A Window for Light Stops and Sbottoms

Ian Low
Argonne/Northwestern

Conference: A First Glance Beyond the Energy Frontier
ICTP, Trieste, September 5th, 2016

Where is Supersymmetry?

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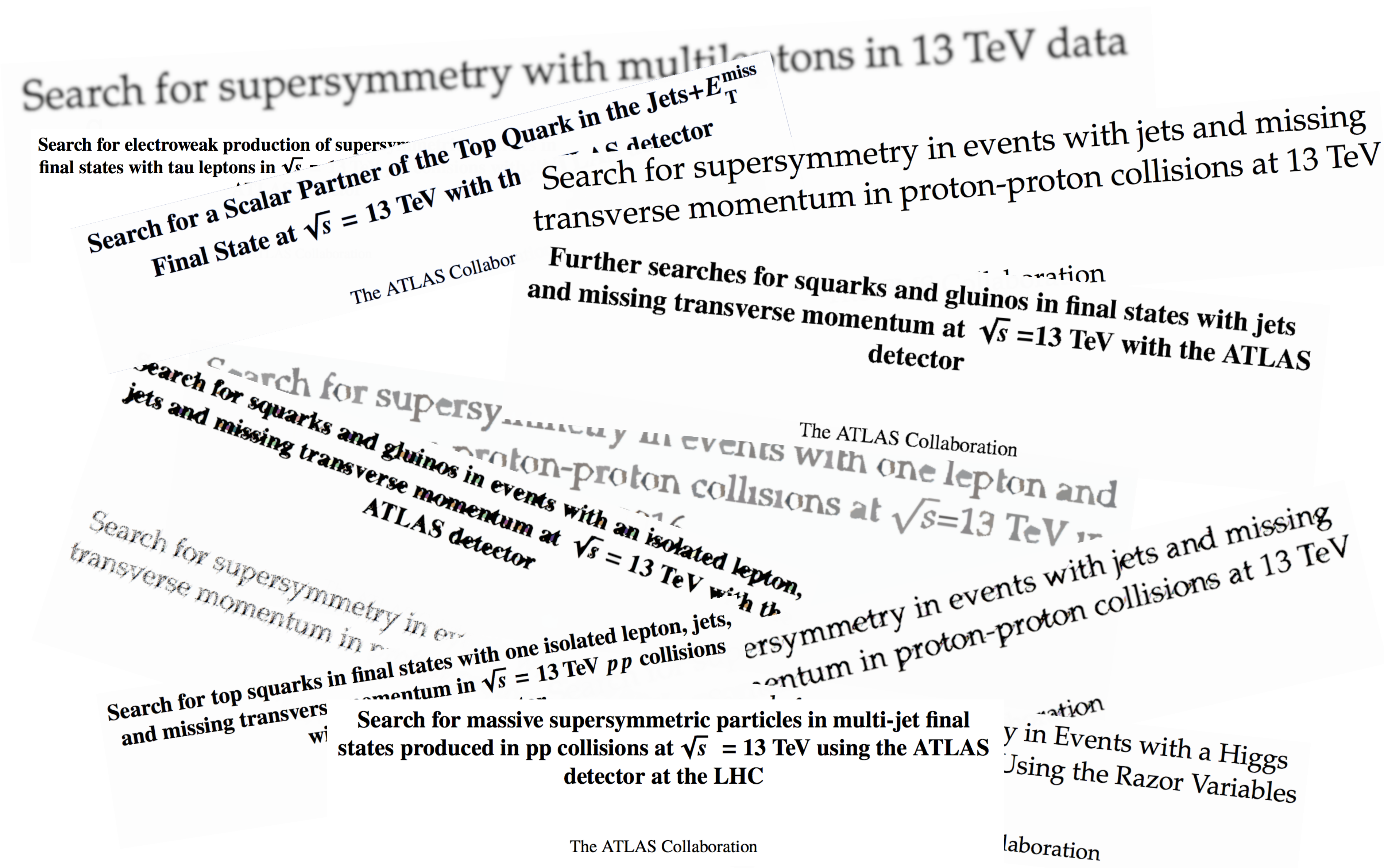

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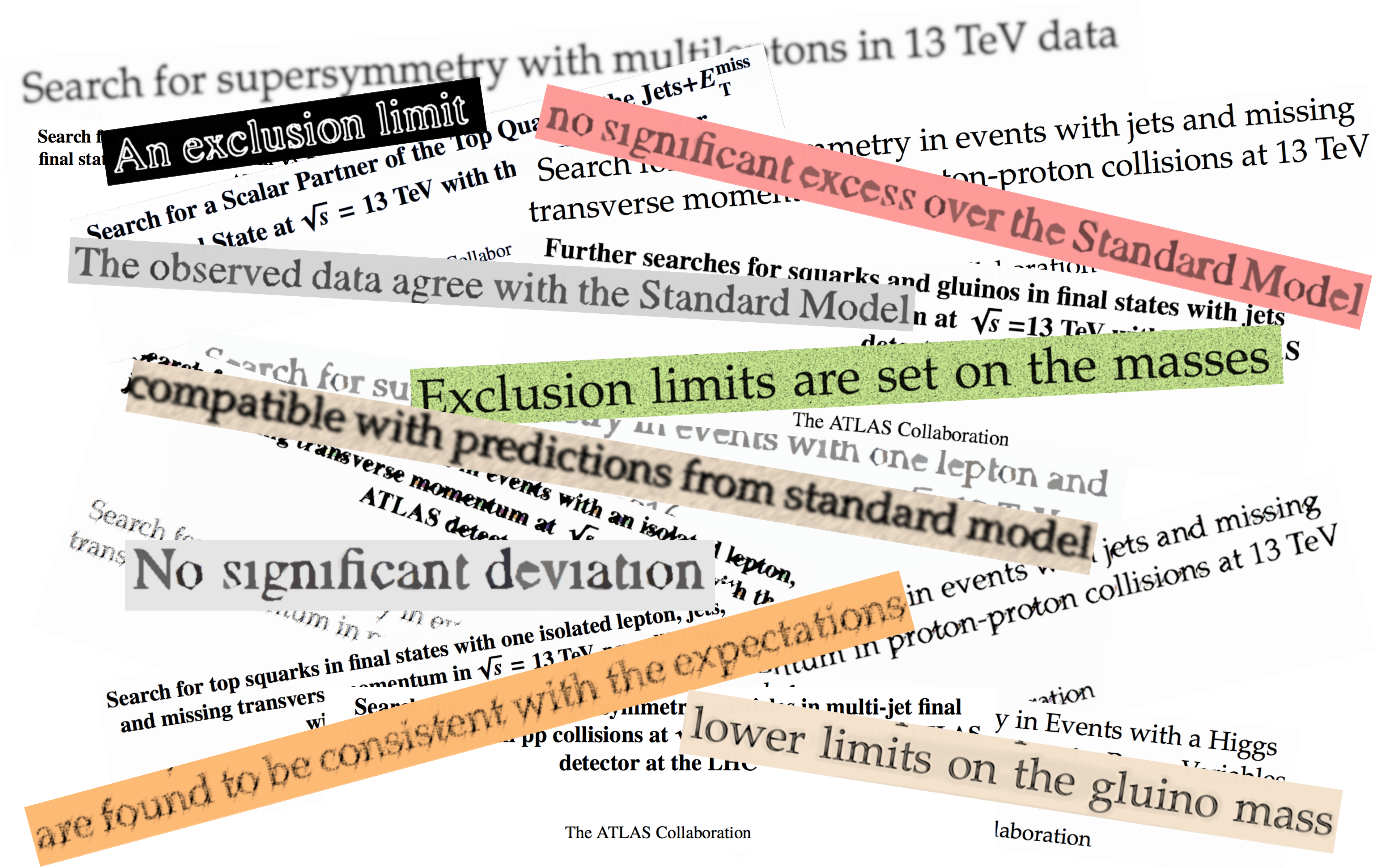

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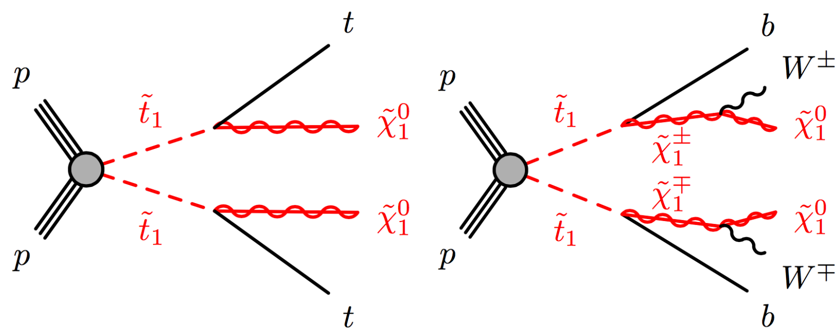

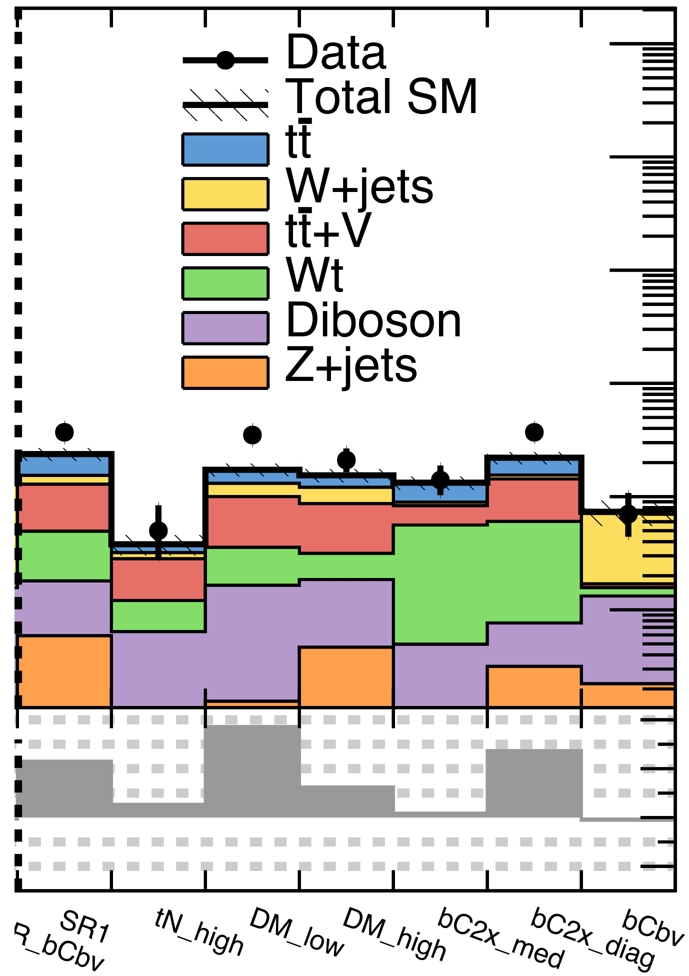

ATLAS-CONF-2016-050

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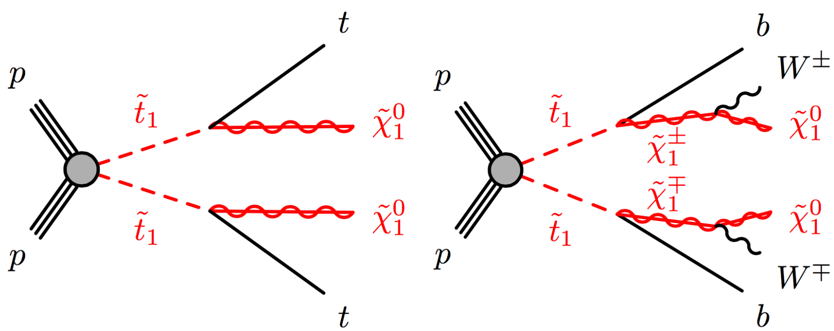
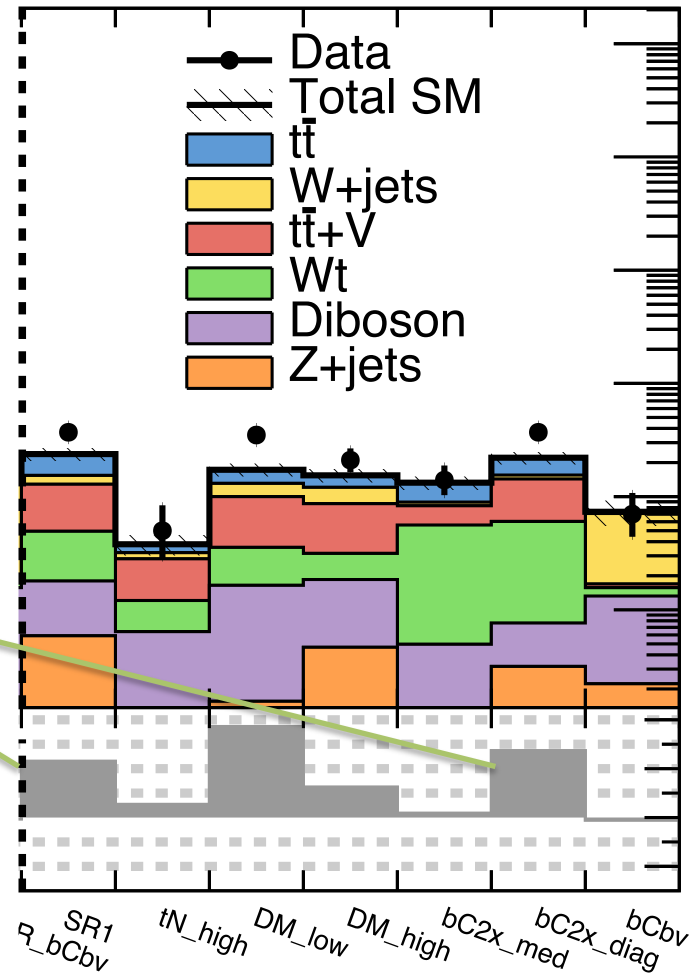


About 2-sigma excesses in SR1 and BC2x_diag regions.



