Lepton flavor violation with four generations

P R E S E N T A T I O N

Koji TSUMURA (NTU)

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mu-e Conversion with Four generations

N. Deshpande, T. Enkhbat, T. Fukuyama, X.-G. He, L.-H. Tsai and K. Tsumura

Phys. Lett. B703 (2011) 26

Outline

- **Lepton flavor violation (LFV)**
- **LFV in SM3 and in SM4**
  - $\mu \to e\gamma$
  - $\mu \to 3e$
  - $\mu \to e$ conversion in nuclei
  - Numerical results
- **Summary**

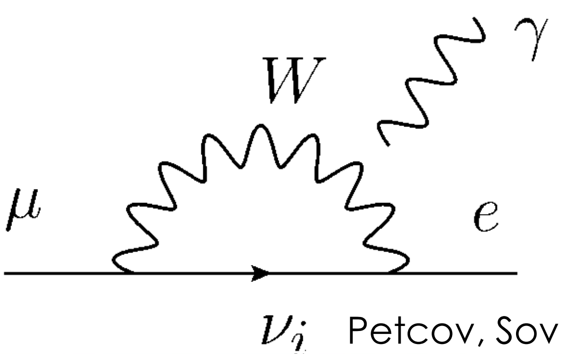
Motivations

- **Quark and neutrino flavor violations has been observed !!**
- **Neutrinos are members of lepton doublet**

  → charged LFV can be induced.

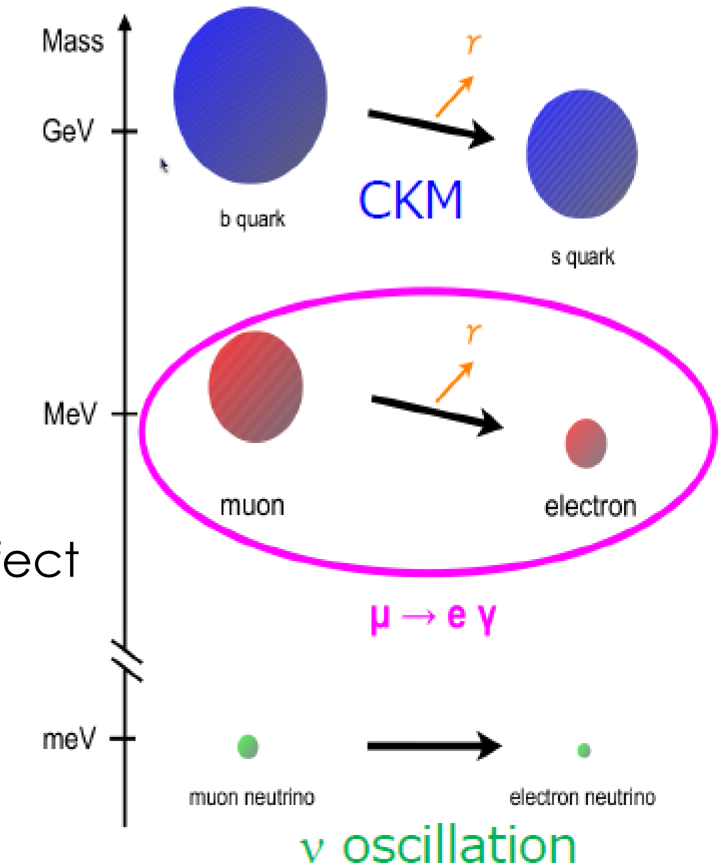
- **Clear evidence of Beyond SM**
  - In SM3 + massive ν

$$\mathcal{B}(\mu \to e\gamma) \approx \frac{3\alpha}{32\pi}\left| U_{ei}\frac{m^2_{\nu\, i}}{m^2_W}U^*_{\mu i}\right|^2 < 10^{-45}$$



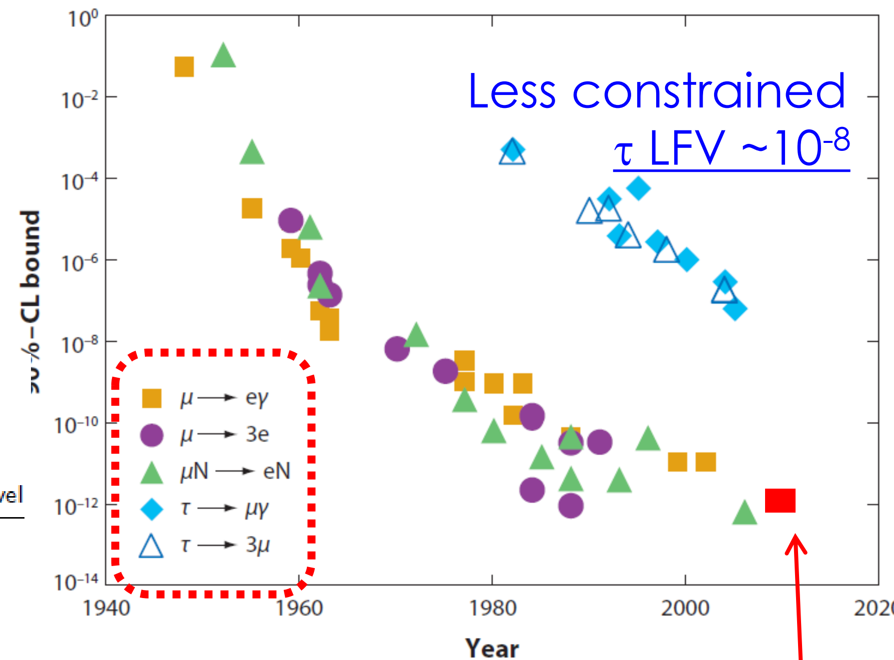
Extremely small SM effect

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



Current experimental limit

- **Muon LFV decays are highly constrained !!**
  - Order of 10 improvement on muon LFV in 60 years



μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$	
Γ_2	$e^- \overline{\nu}_e \nu_\mu \gamma$		[a] $(1.4 \pm 0.4)\ \%$	
Γ_3	$e^- \overline{\nu}_e \nu_\mu e^+ e^-$		[b] $(3.4 \pm 0.4) \times 10^{-5}$	
	Lepton Family number (*LF*) violating modes			
Γ_4	$e^- \nu_e \overline{\nu}_\mu$	*LF*	[c] $< 1.2\ \%$	90%
Γ_5	$e^- \gamma$	*LF*	$< 1.2 \times 10^{-11}$	90%
Γ_6	$e^- e^+ e^-$	*LF*	$< 1.0 \times 10^{-12}$	90%
Γ_7	$e^- 2\gamma$	*LF*	$< 7.2 \times 10^{-11}$	90%

New $\mu \to e\gamma$ limit

$< 2.4 \times 10^{-12}$ since EPS2011 by MEG

It will be improved to 10^{-13}

Current upper limit of $B(\mu \to e\gamma)$ and $BR(\mu \to 3e)$ in ~10^{-12}

Current experimental limit

- **Muon LFV decays are highly constrained !!**
  - **μ-e conversion in nuclei**

LIMIT ON $\mu^- \rightarrow e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^- {}^{32}S \rightarrow e^- {}^{32}S) / \sigma(\mu^- {}^{32}S \rightarrow \nu_\mu {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7 \times 10^{-11}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-10}$	90	BADERT...	77	STRC	SIN

$\sigma(\mu^- Cu \rightarrow e^- Cu) / \sigma(\mu^- Cu \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-8}$	90	BRYMAN	72	SPEC

$\sigma(\mu^- Ti \rightarrow e^- Ti) / \sigma(\mu^- Ti \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.3 \times 10^{-12}$	90	[21] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.6 \times 10^{-12}$	90	AHMAD	88	TPC	TRIUMF
$<1.6 \times 10^{-11}$	90	BRYMAN	85	TPC	TRIUMF

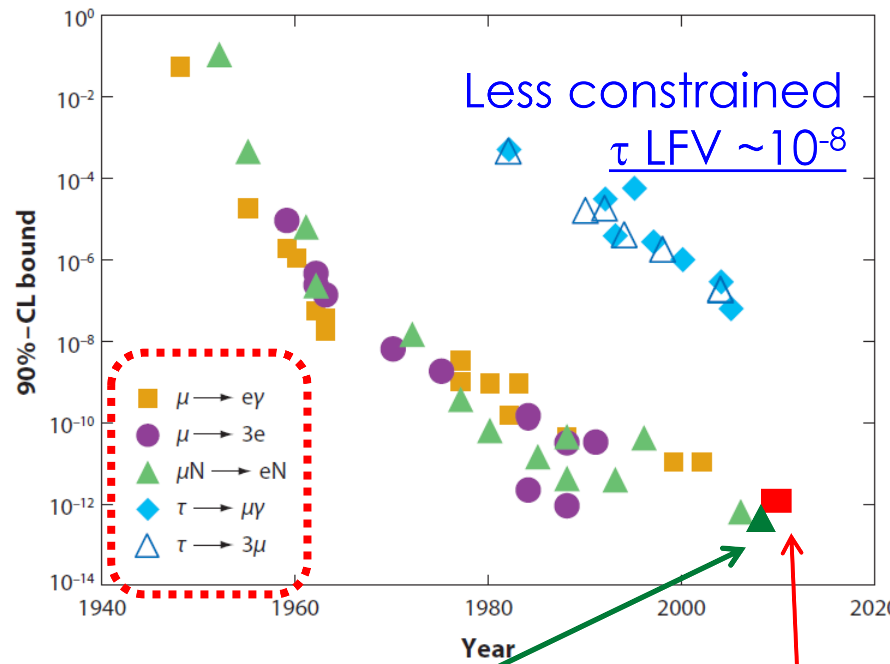
[21] DOHMEN 93 assumes $\mu^- \rightarrow e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

$\sigma(\mu^- Pb \rightarrow e^- Pb) / \sigma(\mu^- Pb \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.6 \times 10^{-11}$	90	HONECKER	96	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.9 \times 10^{-10}$	90	AHMAD	88	TPC	TRIUMF

$\sigma(\mu^- Au \rightarrow e^- Au) / \sigma(\mu^- Au \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
$<7 \times 10^{-13}$	90	BERTL	06	SPEC	–	SINDRUM II



