

HINTS FOR HIGH SCALE SUSY

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*Berkeley Week
Jan 8 - Jan 11, 2019*



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THE UNIVERSITY OF TOKYO

SUSY – HIGH AND LOW

High Scale SUSY

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

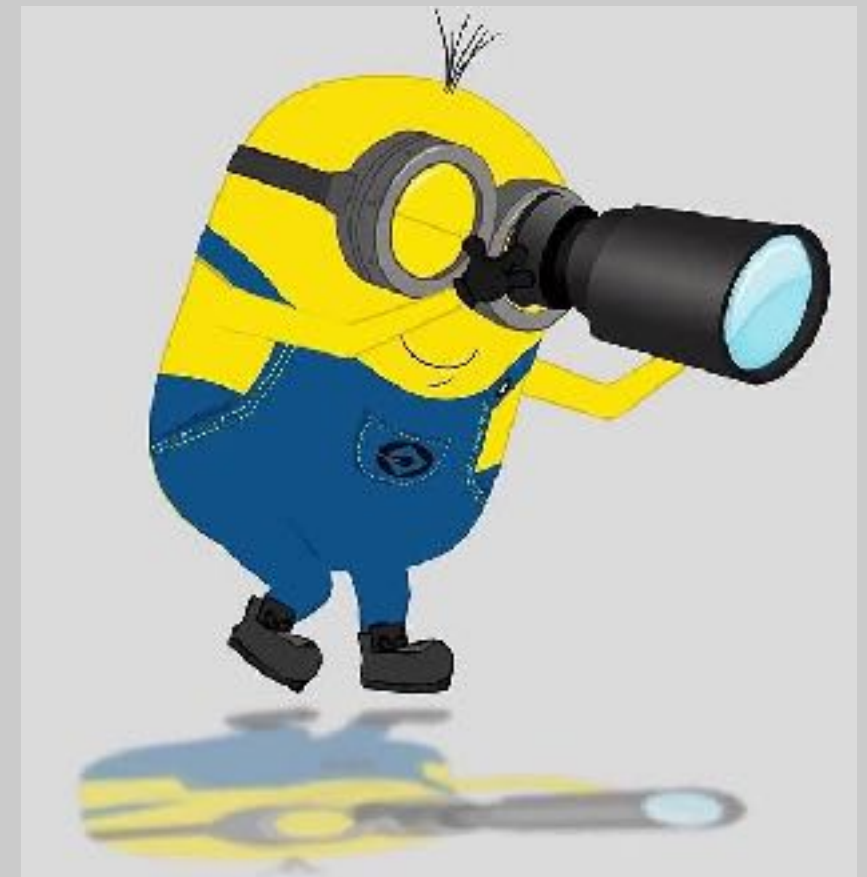


PRAGMATIC POINT OF VIEW

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- Motivation to collider searches.
- Plethora of non-standard particles from low energy BSM scenario.

