# Higgsinos

& sleptons: opening the soft lepton frontier at the LHC

IOP APP & HEPP Conference
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University of Oxford

*Where is the new physics hiding?*

What opportunities remain under the search lamppost?

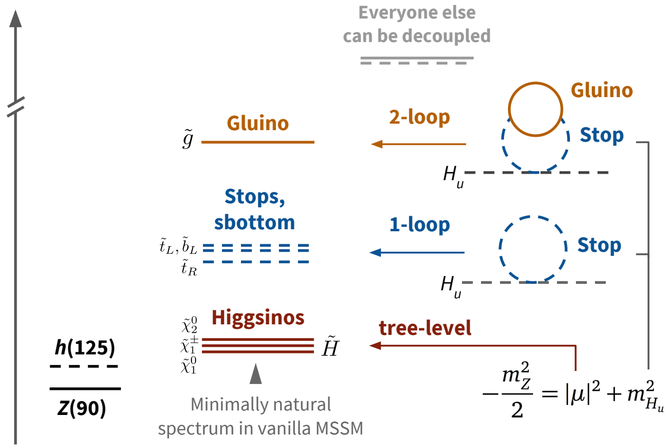
*Case study: hunting Higgsinos*

Why are MSSM compressed scenarios so challenging?

*Surpassing two-decade old LEP limits*

How do we detect Higgsino dark matter at hadron colliders?

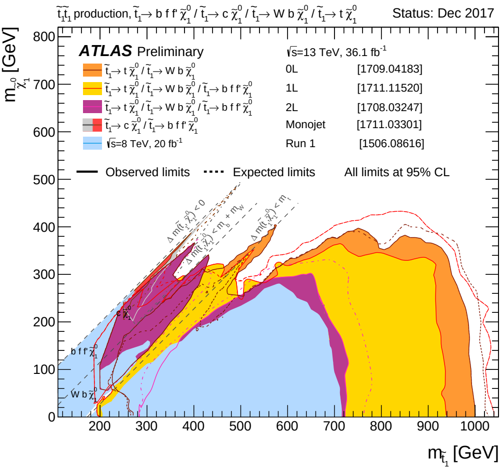
# Naturalness motivates light gluinos, stops, Higgsinos




Adapted from Papucci et al [arXiv:1110.6926]

**Light gluino searches: spectacular jets + MET signatures** — see Mike's talk

# Stop sensitivity approaching 1 TeV

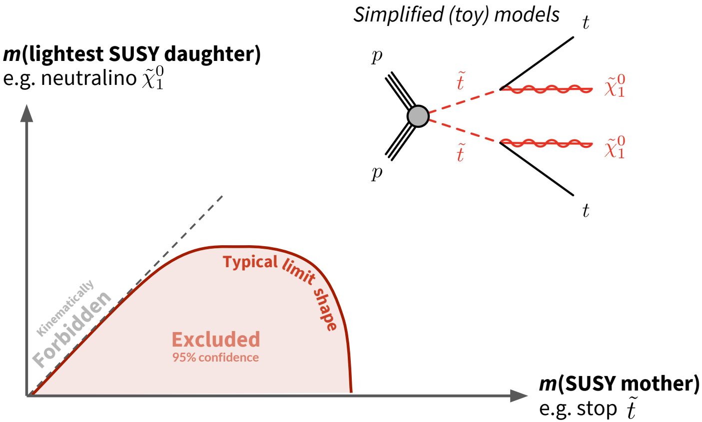



Electroweak naturalness motivates stop $\tilde{t}$ near weak scale

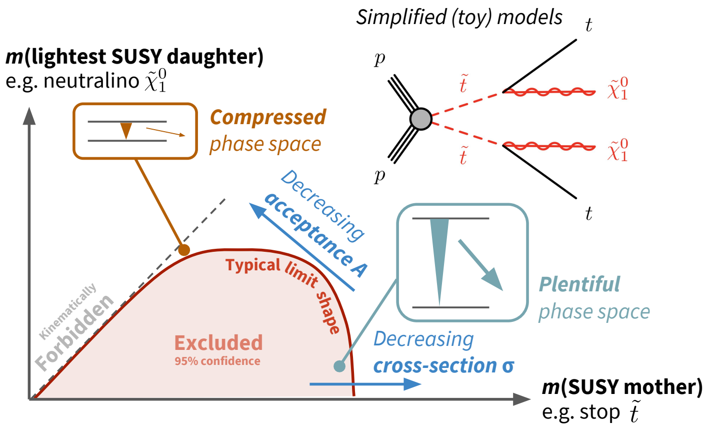
**Dedicated efforts in Run 2 searches closing gaps left after Run 1**

From ATLAS SUSY summary plots

# How to read typical SUSY simplified model exclusion plots



# How to read typical SUSY simplified model exclusion plots



# THE SEARCHLIGHT IS SHIFTING
## from spectacular to subtle discoveries


*Opportunities & challenges for*
***soft, rare, quirky signals***

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**Soft stuff**
*Particle identification*
*Trigger thresholds*

**Rare SUSY**
*Colourless sparticles*
*Dark sector*

**Quirky creatures**
*Displaced difficulties*
*Long-lived exotica*

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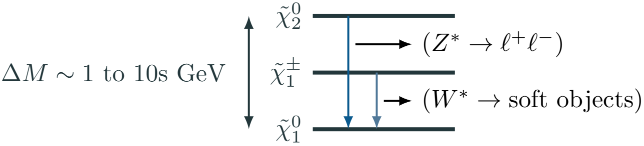
**Case study**
***Higgsino***

