Soft SUSY Searches at ATLAS and CMS

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on behalf of
ATLAS and CMS

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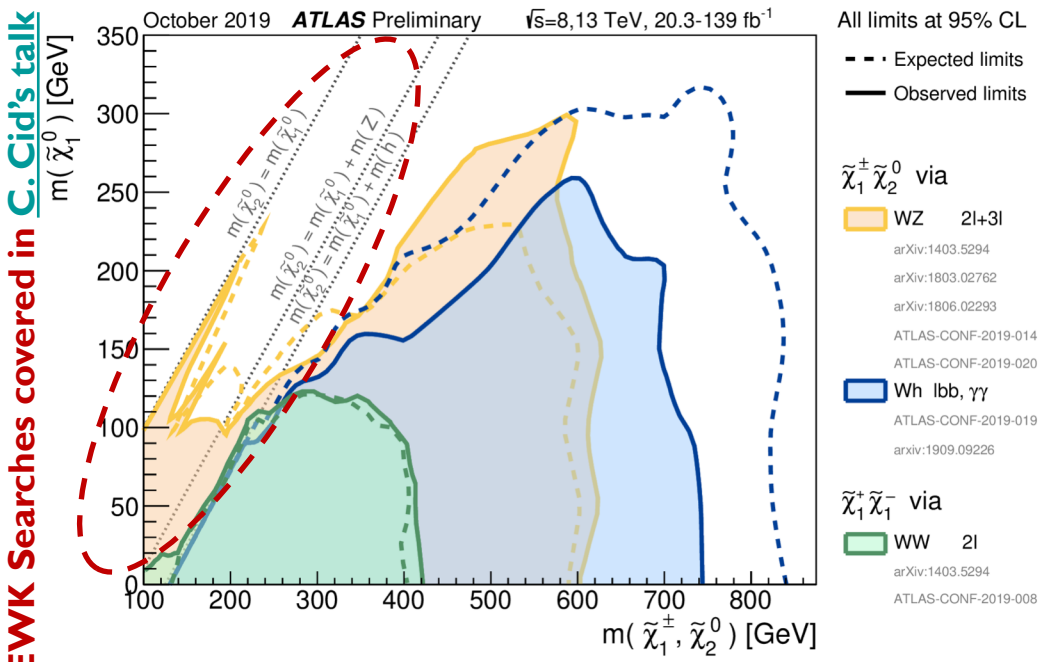
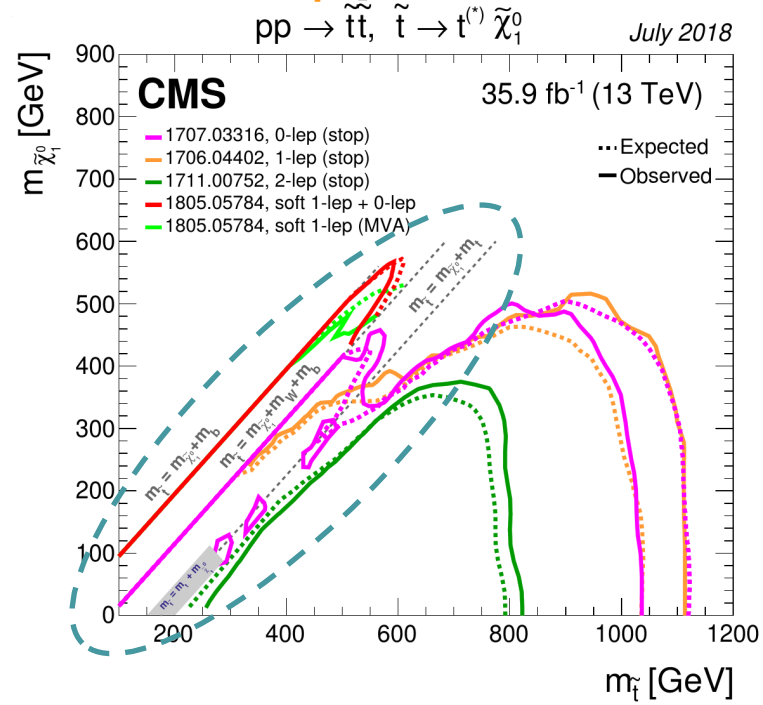
Status Quo

- Wide regions of the SUSY parameter space have been excluded with recent LHC Run II results → putting natural SUSY under extreme pressure!

Chargino-Neutralino Production



Stop Pair-Production



EWK Searches covered in C. Cid's talk

3G Searches covered in M. Hodgkinson's talk

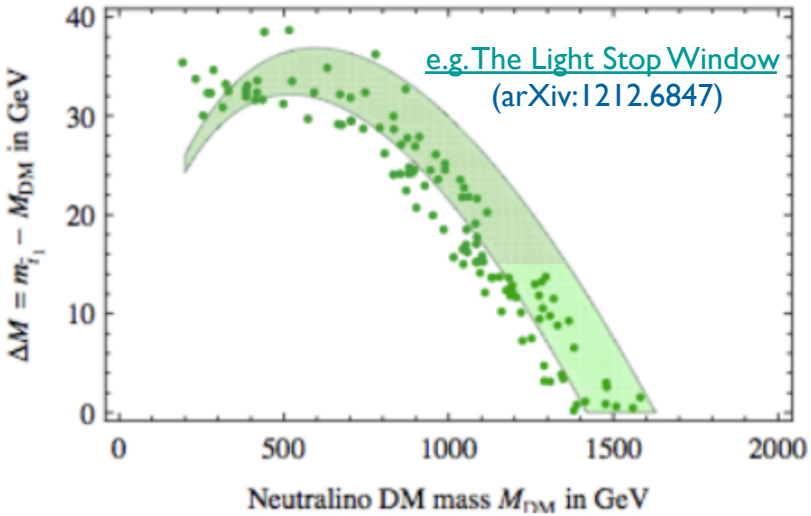
- There are several 'crevasses' of parameter space which are still uncovered
  - This talk focuses on soft SUSY searches with very compressed mass spectra (Δm = small)
  - There is a significant effort at ATLAS and CMS focusing on these regions

Why Soft SUSY?

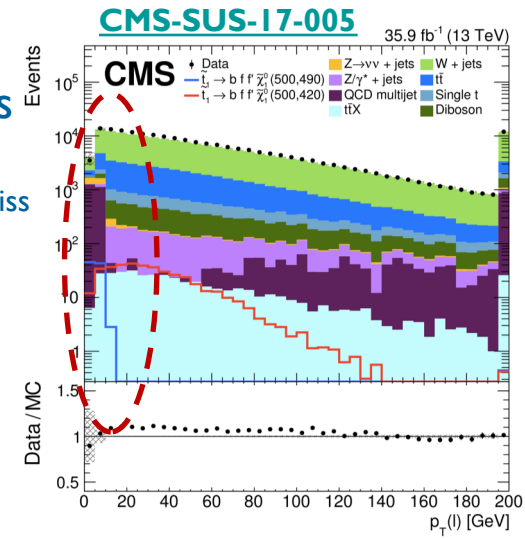
- Natural SUSY requires relatively light stops, higgsinos and gluinos
- Small mass splittings Δm can reproduce the correct cosmological **dark matter** abundance (eg. Phys. Rev. D 56, 1879)
  - co-annihilation of neutralinos and light stops/charginos
- Access to compressed **EWK** SUSY models:
  - lower cross-sections for EWKino production wrt. strong production
  - light higgsinos in EWK models
    = window to natural SUSY
  - more details in Carlos' EWK SUSY talk!

General motivations for SUSY:

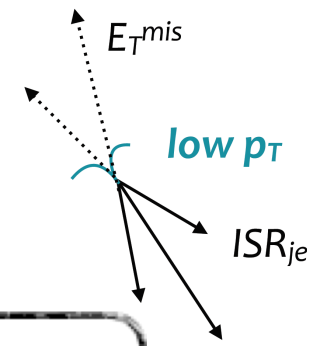
- Solution to **Hierarchy/Naturalness** problem in Standard Model (SM)
- **Unification** of electroweak (EWK) and strong gauge couplings at GUT scale
- Lightest supersymmetric particle (LSP) = **dark matter** candidate



Initial State Radiation



- **Mass splitting Δm** dictates possible decay modes and kinematics
- Small Δm ⇒ little available energy ⇒ soft final states and low E_T^{miss}
  → missed by 'classical' searches (high E_T^{miss} and lepton p_Ts)
- Loss in efficiency for object reconstruction at very low p_Ts
- Visible decay products do **not** pass acceptance thresholds
  ⇒ low threshold triggers and accurate reconstruction essential
- Difficulties with soft products can be mitigated by **initial state radiation** (ISR) = a (quark/gluon) jet originating from partons:
  ⇒ signal vertex is boosted and visible decay products detectable



Signature: hard recoil **ISR jet** (high H_T) and moderate $\mathbf{E_T^{miss}}$ + soft **leptons/jets**
– leptons down to several GeVs + many analyses veto b-tagged jets

- ISR tagging: "large R" jets capturing ISR gluon jets undergone splitting (**CMS-SUS-16-049**)

Soft Multileptons

Soft Dileptons

ATLAS-SUSY-2018-16

Searches for **electroweak** production of supersymmetric particles with **compressed** mass spectra

CMS-SUS-16-048

Search for new physics in events with **two soft oppositely charged leptons** and missing transverse momentum

Trileptons

ATLAS-CONF-2020-015

Search for **chargino-neutralino** pair production in final states with **three leptons** and missing transverse momentum

Soft Dileptons

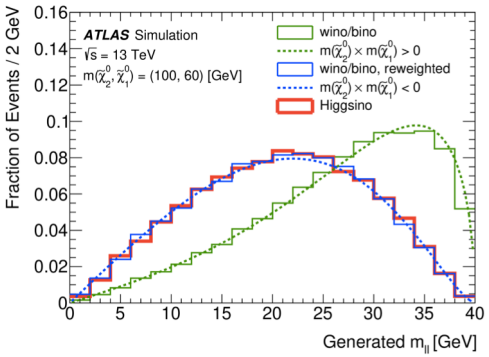
ATLAS-SUSY-2018-16
CMS-SUS-16-048

Two soft opposite-sign (OS) leptons

ATLAS-SUSY-2018-16

- same-flavor leptons ($e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$) in two channels:
  - **2ℓ (p_T > 5 GeV)** and **1ℓ + ≥1 track ($1\ell 1T$)**
    - b-jet veto for 2ℓ
- kinematic: E_T^{miss} >120 GeV (E_T^{miss} trigger)
- muons > 3 GeV (lowPt ID) and electrons > 4.5 GeV
- 3 signal regions targeting EWKinos (SR-E), sleptons (SR-S) and VBF (SR-VBF)

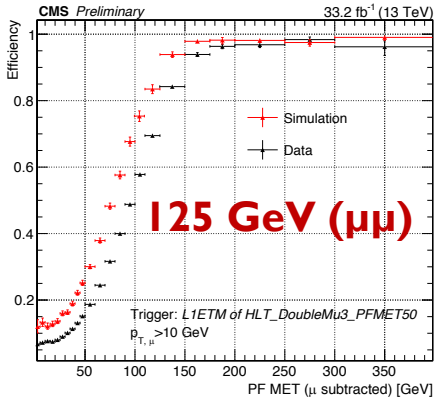
Full Run 2



CMS-SUS-16-048

- same or different flavour ($e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$, $e^{\pm}\mu^{\mp}$)
- muons > 3.5 GeV and electrons > 5 GeV
- EWKino and stop selections
- SR binning in: $m_{\ell\ell}$
- dedicated dimuon + E_T^{miss} trigger → low E_T^{miss} SR

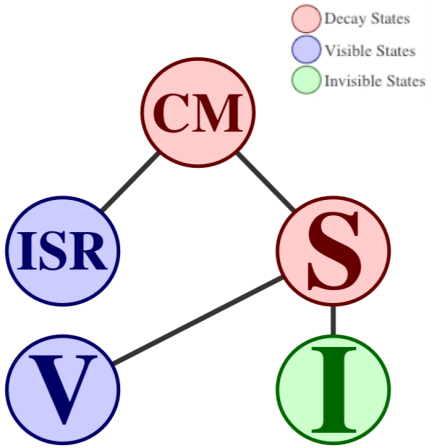
2016



ATLAS-SUSY-2018-16

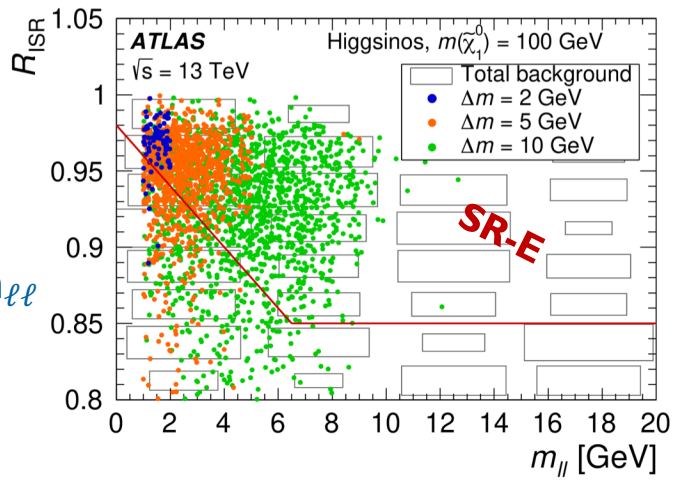
Soft Dileptons

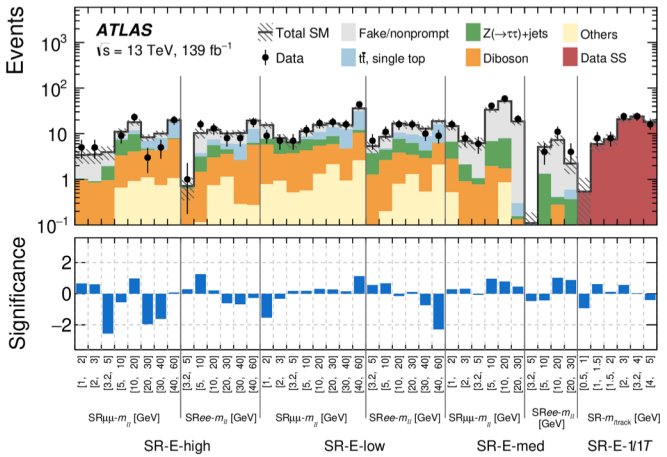
- Recursive Jigsaw Reconstruction (RJR) variables:
  - **ISR recoil**: R_{ISR} = ratio of E_T^{miss} and p_T of the ISR system
  - m_T^S = transverse mass of S (SUSY) system
- The **invariant mass $m_{\ell\ell}$** between two leptons ("off-Z")
- **Transverse mass** of leading lepton **$m_T^{\ell 1}$**
- **E_T^{miss}/H_T^{lep}** where **H_T^{lep}** = scalar sum of the lepton p_T



SR-E

- 4 E_T^{miss} regions
- Binning
  - E_T^{miss}
  - $m_T^{\ell 1}$ and $m_{\ell\ell}$
  - R_{ISR}
  - E_T^{miss}/H_T^{lep}



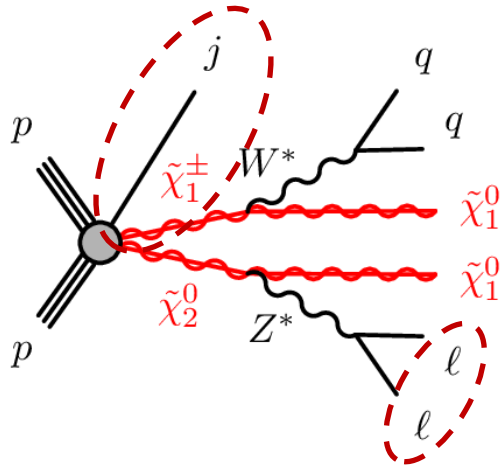


Soft Dileptons

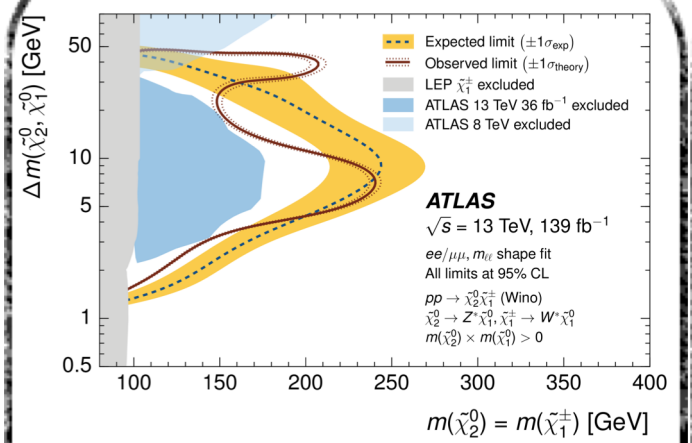
ATLAS-SUSY-2018-16

CMS-SUS-16-048

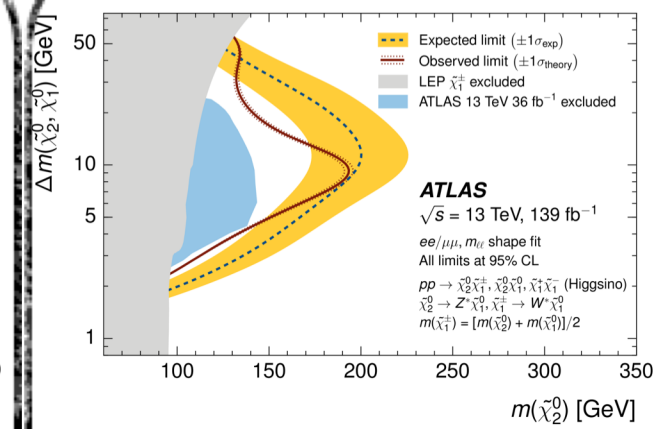
Chargino-Neutralino Production



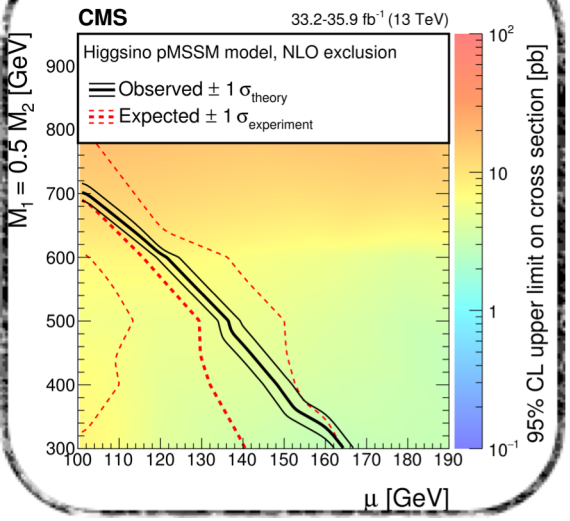
Wino/Bino

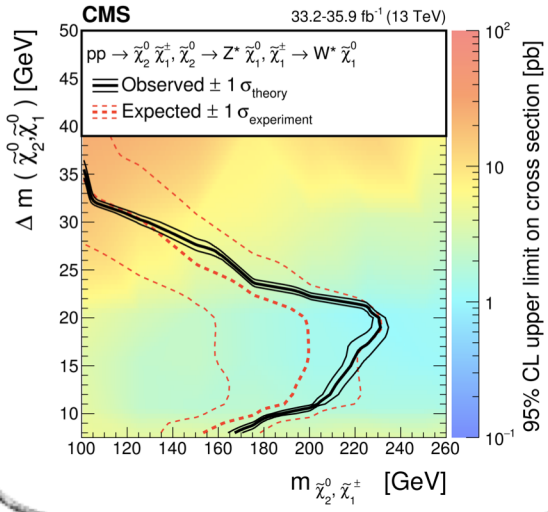


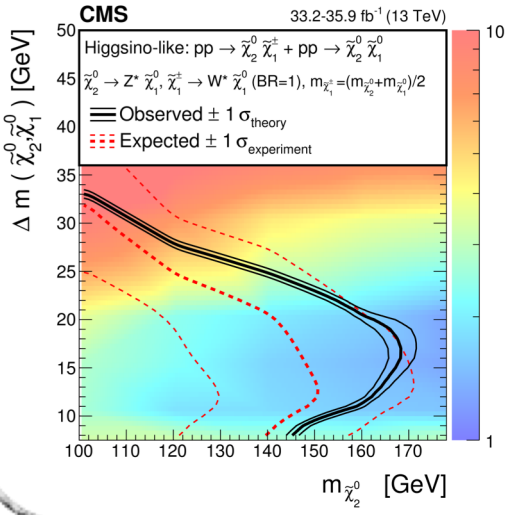
Higgsino



Higgsino pMSSM







(S)Transverse Mass

- The **transvere mass m_T** constructed from lepton p_T and E_T^{miss} used to calculate the mass of particles decaying to a visible + invisible particle:
  - kinematic edge around the mass of the W boson
  - effective in separating single-leptonic SM processes (W+jets, tt-bar)

$$M_T = \sqrt{2 p_T^{\ell} p_T^{miss} \left[1 - \cos\left(\phi_{\ell} - \phi_{\vec{p}_T^{miss}}\right)\right]}$$

Used in a number of leptonic searches!

