Searches for strong production of supersymmetric particles with the ATLAS detector

Chenzheng Zhu

on behalf of ATLAS collaboration

Institute of High Energy Physics, Chinese Academy of Science

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Introduction

- Supersymmetry(SUSY): one of the most appealing BSM theories
  - Introduce new symmetry: R-parity between boson and fermions
  - Brings solutions to problems such as hierarchy problem, grand unification of gauge couplings, dark matter…
- Naturalness arguments for weak-scale supersymmetry favors squarks and gluinos light enough to be produced at the LHC
- ATLAS recorded $139\ fb^{-1}$ of data in Run-2, could we find SUSY in these huge amount of data?
- This talk will present the latest SUSY strong production searches with the ATLAS detector

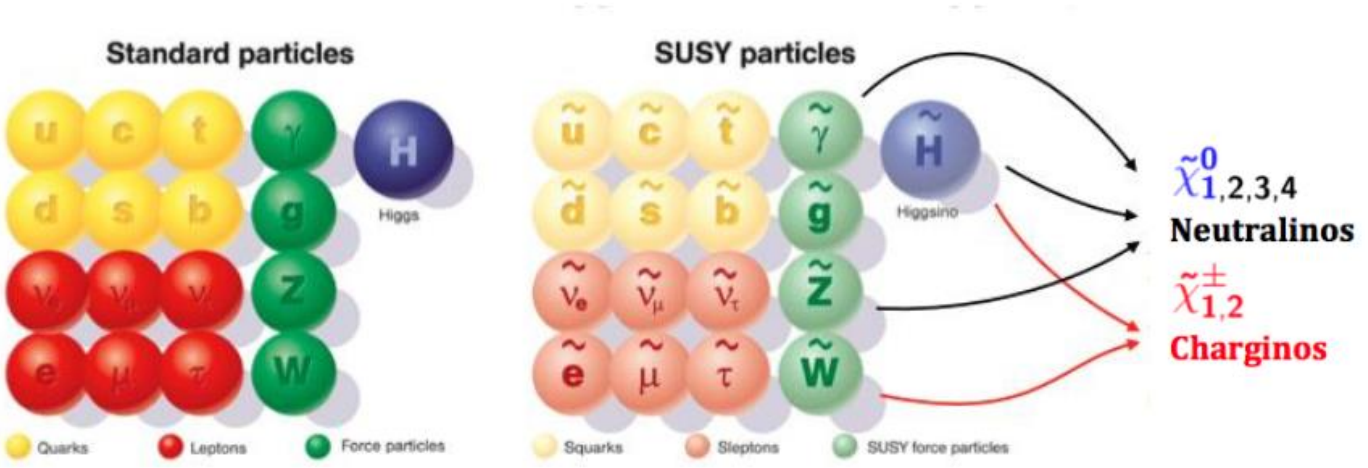
$$m_h^2 = m_{h_0}^2 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 - \mathcal{O}(\log(\Lambda^2))$$

Bare mass

125 GeV

corrections

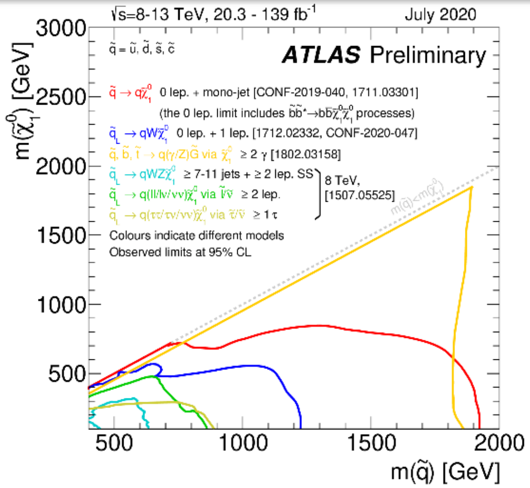
(Λ: cut-off scale ~ 10^{19} GeV)

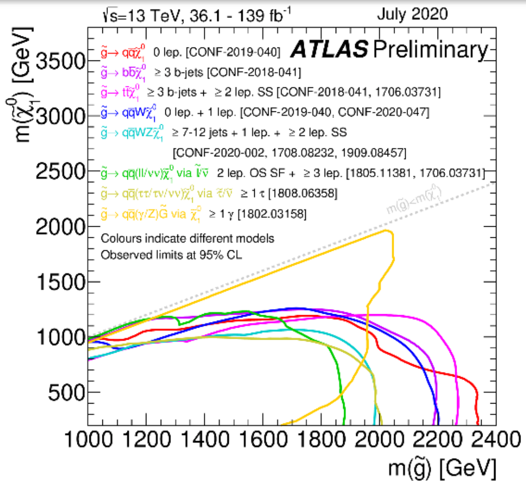


SUSY strong production search with ATLAS detector

Based on the full Run-2, various strong productions with many different final states are studied

– In these study, the models are simplified models. Sparticles not included in the model are set to very large values

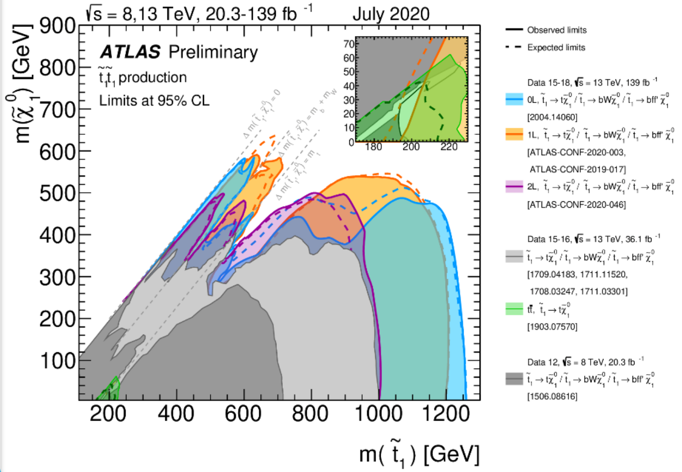


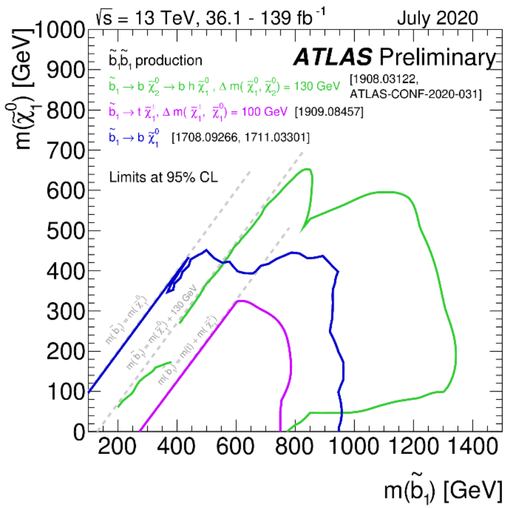


Squark(1^{st} and 2^{nd} gen) and gluino

Gluino and squark prod, 1L final state

Gluino prod, large jet multiplicities final state





Stop and sbottom

Stop prod, 2L + MET final state,

Stop prod, 1L + MET final state,

Stop prod, 0L + MET in final state,

Sbottom prod, bjets and taus in final state,

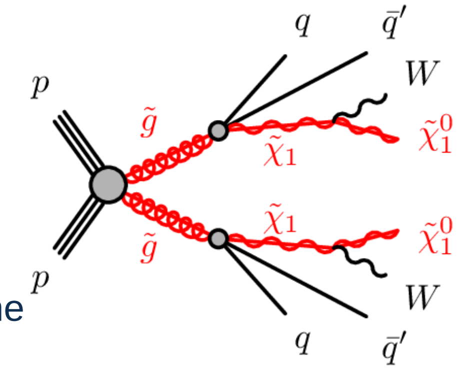
Stop prod, Z and Higgs in final state

More models like RPV models are also studied

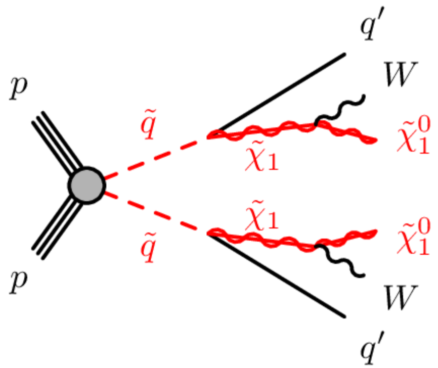
Inclusive 1L: ATLAS-CONF-2020-047

new

- Signal models
  - Squarks(1st and 2nd generation) and gluinos productions
  - Two kinds of signal grid considered:
    - x = 1/2 grid: Free parameters on gluino/squark and $\tilde{\chi}_1^0$ masses while the mass difference between the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ is set to half of the mass difference between the gluino/squark and $\tilde{\chi}_1^0$ mass. ($x = (\tilde{\chi}_1^\pm\ mass - \tilde{\chi}_1^0\ mass)/(\tilde{g}/\tilde{q}\ mass - \tilde{\chi}_1^0\ mass)$)
    - grid-x: Free parameters on gluino/squark and $\tilde{\chi}_1^\pm$ masses, $\tilde{\chi}_1^0$ mass is fixed to 60 GeV



- Signature: 1 lepton + jets + E_T^{miss}
  - One lepton from the $W \to l + \nu$ decay
  - Multiple jets from the gluino and squark decay and W hardonic decay
  - E_T^{miss} mainly from the $\tilde{\chi}_1^0$

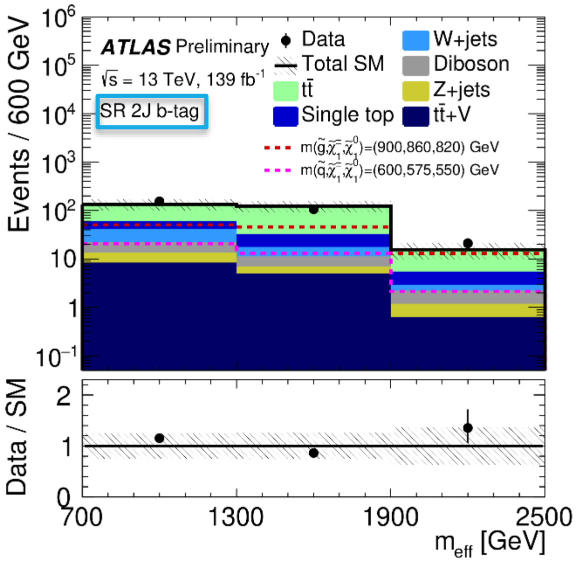


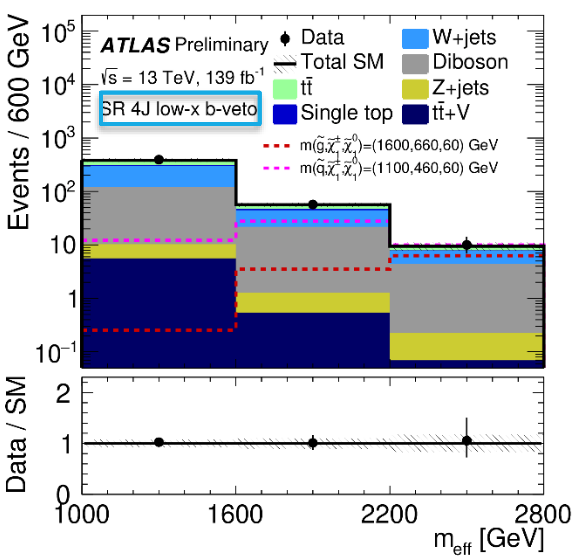
Inclusive 1L: Signal regions

new

- Detailed study has been perform in order to cover different mass regions
  - 2J regions targets compressed SUSY signals
  - 4J high/low x regions target at grid-x mass regions with high/low x
  - 6J regions targets high gluino/squark and low LSP masses
- E_T^{miss} trigger and large E_T^{miss} to reject multi-jet backgrounds
- Likelihood is calculated with multiple bin fit

SR	2J	4J high-x	4J low-x	6J
N_ℓ		$= 1$		
p_T^ℓ [GeV]	$> 7(6)$ for $e(\mu)$ and $< \min(10 \cdot N_{jet}, 25)$	> 25	> 25	> 25
N_{jet}	≥ 2	4–5	4–5	≥ 6
E_T^{miss} [GeV]	> 400	> 300	> 300	> 300
m_T [GeV]	> 100	> 520	150–520	> 225
Aplanarity	-	> 0.01	> 0.01	> 0.05
E_T^{miss}/m_{eff}	> 0.25	> 0.2	> 0.2	-
N_{b-jet} (excl)		$= 0$ for b-veto, ≥ 1 for b-tag		
m_{eff} [GeV] (excl)	3 bins $\in$ [700,2500+]	3 bins $\in$ [1000,2800+]	3 bins $\in$ [1000,2800+]	4 bins $\in$ [700,3500+]
N_{b-jet} (disc)		b-veto		
m_{eff} [GeV] (disc)	$> 1900(1300)$ for gluino (squark)	> 2200	> 2200	$> 2800(2100)$ for gluino (squark)

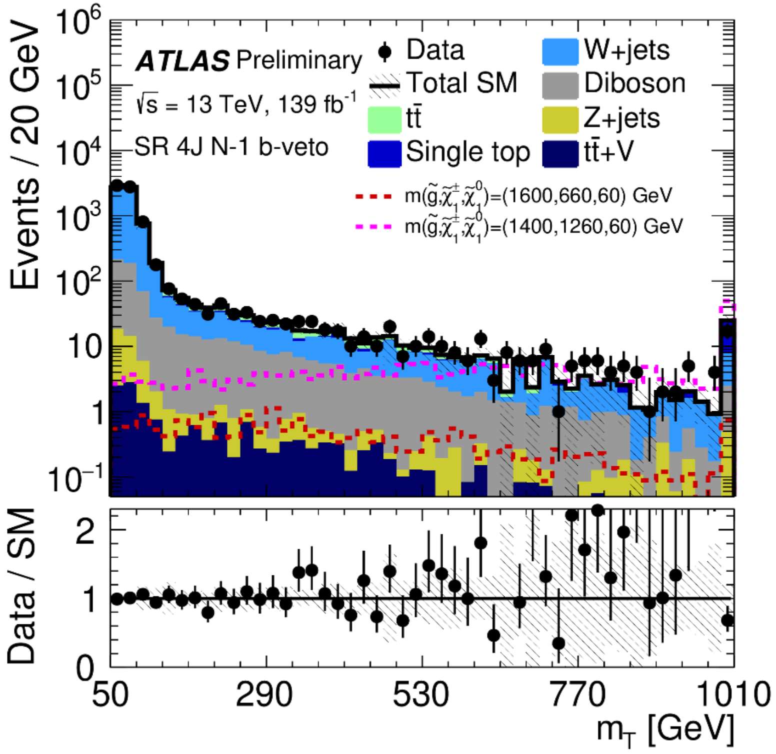




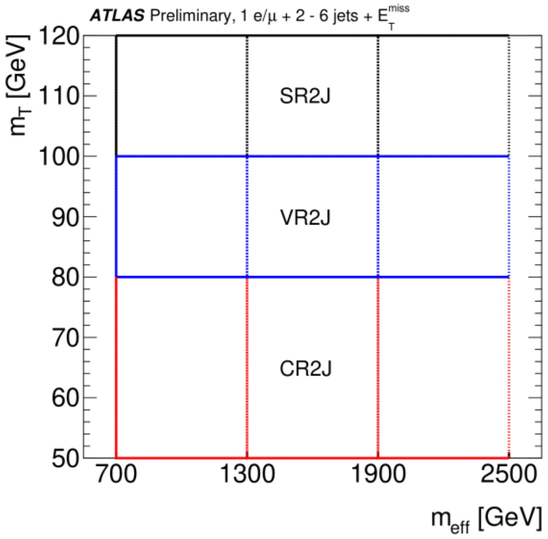
Inclusive 1L: Background estimations

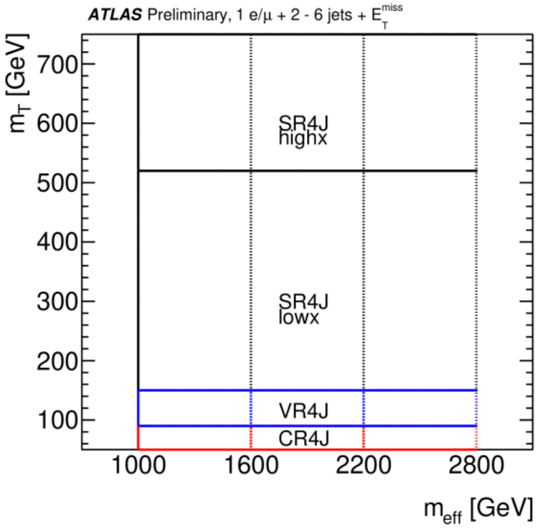
new

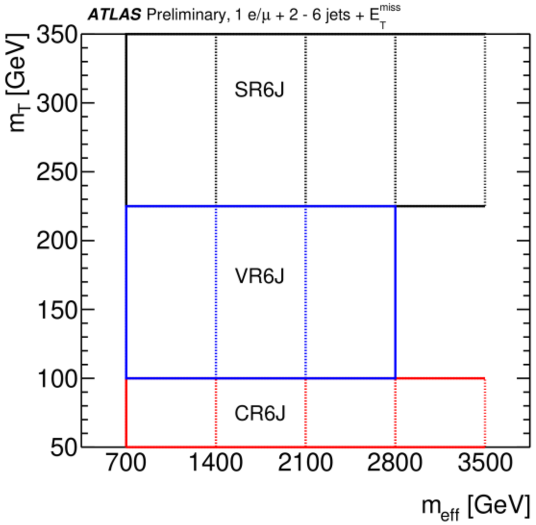
- Main backgrounds are ttbar/Single-top and W+jets
- Define dedicate control and validation regions for them and estimate other small backgrounds using MC
- The variable of the m_T is used to extrapolate from control region to signal region and validated in validation region. Top regions and W+jets regions are split using b-tag and b-veto



The N-1 distribution for 4J SR/CR/VR combined m_T distributions



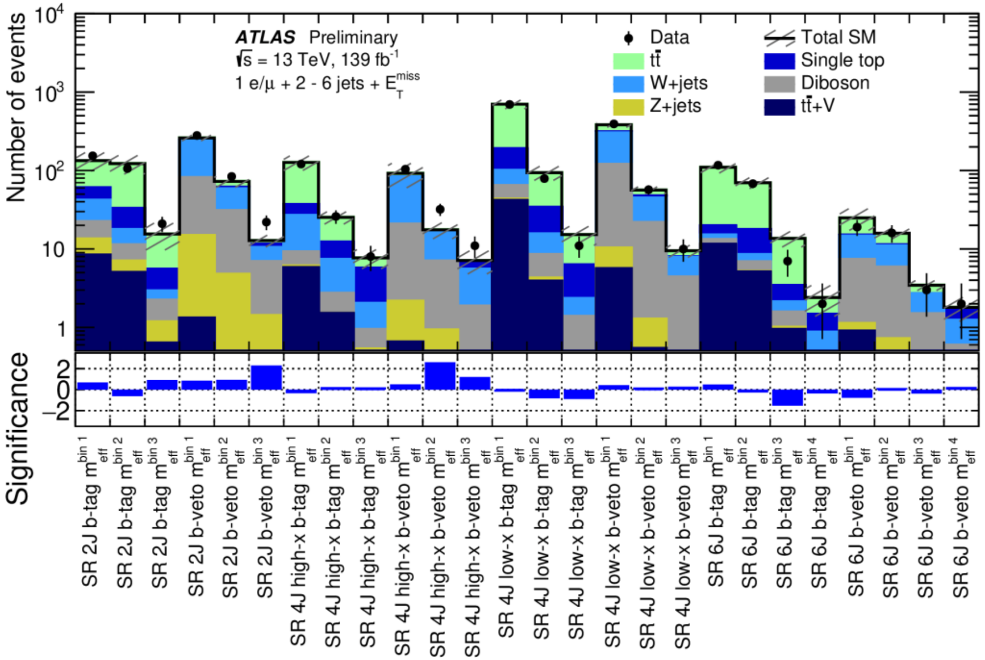


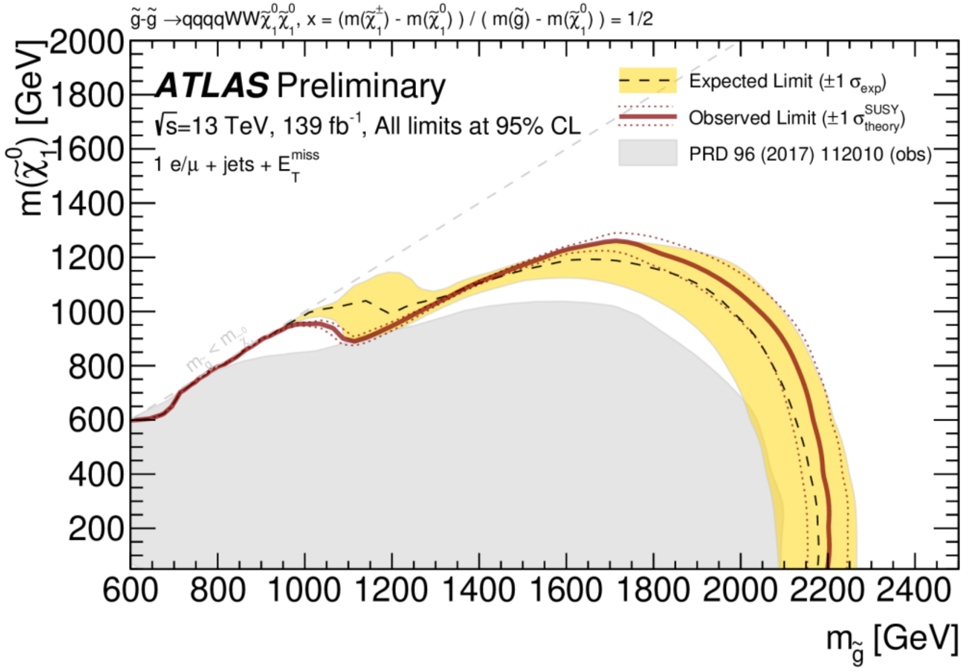


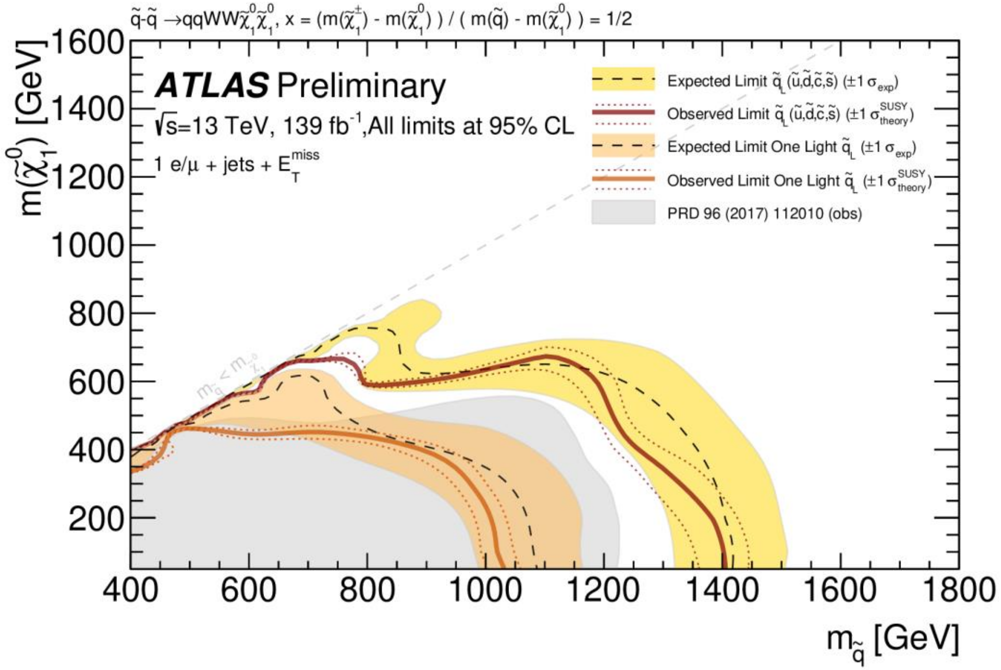
Inclusive 1L: Results

new

- No significant excess over the SM background estimation
- The gluino(squark) mass < 2.2(1.4) TeV are excluded for a low neutralino mass
- For one-flavour scheme, the squark mass up to around 1 TeV are excluded







