Upper bound on the smuon mass from vacuum stability in the light of muon g−2 anomaly

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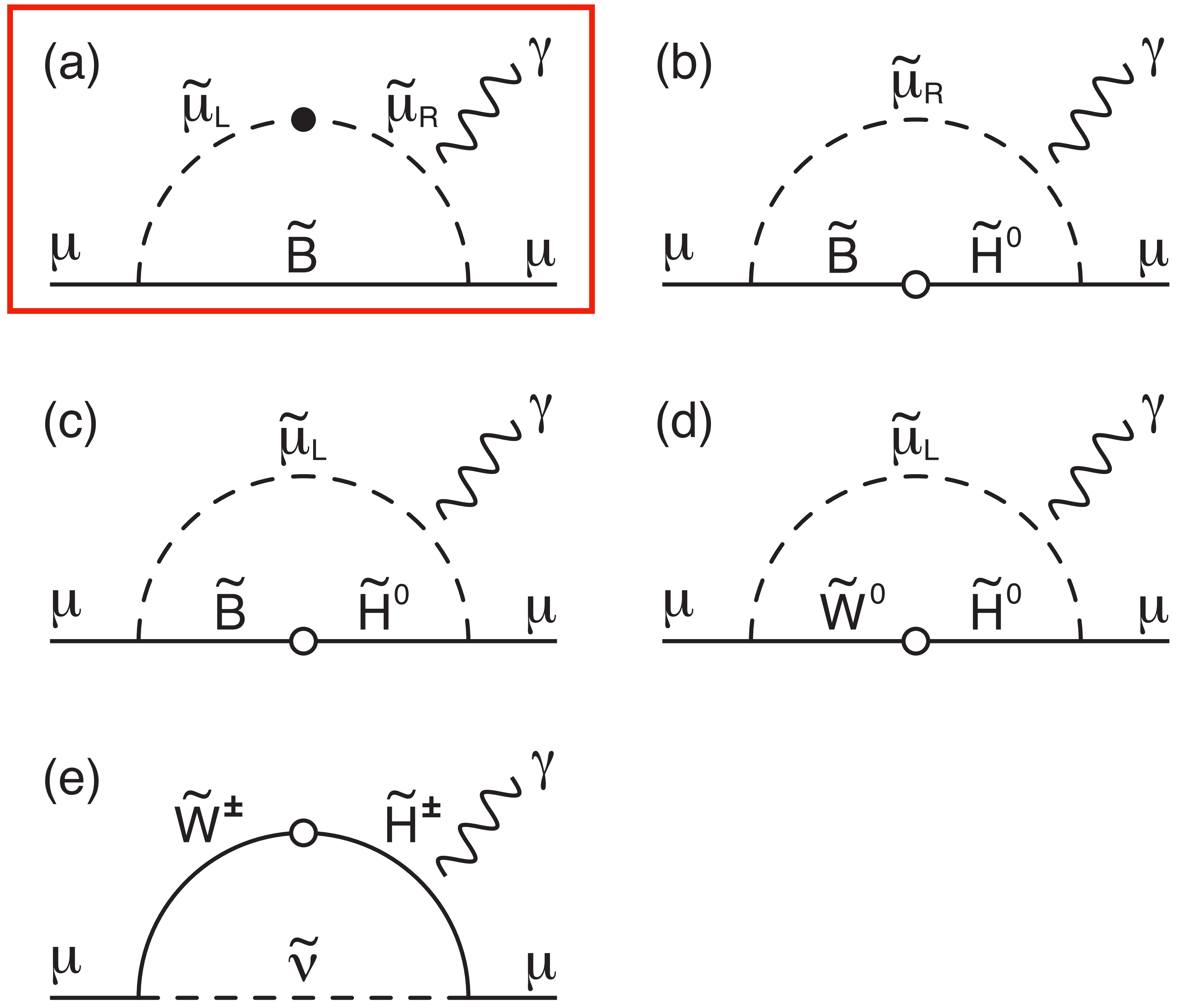
PPC 2022 (6/7) @ St. Louis

