# Stop Searches in the Compressed Region

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w/ Christina Gao, Lingfeng Li, Nicolas Neill, arXiv:1604.00007
and Lingfeng Li, Qin Qin, arXiv:1607.06547

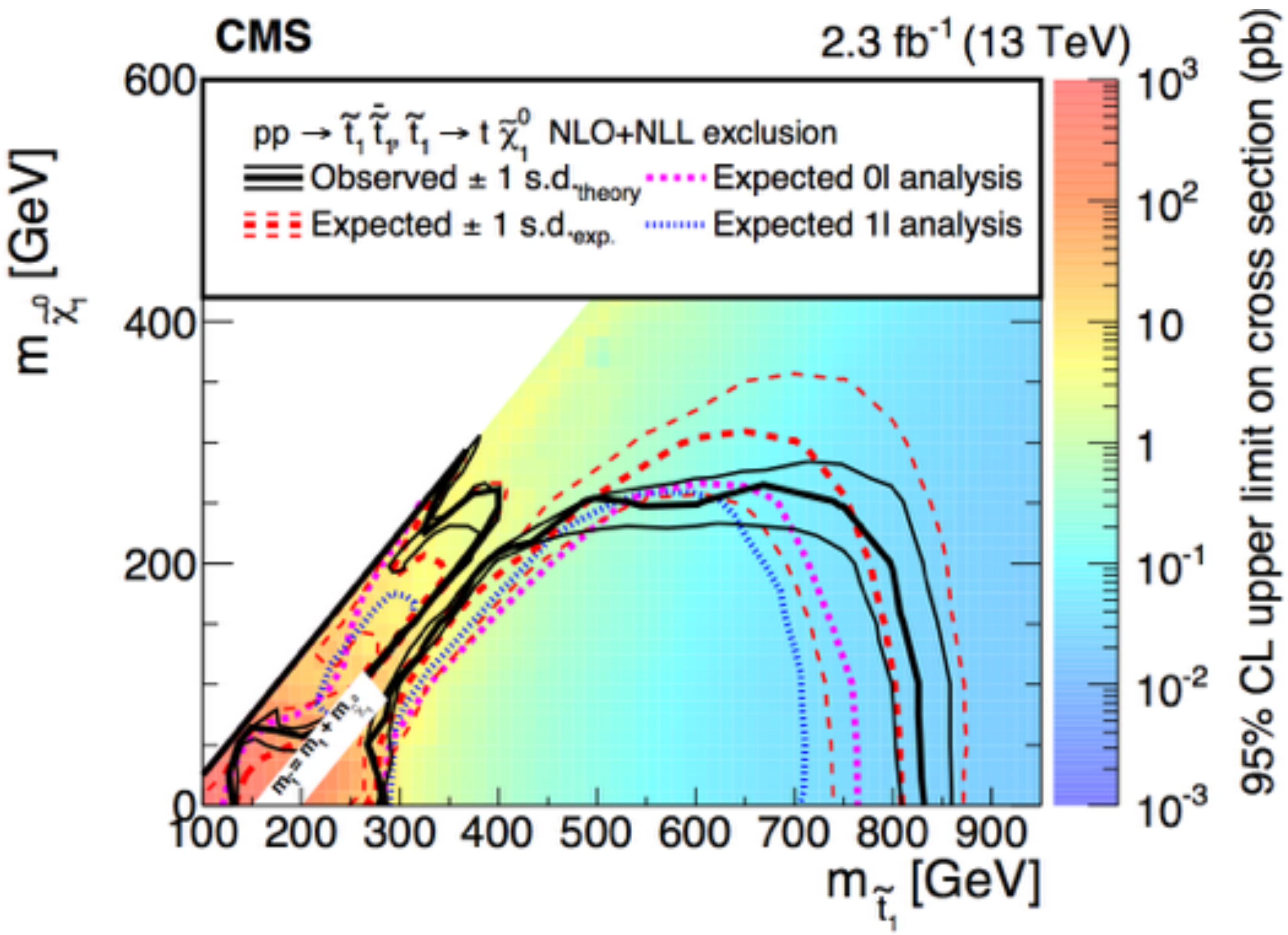
4th International Workshop on
Dark Matter, Dark Energy, and Matter-Antimatter Asymmetry
Dec. 29-31, 2016

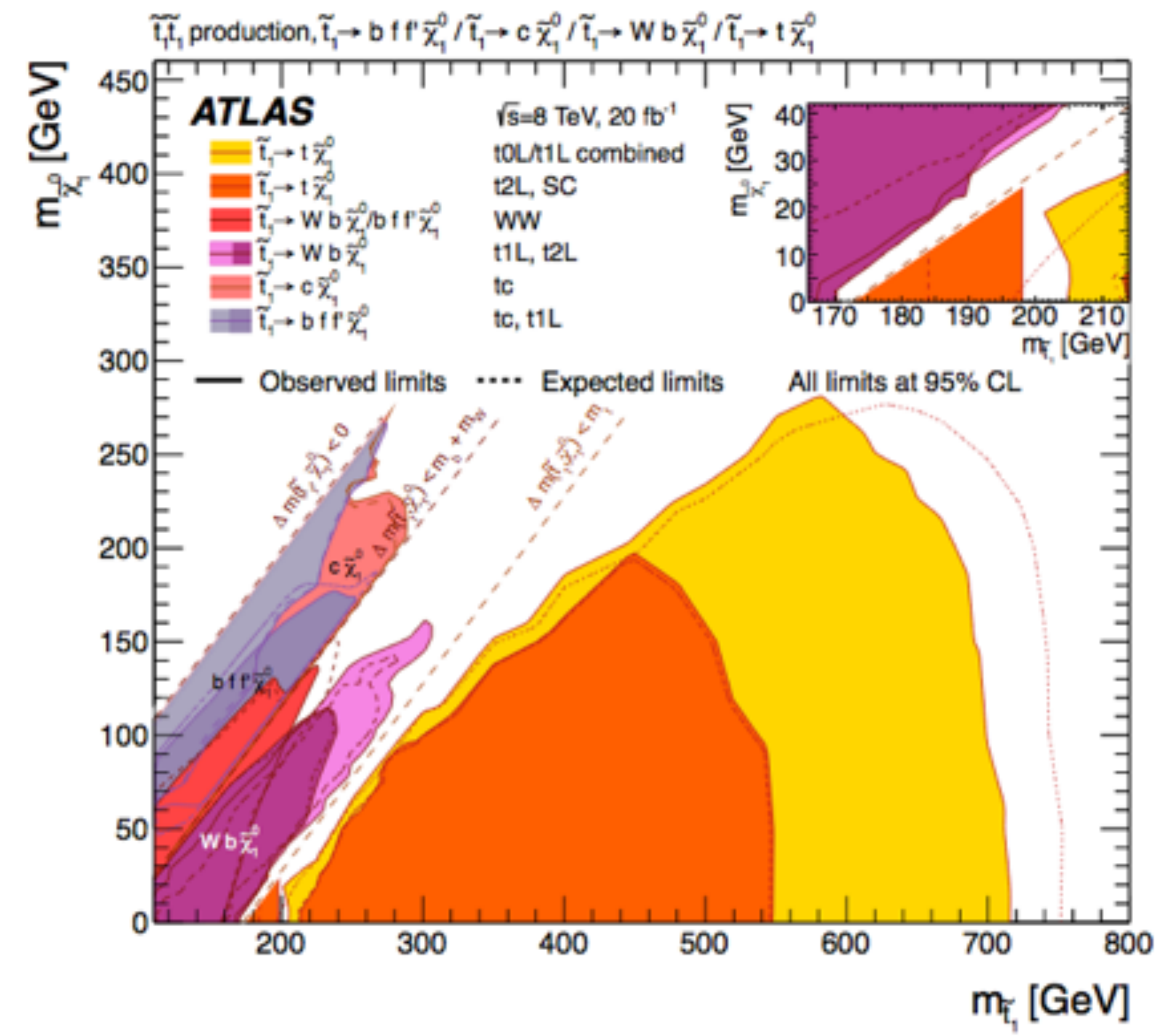
# Introduction

- Supersymmetry (SUSY) is one of the most promising candidates for new physics beyond the standard model.
  - Solution to the hierarchy problem.
  - Lightest SUSY particle is a dark matter candidate if R-parity is conserved.
  - Gauge coupling unification.
  - Consistent with a light Higgs.

# Stop Searches

- Stop may be the most hunted particle after the Higgs discovery for the hierarchy problem



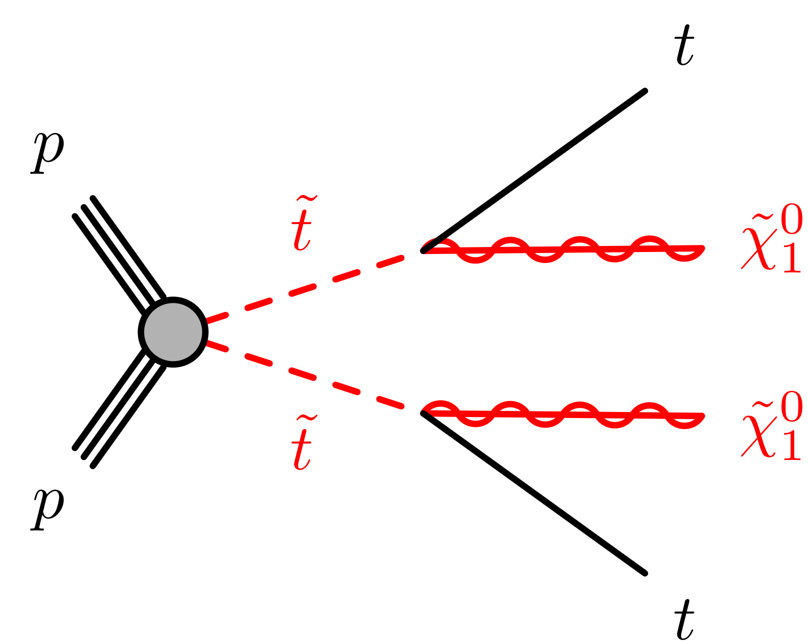




- Stop heavier than 800 GeV would imply fine-tuning worse than 10%.

# Stop in the Compressed Region

- Constraints are weak for $m_{\tilde{t}_1} \approx m_t + m_{\tilde{\chi}_1^0}$

$t$, $\tilde{\chi}_1^0$ are static in the stop rest frame, so they move together in the lab frame, with $\frac{p_{\tilde{\chi}}}{p_{\tilde{t}}} \approx \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}}$

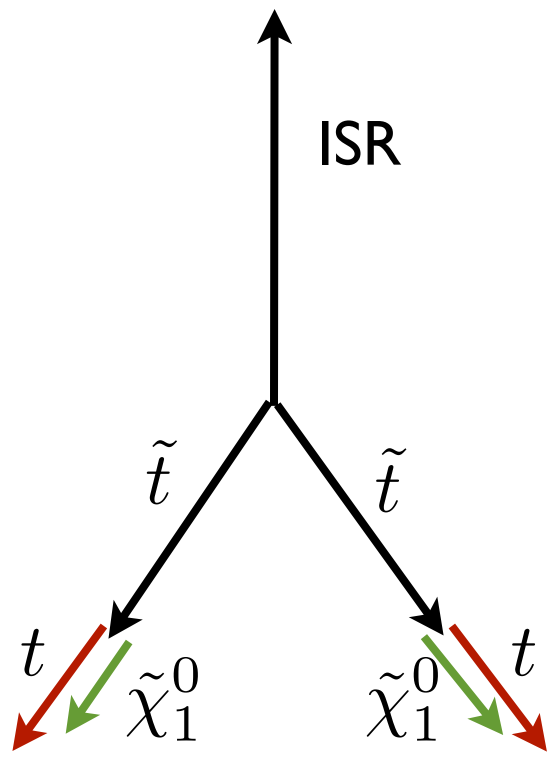



For direct pair-production, stops are back-to-back in the transverse plane. The $p_T$ of the two $\tilde{\chi}_1^0$'s cancel, leaving little MET. It just looks like top pair production.

