The Last Vestiges of Naturalness

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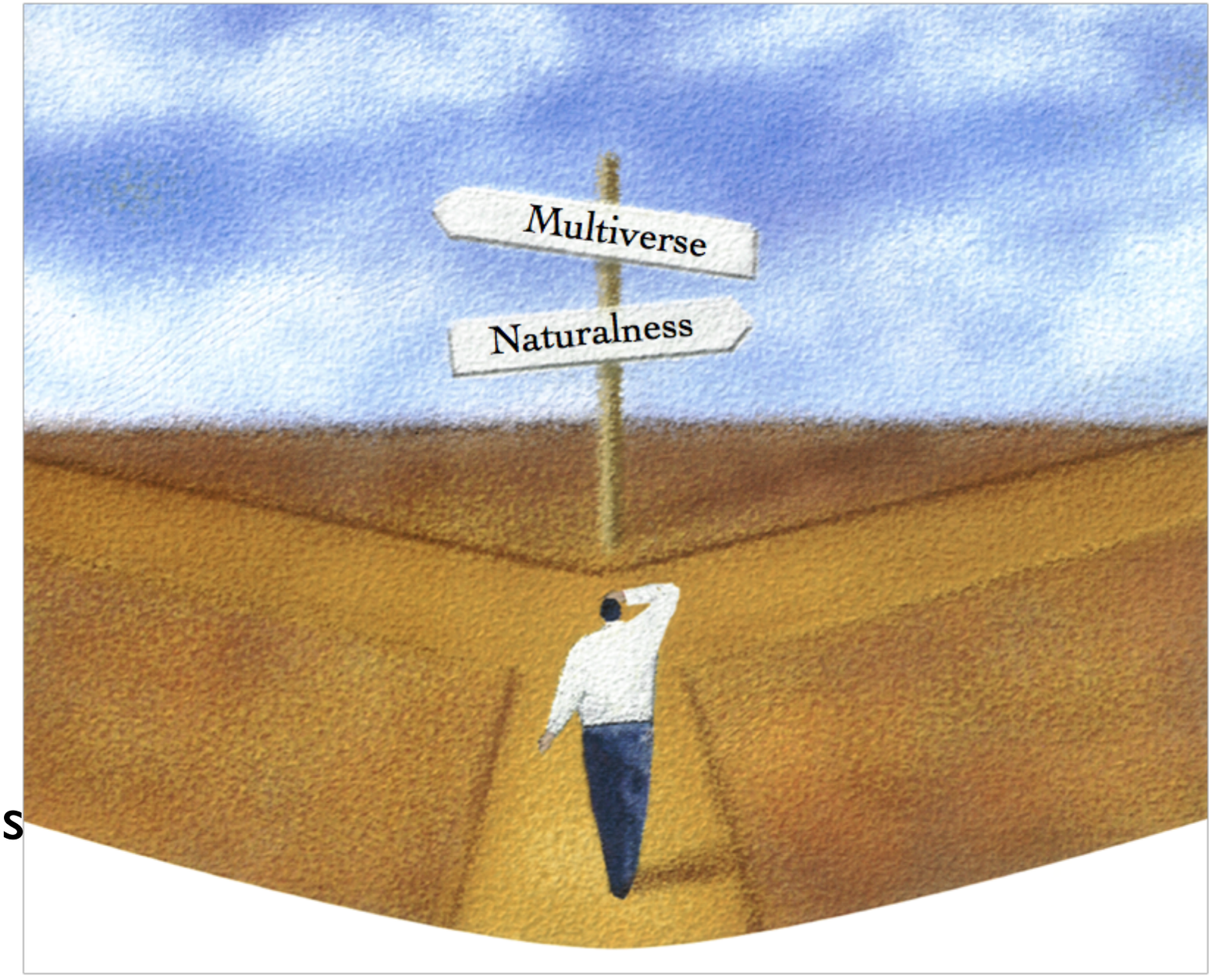
Stanford University

with Asimina Arvanitaki, Xinlu Huang, Ken Van Tilburg, Giovanni Villadoro
[arxiv:1309.xxxx]

Outline

- SUSY and Naturalness
- Fighting the LHC
  - Split Families
  - Baryonic RPV
  - Dirac Gauginos
- SUSY and Unnaturalness



SUSY and Naturalness:

higgs mass contributions

- tree level

$$m_h^2 = -2\left(m_{H_u}^2 + |\mu|^2\right.$$

- one-loop

$$\partial_t m_{H_u}^2 = \frac{6|y_t|^2}{(4\pi)^2}\left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2\right)$$

- two-loop

$$\partial_t m_{\tilde{t}}^2 = -\frac{8\alpha_s}{3\pi} M_3^2$$

SUSY and Naturalness:

higgs mass contributions

- tree level

$$5\% \times \left(\frac{\mu}{400\,\mathrm{GeV}}\right)^{-2}$$

- one-loop

$$5\% \times \left(\frac{m_{\tilde{t}}}{750\,\mathrm{GeV}}\right)^{-2}$$

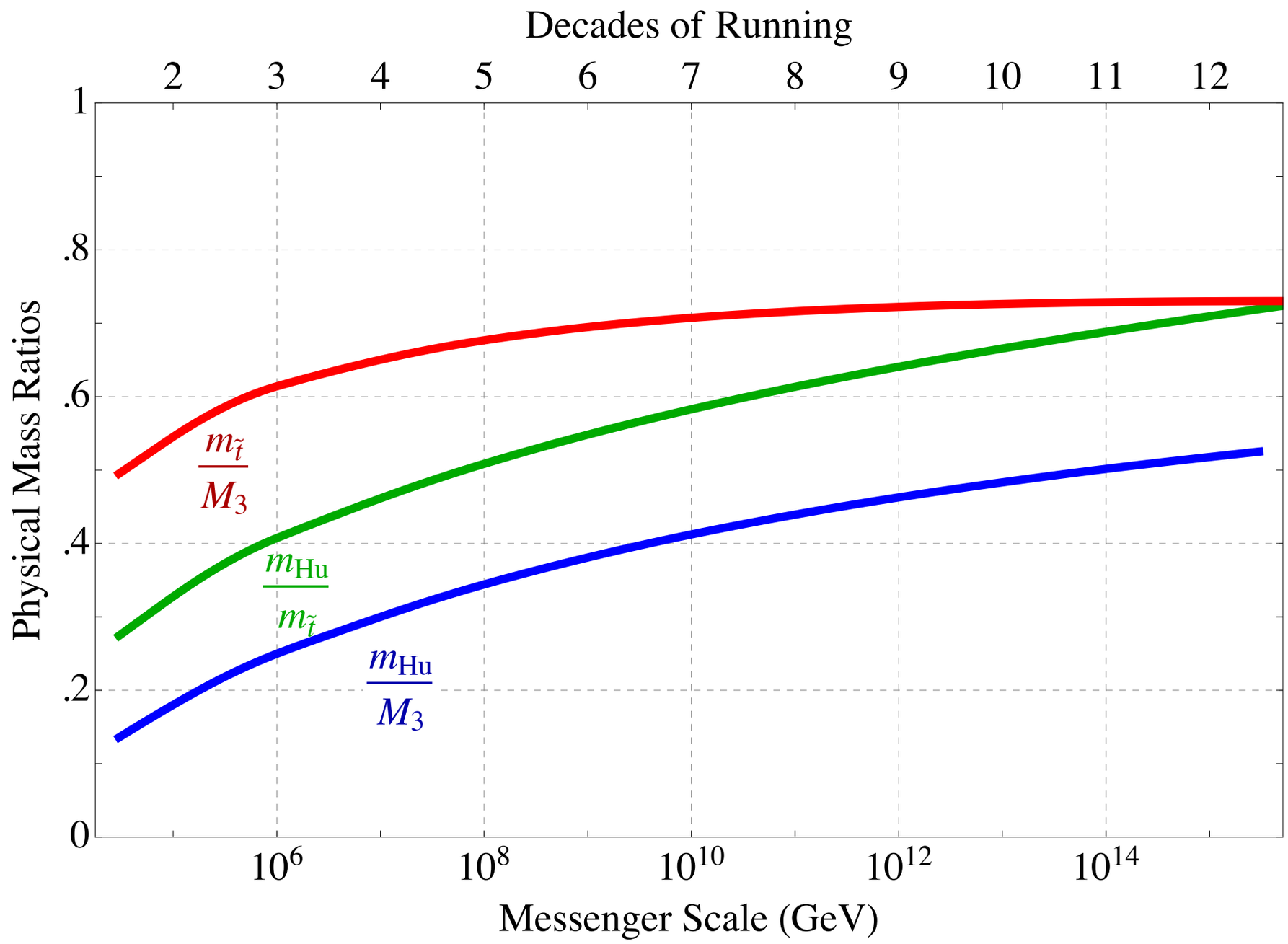
for $\Lambda = 10^4$ TeV

- two-loop

$$5\% \times \left(\frac{M_3}{1000\,\mathrm{GeV}}\right)^{-2}$$

SUSY and Naturalness:

RG evolution



Gluino dominates RG running: strong attractor in the IR

SUSY and Naturalness:

tuning

- Tune with respect to UV parameters; sum in quadrature

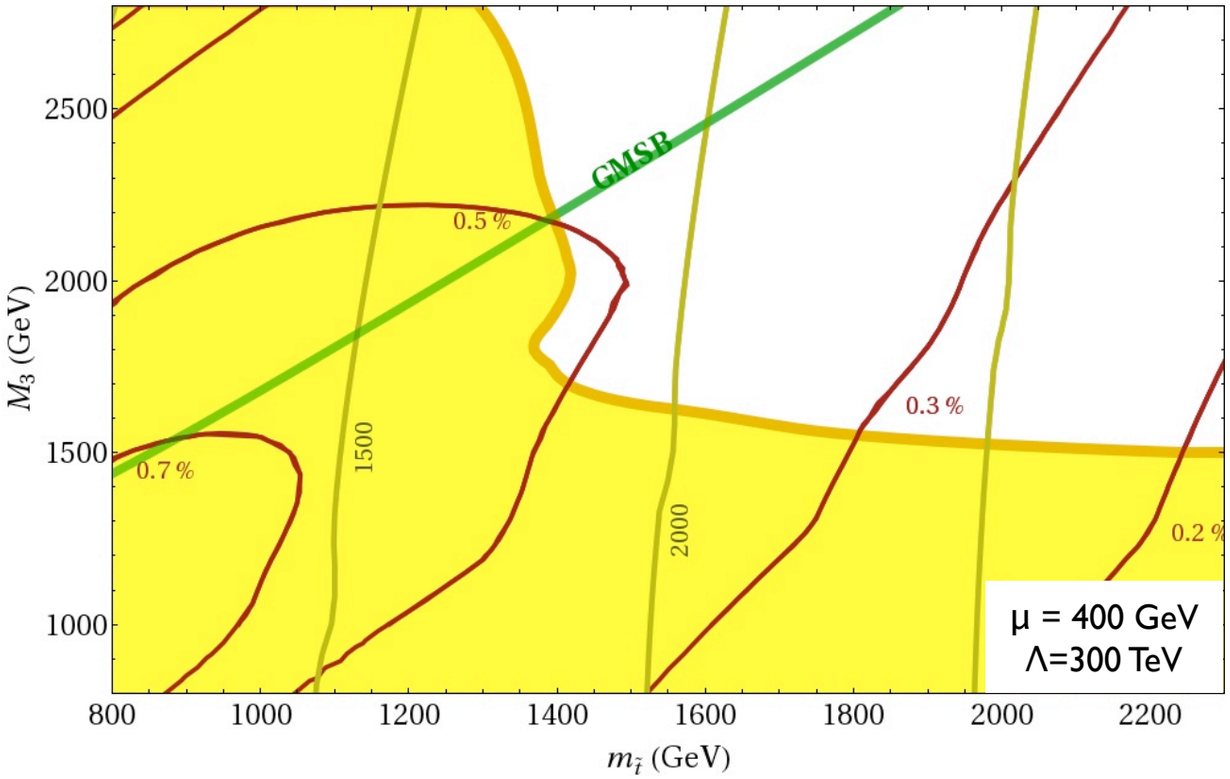
$$\mathrm{FT}_{\mathcal{O}} = \left[\sum_i \left(\frac{\partial \log \mathcal{O}}{\partial \log a_i}\right)^2\right]^{-1/2}$$

- Multiply independent observables

$$\mathrm{FT} = \mathrm{FT}_{m_{\tilde{t}}^2} \times \mathrm{FT}_{m_h^2}$$

SUSY and Naturalness:

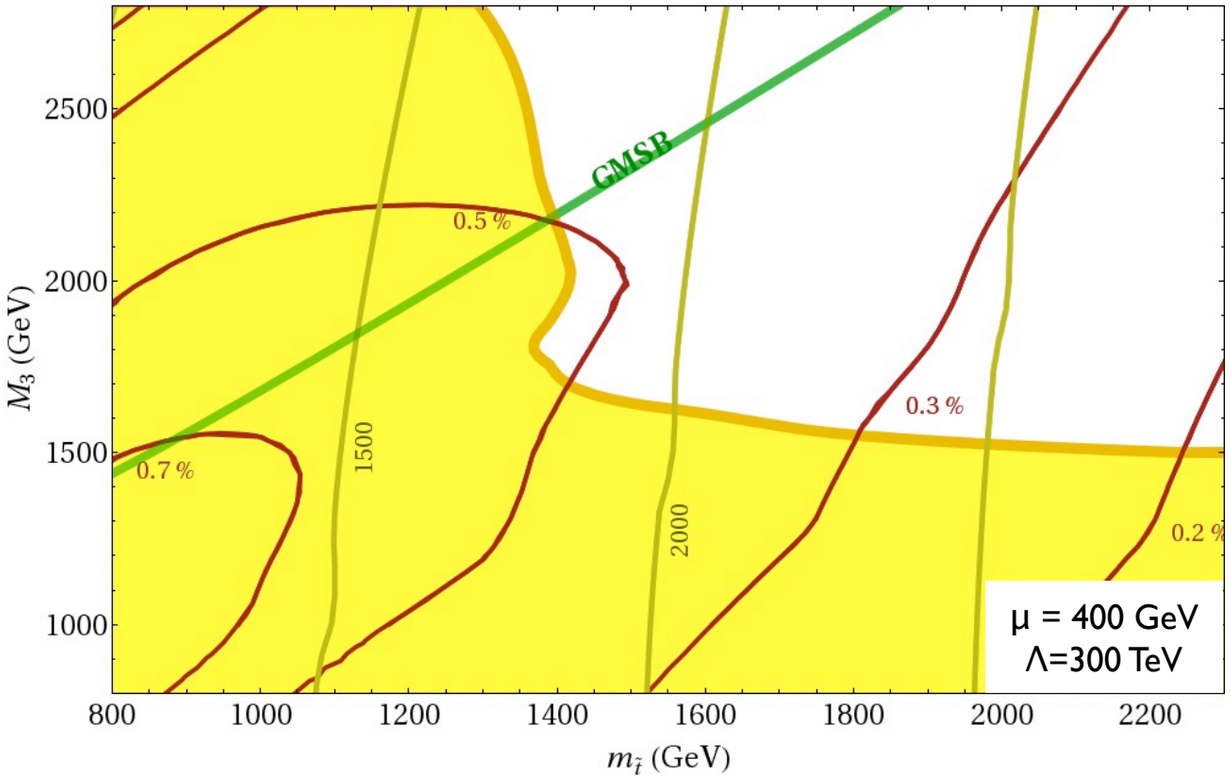
MSSM and NMSSM



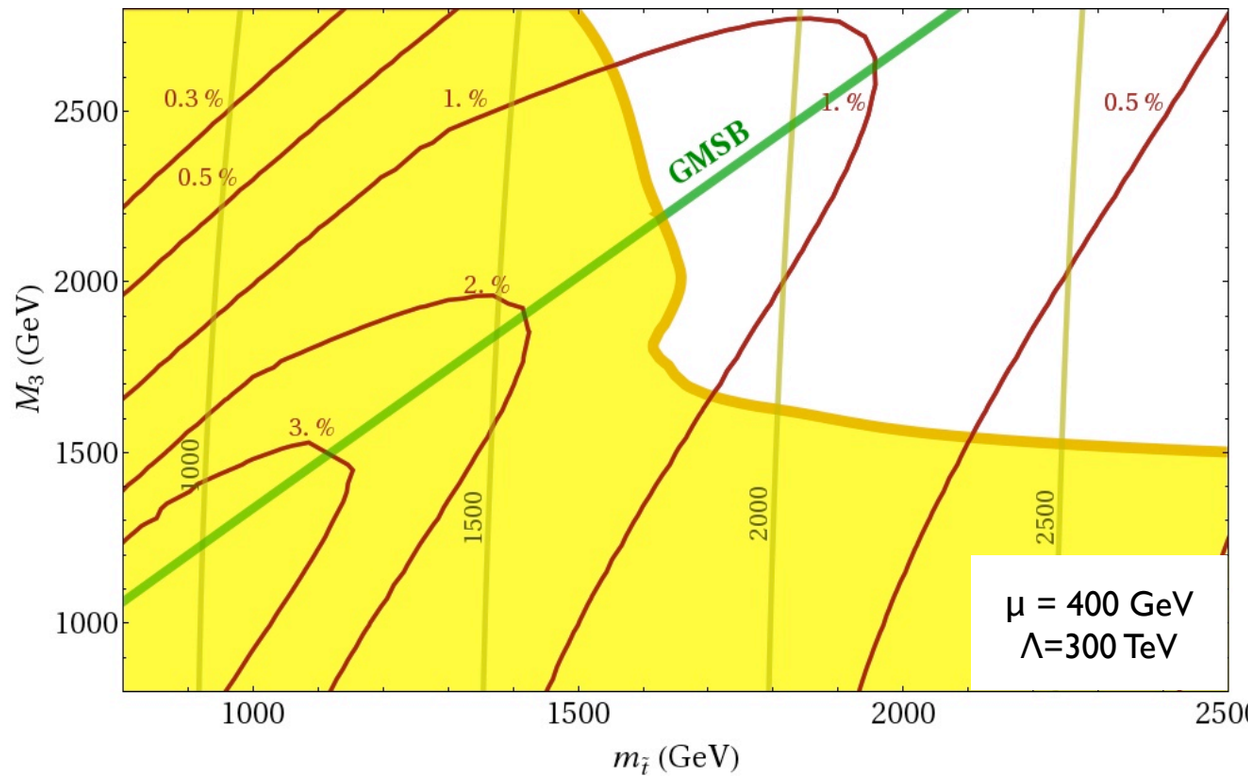
MSSM with A-terms

SUSY and Naturalness:

MSSM and NMSSM



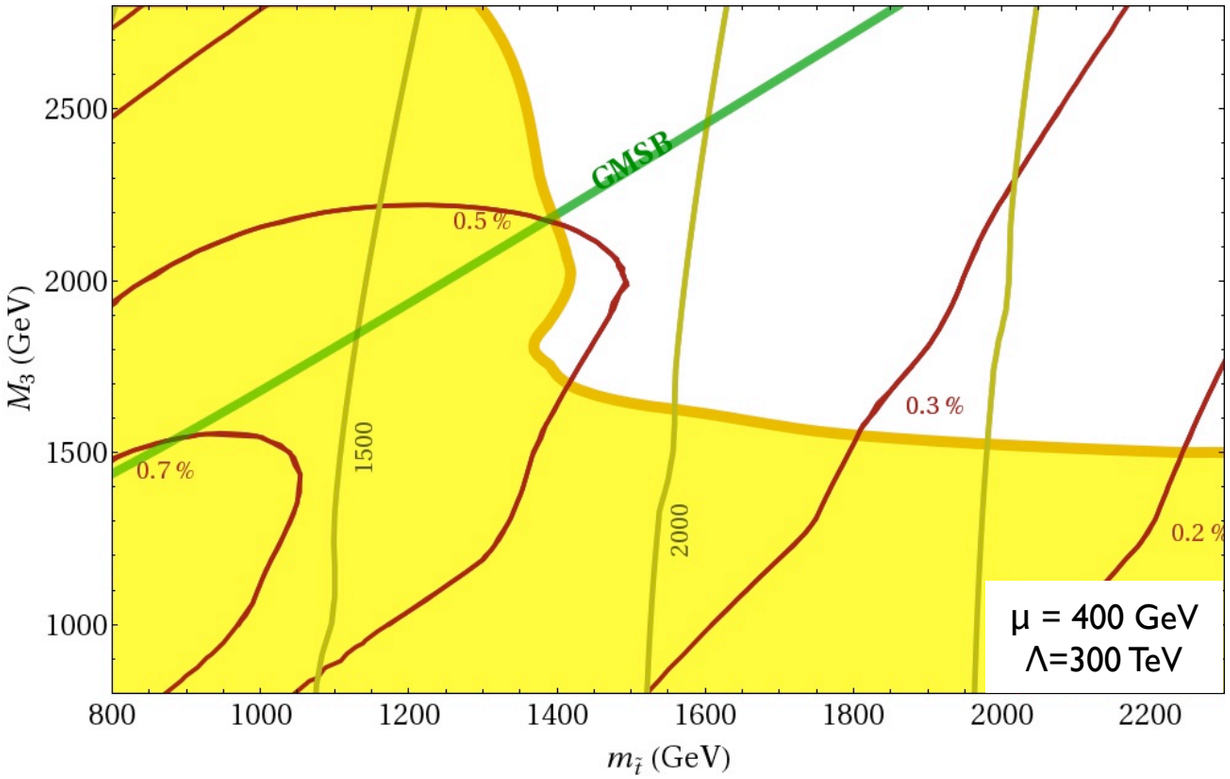
MSSM with A-terms



NMSSM

SUSY and Naturalness:

MSSM and NMSSM



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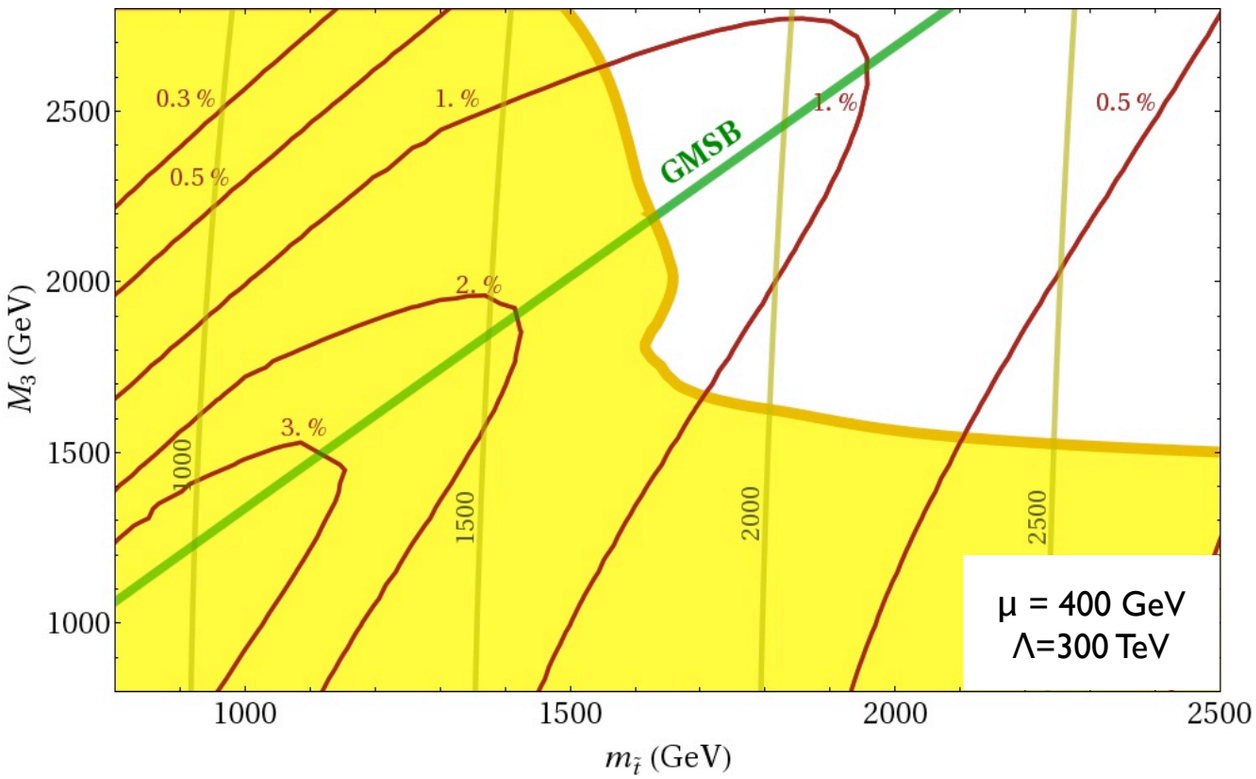
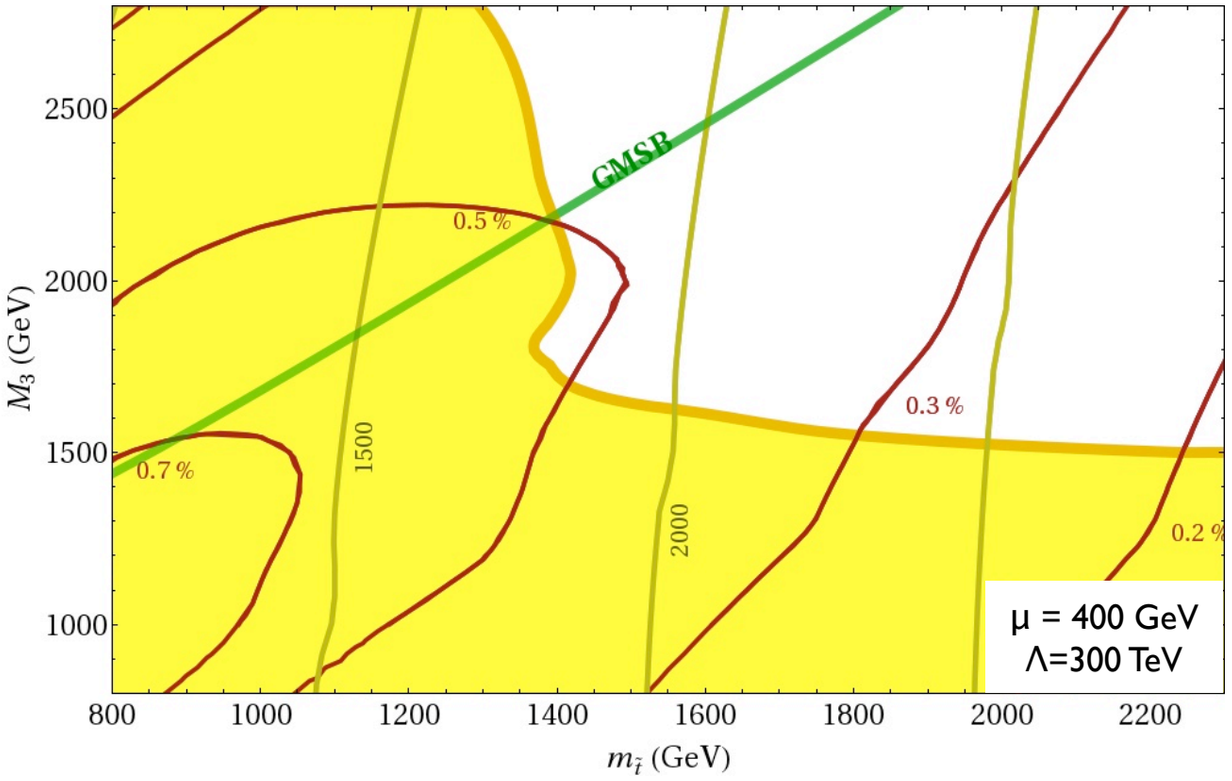


NMSSM

Comparable tuning: limits on sparticles constrain naturalness as much as 125 GeV higgs mass

SUSY and Naturalness:

MSSM and NMSSM



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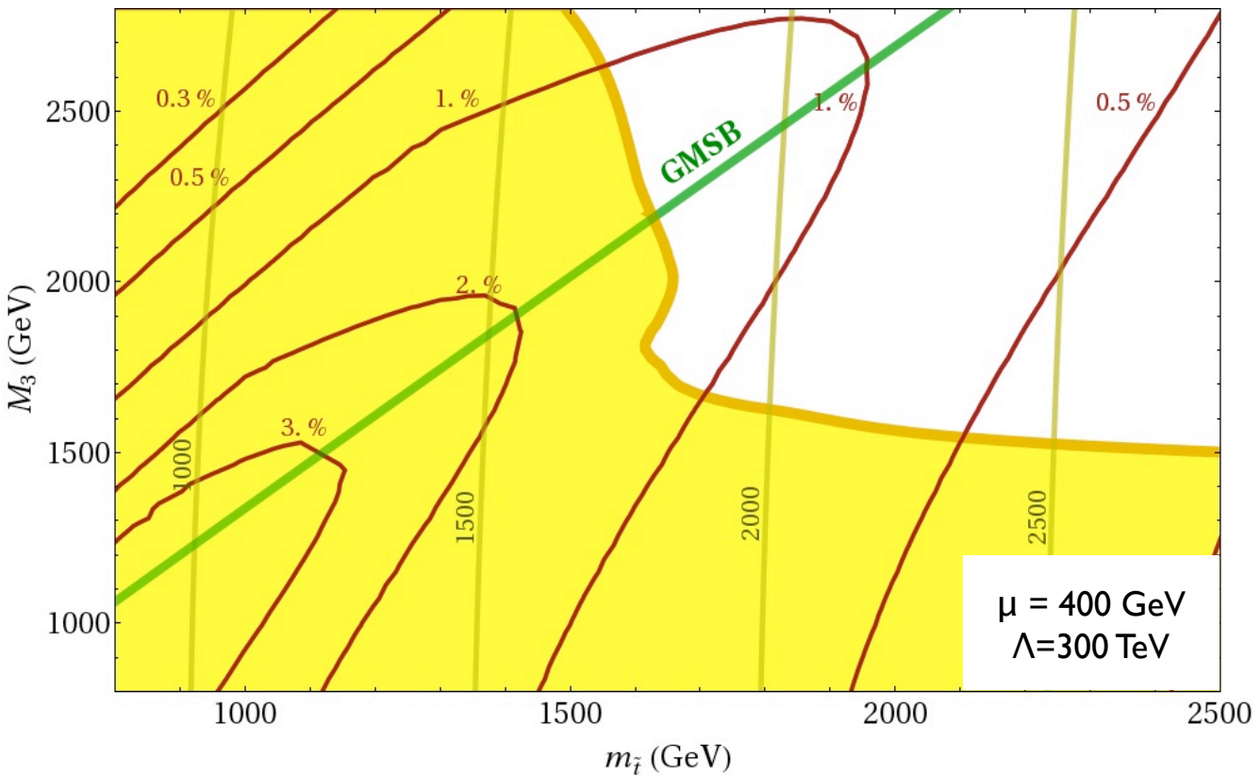
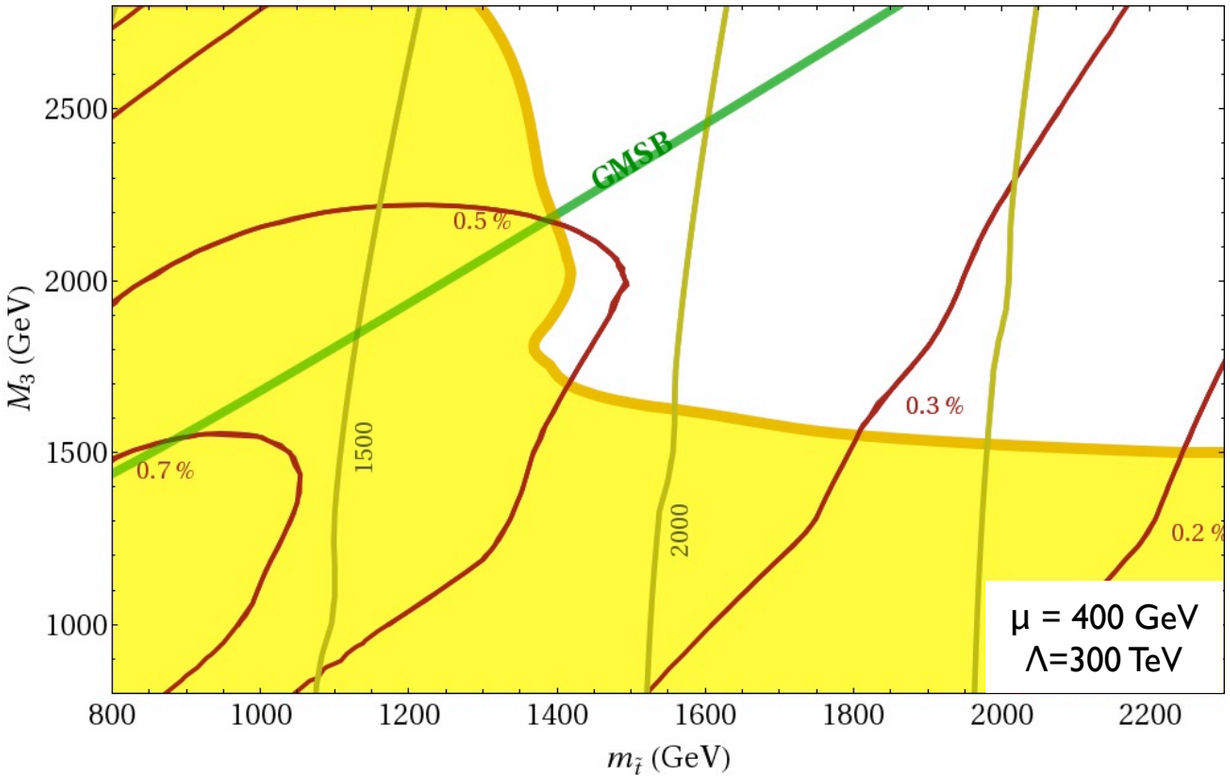