Inclusive 1L: Results

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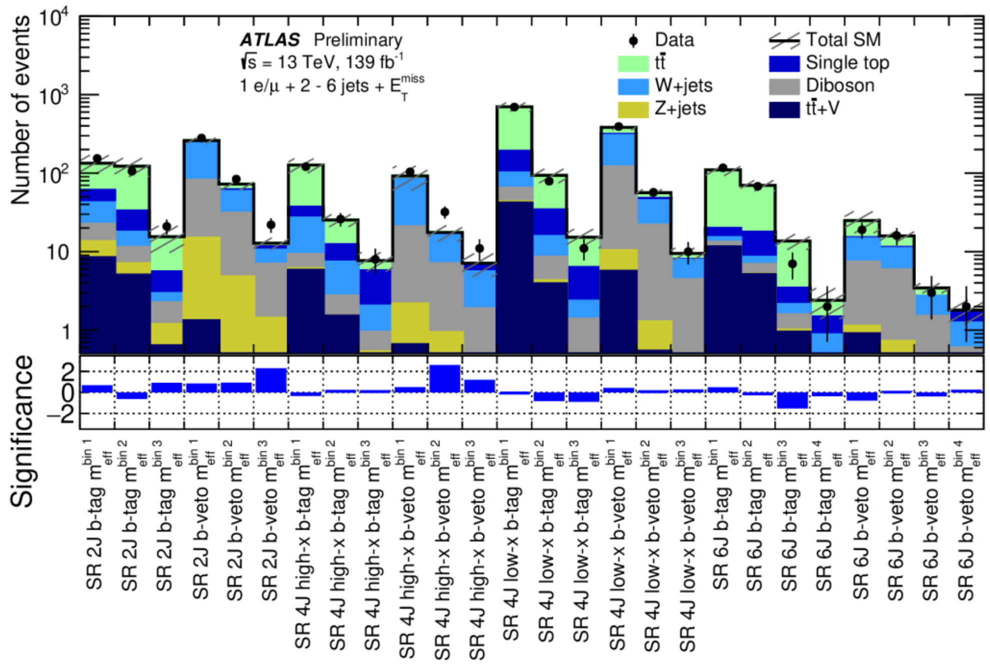
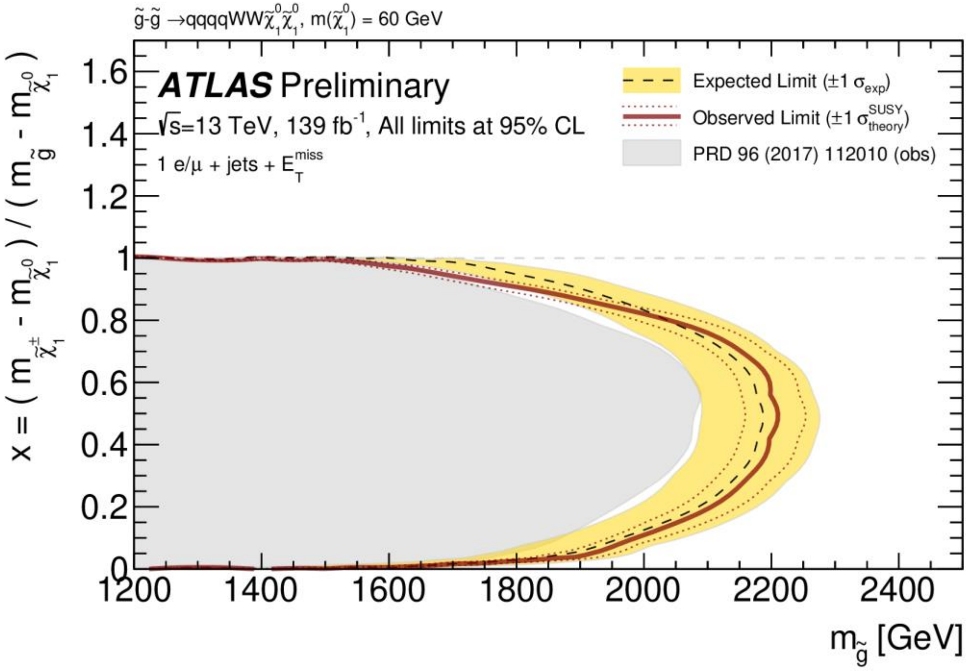
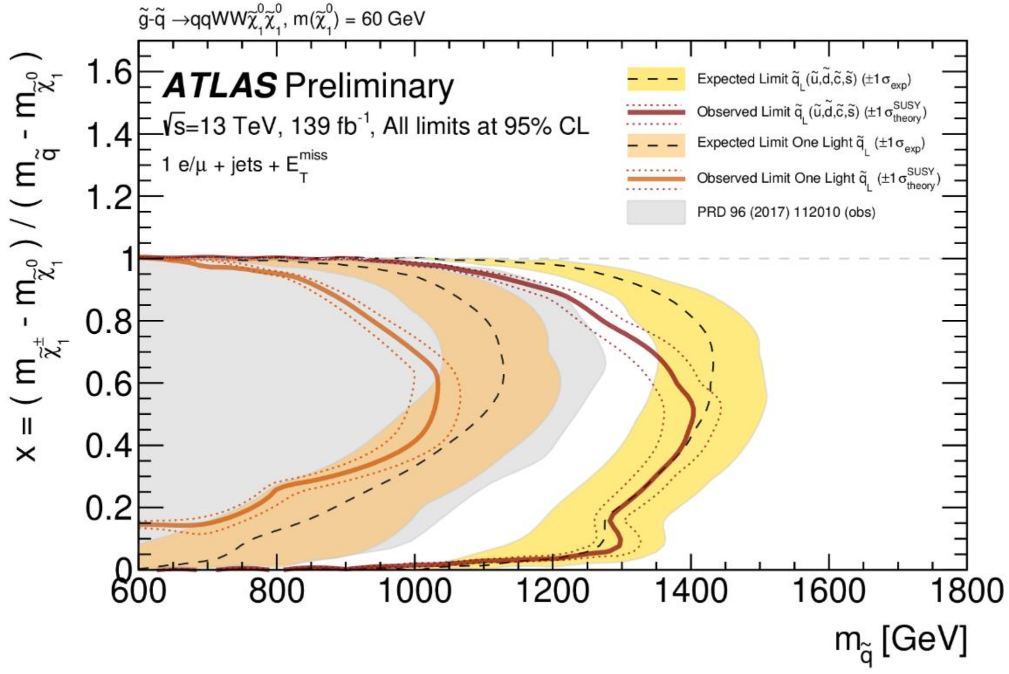


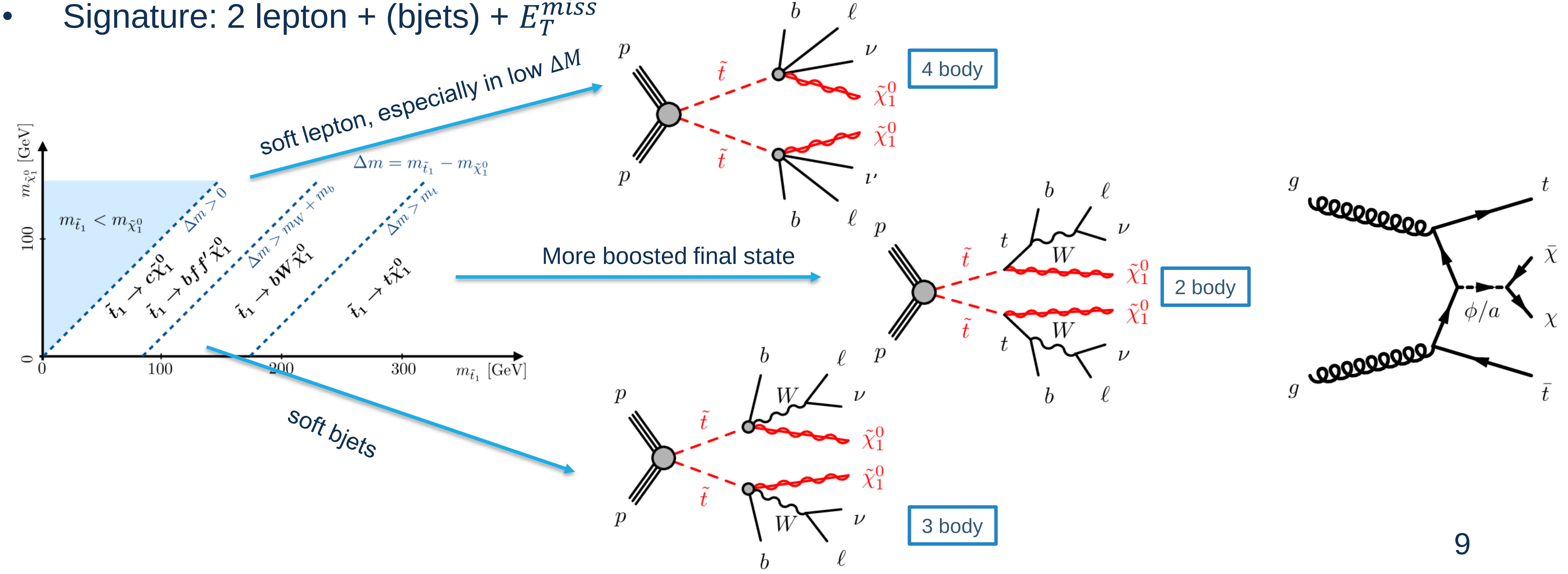




tt2L + E_T^{miss}: ATLAS-CONF-2020-046

new

- Signal models
  - Stop production, then decay through 2-/3-/4- body decay
  - The search for spin-0 mediator DM production associated with top quarks is also proceed
- Signature: 2 lepton + (bjets) + E_T^{miss}



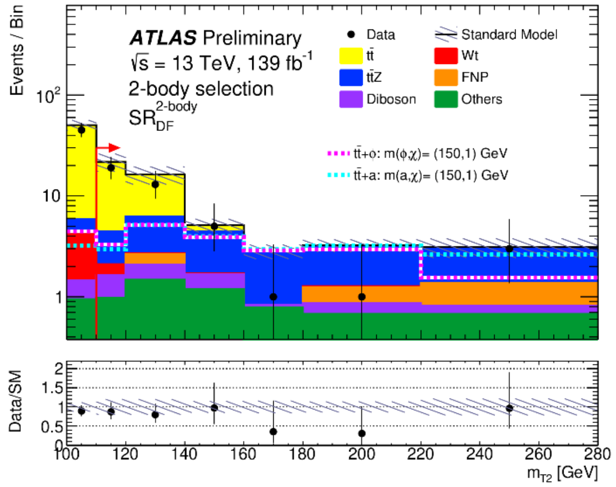
tt2L + E_T^{miss}: Signal regions new

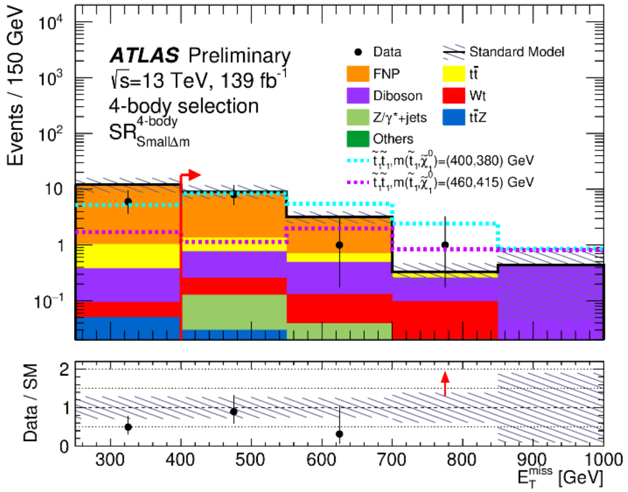
- Considering different 2-/3-/4 body signal model behavior. Three kinds of signal regions are defined to gain the best sensitivity in each models
  - For 2 body, use high E_T^{miss} and stransverse mass m_{T2} to extend the sensitivity of high mass split regions
  - For 3 body and 4 body, the bjet requirement is not strongly required
  - For 4 body small(large) ΔM signal regions, strict(loose) lepton upper cuts are applied to target compressed mass scenario

	$SR^{2\text{-body}}$	
Leptons flavour	DF	SF
$p_T(\ell_1)$ [GeV]	> 25	
$p_T(\ell_2)$ [GeV]	> 20	
$m_{\ell\ell}$ [GeV]	> 20	
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	–	> 20
$n_{b\text{-jets}}$	≥ 1	
$\Delta\phi_{\text{boost}}$ [rad]	< 1.5	
E_T^{miss} significance	> 12	
$m_{T2}^{\ell\ell}$ [GeV]	> 110	

	$SR_W^{3\text{-body}}$		$SR_t^{3\text{-body}}$	
Leptons flavour	DF	SF	DF	SF
$p_T(\ell_1)$ [GeV]	> 25		> 25	
$p_T(\ell_2)$ [GeV]	> 20		> 20	
$m_{\ell\ell}$ [GeV]	> 20		> 20	
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	–	> 20	–	> 20
$n_{b\text{-jets}}$	$= 0$		≥ 1	
$\Delta\phi_\beta^R$ [rad]	> 2.3		> 2.3	
E_T^{miss} significance	> 12		> 12	
$1/\gamma_{R+1}$	> 0.7		> 0.7	
R_{p_T}	> 0.78		> 0.70	
M_Δ^R [GeV]	> 105		> 120	

	$SR^{4\text{-body}}_{\text{Small}\,\Delta m}$	$SR^{4\text{-body}}_{\text{Large}\,\Delta m}$
$p_T(\ell_1)$ [GeV]	$[4.5(4),\ 25]\ e(\mu)$	< 100
$p_T(\ell_2)$ [GeV]	$[4.5(4),\ 10]\ e(\mu)$	$[10,\ 50]$
$m_{\ell\ell}$ [GeV]	> 10	
$p_T(j_1)$ [GeV]	> 150	
$\min \Delta R_{\ell_2, j_i}$	> 1	
E_T^{miss} significance	> 10	
$p_{T,\text{boost}}^{\ell\ell}$ [GeV]	> 280	
E_T^{miss} [GeV]	> 400	
$R_{2\ell}$	> 25	> 13
$R_{2\ell 4j}$	> 0.44	> 0.38

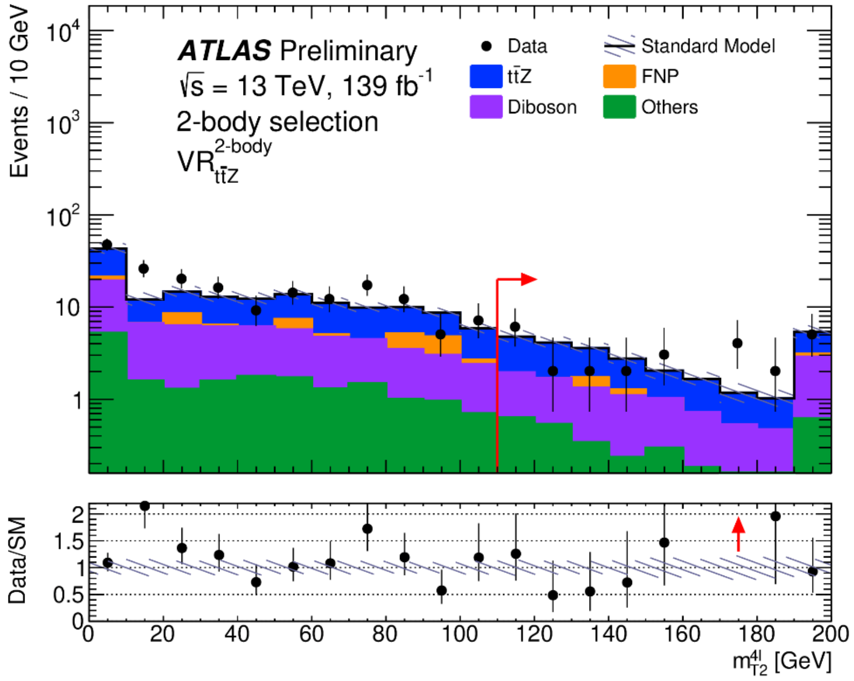


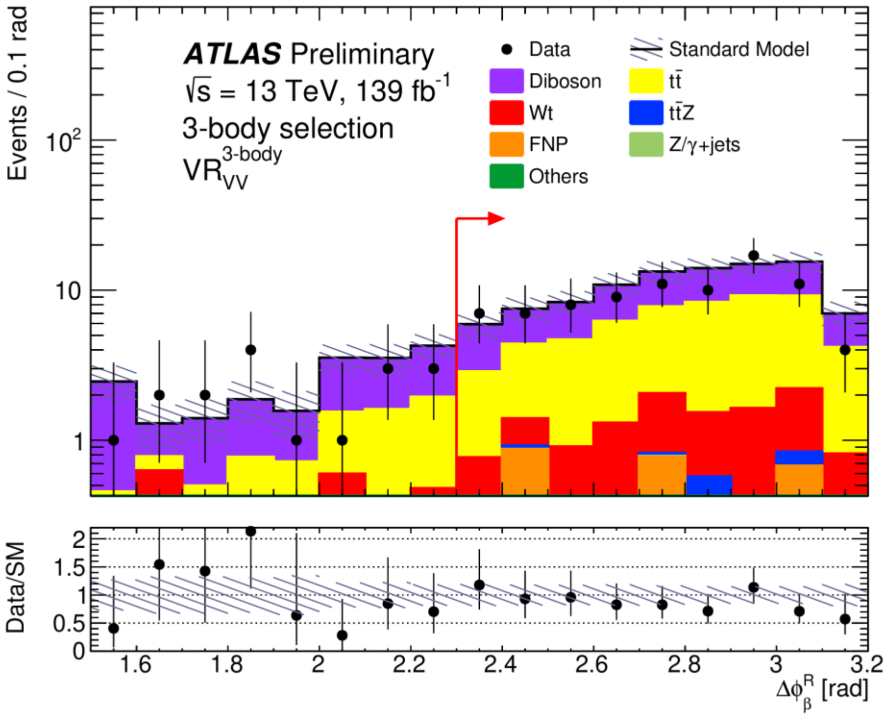


tt2L + E_T^{miss}: Background estimation

new

- Main backgrounds are ttbar, diboson and ttZ. In compressed regions the fake/non-prompt(FNP) become an important source due to low lepton p_T (< 25(100)GeV in small(large) ΔM signal regions)
- Defined dedicate control and validation regions for ttbar, diboson and ttZ if the background contribution is high in relevant SRs
- FNP backgrounds estimated using a data-based method (the so called fake-factor method)

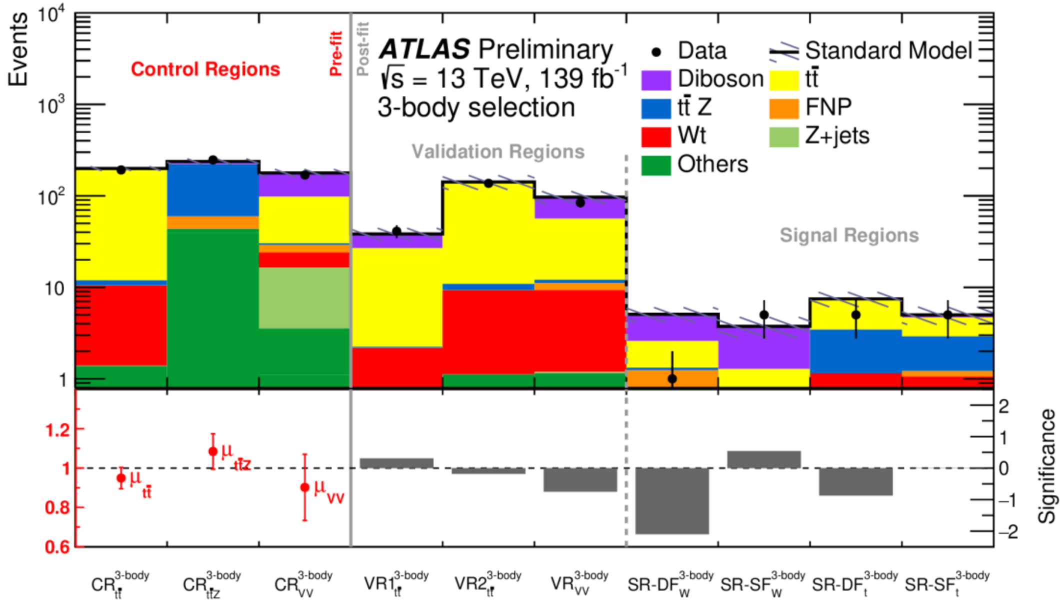




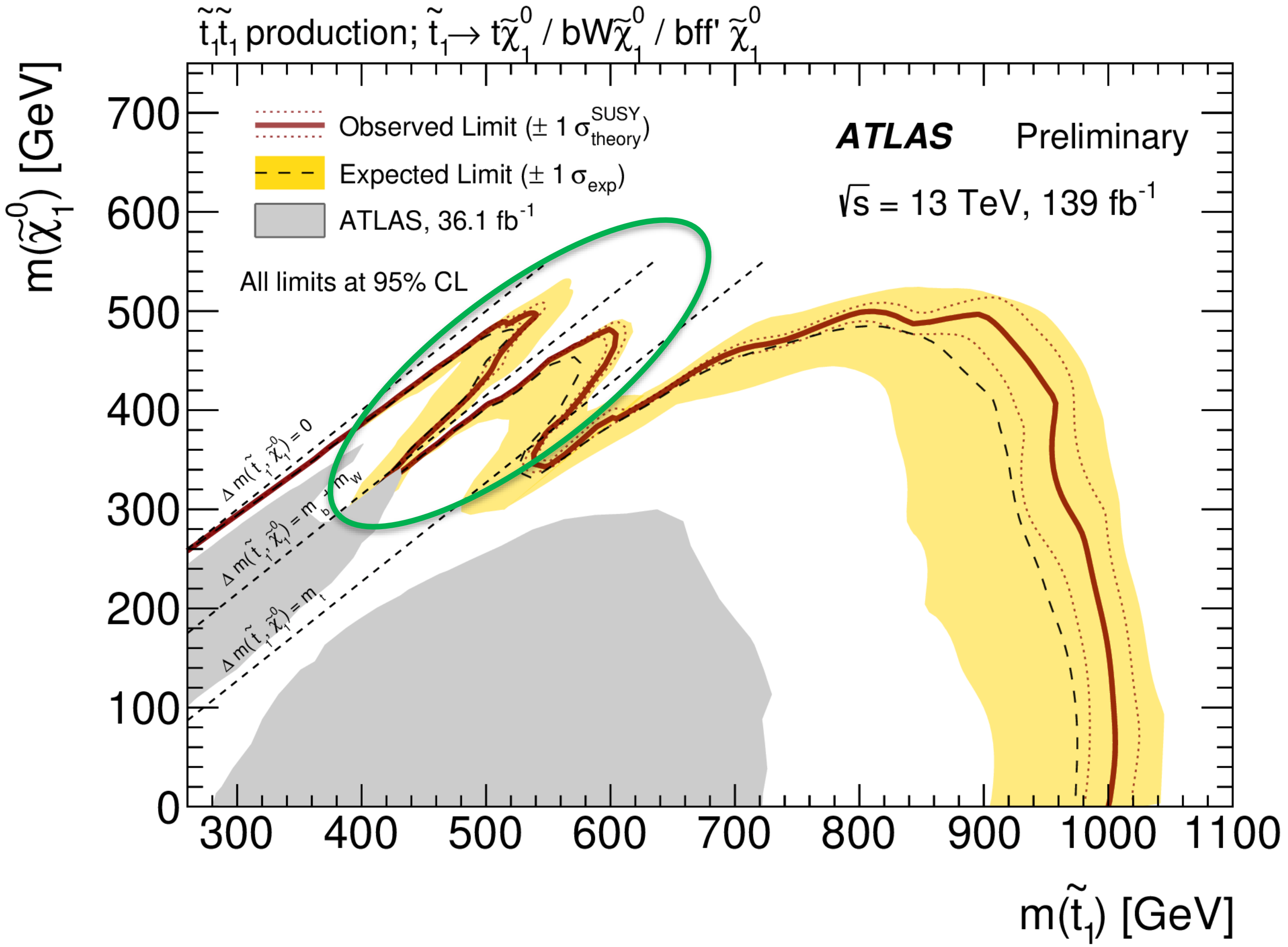
tt2L + E_T^{miss}: Results

new

- No significant excess over the SM background estimation
- The stop mass < 1 TeV are excluded for a low neutralino mass

