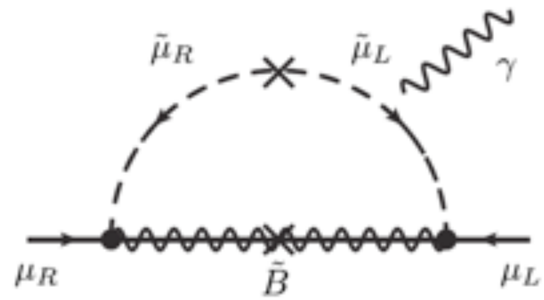


Probing Bino Contribution to Muon g-2

Teppei Kitahara (北原鉄平)

The University of Tokyo

THE UNIVERSITY OF TOKYO

SUSY: Model-building and Phenomenology, December 2-4, 2013, IPMU

Based on

JHEP 1311 (2013) 013 [arXiv:1309.3065] and **Phys. Lett. B** in press [arXiv:1310.4496]

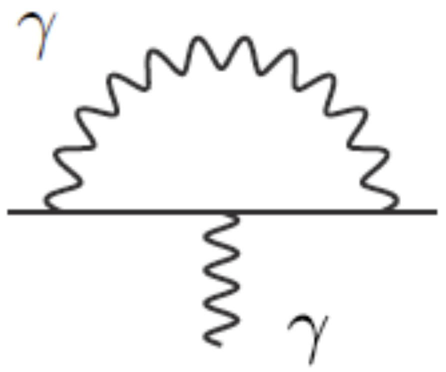
Collaborators : M. Endo, K. Hamaguchi, S. Iwamoto [Kavli IPMU],

T. Moroi, and T. Yoshinaga

Status of the muon g-2

Magnetic dipole moment term

$$\mathcal{L} = -\frac{eQ_\ell}{4m_\ell} a_\ell \bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu}$$



Leading contribution to a_ℓ

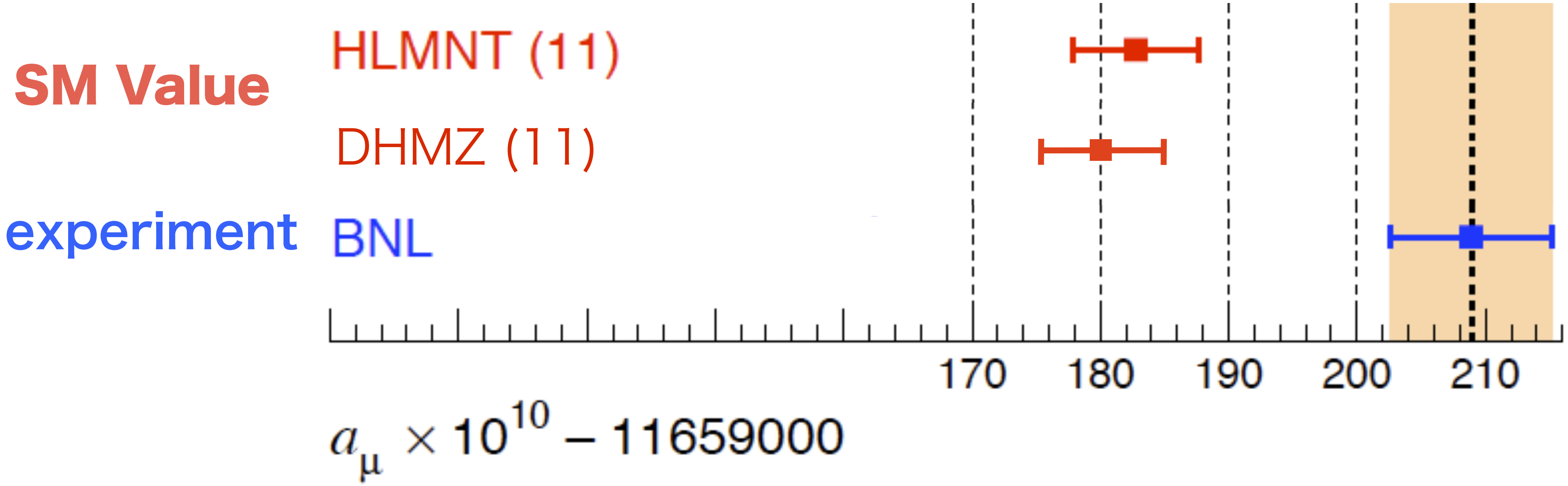
➡ Non-relativistic limit

$$\mathcal{H} = 2(1 + a_\ell)\frac{eQ_\ell}{4m_\ell}\vec{B}\cdot\hat{\vec{s}}$$

- a_μ is generated by radiative corrections (a_μ : muon g-2)
- The muon g-2 has been measured very precisely
- We may be able to discovery some **new physics** indirectly thorough the precise measurement of the muon g-2

■ Status of the muon g-2

The latest result of the muon g-2



[Hagiwara,Liao,Martin,Nomura,Teubner,J. Phys. G 38 (2011)085033]
[Davier,Hoecker,Malaescu,Zhang,Eur. Phys. J. C 71(2011)1515]

$$\Delta a_\mu \equiv a_\mu^{(\mathrm{exp})} - a_\mu^{(\mathrm{SM})} = \begin{cases} (26.1 \pm 8.0) \times 10^{-10}, & \mathbf{3.3\ \sigma} \\ (28.7 \pm 8.0) \times 10^{-10}. & \mathbf{3.6\ \sigma} \end{cases}$$

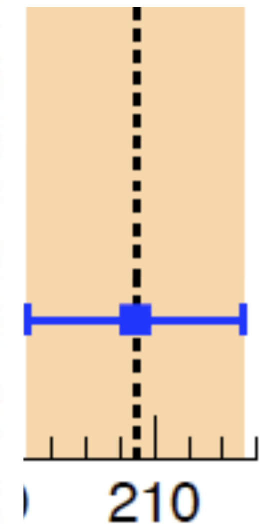
muon g-2 anomaly (possibly a signal of new physics)

■ Status of the muon g-2

The latest re

SM Valu

experim



38 (2011)085033]
C 71(2011)1515]

$$\Delta a_\mu \equiv a_\mu^{(\text{exp})} - a_\mu^{(\text{SM})} = \begin{cases} (26.1 \pm 8.0) \times 10^{-10}, & \textbf{3.3}\ \sigma \\ (28.7 \pm 8.0) \times 10^{-10}. & \textbf{3.6}\ \sigma \end{cases}$$

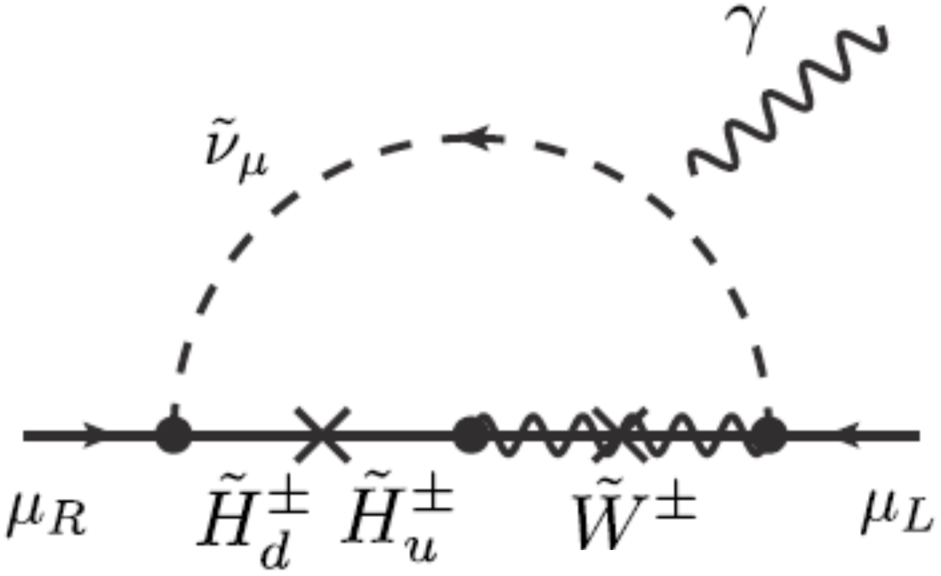
Future prospects:

the error of Δa_μ could be reduce ~ $\pm 3.0 \times 10^{-10}$

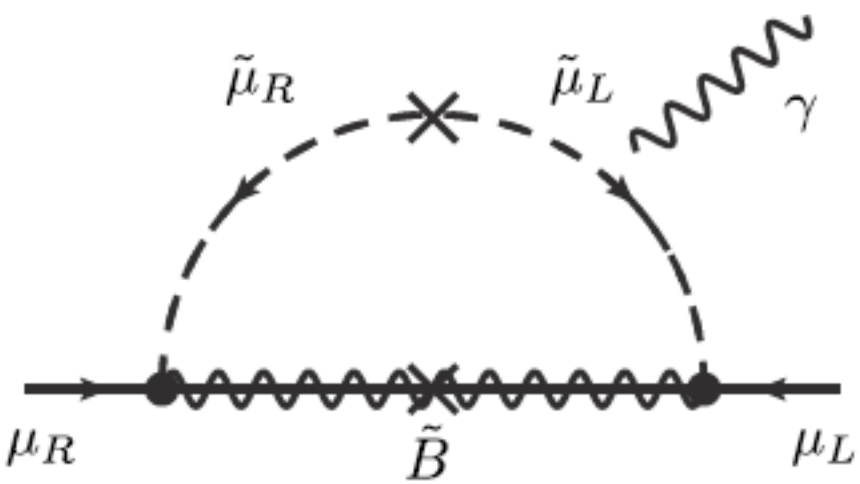
■SUSY contribution to the muon g-2

Dominant two-type SUSY contributions

Chargino-sneutlino loop



Neutralino-smuon loop



$$a_\mu(\mathrm{SUSY}) \sim \frac{\alpha_2(\alpha_Y)}{4\pi}\frac{m_\mu^2}{m_{\mathrm{soft}}^2}\tan\beta$$

[Moroi, Phys. Rev. D. 53(1996)6565]

✓ They have $\tan\beta$ enhancement and can become sizable

✓ $\tan\beta \sim O(10), m_{\mathrm{soft}} \sim O(100)$ GeV, **they can solve the muon g-2 anomaly**

■SUSY contribution to the muon g-2

- Many previous works of SUSY contribution to the muon g-2 assumed that all slepton, Bino, Wino and **Higgsino are light**

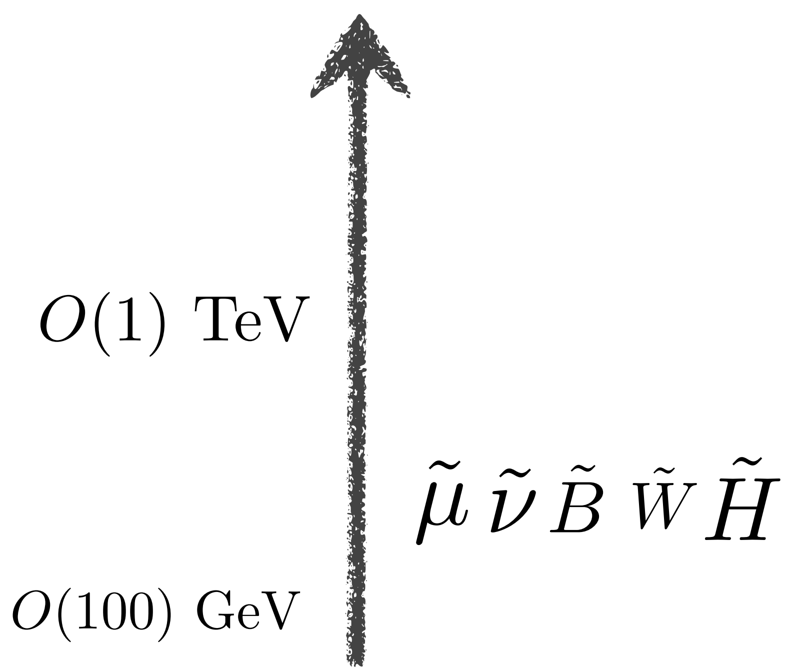
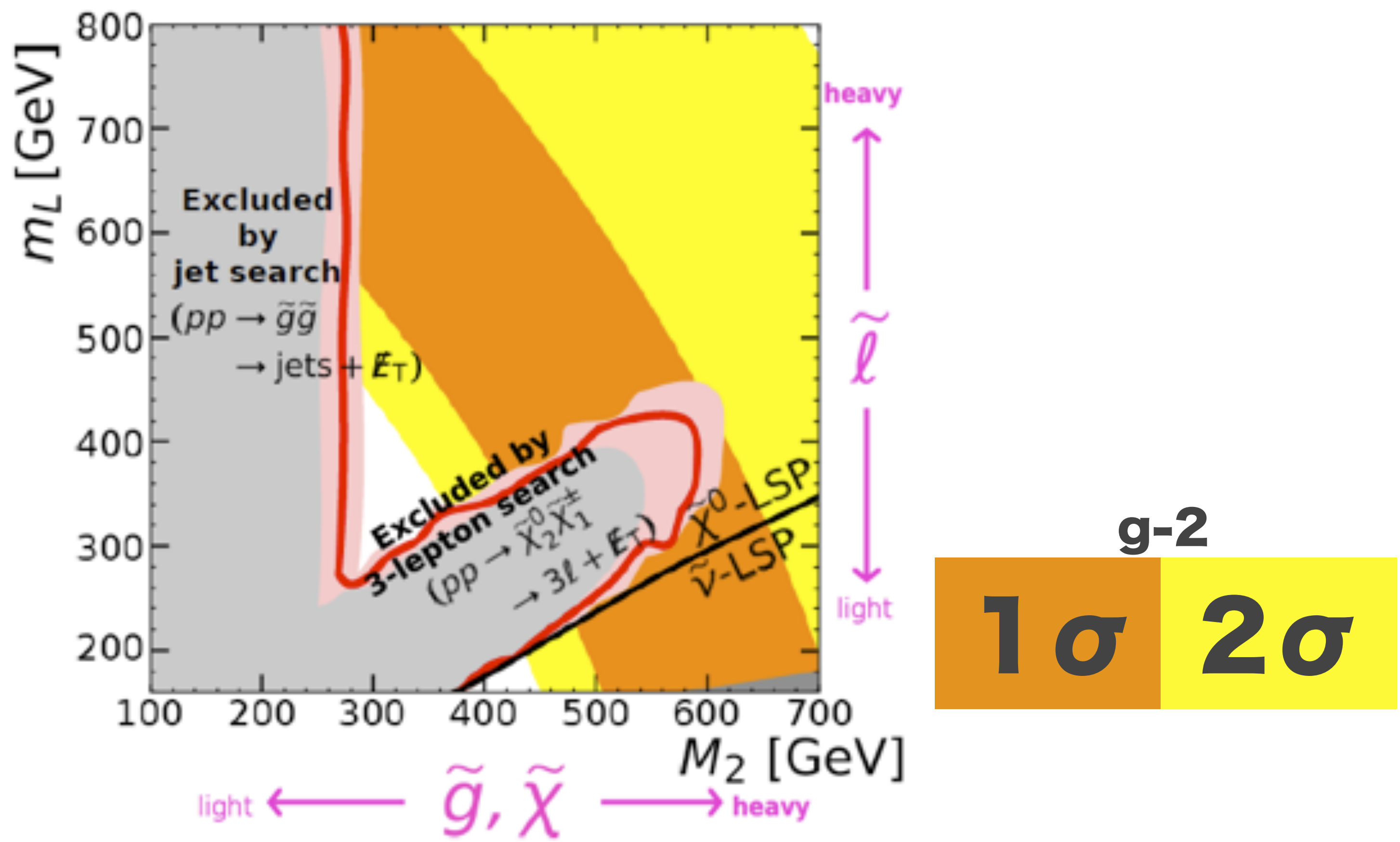


