Cornering natural SUSY at a Tera-Z factory

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Based on 2507.xxxxx in collaboration with Admir Greljo, Ben A. Stefanek

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Outline

1. Motivation
2. Heavy Higgses
3. Stops
4. Higgsino and Gauginos
5. Conclusion

Why?

Why?

Tera-Z allows in-depth exploration of the TeV scale at *loop-level*

Tera-Z: $$\frac{\delta O_Z}{O_Z} \sim 10^{-6} \sim \left(\frac{g_{\rm NP}^2}{16\pi^2}\right)^{n_{\rm loop}} \frac{g_{\rm NP}^2 v_{\rm EW}^2}{\Lambda_{\rm NP}^2} \implies$$

1-loop

$\Lambda_{\rm NP} \sim 10$ TeV $(g_{\rm NP} = 1)$

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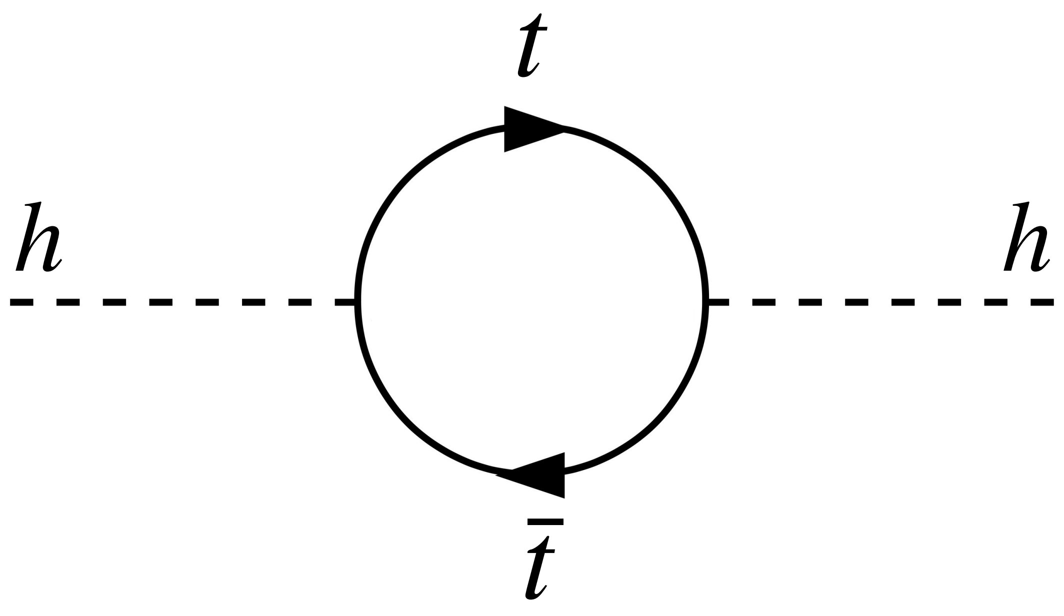
Naturalness is ***the*** motivation for expecting loop-level NP at (~~sub~~-)TeV LEP+ LHC



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_{NP}^2$$

$\Lambda_{NP} \gtrsim$ TeV's $\Longleftrightarrow \left(\frac{\delta m_h^2}{m_h^2}\right)^{-1} \lesssim 1\,\%$

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LEP+LHC

Natural SUSY remains one of the best motivated theoretical frameworks (despite past disappointments)

Key benchmark for future Z and Higgs factories

Steps

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   → **FCC-ee: Scenarios 1 (theory conservative) to 3 (exp. only)**

   Greljo, Stefanek, AV (2025) FSR (2025)
   PDG EW WG (WIP)

   e.g. $\Delta R_b/R_b : 2 \times 10^{-4}$ (**S1**) to 1.8×10^{-6} (**S3**)

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3. Identify and study key sectors efficiently probed at these facilities:

   → **Heavy Higgs doublet, Stops, Higgsino & Gauginos**

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Heavy Higgs doublet

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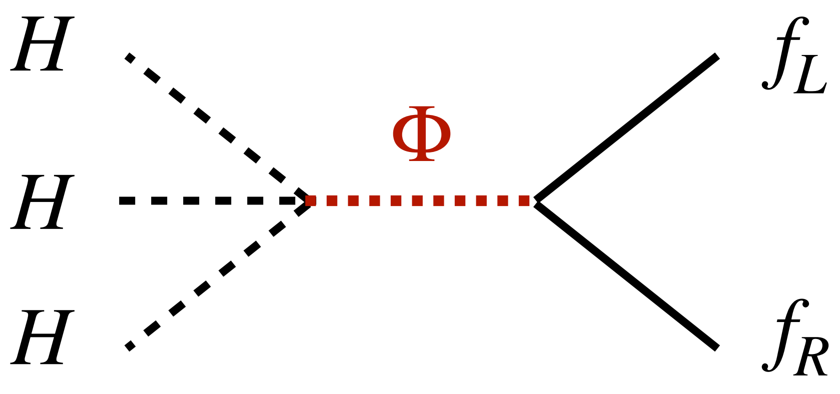
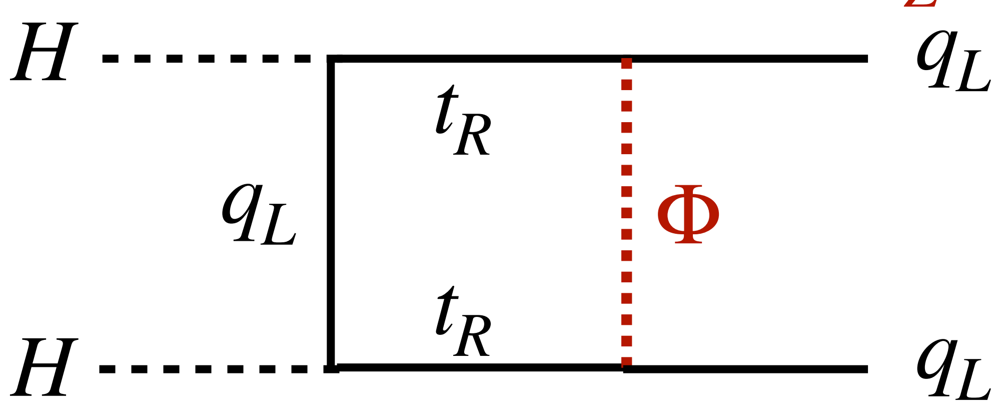
Only field coupling linearly to SM: **TL + 1-loop effects**

