Top quarks and SUSY in ATLAS and CMS

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University of Oregon

on behalf of the ATLAS and CMS Collaborations

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22-27 September 2019

Introduction

- The top quark plays an essential role in understanding the structure of the Standard Model and its extensions (e.g., Supersymmetry)
- "Classic" SM top measurements have played a key role in understanding $t\bar{t}$ backgrounds to SUSY searches : e.g., radiation in $t\bar{t}$ events, differential cross-sections wrt $t\bar{t}$ p_T, jet multiplicity

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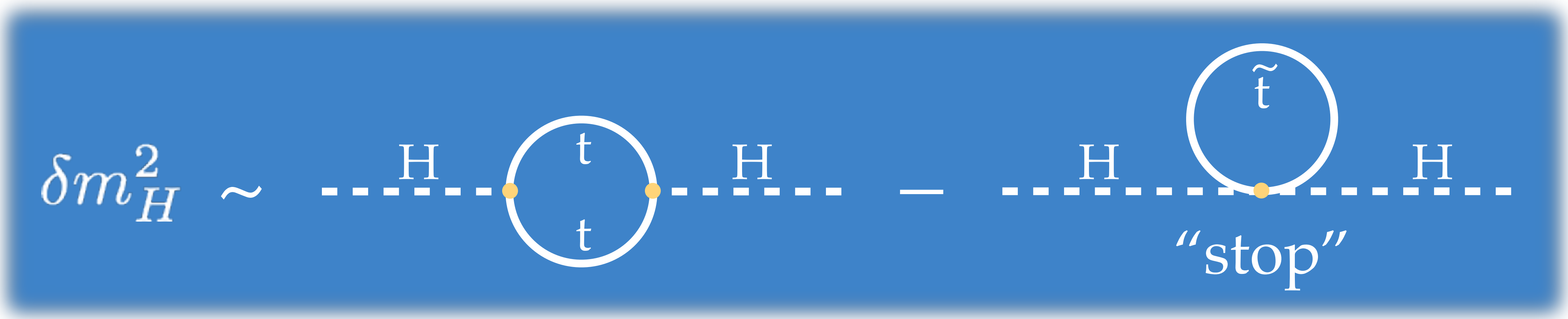
- Naturalness continues to motivate direct searches for top partners, such as the stop in Supersymmetry



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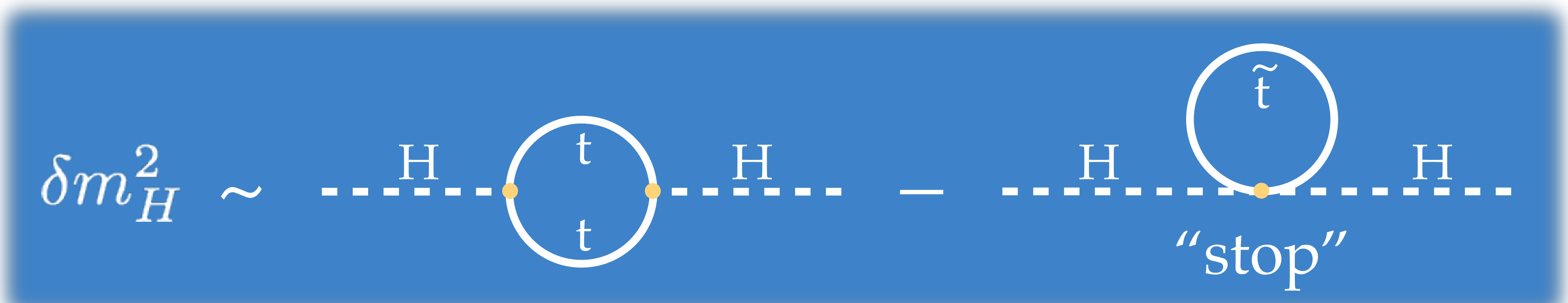
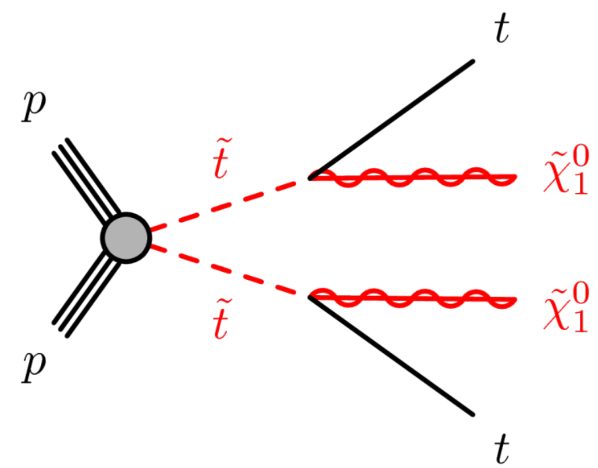
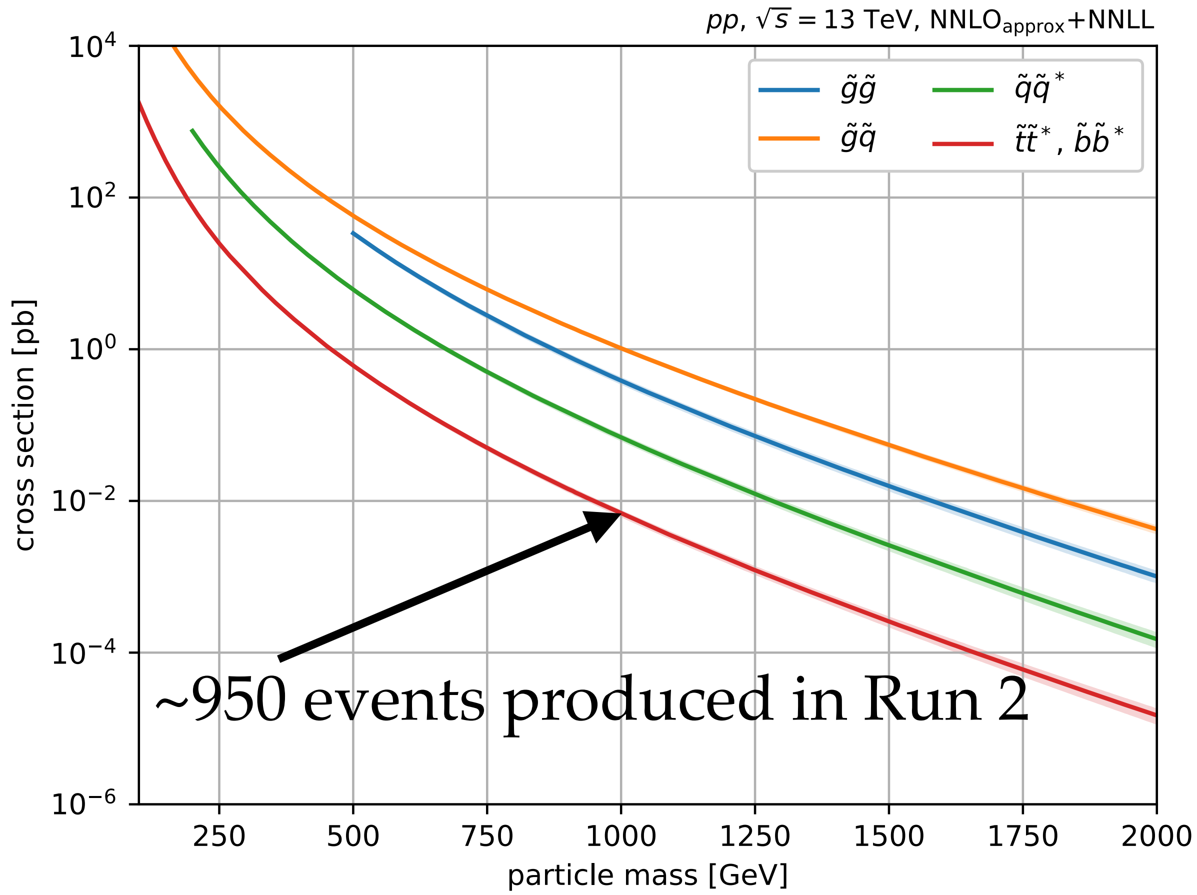


➡ Close interplay between top measurements and searches enable exploration of the "stealth" stop region - has it been excluded?

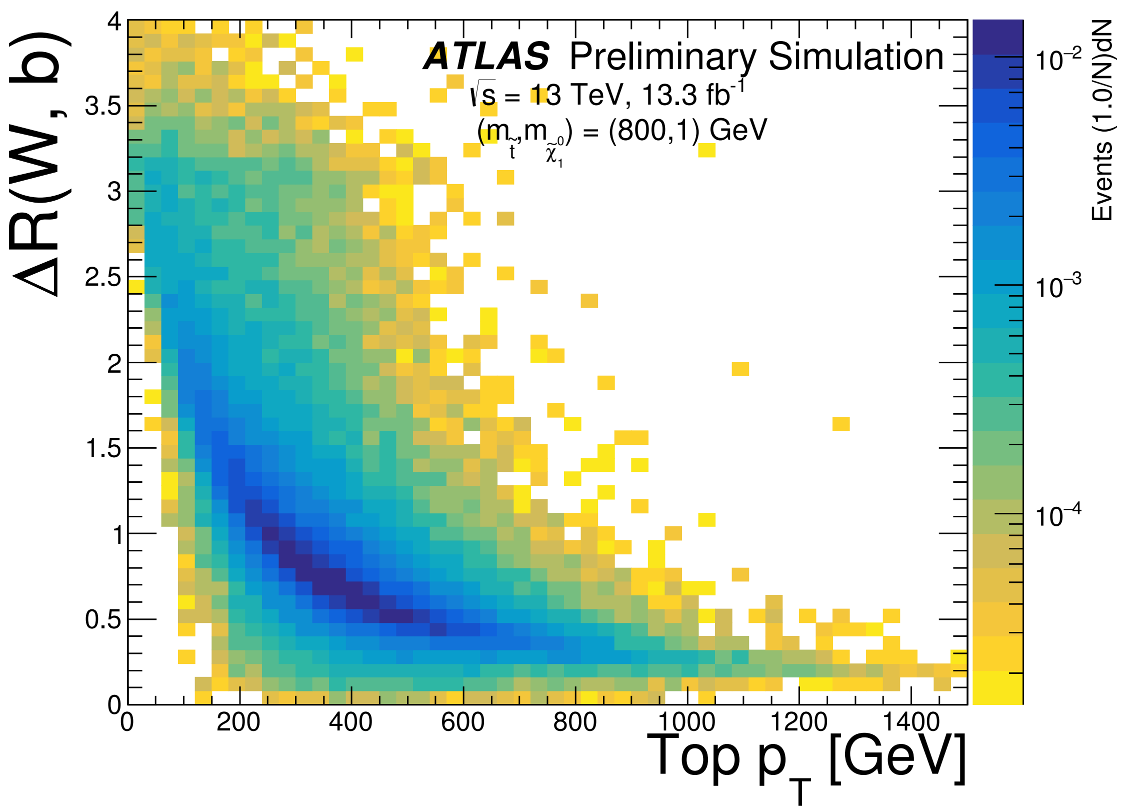
Direct Stop Searches

- Cross-section for direct pair production determined by stop mass (other SUSY particles decoupled)
- Nominal experimental signature: $t\bar{t}$ + MET
- First results based on the full Run 2 dataset (137-139 fb^{-1}) appearing





LHC SUSY Cross Section Working Group



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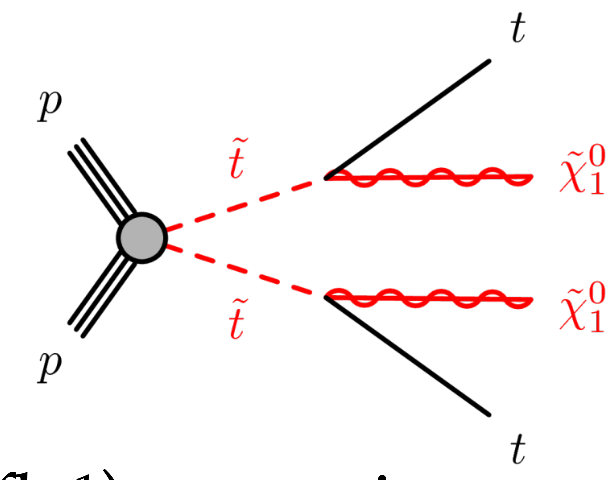
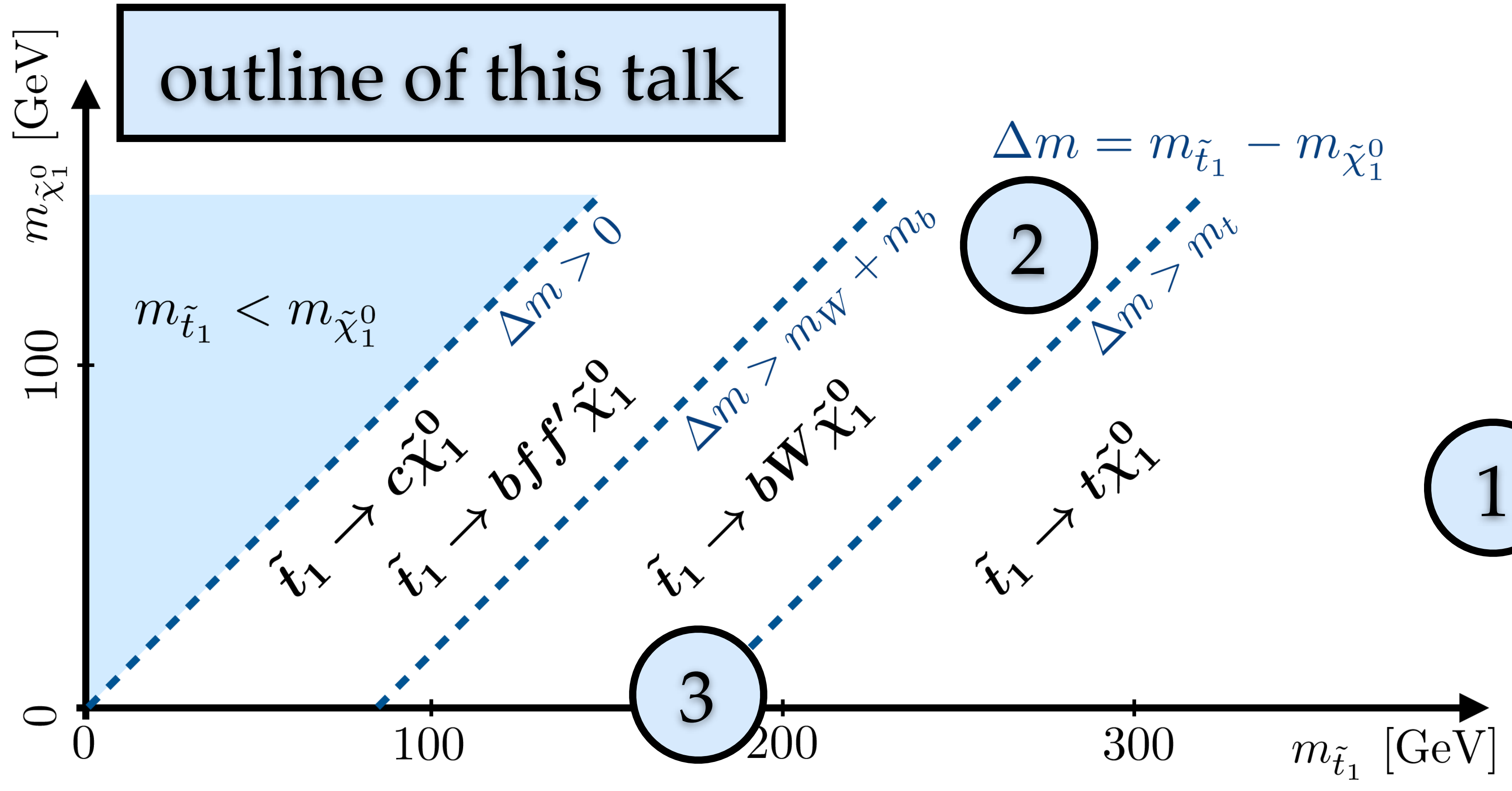
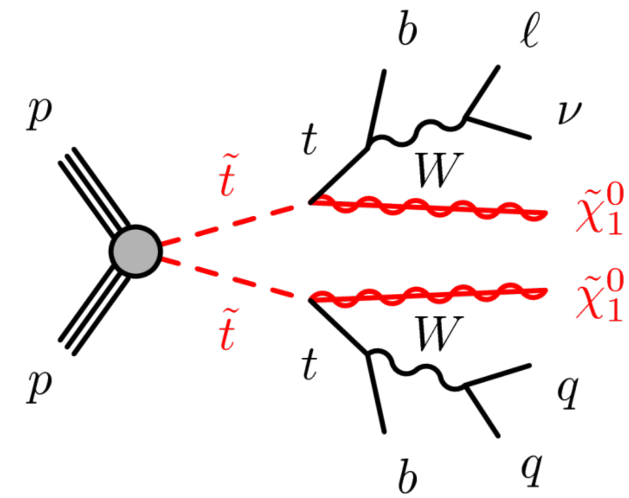


