# Status of SUSY searches in ATLAS

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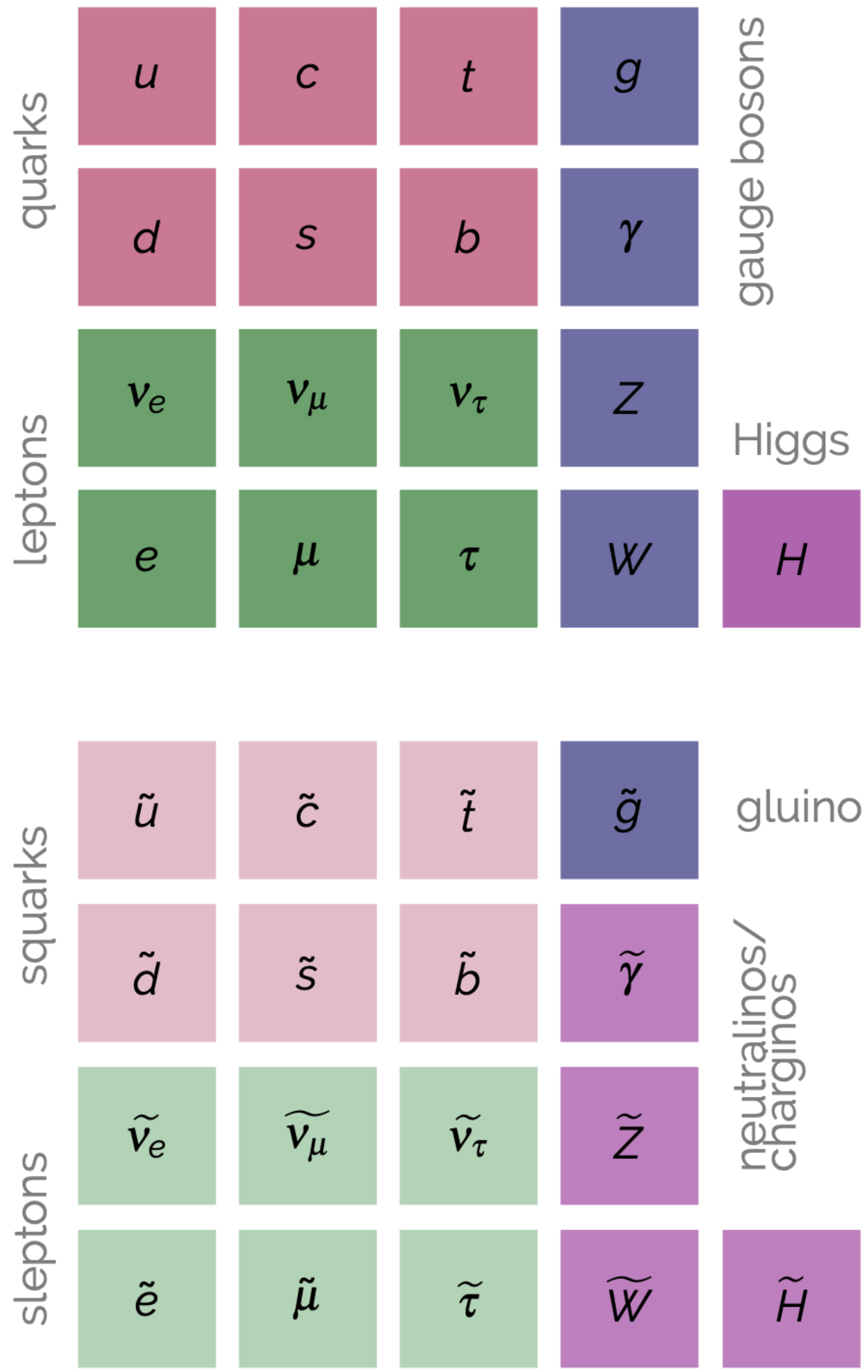
# Introduction

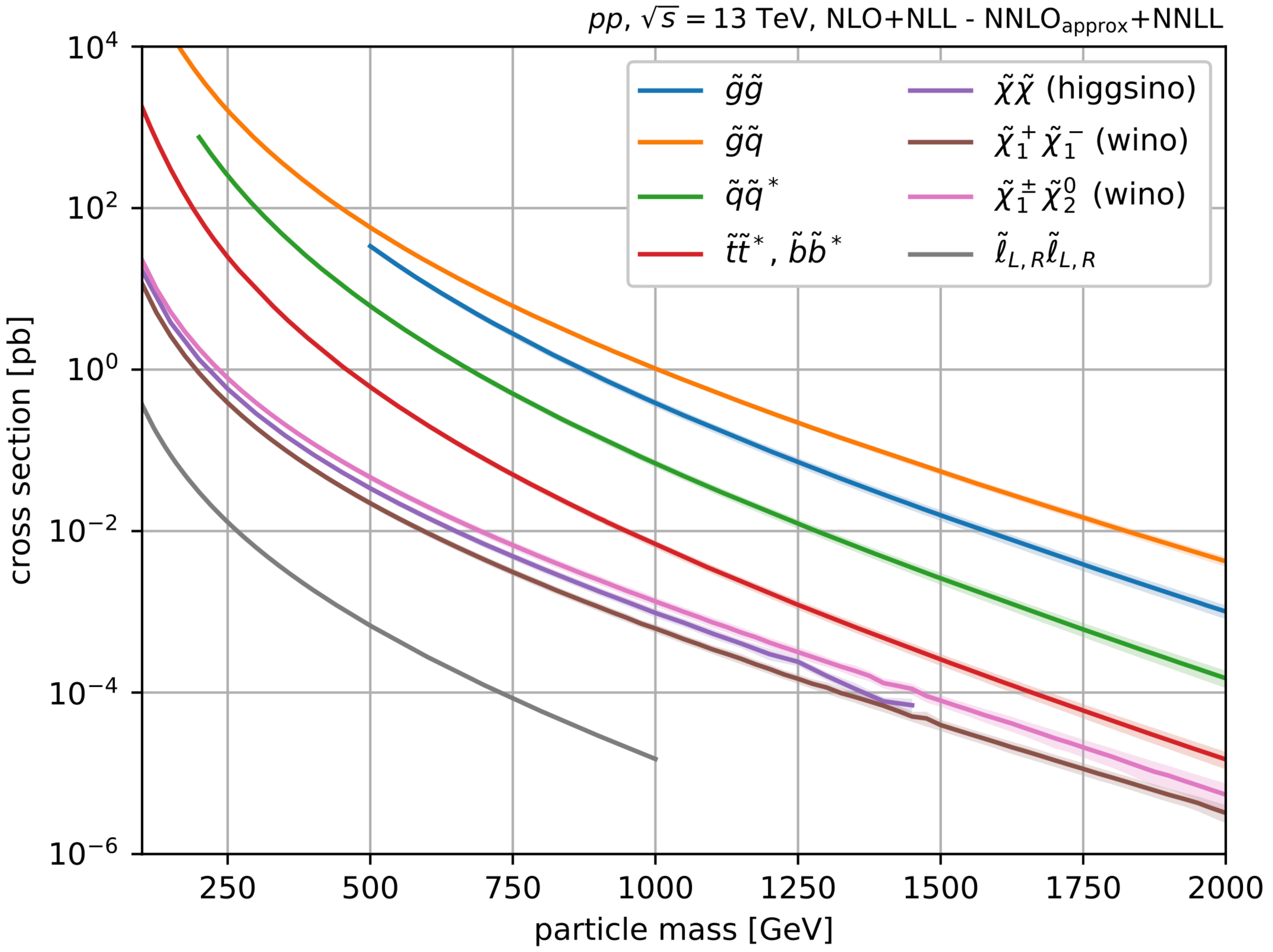
- Supersymmetry (SUSY): promising extension of the SM
  - Additional symmetry relating fermions and bosons
  - Provides natural solution to hierarchy problem
  - Dark matter candidate (if R-parity is conserved)
- SUSY parameter space is huge (SM +105 new parameters)
- Many new particles predicted, some of them can be in the LHC reachable energy
- We reduce the number of parameters to a more manageable number by focusing on very simplified models with well motivated assumptions
  - For example:
    RPC → particles produced in pairs and LSP is stable (MET)
  - Limits on simplified models, not on SUSY



# SUSY searches in ATLAS

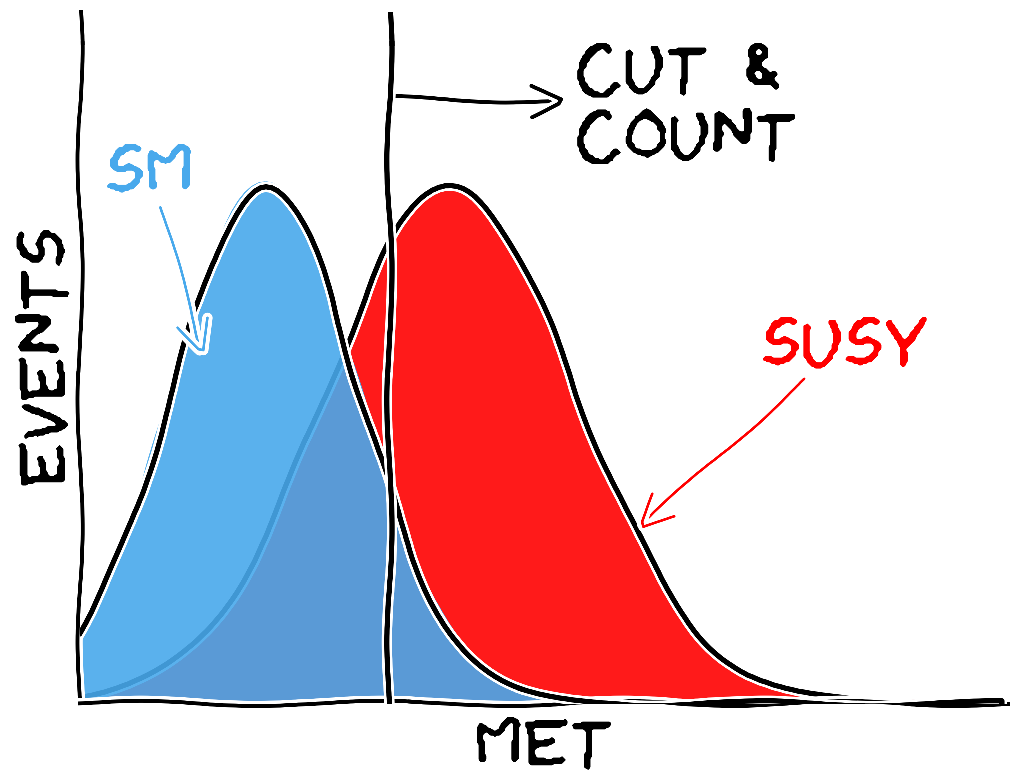
- Comprehensive search programme
- Searches are final state oriented, driven by cross-section and event topology:
  - gluinos/squarks
  - stop/sbottom
  - electroweakinos and sleptons
- Conventional searches with RPC and prompt decays
- Unconventional searches including RPV and long-lived particles
- Combinations and phase space scans
- This talk will cover some of the most recent searches using the full Run-2 data

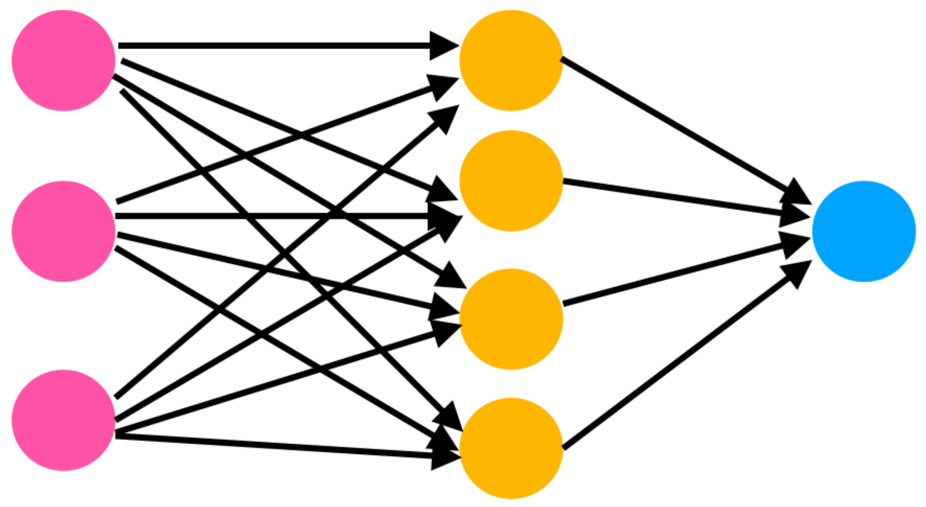
  → $\sqrt{s}$ =13 TeV, ~139 $fb^{-1}$



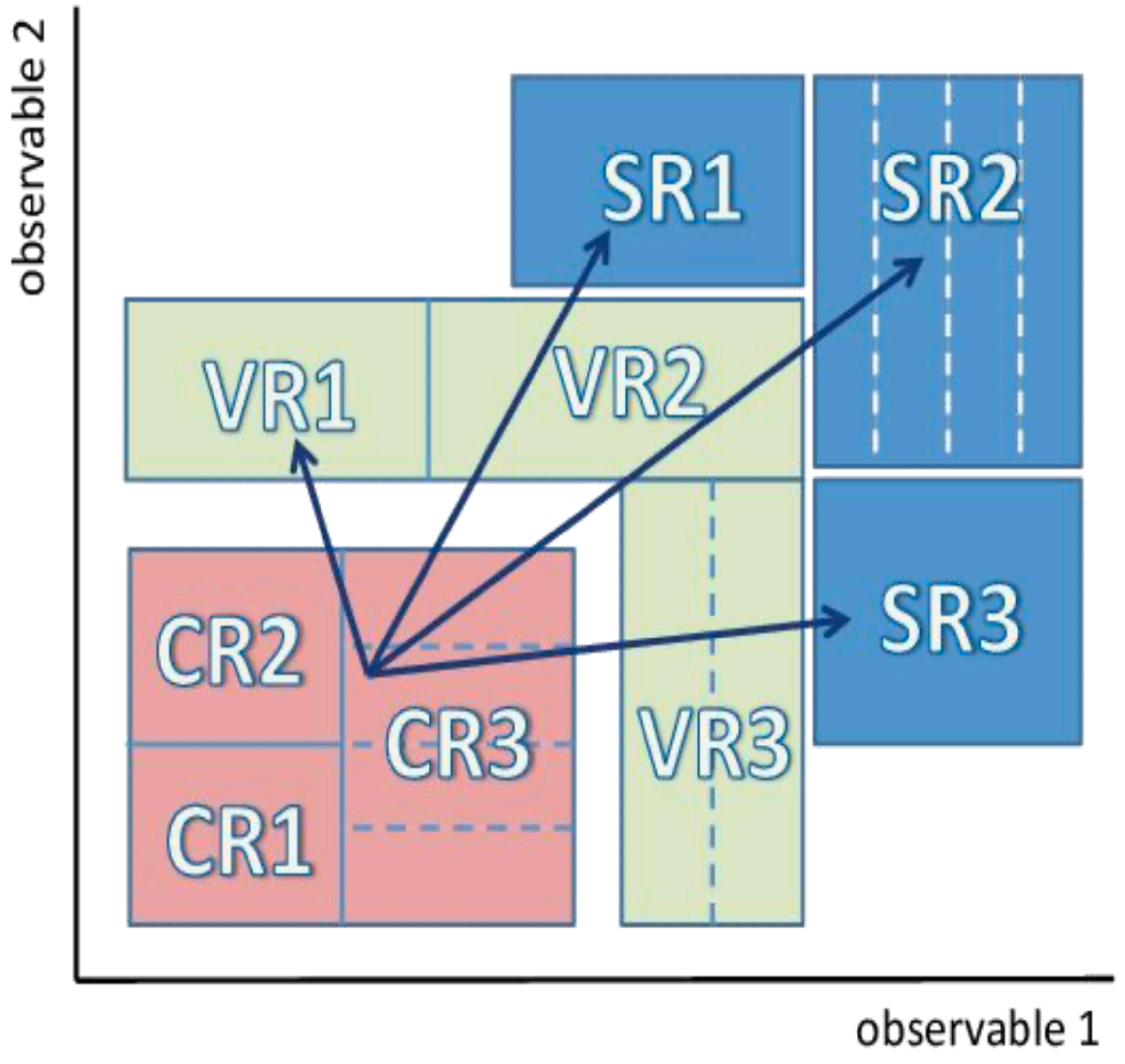
# General analysis strategy

- Signal regions (SR) motivated by SUSY model and enriched optimized to have a good signal/background significance



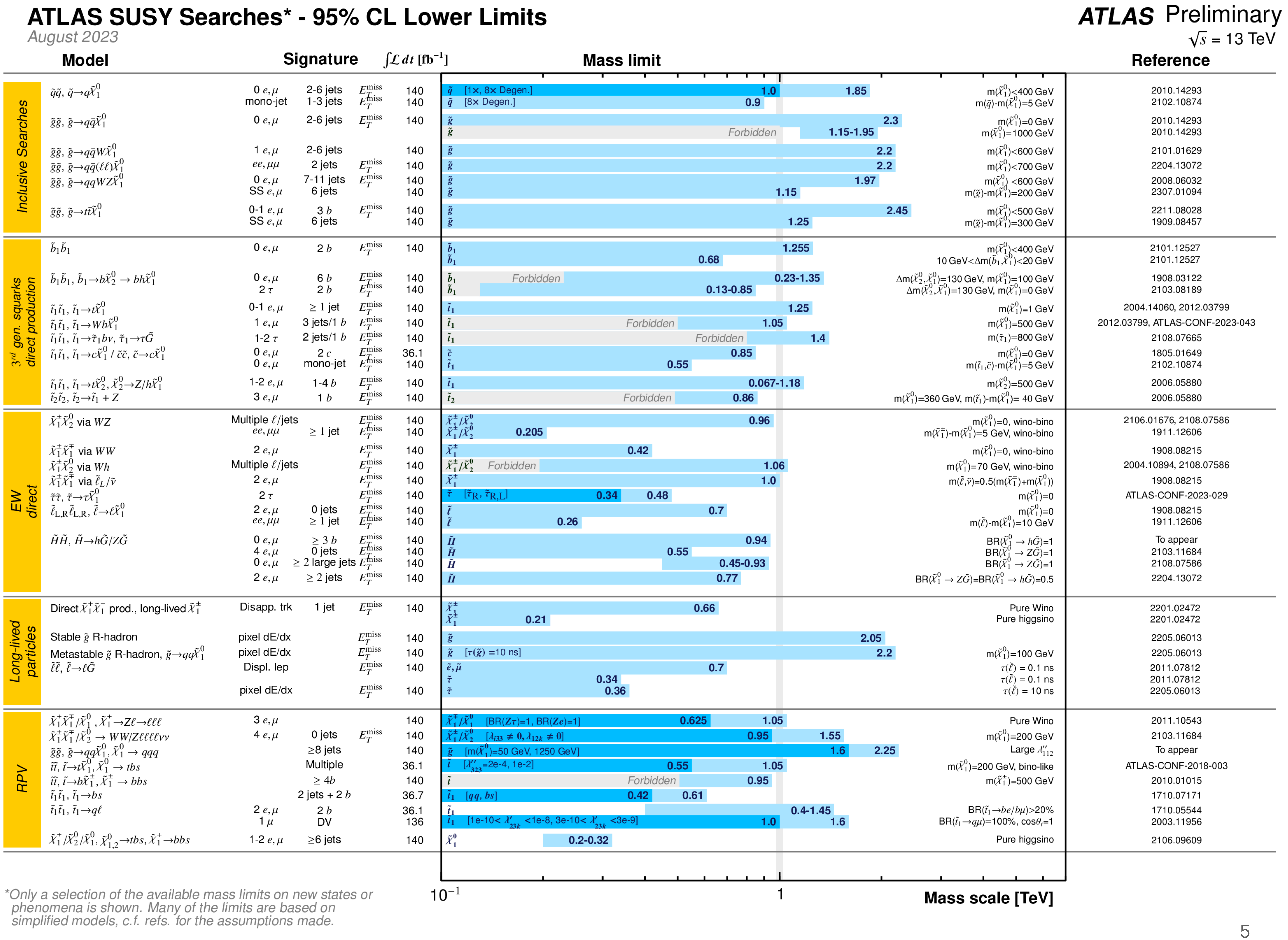
- SM background estimation/modeling
  - Data-driven estimation for fake backgrounds
  - Monte Carlo simulation normalized in dedicated Control Regions (CR)
  - Validation regions (VR) to cross-check estimation in between CR/SR




[1410.1280]

- Statistical interpretation using simultaneous likelihood fit
  - Discovery significance
  - Exclusion limits at 95% CL using CR+SR combined fit for specific SUSY signal model as function of masses and or BR
  - Model independent limits on visible cross section

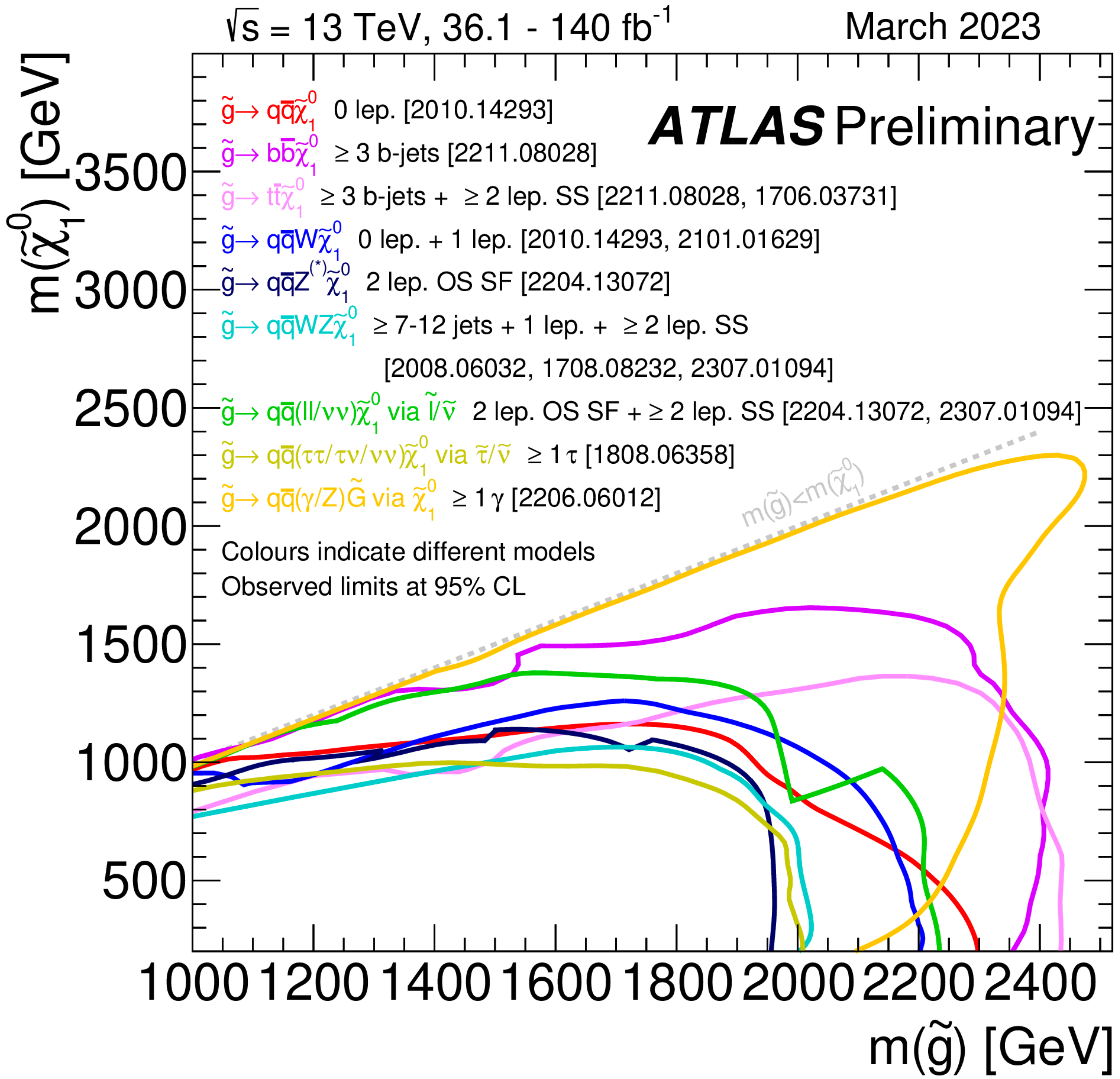
Wide range of searches in ATLAS covering vast regions of SUSY phase space

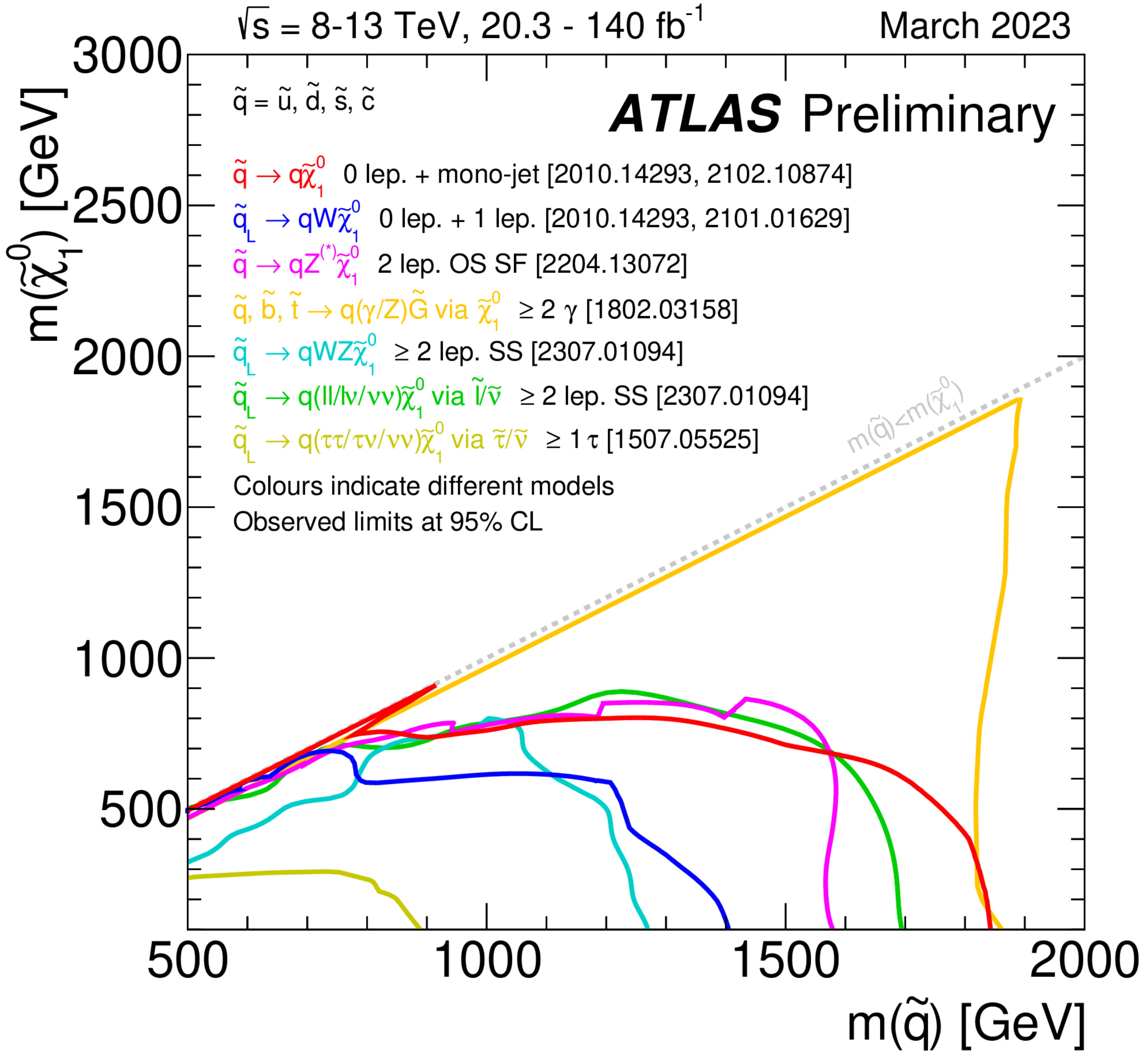



ATLAS Supersymmetry Public Results

# Squarks and gluinos searches

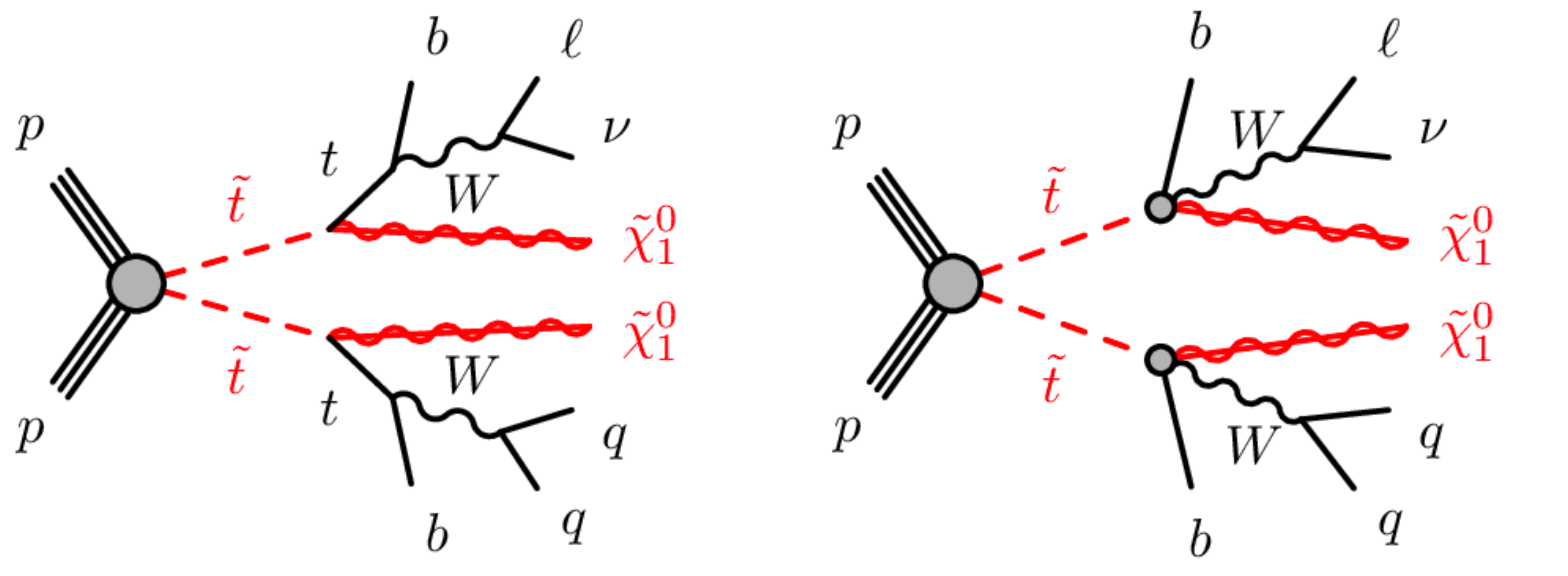
- Analyses covering each corner of the phase space for different gluino/squark decay modes
- Masses excluded up to 1-2 TeV depending the model considered
- Weaker limits in the compressed region for neutralino LSP → work ongoing to improve this with ML

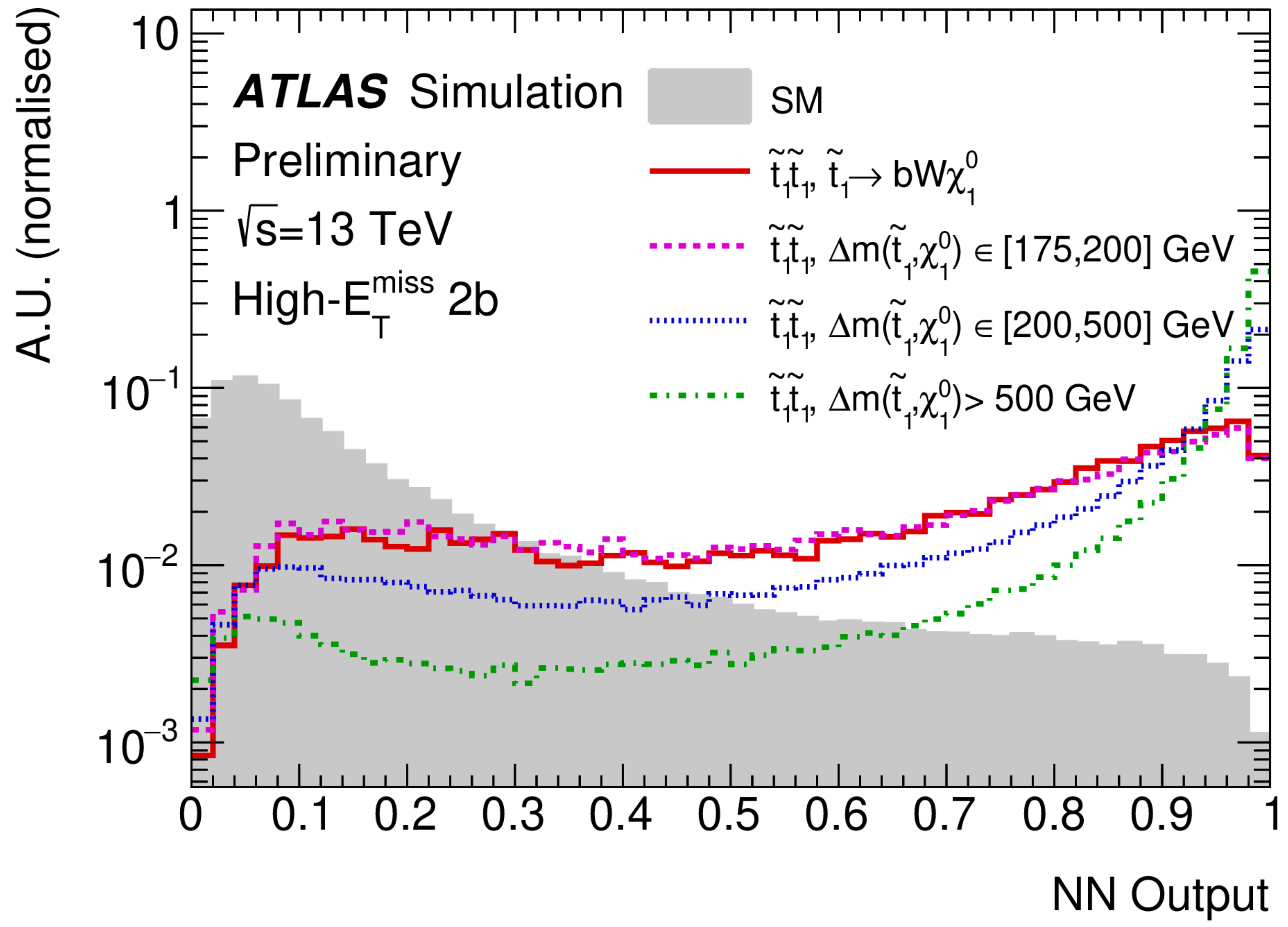


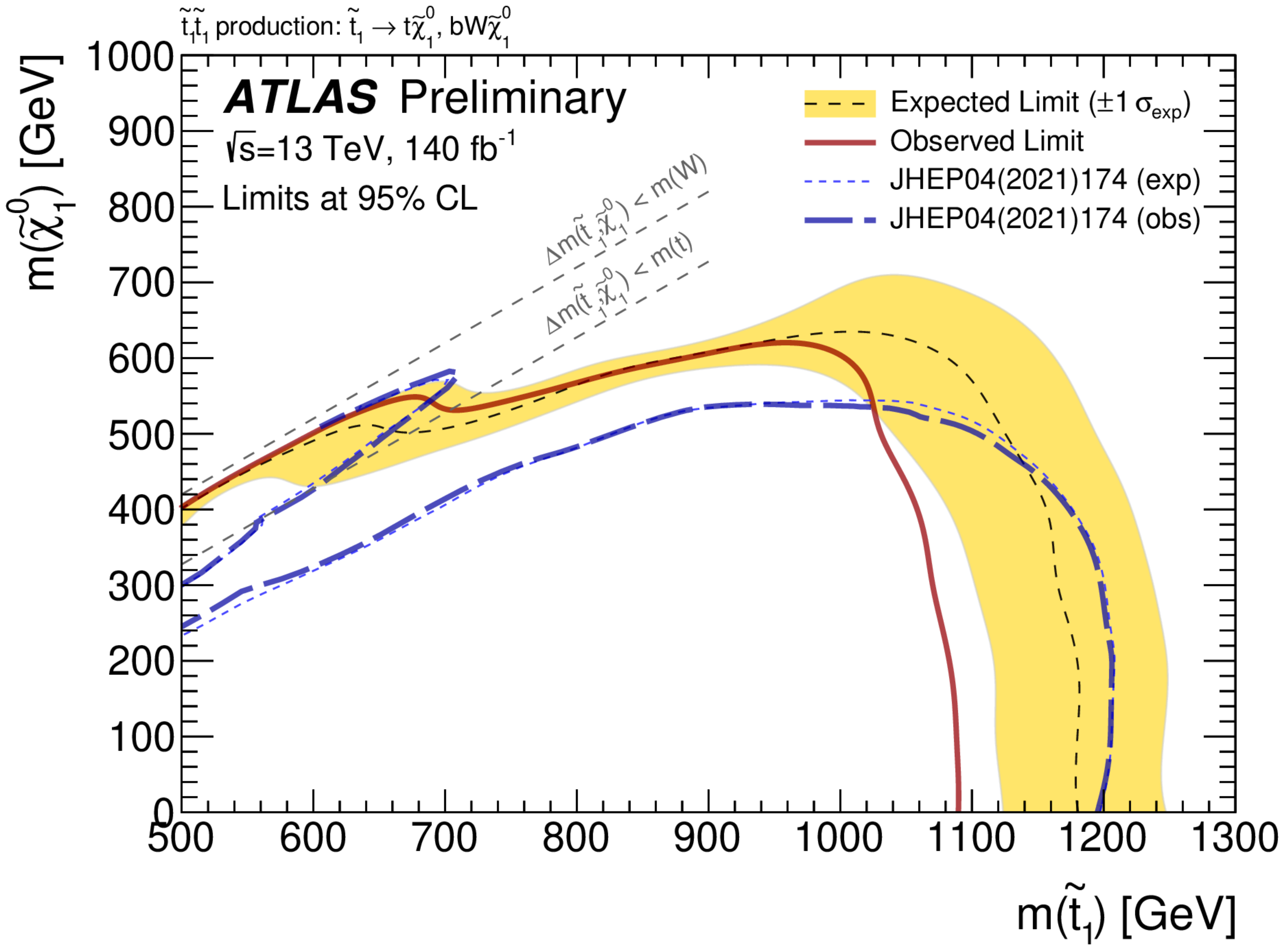



# Stop search: tt+MET

- Search for direct stop pair production with one lepton (from on-shell *W*), jets and high MET
- Orthogonal and inclusive event categories depending on number of *b*-jets and jets from top quarks
- Neural network to discriminate signal/background for each SR
- Exclusion limits
  - Neutralino up to 600 GeV from direct stop decays
  - Stop masses up to 1.1 TeV for low neutralino mass



