Triplet Extended MSSM: Fine Tuning vs Perturbativity & Experiment

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P.Bandyopadhyay, SD, K.Huitu, A.Sabancı; arXiv:1407.4836

SUSY 2014, Manchester

Motivations

- Triplet contributes @ tree level to $m_H \Rightarrow$ less fine-tuning
- Possible enhancement of $H \to \gamma\gamma$
- Spontaneous CP violation $\Rightarrow$ right amount of baryon asymmetry

Triplet Extension of MSSM

Triplet of $SU(2)_L$ (adjoint, $Y=0$) defined by

$$T = \begin{pmatrix} \frac{1}{\sqrt{2}}T^0 & T^+ \\ T^- & -\frac{1}{\sqrt{2}}T^0 \end{pmatrix} .$$

The renormalizable superpontential of TESSM includes only two extra terms as compared to MSSM:

$$W_{\mathrm{TESSM}} = \mu_T \mathrm{Tr}(TT) + \mu_D H_d H_u + \lambda H_d T H_u + y_u U H_u Q - y_d D H_d Q - y_e E H_d L \,,$$

Soft terms:

$$\begin{aligned} V_S \;&=\; \Big[\mu_T B_T \mathrm{Tr}(TT) + \mu_D B_D H_d H_u + \lambda A_T H_d T H_u + y_t A_t \tilde{t}_R^* H_u \tilde{Q}_L + h.c.\Big] \\ &\quad + m_T^2 \mathrm{Tr}(T^\dagger T) + m_u^2 \left|H_u\right|^2 + m_d^2 \left|H_d\right|^2 + \dots \;, \end{aligned}$$

Espinosa, Quiros '92

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T parameter & Higgs Mass at TL

Real vevs for the scalar neutral components:

$$\langle T^0 \rangle = \frac{v_T}{\sqrt{2}} \,, \quad \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}} \,, \quad \langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}} \,,$$

give non-zero tree level contribution to the EW T parameter

$$\alpha T = \frac{\delta m_W^2}{m_W^2} = \frac{4 v_T^2}{v^2} \,, \; \alpha T \leq 0.2 \quad \Rightarrow \quad v_T \lesssim 5 \text{ GeV} \,.$$

In the limit of large $|B_D|$ (favoured by stability):

$$m_{h_1^0}^2 \leq m_Z^2 \left(c_{2\beta} + \frac{\lambda^2}{g_1^2 + g_2^2} s_{2\beta} \right) \,, \quad t_\beta = \frac{v_u}{v_d} \,,$$

Large values of λ reduce quantum corrections $\Rightarrow$ less fine tuning (FT).

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Higgs Mass at 1L

1L contribution to scalar masses obtained from Coleman-Weinberg V

$$V_{\mathrm{CW}} = \frac{1}{64\pi^2}\mathrm{STr}\left[\mathcal{M}^4\left(\log\frac{\mathcal{M}^2}{\mu_r^2} - \frac{3}{2}\right)\right],$$

with $\mathcal{M}^2 =$ mass matrices with fields not replaced by vevs.

Neutral scalar mass matrix 1L contribution, $\Delta\mathcal{M}^2_{h^0}$, given by

$$(\Delta\mathcal{M}^2_{h^0})_{ij} = \left.\frac{\partial^2 V_{\mathrm{CW}}(a)}{\partial a_i \partial a_j}\right|_{\mathrm{vev}} - \frac{\delta_{ij}}{\langle a_i \rangle}\left.\frac{\partial V_{\mathrm{CW}}(a)}{\partial a_i}\right|_{\mathrm{vev}}, \; a_i = \left|H_u^0, H_d^0, T^0\right|/\sqrt{2}$$

Derivatives evaluated numerically at each data point in parameter space.

Espinosa, Quiros '92; Setzer, Spinner '06; Diaz-Cruz et al. '07; SD, Hsieh '08; Delgado et al. '12,'13; Arina et al. '14

Parameter Space Scan

To evaluate the phenomenological viability of TESSM we scan randomly the parameter space in the region defined by:

$$1 \leq t_\beta \leq 10 \;, |\lambda| \leq 2 \;, \; |\mu_D, \mu_T| \leq 2\,\text{TeV} \;, \; |M_1, M_2| \leq 1\,\text{TeV} \;,$$
$$|A_t, A_T, B_D, B_T| \leq 2\,\text{TeV} \;, \; 500\,\text{GeV} \leq m_Q, m_{\tilde{t}}, m_{\tilde{b}} \leq 2\,\text{TeV}$$

and stop after collecting 13347 points satisfying exp constraints

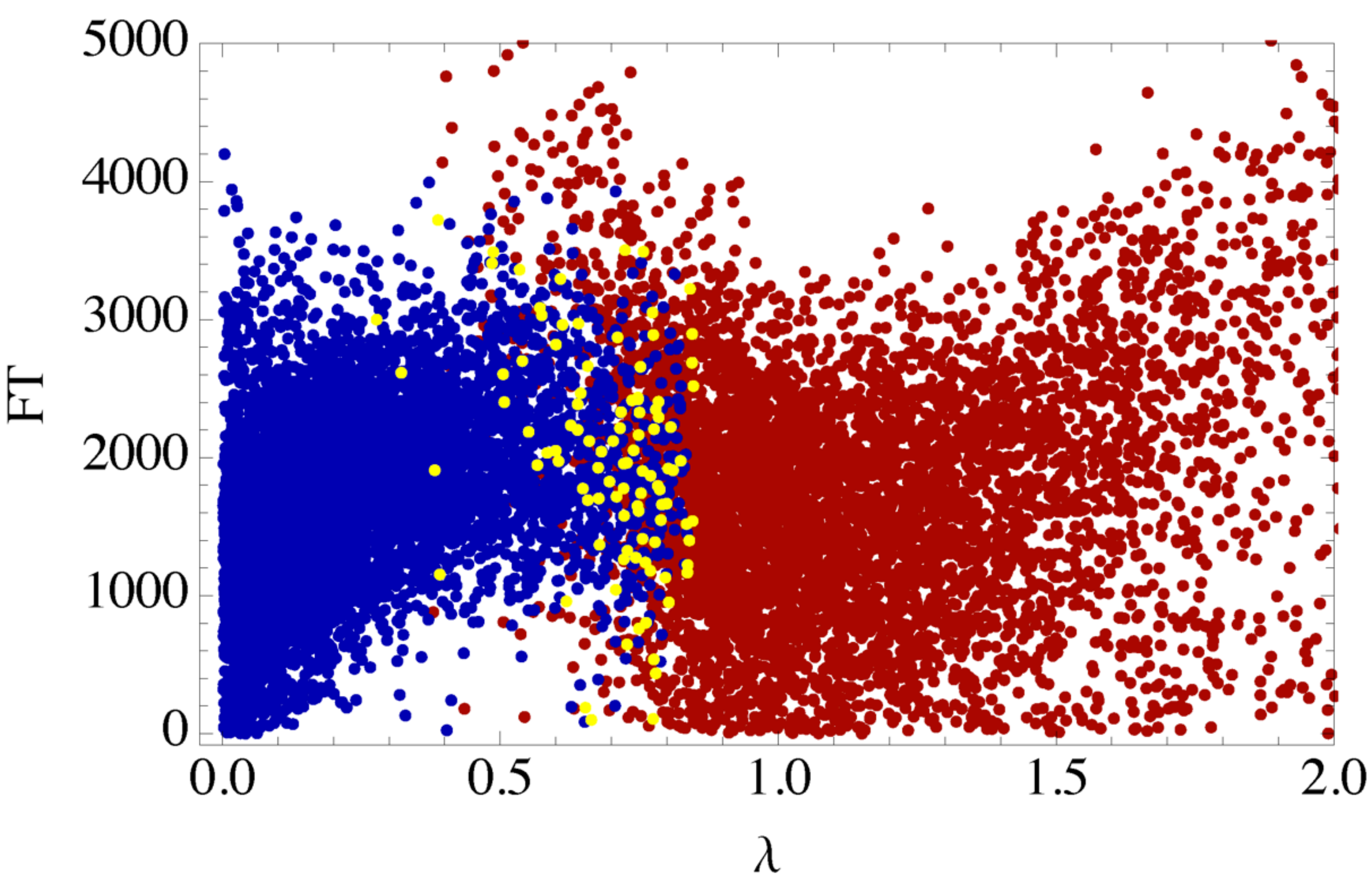
$$\begin{aligned} m_{h_1^0} = 125.5 \pm 0.1\,\text{GeV} \;; \; m_{A_{1,2}}, \; m_{\chi^0_{1,2,3,4,5}} &\geq 65\,\text{GeV} \;; \\ m_{h^0_{2,3}}, m_{h^\pm_{1,2,3}}, m_{\chi^\pm_{1,2,3}} \geq 100\,\text{GeV} \;; \; m_{\tilde{t}_{1,2}}, m_{\tilde{b}_{1,2}} &\geq 650\,\text{GeV} \;. \end{aligned}$$