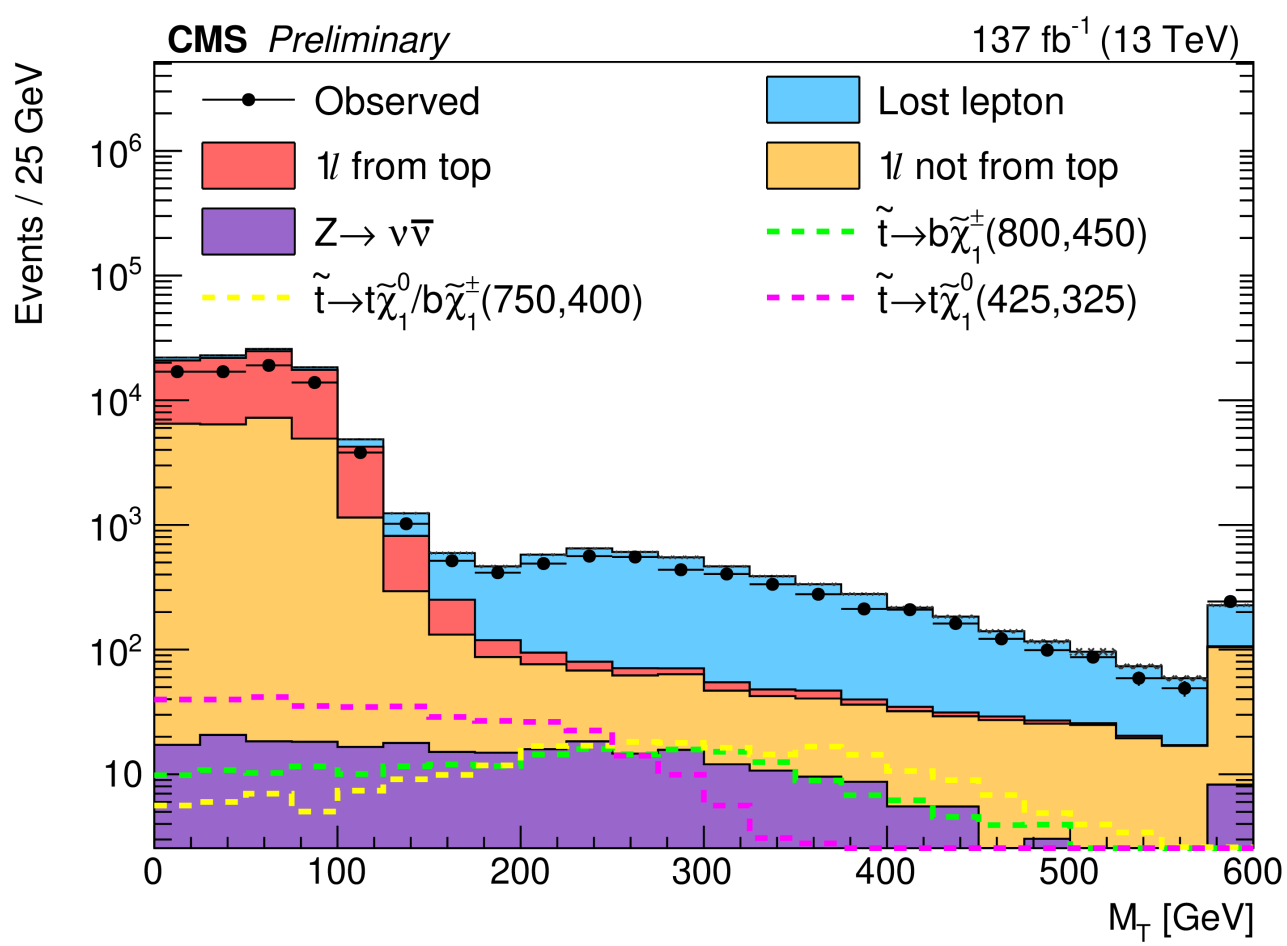


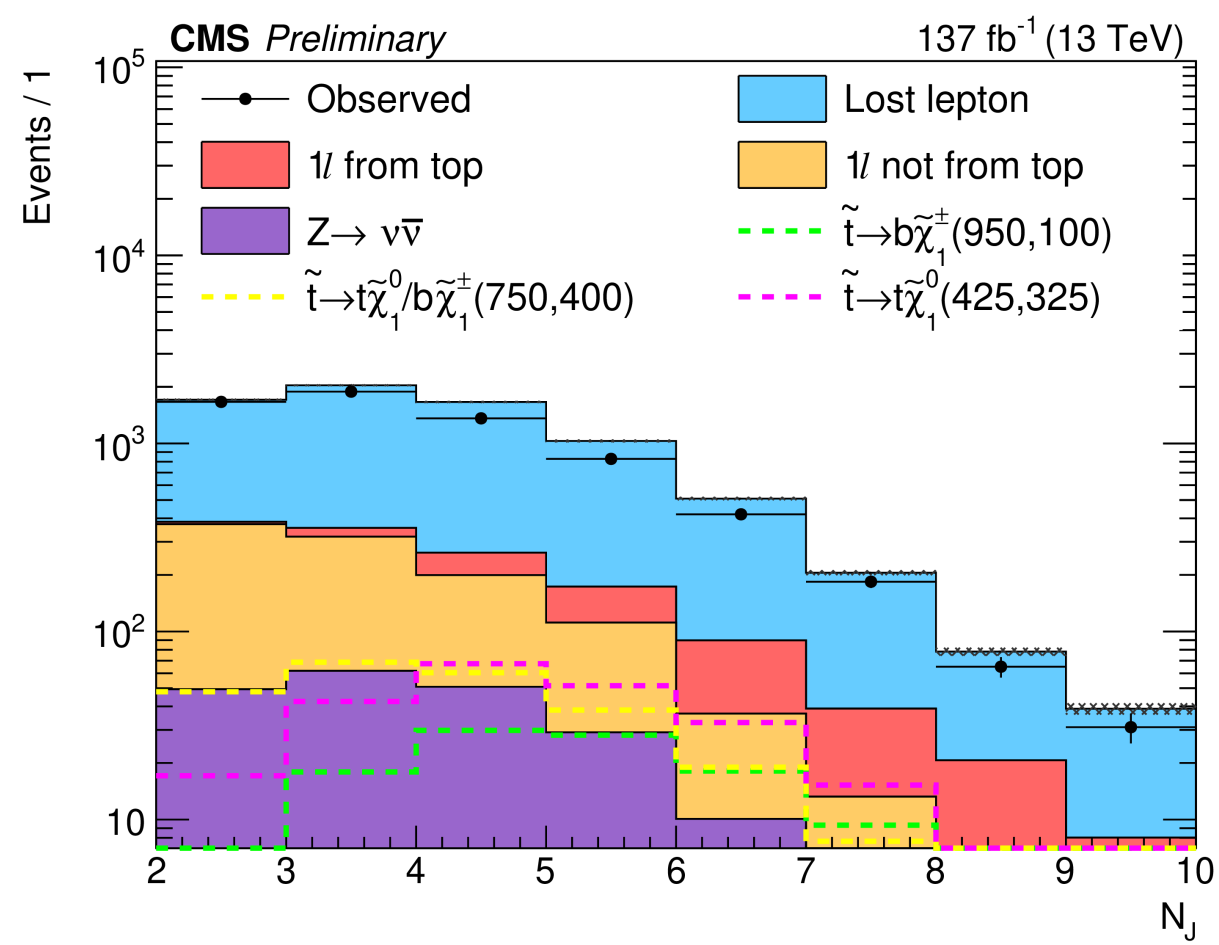
Direct Stop Searches

CMS-PAS-SUS-19-009

- CMS 1-lepton analysis sensitive to heavy stops, based on 137 fb^{-1}
- Resolved and "merged" (boosted) top tagging
- "Lost lepton": $t\bar{t}$ + single top, dominant in many signal regions, validated using control regions







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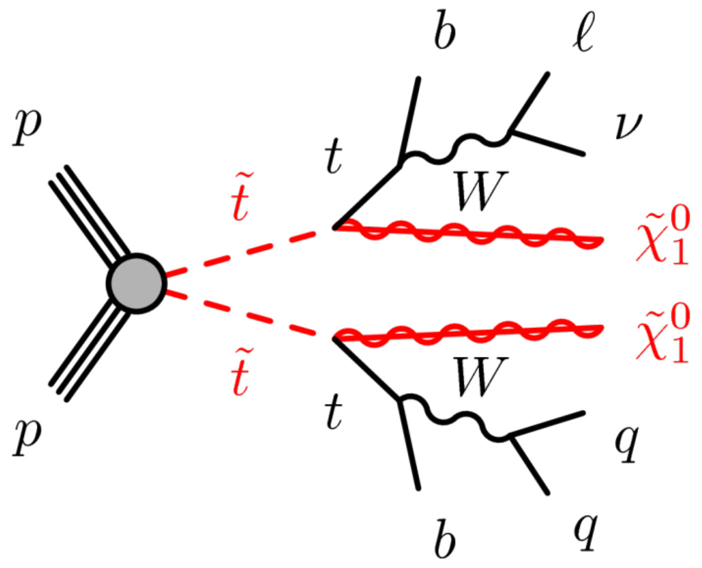
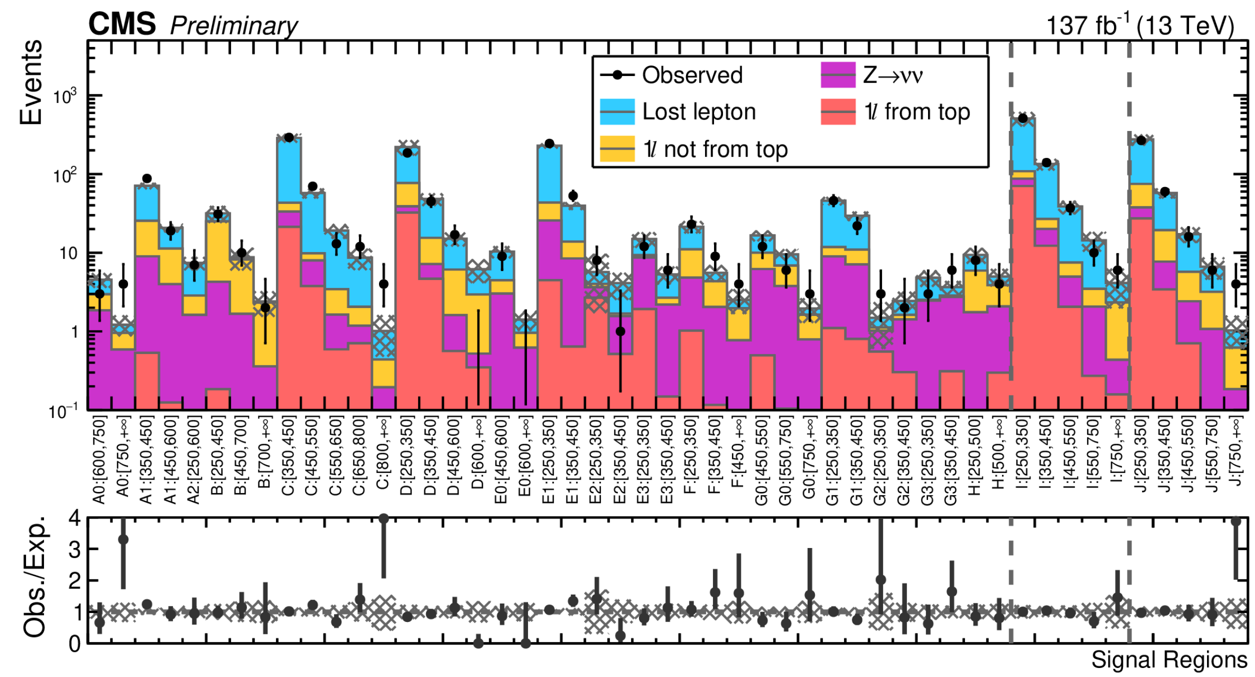
CMS-PAS-SUS-19-009

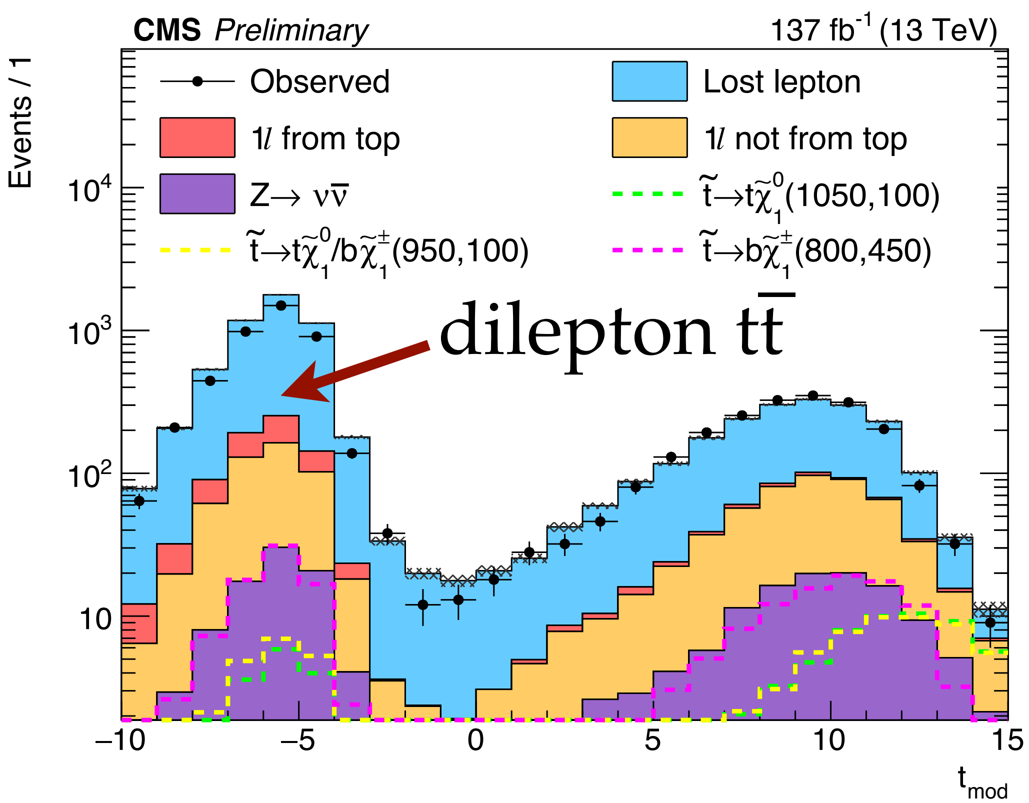




	N_J	t_{mod}	$M_{\ell b}$ [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

X0: Inclusive
X1: Untagged
X2: Boosted top
X3: Resolved top

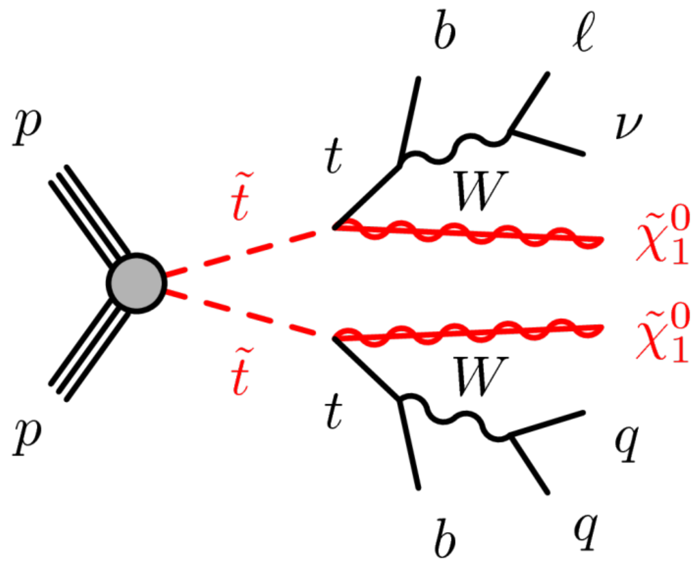
I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$

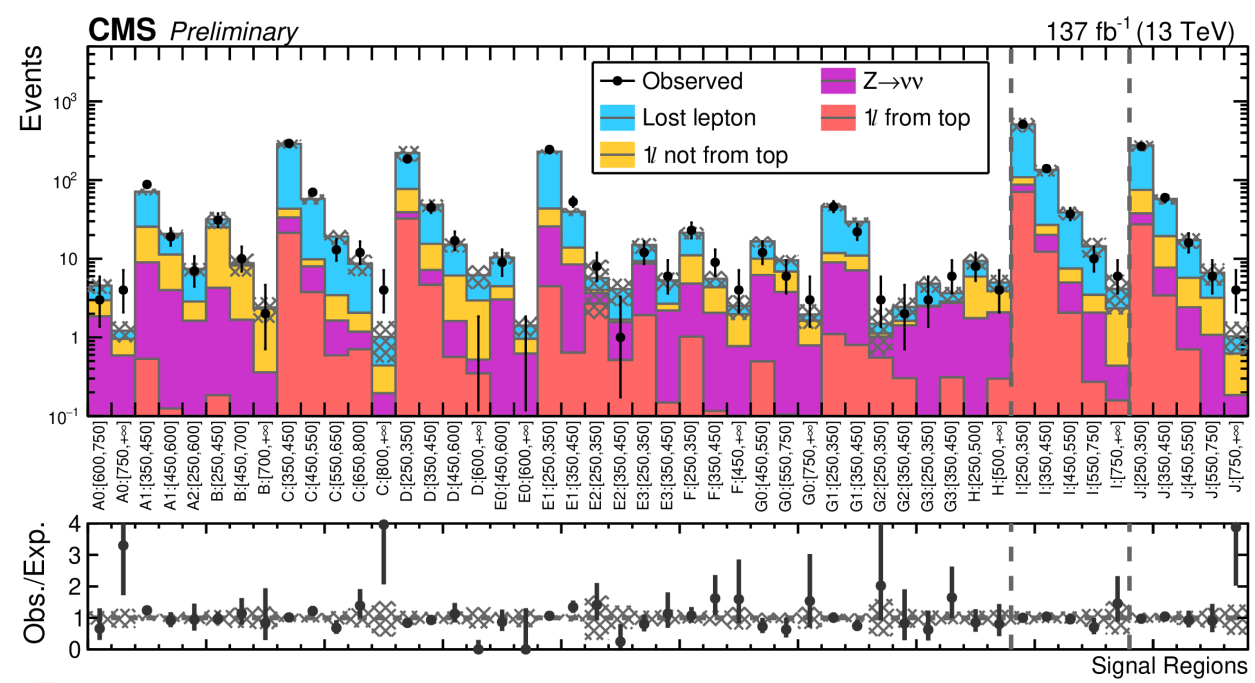


- Detailed analysis of 39 signal regions
- Modified “topness” (t_{mod}) and $M_{\ell b}$ discriminate between $t\bar{t}$ and signal
- Stop masses excluded up to 1.2 TeV

Direct Stop Searches

CMS-PAS-SUS-19-009





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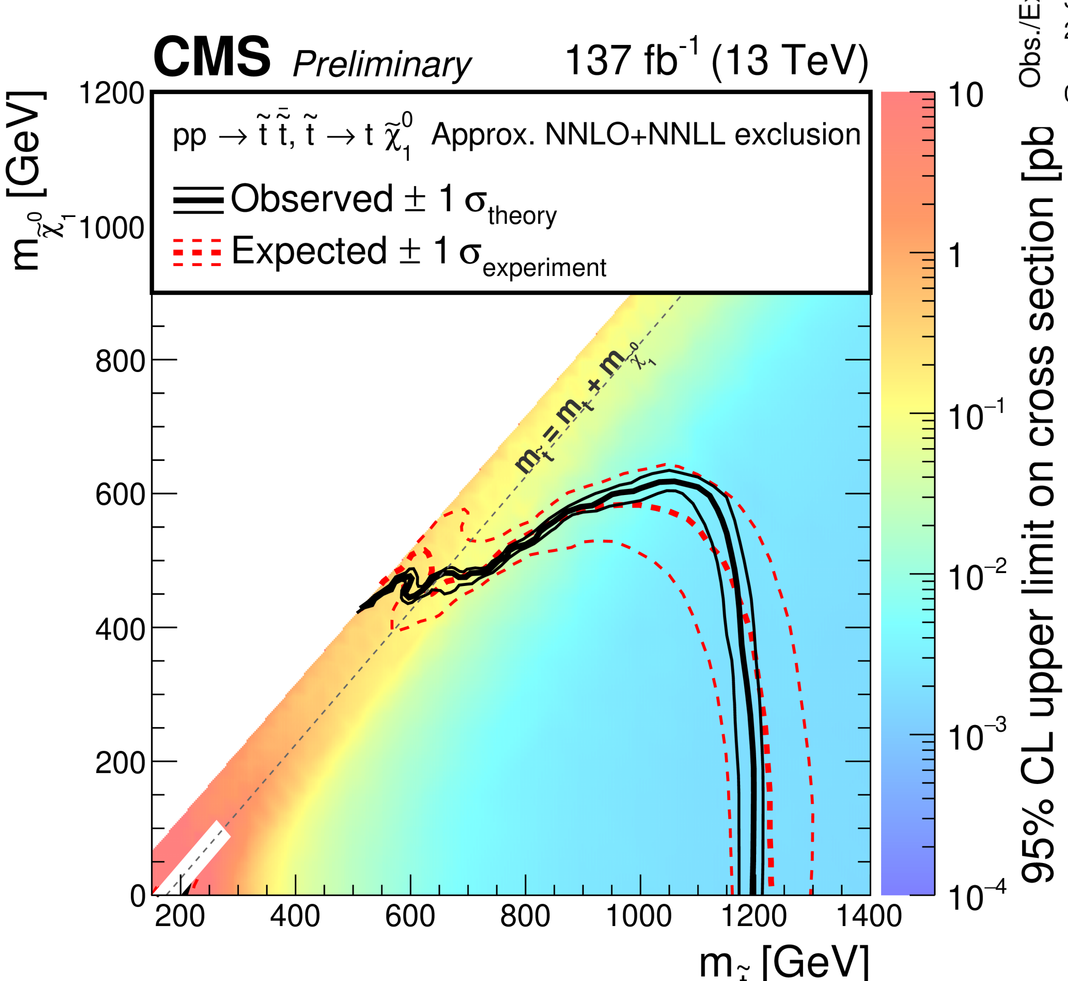

