Direct stau search at LHC

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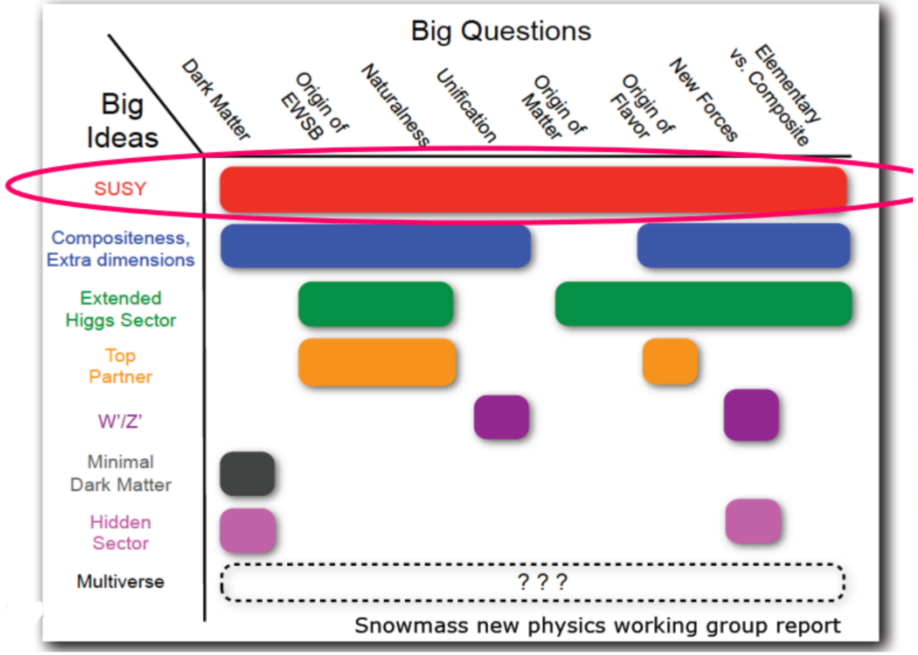
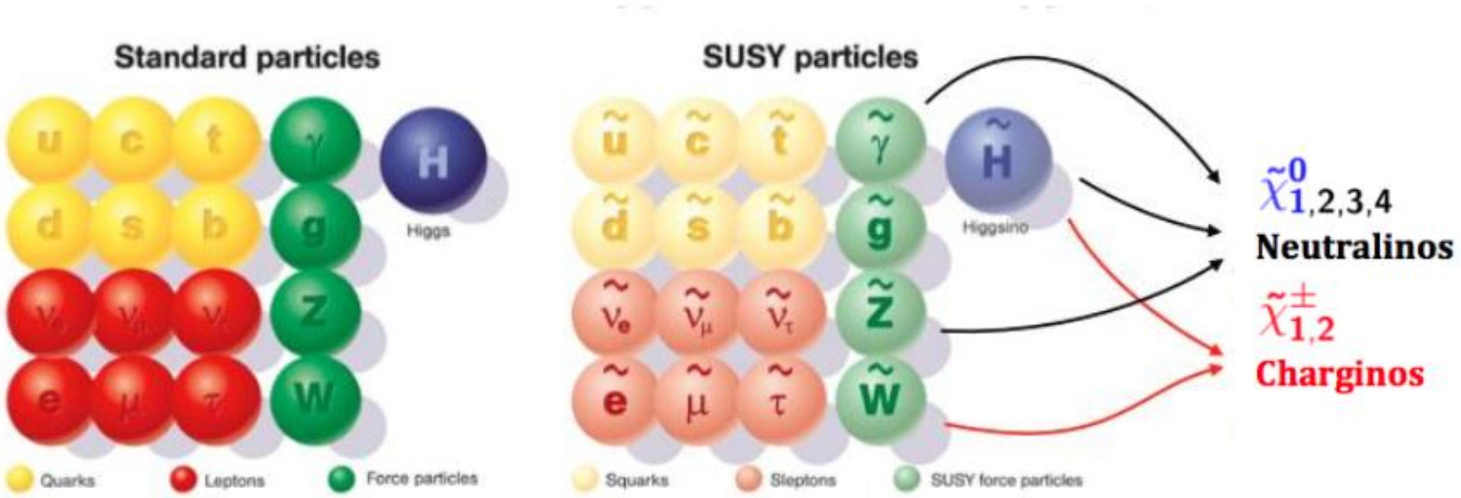
Introduction

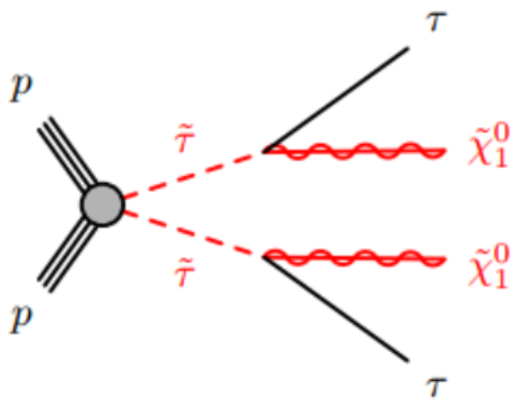




- Supersymmetry: one of the most appealing BSM theories
  - Solve problems such as hierarchy problem, grand unification of gauge couplings, dark matter…
- If SUSY is at TeV scale, it will be produced copiously at LHC.
- SUSY search is one of the most hot topics at LHC and beyond.

Analysis Overview

- **Motivation**
  - Models with light staus can lead to a dark-matter relic density consistent with cosmological observations.
  - In some scenarios, the direct production of sleptons may dominate at the LHC with respect to the production of squarks and gluinos.



- **Signature**
  - Events with two taus, low jet activity and MET.

- **Goal:**
  – Study the sensitivity of direct stau production using 13TeV pp collision data recorded by ATLAS Detector from 2015-2018 with integrated luminosity of 139 fb^{-1}.

