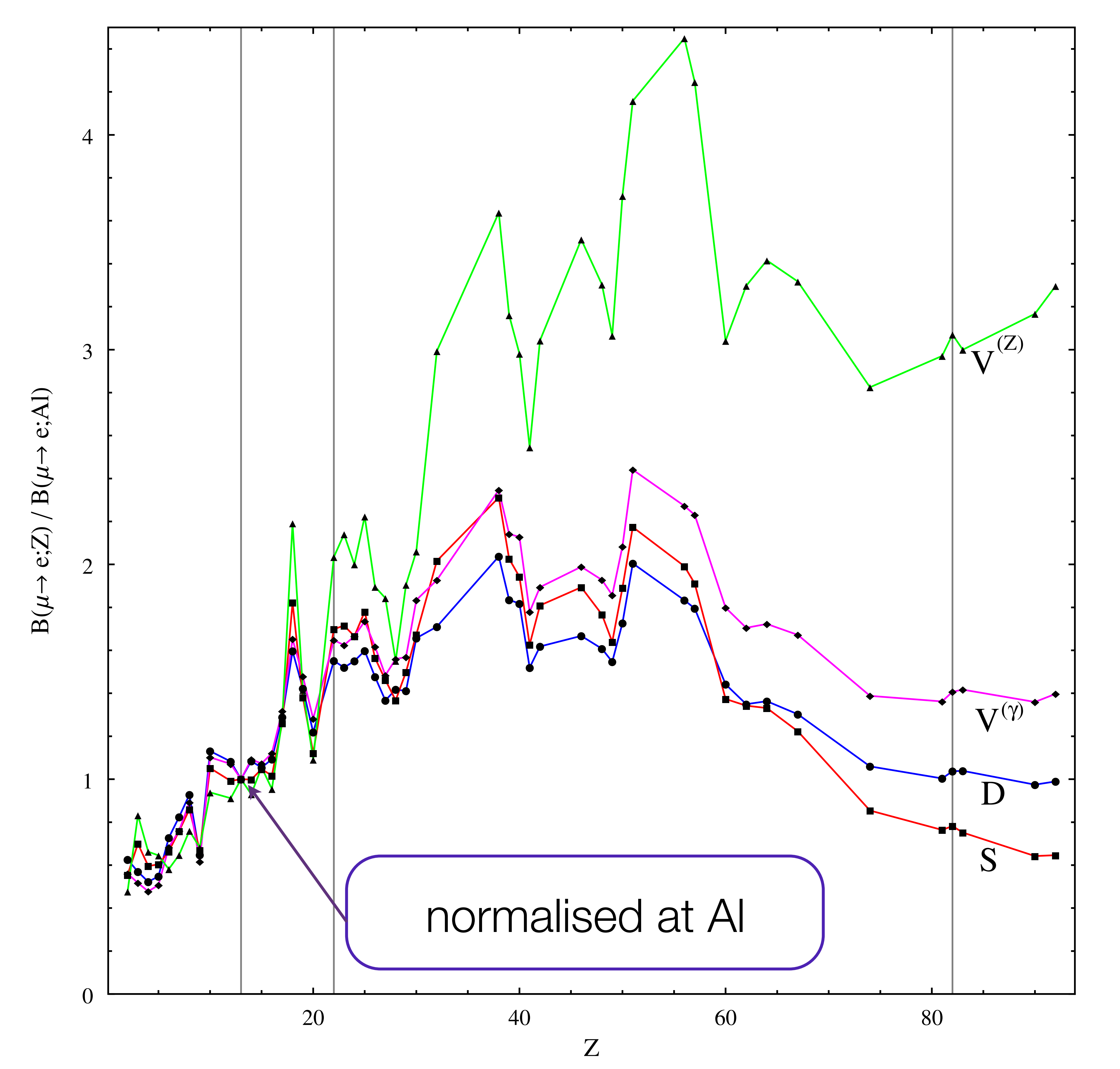

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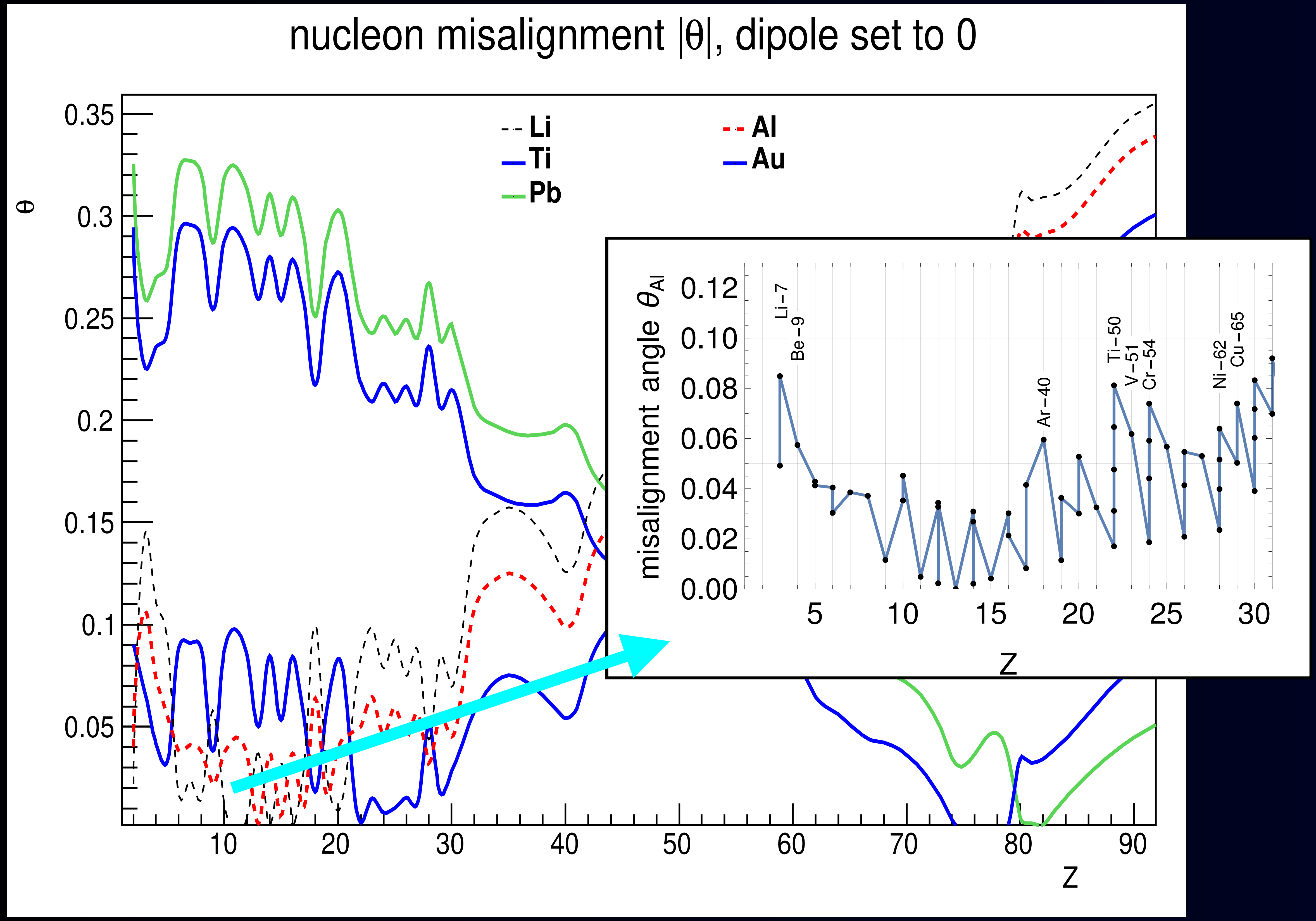
R. Kitano, M. Koike andY. Okada, Phys. Rev. D 66, 096002 (2002)
V. Cirigliano, R. Kitano et al., Phys. Rev. D80, 013002 (2009)
J. Heeck, R. Szafron, Y. Uesaka, Nucl. Phys. B980 (2022) 115833
W.C. Haxton, E. Rule, L. McElvain, et al., Phys. Rev. C 107, 3 (2023)
E. Rule, W.C. Haxton, K. McElvain, Phys. Rev. Lett. 130 131901 (2023)
M. Hoferichter, J.Menendez and F. Noel, Phys. Rev. Lett. 130, 131902 (2023)

