SUSY Search using tau and lepton with ATLAS Detector

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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…
- If SUSY is at TeV scale, it will be produced copiously at LHC
- ATLAS recorded $139\ fb^{-1}$ of data in Run-2, could we find SUSY in these huge amount of data?

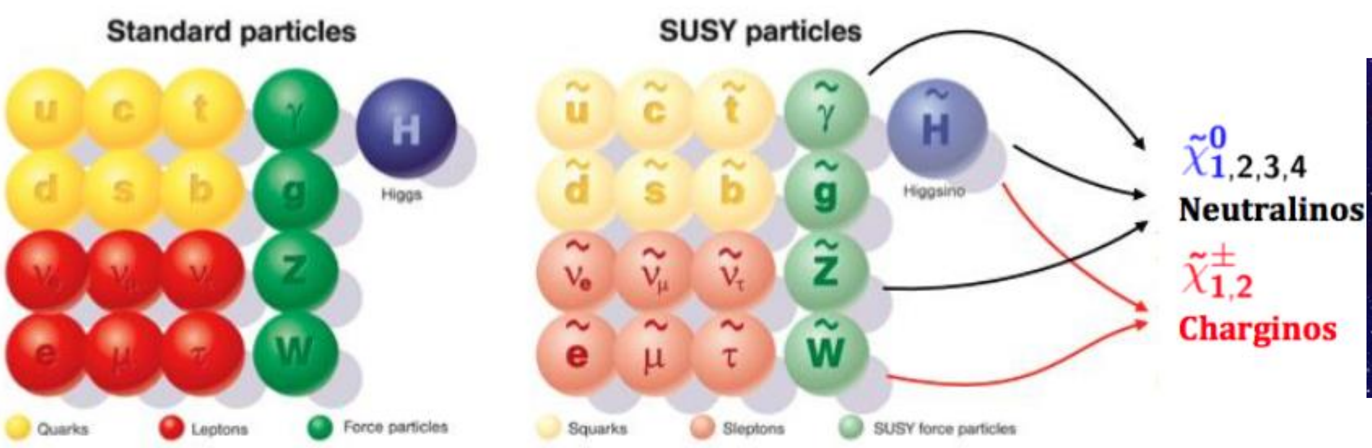
$$m_h^2 = m_{h_0}^2 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 - \mathcal{O}(\log(\Lambda^2))$$

m_h^2: 125 GeV

$m_{h_0}^2$: Bare mass

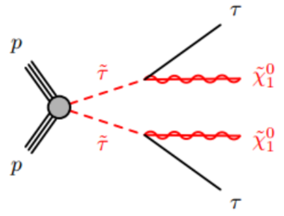
$\mathcal{O}(\log(\Lambda^2))$: corrections

(Λ: cut-off scale ~ 10^{19} GeV)

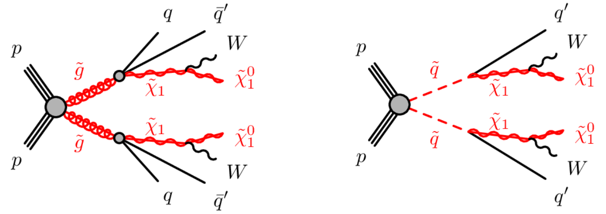


Introduction

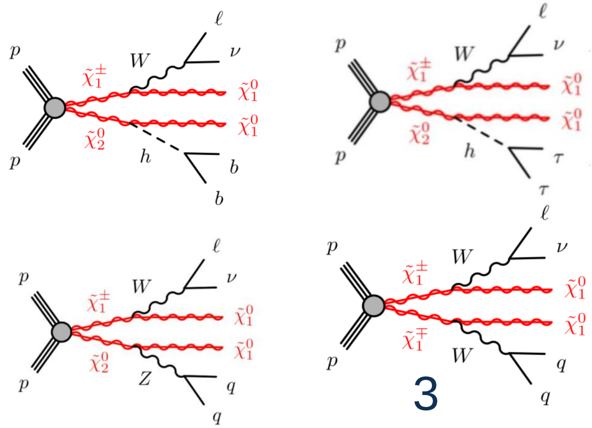
- This talk will present the latest SUSY searches status with the ATLAS detector on di-tau or(and) one lepton final states
- SUSY Direct Stau production search with di-tau
  - In most of SUSY scenarios, the staus are lighter than sleptons, squarks and gluinos. Higher possibility to be found at LHC
  - Models with light staus can lead to a dark-matter relic density consistent with cosmological observations



- SUSY strong production search with one lepton
  - Gluino and Squark production has higher cross-section. Lead to larger search region
  - One lepton requirements could largely suppress the SM backgrounds

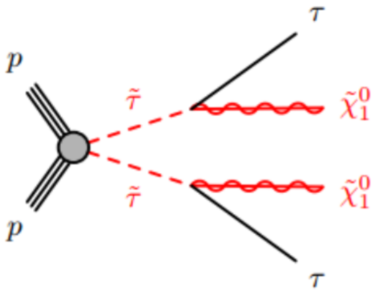


- SUSY gaugino production($\chi_1^{\pm}\chi_1^{\pm}$, $\chi_1^{\pm}\chi_2^{0}$) search with one lepton (and di-tau)
  - If the Gluino and Squark are too heavy to be produced at LHC but gaugino particles not. The gaugino production will dominant at LHC
  - One lepton requirements could largely suppress the SM backgrounds

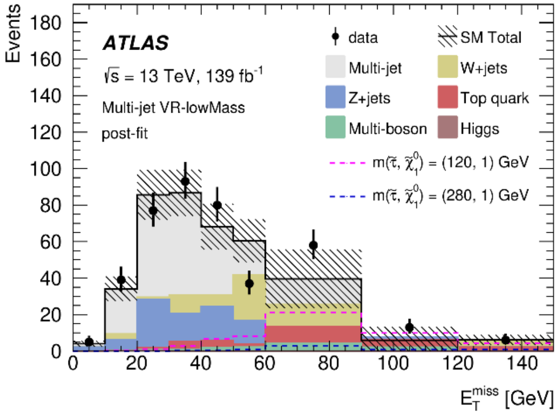


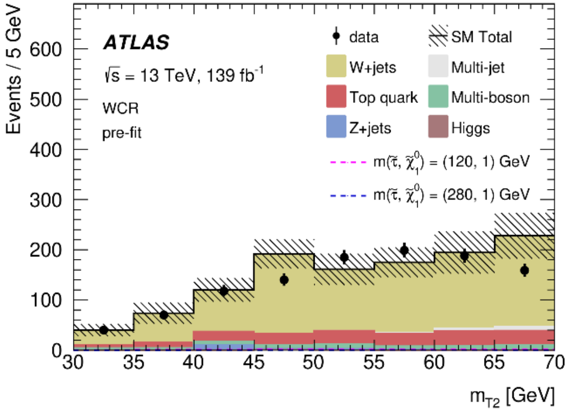
SUSY Direct Stau production search with di-tau

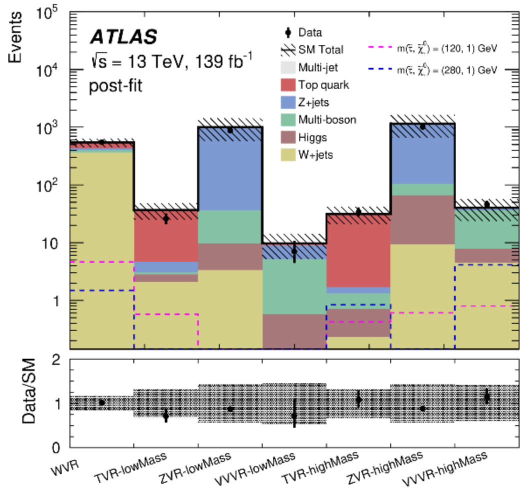
- Signal models
  - Stau pair produced directly from the pp collision, then decay to SM taus and LSP
  - Signature: exactly 2 taus + low jet activity + E_T^{miss}
- Analysis Strategy
  - Two signal regions aiming for different mass differences between $\tilde{\tau}$ and $\tilde{\chi}_1^0$
  - Multi-jet background estimated by ABCD method. W normalized in dedicated control region
  - Irreducible background estimated by MC and validated at validation regions



SR-lowMass	SR-highMass
2 tight τ (OS)	2 medium τ (OS) , ≥ 1 tight τ
asymmetric di-τ trigger	di-τ+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
τ p_{T} cut described in Section 5	
light lepton veto and 3rd medium τ veto	
b-jet veto	
Z/H veto ($m(\tau_1, \tau_2) > 120$ GeV)	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 0.8$	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$m_{\mathrm{T2}} > 70$ GeV	

