Search for direct pair production of supersymmetric partners to the τ lepton in the all hadronic final state $\sqrt{s}$=13 TeV at CMS

CMS Physics Analysis Summary SUS-21-001

Ivan Popov

Supervisor: Michael Holzbock

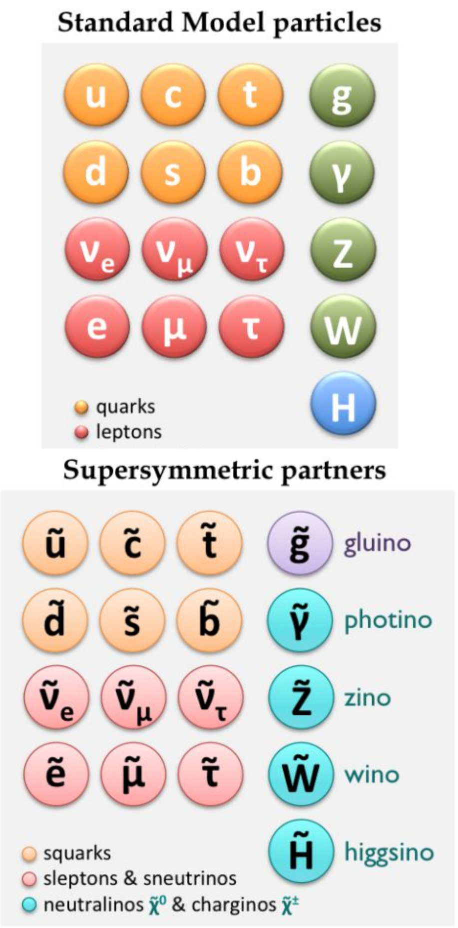
Physics at the LHC Proseminar

01.08.2022

Outline:

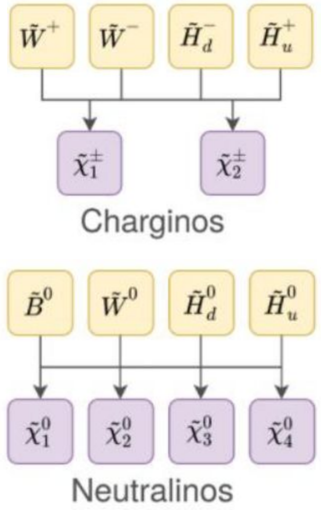
Motivation

- Standard Model has many shortcomings
  - Unknown nature of dark matter and energy
  - Hierarchy Problem
  - CP violation
  - ***Many more***
- Supersymmetry (SUSY) - potential way to solve those
  - *sparticles* - sleptons, squarks, neutralinos, charginos with 1/2 spin difference
  - Softly broken to allow larger particle masses
  - Consists of many models, using the same framework
  - For this talk we focus on **MSSM** (**M**inimal **S**upersymmetric **S**tandard **M**odel)



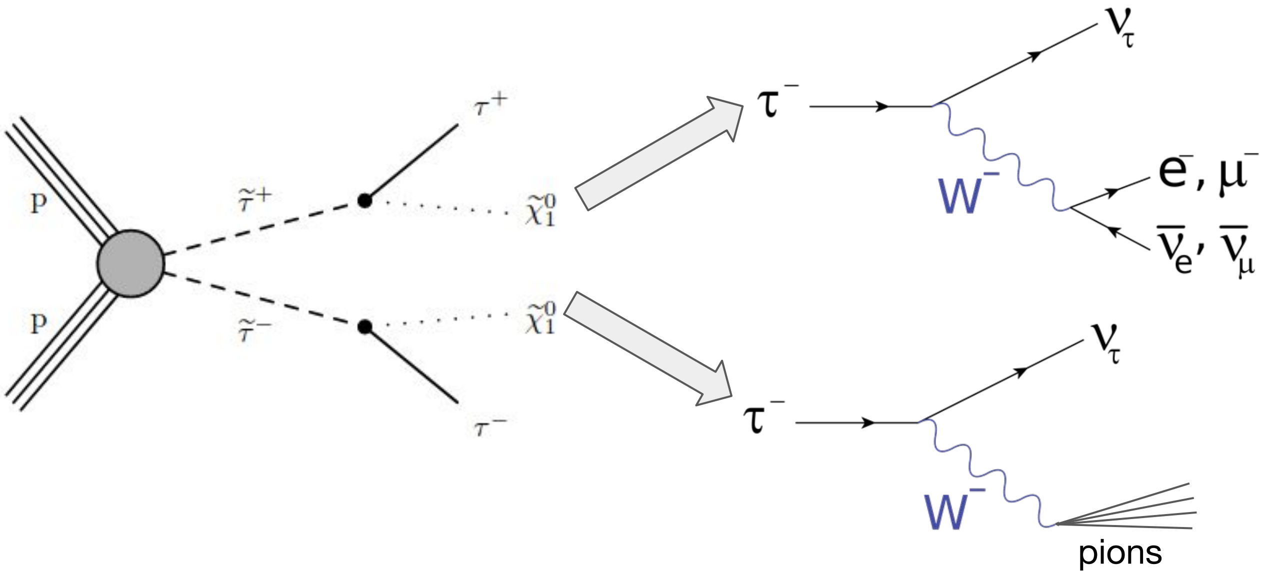
MSSM

- Considers “the [minimum] number of new particle states and new interactions consistent with phenomenology”
- Charginos - S-partners of charged SM gauge and Higgs bosons mix
- Neutralinos - S-partners of neutral SM gauge and Higgs bosons imx
- Conservation of R parity
  - Assumed due to non-observation of proton decay
  - $P_R = (-1)^{3(B-L)+2s}$, P_R (SM) = 1, P_R (SUSY) = -1
  - Consequences:
    - Lightest SUSY (LSP) - **stable!** *(and DM candidate if neutral)*
    - Each sparticle other than LSP decays to state with **odd** number of LSPs
    - In collider experiments sparticles can only be produced in **even** numbers