# HUNTING HIGGSINOS

A benchmark for probing the soft, rare & long-lived frontiers

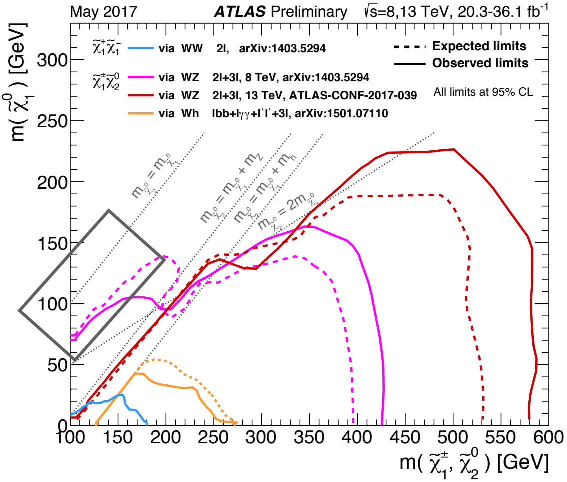
**Higgsinos $\tilde{H}$ are the spin-1/2 fermionic partner of the Higgs bosons**
**Mass should be near weak scale by naturalness arguments**

**Higgsinos realised as multiplet of neutralinos & charginos**




**Challenge to reconstruct intra-Higgsino soft decay products**

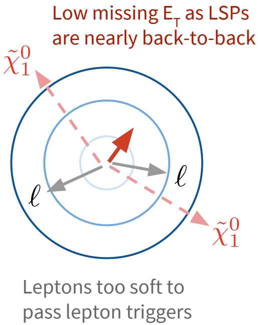
# Striking gaps in ATLAS sensitivity



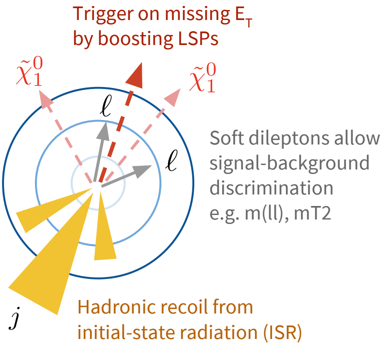

$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm(\text{wino}) \to W^{(*)} Z^{(*)} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \text{leptons} + E_\text{T}^\text{miss}$$

**'Smoking-gun' lamppost** of high $p_\text{T}$ objects is focus of first LHC searches.
Confront the **soft lepton frontier** to open sensitivity to diagonal.

## EXISTING PROBES

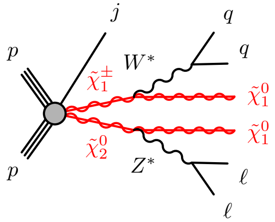


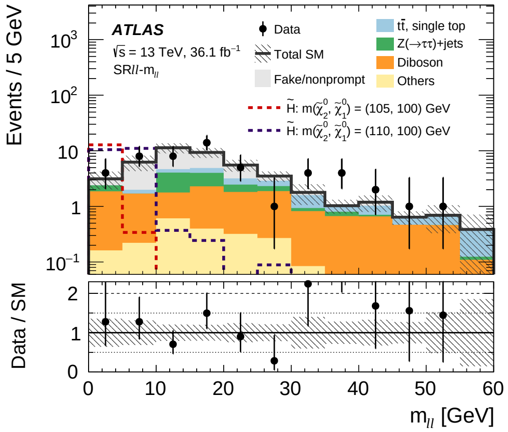

## OUR STRATEGY




New strategy employed by ATLAS [1712.08119]

# Signals localised at low $m_{\ell\ell}$: bump-hunt SUSY style!

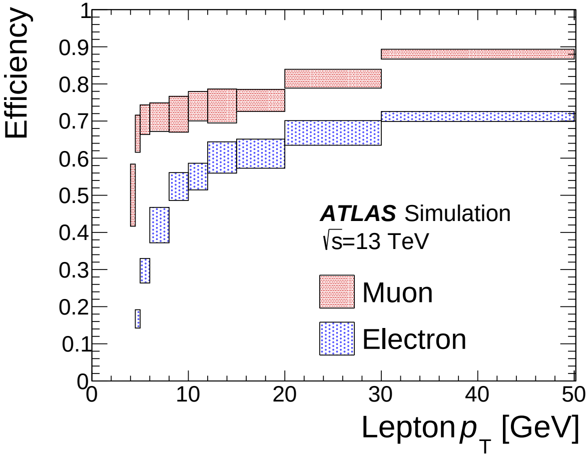



**Sensitivity driven by** $\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$ (same-flavour opposite-sign)

**Signal kinematic endpoint**: $m_{\ell\ell} < \Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ gives dramatic background discrimination

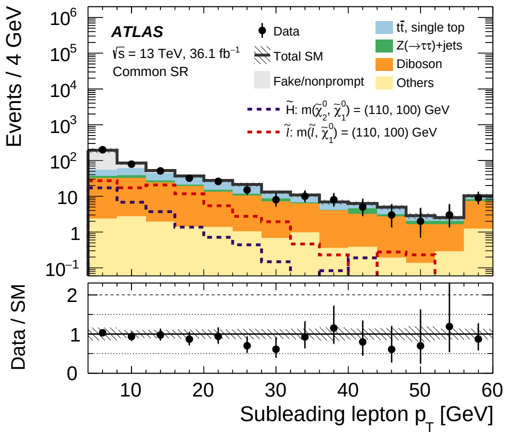
(Foreshadowing: sleptons where leptons come from different legs have endpoint in $m_{\mathrm{T2}}$ variable)




**Confronting experimental limitations of soft lepton reconstruction crucial for sensitivity**

Fun fact: a muon loses 3 GeV of energy before reaching the ATLAS muon spectrometer

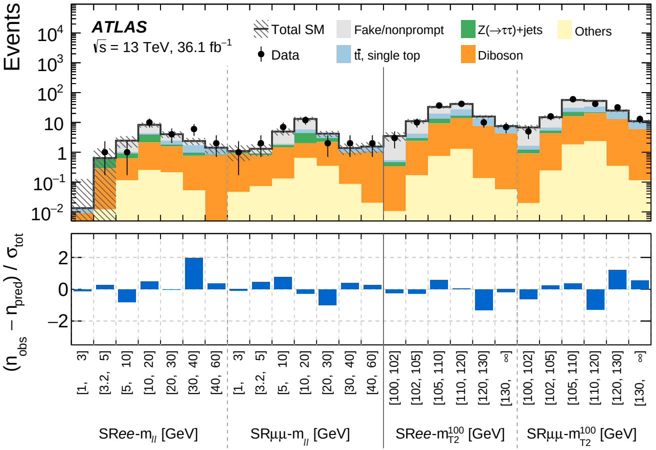
# Must confront 'fake/nonprompt' leptons at soft frontier




