Searches for electroweak production of supersymmetric particles with the ATLAS detector

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on behalf of the ATLAS Collaboration

Electroweak supersymmetry (EWK SUSY) introduction (1)

- Minimal supersymmetric model (MSSM): superpartners to SM particles that differ by spin-$\frac{1}{2}$, and two Higgs doublets
- Leptons and neutrinos have scalar **sleptons** $\tilde{\ell}$ and **sneutrinos** $\tilde{\nu}$
- Fermionic partners to $W^{\pm,0}$ and B^0 bosons are **winos** $\widetilde{W}$ and **binos** $\widetilde{B}$, partners to Higgs are **higgsinos** $\widetilde{H}$
  - After electroweak symmetry breaking, combine into **charginos** $\tilde{\chi}^{\pm}_{1,2}$ and **neutralinos** $\tilde{\chi}^{0}_{1-4}$

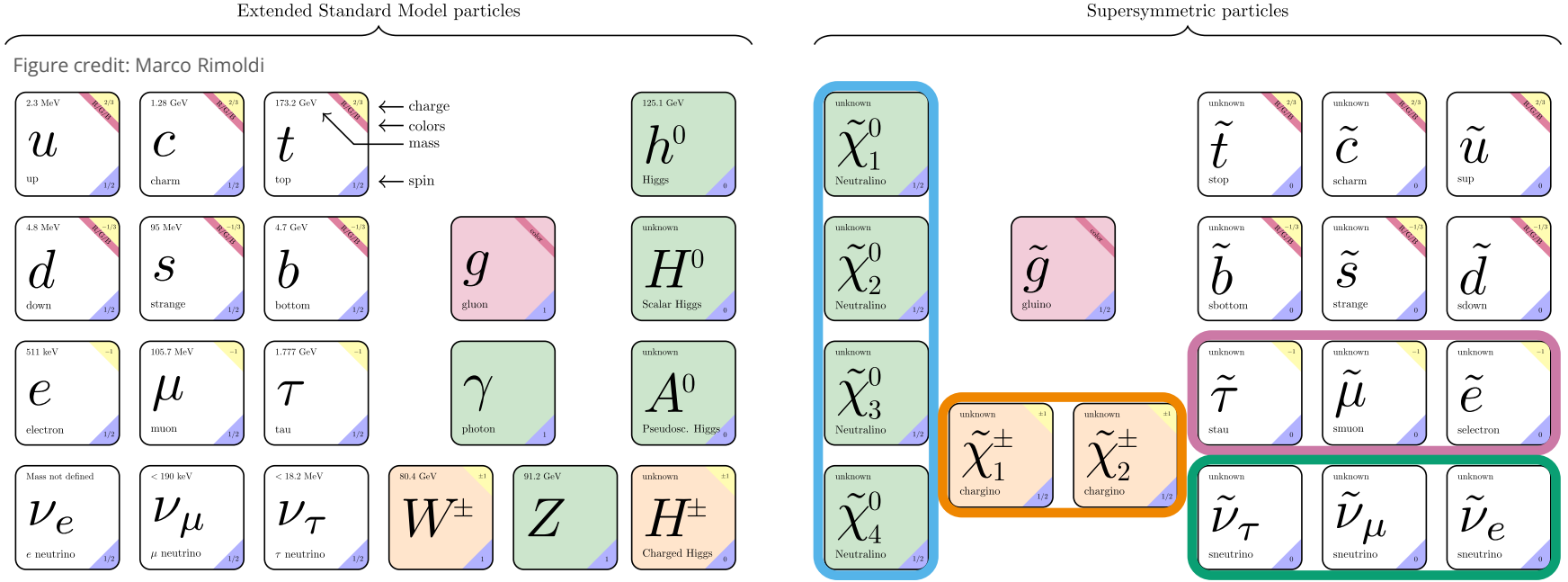
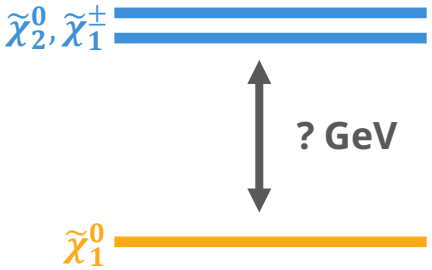


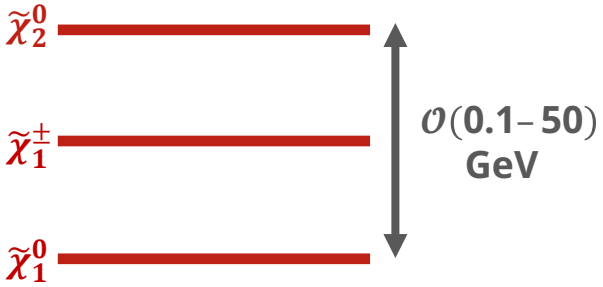
Figure credit: Marco Rimoldi

EWK SUSY introduction (2)

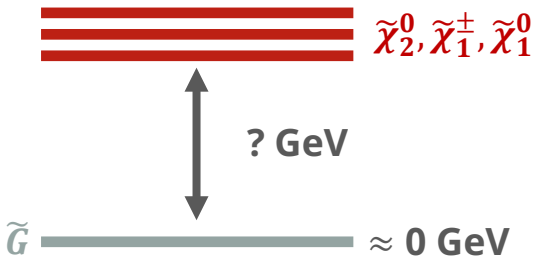
- Potential motivations for (EWK) SUSY:
  - Lightest superpartner (LSP) is a dark matter candidate
  - Provides mechanism for gauge unification
  - If higgsino masses are near EWK scale, can address hierarchy problem
- **Challenge:** If superpartners weakly produced, **smaller cross-section** at pp collider
- Example models for chargino/neutralino LSP and next-to-LSPs (NLSP):



Wino/Bino model



Higgsino model
(naturally compressed)

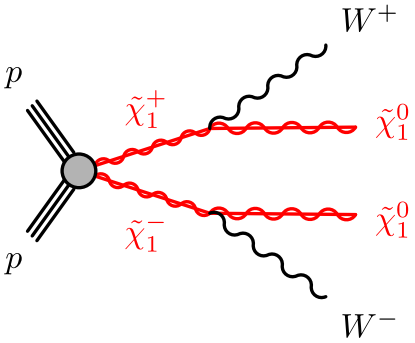


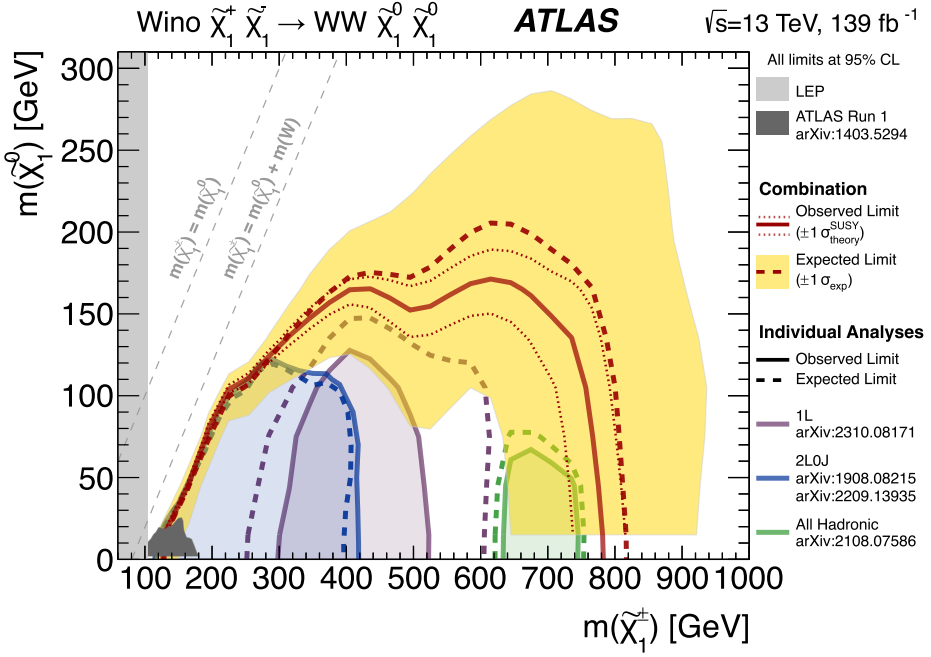
General gauge mediation model

Electroweak simplified model combinations (1)

SUSY-2020-05 [arXiv:2402.08347]

- Simplified model: wino–bino
  - **Pure-wino** $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production with 100% decay BR to W
- $\tilde{\chi}_1^\pm \to W^\pm \chi_1^0$: combination **fills gap at $m(\tilde{\chi}_1^\pm) \approx$ 600 GeV**
  - **1 Lepton**, **2 Lepton 0 Jet**, and **All Hadronic** contribute

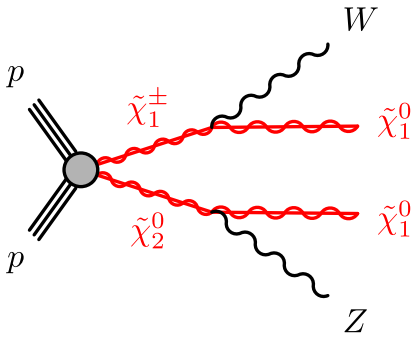


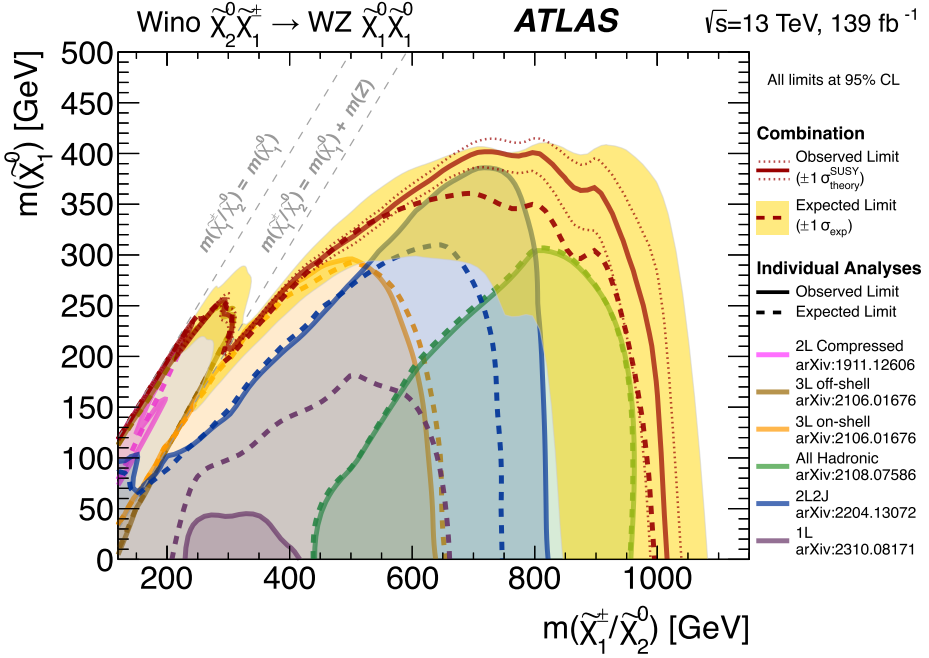


EWK simplified model combinations (2)

SUSY-2020-05
[arXiv:2402.08347]

- Simplified model: wino–bino
  - **Pure-wino $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$** production with 100% decay BR to W, Z
- **$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow WZ\chi_1^0\chi_1^0$: combination extends ULs at large masses**
  - **3 Lepton on-shell**, **2 Lepton 2 Jet** and **All Hadronic** contribute



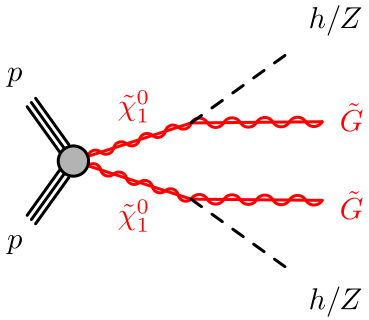


See paper for additional $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow Wh\chi_1^0\chi_1^0$ result!