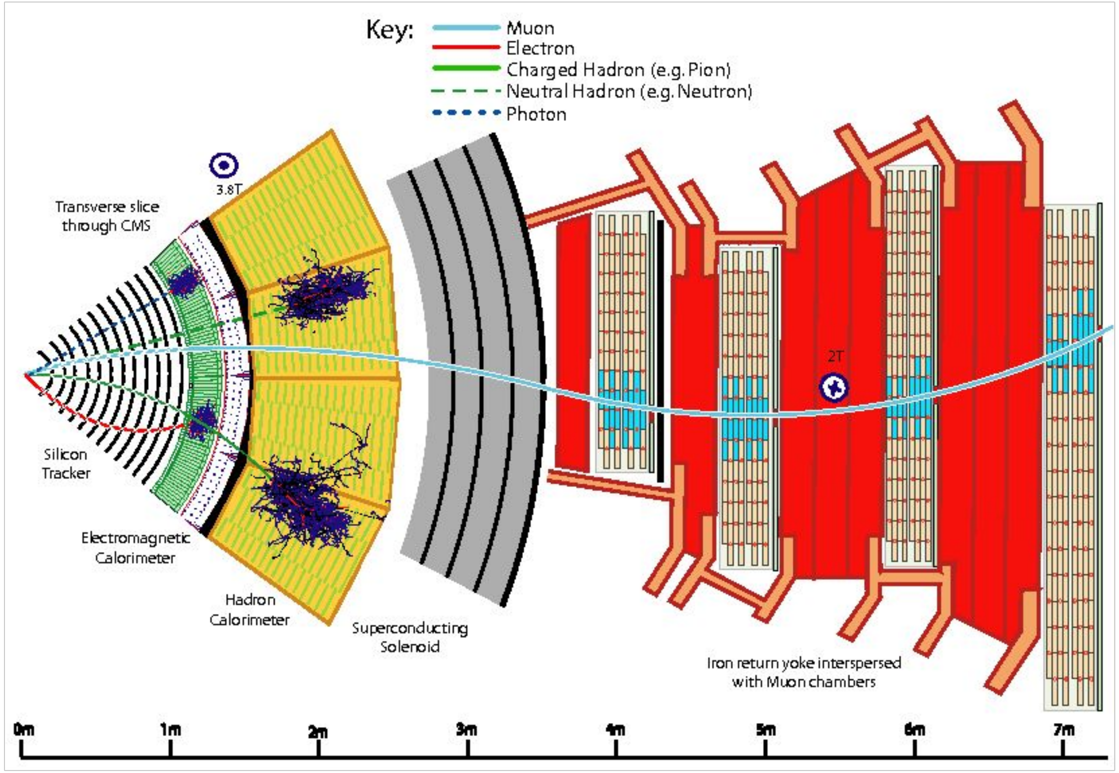
Why stau search?

- Lightest neutralino assumed to be LSP
- Light stau decays to τ and lightest neutralino
- If theory is true - increased rate of τ final states in LHC



This analysis focuses only on hadronic tau decays to suppress SM backgrounds from **diboson** production and **ttbar** production!

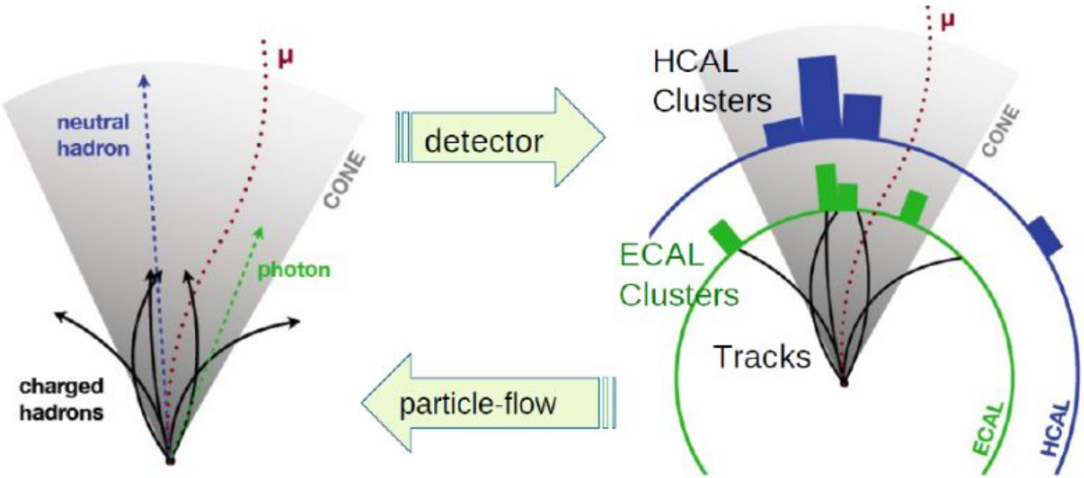
The CMS Detector



Main Features:

- 3.8T, 6m diameter superconducting solenoid
- Silicon pixel and strip tracker
- Lead tungstate crystal ECAL
- Brass and scintillator HCAL
- Gas-ionisation muon chambers

Tau Reconstruction



- Particle Flow algorithm used for event reconstruction
- CMS “DeepTau” DNN algorithm used for tau ID with two working points
  - Loose (80% efficiency, 0.5% misidentification rate)
  - Tight (40% efficiency, 0.06% misidentification rate)
  - MisID stems from quark/gluon originating jets

Event Selection

- Basic event selection - presence of exactly two τ-lepton candidates with opposite charge with $p_T > 40$GeV and $|\eta| < 2.1$
- Multiple vetoes to suppress SM backgrounds
  - Any event with b-tagged jet to reduce top backgrounds
  - $|\Delta\phi(\tau_h^{(1)},\tau_h^{(2)})| > 1.5$ to reduce $Z/\gamma* \to \tau\tau$
  - $p_T^{miss} > 50$GeV to reduce events with two misIDed τ_h
- Further subdivide events in 31 search regions (SR) based on a number of kinematic quantities
- Sum of transverse masses - $\Sigma m_T = m_T(\tau_h^{(1)}, \vec{p}_T^{\,miss}) + m_T(\tau_h^{(2)}, \vec{p}_T^{\,miss})$ where