New μ→eγ limit

Slightly better than μ→eγ and μ→3e

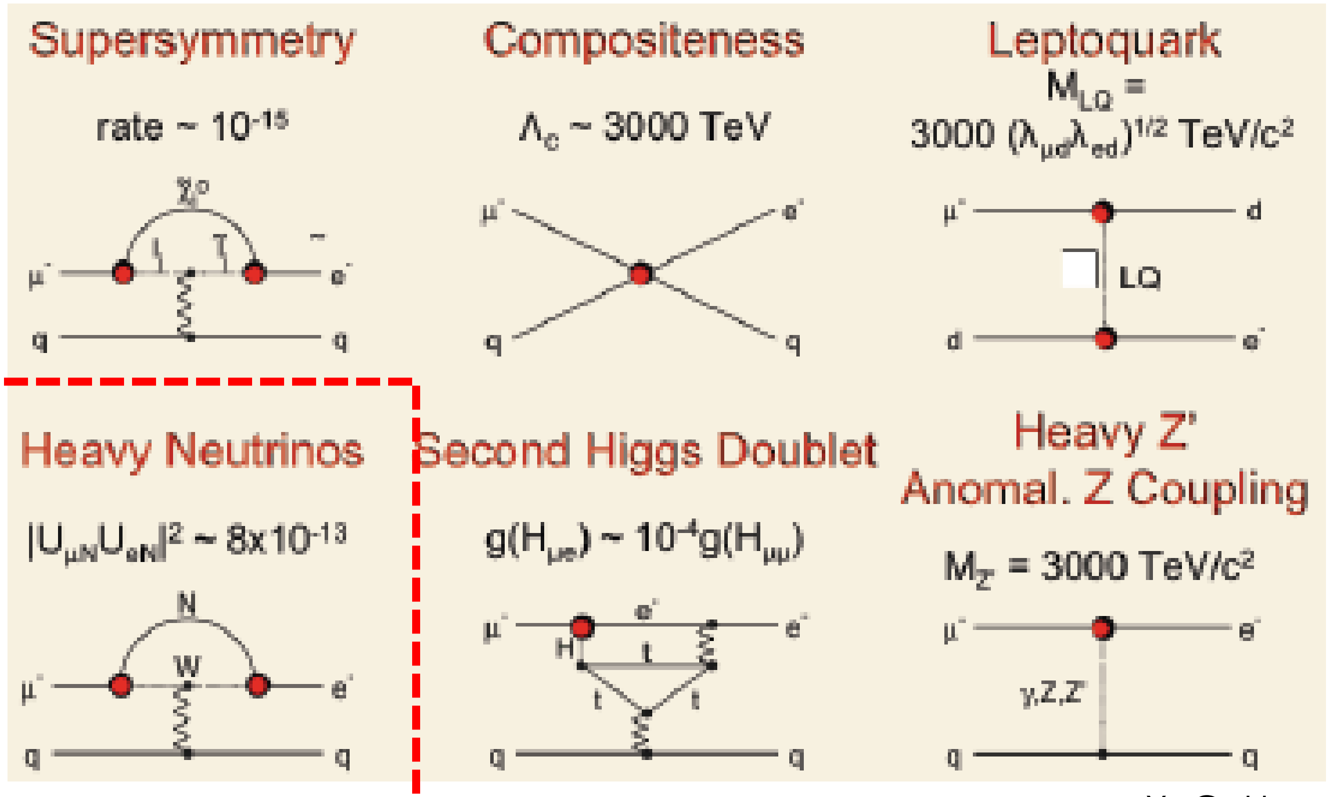
It will be improved to 10^{-18} for Ti !!

(much better future prospects)

Beyond the SM

◻ Possible new physics contributions

Hisano et.al.,PRD53:2442(1996) Nakagawa, Takasu, PTP59,548(1977) Shanker, NPB206,253 (1982)



X.-G. He et.al. (1990)

Fourth generation neutrino !!

Chang, Ng, Ng, PRD50,4589(1994)

μ→eγ in SM4

Chang, Ng, Ng, PRD50,4589(1994), Lacker, Menzel, JHEP07,006(2010)
Buras et.al. JHEP09,104(2010), Deshpande et.al. PLB703,26(2011)

- **Here after, we assume Dirac neutrino for definiteness.**

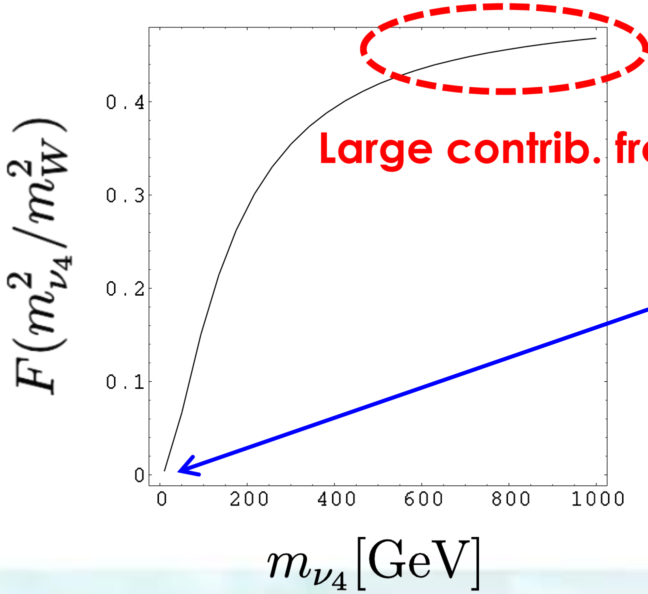
(But, it is true for Majorana neutrino from Type-I seesaw if MR is large.)

$$\mathcal{B}(\mu\to e\gamma)^{\rm SM3}=\frac{3\alpha}{2\pi}\left|U_{ei}U_{\mu i}^{*}\,F_W\left(\frac{m_i^2}{m_W^2}\right)\right|^2\approx\frac{3\alpha}{32\pi}\left|U_{ei}U_{\mu i}^{*}\frac{m_i^2}{m_W^2}\right|^2$$

More precise loop function

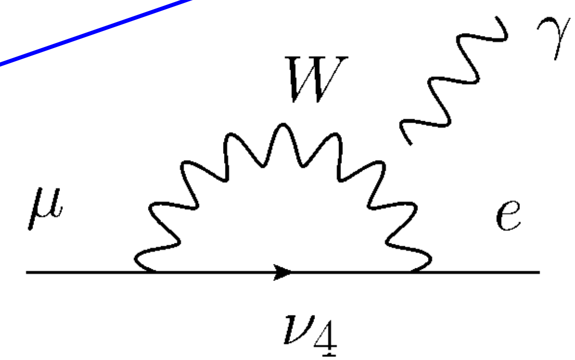
$$F_W(x)=-\frac{x(12+x-7x^2)}{12(x-1)^3}+\frac{x^2(12-10x+x^2)}{6(x-1)^4}\ln x\approx\frac{1}{4}x$$

Small ν mass limit



$\propto\frac{1}{2}+\left(\frac{11}{4}-\frac{3}{2}\ln x\right)\frac{1}{x}$

Large contrib. from heavy neutrinos



Heavy neutrino

4th generation neutrino

- **Mass bound for 4th generation neutrinos**
  - Lower bound from Direct search

Heavy Neutral Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings.

