Searches for Tau Sleptons at the Large Hadron Collider

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On behalf of the ATLAS and CMS Collaborations

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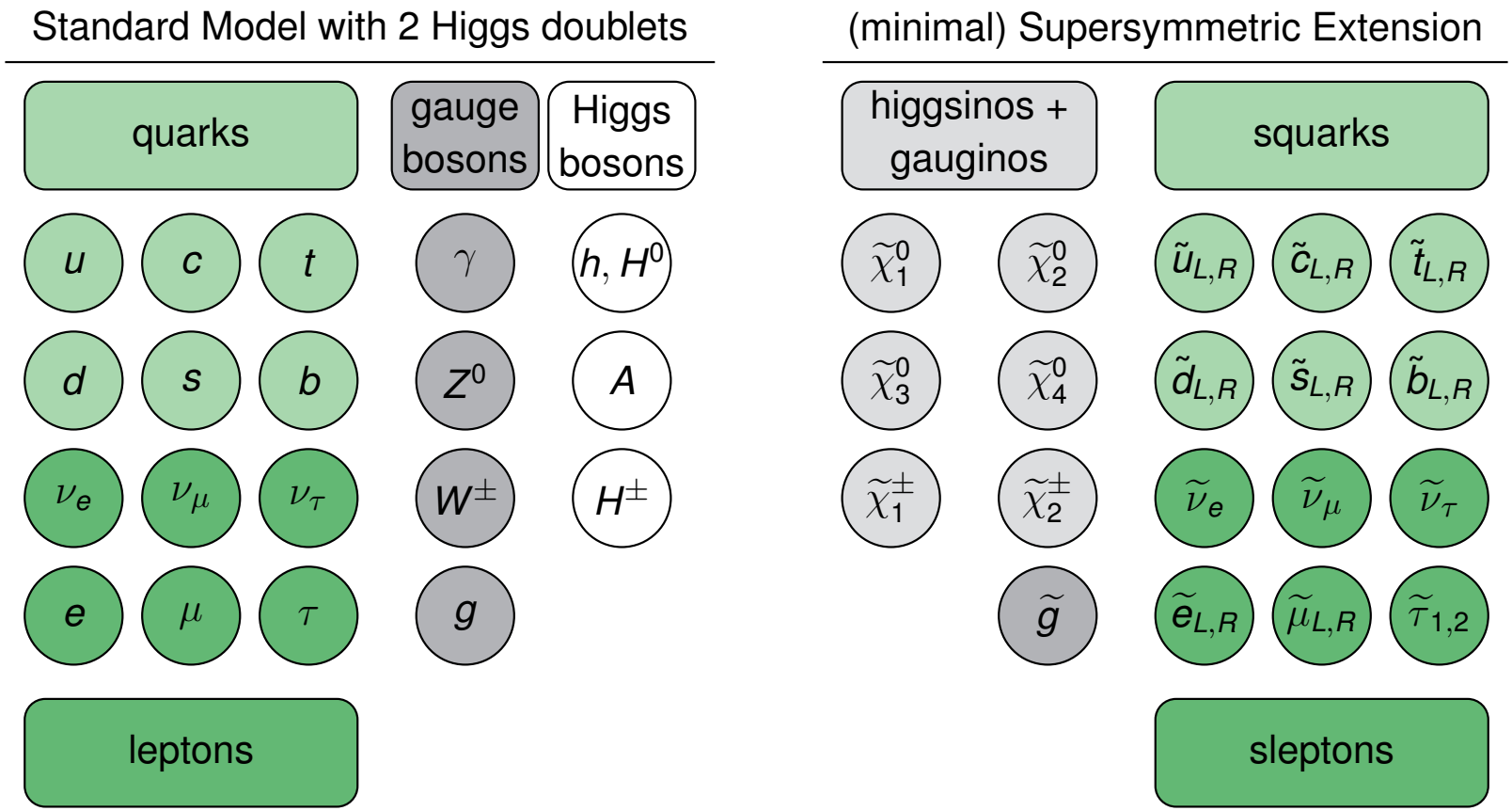
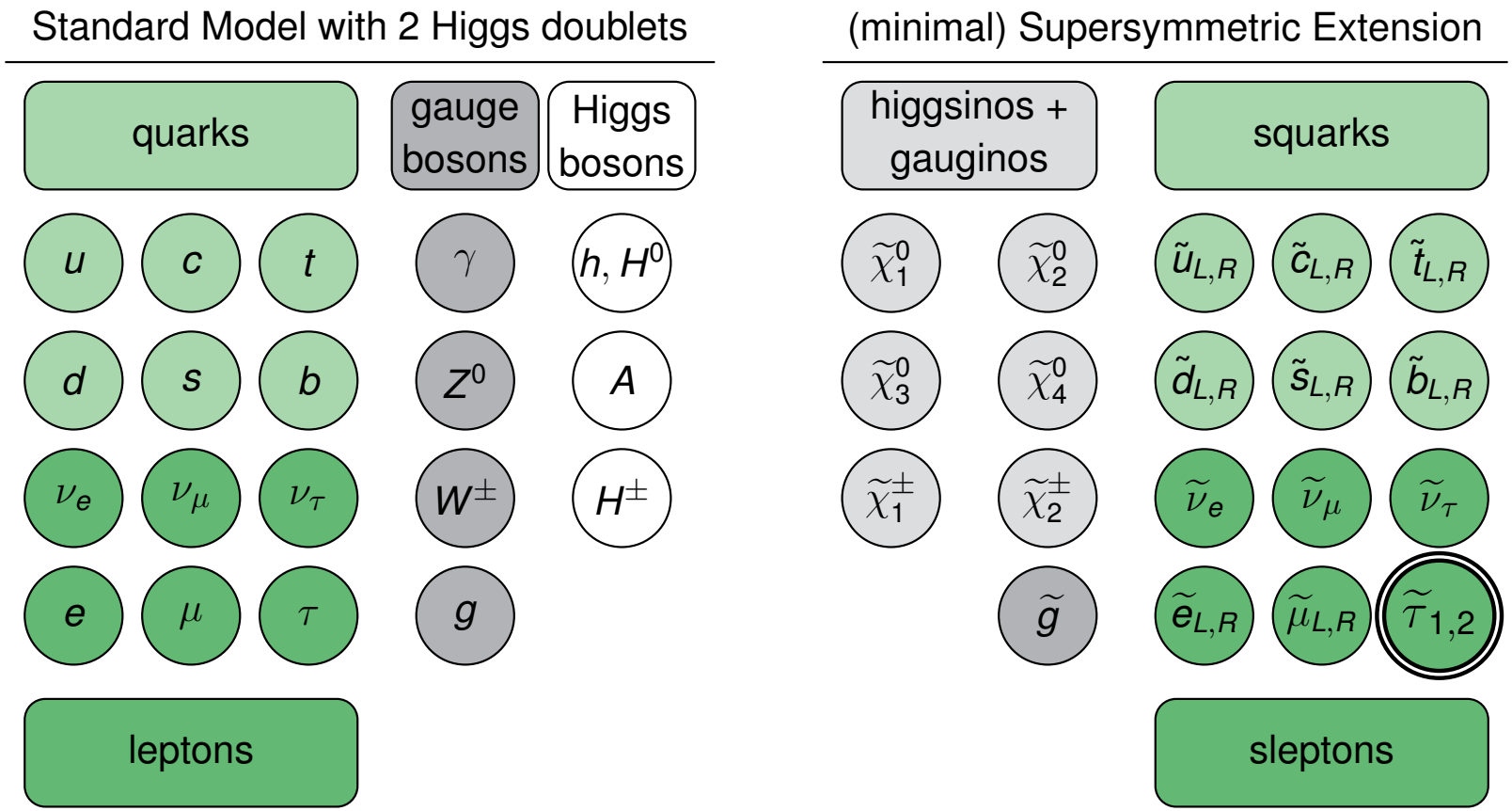
Setting the Scene



Setting the Scene

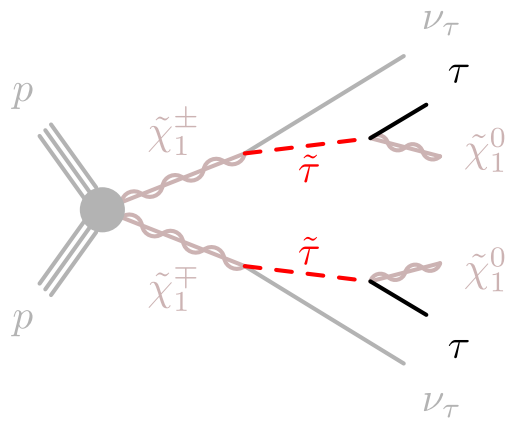


- Topic of this talk: scalar superpartner of tau lepton = “tau slepton” or “stau” ($\widetilde{\tau}_1$)

Tau Leptons: as SUSY Signature

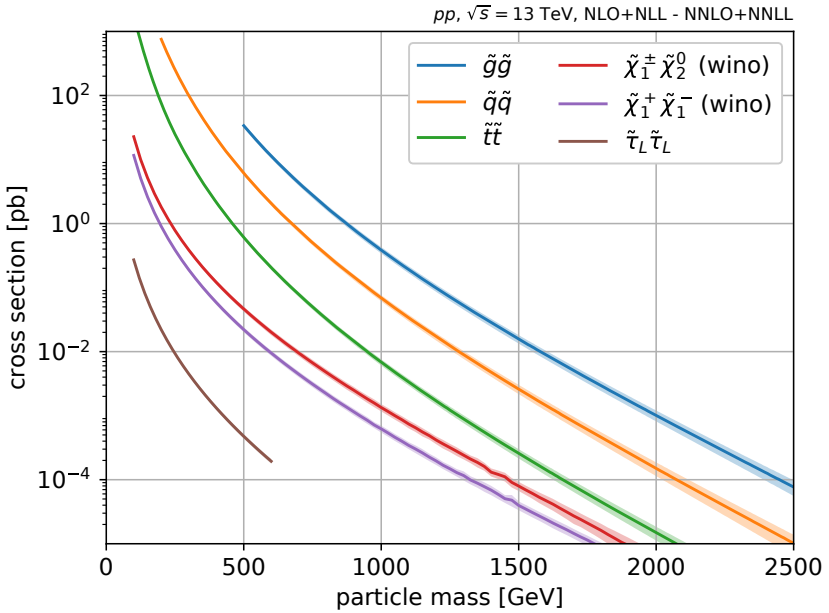
Motivation

- Tau sleptons $\widetilde{\tau}$ in decay chains $\Rightarrow$ final states enriched with tau leptons
  - tau lepton: hadronic (τ_h) or leptonic decay (τ_ℓ)
- Often $m(\widetilde{\tau}) < m(\widetilde{e}), m(\widetilde{\mu})$ — in particular for SUSY scenarios with large $\tan\beta$
  - neutralinos and charginos then decay predominantly via tau sleptons
- Models with low fine-tuning often feature a light tau slepton
- Light $\widetilde{\tau}$ almost degenerate with bino LSP enables co-annihilation
  $\rightarrow$ obtain relic dark-matter density consistent with observations
- Searches with tau leptons complementary to searches with light leptons
  - cover as much of SUSY phenomenology as possible



- Note: will assume R-parity conservation and prompt decays$^{(\star)}$

Different Production Modes of SUSY Particles



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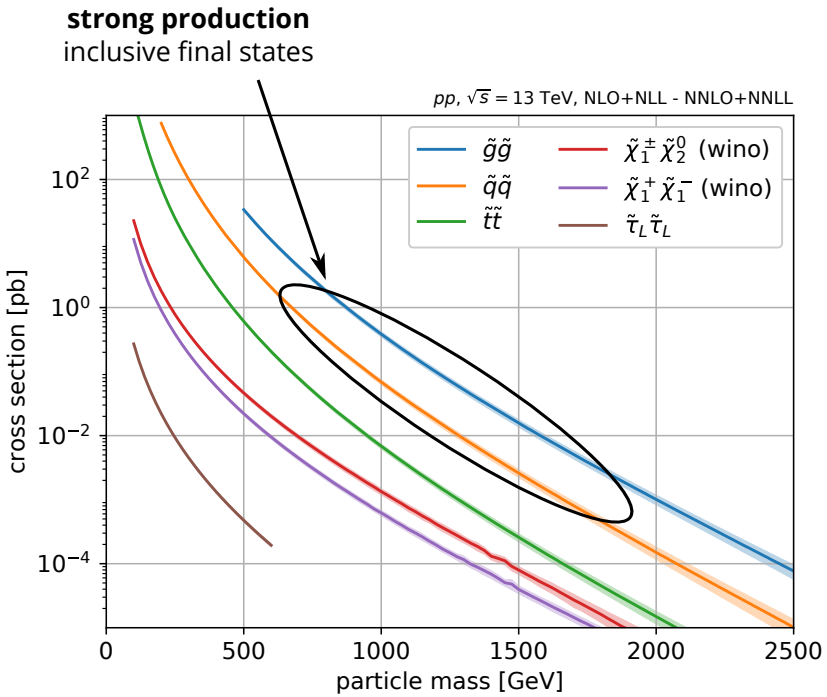
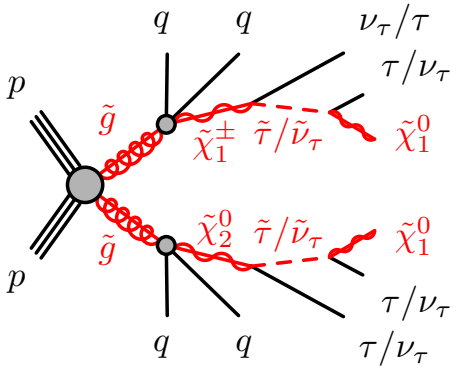


Example simplified model with <u>indirect</u> production of $\widetilde{\tau}$:



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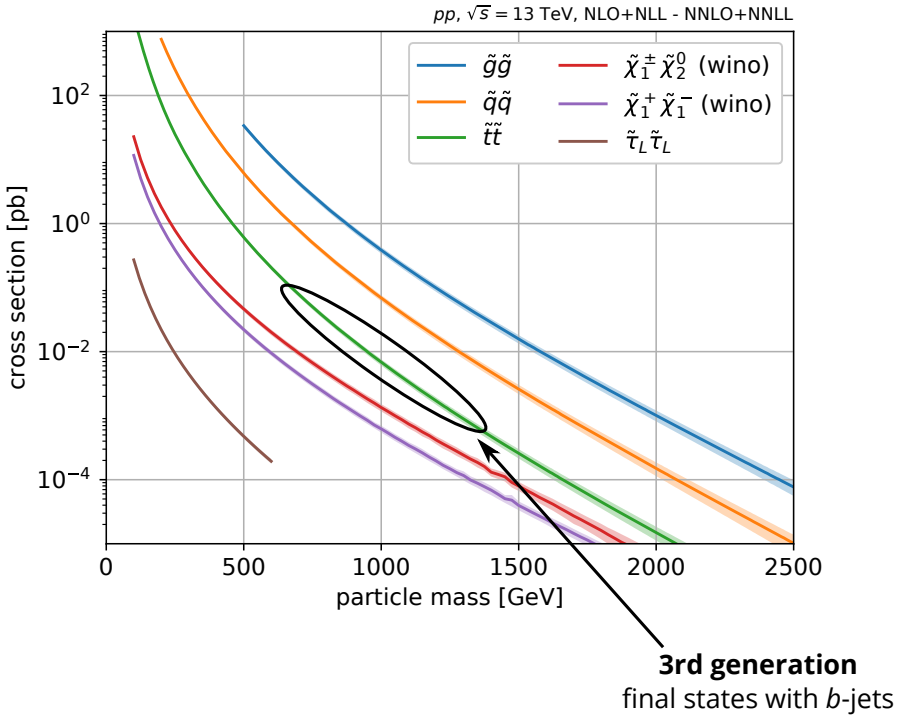

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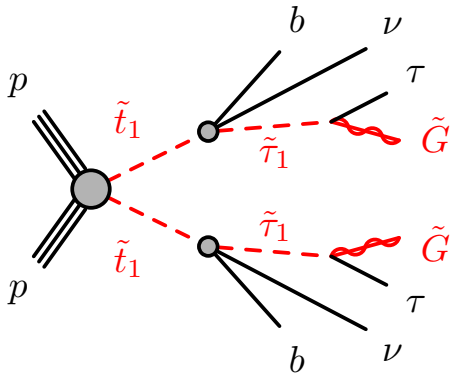

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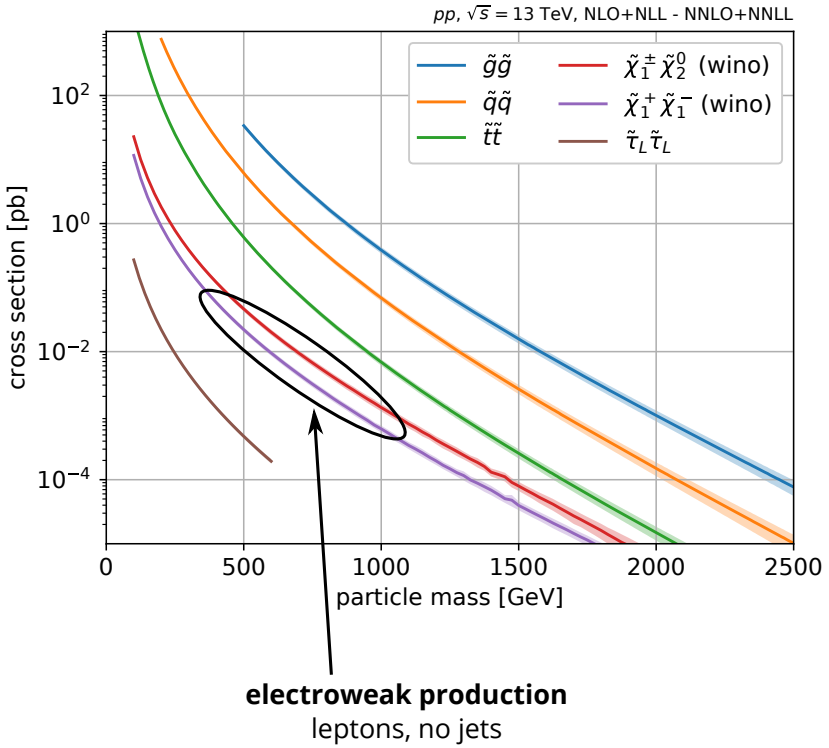

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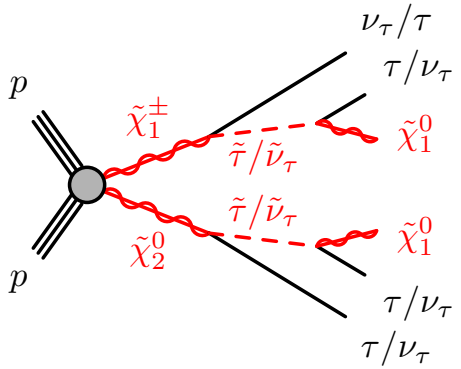

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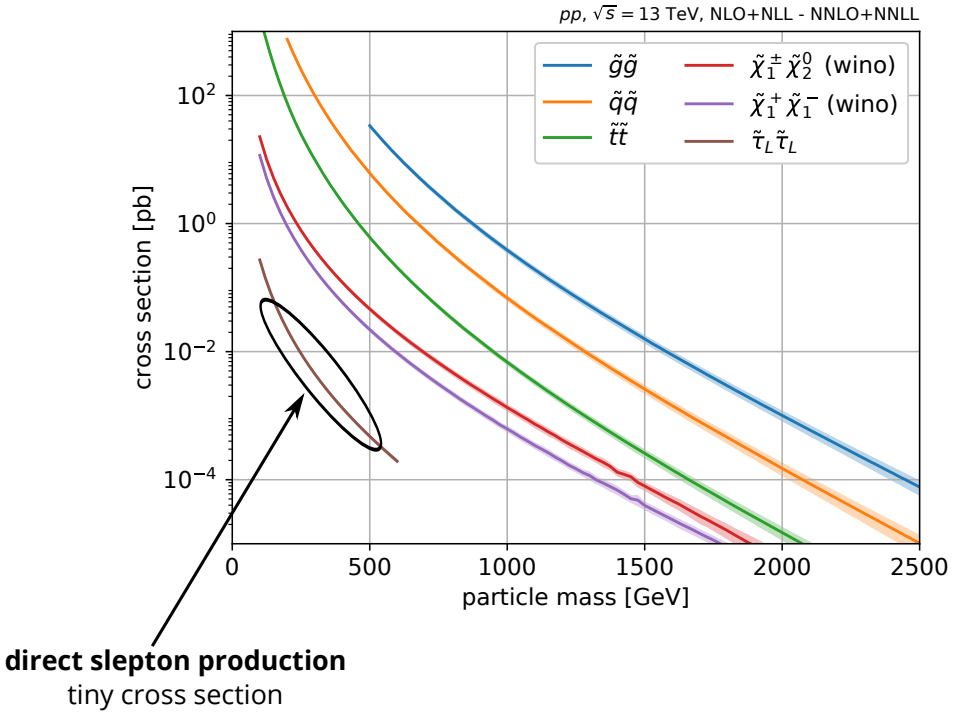
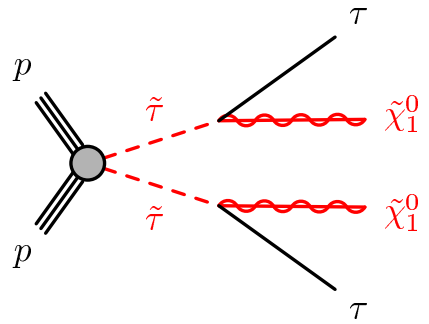
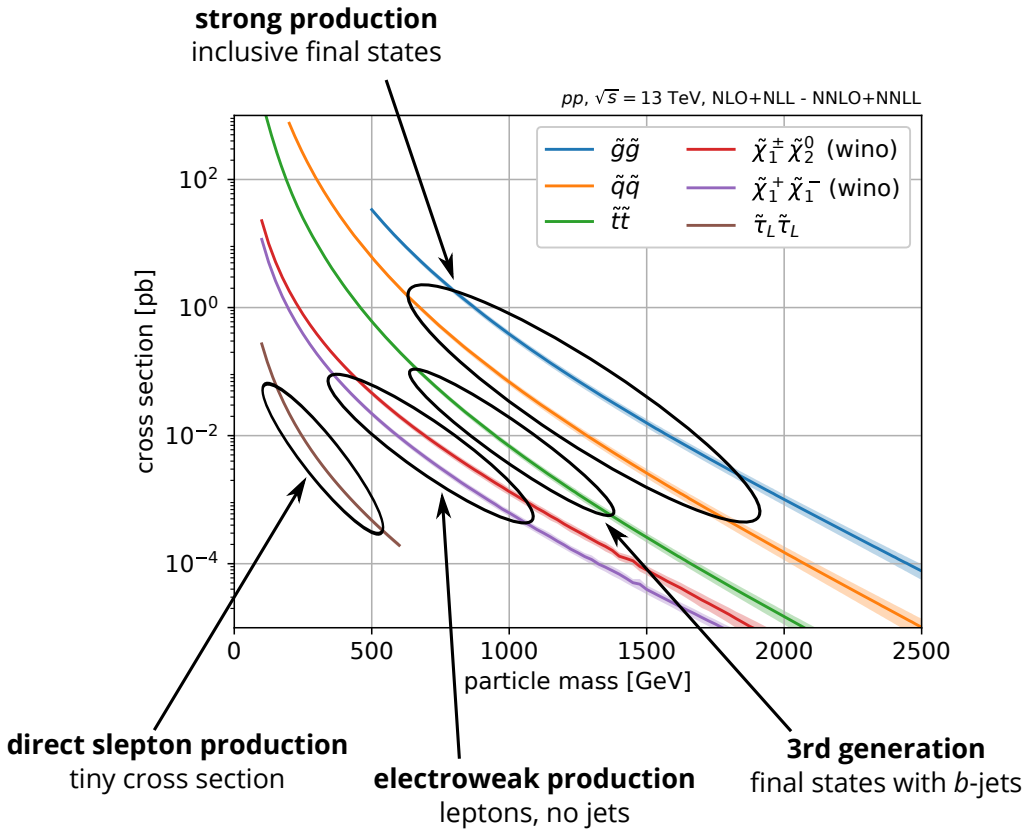


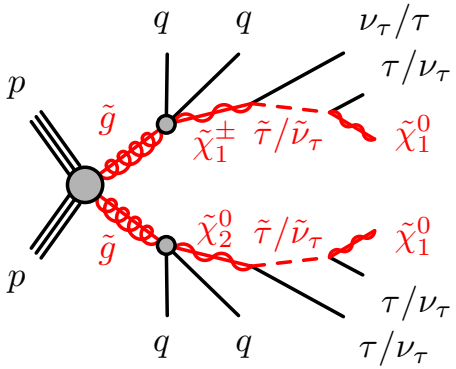
Simplified model of direct production of $\widetilde{\tau}$:

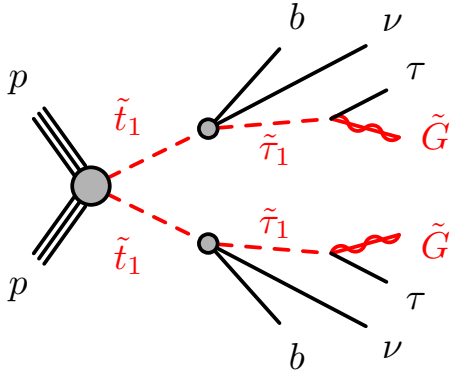


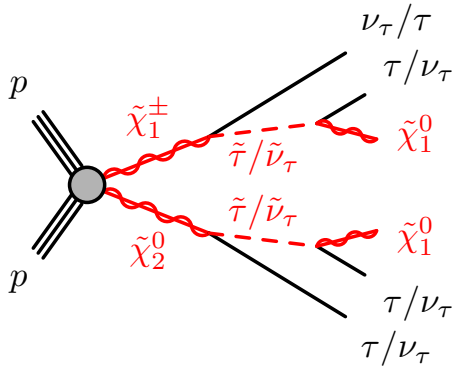
Different Production Modes of SUSY Particles

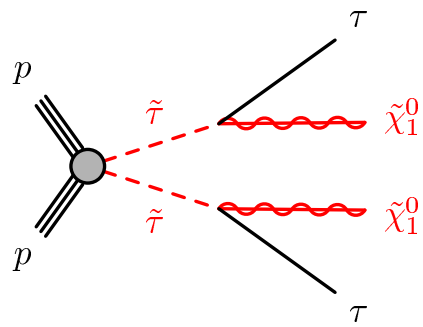


→ from largest to smallest production cross section →

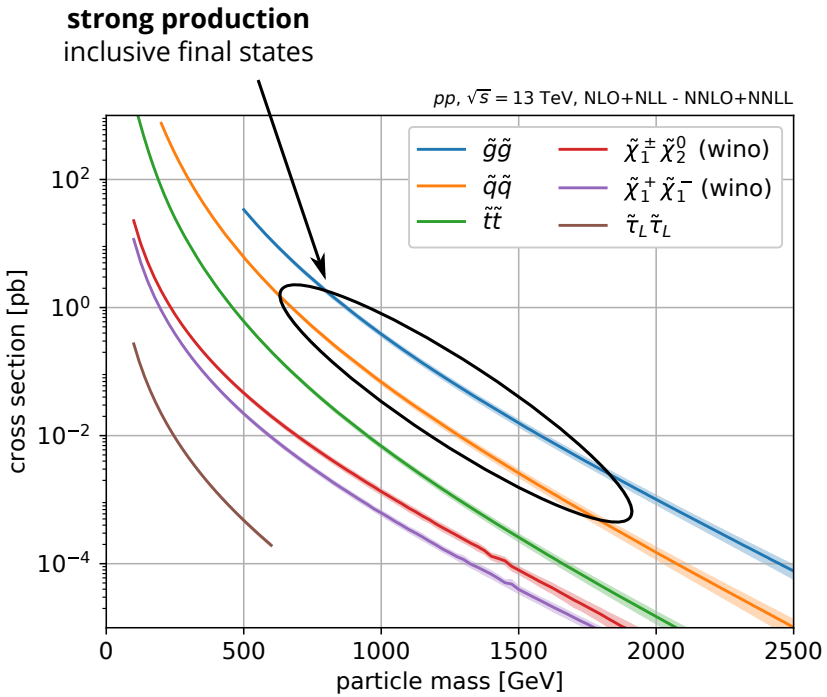




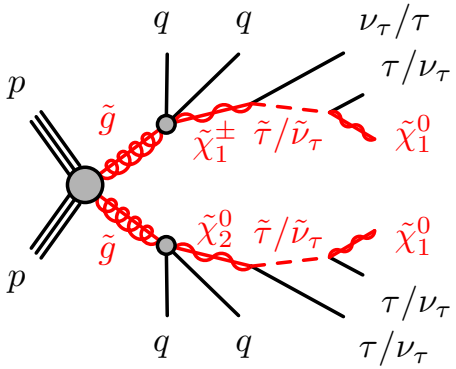




Inclusive / Strong Production

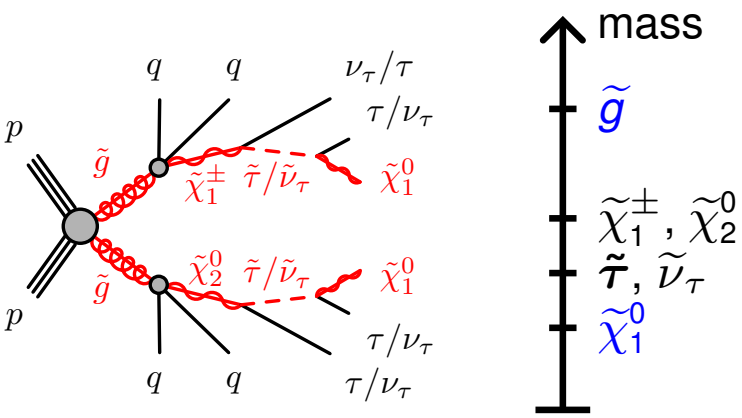


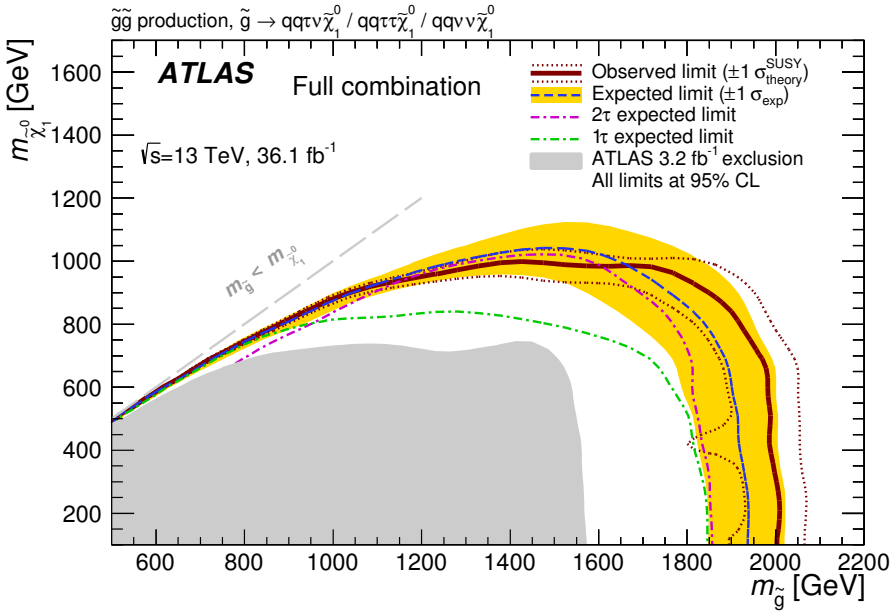
Gluino pair production with decays via staus:



Phys. Rev. D 99 (2019) 012009

- Search for production of gluinos*), 36.1 fb^{-1} @ $\sqrt{s} = 13\,\mathrm{TeV}$
- Targets final states with $\geq$ 2 jets, hadronic tau decays, and $E_{\mathrm{T}}^{\mathrm{miss}}$

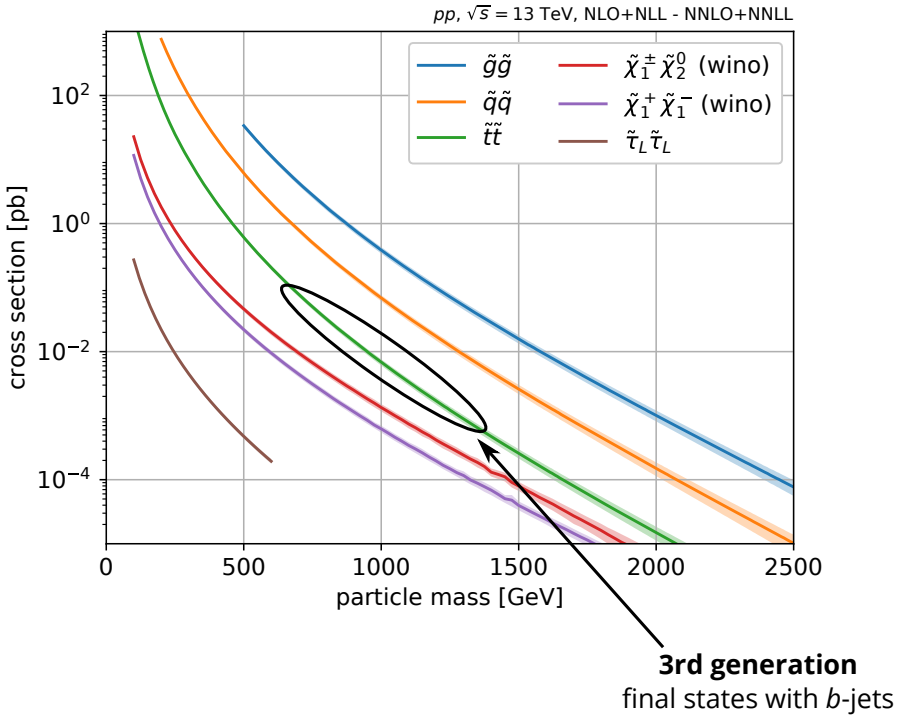




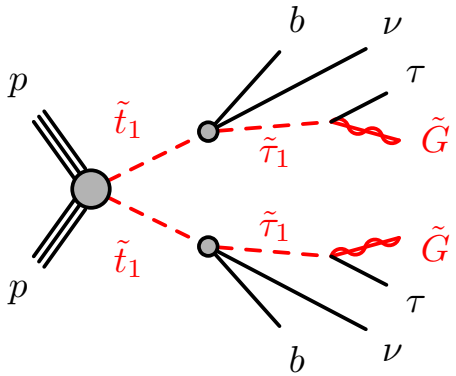
- Observed data in agreement with expected SM background
- $\Rightarrow$ limits at 95 % CL from **combination** of 1τ and 2τ channels

