SUSY searches with τ final states at the CMS experiment

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For the CMS collaboration

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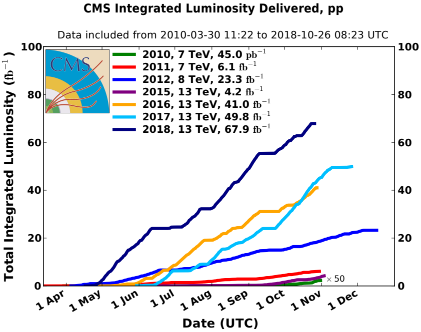
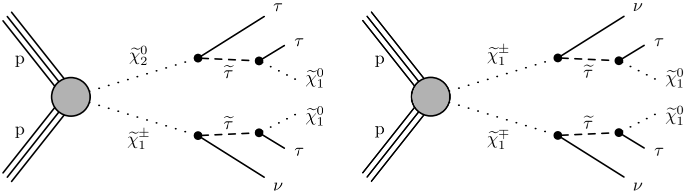
- The LHC **performed very well** in Run-2.
- CMS recorded 137 fb^{-1} of data (2016+17+18).
- **Several SUSY searches** have been performed in various final states.
- Tau final states are typically quite challenging due to large backgrounds.
- **Improved tau reconstruction** techniques (like DNN) have been developed for better sensitivity.
- I will focus on chargino/neutralino, tau slepton and top squark searches in tau final states.



Chargino/neutralino production
[35.9 fb^{-1} (2016 data)]

[JHEP 11 (2018) 151]

Motivation and signal



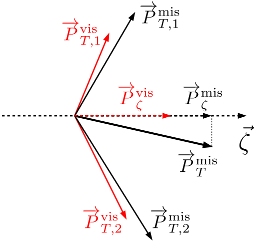
- Models where $\widetilde{\tau}$ is the NLSP are well motivated in early universe $\widetilde{\tau}$-neutralino coannihilation scenarios.
- Light $\widetilde{\tau}$ with relatively small $m_{\widetilde{\tau}} - m_{LSP}$.
- Can explain the observed relic density.
- Increased probability of **final states with τ leptons**.

- $\widetilde{\chi}_1^\pm \rightarrow \widetilde{\tau}_1^\pm \nu_\tau$ or $\tau^\pm \widetilde{\nu}_\tau$
- $m_{\widetilde{\chi}_1^\pm} = m_{\widetilde{\chi}_2^0}$, $m_{\widetilde{\tau}} = 0.5(m_{\widetilde{\chi}_1^\pm} + m_{\widetilde{\chi}_2^0})$, $m_{\widetilde{\nu}_\tau} = m_{\widetilde{\tau}_1}$,
- Search in $e\mu$, $\ell\tau_h$ ($e\tau_h$ and $\mu\tau_h$) and $\tau_h\tau_h$ final states.

Search strategy [1]

	Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Reduces QCD	$\lvert\Delta\phi(\ell_1,\ell_2)\rvert$	>1.5	>1.5	>1.5	>1.5
	$\lvert\Delta\eta(\ell_1,\ell_2)\rvert$	<2	<2	<2	—
	$\Delta R(\ell_1,\ell_2)$	<3.5	<3.5	<3.5	—
Reduces top-quark	b-tagged jet veto	$p_T > 20$ GeV, medium CSV	$p_T > 20$ GeV, medium CSV	$p_T > 20$ GeV, medium CSV	$p_T > 30$ GeV, loose CSV
	Additional jet veto	>1 jet, $p_T > 20$ GeV	>1 jet, $p_T > 20$ GeV	>1 jet, $p_T > 20$ GeV	—
	$\lvert\Delta\eta(\text{jet},\ell_i)\rvert$ (1–jet events)	<3	<3	<3	—
	$\Delta R(\text{jet},\tau_h)$ (1–jet events)	—	<4	<4	—
Reduces DY+jets (low-mass and Z res.)	$m(\ell_1,\ell_2)$ [GeV]	90–250	>50	>50	—
Reduces top-pair and WW	e/μ p_T upper bound [GeV]	<200	—	—	—
Reduces W+jets and other SM	$m_T(e/\mu,\vec{p}_T^{\text{miss}})$ [GeV]	—	20–60 or >120	20–60 or >120	—
	Σm_T [GeV]	—	>50	>50	—

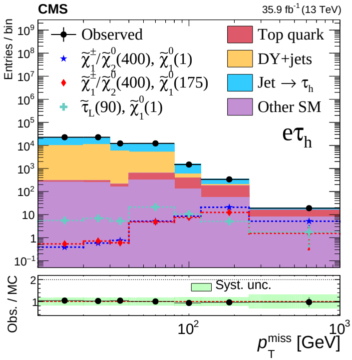
- $m_T^{tot} = \Sigma m_T = [m_T^2(vis1, \vec{p}_T^{\text{miss}}) + m_T^2(vis2, \vec{p}_T^{\text{miss}})]^{1/2}$
- $m_{T2}(vis1, vis2, \vec{p}_T^{\text{miss}}) = \min_{\vec{p}_T^{inv1}+\vec{p}_T^{inv2}=\vec{p}_T^{\text{miss}}} [\max\{m_T^2(\vec{p}_T^{vis1}, \vec{p}_T^{inv1}), m_T^2(\vec{p}_T^{vis2}, \vec{p}_T^{inv2})\}]$
- $D_\zeta = \vec{p}_T^{\text{miss}} \cdot \vec{\zeta} - 0.85(\vec{p}_T^{vis1} + \vec{p}_T^{vis2}) \cdot \vec{\zeta}$

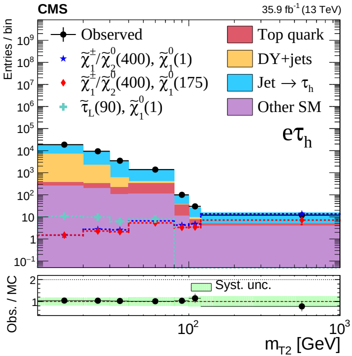


[Here,
$(vis1, vis2) \implies (e,\mu), (\ell,\tau_h)$ and (τ_h,τ_h);
$inv1/2$ are the invisible components of the system.]

Search strategy [2]

- $e\mu$ channel: **22 bins** in both 0-jet and **1-jet** categories, defined in terms of $p_{\mathrm{T}}^{\mathrm{miss}}$, m_{T2}, and D_{ζ}.
- $\ell\tau_{\mathrm{h}}$ channel:: **21 and 23 bins** in **0-jet and 1-jets** categories respectively, defined in terms of $p_{\mathrm{T}}^{\mathrm{miss}}$, m_{T2}, and D_{ζ}.
- $\tau_{\mathrm{h}}\,\tau_{\mathrm{h}}$ channel: **3 bins** defined in terms of m_{T2} and m_{T}^{tot}.