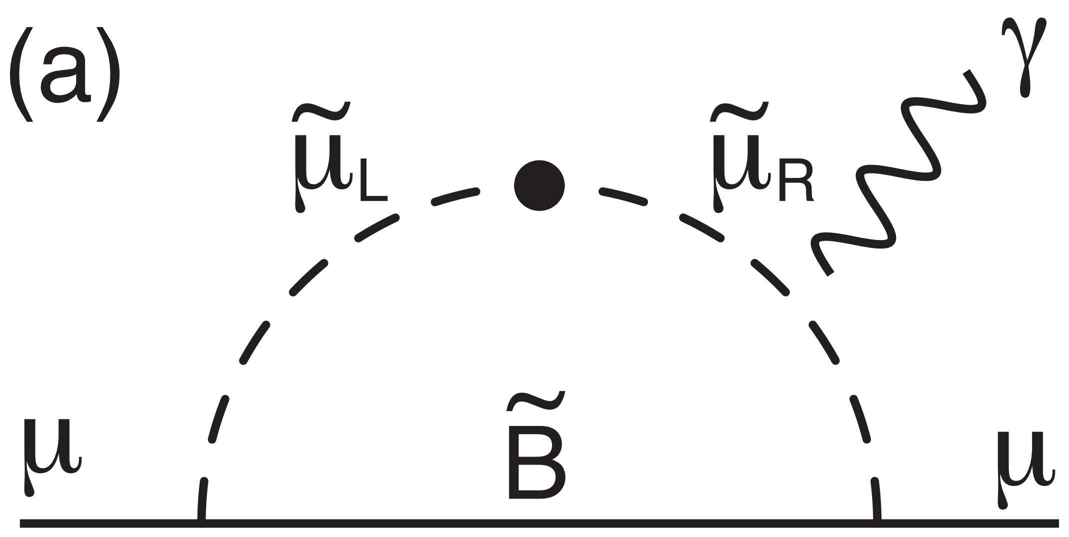
MSSM and muon $g-2$

- Muon $g-2$ anomaly in previous / on-going experiments
  - SM prediction $a_\mu^{\rm SM} = (11\,659\,181.0 \pm 4.3) \times 10^{-10}$ T. Aoyama [2006.04822]
  - BNL + Fermilab 2021 $a_\mu^{\rm BNL+FNAL} = (11\,659\,206.1 \pm 4.1) \times 10^{-10}$ Muon $g-2$ collaboration [2104.03281]
  - Combined $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$, 4.2σ anomaly
- MSSM can resolve this anomaly if its contribution is enhanced with
  - Light sleptons
  - Light EWinos
  - Sizable $\tan\beta$

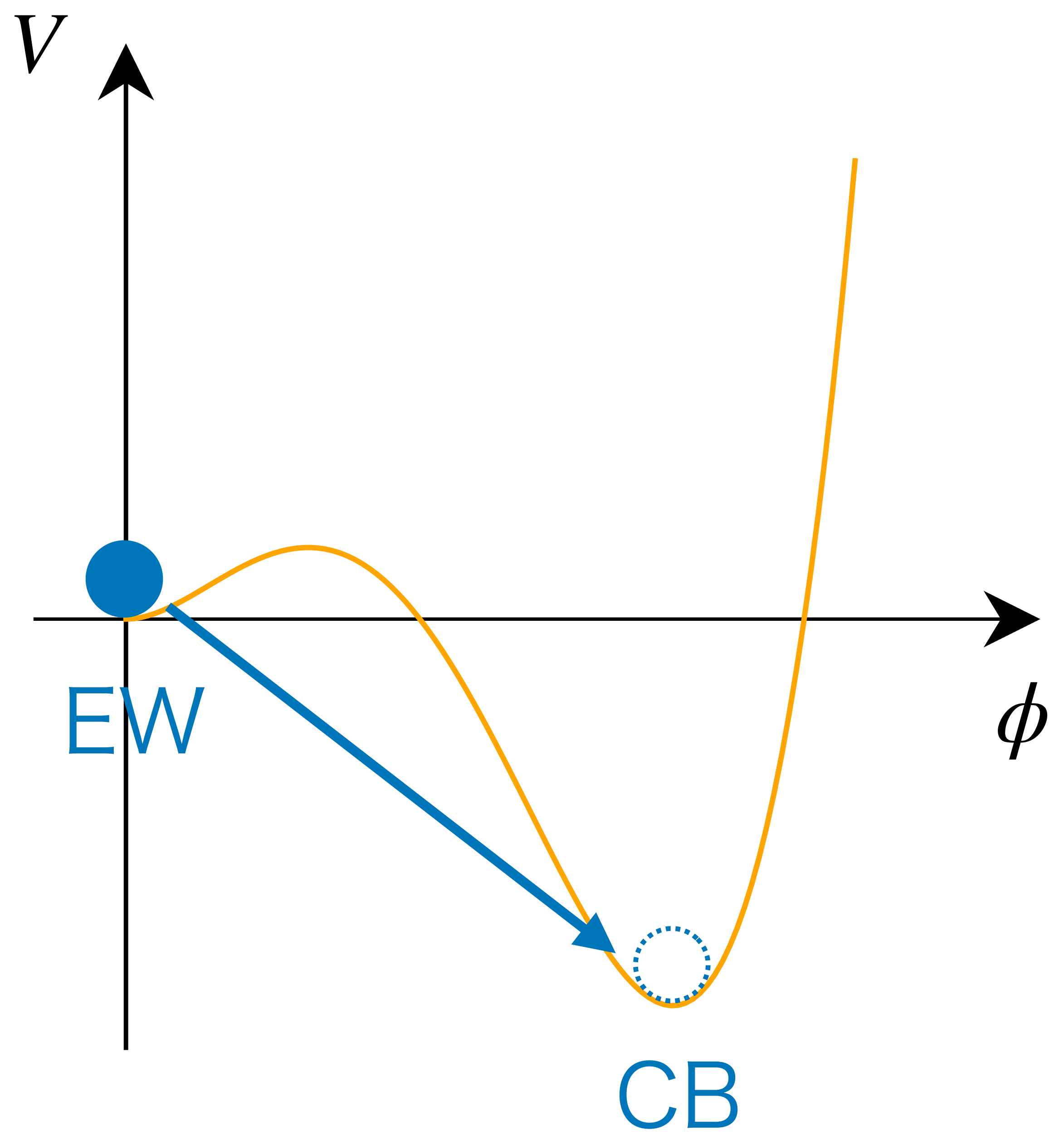


Relation to the EW vacuum stability

- Diagram (a) is also enhanced by large $|\mu|$
  - $a_\mu \simeq \frac{\alpha_Y}{4\pi} \frac{m_\mu^2 M_1 \mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2} \tan\beta \cdot f_N\left(\frac{m_{\tilde{\mu}_L}^2}{M_1^2}, \frac{m_{\tilde{\mu}_R}^2}{M_1^2}\right)$



- Hierarchy $|\mu| \gg m_{\tilde{\mu}}$ may generate a charge breaking minimum
  - $V = V_2 + V_3 + V_4$
  - $V_3 \supset -TH^\dagger \tilde{\ell}_L \tilde{\mu}_R^\dagger$ with $T \simeq Y_\ell \mu \tan\beta$



- Larger $m_{\tilde{\mu}}$ → Need larger μ to explain muon $g-2$

  → More unstable EW vac
  - Stability of the EW vacuum puts an upper bound on $m_{\tilde{\mu}}$ for models that resolve muon $g-2$ anomaly