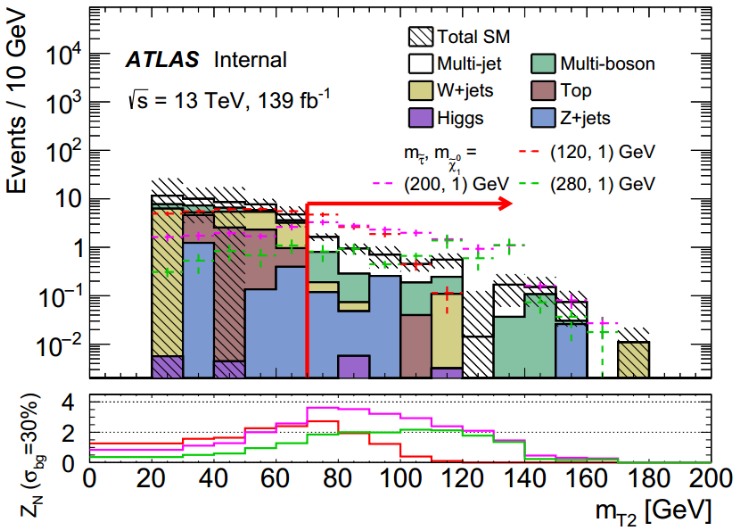
Signal region Optimization

- Method: **Cut and Count** method for each benchmark point based on **Zn**
  - $Z_n = \sqrt{2}\,\mathrm{erf}^{-1}(1-2p)$ where $p \propto \int_0^\infty db\, G(b; N_b, \delta b) \sum_{i=N_{s+b}}^{\infty} \frac{e^{-b} b^i}{i!}$

- Two SRs are designed to improve the sensitivity of signal models with for different mass difference between the $\tilde{\tau}$ and $\tilde{\chi}_1^0$.

SR-lowMass	SR-highMass
2 tight τs (OS)	2 medium τs (OS) , ≥ 1 tight τ
asymmetric di-tau trigger	di-tau+E_T^{miss} trigger
$75 < E_T^{miss} < 150$ GeV	$E_T^{miss} > 150$ GeV
tau p_T and E_T^{miss} cuts 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)	
$\lvert\Delta\phi(\tau_1,\tau_2)\rvert > 0.8$	
$\Delta R(\tau_1,\tau_2) < 3.2$	
$m_{T2} > 70$ GeV	

Summary of selection requirements for the signal regions



The m_{T2} distribution in the SR-lowMass for each background and signal benchmark points

Background estimation strategy

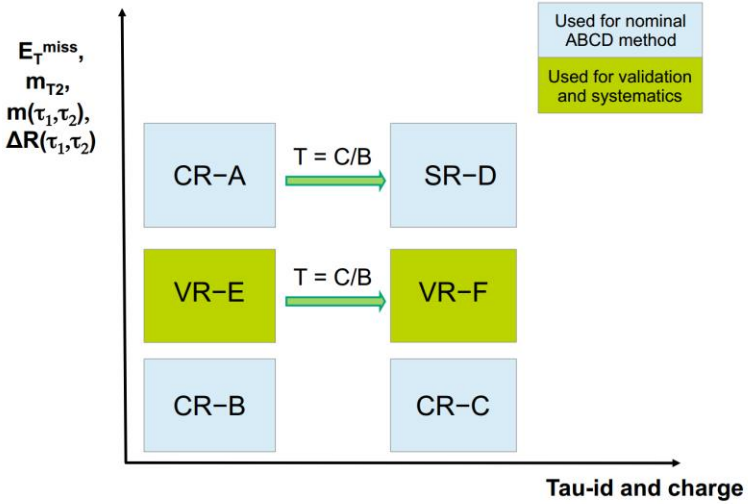
- Reducible backgrounds: (>= 1 fake tau)
  - **Multi-jet background** (>=2 fake taus): Data-driven ABCD method as baseline. Fake factor as crosscheck.
  - **W+jets** (1 real tau; 1 fake tau): Dedicated control region (W-CR). Use tau promotion method to improve statistics in SR.
  - Normalize MC to data in control regions using combined fit.

- Irreducible background estimation
  - mainly from **Top**($t\bar{t}$, single top quark and $t\bar{t}$+V**)**, **Z+jets**, and **Multi-boson** (diboson and triboson)
  - Estimated based on MC simulation.
  - Use dedicated validation regions to validate the MC predictions.