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# Stop search: tc+MET

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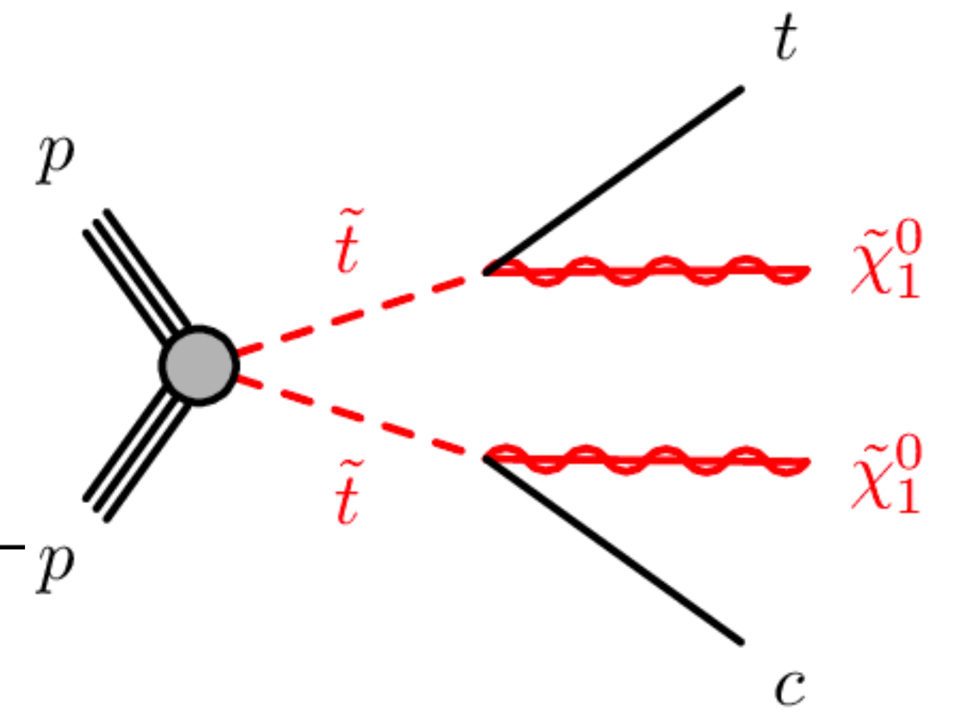
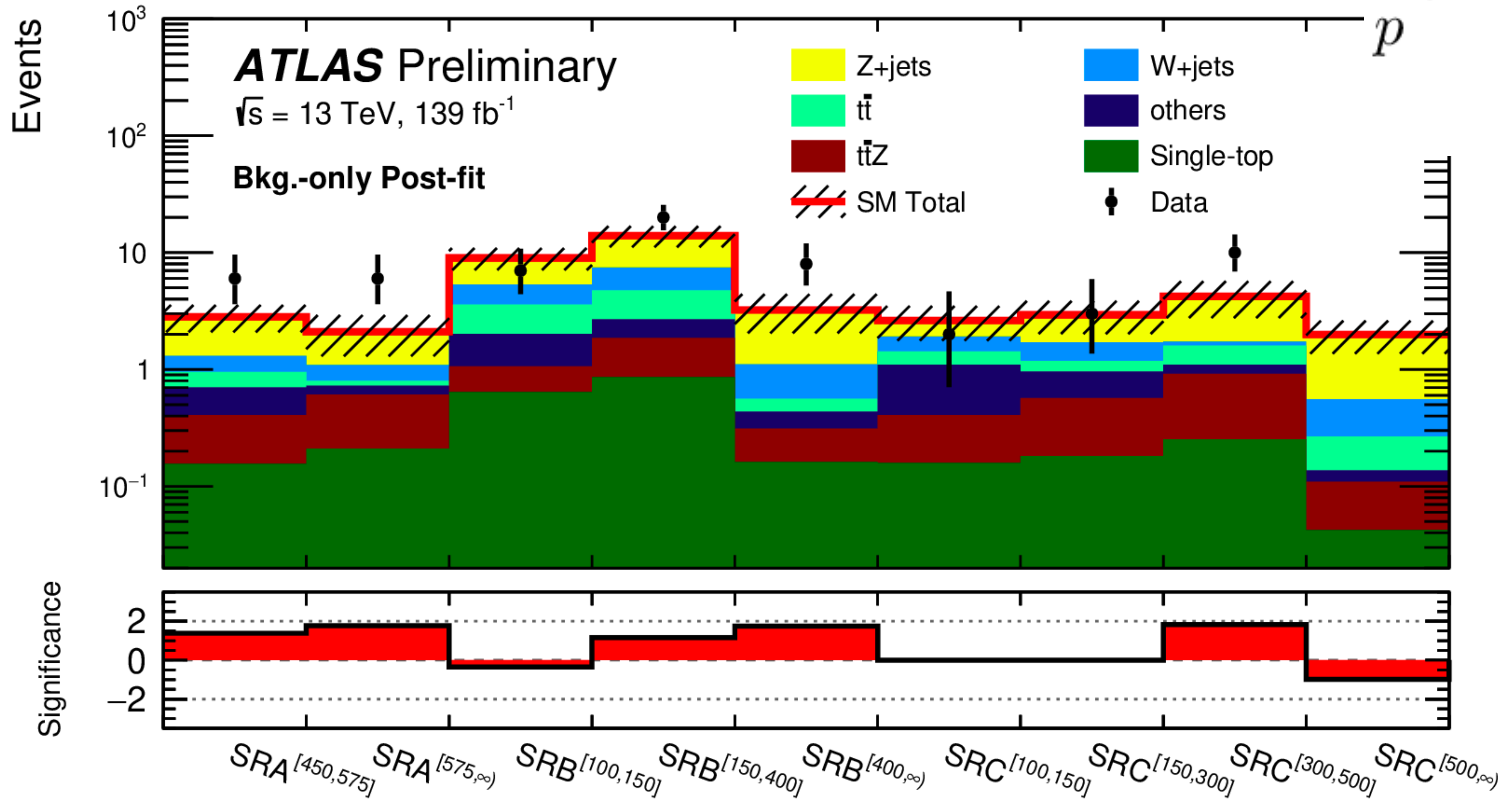
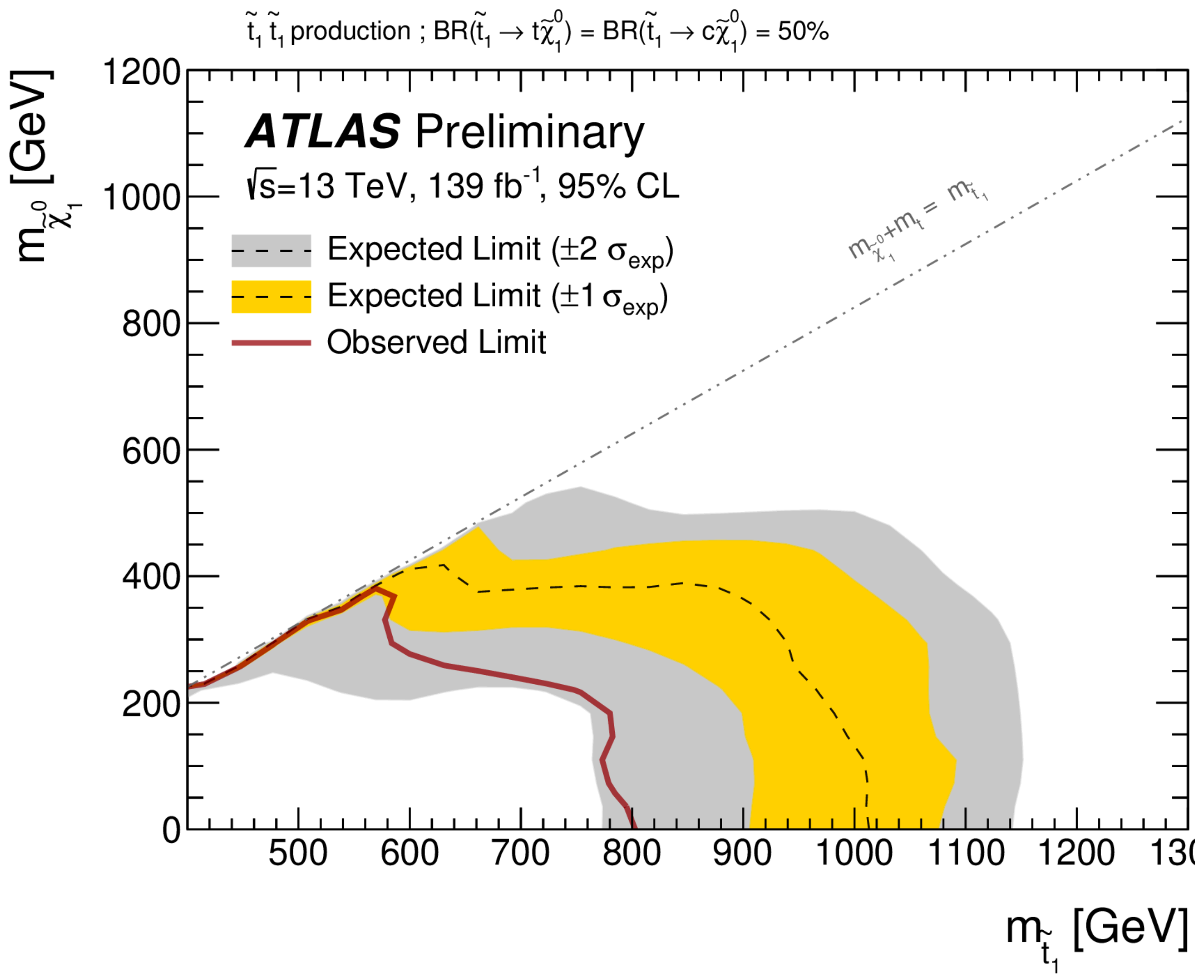
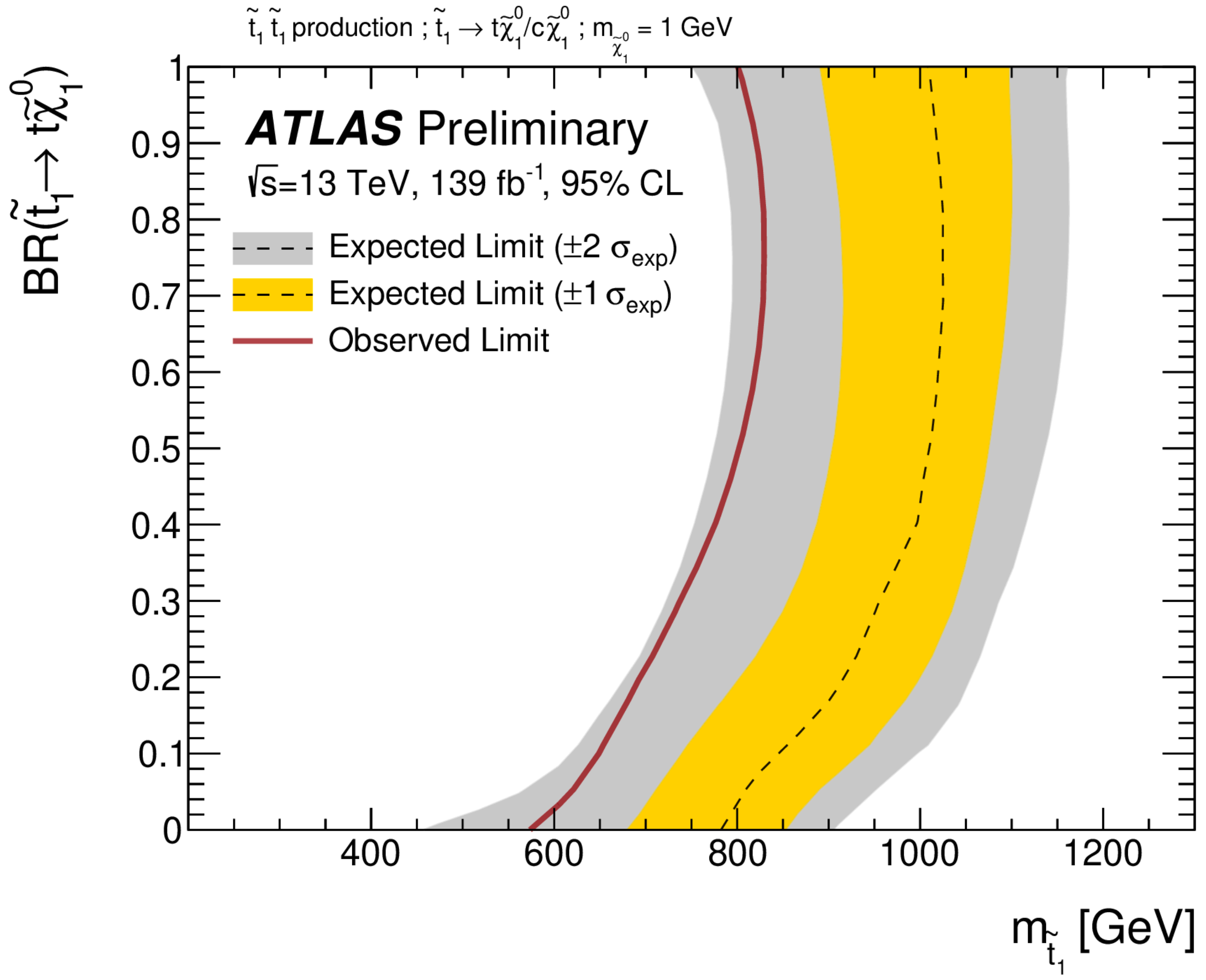



- Dropping assumption of minimal flavor violation allow stop and scharm mixing
  - mixed decays with one hadronic top, one charm jet and MET
  - Scan of $BR(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0/t\tilde{\chi}_1^0)$
- Dedicated charm tagger with 20% c-tag efficiency
- DNN top tagger to identify large-R jets from top decays
- Final state kinematics very dependent on mass splitting
  - 4 orthogonal SRs
  - ISR jet used for compressed region
- Top squark masses excluded up to 800 GeV for light neutralinos and 600 GeV for degenerate case



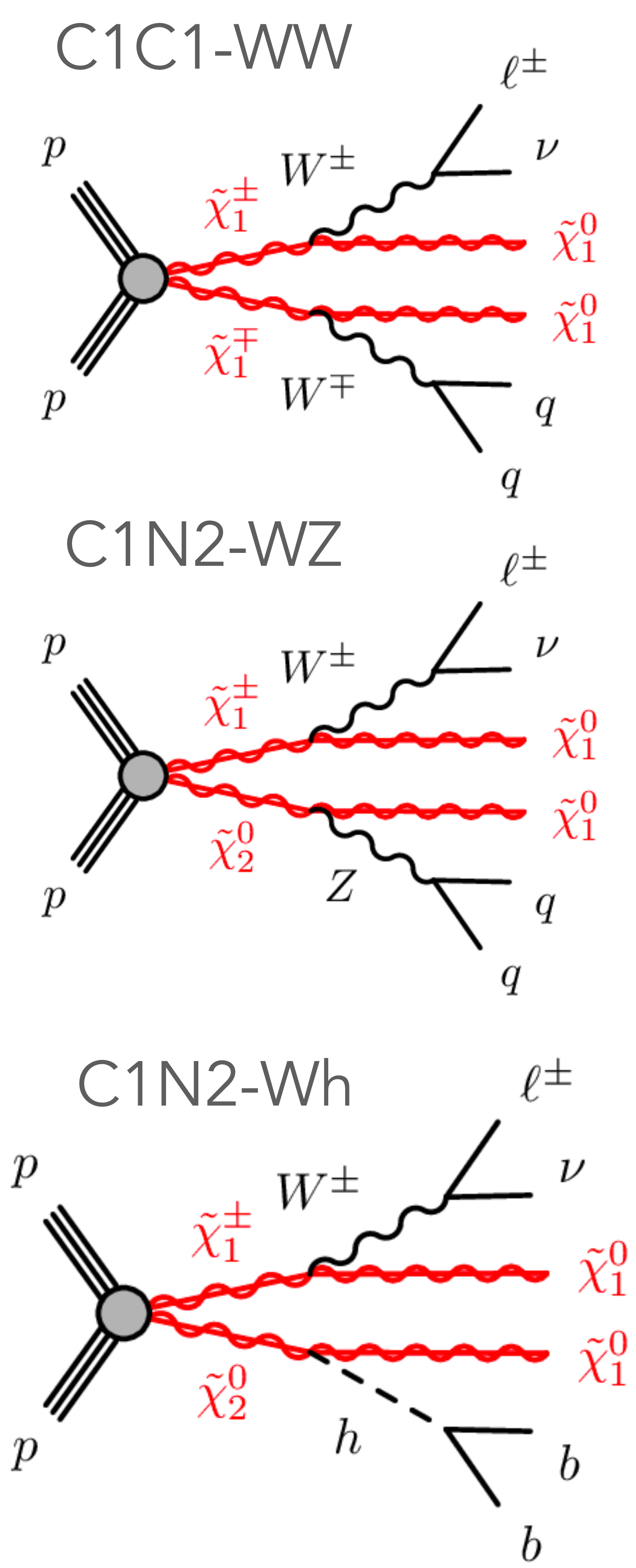



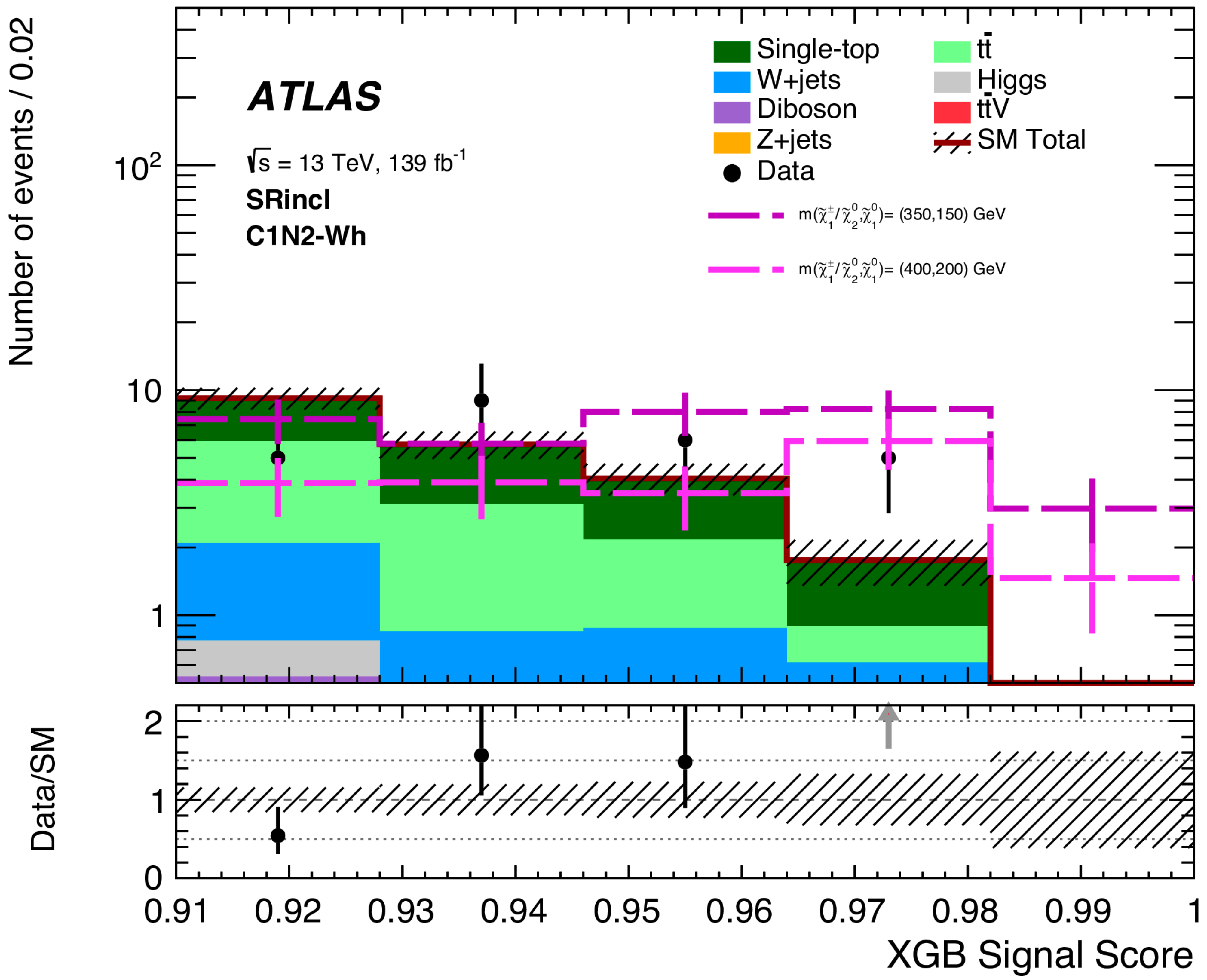



[SUSY-2023-01 [2310.0817]]

# Electroweak searches with one lepton

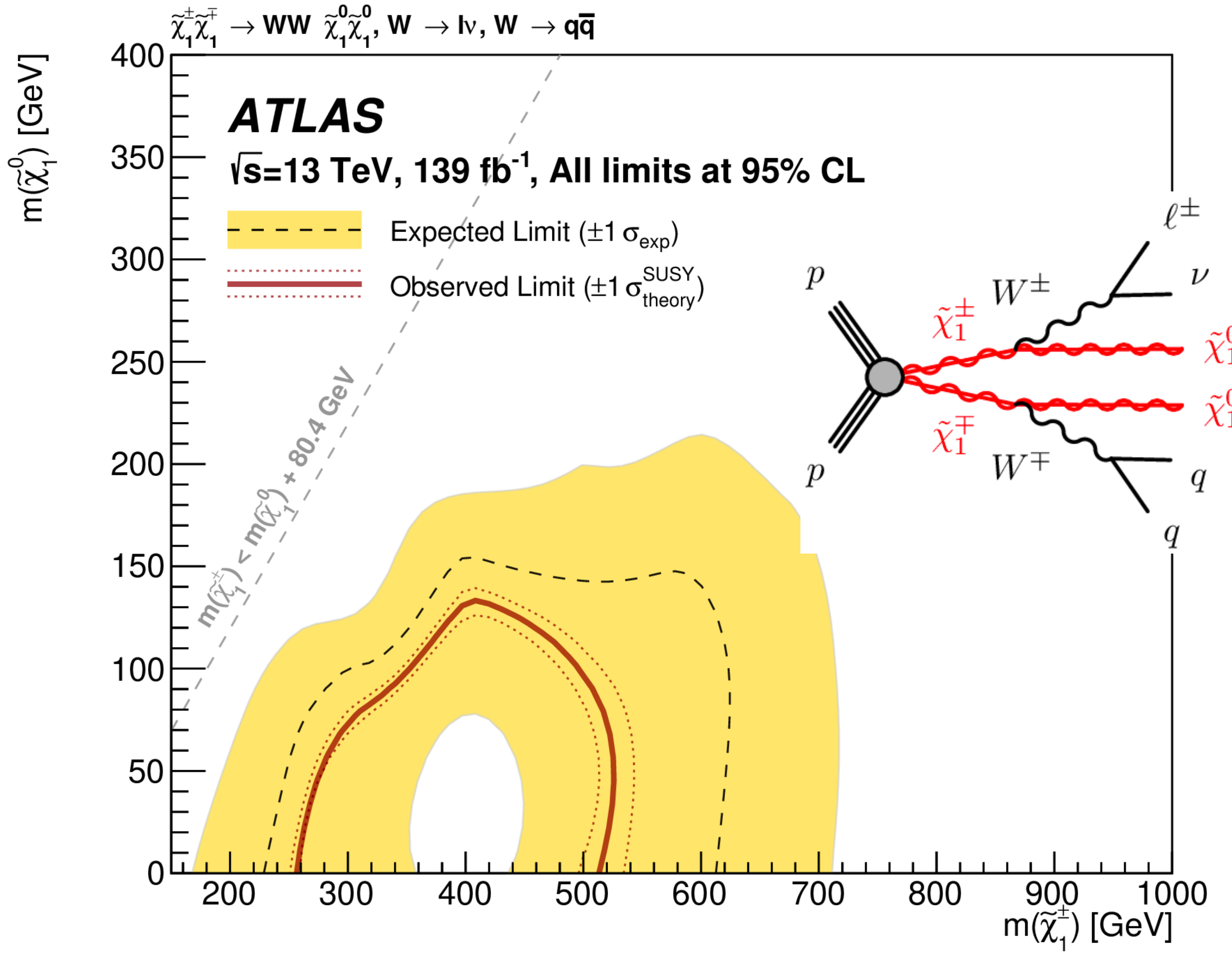
- $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ production
- Single isolated lepton ($e/\mu$), jets and MET
- Three sets of SRs targeting the 3 production/decay models
- WW/WZ channels:
  - One lepton and 3 jets
  - $W$ and $Z$ tagging
- *Wh* channel:
  - 2 b-jets to identify Higgs boson
  - BDT as final discriminant
- Backgrounds from MC with CRs

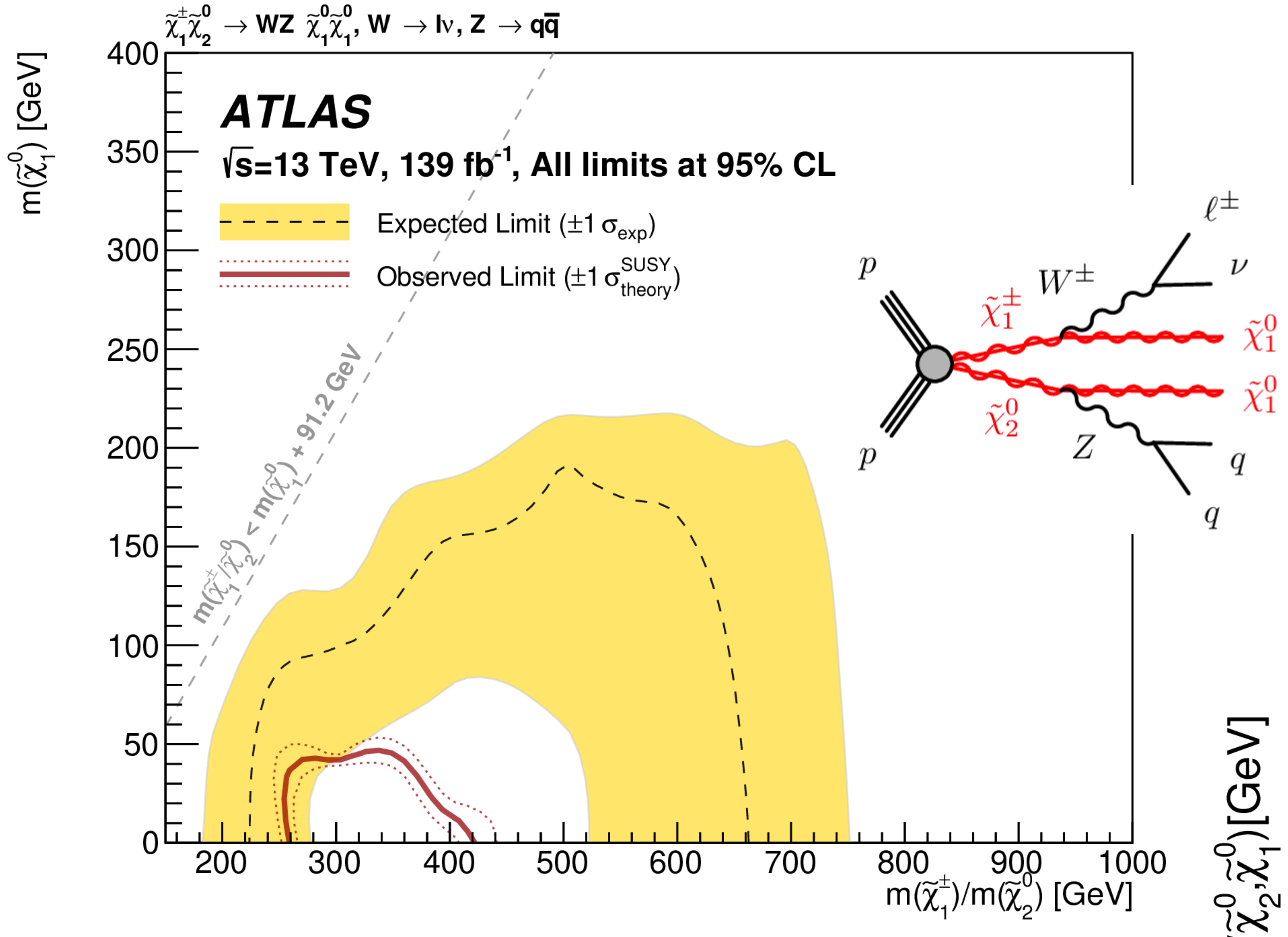


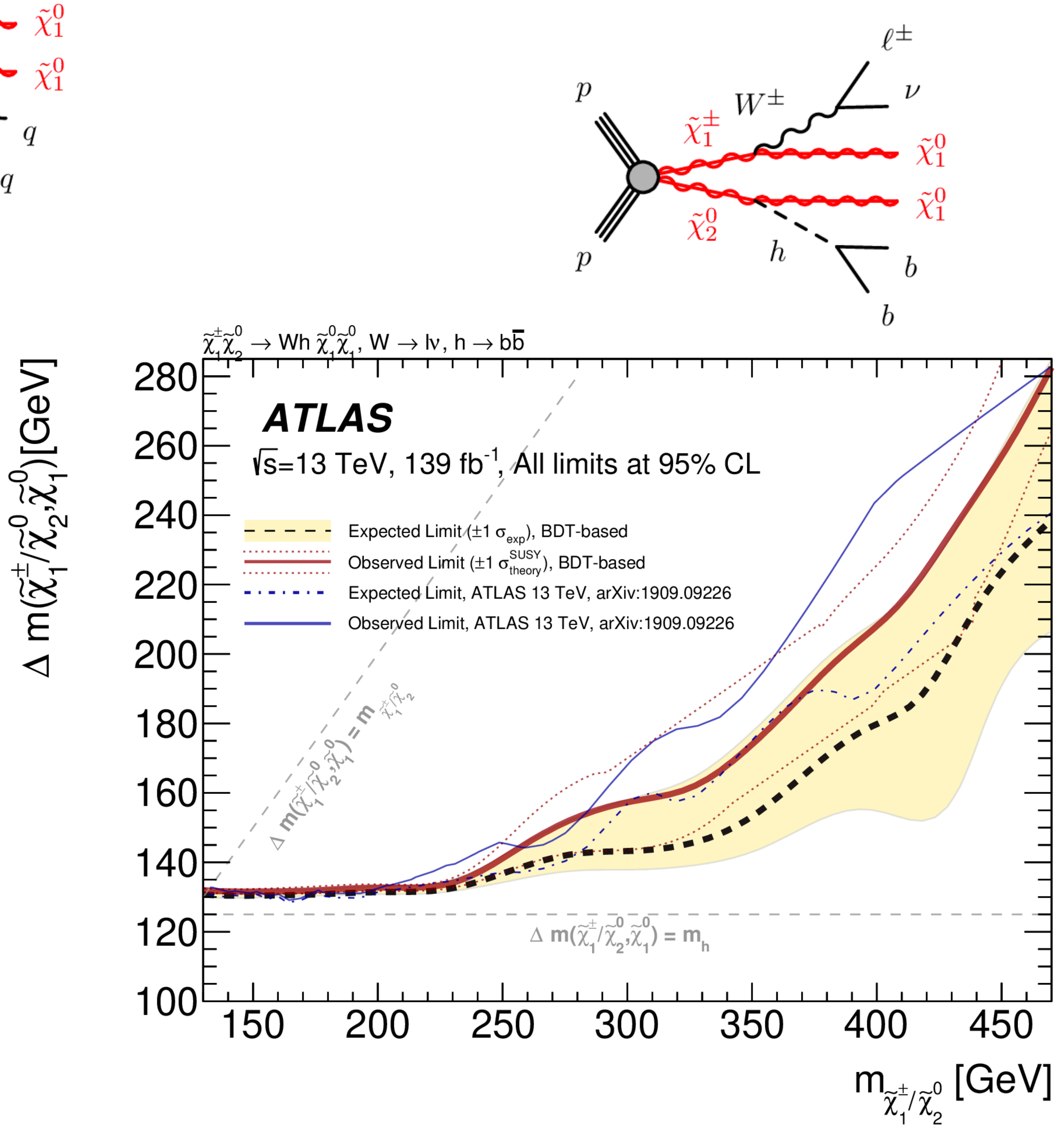



SUSY-2023-01 [2310.0817]

# Electroweak searches with one lepton




- No deviations from SM
- Exclusion limits on the three simplified models:
  - 260 to 520 GeV $\tilde{\chi}_1^{\pm}$ for massless $\tilde{\chi}_1^0$
  - 260 to 420 GeV $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ for massless $\tilde{\chi}_1^0$ for $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$
  - Improved limits by up to 40 GeV in the Wh model