# Recoiling against a Hard Jet

K. Hagiwara & T. Yamada, 1307.1553
H. An & L.-T. Wang, 1506.00653
S. Macaluso, M. Park, D. Shih, B. Tweedie, 1506.07885

- Some MET will arise if the stop pair are produced with a hard ISR jet.




$$p_{T\tilde{t}}(1) + p_{T\tilde{t}}(2) = -p_T(J_{\rm ISR})$$

$$p_{T\tilde{\chi}}(1) + p_{T\tilde{\chi}}(2) \approx \left(p_{T\tilde{t}}(1) + p_{T\tilde{t}}(2)\right)\frac{m_{\tilde{\chi}}}{m_{\tilde{t}}}$$

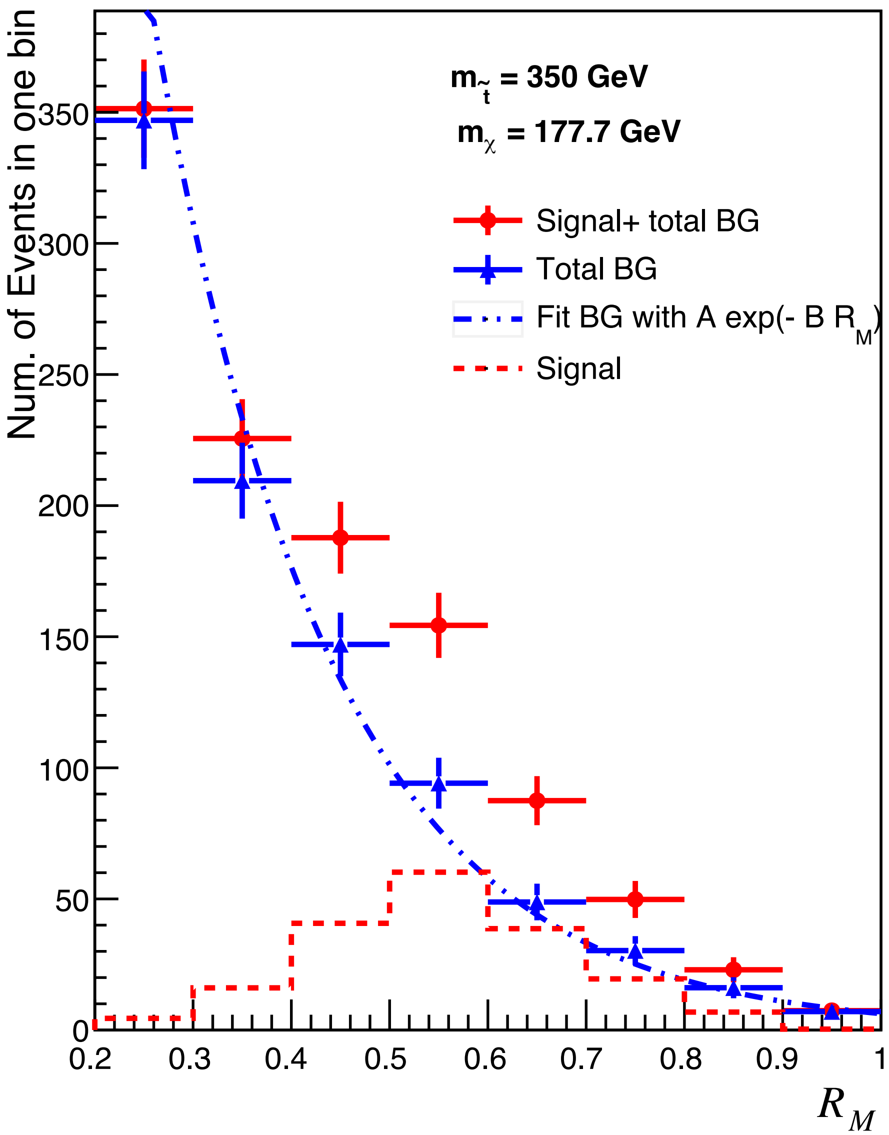
# All Hadronic Channel

- Select events with all hadronic decaying tops, with MET antiparallel to ISR on the transverse plane.

$$R_M \equiv \frac{\not{p}_T}{p_T(J_{\rm ISR})}$$

$$R_M \approx \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}} \quad \text{for signal}$$

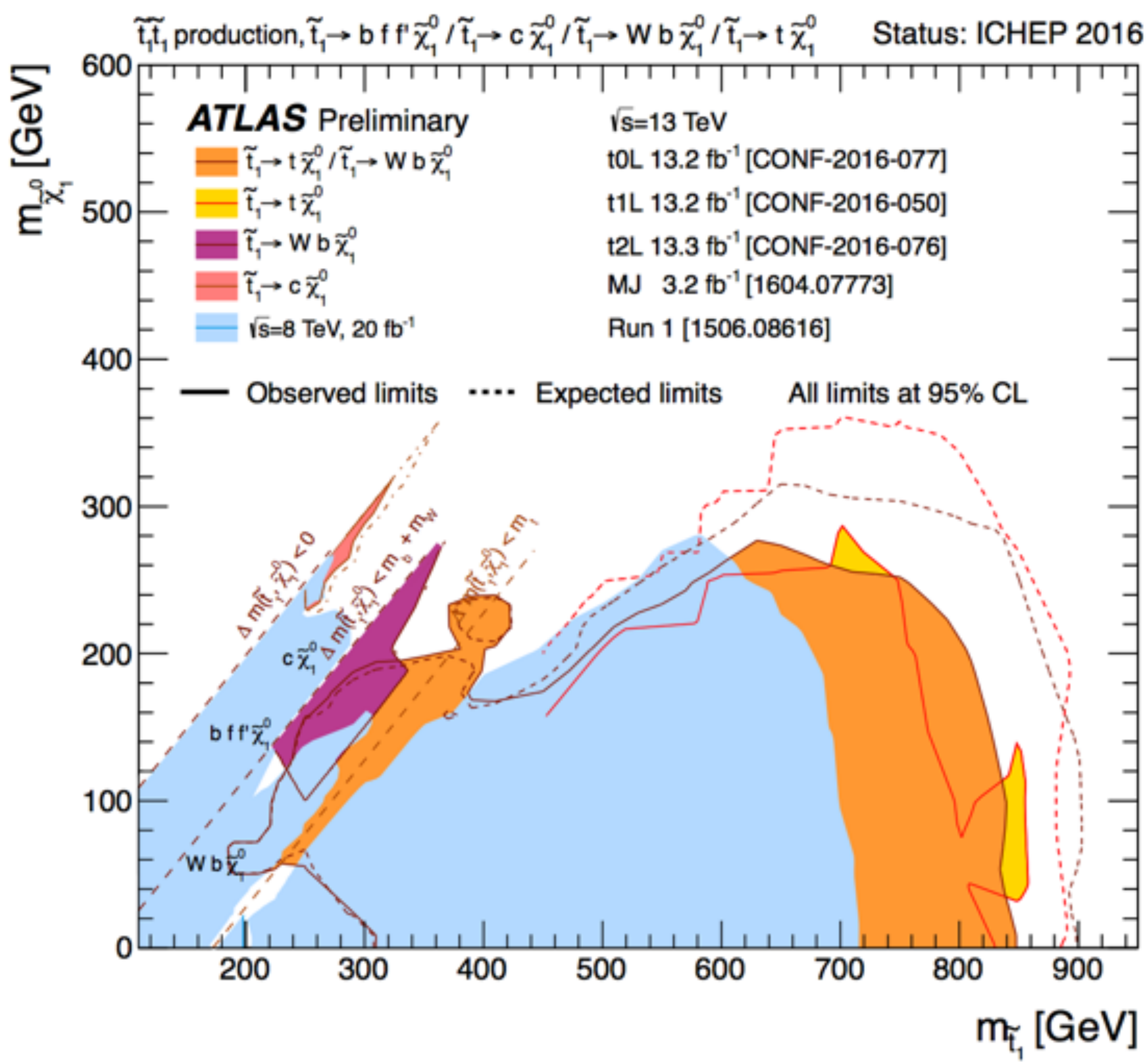
$$R_M \approx 0 \quad \text{for } t\bar{t} \text{ background}$$




H. An & L.-T. Wang, 1506.00653

# All Hadronic Channel

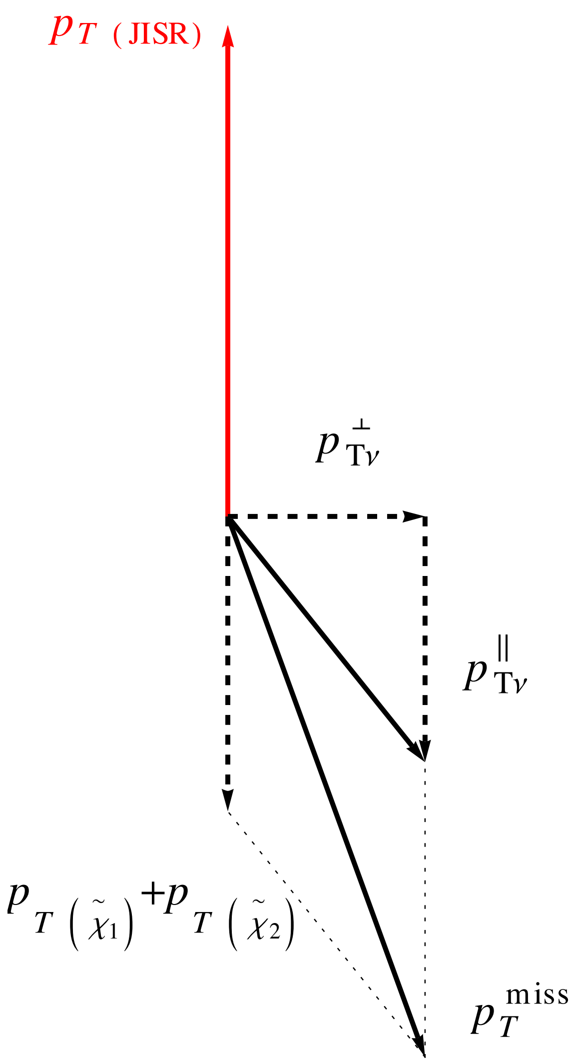
- ATLAS applied this method in Run 2 analysis.



# Semileptonic Channel

HC, Christina Gao, Lingfeng Li, Nicolas Neill, arXiv:1604.00007

- The neutrino from the top decay gives extra MET, but its momentum can be solved.




$$\not{p}^{\parallel}_T \left[= p^{\parallel}_{T\nu} + p^{\parallel}_{T\tilde{\chi}}(1) + p^{\parallel}_{T\tilde{\chi}}(2)\right] \parallel p_T(J_{\text{ISR}})$$

$\not{p}^{\perp}_T = p^{\perp}_{T\nu}$ + 3 mass shell conditions:

$$p_\nu^2 = 0,$$
$$(p_\ell^2 + p_\nu)^2 = m_W^2,$$
$$(p_b + p_\ell + p_\nu)^2 = m_t^2.$$

Can be reduced to a single quadratic equation for $E_\nu$.

After obtaining $p_{T\nu}$, we subtract it from $\not{p}_T$, and define

$$\bar{R}_M \equiv \frac{\not{p}_T - p_{T\nu}}{p_T(J_{\text{ISR}})} \approx \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}}$$

# A Case Study

$$m_{\tilde{t}} = 400 \text{ GeV}$$

$$m_{\tilde{\chi}^0} = 226.5 \text{ GeV}$$

$$\bar{R}_{M,\text{theory}} \approx 0.57$$

# Signal and Background Simulations

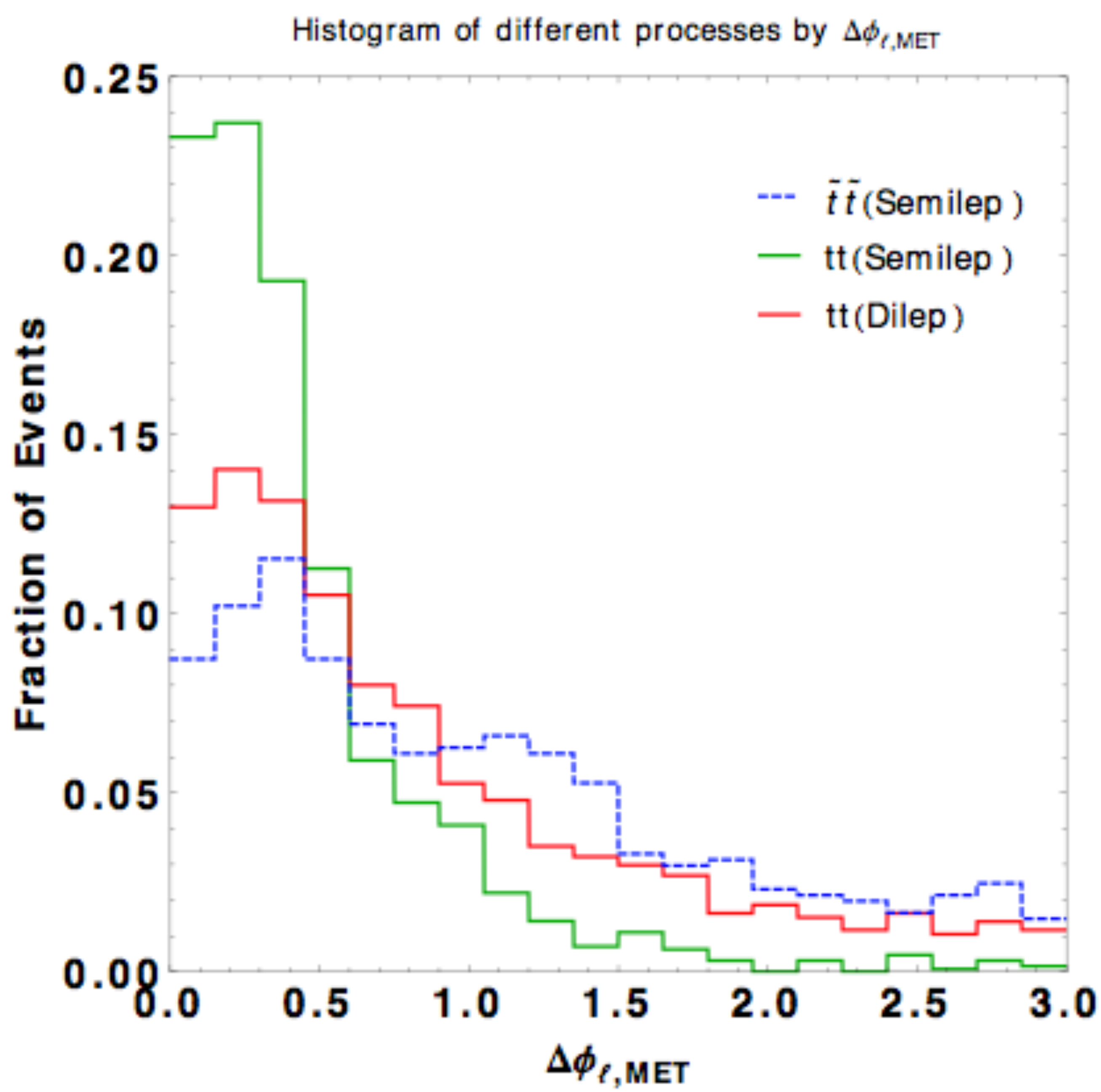
- Signals and backgrounds are simulated with MadGraph 5, Pythia 8 and Delphes 3.
- SM backgrounds:
  - $tt$ (semileptonic)
  - $tt$ (dileptonic)
  - single top production
  - (Multi)-vector bosons with jets
  - $tt$ production with an extra vector boson
- Signal in the compressed region
  - Stop pair (semileptonic)

