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Lepton Flavor Violating Muon Decays and Physics beyond the Standard Model

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Why lepton flavor violation?

Simply because we have a good chance to observe it in near future experiments.

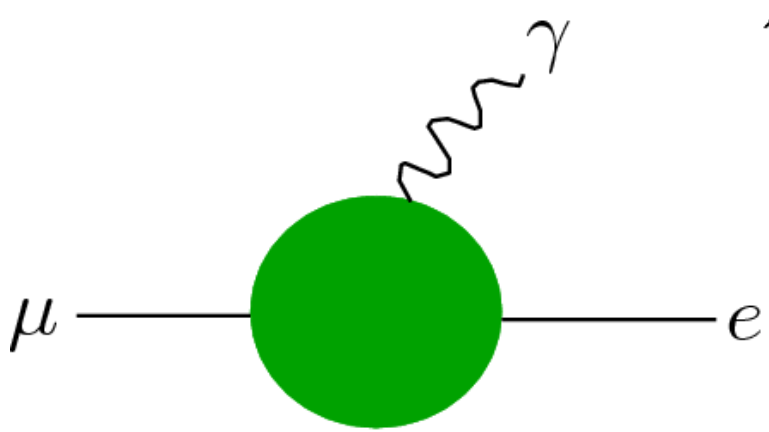
	Mu --> e + gamma	Mu --> e in nuclei
Current		
MEGA (1999)	10^{-11}	
SINDRUM II (1998)		$10^{-(12-13)}$
Future		
MEG (data taking?)	10^{-13}	
COMET		10^{-16}
Mu2e		10^{-16}
PRIME		10^{-18}
Project X		10^{-19}

Why lepton flavor violation?

-- theoretical motivation

Evidences for neutrino oscillation suggest that there is no fundamental symmetry to forbid the muon-to-electron transition.

Phenomenological parametrization:



$$\mathcal{L}_{\rm eff} = \left(\frac{e}{4\pi}\right)\frac{m_\mu \sin\theta_{\mu e}}{\Lambda^2}\bar{\mu}\sigma^{\mu nu} e F_{\mu\nu}$$