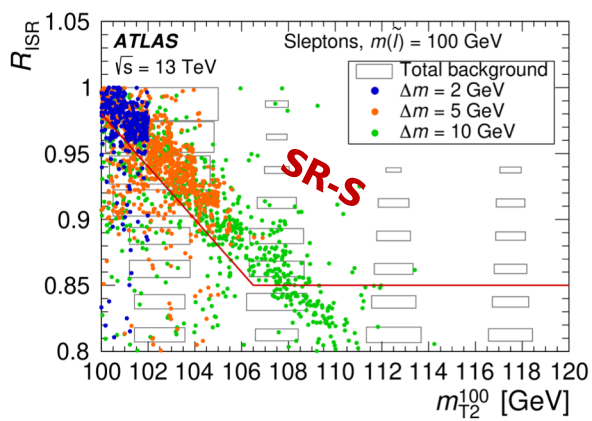
- **Stransverse mass ($m_{T2}^{m\chi}$)** → transverse mass adapted to dileptons:
  - m_χ = hypothesised mass of LSP
  - set to 100 GeV m_{T2}^{100} → kinematic edge

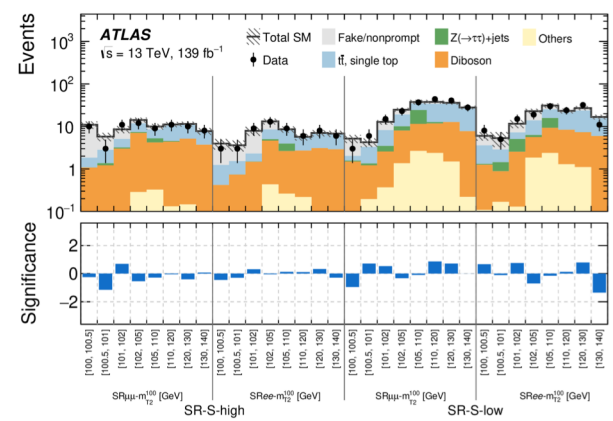
$$m_{T2}^{m_\chi}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_T}(\max[m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T, m_\chi), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss} - \mathbf{q}_T, m_\chi)]),$$

ATLAS-SUSY-2018-16

SR-S

- Binning:
  - E_T^{miss}
  - R_{ISR}
  - m_{T2}^{100}

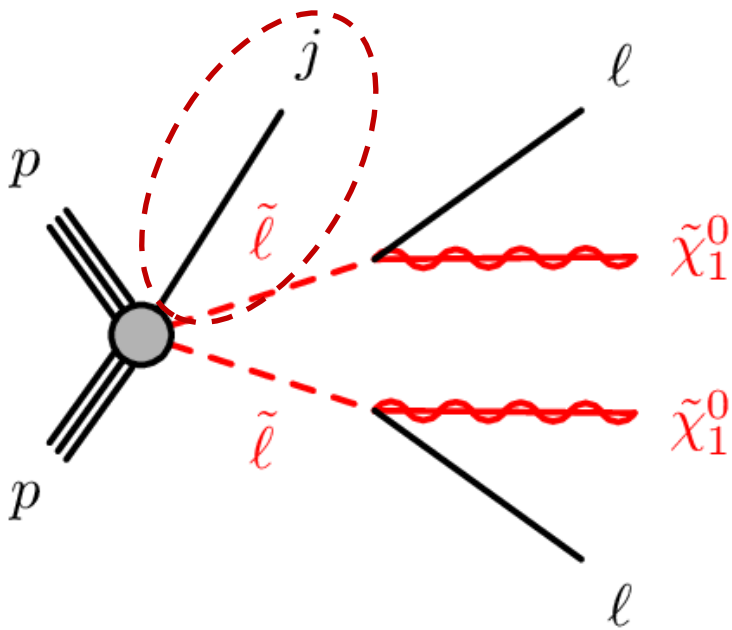


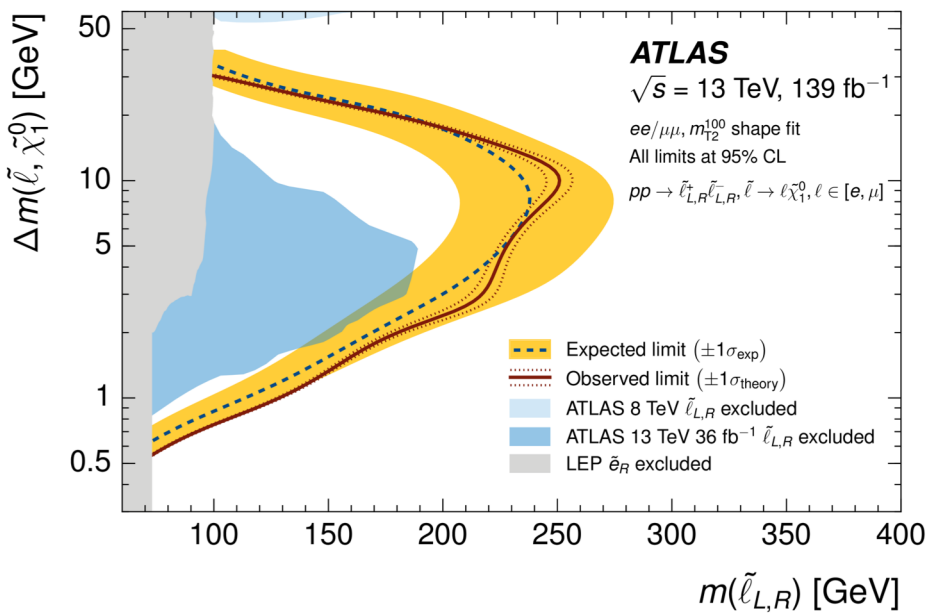


ATLAS-SUSY-2018-16

Soft Dileptons

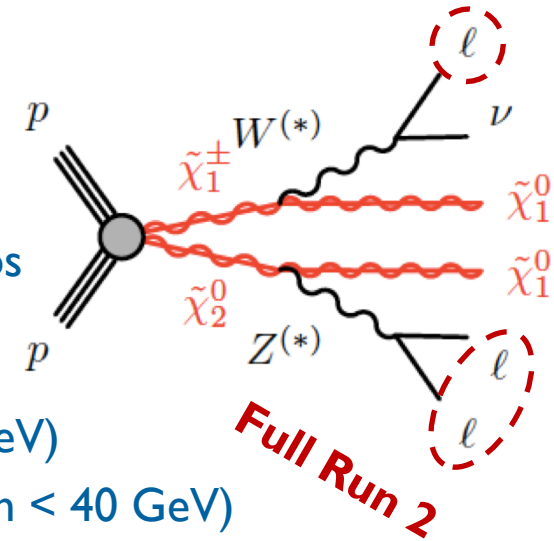
Slepton Production



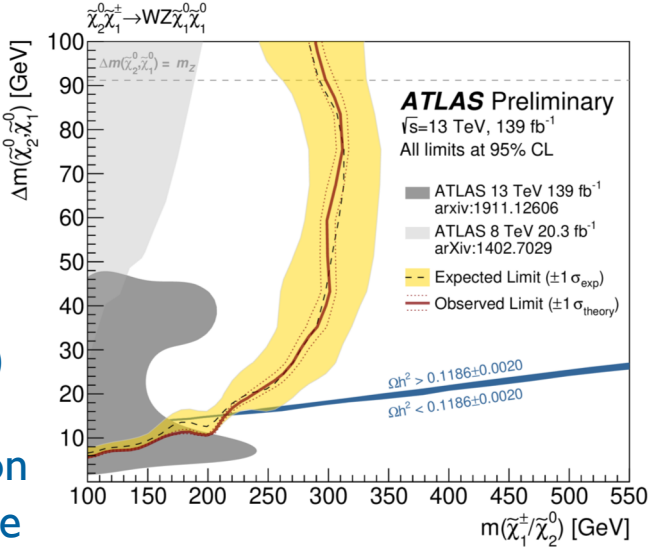


ATLAS-CONF-2020-015

Trileptons



- EWK production with a 3L final state (WZ-mediated)
  - "On-shell" selections covered in Carlos' EWK Talk
  - "Off-shell" WZ selection → compressed EWK scenarios
- SR binning in E_t^{miss} and jet multiplicity
  - SRs targeting moderate mass splittings (Δm = 40 - 90 GeV)
  - Higher E_T^{miss} SR → highly compressed mass spectra (Δm < 40 GeV)
- Primary discriminants:
  - kinematic edge at $\mathbf{m_{\ell\ell}^{min}}$ = Δm
  - kinematic edge in stransverse mass $\mathbf{m_{T2}^{100}}$
  - transverse mass $m_T^{m_{\ell\ell}min}$ using $m^{\ell\ell}_{min}$ assignment
- complementary with soft 2L (**ATLAS-SUSY-2018-16**)
- constraints are calculated in the bino-wino coannihilation dark-matter scenario where $\Omega_{DM}h^2 \leq$ the observed value



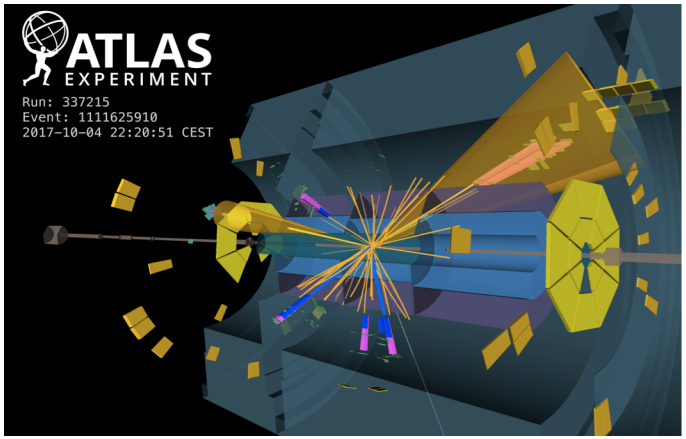
Compressed VBF

ATLAS-SUSY-2018-16

Searches for **electroweak** production of supersymmetric particles with **compressed** mass spectra

CMS-SUS-17-007

Search for supersymmetry with a **compressed** mass spectrum in the **vector boson fusion topology** with **1-lepton** and **0-lepton** final states



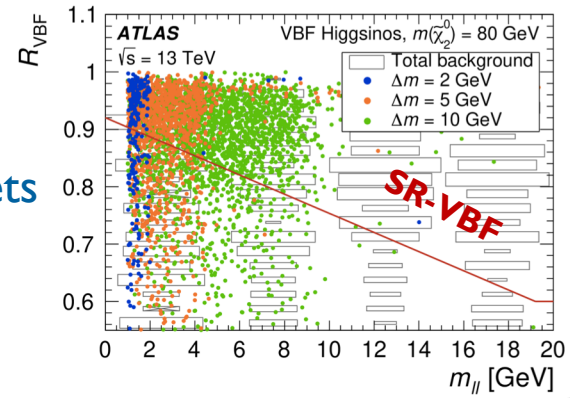
Compressed VBF

ATLAS-SUSY-2018-16
CMS-SUS-17-007

VBF topology: forward jets in opposite hemispheres and large dijet invariant mass

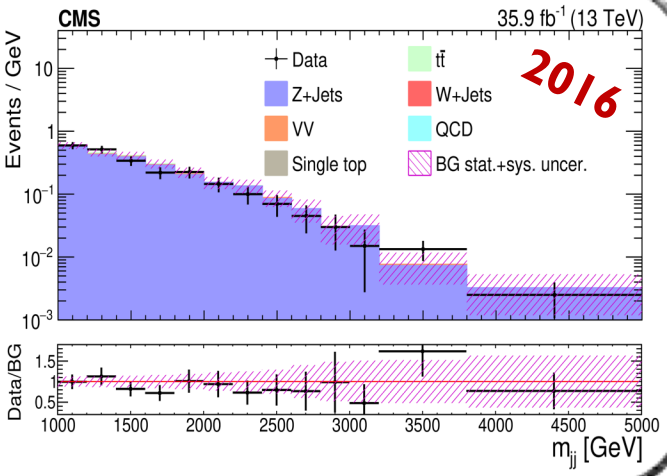
ATLAS-SUSY-2018-16

- SR of Soft 2L search: SR-VBF
- **VBF recoil**: R_{VBF} = RJR with ISR replaced by 2 leading jets
- Large separation: low and high regions
- Binning in R_{VBF} and m_{ll}



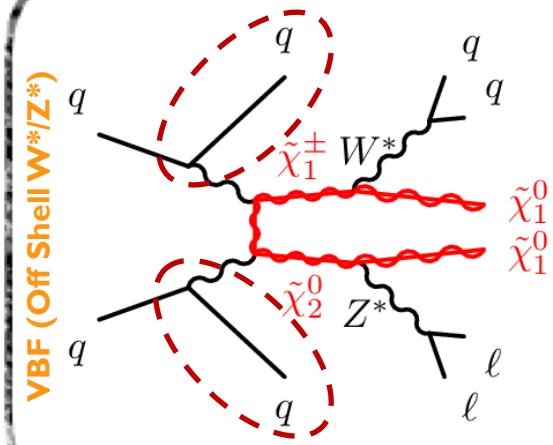
CMS-SUS-17-007

- 1st search of VBF + soft 1L + EWK SUSY search in 0ljj
- low-p_T → difficult to reconstruct and identify leptons:
  - **one** lepton (e, m, τ_h) (**1ℓjj**) binned in m_T
  - **zero** (**0ℓjj**) leptons binned in m_{jj}
- Transverse mass $\mathbf{m_T}$ > 110 GeV (beyond m_W peak)

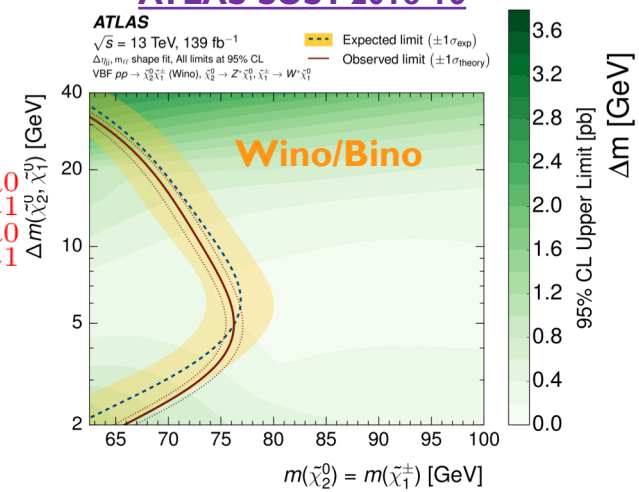


Compressed VBF

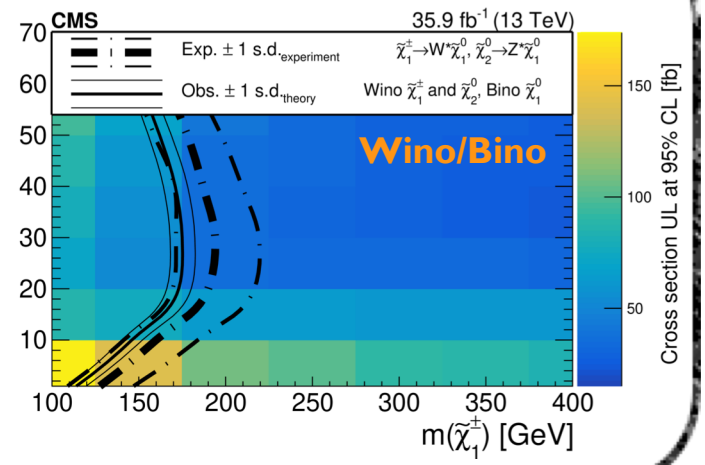
ATLAS-SUSY-2018-16
CMS-SUS-17-007

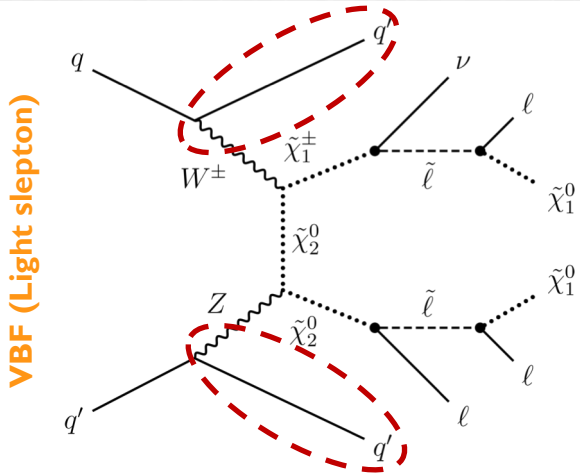


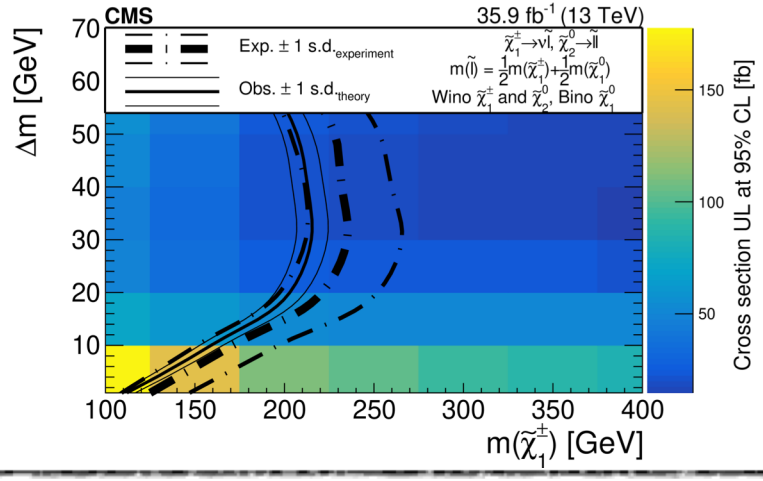
ATLAS-SUSY-2018-16



CMS-SUS-17-007







CMS-SUS-17-007

Δm down to 1 GeV!

Soft Tau

CMS-SUS-19-002

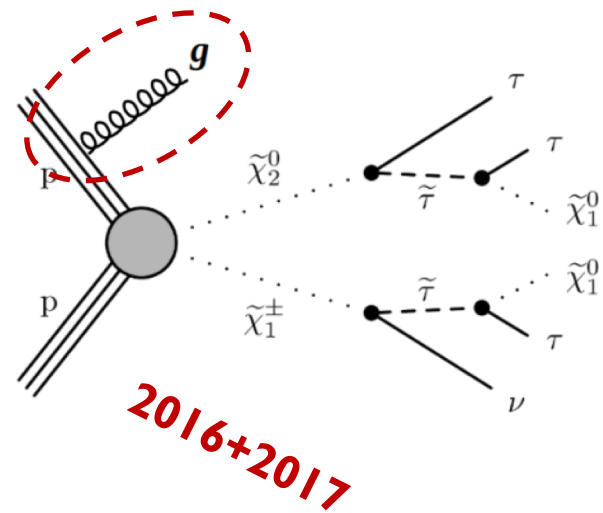
Search for supersymmetry with a compressed mass spectrum in events with a **soft τ lepton**, a **highly energetic jet**, and **large missing transverse momentum**

Soft Tau

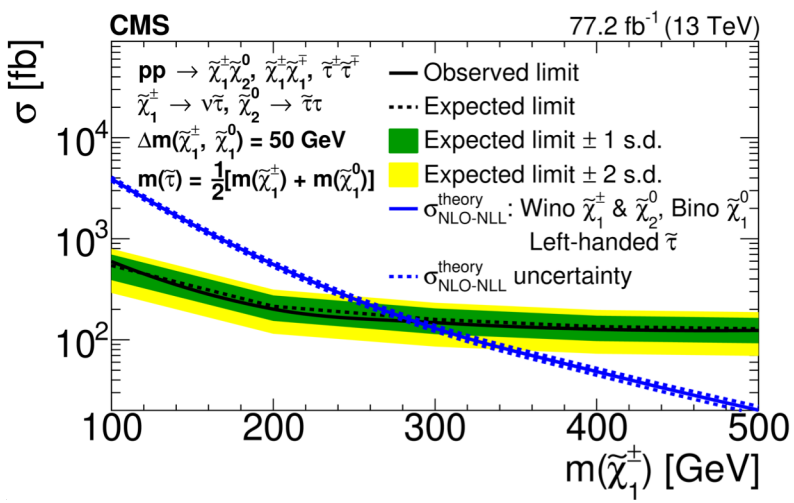
CMS-SUS-19-002

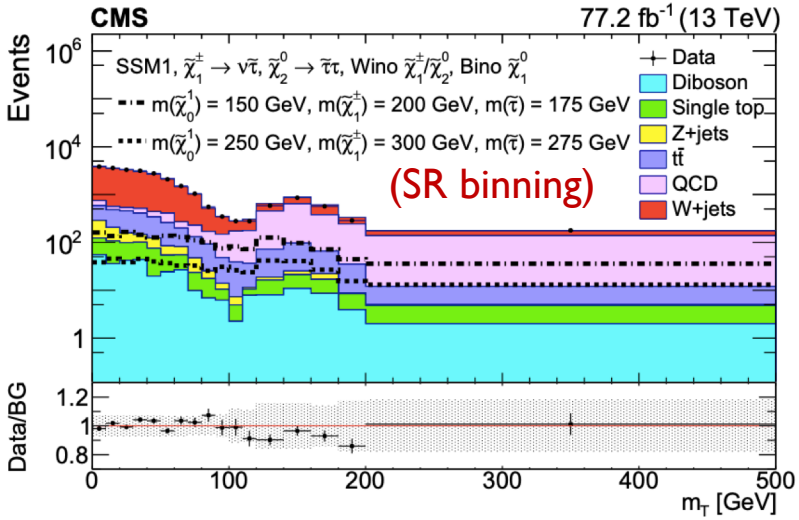
- First search of a soft hadronically-decaying tau:
  - stau decaying to tau and neutralino + ISR
    - $\Delta m(\text{stau}, \chi_1^0) \leq 50$ GeV
- $20 < p_T(\tau_H) < 40$ GeV
- SR binning in terms of transverse mass of τ_H:

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



SSM1: chargino-neutralino + stau production





- First limits to surpass LEP bound of 103.5 GeV for $m(\chi_1^\pm)$ in compressed scenarios

Compressed Stop

ATLAS-SUSY-2018-12

ATLAS-CONF-2020-003

CMS-SUS-19-009

CMS-SUS-18-003

CMS-SUS-17-005

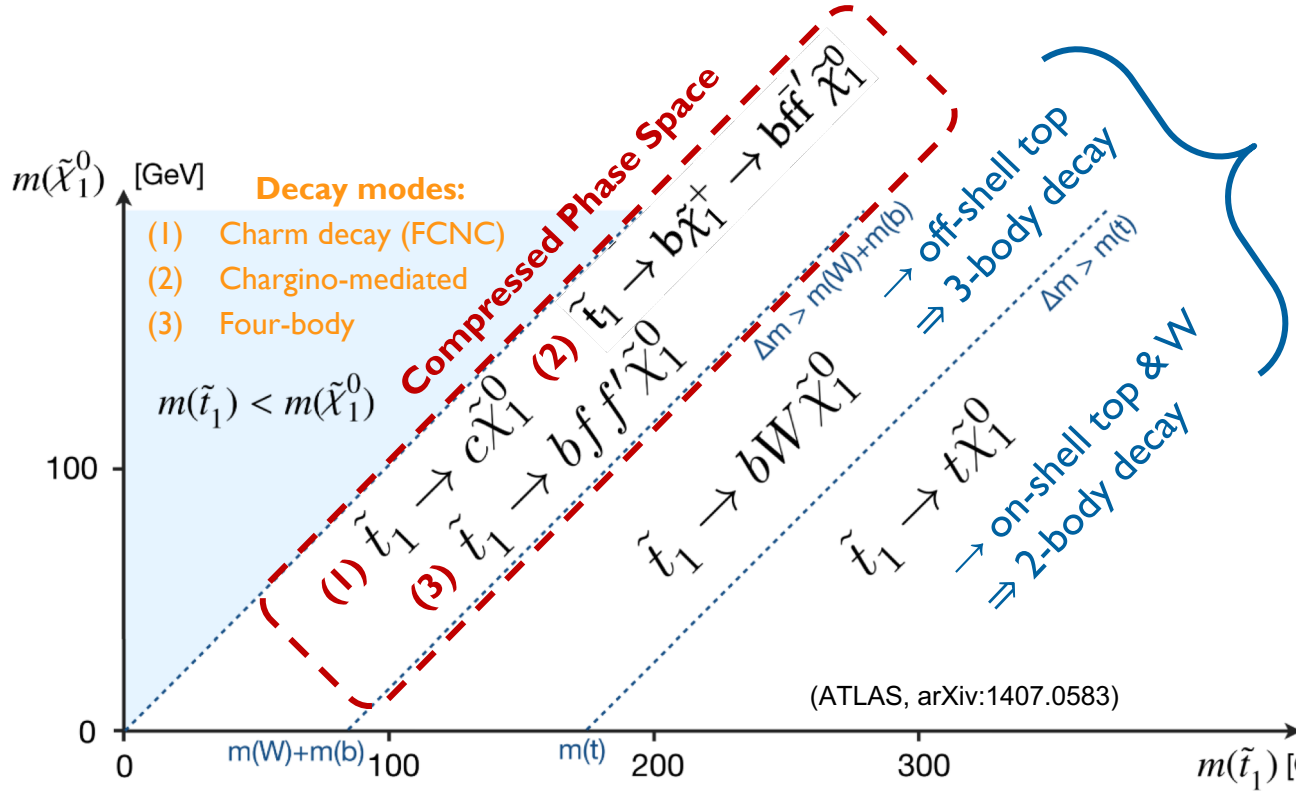
CMS-SUS-16-048

CMS-SUS-16-049

CMS-SUS-16-032

Compressed Stop

- $\Delta m \equiv m_{stop} - m_{LSP}$ dictates decay modes and kinematics:
  - Final states classified according to W decay-modes: hadronic, single- and di-leptonic
- **Very compressed** scenario when: $\Delta m < m_W$ → decay via an off-shell t* and W*