Misidentified jets

$e\mu$ channel

- Jets misidentified as e/μ.
- Uses the standard **"ABCD" method**.

$\ell\tau_h$ channel

- Jets misidentified as τ_h.
- **Extrapolated** from **sideband** (inverted τ_h isolation) to signal region using a transfer factor.

$\tau_h\ \tau_h$ channel

- Jets misidentified as τ_h.
- Uses the measurement of "prompt" and "fake" rates, which are the probabilities of genuine and misidentified τ_h respectively, to pass the isolation requirement.

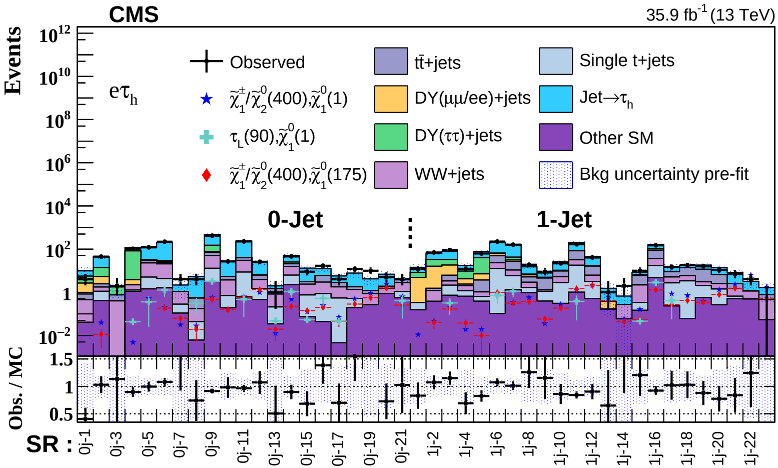
DY+jets

- Correction factors derived from a di-μ control sample are applied to the MC **improve the data-MC comparison the Z-boson mass and p_T spectra**.
- For the $e\mu$ and $\ell\tau_h$ channels, an extra normalization scale factor (derived from a DY-enriched di-μ region) is applied.

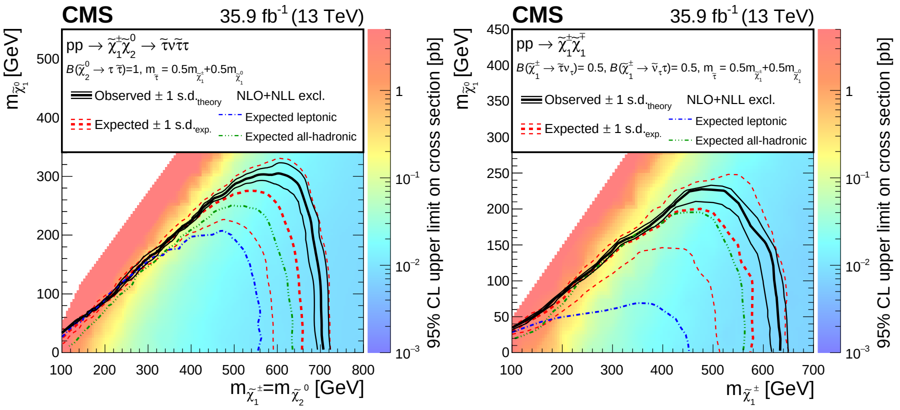
Others

- Other SM backgrounds are obtained from MC.

No significant excess is observed.
Yields in $e\tau_h$ channel shown.



Results [2]

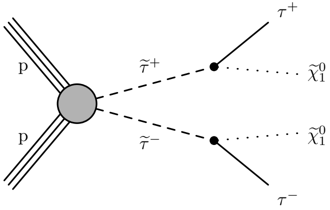


CMS
35.9 fb^-1 (13 TeV)
pp → χ̃±1 χ̃02 → τ̃ντ̃τ
B(χ̃02 → τ τ̃)=1, m τ̃ = 0.5m χ̃±1 +0.5m χ̃01
Observed ± 1 s.d.theory NLO+NLL excl.
Expected ± 1 s.d.exp.
Expected leptonic
Expected all-hadronic
m χ̃01 [GeV]
m χ̃±1 =m χ̃02 [GeV]
95% CL upper limit on cross section [pb]
CMS
35.9 fb^-1 (13 TeV)
pp → χ̃±1 χ̃∓1
B(χ̃±1 → τ̃ντ)= 0.5, B(χ̃±1 → ν̃τ τ)= 0.5, m τ̃ = 0.5m χ̃±1 +0.5m χ̃01
Observed ± 1 s.d.theory NLO+NLL excl.
Expected ± 1 s.d.exp.
Expected leptonic
Expected all-hadronic
m χ̃01 [GeV]
m χ̃±1 [GeV]
95% CL upper limit on cross section [pb]

Direct tau slepton (stau) pair-production

[77.2 fb^{-1} (2016+2017 data)]

[CMS-PAS-SUS-18-006]



- Motivation similar to indirect $\tilde{\tau}$ production via $\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$.

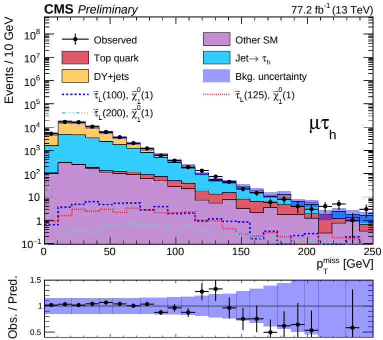
- Both $\tilde{\tau}_L$ and $\tilde{\tau}_R$ have been considered.
- **Difference** in event kinematics between **left and right handed** scenarios due to the **polarization** of the taus.
- Two scenarios studied: Only $\tilde{\tau}_L$ scenario and degenerate $\tilde{\tau}_L$, $\tilde{\tau}_R$ scenario.
- **No mixing** assumed between $\tilde{\tau}_L$ and $\tilde{\tau}_R$.
- Search in $\ell\tau_h$ ($e\tau_h$ and $\mu\tau_h$) and $\tau_h\tau_h$ final states.

