



# Probing Natural SUSY at the LHC

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CLHCP 2017.12, Nanjing

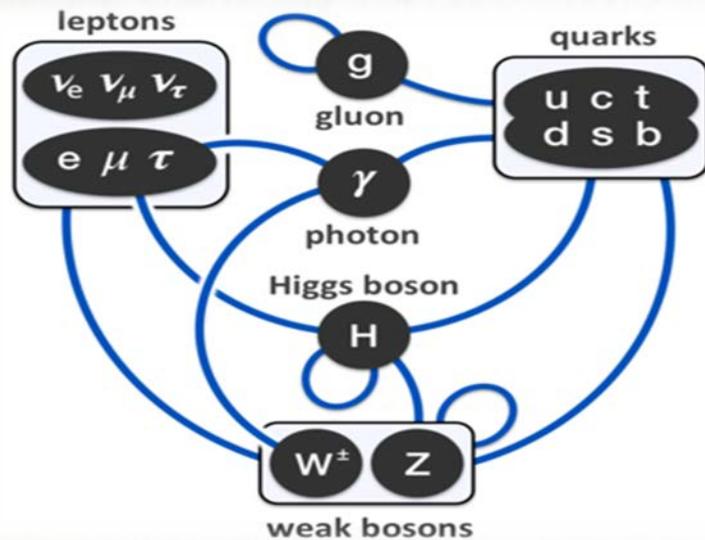
# OUTLINE OF TOPICS

- **Implications of SUSY naturalness for LHC experiment**
- **Stop pair, Mono-stop, Stop bound state production @ LHC**
- **Conclusions**
  - JHEP 1709 (2017) 037, JHEP 1703 (2017) 091,  
EPJC 77 (2017) no2, 93, PRD 93 (2016) 035003  
PLB 755 (2016) 76-78, PRD 92 (2015) 075008  
JHEP 1402 (2014) 049, JHEP 1310 (2013) 216  
JHEP 1211 (2012) 039

# SUSY NATURALNESS FOR LHC

- Gauge Field Theory + Spontaneous Symmetry Breaking + Renormalizable

$$SU_C(3) \times SU(2)_L \times U(1)_Y$$



A diagram illustrating the self-energy correction to the Higgs boson mass. It shows a Higgs boson line (dashed) with a loop of a fermion  $f$  (solid) and a loop of a gauge boson ( $W^\pm, Z$ , wavy) and a loop of a Higgs boson ( $H$ , dashed). The loops are connected by plus signs, indicating they are added to the tree-level mass.

$$\delta m_h^2 = \left[ \frac{1}{4}(9g^2 + 2g'^2 - 6y_t^2 + 6\lambda) \right] \frac{\Lambda^2}{32\pi^2}.$$

one part in  $\sim 10^{15}$

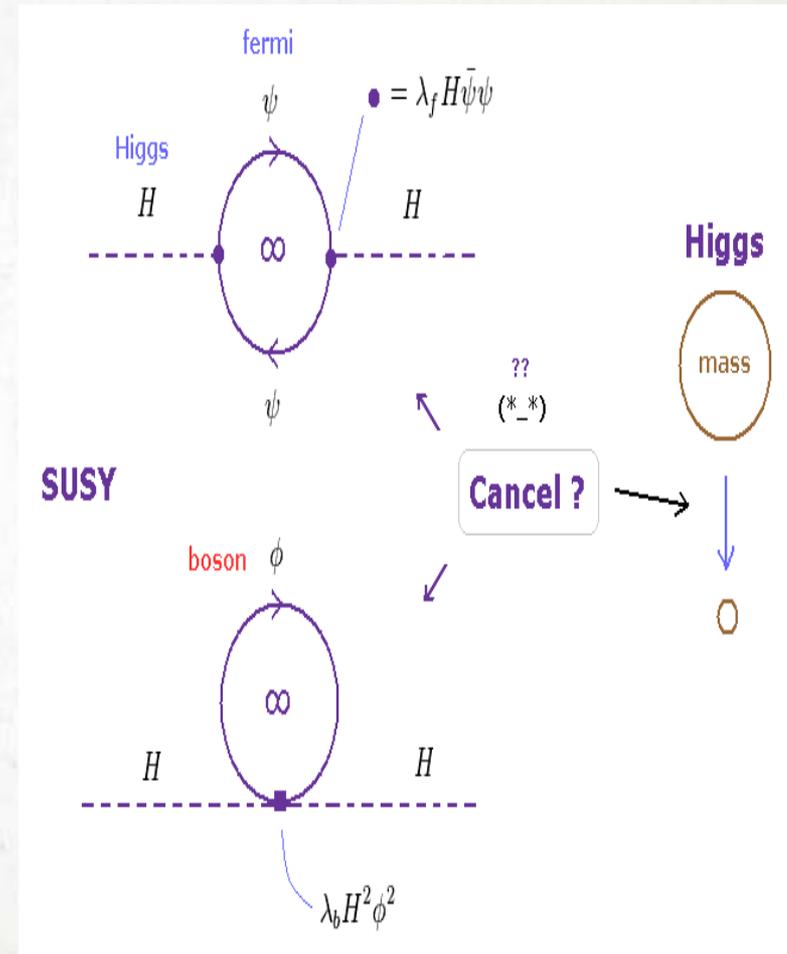
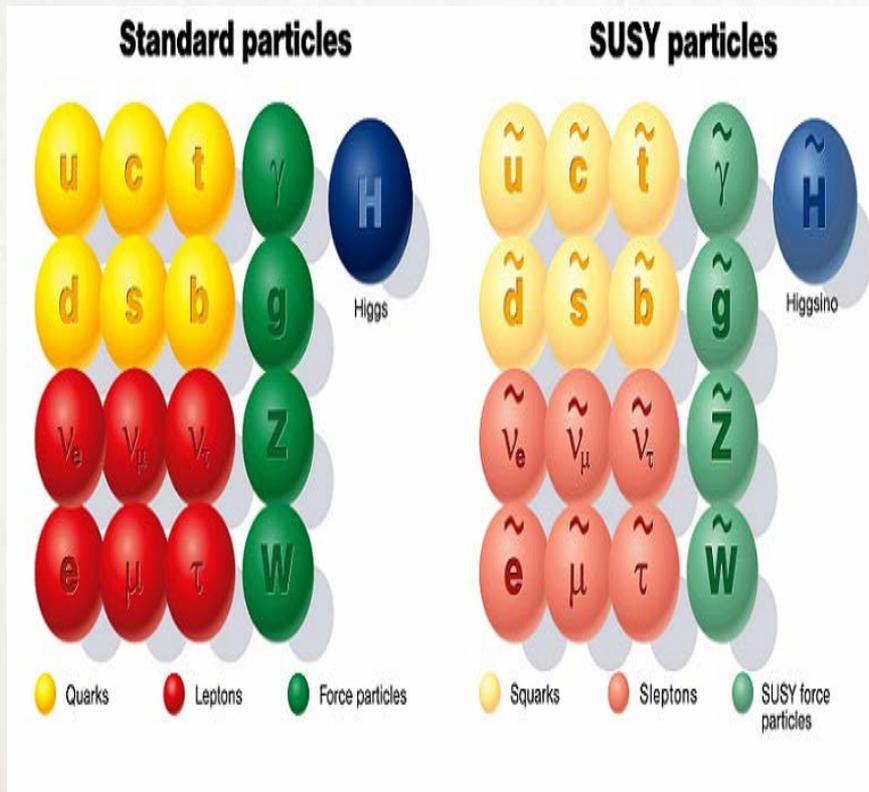
$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ & + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c. \end{aligned}$$

**“Naturalness Problem”**

# Naturalness is one of guiding principles to extend the SM.

$$Q|Boson\rangle = |Fermion\rangle$$

$$Q|Fermion\rangle = |Boson\rangle$$



- In a specific SUSY model, the starting point of discussing SUSY naturalness is from the **minimization condition** of Higgs potential, which determines the Z-boson mass.

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \dots$$

$$\delta m_{H_u}^2 \approx -\frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2} (1 + a^2/2) \log \frac{\Lambda}{m_{\tilde{t}}}$$

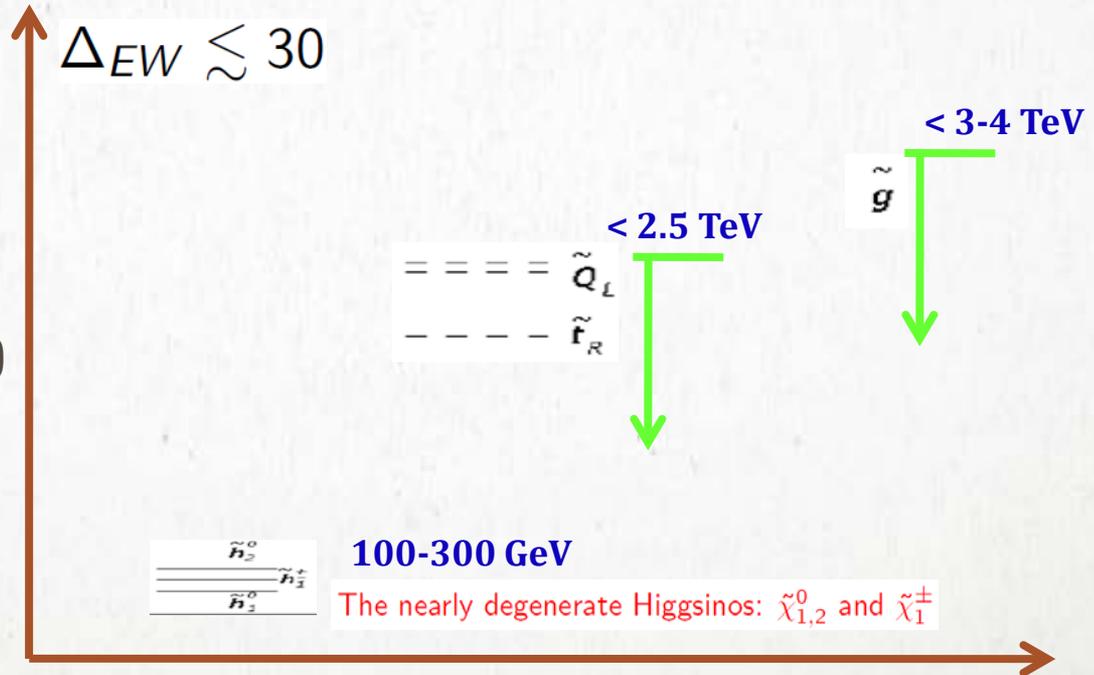
$$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \log \frac{\Lambda}{M_3}$$