NMSSM

Tuning minimized for mgluino ~ mstop

SUSY and Naturalness:

MSSM and NMSSM



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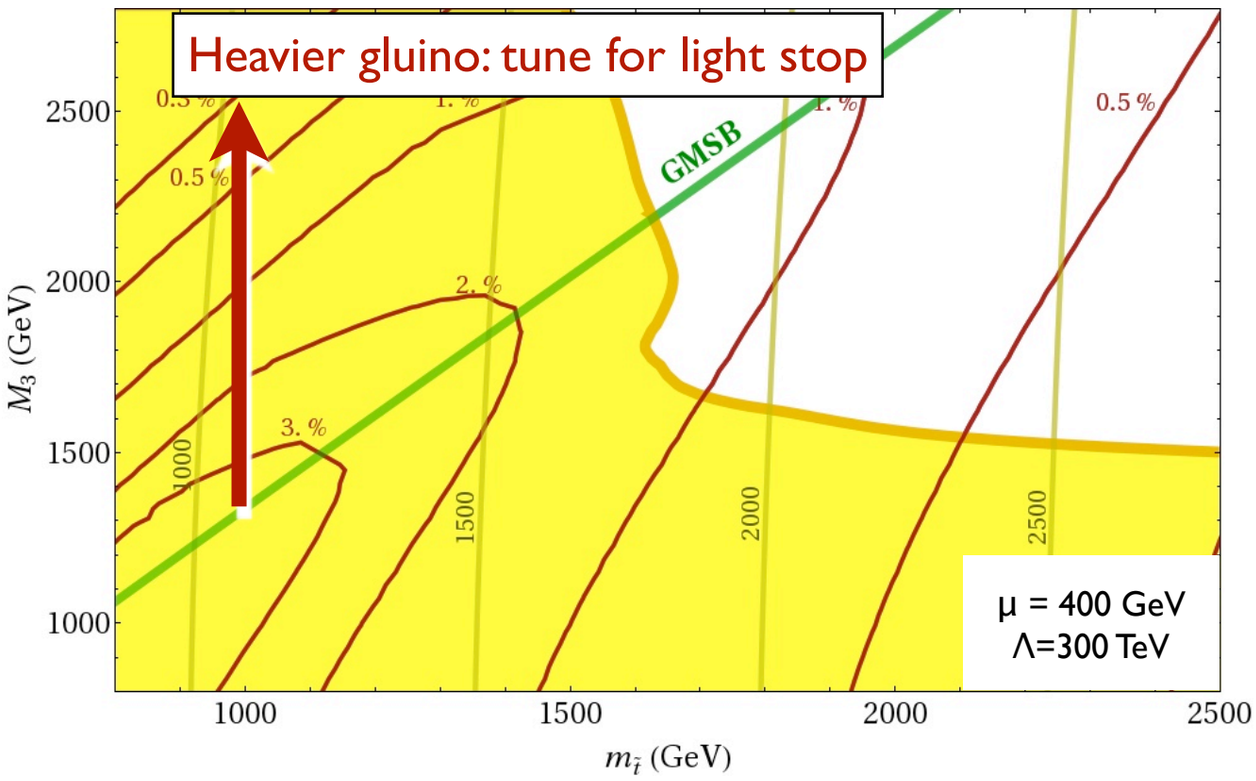

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SUSY and Naturalness:

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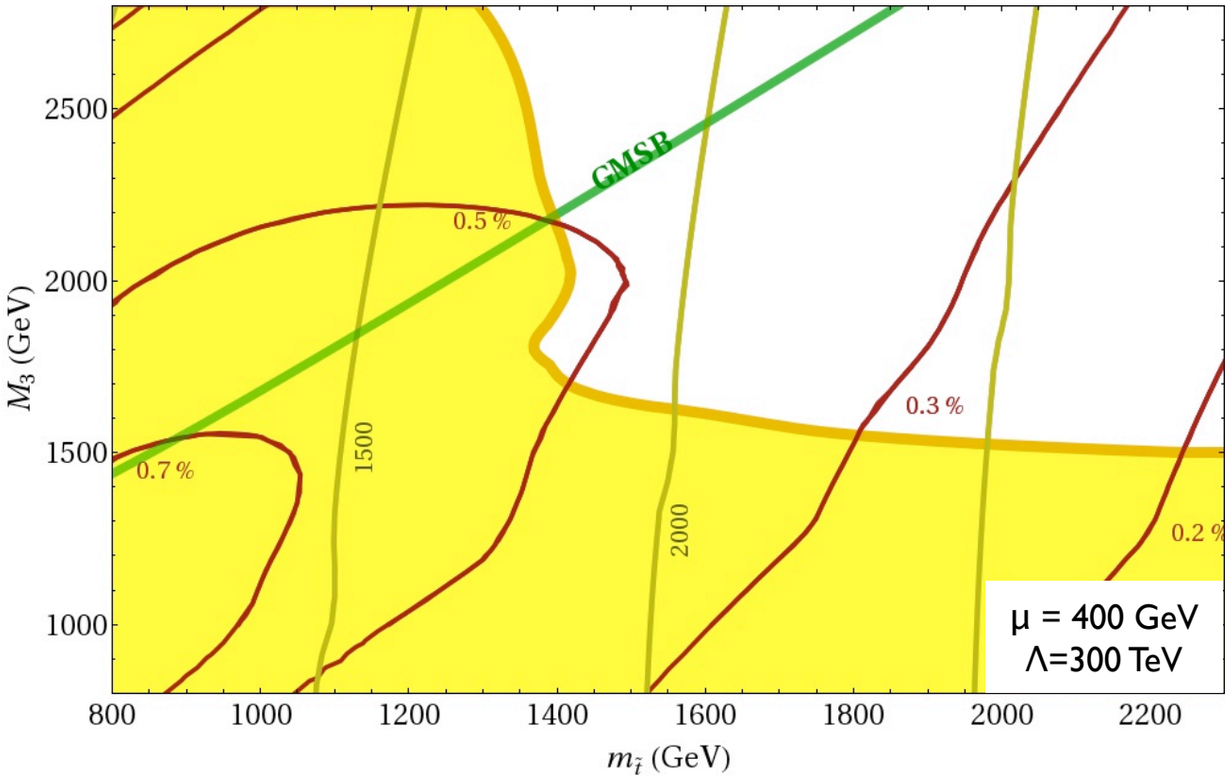

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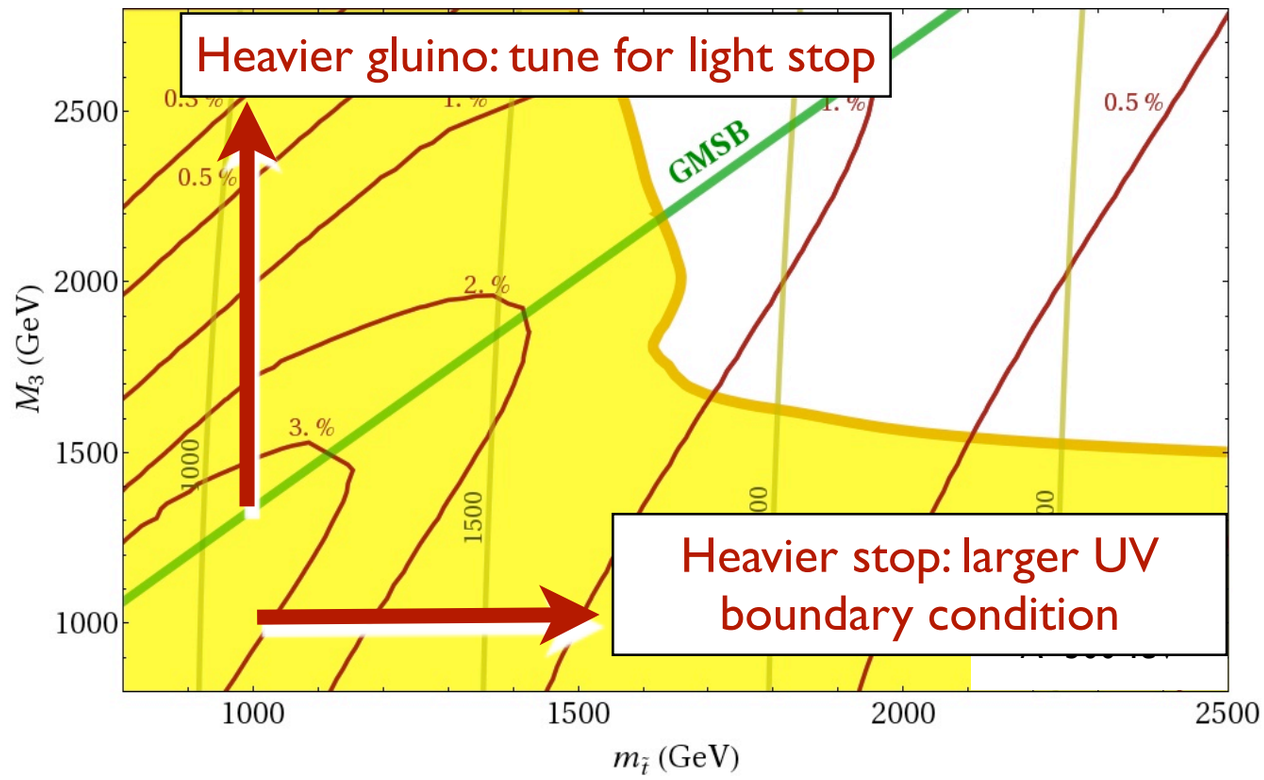

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SUSY and Naturalness:

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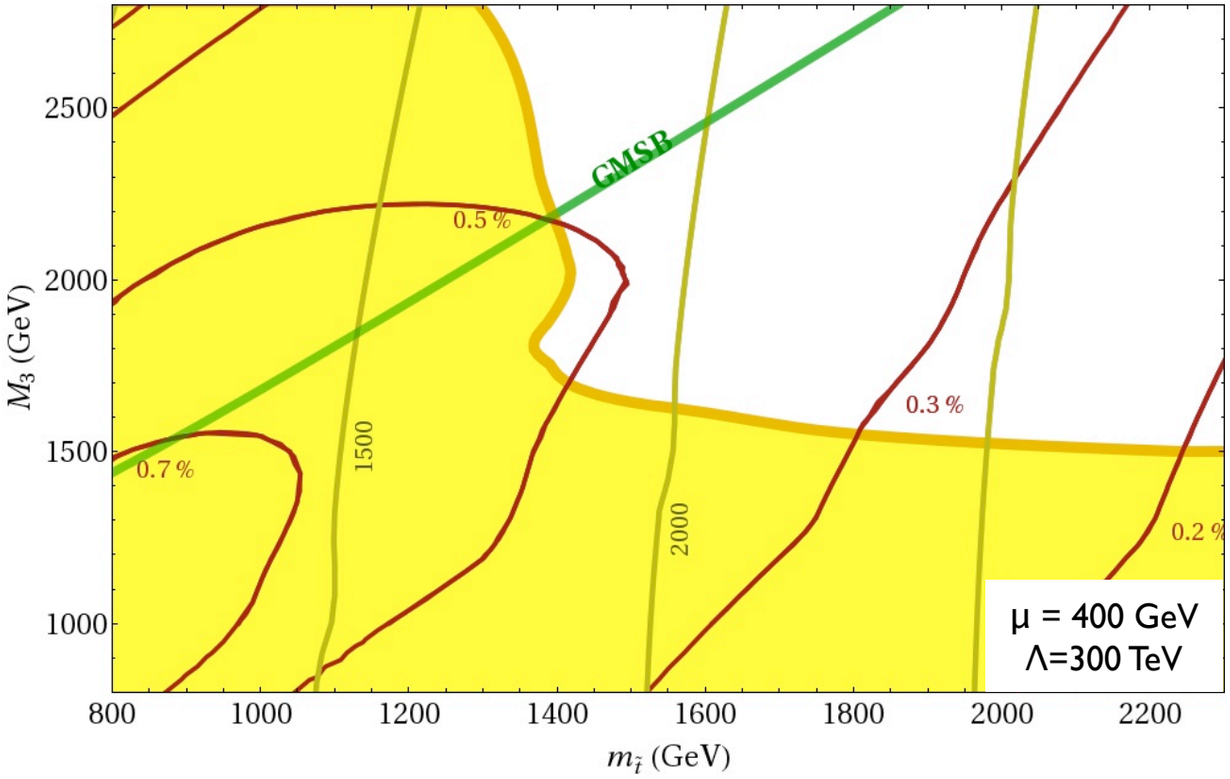

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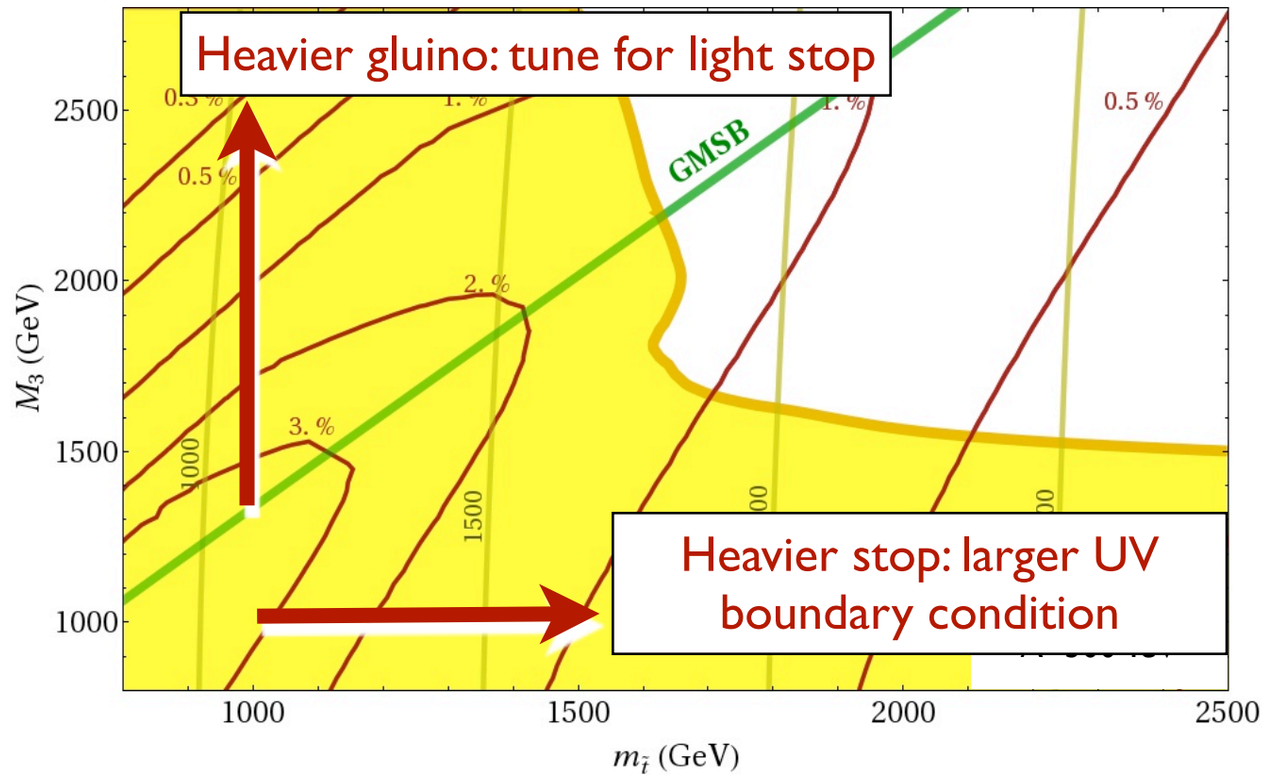