Soft lepton regime dominated by challenging fake/nonprompt lepton* backgrounds

Includes misidentified jets, photon conversions, semi-leptonic decays of *B*-hadrons, pileup

Predicted using data-driven 'Fake Factor' method (details in backup)




**Electroweakinos** use $m_{\ell\ell}$ SRs

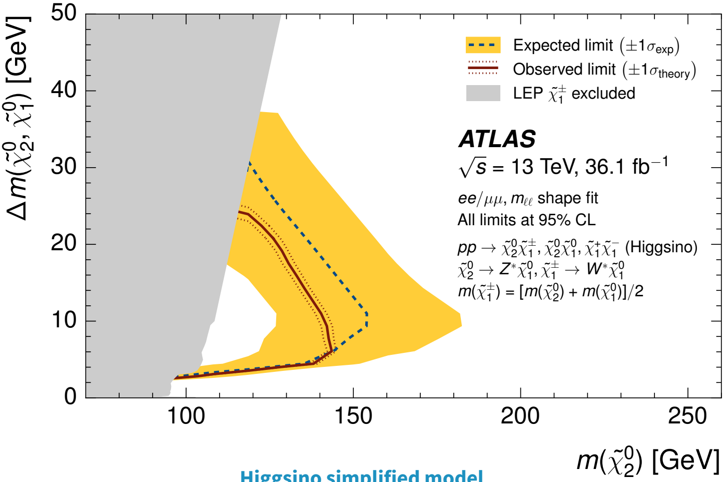
**Sleptons** use $m_{T2}^{100}$ SRs

Make bins orthogonal, split by $ee/\mu\mu$ to statistically combine, improving exclusion.

Showing fit with $\mu_{signal} = 0$.

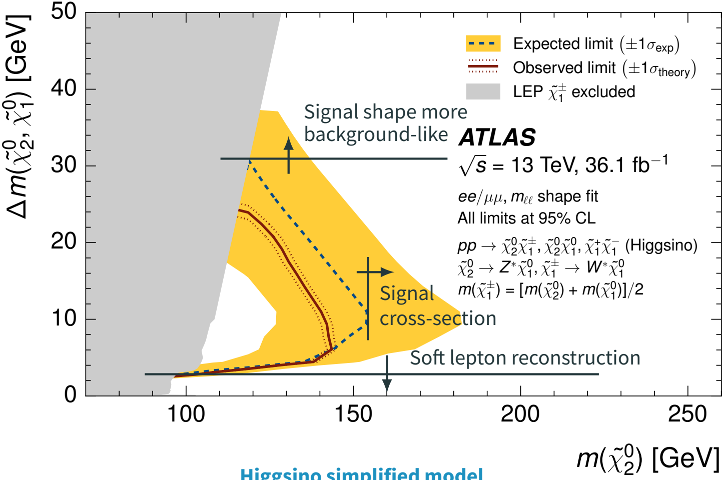
# LHC SENSITIVITY

A hadron collider extends nearly 20 year old LEP limits




**Higgsino simplified model**

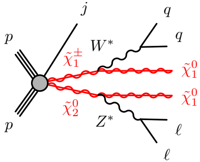
Down to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \sim 3$ GeV | Up to $m(\tilde{\chi}_2^0) \sim 140$ GeV.




**Higgsino simplified model**

Down to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \sim 3$ GeV | Up to $m(\tilde{\chi}_2^0) \sim 140$ GeV.

# From promptly decaying to long-lived Higgsinos

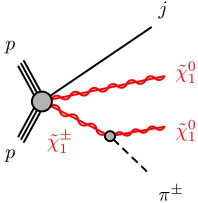




**$2\ell$ compressed**

Soft $p_T^{e,\mu} > 4.5, 4$ GeV

[1712.08119]

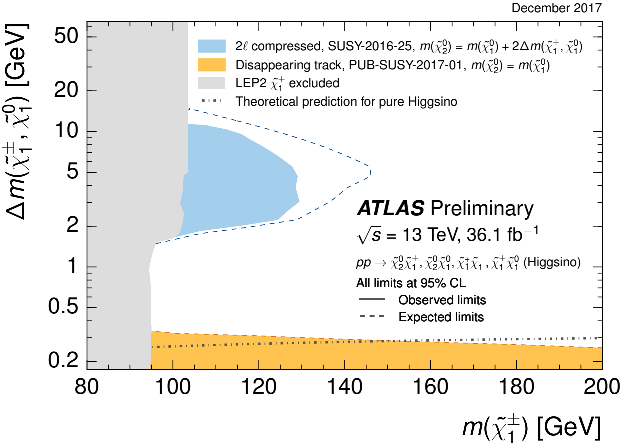




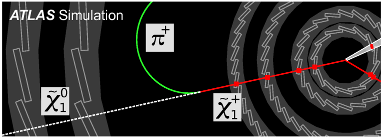
**Disappearing track**

IBL+Pixel tracklets

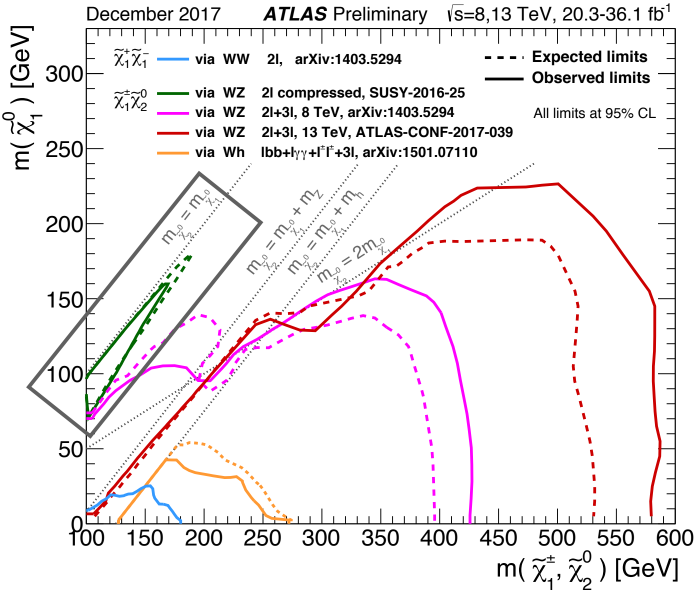
[PHYS-PUB-2017-019]