Disentanglement in $\mu \rightarrow e$ conversion

Disentanglement in $\mu \to e$ conversion

2nd Target selection with different information

misalignment angle



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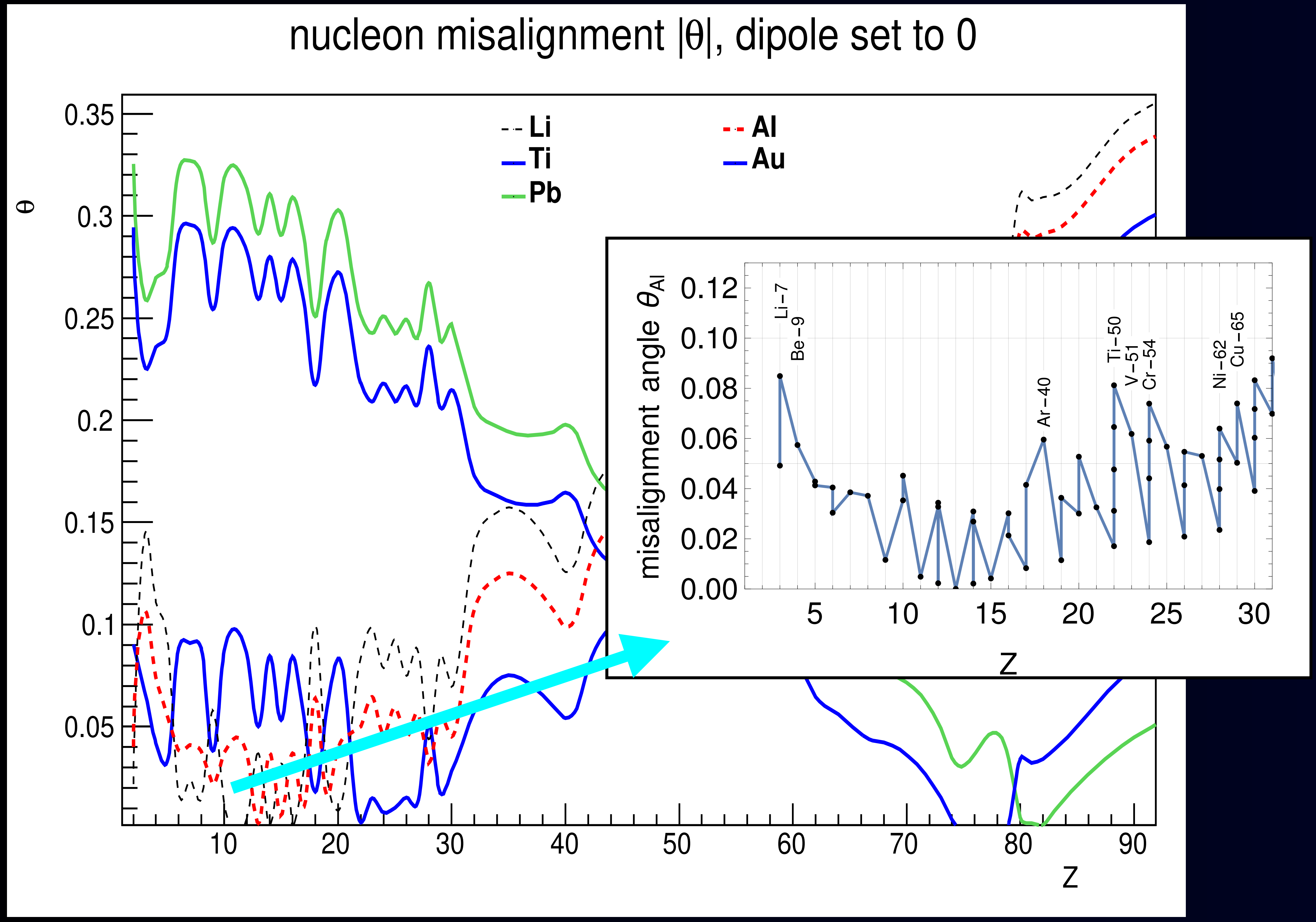

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Spin Dependent $\mu \to e$ conversion

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- Spin dependent (SD) μ-e Conversion: incoherent
- Extract SD, by comparing zero-spin and non-zero spin targets
  - Effect may not be large by $1/N^2$

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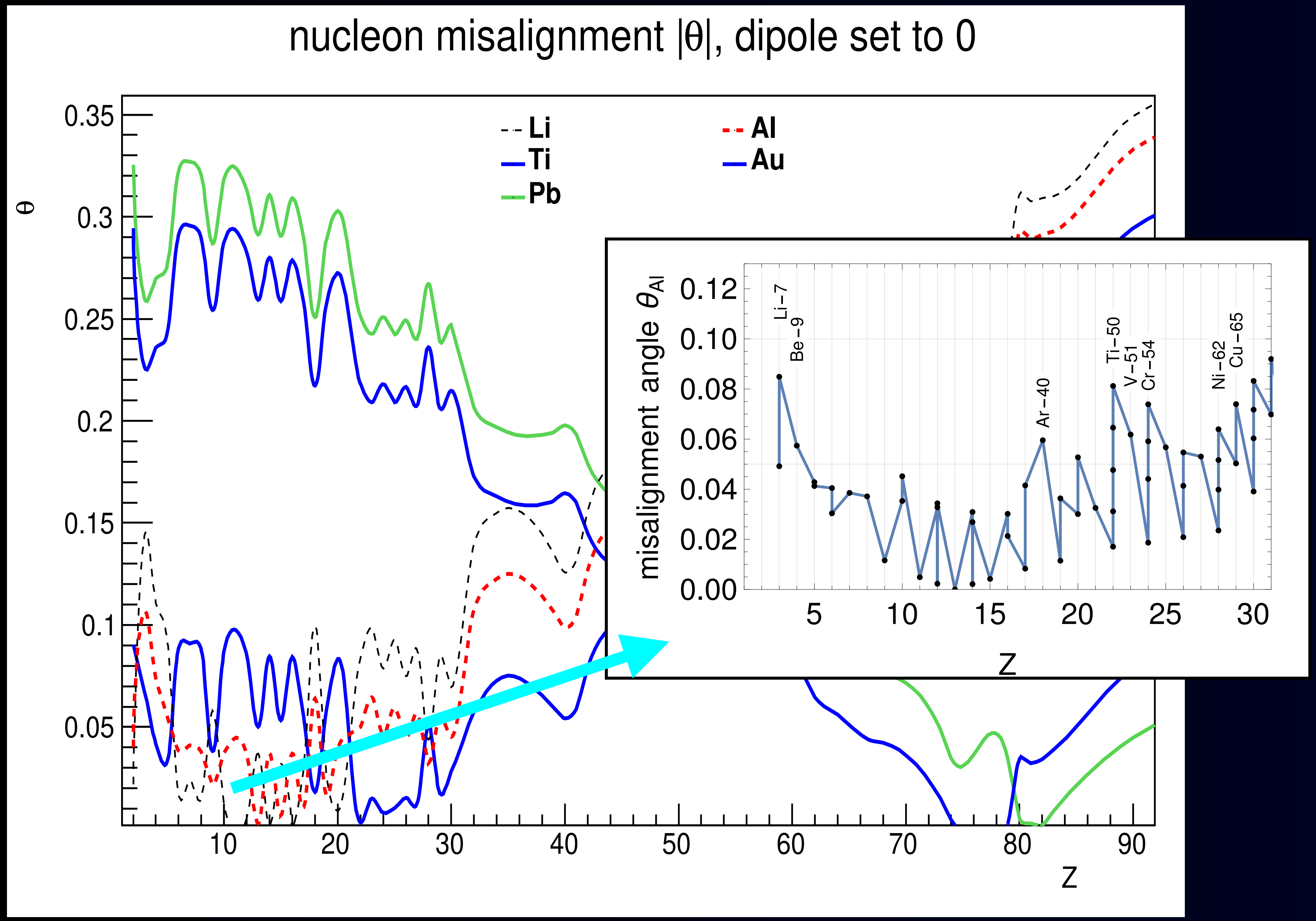

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Spin polarized $\mu \to e$ conversion

- Angular distribution with respect to the spin polarization determines the chirality of an electron.

YK and Y. Okada, RMP 73 (2001) 151

Muon’s Lepton Number Violation and Axion-like Particles

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

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

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

- Lepton number violation (LNV) and CLFV
- short distance TeV LNV Physics

- Event Signature
  - mono energetic positron (to the ground state)
  - $E_{e^+} = m_\mu - B_\mu - E_{rec} - M(A,Z-2) + M(A,Z)$
- Backgrounds
  - Radiative muon capture (RMC) followed by photon conversion
- Current limits (from SINDRUM at PSI)