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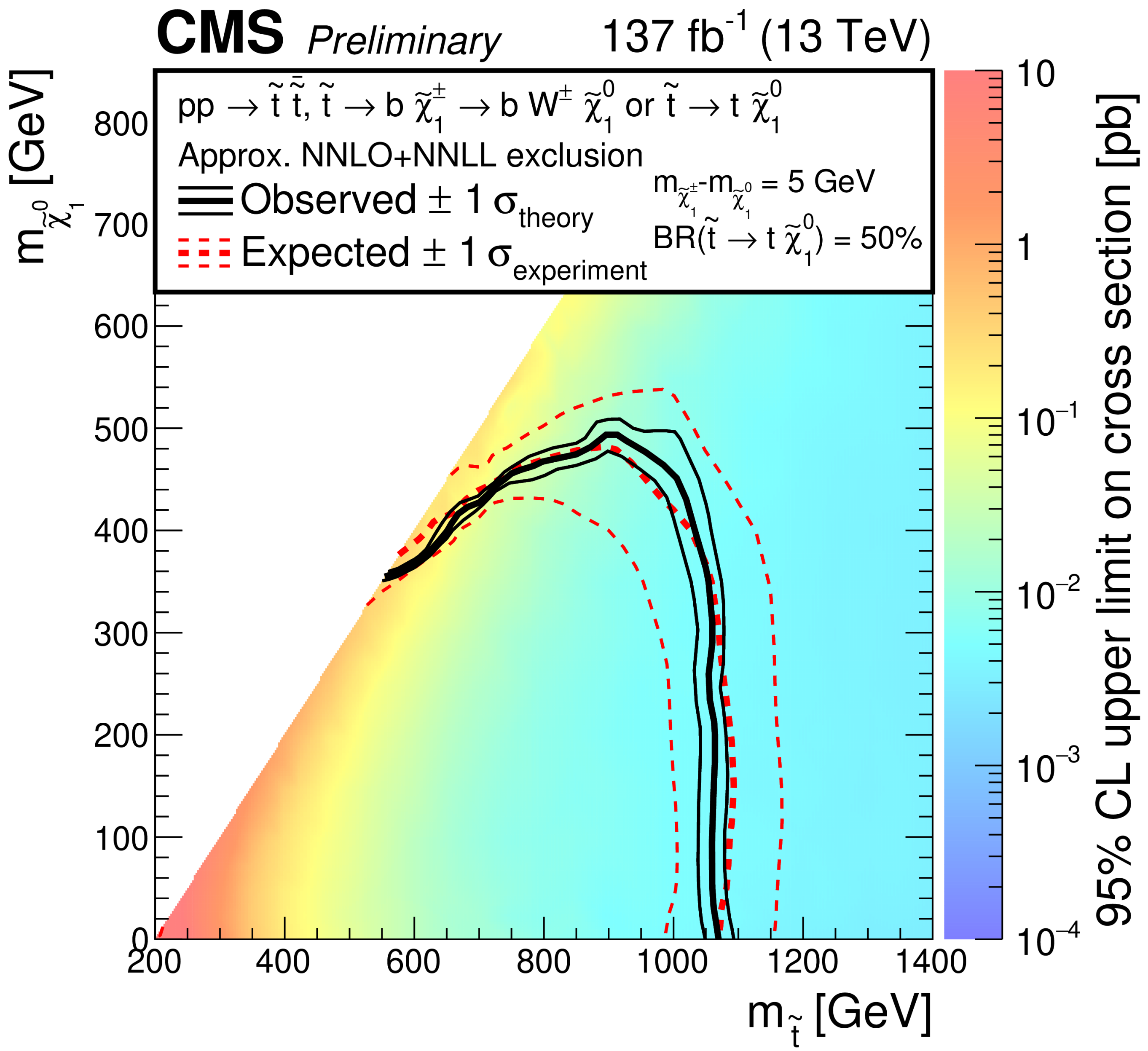
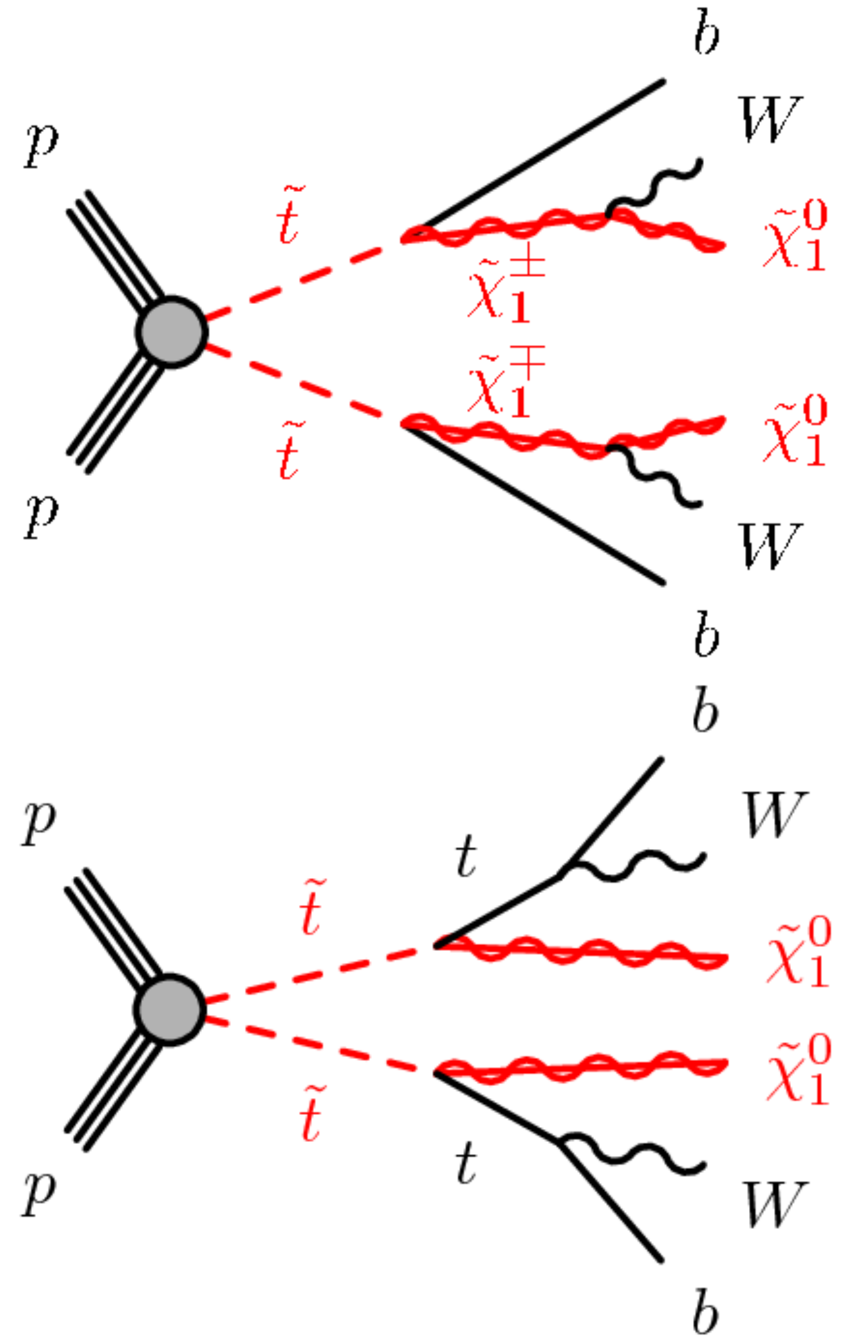
Direct Stop Searches

CMS-PAS-SUS-19-009

- Additional interpretation: 1 TeV exclusion for 50% / 50% BFs, 'natural' compressed higgsino-like $\tilde{\chi}_1$ sector



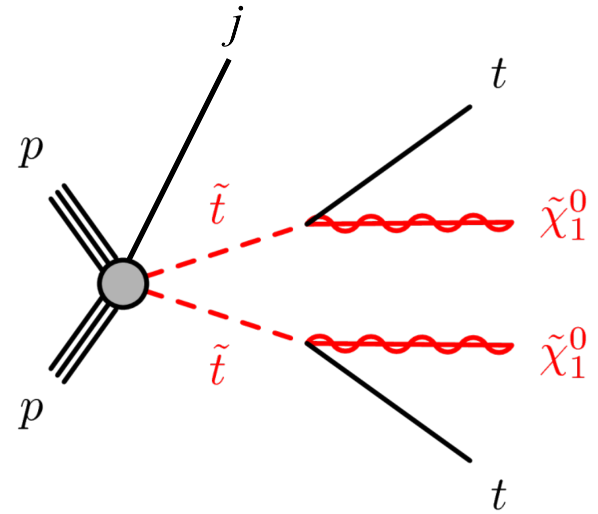


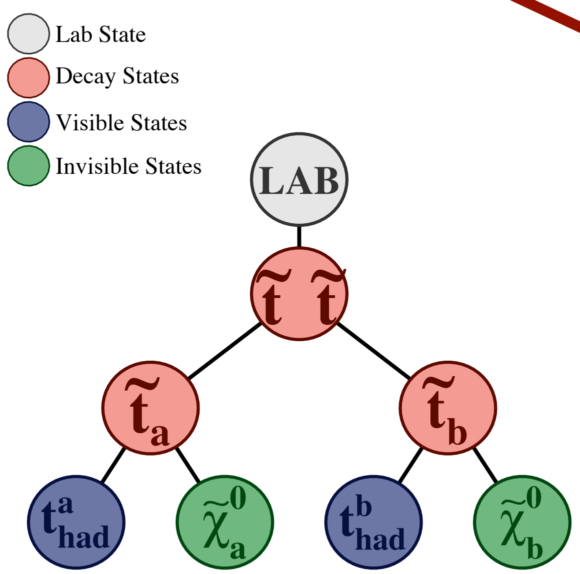
Direct Stop Searches

JHEP 12 (2017) 085
JHEP 06 (2018) 108

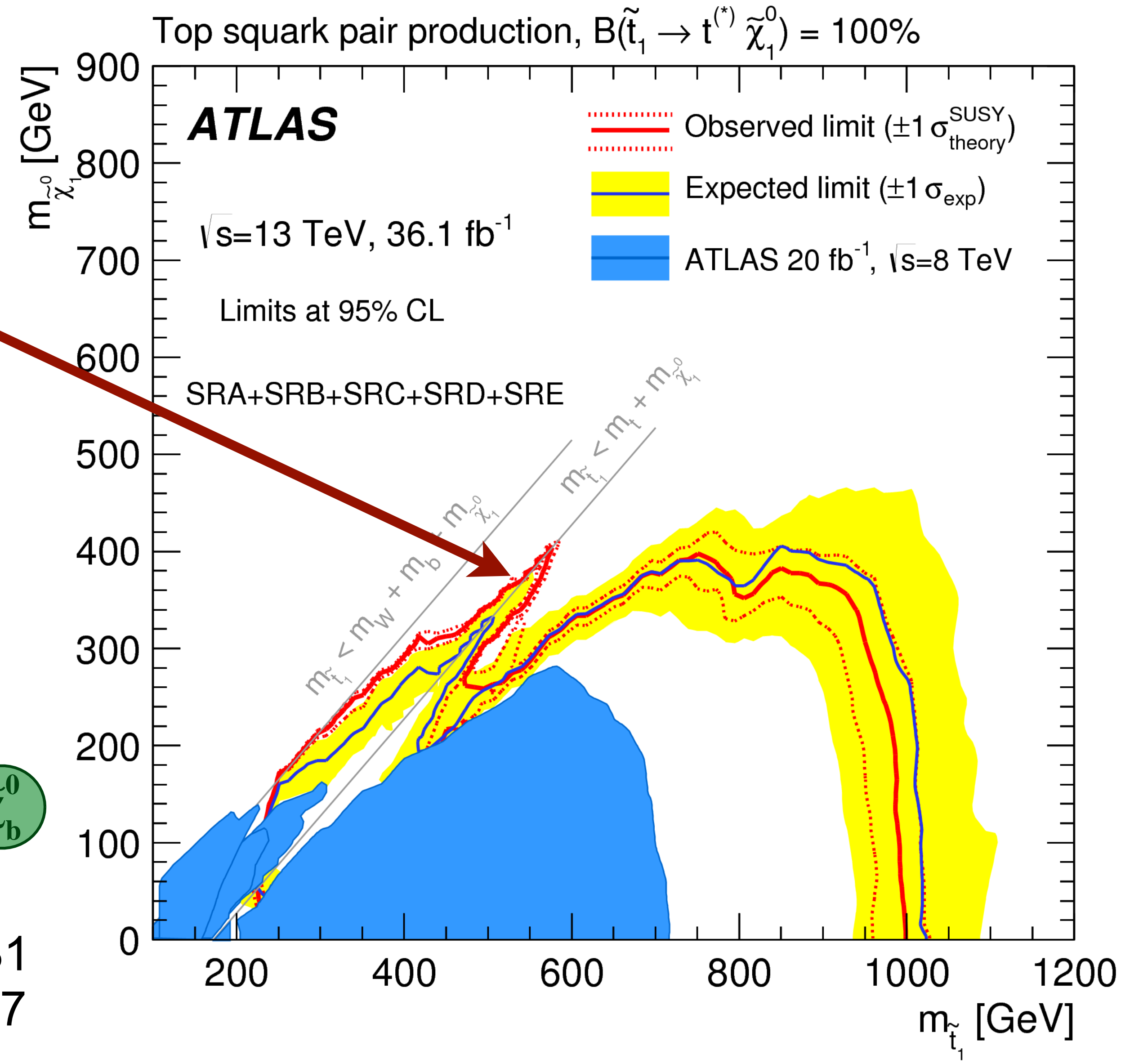
- Improved understanding of radiation in top events opened door to exploiting ISR for access to compressed stop region $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim m_t$

- ATLAS 0- and 1-lepton searches use recursive jigsaw technique to exploit events where $\tilde{t}\tilde{t}$ system recoils against ISR



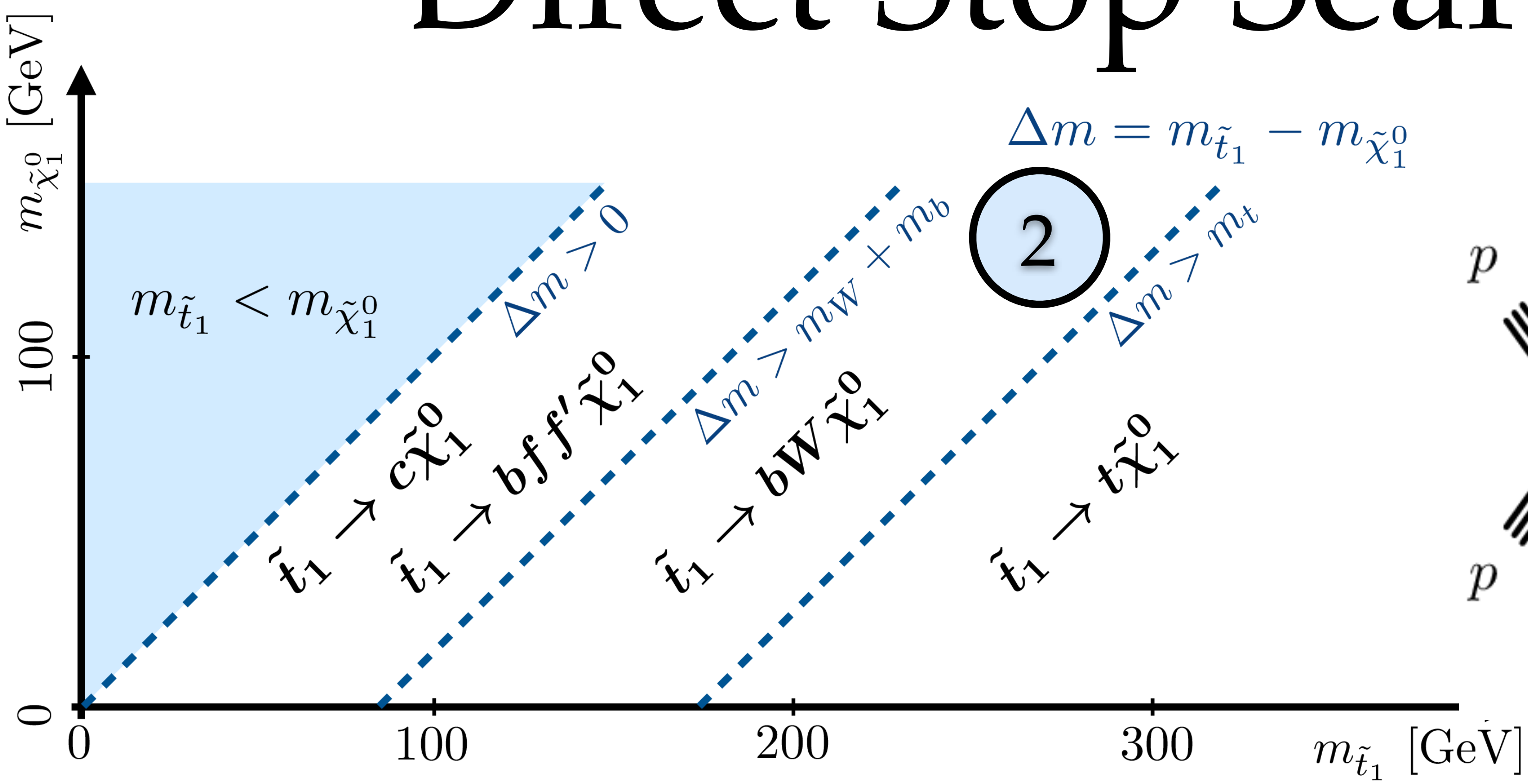


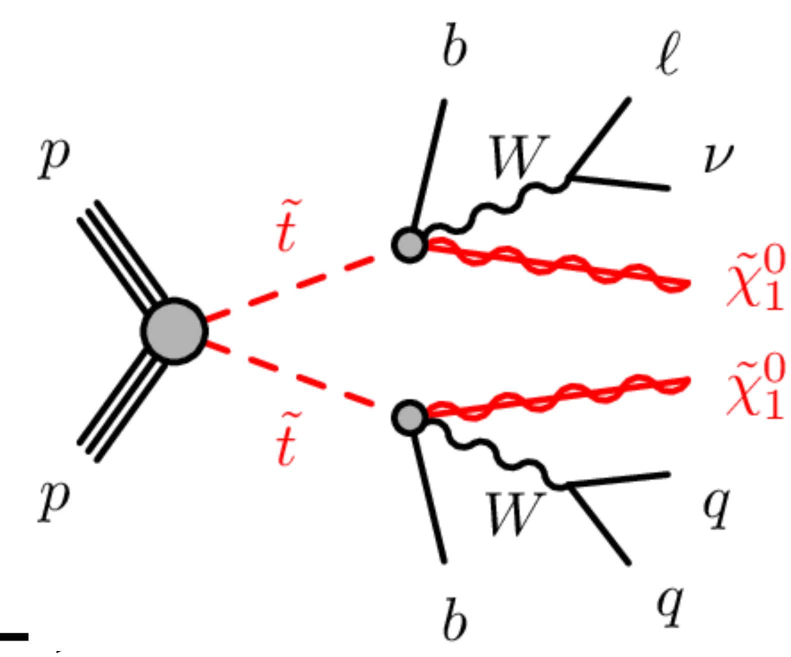
Jackson et al,
PRD 95 (2017) 035031
PRD 96 (2017) 112007



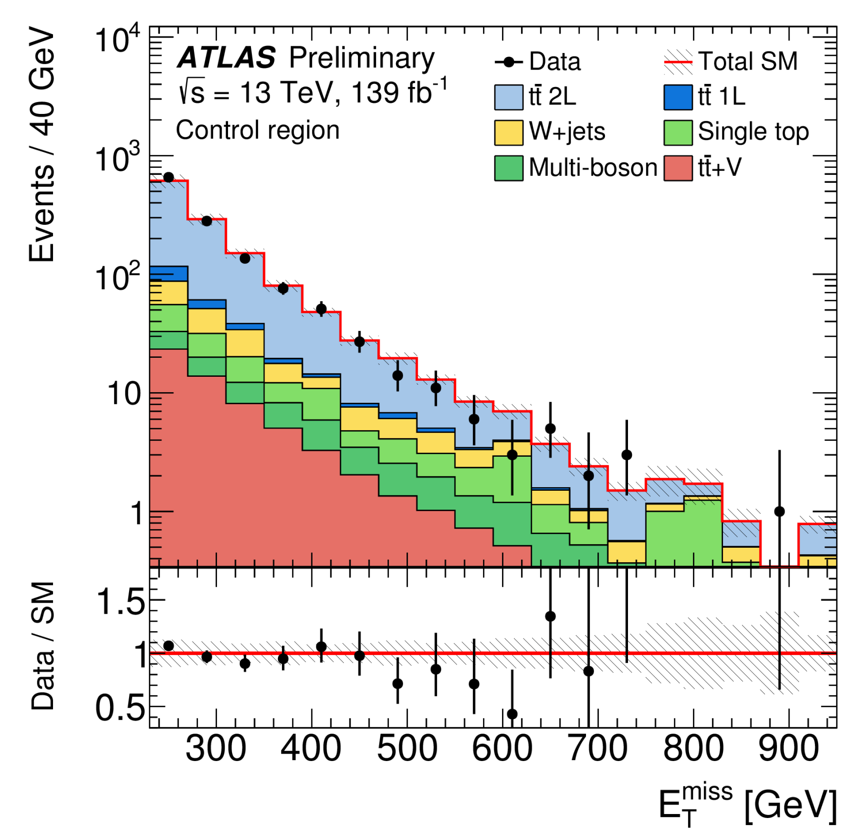
Direct Stop Searches

ATLAS-CONF-2019-017





- ATLAS search for 3-body stop decays, 1-lepton channel, based on 139 fb^{-1}
- Recurrent Neural Network used to compensate for variable #jets in signal; output fed to shallow neural network