In order to obtain the value of  $M_Z$  without fine-tuning, each term of right-handed side should be on the order of  $M_Z$ . Then, we will have upper bounds on sparticles.

$$\Delta_{EW} \equiv \max(C_i)/(M_Z^2/2).$$

Note that  $\Delta_{EW}$  depends only on the weak scale parameters of the theory and hence is essentially fixed by the particle spectrum, independent of how superpartner masses arise<sup>5</sup>.

**NSUSY spectrum  
(roadmap at LHC)**



# Higgsino world

$$\mu \ll M_1, M_2$$



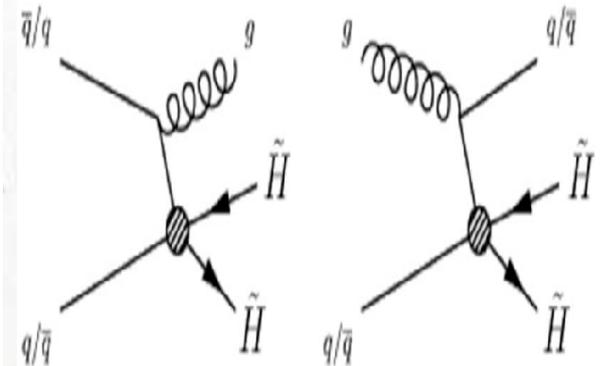
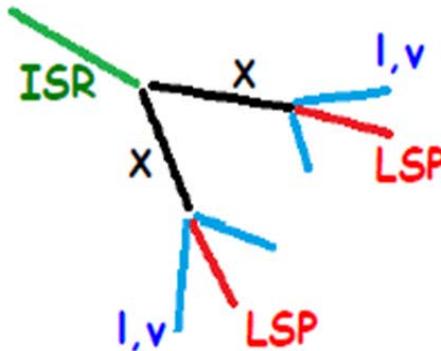
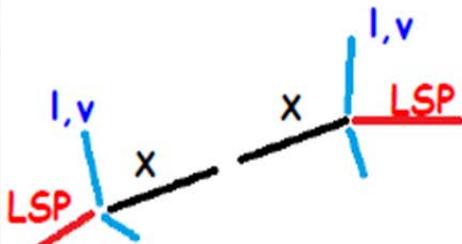
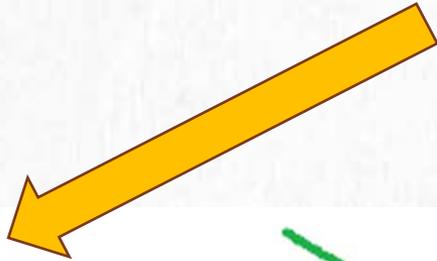
$$m_{\tilde{\chi}_1^0} \simeq \mu;$$

$$\Delta m_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0} = \frac{M_W^2}{2M_2} \left( 1 - \sin 2\beta - \frac{2\mu}{M_2} \right) + \frac{M_W^2}{2M_1} \tan^2 \theta_W (1 + \sin 2\beta)$$

$$\simeq 0;$$

$$\Delta m_{\tilde{\chi}_2^0 - \tilde{\chi}_1^0} = \frac{M_W^2}{2M_2} \left( 1 - \sin 2\beta + \frac{2\mu}{M_2} \right) + \frac{M_W^2}{2M_1} \tan^2 \theta_W (1 - \sin 2\beta)$$

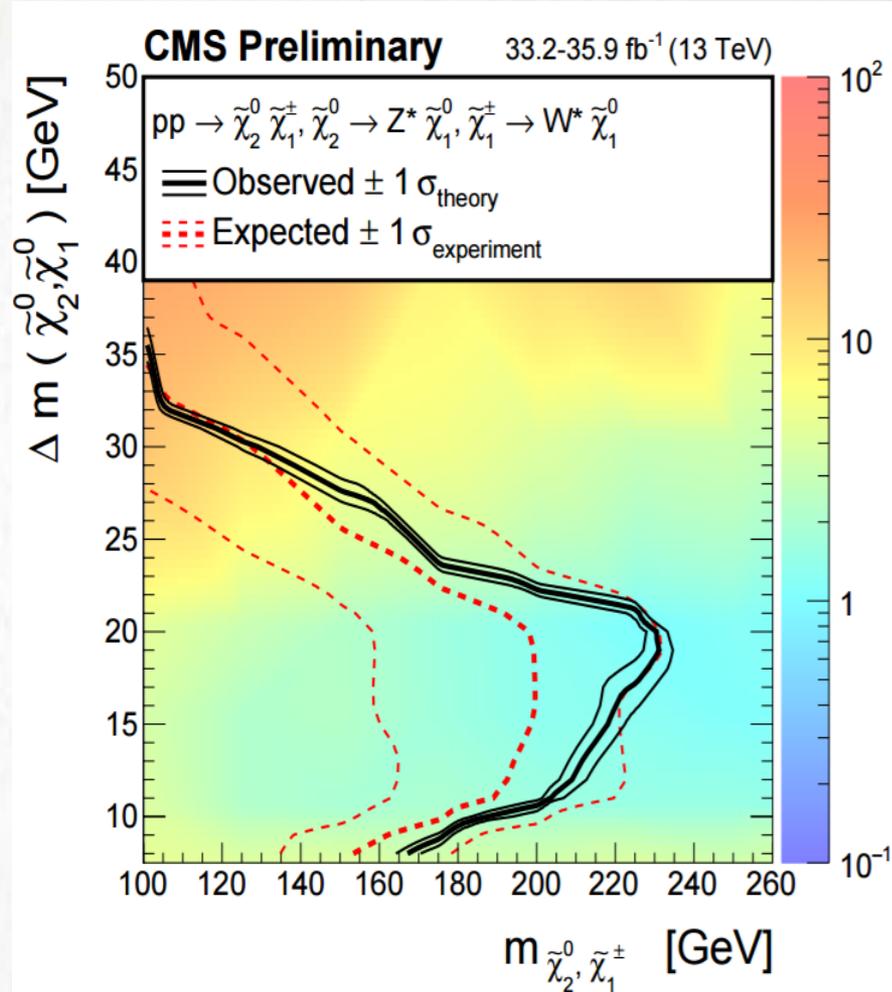
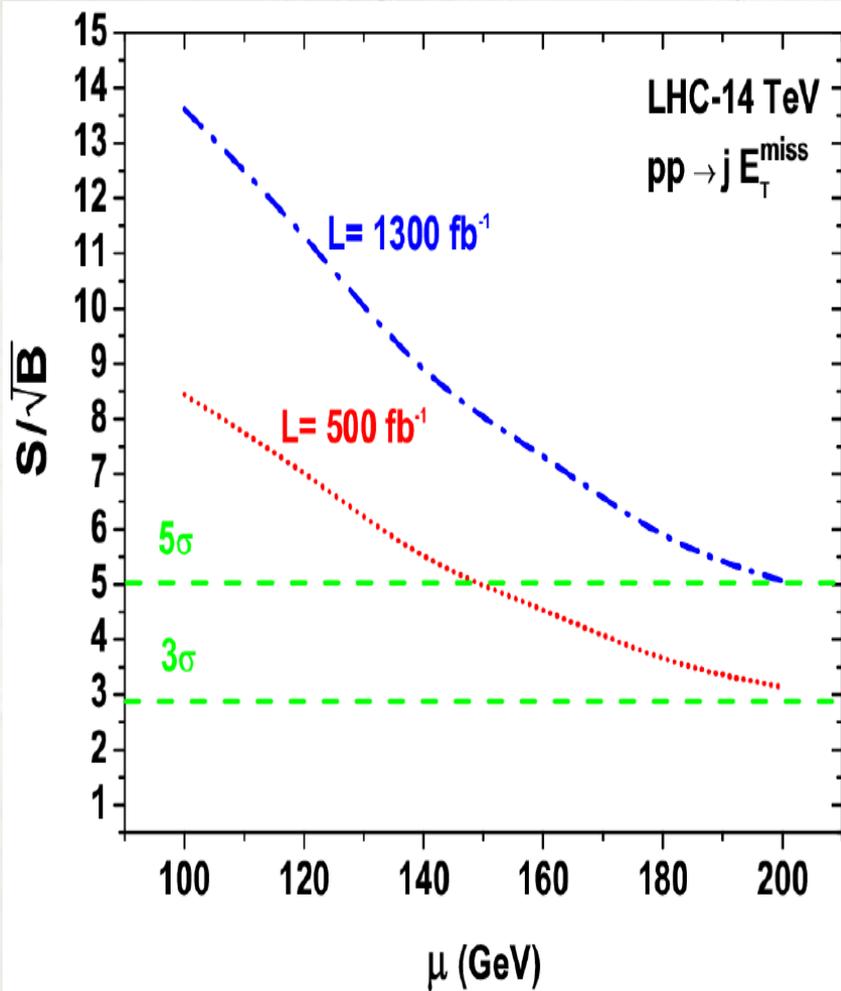
$$\simeq 0.$$



