MODEL AGNOSTIC LIMITS ON COLORED TOP PARTNER MASSES

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WITH ROUVEN ESSIG, PATRICK MEADE AND YIMING ZHONG

TALK OUTLINE

- The Hierarchy Problem and top partner masses
- Effects on Higgs Precision Measurements
- Ways to Hide
- Zh probes on colored top-partners

TOP PARTNER SUMMARY

- Hierarchy problem - huge disparity between Planck and Electroweak (EW) mass scales

- Top partners ubiquitous in theories that invoke symmetries to protect the EW scale

- LEP+Tevatron+LHC see no stops/heavy tops

- Higher Mass of top partners = a more finely tuned theory

EVADING DIRECT SEARCHES

- Direct Search: decay to SM colored and LSP
- DD Caveats: Stealth SUSY, Oddest Little Higgs.

arXiv:1105.5135[Fan,Reece,Ruderman]   arXiv:1506.05130 :Anandakrishnan et al.

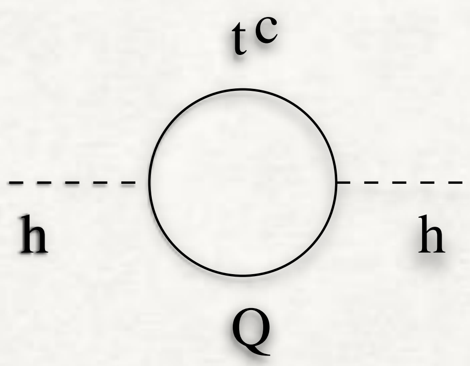
arXiv:1512.05781 [Fan et.al.]

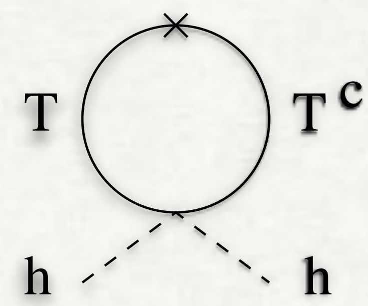
arXiv:1201.4875 [Fan et.al.]

- Top partners could be charged under another SU(3) (not this talk)
- Future lepton colliders will not be producing heavier top partners
- Interesting to explore other avenues

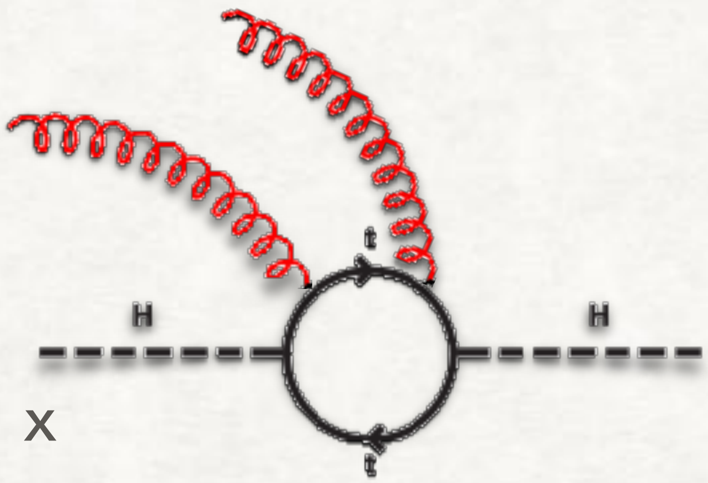
Indirect limits as an independent probe?

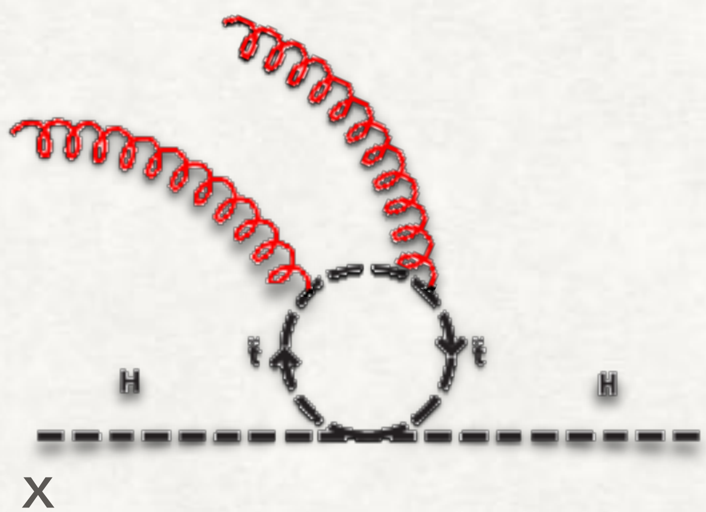
CANCELLATION

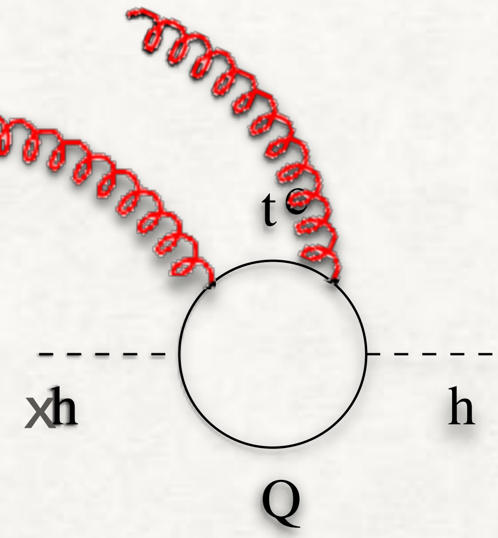


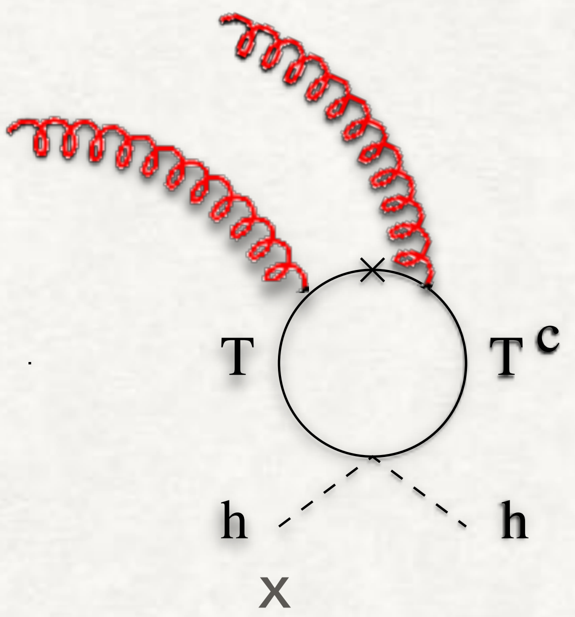


GGF









Both SM and TP contributions start at 1-loop

IS IT POSSIBLE TO SET LIMITS ON TOP PARTNER MASSES SOLELY FROM THIS PROPERTY?

See for e.g.
Fan, Reece arXiv:1401.7671

CANCELLATION VS GGF

$$M_i^2 = \mu_i^2 + a_i h^2$$

TP Mass(Matrix)

cancellation condition

$$\sum_i (-1)^{F_i} n_i a_i = 0$$

$$\frac{v^2}{M_{\hat{t}}^2} \frac{\partial M_{\hat{t}}^2}{\partial v^2} \frac{h}{v} G^{\mu\nu} G_{\mu\nu}$$

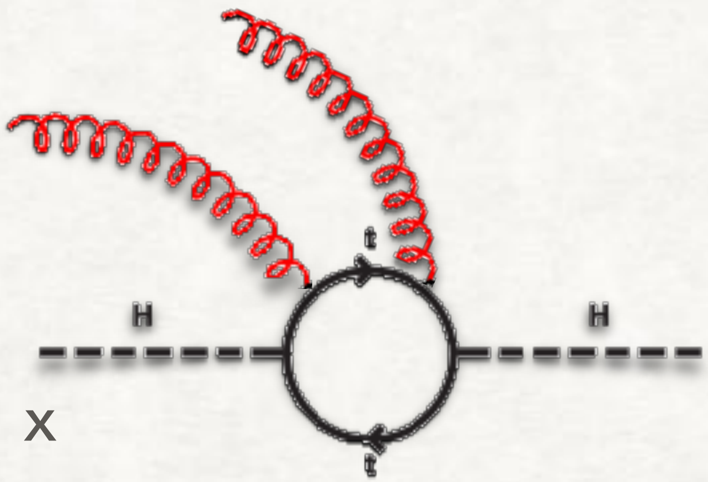
ggF: low energy Higgs theorem

SIGNAL STRENGTH MODIFIERS

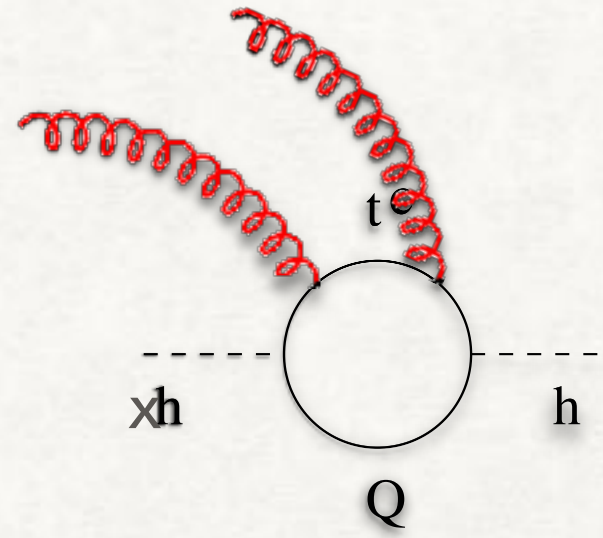
$$r_j = \sum_i \langle h|H_i\rangle \frac{v}{v_i} \frac{d\log[M_j^2]}{d\log[v_i^2]}$$