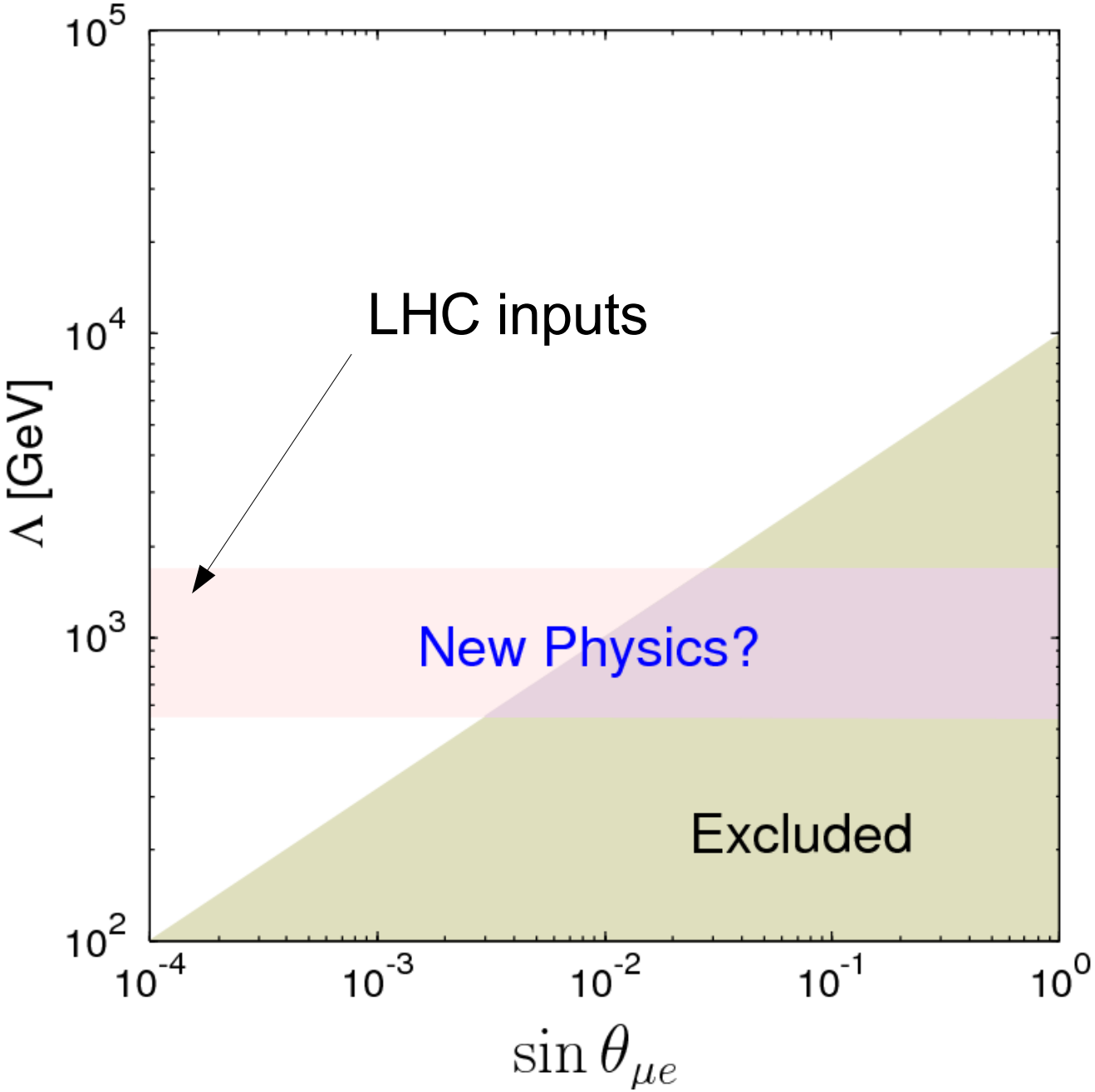
Br < 10^{-11} implies

$$\frac{\Lambda^2}{\sin\theta_{\mu e}} > (10\ \mathrm{TeV})^2$$

We are expecting that there appears a new physics around O(1) TeV energy range.

Experimental bound is already very strong!

LHC-Flavor interplay



We need a fairly small mixing parameter if we assume Λ is O(1) TeV!

Why small mixing?

If there is new physics at O(1) TeV with extension of the lepton sector, some explanation is needed for such a small mixing angle.

Scenario 1.

Maybe mixing is small for the same reason as the small Yukawa couplings in the Standard Model.

Scenario 2.

There is supersymmetry and there is flavor blindness in the supersymmetry breaking/mediation mechanism.

Scenario 1

The Yukawa coupling constants for muon and electron are small. This may be "explained" by some suppression factors associated with each matter field:

$$y_e \sim \epsilon_L^{(e)} \epsilon_R^{(e)} \qquad y_\mu \sim \epsilon_L^{(\mu)} \epsilon_R^{(\mu)}$$

Then, it is reasonable to assume that the mixing angle is like:

$$\sin\theta_{\mu e} \sim \mathrm{Max}[\epsilon_L^{(e)} \epsilon_R^{(\mu)} / y_\mu, \epsilon_R^{(e)} \epsilon_L^{(\mu)} / y_\mu]$$

Therefore,

$$\sin\theta_{\mu e} \gtrsim (\epsilon_L^{(e)} \epsilon_R^{(\mu)} / y_\mu \times \epsilon_R^{(e)} \epsilon_L^{(\mu)} / y_\mu)^{1/2} \sim \sqrt{\frac{m_e}{m_\mu}} \sim \underline{0.07}$$

Still a bit large. If this is the structure, we should see muon LFV processes soon.

Scenario 2

Supersymmetry + flavor universal supersymmetry breaking terms.

This can be naturally realized in

1. Gauge mediated supersymmetry breaking scenario, where the Standard Model gauge interaction is the messenger of the supersymmetry breaking.