$$\mathcal{L}_\Phi \supset -\bar{q}_L \widetilde{\Phi}(\cot\beta\, Y_u^{\rm SM}) u_R + \bar{q}_L \Phi(\tan\beta\, Y_d^{\rm SM}) d_R + \bar{\ell}_L \Phi(\tan\beta\, Y_e^{\rm SM}) e_R - \frac{g_Z^2}{8}\sin 4\beta |H|^2 \Phi^\dagger H + \text{h.c.}$$

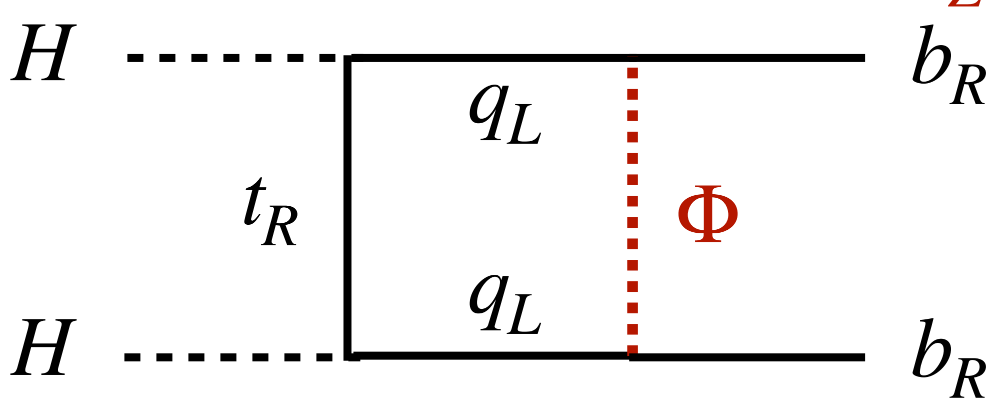
$$C_{fH} \propto g_Z^2 Y_f^{\rm SM} \sin 4\beta \tan\beta$$



$$[C_{Hq}^{(1)}]_{33} \propto \frac{y_t^4}{32\pi^2} \cot^2\beta \log\frac{m_\Phi^2}{m_Z^2}$$



$$[C_{Hd}]_{33} \propto \frac{y_t^2 y_b^2}{32\pi^2} \tan^2\beta \log\frac{m_\Phi^2}{m_Z^2}$$



Heavy Higgs doublet

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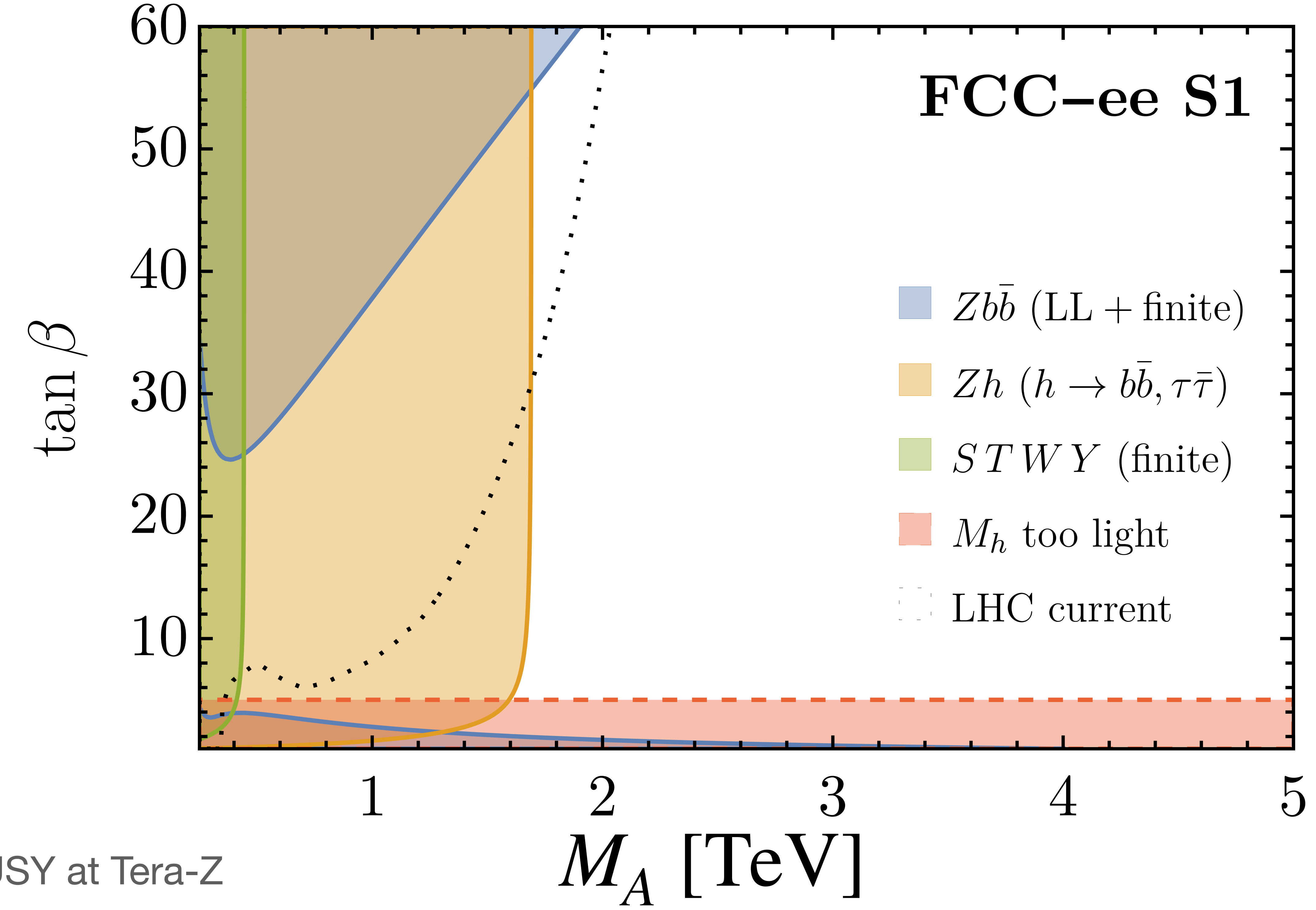

