Higgs-Precision Constraints on Colored Naturalness

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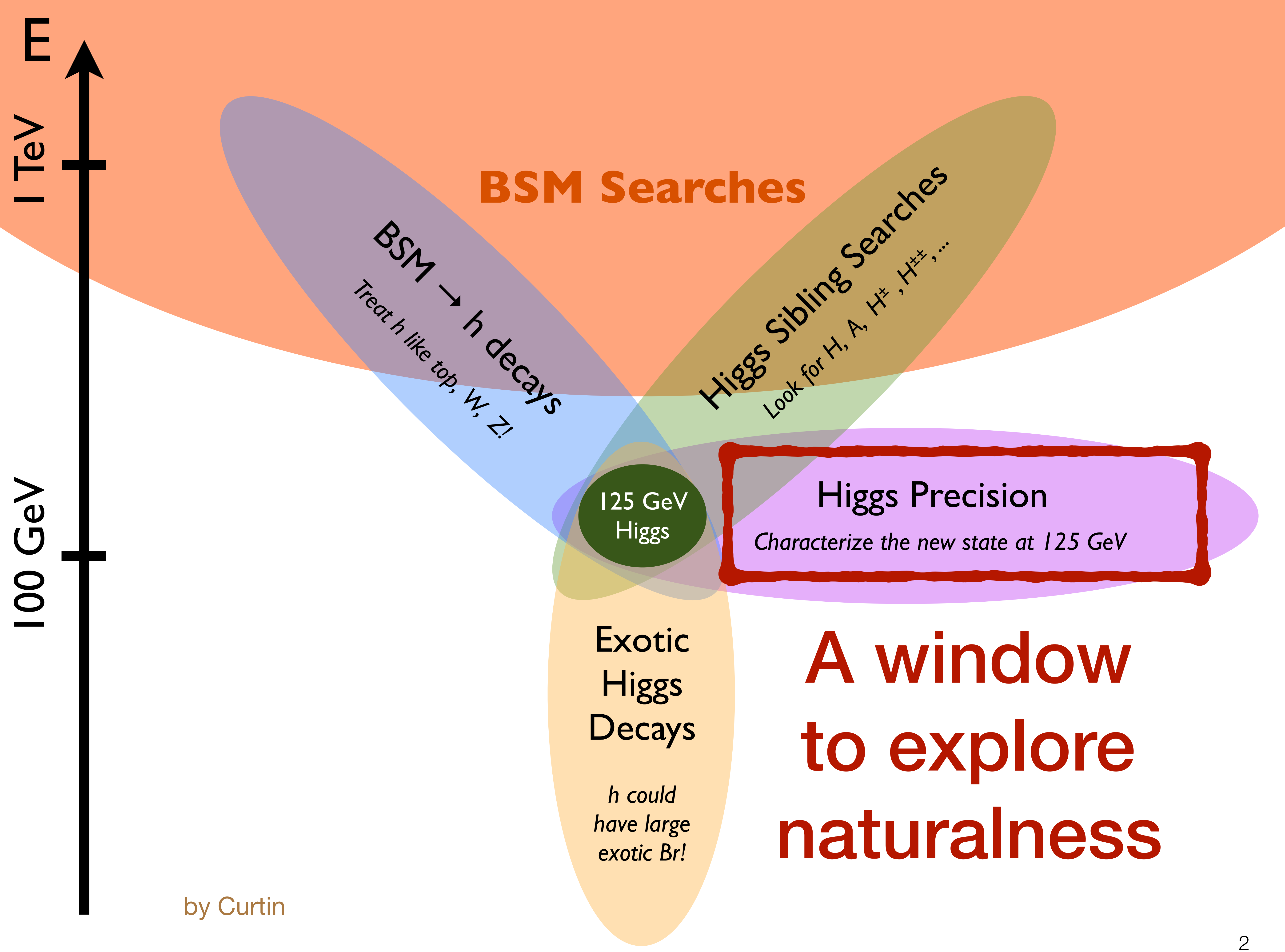
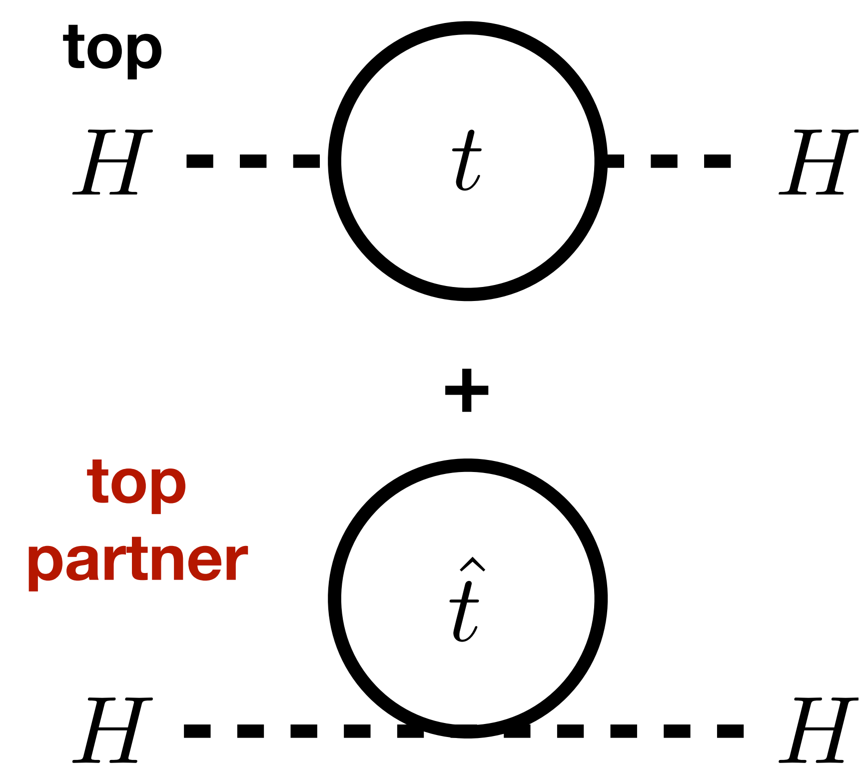
HKUST IAS, 01/12/2018



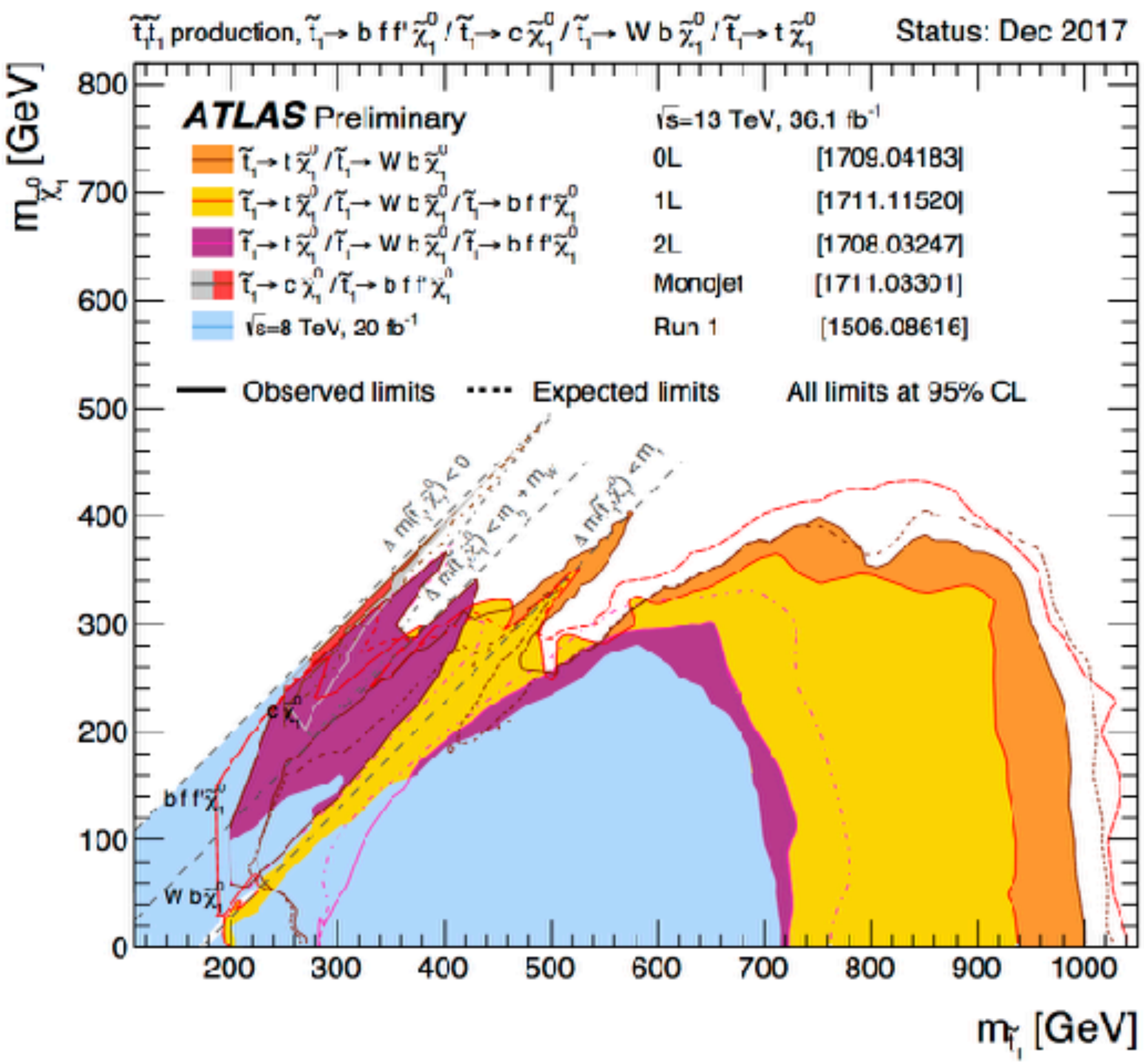
E
1 TeV
100 GeV
BSM Searches
BSM → h decays
Treat h like top, W, Z!
Higgs Sibling Searches
Look for H, A, H±, H±±, ...
125 GeV Higgs
Higgs Precision
Characterize the new state at 125 GeV
Exotic Higgs Decays
h could have large exotic Br!
A window to explore naturalness
by Curtin

