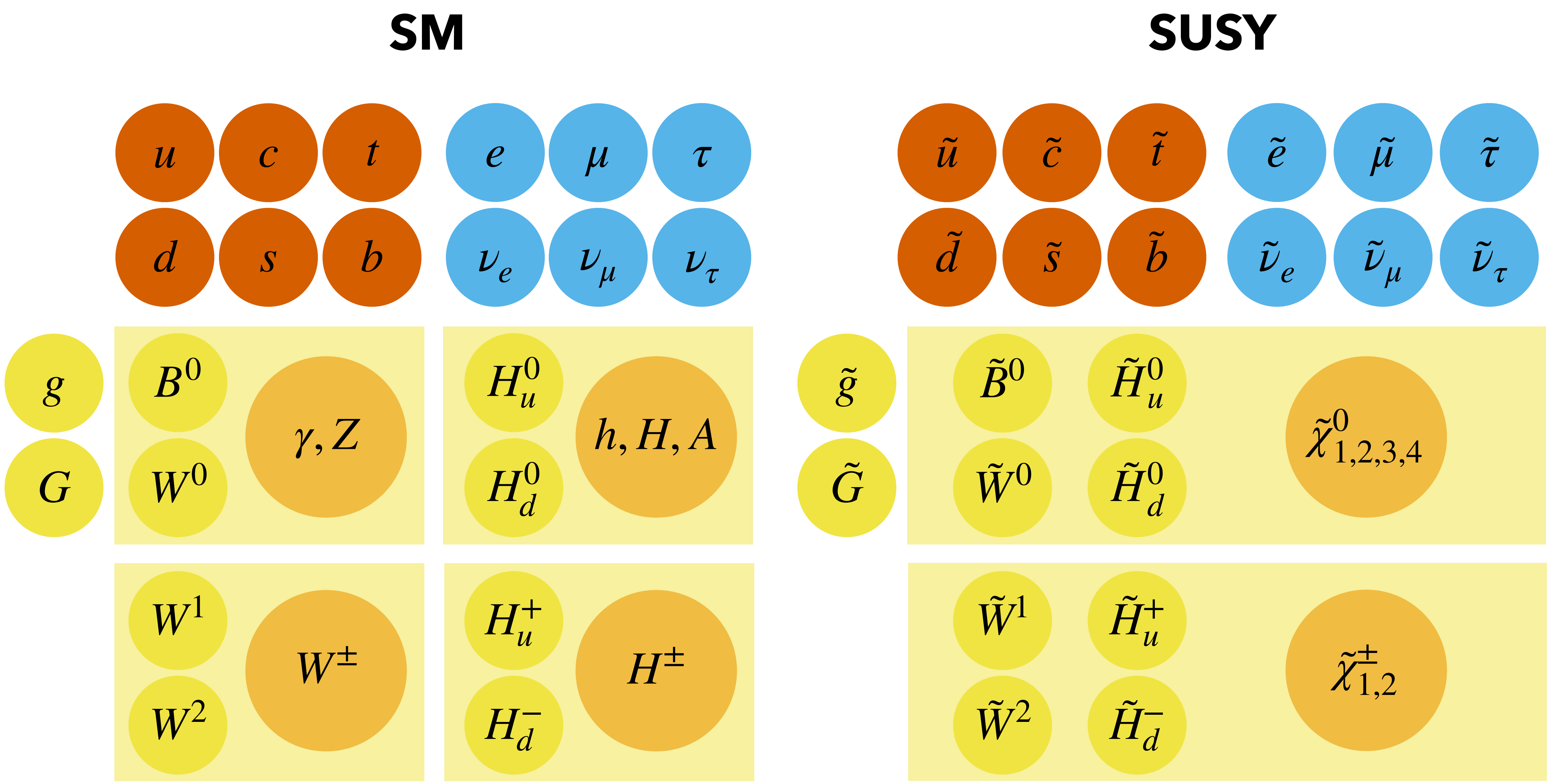
Alessandro Sala on behalf of the ATLAS Collaboration

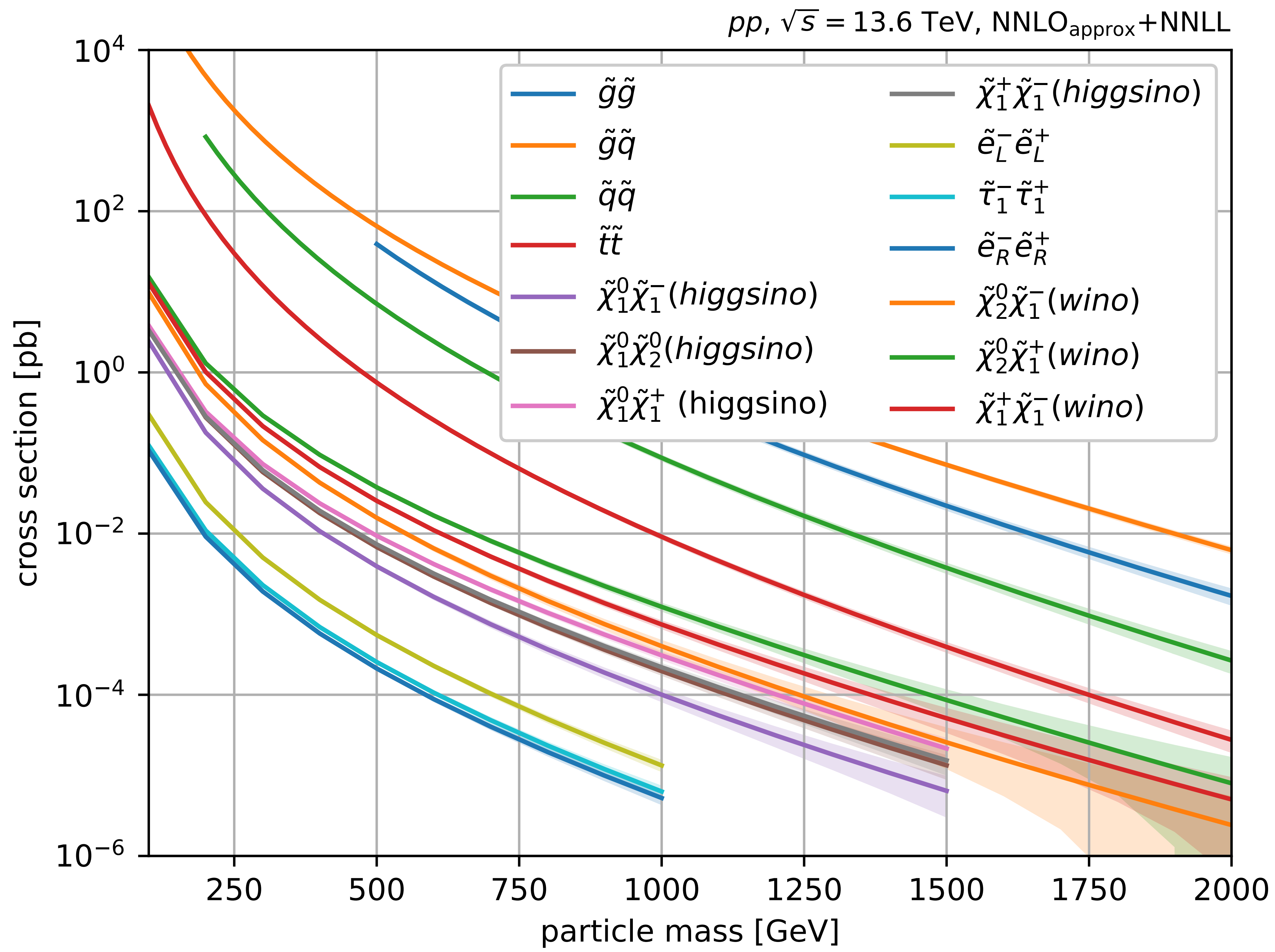
SUSY 2024: The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions

Searches for electroweak production of supersymmetric particles with the ATLAS Detector

Introduction

- **SUSY** as a compelling extension of the SM
  - Natural solution to Higgs hierarchy problem
  - LSP consistent with thermal relic DM density in *R*-parity conserving scenarios
  - Possible explanation to $(g-2)_\mu$ anomaly

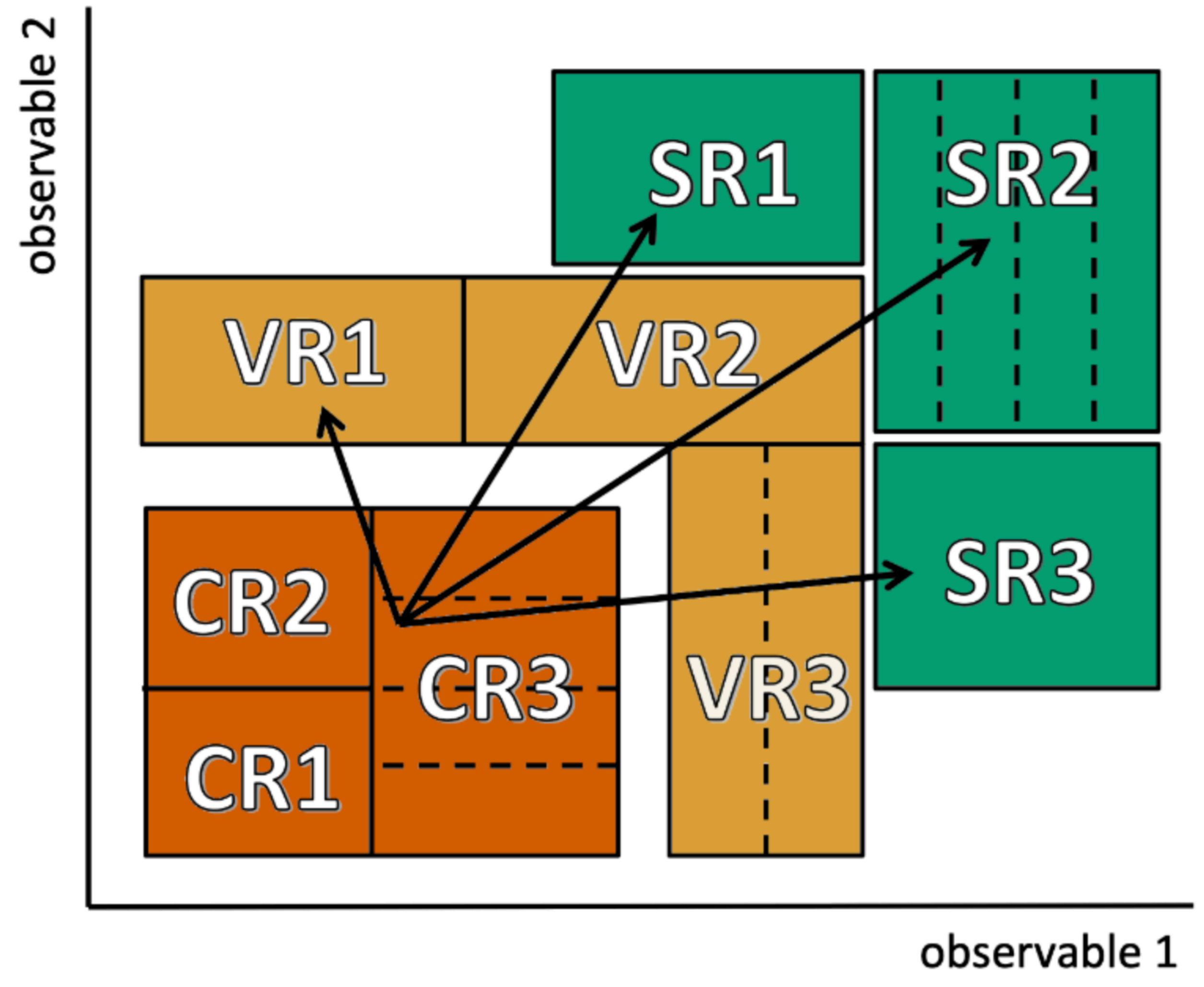




- **Electroweak SUSY (EW-SUSY)** well motivated by naturalness arguments and with many possible signatures at colliders
  - Less constrained than strong production, especially in compressed regimes
  - Really challenging to probe due to small cross-sections and signatures similar to SM processes
  - LHC Run-2 + Run-3 data will help shed light

ATLAS searches for EW-SUSY

- ATLAS has a vast search program for EW-SUSY with many different signatures explored. General strategy:
  - **Control Regions** (CRs) to constrain SM backgrounds in **Signal Regions** (SRs) enriched in SUSY signals
  - **Validation Regions** (VRs) to check goodness of background extrapolation
  - If no data excess is found in SRs, **results interpreted in terms of 95% CL exclusion limits on simplified models and cross section upper limits**