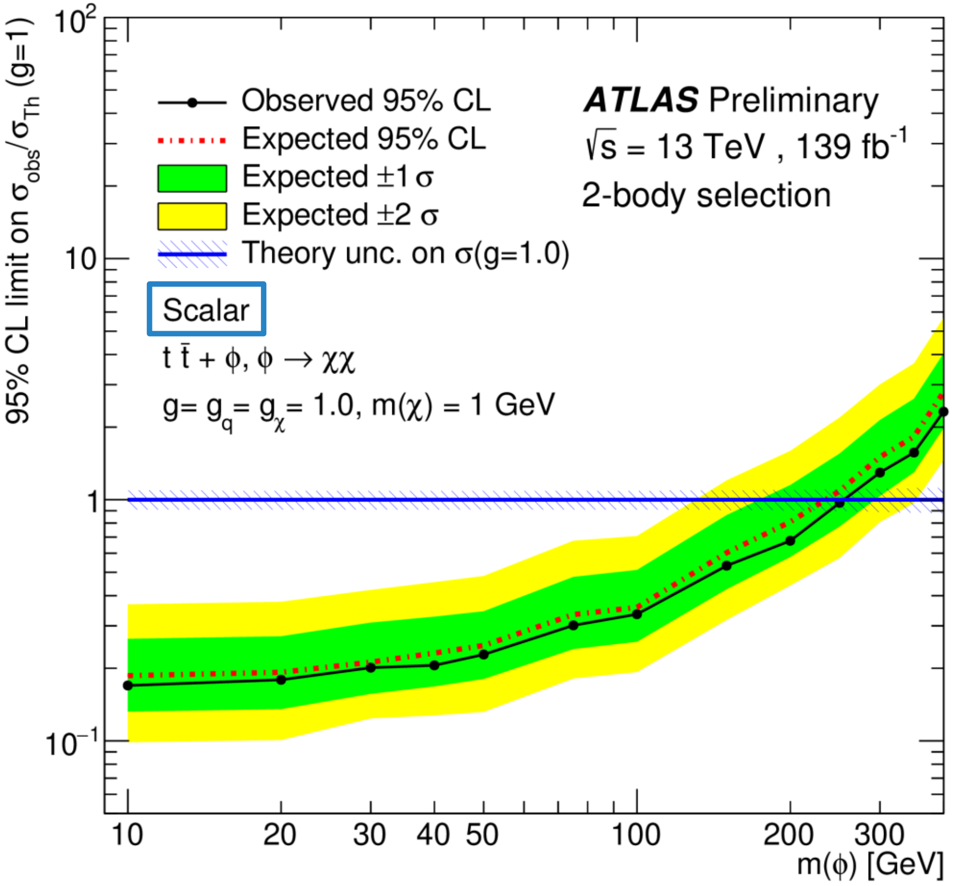


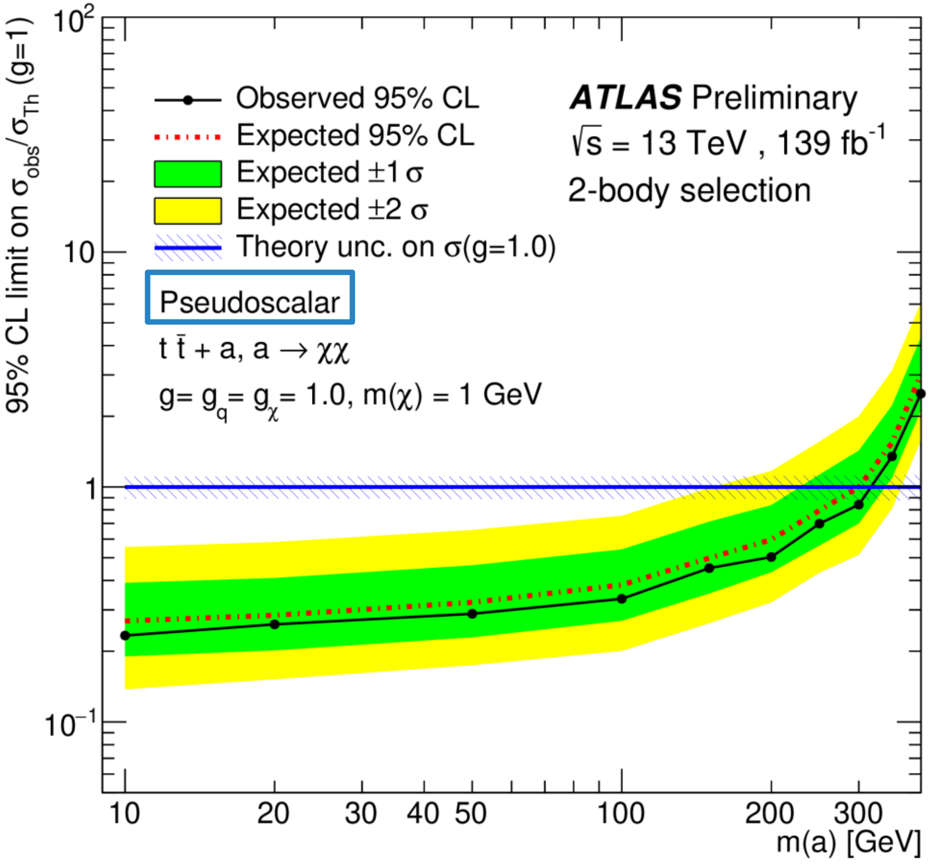
3 body fit results



tt2L + E_T^{miss}: Results

new



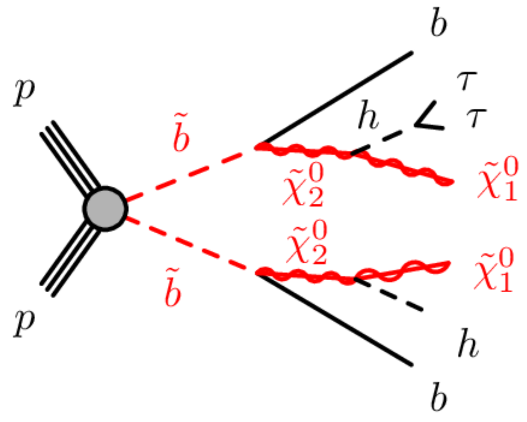


- For the dark matter, the spin-0 scalar(left) and pseudo-scalar(right) mediator masses should be larger than about 250 GeV with a small mass dark matter at 95% confidence level

Sbottom multi-b with taus: ATLAS-CONF-2020-031

new

- Signal model
  - Sbottom production, with 2 taus in final state
  - Assume the mass split between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is 130 GeV
  - Hadronically decay taus bring more E_T^{miss} and more signature to separate the signal and backgrounds. Unique sensitivity at low $\tilde{\chi}_1^0$ masses
- Signature: 2 taus + 2 bjets + E_T^{miss}
  - Taus from the Higgs decay
  - E_T^{miss} mainly from the $\tilde{\chi}_1^0$
  - Multiple b-jets from sbottom decay



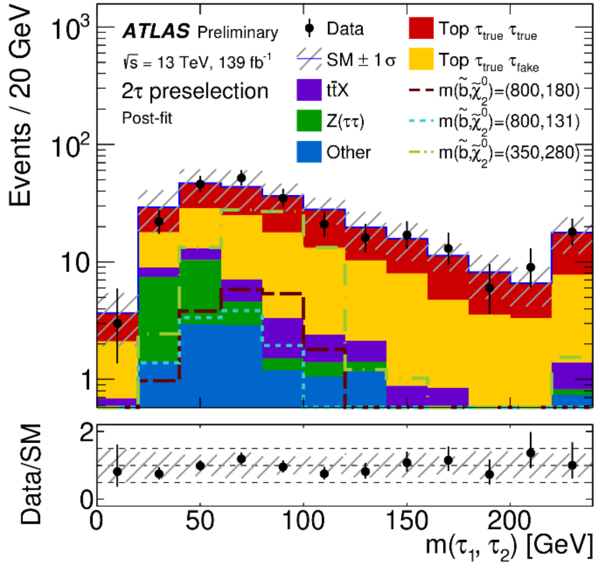
Sbottom multi-b with taus: Signal regions

new

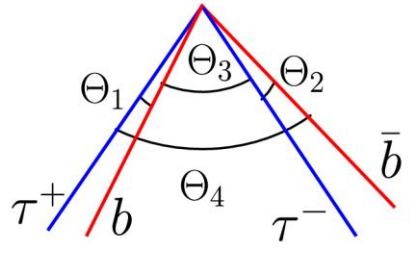
- SR requires $N_{bjet} \geq 2$ and $N_{taus} \geq 2$ with opposite sign
- Multi-jet background is suppressed by requiring the angular separation of both leading jets and the $\vec{P}_T^{miss}$ to be greater than 0.5
- Higgs mass window, stransverse mass m_{T2}, H_T to further reject other backgrounds
- Multi-bin fit using min_Θ variables to discriminate signals with different source of backgrounds

$N_\tau + N_\mu$		≥ 1	
N_{jets}		≥ 3	
$p_T(\text{jet}_1)$		> 140 GeV	
$p_T(\text{jet}_2)$		> 100 GeV	
$\Delta\phi(\text{jet}_{1,2}, \vec{p}_T^{\text{miss}})$		> 0.5	
$N_{b\text{-jets}}$		≥ 2	
$p_T(b\text{-jet}_1)$		> 100 GeV	
Trigger	$E_T^{\text{miss}} + b$-jet	OR	E_T^{miss}
E_T^{miss}	> 160 GeV		> 200 GeV

Common SR requirements		
N_μ	0	
N_τ	≥ 2	
$\text{OS}(\tau_1, \tau_2)$	yes	
$m(\tau_1, \tau_2)$	$[55, 120]$ GeV	
m_{T2}	> 140 GeV	
H_T	> 1100 GeV	
	Single-bin SR	Multi-bin SR
$\min_\Theta$	> 0.6	3 bins: < 0.5, $[0.5, 1.0]$, > 1.0



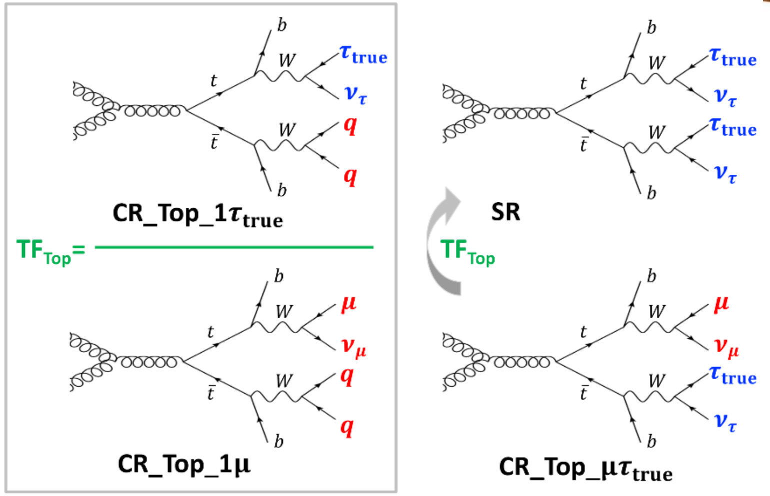
$$\min_\Theta = \min(\Theta_i)$$

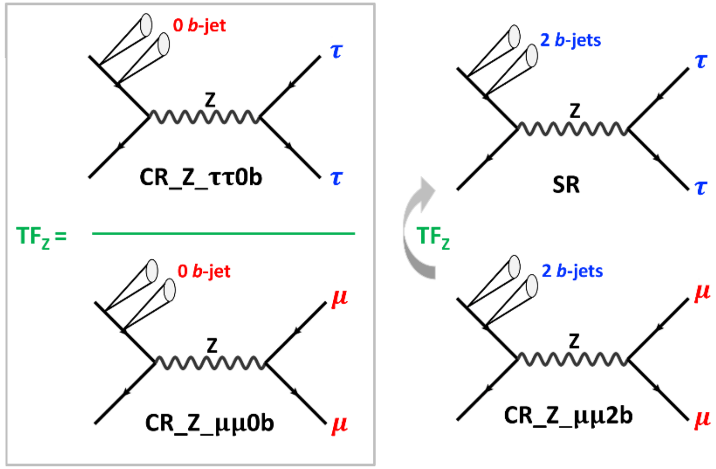


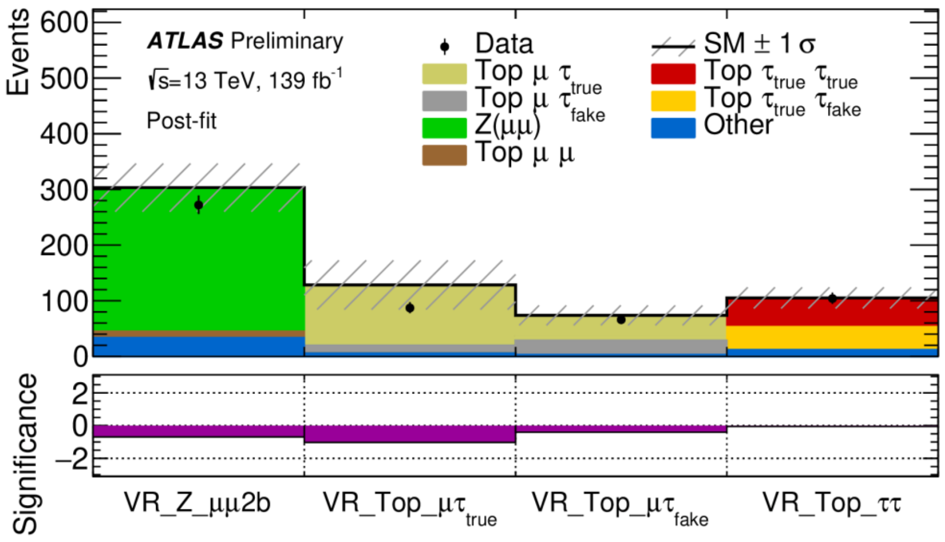
Sbottom multi-b with taus: Background estimations

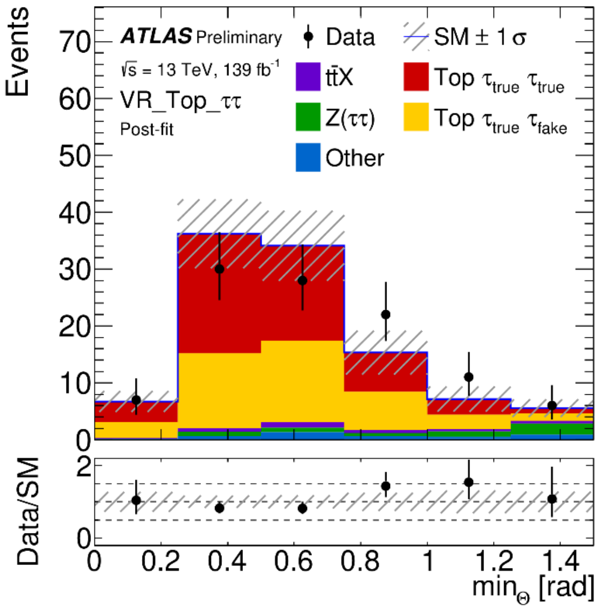
new

- Main backgrounds are ttbar and Ztautau
- The 2tau + 2 bjets statistics are small for those backgrounds
  - Define extra control regions to extrapolate mu-tau(mu-mu) events to tau-tau events for ttbar(Ztautau)
  - Validation regions are defined to validate the estimation and the H_T variable is used to extrapolate from control regions to validation regions





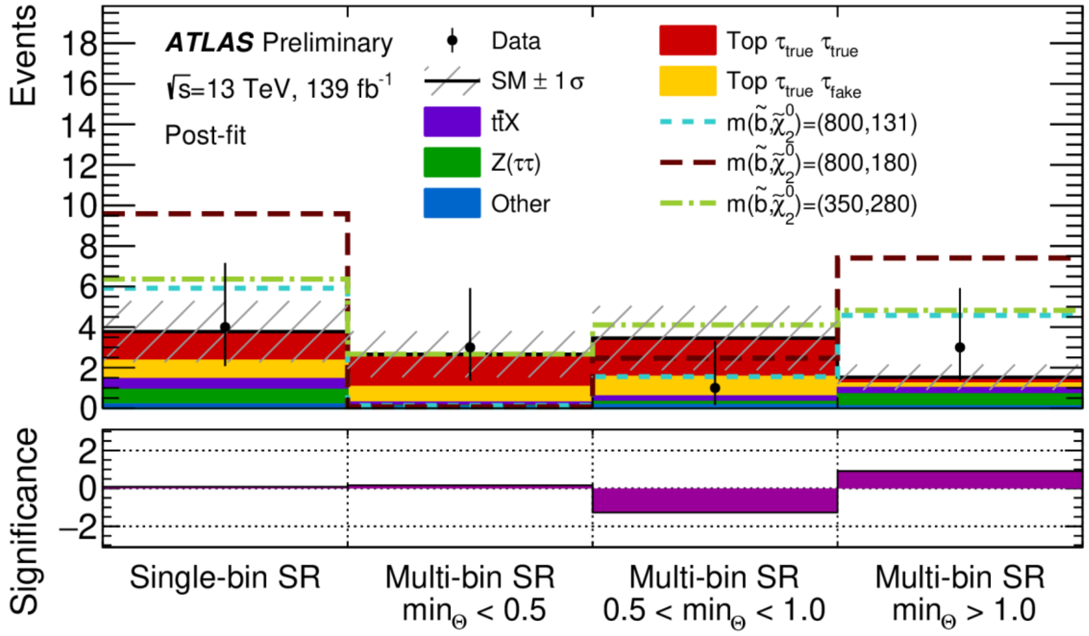


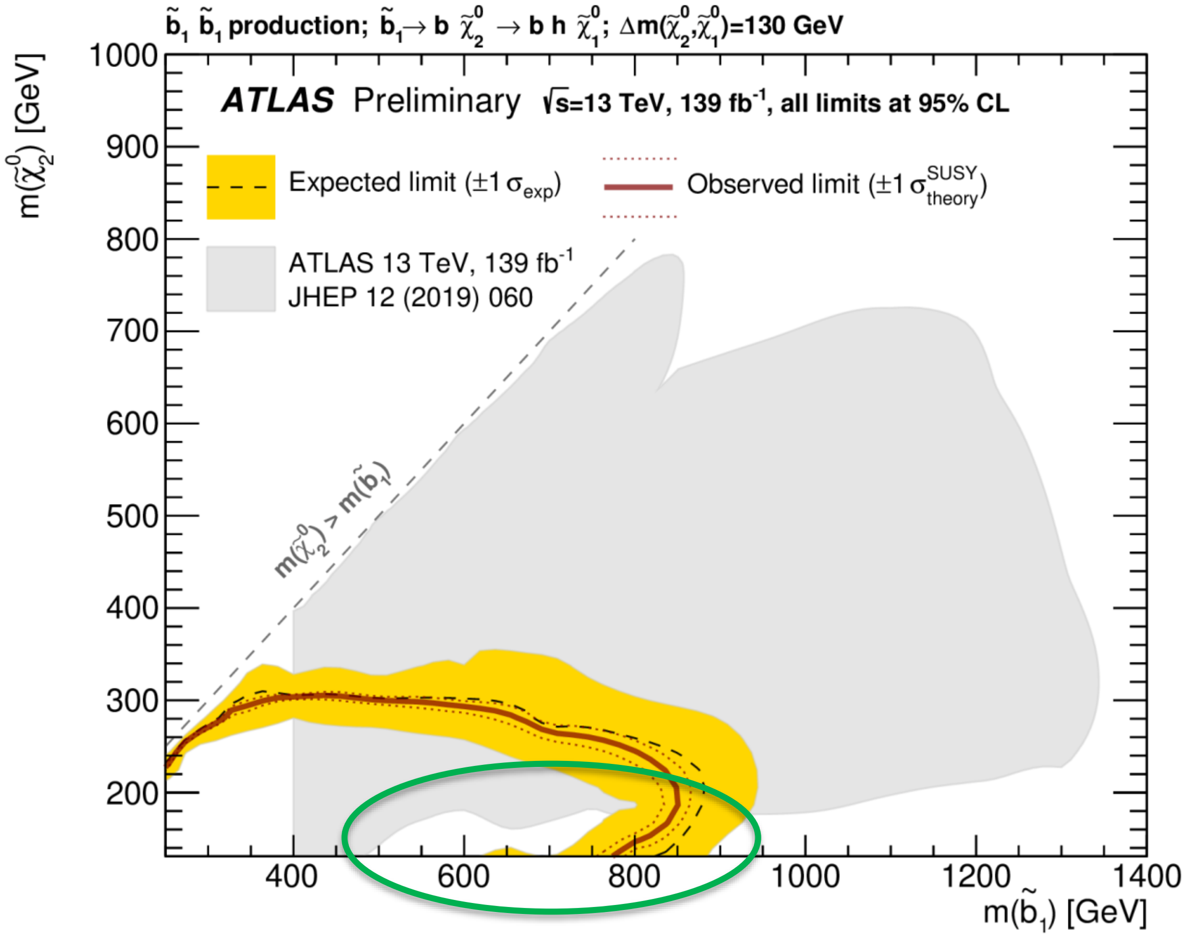


Sbottom multi-b with taus: Results

new

- No significant excesses observed in SRs
- Sbottom masses up to 850 GeV are excluded

