

PRINCETON
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Searches for supersymmetry in final states with τ -leptons with the CMS experiment

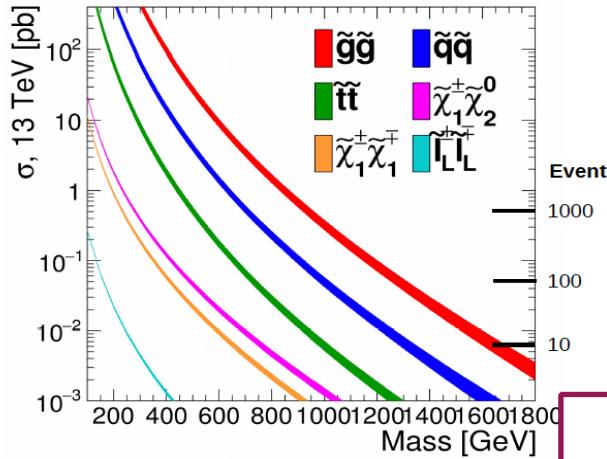
Alexis Kalogeropoulos

for the CMS Collaboration

24 July 2018

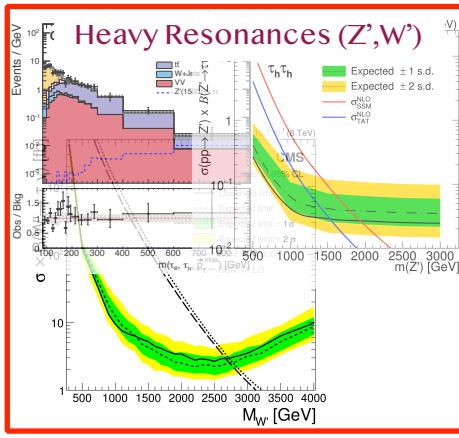
SUSY 2018 / Barcelona

EWK SUSY Searches



► Smallest SUSY production cross-section

- Very challenging analyses
- Need to optimise for specific scenarios
- However, analyses with τ in the final state are still very important for the LHC programme



xsec
measurements

($Z \rightarrow \tau\tau$)

$Z \rightarrow \tau\tau$ (combined)

$\tau_e + \tau_{\text{had}}$

$\tau_\mu + \tau_{\text{had}}$

$\tau_\mu + \tau_\mu$

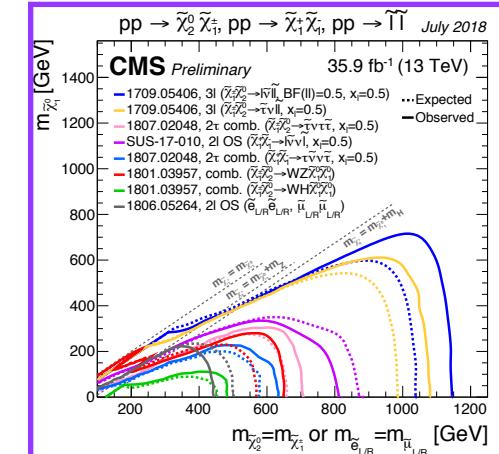
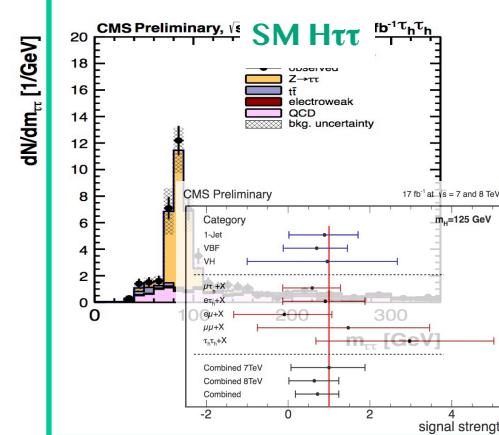
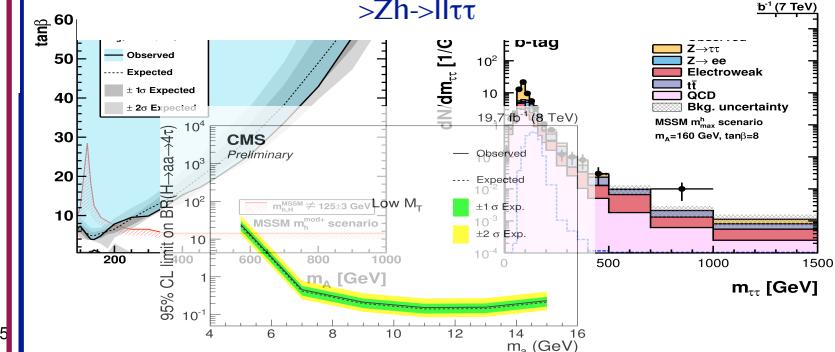
$\tau_e + \tau_\mu$

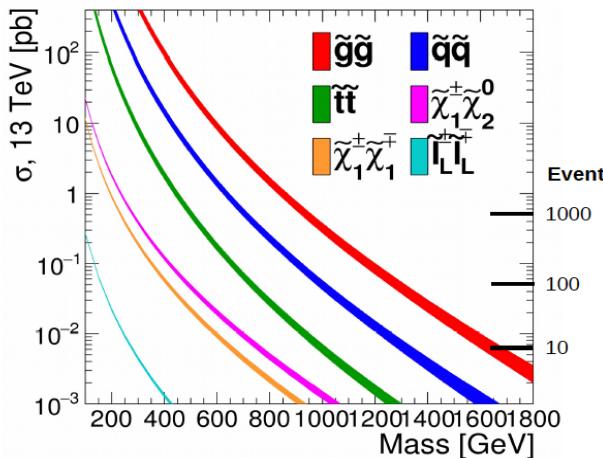
$Z \rightarrow ee, \mu\mu$

luminosity uncertainty not shown

$\sigma(pp \rightarrow ZX) \times B(Z \rightarrow \tau\tau) [\text{nb}]$

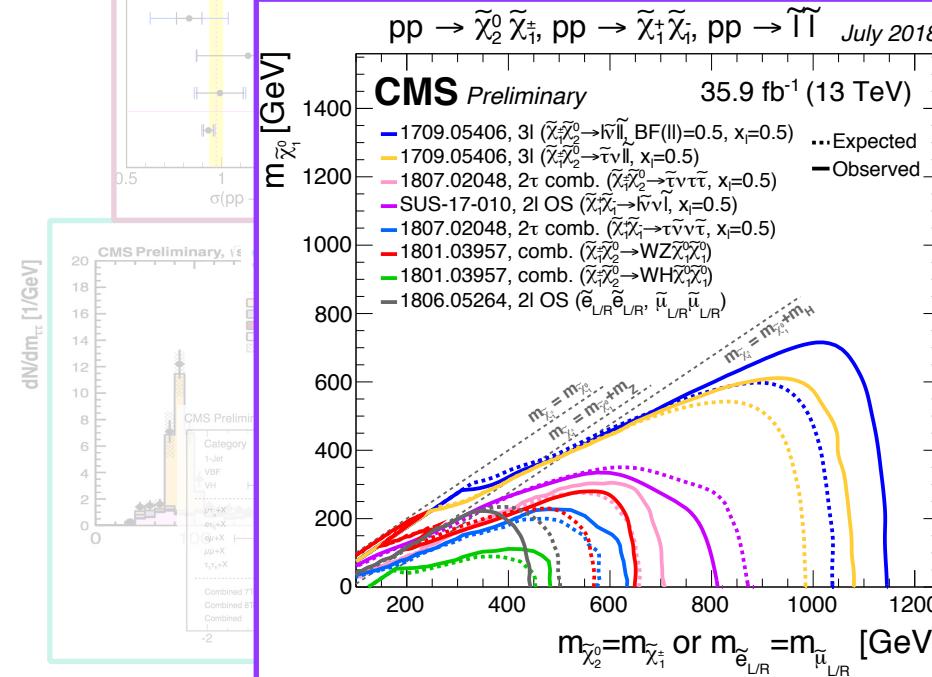
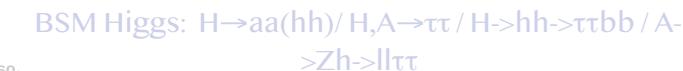
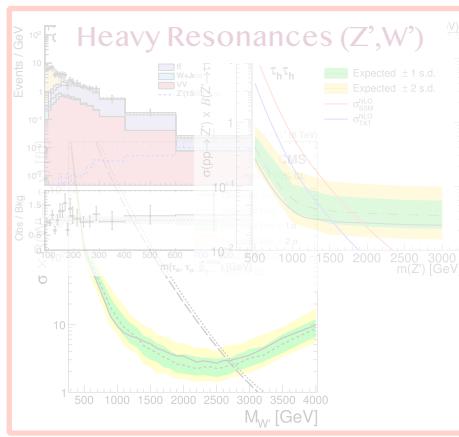
BSM Higgs: $H \rightarrow aa(hh)/H,A \rightarrow \tau\tau/H \rightarrow hh \rightarrow \tau\tau bb/A \rightarrow Zh \rightarrow ll\tau\tau$





