



Lepton-Flavor Violation in Charged Lepton Decay

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Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

The 29th International Symposium on
Lepton Photon Interactions at High Energies
(Toronto, Canada between August 5-10, 2019)

3rd International conference on Charged Lepton Flavor Violation (CLFV 2019)

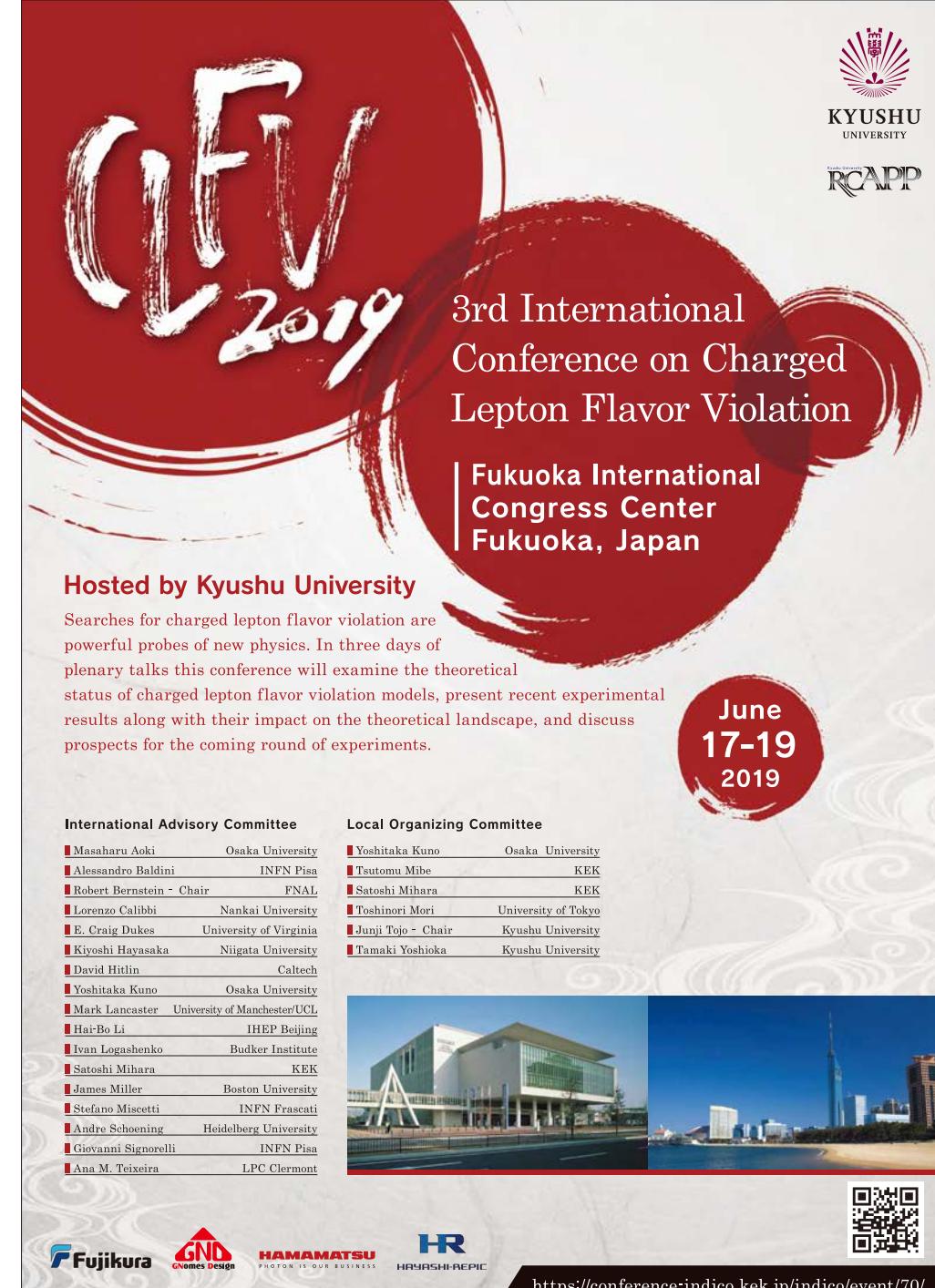
Date: June, 17-19, 2019

Place: Fukuoka, Japan

Latest results were discussed there.

Presentations are

<https://conference-indico.kek.jp/indico/event/70/overview>



The image shows the official flyer for the 3rd International Conference on Charged Lepton Flavor Violation (CLFV 2019). The design features a red and white color scheme with abstract brushstroke patterns. The title "CLFV 2019" is prominently displayed at the top. Below it, the text "3rd International Conference on Charged Lepton Flavor Violation" and "Fukuoka International Congress Center Fukuoka, Japan" are visible. A circular badge on the right indicates the dates "June 17-19 2019". The flyer also includes sections for the "International Advisory Committee" and "Local Organizing Committee", listing names and institutions. At the bottom, there are logos for Fujikura, GND, Hamamatsu Photonics, and Hayashi-Repic, along with a QR code and a link to the conference website.

CLFV 2019

3rd International Conference on Charged Lepton Flavor Violation

Fukuoka International Congress Center
Fukuoka, Japan

Hosted by Kyushu University

Searches for charged lepton flavor violation are powerful probes of new physics. In three days of plenary talks this conference will examine the theoretical status of charged lepton flavor violation models, present recent experimental results along with their impact on the theoretical landscape, and discuss prospects for the coming round of experiments.

June 17-19 2019

International Advisory Committee

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<https://conference-indico.kek.jp/indico/event/70/>

1, Introduction

Shopping list of charged lepton-flavor violation (CLFV)

(Generation of charged lepton is changed in CLFV processes.)

1. $\mu \rightarrow e$ transition processes

- $\mu^+ \rightarrow e^+ \gamma$
- $\mu^+ \rightarrow e^+ e^- e^+$
- $\mu - e$ conversion in nuclei
- muonium-antimuonium transition:
 $(\mu^+ e^-) \rightarrow (\mu^- e^+)$
- B/D/K decaying into mu e such as
 $D^0 \rightarrow h^+ h^- \mu e$ (F.Wilson@parallel session)
 $K^+ \rightarrow \pi^+ \mu e$ (R.Marchevski@parallel session)

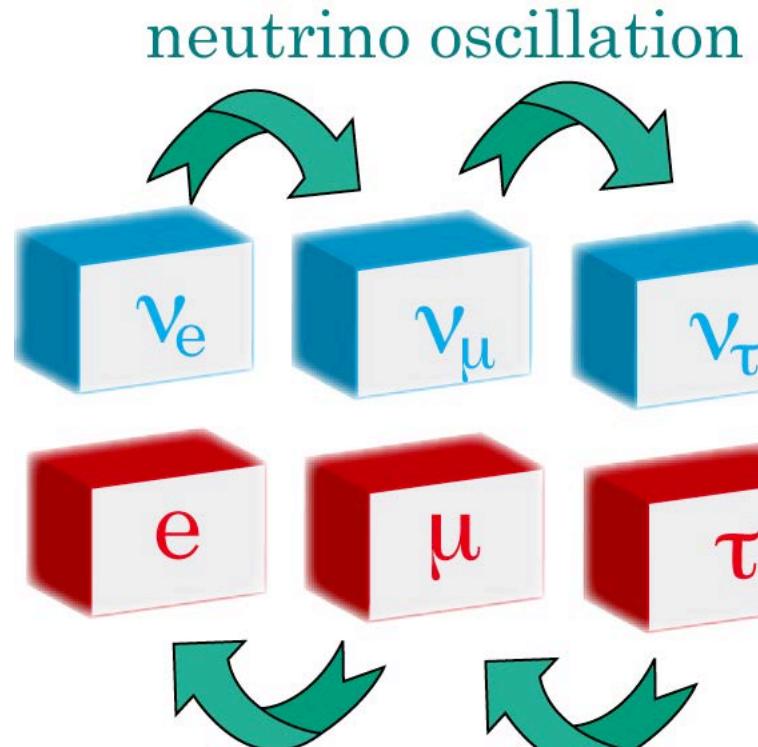
2. $\tau \rightarrow \mu/e$ transition processes

- $\tau \rightarrow \mu/e + \gamma$
- $\tau \rightarrow \mu/e + ll$
- $\tau \rightarrow \mu/e + \text{hadrons}$
- $B^0 \rightarrow \tau \mu$

Nowadays CLFV decays of heavy particles, such as $H \rightarrow \tau \mu$, are available.

In my talk I will mainly concentrate into lepton-flavor violating decay of charged leptons as in my title.

Tiny m_ν does not induce observable effects.

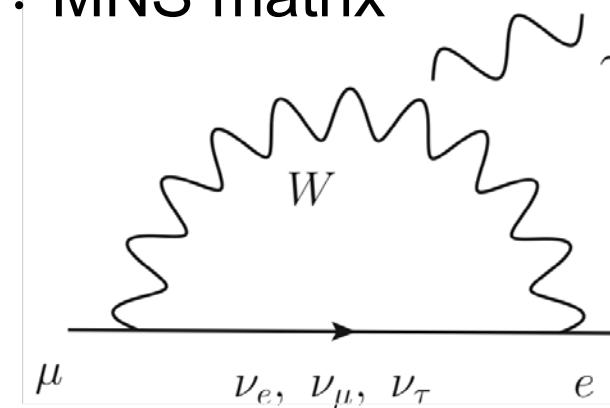


Finite neutrino masses
CLFV processes are suppressed by GIM mechanism.

$$Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{m_W^2} \right|^2 < 10^{-54}$$

$$\Delta m_{i1}^2 \equiv (m_{\nu_i}^2 - m_{\nu_1}^2)$$

U : MNS matrix



However, lepton flavor may not be conserved in BSM. ⁵

Searches for symmetry breaking: Window to BSM

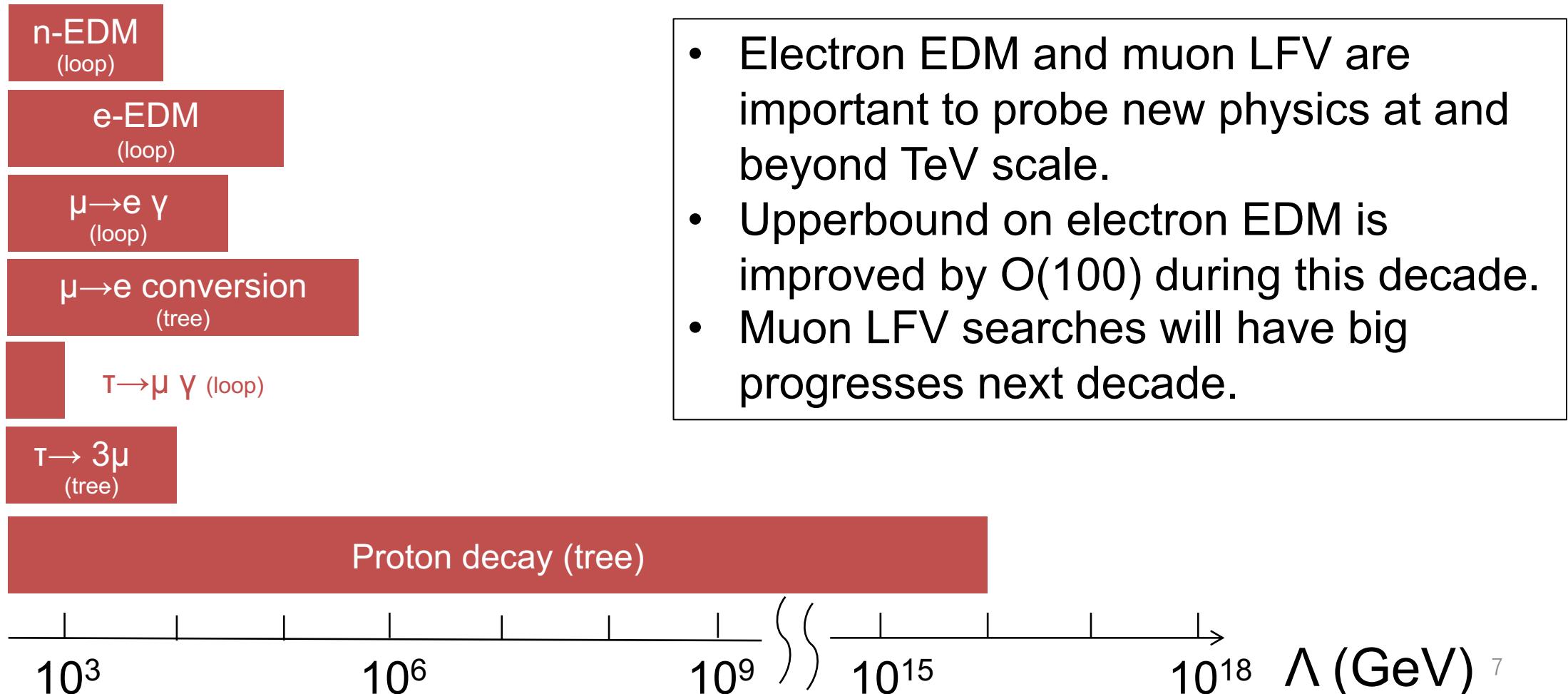
Global symmetries in SM are not exact in nature.

- **CP violation (CKM in the SM)**
EDMs
- **Lepton-flavor violation (neutrino oscillation)**
 - Charged lepton flavor-violating decay
- **Lepton and/or baryon number violation
(B asymmetry in the universe)**
 - 0νββdecay
 - Proton decay

Searches for symmetry breaking

Sensitivities of current experimental bounds to NP scale (Λ).

Only one loop factors are included for the loop processes, EDM and $I \rightarrow I' \gamma$.
Small SB parameters may suppress the sensitivities.