Baseline selections:

- An **isolated electron** with $p_T > 26$ (35) GeV or an **isolated muon** with $p_T > 25$ (38) GeV and $|\eta| < 2.4$ for 2016 (2017).
- An **isolated** τ_h with $p_T > 30$ GeV and $|\eta| < 2.3$.
- **W+jets reduced** by vetoing events containing jets with $p_T > 20$ GeV, and requiring $m_T(\ell, \vec{p}_T^{miss})$ to be between 20-60 GeV or above 120 GeV.
- **DY+jets reduced** by $m(\ell, \tau_h) > 50$ GeV.
- **QCD reduced** by requiring $2.0 < \Delta R(\ell, \tau_h) < 3.5$.

Train BDTs with:

- e/μ and τ_h p_T
- p_T^{miss}
- $m_T(\ell, \vec{p}_T^{miss})$
- $\Delta\eta(\ell, \tau_h)$
- $\Delta\phi(\ell, \tau_h)$
- $\Delta\phi(\tau_h, \vec{p}_T^{miss})$
- $\Delta R(\ell, \tau_h)$
- m_T^{tot}
- m_{T2}
- $m_{CT} = [2p_T^{\ell} p_T^{\tau_h}(1+\cos\Delta\phi(\ell,\tau_h))]^{1/2}$ (endpoint at $(m^2_{\tilde{\tau}} - m^2_{\tilde{\chi}^0_1})/m_{\tilde{\tau}}$)
- D_ζ

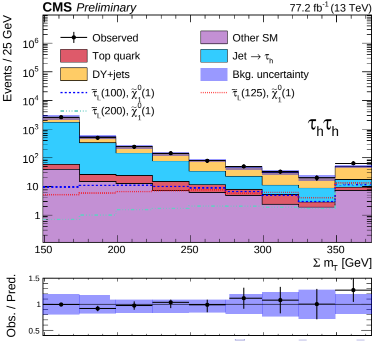


Search strategy ($\tau_h\tau_h$ channel)

Baseline selections:

- Deep Neural Network (DNN) based tau-isolation improves the sensitivity.
- **Two oppositely charged isolated τ_h** with $p_T > 40$ (45) GeV in 2016 (2017) and $|\eta| < 2.1$.
- No additional (Loose) τ_h with $p_T > 30$ GeV.
- No electrons (muons) with $p_T > 20$ GeV and $|\eta| < 2.5$ (2.4).
- **Top quark backgrounds reduced** by vetoing events with b-tagged jets.
- **DY+jets and QCD reduced** by requiring $\Delta\phi(\tau_h^1, \tau_h^2) > 1.5$.
- **QCD reduced** by requiring $p_T^{miss} > 50$ GeV.

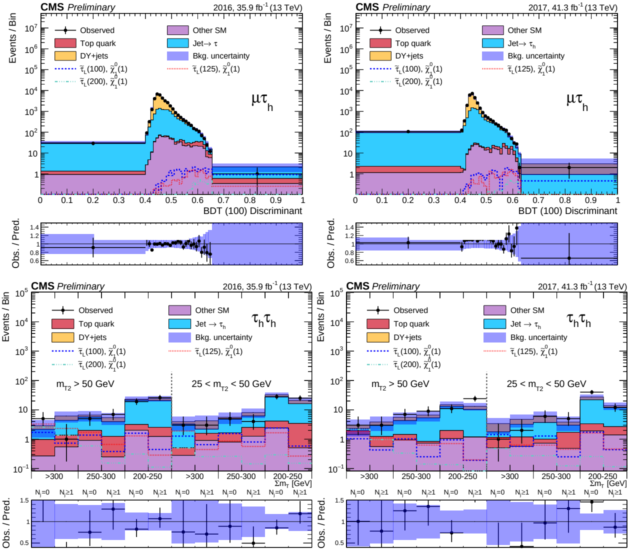
- **Divide the search region in bins of** m_{T2}, m_T^{tot} ($= \Sigma m_T$), and N_j (number of jets).
- Background estimation very similar to the aforementioned chargino/neutralino search.



Results [1]

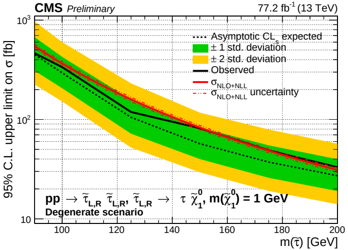
No significant excess is observed.

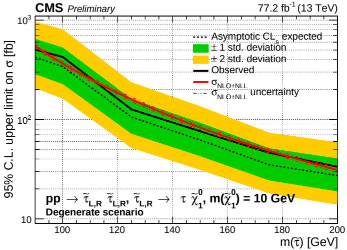
Left: 2016. **Right:** 2017 **Top:** $\mu\tau_h$. **Bottom:** $\tau_h\tau_h$

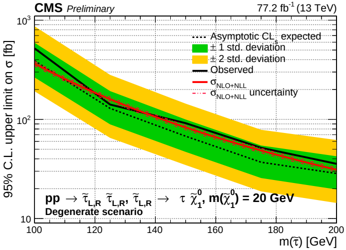


Results [2]

- Purely $\widetilde{\tau}_L$ scenario: For a nearly massless LSP, the strongest limit is observed for a $\widetilde{\tau}$ mass of 125 GeV.
- Degenerate $\widetilde{\tau}_L$, $\widetilde{\tau}_R$ scenario: For a nearly massless LSP, $\widetilde{\tau}$ masses between 90 and 150 GeV are excluded (figures below).





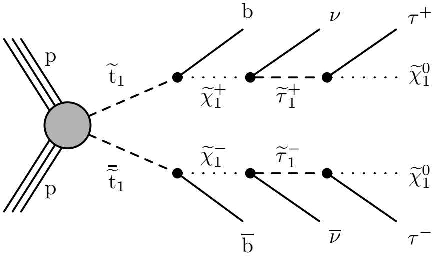


Direct top squark (stop) pair-production

[77.2 fb^{-1} (2016+2017 data)]

[CMS-PAS-SUS-19-003]

Motivation and signal



$$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 0.5\ (m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0})$$
$$m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} = x\ (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})$$
$$\text{Assuming } m_{\tilde{\nu}_\tau} = m_{\tilde{\tau}_1}$$
$$x = [0.25,\ 0.5,\ 0.75]$$

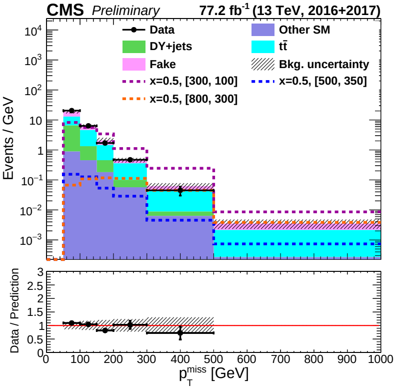
- The chargino/neutralino couples to sleptons as $\sim m_l/\cos\beta$ with the higgsino component.
- In a higgsino-like scenario and/or high $\tan\beta$ scenario, the chargino/neutralino will preferably decay to a τ final state because $m_\tau >> m_e, m_\mu$.
- The **existing top squark exclusions** (hadronic/leptonic) are **not applicable** for the above scenario.

