A search for muon-to-electron conversion at J-PARC:
The COMET Experiment

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on behalf of the COMET Collaboration

5th High Energy Physics in the LHC Era, 16-20.Dec.2013, Valparaíso, Chile

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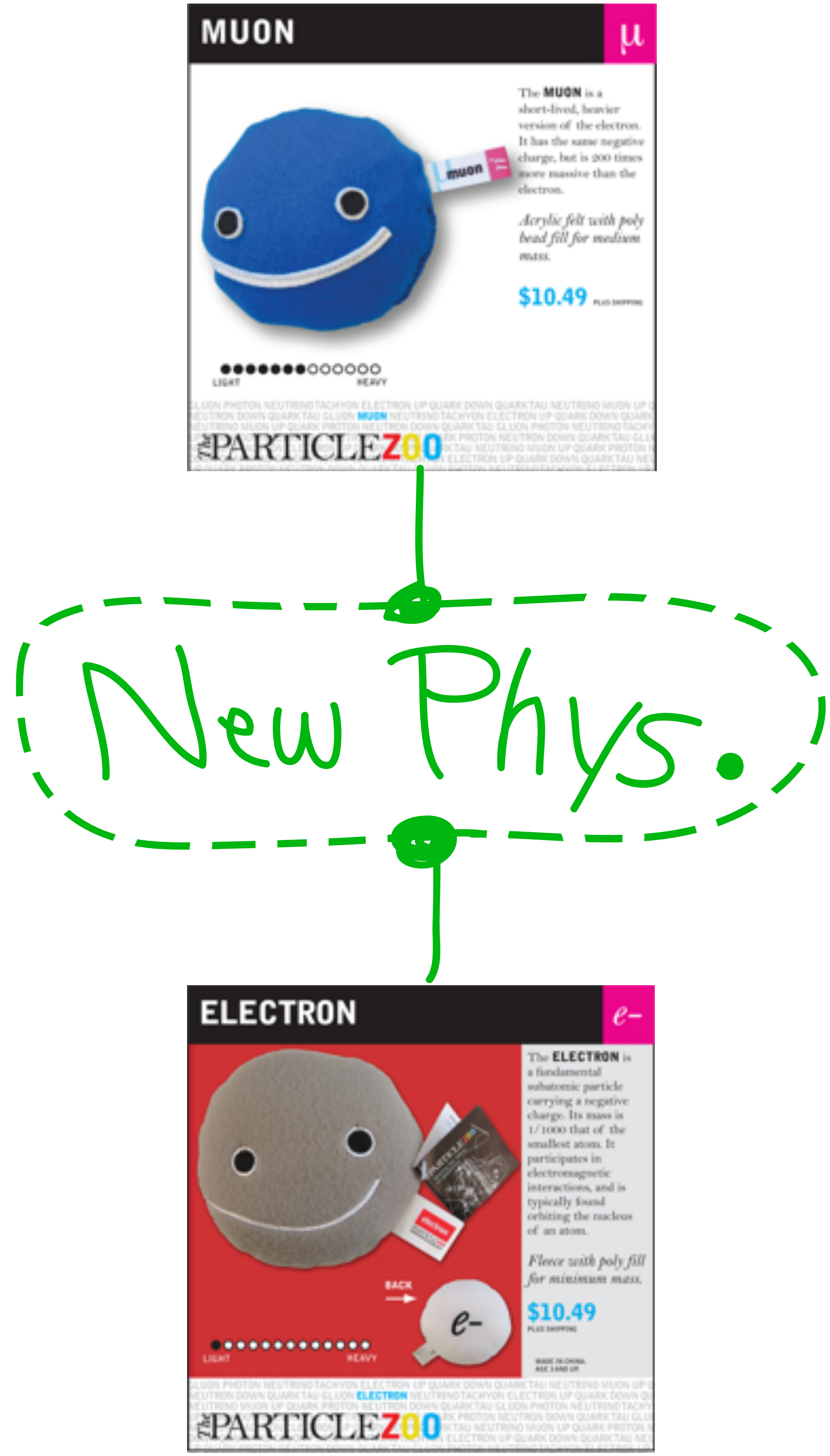
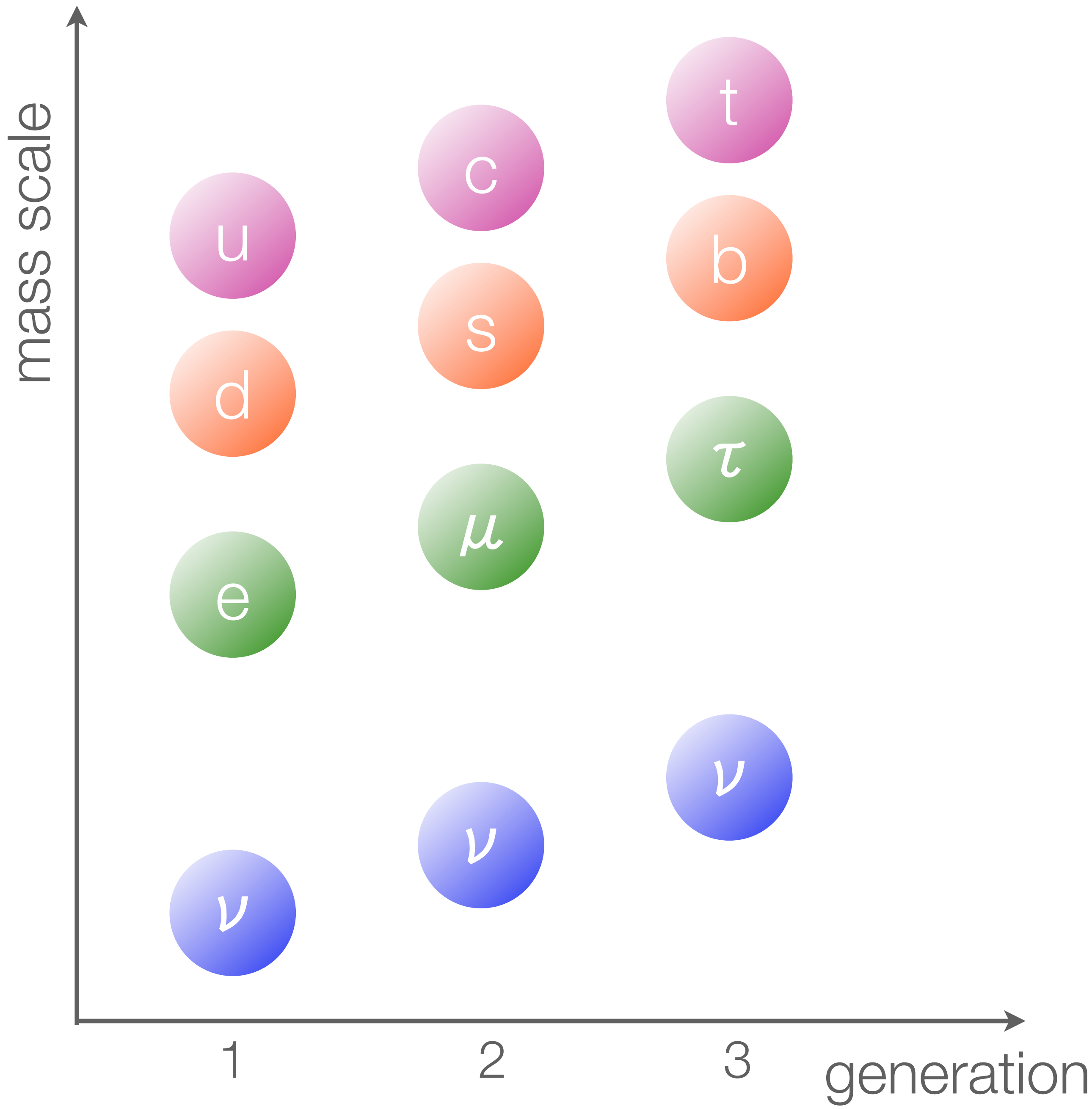


LFV

in particular, among the **muon**...

Flavour Violation



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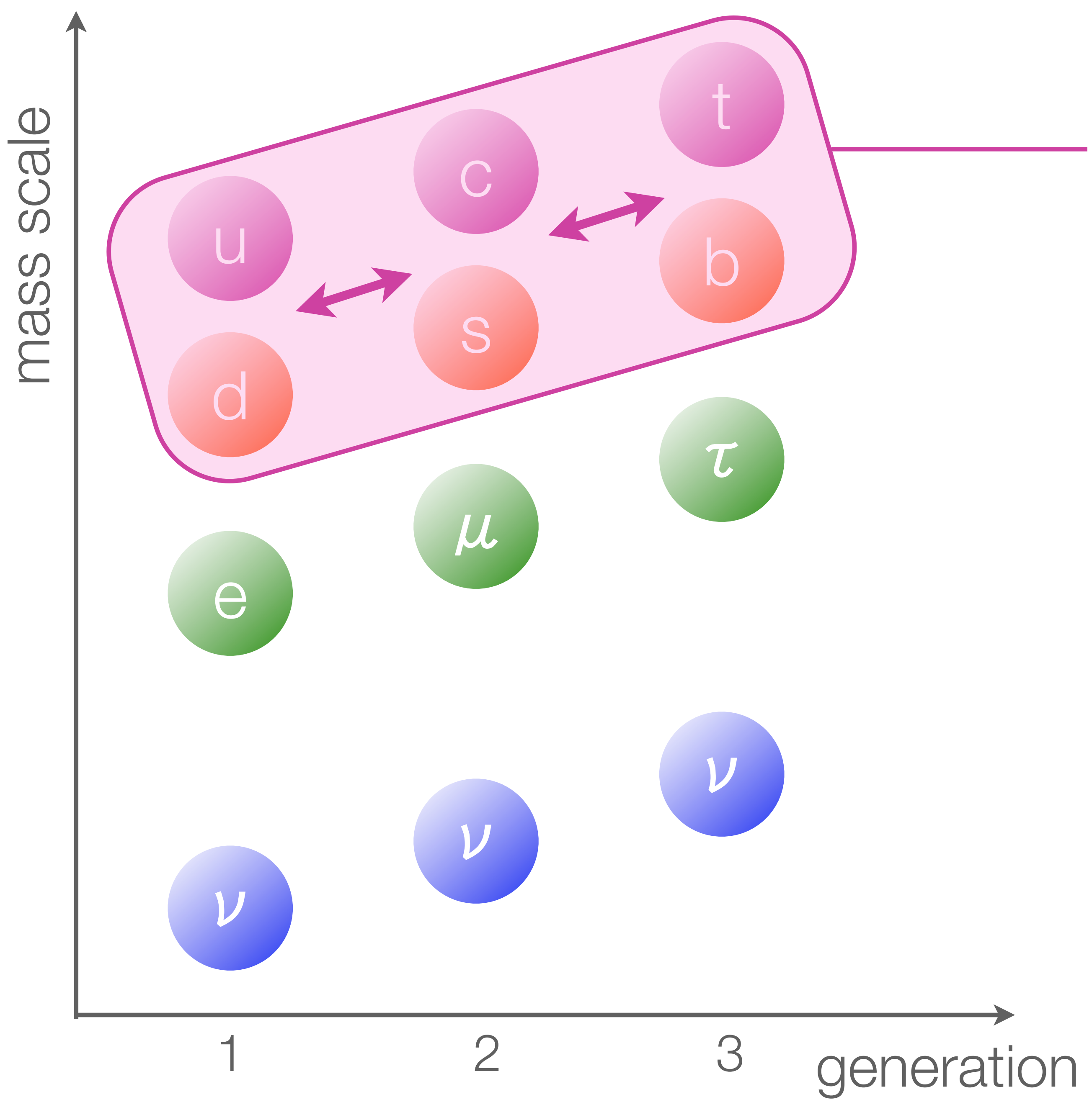
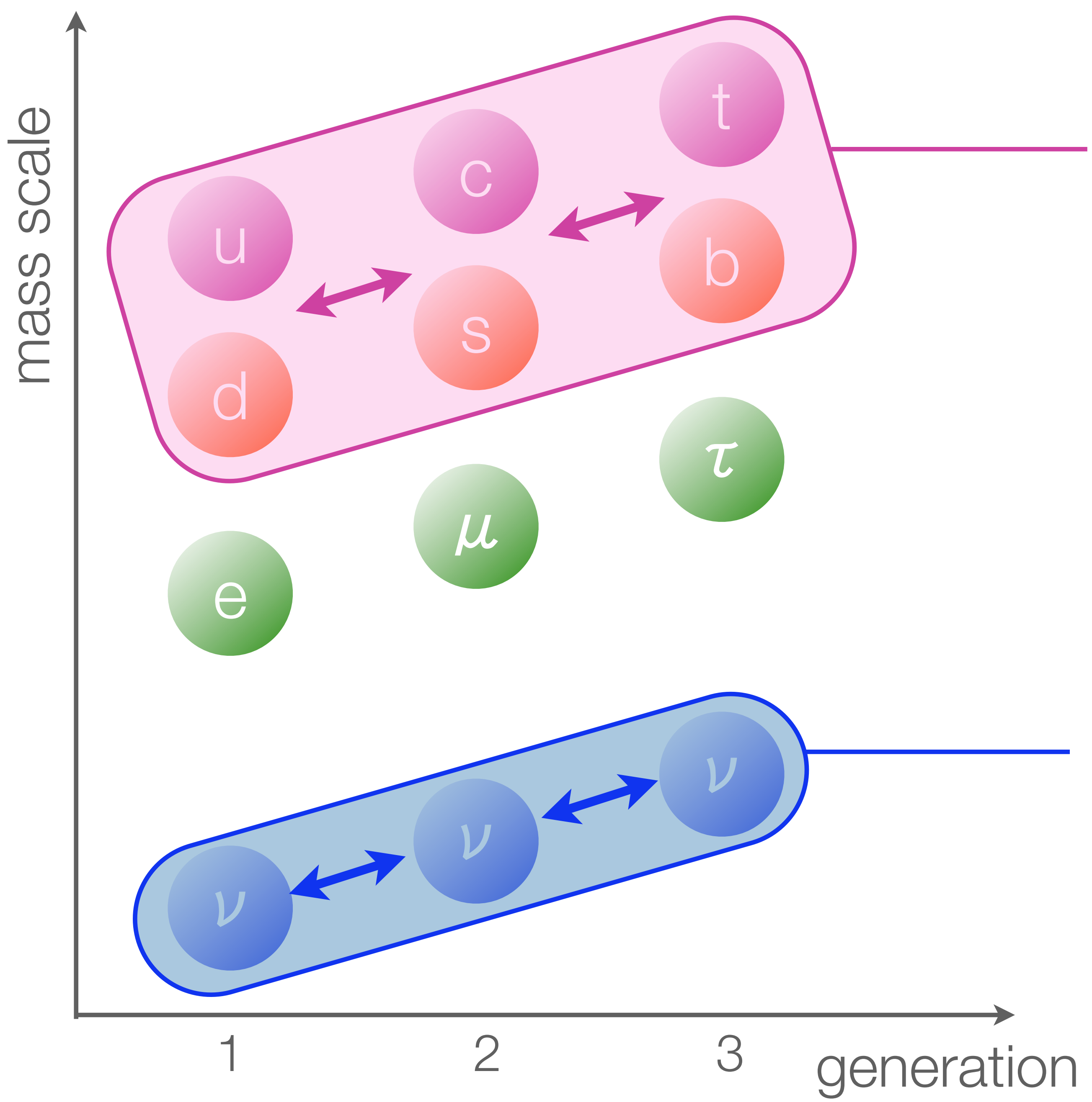