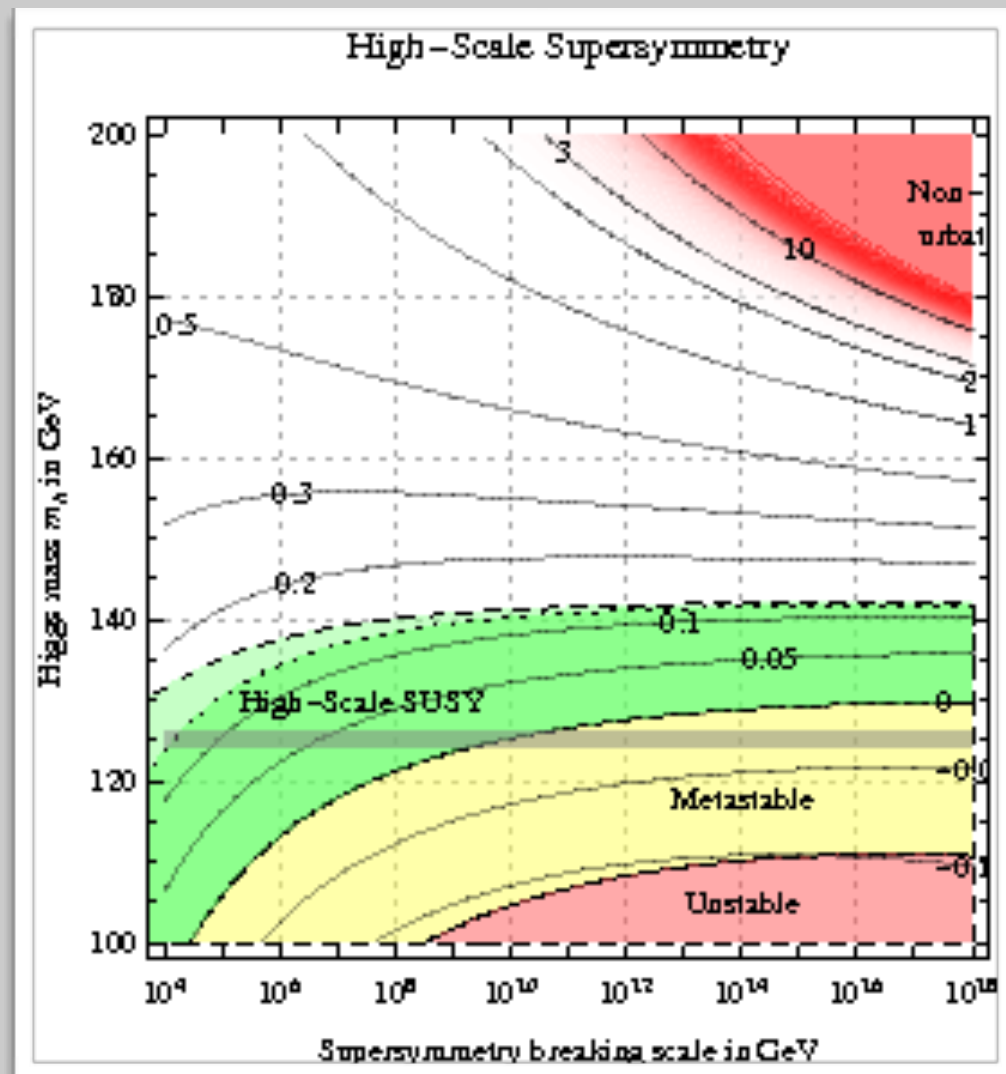
What to look for



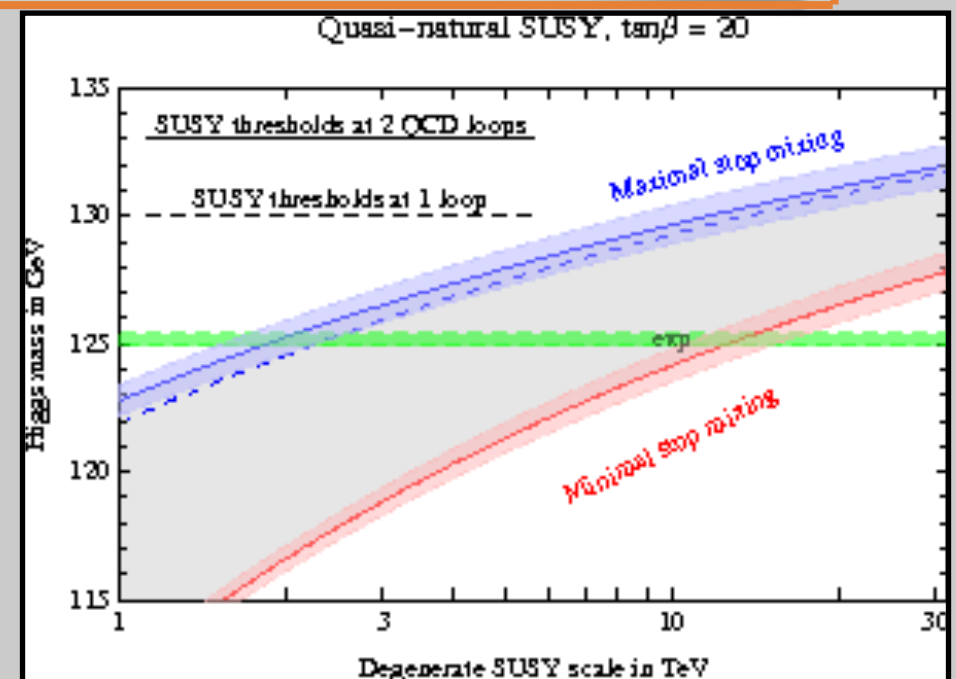
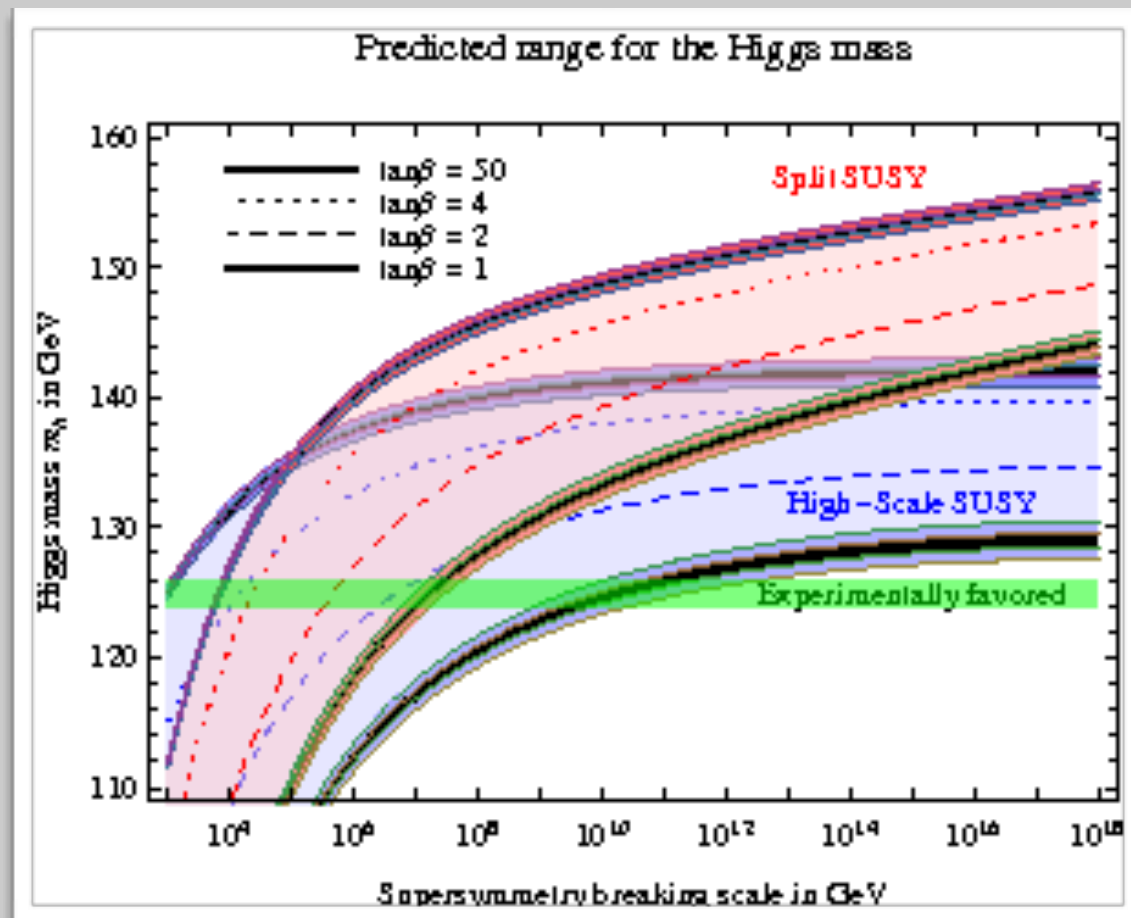
Where to look for?

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

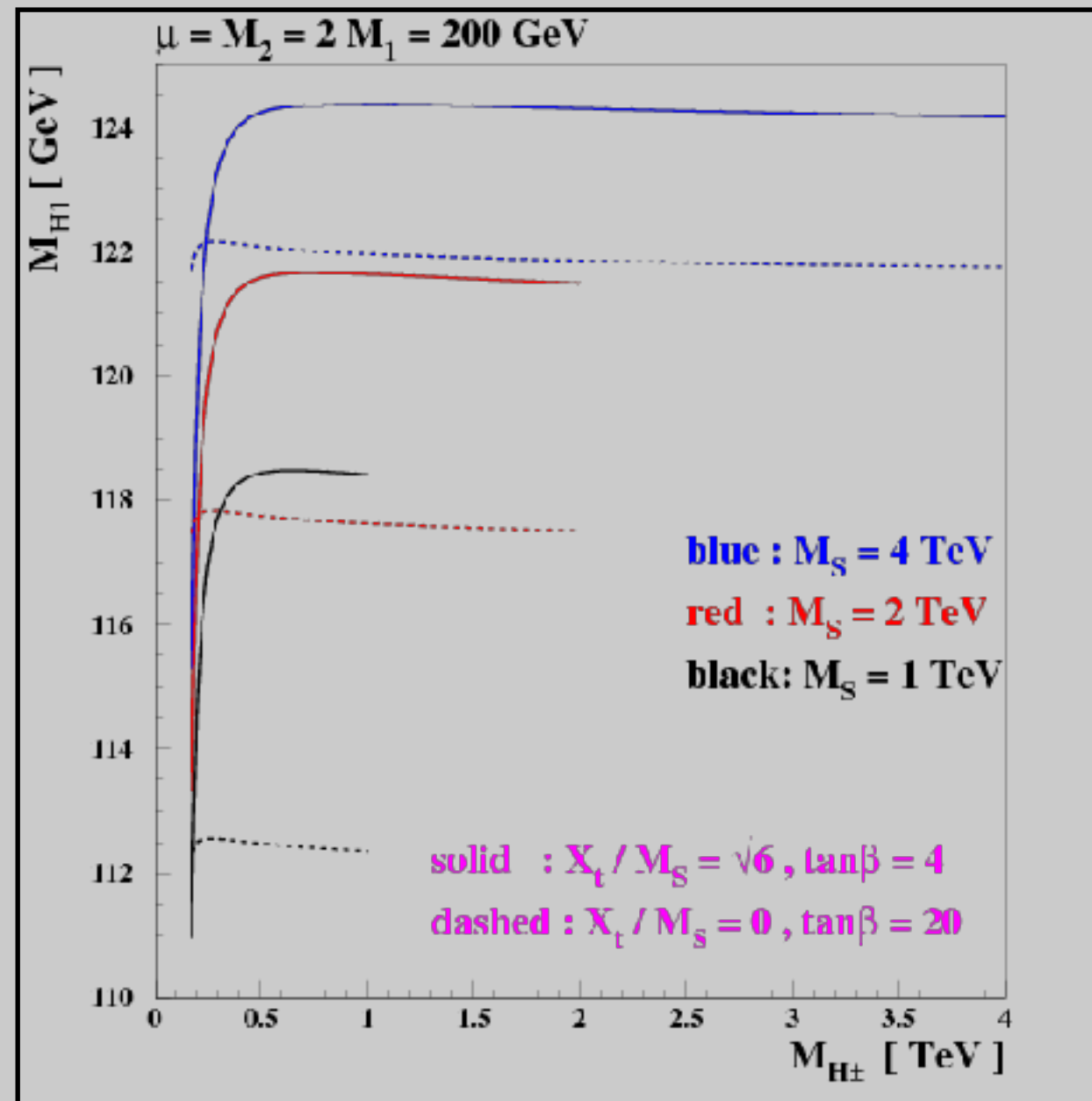


JHEP 1409 (2014) 092
Bagnaschi, Giudice, Slavich, Strumia

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); Staub & Porod (1703.03627); Haber et. al (1708.04461); Chalons et. Al (1709.02332)