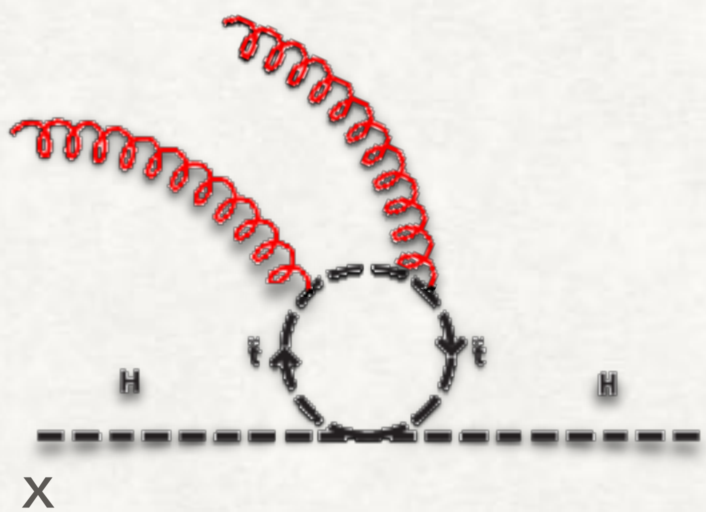
- <h|H_i>: how much of the 125 GeV h is H_i
useful for extended Higgs sectors
- M_j^2: mass square matrix for particle j
- v_i: vev of H_i
- v :246 GeV
- r_j(SM)=1

SIGNAL STRENGTH MODIFIERS

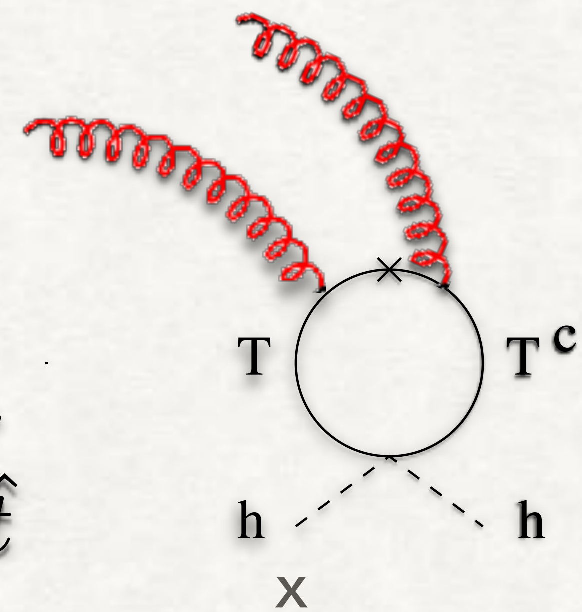


r_t





$r_t \mathcal{N}_{\hat{t}}$



- Mod-ing out r_t removes extended
- Higgs sector dependence of $\mathcal{N}_{\hat{t}}$
- In-fact $\mathcal{N}_{\hat{t}}$ will generically depend only on TP masses

RELATING MASSES TO $\mathcal{N}_{\hat{t}}$

Scalars

Refer Arxiv:1401.7671 Jiji Fan, Matt Reece

- For degenerate stop masses

$$\mathcal{N}_{\tilde{t}} = \frac{m_t^2}{2m_{\tilde{t}}^2}$$

Fermions

$$\mathcal{N}_T = -\frac{m_t^2}{m_T^2}$$

Notice the relative minus sign

*Vector top partner possible: Large contribution in loops.
will talk about it if time permits

HIGGS PRECISION

Production

- ggF
- VBF
- WH
- ZH
- tth

Decay

- AA
- WW,ZZ
- bb
- gg
- invisible

HIGGS PRECISION

Production

- ggF $r_t\,(1+\mathcal{N}_{\hat{t}})$
- VBF
- WH
- ZH
- tth r_t

Decay

- AA 1.28 -0.28 $r_t\,(1+\mathcal{N}_{\hat{t}})$
- WW,ZZ
- bb
- gg $r_t\,(1+\mathcal{N}_{\hat{t}})$
- invisible/exotic

HIGGS PRECISION

Production

- ggF $r_t\ (1+\mathcal{N}_{\hat{t}})$
- VBF $\mathrm{r_V}$
- WH $\mathrm{r_V}$
- ZH $\mathrm{r_V}$
- tth r_t

Decay

- AA 1.28 -0.28 $r_t\ (1+\mathcal{N}_{\hat{t}})$
- WW,ZZ $\mathrm{r_V}$
- bb $\mathrm{r_b}$
- gg $r_t\ (1+\mathcal{N}_{\hat{t}})$
- invisible/exotic $\mathrm{r_{inv}/r_{exo}}$

Notice the degeneracy …

PLAN OF ACTION

- get experimental limits on $r_G = r_t(1+\mathcal{N}_{\hat{t}})$
- This sets limits on $\mathcal{N}_{\hat{t}}$ which will in-turn set limits on top partner masses
- Check which couplings are most potent at hiding $\mathcal{N}_{\hat{t}}$

DATASETS

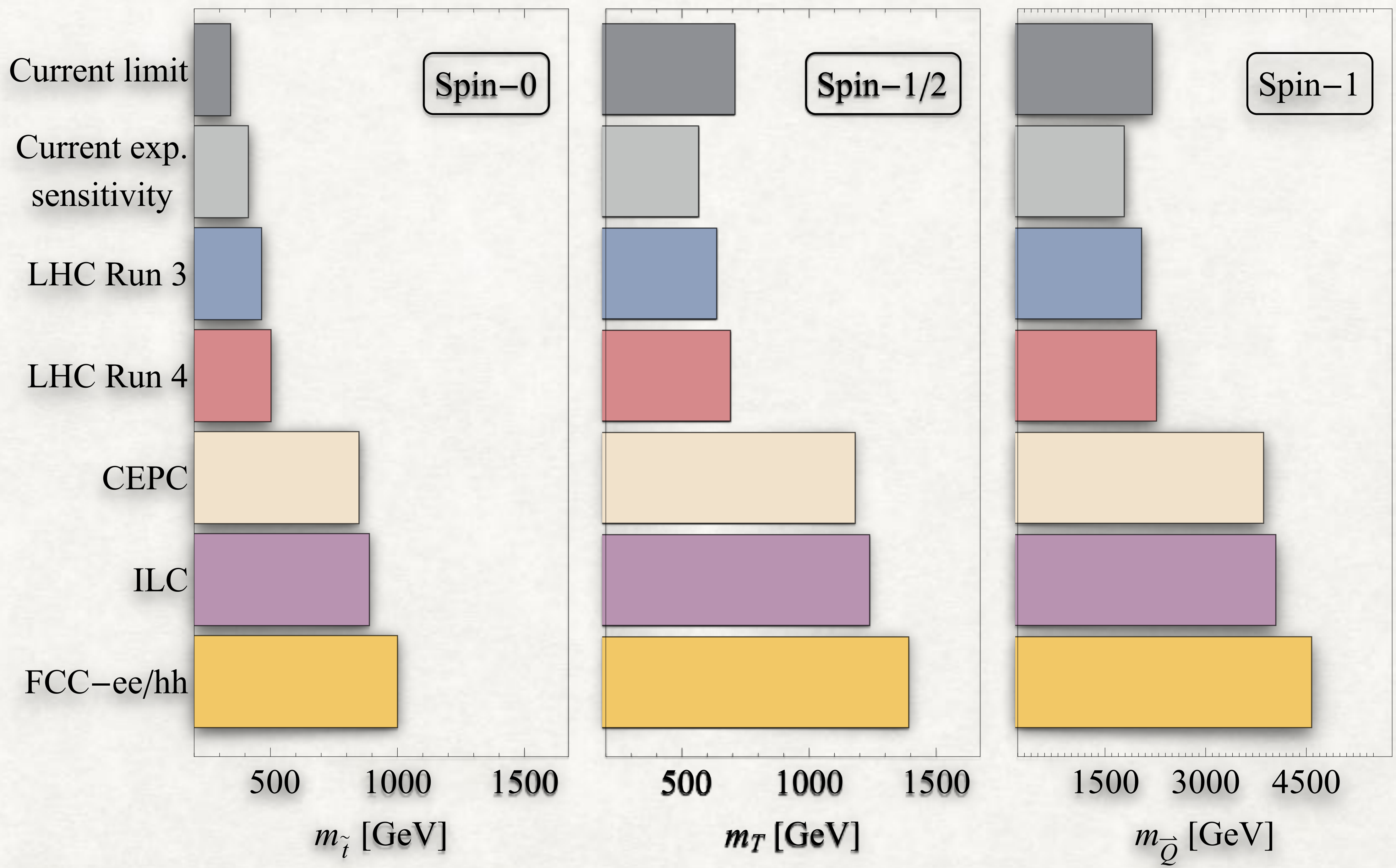
- Current:

Full Run I+Run II updated to EPS 2017

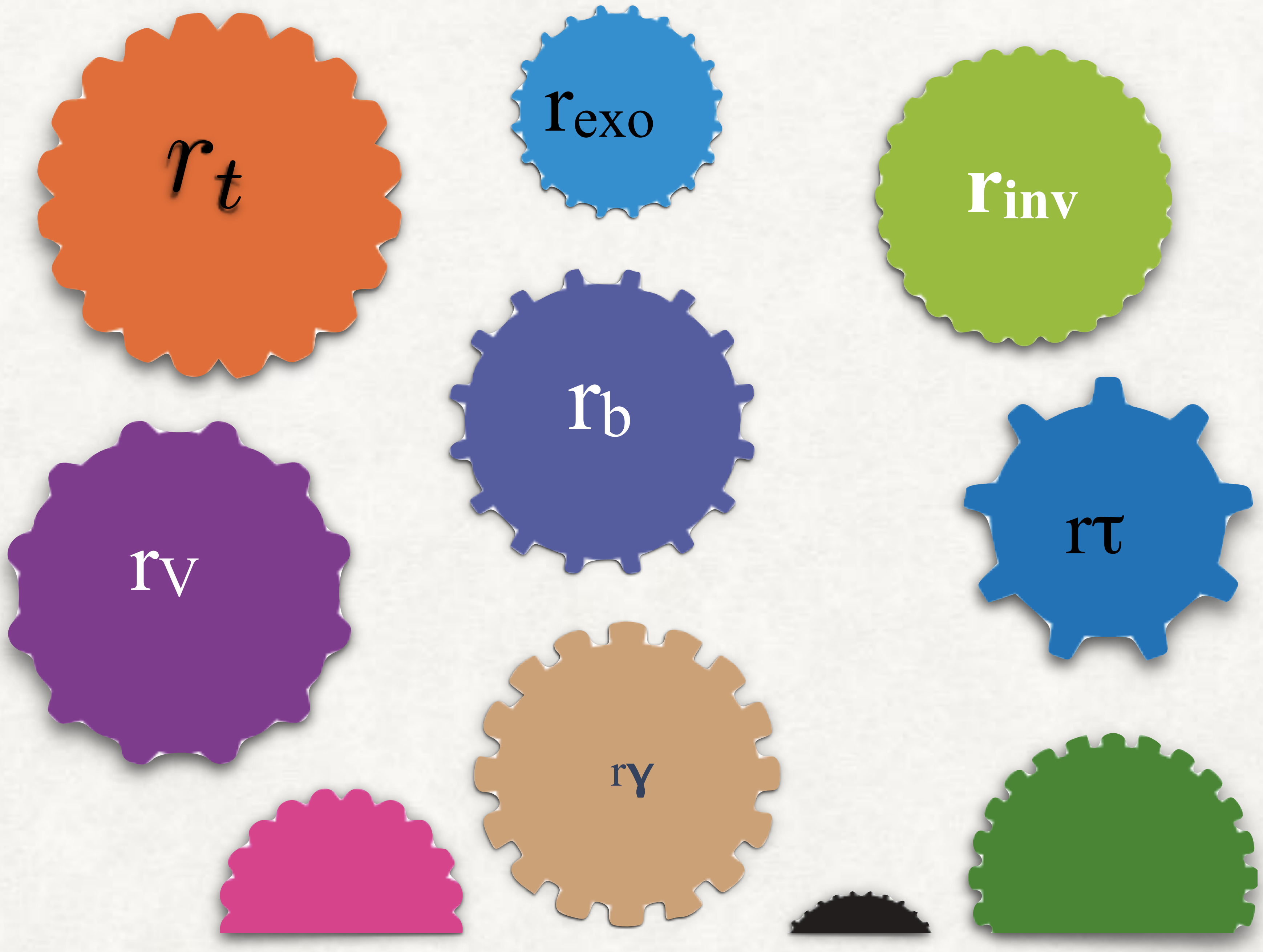
- Future LHC runs

- Proposed Lepton and Hadron colliders

RESULTS WITH ALL SM COUPLINGS =1

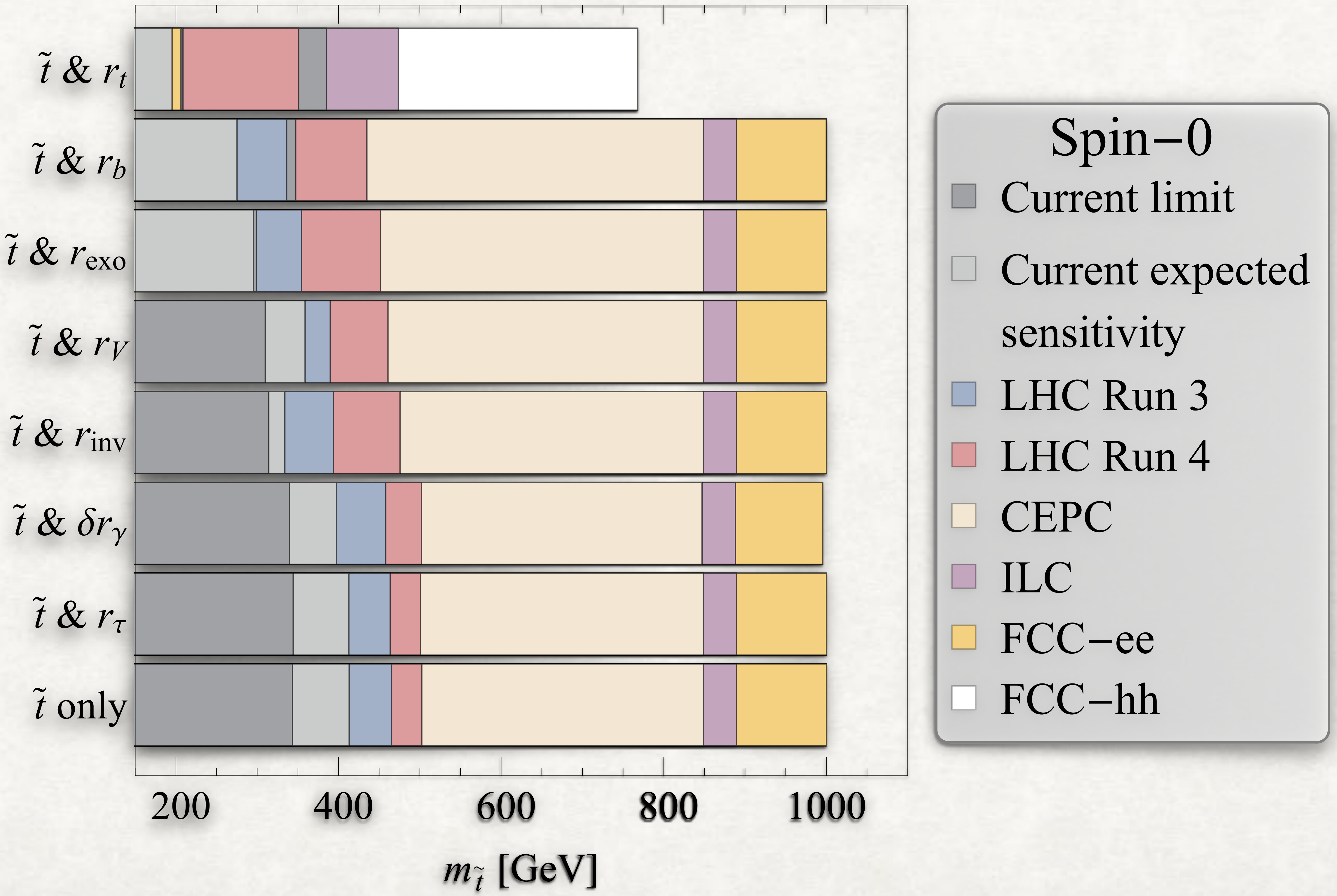


*assumes degenerate

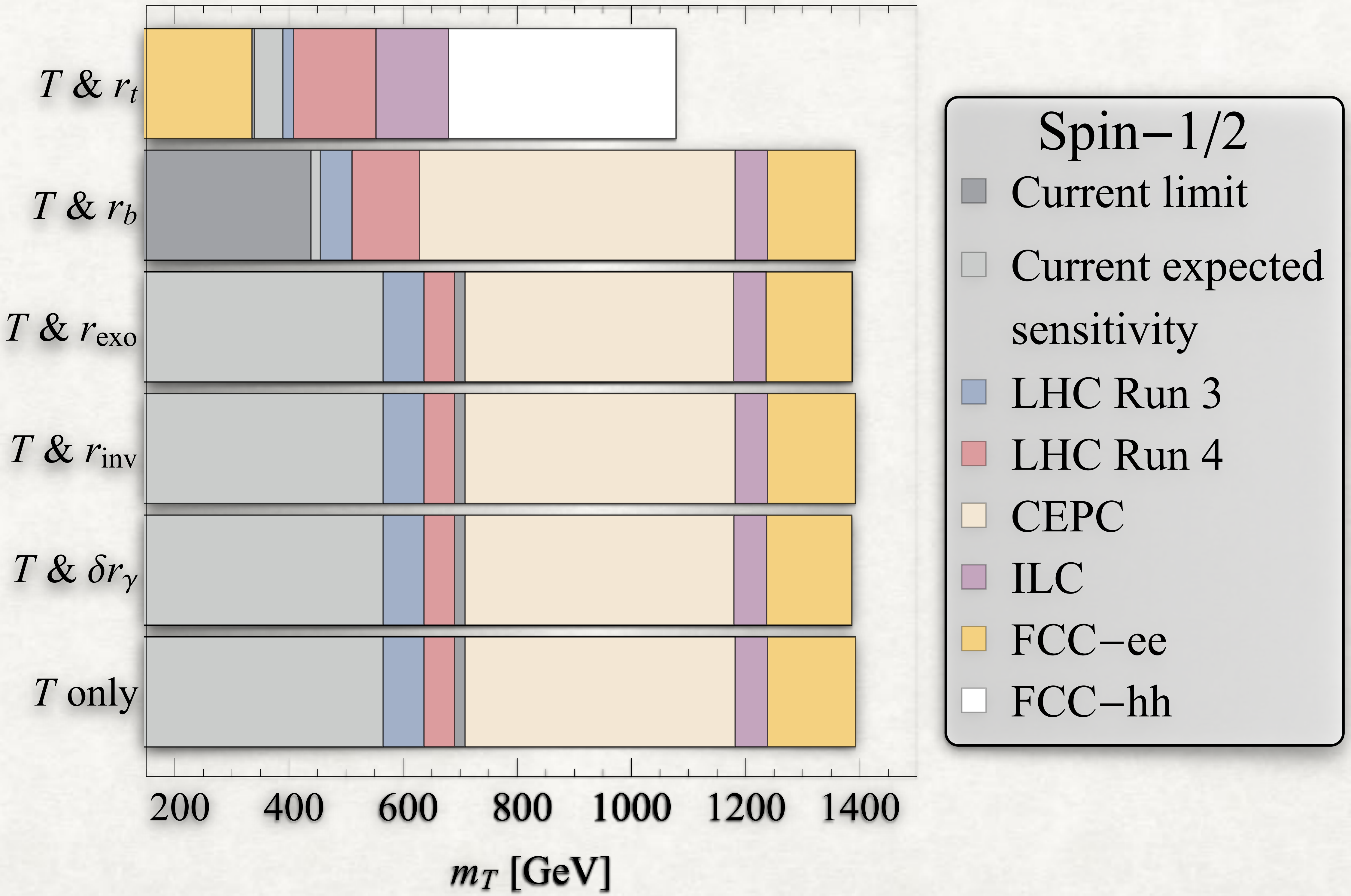