- ## ► Smallest SUSY production cross-section

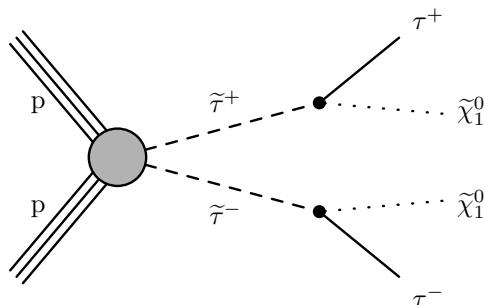
- Very challenging analyses
 - Need to optimise for specific scenarios
 - However, searches with τ in the final state are still very important for the LHC programme



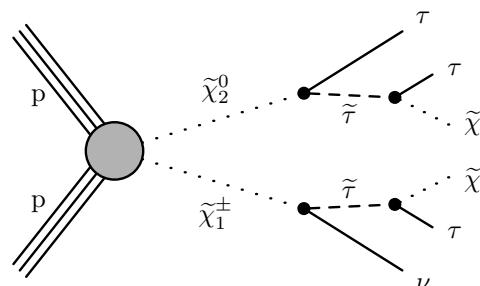
This talk :
SUS-17-003
SUS-16-039

CMS-SUS-17-003, arXiv:1807.02048

NEW

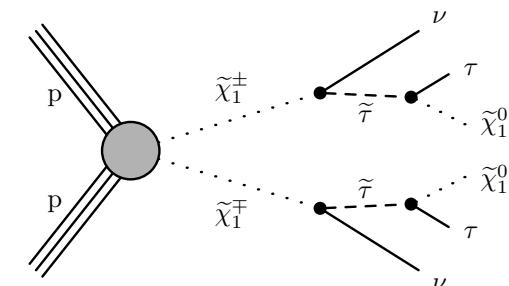


direct $s\tau_h$ pair production



C1N2

indirect $s\tau_h$ production



C1C1

The analysis is the combination of
CMS-PAS-17-002 & CMS-PAS-17-003
covering both direct and indirect stau production

Covered final states : $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$

Lepton Selection

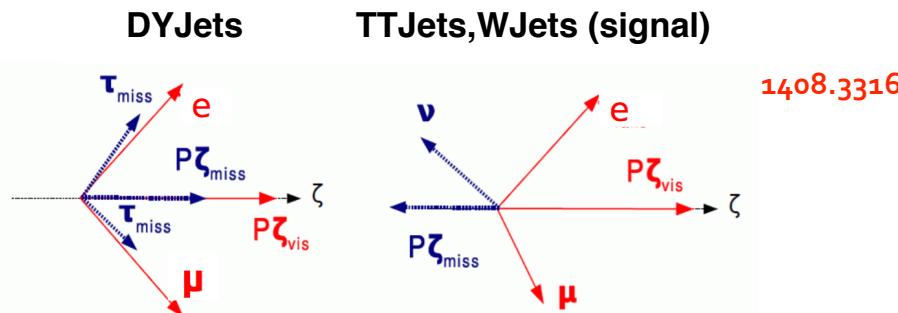
Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Electron p_T [GeV]	>24 (13)	>26	—	—
Electron $ \eta $	<2.5	<2.1	—	—
Electron $ d_{xy} $ [cm]	<0.045	<0.045	—	—
Electron $ d_z $ [cm]	<0.2	<0.2	—	—
Electron I_{rel}	<0.1	<0.1	—	—
Muon p_T [GeV]	>24 (10)	—	>25	—
Muon $ \eta $	<2.4	—	<2.4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

+ Veto 3rd leptons

Baseline selection

Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$ \Delta\phi(\ell_1, \ell_2) $	<1.5	<1.5	<1.5	<1.5
$ \Delta\eta(\ell_1, \ell_2) $	<2	<2	<2	—
$\Delta R(\ell_1, \ell_2)$	<3.5	<3.5	<3.5	—
b-tagged jet veto	$p_T > 20 \text{ GeV},$ medium CSV	$p_T > 20 \text{ GeV},$ medium CSV	$p_T > 20 \text{ GeV},$ medium CSV	$p_T > 30 \text{ GeV},$ loose CSV
Additional jet veto	>1 jet, $p_T > 20 \text{ GeV}$	>1 jet, $p_T > 20 \text{ GeV}$	>1 jet, $p_T > 20 \text{ GeV}$	—
$ \Delta\eta(\text{jet}, \ell_i) $ (1-jet events)	<3	<3	<3	—
$\Delta R(\text{jet}, \tau_h)$ (1-jet events)	—	<4	<4	—
$m(\ell_1, \ell_2)$ [GeV]	90–250	>50	>50	—
$e/\mu p_T$ upper bound [GeV]	<200	—	—	—
$m_T(e/\mu, \vec{p}_T^{\text{miss}})$ [GeV]	—	20–60 or >120	20–60 or >120	—
Σm_T [GeV]	—	>50	>50	—

Exploited variables

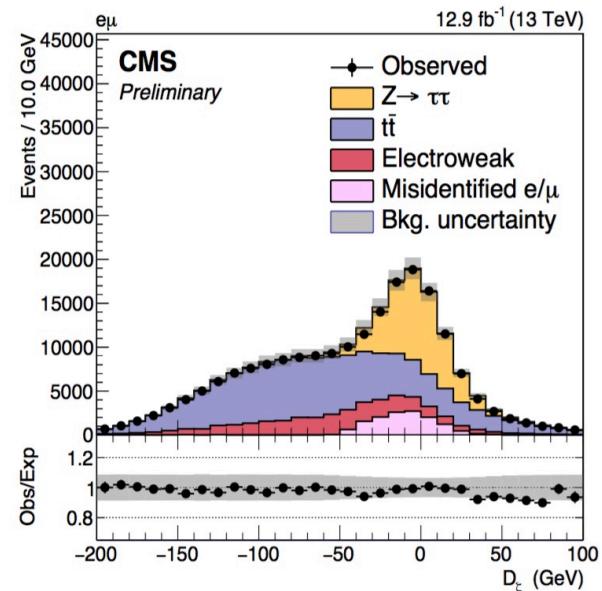


$$D_\zeta = P_{\zeta, \text{mis}} - \alpha \cdot P_{\zeta, \text{vis}}$$

$$P_{\zeta, \text{mis}} = \vec{p}_{\text{T}, \text{mis}} \cdot \vec{\zeta}, \quad P_{\zeta, \text{vis}} = (\vec{p}_{\text{T}, e} + \vec{p}_{\text{T}, \mu}) \cdot \vec{\zeta}$$

ζ – bisector between the direction of the electron and that of the muon

$\alpha = 0.85$ (optimized value)



$Z \rightarrow \tau\tau$: ν 's from τ -decays tend to be collinear with the emitted lepton :

- ▶ $D\zeta$ tends to peak around zero
- ▶ $t\bar{t}$ /signal : The direction of the ν is more random, so $D\zeta$ gives longer tails

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

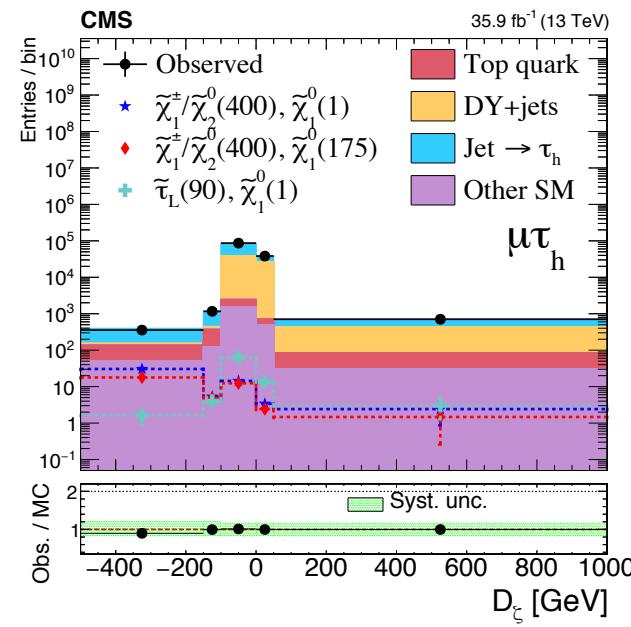
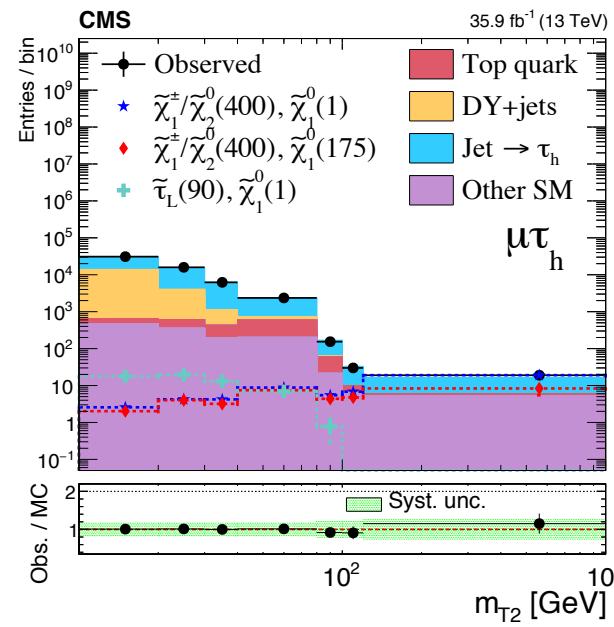
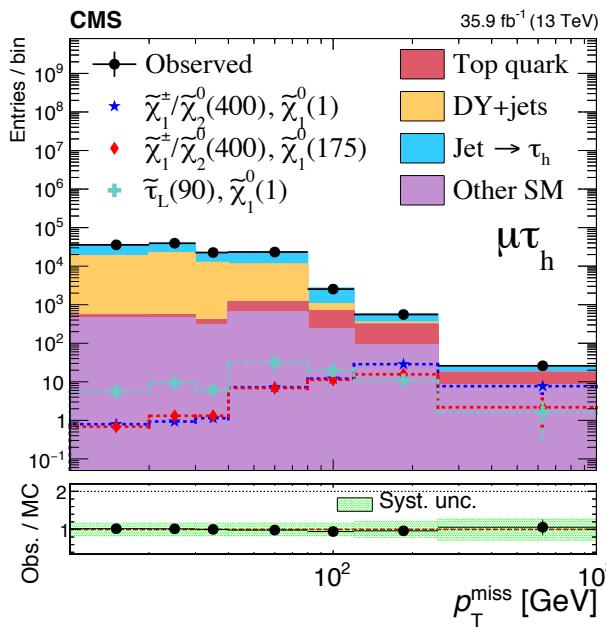
$$m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{\text{miss}}} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right].$$