figure from S.Iwamoto's talk



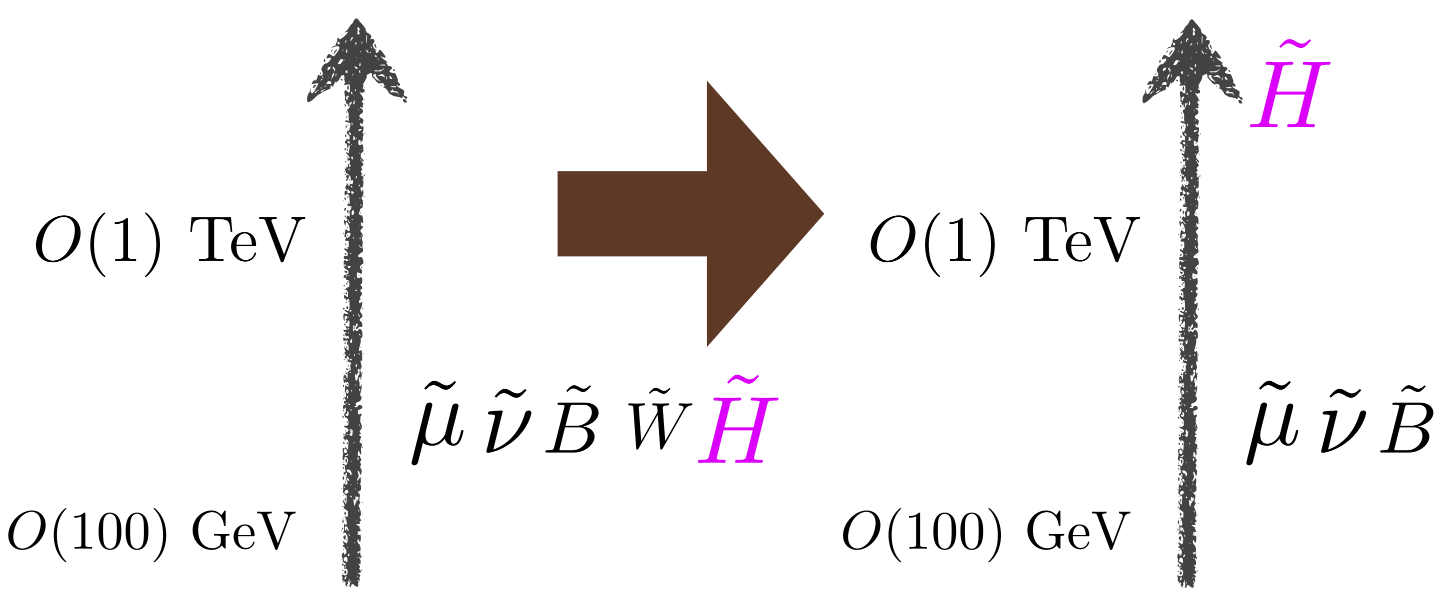
[Endo, Hamaguchi, Iwamoto, Yoshinaga. arXiv:[1303.4256]]

■ SUSY contribution to the muon g-2

- Many previous works of SUSY contribution to the muon g-2 assumed that all slepton, Bino, Wino and **Higgsino are light**

However, if **Higgsino is heavy (O(1-10) TeV)**, then the phenomenology is **changed** sufficiently

(as I discuss later)

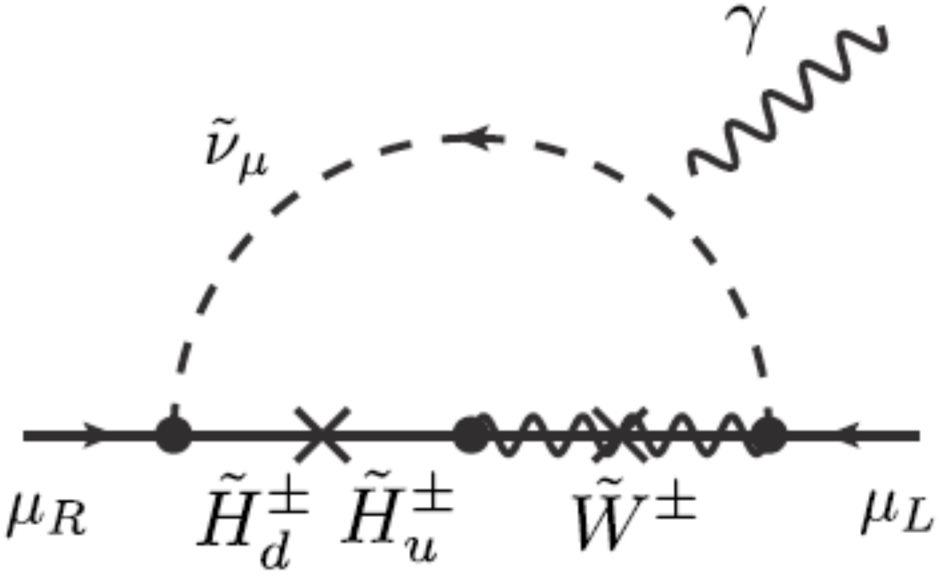


In this talk, We assume that **only slepton and Bino are light**

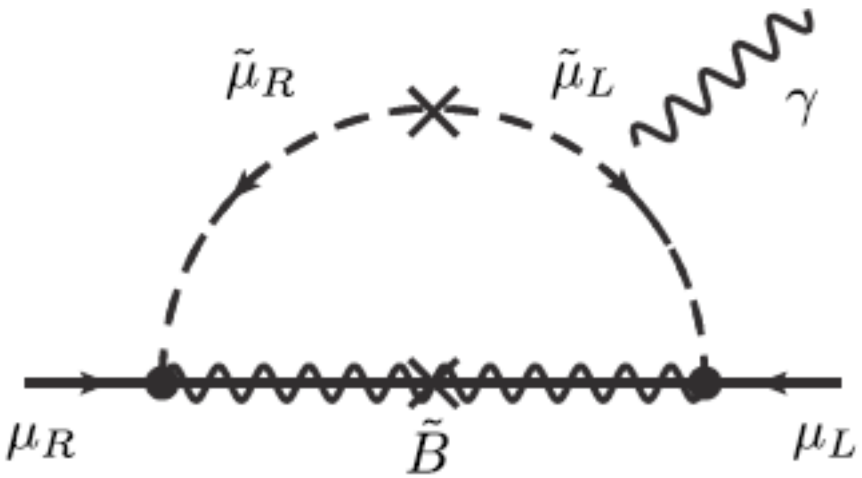
■ SUSY contribution to the muon g-2

Let us consider large μ limit

Chargino-sneutlino loop



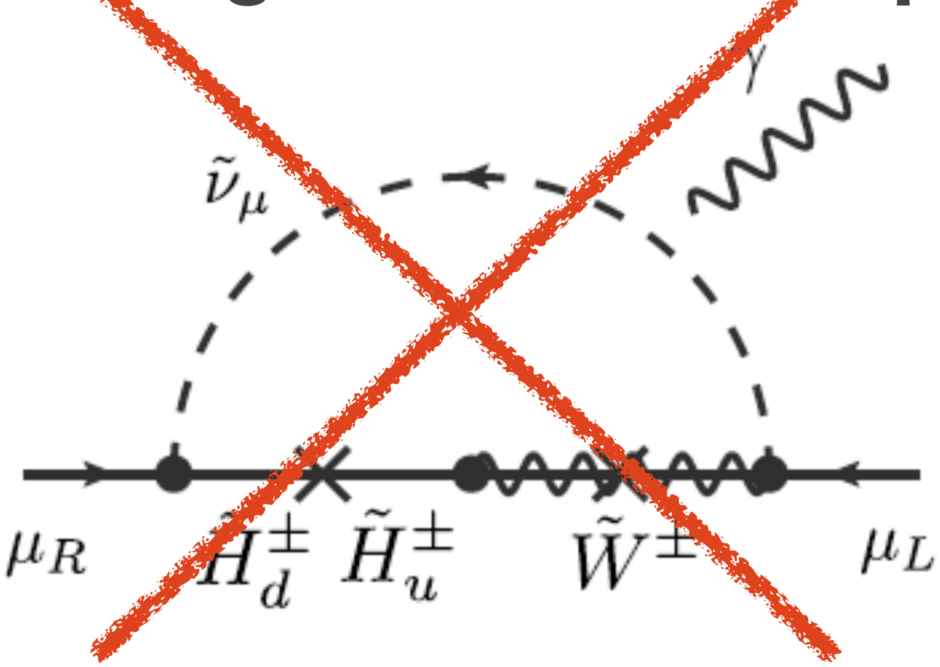
Neutralino-smuon loop



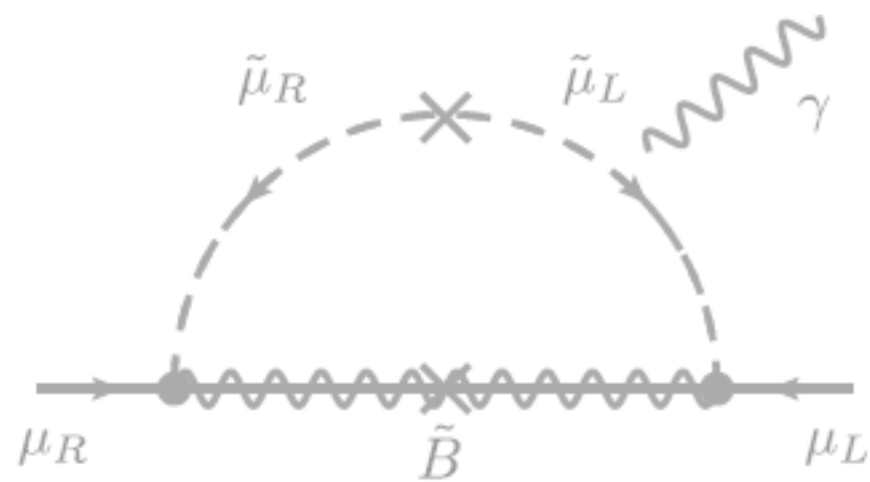
■ SUSY contribution to the muon g-2

Let us consider large μ limit

Chargino-sneutlino loop



Neutralino-smuon loop

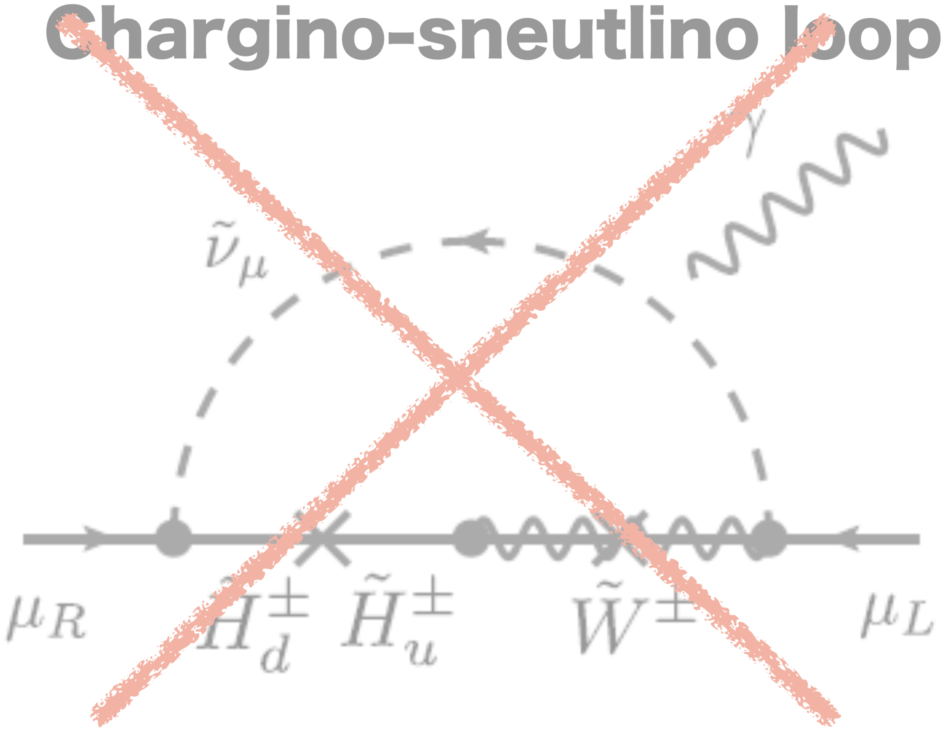


Decouple....

SUSY contribution to the muon g-2

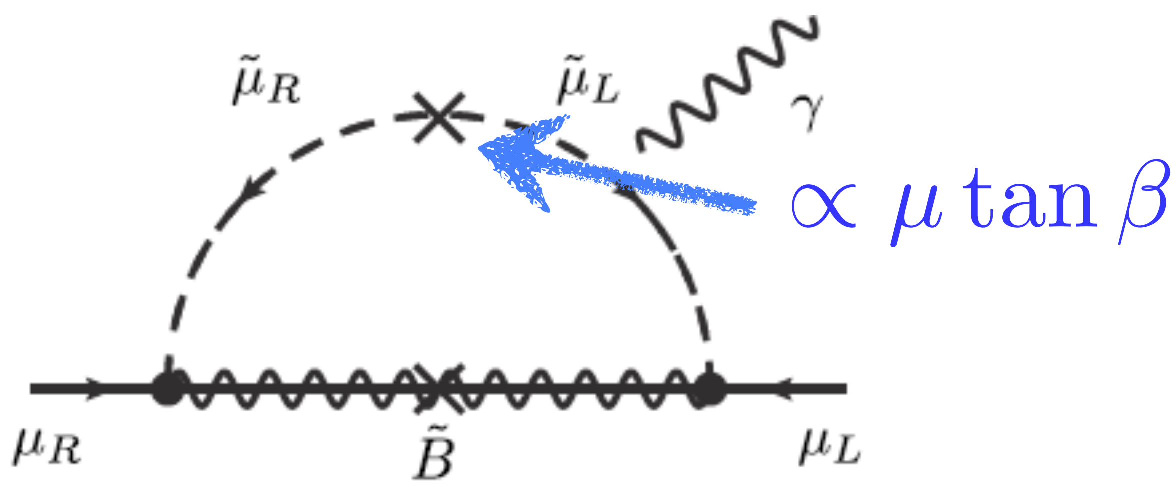
Let us consider large μ limit

Chargino-sneutlino loop



Decouple....