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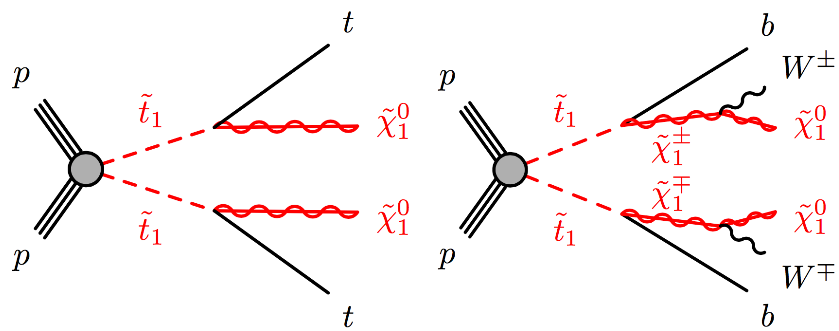
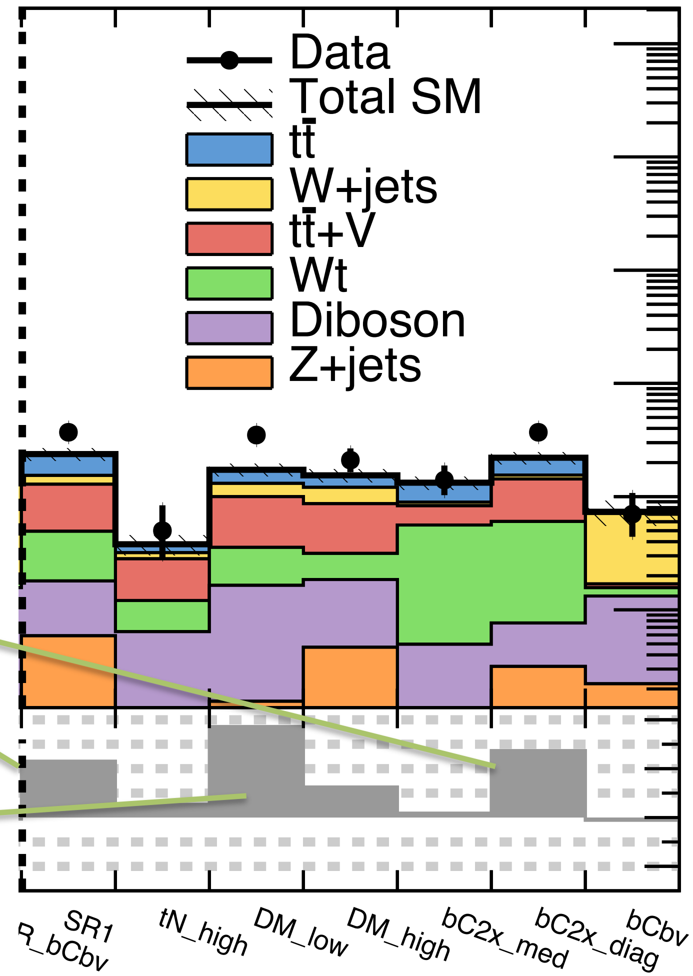


About 2-sigma excesses in SR1 and BC2x_diag regions.

About 3-sigma excesses in DM_low regions.



ATLAS-CONF-2016-050

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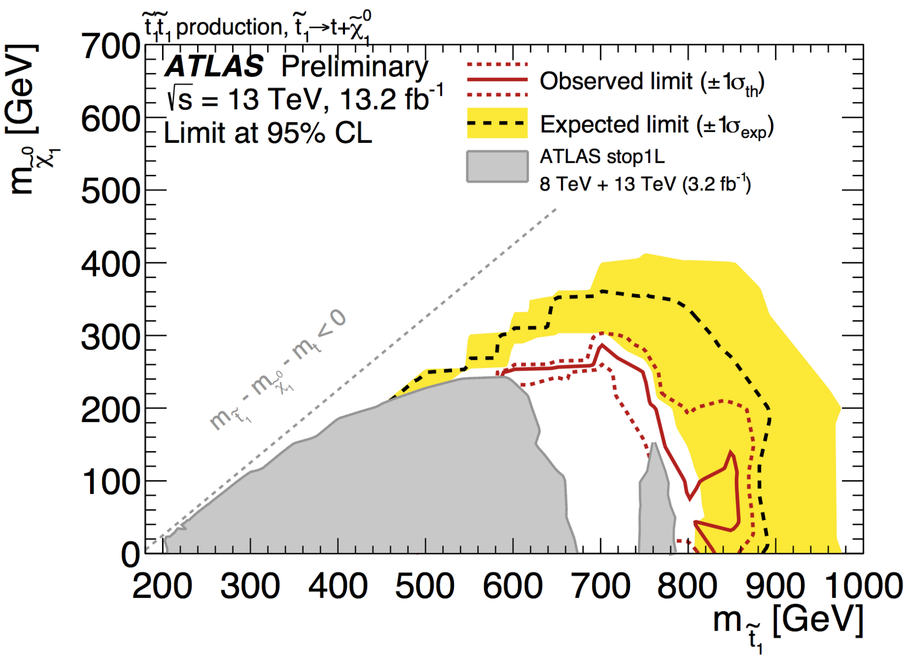

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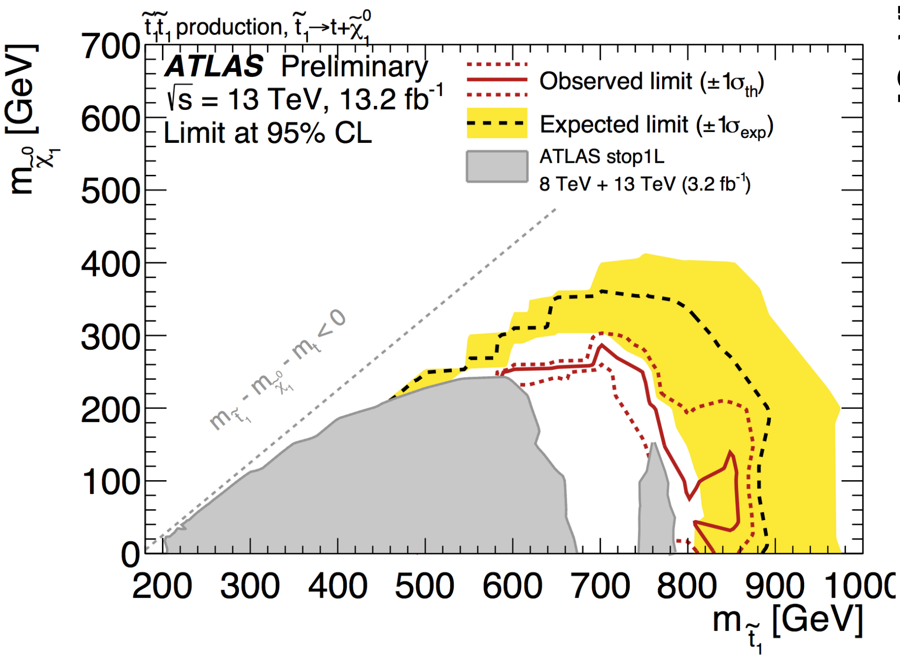
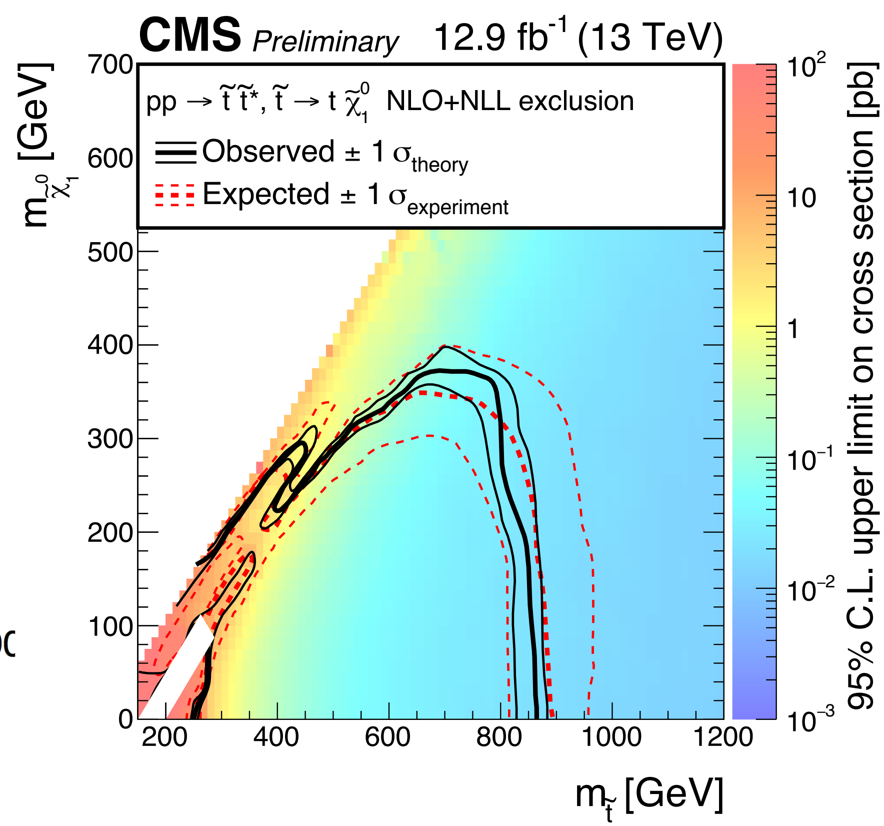


PAS-SUS-16-028



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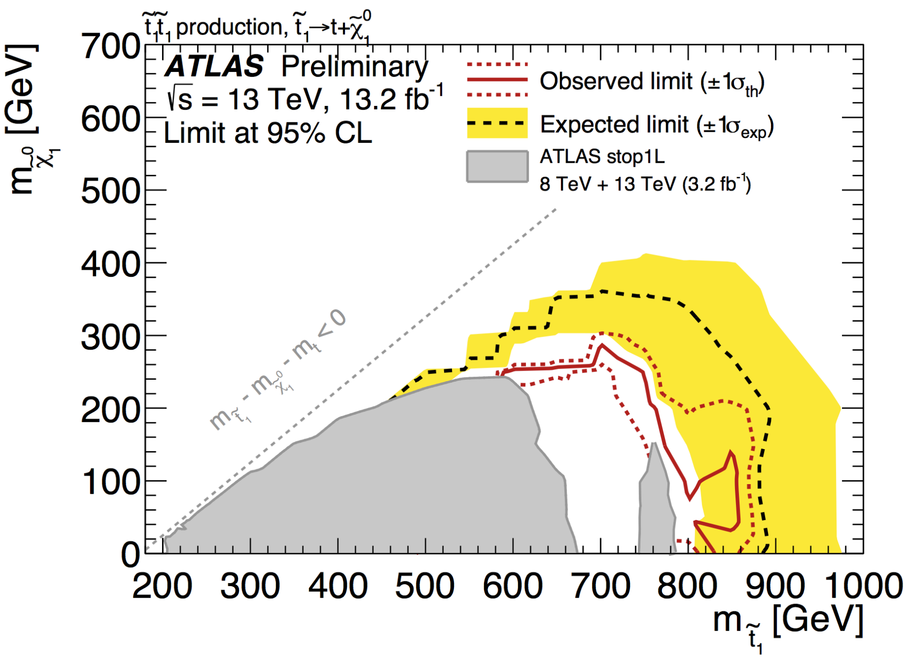
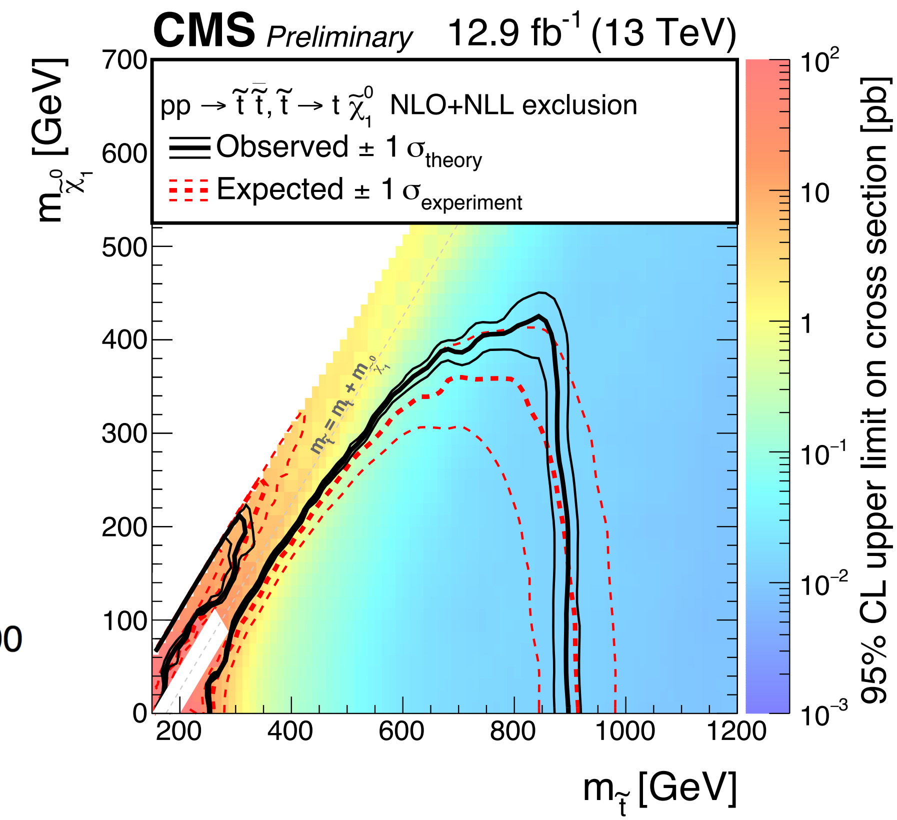


PAS-SUS-16-015



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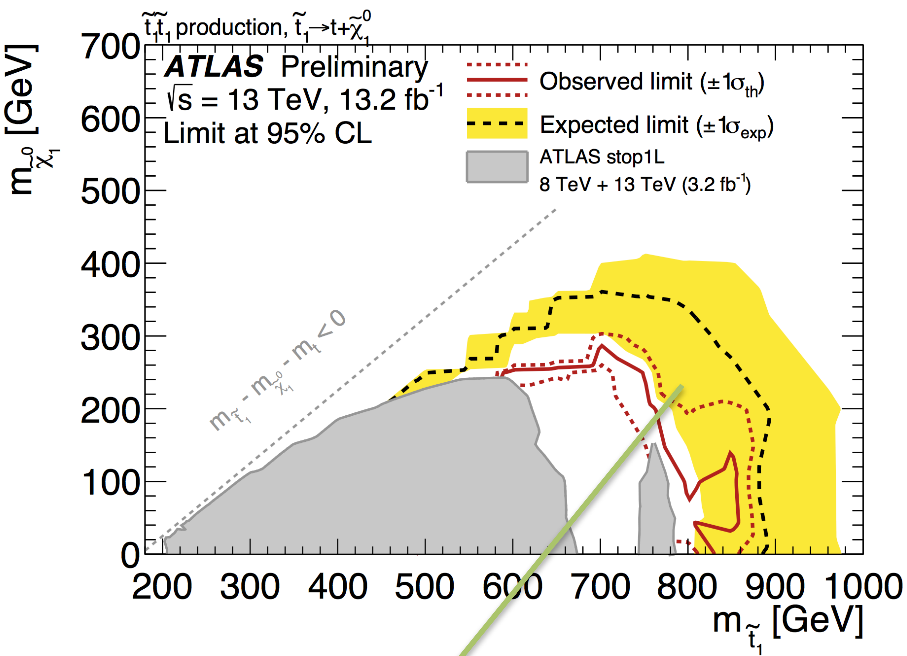

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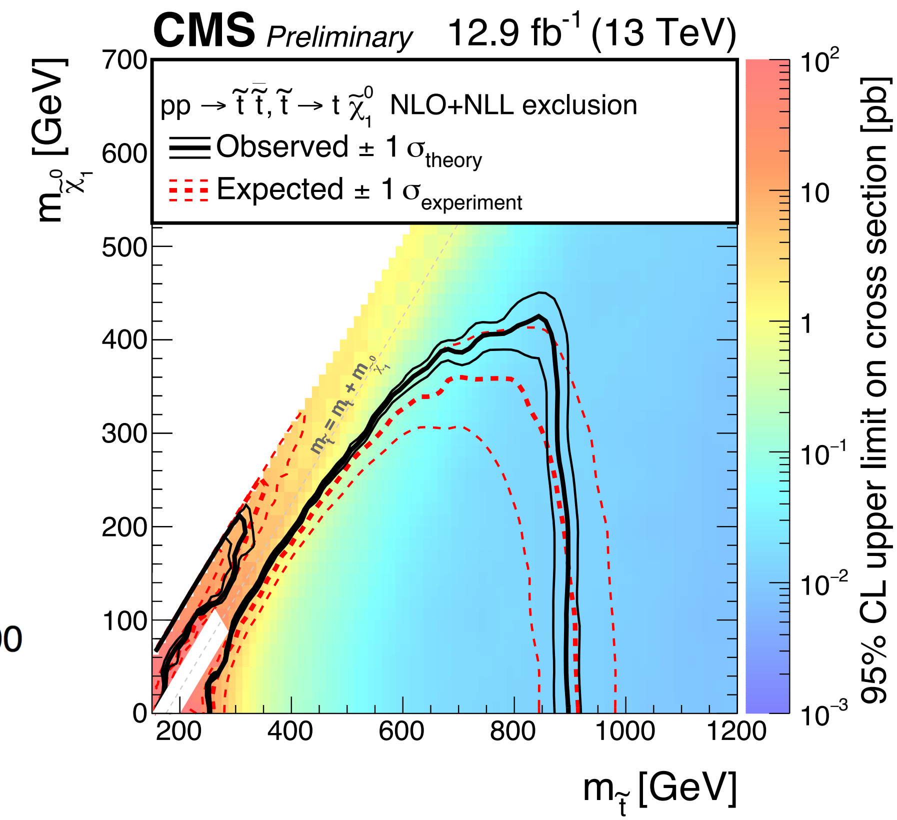

The excess region is excluded by CMS data?