Signal regions

ThTh : Three SR optimized for direct production :

- ▶ **SR1** : $m_{T2} > 90$ GeV targeting high $\tilde{\tau}_h$ masses
- ▶ **SR2, SR3** : targeting lower masses w. m_{T2} [40,90] GeV and high (> 350 GeV) or moderate (300-350 GeV) Σm_T

1-2 ℓ : Signal regions are formed in $[p_T^{\text{miss}}, m_{T2}, D_\zeta, n_{\text{jet}}]$ bins, 144 in total

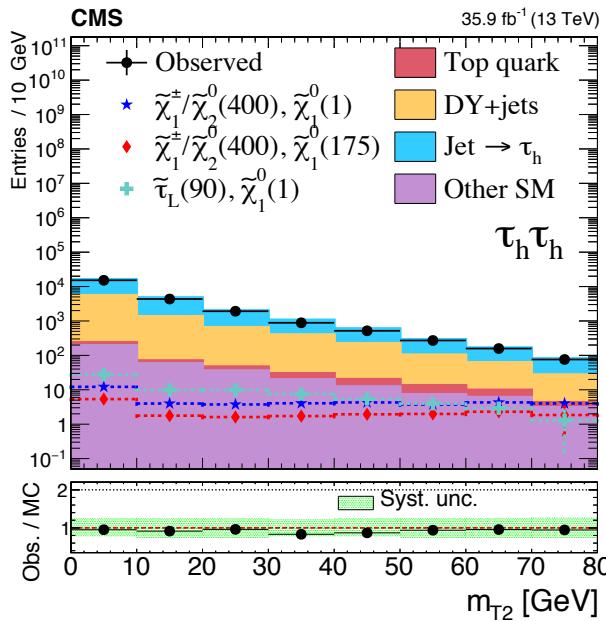
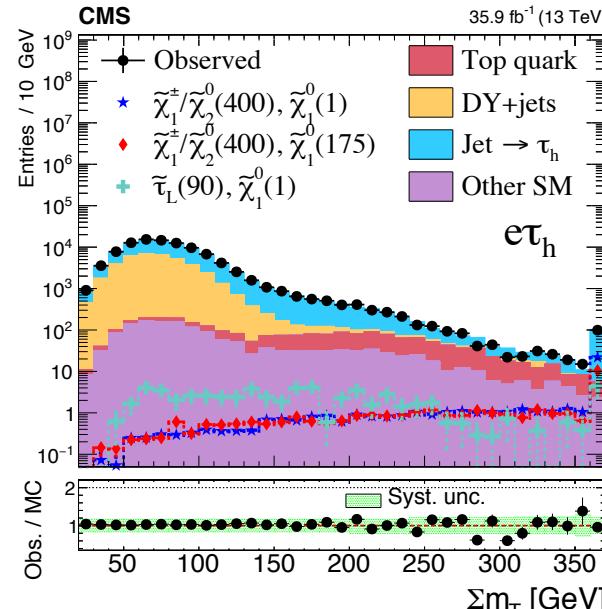


Background estimation

- **mis-ID τ_h :** Dominant when a jet is faking a τ_h , QCD (W+jets) for 0ℓ (1ℓ); taken from data.
- ▶ **$\tau_h\tau_h$:** Looser isolation w. both $\tau_h\tau_h$ SS; estimate the rate that non-prompt or mis-ID τ_h pass the tight selection (~25%). Final result as a function of τ_h 's (p_T , decay mode ;1-3 prong).
- ▶ **1-2 ℓ :** Estimating a Transfer Factor **R** from a sideband region in (p_T, η) of the τ_h , in a W+jets enriched CR ($60 < mT < 120$ GeV, $pT_{miss} > 40$ GeV).
- ▶ Finally, the estimated events in the SR are taken from :

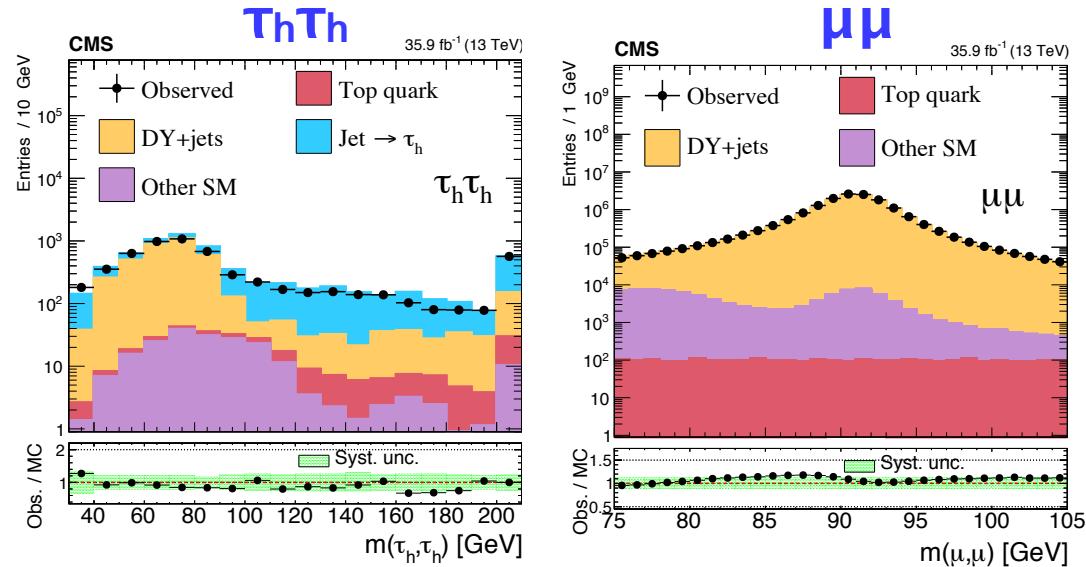
$$R = \frac{N_{\text{data}}^{\text{CS}}(T) - N_{\text{MC no W}}^{\text{CS}}(T)}{N_{\text{data}}^{\text{CS}}(L\&!T) - N_{\text{MC no W}}^{\text{CS}}(L\&!T)}$$

$$N^{\text{SR}}(\text{jet} \rightarrow \tau) = R (N_{\text{data}}^{\text{sideband}} - N_{\text{MC}}^{\text{sideband}}(\text{genuine } \tau)), \text{ in L \& !T}$$

 $\tau_h\tau_h$ **e τ_h** 

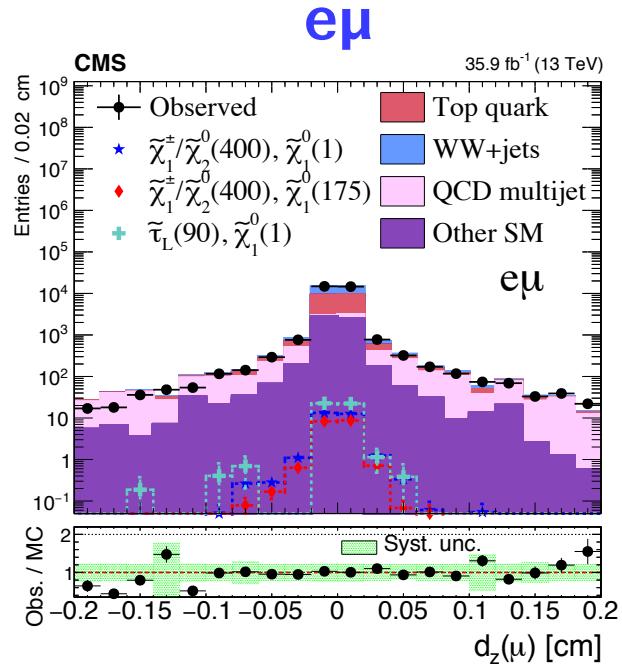
Background estimation

- DY+jets** : Mainly originating from $Z \rightarrow \tau\tau$. Shape is taken from simulation and normalization from data from high purity CRs. Results are validated in MC.