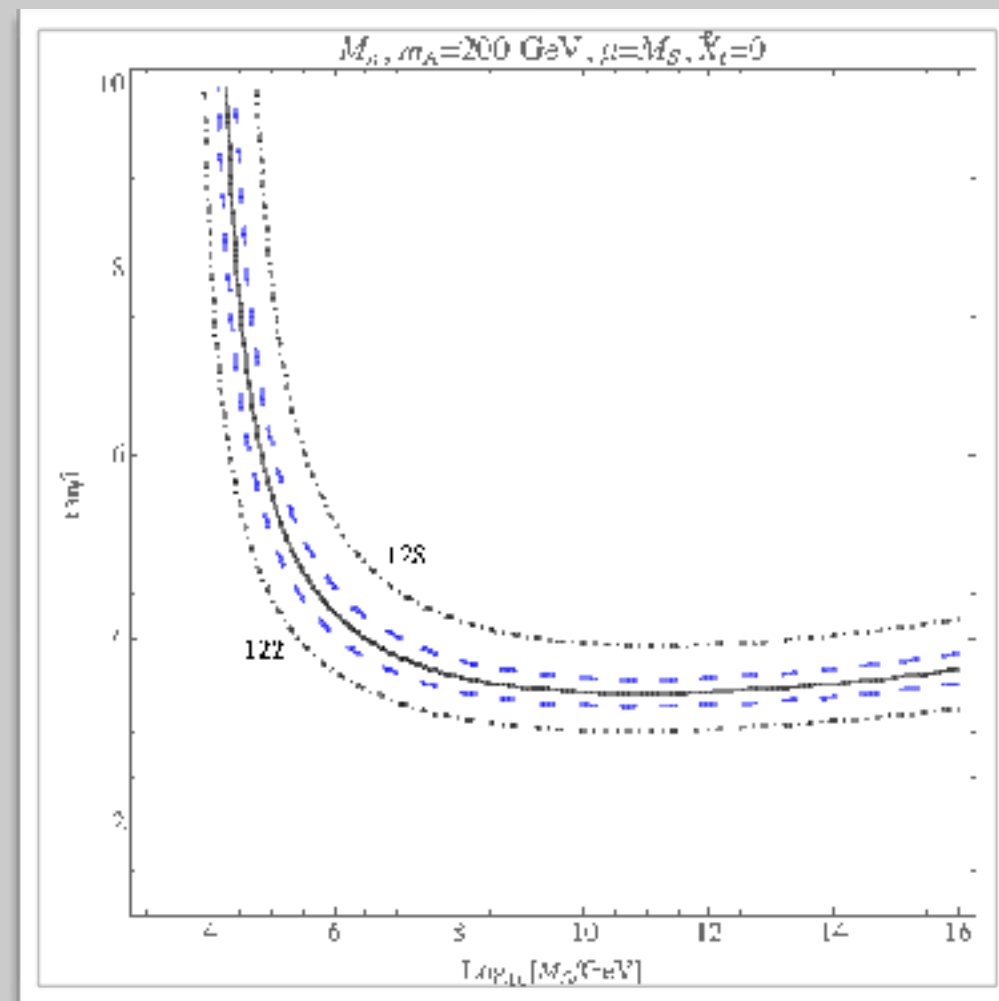


JHEP 1602 (2016) 123

Carena, Ellis, Lee, Pilaftsis, Wagner

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
Lee & Wagner

Similar references: Bagnaschi et al. JHEP 1603 (2016) 158

- *State of the art calculations. Matching at high scale.*

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 Pérez, IS, A. Santamaria, and O. Vives

2HDM PARAMETER COUNTING

$$V_H = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - \left(m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} \left(\phi_1^\dagger \phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\phi_2^\dagger \phi_2 \right)^2 + \lambda_3 \left(\phi_1^\dagger \phi_1 \right) \left(\phi_2^\dagger \phi_2 \right) \\ + \lambda_4 \left(\phi_1^\dagger \phi_2 \right) \left(\phi_2^\dagger \phi_1 \right) + \left[\frac{\lambda_5}{2} \left(\phi_1^\dagger \phi_2 \right)^2 + \left(\lambda_6 \left(\phi_1^\dagger \phi_1 \right) + \lambda_7 \left(\phi_2^\dagger \phi_2 \right) \right) \left(\phi_1^\dagger \phi_2 \right) + \text{h.c.} \right]$$

- *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 λ 's and three bilinear, or,*
 $m_h, m_H, m_A, m_+, \tan \beta, v, \cos(\beta - \alpha), m_{12}^2$

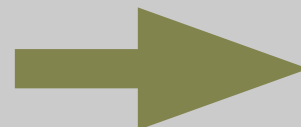
ANALYSIS

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

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

- 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 $\rightarrow \cos(\beta - \alpha), m_+, m_H, m_A$

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

RESULTS: QUALITATIVE UNDERSTANDING

- Evolution of gauge coupling combination,

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

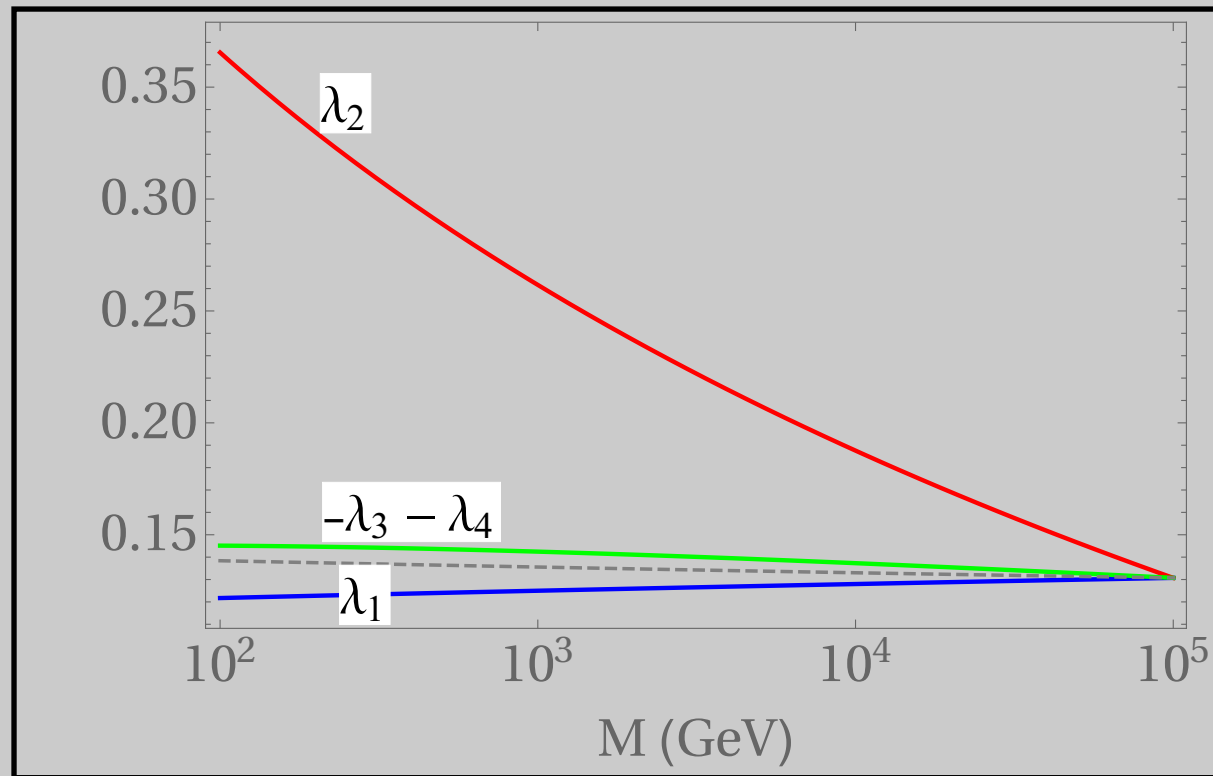
- One-loop RGE of scalar quartics,

$$\begin{aligned} \mathcal{D}\lambda_1 &= \frac{1}{16\pi^2} \left[\frac{3}{4} (3g^4 + g_Y^4 + 2g^2g_Y^2) - 3\lambda_1 (3g^2 + g_Y^2) \right. \\ &\quad \left. + 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 4\lambda_1 (3y_b^2 + y_\tau^2) - 12y_b^4 - 4y_\tau^4 \right] \\ \mathcal{D}\lambda_2 &= \frac{1}{16\pi^2} \left[\frac{3}{4} (3g^4 + g_Y^4 + 2g^2g_Y^2) - 3\lambda_2 (3g^2 + g_Y^2) \right. \\ &\quad \left. + 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 12\lambda_2 y_t^2 - 12y_t^4 \right] \\ \mathcal{D}\lambda_3 &= \frac{1}{16\pi^2} \left[\frac{3}{4} (3g^4 + g_Y^4 - 2g^2g_Y^2) - 3\lambda_3 (3g^2 + g_Y^2) \right. \\ &\quad \left. + 2(\lambda_1 + \lambda_2)(3\lambda_3 + \lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_3 (3y_t^2 + 3y_b^2 + y_\tau^2) - 12y_t^2 y_b^2 \right] \\ \mathcal{D}\lambda_4 &= \frac{1}{16\pi^2} \left[3g^2g_Y^2 - 3\lambda_4 (3g^2 + g_Y^2) \right. \\ &\quad \left. + 2(\lambda_1 + \lambda_2 + 4\lambda_3)\lambda_4 + 4\lambda_4^2 + 2\lambda_4 (3y_t^2 + 3y_b^2 + y_\tau^2) + 12y_t^2 y_b^2 \right] \end{aligned}$$