Master formula of decay rate

$$\gamma = Ae^{-\mathscr{B}}$$

Coleman '77

$\mathscr{B}$: Bounce action (LO part)

A : NLO part

mass dimension 4

can be calculated with, for example,

CosmoTransitions C. L. Wainwright [1109.4189]

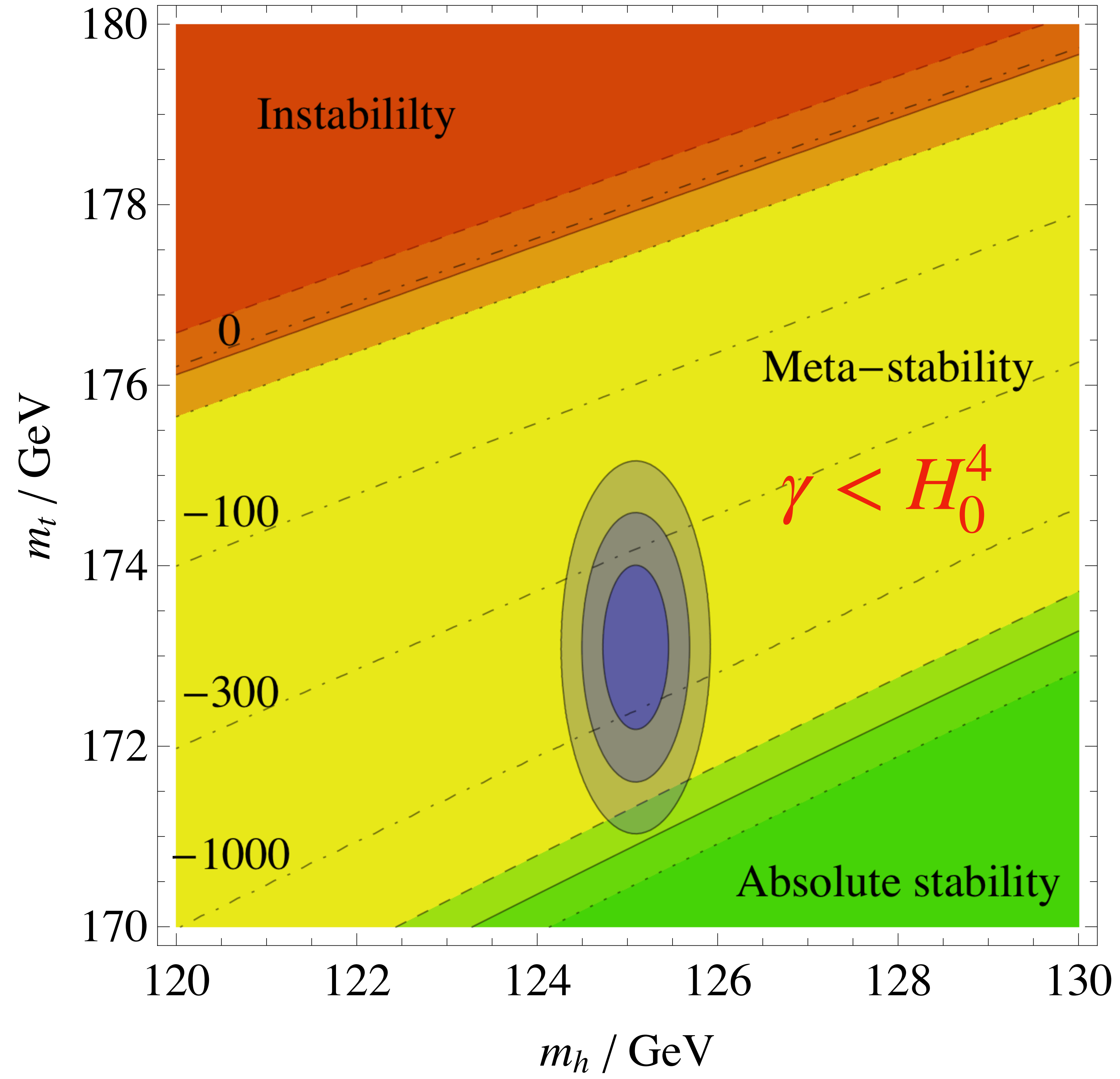
Gradient Flow SC+ [1906.10829]

- Evaluation of A is more involved but important

Recent developments

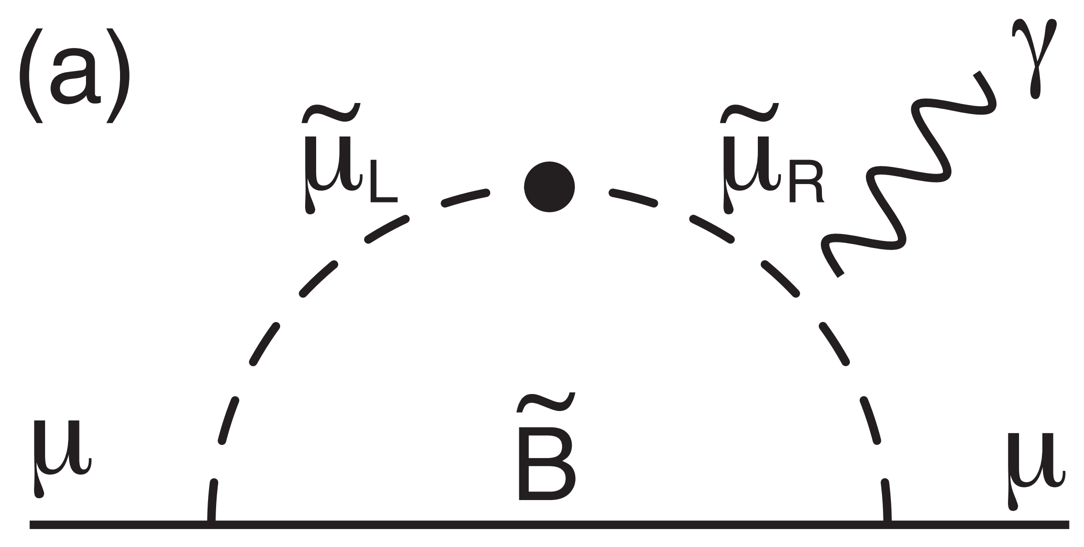
- Single-field bounce
  - General gauge theory
    Endo, Moroi, Nojiri, & Shoji [1703.09304], [1704.03492]
  - Application to the SM (and beyond)
    Isidori, Ridolfi & Strumia [hep-ph/0104016]
    Andreassen, Frost & Schwartz [1707.08124]
    SC, Moroi & Shoji [1707.09301], [1803.03902]
- Multi-field bounce
  - General gauge theory
    SC, Moroi & Shoji [2007.14124]
  - Application to the MSSM
    SC, Moroi & Shoji [2203.08062]