- Assume that $\tilde{\chi}_1^\pm$ decays to $\tilde{\nu}_\tau \tau^\pm$ or $\tilde{\tau}_1^\pm \nu$ with equal probability.
- Search in a $\tau_h\tau_h$ final state.

Baseline selections:

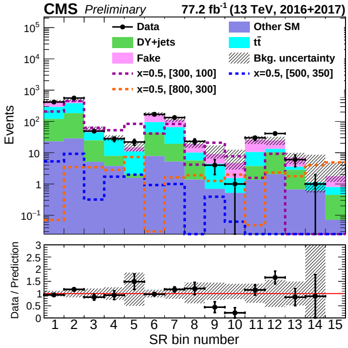
- **Two oppositely charged isolated τ_h** with $p_T > 40$ GeV and $|\eta| < 2.1$.
- **QCD reduced** by requiring $p_T^{miss} > 50$ GeV and $H_T > 100$ GeV.
- **DY+jets and QCD reduced** by requiring at least one b-tagged jet.

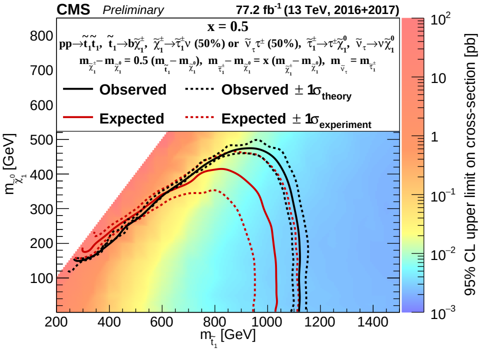
- **Divide the search region into 15 bins** defined in terms of p_T^{miss}, m_{T2} and H_T.
- Major genuine-τ_h background from $t\bar{t}$: Estimated by deriving **scale-factors** from $t\bar{t}$-enriched $e\mu$ and $\mu\mu$ control regions.
- Significant contribution from misidentified-τ_h events: Estimation method similar to stau-pair search.



Results

- **No significant excess is observed.**
- Top squark masses up to 1100 GeV are excluded for a nearly massless LSP.
- Similar exclusions for $x = 0.25$, 0.5 and 0.75.





Summary

- Chargino/neutralino limits have been presented with 35.9 fb^{-1} data.
  Excluded up to $\sim$ 700 GeV.

- Tau slepton limits have been presented with 77.2 fb^{-1} data.
  Masses between 90 and 150 GeV are excluded for the degenerate $\widetilde{\tau}_L$, $\widetilde{\tau}_R$ scenario.
  First CMS result with DNN based tau isolation.

- Top squark limits have been presented with 77.2 fb^{-1} data.
  Excluded up to $\sim$ 1100 GeV.

- **Full Run-2 analyses in the pipeline.**

- LHC now in LS-2, preparing for Run-3.

- **Many more results to come. Stay tuned!**

Backup

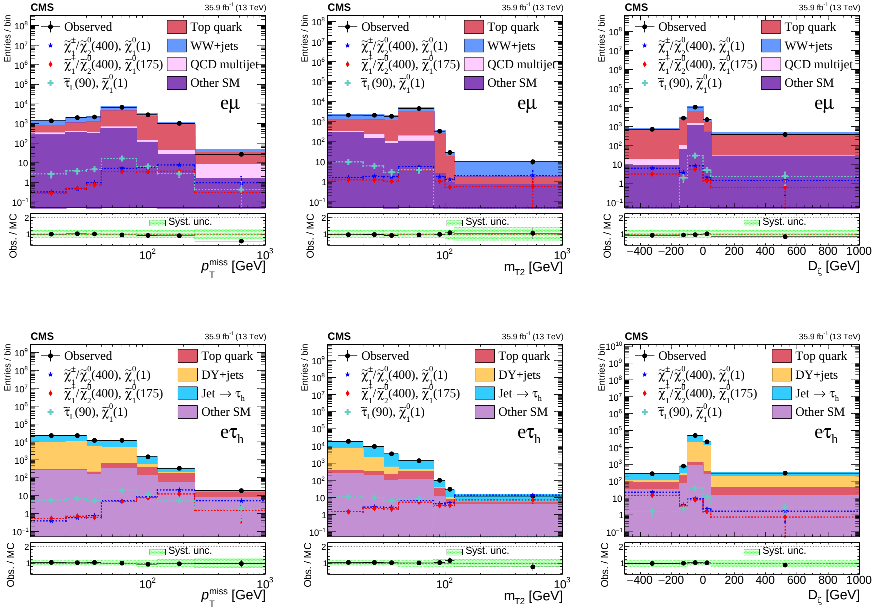
Selection object

Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Electron p_T [GeV]	>24 (13)	>26	—	—
Electron $\|\eta\|$	<2.5	<2.1	—	—
Electron $\|d_{xy}\|$ [cm]	<0.045	<0.045	—	—
Electron $\|d_z\|$ [cm]	<0.2	<0.2	—	—
Electron I_{rel}	<0.1	<0.1	—	—
Muon p_T [GeV]	>24 (10)	—	>25	—
Muon $\|\eta\|$	<2.4	—	<2.4	—
Muon $\|d_{xy}\|$ [cm]	<0.045	—	<0.045	—
Muon $\|d_z\|$ [cm]	<0.2	—	<0.2	—
Muon I_{rel}	<0.15	—	<0.15	—
τ_h p_T [GeV]	—	>20	>20	>40
$\tau_h \|\eta\|$	—	<2.3	<2.3	<2.1
τ_h isolation working point	—	Tight	Tight	Very tight