Neutralino-smuon loop



Not decouple but **enhance!**

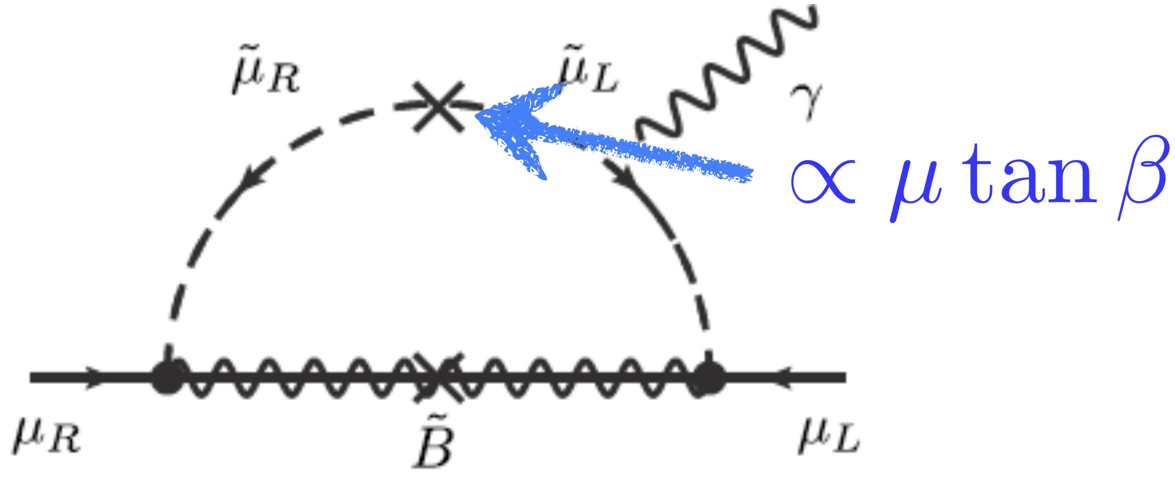
SUSY contributions are dominated by
the Bino contribution.
The Bino contribution can **solve**
the muon g-2 anomaly

Outline

- Introduction
  - The status of muon g-2 anomaly and SUSY contributions
- **Probing** Bino contributions to the muon g-2
  - The vacuum stability and Overview
  - Universal case $m_{\tilde{\mu}} \sim m_{\tilde{\tau}}$
  - Non-universal case $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$
- **Reconstructing** Bino contributions to the muon g-2
- Conclusion

■ Overview of Bino contribution

Bino contribution to the muon g-2



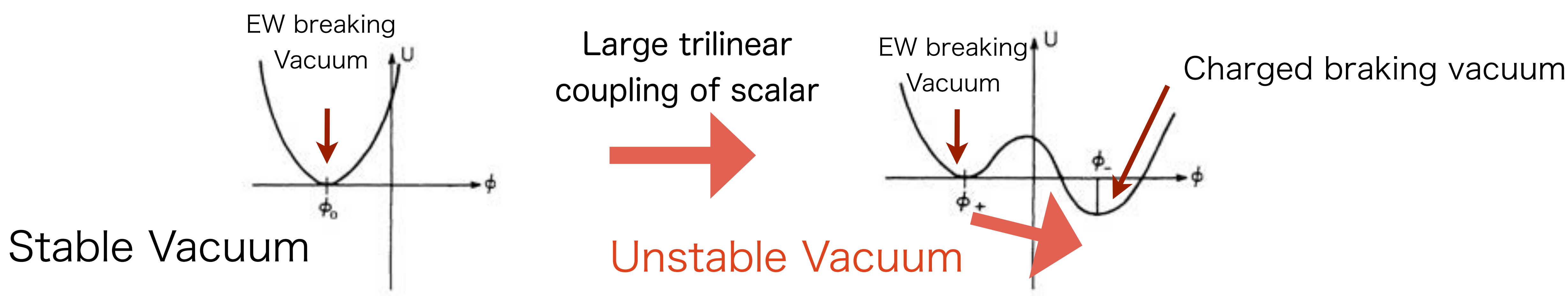
$$a_\mu(\tilde{B}) \simeq \frac{\alpha_Y}{24\pi} \frac{m_\mu^2}{m_{\rm soft}^2} \mu \tan\beta$$

Not decouple but **enhance** at large μ**!**

- Thanks to $\mu\tan\beta$ enhancement, **smuon could be extremely heavy** (O(1) TeV)

[Rattazzi, Sarid, Nucl. Phys. B 501, 297(1997)]

- But, too large $\mu\tan\beta$ spoils stability of the EW vacuum



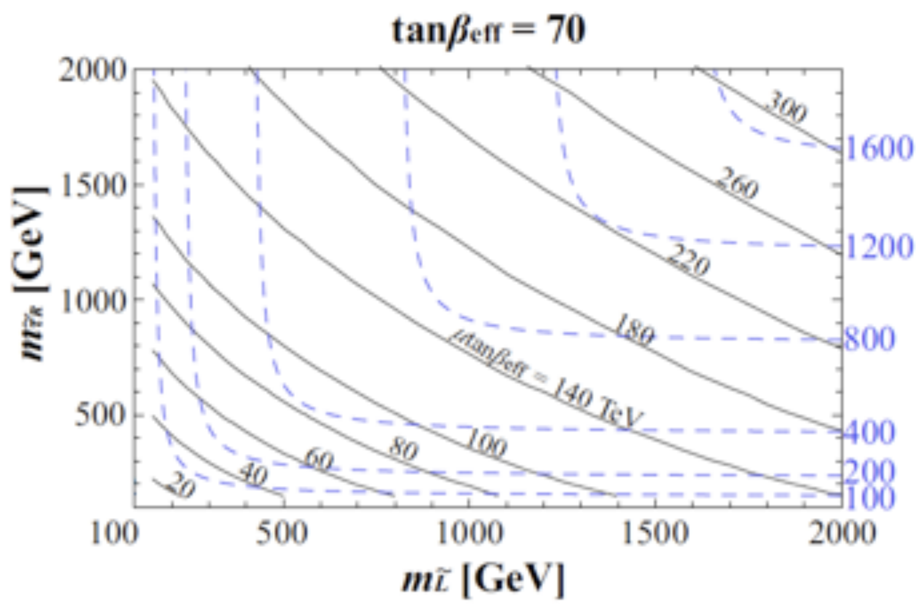
■ Overview of Bino contribution

Vaccum meta-stability condition of slepton $\tilde{\ell}$

$$\left|\frac{m_\ell}{1+\Delta_\ell}\mu\tan\beta\right| \le \eta_\ell \Big[1.01\times10^2\,\mathrm{GeV}\sqrt{m_{\tilde{\ell}_L}m_{\tilde{\ell}_R}} + 1.01\times10^2\,\mathrm{GeV}(m_{\tilde{\ell}_L}+1.03m_{\tilde{\ell}_R}) \\ -2.27\times10^4\,\mathrm{GeV}^2 + \frac{2.97\times10^6\,\mathrm{GeV}^3}{m_{\tilde{\ell}_L}+m_{\tilde{\ell}_R}} - 1.14\times10^8\,\mathrm{GeV}^4\left(\frac{1}{m^2_{\tilde{\ell}_L}}+\frac{0.983}{m^2_{\tilde{\ell}_R}}\right)\Big].$$

[TK and Yoshinaga]

Contour plot for upper bound on $\mu\tan\beta$



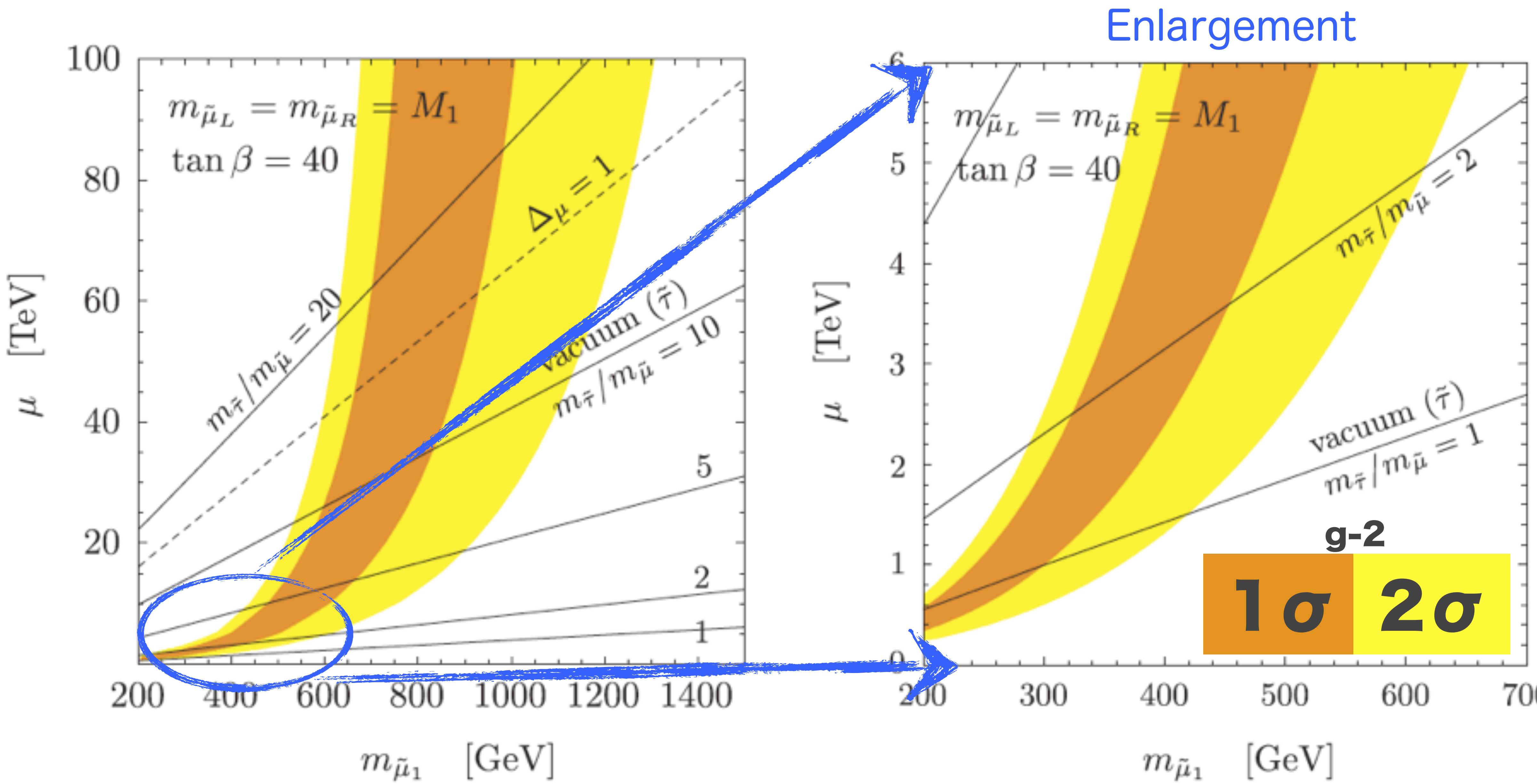
Vacuum meta-stability of staus gives upper bound on $\mu\tan\beta$

→ **Therefore, masses of smuon are bounded**

[Endo, Hamaguchi, TK, Yoshinaga]

■ Bino contribution vs Vacuum stability

The SUSY contribution to the muon g-2

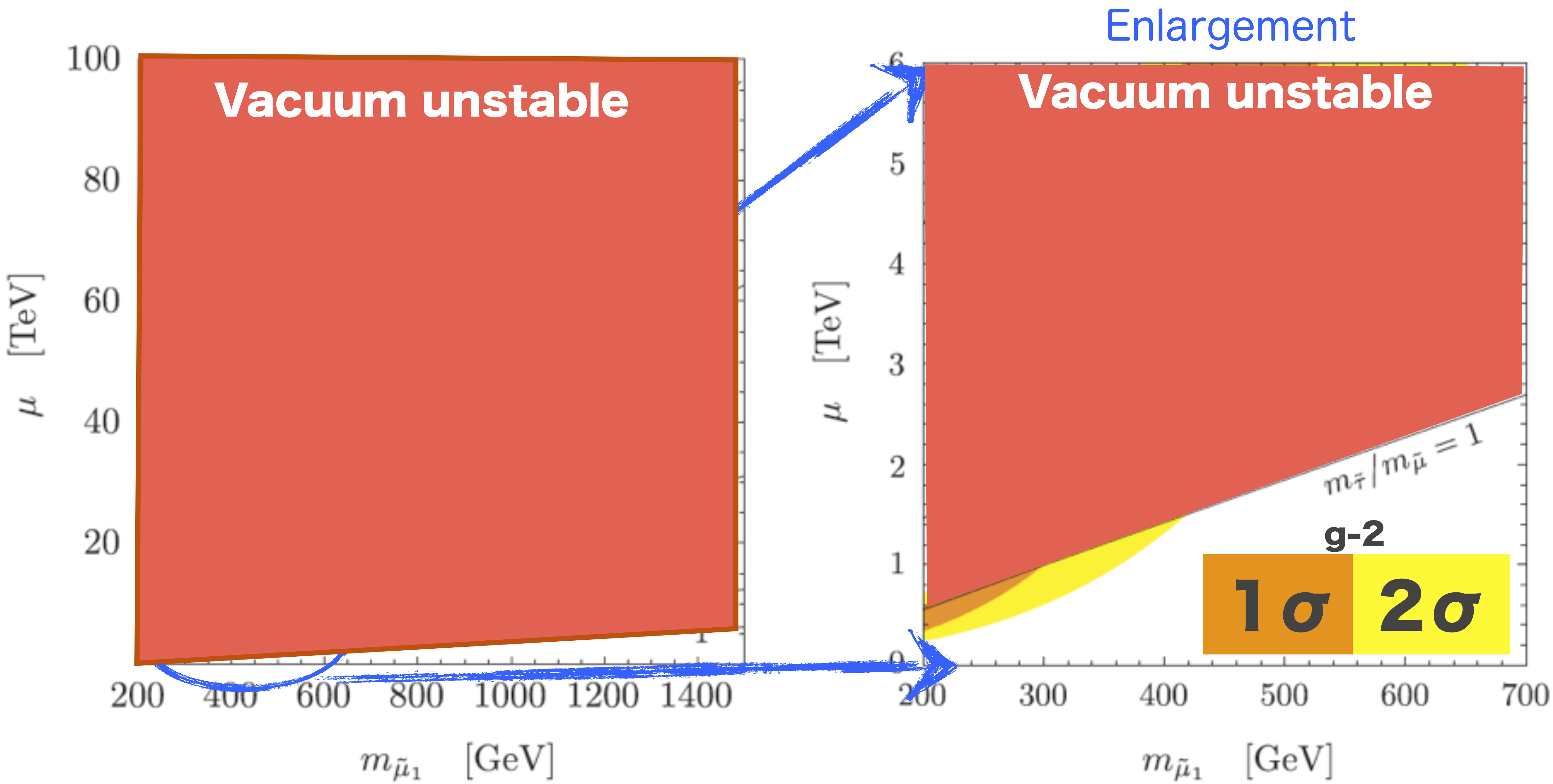


g-2 : 1-loop full + 2 loop LL

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Bino contribution vs Vacuum stability