LFV in BSM at TeV and beyond TeV

Theoretical Motivation:

- Naturalness problem and/or WIMP DM paradigm
Introduction of partners of leptons
such as in SUSY SM, Extra-Dim, and so on.
- Origin of neutrino masses
Low-energy seesaw models

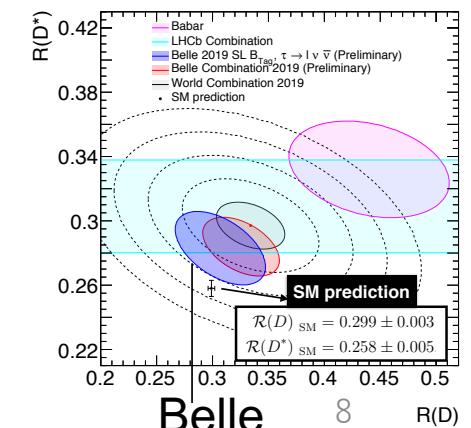
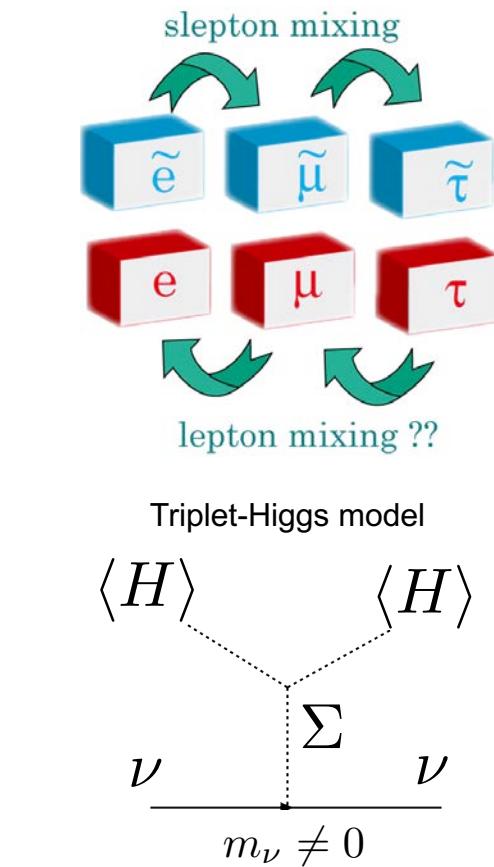
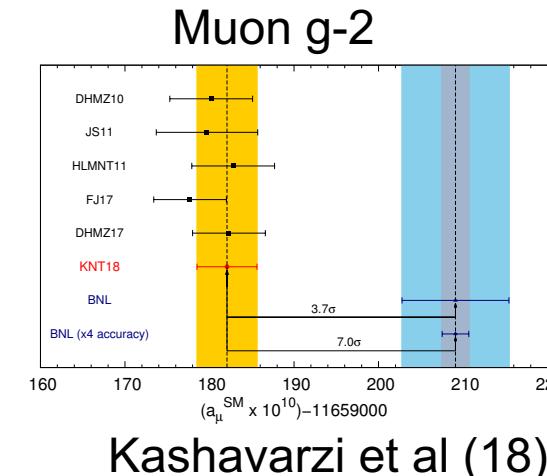
Some of these issues may be solved beyond TeV, so high sensitivities of CLFV searches are quite important.

Anomalies observed in experiments:

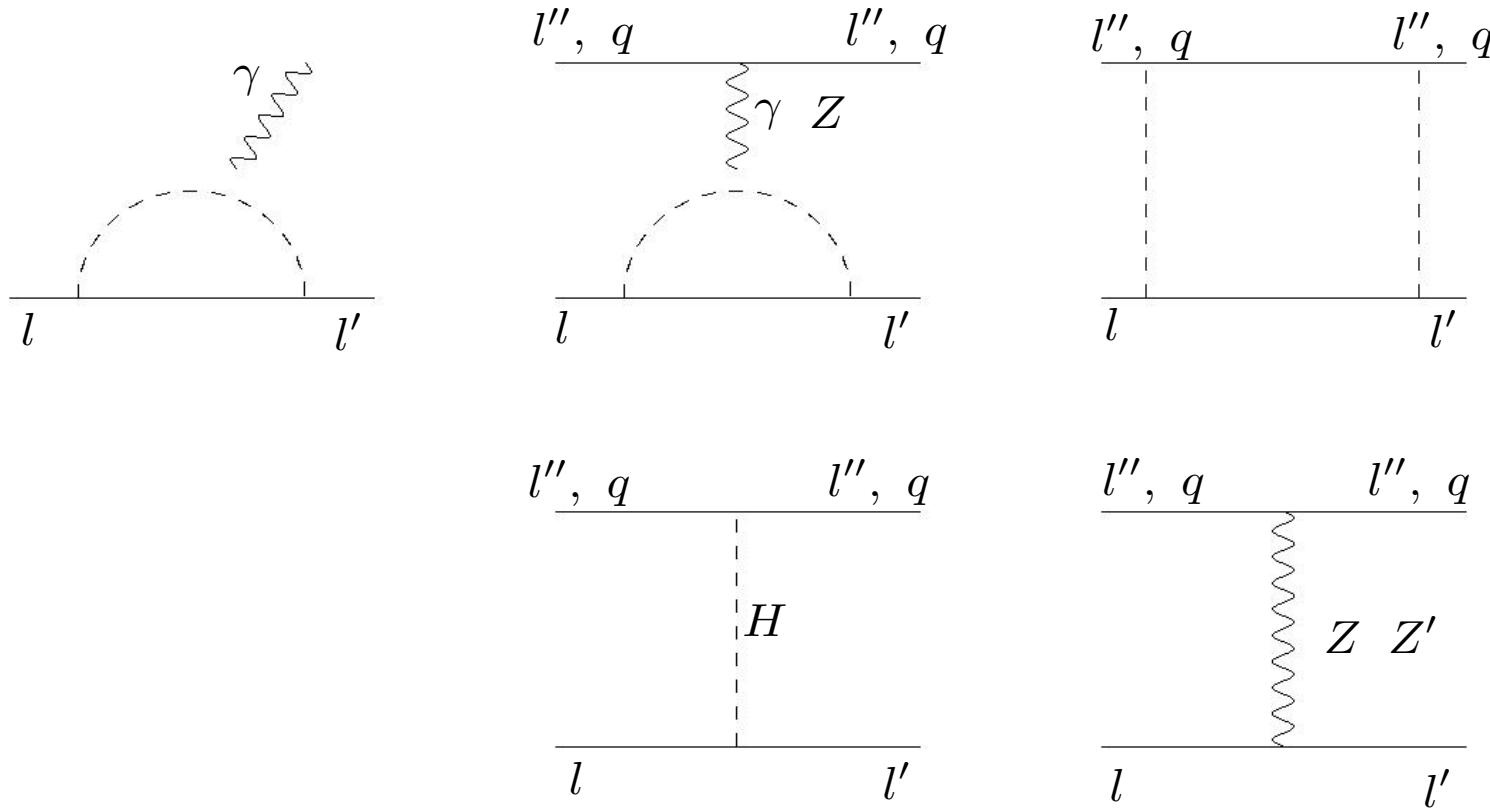
- Muon g-2 (3.7sigma)
- Electron g-2 (2.5 sigma)
- B anomalies

$$B \rightarrow D^{(*)} \tau \nu \text{ (3.1sigma)}$$

$$B \rightarrow K^{(*)} l^+ l^- \text{ (2.0-2.6sigma)}$$



Diagrams of CLFV processes



- In WIMP dark matter/naturalness motivated models, such as SUSY SM, Four-Fermi operators come from loop-diagrams.
- In other models, such as extra Higgs, Z' , and extra matter models, they are induced at tree level.
- Models are discriminated with pattern of CLFV processes.

2, μ -e transition processes

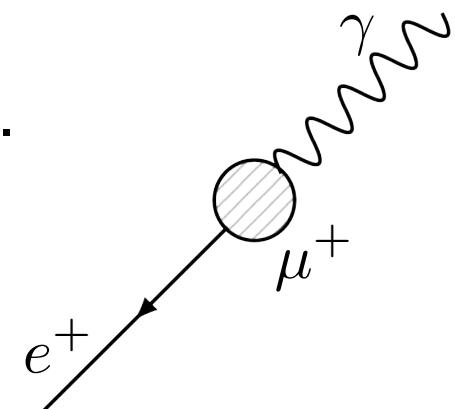
- $\mu^+ \rightarrow e^+ \gamma$
- $\mu^+ \rightarrow e^+ e^- e^+$
- $\mu - e$ conversion in nuclei

MEG and MEG-II experiments ($\mu^+ \rightarrow e^+ \gamma$)

Iwamoto-san's talk
In parallel session

BGs: accidental BGs and radiative muon decay

Signal: monochromatic, back-to-back, and produced at the same time.



PSI has the most intense DC muon beam up to $10^8 \mu/s$.

The final result of MEG (2016)

$$BR < 4.2 \times 10^{-13} \text{ (90\% C.L.)}$$

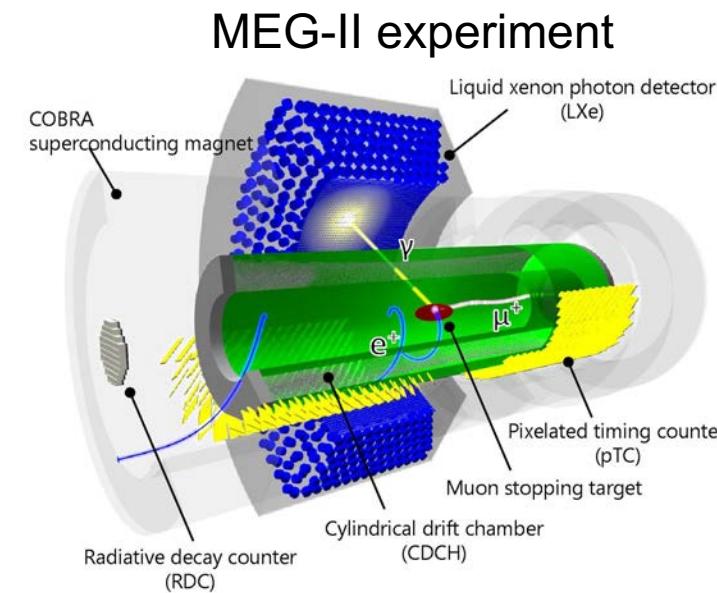
MEG-II is an upgrade of all sub-detectors.

First physics run will start in 2020

Expectation in 3 years run is $BR \sim 6 \times 10^{-14}$.

Future experiments: Next target is $BR \sim 10^{-15}$.

Hear Iwamoto-san or see slide of Renga @ CLFV conf.



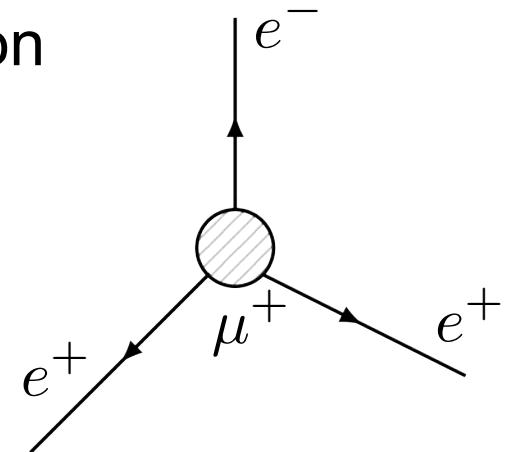
Mu3e experiment ($\mu^+ \rightarrow e^+ e^- e^+$)

BGs: accidental BGs and radiative muon decay with internal conversion

Signal: kinematics, and produced at the same time and same place.

Current bound from SINDUM (1988)

$$BR < 1.0 \times 10^{-12} \text{ (90\% C.L.)}$$

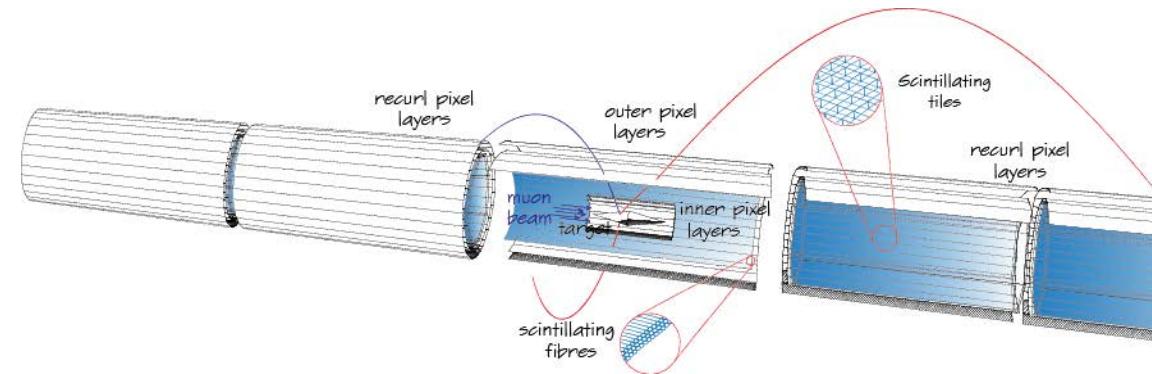


PSI has the most intense DC muon beam up to $10^8 \mu/s$.

Mu2e Phase I detector construction in 2020/21.

Aiming for sensitivity of Mu3e (phase I)

$$BR < 2 \times 10^{-15}$$



"Aiming for sensitivity of phase II is beyond 10^{-16} with $10^9 \mu/s$ (not before 2025, physics up to 2030)." from Schöning@CLFV conf.

Schematic view of
Mu3e experiment

COMET and Mu2e experiments (μ - e conversion in nuclei)

Signal of μ - e conversion: monochromatic electron with

$$E = m_\mu - E_{\text{binding}} - E_{\text{nuclear recoil}}$$

BGs: Muon decay in orbit:

Branching ratio drops near the end point (calculated by Czarnecki (16))

Beam related BG

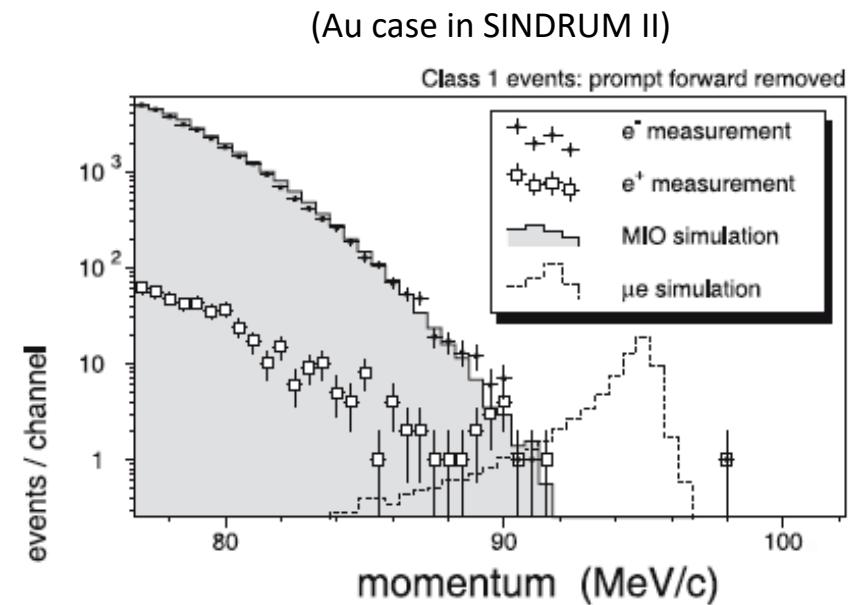
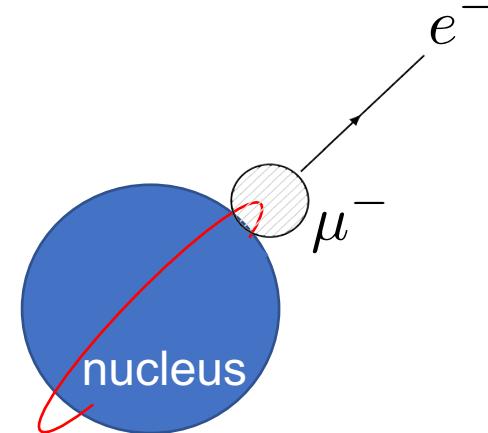
Cosmic ray BG

Current bounds (normalized by capture rate)

$$R_{\mu e}(N) \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')}$$

$$R_{\mu e}(\text{Ti}) < 6 \times 10^{-13} \quad (\text{SINDRUM II, 93'})$$

$$R_{\mu e}(\text{Au}) < 7 \times 10^{-13} \quad (\text{SINDRUM II, 00'})$$



COMET and Mu2e experiment (μ - e conversion in nuclei)

Original idea comes from MELC experiments.