- $pp \rightarrow Z(\rightarrow \nu\bar{\nu}) + j$ , which is the main irreducible background with the same topology as our signals;
- $pp \rightarrow W(\rightarrow \ell\nu) + j$ , this process fakes the signal only when the charged lepton is outside the acceptance of the detector or close to the jet;
- $pp \rightarrow W(\rightarrow \tau\nu) + j$ , this process may fake the signal since a secondary jet from hadronic tau decays tend to localize on the side of  $\cancel{E}_T$ ;
- $pp \rightarrow t\bar{t}$ , this process may resemble the signal, but also contains extra jets and leptons. This allows to highly suppress  $t\bar{t}$  background by applying a b-jet, lepton and light jet veto.

cut	$Z(\nu\bar{\nu}) + j$	$W(\ell\nu_\ell) + j$	$W(\tau\nu_\tau) + j$	$t\bar{t}$	Signal ( $\mu = 100$ GeV)	Signal ( $\mu = 200$ GeV)
$p_T(j_1) > 500\text{GeV}$	69322	241740	119078	210943	1242	415
$\cancel{E}_T > 500\text{GeV}$	26304	28209	16513	2786	950	335
veto on $p_T(j_2) > 100, p_T(j_3) > 30$	16988	12194	7577	306	602	223
veto on $e, \mu, \tau$	16557	3963	3088	102	597	220
veto on b-jets	16303	3867	3046	56	576	214

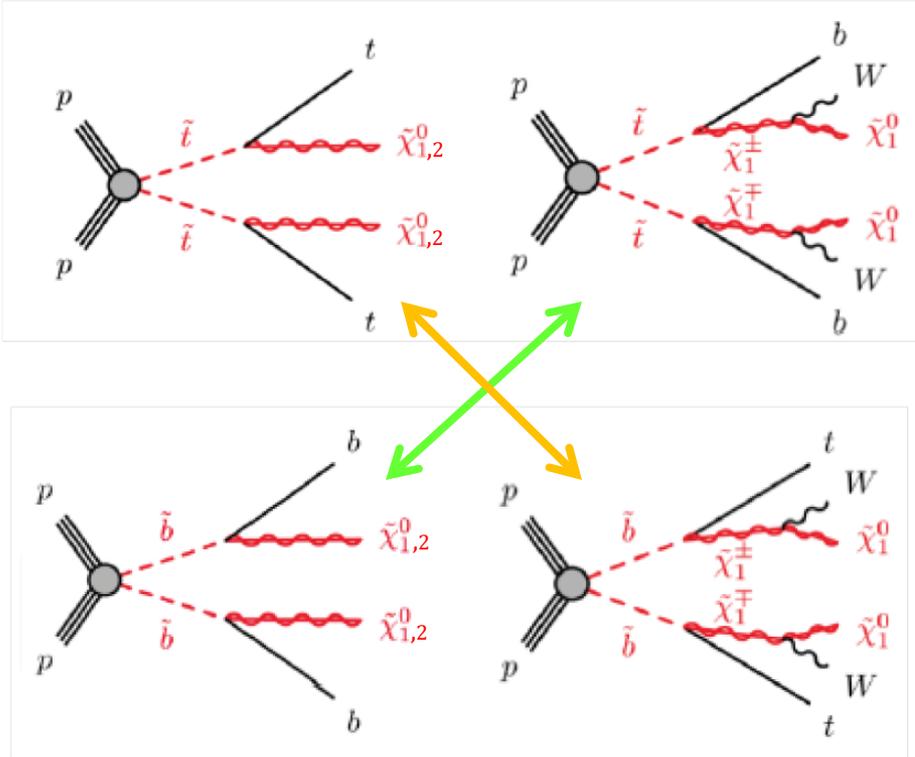
Great Xmas gift from Lesya and Wolfgang, CMS convenor!



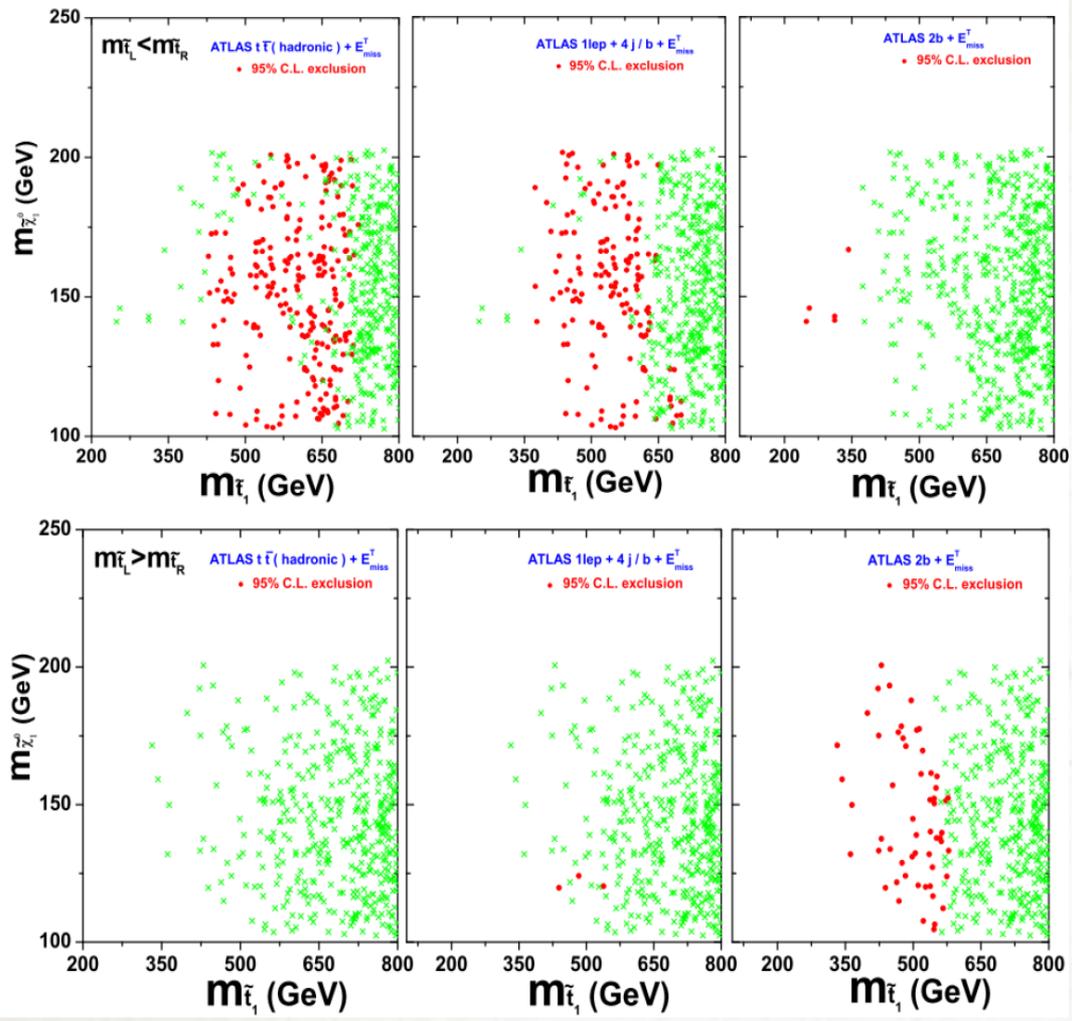
# Stop Pair

Note that: the stop and sbottom pair production will produce the same topologies due to the degenerate Higgsinos  $\tilde{\chi}_{1,2}^0$  and  $\tilde{\chi}_1^\pm$ .  
 (2GeV < Δm < 6GeV)