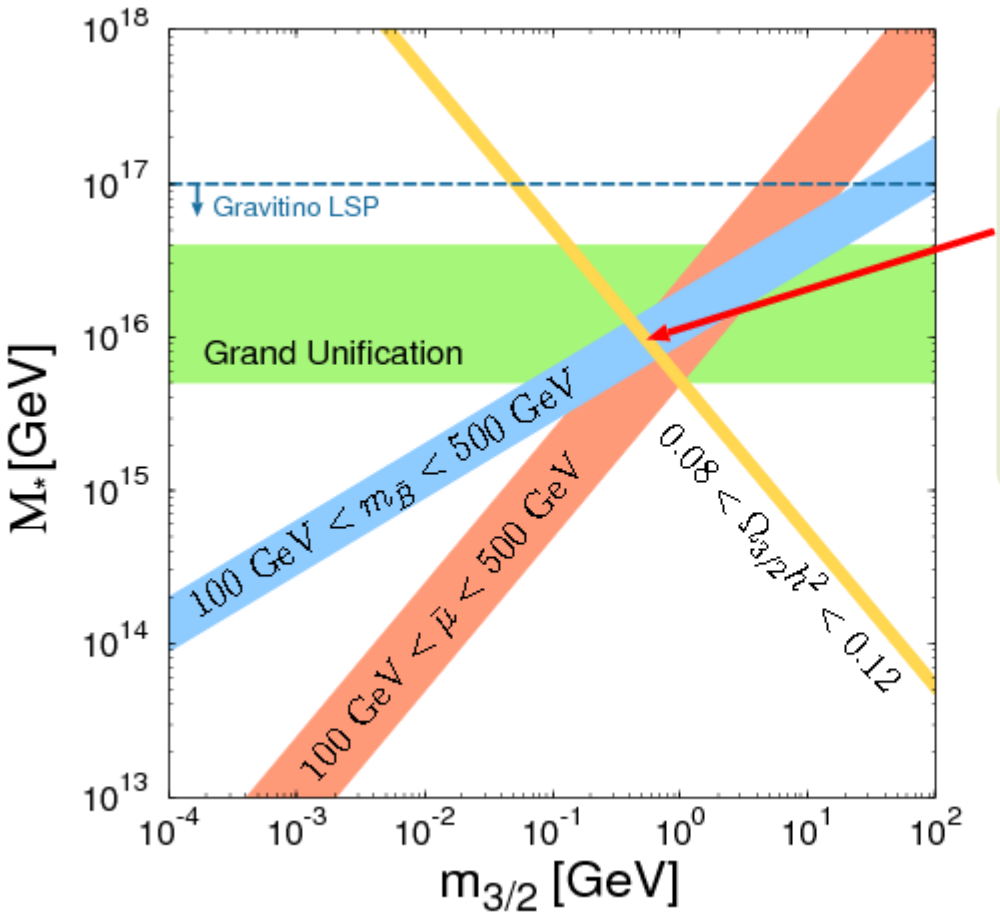
and

2. Anomaly mediated supersymmetry breaking scenario.

Gauge mediation

A very simple and realistic framework: Sweet Spot Supersymmetry

[Ibe,RK '07]



This is a perfect spot:

grand unification
gravitino dark matter
no FCNC/CP problem
no proton decay problem
no mu-problem
no moduli/gravitino problem...

There is a subdominant O(1GeV) contribution from gravity effects to the flavor mixing factor.

The mixing factor is then

$$\sin\theta_{\mu e} \sim \left(\frac{m_{3/2}^2}{m_{\rm SUSY}^2}\right)\tan\beta \sim 10^{-(2-3)}$$

$\longrightarrow$ Br(mu-->e+gamma) ~ $10^{-(11-13)}$

Small enough, but we should see this gravity effects soon!

It is interesting that the future or on-going muon LFV experiments are sensitive to the (quantum) gravity effects.

Anomaly mediation

Yet another way of realizing flavor universality.

An example of realistic model: MSSM+singlet+D-term

[Ibe,RK,Murayama,Yanagida '04]

This model is an example of consistent framework for thermal leptognesis. The threshold effects of the decoupling of the right-handed neutrino induces the flavor mixing terms.

A parameter set consistent with thermal leptogenesis gives

$$\sin\theta_{\mu e} \sim 0.04$$

Again interesting range.

If we observe LFV, that may be a hint for baryon asymmetry of the Universe!

As we have seen, even if there is a mechanism to suppress the flavor mixing, future or on-going experiments are sensitive to subleading effects such as gravity, threshold etc in many kinds of models.

... We should prepare for the discovery! Let's discuss what can we learn when we observe LFV processes.

What can we learn?

Measuring a branching ratio fixes the mixing parameter. We need more observables to extract information on the origin of LFV.

Let me again start with the phenomenological Lagrangian for mu-->e+gamma and mu-->e conversion in nuclei:

dipole

$$\mathcal{L}_{\rm int} = -\frac{4G_{\rm F}}{\sqrt{2}}\left(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L \bar{\mu}\sigma^{\mu\nu}P_R e F_{\mu\nu} + \text{h.c.}\right)$$

$$-\frac{G_{\rm F}}{\sqrt{2}}\sum_{q=u,d,s}\Big[\left(g_{LS(q)}\bar{e}P_R\mu + g_{RS(q)}\bar{e}P_L\mu\right)\bar{q}q$$