- Thick target with SC solenoidal as capture magnet.
- Long muon beam line with momentum selection
- Light detector to provide precise electron measurement

COMET@J-Parc

Phase-I: Under construct. Muon beam measured to study BGs.

$$R_{\mu e} \sim 3 \times 10^{-15} \text{ (S.E.S., 5 months)}$$

Phase-II: Full muon beam line installed.

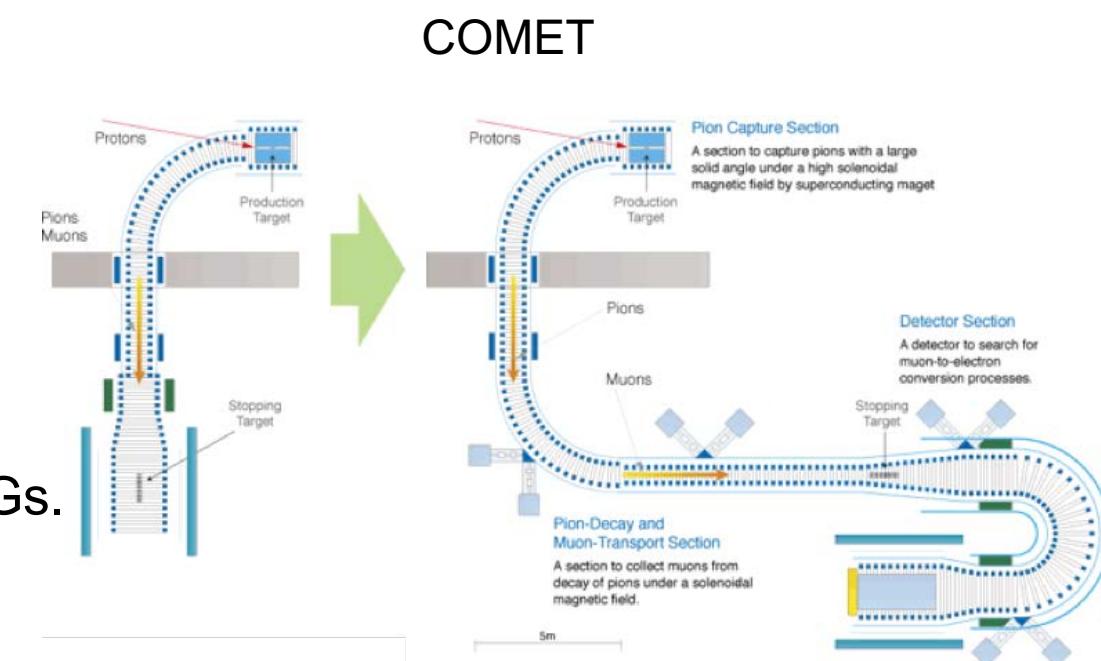
$$R_{\mu e} \sim 2.6 \times 10^{-17} \text{ (S.E.S., 1 year)}$$

“With the same beam power, 10 times better sensitivity ($\mathcal{O}(10^{-18})$) is likely and optimization is on the way. “ from Wu Chen@CLFV.

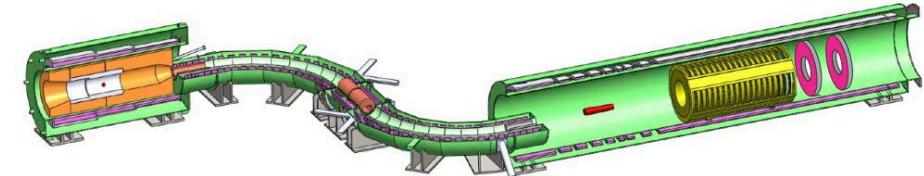
Mu2e@Fermilab (Brendan Kiburg will talk next)

Commissioning expected in 2022.

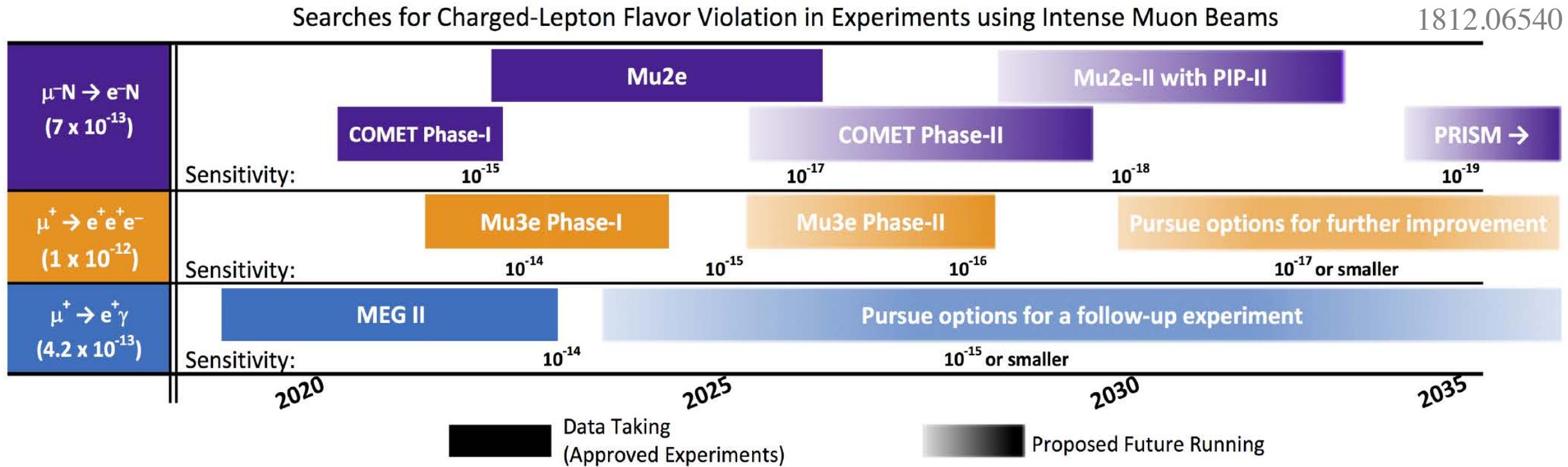
$$R_{\mu e} \sim 2.5 \times 10^{-17} \text{ (S.E.S.)}$$



Mu2e



Schedule of muon LFV searches



Muon LFV searches will be interesting next decade (2020's).

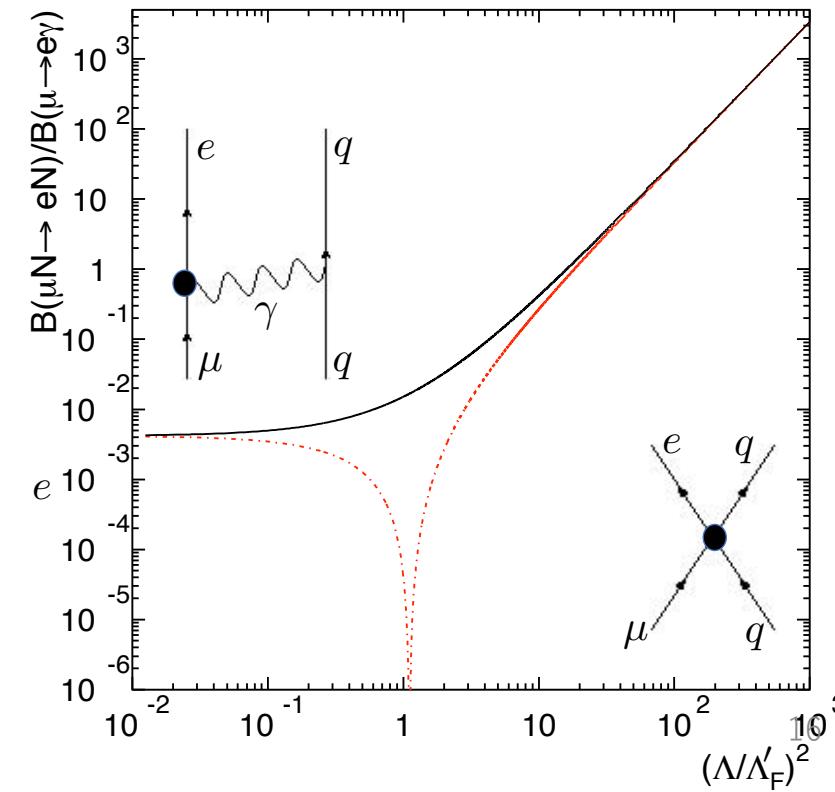
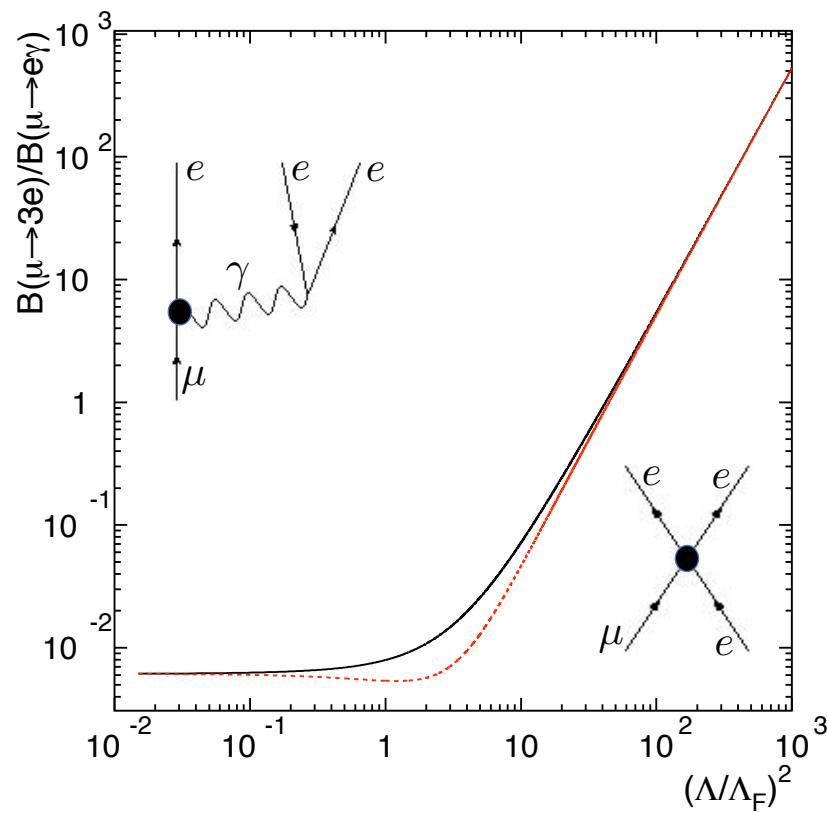
Effective operator approach for muon LFV processes

$$\mathcal{L}_{eff} \sim \frac{m_\mu}{\Lambda^2} \bar{e} (\sigma^{\mu\nu} F_{\mu\nu}) \mu + \frac{1}{\Lambda_F^2} \bar{e} \Gamma_A e \bar{e} \Gamma_A \mu + \frac{1}{\Lambda'_F^2} \bar{q} \Gamma_A q \bar{e} \Gamma_A \mu$$

$\mu \rightarrow e\gamma$

$\mu \rightarrow 3e$

μ - e conversion
in nuclei



Effective operator approach for muon LFV processes

$$\mathcal{L}_{eff} \sim \frac{m_\mu}{\Lambda^2} \bar{e}(\sigma^{\mu\nu} F_{\mu\nu})\mu + \frac{1}{\Lambda_F^2} \bar{e}\Gamma_A e \bar{e}\Gamma_A \mu + \frac{1}{\Lambda'_F{}^2} \bar{q}\Gamma_A q \bar{e}\Gamma_A \mu$$

$\mu \rightarrow e\gamma$ $\mu \rightarrow 3e$ $\mu\text{-}e$ conversion
in nuclei