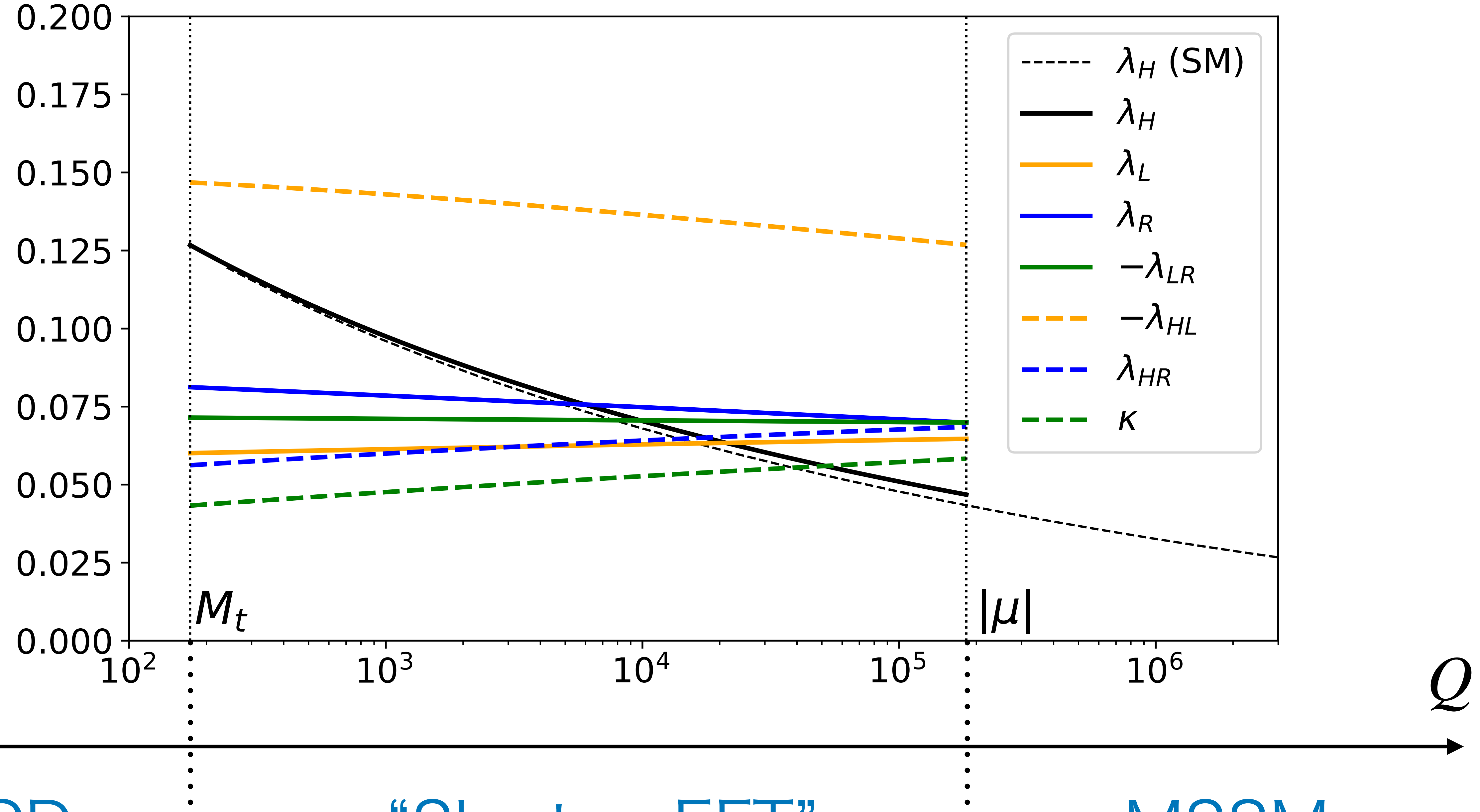
NEW



Model setup

- 2 hierarchical scales of the MSSM particles
  - EW scale M_t : smuon $\tilde{\mu}$, bino $\tilde{B}$
  - SUSY scale $|\mu|$: Other MSSM particles
- EFT analysis