# Event Selections

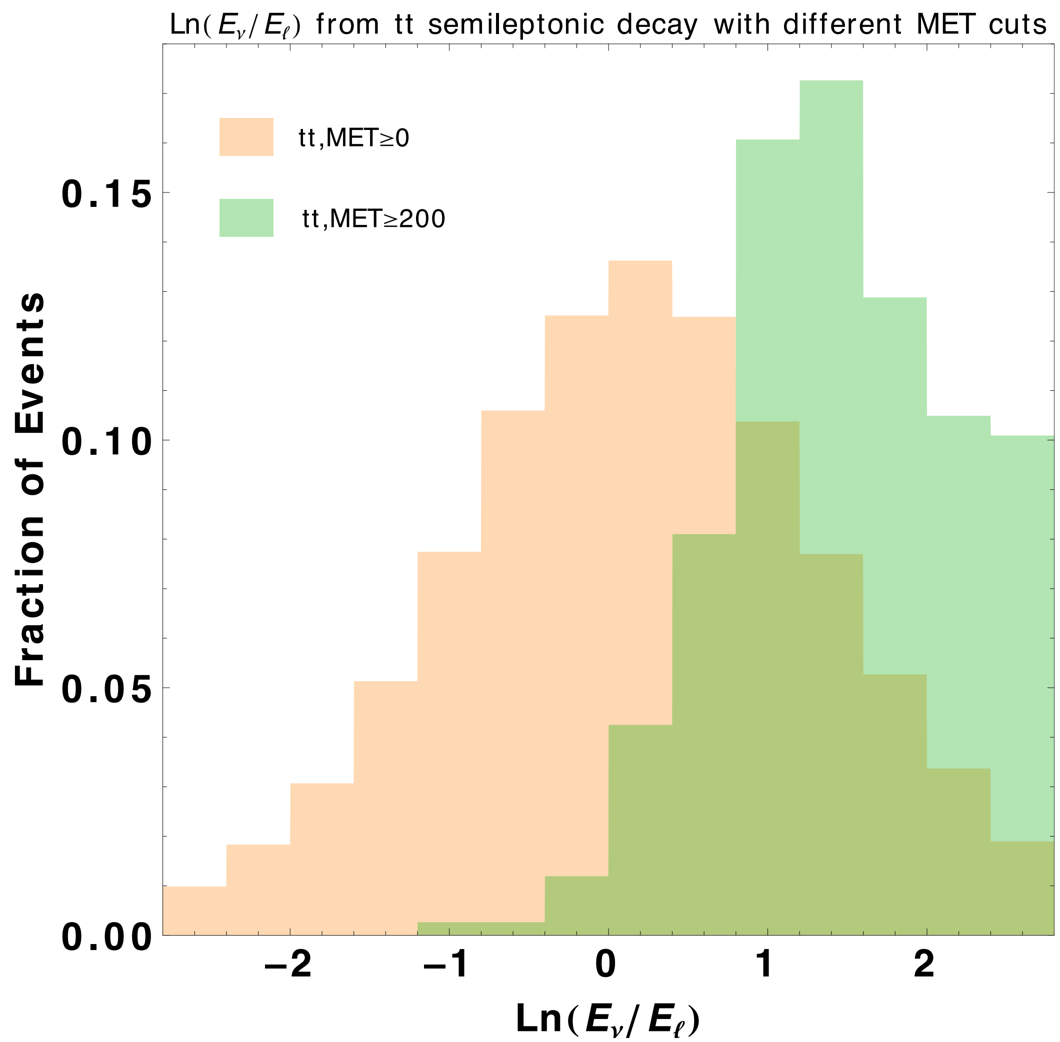
- One isolated lepton, at least 4 jets with one or more $b$ tags. Events with $\tau$ jets are vetoed
- $p_T(J_{\mathrm{ISR}}) \geq 475\mathrm{GeV}$, $p_T(J_{2,3}) \geq 60\mathrm{GeV}$, $p_{Tl} \geq 10$ GeV
- MET > 200 GeV
- $|\phi_{J_{\mathrm{ISR}}} - \phi_{\mathrm{MET}}| \geq 2$
- $|\phi_l - \phi_{\mathrm{MET}}| \geq 0.9$
- Choose the solution with greater $E_\nu$, but with $p_{T\nu} < 180$ GeV, $p_{T\nu} < 6\, p_{Tl}$
- For more than 1 $b$ jets that give solutions, choose the one with a smaller $\bar{R}_M$ .

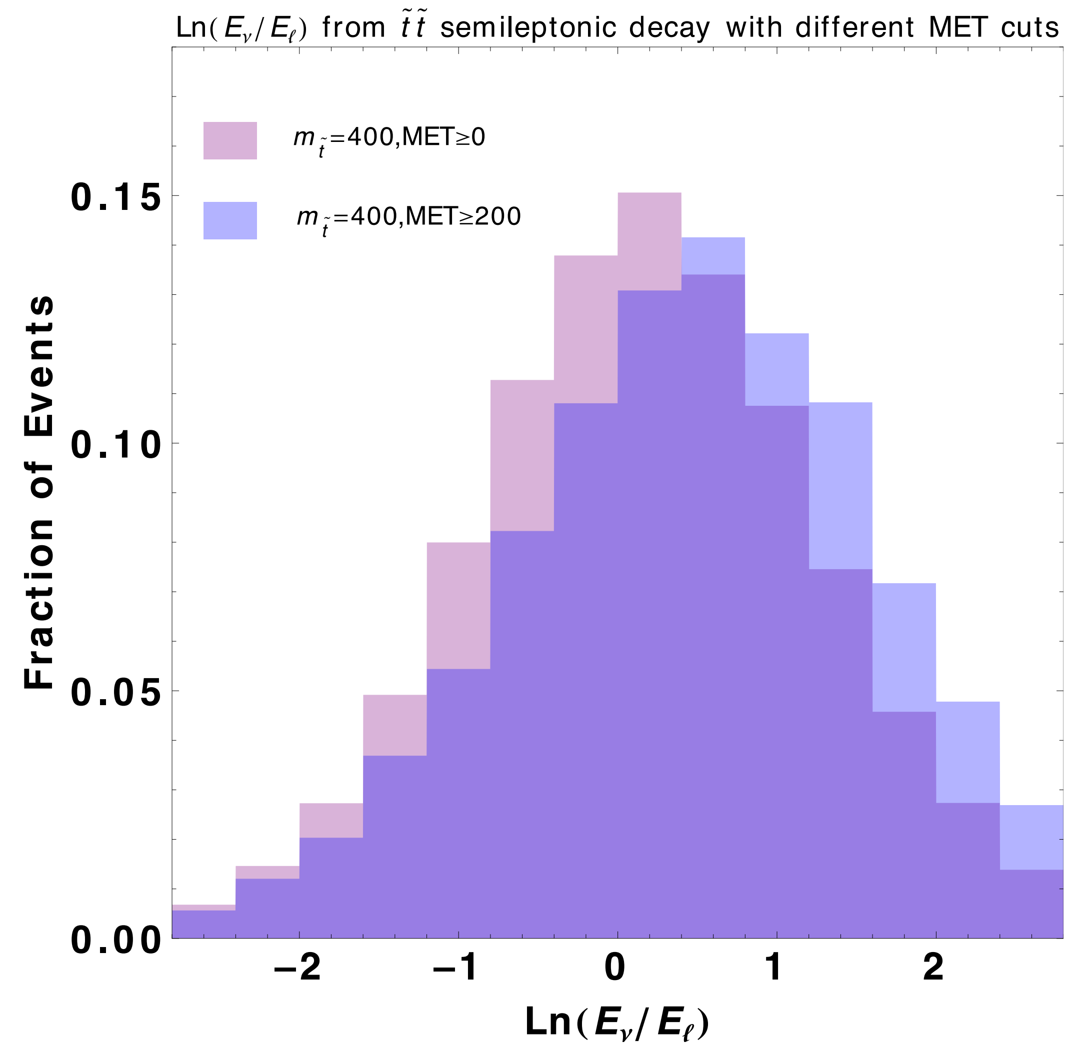
# Azimuthal Distributions

If MET only comes from one neutrino, it tends to be close to the lepton, due to the boosted $W$.