When dipole term is dominated, such as in SUSY SM,

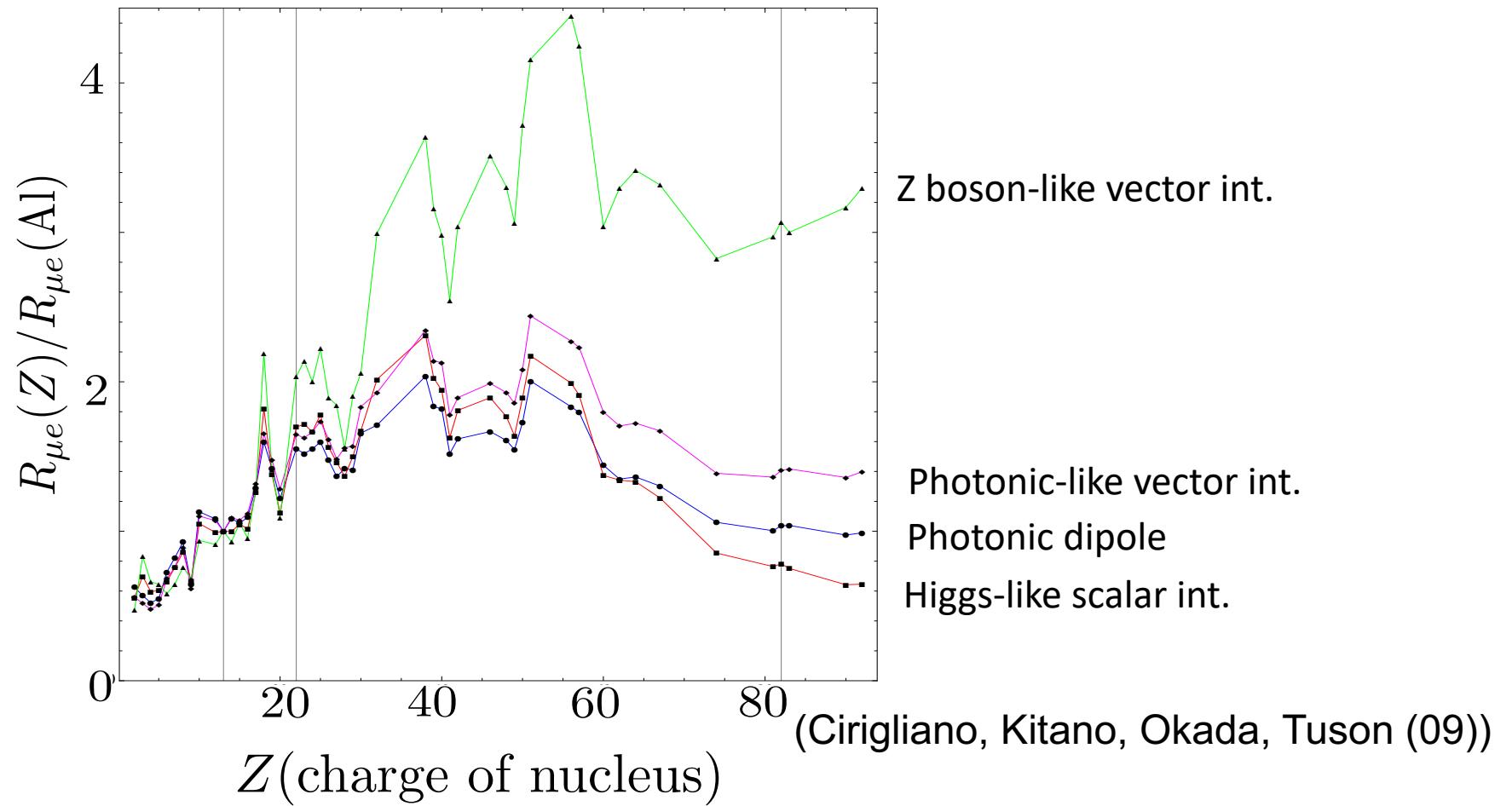
$$BR(\mu \rightarrow 3e) \simeq 6.1 \times 10^{-3} BR(\mu \rightarrow e\gamma)$$

$$R_{\mu e}(\text{Al}) \simeq 3 \times 10^{-3} BR(\mu \rightarrow e\gamma)$$

$$R_{\mu e}(\text{Ti}) \simeq 4 \times 10^{-3} BR(\mu \rightarrow e\gamma)$$

Muon LFV experiments are competitive and complemental to reach others.

Model discrimination with μ -e conversion experiments



Spin-independent coherent int. with nucleus is assumed to dominate the processes.
Spin-dependent noncoherent int. start to be included so that model-discrimination power might be enhanced. (Davidson, Kuno, Saporta (17))

3, τ - μ/e transition processes

- $\tau \rightarrow \mu/e + \gamma$
- $\tau \rightarrow \mu/e + ll$
- $\tau \rightarrow \mu/e + hadrons$

Tau LFV searches in Belle II/SuperKEKB

KEKB is upgraded to SuperKEKB (40 times higher luminosity).

$$4.6 \times 10^{10} \tau^+ \tau^- (\mathcal{L} = 50 ab^{-1})$$

- $\tau \rightarrow \mu\gamma, e\gamma$

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

- Signal side : $\mu\gamma, e\gamma$ (full reconstructed)
- Tag side : 1 prong + missing ($BR \sim 85\%$)

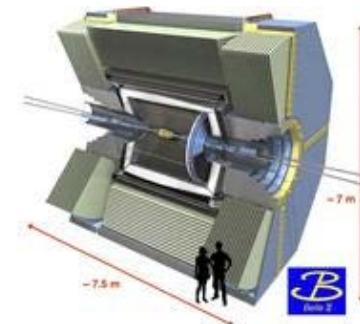
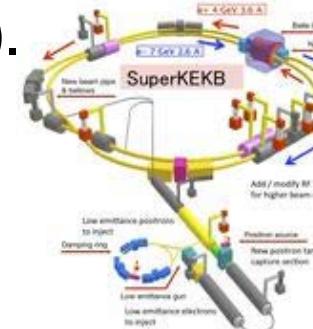
Main BG: $\tau \rightarrow \mu\nu\bar{\nu} + \text{ISR } \gamma$

Belle results: $BR(\tau \rightarrow \mu(e)\gamma) < 4.5(1.2) \times 10^{-8}$ (90% C.L.)

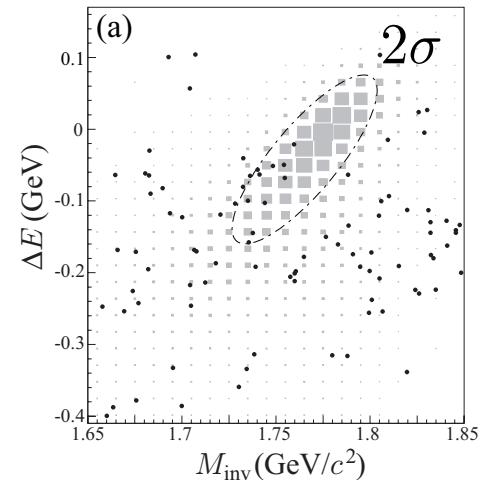
BG reduction in Belle II is being discussed. Prospects are $O(10^{-9})$.

- $\tau \rightarrow l' ll$, such as 3μ

Almost BG free. Belle reached at $BR \sim O(10^{-8})$, and prospects of Belle II are $O(10^{-(9-10)})$



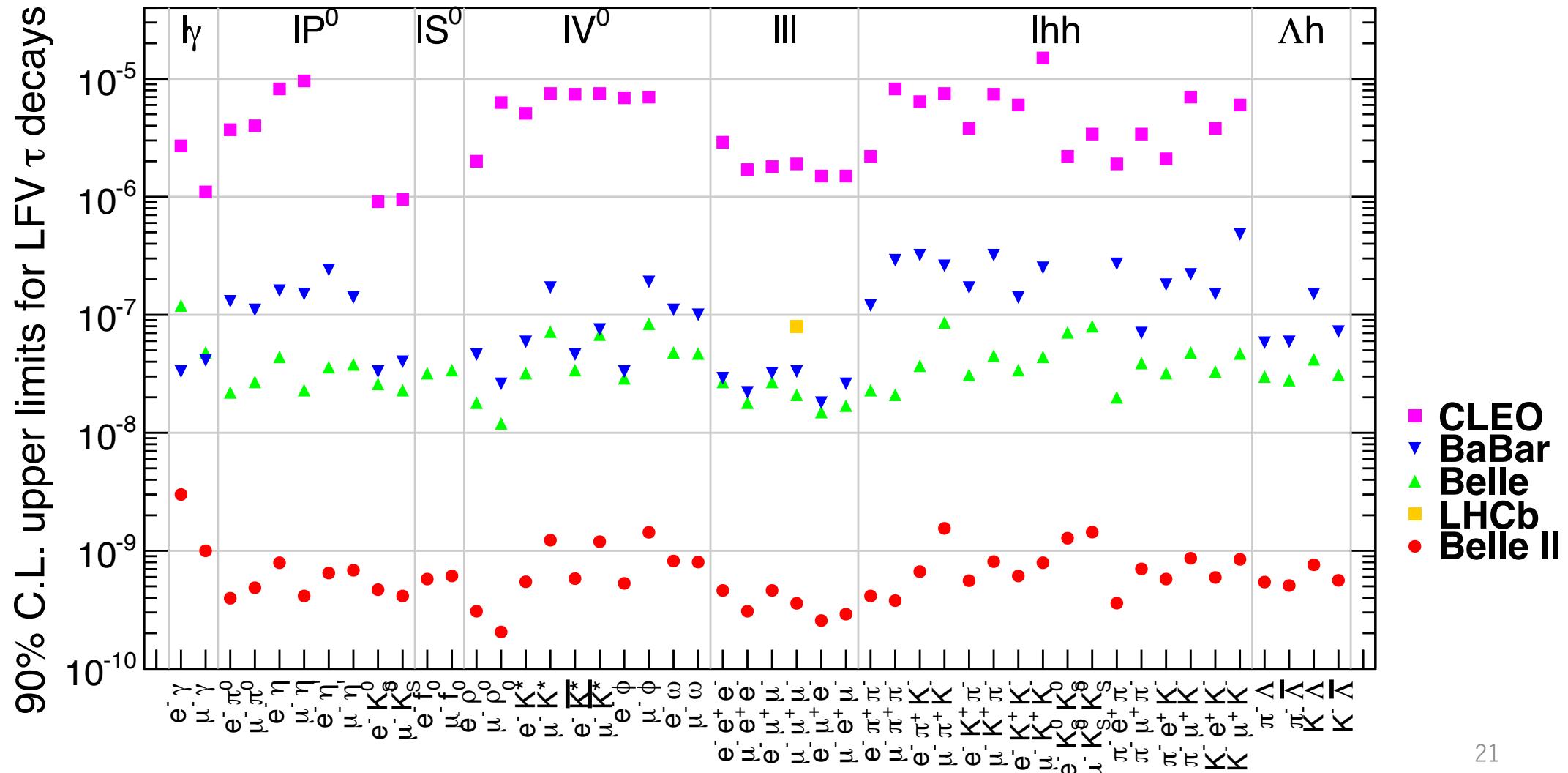
$$\tau \rightarrow \mu\gamma @ \text{Belle (06)}$$



Tau LFV searches in Belle II/SuperKEKB

Various modes will be tested at Belle II:

(The Belle II Physics Book)



Other Tau LFV searches

- $\tau \rightarrow 3\mu$ @ CMS (33 fb^{-1} , 13TeV) (D.Wang@parallel session)

B/D meson decays are main source of tau

$$D_s^- \rightarrow \tau^- (+\bar{\nu}_\tau) \rightarrow 3\mu \quad (\text{Signal channel})$$

$$D_s^- \rightarrow \phi(\mu^+ \mu^-) \pi^- \quad (\text{Normalization channel})$$

Result: $BR < 8.8 \times 10^{-8}$ (90% C.L.)

LHCb: $BR < 4.6 \times 10^{-8}$ (only Ds)

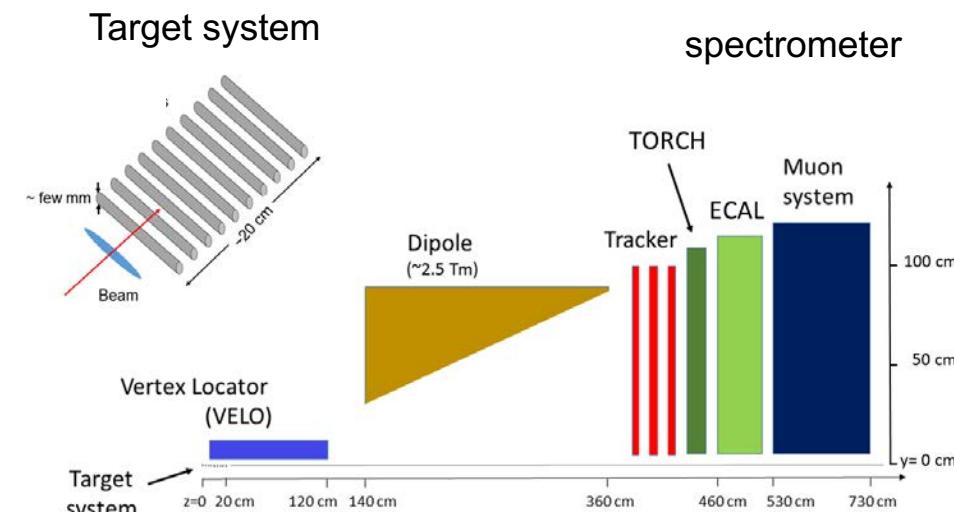
Process	Number of τ leptons (33 fb^{-1})
$\text{pp} \rightarrow c \bar{c} + \dots$	
$D \rightarrow \tau \nu$	4.0×10^{12} (95% D_s , 5% D^\pm)
$\text{pp} \rightarrow b \bar{b} + \dots$	
$B \rightarrow \tau \nu + \dots$	1.5×10^{12} (44% B^\pm , 45% B^0 , 11% B_s^0 , 0% B_c^\pm)
$B \rightarrow D(\tau \nu) + \dots$	6.3×10^{11} (98% D_s , 2% D^\pm)

- TauFV: new proposal for $\tau \rightarrow 3l$ of fixed-target exp.

Using Beam Dump Facility at CERN.

Thin targets are distributed and beam profile is squeezed in order to suppress multiple scattering.

Aiming to $\text{Br} \sim \mathcal{O}(10^{-10})$ in ~ 2030 .