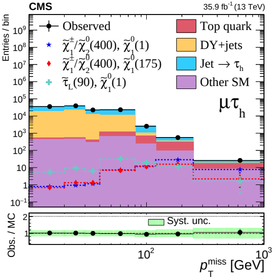
Veto object

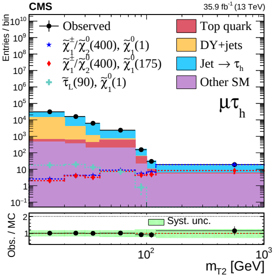
Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Electron p_T [GeV]	>15	>15	>10	>20
Electron $\|\eta\|$	<2.5	<2.5	<2.5	<2.5
Electron $\|d_{xy}\|$ [cm]	<0.045	<0.045	<0.045	<0.1
Electron $\|d_z\|$ [cm]	<0.2	<0.2	<0.2	<0.2
Electron I_{rel}	<0.3	<0.3	<0.3	<0.175
Muon p_T [GeV]	>15	>10	>15	>20
Muon $\|\eta\|$	<2.4	<2.4	<2.4	<2.4
Muon $\|d_{xy}\|$ [cm]	<0.045	<0.045	<0.045	<0.045
Muon $\|d_z\|$ [cm]	<0.2	<0.2	<0.2	<0.2
Muon I_{rel}	<0.3	<0.3	<0.3	<0.25

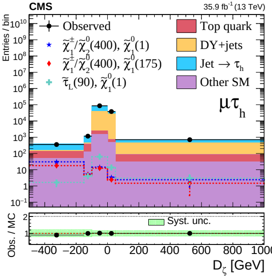
Chargino/neutralino search distributions [1]

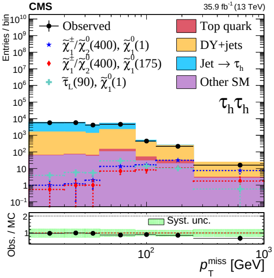


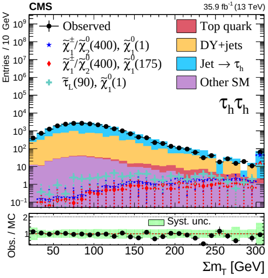
Chargino/neutralino search distributions [2]











Chargino/neutralino search strategy

$e\mu$ (0 and 1 jet categories)

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
0j – 1	<40	<40	< −100
0j – 2			>0
0j – 3		>40	> −500
0j – 4	[40,80]	<40	< −100
0j – 5			>50
0j – 6		[40,80]	< −100
0j – 7			> −100
0j – 8		>80	> −500
0j – 9	[80,120]	<40	< −100
0j – 10			> −100
0j – 11		[40,80]	< −150
0j – 12			> −150
0j – 13		>80	> −500
0j – 14	[120,250]	<40	< −100
0j – 15			> −100
0j – 16		[40,80]	< −150
0j – 17			[−150,−100]
0j – 18			> −100
0j – 19		[80,100]	> −500
0j – 20		[100,120]	> −500
0j – 21		>120	> −500
0j – 22	>250	>0	> −500

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
1j – 1	<40	<40	< −150
1j – 2			[−150,100]
1j – 3			>0
1j – 4		>40	> −500
1j – 5	[40,80]	<40	< −100
1j – 6			>50
1j – 7		[40,80]	> −100
1j – 8		>40	> −500
1j – 9	[80,120]	<40	< −100
1j – 10		[40,80]	< −100
1j – 11		[80,120]	> −500
1j – 12		>120	> −500
1j – 13	[120,250]	<40	< −150
1j – 14			[−150,−100]
1j – 15			> −100
1j – 16		[40,80]	< −150
1j – 17			[−150,−100]
1j – 18			> −100
1j – 19		[80,100]	> −500
1j – 20		[100,120]	> −500
1j – 21		>120	> −500
1j – 22	>250	>80	> −500

$\ell\tau_h$ (0 and 1 jet categories)

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
0j – 1	<40	<40	< −100
0j – 2		>40	> −500
0j – 3	[40,80]	<40	< −100
0j – 4			>50
0j – 5		[40,80]	< −100
0j – 6			> −100
0j – 7		>80	> −500
0j – 8	[80,120]	<40	< −100
0j – 9			> −100
0j – 10		[40,80]	< −150
0j – 11			> −150
0j – 12		>80	> −500
0j – 13	[120,250]	<40	< −100
0j – 14			> −100
0j – 15		[40,80]	< −150
0j – 16			[−150,−100]
0j – 17			> −100
0j – 18		[80,100]	> −500
0j – 19		[100,120]	> −500
0j – 20		>120	> −500
0j – 21	>250	>0	> −500

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
1j – 1	<40	<40	< −150
1j – 2			[−150,100]
1j – 3		>40	> −500
1j – 4	[40,80]	<40	< −100
1j – 5			>50
1j – 6		[40,80]	< −100
1j – 7			> −100
1j – 8		>80	> −500
1j – 9	[80,120]	<40	< −100
1j – 10		[40,80]	< −150
1j – 11			> −150
1j – 12		[80,120]	> −500
1j – 13		>120	> −500
1j – 14	[120,250]	<40	< −150
1j – 15			[−150,−100]
1j – 16			> −100
1j – 17		[40,80]	< −150
1j – 18			[−150,−100]
1j – 19			> −100
1j – 20		[80,100]	> −500
1j – 21		[100,120]	> −500
1j – 22		>120	> −500
1j – 23	>250	>80	> −500

$\tau_h\tau_h$

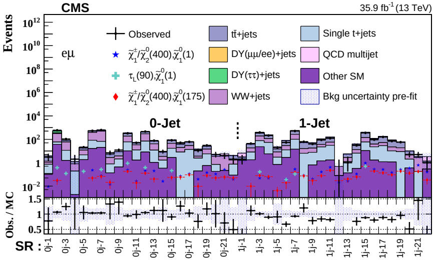
- SR1: $m_{T2} > 90$ GeV
- SR2: $40 < m_{T2} < 90$ GeV, $m_T^{tot} > 350$ GeV
- SR3: $40 < m_{T2} < 90$ GeV, $300 < m_T^{tot} < 350$ GeV

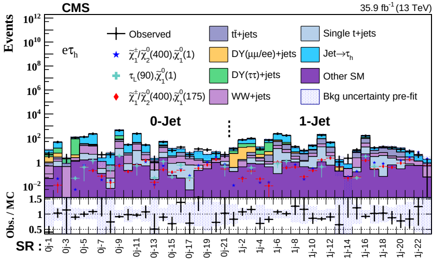
Chargino/neutralino search uncertainties