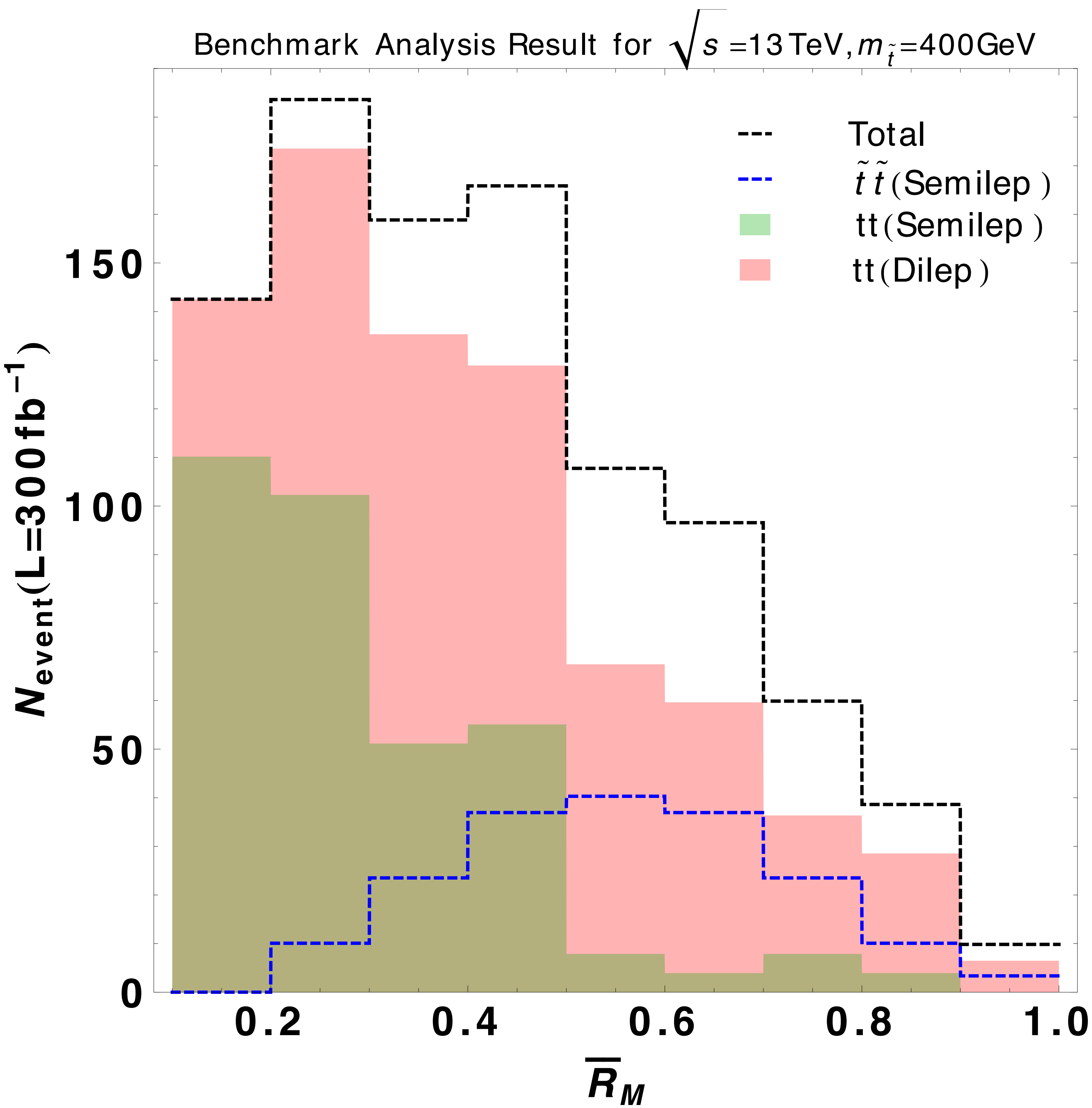
# Lepton Energies



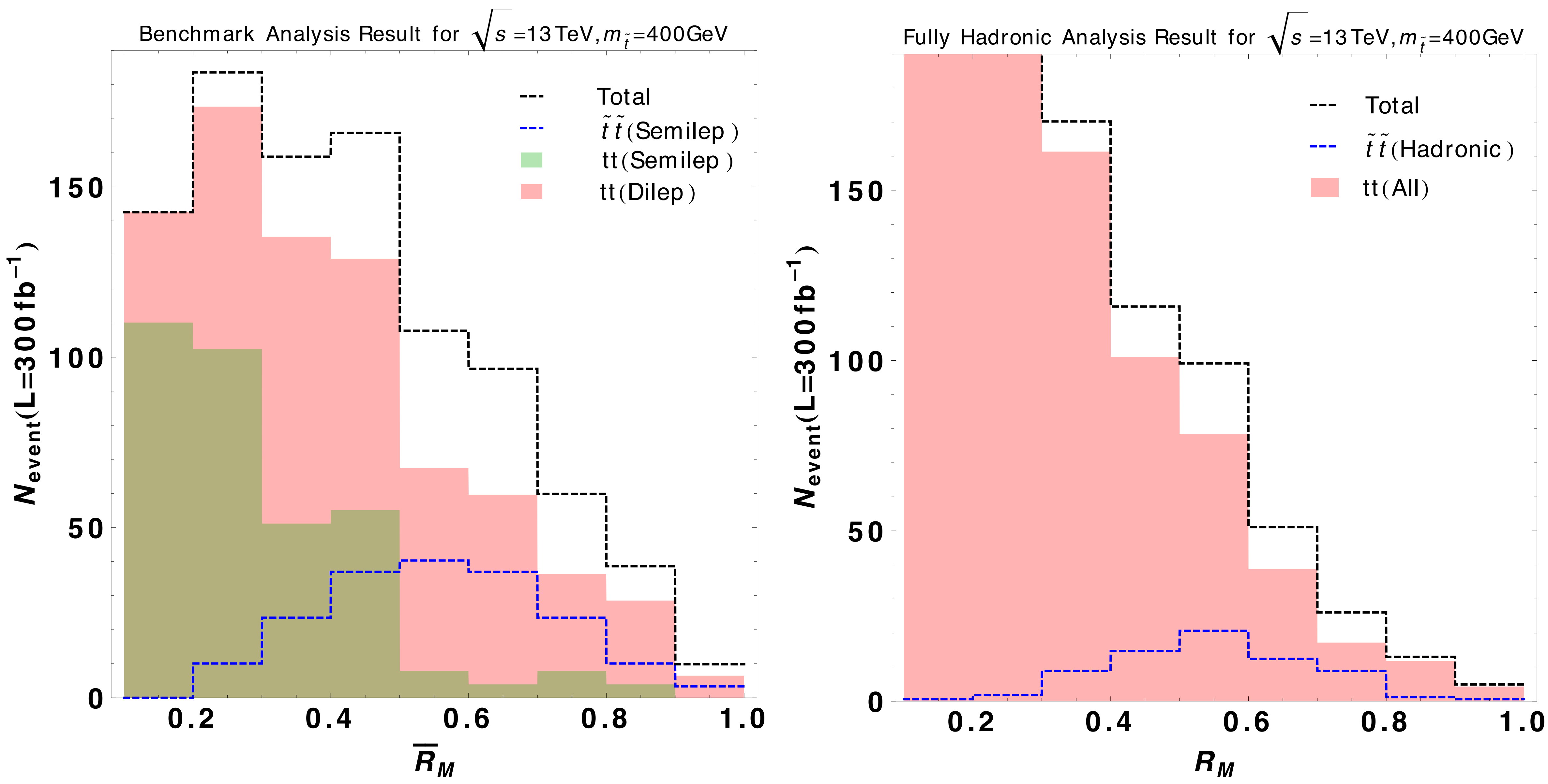

- MET$\geq$ 200 GeV
- Choose the solution with bigger $E_\nu$

# Result

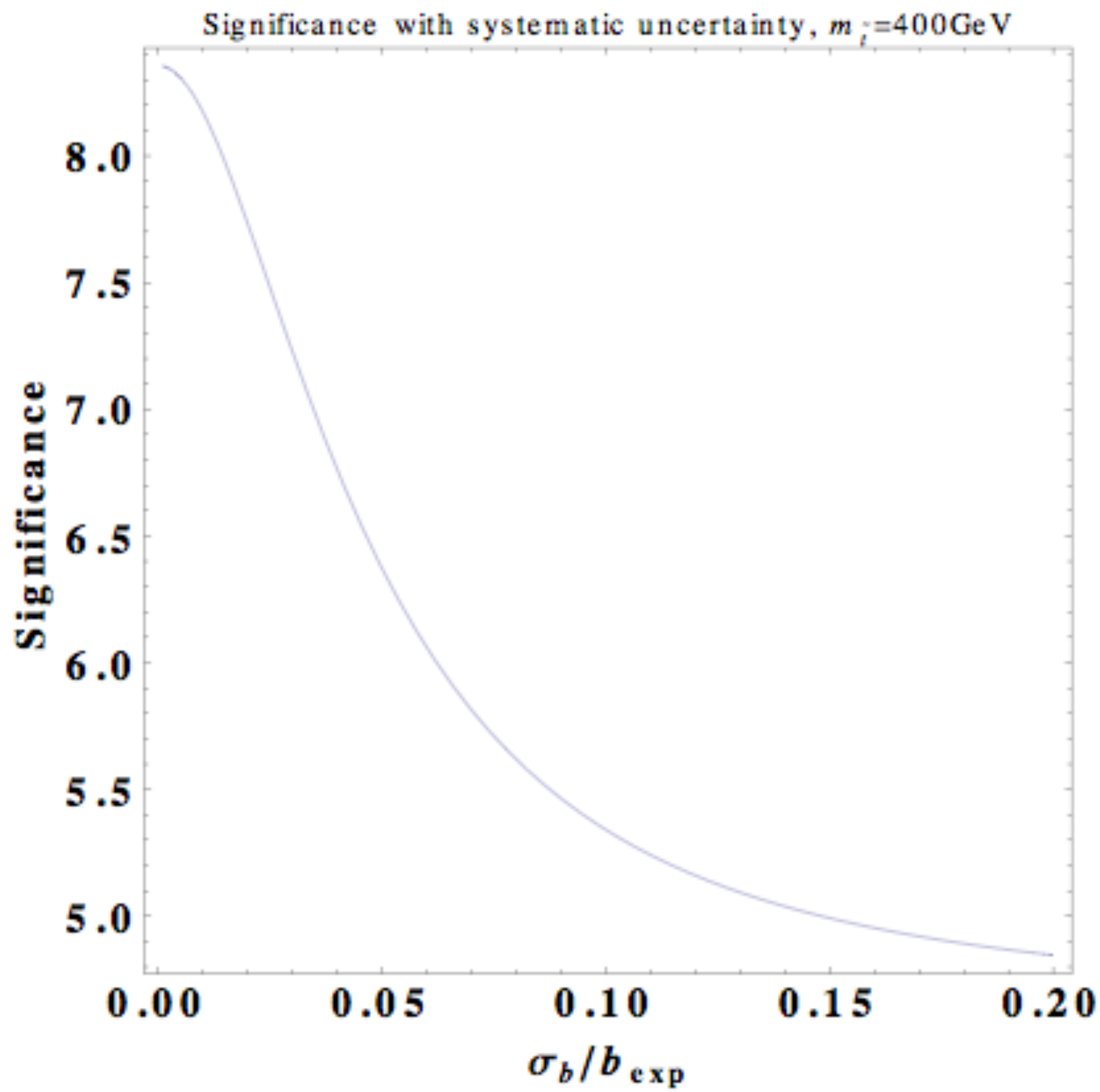


Benchmark Analysis Result for $\sqrt{s}$=13TeV, $m_{\tilde{t}}$=400GeV
Total
$\tilde{t}\tilde{t}$(Semilep)
tt(Semilep)
tt(Dilep)
$N_{event}$(L=300fb$^{-1}$)
0
50
100
150
0.2
0.4
0.6
0.8
1.0
$\overline{R}_M$