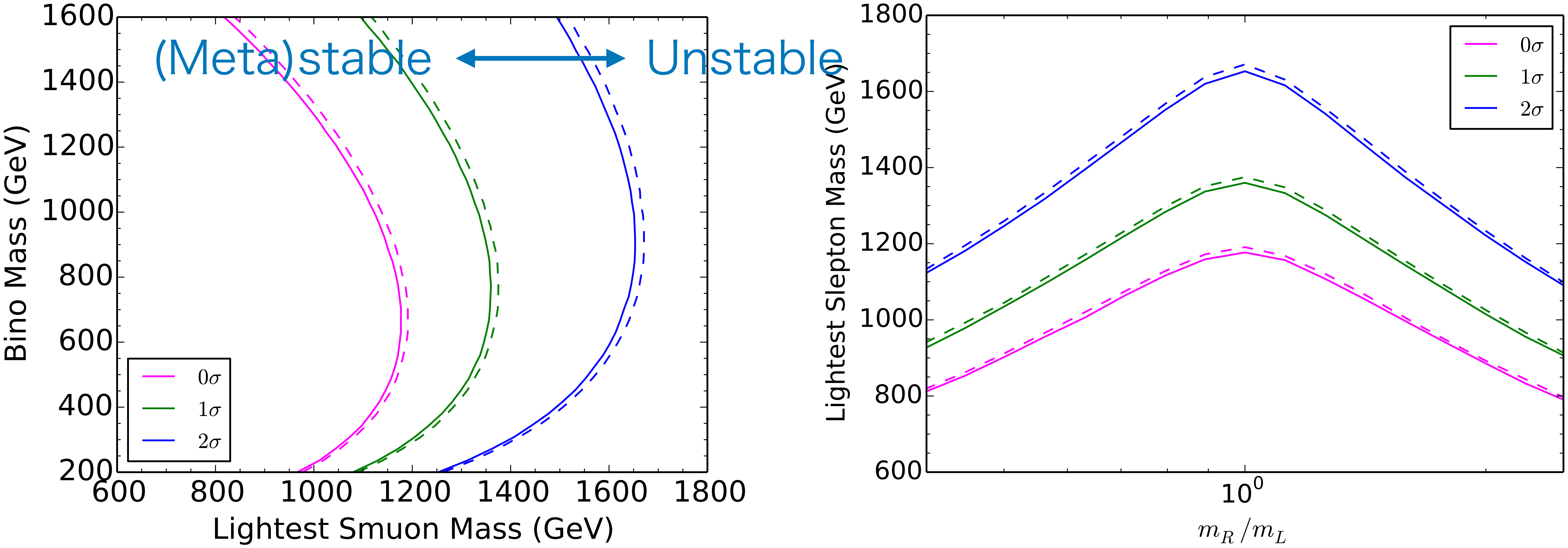




QED+QCD "Slepton EFT" MSSM

MSSM with light smuons

- $|\mu|$ is fixed to resolve the muon $g-2$ anomaly to the $0/1/2$-σ level



- Upper bound on the lightest smuon mass $\lesssim$ 1-2 TeV

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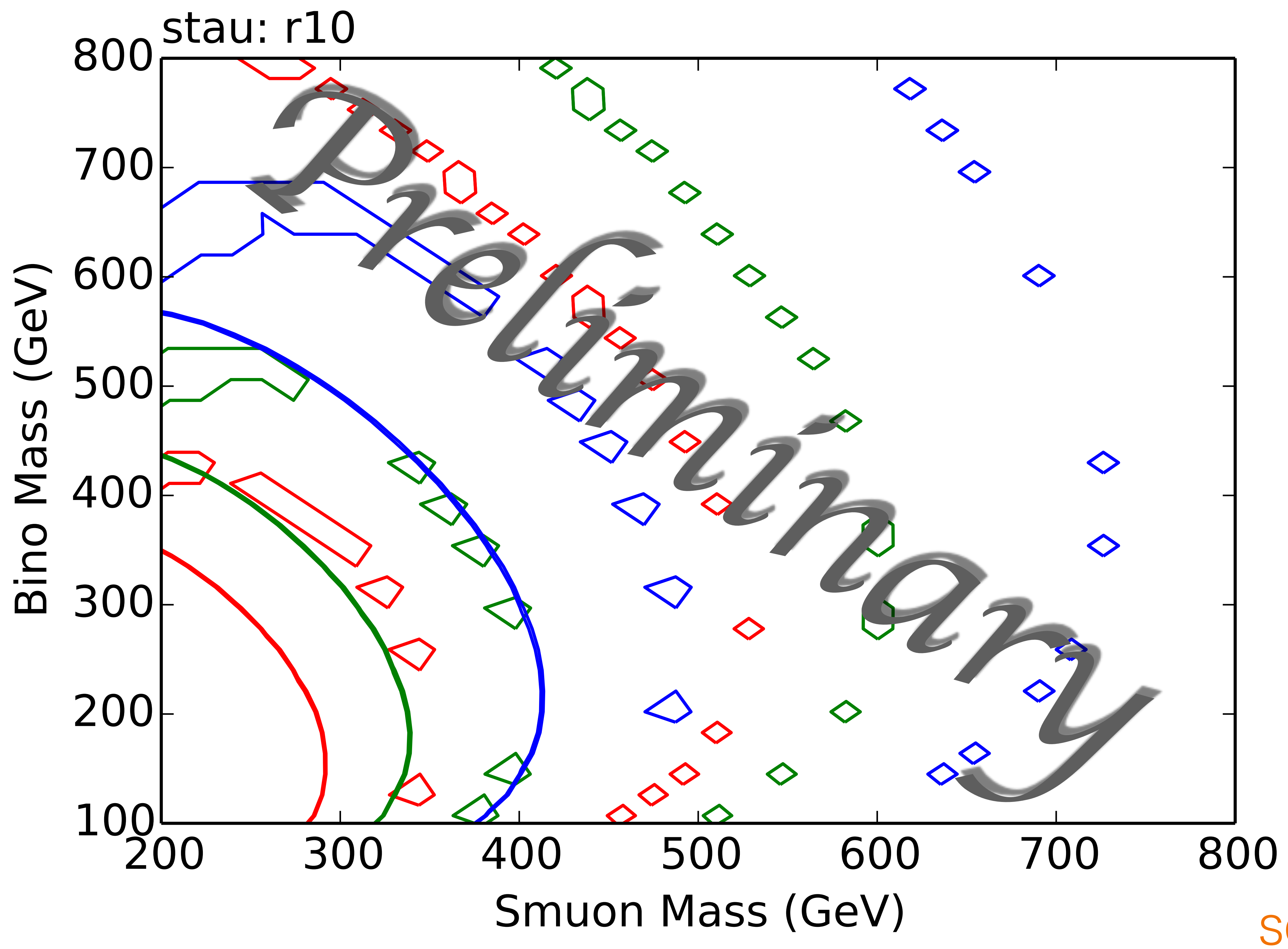
MSSM with light sleptons