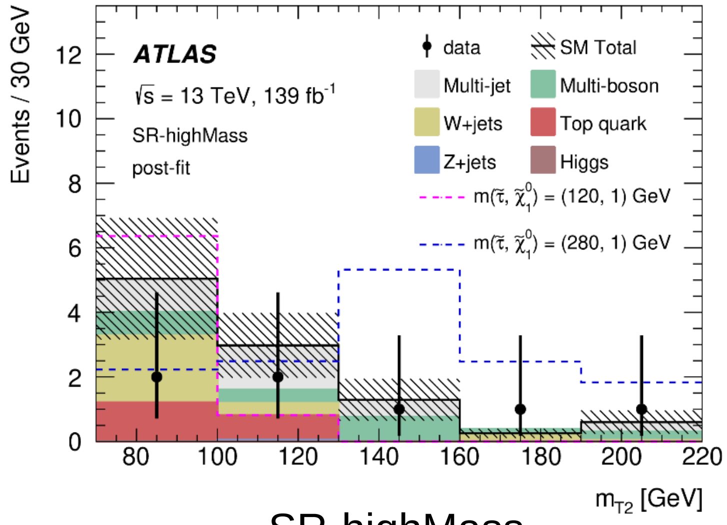




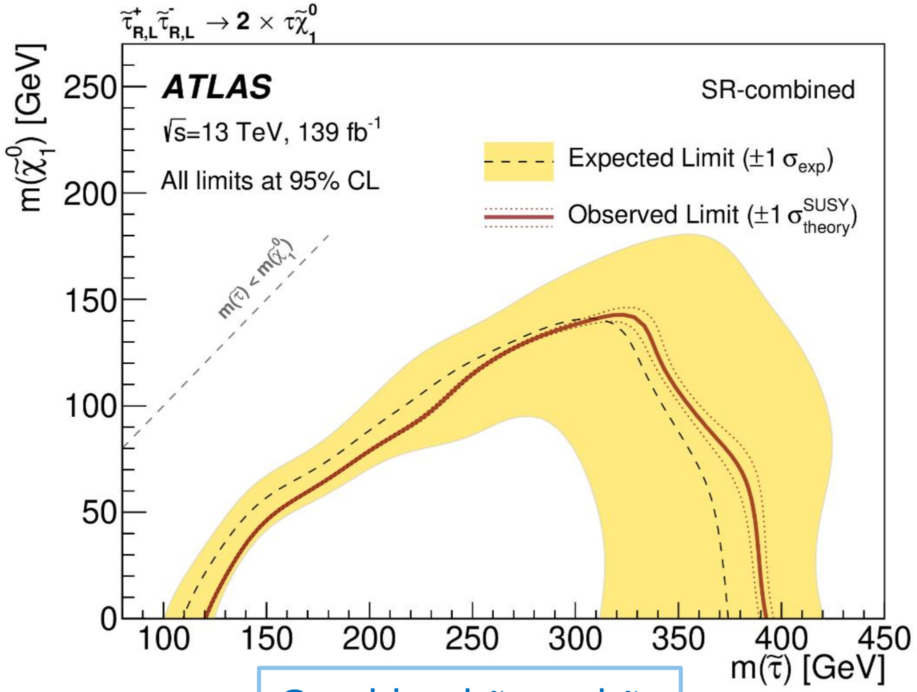


SUSY Direct Stau production search with di-tau

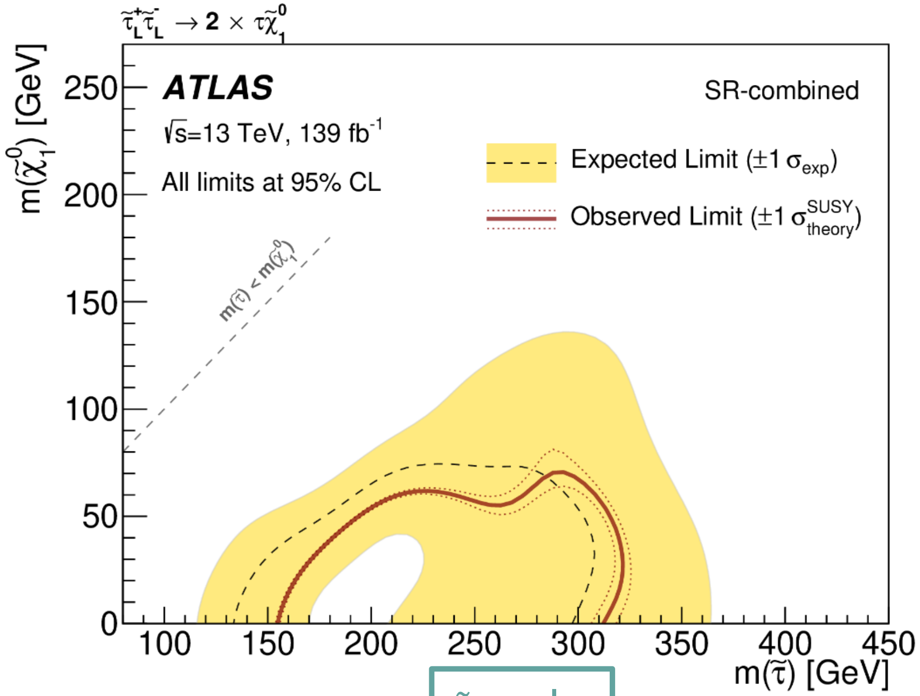
- No significant excess over the SM background observed
- For the combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$ production, the masses from 120 GeV to 390 GeV are excluded for a massless LSP
- For the $\tilde{\tau}_L$ production only , the masses from 160 GeV to 300 GeV are excluded for a massless LSP
- Results published at PhysRevD.101.032009



SR-highMass



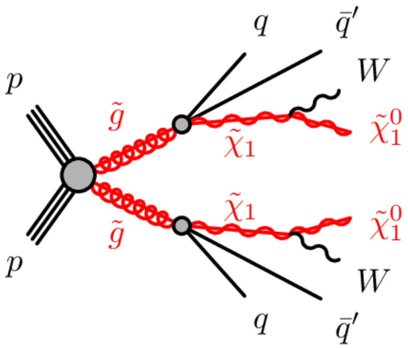
Combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$

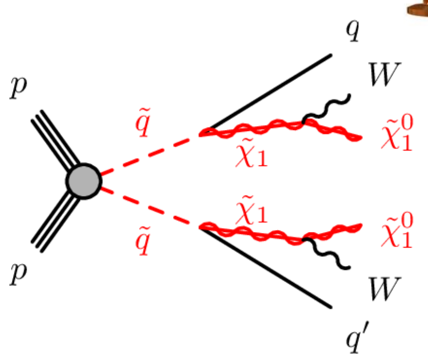


$\tilde{\tau}_L$ only

SUSY strong production search with one lepton

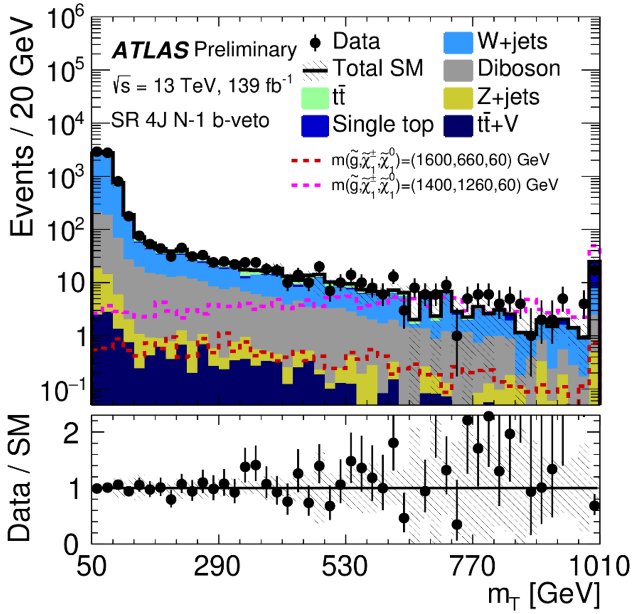
- Signal models
  - Squarks(1st and 2nd generation) and gluinos productions
  - Signature: 1 lepton + jets + E_T^{miss}





- Analysis Strategy
  - Detailed signal regions using different N-Jets, meff to cover different mass regions
  - Likelihood is calculated with multiple bin fit
  - Define dedicate control and validation regions for main backgrounds
  - Other small backgrounds estimated using MC

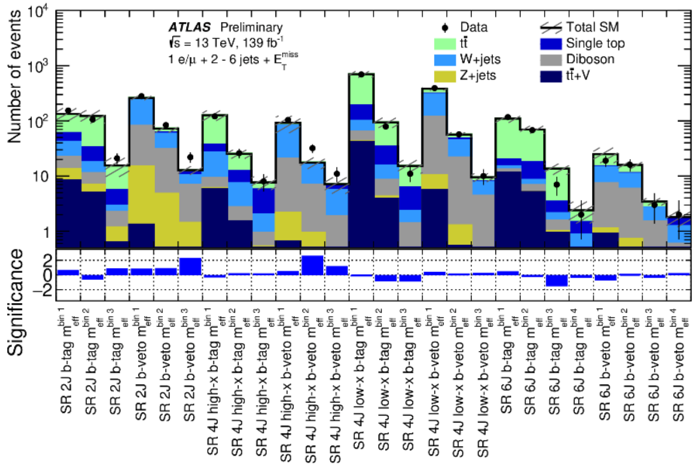
SR	2J	4J high-x	4J low-x	6J
N_ℓ			$= 1$	
p_T^ℓ [GeV]	$> 7(6)$ for $e(\mu)$ and $< \min(10 \cdot N_{jet}, 25)$	> 25	> 25	> 25
N_{jet}	≥ 2	4–5	4–5	≥ 6
E_T^{miss} [GeV]	> 400	> 300	> 300	> 300
m_T [GeV]	> 100	> 520	150–520	> 225
Aplanarity	-	> 0.01	> 0.01	> 0.05
E_T^{miss}/m_{eff}	> 0.25	> 0.2	> 0.2	-
N_{b-jet} (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)

