CAN MEASUREMENT OF 2HDM PARAMETERS PROVIDE A HINT FOR HIGH SCALE SUSY?

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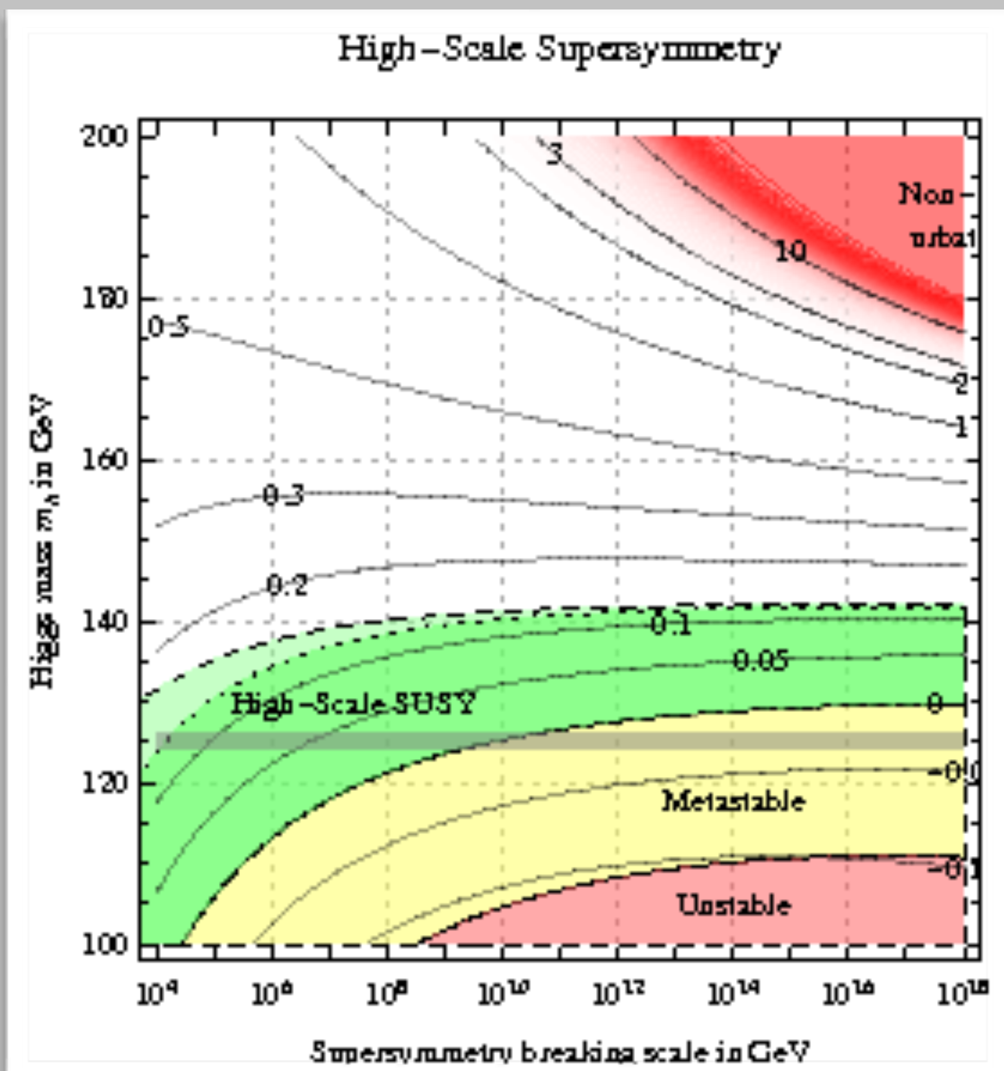
SUSY – HIGH AND LOW

<u>*High Scale SUSY*</u>

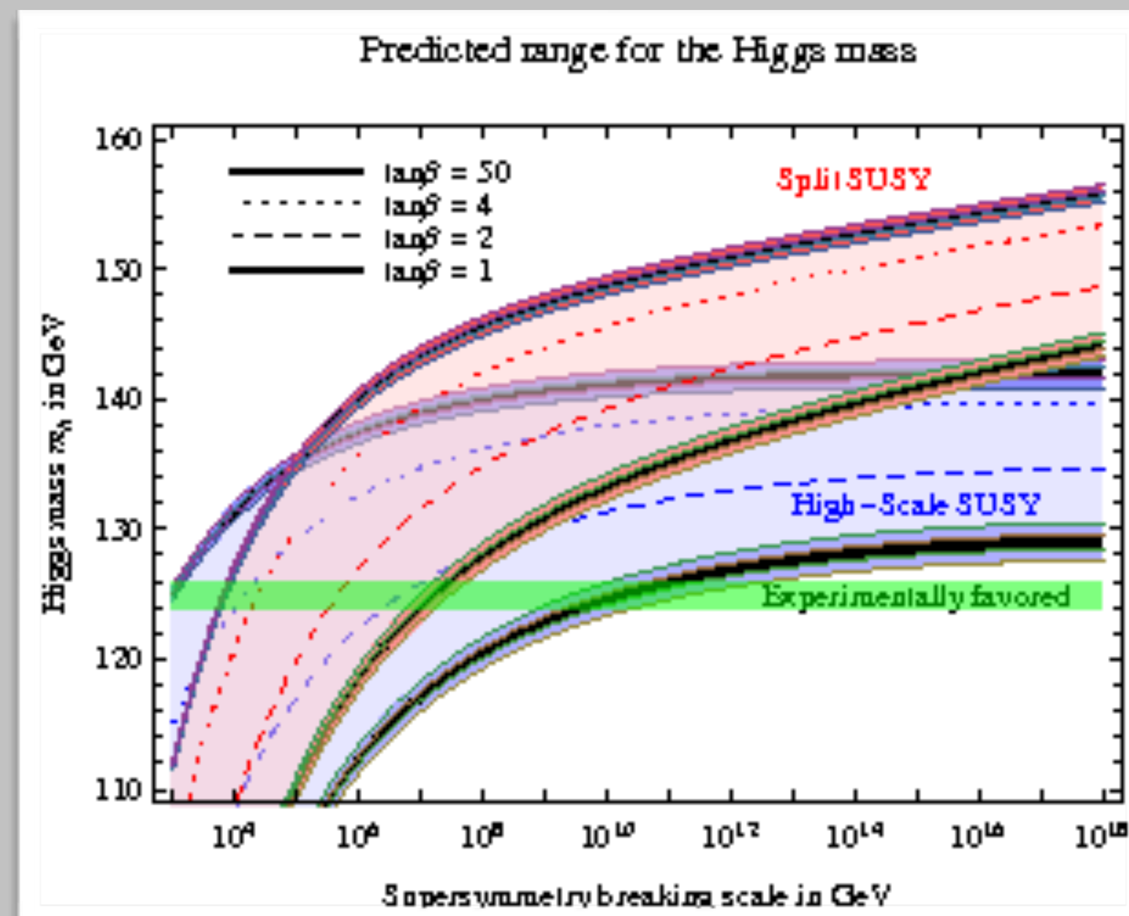
- Naturalness Solution ✗
- Gauge Coupling Unification ✓
- Viable Thermal Dark Matter candidate ✓

HIGH-SCALE SUSY AS AN UV COMPLETE THEORY

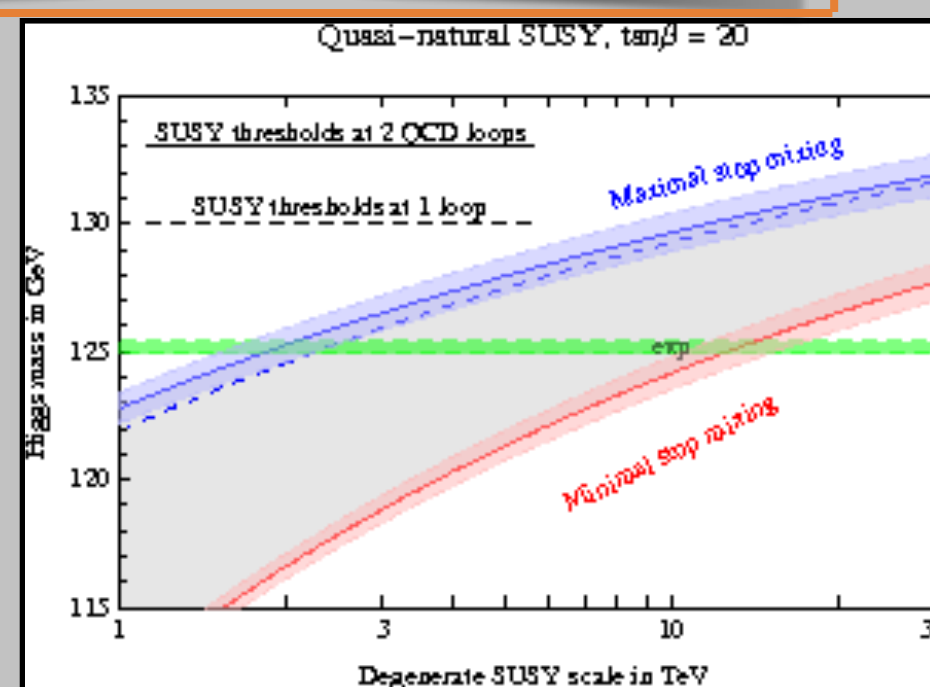
- *SM as the low energy effective theory :* *Vega & Villadoro 1504.05200; Isidori & Pattori 1710.11060;*