NMSSM

Deviating from RG trajectory leads to more tuning

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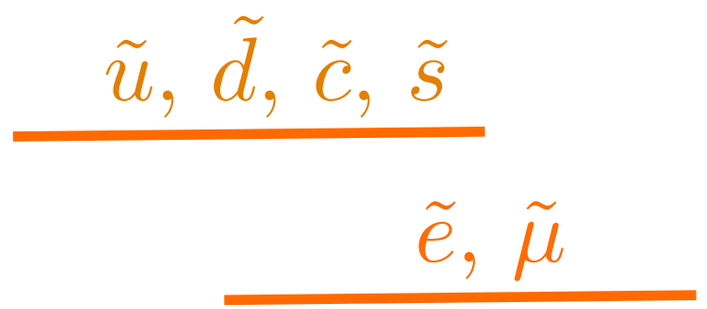
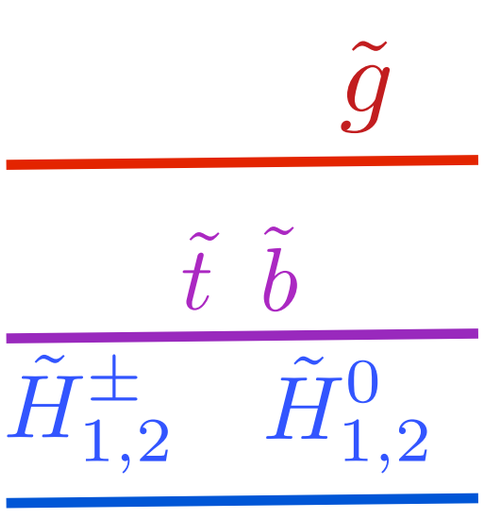
  - Split Families
  - Baryonic RPV
  - Dirac Gauginos
- SUSY and Unnaturalness

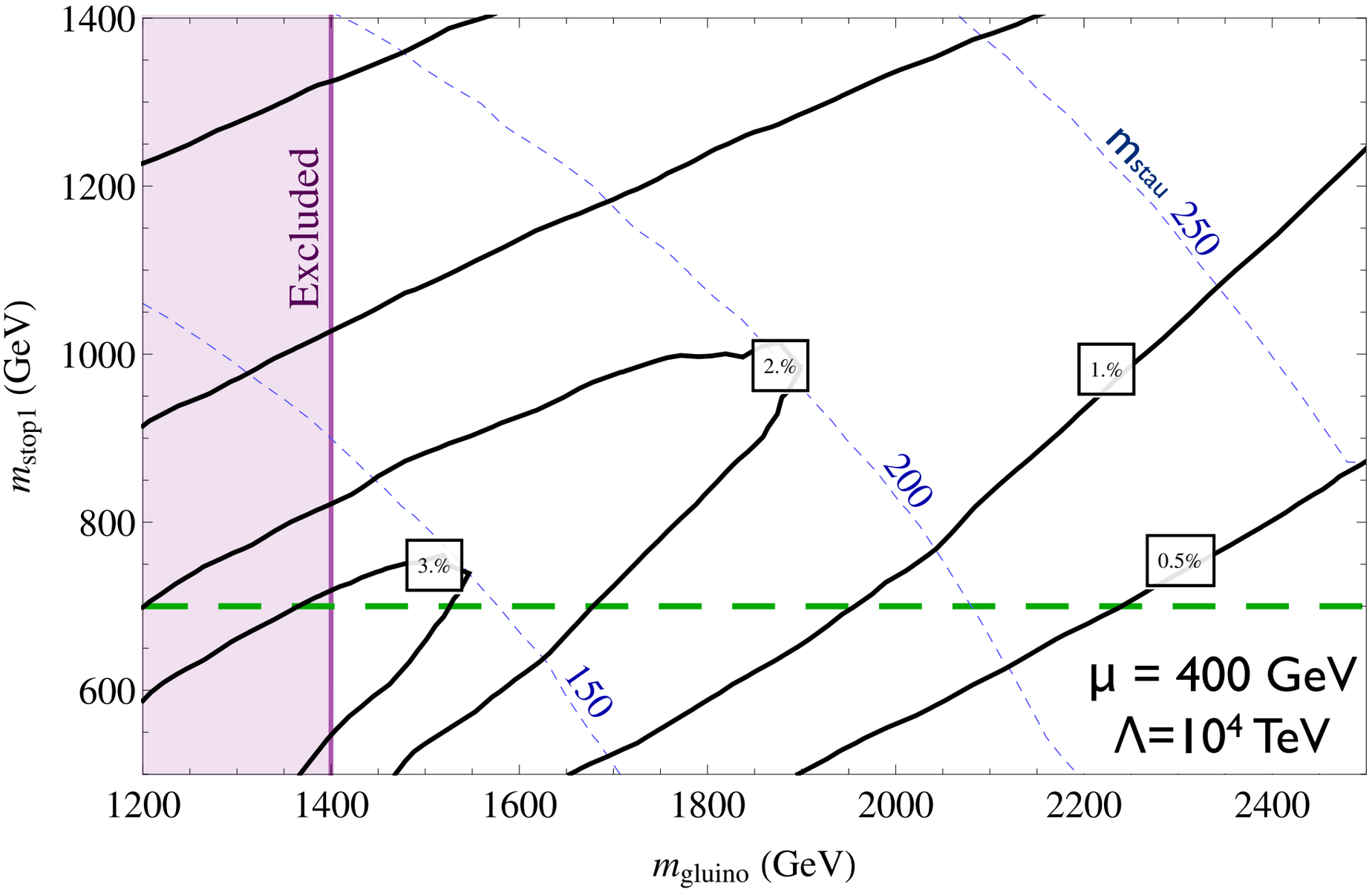
Split Families



- Keep only particles required for naturalness ☺
- No associated production or squark pair production ☺
- Possible flavor problems ☹



Split Families

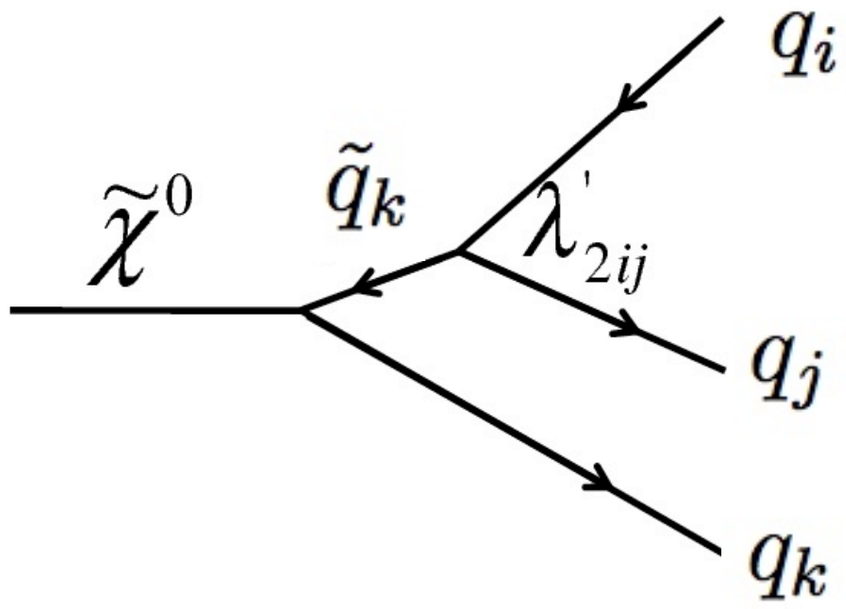


Limits on gluino, stop, stau keep tuning to <3%

Baryonic RPV

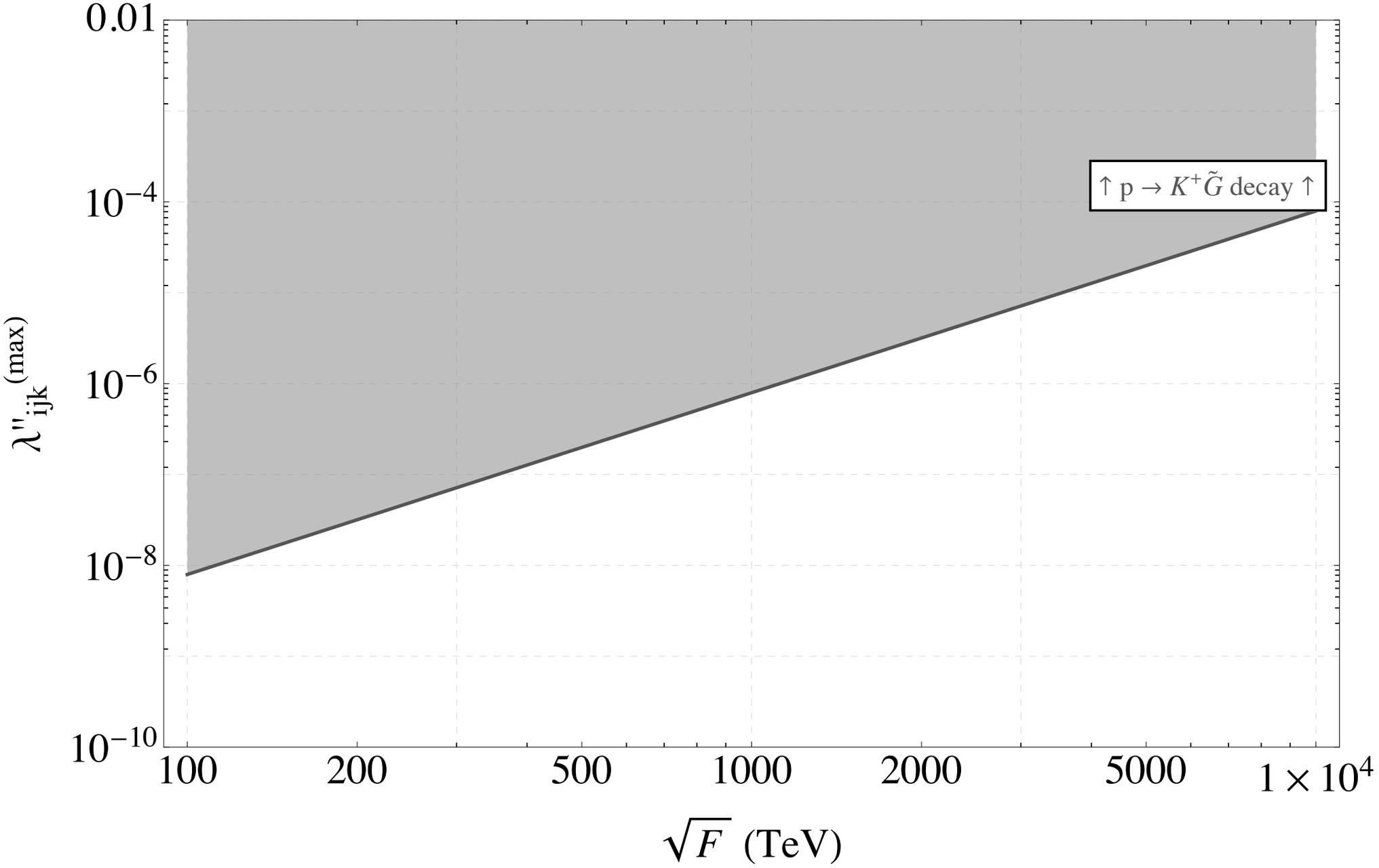
$$\mathcal{W} \supset \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$

- No MET from neutralino ☺
- Mostly hadronic final states ☺
- Stops, higgsinos lead to *t*, *W*, *Z*'s in cascades: MET and leptons ☹
- Decays to the gravitino ☹



Baryonic RPV:

limits on λ_B



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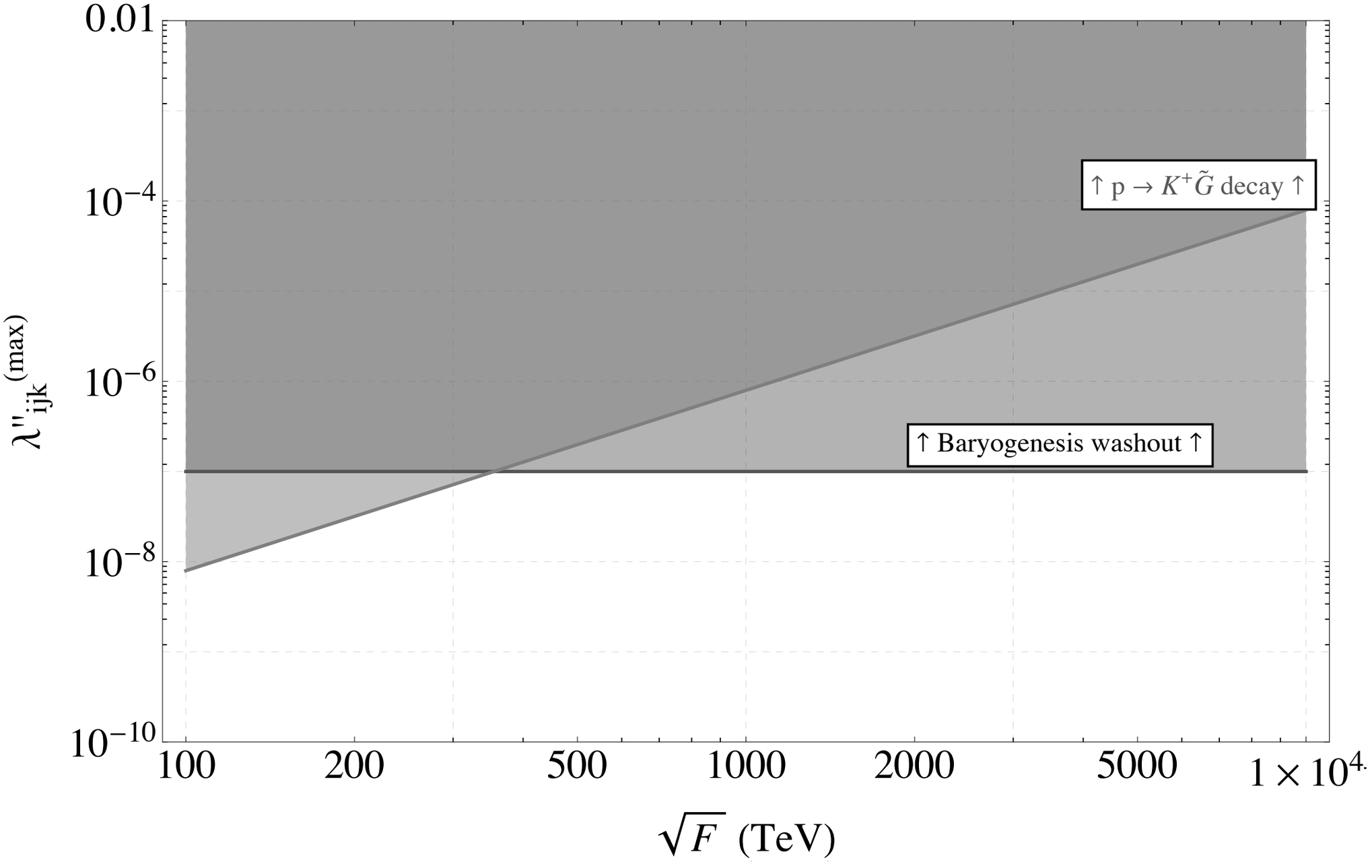