The naturalness problem

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

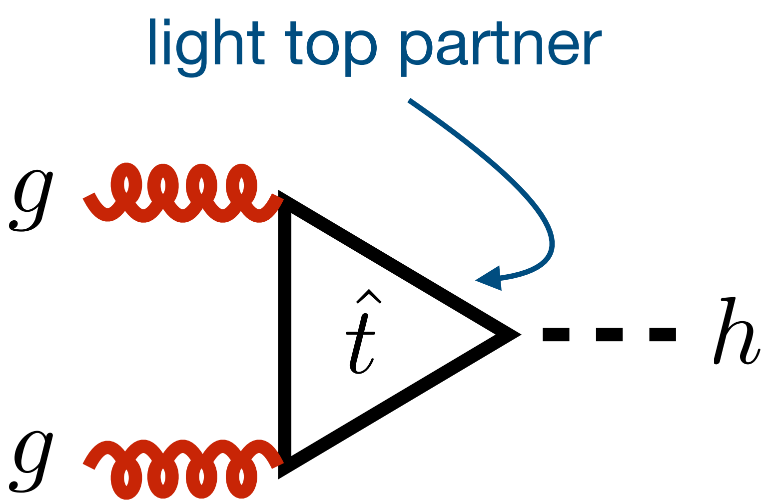


Direct searches for top partners

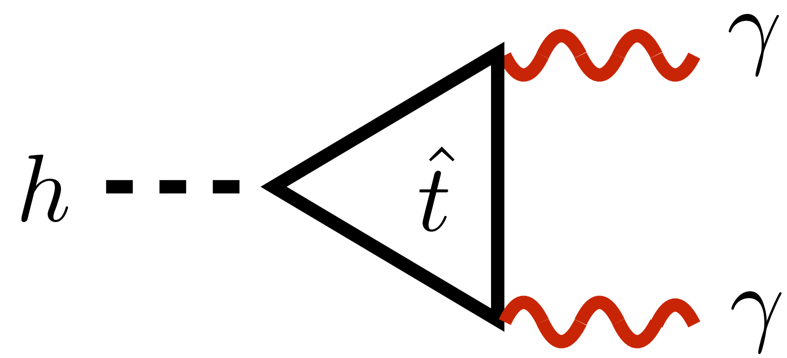


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

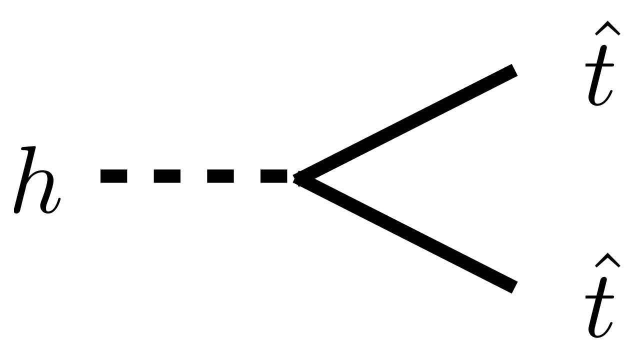
Indirect effects



Change the Higgs production rate



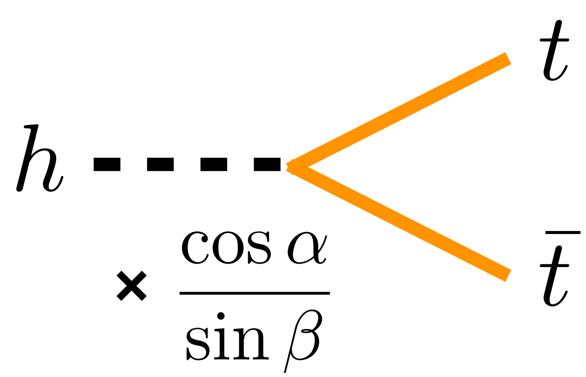
Change the Higgs production rate



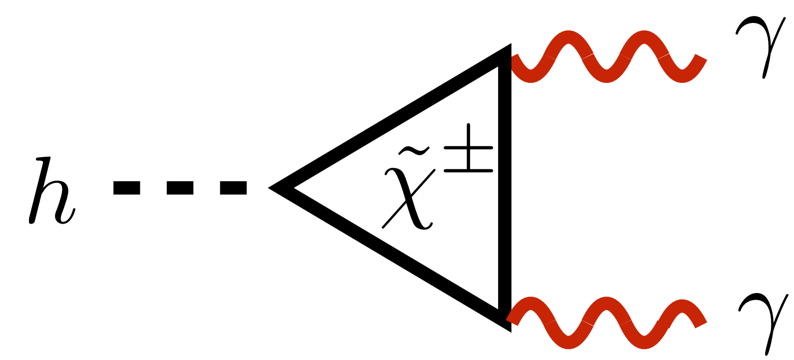
Open exotic decays
(if $m_{\hat{t}} < m_h/2$)

All captured by the Higgs precision measurement

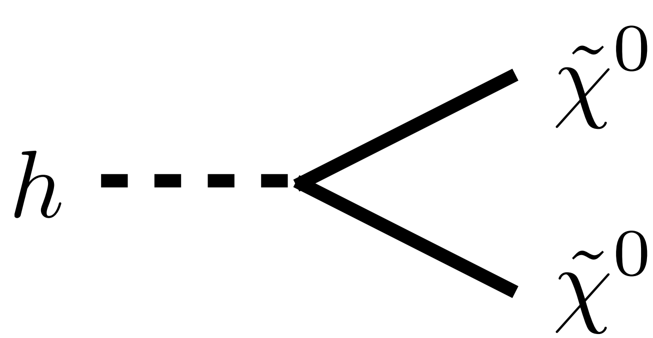
However, NP may also…



Change the
tree-level couplings



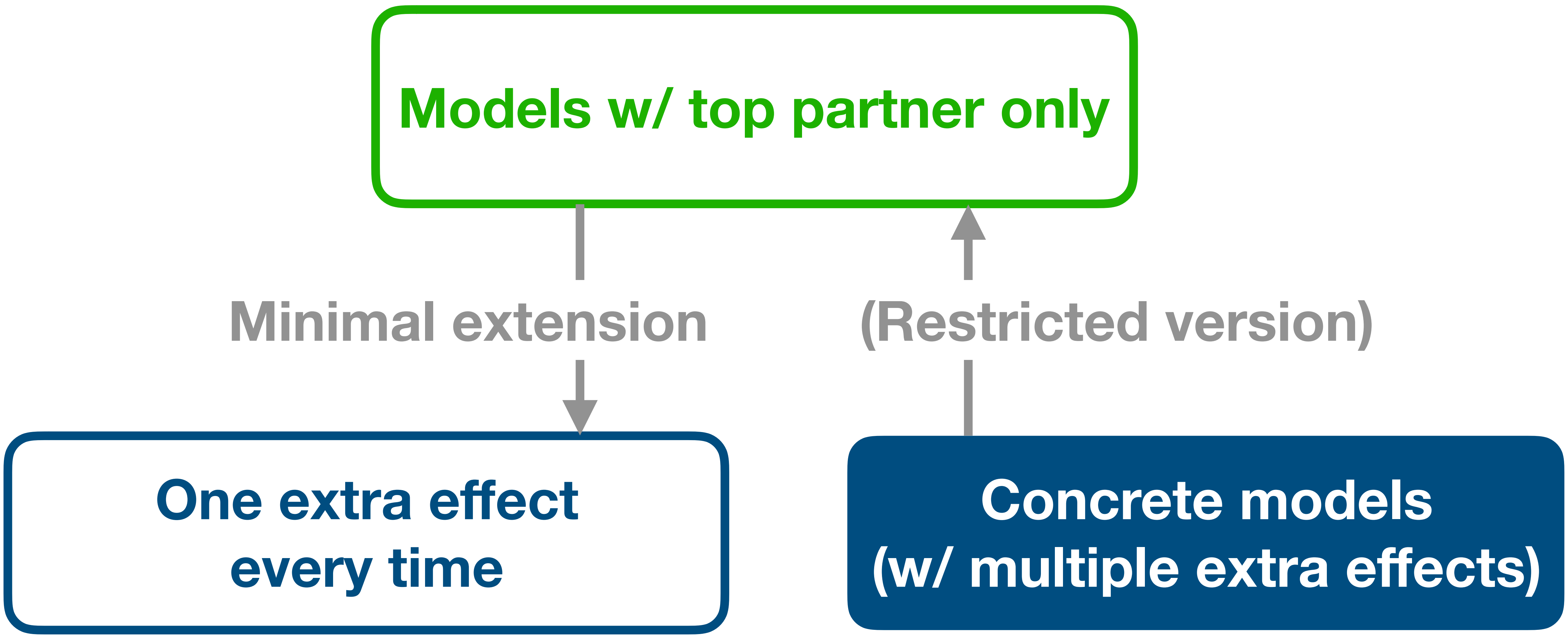
Have extra new particles
running in the loop



Have extra
exotic/invisible decays

May hide the light top partner

How robust is Higgs precision?



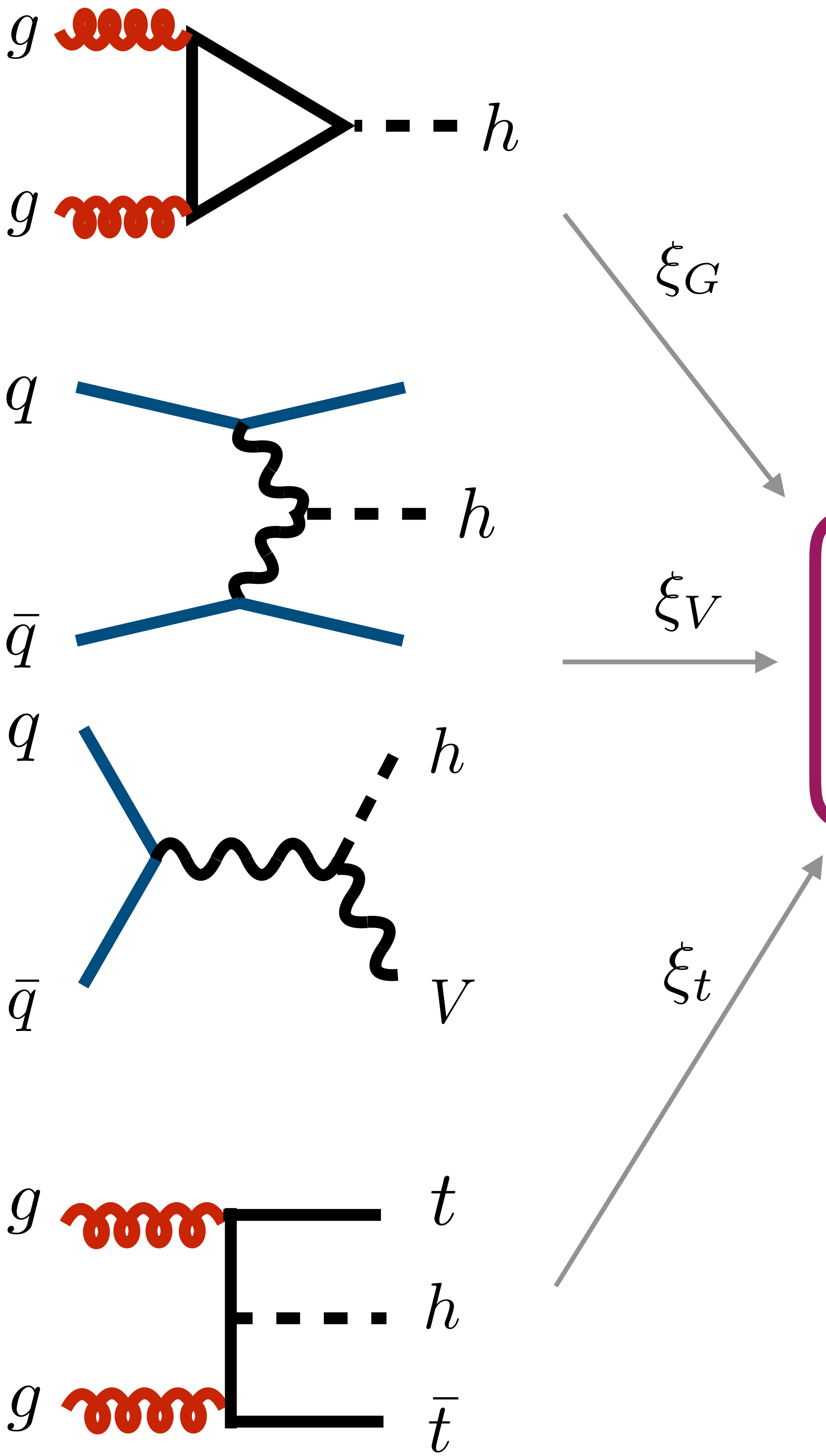
Best way(s) to hide the light top partner?