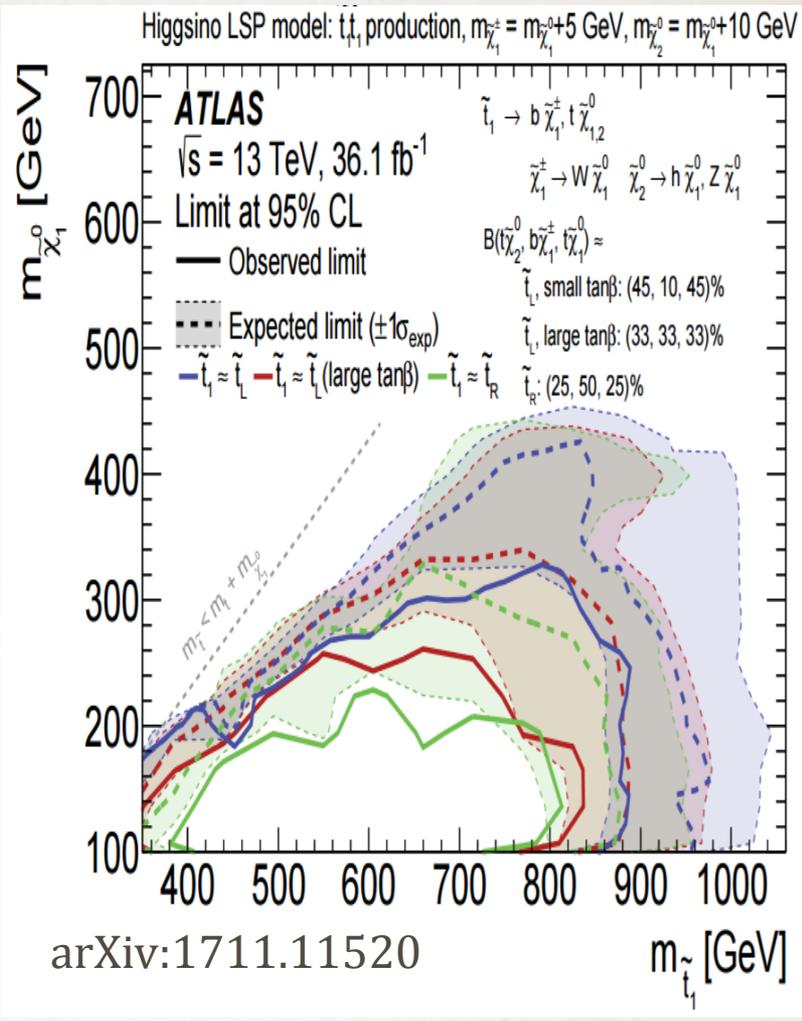
**Left-handed**



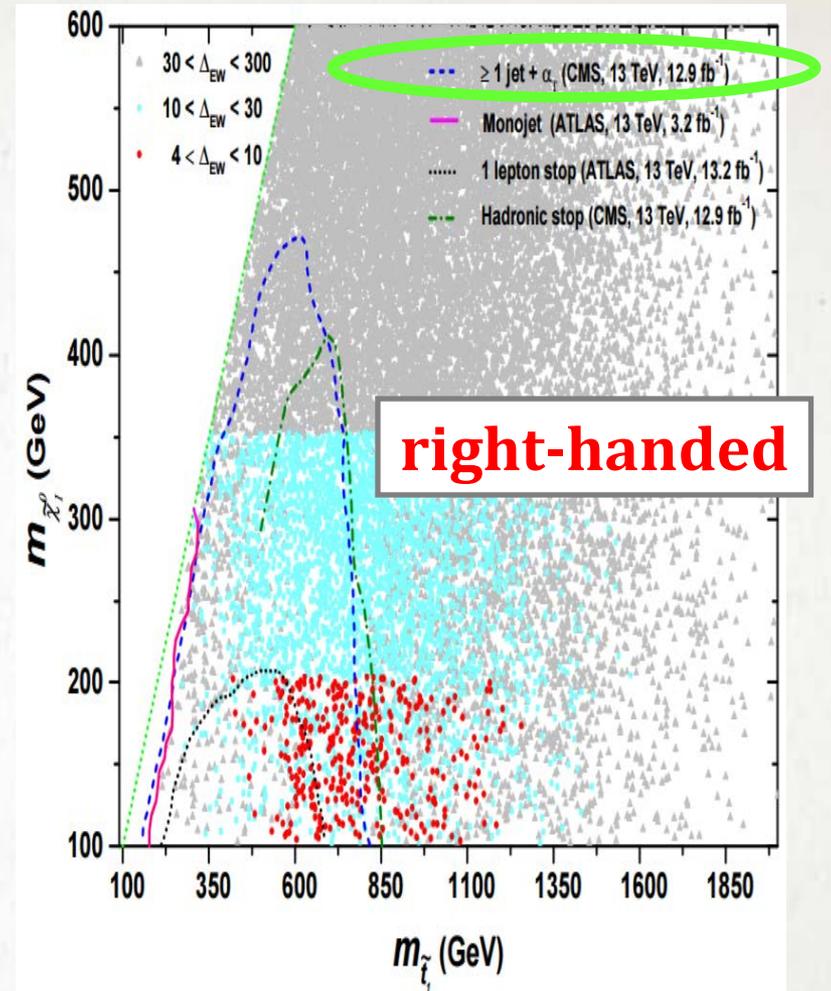
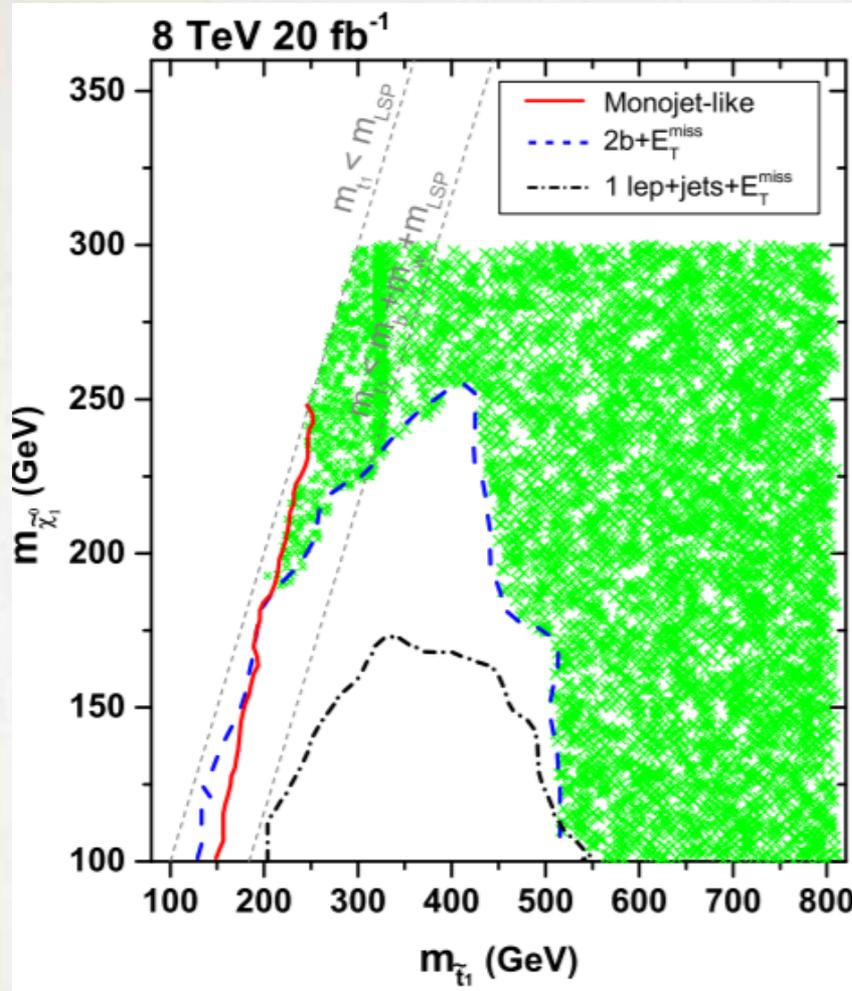
LHC-8TeV, 20 fb-1



I need to complain a little bit, :-)