$m_{h_1^0}$ matched to 125.5 GeV by tuning λ.

Perturbativity

We calculate the 2 loop beta functions for $y_t, y_b, y_\tau, \lambda, g_3, g_2, g_1$ (new result) and require those to be less than $2\pi^*$ at the GUT scale (2×10^{16} GeV): 7732 satisfy perturbativity constraint. Then we calculate FT in $m_{H_u}^2{}^*$ by using its full 1L beta $\beta_{m_{H_u}^2}$ (new result):

$$\text{FT} \equiv \frac{\partial \log v_{\text{EW}}^2}{\partial \log m_{H_u}^2(\Lambda)}, \quad m_{H_u}^2(\Lambda) = m_{H_u}^2(M_Z) + \frac{\beta_{m_{H_u}^2}}{16\pi^2} \log\left(\frac{\Lambda}{M_Z}\right).$$



Ellis et al. '86; Barbieri, Giudice '88

Red= non-perturbative, yellow= perturbative @ 2L, blue= perturbative; λ too small to reduce FT, but

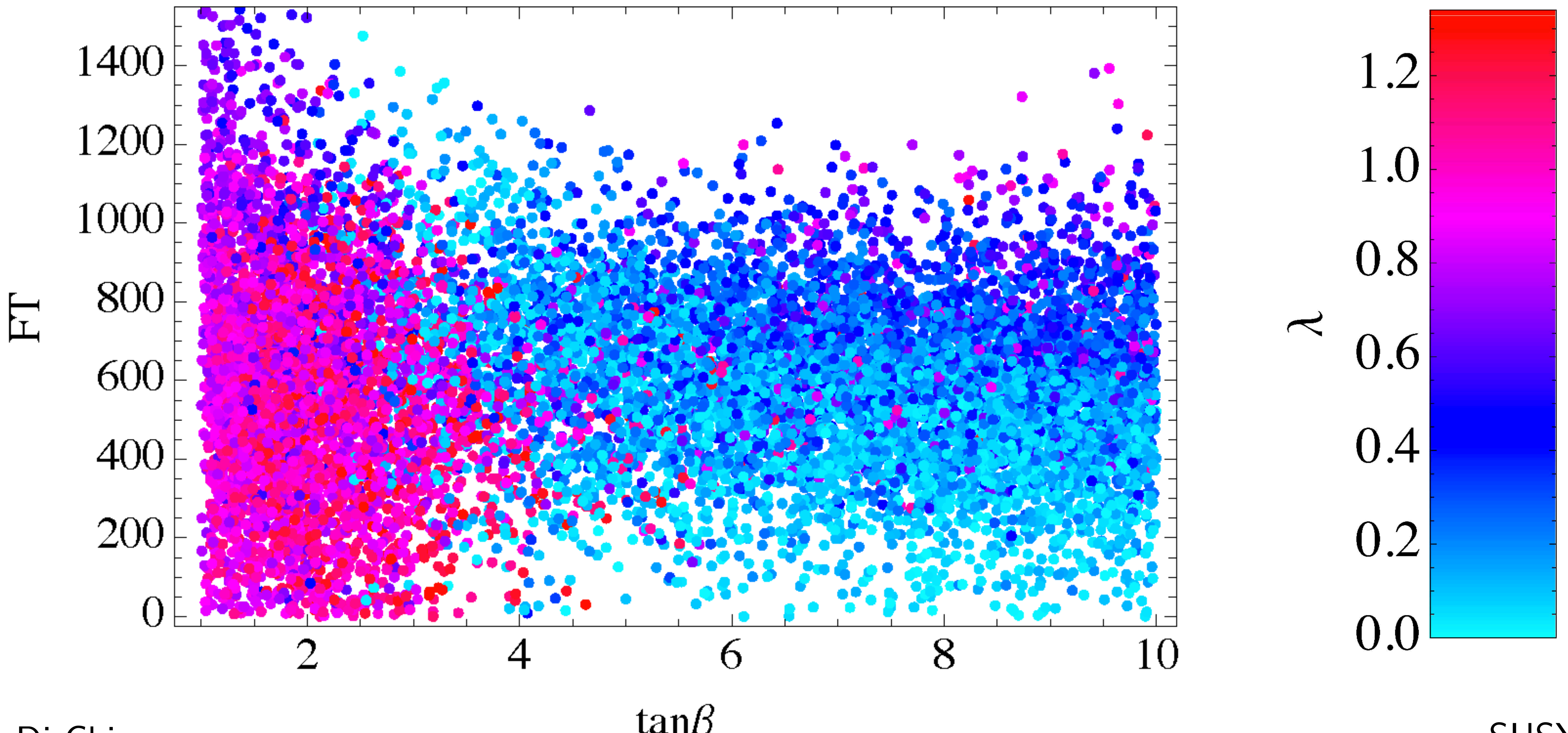
- no GUT for TESSM
- Spontaneous SUSY breaking might change β

We choose $\Lambda_{UV} = 10^4$ TeV.