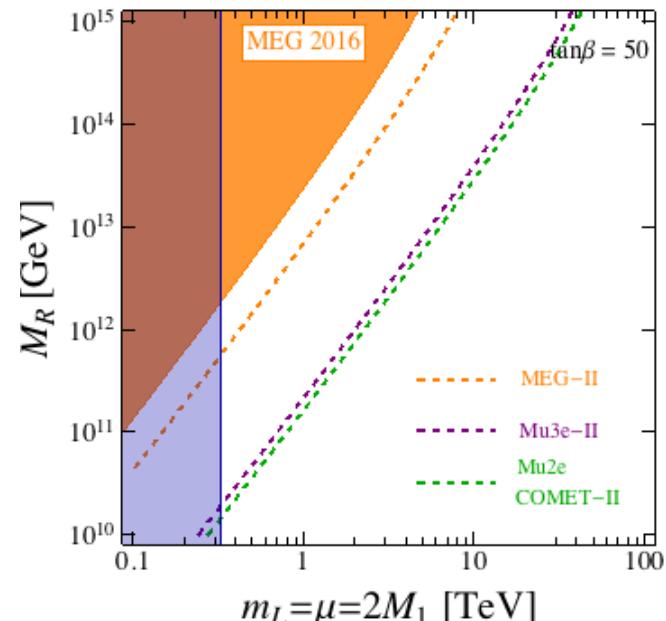
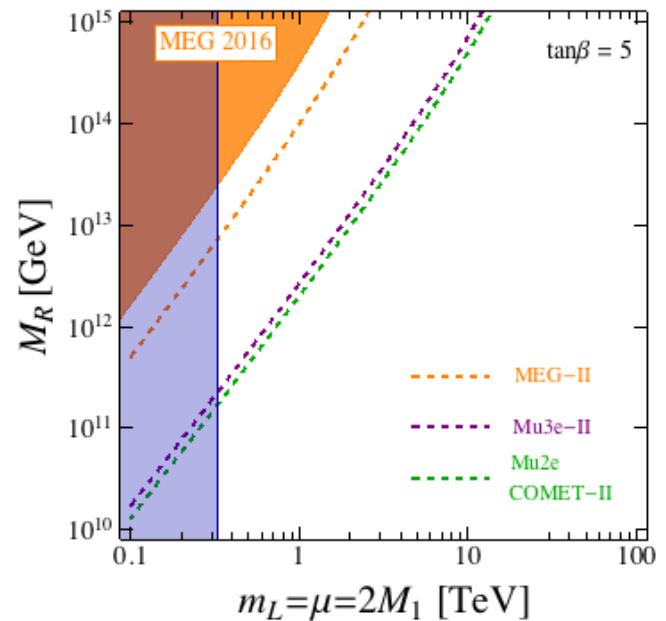
4, CLFV in BSM models

- SUSY SM
- LFV Higgs couplings.
- Low-energy seesaw model.

μ -e transition in SUSY SM

SUSY-breaking mass terms for sleptons are sources of LFV in SUSY SM.

Origin: 1) Slepton coupling to SUSY breaking sector
 2) Radiative correction from LFV int.,
 such as in SUSY Seesaw (10^{12-15} GeV)
 or SUSY GUTs (10^{16} GeV) .



SUSY seesaw:

Neutrino Yukawa coupling (Degenerate RH ν mass, M_R)

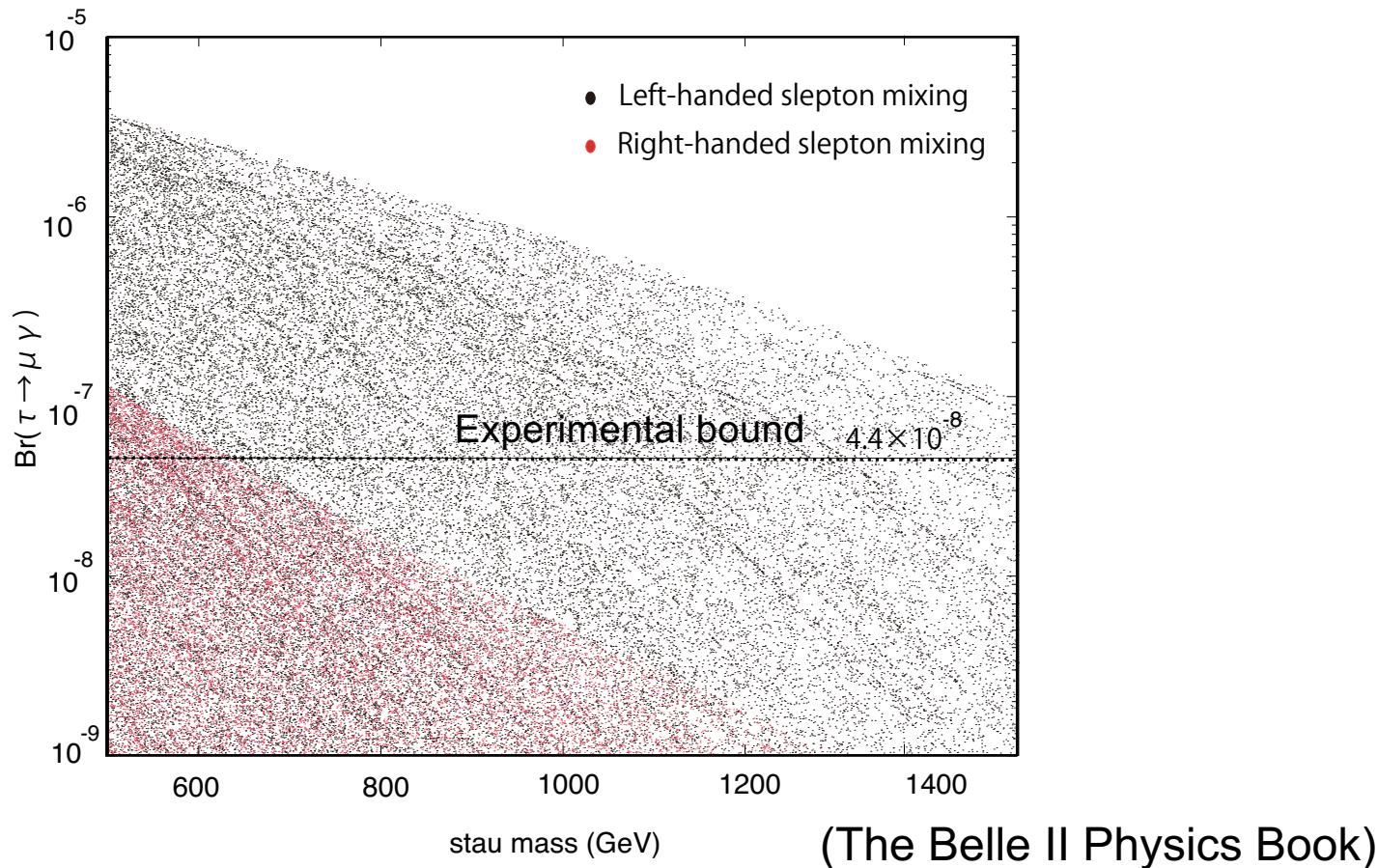
$$Y_\nu = \frac{\sqrt{M_R}}{v_u} \sqrt{\hat{m}_\nu} U^\dagger \quad \begin{aligned} U &: \text{PMNS matrix} \\ \hat{m}_\nu &: \text{LH } \nu \text{ mass} \end{aligned}$$

Universal SUSY breaking para. are assumed at GUT scale.

Large M_R means larger Yukawa so that large CLFVs are induced.

$\tau \rightarrow \mu \gamma$ in SUSY SM

If chargino/neutralino and sleptons have $O(100)$ GeV masses, Belle-II may have chance to discover $\tau \rightarrow \mu \gamma$.

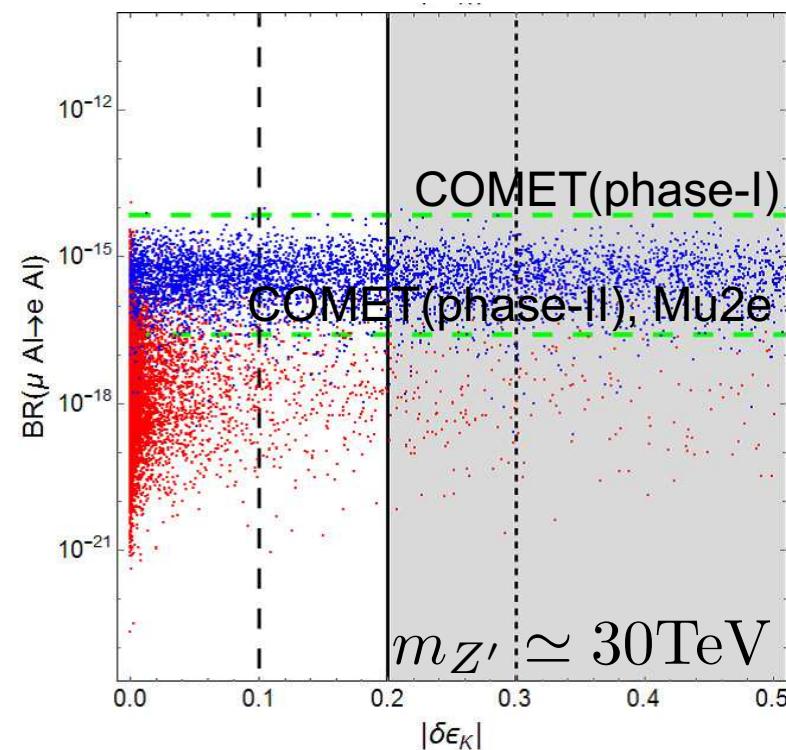
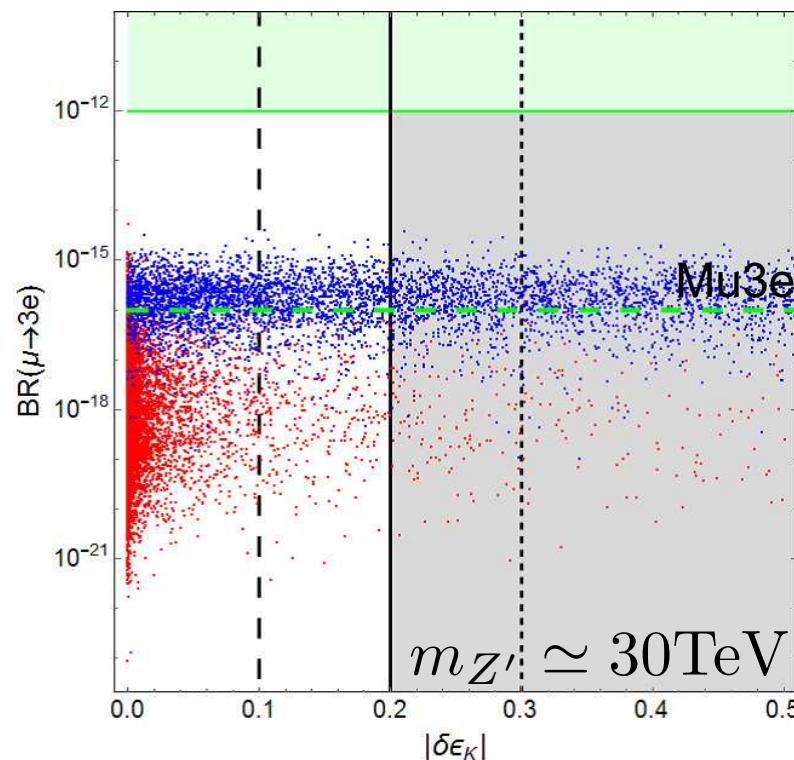


Bino, wino, and Higgsino masses are 250 GeV, 500 GeV, and 1 TeV, respectively, while $\tan\beta$ is 30.

Z' boson

Extra U(1) may be predicted in GUTs, such as SO(10), or E_6 .
If its mass is below $O(10^{1-2})$ TeV and Z' boson has flavor violating coupling, future experiments, Mu3e and COMET/Mu2e, may test it. (sorry for not referring many papers.)

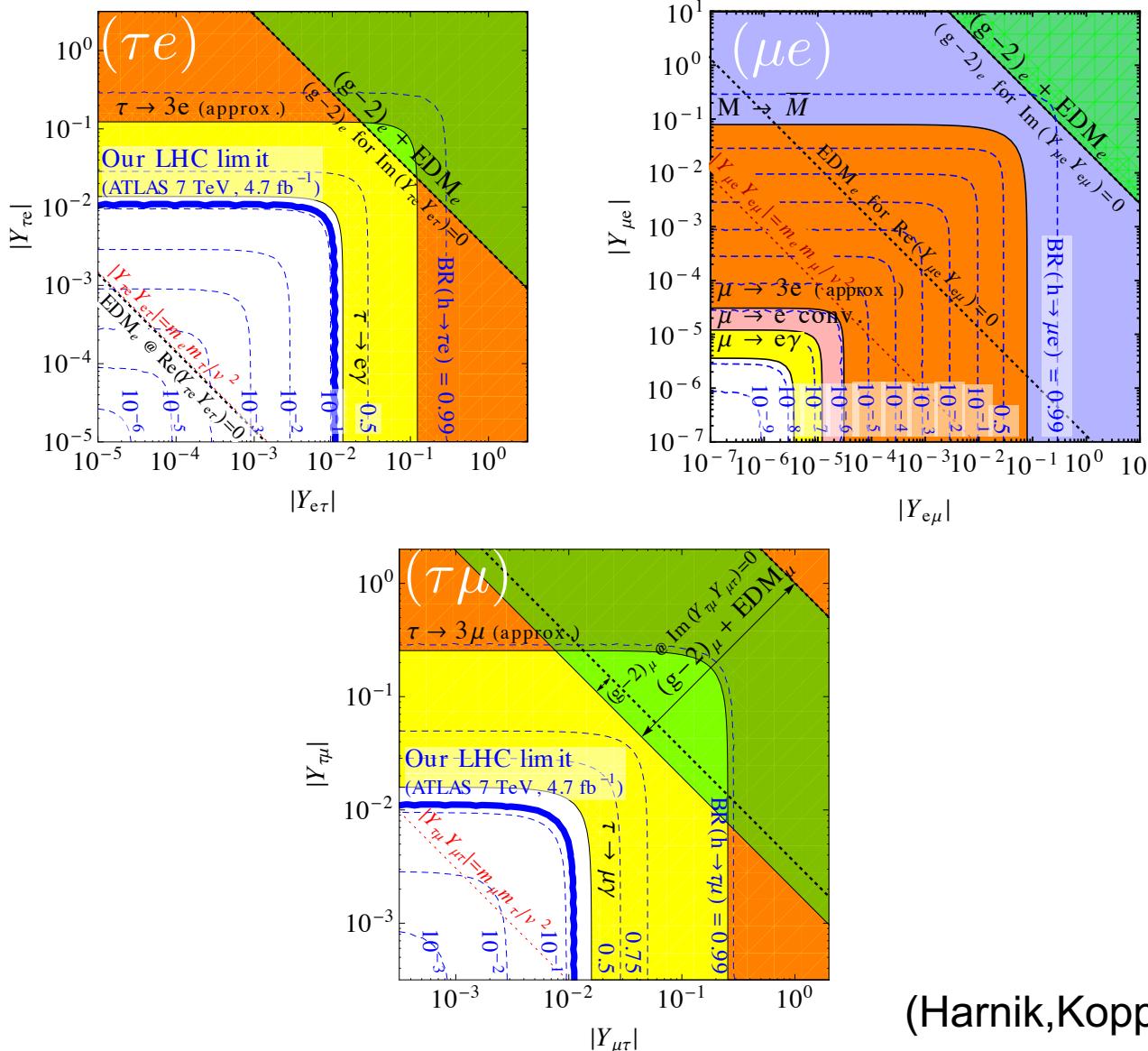
Example: SUSY SM with extra U(1) inspired by SUSY SO(10) GUT
(and also motivated by Minisplit SUSY, $m_{\text{SUSY}} \sim (10^{2-3})$ TeV)



(JH, Muramatsu,
Omura, Shigekami (16))

LFV Higgs coupling

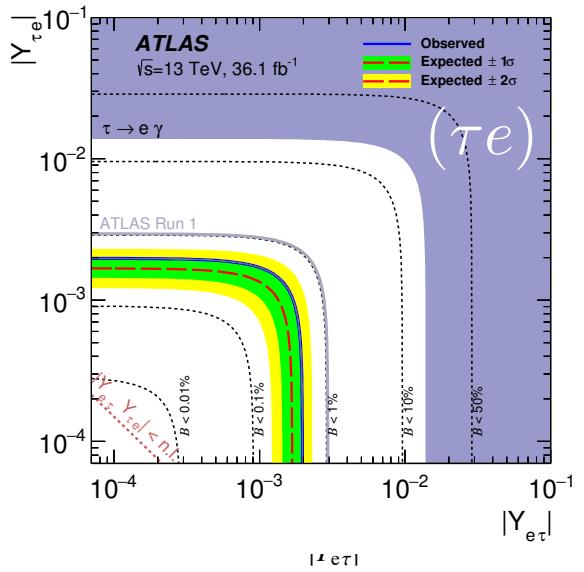
General flavor violating Higgs coupling: $\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij} (\bar{f}_L^i f_R^j) h + h.c. + \dots$



Constraints on $Y_{\tau l}$ and $Y_{l\tau}$ from LHC and $\tau \rightarrow \mu\gamma$ were complimentary at 2012.

