Overview of Lepton Flavor Violation Experiments

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KAON2016, 14-17/9/2016, Birmingham

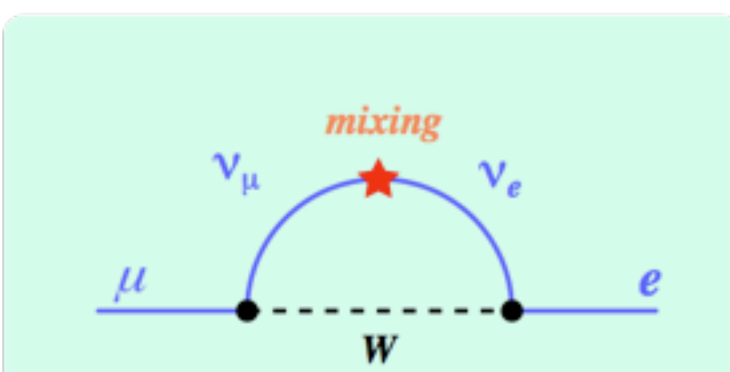
Contents

- Introduction to LFV
  - $\mu \to e \gamma$ [MEG and MEG II]
- μ-e Conversion
  - Comparison between μ-e Conv., $\mu \to e \gamma$ and Kaon-LFV
  - μ-e Conversion Experiments [Mu2e, COMET, DeeMe]
- Other Experiments
- Summary

I will try my best to describe each experiment.
If something is wrong, that is 100% my fault: just blame me.

(charge) Lepton Flavor Violation

- Charged Lepton Flavor Violation (CLFV)
  - Forbidden in the Standard Model of particle physics.
  - $\underline{\mu^- + A \rightarrow e^- + A}$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\tau \rightarrow e(\mu)\gamma$, $\tau \rightarrow e(\mu)h$, $K_L \rightarrow \mu e$, $K \rightarrow \pi\mu e$, and many others ...
- Neutron Oscillation may induce the effective CLFV, but it is very small due to the combination of GIM-like mechanism and smallness of the neutrino masses.



$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U^*_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \simeq 10^{-60} \left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}} \right)^4$$

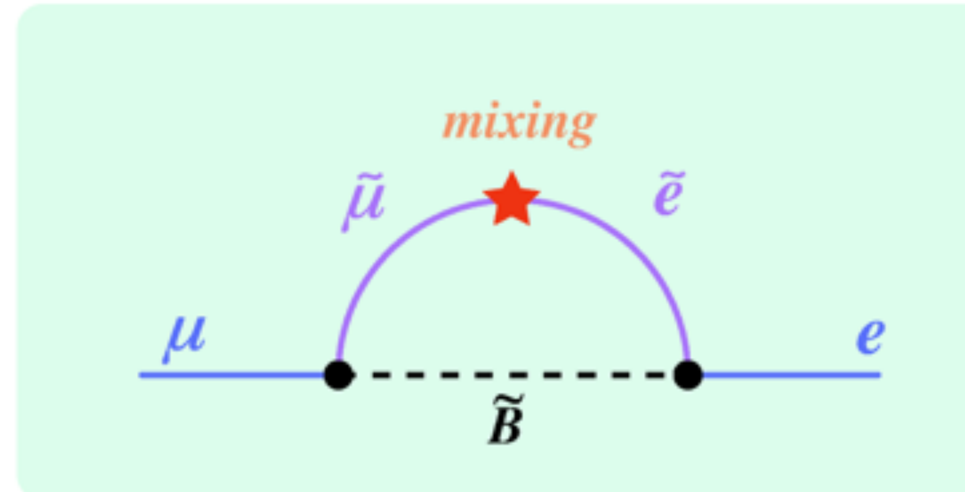
A. de Gouvea

- CLFV →

  Clear evidence of the physics beyond the Standard Model with neutrino-oscillation extension.

Source of CLFV

- Supersymmetry (SUSY)
  - Hierarchy Problem
  - Unification of Force
- If SUSY exists
  → SUSY flavor mixing
  → CLFV



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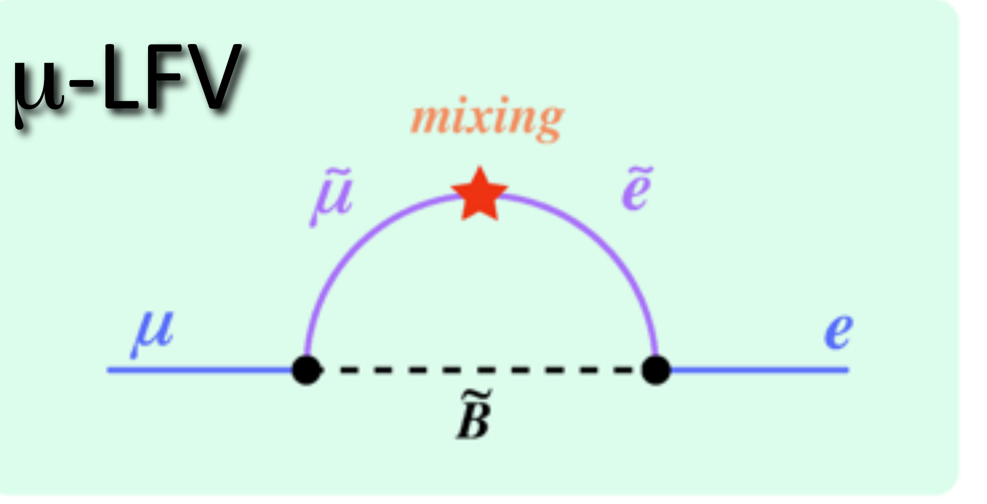

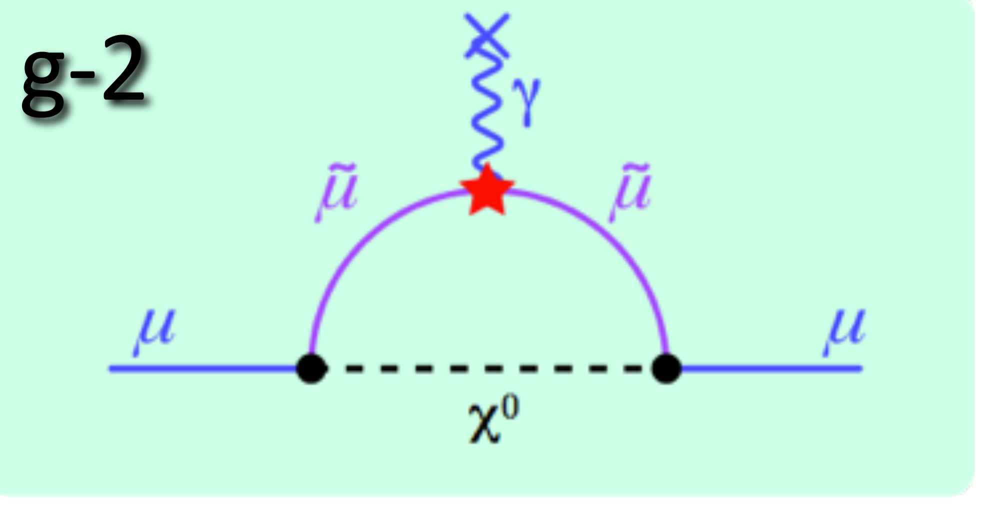

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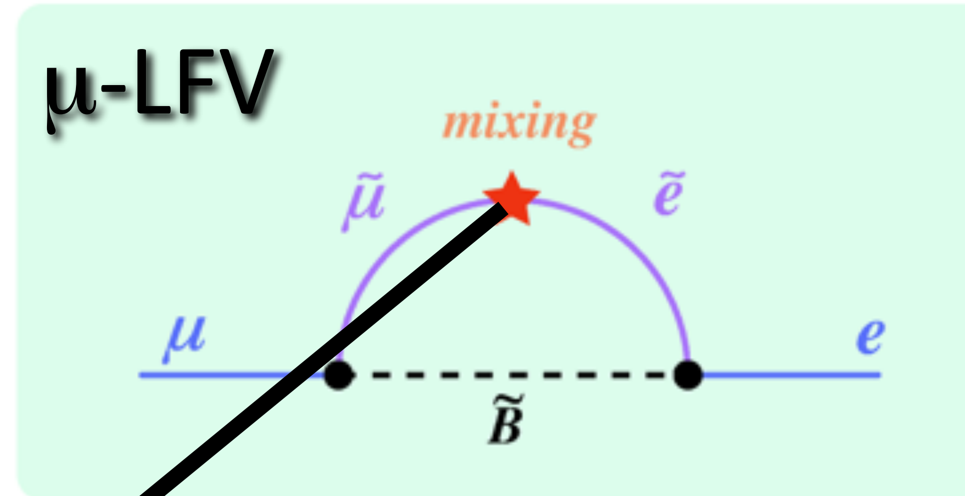
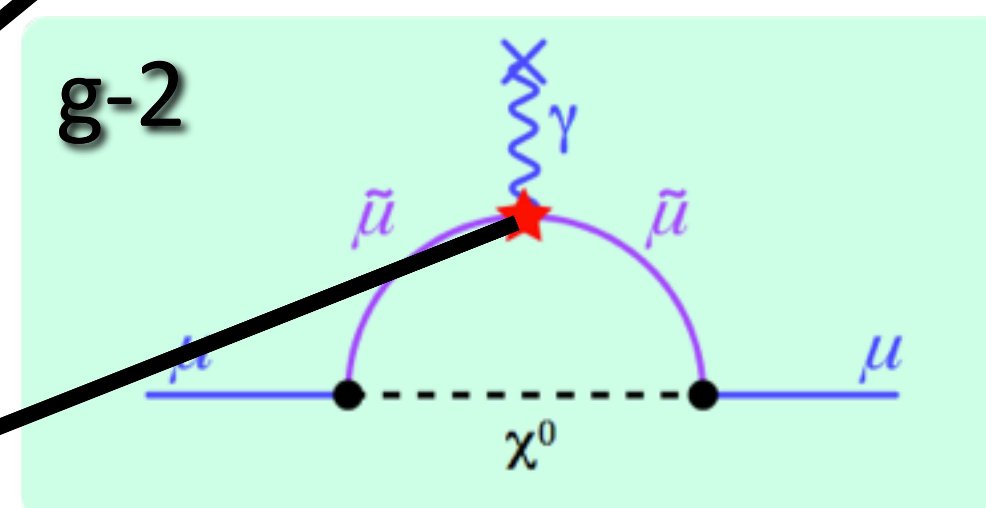