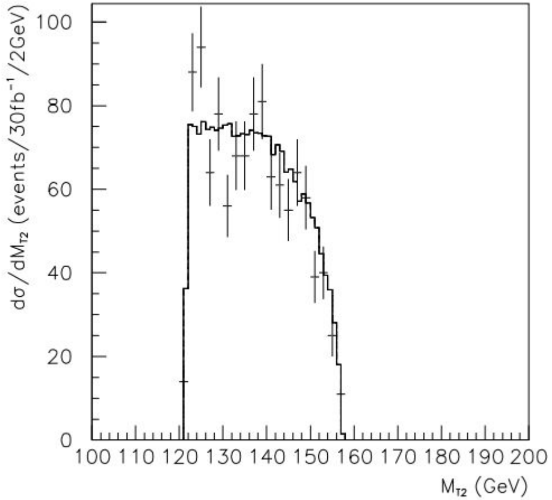
$$m_T(\tau_h, \vec{p}_T^{\,miss}) \equiv \sqrt{2 p_T^{\tau_h} p_T^{miss} [1 - \cos\Delta\phi(\vec{p}_T^{\,\tau_h}, \vec{p}_T^{\,miss})]}$$

Prompt SRs			
SR bin	Σm_T [GeV]	m_{T2} [GeV]	$p_T^{\tau_h 1}$ [GeV]
$N_j = 0$			
1	200 – 250	25 – 50	< 90
2	200 – 250	25 – 50	> 90
3	200 – 250	50 – 75	< 90
4	200 – 250	50 – 75	> 90
5	200 – 250	> 75	—
6	250 – 300	25 – 50	< 90
7	250 – 300	25 – 50	> 90
8	250 – 300	50 – 75	< 90
9	250 – 300	50 – 75	> 90
10	250 – 300	> 75	—
11	300 – 350	25 – 50	—
12	300 – 350	50 – 75	—
13	300 – 350	75 – 100	—
14	300 – 350	> 100	—
15	> 350	25 – 50	—
16	> 350	50 – 75	—
17	> 350	75 – 100	—
18	> 350	> 100	—
$N_j \geq 1$			
19	200 – 250	25 – 50	—
20	200 – 250	> 50	—
21	250 – 300	25 – 50	—
22	250 – 300	50 – 75	—
23	250 – 300	> 75	—
24	300 – 350	25 – 50	—
25	300 – 350	50 – 75	—
26	300 – 350	> 75	—
27	> 350	25 – 75	—
28	> 350	75 – 100	—
29	> 350	> 100	—

Displaced SRs	
SR bin	$p_T^{\tau_h 2}$ [GeV]
30	< 110
31	> 110

Event Selection

- "Stransverse" mass - $m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$
- Transverse momentum of leading tau
- 0 jet and ≥1 jet events
- Fast decaying tau pairs ("prompt" SRs) and long lived tau pairs ("displaced" SRs)
    - Prompt SR criteria - m_{T2} > 25GeV and Σm_T > 200GeV + at least one τ should NOT satisfy the displaced criteria
    - Displaced SR criteria - significance of the τ_h impact parameter relative to the primary vertex in the transverse plane d_{xy} > 5 and three-dimensional impact parameter IP3D > 100μm



M_{T2} distribution for $pp \to X + \tilde{l}_R^+ \tilde{l}_R^- \to X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

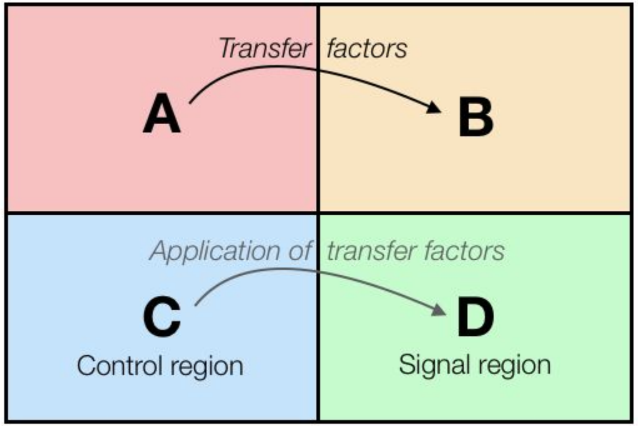
Event Selection

- "Stransverse" mass - $m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)} \right) \right]$
- Transverse momentum of leading tau
- 0 jet and ≥1 jet events
- Fast decaying tau pairs ("prompt" SRs) and long lived tau pairs ("displaced" SRs)
  - Prompt SR criteria - m_{T2} > 25GeV and Σm_T > 200GeV + at least one τ should NOT satisfy the displaced criteria
  - Displaced SR criteria - significance of the τ_h impact parameter relative to the primary vertex in the transverse plane d_{xy} > 5 and three-dimensional impact parameter IP3D > 100μm

Prompt SRs			
SR bin	Σm_T [GeV]	m_{T2} [GeV]	$p_T^{\tau_h 1}$ [GeV]
$N_j = 0$			
1	200 – 250	25 – 50	< 90
2	200 – 250	25 – 50	> 90
3	200 – 250	50 – 75	< 90
4	200 – 250	50 – 75	> 90
5	200 – 250	> 75	—
6	250 – 300	25 – 50	< 90
7	250 – 300	25 – 50	> 90
8	250 – 300	50 – 75	< 90
9	250 – 300	50 – 75	> 90
10	250 – 300	> 75	—
11	300 – 350	25 – 50	—
12	300 – 350	50 – 75	—
13	300 – 350	75 – 100	—
14	300 – 350	> 100	—
15	> 350	25 – 50	—
16	> 350	50 – 75	—
17	> 350	75 – 100	—
18	> 350	> 100	—
$N_j \geq 1$			
19	200 – 250	25 – 50	—
20	200 – 250	> 50	—
21	250 – 300	25 – 50	—
22	250 – 300	50 – 75	—
23	250 – 300	> 75	—
24	300 – 350	25 – 50	—
25	300 – 350	50 – 75	—
26	300 – 350	> 75	—
27	> 350	25 – 75	—
28	> 350	75 – 100	—
29	> 350	> 100	—
Displaced SRs			
SR bin		$p_T^{\tau_h 2}$ [GeV]	
30		< 110	
31		> 110	