r_t
r_{exo}
r_{inv}
r_b
r_V
r_τ
r_γ

SCALAR TOP PARTNER

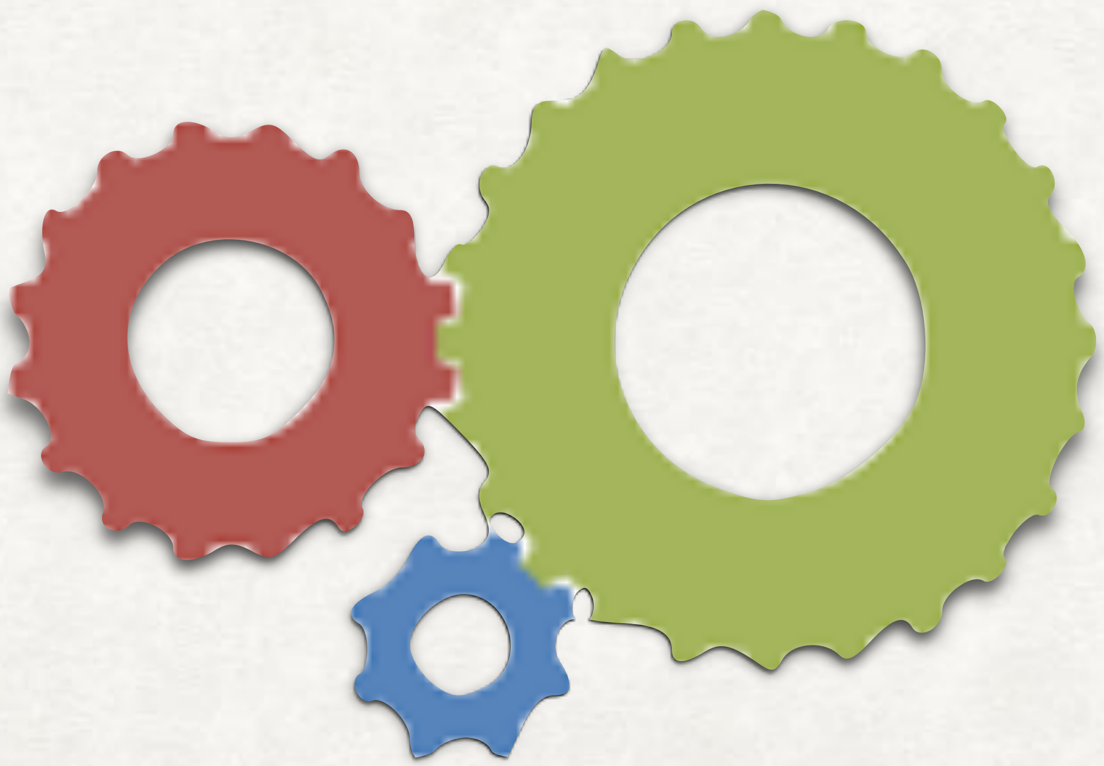


FERMIONIC TOP PARTNER



CONCRETE MODELS

- Can concrete models in literature capture all this freedom?
- Usually not. There are relations between various couplings.