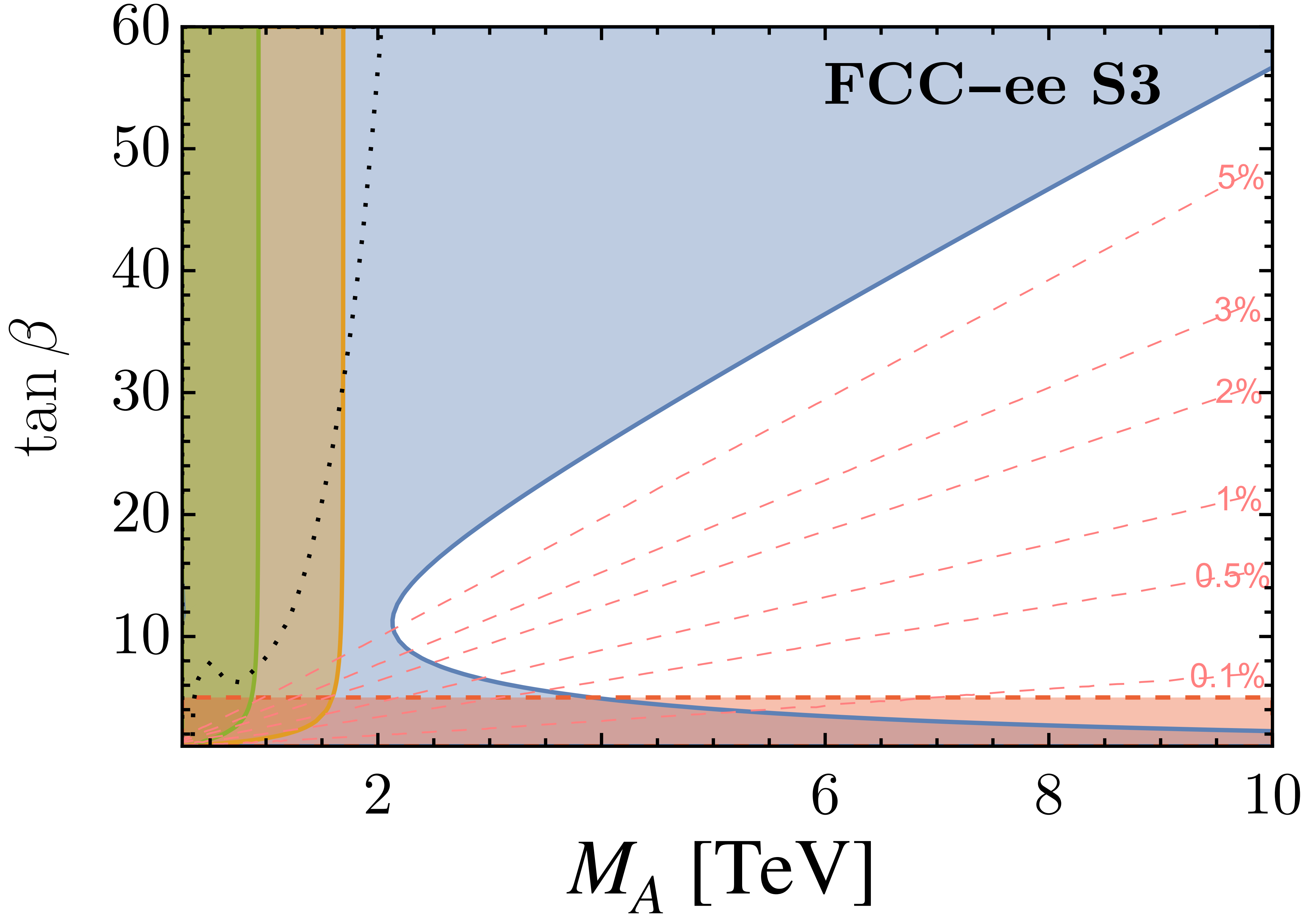

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Stops

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(MSSM TL: $m_h \leq m_Z$)

