Higgs-Precision Constraints on Colored Naturalness

Yi-Ming Zhong

Boston University

In collaboration with R. Essig, P. Meade, H. Ramani
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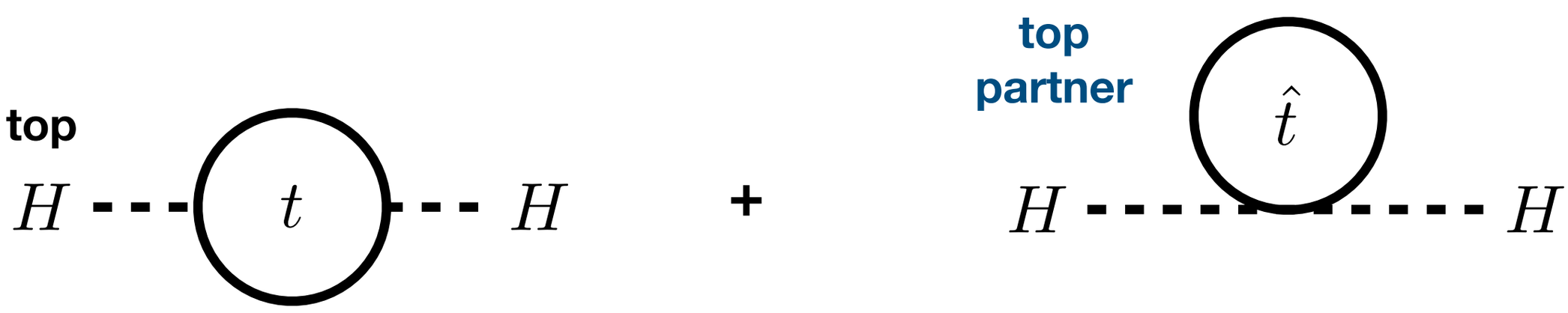
Outline

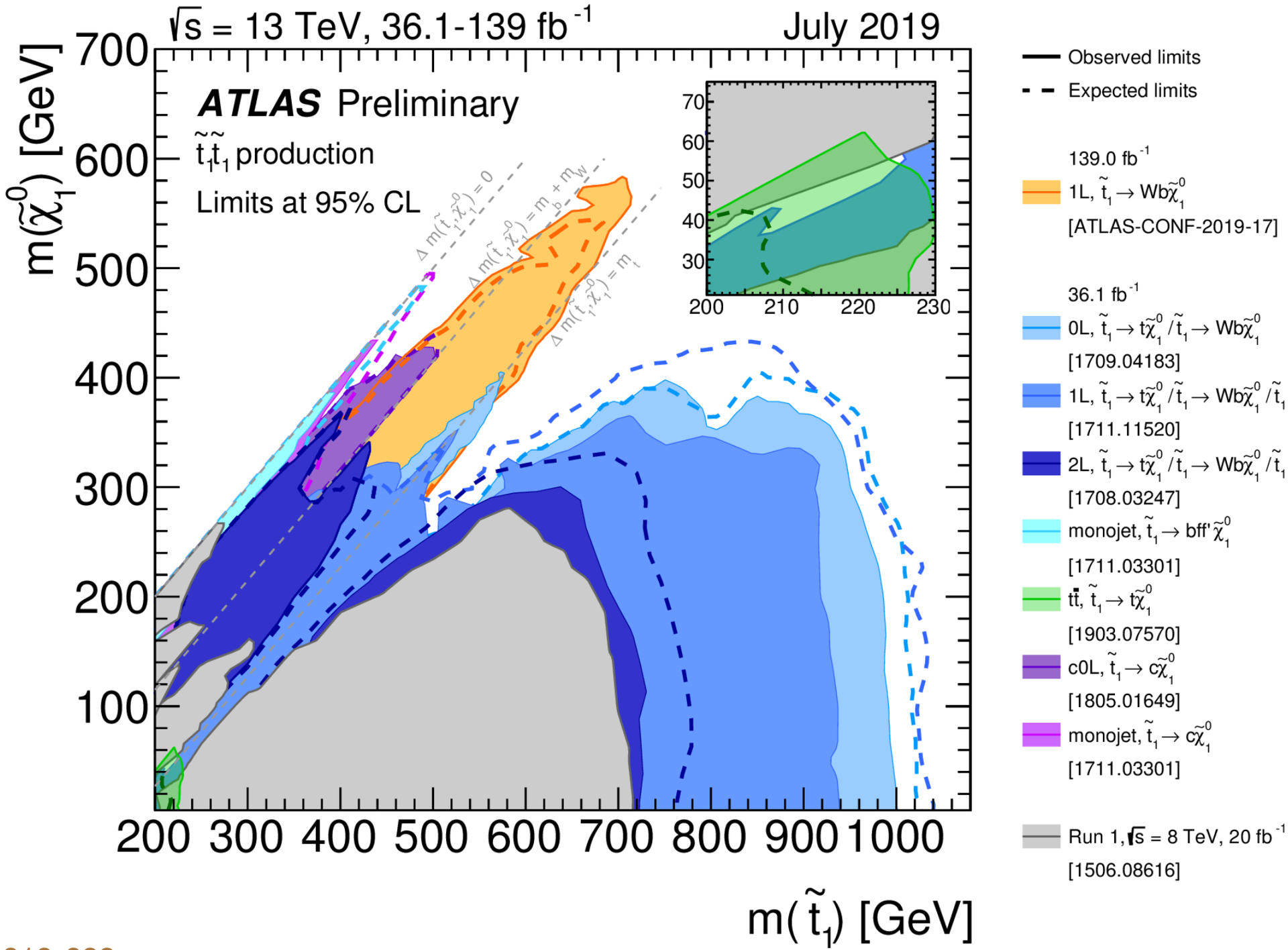
- Motivation
- A first look at signal strength
- Model survey
- Results

The naturalness problem

- m_h^2 are quadratically sensitive to UV
- **New physics (NP) near the electroweak (EW) scale**
- Adding new symmetries: Colored naturalness, Neutral naturalness



Direct searches



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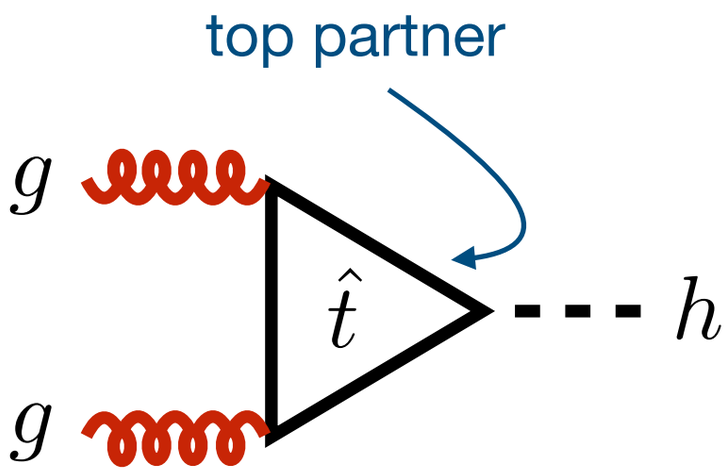
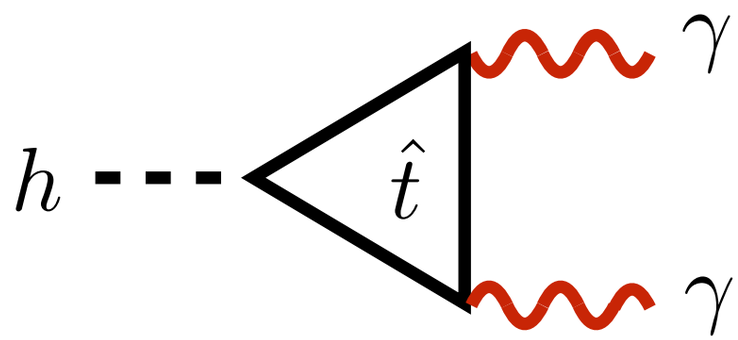
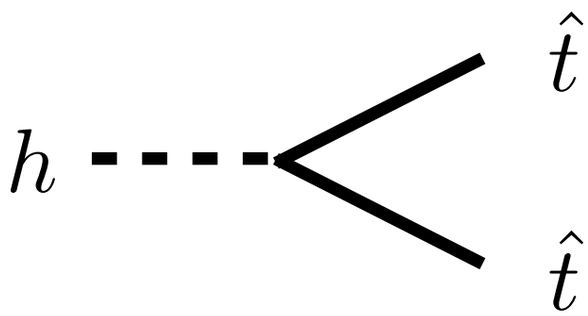
Indirect effects





Change the Higgs production rate



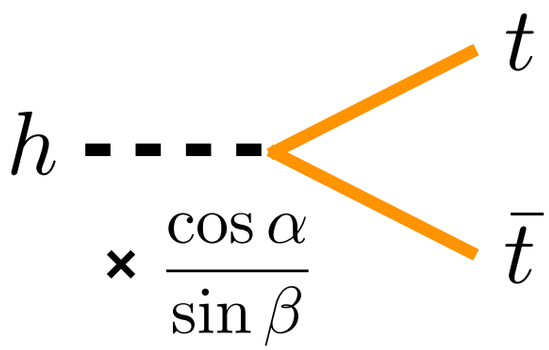
Open exotic decays (if $m_{\hat{t}} < m_h/2$)

Change the Higgs production rate

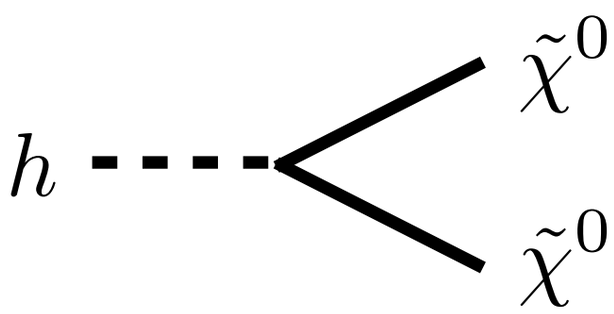
All captured by Higgs precision measurements