Fine Tuning

At $\Lambda_{UV} = 10^4$ TeV 11244 perturbative viable points

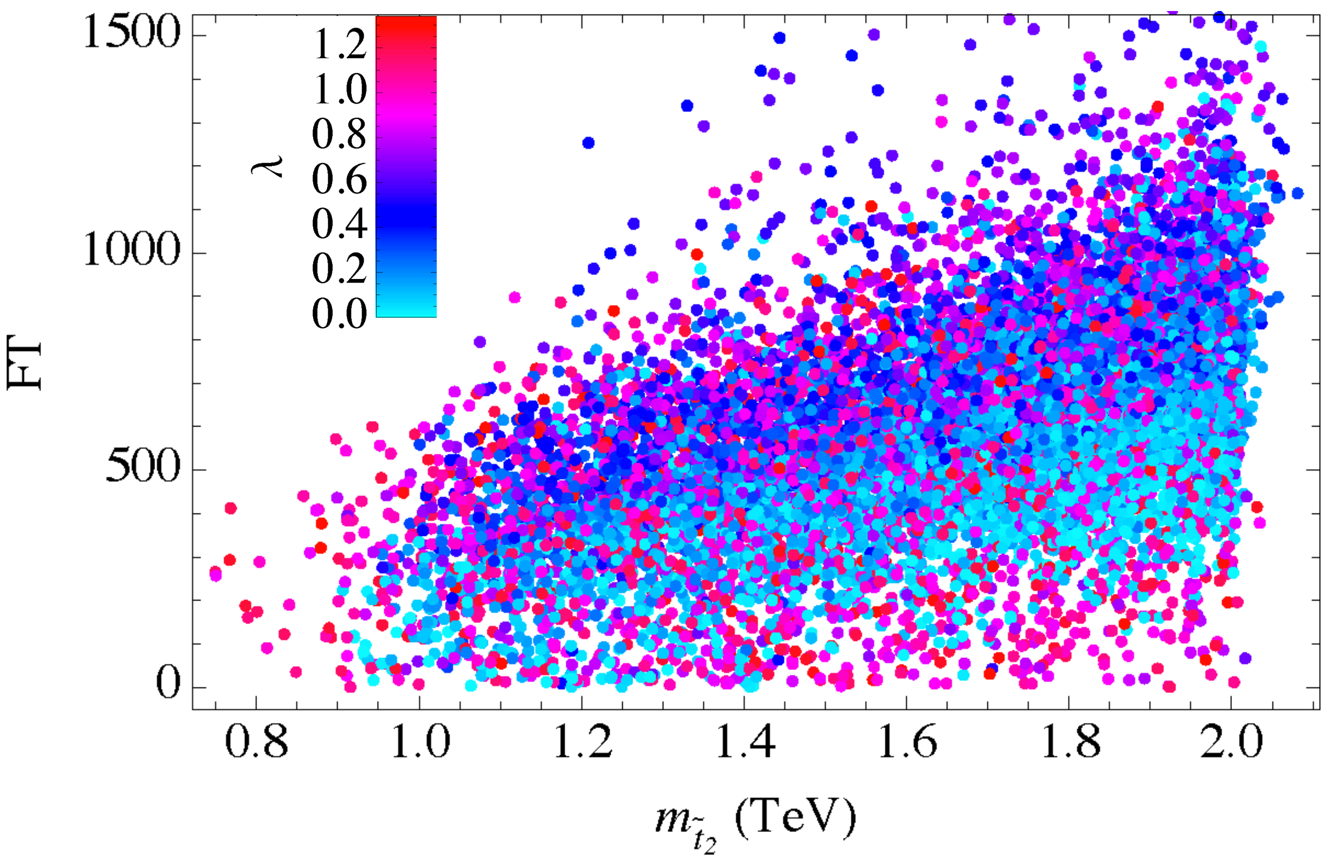
$\tan\beta$ and λ strongly correlated: $\tan\beta \sim 1$ with small FT viable only for large λ