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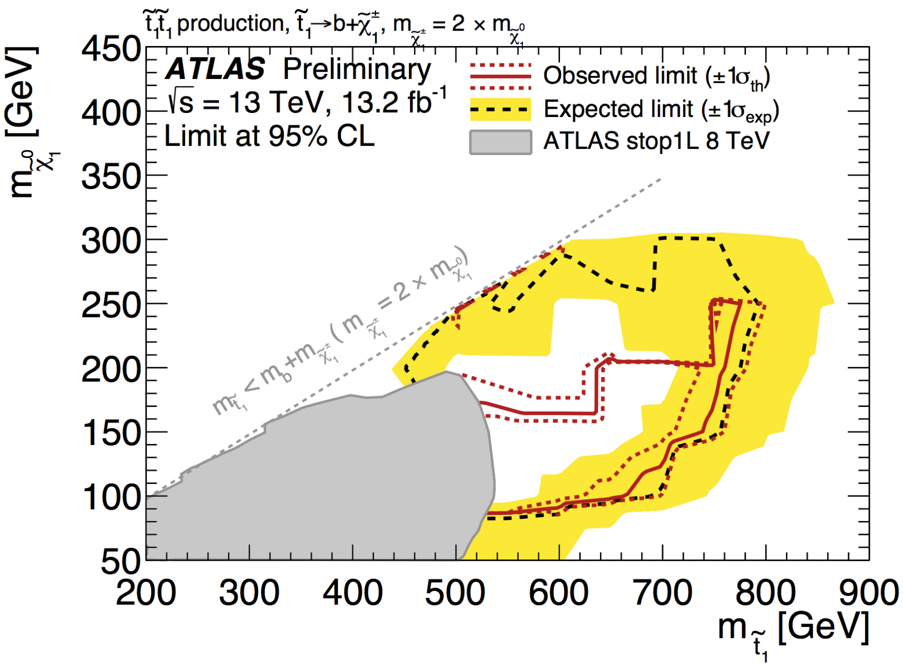
BC2x_diag region is interpreted in stop → b + (chargino → W + LSP)



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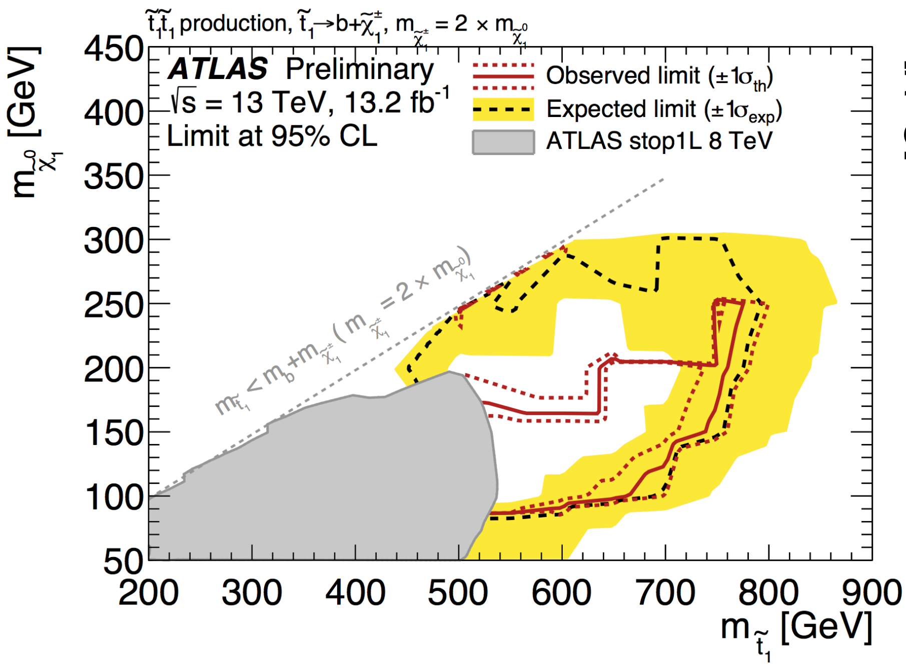

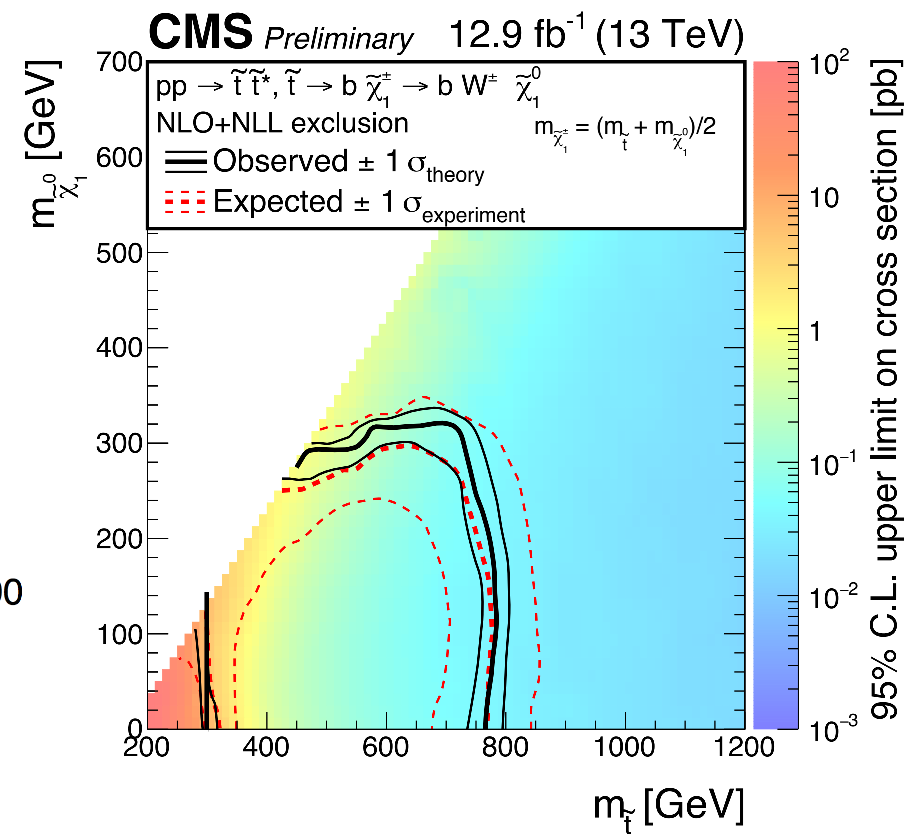

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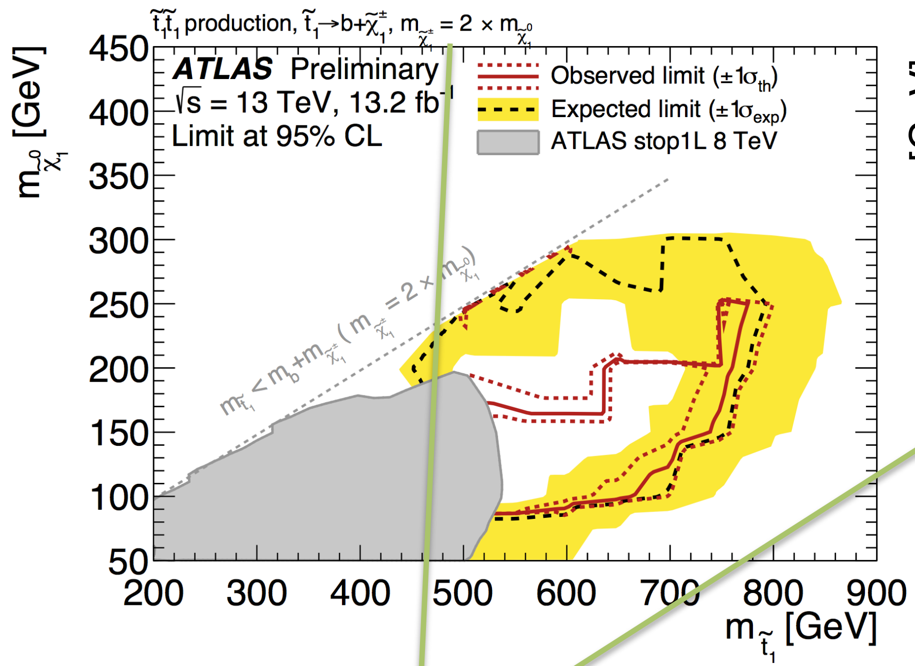

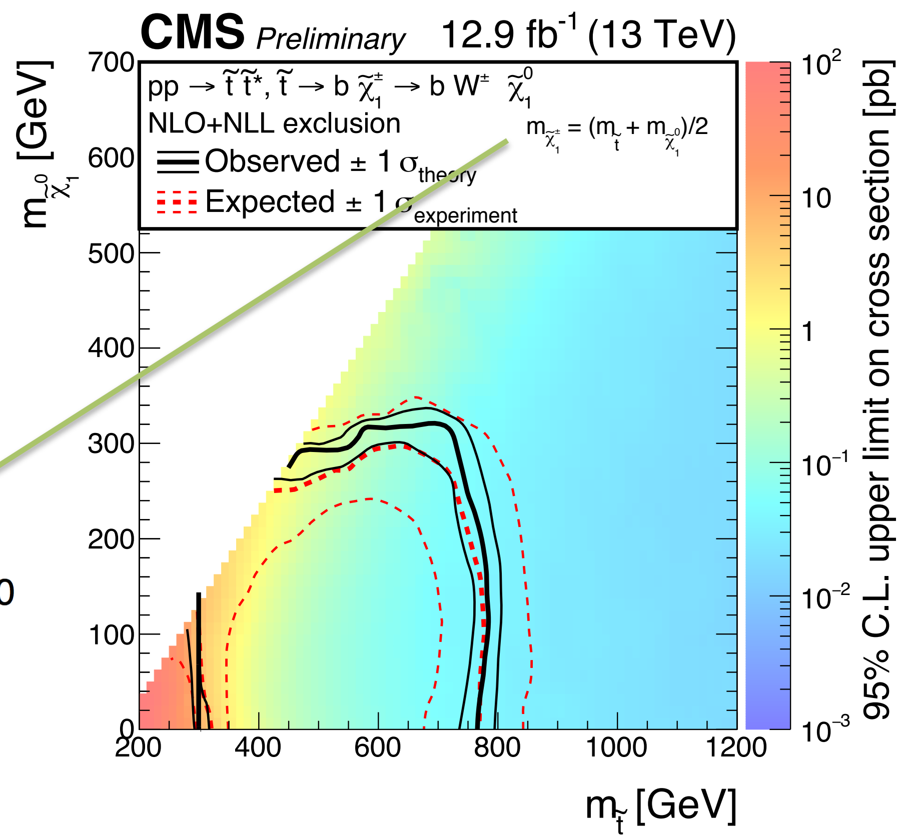

But the kinematic assumptions are different!

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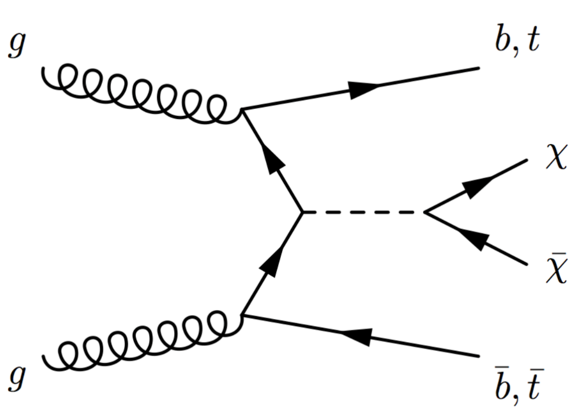
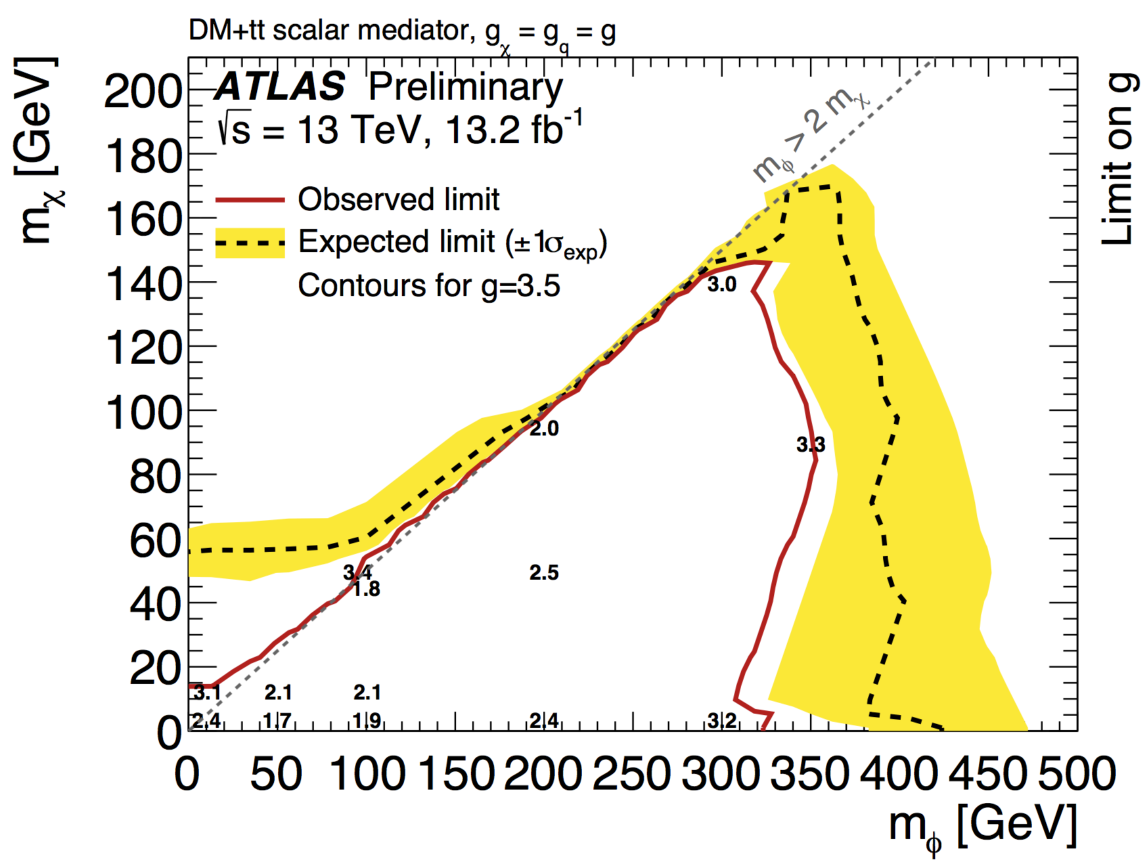
DM_low has a slightly different decay topology:



Buckley, Feld, Goncalves 1410.6497



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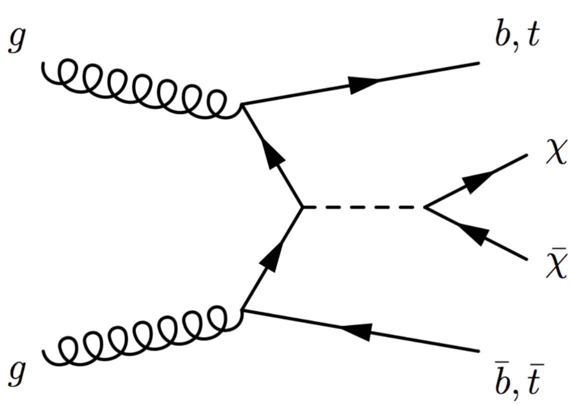

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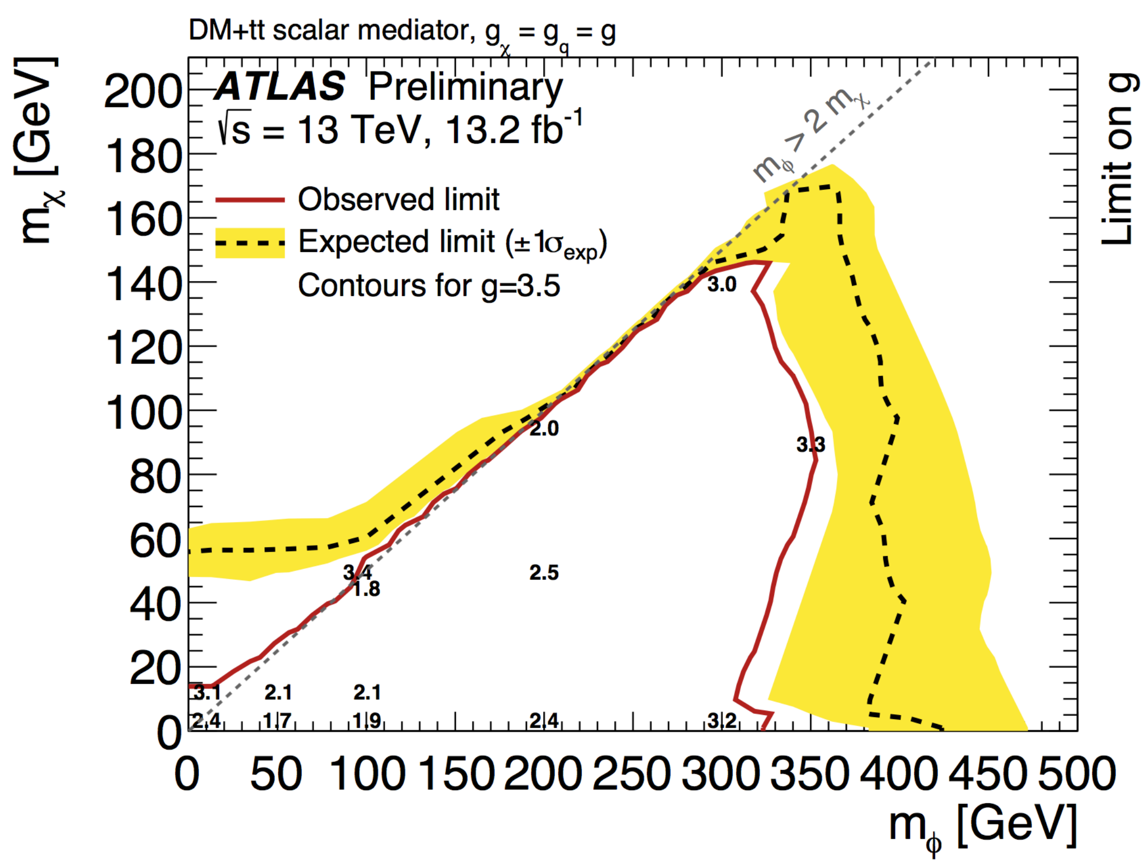

NO corresponding analysis by CMS!

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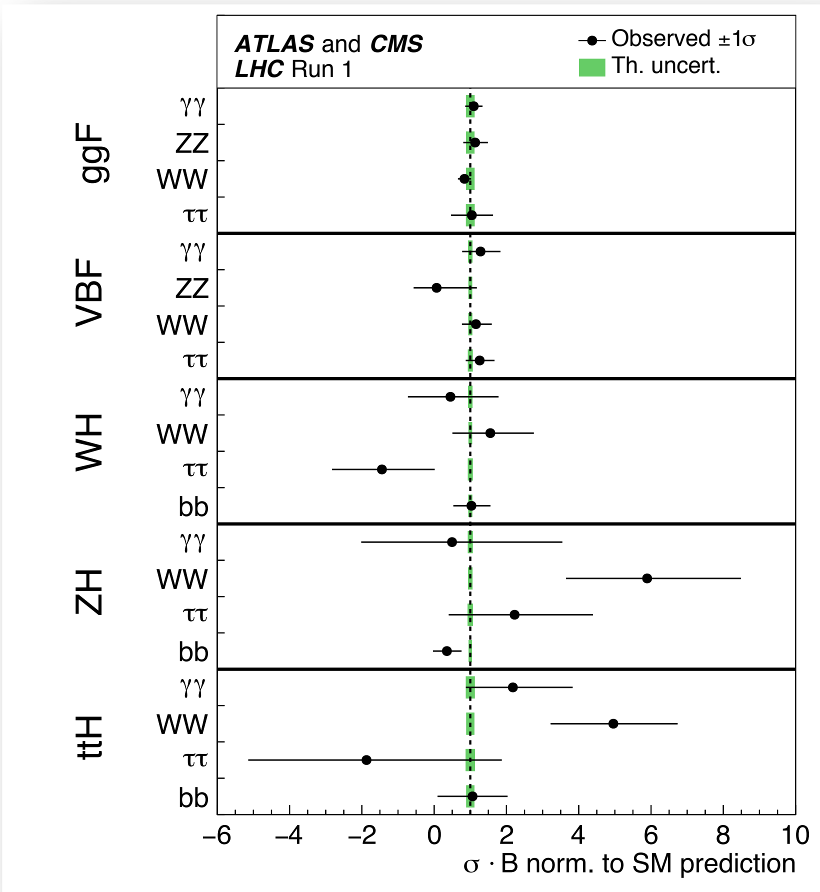

ATLAS+CMS Run 1 legacy combination: 1606.02266

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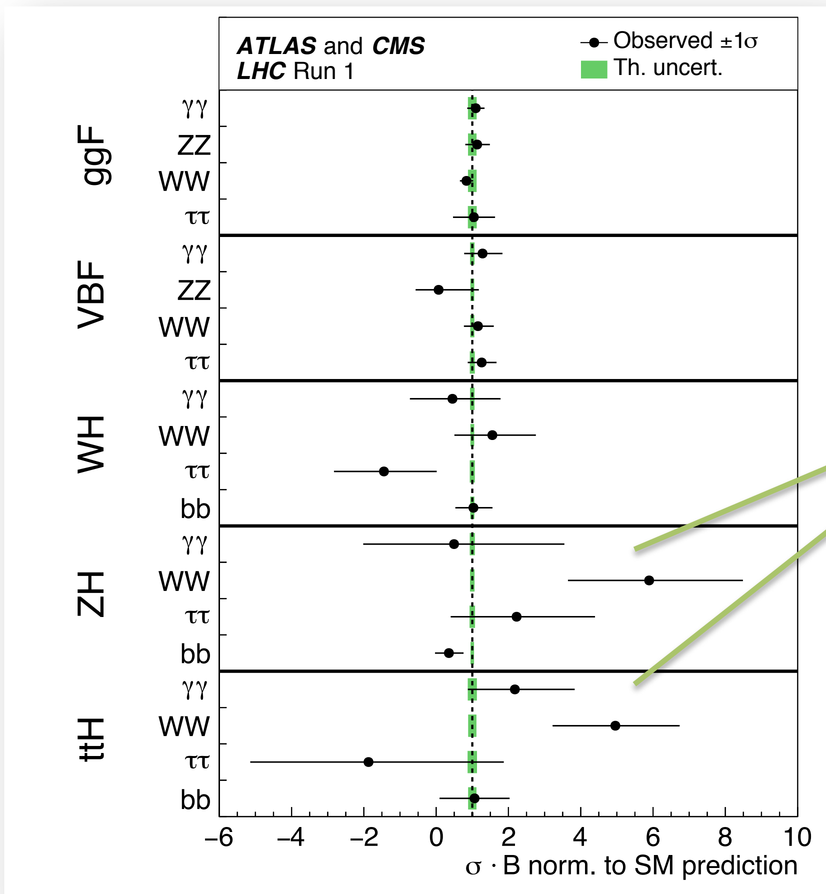

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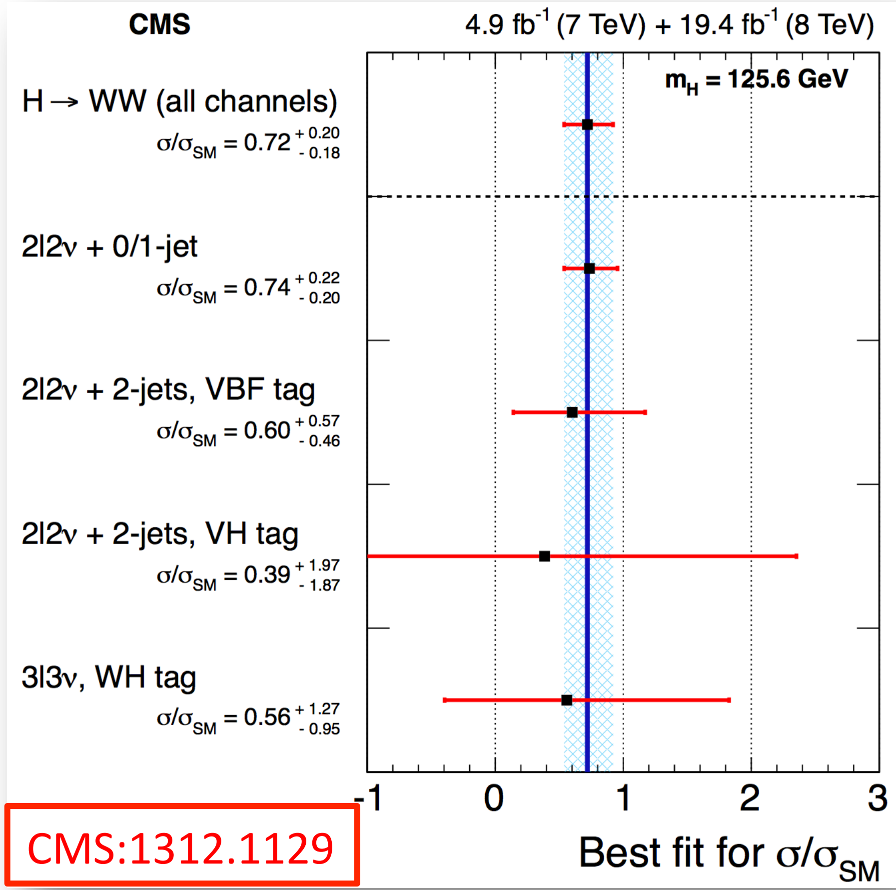
Mild excesses in H->WW
In ZH and ttH production channel

$$\mu_{ZH} = 5.9^{+2.6}_{-2.2}$$

$$\mu_{ttH} = 5.0^{+1.8}_{-1.7}$$

The combination in Z+(H→WW) channel is driven leptonic final states:



CMS:1312.1129

No excess was seen in ggH/VBF/WH tag!

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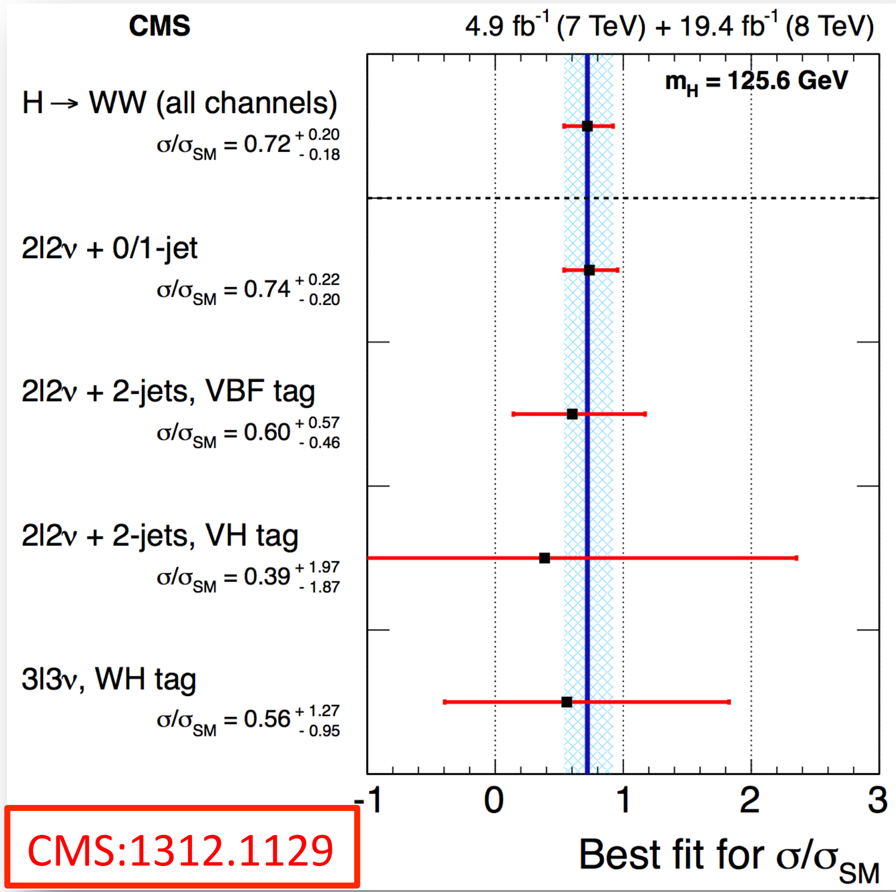

No excess was seen in ggH/VBF/WH tag!

Only ZH tag sees the enhancement.

Figure 23: Observed σ/σ_{SM} for $m_H = 125.6$ GeV for each category used in the combination. The observed σ/σ_{SM} value in the ZH $\to 3\ell\nu$ 2 jets category is $6.41^{+7.43}_{-6.38}$. Given its relatively large uncertainty with respect to the other categories it is not shown individually, but it is used in the combination.