Nucl.Phys. B858 (2012) 63-83
Giudice, Strumia



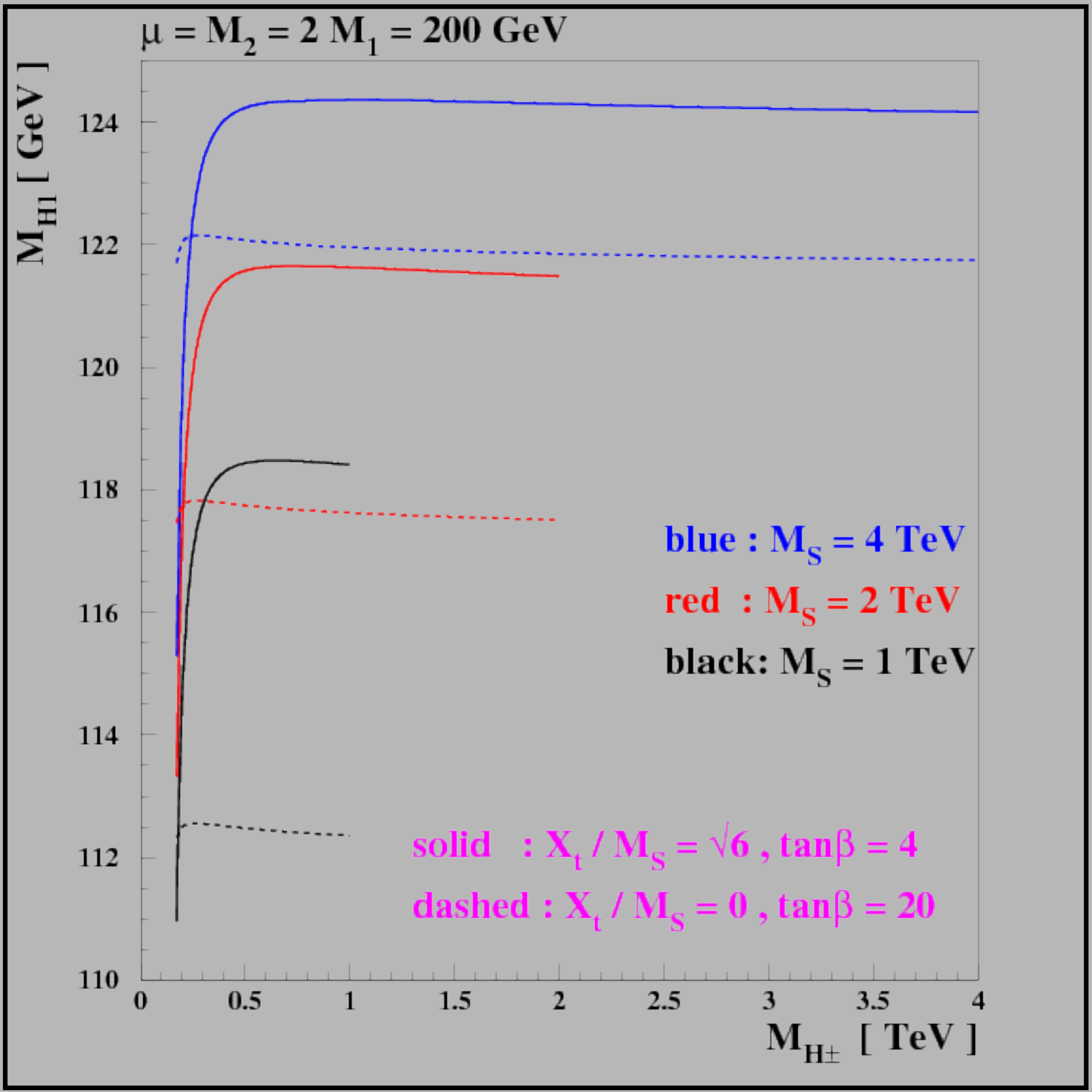
JHEP 1409 (2014) 092
Bagnaschi, Giudice, Slavich, Strumia



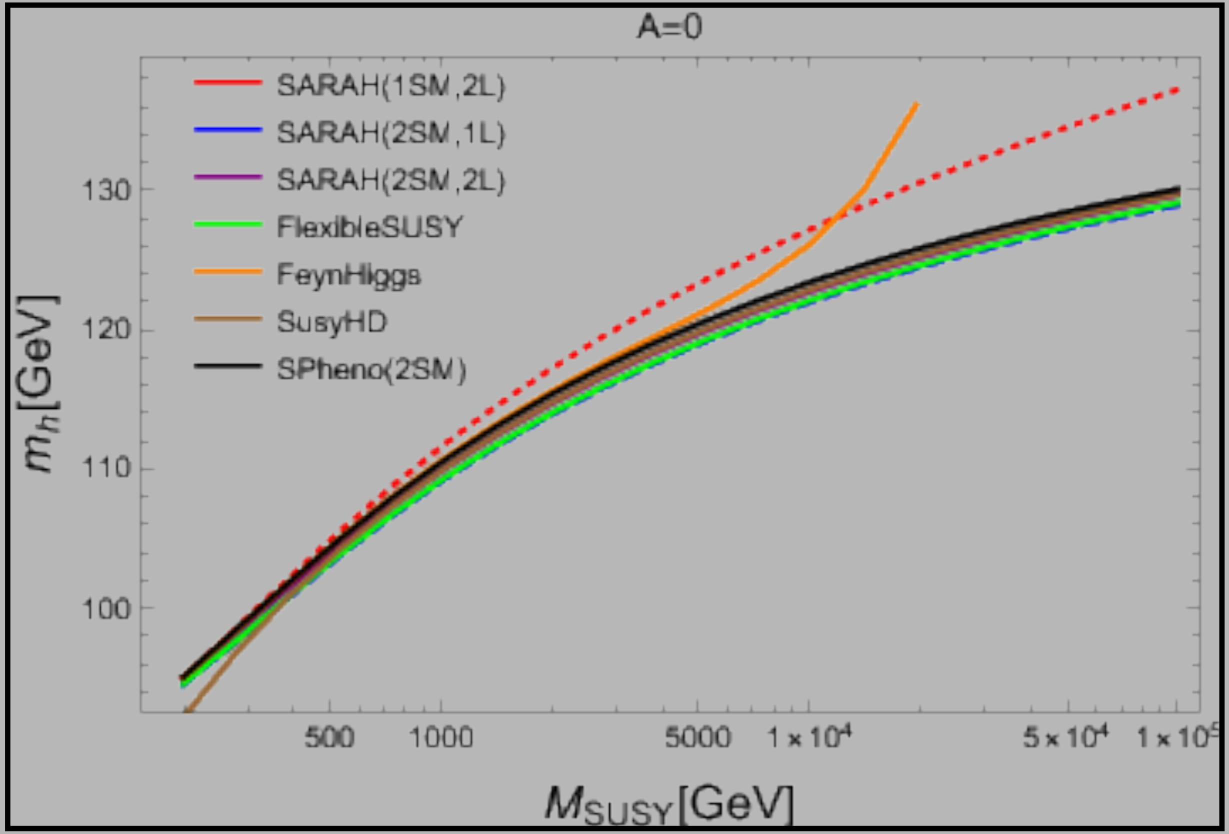
HIGH-SCALE SUSY AS AN UV COMPLETE THEORY

- *2HDM as an low energy effective theory : Moderately high SUSY scale*

Similar references: Athron et. al (1609.00371); Haber et. al (1708.04461); Chalons et. Al (1709.02332)