scalar

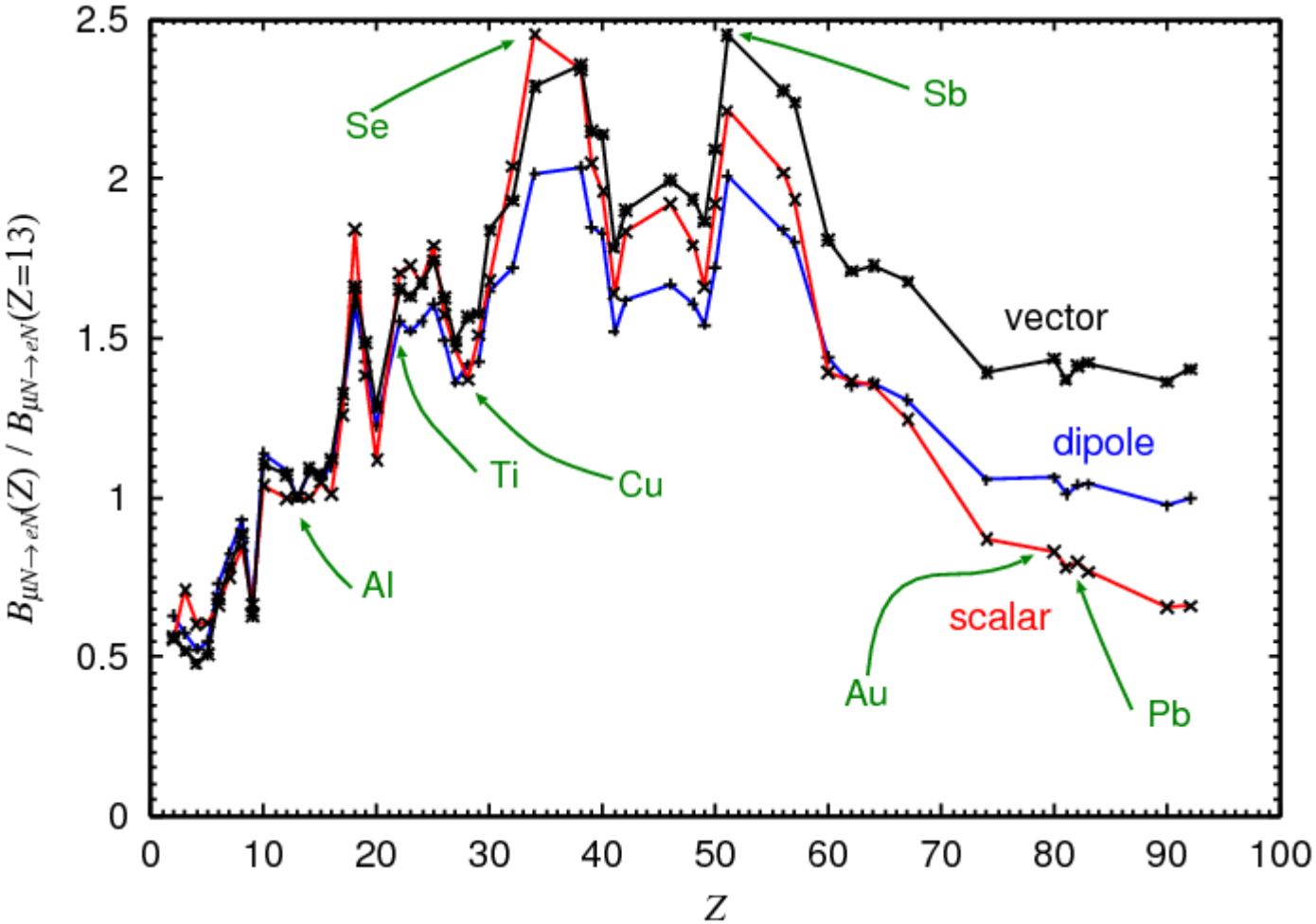
$$+\left(g_{LV(q)}\bar{e}\gamma^\mu P_L\mu + g_{RV(q)}\bar{e}\gamma^\mu P_R\mu\right)\bar{q}\gamma_\mu q + \text{h.c.}\Big]$$

vector

Can we distinguish those operators?

Target atom dependence of the mu-->e conversion ratio

[RK,Koike,Okada '02]



Different Z-dependence for each operator. Measuring conversion ratio in two different nuclei reveals the operator which gives dominant contribution.

$\mu \to e\gamma$ vs $\mu \to e$ conversion

Obviously, the ratio

$$B(\mu \to e; \mathrm{Al})/B(\mu \to e\gamma)$$

shows importance of the scalar/vector operators.