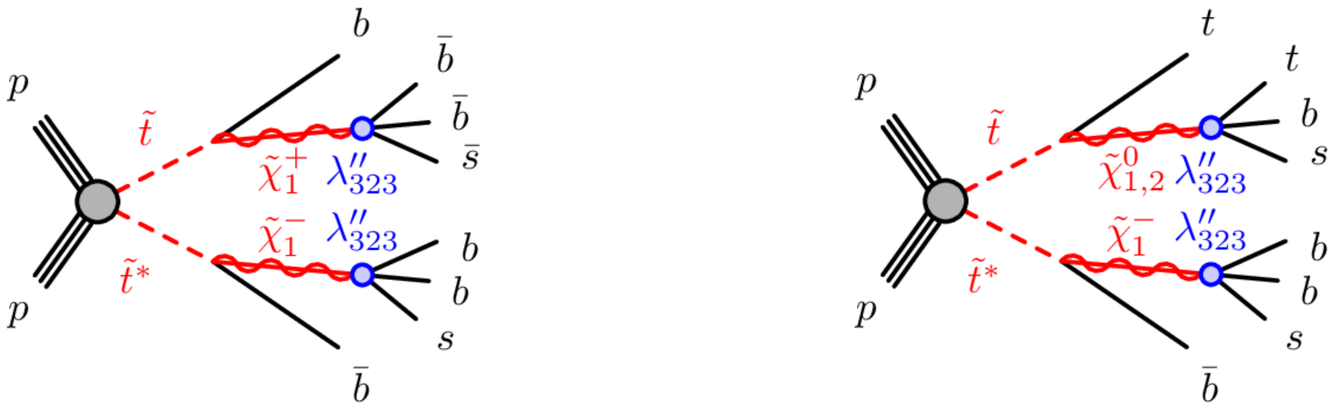




RPV SUSY in multi b-jet: ATLAS-CONF-2020-016

new

- Search for RPV SUSY models where we assume the LSP could decay into SM particles
- Signal models
  - B-violating λ''_{ijk} considered for stop decay. Choose λ''_{323} which favored by Minimal Flavor Violation (MFV) hypothesis
- Signature: Multiple b-jets, no leptons and low E_T^{miss}



RPV SUSY in multi b-jet: Signal regions and background estimation

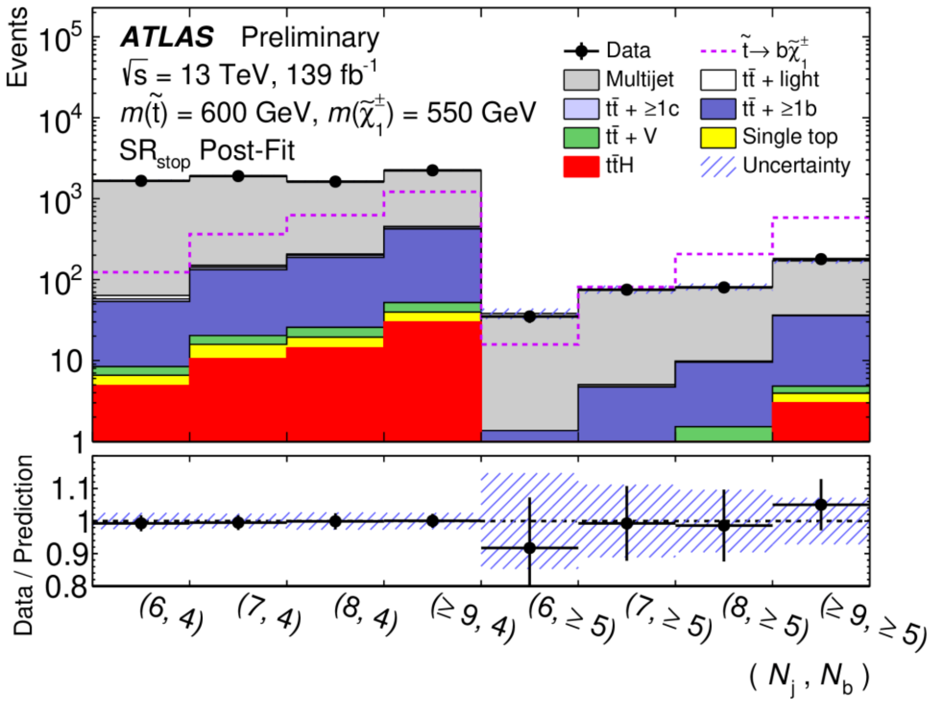
new

- Preselection is made to requires >= 4 jets passing the 4 jet trigger and offline requirement, >=2 b-tagged jets, with no lepton > 10 GeV

- Simultaneous fit binned by different number of jets and bjets

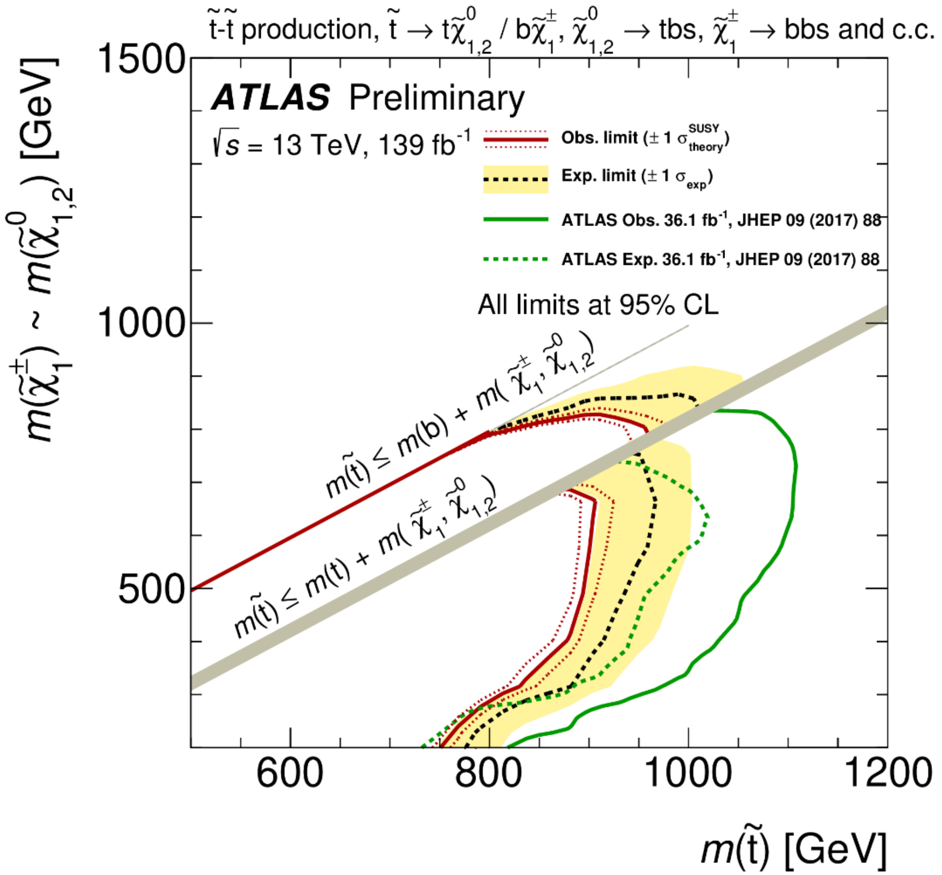
- Multi-jet estimated by a data-based method (Tag-rate-function multi-jet method) and validate in validation regions

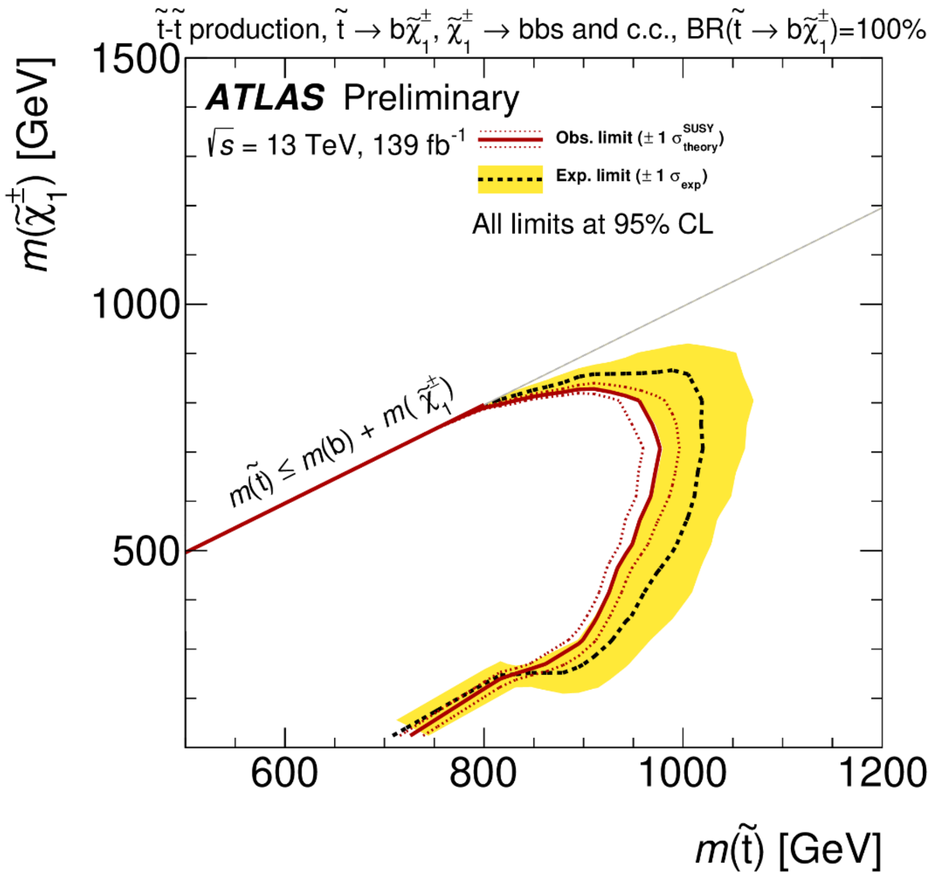
Analysis Regions		N_b: 3	N_b: 4	N_b: ≥ 5
N_j	6		$\longleftarrow$ SR_{stop} $\longrightarrow$	$\longleftarrow$ SR_{stop} $\longrightarrow$
		$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	
	7		$\longleftarrow$ SR_{stop} $\longrightarrow$	$\longleftarrow$ SR_{stop} $\longrightarrow$
		$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	
	8		$\longleftarrow$ SR_{stop} $\longrightarrow$	$\leftarrow$ SR_{stop}, $SR_{discovery}$ $\rightarrow$
		$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	
	≥ 9		$\longleftarrow$ SR_{stop} $\longrightarrow$	$\leftarrow$ SR_{stop}, $SR_{discovery}$ $\rightarrow$
		$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	$\leftarrow$ VR-MJ $\rightarrow C^{max}_{mass}$	



RPV SUSY in multi b-jet: results

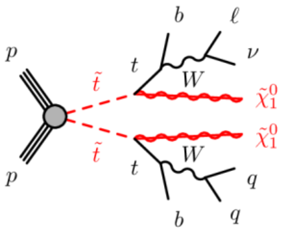
new

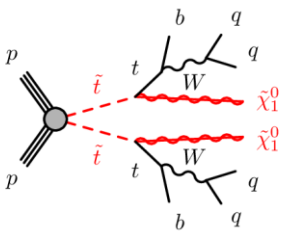




- No significant excess over the SM background estimation
- The stop mass < 950GeV are excluded
- Final state considered for the first time at the LHC

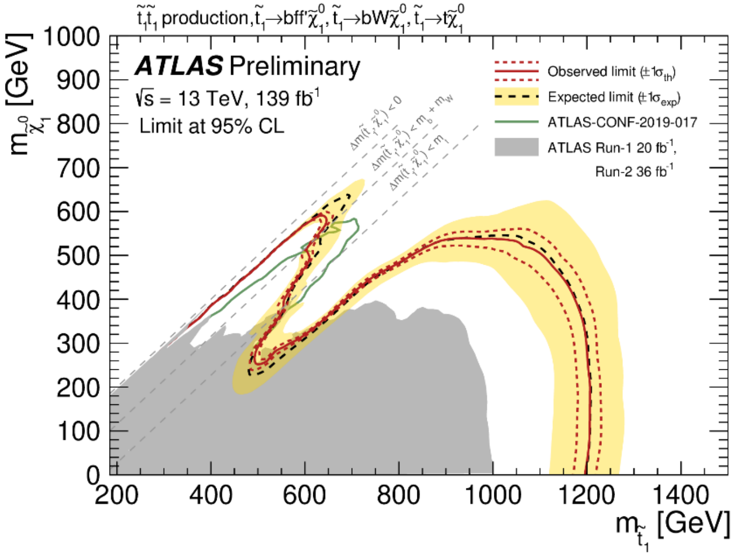
Other results





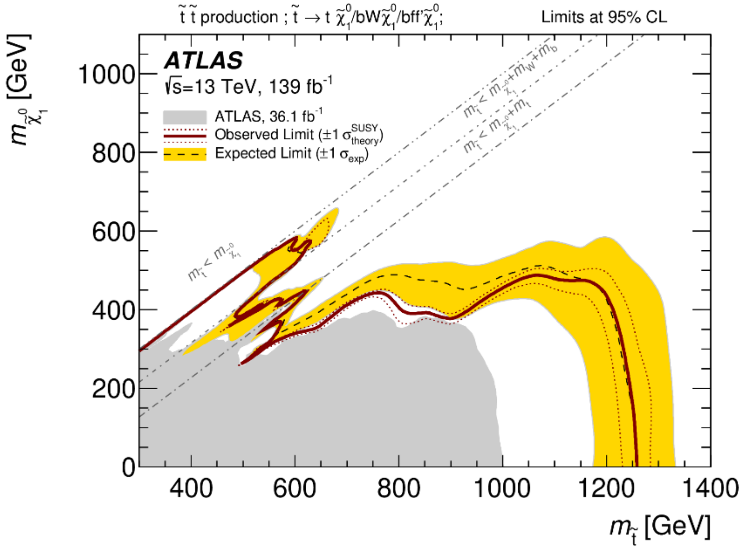
Stop with 1 lepton final state

- 7 SRs defined for different 2/3/4body and DM regions
- Main backgrounds are ttbar, tt+V, and W+jets
- Stop mass < 1.2 TeV are excluded for a low neutralino mass

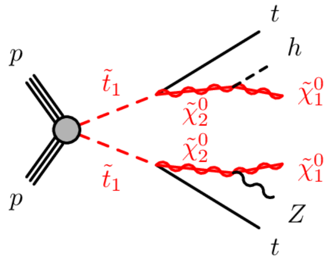


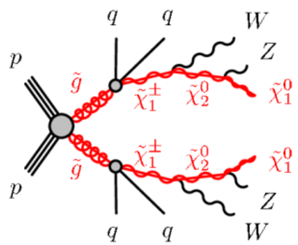
Stop with 0 lepton final state

- 4 SRs defined for different 2-/3-/4-body regions
- Main backgrounds are ttbar, tt+V, Z+jets and W+jets
- Stop mass < 1.25 TeV are excluded for a low neutralino mass



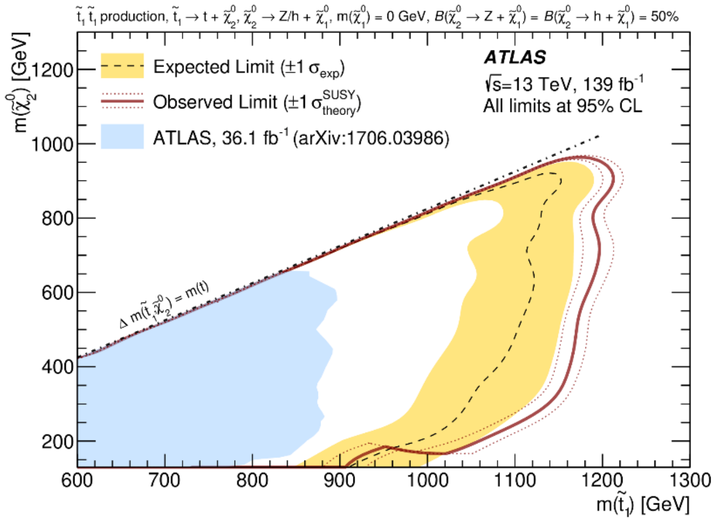
Other results





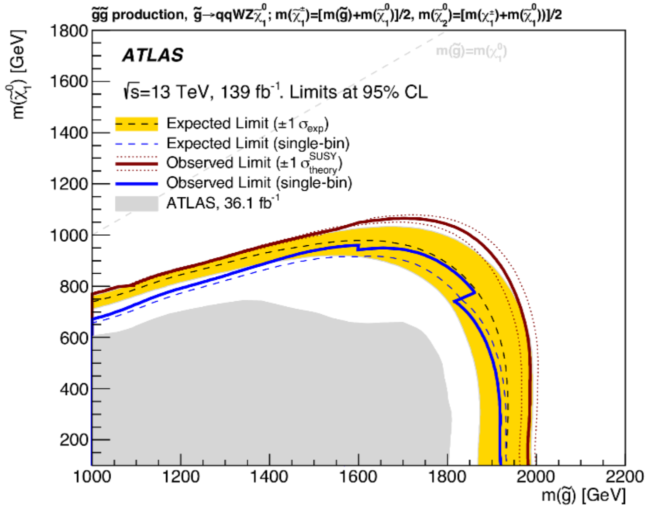
Stop with Higgs and Z final state

- SR relied on the Njets, Nbjets, m_T and p_T of objects
- Main backgrounds are fakes and ttZ, WZ
- $\tilde{t}_1$ mass < 1.22 TeV and $\tilde{t}_2$ mass < 875 GeV are excluded for a low neutralino mass



Gluino with large jet multiplicities

- SR defined by the Njets, Nbjets, E_T^{miss} significance and large R jet mass
- Background dominated by multi-jet and ttbar
- Gluino mass < 2 TeV(1.8 TeV, 1.6 TeV) are excluded for a low LSP mass via different decay



Summary

- Several new results from the SUSY strong side using the full Run 2 dataset are presented
  - Inclusive 1L: ATLAS-CONF-2020-047 , excluded the gluino(squark) mass < 2.2(1.4) TeV and one-flavour squark mass < 1 TeV
  - tt2L + E_T^{miss}: ATLAS-CONF-2020-046 , excluded the stop mass < 1 TeV and dark matter < 250GeV
  - Sbottom multi-b with taus: ATLAS-CONF-2020-031 , excluded sbottom mass < 850 GeV
  - RPV SUSY in multi b-jet: ATLAS-CONF-2020-016 , excluded stop mass < 950GeV
- And don't forget other still recent results
  - Stop with 1 lepton final state: ATLAS-CONF-2020-003
  - Stop with 0 lepton final state : SUSY-2018-12
  - Stop with Higgs and Z final state: SUSY-2018-21
  - Gluino with large jet multiplicities: SUSY-2018-17
- Want to see more results? Look at ATLAS SUSY Public Results!
- More full Run-2 results are coming. So stay tuned!
- Relevant talks:
  - SUSY EWK production: Previous Abhishek' talk at here
  - More BSM models with jets in final state: Elham's talk at here and Vincent's talk at here

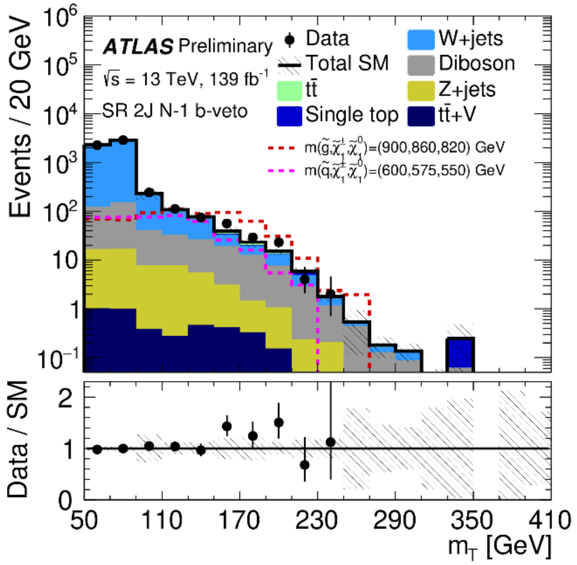
Backup

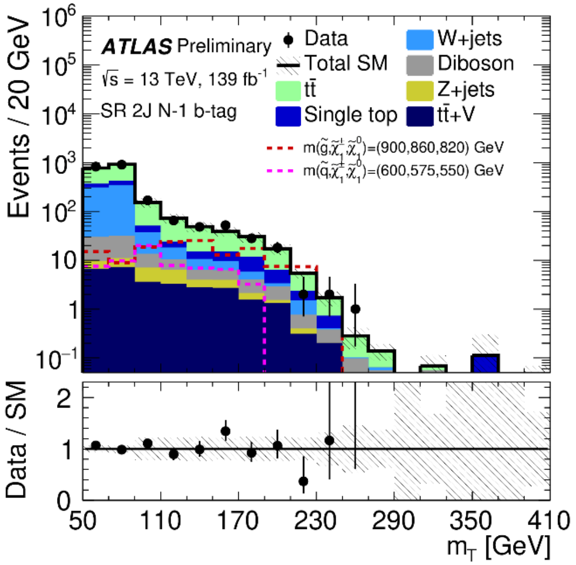
Analysis Strategy

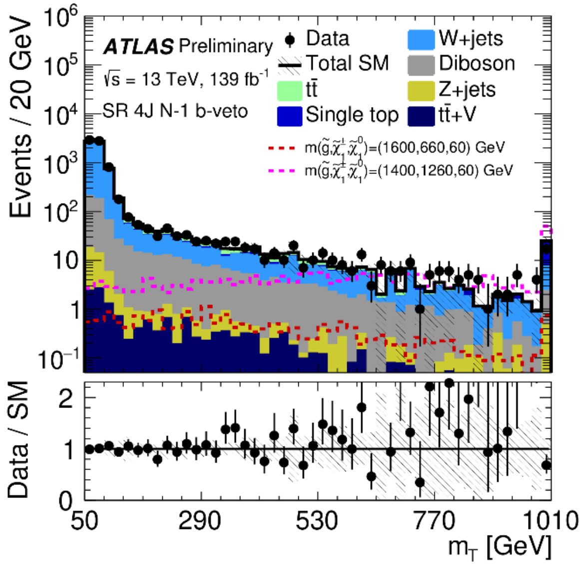
- Signal region
  - Defined to get the best signal sensitivity
  - Ideally with small expected yields of backgrounds(SM) events
- Control region
  - For major SM background, dedicated Control Region is designed as the process enriched region to extrapolate its expectation into SR
  - If some background are hard to estimate using the MC(like multi-jet background), we could also define process enriched control regions to use data-driven method to extrapolate its expectation into SR
- Validation region
  - The region is designed to validate extrapolation from CR
  - It is constructed close to SR but with small expected yields of signal

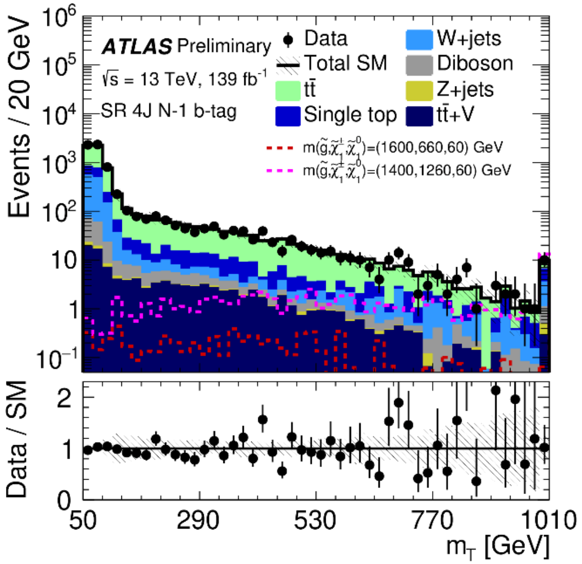
Inclusive 1L:

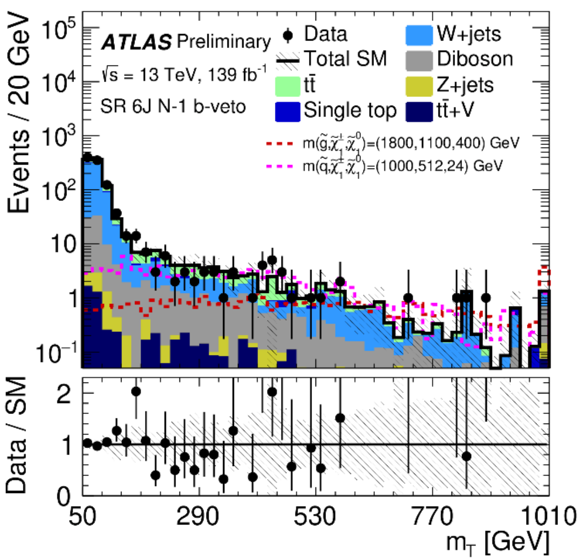
- More N-1 distribution for 4J SR/CR/VR combined m_T distributions
- The left part of each plot shows good MC modeling at each control and validation regions while the right part shows no significant excess over the SM background estimation

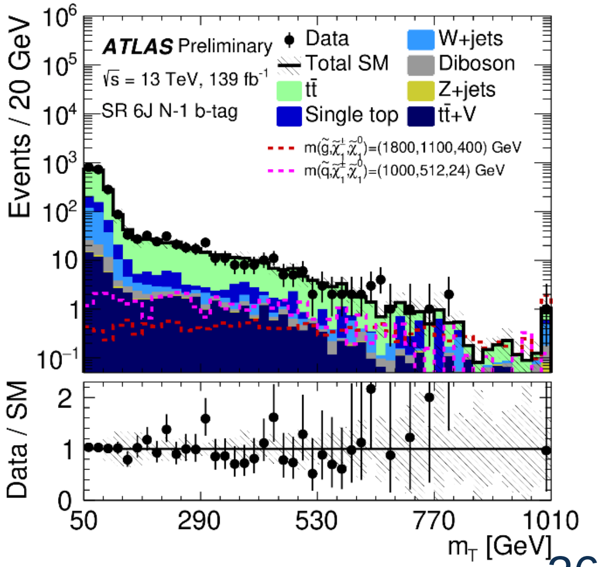






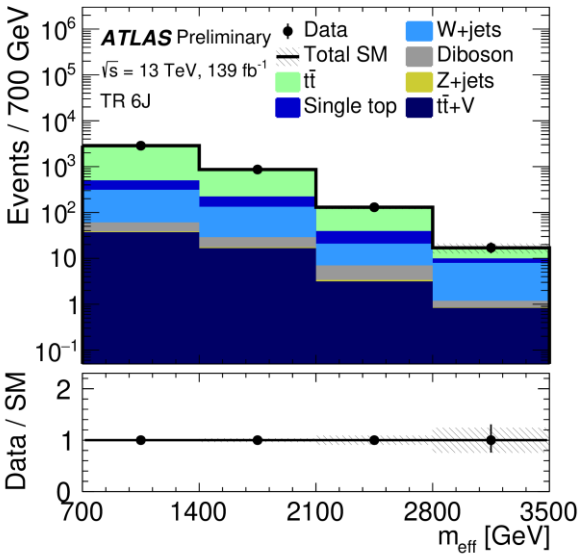


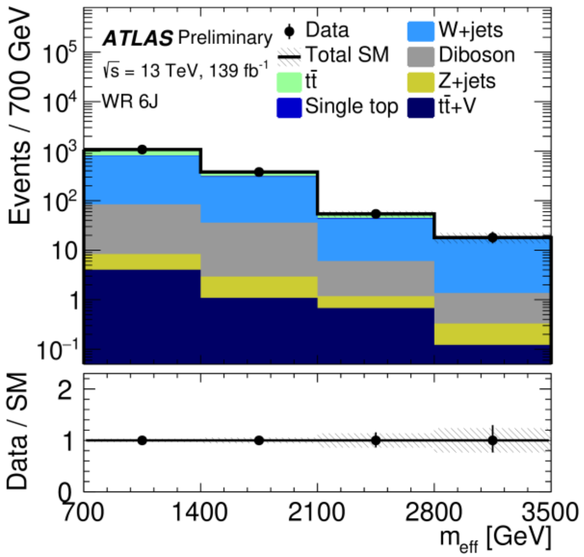


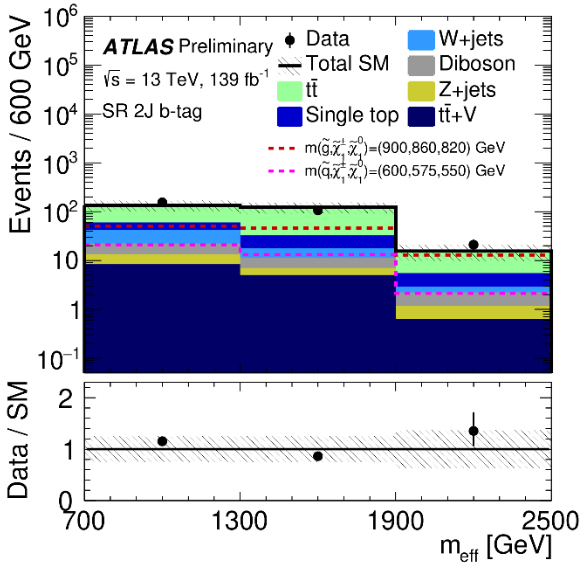


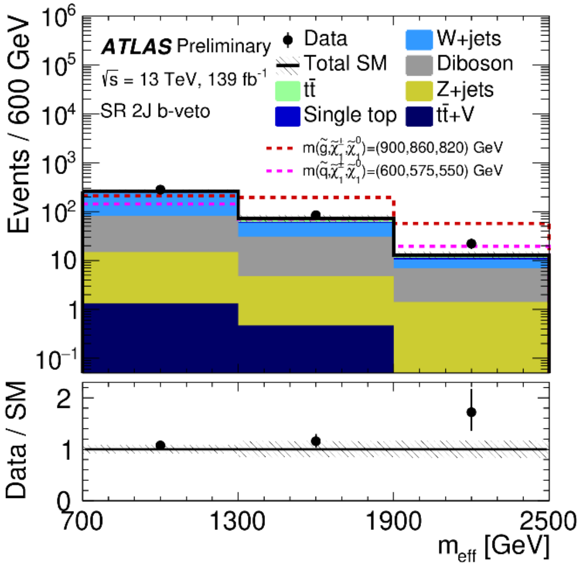
Inclusive 1L:

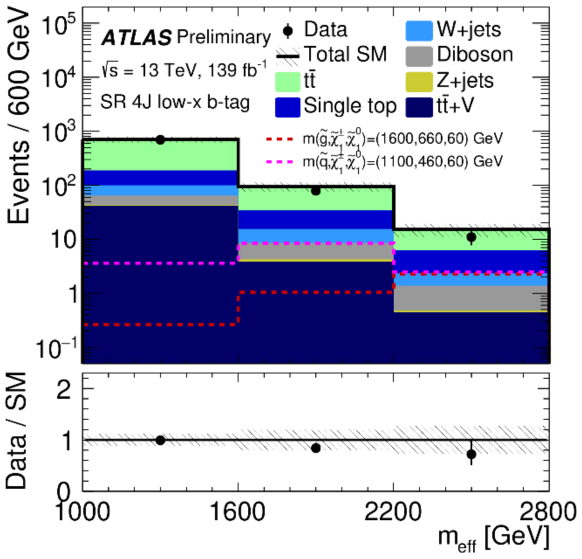
- m_{eff} variable distributions for each post-fit CR and SR
- Good agreement between the data and SM prediction in general and no big excess in SR is observed

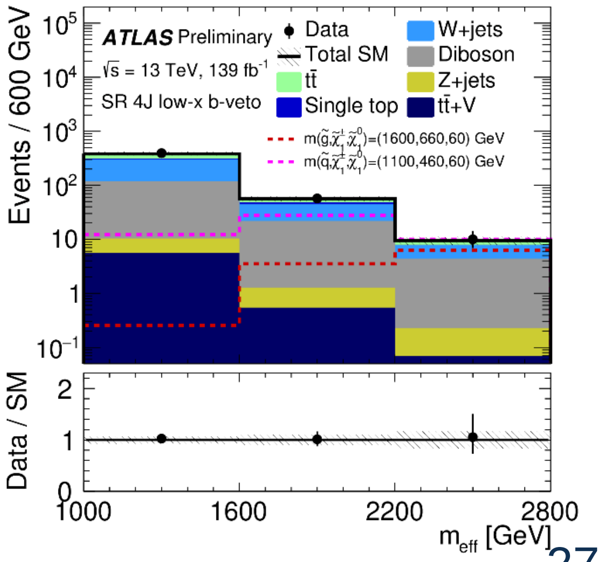












Inclusive 1L:

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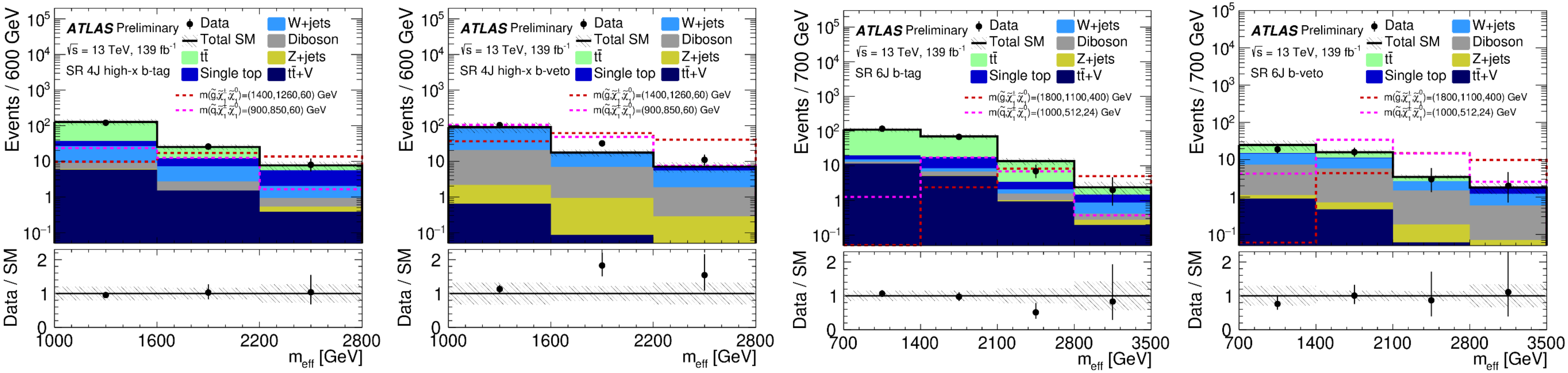


Inclusive 1L:

- Event yields in 2J and 4J high-x regions

2J b-veto	bin 1 [700,1300]	bin 2 [1300,1900]	bin 3 ¿1900 [GeV]
Observed events	280	84	22
Total SM background events	261 ± 22	73 ± 12	12.8 ± 2.2
$t\bar{t}$ events	19 ± 13	11 ± 7	1.3 ± 0.6
W+jets events	155 ± 14	28 ± 5	3.4 ± 1.5
Z+jets events	14 ± 5	4.3 ± 0.6	1.37 ± 0.18
single-top events	5 ± 4	2.9 ± 2.3	1.1 ± 0.9
diboson events	66 ± 8	26.0 ± 3.4	5.5 ± 0.7
$t\bar{t}$ +V events	1.32 ± 0.16	0.47 ± 0.23	0.041 ± 0.018

4J high-x b-veto	bin 1 [1000,1600]	bin 2 [1600,2200]	bin 3 > 2200 [GeV]
Observed events	104	32	11
Total SM background	92 ± 32	18 ± 4	7.1 ± 2.3
$t\bar{t}$ events	9 ± 5	1.2 ± 0.4	0.32 ± 0.11
W+jets events	61 ± 30	9 ± 4	3.6 ± 1.7
Z+jets events	1.5 ± 0.6	0.8 ± 0.4	0.26 ± 0.14
single-top events	$0.3^{+0.5}_{-0.3}$	$0.006^{+0.026}_{-0.006}$	1.3 ± 0.8
diboson events	18.7 ± 2.9	6.1 ± 0.9	1.59 ± 0.29
$t\bar{t}$ +V events	0.65 ± 0.15	$0.09^{+0.13}_{-0.09}$	0.029 ± 0.023

2J b-tag	bin 1 [700,1300]	bin 2 [1300,1900]	bin 3 ¿1900 [GeV]
Observed events	154	106	21
Total SM background	134 ± 36	123 ± 33	16 ± 6
$t\bar{t}$ events	74 ± 35	90 ± 32	10 ± 5
W+jets events	20 ± 6	6.3 ± 2.1	0.7 ± 0.5
Z+jets events	5.0 ± 0.7	2.0 ± 2.0	0.55 ± 0.09
single-top events	18 ± 7	15 ± 6	2.6 ± 1.6
diboson events	9.0 ± 1.4	4.3 ± 1.5	1.04 ± 0.17
$t\bar{t}$ +V events	8.4 ± 0.7	5.0 ± 0.5	0.63 ± 0.09

4J high-x b-tag	bin 1 [1000,1600]	bin 2 [1600,2200]	bin 3 > 2200 [GeV]
Observed events	121	26	8
Total SM background	127 ± 27	25 ± 5	7.7 ± 2.1
$t\bar{t}$ events	90 ± 24	13.1 ± 2.8	2.0 ± 0.5
W+jets events	17 ± 9	4.6 ± 2.4	1.1 ± 0.4
Z+jets events	0.32 ± 0.10	$0.01^{+0.13}_{-0.01}$	0.15 ± 0.09
single-top events	10 ± 4	4.9 ± 1.8	3.6 ± 1.7
diboson events	3.1 ± 0.6	1.20 ± 0.34	0.41 ± 0.15
$t\bar{t}$ +V events	5.8 ± 0.5	1.51 ± 0.17	0.39 ± 0.08

Inclusive 1L:

- Event yields in 4J low-x and 6J regions
- Discovery fit results

4J low-x b-veto	bin 1 [1000,1600]	bin 2 [1600,2200]	bin 3 > 2200 [GeV]
Observed events	393	57	10
Total SM background	383 ± 27	56 ± 6	9.5 ± 1.7
$t\bar{t}$ events	72 ± 15	8.7 ± 1.8	1.56 ± 0.35
W+jets events	179 ± 22	23 ± 4	3.4 ± 1.4
Z+jets events	4.7 ± 0.8	0.73 ± 0.18	0.16 ± 0.04
single-top events	12 ± 5	3.3 ± 1.3	$0.16^{+0.25}_{-0.16}$
diboson events	110 ± 15	20.5 ± 2.8	4.2 ± 0.6
$t\bar{t}$ +V events	5.6 ± 0.6	0.54 ± 0.22	0.070 ± 0.031

4J low-x b-tag	bin 1 [1000,1600]	bin 2 [1600,2200]	bin 3 > 2200 [GeV]
Observed events	695	79	11
Total SM background	701 ± 90	94 ± 19	15 ± 4
$t\bar{t}$ events	510 ± 90	60 ± 18	9.0 ± 2.9
W+jets events	36 ± 9	7.0 ± 1.6	0.96 ± 0.35
Z+jets events	1.7 ± 0.5	0.36 ± 0.08	0.035 ± 0.020
single-top events	88 ± 12	19 ± 6	3.9 ± 2.5
diboson events	21.1 ± 3.2	4.3 ± 0.6	0.90 ± 0.13
$t\bar{t}$ +V events	41.5 ± 3.0	3.9 ± 0.6	0.45 ± 0.10

6J b-veto	bin 1 [700,1400]	bin 2 [1400,2100]	bin 3 [2100,2800]	bin 4 > 2800 [GeV]
Observed events	19	16	3	2
Total SM background	25 ± 8	15.9 ± 2.5	3.5 ± 0.5	1.8 ± 0.6
$t\bar{t}$ events	10 ± 6	4.6 ± 1.7	0.77 ± 0.26	0.09 ± 0.07
W+jets events	7 ± 5	5.2 ± 1.5	1.2 ± 0.5	0.6 ± 0.4
Z+jets events	$0.23^{+0.23}_{-0.23}$	0.25 ± 0.06	0.12 ± 0.05	0.060 ± 0.024
single-top events	$0.5^{+0.8}_{-0.5}$	$0.3^{+0.5}_{-0.3}$	0.0 ± 0.0	0.5 ± 0.4
diboson events	6.2 ± 1.4	5.2 ± 0.9	1.31 ± 0.26	0.52 ± 0.16
$t\bar{t}$ +V events	0.90 ± 0.17	0.47 ± 0.11	0.06 ± 0.04	$0.012^{+0.021}_{-0.012}$

6J b-tag	bin 1 [700,1400]	bin 2 [1400,2100]	bin 3 [2100,2800]	bin 4 > 2800 [GeV]
Observed events	117	68	7	2
Total SM background	110 ± 17	70 ± 11	13.6 ± 3.1	2.4 ± 1.0
$t\bar{t}$ events	90 ± 17	52 ± 10	10.2 ± 2.8	0.9 ± 0.6
W+jets events	2.0 ± 1.3	1.6 ± 0.8	0.53 ± 0.16	0.46 ± 0.19
Z+jets events	$0.05^{+0.09}_{-0.05}$	0.12 ± 0.04	0.06 ± 0.04	0.08 ± 0.04
single-top events	4.6 ± 3.1	9 ± 5	1.3 ± 1.1	$0.6^{+0.8}_{-0.6}$
diboson events	1.62 ± 0.32	1.64 ± 0.31	0.57 ± 0.13	0.14 ± 0.07
$t\bar{t}$ +V events	11.5 ± 1.5	5.1 ± 0.7	0.95 ± 0.24	0.20 ± 0.13

$\mathbf{SR_{disc}}$	Observed events	Total SM background	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$[fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$	CL_B	$p(s=0)$ (Z)
2J (gluino)	22	12.8 ± 2.2	0.14	19.0	$10.1^{+4.0}_{-2.3}$	0.98	0.02 (1.97)
2J (squark)	106	85 ± 12	0.34	47.7	30^{+13}_{-7}	0.91	0.09 (1.35)
4J high-x	11	7.1 ± 2.3	0.09	12.0	$8.3^{+3.5}_{-1.5}$	0.87	0.13 (1.12)
4J low-x	10	9.5 ± 1.7	0.06	8.9	$8.4^{+3.3}_{-2.0}$	0.57	0.42 (0.19)
6J (gluino)	2	1.8 ± 0.6	0.03	4.7	$4.3^{+1.9}_{-0.8}$	0.59	0.41 (0.24)
6J (squark)	5	5.3 ± 0.8	0.04	6.0	$6.0^{+24.0}_{-1.5}$	0.48	0.50 (0)

Variables: Aplanarity and Sphericity

Arxiv:1206.2135

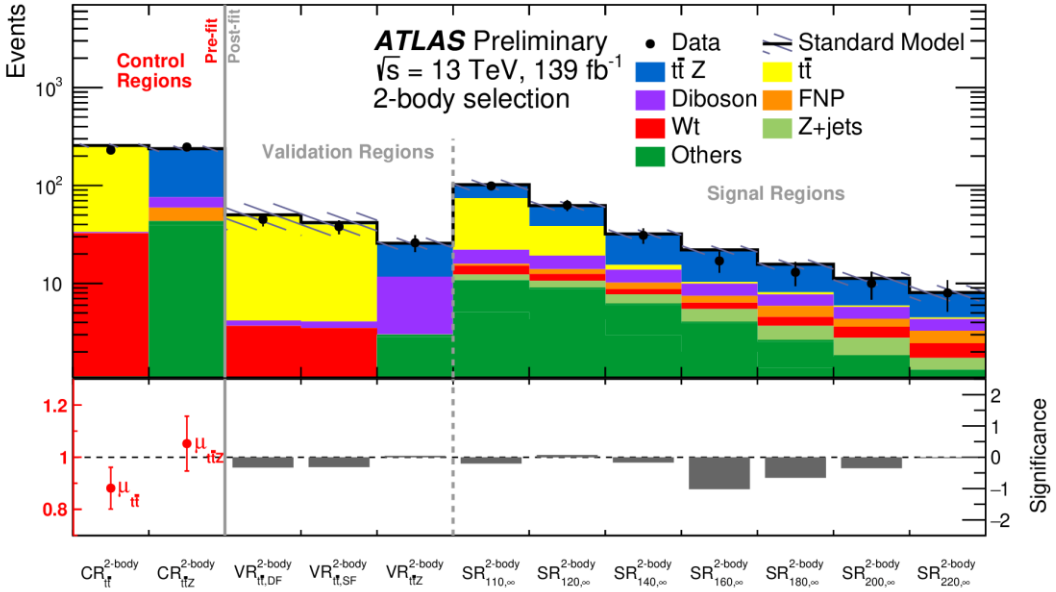
- The Sphericity, Transverse Sphericity and Aplanarity embody more global information about the full momentum tensor of the event M_{xyz} via its eigenvalues λ_1, λ_2 and λ_3. Where the sum run over all jets and the eigenvalues have $\lambda_1 > \lambda_2 > \lambda_3$ and $\sum_i \lambda_i = 1$

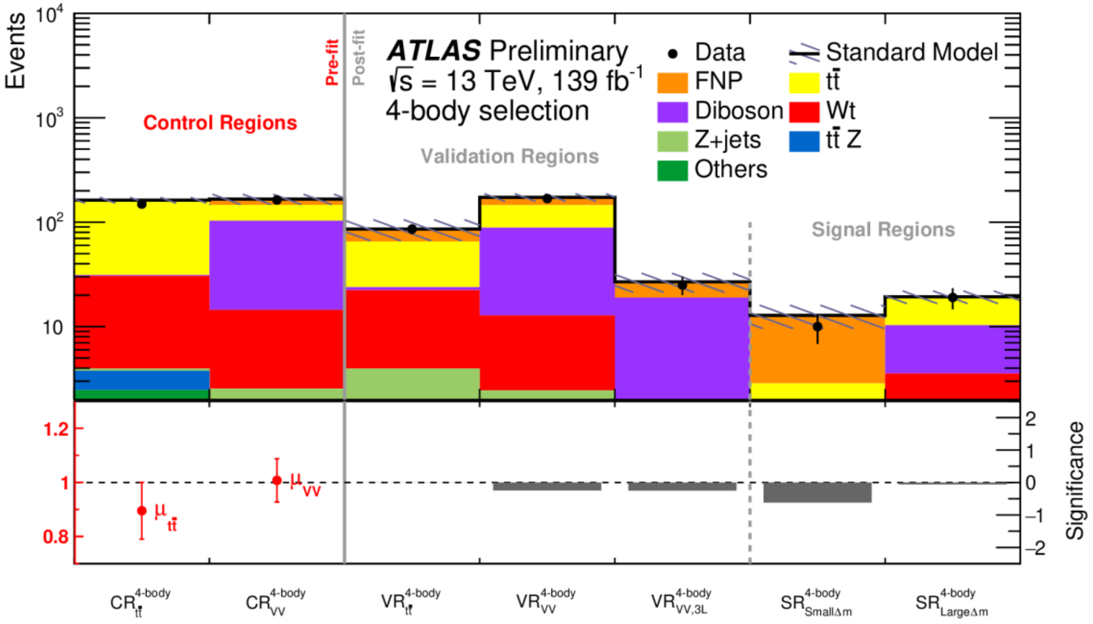
$$M_{xyz} = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