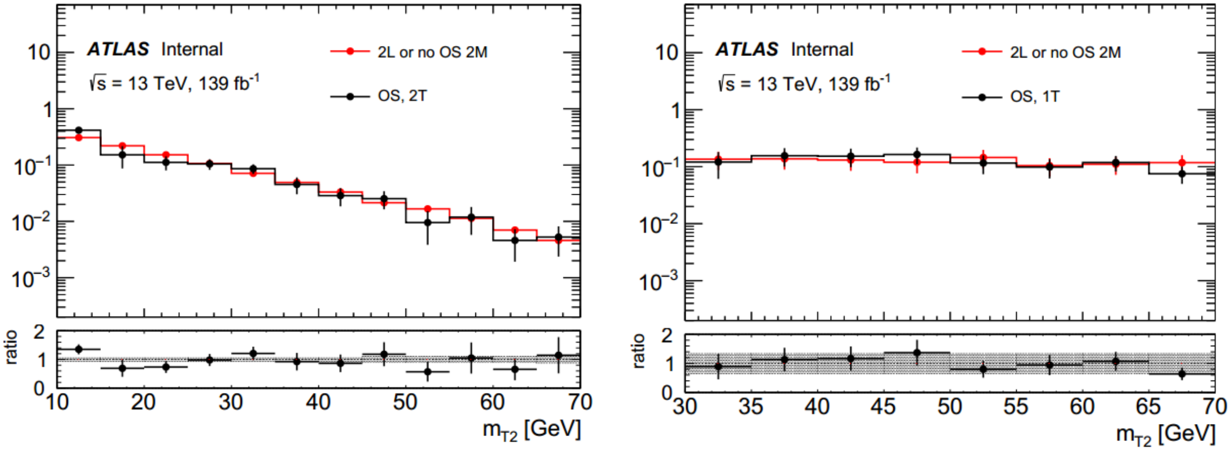
Multi-jet estimation

ABCD Method

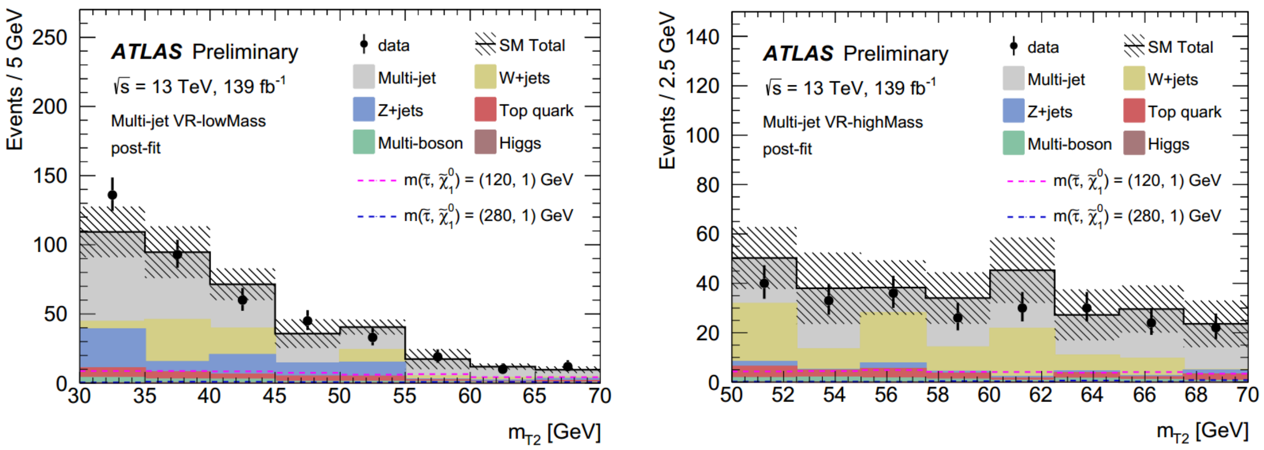
- Four exclusive regions, labelled as A, B, C, and D are defined in a two-dimensional plane as a function of two (or more) uncorrelated discriminating variables.
- Multi-jet in SR_D: $N_D = N_A \times TF$ while $TF = N_C/N_B$.
- Two sets of validation regions (VR), are defined to verify the extrapolation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



• Also used another method: Fake factor method as another method/cross check.



The m_{T2} correlation check for ABCD method in the SR-lowmass(left) and SR-highmass(right)



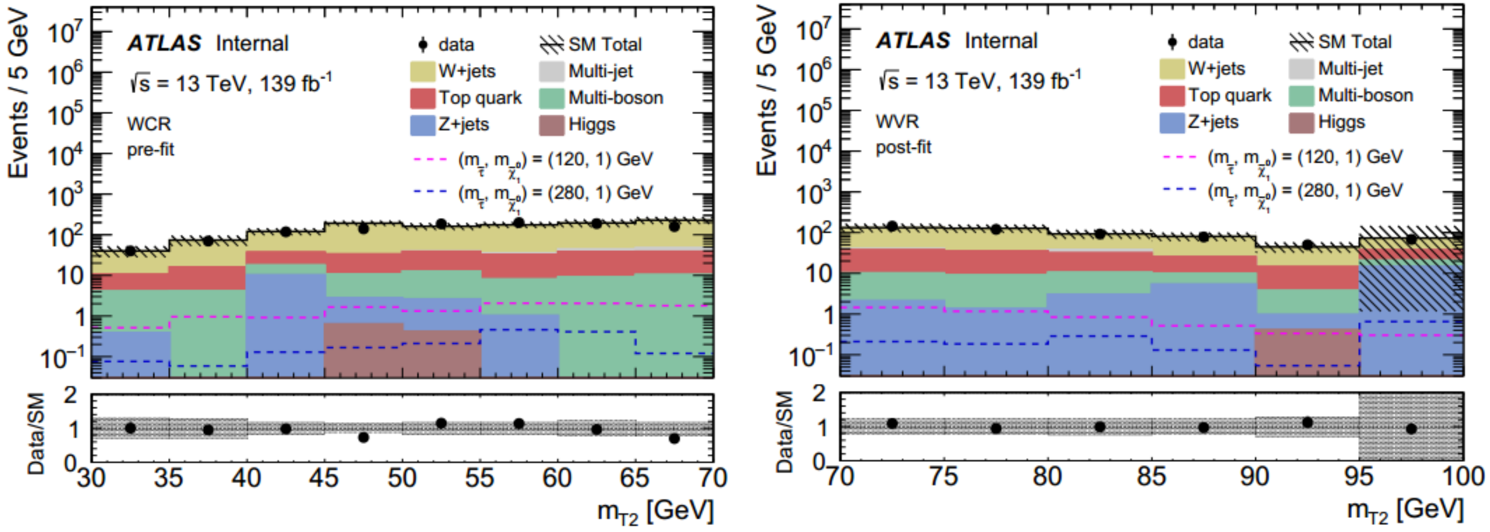
The m_{T2} distributions in the VR-F lowmass(left) and VR-F highmass (right) regions

W+jet estimation

- Derive normalization factor by fitting in W-CR, and apply the NF to W-VR for validation.

- Definition:

W-CR	W-VR
pass TrigHLT_mu20_iloose_L1MU15 (2015) and HLT_mu26_ivarmedium (2016-2018)	
== 1 medium tau and 1 isolated muon (OS)	
$p_{T\tau} > 60$ GeV, $p_{T\mu} > 50$ GeV	
$50 < m_T(\mu) < 150$ GeV	
$m(\mu, \tau) > 70$ GeV	
$E_T^{miss} > 60$ GeV	
$m_T(\tau) + m_T(\mu) > 250$ GeV	
$1 < \Delta R(\tau, \mu) < 3.5$	
b-veto	
Top-tagged events veto	
$30 < m_{T2}(\tau, \mu) < 70$ GeV	$m_{T2}(\tau, \mu) > 70$ GeV



The m_{T2} distributions in the W-CR (left) and W-VR (right) regions after applied the NF derived by WCR

- High W+jets purity .

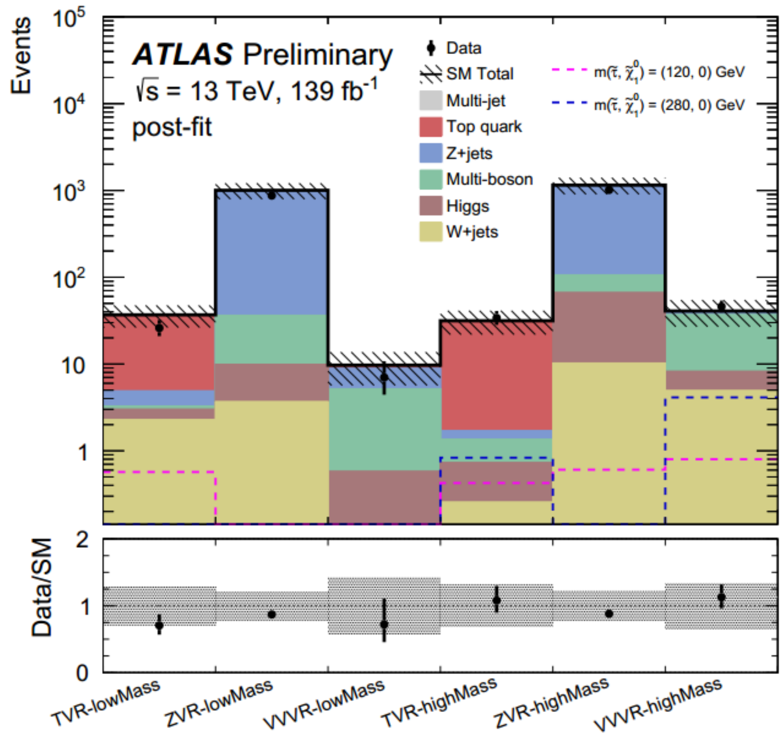
- Reasonable Data/MC agreement.