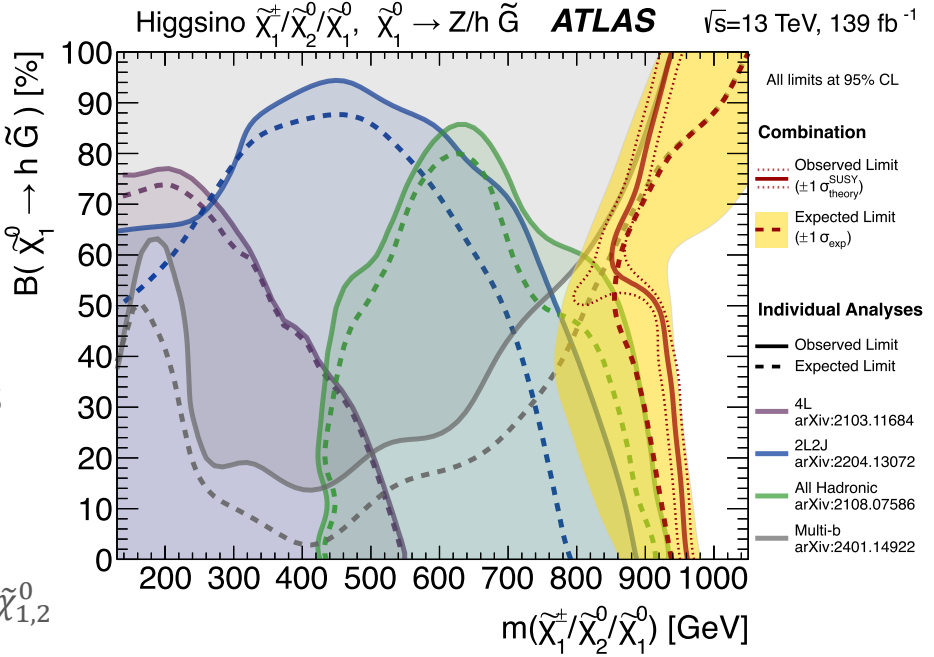
EWK simplified model combinations (3)

SUSY-2020-05
[arXiv:2402.08347]

- Simplified model: higgsino GGM
  - **pure-higgsino** $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_{1,2}^0$ production with soft decays to $\tilde{\chi}_1^0$
  - $\tilde{\chi}_1^0 \rightarrow Z/h\tilde{G}$
- Combination **extends UL by up to 60 GeV** across $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z/h\tilde{G})$
  - From combined sensitivity of **Multi-b** and **All Hadronic** analyses



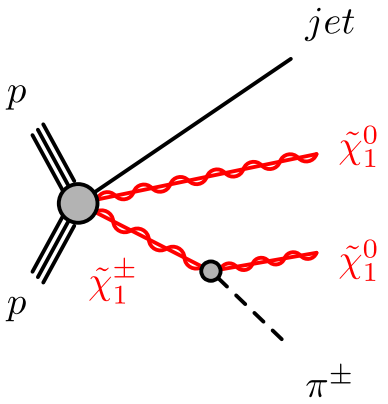
$\tilde{\chi}_1^0$ from $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_{1,2}^0$

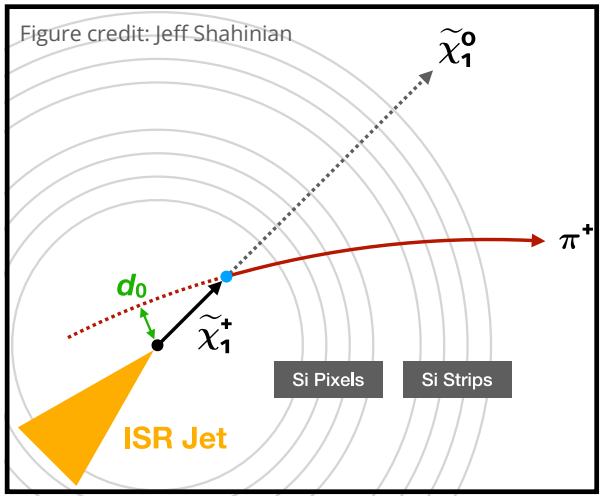


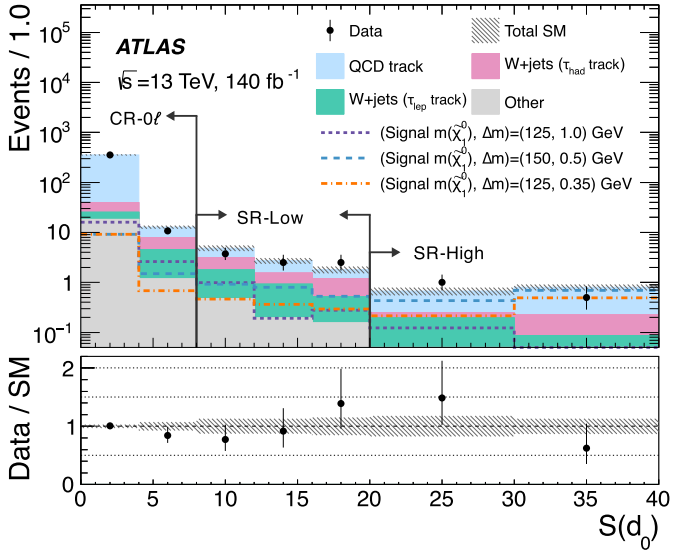
Compressed higgsinos with displaced tracks (1) [SUSY-2020-04 [arXiv:2401.14046]]

- $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \approx 0.3$–$1$ GeV: Not a disappearing track, not a prompt decay
  - "Mildly displaced" track $\mathcal{O}(0.1$–1 mm); require hit in first ID layer
  - Initial state radiation (ISR) jet recoil helps distinguish from $(W \to \ell/\tau\nu)$ + jets
- Discriminate on transverse impact parameter **d_0 significance**

$$S(d_0) = d_0/\sigma(d_0)$$



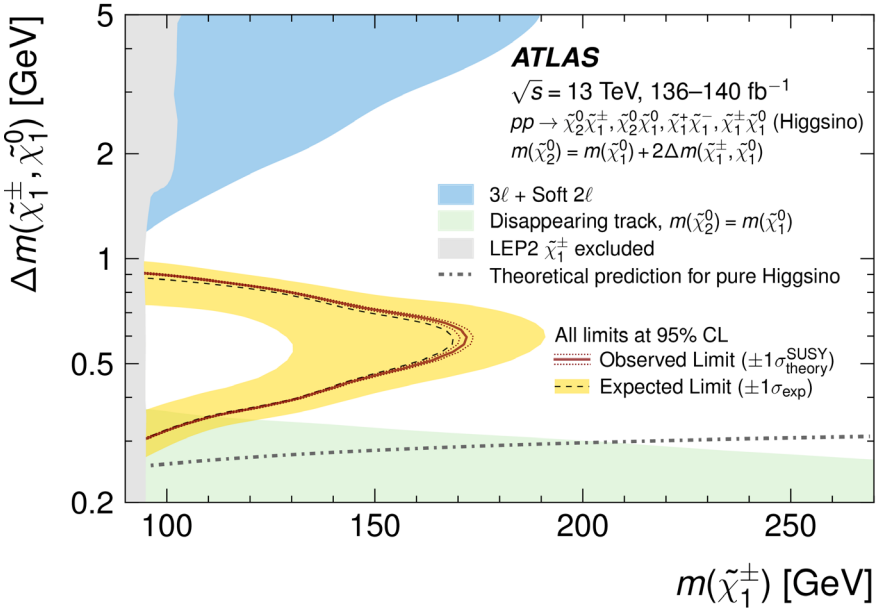




Compressed higgsinos with displaced tracks (2)

SUSY-2020-04 [arXiv:2401.14046]

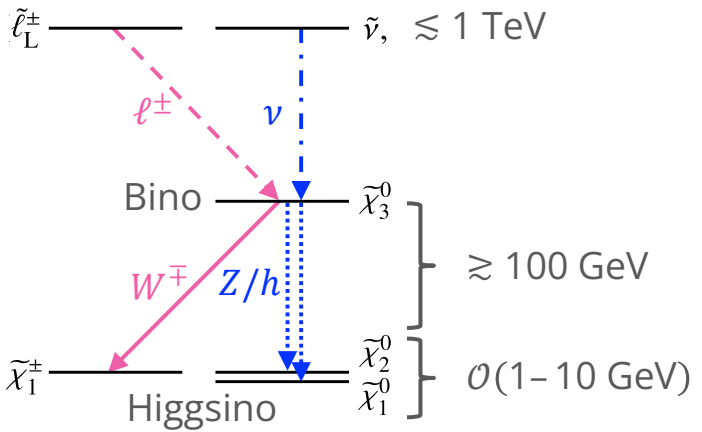
- No significant excess observed
- **Maximum reach of 170 GeV excluded in range from 0.3–0.9 GeV**
- **First time since LEP** phase space is excluded!

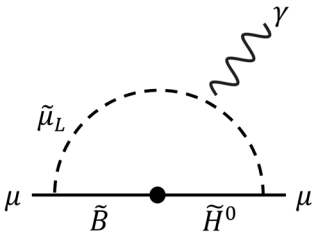


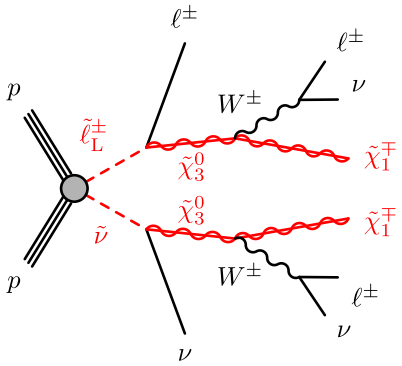
Slepton–Bino–Higgsino (SBH) model (1)

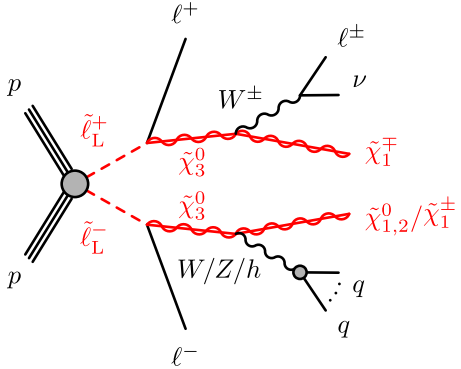
HMBS-2024-11
[arXiv:2503.13135]

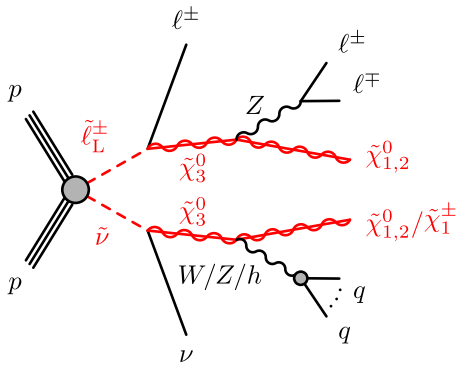
- Spectrum involves slepton, bino, and near-degenerate higgsinos
  - Inspired by (previous) $(g-2)_\mu$ tension
  - Also addresses DM, hierarchy
- $\tilde{\ell}_L^+\tilde{\ell}_L^-$ and $\tilde{\ell}_L^+\tilde{\nu}$ production, cascade decay
- **3 lepton final state** is most sensitive









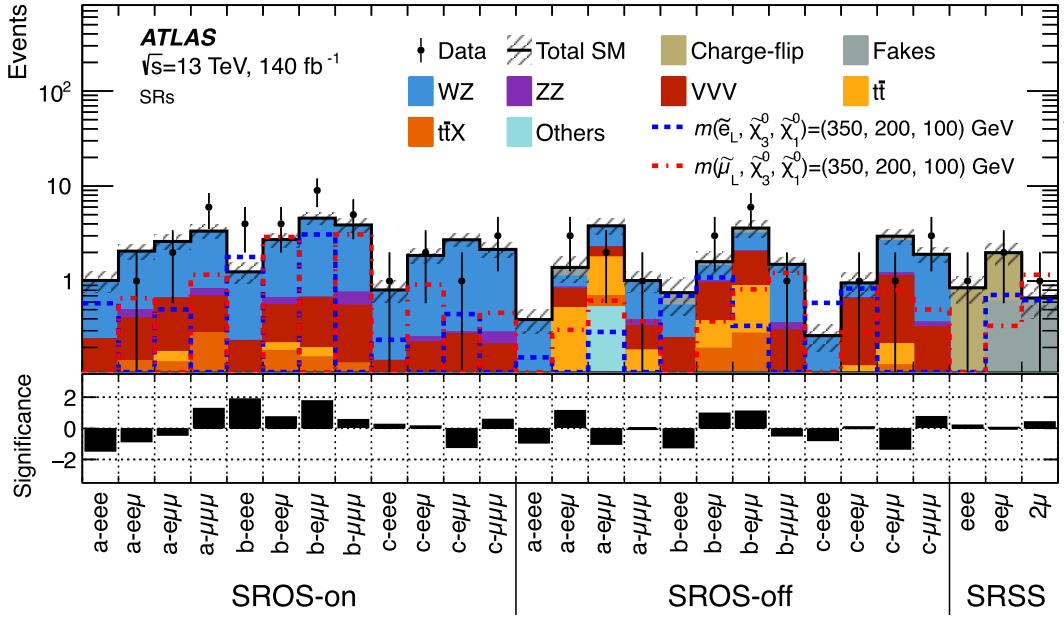


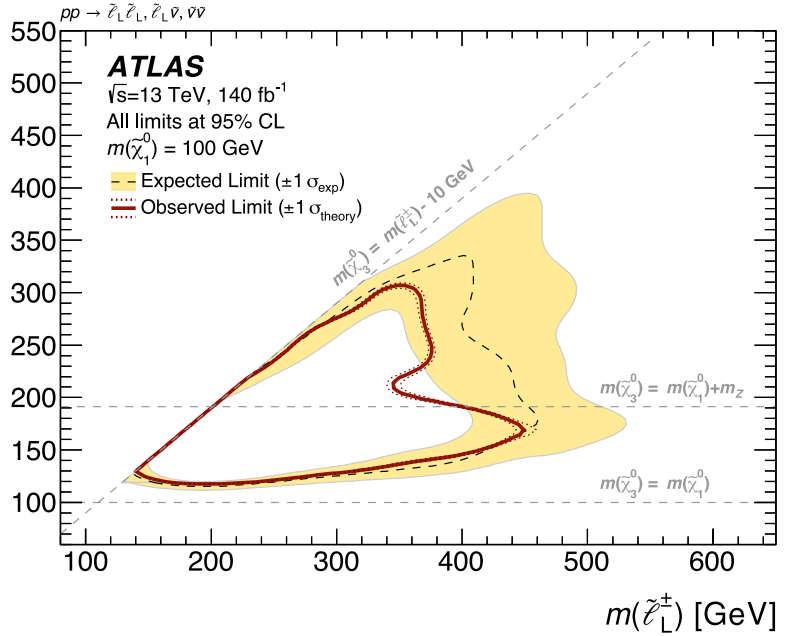
SBH model (2)

HMBS-2024-11
[arXiv:2503.13135]

- Exactly three leptons; same-sign and opposite-sign charge signal regions
  - SROS have on- and off-shell Z, bin in $m_{3\ell}$ since leptons from same $\tilde{\ell}$
- b-jets rejected to eliminate $t\bar{t}$, single-t

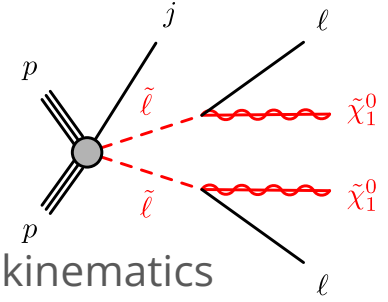
- $m(\tilde{\ell})$ **exclusions up to 450 GeV** assuming $m(\tilde{\chi}_1^0) = 100$ GeV and fourfold degenerate $\tilde{e}_L, \tilde{\mu}_L, \tilde{\nu}_e, \tilde{\nu}_\mu$
- **First sensitivity to $\Delta m(\tilde{\chi}_3^0, \tilde{\chi}_1^0) \gtrsim 100$ GeV**