150+ channels have been measured

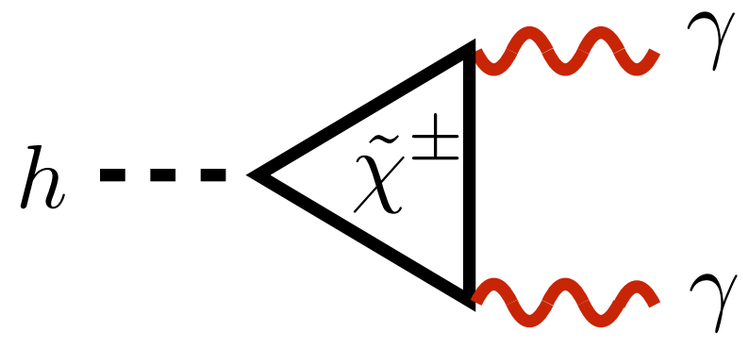
However, NP may also…



Change the
tree-level couplings



Have extra
exotic/invisible decays



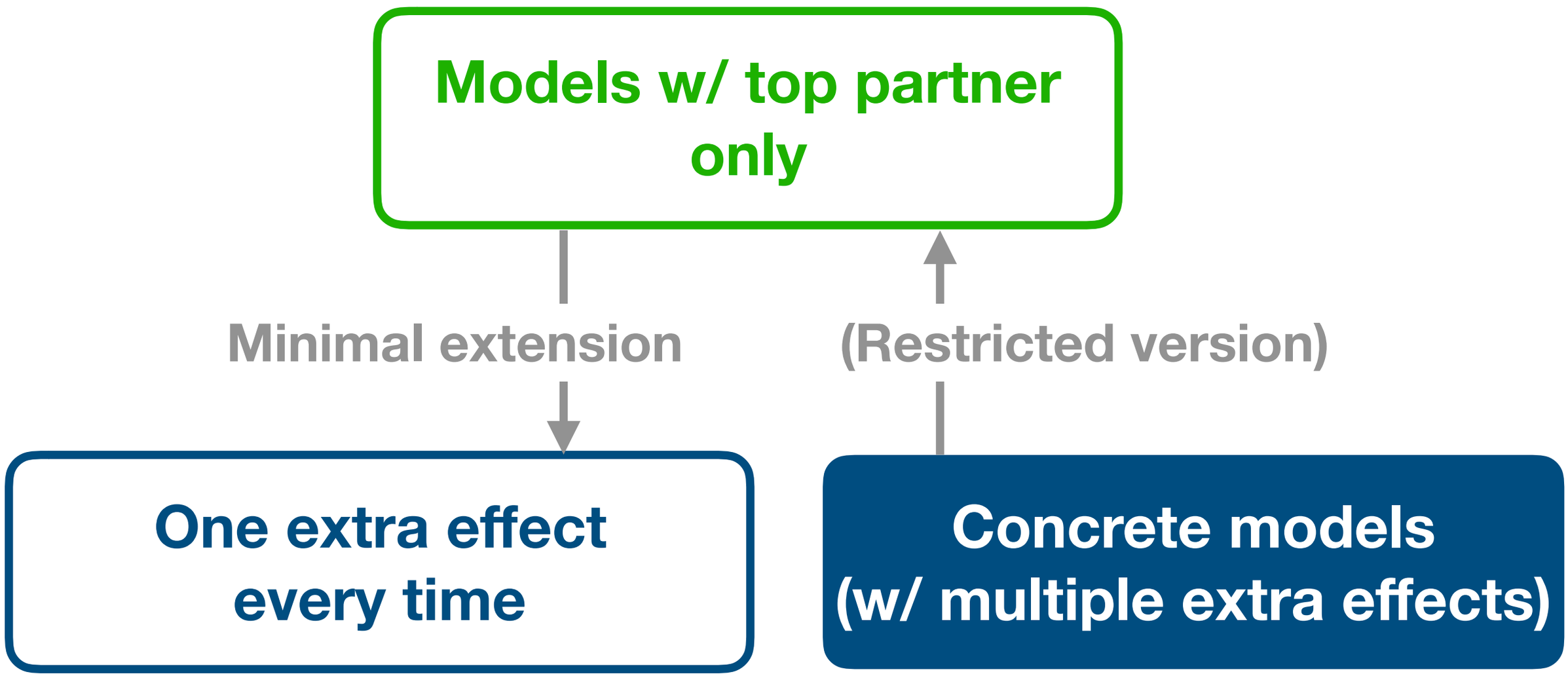
Have extra new particles
running in the loop

**hide the light
top partners…**

How robust is the Higgs precision?

What is the best way to hide the light top partner?

Our strategy



A first look at signal strength

Signal strength

$$\mu \equiv \frac{\sigma^{\rm BSM}_{\rm prod} \times B^{\rm BSM}_{\rm decay}}{\sigma^{\rm SM}_{\rm prod} \times B^{\rm SM}_{\rm decay}}$$

ggF, ttH, VBF, VH

γγ, WW, ZZ, bb, ττ

$$= \left(\frac{\sigma^{\rm BSM}_{\rm prod}}{\sigma^{\rm SM}_{\rm prod}}\right) \left(\frac{\Gamma^{\rm BSM}_{\rm decay}}{\Gamma^{\rm SM}_{\rm decay}}\right) \left(\frac{\Gamma^{\rm SM}_{\rm tot}}{\Gamma^{\rm BSM}_{\rm tot}}\right)$$

invisible, exotic

Signal strength

$$r_G \equiv c_G / c_G^{\rm SM}$$

$$\mu = \left(\frac{r_G^2 \sigma_G^{\rm SM} + \cdots}{\sigma_{\rm prod}^{\rm SM}} \right) \left(\frac{r_b^2 \Gamma_b^{\rm SM} + \cdots}{\Gamma_{\rm decay}^{\rm SM}} \right) \left(\frac{}{\Gamma_{\rm tot}^{\rm vis}} \right.$$

$$= \frac{\left(\sum_i r_i^2 \xi_i \right) \left(\sum_f r_f^2 \zeta_f \right)}{r_h + r_{\rm exo} + r_{\rm inv}}$$

Signal strength

$$r_b \equiv c_b / c_b^{\rm SM}$$

$$\frac{\left(\frac{r_G^2 \sigma_G^{\rm SM} + \cdots}{\sigma_{\rm prod}^{\rm SM}}\right)\left(\frac{r_b^2 \Gamma_b^{\rm SM} + \cdots}{\Gamma_{\rm decay}^{\rm SM}}\right)\left(\frac{\Gamma_{\rm tot}^{\rm SM}}{\Gamma_{\rm tot}^{\rm vis} + \Gamma_{\rm exo} -}\right)\left(\sum_i r_i^2 \xi_i\right)\left(\sum_f r_f^2 \zeta_f\right)}{r_h + r_{\rm exo} + r_{\rm inv}}$$

Signal strength

$$\mu = \left(\frac{r_G^2 \sigma_G^{\rm SM} + \cdots}{\sigma_{\rm prod}^{\rm SM}} \right) \left(\frac{r_b^2 \Gamma_b^{\rm SM} + \cdots}{\Gamma_{\rm decay}^{\rm SM}} \right) \left(\frac{}{\Gamma_{\rm tot}^{\rm vis}} \right.$$

$$= \frac{\left(\sum_i r_i^2 \xi_i\right) \left(\sum_f r_f^2 \zeta_f\right)}{r_h + r_{\rm exo} + r_{\rm inv}}$$

$$r_h \equiv 1 + \sum_{j=G,\gamma,V,b,\tau} (|r_j|^2 - 1) B_{h\to jj}^{\rm SM}$$

$$r_{\rm inv} = \Gamma_{\rm inv}/\Gamma_{\rm tot}^{\rm SM} \quad r_{\rm exo} = \Gamma_{\rm exo}/\Gamma_{\rm tot}^{\rm SM}$$

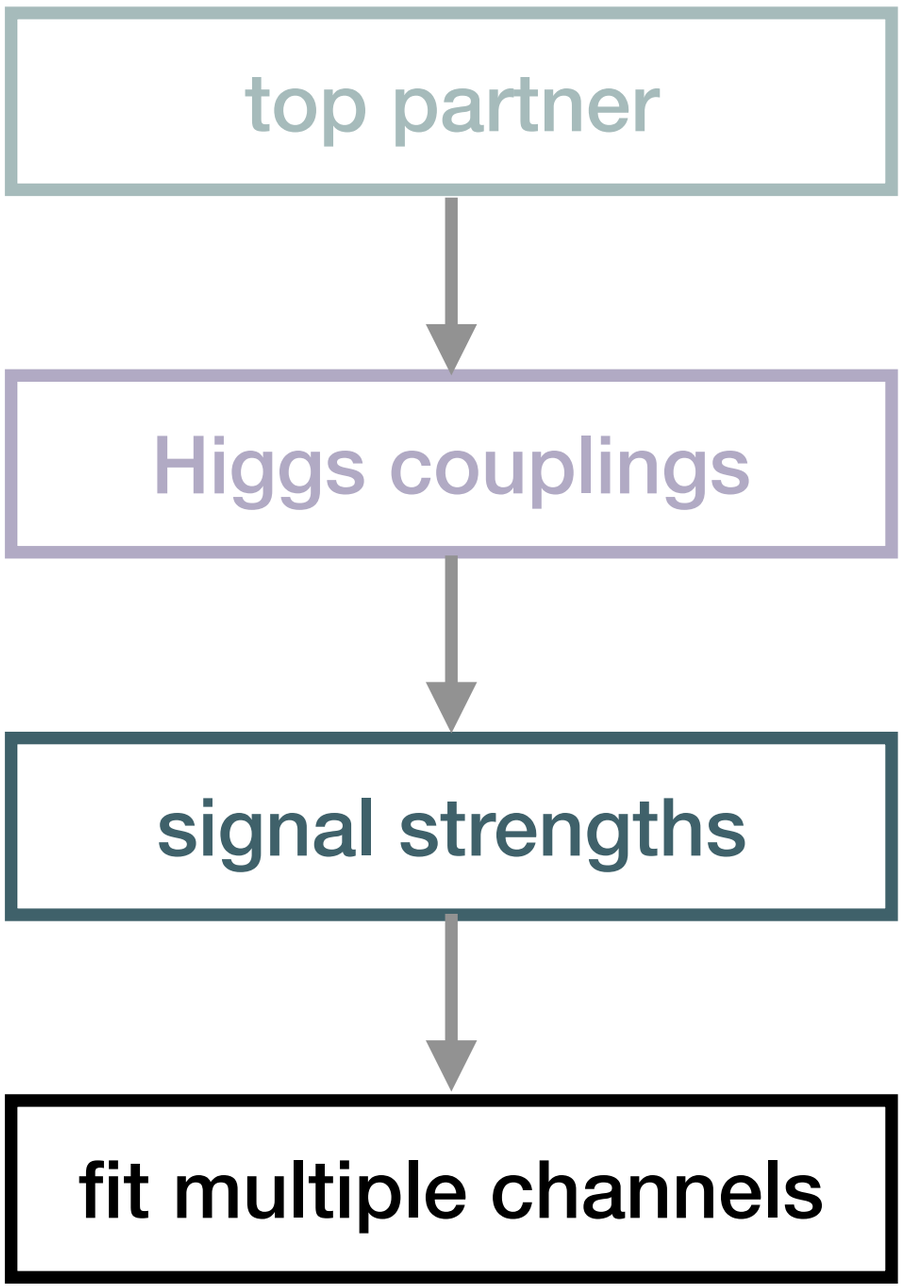
Constrain the light top partner

$$m_{\hat{t}}$$

$$r_G \equiv \frac{c_G}{c_G^{\rm SM}} = 1 + \mathcal{N}_{\hat{t}}$$

$$\mu_f = \frac{|r_G|^2 \xi_G + \xi_V + \xi_t}{1 + (|r_G|^2 - 1) B_{h\to gg}^{\rm SM} + \cdots}$$