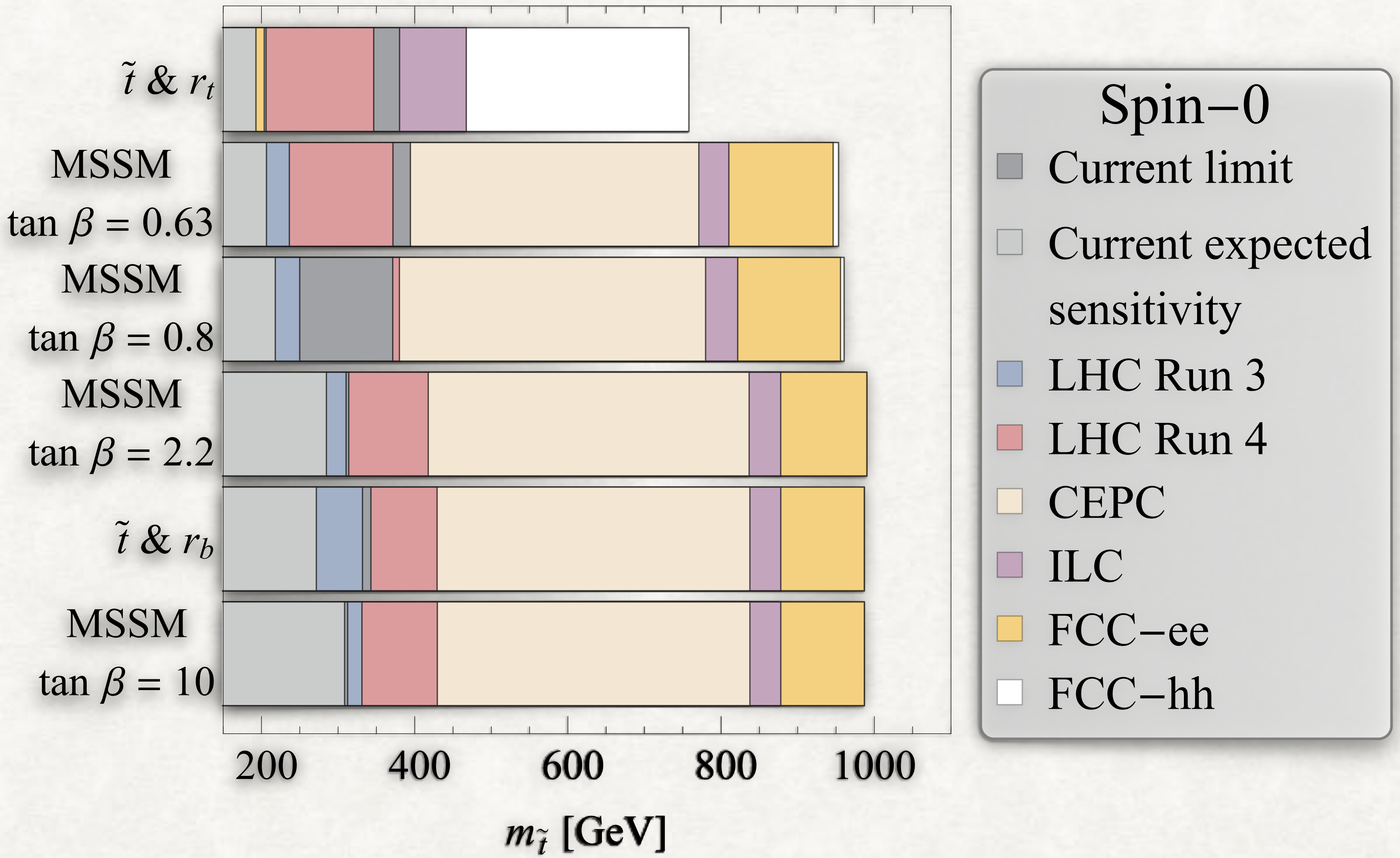
SUSY:MSSM

- MSSM contains a Type II, 2HDM and imposes relations between couplings.

$$r_b = r_\tau = \sqrt{1 + (1 - r_t^2)\tan^2\beta}, \quad r_V = \frac{r_t \tan^2\beta + \sqrt{1 + (1 - r_t^2)\tan^2\beta}}{1 + \tan^2\beta}$$

- Owing to the rich structure, dialing r_t which is poorly measured leads to large changes in r_b and r_V which are well measured.
- Way out: small tan**β**. However limited by RG perturbativity considerations.
- Future Work: extend Higgs section beyond 2HDM.

MSSM

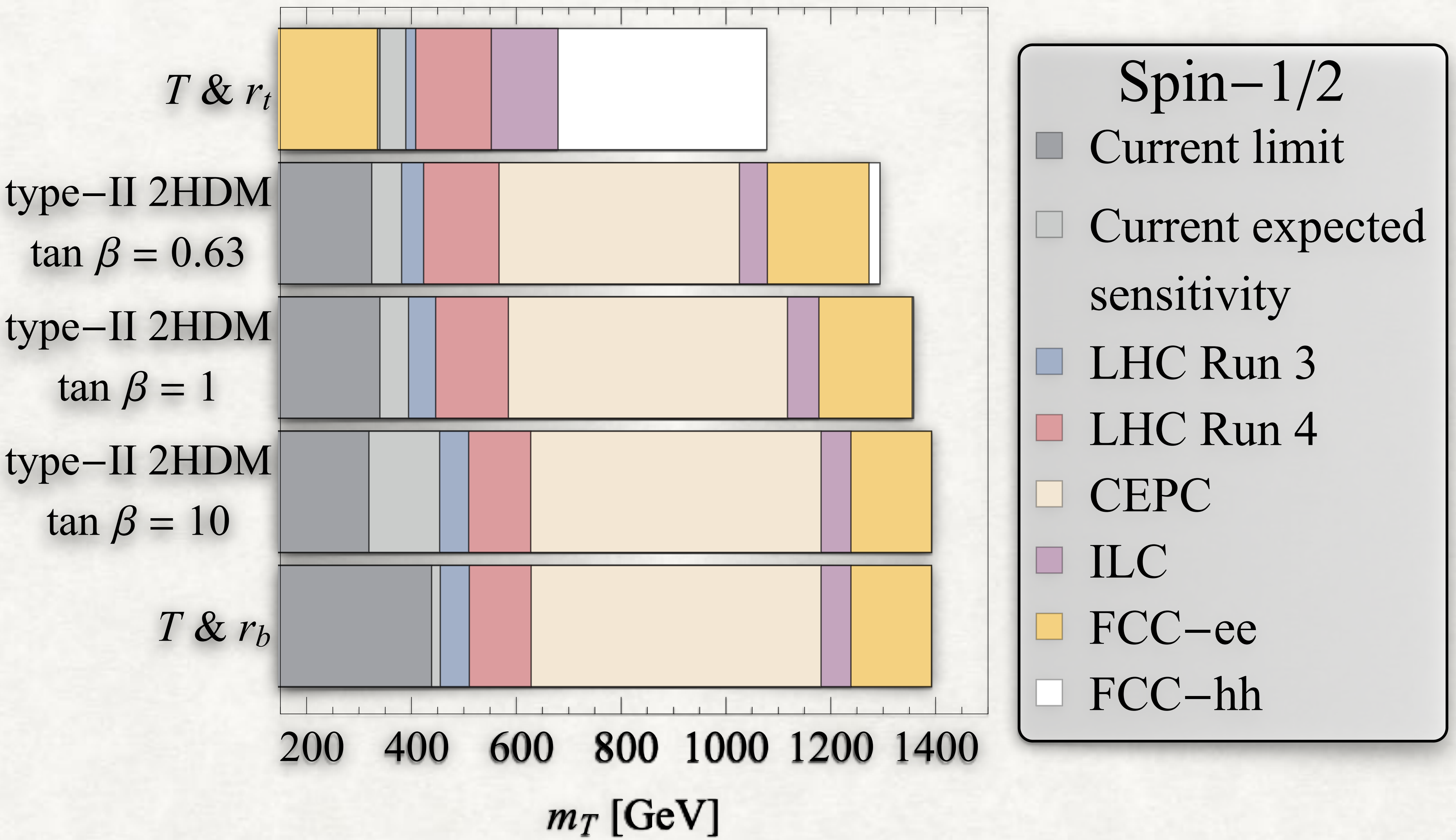


$\tilde{t}$ & r_t
MSSM
$\tan\beta = 0.63$
MSSM
$\tan\beta = 0.8$
MSSM
$\tan\beta = 2.2$
$\tilde{t}$ & r_b
MSSM
$\tan\beta = 10$
200
400
600
800
1000
$m_{\tilde{t}}$ [GeV]
Spin−0
Current limit
Current expected sensitivity
LHC Run 3
LHC Run 4
CEPC
ILC
FCC−ee
FCC−hh

FERMIONIC TOP PARTNERS

- Little Higgs theories do not require a 2HDM.
- Single HDM however give negative definite top Yukawa deviation.
- Beneficial to add 2HDM structure to hide fermionic top partners.
- Type II proves to be the most capable.

FERMIONIC TPS



CAN WE INSTEAD MAKE

$$\frac{v^2}{M_{\hat{t}}^2}\frac{\partial M_{\hat{t}}^2}{\partial v^2}\frac{h}{v}G^{\mu\nu}G_{\mu\nu}$$

$\mathcal{N}_{\hat{t}}$

Vanish?