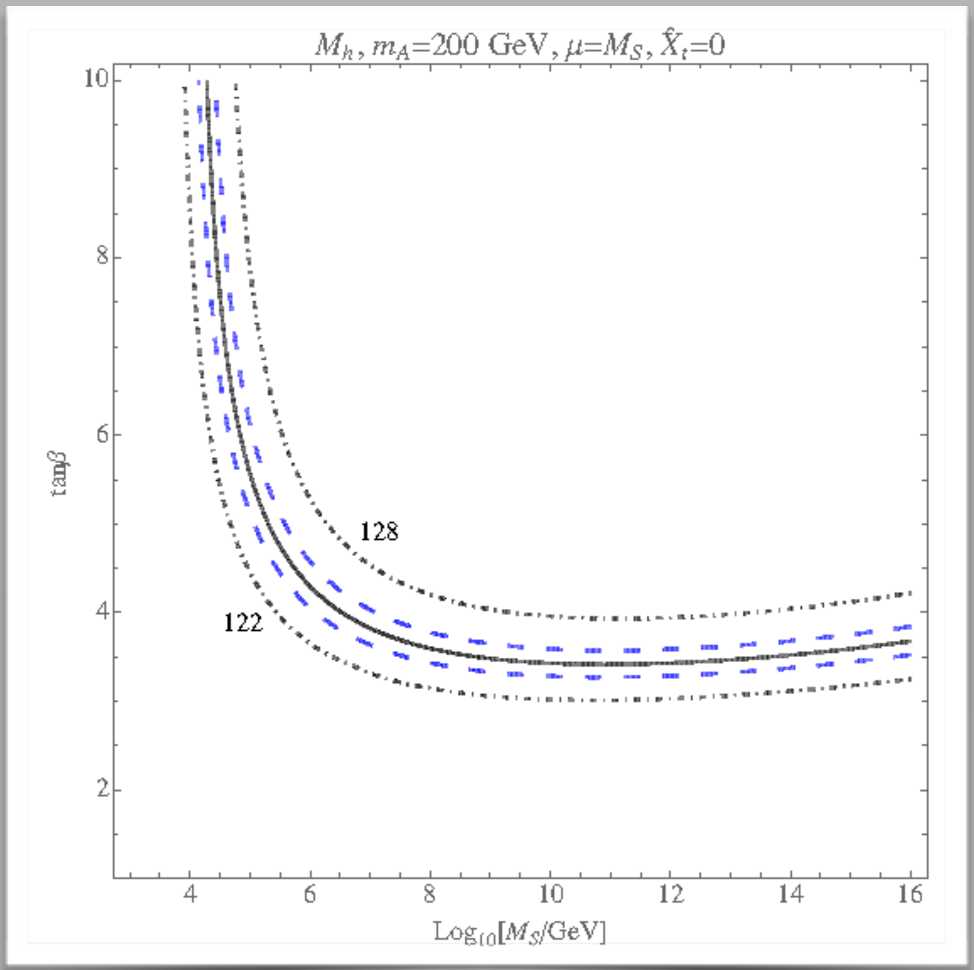
JHEP 1602 (2016) 123
Carena, Ellis, Lee, Pilaftsis, Wagner



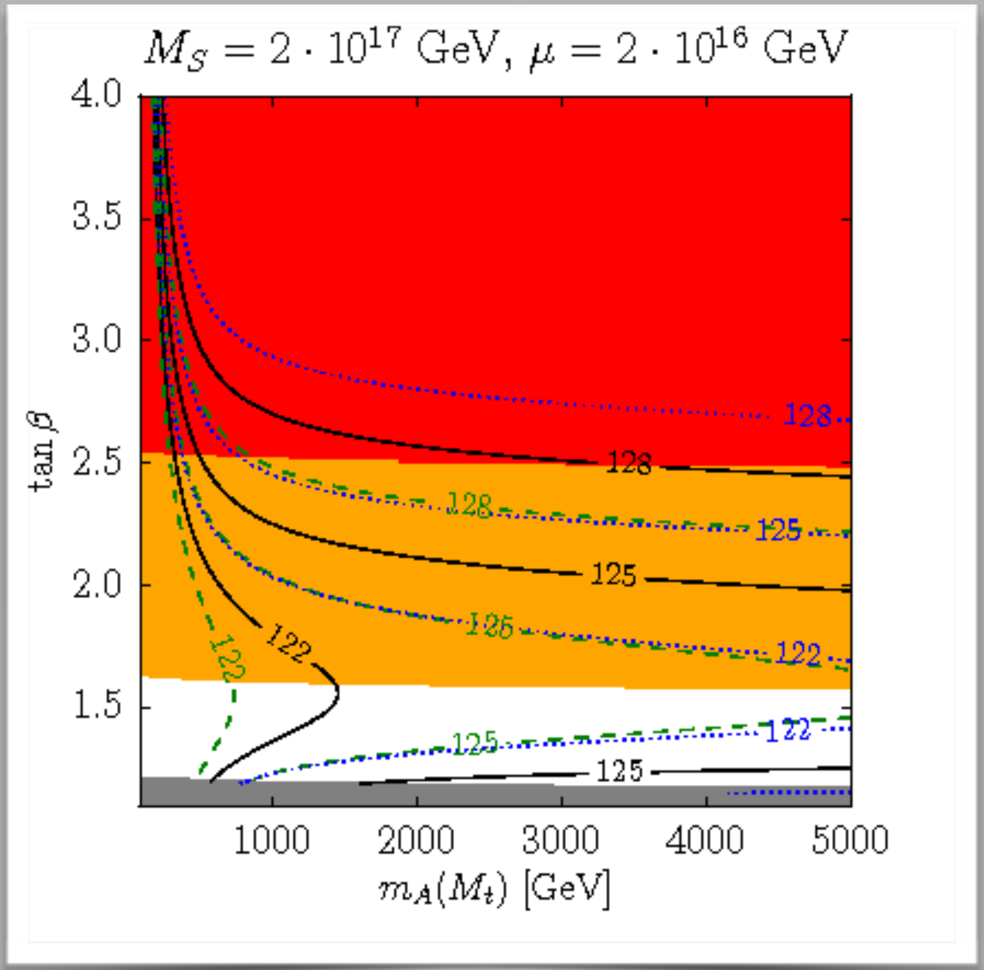
Eur.Phys.J. C77 (2017) no.5, 338
Staub & Pored

HIGH-SCALE SUSY AS AN UV COMPLETE THEORY

- *2HDM as an low energy effective theory : High SUSY scale*



Phys.Rev. D92 (2015) no.7, 075032
Li & Wagner



JHEP 1603 (2016) 158
Bagnaschi, Brummer, Buchmuller, Voigt, Weiblein

- *State of the art calculations. Matching at high scale.*
- *More information for low energy observables will be useful.*

BOTTOM-UP APPROACH

- *Spectrum of scalar masses and mixing measured at the EW scale.*
- *Run from low to high scale using 2HDM RGE.*
- *Check the SUSY boundary conditions at the high scale.*
- *Independent of the detail of the underlying theory of the matching conditions.*

PHYSICAL REVIEW D 97, 095018 (2018)

G.Bhattacharyya, D. Das, M. Jay Pe´rez, IS, A. Santamaria, and O. Vives

2HDM PARAMETER COUNTING

$$V_{II} = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - \left(m_{12}^2\phi_1^\dagger\phi_2 + \mathrm{h.c.}\right) + \frac{\lambda_1}{2}\left(\phi_1^\dagger\phi_1\right)^2 + \frac{\lambda_2}{2}\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right)$$

$$+\lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \left[\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \left(\lambda_6\left(\phi_1^\dagger\phi_1\right) + \lambda_7\left(\phi_2^\dagger\phi_2\right)\right)\left(\phi_1^\dagger\phi_2\right) + \mathrm{h.c.}\right]$$

- *Softly broken* Z_2 *symmetric potential* → $\lambda_6 = \lambda_7 = 0$
- *Type-II Structure :* ϕ_1 *couples only to down type fermions and* ϕ_2 *to up-type fermions*
- *Eight independent parameters* → *Five* $\lambda's$ *and three bilinear, or,*

$m_h, m_H, m_A, m_+, \tan\beta, v, cos(\beta - \alpha), m_{12}^2$

ANALYSIS

- *Higgs quartic couplings, at tree level, are simple functions of gauge couplings.*
- *Matching condition at High scale* Λ_S

$$\lambda_1 = \lambda_2 = \frac{1}{4}\left(g^2 + g_Y^2\right)\ ,\ \ \lambda_3 = \frac{1}{4}\left(g^2 - g_Y^2\right)\ ,\ \ \lambda_4 = -\frac{g^2}{2},\ \ \lambda_5 = \lambda_6 = \lambda_7 = 0$$

- *Only four quartic couplings to be determined.*
- *RG running below follows 2HDM RGEs.*

Run the RGEs at two-loop → *Inputs* $\rightarrow \tan\beta, \Lambda_S$

↓

Outputs $\rightarrow \cos(\beta-\alpha), \mathrm{m_+}, \mathrm{m_H}, \mathrm{m_A}$