$$\chi^2 = \sum_{f,\rm inv} \frac{(\mu_f - \mu_f^{\rm obs})^2}{\sigma_f^2}$$



Add invisible decay

$m_{\hat{t}}$ $\Gamma_{\rm inv}$

$r_G = 1 + \mathcal{N}_{\hat{t}}$

$$\mu_f = \frac{|r_G|^2 \xi_G + \xi_V + \xi_t}{1 + (|r_G|^2 - 1) B^{\rm SM}_{h\to gg} + \cdots + r_{\rm inv}}$$

$$\chi^2 = \sum_{f,\rm inv} \frac{(\mu_f - \mu_f^{\rm obs})^2}{\sigma_f^2}$$

top partner
+ invisible decay

Higgs couplings

signal strengths

fit multiple channels

Change Higgs-top coupling

$$r_t \equiv \frac{c_t}{c_t^{\rm SM}} \qquad m_{\hat{t}}$$

$$r_G = r_t(1 + \mathcal{N}_{\hat{t}})$$

$$\mu_f = \frac{|r_G|^2 \xi_G + \xi_V + |r_t|^2 \xi_t}{1 + (|r_G|^2 - 1) B_{h\to gg}^{\rm SM} + \cdots}$$

$$\chi^2 = \sum_{f,\rm inv} \frac{(\mu_f - \mu_f^{\rm obs})^2}{\sigma_f^2}$$

top partner
+ change *htt*

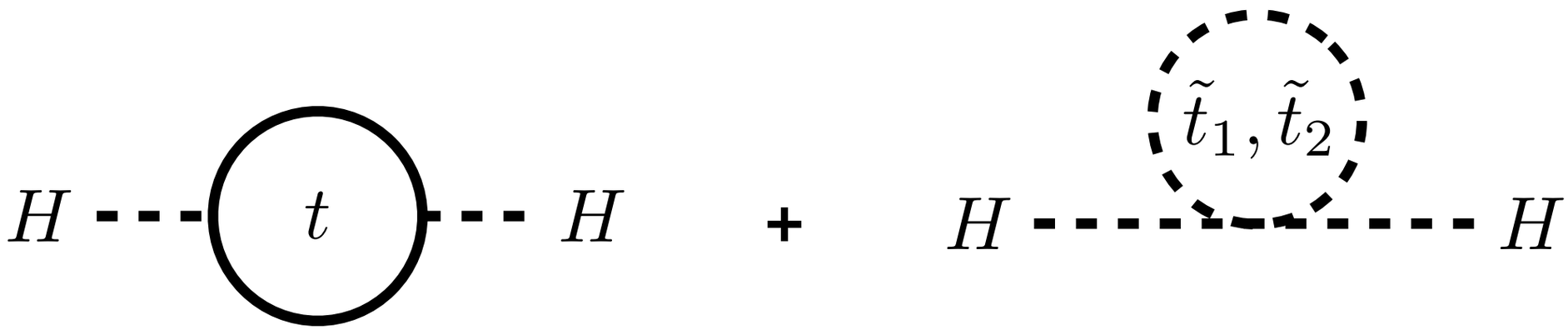
Higgs couplings

signal strengths

fit multiple channels

Model survey

Spin-0



real eigenvalues

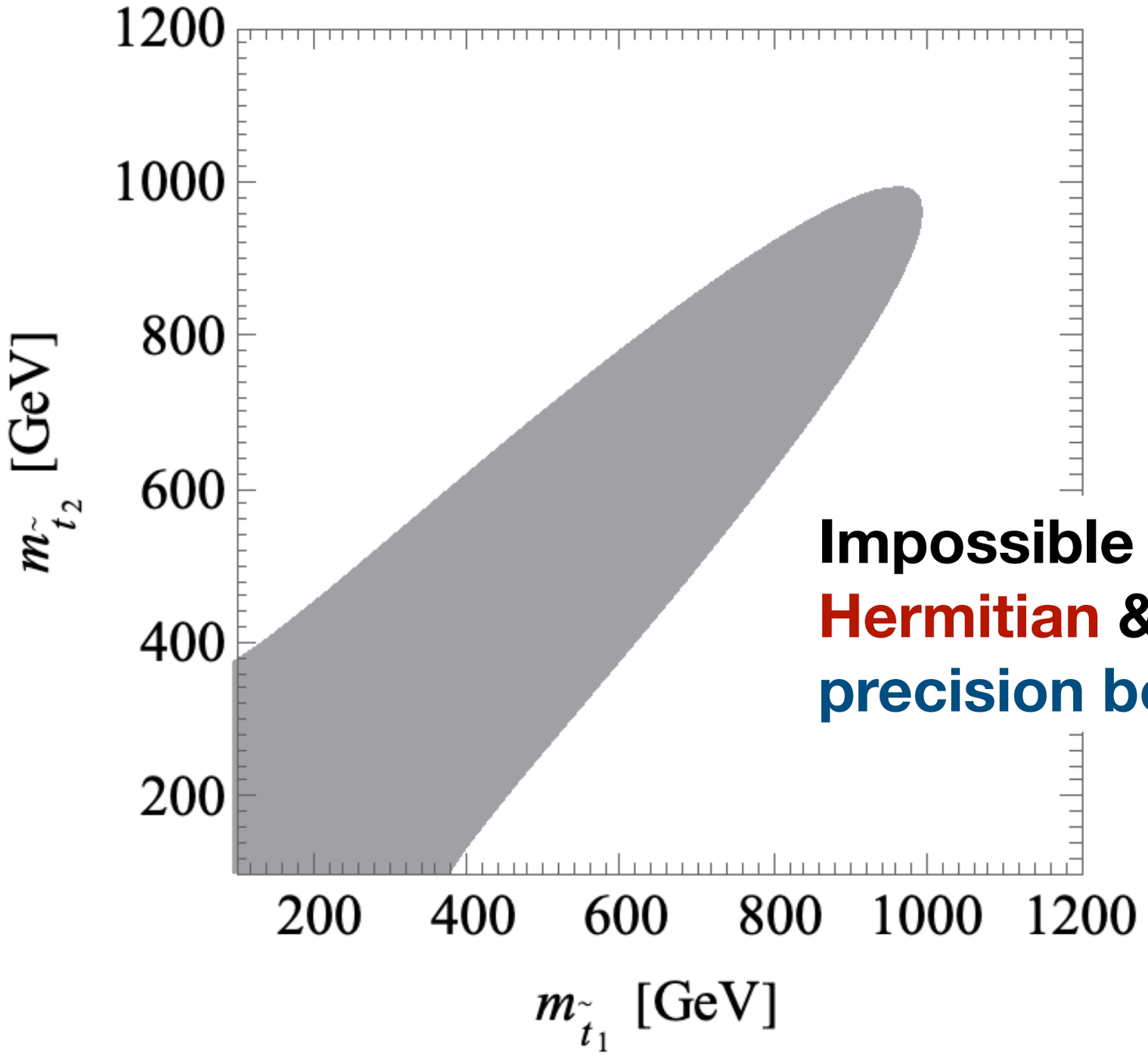
- $$\begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L^t & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + D_R^t \end{pmatrix} \Rightarrow \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$
- *hgg* modification:

$$\mathcal{N}_{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

Bounded by Higgs precision measurement

Dermisek & Low ’08, Blum, D’Agnolo & Fan ’13, Fan & Recce, ’14, Fan, Recce & Wang ’14 Carmi et al ‘15