Crucial to accomodate $m_h \simeq 125$ GeV: need $m_{\tilde{t}_{1,2}} \gtrsim 1$ TeV and $X_t \simeq X_t^{\max}$

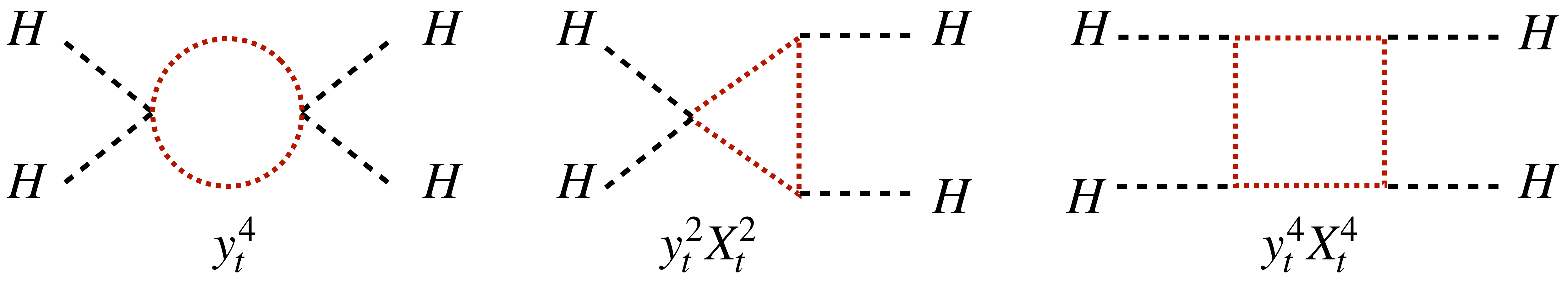
See e.g. Carena, Haber (2002)

Primary source of fine-tuning within MSSM (little hierarchy)

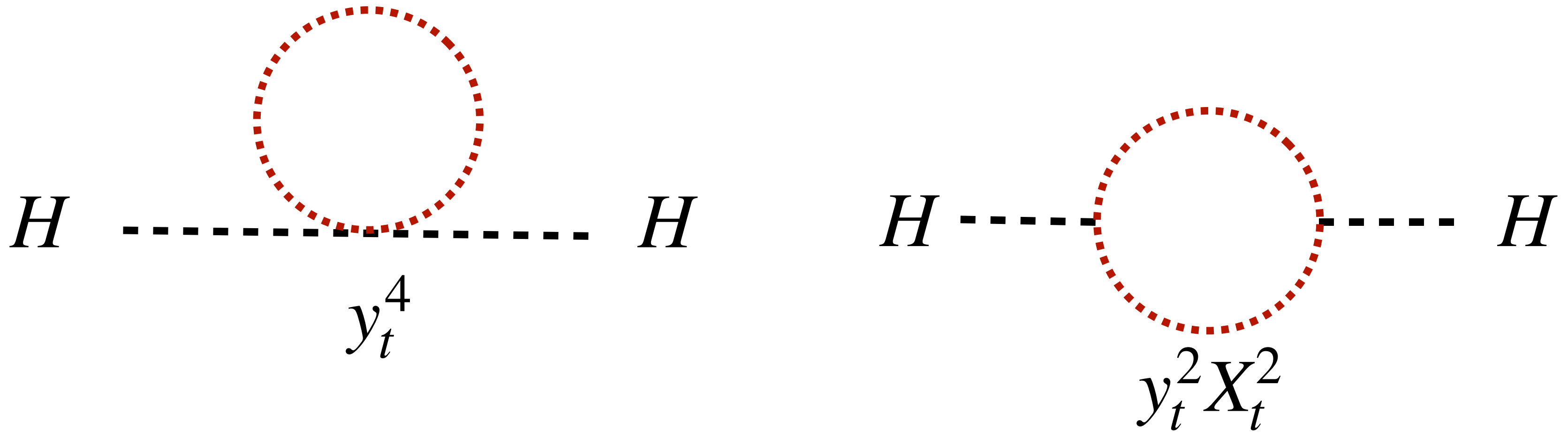
$$\mathcal{L}_{\text{stop}} \supset \boldsymbol{y_u} X_u \, \tilde{u}_R^\dagger H_u \tilde{q}_L - \boldsymbol{y_u} \boldsymbol{y_u}^\dagger (H_u \tilde{q}_L)^\dagger (H_u \tilde{q}_L)$$

$$X_t^{\max} = \sqrt{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$\delta\lambda_H \propto$