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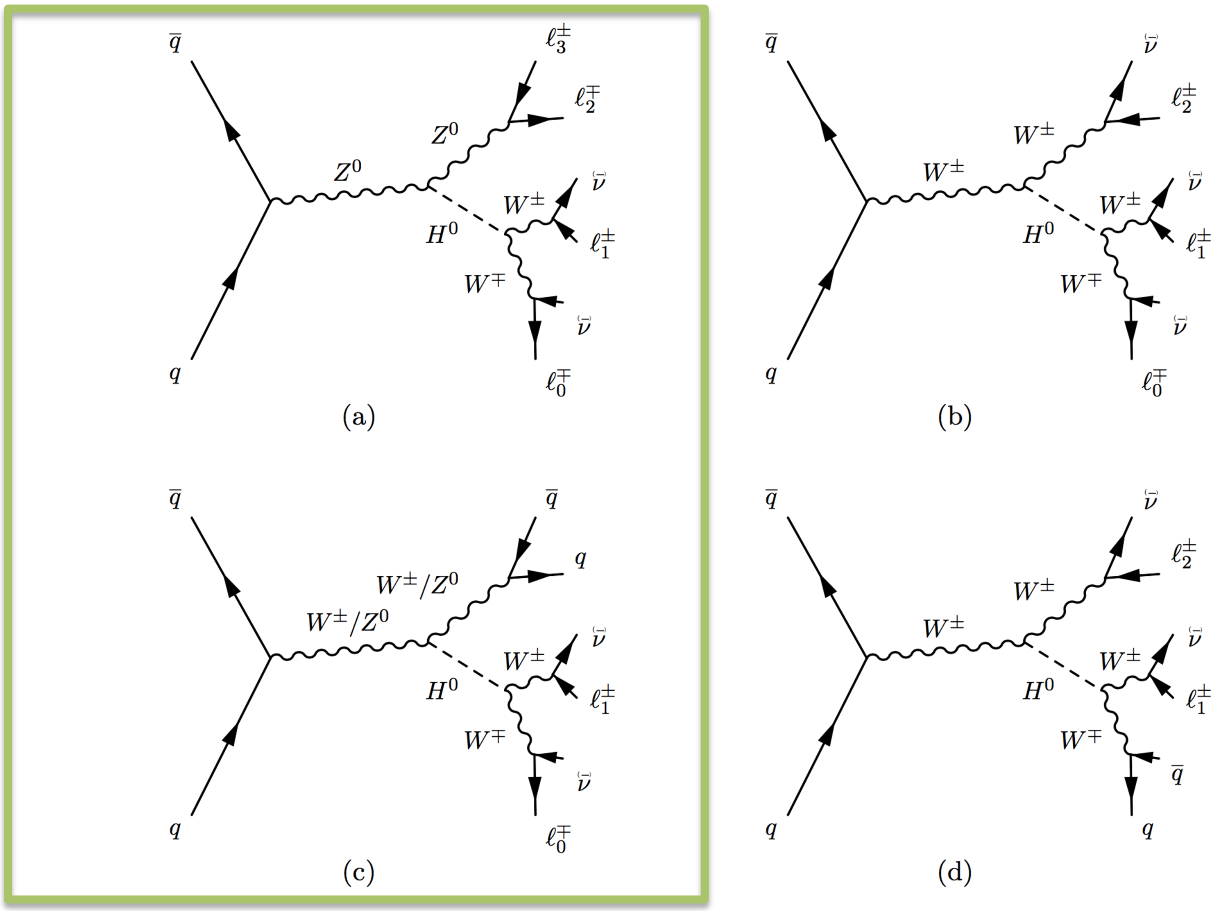

$$\mu_{WH} = 2.1^{+1.5}_{-1.3}\,(\text{stat.})^{+1.2}_{-0.8}\,(\text{sys.}),\quad \mu_{ZH} = 5.1^{+3.8}_{-3.0}\,(\text{stat.})^{+1.9}_{-0.9}\,(\text{sys.})$$

$$\mu_{VH} = 3.0^{+1.3}_{-1.1}\,(\text{stat.})^{+1.0}_{-0.7}\,(\text{sys.}).$$

ATLAS:1506.06641

Did ATLAS and CMS see the same excess in ZH channel?

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ATLAS Channels:

- 4-lepton + 2ν
  (Z → 2L, H → WW → 2L +2ν)
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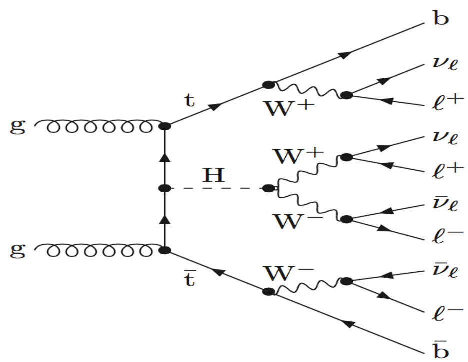
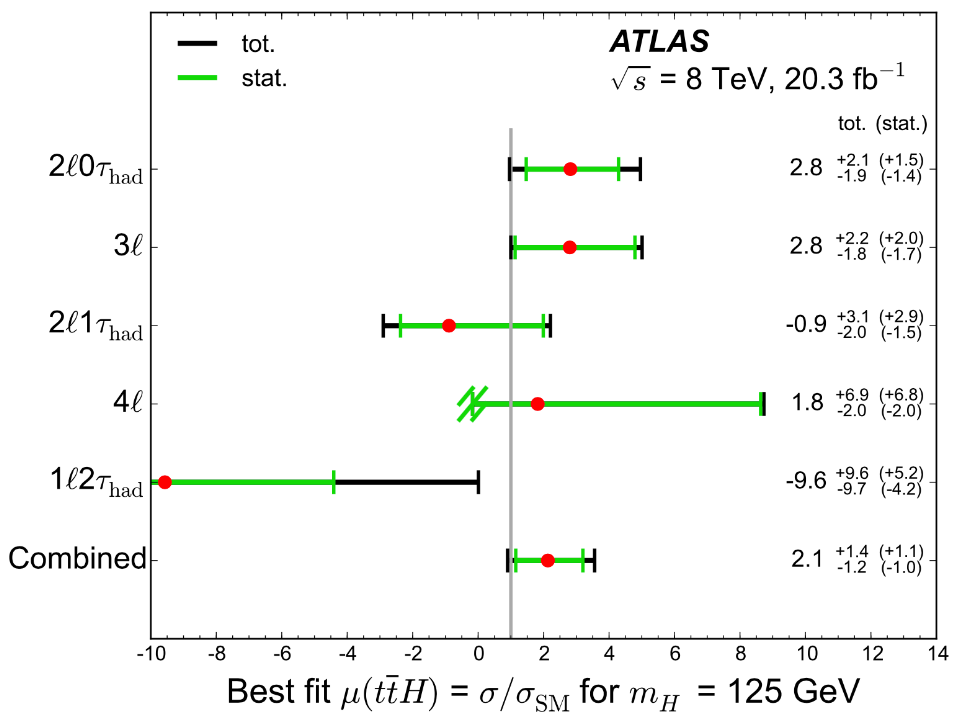
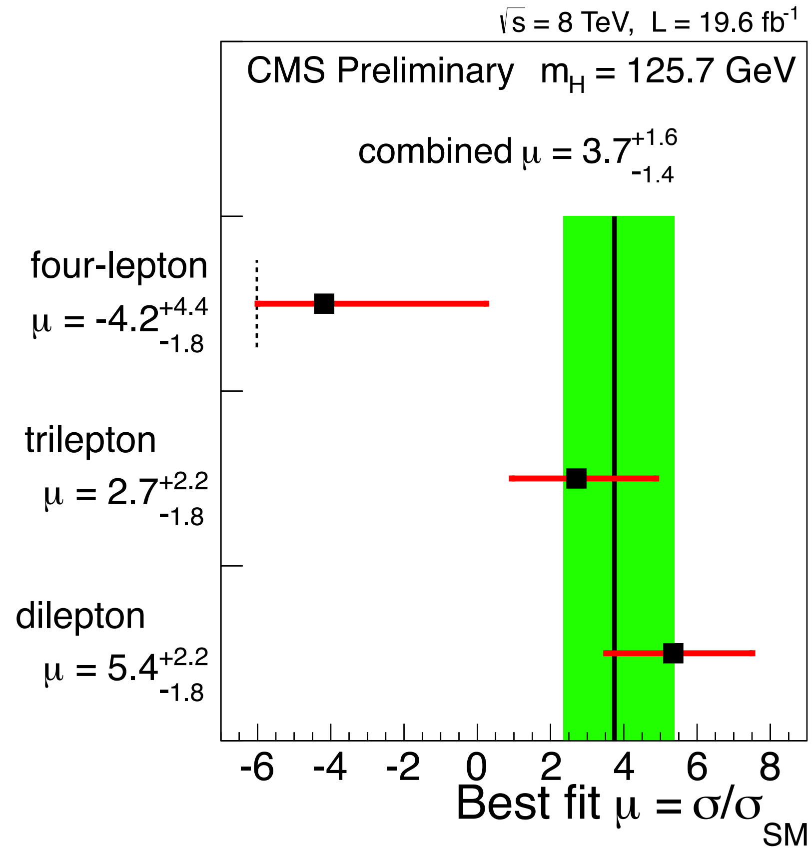
It is not clear that they saw the same excess…

Moreover, there's NO update in this channel at ICHEP. Would be interesting to see what happens at Run 2.

The combination in tt+(H → WW) is also driven by the leptonic channels.







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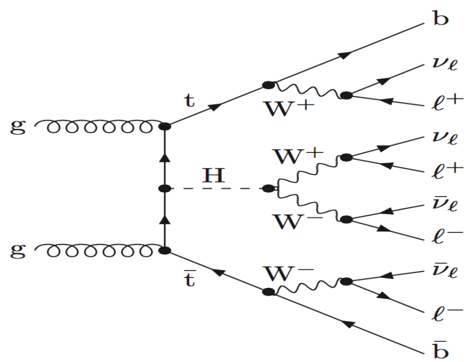

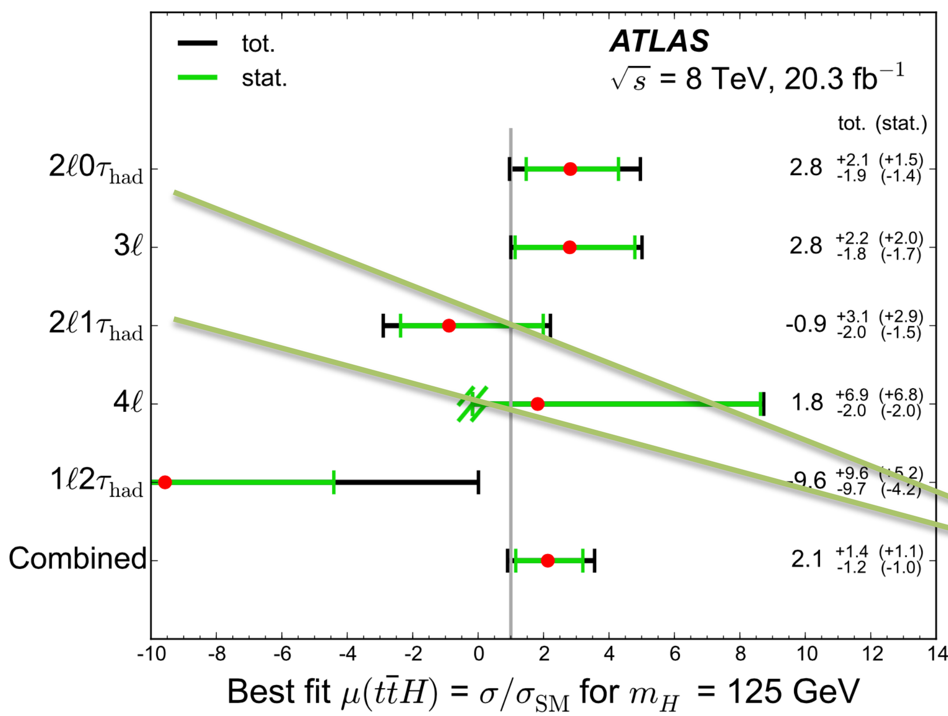

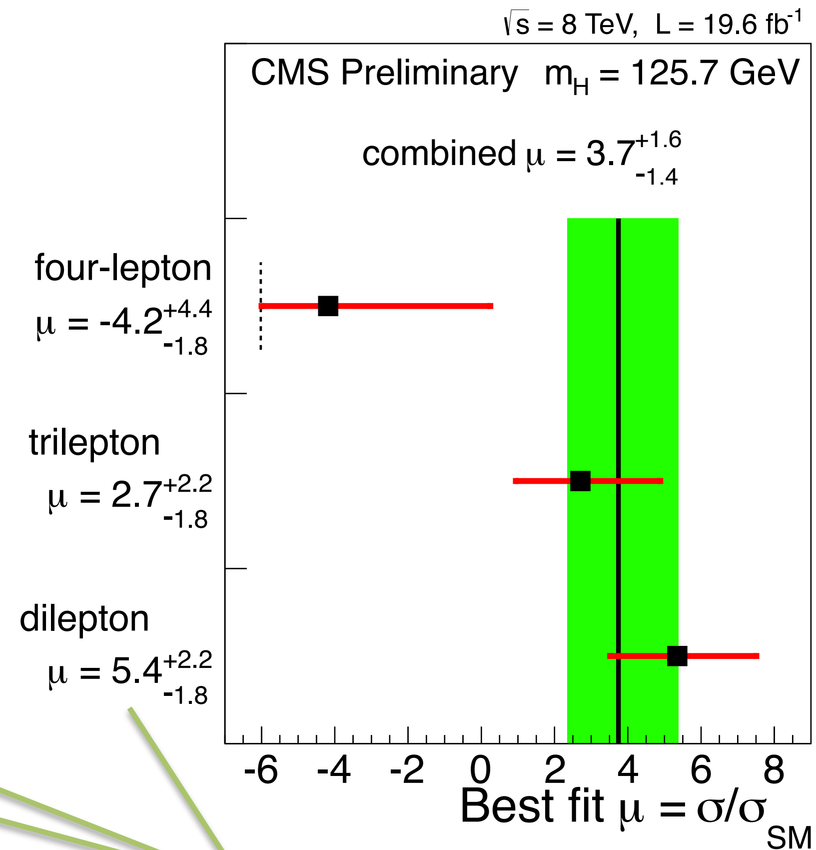

Same-sign dileptons!

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Both ATLAS and CMS looked for

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- 3-lepton + b-jets + MET
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There's strong overlap in the signal regions searched for by ATLAS and CMS!

However, the "Higgs mass" is never reconstructed in the $t\bar{t}$+(H → WW) analyses.

In fact, multilepton + b-jets + MET are quintessential BSM signatures!

At Run 1, it doesn't matter where you look, there seems always an excess in SS2L + b-jets+MET:

- CMS SS2L SUSY search in **arXiv:1311.6736** – A cut-and-count analysis; No p-value is given for the excess.
- ATLAS SS2L SUSY search in **arXiv:1404.2500** – A cut-and-count analysis; the p-value is 0.07.
- CMS SS2L HIGGS search in **arXiv:1408.1682** – A MVA analysis; best-fit $\mu = 5.3^{+2.1}_{-1.8}$.
- ATLAS SS2L Exotica search in **arXiv:1504.04605** – A cut-and-count analysis; the p-value is 0.029.
- ATLAS SS2L HIGGS search in **arXiv:1506.05988** – A cut-and-count analysis; best-fit $\mu = 2.8^{+2.1}_{-1.9}$.
- ATLAS measurements on SM ttW in **arXiv:1509.05276**: expects a significance of 2.8-sigma and observed 5.0-sigma in the SS2L channel.
- CMS measurements on SM ttW in **arXiv:1510.01131**: the observed signal strength (in unit of SM expectation) is $2.04_{-0.61}^{+0.74}$.