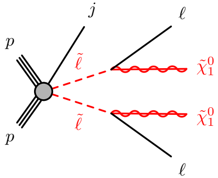


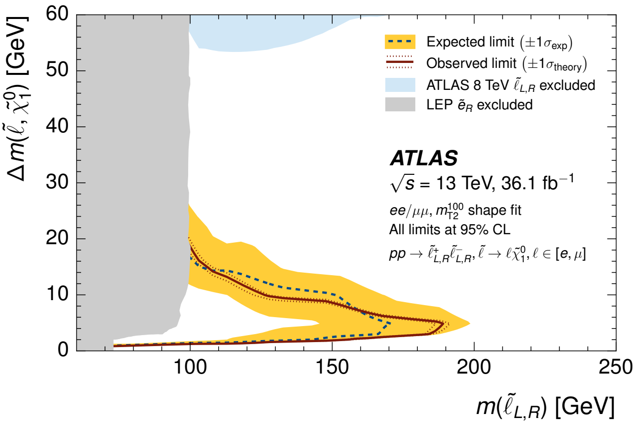


# Closing the ATLAS wino–bino via WZ gap



# Bonus result: 2L search also opens compressed slepton sensitivity



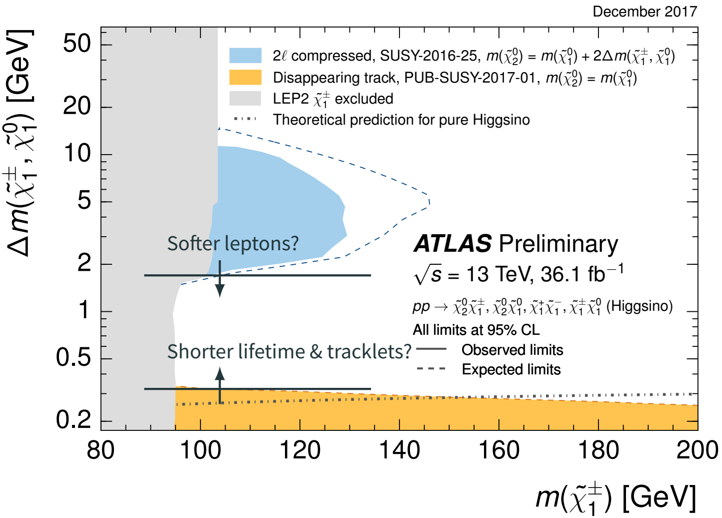

**First hadron collider sensitivity beyond LEP in $\Delta$M $\lesssim$ 55 GeV gap**

**Compressed frontier**: down to $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \sim 1$ GeV

**Mass frontier**: up to $m(\tilde{\ell}) \sim 190$ GeV

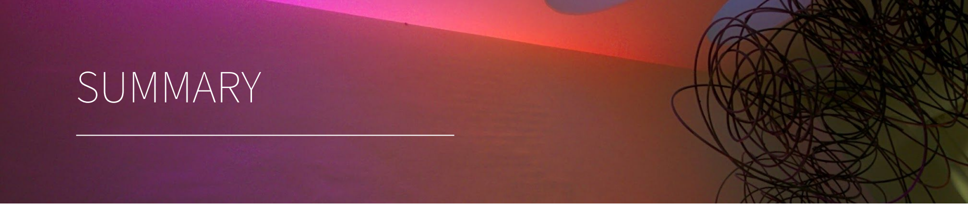
[1712.08119]

# How do we close the Higgsino prompt–long-lived gap?




Need new techniques to overcome limiting factors in sensitivity

# SUMMARY



**Physics opportunities**

Soft $2\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$ + ISR strategy: opened window on sought-after SUSY states.

Search for Higgsino & slepton production with $2\ell$.

**Challenges at the soft lepton frontier**

Recent support for $p_{\mathrm{T}}(e/\mu) > 4.5/4$ GeV critical for small $\Delta M$ sensitivity.

Fake/non-prompt leptons dominate background — used data-driven estimate.

**Sensitivity beyond LEP**

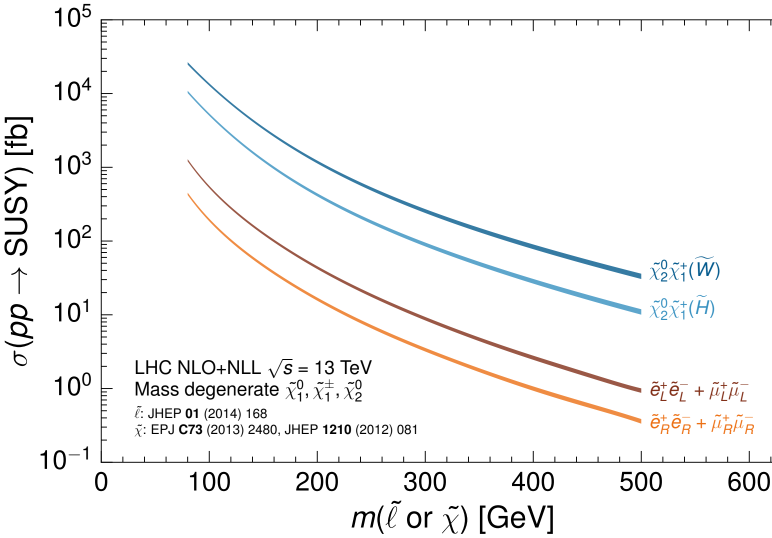
Signal regions binned in $m_{\ell\ell}$ or $m_{\mathrm{T2}}$ for decisive sensitivity.