Outline

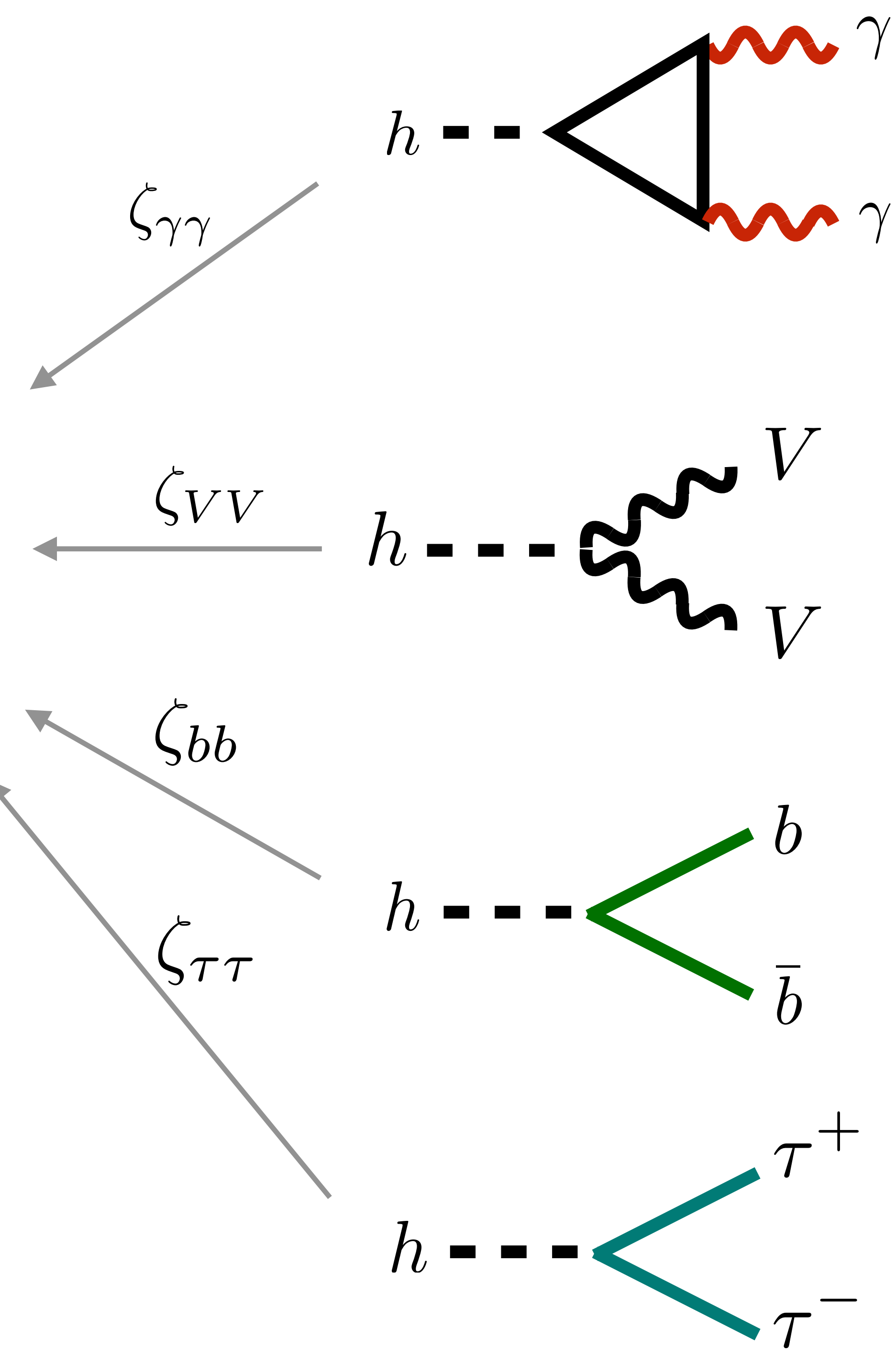
- Fitting
- Top partner models and extensions
- Constraints from Higgs precision
- Complementary probes
- Summary

Fitting

Signal strength



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



$$\mu_{\rm inv} \equiv \frac{\sigma^{\rm BSM}_{\rm prod} \times B^{\rm BSM}_{h\to {\rm inv}}}{\sigma^{\rm SM}_{\rm prod}}$$

Constrain the light top partner

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

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

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

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

e.g. Add invisible width

$m_{\hat{t}}$ Γ_{inv}

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

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

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

e.g. Change Higgs-top coupling

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

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

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

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

Current data sets

- ATLAS & CMS data up to EPS 2017
  [+ Tevatron, 145 visible + 11 invisible in total]
  ⇒ ***Current limit***

- Current data has values slightly differ from their SM values. Statistical fluctuations? New physics?

  - Set $\mu_f = 1\,(\mu_{\rm inv} = 0)$ ⇒ ***Current expected limit***

Future data sets

- Take projections for ATLAS Run 3 (300 /fb) & Run 4 (3 /ab) & assume CMS precision ~ ATLAS precision
  ⇒ ***LHC Run 3***, ***LHC Run 4***

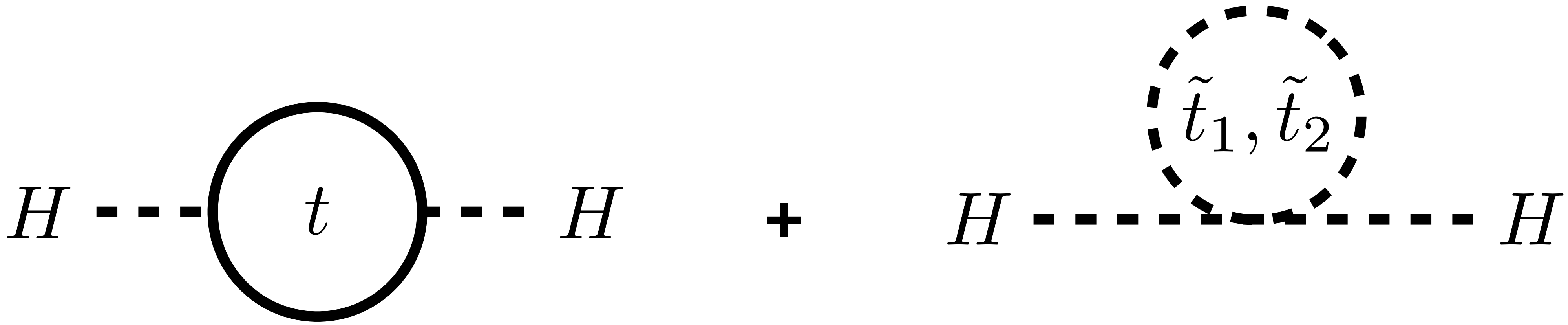
ATL-PHYS-PUB-2014-016
a little bit old!

- Combined coupling fits for ***CEPC***, ***ILC***, ***FCC-ee*** & ***FCC-hh***

CEPC-SPPC pre-CDR, Fujii et al, ’15, d’Enterria ’16, Mangano, ‘17

Top partner models and extensions
(ordered by their spins)

Spin-0



Hermitian!

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

- *hgg* modification:

neglect D-terms

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

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

Spin-0

neglect D-terms

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

- Blind spot @ $X_t^2 = m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2$
- Marginalize over Xt,
  - strong probe @ $m_{\tilde{t}_1} = m_{\tilde{t}_2} (\equiv m_{\tilde{t}}) : \ \mathcal{N}_{\tilde{t}} = \frac{m_t^2}{2m_{\tilde{t}}^2}$
  - weak probe @ $m_{\tilde{t}_h} \gg m_{\tilde{t}_l} : \ \mathcal{N}_{\tilde{t}} \simeq 0$

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

Spin-0: MSSM

- Higgs sector of MSSM: two-Higgs-doublet-model (2HDM) H_u, H_d

- Identify the lighter Higgs to be the 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

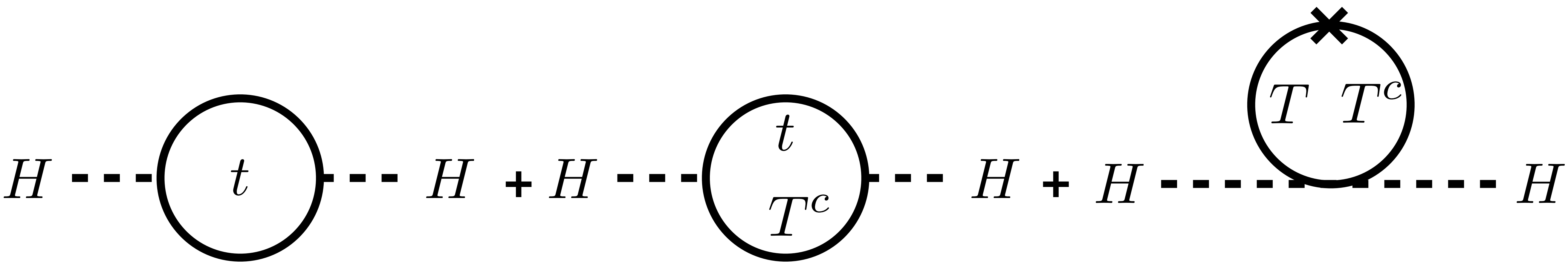
- Higgs sector of MSSM: two-Higgs-doublet-model (2HDM) H_u, H_d
- Identify the lighter Higgs to be the 125 GeV Higgs
- Coupling modifier
- $\tan\beta \ll 1 : r_b, r_V \to 1, r_t$ is free
- $\tan\beta \gg 1 : r_t, r_V \to 1, r_b$ is free

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)
- top & top partner T are in the same multiplet
- *hgg* modification:

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

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

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

Spin-1/2 extensions

- Extend the Higgs sector to be 2HDM

SU(4) Simplest Little Higgs

  - Allow changes on $r_t, r_b, r_V \ldots$
  - Best: type-II 2HDM

Spin-1/2 extensions

- Extend the spin-1/2 top partner sectors
    - Two spin-1/2 top partners: both T_1, T_2 are both in the same multiplet as top
        - *hgg* modification:

$$\mathcal{N}_T = -m_t^2 \left(\frac{\rho}{m_{T_1}^2} + \frac{1-\rho}{m_{T_2}^2} \right)$$

ρ: “fraction” of the cancellation coming from T_1 loop

Spin-1

- Relies on SUSY & an enlarged symmetry
  - Right-handed top ~ Higgsino
  - Top Yukawa ~ gauge coupling