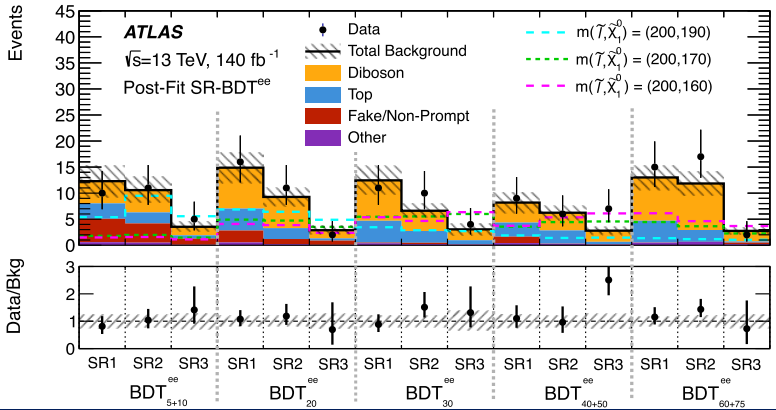


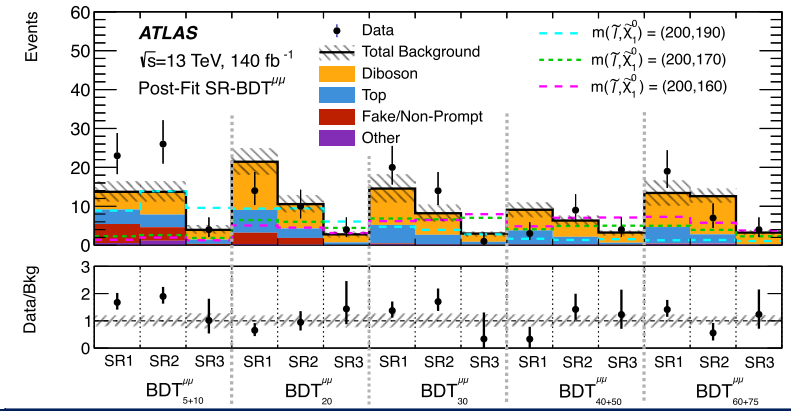
Compressed sleptons (1)

HMBS-2024-64
[arXiv:2503.17186]



- **Compressed $\tilde{\ell}, \tilde{\chi}_1^0$ spectrum**, final state 2 same-flavor opposite-charge leptons plus $E_{\mathrm{T}}^{\mathrm{miss}}$ with ISR jet
  - Previous searches have little sensitivity to $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim m_W$: similar to W^+W^- SM background; ISR boost helps distinguish kinematics
- Complementary search strategies:
  - **Model-independent cut-and-count**: SRs selected on $m_{\mathrm{T}}^{\ell_1}$ and $m_{\mathrm{T2}}^{100\ \mathrm{GeV}}$
  - **Model-dependent BDTs**: many kinematic inputs, lift $\tilde{e}, \tilde{\mu}$ degeneracy



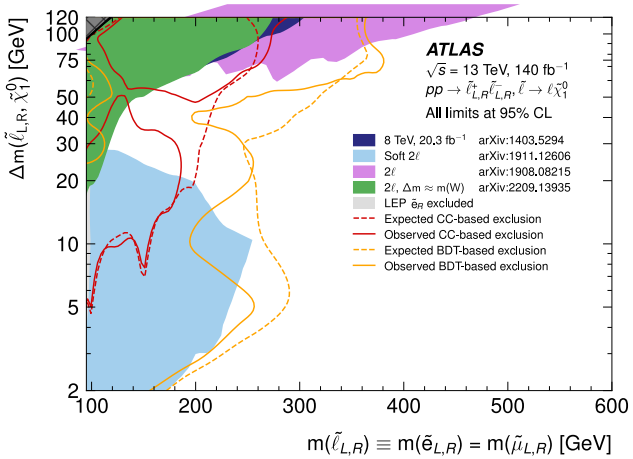


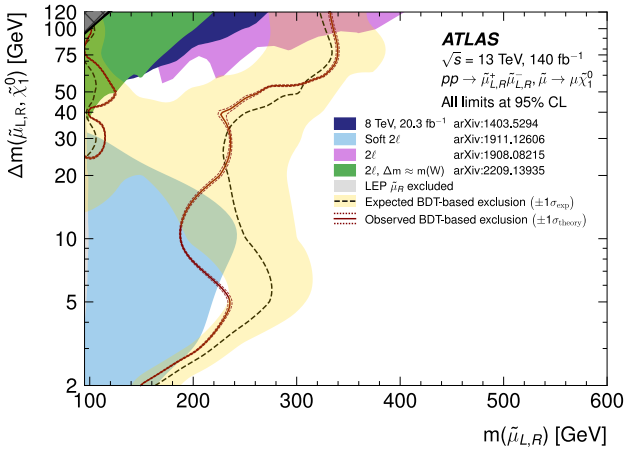
Compressed sleptons (2)

HMBS-2024-64
[arXiv:2503.17186]

- Generally consistent with SM
  - Largest local significance is 2σ for $\tilde{e}$, 2.4σ for $\tilde{\mu}$, reduces sensitivity for $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$ near 10 and 40 GeV
- **Reduces gap in sensitivity** for $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$ between 20–60 GeV
  - Above: four-fold mass degeneracy, cut-and-count provides more model-independent limit
  - Below: two-fold mass degeneracy uses BDT

  95% CL constraints for $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \in$ 2–100 GeV:
    - **up to 300 GeV for $m(\tilde{e})$**
    - **up to 350 GeV for $m(\tilde{\mu})$**





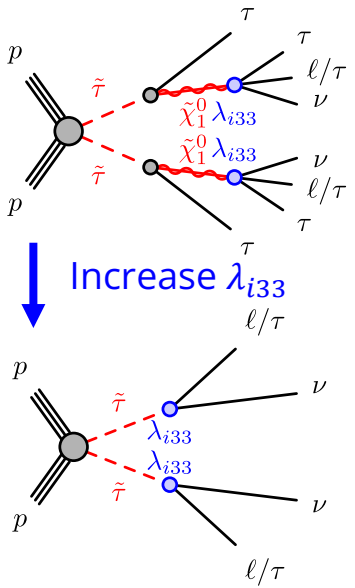
RPV reinterpretation of tau final states (1)

SUSY-2023-25
[ATL-PHYS-PUB-2024-007]

- ***R*-parity violation (RPV)** allows baryon and lepton number violation, and the **lightest superpartner (LSP) to decay to SM particles**
  - Couplings must be smaller to be phenomenologically viable
- RPV superpotential has coupling λ of lepton doublets L_i and singlets E_i

$$\mathcal{W}_{\text{RPV}} \supset \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k$$

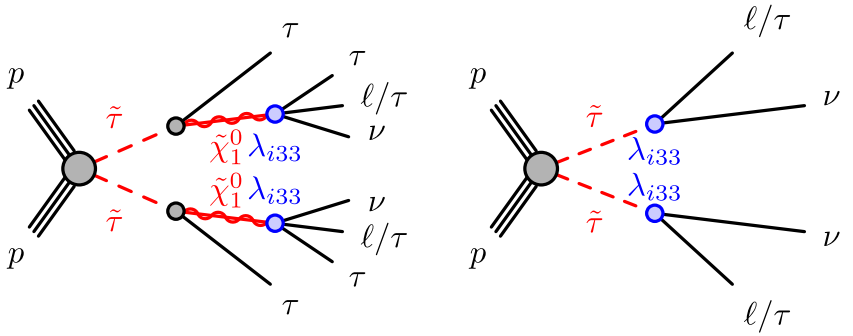
- Focus on couplings to **third-generation τ**:
  - $\boldsymbol{\lambda_{133}}$ with e or $\boldsymbol{\lambda_{233}}$ with μ
- Small $\boldsymbol{\lambda_{i33}}$ leads to long-lived LSP escaping detector: covered by RPC searches with $E_{\text{T}}^{\text{miss}}$
- **Intermediate $\boldsymbol{\lambda_{i33}}$** leads to displaced then prompt LSP decays, then even prompt next-to-LSP decays



RPV reinterpretation of tau final states (2)

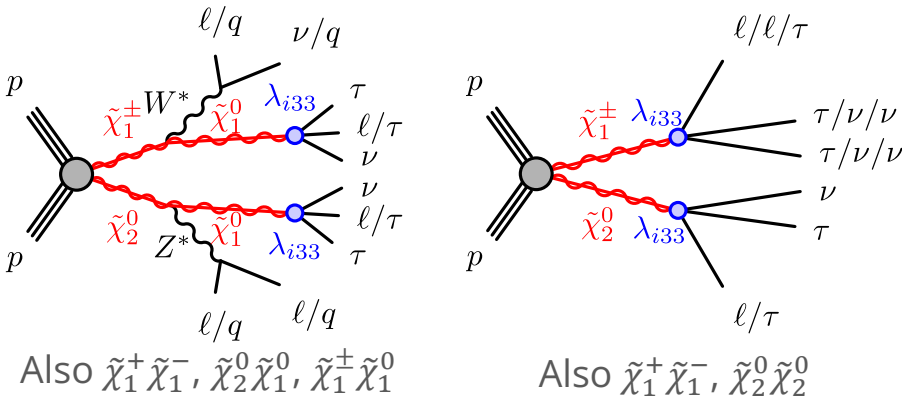
SUSY-2023-25
[ATL-PHYS-PUB-2024-007]

- Stau model
  - $\tilde{\tau}^+\tilde{\tau}^-$ **pair-production**
  - Motivation: Light $\tilde{\tau}$ with similar mass to $\tilde{\chi}_1^0$ can coannihilate, explain DM relic density



Increase λ_{i33}

- Higgsino model
  - near-degenerate (0.25 GeV apart) **Higgsino triplet $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ production**
  - Motivation: EWK naturalness requires light higgsinos



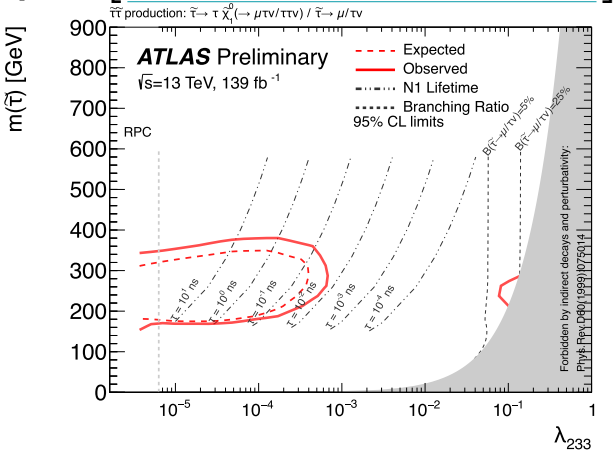
Also $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$

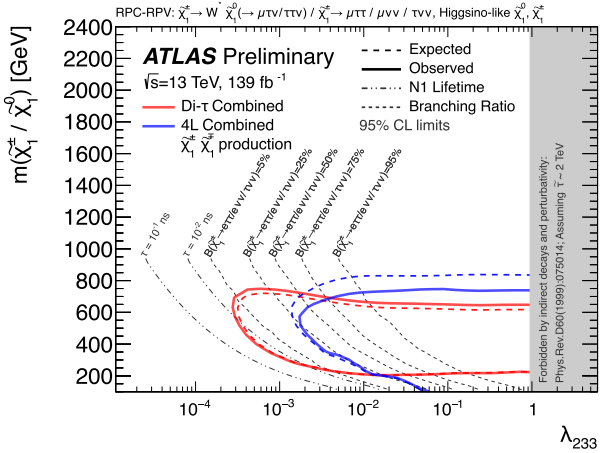
Also $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$

RPV reinterpretation of tau final states (3)

SUSY-2023-25
[ATL-PHYS-PUB-2024-007]

- Reinterpretation of two searches:
  - Di-tau analysis (opposite-charge hadronic taus)
  - 4 Lepton analysis (≥ 2 light, ≤ 2 hadronic taus)
- **$m(\tilde{\tau}) \in [180, 340]$ GeV excluded at 95% CL for $\tilde{\chi}_1^0$ lifetimes exceeding 10^{-1} ns**
  - Left "lobe" from RPC-like unreconstructed $\tilde{\chi}_1^0$, right "lobe" from direct $\tilde{\tau}$ decays in di-tau
- **Higgsino mass excluded up to 800 GeV in scenarios with lifetimes below 10^{-3} ns**
  - Longer lifetimes lead to non-prompt leptons in cascade decays





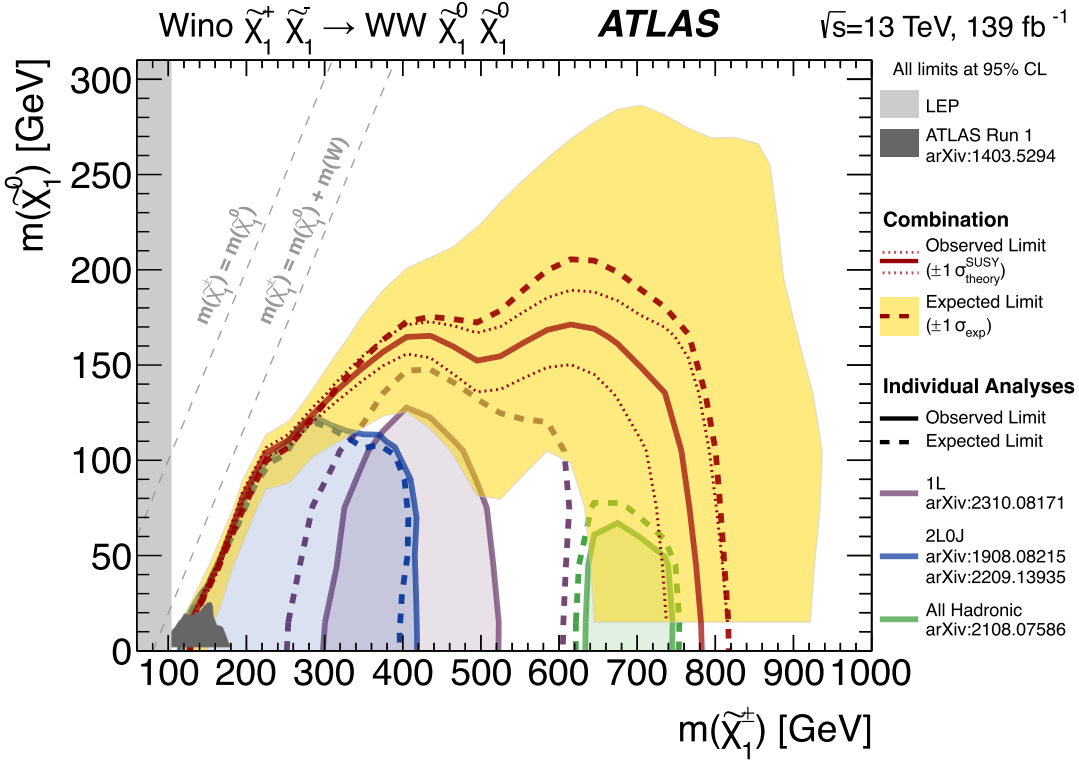
Conclusion

- Several interesting Run 2 results:
  1) SUSY-2020-05 EWK simplified model combinations
  2) SUSY-2020-04 Compressed higgsinos with displaced tracks
  3) HMBS-2024-11 Slepton–Bino–Higgsino model
  4) HMBS-2024-64 Compressed sleptons
  5) ATL-PHYS-PUB-2024-007 RPV reinterpretation of tau final states
  - ➢ For more, see our EWK pMSSM scan, Run 2 report, Run 2 summary plots
- Many thanks to the physics and analysis teams, detector and accelerator operators for all their hard work!
- More Run 2 results on the way, looking forward to Run 3 analyses and combinations!