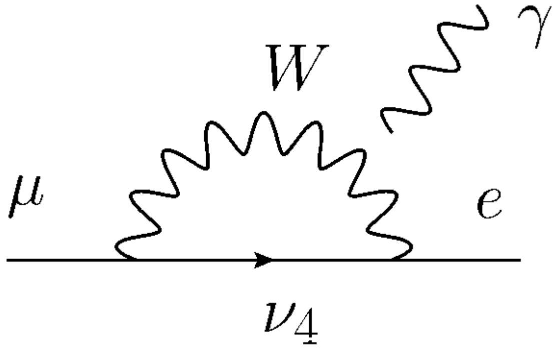
See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited neutral leptons, *i.e.* $\nu^* \to \nu\gamma$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>101.3	95	ACHARD	01B	L3	Dirac coupling to e
>101.5	95	ACHARD	01B	L3	Dirac coupling to μ
> 90.3	95	ACHARD	01B	L3	Dirac coupling to τ
> 89.5	95	ACHARD	01B	L3	Majorana coupling to e
> 90.7	95	ACHARD	01B	L3	Majorana coupling to μ
> 80.5	95	ACHARD	01B	L3	Majorana coupling t

  - Upper bound from unitarity

    1.2 TeV for heavy leptons

    Chanowtz, PLB78,285(1978)



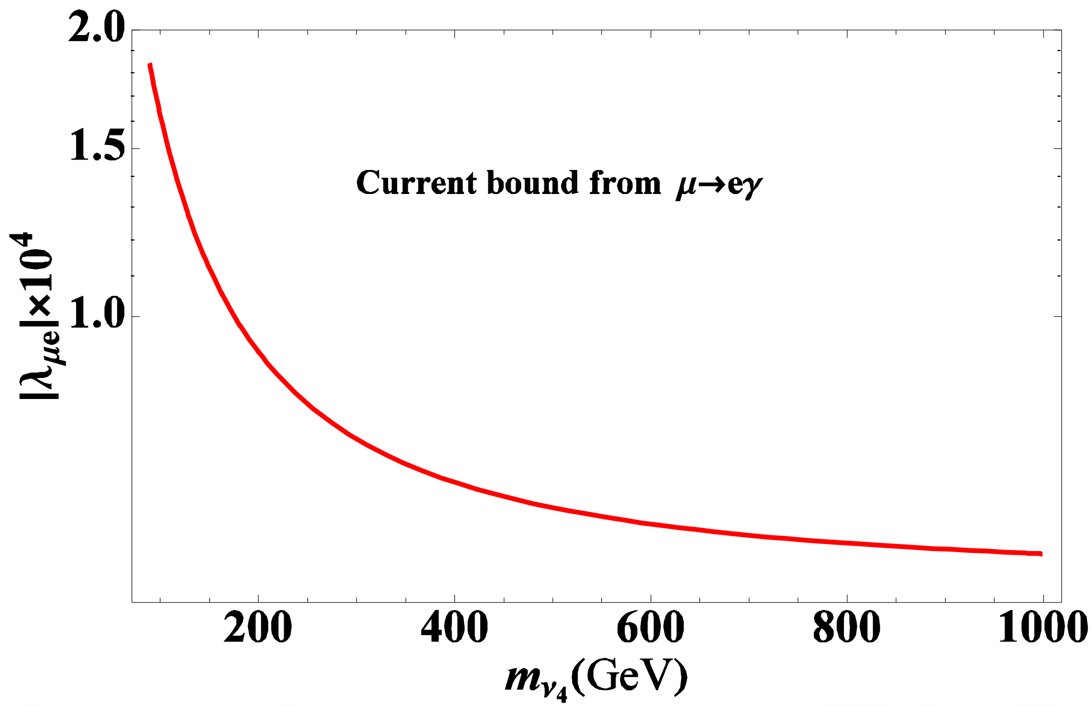
→ v4 can induce observable $\mu \to e\gamma$

$\mu \rightarrow e\gamma$ in SM4

- Large BR possible if neutrino mixing is large

$$\mathcal{B}(\mu \to e\gamma)^{\mathrm{SM4}} \approx \frac{3\alpha}{2\pi} \left| \lambda_{\mu e} F_W\left(\frac{m_{\nu_4}^2}{m_W^2}\right) \right|^2 \quad \text{where } \lambda_{\mu e} = U_{e4} U_{\mu 4}^*$$

→ current experimental bound can be converted to bound on $\lambda_{\mu e}$



$$\lambda_{\mu e} \lesssim 0.6 \times 10^{-4}$$

μ →3e in SM4

Chang, Ng, Ng, PRD50,4589(1994), Buras et.al. JHEP09,104(2010)
Deshpande et.al. PLB703,26(2011)

▫ Effective Lagrangian

$$\mathcal{L}^{\mu\to e\bar{e}e} = -\frac{G_F}{\sqrt{2}}\frac{e^2}{4\pi^2}\lambda_{\mu e}\Big[F_W(x_4)\,\bar{e}\gamma_\mu e\,\frac{q_\nu}{q^2}\,\bar{e}i\sigma^{\mu\nu}m_\mu R\mu + \bar{e}\gamma^\mu\left(a_L(x_4)L + a_R(x_4)R\right)e\,\bar{e}\gamma_\mu L\mu\Big]$$

On-shell photon penguin

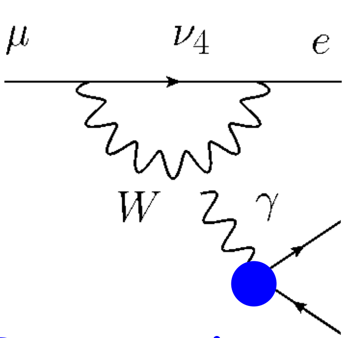
$$a_L(x) = F_{W^*}(x) + \frac{1}{s_W^2}\left(-\frac{1}{2}+s_W^2\right)F_Z(x) - \frac{1}{2s_W^2}F_B(x)\ , \qquad a_R(x) = F_{W^*}(x) + F_Z(x)$$