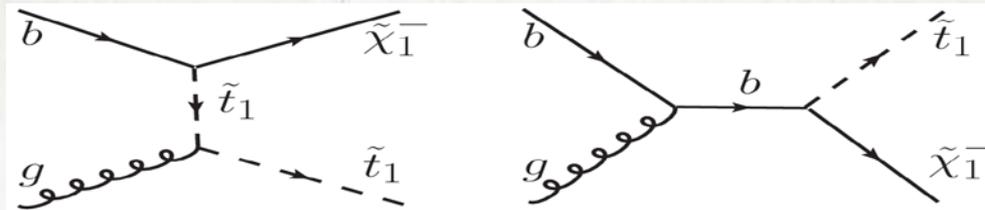


**Left-handed stop is constrained more tightly than right-handed stop!**

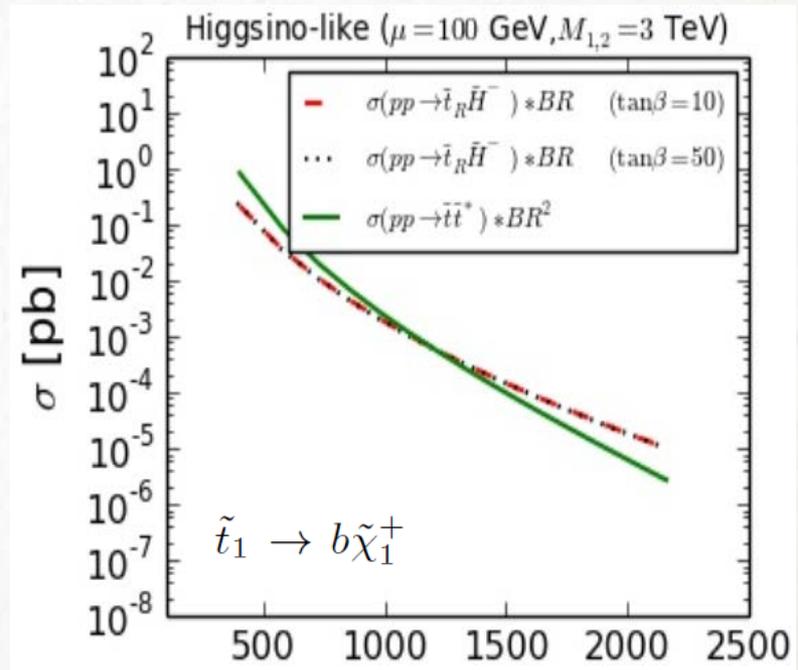
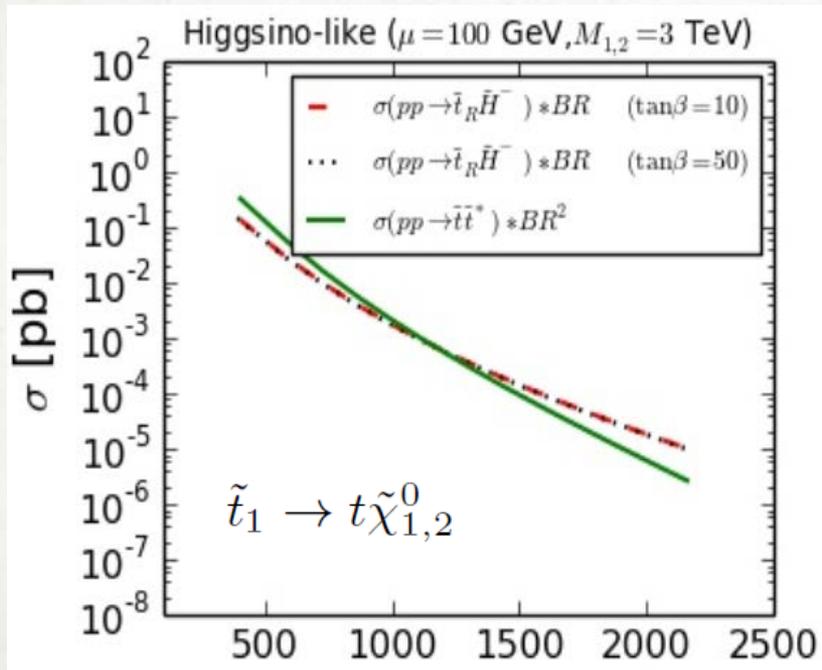


**Inclusive SUSY analysis can give a stronger bound than specific stop searches**

# Mono-stop



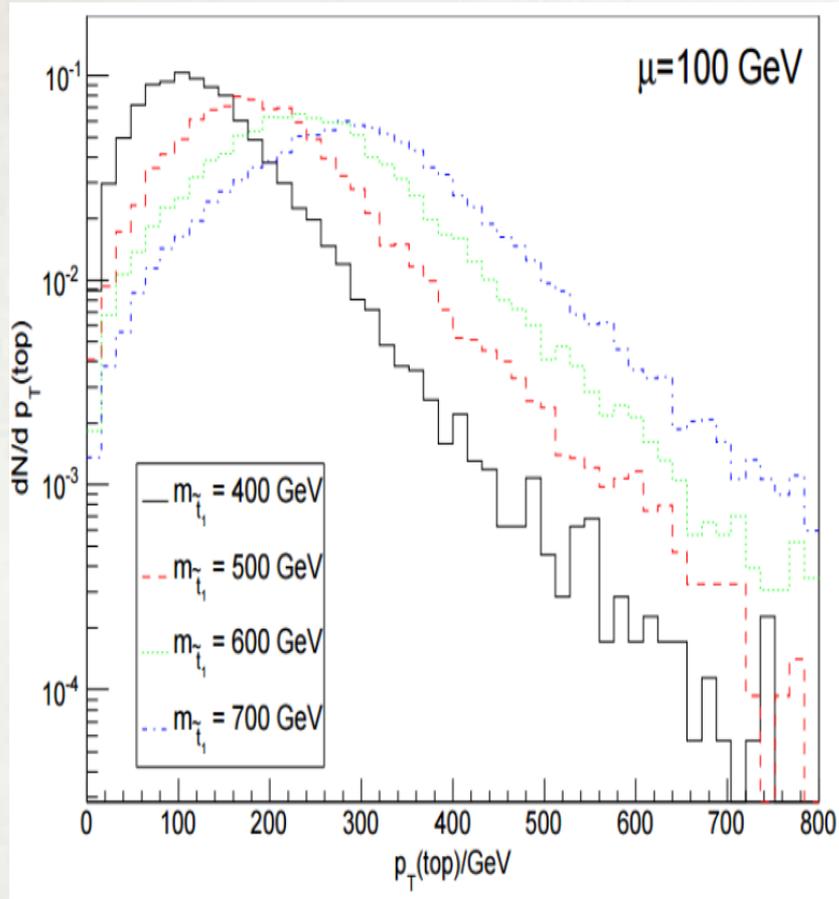
Phys.Rev. D93 (2016) no.3, 035003, [cites 22]



**Its cross section is larger than that of stop pair when stop heavier than about 1.2 TeV**

$$pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^- \rightarrow t \tilde{\chi}_{1,2}^0 \tilde{\chi}_1^- \rightarrow bj\bar{j} + \cancel{E}_T,$$

- The main background is the semi- and full-hadronic  $t\bar{t}$  events, where the missed lepton and the limited jet energy resolution will lead to the relatively large missing transverse energy;
- The processes  $W + \text{jets}$  and  $Z + \text{jets}$  can also fake the signal when one of those light-flavor jets are mis-tagged as a  $b$ -jet;
- The single top and  $t\bar{t} + V$  backgrounds are not considered in our simulations due to their small missing energy or cross sections compared to the above backgrounds.



- Events with any isolated leptons are rejected;
- **Method-1:** We use C-A algorithms in the Fastjet to cluster the jets with  $R = 1.5$  to obtain the top-jet candidates. Each candidate must have the top quark substructure required by the HEPTopTagger. The  $b$ -tagging is also imposed in the top-jet reconstruction. Other energy deposits outside the top-jet are further reconstructed as the normal jets by using anti- $k_t$  algorithm with  $R = 0.4$ ;
- **Method-2:** In normal hadronic top quark reconstruction, a pair of jets is selected with the invariant mass  $m_{jj} > 60$  GeV and the smallest  $\Delta R$ . A third jet closest to this di-jet system is used to constitute the top quark candidate. Among these three jets, at least one  $b$ -jet and  $\Delta\phi(\vec{E}_T, p_T(b_1)) > 1$  is required. The anti- $k_t$  algorithm is used for jet clustering with  $R = 0.4$ ;

- We keep the events with the exact one reconstructed top quark and require  $150 \text{ GeV} < m_t^{\text{rec}} < 200 \text{ GeV}$ ;
- The extra leading jet  $j_1$  outside the reconstructed top quark object is vetoed if  $p_T(j_1) > 30 \text{ GeV}$  and  $|\eta(j_1)| < 2.5$ ;
- We define eight signal regions for each sample according to  $(\cancel{E}_T, p_T(j_{\text{top}}))$  cuts: (200, 100), (250, 150), (300, 200), (350, 250), and  $(p_T(b), \cancel{E}_T)$  cuts: (200, 50), (250, 50), (300, 100), (350, 100) GeV.

**Table 2:** The cross sections of  $V + \text{jets}$ ,  $t\bar{t}$  and  $\tilde{t}_1(\rightarrow t\tilde{\chi}_{1,2}^0)\tilde{\chi}_1^-$  for a benchmark point  $(m_{\tilde{t}_1}, \mu) = (611, 100) \text{ GeV}$  and  $\tan\beta = 10$  in Method-1 and Method-2 at 14 TeV LHC with  $\mathcal{L} = 3000 \text{ fb}^{-1}$ . The cross sections are in unit of fb.

cuts	$W + \text{jets}$	$Z + \text{jets}$	$t\bar{t}$	$S$	$S/B$	$S/\sqrt{B}$
Method-1	$< 10^{-2}$	0.29	1.90	0.13	6.0%	4.9
Method-2	$< 10^{-2}$	0.59	0.74	0.044	3.4%	2.1

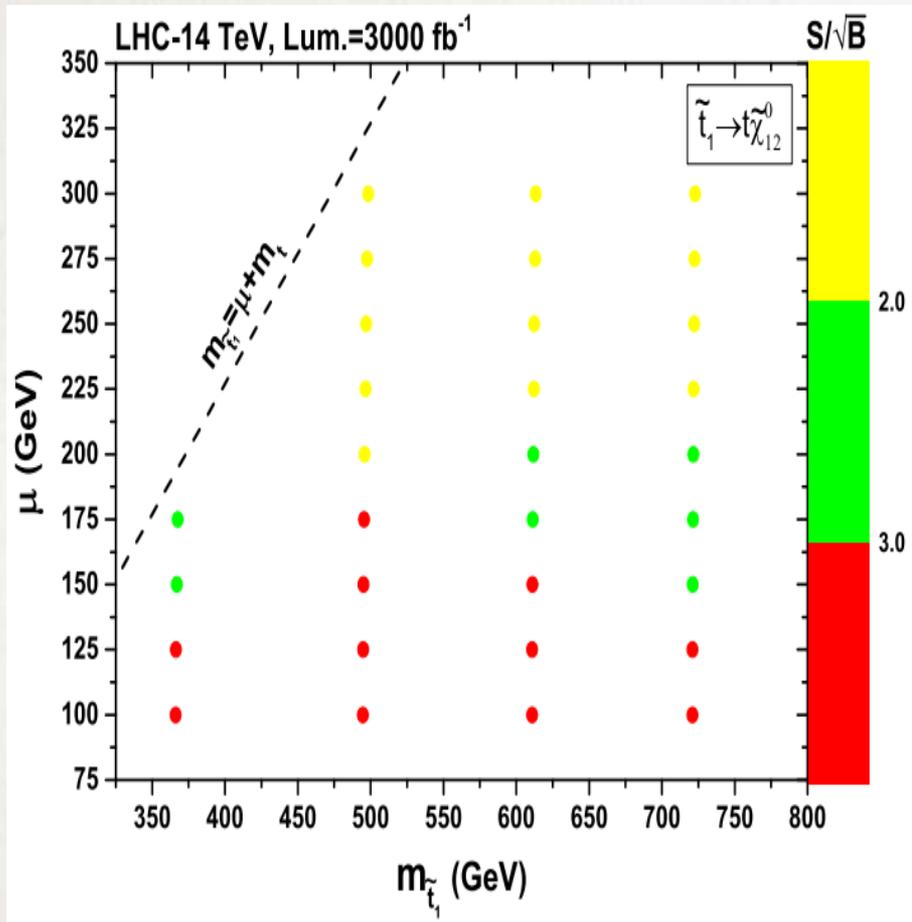
$$pp \rightarrow \tilde{t}_1 \tilde{\chi}_1^- \rightarrow b \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow b + \cancel{E}_T$$

- The main background is the processes  $W + \text{jets}$  and  $Z + \text{jets}$  when the light-flavor jets are mis-identified as  $b$ -jets;
- The  $t\bar{t}$  events become the sub-leading backgrounds due to their large multiplicity.