$\delta v_{\text{EW}}^2 \propto$



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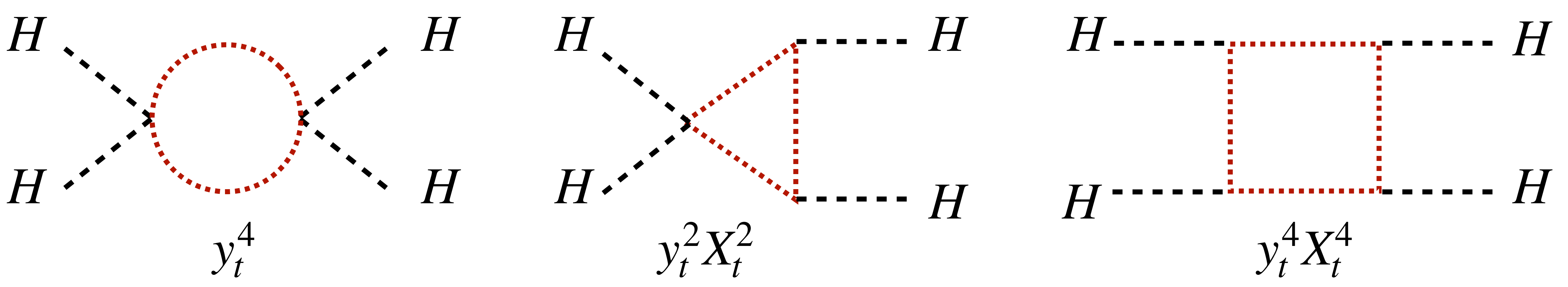
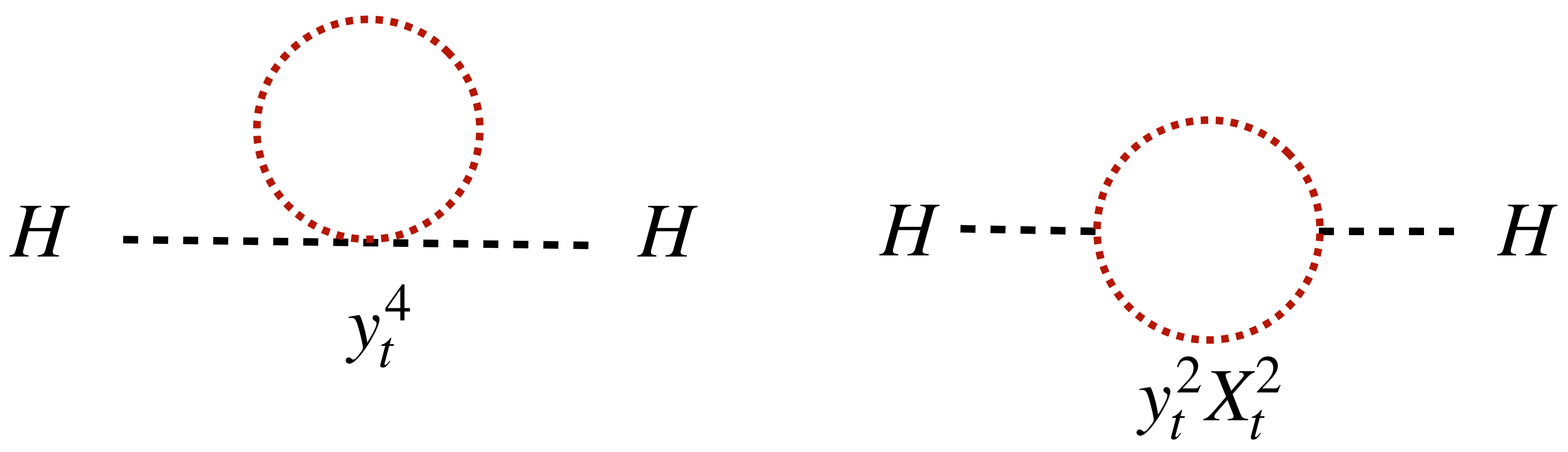
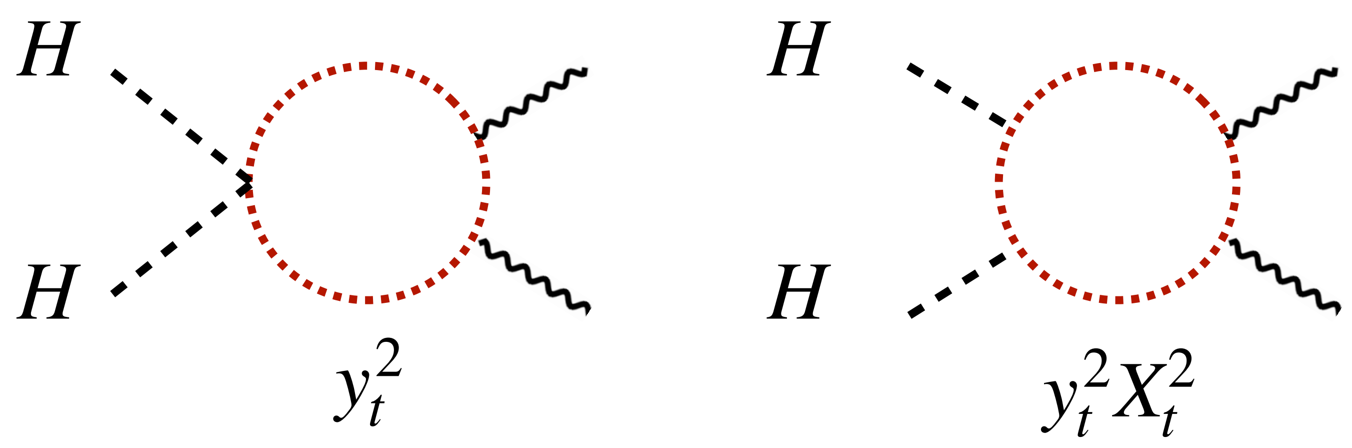


$\Longrightarrow \hat{T}!$ (C_{HD})