✔ **Universal slepton mass case** $m_{\tilde{\mu}} \sim m_{\tilde{\tau}}$



g-2 : 1-loop full + 2 loop LL

[Endo, Hamaguchi, **TK**, Yoshinaga]

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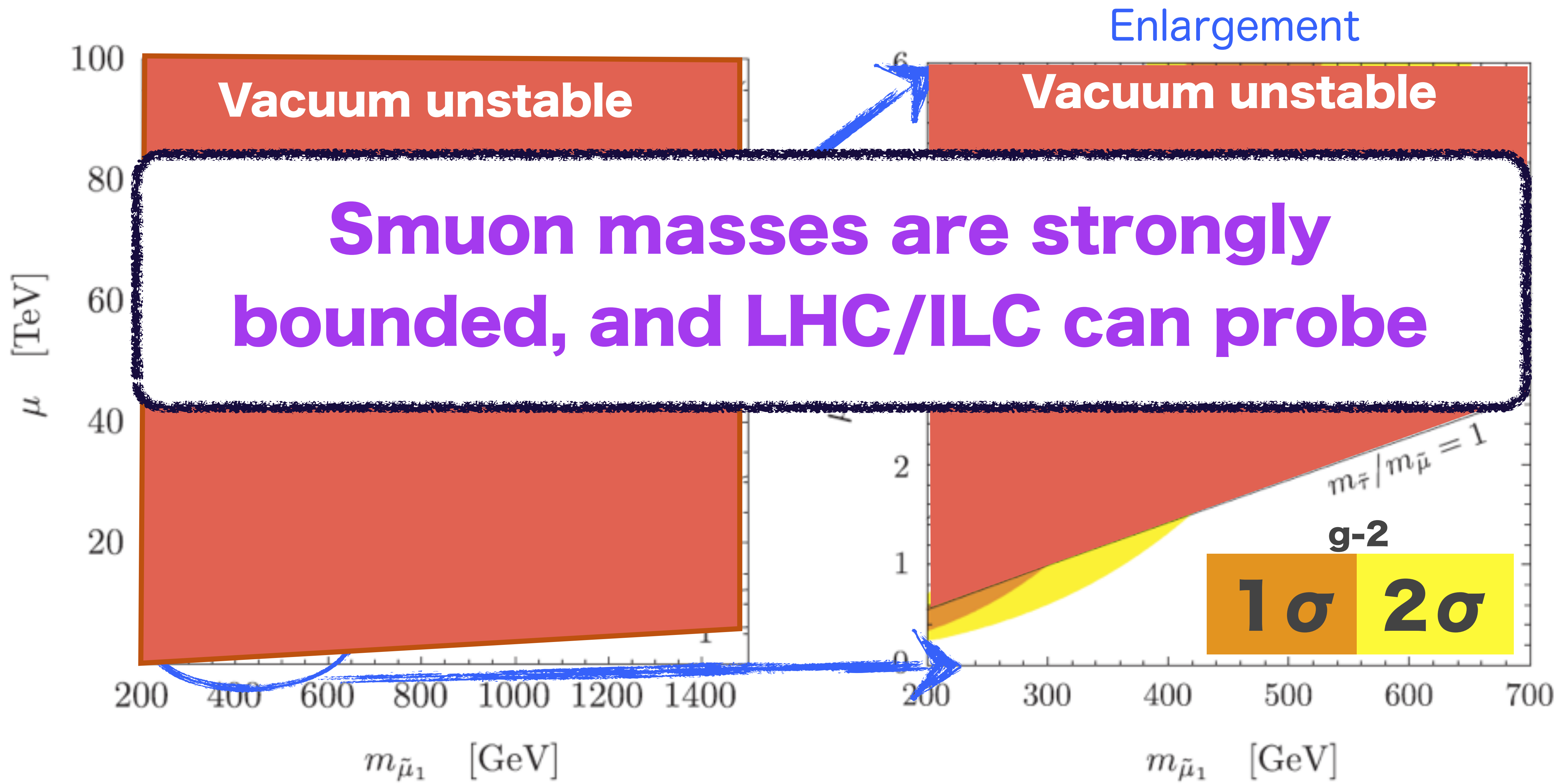


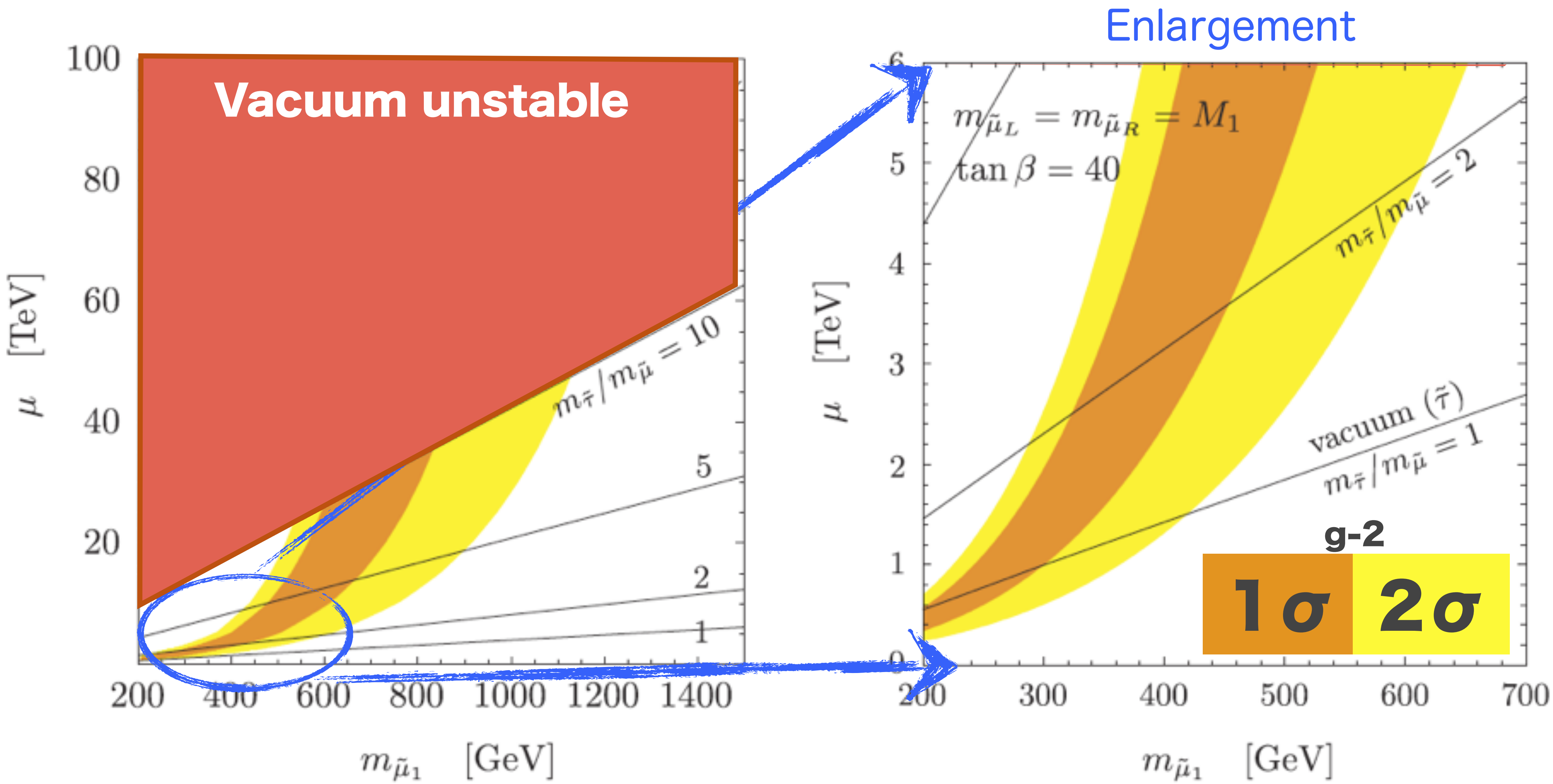
Smuon masses are strongly bounded, and LHC/ILC can probe

g-2 : 1-loop full + 2 loop LL

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Bino contribution vs Vacuum stability

✔ **Non-universal slepton mass case** $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$



g-2 : 1-loop full + 2 loop LL

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Bino contribution vs Vacuum stability

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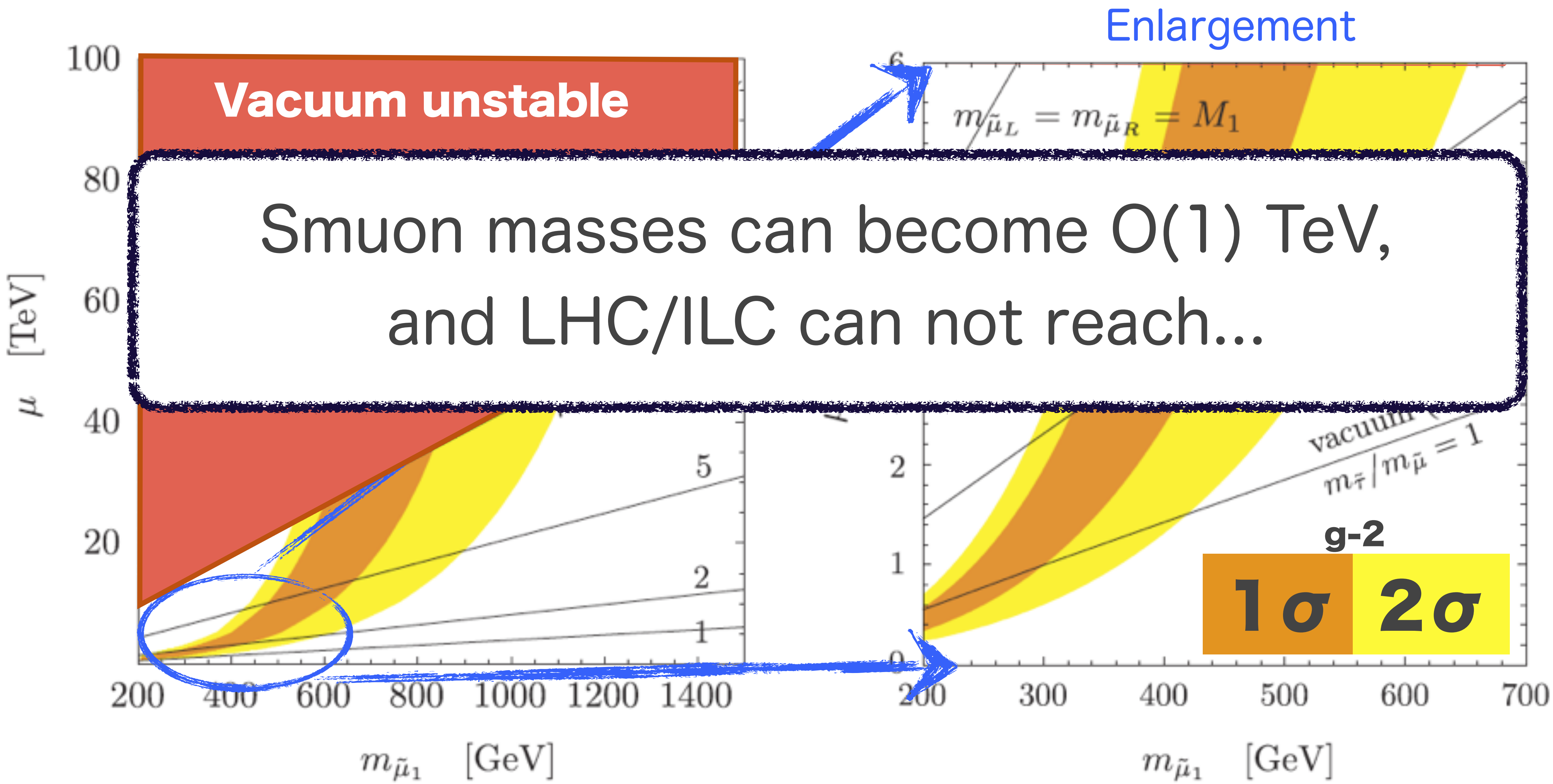