- Quark Sector
  - Mixed by CKM mechanism
  - Experimentally Verified
    - ➡ B factories

Flavour Violation



Quark Sector

- Mixed by CKM mechanism
- Experimentally Verified
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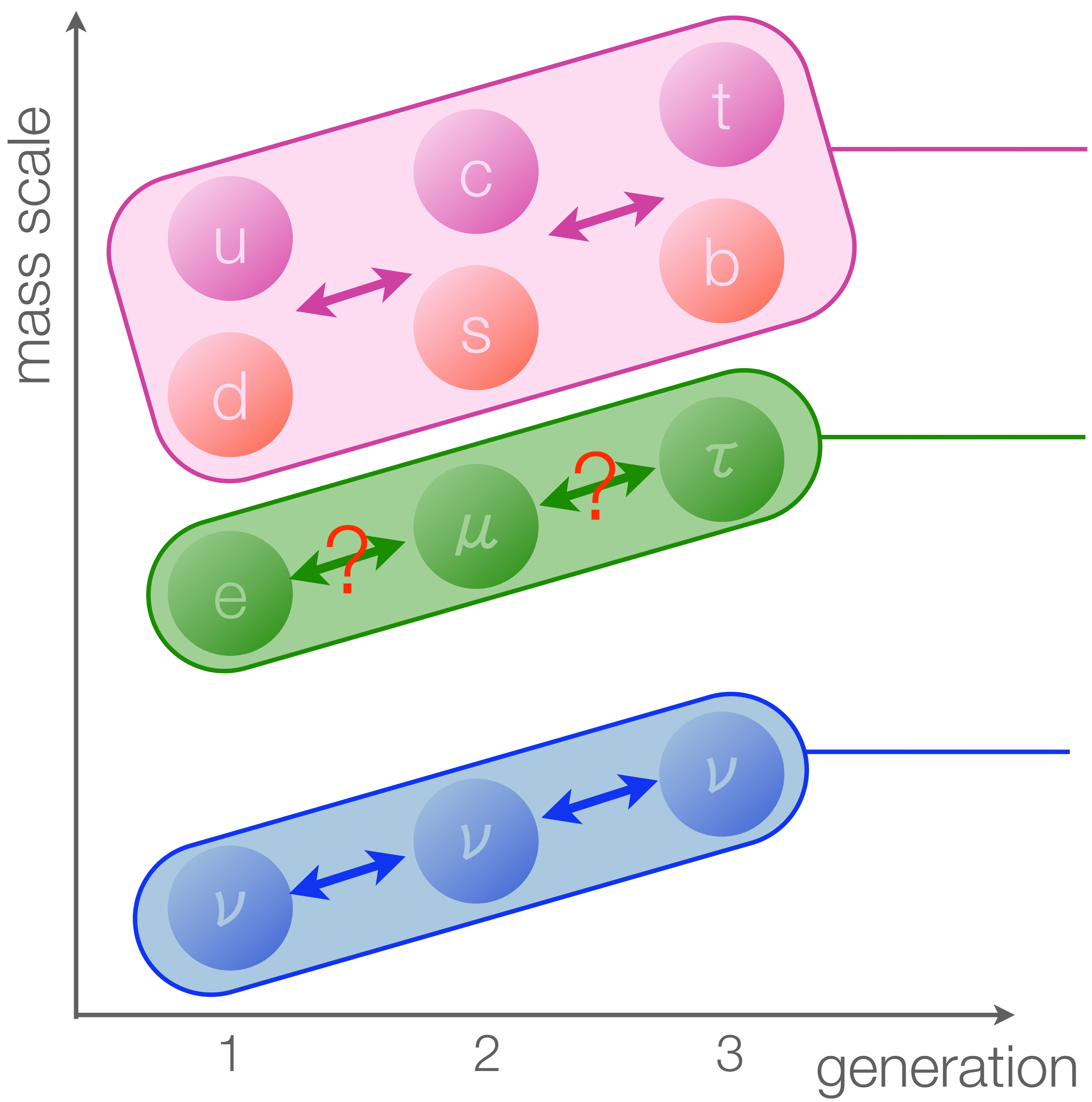
neutral Lepton Sector

- Neutrino Oscillation
- Experimentally Verified
  - ➡ SK, SNO, KamLAND, etc.

Flavour Violation



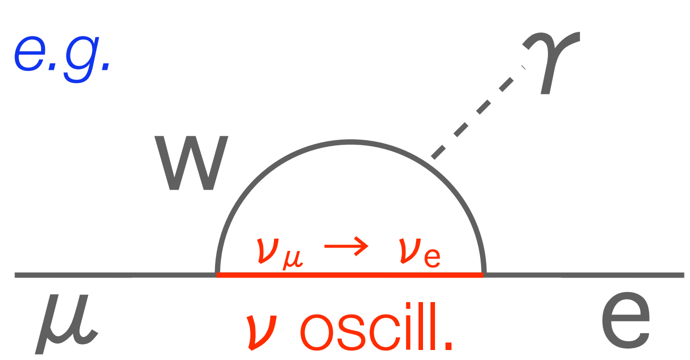
- **Quark Sector**
  - Mixed by CKM mechanism
  - Experimentally Verified
    - ➡ B factories
- **charged Lepton Sector**
  - source from beyond SM ??
  - never observed yet !!
- **neutral Lepton Sector**
  - Neutrino Oscillation
  - Experimentally Verified
    - ➡ SK, SNO, KamLAND, etc.

Why the charged LFV is so attractive ?

Why ? : Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

SM + simple ν Oscillation

- charged LFV is possible



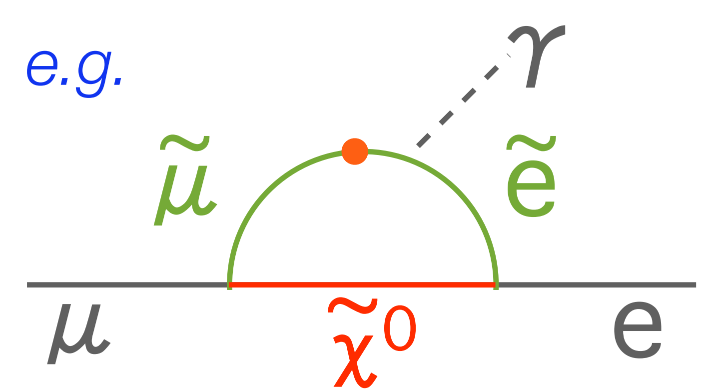
- but extremely rare

$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2$$

- $B(\mu \rightarrow e\gamma) \lesssim 10^{-50}$!!!

beyond SM (SUSY-GUT *etc.*)

- charged LFV is largely enhanced



- still rare but observable level

$$\mathcal{B}(\mu \rightarrow e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

- $B(\mu \rightarrow e\gamma) = 10^{-15} \sim 10^{-11}$!!!

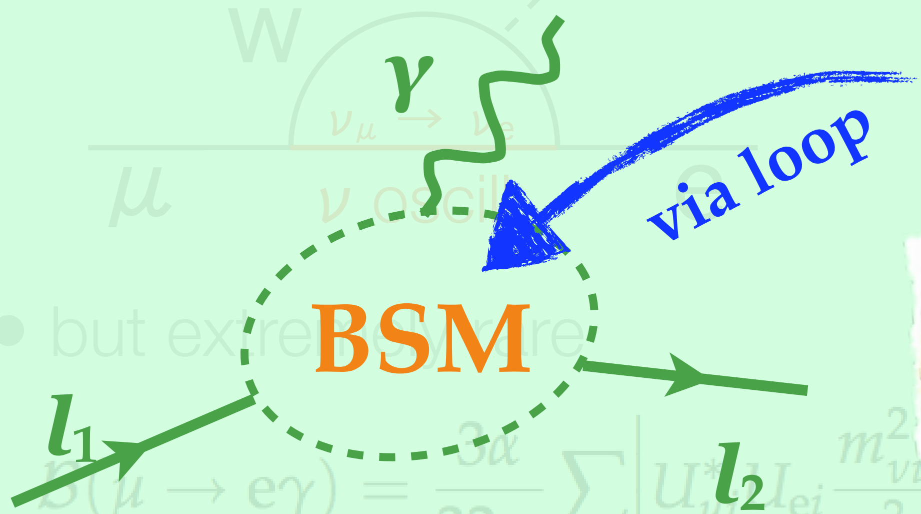
Why the charged LFV is so attractive ?

- **Why ? :** Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

- SM + simple ν Oscillation
  - charged LFV is possible
  - but extremely rare
  - $B(\mu \rightarrow e\gamma) \leq 10^{-50}$!!!

- beyond SM (SUSY-GUT etc.)
  - charged LFV is largely enhanced
  - $B(\mu \rightarrow e\gamma) = 10^{-15} - 10^{-11}$!!!

"charged LFV" = "NEW PHYSICS"



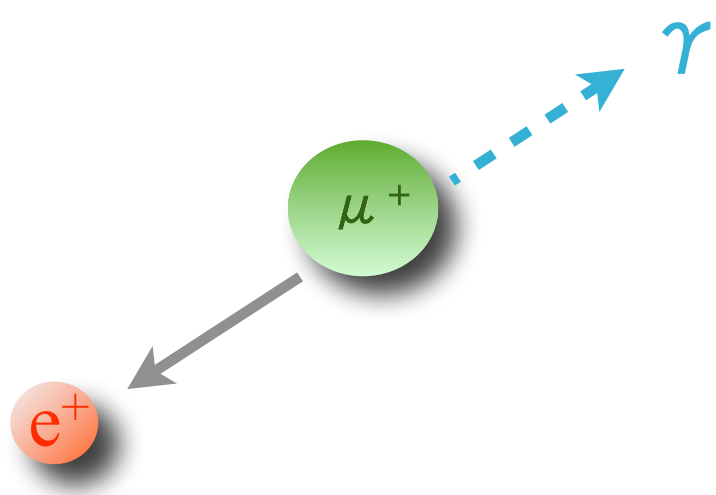
TeV-scale New Physics

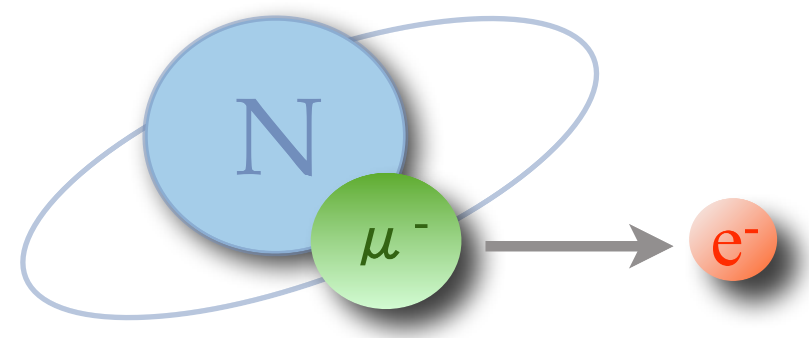
competitive & complementary to LHC !