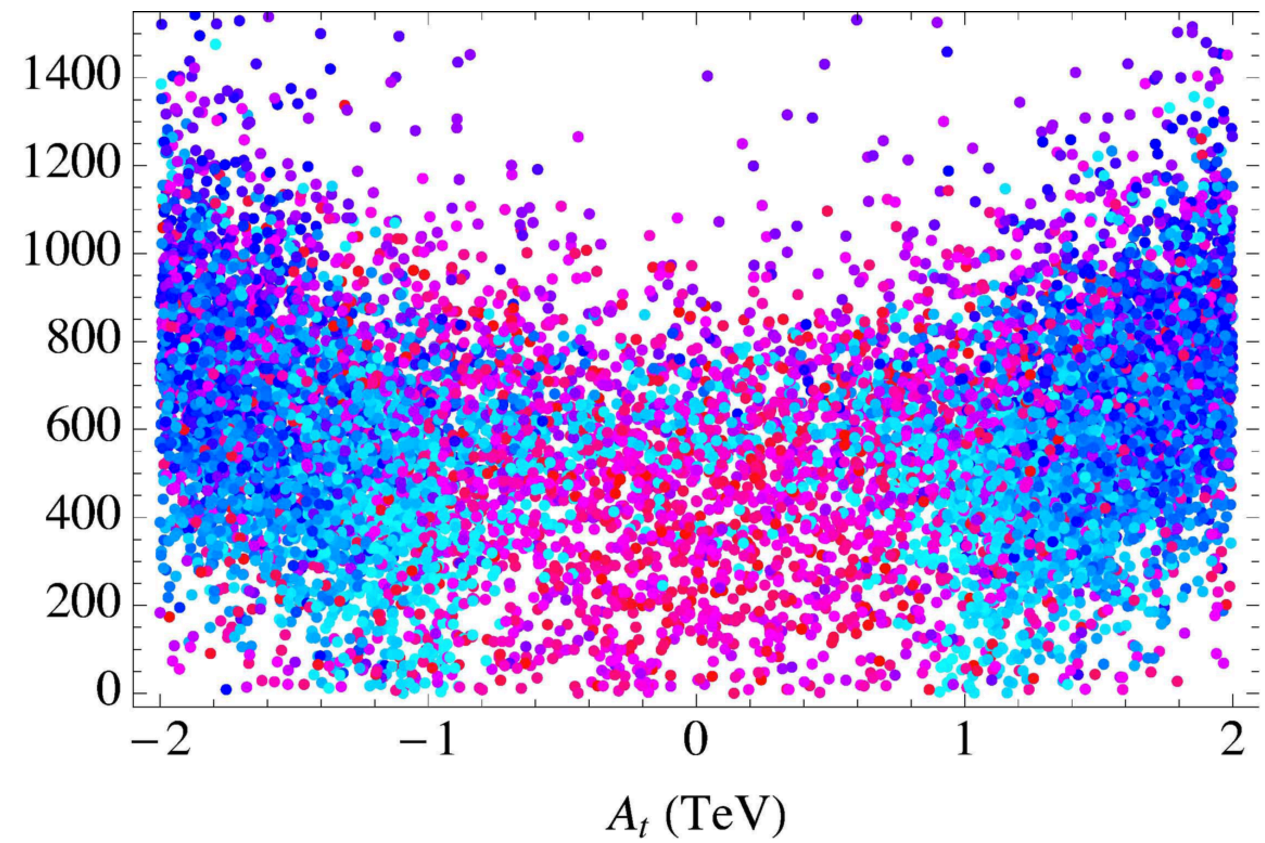


Fine Tuning

Greater heavy stop mass increases FT (as expected)

Small $|A_t|$ with small FT accessible only for large $|\lambda|$ (not in MSSM)





Higgs Physics at LHC

Higgs linear coupling terms accounting for the TESSM contributions:

$$\begin{aligned}\mathcal{L}_{\rm eff} &= a_W \frac{2m_W^2}{v_w} h W_\mu^+ W^{-\mu} + a_Z \frac{m_Z^2}{v_w} h Z_\mu Z^\mu - \sum_{\psi=t,b,\tau} a_\psi \frac{m_\psi}{v_w} h \bar{\psi}\psi \\ & -a_\Sigma \frac{2m_\Sigma^2}{v_w} h \Sigma^* \Sigma - a_S \frac{2m_S^2}{v_w} h S^+ S^-,\end{aligned}$$

where Σ and S are, respectively, coloured and charged scalars, with

$$a_S \equiv -3 \sum_i^3 \left(F_{h_i^\pm} + F_{\chi_i^\pm} \right) - \sum_j^2 \left(4F_{\tilde{t}_j} + F_{\tilde{b}_j} \right), a_\Sigma \equiv -3 \sum_j^2 \left(F_{\tilde{t}_j} + F_{\tilde{b}_j} \right),$$

F_i being decay amplitudes to diphoton/digluon. We impose also lower bound on $m_{h_2^0}$: 10957 out of 11244 perturbative data points satisfy it.

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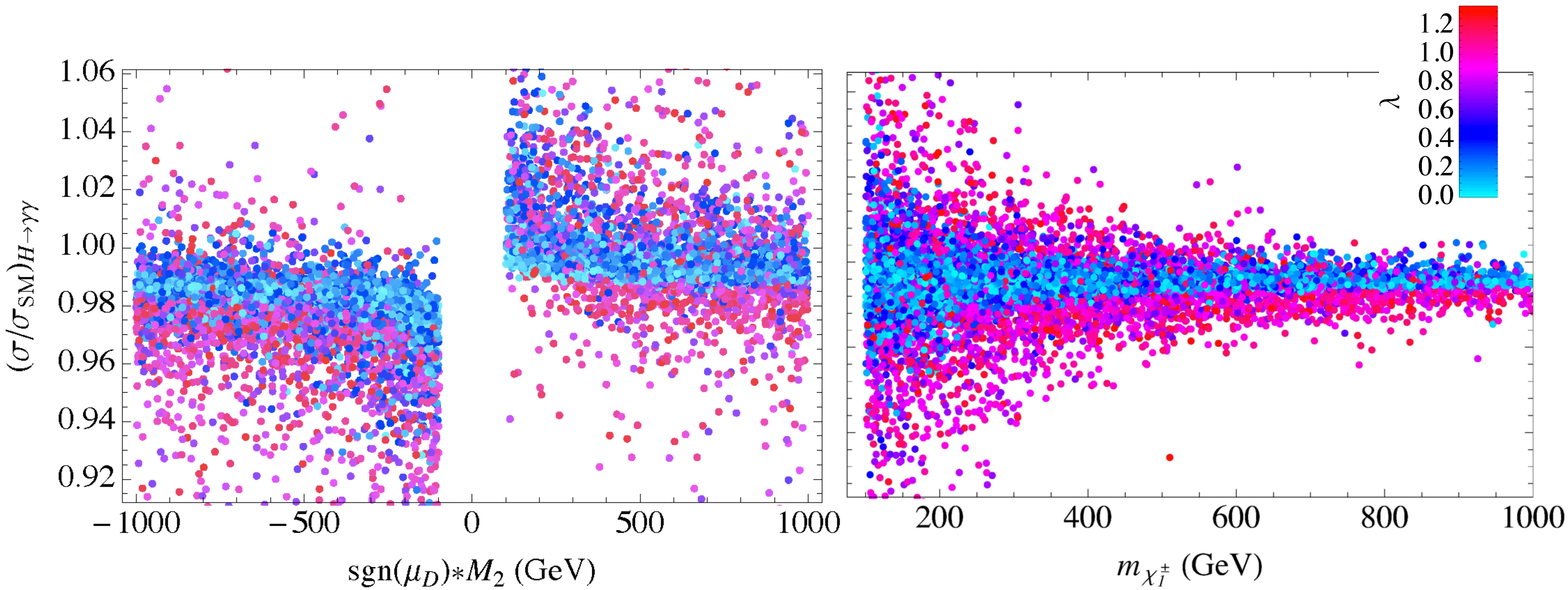
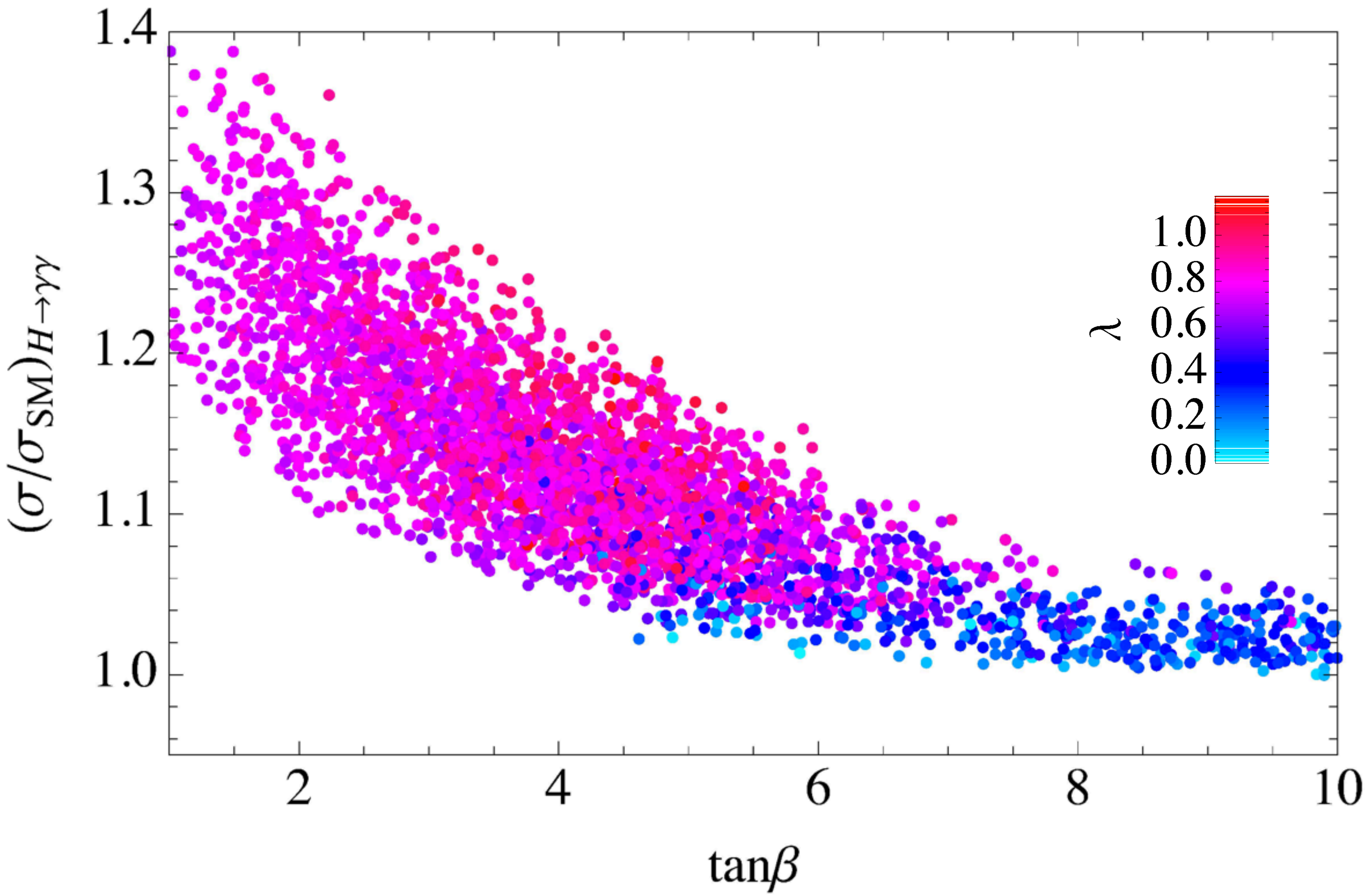
Enhanced & Suppressed $h \to \gamma\gamma$