- What if all 3 generations of sleptons are light?
  - Given that $T_\ell \simeq Y_\ell \mu \tan\beta$ & $Y_\tau \gg Y_\mu$, CCBs in the stau direction are more dangerous



SC, Moroi & Shoji [22xx.xxxxx]

Conclusion

- Hierarchy $|\mu| \gg m_{\tilde{\mu}}$, which is sometimes required to enhance the MSSM contribution to the muon $g-2$, destabilizes the EW vacuum
  - The stability of the EW vacuum puts an upper bound on the smuon mass $m_{\tilde{\mu}}$

- Using recently-developed semi-analytic results, we evaluate the decay rate of the EW vacuum in the MSSM and obtain upper bounds
  - Upper bound on the lightest smuon mass $\lesssim 1\text{-}2\,\mathrm{TeV}$

Thanks!

Backup slides

Functional determinant I

- The decay rate γ is related to the Euclidean partition function

$$Z \equiv \langle \mathrm{FV} \,|\, e^{-HT} \,|\, \mathrm{FV} \rangle \simeq \int_{\phi(t_i)=\mathrm{FV}}^{\phi(t_f)=\mathrm{FV}} \mathscr{D}\phi \, e^{-S_E[\phi]} \propto \exp(i\gamma VT)$$

- The path integral is dominated by solutions of the EOM
  - The imaginary part comes from non-trivial solutions: “bounce”

$$\gamma = \frac{1}{VT} \mathrm{Im} \frac{\int_{1-\mathrm{bounce}} \mathscr{D}\Psi \, e^{-S_E}}{\int_{\mathrm{FV}} \mathscr{D}\Psi \, e^{-S_E}}$$

- Expansion of S_E around the bounce (FV) results in Gaussian integrals
  - $S_E[\bar{\phi} + \Psi] = S_E[\bar{\phi}] + \frac{1}{2} \int d^4x \, \Psi \mathscr{M} \Psi + \mathcal{O}(\Psi^3)$

$$\gamma = A e^{-\mathscr{B}} \; ; \; A = \frac{1}{VT} \left| \frac{\mathrm{Det} \; \mathscr{M}}{\mathrm{Det} \; \widehat{\mathscr{M}}} \right|^p$$

Functional determinant II

- Example: single real scalar field

$$S_E[\phi] = \int d^D x \left[\frac{1}{2} (\partial_\mu \phi)^2 + V(\phi) \right] \quad \Rightarrow \quad \mathscr{M} = -\partial^2 + \left. \frac{\delta^2 V}{\delta \phi^2} \right|_{\bar{\phi}}$$

$$\mathscr{M} = \bigoplus_{\ell=0}^{\infty} \left(\mathscr{M}_\ell \right)^{(\ell+1)^2} \quad ; \quad \mathscr{M}_\ell = -\left(\partial_r^2 + \frac{D-1}{r} \partial_r - \frac{\ell(\ell+2)}{r^2} \right) + \left. \frac{\delta^2 V}{\delta \phi^2} \right|_{\bar{\phi}}$$

- Gel’fand-Yaglom theorem

With Ψ_ℓ & $\widehat{\Psi}_\ell$ s.t. $\mathscr{M}_\ell \Psi_\ell = 0 \ ; \ \widehat{\mathscr{M}}_\ell \widehat{\Psi}_\ell = 0$,

$$\frac{\mathrm{Det}\, \mathscr{M}_\ell}{\mathrm{Det}\, \widehat{\mathscr{M}}_\ell} = \left(\frac{\Psi_\ell (r \to 0)}{\widehat{\Psi}_\ell (r \to 0)} \right)^{-1} \frac{\Psi_\ell (r \to \infty)}{\widehat{\Psi}_\ell (r \to \infty)}$$