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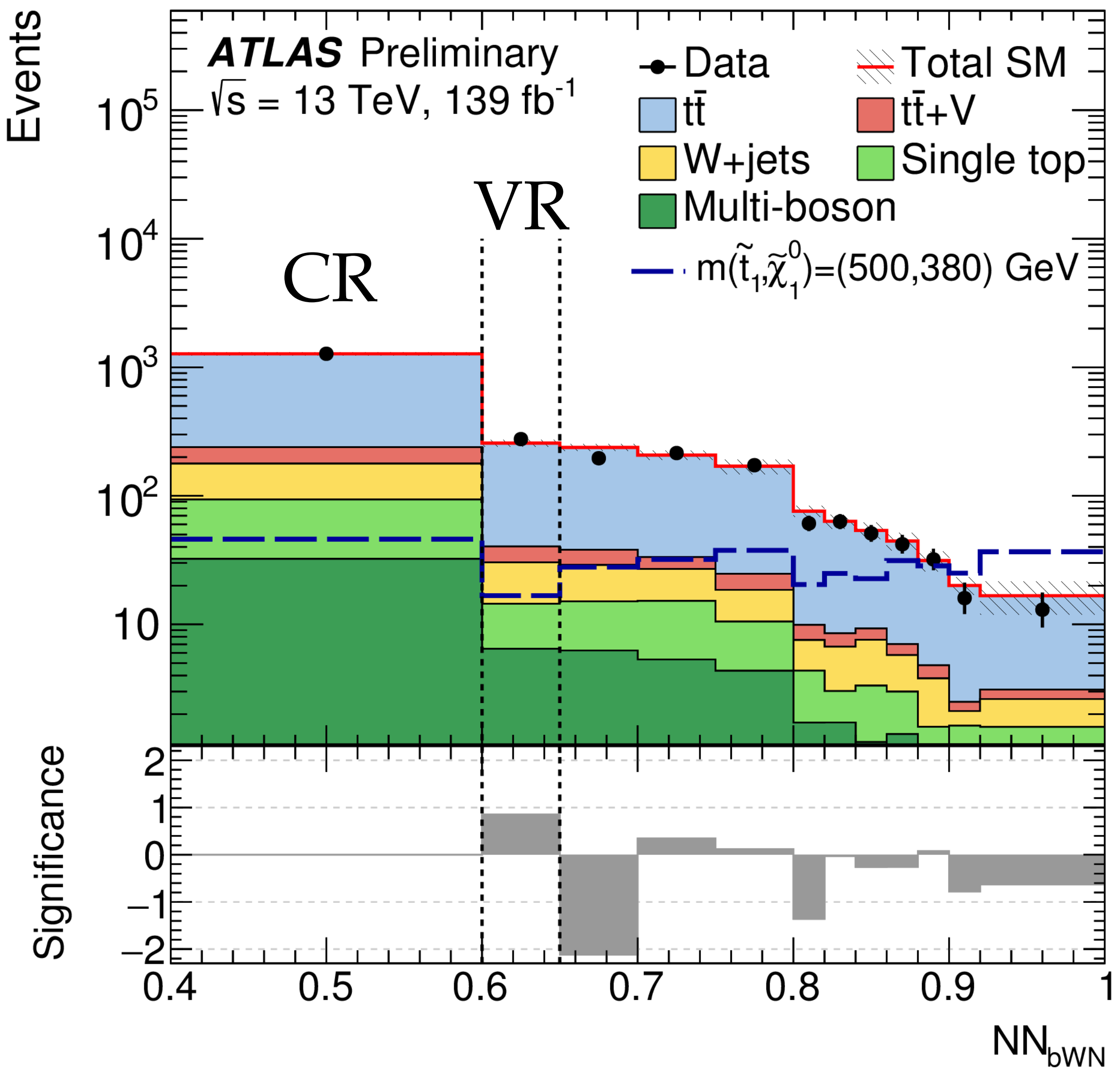

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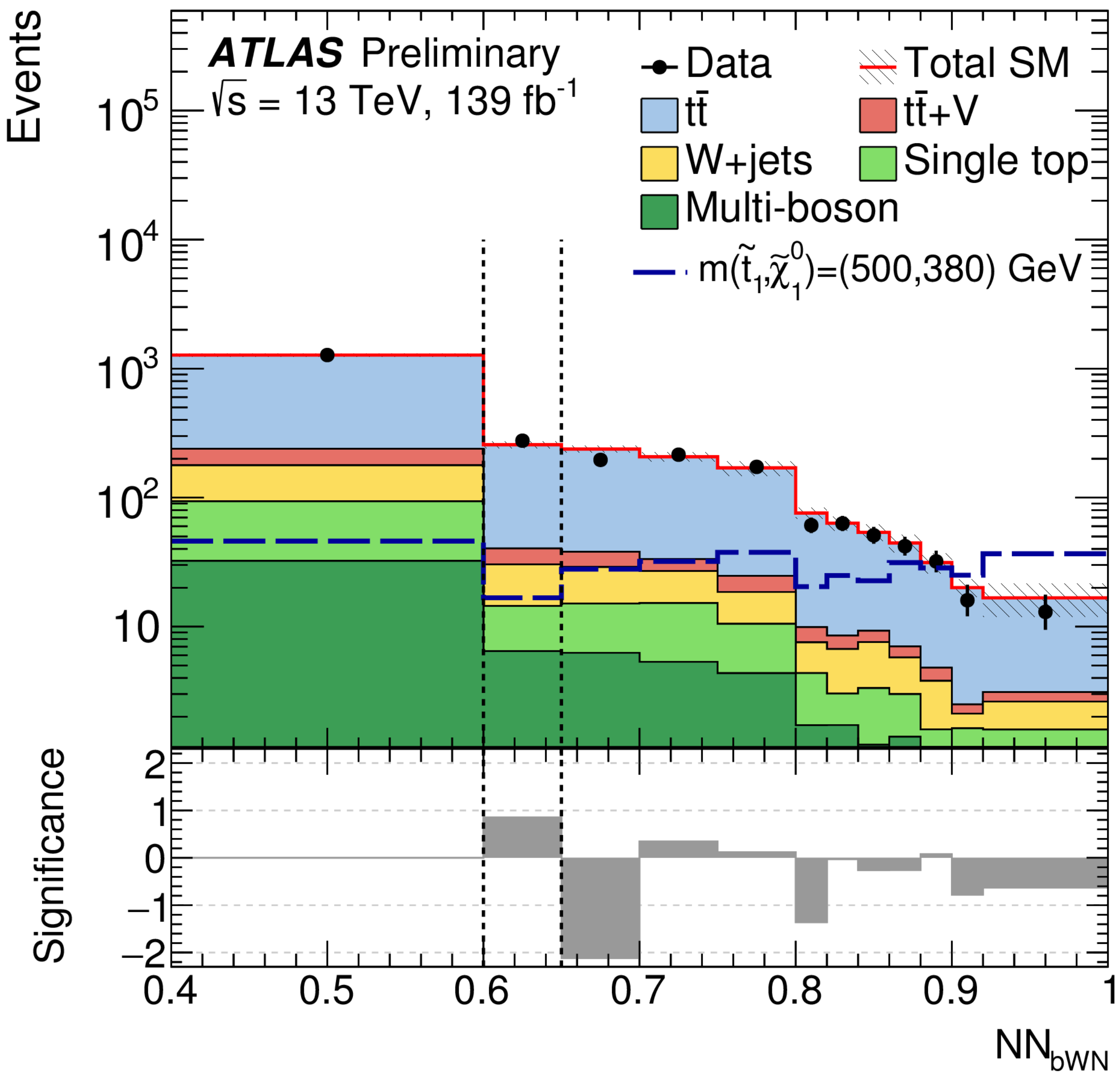


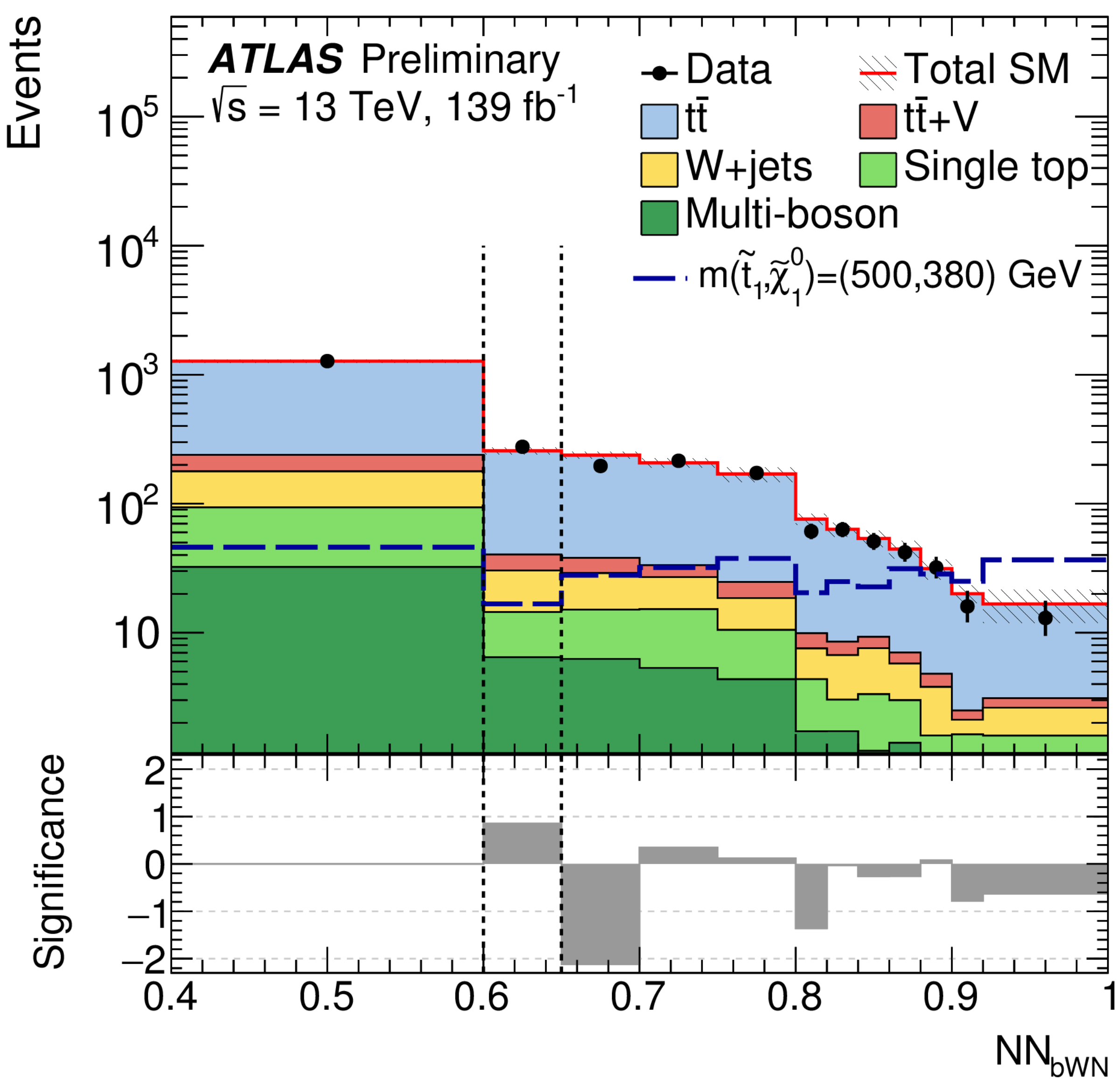
- Dominant systematic uncertainties:

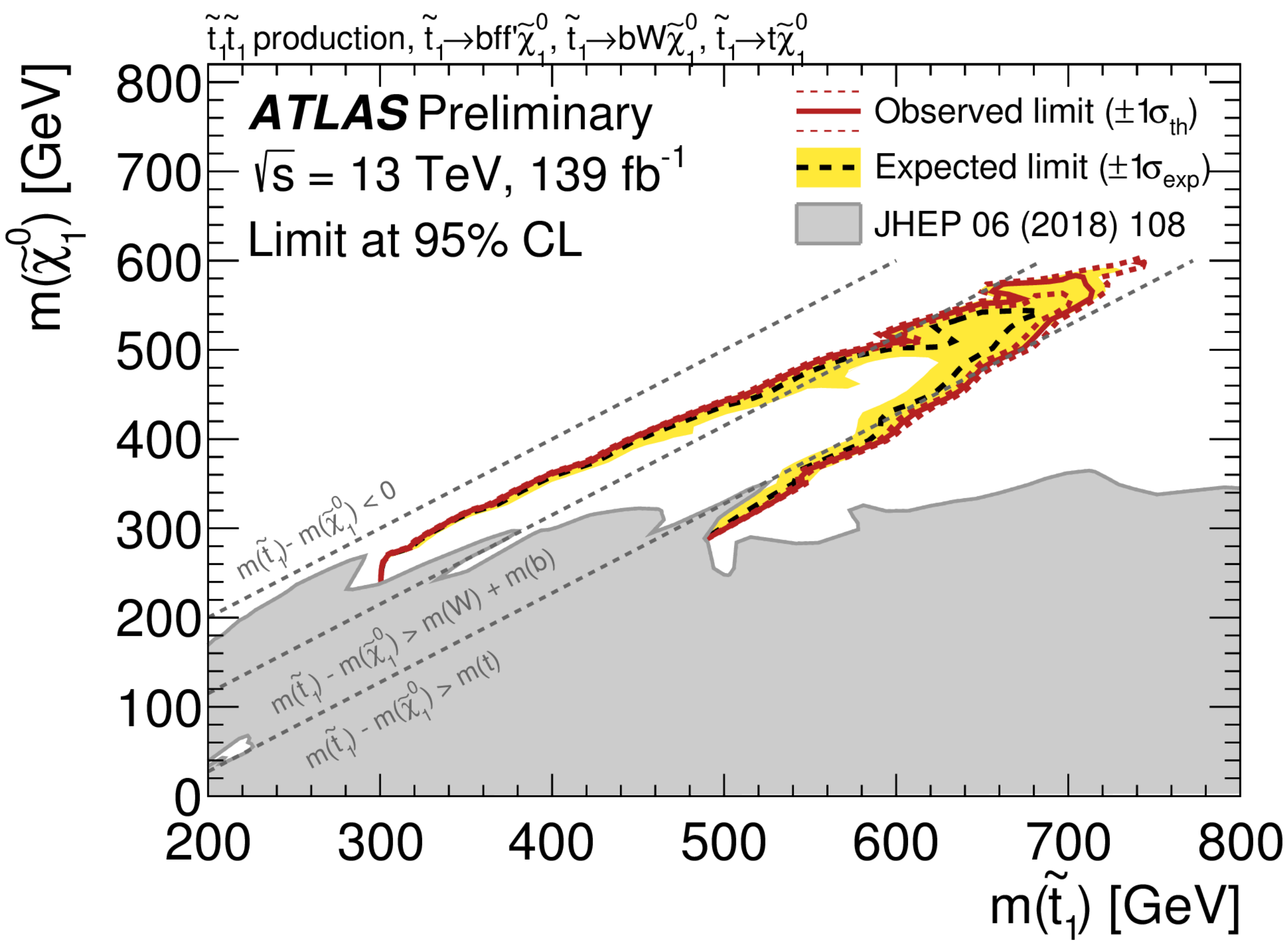
Systematic uncertainty [%]	VR	SR
Total background uncertainty	7.4	20
$t\bar{t}$ hadronisation/fragmentation	3.0	16.3
JER	2.0	6.1
JES	1.4	4.6
$t\bar{t}$ hard-scattering	0.9	1.7
$t\bar{t}$ additional radiation	0.7	3.9
Flavour-tagging efficiency	0.5	1.7
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.5	1.3

tt hadronisation/fragmentation uncertainties evaluated by comparing Powheg-Box+Pythia8 with Powheg-Box+Herwig7