- *Look for data driven region near* $\cos(\beta-\alpha) \simeq 0$

RESULTS: QUALITATIVE UNDERSTANDING

- *Evolution of gauge coupling combination,*

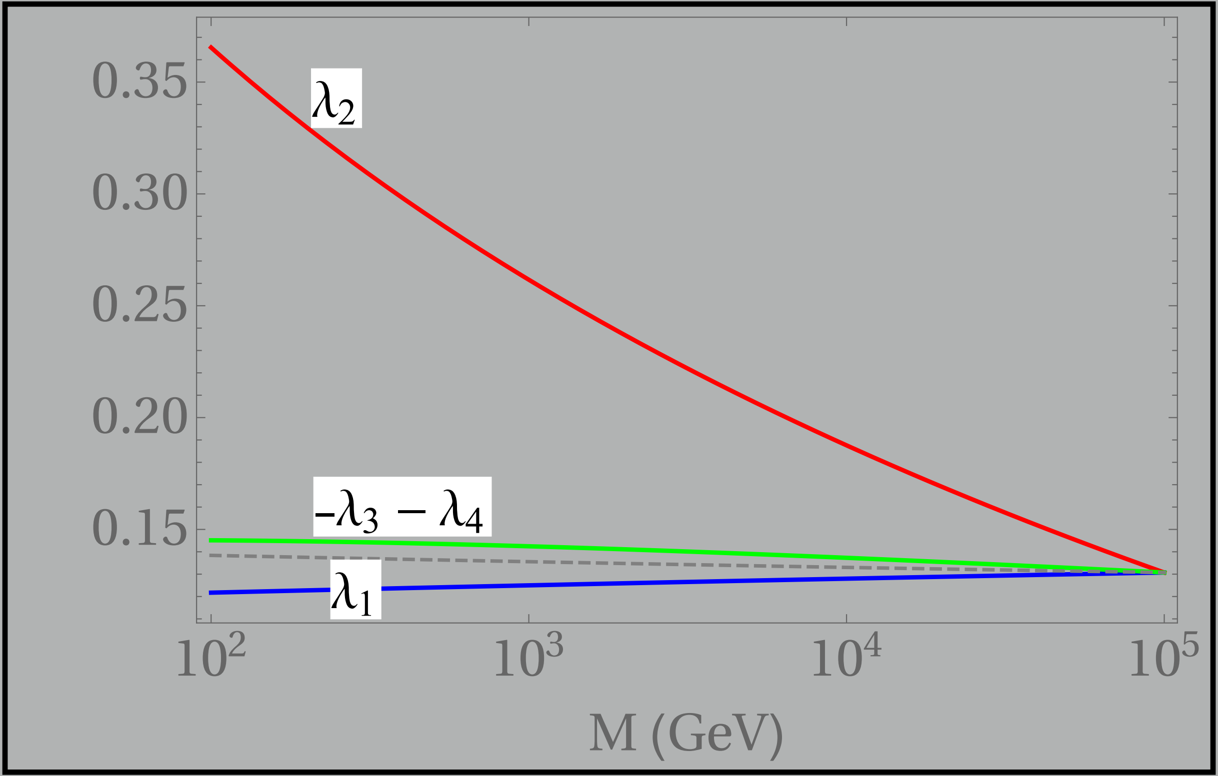
$$\mathscr{D}(g^2 + g_Y^2) = \frac{-3g^4 + 7g_Y^4}{8\pi^2}, \qquad (-3g^4 + 7g_Y^4)/(8\pi^2)\Big|_{M_z} \simeq 0.003$$

- *One-loop RGE of scalar quartics,*

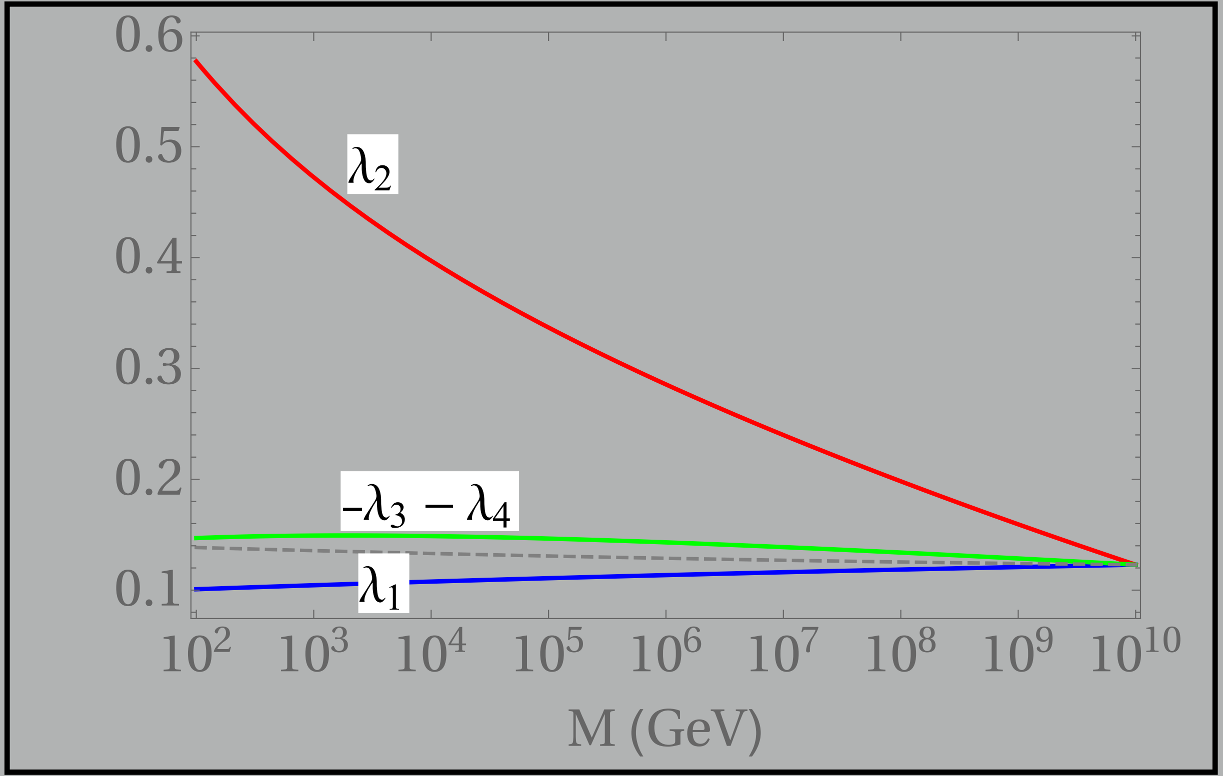
$$\mathscr{D}\lambda_1 = \frac{1}{16\pi^2}\Big[\frac{3}{4}\left(3g^4 + g_Y^4 + 2g^2g_Y^2\right) - 3\lambda_1\left(3g^2 + g_Y^2\right)$$
$$+12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 4\lambda_1\left(3y_b^2 + y_\tau^2\right) - 12y_b^4 - 4y_\tau^4\Big]$$
$$\mathscr{D}\lambda_2 = \frac{1}{16\pi^2}\Big[\frac{3}{4}\left(3g^4 + g_Y^4 + 2g^2g_Y^2\right) - 3\lambda_2\left(3g^2 + g_Y^2\right)$$
$$+12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 12\lambda_2 y_t^2 - 12y_t^4\Big]$$
$$\mathscr{D}\lambda_3 = \frac{1}{16\pi^2}\Big[\frac{3}{4}\left(3g^4 + g_Y^4 - 2g^2g_Y^2\right) - 3\lambda_3\left(3g^2 + g_Y^2\right)$$
$$+2\left(\lambda_1 + \lambda_2\right)\left(3\lambda_3 + \lambda_4\right) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_3\left(3y_t^2 + 3y_b^2 + y_\tau^2\right) - 12y_t^2y_b^2\Big]$$
$$\mathscr{D}\lambda_4 = \frac{1}{16\pi^2}\Big[3g^2g_Y^2 - 3\lambda_4\left(3g^2 + g_Y^2\right)$$
$$+2\left(\lambda_1 + \lambda_2 + 4\lambda_3\right)\lambda_4 + 4\lambda_4^2 + 2\lambda_4\left(3y_t^2 + 3y_b^2 + y_\tau^2\right) + 12y_t^2y_b^2\Big]$$

- *Only* λ_2 *should have significant evolution due to the large top Yukawa coupling* $y_t \sim \mathcal{O}(m_t/(v\sin\beta))$
- *2-loop running is essential in the close proximity of unit* $\tan\beta$