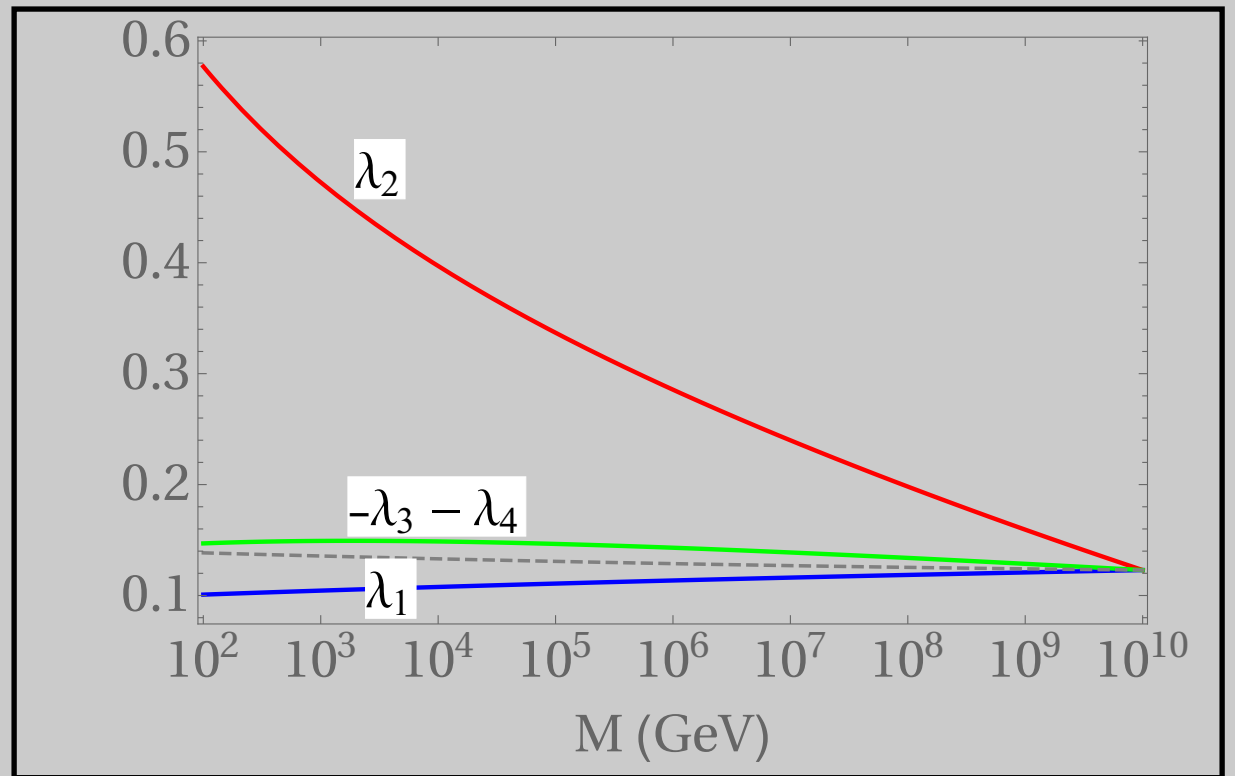
- Only λ_2 should have significant evolution due to the large top Yukawa coupling $y_t \sim \mathcal{O}(m_t/(v \sin \beta))$
- 2-loop running is essential in the close proximity of unit $\tan \beta$

RESULTS: RUNNING QUARTICS

PHYSICAL REVIEW D 97, 095018
(2018)



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



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

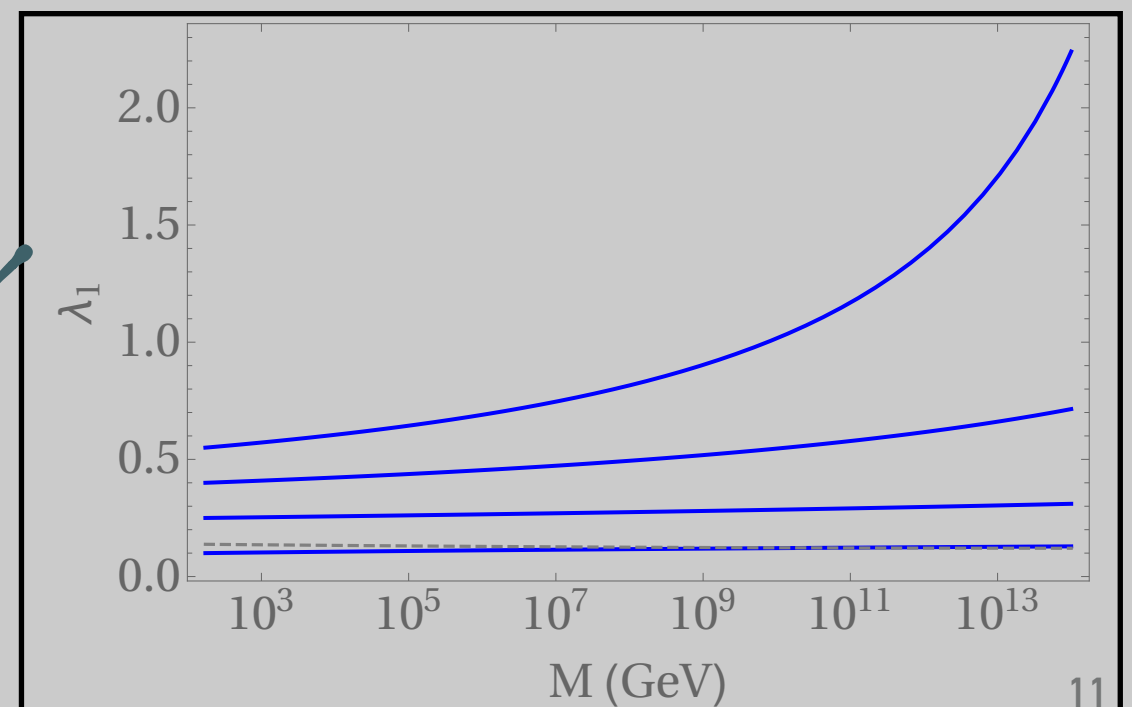
► Comparison with $\frac{(g^2 + g_Y^2)}{4}$ 2-loop matching.