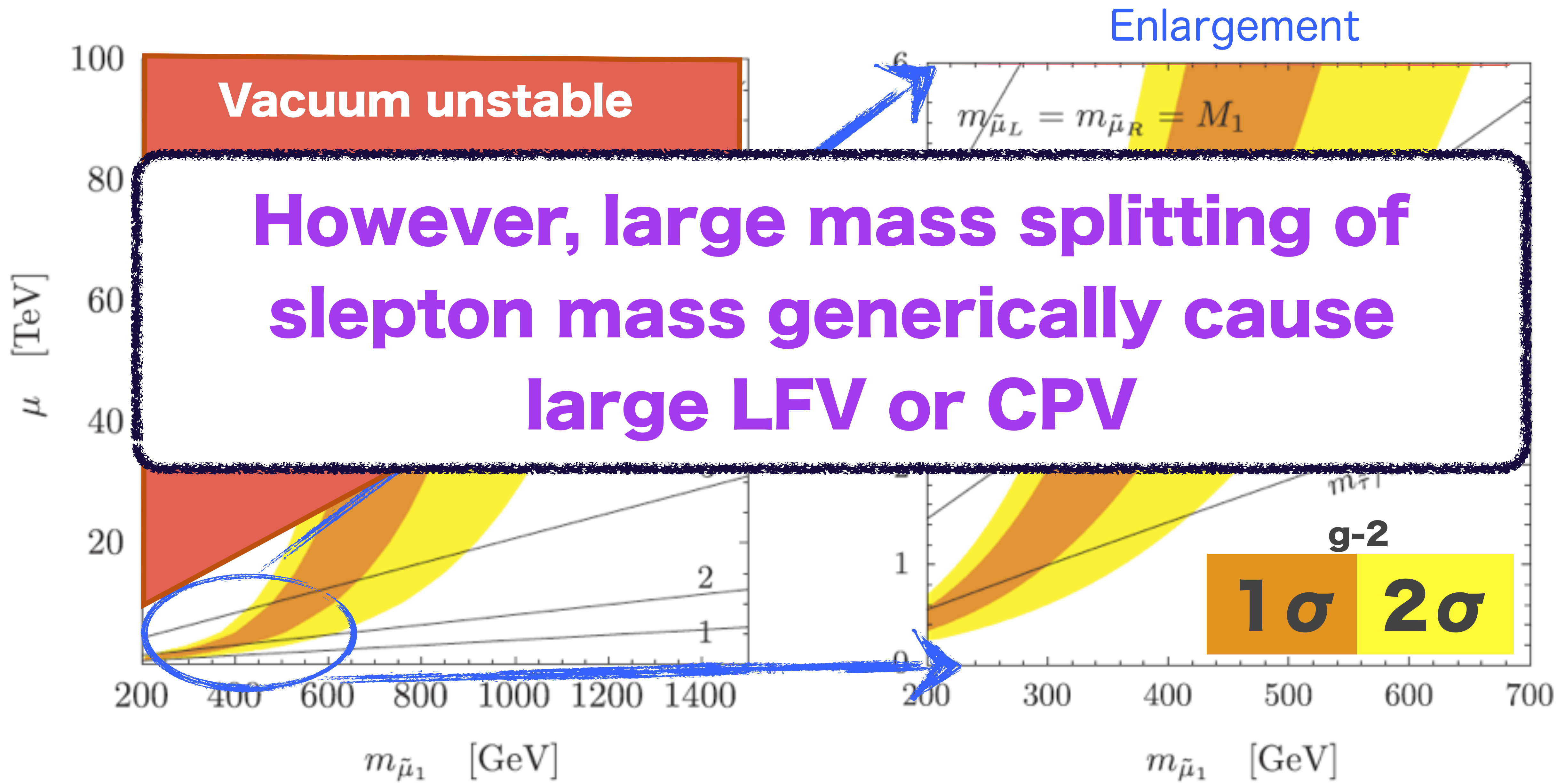
Smuon masses can become O(1) TeV, and LHC/ILC can not reach…

g-2 : 1-loop full + 2 loop LL

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Bino contribution vs Vacuum stability

✔ **Non-universal slepton mass case** $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$



However, large mass splitting of slepton mass generically cause large LFV or CPV

g-2 : 1-loop full + 2 loop LL

[Endo, Hamaguchi, **TK**, Yoshinaga]

Universal slepton mass case

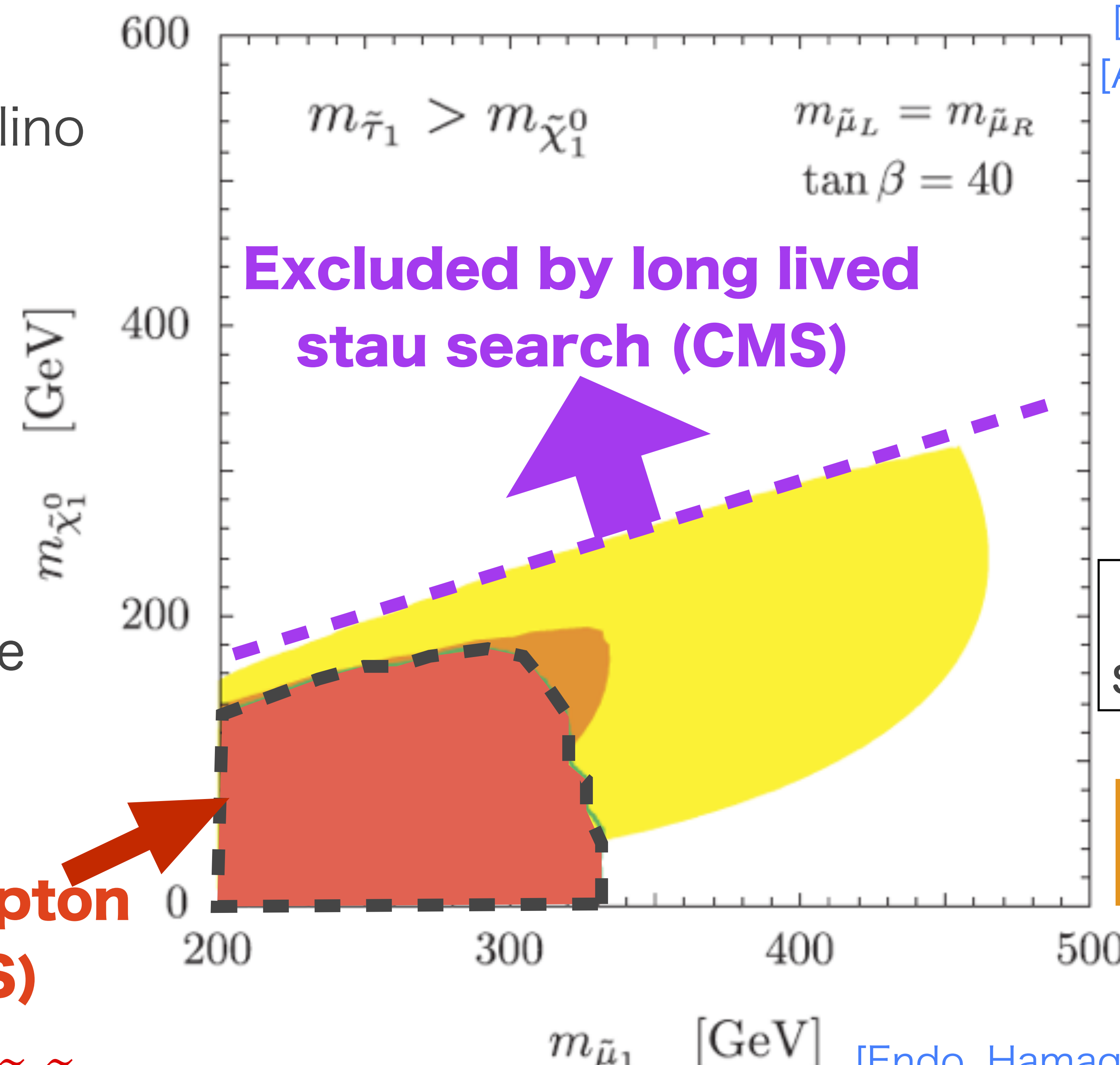
$$m_{\tilde{\mu}} = m_{\tilde{\tau}}$$

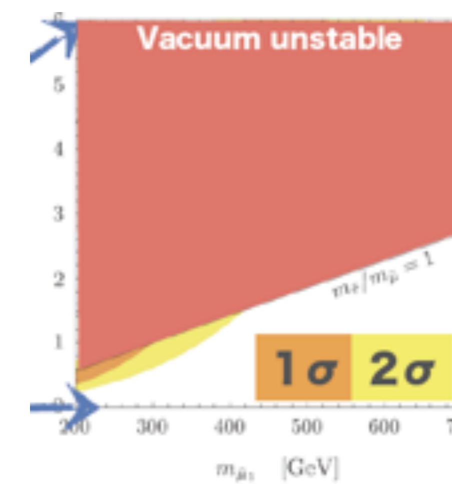
■ Universal slepton mass case $m_{\tilde{\mu}} = m_{\tilde{\tau}}$

SUSY contribution **vs current LHC bound**

[CMS-PAS-SUS-13-006]
[ATLAS-CONF-2013-049]

LSP: Bino-like neutralino
NLSP: stau





Vacuum stability severely constrain

g-2

1σ	2σ

μ: maximize under the Vacuum condition

Excluded by dilepton search (ATLAS)

$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}\tilde{\chi}$

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Universal slepton mass case $m_{\tilde{\mu}} = m_{\tilde{\tau}}$

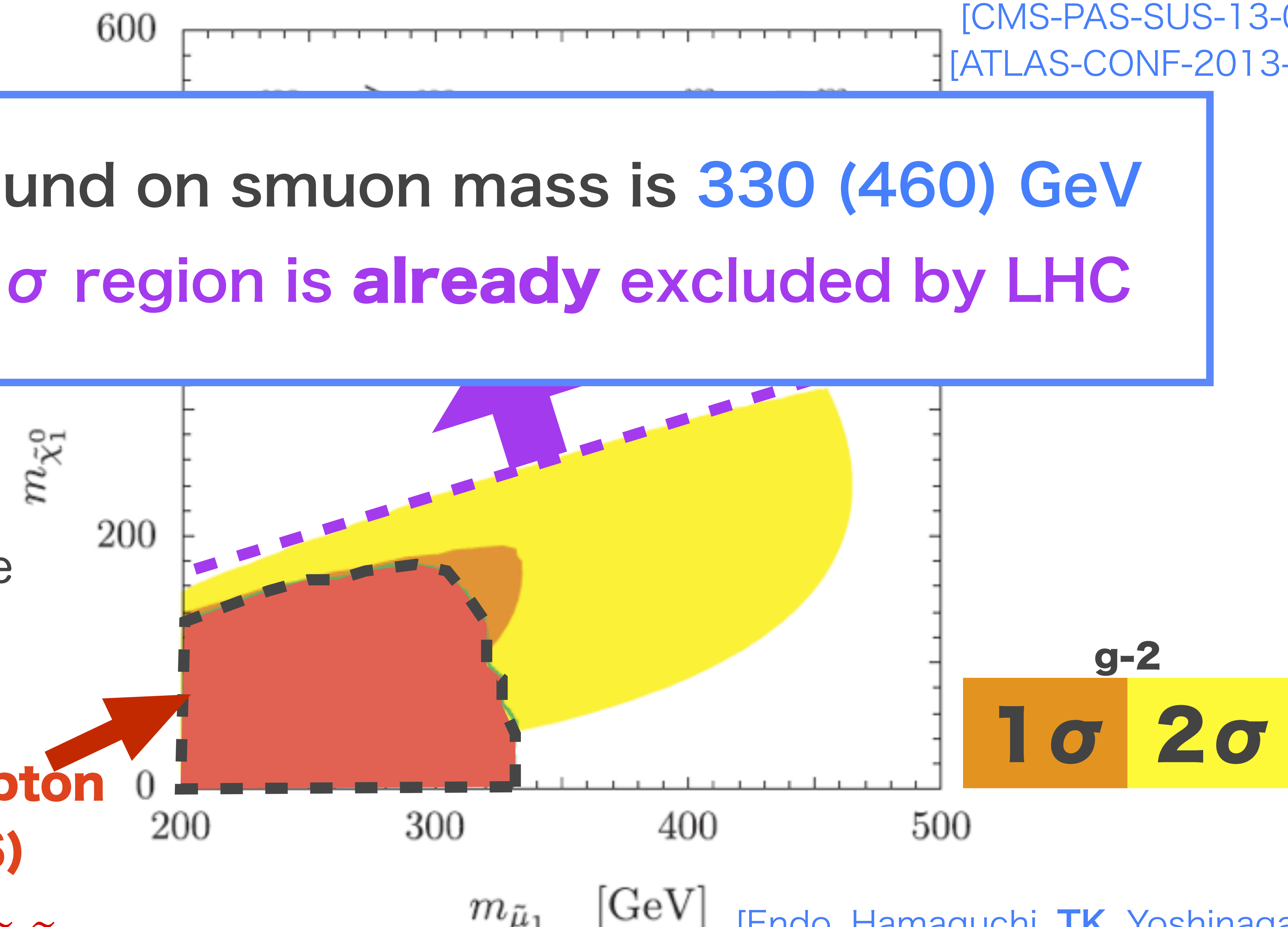
SUSY contribution **vs current LHC bound**

[CMS-PAS-SUS-13-006]
[ATLAS-CONF-2013-049]

LS
NL

1, Upper bound on smuon mass is 330 (460) GeV

2, Almost 1 σ region is **already** excluded by LHC



μ: maximize under the Vacuum condition

Excluded by dilepton search (ATLAS)

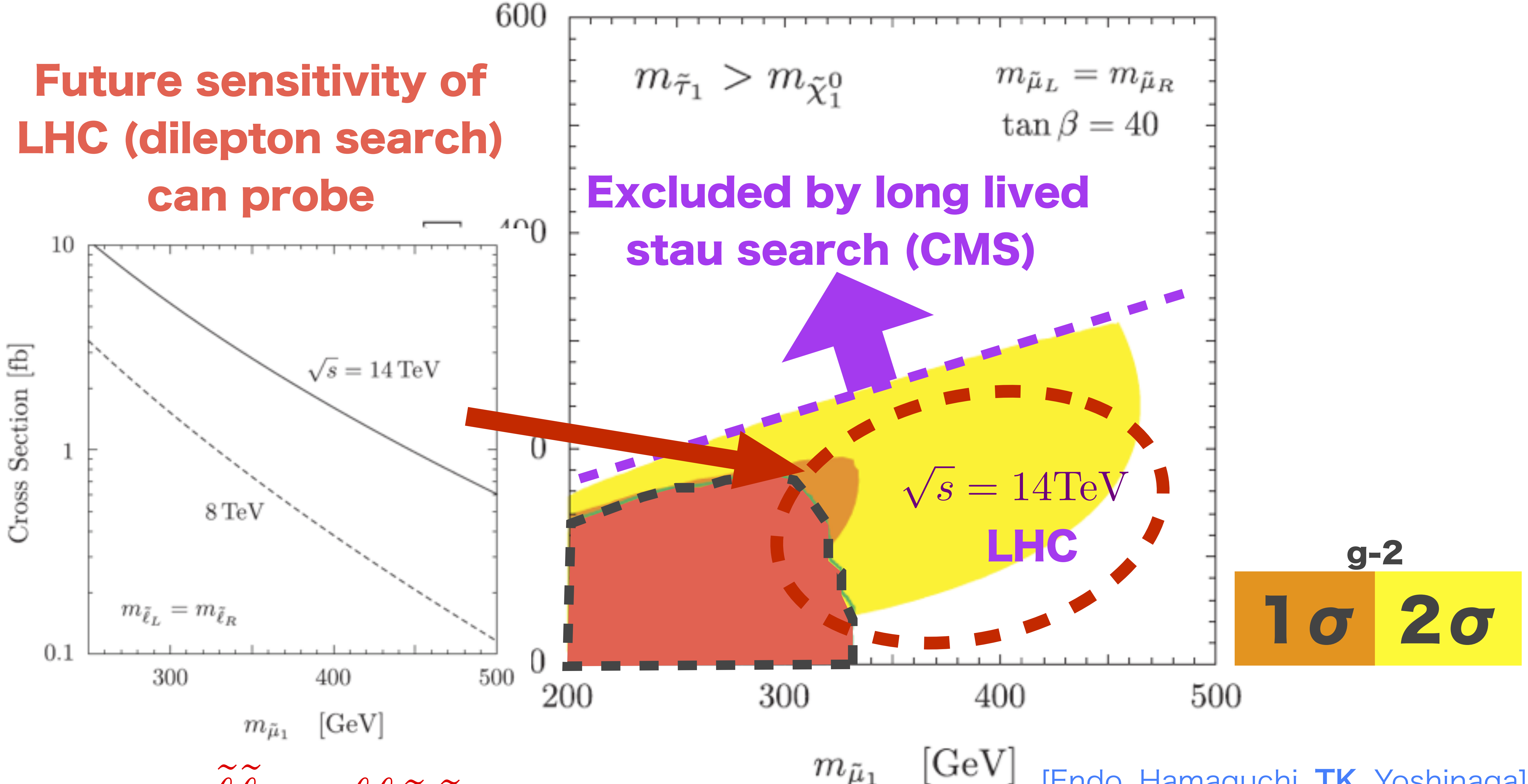
$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}\tilde{\chi}$