We find both enhanced and suppressed Higgs to diphoton decay rates relative to SM: apparently different from results in literature.



Comparison with previous results

Scanning similar* region of parameter space ($\lambda, \mu_D, \mu_T, M_2 > 0$ with light chargino) we get equivalent results (only enhancement)

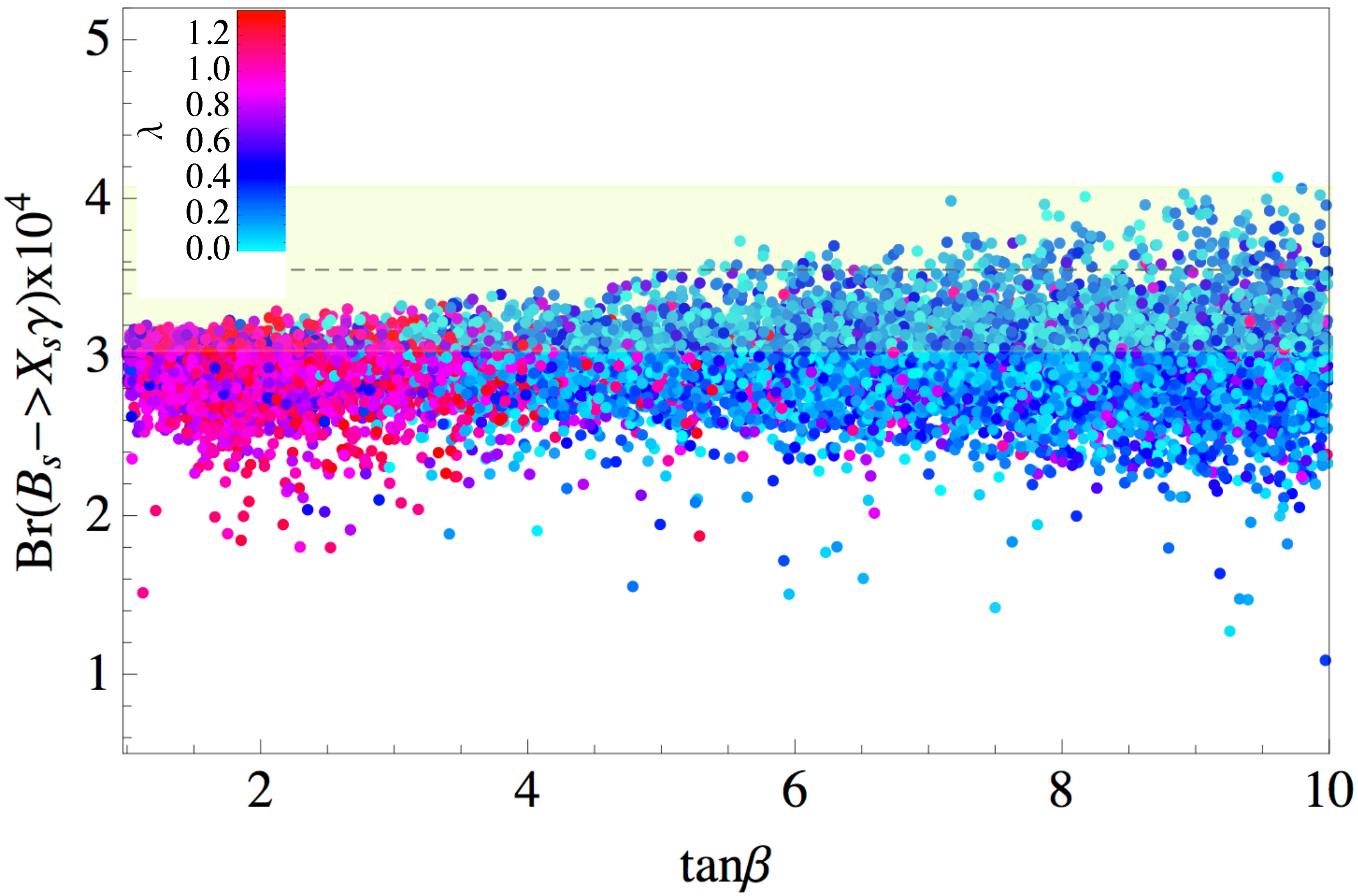


* SD, Hsieh '08; Delgado et al. '12,'13; Arina et al. '14

b to s gamma

Even for low values of $\tan\beta$, $B_s \to X_s\gamma$ branching ratio possibly large: we calculate it at NLO.