Sensitivity down to $\Delta m$ of 3 GeV for Higgsinos, 1 GeV for sleptons.

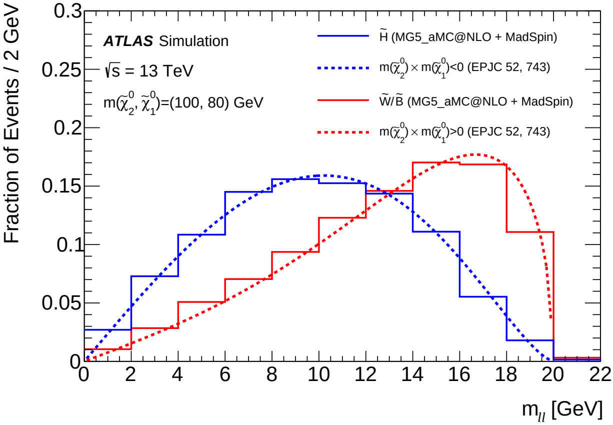
New strategy presented by ATLAS [1712.08119]

# EXTRAS

# LHC cross-sections for wino, Higgsino, slepton production



# Higgsino vs wino–bino dilepton invariant mass shape




**LHC can probe *composition* of electroweakinos i.e. underlying SUSY parameters**

$m_{\ell\ell}$ shape differs for Higgsino $\tilde{H}$ vs wino–bino $\tilde{W}/\tilde{B}$ scenarios.

Using MadSpin to model $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ decays to match predicted shape.

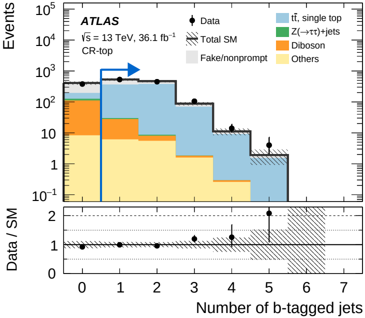
| **Prediction**<br>Mix of data & MC methods | **Signal region**<br>Same flavour leptons | **Validation**<br>Check background modelling | |
|---|---|---|---|
| **Fake Factor**<br>Data-driven method | **≥ 1 lepton fake/non-prompt**<br>> 50% at low lepton pT<br>E.g. W+jets | **VR-SS**<br>MET/HT(lep) > 5.<br>Same sign leptons.<br>Fakes purity > 90%. | **VR-DF**<br>Different flavour leptons.<br><br>Exactly the same kinematic regimes as SRs.<br><br>Global check of background modelling. |
| **CR-top**<br>**N(b-jets) ≥ 1**<br>ttbar, tW<br>MC normalisation | **Top quark**<br>2L ttbar & tW missed b-jet | | |
| **CR-tau**<br>**60 < m($\tau\tau$) < 120 GeV**<br>MC normalisation | **Z → $\tau\tau$**<br>2L decays | | |
| **Monte Carlo only** | **Diboson**<br>WW 2L<br>WZ missed 3rd lepton | **VR-VV**<br>MET/HT(lep) < 3.<br>Diboson purity ~40%. | |
| **Monte Carlo only** | **Others**<br>E.g. $Z \to ee/\mu\mu$, Higgs | | |

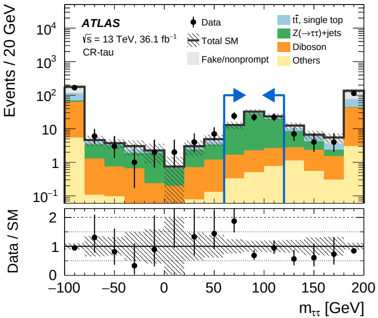
**Irreducible:** 2 real & prompt leptons and MET from neutrinos

**Reducible:** ≥ 1 or more fake/non-prompt lepton(s), instrumental MET (negligible)

List of MC samples in backup p??, more details of strategy in backup p??.

# Control regions for irreducible backgrounds




**CR-top**

$\mu_{\text{top}} = 0.97 \pm 0.09$ for $t\bar{t}$, Single top

**CR-tau**

$\mu_{Z\to\tau\tau} = 0.77 \pm 0.14$ for $Z \to \tau\tau$

| Region | Leptons | $E_T^{miss}/H_T^{lep}$ | | Additional requirements |
|---|---|---|---|---|
| CR-top | $e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $> 5$ | For SR orthogonality | $\geq 1$ $b$-tagged jet(s) |
| CR-tau | $e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $\in [4, 8]$ | | $m_{\tau\tau} \in [60, 120]$ GeV |

**Background-only fit to CR-top & CR-tau (each single-bins).**
This derives normalisation factors $\mu_{\text{top}}$, $\mu_{Z\to\tau\tau}$ respectively.

# Highlight ATLAS $2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ + ISR search

| | Variable | Common requirement |
|---|---|---|
| **Select 2 soft SFOS leptons** | Number of leptons | $= 2$ |
| | Lepton charge and flavour | $e^+e^-$ or $\mu^+\mu^-$ |
| | Leading lepton $p_{\mathrm{T}}^{\ell_1}$ | $> 5$ (5) GeV for electron (muon) |
| | Subleading lepton $p_{\mathrm{T}}^{\ell_2}$ | $> 4.5$ (4) GeV for electron (muon) |
| Conversions/fake muons | $\Delta R_{\ell\ell}$ | $> 0.05$ |
| Drell-Yan resonances | $m_{\ell\ell}$ | $\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV |
| **Select ISR topology** | $E_{\mathrm{T}}^{\mathrm{miss}}$ | $> 200$ GeV |
| | Leading jet $p_{\mathrm{T}}^{j_1}$ | $> 100$ GeV |
| | $\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ | $> 2.0$ |
| Mis-measured jets | $\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$ | $> 0.4$ |
| Top quarks | Number of $b$-jets | $= 0$ |
| $Z \to \tau\tau$ | $m_{\tau\tau}$ | $< 0$ or $> 160$ GeV |