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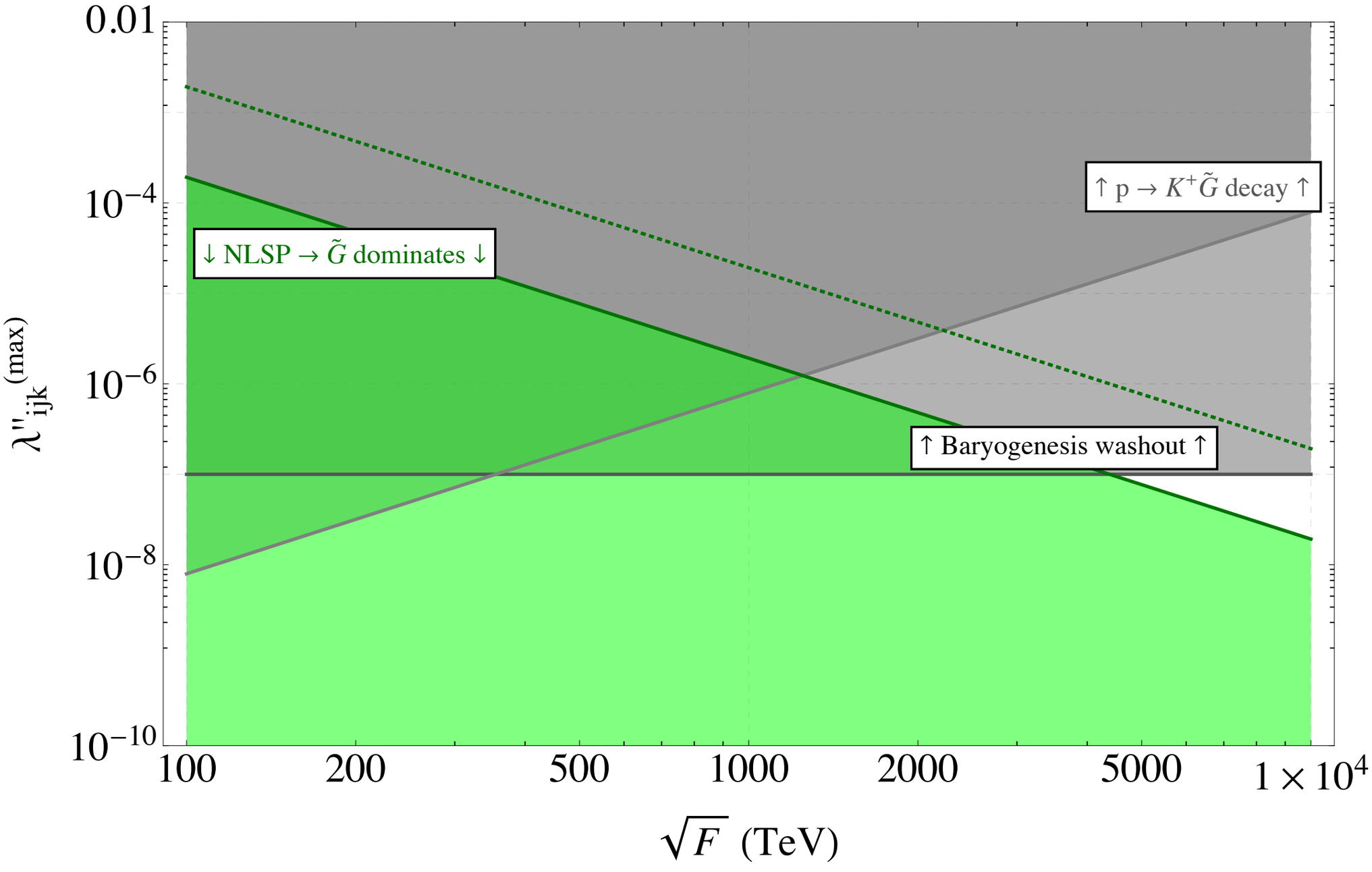

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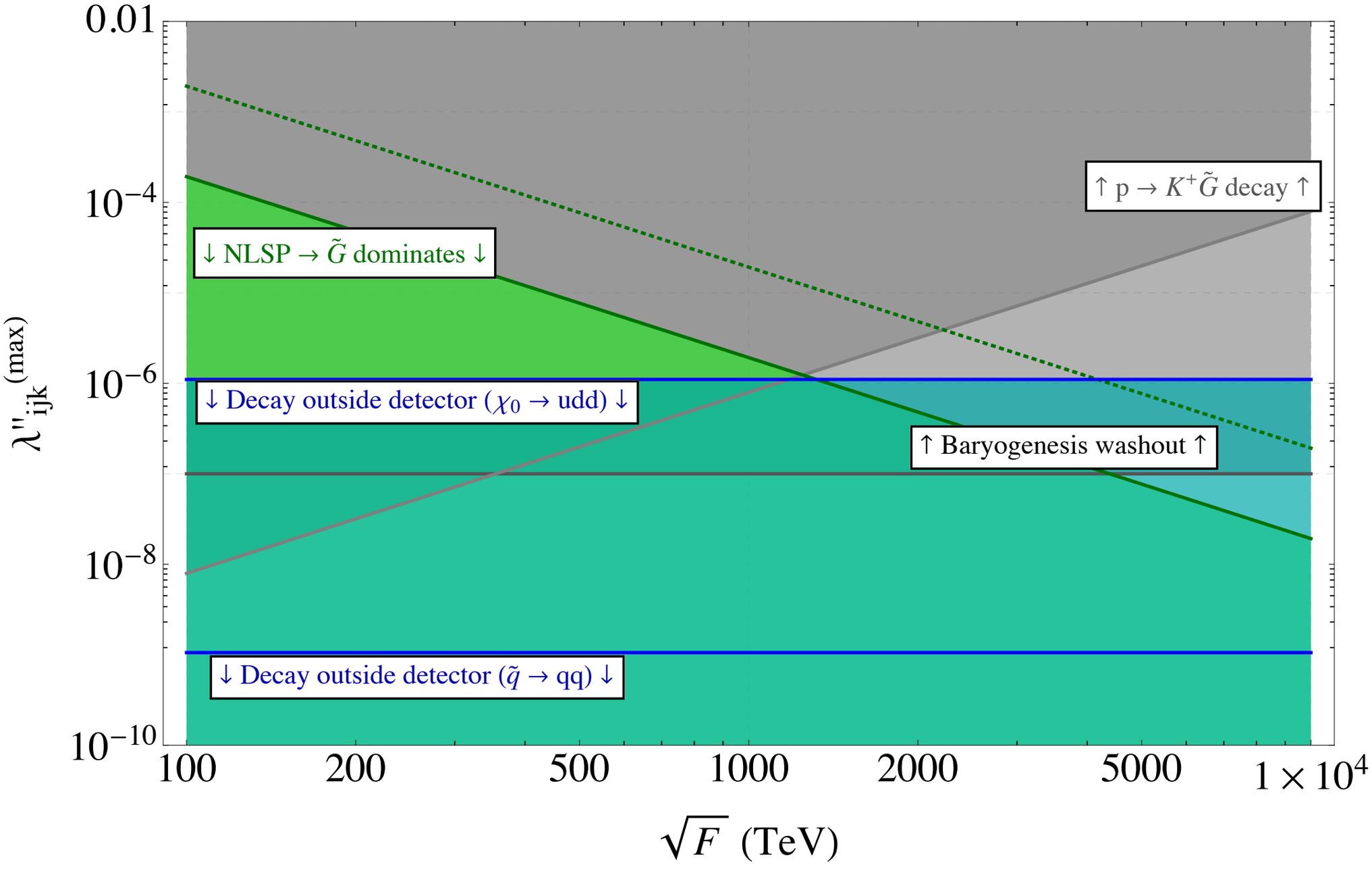
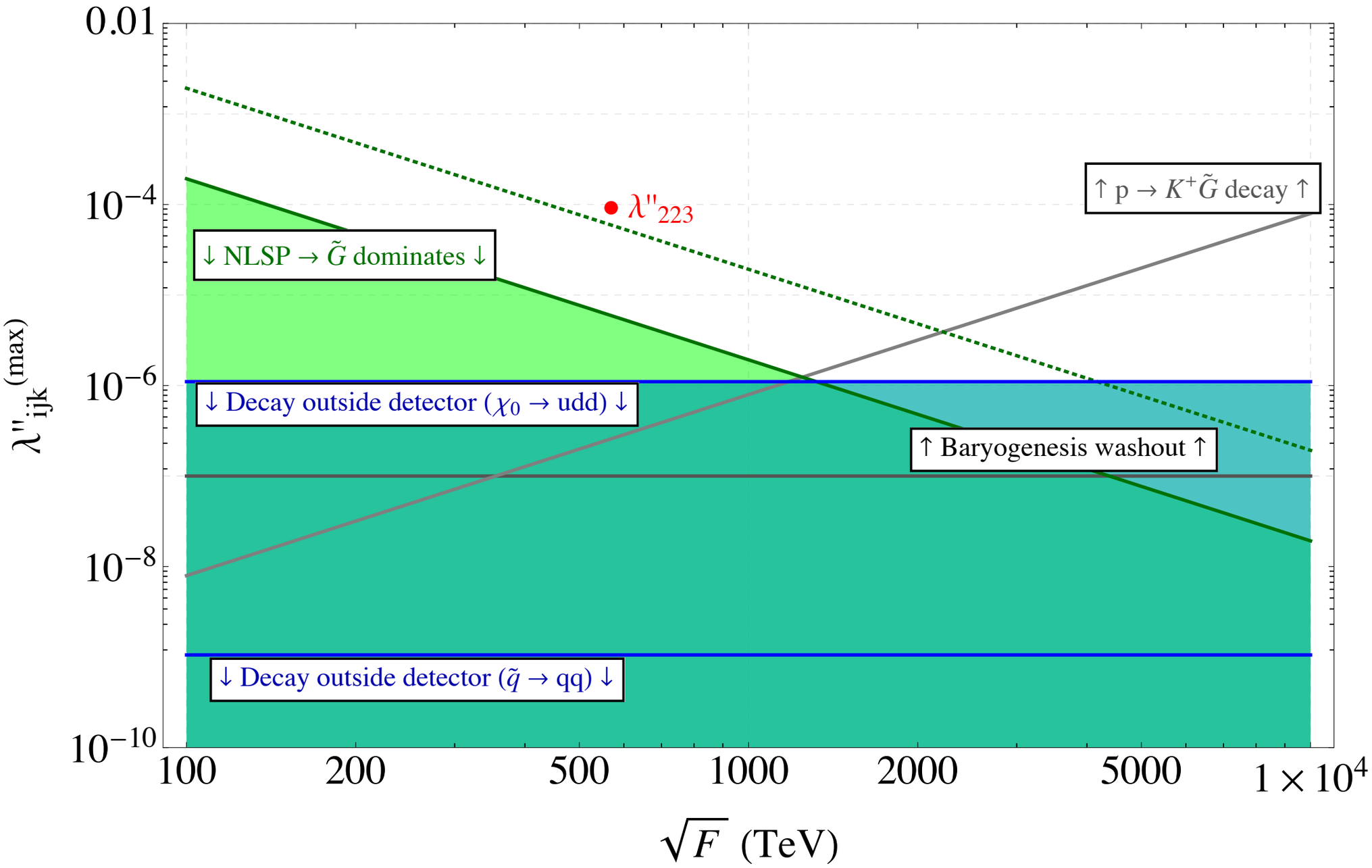


No allowed parameter space for RPV couplings at colliders

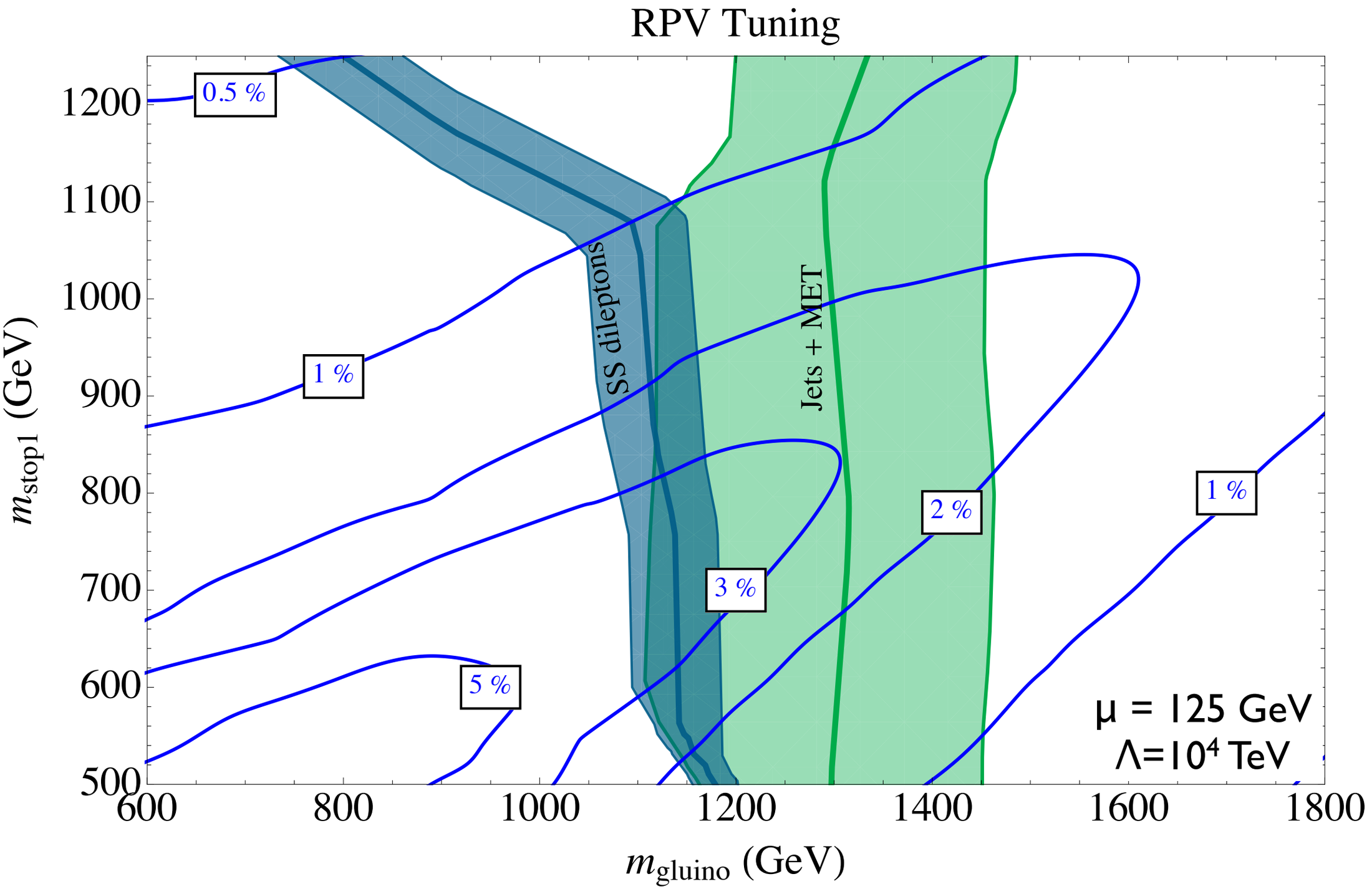
Baryonic RPV:

limits on λ_B



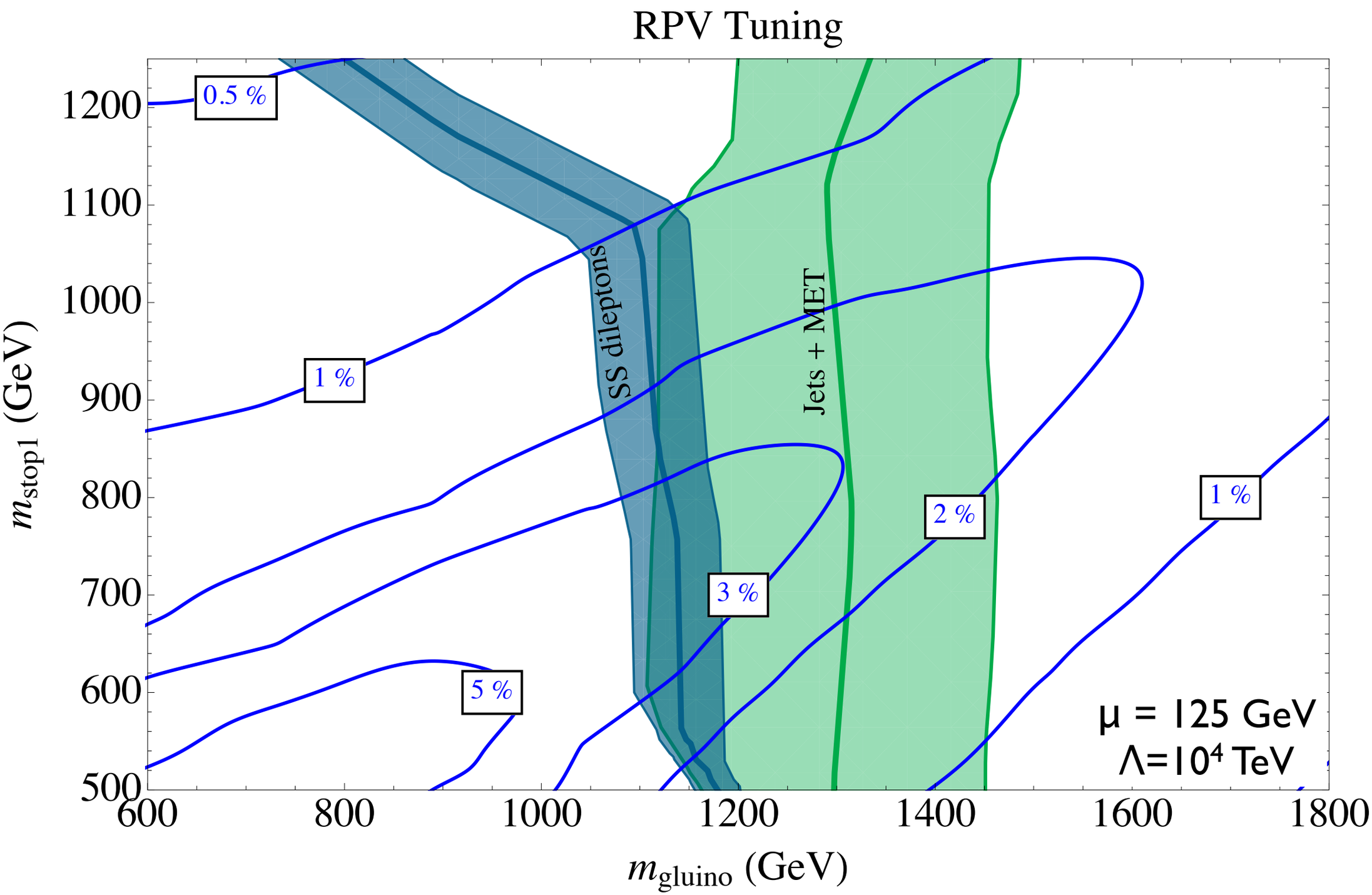
Give up baryogenesis, additional sector to raise gravitino mass