RESULTS: RUNNING QUARTICS



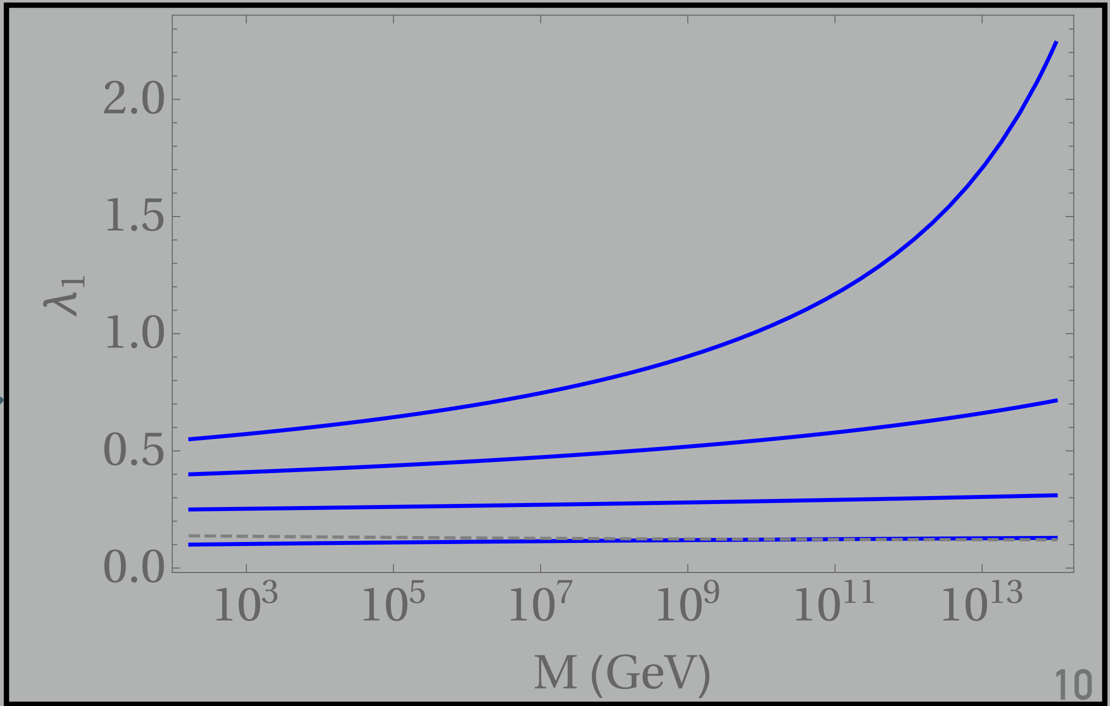
$\tan\beta \sim 3,\ \Lambda_S = 10^5$ GeV



$\tan\beta \sim 2,\ \Lambda_S = 10^{10}$ GeV

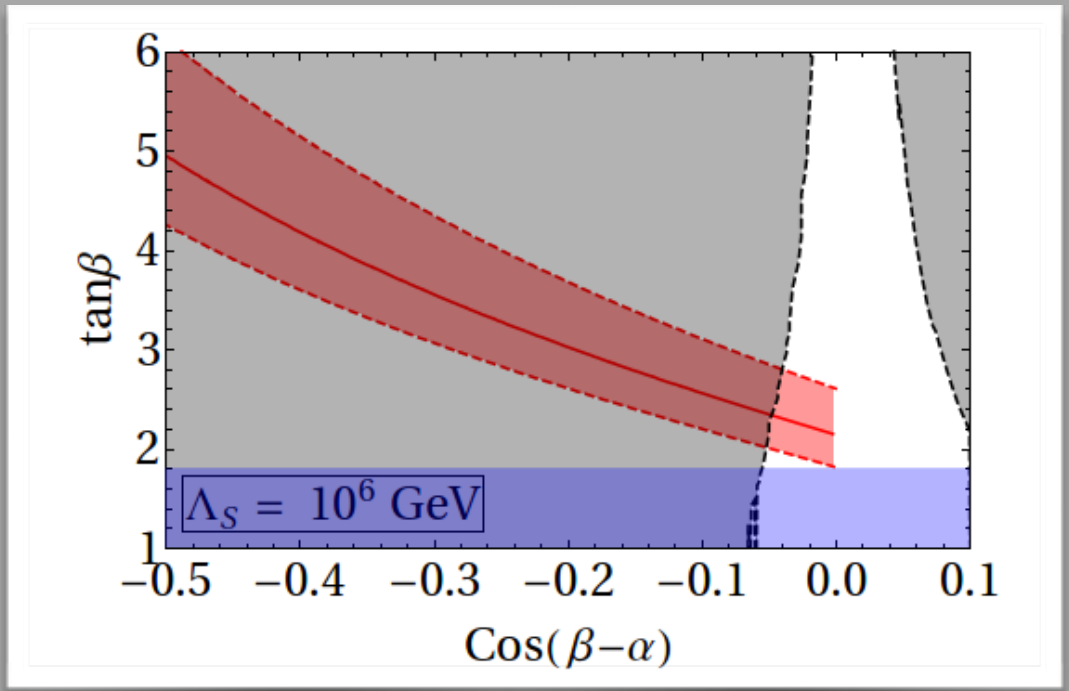
- *Comparison with* $\frac{(g^2+g_Y^2)}{4}$ *2-loop matching.*
- *At the SUSY scale,* $\lambda_1 = \lambda_2 = -(\lambda_3+\lambda_4) = (g^2+g_Y^2)/4$
- *Result is independent of* $\tan\beta$

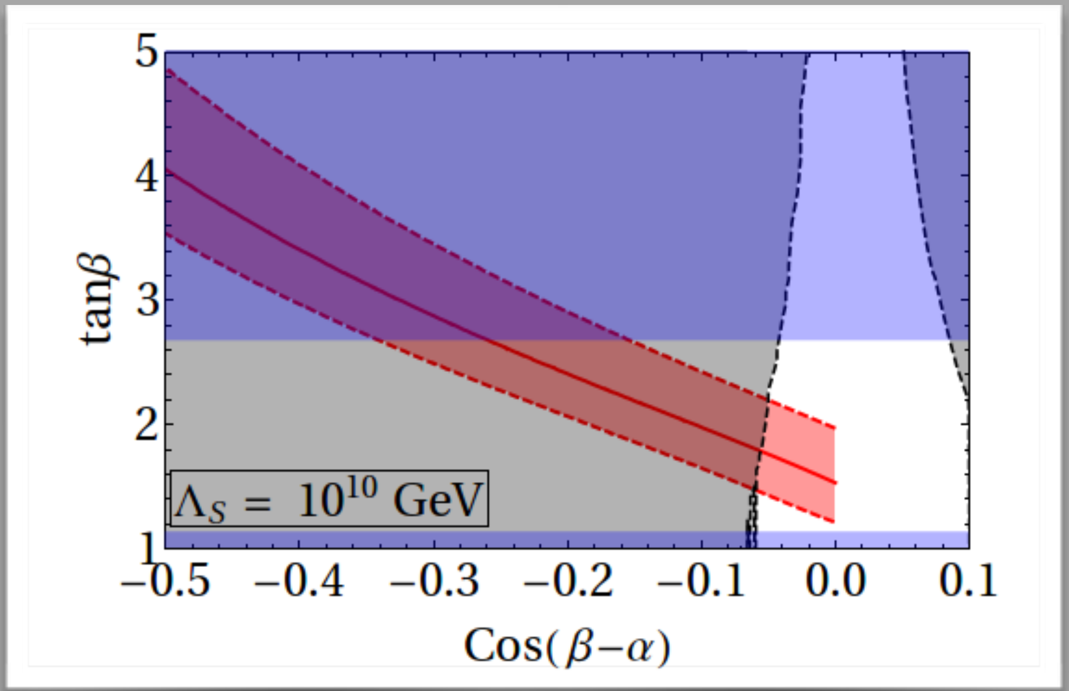
λ_1 running for $\lambda_1|_{(EW)} = 0.1, 0.25, 0.4, 0.55$ with $\lambda_2 = 0.56, \lambda_3 = 0.015$ and $\lambda_4 = -0.16$ for $\tan\beta = 2$.