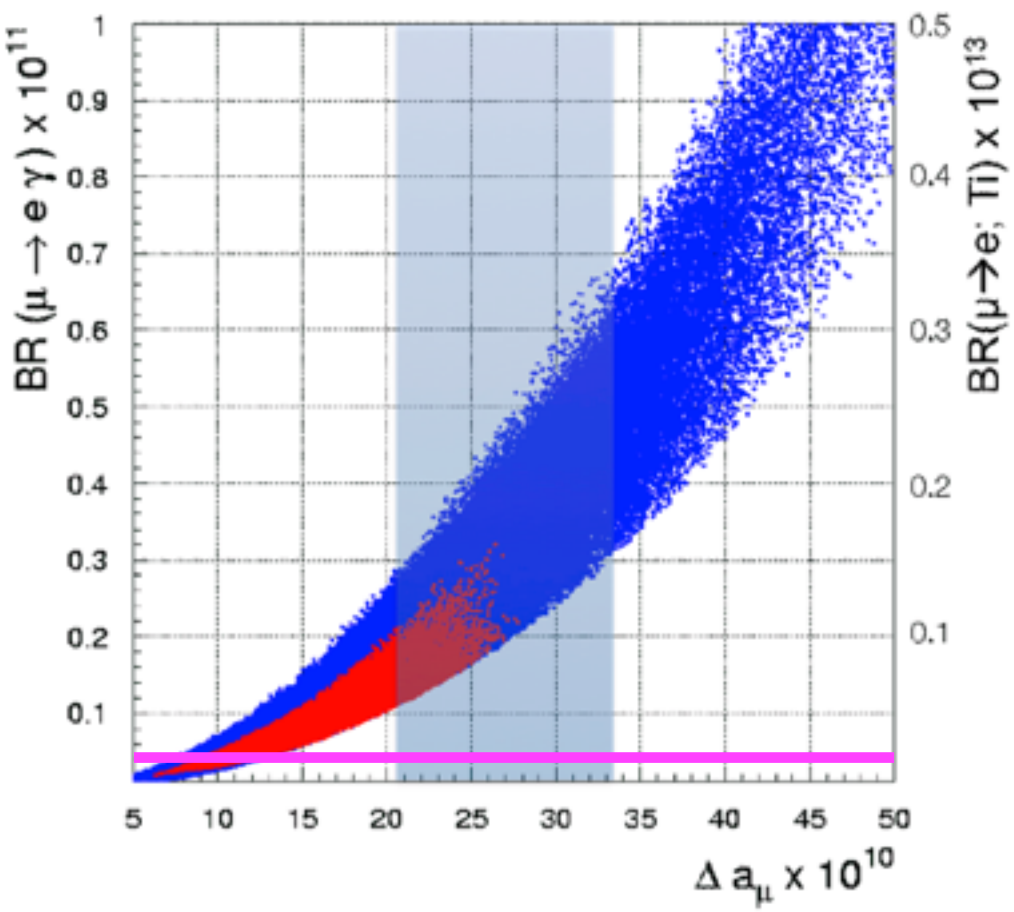


$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

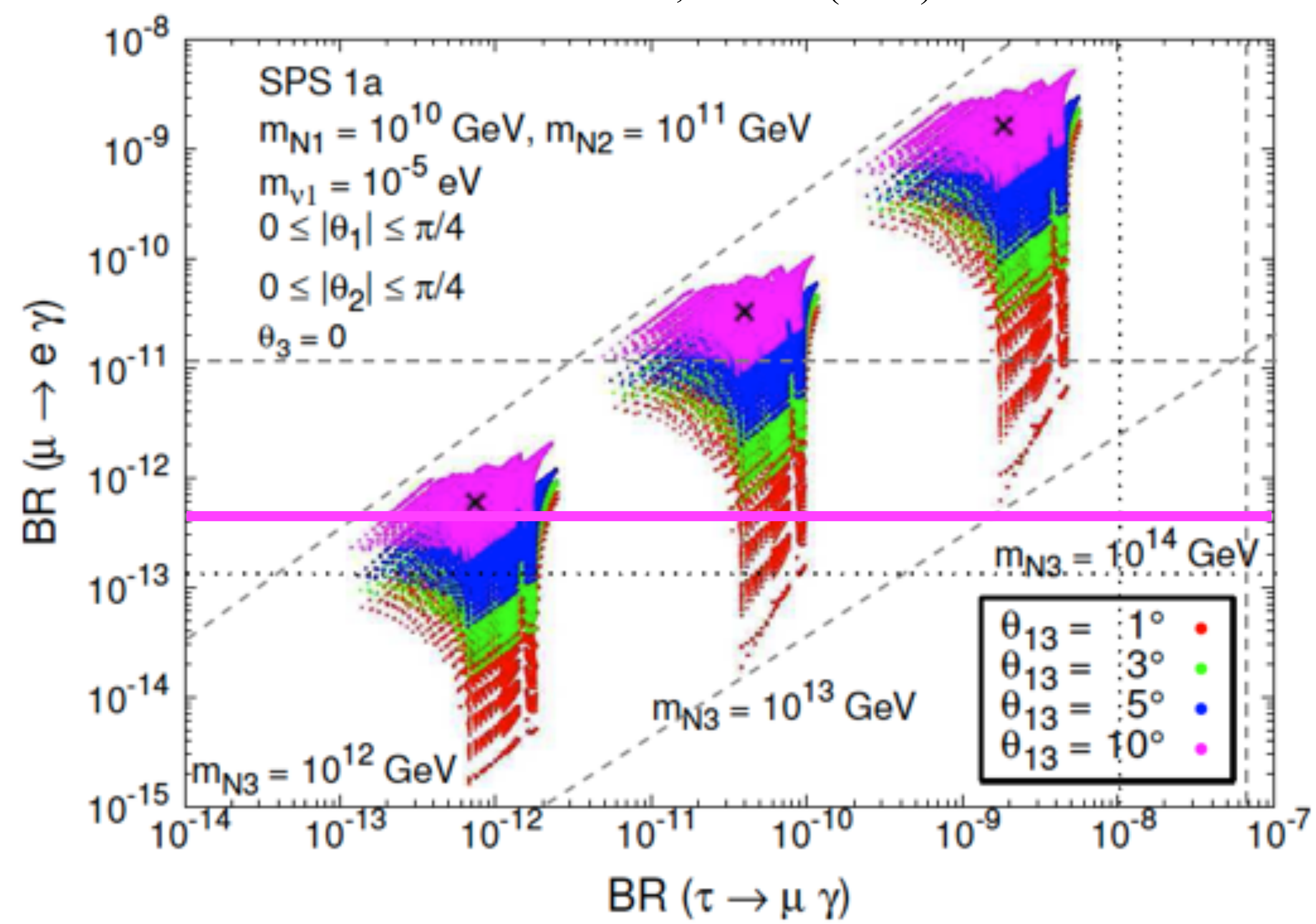
Physics of
slepton mass matrix

(g-2)$_\mu$, ν-Oscillation & μ-LFV

G. Isidori *et al.*, PRD 75 (2007) 115019



S. Antusch *et al.*, JHEP11(2006)090



T2K (2011): $0.03 < \sin^2 2\theta_{13} < 0.3$ (90%C.L.)

$\rightarrow 5^\circ < \theta_{13} < 15^\circ$

Daya Bay (2012): $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$

$\rightarrow \theta_{13} > 8^\circ$

Discovery of μLFV at right around the corner.

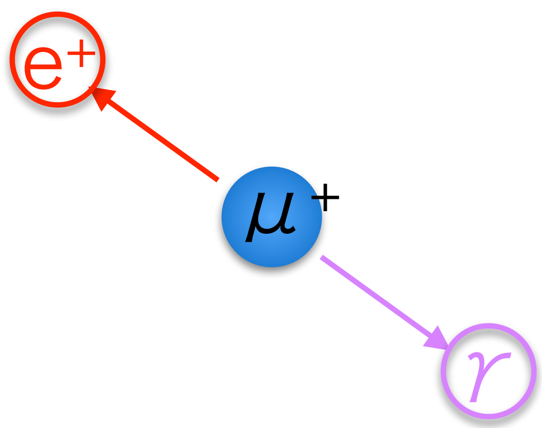
$$\mu \rightarrow e \gamma$$

MEG

MEG II

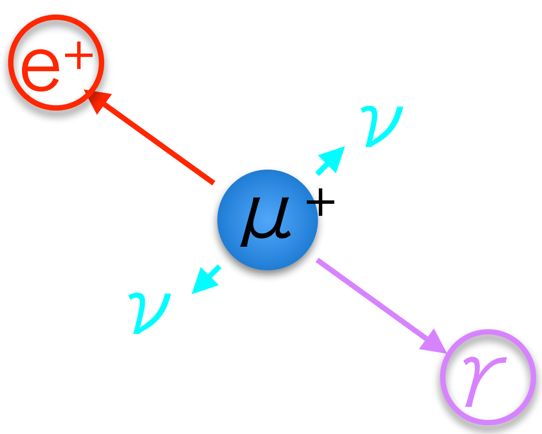
$\mu \rightarrow e\ \gamma$: Signal and Background

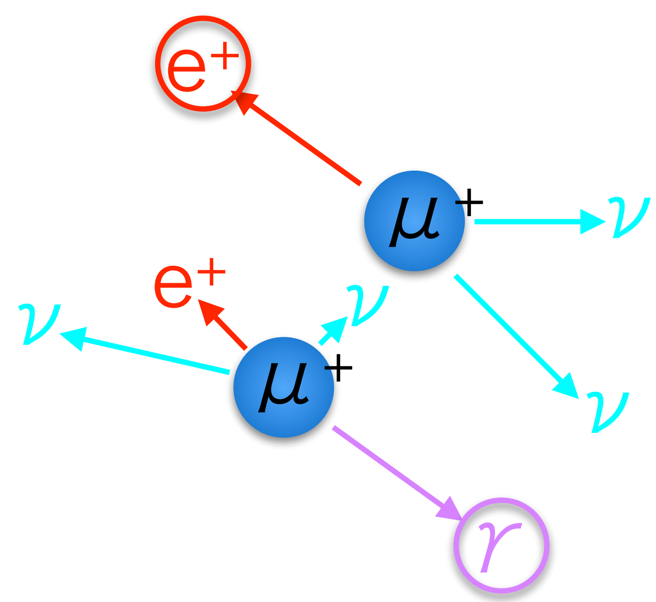
Signal



- $E_{e^+} = 52.8$ MeV
- $E_\gamma = 52.8$ MeV
- $\theta_{e\gamma} = 180°$
- $T_{e\gamma} = 0$ s