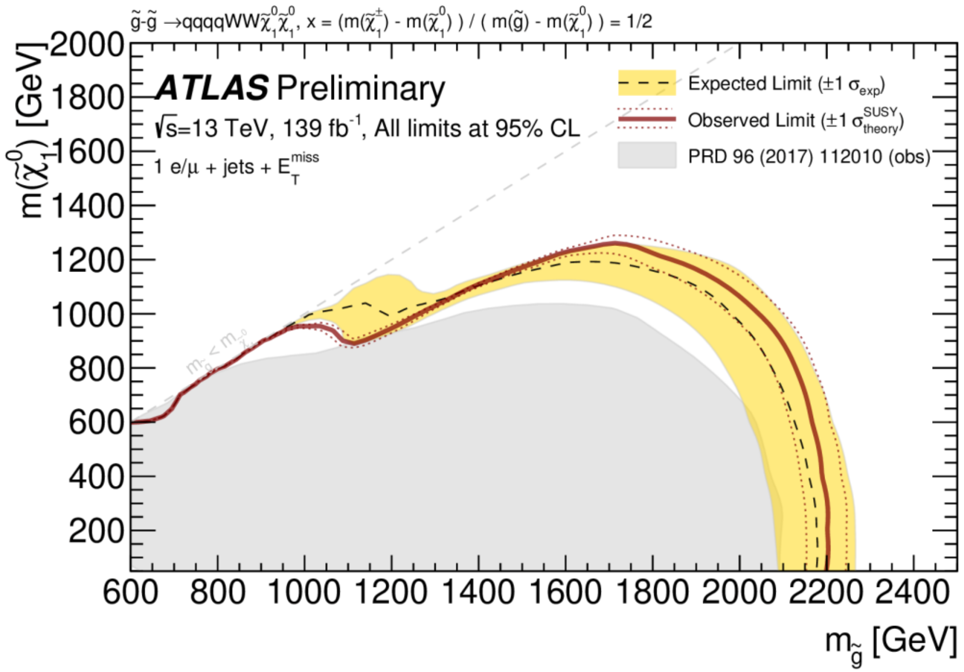


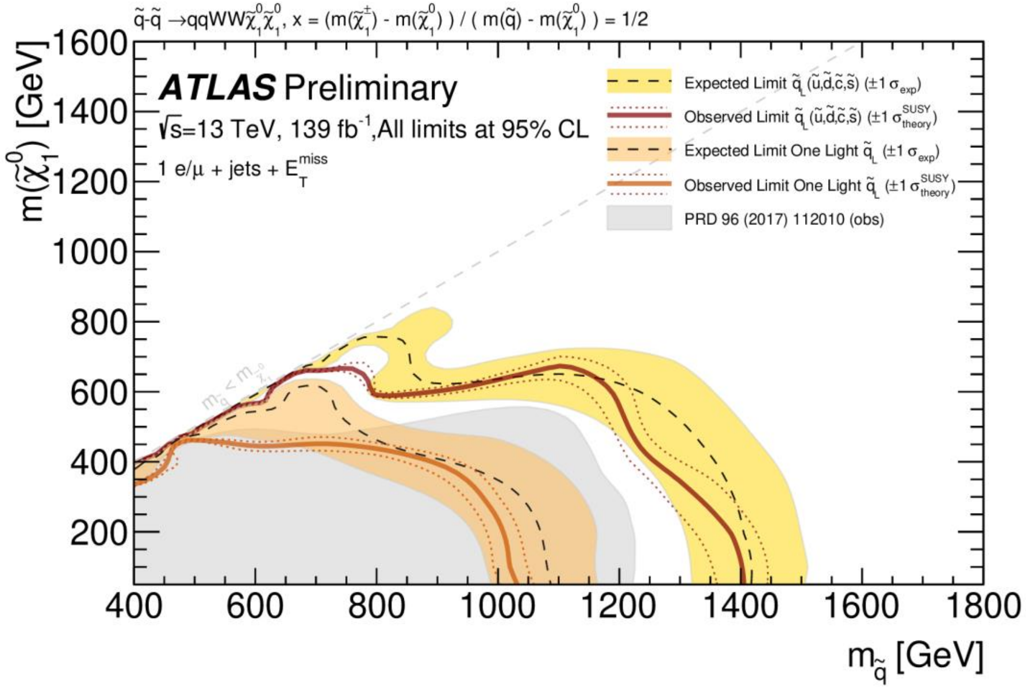
The N-1 distribution for 4J SR/CR/VR combined m_T distributions

SUSY strong production search with one lepton

- No significant excess over the SM background observed
- 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
- Conf note published to ATLAS-CONF-2020-047. will be submitted to EPJC soon







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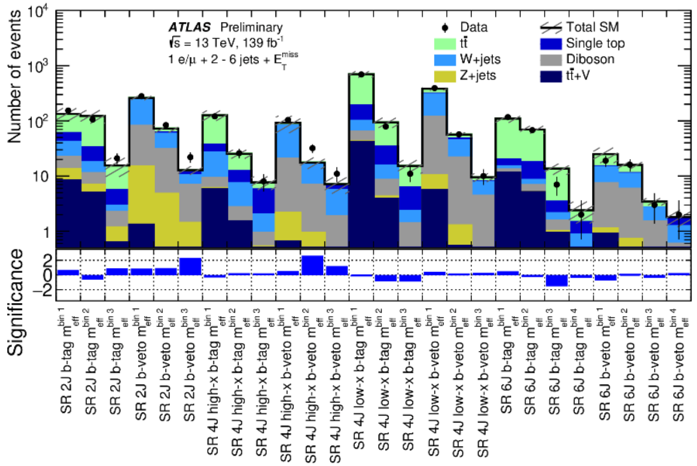
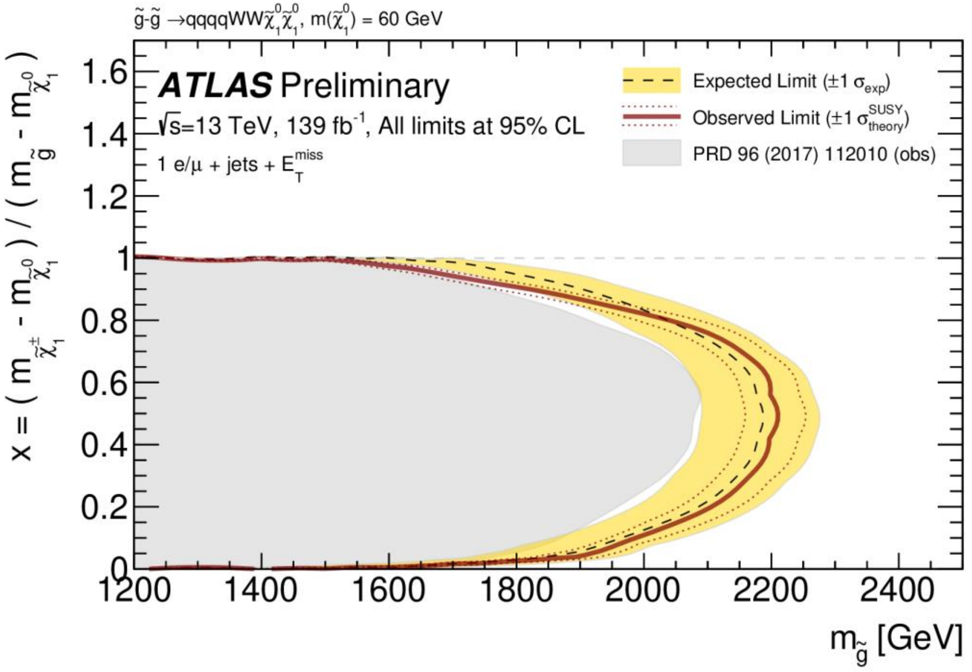
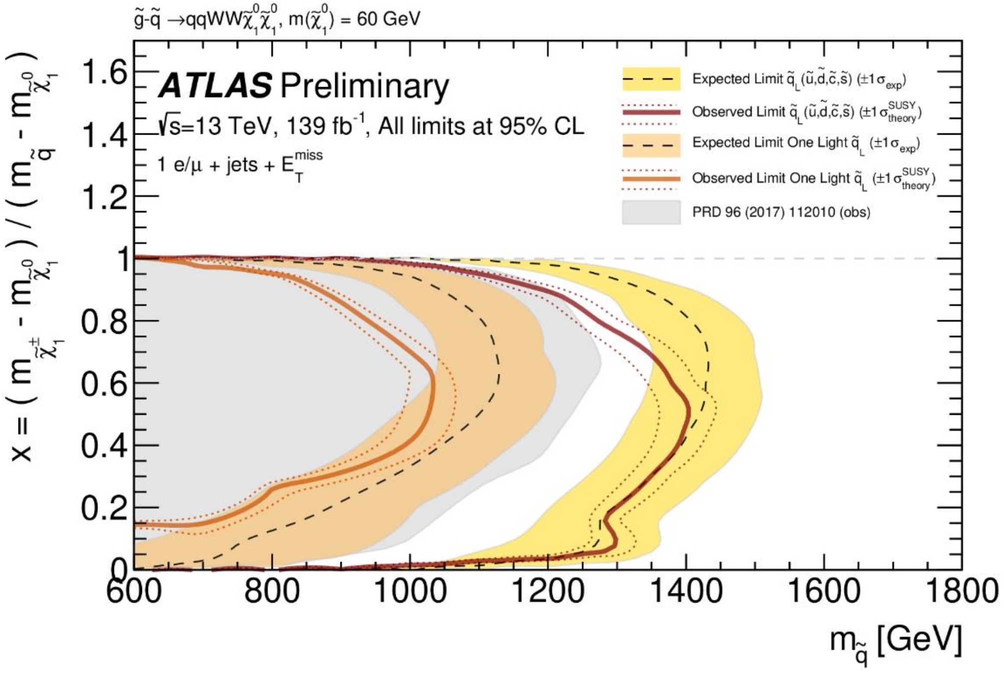
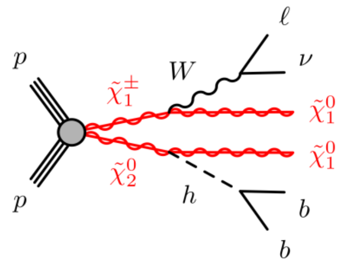




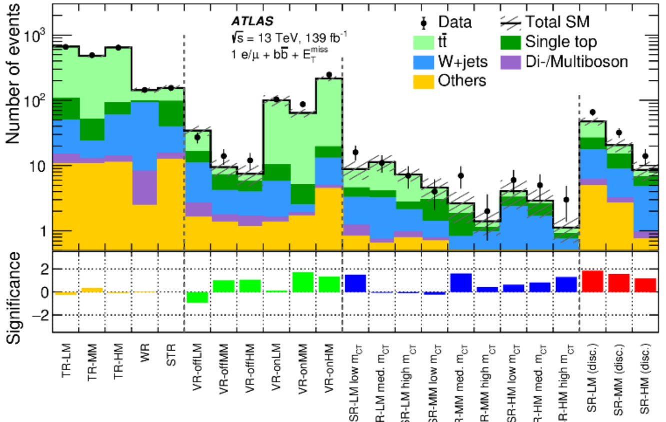


SUSY gaugino production search with one lepton

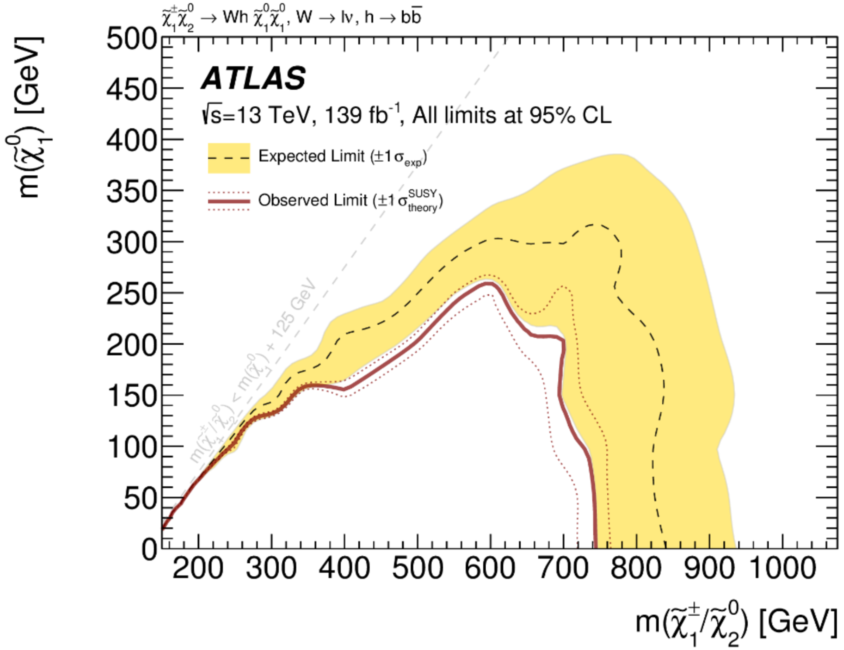
Wh decay channel



- Signal models
  - $\chi_1^{\pm}\chi_1^{\pm}$ and $\chi_1^{\pm}\chi_2^{0}$ production, then decay via W and Higgs boson
  - Signature: 1 lepton + multiple b-jets + E_T^{miss}