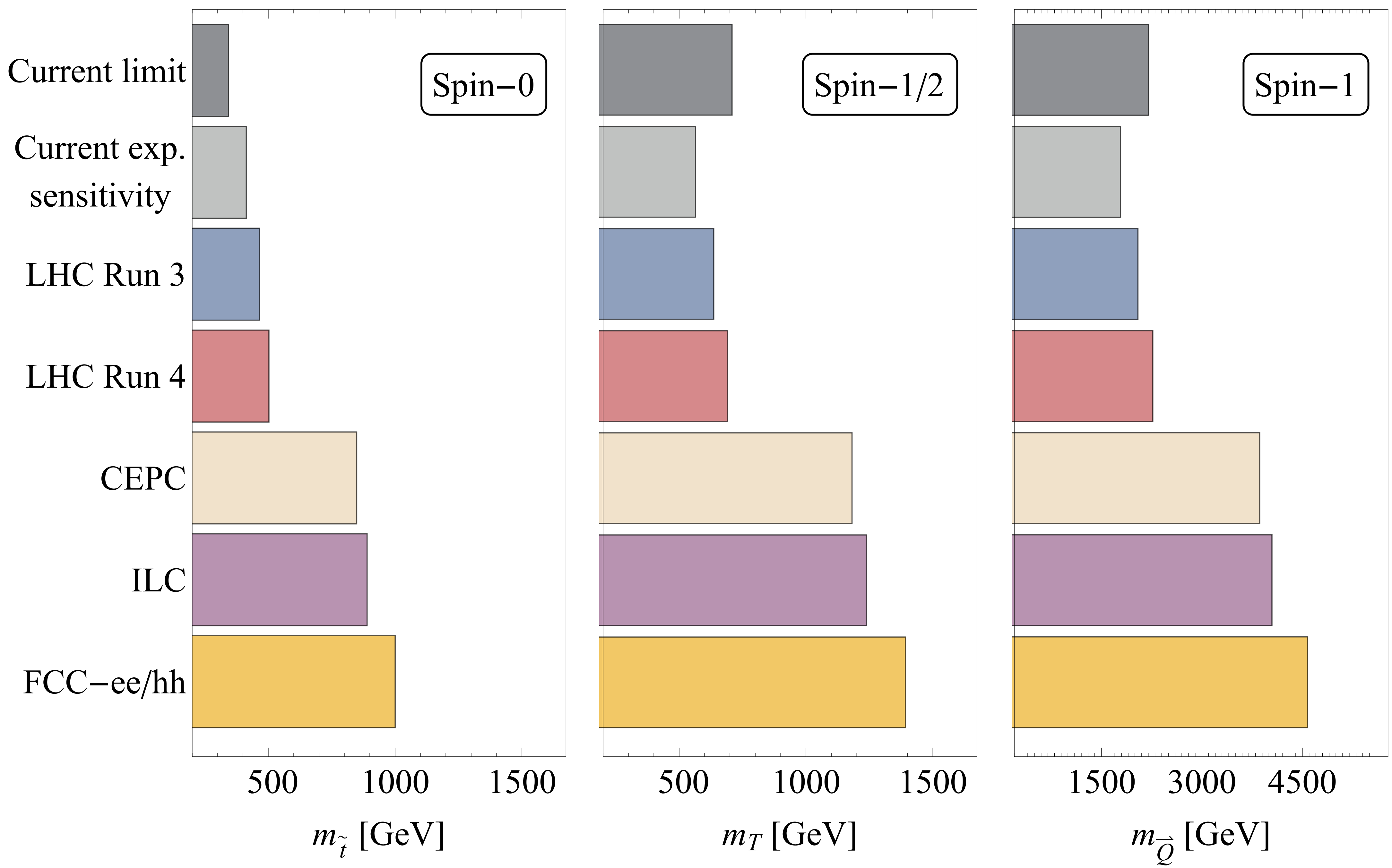
Cai, Cheng & Terning, ‘08

- Take Cai-Cheng-Terning model
  - *hgg* modification $\mathcal{N}_{\vec{Q}} \sim -\frac{21}{4}\frac{m_t^2}{m_{\vec{Q}}^2}$
  - $r_t > 1$; extra W'