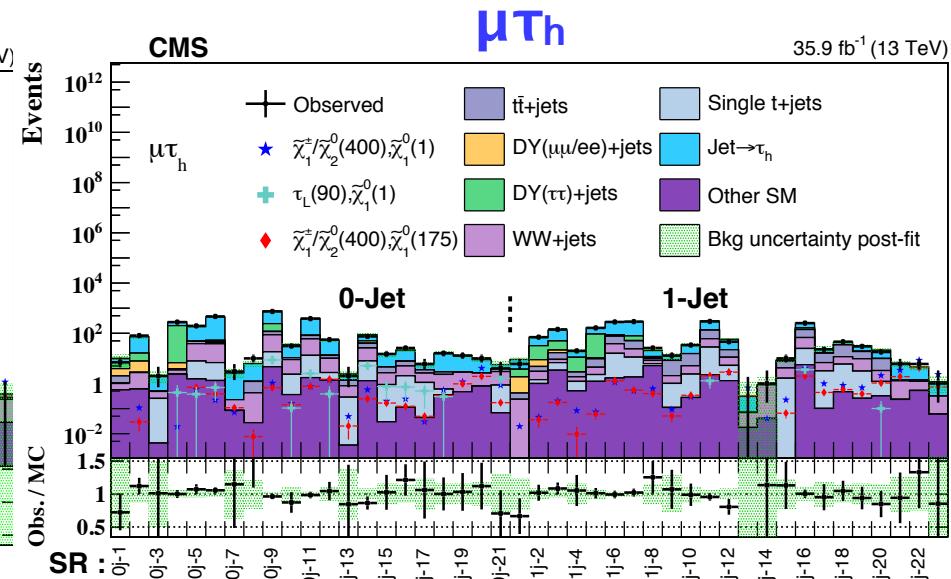
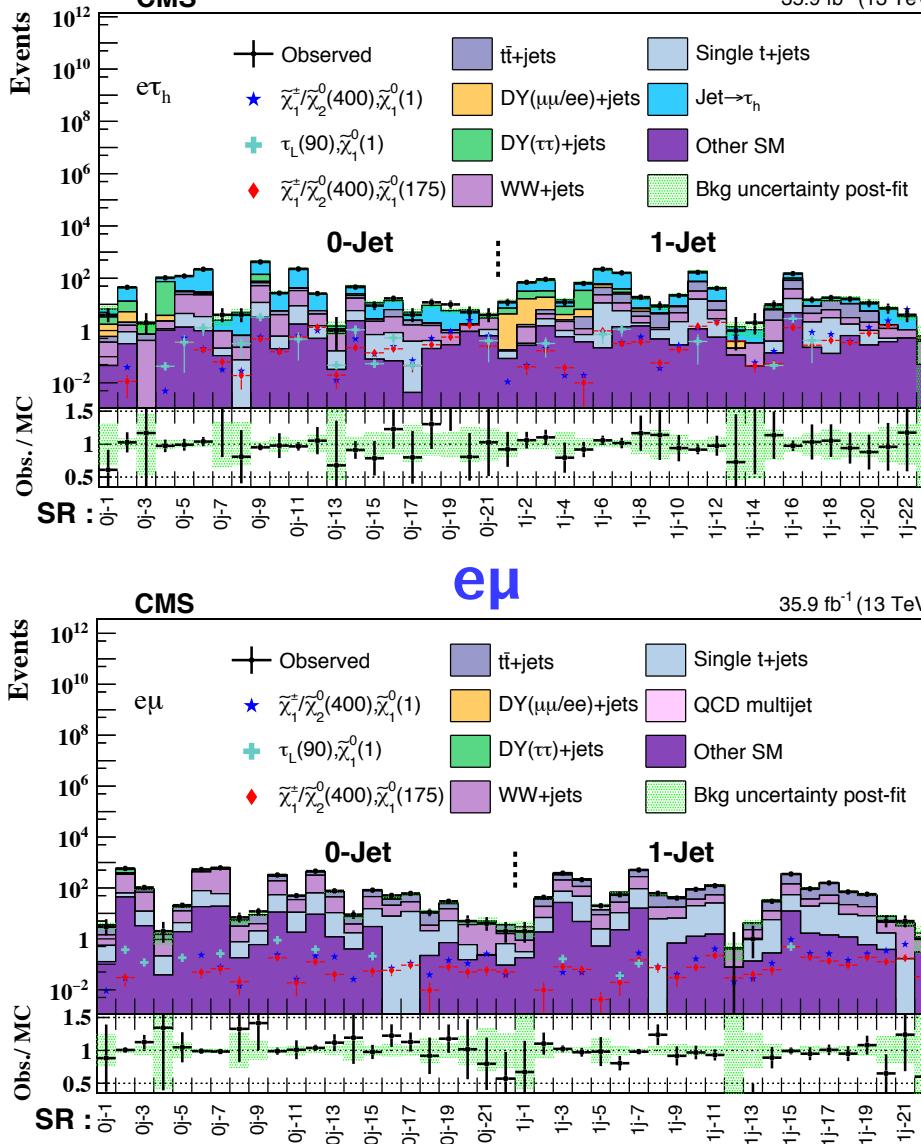


- QCD** : Dominant for $\tau_h \tau_h$ (see previous slide). For $1-2\ell$ from a matrix method; shape is taken from inverted isolation and normalization from OS/SS ratio.

- Other backgrounds** : Taken from simulation

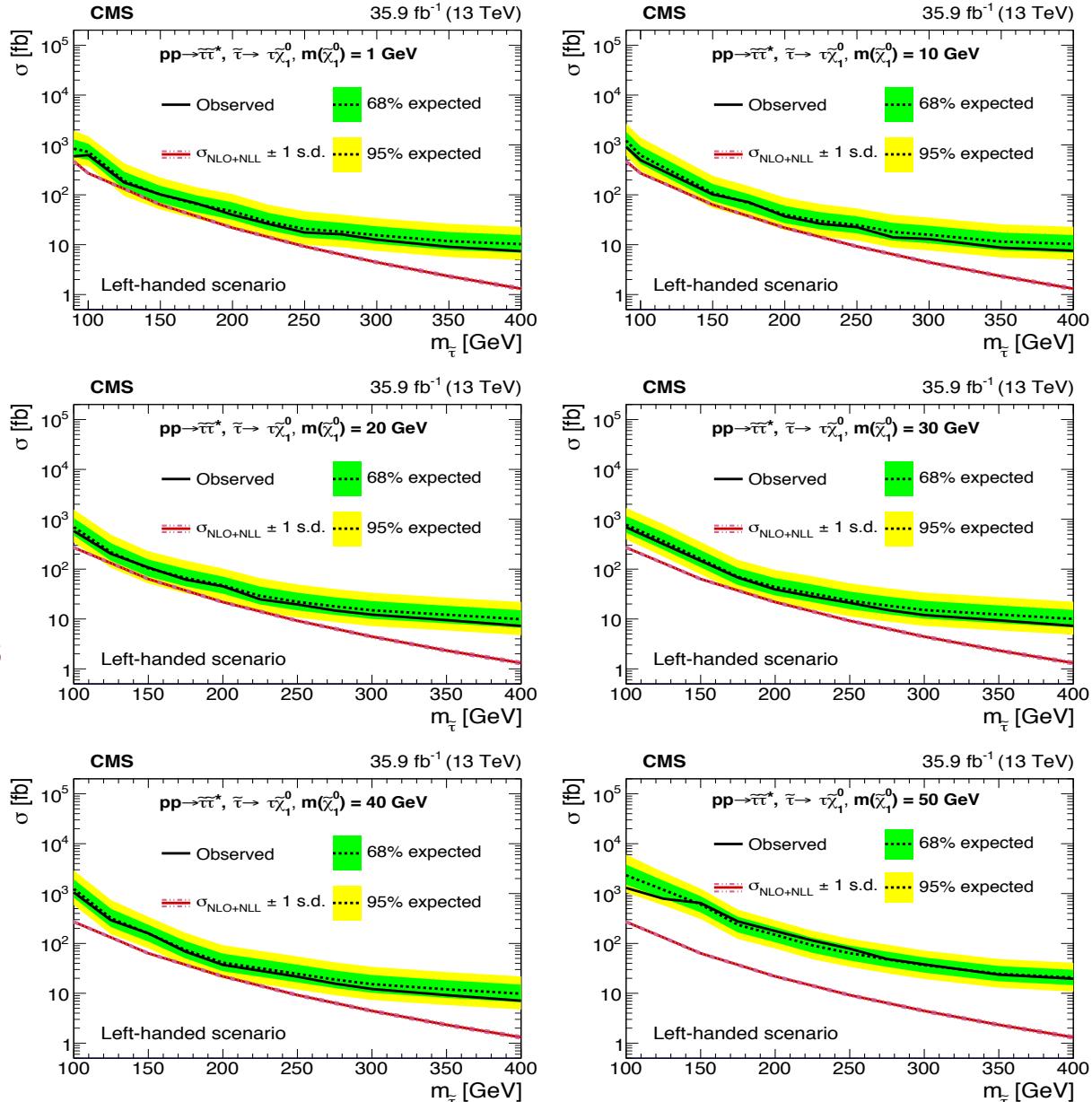
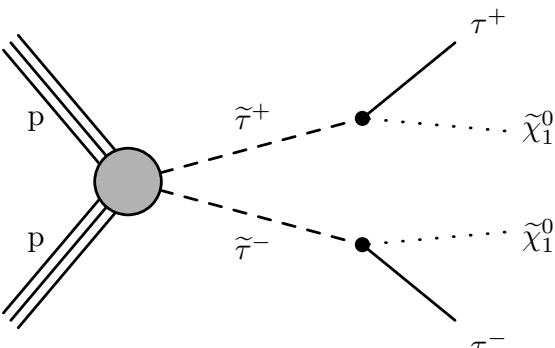