**Same-flavour opposite sign (SFOS) signature**

**Higgsino** sensitivity dominated by $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0(Z^* \to \ell^+\ell^-)$.

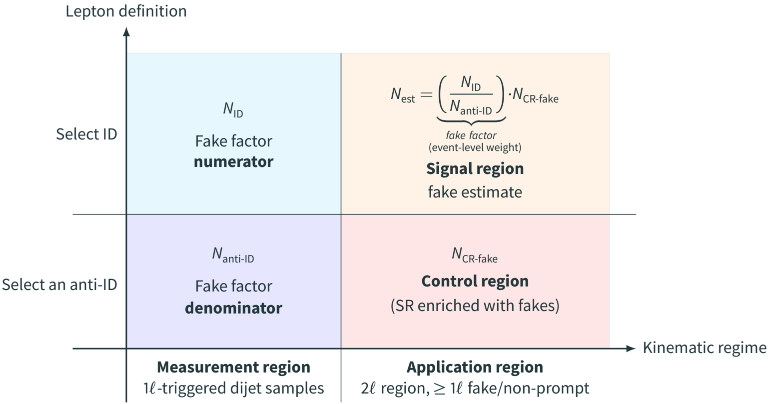
**Select ISR topology**

$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV, $p_{\mathrm{T}}^{j_1} > 100$ GeV, $\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 2.0$.

**Suppress backgrounds**

Other common requirements reduce various backgrounds labelled above.

# Schematic of data-driven *Fake Factor* method




**Numerator (denominator) intuition**: given fake leptons, fraction that **pass (fail)** signal requirements.

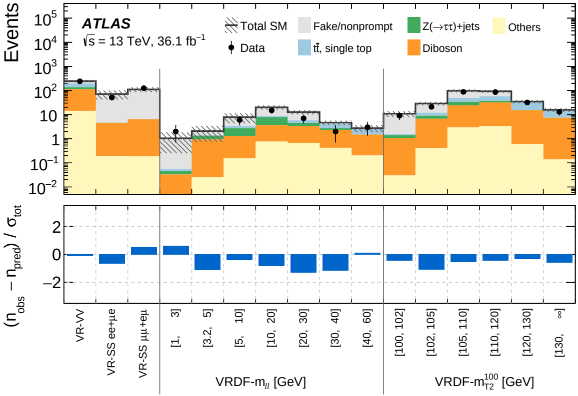
**ID Electrons**: *Tight* identification, *GradientLoose* isolation.
**ID Muons**: *Medium* identification, *FixedCutTightTrackOnly* isolation.

**ID leptons**: same as signal leptons | **Anti-ID leptons**: invert $\geq 1$ ID requirements.

Bin in $p_{\text{T}}$ for $e$ & $\mu$, bin in $N_{\text{b-jet}}$ only for $\mu$ fake factors.

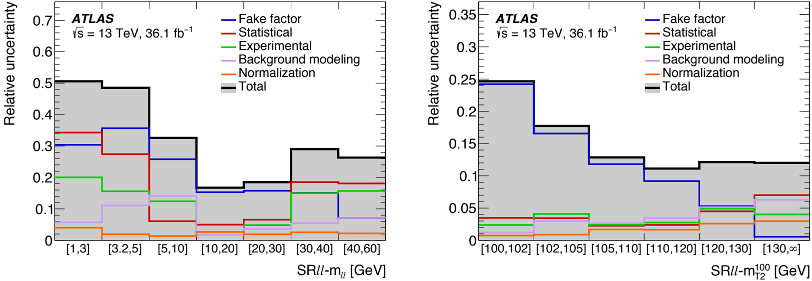
Fake Factor developed in H to WW analysis. Studied fake composition in MC (mostly heavy flavour), optimised object definitions.

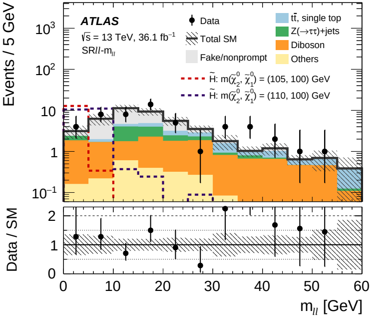
# Summary of background estimation validation

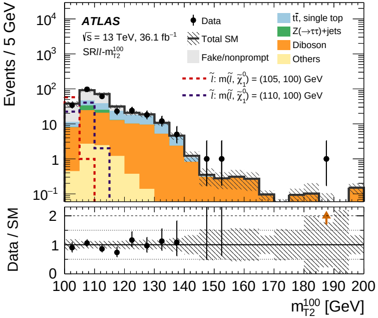



| Region | Leptons | $E_T^{miss}/H_T^{lep}$ | Additional requirements |
|---|---|---|---|
| CR-top | $e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $> 5$ | $\geq 1$ $b$-tagged jet(s) |
| CR-tau | $e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $\in [4, 8]$ | $m_{\tau\tau} \in [60, 120]$ GeV |
| VR-VV | $e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $< 3$ | |
| VR-SS | $e^\pm e^\pm$, $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, $\mu^\pm e^\pm$ | $> 5$ | |
| VRDF-$m_{\ell\ell}$ | $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\text{ GeV}}\right)$ | $\Delta R_{\ell\ell} < 2$, $m_T^{\ell_1} < 70$ GeV |
| VRDF-$m_{T2}^{100}$ | $e^\pm\mu^\mp$, $\mu^\pm e^\mp$ | $> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\text{ GeV}} - 100\right)\right)$ | |