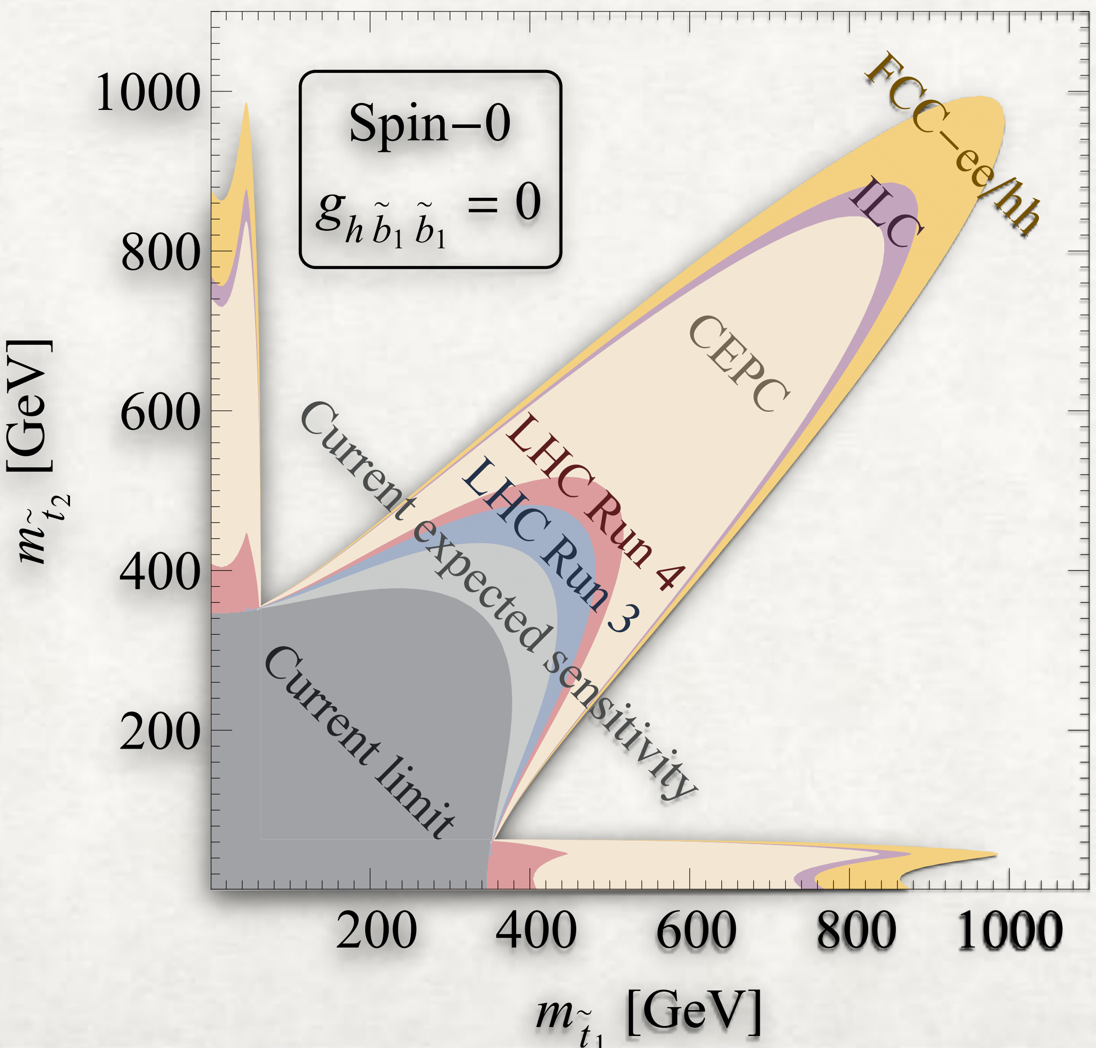
NATURAL SUSY

"Blindspot": arXiv:1412.3107

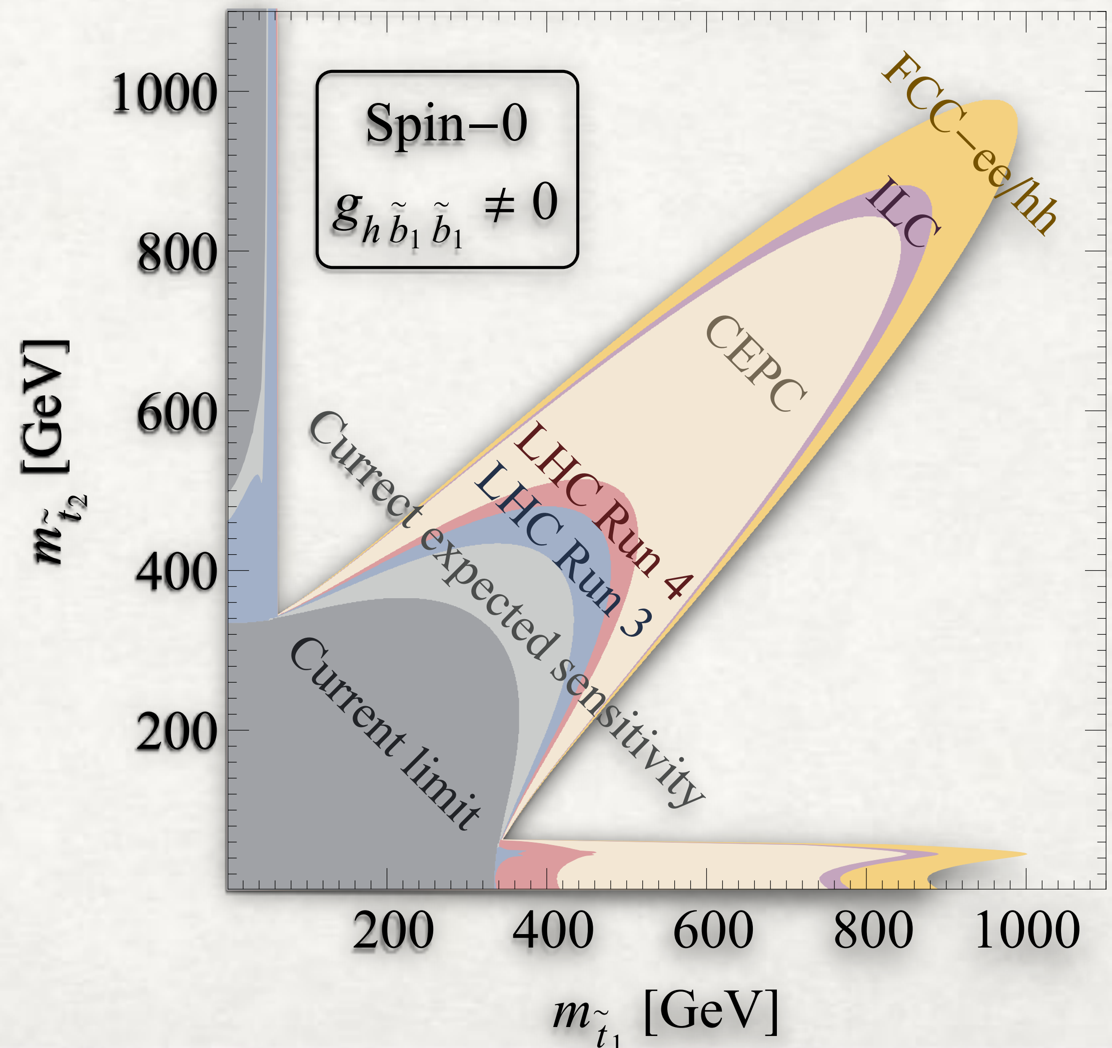
$$\mathcal{N}_{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

$$X_t = A_t - \mu \cot\beta$$

"without D-term"