Dashed line on measured value, 2σ band shaded in yellow



Goodness of Fit

We minimize the quantity

$$\chi^2 = \sum_i \left(\frac{\mathcal{O}_i^{\rm exp} - \mathcal{O}_i^{\rm th}}{\sigma_i^{\rm exp}} \right)^2 ,$$

including ZZ, WW, $\tau\tau$, $b\bar{b}$, $\gamma\gamma$ (all topologies) signal strengths, and $b \to s\gamma$, for a total of 49 observables. In the limit of small deviations from the optimal values, for $a_W = a_Z = 1, a_\psi = a_f$, neglecting $b \to s\gamma$:

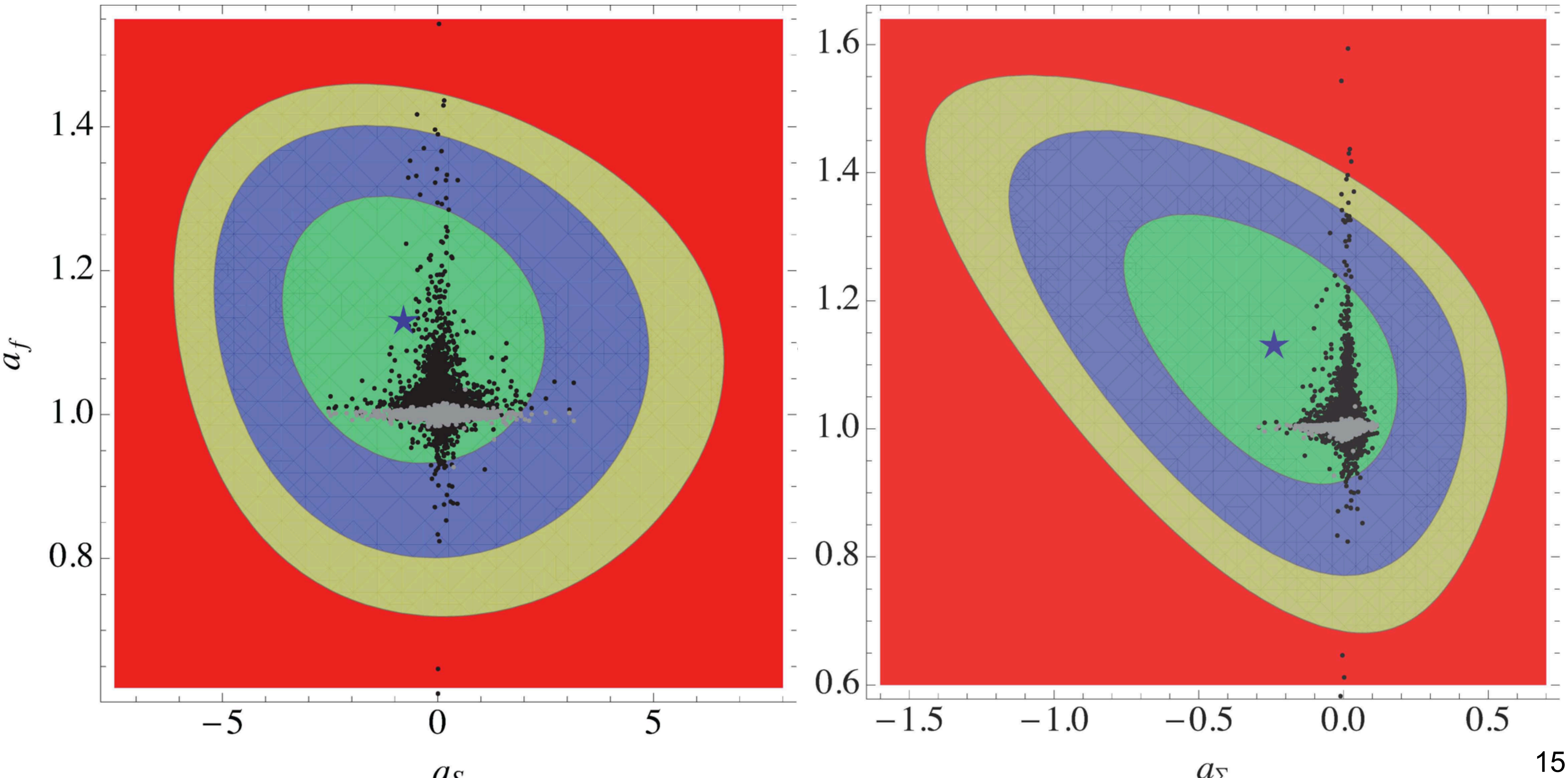
$$\Delta\chi^2 = \chi^2 - \chi^2_{min} = \delta^T \rho^{-1} \delta \,, \;\; \delta^T = \left(\frac{a_f - \hat{a}_f}{\sigma_f}, \frac{a_S - \hat{a}_S}{\sigma_S}, \frac{a_\Sigma - \hat{a}_\Sigma}{\sigma_\Sigma} \right) \;,$$

with

$$\left\{ \begin{array}{l} \hat{a}_f = 1.13 \\ \hat{a}_S = 0.80 \\ \hat{a}_\Sigma = 0.25 \end{array} \right. , \;\; \left\{ \begin{array}{l} \sigma_f = 0.17 \\ \sigma_S = 2.79 \\ \sigma_\Sigma = 0.43 \end{array} \right. , \;\; \rho = \begin{pmatrix} 1 & -0.55 & -0.67 \\ -0.55 & 1 & 0.70 \\ -0.67 & 0.70 & 1 \end{pmatrix} .$$

Viable regions

Values of a_u (a_d) for viable data points shown in gray (black), optimal data point=blue star, 68%, 95%, 99%CL regions in green, blue, yellow, respectively.