Background estimation

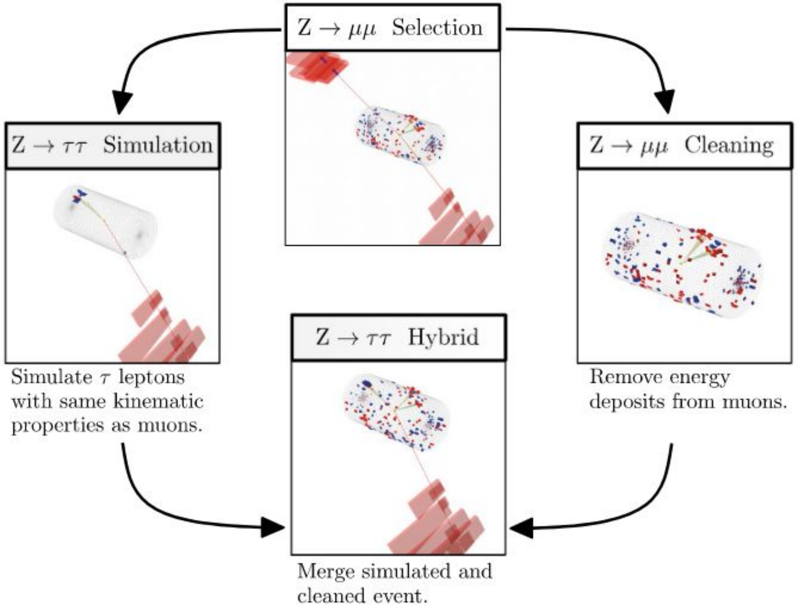
- Reducible background, i.e misidentification in reconstruction of hadronic taus
  - Sources:
    - QCD dijet/multijet production, W+ jet production
  - Estimation:
    - Define control region (CR) with relaxed tau ID requirements (“loose SR”)
    - Measure ratio of “tight” and “loose” taus in sample enriched in multi-jet events
    - Assume that ratio holds in SR so it can be used to extrapolate from the “loose SR” to the SR (*correct to a degree*)
    - Results: **10-15%** misidentified **“loose”** taus as **“tight”** in sample depending on **p_T, τ decay mode**, **pileup events** and **jet flavor**



Contribution of genuine τ_h in CRs also taken in consideration!

Background estimation

- Irreducible background, i.e SM processes with the same final states as the ones the analysis is targeting
  - Main Sources: Z/γ∗ → ττ, ttbar, diboson
  - Estimation through “embedding” method:
    - Z/γ∗ → ττ is a hard process to select, thus select Z/γ∗ → μμ (same type of decay and branching ratio)
    - Remove μ tracks and energy deposits
    - Simulate two taus with same kinematic properties in empty detector
    - Combine energy deposits of simulated taus with original reconstructed event

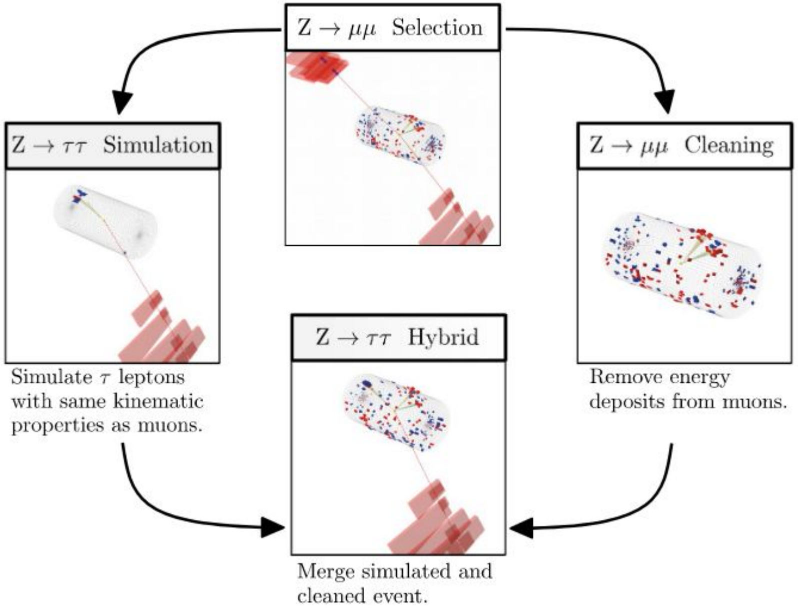


Also applicable for **ttbar**, **single top** and **diboson** processes, but not for **H → τ τ**

Better results than MC simulation!

Background estimation

- Irreducible background, i.e SM processes with the same final states as the ones the analysis is targeting
    - CR defined to calculate normalization factor:
        - 90 GeV > $m_{\tau\tau}$ > 50GeV, $p^T_{\tau\tau}$ > 50GeV (to ensure purity of genuine τ)
        - m_{T2} < 25GeV or Σm_{T2} < 200GeV (orthogonality with SR)
    - CR to calculate overestimation of top events:
        - At least 1 b-tagged jet
        - $m_{\tau\tau}$ > 100GeV
        - p_T^{miss} > 50GeV