Loop function penalty

Constraints from Higgs precision

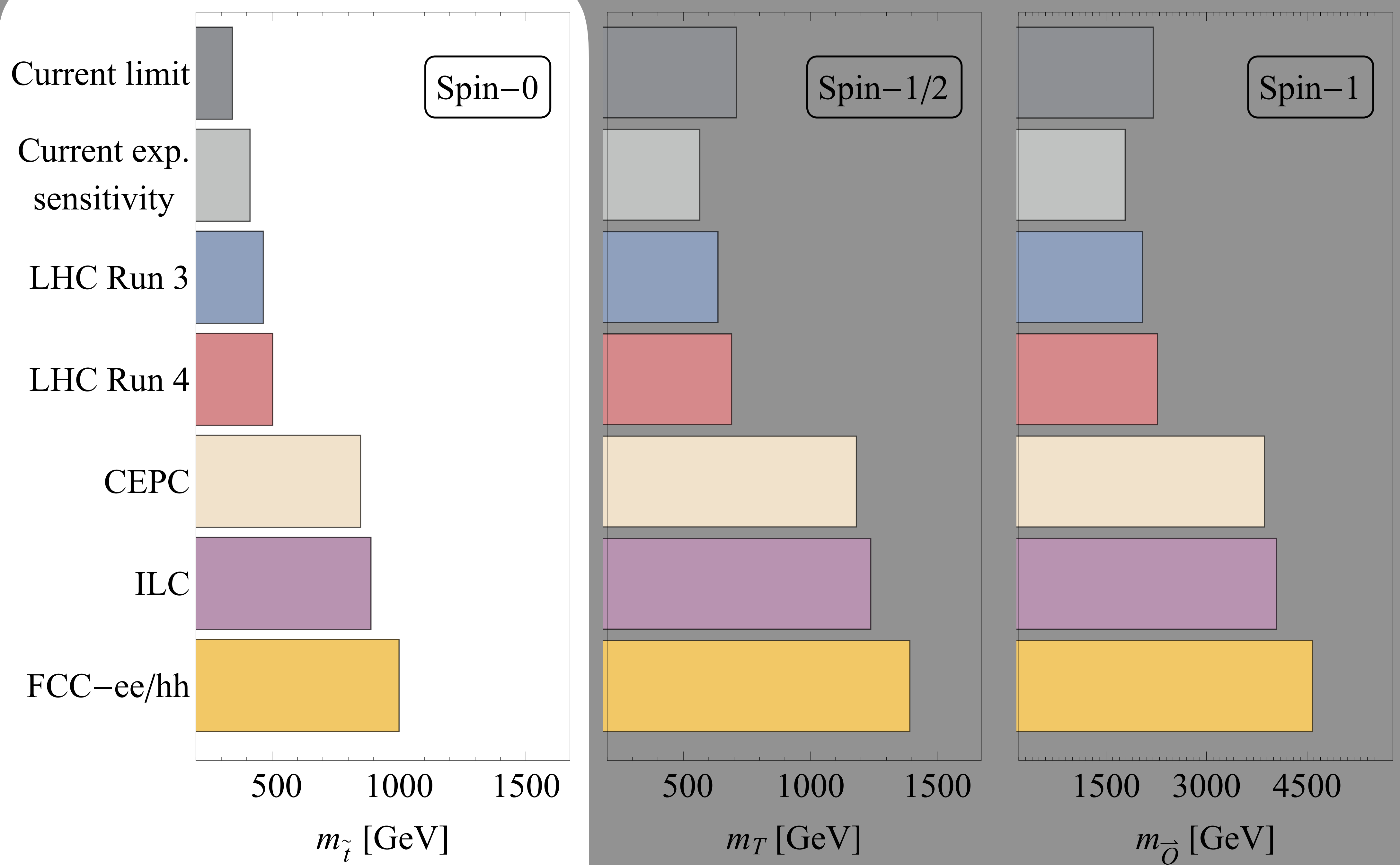
Models w/ top partner only



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

w/ 2σ CL

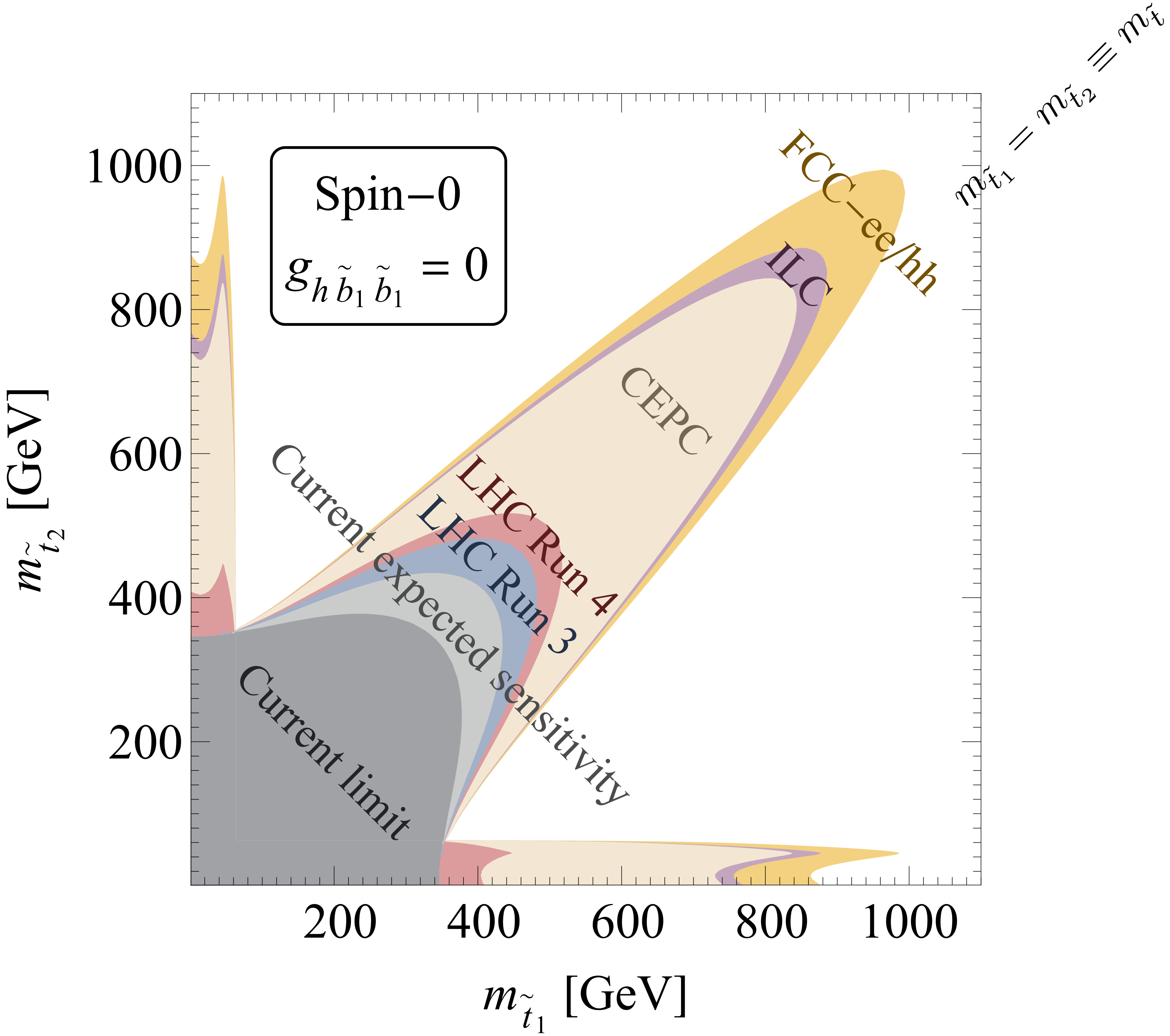
Models w/ top partner only



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

w/ 2σ CL

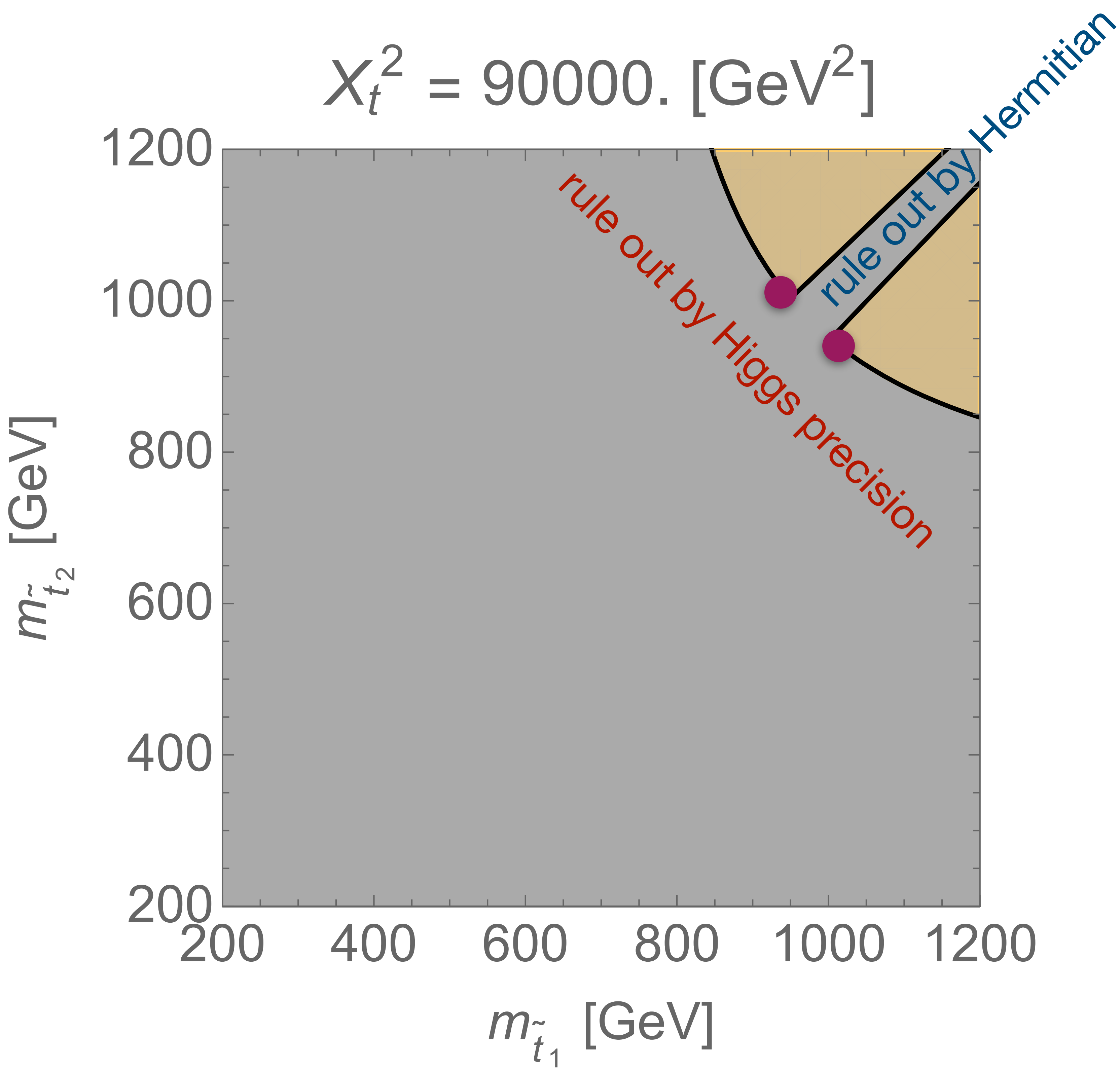
Spin-0



w/ 2σ CL

include D-terms

Marginalize X_t



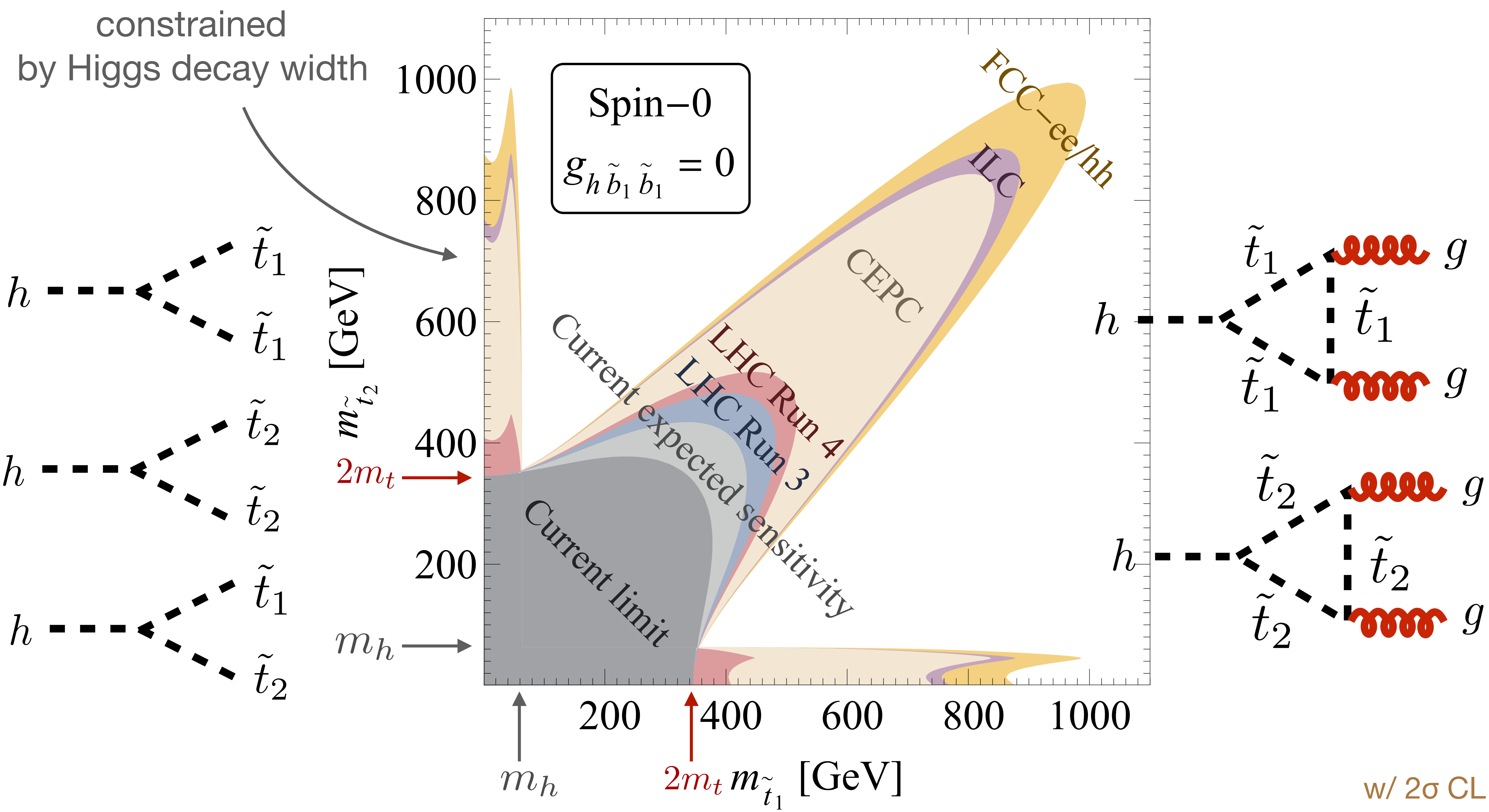
Hermitian stop matrix
+
Higgs precision

Allowed

Not allowed