Direct Stop Searches

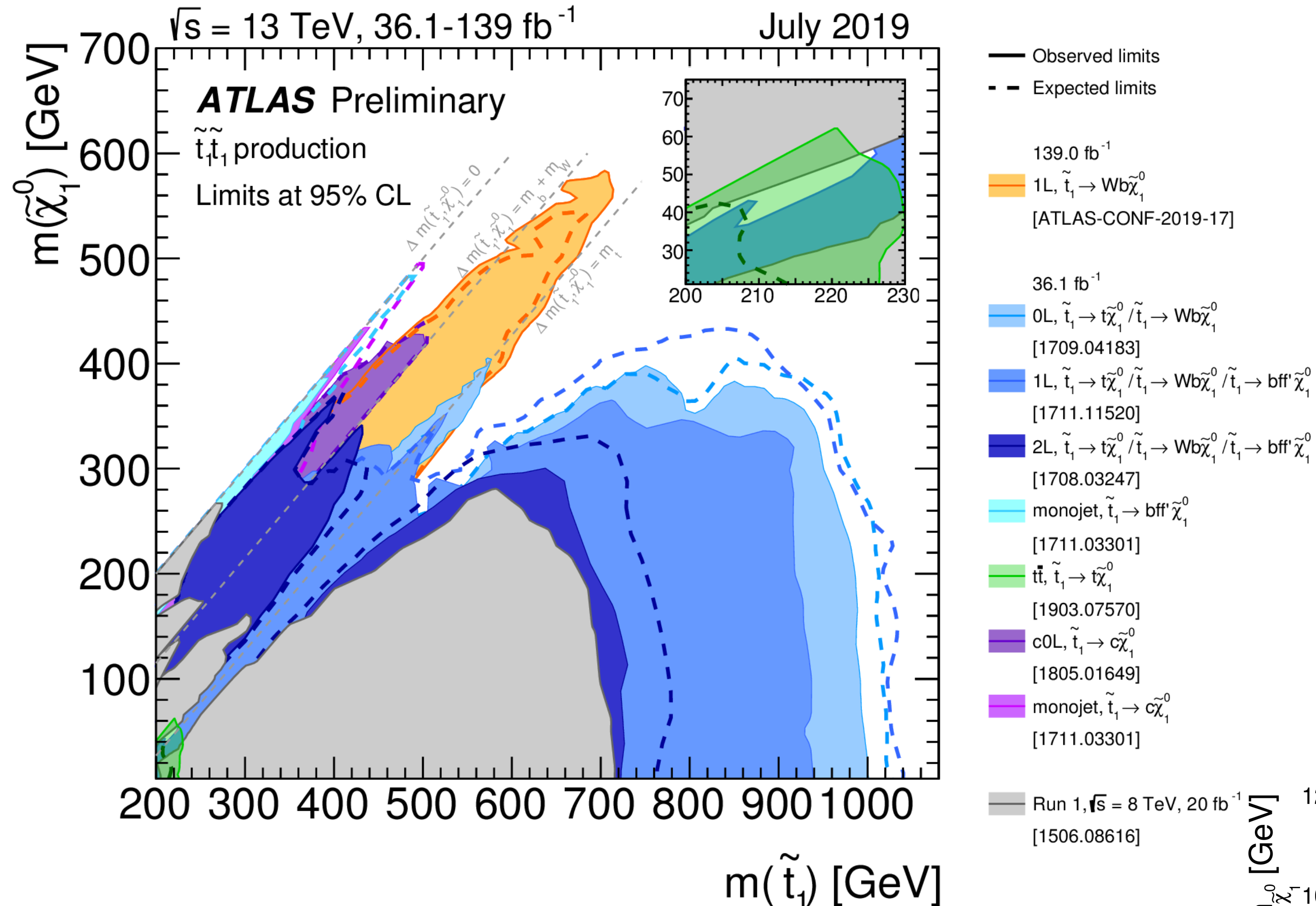
ATLAS-CONF-2019-017

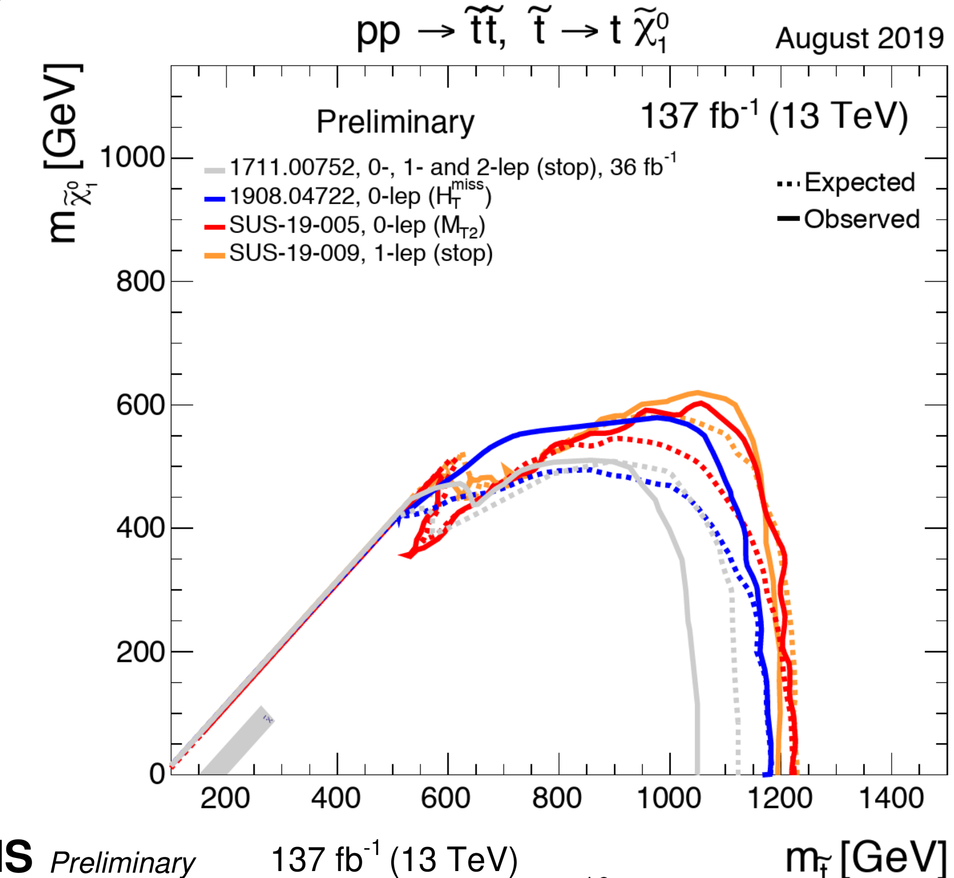


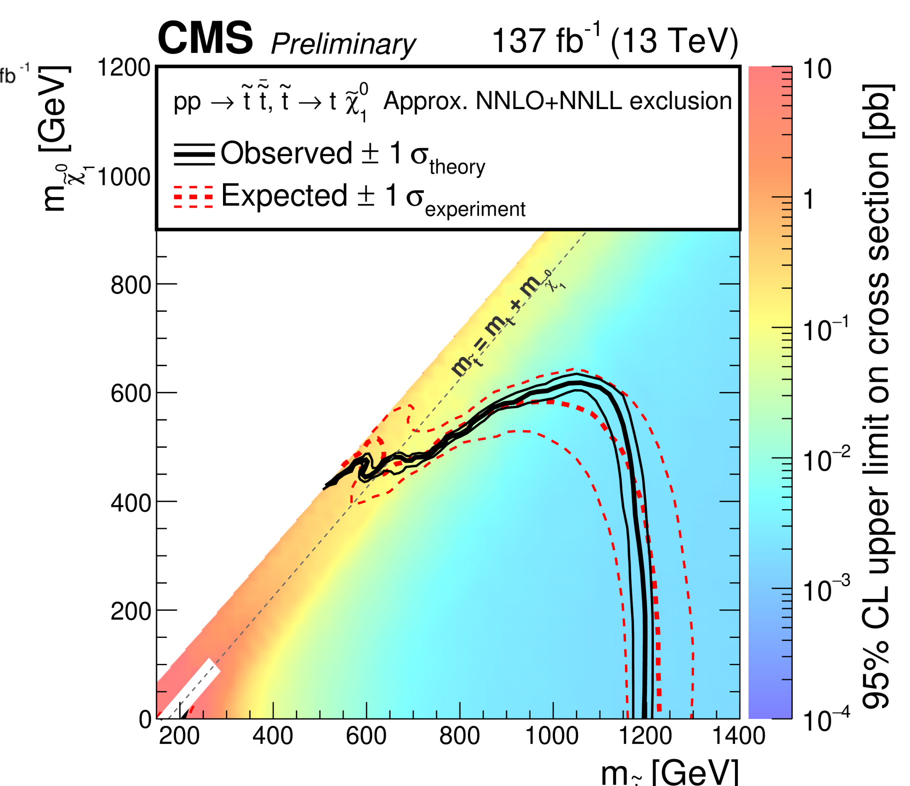


- Greatly expanded sensitivity compared to previous analyses

Stop Summary Plots







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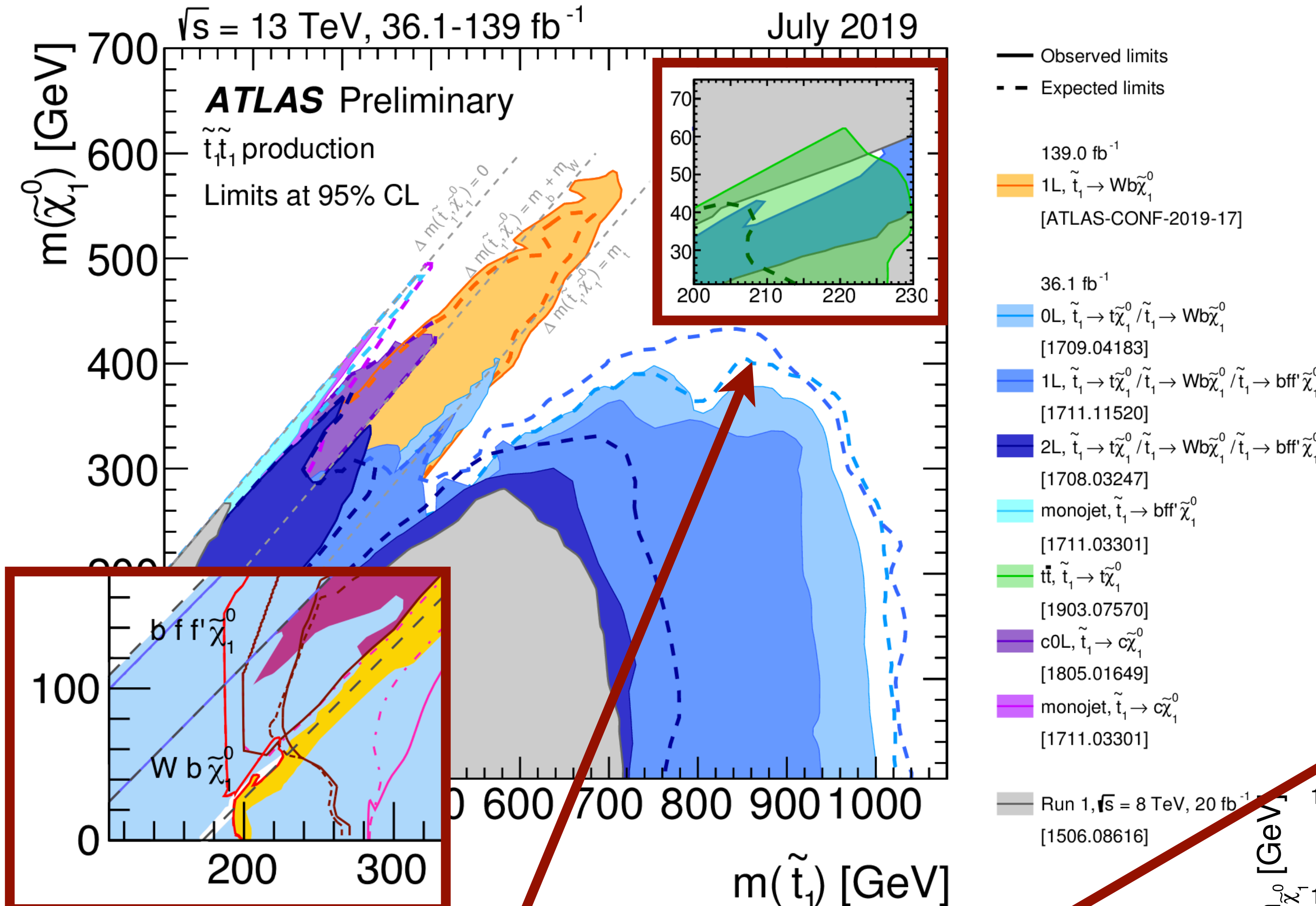
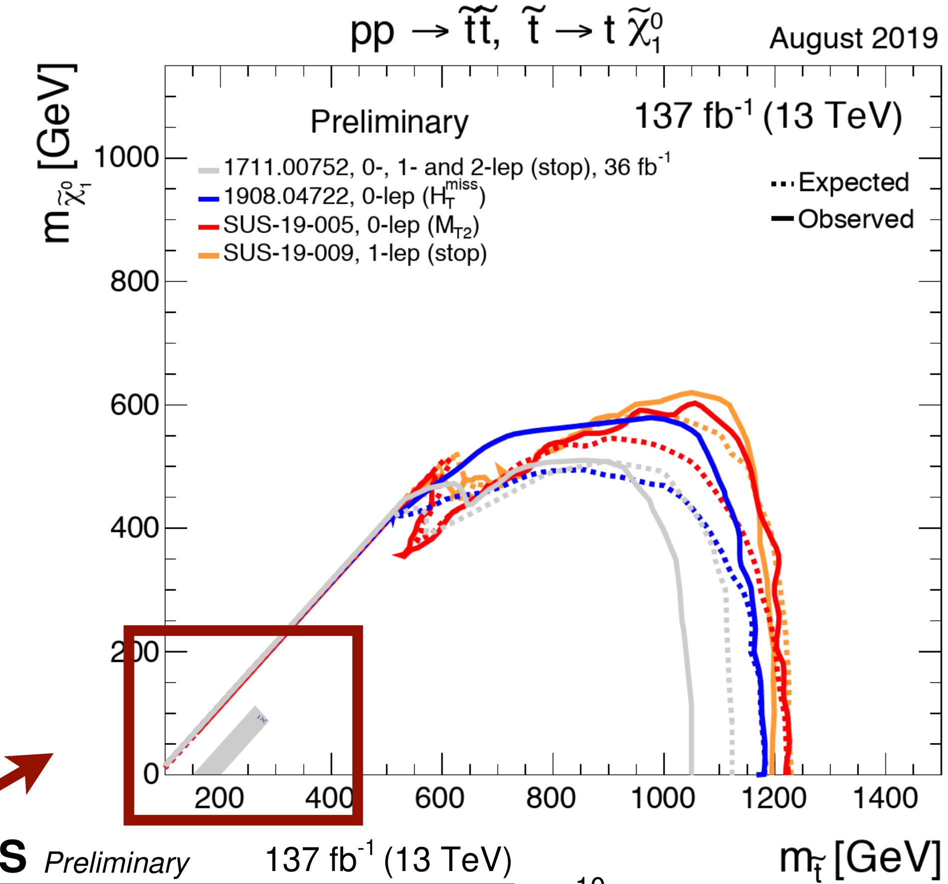
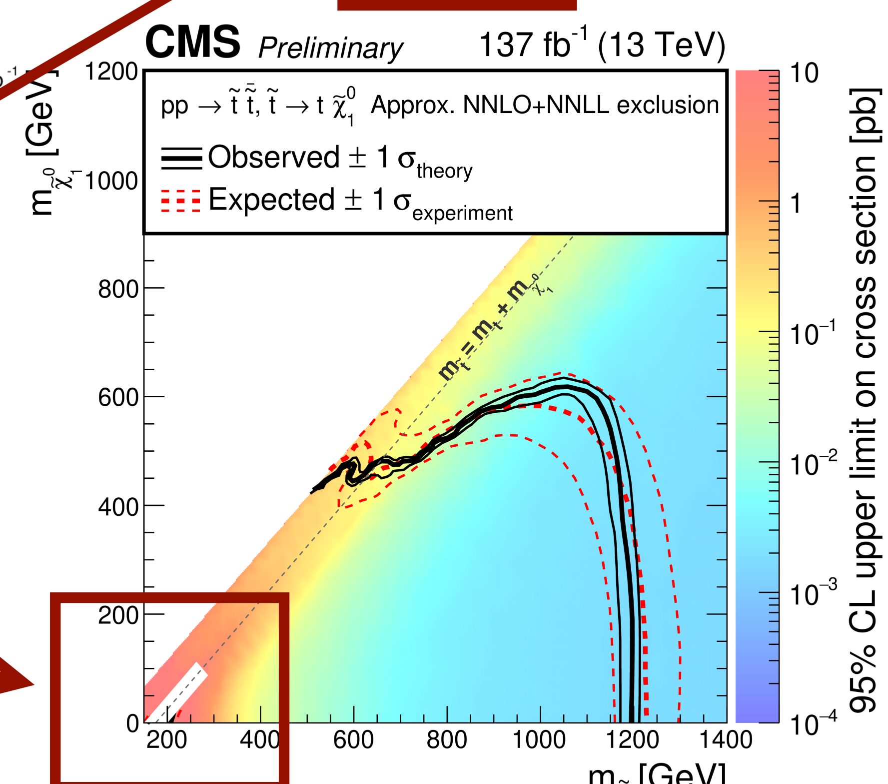


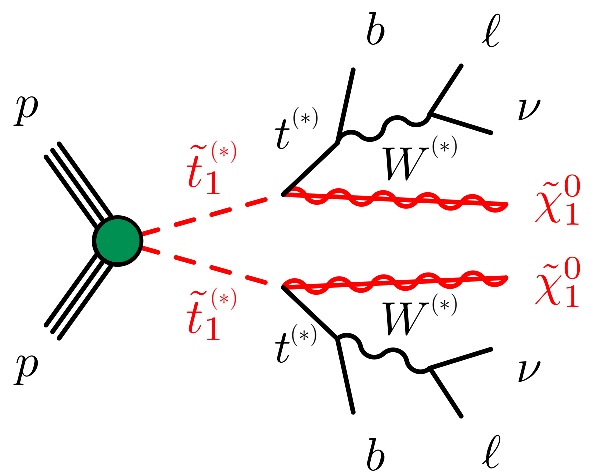
May 2018

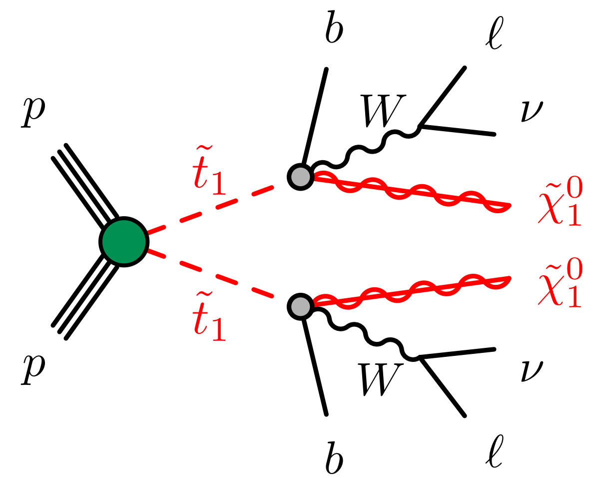


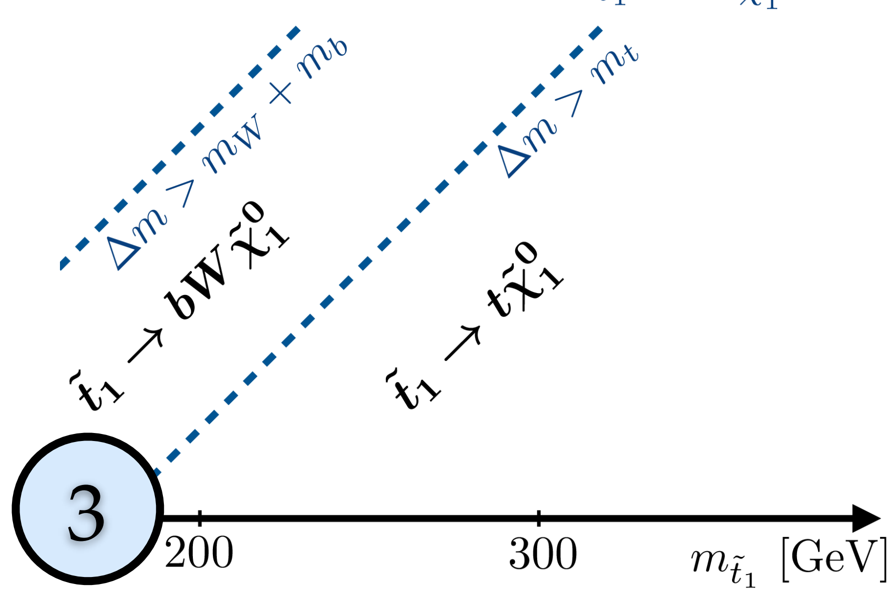


So-called "stealth" stop region

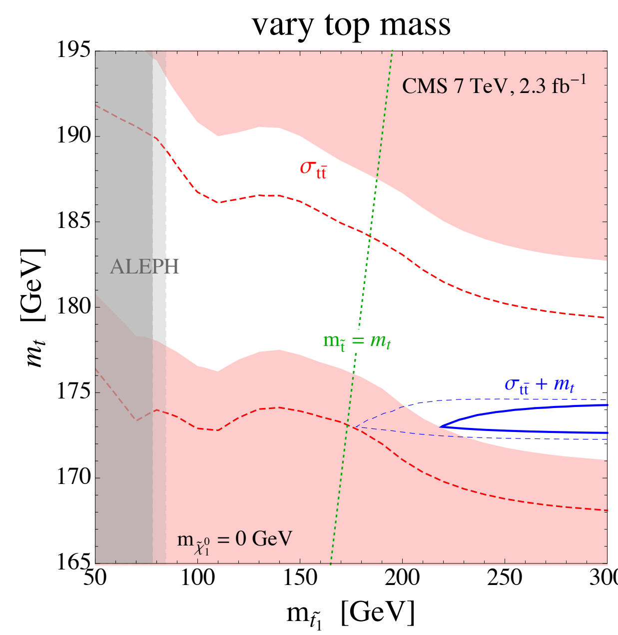
Stealth Stop Searches



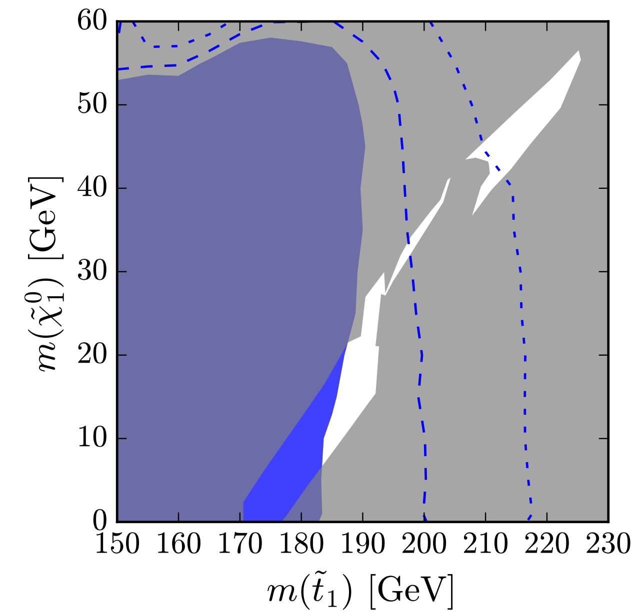




- Important considerations in the stealth stop region:
  - 3-body effects near 2-body threshold (total width)
  - spin correlations
  - stop decays via RH vs LH tops
  - impact of top mass