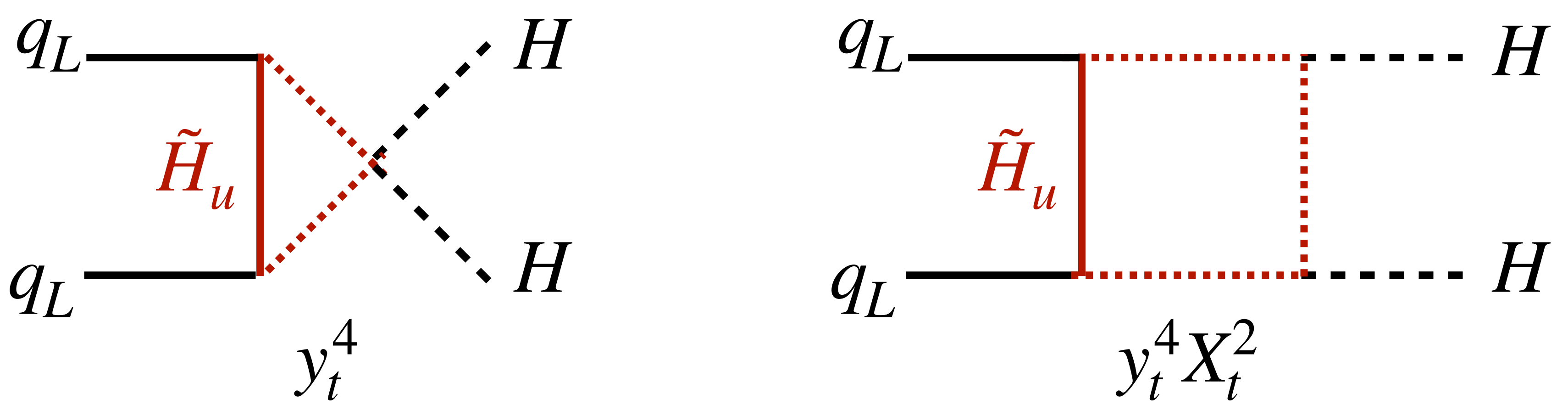
$\delta v_{\rm EW}^2 \propto$



$\kappa_{g,\gamma} \propto$ ($C_{Hg,HB,HW}$)



$R_b \propto$ ($C_{Hq}^{(1,3)}$)



Higgsino depedence (μ)

Stops

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See e.g.
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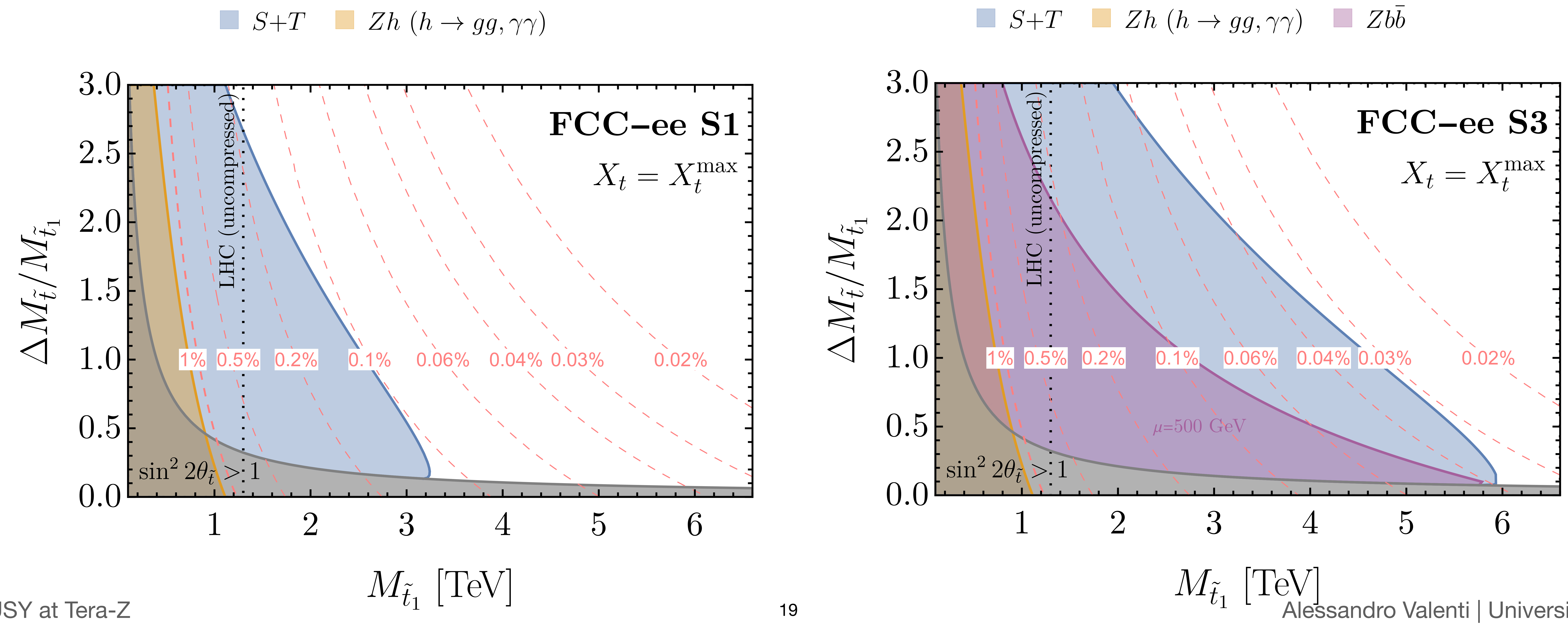

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Higgsinos & EW Gauginos

Naturally light ($\Delta(\mu) = 4\mu^2/m_Z^2$), classical DM candidate (LSP)