Results (SUS-17-003)



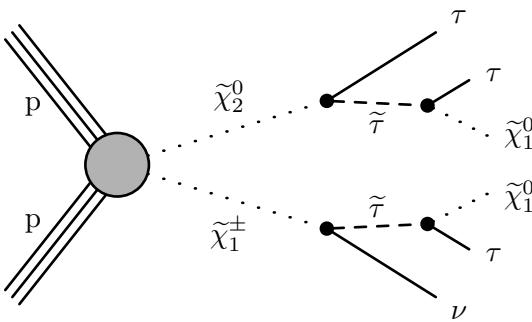
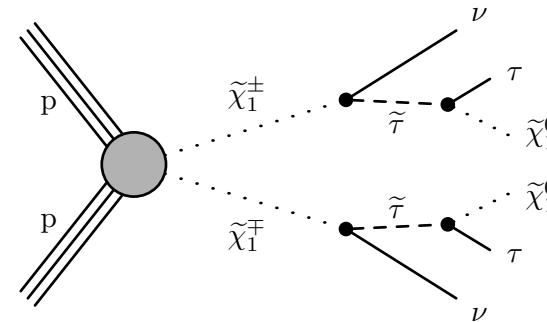
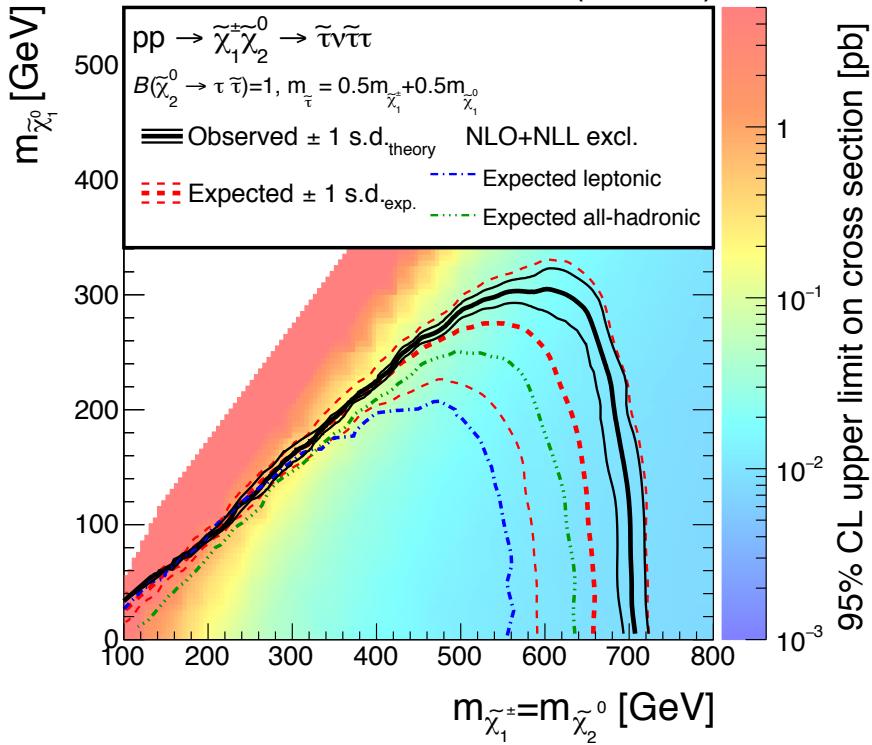
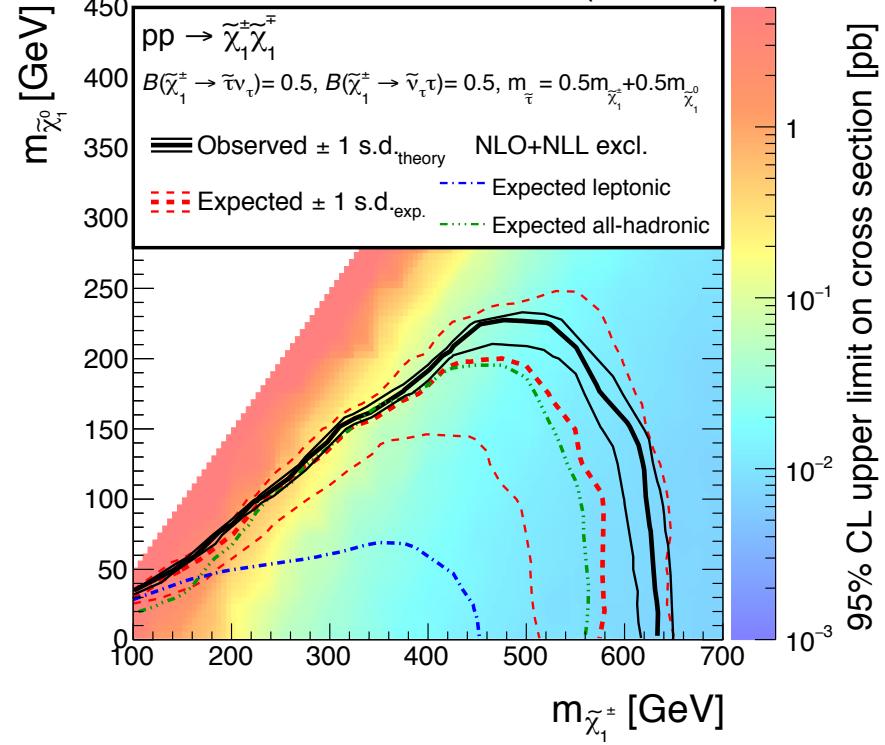
Interpretations - direct production

direct τ_h pair production

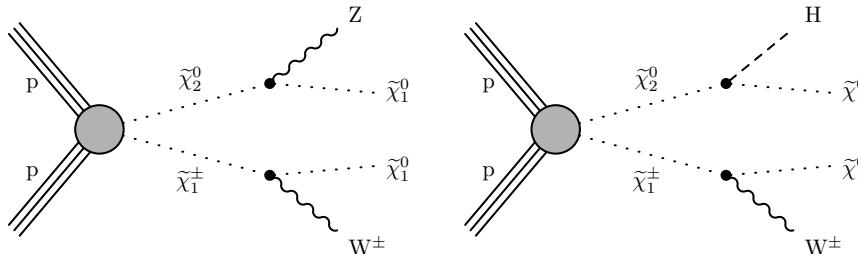


Results also for the right-hand
and maximally mixed scenarios

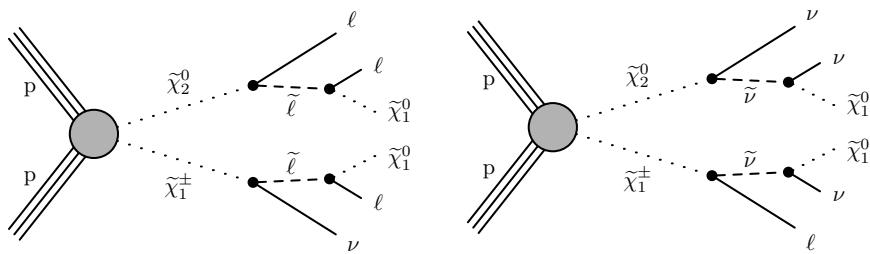
Interpretations - indirect production

C1N2

C1C1

CMS
 35.9 fb^{-1} (13 TeV)

CMS
 35.9 fb^{-1} (13 TeV)