Irreducible background estimation

- Use Z-VR, Top-VR and multiBoson-VR to validate them.

- Definition:

Selections	TVR -lowMass	ZVR -lowMass	$VVVR$ -lowMass	TVR -highMass	ZVR -highMass	$VVVR$ -highMass
	≥ 2 medium τs (OS), ≥ 1 tight τ					
	≥ 1 b-jet	b-jet veto		≥ 1 b-jet	b-jet veto	
$m(\tau_1, \tau_2)$	–	< 70 GeV	< 110 GeV	–	< 60 GeV	< 110 GeV
$\Delta R(\tau_1, \tau_2)$	> 1.2	< 1	–	> 1.2	< 1	–
$m_{T,\tau_1} + m_{T,\tau_2}$	–	–	> 250 GeV	–	–	> 200 GeV
m_{T2}	> 60 GeV	< 60 GeV	> 60 GeV	> 60 GeV	< 60 GeV	> 60 GeV
Trigger	asymmetric di-tau trigger $60 < E_T^{miss} < 150$ GeV			di-tau+E_T^{miss} trigger $E_T^{miss} > 150$ GeV		
	tau p_T and E_T^{miss} cuts described in Section 5					



The event yields in each validation regions

- High background purity in their validation region.

- Agreement between data and SM predictions is observed.

Systematic uncertainties

- **Experimental uncertainties** implemented following CP recommendations:
  - tau lepton and jet energy calibrations and resolution, tau lepton identification, pile-up, uncertainties related to the modelling of E_T^{miss} and so on.
- **Multi-jet estimation uncertainties**:
  - The variable correlation, limited statistics in CRs, subtraction of SM backgrounds.
- **Theoretical uncertainties** for MC samples:
  - Renormalisation and factorisation scale.
  - Value of α_s.
  - PDF uncertainties and alt. PDF uncertainties.

Result: Leading sources of uncertainty in SRs

Dominant uncertainties in the SRs:

- Background:
  - Statistical uncertainty of the MC predictions .
  - tau identification and energy scale.
  - multi-jet background normalization.
- Signal:
  - Tau identification and energy scale.
  - statistical uncertainty of the MC predictions.

Source of systematic uncertainty	SR-lowMass (%)	SR-highMass (%)
Statistical uncertainty of MC samples	11	21
Tau identification and energy scale	19	10
Normalisation uncertainties of the multi-jet background	13	9
Multi-jet estimation	6	11
W+jets theory uncertainty	5	8
Diboson theory uncertainty	5	6
Jet energy scale and resolution	5	8
E_T^{miss} soft-term resolution and scale	2	2
Total	28	33

Source of systematic uncertainty m $(\tilde{\tau}, \tilde{\chi}_1^0)$ GeV	SR-lowMass (%) (120, 1)	SR-highMass (%) (280, 1)
Tau identification and energy scale	29	14
Statistical uncertainty of MC samples	6	10
Signal cross section uncertainty	4	6
Jet energy scale and resolution	3	2
E_T^{miss} soft-term resolution and scale	3	< 1
Total	31	18

Results: 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.

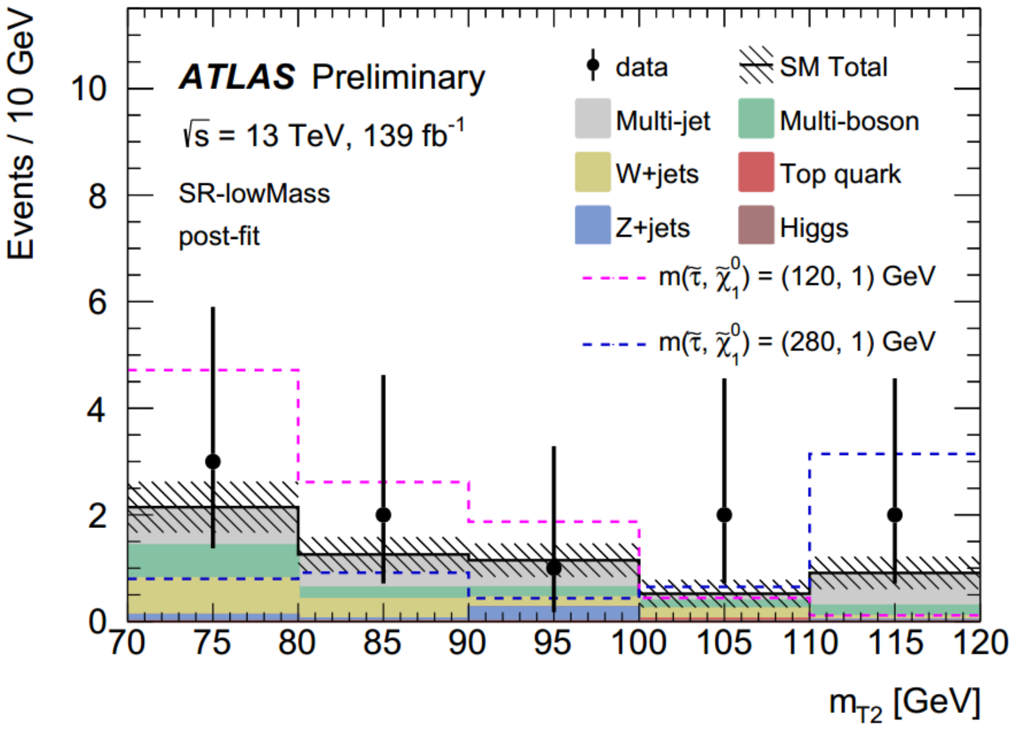
SM process	Multi-jet CR -lowMass	Multi-jet CR -highMass	W-CR	W-VR	SR -lowMass	SR -highMass
Diboson	1.4 ± 0.6	1.9 ± 1.0	63 ± 18	37 ± 11	1.4 ± 0.8	2.6 ± 1.2
W+jets	13 ± 5	4^{+7}_{-4}	850 ± 70	370 ± 120	1.5 ± 0.7	2.5 ± 1.9
Top quark	2.7 ± 0.9	3.3 ± 1.6	170 ± 40	114 ± 31	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.5
Z+jets	$0.3^{+1.4}_{-0.3}$	1.5 ± 0.7	13 ± 7	27 ± 20	$0.4^{+0.5}_{-0.4}$	$0.04^{+0.13}_{-0.04}$
Higgs	$0.01^{+0.33}_{-0.01}$	0.01 ± 0.01	$1.1^{+1.8}_{-1.1}$	$0.5^{+1.0}_{-0.5}$	$0.01^{+0.02}_{-0.01}$	–
Multi-jet	55 ± 10	16 ± 7	3.1 ± 3.1	–	2.6 ± 0.7	3.1 ± 1.5
SM total	72 ± 8	27 ± 5	1099 ± 33	540 ± 130	6.0 ± 1.7	10.2 ± 3.3
Observed	72	27	1099	552	10	7