Easily evade direct searches (compressed spectra): typical LCF benchmark

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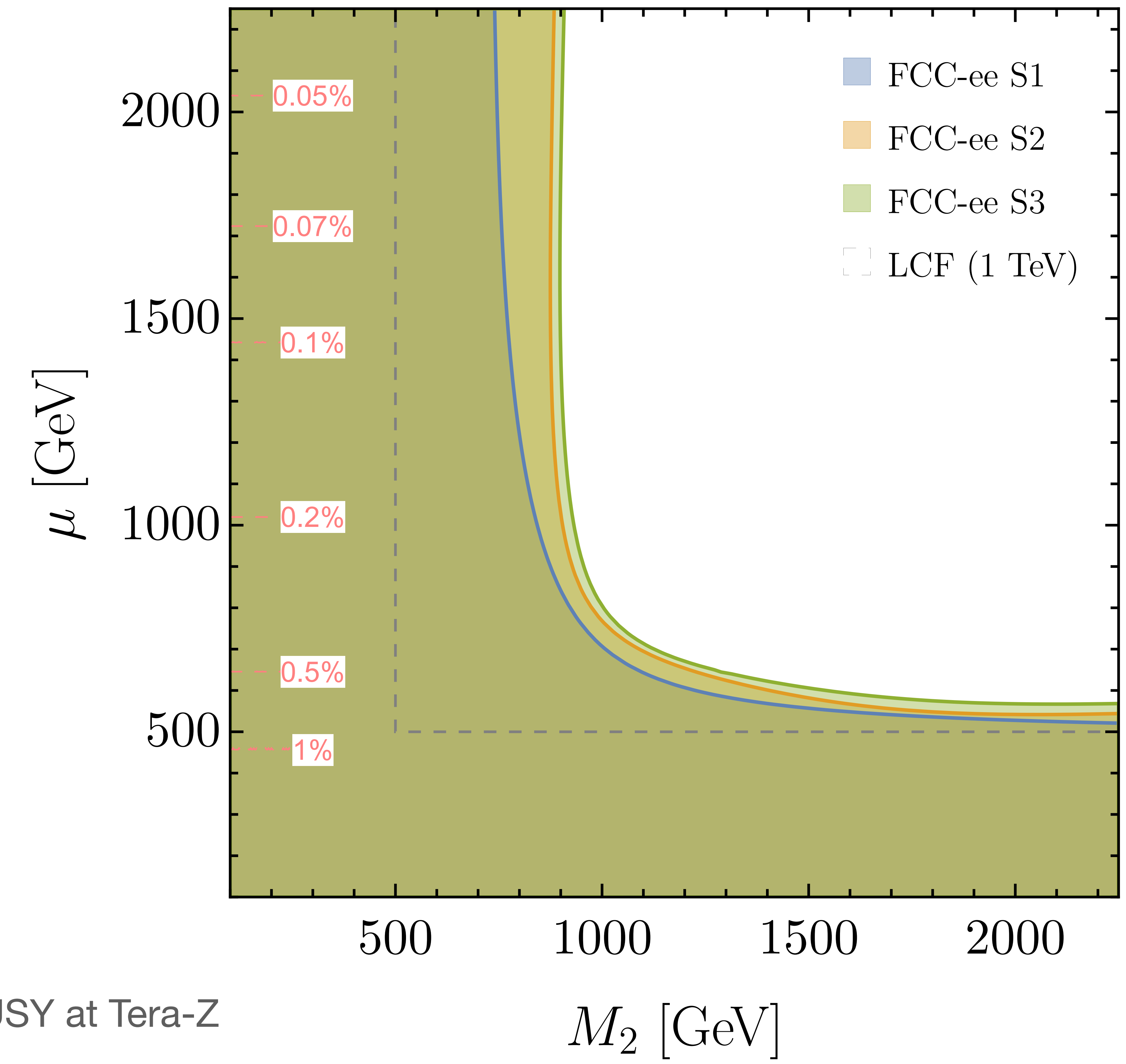

Tera-Z: S, T, W, Y

$$\hat{W} = \frac{\alpha_L m_W^2}{30\pi}\left(\frac{1}{\mu^2} + \frac{2}{M_2^2}\right)$$

leading and ***additive:***

inescapable reach on μ, M_2 up to 500 GeV!

- Closes compressed gaps (uncompressed LHC $M_2 \gtrsim$ TeV)
- Better reach than 1 TeV LCF!

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- Natural SUSY remains a leading candidate for microscopic theory of Higgs boson. Motivates the search for NP in the TeV range at future colliders
- We assessed and elaborated three FCC-ee scenarios for reach on EWPO at Tera-Z
- Employed them to study the discovery potential of key MSSM sectors: Heavy Higgs doublet, Stops, Higgsinos & EW Gauginos
- FCC-ee can exhaustively probe MSSM in multi-TeV range, testing sub-permille naturalness!

Thank you for your attention!