LFV Higgs coupling

General flavor violating Higgs coupling: $\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij} (\bar{f}_L^i f_R^j) h + h.c. + \dots$



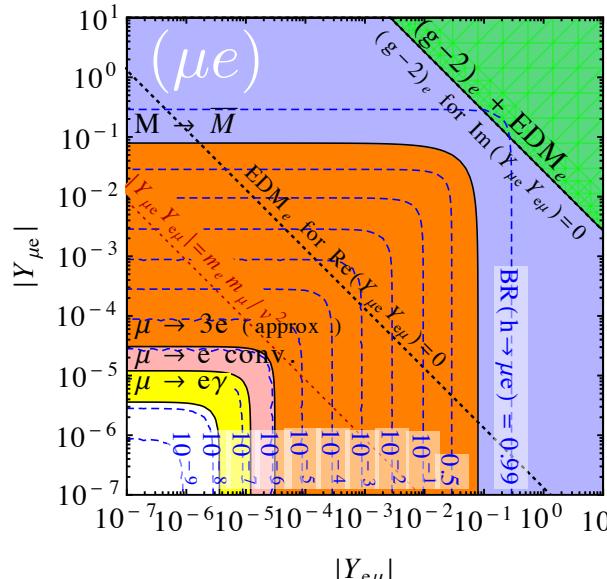
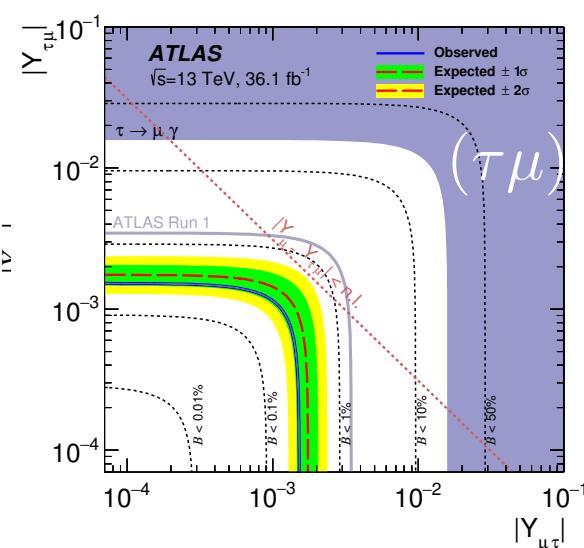
ATLAS (13TeV, 36.1fb^{-1})

$$Br(H \rightarrow e\tau) < 0.47\%$$

$$Br(H \rightarrow \mu\tau) < 0.28\%$$

(1907.06131)

CMS also have similar results.



Constraints from LHC is one-order severer than from $\tau \rightarrow \mu\gamma, \tau \rightarrow e\gamma$.

It seems difficult for low-energy exp. to improve the bounds now.

This does not deny extra Higgs has LFV Yukawa, though we have to tune models.

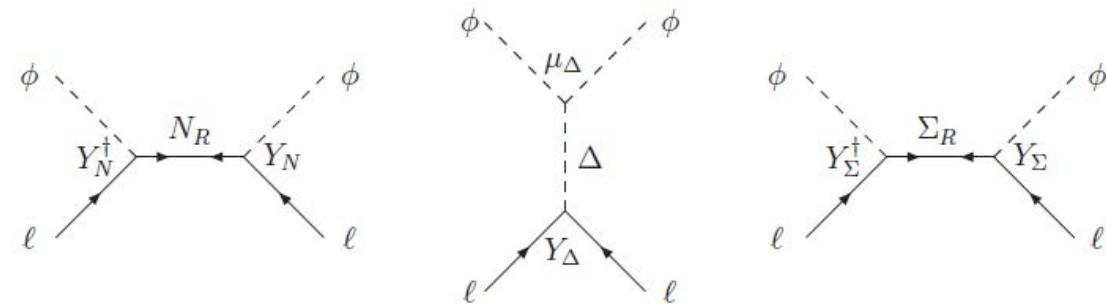
Origin of neutrino mass: seesaw models

In Seesaw models, Majorana neutrino masses are generated.

Type-I: SU(2) singlet fermions

Type-II: SU(2) triplet Higgs boson

Type-III: SU(2) triplet fermions



Inverse (type-I) seesaw model

Two singlet neutrinos are introduced in addition to LH ν , (ν_L, N_1, N_2) . Lepton-number violation is much smaller than EW scale so that the neutrino masses

are suppressed $\begin{pmatrix} 0 & m_{D_1} & 0 \\ m_{D_1} & 0 & M_{N_1} \\ 0 & M_{N_1} & \mu \end{pmatrix}$, $\xrightarrow[\text{Tiny lepton-number violation}]{\mu \ll M_{N_1}} m_\nu \simeq \frac{m_{D_1}^2}{M_{N_1}^2} \mu$ ($m_{D_1} \ll m_{N_1}$)

Type-II model

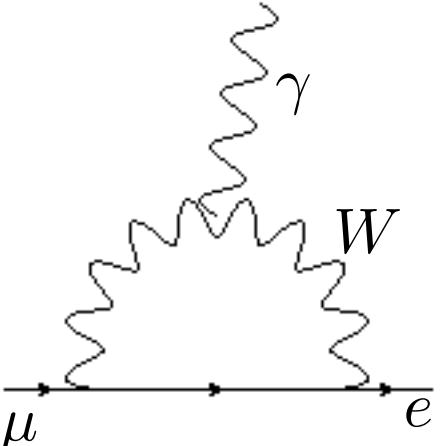
Neutrino mass is suppressed by (lepton-flavor violating) Higgs triplet-doublet coupling .

CLFV in low-energy seesaw models

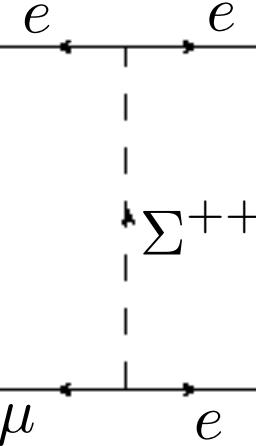
Correlation among CLFV processes:

Model	$\mu \rightarrow eee$	$\mu N \rightarrow eN$	$\frac{\text{BR}(\mu \rightarrow eee)}{\text{BR}(\mu \rightarrow e\gamma)}$	$\frac{\text{CR}(\mu N \rightarrow eN)}{\text{BR}(\mu \rightarrow e\gamma)}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^3$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^3$	$\mathcal{O}(10^3)$

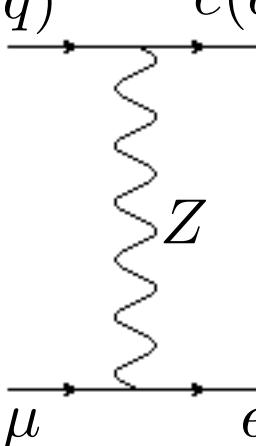
(Calibbi and Signorelli (17)
and references in it)



Type-I



Type-II



Type-III

Summary of my talk

Searches for symmetry breakings are important windows to BSM. Lepton-flavor violating decay of charged lepton is an important tool to probe physics at and beyond TeV in addition to EDMs. After discovering the neutrino oscillation, we have no explicit reason that BSM is lepton-flavor conserving.

MEG-II, Mu3e, COMET and Mu2e will be performed next decade. They are competitive and complementary to each others. Even if BSM is realized at $O(10^{1-2})$ TeV, the experiments may cover it. If signal is found, we may pin down models by taking correlation among the processes.

Tau LFV processes may be found at BELLE-II if BSM is realized at TeV scale. The searches may be complementary to CLFV heavy particle decay and also new particle searches at LHC.



Thank you very much.

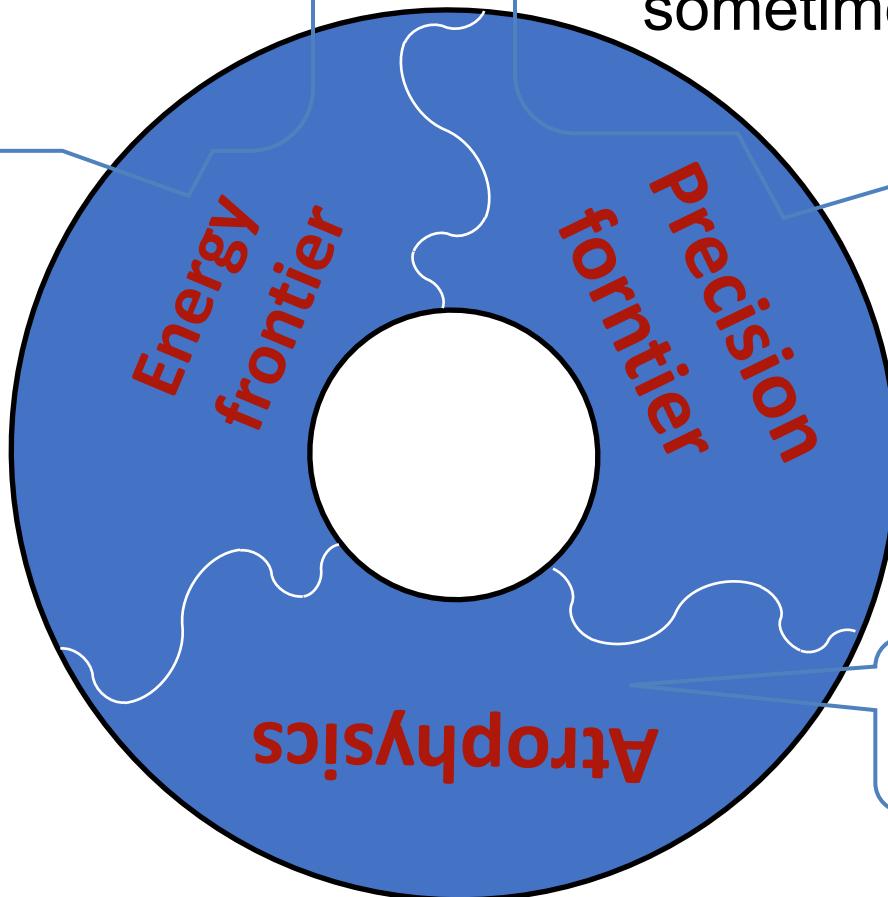
BACKUP

Tools to probe new physics

Direct search for TeV-scale physics

- LHC
- ILC
- FCC

- High statistical experiment
- High precise theoretical prediction, sometimes related to symmetry breaking.



- Underground exp.
- Cosmology

Latest magnetic moments of charged leptons

- Electron

$$a_e^{\text{exp}} = 1\ 159\ 652\ 180.73(28) \times 10^{-12} \text{ (Gabrielse group (08))}$$

$$a_e^{\text{SM}} = 1\ 159\ 652\ 181.61(23) \times 10^{-12} \text{ (Aoyama,Kinoshita,Nio (18)+new } \alpha \text{ using Cs atom (18))}$$

$$\rightarrow \Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -0.88(36) \times 10^{-12} \text{ (2.5 sigma deviation)}$$

- Muon

$$a_\mu^{\text{exp}} = 11\ 659\ 209.1(5.4)(3.3) \times 10^{-10} \text{ (Muon g-2 Collaboration)}$$

$$a_\mu^{\text{SM}} = 11\ 659\ 192.04(3.56) \times 10^{-10} \text{ (Keshavarzi, Nomura, Teubner (18))}$$

$$\rightarrow \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 27.06(7.26) \times 10^{-10} \text{ (3.7 sigma deviation)}$$