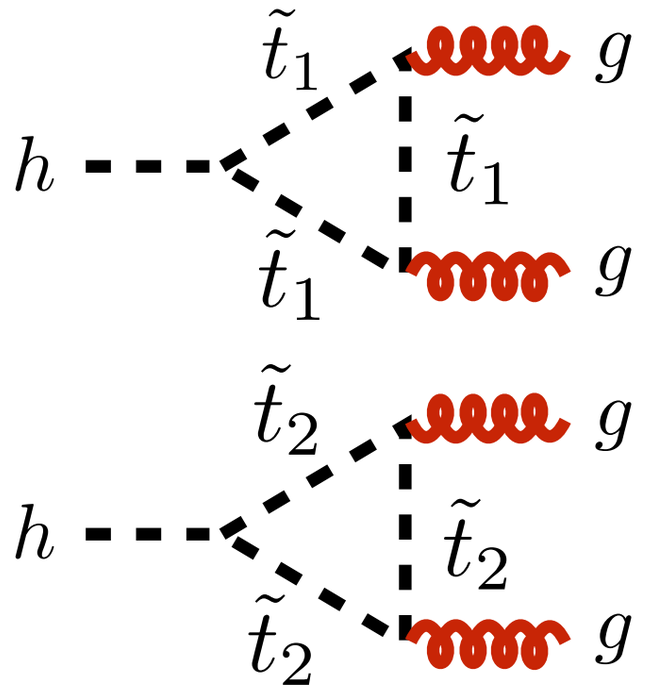
Spin-0

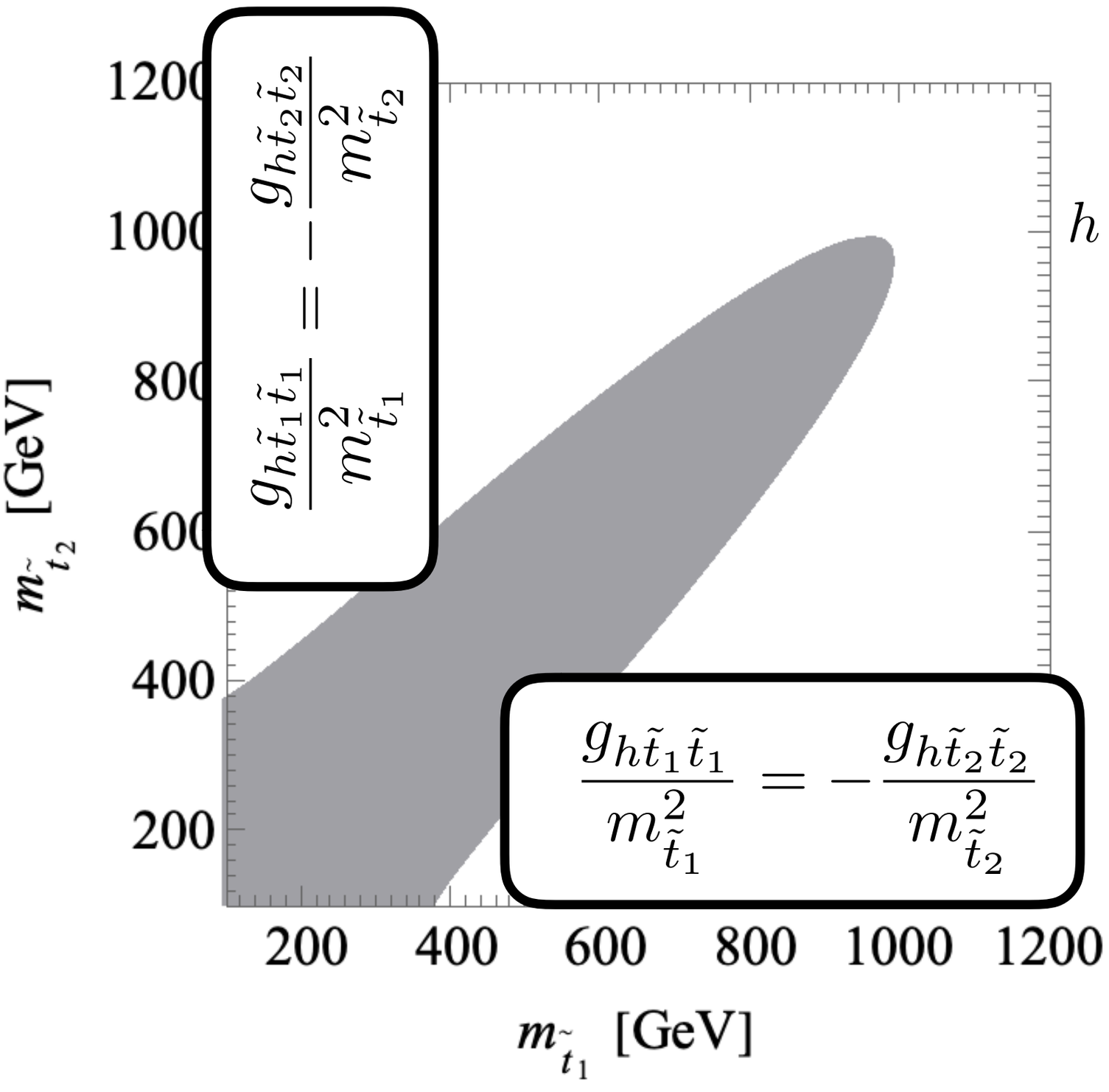


Impossible to satisfy Hermitian & Higgs precision bounds

Fan & Recce, ’14, Fan, Recce & Wang ’14

Spin-0





Fan & Recce, ’14, Fan, Recce & Wang ’14

Spin-0: MSSM

- Higgs sector of MSSM: two-Higgs-doublet-model (2HDM), lighter Higgs = 125 GeV Higgs

- Coupling modifier

type-II 2HDM

$$r_c = r_t = \frac{\cos\alpha}{\sin\beta}, \quad r_b = r_\tau = -\frac{\sin\alpha}{\cos\beta}, \quad r_V = \sin(\beta-\alpha)$$

α : rotation angle in Higgs matrix

$\tan\beta = v_u/v_d$

Spin-0: MSSM

- Higgs sector of MSSM: two-Higgs-doublet-model (2HDM), lighter Higgs = 125 GeV Higgs

- Coupling modifier

- $\tan\beta \ll 1 : r_b, r_V \to 1, r_t$ is free

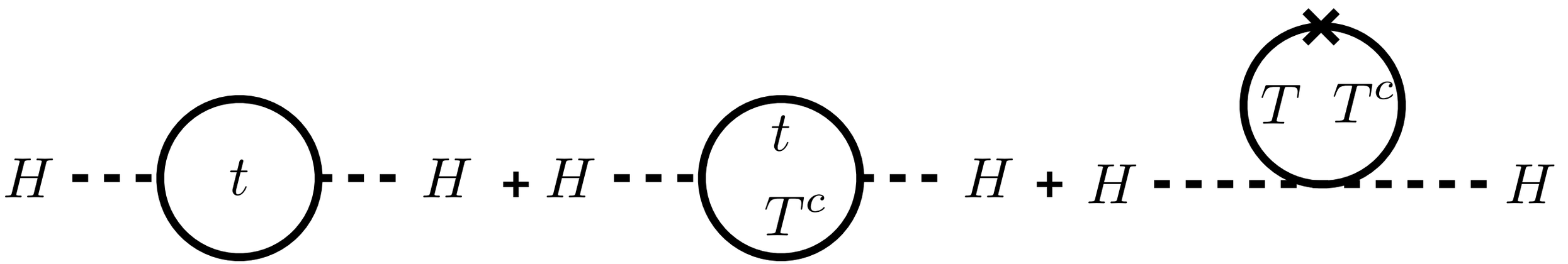
- $\tan\beta \gg 1 : r_t, r_V \to 1, r_b$ is free

type-II 2HDM

$$\tan\beta = v_u/v_d$$

Running of the top Yukawa imposes perturbativity bounds on tan β

Spin-1/2



- Higgs is a PNGB of a larger symmetry that is collectively broken (from a EFT with expansion scale f)

SU(3) Simplest Little Higgs
SU(5) Littlest Little Higgs

- *hgg* modification:

$$\mathcal{N}_T = -\frac{m_t^2}{m_T^2} + \mathcal{O}\left(\frac{v^2}{f^2}\right)$$

$$-1 < \mathcal{N}_T < 0$$

Spin-1/2 extensions

- Extend the Higgs sector to be 2HDM

SU(4) Simplest Little Higgs

- Allow changes on r_t, r_b, r_V …

- Best: type-II 2HDM

Spin-1

- Complicated
  (need SUSY + an enlarged symmetry, right-handed top ~ Higgsino, top Yukawa ~ gauge coupling…)

Cai, Cheng & Terning, ‘08

- *hgg* modification

$$\mathcal{N}_{\vec{Q}} \sim -\frac{21}{4}\frac{m_t^2}{m_{\vec{Q}}^2}$$

Loop function penalty

Results

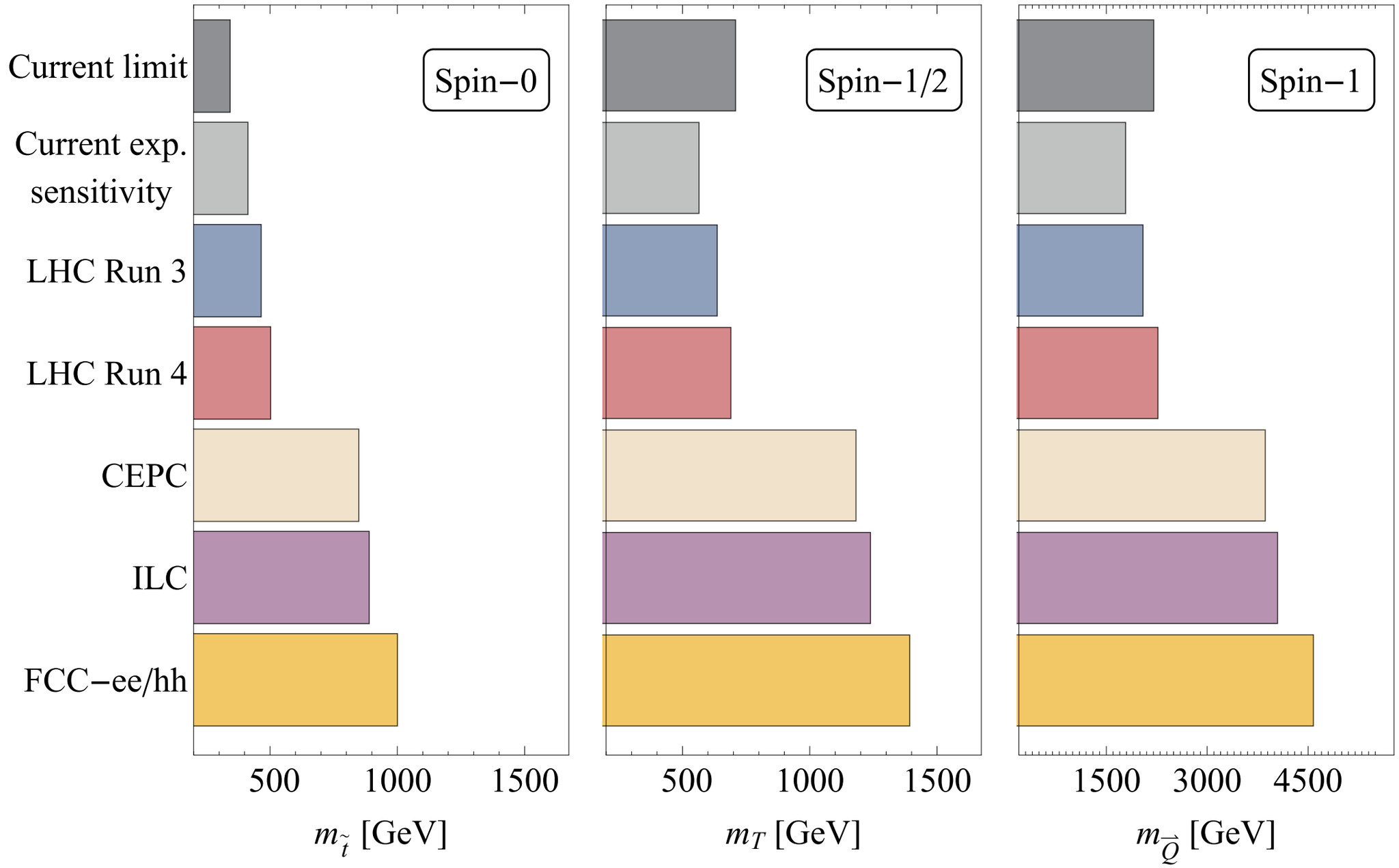
Data sets

	Energy	Int. Luminosity	Measurements
Tevatron	1.96 TeV	6-10/fb	15 channels
ATLAS	7+8 TeV	25/fb	150+ channels
CMS	13 TeV	2.3-36/fb	
LHC Run 3	14 TeV	300/fb	Projected searches
LHC Run 4	14 TeV	3,000/fb	
ILC	250 GeV	2,000/fb	Combined coupling fits
	350 GeV	200/fb	
	500 GeV	4,000/fb	
CEPC	240 GeV	10,000/fb	
FCC-ee	240 GeV	10,000/fb	
	350 GeV	2,600/fb	
FCC-hh	100 TeV	30,000/fb	