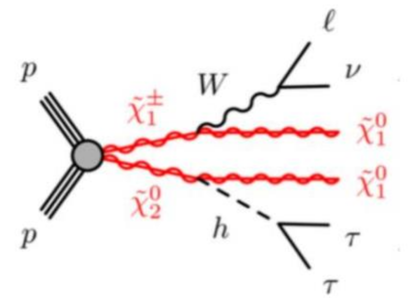
- Analysis Strategy
  - Multi-Bin signal regions to get the best sensitivity for different mass split regions
  - W, Top normalized in dedicated control region. Bkgs validated at validation regions



- No discovery. The $\chi_1^{\pm}/\chi_2^{0}$ mass < 740 GeV are excluded for a low χ_1^{0} mass
- Results published at Eur. Phys. J. C 80 (2020) 691

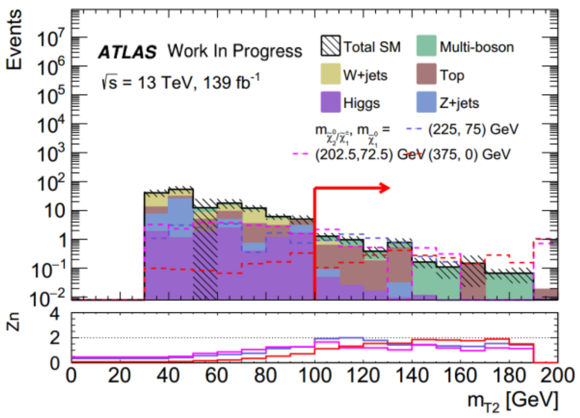
SUSY gaugino production search with one lepton and di-tau

Wh decay channel

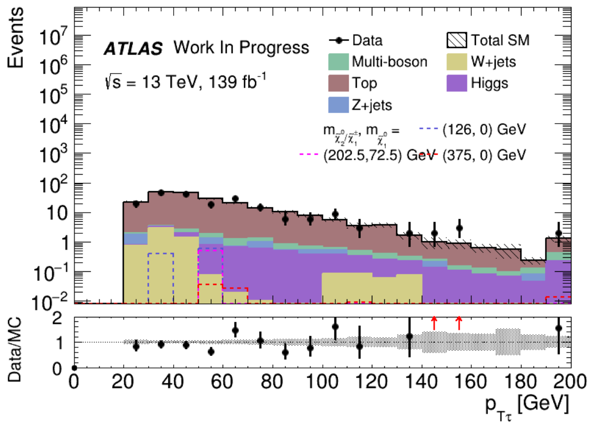


- Signal models
  - $\chi_1^{\pm}\chi_2^0$ production, then decay via W and Higgs boson
  - Signature: 1 lepton + exactly 2 taus + low jet activity + E_T^{miss}
- Analysis Strategy
  - Two signal regions aiming for different mass differences between $\chi_1^{\pm}/\chi_2^0$ and $\tilde{\chi}_1^0$
  - MultiBoson and Top normalized in dedicated control region and validated at validation regions
  - Fake backgrounds estimated using Fake Factor method

SRLowMass	SRHighMass
1 baseline light lepton passing the signal lepton requirements	
>= 2 medium taus (OS)	
b-jet veto	
$\lvert\Delta\phi(\tau_1,\tau_2)\rvert < 3$	
$m_{T2} > 100 GeV$	$m_{T2} > 80 GeV$
$90 GeV < m(\tau_1,\tau_2) < 130 GeV$	$80 GeV < m(\tau_1,\tau_2) < 160 GeV$
$p_T(tau_1) > 50 GeV$	$M_{Tsum} > 450 GeV$
	$M_{Tlep} > 80 GeV$
	$\Delta R(\tau_1,\tau_2) < 2.2$



SR-low mT2 N-1 distribution

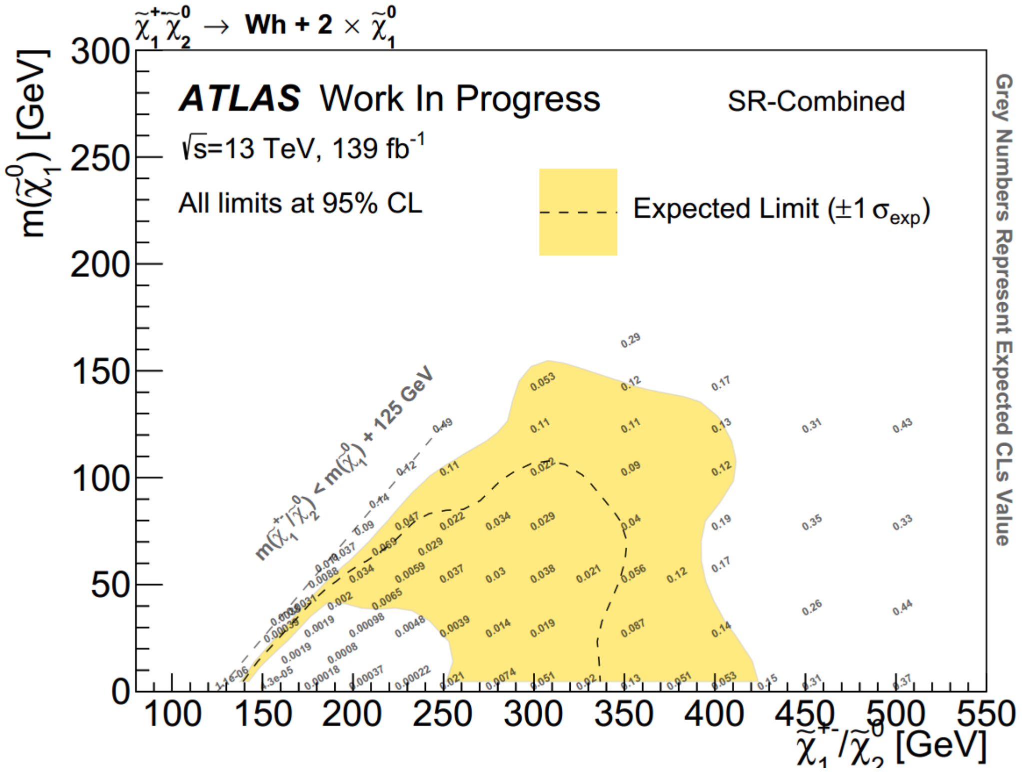


TCR-high tau1Pt distribution

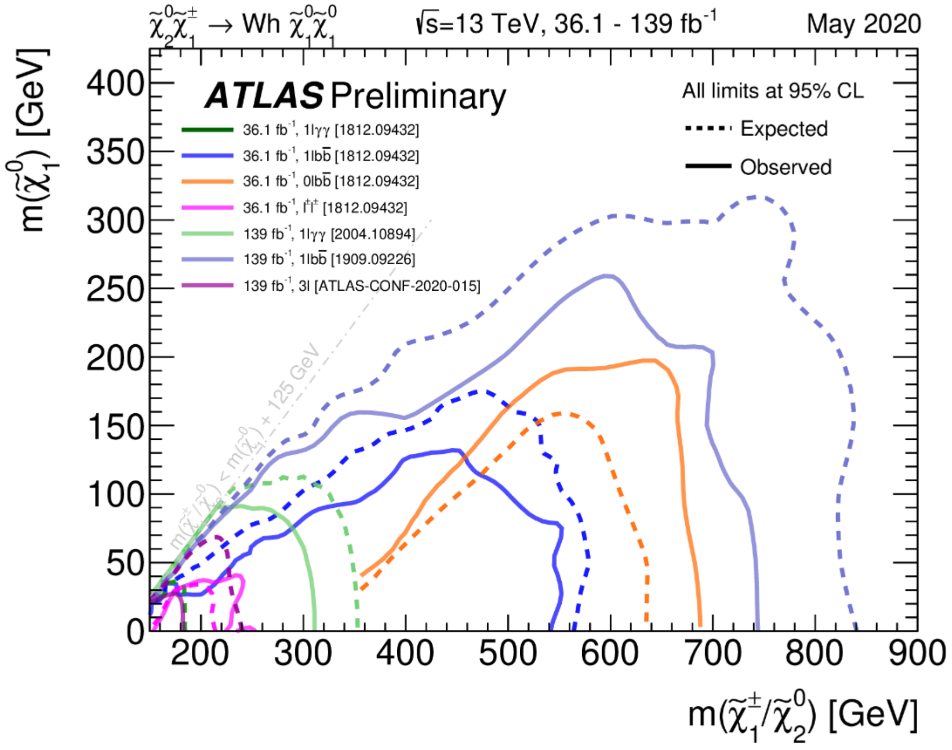
SUSY gaugino production search with one lepton (and di-tau)

Wh decay channel

- Fit results still blinded
- The $\chi_1^{\pm}/\chi_2^0$ mass < 340 GeV are excluded for a low χ_1^0 mass
- Signal region orthogonal with other study. Could improve the exclusion power by the combinations
- Will go to EB request and FAR approval soon



SR Combined expected exclusion limit

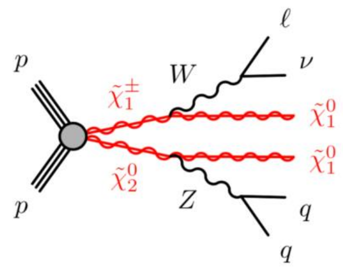


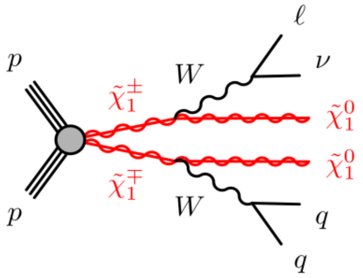
Summary of the $\chi_1^{\pm}\chi_2^0$ production Wh decay channel published results