Baryonic RPV



Many energetic jets: even few ν, l give strong limits, tuning <3%

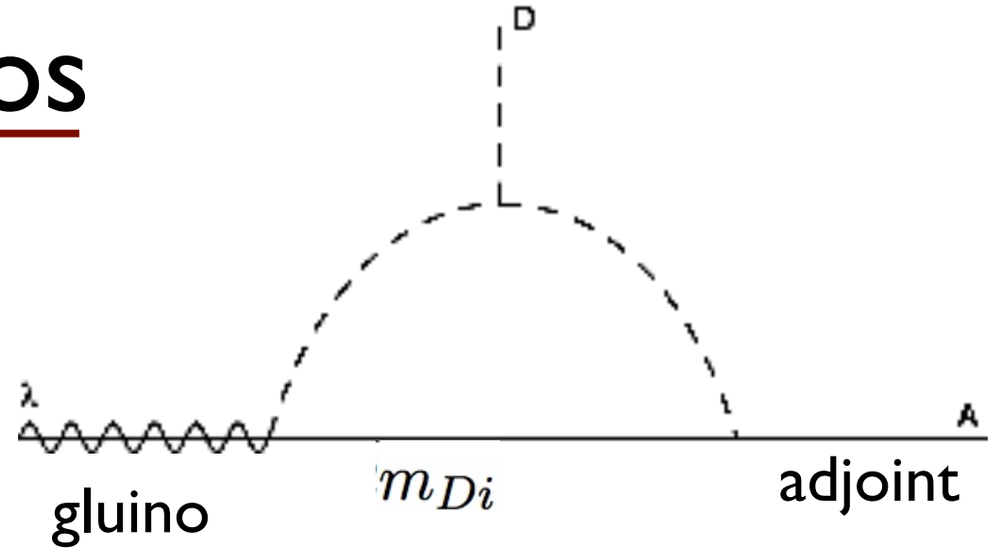
Baryonic RPV



Deviating from spectrum can improve limits slightly, but generally increases tuning

Dirac Gauginos

- Finite gluino contribution to stops at 1 loop ☺
- Perturbative unification difficult ☹



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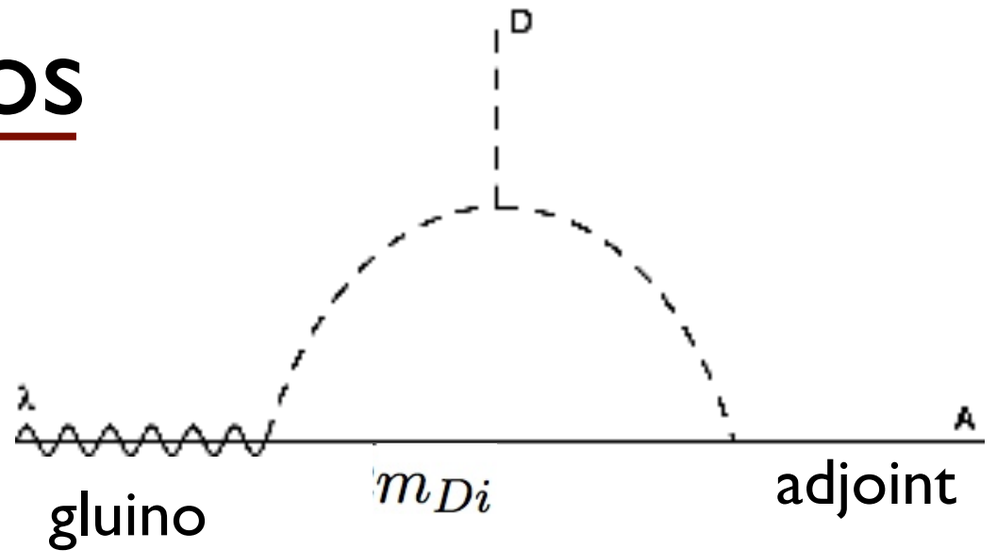

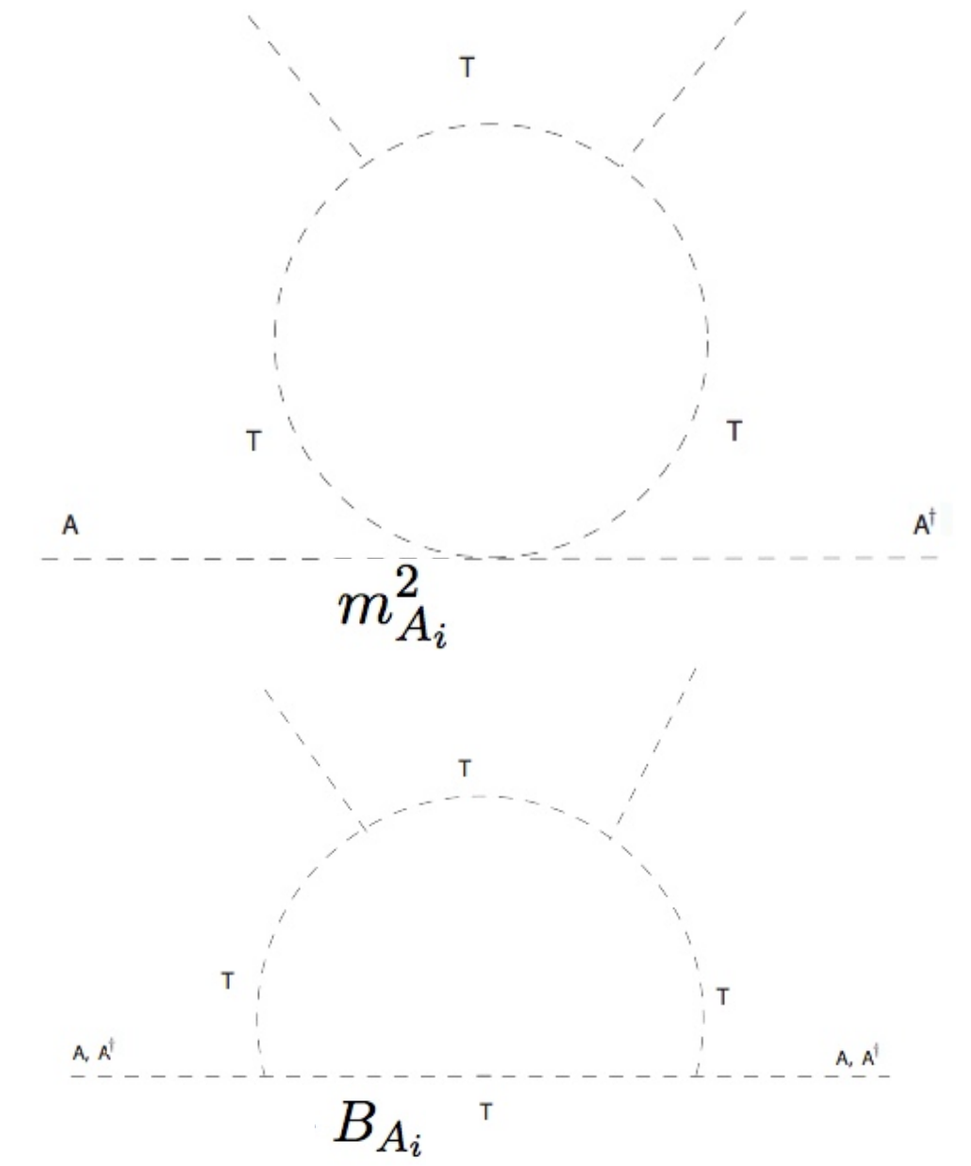

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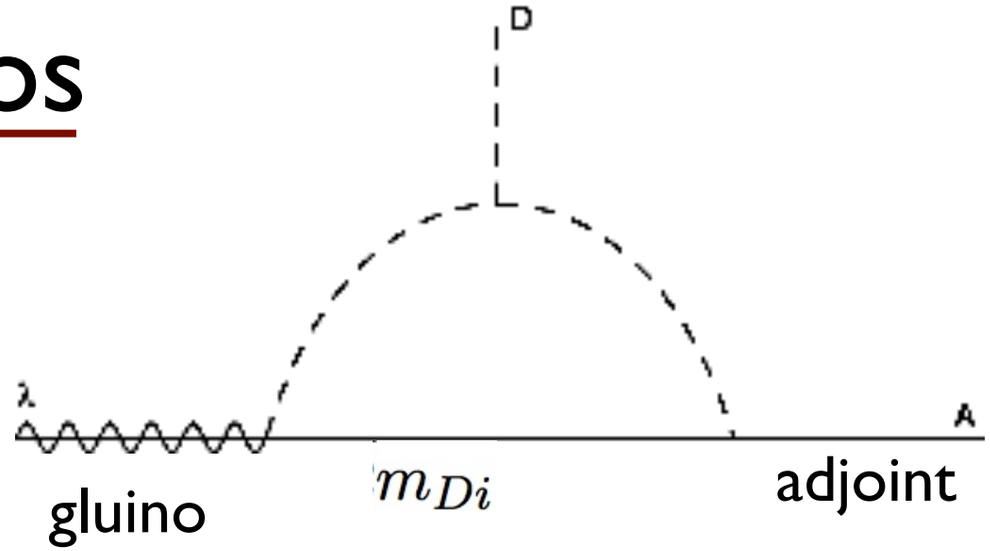
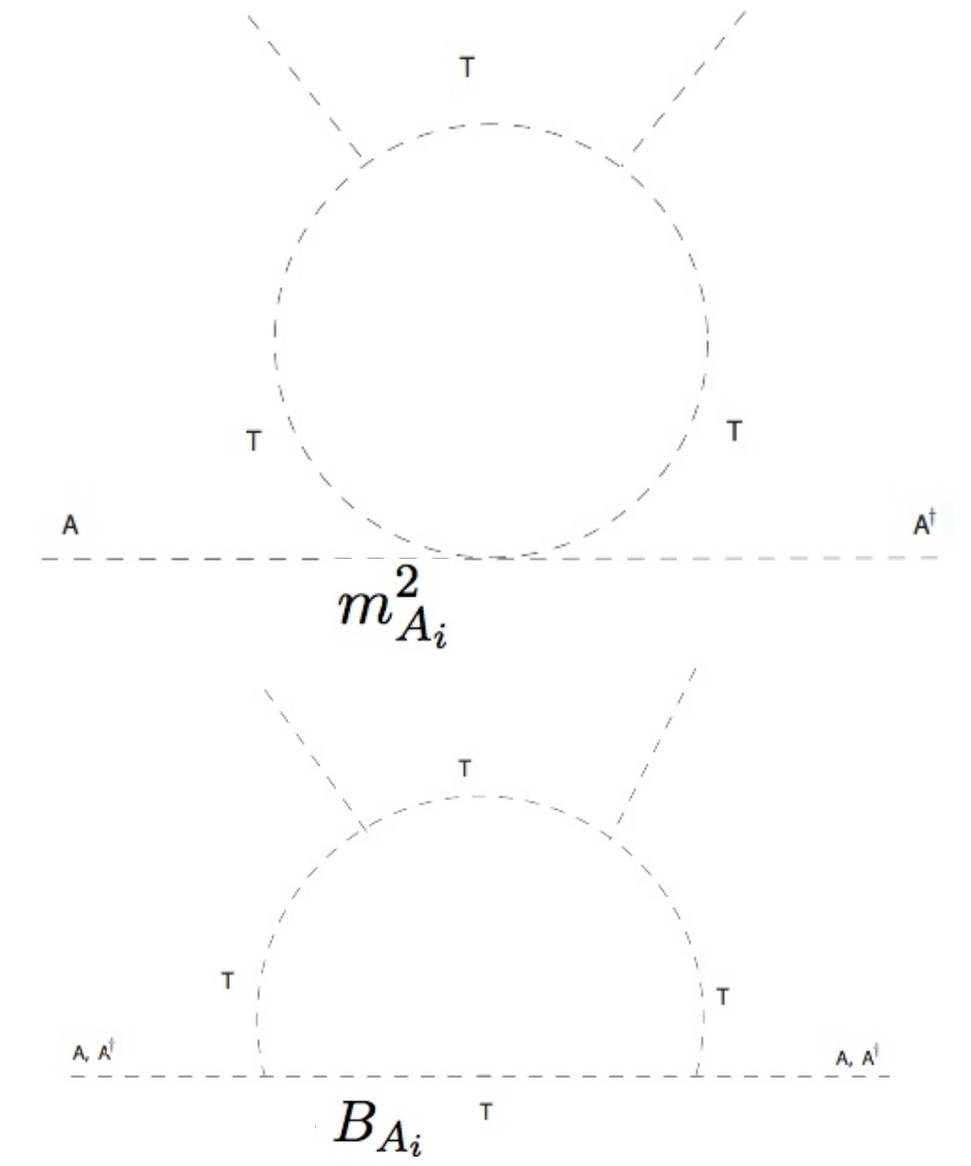