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

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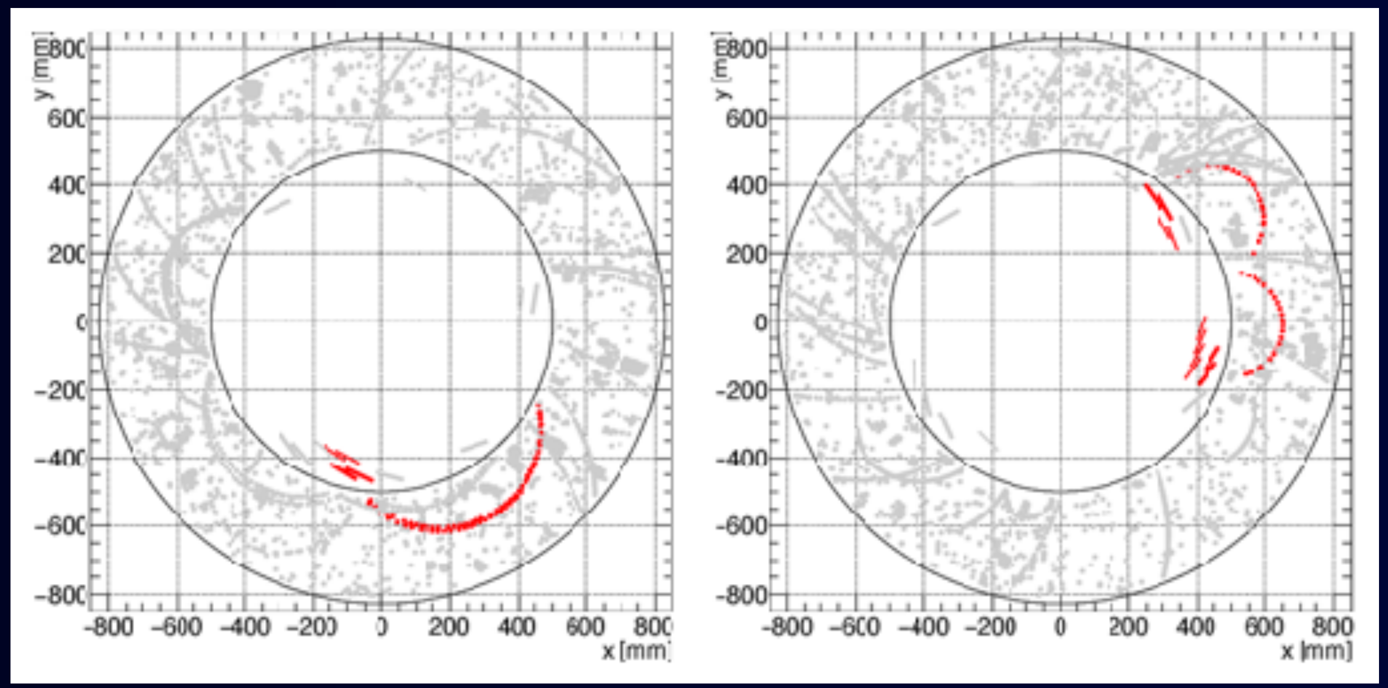
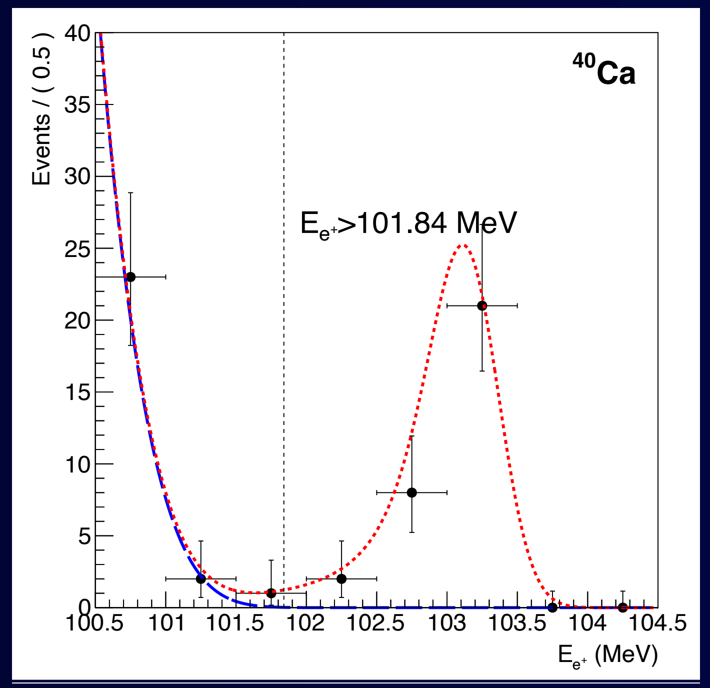
- requirement of candidate target $N(A,Z)$

$$E_{\mu^- e^+} > E^{end}_{RMC} \longrightarrow M(A,Z-1) > M(A,Z-2)$$

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

- Mu2e and COMET are trying to measure at the same time of $\mu^- \rightarrow e^-$ conversion
  - x10000 improvement can be expected
  - RMC background spectrum, better to measured.





$\mu \to ea$ and $\mu \to ea\gamma$

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	upper limits	$F_{e\mu}$ (GeV)	
TRIUMF	$\mathrm{BR}(\mu^+ \to e^+ a_{\mathrm{RH}}) < 2.6 \times 10^{-6}$	$> 5.5 \times 10^9$	1988
online	$\mathrm{BR}(\mu^+ \to e^+ a) < 5.8 \times 10^{-5}$	$> 1.2 \times 10^9$	2015
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MEG-II forward	$\mathrm{BR}(\mu^+ \to e^+ a_{\mathrm{RH}}) < 10^{-7}$	$> 10^{10}$	?
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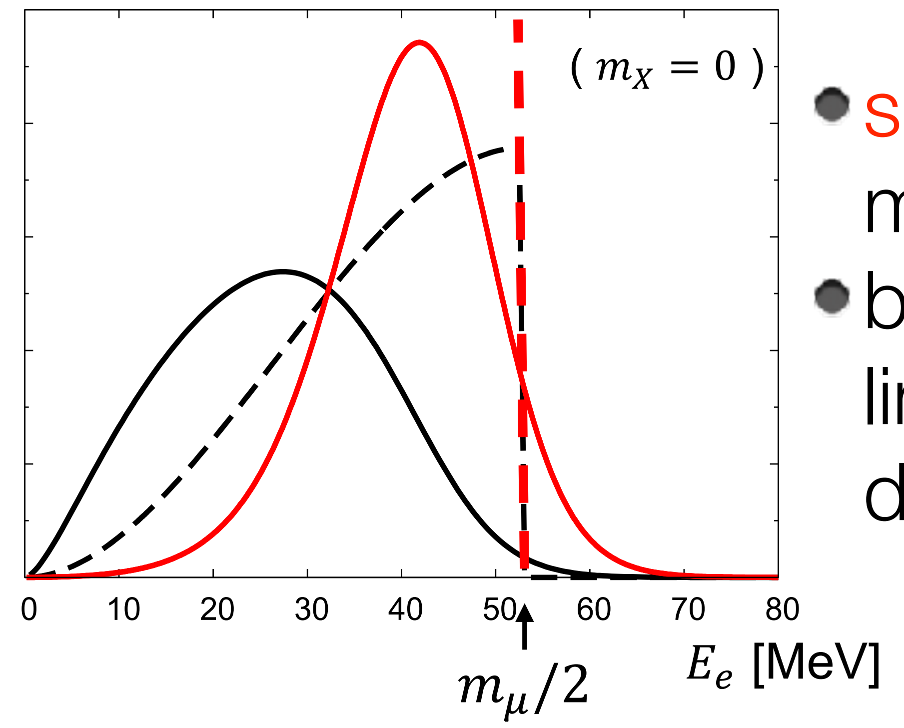
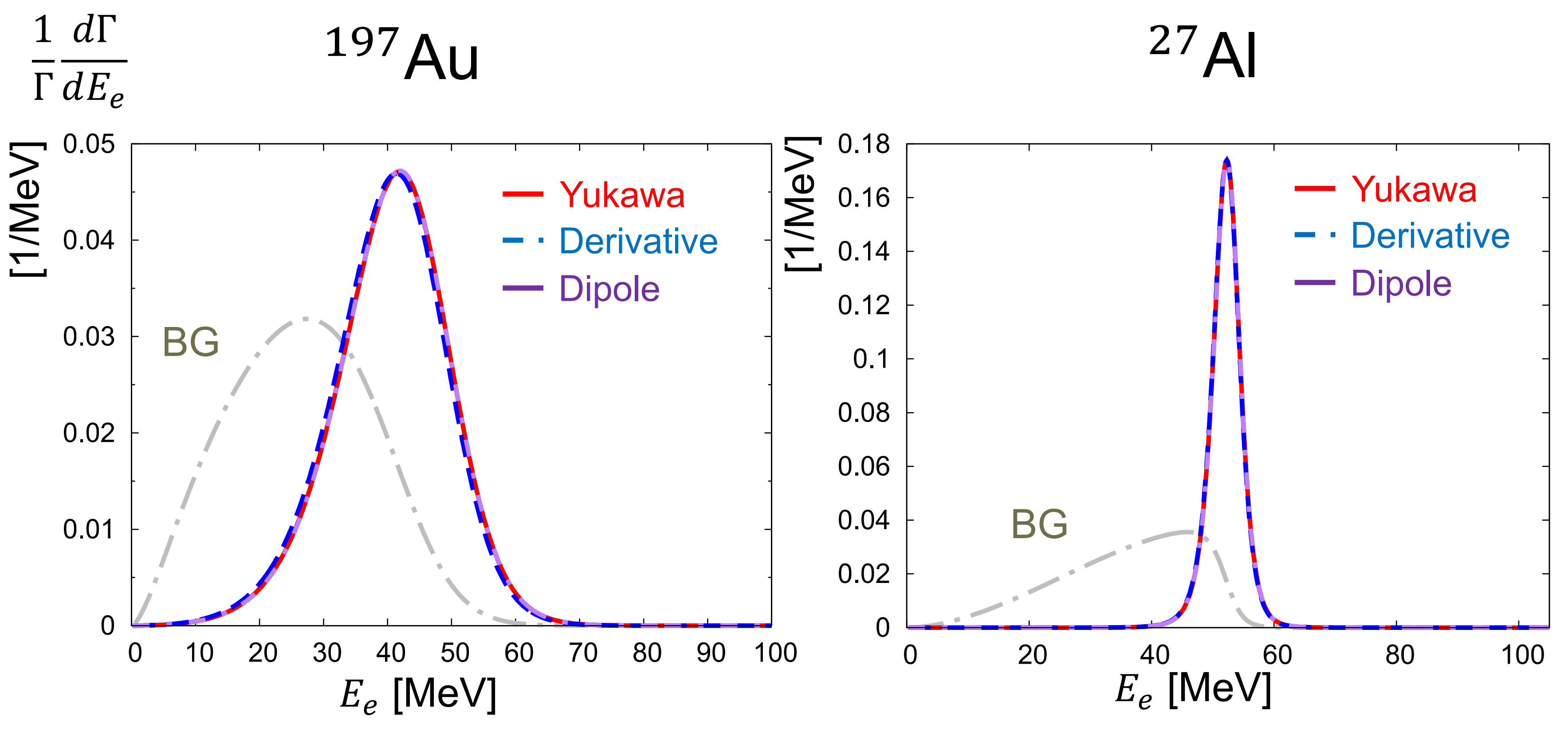
bound $\mu^- \to e^- a$

electron spectra (normalized by rate)



- 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)
Tianyu Xing et al., Chin. Phys. C47, 013108 (2023)

Muonium

Muonium to Antimuonium Conversion

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$$\Delta L_\mu = 2, \ \Delta L_e = 2$$