# Breakdown of systematics in SRs





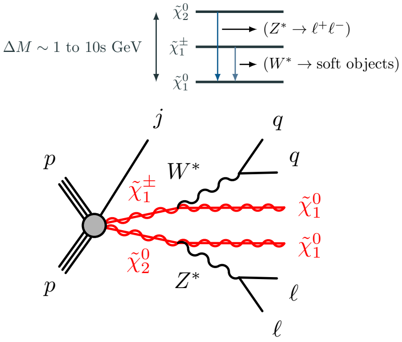




| Variable | Common requirement | |
|---|---|---|
| Number of leptons | $= 2$ | |
| Lepton charge and flavour | $e^+e^-$ or $\mu^+\mu^-$ | |
| Leading lepton $p_T^{\ell_1}$ | $> 5$ (5) GeV for electron (muon) | |
| Subleading lepton $p_T^{\ell_2}$ | $> 4.5$ (4) GeV for electron (muon) | |
| $\Delta R_{\ell\ell}$ | $> 0.05$ | |
| $m_{\ell\ell}$ | $\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV | |
| $E_T^{miss}$ | $> 200$ GeV | |
| Leading jet $p_T^{j_1}$ | $> 100$ GeV | |
| $\Delta\phi(j_1, \mathbf{p}_T^{miss})$ | $> 2.0$ | |
| $\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{miss}))$ | $> 0.4$ | |
| Number of $b$-jets | $= 0$ | |
| $m_{\tau\tau}$ | $< 0$ or $> 160$ GeV | |
| | Electroweakino SRs | Slepton SRs |
| $\Delta R_{\ell\ell}$ | $< 2$ | — |
| $m_T^{\ell_1}$ | $< 70$ GeV | — |
| $E_T^{miss}/H_T^{lep}$ | $> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\text{ GeV}}\right)$ | $> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\text{ GeV}} - 100\right)\right)$ |
| Binned in | $m_{\ell\ell}$ | $m_{T2}^{100}$ |

# SR binning scheme (paper main text)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Electroweakino SRs | | | | | | | | |
| Exclusive | SR$ee$-$m_{\ell\ell}$, SR$\mu\mu$-$m_{\ell\ell}$ | [1, 3] | [3.2, 5] | [5, 10] | [10, 20] | [20, 30] | [30, 40] | [40, 60] |
| Inclusive | SR$\ell\ell$-$m_{\ell\ell}$ | [1, 3] | [1, 5] | [1, 10] | [1, 20] | [1, 30] | [1, 40] | [1, 60] |
| Slepton SRs | | | | | | | | |
| Exclusive | SR$ee$-$m_{T2}^{100}$, SR$\mu\mu$-$m_{T2}^{100}$ | | [100, 102] | [102, 105] | [105, 110] | [110, 120] | [120, 130] | [130, $\infty$] |
| Inclusive | SR$\ell\ell$-$m_{T2}^{100}$ | | [100, 102] | [100, 105] | [100, 110] | [100, 120] | [100, 130] | [100, $\infty$] |

# Signal models: 2 ways to realise dilepton decay chain with MET



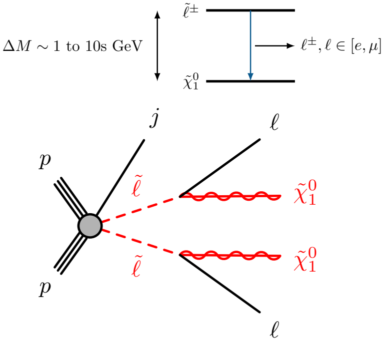

## Electroweakinos

Target $\ell^+\ell^-$ from **same** leg

Bump in **dilepton invariant mass** $m_{\ell\ell}$

Higgsino: $m(\tilde{\chi}_1^\pm) = [m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]/2$

Sensitivity driven by $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$




## Sleptons

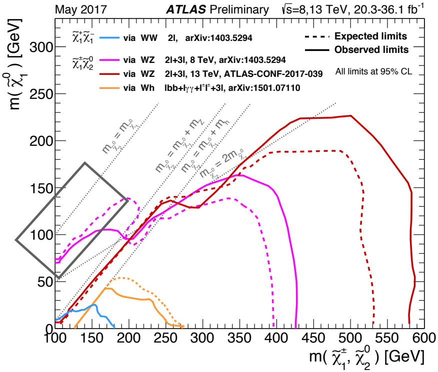
Target $\ell^+\ell^-$ from **different** legs

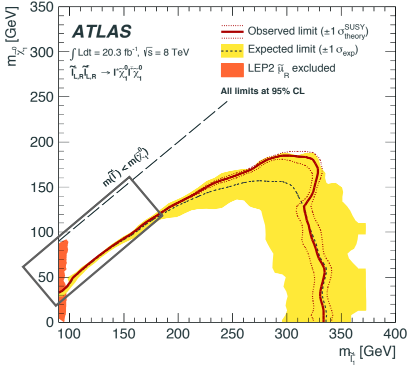
Bump in **stransverse mass** $m_{\mathrm{T2}}$

$m(\tilde{e}_L) = m(\tilde{e}_R) = m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$

$\sigma \times \mathrm{BR}_{2\ell}$ similar to electroweakinos

# Striking gaps in ATLAS sensitivity



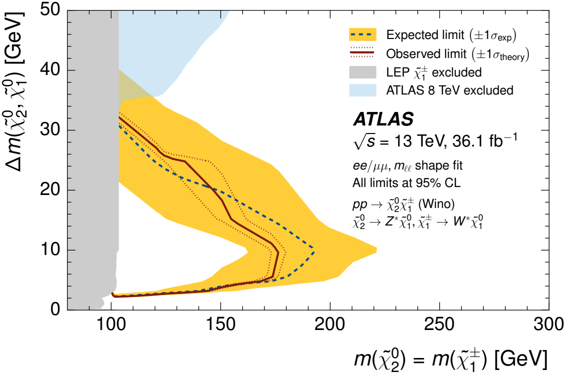



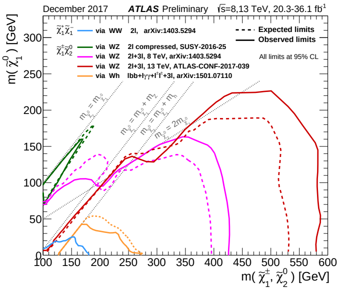

Wino $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to W^{(*)} Z^{(*)} \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \lesssim 40$ GeV

Sleptons $\tilde{\ell}^+ \tilde{\ell}^- \to \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim 60$ GeV




Zoom into diagonal.