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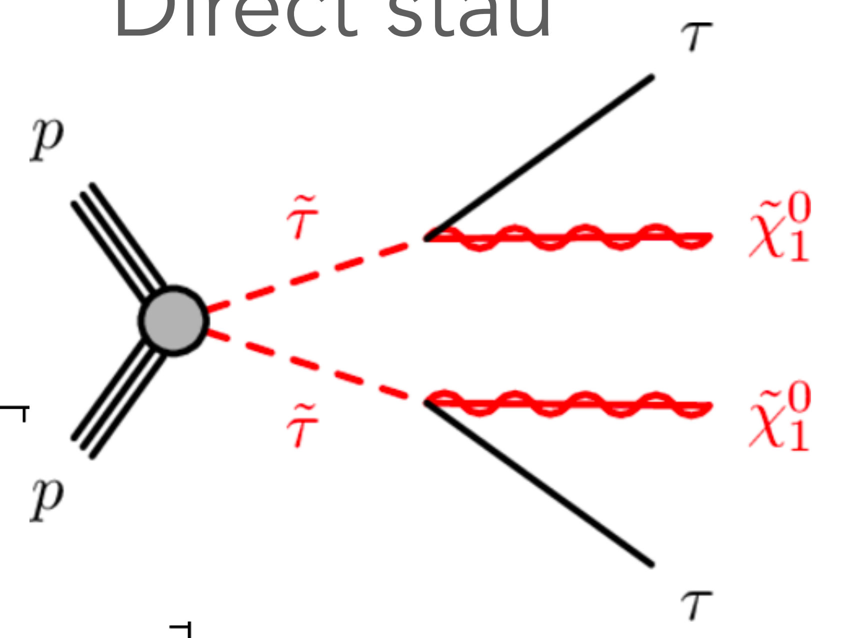
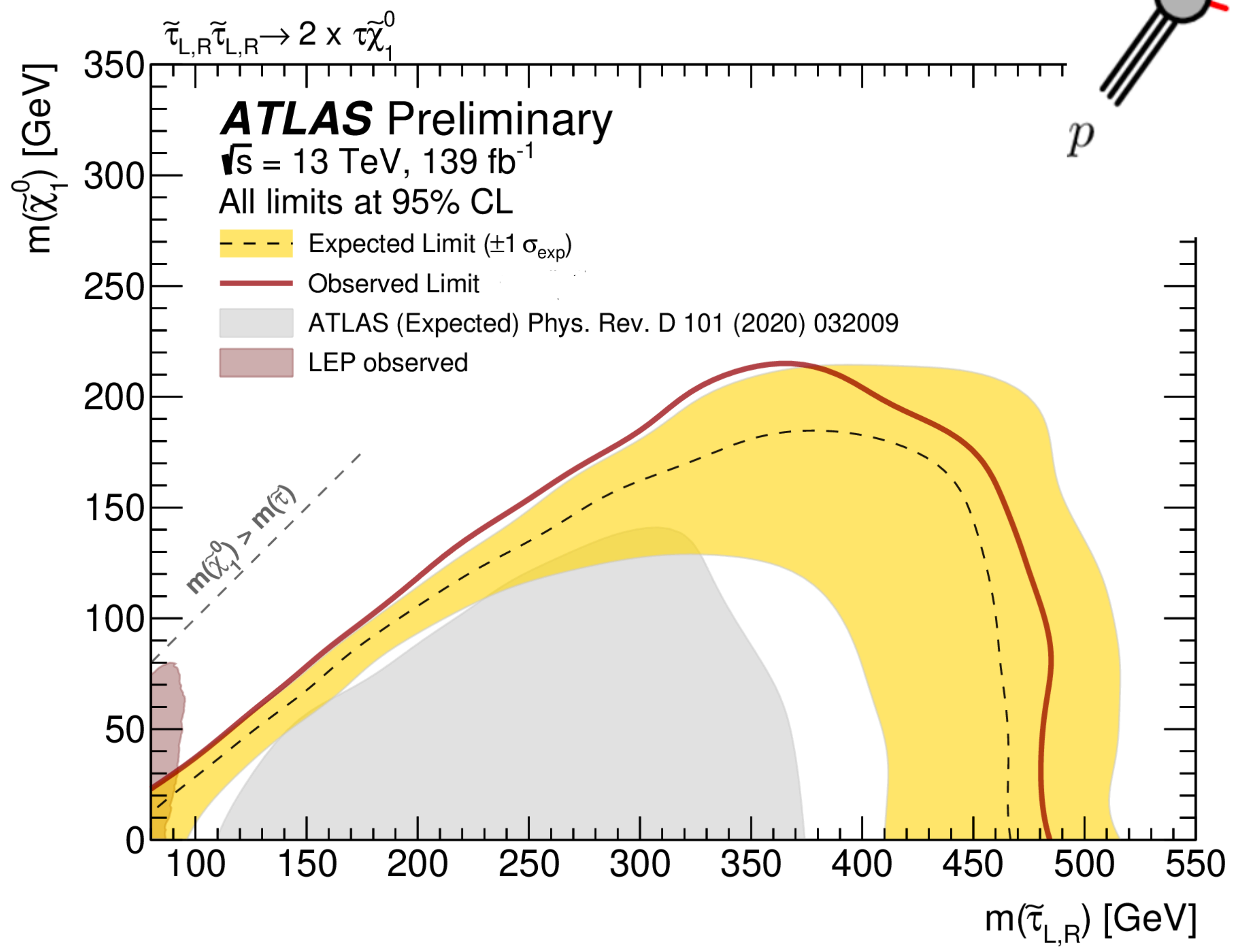
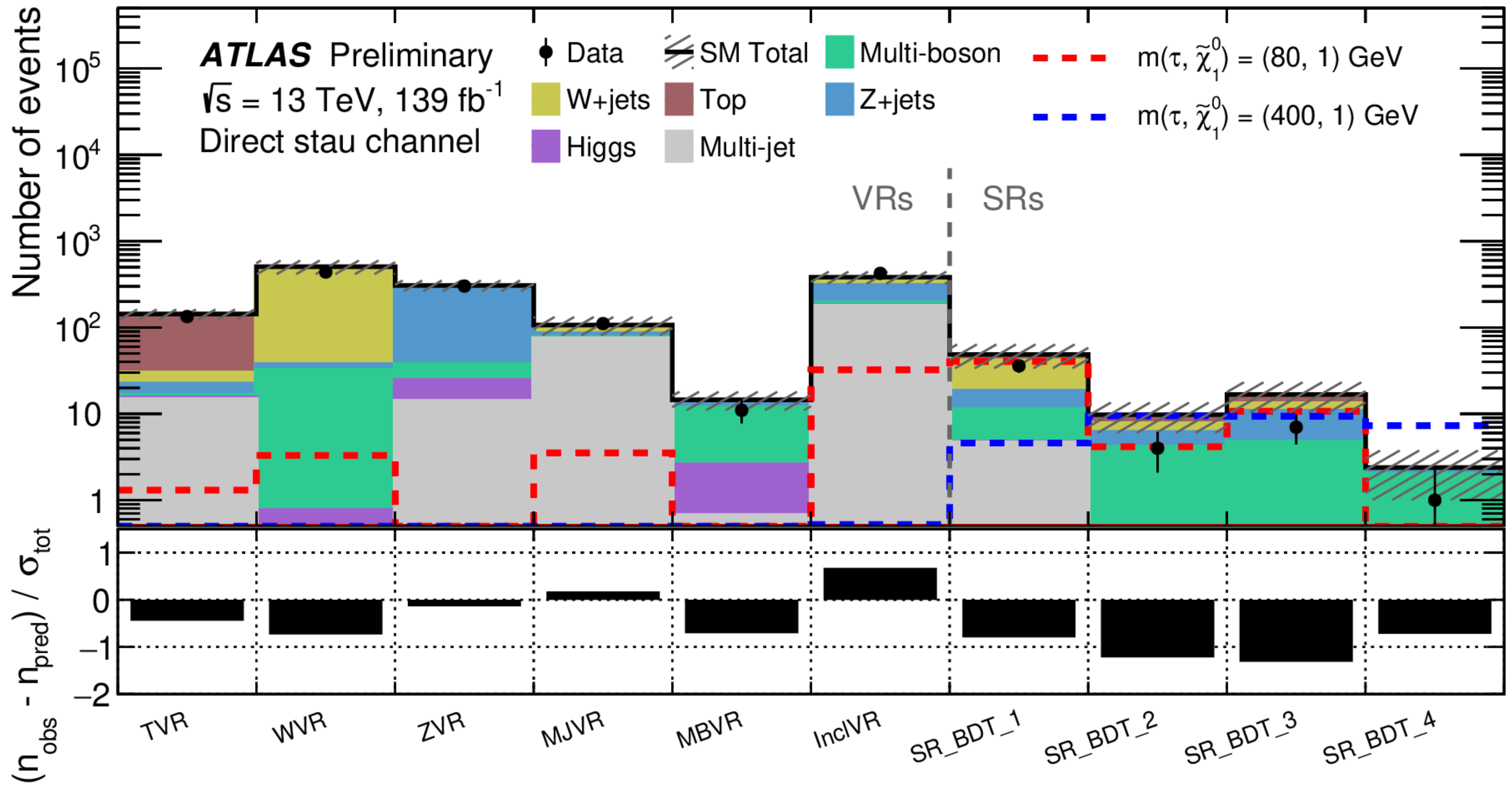
# Electroweak with taus: direct $\tilde{\tau}$

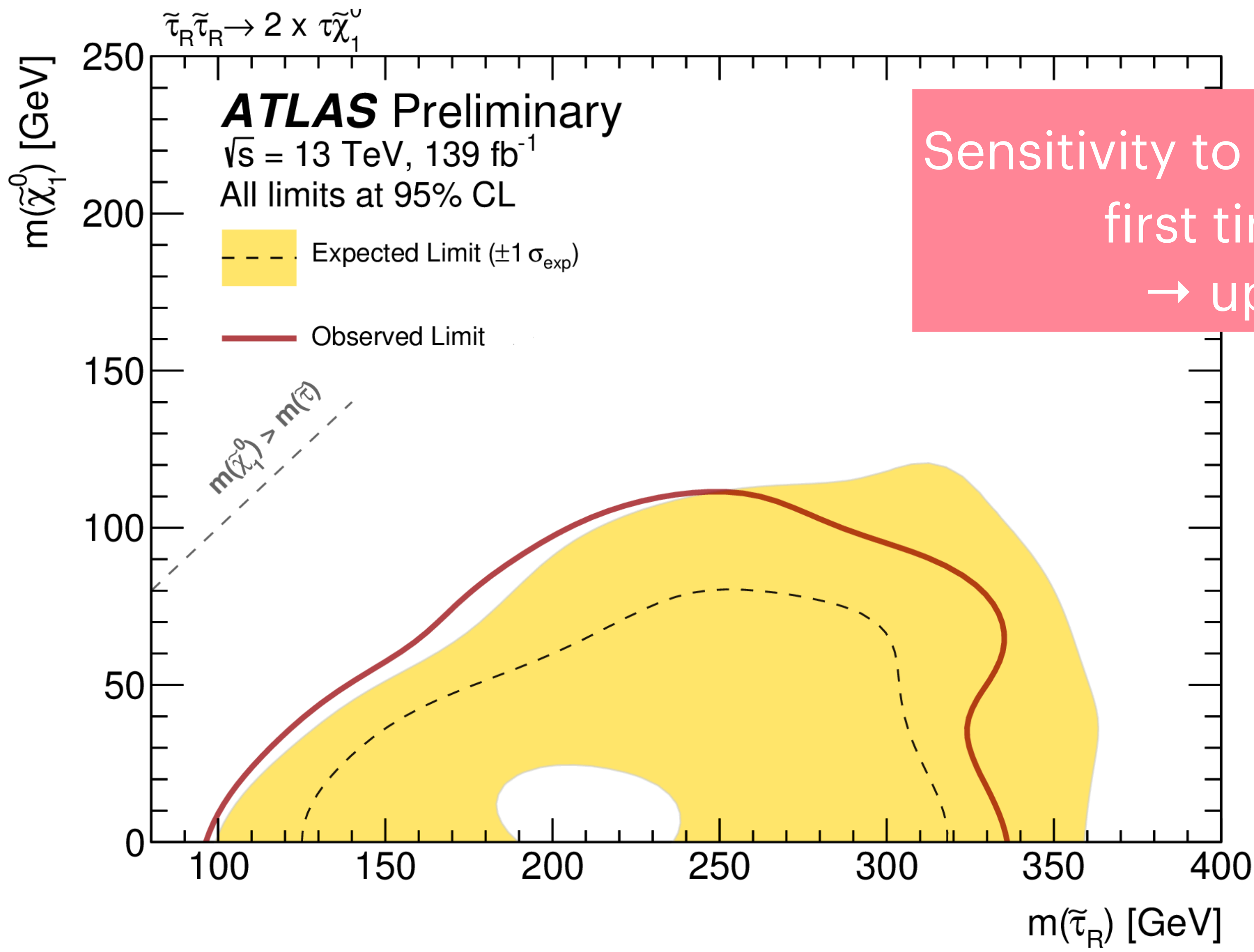
- Search for direct left and/or right handed stau production decaying to tau and LSP 100% of the time
- Mass degenerate or non-degenerate $\tilde{\tau}_{L,R}$
- 4 BDT models trained for different mass spaces
  - QCD multijets background data-driven
  - W/Z+jets and top backgrounds normalized in CRs
- Extended sensitivity to 480 GeV for $\tilde{\tau}_{L,R}$

Direct stau






Sensitivity to $\tilde{\tau}_R$ production for the first time in the LHC → up to 330 GeV

# Electroweak higgsinos with multi b-jets

- Production of higgsinos decaying to $h(bb)h(bb)$ + MET in GMSB models
- New method for pairing *b*-jets into Higgs boson candidates, improved jet reconstruction and *b*-tagging, MVA techniques
- Two complementary analyses:

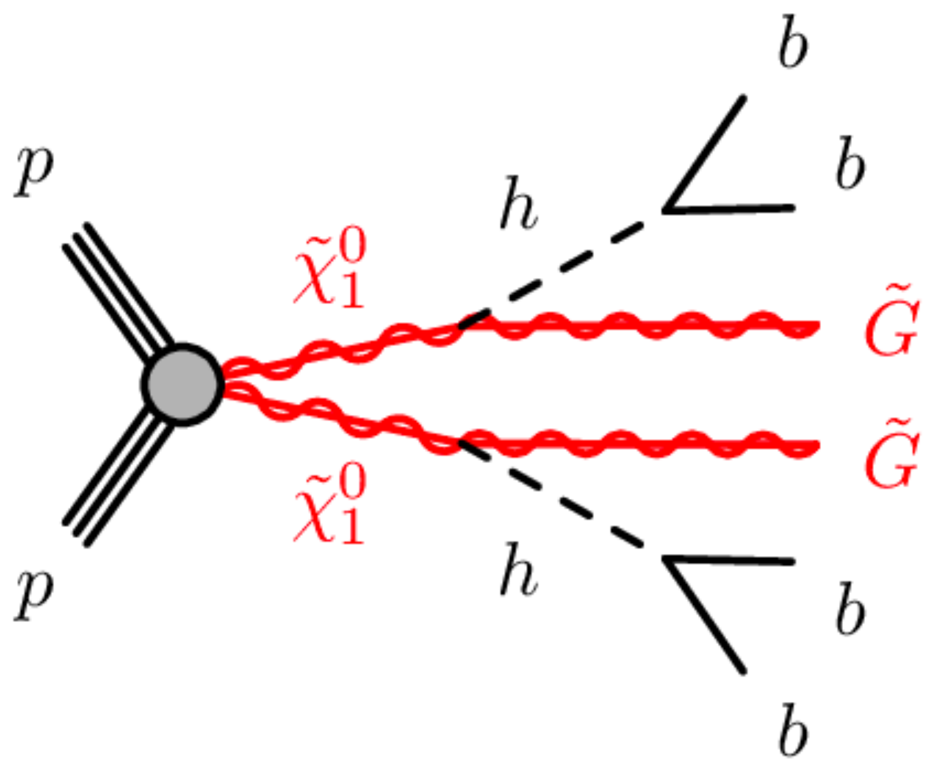
**Low higgsino mass (<250 GeV)**

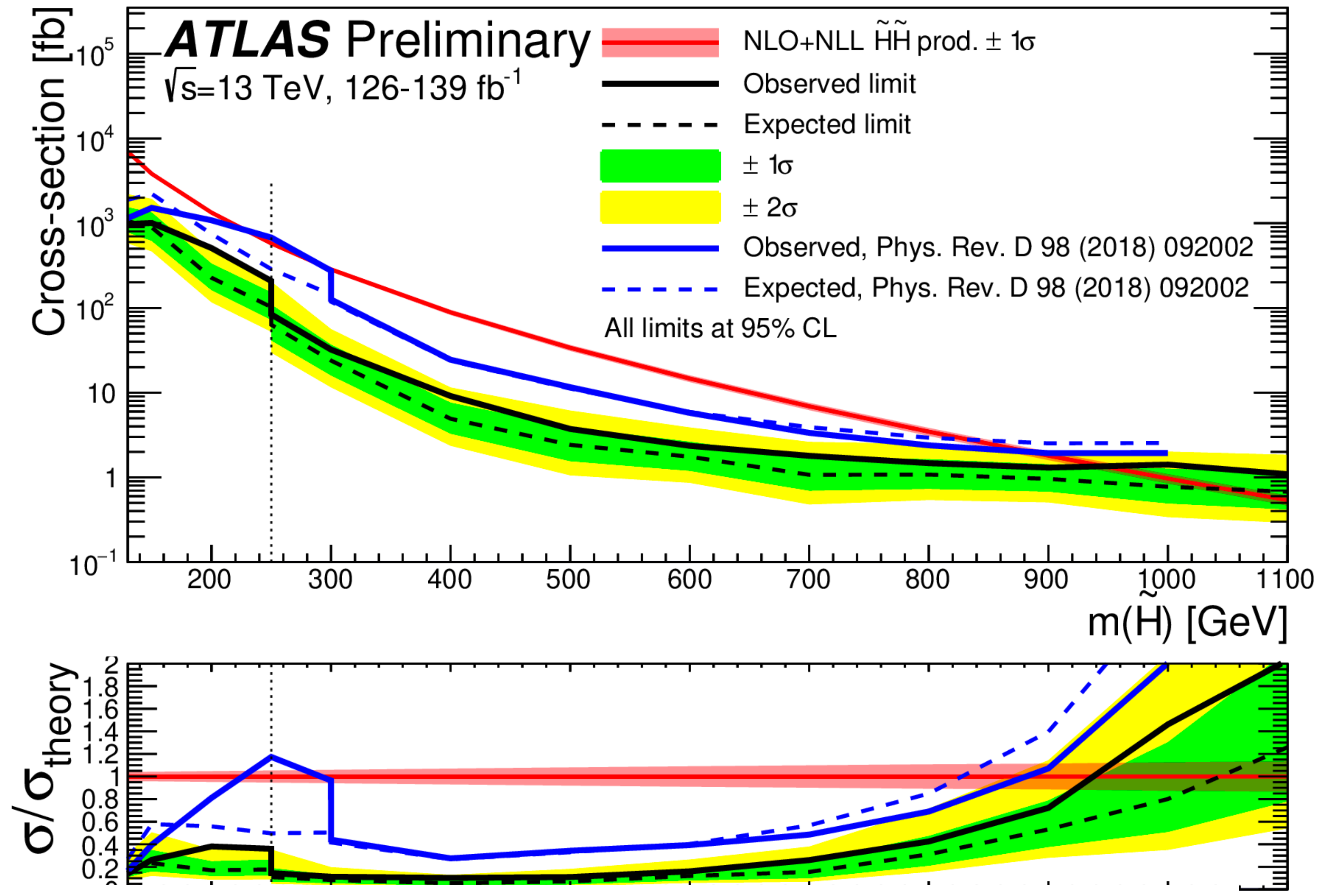
- Low MET (*b*-jet triggers)
- Four or more *b*-jets to reconstruct Higgs bosons
- QCD multijet and $t\bar{t}$ estimated using ABCD method

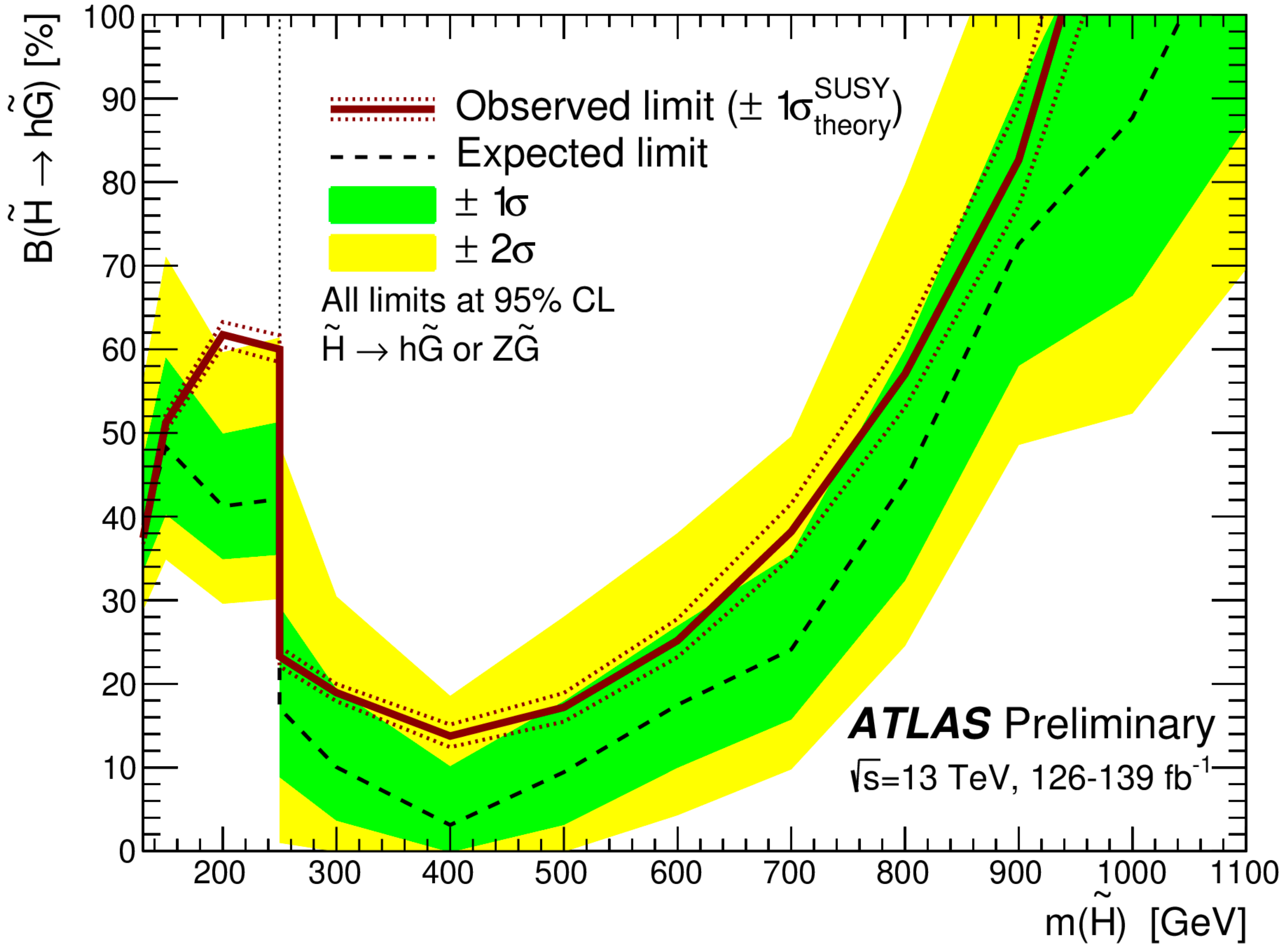
**High higgsino mass (>250 GeV)**

- High MET (MET based triggers)
- At least 3 *b*-jets
- *Z*+jets and $t\bar{t}$ CR and QCD multijet data-driven
- BDT signal/background discrimination

- Higgsino masses excluded up to 940 GeV for 100% $BR(\rightarrow h\tilde{G})$



# Electroweak combination

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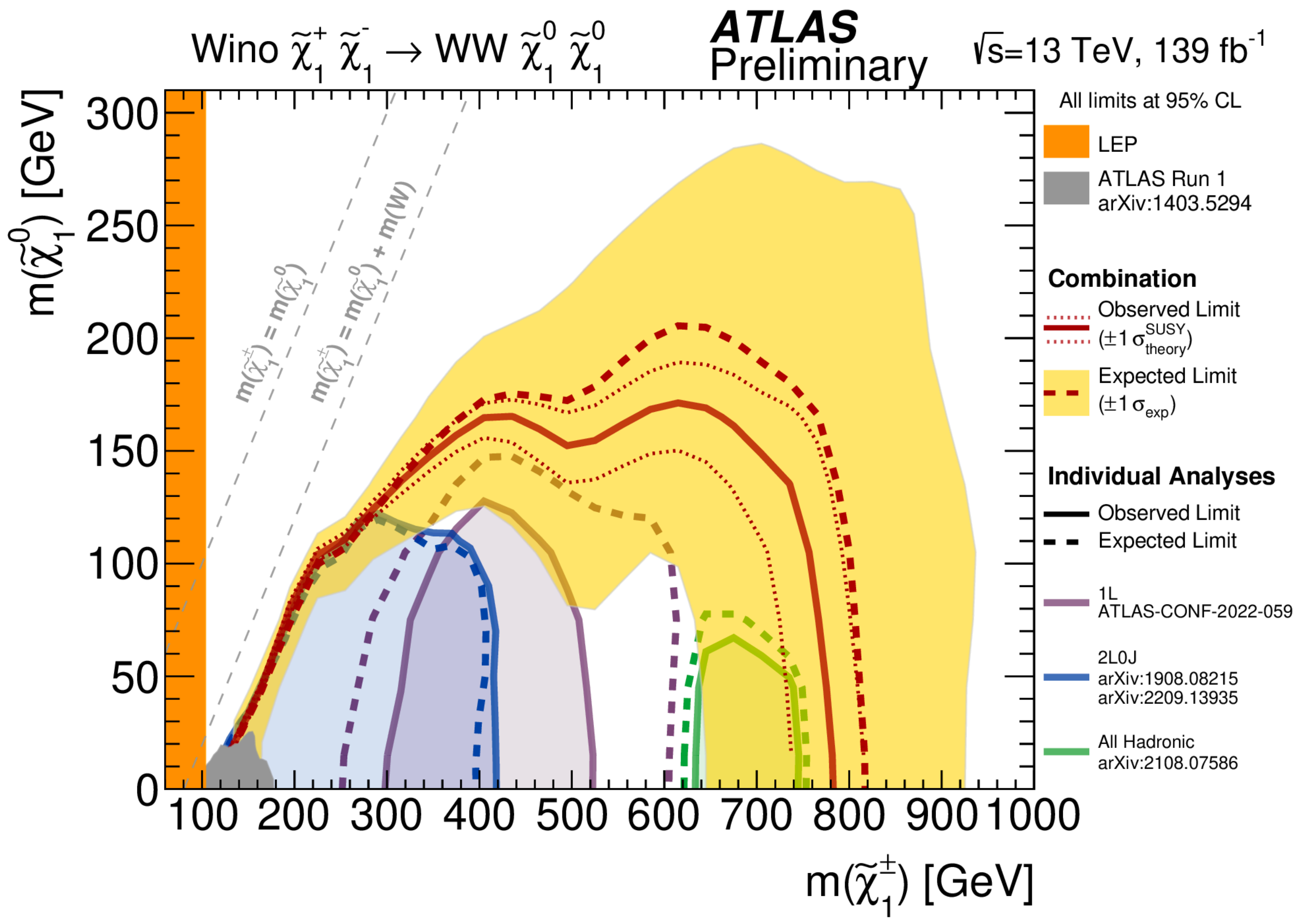
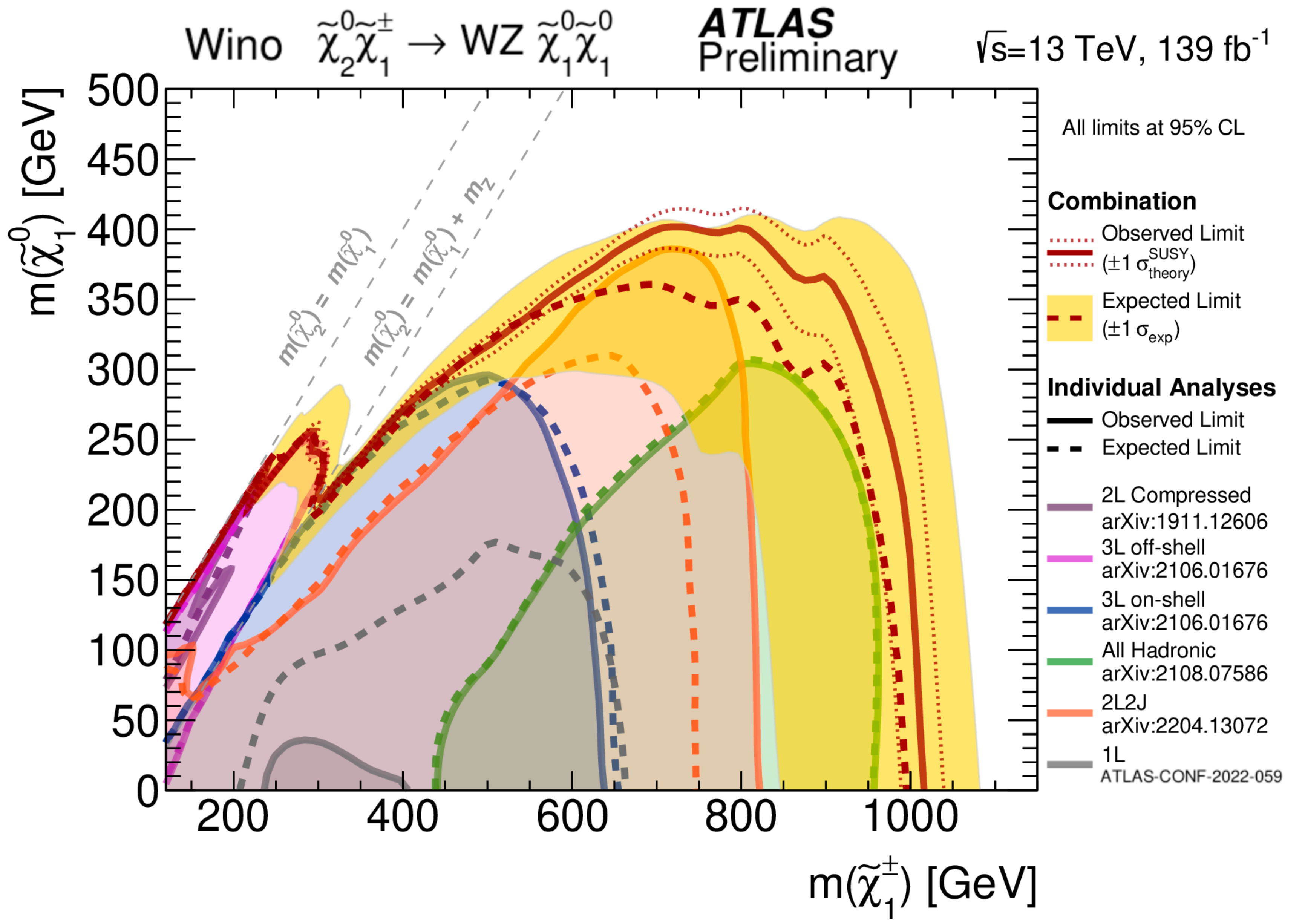
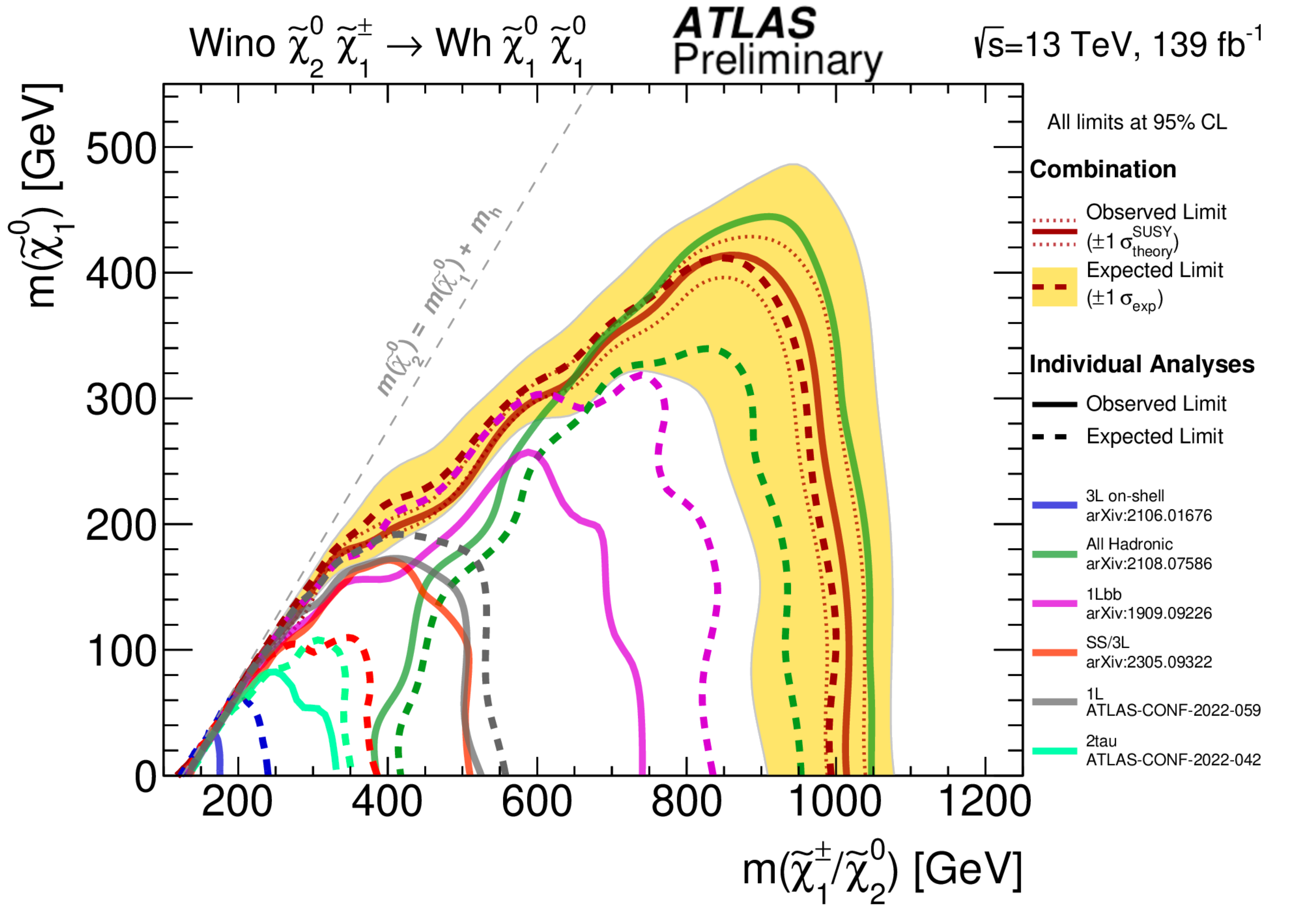
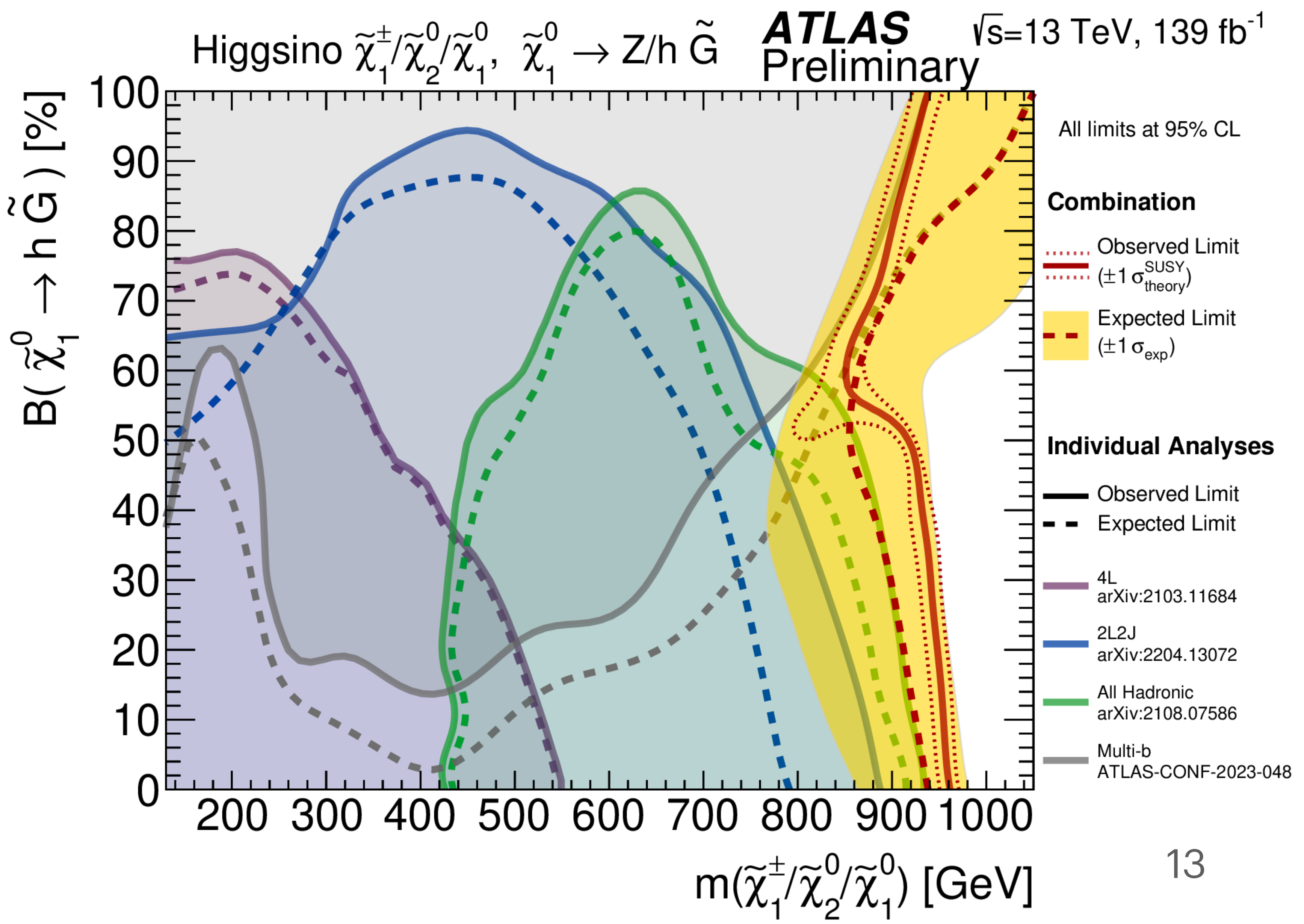
- Statistical combination of wino/higgsino searches using various decay channels via *W*, *Z* and *h*
- Analyses harmonized to allow the statistical combination
  - Different lepton multiplicity
- Mass reach extended 30-100 GeV
- Cross section limit improved by up to 40%