Off-shell photon Z photon Box diagrams

▫ On-shell photon penguin dominant case (in general)

$$\frac{\mathcal{B}(\mu\to 3e)}{\mathcal{B}(\mu\to e\gamma)} = \frac{\alpha}{3\pi}\left(\frac{m_\mu^2}{m_e^2}-\frac{11}{4}\right) \approx 0.006$$

Hisano, Nomura, PRD59,116005(1999)



2-3 orders magnitude smaller

Additional QED suppression

$\mu \rightarrow 3e$ in SM4

Effective Lagrangian

$$\mathcal{L}^{\mu\to e\bar{e}e} = -\frac{G_F}{\sqrt{2}}\frac{e^2}{4\pi^2}\lambda_{\mu e}\left[F_W(x_4)\,\bar{e}\gamma_\mu e\,\frac{q_\nu}{q^2}\,\bar{e}i\sigma^{\mu\nu}m_\mu R\mu + \bar{e}\gamma^\mu\left(a_L(x_4)L + a_R(x_4)R\right)e\,\bar{e}\gamma_\mu L\mu\right]$$

On-shell photon penguin

$$a_L(x) = F_{W^*}(x) + \frac{1}{s_W^2}\left(-\frac{1}{2} + s_W^2\right)F_Z(x) - \frac{1}{2s_W^2}F_B(x)\,, \qquad a_R(x) = F_{W^*}(x) + F_Z(x)$$

Off-shell photon   Z photon   Box diagrams

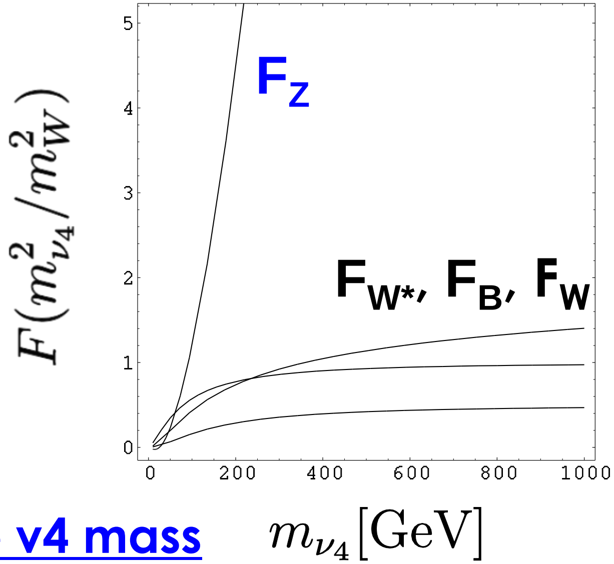
Z penguin becomes important in SM4

$$F_{W^*}(x) = \frac{x(12+x-7x^2)}{12(x-1)^3} - \frac{x^2(12-10x+x^2)}{6(x-1)^4}\ln x$$

$$F_W(x) = \frac{x(1-5x-2x^2)}{4(x-1)^3} + \frac{3x^3}{2(x-1)^4}\ln x$$

$$F_Z(x) = \frac{x(x^2-7x+6)}{4(x-1)^2} + \frac{x(2+3x)}{4(x-1)^2}\ln x$$

$$F_B(x) = \frac{x}{x-1} - \frac{x}{(x-1)^2}\ln x$$



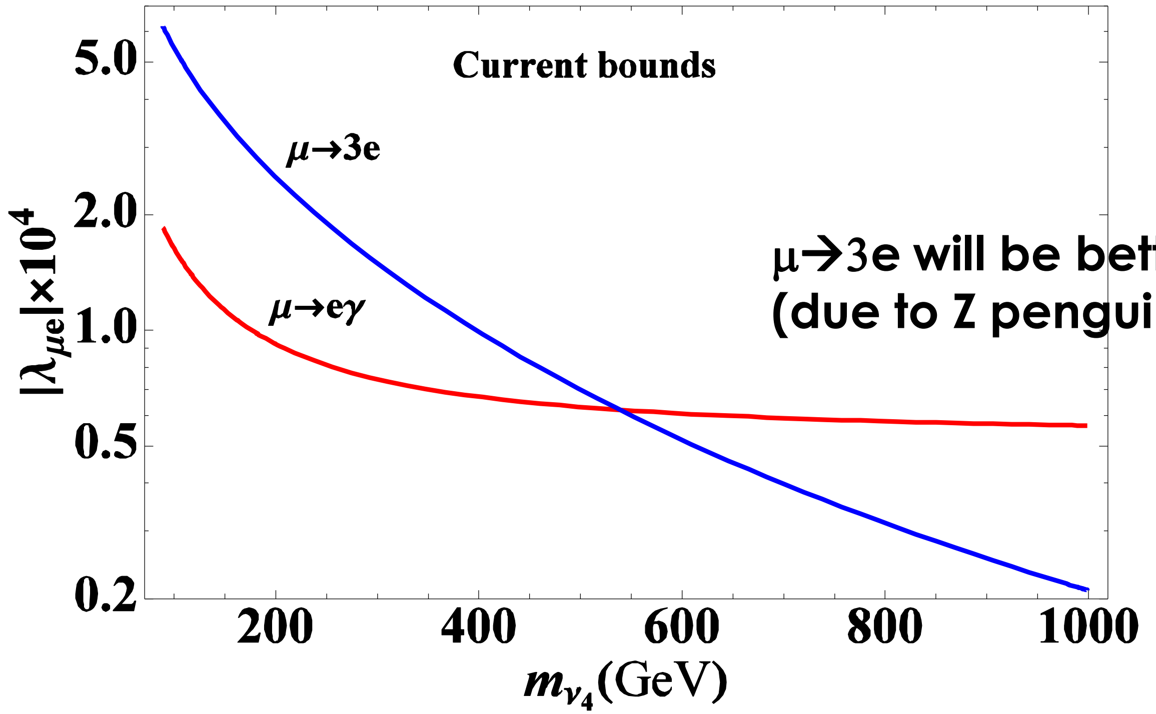
Increase for large v4 mass

μ →3e and μ →eγ in SM4

- Compare two results:

$$\mathcal{B}(\mu \to e\bar{e}e) = \frac{\alpha^2}{16\pi^2}\left[a_R^2(x_4) + 2a_L^2(x_4) - 4F_W(x_4)(a_R(x_4) + 2a_L(x_4)) + 4F_W^2(x_4)\left(4\ln\frac{m_\mu}{m_e} - \frac{11}{2}\right)\right]$$