*) and squarks

Top-Squark Production

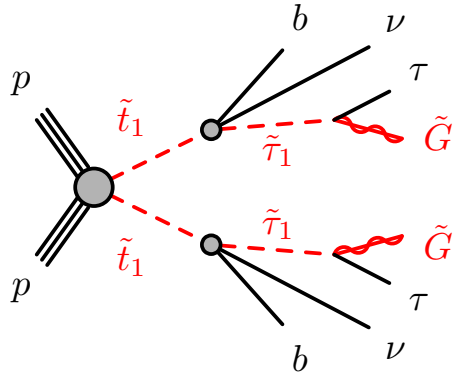


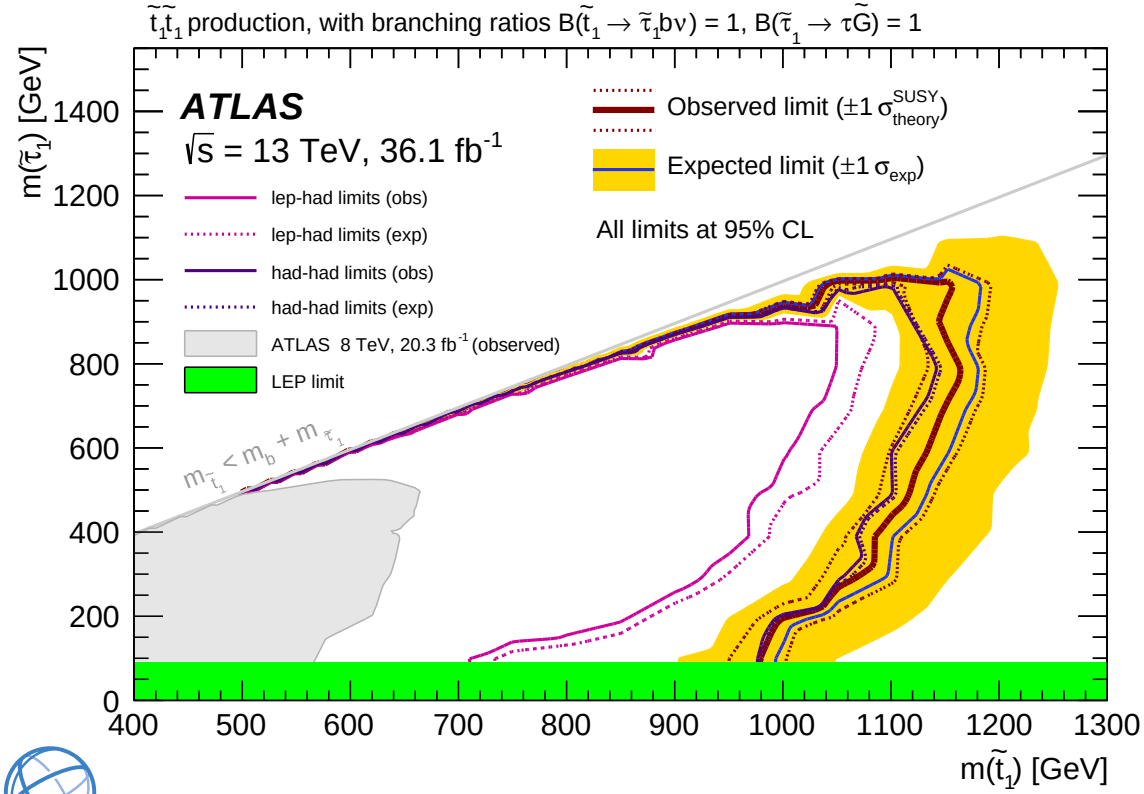
Stop pair production with decays via staus:



Phys. Rev. D 98 (2018) 032008

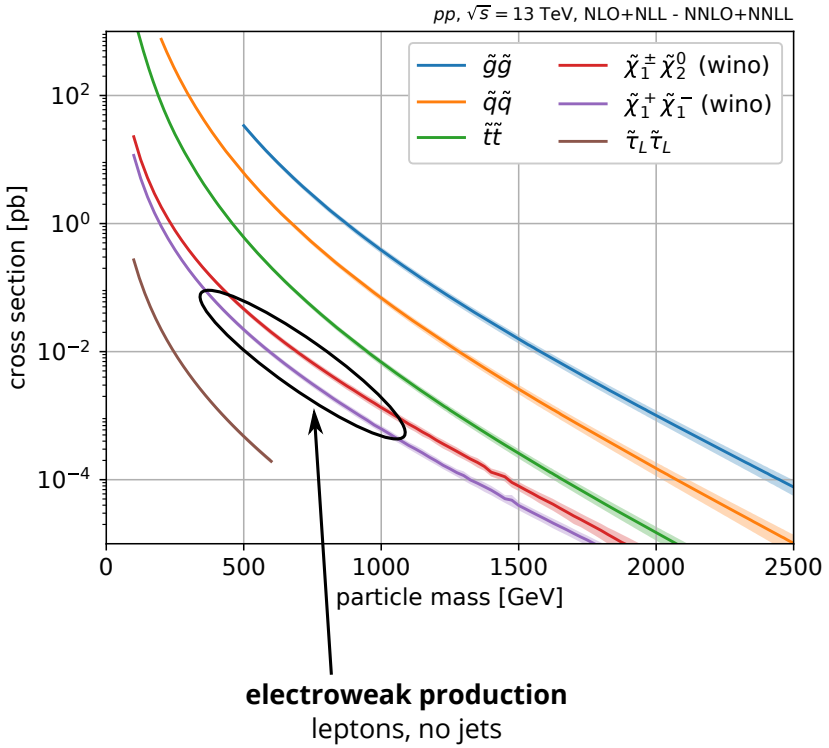
- Model assumes these three SUSY particles within reach:
  $\tilde{t}$ $\widetilde{\tau}$ $\sim$ massless $\widetilde{G}$
- Interesting model with intriguing detector signature:
  b-jets tau leptons $E_{\mathrm{T}}^{\mathrm{miss}}$



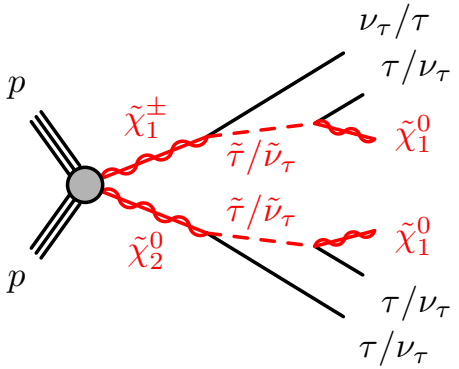


- 36.1 fb^{-1} @ $\sqrt{s} = 13$ TeV
- Variables used to discriminate signal vs bg: m_{T2} and $E_{\mathrm{T}}^{\mathrm{miss}}$
- No significant excess observed
- Limits from **combination** of **lep-had** and **had-had** channel
- Exclusion of $m(\widetilde{\tau}_1)$ up to 1.0 TeV
  - and of $m(\tilde{t}_1)$ up to 1.16 TeV
  - CMS result: talk by J. Pastika

Electroweak Production



Electroweakino pair production with decays via staus:



Goal

- Search for electroweak production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ or $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{0}$
- Final states with tau leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ but no high-p_{T} jets
- $36\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 13\,\mathrm{TeV}$ from (2015 and) 2016

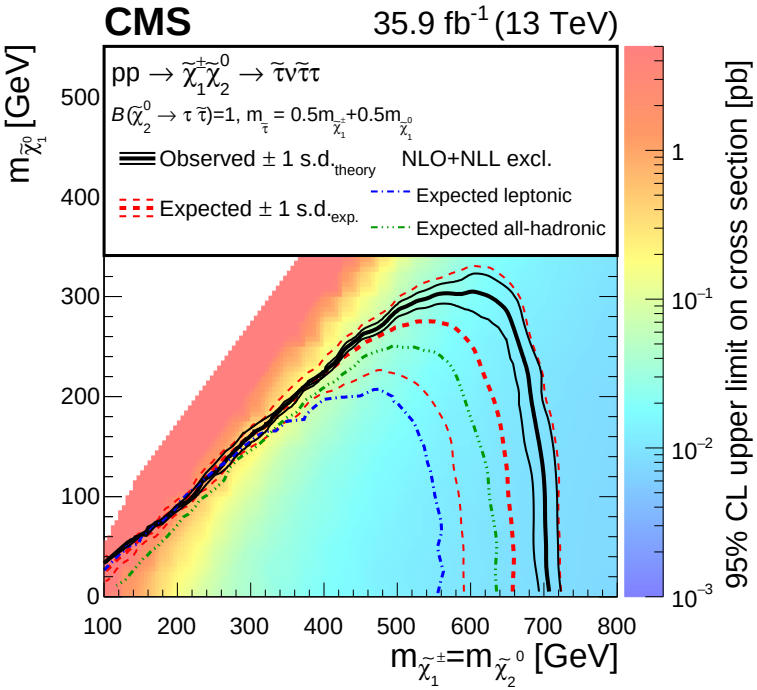
CMS *(JHEP 11 (2018) 151)*

- Covers all tau-decay modes
  - channels: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- 3 SRs in $\tau_h\tau_h$ channel, 44 in $\ell\tau_h$, 44 in $e\mu$
- Data-driven estimates for multi-jet and W + jets backgrounds (fake tau leptons)

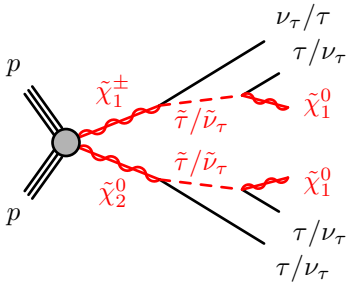
ATLAS *(Eur. Phys. J. C 78 (2018) 154)*

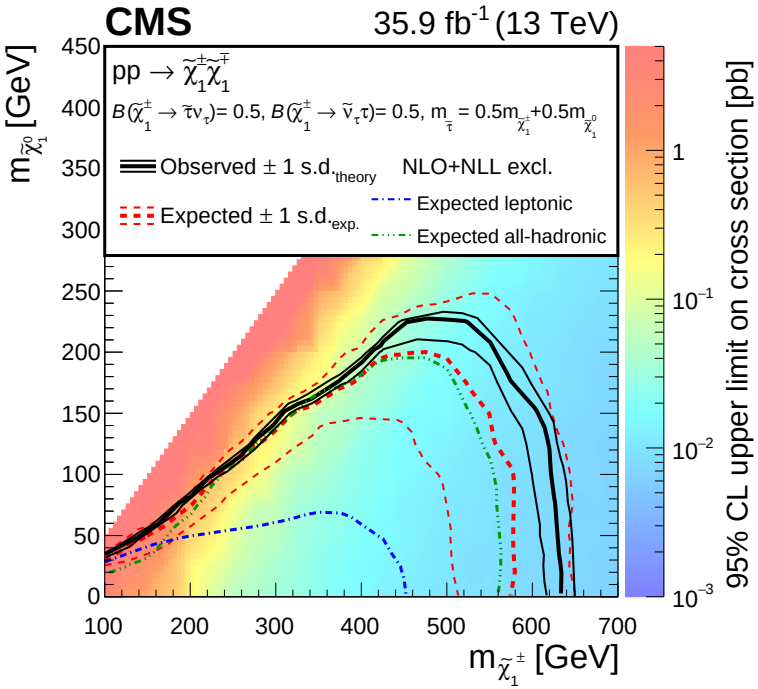
- Only hadronic decays of tau leptons
- 2 SRs, optimized for low and high mass
- Data-driven multi-jet estimate and normalization of W + jets

- No significant deviations from expected SM background observed
- Exp. exclusion driven by $\tau_h\tau_h$ channel, 20 – 30 GeV improvement from leptonic channels

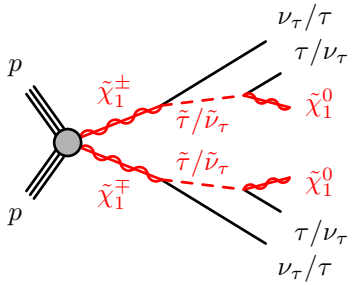


$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production, 1 – 3 τ

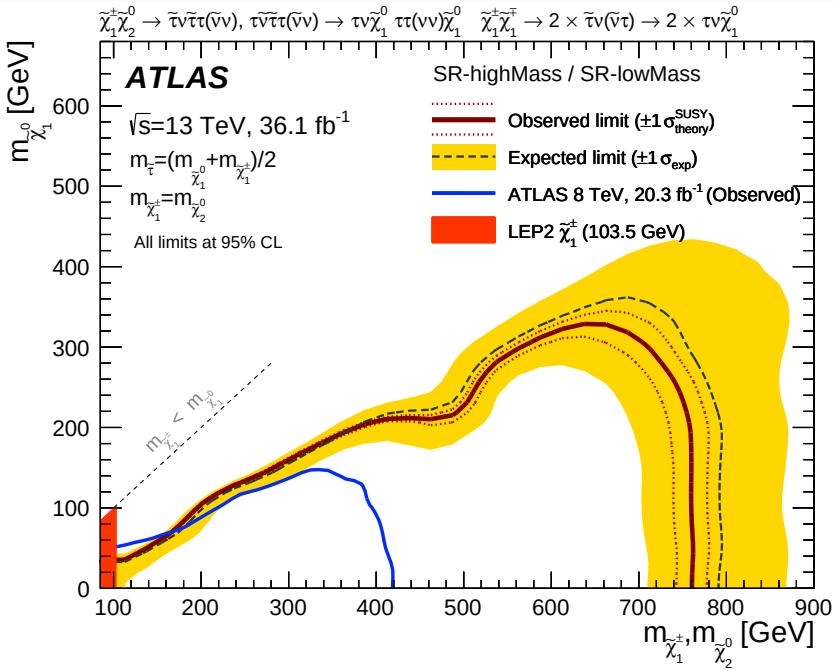




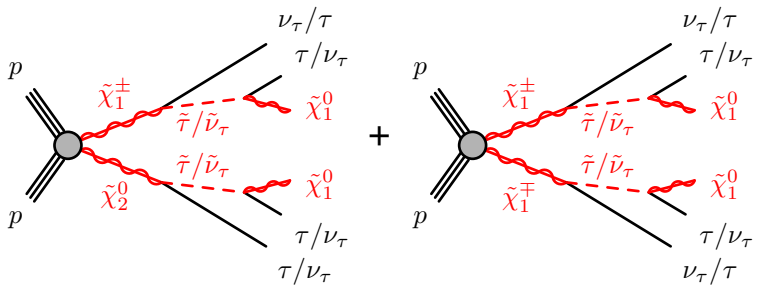
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production, 2 τ

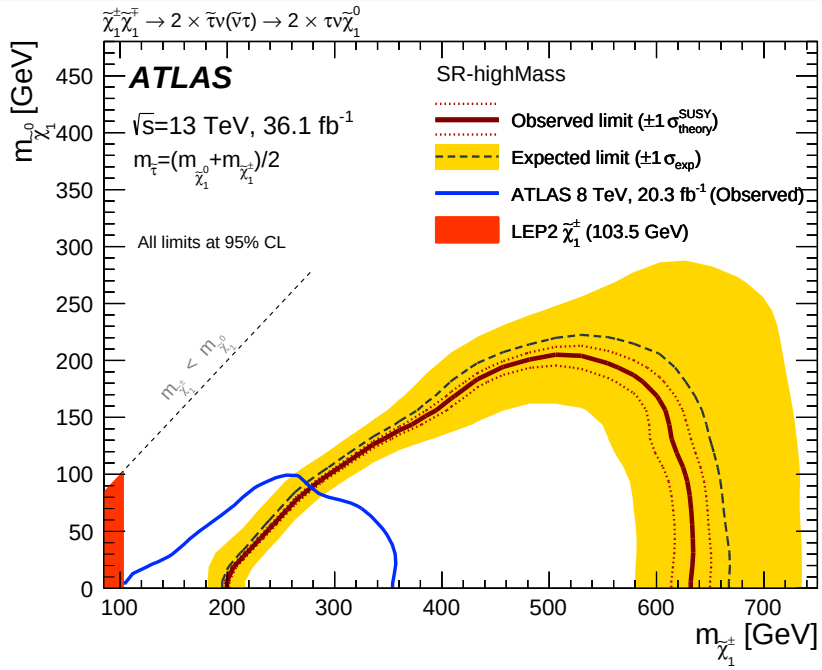


- Also no significant excess observed
- Excluded mass range similar to CMS result

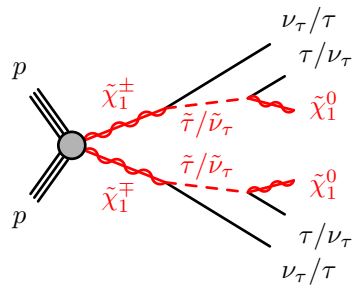


$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production



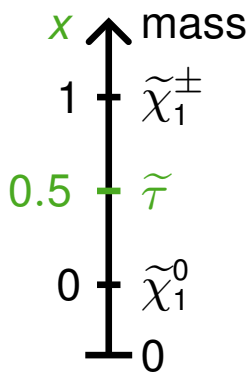


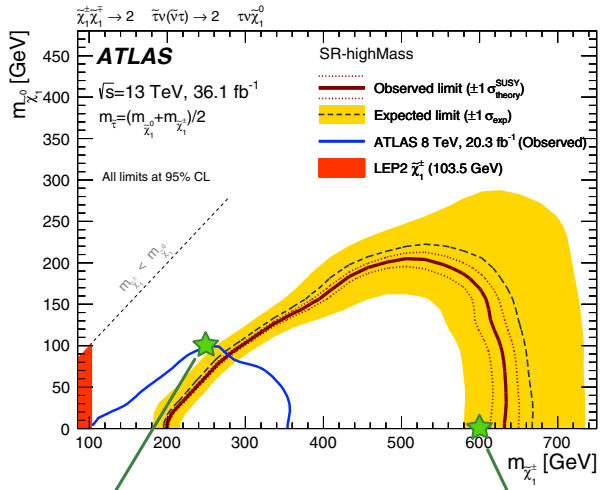
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production

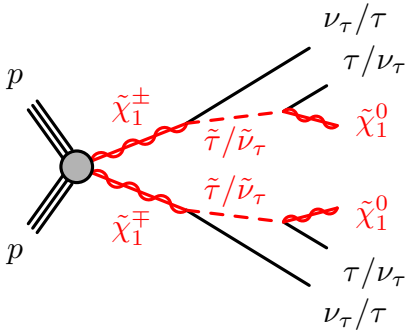


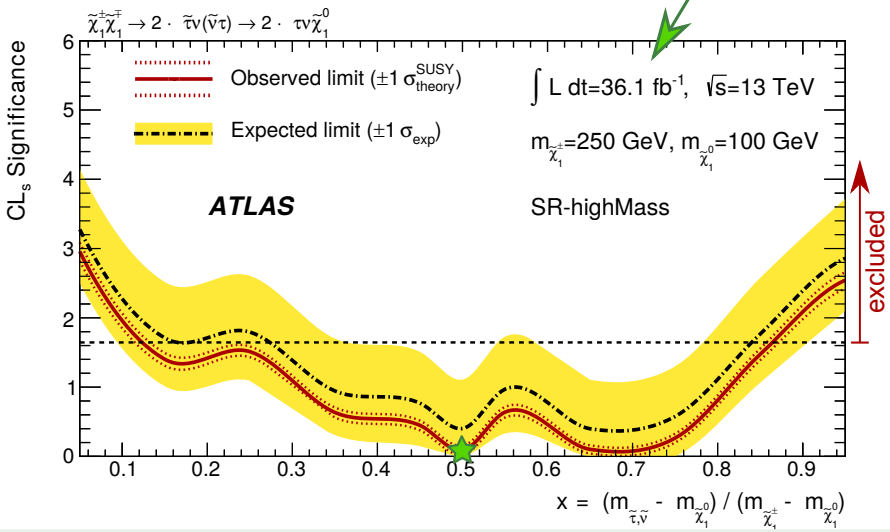
Impact of Stau-Mass Assumption (e. g. $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ Limits)

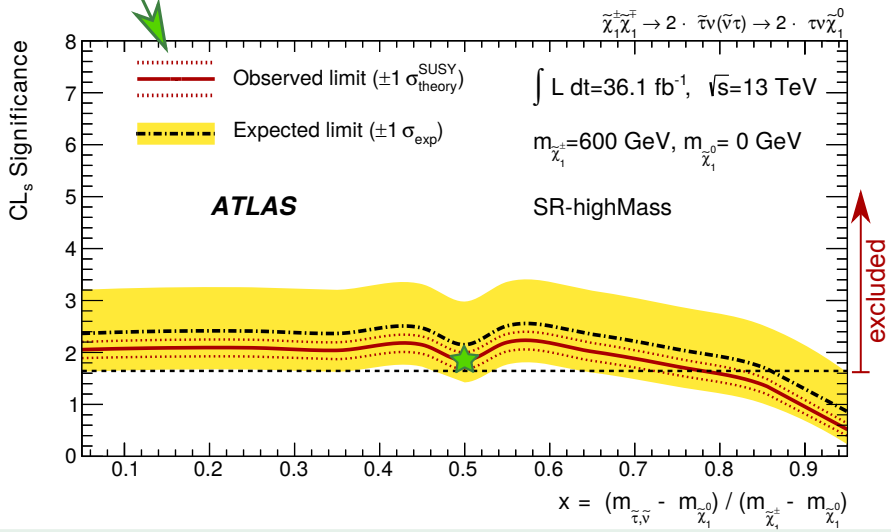
Eur. Phys. J. C 78 (2018) 154



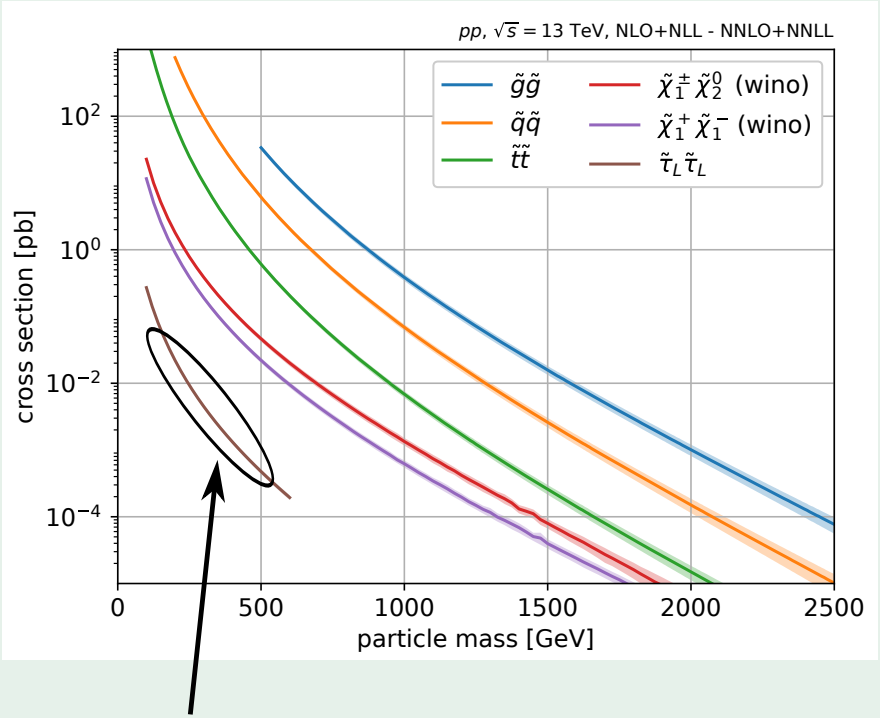




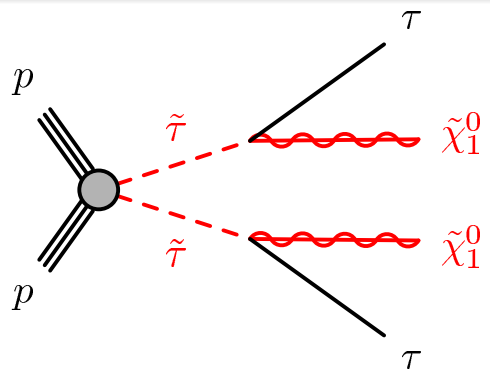




- CL$_s$ significance as function of mass parameter x (nominal analysis: $x = 0.5$)
  - $> 1.64 \Leftrightarrow$ exclusion at 95 % confidence level
- compressed scenario (left):
  small & large $x \Rightarrow m_{T2}$ distribution broader
- large mass splitting (right):
  large $x \Rightarrow p_T(\tau)$ too soft

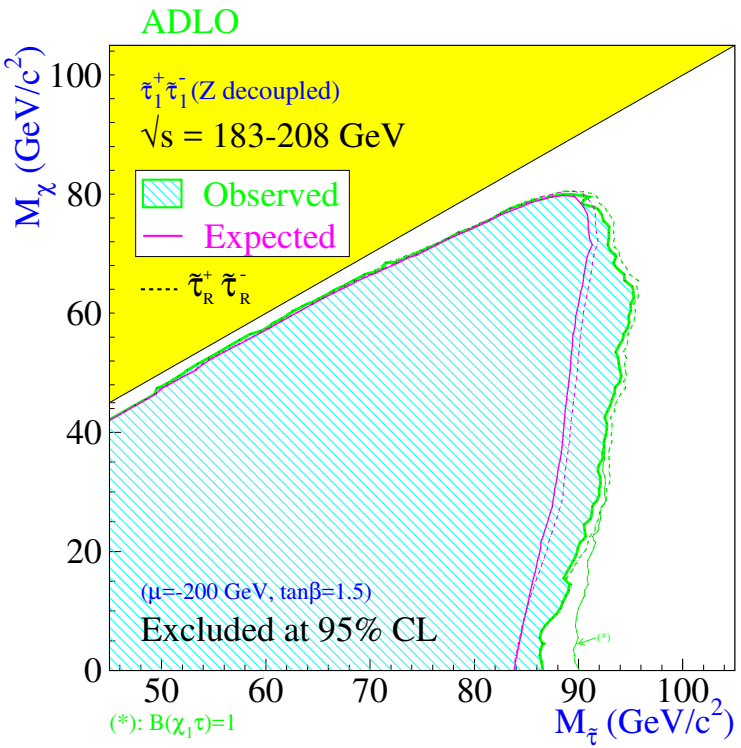


- Very small cross section
  - for $\widetilde{\tau}_R\widetilde{\tau}_R$ yet $\sim$ factor 3 smaller

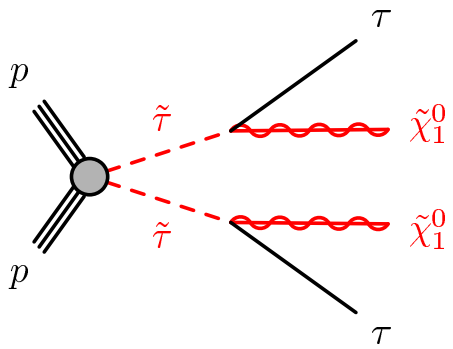


Combined LEP Result (from 2004)

- Strong result from search for $\widetilde{\tau} \rightarrow \tau\widetilde{\chi}_1^0$
- Lower limit on $m(\widetilde{\tau}_R)$: around 90 GeV
  - for almost all $m(\widetilde{\chi}_1^0)$
  - LEP result still prevails



- Latest CMS result, made public for Moriond 2019
- Dataset of 77.2 fb^{-1} @ $\sqrt{s} = 13\,\mathrm{TeV}$ from 2016 + 2017
- Combines $\tau_h\tau_h$ and $\ell\tau_h$ channels
- Background estimate: as in $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$/ $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{0}$ search



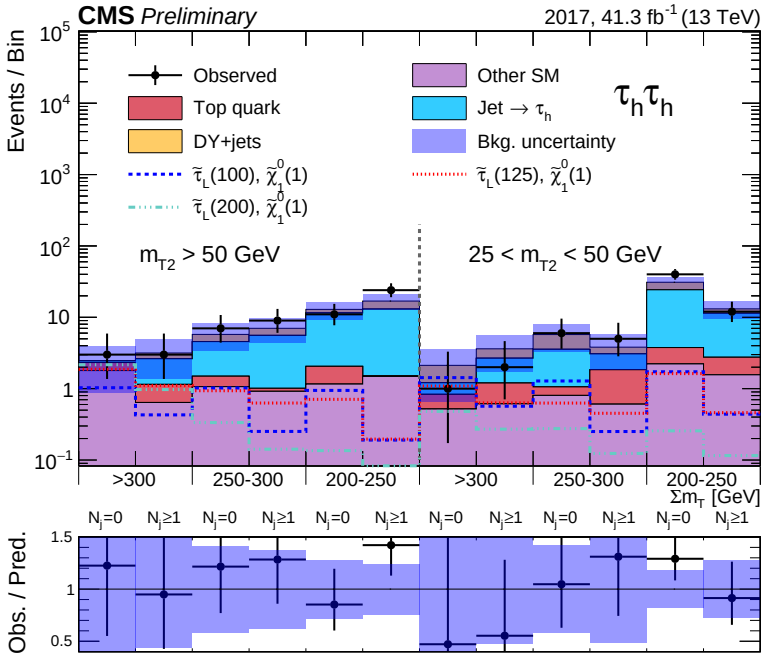
$\tau_h\tau_h$ channel

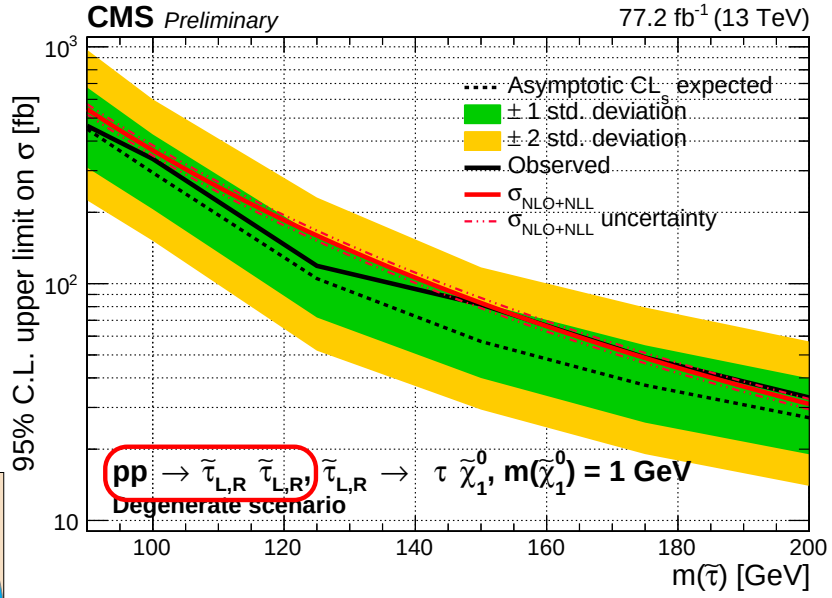
- Di-tau trigger (plus $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger at $E_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$)
- Select $\tau_h^+\tau_h^-$ with $p_{\mathrm{T}}(\tau_h) > 40\ (45)\,\mathrm{GeV}$ for 2016 (2017) data
- Veto additional leptons and *b*-jets
- 6 SRs in m_{T2} and $\sum m_T$ à two jet categories ($N_j = 0, \geq 1$)

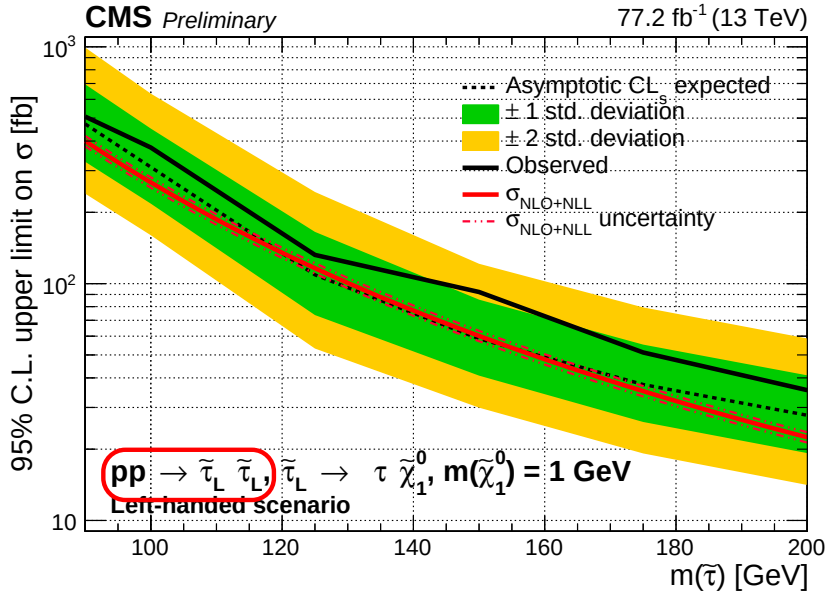
$\ell\tau_h$ channel

- τ_h + *e* or μ, single-lepton triggers
- Train BDTs for 3 different stau-mass hypotheses on high-level variables

- Data well described by predicted SM background
  - right: SR yields in $\tau_h\tau_h$ channel, 2017 dataset $\rightarrow$
- Cross-section limits from statistical combination of all SRs and full BDT distributions
- Degenerate scenario (left): $m(\widetilde{\tau}_{L,R}) \overset{!}{>} 150\,\mathrm{GeV}$
- Left-handed scenario (bottom right): close but no exclusion observed





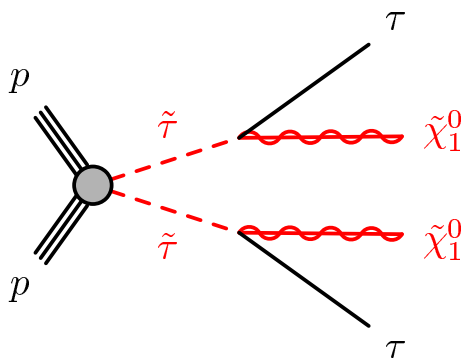


$\rightarrow$

Search for Direct Production of Staus (ATLAS)

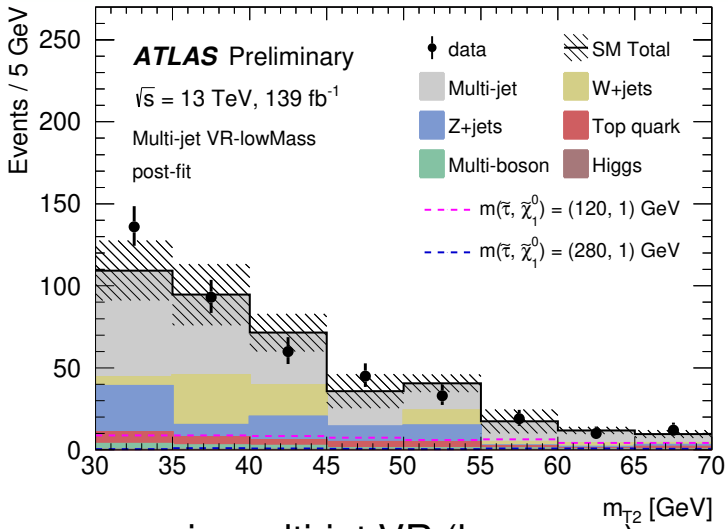
ATLAS-CONF-2019-018

- Made public for this conference
- First stau search to use full 139 fb^{-1} of Run-2 dataset
- Based on $\tau_h\tau_h$ channel
- Background estimated as in $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$/ $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{0}$ search with new developments:
  - "tau promotion": simulation-based fake-factor method (on 2nd τ) to reduce statistical uncertainty in W + jets background
  - fake-factor method to cross check estimate for multi-jet background from ABCD method