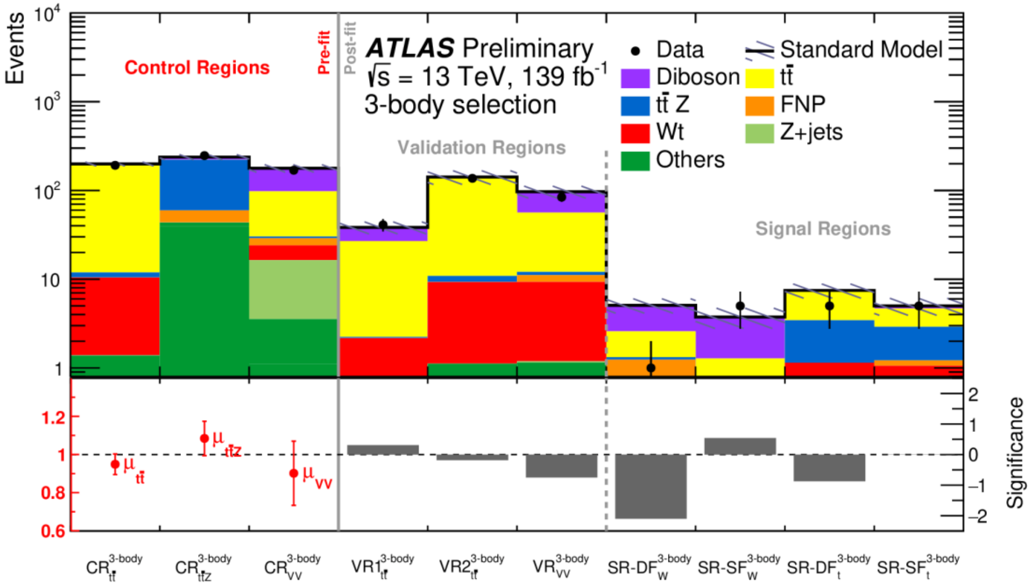
- Sphericity and Aplanarity are usually used to measure how closely the shape of an object resembles that of a perfect sphere. The Sphericity: $S = \frac{3}{2}(\lambda_2 + \lambda_3)$ and transverse sphericity: $S_\perp = \frac{2\lambda_2}{\lambda_1+\lambda_2}$ measures the total transverse momentum with respect to the sphericity axis while the Aplanarity $A = \frac{3}{2}\lambda_3$ measures how spherical the shape in general
- In inclusive 1L study, The signals have multiple objects emitted in the gluino/squark decay chains so they are more spherical than backgrounds(higher Aplanarity)

tt2L + E_T^{miss}:

- Fit results in each signal region
- No significant excess over the SM background estimation



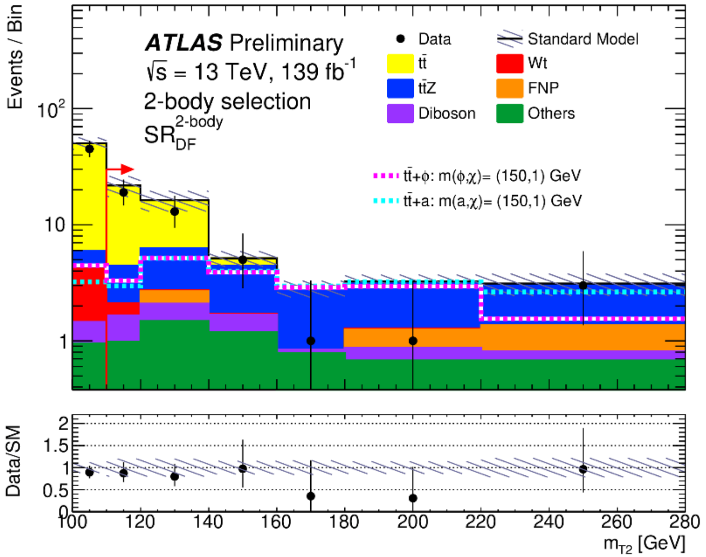


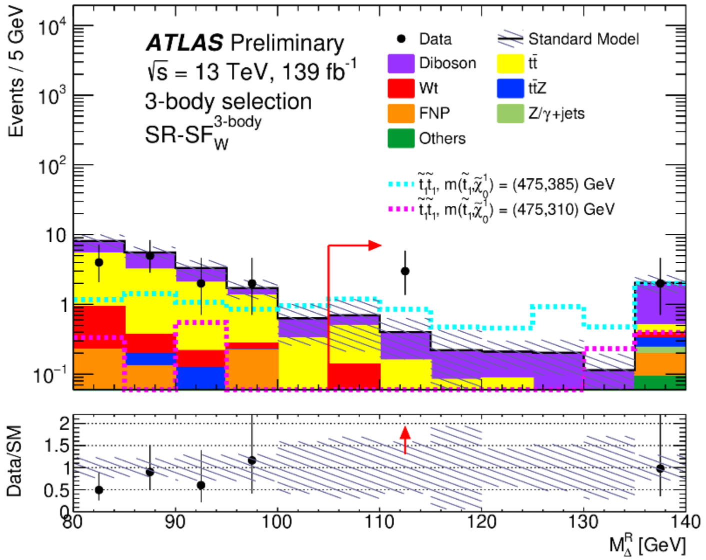


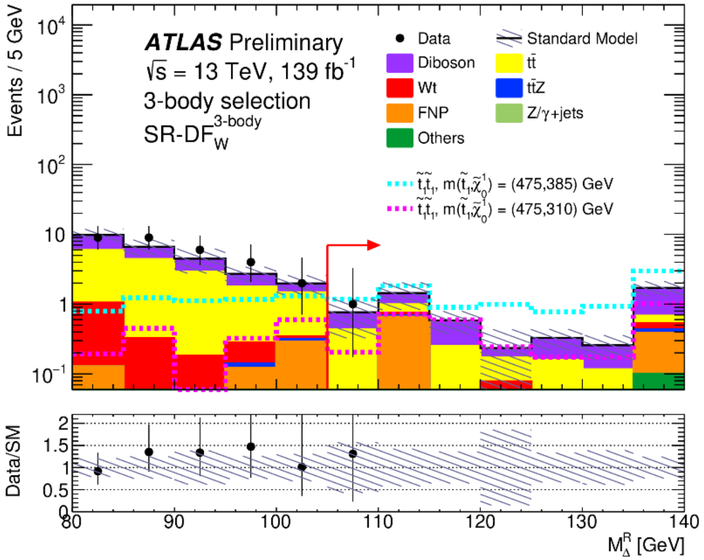
tt2L + E_T^{miss}:

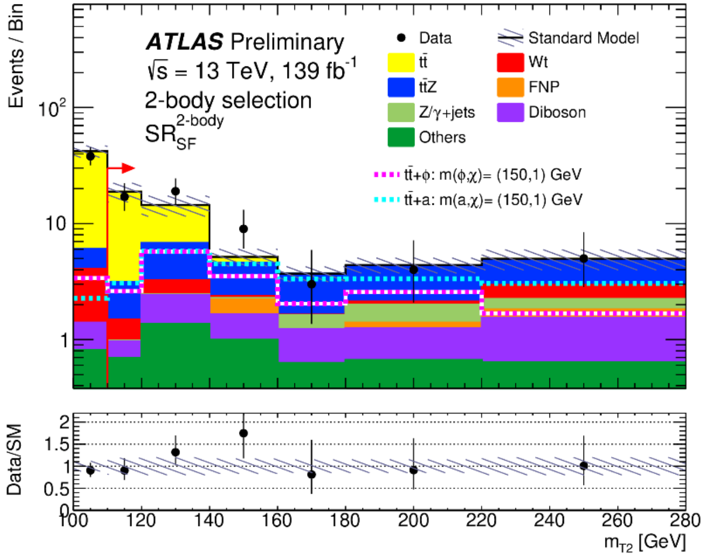
- m_{T2} variable distributions for each post-fit SR

- Good agreement between the data and SM prediction in general and no big excess in SR is observed









tt2L + E_T^{miss}:

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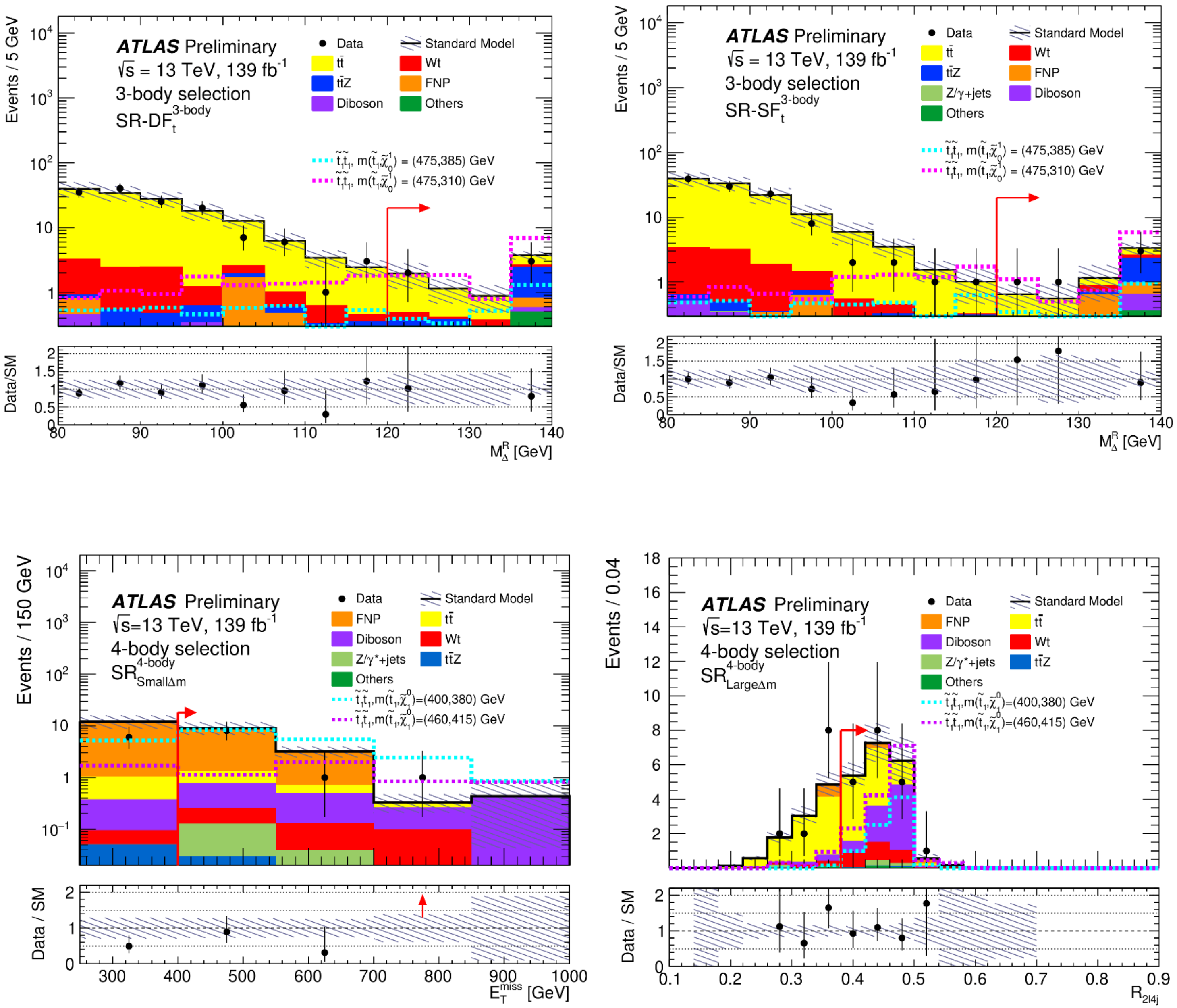


tt2L + E_T^{miss}:

- Event yields in SR - 2 body

	SR-DF$^{2\text{-body}}_{[110,120)}$	SR-DF$^{2\text{-body}}_{[120,140)}$	SR-DF$^{2\text{-body}}_{[140,160)}$	SR-DF$^{2\text{-body}}_{[160,180)}$	SR-DF$^{2\text{-body}}_{[180,220)}$	SR-DF$^{2\text{-body}}_{[220,\infty)}$
Observed events	19	13	5	1	1	3
Fitted bkg events	22 ± 4	16.3 ± 3.2	5.1 ± 0.8	2.83 ± 0.45	3.25 ± 0.45	3.11 ± 0.67
Post-fit, $t\bar{t}$	17 ± 4	10.0 ± 3.2	0.7 ± 0.5	$0.01^{+0.10}_{-0.01}$	0.13 ± 0.11	–
Post-fit, $t\bar{t}+Z$	2.3 ± 0.5	3.5 ± 0.7	2.7 ± 0.7	2.0 ± 0.4	1.9 ± 0.4	1.7 ± 0.6
Wt	0.47 ± 0.27	$0.05^{+0.33}_{-0.05}$	0.025 ± 0.012	–	0.033 ± 0.013	–
Z/γ^* + jets	–	–	–	–	–	–
Diboson	0.67 ± 0.27	0.61 ± 0.24	0.49 ± 0.16	$0.05^{+0.07}_{-0.05}$	0.19 ± 0.13	0.14 ± 0.07
Others	0.97 ± 0.19	1.48 ± 0.28	1.19 ± 0.16	0.78 ± 0.12	0.68 ± 0.13	0.67 ± 0.11
Fake and non-prompt	$0.0^{+0.5}_{-0.0}$	0.6 ± 0.6	$0.0^{+0.5}_{-0.0}$	$0.0^{+0.5}_{-0.0}$	0.37 ± 0.23	0.6 ± 0.4

	SR-SF$^{2\text{-body}}_{[110,120)}$	SR-SF$^{2\text{-body}}_{[120,140)}$	SR-SF$^{2\text{-body}}_{[140,160)}$	SR-SF$^{2\text{-body}}_{[160,180)}$	SR-SF$^{2\text{-body}}_{[180,220)}$	SR-SF$^{2\text{-body}}_{[220,\infty)}$
Observed events	17	19	9	3	4	5
Fitted bkg events	18.8 ± 3.5	14.4 ± 2.9	5.1 ± 0.9	3.7 ± 0.6	4.4 ± 0.7	5 ± 1
Post-fit, $t\bar{t}$	15.7 ± 3.4	7.6 ± 2.3	0.6 ± 0.4	$0.007^{+0.020}_{-0.007}$	0.10 ± 0.08	$0.16^{+0.18}_{-0.16}$
Post-fit, $t\bar{t}+Z$	1.65 ± 0.35	3.5 ± 0.7	2.2 ± 0.5	2.1 ± 0.4	2.18 ± 0.45	1.9 ± 0.6
Wt	0.5 ± 0.5	0.8 ± 0.8	0.10 ± 0.04	$0.018^{+0.019}_{-0.018}$	0.12 ± 0.06	0.71 ± 0.29
Z/γ^* + jets	0.020 ± 0.014	0.044 ± 0.003	$0.07^{+0.17}_{-0.07}$	0.38 ± 0.13	0.60 ± 0.33	0.4 ± 0.4
Diboson	0.27 ± 0.20	1.0 ± 0.6	0.65 ± 0.24	0.6 ± 0.4	0.59 ± 0.28	0.9 ± 0.5
Others	0.69 ± 0.13	1.37 ± 0.21	0.99 ± 0.16	0.63 ± 0.11	0.67 ± 0.14	0.64 ± 0.10
Fake and non-prompt	$0.0^{+0.4}_{-0.0}$	$0.0^{+0.4}_{-0.0}$	0.56 ± 0.06	$0.0^{+0.7}_{-0.0}$	0.15 ± 0.12	0.28 ± 0.21

tt2L + E_T^{miss}:

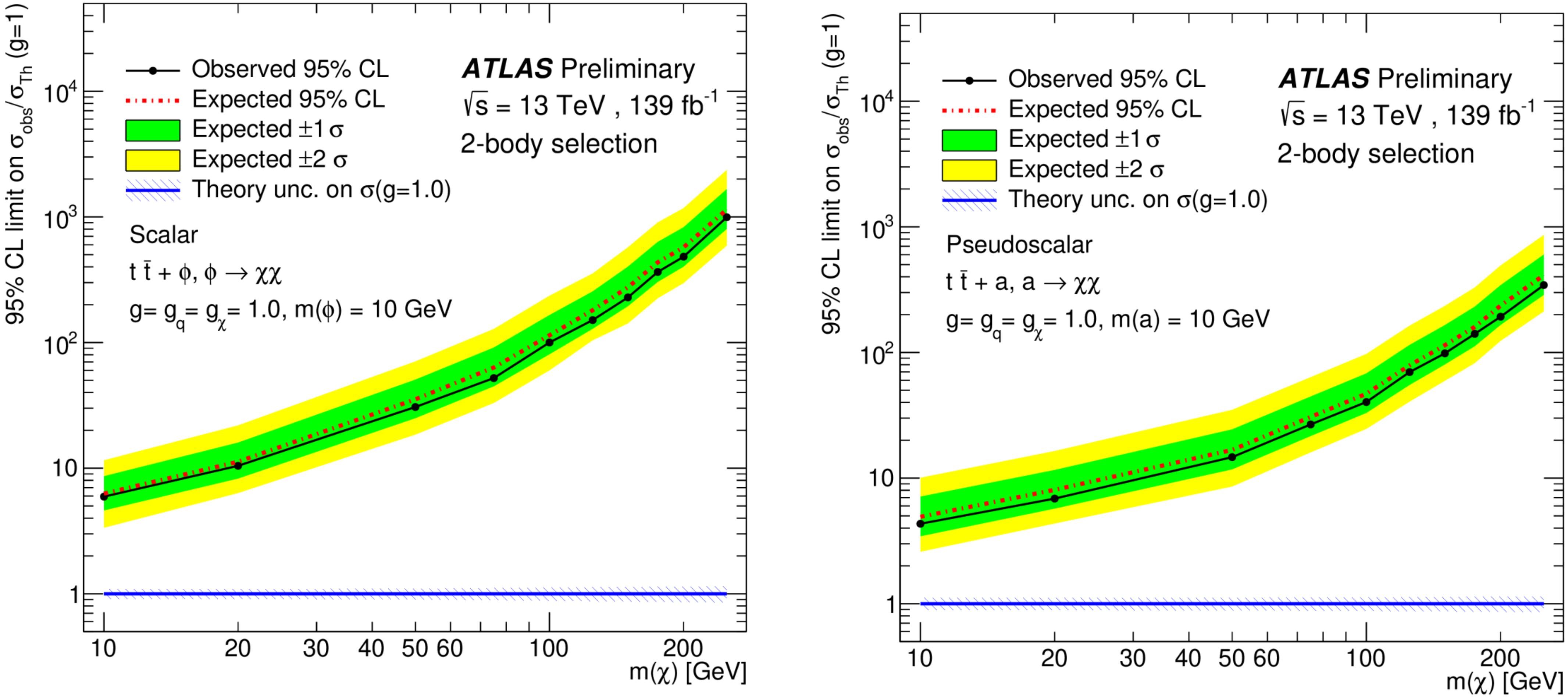
- Event yields in SR - 3 body and SR - 4 body
- Discovery fit results

	SR-DF$_W^{\text{3-body}}$	SR-SF$_W^{\text{3-body}}$	SR-DF$_t^{\text{3-body}}$	SR-SF$_t^{\text{3-body}}$
Observed events	1	5	5	5
Total (post-fit) SM events	5.1 ± 1.0	4.0 ± 1.0	7.5 ± 1.4	5.0 ± 1.1
Post-fit, $t\bar{t}$	1.3 ± 0.5	0.76 ± 0.32	3.9 ± 1.1	1.8 ± 0.7
Post-fit, $t\bar{t} + Z$	0.085 ± 0.034	0.08 ± 0.05	2.3 ± 0.4	1.69 ± 0.35
Post-fit, diboson	2.5 ± 1.0	2.5 ± 1.0	0.17 ± 0.09	0.34 ± 0.14
Wt	0.30 ± 0.05	0.211 ± 0.030	$0.4^{+0.5}_{-0.4}$	0.54 ± 0.19
Z/γ^* +jets	–	0.044 ± 0.019	–	$0.015^{+0.027}_{-0.015}$
Others	0.232 ± 0.020	0.25 ± 0.05	0.70 ± 0.12	0.49 ± 0.08
Fake and non-prompt	0.70 ± 0.09	$0.00^{+0.25}_{-0.00}$	$0.00^{+0.23}_{-0.00}$	$0.16^{+0.23}_{-0.16}$

	SR$^{\text{4-body}}_{\text{Small}\,\Delta m}$	SR$^{\text{4-body}}_{\text{Large}\,\Delta m}$
Observed events	10	19
Total (post-fit) SM events	12.8 ± 3.2	19.3 ± 2.7
Post-fit, $t\bar{t}$	0.87 ± 0.26	8.7 ± 1.5
Post-fit, diboson	1.5 ± 0.5	6.8 ± 2.3
Wt	0.32 ± 0.08	2.7 ± 0.5
Z/γ^* +jets	0.128 ± 0.023	0.46 ± 0.19
$t\bar{t}Z$	0.047 ± 0.010	0.126 ± 0.033
Others	$0.019^{+0.021}_{-0.019}$	0.26 ± 0.07
Fake and non-prompt	10.0 ± 3.1	0.24 ± 0.09

Selection	Signal Region	σ_{vis} [fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
Two-body	SR$^{\text{2-body}}_{110,\infty}$	0.21	29.3	31^{+11}_{-8}	0.5
	SR$^{\text{2-body}}_{120,\infty}$	0.15	21.4	21^{+8}_{-6}	0.40
	SR$^{\text{2-body}}_{140,\infty}$	0.10	13.2	14^{+5}_{-4}	0.5
	SR$^{\text{2-body}}_{160,\infty}$	0.06	8.2	$11^{+5}_{-3.0}$	0.5
	SR$^{\text{2-body}}_{180,\infty}$	0.06	7.9	$9.6^{+3.8}_{-2.8}$	0.5
	SR$^{\text{2-body}}_{200,\infty}$	0.06	7.6	$8.4^{+3.6}_{-2.3}$	0.5
	SR$^{\text{2-body}}_{220,\infty}$	0.05	7.6	$7.5^{+3.1}_{-2.0}$	0.5
Three-body	SR-DF$_W^{\text{3-body}}$	0.023	3.2	$5.7^{+2.3}_{-1.5}$	0.5
	SR-SF$_W^{\text{3-body}}$	0.05	7.0	$5.6^{+2.3}_{-1.5}$	0.27
	SR-DF$_t^{\text{3-body}}$	0.04	5.5	$6.9^{+2.9}_{-1.9}$	0.5
	SR-SF$_t^{\text{3-body}}$	0.04	6.3	$6.1^{+2.6}_{-1.6}$	0.5
Four-body	SR$^{\text{4-body}}_{\text{Small}\,\Delta m}$	0.06	8.2	$9.6^{+3.8}_{-2.5}$	0.5
	SR$^{\text{4-body}}_{\text{Large}\,\Delta m}$	0.08	11.1	$11.1^{+4.5}_{-3.0}$	0.5

tt2L + E_T^{miss}:



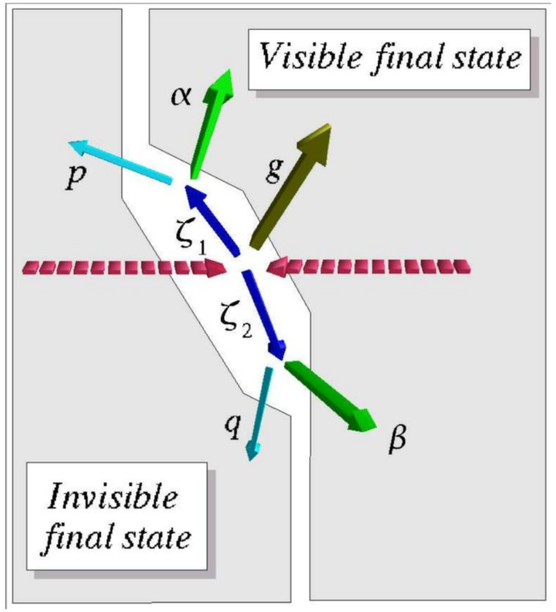
- The 95% confidence level limit for dark matter mass when the spin-0 scalar(left) and pseudoscalar(right) mediator masses is 10 GeV

Variables: stransverse mass m_{T2}

ArXiv:1206.2135

- The stransverse mass m_{T2} can be shown to have a kinematic endpoint for events where two massive pair produced particles each decay to two objects, one of which is detected and the other escapes undetected

$$m_{\mathrm{T2}} = \min_{\mathbf{q}_\mathrm{T}} \left[\max \left(m_{\mathrm{T},\tau 1}(\mathbf{p}_{\mathrm{T},\tau 1}, \mathbf{q}_\mathrm{T}), m_{\mathrm{T},\tau 2}(\mathbf{p}_{\mathrm{T},\tau 2}, \mathbf{p}_\mathrm{T}^{\mathrm{miss}} - \mathbf{q}_\mathrm{T}) \right) \right]$$

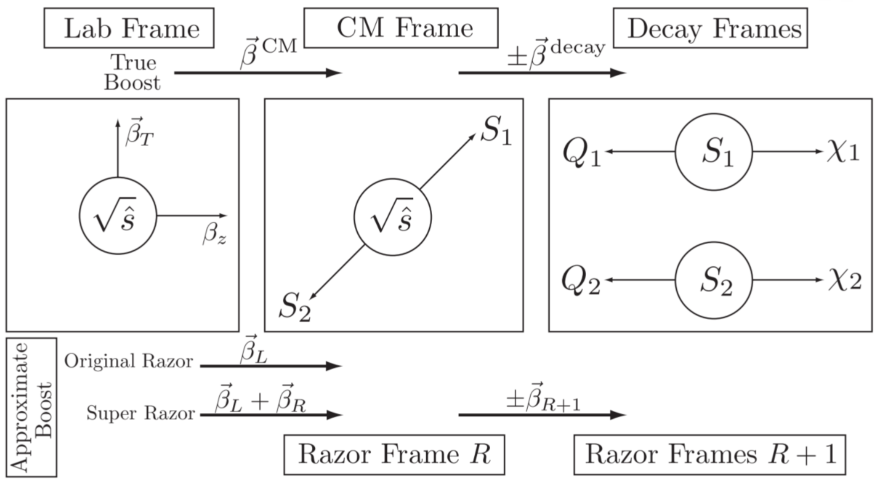


- Where the $m_\mathrm{T}(\mathbf{p}_\mathrm{T}, \mathbf{q}_\mathrm{T}) = \sqrt{2(p_\mathrm{T} q_\mathrm{T} - \mathbf{p}_\mathrm{T} \cdot \mathbf{q}_\mathrm{T})}$
- The min_{q_T} forced to introduce a pair of dummy vectors which constrained by the minimisation condition
- Due to the two massive SUSY particles are pair produced and LSP are expected to be larger than neutrinos, the m_{T2} of the SUSY signals are usually larger than standard model backgrounds

Variables used in tt2L + E_T^{miss} study: Razor Frame variables

Arvix:1310.4827

- The Razor Frame is target to make a approximate of the center-of-mass energy(CM) frame of two parent particles (i.e. top squarks) and the decay frames using the object information in lab frame
  - Each parent particle is assumed to decay into a set of visible and invisible particles
  - To build the frame for our targeting scenarios and transform the E_T^{miss} to CM frame invisible particles, a series of assumption is made



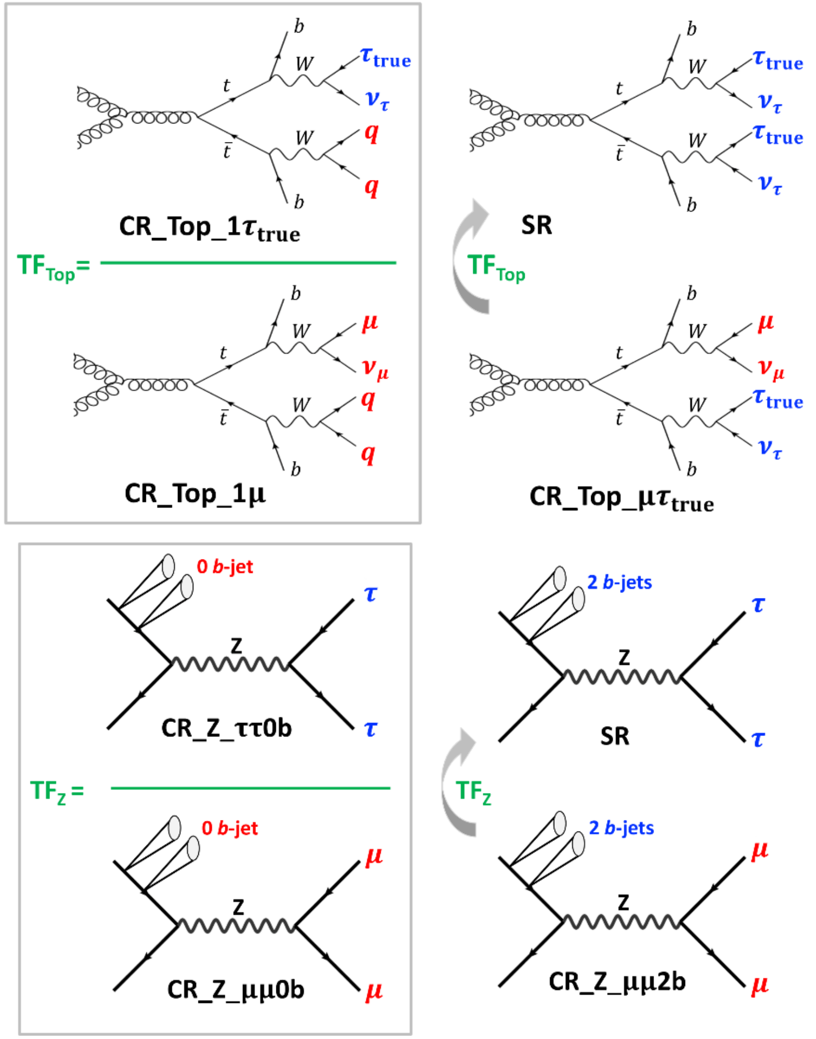
- R_{p_T}: $R_{p_T} = |\vec{J}_T|/(|\vec{J}_T| + \sqrt{\hat{S}_R}/4)$. The $\vec{J}_T$ is the vector sum of the transverse momenta of the visible particles and $\boldsymbol{E_T^{miss}}$, $\sqrt{\hat{S}_R}$ is the estimated Razor Frame energy
- γ_{R+1}: The Lorentz factor, is associated with the boost from the razor frame R to the approximation of the two decay frames of the parent particles
- $\Delta\varphi_\beta^R$: The azimuthal angle between the razor boost from the laboratory to the R frame and the sum of the visible momenta as evaluated in the R frame
- M_Δ^R: the mass-splitting between the parent particle and the invisible particle

Other variables used in tt2L + E_T^{miss} study

- $p_{T,boost}^{ll}$: The vectorial sum of $\vec{P}_T^{miss}$ and $\vec{P}_T^{l1}$ and $\vec{P}_T^{l2}$
- $\Delta\phi_{boost}$: The azimuthal angle between the $\vec{P}_T^{miss}$ and $p_{T,boost}^{ll}$
- $R_{2l} = E_T^{miss}/(p_T(l_1) + p_T(l_2))$
- $R_{2l4j} = E_T^{miss}/(p_T(l_1) + p_T(l_2) + \sum_{i=1}^{4} p_T(j_i))$
- $min\ \Delta R_{l_2,j_i} = \min_{j\epsilon[jets]}(\Delta R(l_2, j))$

Sbottom multi-b with taus:

Normalization / transfer factor	Fitted value	Control region	Purity
$\omega_{\text{true tau}}$	0.88 ± 0.16	CR_Top_$\mu\tau_{\text{true}}$	86%
		CR_Top_$\mu\tau_{\text{fake}}$	53%
$\omega_{\text{fake tau}}$	0.79 ± 0.30	CR_Top_$\mu\tau_{\text{fake}}$	43%
		CR_Top_$\mu\tau_{\text{true}}$	9%
ω_{1mu}	0.91 ± 0.10	CR_Top_μ	94%
$\text{TF}_{\text{Top}} \equiv \omega_{\text{1tau}}/\omega_{\text{1mu}}$	0.98 ± 0.04	CR_Top_τ_{true}	88%
ω_{Zmumu2b}	1.28 ± 0.12	CR_Z_$\mu\mu$2b	89%
ω_{Zmumu0b}	1.00 ± 0.05	CR_Z_$\mu\mu$0b	96%
$\text{TF}_{Z} \equiv \omega_{\text{Ztautau0b}}/\omega_{\text{Zmumu0b}}$	0.99 ± 0.17	CR_Z_$\tau\tau$0b	79%



- The transfer factor calculated in each control regions

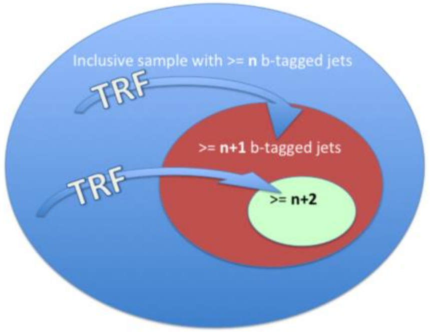
Sbottom multi-b with taus:

	Single-bin SR	Multi-bin SR		
		$\min_\Theta < 0.5$	$0.5 < \min_\Theta < 1.0$	$\min_\Theta > 1.0$
Observed events	4	3	1	3
Total SM background	3.8 ± 1.5	2.7 ± 1.1	3.5 ± 1.6	1.5 ± 0.6
top quark $\tau_{\text{true}}\ \tau_{\text{true}}$	1.4 ± 0.9	1.6 ± 0.7	1.9 ± 1.0	$0.30\ ^{+\ 0.41}_{-\ 0.30}$
top quark $\tau_{\text{true}}\ \tau_{\text{fake}}$	0.92 ± 0.62	0.76 ± 0.43	0.96 ± 0.69	0.22 ± 0.17
top quark $\tau_{\text{fake}}\ \tau_{\text{fake}}$	$0.11\ ^{+\ 0.26}_{-\ 0.11}$	0.06 ± 0.06	$0.12\ ^{+\ 0.23}_{-\ 0.12}$	$0.04\ ^{+\ 0.05}_{-\ 0.04}$
$t\bar{t}X$	0.52 ± 0.42	0.18 ± 0.10	$0.26\ ^{+\ 0.31}_{-\ 0.26}$	0.31 ± 0.22
$Z(\tau\tau)$+jets	0.73 ± 0.25	0.05 ± 0.05	0.17 ± 0.16	0.59 ± 0.22
other	0.07 ± 0.04	—	0.04 ± 0.01	0.06 ± 0.03
$m(\tilde{b}, \tilde{\chi}_2^0) = (800, 131)$ GeV	5.6 ± 1.4	0.14 ± 0.06	1.5 ± 0.4	4.3 ± 1.1
$m(\tilde{b}, \tilde{\chi}_2^0) = (800, 180)$ GeV	9.3 ± 2.2	$0.08\ ^{+\ 0.14}_{-\ 0.08}$	2.4 ± 0.6	7.1 ± 1.7

- The event yields in each post-fit signal regions

Sbottom multi-b with taus: Tag-rate-function multi-jet method

- In signal regions, the MC statistics for multi-jets with many jets are small
  - If we could get the tag rate of a normal jet to the b-jet. Then we could increase the statistics by promoting a normal jet to the bjet then multiple its possibilities
- Method:
  - In $N_{jet} = 5$ region, measure the tag rate of 2 bjets Multijet events to 3 bjets events: ϵ_2 and the tag rate of 3 bjets Multijet events to 4 bjets events: ϵ_3
  - When doing the $\epsilon_2(\epsilon_3)$ measurement, the already tagged 2(3) bjets are removed since we are calculating the tag rate of a normal jet promotion
  - The ϵ are measured by the function of p_T/H_T and $\Delta R_{min}(jets, bjets)$
  - The Multi-jet events are data driven: $N_{MJ} = N_{data} - N_{other\ Bkg}$
  - Finally randomly promote jet to bjet to the target N_{bjets} rejoins and multiple corresponding ϵ
  - To gain more accuracy we first use ϵ_2 to get N_{3bjets} then use ϵ_3 to get $N_{\geq 4bjets}$



Probabilities of having n+m *b*-tag jets (m=0,1,2)

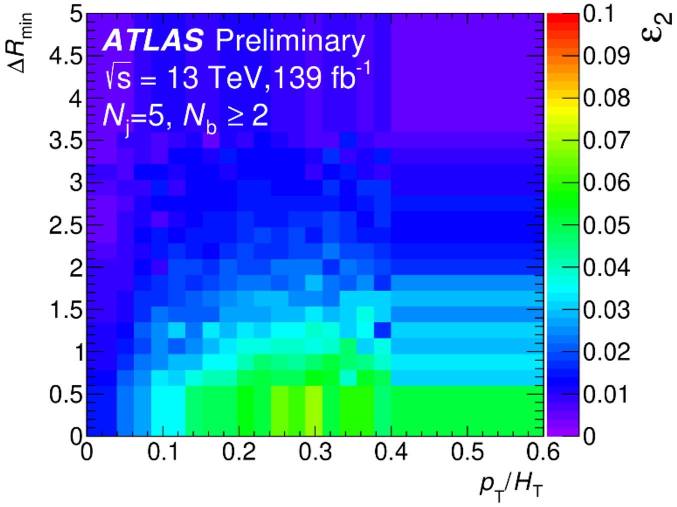
$$P_{m=0} = \prod_{i=1}^{N_{jet}-n} (1-\epsilon_i),$$

$$P_{m=1} = \sum_{j=1}^{N_{jet}-n} \left(\epsilon_j \prod_{i\neq j}(1-\epsilon_i)\right),$$

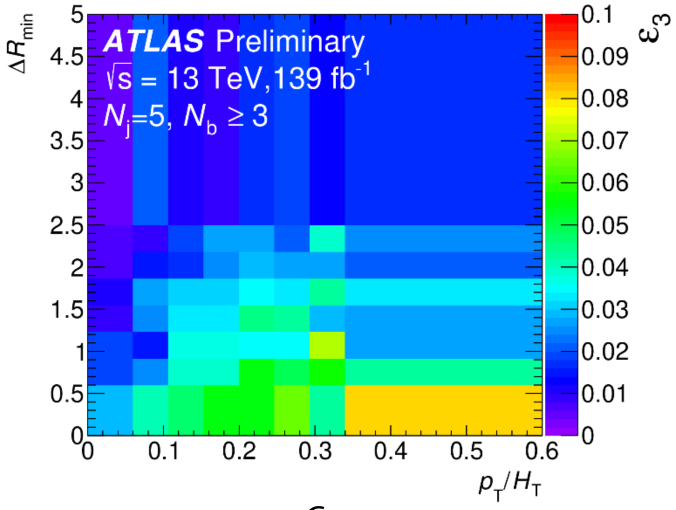
...

Sbottom multi-b with taus: Tag-rate-function multi-jet method

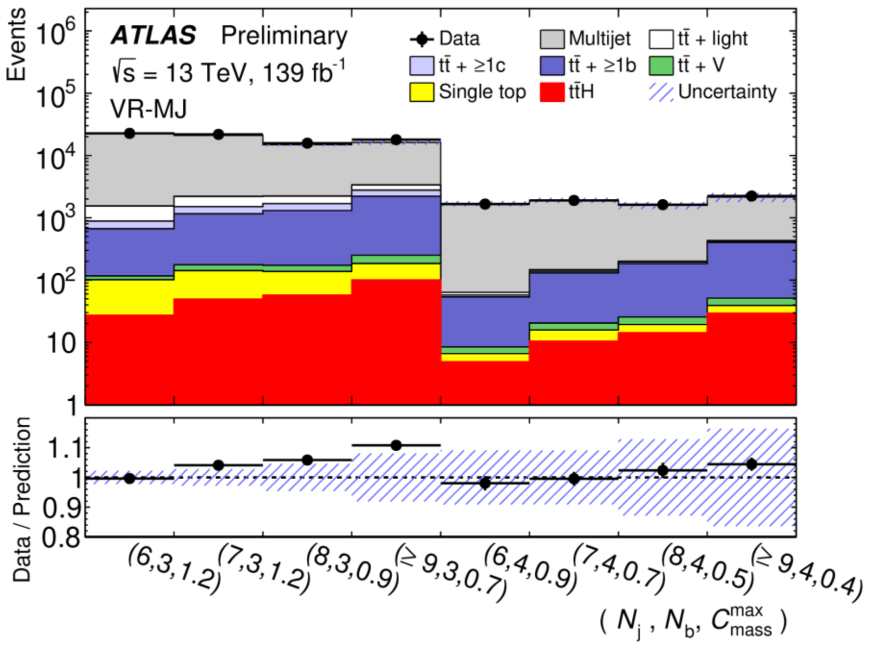
- Fine agreement between the data and predictions in validation regions

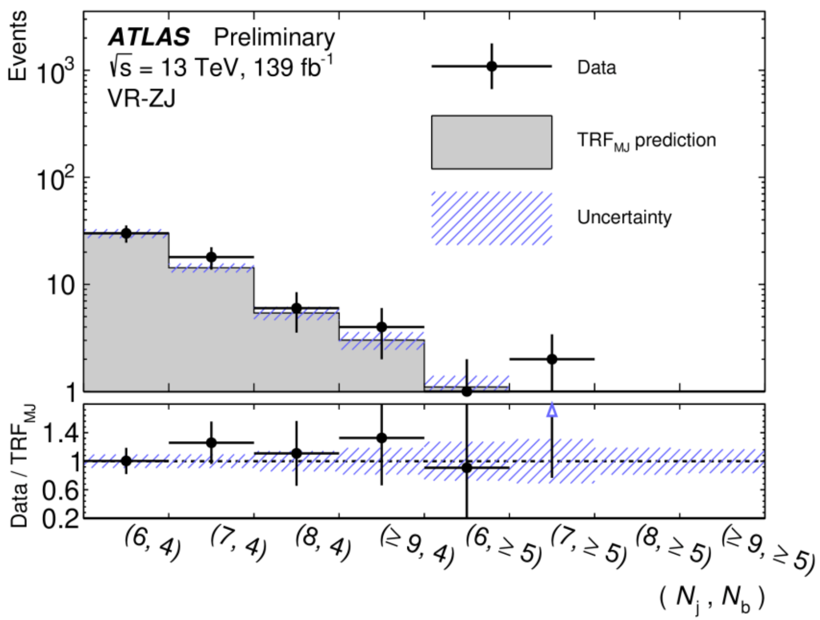


ϵ_2



ϵ_3





RPV SUSY in multi b-jet:

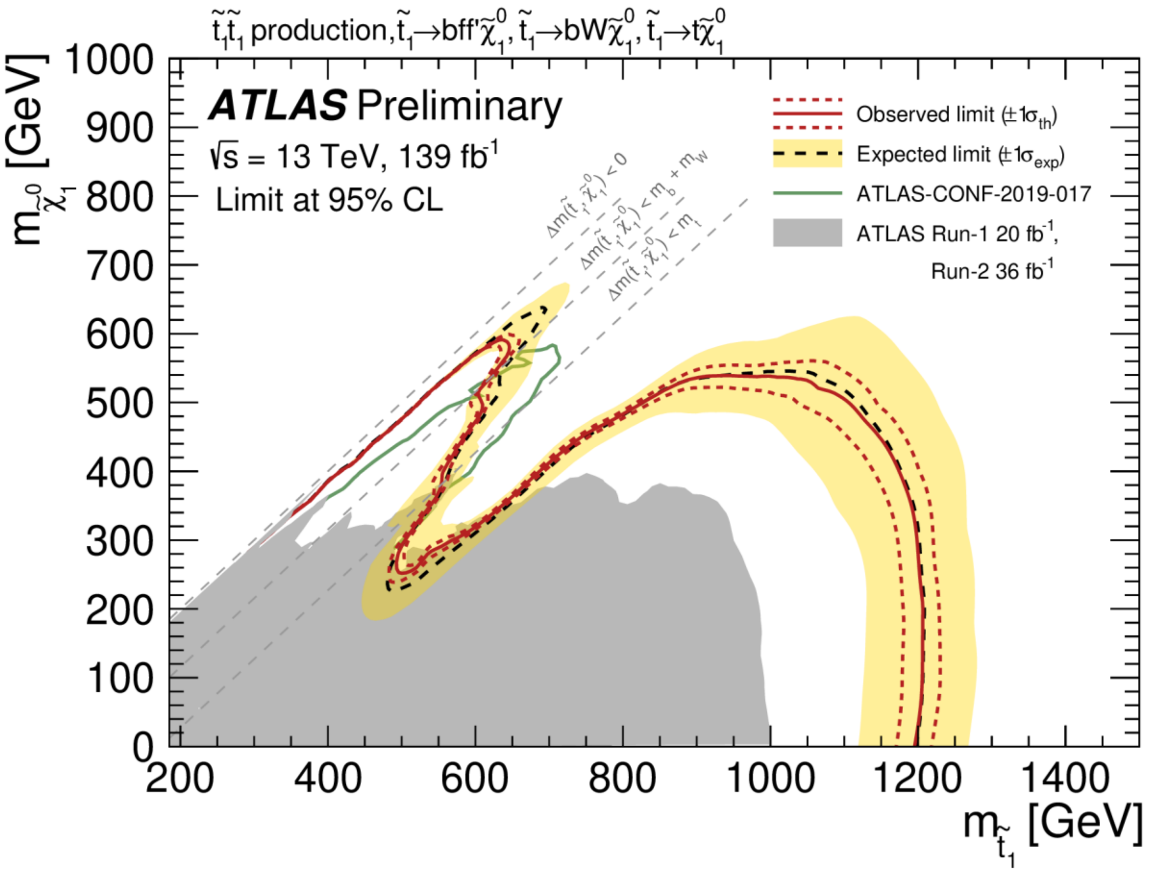
- The event yields in each post-fit discovery signal regions
- Discovery fit results