SUSY gaugino production search with one lepton

WW and WZ decay channel

- Signal models
  - $\chi_1^{\pm}\chi_1^{\pm}$ and $\chi_1^{\pm}\chi_2^{0}$ production, then various decay with1 lepton
  - Signature: 1 lepton + multiple (b)jets + E_T^{miss}

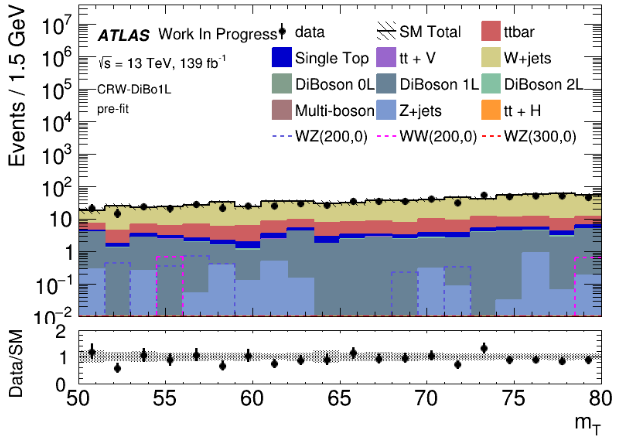




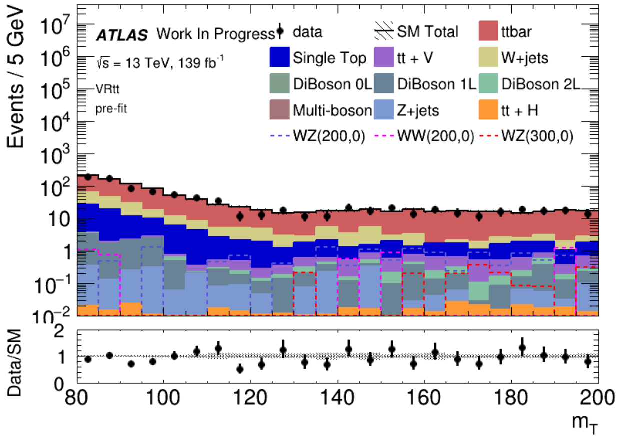
- Analysis Strategy
  - Multi-Bin signal regions using different NlargeRJet and mT to cover different mass regions
  - W, Diboson-1L and Top normalized in dedicated control region and validated at validation regions

Variable	Cuts				
	SRLM resolved	SRHM resolved	SRLM boosted	SRMM boosted	SRHM boosted
N_{lep}	1		1		
p_T^{ℓ}[GeV]	> 25		> 25		
N_{jet} (p_T^{jets}> 30 GeV)	2 - 3		≤ 3		
N_{b-jet} (p_T^{jets}> 30 GeV)	0		0		
E_T^{miss} [GeV]	> 200		> 200		
$\Delta\phi(\ell, E_T^{miss})$	< 2.8		< 2.9		
m_{jj}[GeV]	70 - 105		-		
$N_{large-Rjets}$	0		≥ 1		
W-tagged large-R jet	-		yes		
$p_T^{large-Rjet}$[GeV]	-		> 300		
E_T^{miss} significance	-		> 14		
m_T[GeV]	200 - 380	> 380	120 - 240	240 - 360	> 360

Signal regions for C1C1 -> WW analysis



W-Diboson1L CR resolved mT distribution

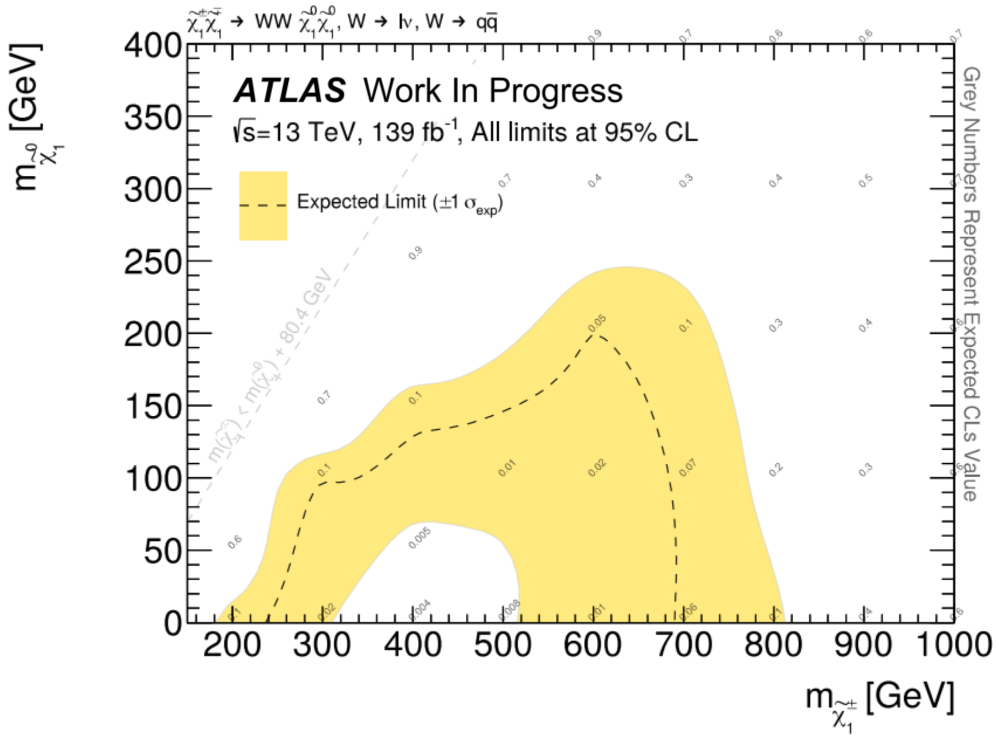


TTbar VR resolved mjj distribution

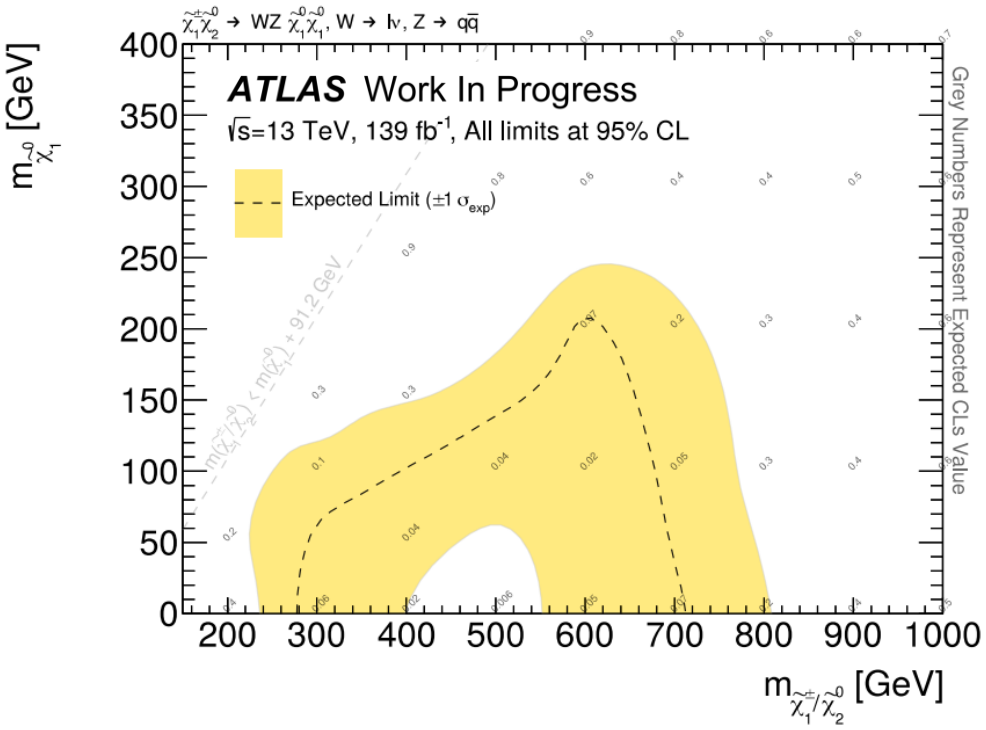
SUSY gaugino production search with one lepton

WW and WZ decay channel

- Fit results still blinded and currently C1C1->WW and C1N2->WZ results comes out
- The $\chi_1^{\pm}/\chi_2^0$ mass < 690(700) GeV are excluded for a low χ_1^0 mass for C1C1(C1N2) signal models
- Will go to EB request and FAR approval soon



C1C1 Combined expected exclusion limit



C1N2 Combined expected exclusion limit

Summary

- A short overview on the latest SUSY searches status with the ATLAS detector on di-tau or(and) one lepton final states
- SUSY Direct Stau production search with di-tau
  - For the combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$ production ($\tilde{\tau}_L$ production only), the masses from 120(160) GeV to 390(300) GeV are excluded for a massless LSP
- SUSY strong production search with one lepton
  - The gluino(squark) mass < 2.2(1.4) TeV are excluded for a low neutralino mass
- SUSY gaugino production search with one lepton (and di-tau)
  - $\chi_1^{\pm}\chi_2^0$ production Wh decay, 1lbb channel: The $\chi_1^{\pm}/\chi_2^0$ mass < 740 GeV are excluded for a low χ_1^0 mass
  - $\chi_1^{\pm}\chi_2^0$ production Wh decay, 1l$\tau\tau$ channel: The $\chi_1^{\pm}/\chi_2^0$ mass < 340 GeV are excluded for a low χ_1^0 mass
  - $\chi_1^{\pm}\chi_1^{\pm}$, $\chi_1^{\pm}\chi_2^0$ production, 1 lepton final states: $\chi_1^{\pm}/\chi_2^0$ mass < 690(700) GeV are excluded for a low χ_1^0 mass for C1C1(C1N2)
- The ongoing analysis are expected to be approved and go un-blinding soon. So stay tuned!
- Want to see more results? Look at ATLAS SUSY Public Results!