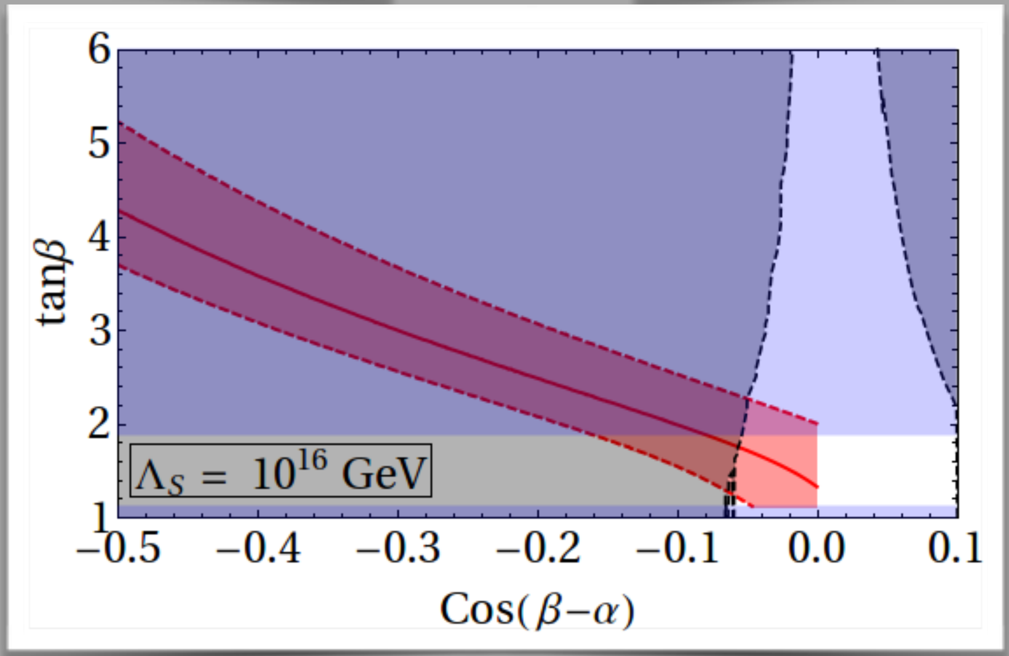


SUSY SCALE DETERMINATION

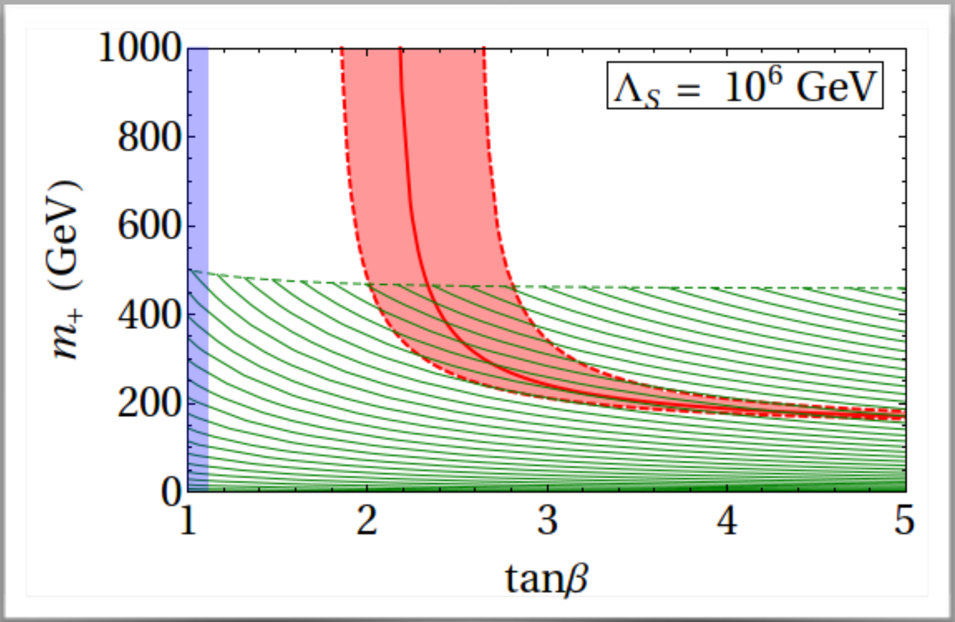
- *The shaded blue region corresponds to absolute vacuum of the potential.*
- *The current or projected value of* $\cos(\beta - \alpha)$ *will narrow down the region of all the scalar masses and* $\tan\beta$