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Universal slepton mass case $m_{\tilde{\mu}} = m_{\tilde{\tau}}$

SUSY contribution **vs current LHC bound**

Future sensitivity of LHC (dilepton search) can probe



[Endo, Hamaguchi, **TK**, Yoshinaga]

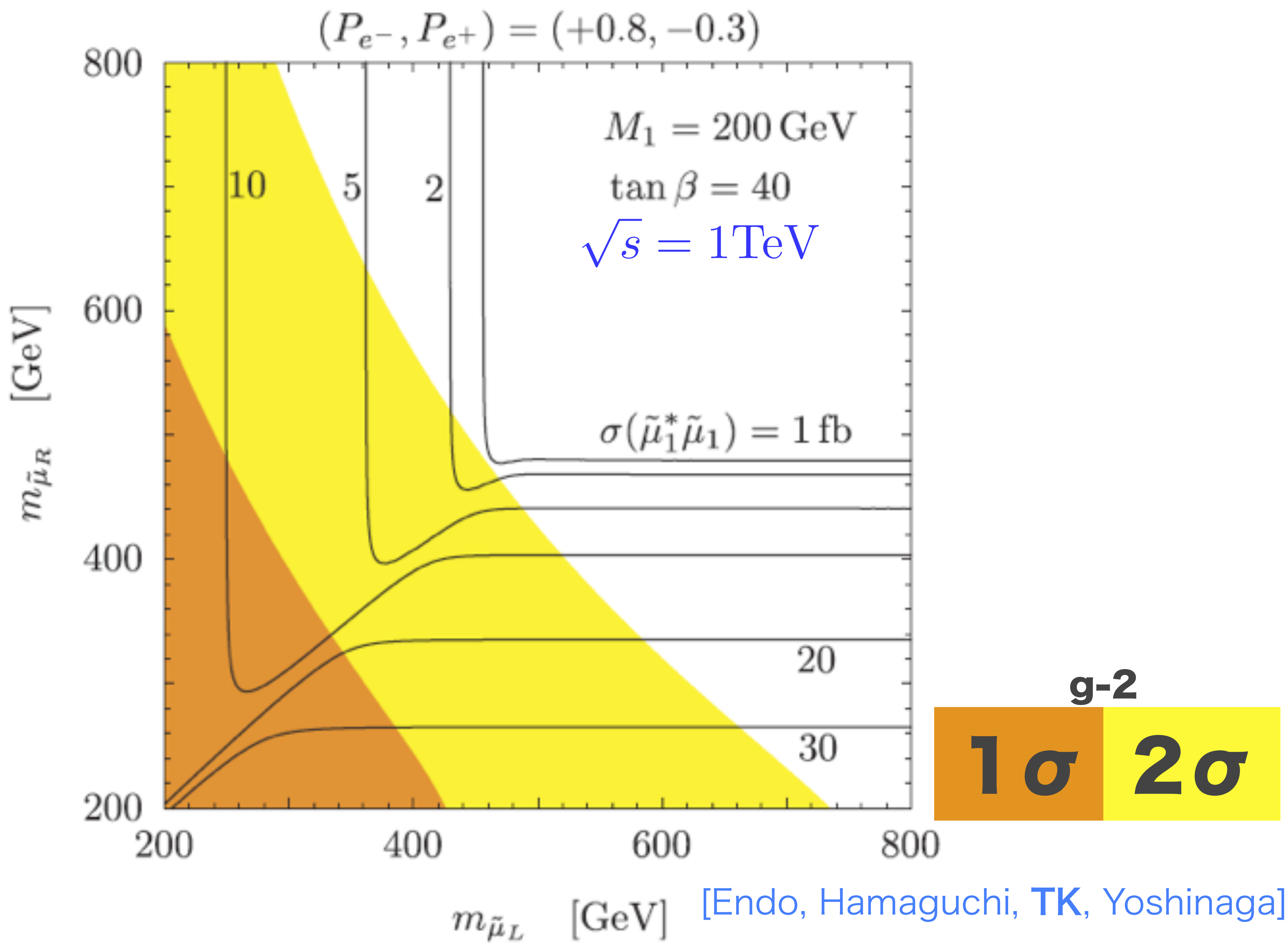
$$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}\tilde{\chi}$$

■ Universal slepton mass case $m_{\tilde{\mu}} = m_{\tilde{\tau}}$

SUSY contribution **vs ILC**

ILC can probe the Bino contribution

- Lightest smuon is within kinematical reach of ILC
- cross section > 1fb @$\sqrt{s} = 1\mathrm{TeV}$



[Endo, Hamaguchi, **TK**, Yoshinaga]

Non-universal slepton mass case

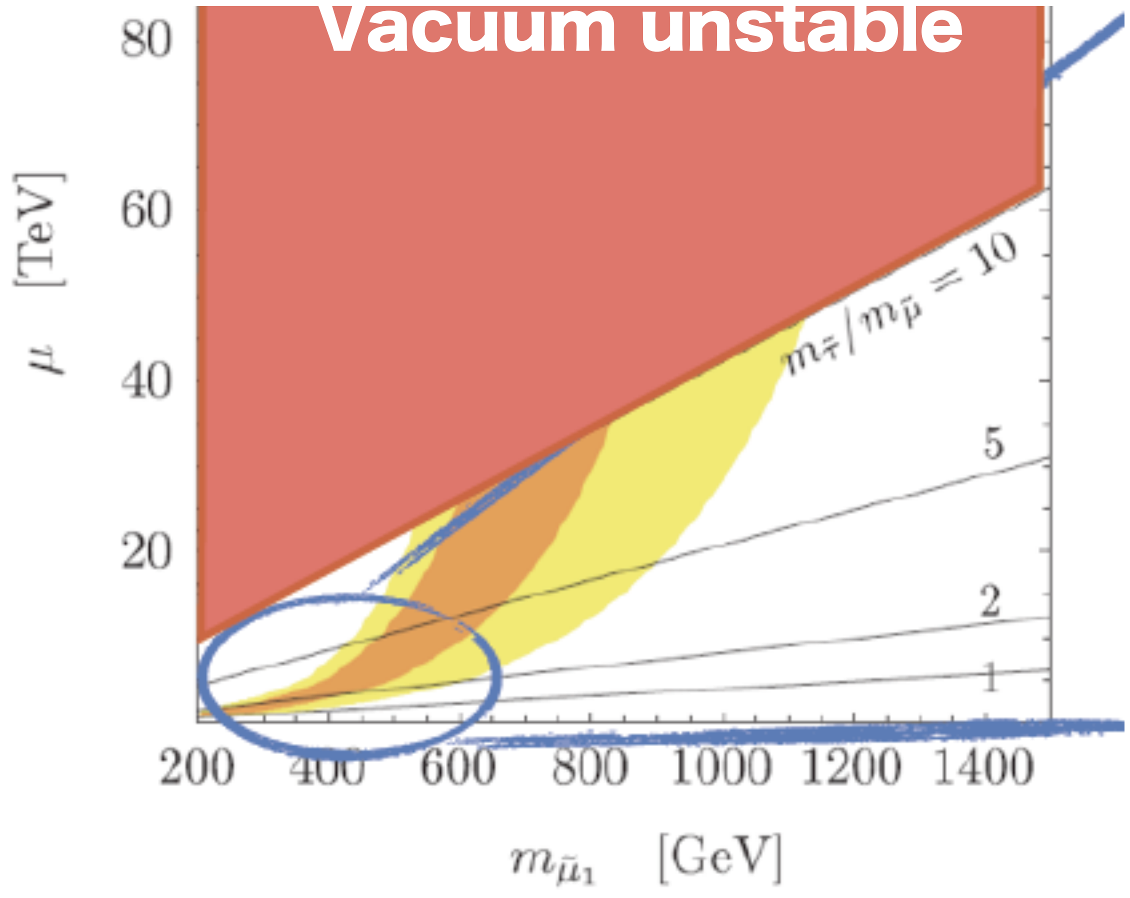
$$m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$$

■ Non-universal slepton mass case $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$

- Vacuum stability bound is relaxed by heavy staus
- Smuon masses become O(1)TeV, and LHC/ILC can not probe

→ However we can probe the Bino contribution **indirectly**

- Generally, slepton mass matrix has **off-diagonal generation mixing components**
- Thanks for the super GIM mechanism, SUSY LFV/CPV problem is avoided in universal case



Non-universal slepton mass case $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$

- Vacuum stability bound is relaxed by heavy staus
- Smuon masses become O(1)TeV, and LHC/ILC can not probe

⇒ However we can probe the Bino contribution indirectly

- Generally, slepton mass matrix has off-diagonal generation mixing components
- Thanks for the super GIM mechanism, SUSY LFV/CPV problem is avoided in universal case

- On the other hand, **non-universality of slepton mass** cause large LFV/CPV generally

Non-universal slepton mass case $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$

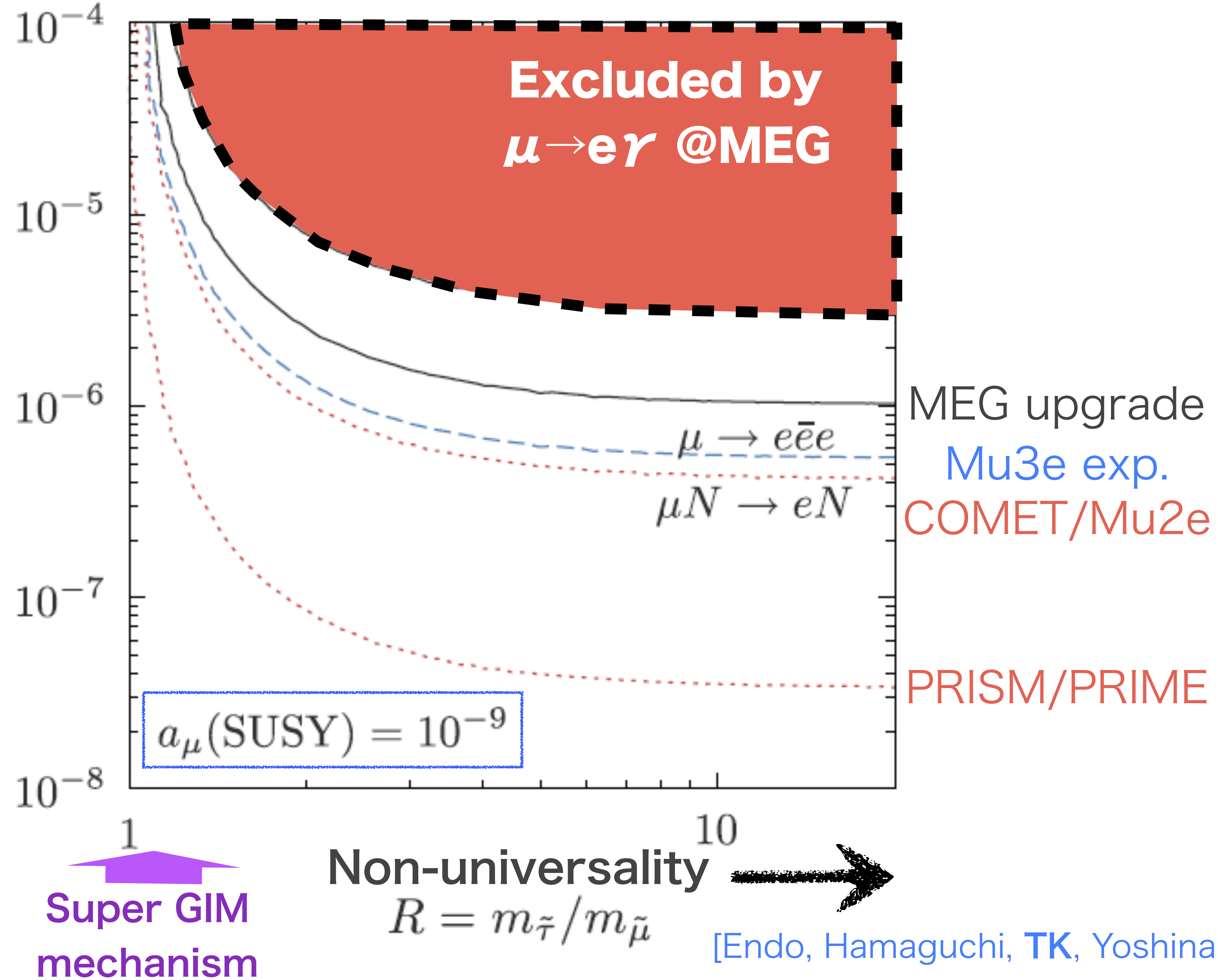
SUSY contribution **vs LFV ($\mu \to e\gamma$)**

flavor diagonal basis of SUSY breaking mass

Unitary matrix

off-diagonal component

charged lepton mass eigenstate basis



[Endo, Hamaguchi, **TK**, Yoshinaga]

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- Conclusion

■ Reconstructing Bino contributions

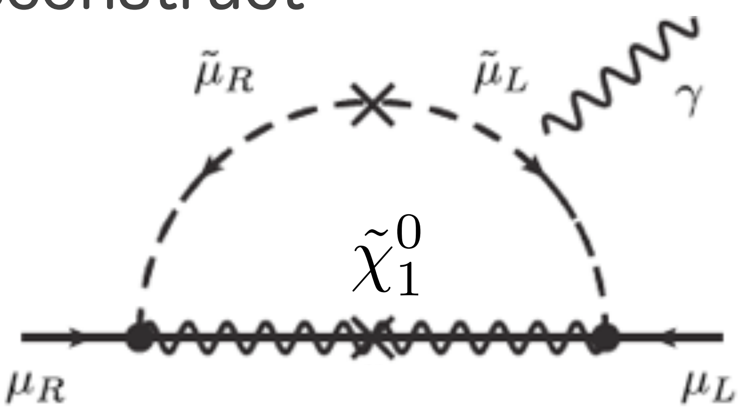
- If SUSY particles are discovered, it is possible to **reconstruct** the Bino(-like neutralino) contribution to the muon g-2 **at ILC** under some conditions