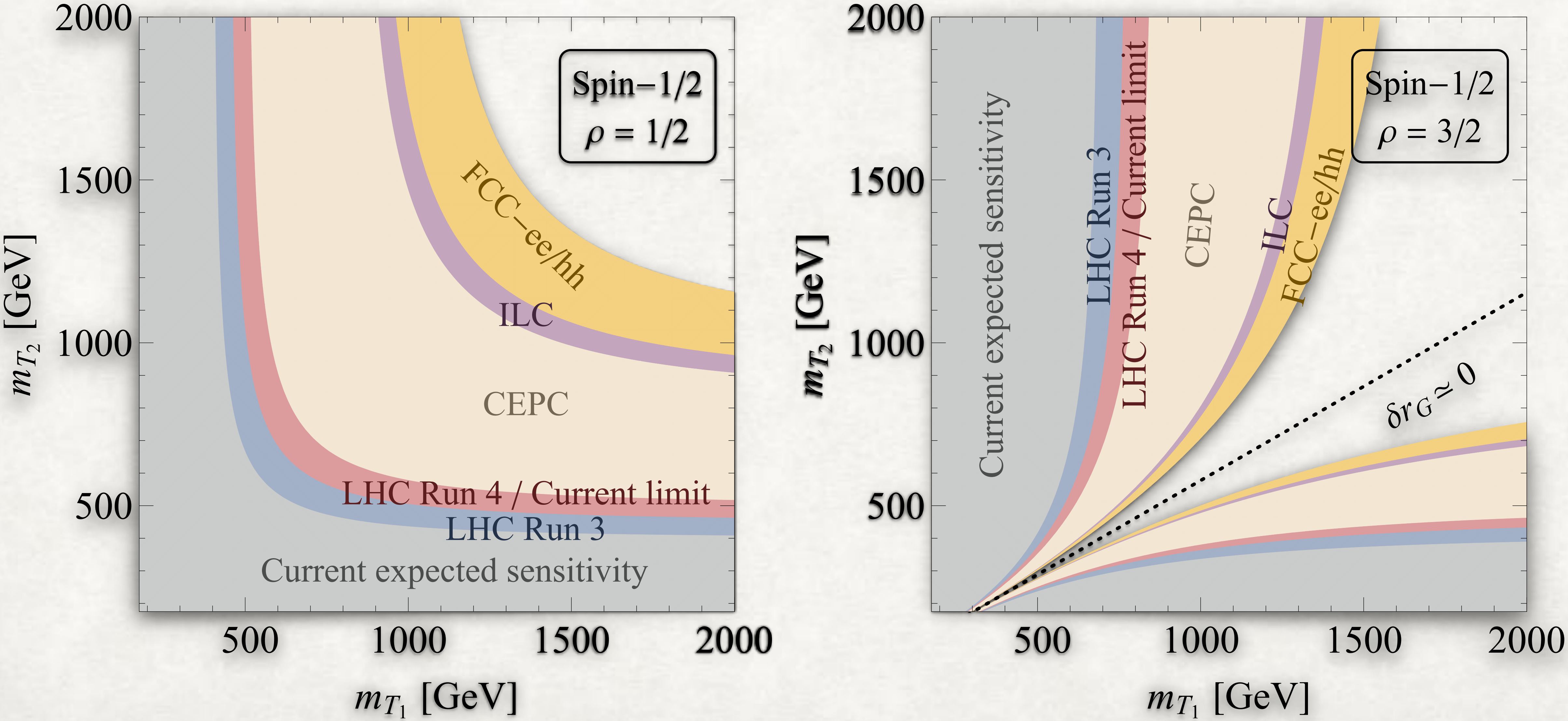
with D-terms



TWO FERMIONIC TOP PARTNERS

CAPTURES % QUAD DIV CANCELLATIONS

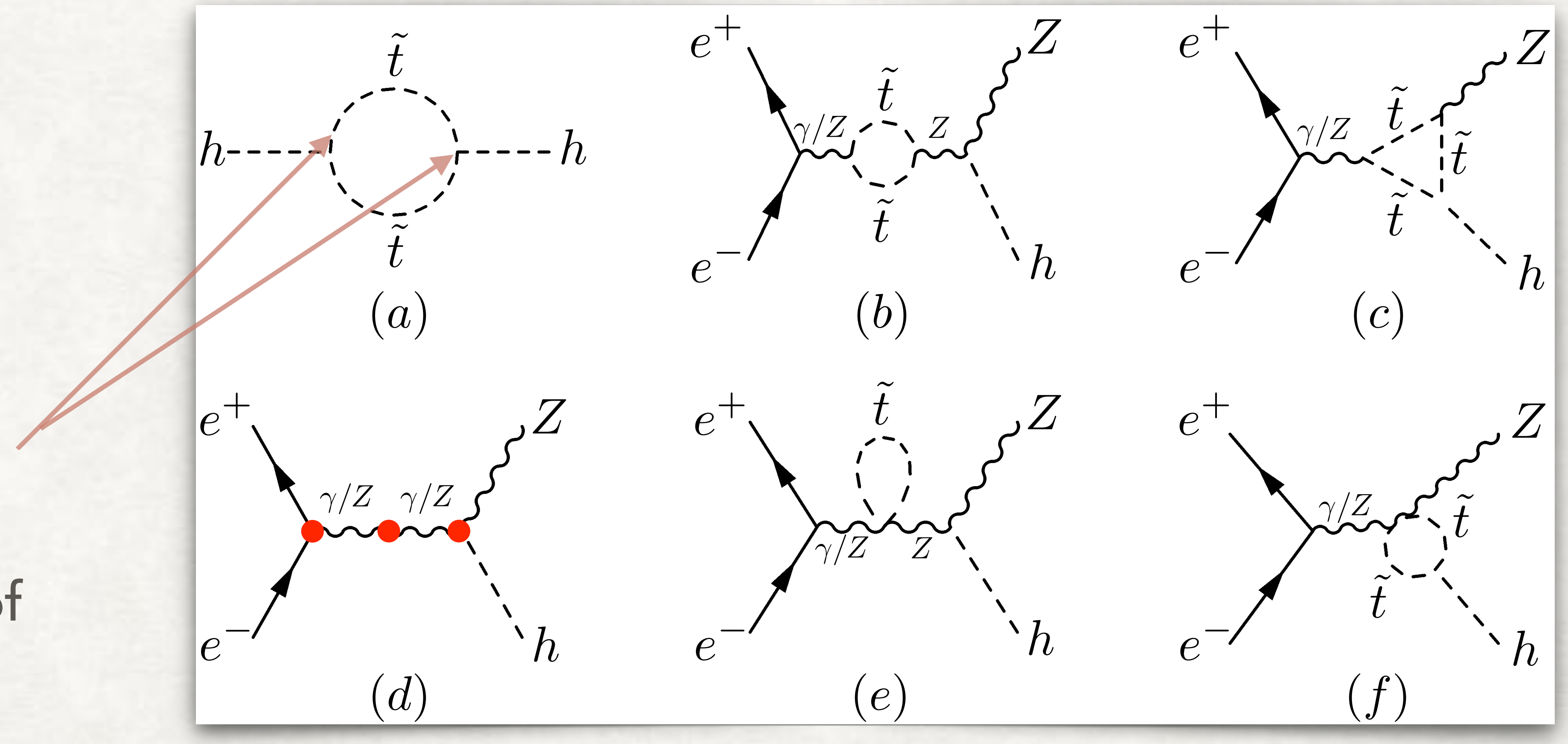
$$\mathcal{N}_T \equiv y_{T_1} + y_{T_2} = -m_t^2 \left(\frac{\rho}{{m_{T_1}}^2} + \frac{1-\rho}{{m_{T_2}}^2} \right)$$



ZH PROBES

Refer Craig et.al. arXiv:1305.5251

- Colored Top Partners acting like neutral Top Partners
- Fall back on neutral Top Partner probes
- $e^+ e^-$ -> Zh