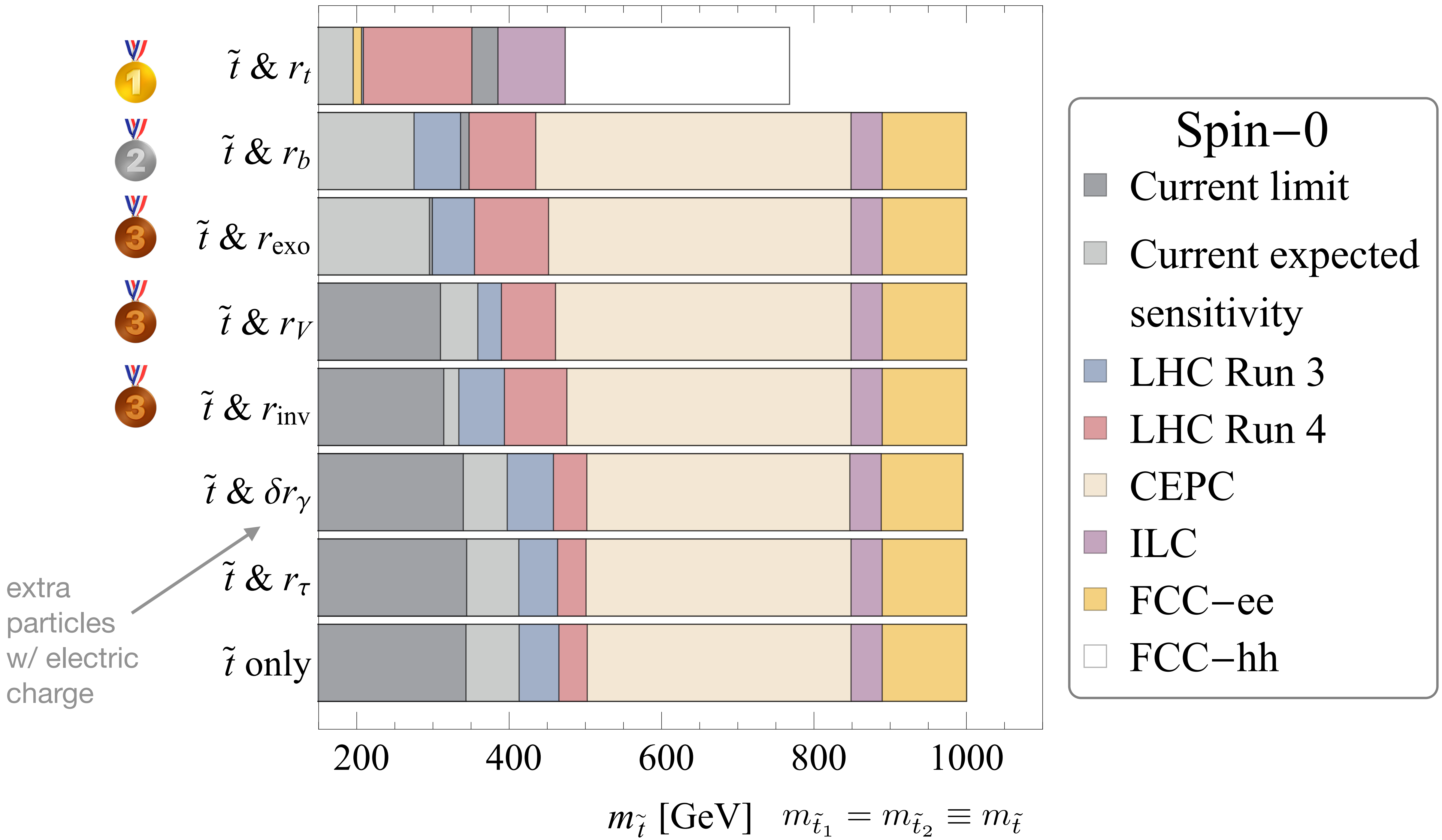
w/ 2σ CL

Spin-0



include D-terms

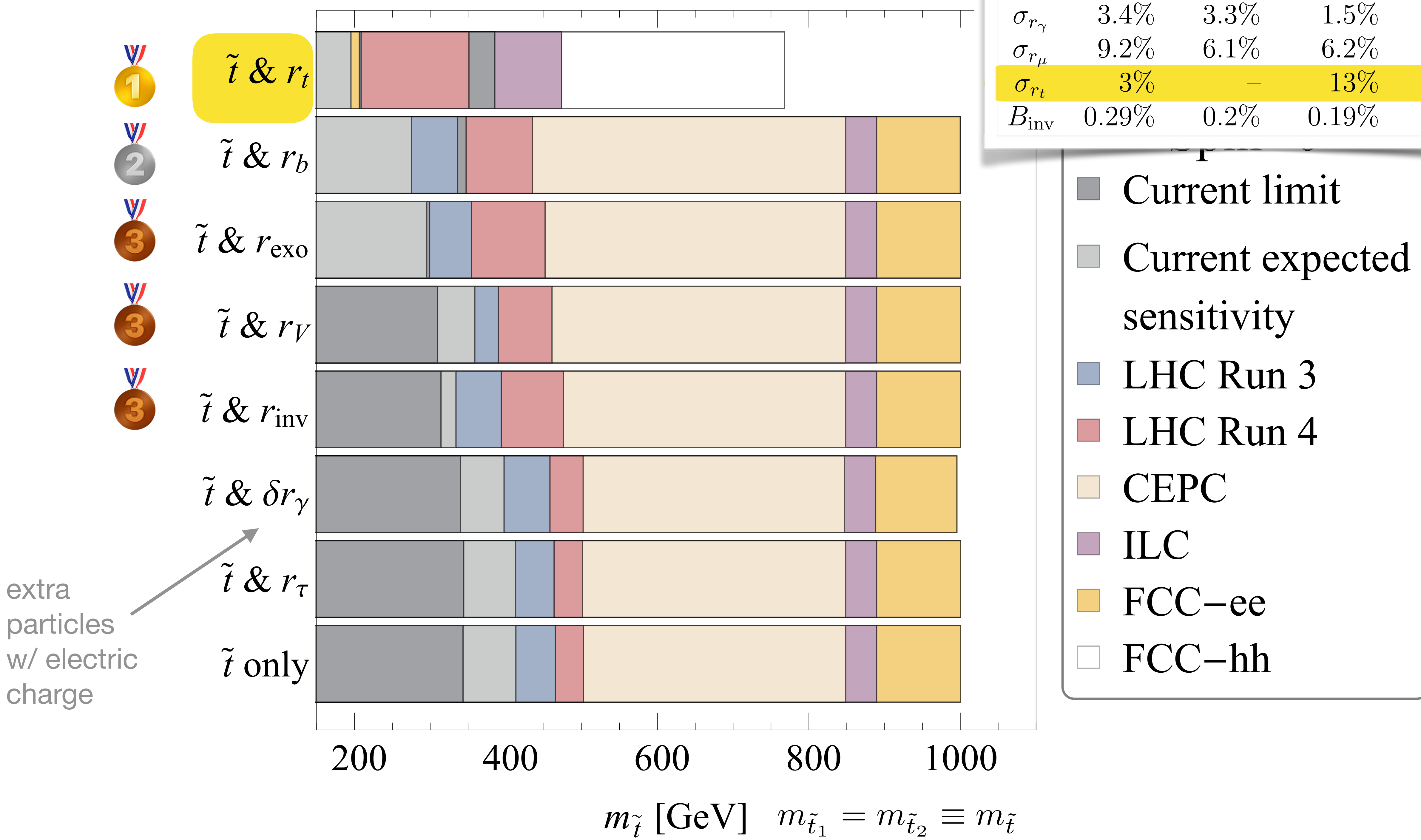
Minimal ext. of spin-0



w/ 2σ CL

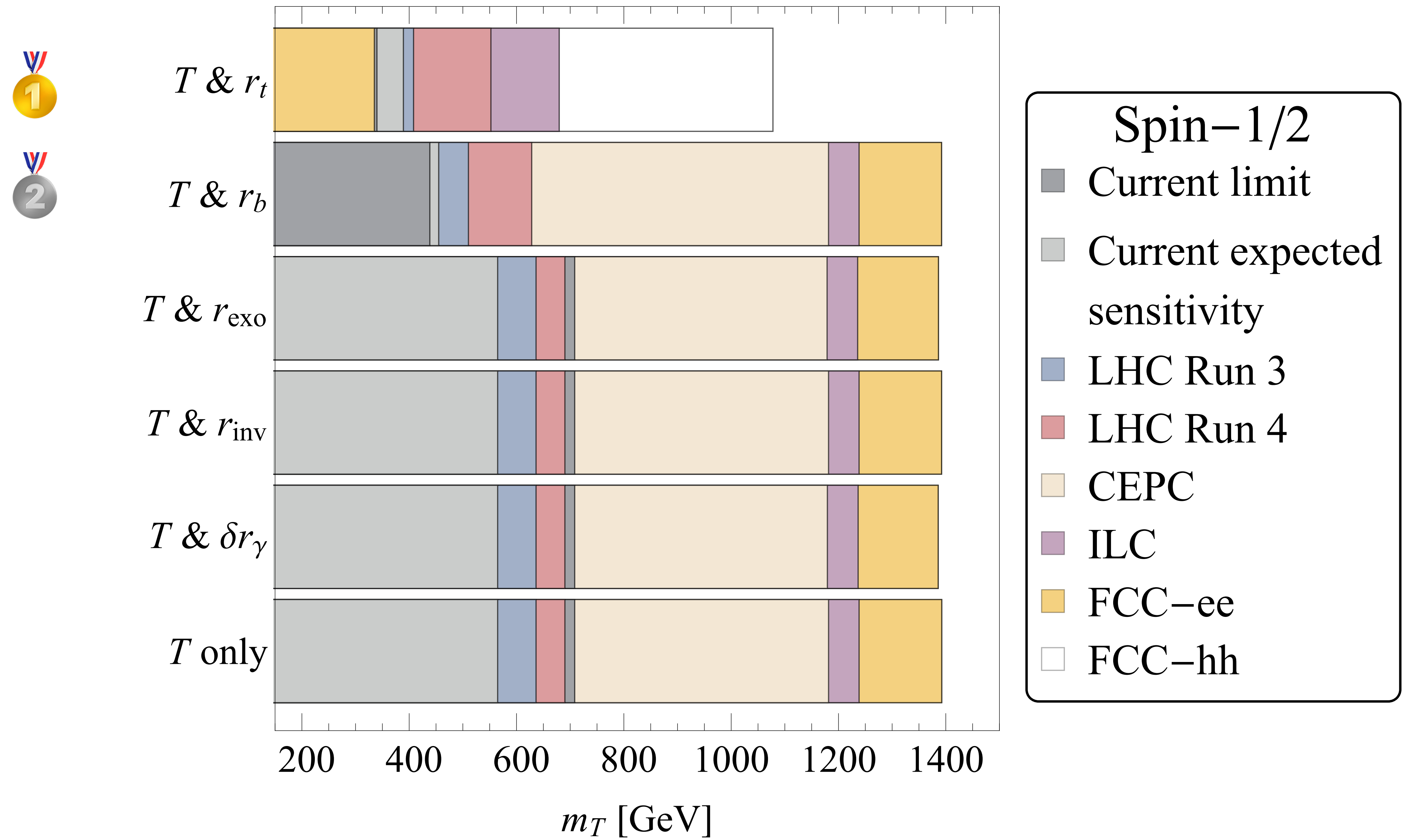
Minimal ext. of

	ILC	CEPC	FCC-ee	FCC-hh
σ_{Γ_h}	1.8%	1.9%	1%	–
σ_{r_b}	0.7%	0.92%	0.42%	–
σ_{r_c}	1.2 %	1.2%	0.71%	–
σ_{r_G}	1%	1.1%	0.8%	–
σ_{r_W}	0.42%	0.87%	0.19%	–
σ_{r_τ}	0.9%	1%	0.54%	–
σ_{r_Z}	0.32%	0.18%	0.15%	–
σ_{r_γ}	3.4%	3.3%	1.5%	–
σ_{r_μ}	9.2%	6.1%	6.2%	–
σ_{r_t}	3%	–	13%	1%
$B_{\rm inv}$	0.29%	0.2%	0.19%	–