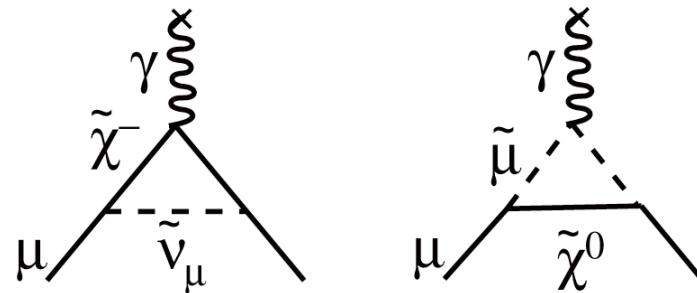
- Tau

$$-0.052 < a_\tau^{\text{exp}} < +0.013 \text{ (LEP2 (04))}$$

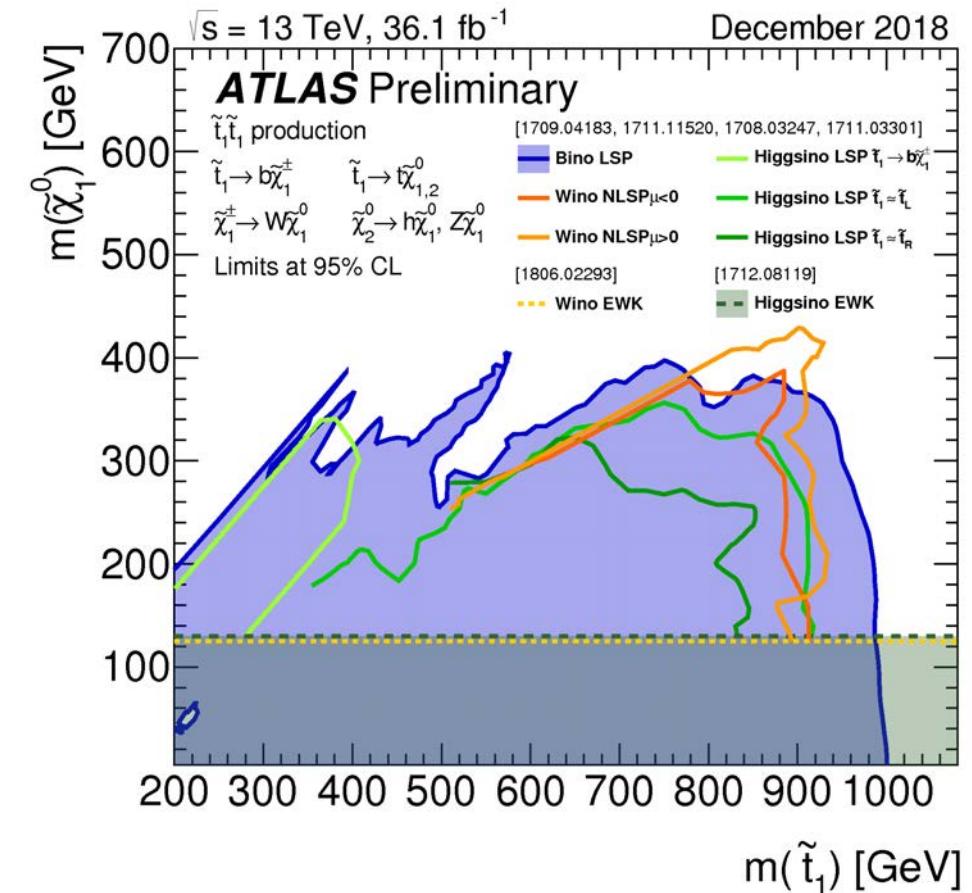
$$a_\tau^{\text{SM}} = 0.00117721(5) \text{ (Eidelman, Passera (07))}$$

BSM explanation of muon g-2

MSSM had been considered to be a leading candidate for explanation of muon g-2.



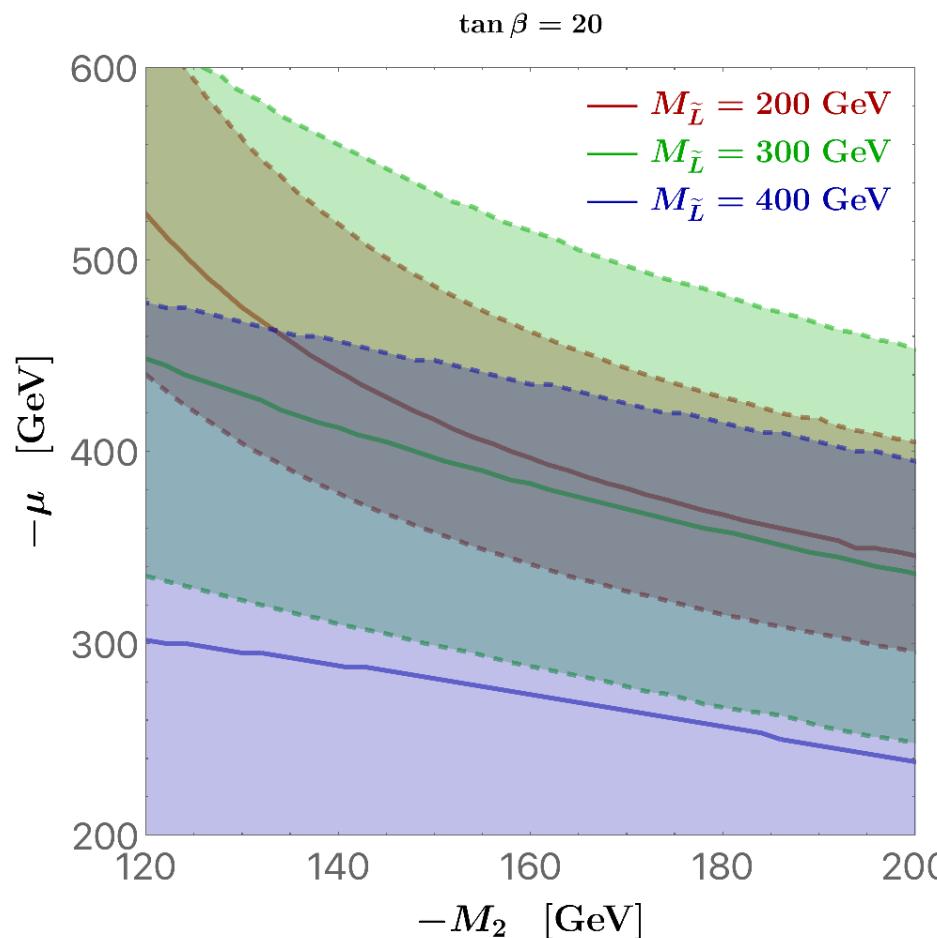
$$\begin{aligned} \delta a_\mu &\sim \frac{5\alpha_2 + \alpha_Y}{48\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \tan \beta \\ &= 3 \times 10^{-9} \left(\frac{\tan \beta}{10} \right) \left(\frac{M_{\text{SUSY}}}{200\text{GeV}} \right)^{-2} \\ (\tan \beta &\equiv \langle H_2 \rangle / \langle H_1 \rangle) \end{aligned}$$



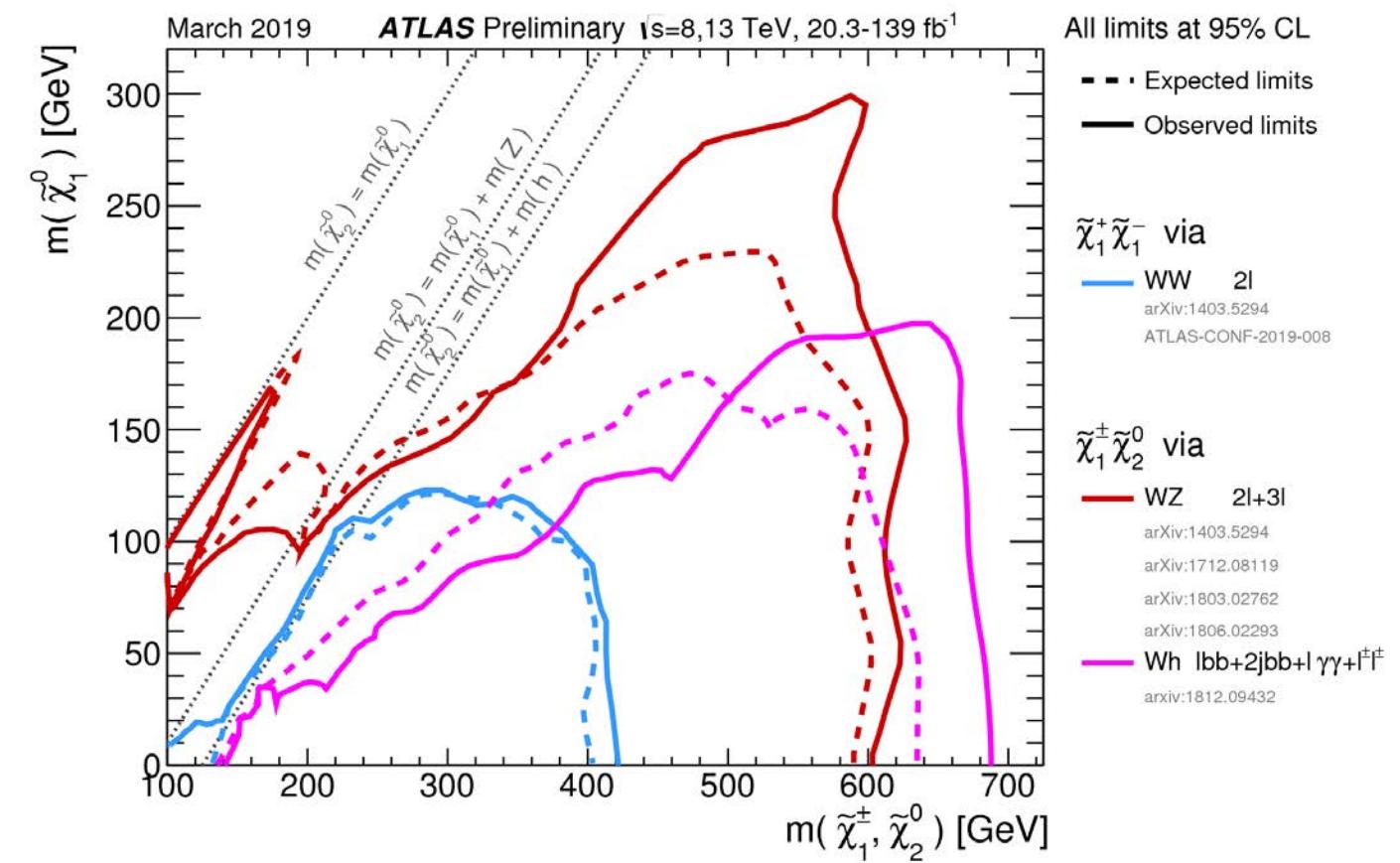
Colored SUSY particles are heavier than 1 TeV.

BSM explanation of muon g-2

Still we have rooms to explain muon g-2, where sleptons are heavier than chargino/neutralino2.



(Carena, Osborn, Shah, Wagner (18))



BSM explanation of muon g-2

Still we have rooms to explain muon g-2, where sleptons are heavier than charginos/neutralinos

Benchmark: (Carena, Osborn, Shah, Wagner (18))

Param.	[GeV]	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
μ	-300	M_2	-172	$M_{\tilde{L}}$	400	M_H	1500
M_1	63.5	M_3	2000	$M_{\tilde{Q}}$	2000	A_t	3000

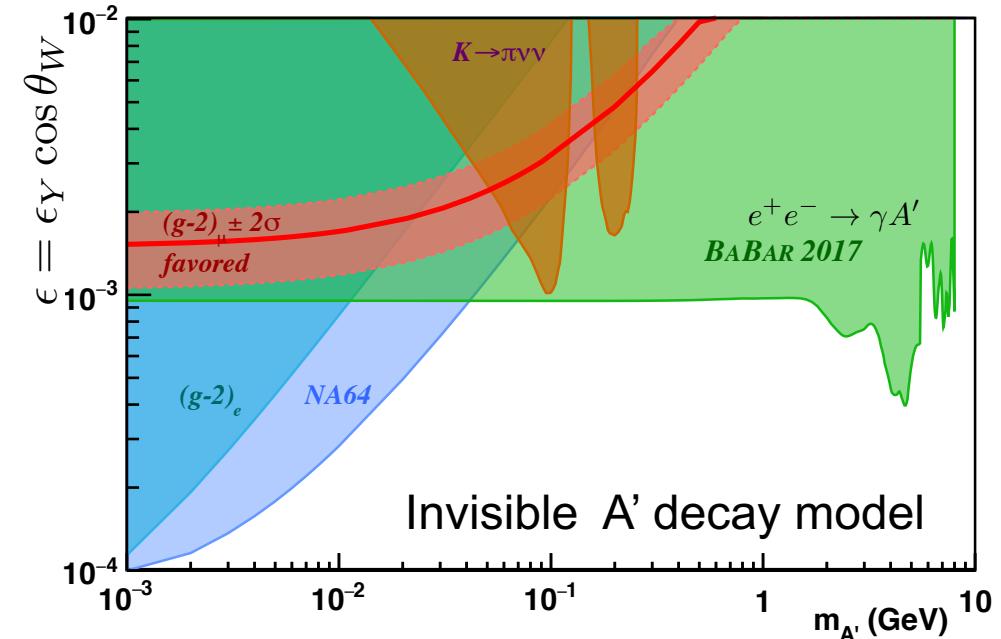
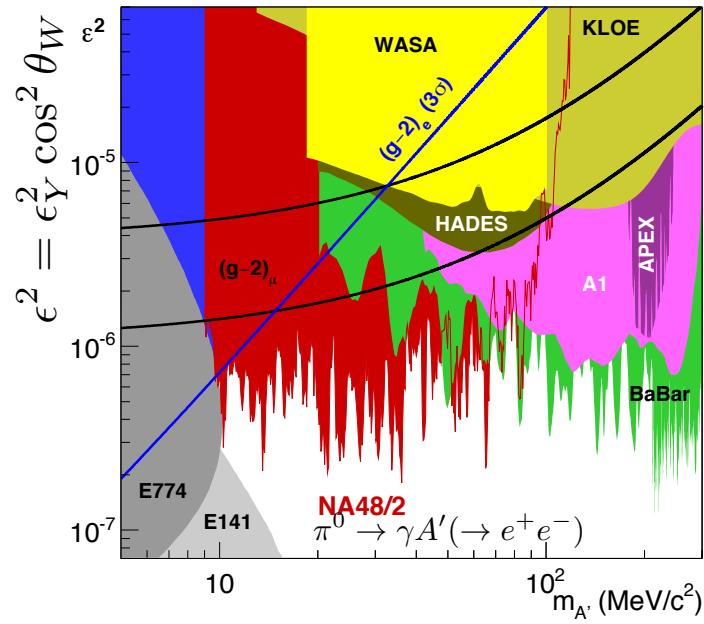
Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]
h	125.84	$\tilde{\chi}_1^\pm$	165.0	$\tilde{\nu}_e$	395.0	\tilde{u}_R	2069.8
H	1500.03	$\tilde{\chi}_2^\pm$	333.6	$\tilde{\nu}_\mu$	395.0	\tilde{u}_L	2069.5
H_3	1500.00	$\tilde{\tau}_1$	389.5	$\tilde{\nu}_\tau$	395.0	\tilde{d}_R	2070.3
H^\pm	1502.38	$\tilde{\tau}_2$	415.0	\tilde{g}	2129.2	\tilde{d}_L	2071.0
$\tilde{\chi}_1^0$	61.7	\tilde{e}_R	402.4	\tilde{t}_1	1927.7	\tilde{s}_R	2070.3
$\tilde{\chi}_2^0$	164.8	\tilde{e}_L	402.6	\tilde{t}_2	2131.6	\tilde{s}_L	2071.0
$\tilde{\chi}_3^0$	314.2	$\tilde{\mu}_R$	402.4	\tilde{b}_1	2067.1	\tilde{c}_R	2069.8
$\tilde{\chi}_4^0$	331.2	$\tilde{\mu}_L$	402.6	\tilde{b}_2	2074.1	\tilde{c}_L	2069.5

$$\rightarrow a_\mu^{\text{MSSM}} = 248 \times 10^{-11}$$

BSM explanation of muon g-2

Light particles may explain muon g-2 even if their couplings are weak.