$\mu N \rightarrow eN$

muon to electron conversion in nuclei

Two Famous Muon LFV Processes



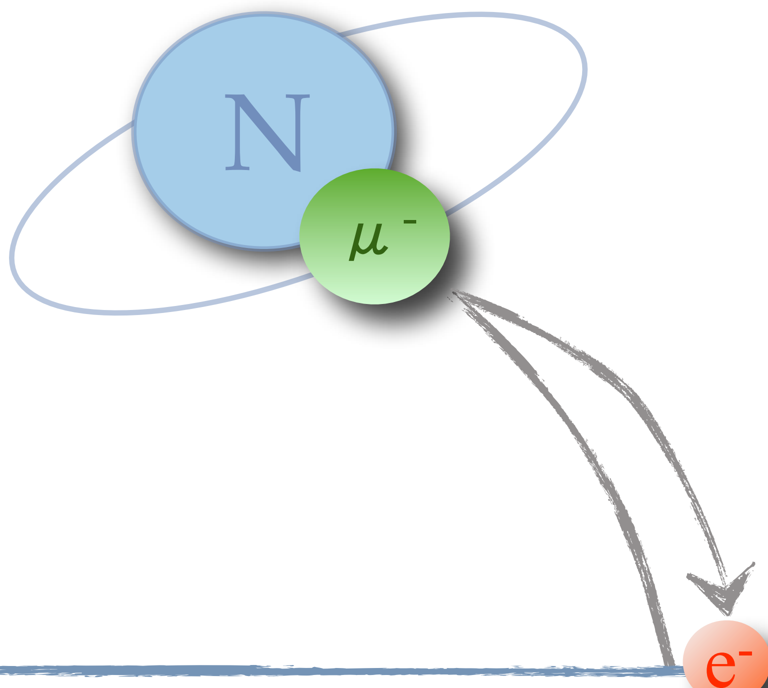


$\mu \to e\gamma$

$\mu N \to eN$

What is the Muon-to-Electron Conversion ?

- *1S* state in a muonic atom



Muon Decay in Orbit (DIO)

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

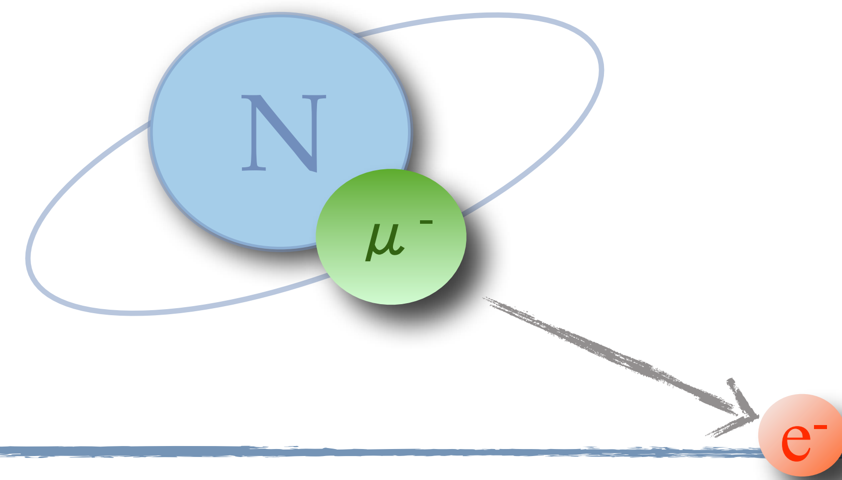
or

e-

Nuclear Muon Capture

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

- If μ-e Conversion is Occurred ...



Neutrino-less Muon Nuclear Capture

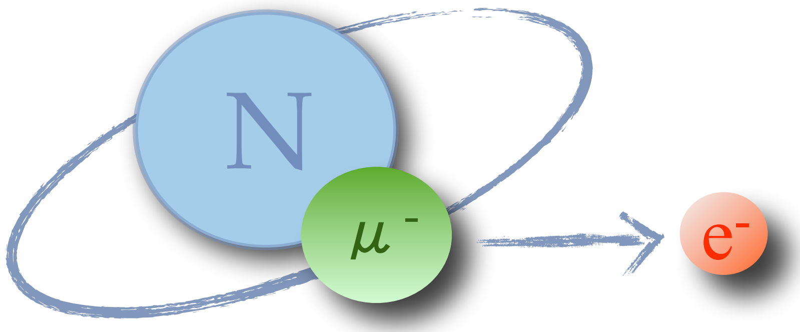
$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

- Branching Ratio is Determined as

$$\mathcal{B}(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Experimental Signature

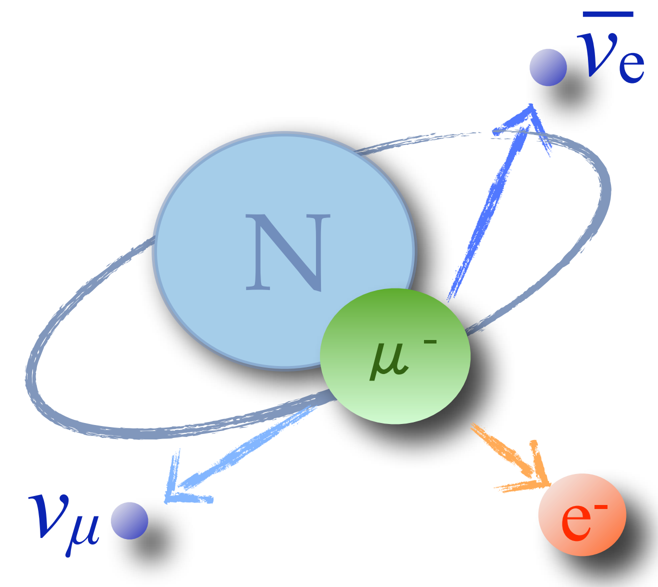
- **Signal**



- ***$E_e = m_\mu - B_\mu$ ~ 105MeV***
- Coherent Process (Z_{ini}=Z_{end})

Signal : Single Mono-Energetic Electron
Sensitivity : Limited by Beam Quality
- **Wait until Pion decays**
- **Pulsed Beam is the BEST**

- **Backgrounds**
  - **Muon Decay in Orbit (DIO)**

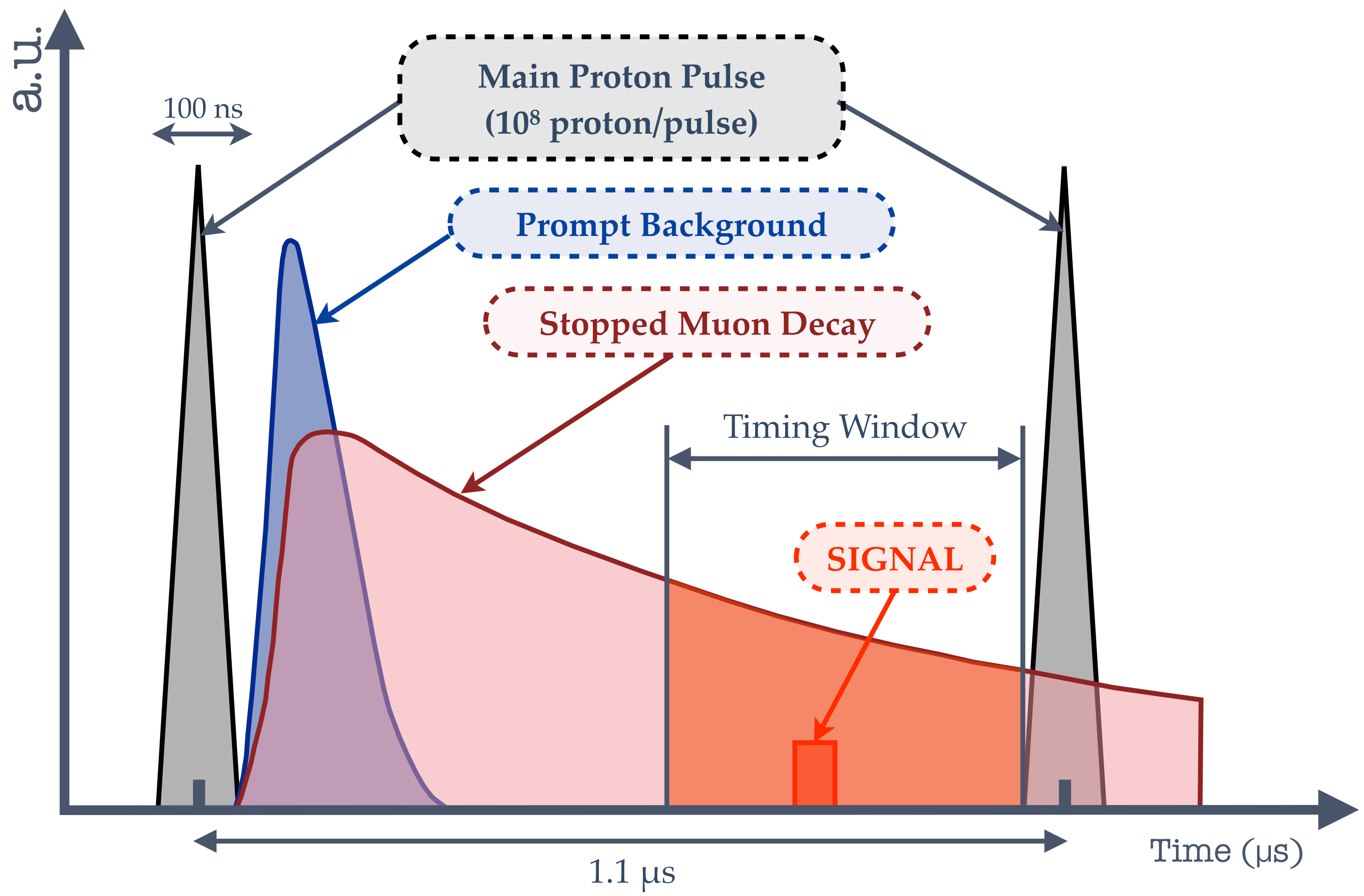


- Radiative Muon Capture
- Radiative Pion Capture
- Electrons from Muon DIF
- Cosmic Rays, *etc.*

Proton Pulsing = Good Proton "Extinction"

- **Extinction** (= Residual protons in between the pulses)

- Dominant Backgrounds
  - Beam Pion Capture
    - π+(A,Z)→(A,Z-1)* →γ+(A,Z-1), γ→e^+e^-
    - Prompt Timing
    - *cf.* **$\tau_{(\text{muonic Al})}$=0.88μs**
  - Muon DIO, e^- scattering



Extinction should be <10^{-9} : To achieve 10^{-17} Single Event Sensitivity

COMET Experiment

COMET Experiment - Overview -

High Intensity Muon

Pion capture and muon transport by superconducting solenoids would provide high beam intensity.

Pulsed Muon Source

Beam pulsing is very important in order to suppress prompt BG. Pulse Separation should be ≳ 1μsec.

Special Muon Transport

A muon beam line should be sufficient long to eliminate pions in a muon beam, and dedicated to reject DIO electrons.

High Resolution Detectors

Endpoint of spectrum of DIO electron comes to the signal region. Good σ_E is mandatory.