The prediction of the pure dipole operator is

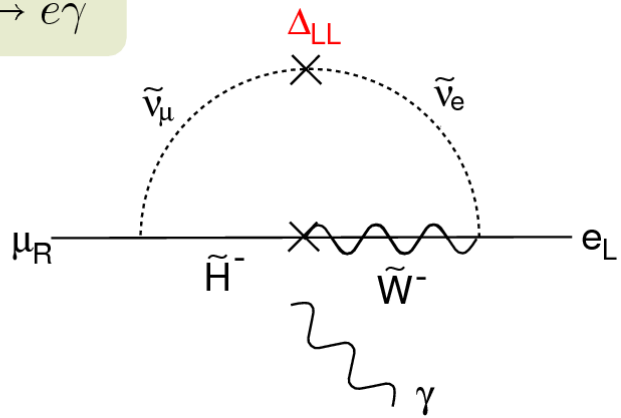
$$B(\mu \to e; \mathrm{Al})/B(\mu \to e\gamma) = 0.002$$

deviation from this value is the contribution from scalar and vector operators.

If we know the model, this quantity actually tells more.

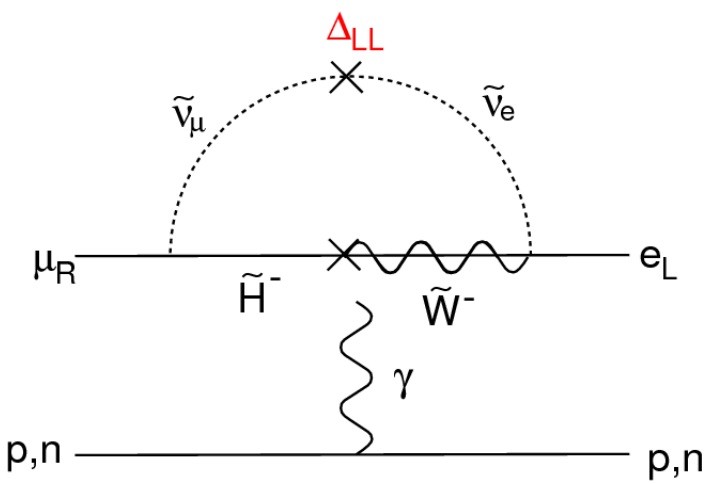
Example: Supersymmetric model