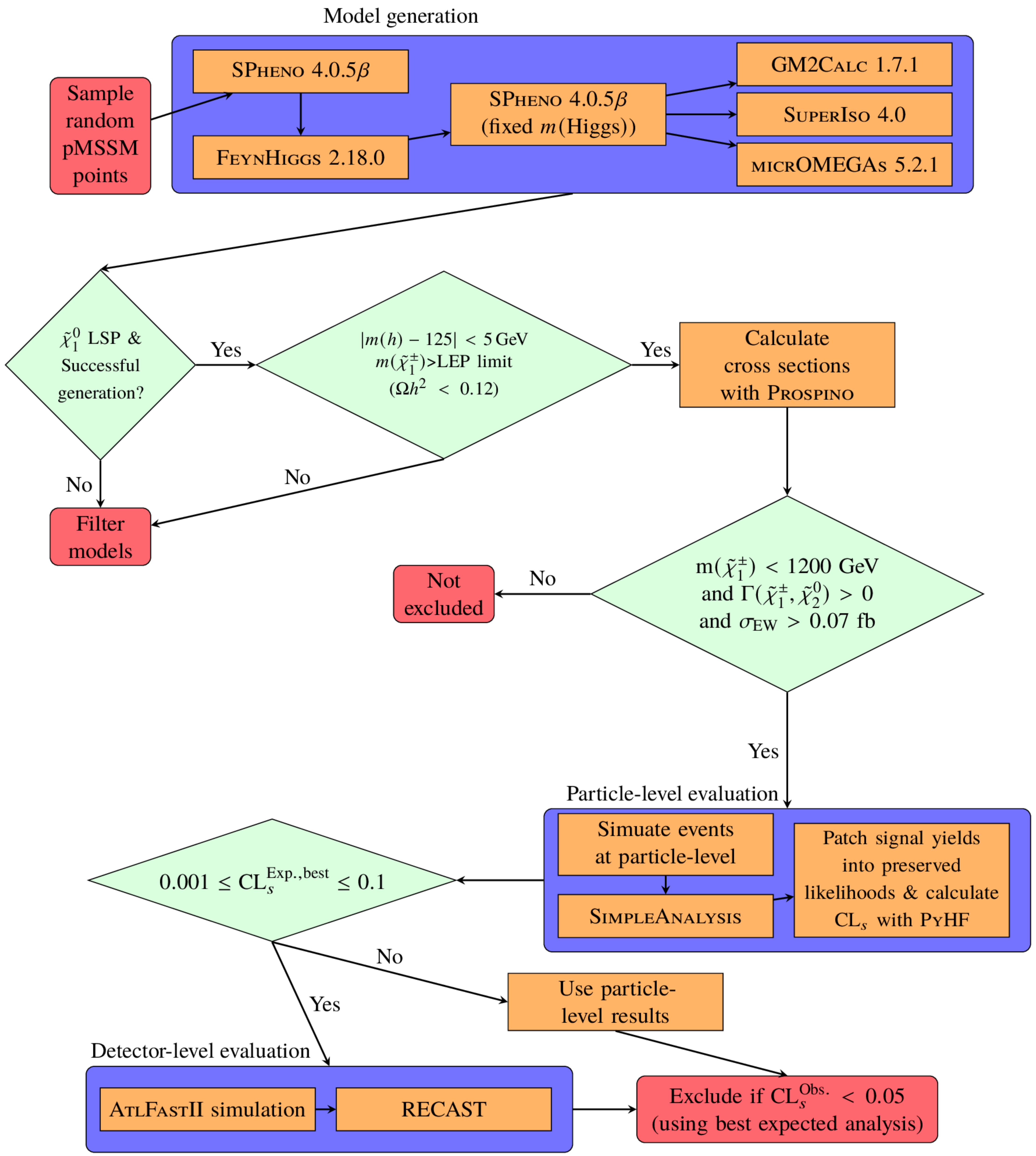



# Electroweak pMSSM Scan

- LHC exclusion limits on "simplified models"
  → not exhaustive exploration of MSSM
- Phenomenological MSSM:
  - CP-conserved, R-parity conservation, minimal flavour violation
  - SUSY parameter space reduced to 19 parameters
- pMSSM electroweak parameter space randomly scanned
  - General EWKino scan
  - Bino-DM scan
- Using eight Run-2 electroweak ATLAS analyses
  - + $\mathrm{BR}(h \to \mathrm{inv}) < 0.107$, $m(A) > 480\,\mathrm{GeV}$
- Constraints from previous EWK, flavour and DM related measurements are considered



# Electroweak pMSSM General Scan

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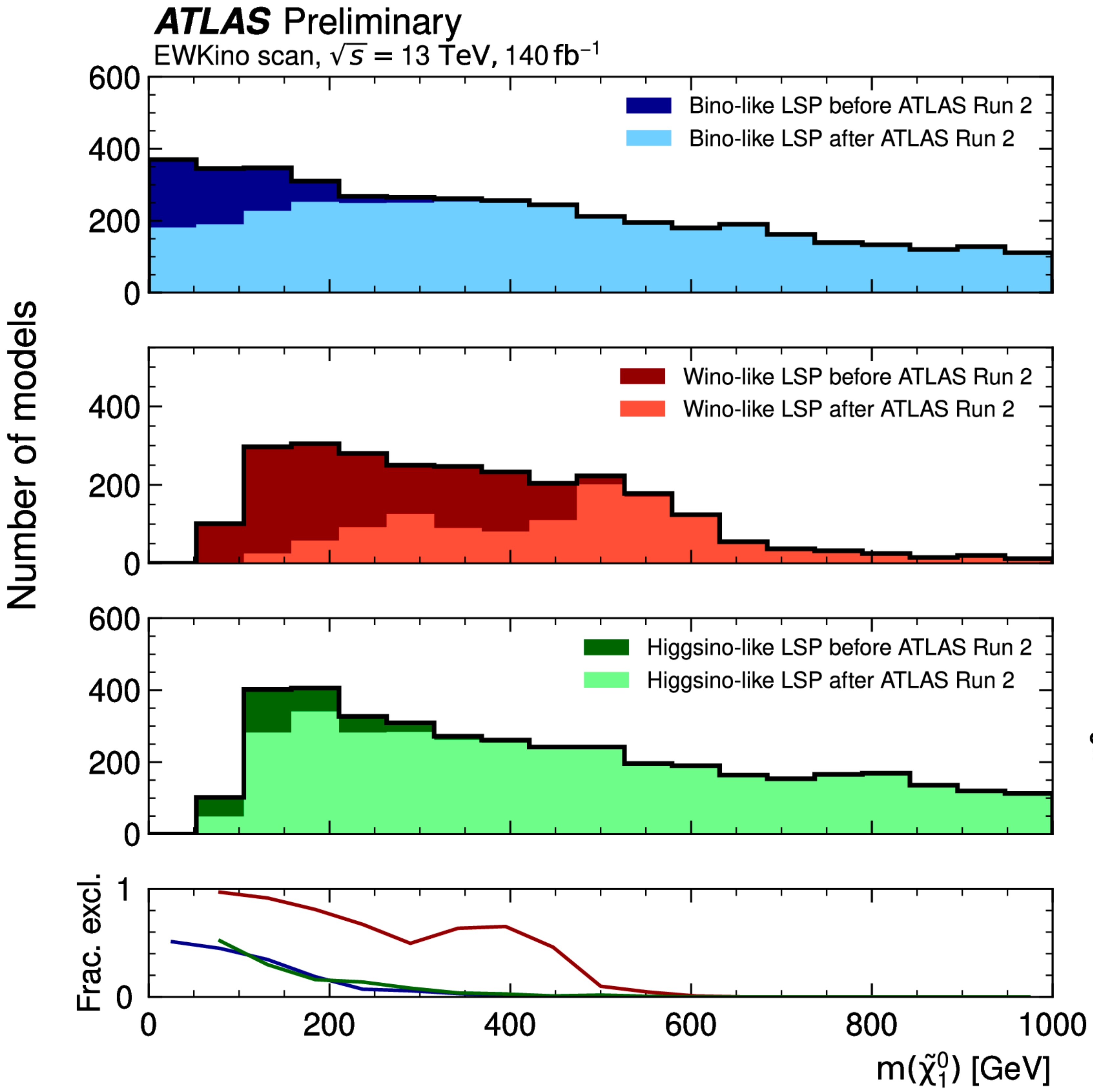
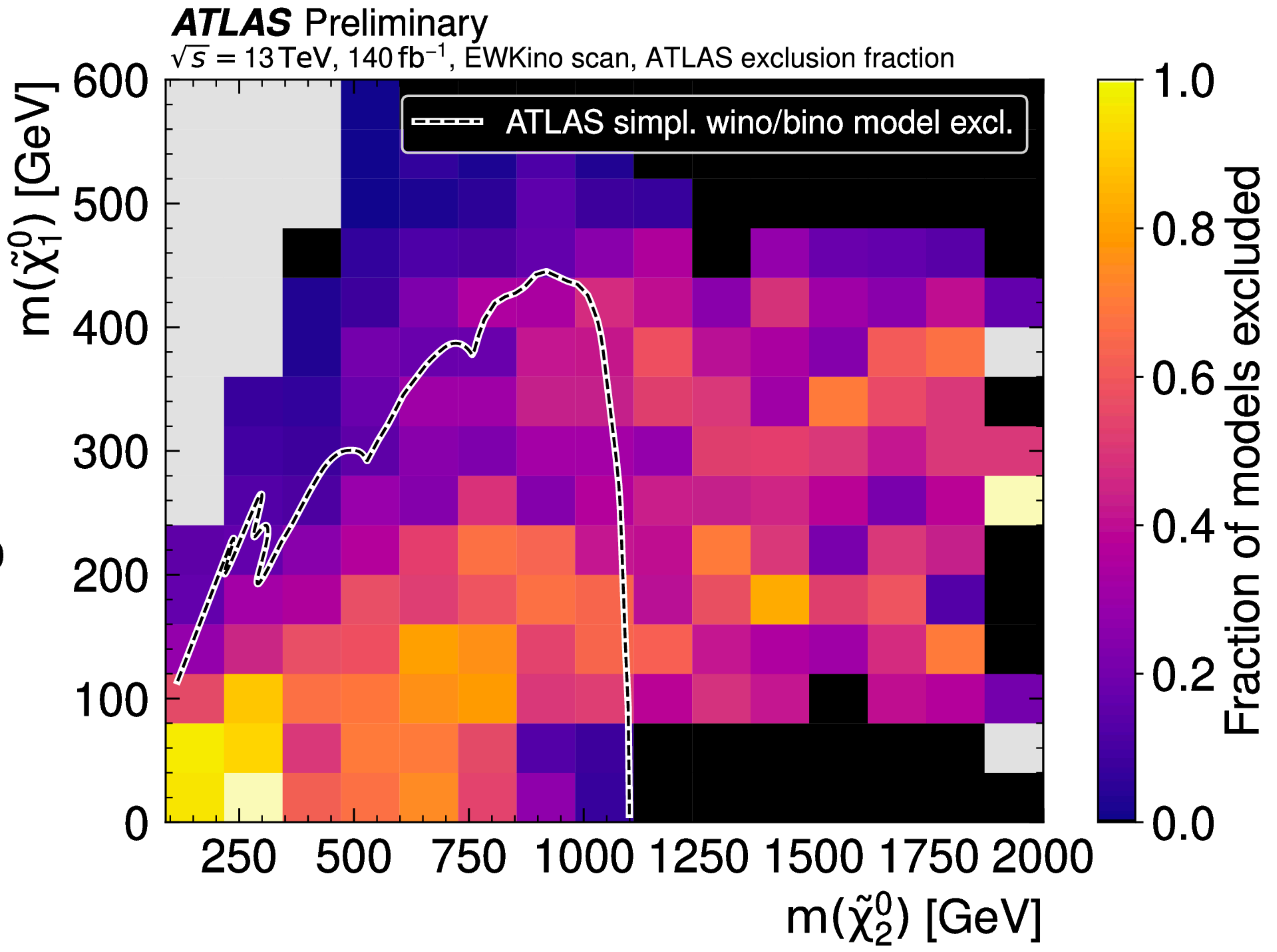
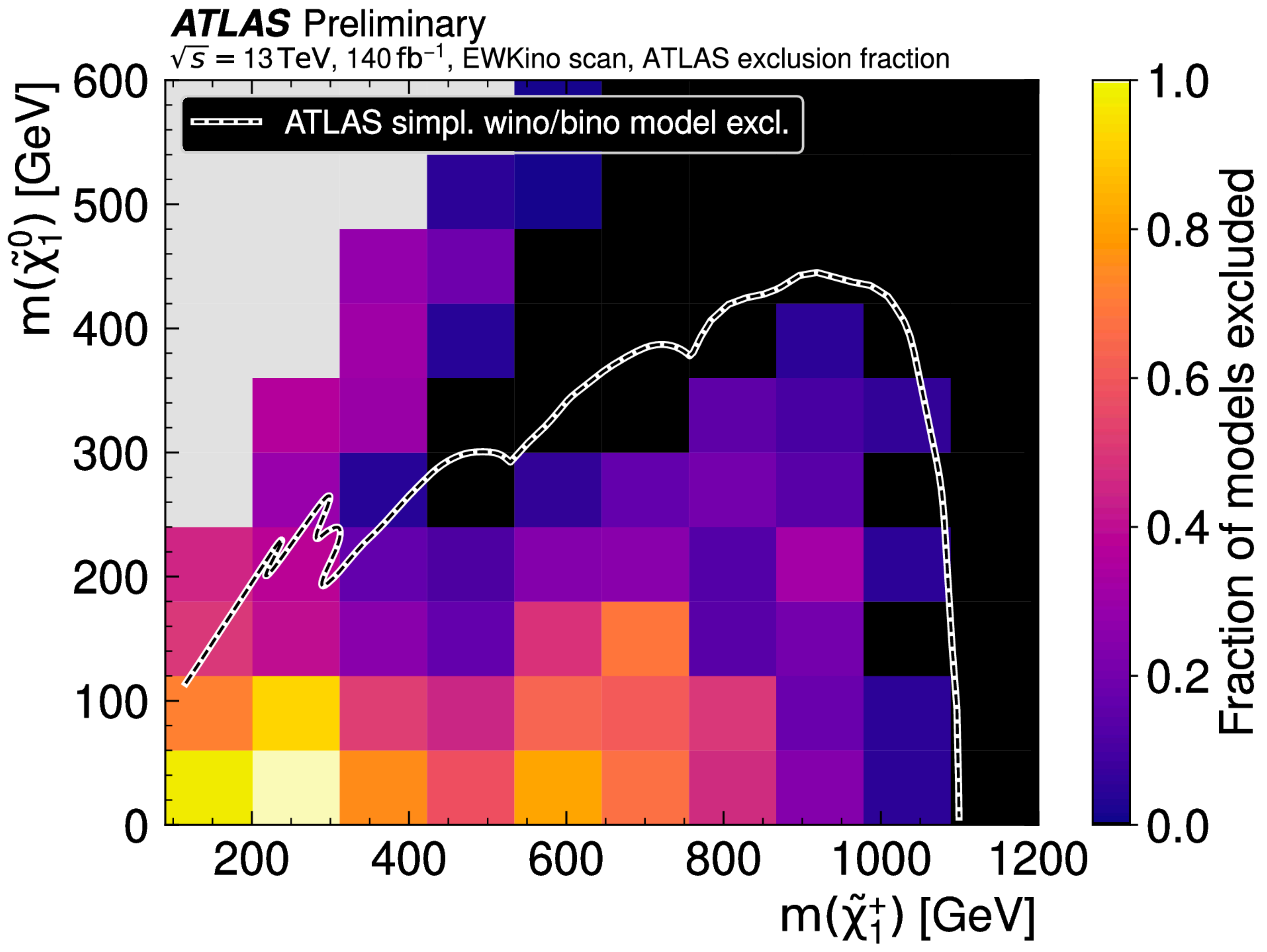
- Fraction of models excluded by ATLAS Run-2 searches
- Exclude at least 50% of models up to chargino mass of 400 GeV (even outside simplified model contour)
- Almost all models excluded for low mass LSP

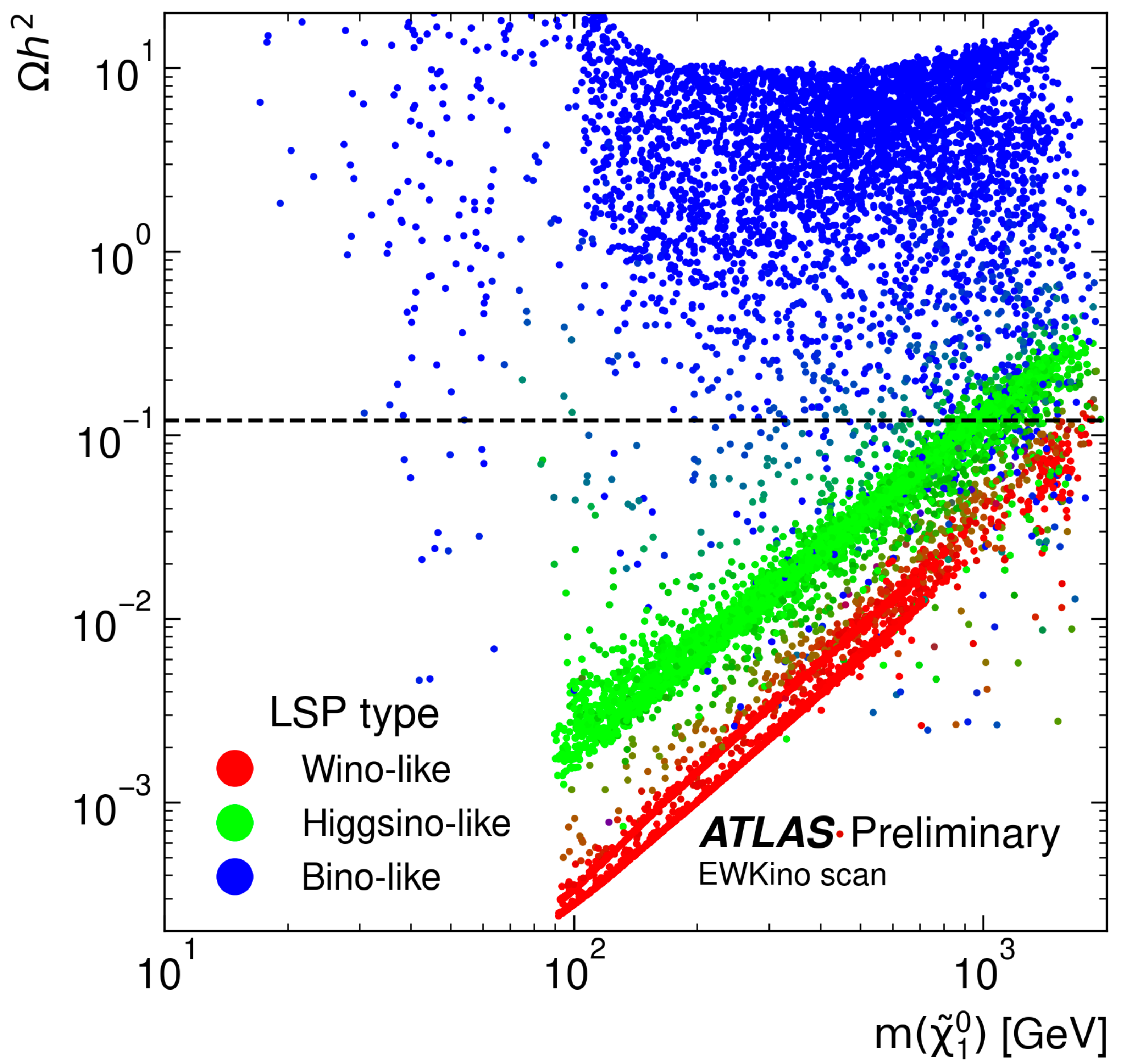


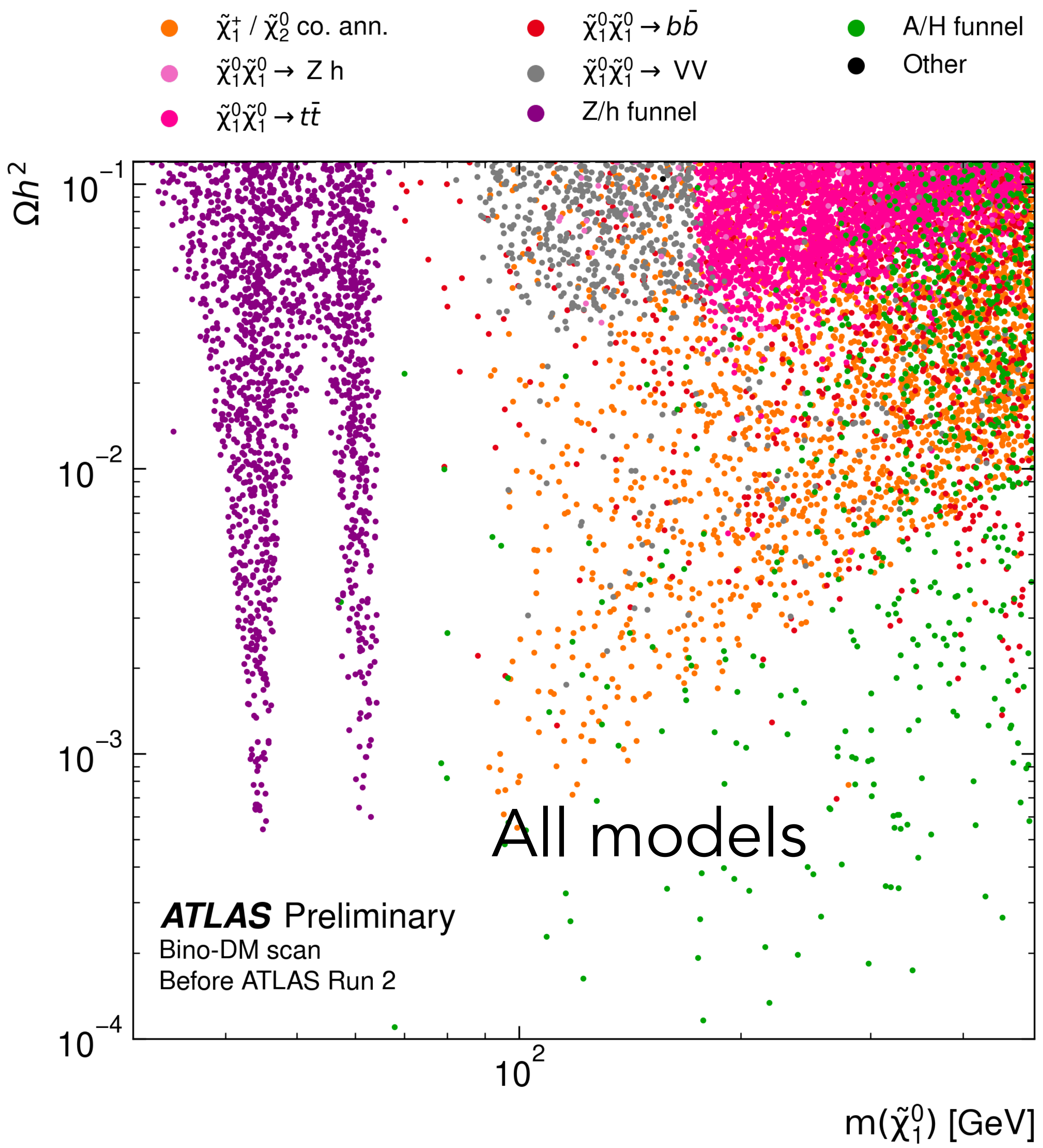



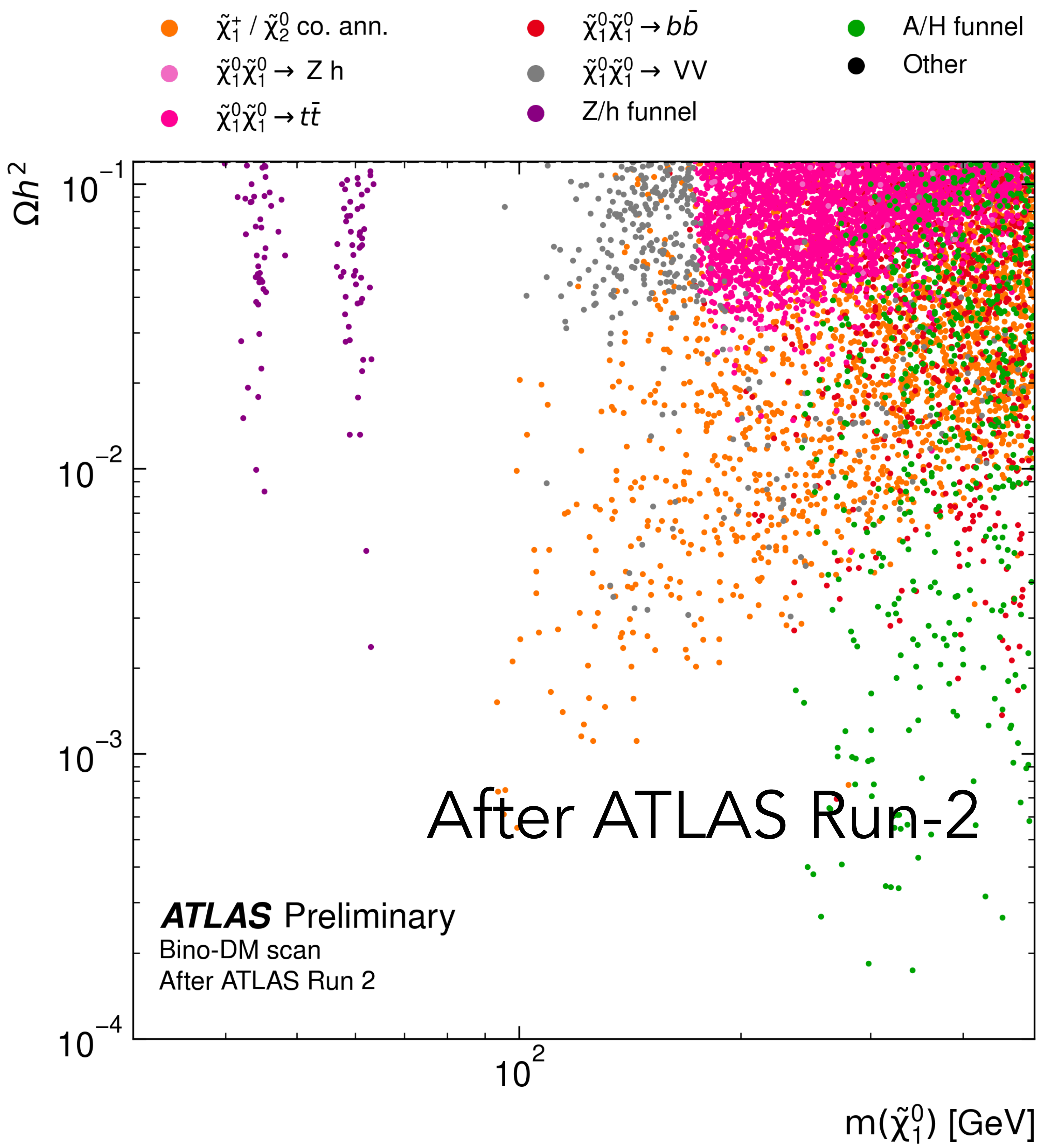



# Electroweak pMSSM Bino-DM Scan

- Bino-like LSP models typically overestimate the relic dark matter density
- Additional annihilation mechanisms are required:
  - compress mass splitting between LSP and $\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}$
  - Z/h funnel regions where LSP mass is half of the *Z/H* mass
- Special scan with $|M_1| < 500$ GeV to focus on low-mass bino models
- Z/h funnel region almost completely excluded by ATLAS Run-2 data

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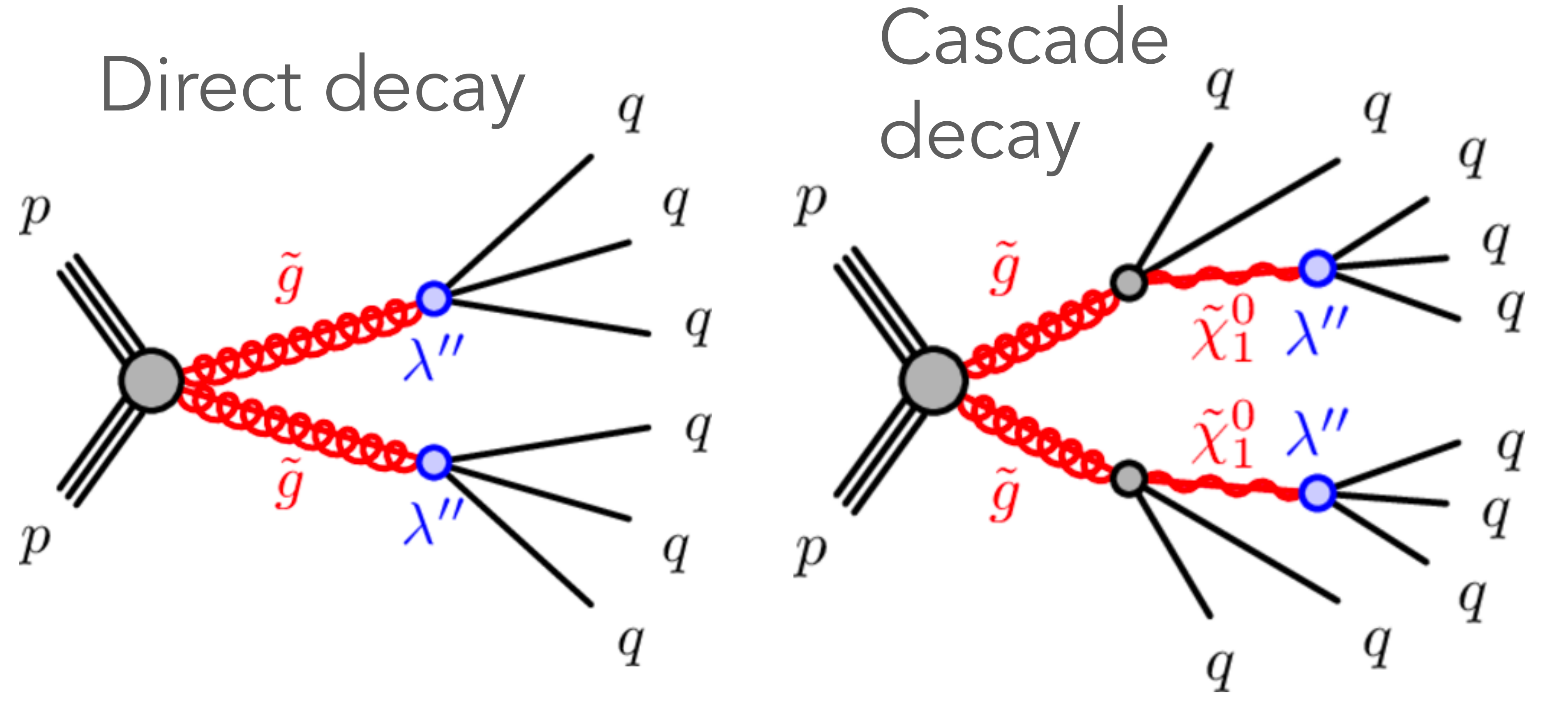
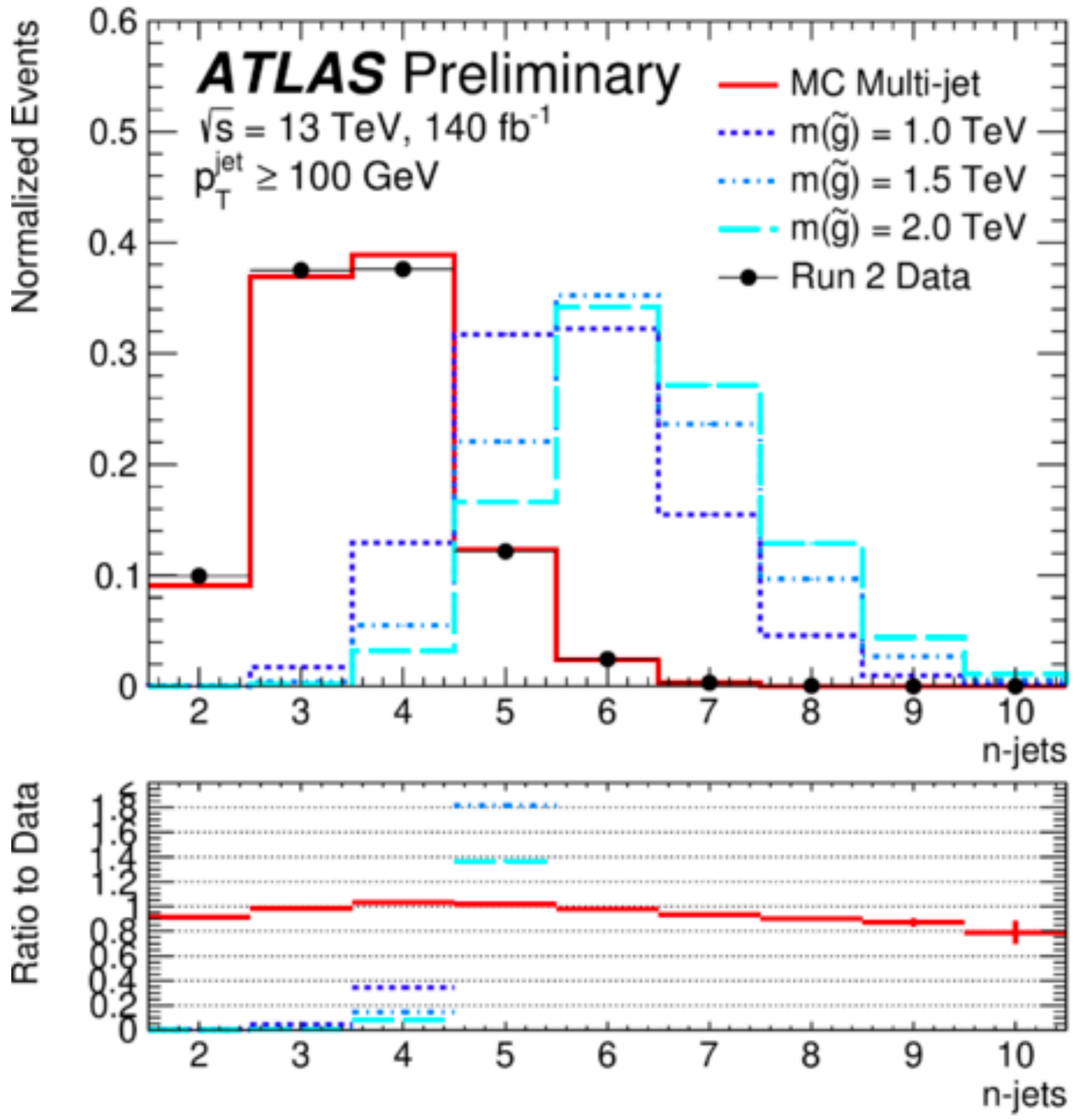
# RPV Multijet search

- Dropping R-parity conservation assumptions, UDD RPV coupling leads to decays to quarks
  → pure multijet final state
- Main challenge: massive QCD multi jet background