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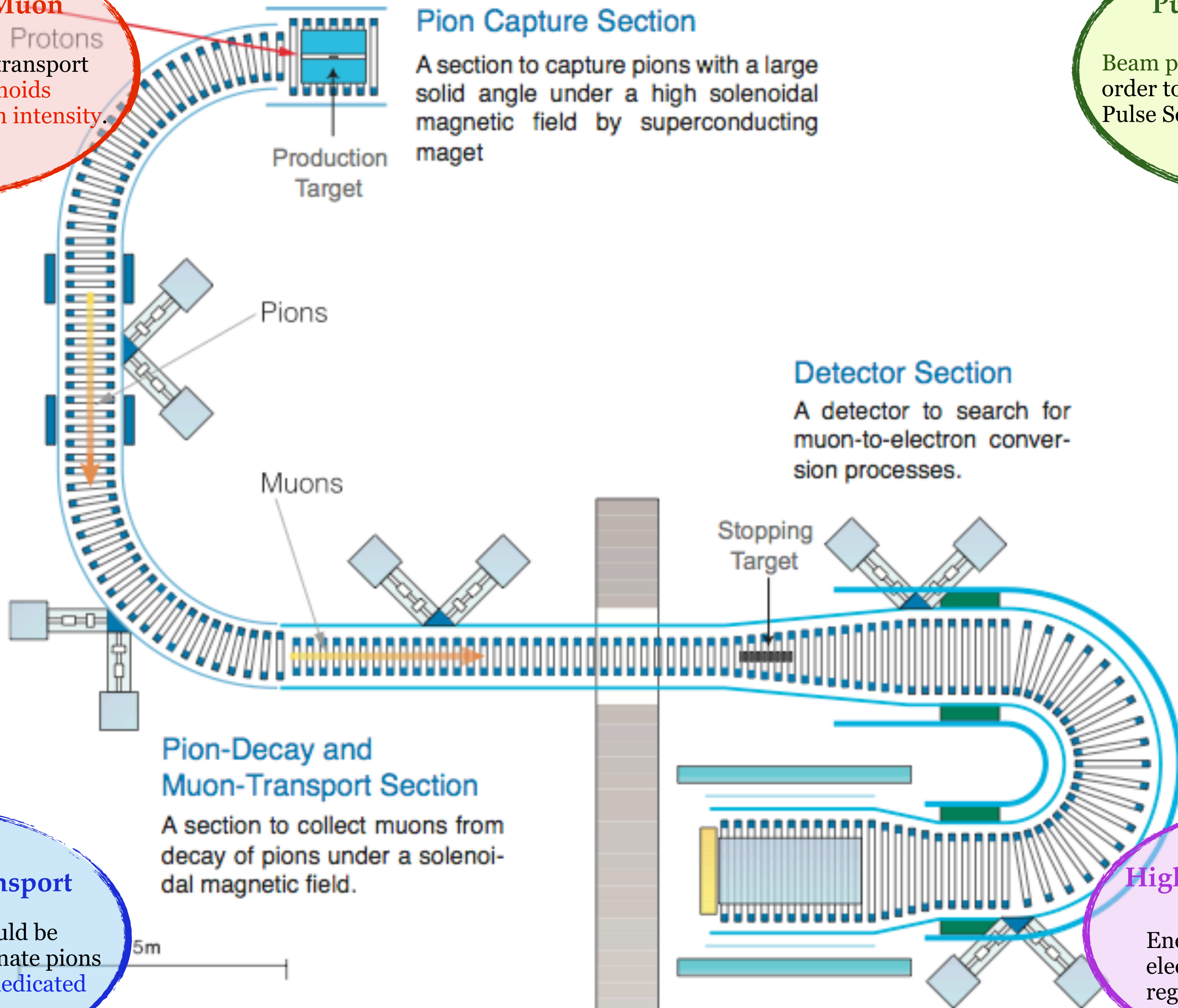

Special Muon Transport

A muon beam line should be sufficient long to eliminate pions in a muon beam, and dedicated to reject DIO electrons.

High Resolution Detectors

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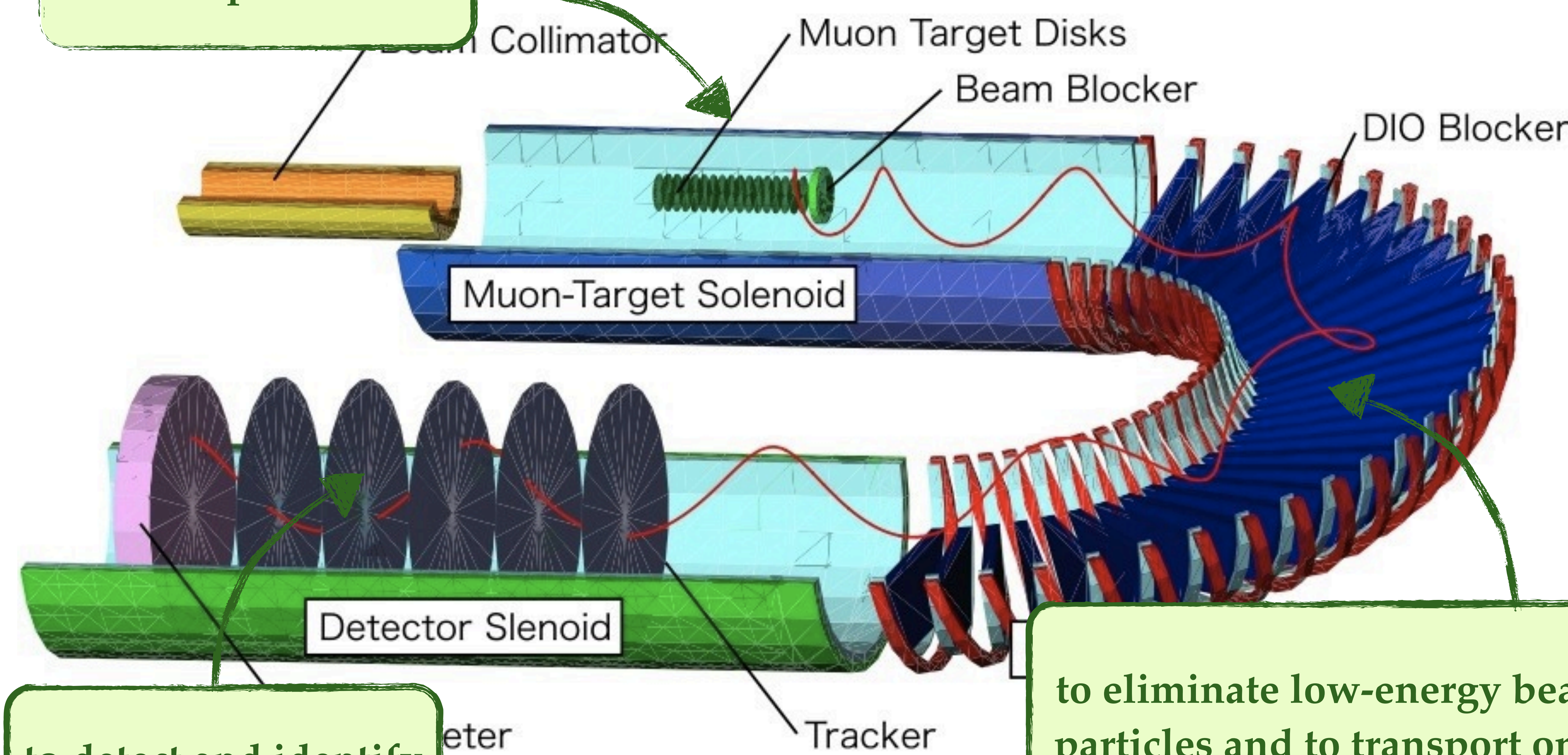
COMET Detector Apparatus

to stop muons



to detect and identify 100 MeV electrons

to eliminate low-energy beam particles and to transport only ~100 MeV electrons

COMET Expected Sensitivity

- Single Event Sensitivity (2×10^7 sec running):

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

  - N_μ is a # of stopped muons
    - 2.0×10^{18} muons
  - f_{cap} is a fraction of muon capture
    - 0.6 for aluminum
  - A_e is the detector acceptance
    - 0.031

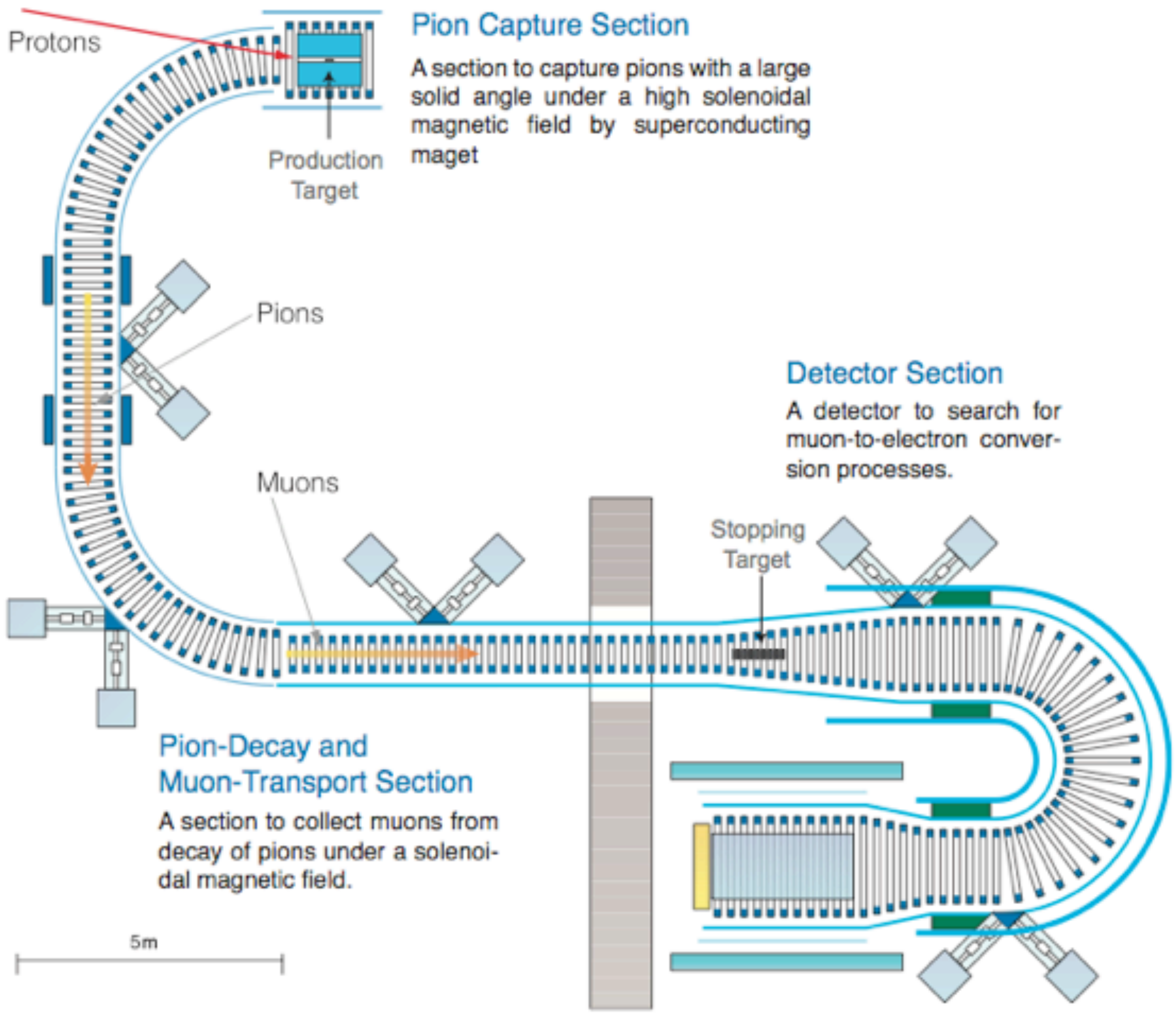
total # of p's	**8.5×10^{20}**
μ yield / p	**0.0035**
μ stopping ε	**0.66**
# of stopped μ's	**2.0×10^{18}**