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$$P_{Mu\overline{Mu}} = \sin^2(\frac{t \times \Delta}{2})\exp[-\frac{t}{\tau_\mu}]$$

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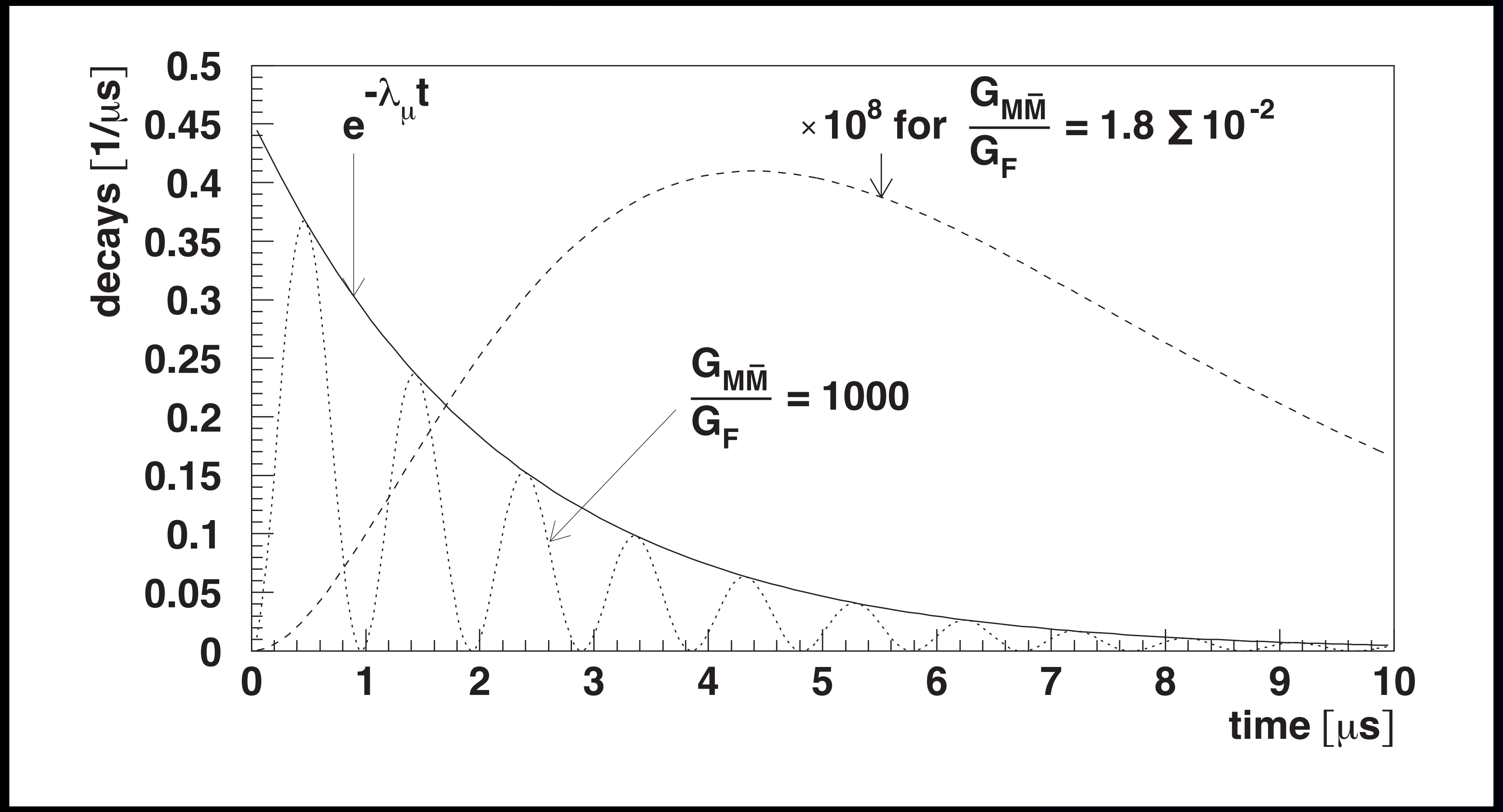

Oscillation maximum at $t = 2\tau_\mu$

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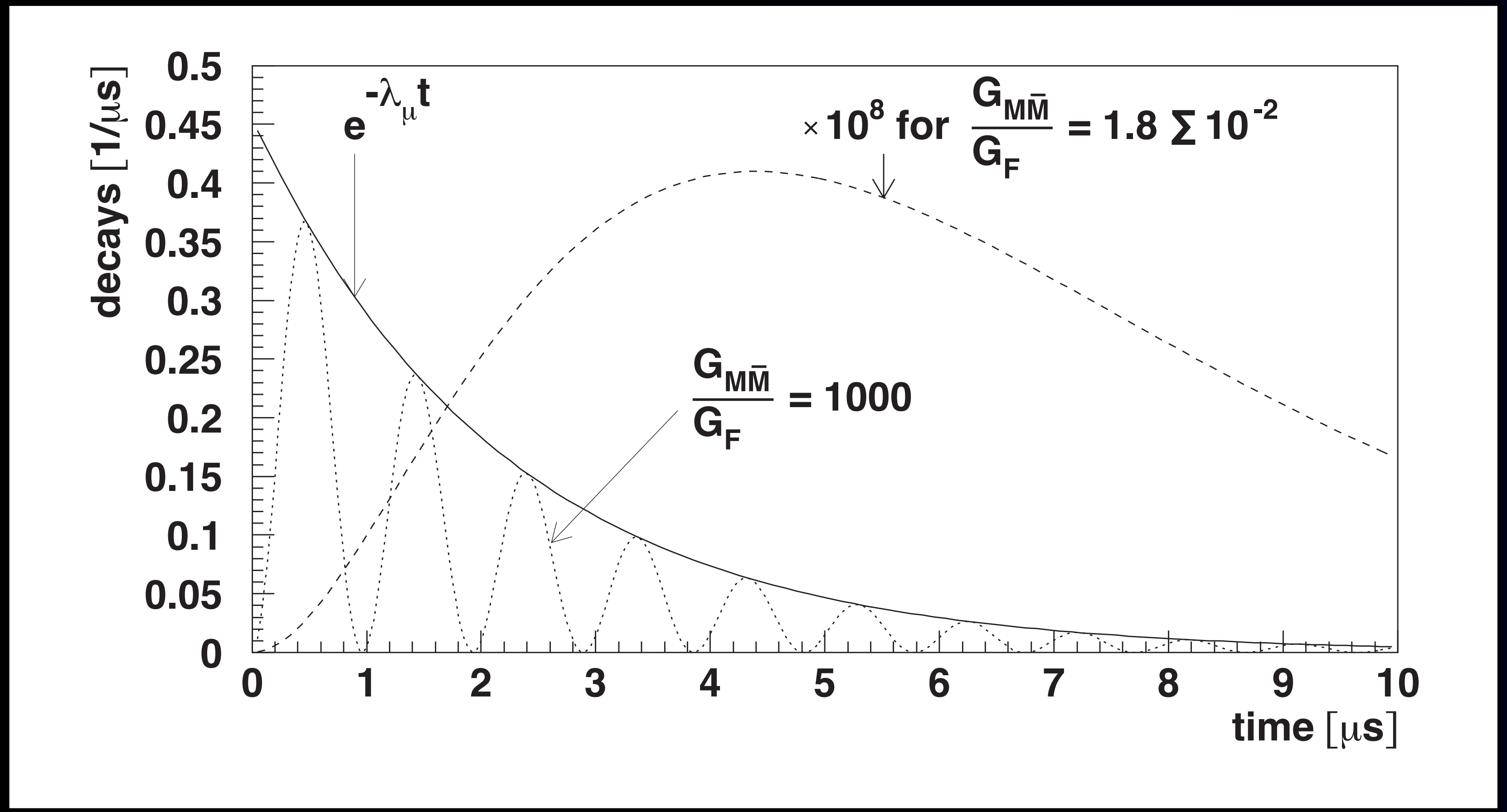
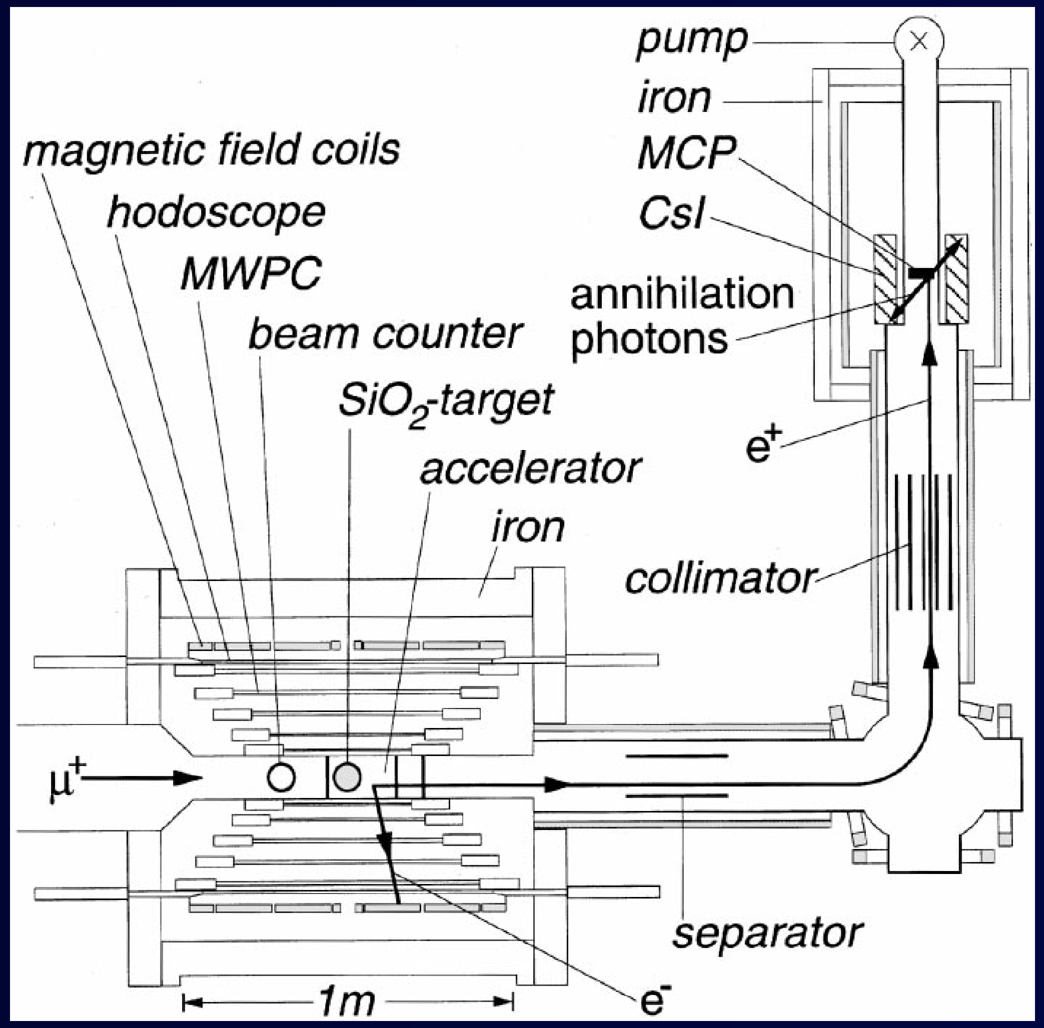