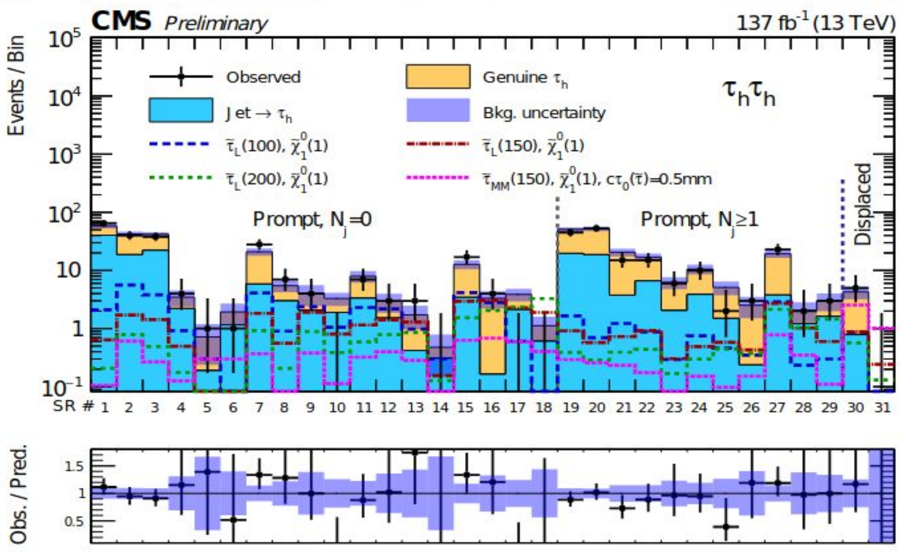
Uncertainties

	Uncertainty [%]		
Source	Genuine τ_h	Misidentified τ_h	Signal
Statistical	8.3–141	5.0–100	6.3–52
τ_h ID efficiency	7.2–7.8	—	6.2–6.4
τ_h ID vs displacement	—	—	3.0
τ_h trigger efficiency	3.1–4.2	—	6.9–14
τ_h energy scale	0.1–35	—	1.6–44
τ_h misidentification rate	—	30–56	—
p_T^{miss} trigger efficiency	1.0	—	1.5
Embedded normalization	19	—	—
Embedded top quark fraction	1.0–3.8	—	—
Jet energy scale	—	—	0.7–32
Jet energy resolution	—	—	1.3–55
Unclustered energy	—	—	0.5–32
B–tagging	—	—	0.2–1.1
Pileup	—	—	1.0–28
Pre-fire	—	—	0.1–0.4
Integrated luminosity	—	—	1.8
ISR	—	—	0.1–16
Renormalization/factorization scale	—	—	0.4–3.6

Most impactful uncertainties:

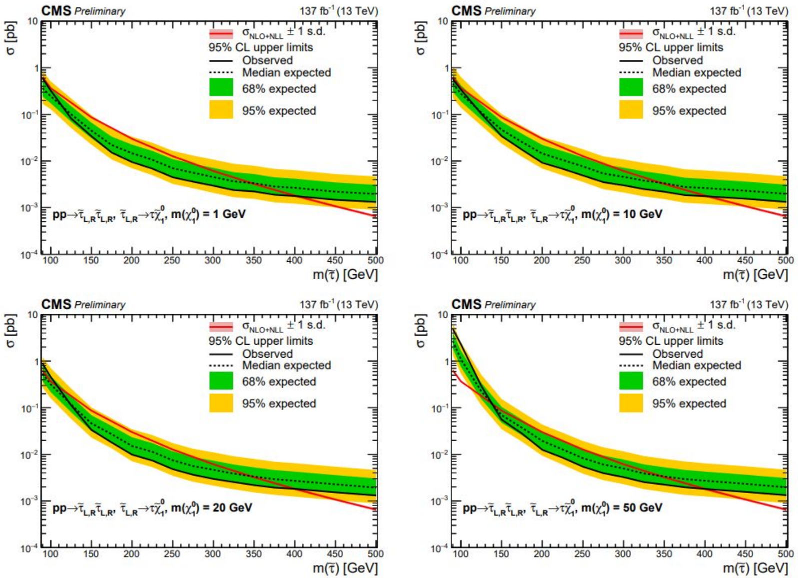
- Statistical uncertainty (limited event counts)
- Tau misidentification rate
- Embedding method: normalization uncertainty and uncertainty due to top quark contamination

Results

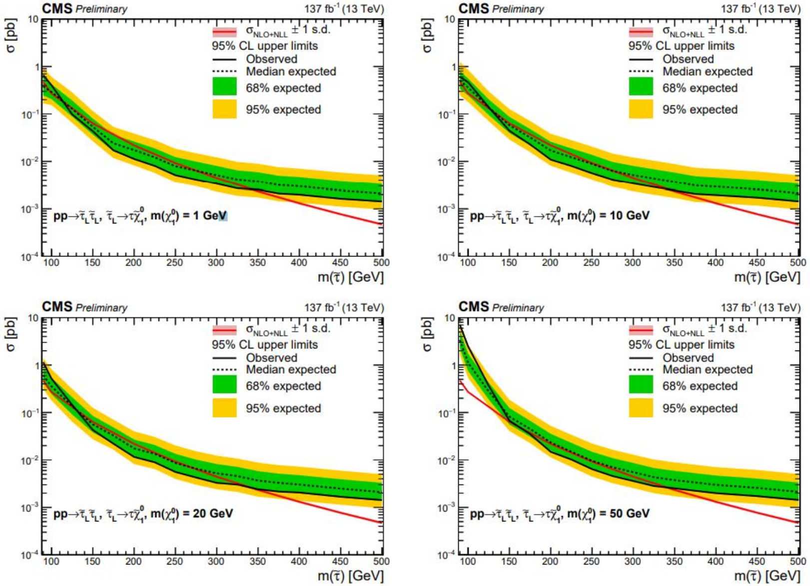


- Plot shows background predictions after the maximum likelihood fit to data under background-only hypothesis
- Added expected yields for 3 models of left-handed stau pair production assuming prompt decay and 1 model model of maximally-mixed long-lived stau pairs
- Most of the sensitivity comes from SRs with 0 jets
- Consistent with prediction for SM background
- Used to set upper limits on cross section for the stau pair production