- Supersoft limit not protected by symmetry ☹



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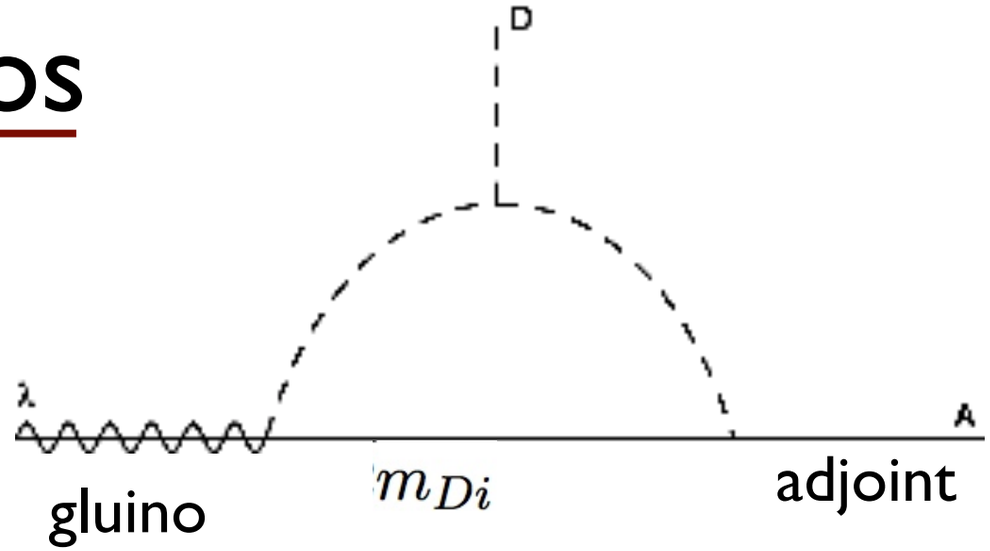
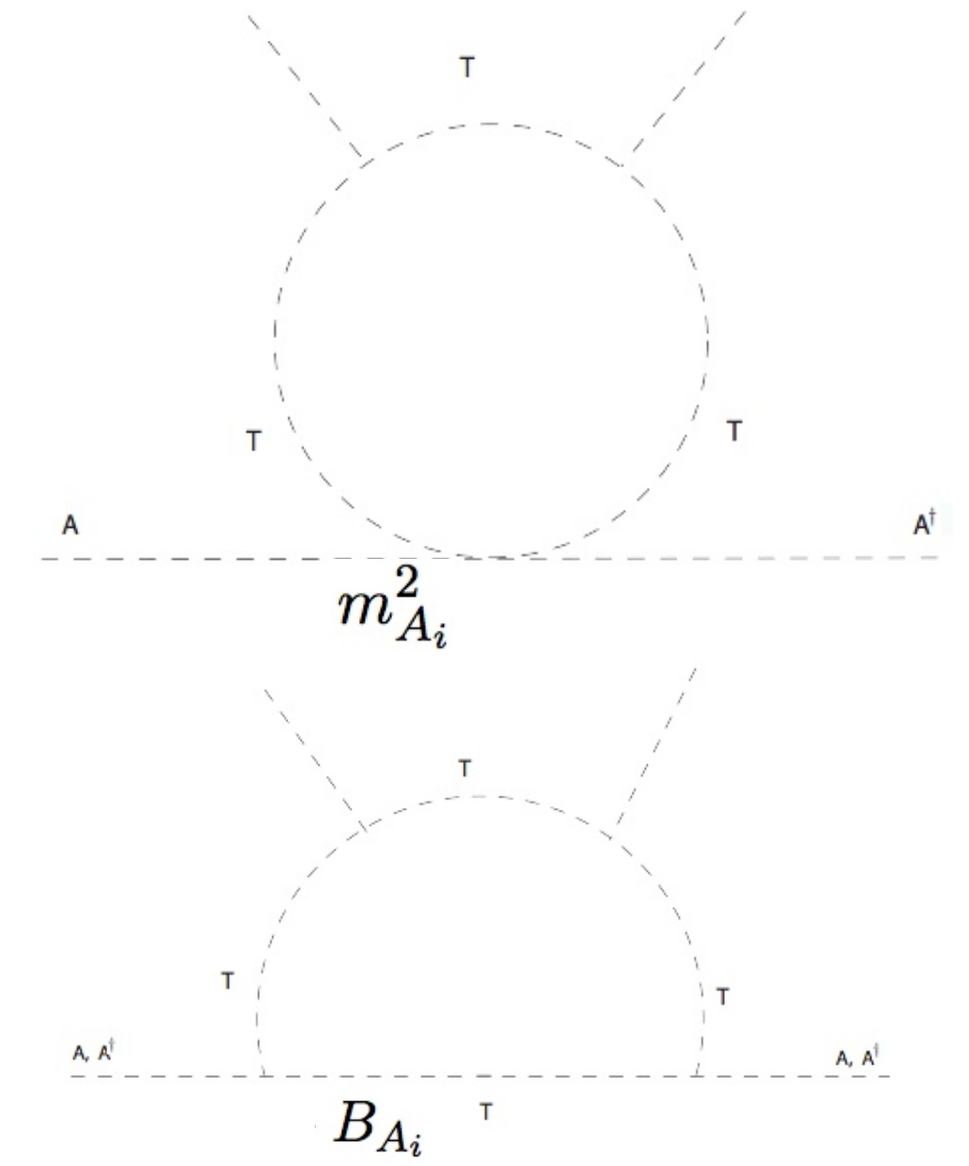
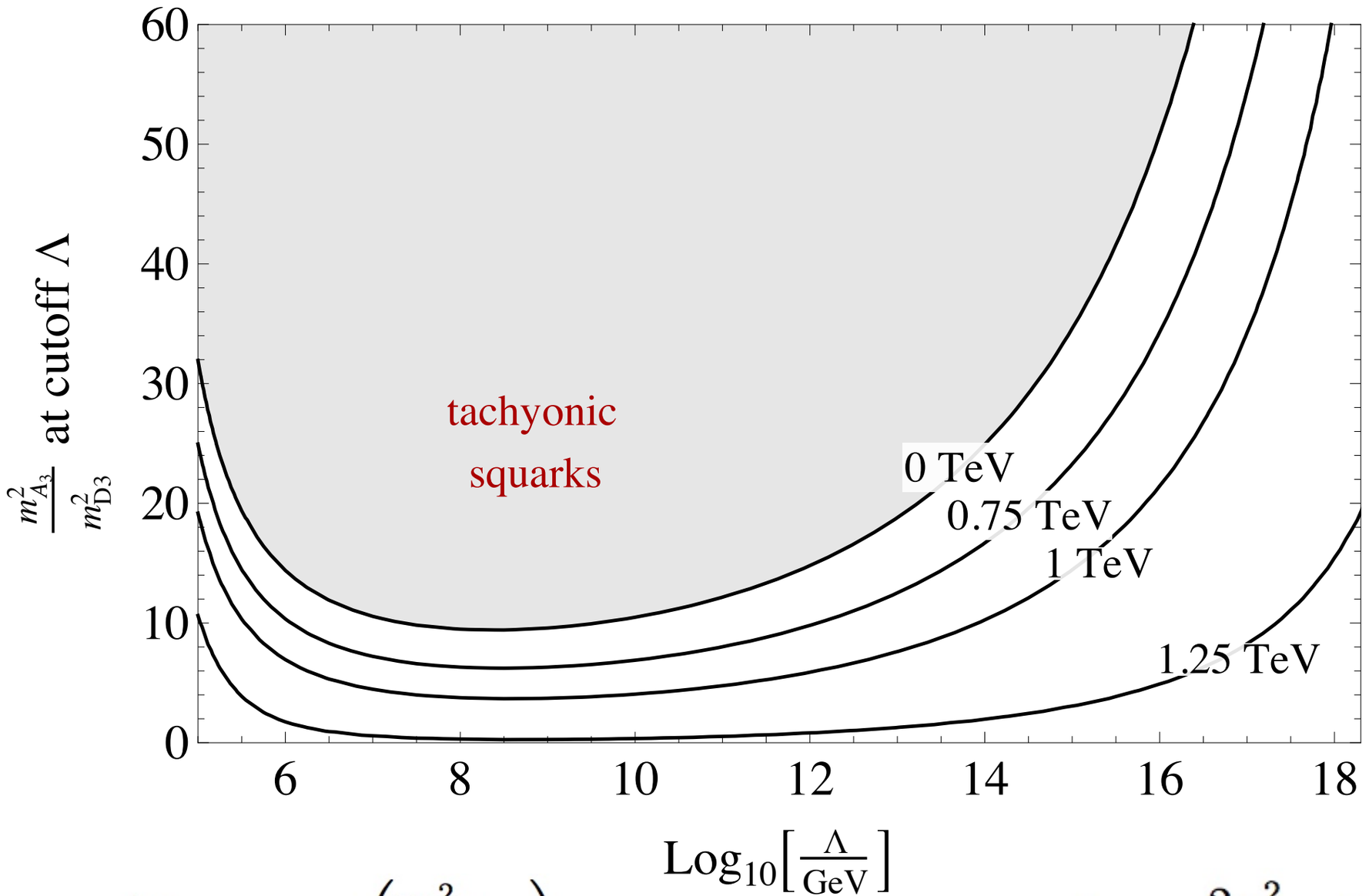


- Supersoft limit not protected by symmetry ☹
- Adjoint scalar masses parametrically large ☹



Dirac Gauginos



$$\Delta_{\rm finite} m^2_{\tilde{q}} \simeq \frac{4\alpha_3}{3\pi}\, m^2_{D_3} \log\left(\frac{m^2_{\rm Re(A)}}{m^2_{D3}}\right)$$

$$\delta m^2_{\tilde{q}} \simeq -\frac{2\alpha_3^2}{\pi^2}\, m^2_{A_3} \log\left(\frac{\Lambda^2}{m^2_{\rm Re(A)}}\right)$$

Tuning (<1%) needed to avoid tachyonic squarks at 2 loops

Conclusions

- Tuning no longer dominated by higgs mass
- Relaxing limits on sparticles
    - imposes new constraints
    - does not significantly improve tuning
- 3% tuning....
    - natural or anthropic?

Stay Tuned!

In the soviet era agricultural land was increasingly intensively cultivated. Drainage robbed the huge fields, which had been created, of the last vestiges of naturalness. Most landscapes became more natural; at the same time agricultural land became more and more unnatural.

- Estonian Biodiversity Strategy and Action Plan, 1999

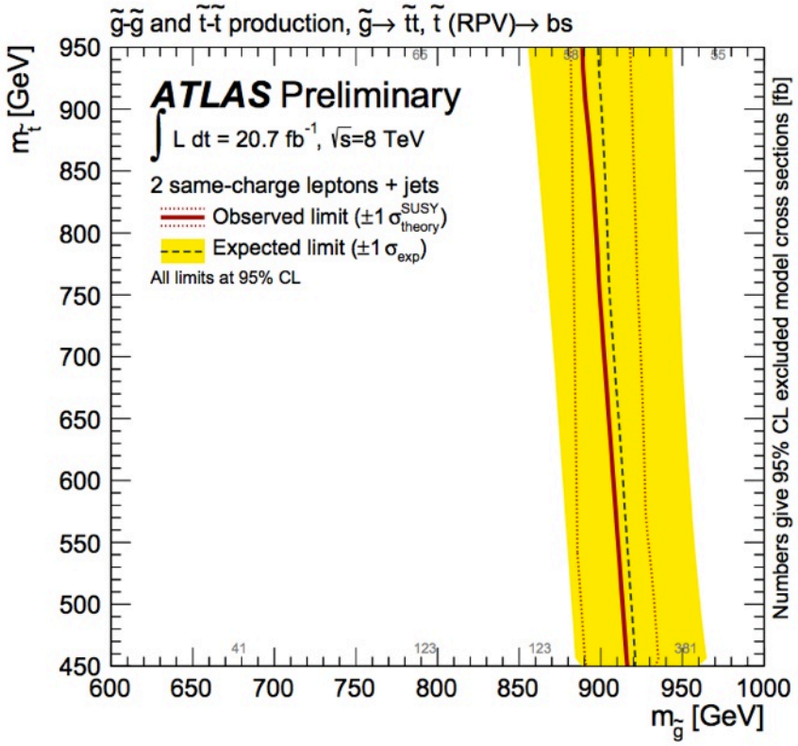
Stay Tuned!

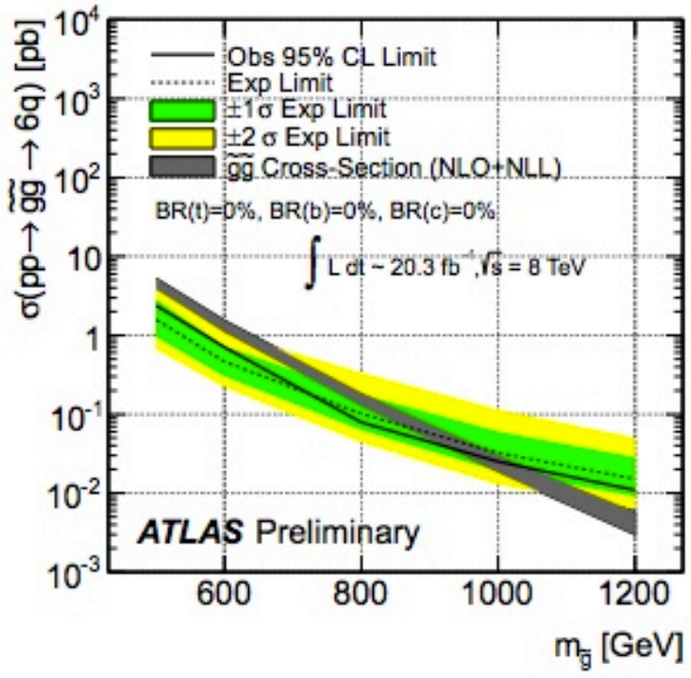
In the LHC era, model-building was increasingly intensively cultivated. Experimentalists robbed the huge fields, which had been created, *of the last vestiges of naturalness*. Most *landscapes became more natural*; at the same time natural model-building became more and more unnatural.

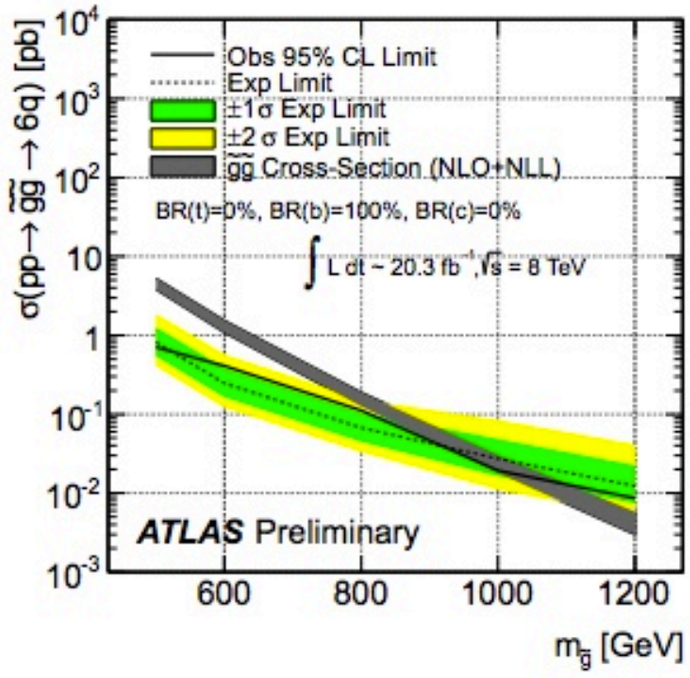
- Estonian Biodiversity Strategy and Action Plan, 1999