Oscillation maximum at $t = 2\tau_\mu$

- Experimental methods
  - Production of Mu in vacuum
    - reduce residual EM fields
  - Detection of $\overline{\mathrm{Mu}}$ decay
  - Current limit (from PSI, 1999)
  - $P_{Mu\overline{Mu}} \leq 8.3\times10^{-11}$ (90% C.L.)



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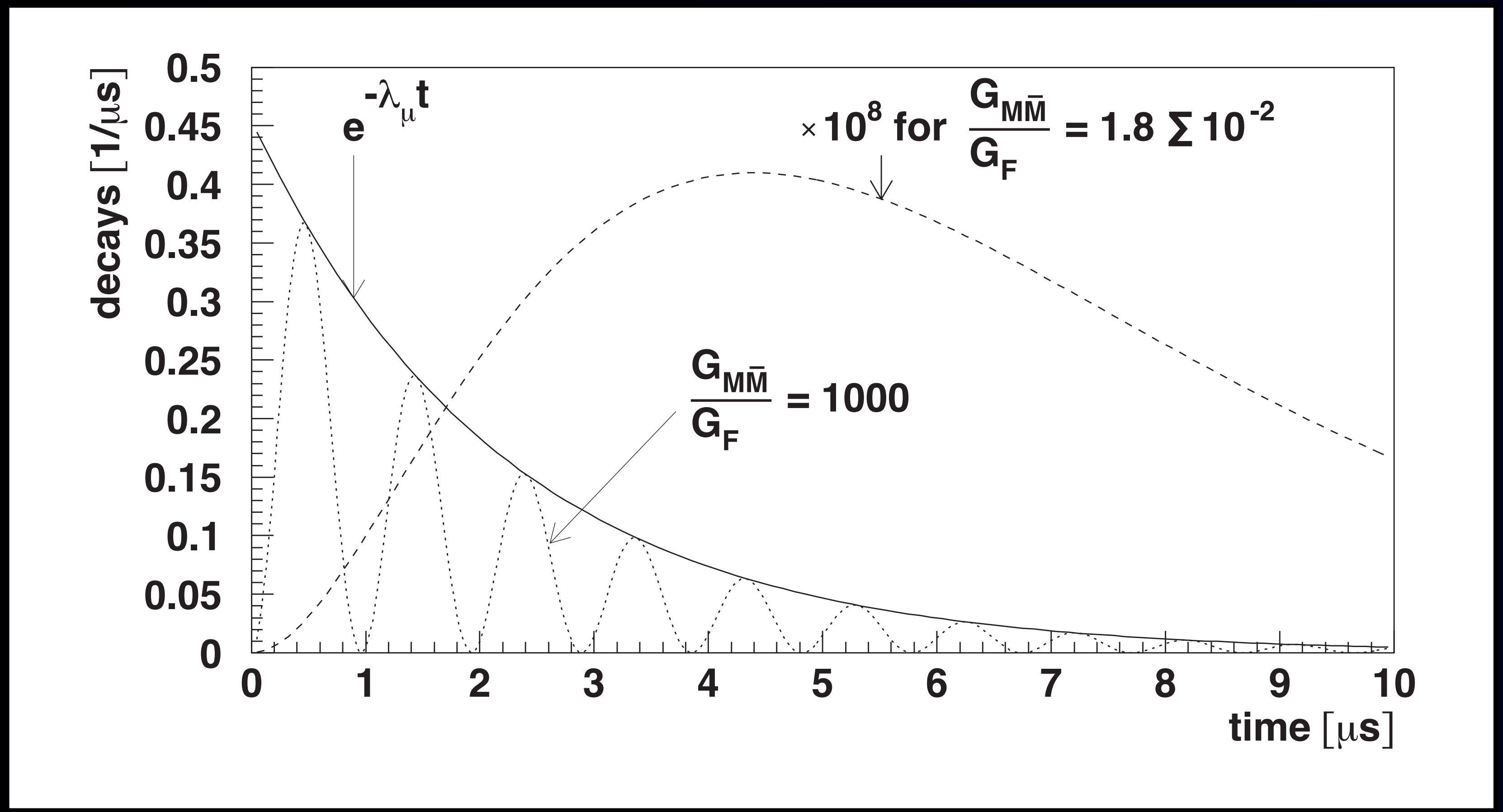

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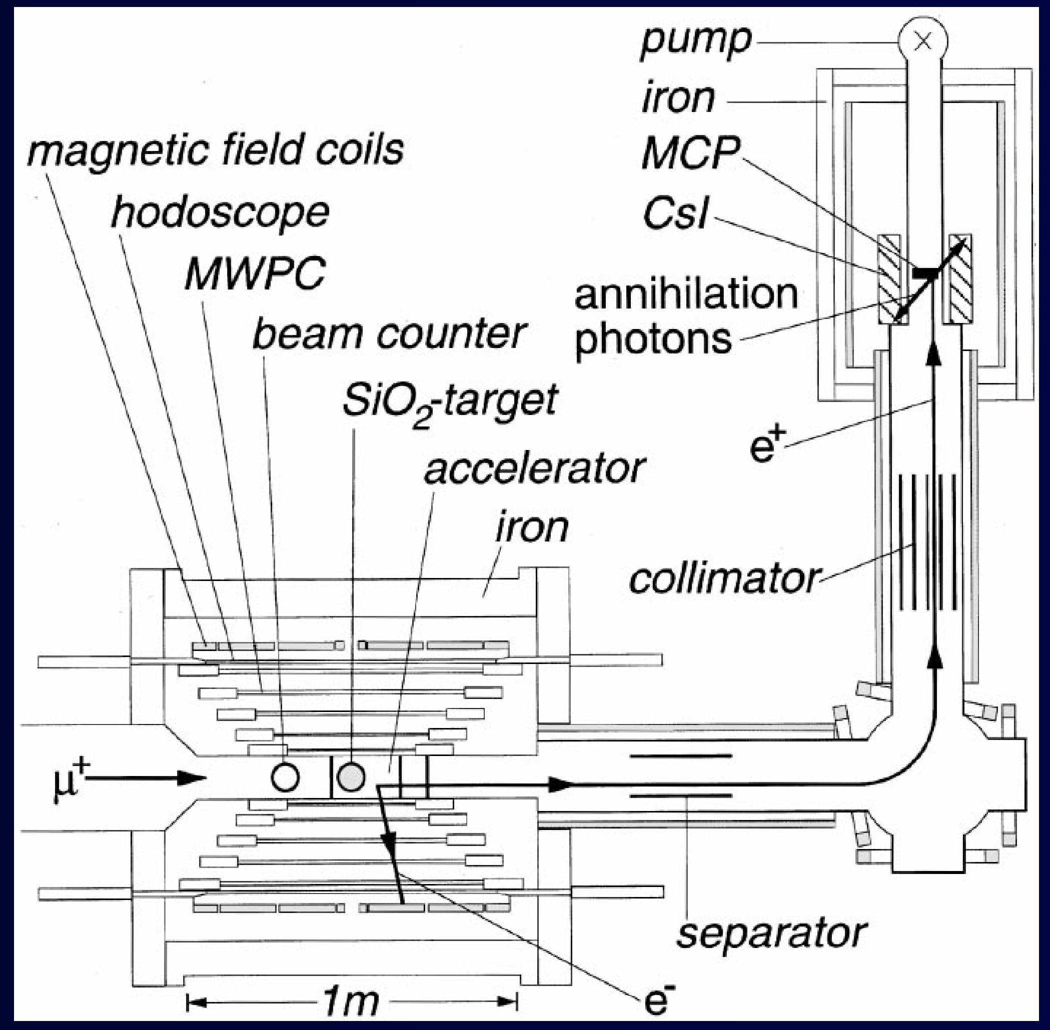