Background only fit yields table

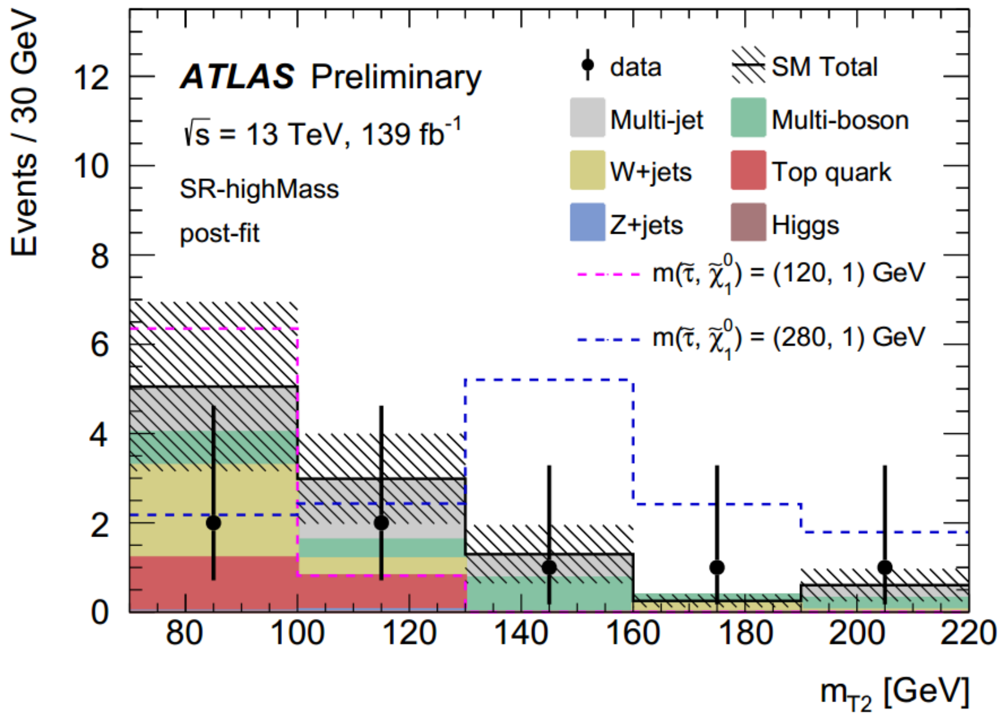
	SR-lowMass	SR-highMass
$m\,(\tilde{\tau},\tilde{\chi}_1^0) = (120, 1)$ GeV	9.8 ± 3.1	7.2 ± 2.2
$m\,(\tilde{\tau},\tilde{\chi}_1^0) = (280, 1)$ GeV	5.9 ± 1.5	14.0 ± 2.5
p_0	0.11	0.50
Expected σ_{vis}^{95} [fb]	$0.055^{+0.025}_{-0.014}$	$0.065^{+0.025}_{-0.019}$
Observed σ_{vis}^{95} [fb]	0.08	0.05

Upper limits on the visible non-SM cross section

Results: m_{T2} kinematics in SR



SR-lowMass



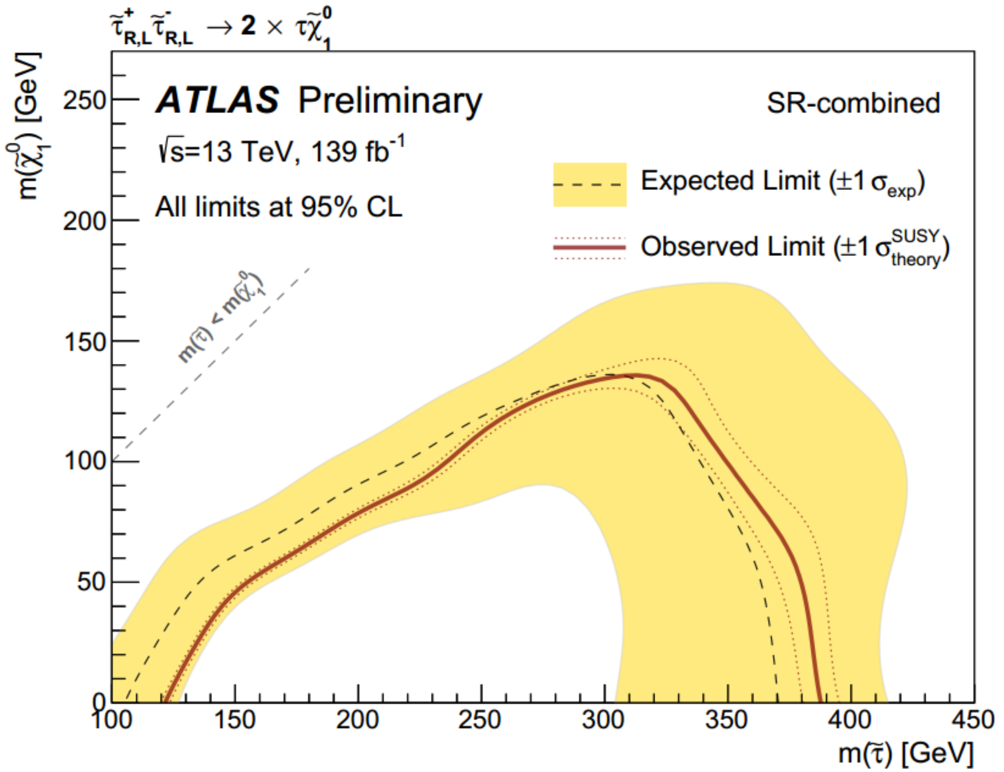
SR-highMass

Agreement is shown between observations and background expectations within uncertainties.