C1N2 w. W/Z/H boson mediated decays

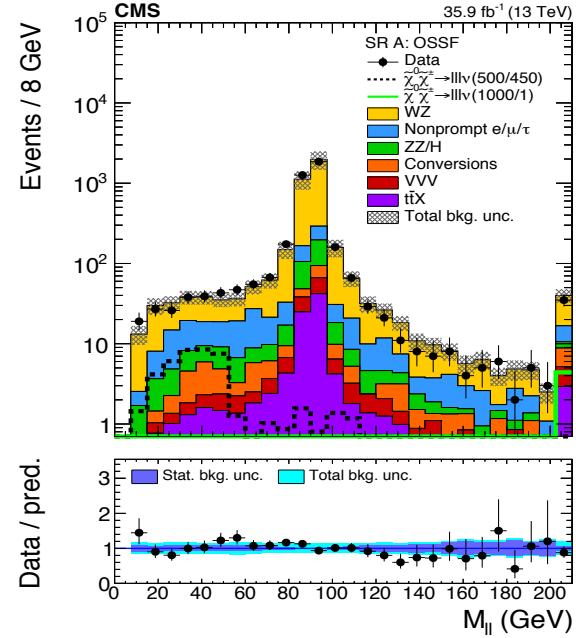
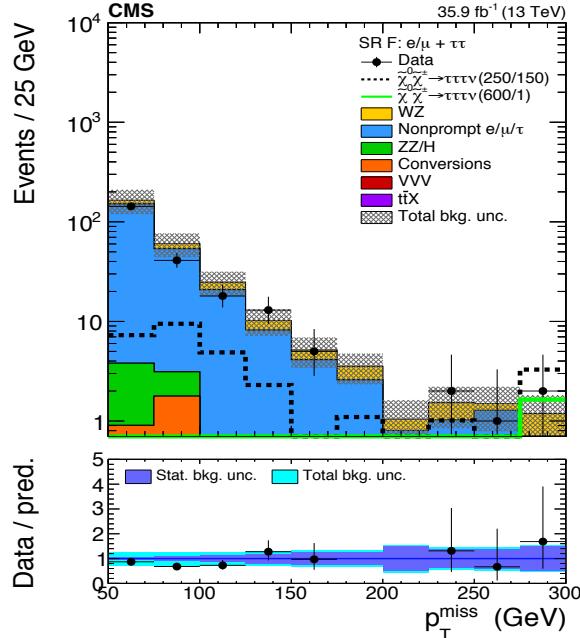
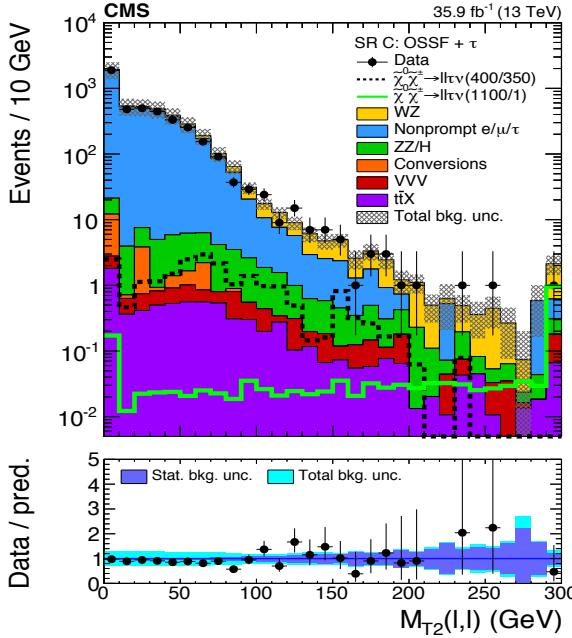


C1N2 w decays mediated by $\tilde{\ell}, \tilde{\nu}$



Events are categorized according to

flavour/ n_ℓ/n_τ (up to 2), n_{jet} , p_T^{miss} , m_τ , $m_{\ell\ell}$, $p_T^{\ell\ell}$, SS or OS

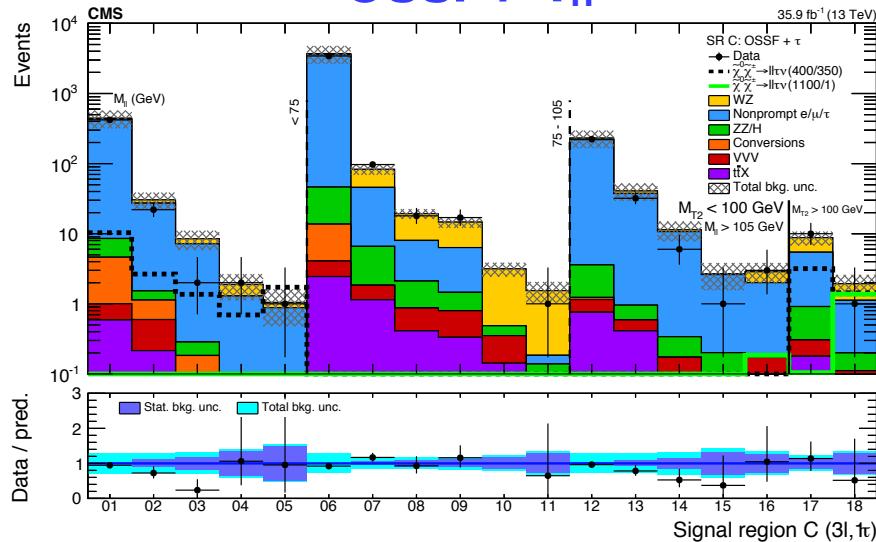


Background estimation

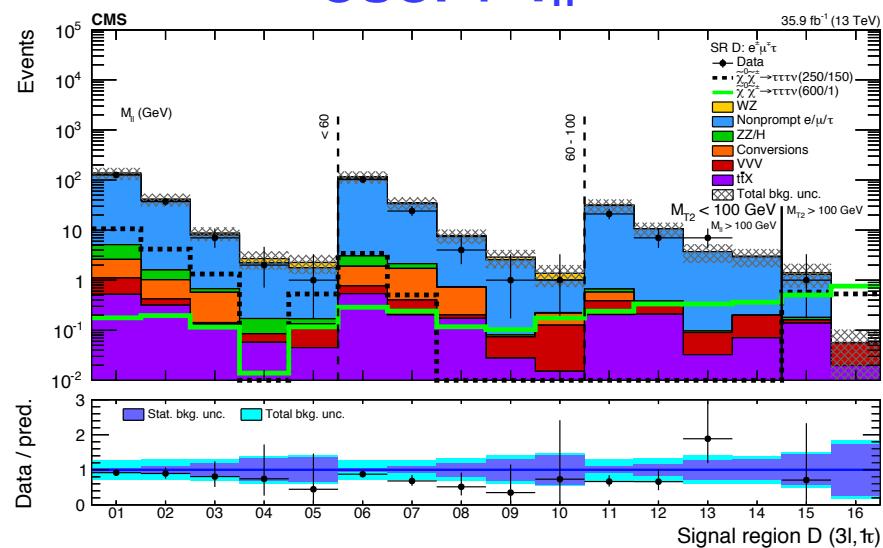
- **WZ or W γ^*** : Dominant with 3 ℓ w. a OSSF pair. Taken from a CR w. $75 < M_{\ell\ell} < 105$ GeV, $m_T < 100$ GeV , $35 < p_T^{\text{miss}} < 100$ GeV.
- **Non-prompt e, μ , τ_h** : Depending on n_ℓ , this is dominated by WJets/DY/tt. Greatest in 3ℓ SR w/o OSSF and those with a τ_h . Estimated from “tight-to-loose” ratio in CR from data.
- **Conversion** : W/Z radiates a γ which converts. Present in OSSF pair and when 2SS ℓ . It is estimated in a CR comparing the $Z \rightarrow \ell\ell$ with $\gamma^* \rightarrow \ell\ell$ where 1 ℓ is out of acceptance compared to full prediction from simulation w. $|M_{\ell\ell} - M_Z| > 15$ GeV
- **Charge mis-ID** : When one ℓ from OS pair is mis-ID'ed (bremsstrahlung in tracker). Relatively small background in SS. Estimated by reweighing OS events w. mis-ID probability (obtained from simulation); relatively small overall.
- **Rare w. multiple ℓ** : SS ℓ s or $> 2\ell$ from rare processes (VVX, ttH). Can be suppressed by a b-jet veto and it is estimated from simulation.