Backgrounds





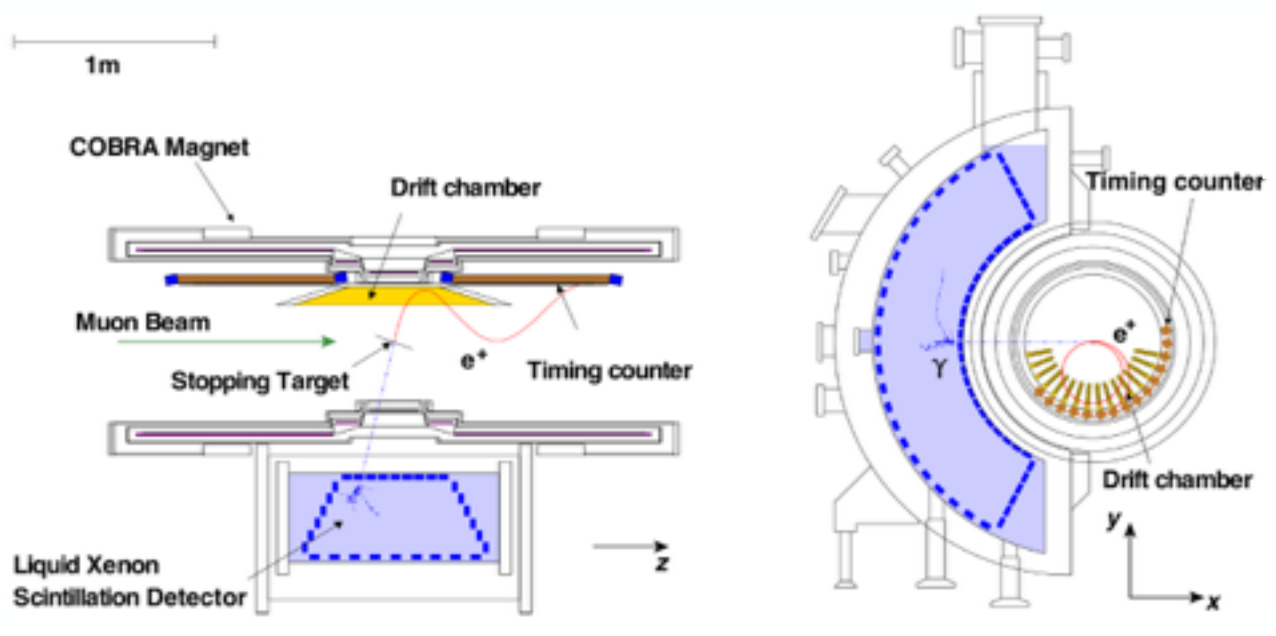
- $E_{e^+} < 52.8$ MeV
- $E_\gamma < 52.8$ MeV
- $\theta_{e\gamma} <= 180°$

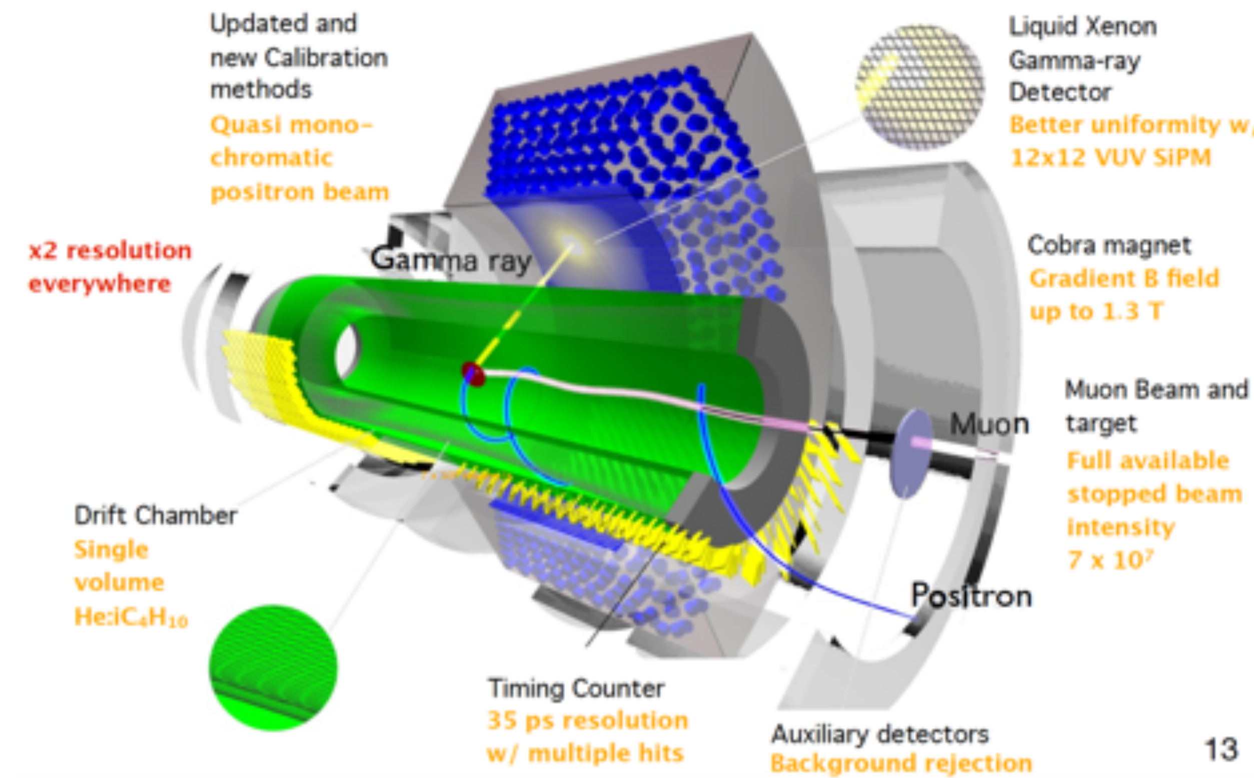
- $T_{e\gamma} = 0$ s
- $T_{e\gamma}$ = flat-distribution

Accidental Background dominate:

$$\propto R_\mu \times \Delta E_e \times \Delta E_\gamma{}^2 \times \Delta \theta_{e\gamma}{}^2 \times \Delta T_{e\gamma}$$

MEG, MEG II @PSI





- MEG
  - DC muon beam, $R_{\mu^+} = 3 \times 10^7$ /sec
  - LXe photon detector
  - ultra-light DC, Gradient B-field
  - DAQ: 2008 ~ 2013
  - Final Result: BR < 4.2×10^{-13} (90% C.L.)
- MEG II
  - Run 2017 ~ 2020
  - Sensitivity: 4×10^{-14}

Resolution	MEG	MEGII
γ-position (mm)	5~6	2.2~3.1
E_γ	1.7~2.4%	1.0~1.1%
t_γ (ps)	67	60
p_e (keV)	306	130
θ_e (mrad)	9.4	5.3
ϕ_e (mrad)	8.7	4.8
e^+ efficiency	40	88

μ-e Conversion

Mu2e

COMET

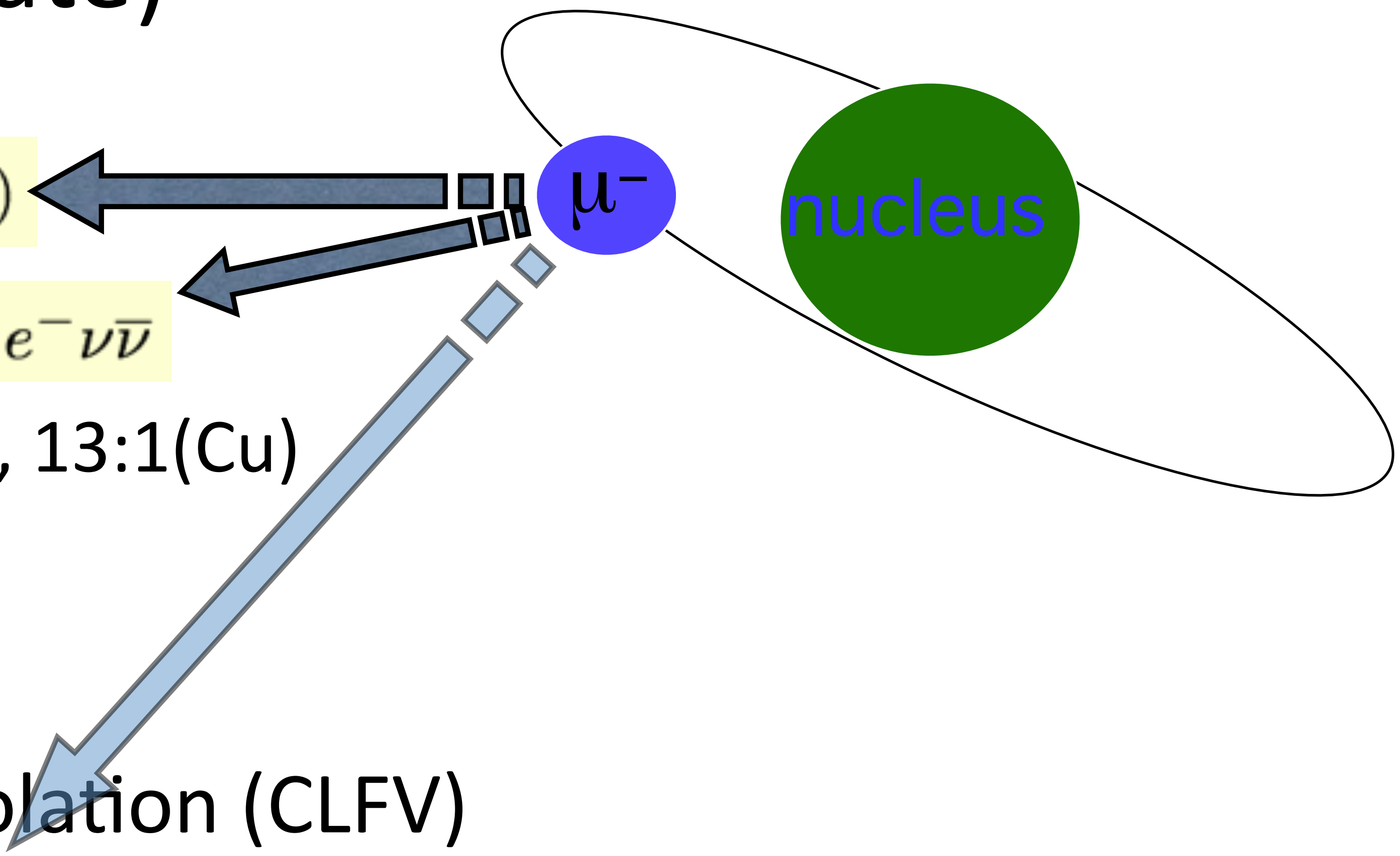
DeeMe

μ–e Conversion in Nuclear Field

- Muonic Atom (1S state)

Muon Capture(MC)

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



Muon Decay in Orbit (DIO) $\mu^- \rightarrow e^- \nu \bar{\nu}$

  - MC:DIO = 1:1000(H), 2:1(Si), 13:1(Cu)
  - τ(free μ-) = 2.2 μs
  - τ(μ⁻;Si) = 0.76 μs

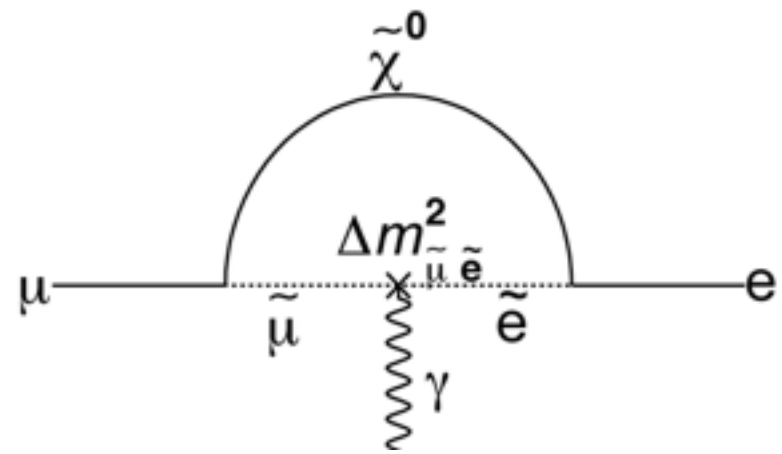
- Charged Lepton Flavor Violation (CLFV)