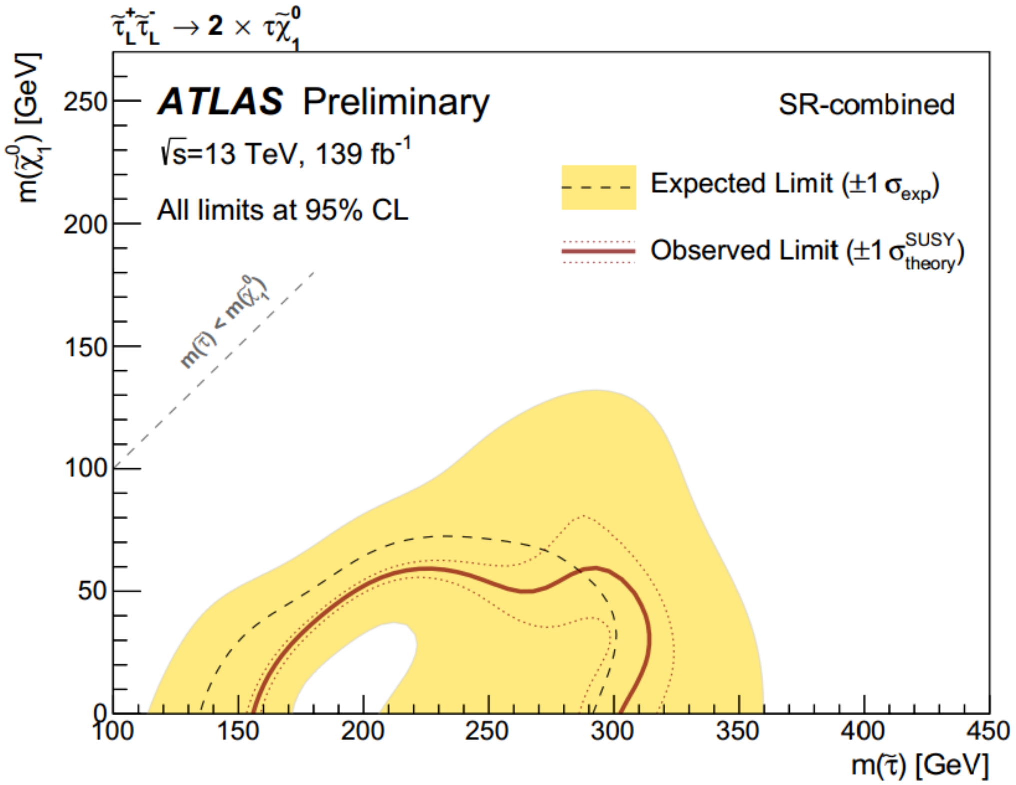
ATLAS-CONF-2019-018

Interpretation

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



$\tilde{\tau}_L$ only

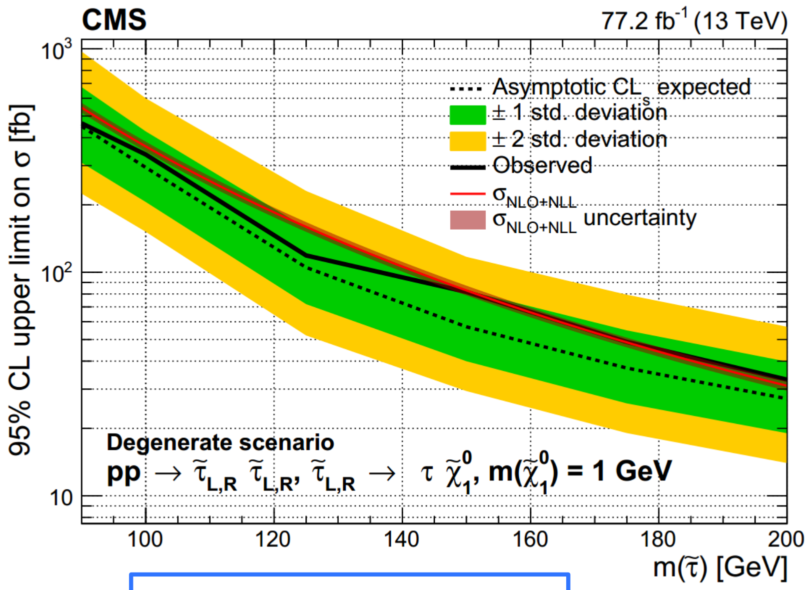


- For the combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$ production, the masses from 120 GeV to 390 GeV are excluded for a massless LSP.
- For the $\tilde{\tau}_L$ production only , the masses from 160 GeV to 300 GeV are excluded for a massless LSP.

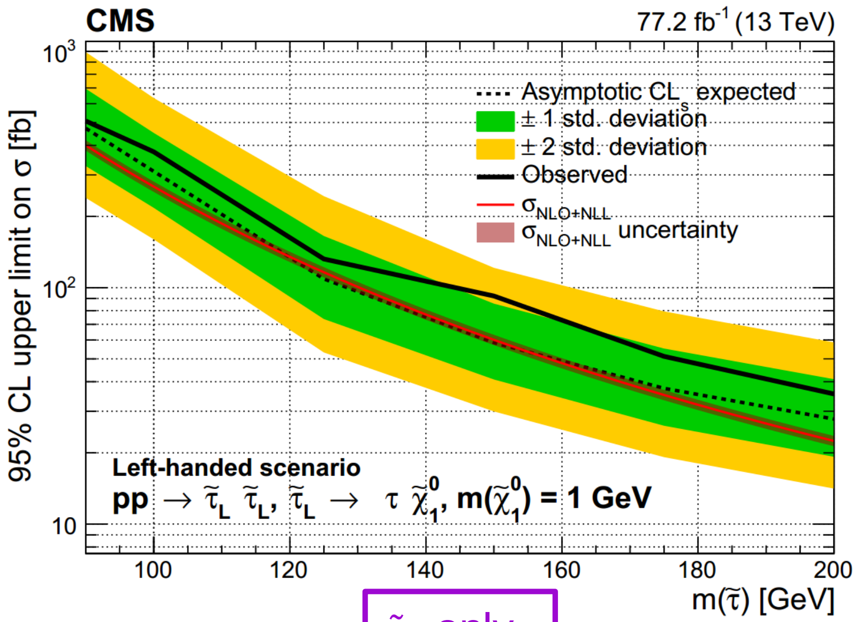
CMS results

arXiv:1907.13179

- Got some 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
  - 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 $\tilde{\tau}_R$