Backup

SUSY Direct Stau production search with di-tau: SR definition

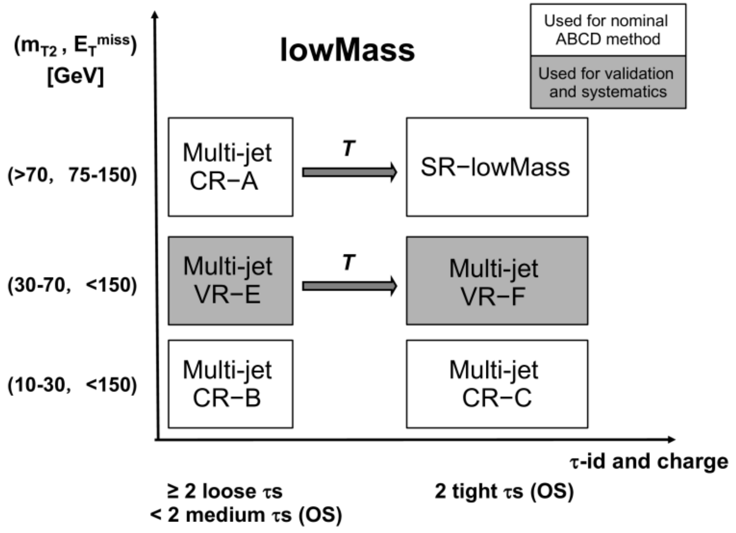
- Two SRs separated by MET to cover the different signal models

SR-lowMass	SR-highMass
2 tight τ (OS)	2 medium τ (OS) , $\geq$ 1 tight τ
asymmetric di-τ trigger	di-τ+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
τ p_{T} cut described in Section 5	
light lepton veto and 3rd medium τ veto	
b-jet veto	
Z/H veto ($m(\tau_1, \tau_2) > 120$ GeV)	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 0.8$	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$m_{\mathrm{T2}} > 70$ GeV	

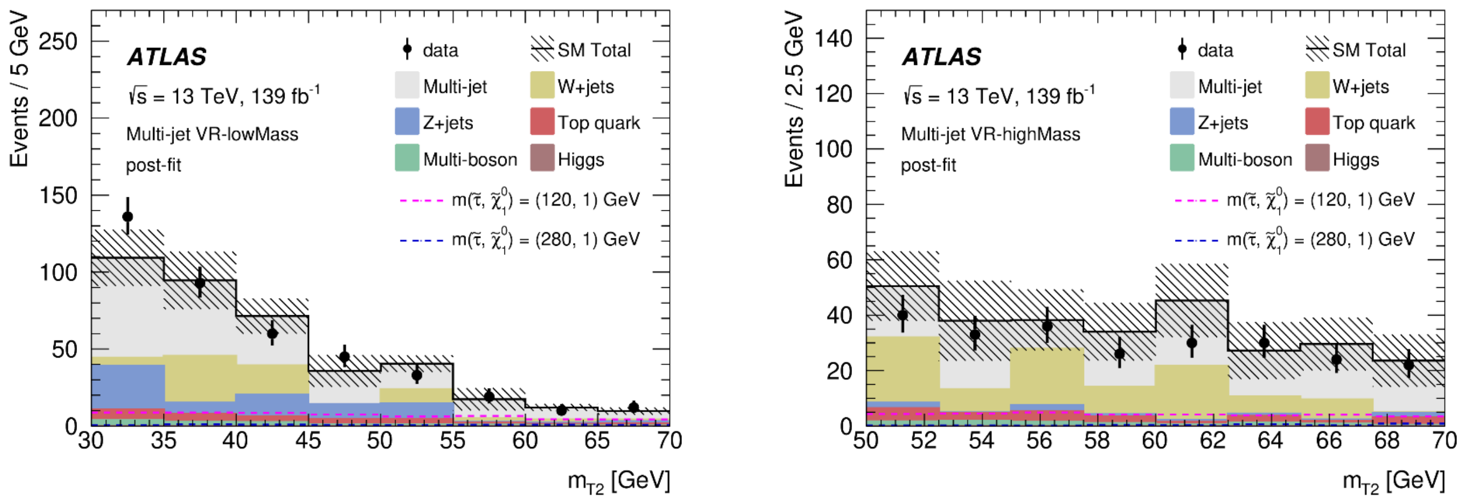
SUSY Direct Stau production search with di-tau: Multi-jet estimation

ABCD Method

- Four exclusive regions, labelled as A, B, C, and D are defined in a two-dimensional plane as a function of two (or more) uncorrelated discriminating variables.
- Multi-jet in SR_D: $N_D = N_A \times TF$ while $TF = N_C/N_B$.
- Two sets of validation regions (VR), are defined to verify the extrapolation of the ABCD estimation to the SRs and estimate the systematic uncertainty.



The ABCD strategy in SRlow



The m_{T2} distributions in the VR-F lowmass(left) and VR-F highmass (right) regions

SUSY Direct Stau production search with di-tau: Yields table and model independent upper limit

- Dominant contribution in SR: multijet, diboson, W+jets.
- In both signal regions, observations and background predictions are found to be compatible within uncertainties.

SM process	Multi-jet CR-A -lowMass	Multi-jet CR-A -highMass	W CR	SR -lowMass	SR -highMass
Diboson	1.4 ± 0.6	1.9 ± 1.0	63 ± 21	1.4 ± 0.8	2.6 ± 1.4
W+jets	13 ± 4	4^{+7}_{-4}	850 ± 70	1.5 ± 0.7	2.5 ± 1.8
Top quark	2.7 ± 0.9	3.3 ± 1.6	170 ± 40	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.6
Z+jets	$0.25^{+1.43}_{-0.25}$	1.5 ± 0.8	13 ± 7	$0.4^{+0.5}_{-0.4}$	$0.05^{+0.13}_{-0.05}$
Multi-jet	55 ± 10	16 ± 6	–	2.6 ± 0.7	3.1 ± 1.4
SM total	72 ± 8	27 ± 5	1099 ± 33	6.0 ± 1.7	10.2 ± 3.3
Observed	72	27	1099	10	7

Background only fit yields table

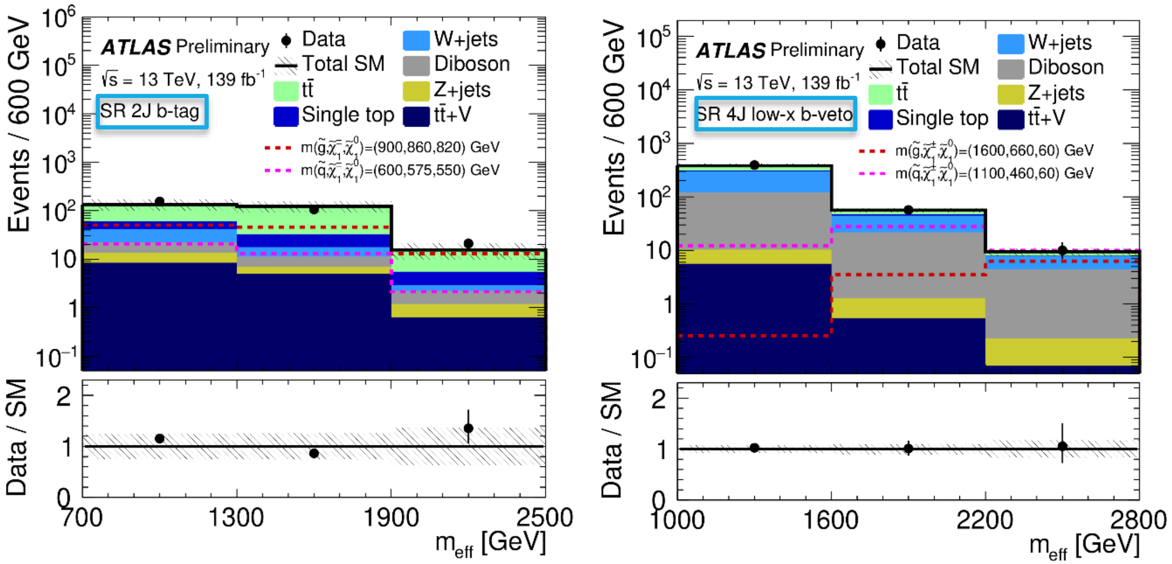
	SR-lowMass	SR-highMass
$m\ (\tilde{\tau},\tilde{\chi}_1^0) = (120,\ 1)$ GeV	9.8 ± 3.0	7.2 ± 2.2
$m\ (\tilde{\tau},\tilde{\chi}_1^0) = (280,\ 1)$ GeV	6.1 ± 1.5	14.4 ± 2.5
p_0	0.11	0.50
Expected σ_{vis}^{95} [fb]	$0.055^{+0.025}_{-0.014}$	$0.065^{+0.025}_{-0.019}$
Observed σ_{vis}^{95} [fb]	0.08	0.05

Upper limits on the visible non-SM cross section

SUSY strong production search with one lepton

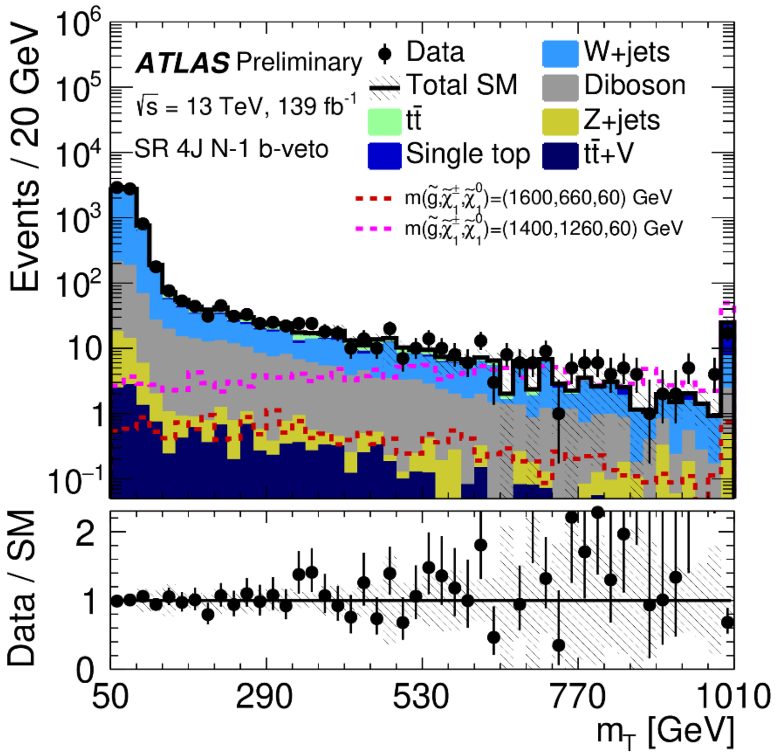
- Detailed study has been perform in order to cover different mass regions
  - 2J regions targets compressed SUSY signals
  - 4J high/low x regions target at grid-x mass regions with high/low x
  - 6J regions targets high gluino/squark and low LSP masses
- E_T^{miss} trigger and large E_T^{miss} to reject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