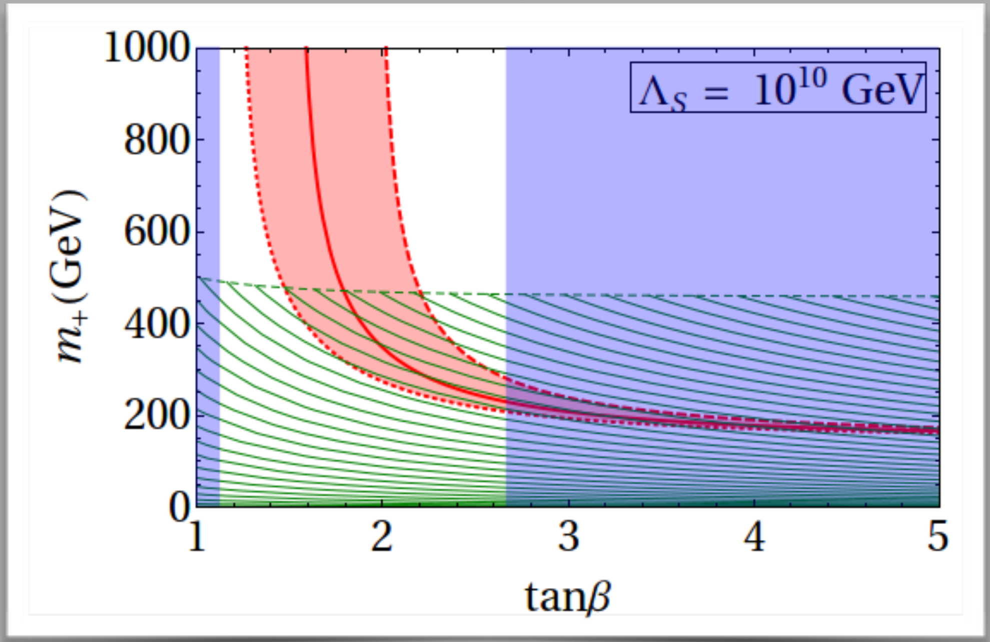


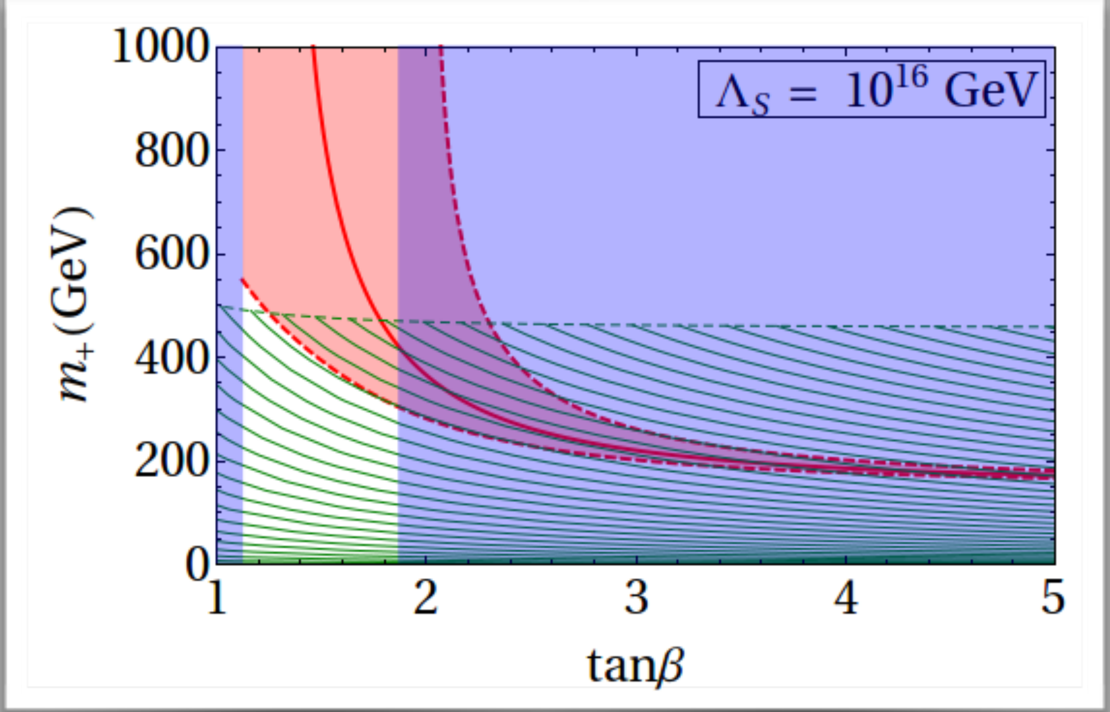




SUSY SCALE DETERMINATION

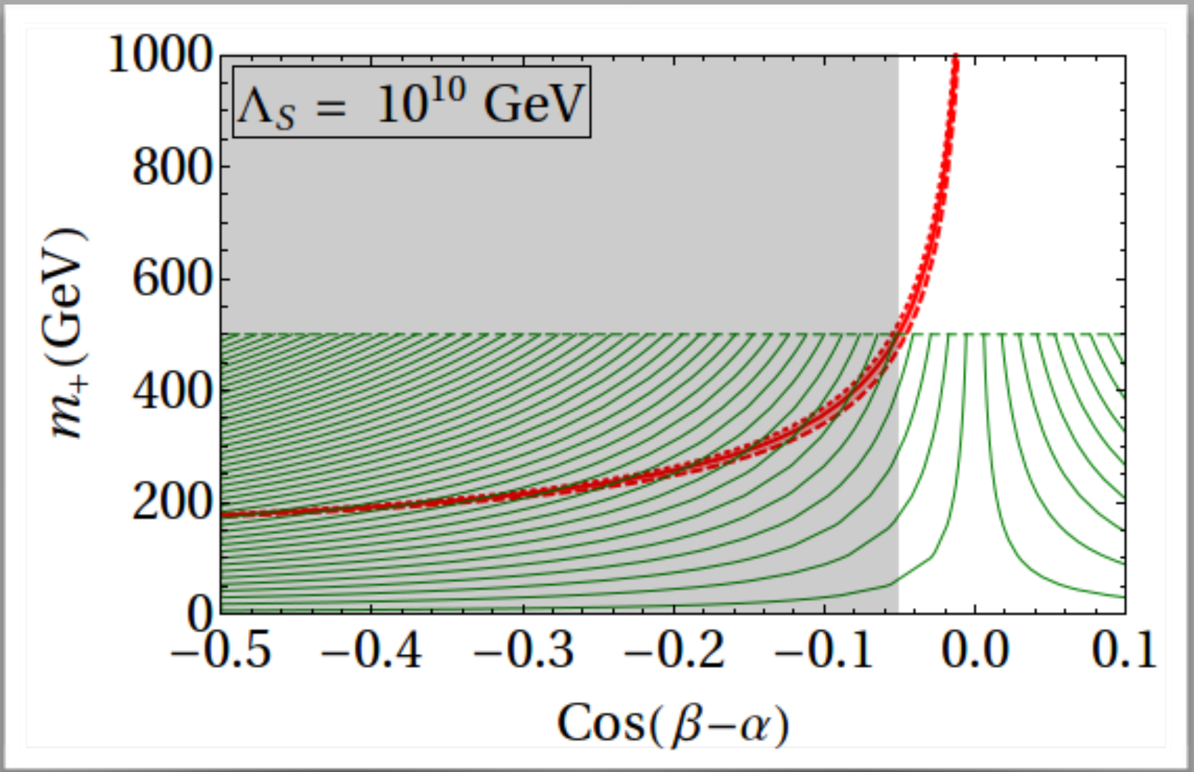


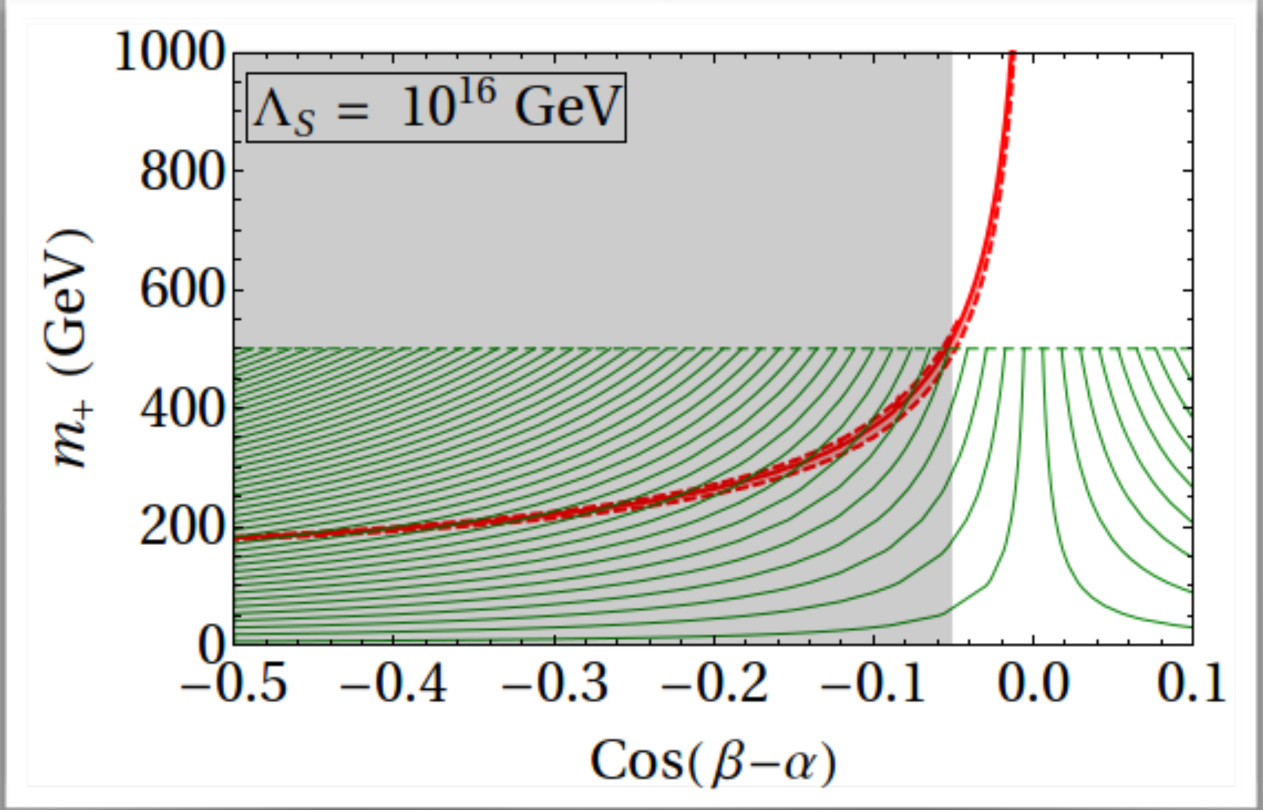




- *Dashed region denotes the constraints on charged Higgs mass from flavor observable $b \to s\gamma$*