► At the SUSY scale,

$$\lambda_1 = \lambda_2 = -(\lambda_3 + \lambda_4) = (g^2 + g_Y^2)/4$$

► Result is independent of $\tan \beta$

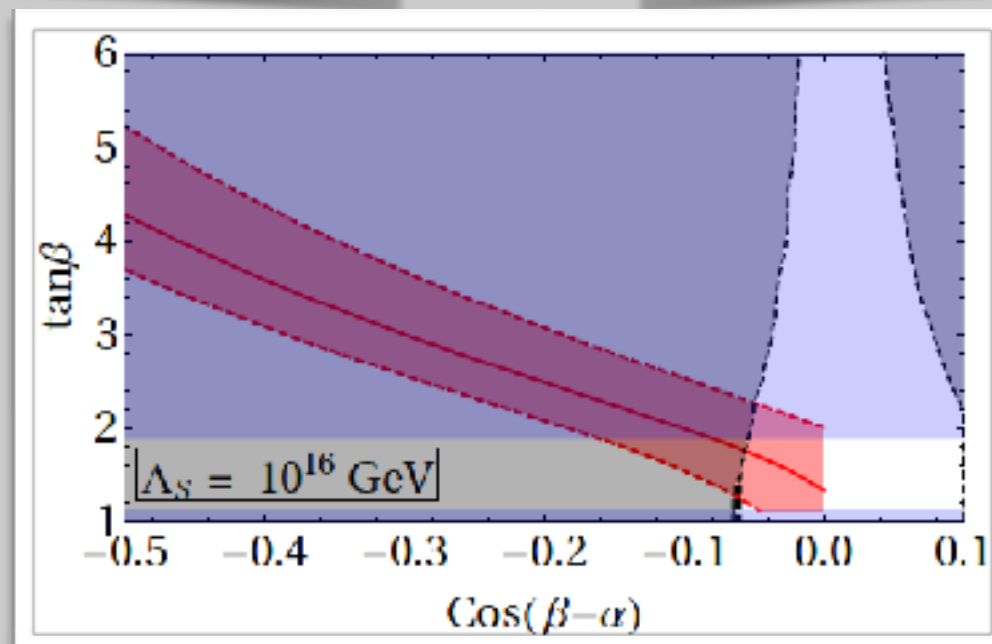
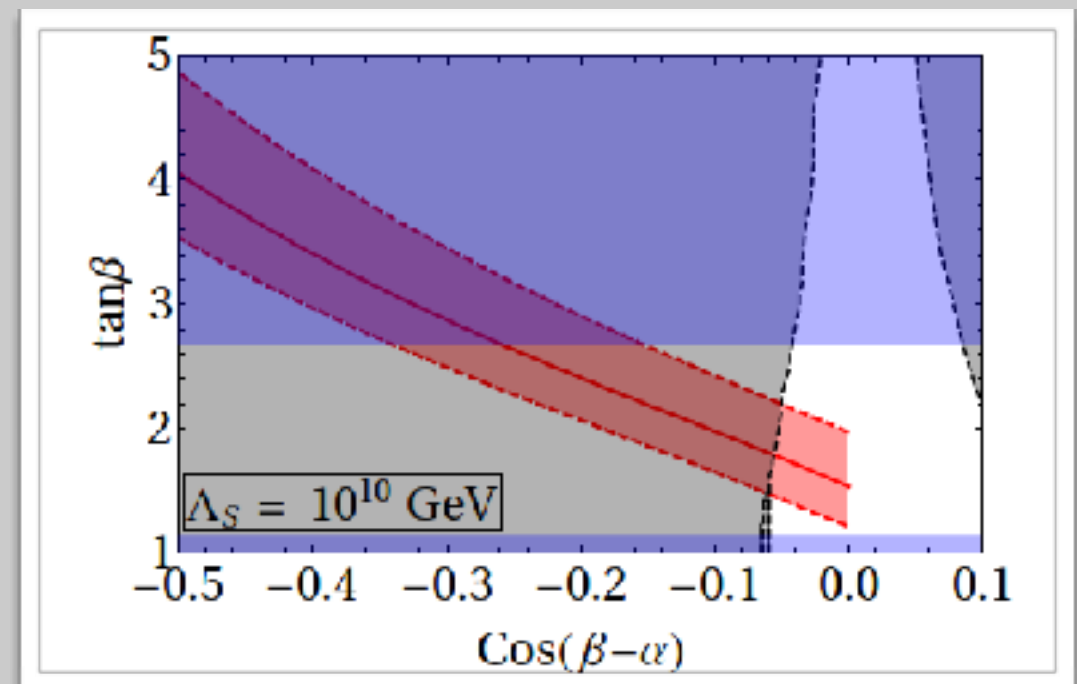
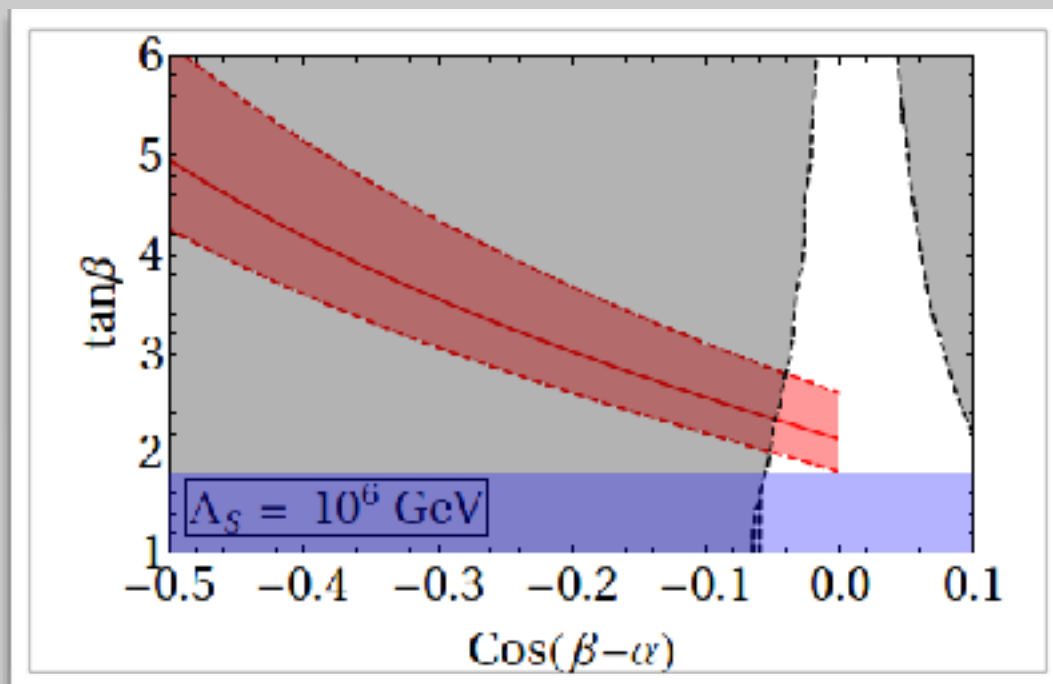
λ_1 running for $\lambda_1|_{(EW)} = 0.1, 0.25, 0.4, 0.55$ with $\lambda_2 = 0.56, \lambda_3 = 0.015$ and $\lambda_4 = -0.16$ for $\tan \beta = 2$.

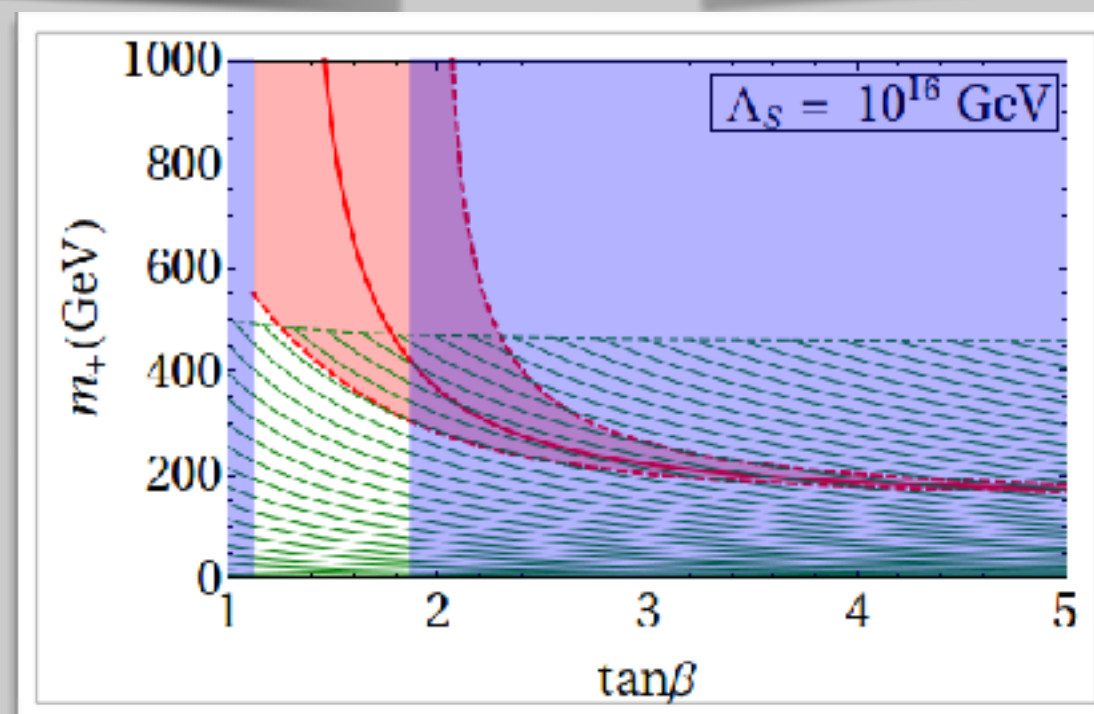
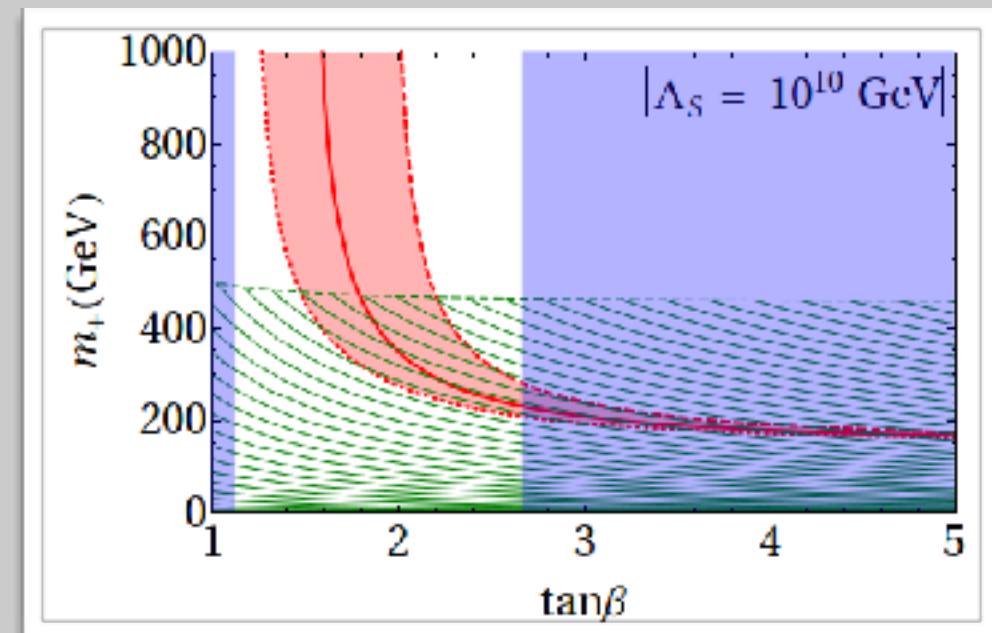
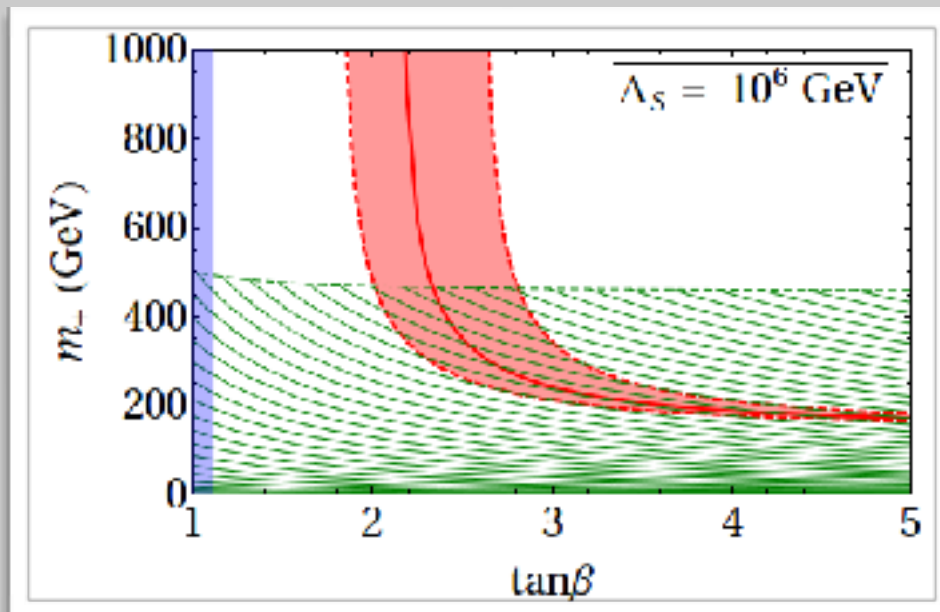