Czakon, et al
PRL 113 (2014) 201803

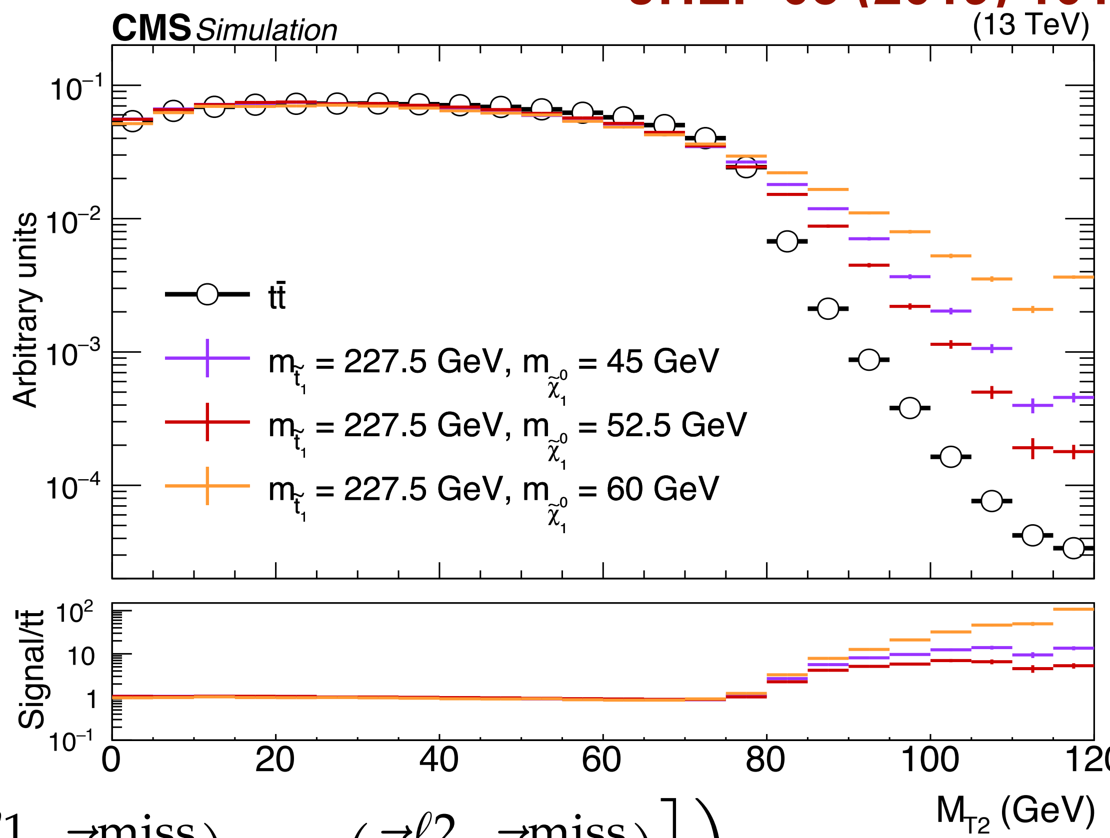


Cohen, et al
JHEP 07 (2018) 042

Stealth Stop Searches

JHEP 03 (2019) 101

- CMS eμ search, based on 36 fb^{-1}
- M_{T2} main discriminating variable; endpoint @ m_W for $t\bar{t}$ events, changes with Δm(stop-neutralino) and MET

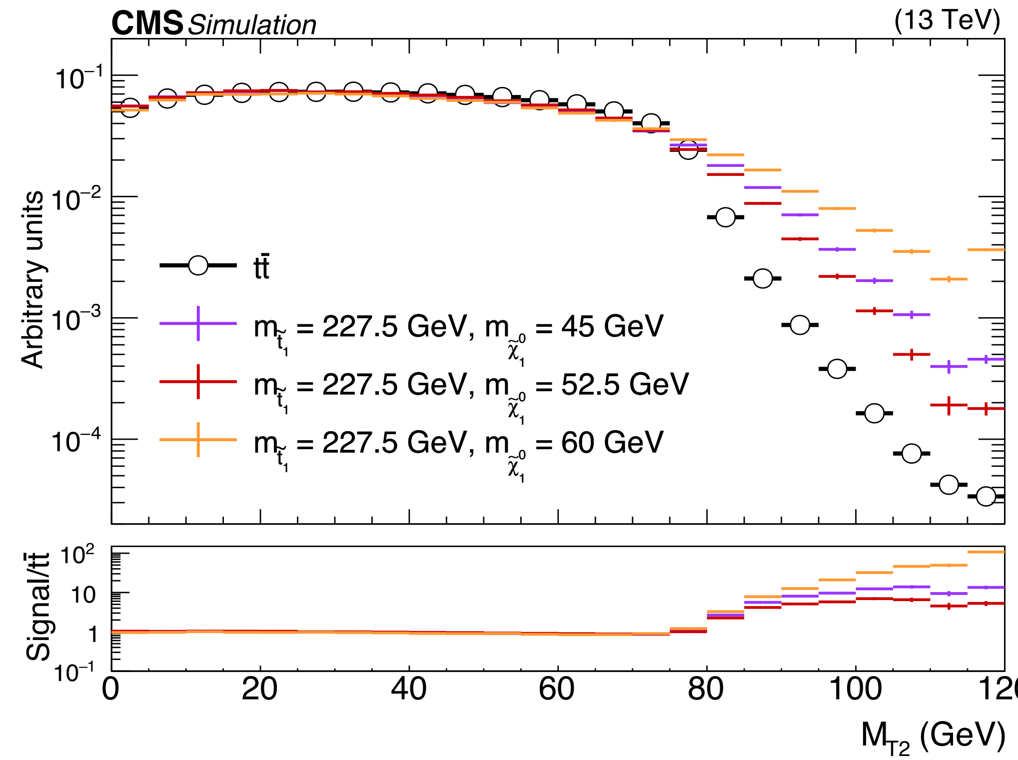


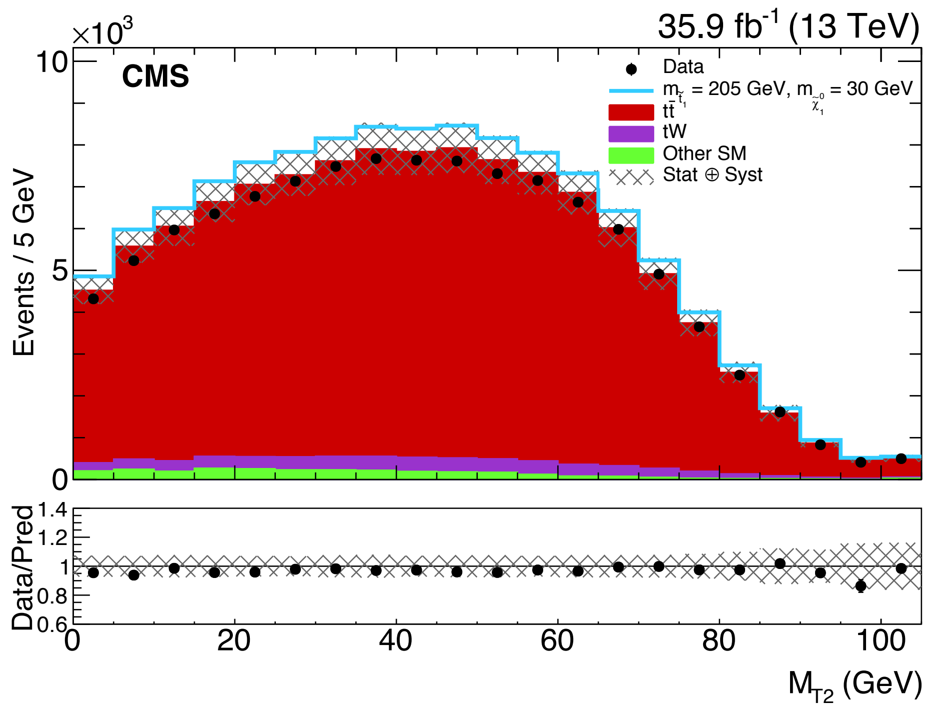
$$M_{T2} = \min_{\vec{p}_{T,1}^{miss} + \vec{p}_{T,2}^{miss} = \vec{p}_T^{miss}} \left(\max \left[m_T(\vec{p}_T^{\ell 1}, \vec{p}_{T,1}^{miss}), m_T(\vec{p}_T^{\ell 2}, \vec{p}_{T,2}^{miss}) \right] \right)$$

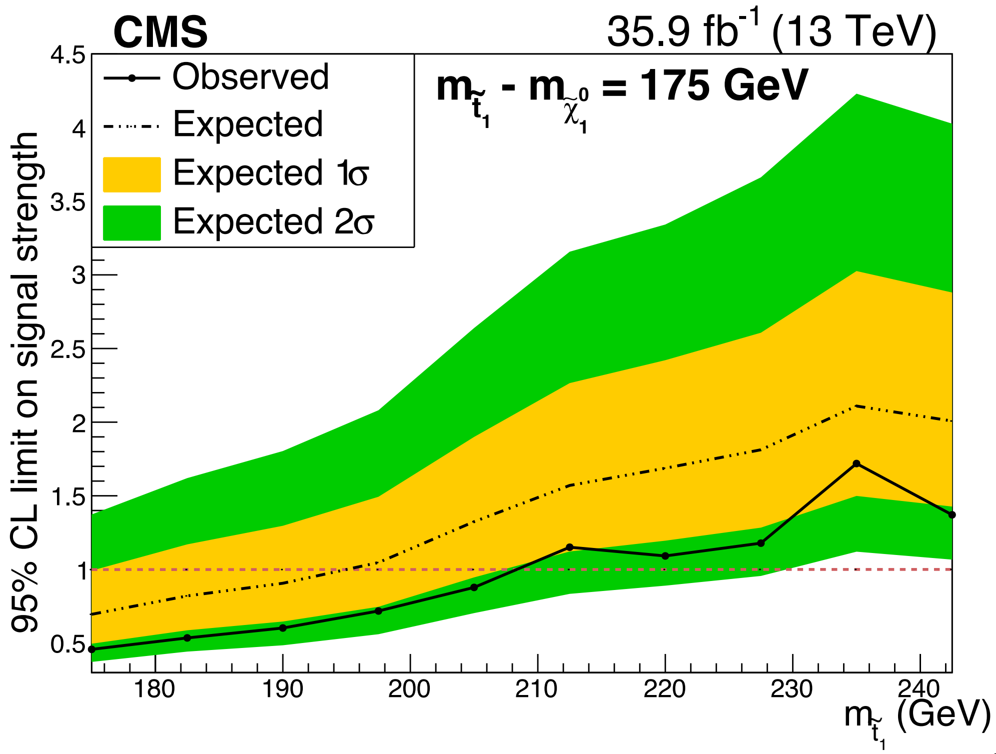
Stealth Stop Searches

JHEP 03 (2019) 101

- CMS eμ search, based on 36 fb^{-1}
- M_{T2} main discriminating variable; endpoint @ m_W for $t\bar{t}$ events, changes with Δm(stop-neutralino) and MET
- Results interpreted for stop masses between 170 and 250 GeV; $\tilde{t} \rightarrow t\chi_0$ decay mode considered



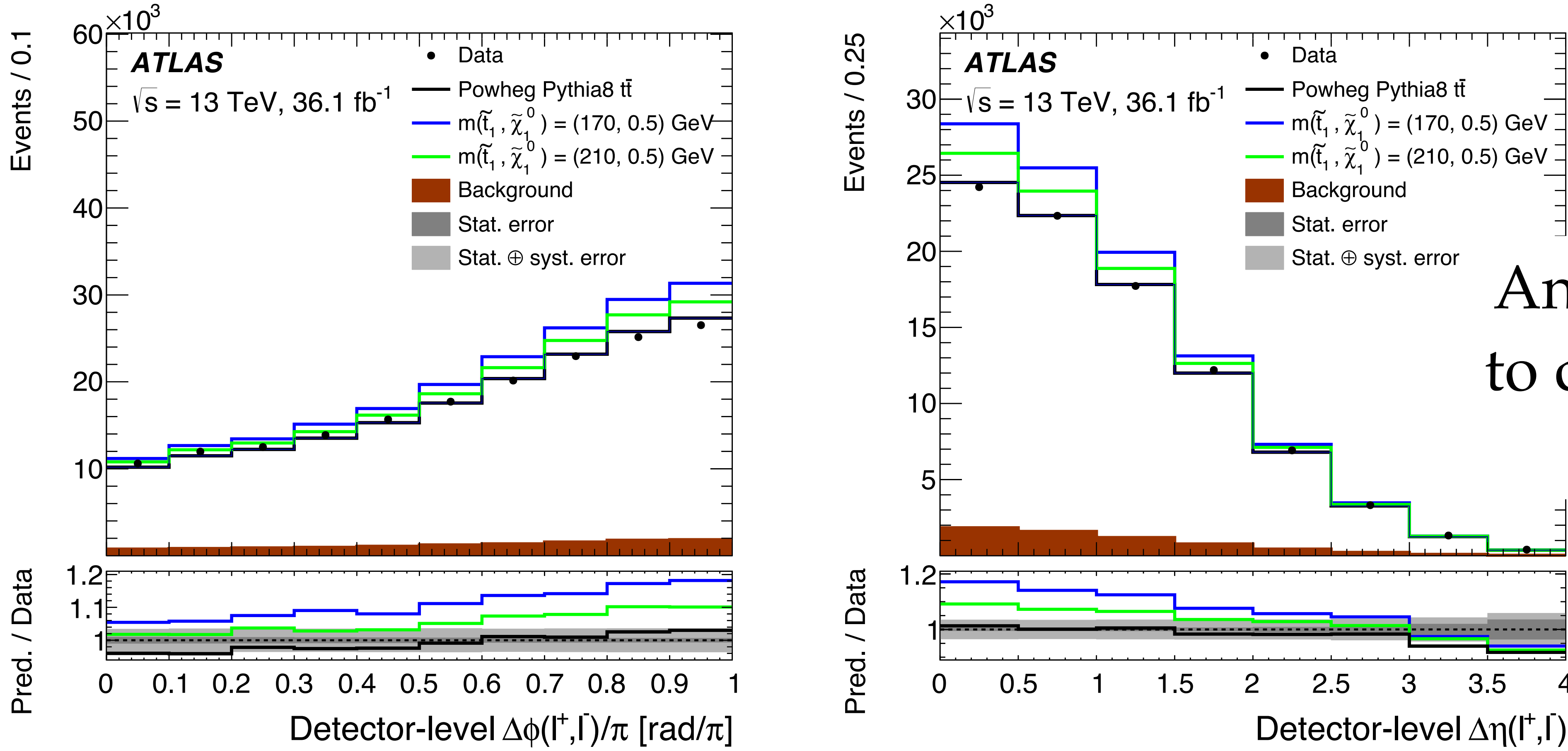




Stealth Stop Searches

arXiv:1903.07570, submitted to EPJC

- ATLAS SUSY interpretation of spin correlation measurement, eμ events, based on 36 fb^{-1}
- left-handed stops considered; signal events simulated with MadSpin & tops allowed to be off-shell



Analysis sensitive to changes in yield and shape

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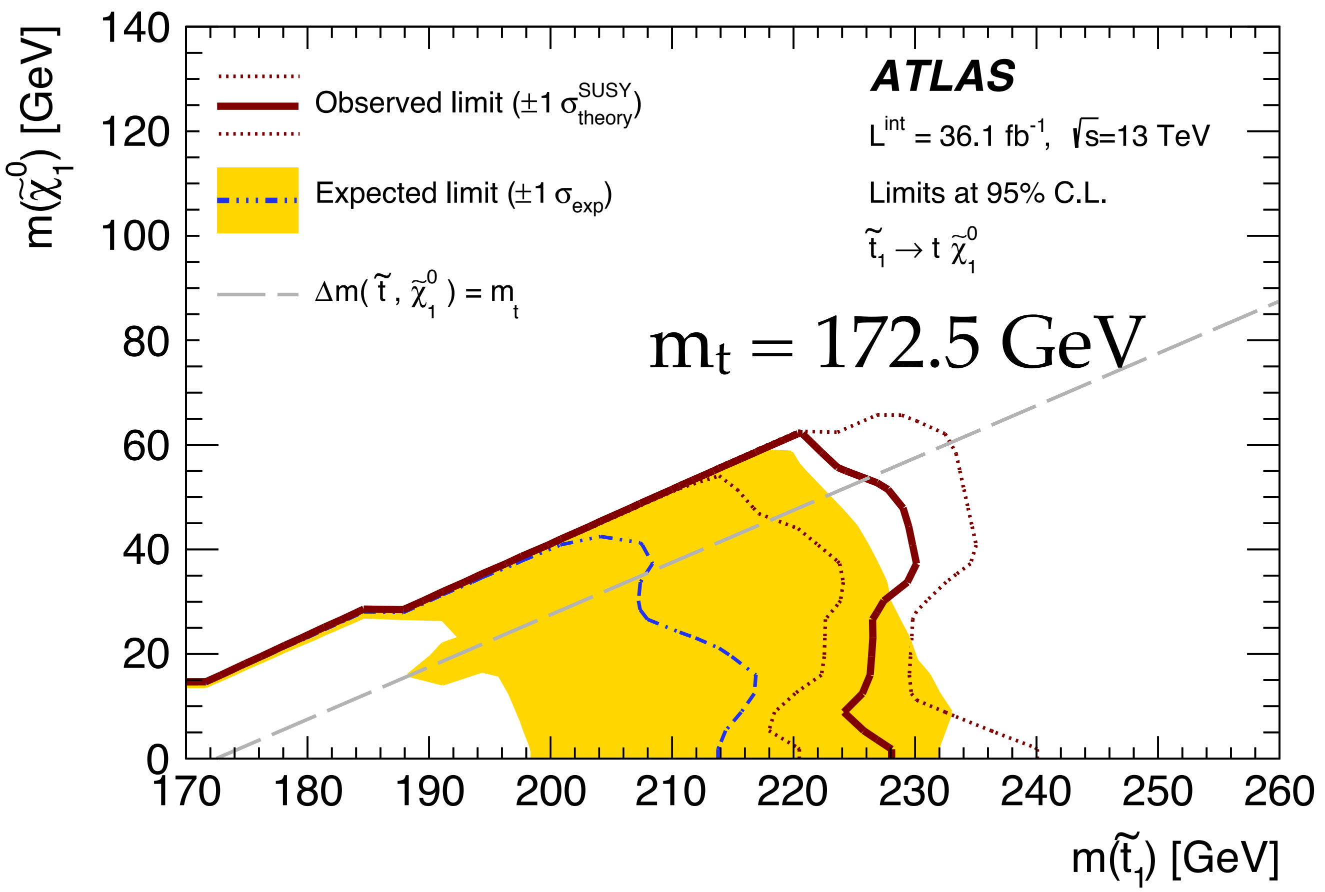
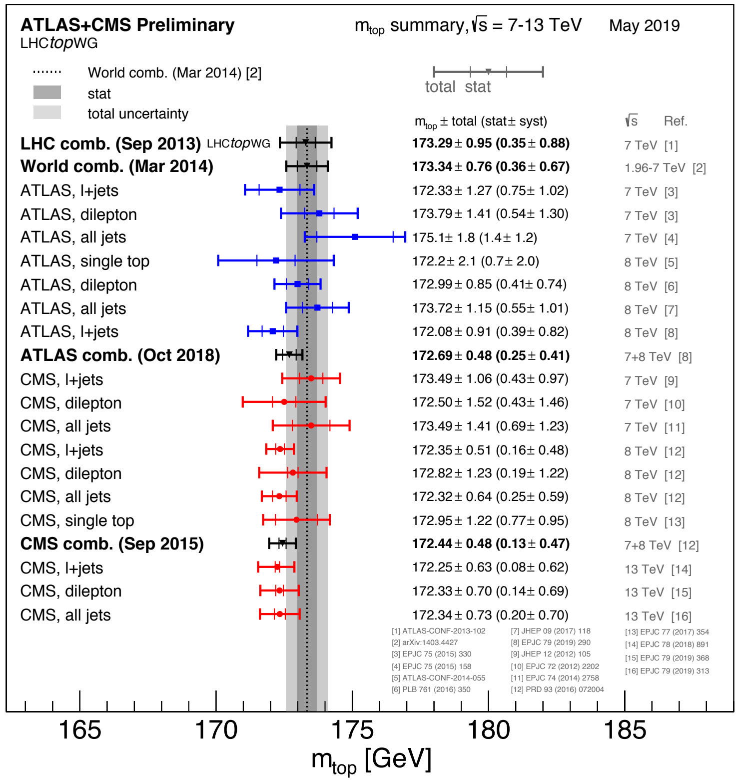
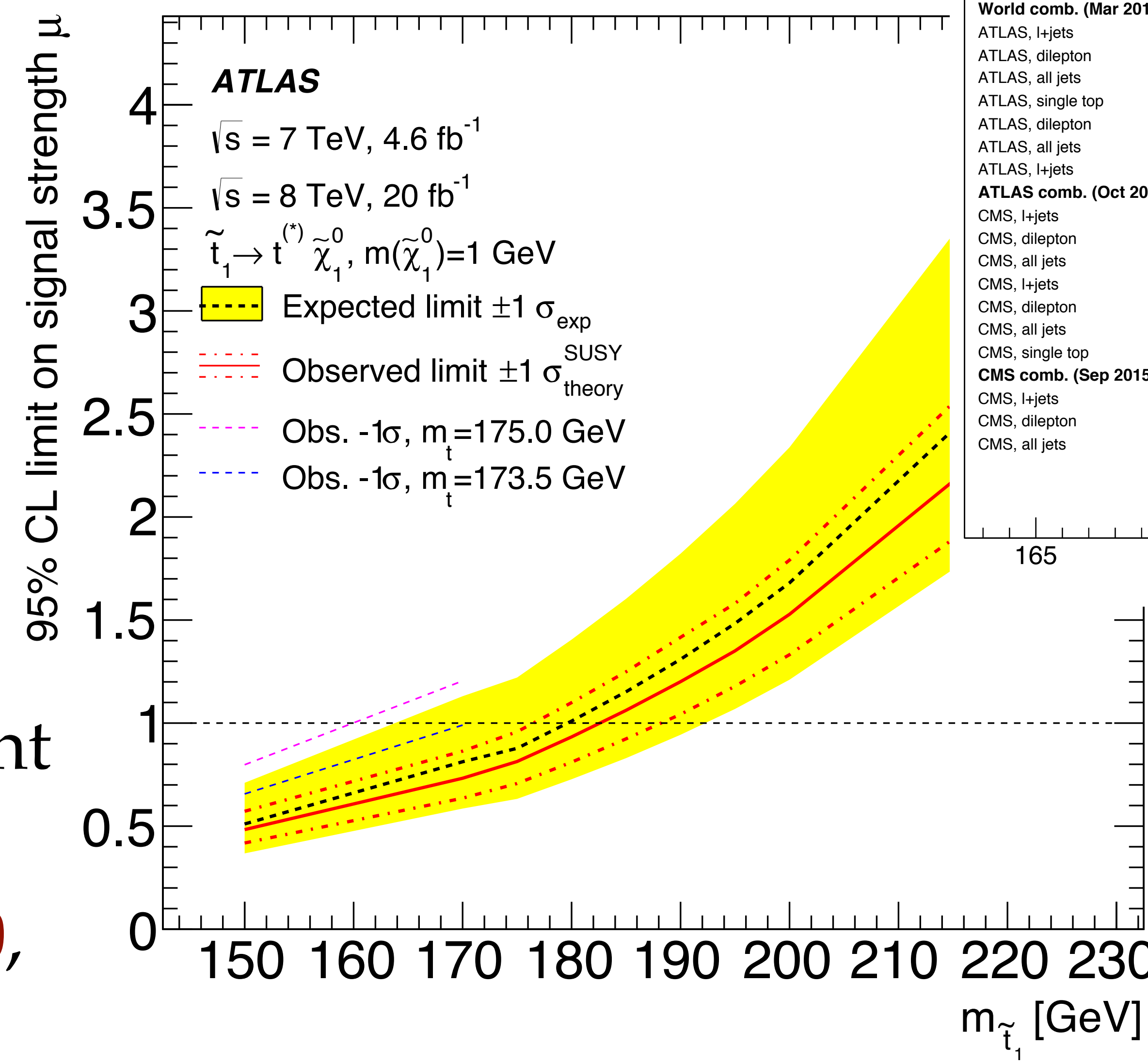