When we observe

$$\tilde{e}_1 \quad \tilde{e}_2 \quad \tilde{\mu}_1 \quad \tilde{\mu}_2 \quad \tilde{\tau}_1 \quad \tilde{\tau}_2 \quad \tilde{\chi}_1^0 \quad \tilde{\chi}_1^{\pm}$$

We assume absent signals of charginos

then we can reconstruct



reconstructed SUSY contribution $a_\mu^{\rm ILC}$

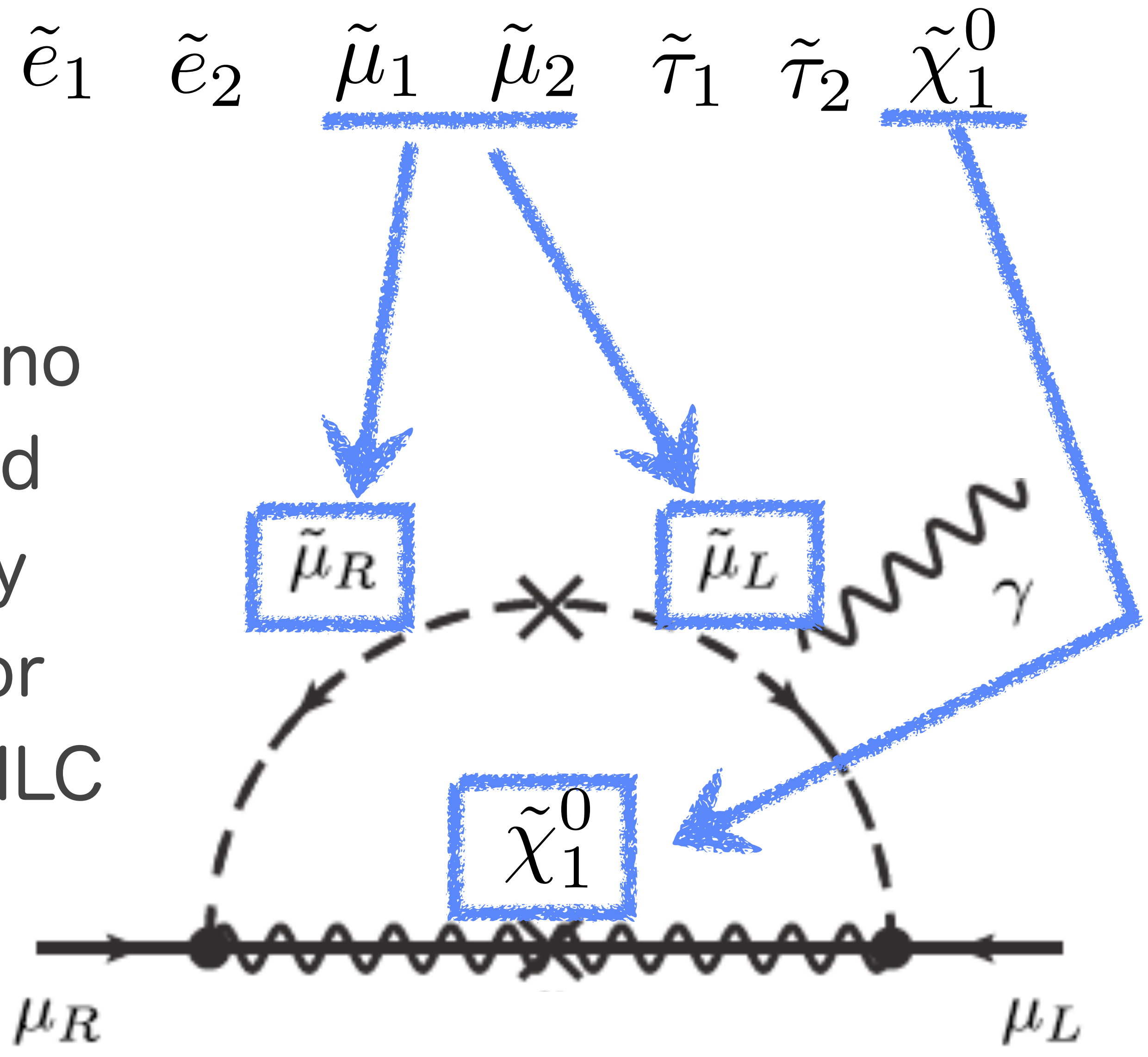
$\pm\delta a_\mu^{\rm ILC}$ uncertainty

$\pm\delta a_\mu^{\rm SUSY,th}$ other SUSY loop contributions

[Endo, Hamaguchi, Iwamoto, **TK**, Moroi]

■ Reconstructing Bino contributions

Reconstruction method <<Overview>>



Smuon and neutralino masses are mesured **very precisely** by studying endpoint or threshold scans at ILC

[Endo, Hamaguchi, Iwamoto, **TK**, Moroi]

Reconstructing Bino contributions

Reconstruction method <<Overview>>

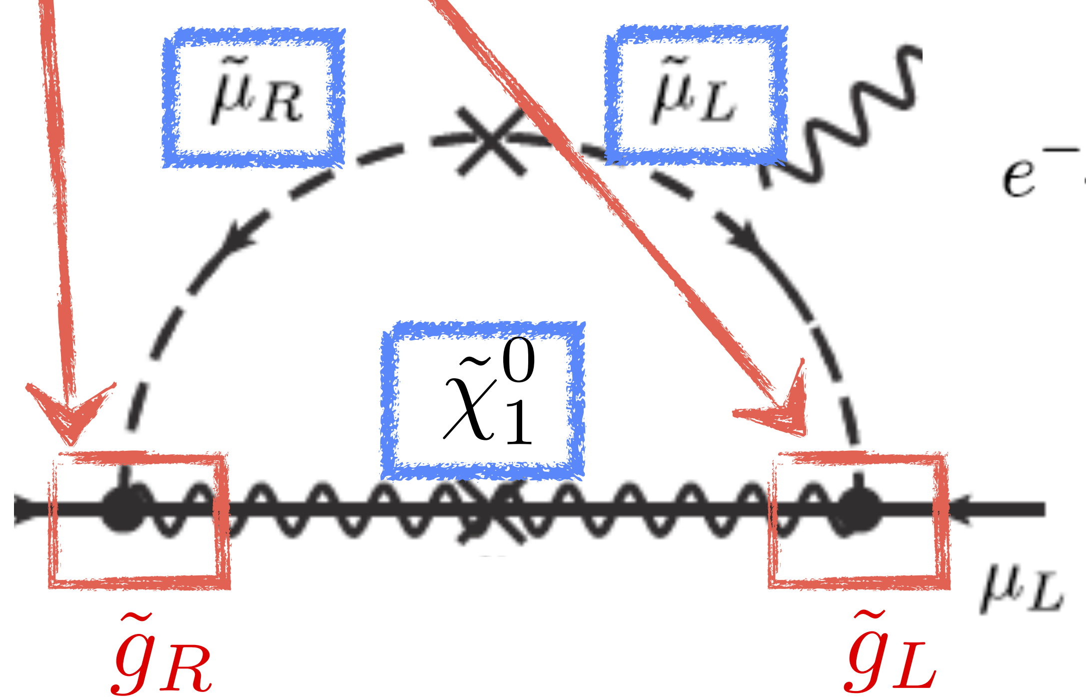
$\tilde{e}_1 \quad \tilde{e}_2 \quad \tilde{\mu}_1 \quad \tilde{\mu}_2 \quad \tilde{\tau}_1 \quad \tilde{\tau}_2 \quad \tilde{\chi}_1^0$

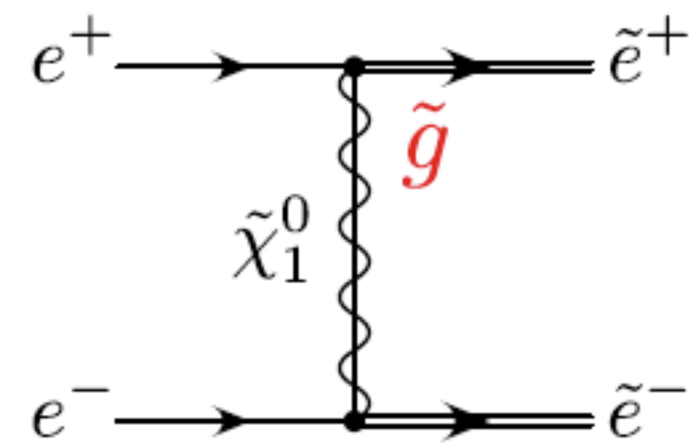
$\sigma(e^+e^- \to \tilde{e}\tilde{e})$

gaugino coupling

$\tilde{g}_L \quad \tilde{g}_R$

The gaugino couplings can be determined directly at ILC in O(1) % accuracy





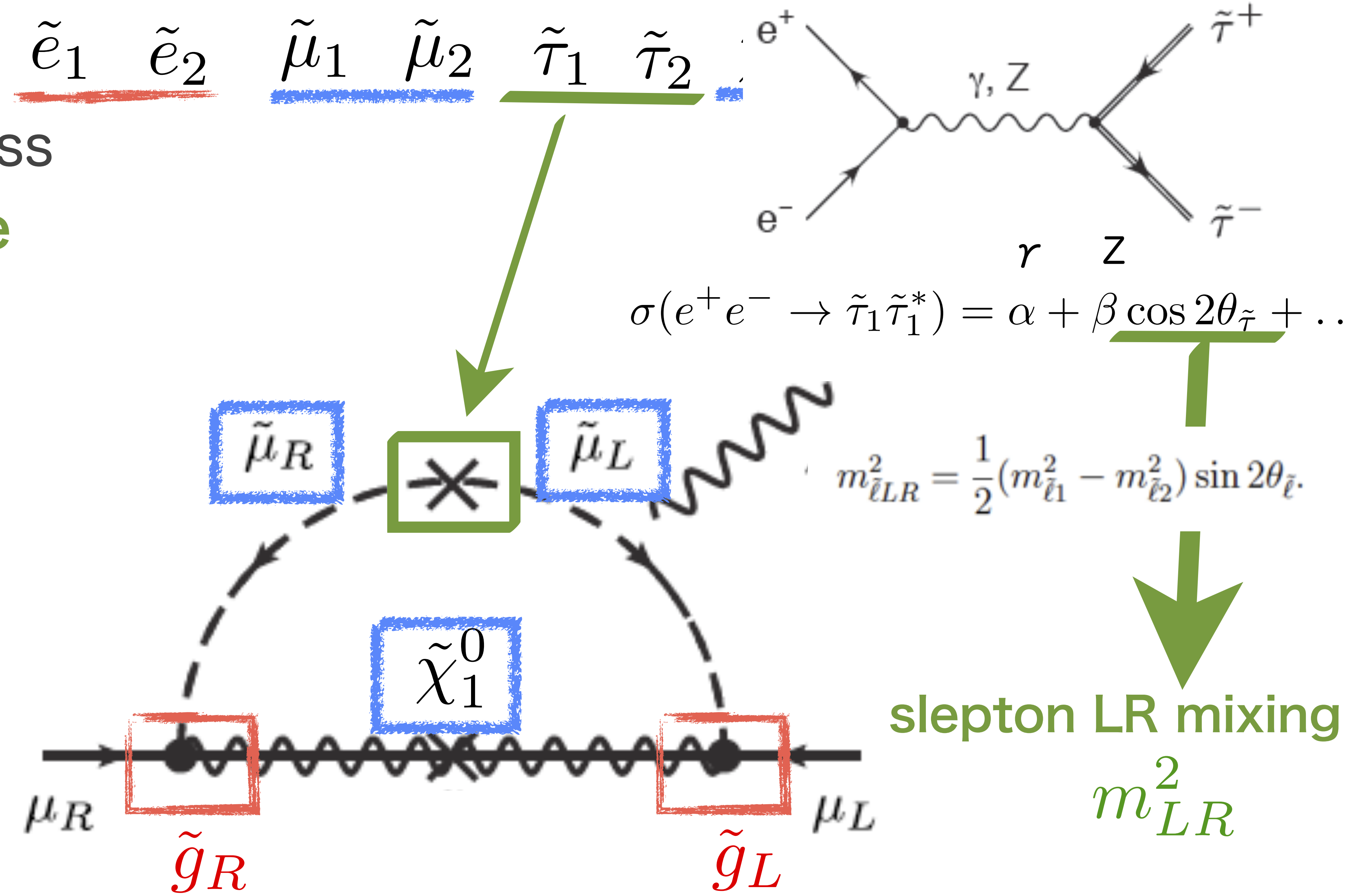
[Endo, Hamaguchi, Iwamoto, **TK**, Moroi]

■ Reconstructing Bino contributions

Reconstruction method <<Overview>>

Stau production cross section depends **the mixing angle** via s-channel Z exchange

Then, **slepton LR mixing** can be determined at ILC



[Endo, Hamaguchi, Iwamoto, **TK**, Moroi]

Reconstructing Bino contributions

Our sample point [Endo, Hamaguchi, Iwamoto, **TK**, Moroi]

Parameters	$m_{\tilde{\ell}1}$	$m_{\tilde{\ell}2}$	$m_{\tilde{\tau}1}$	$m_{\tilde{\tau}2}$	$m_{\tilde{\chi}_1^0}$	$\sin\theta_{\tilde{\mu}}$	$\sin\theta_{\tilde{\tau}}$	$a_\mu^{(\mathrm{ILC})}$
Values	126	200	108	210	90	0.027	0.36	2.6×10^{-9}

$(\tilde{\ell} = \tilde{e}, \tilde{\mu})$

* other SUSY particles [Wino,Higgsino,colored] are decoupled.

reconstructed SUSY contribution

uncertainty

$$\delta a_\mu^{(\mathrm{ILC})} / a_\mu^{(\mathrm{ILC})} \simeq 13\,\%$$

other SUSY loop contributions $\delta a_\mu^{(\mathrm{SUSY,th})} / a_\mu^{(\mathrm{ILC})} \simeq 4\%(1\%)$ Wino, Higgsino mass > 1TeV(1.5TeV)

- We find that **the uncertainty is dominated by determination of slepton LR mixing**

■ Conclusion

- At **large μ** and large $\tan\beta$ regions in SUSY models, **the Bino contribution** to the muon g-2 becomes sizable and can **solve the muon g-2 anomaly**. But the Bino contribution is constrained by **the vacuum stability** of staus.