On-shell photon penguin



μ→3e will be better for heavy v4
(due to Z penguin)

$\mu \to e$ conversions in SM4

Buras et.al. JHEP09,104(2010)
Deshpande et.al. PLB703,26(2011)

◻ Effective Lagrangian

$$\mathcal{L}^{\mu\to e} = -\frac{G_F}{\sqrt{2}}\frac{e^2}{4\pi^2}\lambda_{\mu e}\left[F_W(x_4)\,\bar{q}\gamma_\mu q\,\frac{q_\nu}{q^2}\,\bar{e}i\sigma^{\mu\nu}m_\mu R\mu + \bar{q}\gamma^\mu\left(V_q(x_4)+A_q(x_4)\gamma_5\right)q\,\bar{e}\gamma_\mu L\mu\right]$$

On-shell photon penguin

$$V_q(x) = -Q^q F_{W^*}(x) + \frac{1}{s_W^2}\left(I_3^q - Q^q s_W^2\right)F_Z(x) - \frac{1}{4s_W^2}F_B(x)\,, \quad A_q(x) = -\frac{1}{s_W^2}I_3^q F_Z(x) + \frac{1}{4s_W^2}F_B(x)$$

Off-shell photon Z photon Box diagrams

◻ $\mu \to e$ conversion rate for nucleus A:

$$\frac{\mathcal{B}^A_{\mu\to e}}{\mathcal{B}(\mu\to e\gamma)} = R^0_{\mu\to e}\left|1 + \frac{8\pi\, e}{F_W(x_4)D(A)}\left[(2V_u+V_d)V_A^{(p)} + (V_u+2V_d)V_A^{(n)}\right]\right|^2$$

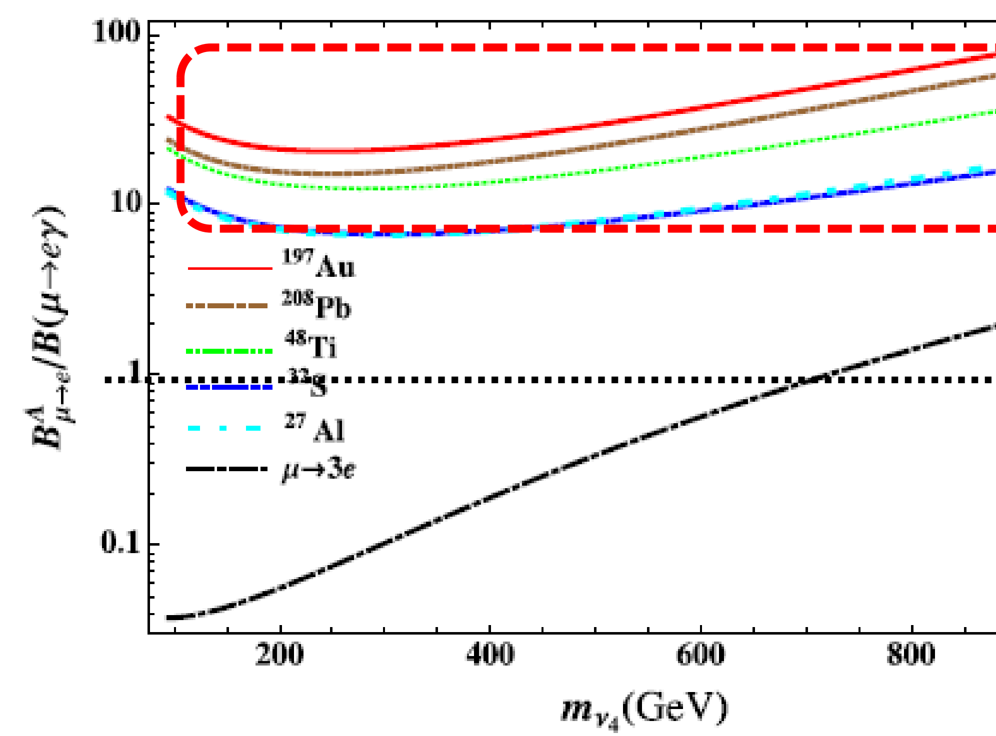
Nucleus dependent parts were calculated several methods.

Kitano, Koike, Okada, PRD66,096002(2002)
Weinberg, Feinberg, PRL3,111(1959)
Shanker, PRD20,1608(1979)