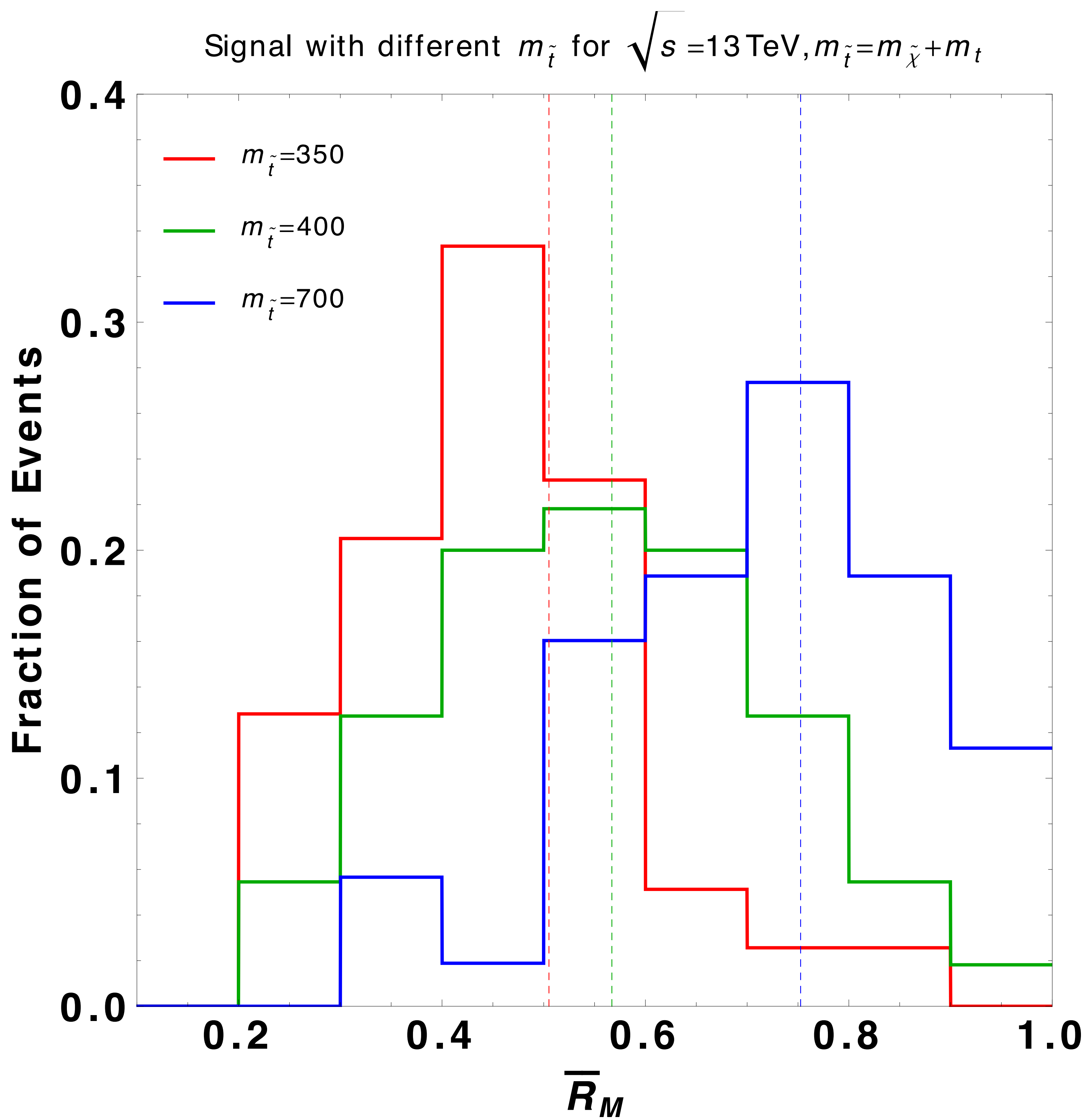
# Compared to hadronic channel



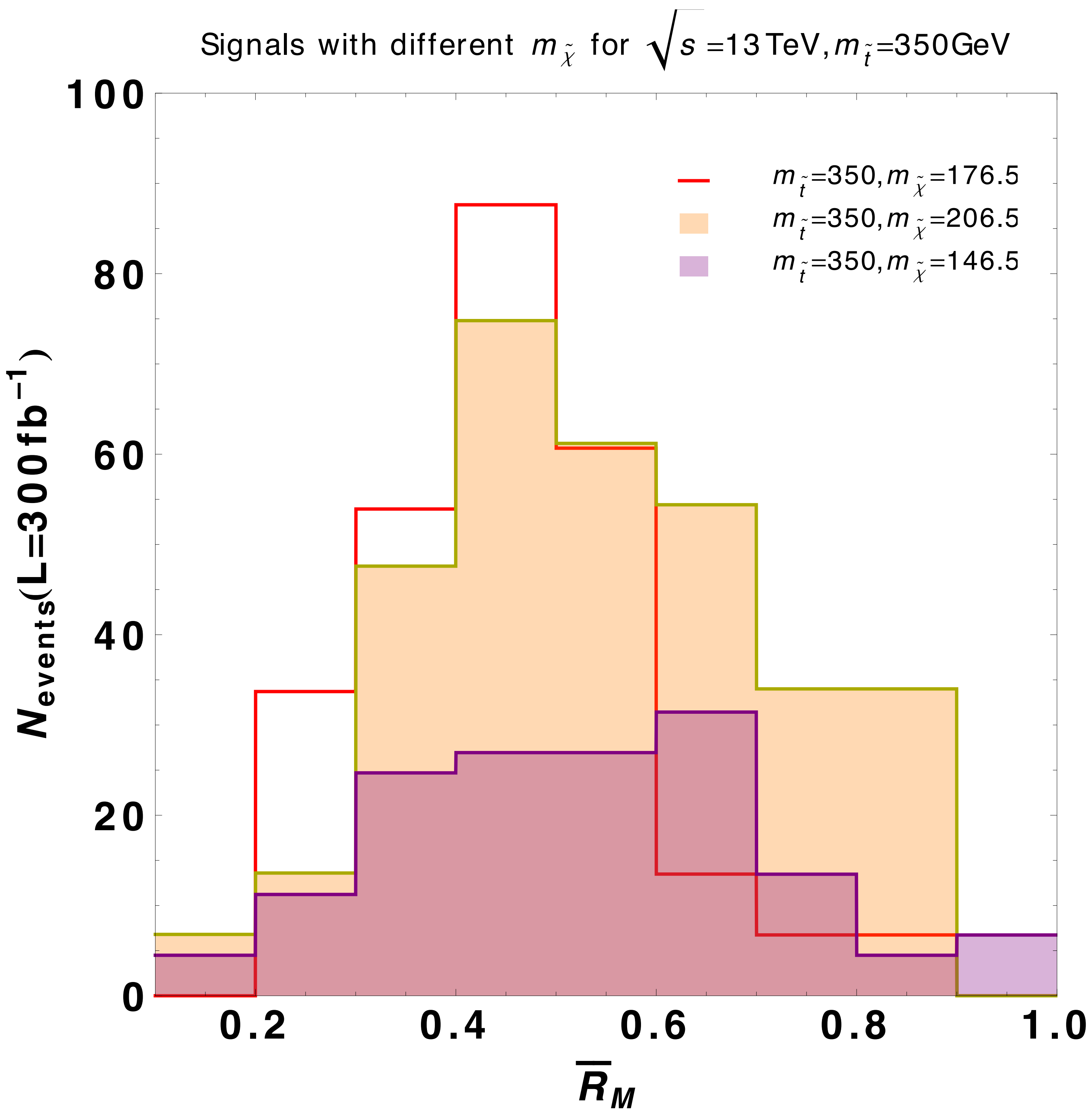
# Significance vs Background Uncertainty



# Moving along $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx m_t$

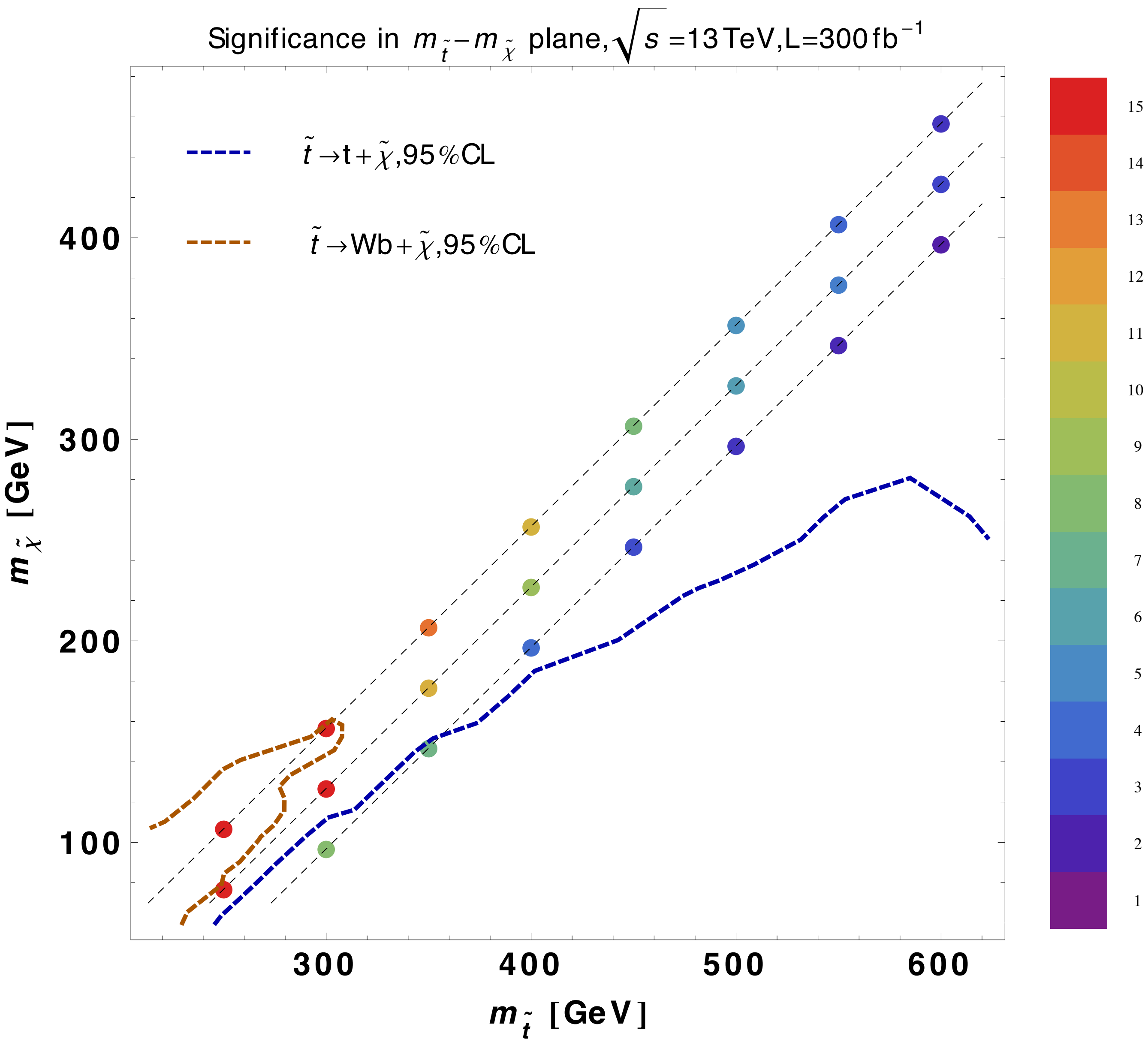


# Moving away from $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx m_t$



# Significances

| $m_{\tilde{t}}$ (GeV) | 250 | 300 | 350 | 400 | 450 | 500 | 550 | 600 |
|---|---|---|---|---|---|---|---|---|
| $\sigma_{m_{\tilde{t}}-(m_{\tilde{\chi}}+m_t)=0}$ | 19.7 | 15.8 | 11.0 | 8.4 | 5.8 | 5.1 | 3.8 | 2.1 |
| $\sigma_{m_{\tilde{t}}-(m_{\tilde{\chi}}+m_t)=-30}$ | 22 | 19 | 13 | 11 | 7.2 | 4.7 | 3.1 | 1.7 |
| $\sigma_{m_{\tilde{t}}-(m_{\tilde{\chi}}+m_t)=30}$ | – | 7.6 | 5.3 | 3.3 | 2.4 | 1.7 | 1.3 | 0.9 |




## for 13 TeV, 300 fb$^{-1}$

- If $m_{\tilde{\chi}} \geq m_{\tilde{t}} - m_t$, choose $\frac{m_{\tilde{\chi}}}{m_{\tilde{t}}} - 0.15 < \bar{R}_M < 1$
- If $m_{\tilde{\chi}} < m_{\tilde{t}} - m_t$, choose $\frac{m_{\tilde{t}} - m_t}{m_{\tilde{t}}} - 0.15 < \bar{R}_M < 1$

$$\sigma = \sqrt{2\left[(S+B)\log\left(\frac{S+B}{B}\right) - S\right]}$$

# $\tilde{t}_2, \tilde{b}_1$ Searches with a Stealth $\tilde{t}_1$

HC, Lingfeng Li, Qin Qin, arXiv:1607.06547

- To solve the naturalness problem, both stops and the left-handed sbottom cannot be too heavy.
- If $\tilde{t}_1$ is stealth, $\tilde{t}_2$ and $\tilde{b}_1$ may be accessible.
- ATLAS and CMS have searched $\tilde{t}_2$ , $\tilde{b}_1$ using simplified models with the decay channels:

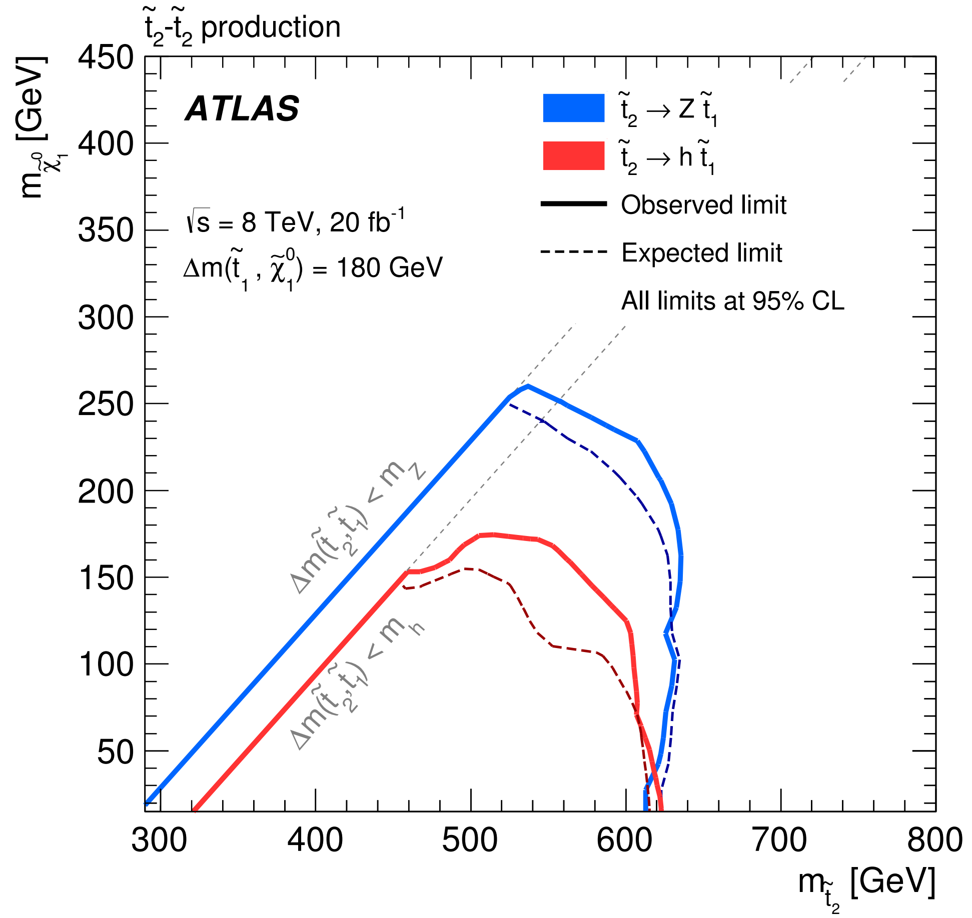
$$\tilde{t}_2 \to \tilde{t}_1 + Z \text{ or } h$$