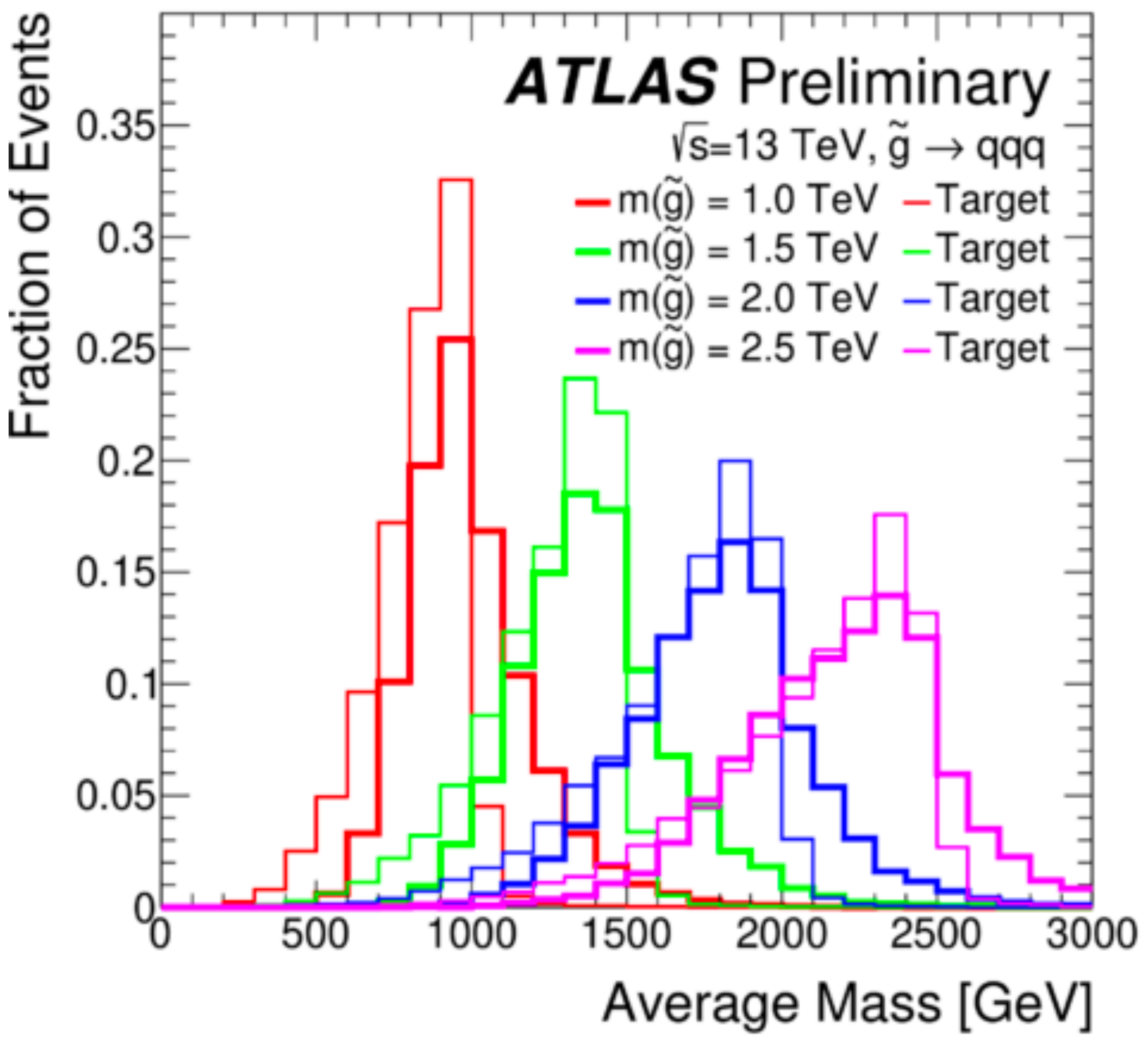

**Jet counting analysis**

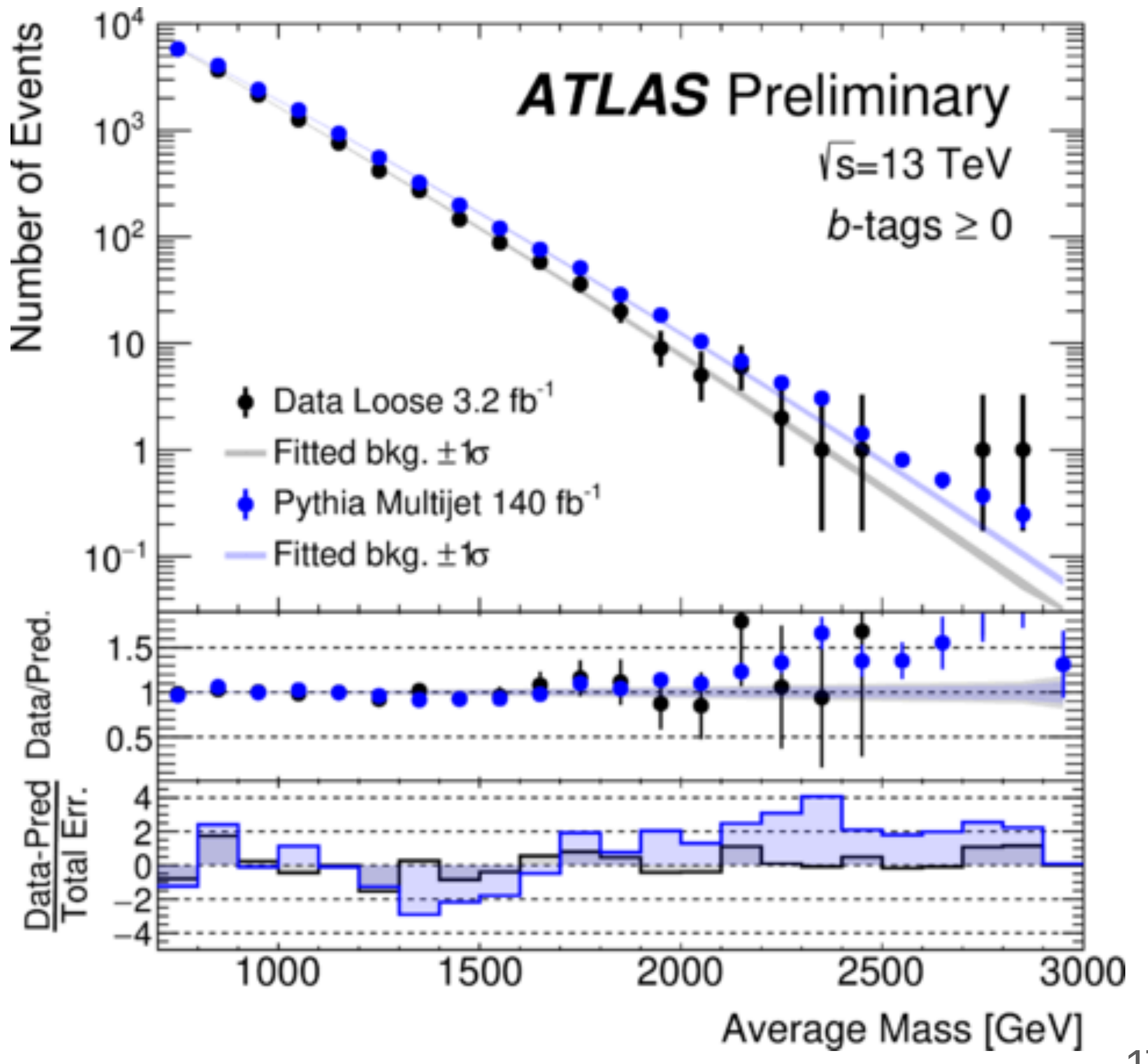
- SRs depending on number of jets, energy isotropy and number of b-tags




**Mass resonance analysis**

- NN model to reconstruct gluino mass and bump hunt

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# RPV Multijet results

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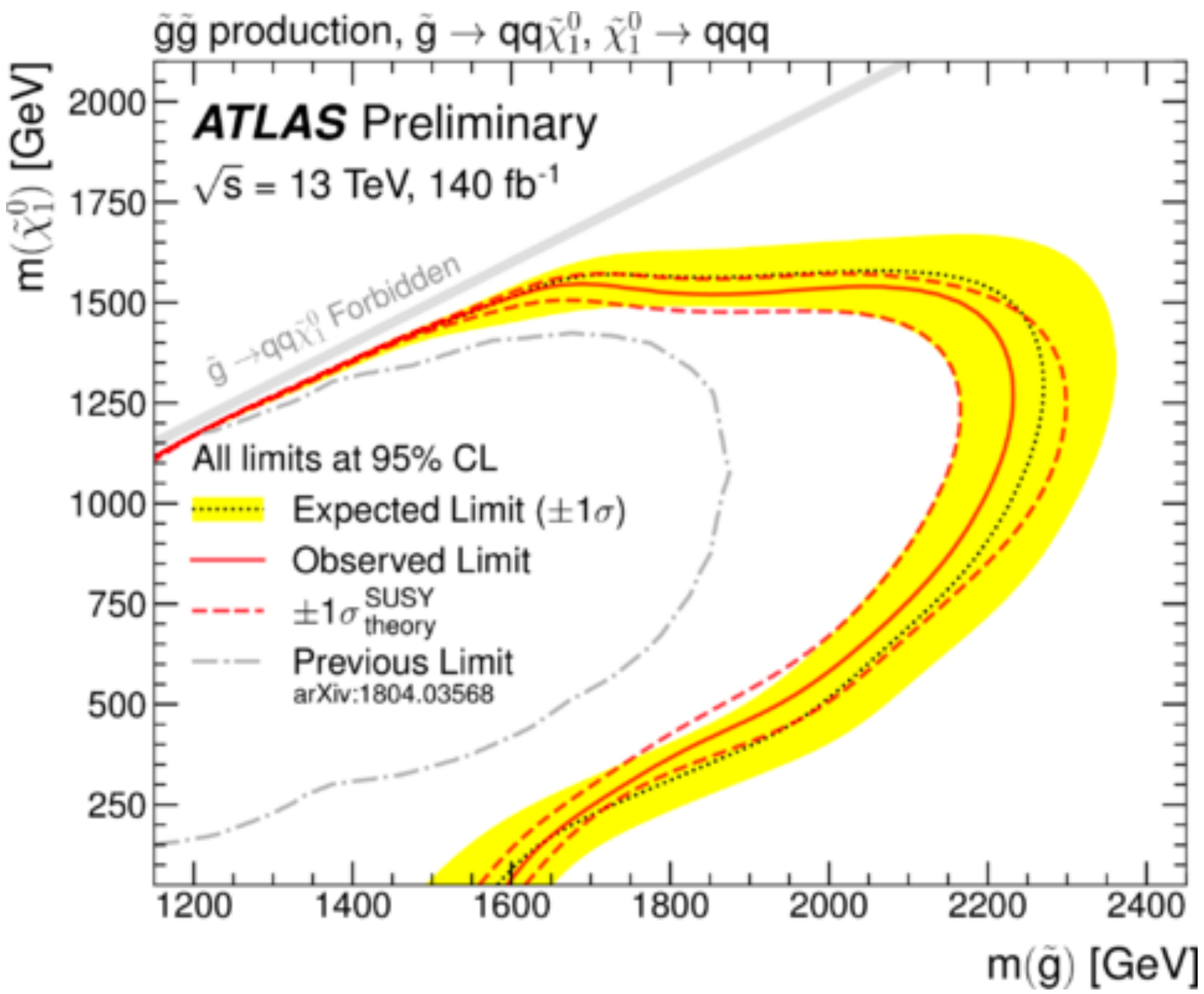
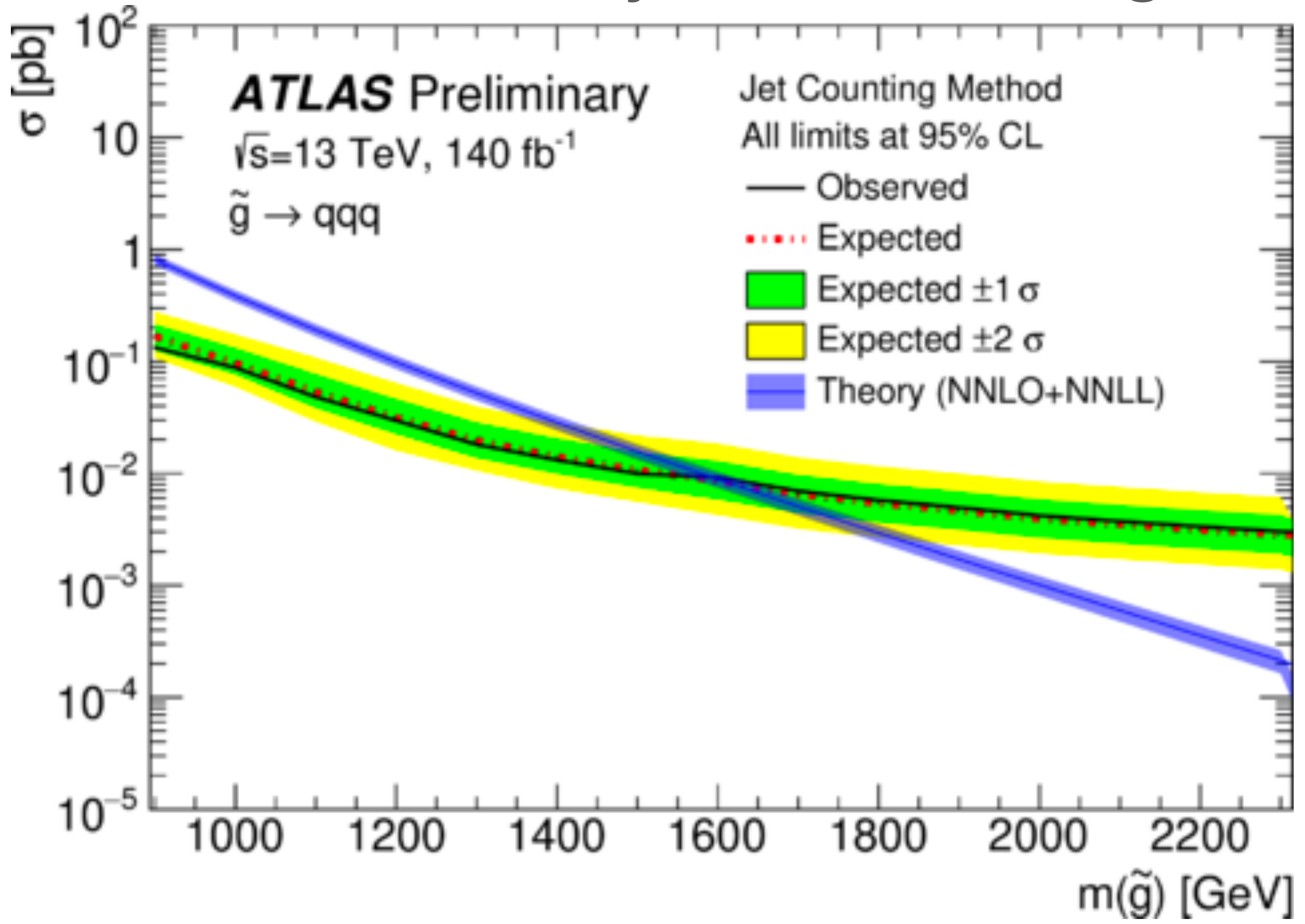
- Data consistent with background expectation in all the SRs
- Improved limits thanks to the new analysis techniques

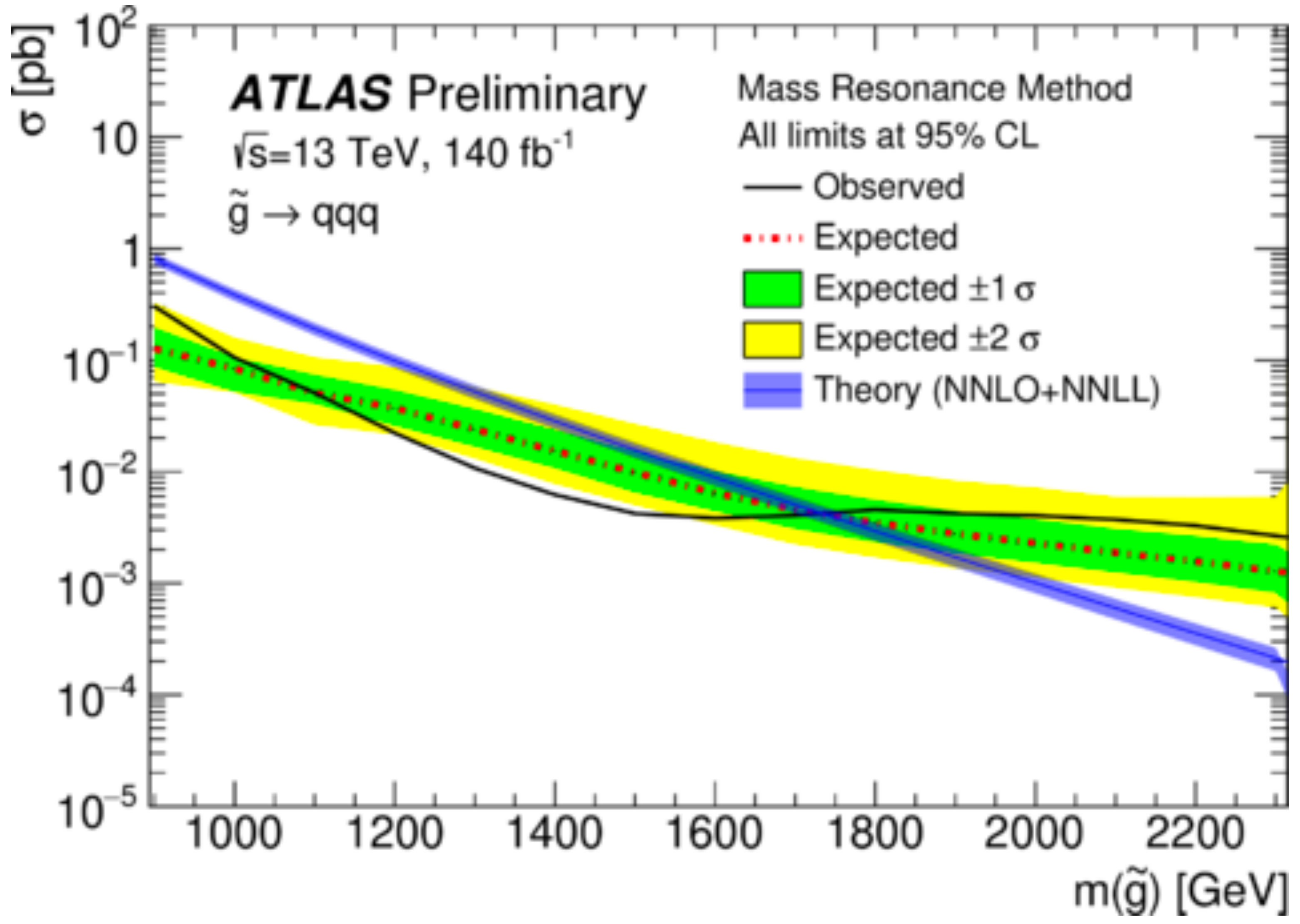
Cascade decay - Jet counting




Direct decay - Jet counting



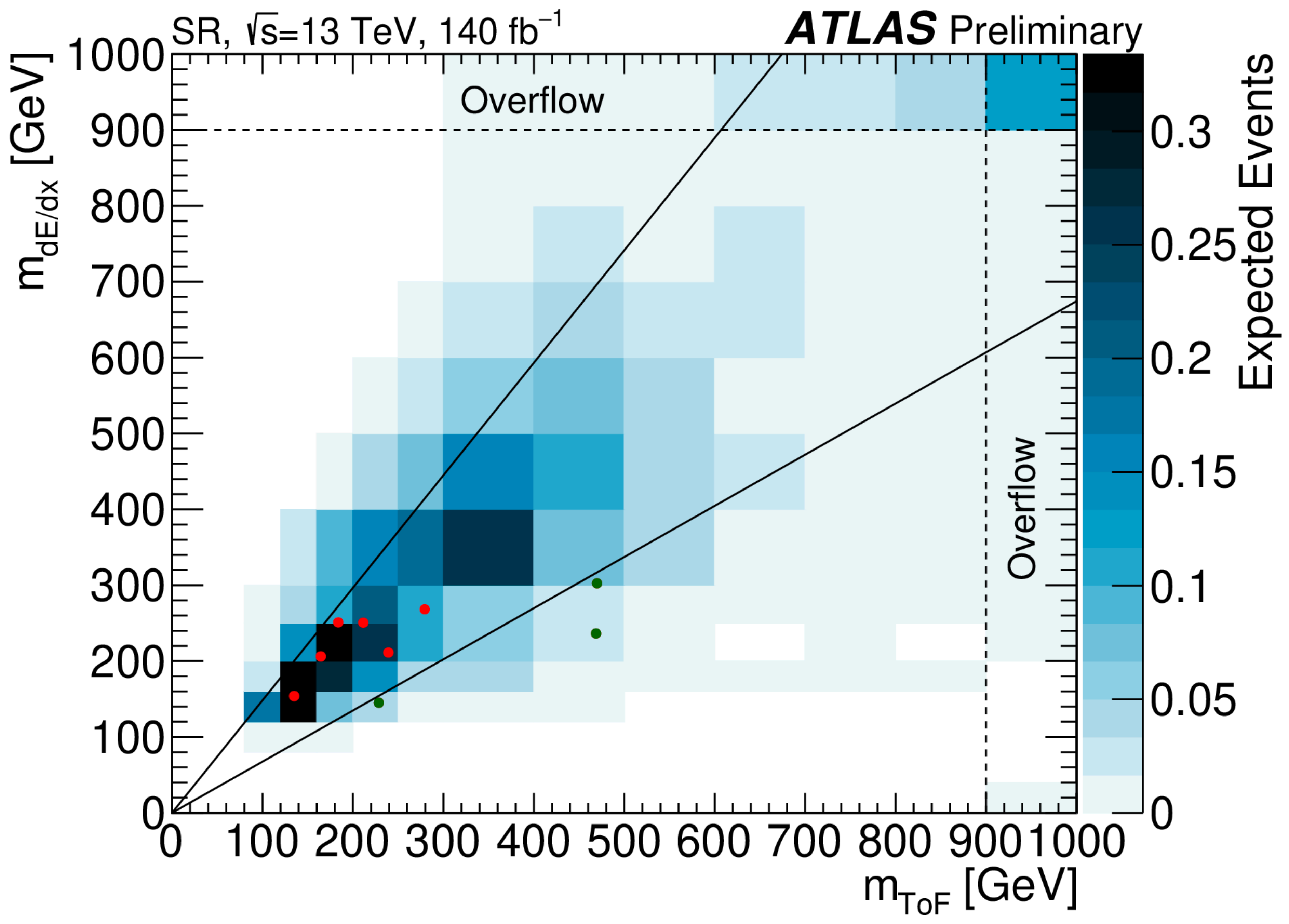

Direct decay - Mass resonance

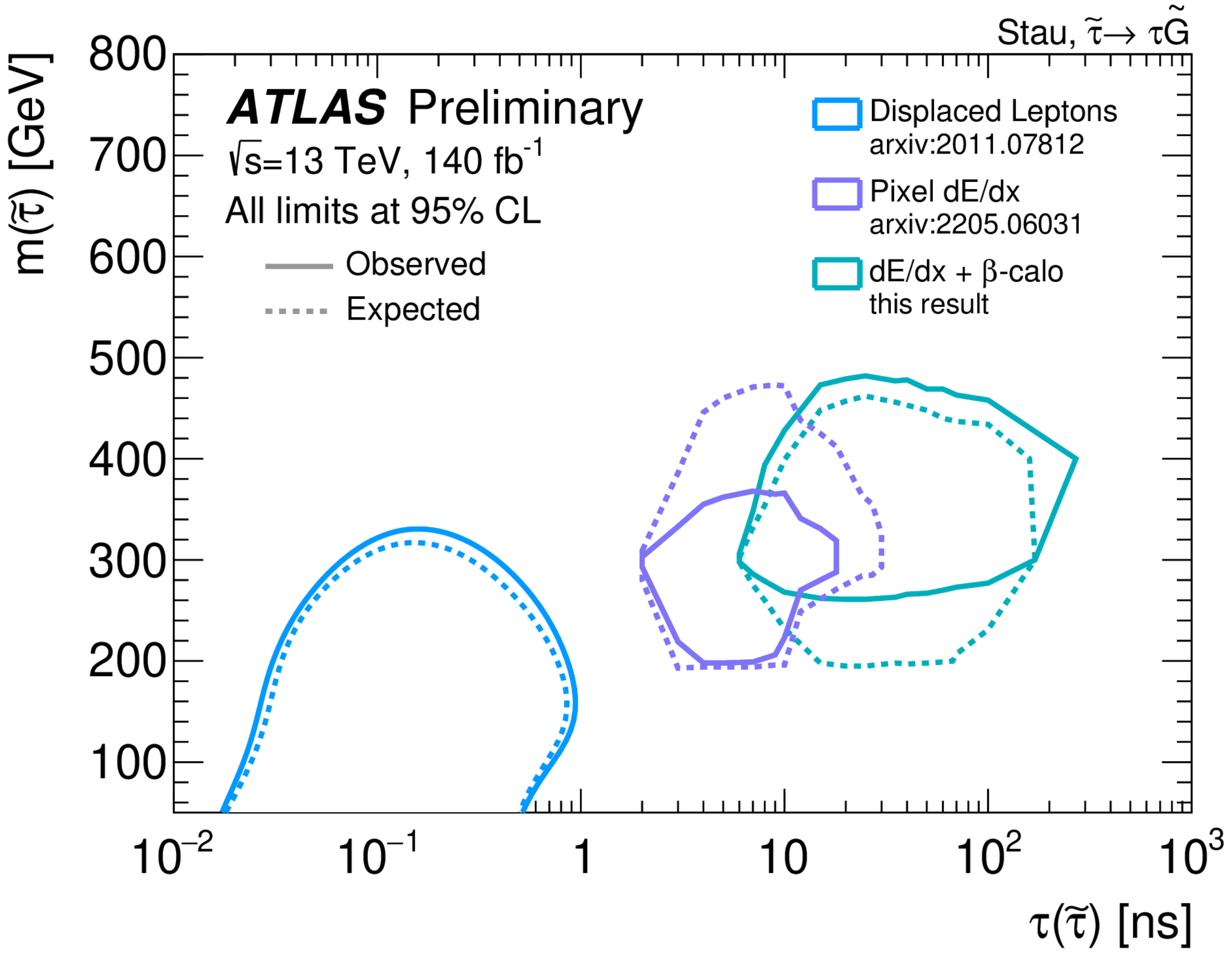


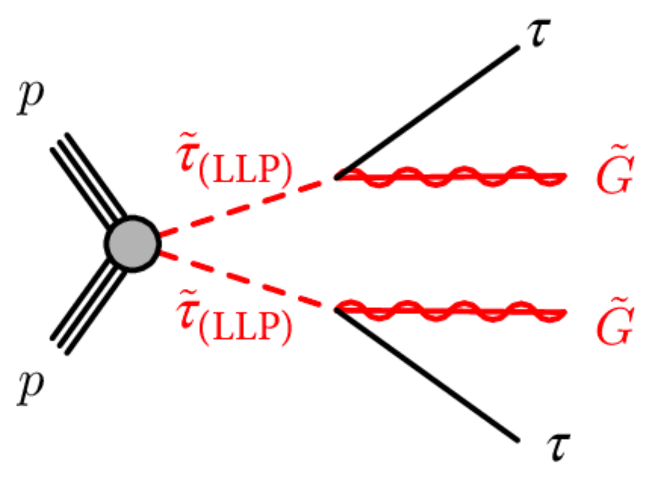
# Long-lived heavy particles

- Hypothetical massive charge long-lived particles move significantly slower than *c* and can be identified as:
  - Isolated high momentum track with large ionisation energy loss $(dE/dx)$ measured in the pixel detector
  - Significantly slower as measured by the calorimeter time-of-flight
- Main observable is the mass of the particle associated to the track $m \equiv p/\beta\gamma$
- Constraints on SUSY pair production of long-lived *R*-hadrons and staus
- Agreement with background expectation

  → 6 observed, 3.7 ± 0.4 expected
- Most stringent limits to date for detector unstable LLPs in the LHC for lifetime range above 10 ns



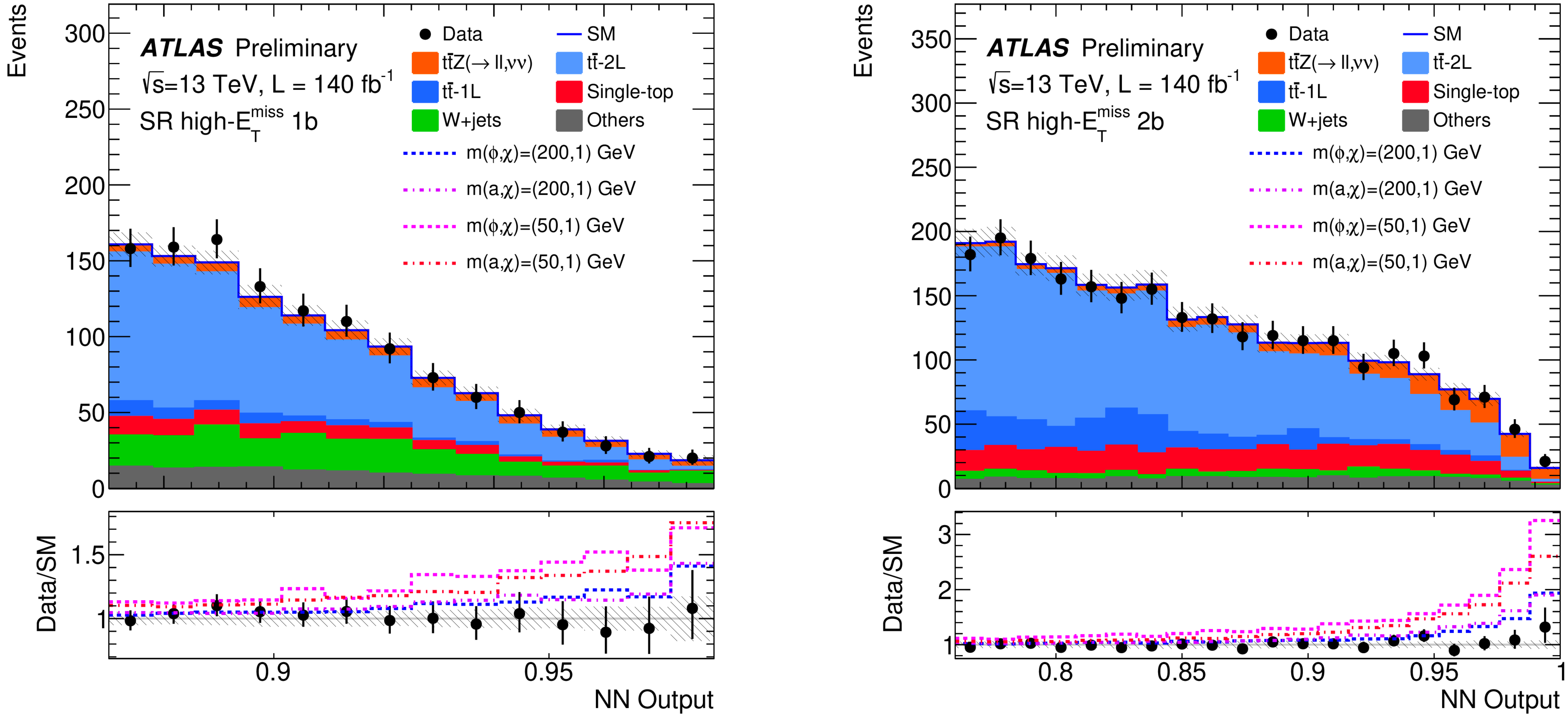



# Summary

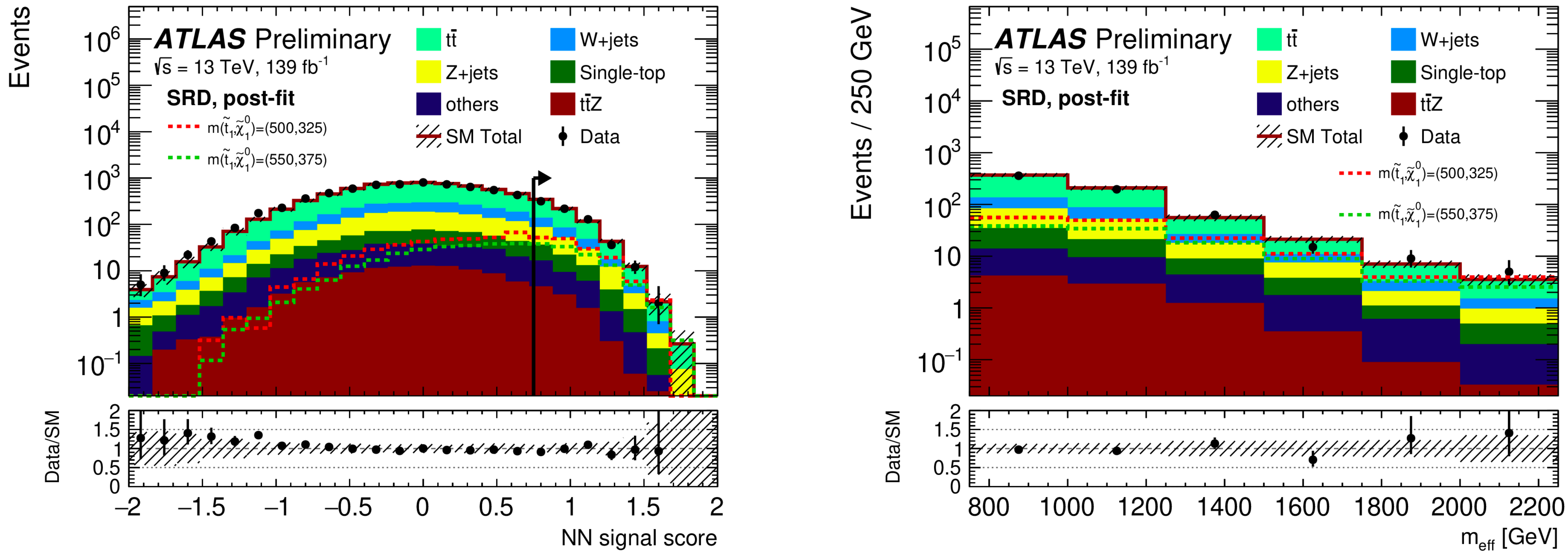
- Comprehensive ATLAS SUSY search programme using the full Run-2 data from LHC
  - Probing large part of the SUSY phase space including very difficult final state signatures with compressed scenarios and unconventional signatures
  - Find all the ATLAS SUSY results here
- For the moment good agreement between observed data and SM expectation in all final states
  - Stringent limits on several simplified models
  - Chargino/neutralino mass excluded up to ~1 TeV
  - First limits set on $m(\tilde{\tau}_R)$ at the LHC
- Results with LHC Run-3 data are coming not only including more data:
  - More sophisticated ML techniques improving object reconstruction/identification and also signal and background discrimination
  - More combinations and SUSY parameter scans
  - More public data for re-interpretation: model independent limits, code snippets, likelihoods (https://www.hepdata.net)