Current limit

Current expected limit

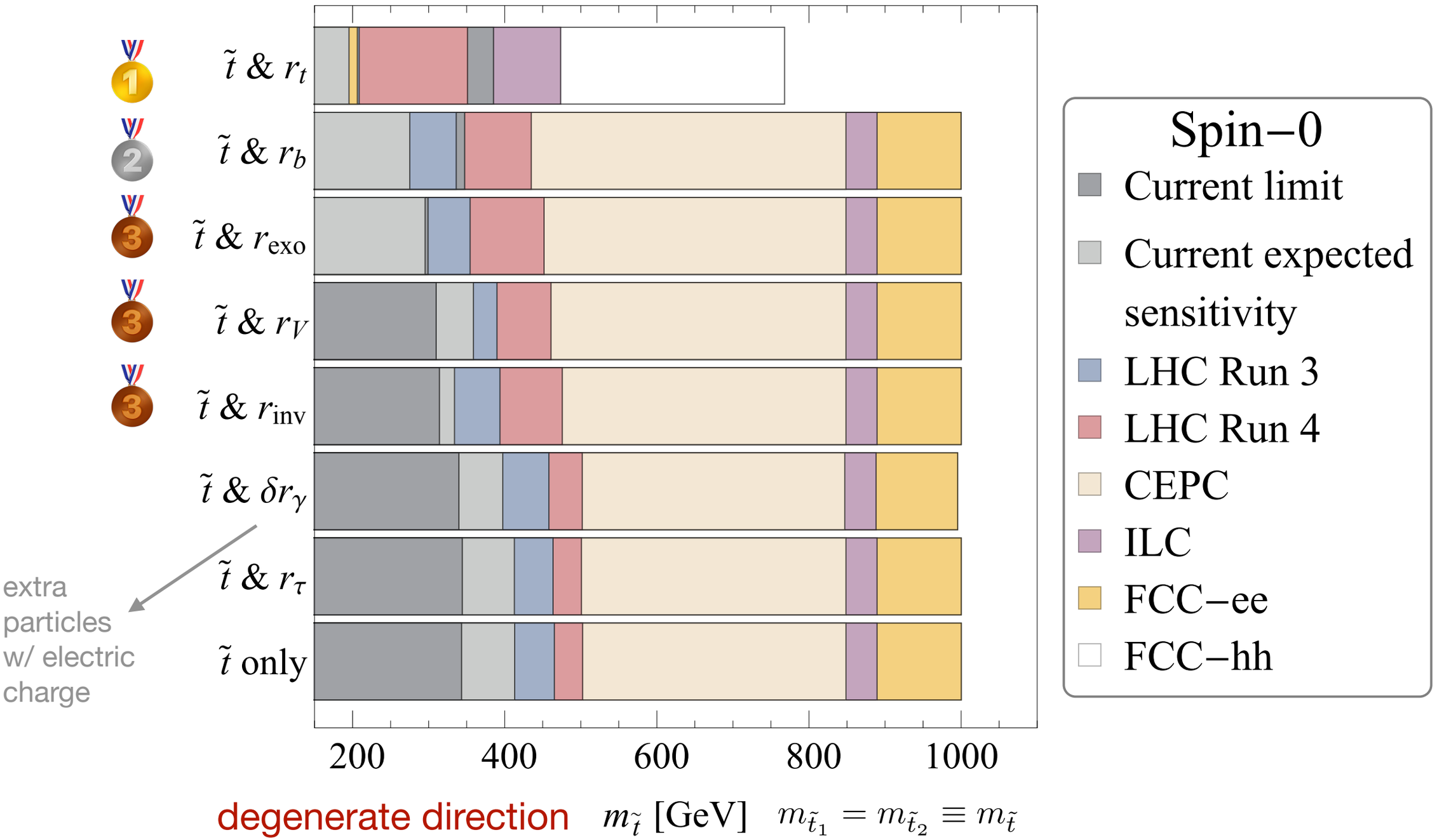
Models w/ top partner only



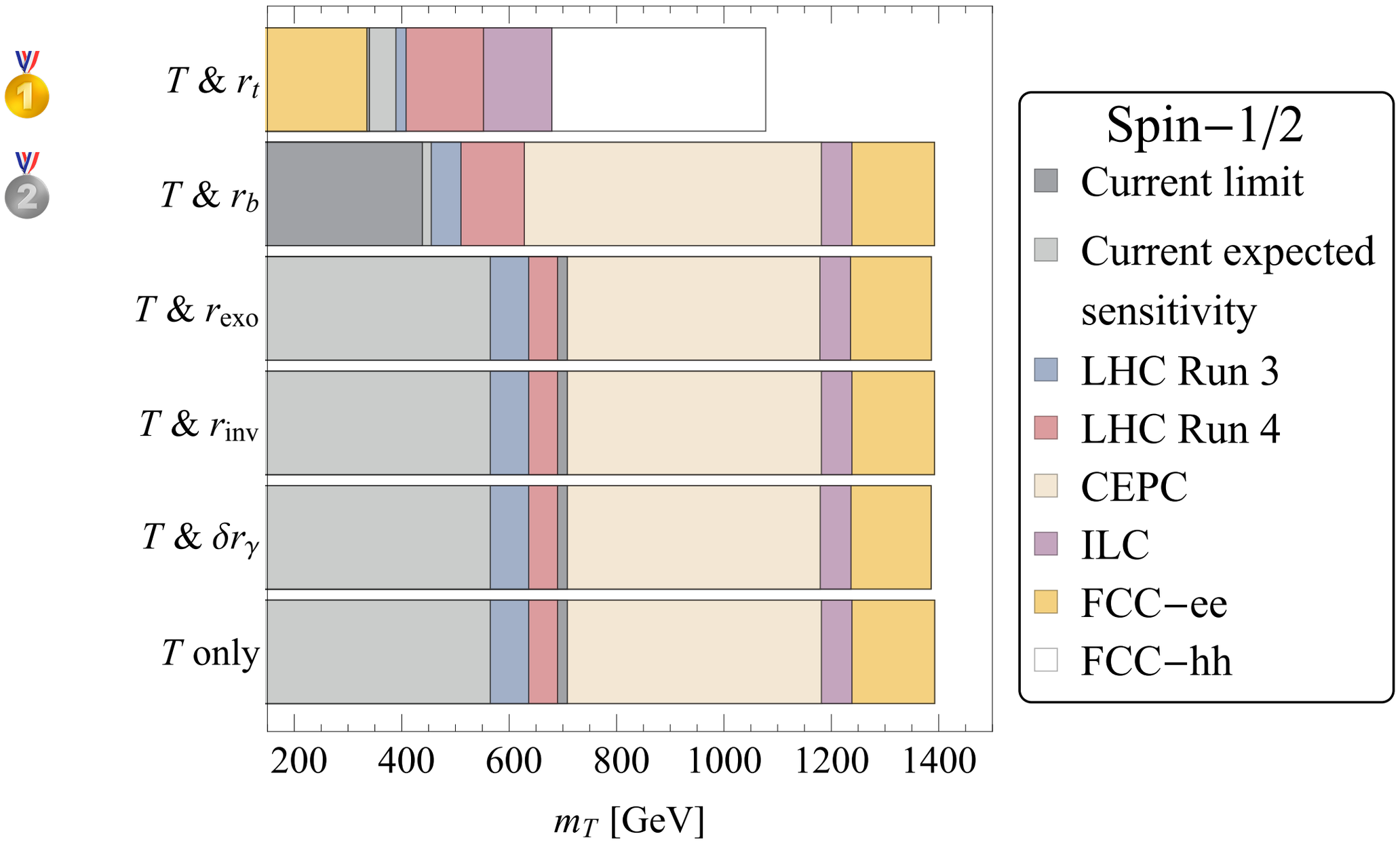
degenerate direction $m_{\tilde{t}_1} = m_{\tilde{t}_2} \equiv m_{\tilde{t}}$