Backup

EWPO scenarios

	Scenario S1	Scenario S2	Scenario S3
Observable	**TH PO+TH agg.+EXP** (10^{-5})	**TH agg.+EXP** (10^{-5})	**EXP Only** (10^{-5})
Γ_Z	1.55	0.820	0.510
σ_{had}	4.33	2.06	1.93
R_e	2.21	1.05	0.410
R_μ	2.20	1.02	0.330
R_τ	2.20	1.03	0.350
R_b	20.1	1.63	0.180
R_c	100	1.19	0.260
A_{FB}^e	126	25.7	25.2
A_{FB}^μ	125	21.1	20.6
A_{FB}^τ	126	23.3	22.8
A_{FB}^b	87.8	6.42	5.50
A_{FB}^c	89.1	10.2	9.62
A_{FB}^s	88.2	10.7	10.2
$\sin^2\theta_W$	6.87	0.780	0.730
A_e	87.9	9.78	9.20
A_μ	90.1	22.1	21.8
A_τ	90.5	23.4	23.2
A_b	11.7	10.5	10.5
A_c	16.9	9.00	8.99
A_s	14.2	13.2	13.2
M_W	0.490	0.320	0.300
Γ_W	16.1	16.1	16.1

EWPO scenarios

S1

$$\begin{pmatrix} \hat{S} \\ \hat{T} \\ \hat{W} \\ \hat{Y} \end{pmatrix} = \pm \begin{pmatrix} 2.42 \\ 1.29 \\ 0.48 \\ 1.55 \end{pmatrix} \times 10^{-5}$$

$$\rho = \begin{pmatrix} 1. & 0.856 & 0.315 & 0.672 \\ 0.856 & 1. & 0.154 & 0.352 \\ 0.315 & 0.154 & 1. & 0.221 \\ 0.672 & 0.352 & 0.221 & 1. \end{pmatrix}$$

S2

$$\begin{pmatrix} \hat{S} \\ \hat{T} \\ \hat{W} \\ \hat{Y} \end{pmatrix} = \pm \begin{pmatrix} 1.74 \\ 0.73 \\ 0.47 \\ 1.55 \end{pmatrix} \times 10^{-5}$$

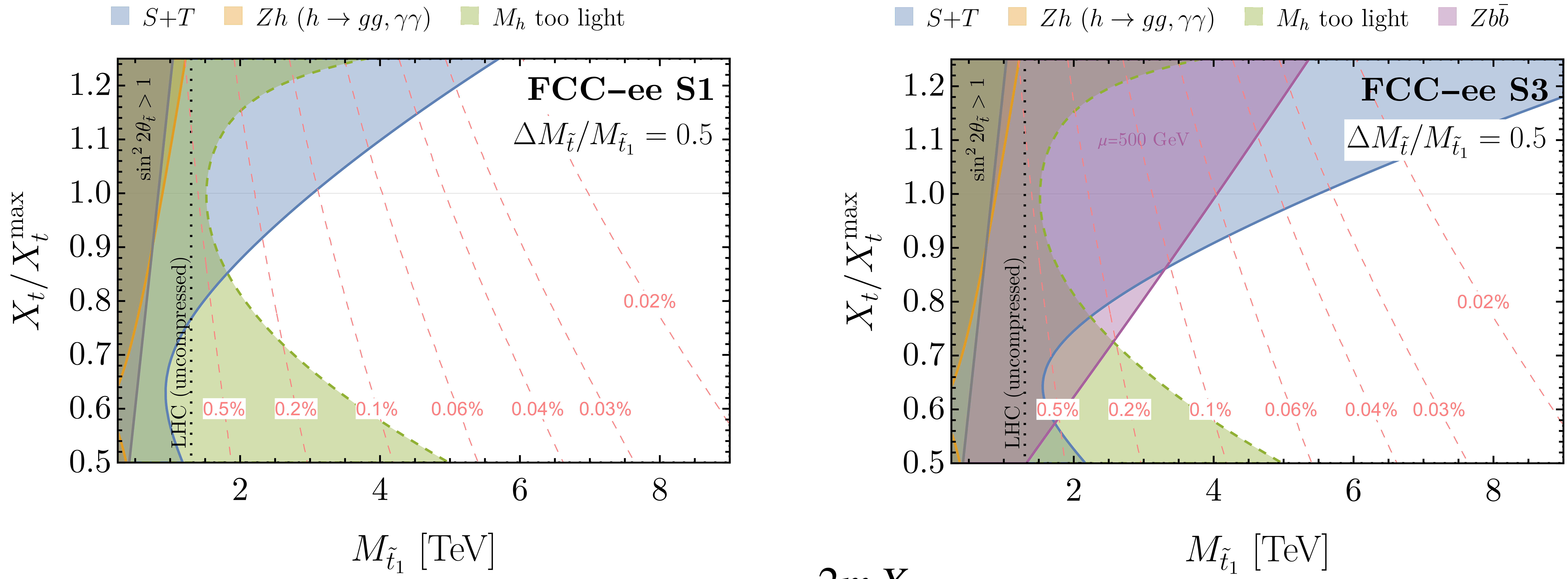
$$\rho = \begin{pmatrix} 1. & 0.825 & 0.394 & 0.937 \\ 0.825 & 1. & 0.248 & 0.63 \\ 0.394 & 0.248 & 1. & 0.216 \\ 0.937 & 0.63 & 0.216 & 1. \end{pmatrix}$$

S3

$$\begin{pmatrix} \hat{S} \\ \hat{T} \\ \hat{W} \\ \hat{Y} \end{pmatrix} = \pm \begin{pmatrix} 1.71 \\ 0.63 \\ 0.46 \\ 1.55 \end{pmatrix} \times 10^{-5}$$

$$\rho = \begin{pmatrix} 1. & 0.885 & 0.414 & 0.952 \\ 0.885 & 1. & 0.365 & 0.749 \\ 0.414 & 0.365 & 1. & 0.211 \\ 0.952 & 0.749 & 0.211 & 1. \end{pmatrix}$$

Stops: additonal plots



$$\sin 2\theta_{\tilde{t}} = \frac{2m_t X_t}{m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}}$$