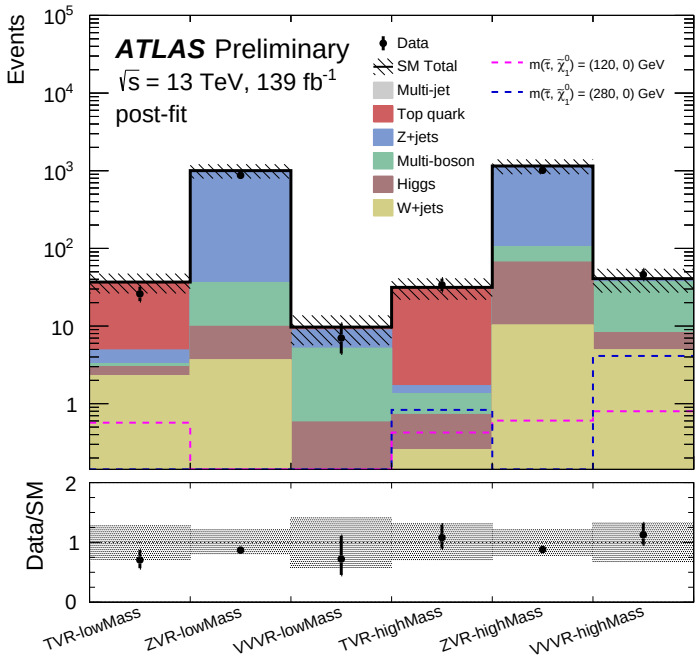
$\tau_h\tau_h$ channel

- 2 non-overlapping SRs, optimized for *low* and *high* stau masses
  - select $\tau_h^+\tau_h^-$, veto on 3rd lepton, on *b*-jet, and on *Z* and *h* boson
- low-mass SR
  - asymmetric di-tau trigger
  - 75 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 150 GeV
  - 70 GeV $< m_{\mathrm{T2}}$
- high-mass SR
  - di-tau + $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - 150 GeV $< E_{\mathrm{T}}^{\mathrm{miss}}$
  - 70 GeV $< m_{\mathrm{T2}}$

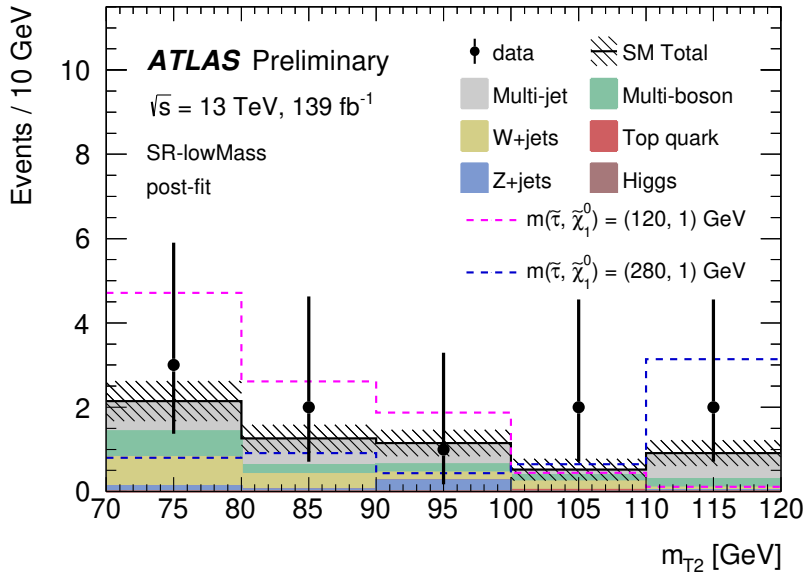


m_{T2} in multi-jet VR (low-mass)

- Validation regions confirm good modelling of SM backgrounds
- SRs: also good agreement of data with expected SM background



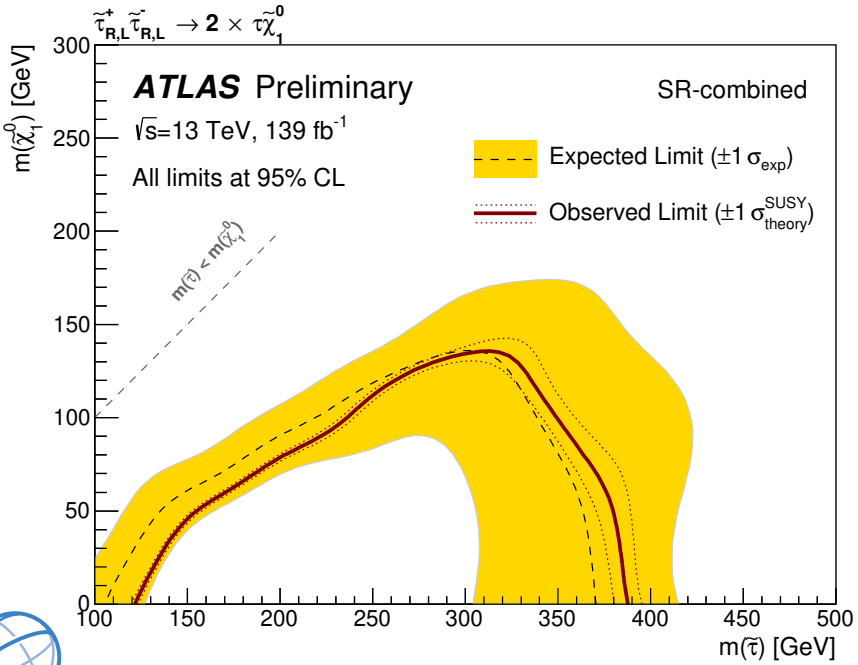
top / Z / VV VRs (low-mass + high-mass)



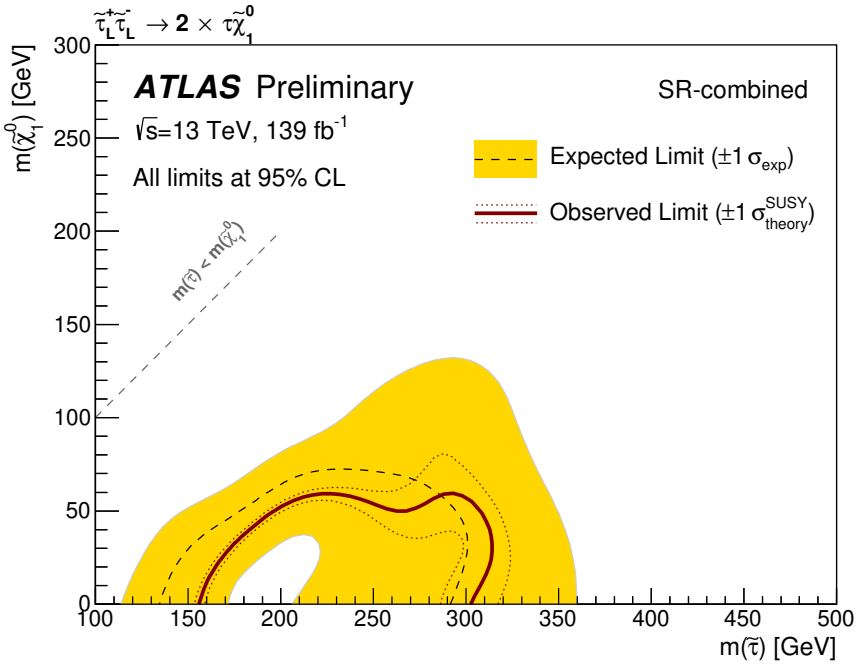
m_{T2} in SR (low-mass)

- Model-dependent exclusion limits @ 95 % CL:
  - $120\,\mathrm{GeV} < m(\widetilde{\tau}_{L,R}) < 390\,\mathrm{GeV}$
  - $160\,\mathrm{GeV} < m(\widetilde{\tau}_{L}) < 300\,\mathrm{GeV}$
- First exclusion of *non-degenerate* staus at LHC!
  - for $m(\widetilde{\chi}_1^0)$ up to 60 GeV
- No sensitivity to $\widetilde{\tau}_R$ production due to slight excess in the more sensitive SR-lowMass

SM process	SR-lowMass	SR-highMass
Diboson	1.4 ± 0.8 ○	2.6 ± 1.2 ○
W+jets	1.5 ± 0.7 ○	2.5 ± 1.9 ○
Top quark	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.5 ○
Z+jets	$0.4^{+0.5}_{-0.4}$	$0.04^{+0.13}_{-0.04}$
Higgs	$0.01^{+0.02}_{-0.01}$	0.00 ± 0.00
Multi-jet	2.6 ± 0.7 ●	3.1 ± 1.5 ●
SM total	6.0 ± 1.7	10.2 ± 3.3
Observed	10	7
$m(\widetilde{\tau}, \widetilde{\chi}_1^0) = (120, 1)$ GeV	9.8 ± 3.1	7.2 ± 2.7
$m(\widetilde{\tau}, \widetilde{\chi}_1^0) = (200, 1)$ GeV	14 ± 4	20 ± 5
$m(\widetilde{\tau}, \widetilde{\chi}_1^0) = (280, 1)$ GeV	5.9 ± 2.4	14 ± 4



degenerate scenario ($\widetilde{\tau}_L\widetilde{\tau}_L + \widetilde{\tau}_R\widetilde{\tau}_R$)



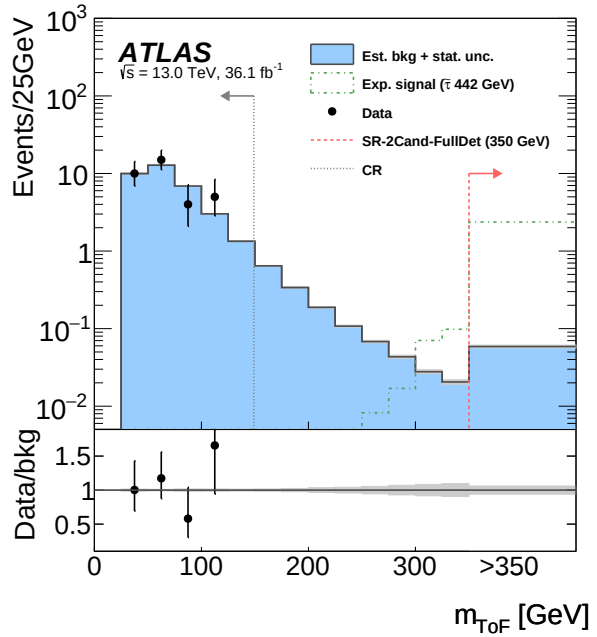
left-handed scenario ($\widetilde{\tau}_L\widetilde{\tau}_L$ production)

→

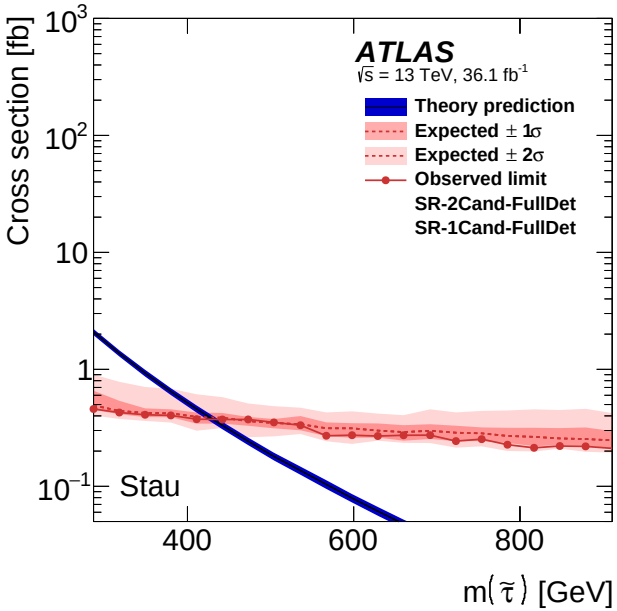
Heavy Charged Long-Lived Particles

arXiv:1902.01636 (accepted by PRD)

- All other searches assume SUSY particles to decay promptly
- Here: search for *long-lived* staus
  - GMSB model with $\widetilde{G}$ LSP and long-lived $\widetilde{\tau}$ NLSP
- Charged $\Rightarrow$ track: measure momentum p in ID and MS
- Heavy $\Rightarrow \beta \ll 1$: measure ToF in Tile Calorimeter and MS
- Mass hypothesis $m_{\text{ToF}} = p/\beta\gamma$ for candidate tracks

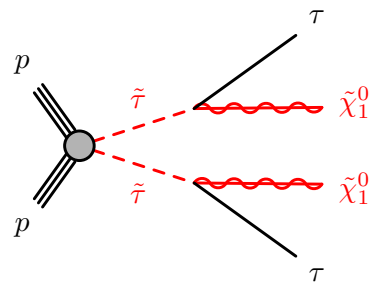


CR (grey) and SR (red arrow)



exclude $m(\widetilde{\tau}_R) < 430\ \text{GeV}$ (420 exp.)

- Custom timing calibration
- Fully data-driven background estimate
- No significant excess observed



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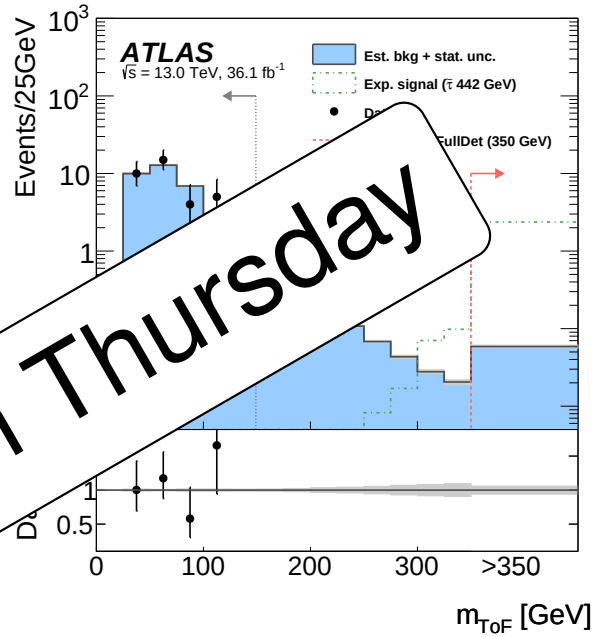

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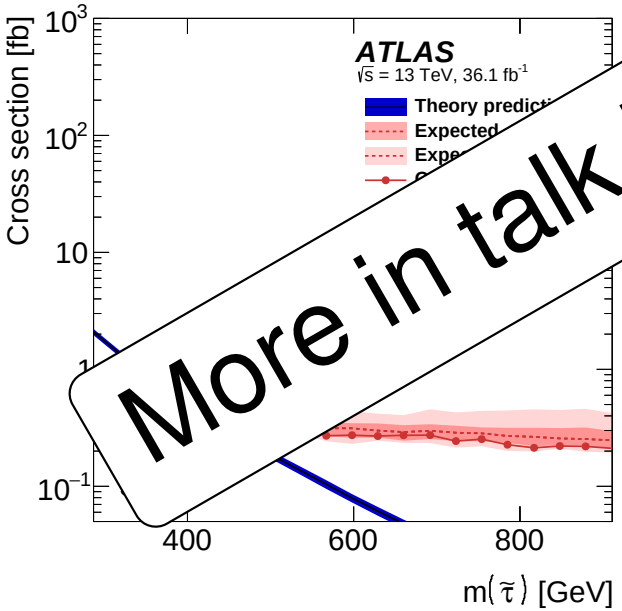

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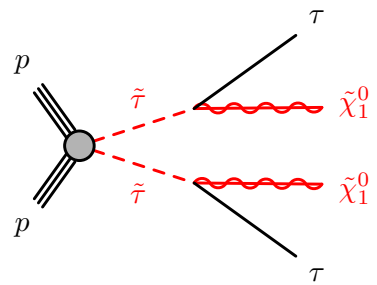
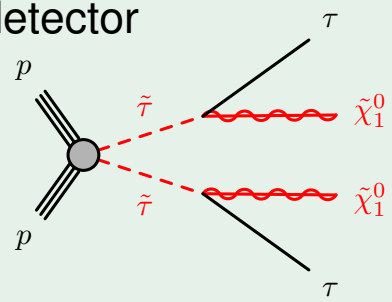
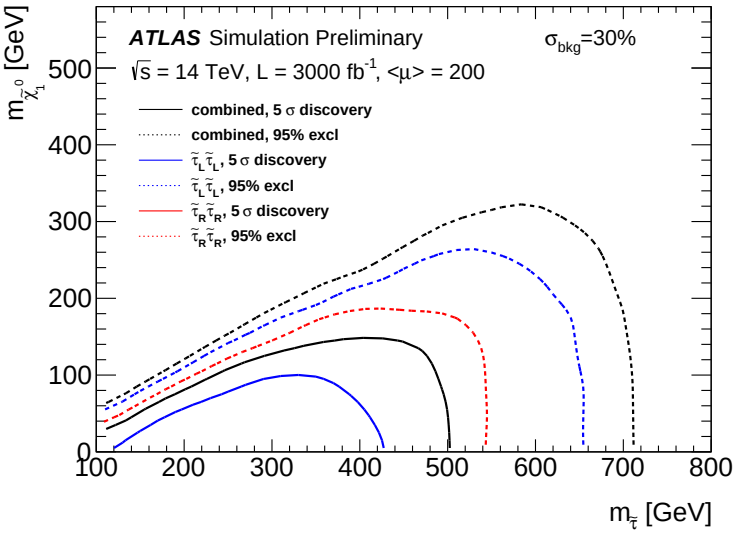


More in talk by Sascha on Thursday

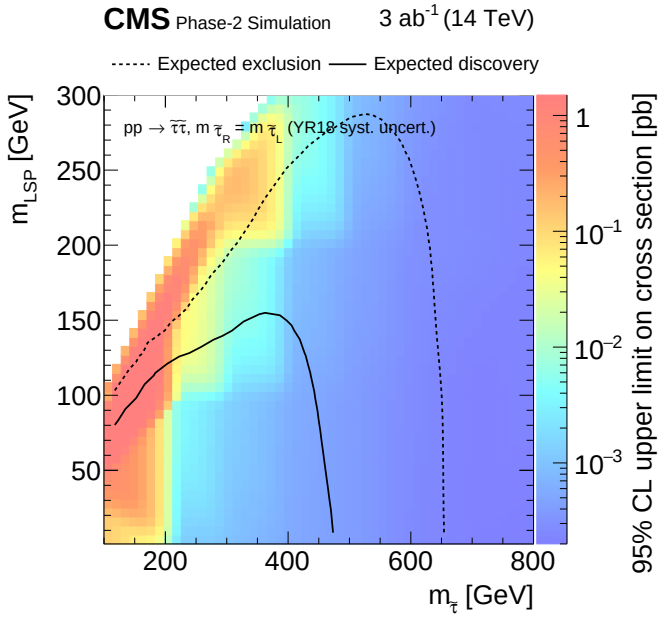
- High-luminosity upgrade of the LHC: expect 3000 fb^{-1} @ $\sqrt{s} = 14\,\mathrm{TeV}$, $\langle\mu\rangle \sim 200$
- Parametrized simulations of performance of upgraded ATLAS or CMS detector
- Assume trigger thresholds similar to current despite higher pile-up
- Selections based mainly on m_{T2}, $\sum m_T$, $E_{\mathrm{T}}^{\mathrm{miss}}$
- Dominant backgrounds: $t\bar{t}$, W + jets



- Predicted sensitivity for ATLAS and CMS rather similar



ATLAS: exp. exclusion: $m(\widetilde{\tau}_{L,R}) > \mathbf{710}\,\mathrm{GeV}$
$(m(\widetilde{\tau}_L) > 650\,\mathrm{GeV}, m(\widetilde{\tau}_R) > 540\,\mathrm{GeV})$
exp. discovery (5σ): $m(\widetilde{\tau}_{L,R}) < \mathbf{500}\,\mathrm{GeV}$

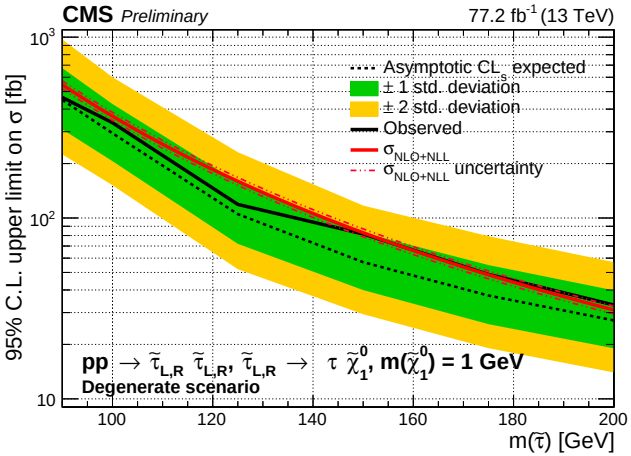


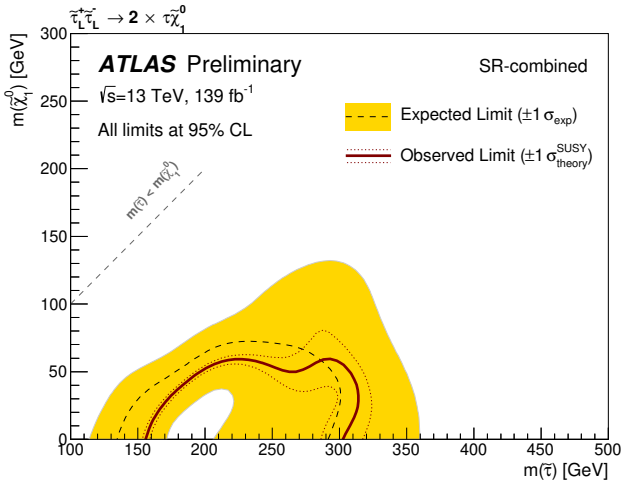
CMS: exp. exclusion: $m(\widetilde{\tau}_{L,R}) > 650\,\mathrm{GeV}$
exp. discovery (5σ): $m(\widetilde{\tau}_{L,R}) < 470\,\mathrm{GeV}$ →

Summary & Outlook

Searches for Tau Sleptons

- $\widetilde{\tau}$ appears in many searches for SUSY at the LHC
- Presented latest public ATLAS and CMS results
- Highlights: two recent analyses with first-time sensitivity for direct production of tau sleptons at the LHC!





new ATLAS result ($\widetilde{\tau}_L\widetilde{\tau}_L$ production)

What's next?

- Obvious opportunities for improvements in stau searches:
  - ATLAS: add $\ell\tau_h$ channel (like CMS does)
  - CMS: add 2018 data (like ATLAS has already)
  - likely modest gains, but CMS probably able to exclude $\widetilde{\tau}_L$, plus first LHC exclusion of $\widetilde{\tau}_R$? (if "luckier" than ATLAS)
- Need to close gaps in "compressed" and light-$\widetilde{\tau}$ scenarios:
  - employ multi-variate analysis techniques and shape fits
  - improve tau-reconstruction and identification techniques
  - ATLAS + CMS combination?
    - not attempted for searches yet but useful for $\widetilde{\tau}_R$?
  - think about Run-3 tau triggers

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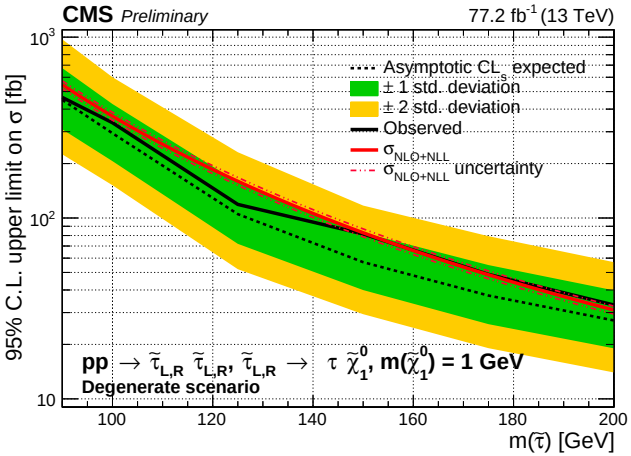

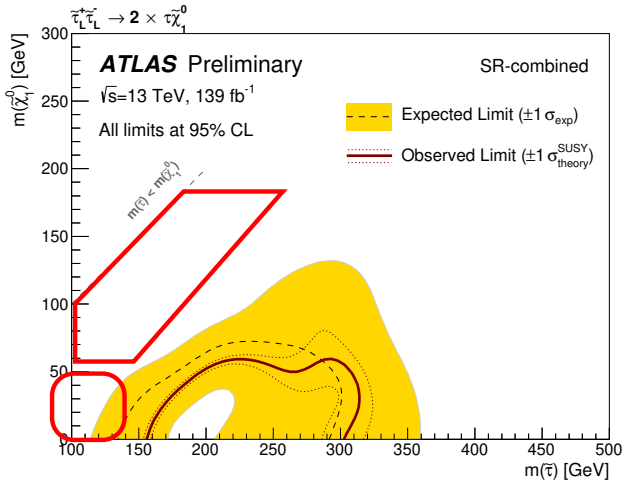

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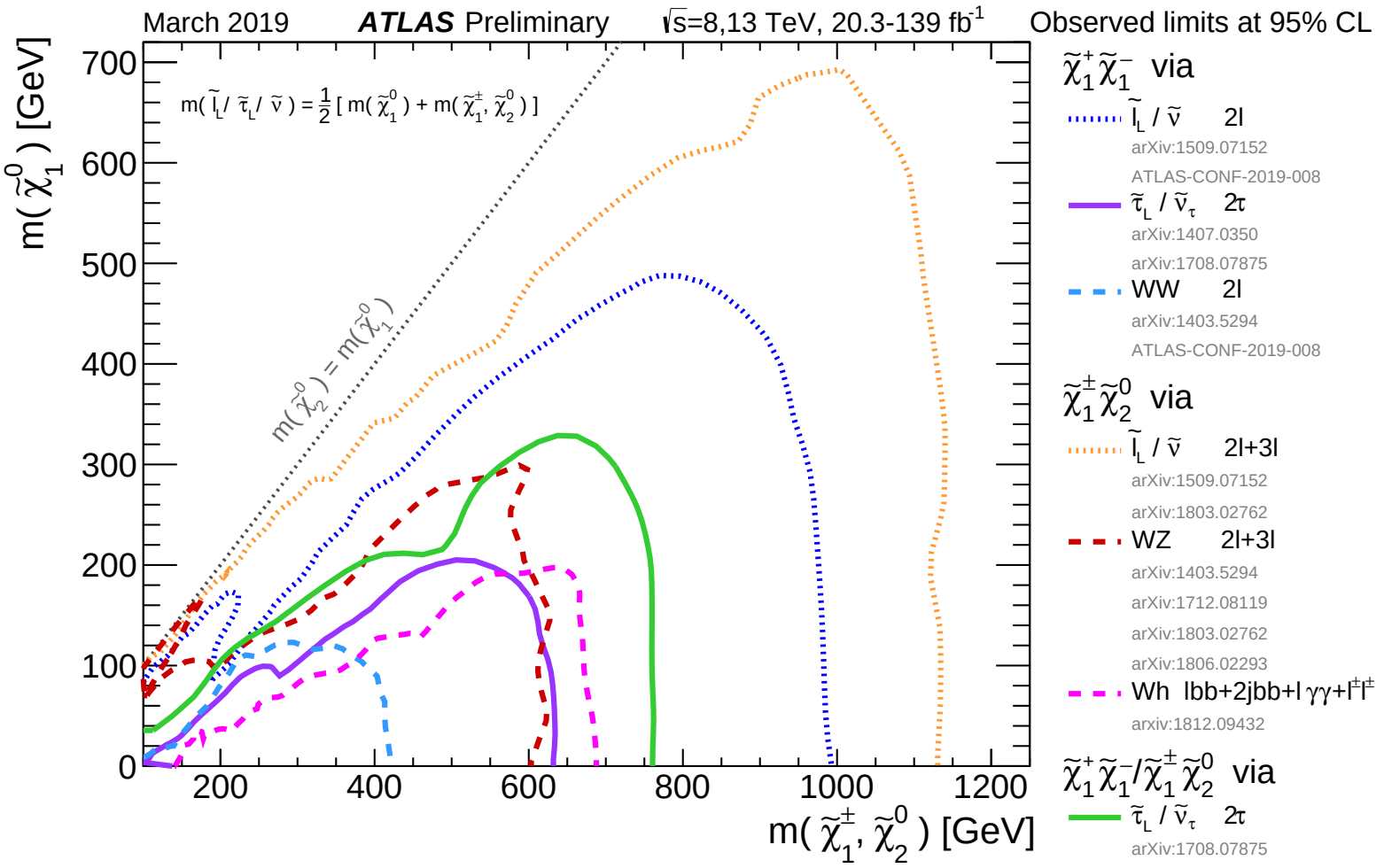
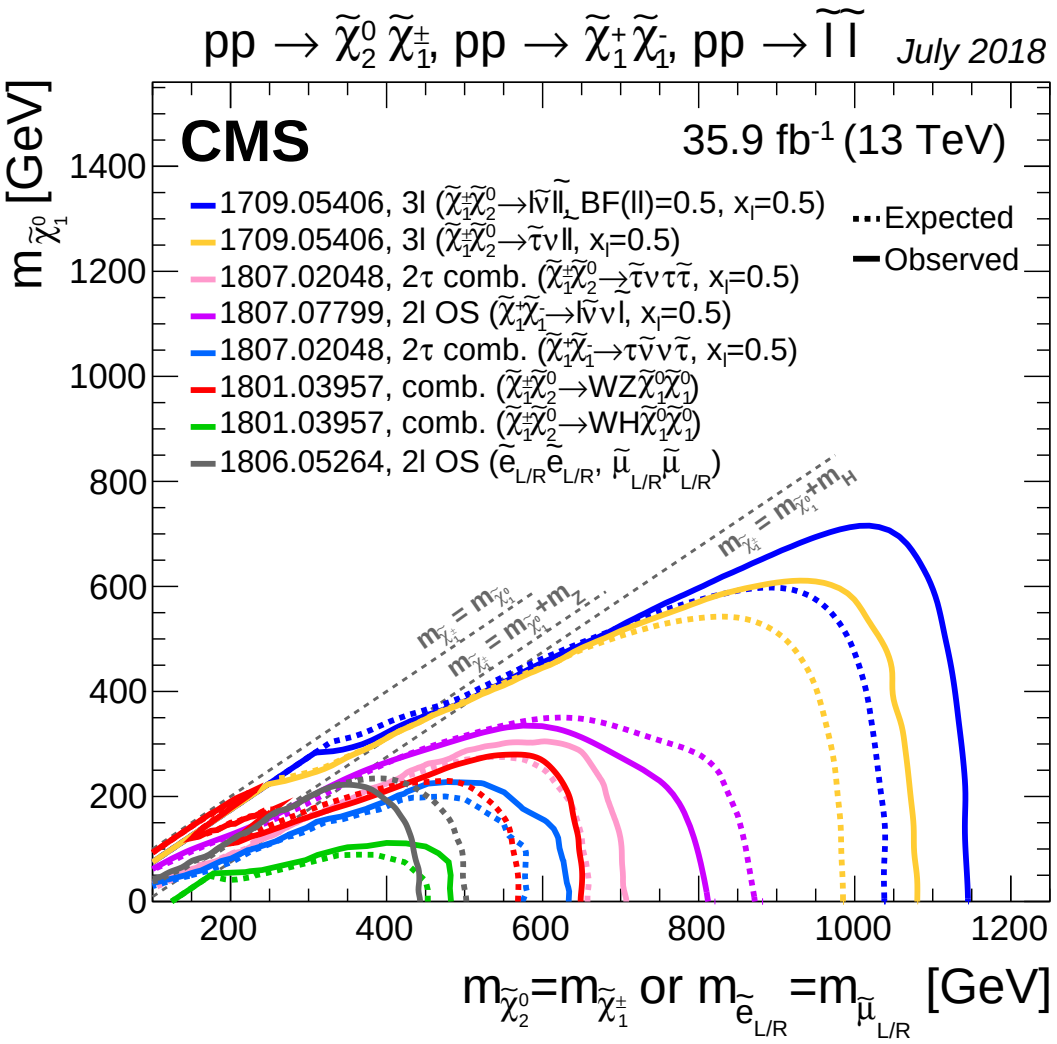
Extra Material