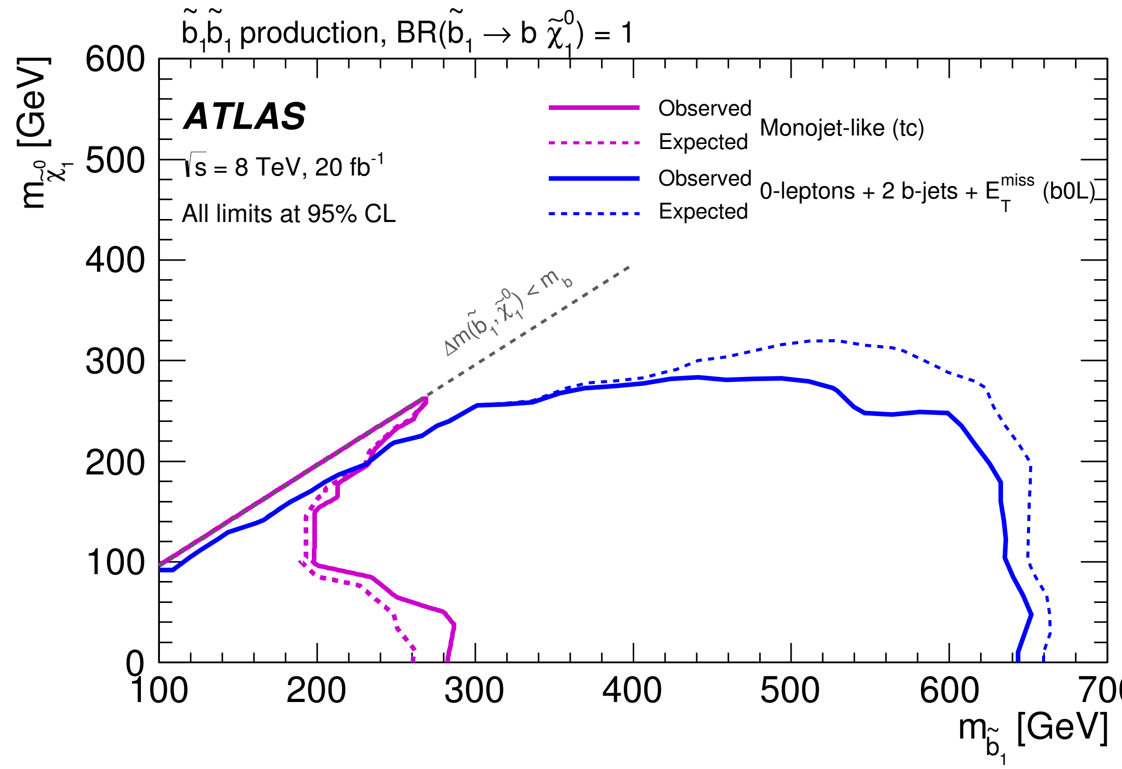
$$\tilde{b}_1 \to b + \tilde{\chi}_1^0,$$

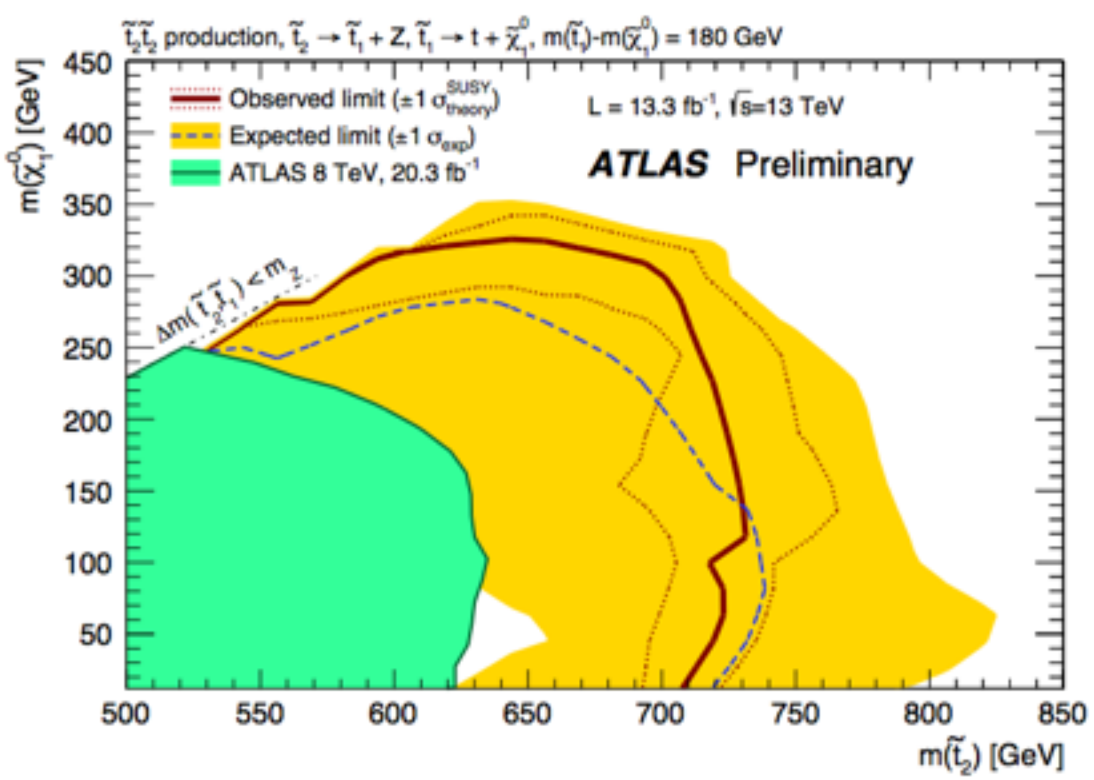
$$\tilde{b}_1 \to t + \tilde{\chi}_1^\pm,$$

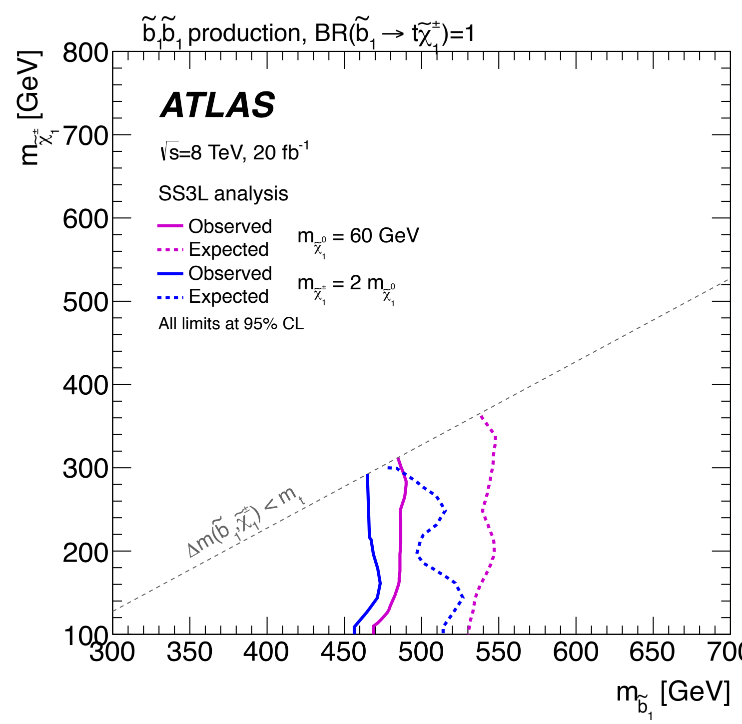
$$\tilde{b}_1 \to b + \tilde{\chi}_2^0, \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h$$

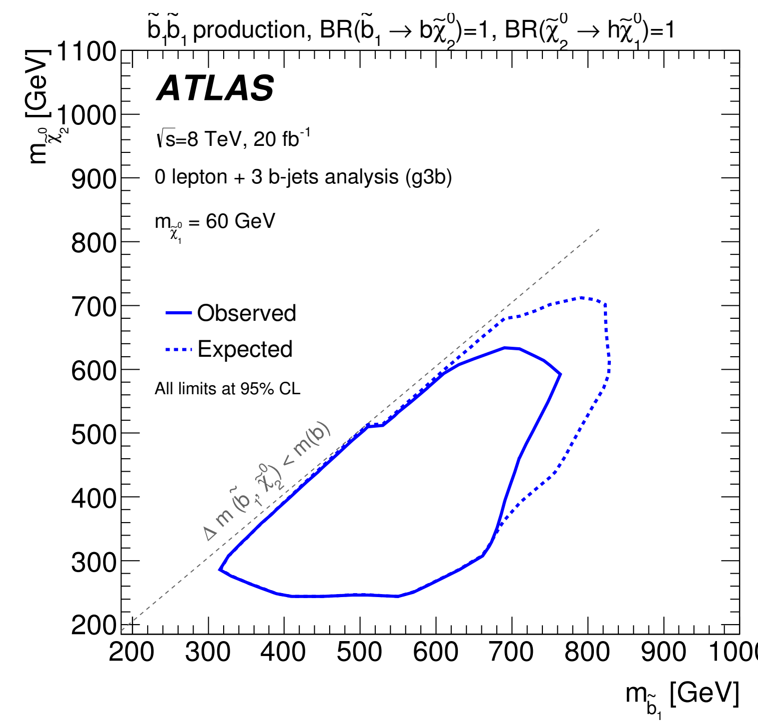
# $\tilde{t}_2$, $\tilde{b}_1$ Searches with a Stealth $\tilde{t}_1$