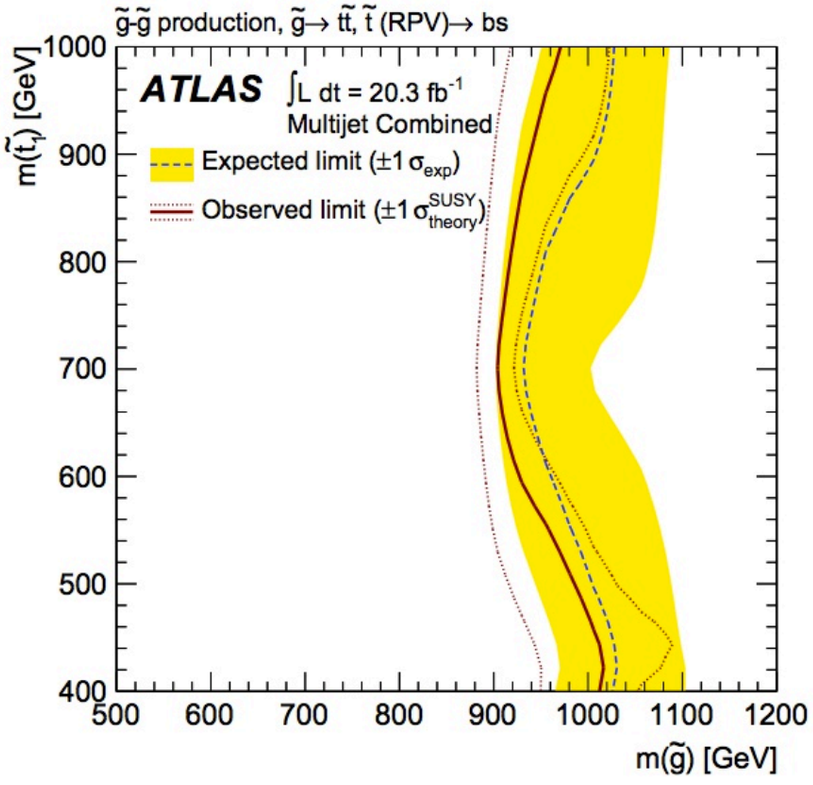
Backup

Baryonic RPV:
experimental limits

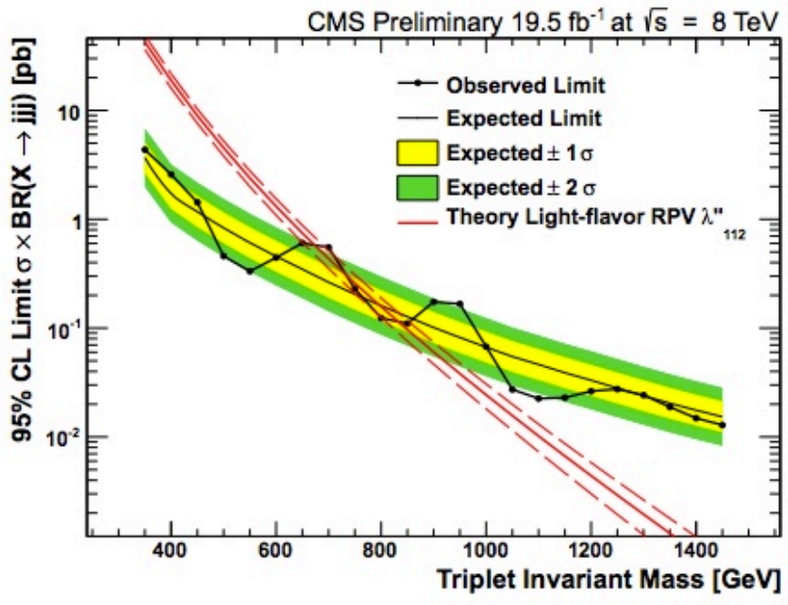




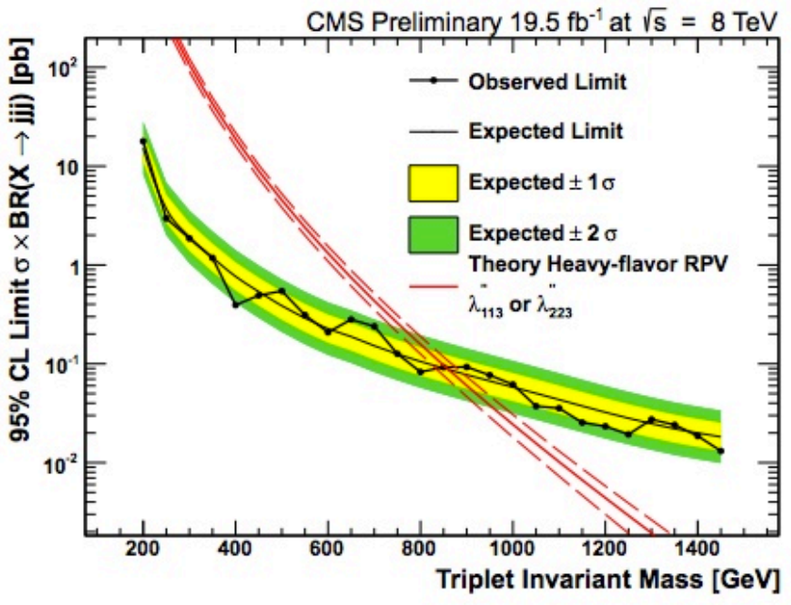




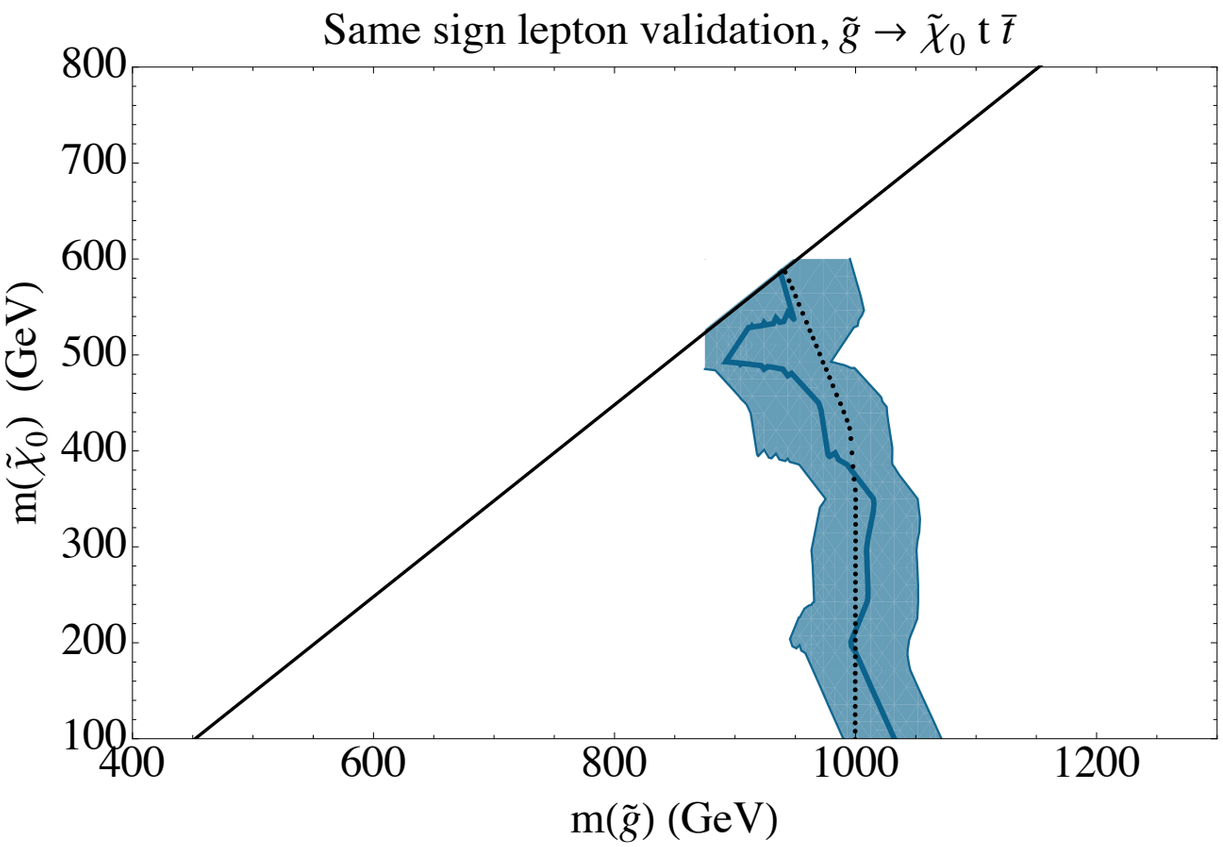
(a) (BR(t), BR(b), BR(c))=(0%,0%,0%)

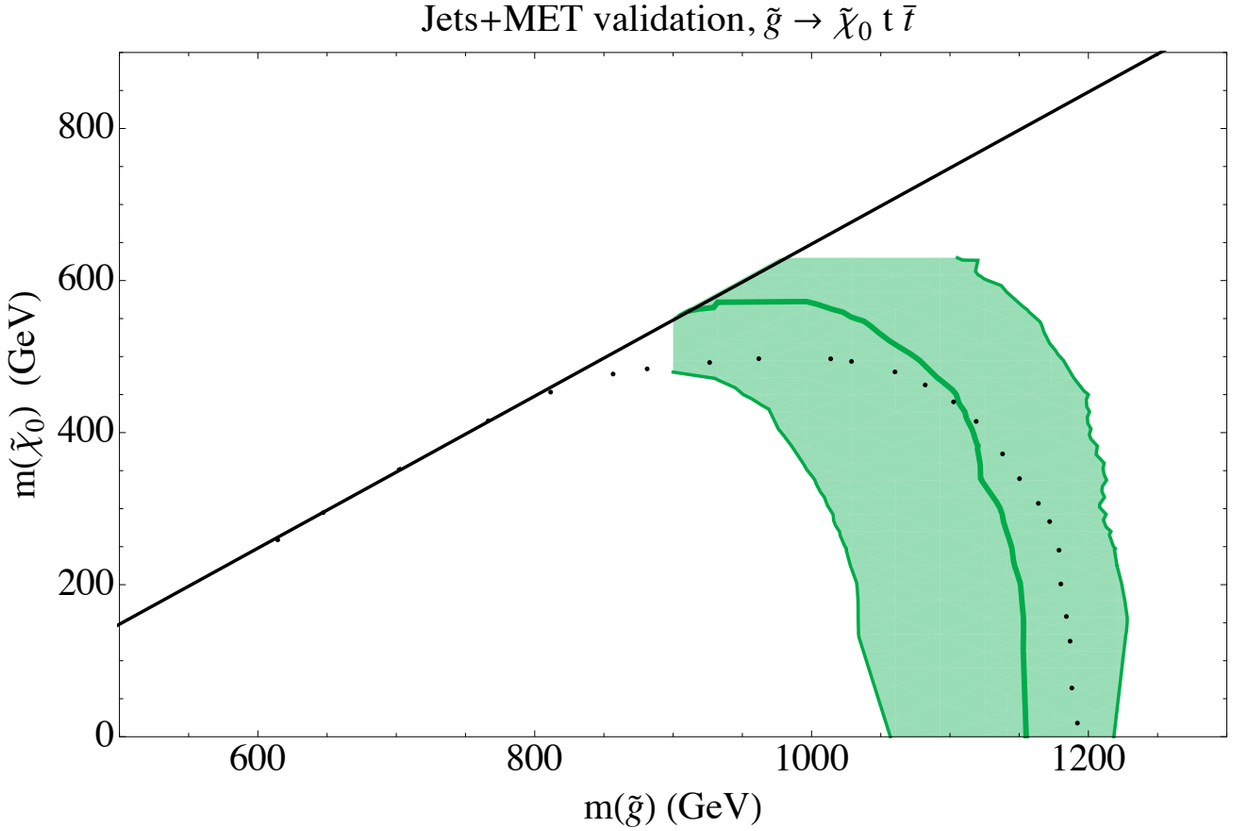


(b) (BR(t), BR(b), BR(c))=(0%,100%,0%)

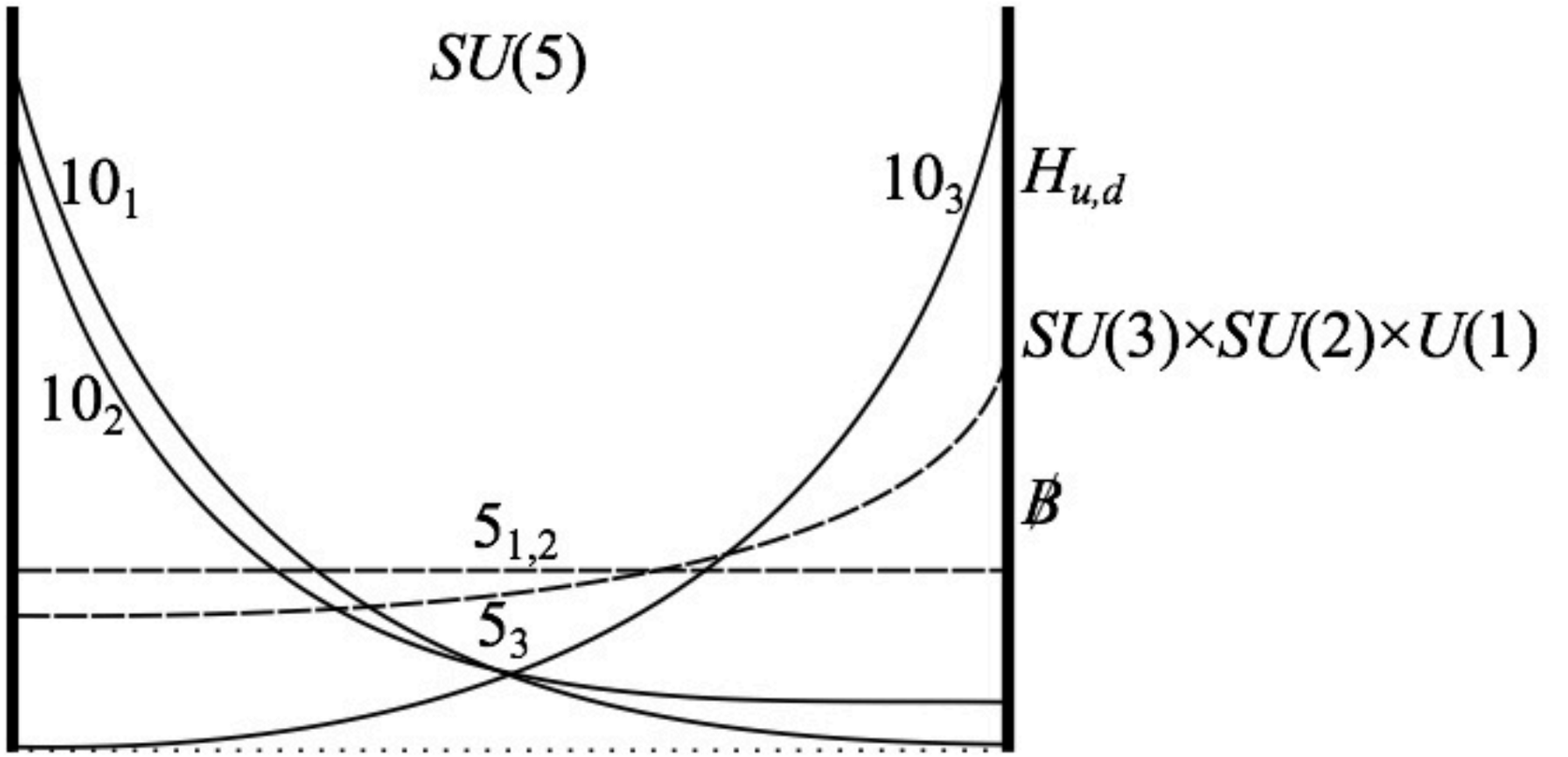


Baryonic RPV:
validation of recasting





RPV
model

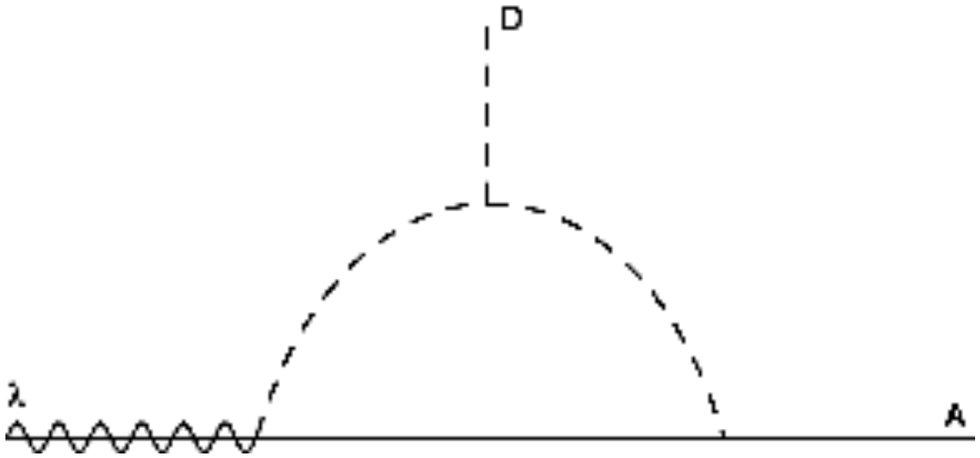


$$\mathcal{W}_{\not B} = \frac{\langle \Phi \rangle^2}{M_D^2} \, UDD|_{z=0}$$

Dirac Gauginos

$$\mathcal{L} \supset \underbrace{-m_{Di}\lambda_i^a \tilde{A}_i^a - \sqrt{2}m_{Di}\left(A_i^a + A_i^{a\dagger}\right) D_i}_{\text{`supersoft'}} + m_{A_i}^2 A_i^{a\dagger} A_i^a + B_{A_i}\left(A_i^a A_i^a + \text{h.c.}\right)$$

$$m^2_{\mathrm{Re}(A_i)} = 4m^2_{Di} + m^2_{A_i} + B_{A_i} \qquad m^2_{\mathrm{Im}(A_i)} = m^2_{A_i} - B_{A_i}$$



Split Families
model

$$\mathcal{W}_{\rm mess} = X_D(D'\overline{D}' + L'\overline{L}') + X_N N\overline{N}.$$

$$m^2_{\phi_i} \sim 2\sum_a C_a(i)\left(\frac{\alpha_a}{4\pi}\frac{F}{m_D}\right)^2 + (\delta_{1i}+\delta_{2i})\left(\frac{\alpha_\phi}{4\pi}\frac{F}{m_N}\right)^2$$

$$\begin{aligned}\mathcal{W}_{\rm MSSM} =& y^u_{ij} H_u Q_i U_j + y^u_3 H_u Q_3 U_3 + y^d_{ij} H_d Q_i D_j + y^d_3 H_d Q_3 D_3 + \\ & y^e_{ij} H_d L_i E_j + y^e_3 H_d L_3 E_3 + \mu H_u H_d \quad (i,j=1,2)\end{aligned}$$

$$\mathcal{W} \supset \lambda_i H_d Q_i D'' + \Phi \overline{D}'' D_3 + m_{D''} D''\overline{D}'' + V(\Phi)_{U(1)'\text{-breaking}} \qquad (i=1,2).$$

$$\mathcal{W}_{\rm mixing} = \lambda_i \frac{\langle\Phi\rangle}{m_{D''}} H_d Q_i D_3$$

$$m_{D''} > m_D > m_N \gtrsim \langle\Phi\rangle.$$