**Wino–bino simplified model**

Down to $\Delta M \sim 2.5$ GeV | Up to $m(\tilde{\chi}_2^0) \sim 170$ GeV.

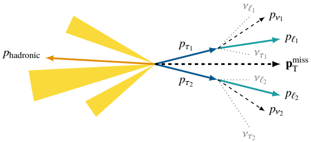
Priority in 2018: close gap at $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) \approx 30$ GeV.

# Simplified models motivated by 3 compressed spectra scenarios

| Simplified models considered | Higgsino LSP | Slepton<br>Bino LSP | Wino<br>Bino LSP |
|---|---|---|---|
| **Use in this analysis** | Optimisation & interpretation | | Interpretation |
| **Compression** | Radiative/mixing | Accidental | |
| **SM splitting analogy** | W/Z bosons ~10% apart | Charm quark & tau lepton mass ~30% apart | |
| **Desirable feature** | Weak scale naturalness[§] | Resolve $(g\text{-}2)_\mu$ tension[%] | Favoured by global fits[**] |
| **LSP as dark matter** | 'Well-tempered' mixing[£] | Bino saturates relic density via coannihilation[^] | |
| **E.g. cross-sections[#]** | $m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) = (110, 105)$ GeV<br>$\sigma(pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm) = 4.3$ pb | $m(\tilde{\ell}_{L,R}) = 110$ GeV<br>$\sigma(pp \to \tilde{\ell}_{L,R}\tilde{\ell}_{L,R}) = 0.55$ pb | $m(\tilde{\chi}_2^0 = \tilde{\chi}_1^\pm) = 110$ GeV<br>$\sigma(pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm) = 16$ pb |

*E.g.* arXiv: [§]1110.6926, [%]1505.05896, **1504.0326, [£]hep-ph/0601041 [^]1508.06608, [#]Resummino NLO+NLL 1304.0790

# Definition of $m_{\tau\tau}$




$$m_{\tau\tau} = \text{sign}(m_{\tau\tau}^2)\sqrt{|m_{\tau\tau}^2|} \quad (1)$$

The construction assumes the $\tau$ leptons decay products are nearly collinear.

$p_{\tau_i} = p_{\ell_i} + p_{\nu_i}$. Then the $\tau$ momentum is a rescaling of the observable lepton momenta $p_{\ell_i}$

$$p_{\tau_i} = (1 + \xi_i)p_{\ell_i} \equiv f_i p_{\ell_i}, \quad (7)$$

where $f_i \equiv 1 + \xi_i$. To solve for the two unknown scalars $\xi_i$, one constrains the neutrino momenta using the missing transverse momentum [1] as Ref. [46] prescribes

$$\mathbf{p}_{\mathrm{T}}^{\text{miss}} = \xi_1 \mathbf{p}_{\mathrm{T}}^{\ell_1} + \xi_2 \mathbf{p}_{\mathrm{T}}^{\ell_2}. \quad (8)$$

Equation (8) assumes the lepton–invisible colinearity limit $p_{\nu_i} \simeq \xi_i p_{\ell_i}$ and comprises two independent constraints in the transverse plane for the two unknown scalars $\xi_i$. This is solved by performing $2 \times 2$ matrix inversion in for example the $x$-$y$ transverse plane

$$\begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} = \frac{1}{p_x^{\ell_1} p_y^{\ell_2} - p_x^{\ell_2} p_y^{\ell_1}} \begin{pmatrix} p_x^{\text{miss}} p_y^{\ell_2} - p_x^{\ell_2} p_y^{\text{miss}} \\ p_y^{\text{miss}} p_x^{\ell_1} - p_x^{\text{miss}} p_y^{\ell_1} \end{pmatrix}. \quad (9)$$

Assuming highly boosted taus such that $m_{\tau_i}^2 \simeq 0$, the di-tau invariant mass squared is then given by

$$m_{\tau\tau}^2 = (p_{\tau_1} + p_{\tau_2})^2 \simeq 2 p_{\ell_1} \cdot p_{\ell_2} (1 + \xi_1)(1 + \xi_2). \quad (10)$$

$m_{\tau\tau}^2$ can go negative when $f_i \equiv 1 + \xi_i < 0$ . This happens when one of the leptons is anti-aligned with $\mathbf{p}_{\mathrm{T}}^{\text{miss}}$ and $E_{\mathrm{T}}^{\text{miss}} > |\mathbf{p}_{\mathrm{T}}^{\ell_i}|$, such that the rescaling has to invert the direction to approximate the tau-momentum.

In slepton-pair production (Figure 1(b)), the event topology can be used to infer the slepton mass given the LSP mass. The stransverse mass [37, 38] is defined by

$$m_{\mathrm{T2}}^{m_\chi}\left(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right) = \min_{\mathbf{q}_{\mathrm{T}}}\left(\max\left[m_{\mathrm{T}}\left(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{q}_{\mathrm{T}}, m_\chi\right), m_{\mathrm{T}}\left(\mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}}, m_\chi\right)\right]\right),$$

where the transverse vector $\mathbf{q}_{\mathrm{T}}$ is chosen to minimize the larger of the two transverse masses, defined by

$$m_{\mathrm{T}}\left(\mathbf{p}_{\mathrm{T}}, \mathbf{q}_{\mathrm{T}}, m_\chi\right) = \sqrt{m_\ell^2 + m_\chi^2 + 2\left(\sqrt{p_{\mathrm{T}}^2 + m_\ell^2}\sqrt{q_{\mathrm{T}}^2 + m_\chi^2} - \mathbf{p}_{\mathrm{T}} \cdot \mathbf{q}_{\mathrm{T}}\right)}.$$

The values of $m_{\mathrm{T2}}^{m_\chi}$ are bounded by the slepton mass from above when the hypothesis invisible mass $m_\chi$ is set to the LSP mass. The stransverse mass $m_{\mathrm{T2}}^{100}$ with $m_\chi = 100$ GeV is used to define the binning of the slepton SRs as further described below. The value of 100 GeV is chosen based on the expected LSP masses of the slepton signals targeted by this analysis.