- New proposals
  - CSNS in China: X(10-100) sensitivity

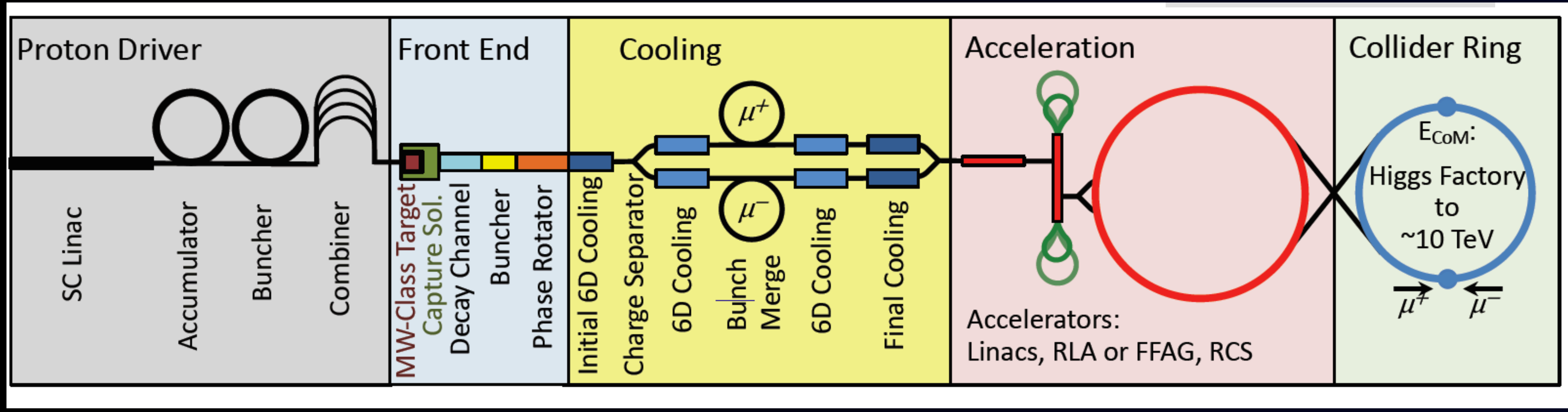
See the talk by Yuhang Guo

Muon Colliders

Muon Colliders

Muon Colliders

MAP (US)



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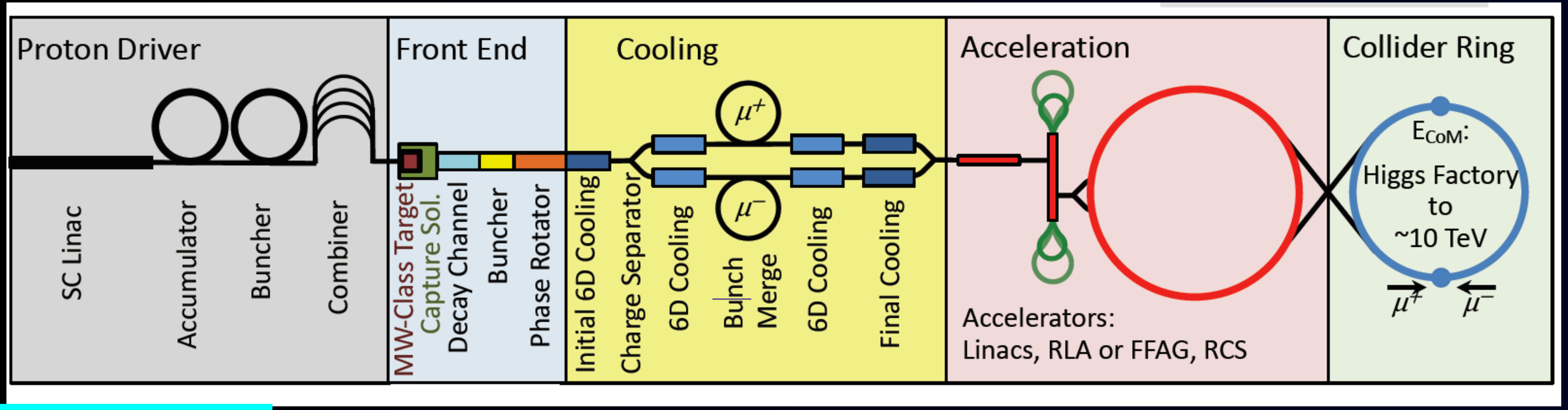
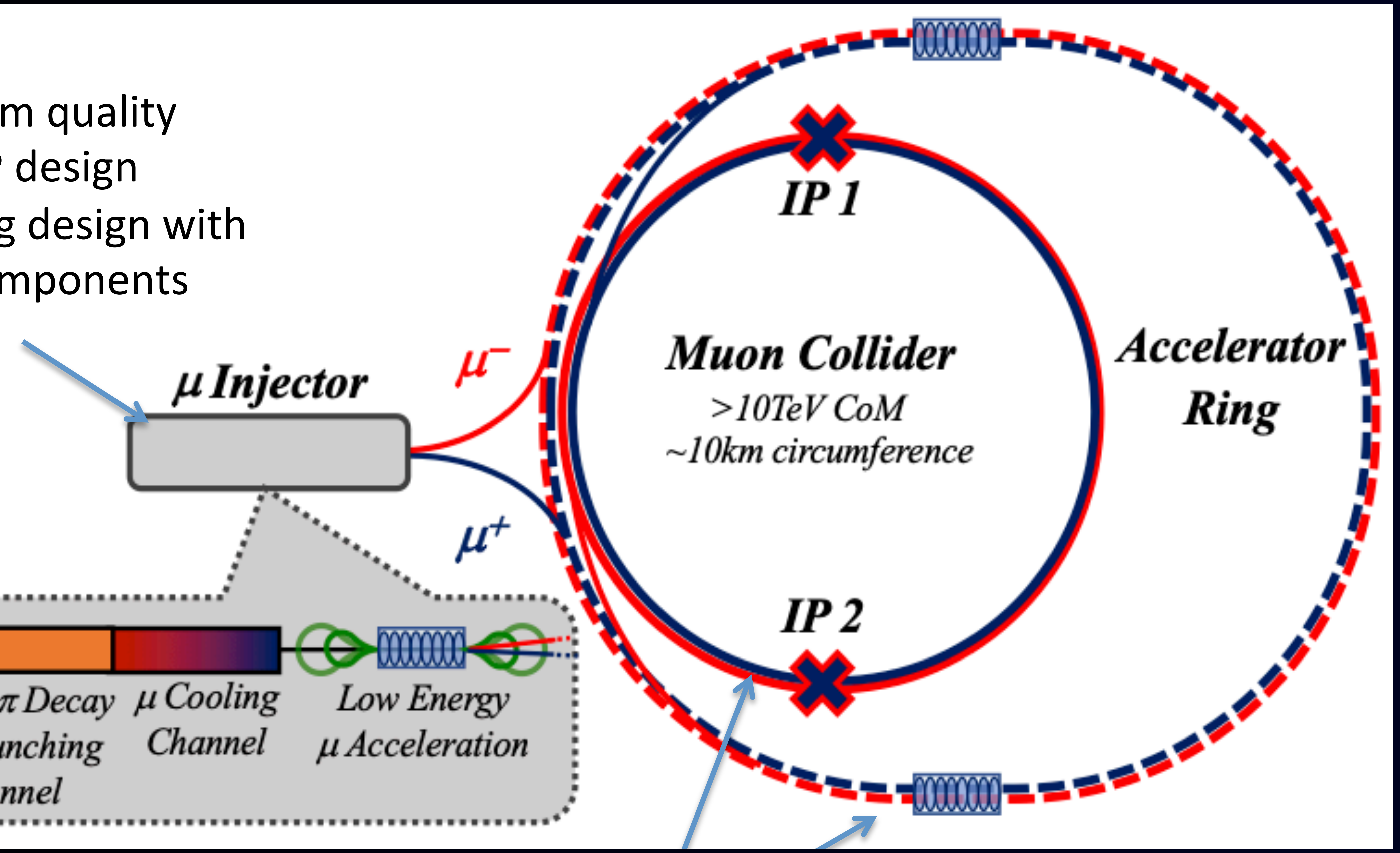


CERN

Drives the beam quality similar to MAP design
still challenging design with challenging components



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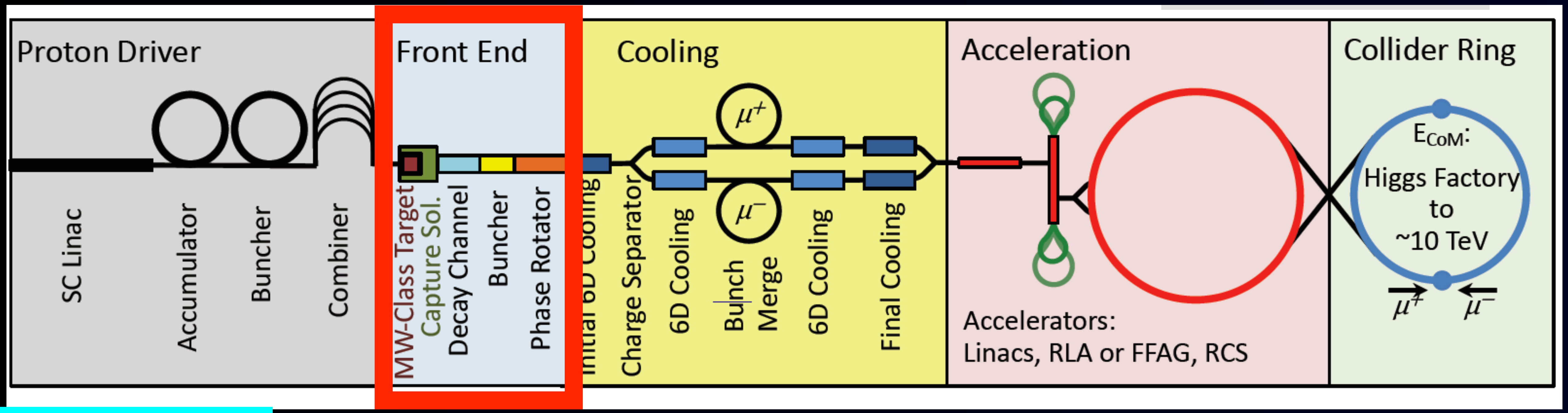