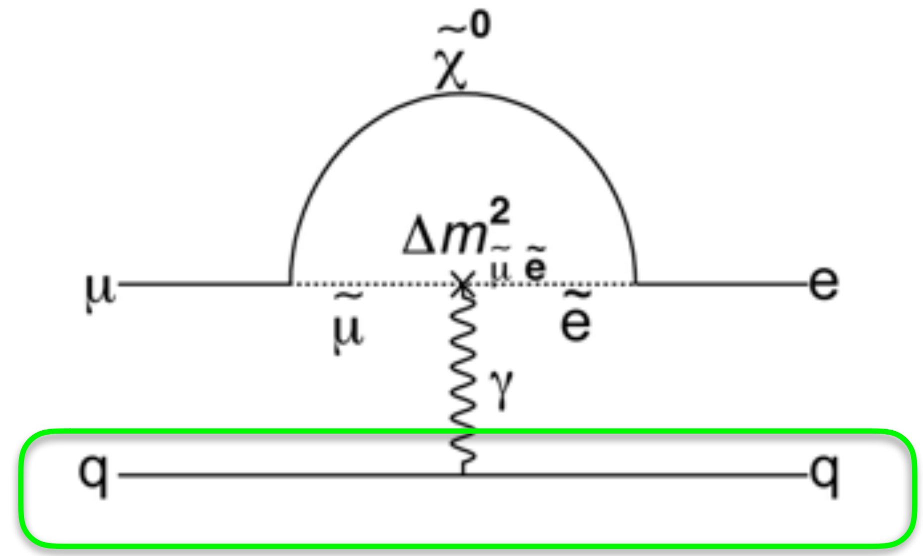
$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

μ-e Conversion in Nuclear Field

$$\mathrm{BR}[\mu^- + (A, Z) \rightarrow e^- + (A, Z)] \equiv \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)]}$$

μ → e γ & μ-e Conversion





$B[\mu \to e\gamma]$

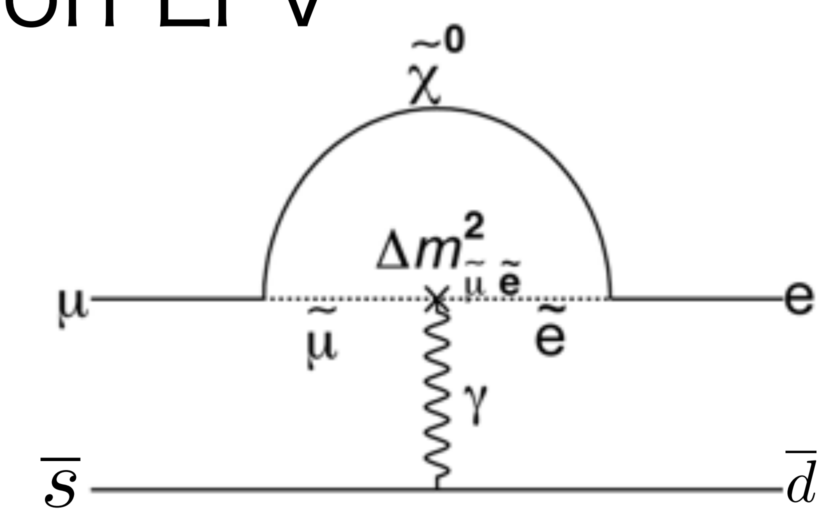
$\to$ MEG II: 4×10^{-14}

$B[\mu\text{-e conv.}] = \alpha \times B[\mu \to e\gamma]$

$\to 2 \times 10^{-16}$

$\to$ Mu2e: 2.5×10^{-17}

Kaon LFV



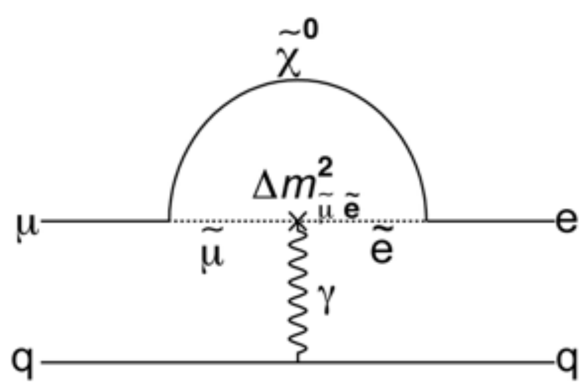
$B = \varepsilon_{FCNC} \times \alpha \times BR[\mu \to e\gamma]$

$\to 10^{-25}$

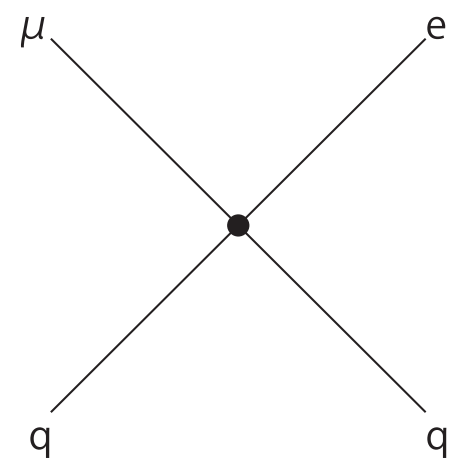
$\varepsilon_{FCNC} \sim B[K^+ \to \pi^+\nu\nu]/B[K^+ \to \pi^0 e\nu]$

μ → e γ & μ-e Conversion (2)

$$\mathcal{L} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu + \frac{\kappa}{(1+\kappa)\Lambda_F^2}\bar{e}\mu(\bar{q}q + \bar{e}e)$$

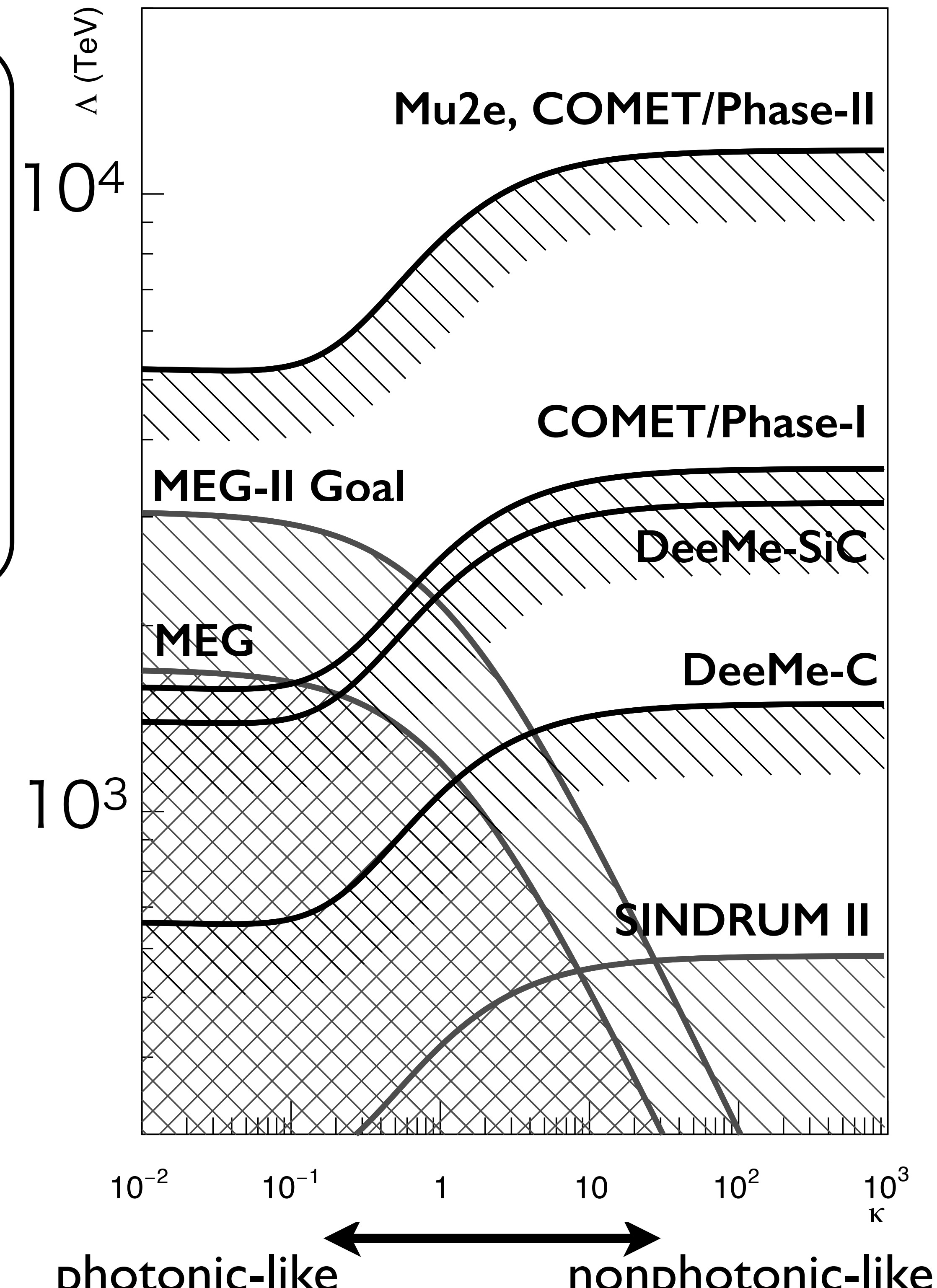


photonic



non-photonic

- SUSY-GUT, SUSY-seesaw
  - higgs mediated processes
- Doubly Charged Higgs Boson (LRS *etc.*)
- Little Higgs Models
- Randall-Sundrum Models
- SUSY with R-parity Violation
- Leptquarks
- Heavy Z'
- Multi-Higgs Models



original plot by Andre de Gouvea

μ-e Conv. and Kaon-LFV

Comparison with hypothetical horizontal boson: X

R.N. Cahn and H. Harari Nucl. Phys. B176 (1980) 135 w/updates

	Current UL	LL on M_X (TeV/c^2)	Future	Future in M_X (TeV/c^2)	ΔG
$K_L \to \mu e$	4.7×10^{-12}	150			0
$K_L \to \pi^0 \mu e$	7.6×10^{-11}	53			0
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	80	10^{-12}	152	0
$\mu^+ \to e^+ \gamma$	4.2×10^{-13}	49	4×10^{-14}	87	1
μ-e Conv.	7×10^{-13}	378	2.5×10^{-17}	4890	1
$\mu^+ \to eee$	1×10^{-12}	86	10^{-15}	484	1

μ-e Conv. surpasses the others.

or “the potential ΔG suppression considered, muons and kaons are complementary”