Single Event Sensitivity
2.6×10^{-17}

Upper Limit (CL.90)
6.0×10^{-17}

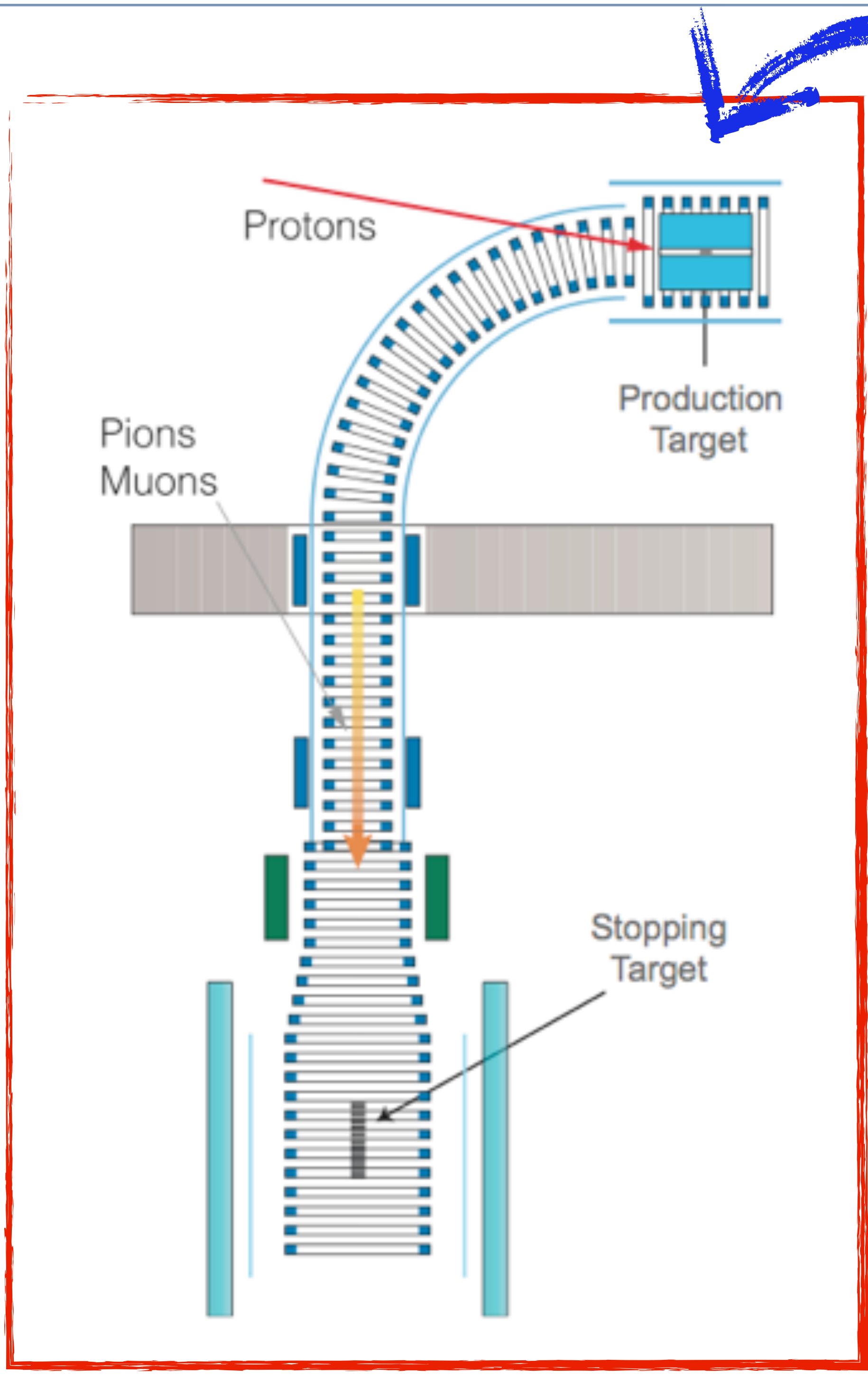
COMET
Staging Approach

Staging Approach for the COMET Realization

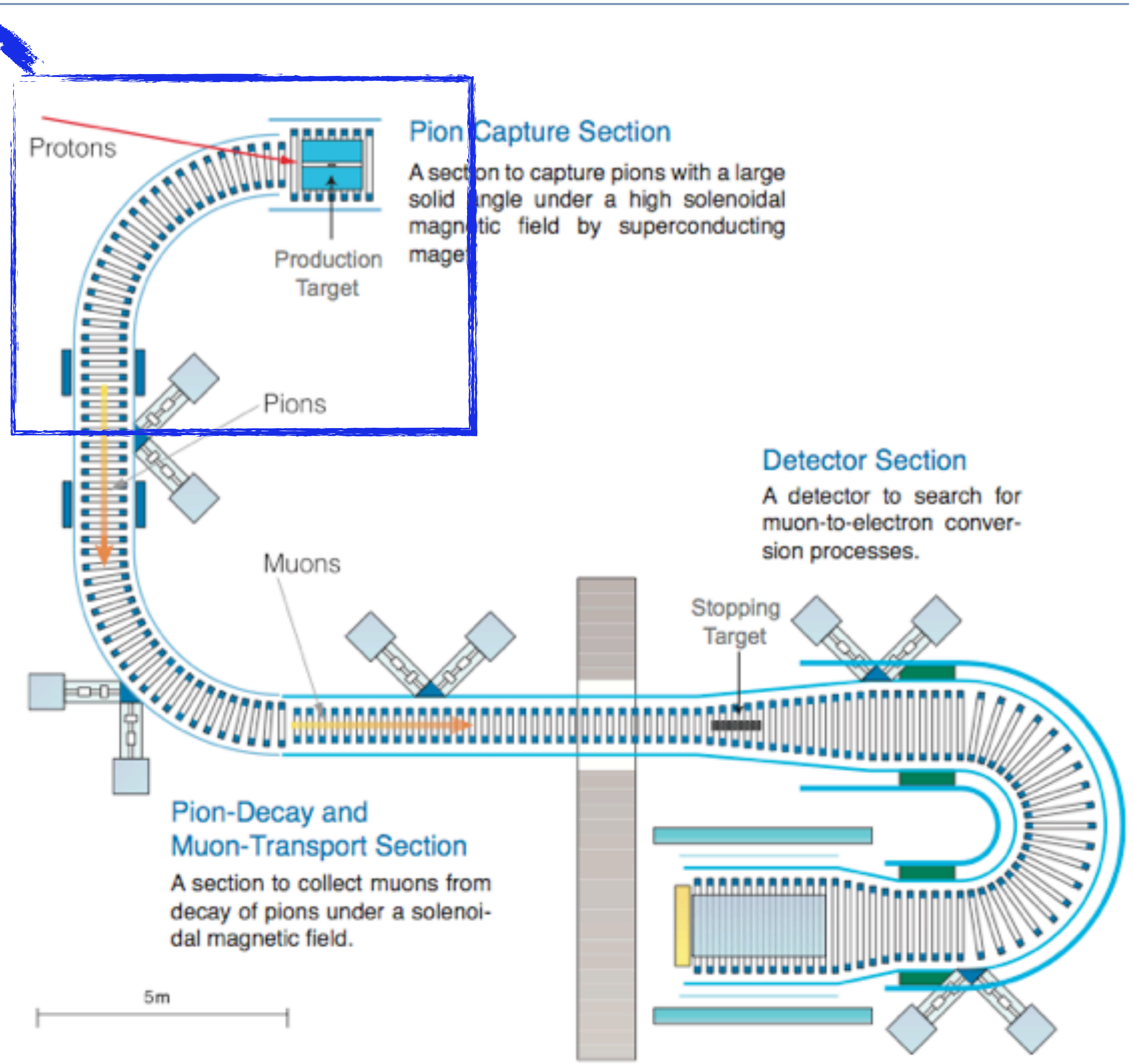


full COMET (phase-II)

Staging Approach for the COMET Realization



(phase-I)



full COMET (phase-II)

Goal of COMET phase-I

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① Background Study for the full COMET (phase-II)

- direct measurement of potential background sources for the full COMET experiment by using the actual COMET beam line

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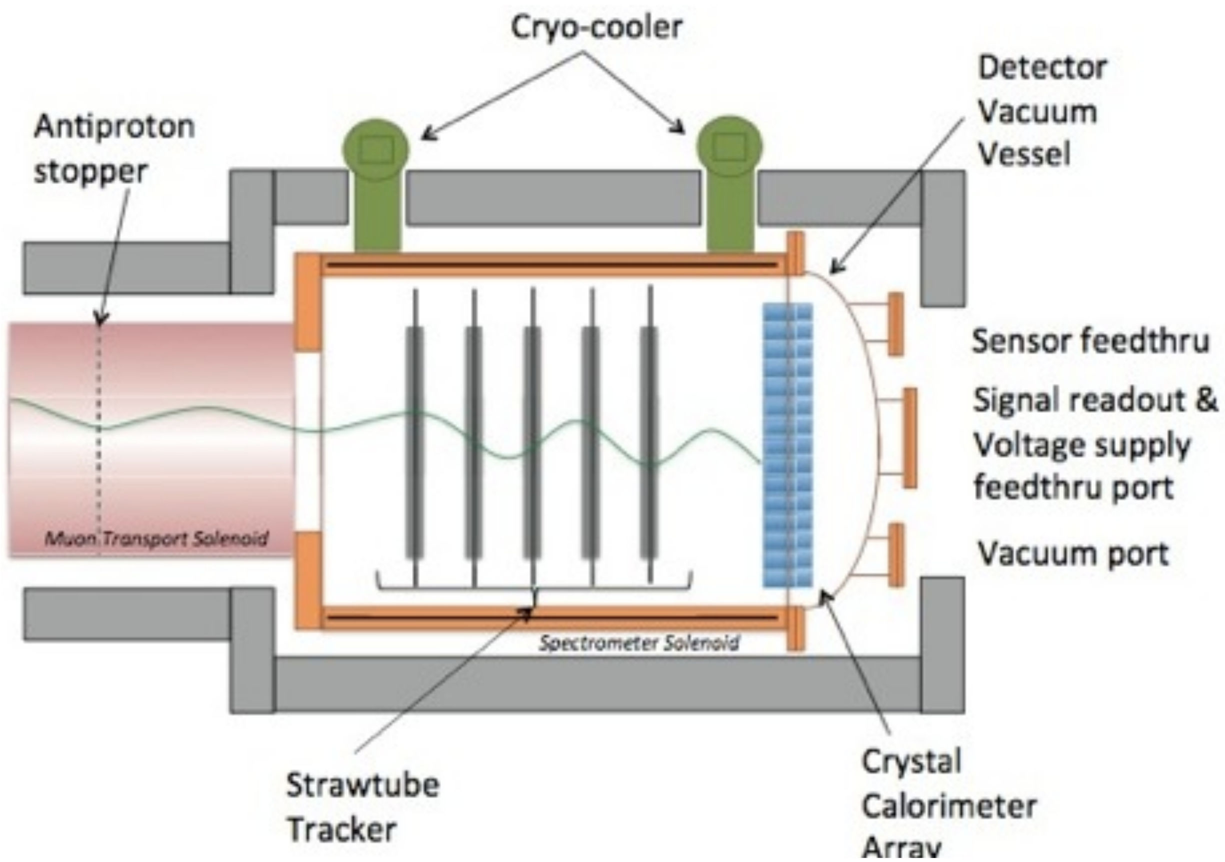
① Background Study for the full COMET (phase-II)

- direct measurement of potential background sources for the full COMET experiment by using the actual COMET beam line