Original dark photon A'_μ model: $\mathcal{L} \supset \frac{\epsilon_Y}{2} F'_{\mu\nu} B^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu$ (B_μ : U(1)_Y gauge boson)



Variant dark photon models, $A' \rightarrow \psi_1 \psi_2 (\rightarrow \psi_1 + f\bar{f})$ (Mohlabeng (19))

Generation-dependent B-L or $L_\mu - L_\tau$ gauge bosons (Shigekami, Kang (19))

Light scalar models.

BSM explanation of both muon and electron g-2s

Two anomalies:

$$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -0.88(36) \times 10^{-12} \quad (\text{2.5 sigma deviation})$$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 27.06(7.26) \times 10^{-10} \quad (\text{3.7 sigma deviation})$$

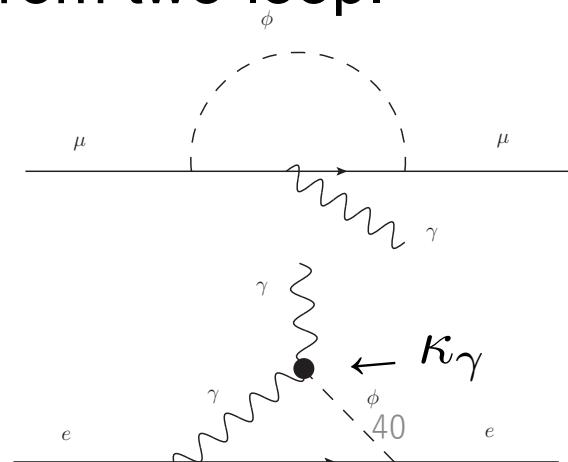
$$\rightarrow \Delta a_e^{\text{exp}} / \Delta a_\mu^{\text{exp}} \sim -3.3 \times 10^{-4}$$

Lepton-universality: $\Delta a_e / \Delta a_\mu = m_e^2 / m_\mu^2 \sim +2.4 \times 10^{-5}$

Light scalar particle models (Dovoudiasl, Marciano (18))

Deviation of muon g-2 comes from one-loop while electron's one is from two-loop.

$$\mathcal{L}_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \sum_f \lambda_f \phi \bar{f}f - \frac{\kappa_\gamma}{4} \phi F_{\mu\nu}F^{\mu\nu},$$



Benchmark:

$$m_\phi = 250 \text{ MeV} \quad \lambda_\mu = 10^{-3}, \quad \lambda_e = 4 \times 10^{-4}$$

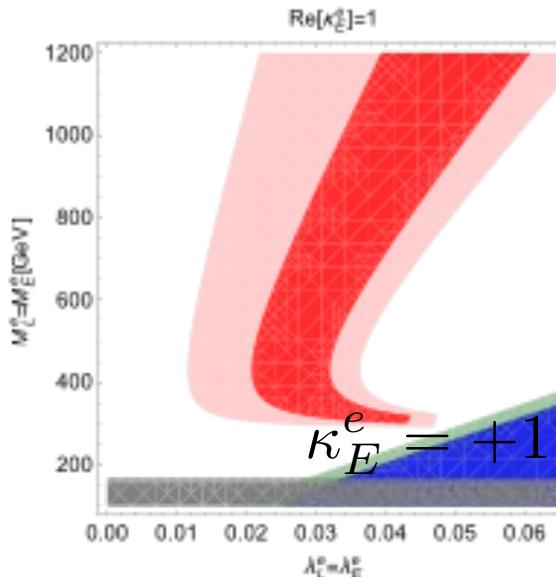
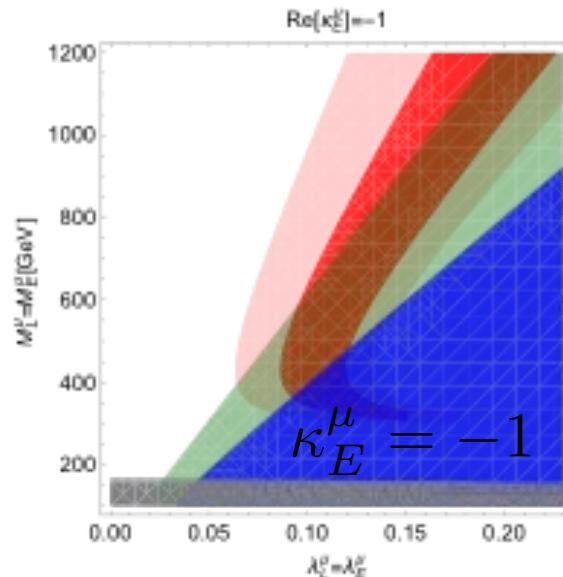
κ_γ comes from loop of tau or new particles with masses few 100GeV.

BSM explanation of muon and electron g-2

Heavy particle models (Crivellin, Hoferichter, Schmidt-Wellenburg (18))

Intro. of vector-like fermions with the same quantum numbers as doublet and singlet leptons. Large chirality enhancement by internal fermions in one-loop diagrams may explain both anomalies.

$$\begin{aligned}\mathcal{L} = & -M_L \bar{L}_L L_R - M_E \bar{E}_L E_R && \text{(vector-like fermion masses)} \\ & - \kappa_L \bar{L}_L h E_R - \kappa_E \bar{L}_R h E_L && \text{(vector-like fermion Yukawa coupl with Higgs)} \\ & - \lambda_L \bar{L}_L l_R h - \lambda_E \bar{E}_R l_L h && \text{(vector-like and SM fermion Yukawa coupl)} \\ & + \text{h.c.}\end{aligned}$$



We can avoid constraints from leptonic Z and Higgs decay if we introduce a new scalar field.

Benchmark models

High-scale SUSY

SUSY GUTs $\sim 10^{16}$ GeV

Motivation of High-scale SUSY ($\sim \mathcal{O}(10^{2-3})$ TeV).

- Solution of following problems
 - FCNC and CP problems
 - Gravitino problem in nucleosynthesis
 - D=5 proton decay in SUSY GUTs
 - 125GeV Higgs mass
- Easy model building of SUSY breaking
- WIMP dark matter
- Improved gauge coupling unification

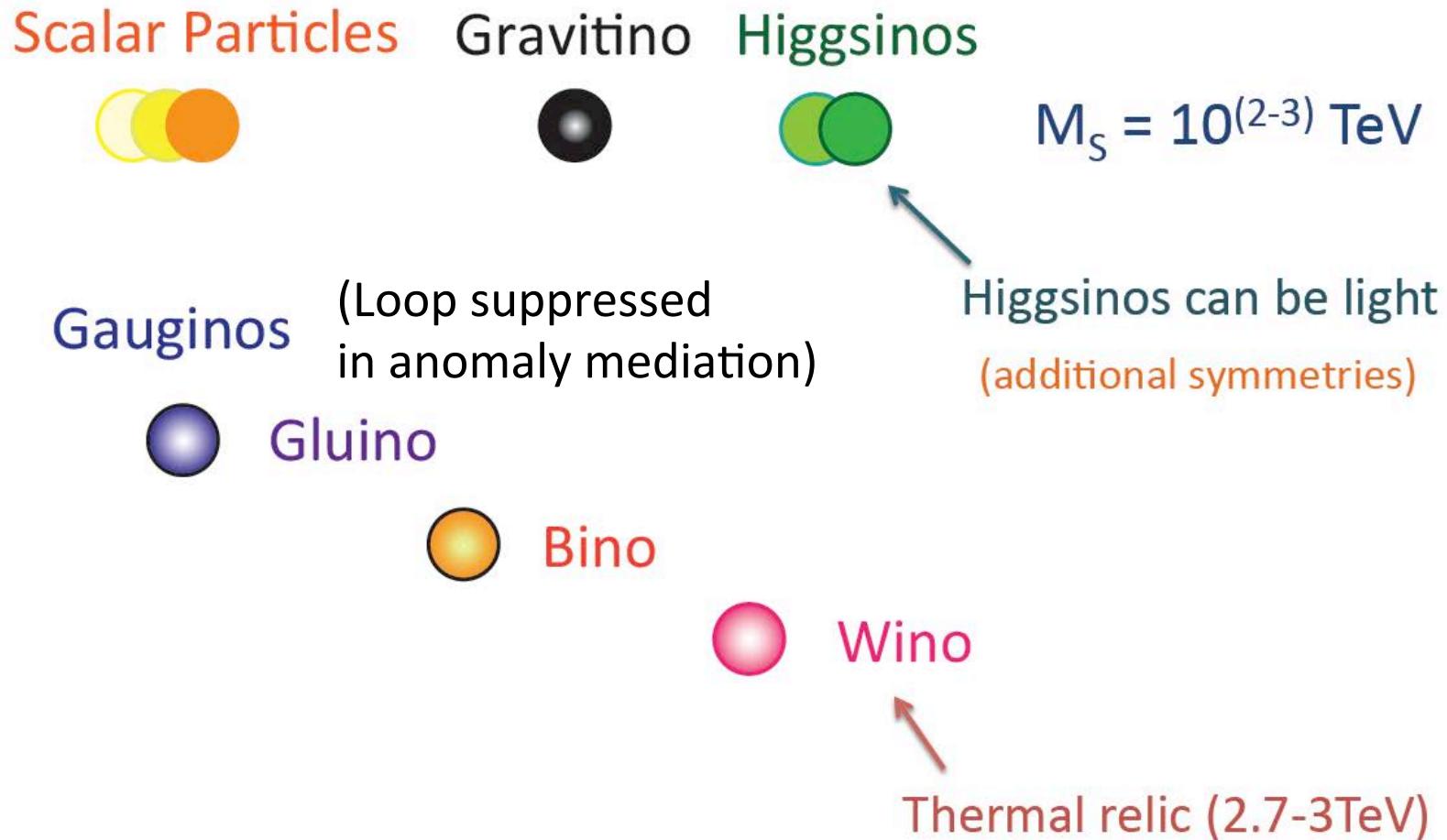
MSSM @ $\mathcal{O}(10^{2-3})$ TeV

Standard model

Phenomenology of this model works well !

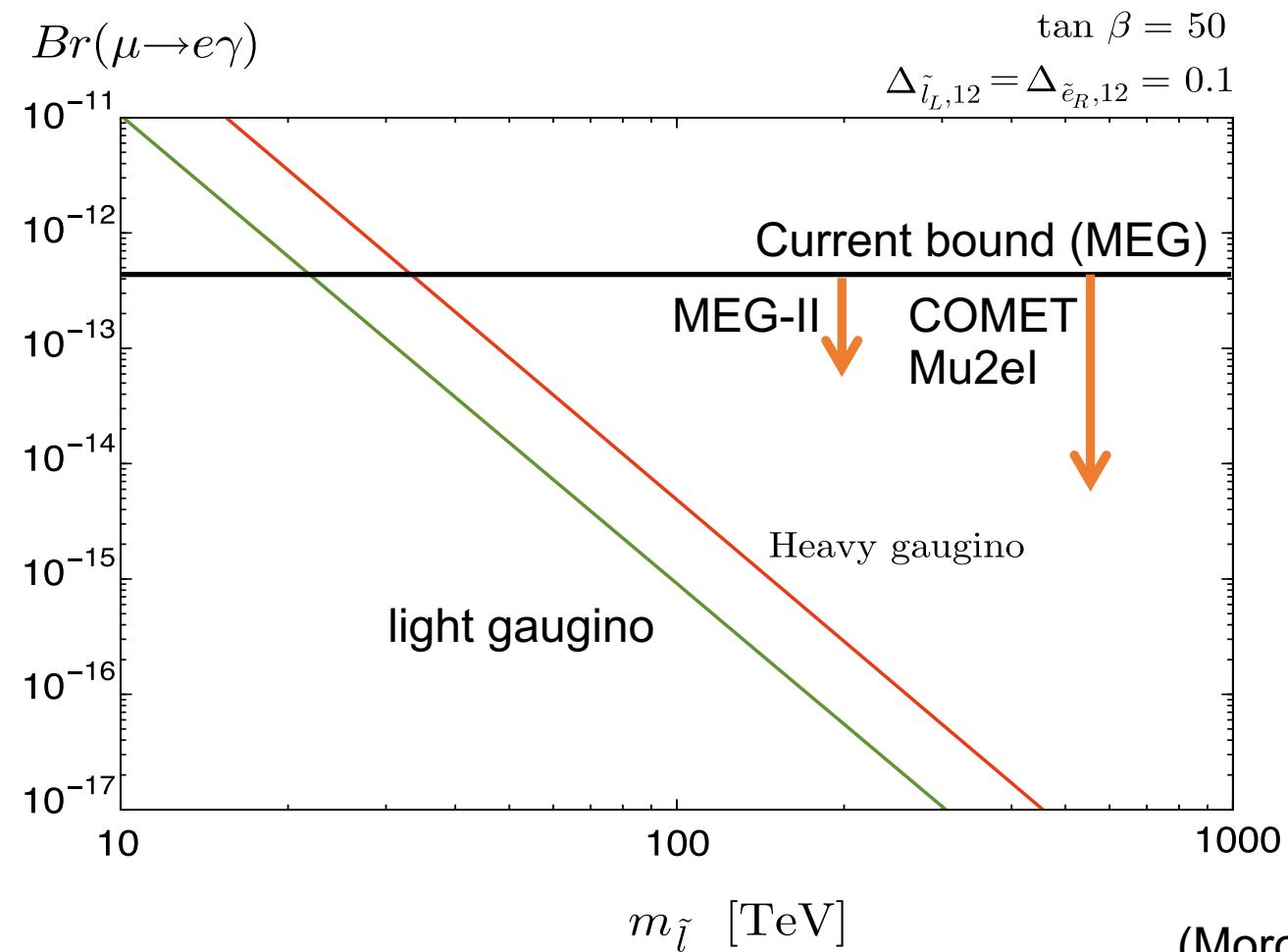
Benchmark models

Mass spectrum in High-scale SUSY



$\mu \rightarrow e\gamma$ in high-scale SUSY

Off-diagonal components in slepton mass matrices generate charged LFV processes, such as $\mu \rightarrow e\gamma$.



Electron EDM induced by flavor violation

When both Off-diagonal components in left-handed and right-handed slepton mass matrices are nonzero, electron EDM is generated.