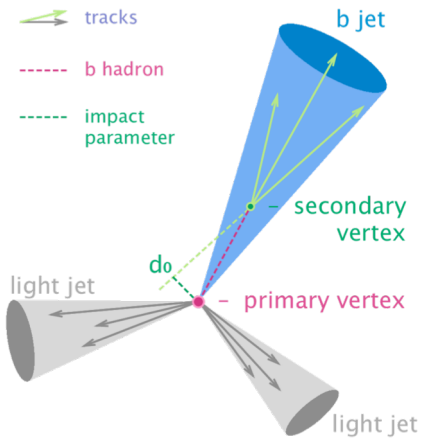
'Classical' searches
(also targeting compressed):

All-hadronic:
- ATLAS-SUSY-2018-12
- CMS-SUS-16-049

Single leptonic:
- ATLAS-CONF-2020-003
- CMS-SUS-19-009

Top corridor ($\Delta m \sim m_t$):
- CMS-SUS-18-003

Soft B-Tagging

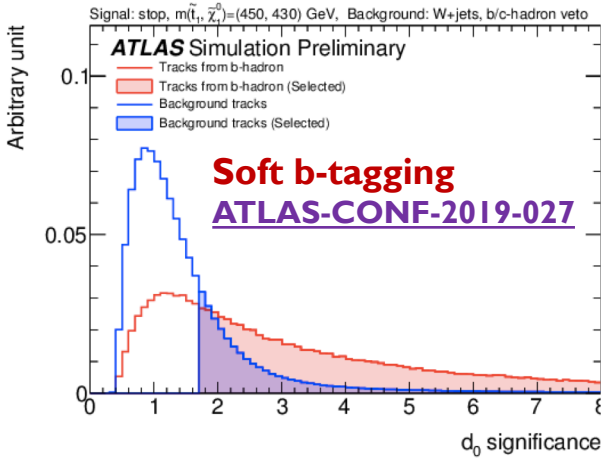


Stop decays → top decays → final states with **b-jets**

- tagging b-jets with $p_T > 1$ GeV
- sensitivity to compressed models
  - signal efficiency and background rejection

- **Soft b-tagging** algorithms:
  - **Inclusive Vertex Finder (IVF)** (JHEP03(2011)136)
    - used in all-hadronic (CMS-SUS-16-049)
    - used in stop 1L (CMS-SUS-19-009) for $\Delta m \sim m_W$
  - **Track-based Low-p_T Vertex Tagger (T-LVT)** (ATLAS-CONF-2019-027)
    - used in all-hadronic (ATLAS-CONF-2020-003)
    - used in stop 1L (ATLAS SUSY-2018-12)
  - DeepJet/DeepCSV
    - used in 1L (CMS-SUS-19-009) for $\Delta m \sim m_t$

- jets reconstructed from tracks
- identifying SVs without the presence of a jet

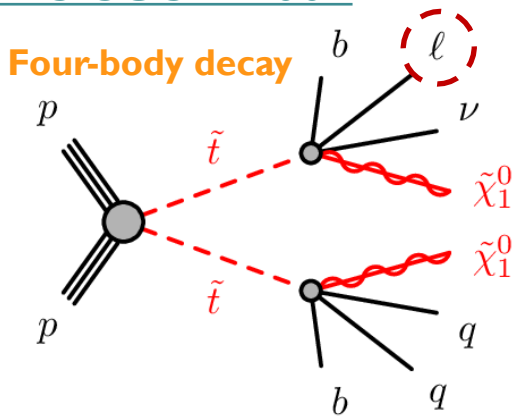


Full Run 2

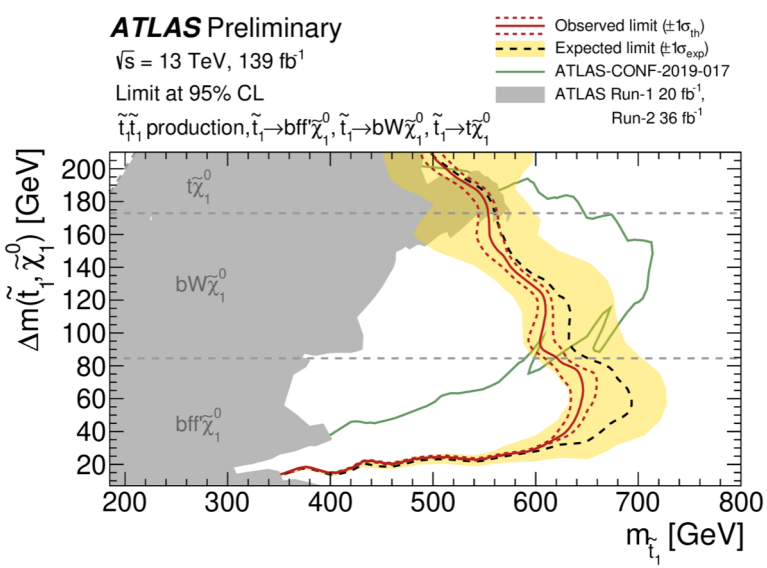
Single Leptonic

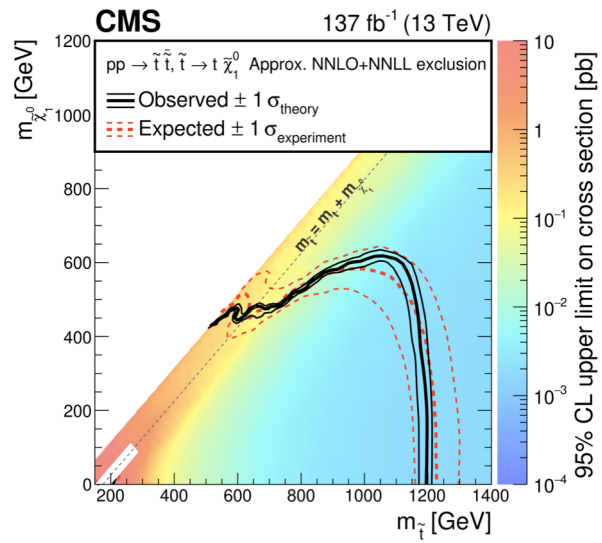
ATLAS-CONF-2020-003
CMS-SUS-19-009

- Stop pair-production in **single lepton** channel
- Analysis strategy and non-compressed scenarios covered in Mark's 3G talk
  - dedicated signal regions for compressed scenarios: **ISR**
  - dedicated **soft b-tagging** techniques for very small Δm's



ATLAS-CONF-2020-003



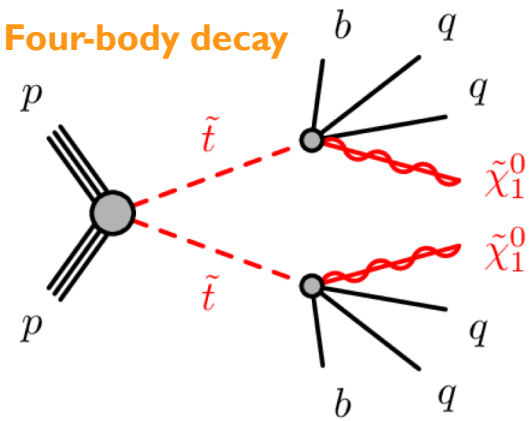


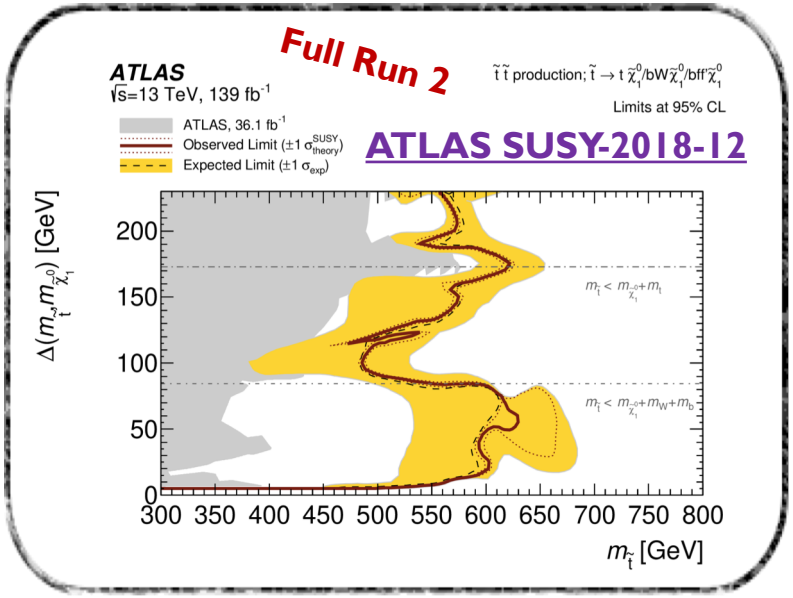
CMS-SUS-19-009

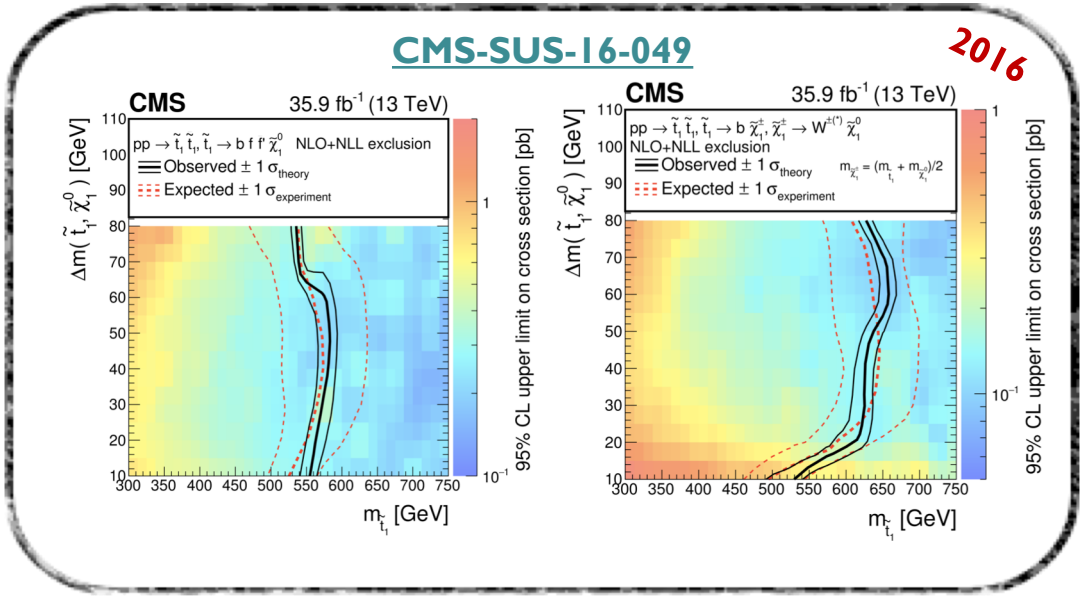
All Hadronic

ATLAS SUSY-2018-12
CMS-SUS-16-049

- Stop pair-production in **all-hadronic** channel
- Analysis strategy and non-compressed scenarios covered in Mark's 3G talk
  - dedicated signal regions for compressed scenarios: **ISR**
  - dedicated **soft b-tagging + R_{ISR}** for very small Δm's







Other Searches

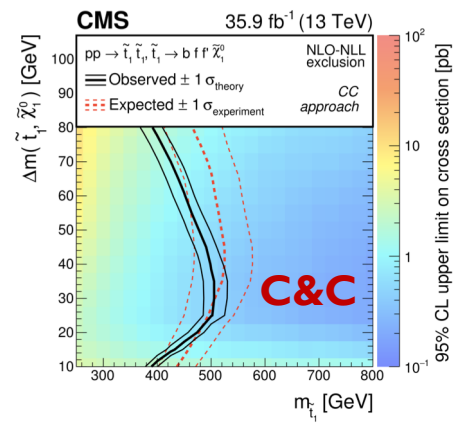
CMS-SUS-17-005
CMS-SUS-16-032

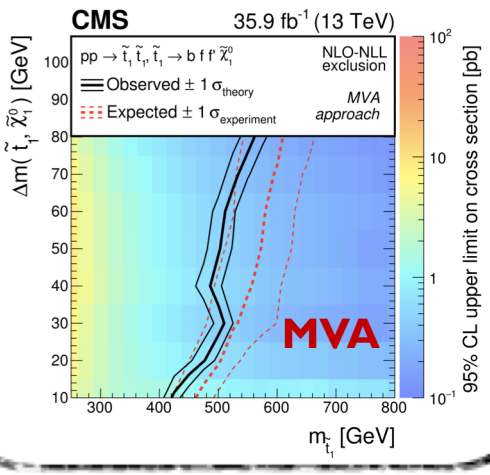
CMS-SUS-16-048
CMS-SUS-16-049

- There are a number of other searches covering compressed phase-spaces:

Four-body decay

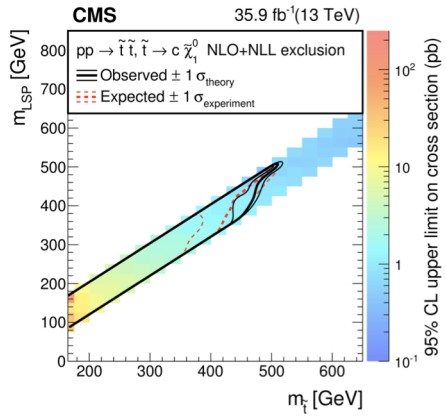
CMS-SUS-17-005



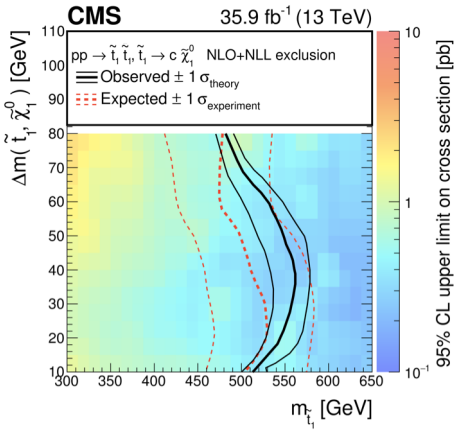


Charm decay (FCNC)

CMS-SUS-16-032

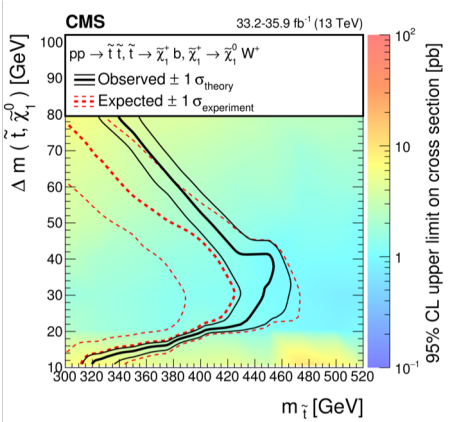


CMS-SUS-16-049

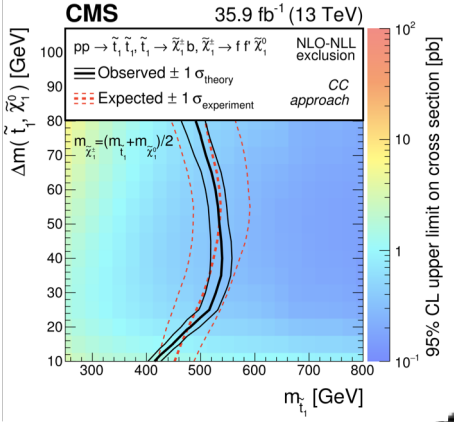


Chargino-mediated decay

CMS-SUS-16-048

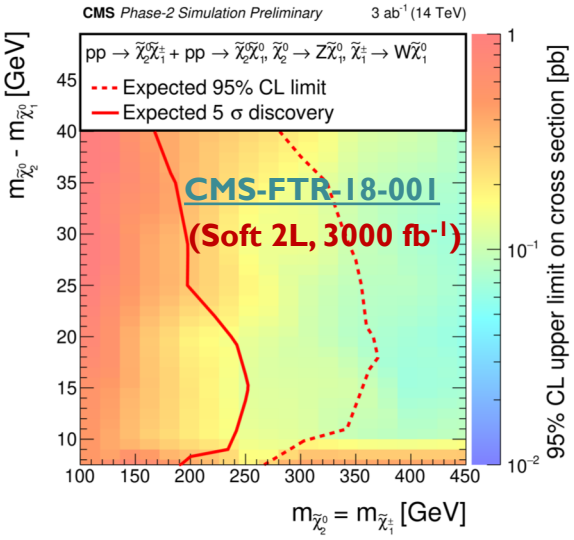


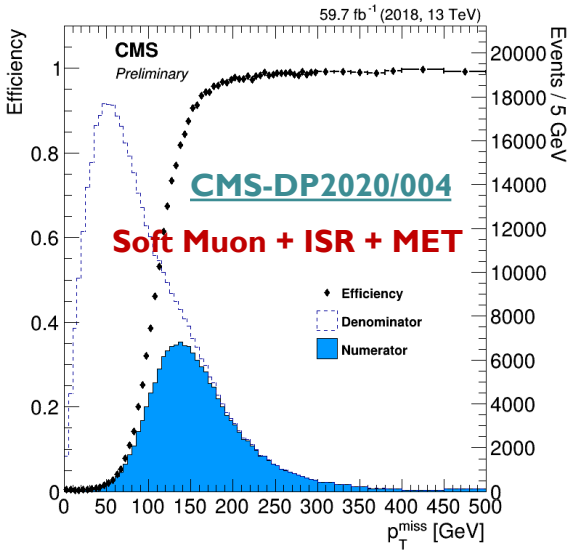
CMS-SUS-17-005



Improvements

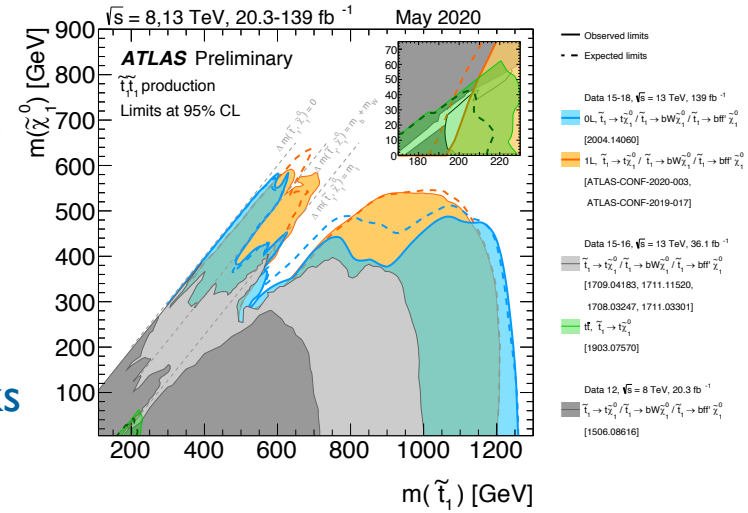
- Solely increased integrated luminosity is not expected to bring large gains in sensitivity ⇒ improve techniques:
  - **Soft lepton** reconstruction and identification:
    - ATLAS low-p_T ID (Eur. Phys. J. C 76, 292 (2016))
    - MVA/DeepNN discriminators for low p_T leptons
  - **Soft b-tagging** techniques
  - **Soft tracks** (eg. 1ℓ + 1T EWKino SR in Soft 2L)
  - **ISR tagging**:
    - recoil: Recursive Jigsaw (RJR) or H_T/MET
    - "large-R" jets → used in CMS-SUS-16-049
    - quark-gluon likelihood QGL-discriminator
- Dedicated **cross-triggers** to lower MET and lepton thresholds
  - soft object(s) + ISR + MET (CMS-DP 2020/004)
  - VBF + soft lepton (CMS-DP 2020/014)
- Shift to more sophisticated **signal models** eg. extensions to long-lived particles (for very small Δm, particles are displaced)





Summary & Outlook

- Soft SUSY = small Δm → soft visible decay products (leptons/jets/E_T^{miss})
  - characteristic: **ISR** boost of signal vertex
- Significant **effort** at ATLAS and CMS focusing on these regions to ensure phase-space is well covered
  - brand new full Run 2 results with strongest limits in a number of **compressed** models
  - many dedicated analyses are currently in the works
    - stay tuned for more incoming results!
  - all analyses use specialized **methods** to target these regions (soft lepton ID, RJR, soft b-tagging, soft tracks, ISR tagging, triggers, new signal models, …)



We need to take advantage of these innovative methods to really push to the limits detection, analysis and theory!