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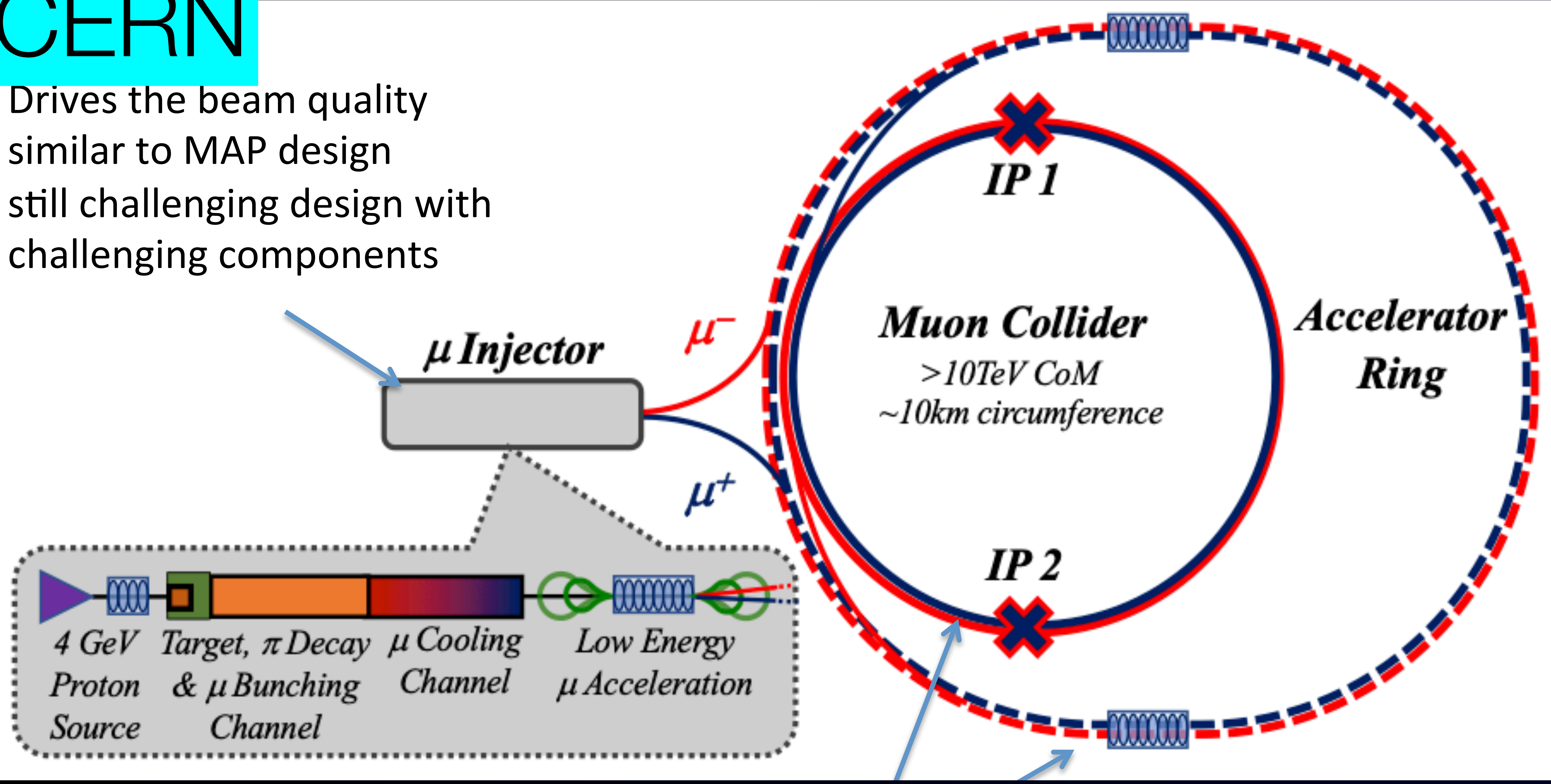
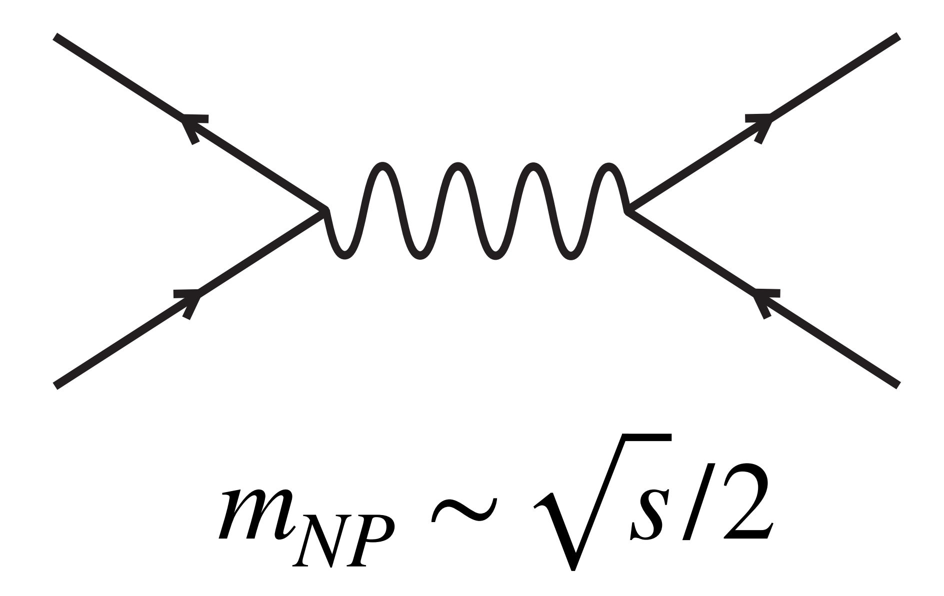


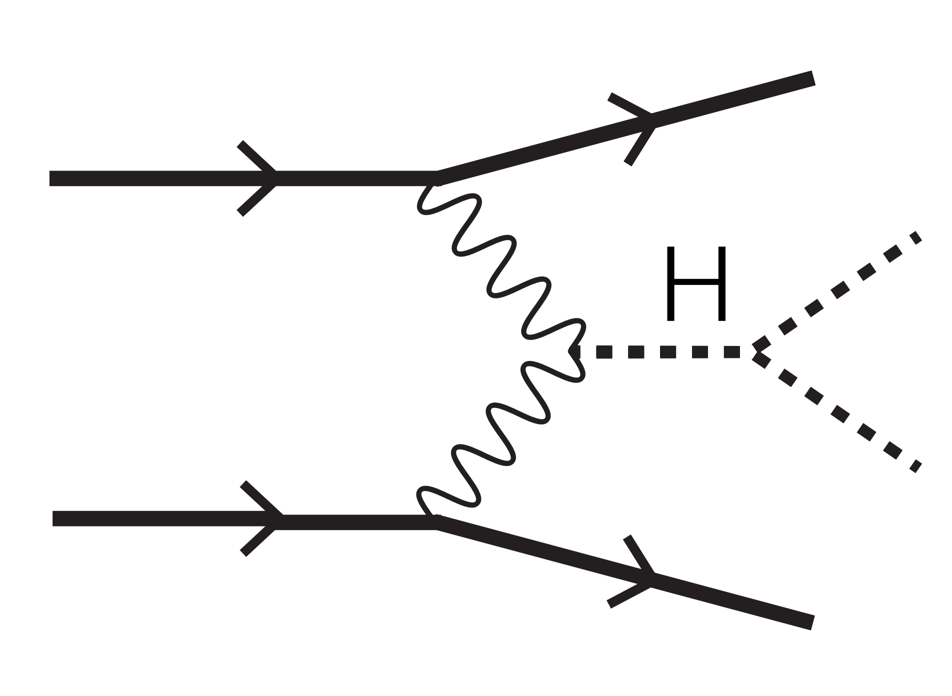
Muon collider physics

$\sqrt{s} \sim 10+$ TeV

- Discovery
  - direct or indirect BSM production
- Precision
  - Higgs production with vector boson fusion
- μTristan at KEK