w/ 2σ CL

Minimal ext. of spin-0



Minimal ext. of spin-1/2

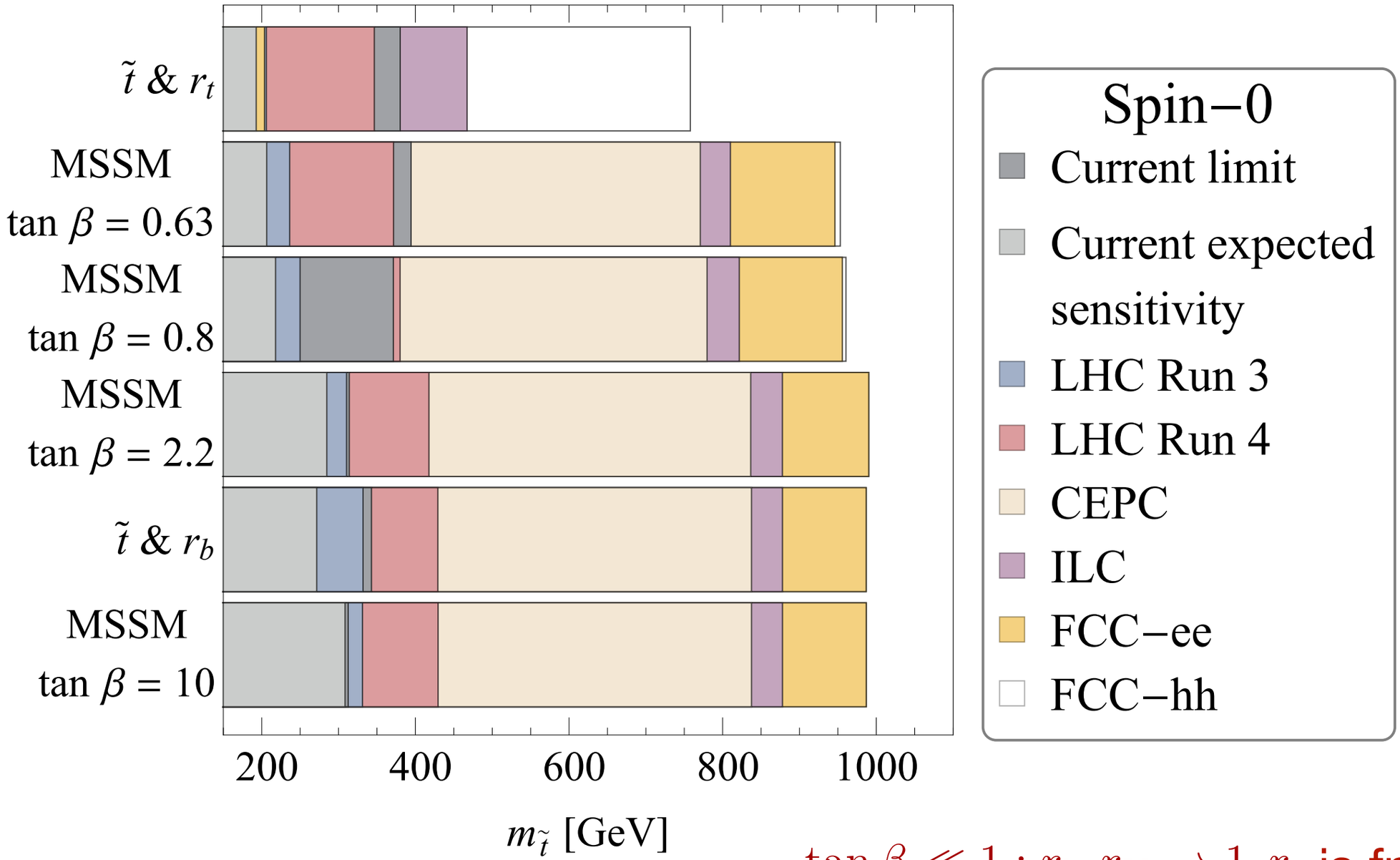


w/ 2σ CL

MSSM

w/ 2σ CL

easy to hide w/ small tan β



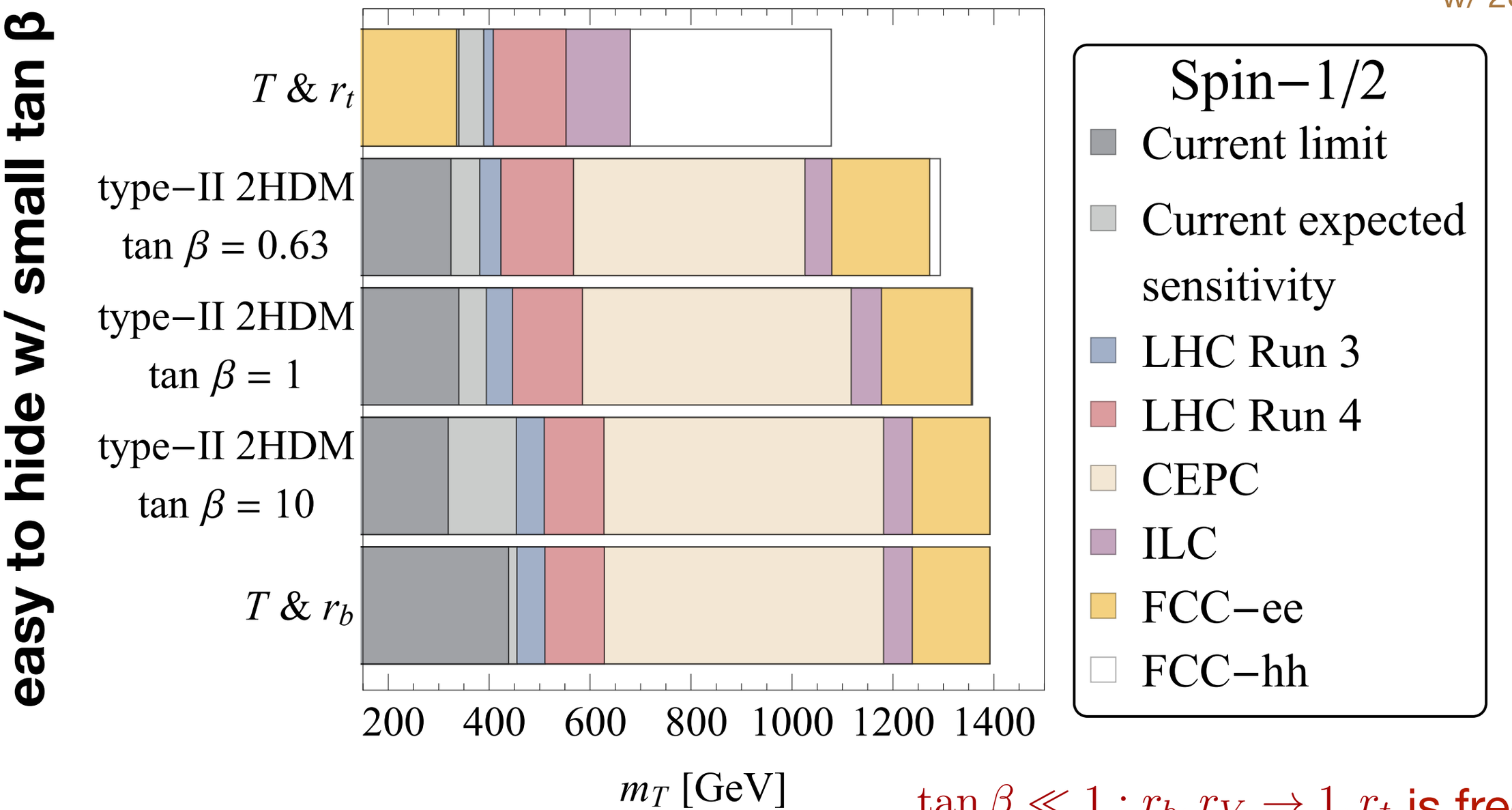
degenerate direction $m_{\tilde{t}_1} = m_{\tilde{t}_2} \equiv m_{\tilde{t}}$

$\tan\beta \ll 1 : r_b, r_V \to 1, r_t$ is free

$\tan\beta \gg 1 : r_t, r_V \to 1, r_b$ is free

Spin-1/2 w/ 2HDM

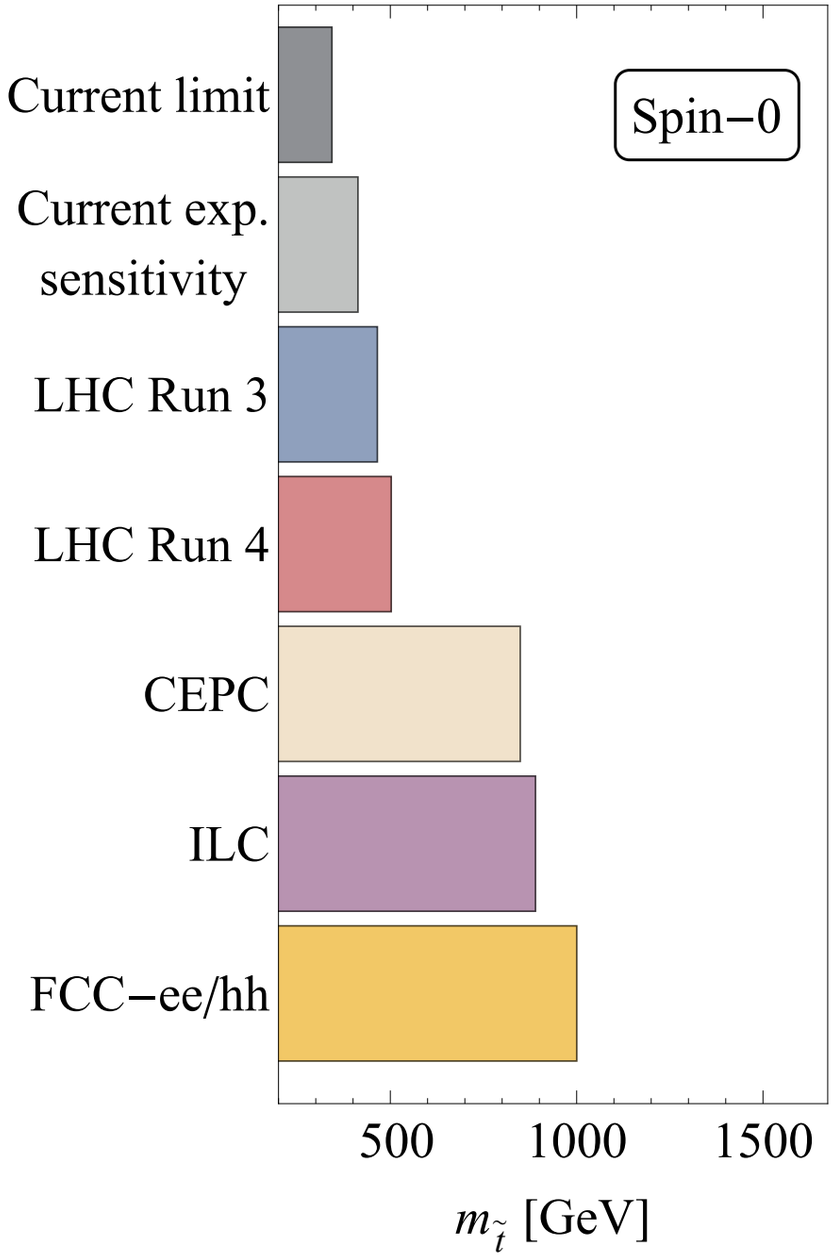
w/ 2σ CL



$\tan\beta \ll 1 : r_b, r_V \to 1, r_t$ is free

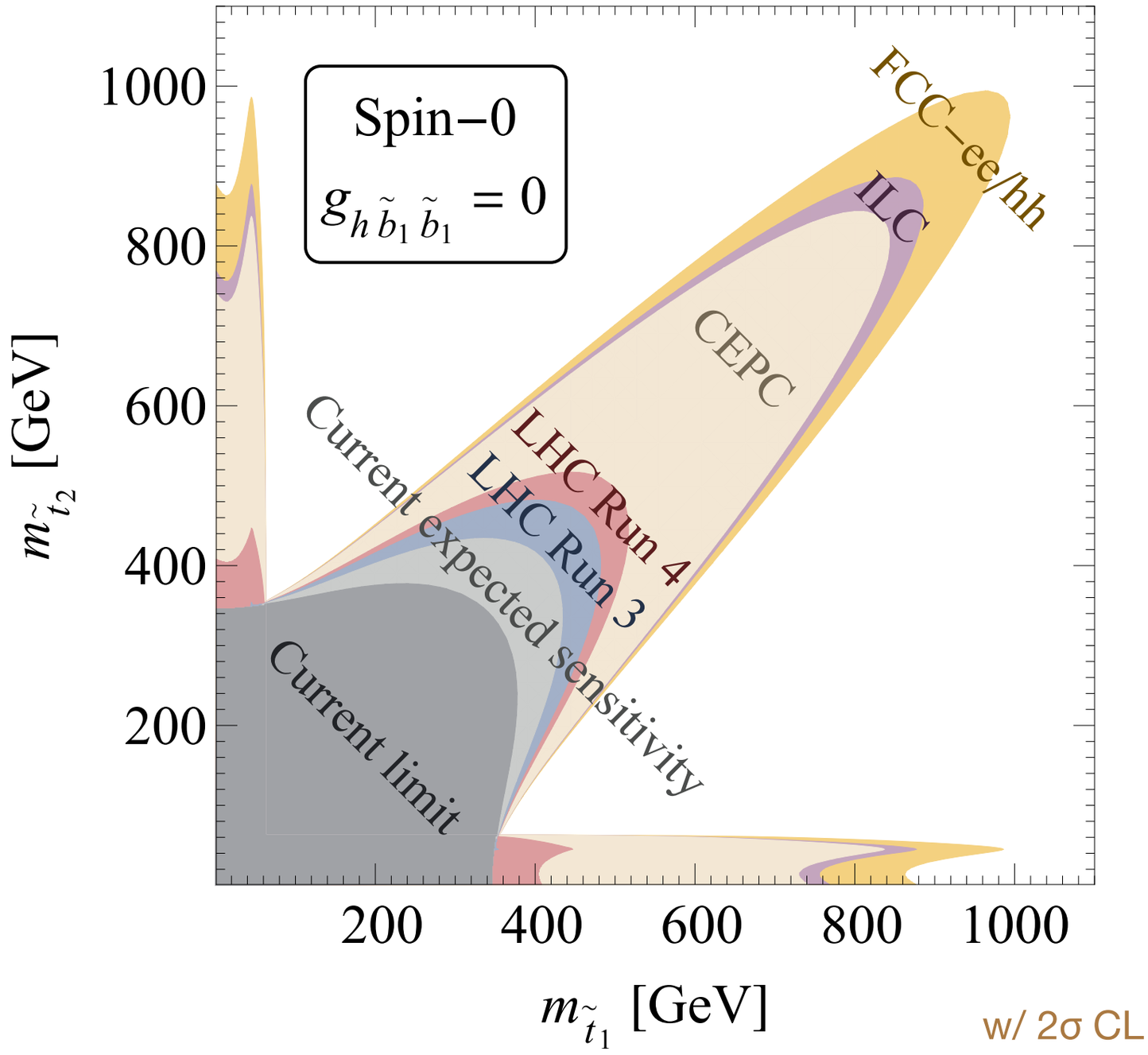
$\tan\beta \gg 1 : r_t, r_V \to 1, r_b$ is free