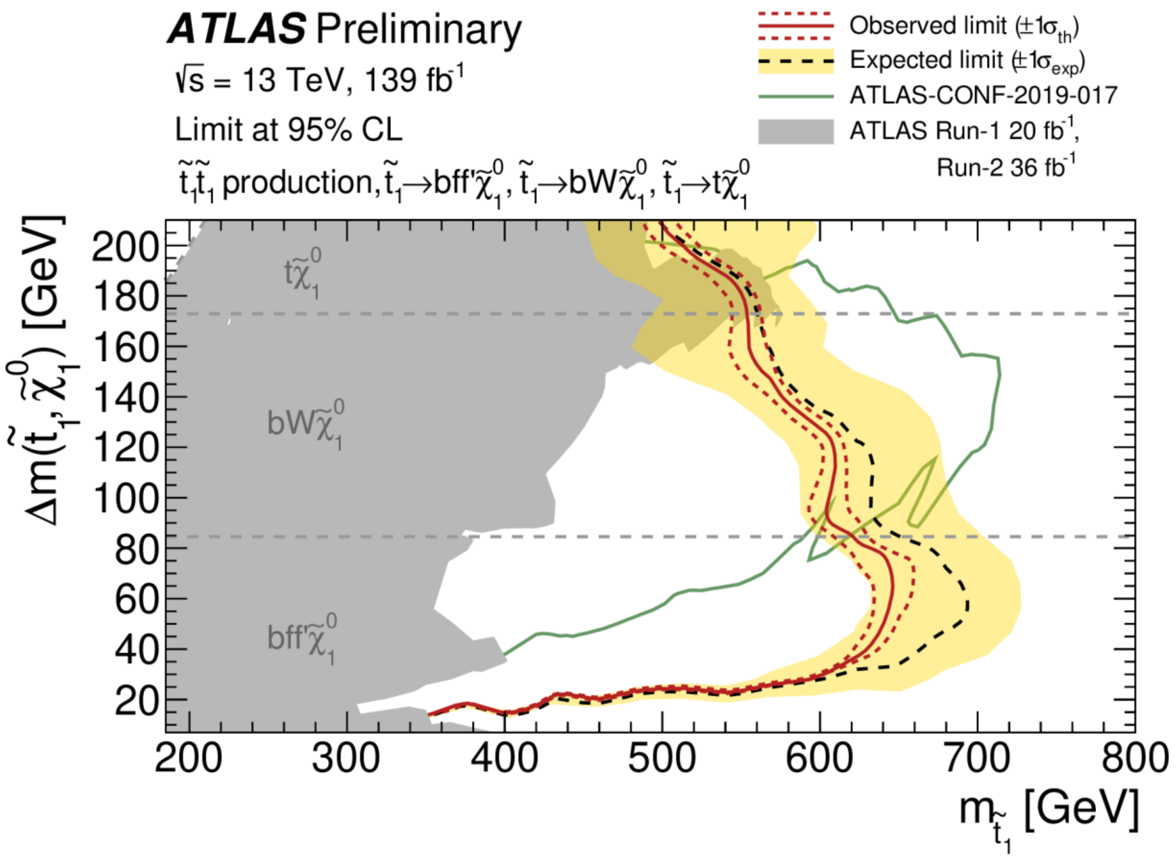
Process	$N_j \geq 8,\ N_b \geq 5$	$N_j \geq 9,\ N_b \geq 5$
Multijet	200 ± 40	123 ± 20
$t\bar{t} + \geq 1c$	0.6 ± 0.6	0.29 ± 0.33
$t\bar{t} + \geq 1b$	26 ± 20	20 ± 15
$t\bar{t} + W$	0.11 ± 0.05	0.09 ± 0.04
$t\bar{t} + Z$	1.4 ± 0.7	0.8 ± 0.7
Wt channel	0.9 ± 0.8	0.9 ± 1.2
$t\bar{t}H$	3.7 ± 1.6	2.9 ± 1.4
Total background	230 ± 40	147 ± 20
Data	259	179

Signal region	$\sigma^{95}_{\mathrm{obs}}$ [fb]	N^{95}_{obs}	N^{95}_{exp}	p_0 (Z)
$N_{\mathrm{j}} \geq 8,\ N_{\mathrm{b}} \geq 5$	0.76	105	85^{+30}_{-24}	0.24 (0.7)
$N_{\mathrm{j}} \geq 9,\ N_{\mathrm{b}} \geq 5$	0.54	75	52^{+20}_{-15}	0.11 (1.2)

Stop with 1 lepton final state results

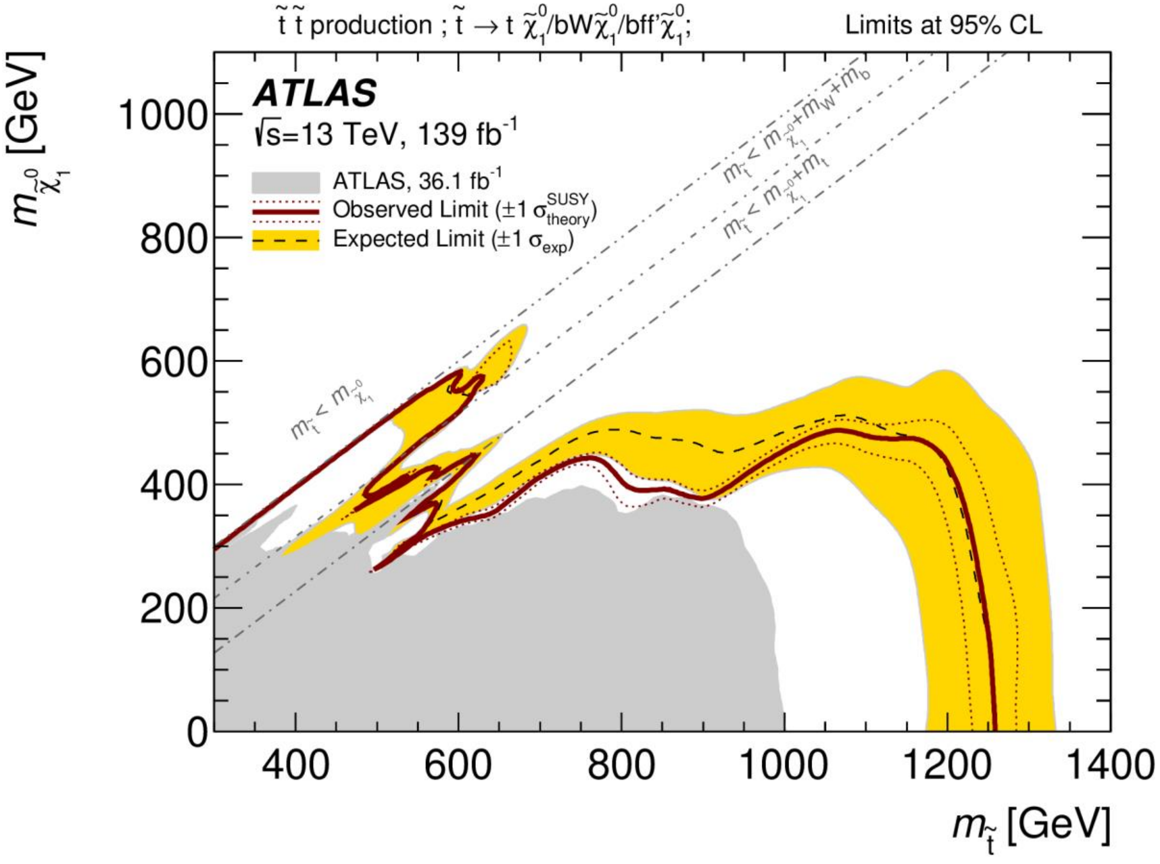
- The Stop mass < 1.2 TeV are excluded for a low neutralino mass
- In compressed mass regions, the Stop mass < 640 GeV are excluded

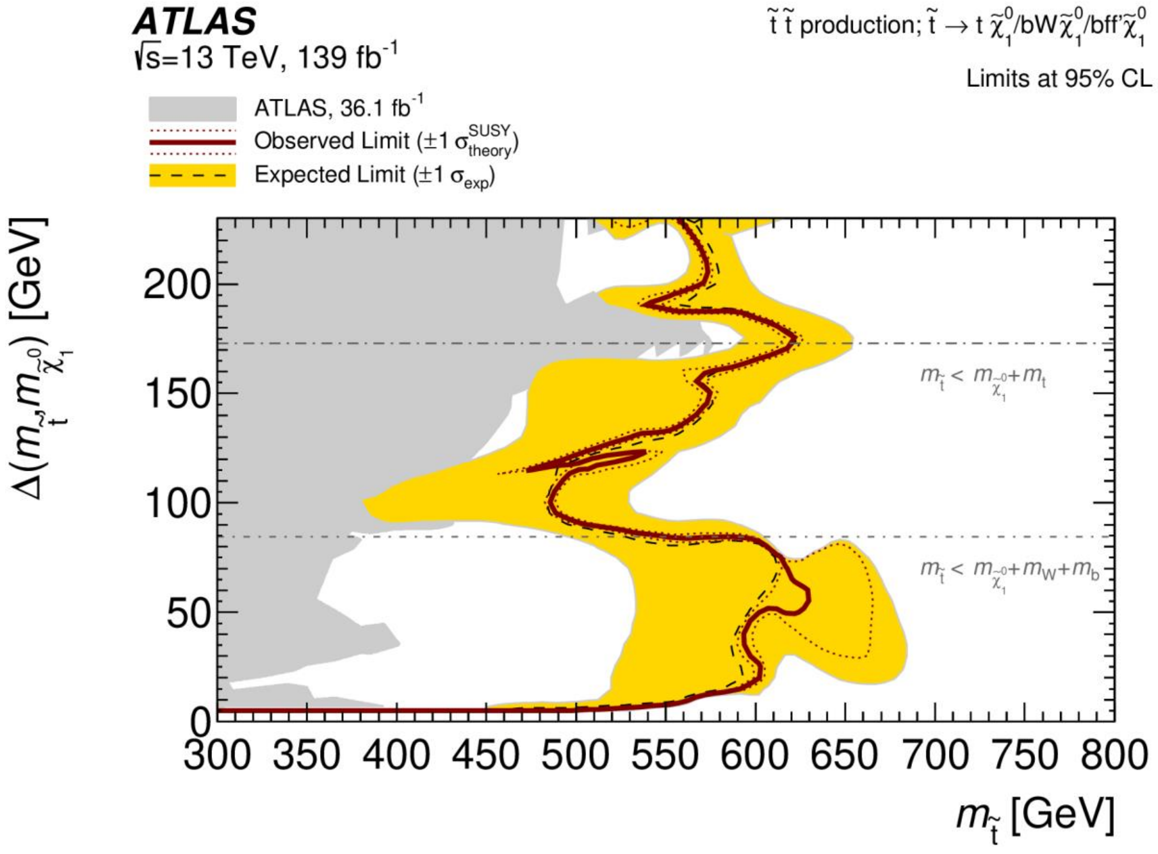




Stop with 0 lepton final state results

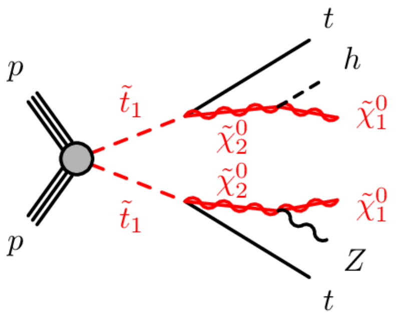
- The Stop mass < 1.25 TeV are excluded for a low neutralino mass
- In compressed mass regions, the Stop mass < 630 GeV are excluded

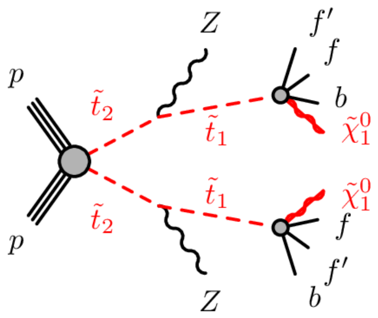


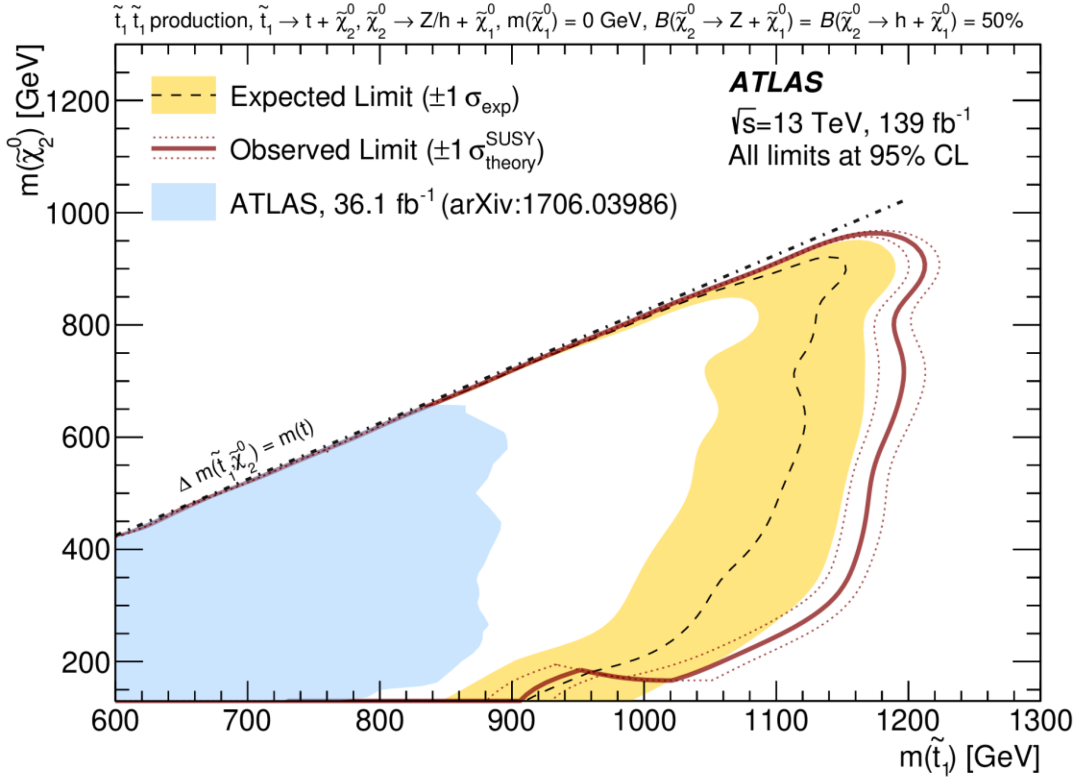


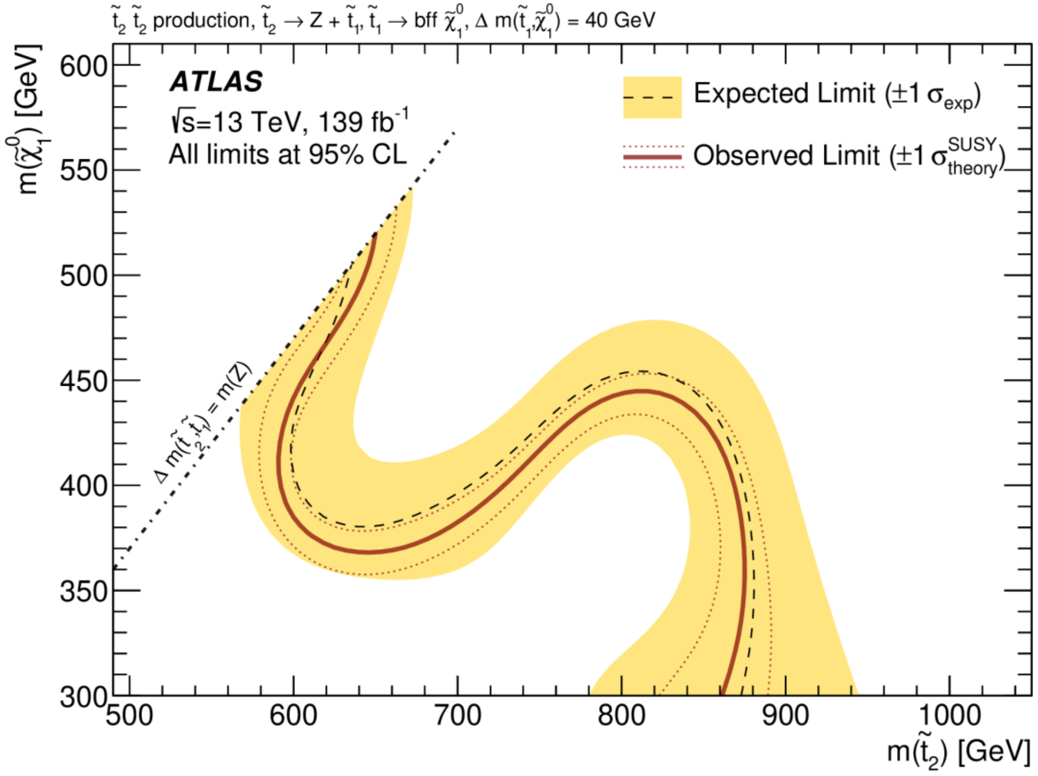
Stop with Higgs and Z final state results

- $\tilde{t}_1$ mass < 1.22 TeV and $\tilde{t}_2$ mass < 875 GeV are excluded for a low neutralino mass



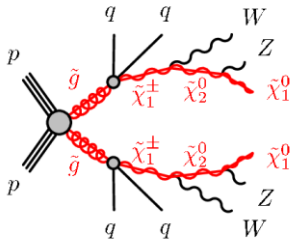


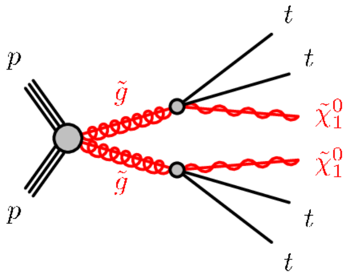


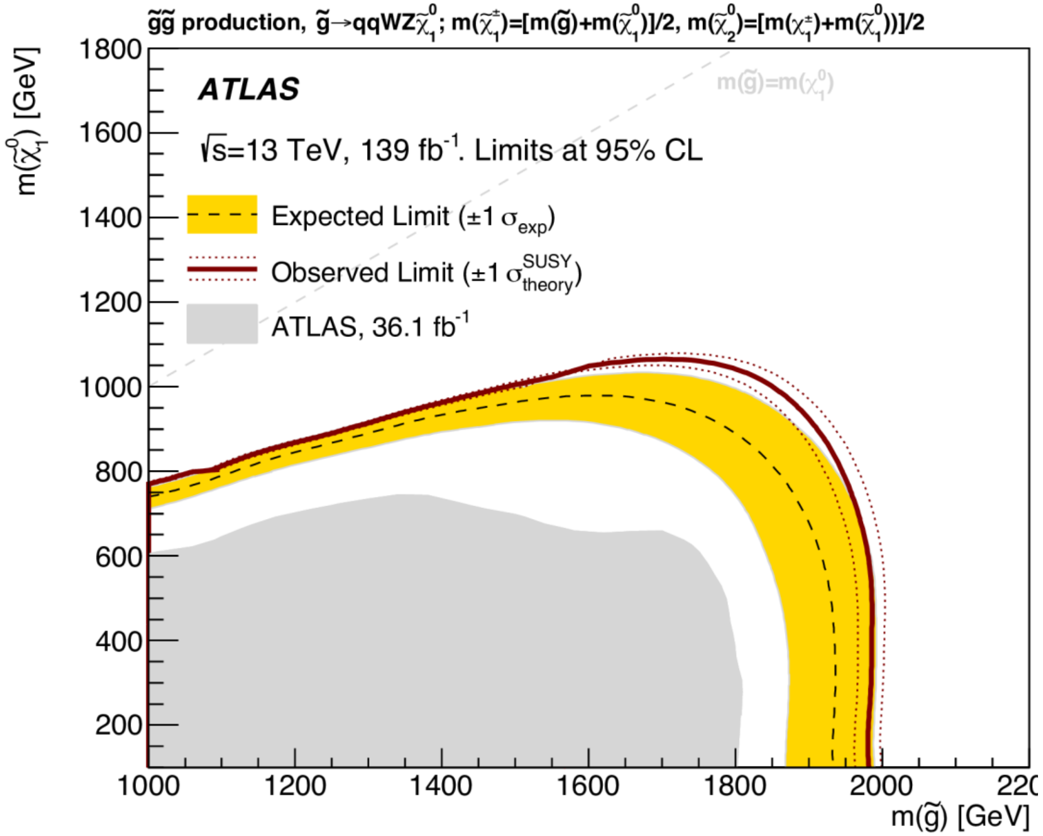


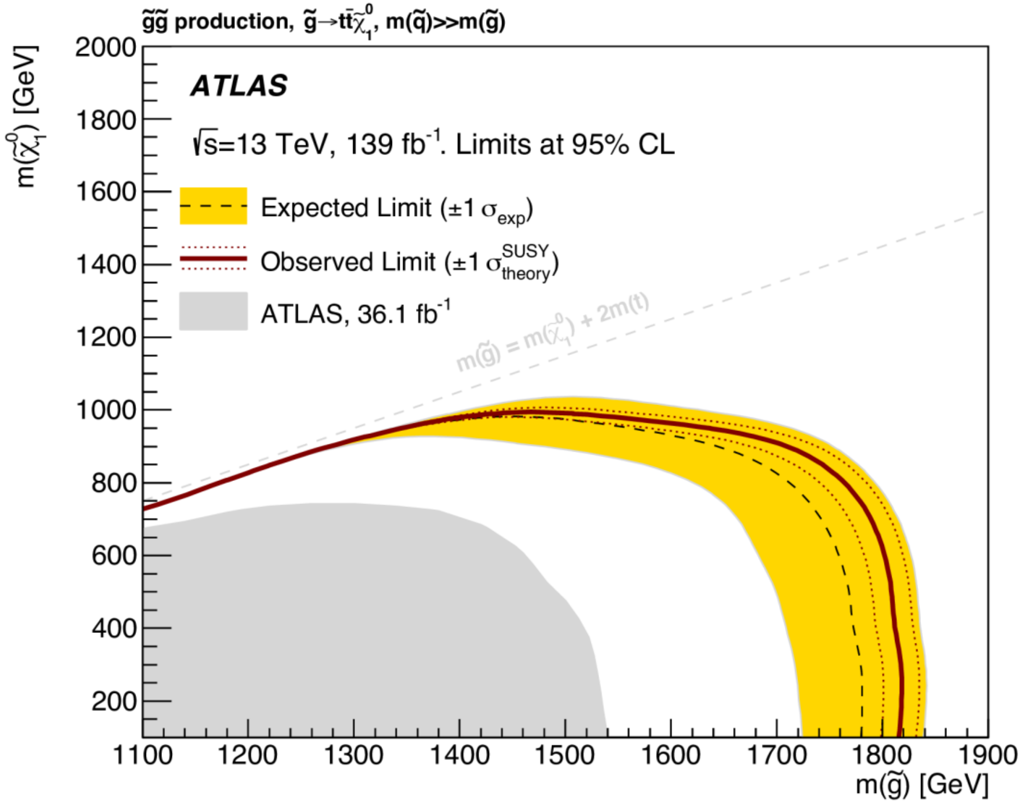
Gluino with large jet multiplicities resultsfor various models

- Gluino mass < 2 TeV(1.8 TeV, 1.6 TeV) are excluded for a low LSP mass via different decay









Gluino with large jet multiplicities resultsfor various models

- Gluino mass < 2 TeV(1.8 TeV, 1.6 TeV) are excluded for a low LSP mass via different decay