μ-e Conv. and Kaon-LFV

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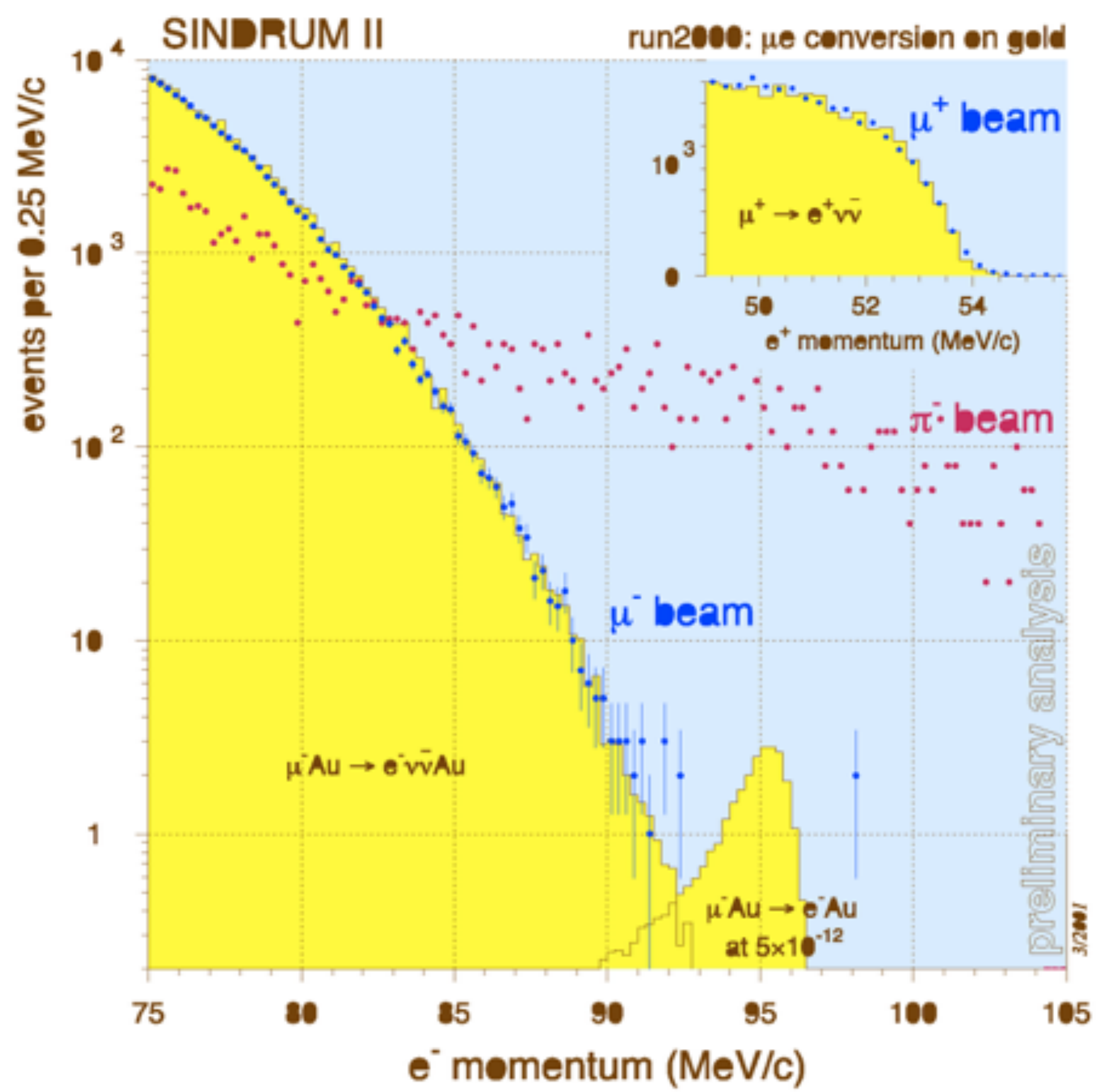
muons and kaons are complementary"

μ-e Conv. Signal & Backgrounds

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed : ~1μS
- No accidental backgrounds
- Physics backgrounds
  - **<u>Muon Decay in Orbit (DIO)</u>**
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - Prompt timing

SINDRUM II



μ-e Conv. Signal & Backgrounds

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed：~1μS
- <u>No accidental backgrounds</u>
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
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  - **<u>Beam Pion Capture</u>**
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
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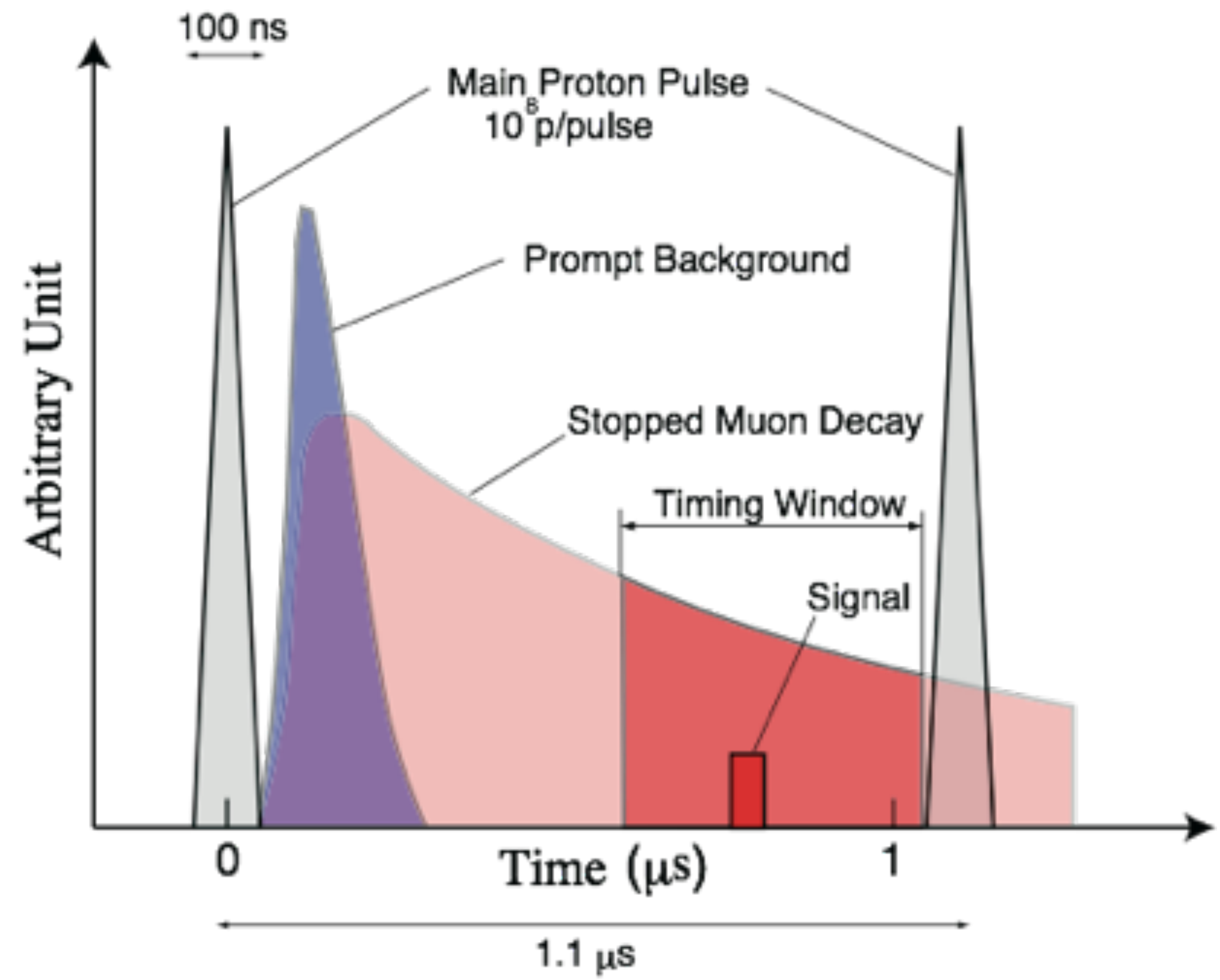
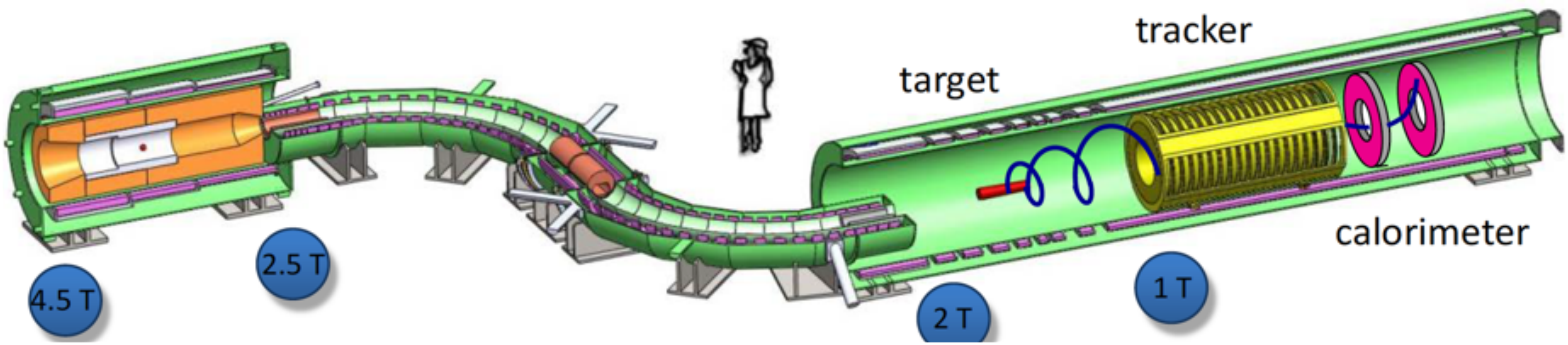
    - <u>Prompt timing</u>



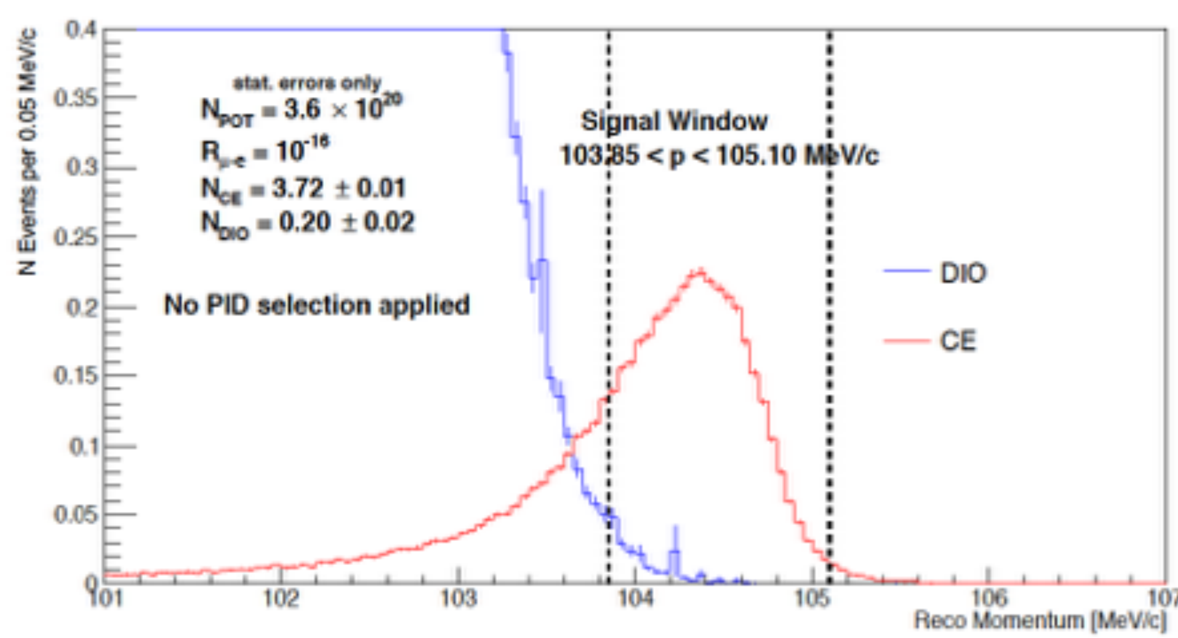
Pulsed proton beam

\+ Extremely high muon rate w/ state-of-the-art tech.