Results and interpretations (SUS-16-039)

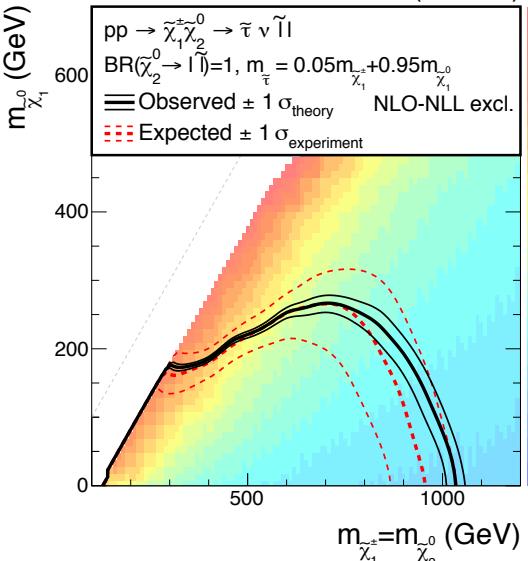
OSSF+ τ_h



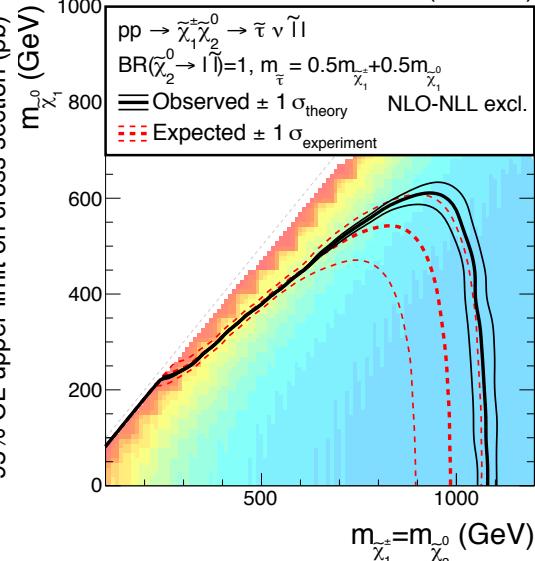
OSOF+ τ_h



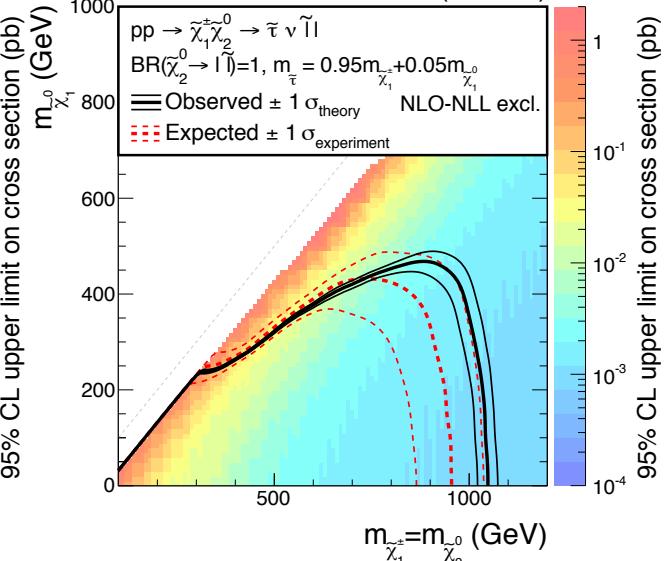
CMS 35.9 fb⁻¹ (13 TeV)



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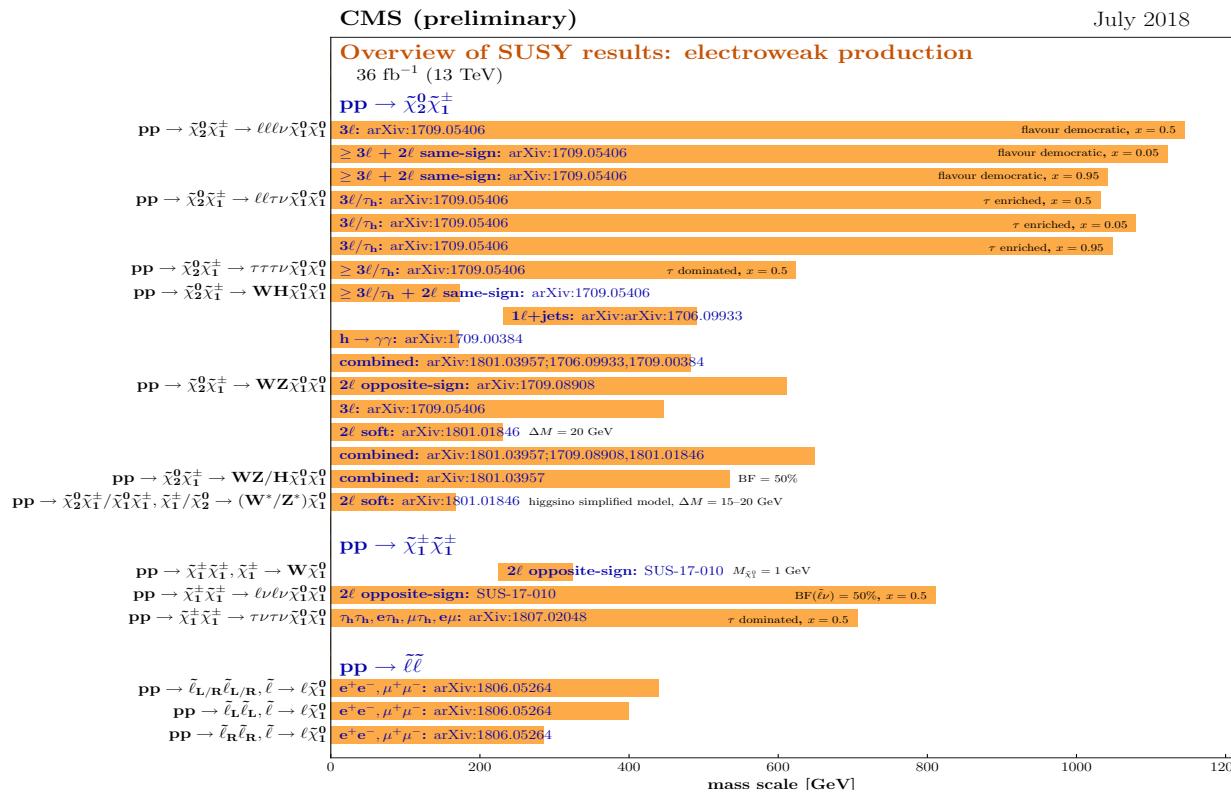
CMS 35.9 fb⁻¹ (13 TeV)



Summary

CMS has in place very rich program for SUSY searches

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>



- ❖ Unfortunately, no signs of SUSY, not yet!
- ❖ First CMS combined Run2 SUSY $\tilde{\tau}$ result sets strong limits
- ❖ CMS is currently taking more data, meaning new results to come soon!

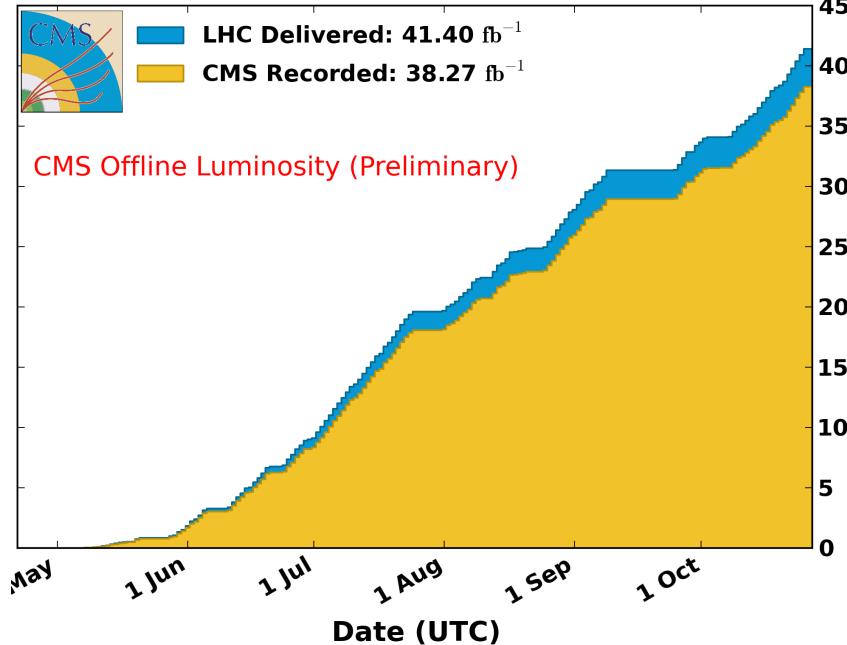
Stay tuned !!!