These analyses looked at two independent datasets with different cuts and different background subtraction methods. They all saw an excess.

What did Run 2 see in $t\bar{t}$+(H $\rightarrow$ WW) so far?

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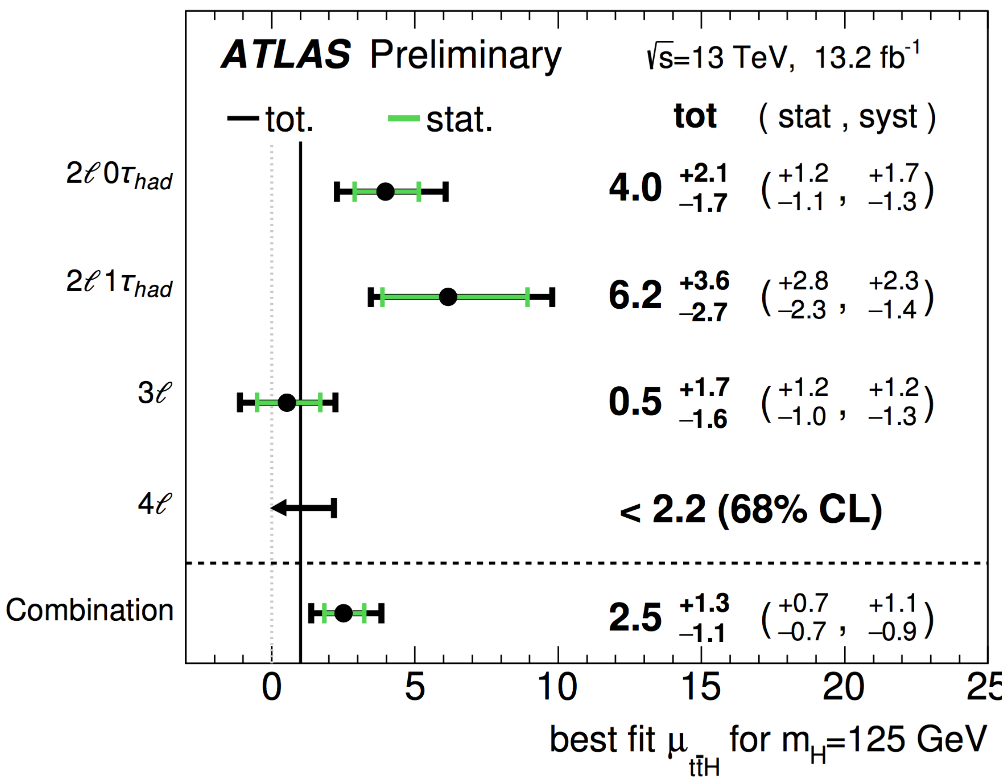
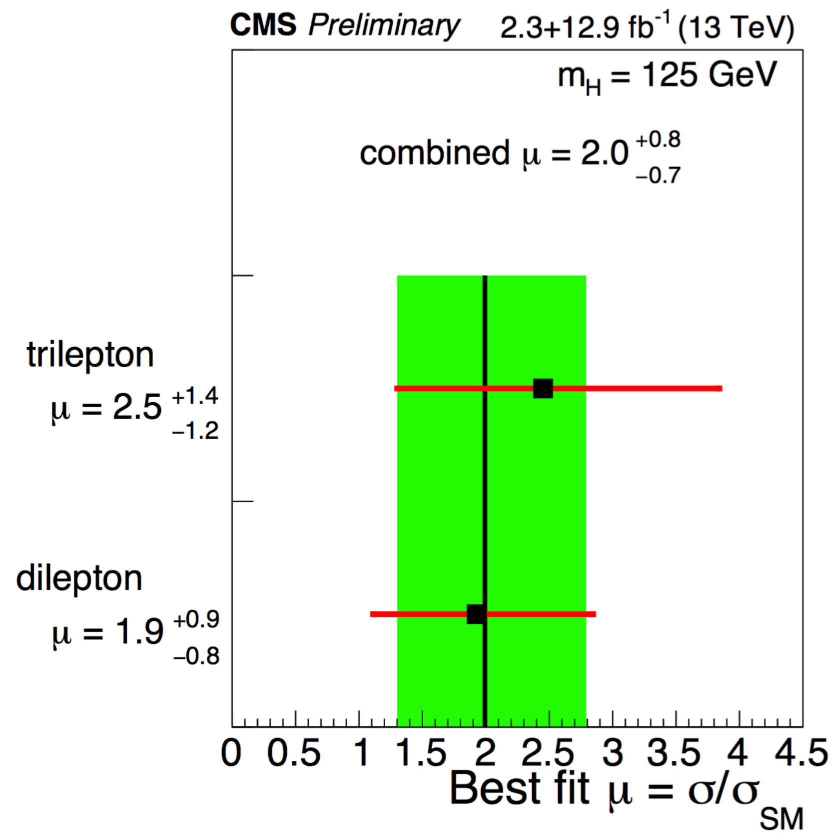
ATLAS@ICHEP: $\mu = 2.5_{-1.1}^{+1.3}$

CMS@ICHEP: $\mu = 2.0_{-0.7}^{+0.8}$

(ATLAS+CMS@Run1: $\mu = 5.0_{-1.7}^{+1.8}$)





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- Systematic uncertainties that are missed by ATLAS and CMS at both Run 1 and Run 2??
- Underestimated SM rates (such as ttbar+W/H)??
- We are on the verge of seeing BSM physics?

Broadly speaking, the multilepton + b-jets + MET excess can be characterized as

$$2\,b + 4\,W + X$$

If X = MET, then we have 2 b + 4 W + MET final states.

However "X" could contain MET + additional visible or soft particles.

Example: four tops final state!

If we assume the final state comes from pair production of heavy particles proceeding through identical decay chains,

Could this be a window for light stops/sbottoms?

P. Huang, A. Ismail, IL and C. Wagner: 1507.01601

Under these assumptions, the electric charge of the heavy particle can be classified, assuming a neutral stable particle *N* giving rise to additional MET.

- Charge (-1/3) particle with the decay topology:

$$\mathcal{B} \to t + W^- + N$$

This case includes the sbottom in SUSY,

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

or the T-odd B-prime fermion in little Higgs theories with T-parity,

$$b' \to t + (W_H^- \to W^- A_H)$$

Under these assumptions, the electric charge of the heavy particle can be classified, assuming a neutral stable particle *N*.

- Charge (+2/3) particle with the decay topology:

$$\mathcal{T} \to t + W^{\pm} + C^{\mp}$$

where $C^{\pm}$ is nearly degenerate with N and subsequently decays

$$C^{\pm} \to N + \text{soft charged particles}$$

Will see an example of this from top squarks.

Under these assumptions, the electric charge of the heavy particle can be classified, assuming a neutral stable particle *N*.

- Charge (+5/3) particle with the decay topology:

$$\mathcal{X}_{5/3} \to t + W^{+} + N$$

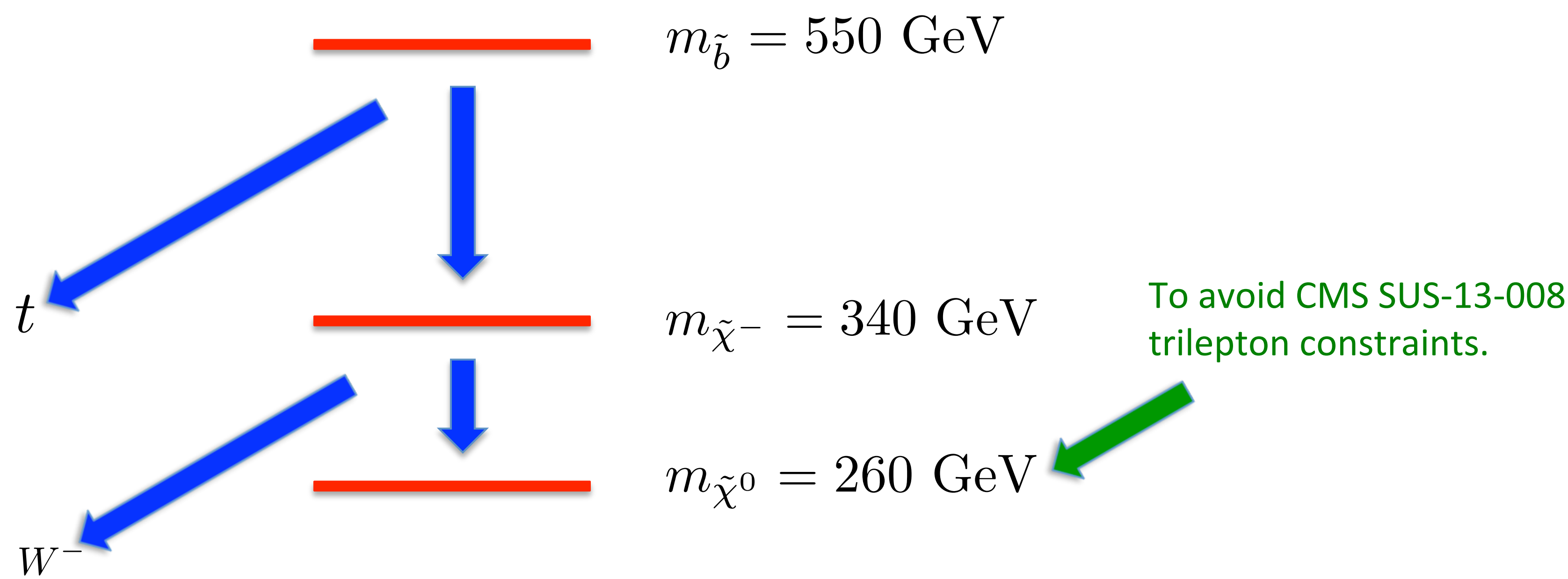
One closely related illustration is the charged-5/3 fermions in composite Higgs models

$$X_{5/3} \to t + W^{+}$$

In which case the MET comes solely from the neutrino in W-decay.

We normalize any BSM signal to the SM ttH strength.

For example, one could consider the sbottom decays with the spectrum:



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$$\mu_{tot} = 2.8$$

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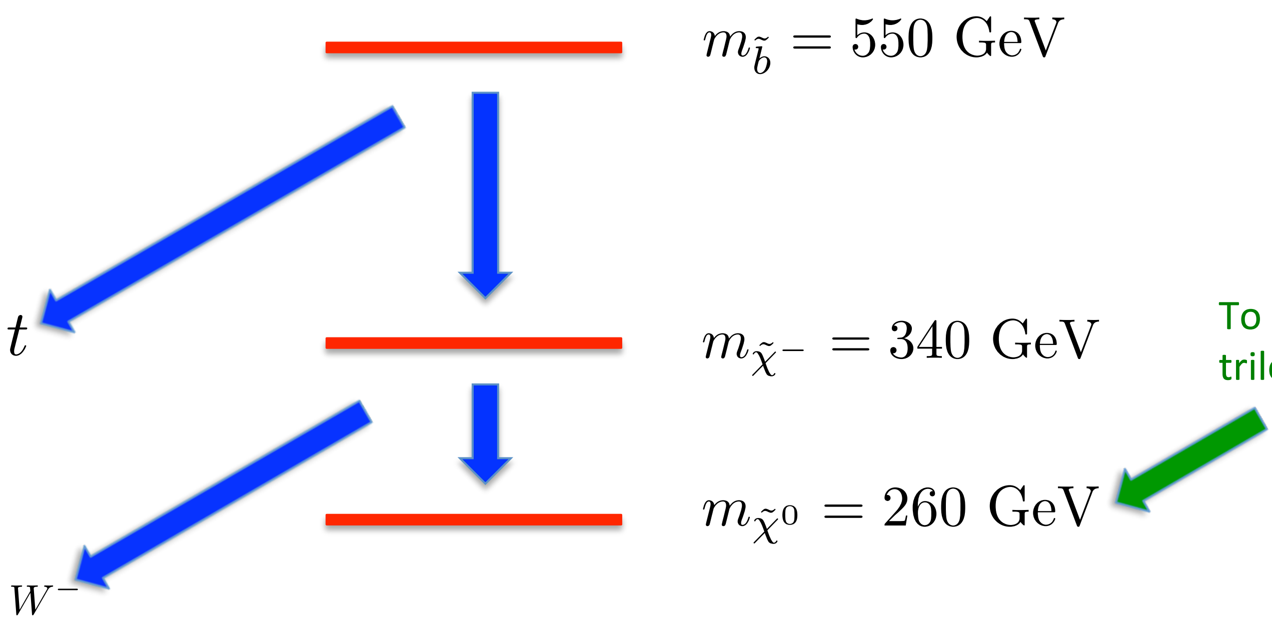


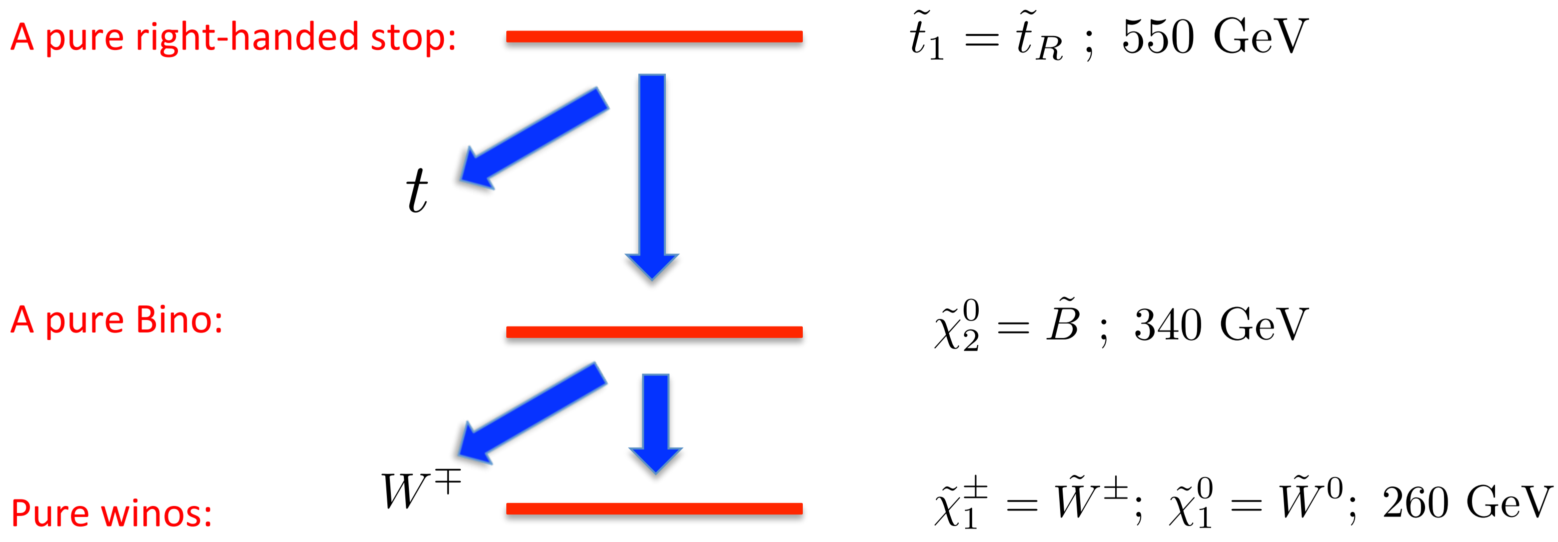
To avoid CMS SUS-13-008 trilepton constraints.