Mu2e @ FNAL

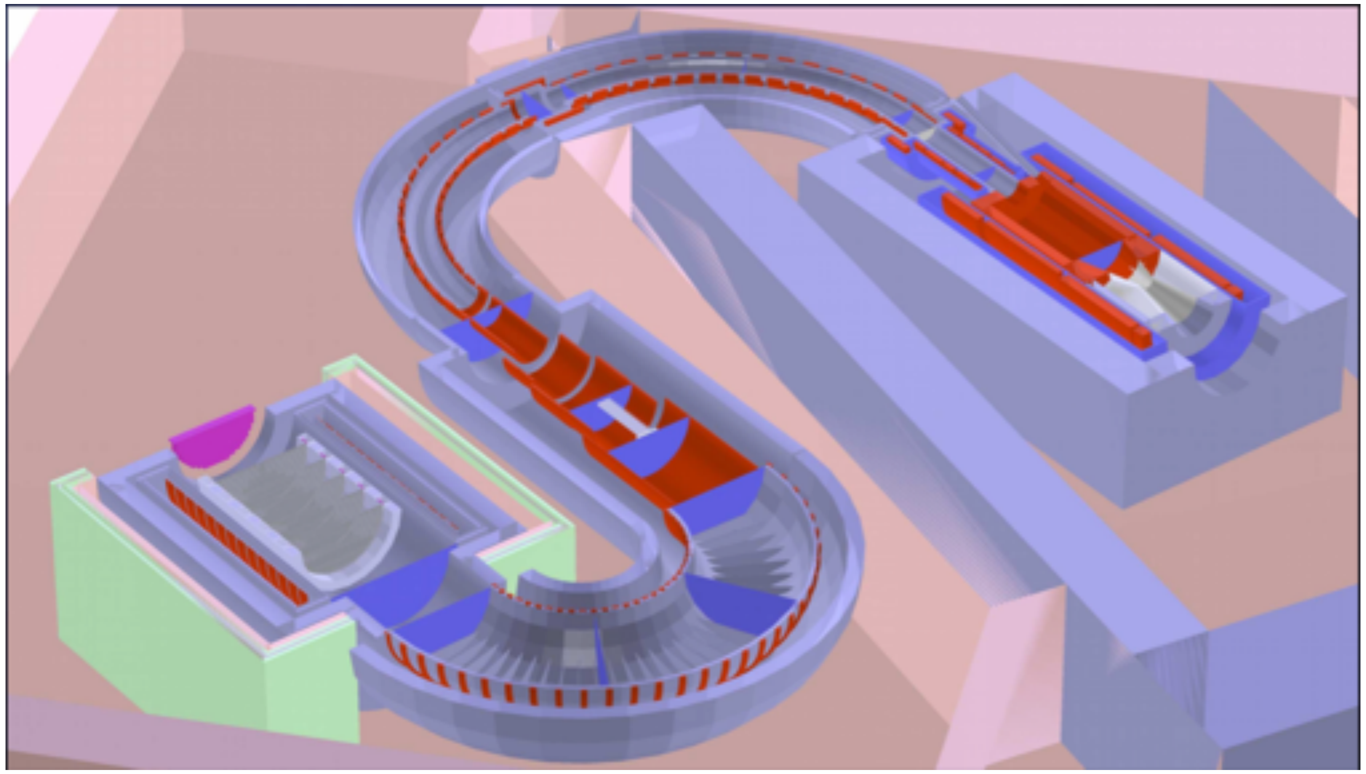


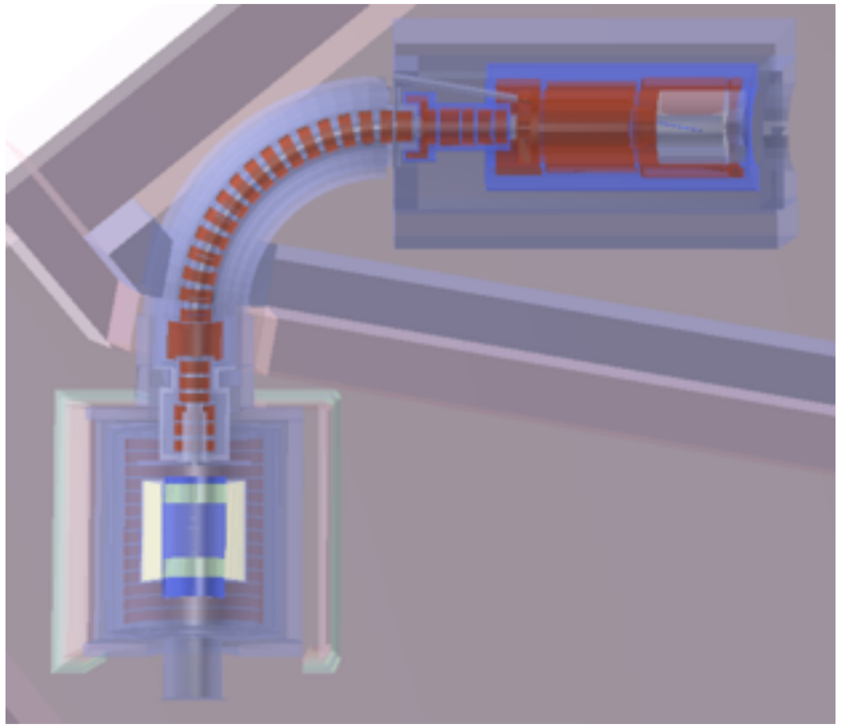
- Long superconducting solenoid: $R_{\mu^-} > 10^{10}$ /sec
  - S.E.S = 2.5×10^{-17}
- Convert FNAL Tevatron rings: pulsed proton
  - Backgrounds < 0.5
- >$200M Project. Physics run 2021~



COMET @ J-PARC MR

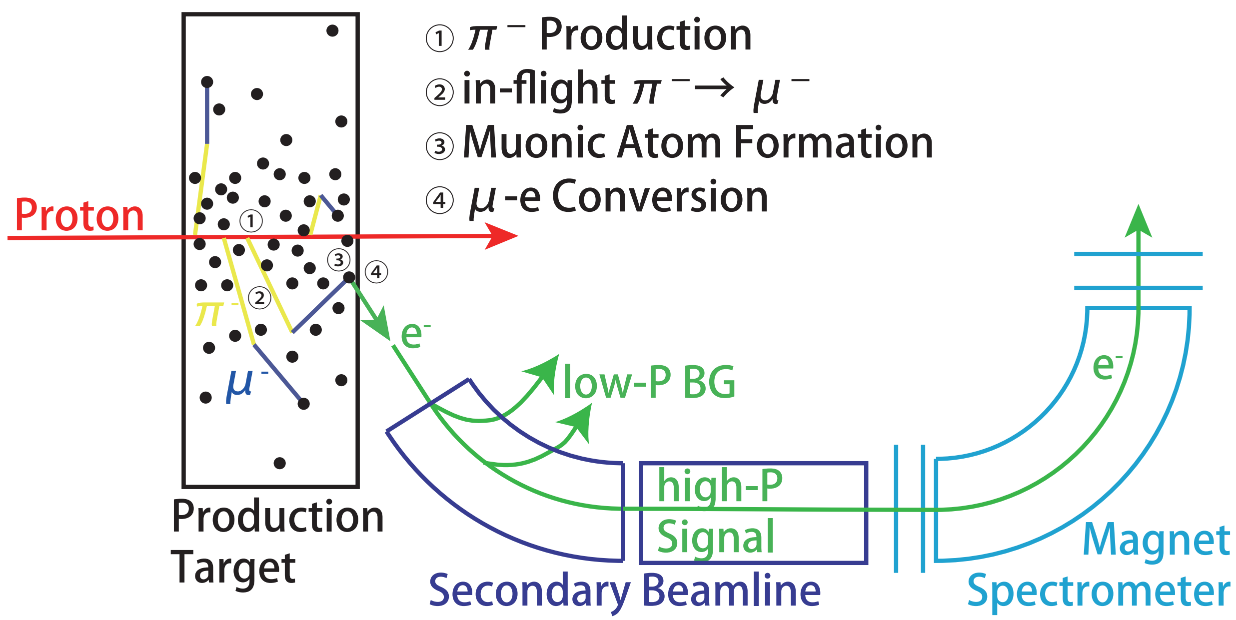
- a long superconducting solenoid
- Phase-I
  - Beam BG Study
  - S.E.S. = 3×10^{-15}
  - 2018 ~ 2020
- Phase-II
  - S.E.S. = 2.6×10^{-17}
  - 2022 ~