- This talk:
  - Combination of searches, arXiv:2402.08347
  - "1L + jets + MET", JHEP12(2023)167
  - "2τ + MET", JHEP05(2024)150
  - "Multi-b + MET", arXiv:2401.14922
  - "$\gamma\gamma bb$ + MET", arXiv:2404.01996

- Other talks including EW-SUSY searches:
  - SUSY searches at ATLAS (Joaquin Hoya)
  - Search for electroweak supersymmetry with compressed spectra (Jeff Shahinian)
  - Searches for supersymmetry in non-minimal models (Ying Wun Yvonne Ng)

Electroweak Combination

arXiv:2402.08347

Generally extends sensitivity to NLSP/LSP masses by 100 GeV, improves cross-section upper limits by 15%-40%

- Statistical independence checked by inspecting yields on data and simulations in SRs + CRs
- Combination performed for searches with **overlap < 10%**, otherwise search with best expected sensitivity is used
- Experimental systematics and theory uncertainties left **uncorrelated**

- Simplified models of **pure-wino** or **pure-higgsino** NLSPs pair production decaying to LSPs via **SM V, h bosons**
- Using all available EW searches with 139 fb^{-1}

Production mode	Wino $\tilde{\chi}_1^+\tilde{\chi}_1^-$	Wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	Wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	Higgsino GGM $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_{1,2}^0, \tilde{\chi}_1^0\tilde{\chi}_2^0$
Decay mode	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \to Z/h\tilde{G}$
Searches				
All Hadronic	✓	✓	✓	✓
1L *	✓	✓		
1Lbb			✓	
2L Compressed		✓		
2L0J $\Delta m > m(W)$	✓			
2L0J $\Delta m \sim m(W)$	✓			
2L2J		✓		✓
2τ *			✓	
3L		✓	✓	
SS/3L		✓	✓	
4L				✓
Multi-b *				✓

*Covered by this talk

*Covered by this talk

Electroweak Combination

arXiv:2402.08347

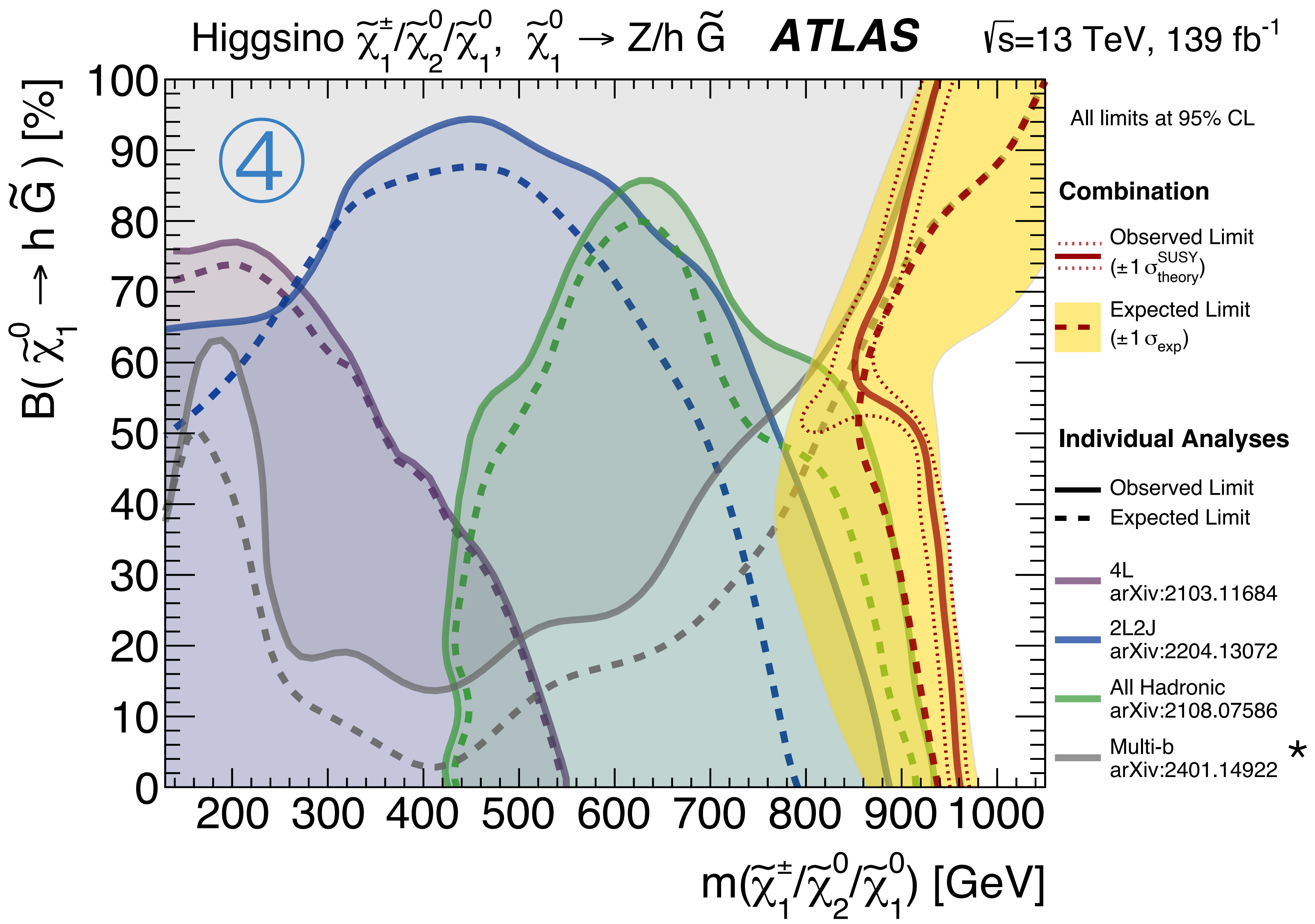
❖ Overall improvements in cross-section upper limits from 15% to 40%. Additionally:

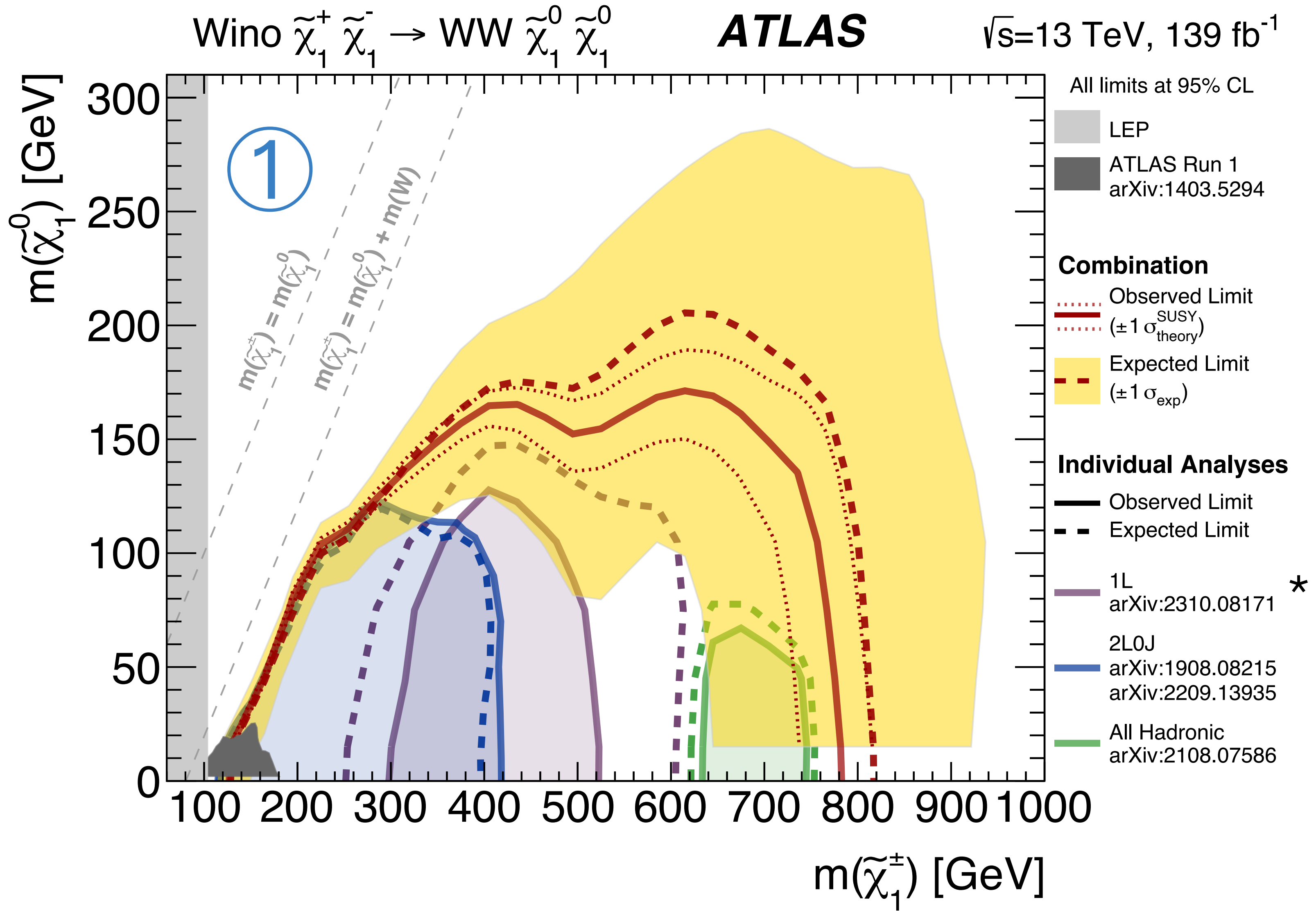
① Closes gap between individual searches, improves sensitivity to high $\tilde{\chi}_1^0$ mass

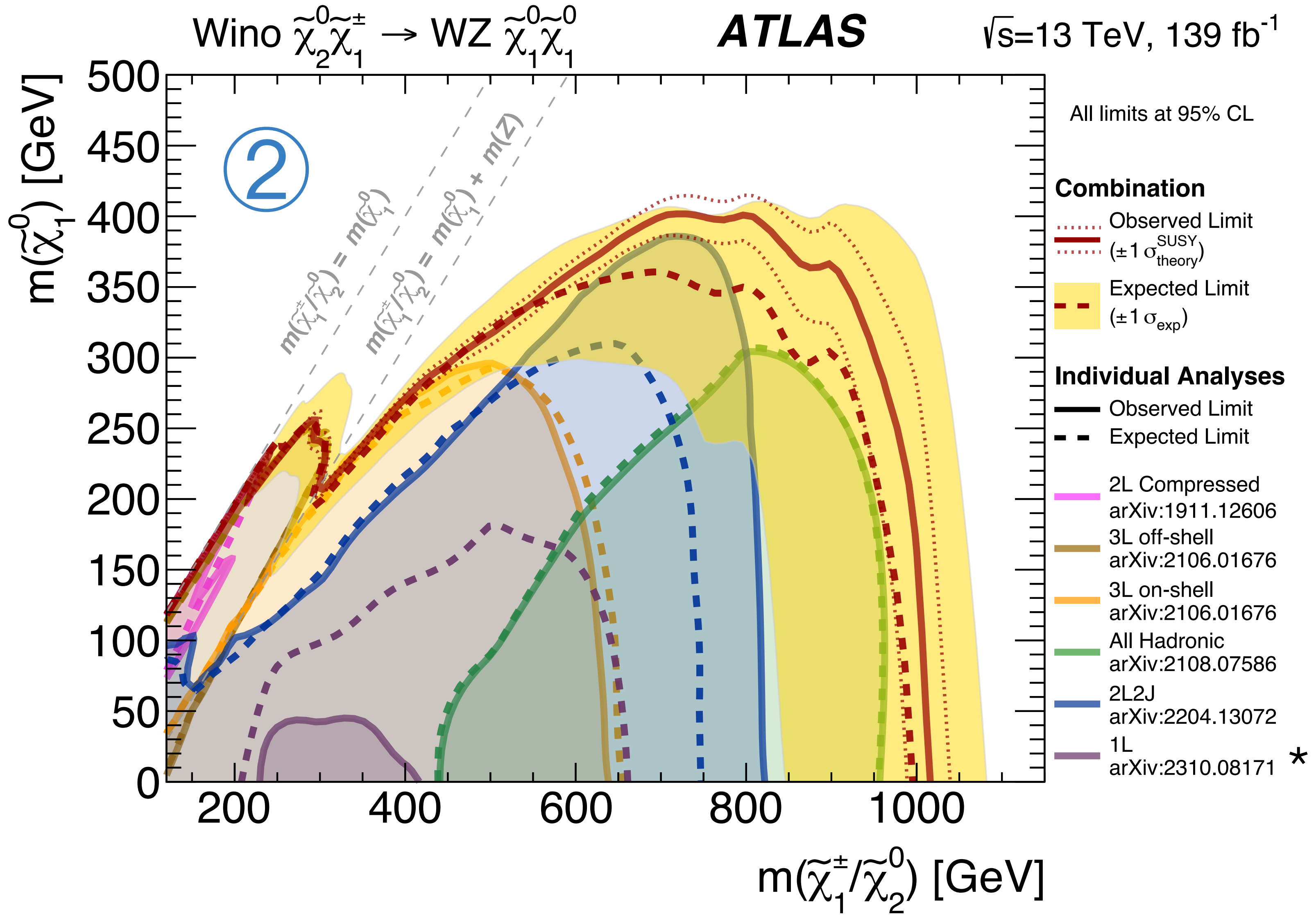
② Extends limits everywhere besides compressed region