FEATURES

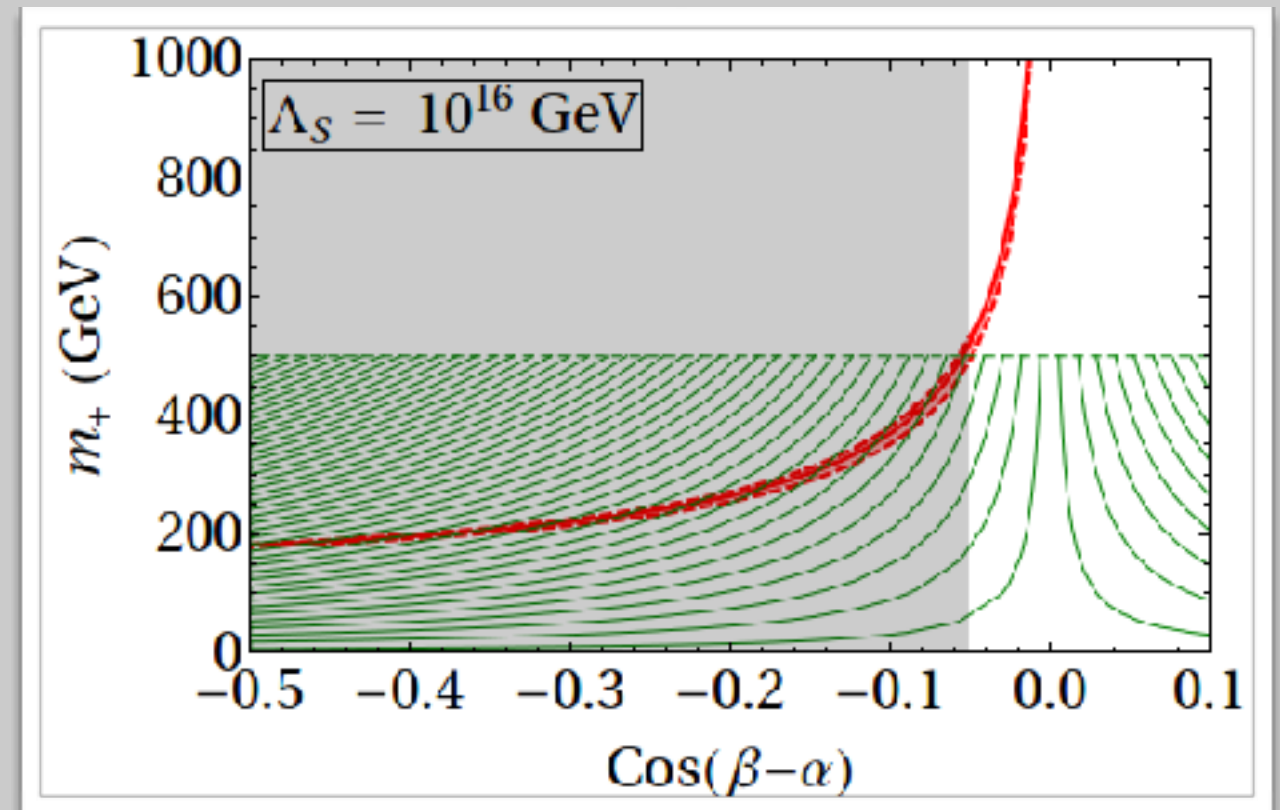
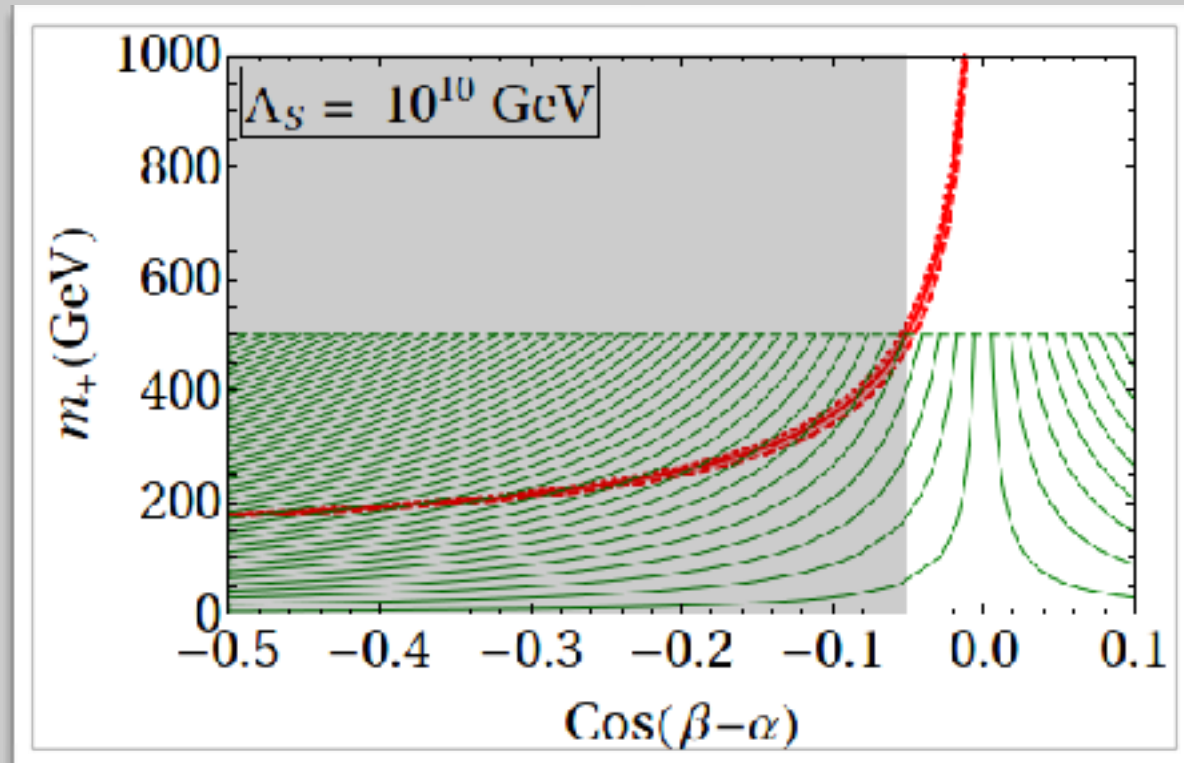
- *The values of λ_1 and $-(\lambda_3 + \lambda_4)$, at the EWS, are in the vicinity of $\frac{(g^2 + g_Y^2)}{4} \simeq 0.14$.*
- *The value of λ_2 should then be significantly larger than $\frac{(g^2 + g_Y^2)}{4}$, due to the large negative contribution to the RGE from the top Yukawa coupling.*
- *We can get a qualitative estimate of the SUSY scale, Λ_S , as the scale where λ_2 reaches its high scale boundary value, $\frac{(g^2 + g_Y^2)}{4}$.*
- *If λ_1 (or $-(\lambda_3 + \lambda_4)$) at the EWS is found to be larger than ~ 0.4 , it will be impossible to satisfy the MSSM boundary conditions at a higher scale.*