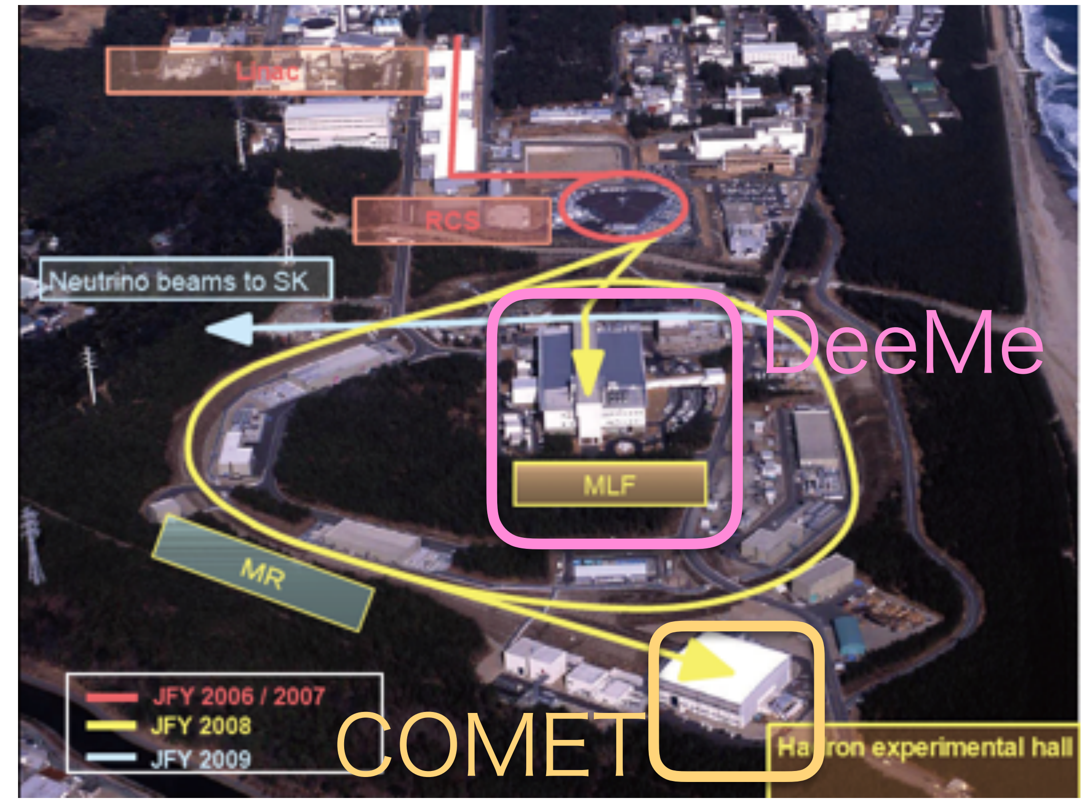


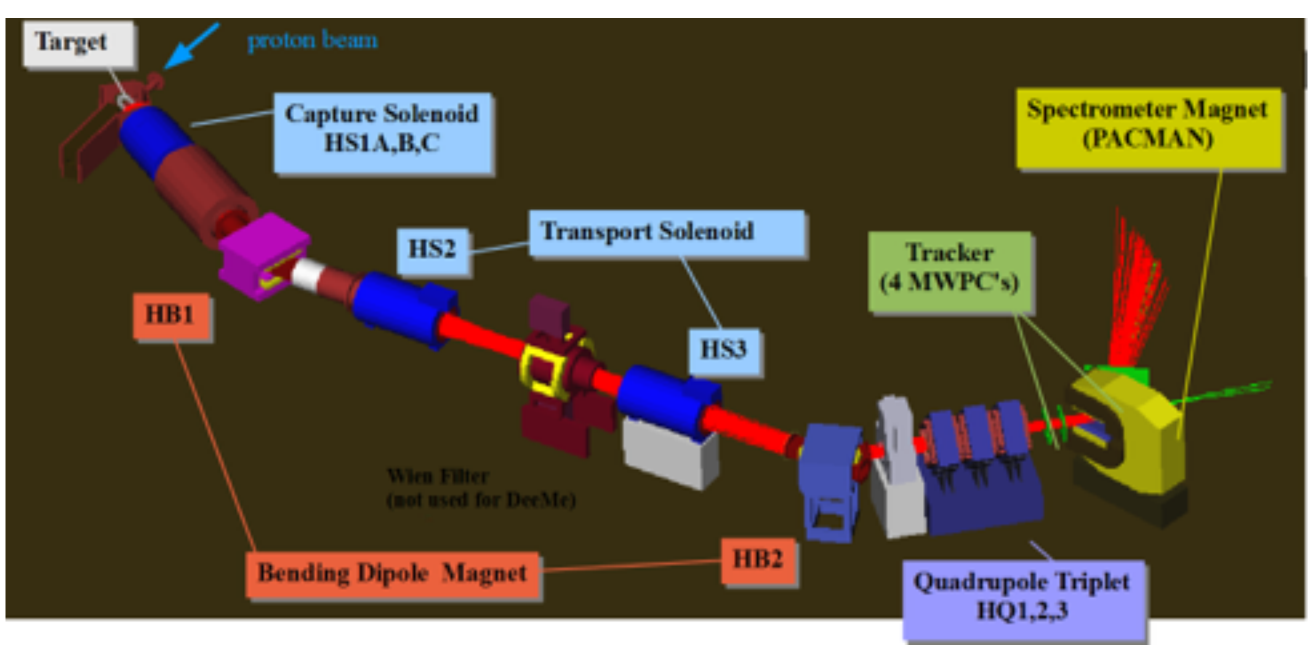


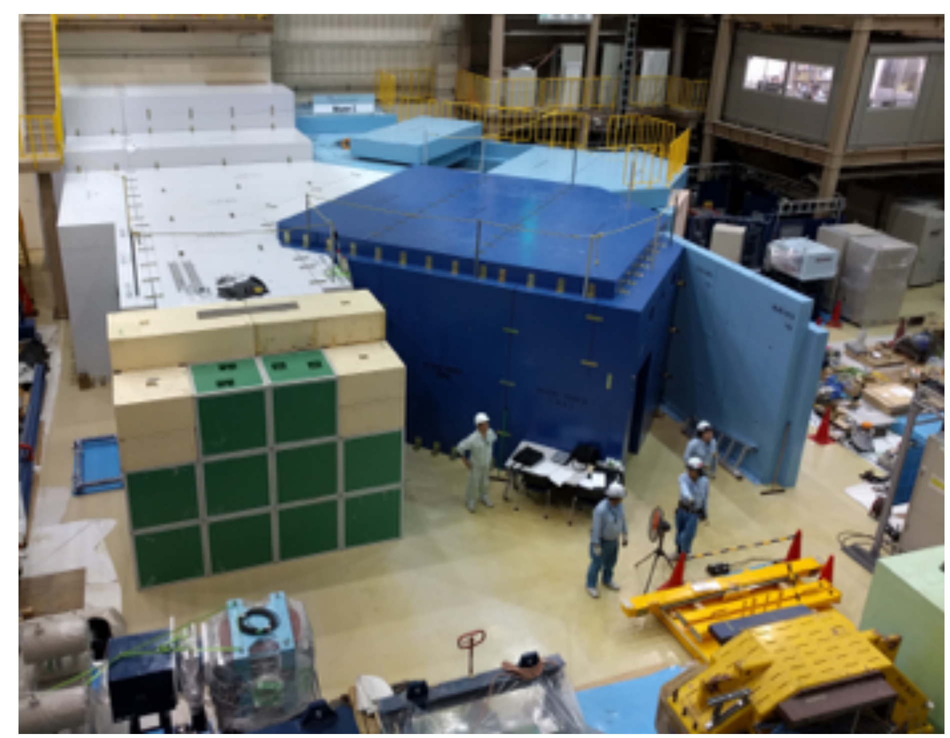
DeeMe @J-PARC MLF

- MELC → MECO → Me2e, COMET
- DeeMe: Completely different idea
- S.E.S. = 10^{-13} (C) ~ 5×10^{-14} (SiC)