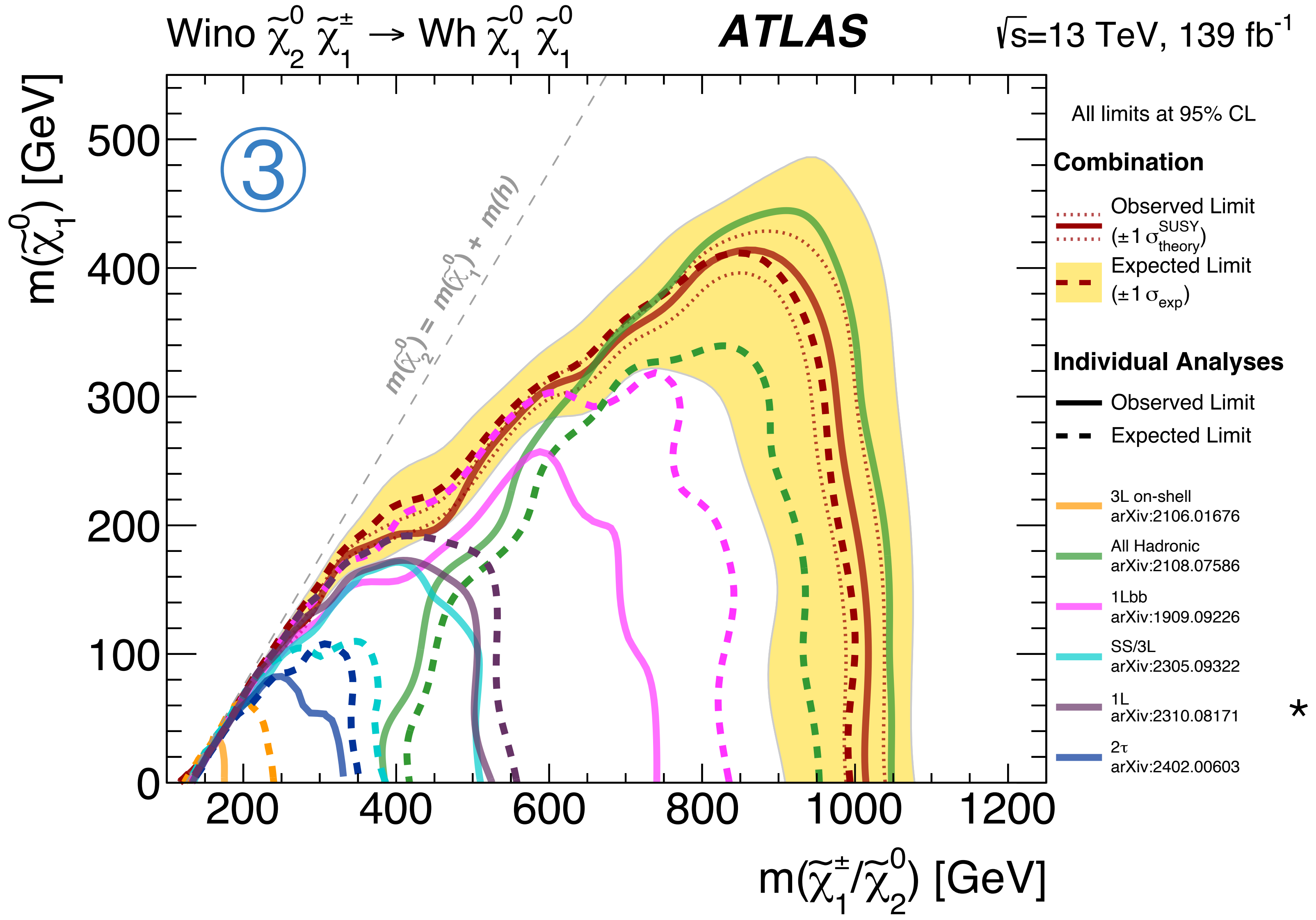
③ Smooths out deficit/excess effects of individual searches

④ Fully covers all branching ratio possibilities in gauge-mediated SUSY-breaking (GMSB) scenarios