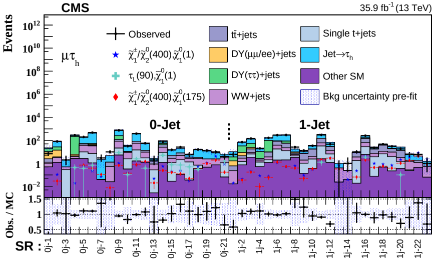
Uncertainty (%)	Signal	Misidentified $e/\mu/\tau_h$	DY+jets	Top quark backgrounds	Rare SM
τ_h efficiency	5–11	0.1–5	5–10	4–10	0.1–10
Electron efficiency ($e\mu$, $e\tau_h$)	3	—	3	3	3
Muon efficiency ($e\mu$, $\mu\tau_h$)	2	—	2	2	2
Isolation extrapolation ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)	—	15–35	—	—	—
Misidentified τ_h correlations ($\tau_h\tau_h$)	—	8–13	—	—	—
QCD multijet normalization ($e\mu$)	—	50	—	—	—
τ_h energy scale ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)	0.1–23	—	1–34	0.1–24	0.1–33
Jet energy scale	0.1–45	—	0.5–24	0.5–39	0.1–67
Jet energy resolution	1–4	—	29–61	3–10	11–31
Unclustered energy	0.1–41	—	2–42	0.1–41	0.1–100
Electron energy scale ($e\mu$, $e\tau_h$)	0.1–22	—	0.5–5	0.1–13	0.1–100
Muon energy scale ($e\mu$, $\mu\tau_h$)	0.1–11	—	0.1–18	0.1–11	0.1–100
b tagging	0.5–3	1–4	0.1–3	4–20	0.1–2
Drell-Yan mass and p_T	—	—	0.5–29	—	—
Background cross sections	—	—	2–20	5–20	10–20
Fast vs. full simulation	1–30	—	—	—	—
Integrated luminosity	2.5	—	—	—	2.5

Chargino/neutralino search results [1]

No significant excess is observed.







	SR1	SR2	SR3
Nonprompt and misidentified τ_h	$0.68\,^{+0.90}_{-0.68}$	2.49 ± 1.83	<1.24
Drell-Yan+jets background	$0.80^{+0.97}_{-0.80}$	<0.71	<0.71
Top quark backgrounds	$0.02^{+0.03}_{-0.02}$	0.73 ± 0.31	1.76 ± 0.68
Rare SM processes	0.72 ± 0.38	0.20 ± 0.15	$0.20\,^{+0.25}_{-0.20}$
Total background	$2.22^{+1.37}_{-1.12}$	$4.35^{+1.75}_{-1.53}$	$3.70^{+1.52}_{-1.08}$
Left (150,1)	1.25 ± 0.40	2.91 ± 0.59	1.53 ± 0.33
Right (150,1)	1.09 ± 0.26	1.27 ± 0.20	0.74 ± 0.17
Mixed (150,1)	1.04 ± 0.22	1.39 ± 0.27	0.92 ± 0.15
Observed	0	5	2

Stau search bins

m_{T2} [GeV]	> 50						25–50					
Σm_T [GeV]	> 300		250–300		200–250		> 300		250–300		200–250	
N_j	0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1

Uncertainty (%)	Signal	Misidentified τ_h	DY+jets	Top quark	Other SM
τ_h efficiency	5–13	—	5–15	1–14	10–51
e/μ efficiency ($\ell\tau_h$)	2–3	—	2–3	2–3	2–3
τ_h energy scale	0.5–12	—	2.6–27	1.2–11	4.1–13
e/μ energy scale ($\ell\tau_h$)	0.1–25	0.1–5	0.1–30	0.1–20	0.1–10
Jet energy scale	0.5–38	—	1.1–19	0.6–13	2.4–14
Jet energy resolution	0.3–22	—	1.9–10	0.7–22	0.2–11
Unclustered energy	0.3–21	—	2.6–30	0.2–6.4	1.7–14
B–tagging	0.2–0.9	—	0.2–23	1.7–25	0.2–1.2
Pileup	0.9–9.1	—	2–22	0.1–24	0.3–25
BDT shape ($\ell\tau_h$)	9	—	9	9	9
$\ell \to \tau_h$ misidentification rate ($\ell\tau_h$)	—	—	—	1	1
Integrated luminosity	2.3–2.5	—	2.3	2.3	2.3–2.5
Background normalization	—	10	5–15	2.5–15	15–25
Drell–Yan mass and p_T	—	—	0.2–11	—	—
τ_h misidentification rate	—	4.6–51	—	—	—
Signal ISR	0.2–8.2	—	—	—	—
Renormalization/factorization scale	1.6–7	—	0.7–14	0.7–30	6.7–16
PDF	—	—	0.1–1.2	0.1–0.4	0.1–0.6

Stau search yields ($\widetilde{\tau}_L$, $\ell\tau_h$)

2016

BDT training	BDT($\mu\tau_h$,100,1)	BDT($\mu\tau_h$,150,1)	BDT($\mu\tau_h$,200,1)	BDT($e\tau_h$,100,1)	BDT($e\tau_h$,150,1)	BDT($e\tau_h$,200,1)
Misidentified τ_h	$1.6 \pm 0.8 \pm 0.3$	$2.3 \pm 1.0 \pm 0.4$	$1.5 \pm 0.8 \pm 0.3$	$3.3 \pm 1.1 \pm 0.5$	$0.2 \pm 0.4 \pm 0.1$	$0.5 \pm 0.7 \pm 0.3$
DY+jets	<0.1	$0.8 \pm 0.8 \pm 0.1$	<0.1	< 0.1	<0.1	$0.1 \pm 0.1 \pm 0.1$
Top quark	$0.3 \pm 0.3 \pm 0.1$	$1.8 \pm 1.2 \pm 0.2$	$1.7 \pm 1.2 \pm 0.6$	$0.2 \pm 0.2 \pm 0.1$	$0.2 \pm 0.2 \pm 0.1$	$1.4 \pm 0.8 \pm 2.0$
Other SM	$0.3 \pm 0.3 \pm 0.1$	$1.4 \pm 0.6 \pm 0.5$	$1.5 \pm 0.6 \pm 0.4$	$0.9 \pm 0.5 \pm 0.4$	$0.6 \pm 0.4 \pm 0.5$	$2.0 \pm 0.7 \pm 1.0$
Total prediction	$2.1 \pm 0.9 \pm 0.4$	$6.4 \pm 1.8 \pm 1.0$	$4.6 \pm 1.6 \pm 0.9$	$4.5 \pm 1.3 \pm 0.8$	$1.0 \pm 0.6 \pm 0.5$	$4.2 \pm 1.3 \pm 1.8$
Observed	1	6	7	5	2	7
Signal	$1.3 \pm 0.4 \pm 0.2$	$0.9 \pm 0.2 \pm 0.1$	$0.7 \pm 0.1 \pm 0.5$	$1.5 \pm 0.4 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$	$1.0 \pm 0.1 \pm 0.2$