# Backup slides

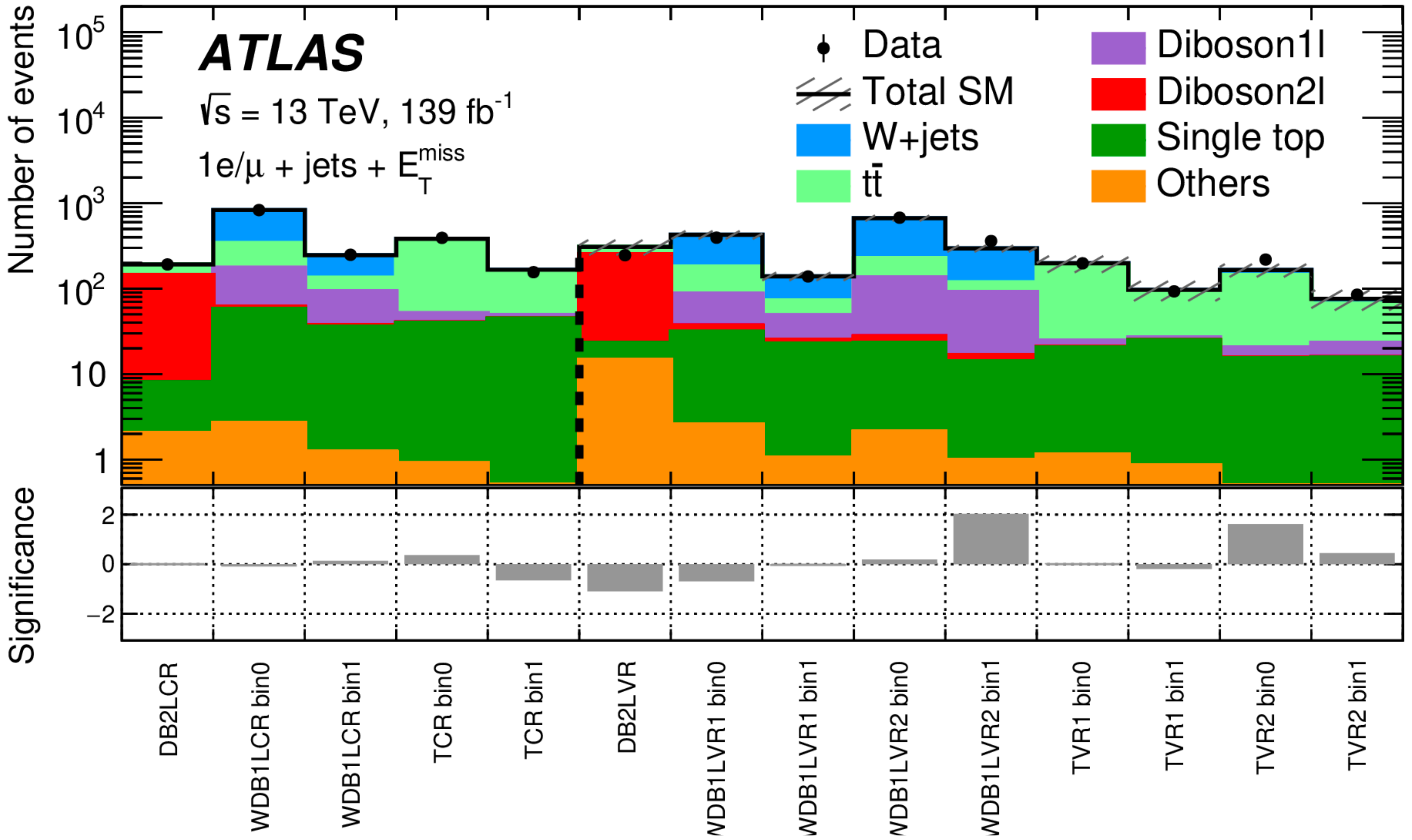
# Stop search: tt+MET

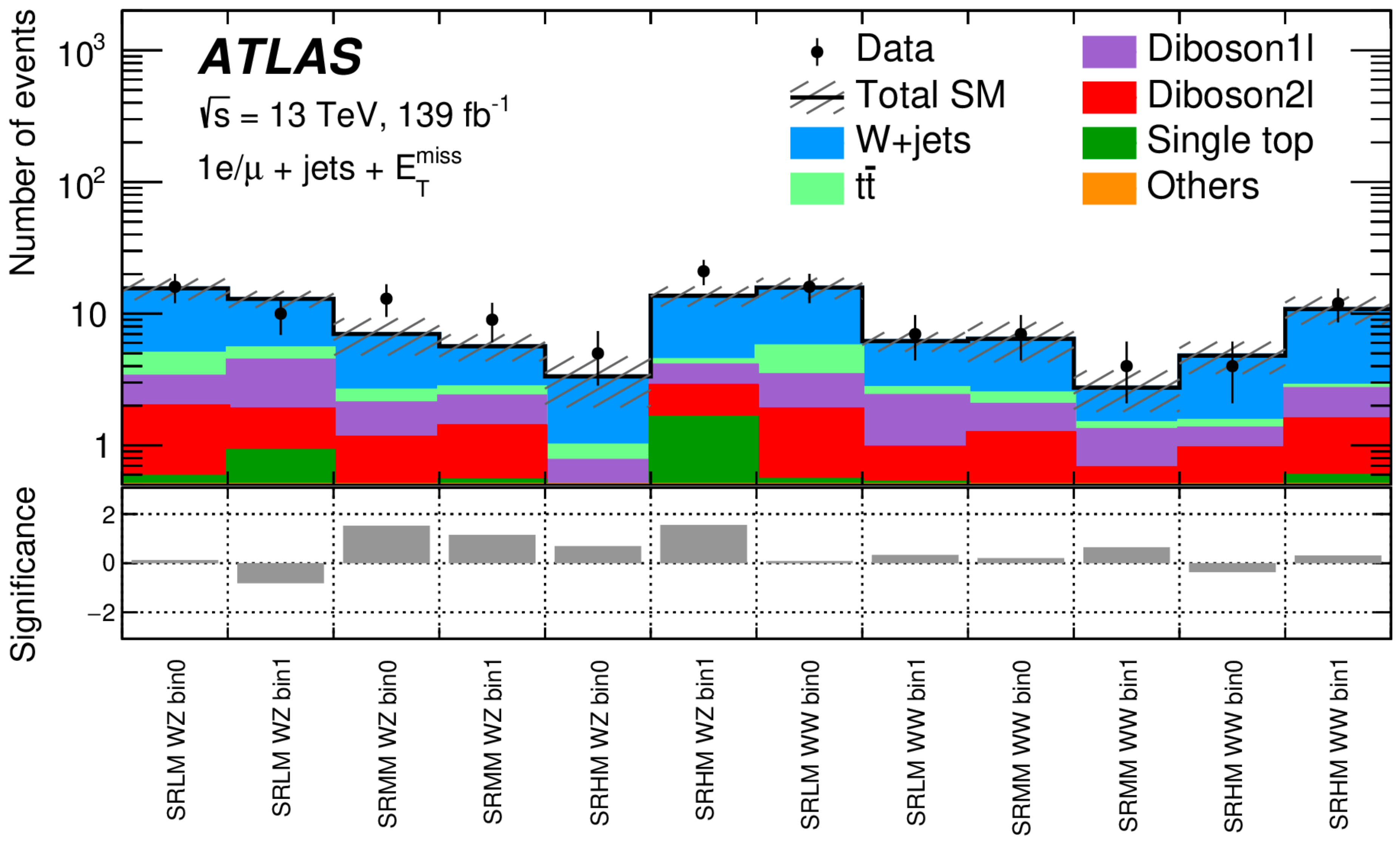


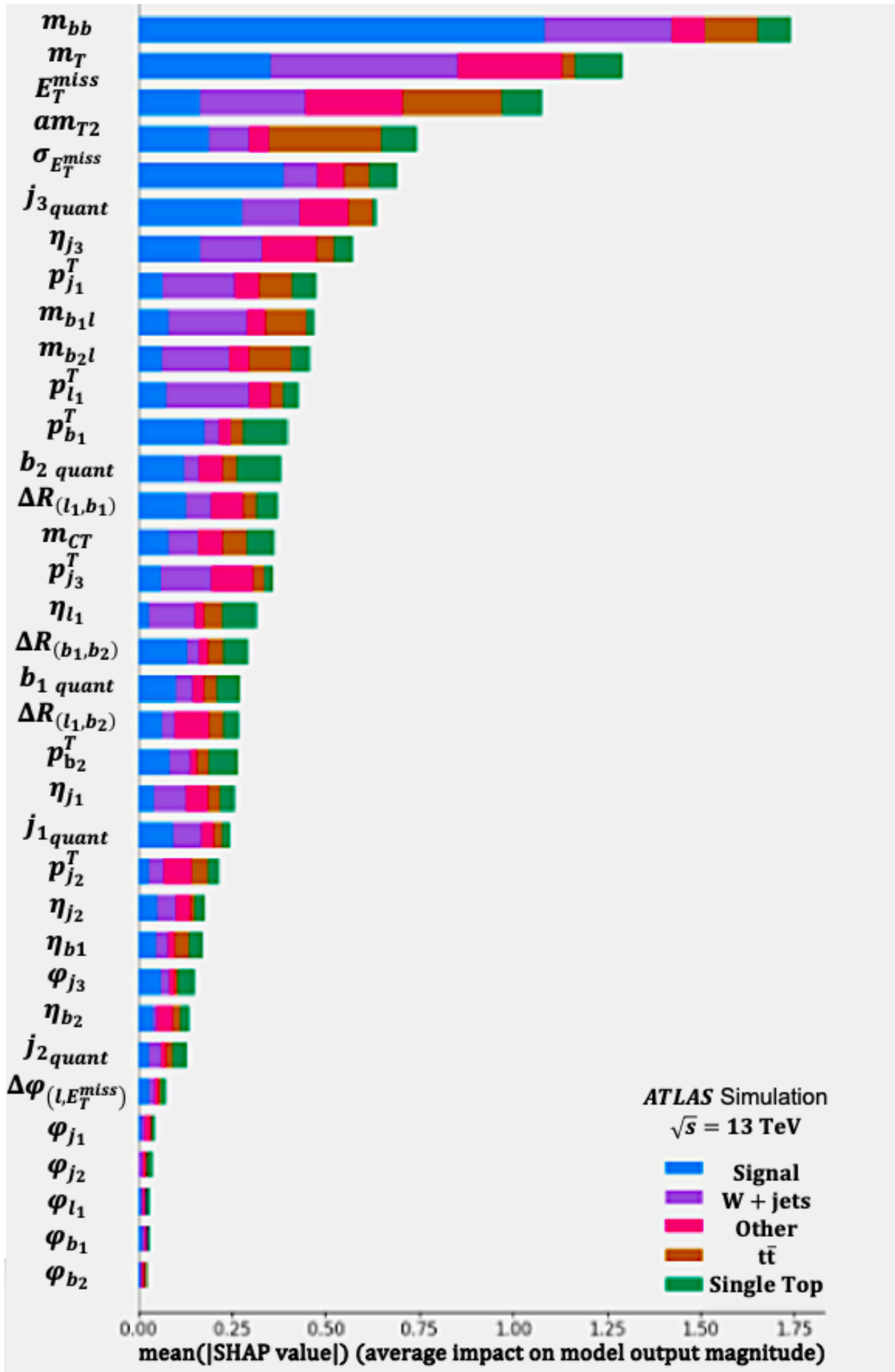
# Stop search: tc+MET

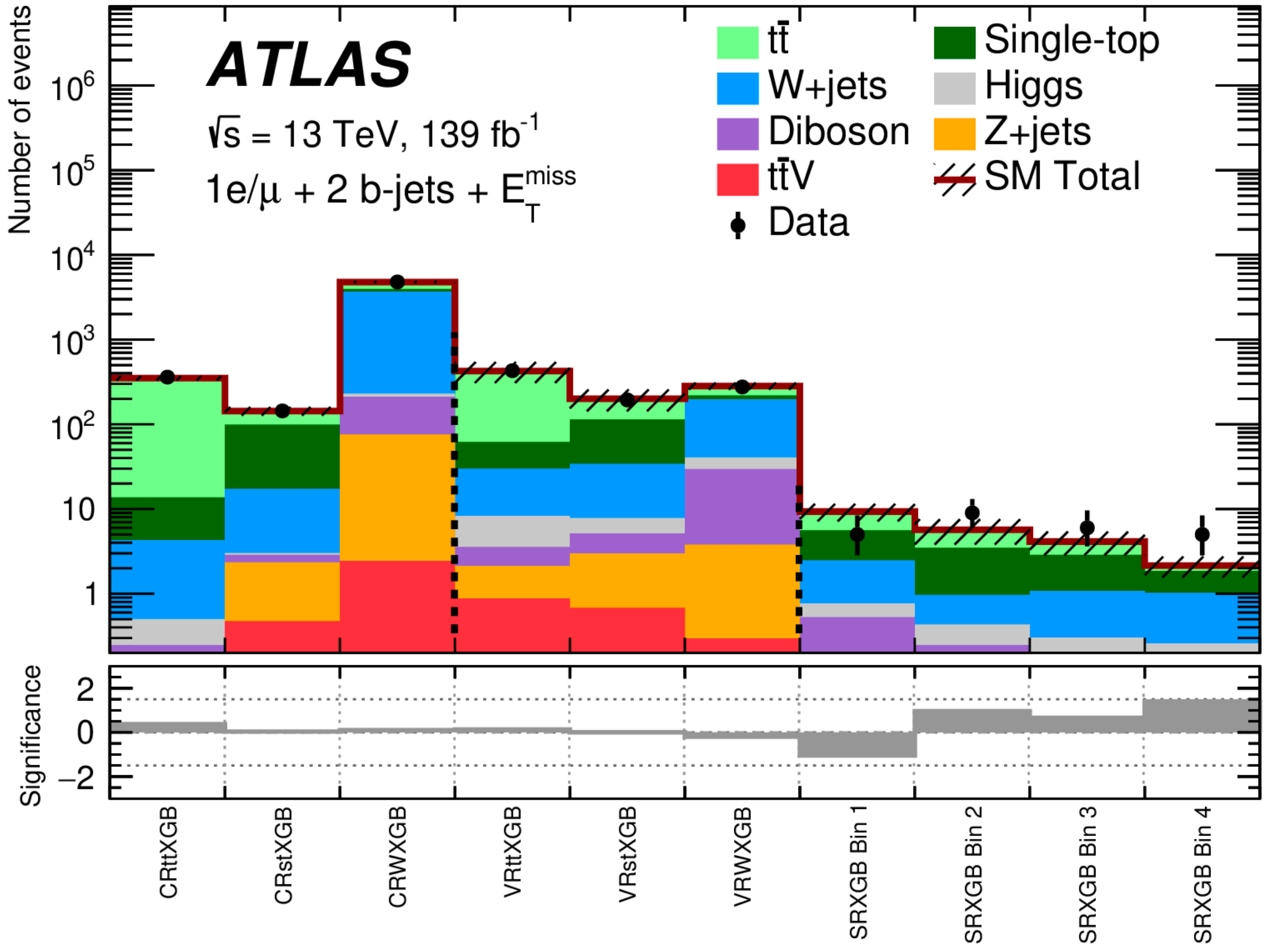


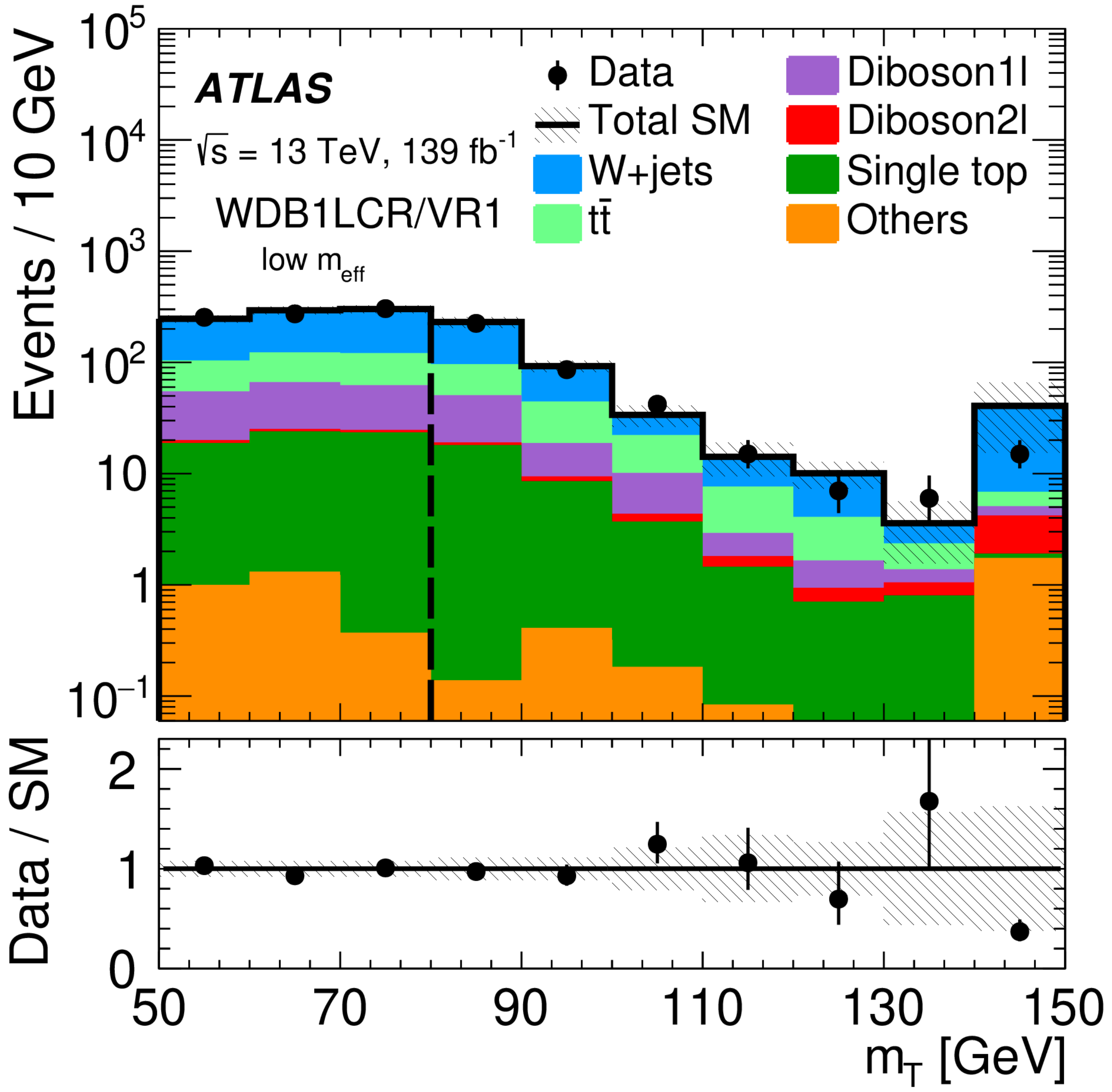
# Electroweak with one lepton



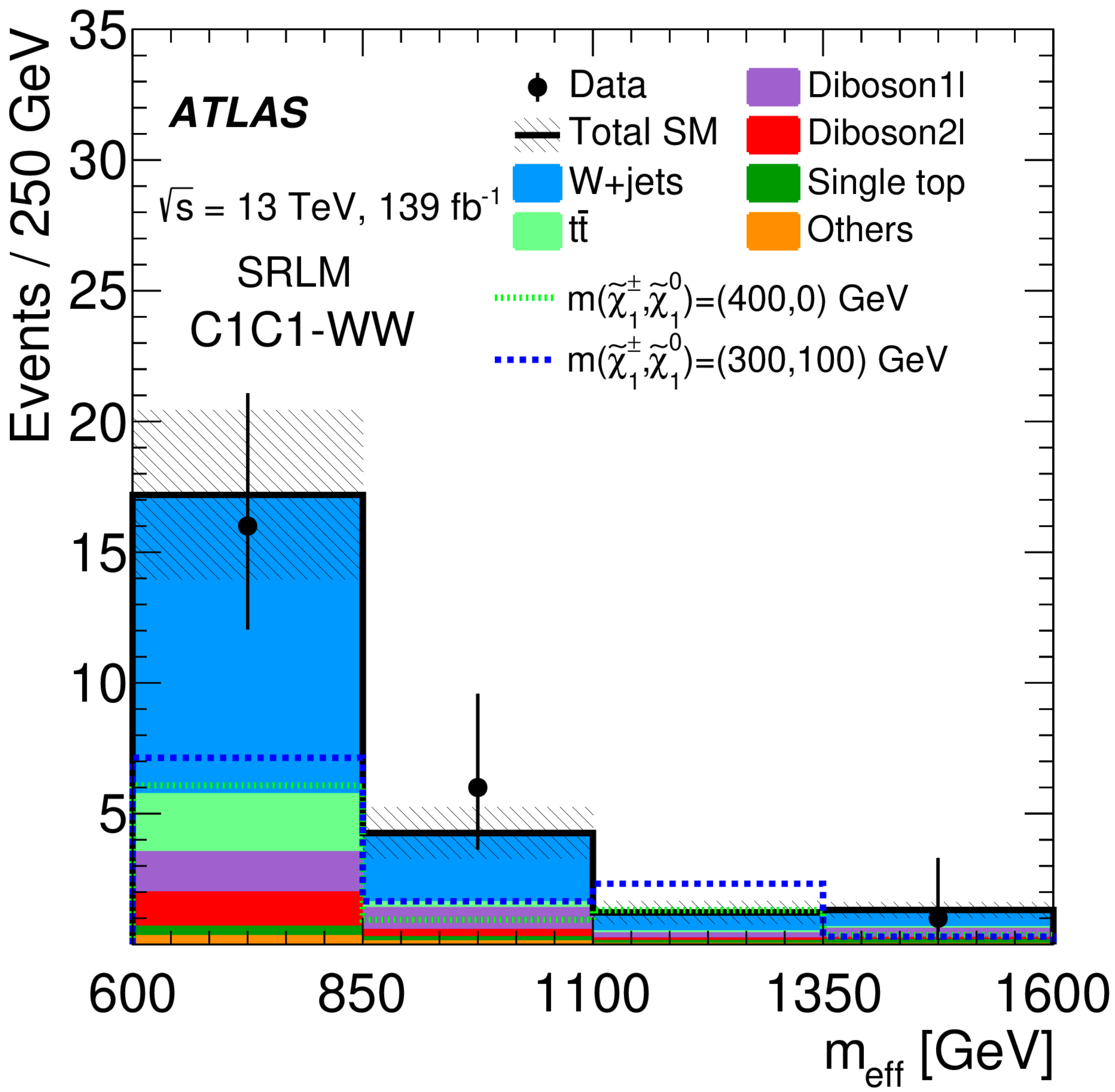



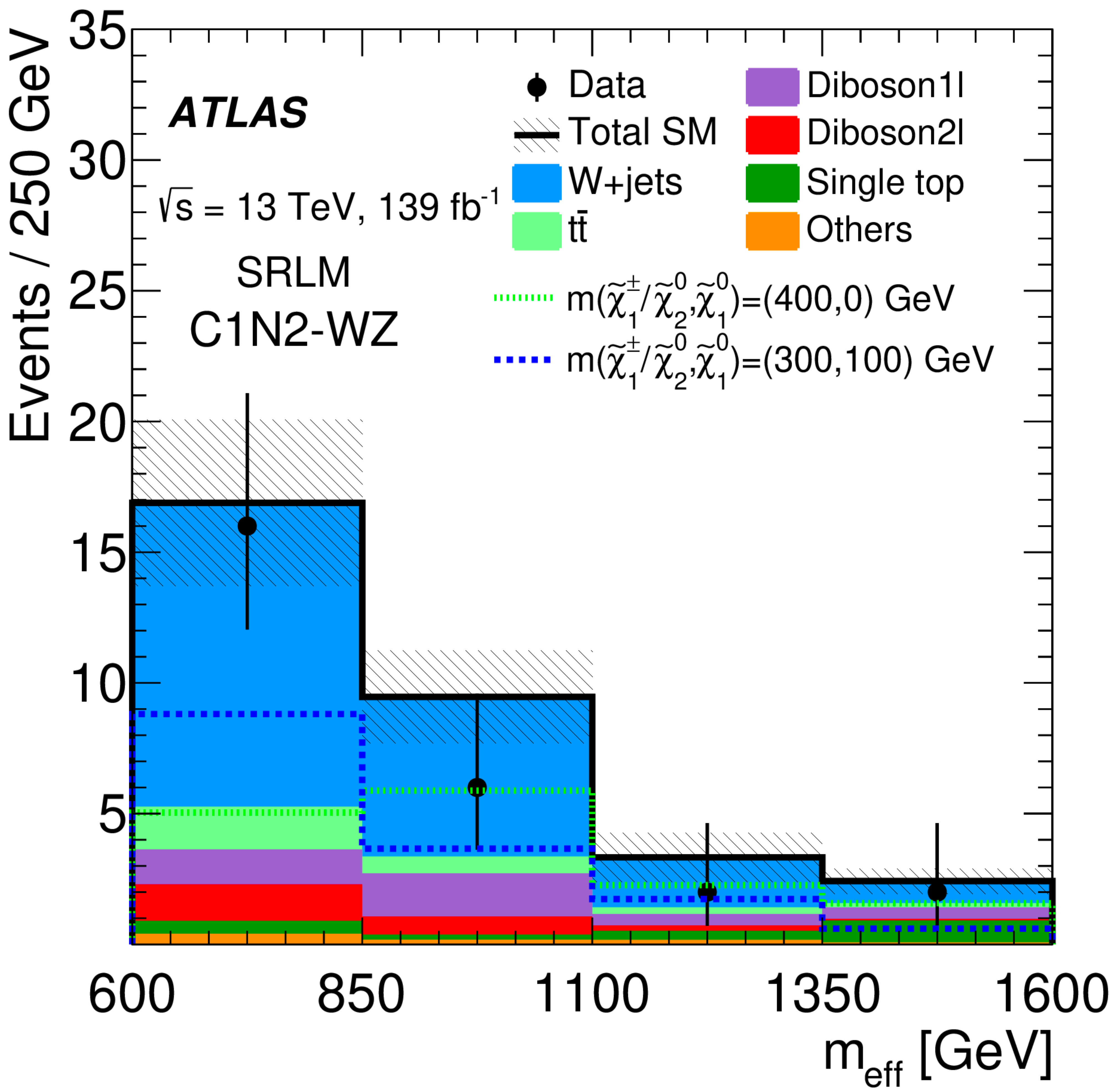



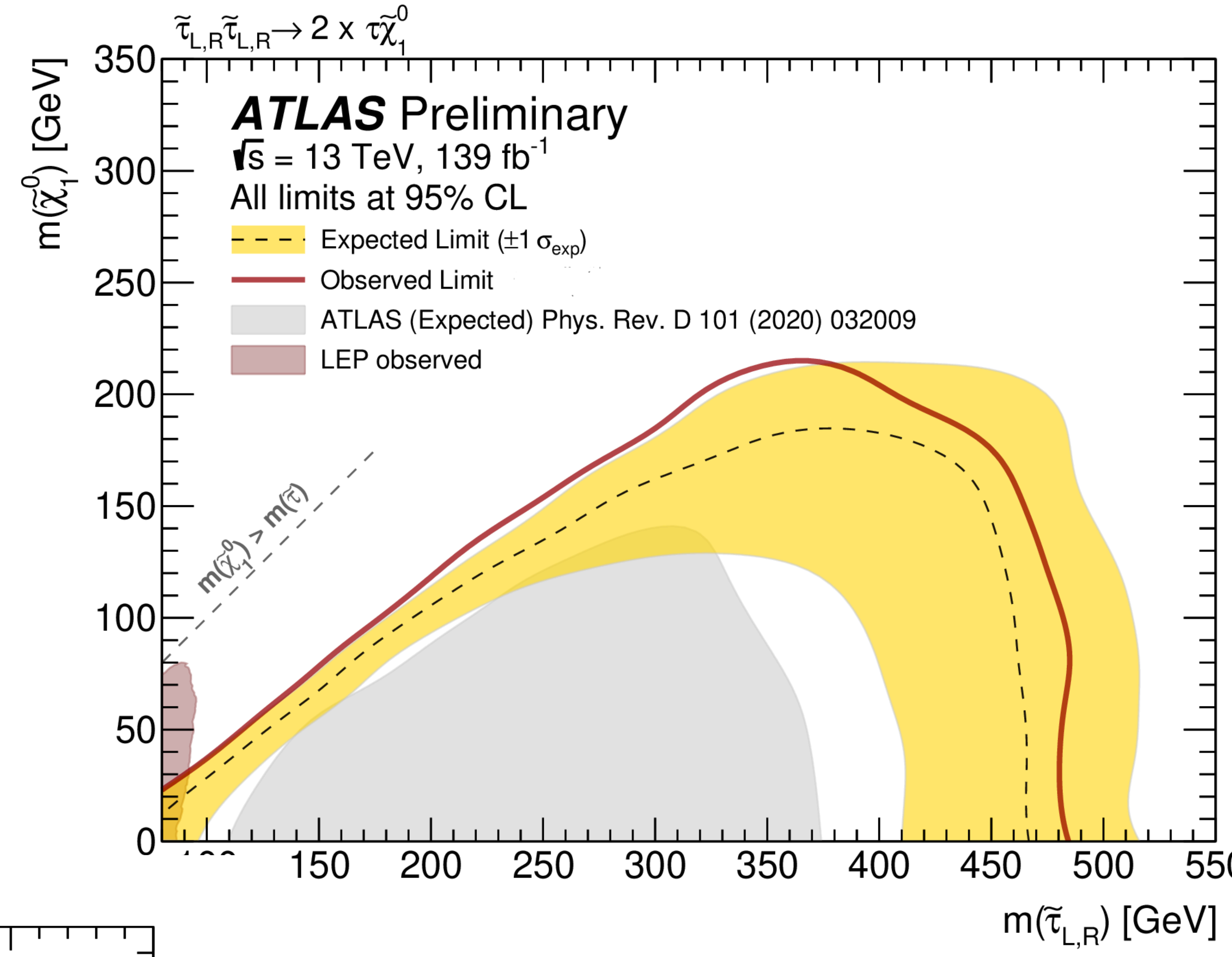



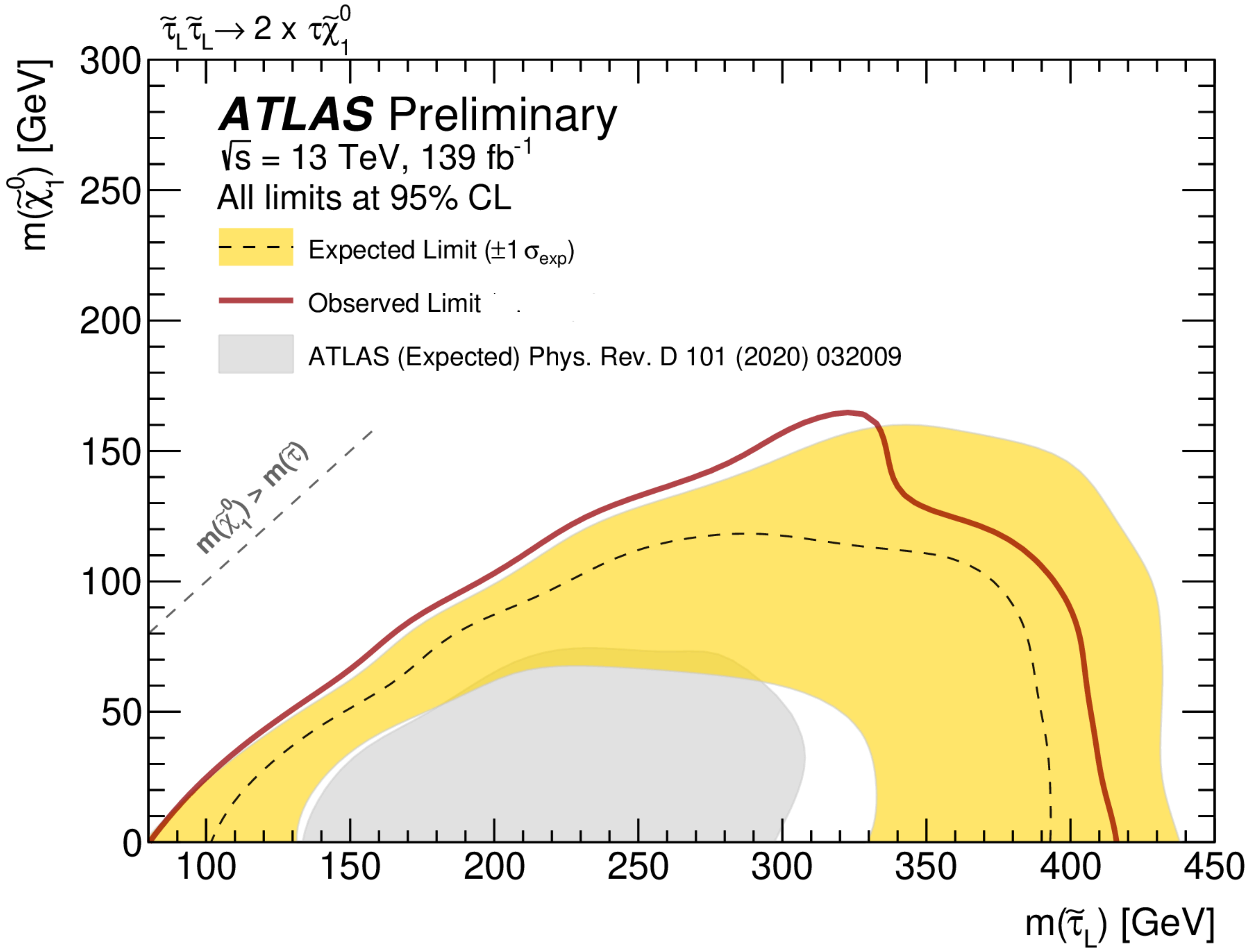
# Electroweak with one lepton

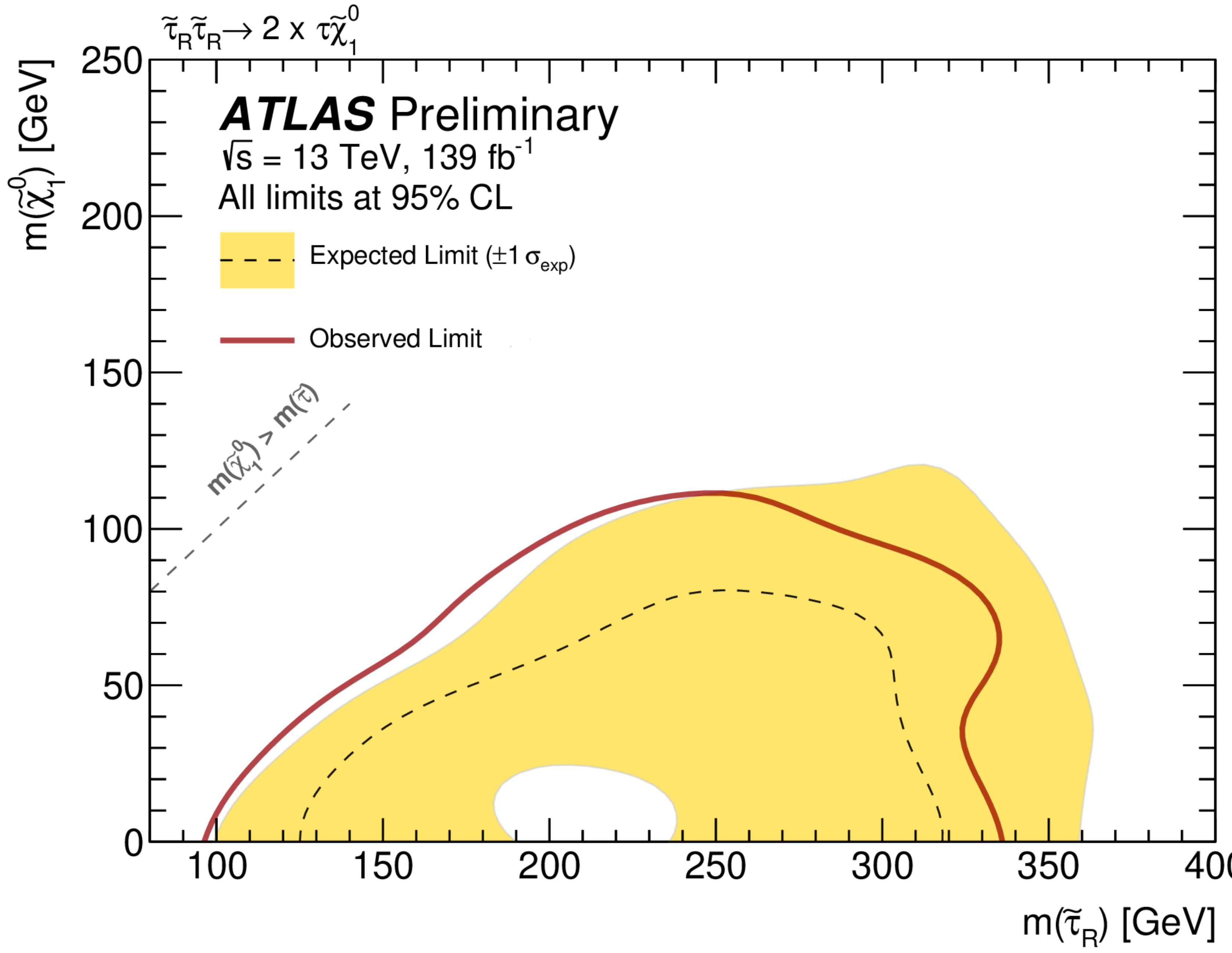


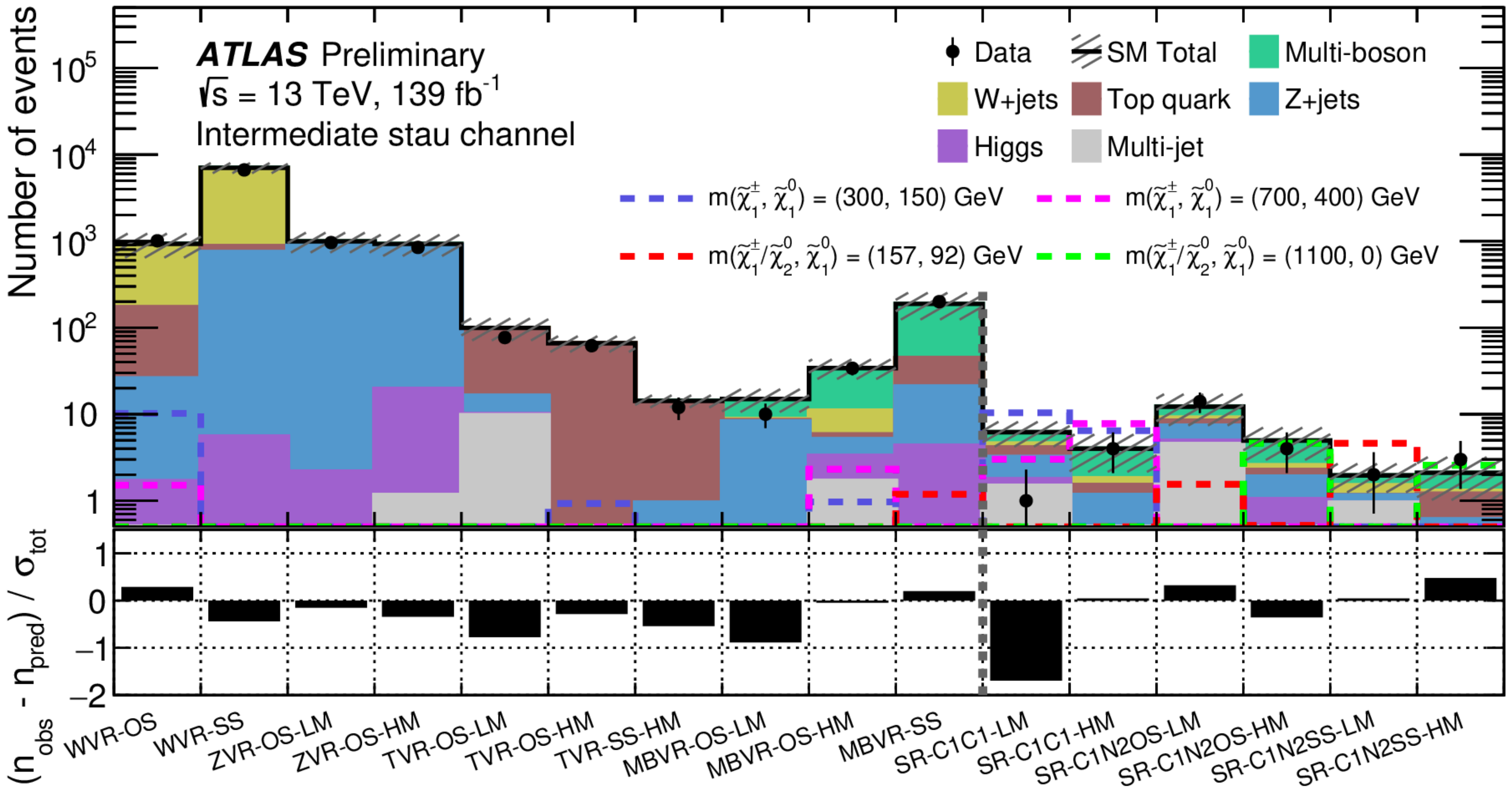
# Electroweak with taus: direct $\tilde{\tau}$