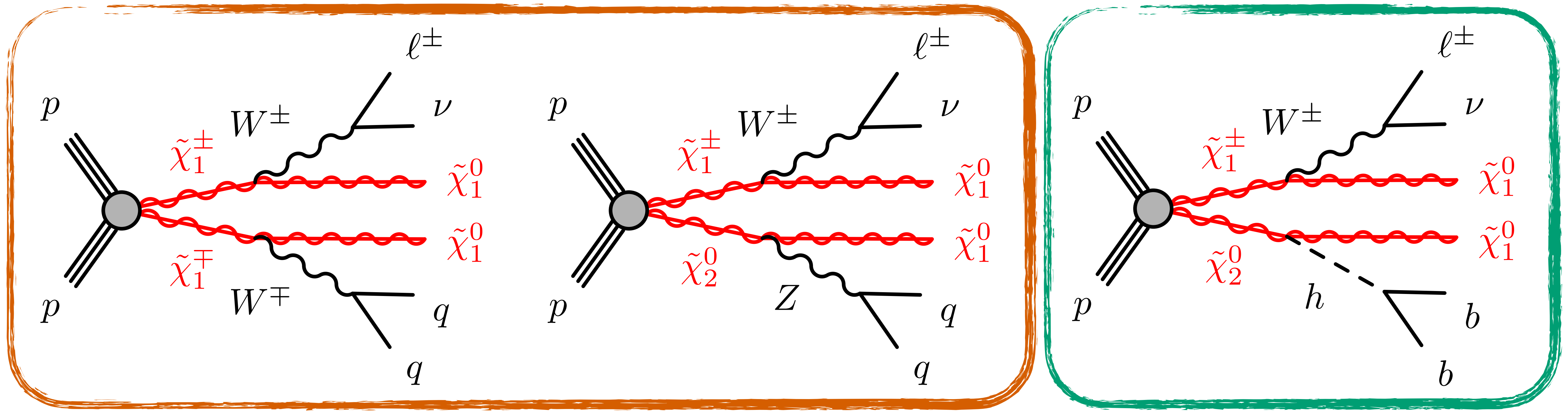






1L + jets + MET

JHEP12(2023)167

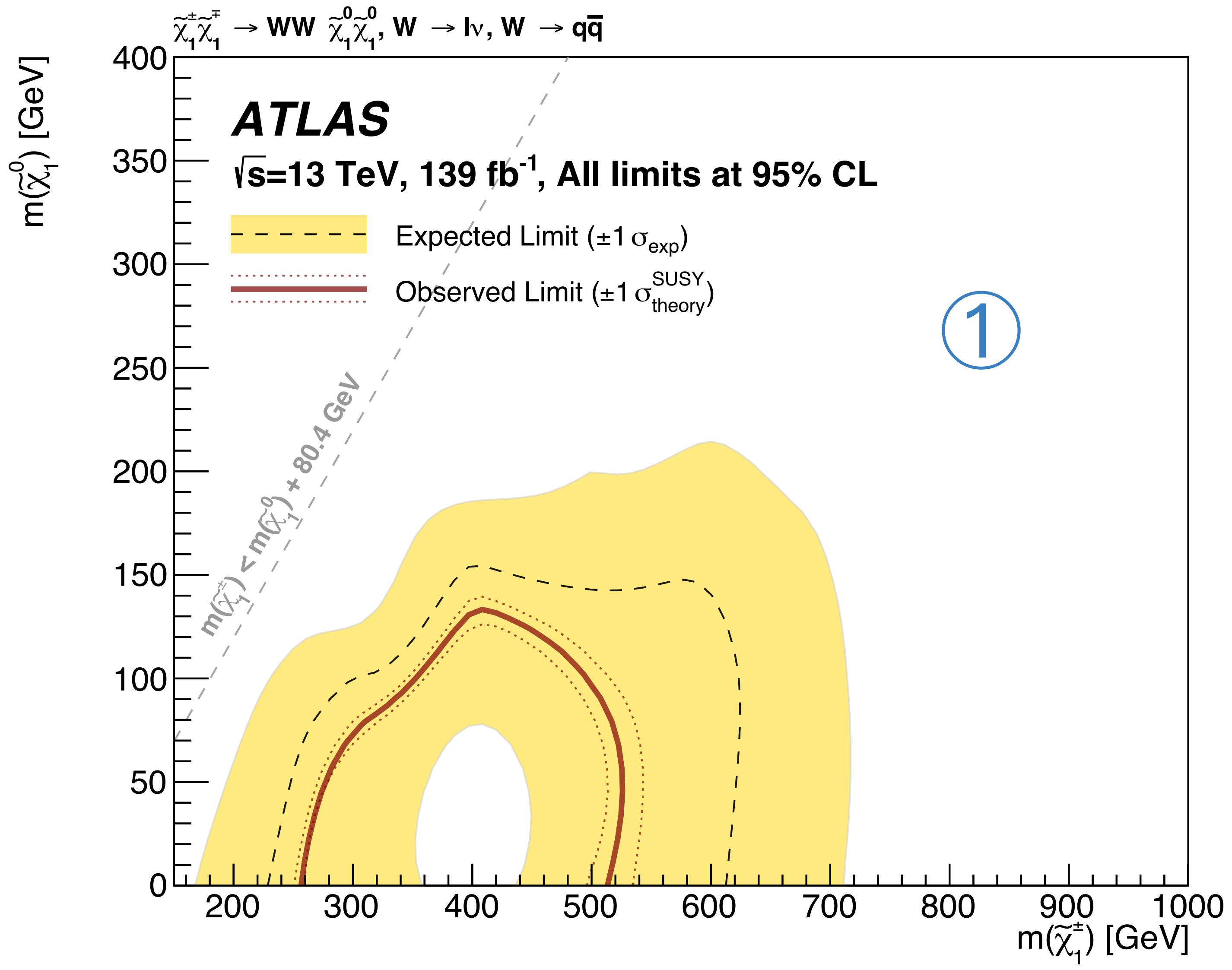


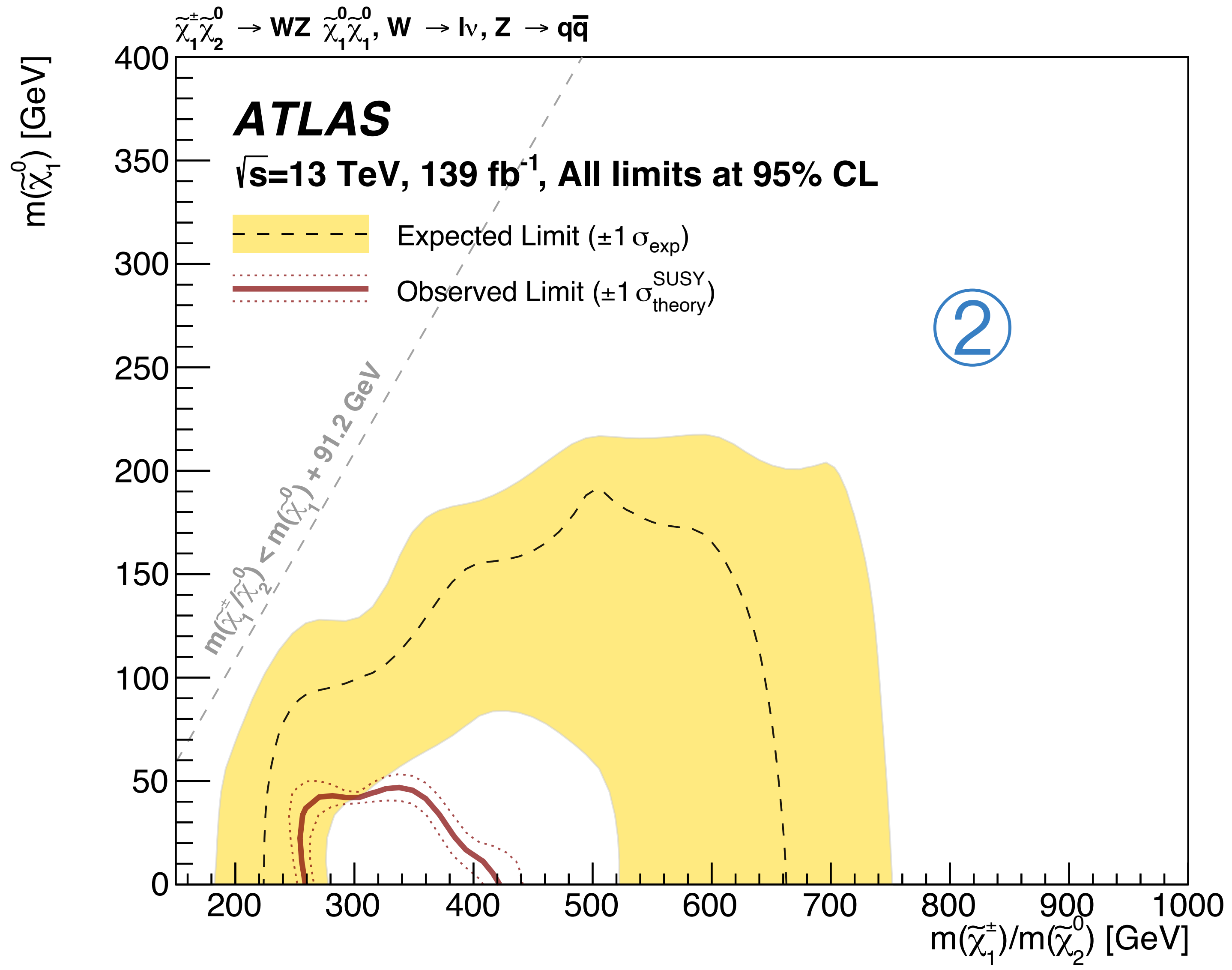
First 1L + jets search using jet-substructure information + BDT to improve sensitivity

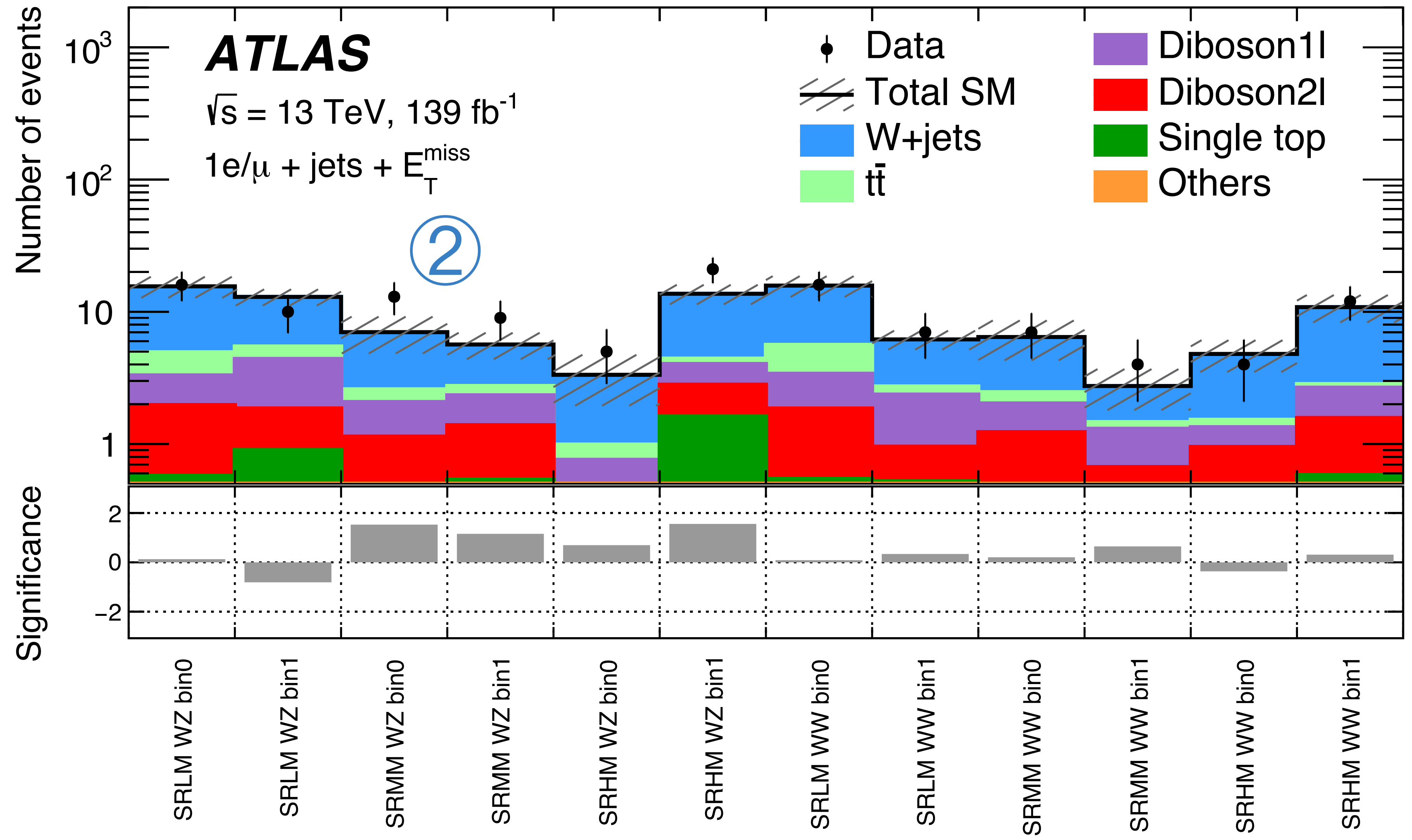
- **Wino-like** mass degenerate $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pairs decaying to bino-like LSPs via **SM V, h bosons**
- Three sets of SRs all requiring one isolated lepton (e, μ) + max. three jets. Additionally:
  - C1C1-WW, C1N2-WZ SRs binned in mass ($m_T \times m_{eff} = 6$), with $E_T^{miss} > 200$ GeV + **at least one large-R** boson-tagged **jet**
    - Dominant W+jets, diboson estimated with MC-to-data normalisation, others taken directly from MC
  - C1N2-Wh SRs with exactly **two *b*-jets** and binned in output score of **Boosted Decision Tree** (BDT) to increase sensitivity to $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \geq m_h$
    - $t\bar{t}$, single top, W+jets giving largest contributions and estimated from CRs, others from MC simulations