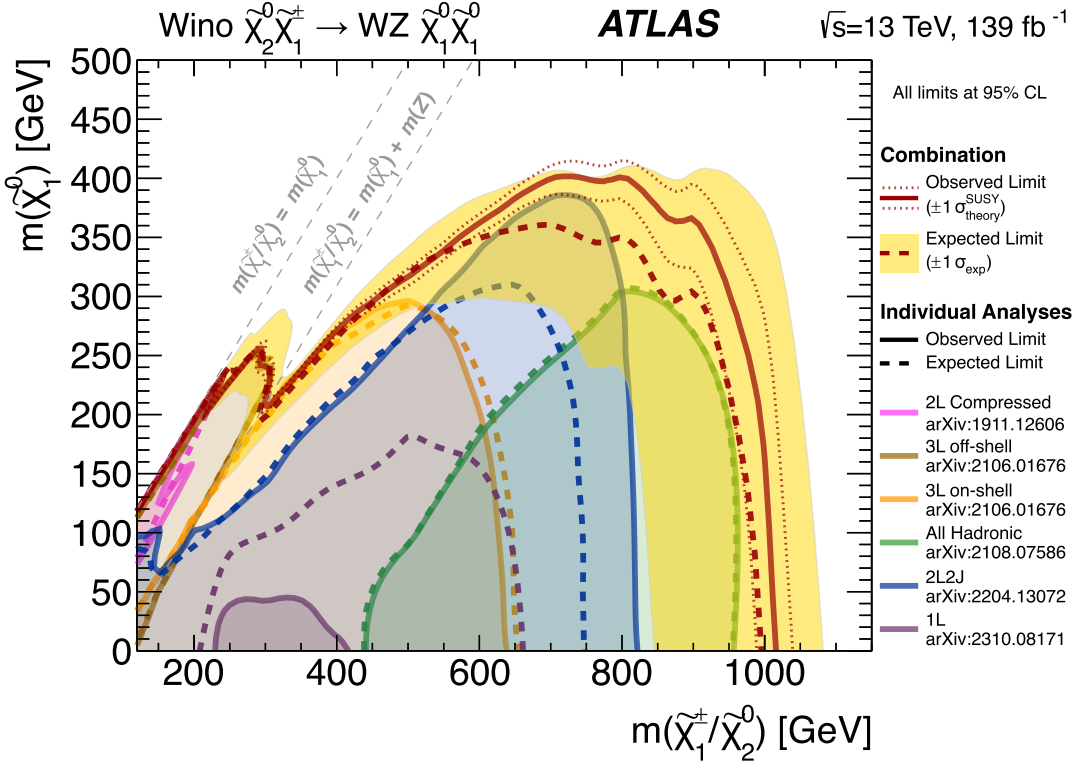
Thank you for your time!

Backup

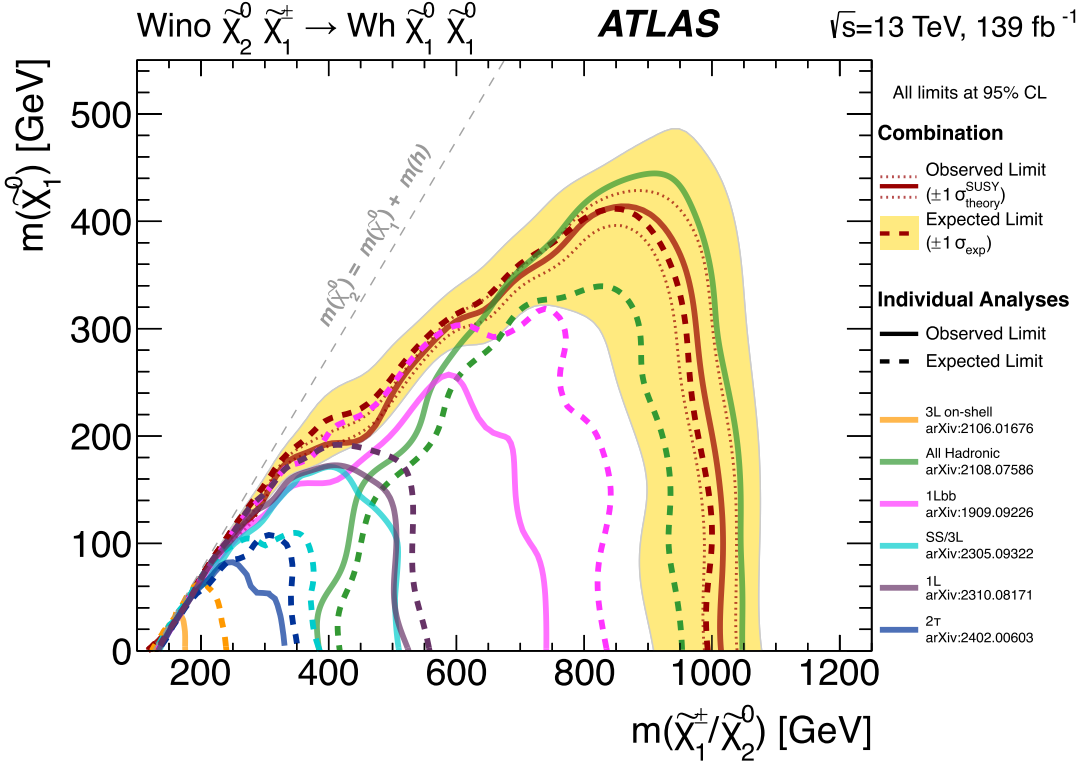
SUSY-2020-05
[arXiv:2402.08347]



SUSY-2020-05
[arXiv:2402.08347]



SUSY-2020-05
[arXiv:2402.08347]



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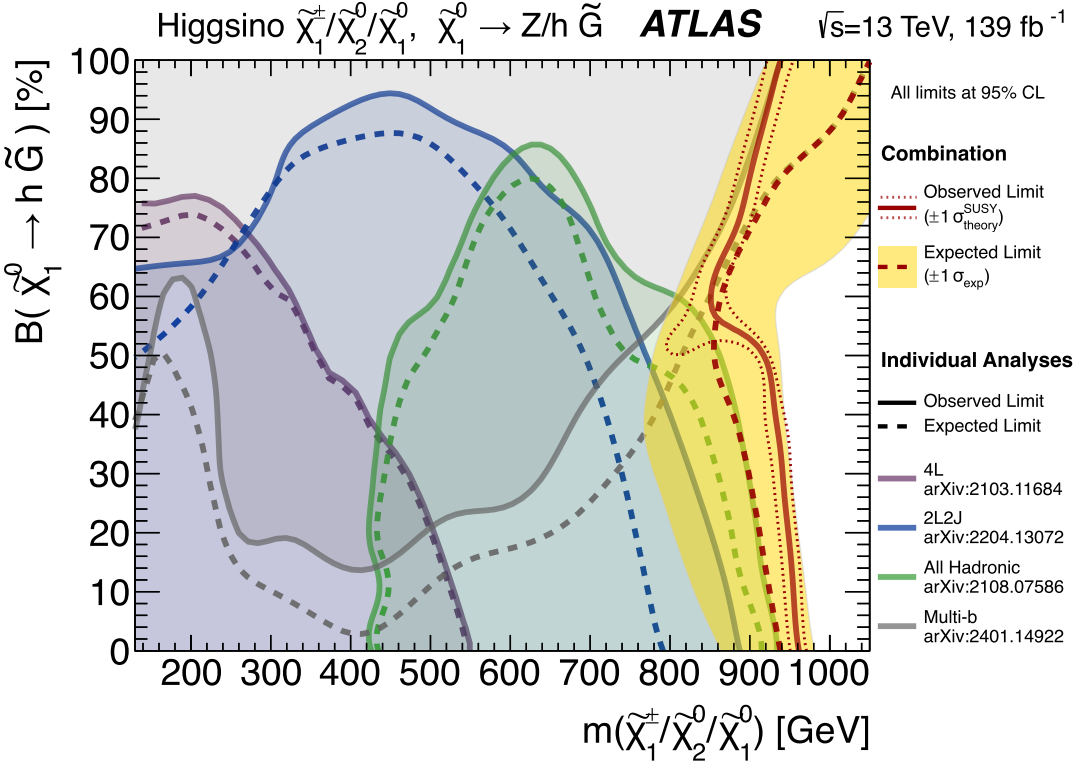

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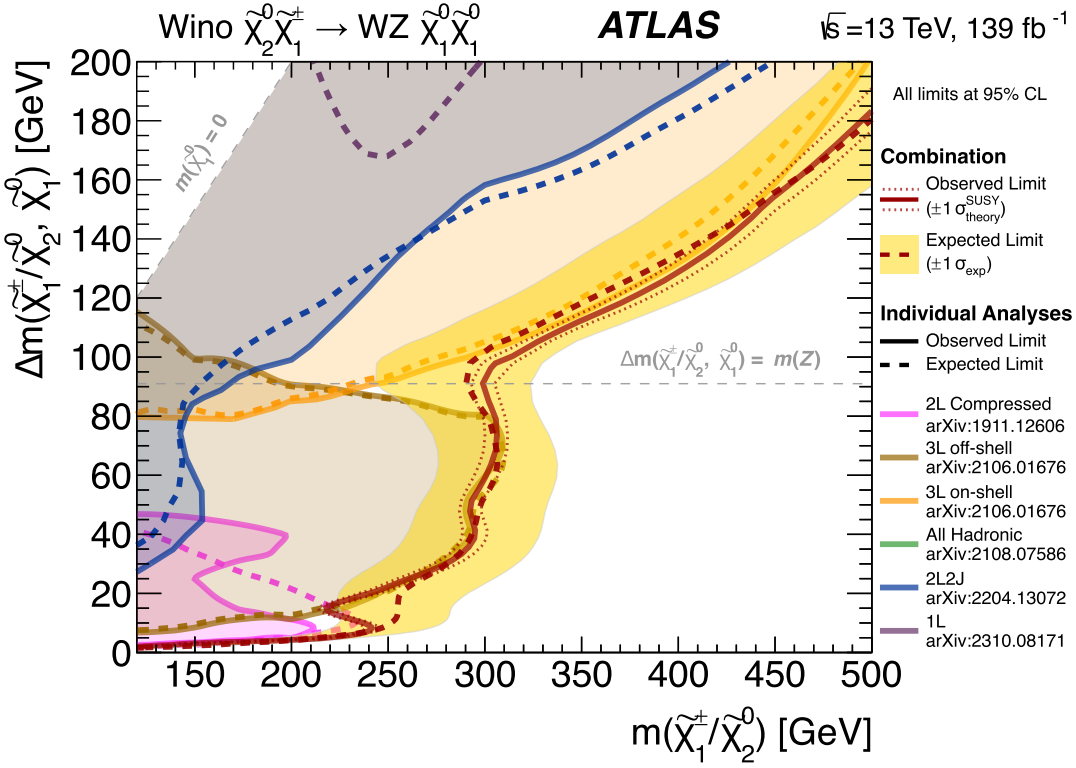