Results - prompt SRs

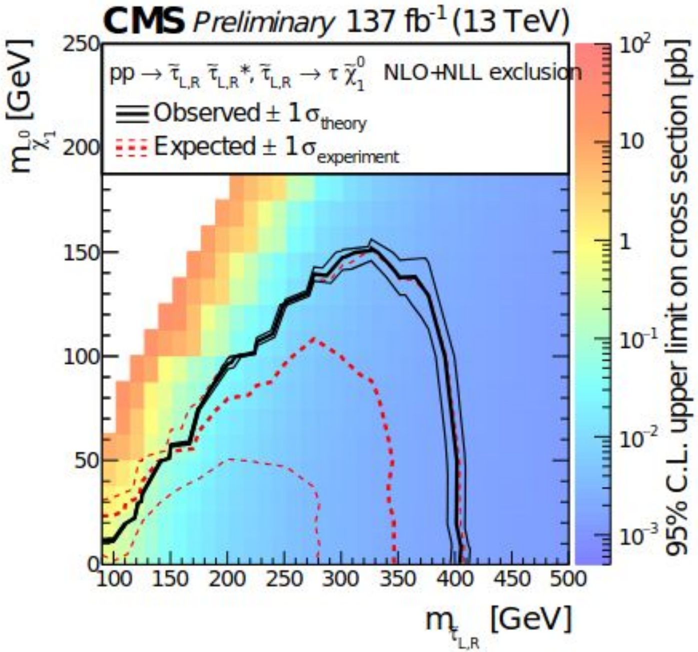


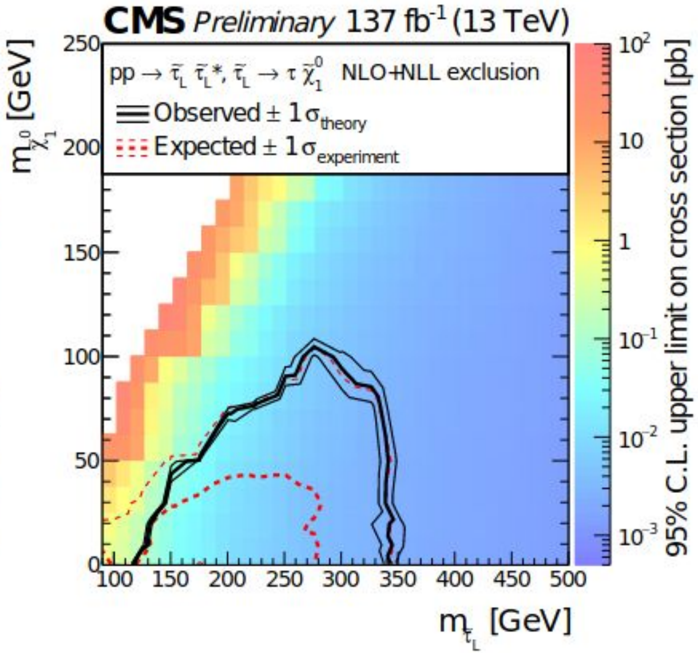
Expected and observed 95% CL cross section upper limits in degenerate stau scenario



Expected and observed 95% CL cross section upper limits in purely left-handed stau scenario

Results - prompt SRs

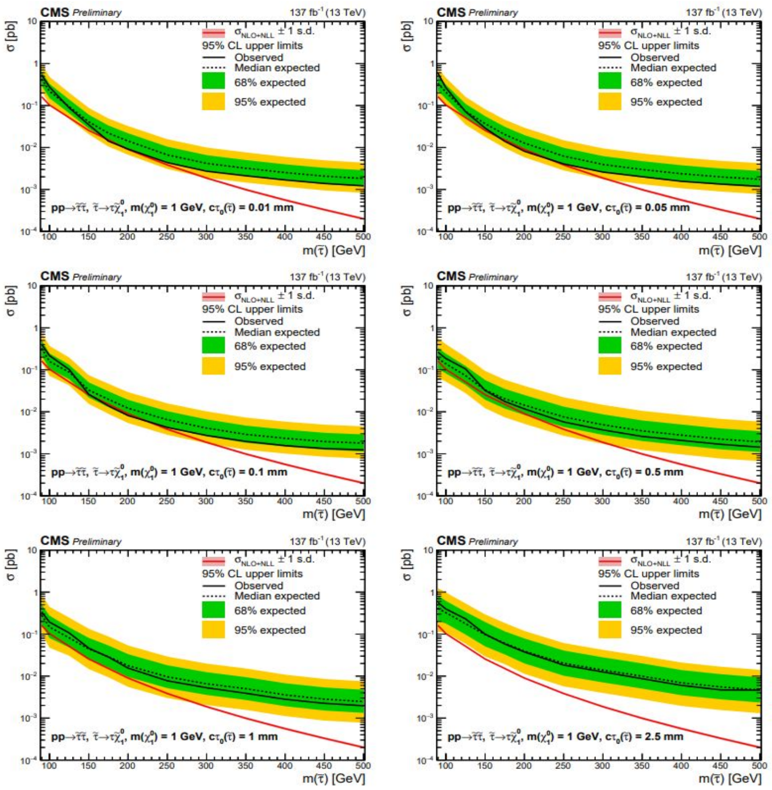




Higher values of LSP mass lead to decreasing probability for tau to exceed 40 GeV threshold, thus less stringent cross section limits (top left of both plots)

Exclusion limits in the **stau** vs **LSP** mass plane for promptly decaying stau in degenerate (left) and purely left-handed (right) scenarios. Stau masses between **115GeV** and **340GeV** are excluded for the case of near massless LSP for prompt purely left-handed scenarios!

Results - displaced SRs



- Plots show expected and observed 95% CL cross section upper limits in a maximally mixed stau scenario with 1GeV LSP mass and varying $c\tau_0$
- For $c\tau_0$ = 0.1mm masses between 150 and 220 GeV are excluded for the case that the LSP is nearly massless

Comparison to ATLAS stau search

Event selection - only two SRs!

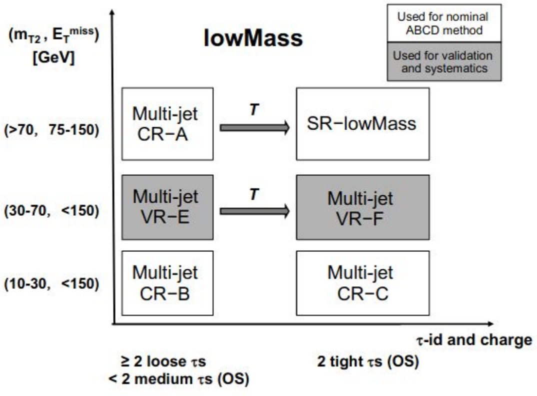
SR-lowMass	SR-highMass
2 tight τ (OS)	2 medium τ (OS) , ≥ 1 tight τ
asymmetric di-τ trigger	di-τ+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
τ p_{T} cut described in Section 5	
light lepton veto and 3rd medium τ veto	
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	

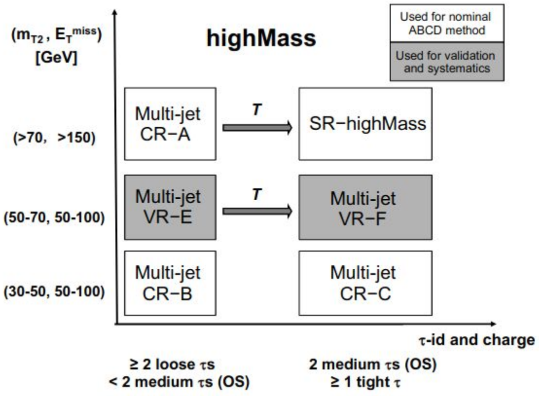
Main differences to CMS event selection:

- Overall different search strategy focusing on distinguishing between low mass stau scenarios and high mass stau scenarios
- Much stricter stransverse mass requirements: m_{T2} > 70GeV (ATLAS) vs m_{T2} > 25GeV (CMS)
- $p_{T\ lead}$ > 95GeV (50GeV) and
  $p_{T\ sublead}$ > 60GeV (40GeV) for lowMass (highMass)
  vs p_T > 40GeV

popov@mpp.mpg.de

Comparison to ATLAS stau search



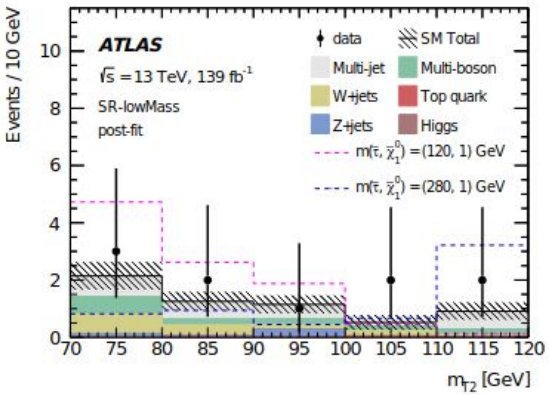


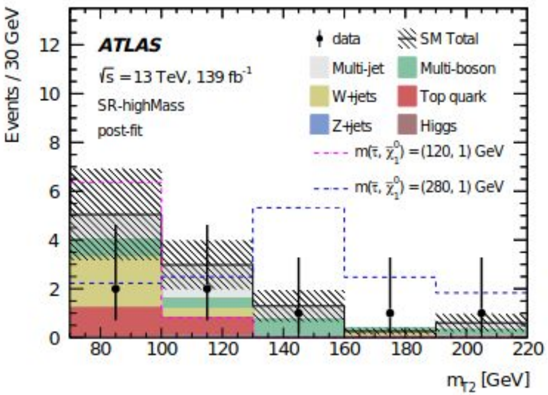
WCR	*WVR*
1 medium τ and 1 isolated μ (OS)	
single-muon trigger	
$p_T(\tau) > 60$ GeV, $p_T(\mu) > 50$ GeV	
$E_T^{miss} > 60$ GeV	
b-jet veto and top-tagged events veto	
$m(\mu, \tau) > 70$ GeV	
$1 < \Delta R(\mu, \tau) < 3.5$	
$50 < m_{T,\mu} < 150$ GeV	
$m_{T,\mu} + m_{T,\tau} > 250$ GeV	
$30 < m_{T2} < 70$ GeV	$m_{T2} > 70$ GeV

Selections	*TVR* -lowMass	*ZVR* -lowMass	*VVVR* -lowMass	*TVR* -highMass	*ZVR* -highMass	*VVVR* -highMass
	≥ 2 medium τ (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-τ trigger $60 < E_T^{miss} < 150$ GeV			di-τ+E_T^{miss} trigger $E_T^{miss} > 150$ GeV		
	τ p_T and E_T^{miss} cuts described in Section 5					

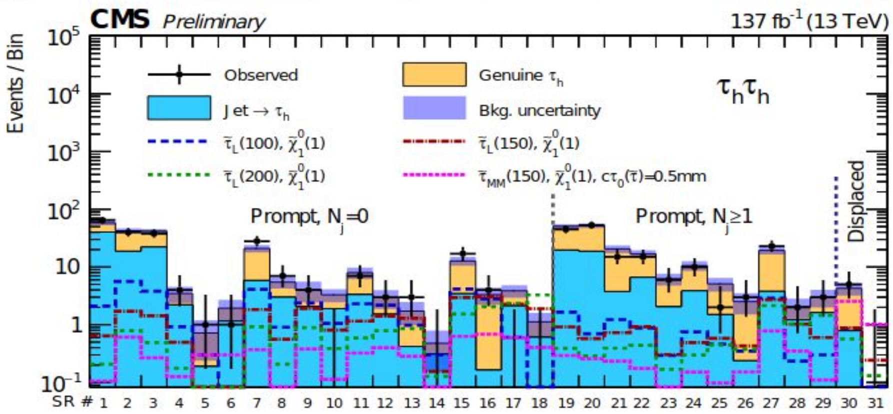
- **ABCD method** for Multijet (τ misID)
- **MC simulation** for W+ jets (τ misID)
- **MC simulation** for Z/γ∗ → ττ, ttbar, diboson (SM processes with same final states as the ones targeted by this analysis)