$$\mu_{\tilde{b}}/\mu_{ttH} = 1.8$$

$$\mu_{tot} = 2.8$$

It's difficult to make this decay BR 100% in SUSY because of sbottom → bottom+LSP

We can also generate the signal with light stops in a "realistic" MSSM spectrum with almost 100% decay BR:



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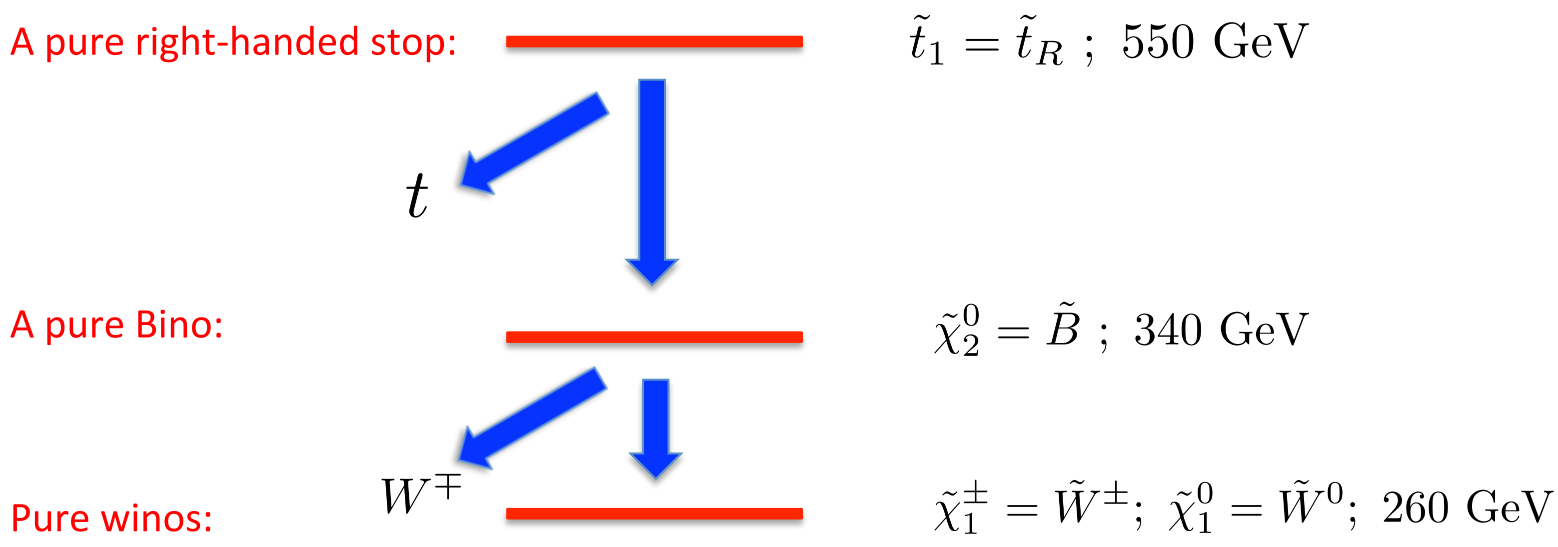

$$\mu_{\tilde{t}} = 1.83$$

$$\mu_{\rm tot} = 2.83$$

W-boson can have either sign, which gives a spectacular Same-sign 3L+b-jet+MET signal!

At 13 TeV, this benchmark predicts a signal strength in tt+(H→WW):

$$\mu(13\ \text{TeV}) = 3.69$$

In 2016 data the 95% C.L. upper limit on this signal strength is

$$\mu_{ATLAS}(13\text{TeV}) \leq 4.9$$
$$\mu_{CMS}(13\text{TeV}) \leq 3.9$$

For “natural SUSY,” however, both (stop_L, stop_R) and sbottom_L cannot be too heavy!

- If we make stop1 “stealth,” then stop2 and sbottom1 may be accessible.
- Typical stop2 and sbottom1 search channels are:

$$
\begin{aligned}
&\tilde{t}_2 \to \tilde{t}_1 + Z \text{ or } h \\
&\tilde{b}_1 \to b + \tilde{\chi}_1^0, \\
&\tilde{b}_1 \to t + \tilde{\chi}_1^\pm, \\
&\tilde{b}_1 \to b + \tilde{\chi}_2^0, \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h
\end{aligned}
$$

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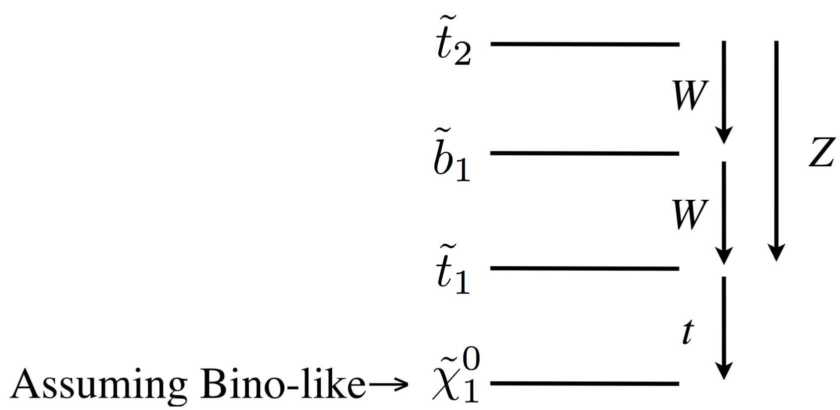
It’s useful to recall that SUSY searches all adopt the “Simplified Model” approach, with 100% BR!

For light (stop1, stop2) and sbottom1, with a stealth stop1, there could be two types of spectra:

- Type A: charginos and NLSP are **heavier** than stop2 and decouple. LSP is Bino-like.



H.-C. Cheng, L. Li and Q. Qin: 1607.06547

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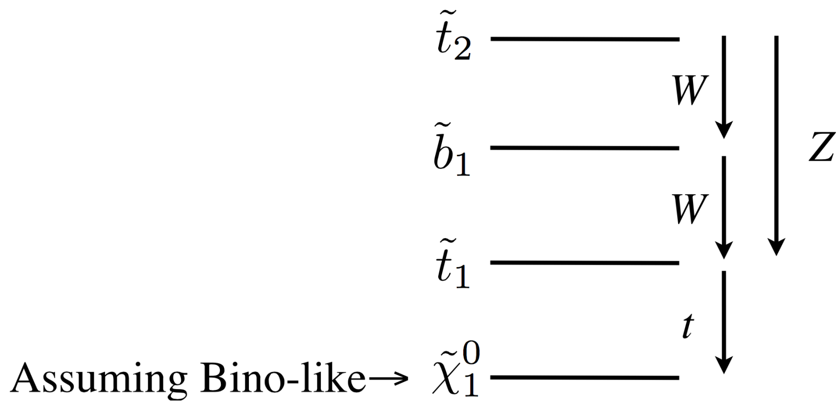

- Type B: charginos and NLSP are **lighter** than stop2 and appear in the decay chain. LSP can be either Wino- or Higgsino-like.

H.-C. Cheng, L. Li and Q. Qin: 1607.06547

Two out of nine (9!) benchmarks in 1607.06547:

Spectrum	A1	A2
$m_{\tilde{t}_2}$(GeV)	751.3	815.4
$m_{\tilde{b}_1}$(GeV)	524.6	693
$m_{\tilde{t}_1}$(GeV)	409.4	491
$m_{\tilde{\chi}_1^0}$(GeV)	220.9	304.9
$X_t/m_{\tilde{t}}$	1.89	-1.81
m_h(GeV)	122.1	122.8

Decay branching ratios

Channel	A1	A2
$\tilde{t}_2 \to \tilde{b}_1 + W^+$	47.8	16.5
$\tilde{t}_2 \to \tilde{t}_1 + Z$	44	74.5
$\tilde{t}_2 \to \tilde{t}_1 + h$	4.6	5.9
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The BR's into typical search channels are very small!

ATLAS does have a result on stop2 → stop1 + Z, stop1 → top + LSP, but the limit is not strong:

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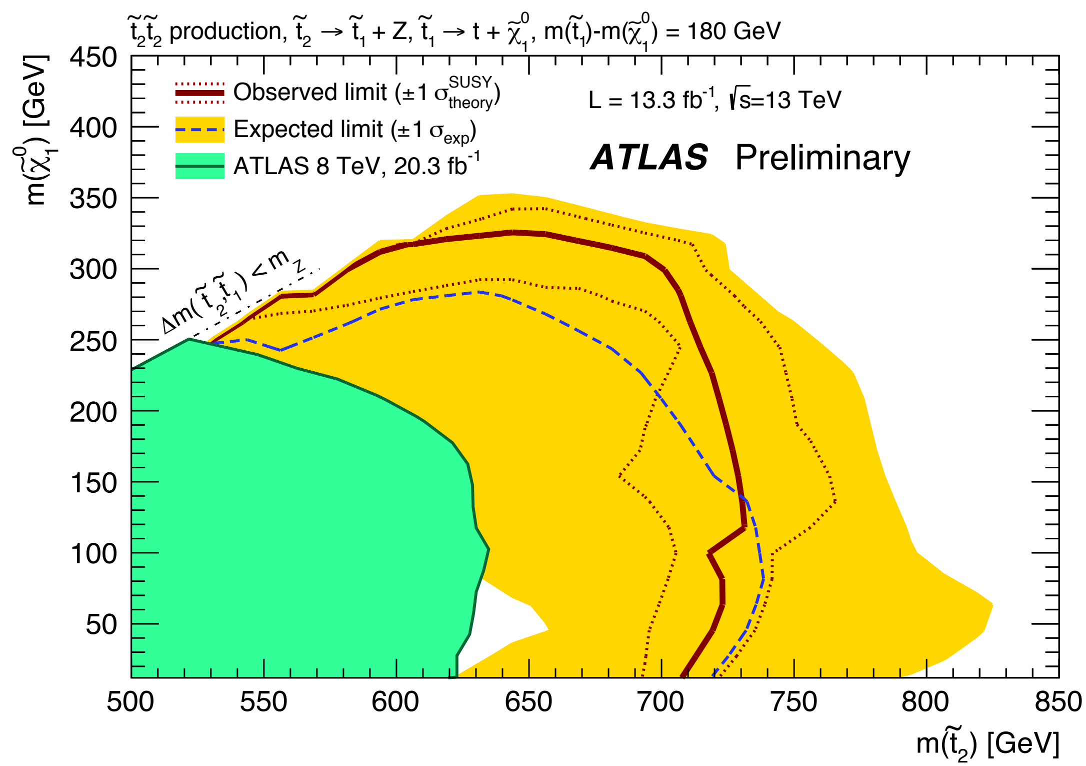

ATLAS-CONF-2016-038

The decay phenomenology is quite rich and interesting.

Final state percentages

	A1	A2
$\sigma(\tilde{t}_2\tilde{t}_2)(fb)$	57.6	33.8
$ttZZ$	19.4	55.5
$ttZWW$	42.0	24.6
$ttZh$	4.0	8.8
$tt4W$	22.8	2.7
$tthWW$	4.4	1.9
$tthh$	0.2	0.4
$\sigma(\tilde{b}_1\tilde{b}_1)(fb)$	500	97
$ttWW$	92.7	98
tbW	7.1	2

Slides from Hsin-Chia Cheng

The decay phenomenology is quite rich and interesting.

Both benchmarks contribute to the multilepton + b-jets +MET excess.

SS2l signal strength compared to SM *tth* @ 8 TeV

A1:

$\mu_{\tilde{b}_1} \approx 1.9$

$\mu_{\tilde{t}_2} \approx 0.3$

$\mu_{\rm tot} \approx 3.2$

A2:

$\mu_{\tilde{b}_1} \approx 0.5$

$\mu_{\tilde{t}_2} \approx 0.1$

$\mu_{\rm tot} \approx 1.6$

CMS

$\mu = 5.3^{+2.1}_{-1.8}$

ATLAS

$\mu = 2.8^{+2.1}_{-1.9}$

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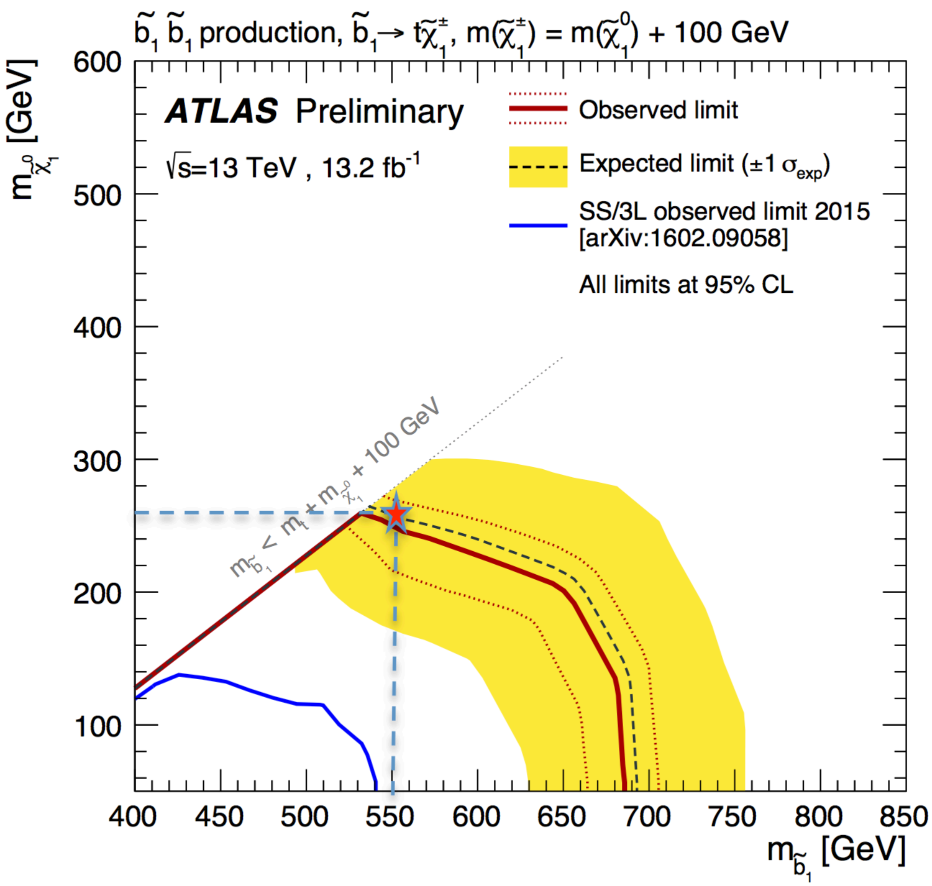
If the multilepton excess is real, we should