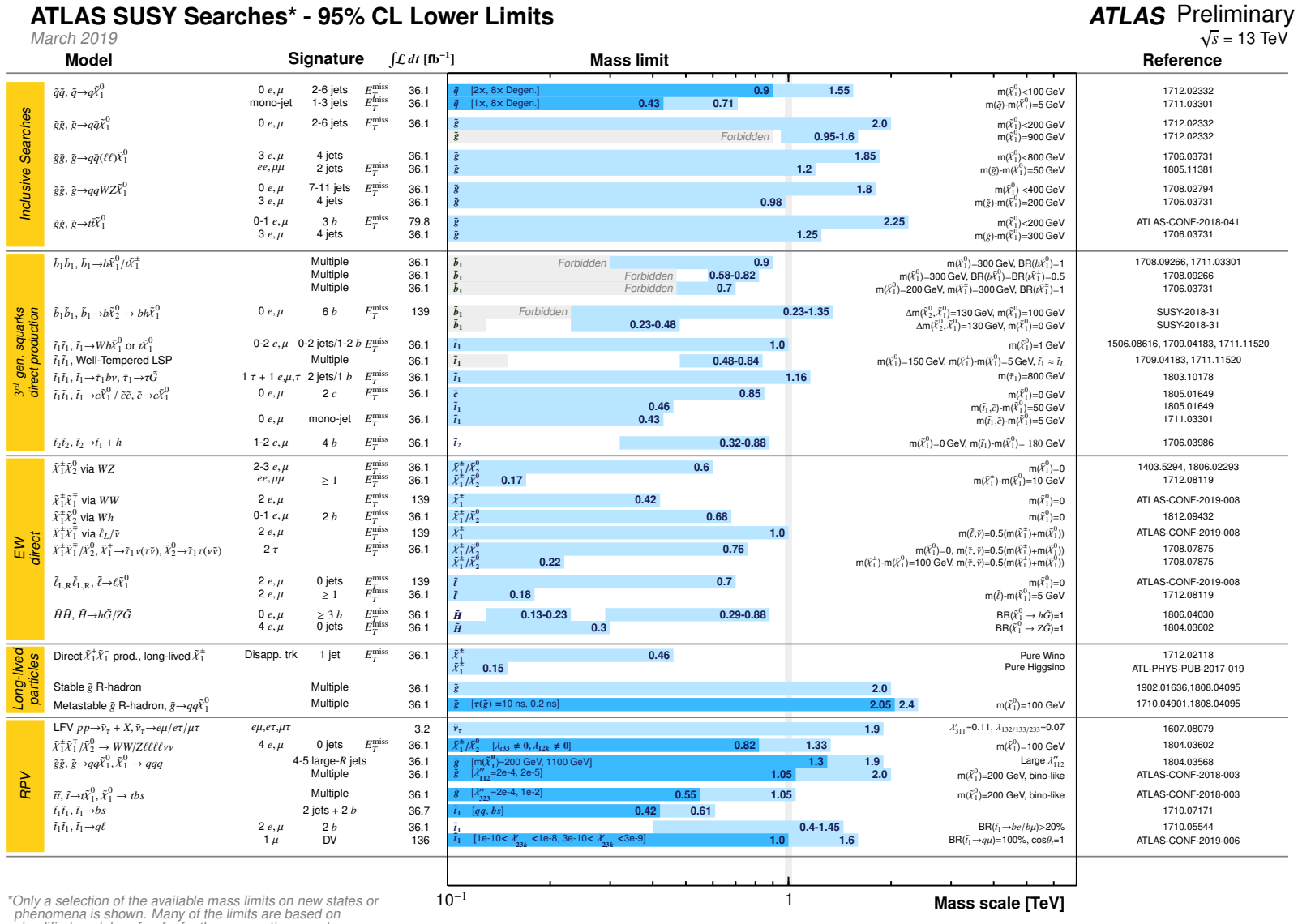
ATLAS Electroweak SUSY Summary Plot (March 2019)



CMS Electroweak SUSY Summary Plot (July 2018)

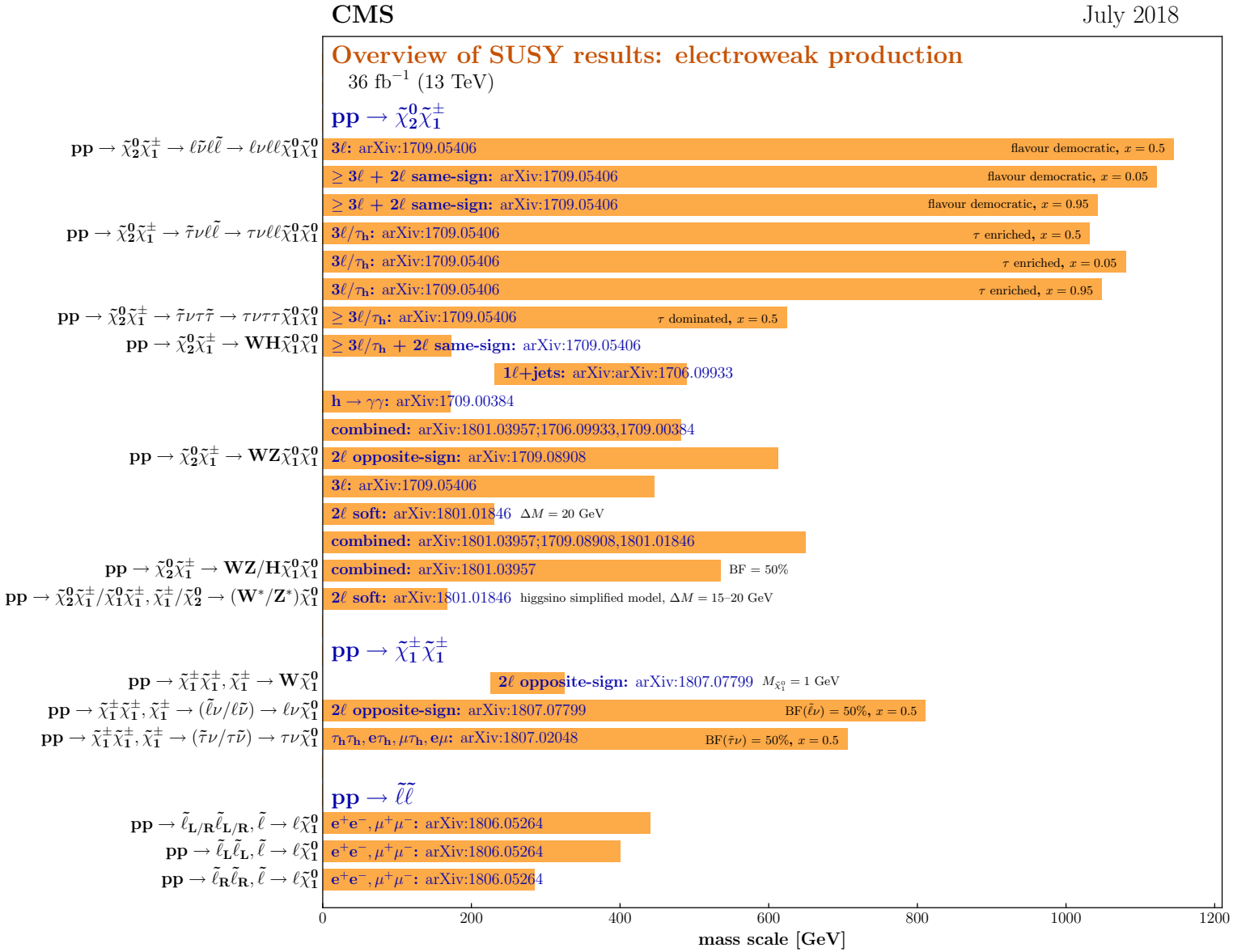


Summary of Exclusion Ranges from ATLAS SUSY Searches (March 2019)



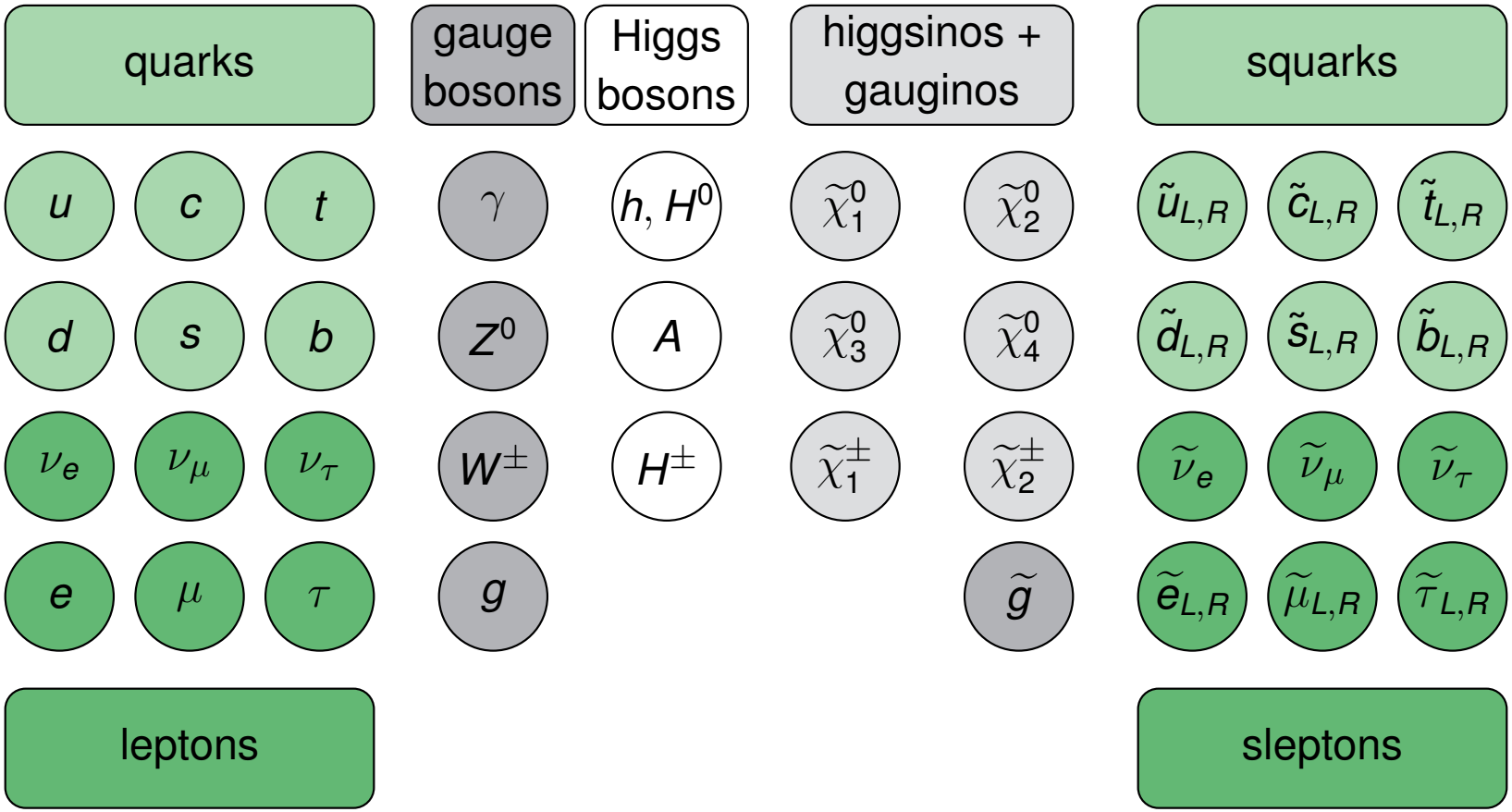
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Summary of Exclusion Ranges from CMS EWK SUSY Searches (March 2018)



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Particle content of the **M**inimal **S**upersymmetric **S**tandard **M**odel (MSSM)



- "For every fermion there is a boson and v.v."
- Exception: Higgs sector — need two complex Higgs doublets (2×SM) $\Rightarrow$ 5 Higgs bosons
- "electroweakinos" ($\widetilde{B}$, $\widetilde{W}_{1,2,3}$) and higgsinos ($\widetilde{H}_u^0$, $\widetilde{H}_d^0$, $\widetilde{H}_u^+$, $\widetilde{H}_d^-$)
  mix to neutralinos $\widetilde{\chi}_{1,2,3,4}^0$ and charginos $\widetilde{\chi}_{1,2}^\pm$

SUSY Models

mSUGRA / CMSSM Parameters

- $\rightarrow$ gravity-mediated SUSY breaking
- m_0: mass of scalar particles
- $m_{1/2}$: gaugino masses
- A_0: trilinear Higgs-sfermion-sfermion coupling parameter
- $\tan\beta = \nu_u/\nu_d$: ratio of the vacuum expectation values of the two Higgs doublets
- sign of the Higgsino mass parameter μ
- NUHM2: adds m_{H_u}, m_{H_d}, trade for μ, m_A

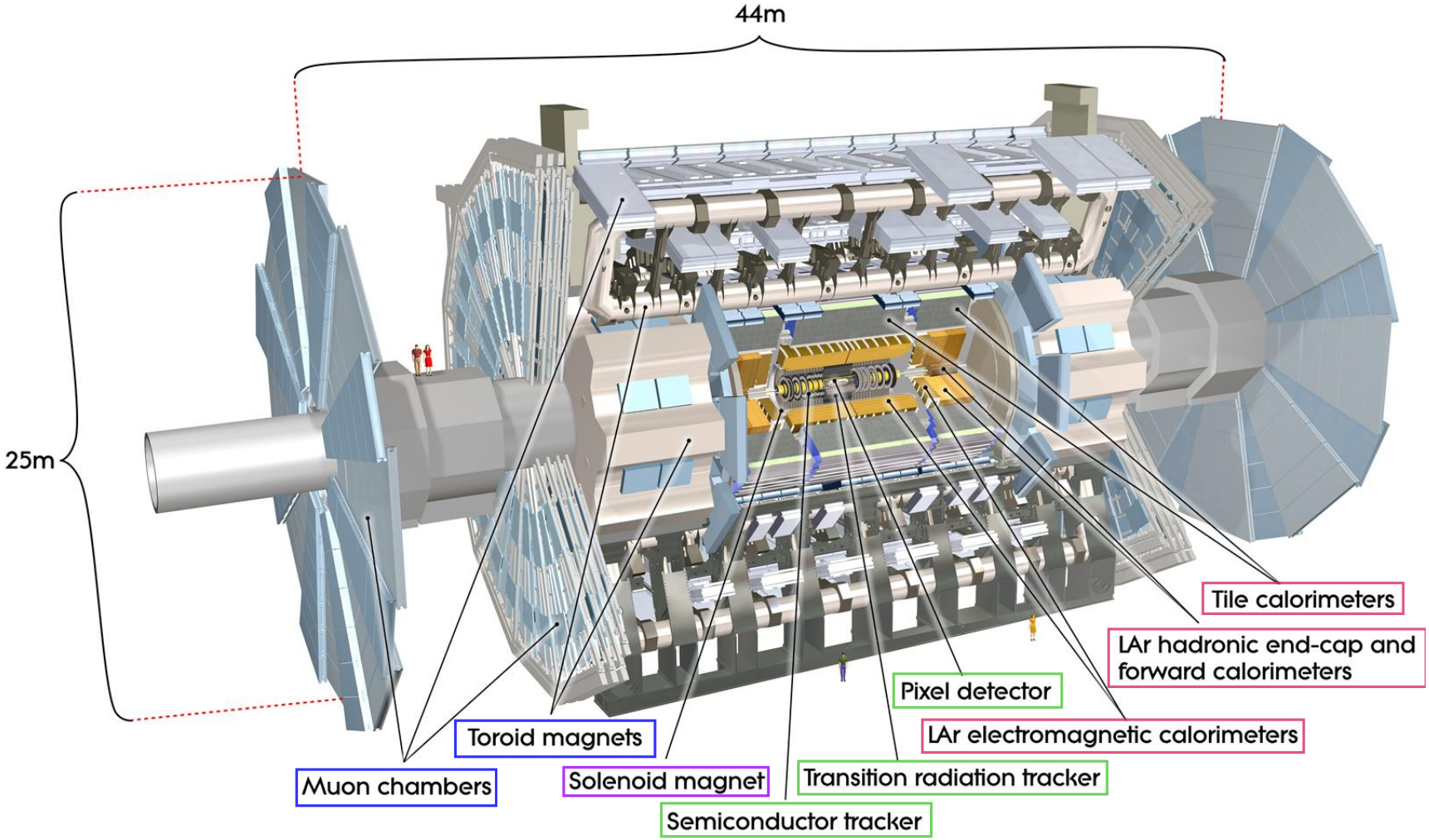
GMSB Parameters

- $\rightarrow$ gauge-mediated SUSY breaking
- Λ: SUSY breaking mass scale felt by the low-energy sector
- M_{mes}: mass scale of the messenger fields
- N_5: number of SU(5) messenger fields
- C_{grav}: scale factor of the gravitino coupling
- $\tan\beta = \nu_u/\nu_d$: ratio of the vacuum expectation values of the two Higgs doublets
- sign of the Higgsino mass parameter μ

NGM

- starts from General Gauge Mediation
- GGM: no specific SUSY mass hierarchy is predicted for colored and uncolored states
  $\Rightarrow$ gluinos and squarks can be below the TeV scale = within reach of LHC
- NGM: decouple all sparticles not related to fine-tuning of Higgs sector
  $\Rightarrow$ light stop and light gluino as only light (relevant) coloured sparticle
- some additional mechanism needed (as in GMSB) to produce “correct” Higgs mass

The ATLAS Detector

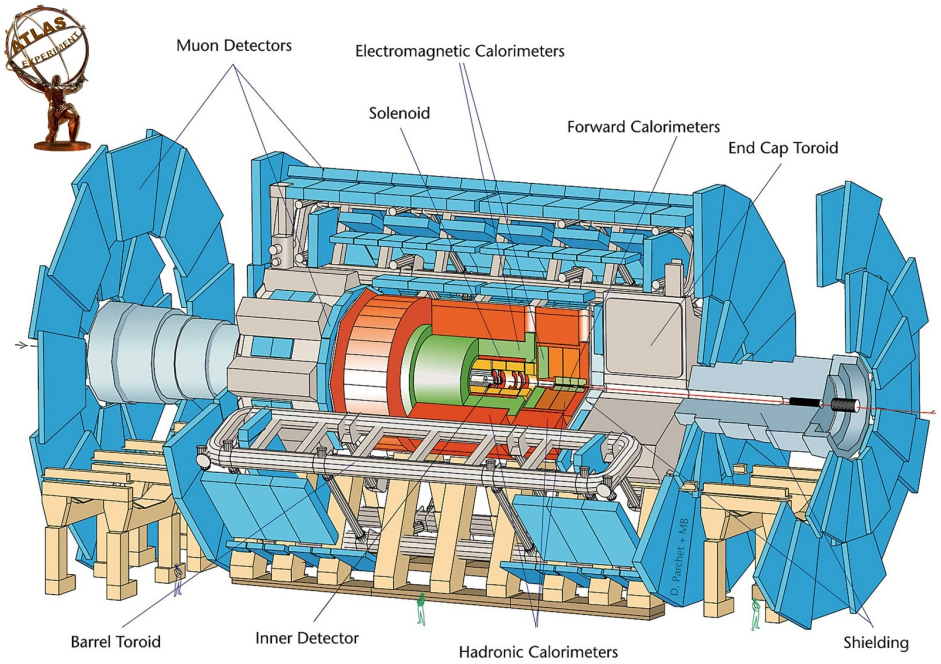


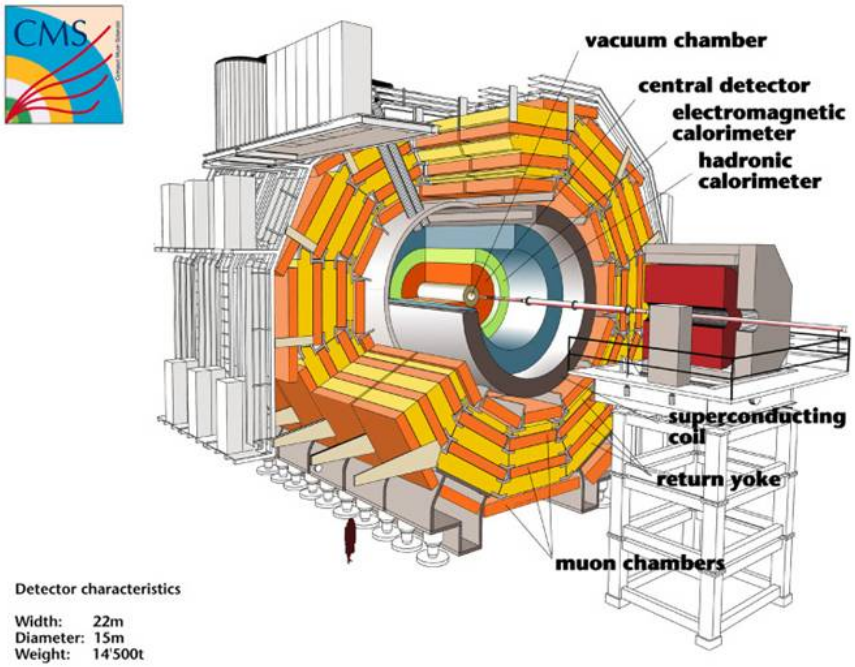
- 44 m $\times$ 25 m $\times$ 25 m, 7000 tonnes
- Subdetectors = concentrical cylinders surrounding nominal IP
- Tracking detectors — solenoid magnet — calorimeters — muon spectrometer

The Two Big Experiments at the LHC

ATLAS and CMS

- Two big, independent, multi-purpose detectors: ATLAS and CMS
- Situated at Interaction Points 1 and 5 of the LHC
- Different concepts, but same basic structure
  - almost 4π coverage, forward-backward symmetric cylindrical geometry:
  - tracking detectors, electromagnetic and hadronic calorimeters, muon system (+ magnets)
- Sophisticated trigger system to select collision events to be recorded (online filter)



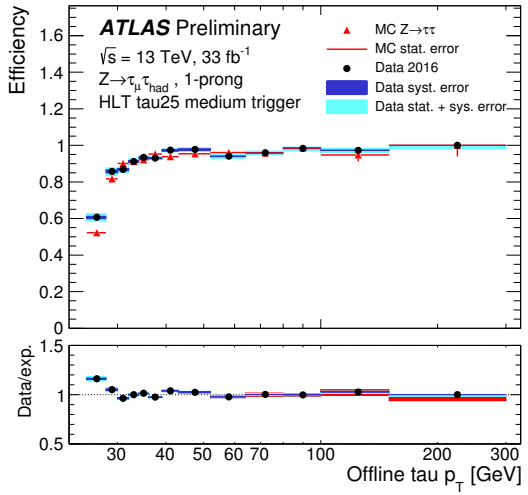


Di-Tau Triggers Thresholds

Experiment	Trigger	Year	Online [GeV]	Offline [GeV]	Efficiency [%]
ATLAS	di-tau + $E_{\mathrm{T}}^{\mathrm{miss}}$	2015–2016	35,25,50	50,40,150	80
	di-tau	2015–2016	85,50	95,65	80
ATLAS	di-tau + $E_{\mathrm{T}}^{\mathrm{miss}}$	2015–2018		50–75,40,150	75–80
	di-tau	2015–2018		95,60–75	75–80
CMS	di-tau	2016	35,35	40,40	60–95
CMS	di-tau	2017	40,40	45,45	

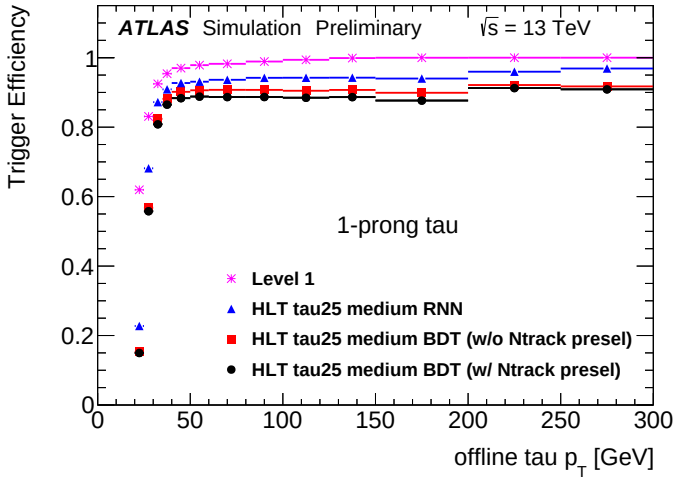
(based on ATLAS-SUSY-2016-23, ATLAS-CONF-2019-018, CMS-PAS-SUS-18-006, CMS-SUS-17-003)

Di-Tau Trigger Efficiencies



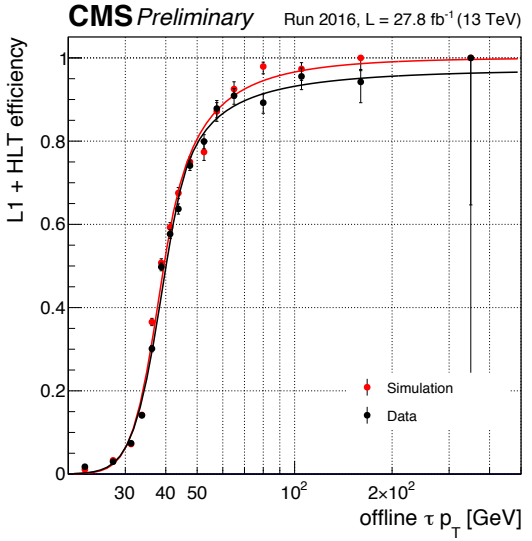
ATLAS-CONF-2017-061

MC and data16



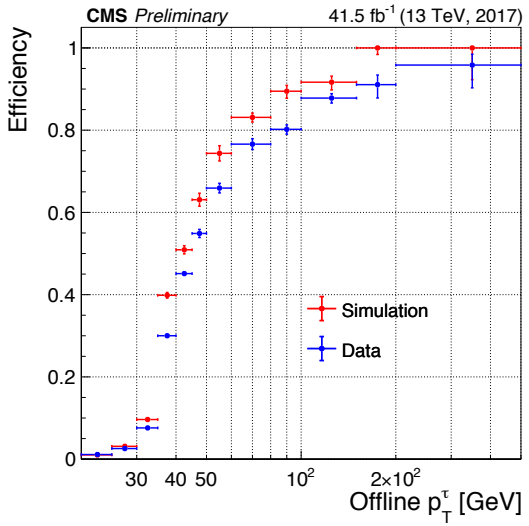
TauTriggerPublicResults

Simulation 2018



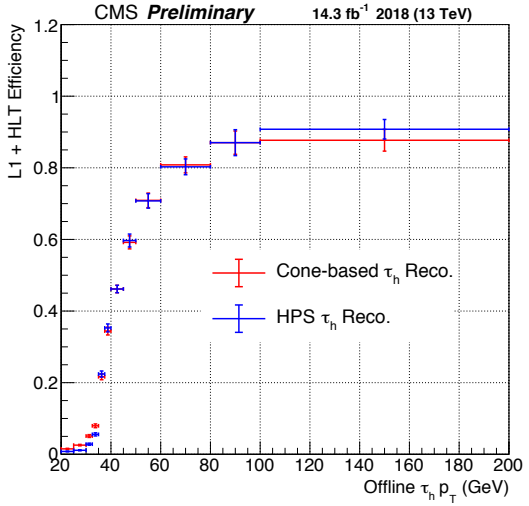
DP2017_031

HLT_DoubleMediumIsoPFTau35_-Trk1_eta2p1_Reg seeded by L1_DoubleIsoTau28er



DP2018_009

combination of Medium/TightChargedIsoPFTau35/40

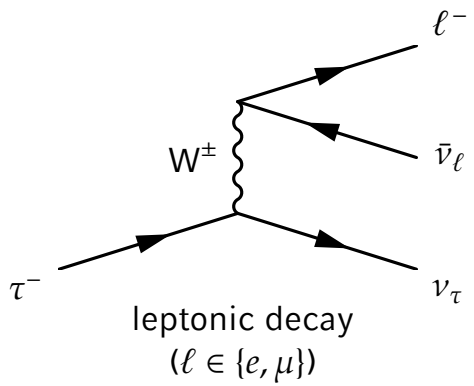


DP2018_035

$\tau_h(35)\tau_h(35)$ trigger at $\langle\mu\rangle = 50$

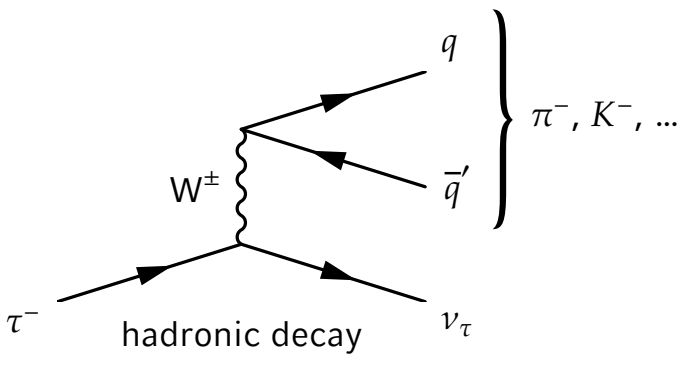
Tau Leptons: Properties

- Tau lepton: heaviest known lepton, $m(\tau) = 1777\,\mathrm{MeV}$
  - heavier than lightest mesons $\rightarrow$ can decay both to leptons or to hadrons
- Tau lepton: short lifetime, $c\tau = 0.087\,\mathrm{mm}$
  - decay before reaching active detector regions



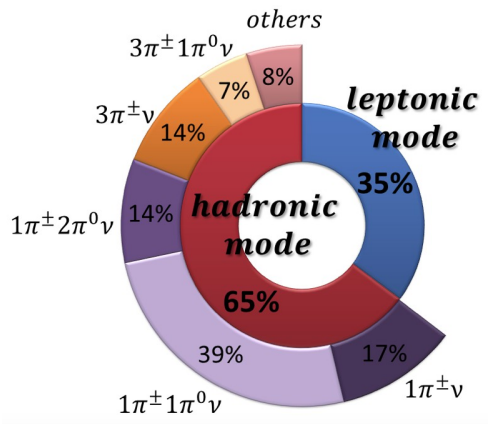
leptonic decay
($\ell \in \{e, \mu\}$)

$\mathrm{BR}(\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau) \sim \frac{1}{6}$



hadronic decay

$\mathrm{BR}(\tau^- \rightarrow \mathrm{hadrons} + \nu_\tau) \sim \frac{4}{6}$



- Leptonic decays: leptons (e, μ) from tau decay register as “prompt” light leptons
- Hadronic decays: can be reconstructed from detector signature of decay
- Part of momentum / energy detector-invisible due to neutrinos

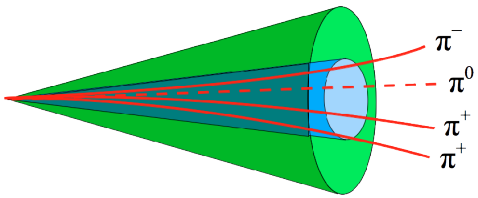
Tau Leptons: Reconstruction & Identification

ATLAS

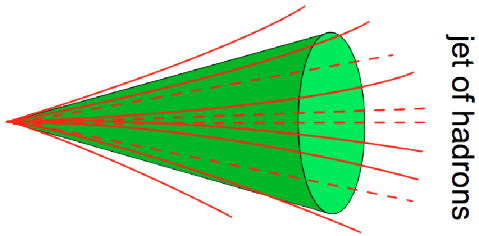
- seeded by jets
- tracks assigned to core and isolation cone
- BRT for energy calibration combines
  - measured energy of calorimeter clusters
  - momentum measurement from tracker
  - using “Tau Particle Flow”
- BDT-based discriminant against q/g jets
- overlap-based e veto

CMS

- Particle Flow algorithm
  $\Rightarrow$ charged + neutral hadrons, e, μ, γ
- Hadrons-plus-strips algorithm $\Rightarrow \tau$
  - seeded by jets
  - cluster $e + \gamma$ constituents of jet in “strips”
    $\Rightarrow \pi^0$ candidates
  - combine charged hadrons and π^0 cand’s
    $\Rightarrow \tau$ decay candidates
  - BDT-based discriminant against q/g jets
  - plus BDT against e
    and tracks in MS against μ

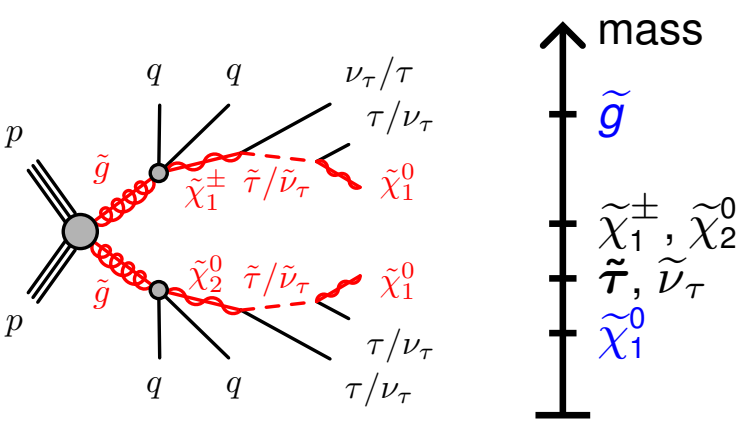


hadronically decaying tau lepton

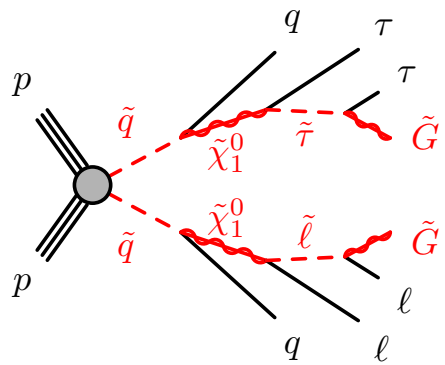


jet arising from a quark

- Search for production of squarks and gluinos, 36.1 fb^{-1} @ $\sqrt{s} = 13\,\mathrm{TeV}$
- Targets final states with $\geq$ 2 jets (strong production), hadronic tau decays, and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Interpretation: simplified model and gauge-mediated supersymmetry breaking (GMSB)



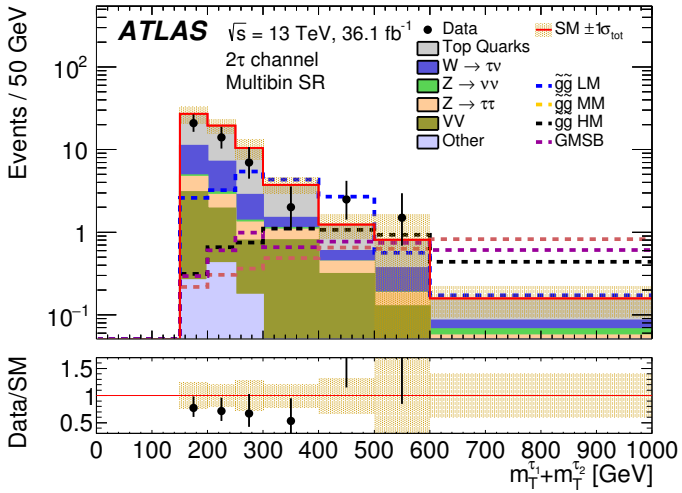
simplified model two parameters,



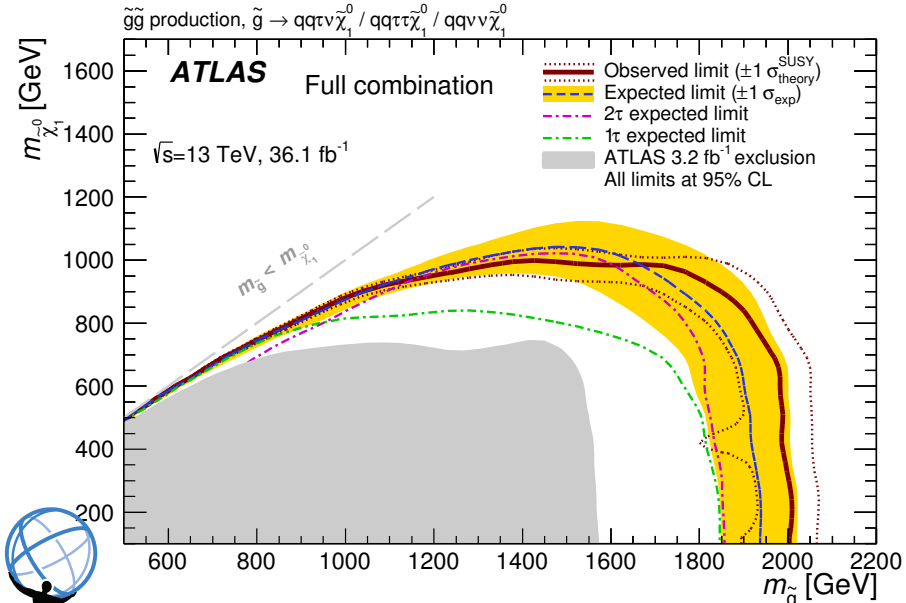
typical decay chain in GMSB model
production of squarks dominant at large Λ

- Two mutually exclusive channels:
  - $= 1\,\tau_{\mathrm{had}}$: 2 SRs (1 for low-p_{T} taus in compressed scenarios)
  - $\geq 2\,\tau_{\mathrm{had}}$: 4 SRs (1 for GMSB model)

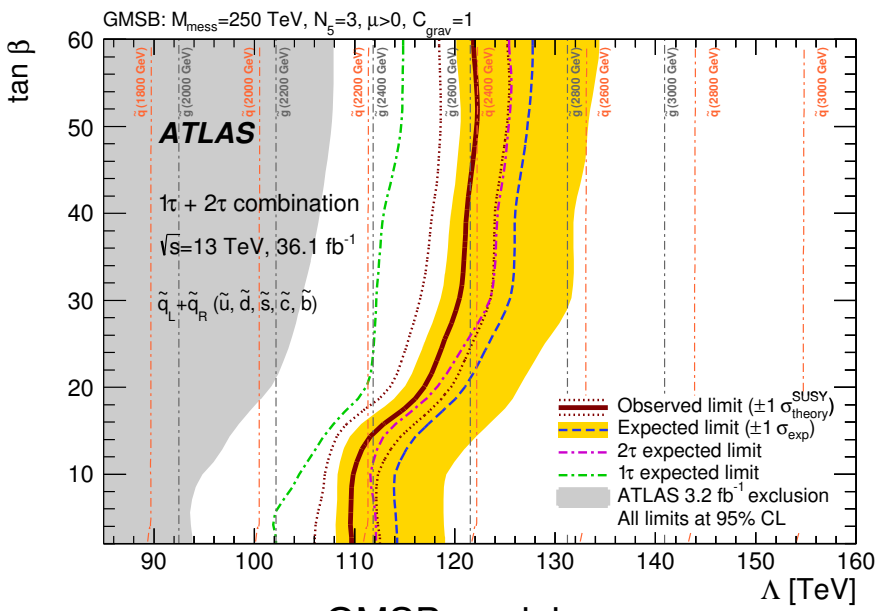
- No relevant deviation from SM prediction in any SR
  - two (correlated) $< 2\sigma$ excesses at high H_T in 2τ
- Improved analysis w.r.t. $3.2\,\mathrm{fb}^{-1}$ results,
  1τ and 2τ channel combined in global fit
- GMSB: production of $\tilde{q}\tilde{q}$ dominates at large Λ



$\sum m_T$ in 2τ multibin SR



simplified model



GMSB model

Subject of selection	1τ channel	2τ channel
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}} > 180\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{jet}_1} > 120\,\mathrm{GeV}$	
Jets	$N_{\mathrm{jet}} \geq 2$, $p_{\mathrm{T}}^{\mathrm{jet}_2} > 25\,\mathrm{GeV}$	
Multijet events	$\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{jet}_{1,2}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$	
τ-leptons	$N_\tau = 1$	$N_\tau \geq 2$

Subject of selection	1τ SRs	
	Compressed	Medium-mass
τ-leptons	$20 < p_{\mathrm{T}}^{\tau} < 45\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\tau} > 45\,\mathrm{GeV}$
Event kinematics	$E_{\mathrm{T}}^{\mathrm{miss}} > 400\,\mathrm{GeV}$ $m_{\mathrm{T}}^{\tau} > 80\,\mathrm{GeV}$ —	$m_{\mathrm{T}}^{\tau} > 250\,\mathrm{GeV}$ $H_{\mathrm{T}} > 1000\,\mathrm{GeV}$

Subject of selection	2τ SRs			
	Compressed	High-mass	Multibin	GMSB
Event kinematics	$m_{\mathrm{T2}}^{\tau\tau} > 70\,\mathrm{GeV}$ $H_{\mathrm{T}} < 1100\,\mathrm{GeV}$ $m_{\mathrm{T}}^{\mathrm{sum}} > 1600\,\mathrm{GeV}$	$m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} > 350\,\mathrm{GeV}$ $H_{\mathrm{T}} > 1100\,\mathrm{GeV}$ —	$m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} > 150\,\mathrm{GeV}$ $H_{\mathrm{T}} > 800\,\mathrm{GeV}$ $N_{\mathrm{jet}} \geq 3$ 7 bins in $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$	$m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} > 150\,\mathrm{GeV}$ $H_{\mathrm{T}} > 1900\,\mathrm{GeV}$ —

Table 5: Summary of the W and top control regions. These requirements are applied in addition to the trigger, jet, and multijet requirements of the preselection. The variables N_τ, N_{jet}, N_μ and $N_{b\text{-jet}}$ are the number of τ-leptons, jets, muons, and b-tagged jet, respectively; other variables are defined in the text.