Spin-0



degenerate direction

⇑

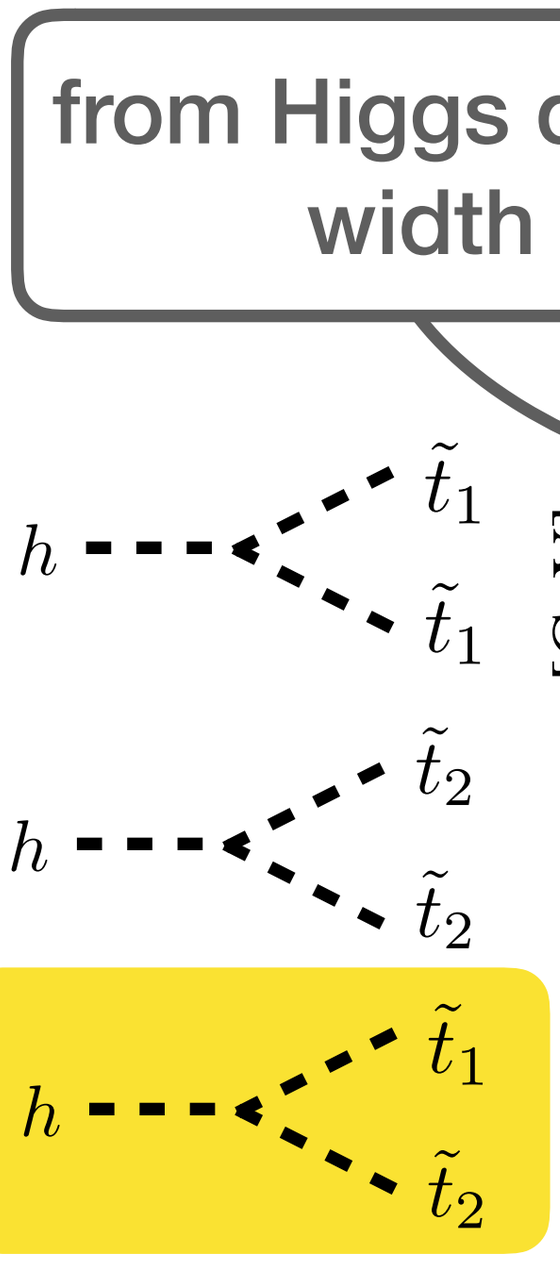


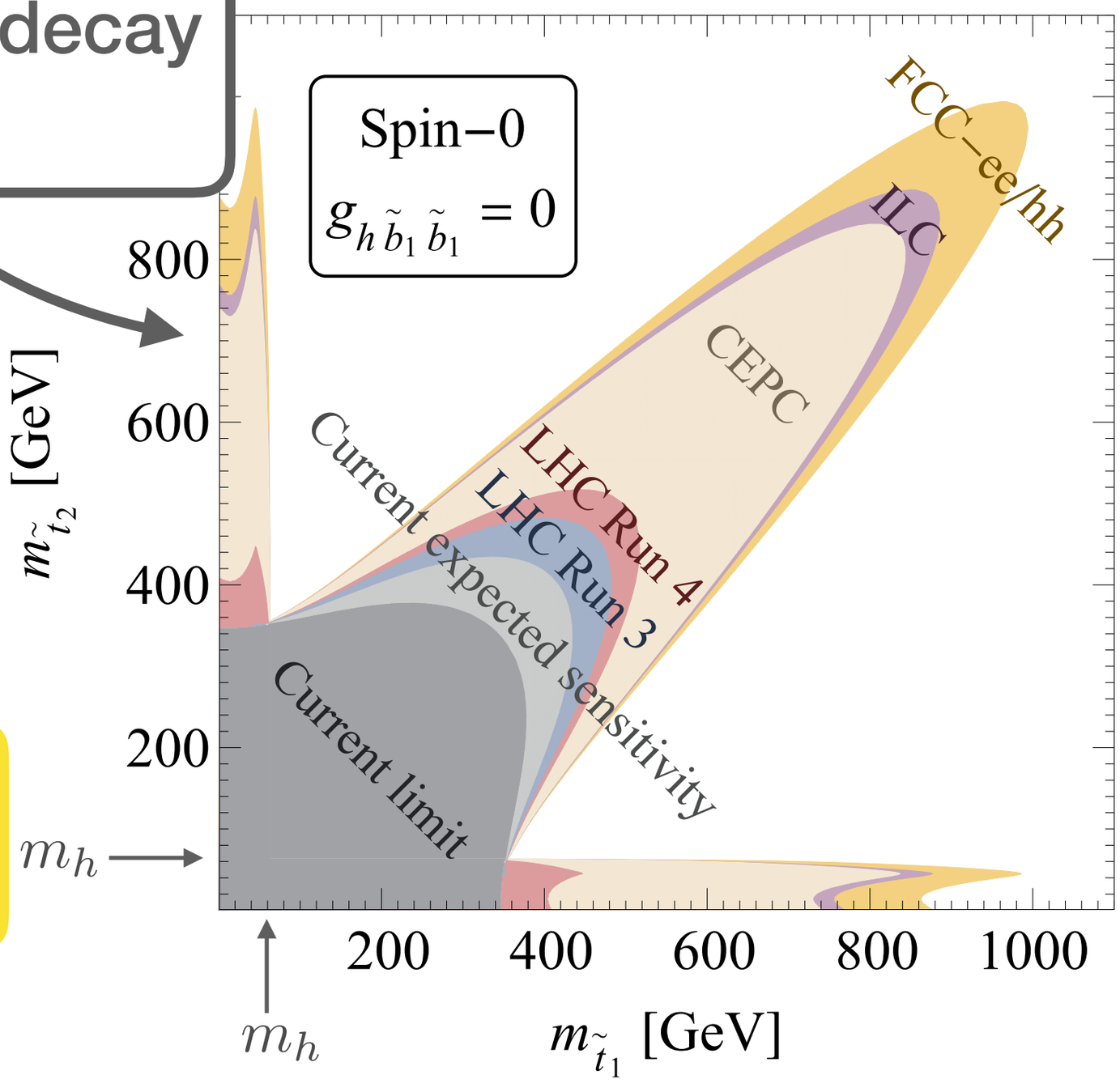
w/ 2σ CL

include D-terms

Spin-0

from Higgs decay width



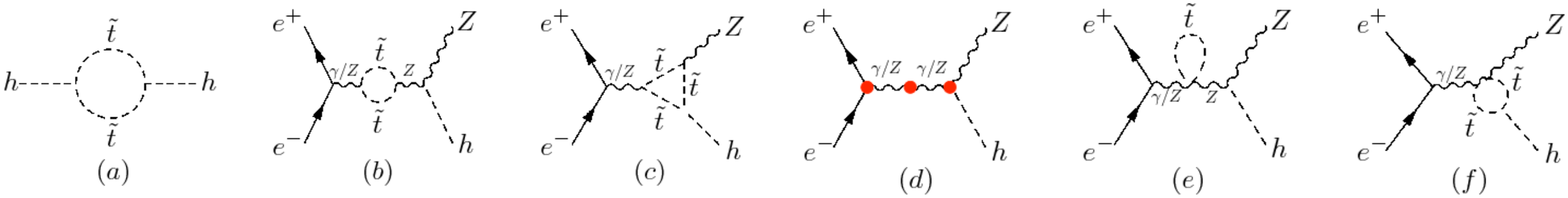


w/ 2σ CL

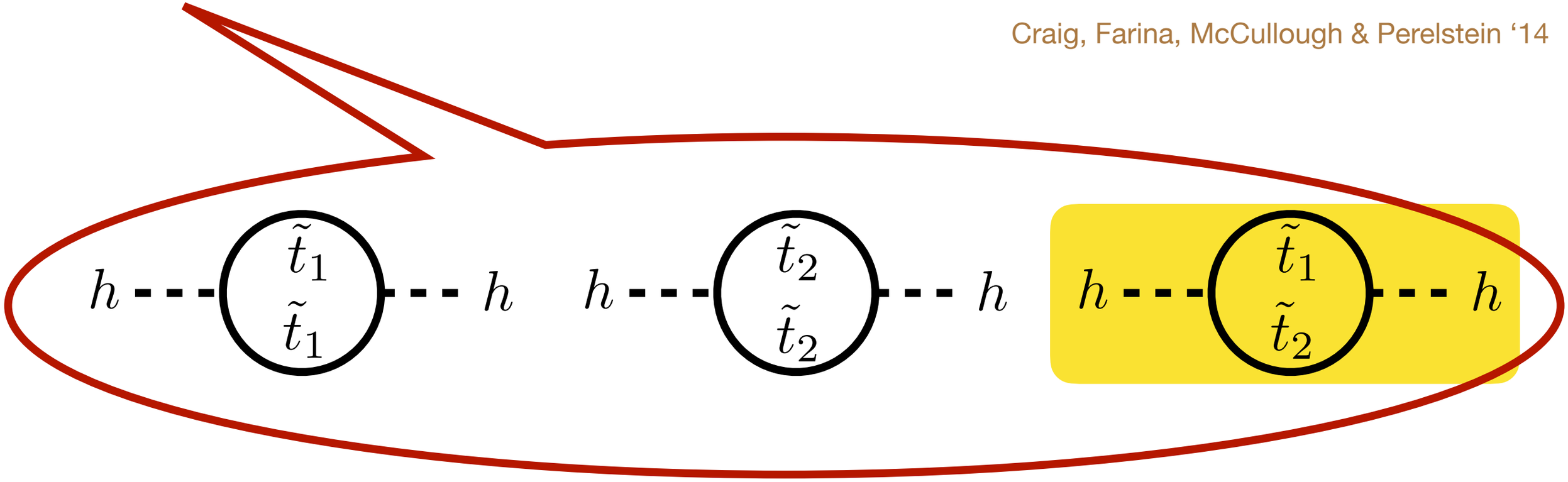
include D-terms

Complementary probes

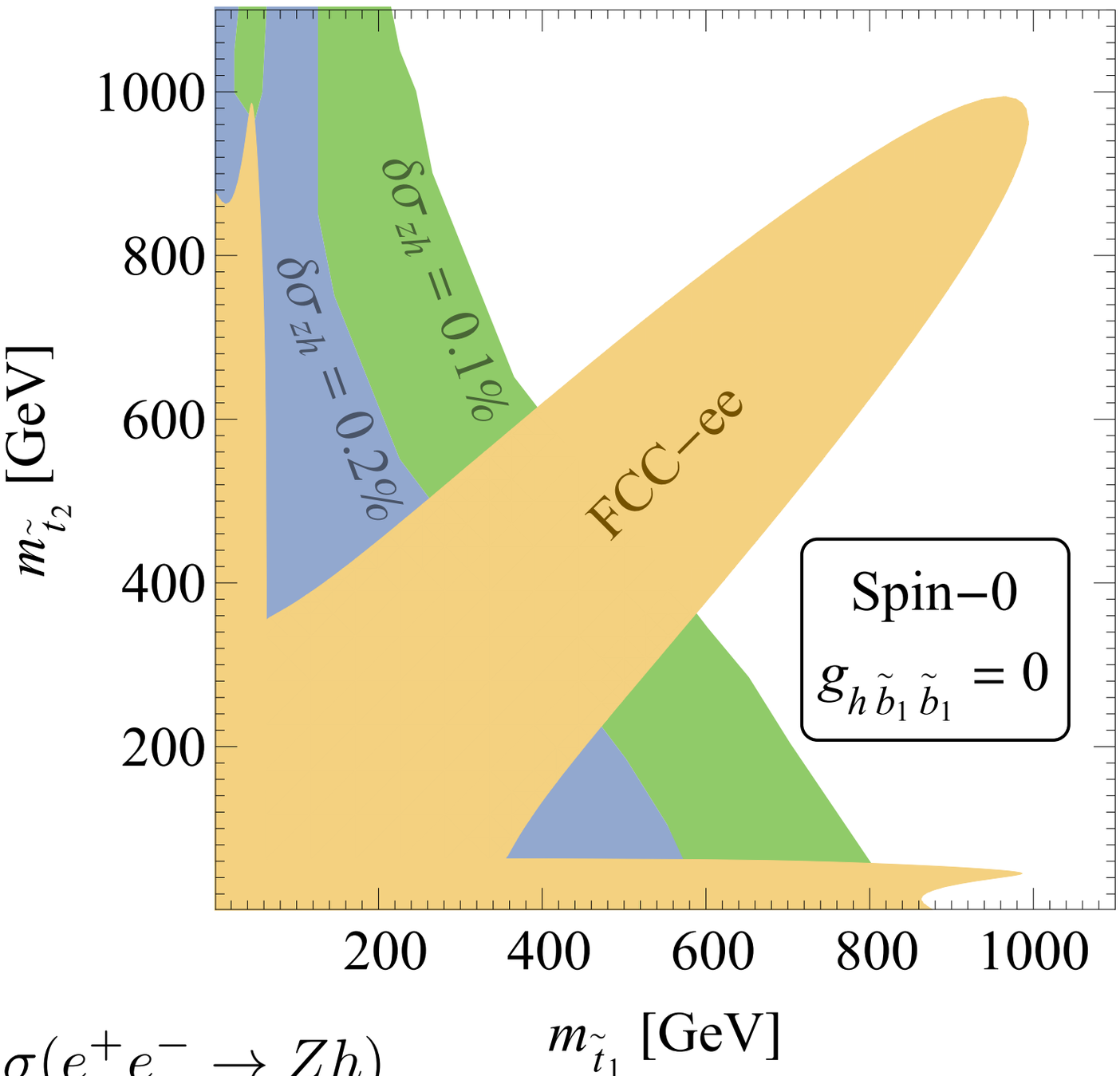
Measure $\sigma(e^+e^- \to Zh)$



Craig, Farina, McCullough & Perelstein ‘14



MSSM



Full 1-loop cal. of $\sigma(e^+e^- \to Zh)$