SUSY-2020-04
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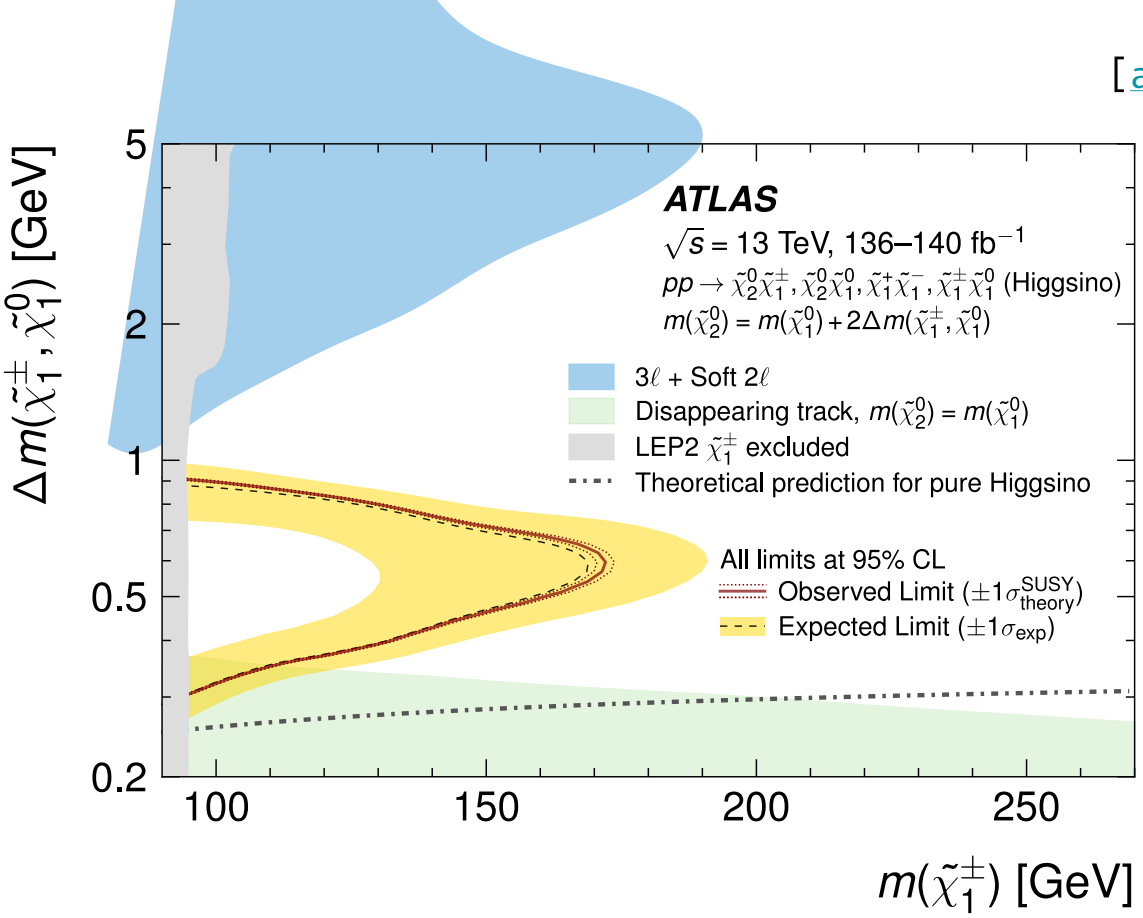
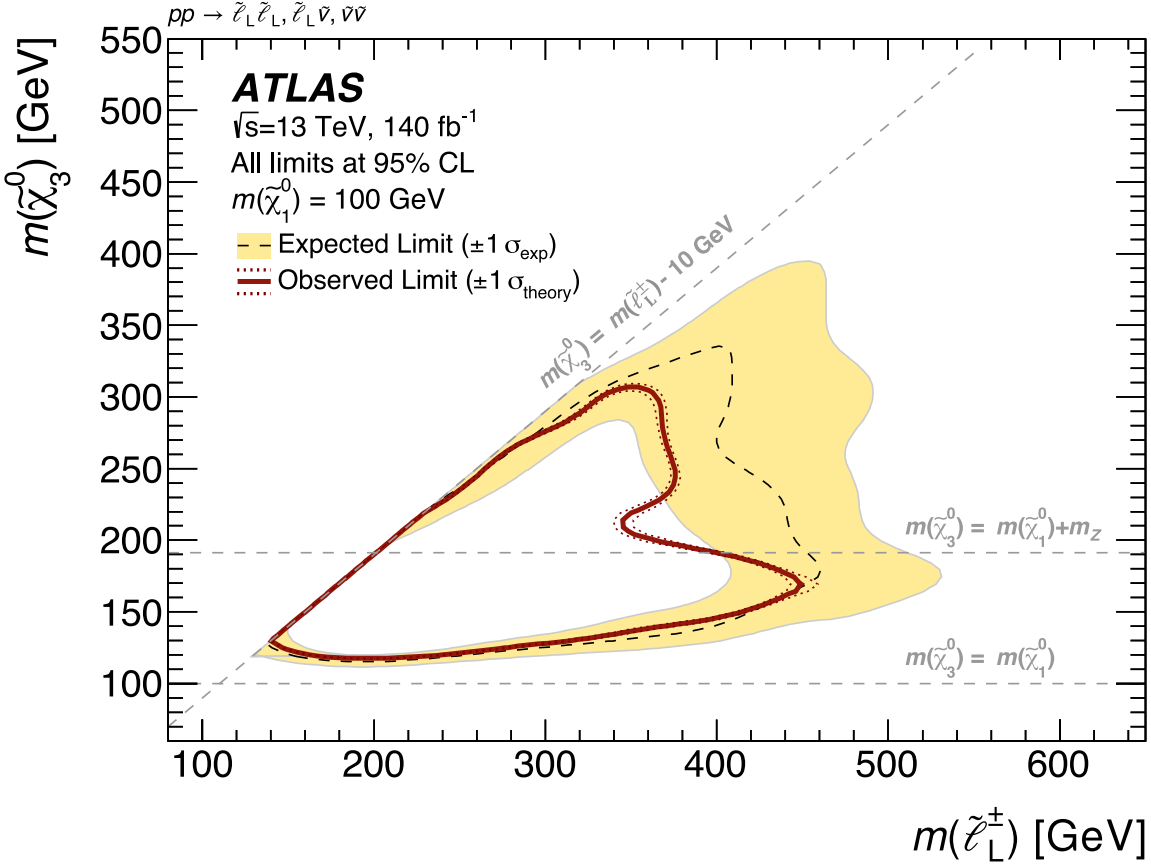


HMBS-2024-11
[arXiv:2503.13135]



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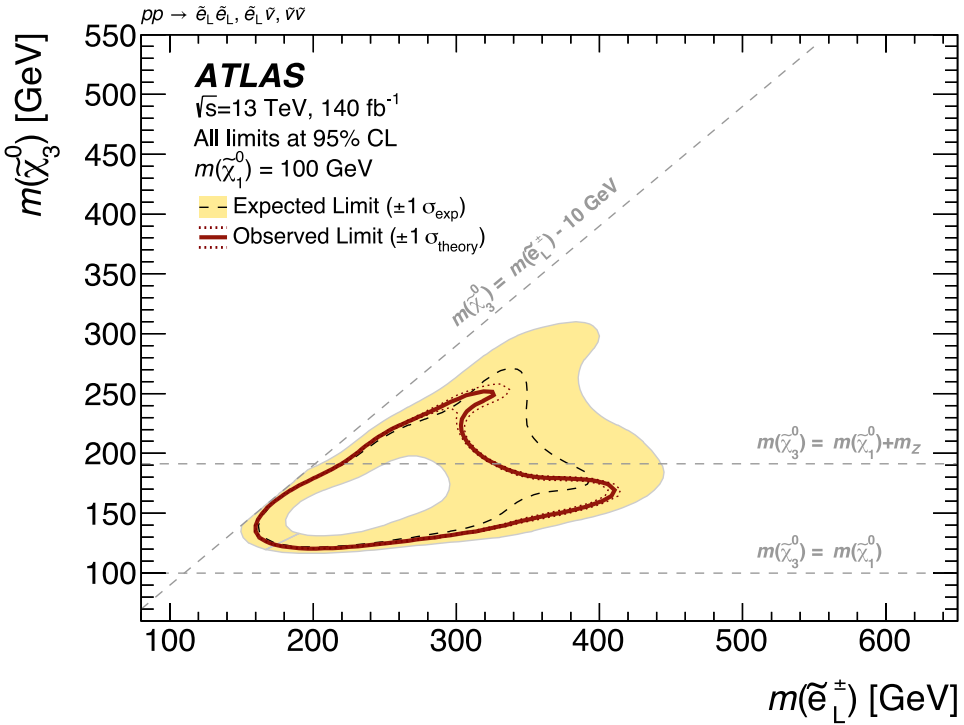

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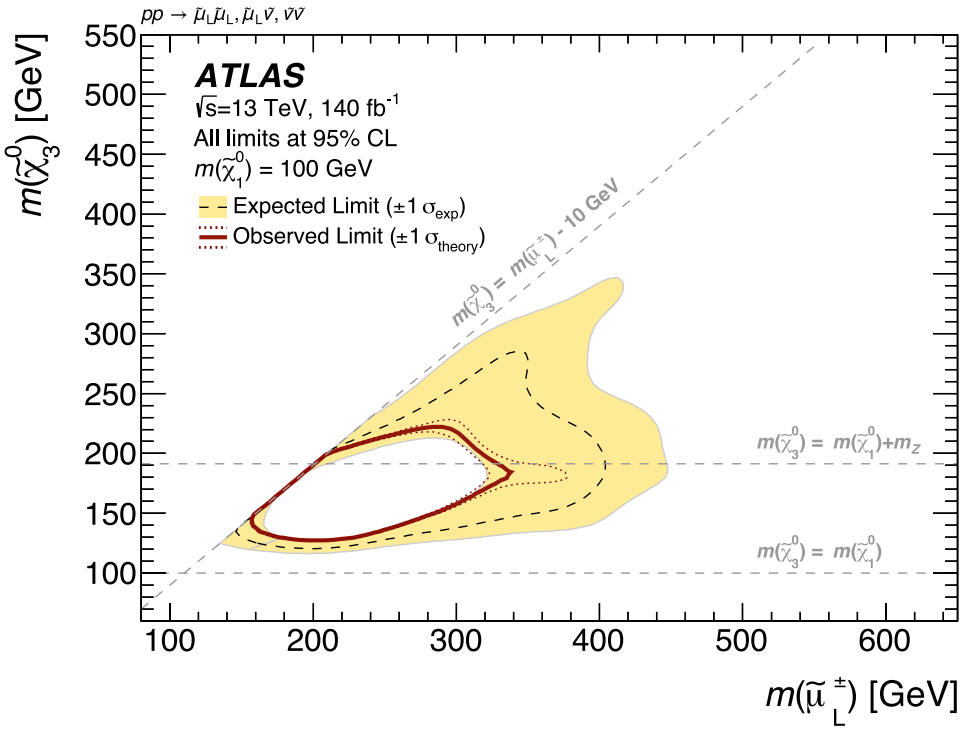


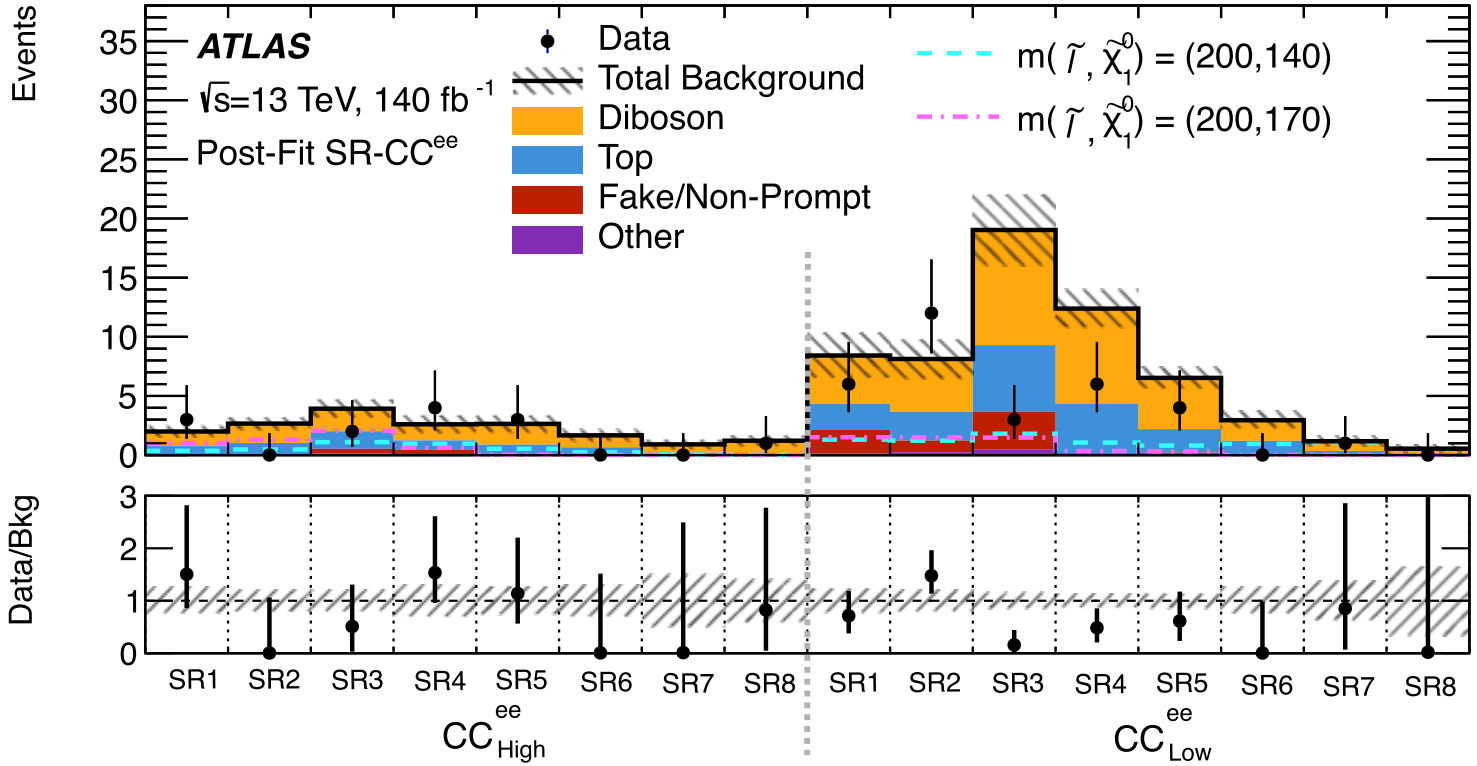
4 m_{T2}^{χ} definition

HMBS-2024-64
[arXiv:2503.17186]