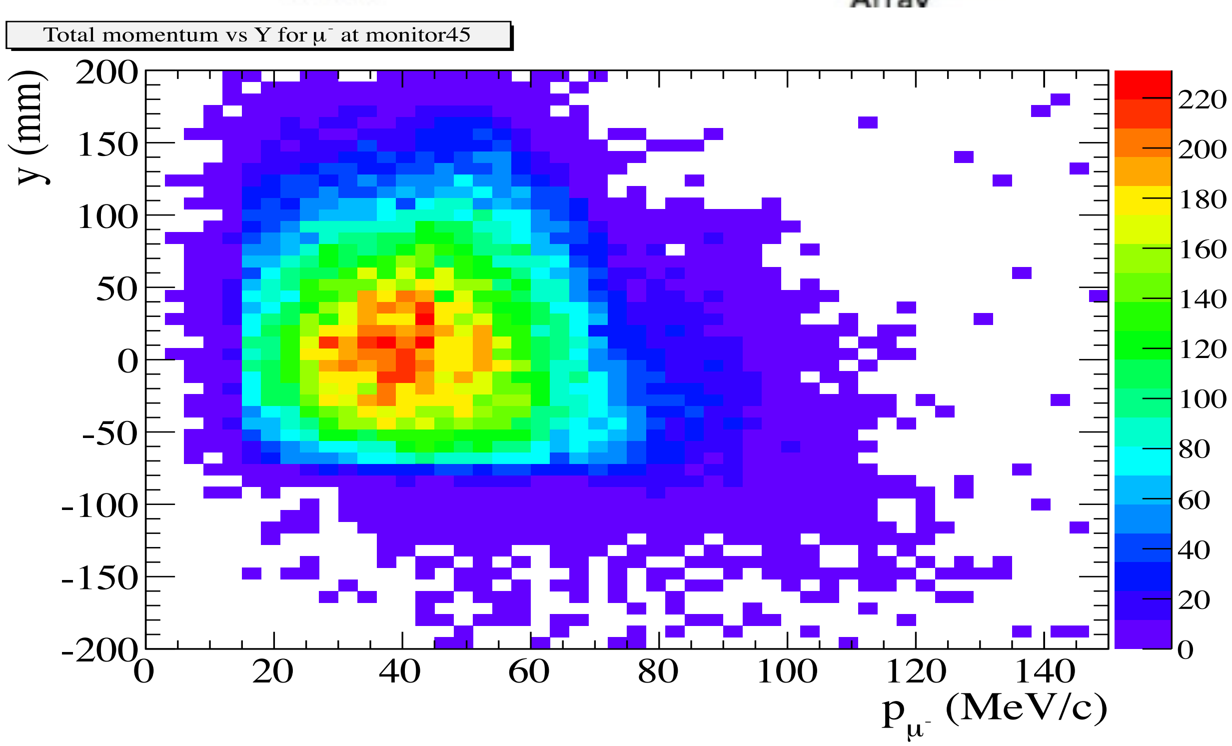
② Search for μ-e Conversion

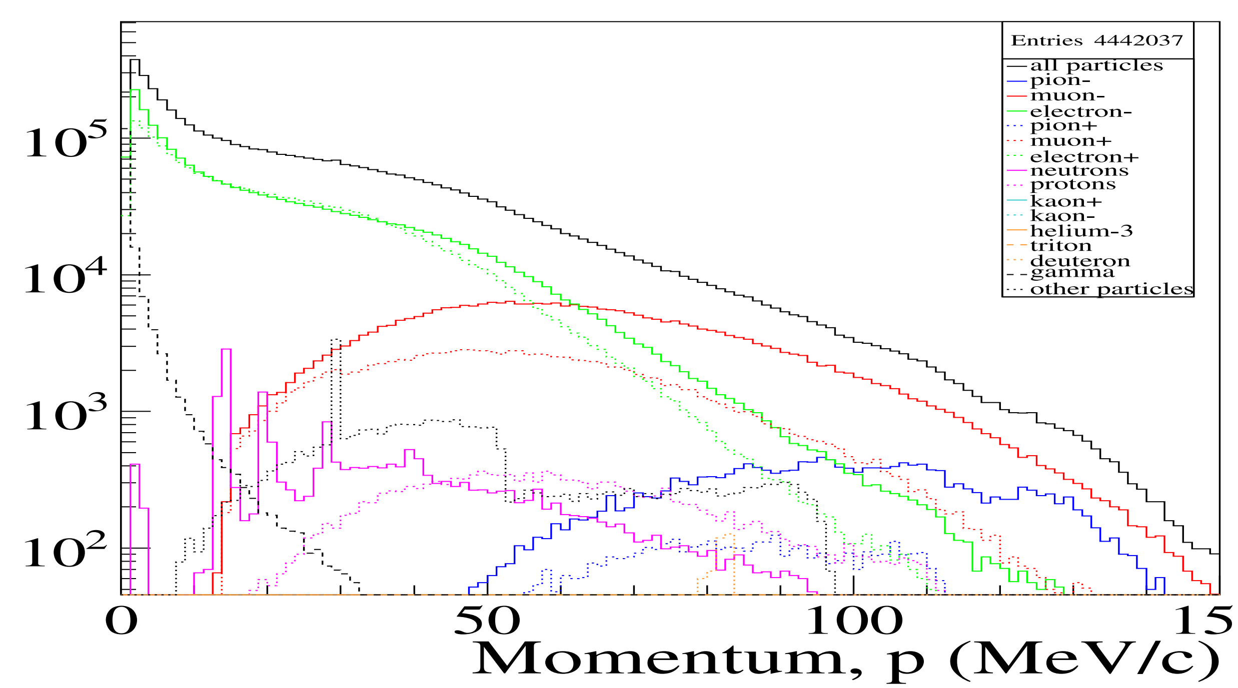
- a search for μ-e Conversion at the intermediate sensitivity which would be 100-times better than the present limit (SINDRUM-II)

Background Study



- **Measure almost all particles**
- **Same detector technology for phase-II**
  - SC spectrometer solenoid
  - Straw Tube Transverse Tracker
  - Crystal Calorimeter
- Particle ID with dE/dx and E/p



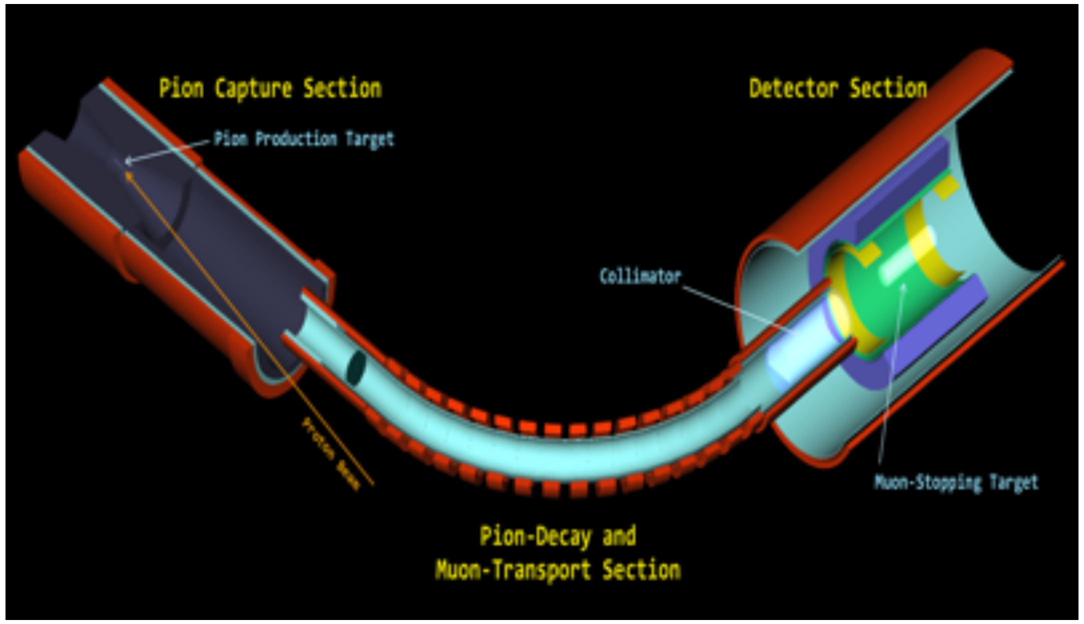


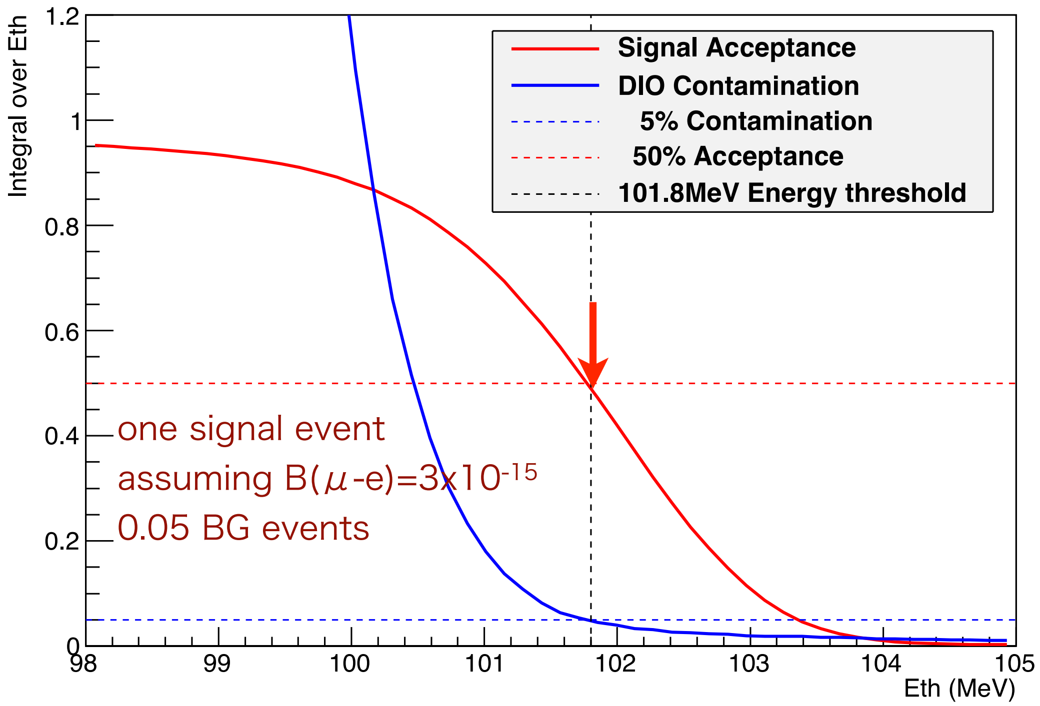
Search for μN→eN by the COMET phase-I

- 8GeV, 3.2kW proton beam is assumed
  - 2.5×10^{12} protons/sec
  - 10^{-9} of extinction is supposed
- 12 days (10^6 sec) running time
- Expected single event sensitivity

$$\mathcal{B}(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{N_\mu^{stop} \cdot f_{cap} \cdot \mathcal{A}_{\mu-e}}$$

  - $\mathcal{B}(\mu+Al\rightarrow e+Al) = 3.1\times10^{-15}$
- Upper limit at 90% C.L.
  - $\mathcal{B}(\mu+Al\rightarrow e+Al) < 7.0\times10^{-15}$
  - *cf.* present limit < 7×10^{-13} (SINDRUM-II)





Summary of COMET phase-I/II

	COMET-Phase-I	COMET-Phase-II
experiment starts (*)	in 2016 / 2017	in 2019 / 2021
beam intensity	3.2kW (8GeV)	56kW (8GeV)
running time	1.5×10^{6} (sec)	2.0×10^{7} (sec)
# of protons	3.8×10^{18}	8.5×10^{20}
# of muon stops	8.7×10^{15}	2.0×10^{18}
muon rate	5.8×10^{9}	1.0×10^{11}
# of muon stops / proton	0.0023	0.0023
# of BG	0.03	0.3
S.E.S.	3.1×10^{-15}	2.6×10^{-17}
U.L. (90%CL.)	7.0×10^{-15}	6.0×10^{-17}

(*) Engineering runs and Physics runs

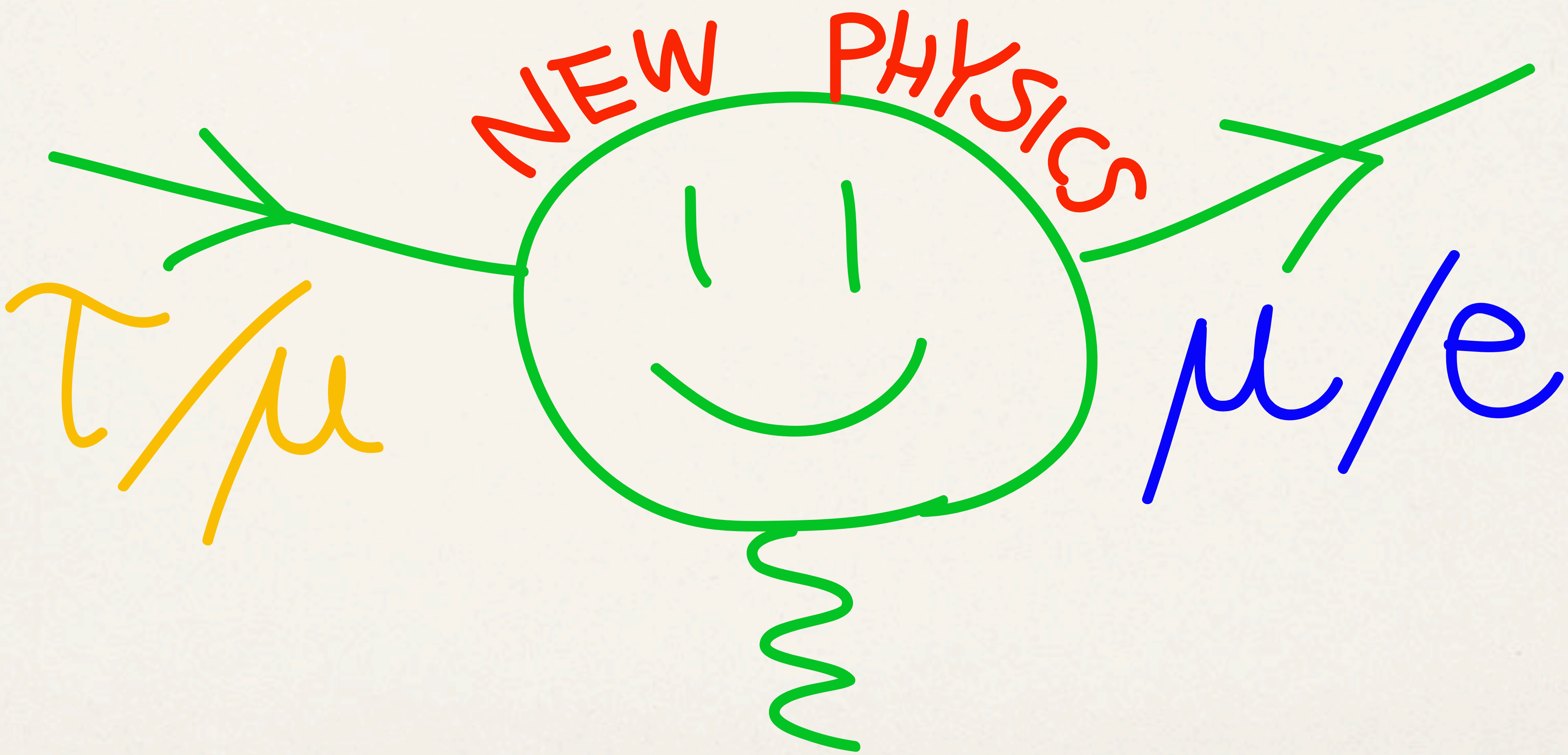
Current Status

- Even after the J-PARC radioactivity accident, design works on the beam-line and detector R&D has been ongoing → **Still On-Schedule**.
- Proton Extinction at J-PARC was directory measured, extinction of 1.5×10^{-11} was confirmed → Enough good to start the COMET experiment !!
- Beam-line and facility **construction will start next month**.
  - Budget for beam-line construction has been already secured for Phase-I.
- Detector R&Ds are approaching to the end.
  - Currently the final prototyping is ongoing, "1-to-1" size for engineering
  - Construction will start in next year and finish at the beginning of 2016
- SC solenoid construction will also start soon.
  - Conductor production is ongoing.
  - Neutron irradiation test has been carried out in order to establish the power cycle procedure since very high neutron dose is expected.
- Staging approach has been endorsed by J-PARC and KEK, stage-1 (of 2 stages) of approval was secured. **Aiming the full approval.**
- Detector group (construction/operation/analysis) is suffering from the lack of man-power, if you are interesting in joining us. Very-very welcome !!