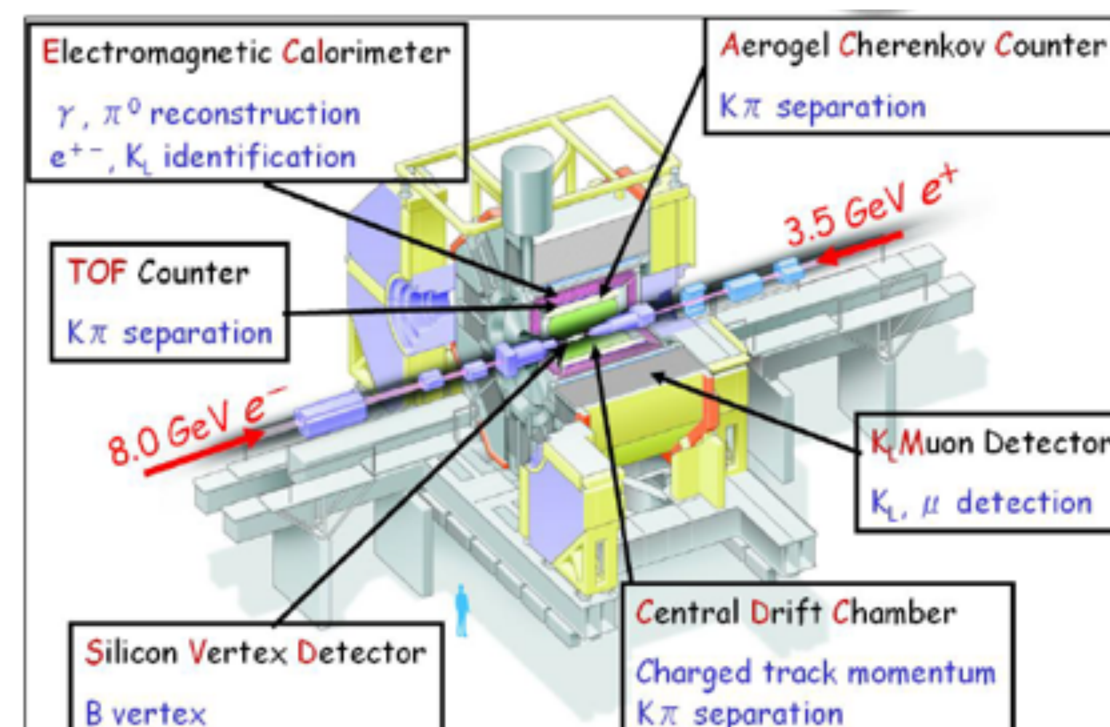




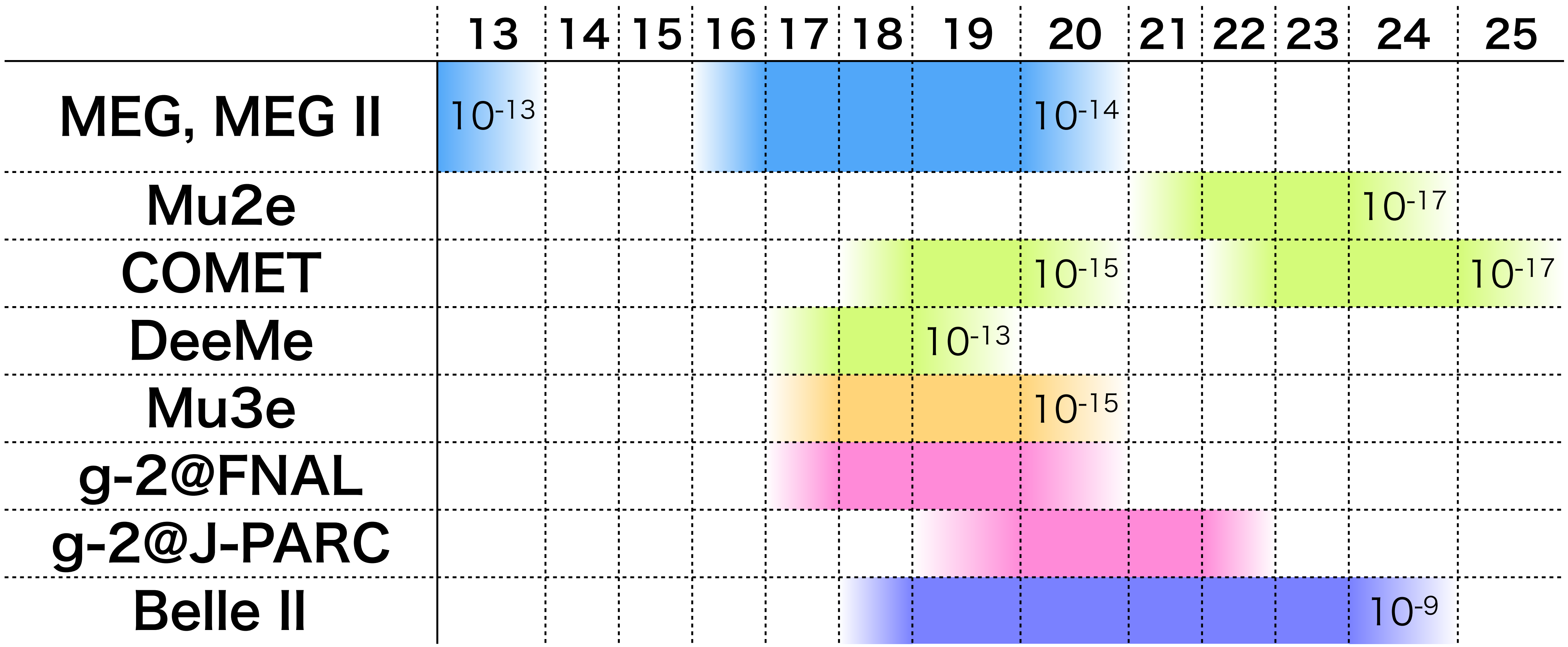


Other Processes

- $\mu^+ \rightarrow$ e e e: Mu3e
  - Phase I [2018~20] ~ 10^{-15}
  - Phase II [202x] ~ 10^{-16}
- τ-LFV: Belle II
  - Current Limits: 10^{-7} ~ 10^{-8}
  - Future prospects: 10^{-9} ~ 10^{-10}
  - Theory: 10^{-7} ~ 10^{-10}
- g-2
  - BNL-E821: 3.5σ discrepancy
  - FNAL: 170ppb $\rightarrow$ 70 ppb
  - J-PARC: different tech.
- h $\rightarrow$ τ μ
  - updates consistent with SM.



Timelines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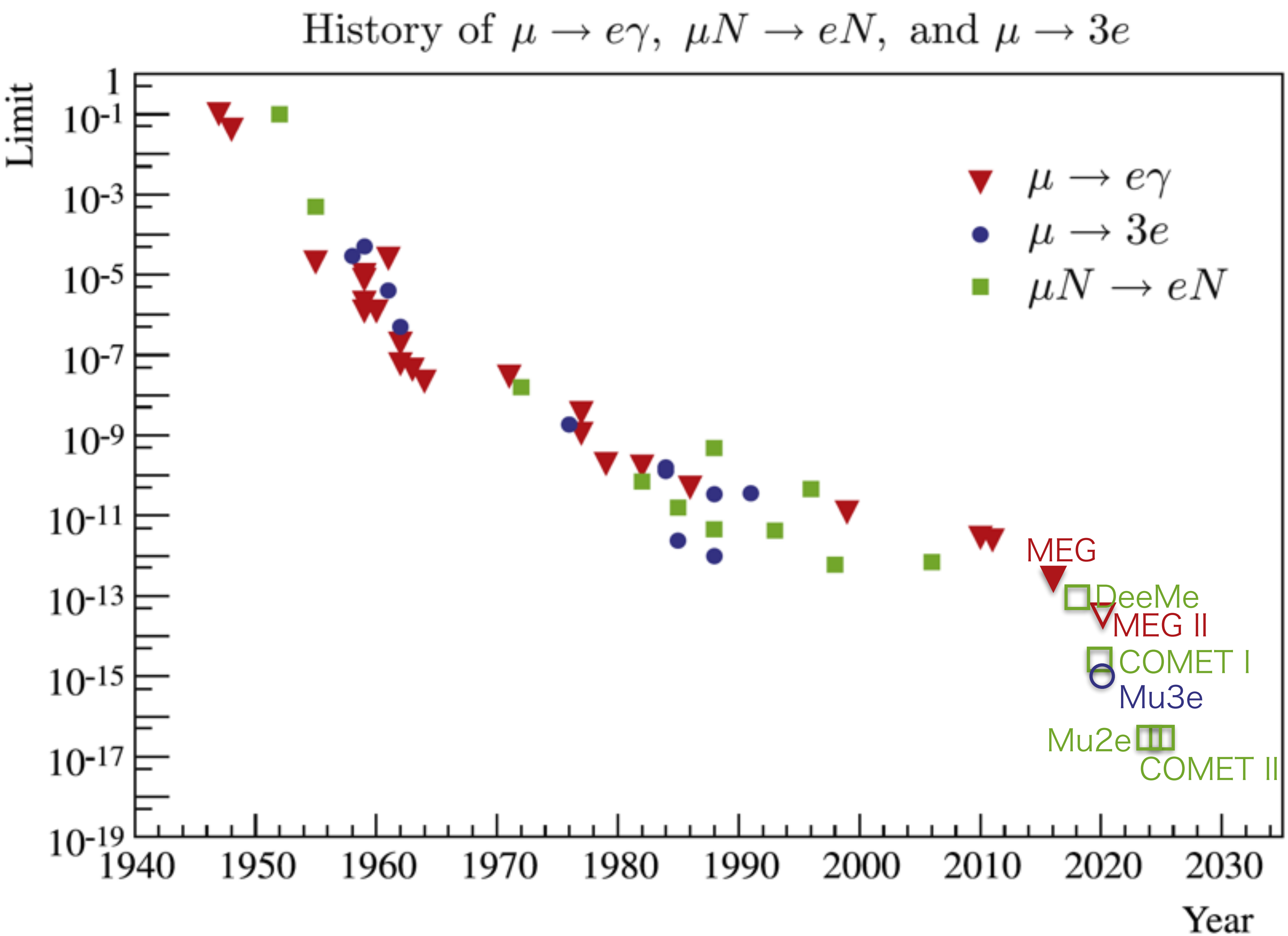
MEG, MEG II
10^{-13}
10^{-14}
Mu2e
10^{-17}
COMET
10^{-15}
10^{-17}
DeeMe
10^{-13}
Mu3e
10^{-15}
g-2@FNAL
g-2@J-PARC
Belle II
10^{-9}



R.H. Bernstein and P.S. Cooper, Phys. Rept. 532 (2013) 27 **w/updates**

Summary

- Lepton Flavor Violation is one of important gateways to the physics beyond the SM.
- $\mu \rightarrow e \gamma$ already provides constrains to new physics.
- Muon-electron conversion is surpasses the other processes, and the “MUST DO” search.
- Mu2e and COMET will reach 10^{-17} in the middle of 2020’s.
- Quick startups of DeeMe and COMET/Phase-I are awaited.
- Preparations for many other experiments are ongoing: Mu3e, g-2, τ-LFV, etc.
- **This decade will be very exciting**.

Incomplete List of References

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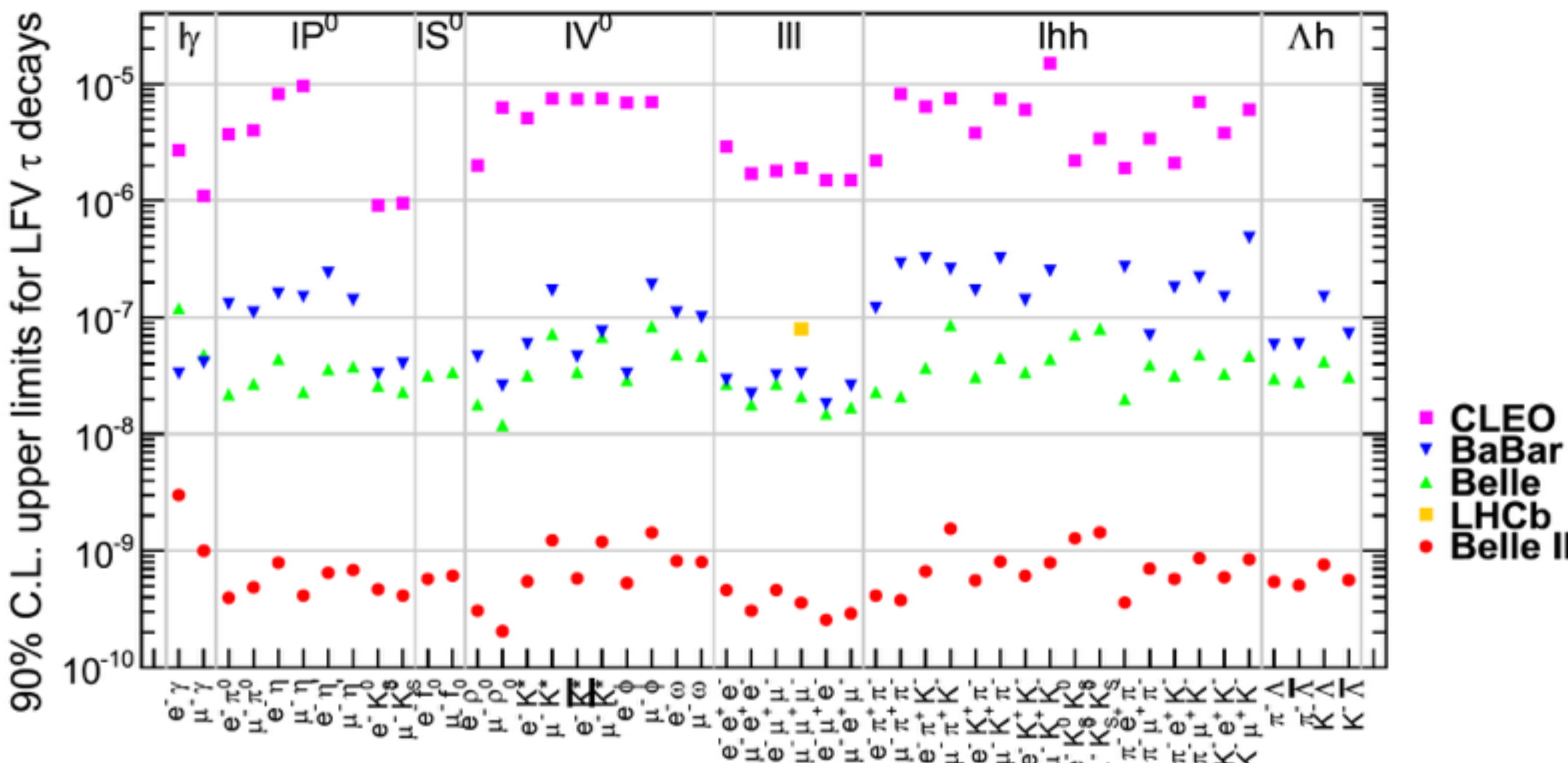
Backups

LFV Upper limits @ B factories

- Current estimation with Belle II final statistics : ~10^{-2} lower
  - Many decay modes are accessible



KEK Report 2009-12 (arXiv:1002.5012)
belle II internal node #21

T. Konno @ Nufact2016