2017

BDT training	BDT($\mu\tau_h$,100,1)	BDT($\mu\tau_h$,150,1)	BDT($\mu\tau_h$,200,1)	BDT($e\tau_h$,100,1)	BDT($e\tau_h$,150,1)	BDT($e\tau_h$,200,1)
Misidentified τ_h	$0.9 \pm 0.5 \pm 0.4$	<0.1	<0.1	$2.5 \pm 0.9 \pm 1.3$	$0.3 \pm 0.3 \pm 0.1$	< 0.1
DY+jets	$2.1 \pm 2.1 \pm 3.3$	< 0.1	<0.1	< 0.1	<0.1	< 0.1
Top quark	< 0.1	$0.9 \pm 0.4 \pm 0.8$	$0.6 \pm 0.5 \pm 0.5$	$0.3 \pm 0.3 \pm 0.1$	<0.1	$0.2 \pm 0.2 \pm 0.2$
Other SM	< 0.1	$1.0 \pm 0.7 \pm 1.6$	$0.6 \pm 0.6 \pm 1.1$	$1.0 \pm 0.7 \pm 1.5$	$0.2 \pm 0.2 \pm 0.5$	$1.0 \pm 0.6 \pm 1.6$
Total prediction	$3.0 \pm 2.2 \pm 3.1$	$2.0 \pm 1.0 \pm 2.0$	$1.2 \pm 0.7 \pm 1.3$	$3.7 \pm 1.1 \pm 2.3$	$0.4 \pm 0.4 \pm 0.5$	$1.2 \pm 0.7 \pm 1.6$
Observed	2	6	2	2	1	1
Signal	$0.6 \pm 0.3 \pm 0.1$	$0.4 \pm 0.1 \pm 0.8$	$0.6 \pm 0.1 \pm 0.3$	$1.0 \pm 0.4 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$

Stau search yields ($\widetilde{\tau}_L$, $\tau_h\tau_h$)

2016

m_{T2} [GeV]	> 50					
Σm_T [GeV]	> 300		250 – 300		200 – 250	
N_j	0	≥ 1	0	≥ 1	0	≥ 1
Misidentified τ_h	$1.1 \pm 0.6 \pm 0.6$	$2.9 \pm 0.8 \pm 1.6$	$3.7 \pm 1.0 \pm 2.2$	$2.7 \pm 1.1 \pm 0.5$	$18.2 \pm 2.8 \pm 9.5$	$18.1 \pm 2.9 \pm 6.0$
DY+jets	< 0.7	$1.3 \pm 0.8 \pm 0.5$	$0.5 \pm 0.5 \pm 0.1$	$1.0 \pm 0.7 \pm 0.1$	$1.1 \pm 0.8 \pm 0.2$	$3.3 \pm 1.3 \pm 0.7$
Top quark	$0.7 \pm 0.2 \pm 0.1$	$0.8 \pm 0.2 \pm 0.1$	$1.1 \pm 0.2 \pm 0.2$	$1.0 \pm 0.2 \pm 0.1$	$1.1 \pm 0.3 \pm 0.1$	$1.3 \pm 0.2 \pm 0.3$
Other SM	$0.3 \pm 0.1 \pm 0.1$	$0.5 \pm 0.2 \pm 0.2$	$0.9 \pm 0.4 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$	$2.0 \pm 0.6 \pm 0.3$	$1.2 \pm 0.4 \pm 0.2$
Total prediction	$2.1 \pm 0.6 \pm 0.6$	$5.5 \pm 1.2 \pm 1.7$	$6.2 \pm 1.2 \pm 2.2$	$4.9 \pm 1.3 \pm 0.5$	$22.5 \pm 3.0 \pm 9.5$	$23.9 \pm 3.3 \pm 6.0$
Observed	5	1	5	7	19	26
$m(\widetilde{\tau}_L) = 100\,\mathrm{GeV}$	$1.7 \pm 0.2 \pm 0.4$	$0.7 \pm 0.2 \pm 0.2$	$1.4 \pm 0.2 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$	$1.6 \pm 0.2 \pm 0.3$	$0.4 \pm 0.1 \pm 0.1$

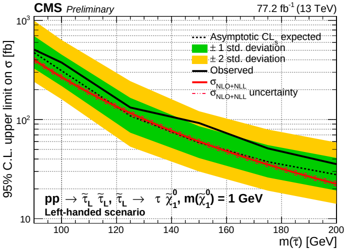
m_{T2} [GeV]	25 – 50					
Σm_T [GeV]	> 300		250 – 300		200 – 250	
N_j	0	≥ 1	0	≥ 1	0	≥ 1
Misidentified τ_h	$2.8 \pm 0.8 \pm 1.8$	$0.5 \pm 0.5 \pm 0.2$	$3.1 \pm 1.0 \pm 1.7$	$3.6 \pm 1.1 \pm 2.0$	$23.5 \pm 2.9 \pm 9.8$	$12.7 \pm 2.4 \pm 4.2$
DY+jets	< 0.7	$1.5 \pm 0.9 \pm 0.5$	$0.4 \pm 0.4 \pm 0.1$	$1.6 \pm 0.9 \pm 0.3$	$4.3 \pm 2.1 \pm 0.7$	$4.5 \pm 1.5 \pm 0.9$
Top quark	$0.2 \pm 0.1 \pm 0.1$	$0.6 \pm 0.2 \pm 0.2$	$0.8 \pm 0.2 \pm 0.1$	$1.3 \pm 0.2 \pm 0.2$	$1.7 \pm 0.3 \pm 0.3$	$2.9 \pm 0.4 \pm 0.3$
Other SM	$0.3 \pm 0.2 \pm 0.1$	$0.9 \pm 0.4 \pm 0.2$	$0.7 \pm 0.4 \pm 0.1$	$1.2 \pm 0.5 \pm 0.3$	$2.4 \pm 0.7 \pm 0.4$	$0.5 \pm 0.2 \pm 0.1$
Total prediction	$3.2 \pm 0.9 \pm 1.8$	$3.5 \pm 1.1 \pm 0.6$	$5.1 \pm 1.2 \pm 1.7$	$7.7 \pm 1.5 \pm 2.1$	$31.9 \pm 3.7 \pm 9.8$	$20.6 \pm 2.9 \pm 4.3$
Observed	3	3	5	4	28	25
$m(\widetilde{\tau}_L) = 100\,\mathrm{GeV}$	$1.3 \pm 0.2 \pm 0.4$	$0.7 \pm 0.2 \pm 0.2$	$1.6 \pm 0.2 \pm 0.2$	$0.8 \pm 0.2 \pm 0.1$	$2.4 \pm 0.3 \pm 0.4$	$0.6 \pm 0.2 \pm 0.1$