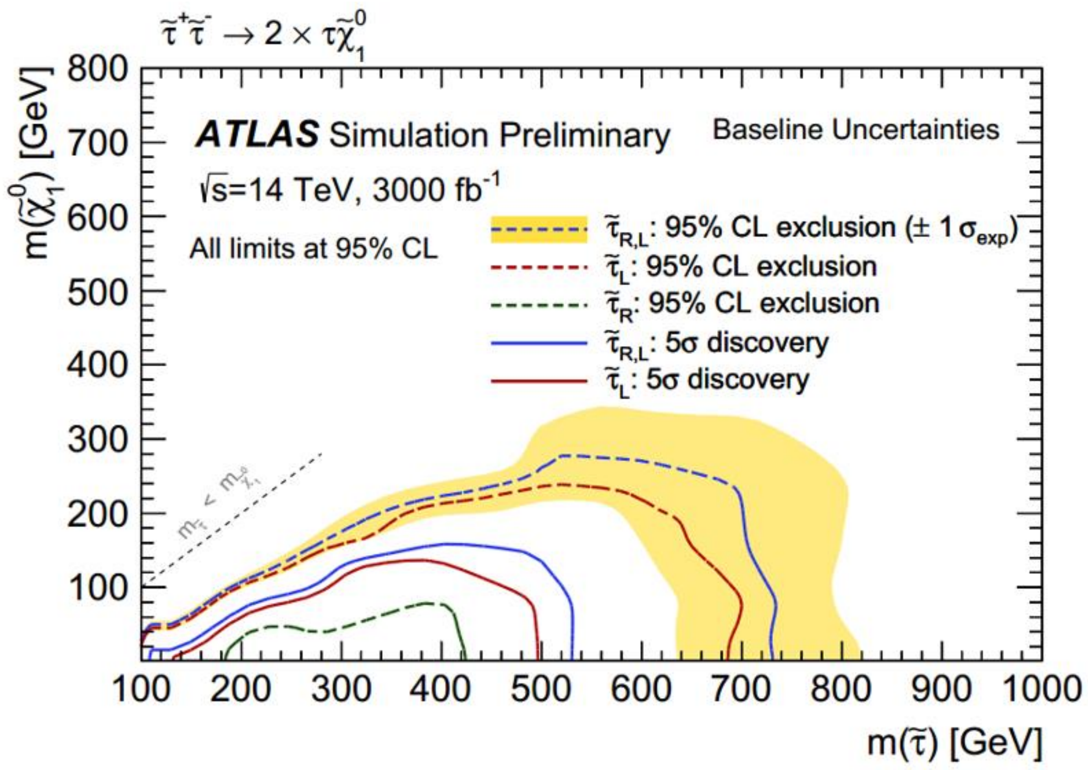


$\tilde{\tau}_L$ only

ATLAS Upgrade Prospect Result

ATL-PHYS-PUB-2018-048

- The prospect of searching direct stau on HL-LHC using ATLAS detector is also performed
- There is a discovery potential from 120 to 530 GeV with a massless LSP for the combined production, while 140 – 500 GeV for LH production only.
- The exclusion limit reaches to 730 GeV for the combined production while 690 GeV for the LH production and 420 GeV for RH production.



Summary

- The direct stau production search with two hadronically decaying taus in the final state is performed with full run-2 data (139 fb-1).
- No excess beyond the SM expectation in all signal regions.
- 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.
- Conf note published at ATLAS-CONF-2019-018 and will be submitted to PRD soon.
- CMS also get exclusion for combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$ production from 90 GeV to 150 GeV for a massless LSP using 2016+2017 data.
- It’s expected to get a wider search space on HL-LHC.
- The compressed $\tilde{\tau}$ (ISR, VBF scenarios) study is going on for Run-2 and Run-3.

BackUp

Signal and background samples

- Signal samples:
  - Generated by MadGraph5_aMC@NLO 2.6.2 interfaced to Pythia 8.186 with the A14 tune
  - The left and right staus are assumed to have the same mass, varied between 100 and 440 GeV and no mixing is assumed between the gauge and mass eigenstates
  - The mass of the bino-like $\tilde{\chi}_1^0$ is varied in the range 0-200 GeV
  - Use point (120,1) and (280,1) as benchmark for the Signal Region Optimization
- Background samples:

Process	ME Generator	Parton Shower	PDF	Tune
$Z/\gamma^* \to ll\ and\ W \to ll$	Sherpa 2.2.1	Sherpa	NNPDF3.0NNLO	Sherpa
VV/VVV	Sherpa 2.2.1/2.2.2	Sherpa	NNPDF3.0NNLO	Sherpa
$\mathrm{t}\bar{t} + V$, $\mathrm{t}\bar{t} + H$, 3 top, 4 top	MG5_aMC	Pythia 8	NNPDF 2.3 LO	A14
$\mathrm{t}\bar{t}$, s/t-channel and Wt single top	Powheg-BOX	Pythia 8	CT10/CTEQ6L1	Perugia2012
Z/W + H	Pythia 8	Pythia 8	NNPDF 2.3 LO	A14
VBF H, gg + H	Powheg-BOX	Pythia 8	NNPDF 3.0/CTEQ6L1	AZN

Object definitions & Overlap removal

- Object definition :
  - Baseline taus
    - medium, pt > 20 GeV, $|\eta|$ < 2.5, exclude 1.37 < $|\eta|$ < 1.52, 1 or 3 tracks (prongs) and a total track charge equals ± 1
  - Baseline electrons
    - pt > 27 GeV, $|\eta|$ < 2.47, MediumLH or TightLH, $|z_0 sin\theta| < 0.5mm$, $\left|\frac{d_0}{\sigma(d_0)}\right| < 5$
  - Baseline muons
    - pt > 27 GeV, $|\eta|$ < 2.5, medium, $|z_0 sin\theta| < 0.5mm$, $\left|\frac{d_0}{\sigma(d_0)}\right| < 3$, ptvarcone < 1.25GeV
  - Baseline jets
    - anti-kt4 jets, pt > 25 GeV, $|\eta|$ < 2.5, JVT > 0.59 (or pt > 60GeV, or 2.4 < $|\eta|$ < 2.5). For b-tag, use MV2c10 @ 70%OP
- Overlap Removal

Step	Object removed	Object compared against	Condition	Comment
1.	electron	electron	shared track	If exactly one electron was reconstructed with AuthorAmbiguous, it is removed else the electron with the lower p_T is removed
2.	tau	electron	$\Delta R < 0.2$	
3.	tau	muon	$\Delta R < 0.2$	
4.	electron	muon	shared ID track	
5.	jet	electron	$\Delta R < 0.2$	
6.	electron	jet	$\Delta R < 0.4$	
7.	jet	muon	NumTrack < 3 and (ghost-associated or $\Delta R < 0.2$)	
8.	muon	jet	$\Delta R < 0.4$	
9.	jet	tau	$\Delta R < 0.2$	

Trigger

- The asymmetric di-tau trigger and di-tau+MET trigger are used in SR-lowMass and SR-highMass