- Start seeing “something” in dedicated SS2L sbottom searches **very soon:**



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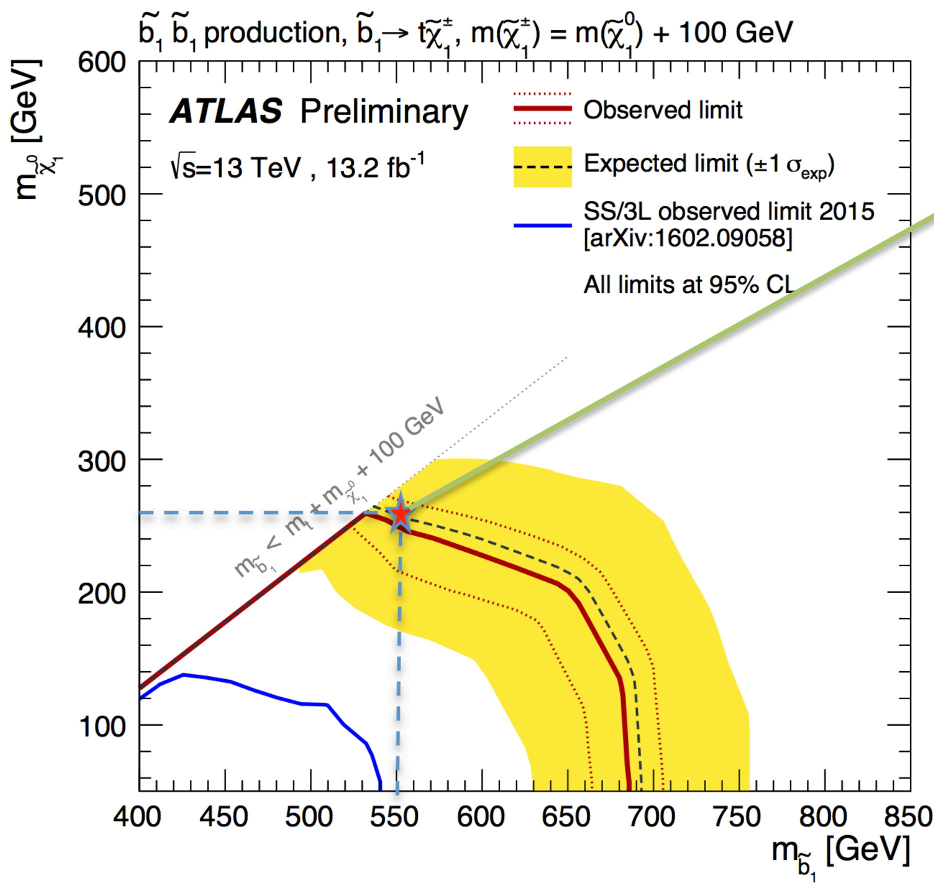

ATLAS@ICHEP is just starting to be sensitive to a 550 GeV sbottom decaying to a 260 GeV LSP!

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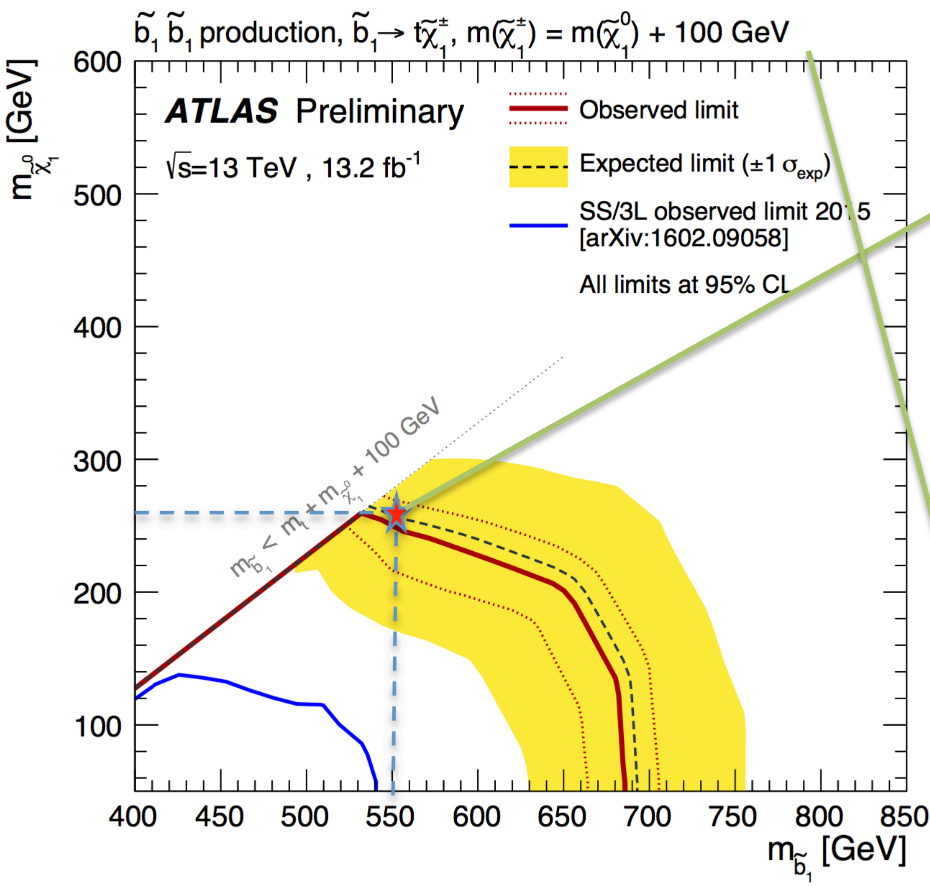


ATLAS@ICHEP is just starting to be sensitive to a 550 GeV sbottom decaying to a 260 GeV LSP!

However, our benchmark has

M_chargino – M_LSP = 80 GeV

As a result the acceptance will be smaller and bound be weaker!

If the multilepton excess is real, we should

- Observe correlated activities in 1L+jets+MET and multi-jet hadronic channels:

By Brian Petersen at KITP LHC Workshop

ATLAS 8 TeV Acceptance

- Most significant in same-sign-1b signal region
  - Expect ~3.5 events in 8 TeV analysis (cross section is 45fb)

SR	Leptons	$N_{b-\text{jets}}$	Other variables	Additional requirement on m_{eff}
SR3b	SS or 3L	≥ 3	$N_{\text{jets}} \geq 5$	m_{eff}>350 GeV
SR0b	SS	$= 0$	$N_{\text{jets}} \geq 3$, E_T^{miss}> 150 GeV, m_T> 100 GeV	m_{eff}>400 GeV
SR1b	SS	≥ 1	$N_{\text{jets}} \geq 3$, E_T^{miss}> 150 GeV, m_T>100 GeV, SR3b veto	m_{eff}>700 GeV
SR3Llow	3L	-	$N_{\text{jets}} \geq 4$, $50 < E_T^{\text{miss}} <$ 150 GeV, Z boson veto, SR3b veto	m_{eff}>400 GeV
SR3Lhigh	3L	-	$N_{\text{jets}} \geq 4$, E_T^{miss}> 150 GeV, SR3b veto	m_{eff}>400 GeV

	SR3b	SR0b	SR1b	SR3Llow	SR3Lhigh
Observed events	1	14	10	6	2
Total expected background events	2.2 ± 0.8	6.5 ± 2.3	4.7 ± 2.1	4.3 ± 2.1	2.5 ± 0.9
$p(s=0)$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

1.5 event expected here

- ~2 events expected in loose Stop 0/1-lepton searches, but background yields higher

If the multilepton excess is real, we should

- Observe correlated activities in 1L+jets+MET and multi-jet hadronic channels:

By Brian Petersen at KITP LHC Workshop

ATLAS 13 TeV Acceptances

- Same region most promising in 13 TeV searches
  - Now expect ~2.5 events (cross section is 300 fb)

Signal region	$N_{\rm lept}^{\rm signal}$	$N_{b-\rm jets}^{20}$	$N_{\rm jets}^{50}$	$E_{\rm T}^{\rm miss}$ [GeV]	$m_{\rm eff}$ [GeV]
SR0b3j	≥ 3	$=0$	≥ 3	>200	>550
SR0b5j	≥ 2	$=0$	≥ 5	>125	>650
SR1b	≥ 2	≥ 1	≥ 4	>150	>550
SR3b	≥ 2	≥ 3	-	>125	>650

Asking for 3 leptons kills 85% of signal

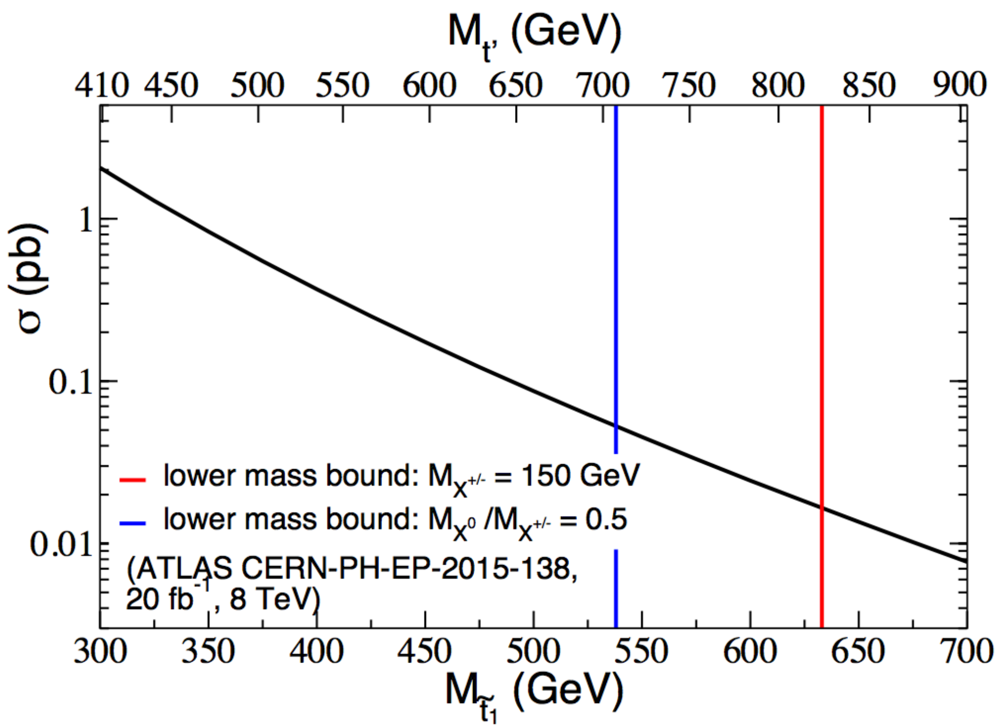
	SR0b3j	SR0b5j	SR1b	SR3b
Observed events	3	3	7	1
Total background events	1.5 ± 0.4	0.88 ± 0.29	4.5 ± 1.0	0.80 ± 0.25
$p(s=0)$	0.13	0.04	0.15	0.36
Fake/non-prompt leptons	< 0.2	0.05 ± 0.18	0.8 ± 0.8	0.13 ± 0.17
Charge-flip	–	0.02 ± 0.01	0.60 ± 0.12	0.19 ± 0.06
$t\bar{t}W$	0.02 ± 0.01	0.08 ± 0.04	1.1 ± 0.4	0.10 ± 0.05
$t\bar{t}Z$	0.10 ± 0.04	0.05 ± 0.03	0.92 ± 0.31	0.14 ± 0.06
WZ	1.2 ± 0.4	0.48 ± 0.20	0.18 ± 0.11	< 0.02
$W^{\pm}W^{\pm}jj$	–	0.12 ± 0.07	0.03 ± 0.02	< 0.01
ZZ	< 0.03	< 0.04	< 0.03	< 0.03
Rare	0.14 ± 0.08	0.07 ± 0.05	0.8 ± 0.4	0.24 ± 0.14

- ~5 events in 7-10 jet search, but much larger bkgd

It's also interesting to ask whether a fermionic "top partner" could explain the excess.

$$pp \to b'\bar{b}' \to (tW_H^-)(\bar{t}W_H^+) \to (tW^- A_H)(\bar{t}W^+ A_H)$$

- At the same mass, fermions have a larger cross-section than scalars:



C.-R. Chen, H.-C. Cheng and IL: 1511.01452

It's also interesting to ask whether a fermionic "top partner" could explain the excess.

- The signal strengths for the b-prime benchmark at 8 and 13 TeV are

$$m_{b'} = 750 \text{ GeV} , \qquad m_{W_H} = 320 \text{ GeV} , \qquad m_{A_H} = 66 \text{ GeV}$$

$$\mu(8 \text{ TeV}) = 2.0$$
$$\mu(13 \text{ TeV}) = 3.2$$

$$\mu_{ATLAS}(13\text{TeV}) \leq 4.9$$
$$\mu_{CMS}(13\text{TeV}) \leq 3.9$$

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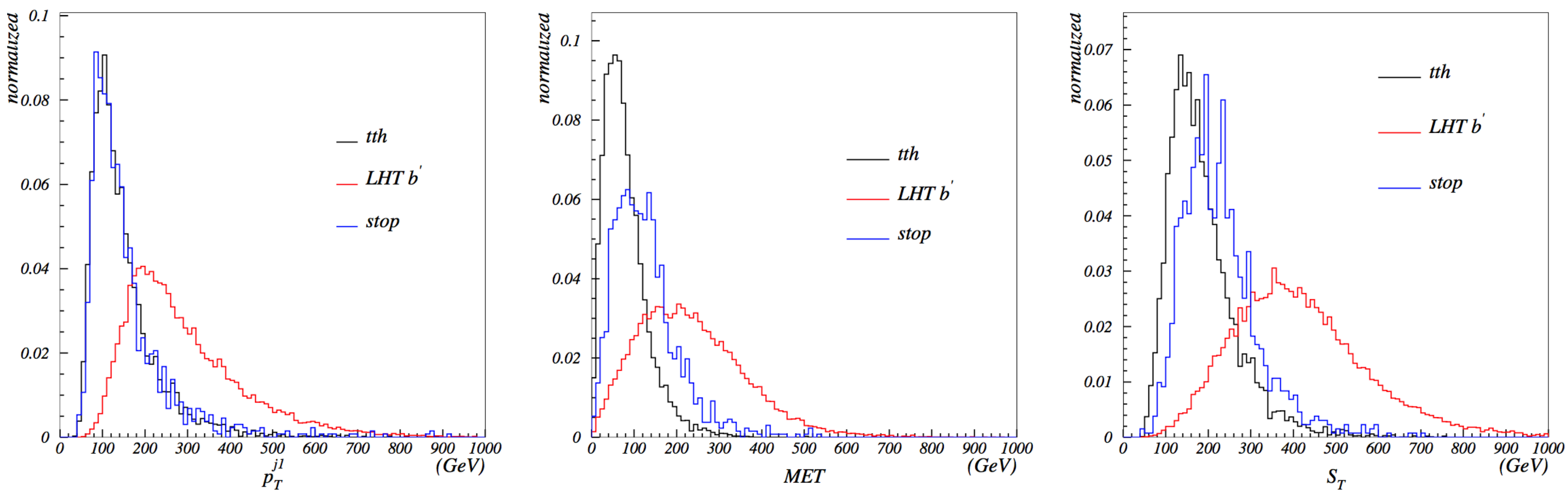
It's also interesting to ask whether a fermionic "top partner" could explain the excess.

$$pp \to b'\bar{b}' \to (tW_H^-)(\bar{t}W_H^+) \to (tW^- A_H)(\bar{t}W^+ A_H)$$

- As a result, fermionic benchmarks generically have more energetic spectra and, therefore, larger acceptances:



(a) (b) (c)

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Remark:

- Stay tuned for the multilepton ttH analyses in the near future.

- Watch out for correlated, if any, activities in hadronic searches.

- Need a way (for theorists) to cross-check if a particular benchmark is excluded by inclusive searches.