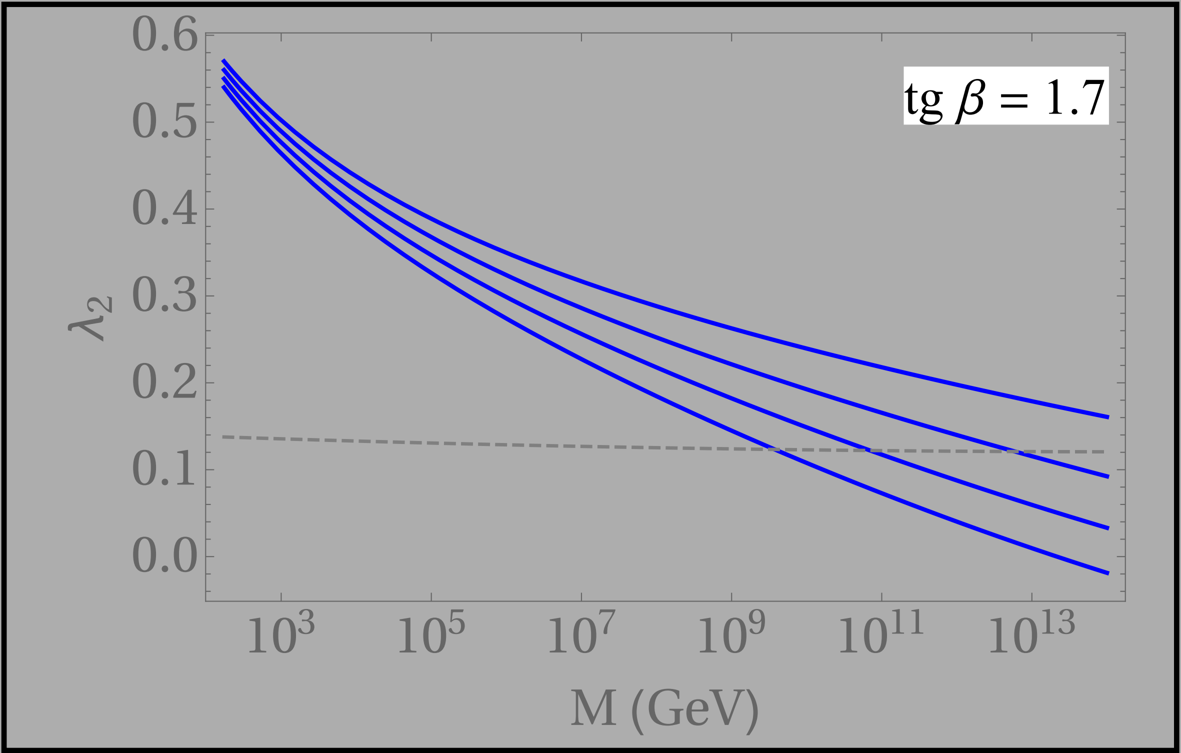
SUSY SCALE DETERMINATION

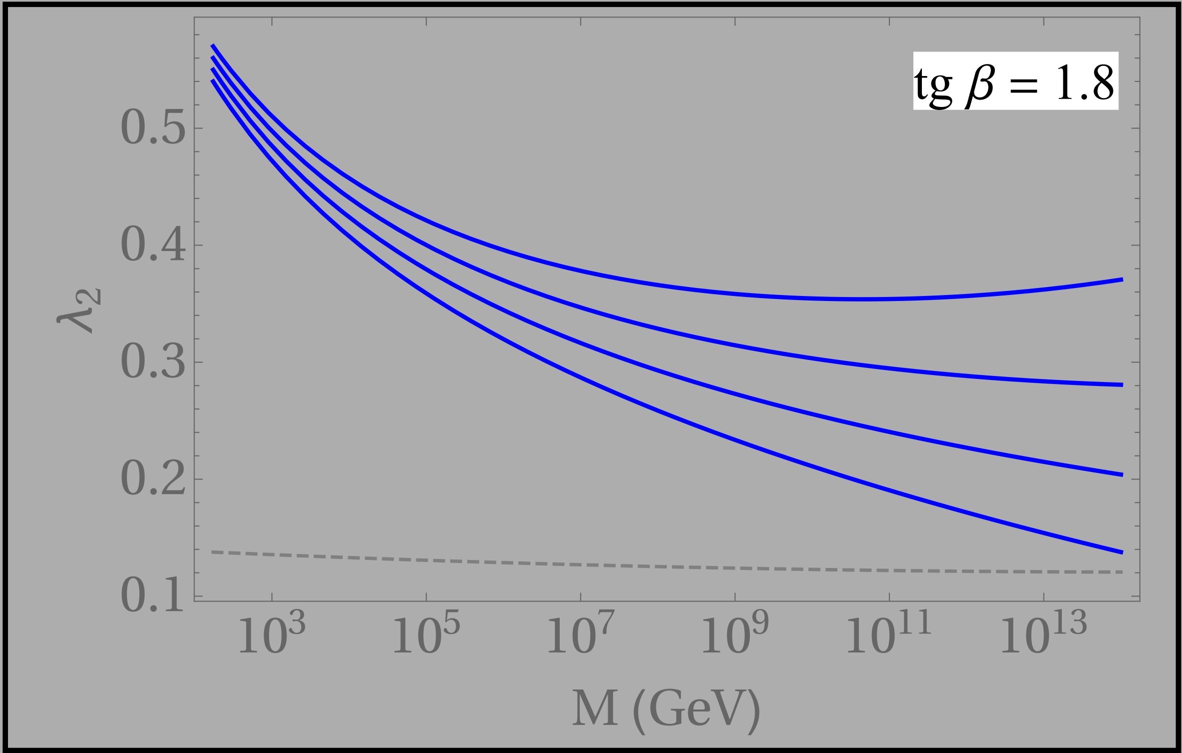




- *The* m_+ *and* $\cos(\beta - \alpha)$ *is strongly correlated despite input uncertainties.*
- *The bounds on one can be translated to the other.*

AN A POSTERIORI EXPLANATION





- *The Solution is sensitive to* m_t *and* $\tan\beta$. *Uncertainties can be translated as*

$$\Delta \tan\beta = \tan\beta(1+\tan^2\beta)(\Delta m_t/m_t)$$

- *To a good approximation,*

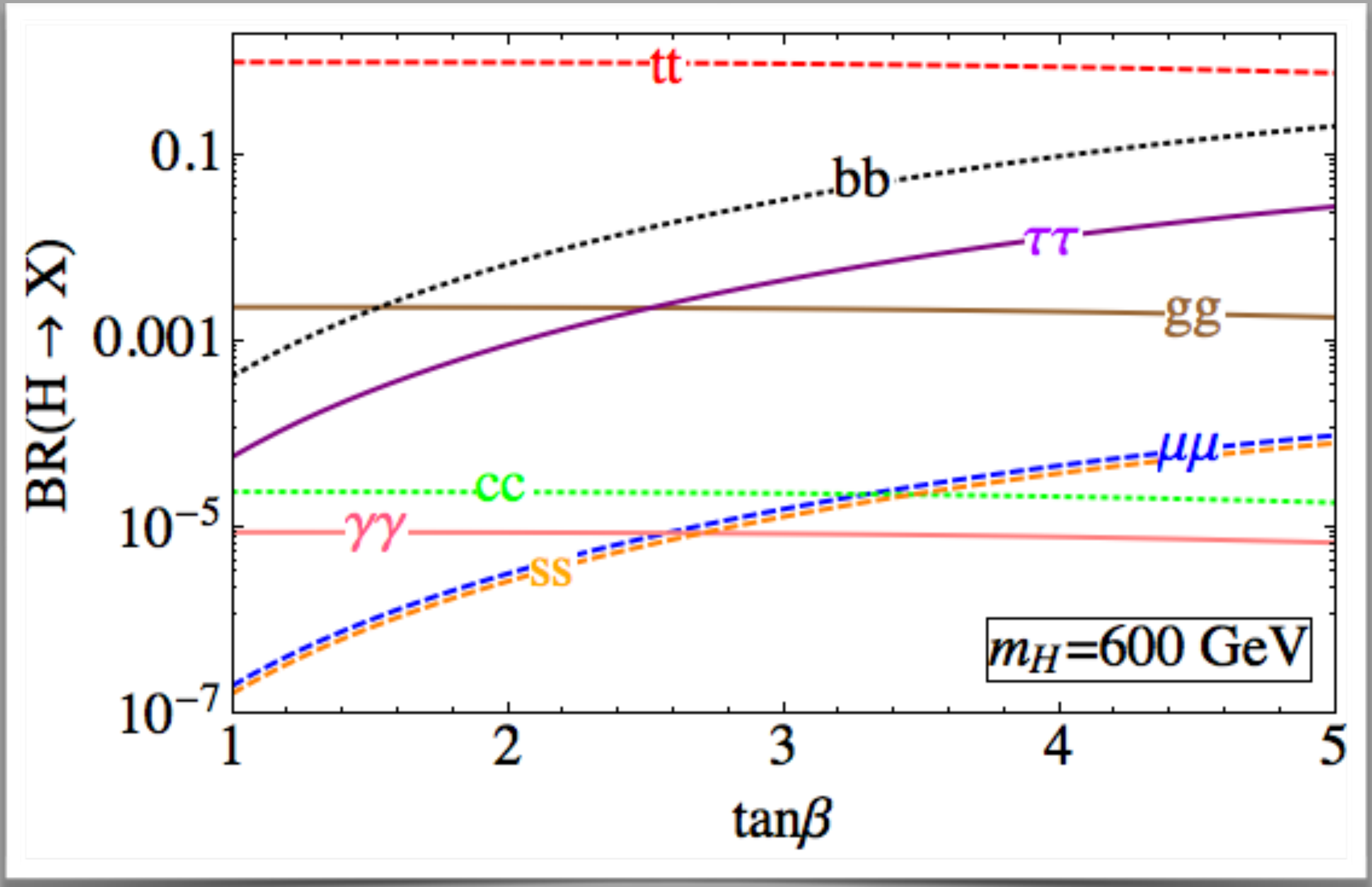
$$\lambda_1(M_Z) \simeq \lambda_1(\Lambda_S) = \lambda_2(\Lambda_S) = \frac{(g^2+g_Y^2)}{4} = -\left\{\lambda_3(\Lambda_S)+\lambda_4(\Lambda_S)\right\} \simeq -\left\{\lambda_3(M_Z)+\lambda_4(M_Z)\right\}$$

- *The Higgs mass,*

$$m_h^2 = M_Z^2\cos^2(2\beta) + \Delta\lambda_2 v^2\,\frac{\tan^4\beta}{\left(1+\tan^2\beta\right)^2}, \qquad \Delta\lambda_2 = \lambda_2(M_Z) - \lambda_2(\Lambda_S\,.)$$

PHENOMENOLOGICAL IMPLICATIONS

- *Branching ratios of different decay channels mainly depend on* $\tan\beta$
- *Observation of extra scalars can be tested.*
- *An example plot for* $m_H = 600$ GeV



CONCLUSIONS

- *We have considered a general framework for fixing the 2HDM parameter space.*
- *We assume that the low energy effective 2HDM is embedded in a large theoretical framework at UV.*
- *The quartic couplings are unambiguously determined at High scale.*
- *MSSM is a well motivated scenario. Even if super-partners are super-heavy, the ancestral symmetry leaves it imprints on low scale observables and observation of nonstandard scalar provide a hint towards the high SUSY scale.*
- *This strategy, however, crucially depends on whether* $\tan\beta$ *can be determined with a percent level precision in order to make a reasonable prediction for the MSSM scale.*
- *Our methodology is quite general, can be applied to a wide category of UV scenarios.*

THANK YOU

BACK UPS

A RECENT STUDY

Heavy Higgs bosons at low $\tan\beta$ *: from the LHC to 100 TeV*

Craig, Hajer, Li, Liu and Zhang : JHEP 01(2017) 018