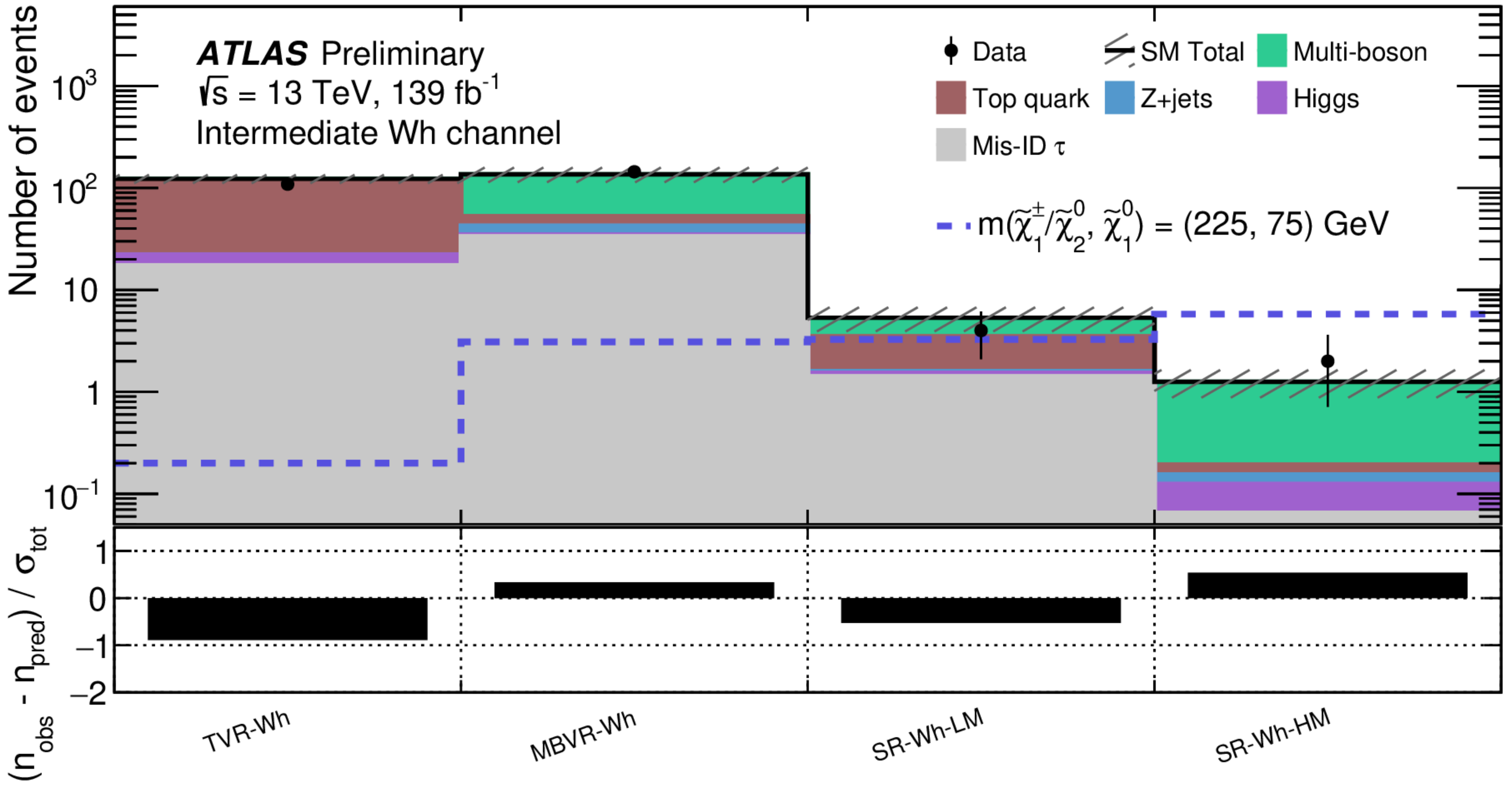


# Electroweak with taus: intermediate stau/Wh



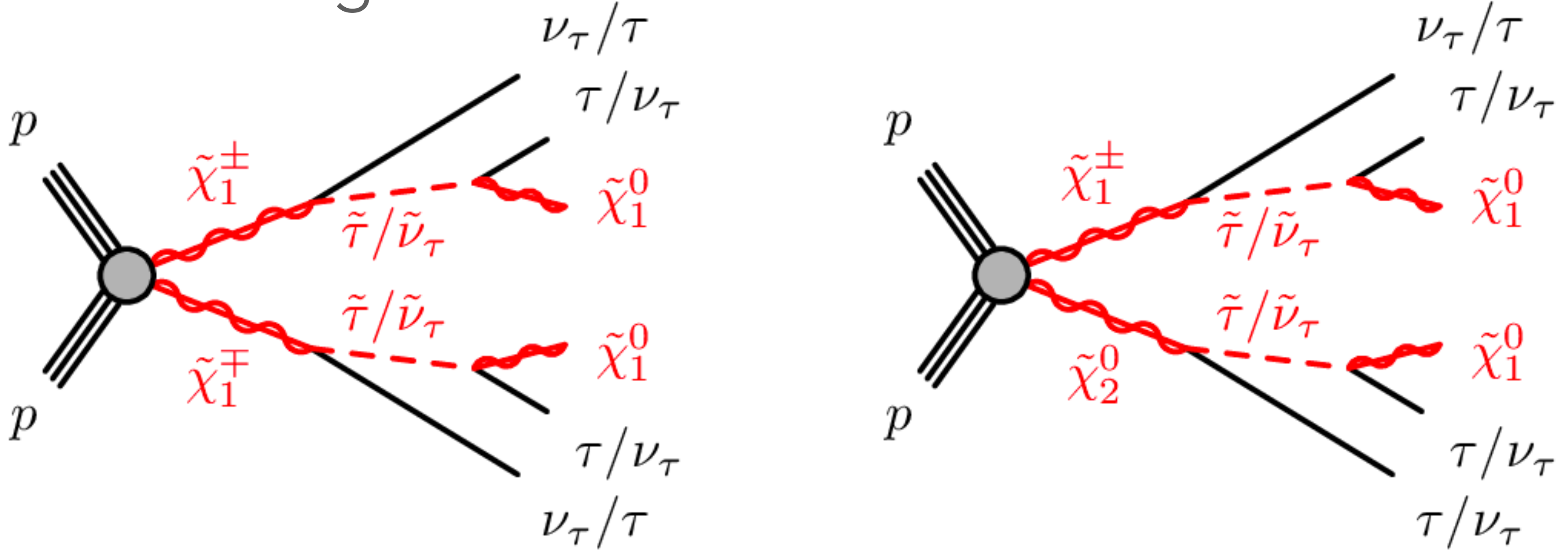



# Electroweak with taus: intermediate $\tilde{\tau}$/Wh

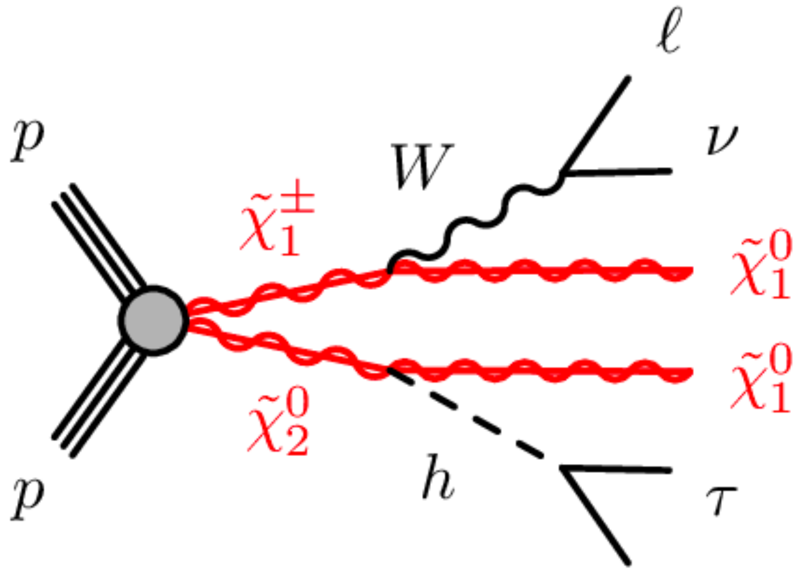
ATLAS-CONF-2023-029

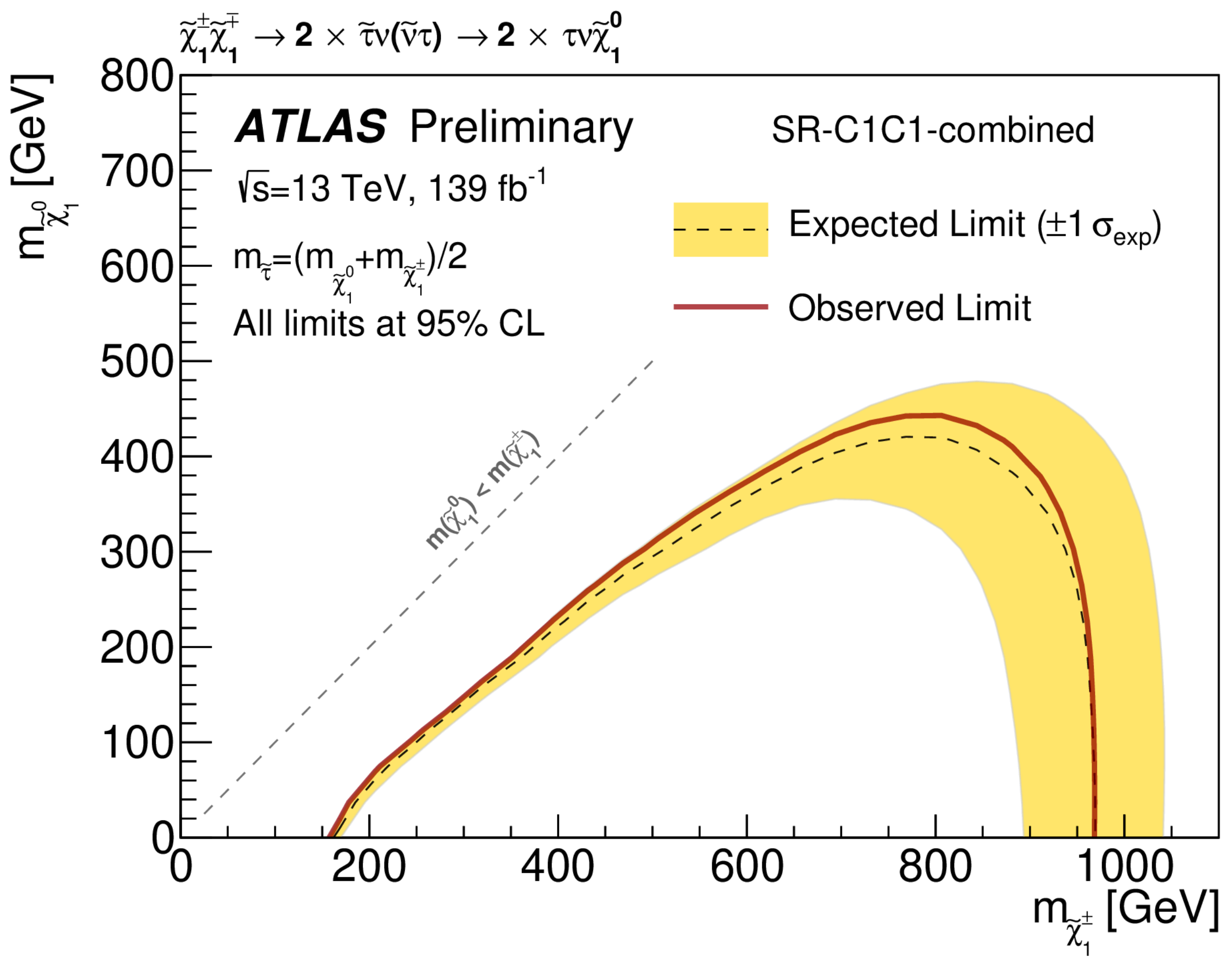
- Two hadronically decaying taus, low jet activity and large MET (from neutralinos and neutrinos)
- Neutralino/chargino production
    - decaying to LSP through intermediate staus or tau sneutrinos with same BR
    - decaying through W and Higgs boson

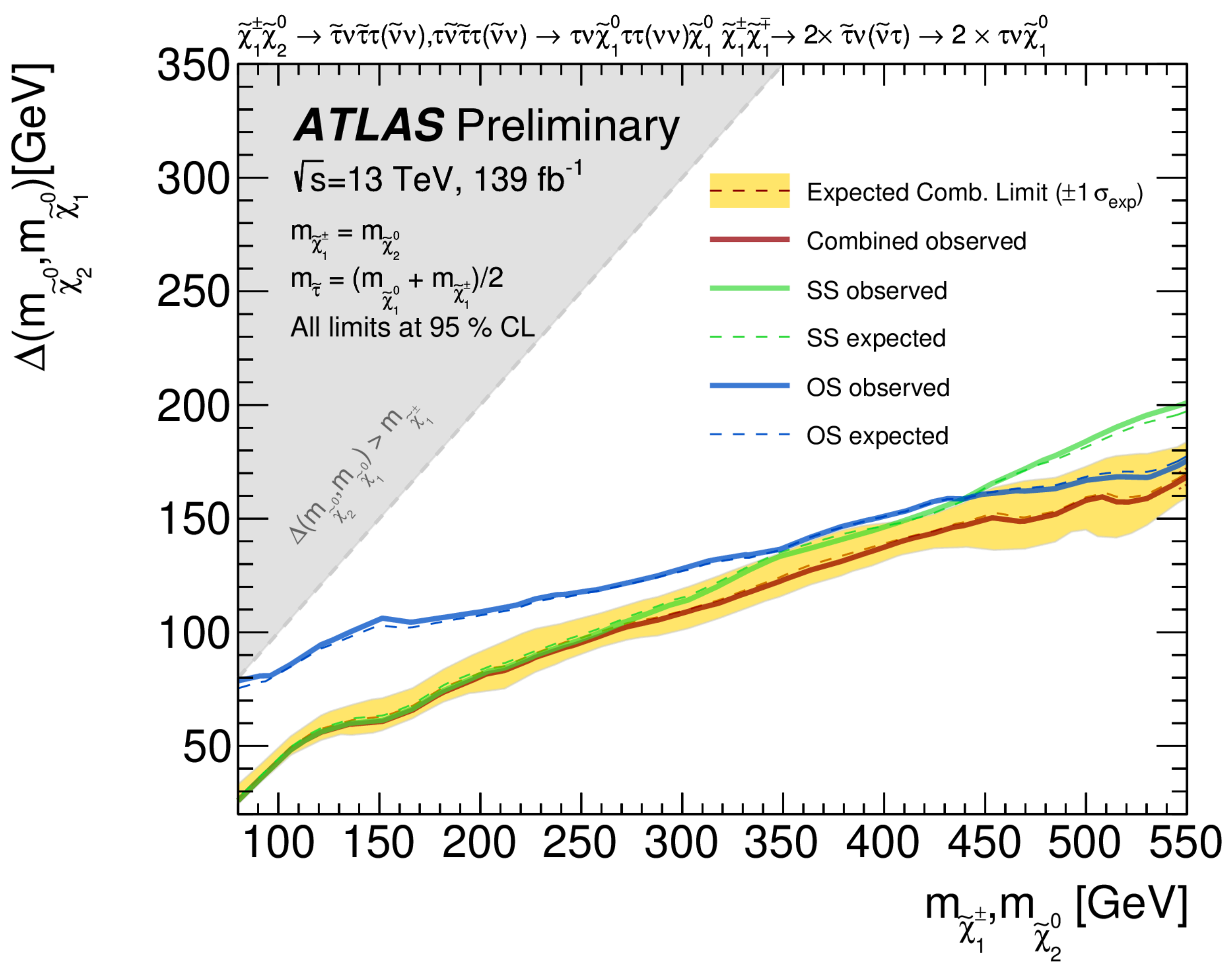
Chargino/neutralino via intermediate stau

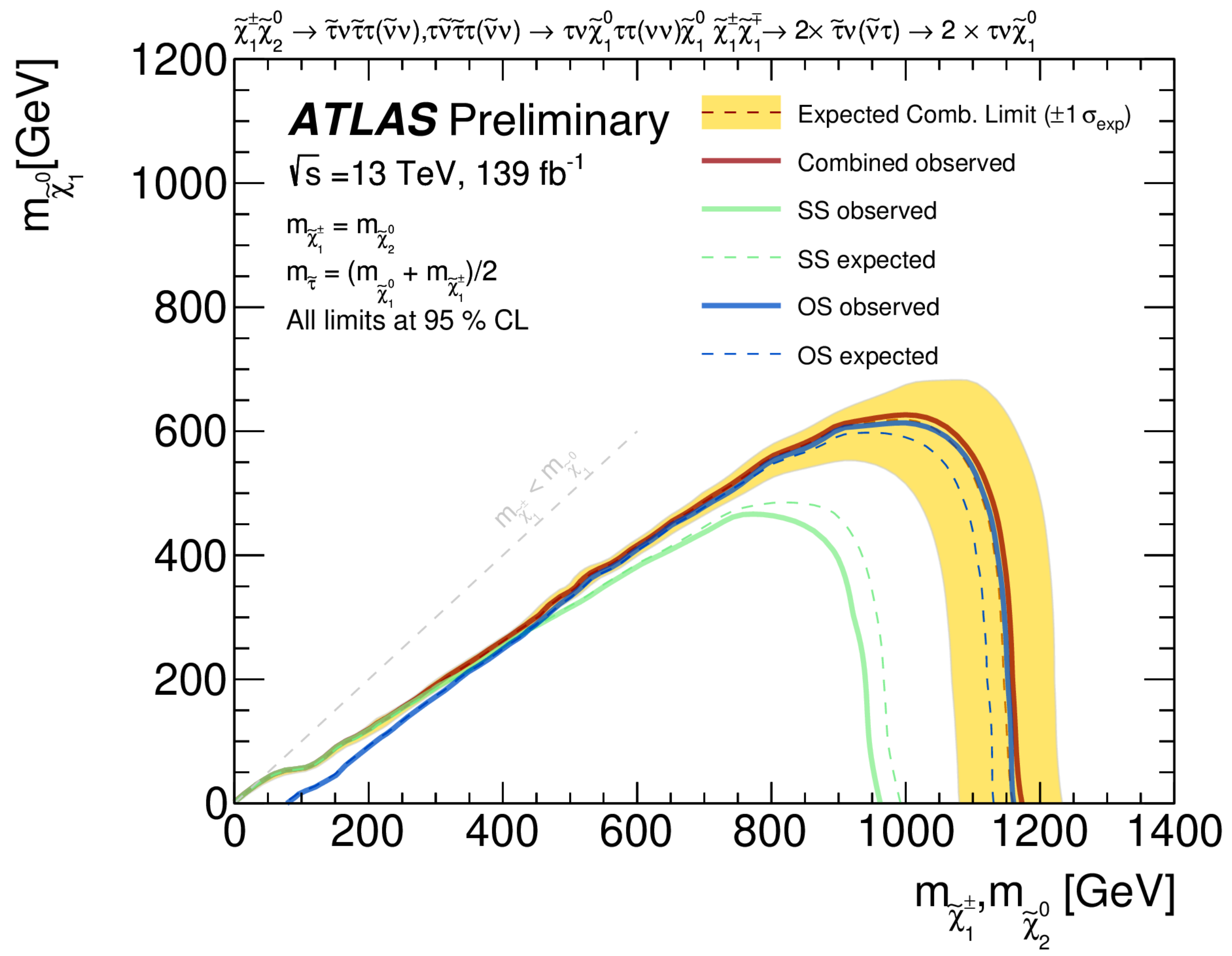


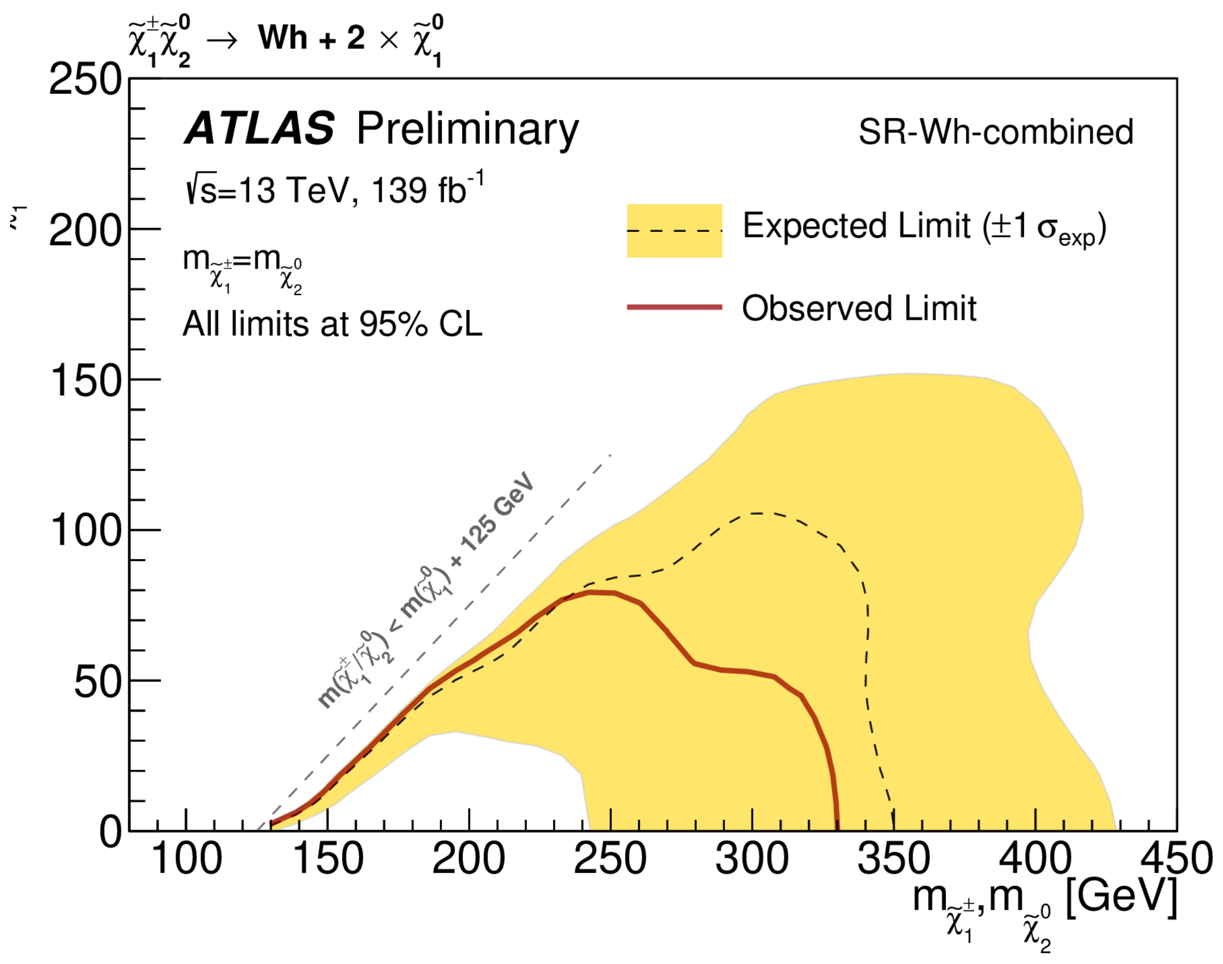
Intermediate Wh channel



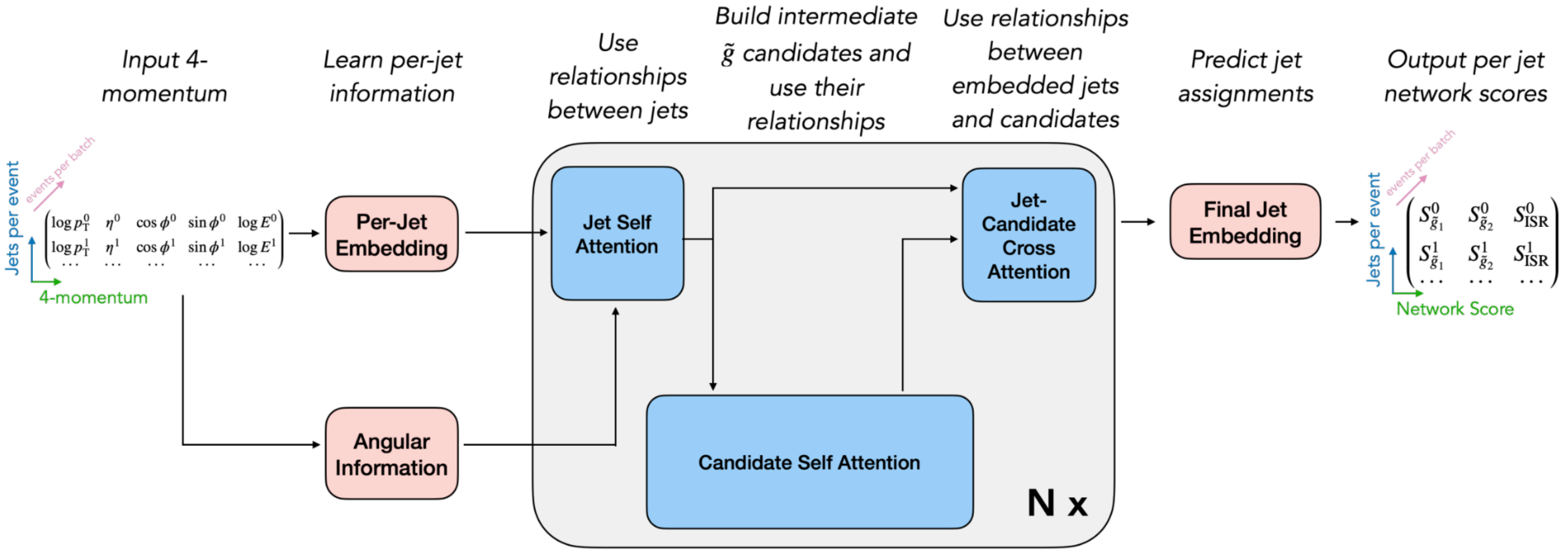


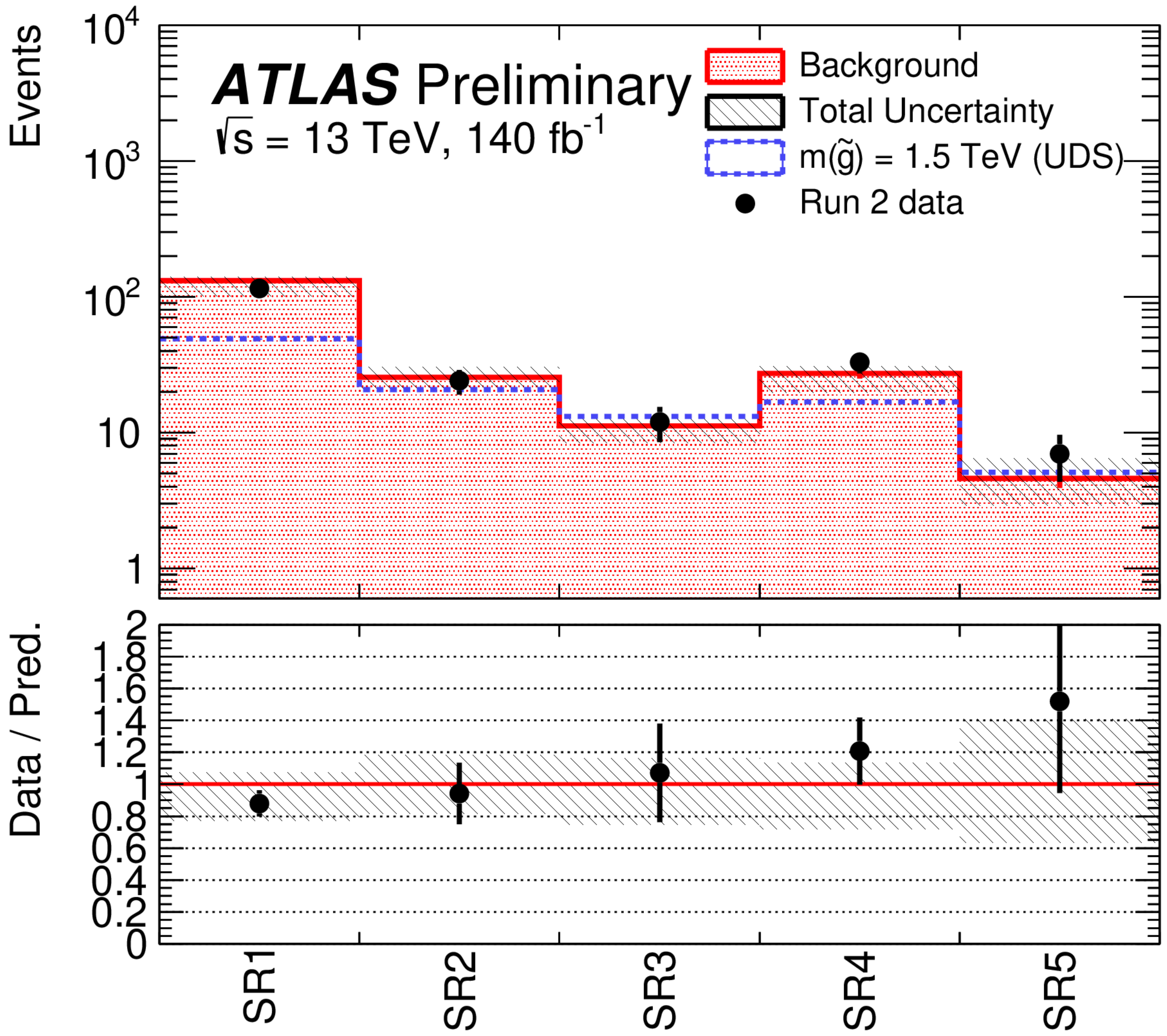



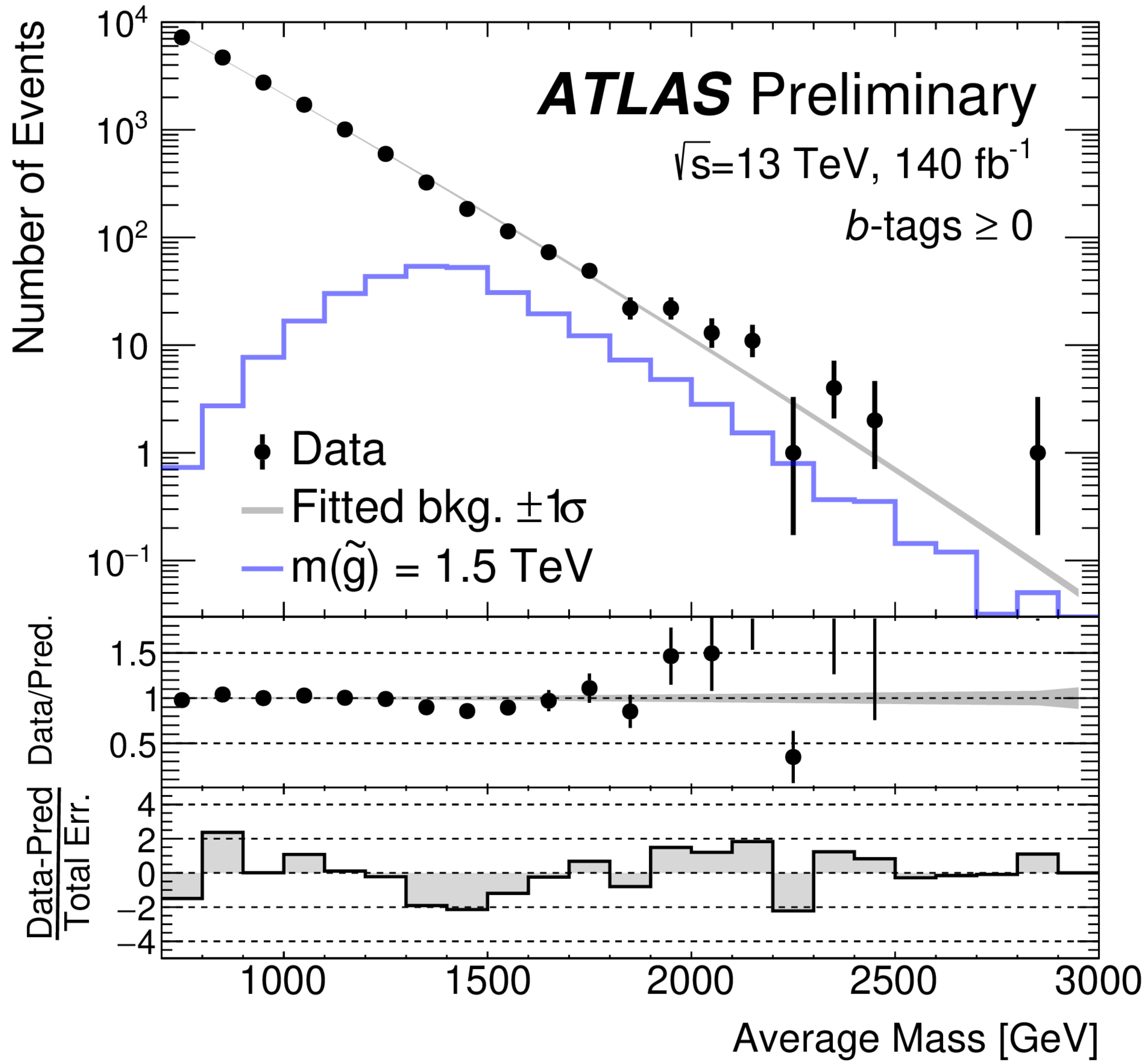



# RPV Multijet neural network



# RPV Multijet: Results in SR



# pMSSM Interpretation: external constraints

| Category | Constraint | Lower bound | Upper bound | Notes |
|---|---|---|---|---|
| Flavour | $\mathrm{BR}(b \to s\gamma)$ | $3.11 \times 10^{-4}$ | $3.87 \times 10^{-4}$ | 2022 PDG average [58] |
| | $\mathrm{BR}(B_s \to \mu\mu)$ | $1.87 \times 10^{-9}$ | $4.31 \times 10^{-9}$ | Most recent LHCb result [59] |
| | $\mathrm{BR}(B^+ \to \tau\nu)$ | $6.10 \times 10^{-5}$ | $1.57 \times 10^{-4}$ | 2022 PDG average [58] |
| Precision EWK | $\Delta\rho$ | $-0.0004$ | 0.0018 | Updated global electroweak fit by GFitter group [60] (not including CDF $W$-mass measurement [61]) |
| | $\Gamma_{\mathrm{inv}}(Z)$ | $--$ | 2 MeV | Precision electroweak measurements on the $Z$-resonance from experiments at the SLC and LEP colliders [62]. |
| | $\mathrm{m}(W)$ | 80.347 GeV | 80.407 GeV | 2022 PDG result (excluding CDF $W$-mass measurement [61]) [58] but with the $2\sigma$ window expanded by 6 MeV to allow for uncertainty due to the top-quark mass in the MSSM Higgs calculation [63] |
| Dark matter | Relic density | $--$ | 0.12 | Latest bound from Planck [64] |
| | Direct detection $\sigma_{\text{Spin-independent}}$ | | | Exclusion contour on direct-detection of DM from the LZ collaboration [65] |
| | Direct detection $\sigma_{\text{Spin-dependent}}$ | | | Exclusion contour on direct-detection of DM from PICO-60 [66] |

# pMSSM Interpretation: Analyses

Table 5: EWK analyses considered in this work.

| Analysis | Simplified models targeted |
| --- | --- |
| FullHad [24] | Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $WZ$, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $Wh$, Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via $WW$, Higgsino GGM |
| 1Lbb [15] | Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $Wh$ |
| 2L0J [19] | Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via $WW$, slepton pairs |
| 2L2J [25] | Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $WZ$, Higgsino GGM |
| 3L [23] | Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $WZ$, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $Wh$, Higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$ , Higgsino GGM |
| 4L [22] | Higgsino GGM |
| Compressed [20] | Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $WZ$, Higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$ |
| Disappearing-track [27] | Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ |

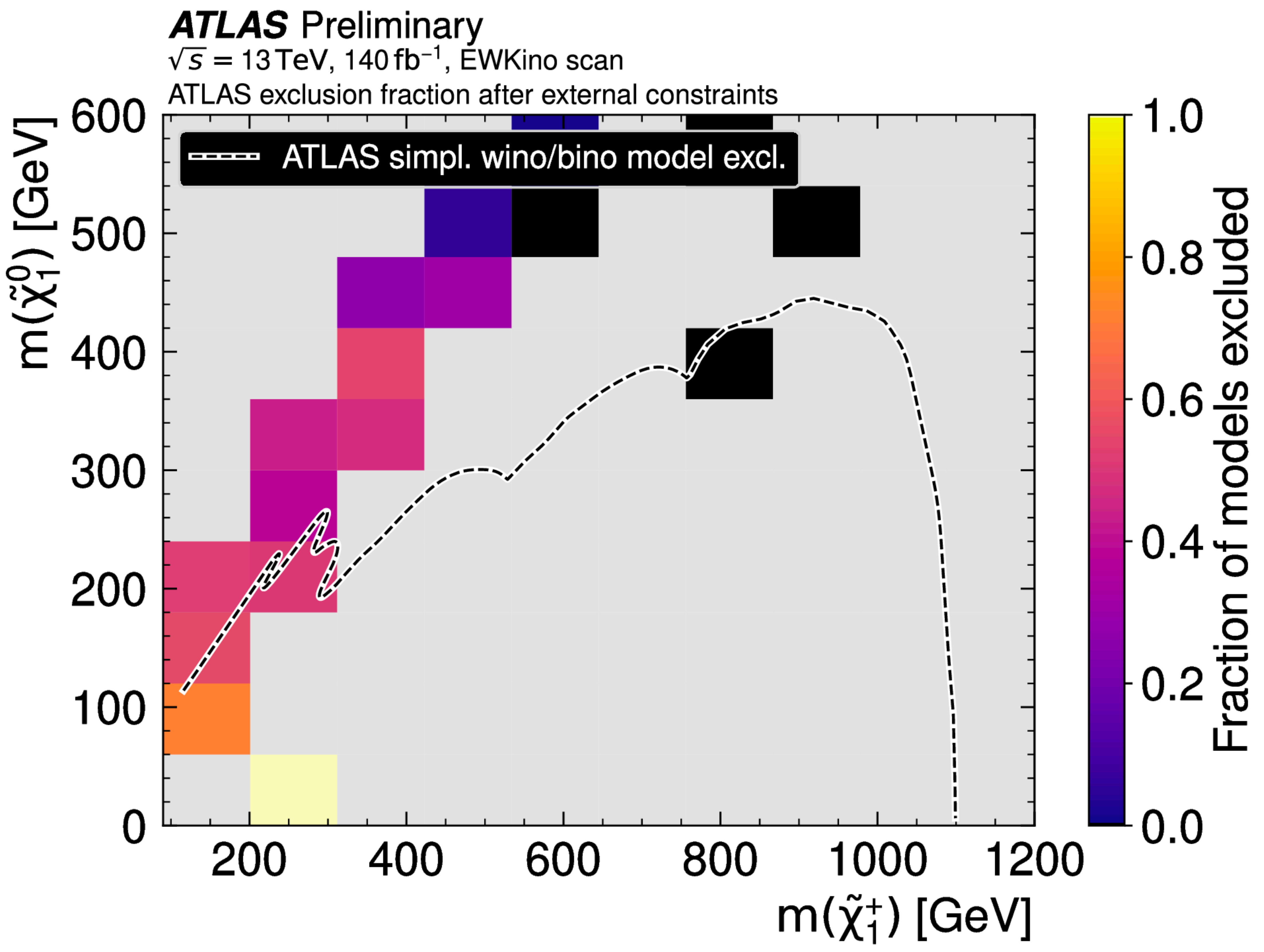
# pMSSM Interpretation: Scan

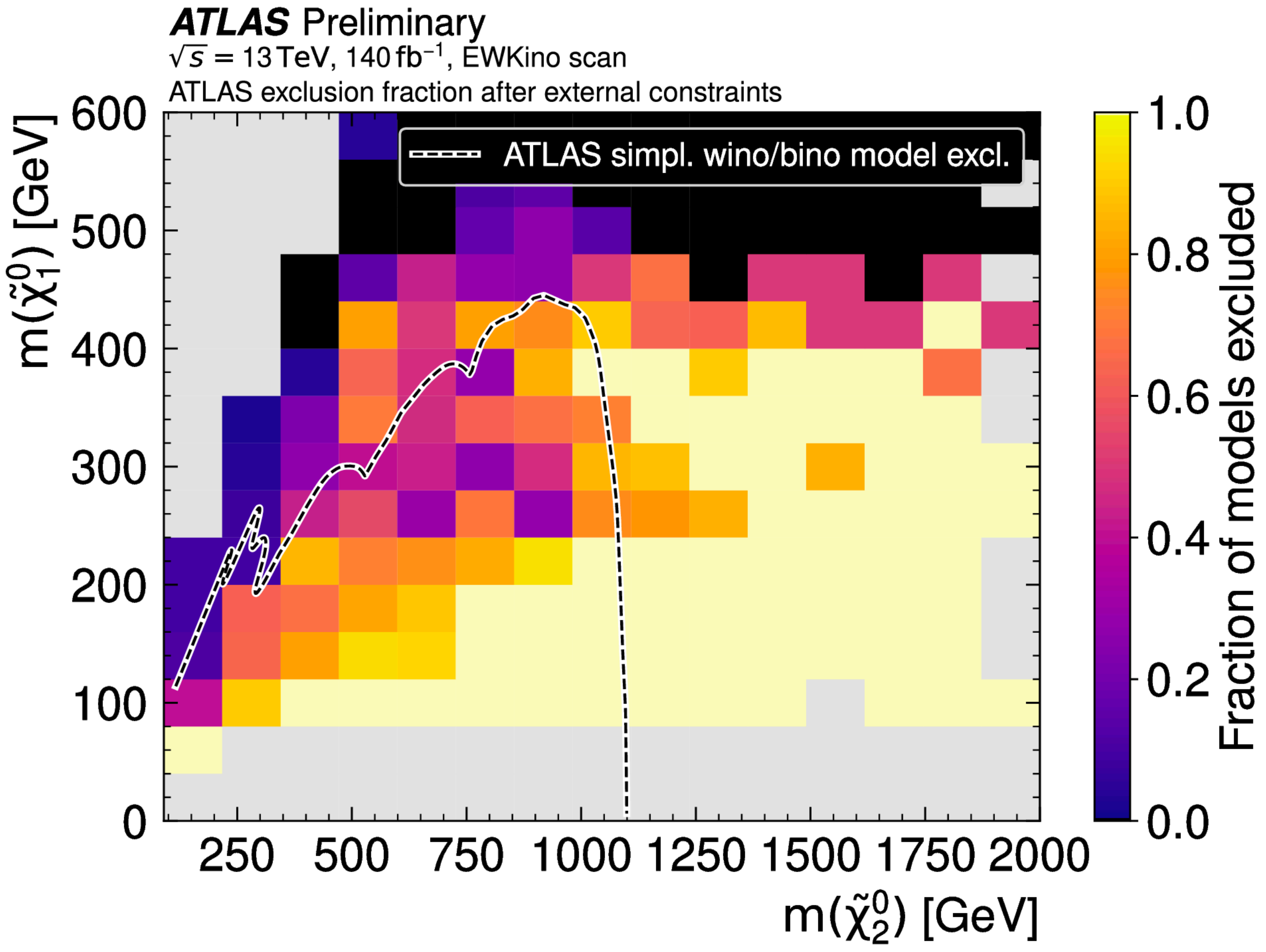
| Parameter | min | max | Note |
|---|---|---|---|
| $M_{\tilde{L}_1}$ $(=M_{\tilde{L}_2})$ | 10 TeV | 10 TeV | Left-handed slepton (first two gens.) mass |
| $M_{\tilde{e}_1}$ $(=M_{\tilde{e}_2})$ | 10 TeV | 10 TeV | Right-handed slepton (first two gens.) mass |
| $M_{\tilde{L}_3}$ | 10 TeV | 10 TeV | Left-handed stau doublet mass |
| $M_{\tilde{e}_3}$ | 10 TeV | 10 TeV | Right-handed stau mass |
| $M_{\tilde{Q}_1}$ $(=M_{\tilde{Q}_2})$ | 10 TeV | 10 TeV | Left-handed squark (first two gens.) mass |
| $M_{\tilde{u}_1}$ $(=M_{\tilde{u}_2})$ | 10 TeV | 10 TeV | Right-handed up-type squark (first two gens.) mass |
| $M_{\tilde{d}_1}$ $(=M_{\tilde{d}_2})$ | 10 TeV | 10 TeV | Right-handed down-type squark (first two gens.) mass |
| $M_{\tilde{Q}_3}$ | 2 TeV | 5 TeV | Left-handed squark (third gen.) mass |
| $M_{\tilde{u}_3}$ | 2 TeV | 5 TeV | Right-handed top squark mass |
| $M_{\tilde{d}_3}$ | 2 TeV | 5 TeV | Right-handed bottom squark mass |
| $M_1$ | -2 TeV | 2 TeV | Bino mass parameter |
| $M_2$ | -2 TeV | 2 TeV | Wino mass parameter |
| $\mu$ | -2 TeV | 2 TeV | Bilinear Higgs mass parameter |
| $M_3$ | 1 TeV | 5 TeV | Gluino mass parameter |
| $A_t$ | -8 TeV | 8 TeV | Trilinear top coupling |
| $A_b$ | -2 TeV | 2 TeV | Trilinear bottom coupling |
| $A_\tau$ | -2 TeV | 2 TeV | Trilinear $\tau$ lepton coupling |
| $M_A$ | 0 TeV | 5 TeV | Pseudoscalar Higgs boson mass |
| $\tan\beta$ | 1 | 60 | Ratio of the Higgs vacuum expectation values |

| **Scan name** | **EWKino** | **Bino-DM** |
|---|---|---|
| $\lvert M_1 \rvert$ range | 0 – 2 TeV | 0 – 500 GeV |
| LSP type | Neutralino | Bino-like neutralino |
| **Number of models generated:** | | |
| Sampled | 20,000 | 437,500 |
| Successful generation | 16,667 | 370,017 |
| Correct LSP type | 15,321 | 286,267 |
| Pass DM relic density constraint $\Omega h^2 \leq 0.12$ | N/A | 11,122 |
| Pass LEP chargino mass constraint | 13,969 | 10,174 |
| 120 GeV $<$ m($h$) $<$ 130 GeV | 12,280 | 8,897 |

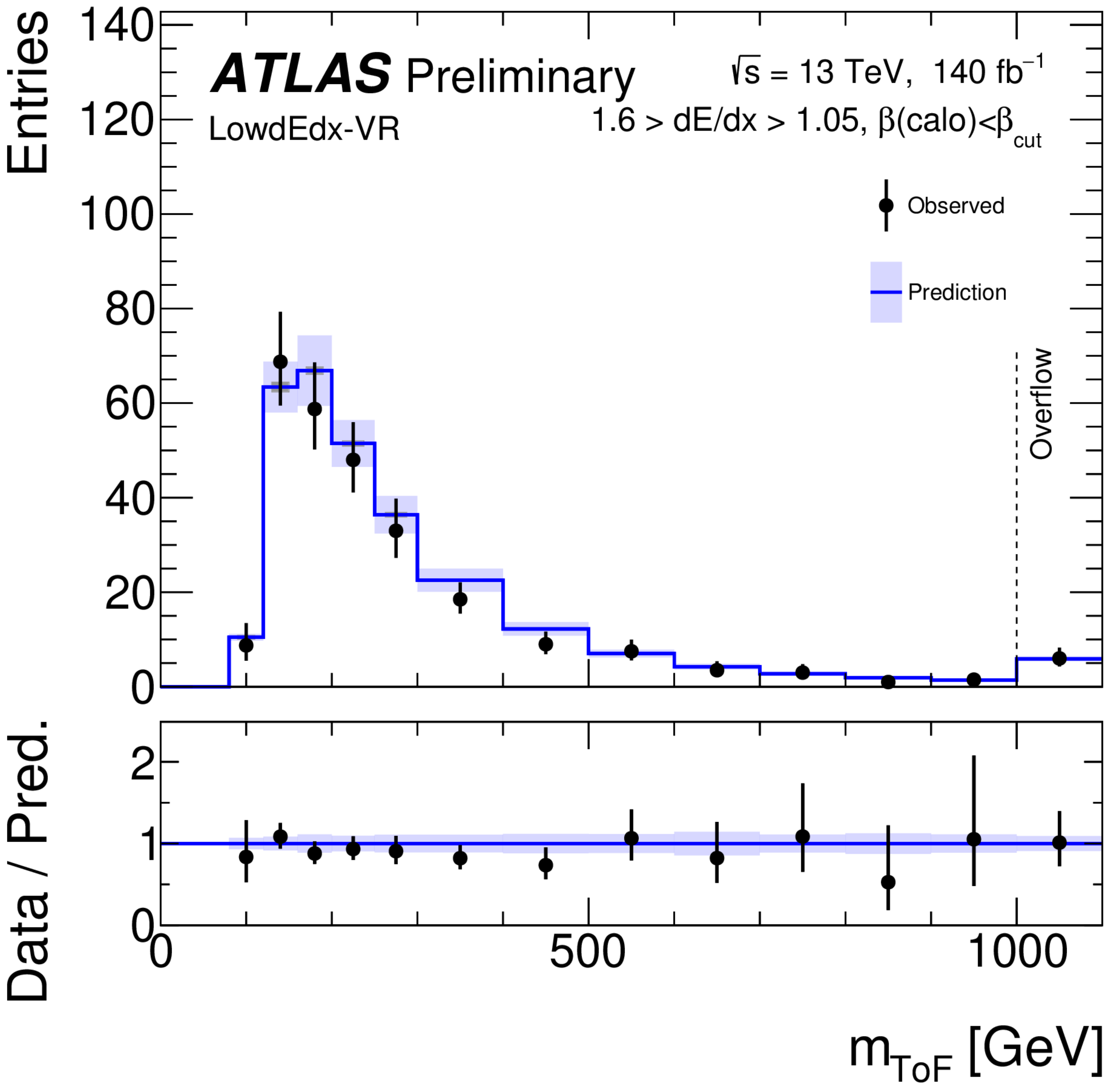
# pMSSM Interpretation

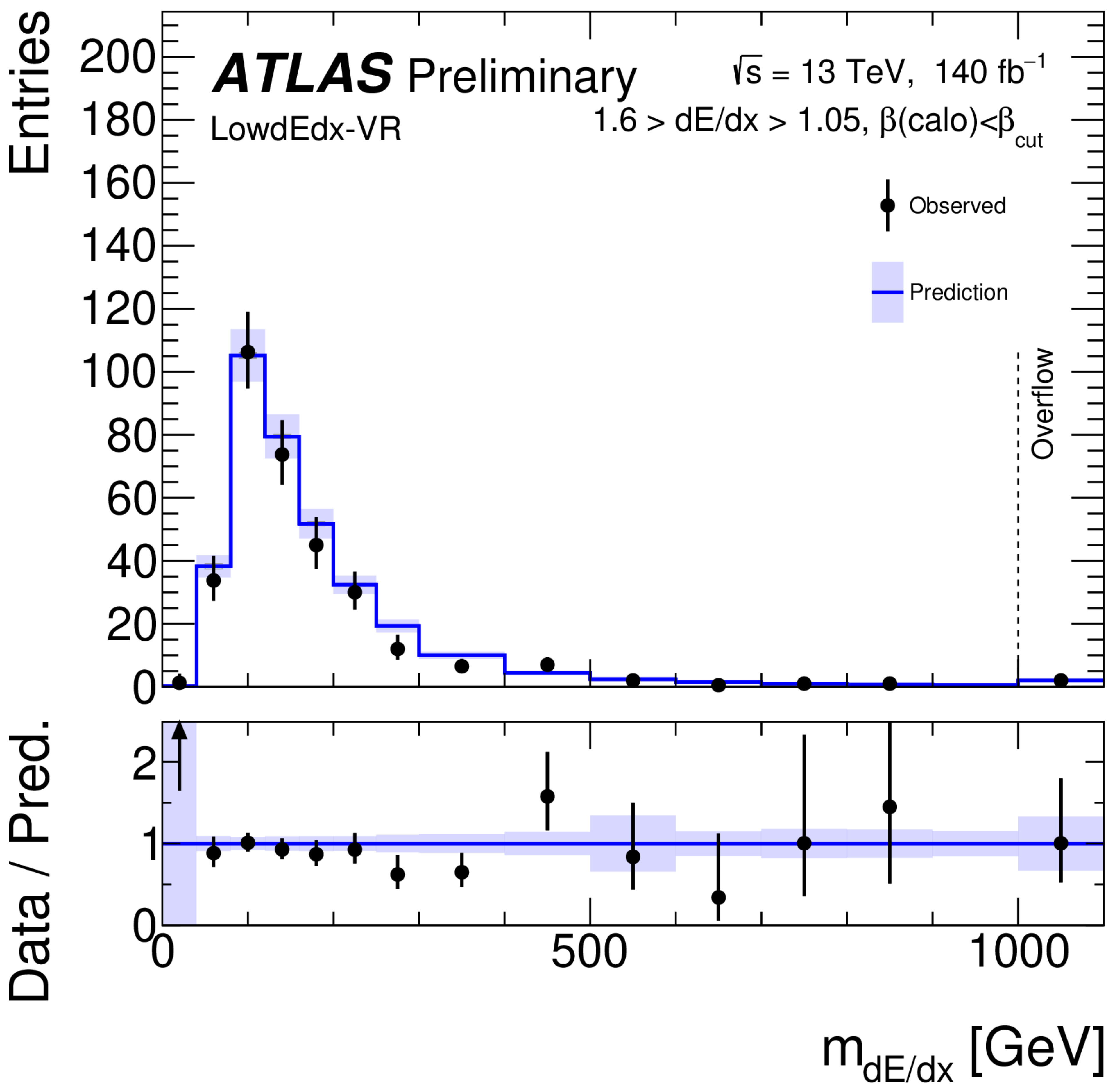
- Only models passing all external constraints



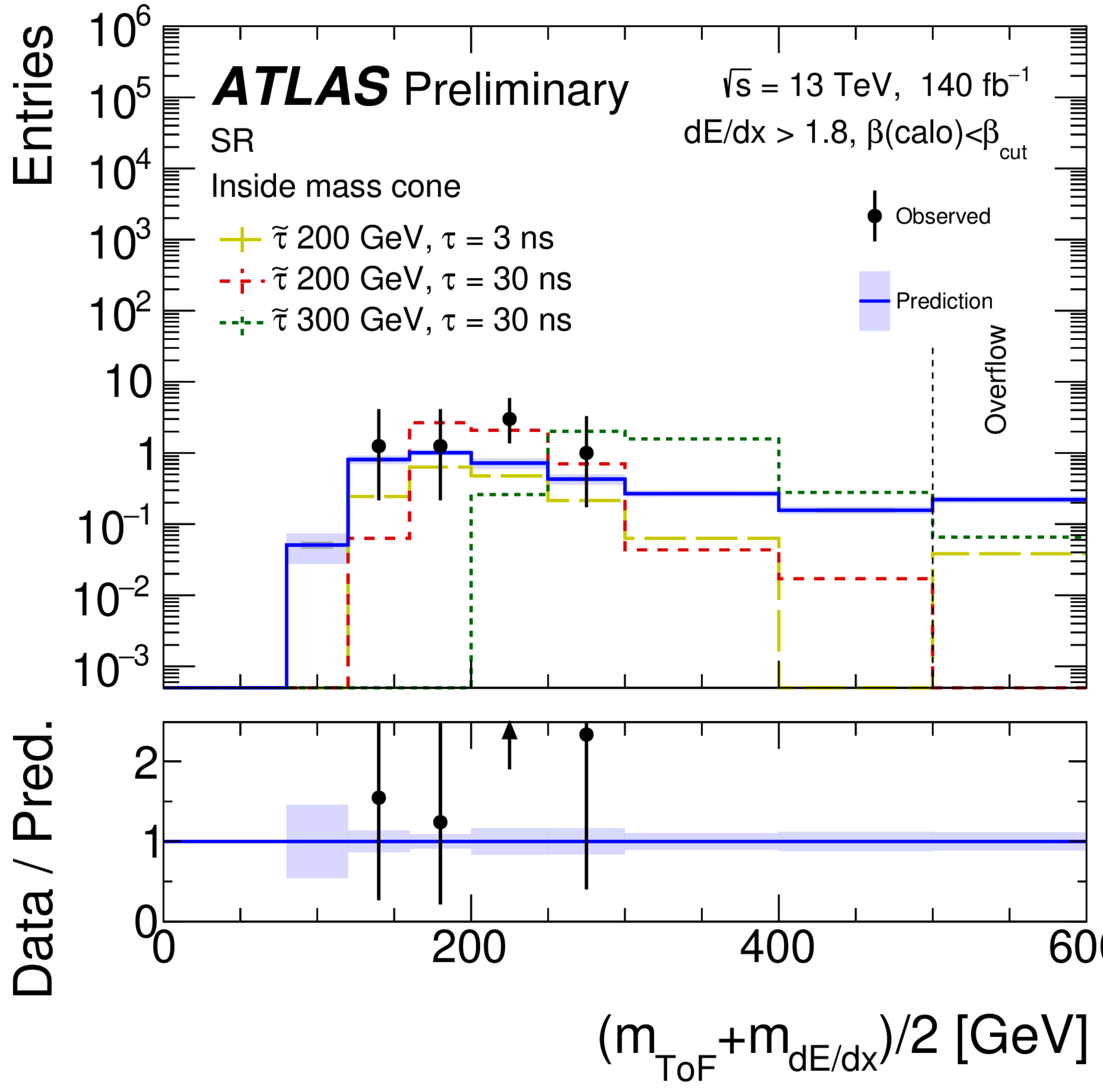



# Long-lived particles search

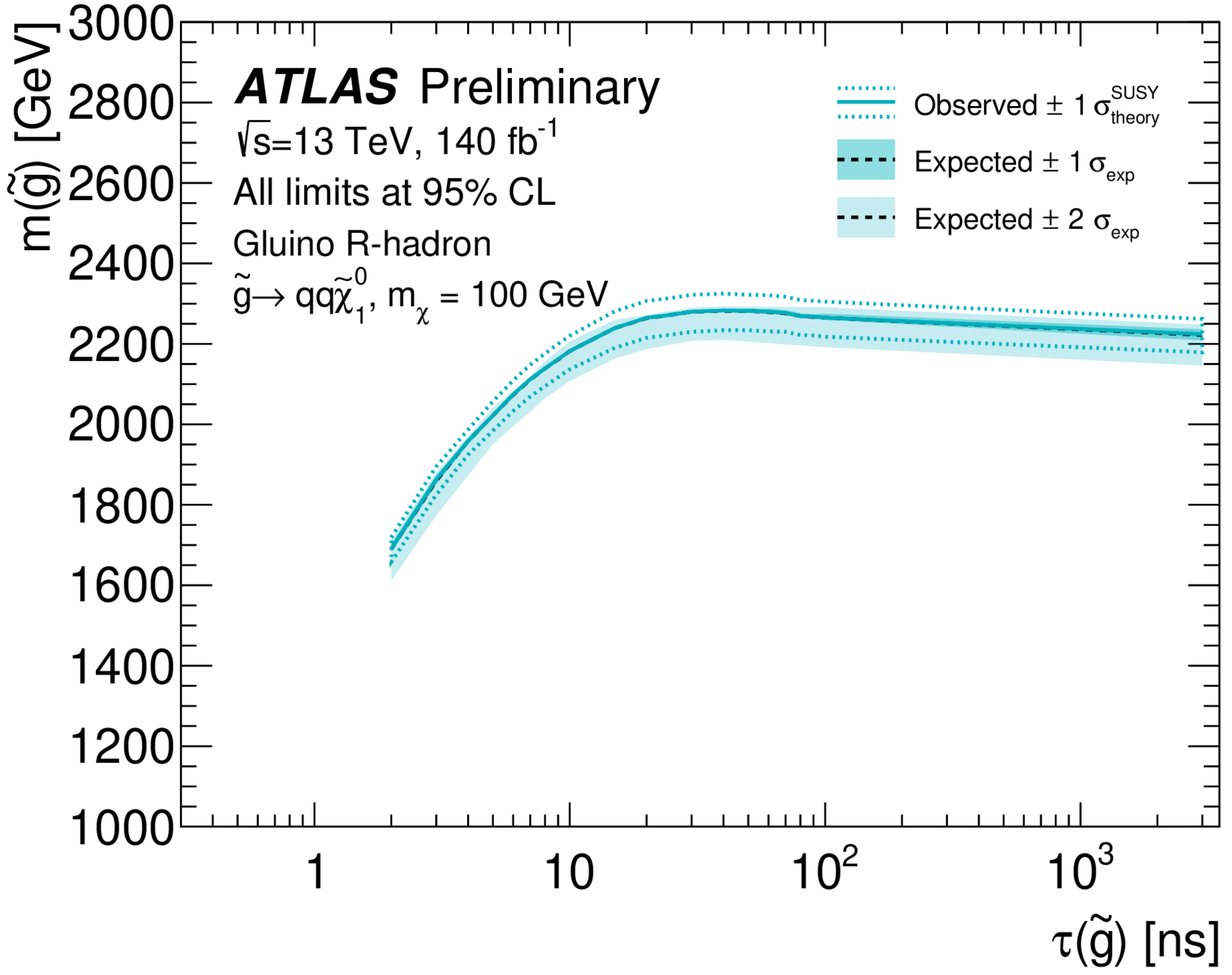


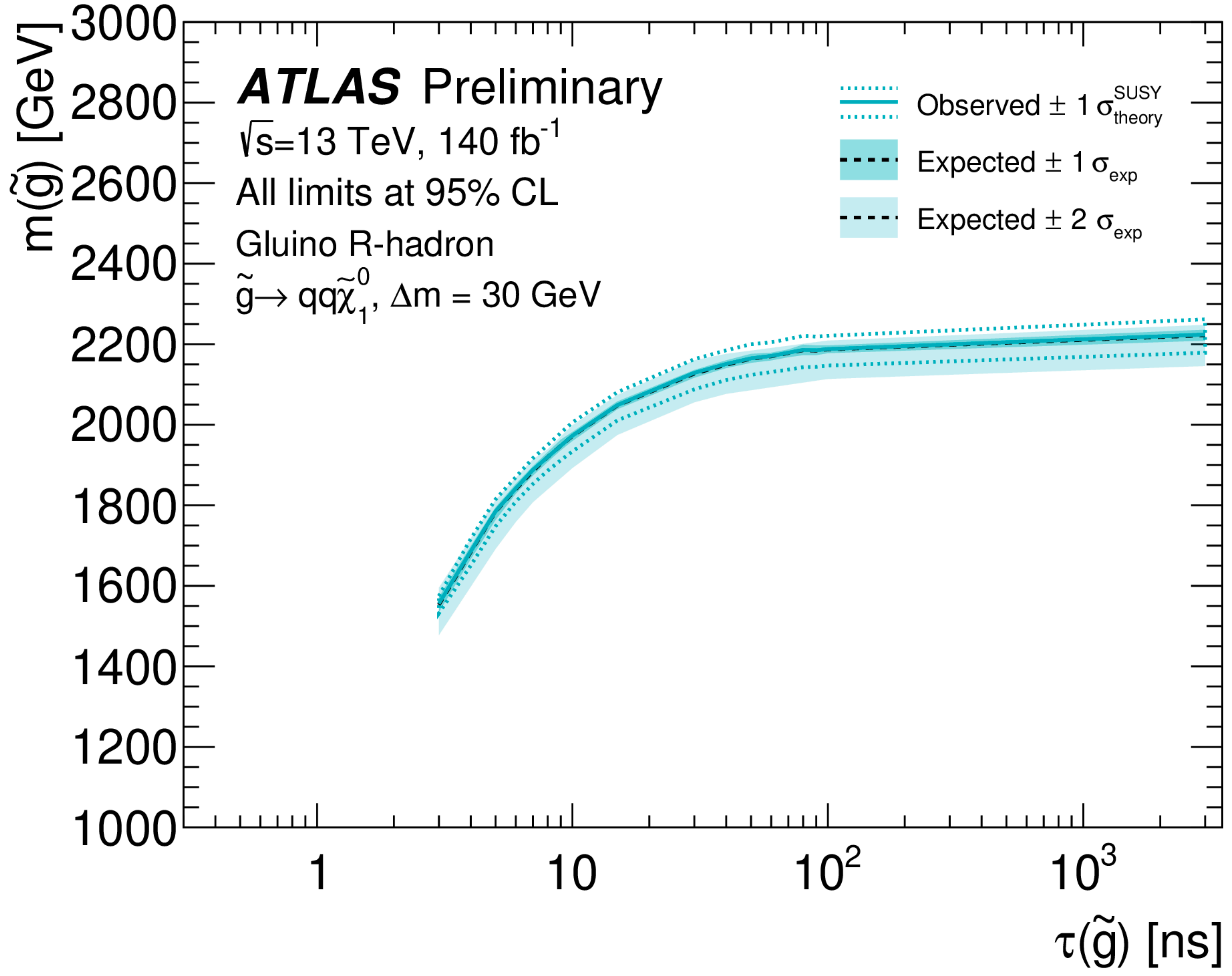



# Long-lived particles search



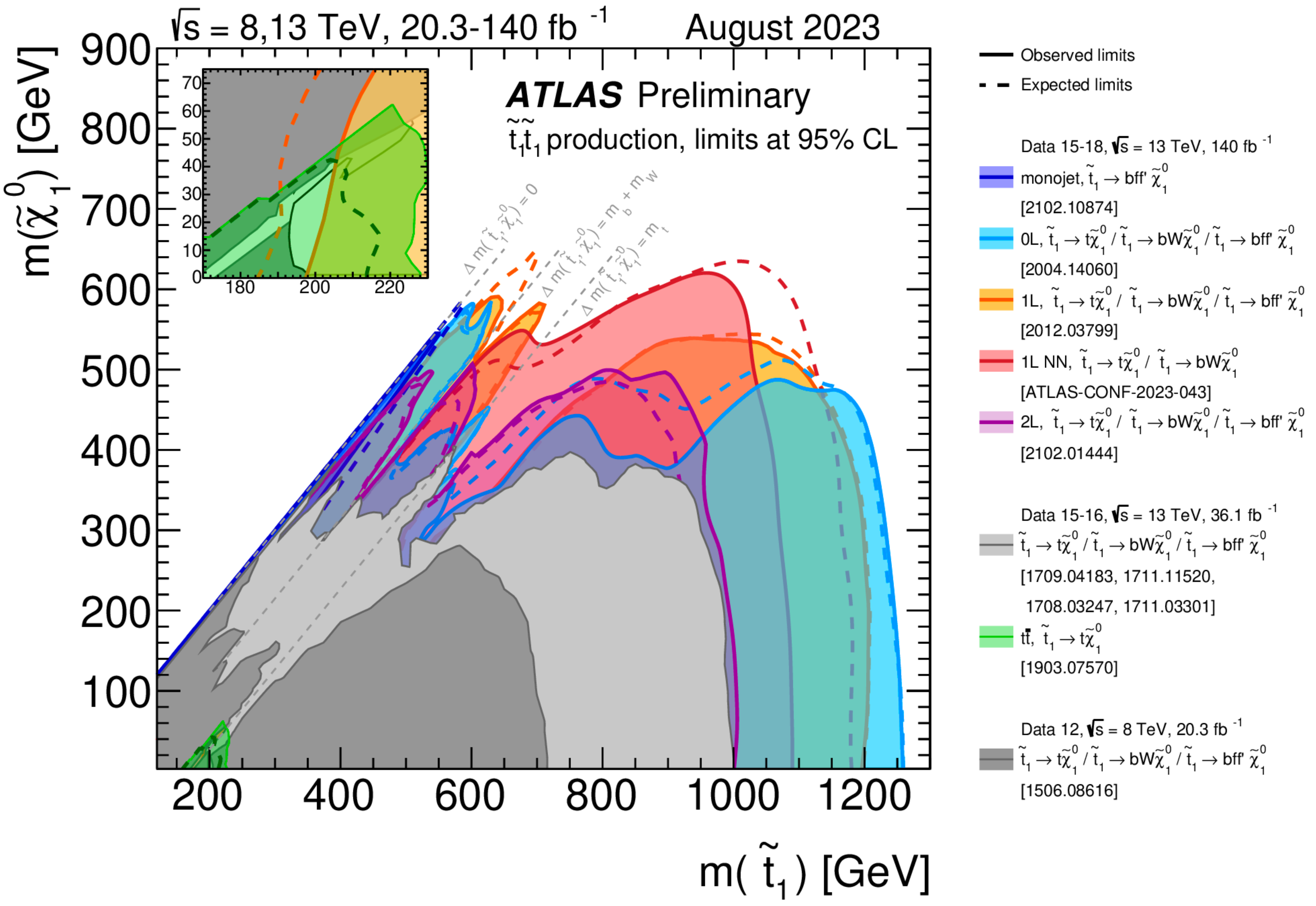
# Long-lived particles search

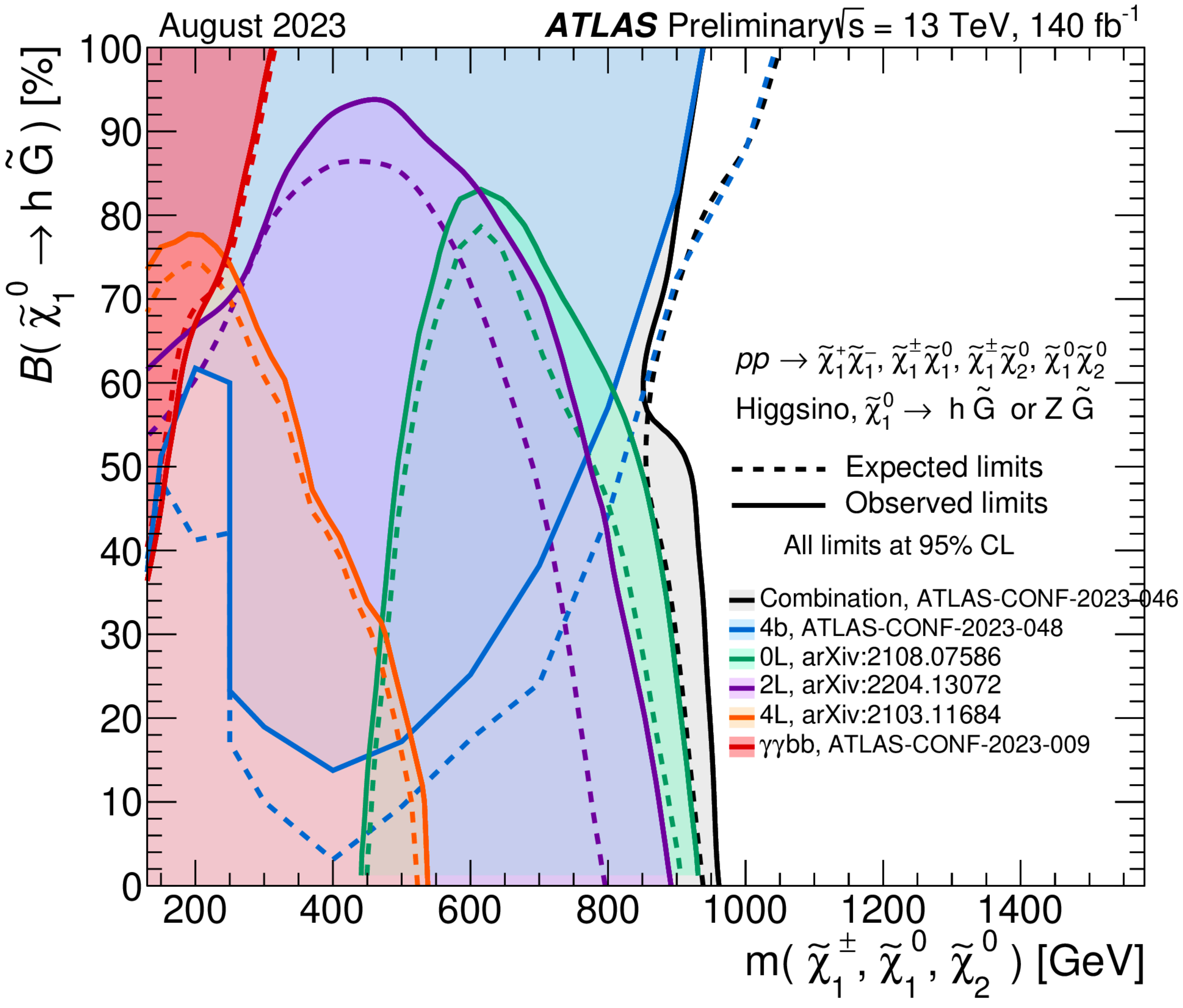


# Summary plots

[ATLAS Supersymmetry Public Results](#)



# Summary plots