- The shaded blue region corresponds to constraints from the 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 $\tan \beta$

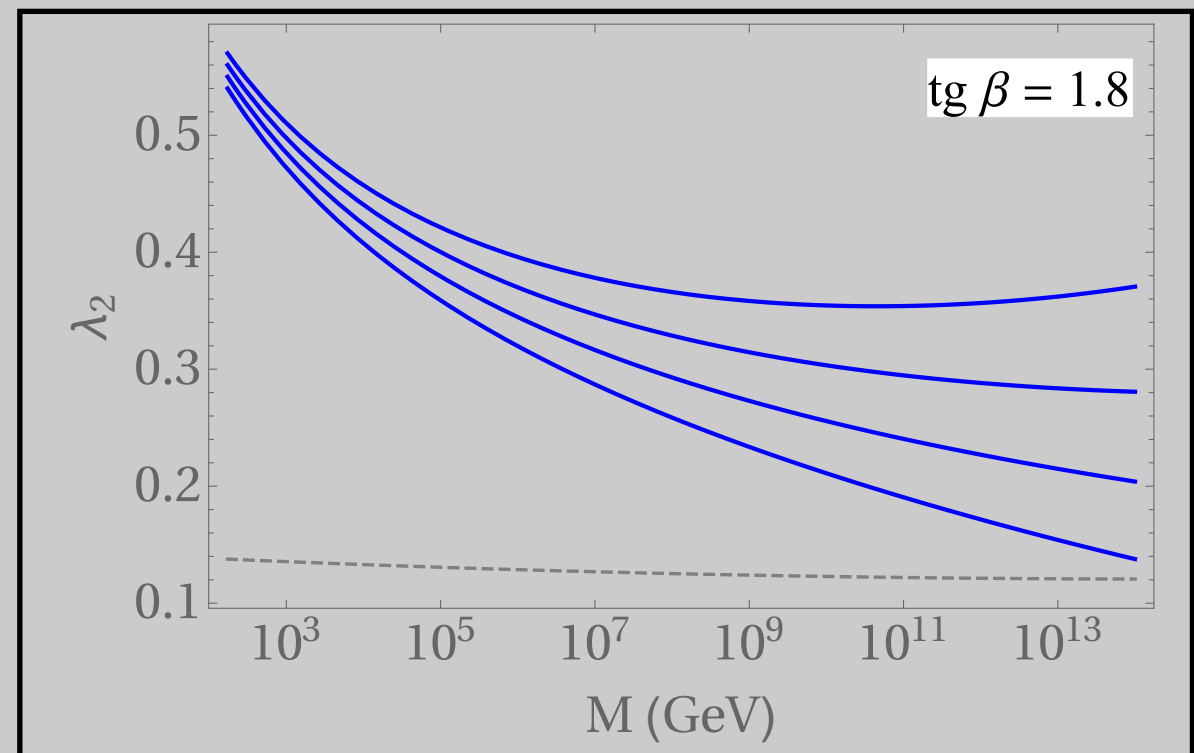
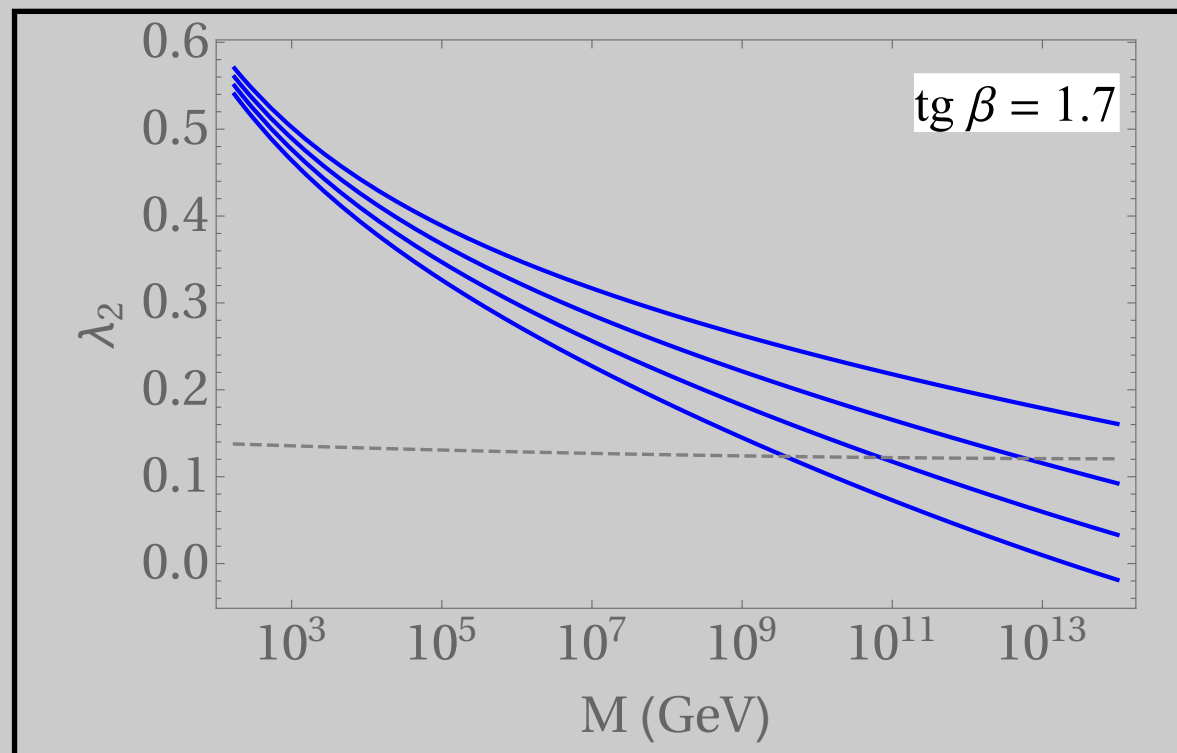




- Dashed region denotes the constraints on charged Higgs mass from flavor observable $b \rightarrow s\gamma$