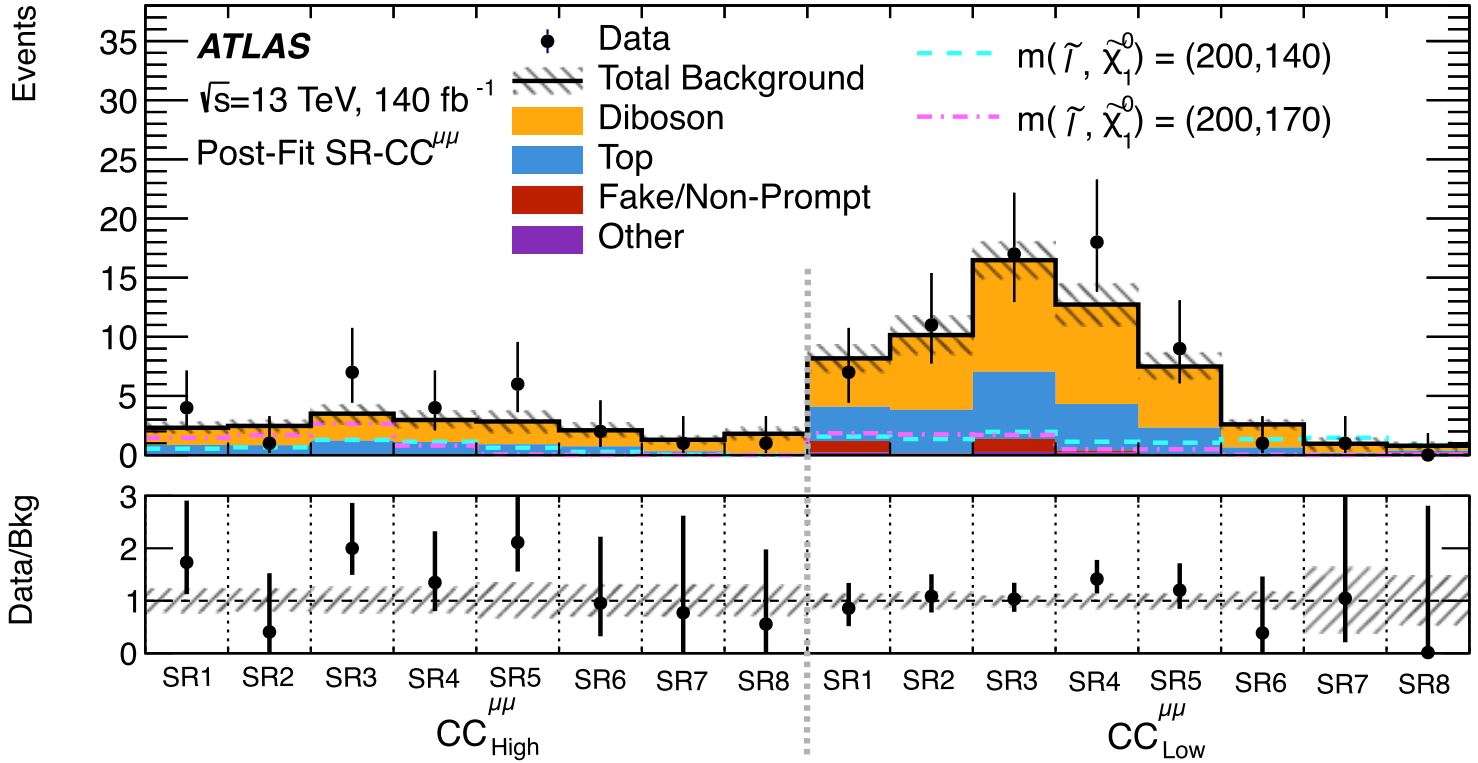
$$m_T(\boldsymbol{p}_{\mathrm{T}}, \boldsymbol{q}_{\mathrm{T}}, m_\chi) = \sqrt{m_\ell^2 + m_\chi^2 + 2\left(E_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{q} - \boldsymbol{p}_{\mathrm{T}} \cdot \boldsymbol{q}_{\mathrm{T}}\right)}$$

$$m_{\mathrm{T2}}^{\chi}\left(\boldsymbol{p}_{\mathrm{T},1}, \boldsymbol{p}_{\mathrm{T},2}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}\right) = \min_{\boldsymbol{q}_{\mathrm{T},1}+\boldsymbol{q}_{\mathrm{T},2}=\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}} \max\left\{m_T\left(\boldsymbol{p}_{\mathrm{T},1}, \boldsymbol{q}_{\mathrm{T},1}, m_\chi\right), m_T\left(\boldsymbol{p}_{\mathrm{T},2}, \boldsymbol{q}_{\mathrm{T},2}, m_\chi\right)\right\}$$

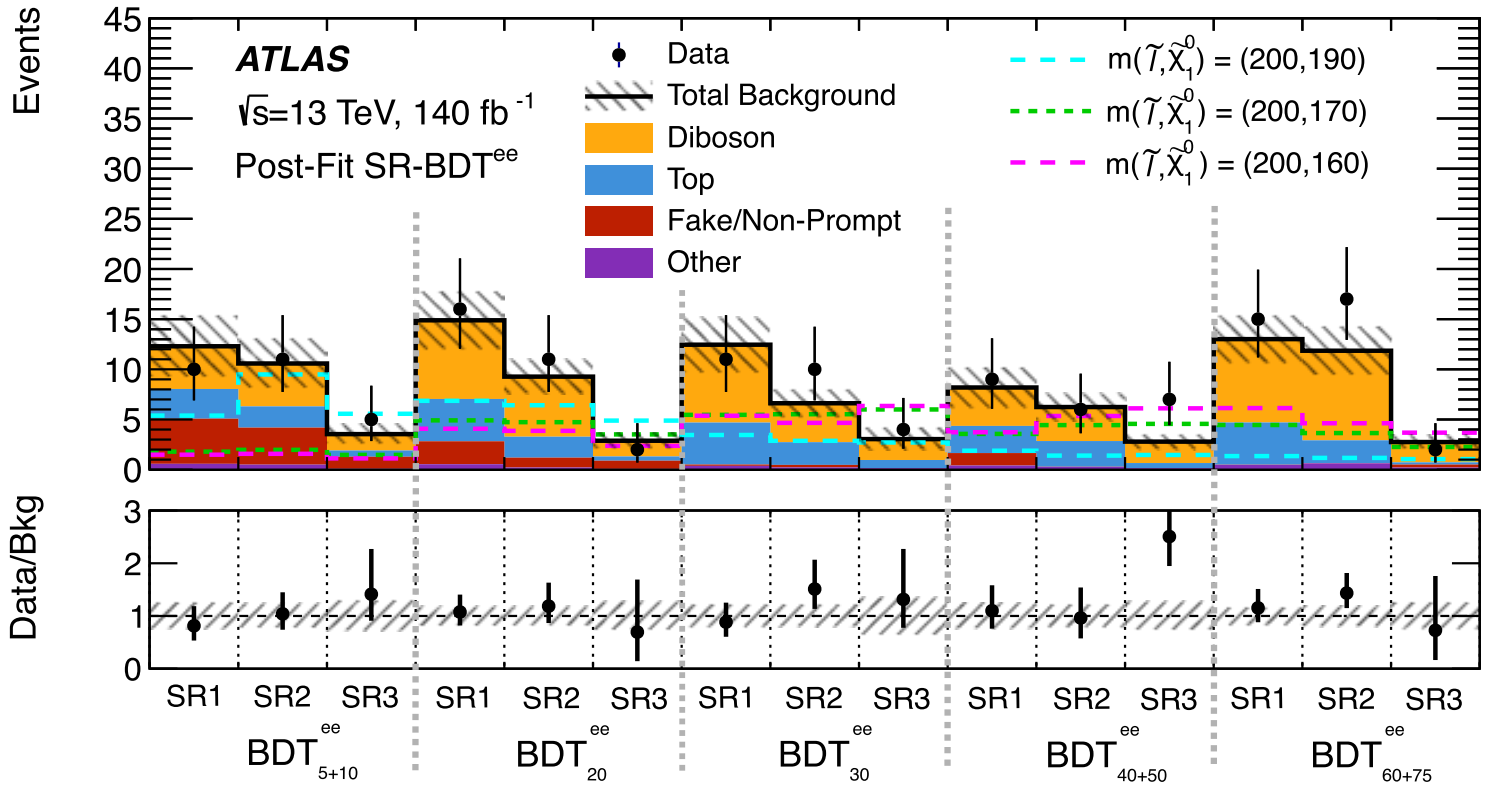
HMBS-2024-64
[arXiv:2503.17186]



HMBS-2024-64
[arXiv:2503.17186]



HMBS-2024-64
[arXiv:2503.17186]



HMBS-2024-64
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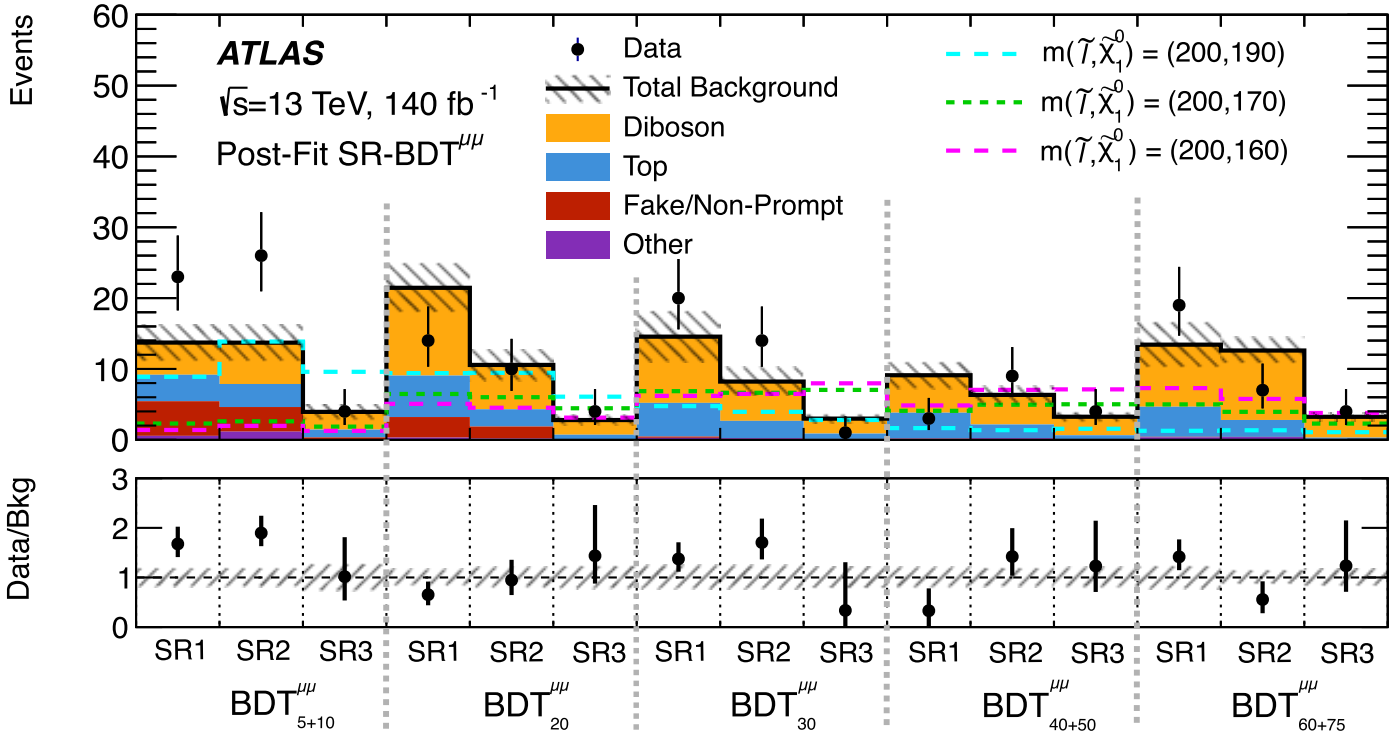