Gel’fand+ '60, Kirsten+ '03, '04

M. Endo+ [1704,03492] for proof in this context

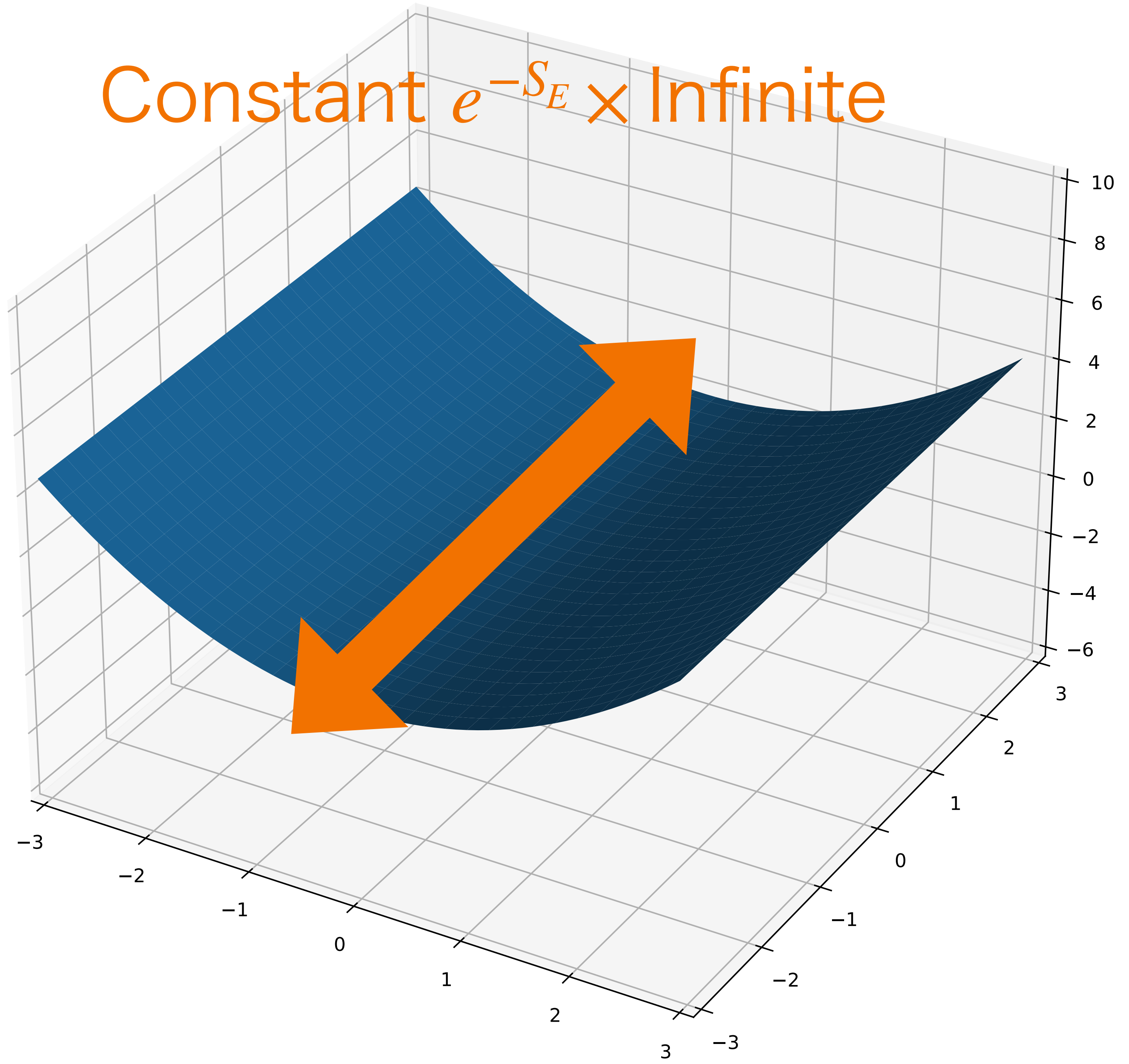
Next Task

Solve differential equation

$\mathscr{M}_\ell \Psi_\ell = 0$

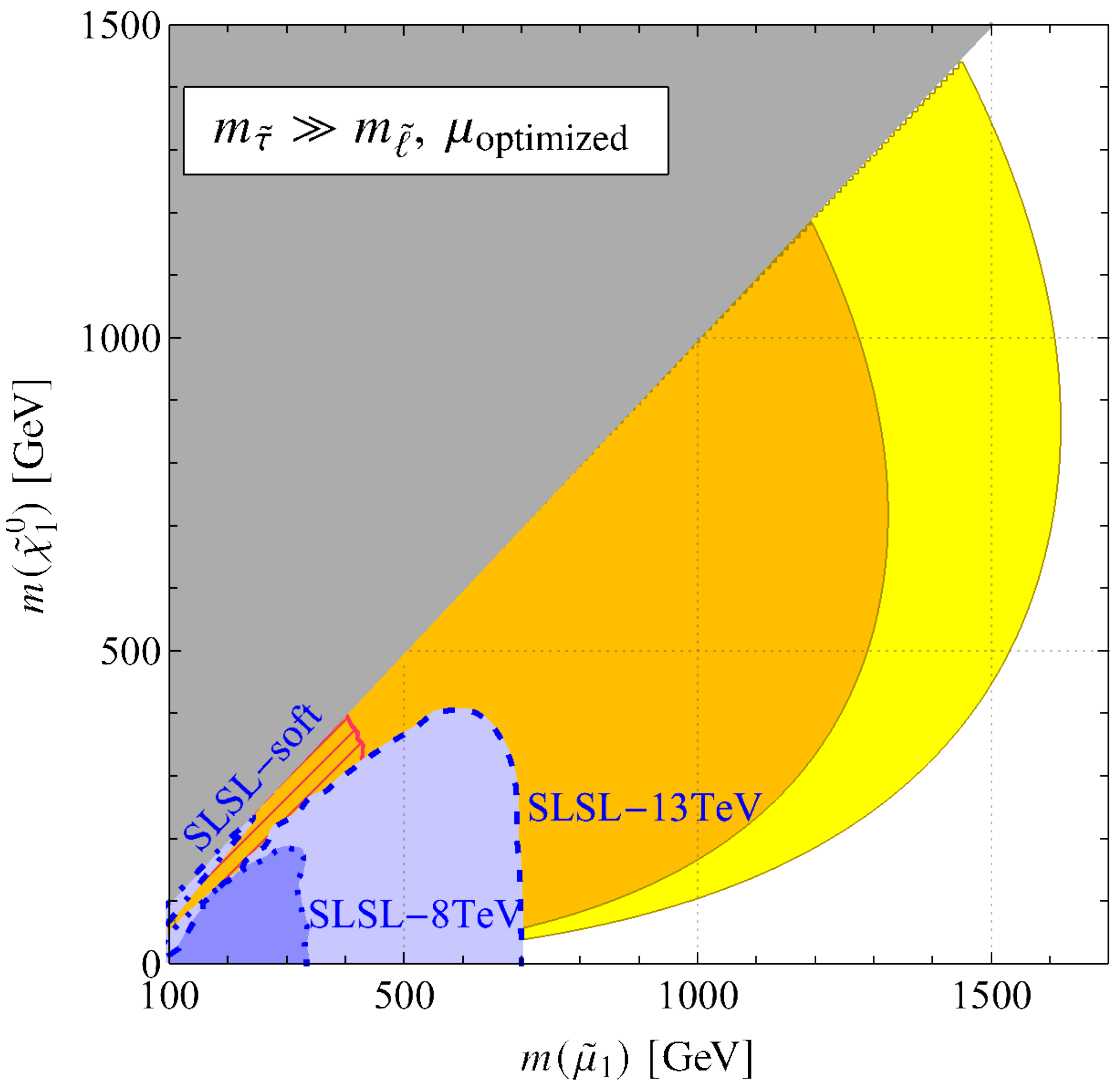
Zero mode

- $\mathrm{Det}\,\mathscr{M}_\ell = 0$ leads to divergence
  - equivalent to existence of zero mode $\mathscr{M}_\ell \Psi_\ell = 0$ & $\lim_{r\to\infty} \Psi(r) = 0$