Comparison to ATLAS stau search



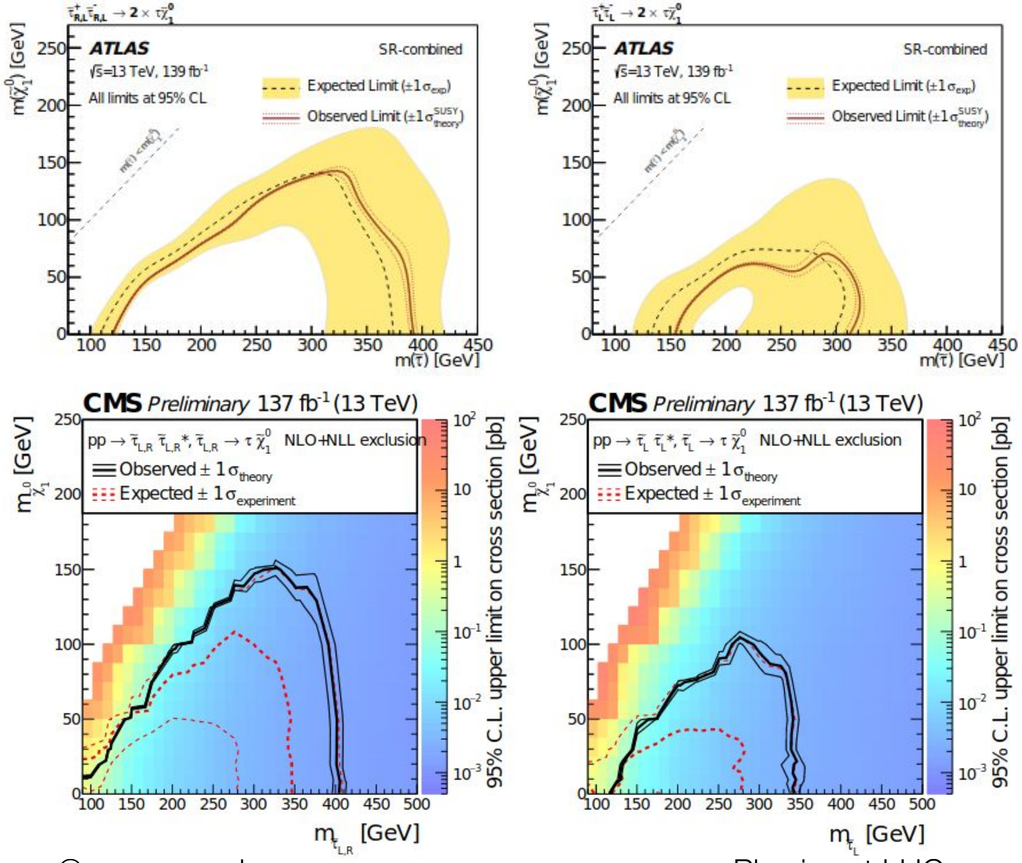


The post-fit m_{T2} distributions for both signal regions; backgrounds are again consistent with SM predictions



- SR 1,2,6,15,19,21,24: 25GeV < m_{T2} < 50GeV
- SR 3,4,8,9,12,16,22,25: 50GeV < m_{T2} < 75GeV

Comparison to ATLAS stau search

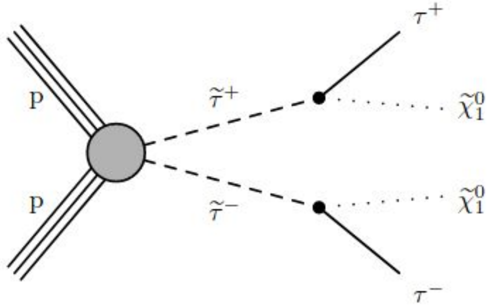


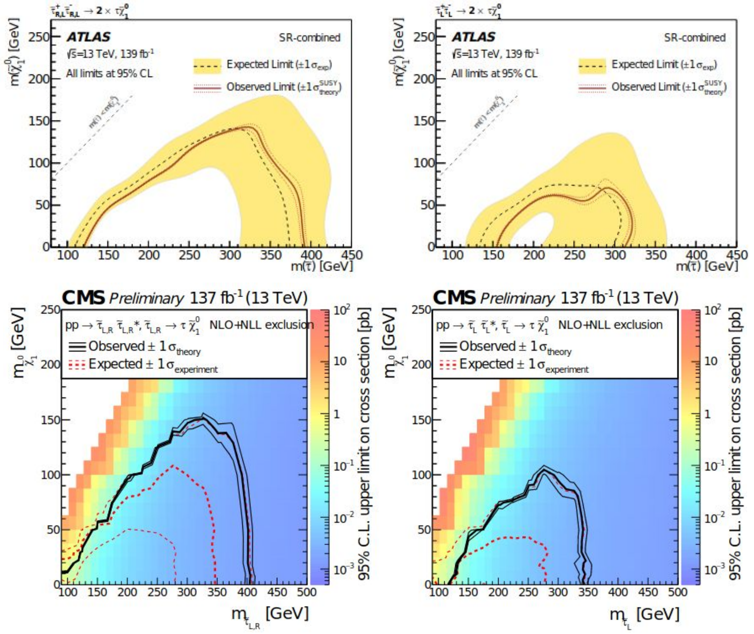
Exclusion limits in the **stau** vs **LSP** mass plane in combined left+right (left plot) and purely left-handed (right plot) scenarios. Stau masses between **120GeV** and **390GeV** are excluded for the combined scenario and stau masses between **155GeV** and **310GeV** for purely left-handed!

CMS exclusion limits:
between **115GeV** and **340 GeV** for purely left-handed prompt stau decays

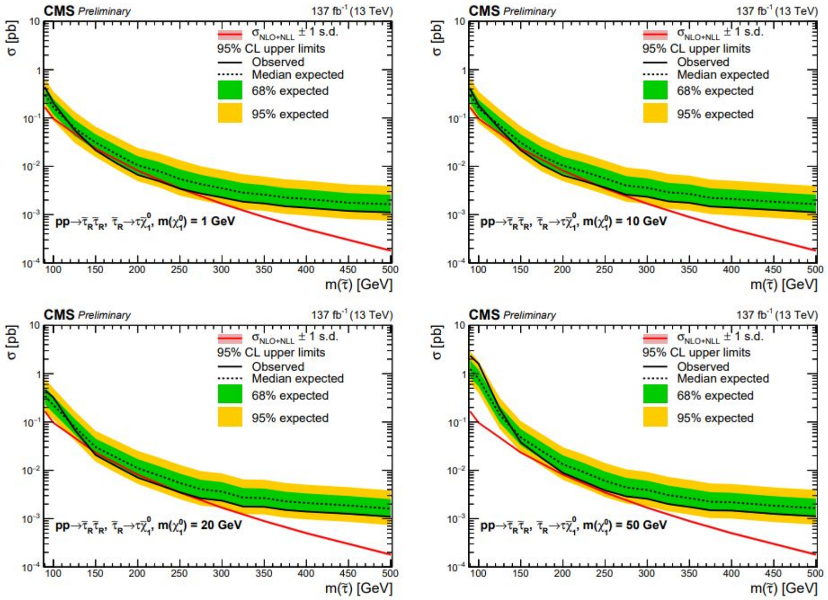
Conclusion

- In SUSY models with R-Parity conservation the LSP is stable and potential DM candidate
- Light stau decays to τ and LSP, thus increased rates of τs are expected at pp collider experiments
- Both ATLAS and CMS performed stau searches within 400GeV mass
- CMS analysis excludes stau masses between **115GeV** and **340GeV** for prompt purely left-handed states and stau masses between **50GeV** and **220GeV** for displaced ($c\tau_0$ = 0.1mm) scenarios with maximally mixed states
- ATLAS analysis excludes stau masses between **155GeV** and **310GeV** for purely left-handed states and stau masses between **120GeV** and **390GeV** for mixed states





Results - prompt SRs



Expected and observed 95% CL cross section upper limits in purely right-handed stau scenario

Due to lack of sensitivity for this model no hard exclusion limits can be set