Backup

2016 Data taking performance

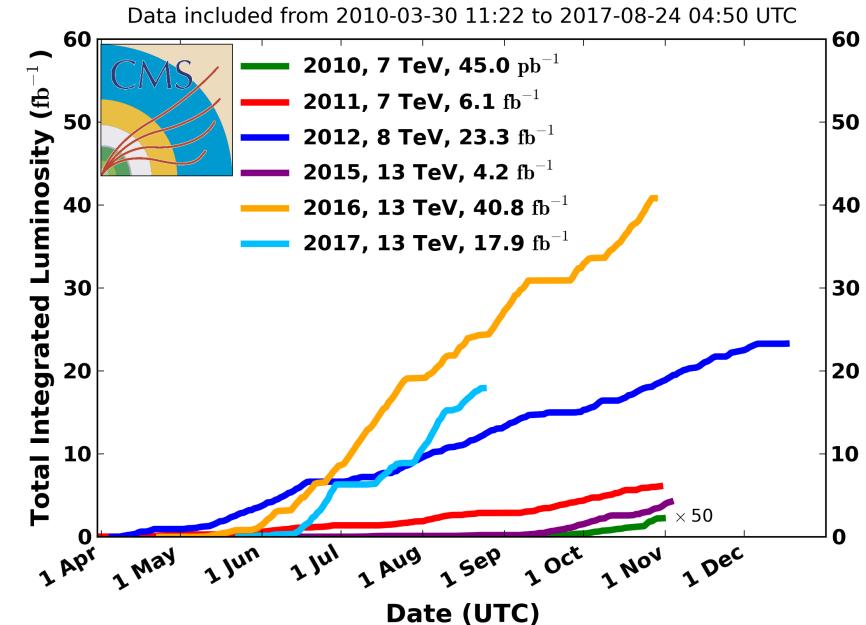
CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = 13$ TeV

Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC

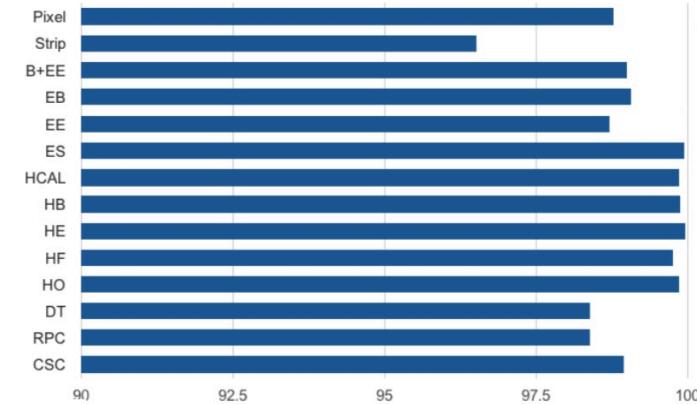


CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2017-08-24 04:50 UTC



Detector Active Fraction



Very successful data-taking 2016 :

Data collection efficiency > 92%

Subdetectors active fraction > 95% (2016)

Currently taking data, already ~100 fb^{-1} and counting!

SUSY Interpretations

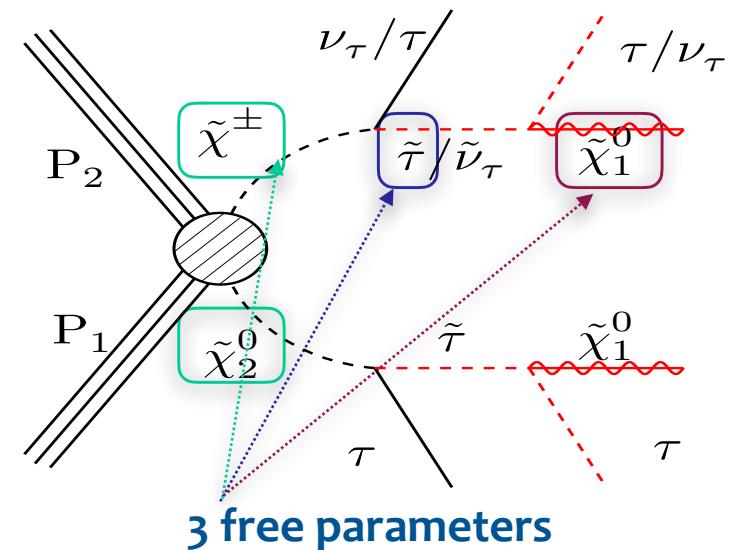
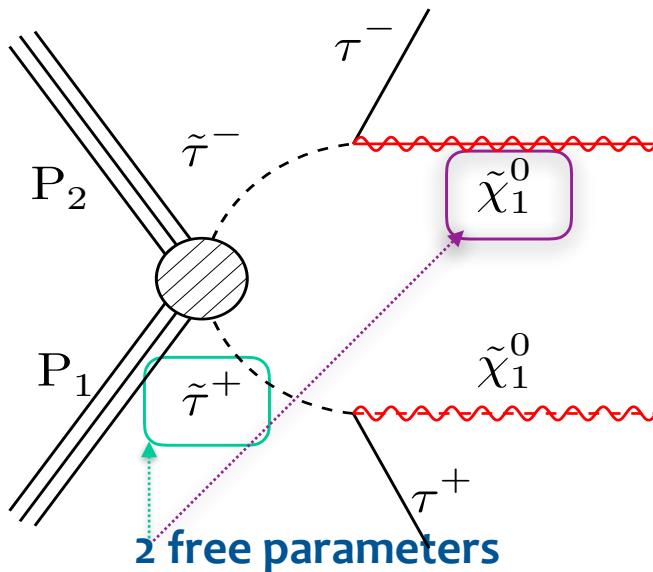
No excess ? → Set upper limits on the cross-section x branching ratio with the use of **Simplified Models of Supersymmetry (SMS)**

SMS are :

- ✓ A bottom-up approach : more emphasis on the experimental signature
- ✓ Very practical due to **small number of free parameters** (usually 2-3)

Example :

- Core process produces a pair of SUSY-particles (other s-particles are decoupled)
- Use of a **single decay chain** producing a well defined final state/topology



Systematics - SUS-17-003

Uncertainty (%)	Signal	Misidentified e/ μ / τ_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

SR C, SR D - SUS-16-039

SR -C, OSSF+ τ_h

p_T^{miss} (GeV)	$75 \leq M_{\ell\ell} < 105$ GeV		$M_{\text{T2}}(\ell_1, \ell_2)$ (GeV)	$M_{\ell\ell} < 75$ GeV		$M_{\ell\ell} \geq 105$ GeV		
50 – 100	3700 ± 1100	3427	0 – 100	440 ± 130	420	231 ± 65	223	
100 – 150	83 ± 14	97		30 ± 8	22	41 ± 11	32	
150 – 200	19.4 ± 3.1	18		8.5 ± 2.6	2	11 ± 4	6	
200 – 250	14.6 ± 2.6	17		1.9 ± 0.8	2	2.7 ± 1.1	1	
250 – 300				1.1 ± 0.6	1	2.9 ± 1.0	3	
300 – 400	3.2 ± 0.7	0		8.8 ± 2.0		10		
≥ 400	1.5 ± 0.6	1		1.9 ± 0.7		1		
50 – 200				≥ 100				
≥ 200								

SR D, OSOF+ τ_h

$M_{\text{T2}}(\ell_1, \ell_2)$ (GeV)	p_T^{miss} (GeV)	$M_{\ell\ell} < 60$ GeV		$60 \leq M_{\ell\ell} < 100$ GeV		$M_{\ell\ell} \geq 100$ GeV	
0 – 100	50 – 100	140 ± 40	126	117 ± 32	102	32 ± 10	21
	100 – 150	41 ± 12	37	35 ± 10	24	11 ± 4	7
	150 – 200	8.7 ± 2.7	7	7.8 ± 2.5	4	3.7 ± 1.5	7
	200 – 250	2.7 ± 1.1	2	2.9 ± 1.2	1	3.0 ± 1.2	
	≥ 250	2.3 ± 0.9	1	1.4 ± 0.6	1		
≥ 100	50 – 200	1.4 ± 0.7				1	
	≥ 200	0.06 ± 0.05				0	

Source	Estimated uncertainty (%)	Treatment
e/ μ selection	3	normalization
τ_h selection	5	normalization
Trigger efficiency	3	normalization
Jet energy scale	2–10	shape
b tag veto	1–2	shape
Pileup	1–5	shape
Integrated luminosity	2.5	normalization
Scale variations and PDF ($t\bar{t}Z$ and $t\bar{t}W$)	15	normalization
Theoretical (ZZ)	25	normalization
Conversions	15	normalization
Other backgrounds	50	normalization
Monte Carlo statistical precision	1–30	normalization
Nonprompt leptons (closure)	30	normalization
Nonprompt leptons (W/Z bkg. subtraction)	5–20	shape
Charge misidentification	20	normalization
WZ normalization	10	normalization
WZ shape	5–50	shape
ISR uncertainty	1–5	shape
Scale variations for signal processes	1–2	shape
Lepton efficiencies	2	normalization
Signal acceptance (p_T^{miss} modeling)	1–5	shape

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Model	Categories used	Figure
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, flavor-democratic, $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + 0.5 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	A	14
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, flavor-democratic, $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + 0.05 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	SS, A	15 (left)
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, flavor-democratic, $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + 0.95 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	SS, A	15 (right)
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, τ -enriched, $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + 0.05 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	A, C	16 (left)
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, τ -enriched, $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + 0.5 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	A, C	16 (center)
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, τ -enriched, $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + 0.95 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	A, C	16 (right)
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, τ -dominated, $m_{\tilde{\tau}} = m_{\tilde{\chi}_1^0} + 0.5 \cdot (m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$	B–F	17
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, heavy sleptons, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WZ$	A	18 (left)
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, heavy sleptons, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WH$	SS, A–K	18 (right)
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow ZZ\tilde{G}\tilde{G}$	A–K	19 (upper)
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow HZ\tilde{G}\tilde{G}$	A–K	19 (middle)
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow HH\tilde{G}\tilde{G}$	A–K	19 (lower)