Backup

Simplified SUSY Models

- We can categorise SUSY signals in terms of **production** and **decay** modes:

SUSY Production:

- Typically pair-produced (R-parity conservation)
- Production modes → choice guided by cross-sections

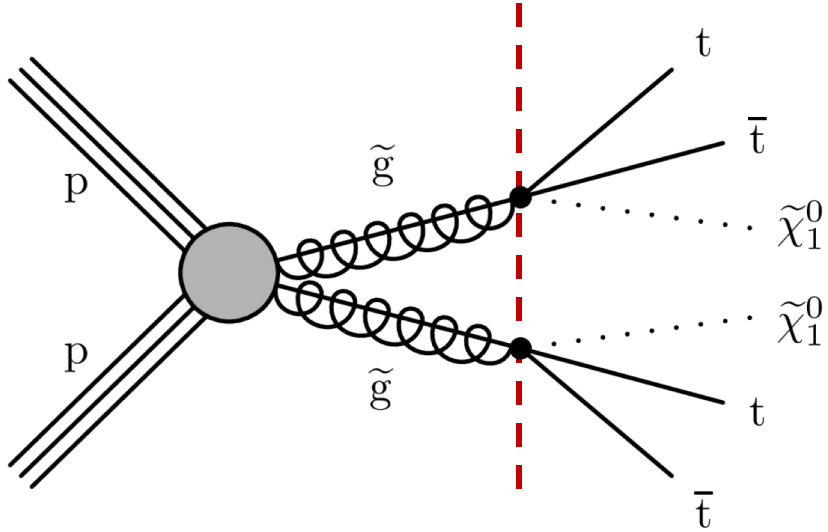
SUSY Decay:

- Decay into SUSY and detectable SM particles → final states
- **Mass splitting Δm** dictates possible decay modes and kinematics

Production modes:

Strong: gluinos, squarks

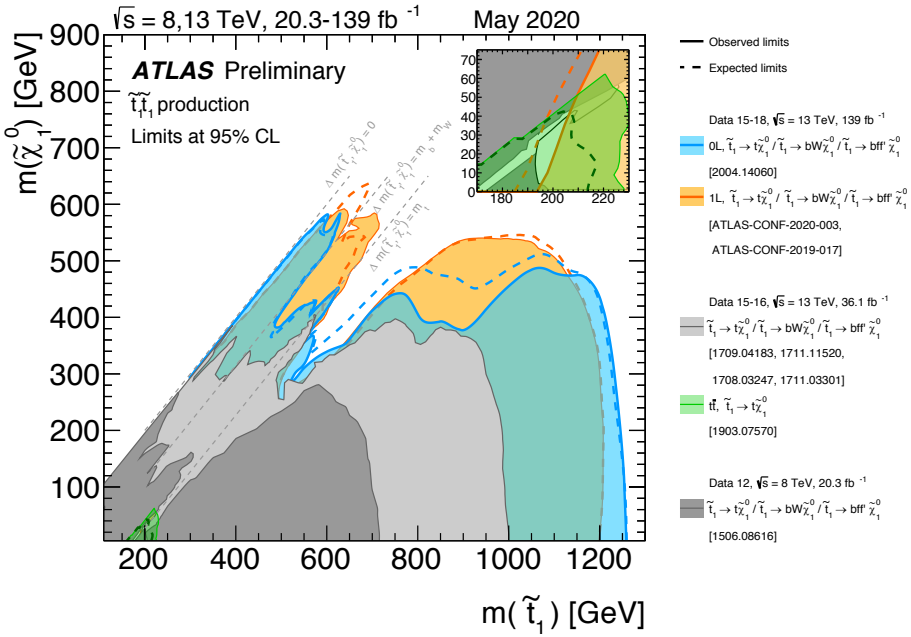
EWK: charginos, neutralinos, sleptons

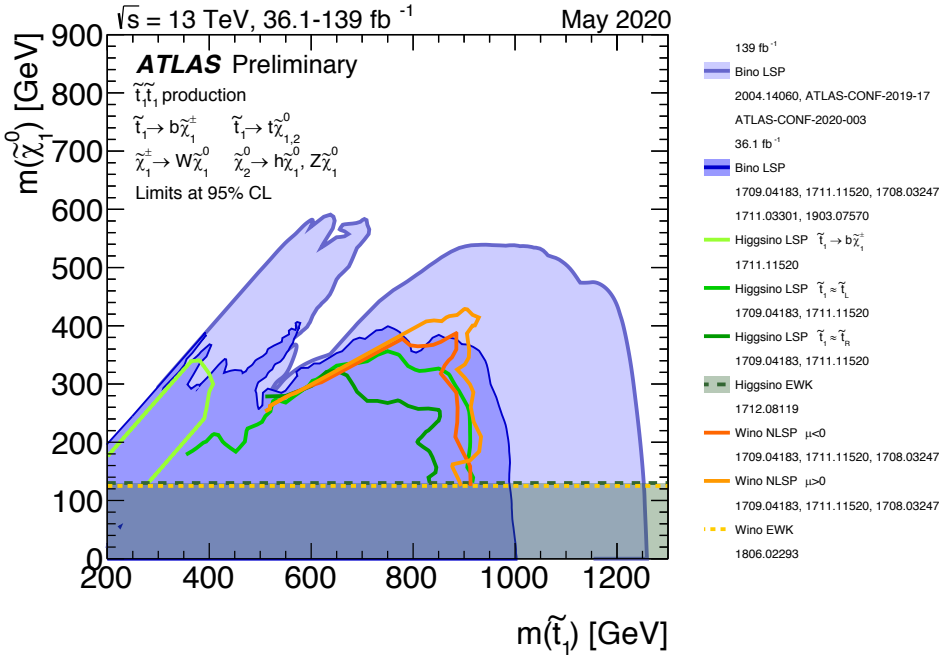


Final states:

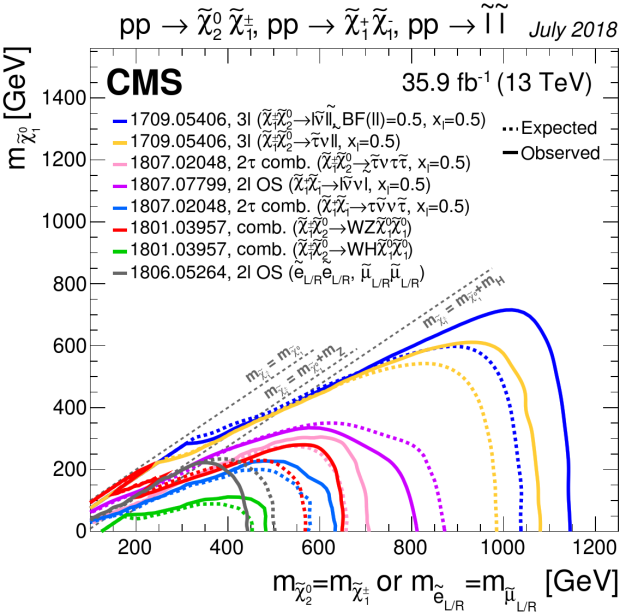
- Hadronic (0ℓ) = **jets**
- Single-**leptonic** (1ℓ)
- Multi-**leptonic** (2ℓ+)
- **MET** in the form of LSPs (R-parity conserving)
- **b-jets** from top decays

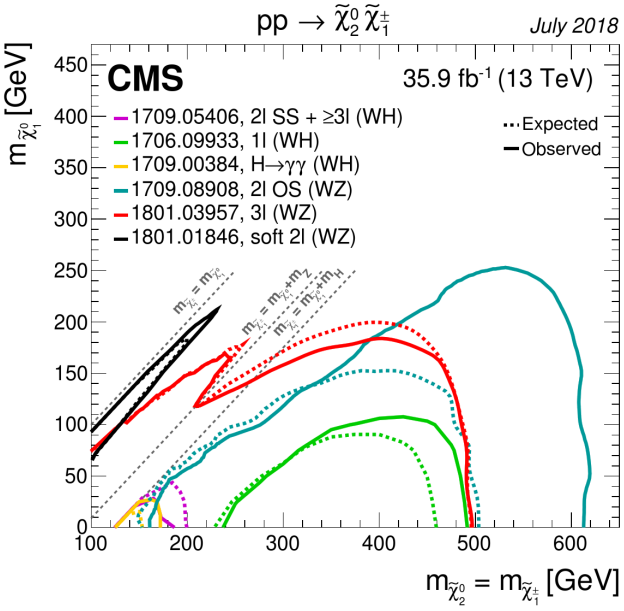
ATLAS Summary

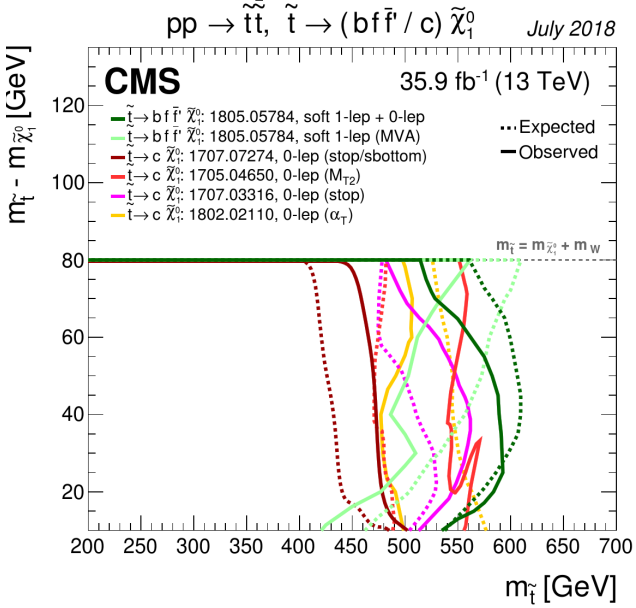




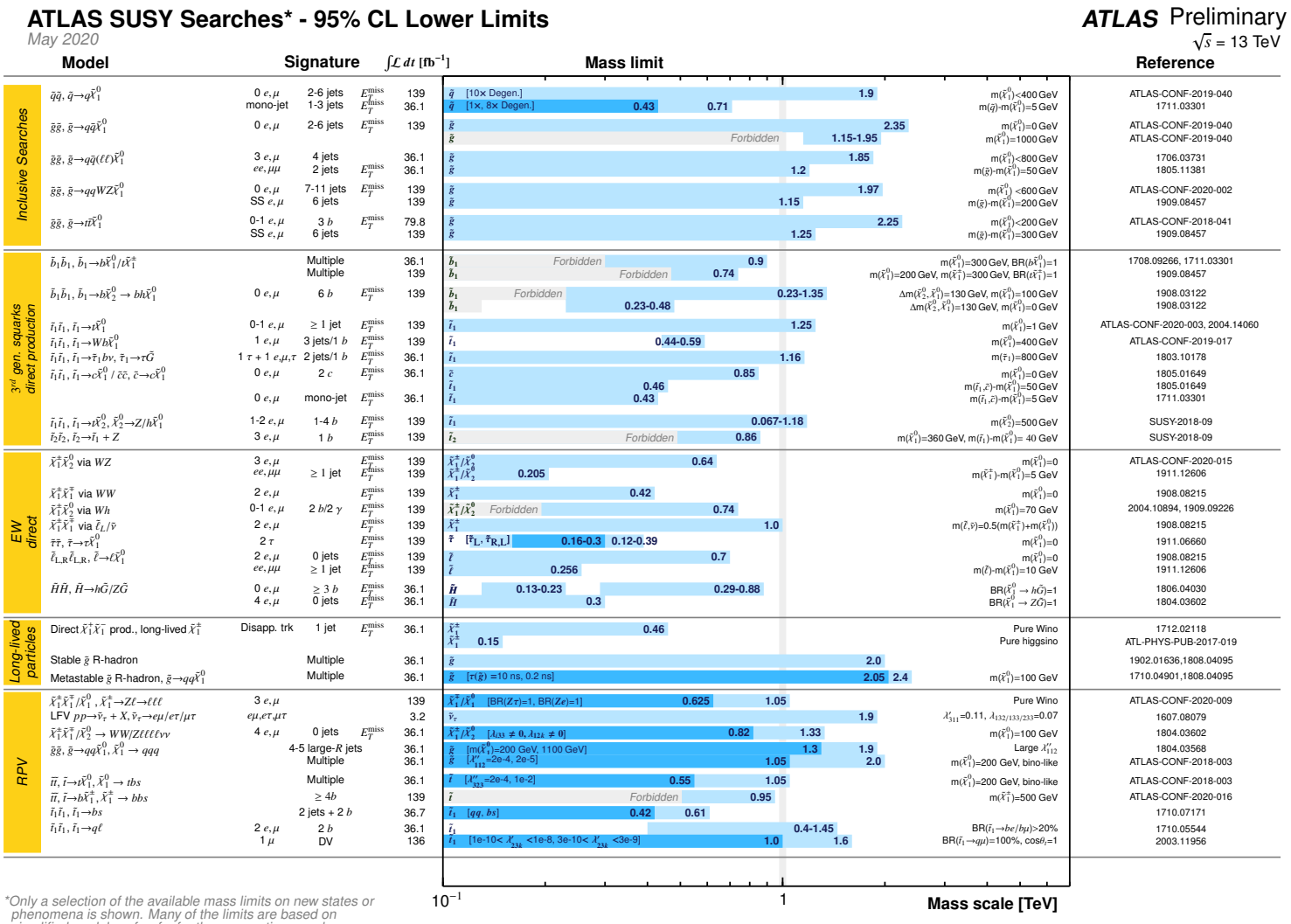
CMS Summary


pp → $\tilde{\chi}^0_2 \tilde{\chi}^\pm_1$, pp → $\tilde{\chi}^+_1 \tilde{\chi}^-_1$, pp → $\tilde{l}\tilde{l}$
July 2018
CMS
35.9 fb^{-1} (13 TeV)
1709.05406, 3l ($\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to l\tilde{\nu}\tilde{l}_L$, BF(ll)=0.5, x_l=0.5)
1709.05406, 3l ($\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to \tilde{\tau}\nu ll$, x_l=0.5)
1807.02048, 2τ comb. ($\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to \tilde{\tau}\nu\tau\tilde{\tau}$, x_l=0.5)
1807.07799, 2l OS ($\tilde{\chi}^+_1\tilde{\chi}^-_1 \to l\tilde{\nu}\nu l$, x_l=0.5)
1807.02048, 2τ comb. ($\tilde{\chi}^+_1\tilde{\chi}^-_1 \to \tau\tilde{\nu}\nu\tilde{\tau}$, x_l=0.5)
1801.03957, comb. ($\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to WZ\tilde{\chi}^0_1\tilde{\chi}^0_1$)
1801.03957, comb. ($\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to WH\tilde{\chi}^0_1\tilde{\chi}^0_1$)
1806.05264, 2l OS ($\tilde{e}_{L/R}\tilde{e}_{L/R}$, $\tilde{\mu}_{L/R}\tilde{\mu}_{L/R}$)
Expected
Observed
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{\chi}^0_2}$=$m_{\tilde{\chi}^\pm_1}$ or $m_{\tilde{e}_{L/R}}$=$m_{\tilde{\mu}_{L/R}}$ [GeV]

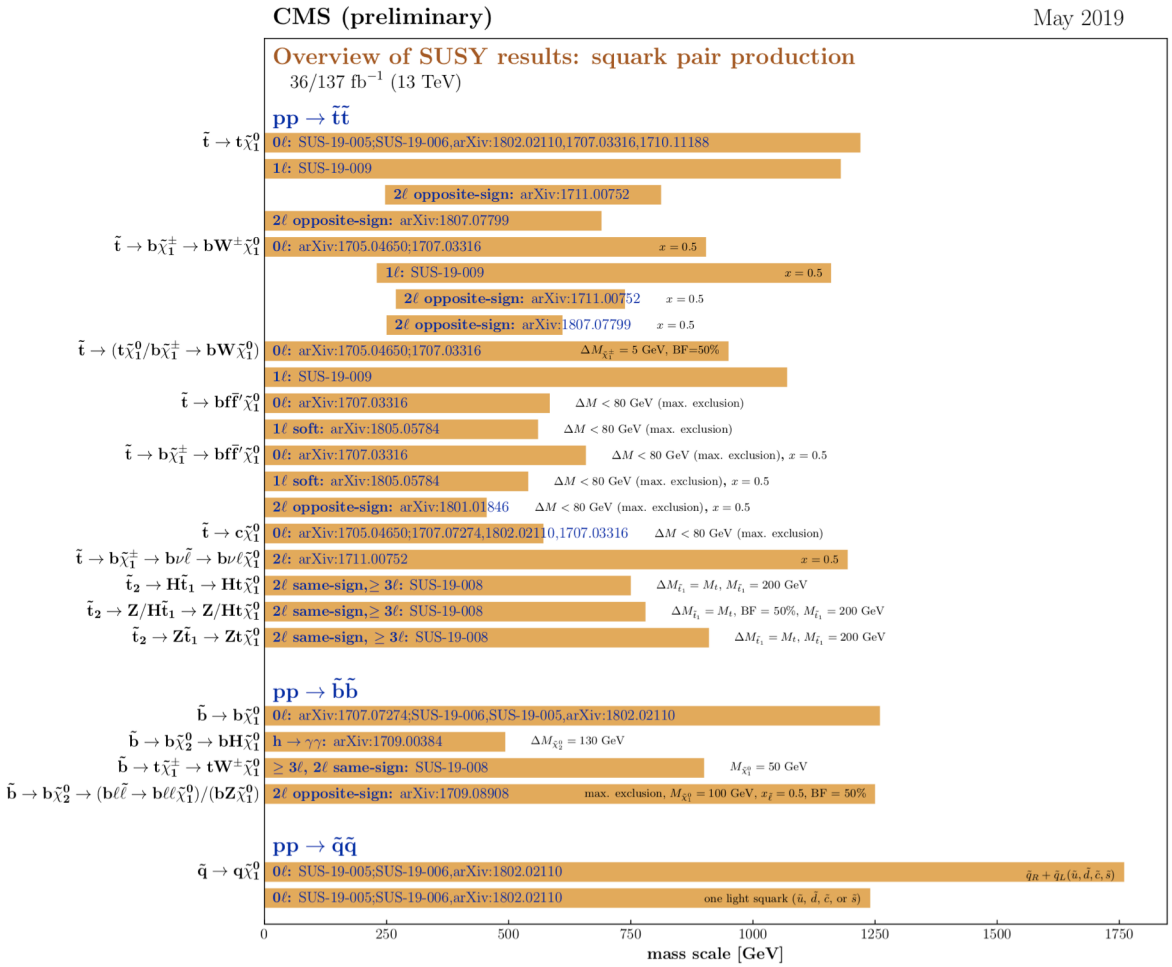

pp → $\tilde{\chi}^0_2 \tilde{\chi}^\pm_1$
July 2018
CMS
35.9 fb^{-1} (13 TeV)
1709.05406, 2l SS + ≥3l (WH)
1706.09933, 1l (WH)
1709.00384, H→γγ (WH)
1709.08908, 2l OS (WZ)
1801.03957, 3l (WZ)
1801.01846, soft 2l (WZ)
Expected
Observed
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{\chi}^0_2}$ = $m_{\tilde{\chi}^\pm_1}$ [GeV]


pp → $\tilde{t}\tilde{\bar{t}}$, $\tilde{t}$ → (b f $\bar{f}$' / c) $\tilde{\chi}^0_1$
July 2018
CMS
35.9 fb^{-1} (13 TeV)
$\tilde{t}$→ b f $\bar{f}$' $\tilde{\chi}^0_1$: 1805.05784, soft 1-lep + 0-lep
$\tilde{t}$→ b f $\bar{f}$' $\tilde{\chi}^0_1$: 1805.05784, soft 1-lep (MVA)
$\tilde{t}$→ c $\tilde{\chi}^0_1$: 1707.07274, 0-lep (stop/sbottom)
$\tilde{t}$→ c $\tilde{\chi}^0_1$: 1705.04650, 0-lep (M_{T2})
$\tilde{t}$→ c $\tilde{\chi}^0_1$: 1707.03316, 0-lep (stop)
$\tilde{t}$→ c $\tilde{\chi}^0_1$: 1802.02110, 0-lep (α_T)
Expected
Observed
$m_{\tilde{t}}$ - $m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}}$ [GeV]

ATLAS Summary

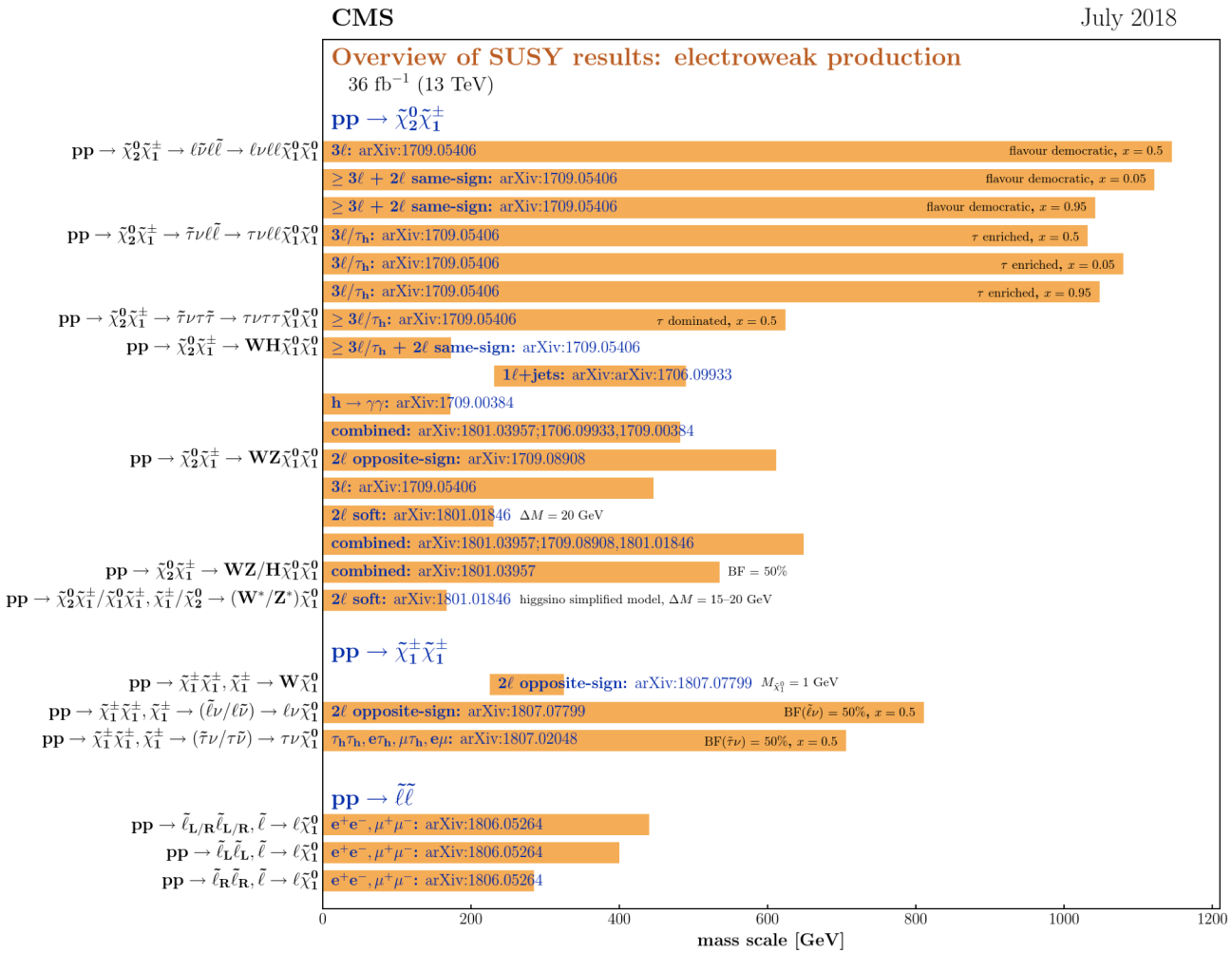


CMS Summary



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.