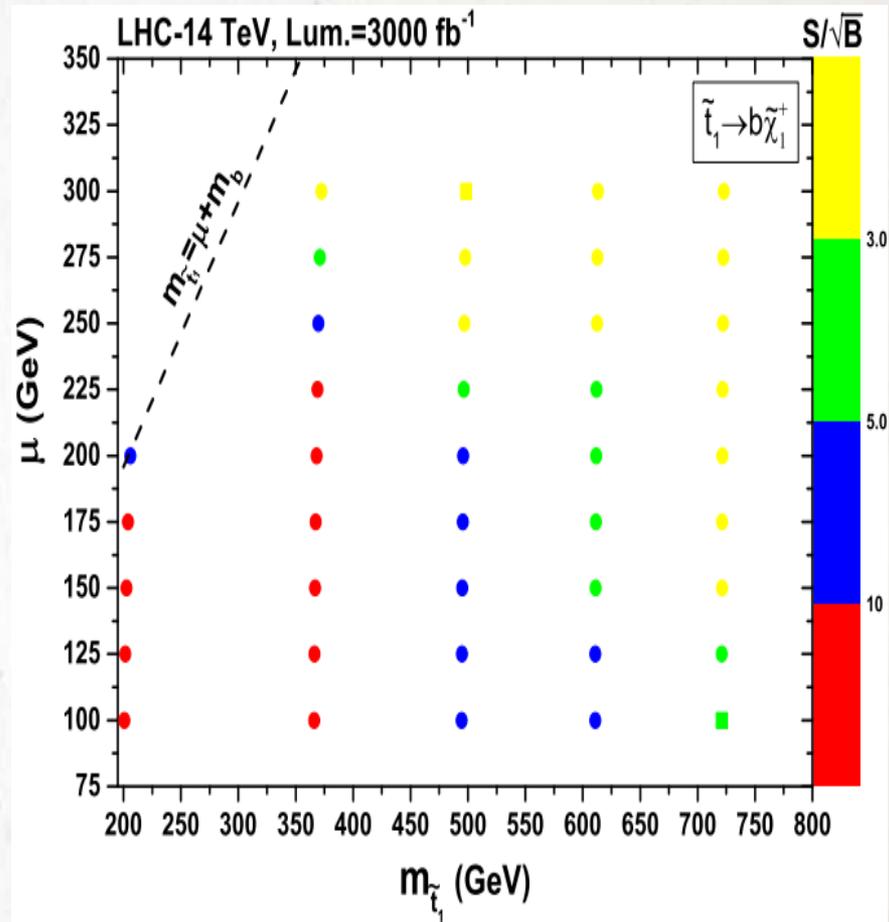
The signal events are selected to satisfy the following criteria:

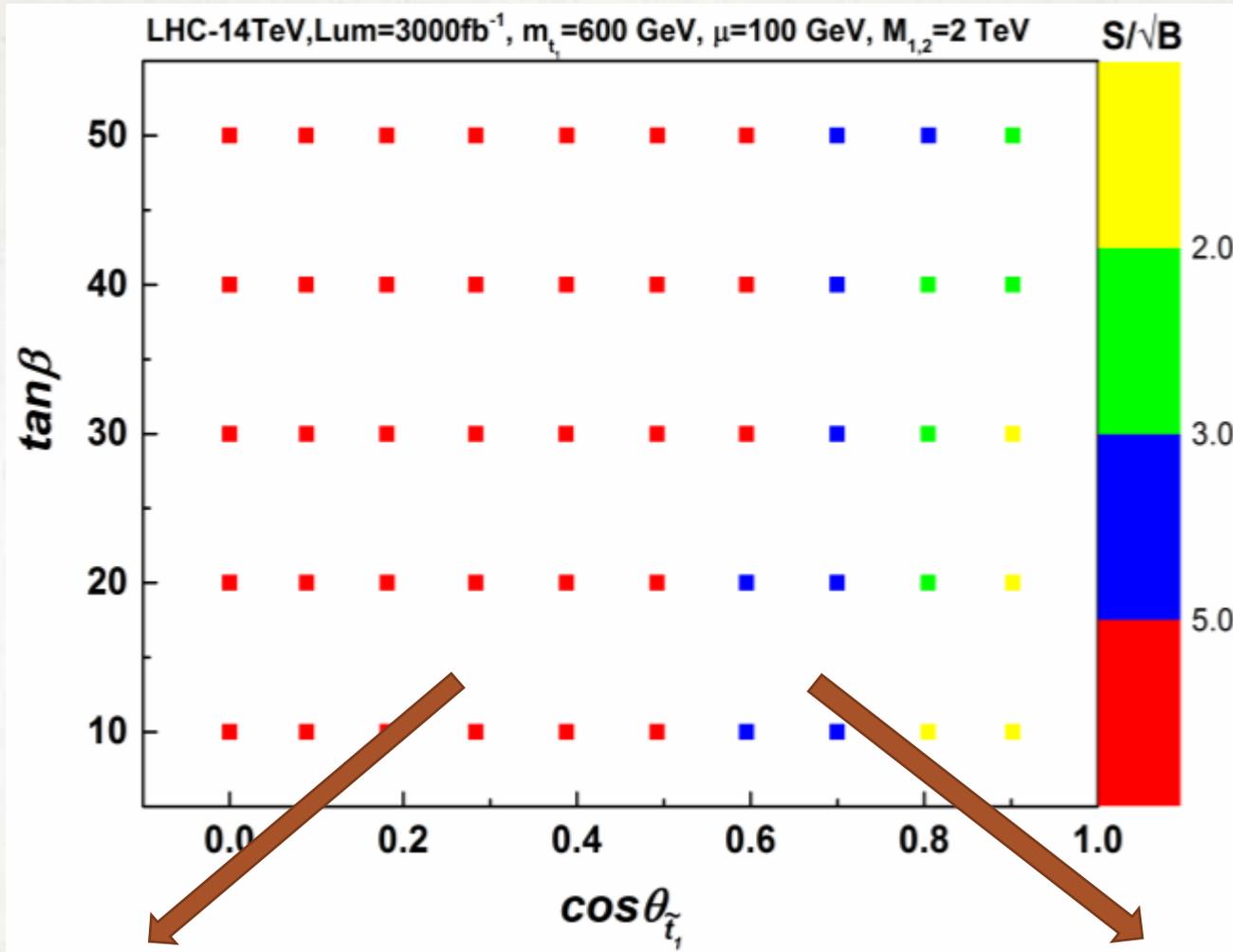
- Events with any isolated leptons are rejected;
- Exact one hard  $b$ -jet in the final states, but allow an additional softer jet with  $p_T(j_1) < 30 \text{ GeV}$  and  $\Delta\phi(\cancel{E}_T, p_T(j_1)) > 2$ .
- Since the hardness of  $b$ -jet from stop decay depends on the mass splitting between  $\tilde{t}_1$  and  $\tilde{\chi}_1^-$ , we define four signal regions for each sample according to  $(\cancel{E}_T, p_T(b))$  cuts: (30, 20), (70, 40), (150, 100) and (250, 200) GeV.