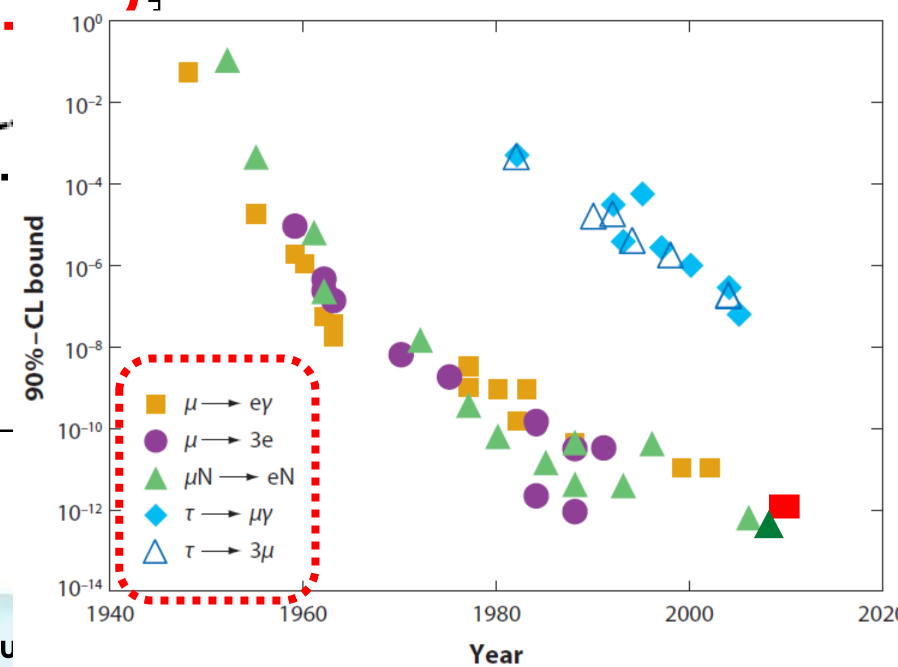
A	$D(A)$	$V^{(p)}(A)$	$V^{(n)}(A)$	$R^0_{\mu\to e}(A)$
$^{27}_{13}$Al	0.0362	0.0161	0.0173	0.0026
$^{32}_{16}$S	0.0524	0.0236	0.0236	0.0028
$^{48}_{22}$Ti	0.0864	0.0396	0.0468	0.0041
$^{197}_{79}$Au	0.189	0.0974	0.146	0.0039
$^{208}_{82}$Pb	0.161	0.0834	0.128	0.0027

LFV in SM4

- Loop induced LFV always proportional to $\lambda_{\mu e} = U_{e4} U^*_{\mu 4}$
- Compare LFV processes by taking ratio (cancel λμe)



μ→e conv. would be better
if exp. limit are the same level

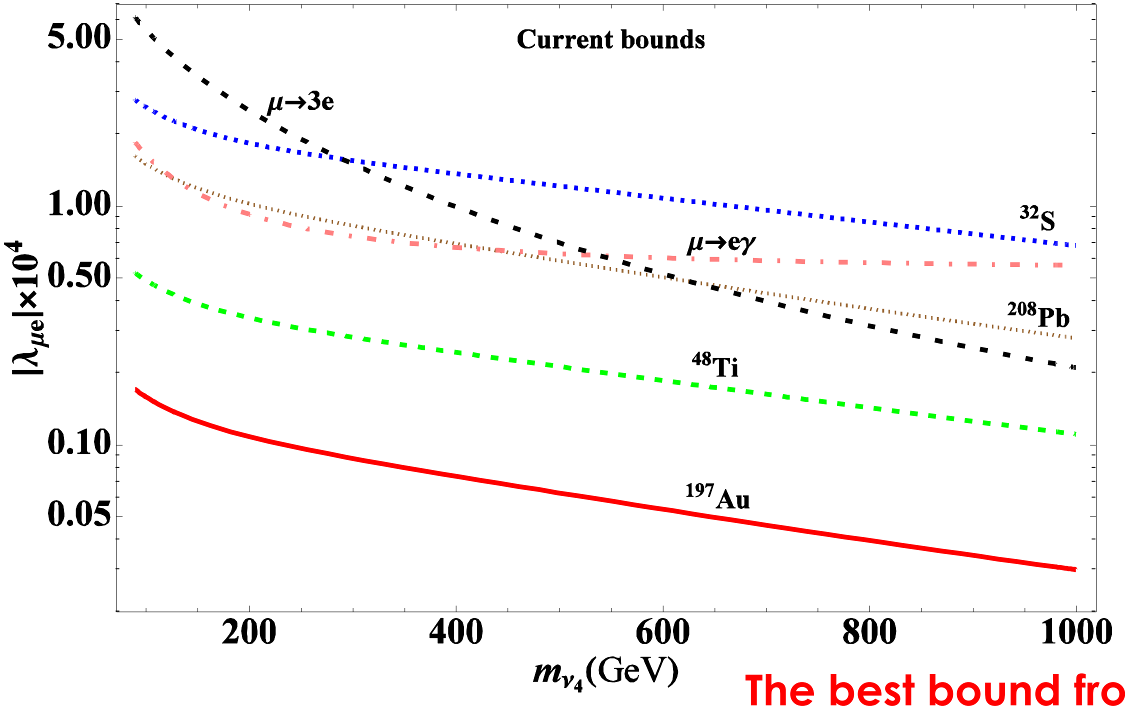


LFV in SM4

- **Large BR possible if neutrino mixing is large**

$$\mathcal{B}(\mu \to e\gamma)^{\rm SM4} \approx \frac{3\alpha}{2\pi}\left|\lambda_{\mu e}\, F_W\left(\frac{m_{\nu_4}^2}{m_W^2}\right)\right|^2 \quad \text{where } \lambda_{\mu e} = U_{e4}U_{\mu 4}^*$$