$\mu \to e\gamma$

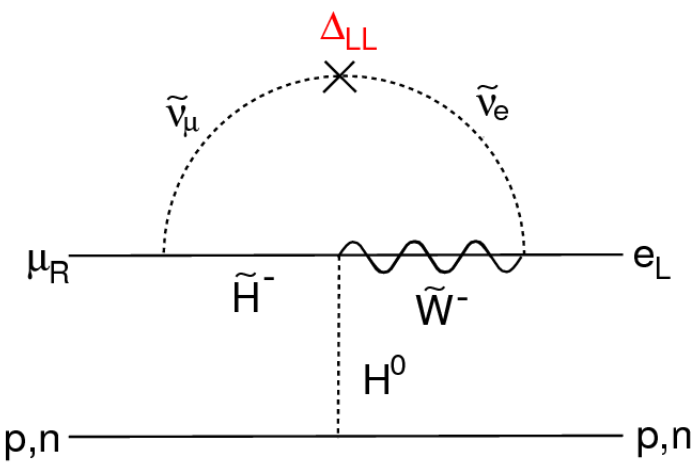


$\propto \tan\beta$

$\mu \to e$ conversion



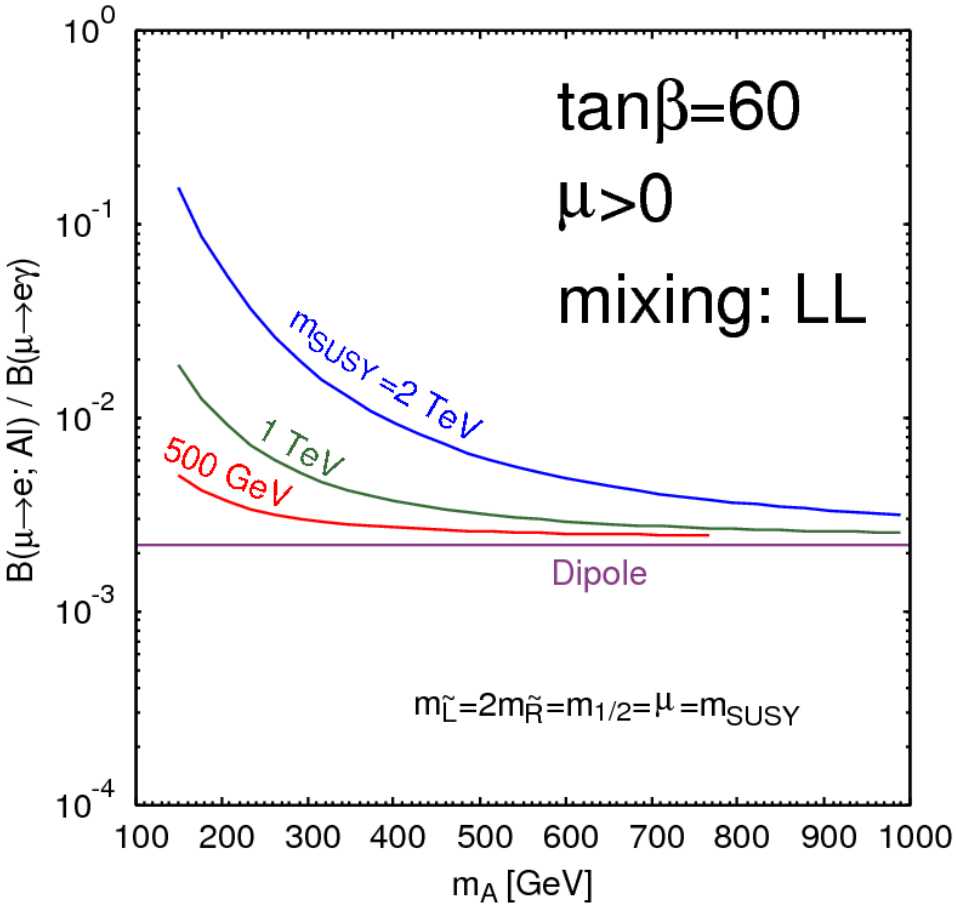
dipole $\propto \tan\beta$

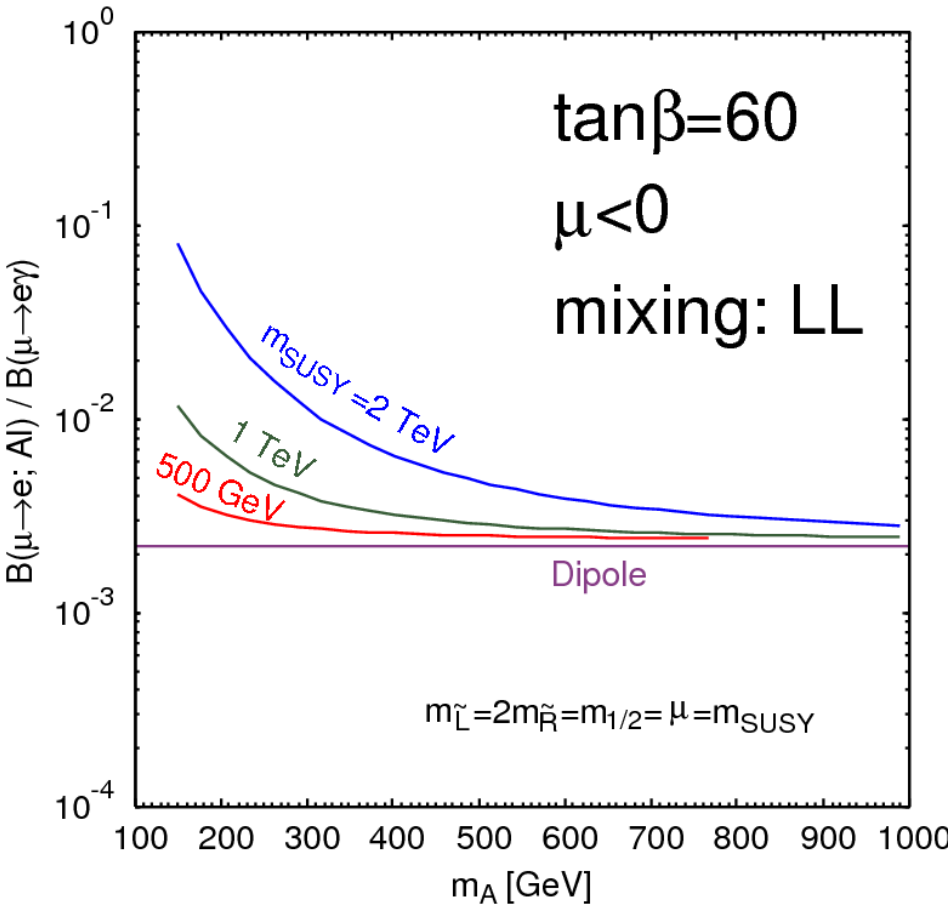


scalar $\propto \tan^3\beta$

different parameter dependences

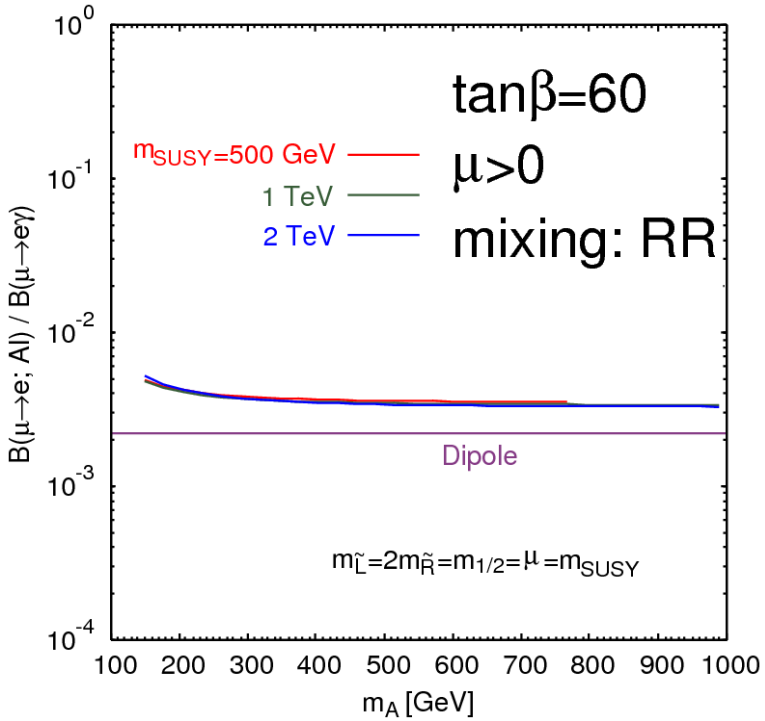
$B(\mu \to e; \mathrm{Al})/B(\mu \to e\gamma)$