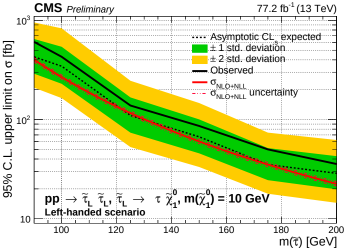
2017

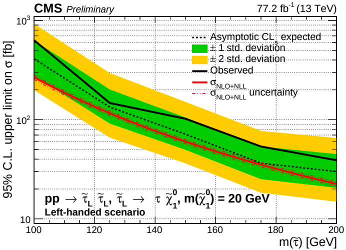
m_{T2} [GeV]	> 50					
Σm_T [GeV]	> 300		250 – 300		200 – 250	
N_j	0	≥ 1	0	≥ 1	0	≥ 1
Misidentified τ_h	$0.2 \pm 0.7 \pm 0.5$	$1.6 \pm 0.8 \pm 0.2$	$2.8 \pm 1.3 \pm 0.3$	$4.5 \pm 1.4 \pm 1.8$	$11.2 \pm 2.3 \pm 4.7$	$9.0 \pm 2.6 \pm 1.1$
DY+jets	< 0.7	$0.5 \pm 0.5 \pm 0.1$	$1.0 \pm 0.6 \pm 0.1$	$1.0 \pm 0.6 \pm 0.1$	$1.3 \pm 0.8 \pm 0.2$	$2.6 \pm 1.0 \pm 0.4$
Top quark	$0.4 \pm 0.3 \pm 0.1$	$0.6 \pm 0.5 \pm 0.2$	$0.3 \pm 0.3 \pm 0.1$	$0.1 \pm 0.1 \pm 0.0$	$0.8 \pm 0.4 \pm 0.1$	< 0.2
Other SM	$1.4 \pm 0.7 \pm 0.3$	$0.6 \pm 0.4 \pm 0.2$	$0.9 \pm 0.5 \pm 0.1$	$0.7 \pm 0.5 \pm 0.1$	$1.0 \pm 0.4 \pm 0.2$	$1.2 \pm 0.6 \pm 0.2$
Total prediction	$2.0 \pm 1.0 \pm 0.6$	$3.2 \pm 1.1 \pm 0.4$	$5.1 \pm 1.5 \pm 0.3$	$6.3 \pm 1.6 \pm 1.8$	$14.3 \pm 2.5 \pm 4.7$	$12.8 \pm 2.8 \pm 1.2$
Observed	3	3	7	9	11	24
$m(\widetilde{\tau}_L) = 100\,\mathrm{GeV}$	$1.0 \pm 0.2 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$	$1.0 \pm 0.2 \pm 0.2$	$0.3 \pm 0.1 \pm 0.0$	$0.9 \pm 0.2 \pm 0.1$	$0.2 \pm 0.1 \pm 0.0$

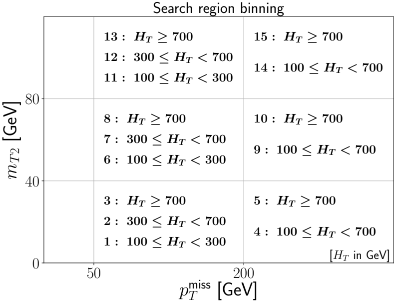
m_{T2} [GeV]	25 – 50					
Σm_T [GeV]	> 300		250 – 300		200 – 250	
N_j	0	≥ 1	0	≥ 1	0	≥ 1
Misidentified τ_h	$0.5 \pm 0.5 \pm 0.1$	$1.9 \pm 0.8 \pm 1.3$	$2.7 \pm 0.9 \pm 1.0$	$1.1 \pm 0.8 \pm 0.3$	$18.6 \pm 3.1 \pm 3.6$	$9.4 \pm 2.1 \pm 1.7$
DY+jets	$1.1 \pm 0.8 \pm 0.3$	$1.0 \pm 0.8 \pm 0.1$	$1.9 \pm 1.4 \pm 0.5$	$0.6 \pm 0.4 \pm 0.2$	$5.0 \pm 2.0 \pm 0.7$	$1.5 \pm 0.7 \pm 0.2$
Top quark	$0.3 \pm 0.3 \pm 0.1$	$0.5 \pm 0.2 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$	$1.0 \pm 0.6 \pm 0.1$	$1.2 \pm 0.6 \pm 0.2$	$1.1 \pm 0.5 \pm 0.2$
Other SM	$0.5 \pm 0.3 \pm 0.1$	$0.6 \pm 0.4 \pm 0.3$	$0.7 \pm 0.5 \pm 0.1$	$0.5 \pm 0.5 \pm 0.1$	$1.9 \pm 0.7 \pm 0.4$	$1.4 \pm 0.6 \pm 0.4$
Total prediction	$2.4 \pm 1.0 \pm 0.4$	$4.0 \pm 1.2 \pm 1.4$	$5.5 \pm 1.8 \pm 1.1$	$3.2 \pm 1.2 \pm 0.4$	$26.7 \pm 3.8 \pm 3.7$	$13.3 \pm 2.3 \pm 1.8$
Observed	1	2	6	5	40	12
$m(\widetilde{\tau}_L) = 100\,\mathrm{GeV}$	$1.4 \pm 0.2 \pm 0.4$	$0.6 \pm 0.1 \pm 0.2$	$1.3 \pm 0.2 \pm 0.2$	$0.3 \pm 0.1 \pm 0.0$	$1.7 \pm 0.2 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$

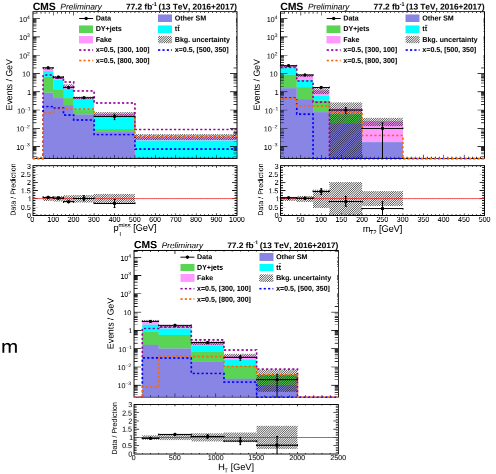
Stau search limit (purely $\tilde{\tau}_L$ scenario)











- Major genuine-τ_h background from $t\bar{t}$: Estimated by deriving **scale-factors** from $t\bar{t}$-enriched $e\mu$ and $\mu\mu$ control regions.
- Significant contribution from misidentified-τ_h events: Estimation method similar to stau-pair search.