  - implies existence of flat direction of Euclidean action
- Flat direction is often result of symmetry
  - Spacetime translation of bounce ($\ell = 1$ of h)
  - Classical dilatation ($\ell = 0$ of h)
  - Gauge symmetry ($\ell = 0$ of gauge field)

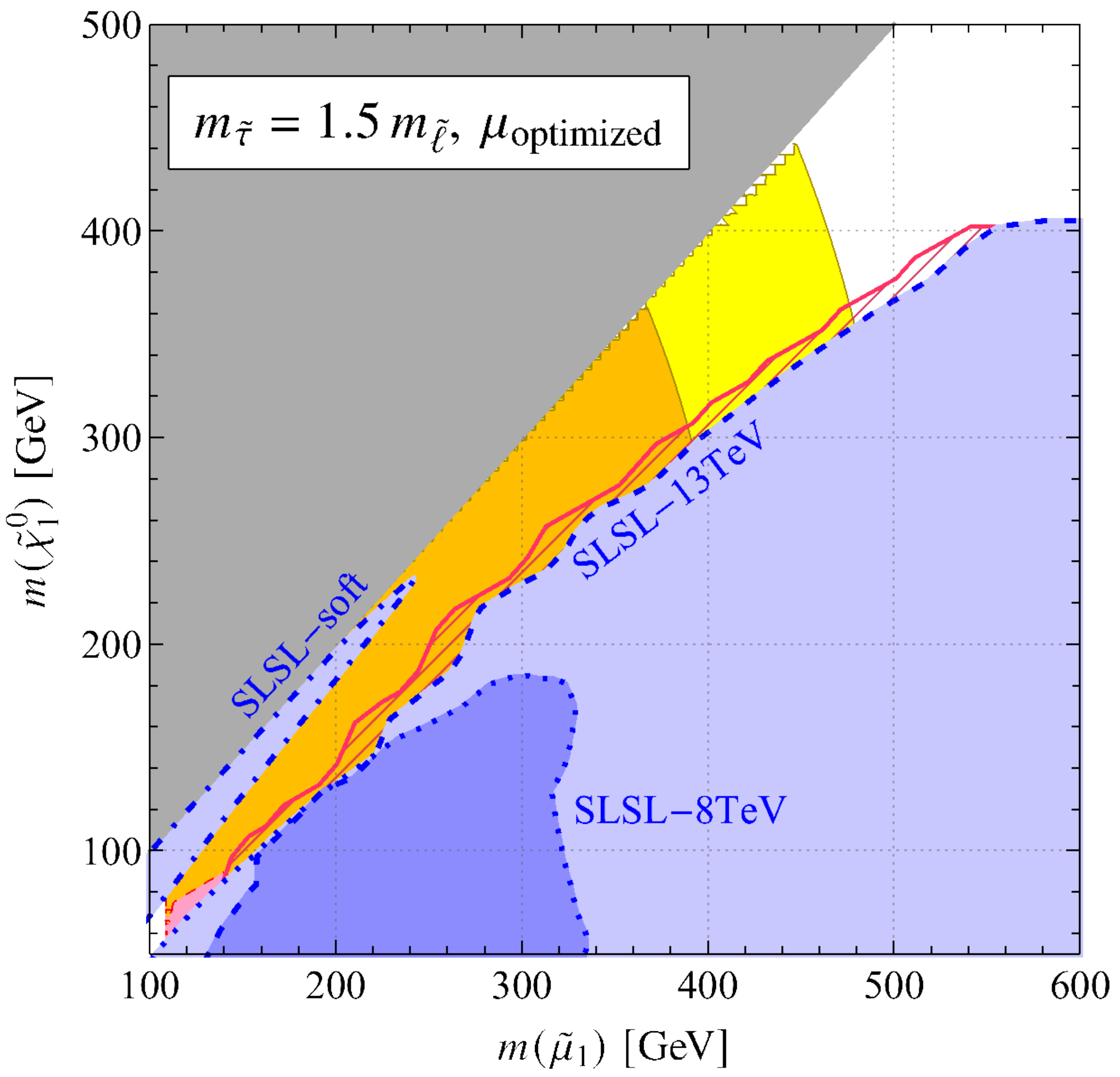


Collider constraints

M. Endo+ [2104.03217]



- Smuon only



- 3 generations