Subject of selection	W/ Top kinematic CR	W/ Top true-τ CR	W/ Top fake-τ CR
τ-leptons	$N_\tau = 0$	$N_\tau = 1$	
Jets	$N_{\mathrm{jet}} \geq 3$		—
Muons	$N_\mu = 1$	$N_\mu = 0$	$N_\mu = 1$
W/top separation	$N_{b\text{-jet}} = 0/\geq 1$		
Event kinematics	$H_{\mathrm{T}} < 800\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} < 300\,\mathrm{GeV}$ $m_{\mathrm{T}}^{\mu} < 100\,\mathrm{GeV}$ —	$m_{\mathrm{T}}^{\tau} < 80\,\mathrm{GeV}$ —	$m_{\mathrm{T}}^{\mu} < 100\,\mathrm{GeV}$ $m_{\tau\mu} > 60\,\mathrm{GeV}$ (W CR)

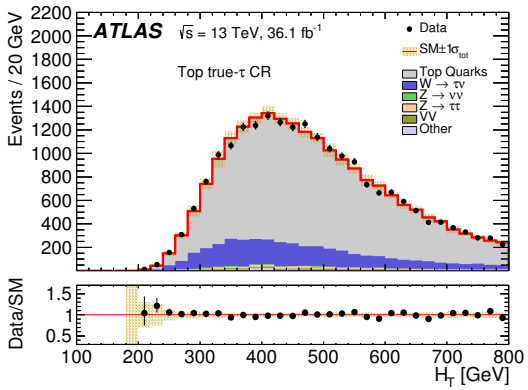
Table 6: Summary of the $Z(\nu\nu)$, $Z(\tau\tau)$ and multijet control regions. These requirements are applied in addition to the trigger, and jet requirements of the preselection. The variables N_τ and N_μ are the number of τ-leptons, and muons, respectively; q_{τ_i} is the charge of τ-lepton i; other variables are defined in the text.

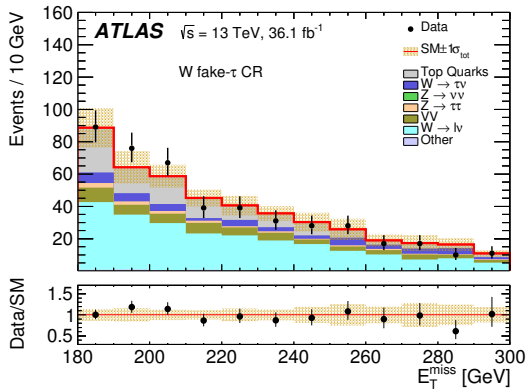
Subject of selection	$Z(\nu\nu)$ CR	$Z(\tau\tau)$ CR	Multijet CR
τ-leptons	$N_\tau = 1$	$N_\tau \geq 2$, $q_{\tau_1} = -q_{\tau_2}$	$N_\tau = 1$
Multijet events	$\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{jet}_{1,2}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$		$\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{jet}_{1,2}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) < 0.3$
Muons	$N_\mu = 0$	—	—
Top suppression	$N_{b\text{-jet}} = 0$		—
Event kinematics	$H_{\mathrm{T}} < 800\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} < 300\,\mathrm{GeV}$ $100 \leq m_{\mathrm{T}}^{\tau} < 200\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.3$ $\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{jet}_1}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) > 2.0$ $\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\tau_1}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) > 1.0$	— $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} < 100\,\mathrm{GeV}$ $m_{\mathrm{T2}} < 70\,\mathrm{GeV}$ — —	— — $100 < m_{\mathrm{T}}^{\tau} < 200\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} < 0.2$ — —

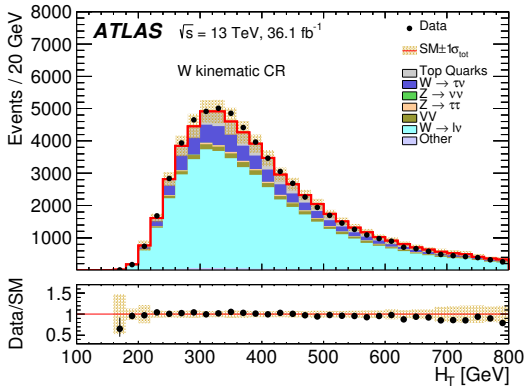
Inclusive Search for Tau Final States

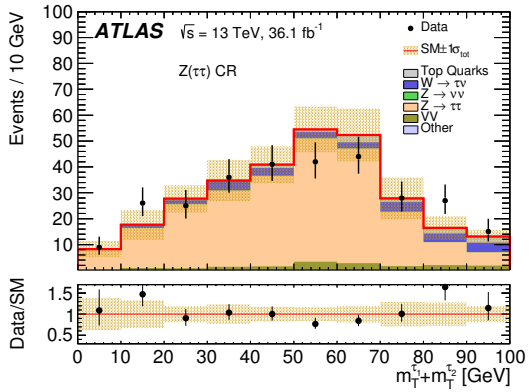
Phys. Rev. D 99 (2019) 012009

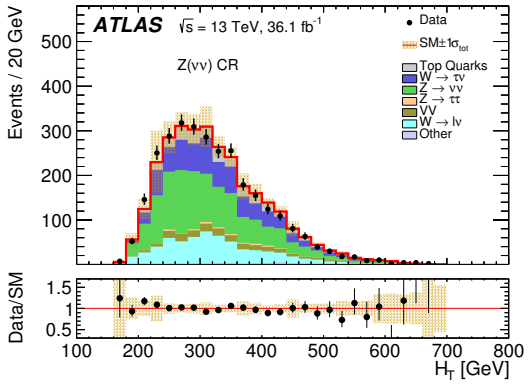
- NF for $Z \to \nu\nu$, $Z \to \tau\tau$ and multijet from 3 CRs
- W / top: 3 NFs from 2 · 3 CRs
  - kinematic (modelling of bg kinematics and acceptance, measured in single-muon events)
  - true-tau (tau reco+ID efficiencies, measured in single-tau events)
  - fake-tau (mismodelling in simulation, measured in tau-muon channel)
- multijet from jet smearing (very small contribution)

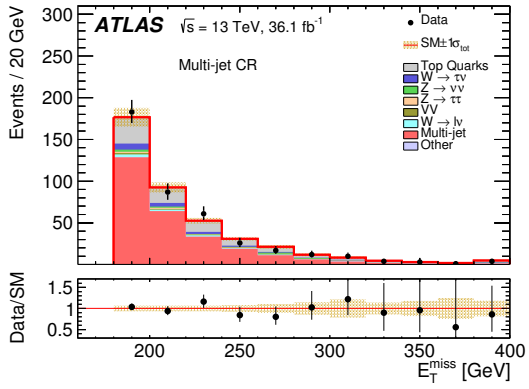












Phys. Rev. D 99 (2019) 012009

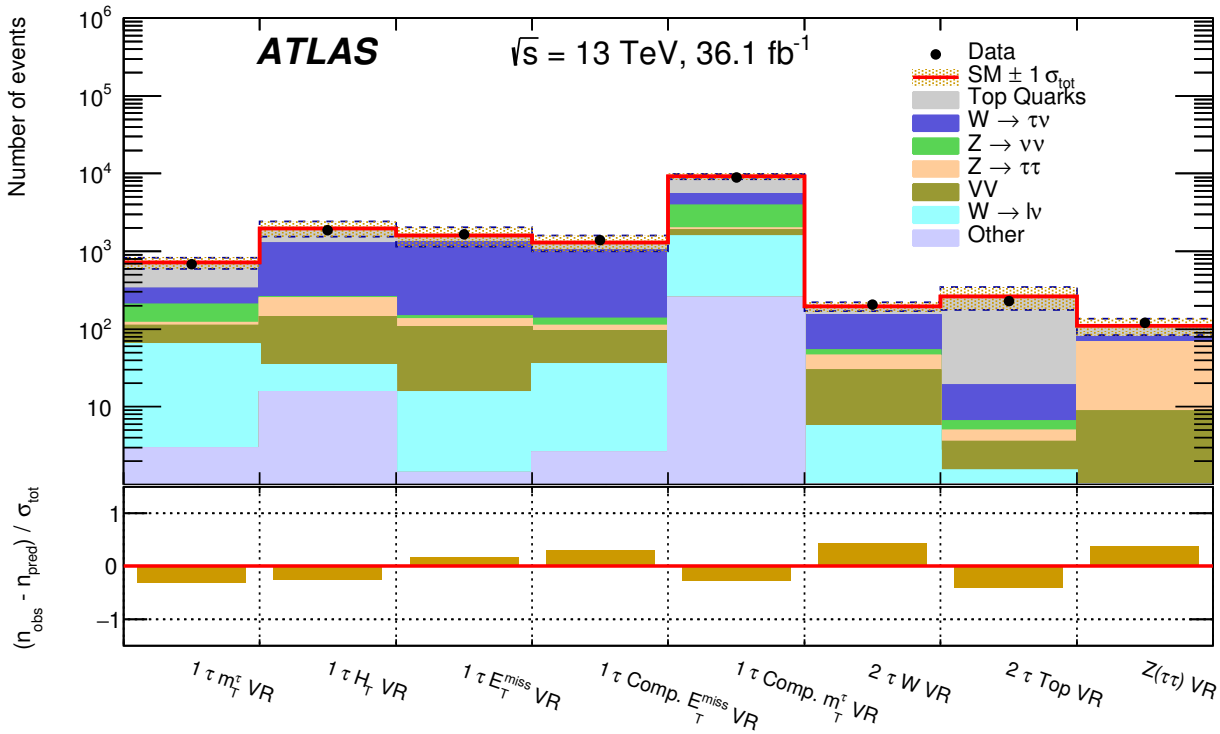
- 5 VRs for 1τ
  - validate H_T, E_T^{miss}, m_T^{τ} modelling
- 3 VRs for 2τ
  - validate W/top and $Z \to \tau\tau$

Table 7: Validation regions for the 1τ channel. These requirements are applied in addition to the preselection. The variables are defined in the text.

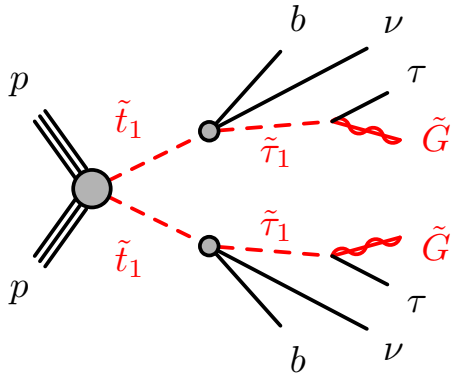
Subject of selection	1τ medium-mass VRs			1τ compressed VRs	
	H_T	E_T^{miss}	m_T^{τ}	E_T^{miss}	m_T^{τ}
τ-leptons	$p_T^{\tau} > 45$ GeV			$20 < p_T^{\tau} < 45$ GeV	
Event kinematics	$m_T^{\tau} < 250$ GeV, $E_T^{miss} < 400$ GeV, $H_T > 1000$ GeV	$m_T^{\tau} < 250$ GeV, $E_T^{miss} > 400$ GeV, $H_T < 1000$ GeV	$m_T^{\tau} > 250$ GeV, $E_T^{miss} < 400$ GeV, $H_T < 1000$ GeV	$m_T^{\tau} < 80$ GeV, $E_T^{miss} > 400$ GeV, —	$m_T^{\tau} > 80$ GeV, $E_T^{miss} < 400$ GeV, —

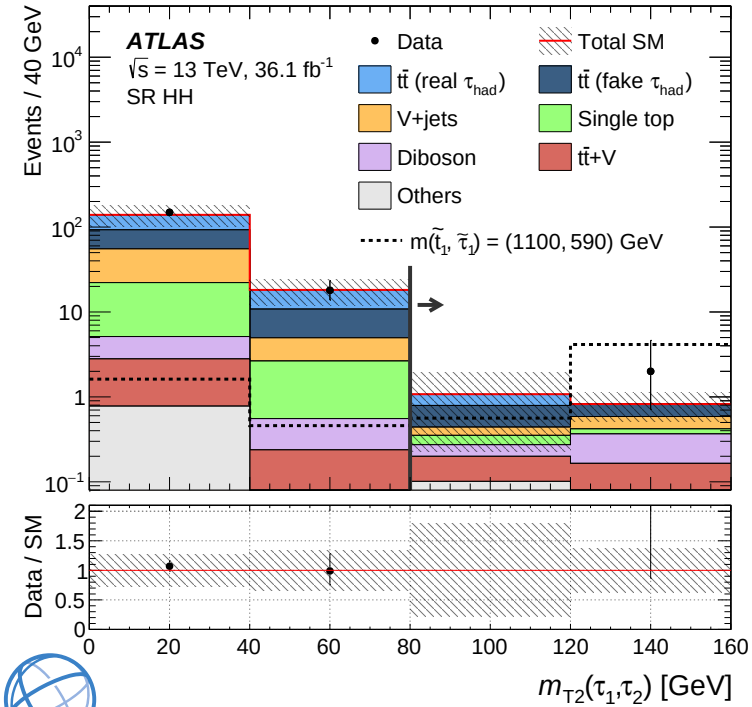
Table 8: Validation regions for the 2τ channel. These requirements are applied in addition to the preselection. The variables are defined in the text.

Subject of selection	2τ W/Top VR	$Z(\tau\tau)$ VR
W/top separation	$N_{b\text{-jet}} = 0/\geq 1$	—
Event kinematics	$H_T < 800$ GeV, $m_T^{\tau_1} + m_T^{\tau_2} > 150$ GeV, $m_{T2}^{\tau\tau} < 60$ GeV	$H_T > 800$ GeV, $m_T^{\tau_1} + m_T^{\tau_2} < 150$ GeV



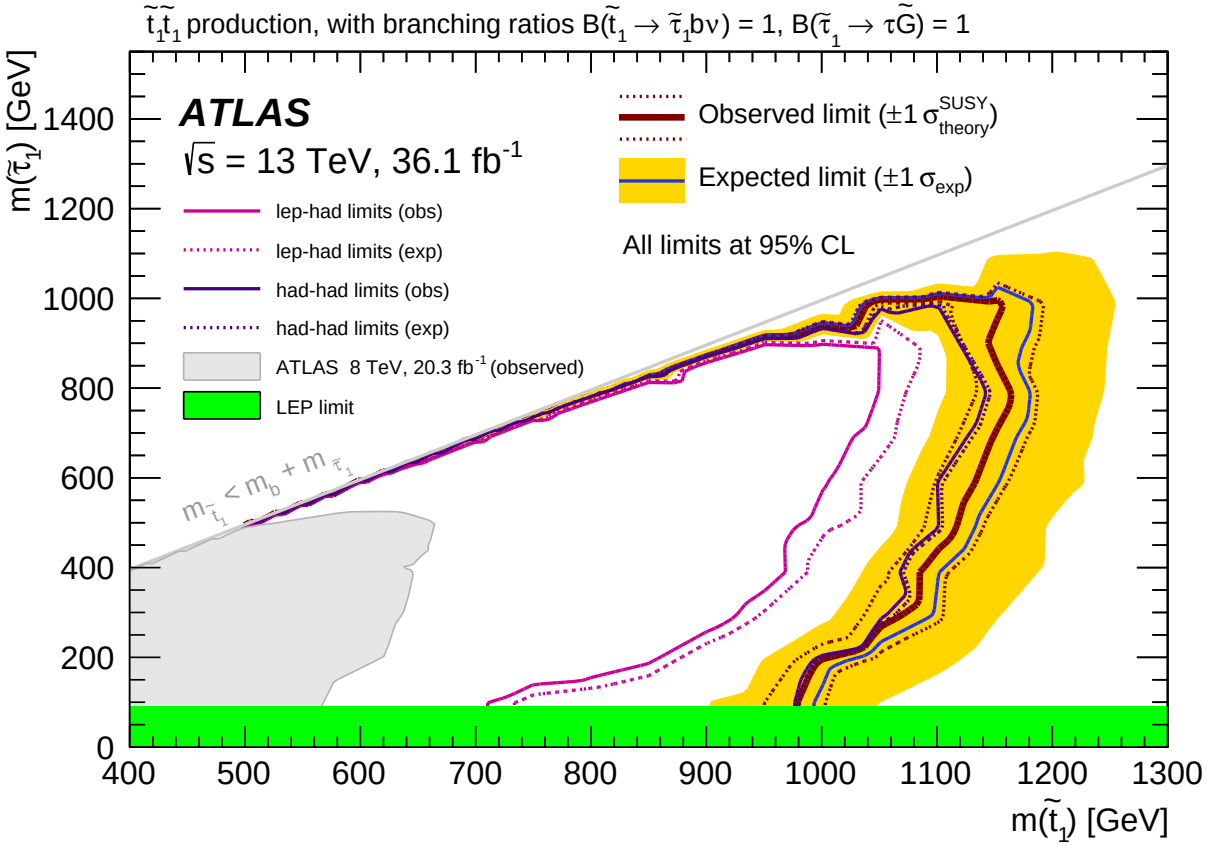
- Model assumes these three SUSY particles within reach:
  $\tilde{t}$ $\widetilde{\tau}$ $\sim$ massless $\widetilde{G}$
- Interesting model with intriguing detector signature:
  b-jets tau leptons $E_{\mathrm{T}}^{\mathrm{miss}}$





- $36.1\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 13\,\mathrm{TeV}$
- Analysis selections:
  "lep-had" ($\tau_\ell \tau_h$) and "had-had" ($\tau_h \tau_h$) channels
- Dominant background:
  top-quark pair production ($t\bar{t}$)

- Observed event yields in signal selections in good agreement with SM expectation
- Limits derived from statistical **combination** of **lep-had** and **had-had** channel
- Exclusion of $m(\tilde{\tau}_1)$ up to 1.0 TeV at 95 % confidence level
  - and of $m(\tilde{t}_1)$ up to 1.16 TeV



	SR LH	SR HH
Observed events	3	2
Total background	2.2 ± 0.6	1.9 ± 1.0
Fake $\tau_{had} + e/\mu$	1.4 ± 0.5	—
$t\bar{t}$ (fake τ_{had})	—	$0.6 \pm {}^{0.7}_{0.6}$
$t\bar{t}$ (real τ_{had})	0.22 ± 0.12	$0.28 \pm {}^{0.30}_{0.28}$
$t\bar{t} + V$	0.25 ± 0.14	0.26 ± 0.12
Diboson	0.15 ± 0.11	0.28 ± 0.13
Single-top	$0.10 \pm {}^{0.24}_{0.10}$	0.13 ± 0.11
V + jets	0.032 ± 0.014	0.26 ± 0.09
Others	0.082 ± 0.022	0.09 ± 0.04
Signal ($m(\tilde{t}_1) = 1100$ GeV, $m(\tilde{\tau}_1) = 590$ GeV)	3.3 ± 0.7	4.7 ± 1.2

Phys. Rev. D 98 (2018) 032008

Preselection	lep-had	had-had
Trigger	single-electron or single-muon trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ or di-tau trigger
Leptons	exactly one τ_{had} + one signal electron or muon no additional baseline electron or muon or τ_{had}	exactly two τ_{had} no baseline electron or muon
Trigger-related requirements	$p_{\mathrm{T}}(e,\mu) > 27$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 180$ GeV or $p_{\mathrm{T}}(\tau_{1,2}, \mathrm{jet}_1) > 50, 40, 80$ GeV
$p_{\mathrm{T}}(\mathrm{jet}_2)$	> 26 GeV	> 20 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	> 70 GeV	> 70 GeV
$n_{b\text{-jet}}$	≥ 1	≥ 1

Variable	CR LH $t\bar{t}$-real	VR LH $t\bar{t}$-real	VR LH $t\bar{t}$-fake (OS)	VR LH $t\bar{t}$-fake (SS)	SR LH
Charge(ℓ,τ_{had})	opposite	opposite	opposite	same	opposite
$m_{\mathrm{T2}}(\ell, \tau_{\mathrm{had}})$	< 60 GeV	[60, 100] GeV	[60, 100] GeV	> 60 GeV	> 100 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 210 GeV	> 210 GeV	> 150 GeV	> 150 GeV	> 230 GeV
$m_{\mathrm{T}}(\ell)$	> 100 GeV	> 100 GeV	< 100 GeV	—	—
$m(\ell, \tau_{\mathrm{had}})$	—	—	> 60 GeV	—	—

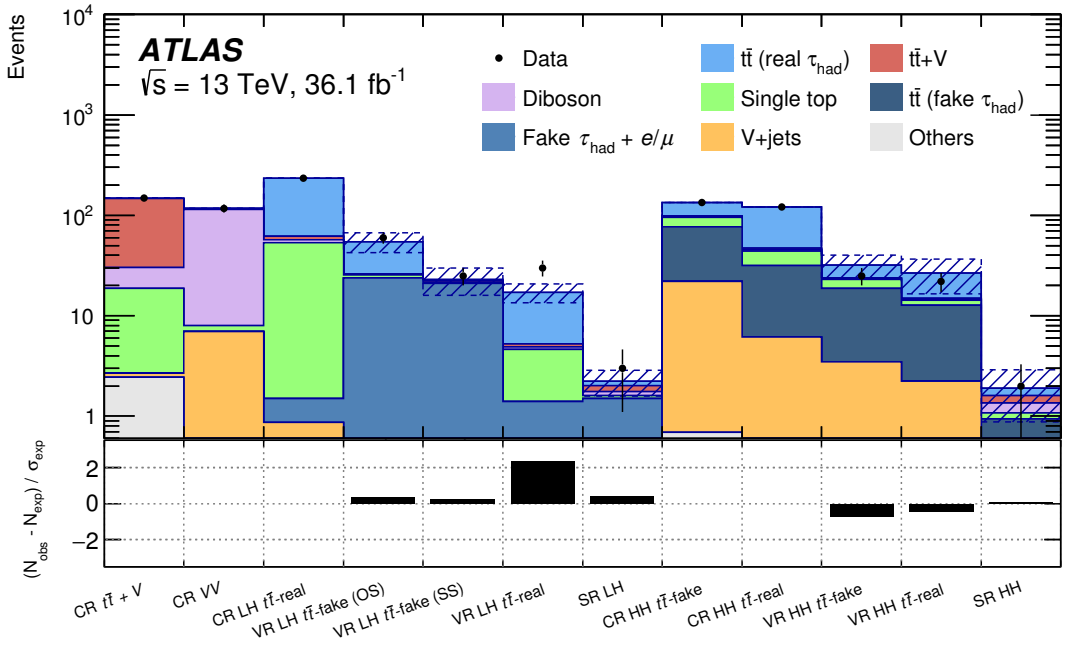
	CR HH $t\bar{t}$-fake	CR HH $t\bar{t}$-real	VR HH $t\bar{t}$-fake	VR HH $t\bar{t}$-real	SR HH
Charge(τ_1,τ_2)	—	opposite	—	opposite	opposite
$m_{\mathrm{T2}}(\tau_1, \tau_2)$	< 30 GeV	< 30 GeV	[30, 80] GeV	[30, 80] GeV	> 80 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 120 GeV	> 120 GeV	> 160 GeV	> 160 GeV	> 200 GeV
$m_{\mathrm{T}}(\tau_1)$	< 70 GeV	> 70 GeV	< 100 GeV	> 100 GeV	—
$m(\tau_1, \tau_2)$	> 70 GeV	> 70 GeV	—	—	—

Phys. Rev. D 98 (2018) 032008

	SR LH	SR HH
Total systematic uncertainty	±29%	±53%
Fake-factor method	±23%	—
Jet-related	±9.4%	±36%
Tau-related	±7.2%	±32%
Other experimental	±6.2%	±12%
Theory modelling	±8.4%	±20%
MC statistics	±7.5%	±17%
Normalization factors	±4.8%	±14%
Luminosity	±0.3%	±0.8%

Signal channel	$\langle A\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	$p(s=0)$ (Z)
SR LH	0.15	5.4	$4.5^{+2.6}_{-1.5}$	0.65	0.32 (0.47)
SR HH	0.13	4.7	$4.6^{+2.5}_{-1.5}$	0.52	0.48 (0.05)

	SR LH	SR HH
Observed events	3	2
Total background	2.2 ± 0.6	1.9 ± 1.0
Fake $\tau_{\text{had}} + e/\mu$	1.4 ± 0.5	—
$t\bar{t}$ (fake τ_{had})	—	$0.6 \pm ^{0.7}_{0.6}$
$t\bar{t}$ (real τ_{had})	0.22 ± 0.12	$0.28 \pm ^{0.30}_{0.28}$
$t\bar{t} + V$	0.25 ± 0.14	0.26 ± 0.12
Diboson	0.15 ± 0.11	0.28 ± 0.13
Single-top	$0.10 \pm ^{0.24}_{0.10}$	0.13 ± 0.11
V + jets	0.032 ± 0.014	0.26 ± 0.09
Others	0.082 ± 0.022	0.09 ± 0.04
Signal	3.3 ± 0.7	4.7 ± 1.2
$(m(\tilde{t}_1) = 1100\,\text{GeV}, m(\tilde{\tau}_1) = 590\,\text{GeV})$		

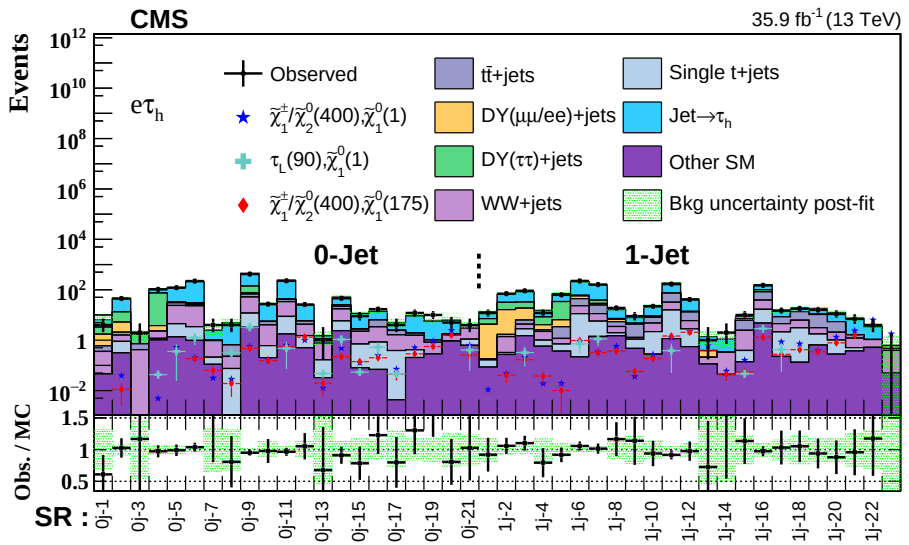


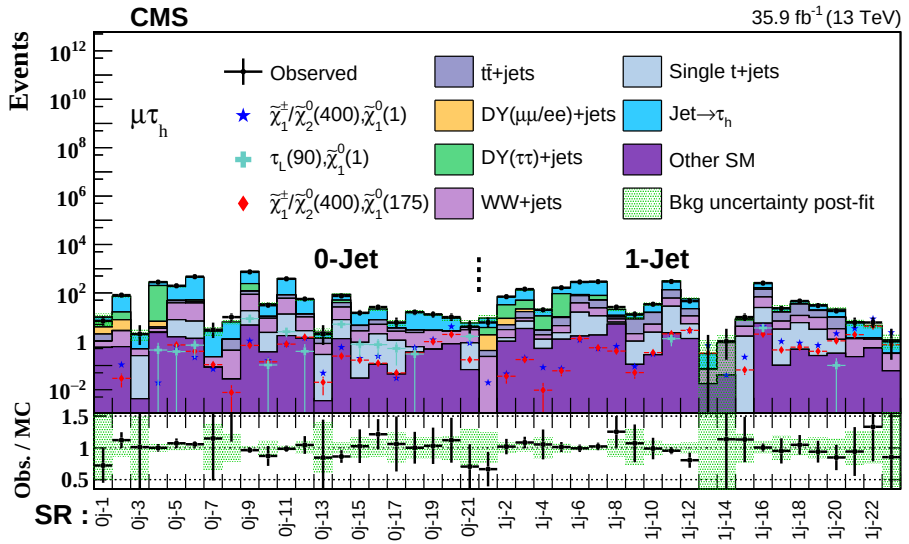
SRs for $\ell\tau_h$ channels

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

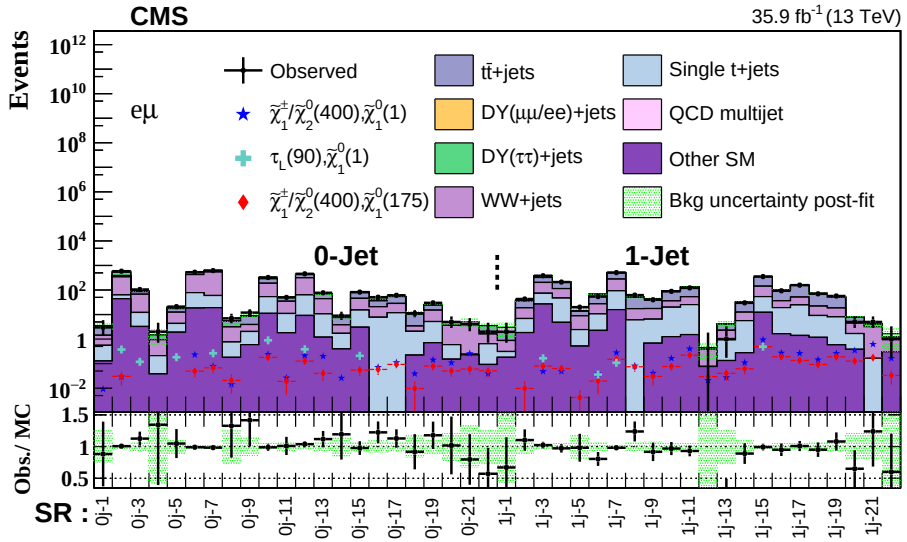
- $D_\zeta = P_{\zeta,\text{miss}} - 0.85 P_{\zeta,\text{vis}}$ with
  - $P_{\zeta,\text{miss}} = \vec{p_T}^{\text{miss}} \cdot \vec{\zeta}$
  - $P_{\zeta,\text{vis}} = (\vec{p_T}(\ell_1) + \vec{p_T}(\ell_2)) \cdot \vec{\zeta}$
  - $\vec{\zeta}$ = bisector between directions of leptons
- helps to discriminate other processes from events in which E_T^{miss} originates from decay of 2 τ leptons