HMBS-2024-64
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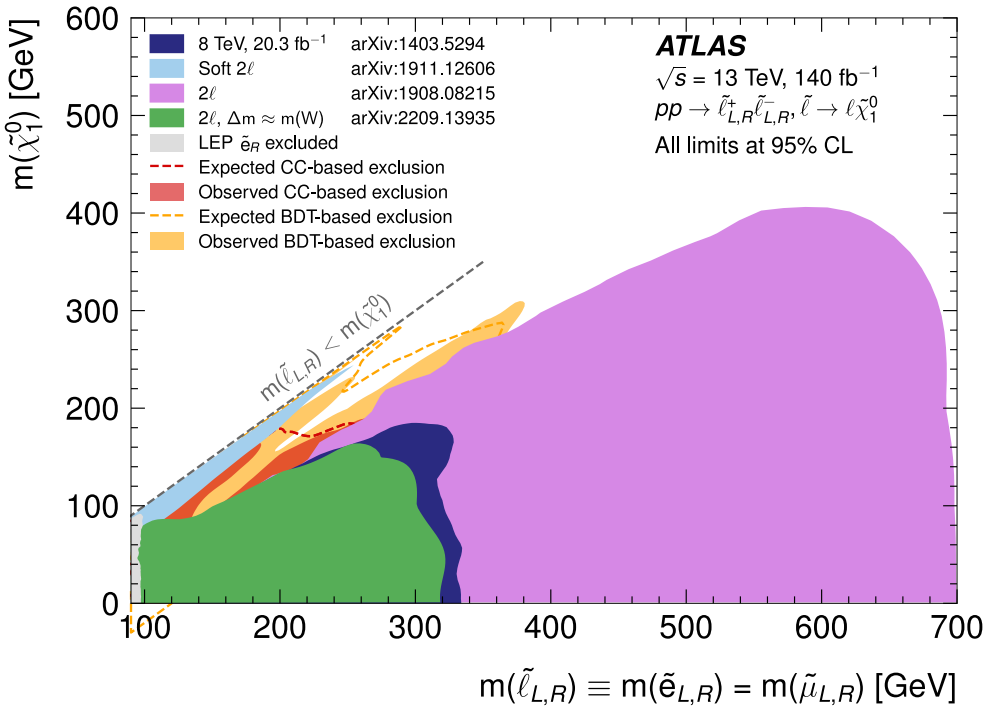
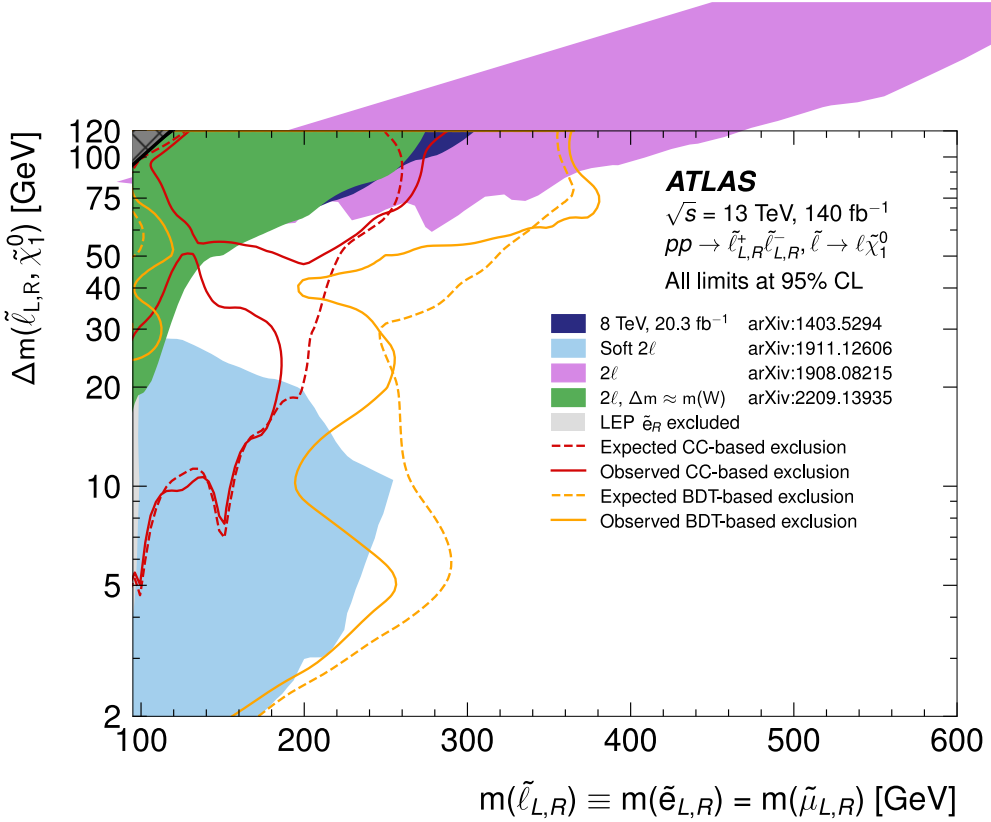


HMBS-2024-64
[arXiv:2503.17186]



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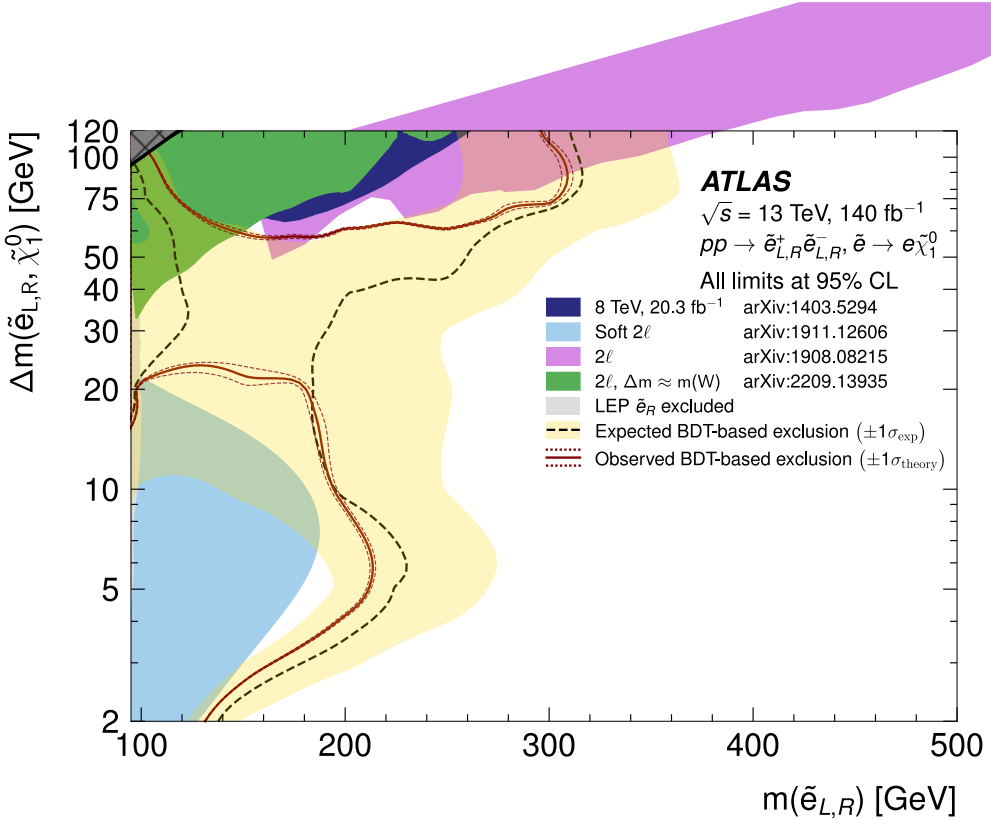

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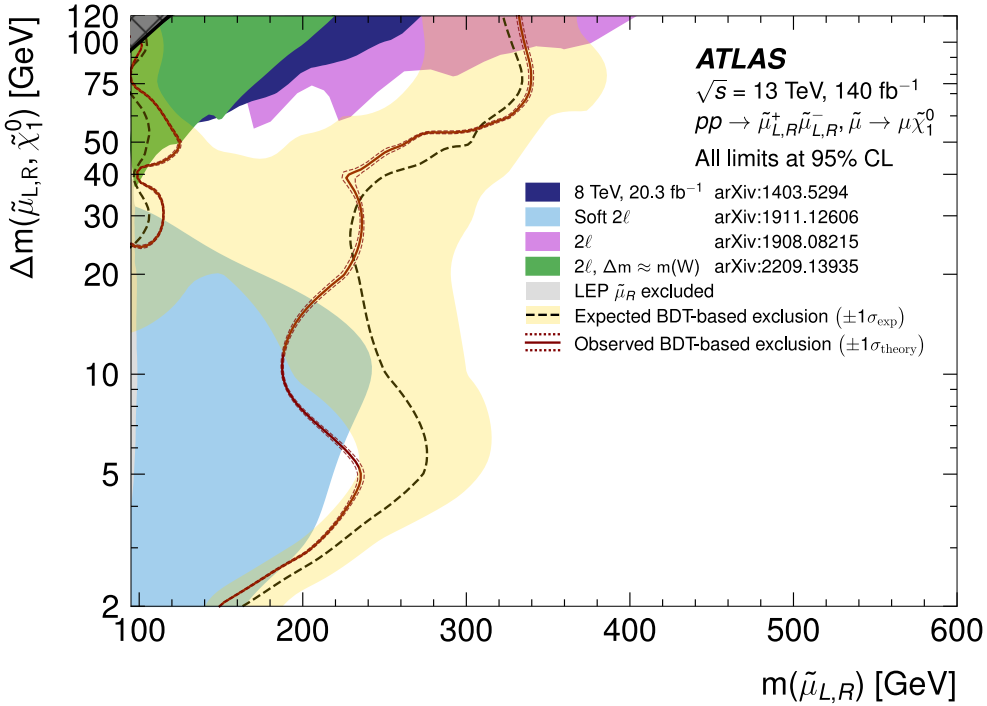
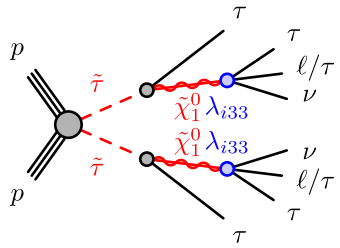
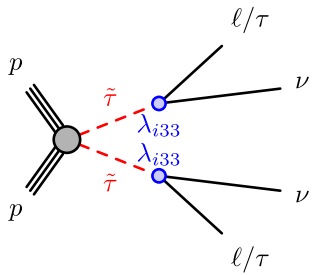
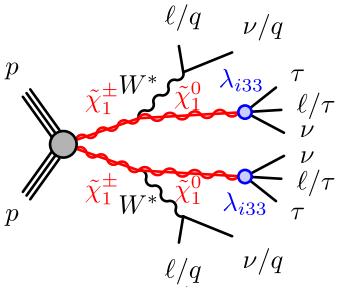


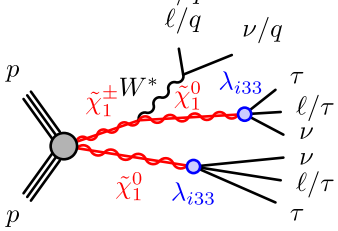
SUSY-2023-25
[ATL-PHYS-PUB-2024-007]