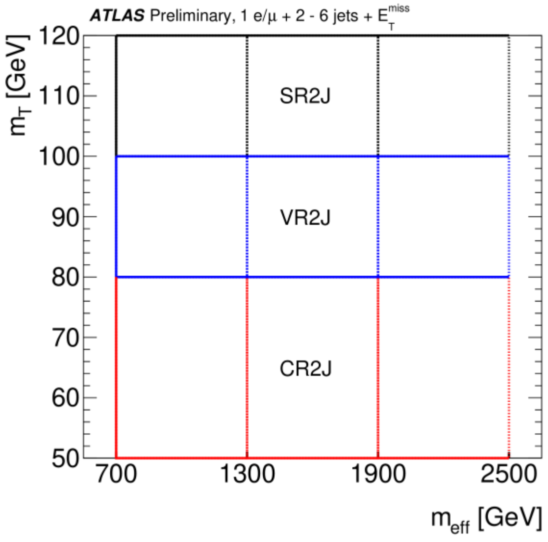


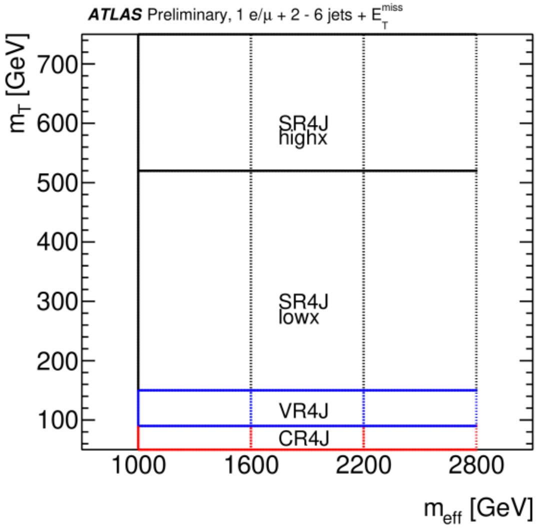
SUSY strong production search with one lepton

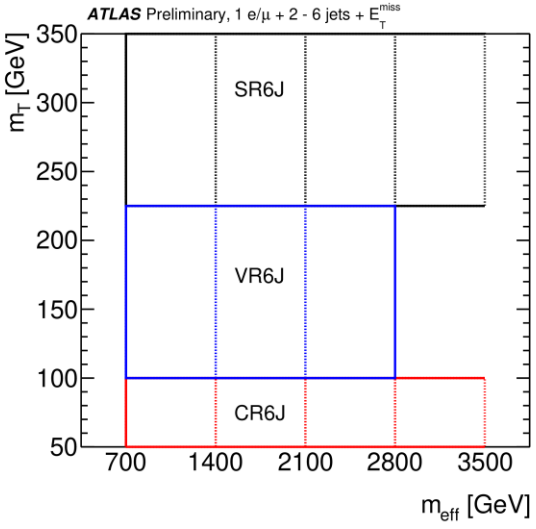
- Main backgrounds are ttbar/Single-top and W+jets
- Define dedicate control and validation regions for them and estimate other small backgrounds using MC
- The variable of the m_T is used to extrapolate from control region to signal region and validated in validation region. Top regions and W+jets regions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



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







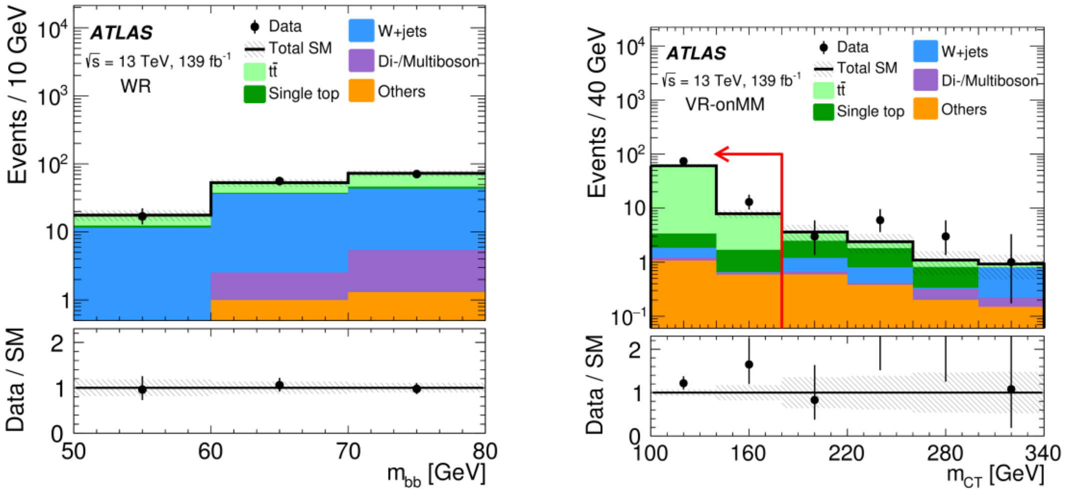
SUSY gaugino production search with one lepton: Region definitions

- Detailed signal regions has been defined in order to cover different mass regions
- E_T^{miss} trigger and large E_T^{miss} to reject multi-jet backgrounds
- Likelihood is calculated with multiple bin fit with variable m_T and m_{CT}

	SR-LM	SR-MM	SR-HM
N_{lepton}		$= 1$	
p_T^{ℓ} [GeV]		$> 7(6)$ for $e(\mu)$	
N_{jet}		$= 2$ or 3	
$N_{b\text{-jet}}$		$= 2$	
E_T^{miss} [GeV]		> 240	
$m_{b\bar{b}}$ [GeV]		$\in [100, 140]$	
$m(\ell, b_1)$ [GeV]	–	–	> 120
m_T [GeV] (excl.)	$\in [100, 160]$	$\in [160, 240]$	> 240
m_{CT} [GeV] (excl.)		$\{\in [180, 230], \in [230, 280], > 280\}$	
m_T [GeV] (disc.)	> 100	> 160	> 240
m_{CT} [GeV] (disc.)		> 180	

- Main backgrounds are W and Top. Define dedicate control regions for them and validate in VRs

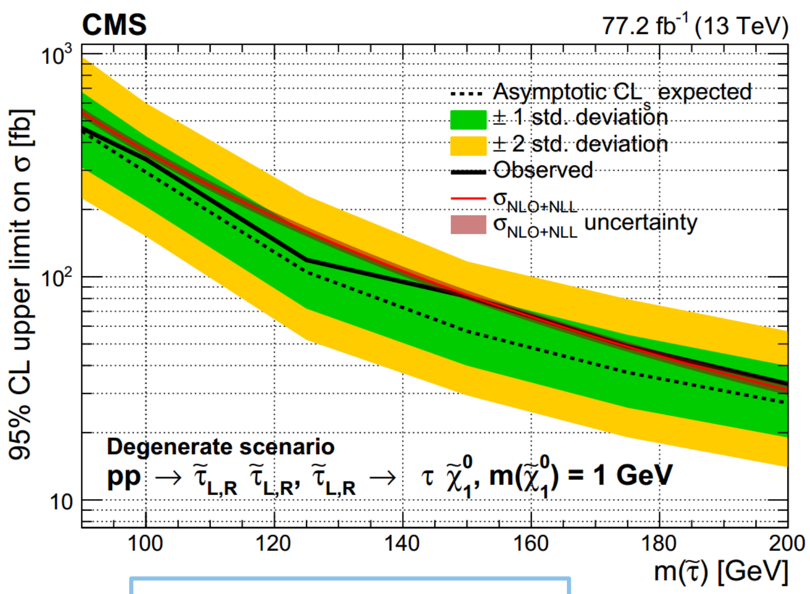
CR	TR-LM	TR-MM	TR-HM	WR	STR	
$m_{b\bar{b}}$ [GeV]		<100 or >140		$\in [50, 80]$	>195	
m_T [GeV]	$\in [100, 160]$	$\in [160, 240]$	>240	$\in [50, 100]$	>100	
m_{CT} [GeV]		<180		>180	>180	
VR	**VR-onLM**	**VR-onMM**	**VR-onHM**	**VR-offLM**	**VR-offMM**	**VR-offHM**
$m_{b\bar{b}}$ [GeV]		$\in [100, 140]$		$\in [50, 80] \cup [160, 195]$	$\in [50, 80] \cup [160, 195]$	$\in [50, 75] \cup [165, 195]$
m_T [GeV]	$\in [100, 160]$	$\in [160, 240]$	>240	$\in [100, 160]$	$\in [160, 240]$	>240
m_{CT} [GeV]		<180			>180	



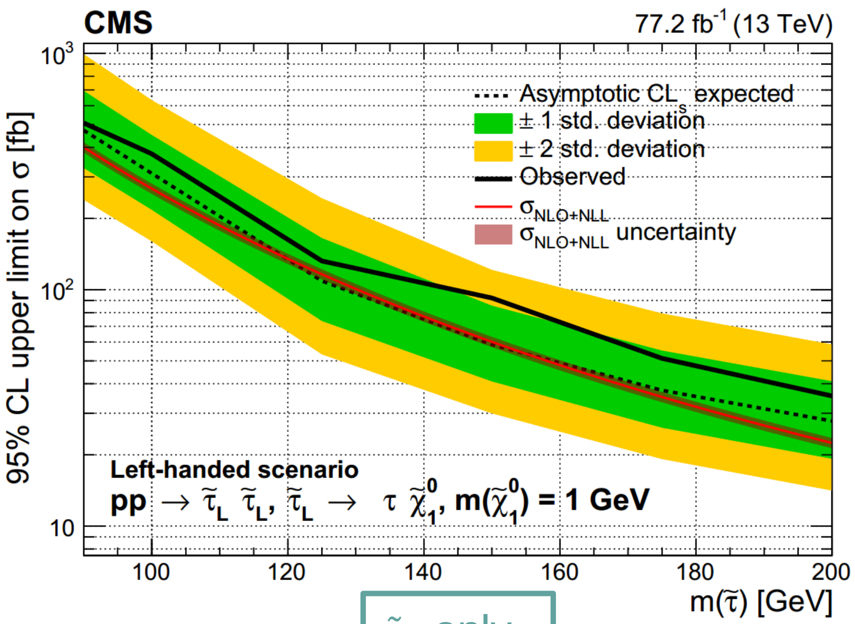
Variable distributions in WCR and VR-onMM