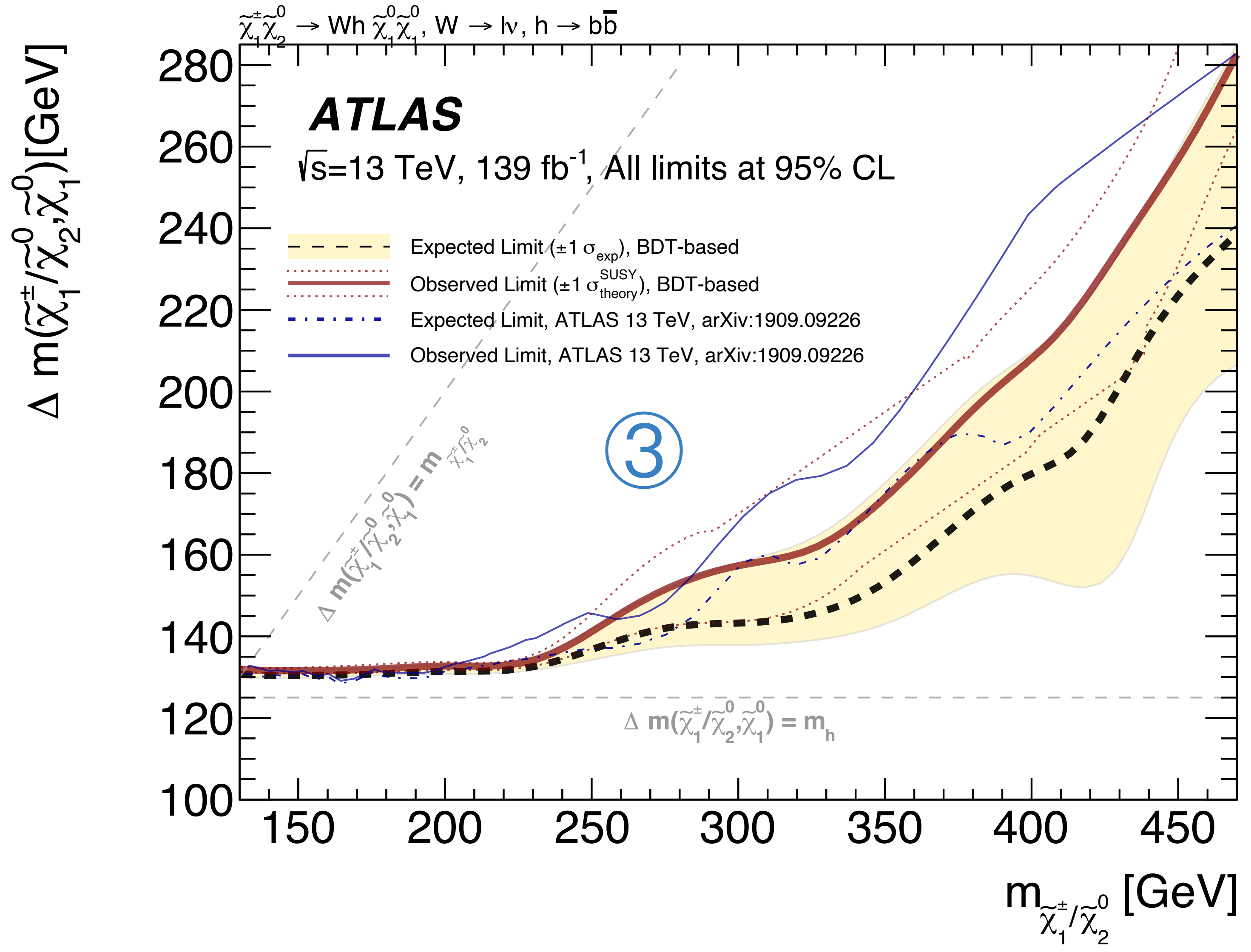
1L + jets + MET

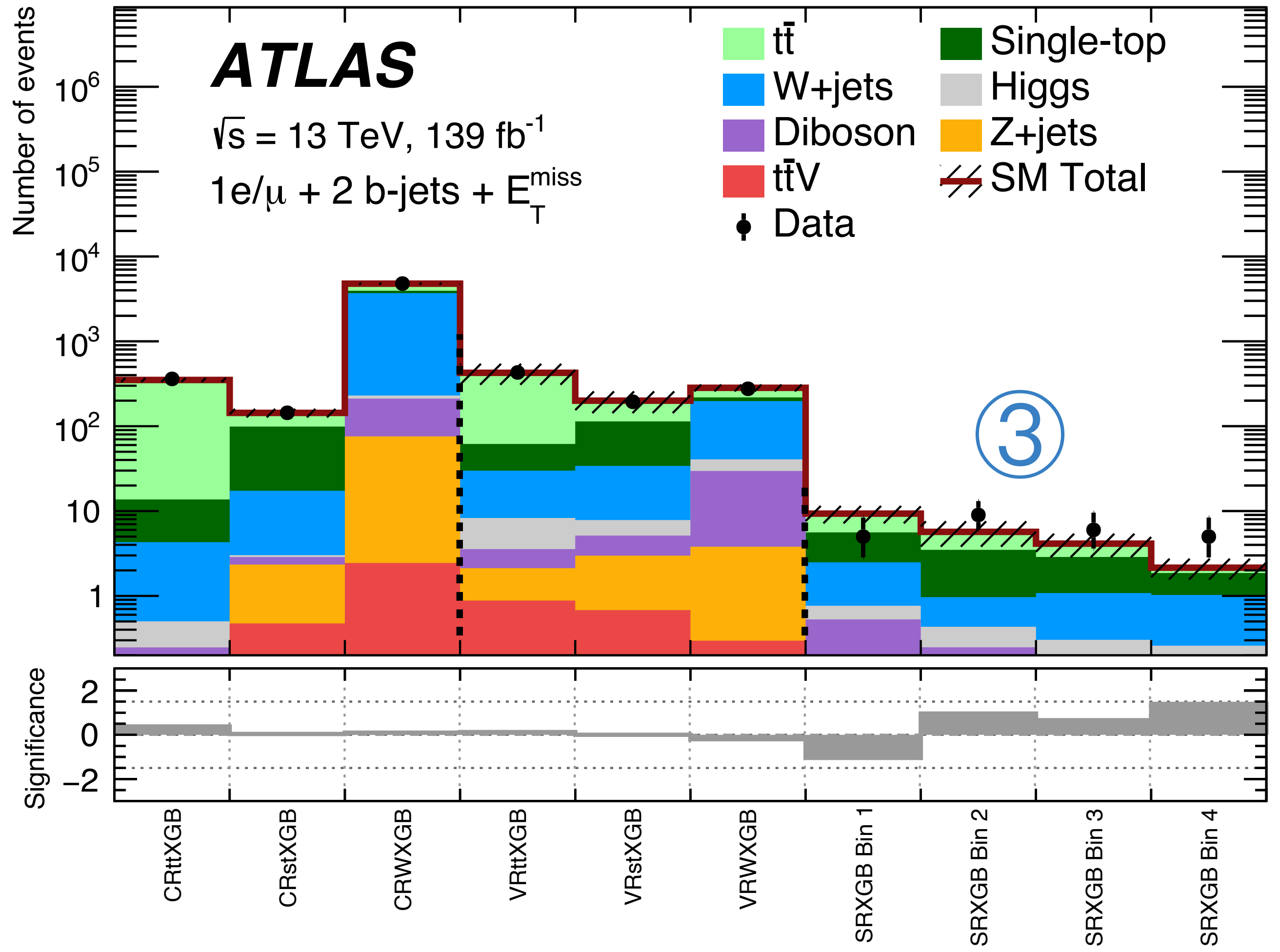
JHEP12(2023)167











① New limits complementing those from 0L and 2L searches

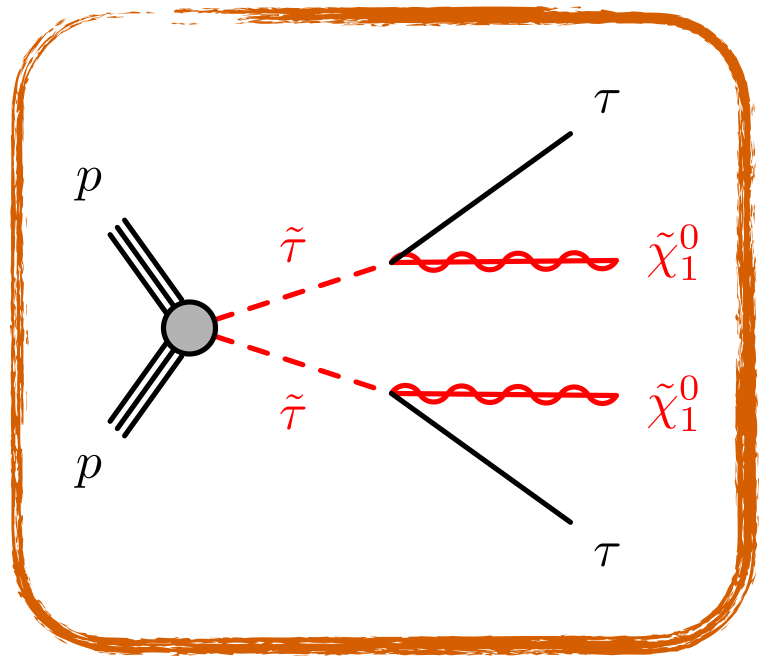
② Weak observed limits due to **2.1σ excess** in SRMM-WZ bins

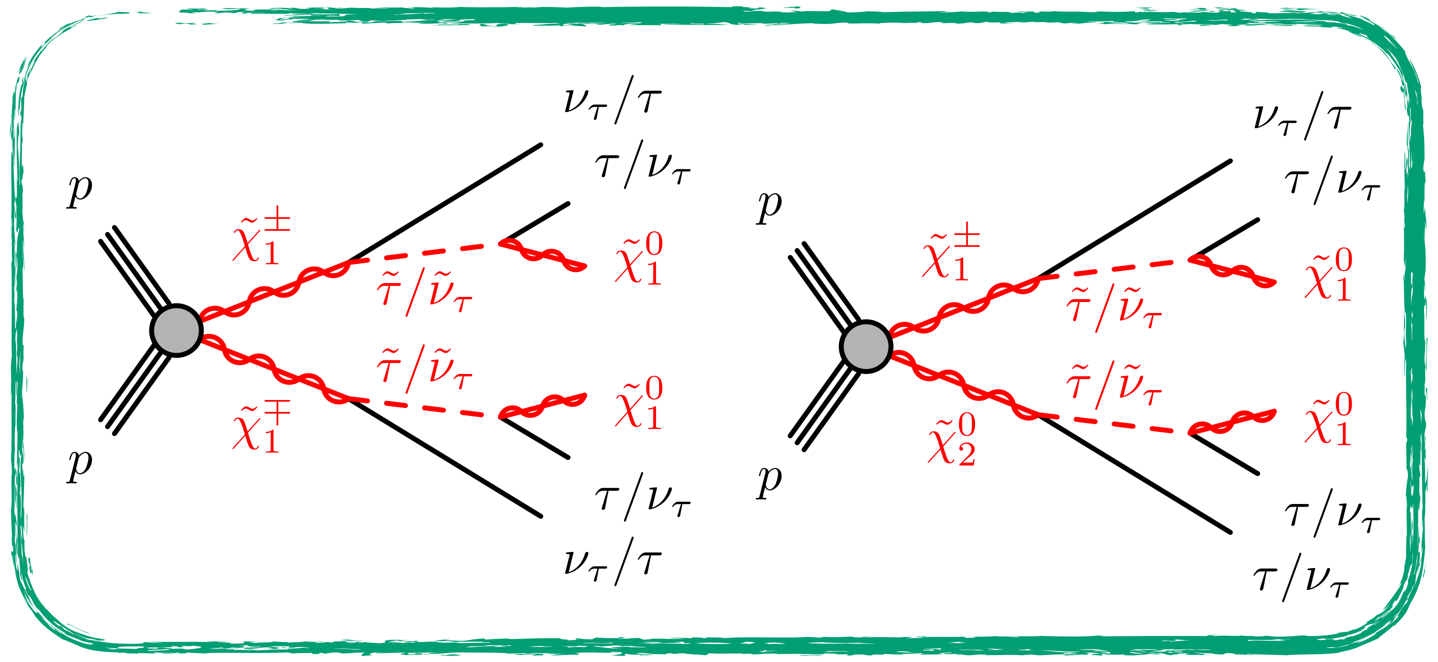
③ Similar weak observed limits in Wh channel due to small data excess, **improvements driven by BDT**

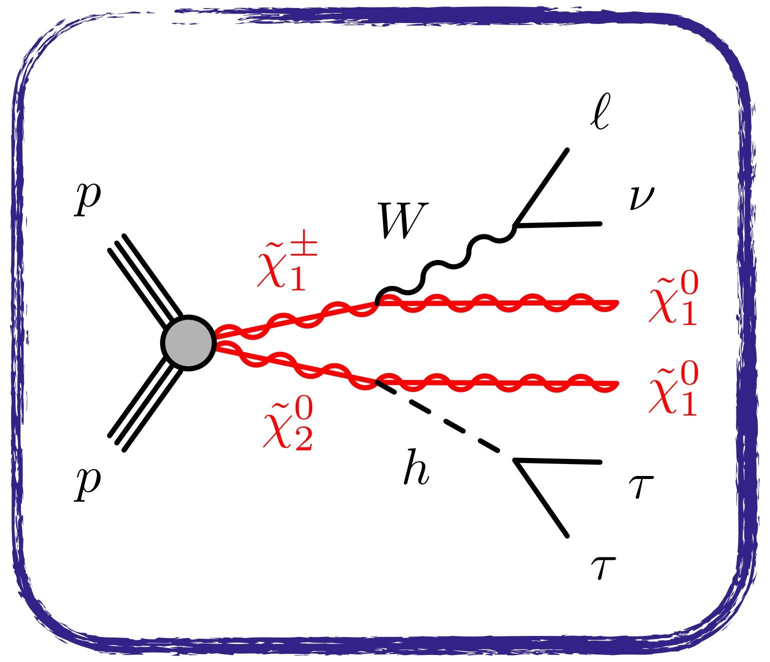
2τ + MET

JHEP05(2024)150

Extends partial Run-2 results, first time ATLAS sensitivity to $\tilde{\tau}_{R}$