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



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

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

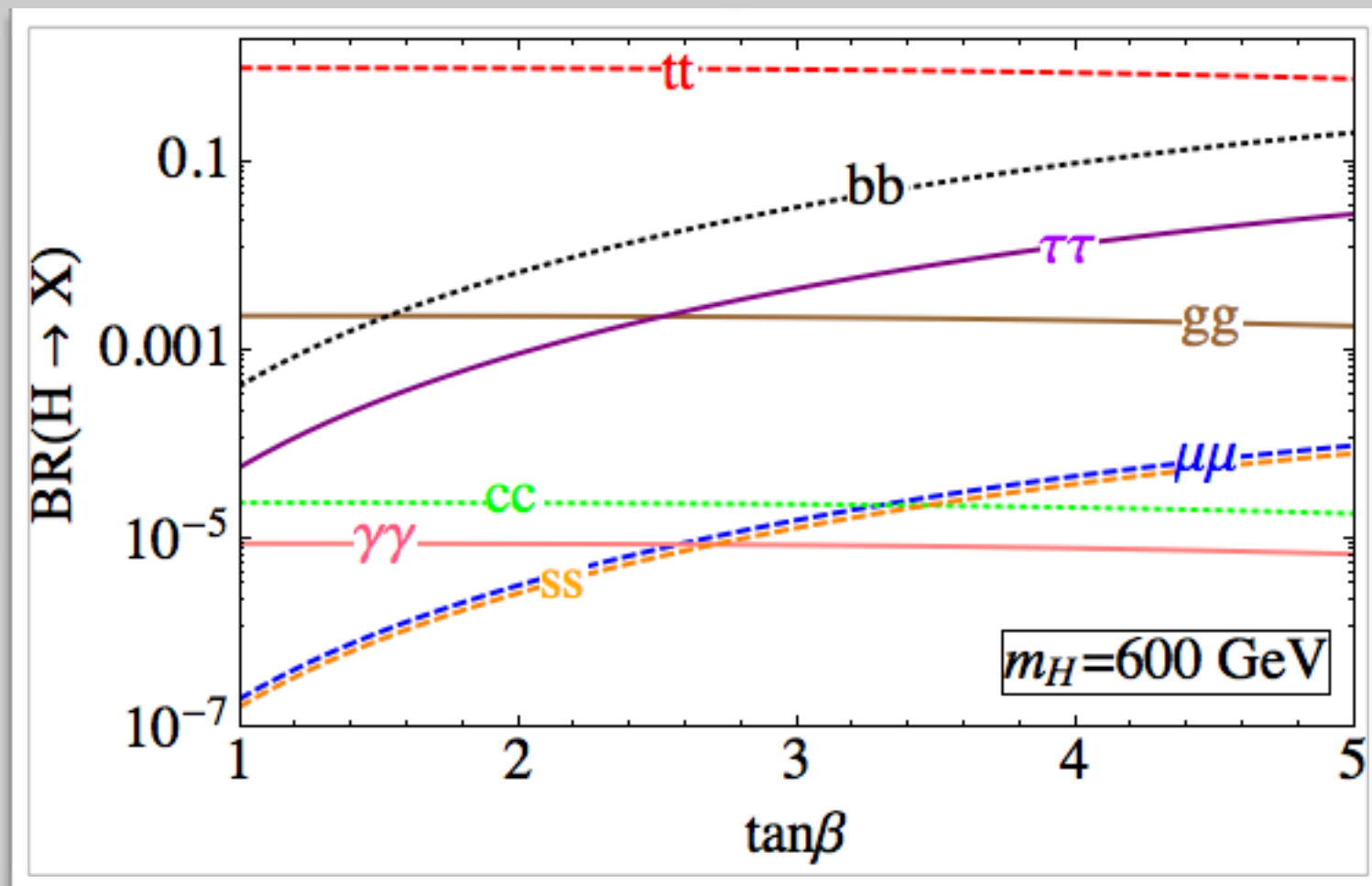
- To a good approximation,

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

- The Higgs mass,

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

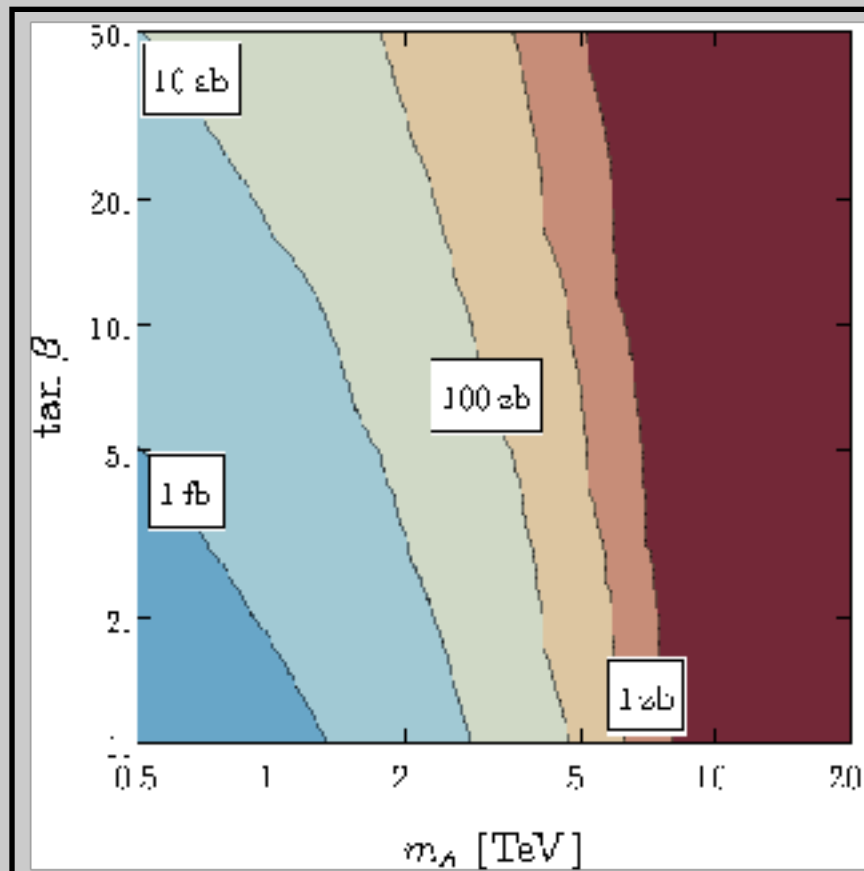
- Branching ratios of different decay channels mainly depend on $\tan\beta$
- Observation of extra scalars can be tested.
- An example plot for $m_H = 600$ GeV



A STUDY ON COLLIDER SIGNAL

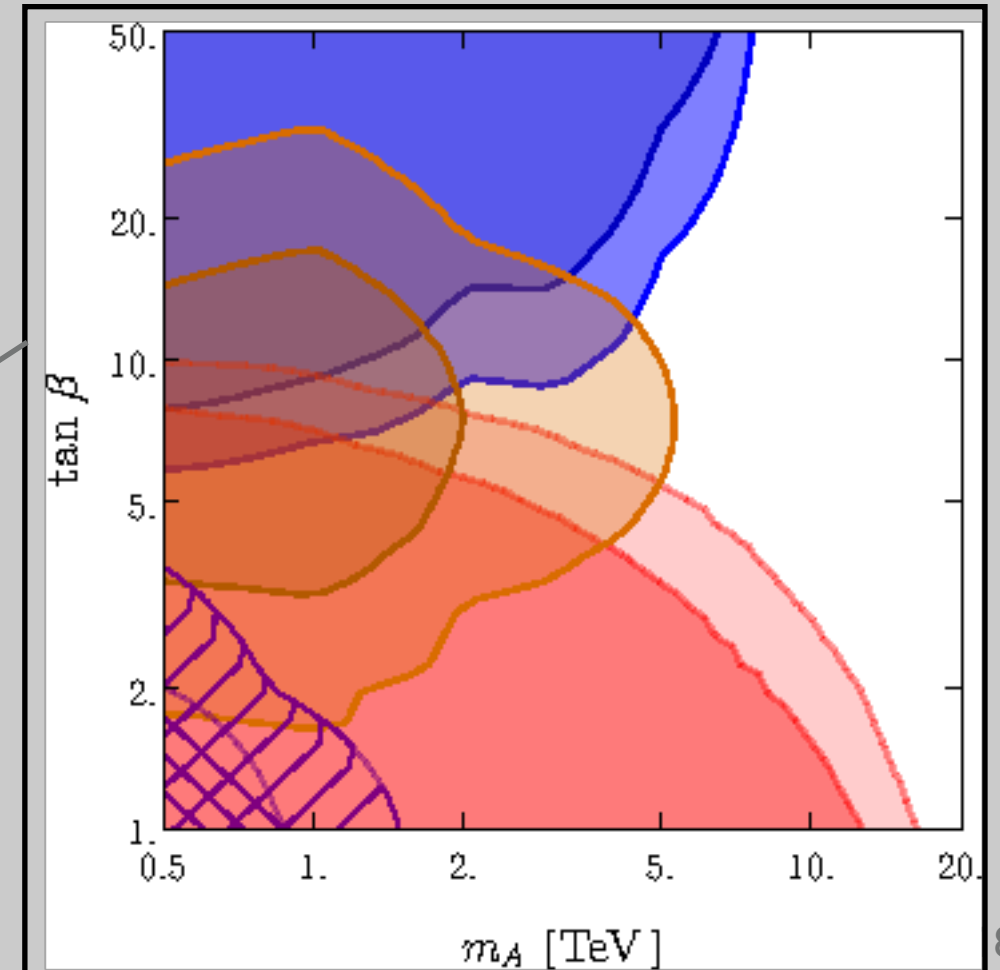
Heavy Higgs bosons at low $\tan \beta$: from the LHC to 100 TeV

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



Contours of the $tt(H + A)$ associated production cross-section of heavy neutral Higgs bosons at the 14 TeV LHC.

Discovery limits from 14 and 100 TeV collider from 3 to 30 inverse ab luminosity



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