SUSY Direct Stau production search with di-tau: CMS results

- Results using the 2016+2017 data
  - No excess above the expected standard model background has been observed.
  - For the combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$ production, the masses from 90 GeV to 150 GeV are excluded for a massless LSP.
  - No exclusion for $\tilde{\tau}_L$ production.
- Main differences Eur. Phys. J. C 80 (2020) 189
  - CMS use the 2016+2017 data while ATLAS use full run-2 data.
  - CMS combined the Lep-Had channel and Had-Had channel while ATLAS used only the Had-Had channel.
  - Detector performance, trigger, optimization method and etc…



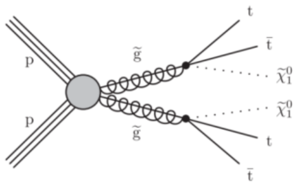
Combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$

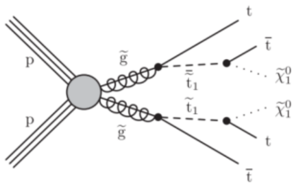


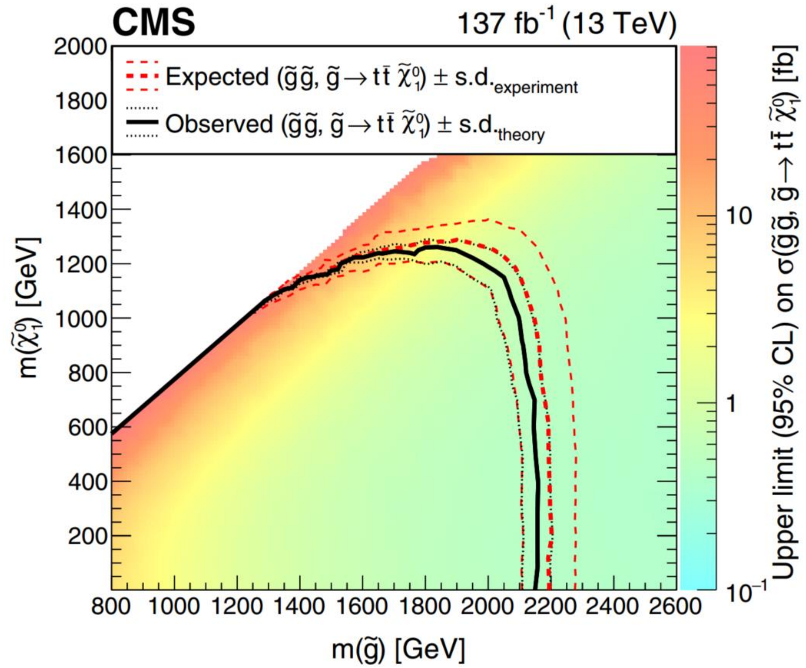
$\tilde{\tau}_L$ only

SUSY strong production search with one lepton: CMS results

- Results using the full Run-2 data ($137\ fb^{-1}$)
  - No excess above the expected standard model background has been observed.
  - The gluino mass < 2.2 TeV are excluded for a low neutralino mass







- Main differences
  - CMS use different models while the gluino will decay to tops
  - MultiBin fit approach with Njets, Nbjets, MET and M_J, while ATLAS use Njets and meff
  - Detector performance, trigger, optimization method and etc…

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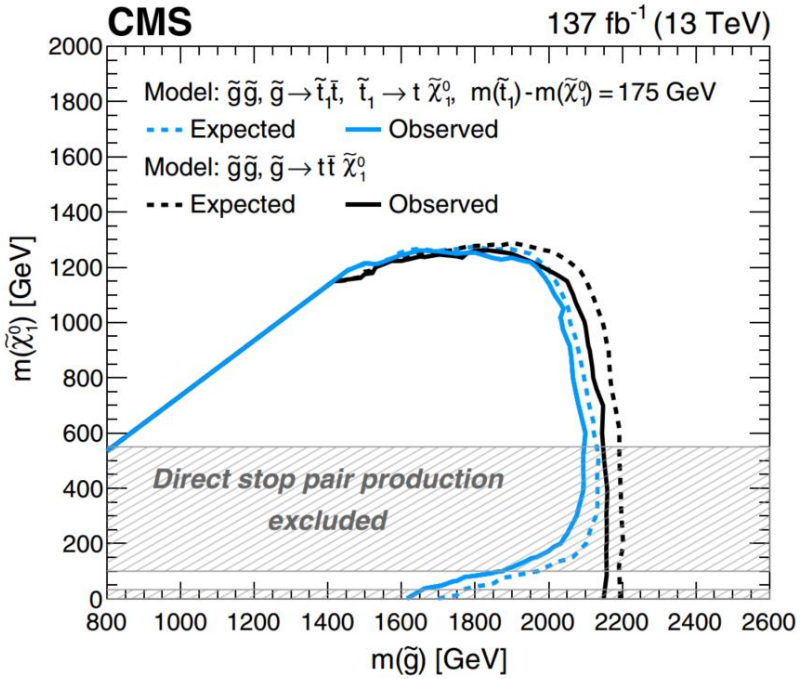
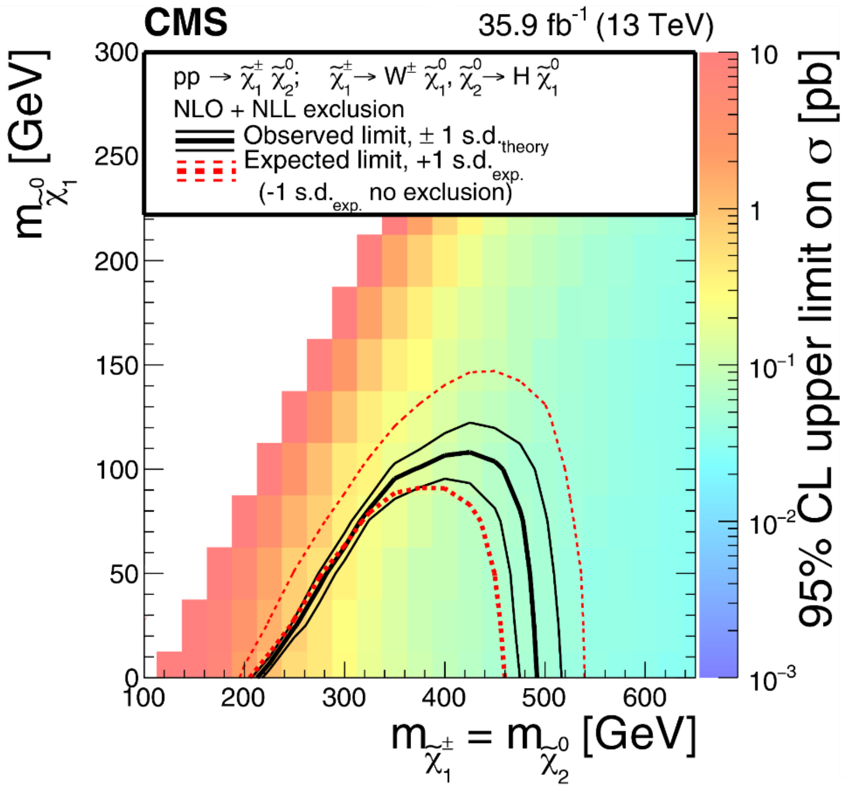


SUSY gaugino production search with one lepton: CMS results

- Results using the 2016 Run-2 data (35.9 fb^{-1})
  - No excess above the expected standard model background has been observed.
  - The $\chi_1^{\pm}/\chi_2^0$ mass < 490 GeV are excluded for a low χ_1^0 mass



- Main differences

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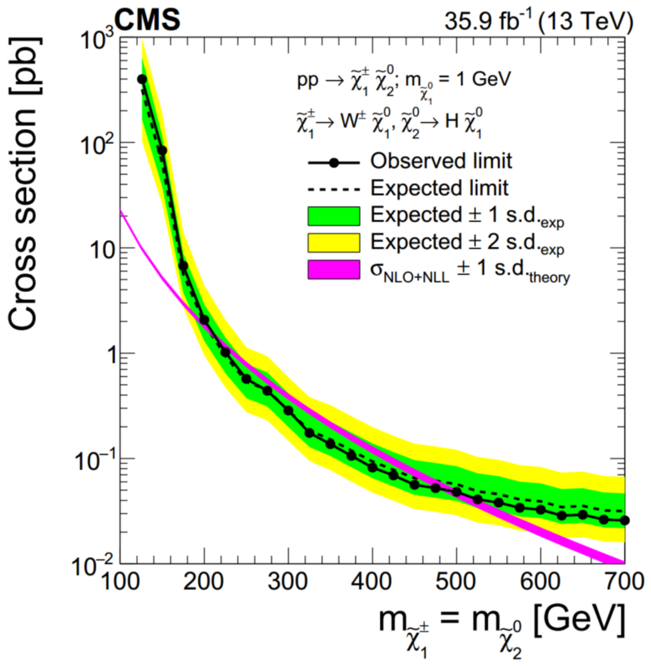
  - CMS use the 2016+2017 data while ATLAS use full run-2 data
  - Two signal regions separated by MET. While ATLAS use Multi-Bin fit using m_T and m_{CT}
  - Detector performance, trigger, optimization method and etc…



Variables Definition

- the "stransverse mass", m_{T2}, which 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 (the lepton in our case) and the other escapes undetected (the neutralino) [16, 17]. It is defined as:

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

  where $\mathbf{p}_{T,\tau 1}$ and $\mathbf{p}_{T,\tau 2}$ are the transverse momenta of the two taus, and $\mathbf{q}_T$ is the transverse vector that minimises the larger of the two transverse masses $m_{T,\tau 1}$ and $m_{T,\tau 2}$. The latter is defined by

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}.$$

  In events with more than two taus, m_{T2} is calculated using all possible tau pairs and the largest value is chosen (the reason for this choice can be found in Section H.4);

- $m_{T\tau 1} + m_{T\tau 2}$, the sum of the transverse mass values of the leading and next-to-leading taus;

- m_{eff}, the scalar sum of the missing transverse energy (E_T^{miss}) and the transverse momenta of the leading and next-to-leading taus;

- $\Delta R(\tau, \tau)$, the cone size between the leading and next-to-leading tau. An upper cut on this variable is powerful to discriminate against back-to-back events such as di-jets or Z decays.