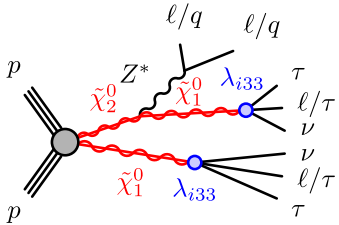


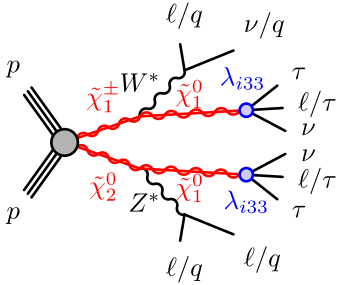


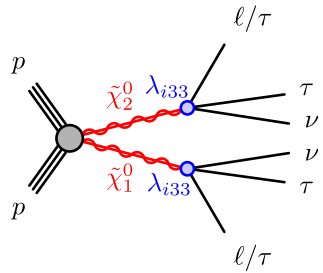
Increasing λ_{i33}

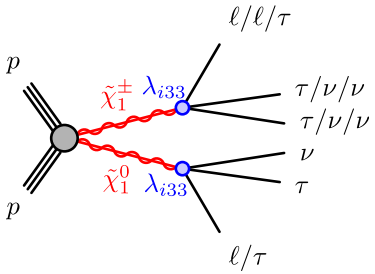


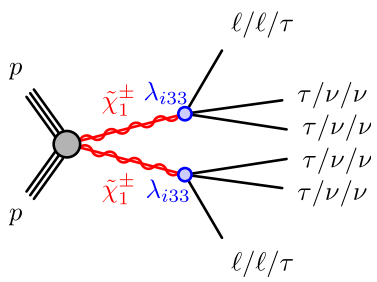


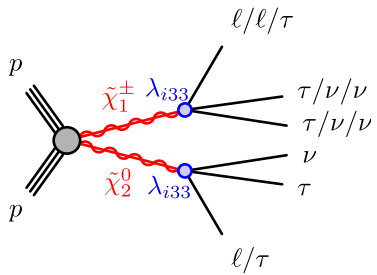




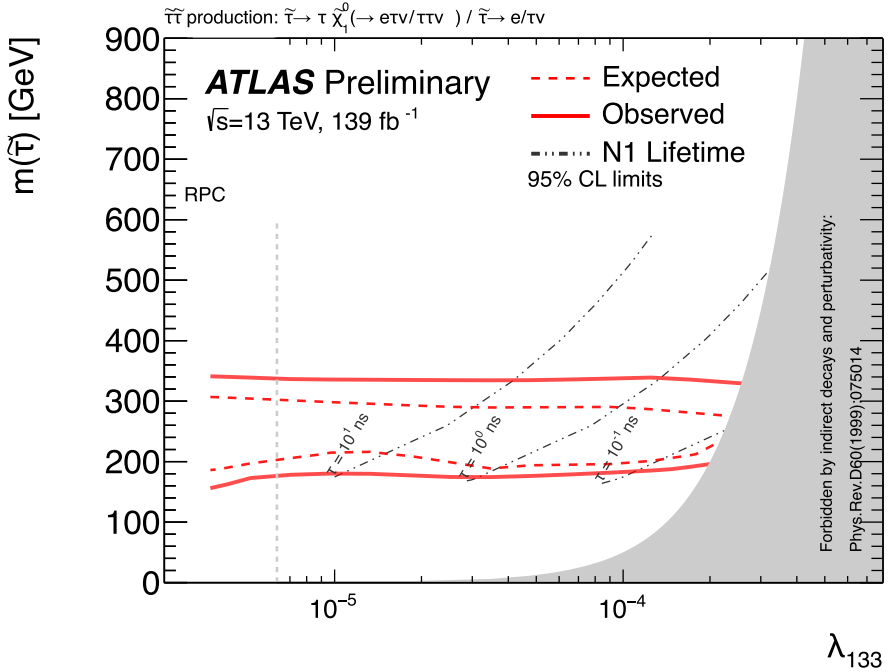


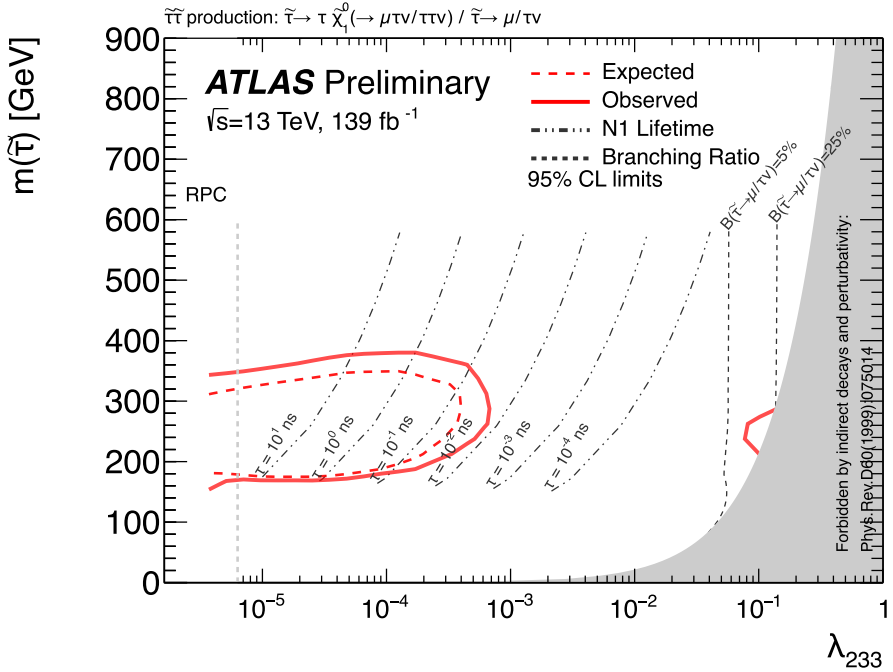




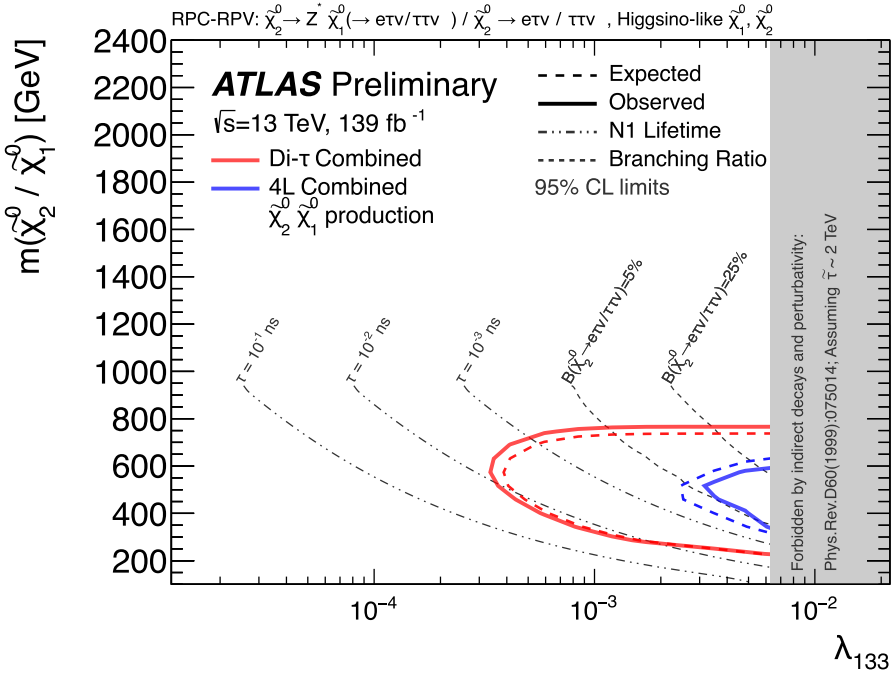


SUSY-2023-25
[ATL-PHYS-PUB-2024-007]

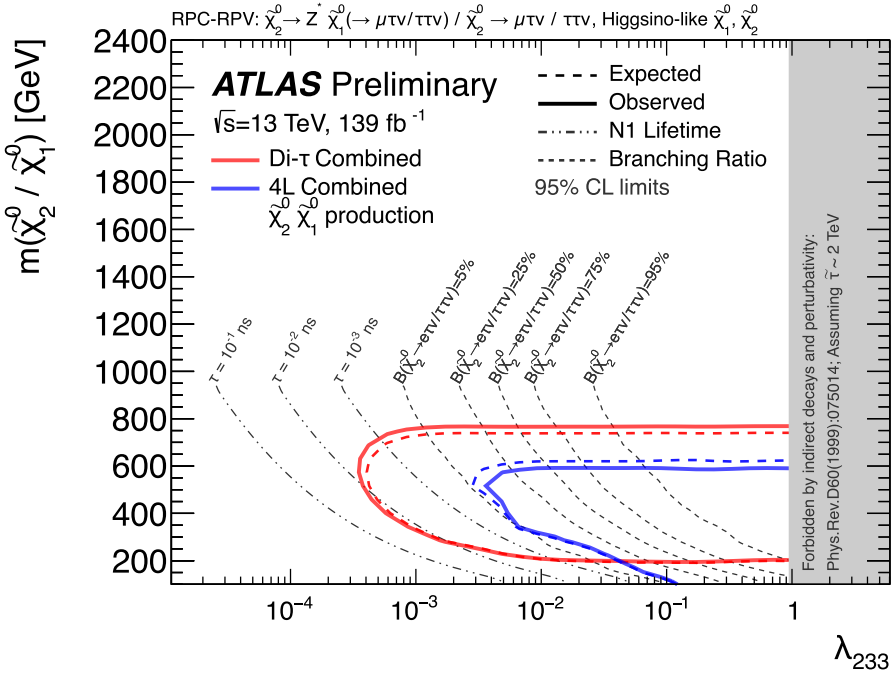



$\tilde{\tau}\tilde{\tau}$ production: $\tilde{\tau} \to \tau\, \tilde{\chi}_1^0 (\to \mu\tau\nu/\tau\tau\nu)$ / $\tilde{\tau} \to \mu/\tau\nu$
ATLAS Preliminary
$\sqrt{s}$=13 TeV, 139 fb^{-1}
Expected
Observed
N1 Lifetime
Branching Ratio
95% CL limits
RPC
$m(\tilde{\tau})$ [GeV]
λ_{233}
$\tau = 10^{1}$ ns
$\tau = 10^{0}$ ns
$\tau = 10^{-1}$ ns
$\tau = 10^{-2}$ ns
$\tau = 10^{-3}$ ns
$\tau = 10^{-4}$ ns
$B(\tilde{\tau} \to \mu/\tau\nu)$=5%
$B(\tilde{\tau} \to \mu/\tau\nu)$=25%
Forbidden by indirect decays and perturbativity:
Phys. Rev. D80 (1999) 075014

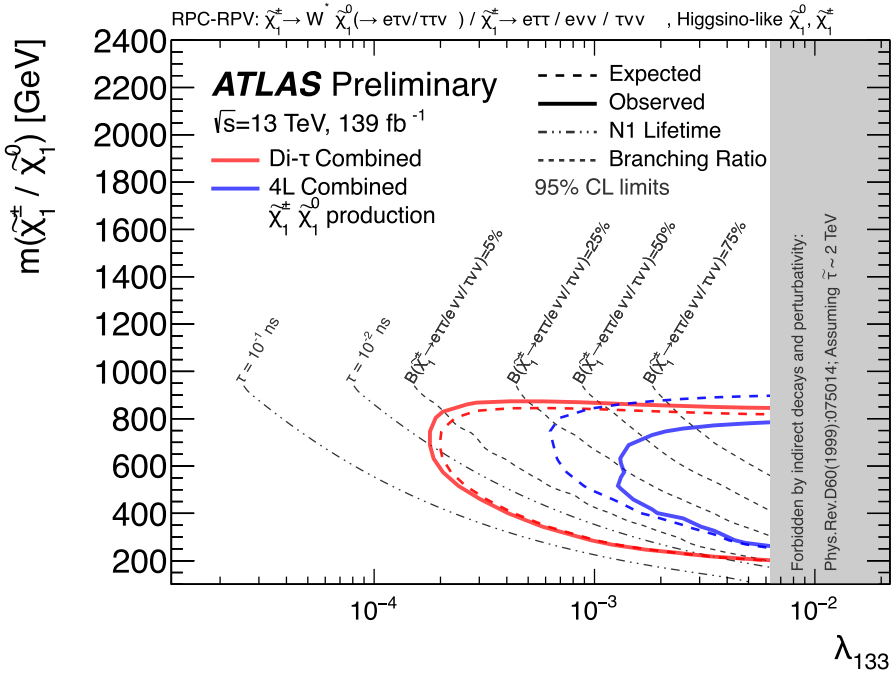
SUSY-2023-25
[ATL-PHYS-PUB-2024-007]



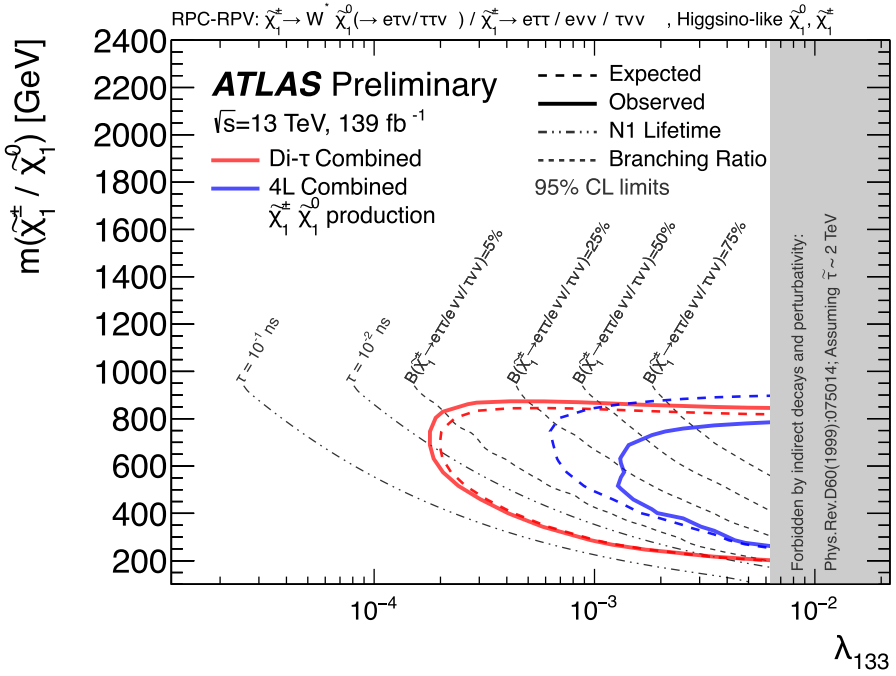
SUSY-2023-25
[ATL-PHYS-PUB-2024-007]



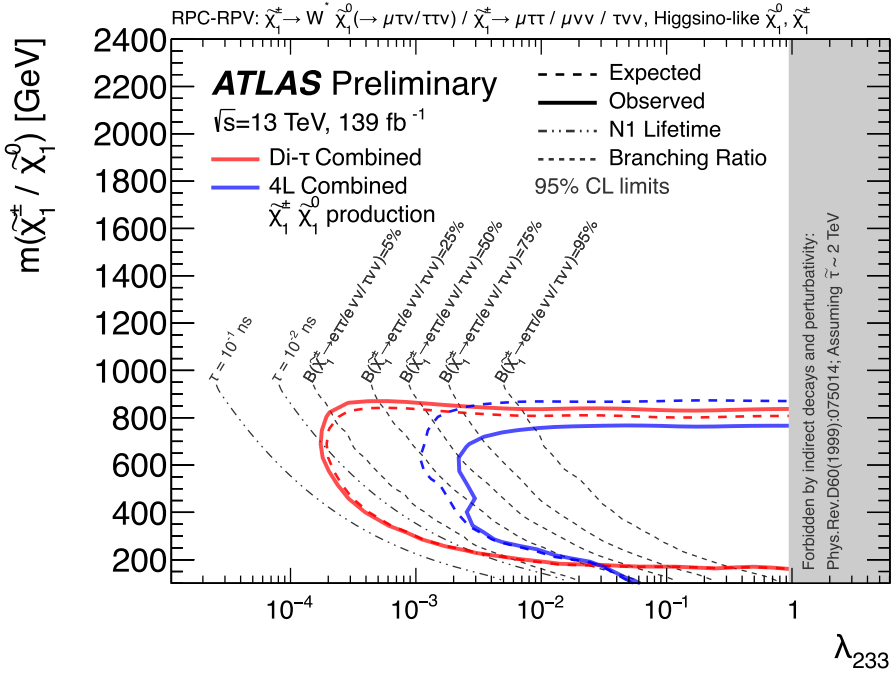
SUSY-2023-25
[ATL-PHYS-PUB-2024-007]



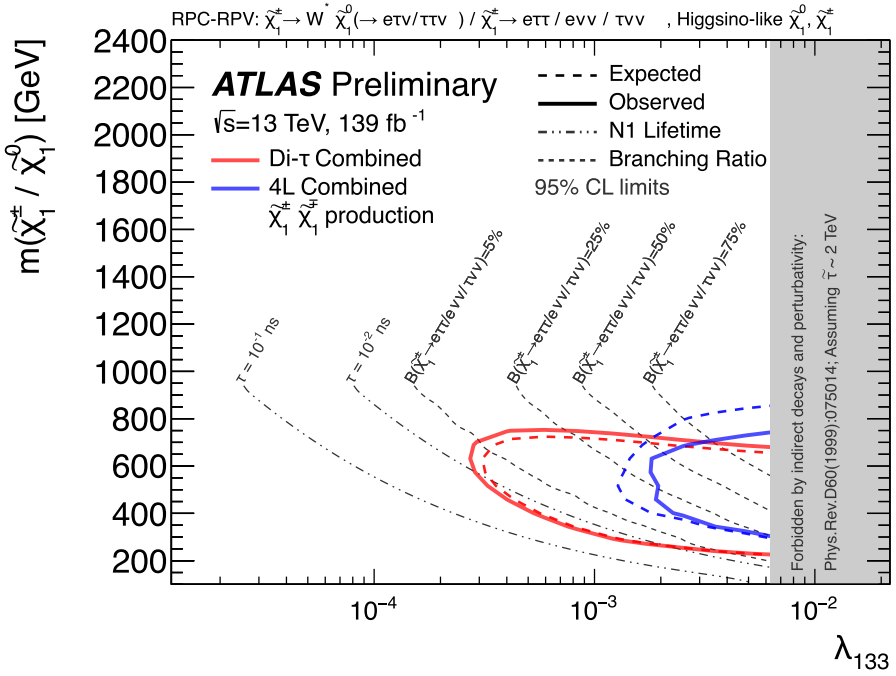
SUSY-2023-25
[ATL-PHYS-PUB-2024-007]



SUSY-2023-25
[ATL-PHYS-PUB-2024-007]



SUSY-2023-25
[ATL-PHYS-PUB-2024-007]



SUSY-2023-25
[ATL-PHYS-PUB-2024-007]