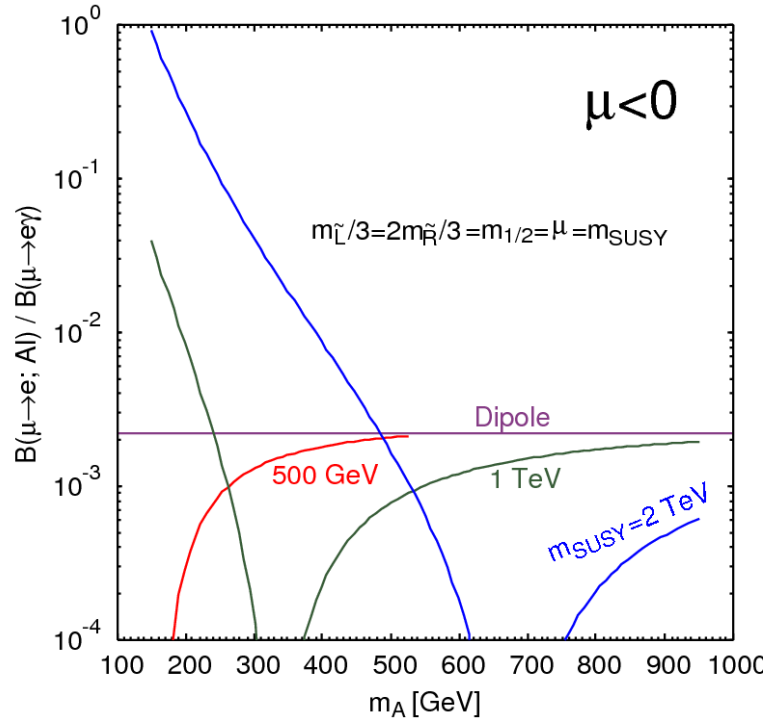




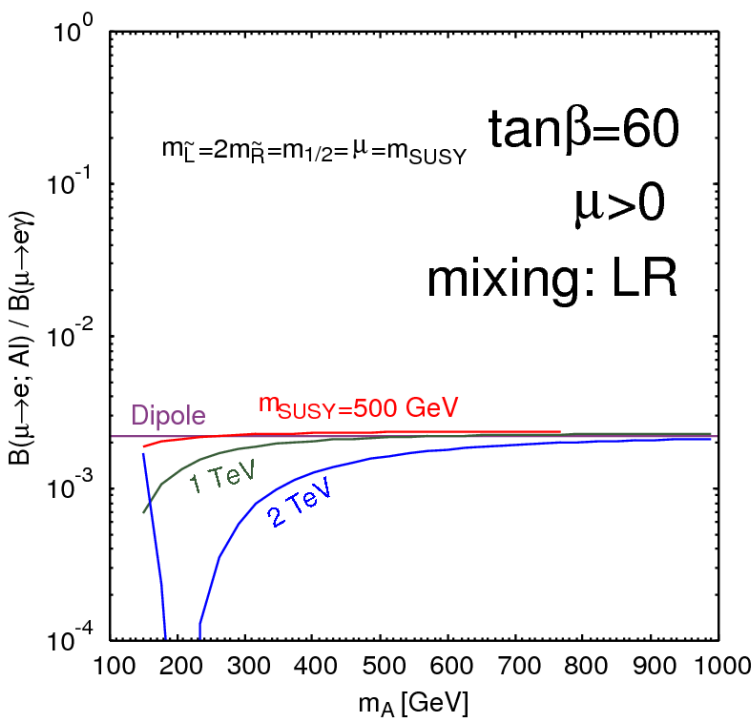
Significant enhancement of this ratio is possible depending on parameters.

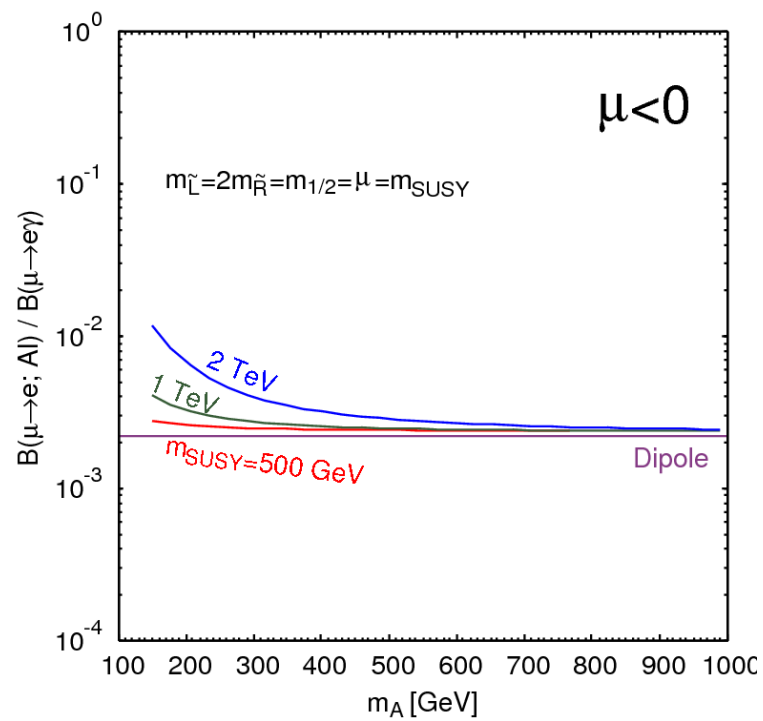
Combination with LHC results will be important!


tanβ=60
μ>0
mixing: RR
m_SUSY=500 GeV
1 TeV
2 TeV
Dipole
m_L̃=2m_R̃=m_1/2=μ=m_SUSY
B(μ→e; Al) / B(μ→eγ)
m_A [GeV]


μ<0
m_L̃/3=2m_R̃/3=m_1/2=μ=m_SUSY
Dipole
500 GeV
1 TeV
m_SUSY=2 TeV
B(μ→e; Al) / B(μ→eγ)
m_A [GeV]

Quite rich!!


m_L̃=2m_R̃=m_1/2=μ=m_SUSY
tanβ=60
μ>0
mixing: LR
Dipole
m_SUSY=500 GeV
1 TeV
2 TeV
B(μ→e; Al) / B(μ→eγ)
m_A [GeV]


μ<0
m_L̃=2m_R̃=m_1/2=μ=m_SUSY
2 TeV
1 TeV
m_SUSY=500 GeV
Dipole
B(μ→e; Al) / B(μ→eγ)
m_A [GeV]

Summary

Current experimental constraint on LFV mixing parameter is already quite strong.

If there is new physics at O(1) TeV energy scale, the smallness of the mixing parameter must be explained. I presented examples of mechanisms for suppressing the parameter, but there are often sub-leading contributions such as gravity(!). In those models, this sub-leading contribution is big enough to be observed soon.

Once a LFV process is discovered, it is important to combine with data from LHC experiments.

Ratio of the branching ratio of various LFV processes gives information on nature of LFV.