CMS Summary

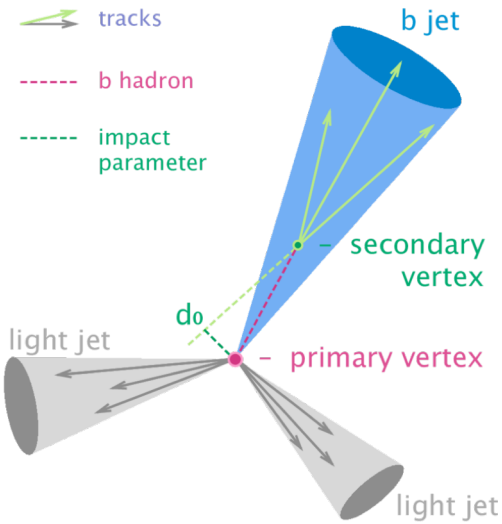


Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate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

Event Topologies

- We can draw similarities in the **event topologies** that are targeted:
  - Expect large **hadronic activity** in the event:
    - high $\mathbf{H_T}$ (scalar sum of jets p_Ts)
    - larger **jet multiplicity ($\mathbf{N_{jets}}$)**
      - **b-jets ($\mathbf{N_b}$)** from top quark decays
        - » arise in many models eg. T1tttt or T5tttt
        - » no b-jets for eg. T5qqqqVV or T5qqqqWW
  - Significant **missing transverse energy $\mathbf{p_T^{miss}}$** from LSPs which are undetected
    - Standard signature of R-parity conserving models
- **Final states** typically consist of:

lepton(s) + jets (b-jets) + p_T^{miss}



Toolbox

- We can draw similarities in the **tools** that are used → observables:
  - Kinematic variables – calculation of energy sums: $\mathbf{H_T}$, $\mathbf{p_T^{miss}}$
    - distinguishing compressed vs. uncompressed mass spectra
  - Jet multiplicities: $\mathbf{N_{jets}}$ and $\mathbf{N_b}$:
    - all presented analyses require at least 2 jets
    - N_b categorisation can provide sensitivity to different models
  - The **transvere mass $\mathbf{m_T}$** constructed from lepton p_T and MET used to calculate the mass of particles decaying to a visible + invisible particle:

$$M_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\left(\phi_{\ell} - \phi_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}\right)\right]}$$

    - sharp decline around the mass of the W boson
    - effective in separating single-leptonic SM processes (W+jets, tt-bar)
  - The **invariant mass $\mathbf{m_{\ell\ell}}$** between two leptons targeting dileptonic signatures:
    - "on-Z" signature: decays involving an on-shell Z boson produce peak in m_{ll}

Soft SUSY Searches at ATLAS and CMS

<table>
<tr><th>Lep.</th><th>EWK</th><th>Strong</th><th>VBF</th></tr>
<tr><td>3+</td><td colspan="2">ATLAS CONF-2020-015 (3L)</td><td></td></tr>
<tr><td rowspan="2">2</td><td>ATLAS-SUSY-2018-16 (Soft 2L)
CMS-SUS-19-002
(Soft Stau)</td><td>CMS-SUS-18-003 (Top Corridor)</td><td rowspan="2">ATLAS-SUSY-2018-16 (Soft 2L: SR-VBF)</td></tr>
<tr><td colspan="2">CMS-SUS-16-048 (Soft 2L)</td></tr>
<tr><td rowspan="3">1</td><td></td><td>ATLAS-CONF-2020-003 (Stop 1L)
CMS-SUS-19-009 (Stop 1L)</td><td rowspan="3">CMS-SUS-17-007 (Soft VBF 1/0L)</td></tr>
<tr><td></td><td>CMS-SUS-17-005 (Soft 1L)</td></tr>
<tr><td></td><td>ATLAS-SUSY-2018-12 (All had.)
CMS-SUS-16-049 (All had.)</td></tr>
<tr><td>0</td><td></td><td></td><td></td></tr>
</table>

Compressed @ ATLAS

Prod.	Analysis	Number	Description	Ref.
EWK	Soft 2L	ATLAS SUSY-2018-16	Searches for electroweak production of supersymmetric particles with compressed mass spectra	Phys. Rev. D 101 (2020) 052005
EWK	3L	ATLAS-CONF-2020-015	Search for chargino-neutralino pair production in final states with three leptons and missing transverse momentum	ATLAS-CONF-2020-015
Stop	Stop 1L	ATLAS-CONF-2020-003	Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum	ATLAS-CONF-2020-003
Stop	All Hadronic	ATLAS SUSY-2018-12	Search for a scalar partner of the top quark in the all-hadronic tt plus missing transverse momentum final state	Submitted to EPJC

Compressed @ CMS

Prod.	Analysis	Number	Description	Ref.
EWK	Soft Tau + ISR + MET	CMS-SUS-19-002	Search for supersymmetry with a compressed mass spectrum in events with a soft ττ lepton, a highly energetic jet, and large missing transverse momentum	Phys. Rev. Lett. 124 (2020) 041803
VBF	VBF + SUSY	CMS-SUS-17-007	Search for supersymmetry with a compressed mass spectrum in the vector boson fusion topology with 1-lepton and 0-lepton final states	JHEP 08 (2019)150
EWK + Stop	SOS	CMS-SUS-16-048	Search for new physics in events with two soft oppositely charged leptons and missing transverse momentum	Phys. Lett. B 782 (2018) 440
Stop	Soft 1L	CMS-SUS-17-005	Search for top squarks decaying via four-body or chargino-mediated modes in single-lepton final states	JHEP 09 (2018) 065
Stop	All hadronic	CMS-SUS-16-049	Search for direct production of supersymmetric partners of the top quark in the all-jets final state	J. High Energy Phys. 10 (2017) 005
Stop	Stop 1L	CMS-SUS-19-009	Search for direct top squark pair production in events with one lepton, jets, and missing transverse momentum	JHEP 05 (2020) 032
Stop	Compressed charm	CMS-SUS-16-032	Search for the pair production of third-generation squarks with two-body decays to a bottom or charm quark and a neutralino	Phys. Lett. B 778 (2018) 263

ATLAS-SUSY-2018-16

Soft 2L

Full Run 2

- Baseline selection:
  - 2 OS same-flavor leptons ($e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$) as two channels:
    - **2ℓ (p_T > 5 GeV)** and **1ℓ + ≥1 track ($1\ell 1T$)**
      - b-jet veto for 2ℓ
  - Kinematic: E_T^{miss} >120 GeV (E_T^{miss} trigger) + ISR: leading jet p_T ≥100 GeV
  - Muons > 3 GeV and $|\eta|$ < 2.5 (lowPt identification criterion)
  - Electrons > 4.5 GeV and $|\eta|$ < 2.47
  - Jets > 30 GeV and $|\eta|$ < 2.8 (VBF $|\eta|$ < 4.5)
  - B-tagged jets: jets within $|\eta|$ < 2.5 (MV2c1 algorithm)

- Main backgrounds:
  - reducible backgrounds: fake/nonprompt leptons
    - fake factor method
  - irreducible backgrounds: tt/tW, WW/WZ, and Z^*/γ ($\rightarrow \tau\tau$) + jets
    - estimated using MC simulations normalized to data in dedicated CRs

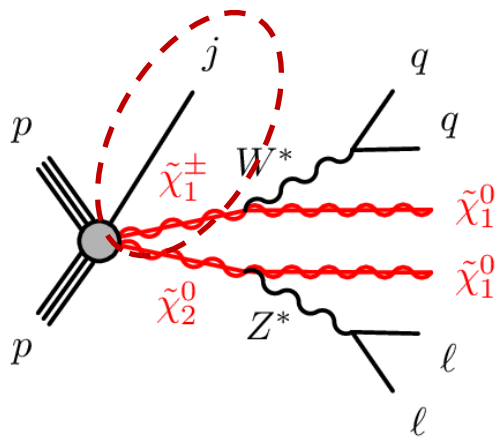
ATLAS-SUSY-2018-16

Soft 2L

- Signal regions split into three categories each targeting different models:

SOS (CMS-SUS-16-048)

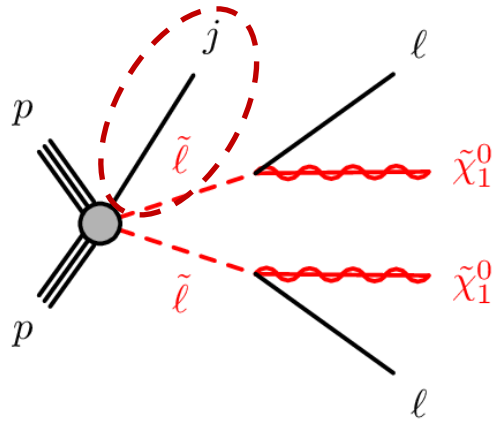
Chargino-Neutralino Production



SR-E

- 4 E_T^{miss} regions (different Δm)
- Binning:
  - E_T^{miss}
  - $m_T^{\ell 1}$ and m_{ll}
  - R_{ISR}
  - E_T^{miss}/H_T^{lep}

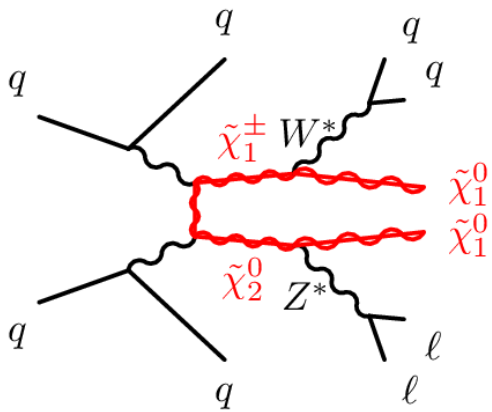
Slepton Production



SR-S

- Binning:
  - E_T^{miss}
  - R_{ISR}
  - m_{T2}^{100}

VBF Production



SR-VBF

- Large dijet invariant mass
- Large separation: low and high regions
- Binning in R_{VBF} and m_{ll}

VBF SUSY (CMS-SUS-17-007)

ATLAS-SUSY-2018-16

Soft 2L

- Preselection:

Variable	Preselection requirements	
	2ℓ	$1\ell 1T$
Number of leptons (tracks)	= 2 leptons	= 1 lepton and ≥ 1 track
Lepton p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_1} > 5$	$p_{\mathrm{T}}^{\ell} < 10$
$\Delta R_{\ell\ell}$	$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.2$	$0.05 < \Delta R_{\ell\mathrm{track}} < 1.5$
Lepton (track) charge and flavor	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
Lepton (track) invariant mass [GeV]	$3 < m_{ee} < 60$, $1 < m_{\mu\mu} < 60$	$0.5 < m_{\ell\mathrm{track}} < 5$
J/ψ invariant mass [GeV]	veto $3 < m_{\ell\ell} < 3.2$	veto $3 < m_{\ell\mathrm{track}} < 3.2$
$m_{\tau\tau}$ [GeV]	< 0 or > 160	no requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 120	> 120
Number of jets	≥ 1	≥ 1
Number of b-tagged jets	$= 0$	no requirement
Leading jet p_{T} [GeV]	≥ 100	≥ 100
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$	> 0.4	> 0.4
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ †	≥ 2.0	≥ 2.0

ATLAS-SUSY-2018-16

Soft 2L

- EWKino SR:

	Electroweakino SR Requirements			
Variable	SR–E–low	SR–E–med	SR–E–high	SR–E–$1\ell 1T$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	[120, 200]	[120, 200]	> 200	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	< 10	> 10	–	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	–	–	–	< 1.0
Lepton or track p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_2} > 5 + m_{\ell\ell}/4$	–	$p_{\mathrm{T}}^{\ell_2} > \min(10, 2 + m_{\ell\ell}/3)$	$p_{\mathrm{T}}^{\mathrm{track}} < 5$
$M_{\mathrm{T}}^{\mathrm{S}}$ [GeV]	–	< 50	–	–
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	[10, 60]	–	< 60	–
R_{ISR}	[0.8, 1.0]	–	$[\max(0.85, 0.98 - 0.02 \times m_{\ell\ell}),\ 1.0]$	–

ATLAS-SUSY-2018-16

Soft 2L

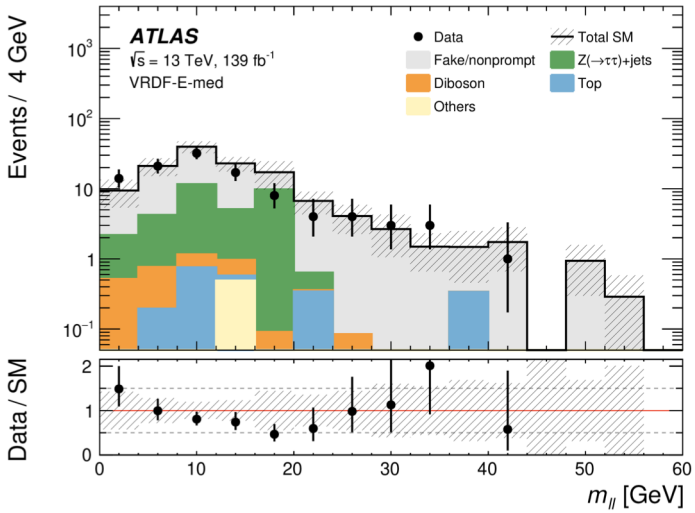
- VBF and Slepton SRs:

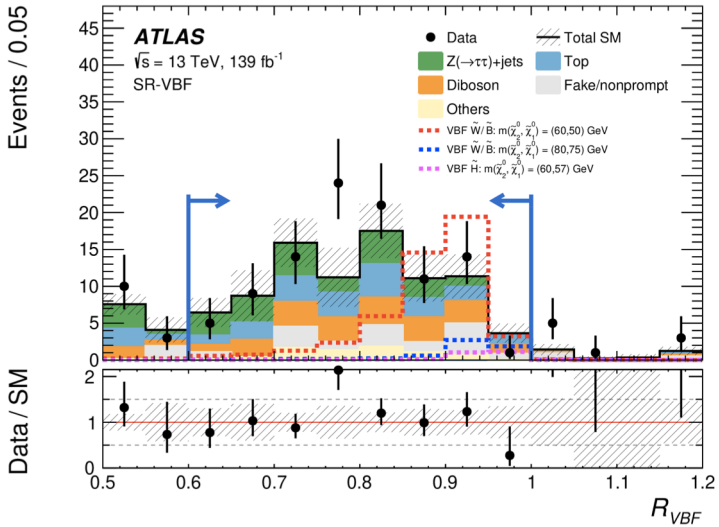
Variable	VBF SR Requirements
$m_{\ell\ell}$ [GeV]	< 40
Number of jets	≥ 2
$p_{\mathrm{T}}^{j_2}$ [GeV]	> 40
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	> 2
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$> \min(10, 2 + m_{\ell\ell}/3)$
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	< 60
R_{VBF}	$[\max(0.6, 0.92 - m_{\ell\ell}/60),\ 1.0]$
$\eta_{j_1} \cdot \eta_{j_2}$	< 0
m_{jj} [GeV]	> 400
$\Delta\eta_{jj}$	> 2

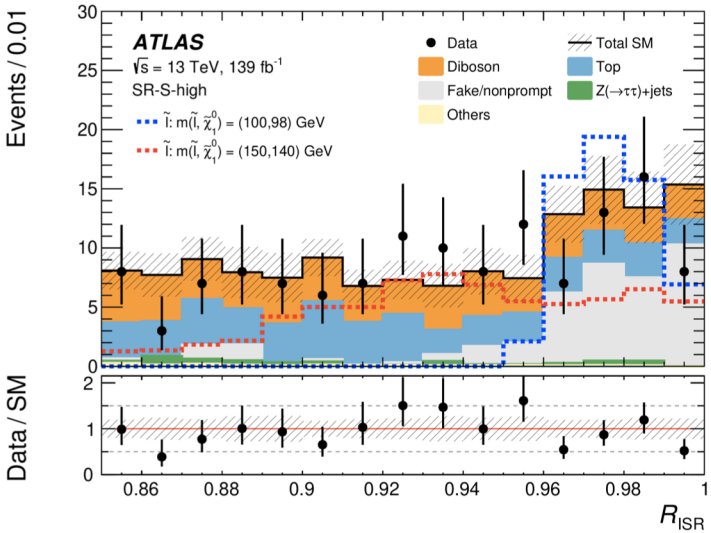
	Slepton SR Requirements	
Variable	SR–S–low	SR–S–high
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$[150, 200]$	> 200
m_{T2}^{100} [GeV]	< 140	< 140
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$> \min(15, 7.5 + 0.75 \times (m_{\mathrm{T2}} - 100))$	$> \min(20, 2.5 + 2.5 \times (m_{\mathrm{T2}} - 100))$
R_{ISR}	$[0.8,\ 1.0]$	$[\max(0.85, 0.98 - 0.02 \times (m_{\mathrm{T2}} - 100)),\ 1.0]$

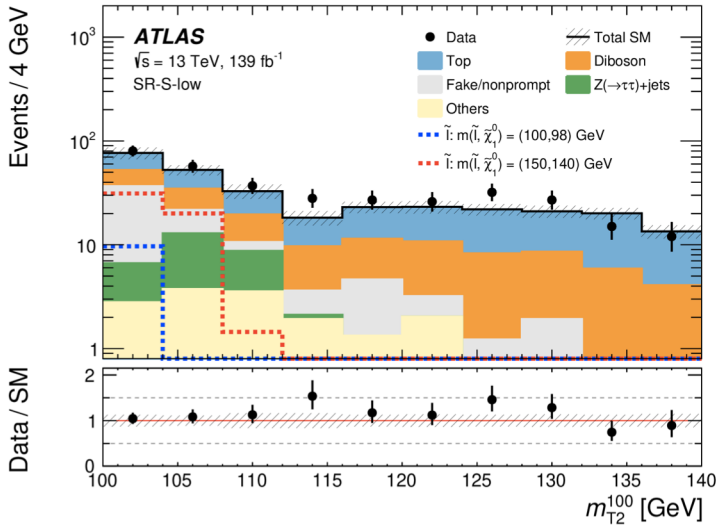
ATLAS-SUSY-2018-16

Soft 2L





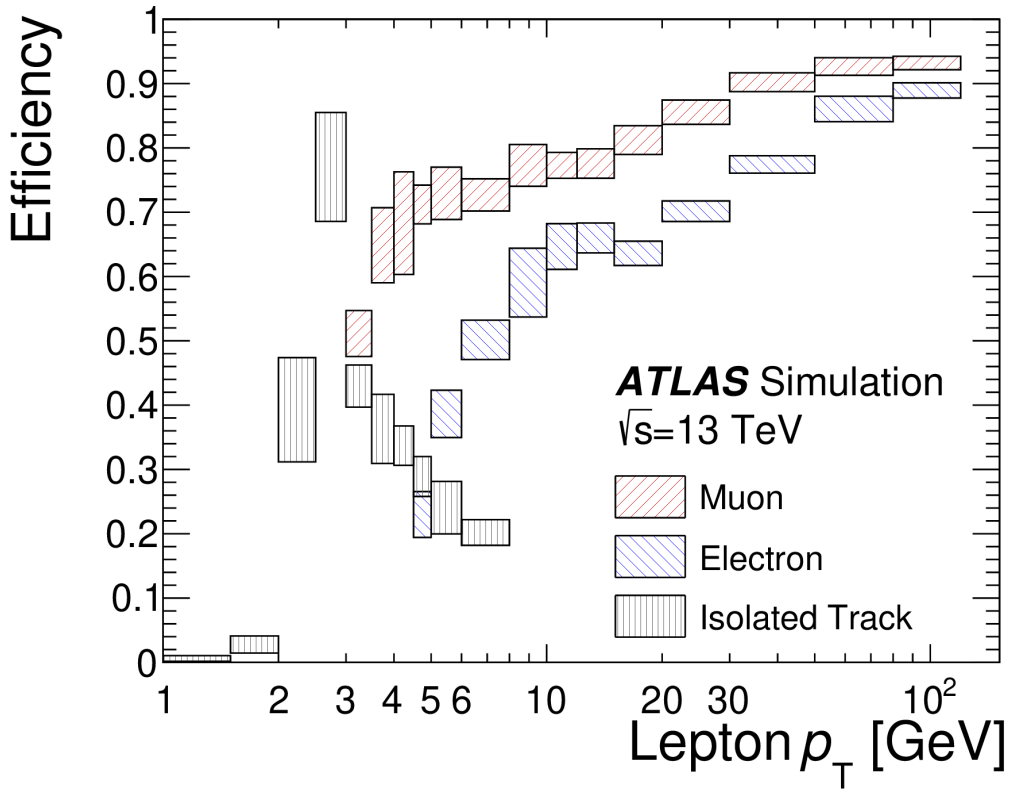




ATLAS-SUSY-2018-16

Soft 2L

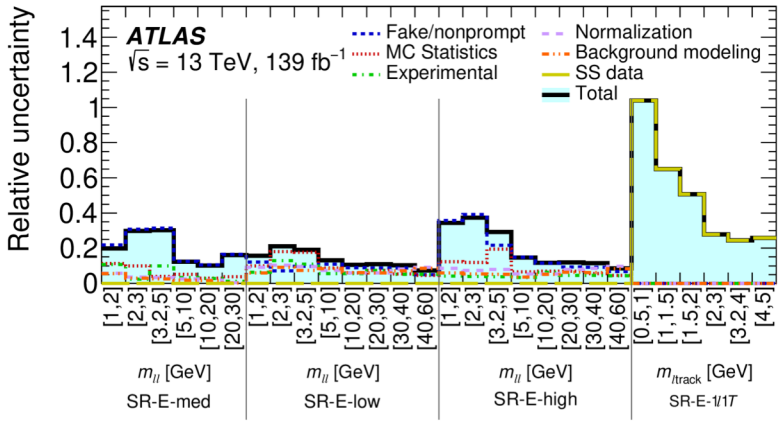
- Efficiencies:

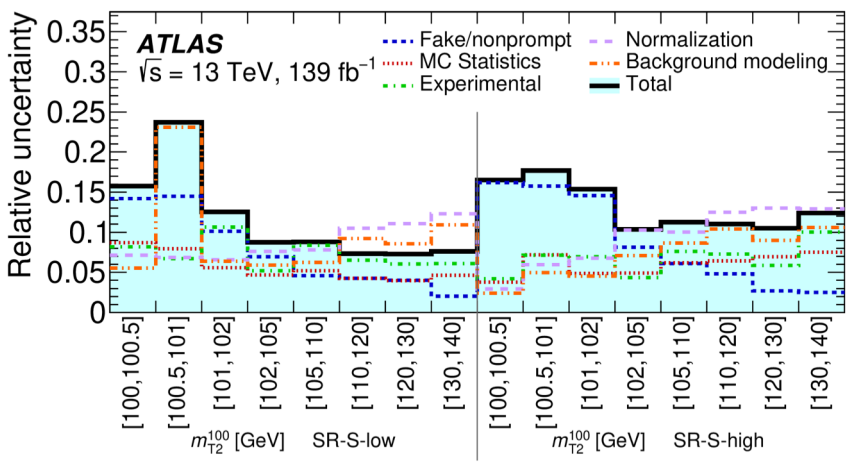


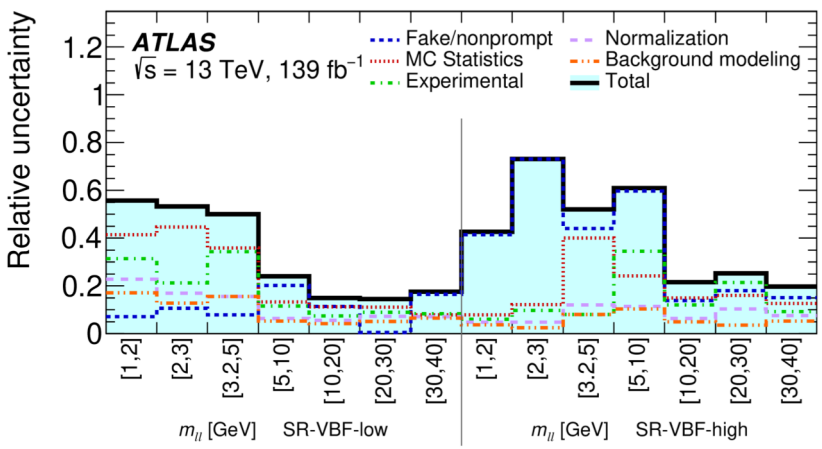
ATLAS-SUSY-2018-16

Soft 2L

- Uncertainties:







ATLAS-SUSY-2018-16

Soft 2L

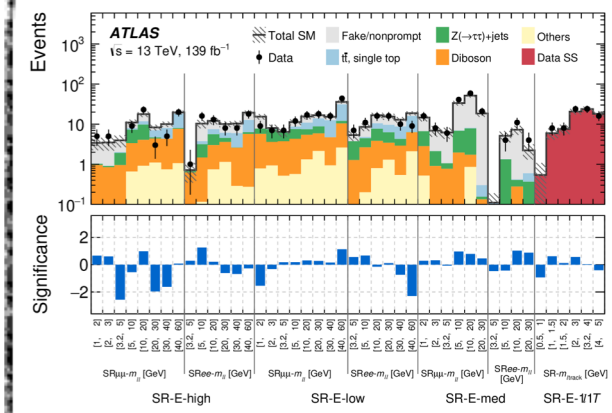
- Results:

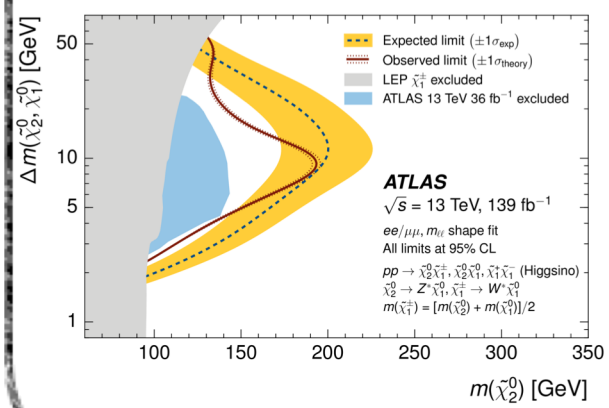
	Signal Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
SR–E	$m_{\ell\ell} < 1$	0	1.0 ± 1.0	0.022	3.0	$3.0^{+1.3}_{-0.0}$	0.50
	$m_{\ell\ell} < 2$	46	44 ± 6.8	0.15	21	19^{+7}_{-5}	0.38
	$m_{\ell\ell} < 3$	90	77 ± 12	0.29	41	31^{+11}_{-9}	0.18
	$m_{\ell\ell} < 5$	151	138 ± 18	0.38	52	43^{+16}_{-11}	0.24
	$m_{\ell\ell} < 10$	244	200 ± 19	0.62	86	49^{+26}_{-13}	0.034
	$m_{\ell\ell} < 20$	383	301 ± 23	0.95	132	61^{+22}_{-16}	0.0034
	$m_{\ell\ell} < 30$	453	366 ± 27	1.04	144	70^{+26}_{-20}	0.0065
	$m_{\ell\ell} < 40$	492	420 ± 30	0.96	134	74^{+29}_{-20}	0.027
	$m_{\ell\ell} < 60$	583	520 ± 35	0.97	135	84^{+32}_{-23}	0.063
SR–VBF	$m_{\ell\ell} < 2$	0	2.8 ± 1.6	0.022	3.0	$3.9^{+1.6}_{-0.9}$	0.50
	$m_{\ell\ell} < 3$	1	3.1 ± 1.7	0.030	3.6	$4.4^{+2.0}_{-1.0}$	0.50
	$m_{\ell\ell} < 5$	2	3.3 ± 1.7	0.035	4.8	$5.2^{+2.1}_{-1.1}$	0.50
	$m_{\ell\ell} < 10$	9	8.4 ± 2.7	0.068	9.5	$8.8^{+3.2}_{-2.2}$	0.43
	$m_{\ell\ell} < 20$	36	32 ± 5	0.14	20	16^{+6}_{-4}	0.27
	$m_{\ell\ell} < 30$	58	52 ± 7	0.19	26	21^{+8}_{-6}	0.28
	$m_{\ell\ell} < 40$	82	74 ± 10	0.24	33	27^{+10}_{-7}	0.27
SR–VBF–high	$m_{\ell\ell} < 2$	0	2.4 ± 1.1	0.022	3.0	$4.0^{+1.6}_{-0.9}$	0.50
	$m_{\ell\ell} < 3$	1	3.0 ± 1.4	0.025	3.5	$4.6^{+1.8}_{-1.2}$	0.50
	$m_{\ell\ell} < 5$	2	3.0 ± 1.4	0.034	4.7	$5.1^{+2.0}_{-1.3}$	0.50
	$m_{\ell\ell} < 10$	3	3.8 ± 1.7	0.041	5.6	$5.8^{+2.1}_{-1.3}$	0.50
	$m_{\ell\ell} < 20$	9	11.7 ± 2.8	0.055	8	$9^{+4}_{-2.3}$	0.50
	$m_{\ell\ell} < 30$	17	20 ± 5	0.079	11	$13^{+5}_{-3.2}$	0.50
	$m_{\ell\ell} < 40$	26	28 ± 6	0.10	14	15^{+6}_{-4}	0.50
SR–S	$m_{T2}^{100} < 100.5$	24	27 ± 4.8	0.09	13	14^{+5}_{-4}	0.50
	$m_{T2}^{100} < 101$	41	46 ± 6.5	0.11	16	18^{+7}_{-5}	0.50
	$m_{T2}^{100} < 102$	91	82 ± 10	0.25	35	28^{+10}_{-8}	0.25
	$m_{T2}^{100} < 105$	158	158 ± 17	0.30	41	41^{+16}_{-11}	0.50
	$m_{T2}^{100} < 110$	243	242 ± 21	0.38	52	52^{+19}_{-14}	0.36
	$m_{T2}^{100} < 120$	328	312 ± 24	0.51	71	60^{+22}_{-17}	0.26
	$m_{T2}^{100} < 130$	419	388 ± 28	0.66	92	68^{+27}_{-18}	0.17
	$m_{T2}^{100} < 140$	472	443 ± 31	0.69	95	74^{+28}_{-21}	0.19

ATLAS-SUSY-2018-16

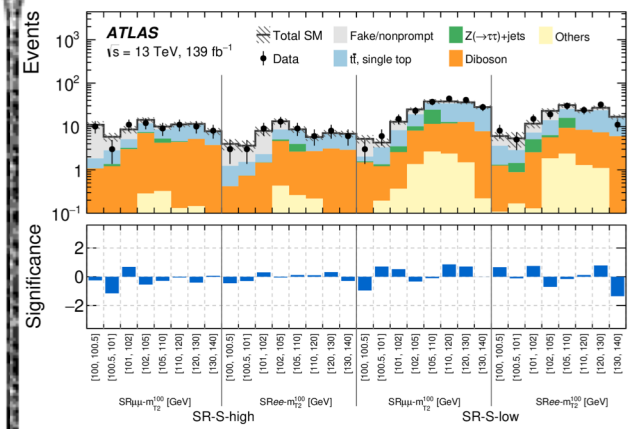
Soft 2L

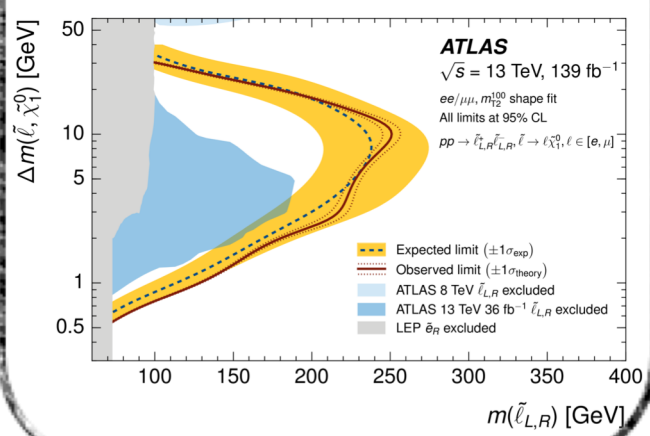
SR-E



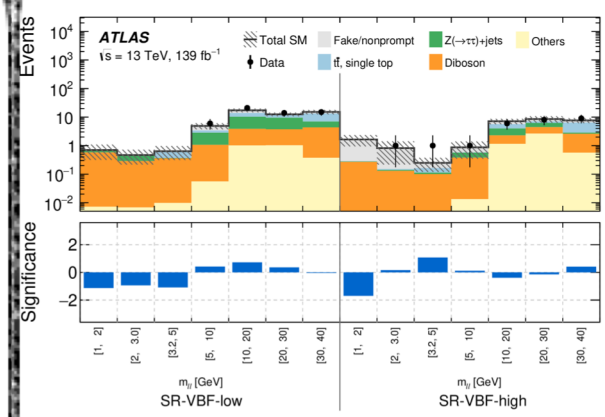


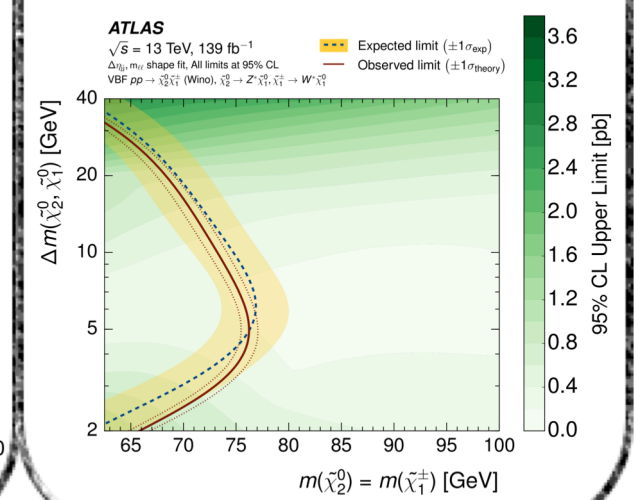
SR-S





SR-VBF

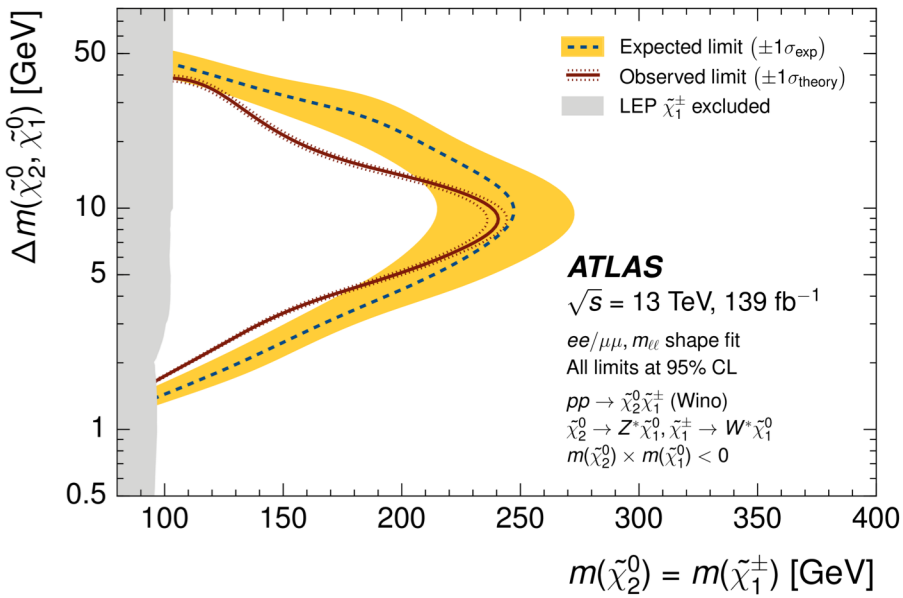


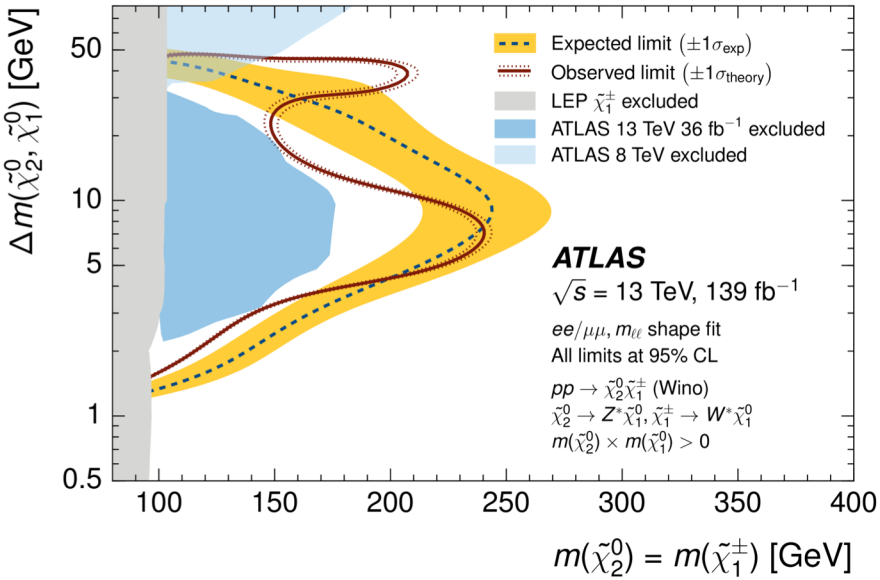


ATLAS-SUSY-2018-16

Soft 2L

- Limits on EWKino:

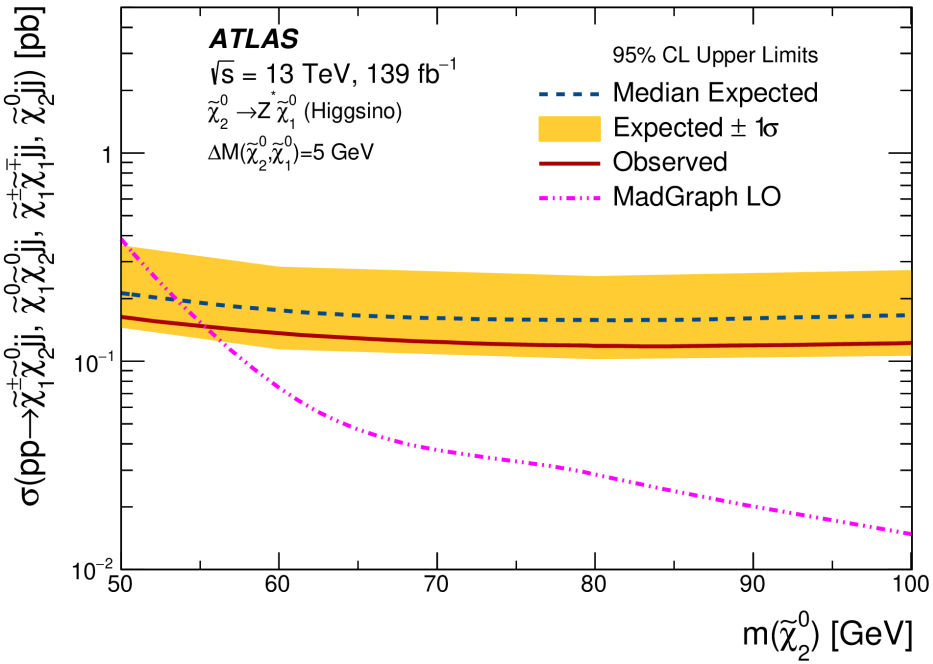




ATLAS-SUSY-2018-16

Soft 2L

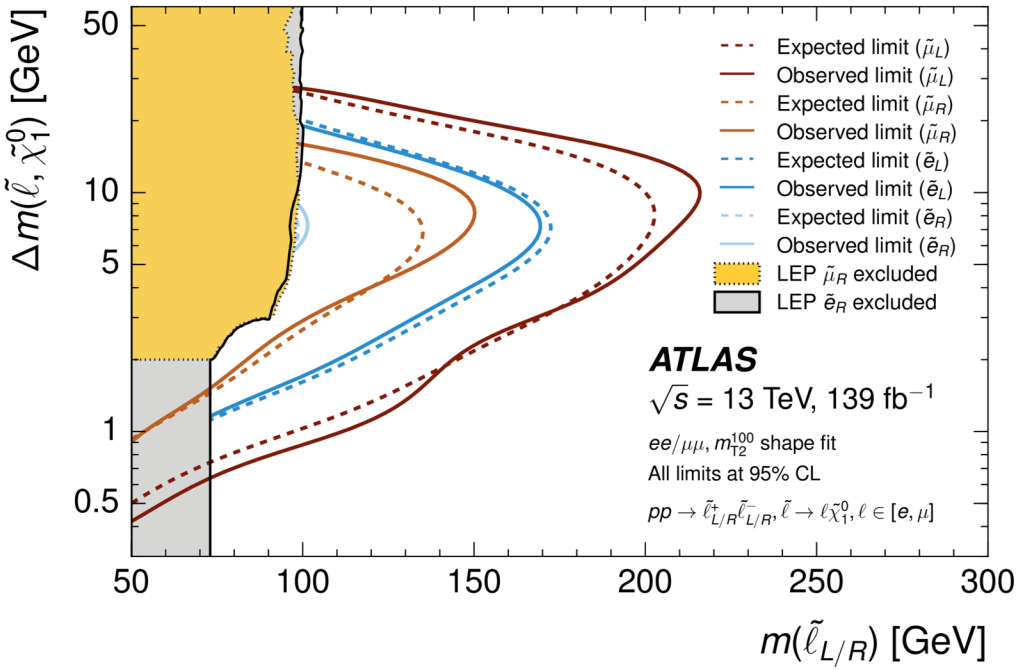
- Limits on VBF:



ATLAS-SUSY-2018-16

Soft 2L

- Limits on sleptons (no mass degeneracy assumed):

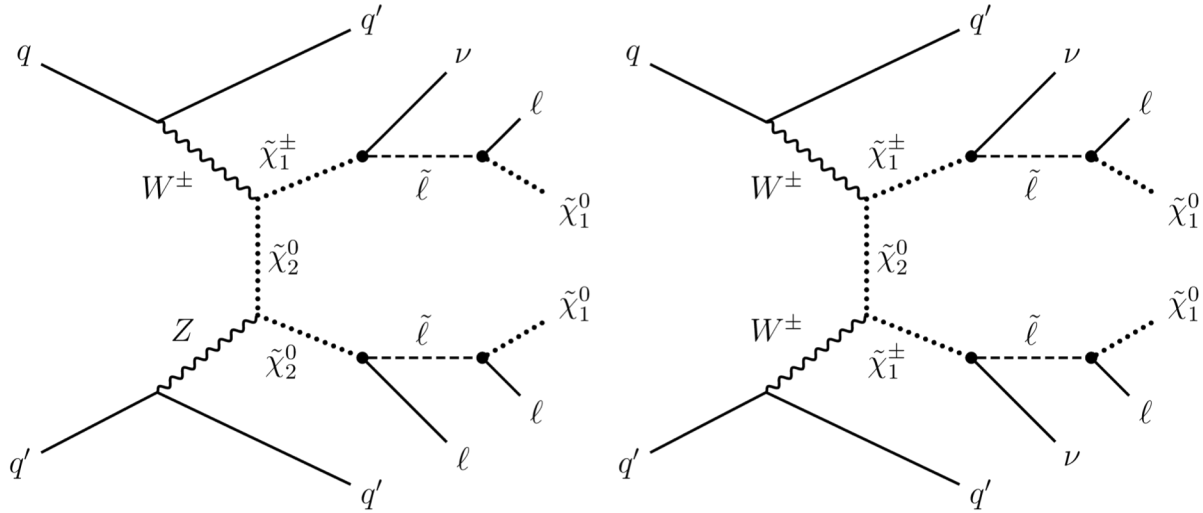


Compressed VBF

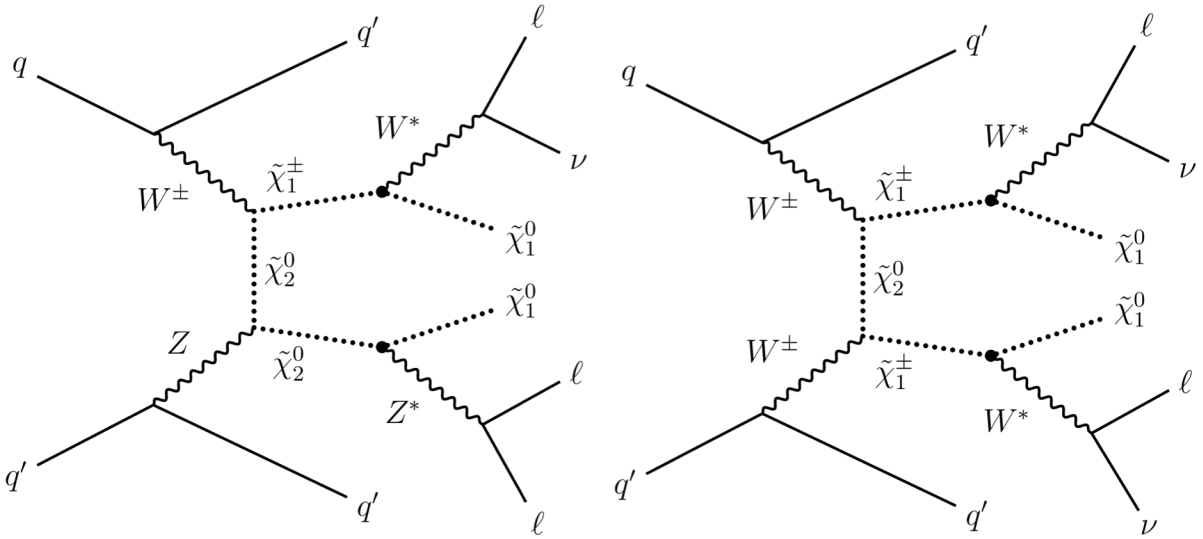
CMS-SUS-17-007

- Models:

Light slepton models

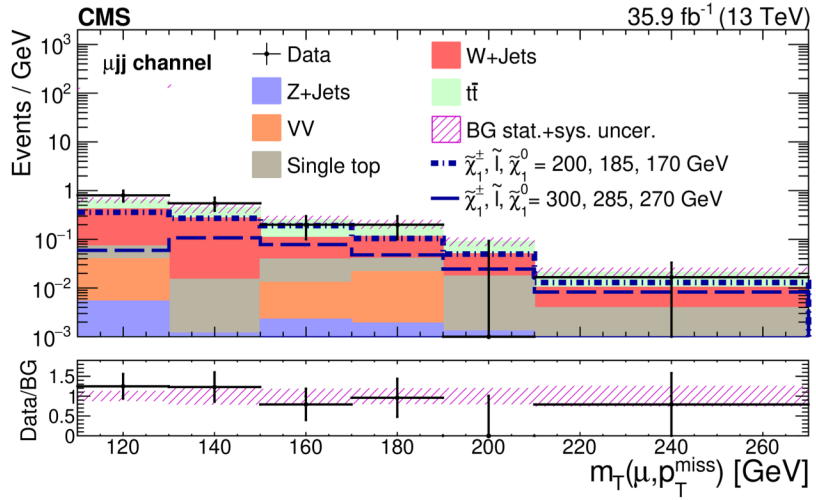


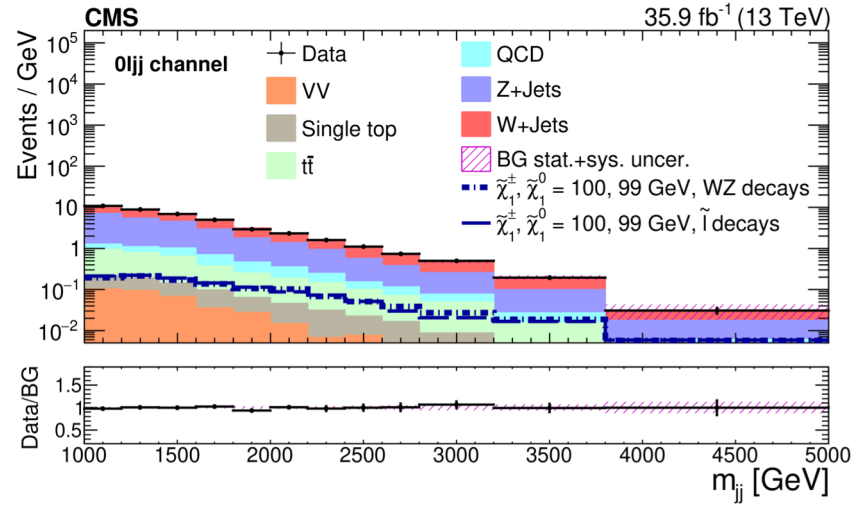
Off-shell W*/Z*

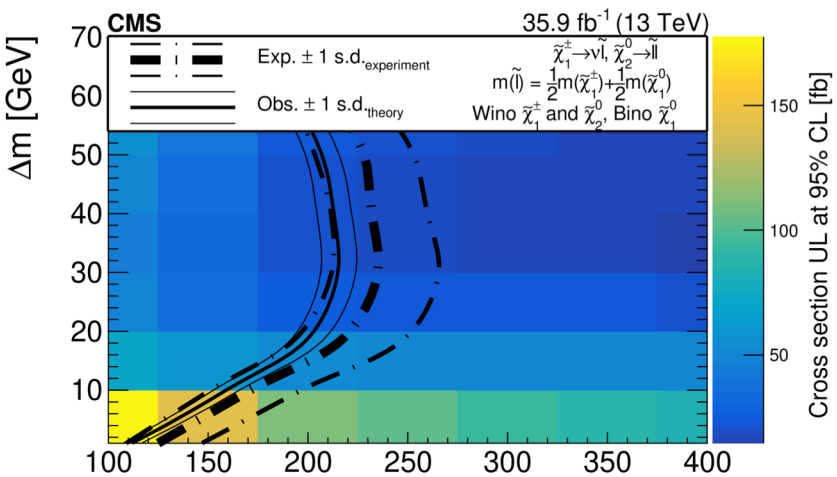


Compressed VBF

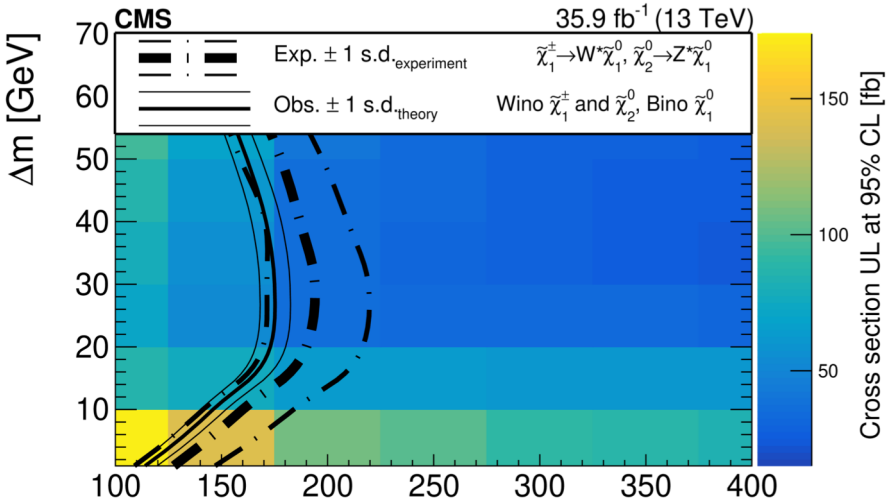
CMS-SUS-17-007







Light slepton model

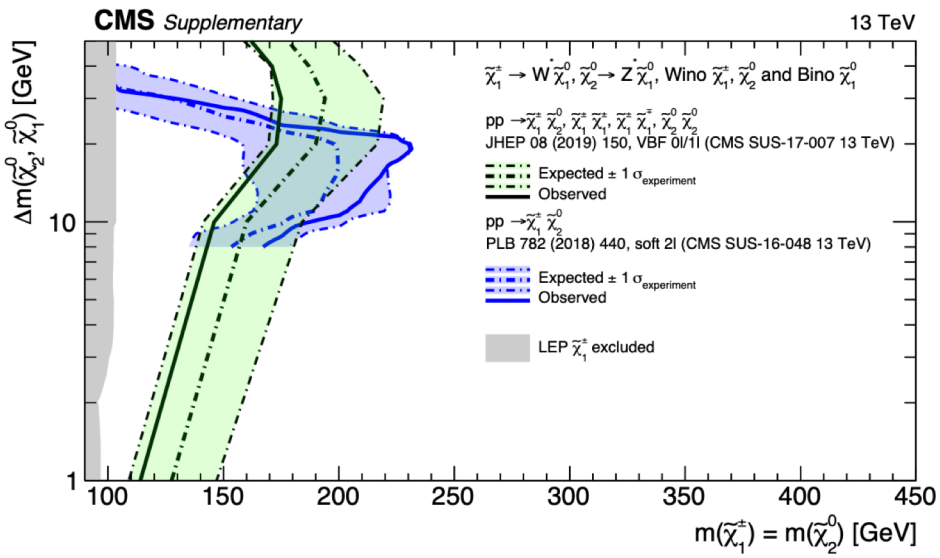


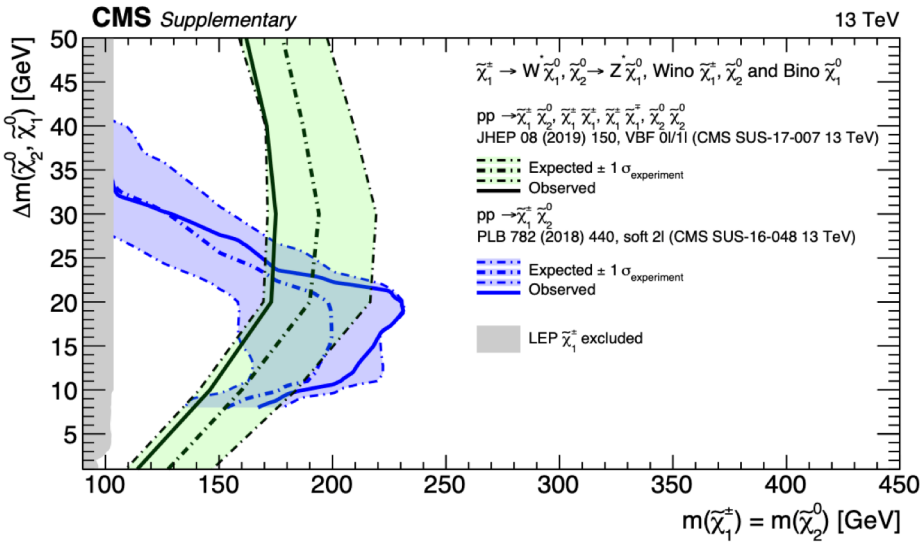
Off-shell W*/Z*

Compressed VBF

CMS-SUS-17-007

- Comparison to **SOS** (**CMS-SUS-16-048**):
  - Competitive also for EWK models





Compressed VBF

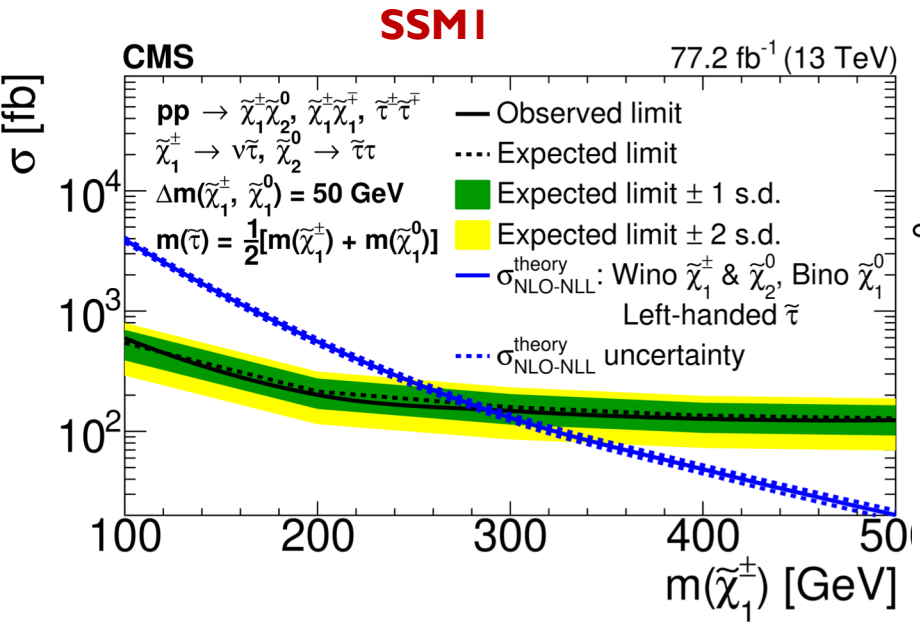
CMS-SUS-17-007

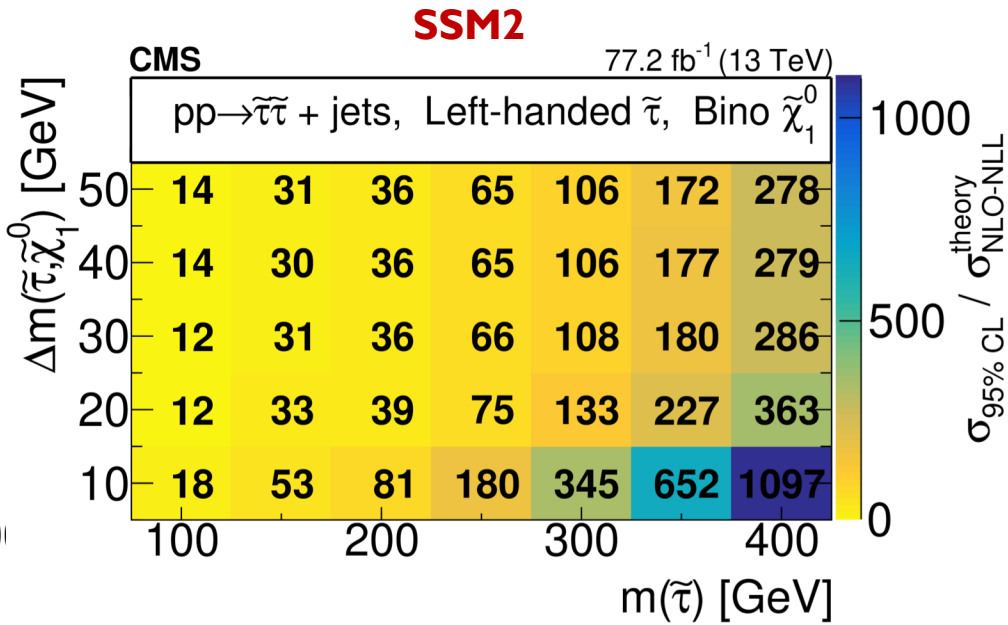
Process	μjj	ejj	$\tau_h$jj	0ℓjj
DY+jets	0.20 ± 0.07	0.10 ± 0.04	0.10 ± 0.04	3714 ± 760
W+jets	13 ± 3	6 ± 1	7 ± 2	2999 ± 620
VV	1.7 ± 0.7	1.5 ± 0.6	0.9 ± 0.9	77 ± 18
$t\bar{t}$	13 ± 4	11 ± 4	5 ± 3	577 ± 128
Single top quark	2.2 ± 0.9	0.2 ± 0.1	0.6 ± 0.3	104 ± 10
QCD	$0^{+0.2}_{-0}$	$0^{+1.2}_{-0}$	23 ± 5	546 ± 69
Total BG	31 ± 5	19 ± 5	37 ± 6	8017 ± 992
Data	36	29	38	8408

Soft Tau

CMS-SUS-19-002

- Limits set on two models:
  - **SSM1**: sum of chargino-neutralino production with stau production
  - **SSM2**: direct production of left-handed stau pairs



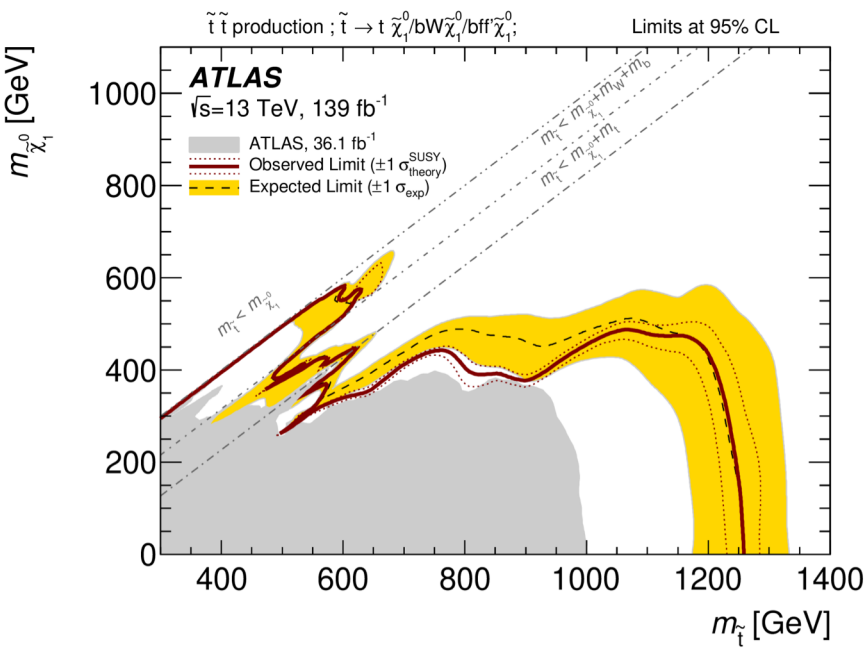


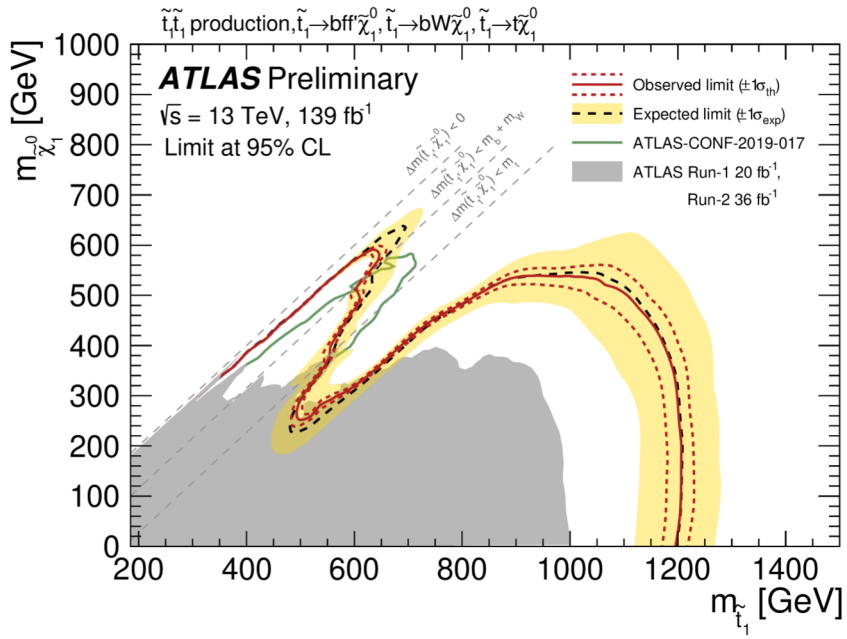
- **SSM1**: First limits to surpass LEP bound of 103.5 GeV for $m(\chi_1^{\pm})$ in compressed scenarios
- **SSM2**: 4x improvement wrt. previous non-ISR searches

Stop 0L + 1L

ATLAS-SUSY-2018-12
ATLAS-CONF-2020-003

- Analysis strategy and non-compressed scenarios covered in Mark's 3G Talk
  - Compressed: require an ISR is used to improve sensitivity to the targeted decays
  - Take advantage of new, dedicated soft b-tagging techniques to target the compressed states (ATLAS-CONF-2019-027): track-jet b-tagging





CMS-SUS-19-009

Stop 1L

Compressed spectra with $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim m_t$		
Label I	Selection criteria	$N_j \geq 5$, leading-p_T jet not b-tagged, $N_{b,\,med} \geq 1$, $p_T^\ell < \max\,(50,\ 250 - 100 \times \Delta\phi(\vec{p}_T^{\,miss}, \vec{p}_T^{\,\ell}))$ GeV,
	p_T^{miss} bins [GeV]	[250, 350, 450, 550, 750, $+\infty$]
Compressed spectra with $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim m_W$		
Label J	Selection criteria	$N_j \geq 3$, leading-p_T jet not b-tagged, $N_{b,\,soft} \geq 1$, $p_T^\ell < \max\,(50,\ 250 - 100 \times \Delta\phi(\vec{p}_T^{\,miss}, \vec{p}_T^{\,\ell}))$ GeV,
	p_T^{miss} bins [GeV]	[250, 350, 450, 550, 750, $+\infty$]

Label	N_j	$N_{b,\,med}$	$N_{b,\,soft}$	p_T^{miss} [GeV]	Lost lepton	1ℓ (not from t)	1ℓ (from t)	$Z \to \nu\bar{\nu}$	Total expected	Total observed
				250–350	403 ± 40	21 ± 8	71 ± 71	17 ± 4	511 ± 81	513
				350–450	108 ± 15	6.8 ± 2.5	12 ± 12	7.8 ± 1.6	134 ± 19	140
I	≥ 5	≥ 1	≥ 0	450–550	31 ± 8	2.5 ± 1.0	2.0 ± 2.0	2.9 ± 0.8	39 ± 8	37
				550–750	11 ± 5	1.4 ± 0.6	0.27 ± 0.27	1.8 ± 0.5	14 ± 5	10
				750–$+\infty$	1.8 ± 1.1	$1.9^{+2.5}_{-1.9}$	0.16 ± 0.16	0.28 ± 0.10	4.1 ± 2.5	6
				250–350	201 ± 21	37 ± 7	27 ± 27	10.4 ± 1.5	276 ± 35	268
				350–450	38 ± 7	11.6 ± 2.2	3.4 ± 3.4	4.3 ± 0.9	58 ± 8	60
J	≥ 3	≥ 0	≥ 1	450–550	11.5 ± 3.5	3.3 ± 0.6	0.7 ± 0.7	1.7 ± 0.6	17 ± 4	16
				550–750	3.5 ± 2.3	2.1 ± 0.5	—	1.1 ± 0.8	6.6 ± 2.5	6
				750–$+\infty$	0.4 ± 0.4	0.44 ± 0.16	0.02 ± 0.02	0.2 ± 0.4	1.0 ± 0.6	4

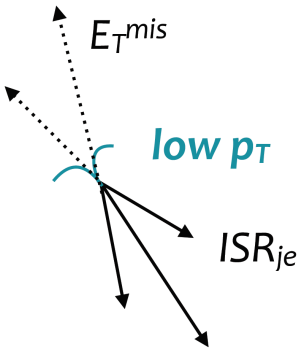
Compressed Analyses

Will take look at three examples of compressed analyses in more detail:

1. Fully-hadronic: (CMS-SUS-16-049)
2. Soft single-lepton (CMS-SUS-17-005)
3. Soft opposite-sign dileptons SOS (CMS-SUS-16-048):

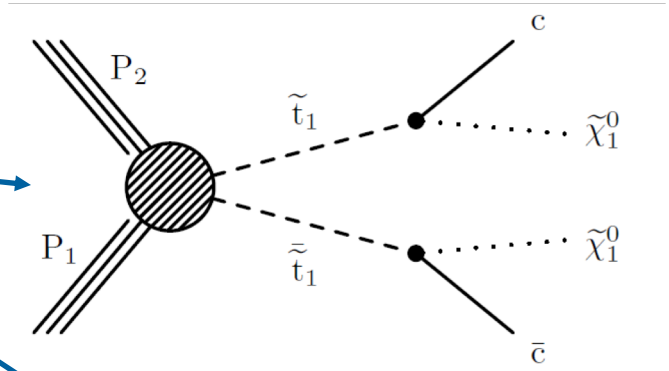
Common aspects of these searches:

- Moderate **MET** (incl. triggers): dominant QCD-multijet events in p-p colliders significantly reduced (as with the majority of SUSY searches)
- Presence of **ISR**:
  - Decay products typically aligned with boost direction of LSP
  - high hadronic energy $\mathbf{H_T}$
- Backgrounds:
  - **W+jets** and **tt-bar** dominate:
    - Suppressed/isolated using **transverse mass $\mathbf{M_T(l, MET)}$** [or M_T(b, MET) for fully-hadronic (if there are any b-tagged jets)]
    - Estimation: Data/simulation scale factors dedicated sideband **Control Regions** (**CRs**) and extrapolating to the **Signal Regions** (**SRs**) using MC

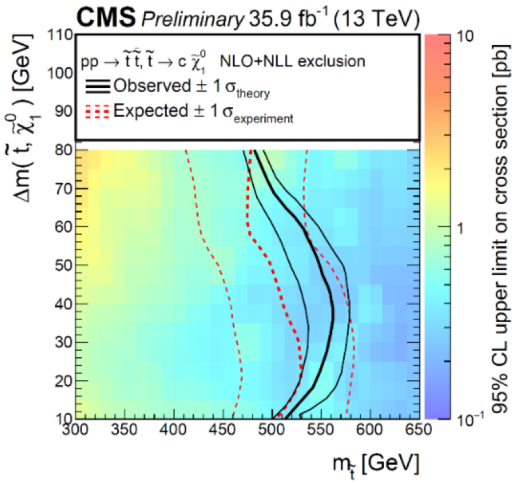


Fully-Hadronic

- Search for direct **stop pair-production** in events with **jets** and large MET
- More 'inclusive' search: target both un-compressed and compressed models:
  - T2tt-4bd: Four-body decay
  - T2bW: Chargino-mediated
  - T2cc: Flavour-violating: (FCNC)



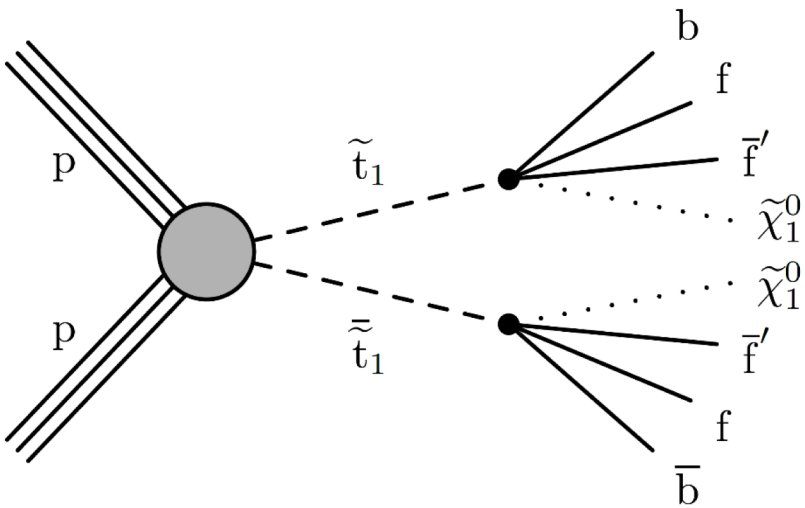
- Additional baseline selection:
  - **Lepton veto** reducing leptonic tt-bar and W+jets events
  - Minimum 2 jets
  - Veto top or W objects (using special tagging methods)
  - Low m_T(b, MET), if there are any b-tagged jets

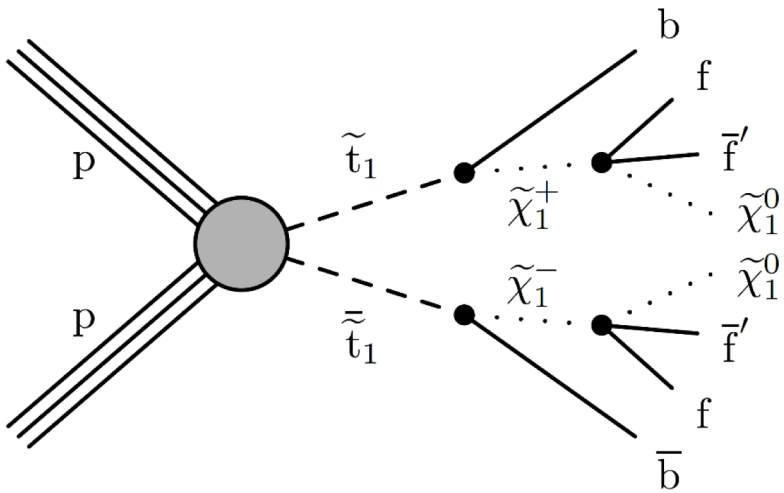


- Main backgrounds: **tt-bar** and **W+Jets**
  - decaying <u>leptonically</u> where lepton is lost
    = **'lost lepton' (LL) background**

Interpretations

- Signal models for stop pair-production followed by decays:





T2tt-4bd: **four-body** stop decay via t*/W*

T2bW: **chargino-mediated** stop decay via W*

- chargino mass halfway in between stop and LSP
- Provides solution for small width issue (long lifetime) for very small Δm

Fully-Hadronic

- Background estimations:
  - Lost lepton (LL) from single-lepton control samples (TF = 0l/1l)
  - Z(→νν)+jets decays (to neutrinos) estimated from decays to dilepton pairs Z→ll
  - QCD (< 10%) estimated from data control sample

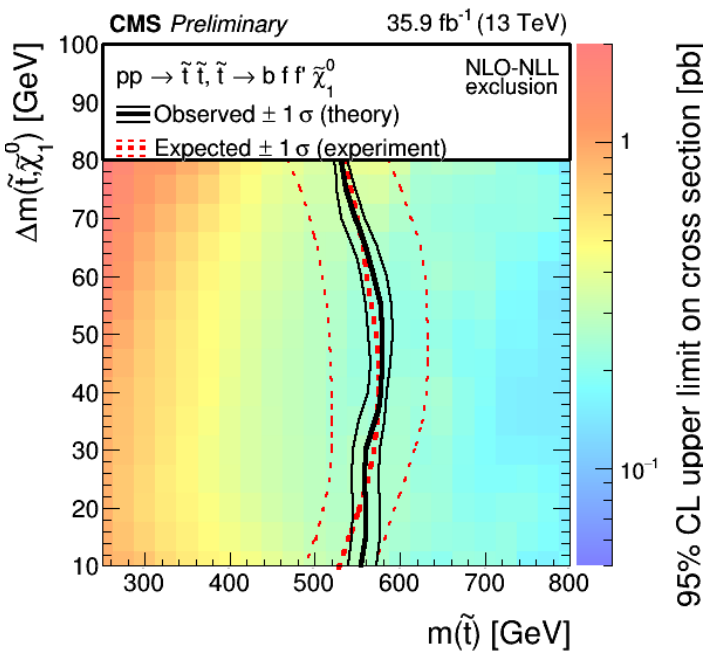
- SRs defined using: Njets, Nbjets, N_{SV}, p_T(ISR), MET

- **ISR-tagging**:
  - 'fat' definition for jets (large cone size R = 0.8)
    - to catch ISR gluon undergoing large splitting
  - fail 'Loose' b-tag working point

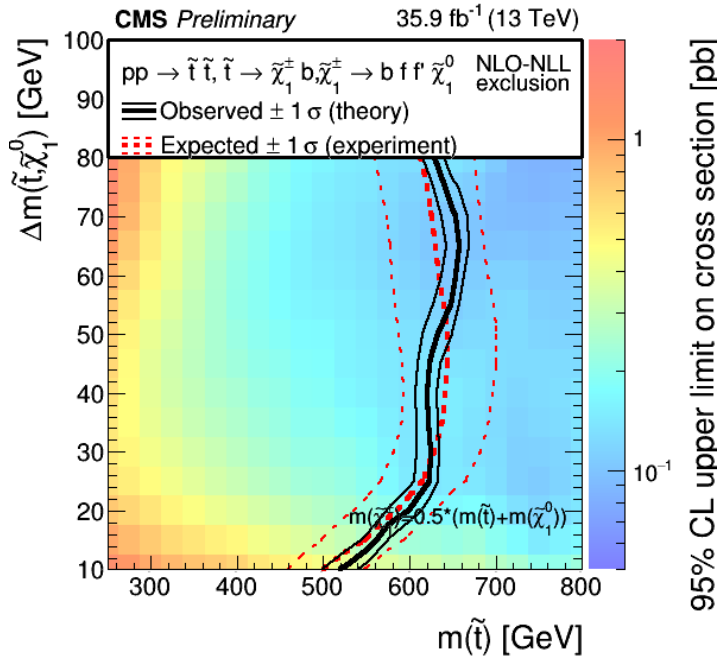
- **Soft b-tagging** via reconstructing secondary vertices (SVs) not associated to a jet [using the IVF (inclusive vertex finder) algorithm]

Fully-Hadronic Limits

- Results of the analysis targeting the fully-hadronic models:



T2tt-4bd: **four-body** stop decay via t*/W*



T2bW: **chargino-mediated** stop decay via W*

Soft Single Lepton

- Search for direct **stop pair-production** in events with at least one **soft lepton**, low jet multiplicity and moderate MET
- Compressed models:
  - T2tt-4bd: Four-body decay
  - T2bW: Chargino-mediated
- Two sets of SRs, defined by lepton p_T < 30 GeV:
  - SR1 (very low Δm): veto b-jets
  - SR2 (higher Δm): allow soft b-jet (< 60 GeV)
- SRs binned in lepton p_T, transverse mass m_T and simultaneous selection on MET and H_T (or p_T(ISR)) ≡ C_T

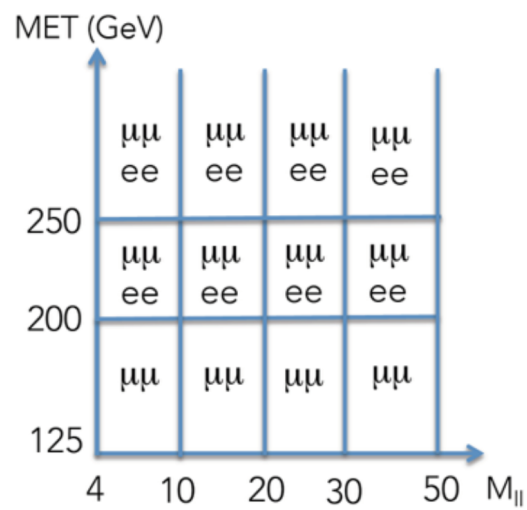
Preselection:

- MET > 200 GeV
- H_T > 300 GeV
- ISR-jet p_T > 100 GeV
- At least one lepton and 2nd lep. veto (p_T > 20 GeV)
- Tau veto
- 3rd hard jet veto } anti-QCD
- $\Delta\phi_{(j1,j2)}$ < 2.5 rad. } anti-QCD

- Main prompt backgrounds (**tt-bar** and **W+Jets**): data/MC scaling is extrapolated from a high p_T (> 30 GeV) CRs to the low p_T SRs
- Nonprompt backgrounds (QCD, Z(→νν)+jets) estimated using TL 'Fake-Rate' method

Soft Dileptons SOS

- Search for **two low momentum opposite-sign (OS) leptons** and moderate MET
- Requirement of 2 leptons ⇒ cleaner vs hadronic (QCD multijet, Z(→νν)+jets)
- Additional baseline selection:
  - 2 OS leptons (same or different flavour)
  - Moderate MET
  - At least 1 jet
  - B-tagged jets rejected → reduces tt-bar
- Main backgrounds:
  - W+jets + nonprompt lepton
  - Fully leptonic tt-bar decays
  - Drell-Yan and VV
- SRs binned in terms of dilepton invariant mass M(ll) and MET

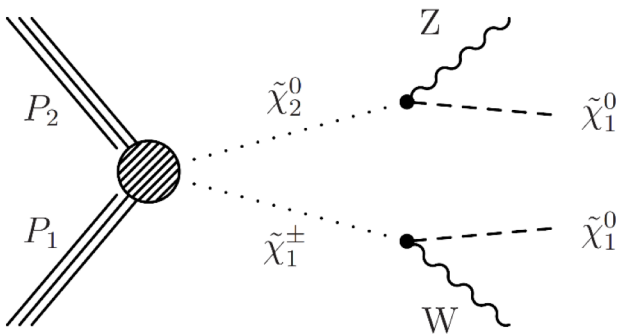


Soft Dileptons SOS

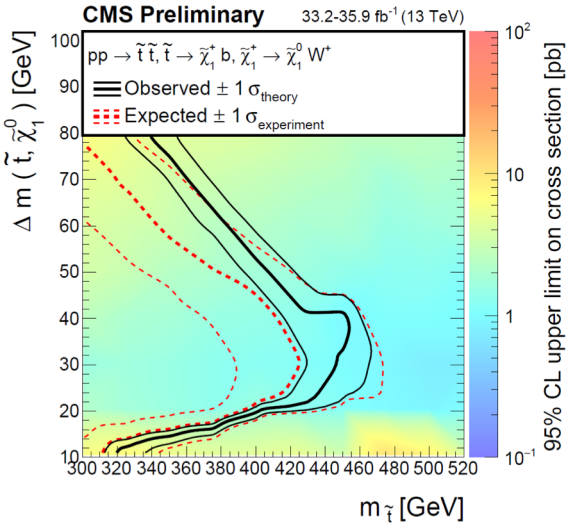
Variable	SR selection criteria
N_ℓ	2 ($\mu\mu$, μe, ee)
$q(\ell_1)q(\ell_2)$	-1
$p_T(\ell_1)$, $p_T(\ell_2)$	[5, 30] GeV
$p_T(\mu_2)$ for high-p_T^{miss} $\tilde{\tau}$-like SR	[3.5, 30] GeV
$\lvert\eta_\mu\rvert$	<2.4
$\lvert\eta_e\rvert$	<2.5
IP_{3D}	<0.01 cm
SIP_{3D}	<2
$Iso_{rel}(\ell_{1,2})$	<0.5
$Iso_{abs}(\ell_{1,2})$	<5 GeV
p_T(jet)	>25 GeV
$\lvert\eta\rvert$(jet)	<2.4
N_b (p_T >25 GeV, CSV)	0
$M(\ell\ell)$	[4, 9] or [10.5, 50] GeV (for $\mu\mu$ and ee)
$p_T(\ell\ell)$	>3 GeV
p_T^{miss}	>125 GeV (for $\mu\mu$)
	>200 GeV (for μe, ee)
p_T^{miss} (muon corrected)	>125 GeV (for $\mu\mu$)
	>200 GeV (for μe, ee)
p_T^{miss}/H_T	[0.6, 1.4]
H_T	>100 GeV
$M(\tau\tau)$	veto [0, 160] GeV
$M_T(\ell_i, p_T^{miss})$, $i = 1, 2$	<70 GeV (electroweakino selection only)

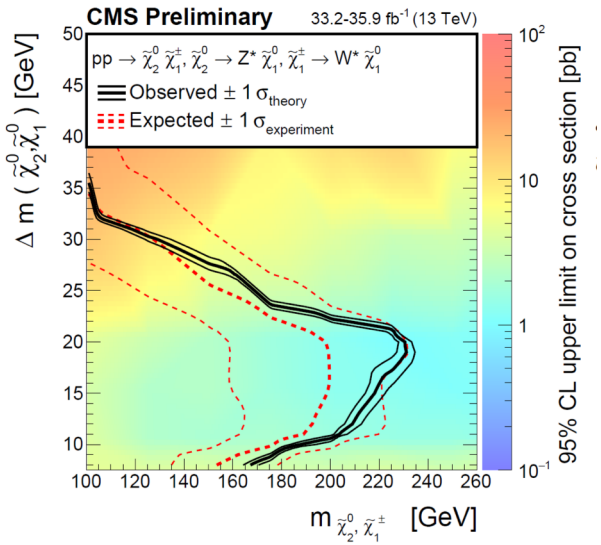
Soft Dileptons SOS

- Background estimations:
  - Prompt: CR enriched in tt, DY and VV
  - Nonprompt: TL 'Fake-Rate' Method
- Compressed models:
  - T2bW: Chargino-mediated decay
  - **TChiWZ (EWK):** pair-production of neutralinos and charginos (compressed higgsino spectrum):
    - decays via virtual Z* and W*



- EWK limits update LEP results





Compressed Analyses

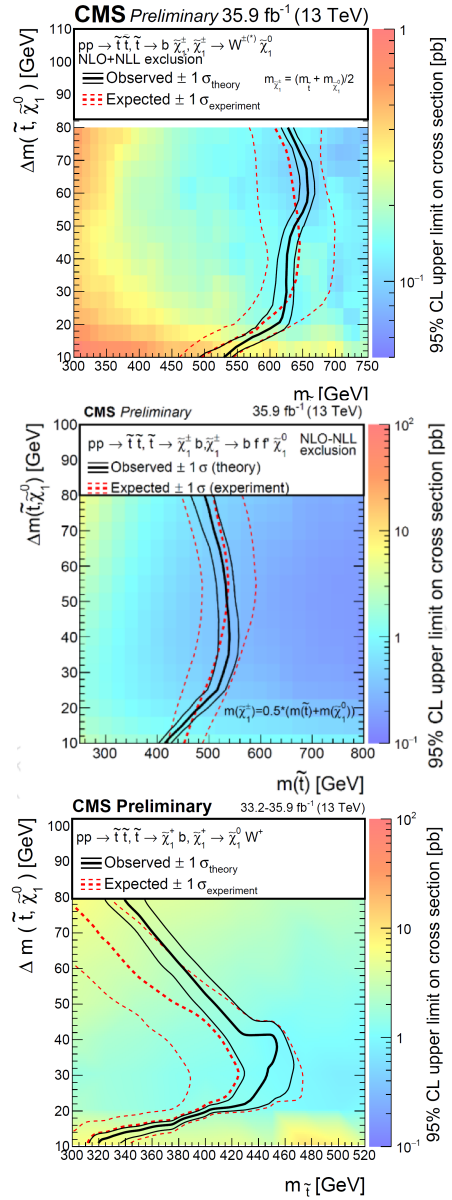
Summary of interpretations of compressed SUSY signals:

1. **Fully-hadronic**: (SUS-16-049) compressed models:
   - T2tt-4bd: Four-body decays
   - T2bW: Chargino-mediated decays
   - T2cc: 2-body decay (FCNC)

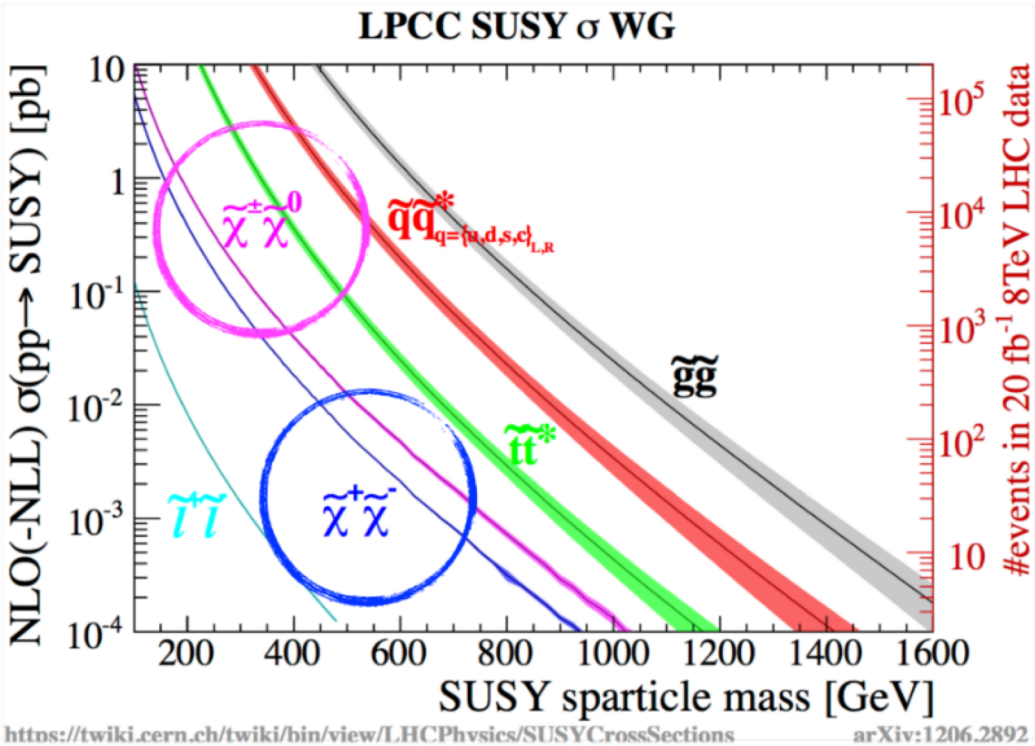
2. **Single-lepton (SUS-17-005):**
   - T2tt-4bd: Four-body decays
   - T2bW: Chargino-mediated decays

3. **Soft dileptons** SOS (SUS-16-048):
   - T2bW: Chargino-mediated decays
   - TChiWZ (**EWK**): pair-production of neutralinos and charginos

T2bW: Chargino-mediated decays



EWK Cross-Sections



Higgsino pMSSM

- Higgsino pMSSM model:

pMSSM:

- μ = higgsino mass parameter
- M_1 = bino mass parameter
- M_2 = wino mass parameter
- M_3 = gluino mass parameter

- Grid: μ and M_1 ($M_2 = 2M_1$ for gaugino unification at GUT scale; M_3 decoupled)

QG Likelihood

- Motivation: many analyses have signal with jets originating from quarks and backgrounds with gluon-enriched jets
  - In our case, we would like to reduce the W background

- Variables to distinguish between jets originating from quarks vs gluons:
  - Quark-gluon likelihood discriminant **qgl** = probability of the jet to originate from a quark parton (1 for light-quark jets and at 0 for gluon jets)
  - Jet energy sharing variable: **ptD** (0 for ∞ particles and 1 for 1 particle in jets)
  - Angular spread measured by minor axis σ_2 in the η-ϕ plane: **axis2**
  - Multiplicity: total number of PF candidates reconstructed within jet

- Links:
  - CADI: http://cms.cern.ch/iCMS/analysisadmin/cadilines?line=JME-13-002
  - 2016: http://cds.cern.ch/record/2234117/files/DP2016_070.pdf

Recoil and Jigsaw

- Motivation: we rely strongly on the recoil of the decay products vs ISR:
  - Visible decay products + MET boosted
- Since ISR ~ opposite MET one can define the recoil of the system wrt. ISR in terms of MET: Recoil ≡ MET/ISR jet p_T
- Other proxies:
  - Recoil = MET/leading jet p_T
  - Recoil = MET/sqrt(H_T)
  - Recoil = MET/Wp_T (where Wp_T = lep. p_T + MET summed vectorially)
- Jigsaw uses an estimator for this quantity:
  - $R_{ISR} = |p_I \cdot \hat{p}_{ISR}|/|p_{ISR}|$ (I associated with MET)
  - Reference frame dependent quantities
  - Talk at EPS by P. Jackson
  - Paper 2 and Paper 1