Universal case $m_{\tilde{\mu}} \sim m_{\tilde{\tau}}$

Vacuum stability of staus severely constrains the Bino contribution

→ $m_{\tilde{\mu}} \lesssim 330\ (460)\mathrm{GeV}$ → **Detectable at LHC/ILC**

Non-universal case $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$

Vacuum stability is relaxed, and $m_{\tilde{\mu}}$ can become $O(1)\mathrm{TeV}$

→ But **too large LFV/EDM** are predicted

LHC/ILC and LFV/EDM search can complementarily probe the Bino contribution!

Conclusion

- At **large μ** and large $\tan\beta$ regions in SUSY models, **the Bino contribution** to the muon g-2 becomes sizable and can **solve the muon g-2 anomaly**. But the Bino contribution is constrained by **the vacuum stability** of staus.

- LHC/ILC and LFV/EDM search can complementarily probe the Bino contribution!

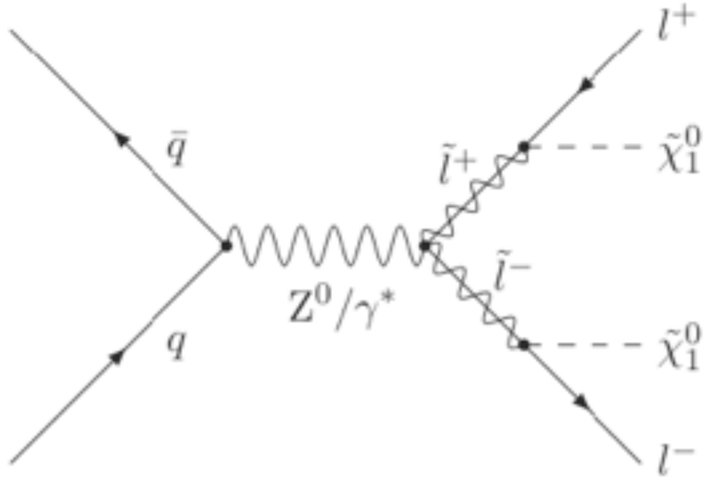
- **It is possible to reconstruct the Bino contribution by ILC, if all the sleptons are measured.**

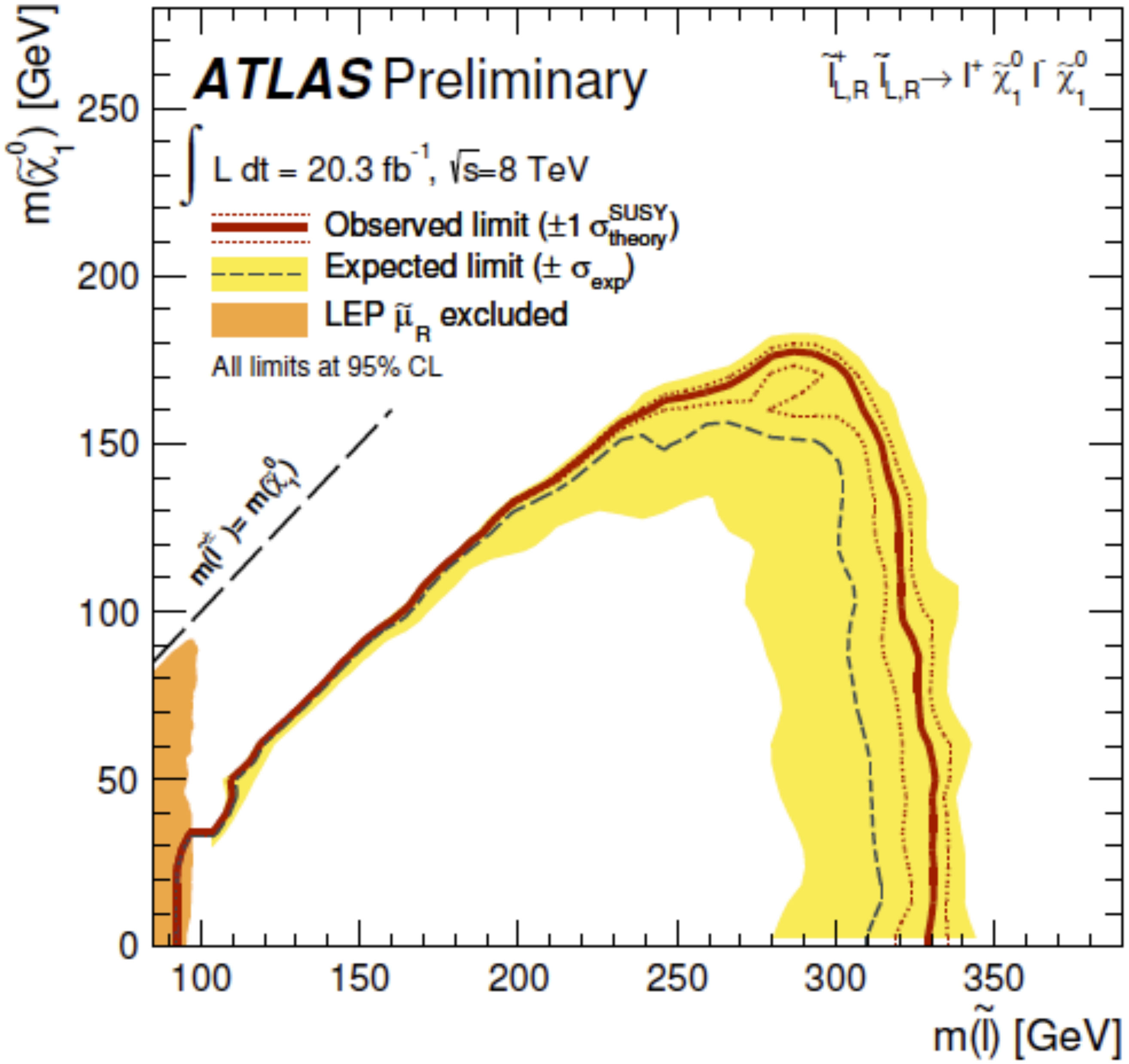
$$\delta a_\mu^{(\mathrm{ILC})} / a_\mu^{(\mathrm{ILC})} \simeq 13\,\%$$ at our model point

- The uncertainty is dominated by smuon left-right mixing

Backup slide

Result of dilepton search (ATLAS)





[ATLAS-CONF-2013-049]

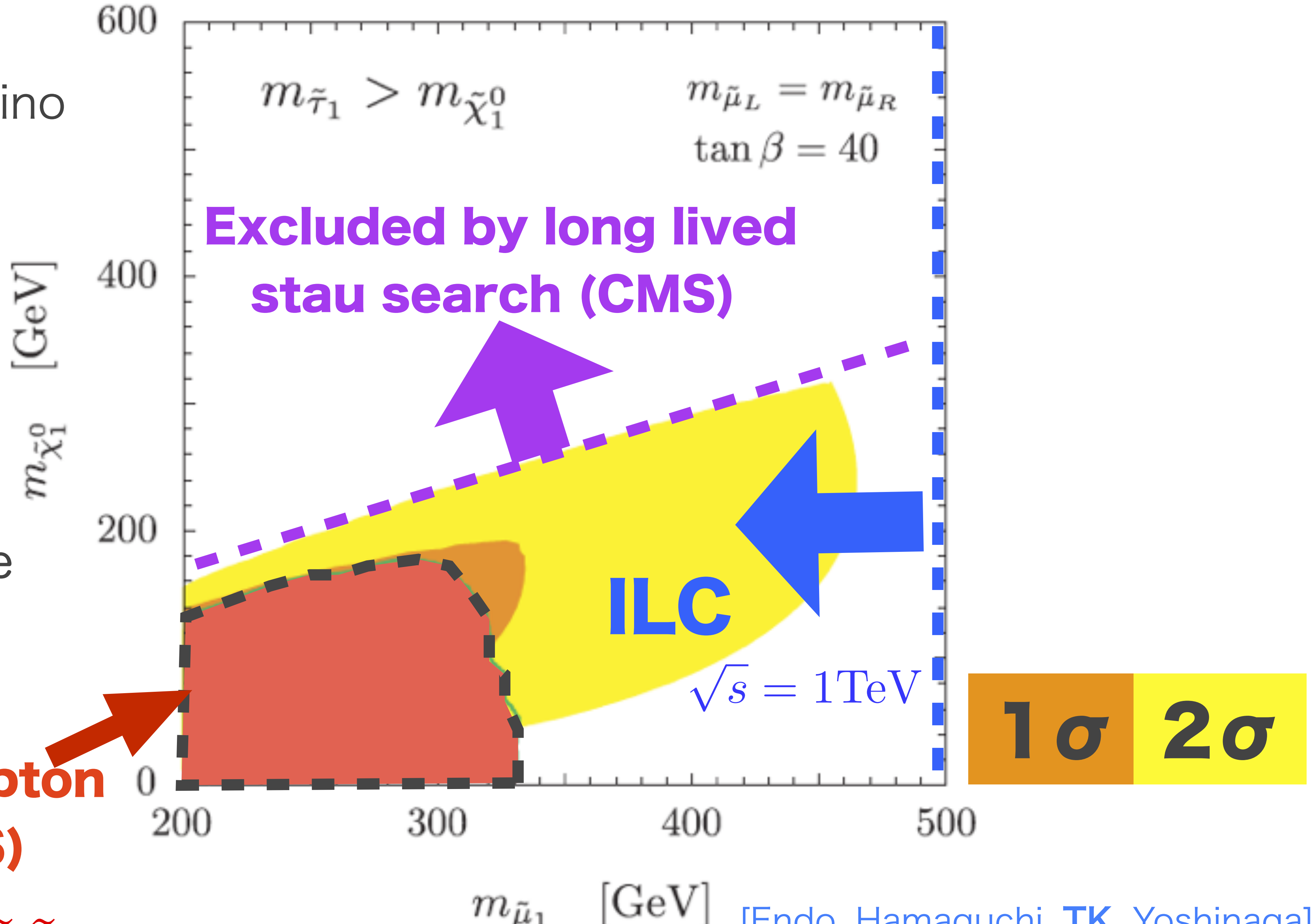
■ Universal slepton mass case $m_{\tilde{\mu}} = m_{\tilde{\tau}}$

SUSY contribution **vs current LHC bound**

LSP: Bino-like neutralino

NLSP: stau

μ : maximize under the Vacuum condition



$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}\tilde{\chi}$

[Endo, Hamaguchi, **TK**, Yoshinaga]

■ Non-universal slepton mass case $m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$

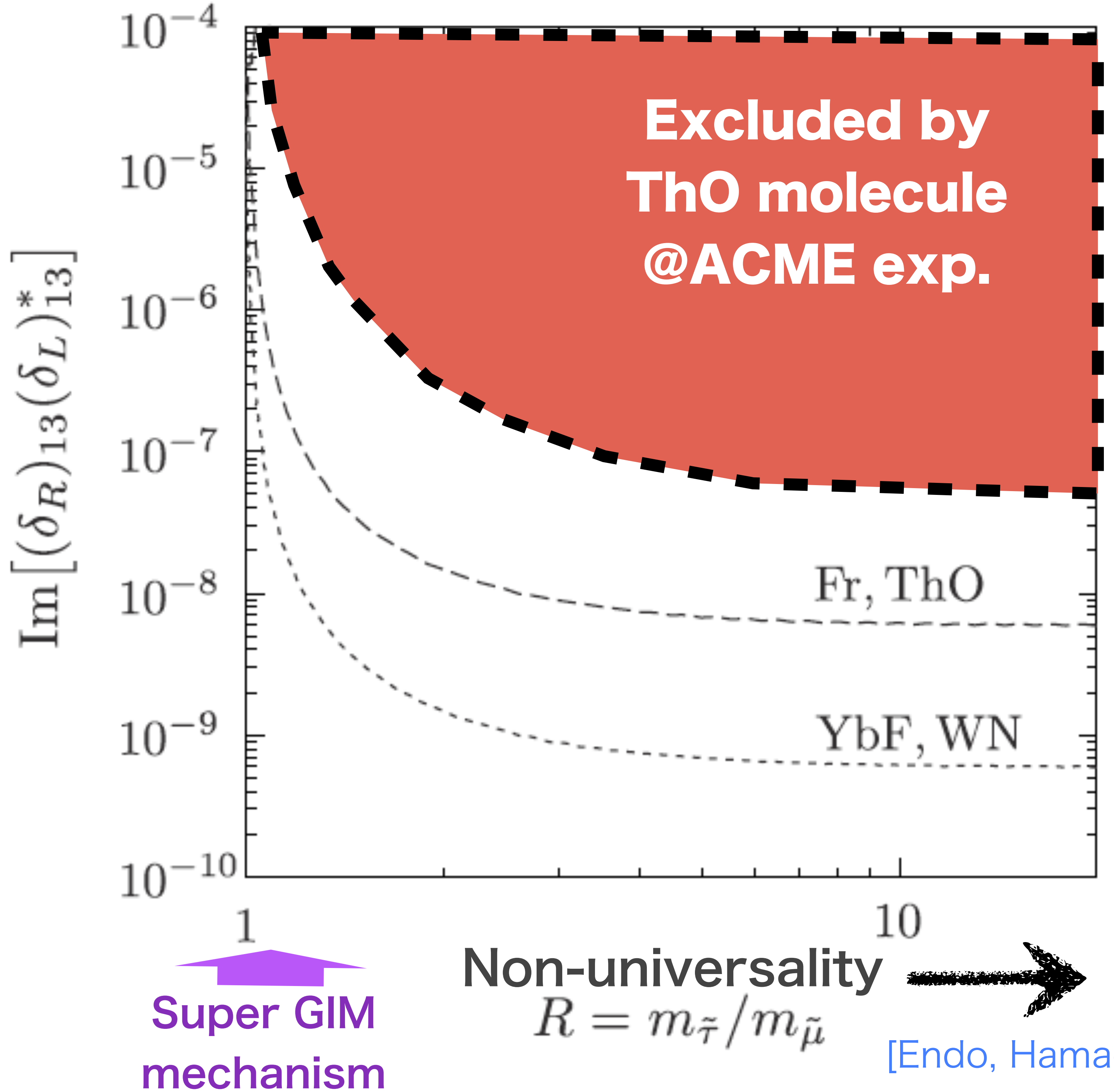
SUSY contribution **vs electron EDM**

flavor diagonal basis of SUSY breaking mass

Unitary matrix

off-diagonal component

charged lepton mass eigenstate basis



[Endo, Hamaguchi, **TK**, Yoshinaga]

Electroweak precision

[Cho, Hagiwara, Matsumoto, Nomura, JHEP 1111 (2011) 068]