### Mono-top



### Mono-b





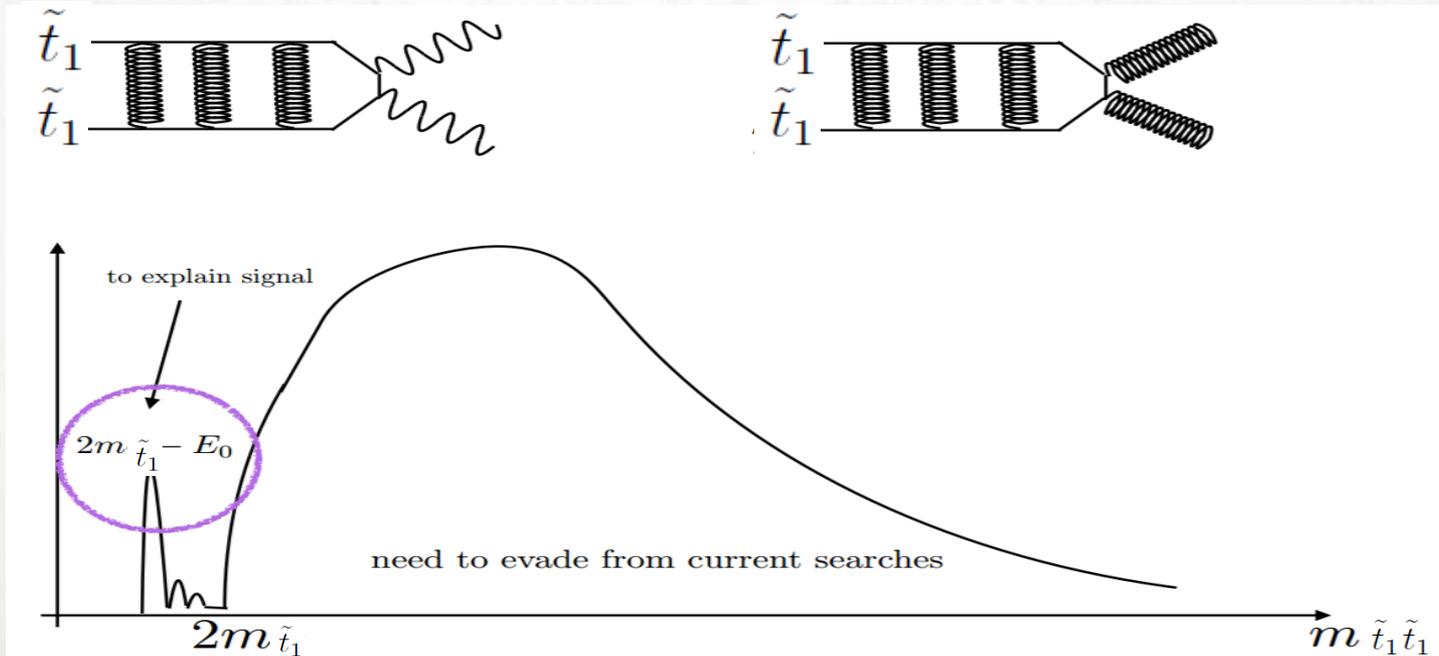
right-handed like

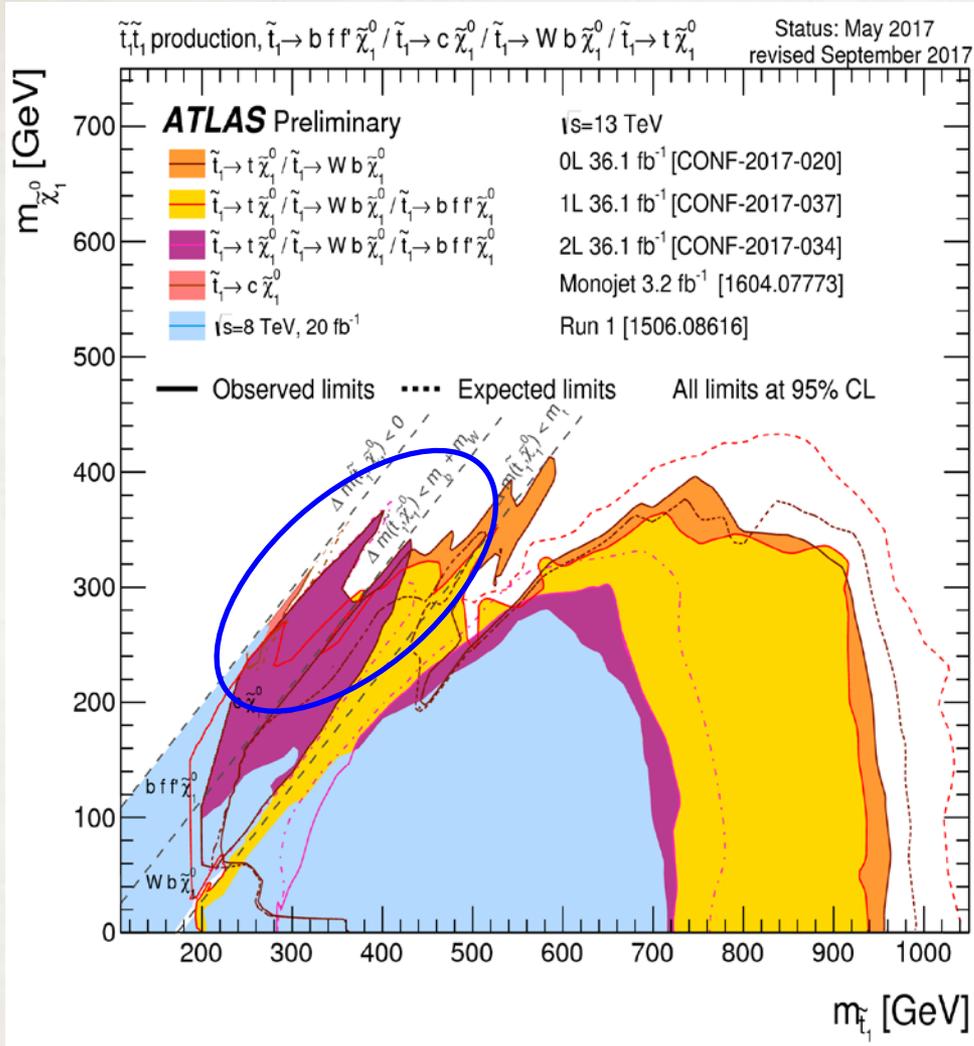
left-handed like

# Stoponium

When two-body decay of stop are forbidden, the stops can form bound state near the threshold, if:

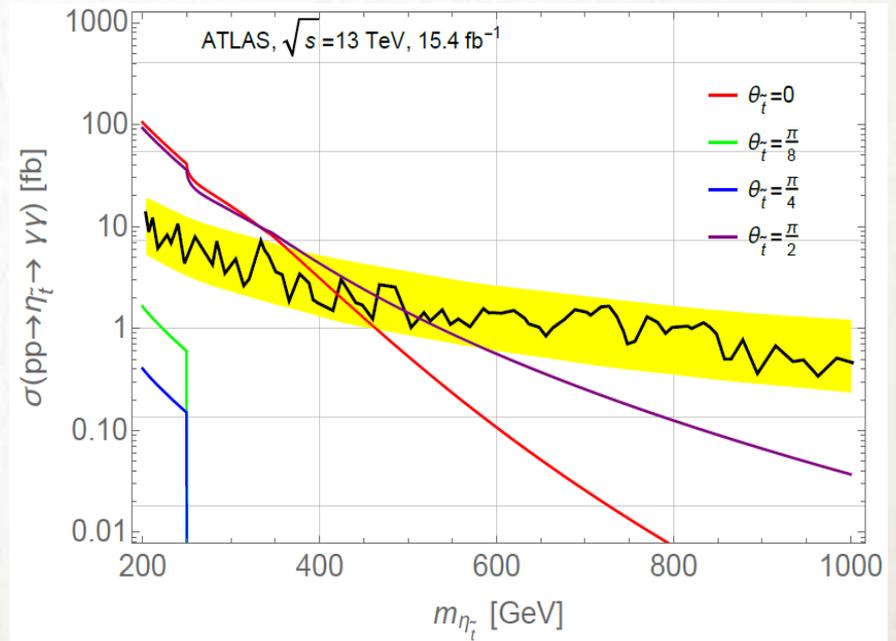
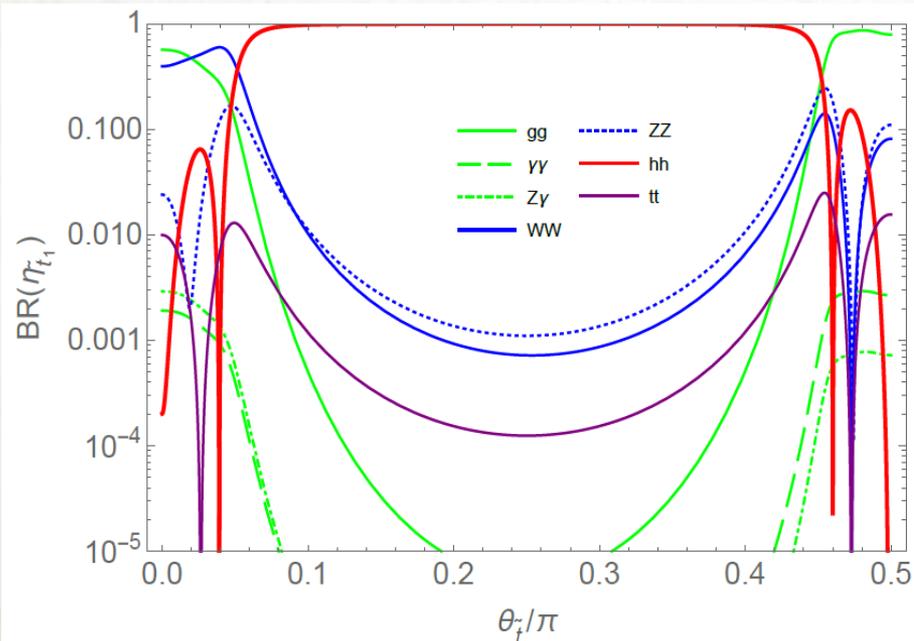
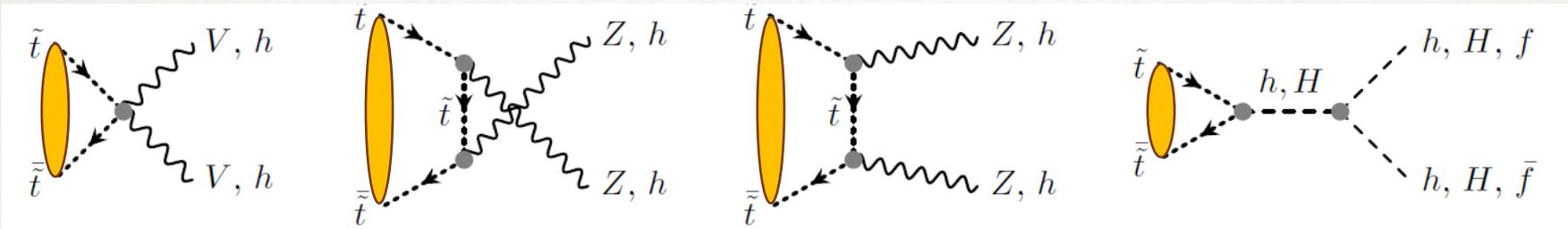
$$\Gamma_{\tilde{t}_1} \lesssim E_b = \frac{C^2 \bar{\alpha}_S^2 m_{\tilde{t}}}{4} (\sim 1 \text{ GeV})$$