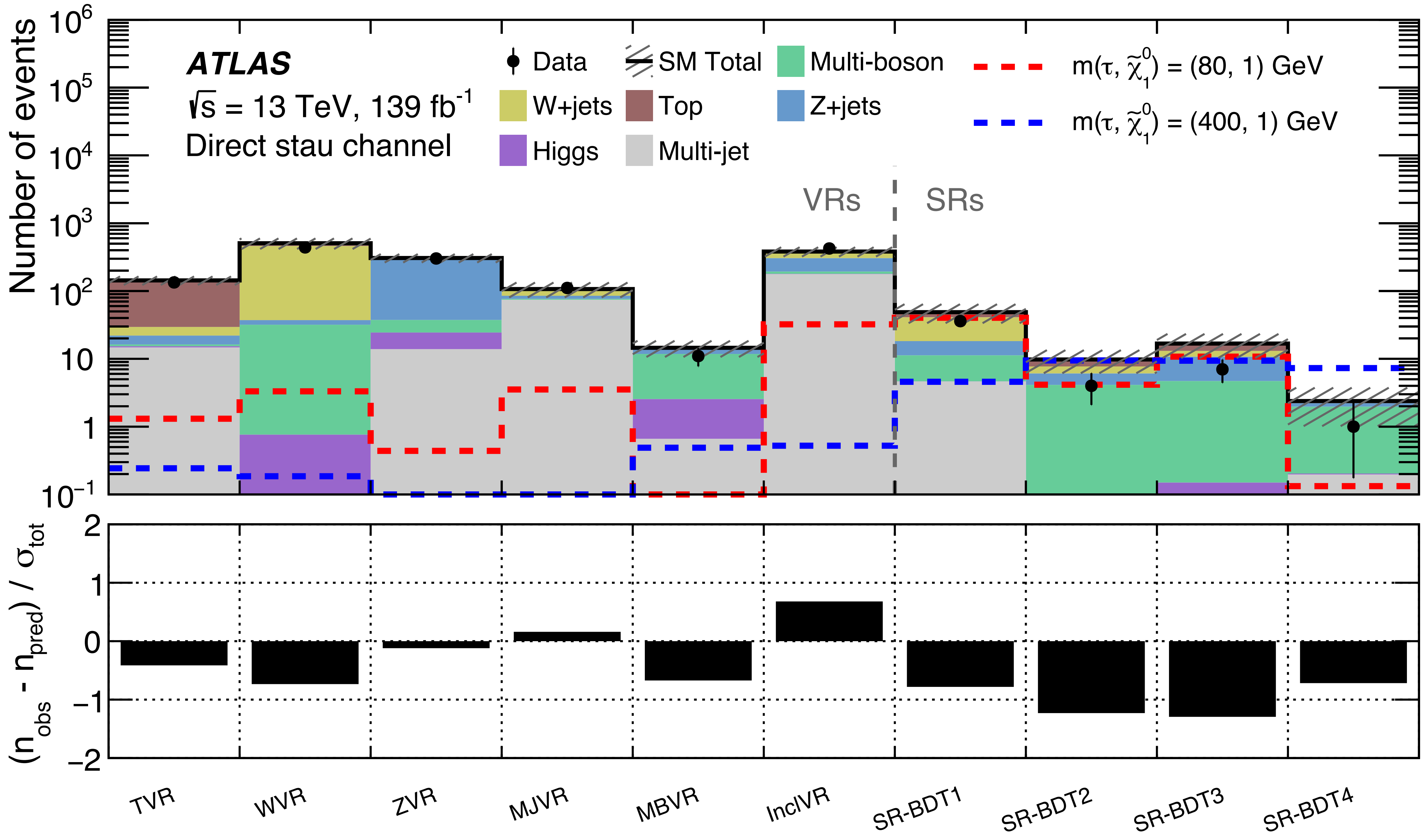


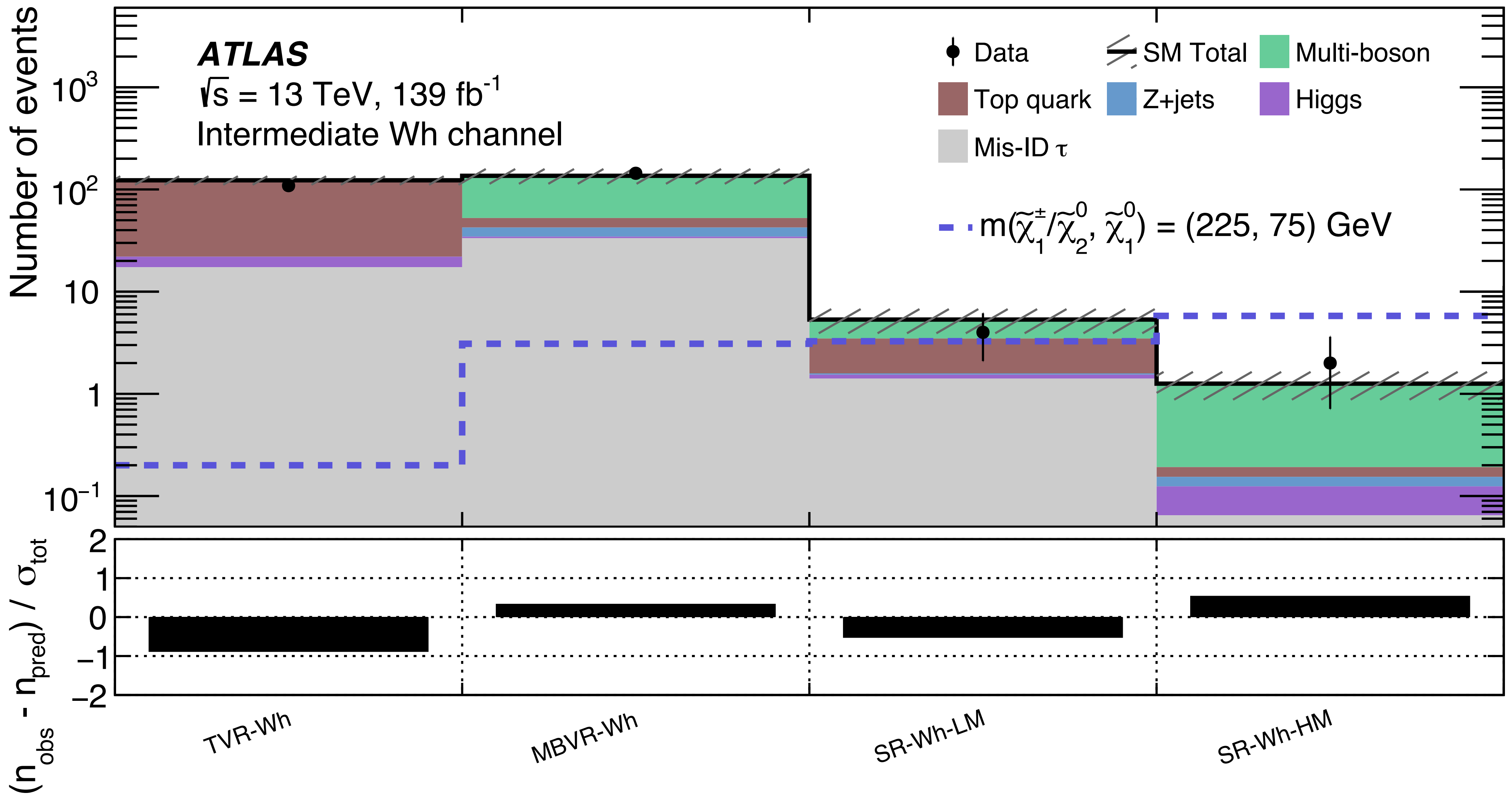
- **Direct staus** and **higgsino** pair production with a signature of at least **two hadronically decaying τ**
- Search performed in three channels
  - Direct staus production:
    - **Four BDT-SRs** to target different mass/mass splitting hypotheses, trained on events with two OS τ
    - ABCD estimate of multi-jet faking taus, V+jets and *top* estimated normalising MC to data, others taken from MC
  - $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production, decays via intermediate staus:
    - **Six SRs** obtained considering SS/OS τ + high-mass/low-mass higgsinos (m_{T})
    - Same backgrounds as in direct staus channel with multi-jet and W+jets estimated as above, others from MC
  - $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production, decays via intermediate Wh bosons:
    - **Two SRs** requiring two OS τ + e or μ, targeting high-mass/low-mass hypotheses (m_{T})
    - Fake taus in W+jets events estimated via data-driven fake factor method, *top* from CRs, multi-boson from MC

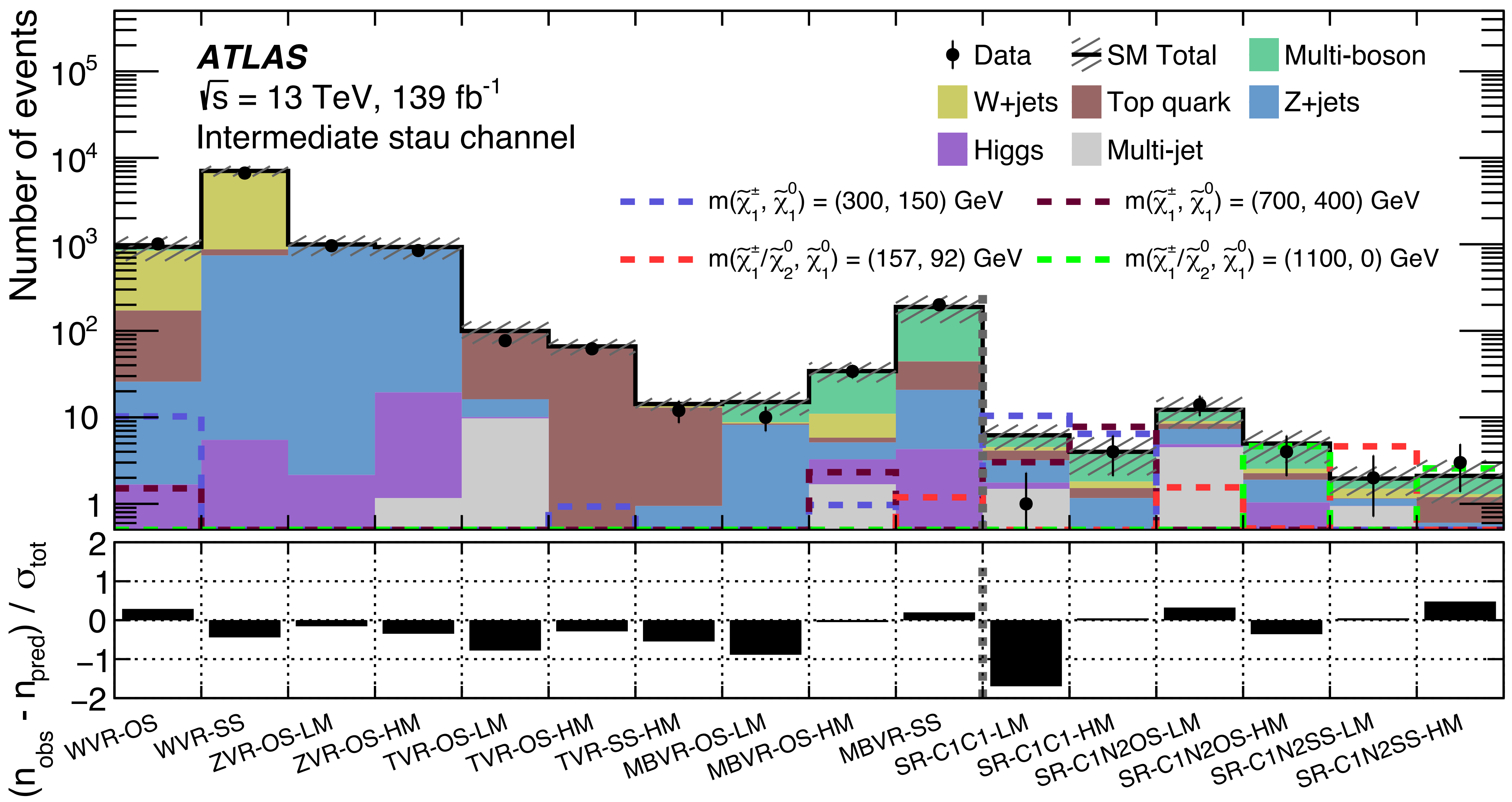
2τ + MET

JHEP05(2024)150

- Good agreement between data and SM predictions in all SRs
- In direct staus deficit of 0.7σ-1.3σ, limits drawn from SR with best CLs due to **overlap between BDTs**
- Orthogonal SRs in intermediate staus/Wh channels **statistically combined**