SRs for $e\mu$ channel

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



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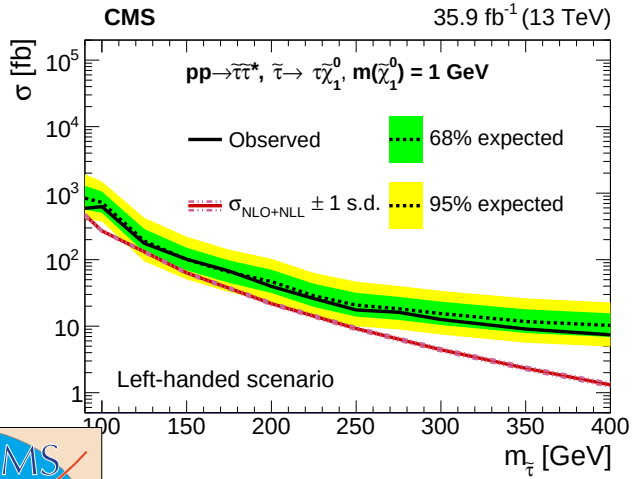
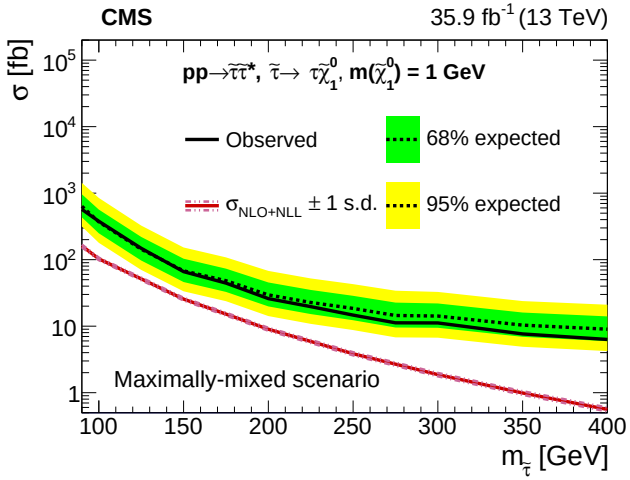
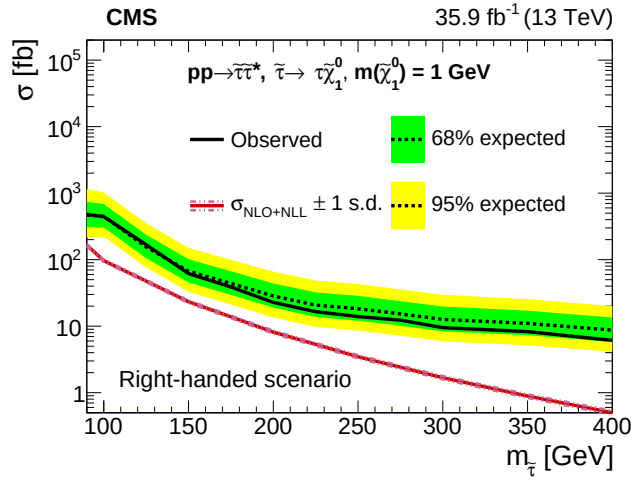






Eur. Phys. J. C 78 (2018) 154

W-CR	W-VR
One isolated muon and one medium tau lepton with opposite sign	
b-jet veto	
$m(\mu,\tau) > 70$ GeV	
$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV	
$50 < m_{\mathrm{T},\mu} < 150$ GeV	
$m_{\mathrm{T},\mu} + m_{\mathrm{T},\tau} > 80$ GeV	
$0.5 < \Delta R(\mu,\tau) < 3.5$	$0.5 < \Delta R(\mu,\tau) < 4.5$
$10 < m_{\mathrm{T2}} < 60$ GeV	$m_{\mathrm{T2}} > 60$ GeV

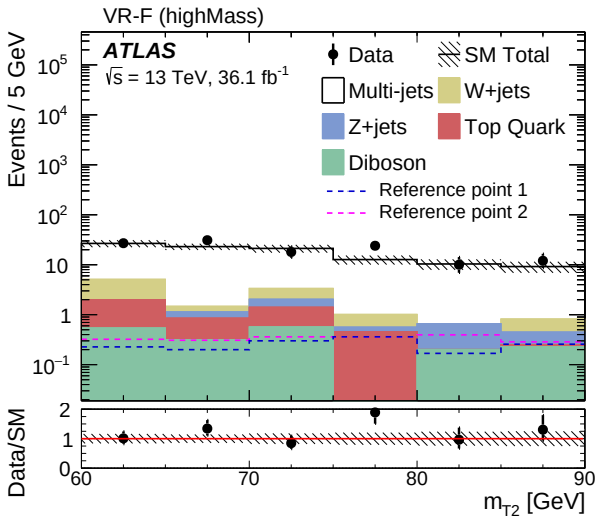
Z-VR	Top-VR
At least one opposite-sign tau lepton pair	
Tau $p_{\mathrm{T}} > 50, 40$ GeV	
$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV	
At least two medium tau leptons	at least one medium and one loose tau lepton
b-jet veto	at least one b-jet
$m_{\mathrm{T2}} < 10$ GeV	$m_{\mathrm{T2}} > 10$ GeV
	m_{CT} top-tagged

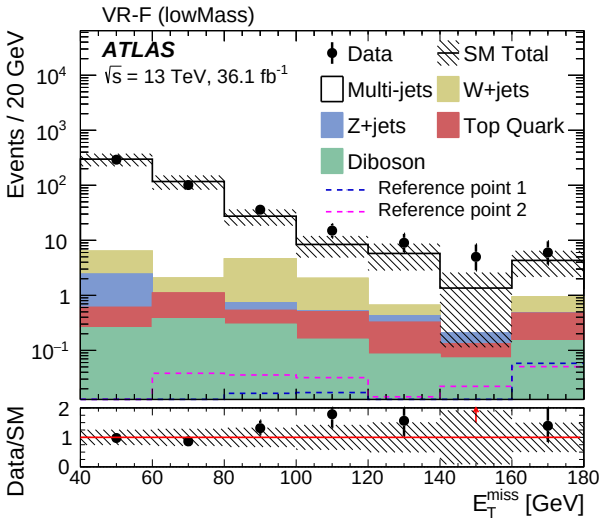
Source of systematic uncertainty	SR-lowMass	SR-highMass
Normalisation uncertainties of the multi-jet background	32	32
Statistical uncertainty of MC samples	18	24
Multi-jet estimation	14	13
Pile-up reweighting	8	8
Jet energy scale and resolution	11	4
Tau identification and energy scale	6	8
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	2	6
Total	40	38

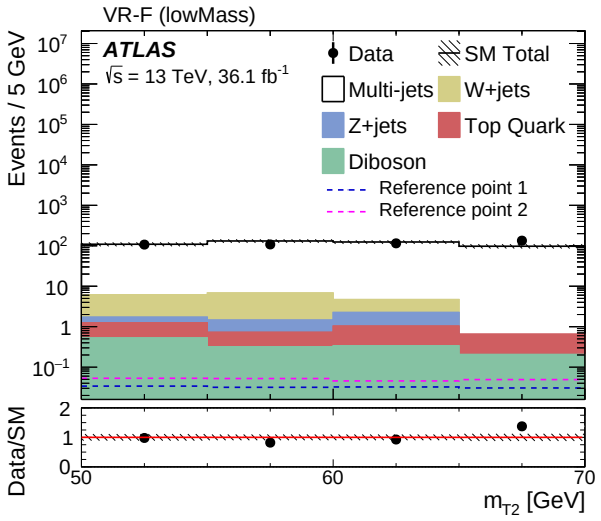
SR-lowMass	SR-highMass	
At least one opposite-sign tau pair		
b-jet veto		
Z-veto		
At least two medium tau candidates	at least one medium and one tight tau candidates	
	$m(\tau_1,\tau_2) > 110$ GeV	
$m_{\mathrm{T2}} > 70$ GeV	$m_{\mathrm{T2}} > 90$ GeV	
Di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	asymmetric di-tau trigger
$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 110$ GeV
$p_{\mathrm{T},\tau_1} > 50$ GeV	$p_{\mathrm{T},\tau_1} > 80$ GeV	$p_{\mathrm{T},\tau_1} > 95$ GeV
$p_{\mathrm{T},\tau_2} > 40$ GeV	$p_{\mathrm{T},\tau_2} > 40$ GeV	$p_{\mathrm{T},\tau_2} > 65$ GeV

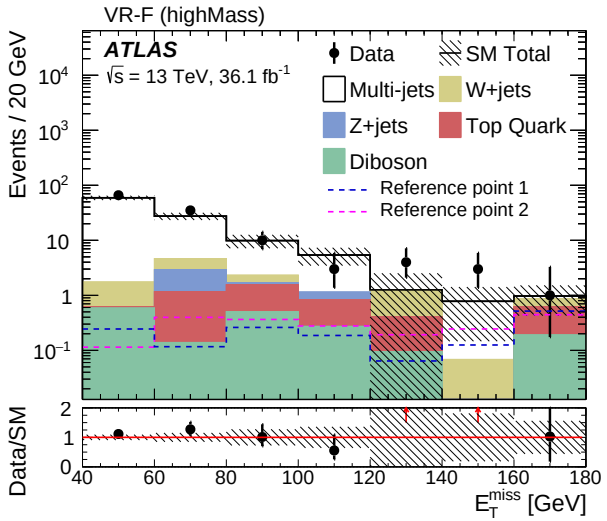
SM process	SR-lowMass	SR-highMass
Diboson	5.9 ± 2.2	1.0 ± 0.8
W+jets	1.8 ± 1.1	0.7 ± 0.5
Top quark	1.2 ± 1.0	$0.03^{+0.26}_{-0.03}$
Z+jets	$0.6^{+0.7}_{-0.6}$	0.6 ± 0.5
Multi-jet	4.3 ± 4.0	1.3 ± 1.1
SM total	14 ± 6	3.7 ± 1.4
Observed	10	5
Reference point 1	11.8 ± 2.8	11.6 ± 2.6
Reference point 2	11.4 ± 2.6	10.0 ± 2.1
p_0	0.5	0.3
Expected $\sigma_{\mathrm{vis}}^{95}$ [fb]	$0.31^{+0.12}_{-0.08}$	$0.17^{+0.08}_{-0.05}$
Observed $\sigma_{\mathrm{vis}}^{95}$ [fb]	0.26	0.20

SR	Sample	CR-B	CR-C	CR-A	T = C/B	Multi-jet in SR-D
lowMass	**Data**	**556**	**674**	**8**	1.16 ± 0.07	4.3 ± 4.0
	Z+jets	3.4 ± 2.1	19 ± 5	0.8 ± 0.4		
	W+jets	8.9 ± 1.8	20 ± 5	1.8 ± 1.0		
	Diboson	0.94 ± 0.12	3.3 ± 0.2	0.29 ± 0.07		
	Top	1.61 ± 0.30	4.7 ± 0.5	1.4 ± 1.1		
	Multi-jet	*541 ± 24*	*627 ± 27*	*3.7 ± 1.6*		
	Reference point 1	0.06 ± 0.01	0.16 ± 0.02	1.68 ± 0.16		
highMass	**Data**	**1565**	**836**	**5**	0.43 ± 0.04	1.3 ± 1.1
	Z+jets	56 ± 31	93 ± 42	0.02 ± 0.29		
	W+jets	151 ± 22	125 ± 17	1.1 ± 0.4		
	Diboson	9.6 ± 1.1	20.5 ± 2.0	0.8 ± 0.4		
	Top	9.2 ± 1.5	25.4 ± 3.4	0.01 ± 0.01		
	Multi-jet	*1340 ± 50*	*570 ± 50*	*3.1 ± 0.6*		
	Reference point 2	0.53 ± 0.08	2.37 ± 0.21	1.92 ± 0.16		

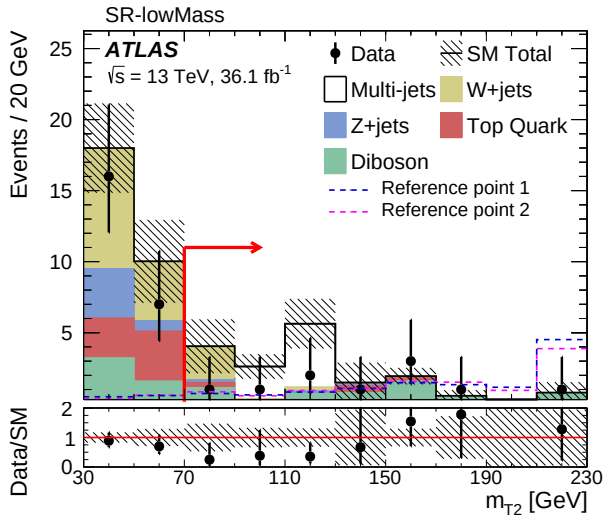


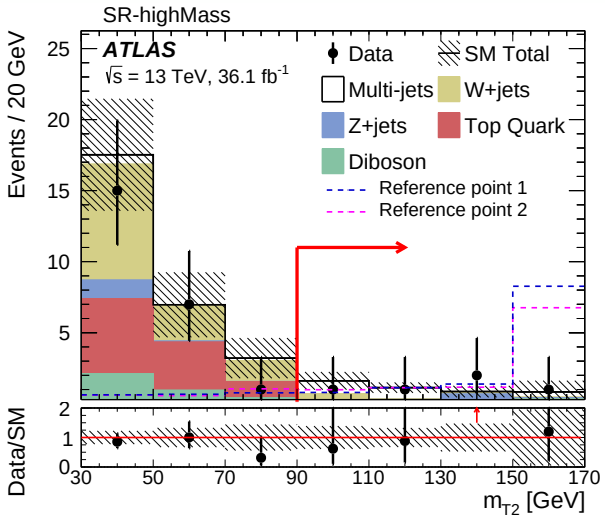


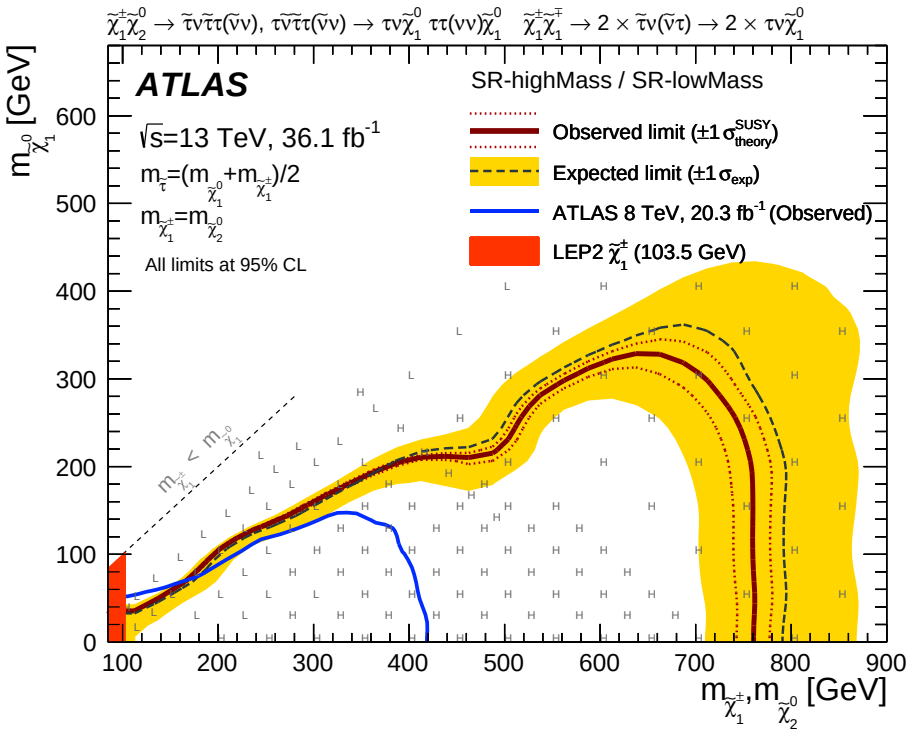




Eur. Phys. J. C 78 (2018) 154

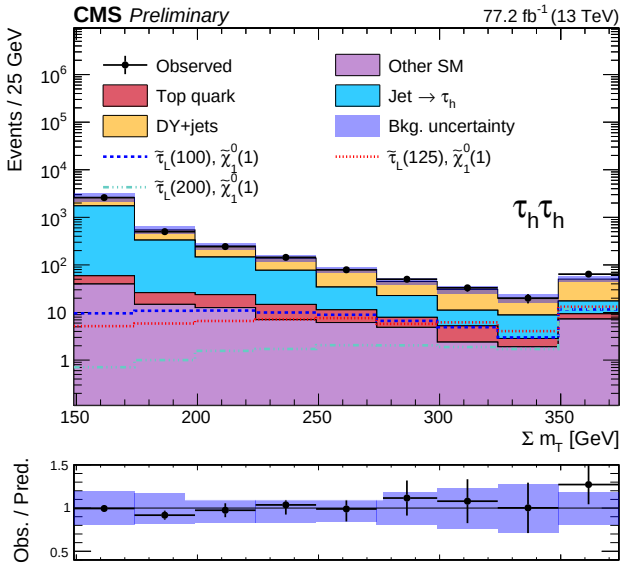


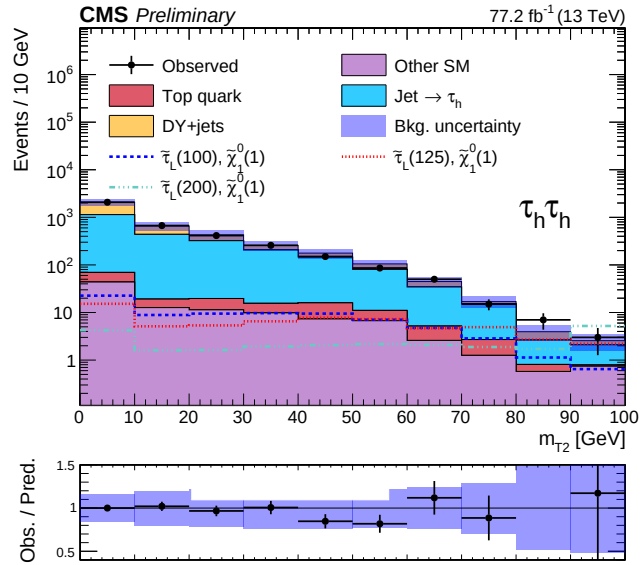




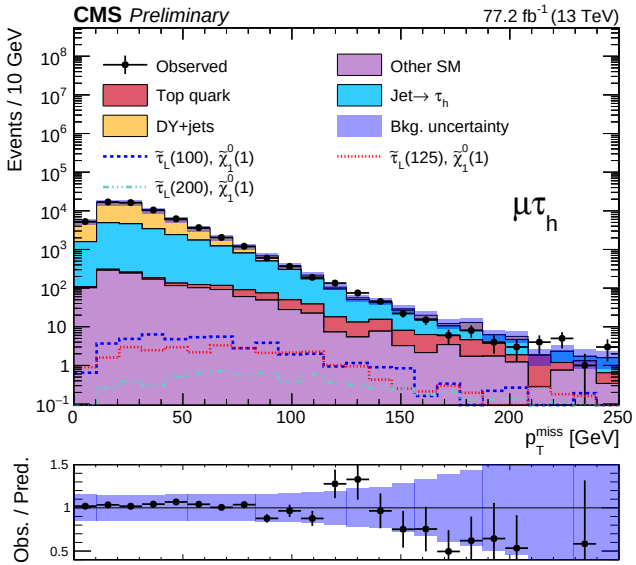
more sensitive signal region, “H” corresponds to SR-highMass and “L” to SR-lowMass

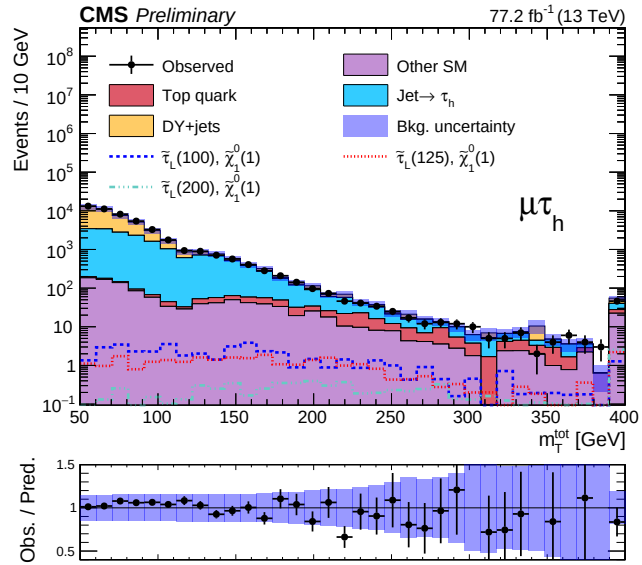
$\sum m_T$ and m_{T2} distributions after baseline selection in $\tau_h\tau_h$ channel



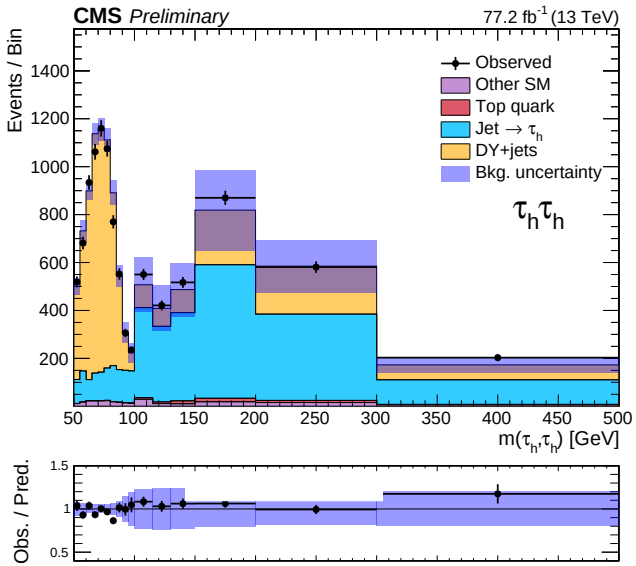


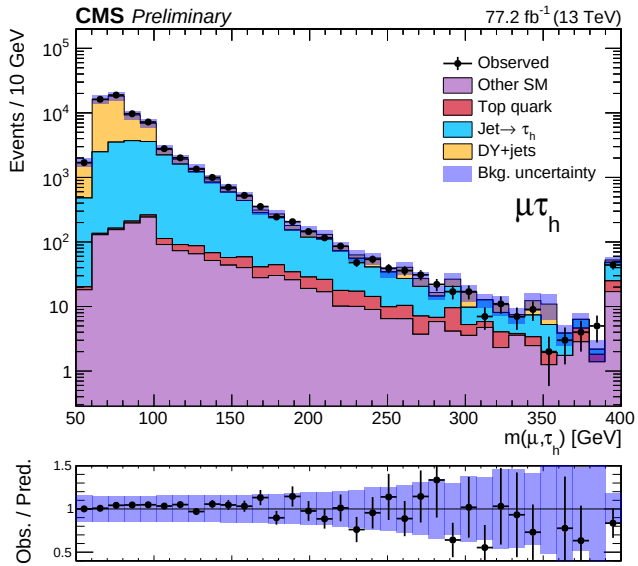
E_T^{miss} and $m_T^{tot} = \sqrt{m_T^2(\ell, \vec{p}_T^{miss}) + m_T^2(\tau_h, \vec{p}_T^{miss})}$ distributions after baseline selection in $\mu\tau_h$ channel





visible mass spectrum of τ lepton pair system in $\tau_h\tau_h$ DY+jets validation sample (left, after 2-D correction of Z mass and p_T from $Z \to \mu\mu$ control sample) and $\ell\tau_h$ DY+jets validation sample (right, after normalization SF + correction of Z p_T from from $Z \to \mu\mu$ control sample)

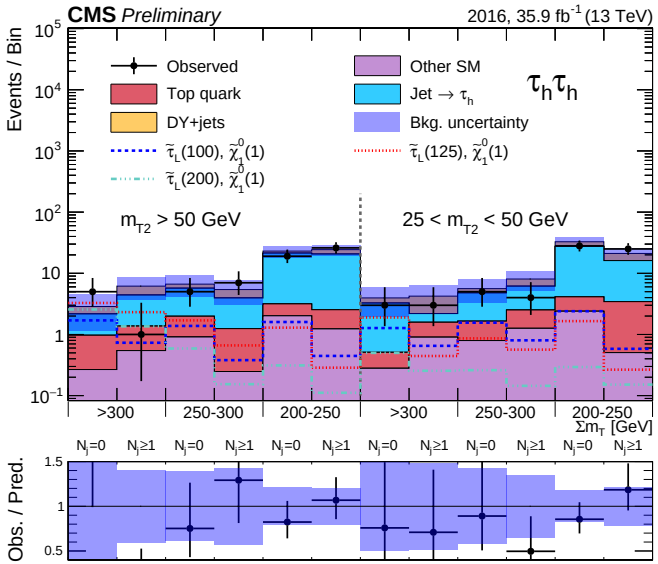


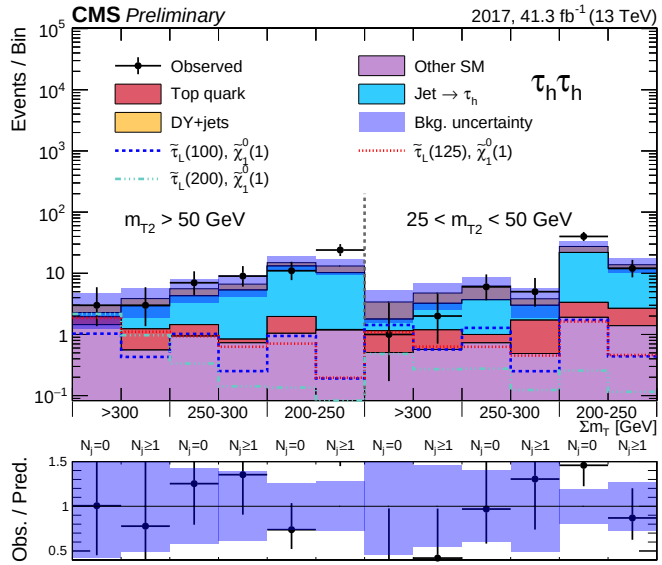


systematic uncertainties

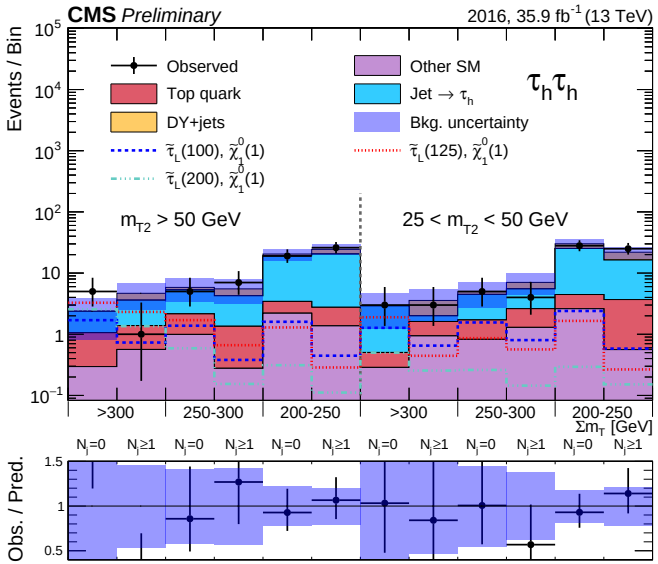
Uncertainty (%)	Signal	Misidentified τ_h	DY+jets	Top quark	Other SM
τ_h efficiency	5–13	—	5–15	1–14	10–51
e/μ efficiency ($\ell\tau_h$)	2–3	—	2–3	2–3	2–3
τ_h energy scale	0.5–12	—	2.6–27	1.2–11	4.1–13
e/μ energy scale ($\ell\tau_h$)	0.1–25	0.1–5	0.1–30	0.1–20	0.1–10
Jet energy scale	0.5–38	—	1.1–19	0.6–13	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

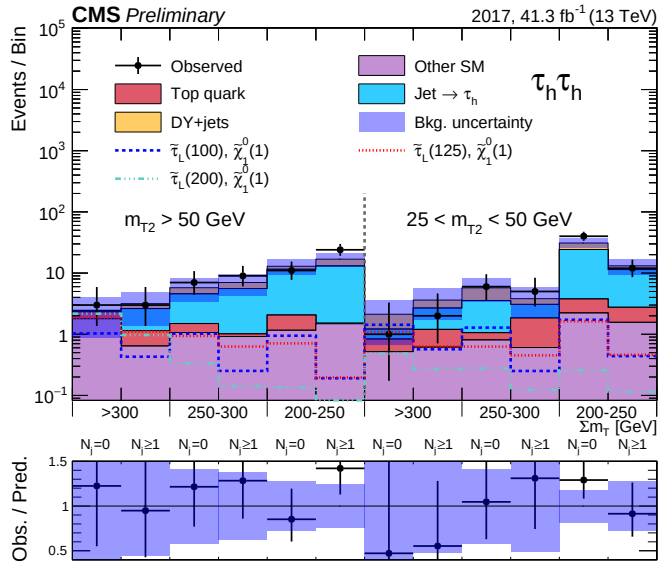
observed event counts and predicted background yields ($\sum m_T$, $\tau_h\tau_h$, prefit) (2016 and 2017)



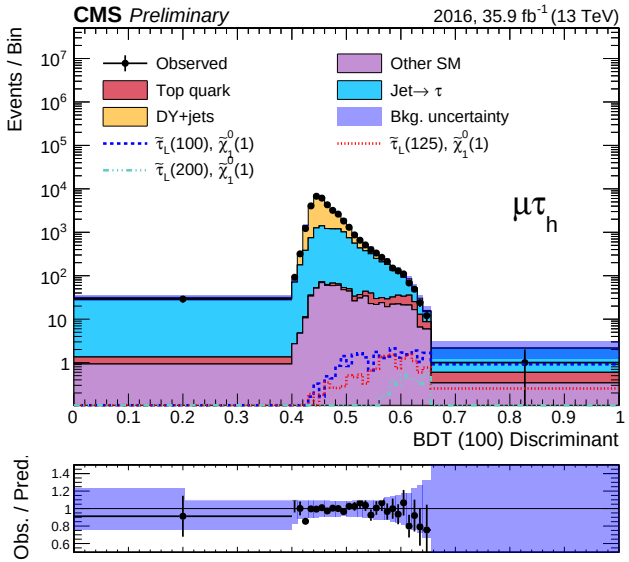


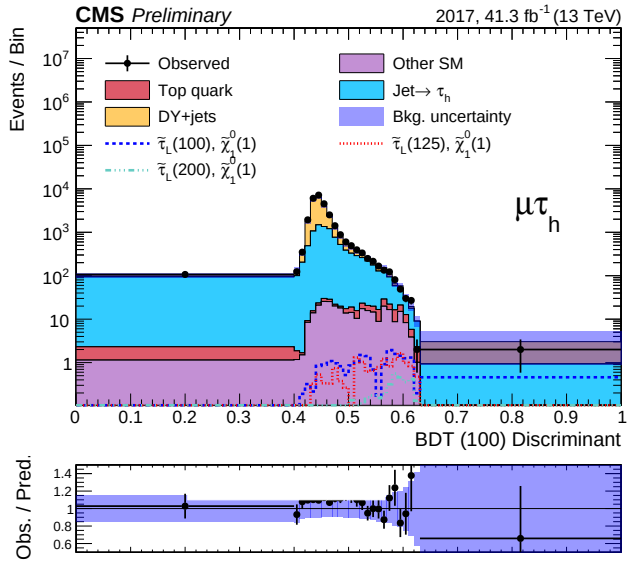
observed event counts and predicted background yields ($\sum m_T$, $\tau_h\tau_h$, postfit) (2016 and 2017)



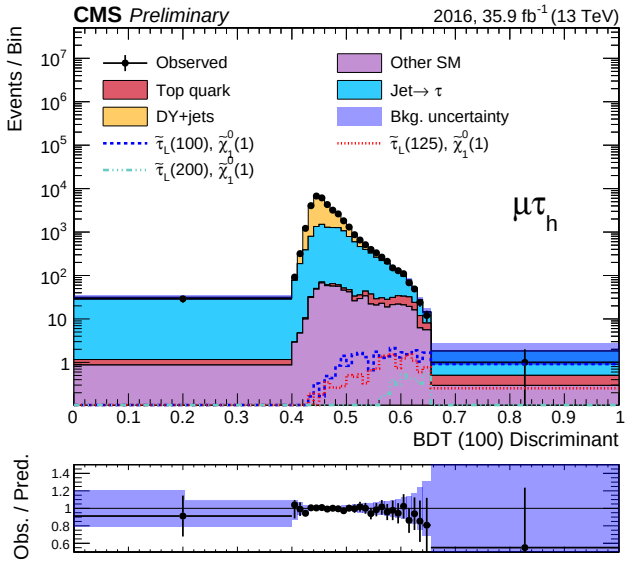


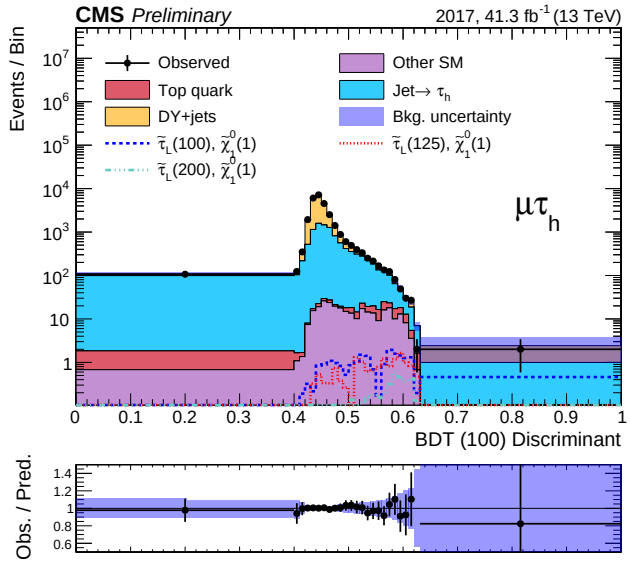
observed event counts and predicted background yields (BDT100, $\mu\tau_h$, prefit) (2016 and 2017)