Year	Trigger
	di-tau + E_T^{miss}
2015 - 2017	HLT_tau35_medium1_tracktwo_tau25_medium1_tracktwo_xe50
2018	HLT_tau60_medium1_tracktwoEF_tau25_medium1_tracktwoEF_xe50
	asymmetric di-tau
2015 - 2017	HLT_tau80_medium1_tracktwo_L1TAU60_tau50_medium1_tracktwo_L1TAU12
2018	HLT_tau80_medium1_tracktwoEF_L1TAU60_tau60_medium1_tracktwoEF_L1TAU40

- To ensure that only events in the plateau region of the trigger are selected, additional requirements are applied

Trigger	Trigger leg	Year	HLT	Offline
di-tau + E_T^{miss} trigger	leading tau p_{T} [GeV]	2015-2017	35	50
		2018	60	75
	2nd leading tau p_{T} [GeV]	2015-2018	25	40
	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	2015-2018	50	150
asymmetric di-tau trigger	leading tau p_{T} [GeV]	2015-2018	80	95
	2nd leading tau p_{T} [GeV]	2015-2017	50	60
		2018	60	75

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);

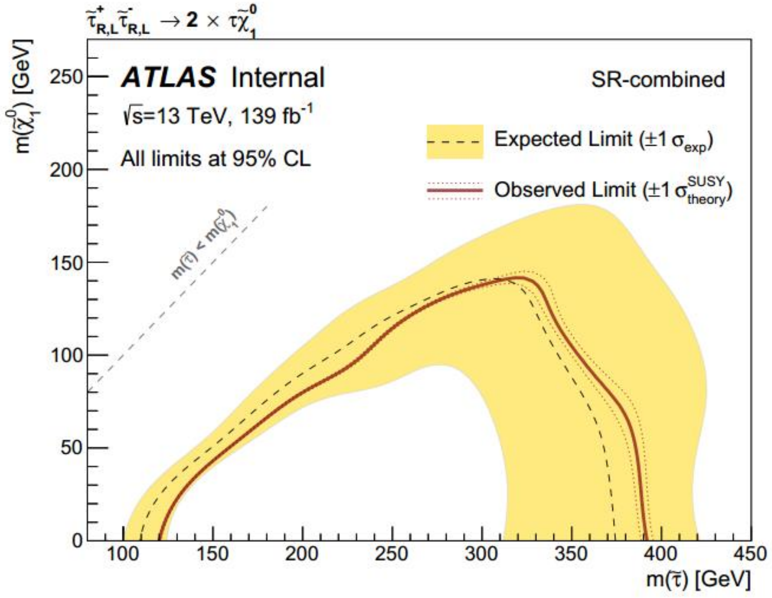
- $m_{T\tau 1} + m_{T\tau 2}$, the sum of the transverse mass values of the leading and next-to-leading taus;

- 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;

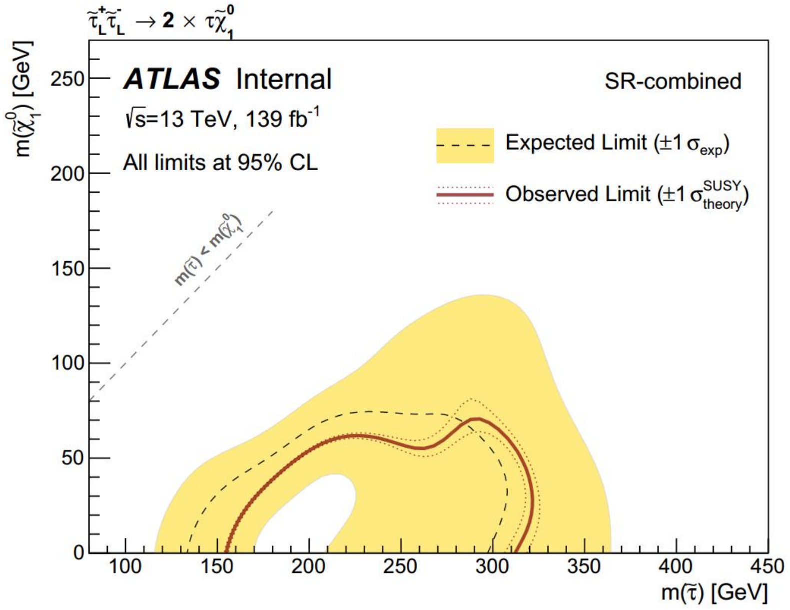
- $\Delta R(\tau, \tau)$, the cone size between the leading and next-to-leading tau. An upper cut on this variable is powerful to discriminate against back-to-back events such as di-jets or Z decays.

Interpretation: Newest version of the result for all kinds of the production

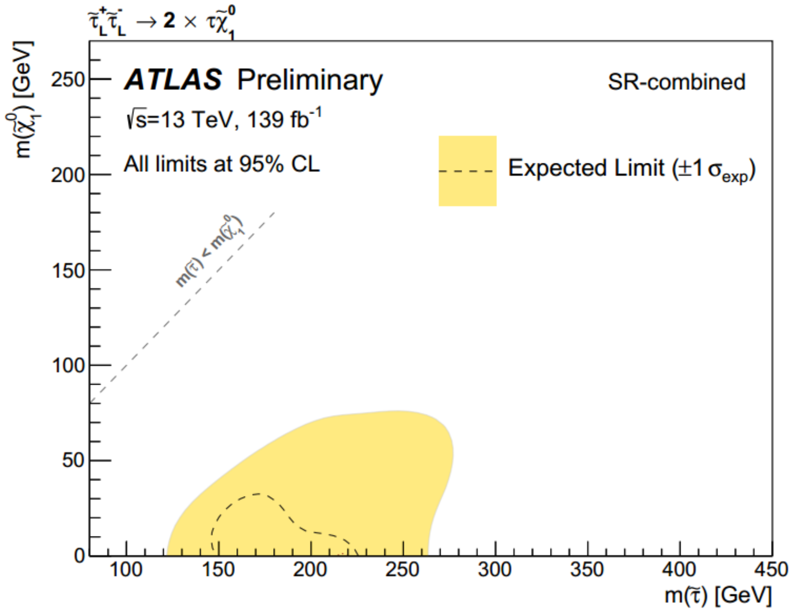
Combined $\tilde{\tau}_L$ and $\tilde{\tau}_R$



$\tilde{\tau}_L$ only



$\tilde{\tau}_R$ only



- Few small update during the second wave circulation preparation
- Limit is extended a bit compared with the CONF version result with smaller error bands
- Main reason is the signal crossection is updated with a more accurate value while the error is a little smaller than the previous one

Interpretation: observed upper limits on the model cross-section in units of pb

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

$\tilde{\tau}_L$ only