  $\mu^+\mu^+$ or μ^+e^- @ 1 TeV





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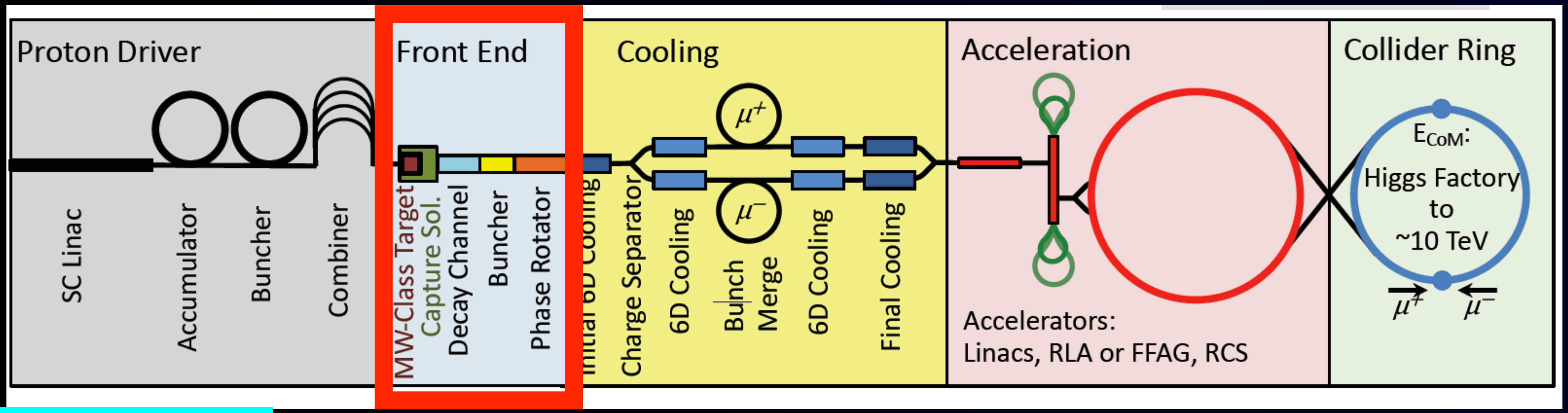

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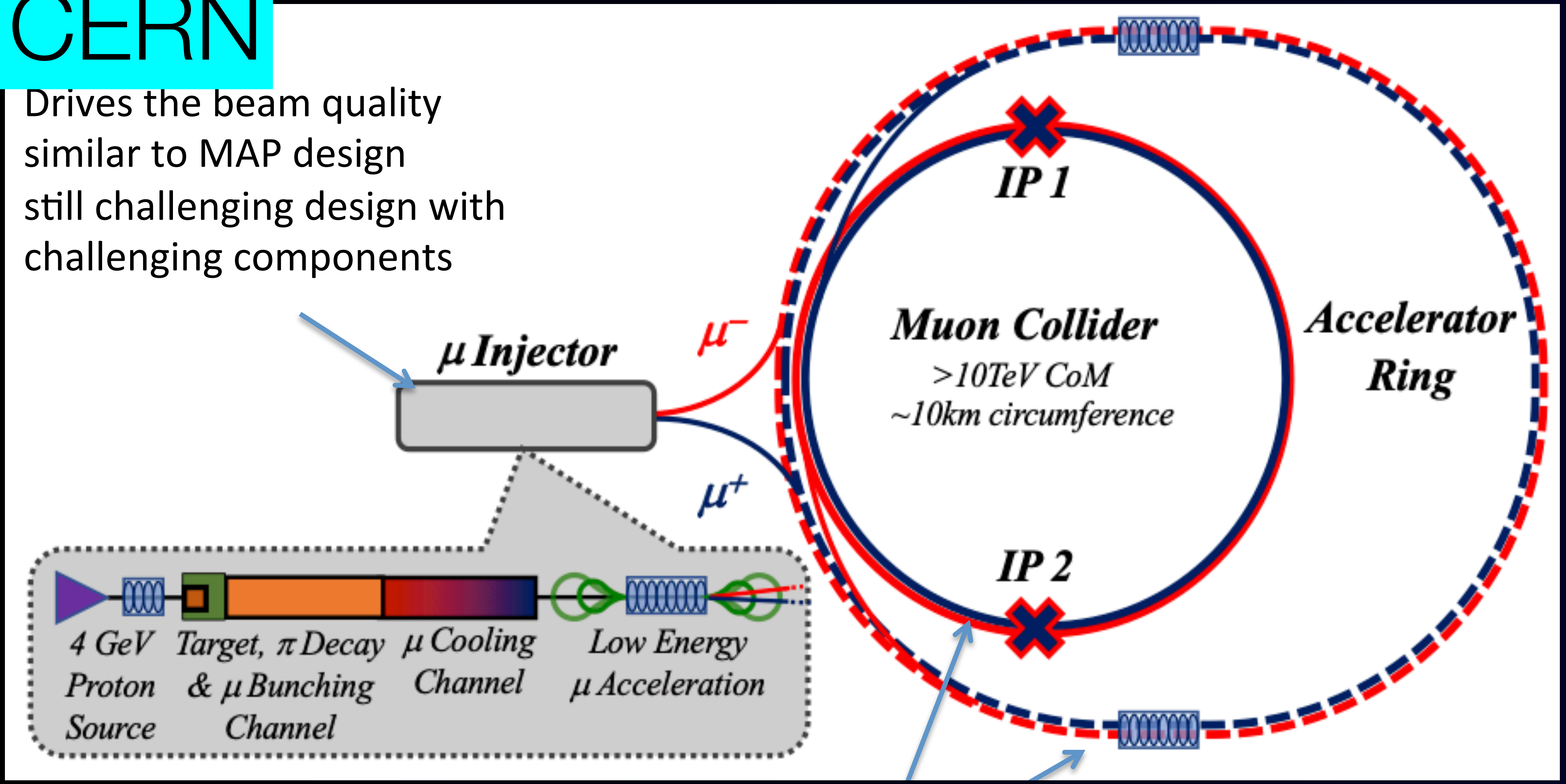

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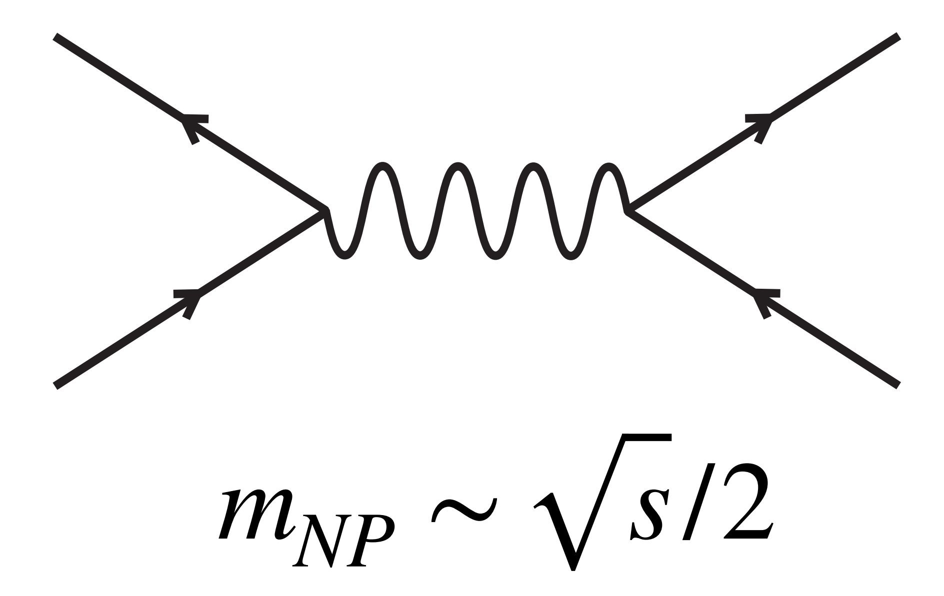

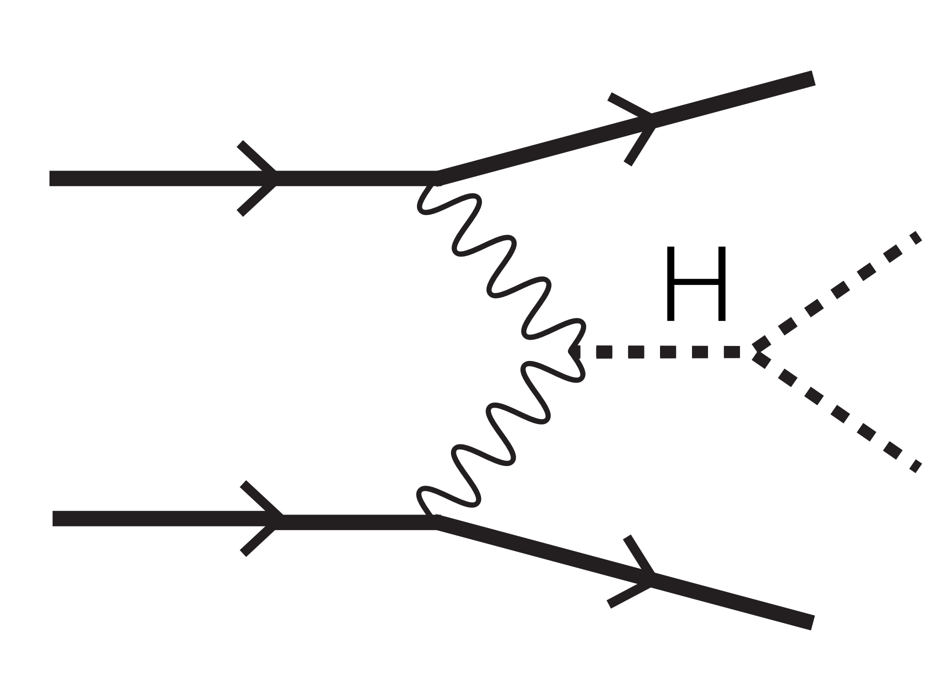

Highly intense muon source

phase-rotation, muon cooling, etc.

Some More with Muons

Some More with Muons

Some of muon particle physics topics which were not covered are :

- Normal muon decay
  - precise measurements of Michel parameters
- CLFV
  - $\mu \to e\gamma\gamma$
  - $\mu^- e^- \to e^- e^-$ in a muonic atom
  - $\mu N \to \tau N$ DIS scattering
- Muonium
  - Muonium hyperfine splitting
  - Muonium 1s-2s spectroscopy

any missing !

Summary

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Thank you for your attention!

my dog, IKU

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