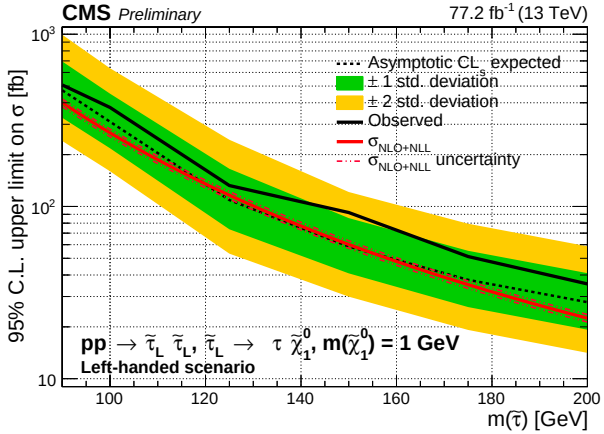
observed event counts and predicted background yields (BDT100, $\mu\tau_h$, postfit) (2016 and 2017)

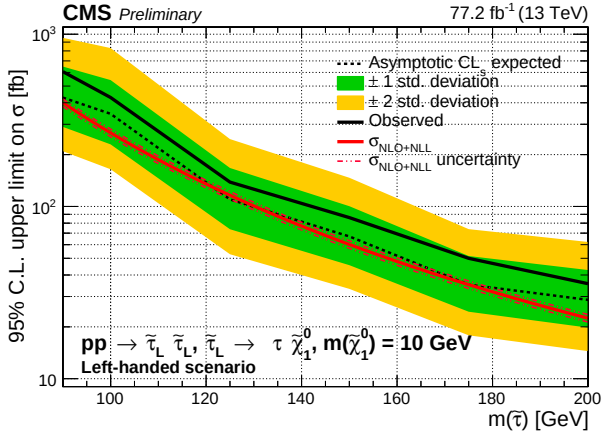


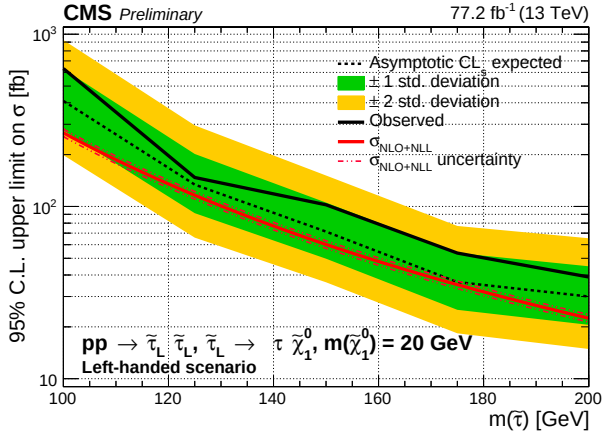


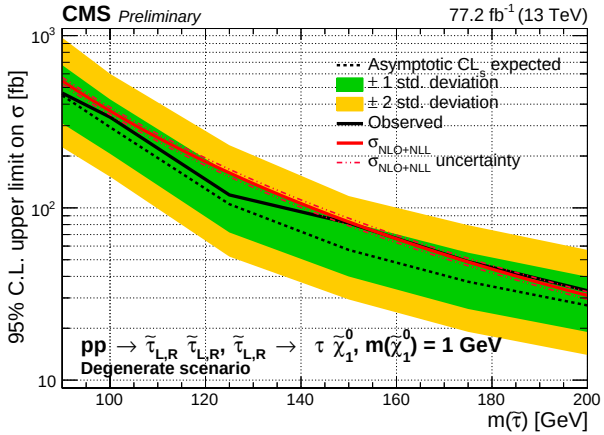
Search for Direct Production of Staus (CMS)

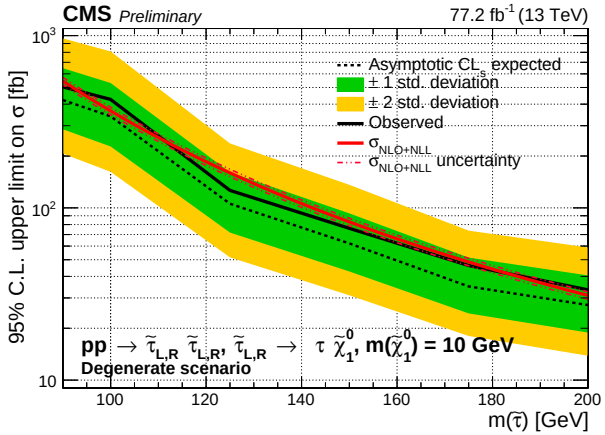
CMS-PAS-SUS-18-006

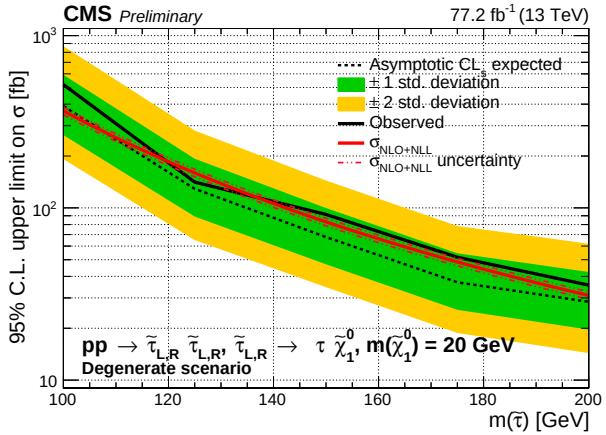












$m(\tilde{\chi}_1^0) = 1\,\mathrm{GeV}$ $m(\tilde{\chi}_1^0) = 10\,\mathrm{GeV}$ $m(\tilde{\chi}_1^0) = 20\,\mathrm{GeV}$

top: left-handed, bottom: degenerate scenario

left-handed scenario (bottom right): exclude 1.14σ (132 fb) at 125 GeV

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

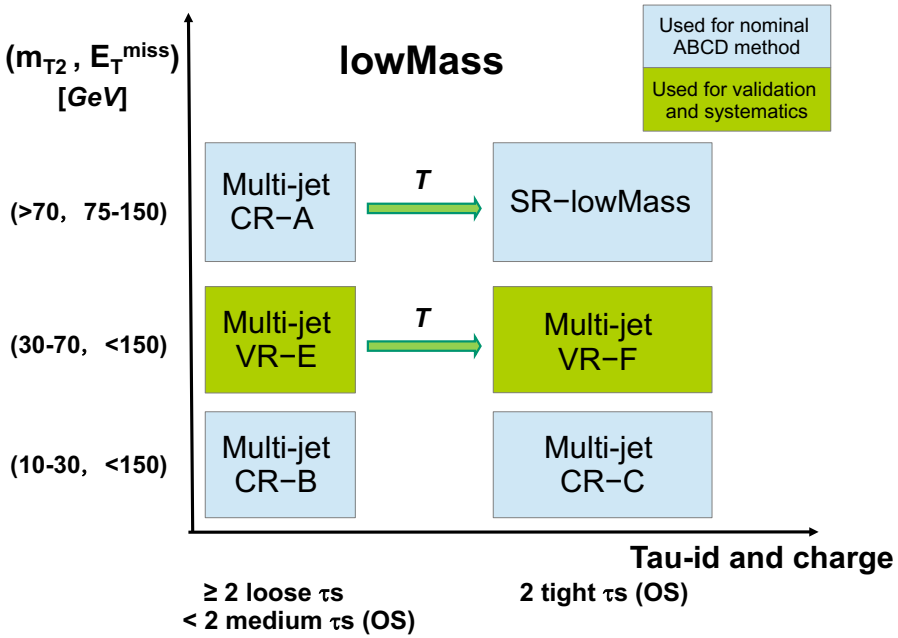
Region definitions

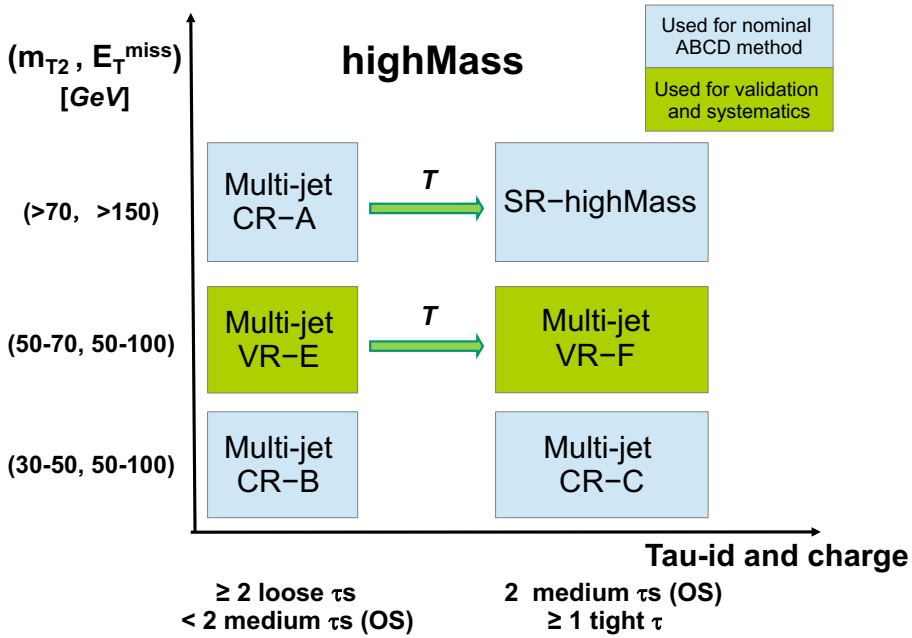
Selections	TVR -lowMass	ZVR -lowMass	$VVVR$ -lowMass	TVR -highMass	ZVR -highMass	$VVVR$ -highMass
	≥ 2 medium τs (OS), ≥ 1 tight τ					
	≥ 1 b-jet	b-jet veto		≥ 1 b-jet	b-jet veto	
$m(\tau_1,\tau_2)$	–	< 70 GeV	< 110 GeV	–	< 60 GeV	< 110 GeV
$\Delta R(\tau_1,\tau_2)$	> 1.2	< 1	–	> 1.2	< 1	–
$m_{\mathrm{T},\tau_1}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

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

CR – A (lowMass)	**SR – lowMass**
≥ 2 loose τs	2 tight τs (OS)
< 2 medium τs (OS)	–
$\Delta R(\tau_1,\tau_2) < 3.2$	$\Delta R(\tau_1,\tau_2) < 3.2$
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV
$m_{\mathrm{T2}} > 70$ GeV	$m_{\mathrm{T2}} > 70$ GeV
VR – E (lowMass)	**VR – F (lowMass)**
≥ 2 loose τs	2 tight τs (OS)
< 2 medium τs (OS)	–
$\Delta R(\tau_1,\tau_2) < 3.2$	$\Delta R(\tau_1,\tau_2) < 3.2$
$E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV
$30 < m_{\mathrm{T2}} < 70$ GeV	$30 < m_{\mathrm{T2}} < 70$ GeV
CR – B (lowMass)	**CR – C (lowMass)**
≥ 2 loose τs	2 tight τs (OS)
< 2 medium τs (OS)	–
no $\Delta R(\tau_1,\tau_2)$ cut	no $\Delta R(\tau_1,\tau_2)$ cut
$E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV
$10 < m_{\mathrm{T2}} < 30$ GeV	$10 < m_{\mathrm{T2}} < 30$ GeV

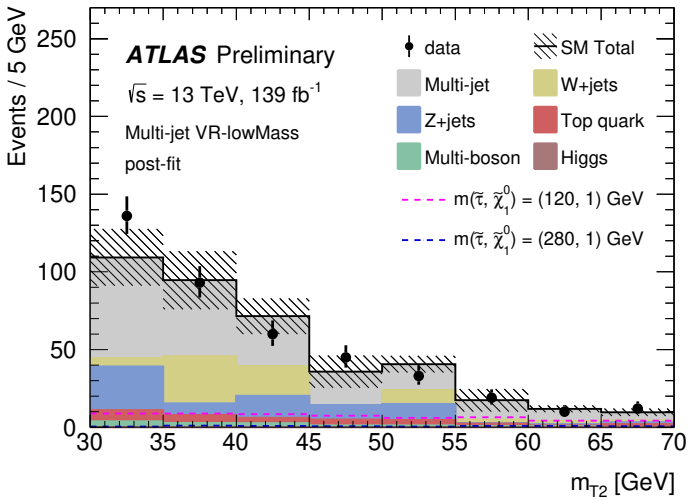
CR – A (highMass)	**SR – highMass**
≥ 2 loose τs	2 medium τs (OS)
< 2 medium τs (OS)	≥ 1 tight τ
$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
$\Delta R(\tau_1,\tau_2) < 3.2$	$\Delta R(\tau_1,\tau_2) < 3.2$
$m_{\mathrm{T2}} > 70$ GeV	$m_{\mathrm{T2}} > 70$ GeV
VR – E (highMass)	**VR – F (highMass)**
≥ 2 loose τs	2 medium τs (OS)
< 2 medium τs (OS)	≥ 1 tight τ
$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV
$\Delta R(\tau_1,\tau_2) < 3.2$	$\Delta R(\tau_1,\tau_2) < 3.2$
$50 < m_{\mathrm{T2}} < 70$ GeV	$50 < m_{\mathrm{T2}} < 70$ GeV
CR – B (highMass)	**CR – C (highMass)**
≥ 2 loose τs	2 medium τs (OS)
< 2 medium τs (OS)	≥ 1 tight τ
no $\Delta R(\tau_1,\tau_2)$ cut	no $\Delta R(\tau_1,\tau_2)$ cut
$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV
$30 < m_{\mathrm{T2}} < 50$ GeV	$30 < m_{\mathrm{T2}} < 50$ GeV

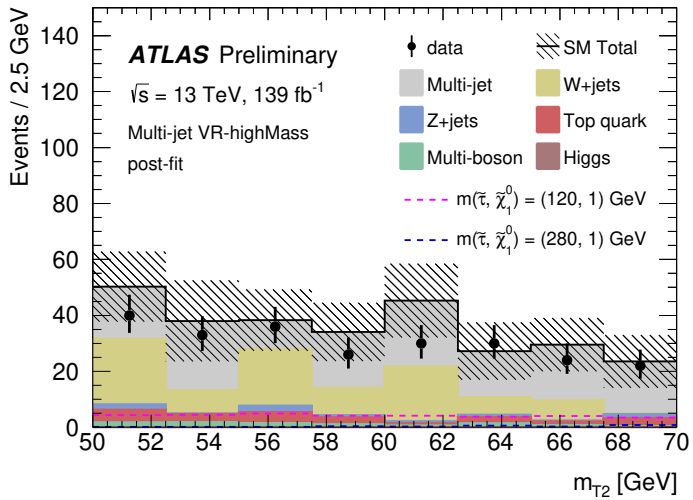




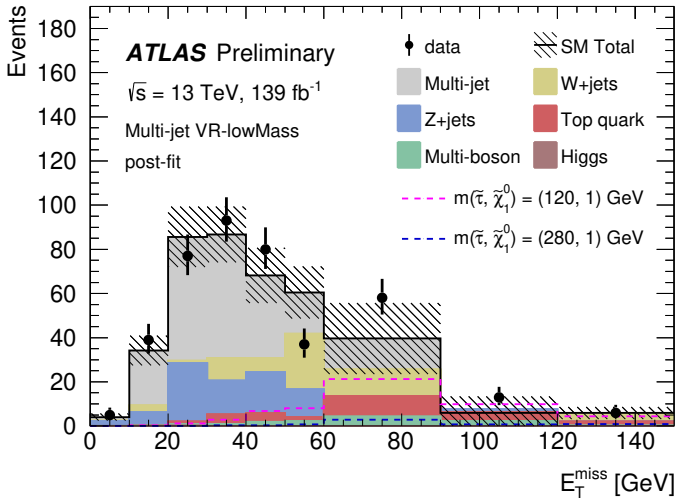
ABCD method for low-mass SR (left) and high-mass SR (right)

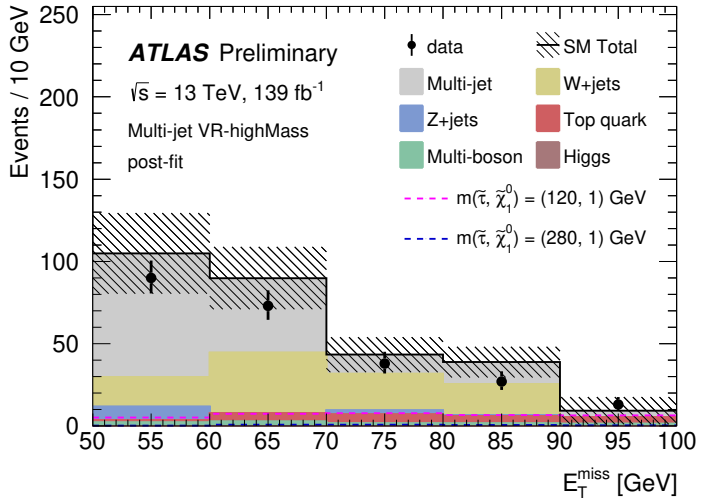
m_{T2} and . . .

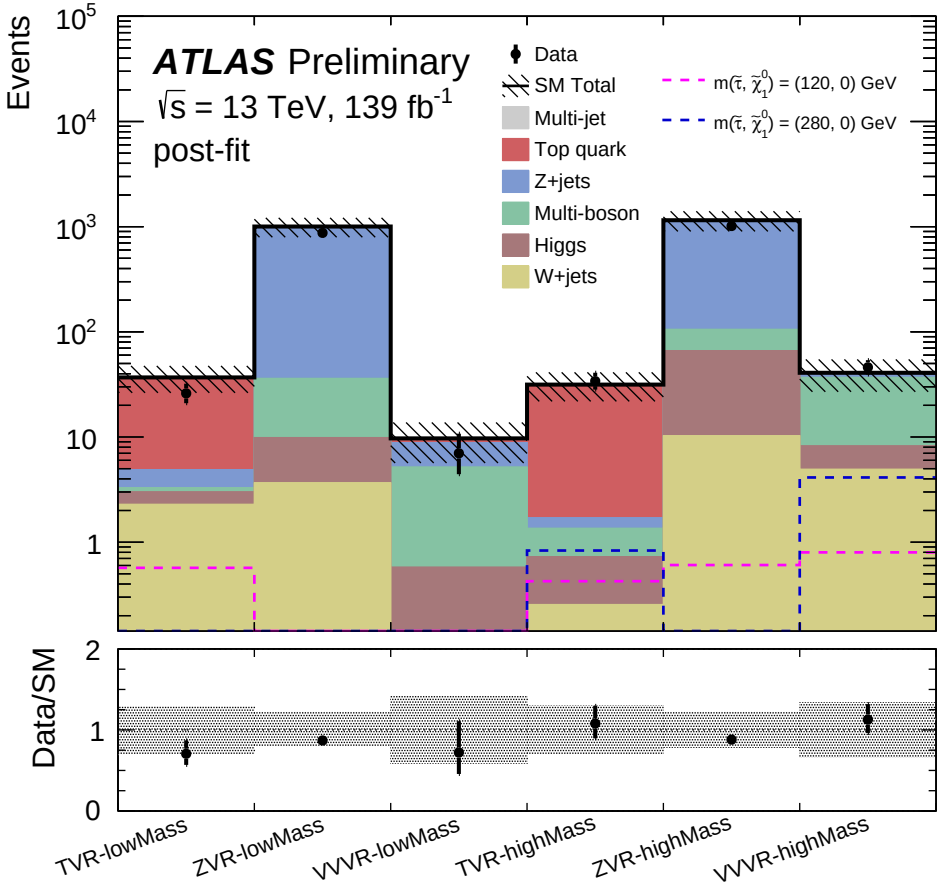




. . . E_T^{miss} in multi-jet low-mass and high-mass VR-F

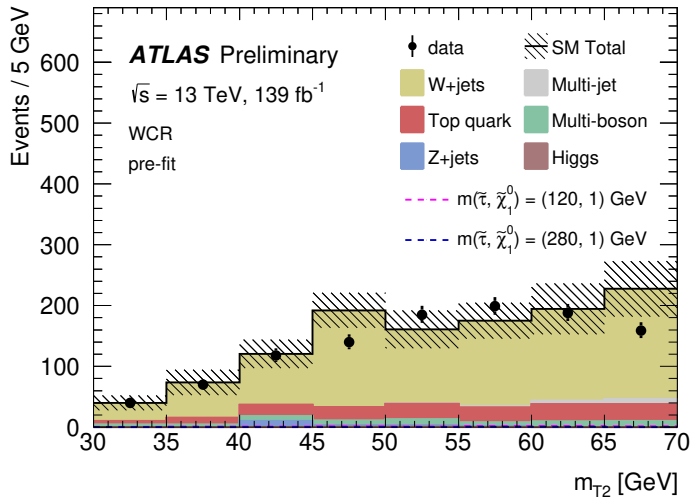




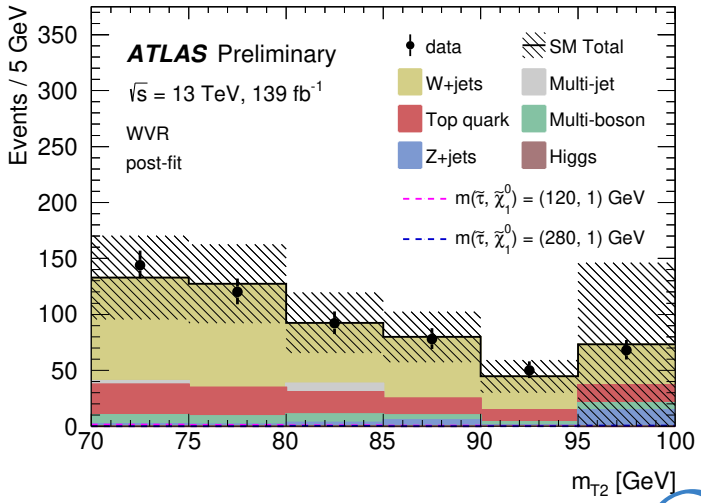


top / Z / VV VRs low-mass | top / Z / VV VRs high-mass

m_{T2}, W CR, pre-fit



m_{T2}, W VR, post-fit



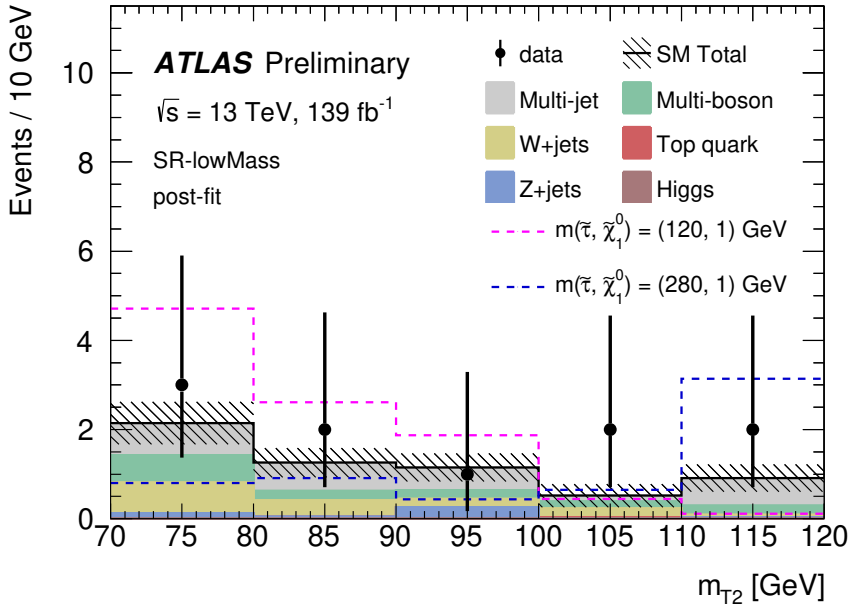
Source of systematic uncertainty	SR-lowMass (%)	SR-highMass (%)
Statistical uncertainty of MC samples	11	21
Tau identification and energy scale	19	10
Normalisation uncertainties of the multi-jet background	13	9
Multi-jet estimation	6	11
W+jets theory uncertainty	5	8
Diboson theory uncertainty	5	6
Jet energy scale and resolution	5	8
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	2	2
Total	28	33
Source of systematic uncertainty	SR-lowMass (%)	SR-highMass (%)
m $(\tilde{\tau},\tilde{\chi}_1^0)$ GeV	(120, 1)	(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
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	3	< 1
Total	31	18

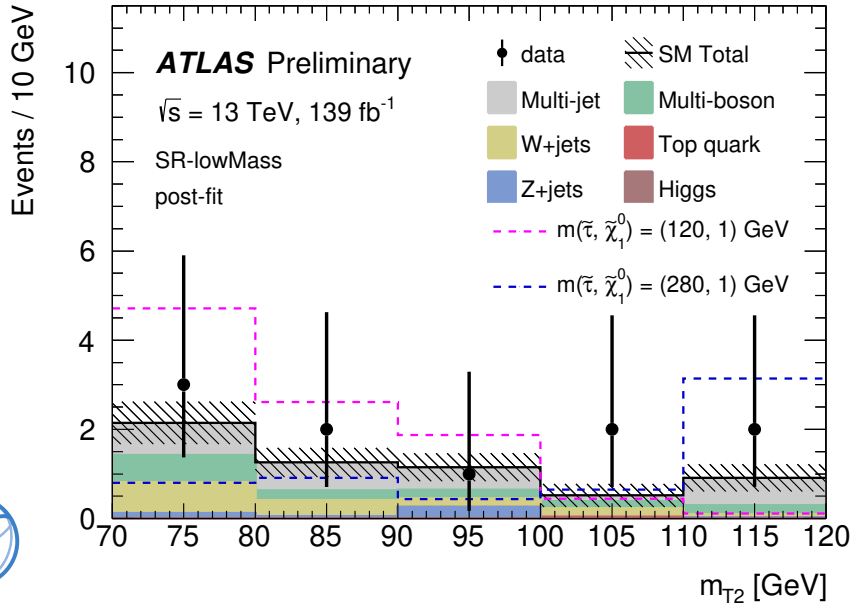
systematic uncertainties

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

observed and expected numbers of events in CRs (multijet: CR A), VR, SRs

m_{T2} in low-mass SR (top) and high-mass SR (bottom)





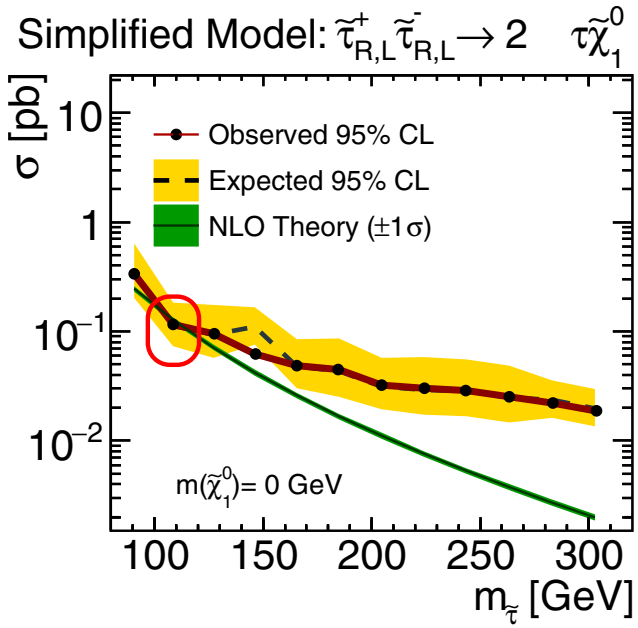
SR definitions

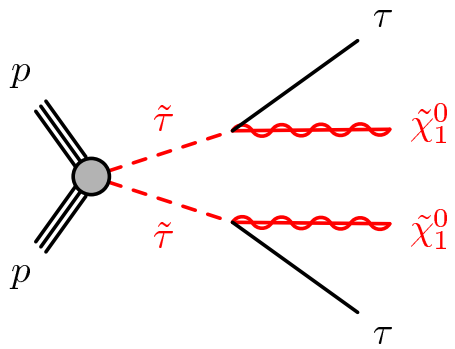
SR-lowMass	SR-highMass
2 tight τs (OS)	2 medium τs (OS) , ≥ 1 tight τ
asymmetric di-tau trigger	di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
tau p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$ cuts described in Section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

expected event yields for the SUSY reference points, one-sided p_0-values (>0.5 truncated at 0.5), obs. and exp. 95 % CL upper limits on visible non-SM cross section

	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 $\sigma_{\mathrm{vis}}^{95}$ [fb]	$0.055^{+0.025}_{-0.014}$	$0.065^{+0.025}_{-0.019}$
Observed $\sigma_{\mathrm{vis}}^{95}$ [fb]	0.08	0.05

Phys. Rev. D 93, 052002 (2016)



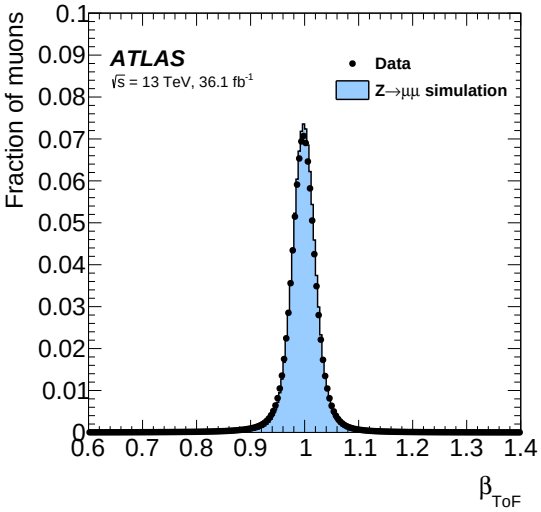


- ATLAS Run-1 analysis (MVA)
  - BDT trained on 12 input variables ($E_{\mathrm{T}}^{\mathrm{miss}}$, m_{eff}, m_{T2}, $m_{\tau\tau}$, ...)
- (Only) one scenario excluded with $m(\tilde{\tau}) \approx 110\,\mathrm{GeV}$ and massless LSP
  - cross sections above 0.115 pb excluded, theoretical cross-section at NLO 0.128 pb

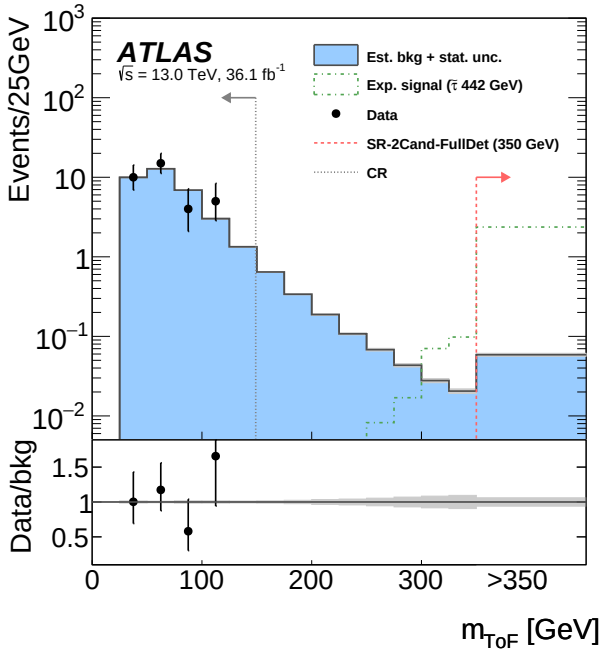
Heavy Charged Long-Lived Particles

arXiv:1902.01636 (accepted by PRD)

- All other searches assume SUSY particles to decay promptly
- Here: search for *long-lived* staus
  - GMSB model with $\widetilde{G}$ LSP and long-lived $\widetilde{\tau}$ NLSP
- Charged $\Rightarrow$ track: measure momentum p in ID and MS
- Heavy $\Rightarrow \beta \ll 1$: measure ToF in Tile Calorimeter and MS
- Mass hypothesis $m_{\text{ToF}} = p/\beta\gamma$ for candidate tracks



$\beta_{\text{ToF}}(\mu)$ for $Z \to \mu\mu$ events

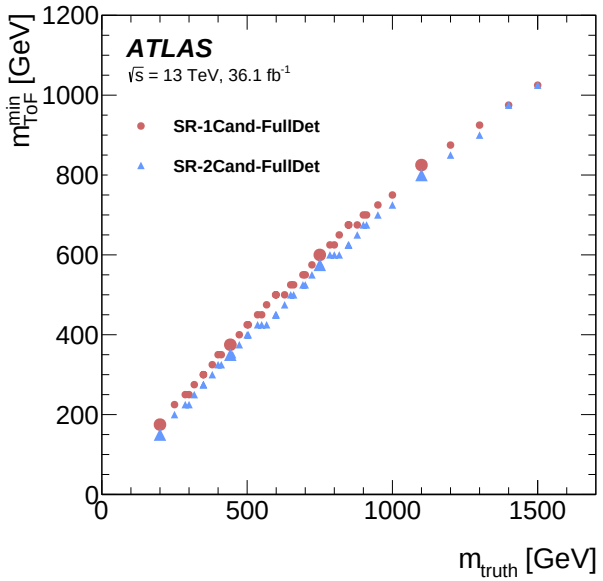


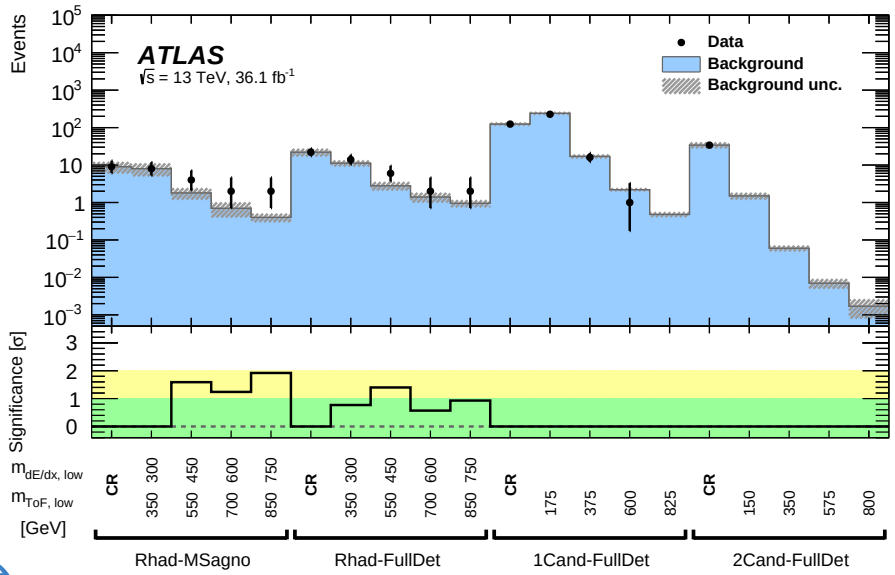
Comparison data vs expected background

- Analysis of 36.1 fb^{-1} @ $\sqrt{s} = 13\ \text{TeV}$
- Custom timing calibration
- Fully data-driven background estimate
- Obtained by random sampling from PDFs (momentum, β_{ToF}) measured in sidebands
- Remove effect of implicit correlation by binning in η
- Normalized to data in CR at low mass
- Almost background-free search

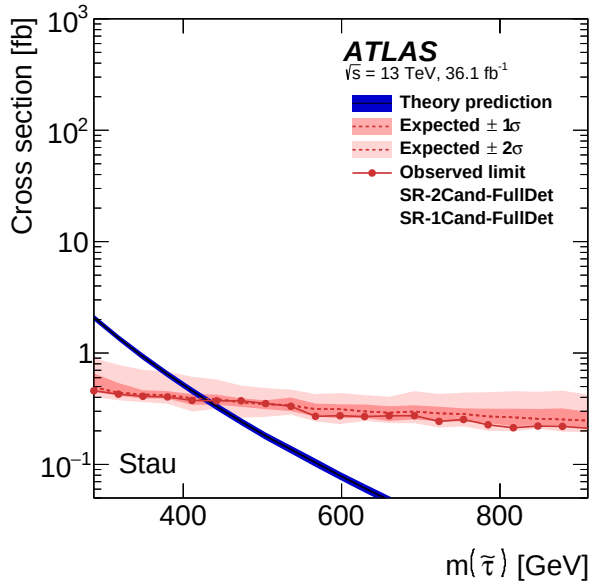
arXiv:1902.01636 (accepted by PRD)

- Combination of 2 SRs
  - with 2 loose or 1 tight track candidate
- Minimum requirement on track mass $m_{\mathrm{ToF}}^{\mathrm{min}}$
  adapted to signal-mass hypothesis m_{truth} →
- No significant excess observed
  - upper limits on production cross section
  - stau result driven by SR-2Cand-FullDet ↘





expected and observed yields in discovery regions



exclude $m(\widetilde{\tau}_R) < 430\ \mathrm{GeV}$ (420 exp.)