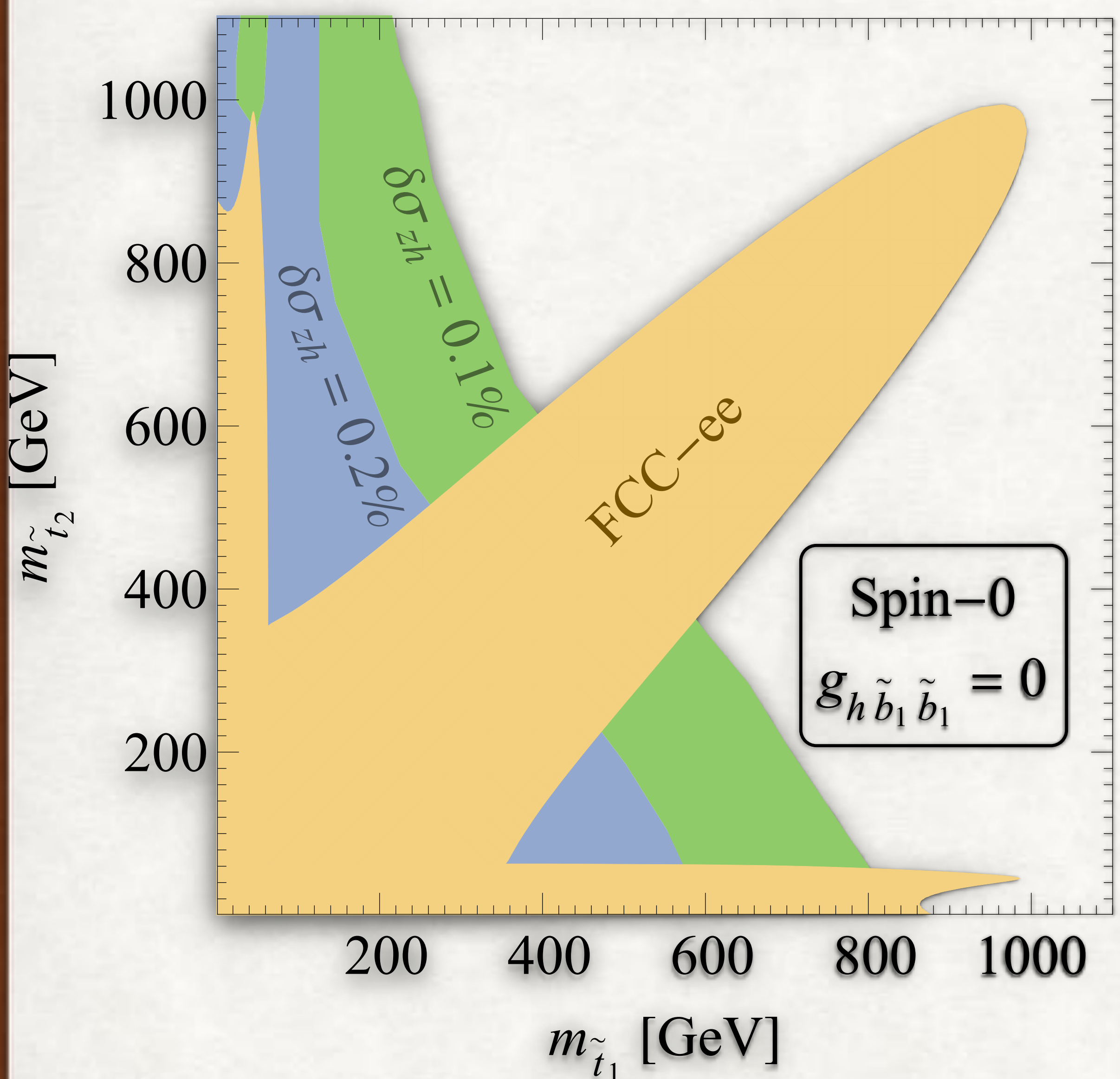


Two powers of coupling

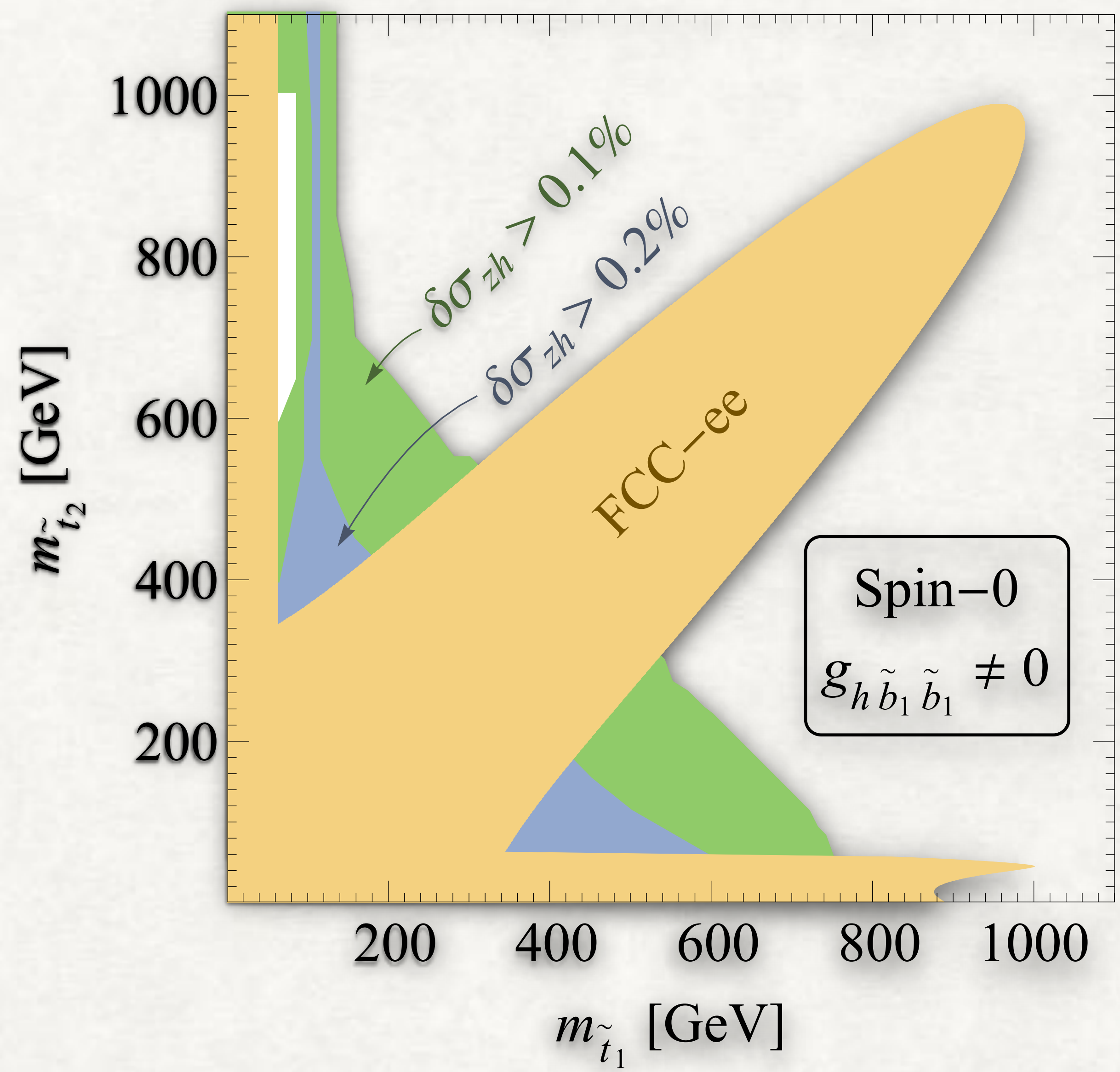
Fig. from Craig, et.al arXiv:1411.0676

GGF VS ZH SUSY:

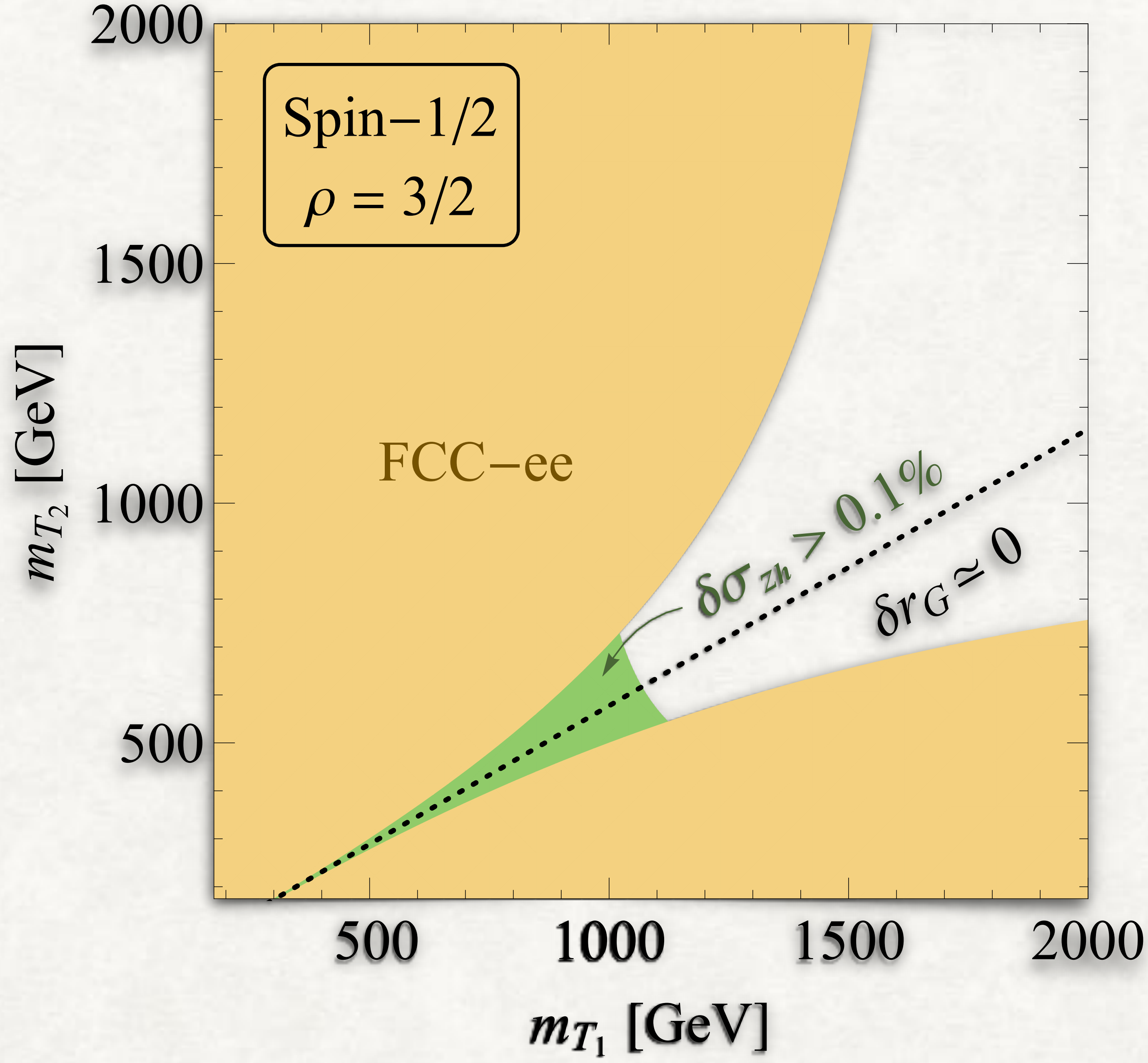
"without D-term"



large D-terms



GGF+ZH - FERMIONIC TPS



Caveat: Depends on UV completion

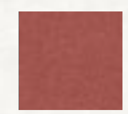
SUMMARY

- Independent probe of TPs through ggf
- Even after dialing other signal strengths, limits reach over a TeV
- Certain chance cancellations possible
- Supplemented by limits from Zh

y’all should build a collider *this* big

VECTOR TOP PARTERS

Cai, Cheng, Terning arXiv:0806.0386, Farina et.al arXiv:1406.1221

- Again require a SUSY theory
- Vectors cannot be charged as a 
- Observation:SU(5) has gauge bosons transforming as (3,2) under the SU(3)x SU(2) subgroups
- top is the gaugino => top-partner is a vector

$$\mathcal{N}_{\vec{Q}} = -\frac{1}{\cos\beta}\frac{21}{4}\frac{m_t^2}{m_Q^2}$$

BACKUP

FUTURE COLLIDERS DATA

	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_{inv}	0.29%	0.2%	0.19%	–