follow Craig, Farina, McCullough & Perelstein ‘14

w/ 2σ CL

include D-terms

Summary

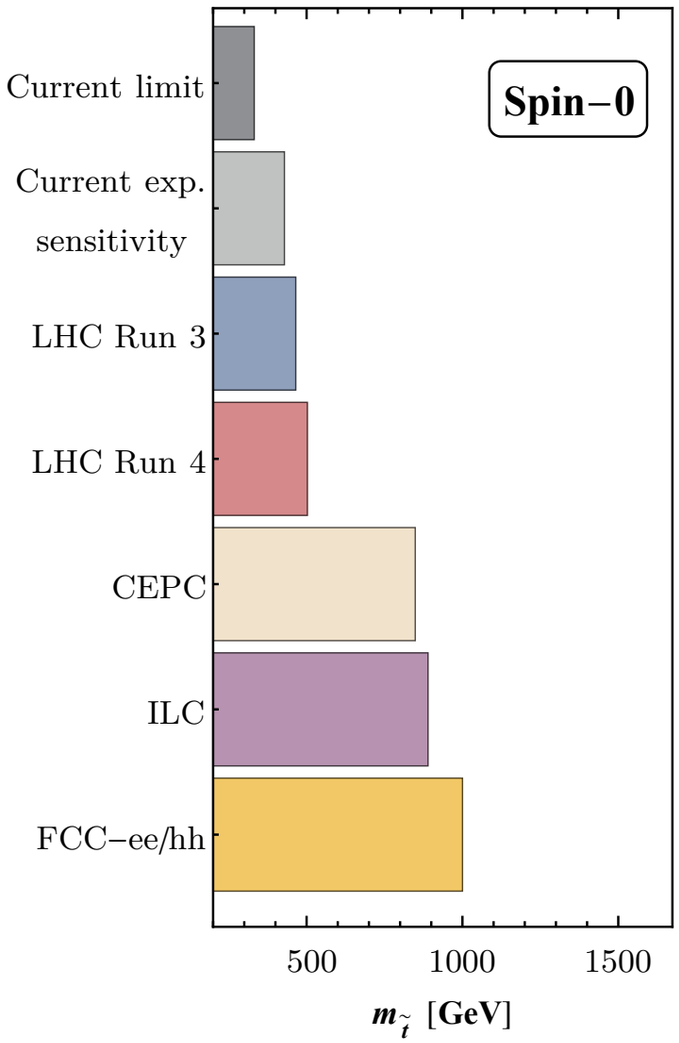
- Higgs precision measurements, on their own, are quite robust.

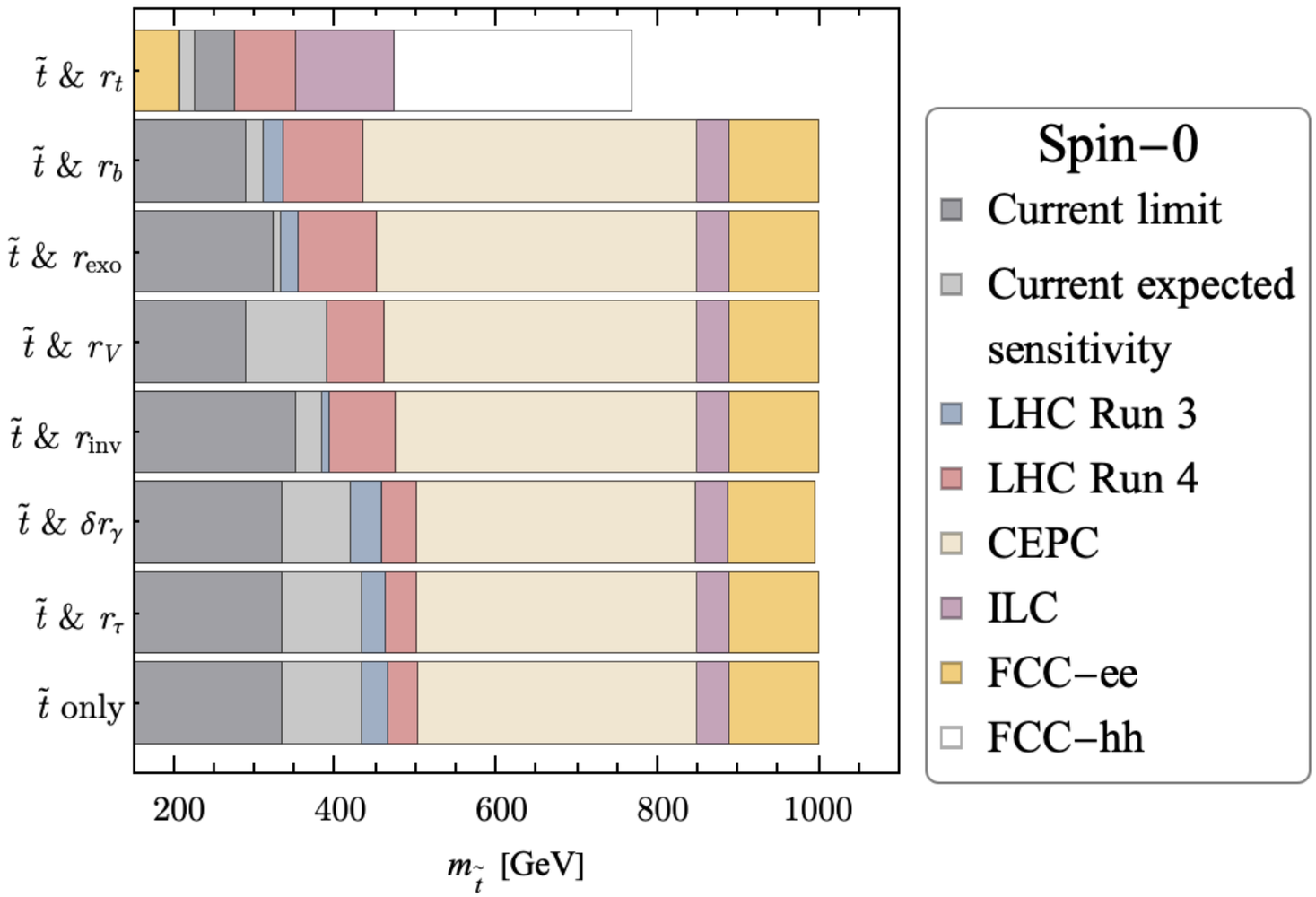
- ***Change r_t*** can also hide light colored top partners effectively**.**

- "Blind spots" exist when there are ***multiple top partners.***

Backup

After Moriond 2019





based on ATLAS-CONF-2019-005, ATLAS-CONF-2018-054, CMS-HIG-17-031, CMS-HIG-17-023