Table 1: Summary of the five sets of SRs. The trigger as well as the track candidate selection and the number of candidates per event required for the respective SR are given. Also the final selection requirements together with the mass window (one- or two-dimensional) for the final counting are stated. SRs in one block (delimited by horizontal lines) are combined for the statistical interpretation of the results. For SR-Rhad-FullDet, the ID+CALO is used as a fallback only if no LOOSE candidates are found in the event; hence the two SRs are mutually exclusive.

Signal region	Trigger	Candidate selection	Candidates per event	Final requirements $\lvert\eta\rvert$	p [GeV]	β_{ToF}	$(\beta\gamma)_{dE/dx}$	Mass
SR-Rhad-MSagno	$E_{\text{T}}^{\text{miss}}$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-Rhad-FullDet	$E_{\text{T}}^{\text{miss}}/\mu$	LOOSE	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.3	ToF & dE/dx
SR-Rhad-FullDet	$E_{\text{T}}^{\text{miss}}/\mu$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-2Cand-FullDet	$E_{\text{T}}^{\text{miss}}/\mu$	LOOSE	$= 2$	≤ 2.00	≥ 100	≤ 0.95	-	ToF
SR-1Cand-FullDet	$E_{\text{T}}^{\text{miss}}/\mu$	TIGHT	$= 1$	≤ 1.65	≥ 200	≤ 0.80	-	ToF

Table 2: Summary of systematic uncertainties. Ranges indicate a dependence on the mass hypothesis.

	Relative uncertainty [%]			
Source	MS-agnostic R-hadrons	Full-detector R-hadrons	Staus	Charginos
Theoretical inclusive cross section	14–57	14–57	6–10	4–10
Total uncertainty in signal efficiency	17–19	18–30	7–15	9–18
Trigger efficiency	1.6	1.9	4.5	3.9
$E_{\text{T}}^{\text{miss}}$	1.6	1.6	2.0	2.5
Single-muon		1.0	4.0	3.0
Theoretical uncertainty (ISR/FSR)	15	15	4	7
Pileup	0.2–3.8	0.3–5.5	0.1–3.1	0.2–4.4
Full-detector track reconstruction	-	1.7–14.8	0.2–12.8	0.8–13.0
Track hit requirements	2	2	2	2
Pixel $\beta\gamma$ measurement	6.0–11.6	6.0–13.0	0.5	0.5
ToF β measurement	0.5–3.6	9.8–21.9	1.0–3.6	2.0–12.0
Calorimeter β measurement	0.1–0.5	0.1–1.1	0.1–0.5	0.1–0.5
Calorimeter OFA correction	0.4–3.6	1.2–3.1	0.1–0.4	0.1–1.3
MS β measurement	-	9.7–21.7	1.0–3.5	2.0–12.0
Luminosity	2.1	2.1	2.1	2.1
Uncertainty in background estimate	33–34	27–53	9–31	9–34

Table 5: p_0-values and model-independent upper limits on cross section (σ) × acceptance (a) × efficiency (ε) for the 16 discovery regions.

	Lower mass requirements						
Selection	$m_{\text{ToF}}^{\text{min}}$ [GeV]	$m_{dE/dx}^{\text{min}}$ [GeV]	$N_{\text{est.}} \pm \sigma_{N_{\text{est.}}}$	$N_{\text{obs.}}$	p_0	Significance [σ]	95% CL upper limit $\sigma \times a \times \varepsilon$ [fb]
SR-Rhad-MSagno	350	300	8.0±3.0	8	0.5		0.25
	550	450	1.8±0.6	4	0.056	1.59	0.20
	700	600	0.7±0.3	2	0.11	1.24	0.17
	850	750	0.4±0.1	2	0.028	1.92	0.17
SR-Rhad-FullDet	350	300	11±2	14	0.22	0.77	0.42
	550	450	2.8±0.7	6	0.081	1.40	0.25
	700	600	1.4±0.4	2	0.28	0.57	0.14
	850	750	0.95±0.2	2	0.18	0.93	0.14
SR-1Cand-FullDet	175		240±20	227	0.5		1.26
	375		17±2	16	0.5		0.24
	600		2.2±0.2	1	0.5		0.10
	825		0.48±0.07	0	0.5		0.08
SR-2Cand-FullDet	150		1.5±0.3	0	0.5		0.09
	350		0.06±0.01	0	0.5		0.08
	575		0.007±0.002	0	0.5		0.08
	800		0.0017±0.0009	0	0.5		0.08

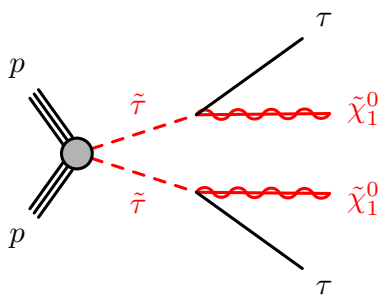
arXiv:1902.01636 (accepted by PRD)

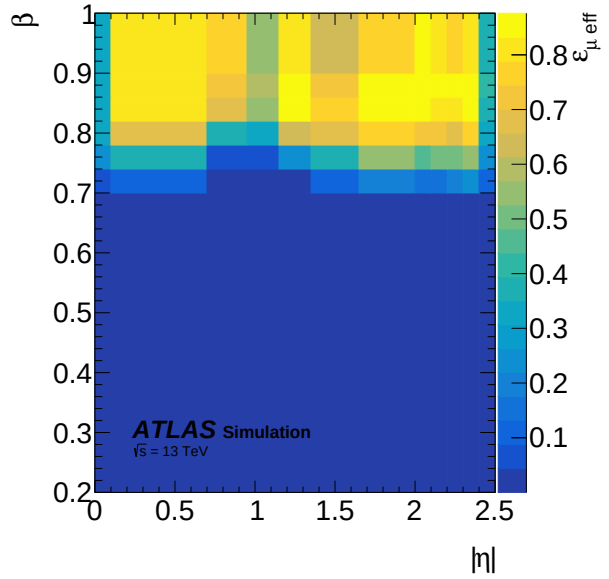
Table 7: Expected signal yield ($N_{\text{exp.}}$) and acceptance (a) × efficiency (ε), estimated background ($N_{\text{est.}}$) and observed number of events in data ($N_{\text{obs.}}$) for the full range of simulated masses in the full-detector direct-stau search.

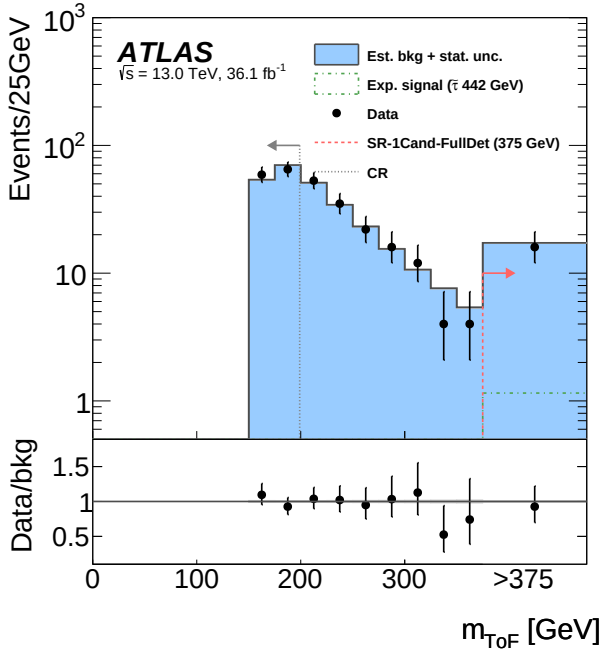
	SR-2Cand-FullDet				SR-1Cand-FullDet			
Simulated mass [GeV]	$N_{\text{exp.}} \pm \sigma_{N_{\text{exp.}}}$	$a \times \varepsilon \pm \sigma_{a\times\varepsilon}$	$N_{\text{est.}} \pm \sigma_{N_{\text{est.}}}$	$N_{\text{obs.}}$	$N_{\text{exp.}} \pm \sigma_{N_{\text{exp.}}}$	$a \times \varepsilon \pm \sigma_{a\times\varepsilon}$	$N_{\text{est.}} \pm \sigma_{N_{\text{est.}}}$	$N_{\text{obs.}}$
287	13±1	0.167±0.005	0.33±0.06	0	5.1±0.6	0.068±0.003	80.0±7.0	74
318	9±1	0.179±0.007	0.22±0.04	0	3.6±0.4	0.073±0.004	56.0±5.0	52
349	6.1±0.7	0.181±0.005	0.15±0.03	0	2.5±0.2	0.076±0.003	41.0±4.0	36
380	4.3±0.6	0.184±0.006	0.11±0.02	0	2.1±0.2	0.089±0.005	30.0±3.0	24
411	3.2±0.4	0.196±0.005	0.08±0.02	0	1.5±0.1	0.093±0.004	23.0±2.0	20
442	2.4±0.3	0.198±0.007	0.06±0.01	0	1.2±0.2	0.096±0.005	17.0±2.0	16
473	1.8±0.3	0.204±0.005	0.045±0.009	0	0.92±0.09	0.105±0.004	13.0±1.0	15
504	1.4±0.2	0.210±0.005	0.035±0.007	0	0.68±0.06	0.105±0.004	10.1±1.0	11
536	1.0±0.1	0.208±0.005	0.027±0.006	0	0.55±0.06	0.111±0.004	7.9±0.8	7
567	0.84±0.10	0.224±0.006	0.027±0.006	0	0.43±0.04	0.113±0.004	6.3±0.6	4
598	0.65±0.09	0.227±0.006	0.022±0.005	0	0.34±0.03	0.118±0.004	5.0±0.5	3
629	0.50±0.07	0.227±0.006	0.017±0.004	0	0.27±0.02	0.124±0.004	5.0±0.5	3
660	0.40±0.05	0.234±0.006	0.014±0.003	0	0.22±0.02	0.125±0.005	4.0±0.4	3
692	0.30±0.05	0.224±0.008	0.011±0.003	0	0.17±0.02	0.125±0.005	3.2±0.3	2
723	0.24±0.03	0.229±0.007	0.009±0.002	0	0.13±0.01	0.120±0.005	2.6±0.3	1
754	0.19±0.02	0.224±0.006	0.008±0.002	0	0.112±0.009	0.132±0.004	2.2±0.2	1
785	0.15±0.02	0.222±0.006	0.007±0.002	0	0.091±0.007	0.135±0.005	1.8±0.2	0
817	0.12±0.01	0.219±0.006	0.007±0.002	0	0.073±0.006	0.134±0.004	1.5±0.1	0
848	0.09±0.01	0.215±0.005	0.006±0.001	0	0.061±0.005	0.138±0.004	1.3±0.1	0
879	0.08±0.01	0.212±0.005	0.005±0.001	0	0.052±0.005	0.146±0.005	1.3±0.1	0
911	0.065±0.007	0.225±0.006	0.004±0.001	0	0.041±0.003	0.144±0.005	1.1±0.1	0

MET Trigger efficiency for a charged LLP ↗

Background estimate for the one-tight-candidate SR →





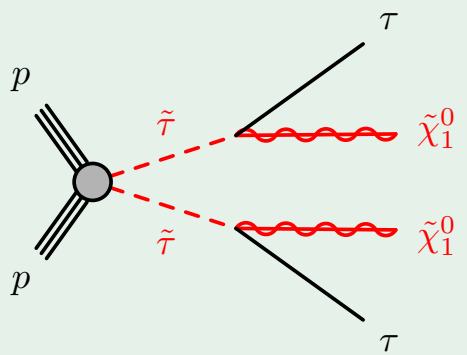


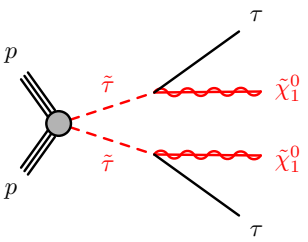
Performance Study...

- High-luminosity upgrade of the LHC (HL-LHC)
  - 3000 fb^{-1} @ centre-of-mass energy of $\sqrt{s} = 14\,\mathrm{TeV}$
  - average pile-up of $\langle\mu\rangle \sim 200$ (instantaneous luminosity up to $7 \cdot 10^{34}\,\mathrm{Hz/cm^2}$)
- Parametrized simulation of performance of upgraded ATLAS detector
  - in turn based on MC simulations, CERN-LHCC-2015-020
  - describes reconstruction eff's and resolution and misidentification probabilities for taus and *b*-jets
  - taking into account fake taus in backgrounds

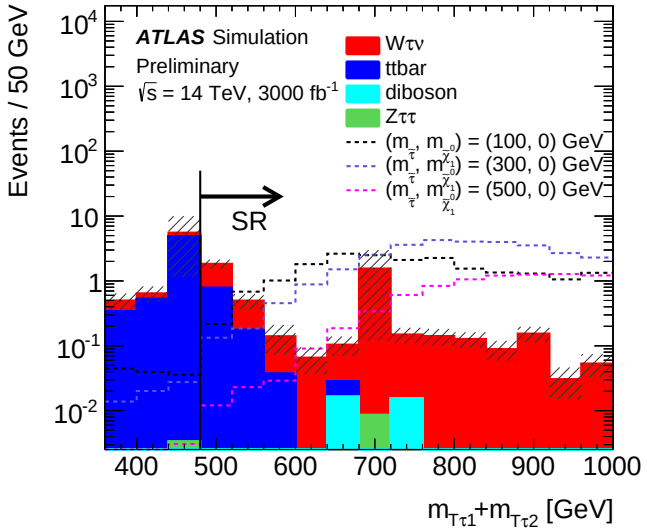
...for Direct Stau

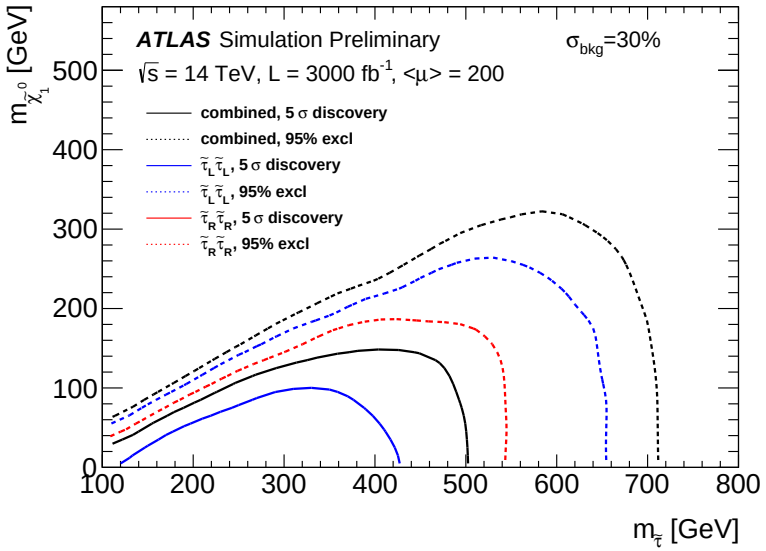
- Consider $\widetilde{\tau}_R\widetilde{\tau}_R$ and $\widetilde{\tau}_L\widetilde{\tau}_L$ production
- Select events with $\geq 2\tau_{\mathrm{had}}$, low jet activity and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Assume di-tau triggers available roughly with current online thresholds despite higher instantaneous luminosity
- Optimized selection for high luminosity
- Dominant backgrounds: $t\bar{t}$, W + jets





SR Definition
≥ 2 OS taus
loose jet-veto
Z-veto
$\Delta R(\tau 1, \tau 2) < 3.5$
$E_{\mathrm{T}}^{\mathrm{miss}} > 280$ GeV
$m_{\mathrm{T}2} > 40$ GeV
$m_{\mathrm{T}\tau 1} + m_{\mathrm{T}\tau 2} > 480$ GeV





SM process	Event yields
W+jets	1.91 ± 0.19
$t\bar{t}$	0.97 ± 0.23
Z+jets	0.009 ± 0.009
diboson	0.03 ± 0.02
SM total	2.9 ± 0.3
$m(\tilde{\tau}) = 100$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	19.1 ± 0.9
$m(\tilde{\tau}) = 300$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	31.6 ± 0.4
$m(\tilde{\tau}) = 500$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	14.21 ± 0.11

- Discovery and exclusion sensitivity: combined up to 710 GeV and 500 GeV
- Depends on systematic uncertainties, here assume 30 %
- No discovery sensitivity to pure $\widetilde{\tau}_R\widetilde{\tau}_R$ production even at HL-LHC

Selection requirement	$\ell\tau_h$	$\tau_h\tau_h$
Muon (electron) p_T	> 30 GeV	—
Muon (electron) p_T (veto)	> 30 GeV	> 20 GeV
Muon (electron) $\lvert\eta\rvert$	$< 2.4(1.6)$	—
Muon (electron) $\lvert\eta\rvert$ (veto)	< 2.7	< 2.7
τ_h p_T	> 40 GeV	> 50 GeV
τ_h $\lvert\eta\rvert$	< 2.3	< 2.3
p_T (τ_h τ_h)	—	> 50 GeV
jet p_T (veto)	> 30 GeV	> 30 GeV
jet $\lvert\eta\rvert$ (veto)	< 2.7	< 2.7
b jet p_T (veto)	> 20 GeV	> 30 GeV

Selection requirement	$\ell\tau_h$	$\tau_h\tau_h$
Muon (electron) p_T	> 30 GeV	—
Muon (electron) p_T (veto)	> 30 GeV	> 20 GeV
Muon (electron) $\lvert\eta\rvert$	$< 2.4(1.6)$	—
Muon (electron) $\lvert\eta\rvert$ (veto)	< 2.7	< 2.7
τ_h p_T	> 40 GeV	> 50 GeV
τ_h $\lvert\eta\rvert$	< 2.3	< 2.3
p_T (τ_h τ_h)	—	> 50 GeV
jet p_T (veto)	> 30 GeV	> 30 GeV
jet $\lvert\eta\rvert$ (veto)	< 2.7	< 2.7
b jet p_T (veto)	> 20 GeV	> 30 GeV

$\tau_h\tau_h$:

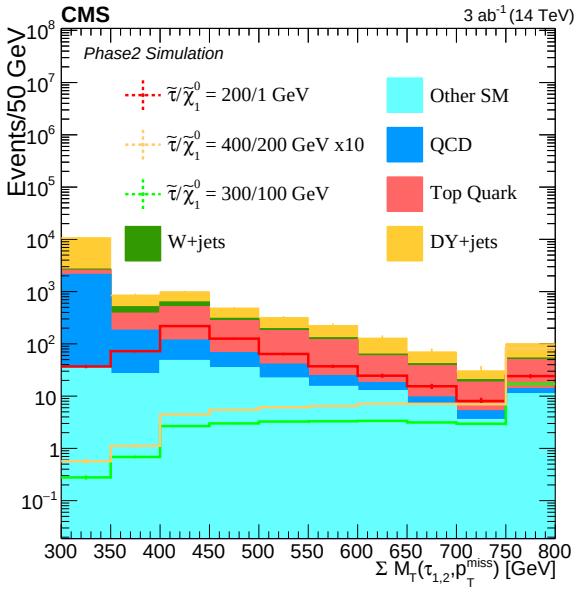
Variable	Bin 0	Bin 1	Bin 2	Bin 3
M_{T2}	$50 < M_{T2} < 100$ GeV	$100 < M_{T2} < 150$ GeV	$150 < M_{T2} < 200$ GeV	$M_{T2} > 200$ GeV
ΣM_T	$400 < \Sigma M_T < 500$ GeV	$500 < \Sigma M_T < 600$ GeV	$\Sigma M_T > 600$ GeV	—
n_{jet}	$= 0$	> 0	—	—

(18/24 bins used)

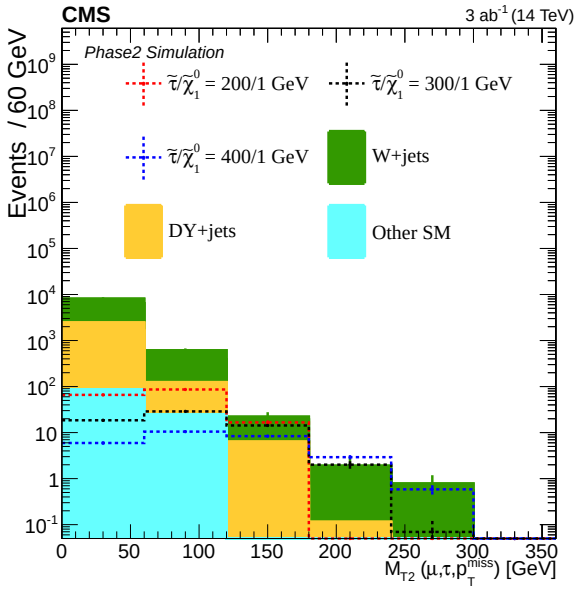
$\ell\tau_h$:

Variable	Bin 0	Bin 1	Bin 2	Bin 3
M_{T2}	$M_{T2} > 120$ GeV	$M_{T2} > 120$ GeV	$80 < M_{T2} < 120$ GeV	$80 < M_{T2} < 120$ GeV
$p_T(\tau_h)$	> 200 GeV	$40 < p_T(\tau_h) < 200$ GeV	> 200 GeV	$40 < p_T(\tau_h) < 120$ GeV

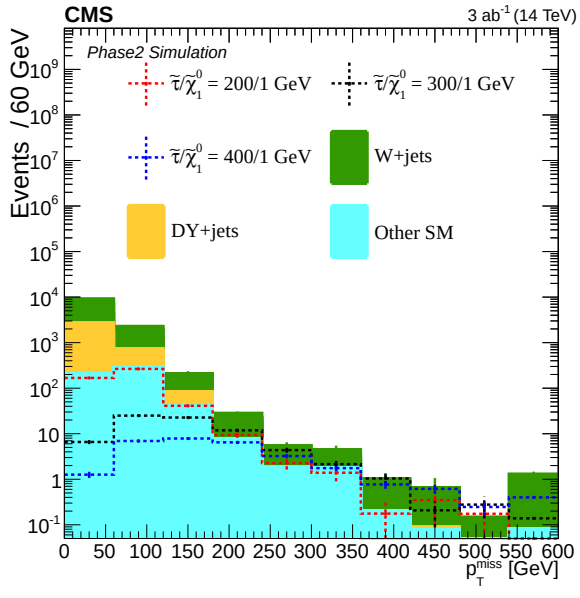
(4 bins)



$\sum M_T$ in $\tau_h\tau_h$



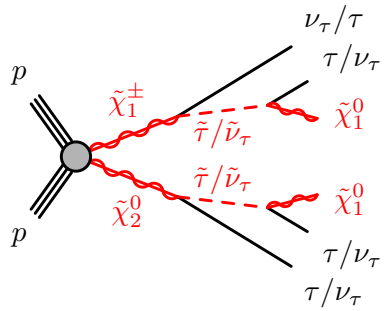
m_{T2} in $e\tau_h$

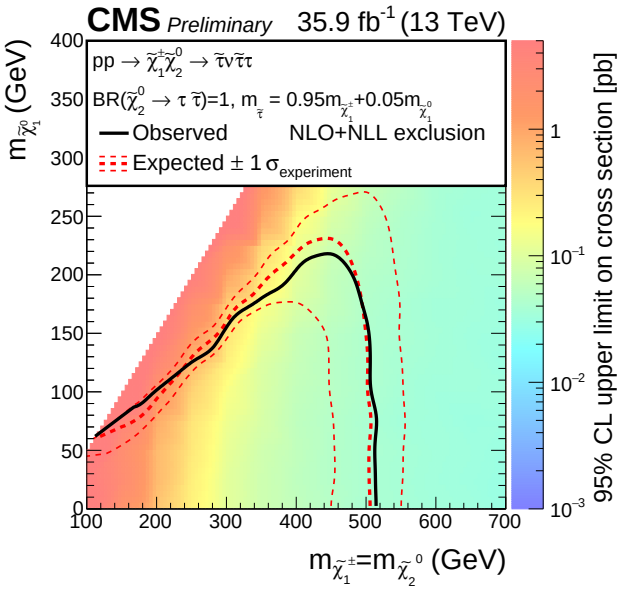


E_T^{miss} in $\mu\tau_h$

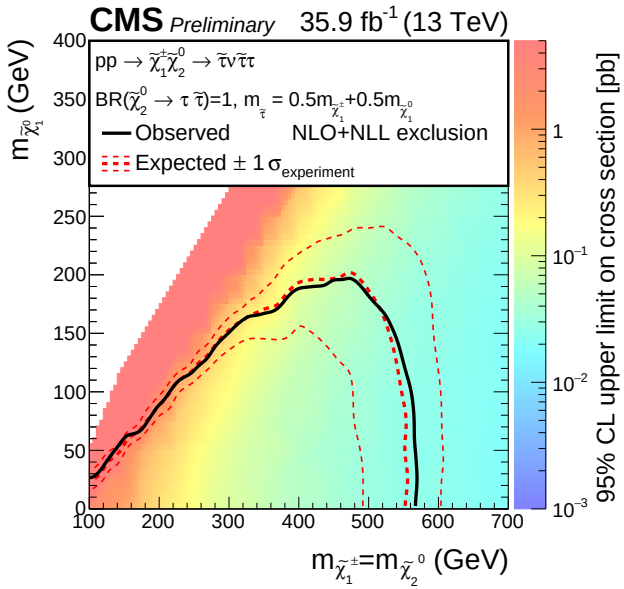
- Study of different assumptions on mass of intermediate particle ($\widetilde{\tau}$)

$$m(\widetilde{\tau}) = m(\widetilde{\chi}_1^0) + x \cdot (m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^\pm) - m(\widetilde{\chi}_1^0))$$

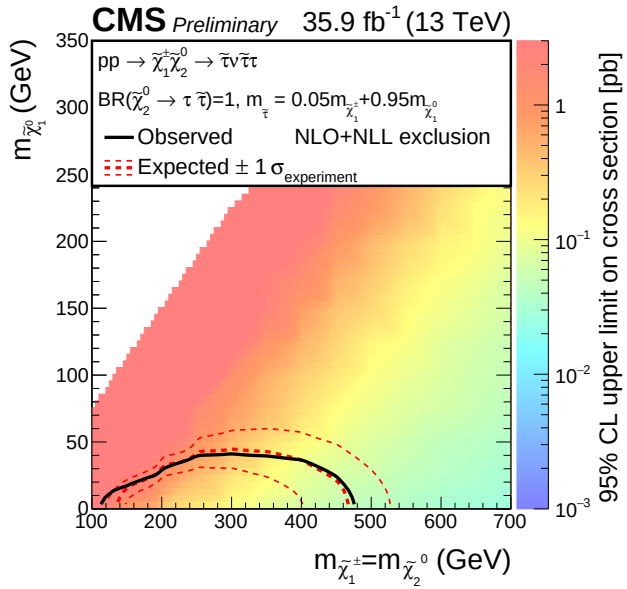




heavy stau ($x = 0.95$)
$\Rightarrow m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^\pm) > 510\,\mathrm{GeV}$



mass half-way ($x = 0.5$)
$\Rightarrow m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^\pm) > 560\,\mathrm{GeV}$



light stau ($x = 0.05$)
$\Rightarrow m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^\pm) > 480\,\mathrm{GeV}$

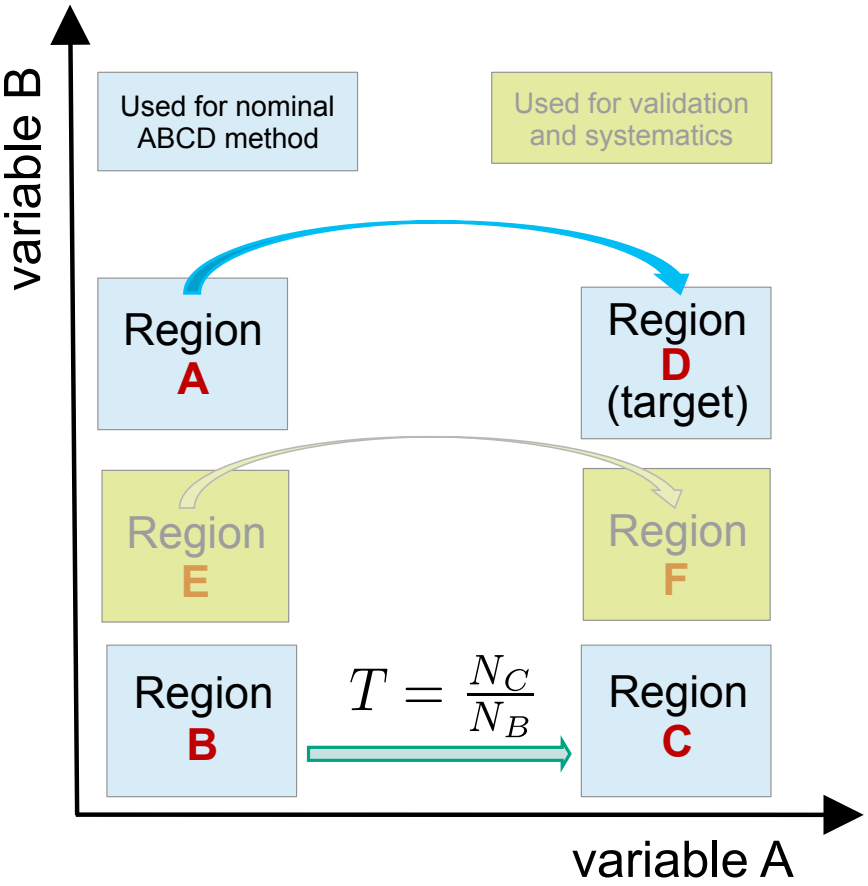
How We Model Backgrounds

The ABCD Method

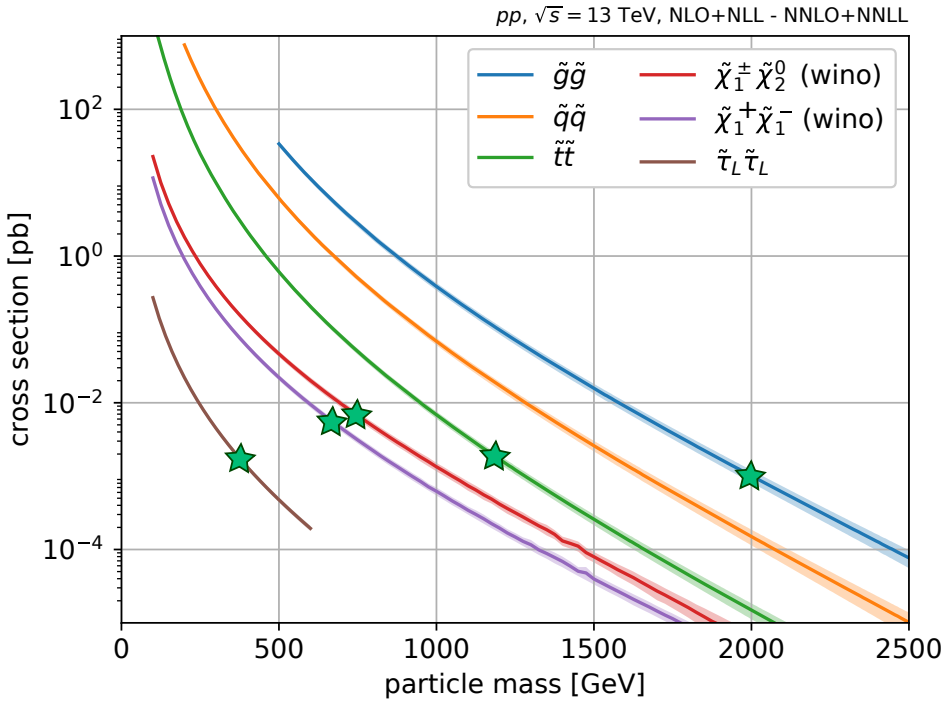
- Goal: estimate background in signal region D
- Pick 2 uncorrelated variables from selection defining D
- Define 3 additional regions A, B, C enriched in background
- Compute:

$$N_D = T \cdot N_A \quad \text{with} \quad T = \frac{N_C}{N_B}$$

- Validate in additional regions E, F
- Caveats:
  - correlations ($\rightarrow$ systematic uncertainty)
  - too low statistics
  - purity / background-to-background subtraction ($\rightarrow$ simulation dependence)



Observed Limits in SUSY Searches with Tau Leptons



- ATLAS, strong, 36 fb^{-1}: 2000 GeV ($\widetilde{g}\widetilde{g}$)
- ATLAS, electroweak, 36 fb^{-1}: 760 GeV ($\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 + \widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$), 630 GeV ($\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$)
- ATLAS, stop, 36 fb^{-1}: 1160 GeV ($\tilde{t}\tilde{t}$)
- CMS, electroweak, 36 fb^{-1}: 710 GeV ($\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$), 630 GeV ($\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$)
- ATLAS, direct, 139 fb^{-1}: 390 GeV