2τ + MET

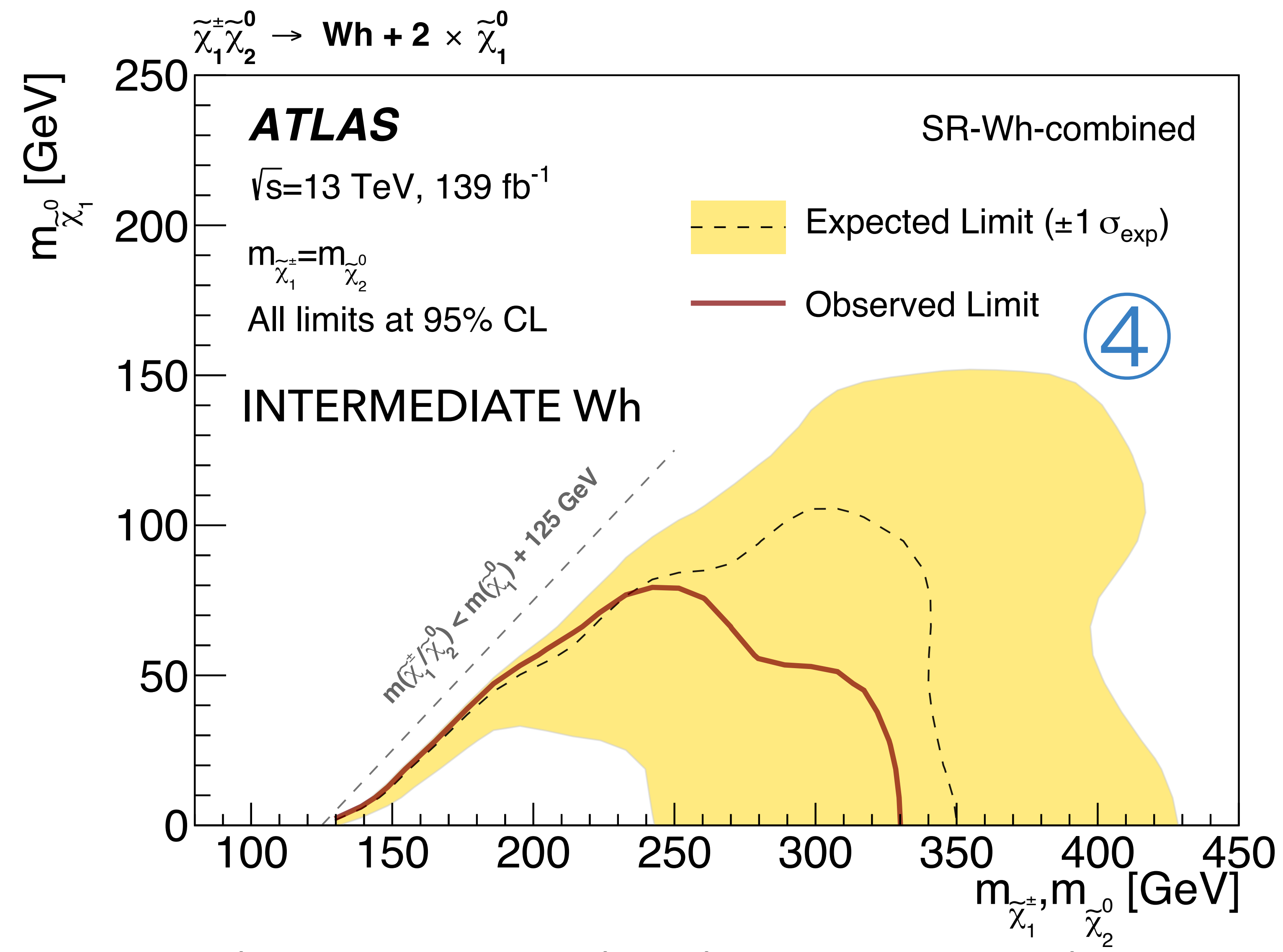
JHEP05(2024)150

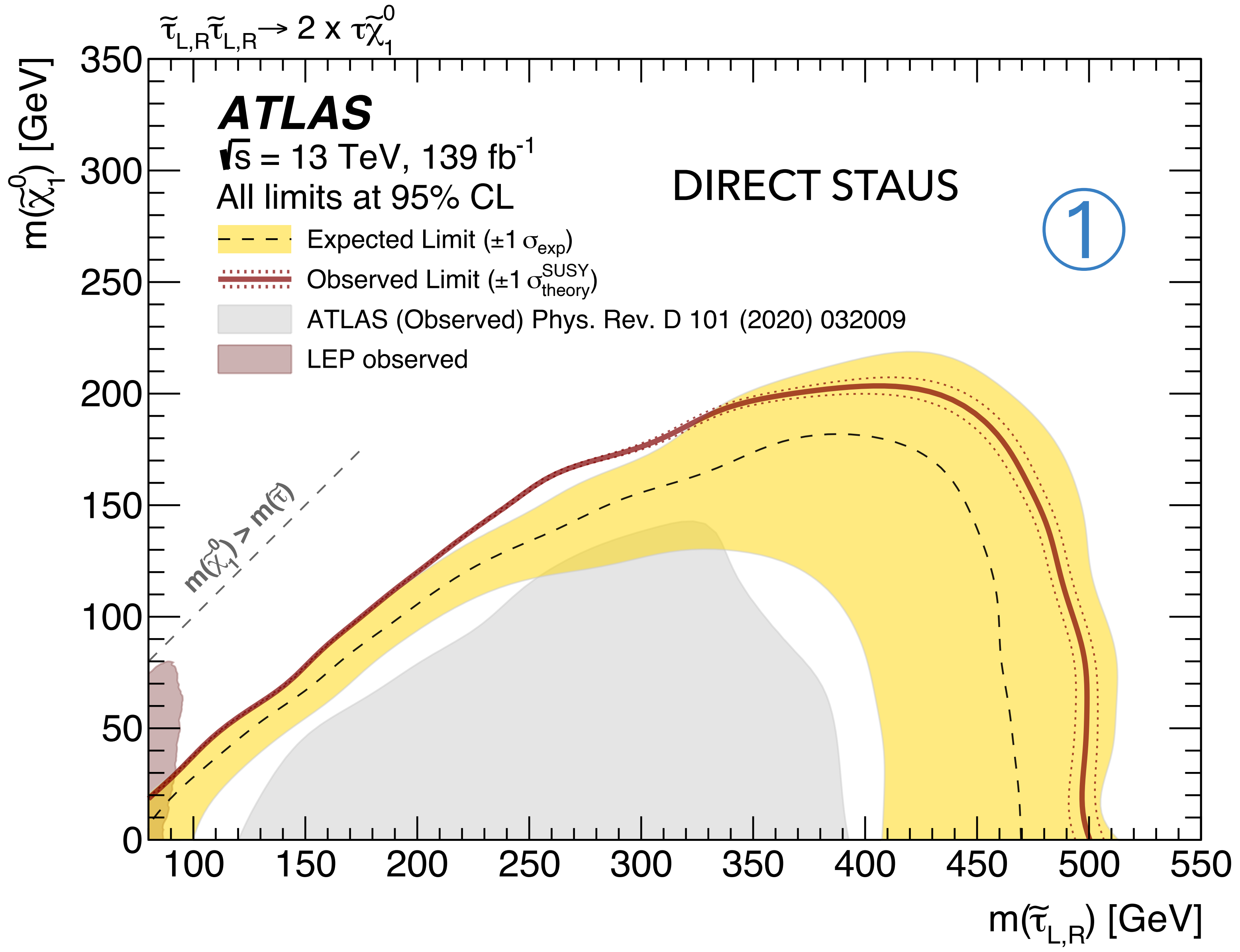
① Improved sensitivity at higher (lower) stau masses (mass splittings)

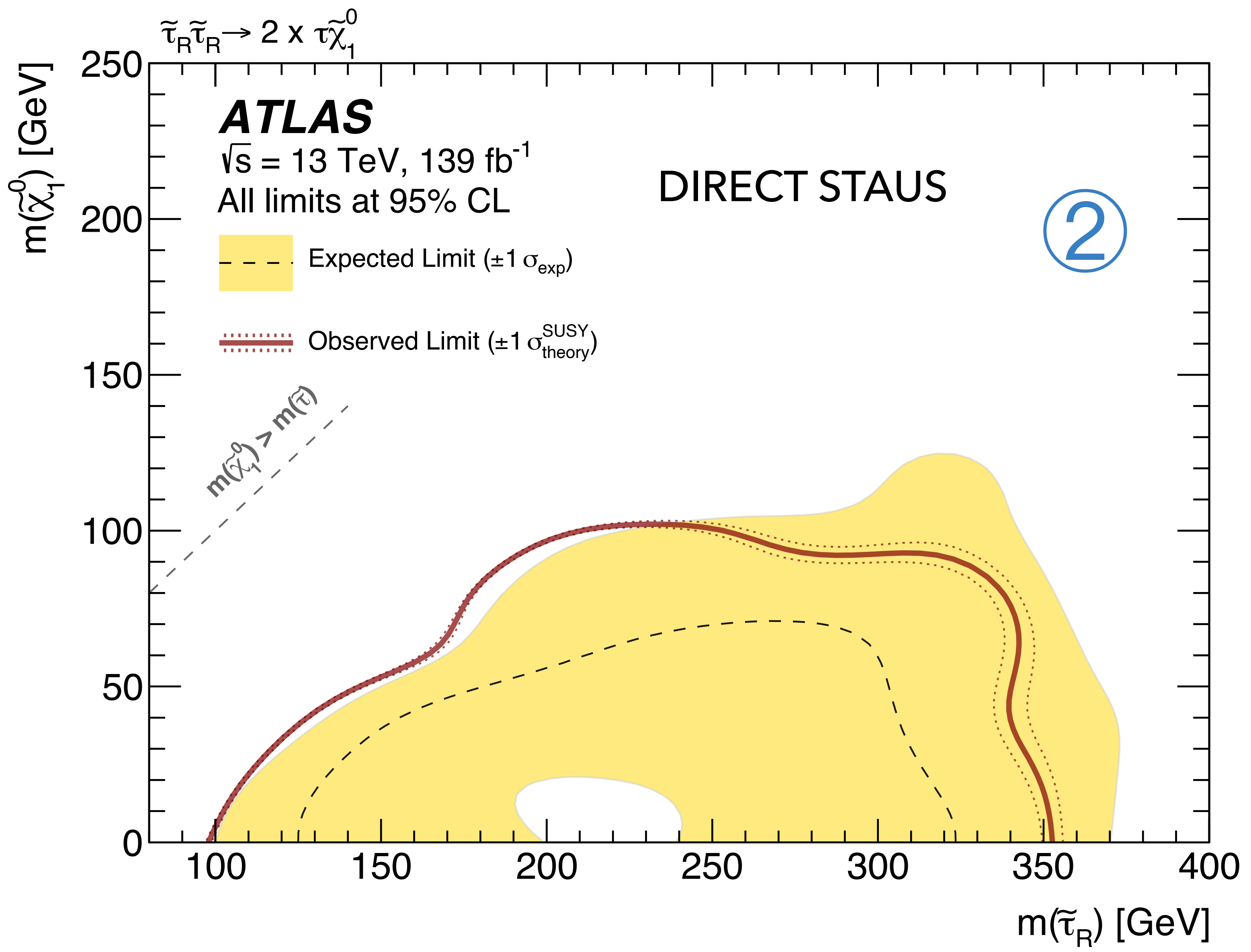
② First time limits are set by ATLAS on $\tilde{\tau}_R\tilde{\tau}_R$ production

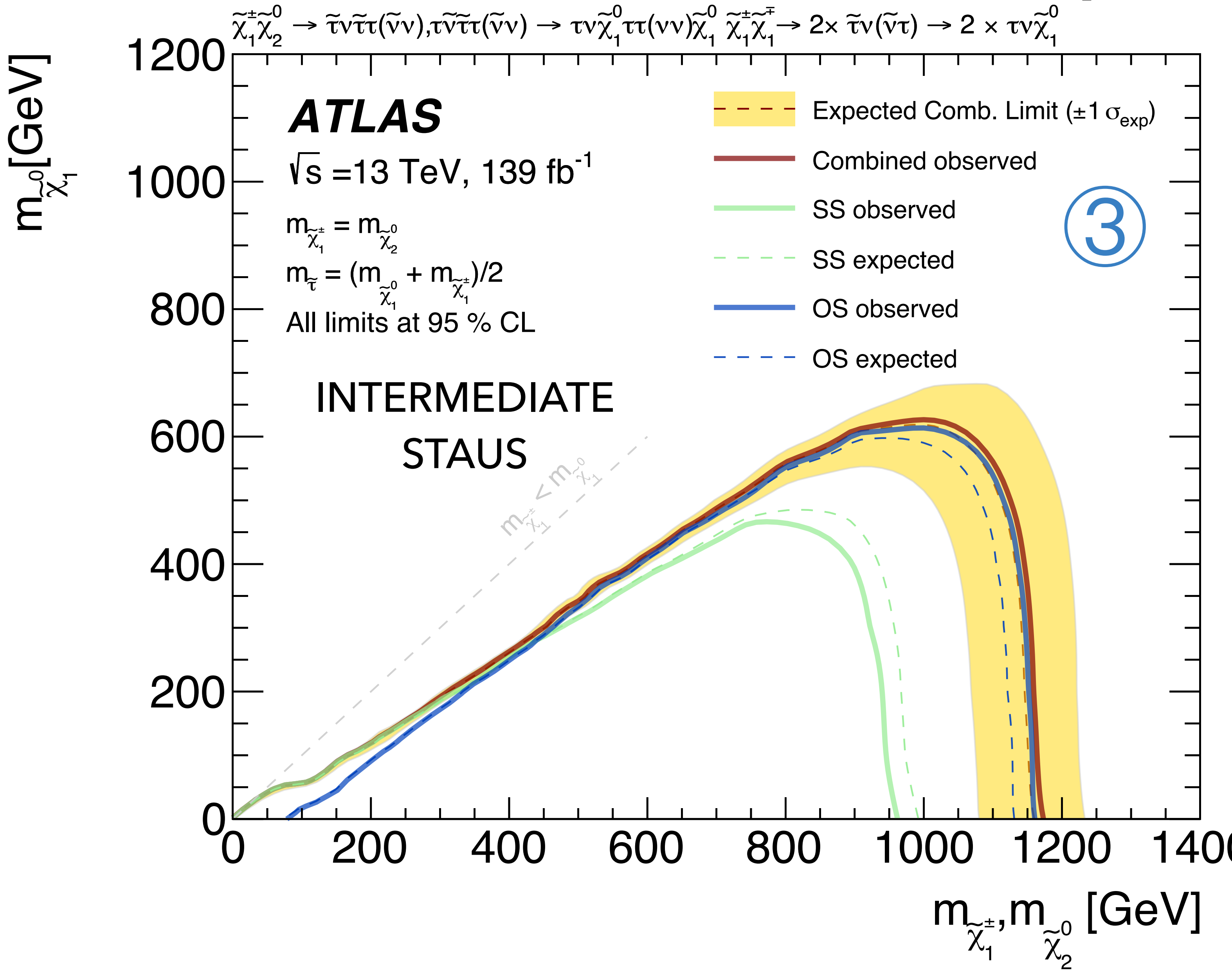
③ Combination of SS and OS channels improves sensitivity w.r.t. individual searches at high (low) masses (mass splittings)