Conclusions

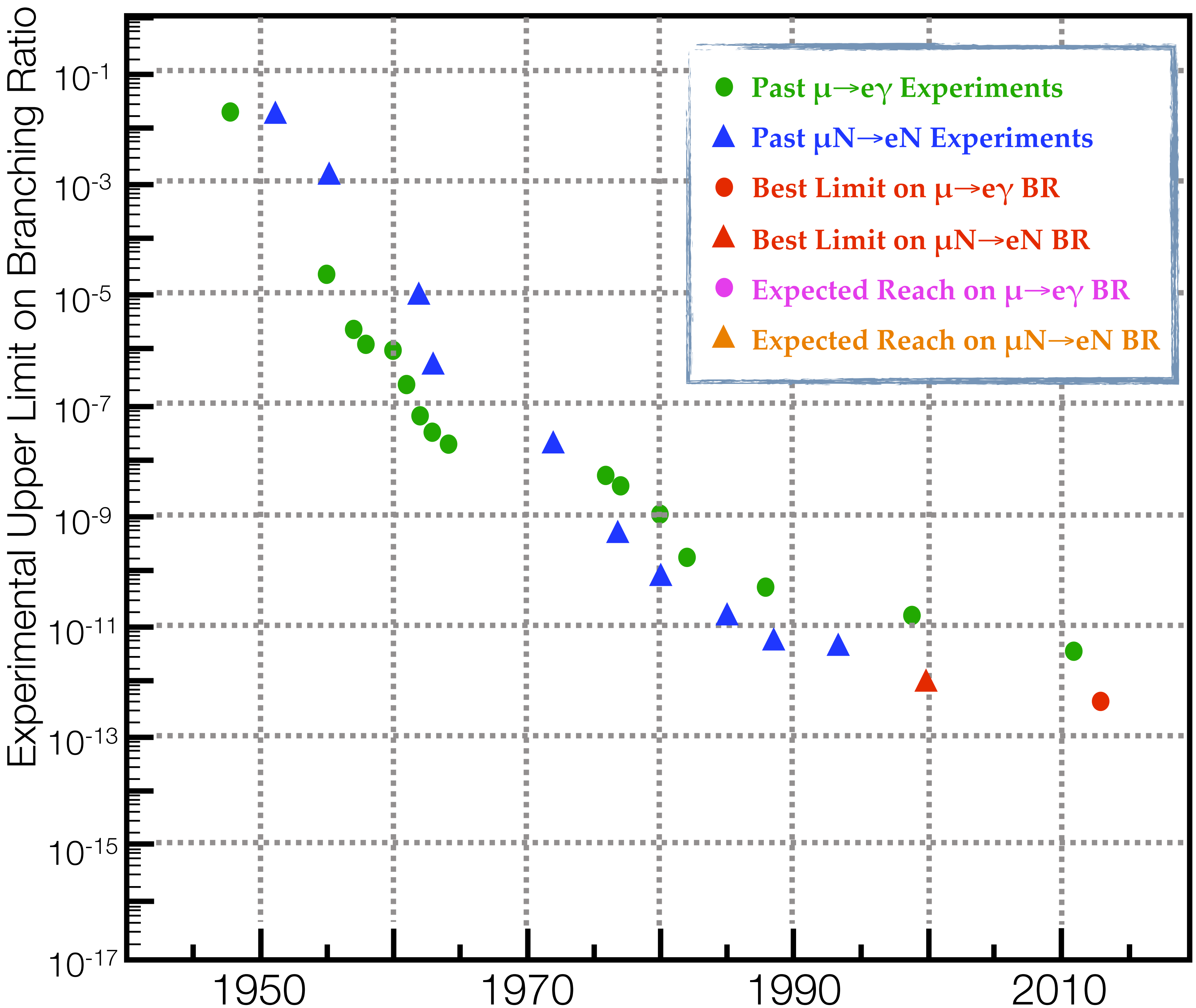
- **Charged LFV** is very attractive to explore the new physics.
- Charged LFV have no observable SM rate and not withstanding backgrounds. Excellent probes of beyond SM.
- In particular, muon decay is one of the most sensitive probe. (**$\mu \rightarrow e\gamma$** & **$\mu N \rightarrow eN$**)
- **$\mu N \rightarrow eN$** : COMET experiment was proposed to J-PARC.
  - CDR completed in 2009 and secured stage-1 (of 2 stages) approval from J-PARC Program Advisory Committee.
  - Significant Milestones have already been reached in Proton Extinction, SC magnet design and Pion Capture System.
  - Staging approach is adopted to realize experiment quickly and successfully.
    - **Phase-1** : "**BG study**" & "**$\mu N \rightarrow eN$ Search** with **2** orders of magnitude better sensitivity" than the present limit will start in 2016(eng.run), 2017(phys.run)
    - **Stage-2** : "**$\mu N \rightarrow eN$ Search** with **4** orders of magnitude better sensitivity" than the present limit will start in 2019(eng.run), 2020(phys.run) with fully equipped beam-line/detectors.

Thank You !!



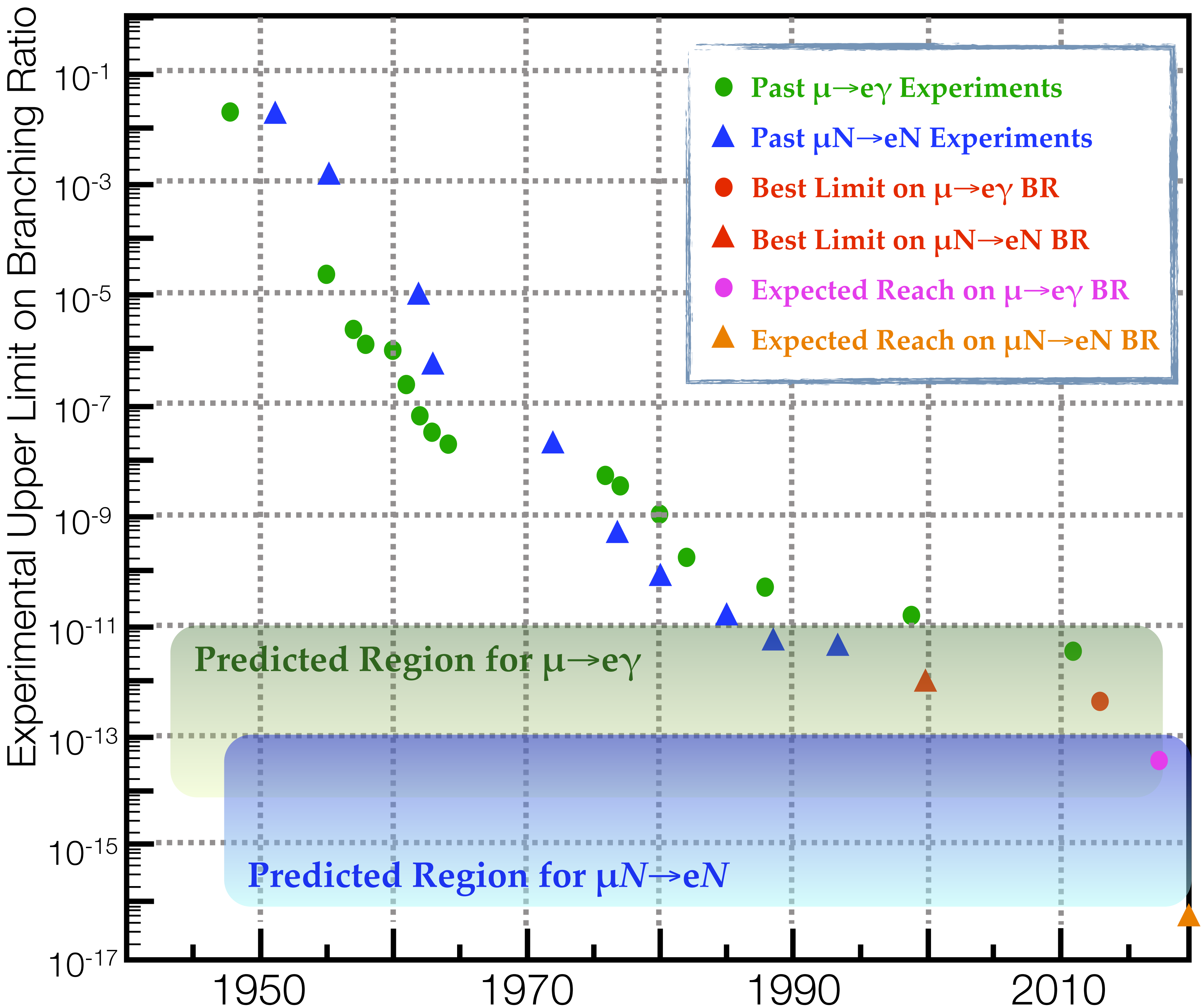
appendices

History of Muon LFV Search Experiment



- Long Tradition on the **μ→eγ / μN→eN** Search Experiment
- Started right after the muon discovery
- **μ→eγ** has already entered the predicted region !!
- **μN→eN** is sitting at just in front of the predicted region !!
- **NOW VERY VERY ATTRACTIVE !!!!!**

History of Muon LFV Search Experiment



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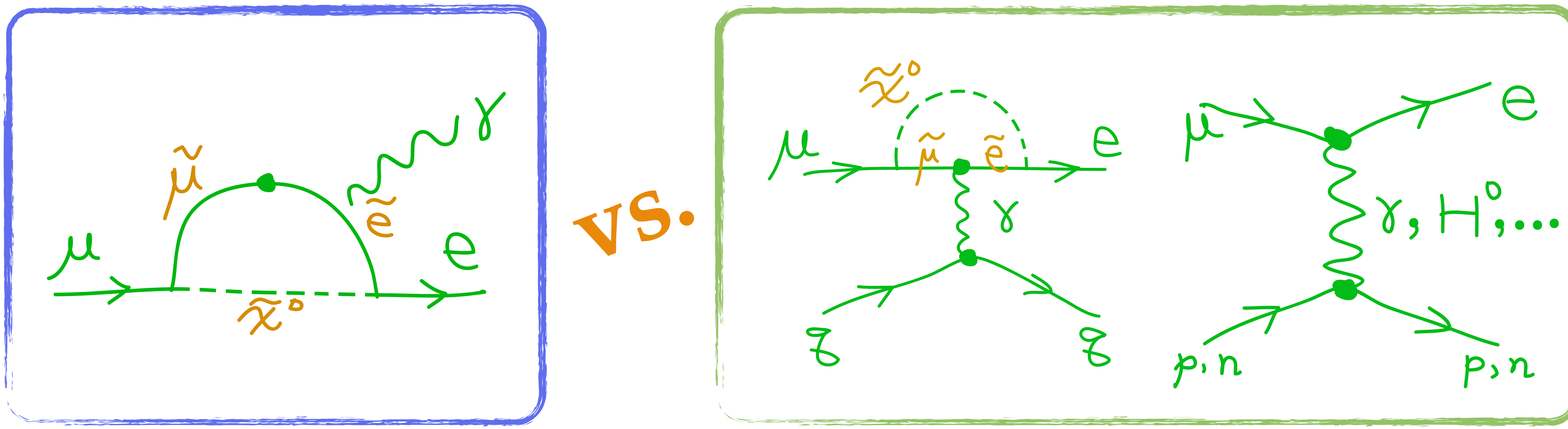
"$\mu \to e\gamma$" vs. "$\mu N \to eN$"

Physics Point of view

- **Sensitivity for "photonic" and "non-photonic" processes is different.**



	$\mu \to e\gamma$	$\mu N \to eN$
photonic (*eg*. SUSY-base models, *etc*.)	**YES** (on-shell)	**YES** (off-shell)
non-photonic (*eg*. Extra-D, Little-Higgs, *etc*.)	**NO**	**YES !!**

_eg_. SUSY-based case, $\mathcal{B}(\mu \to e\gamma)/\mathcal{B}(\mu N \to eN) \sim O(100)$ (depends on N)

"$\mu \to e\gamma$" vs. "$\mu N \to eN$"

Experimental
Point of view

	$\mu \to e\gamma$	$\mu N \to eN$
Dominant B.G.	Accidental	Beam related
Challenge	Detector Performance	Beam Quality
Suitable Muon Source	DC Muon Beam	Pulsed Muon Beam
Beam Intensity	(almost) Limited	No Limitation