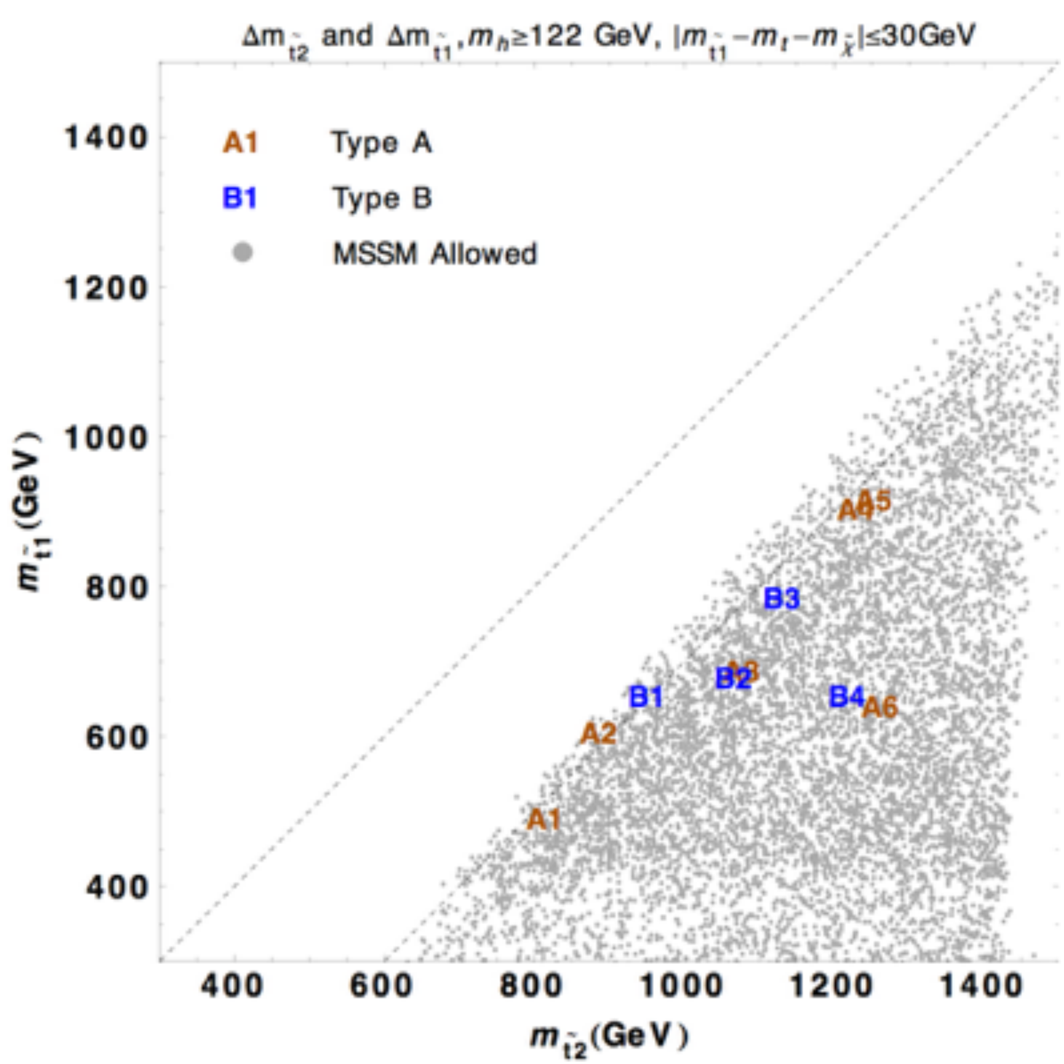



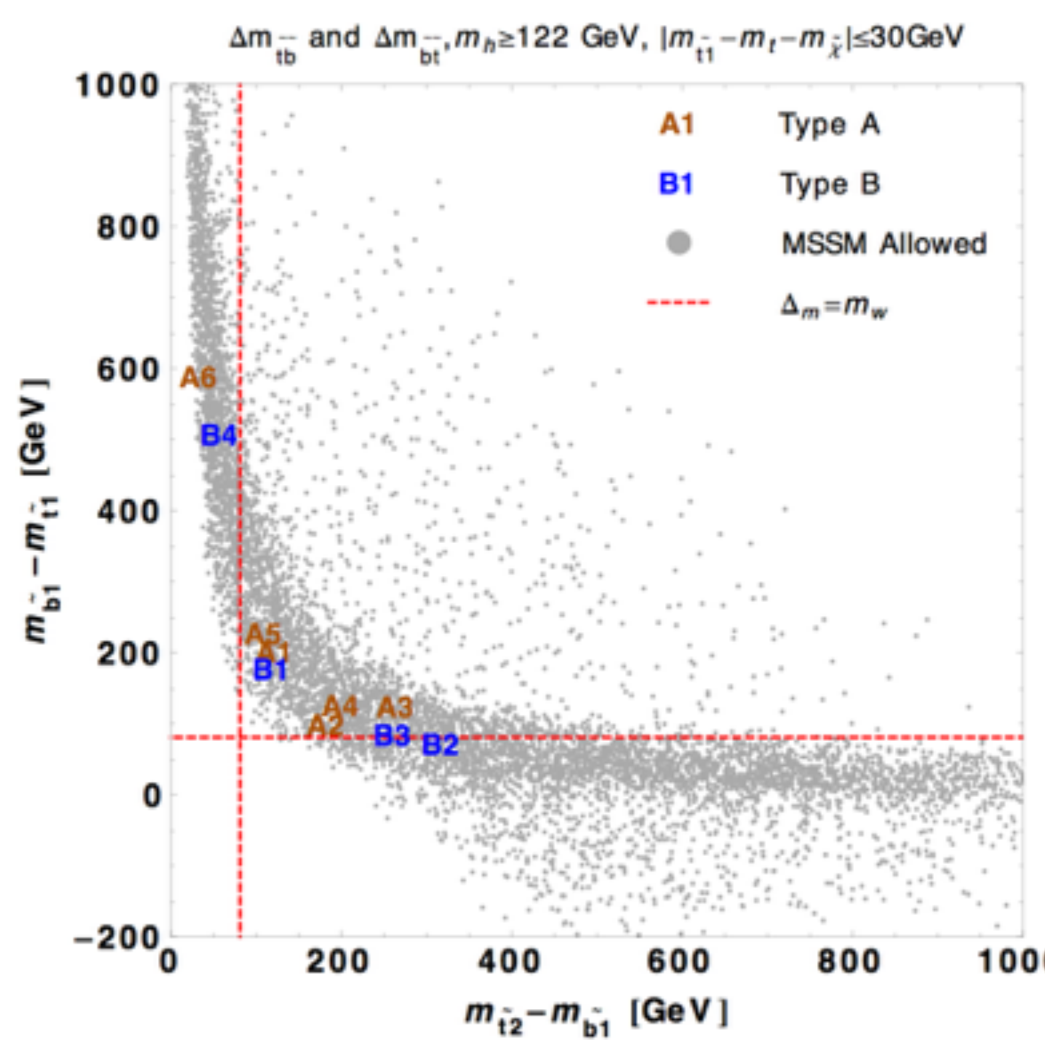



# Stop/Sbottom Spectrum

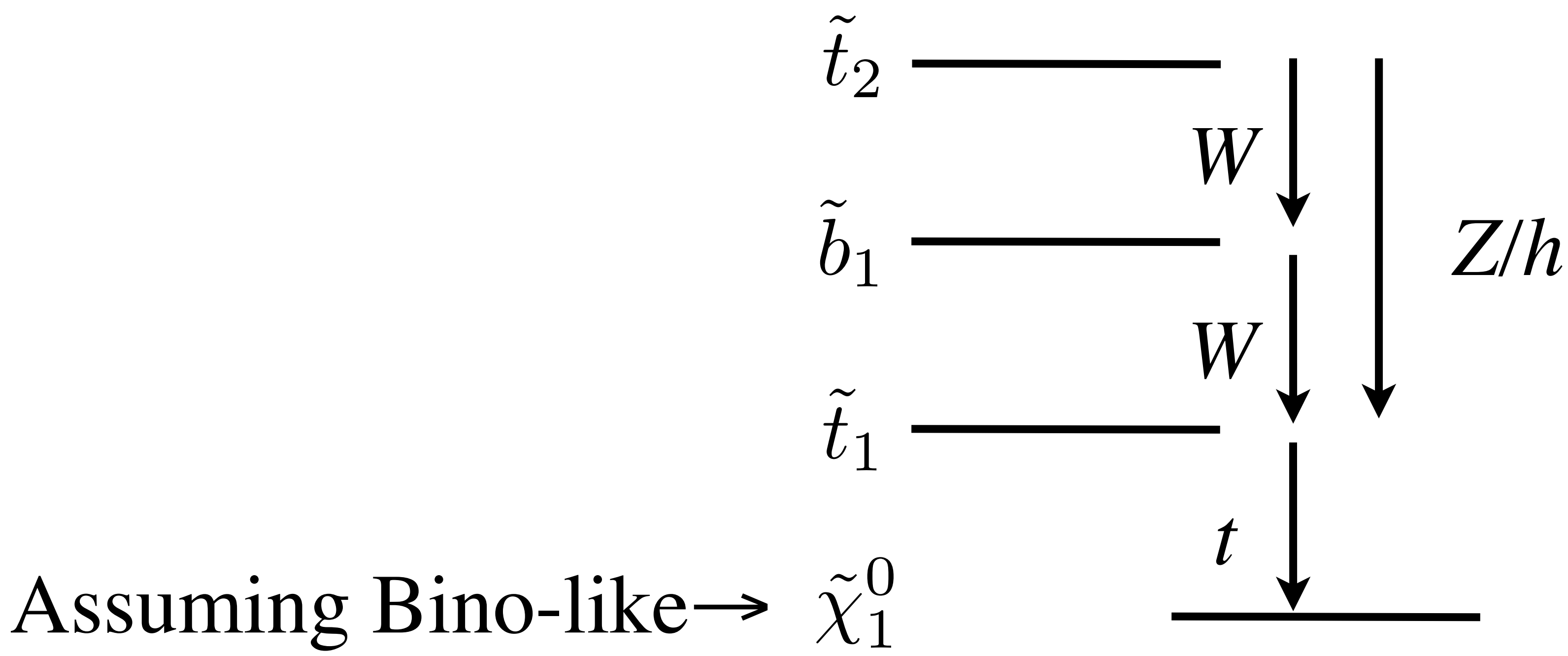
- In MSSM, if both stops are light, a large left-right mixing term $X_t = A_t - \mu\cot\beta$ is needed to get 125 GeV Higgs. The stop-sbottom spectrum will be split by $X_t$.



# Stop/Sbottom Spectrum

- A typical spectrum and the major decay chains:




- More complicated decay chains if additional neutralinos and charginos are present.

⇒ Simplified models seldom are good approximations for the stop/sbottom system.

See also: M. Adeel Ajaib, T. Li and Q. Shafi, 1104.0251; E. Alvarez and Y. Bai, 1204.5182; H. M. Lee, V. Sanz and M. Trott, 1204.0802; X. J. Bi, Q. S. Yan and P. F. Yin, 1209.2703; J. Guo, Z. Kang, J. Li, T. Li, 1308.3075; B. Dutta et al., 1507.01001; T. Han, S. Su, Y. Wu, B. Zhang and H. Zhang, 1507.04006; H. Li, W. Parker, Z. Si and S. Su, 1009.6042; A. Datta and S. Niyogi, 1111.0200; J. Beuria, A. Chatterjee, A. Datta and S. K. Rai, 1505.00604; J. Beuria, A. Chatterjee and A. Datta, 1603.08463

# Useful Signal Channels

- ***0l3b***: no lepton, $\geq$ 3b jets, additional jets & large MET
- ***1l3b***: 1 lepton, $\geq$ 3b jets, additional jets & MET, $M_T$ >160 GeV
- ***Z2b***: 2 OSSF leptons forming a Z, $\geq$ 2b jets, additional jets & MET
- ***SS+nb***: same-sign dileptons, $\geq$ 1b jets, additional jets & MET
- ***Multi-l***: $\geq$ 3 leptons, $\geq$ 1b jets, MET

gluon searches with decays thru bottom (← 0l3b)

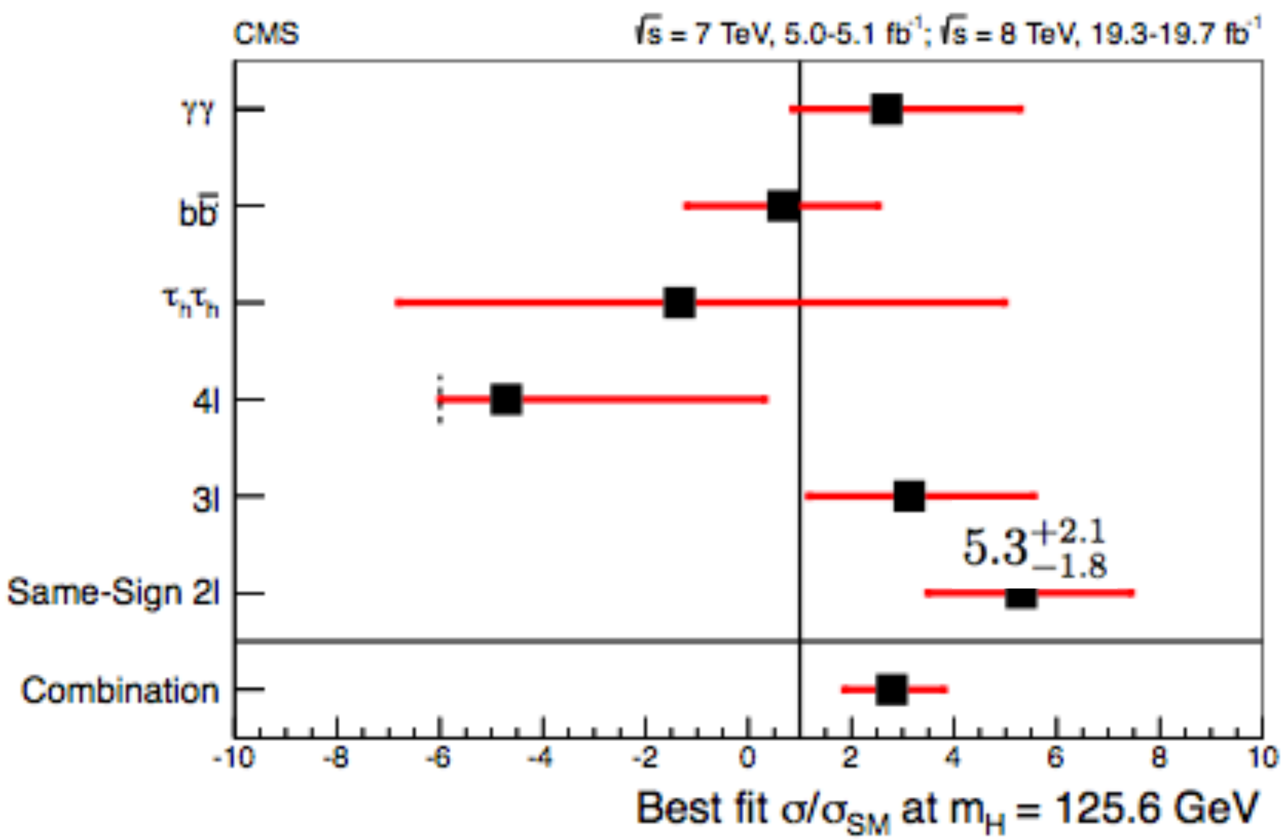
current $\tilde{t}_2$ searches (← 1l3b, Z2b)

used for $\tilde{b}_1$ searches, but different spectrum and decay chains (← SS+nb, Multi-l)

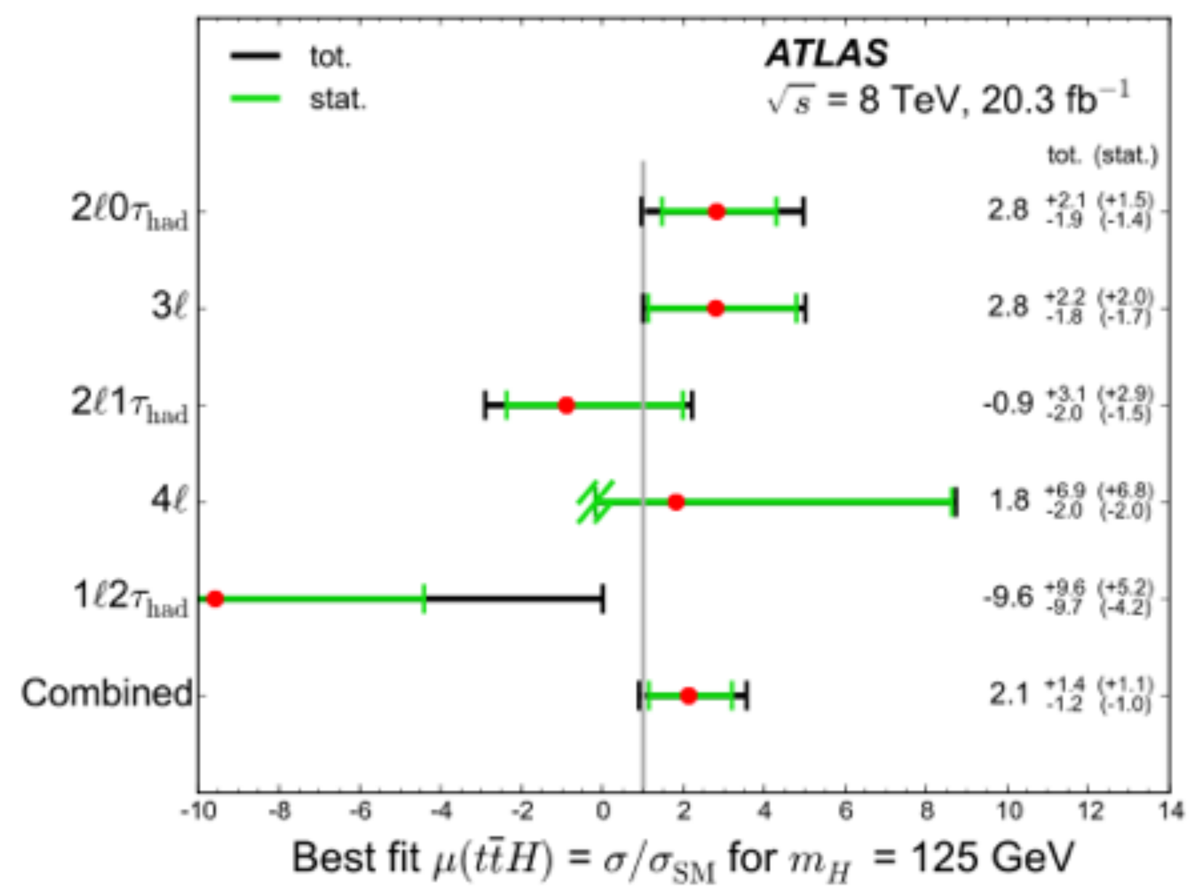
# SS2l Excesses in Run 1

- SS2l excesses present in Run 1 ATLAS and CMS SUSY searches, *tth* searches, and ATLAS exotica search.