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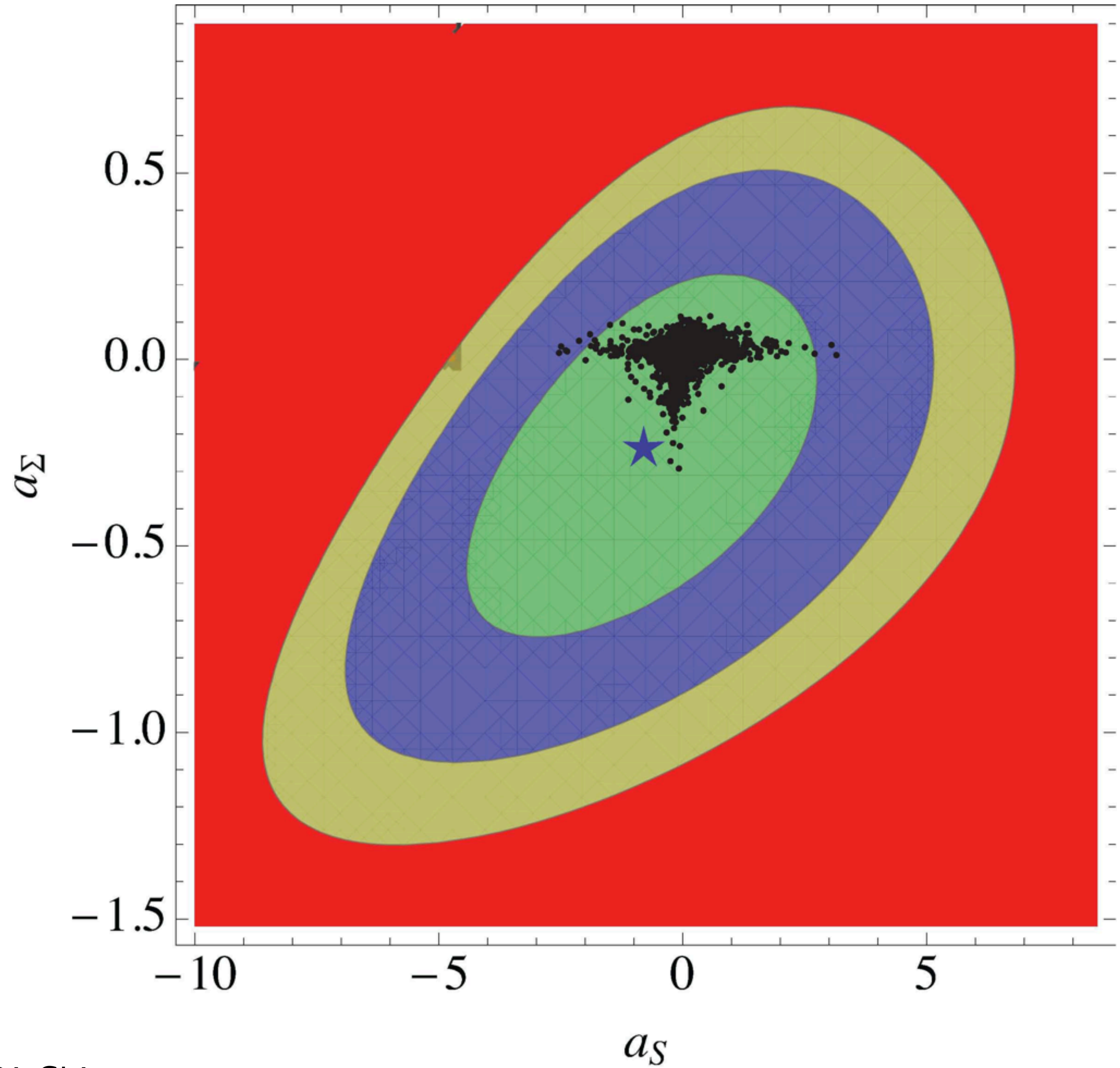
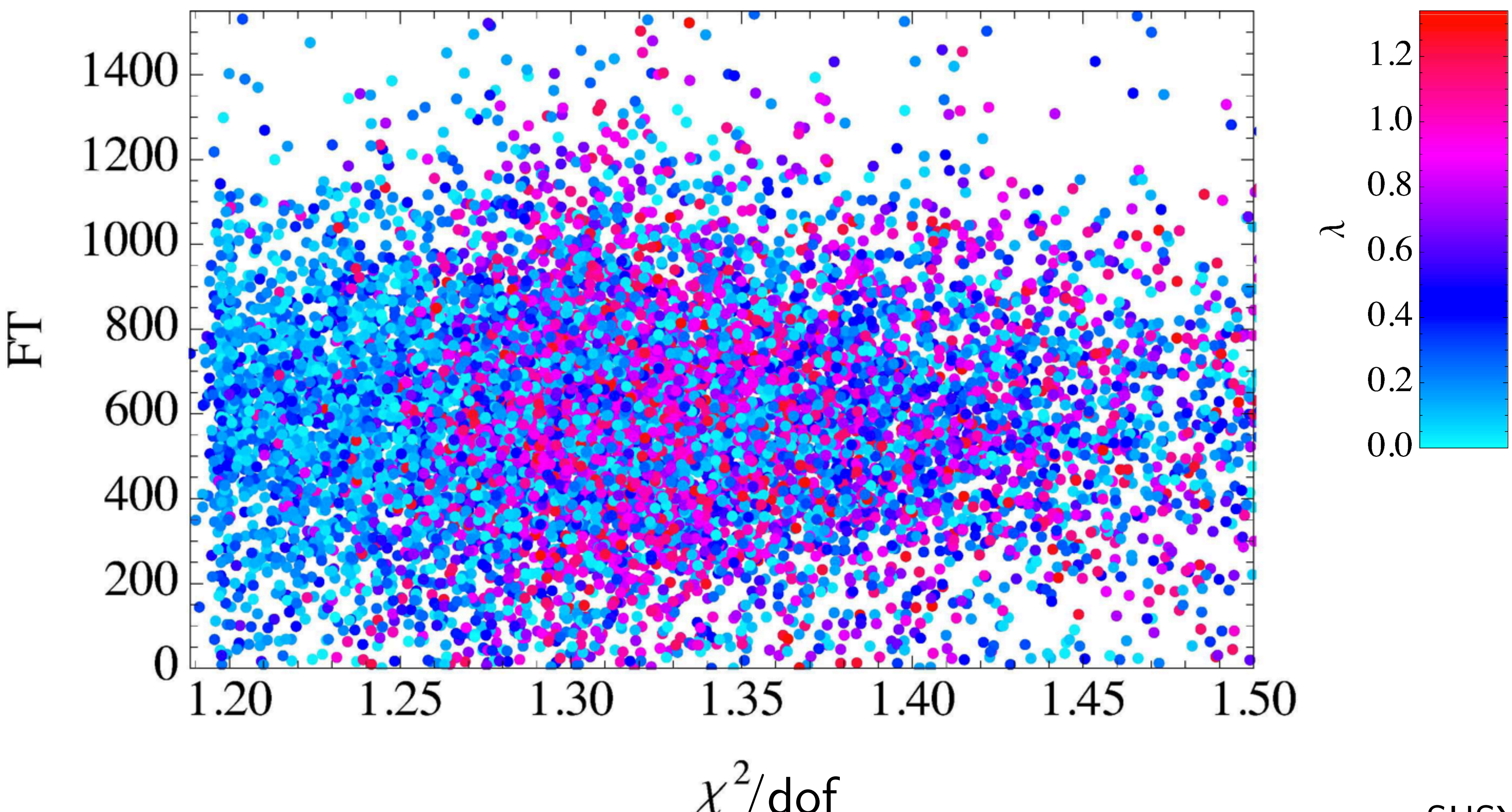


Viable data points in black: no point matches optimal a_Σ value.