Stealth Stop Searches

ATLAS, EPJC 74 (2014) 3109
ATLAS, EPJC 75 (2015) 510
CMS, EPJC 79 (2019) 313

- $t\bar{t}$ cross-section ratio allows unique testing ground for new physics
- Demonstrates potential impact of top mass on stop limits
- Could stealth stop bias the measurement of the top mass…? see arXiv:1909.09670, PLB 743 (2015) 218

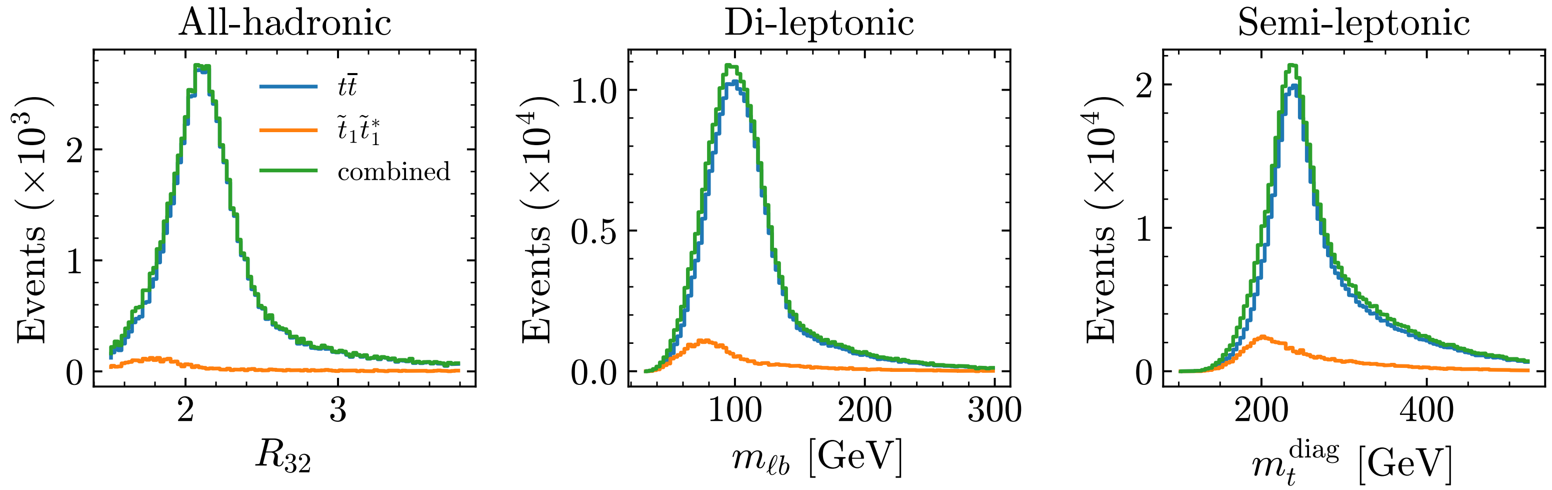


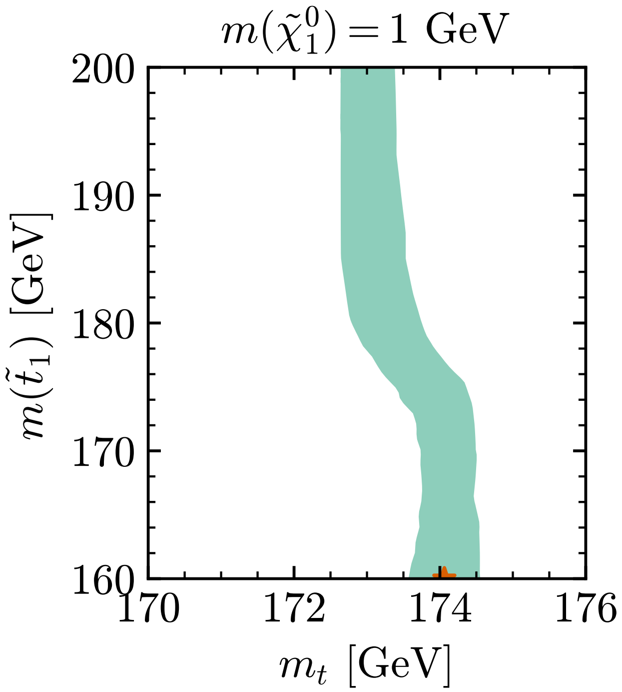


Stealth Stop Searches

Cohen, SM, Ostdiek, Zheng
arXiv:1909.09670

recast of top mass measurements with stop contamination





	All-hadronic	Di-leptonic	Semi-leptonic
$m(\tilde{t}_1)$	172.2 GeV	166.5 GeV	160.8 GeV
Bias	−0.5 GeV	−2.0 GeV	−1.3 GeV

Table 1: Summary of the maximum bias on the measured m_t due to stop contamination in each channel, assuming $m(\tilde{\chi}_1^0) = 1$ GeV. The top row shows the mass of the stop that maximally biases the experimentally measured mass from the Monte Carlo truth mass. The size of the bias in the measurement for each channel is shown in the bottom row.

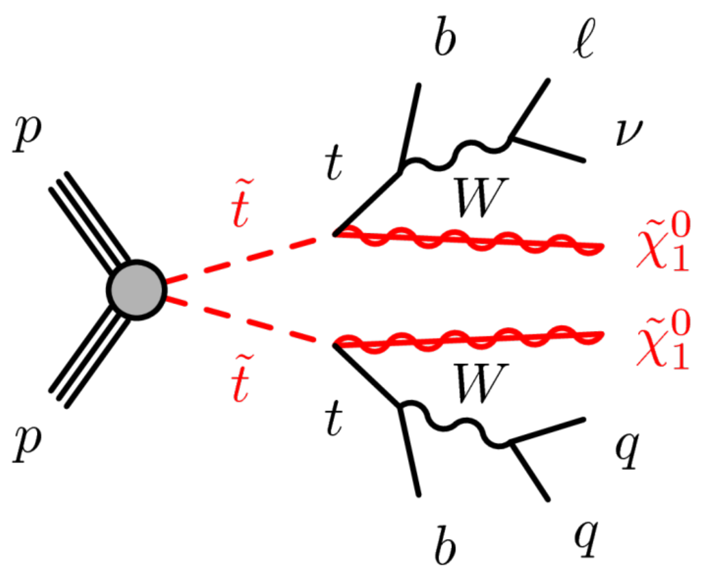
Summary & Outlook

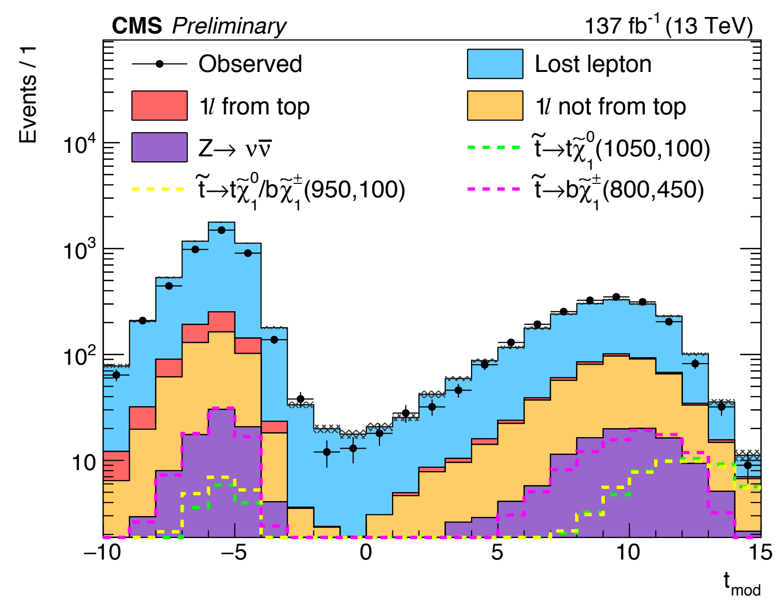
- Over 20 years after its discovery, the massive top quark plays a central role in searching for new physics at the LHC
- Measurements have **improved our background estimates** and **increased our sensitivity to new physics** in *challenging* regions of phase space; continued synergies are needed!
- Care must be taken when interpreting limits in the 'stealth' region — a thorough treatment is needed to ensure stops are not hiding here!
- ATLAS and CMS results using the full Run 2 dataset have begun to appear; stay tuned for the full suite of updated stop searches

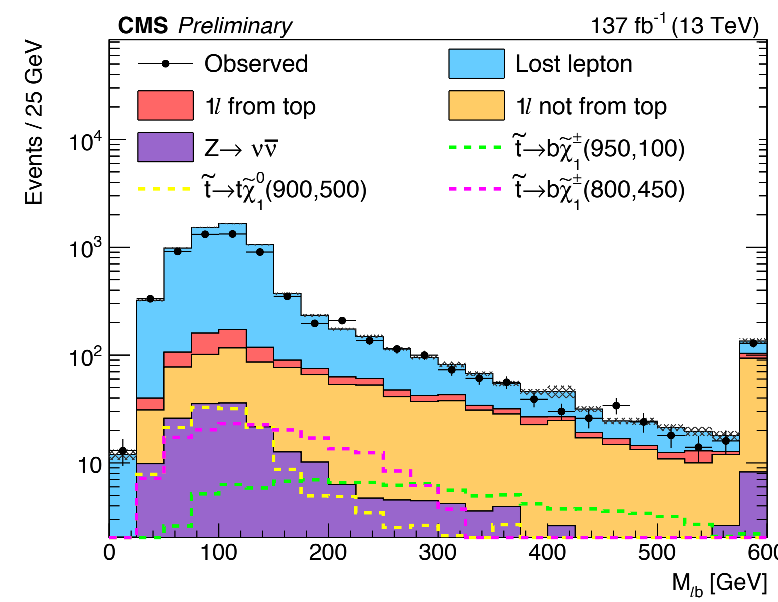
Additional Material

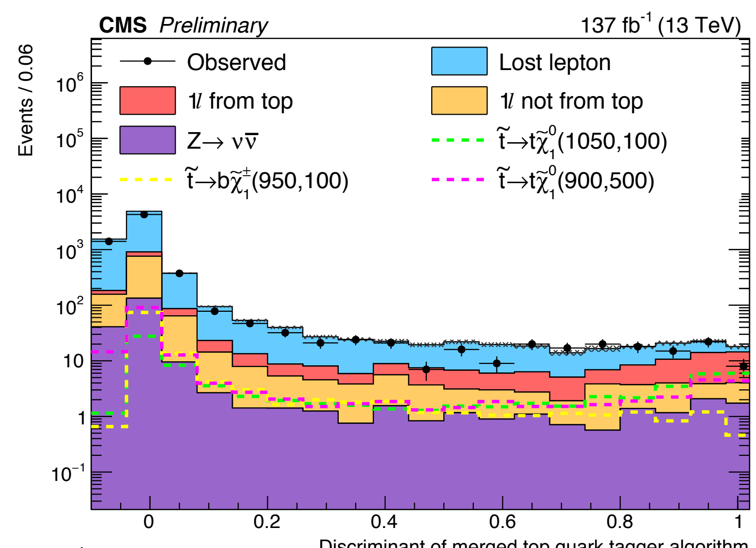
Direct Stop Searches

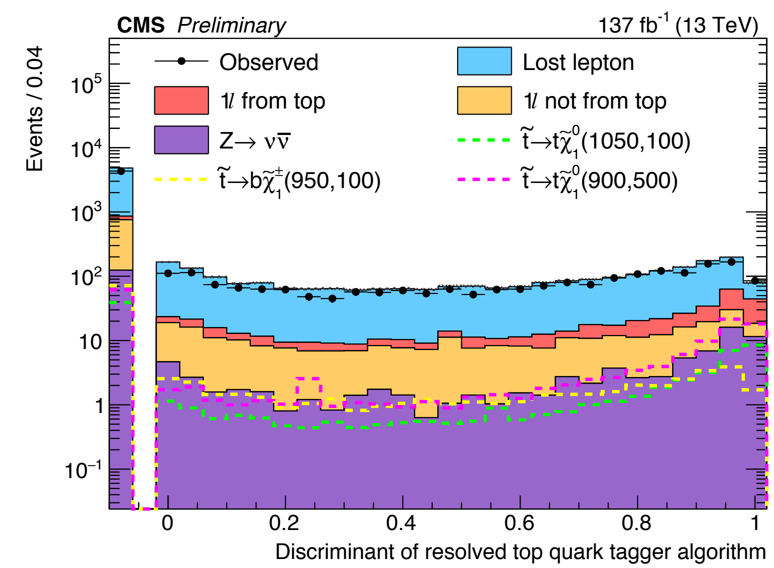
CMS-PAS-SUS-19-009











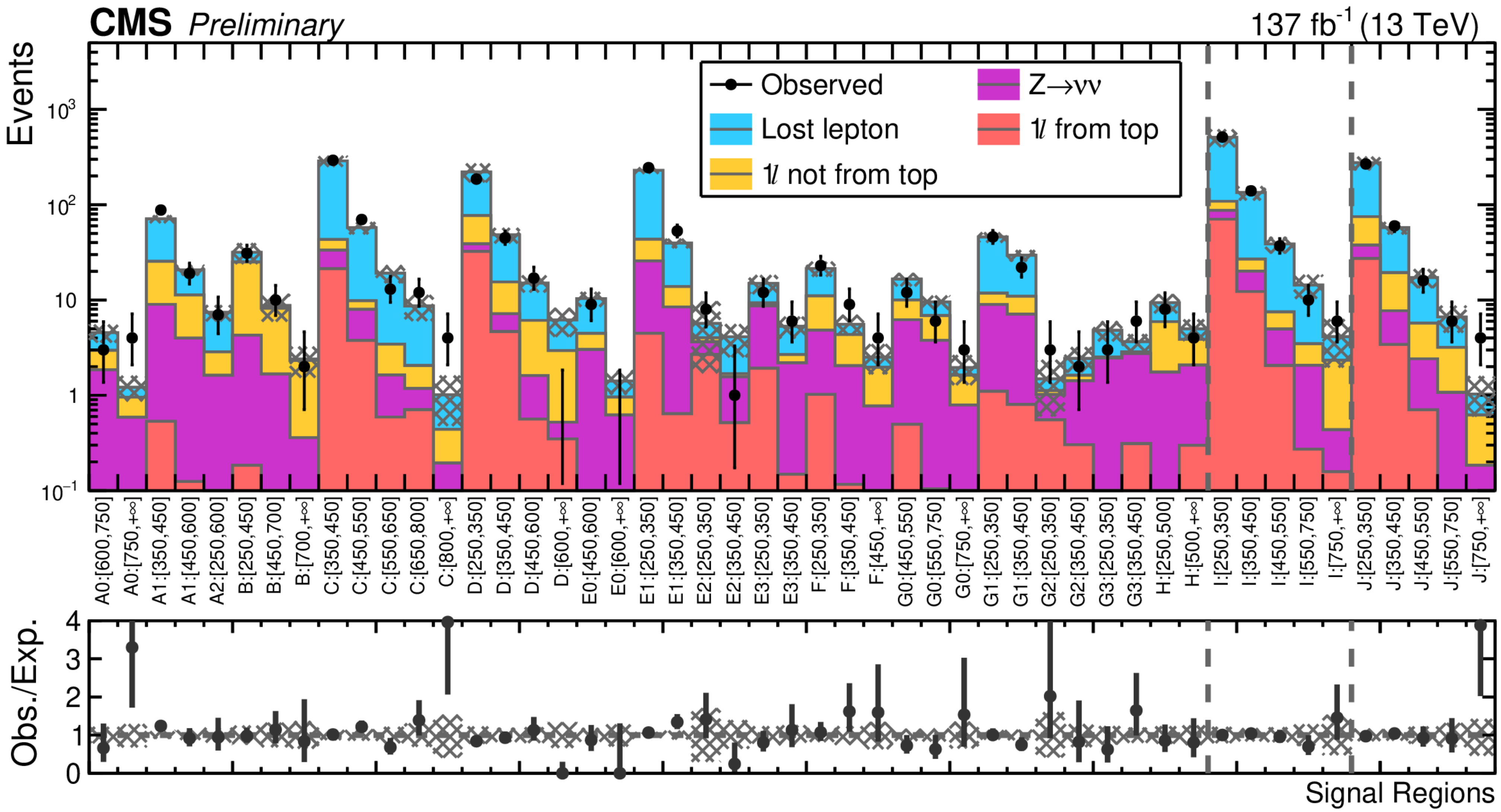
- Modified "topness" (t_{mod})

$$t_{mod} = \ln(\min S), \text{ with } S = \frac{\left(m_W^2 - (p_\nu + p_\ell)^2\right)^2}{a_W^4} + \frac{\left(m_t^2 - (p_b + p_W)^2\right)^2}{a_t^4}$$

modified from "topness" defined in: Graesser and Shelton, PRL **111**, 121802 (2013)

Direct Stop Searches

CMS-PAS-SUS-19-009



	N_J	t_{mod}	$M_{\ell b}$ [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

X0: Inclusive
X1: Untagged
X2: Boosted top
X3: Resolved top

I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{\overline{b,soft}} \geq 1$

Direct Stop Searches

CMS-PAS-SUS-19-009

Table 8: The observed and expected yields for signal regions targeting scenarios of top squark production with a compressed mass spectrum.