CMS tth search, 1408.1682

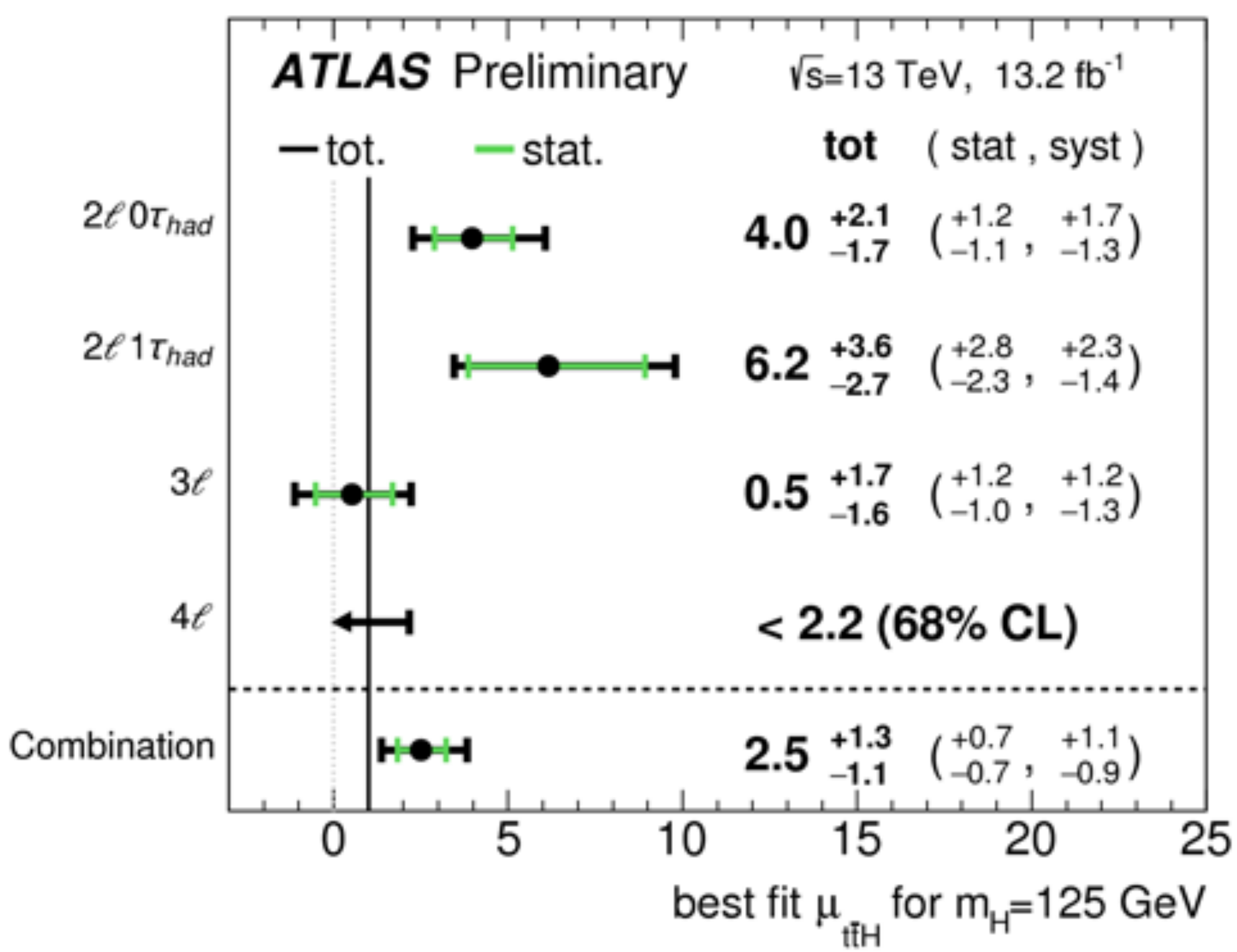


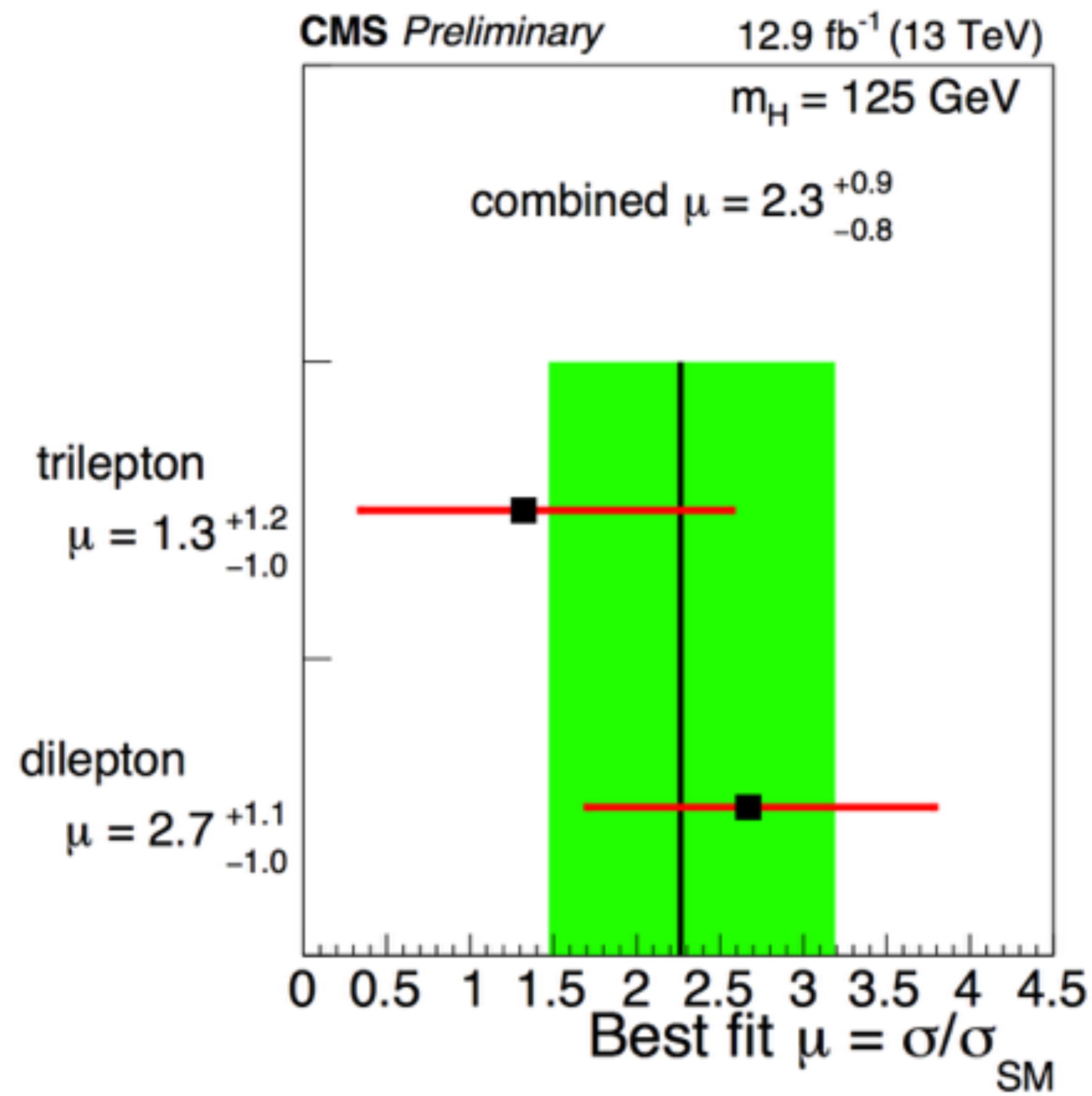

ATLAS tth search, 1506.05988



# SS2l Excesses in Run 2

- SS2l excesses persist in Run 2 ATLAS and CMS *tth* searches, though no excess in SUSY searches.



# Possible Interpretations

- Simplified model in ATLAS and CMS SUSY searches:

$$\tilde{b} \to t + \tilde{\chi}^- \to t + W^- + \tilde{\chi}_1^0$$

but $\tilde{b} \to b + \tilde{\chi}_{2,1}^0$ always compete and they give stronger constraints.

- P. Huang, A. Ismail, I. Low, C. Wagner, 1507.01601

$$\tilde{t}_1 \to t + \tilde{\chi}_2^0 \to t + W^\pm + \tilde{\chi}_1^\mp$$

$$\tilde{t}_1 \downarrow \tilde{t}_R, \quad \tilde{\chi}_2^0 \downarrow \tilde{B}, \quad \tilde{\chi}_1^\mp \downarrow \tilde{W}$$

$$m_{\tilde{t}_1} \approx 550\,\text{GeV},\ m_{\tilde{\chi}_2^0} \approx 340\,\text{GeV},\ m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_1^0} \approx 260\,\text{GeV}$$

$$\mu(8\ \text{GeV}) = 2.83$$

# Example Spectra

| Spectrum | A1 | A2 |
|---|---|---|
| $m_{\tilde{t}_2}$(GeV) | 815.4 | 887.1 |
| $m_{\tilde{b}_1}$(GeV) | 693.0 | 704.5 |
| $m_{\tilde{t}_1}$(GeV) | 491.0 | 605.5 |
| $m_{\tilde{\chi}_1^0}$(GeV) | 304.9 | 414.2 |
| $X_t/m_{\tilde{t}}$ | -1.81 | 1.58 |
| $m_h$(GeV) | 122.8 | 122.7 |

Decay branching ratios

| Channel | A1 | A2 |
|---|---|---|
| $\tilde{t}_2 \to \tilde{b}_1 + W^+$ | 16.5 | 42.0 |
| $\tilde{t}_2 \to \tilde{t}_1 + Z$ | 74.5 | 47.6 |
| $\tilde{t}_2 \to \tilde{t}_1 + h$ | 5.9 | 3.9 |
| $\tilde{t}_2 \to t + \tilde{\chi}_1^0$ | 3.1 | 6.5 |
| $\tilde{b}_1 \to \tilde{t}_1 + W^-$ | 99 | 90.1 |
| $\tilde{b}_1 \to b + \tilde{\chi}_1^0$ | 1.0 | 9.9 |

Final state percentages

| | A1 | A2 |
|---|---|---|
| $\sigma(\tilde{t}_2\tilde{t}_2)(fb)$ | 33.8 | 19.4 |
| $ttZZ$ | 55.5 | 22.6 |
| $ttZWW$ | 24.6 | 40.0 |
| $ttZh$ | 8.8 | 3.7 |
| $tt4W$ | 2.7 | 17.6 |
| $tthWW$ | 1.9 | 3.3 |
| $tthh$ | 0.4 | 0.1 |
| $\sigma(\tilde{b}_1\tilde{b}_1)(fb)$ | 94.5 | 85.2 |
| $ttWW$ | 98 | 81 |
| $tbW$ | 2 | 19.6 |

# Signal Strengths for Benchmarks

SS2l signal strength compared to SM *tth* @ 13 TeV

| Spectrum | A1 | A2 |
|---|---|---|
| $m_{\tilde{t}_2}$(GeV) | 815.4 | 887.1 |
| $m_{\tilde{b}_1}$(GeV) | 693.0 | 704.5 |
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| $X_t/m_{\tilde{t}}$ | -1.81 | 1.58 |
| $m_h$(GeV) | 122.8 | 122.7 |

A1:

$\mu_{\tilde{b}_1} \approx 1.1$

$\mu_{\tilde{t}_1} \approx 0.3$

$\mu_{\text{tot}} \approx 2.4$

A2:

$\mu_{\tilde{b}_1} \approx 0.6$

$\mu_{\tilde{t}_1} \approx 0.2$

$\mu_{\text{tot}} \approx 1.8$

CMS 2LSS

$\mu = 2.7^{+1.1}_{-1.0}$

ATLAS 2l0τ

$\mu = 4.0^{+2.1}_{-1.7}$

# Conclusions

- There are gaps in stop searches at low masses. Natural SUSY could still be alive before they are ruled out.
- New methods to cover these gaps need to be developed.
- Searches for the heavier stop and the sbottom are also important. The simplified models that the current searches are based are often not good approximations to realistic models. A combination of various search channels is needed to cover the ground.