→ **current experimental bound can be converted to bound on $\lambda_{\mu e}$**



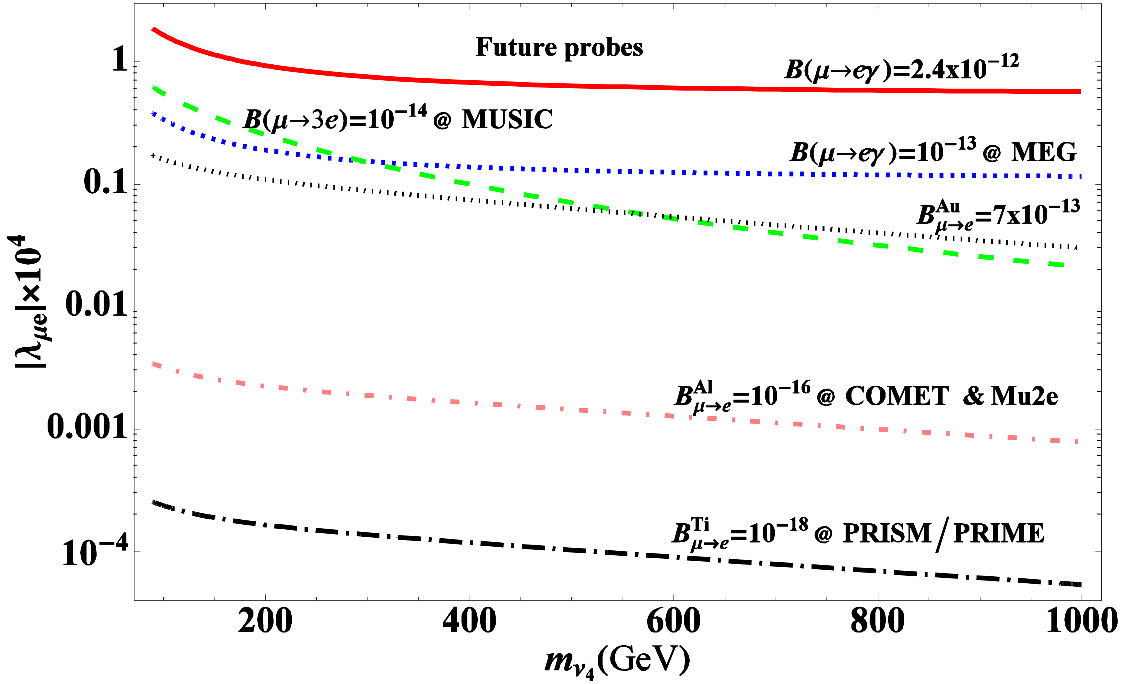
The best bound from μ→e conv. in Au.

LFV in SM4 (Prospects)

- Large BR possible if neutrino mixing is large

$$\mathcal{B}(\mu \to e\gamma)^{\mathrm{SM4}} \approx \frac{3\alpha}{2\pi}\left|\lambda_{\mu e}\, F_W\left(\frac{m_{\nu_4}^2}{m_W^2}\right)\right|^2 \quad \text{where } \lambda_{\mu e} = U_{e4}U_{\mu 4}^*$$

→ current experimental bound can be converted to bound on $\lambda_{\mu e}$



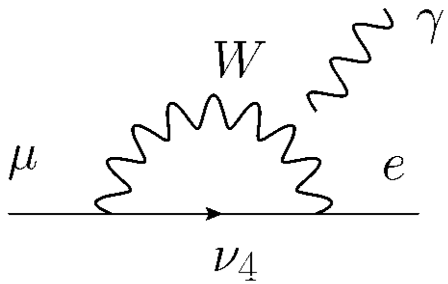
Several projects are proposed.

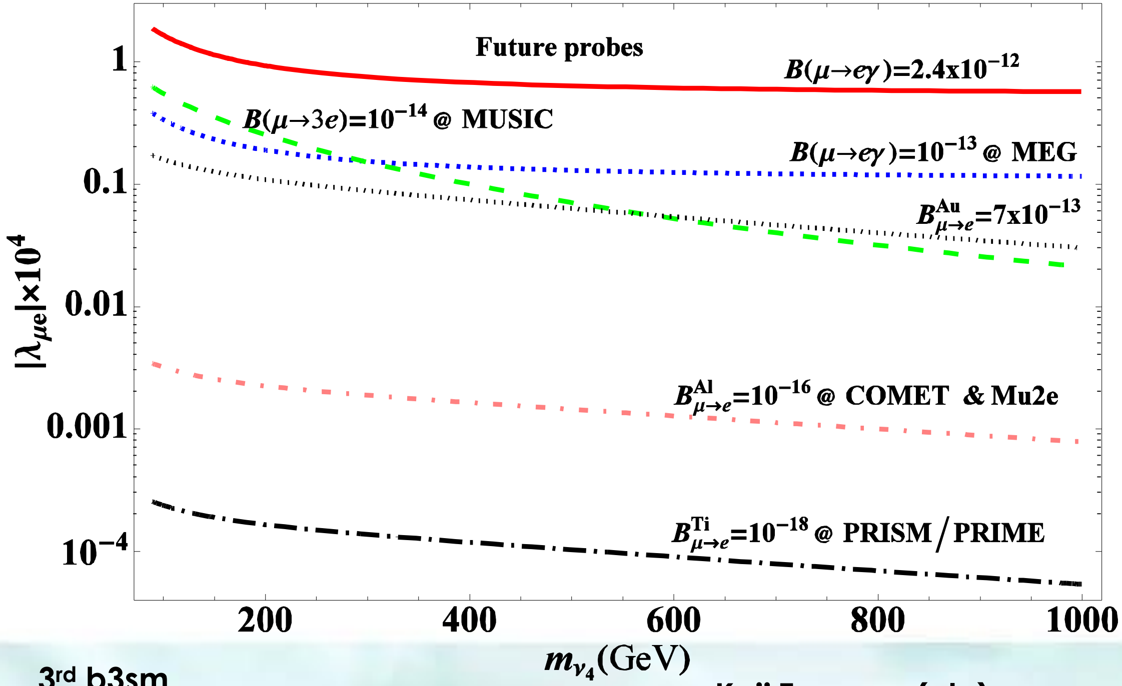
Current bound from μ→e in Au is comparable level with projected μ →e γ and μ →3e exp in SM4.

μ→e conv. can improve $\lambda_{\mu e}$ by 3 orders of magnitude in future.

Summary

- LFV in SM4
  - GIM suppression in SM3
  - ν4 enhance LFV rate significantly
  - μ→3e is better than μ→eγ for heavy ν4 (due to Z penguin)
  - μ→e conversion in Au gives the best bound on λμe





μ→e conv. can improve λμe
by 3 orders of magnitude in future.