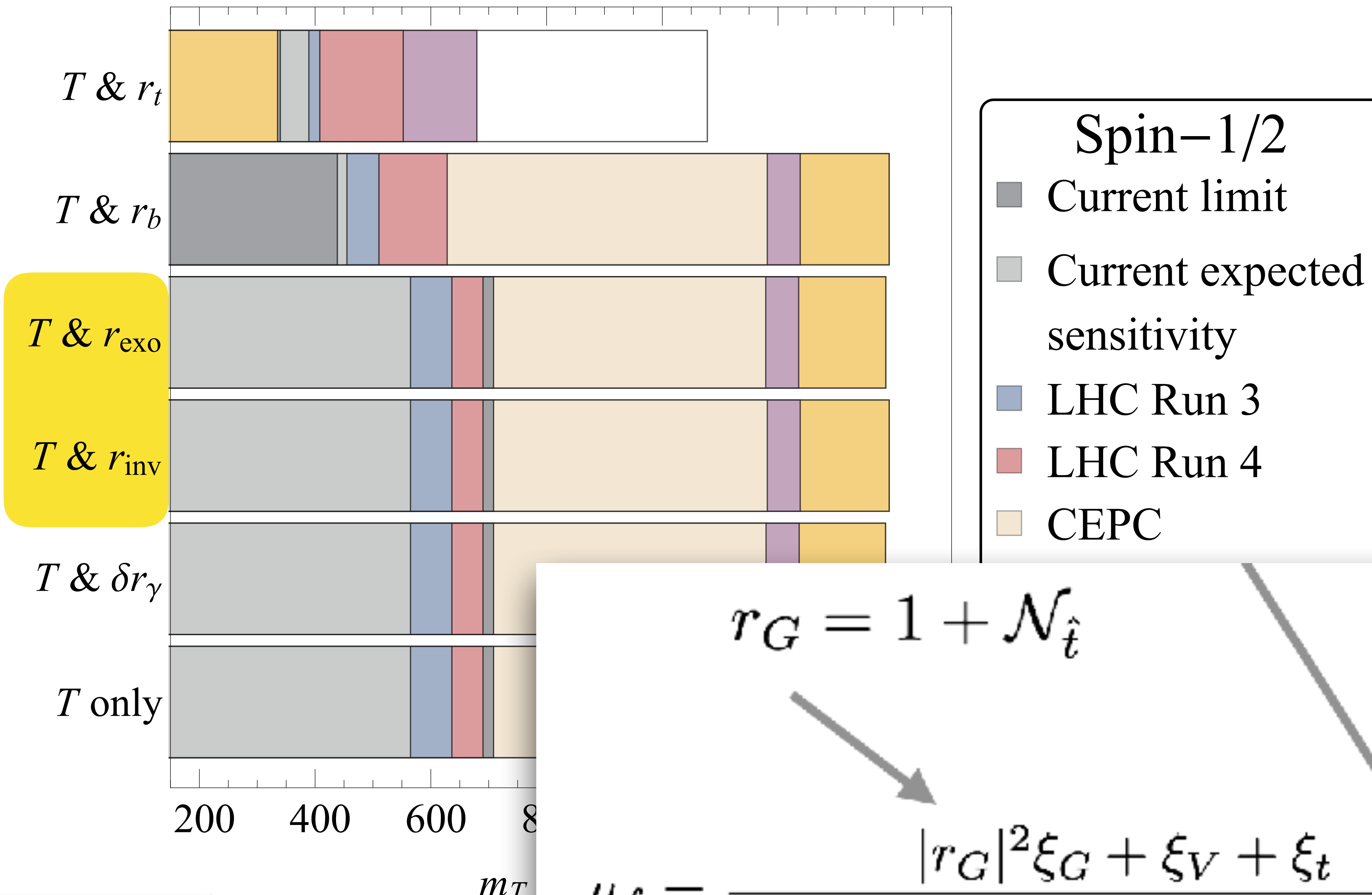
w/ 2σ CL

Minimal ext. of spin-1/2



w/ 2σ CL

Minimal ext. of spin-1/2



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

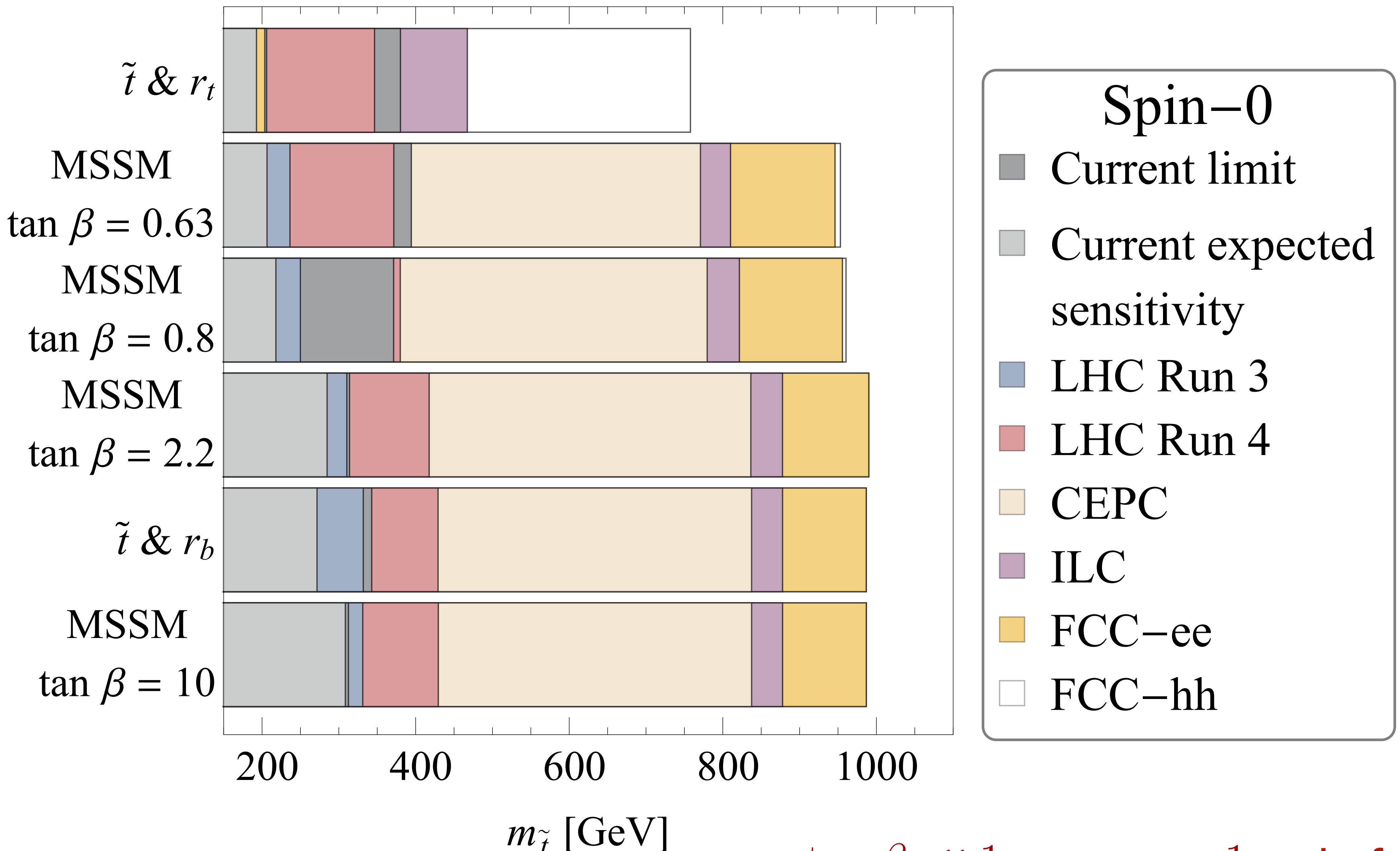
$$\mu_f = \frac{|r_G|^2 \xi_G + \xi_V + \xi_t}{1 + (|r_G|^2 - 1) B^{\rm SM}_{h\to gg} + \cdots + r_{\rm inv}}$$

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

MSSM

w/ 2σ CL

easy to hide w/ small tan β



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

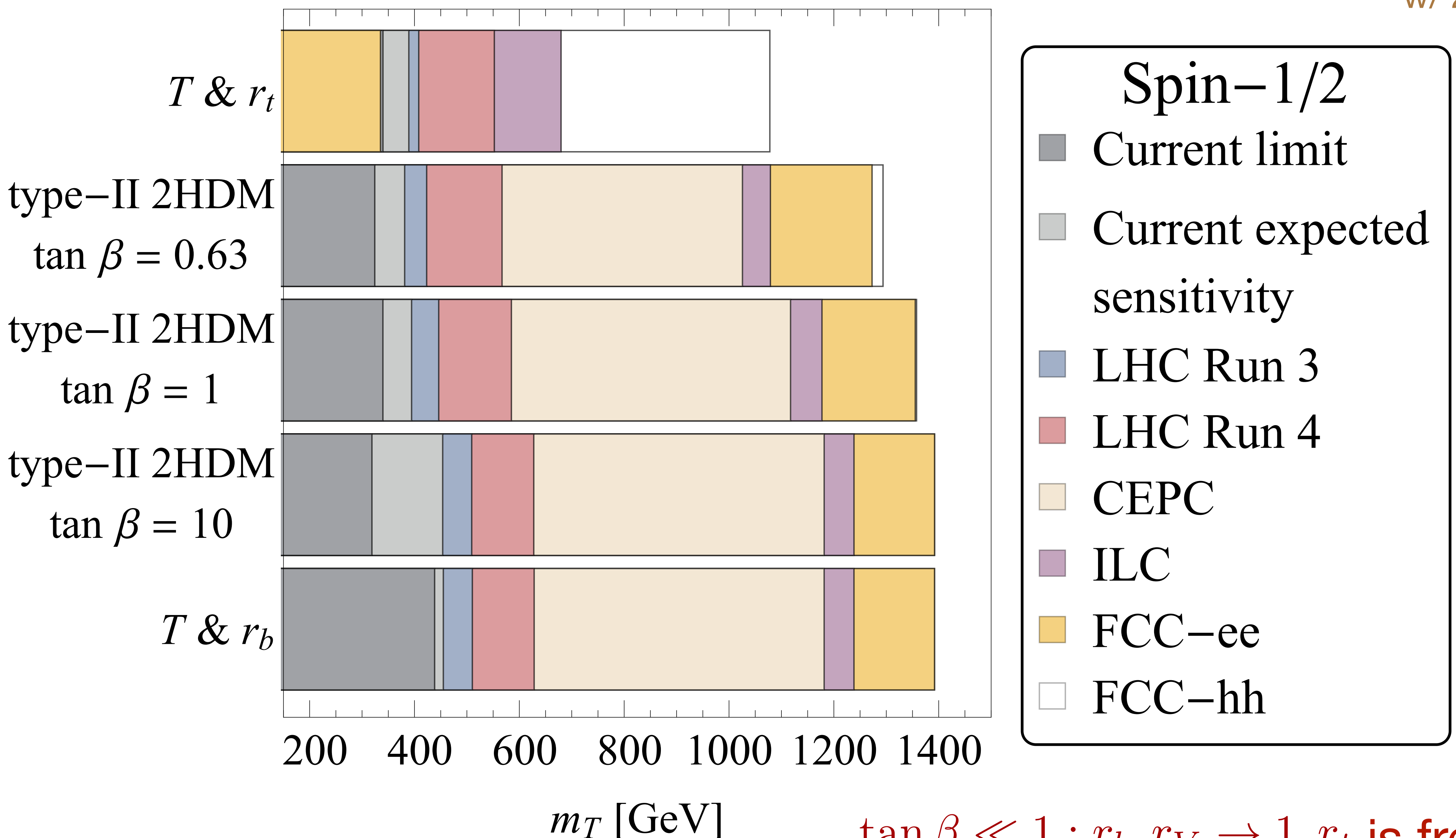
$\tan\beta \ll 1 : r_b, r_V \to 1, r_t$ is free