- **$\mu \to e\gamma$** : accidental B.G. ∝ (rate)2
  - MEG (and its upgrade) may be the final experiment

discovery

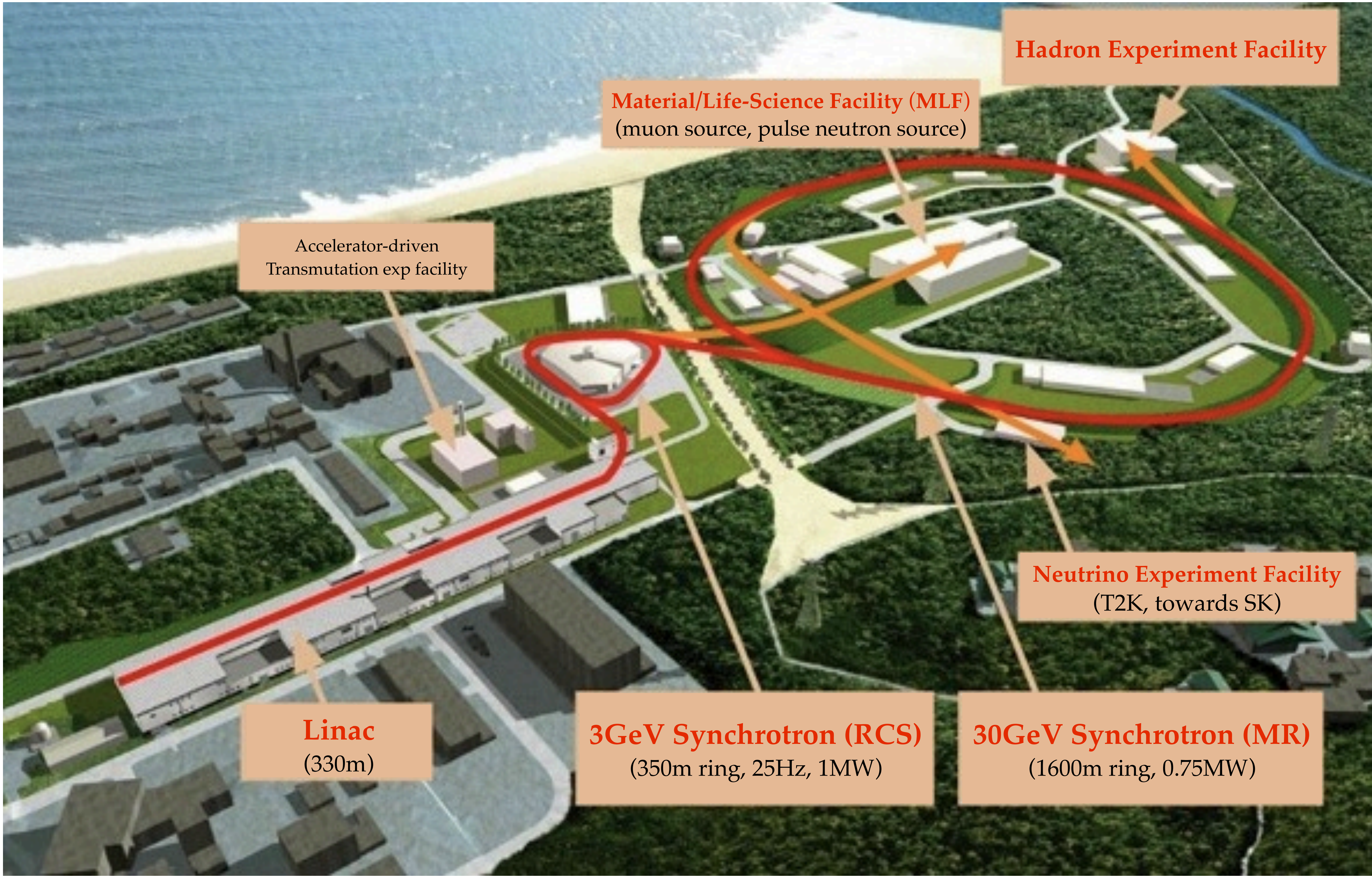
- **$\mu N \to eN$** : Required Beam is recently / finally achievable
  - Once we get a required beam, **$\mu N \to eN$** experiment might be a next experiment after the MEG.

measurement

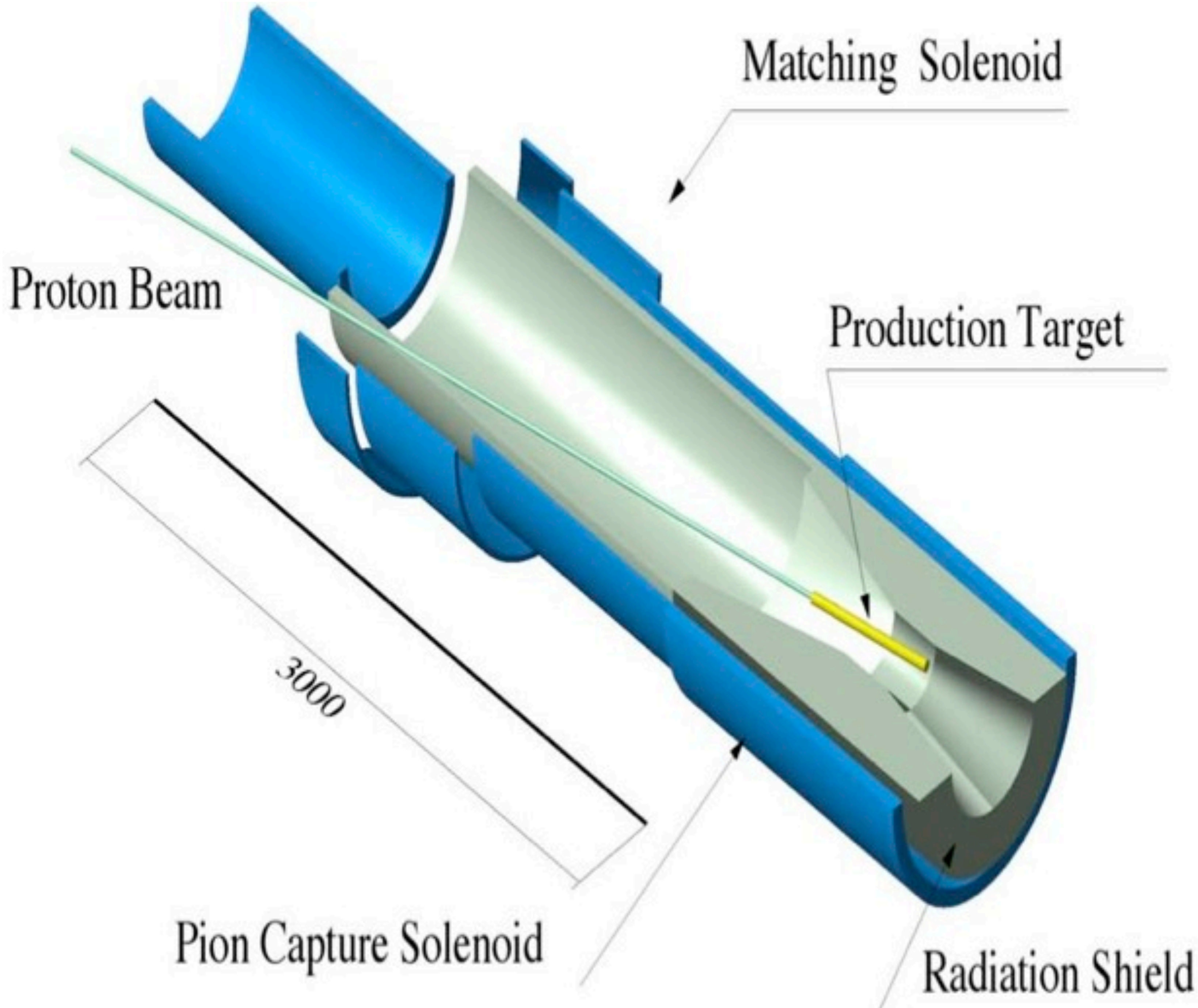
J-PARC

- J-PARC : **J**apan **P**roton **A**ccelerator **R**esearch **C**omplex
- Joint project between **KEK** and **JAEA**
- New and exciting accelerator research facility, using MW-class high power proton beams at both 3 GeV and 30 GeV (currently)
- Various secondary particle beams
  - n, μ, K, ν, etc. produced in proton-nucleus reactions
- Three major scientific goals using these secondary beams
  - Particle and Nuclear Physics
  - Material and Life Sciences
  - R&D for nuclear transmutation (in phase-2)
- The anticipated goal is 1 MW

J-PARC


Hadron Experiment Facility
Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)
Accelerator-driven
Transmutation exp facility
Neutrino Experiment Facility
(T2K, towards SK)
Linac
(330m)
3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)
30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

Pion Capture Solenoid System



- Large muon yield by Large Solid Angle
  - Powerful Solenoid
  - Surround p target

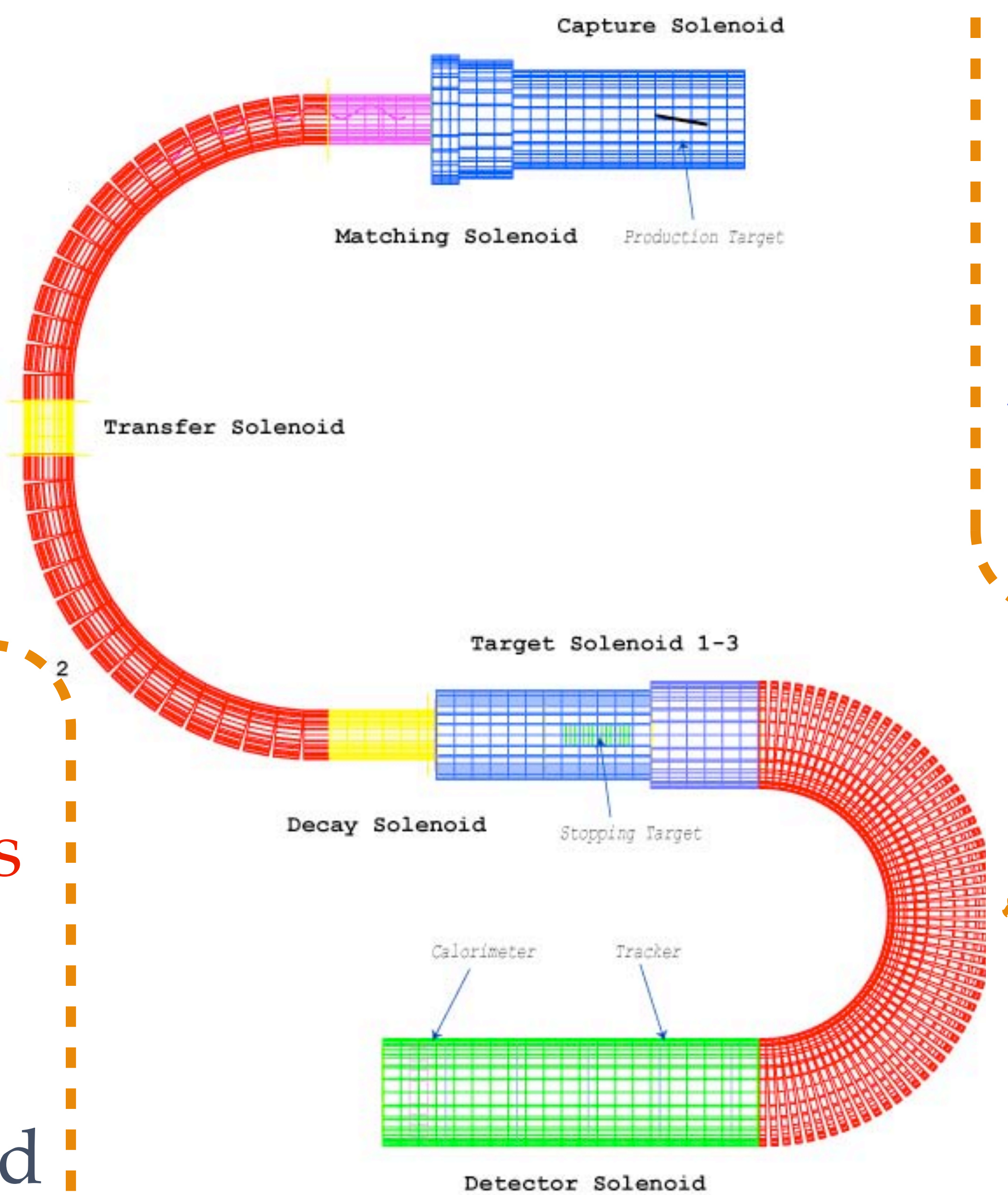
$$P_T(\mathrm{GeV}/c) = 0.3 \times B(\mathrm{T}) \times \left[\frac{R(m)}{2}\right]$$

B=5T, R=0.2m → P_T=150MeV/c

- Super-conducting solenoidal magnet
  - 15cm radium bore
  - **5T**
  - 30 cm thick W shield.
- Issue : Heat Load

Curved Solenoid System

B_{max}=3.5T



Select high-*p* **e$^-$** (& reject low-*p* **BGs.**) using **C-shaped** **"transport"** solenoid

Select low-*p* muons (& reject high-*p* π) using **C-shaped** **"transport"** solenoid

B_{max}=1T