N_J	$N_{b,med}$	$N_{b,soft}$	E_T^{miss} [GeV]	Lost lepton	1ℓ (not from t)	1ℓ (from t)	$Z \to \nu\bar{\nu}$	Total expected	Total observed
≥ 5	≥ 1	≥ 0	250 – 350	403^{+40}_{-39}	21^{+8}_{-8}	71 ± 71	17 ± 4	511^{+81}_{-81}	513
			350 – 450	108^{+15}_{-15}	$6.8^{+2.6}_{-2.5}$	12 ± 12	7.8 ± 1.6	134^{+20}_{-19}	140
			450 – 550	31^{+8}_{-8}	$2.5^{+1.0}_{-0.9}$	2.0 ± 2.0	2.9 ± 0.8	39^{+9}_{-8}	37
			550 – 750	11^{+5}_{-4}	$1.4^{+0.7}_{-0.6}$	0.3 ± 0.3	1.8 ± 0.5	14^{+5}_{-4}	10
			> 750	$1.8^{+1.2}_{-1.0}$	$1.9^{+2.5}_{-1.9}$	0.2 ± 0.2	0.3 ± 0.1	$4.1^{+2.7}_{-2.2}$	6
≥ 3	≥ 0	≥ 1	250 – 350	201^{+21}_{-20}	37^{+7}_{-7}	27 ± 27	10.4 ± 1.5	276^{+35}_{-35}	268
			350 – 450	38^{+7}_{-6}	$11.6^{+2.2}_{-2.2}$	3.4 ± 3.4	4.3 ± 0.9	58^{+8}_{-8}	60
			450 – 550	11^{+4}_{-3}	$3.3^{+0.6}_{-0.6}$	0.7 ± 0.7	1.7 ± 0.6	17^{+4}_{-3}	16
			550 – 750	$3.5^{+2.6}_{-1.9}$	$2.1^{+0.5}_{-0.5}$	–	1.1 ± 0.8	$6.6^{+2.8}_{-2.1}$	6
			> 750	$0.4^{+0.4}_{-0.4}$	$0.4^{+0.2}_{-0.2}$	0.02 ± 0.02	0.2 ± 0.4	$1.0^{+0.6}_{-0.6}$	4

Direct Stop Searches

CMS-PAS-SUS-19-009

Table 6: Summary of systematic uncertainties. The range of values reflect their impact on the estimated backgrounds and signal yields in different signal regions.

Source	Signal	Lost lepton	1ℓ background	$Z \to \nu\bar{\nu}$
Data statistical uncertainty	—	5–50%	4–30%	—
Simulation statistical uncertainty	6–36%	3–68%	5–70%	4–41%
$t\bar{t}$ E_T^{miss} modeling	—	3–50%	—	—
QCD scales	1–5%	0–3%	2–5%	1–40%
Parton distribution	—	0–4%	1–8%	1–12%
Pileup	1–5%	1–8%	0–5%	0–7%
Luminosity	2.3–2.5%	—	—	2.3–2.5%
$W + b$ cross section	—	—	20–40%	—
$Z \to \nu\nu$ estimate	—	—	—	5–10%
System recoil (ISR)	1–13%	0–3%	—	—
Jet energy scale	2–24%	1–16%	1–34%	1–28%
E_T^{miss} resolution	—	1–10%	1–5%	—
Trigger	2–3%	1–3%	—	2–3%
Lepton efficiency	3–4%	2–12%	—	1–2%
Merged top tagging efficiency	3–6%	—	—	5–10%
Resolved top tagging efficiency	5–6%	—	—	3–5%
b tagging efficiency	0–2%	0–1%	1–7%	1–10%
Soft b tagging efficiency	2–3%	0–1%	0–1%	0–5%

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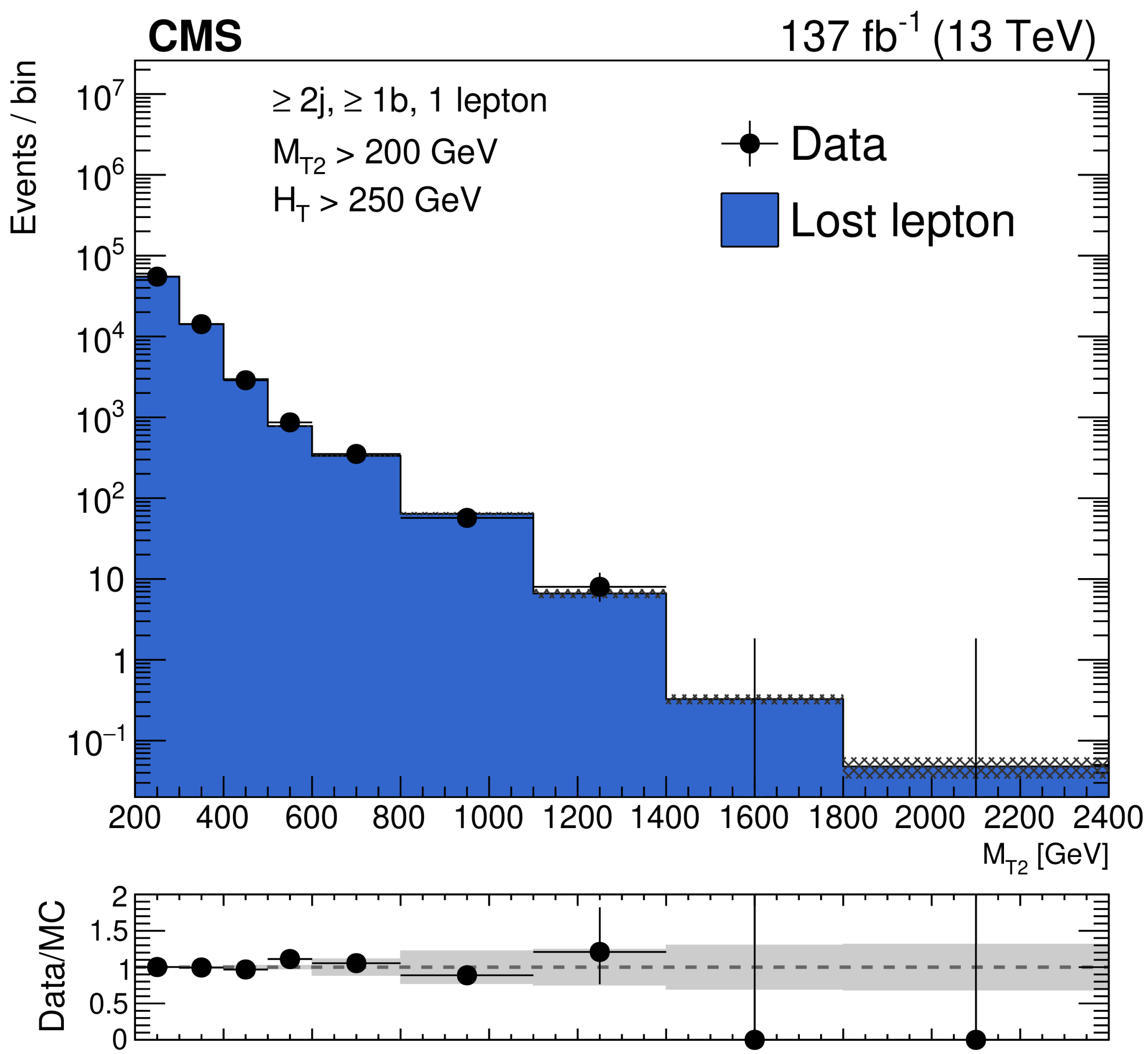

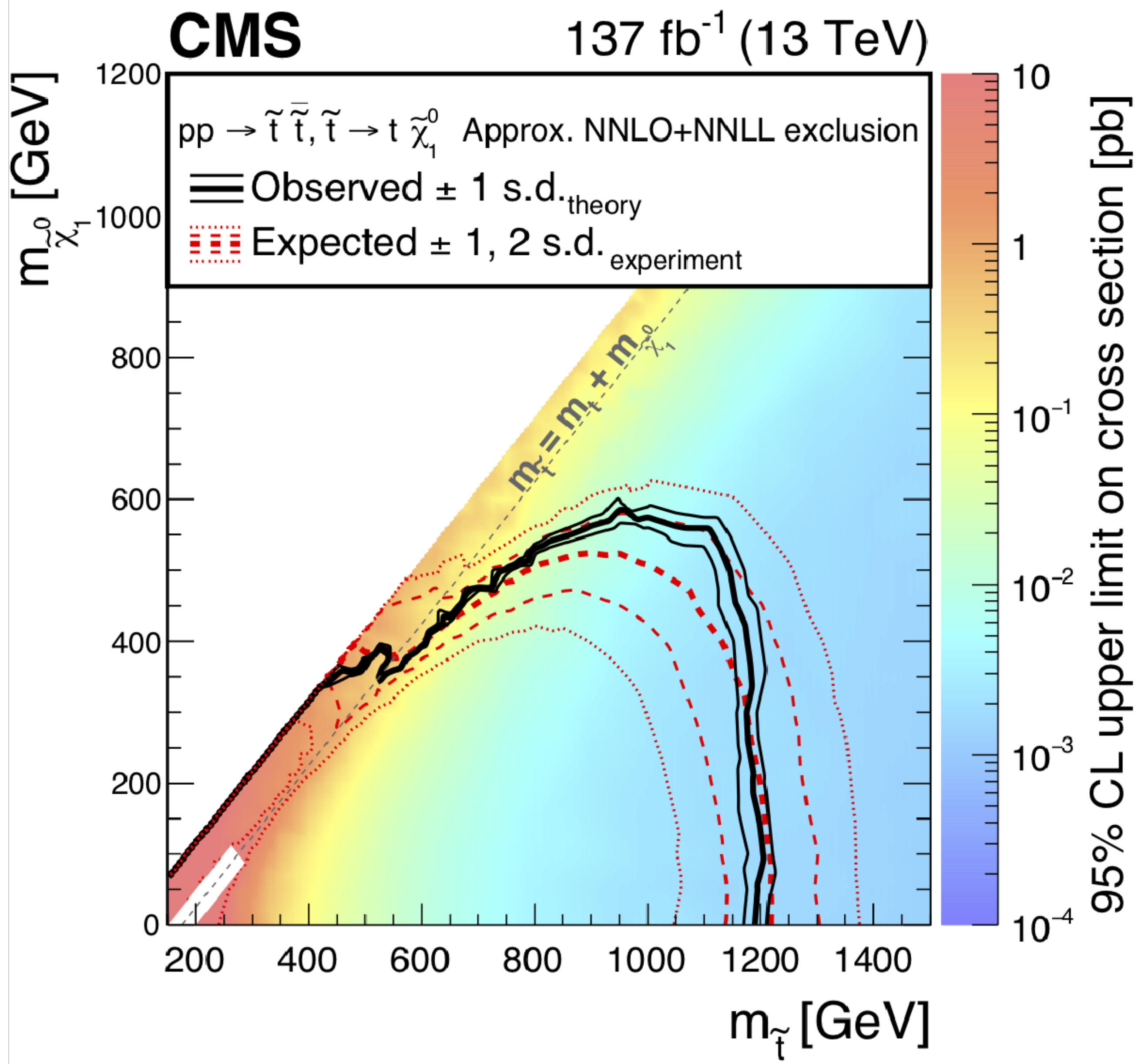

Stealth Stop Searches

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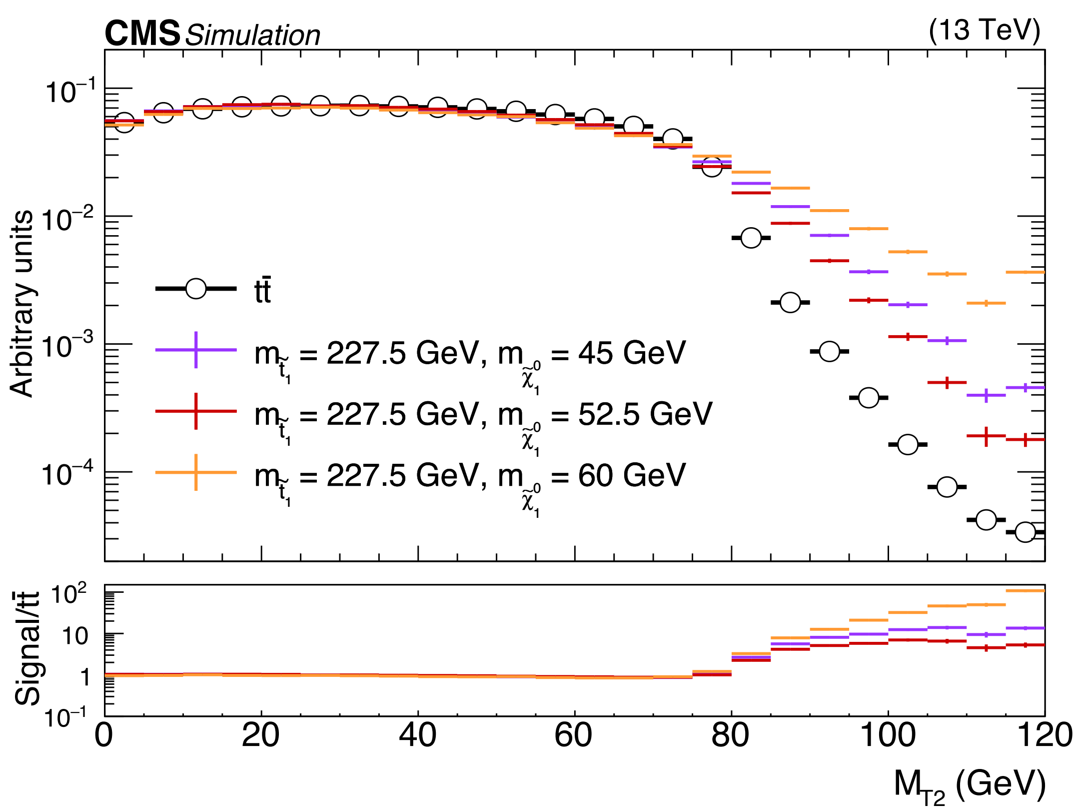
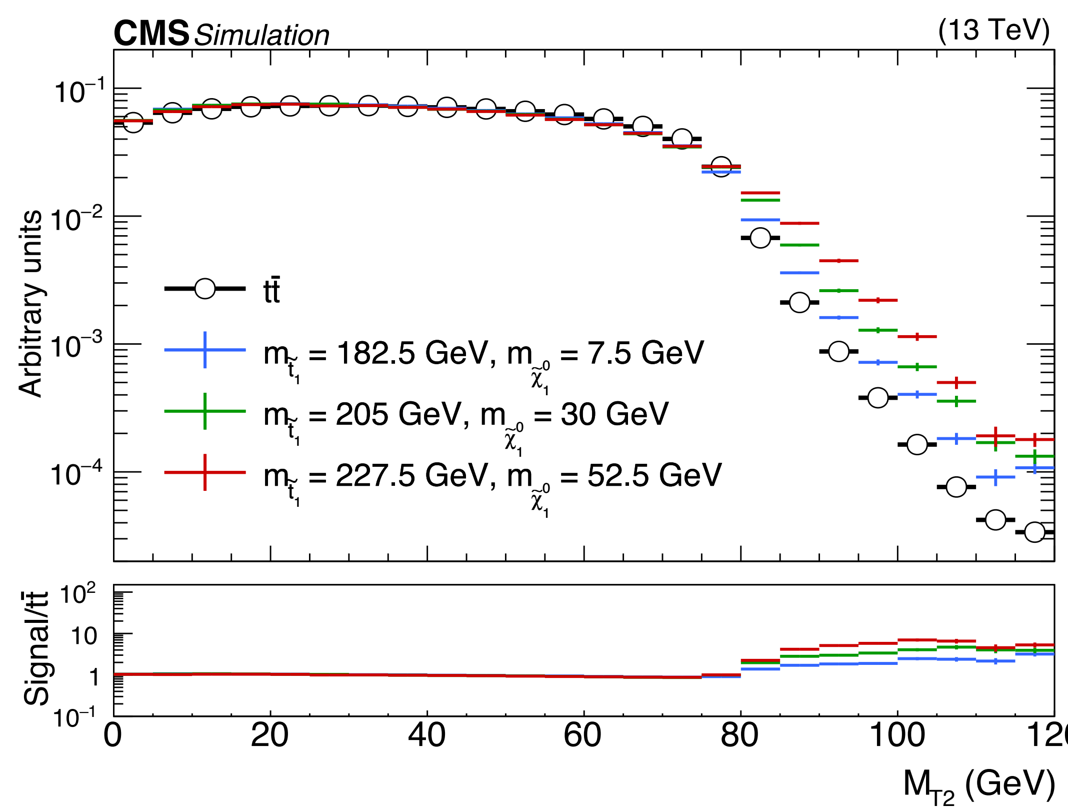
- CMS eμ search, based on 36 fb^{-1}
- M_{T2} main discriminating variable; endpoint @ m_W for tt events, changes with Δm(stop-neutralino) and MET

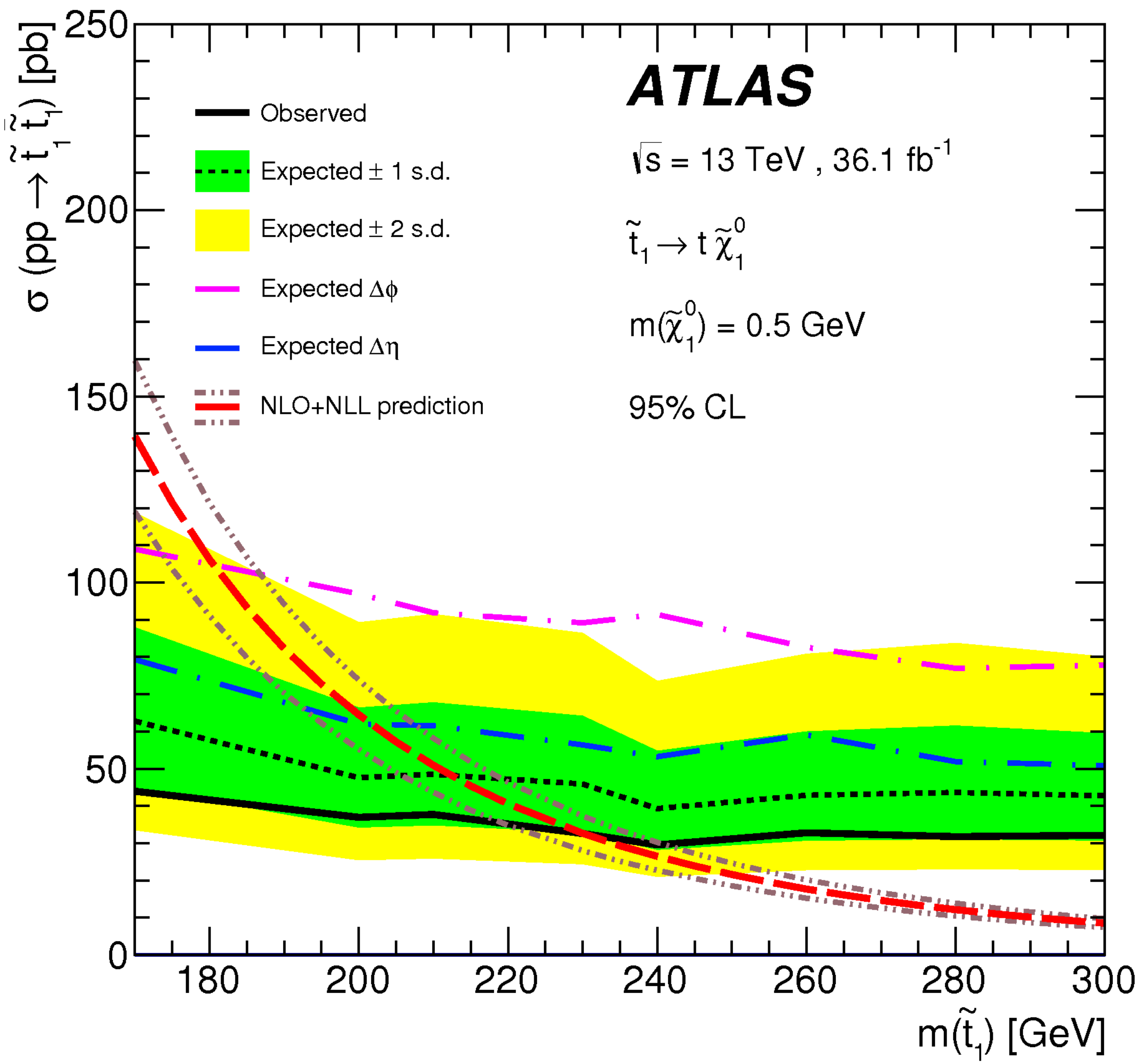
$$M_{T2} = \min_{\vec{p}_{T,1}^{\,miss}+\vec{p}_{T,2}^{\,miss}=\vec{p}_{T}^{\,miss}} \left(\max \left[m_T(\vec{p}_T^{\,\ell 1}, \vec{p}_{T,1}^{\,miss}), m_T(\vec{p}_T^{\,\ell 2}, \vec{p}_{T,2}^{\,miss}) \right] \right)$$





Stealth Stop Searches

arXiv:1903.07570, submitted to EPJC



- Δη provides more stringent limit than Δφ

Stealth Stop Searches

Cohen, SM, et al
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