In contrast to the existing direct stop pair searches, stononium if formed, will resonantly decay to a pair of the SM particles and can be independent of the assumptions of the LSP mass and the branching ratios of the stop. Therefore, the search of stononium can provide a complementary probe to the direct stop pair production at the LHC.

$$\sigma_{\text{LO}}(pp \rightarrow \eta_{\tilde{t}}) = \frac{\pi^2}{8m_{\eta_{\tilde{t}}}^3} \Gamma(\eta_{\tilde{t}} \rightarrow gg) \mathcal{P}_{gg}(\tau),$$



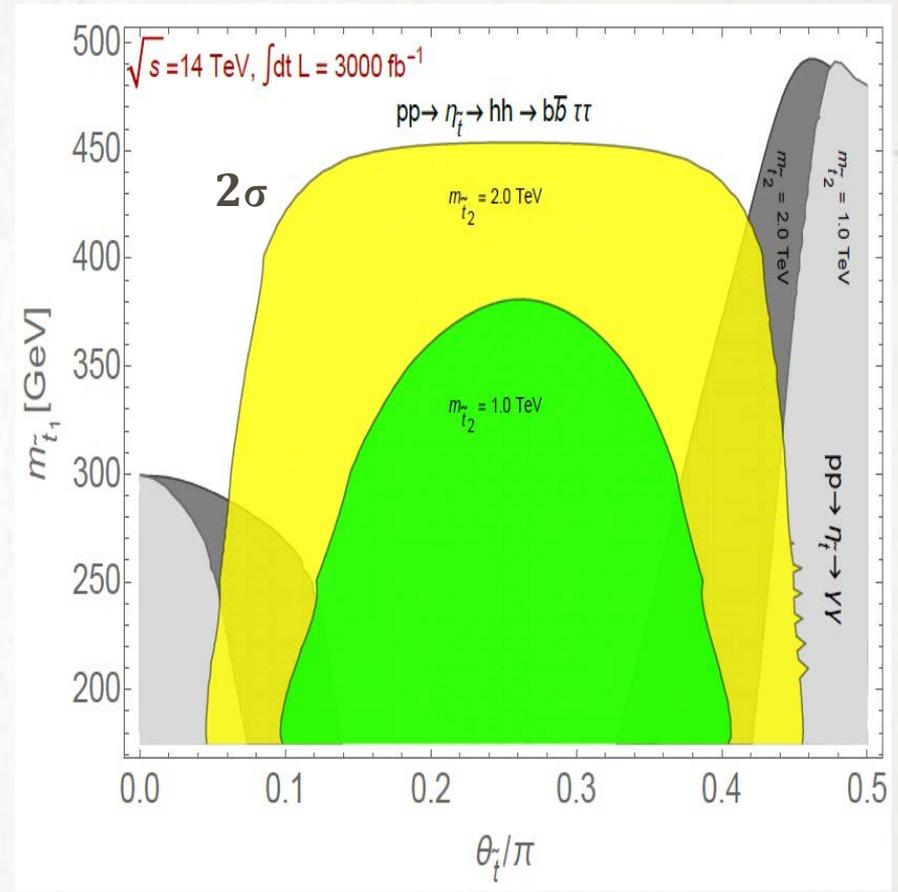
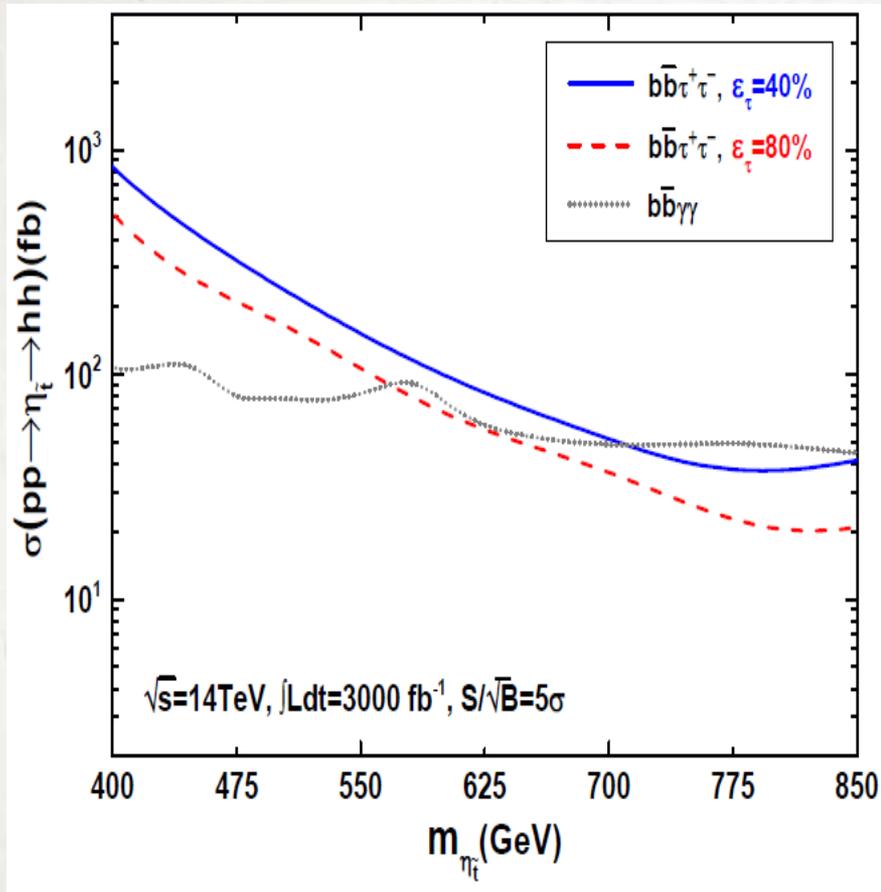
$$pp \rightarrow \eta_{\tilde{t}} \rightarrow hh \rightarrow b\bar{b}\tau^+\tau^-$$

- We require exactly one lepton ( $e$  or  $\mu$ ) with  $p_T(\ell) > 26$  GeV,  $|\eta_e| < 2.47$  or  $|\eta_\mu| < 2.5$ . We further require the presence of a hadronically decayed tau  $\tau_h$  carrying opposite electric charge with  $p_T(\tau_h) > 20$  GeV and  $|\eta_{\tau_h}| < 2.5$ .
- We require at least two jets with  $p_T(j) > 30$  GeV and  $|\eta_j| < 2.5$  and two of them are b tagged.
- We require  $80 \text{ GeV} < m_{bb} < 150 \text{ GeV}$ ,  $80 \text{ GeV} < m_{\tau\tau} < 150 \text{ GeV}$ ,  $m_T^{\ell\nu} < 50 \text{ GeV}$ ,  $p_T^{\tau\tau} > 120 \text{ GeV}$  and  $|m_{bb\tau\tau} - m_{\eta_{\tilde{t}}}| < 0.08m_{\eta_{\tilde{t}}}$ .

**Table 1:** Cut flow analysis of the cross sections (fb) for the signal and backgrounds at 14 TeV LHC. The benchmark point is chosen as  $m_{\eta_{\tilde{t}}} = 500$  GeV and  $\sigma(gg \rightarrow \eta_{\tilde{t}} \rightarrow hh) = 1$  pb.

Cuts	$m_{bb}$ $\in [80, 150] \text{ GeV}$	$m_{\tau\tau}$ $\in [80, 150] \text{ GeV}$	$m_T^{\ell\nu}$ $< 50 \text{ GeV}$	$p_T^{\tau\tau}$ $> 120 \text{ GeV}$	$ m_{bb\tau\tau} - m_{\eta_{\tilde{t}}} $ $< 0.08m_{\eta_{\tilde{t}}}$
$t\bar{t}$	445.48	128.79	55.32	12.46	0.29
$Z(\tau\tau)bb$	7.40	5.35	4.70	0.62	$< 0.02$
$Z(\tau\tau)jj$	11.87	7.92	7.04	1.62	0.13
signal( $m_{\eta_{\tilde{t}}} = 500 \text{ GeV}$ )	1.55	0.82	0.64	0.54	0.25

$$pp \rightarrow \eta_t \rightarrow hh$$



A close-up photograph of a baby with light brown hair and blue eyes, looking slightly to the right with a pouting expression. The baby is wearing a green and white long-sleeved shirt and is holding a small amount of sand in their right hand. The background is a blurred beach scene with sand and the ocean.

*Conclusions*

**Keep Your Faith:**

**“Naturalness  
&  
Supersymmetry”**

**Wait for LHC Run-3 !**

*Thanks for your attention!*