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

Spin-1/2 w/ 2HDM

easy to hide w/ small tan β

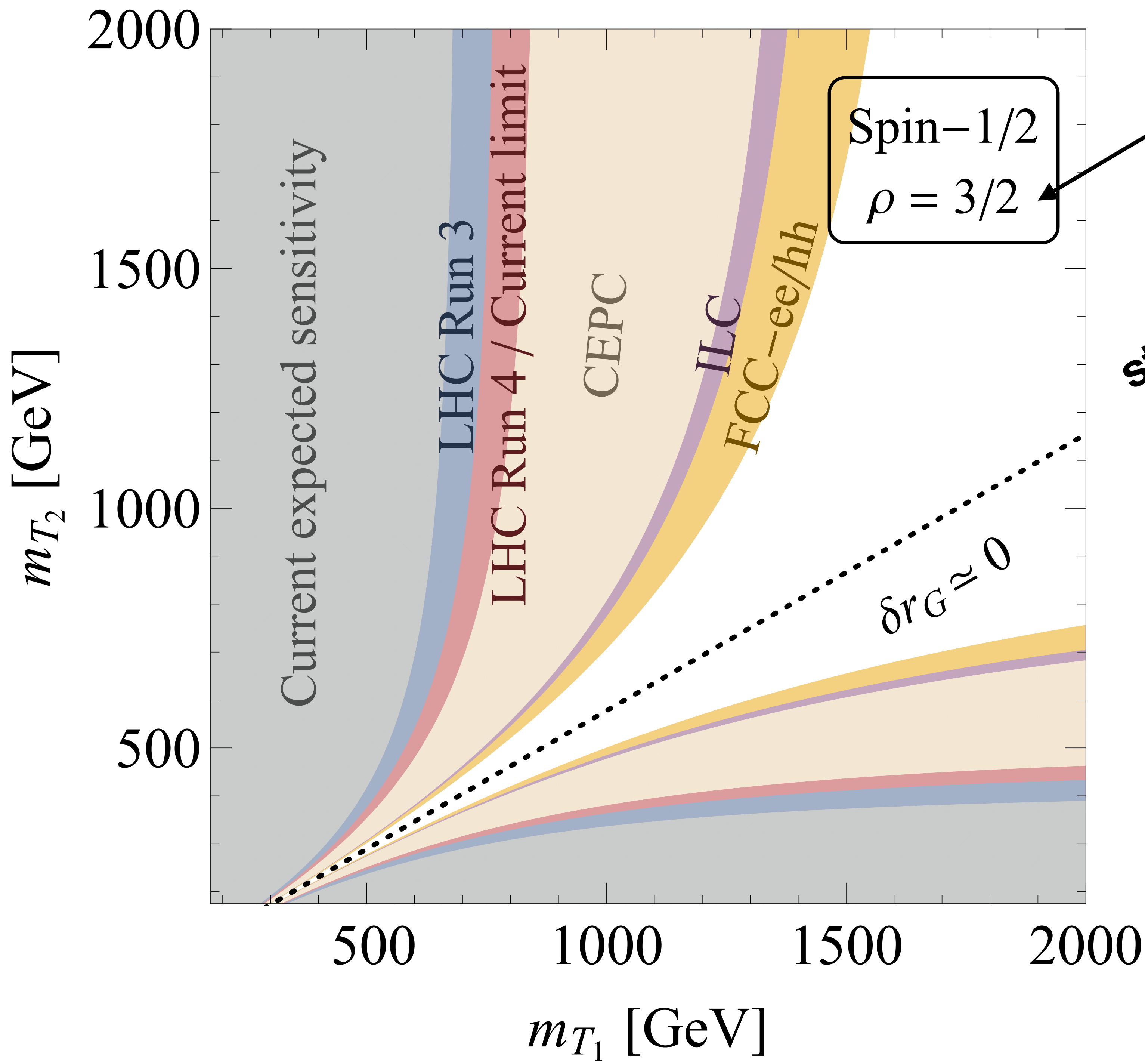
w/ 2σ CL



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

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

Two spin-1/2 top partners



T₂ loop cancels Higgs loop + T₁ loop

stealth limit

$$\frac{\rho}{m_{T_1}^2} = -\frac{1-\rho}{m_{T_2}^2}$$

w/ 2σ CL

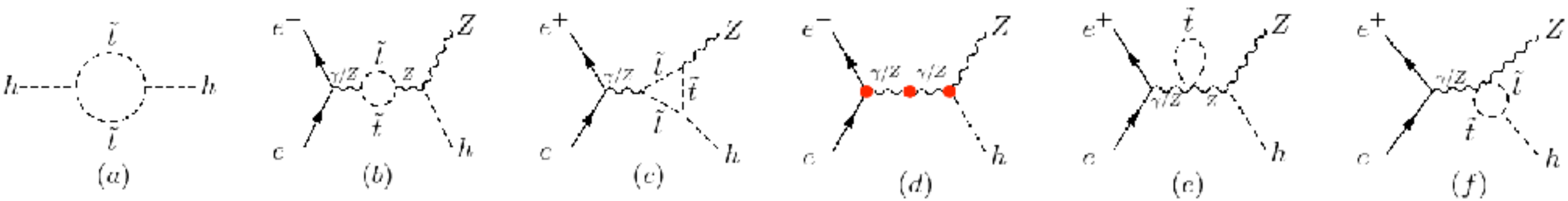
Complementary probes

Loop holes in Higgs precision

- Multiple top partners
  - Spin-0: $$\frac{g_{h\tilde{t}_1\tilde{t}_1}}{m^2_{\tilde{t}_1}} = -\frac{g_{h\tilde{t}_2\tilde{t}_2}}{m^2_{\tilde{t}_2}}$$
  - Spin-1/2: $$\frac{\rho}{m^2_{T_1}} = -\frac{1-\rho}{m^2_{T_2}}$$
- Blind spot / stealth limit
- Need complementary probes

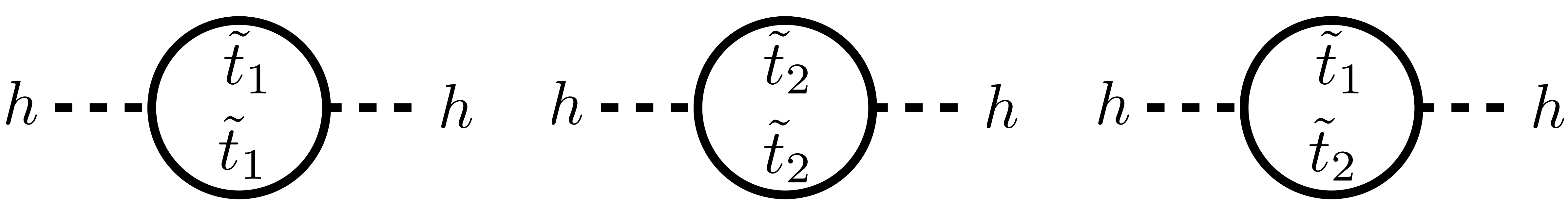
$\sigma(e^+e^- \to Zh)$ measurement

- $\sigma(e^+e^- \to Zh)$ can be useful

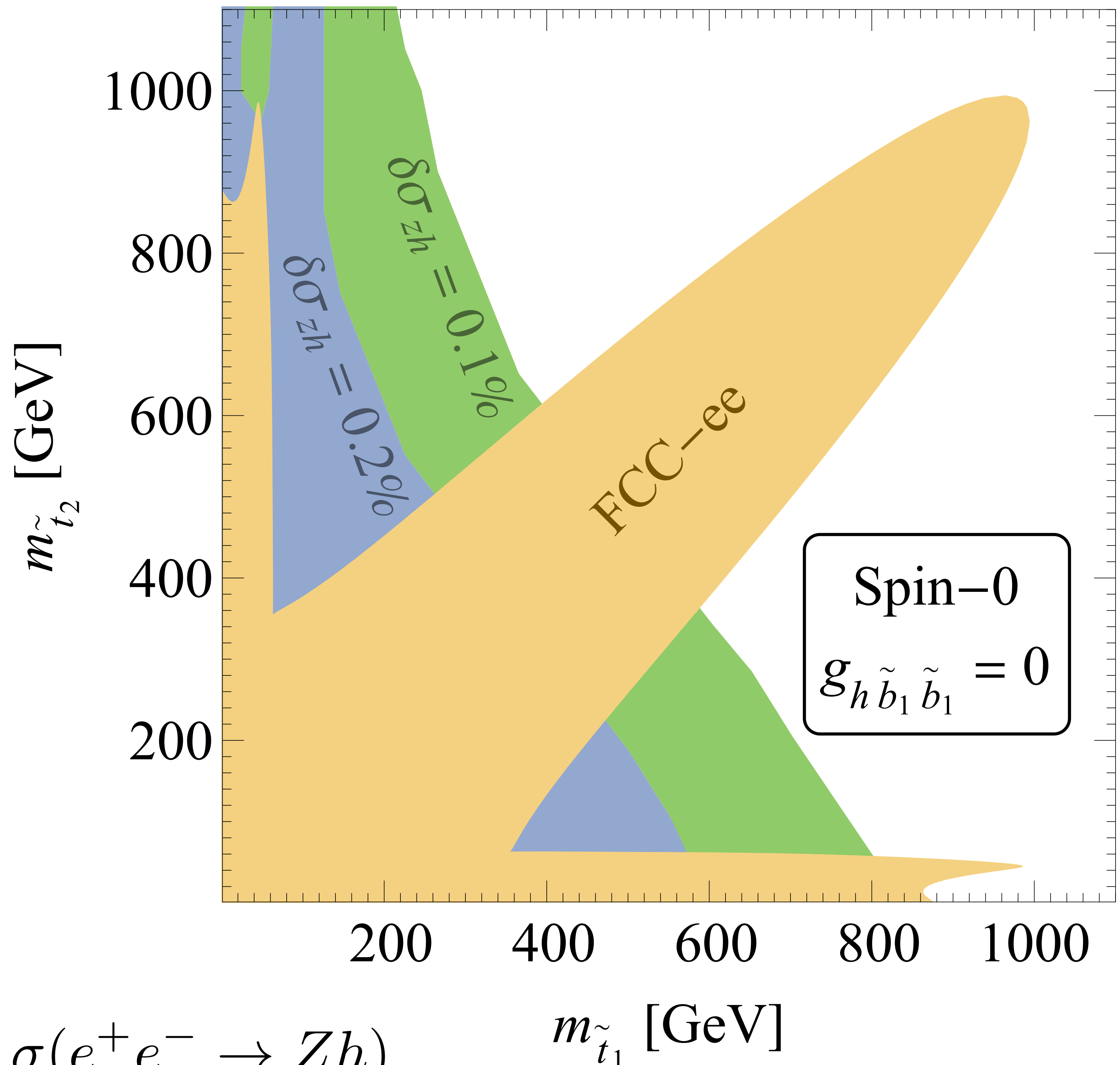


Craig, Farina, McCullough & Perelstein '14

- e.g. Higgs wave-function renormalization



MSSM



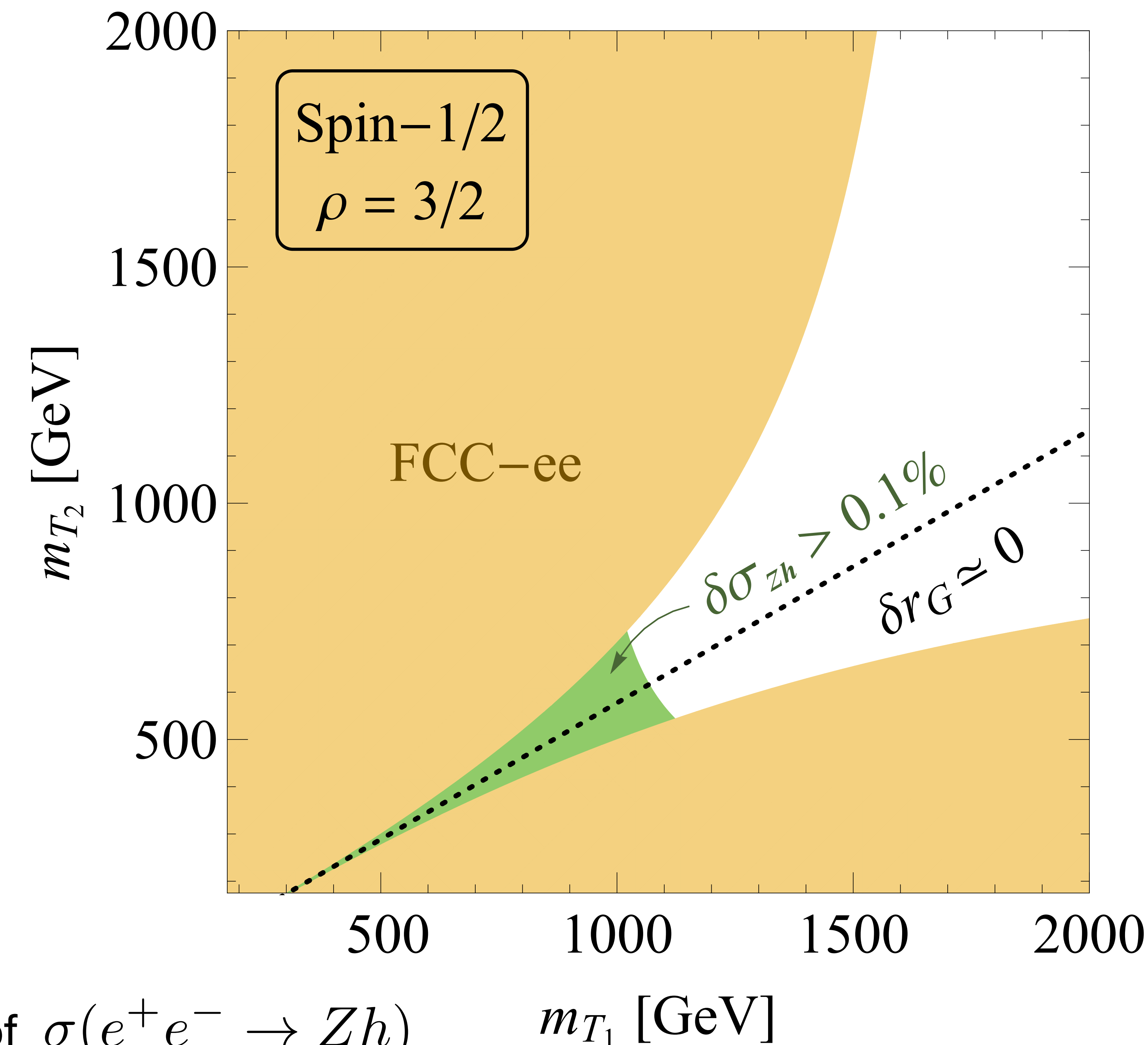
Full 1-loop cal. of $\sigma(e^+e^- \to Zh)$

w/ 2σ CL

follow Craig, Farina, McCullough & Perelstein '14

include D-terms

Two spin-1/2 top partners



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

w/ 2σ CL

follow Craig, Farina, McCullough & Perelstein '14

Summary

- ***Higgs precision tests, on their own, are quite robust.***
    - HL-LHC can constraint spin-0, spin-1/2 top partner ~ 500 GeV, spin-1 ~ multi-TeV.
- ***“Blind spots” exist when there are multiple top partners.***
    - Probed by Higgs decay width or Zh cross-section.
- ***Change r_t can also hide light colored top partners effectively.***
    - Future LHC runs or FCC-hh can extensively probe this possibility.