In general TESSM under constrained by Higgs physics, but that might change at LHC2.

chi^2 vs FT

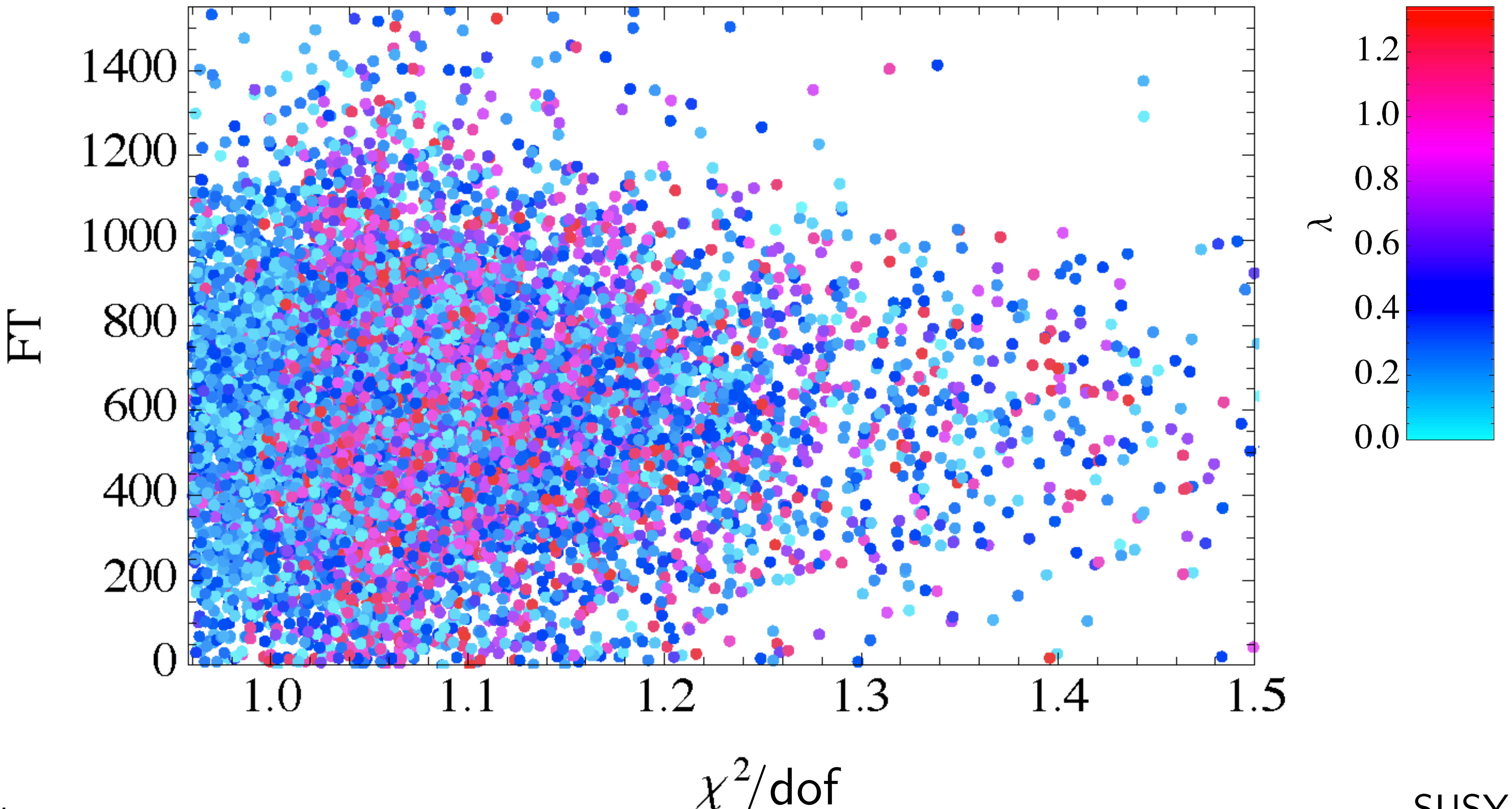
Large values of λ disfavored as compared to MSSM-like data points, because of Br($B_s \to X_s\gamma$). If large enhancement/suppression of $h \to \gamma\gamma$ (ATLAS/CMS) confirmed at LHC2, TESSM well suited to explain (=fit) it.



New chi^2 vs FT

Fit with new CMS data (arxiv:1407.0558,CMS PAS HIG-14-009)!

- TESSM: $\chi^2_{min}/dof = 1.19_{previous} \to 0.96_{new}$
- SM: $\chi^2_{min}/dof = 1.12_{previous} \to 0.91_{new}$



Conclusions

- TESSM can have much smaller fine-tuning than MSSM
- Large enhancement/suppression of $H \to \gamma\gamma$ both possible
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THANK YOU!

Backup Slides

Higgs to diphoton

$$\Gamma_{h\to\gamma\gamma} = \frac{\alpha_e^2 m_h^3}{256\pi^3 v_w^2}\left|\sum_i N_i e_i^2 a_i F_i\right|^2 \,,\ i = W, t, b, \tau, c, S \ ,$$

with N_i number of colors, e_i electric charge, and F_i partial amplitudes. In the limit of heavy $S^\pm$, one finds

$$F_S = -\frac{1}{3}\,,\ a_S \equiv -3\left[\sum_i^3\left(F_{h_i^\pm} + F_{\chi_i^\pm}\right) + \sum_j^2\left(\frac{4}{3}F_{\tilde{t}_j} + \frac{1}{3}F_{\tilde{b}_j}\right)\right] \ .$$

Gunion et al. - The Higgs Hunter's Guide

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Higgs to 2 gluons & mH constraint

$$\Gamma_{h\to gg} = \frac{\alpha_s^2 m_h^3}{128\pi^3 v_w^2}\left|\sum_i a_i F_i\right|^2 \quad , \qquad i = t, b, c, \Sigma \ ,$$

where

$$a_\Sigma \equiv -3\sum_j^2 \left(F_{\tilde{t}_j} + F_{\tilde{b}_j}\right) \ .$$

Applying the formulas above to the heavy Higgs, we impose the constraint:

$$a_g' \frac{(770\ \mathrm{GeV})^2}{m_{h_2^0}^2} < 0.8 \ , \qquad a_g' = \Gamma_{h_2^0\to gg}/\Gamma_{h\to gg}^{SM} \ .$$

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CMS-HIG-13-014-PAS

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