④ Excluding next-to-LSP with masses < 330 GeV, for massless $\tilde{\chi}_1^0$





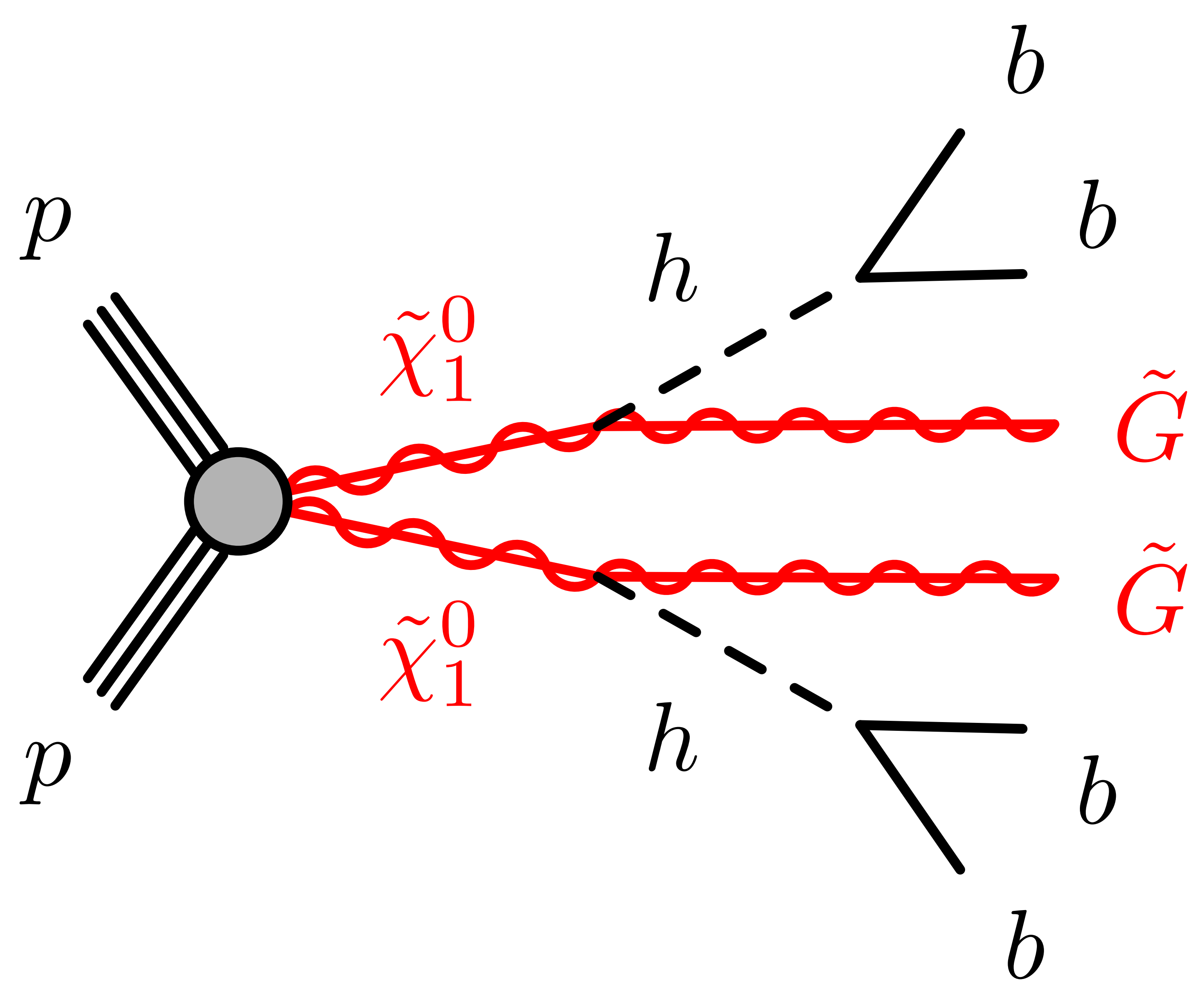




Multi-b + MET

arXiv:2401.14922

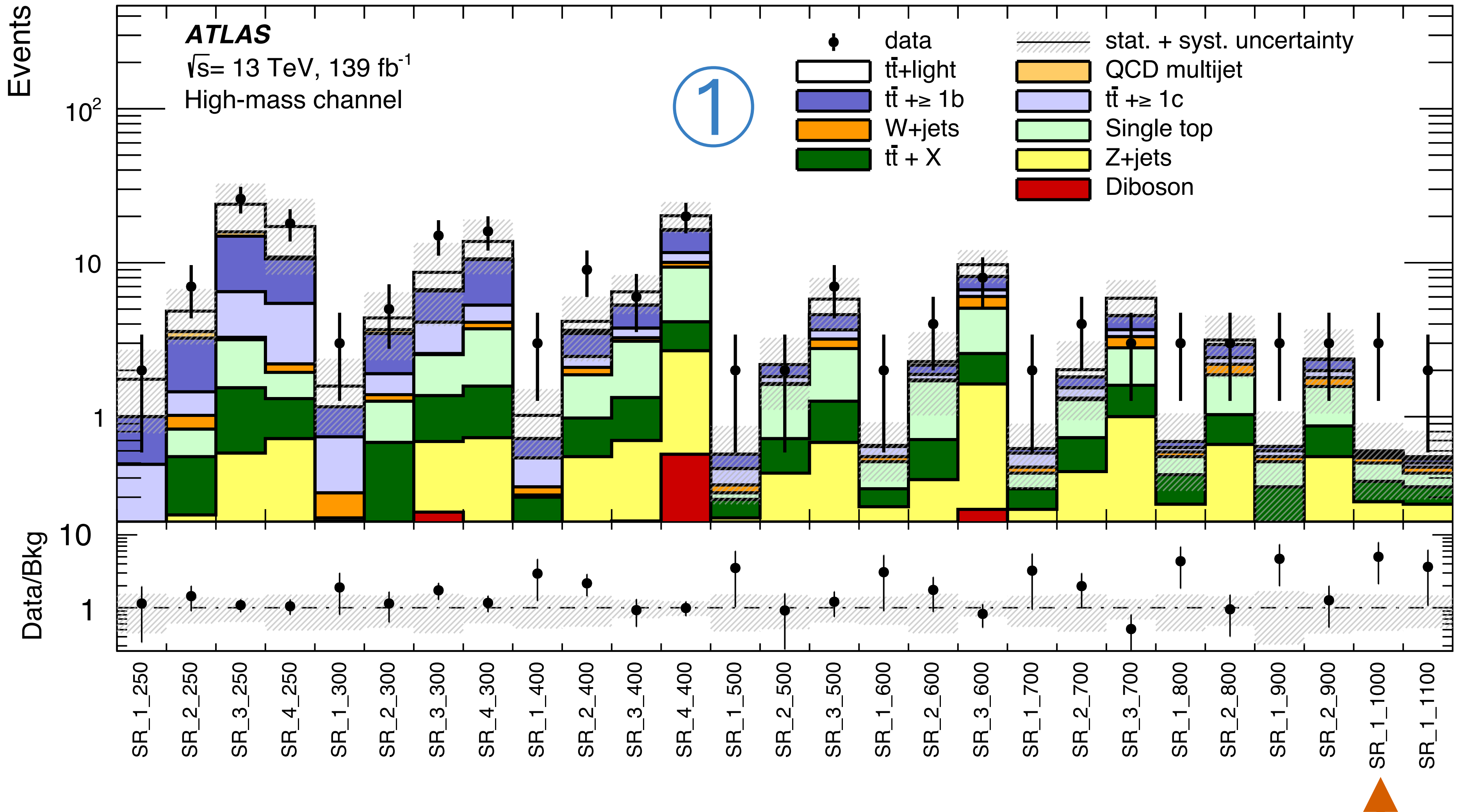
Full Run-2 update using new techniques to achieve highest sensitivity to date

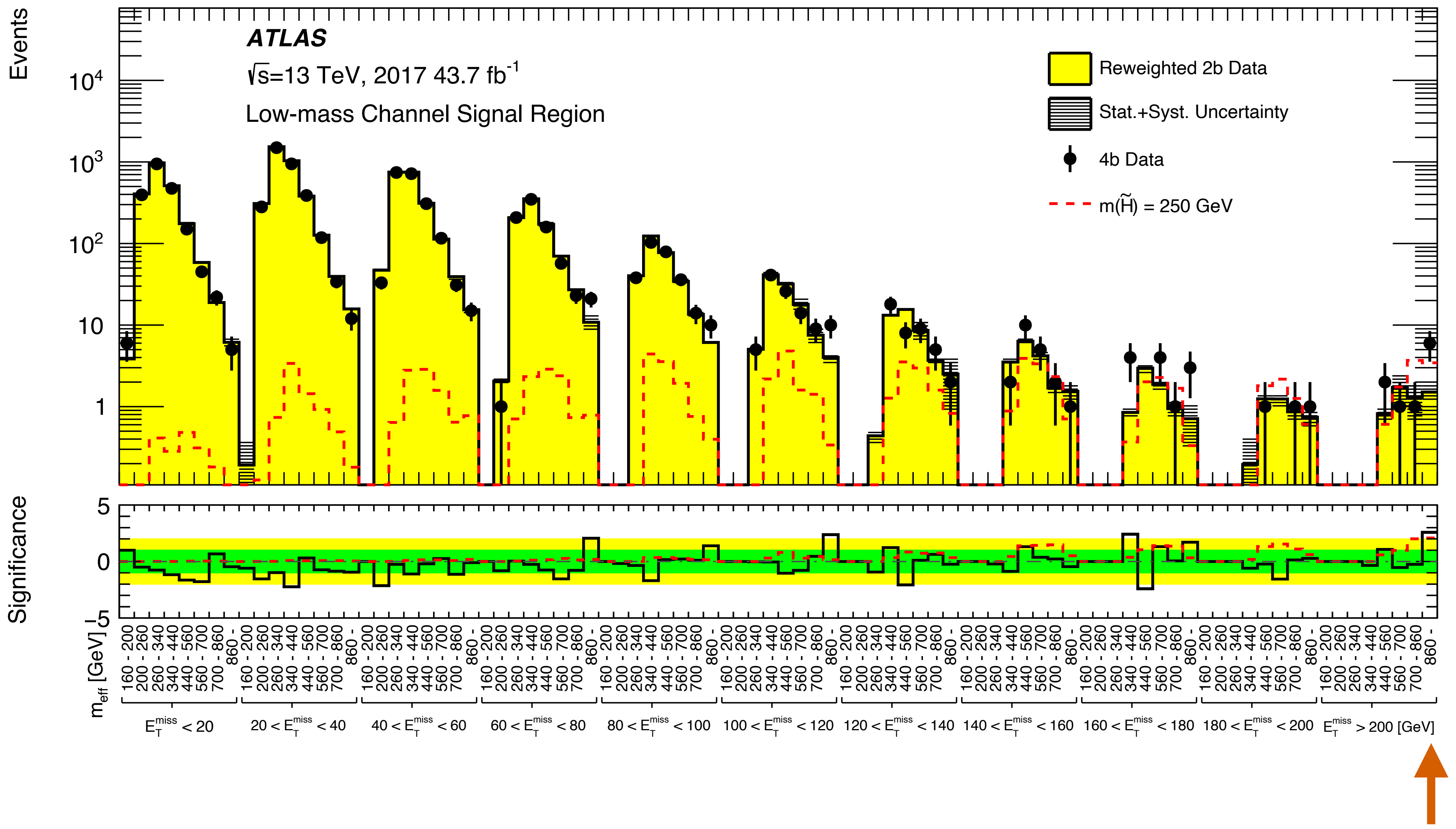


- **GMSB scenario** with neutralino decaying to nearly massless $\tilde{G}$ via **SM** $h(\to b\bar{b})$ **boson**
- Search performed in two channels
  - **High-mass** ($m(\tilde{H}) > 250$ GeV): large E_T^{miss} + E_T^{miss} trigger + at most seven jets, at least three b-tagged
  - **Low-mass** ($m(\tilde{H}) < 250$ GeV): low E_T^{miss} + b-jet triggers + at least four b-jets
- Relying on new techniques w.r.t. partial Run-2 analysis
  - Improved jet reconstruction and b-tagging
  - New b-jets pairing to Higgs boson (backup)
  - SRs of High-mass channel binned (x4) in BDTs output score to better discriminate signal from backgrounds
- $t\bar{t}$, $Z(\to \nu\nu)$+jets estimated via normalisation in CRs, QCD multi-jet constrained using data-driven ABCD method

Multi-b + MET

arXiv:2401.14922

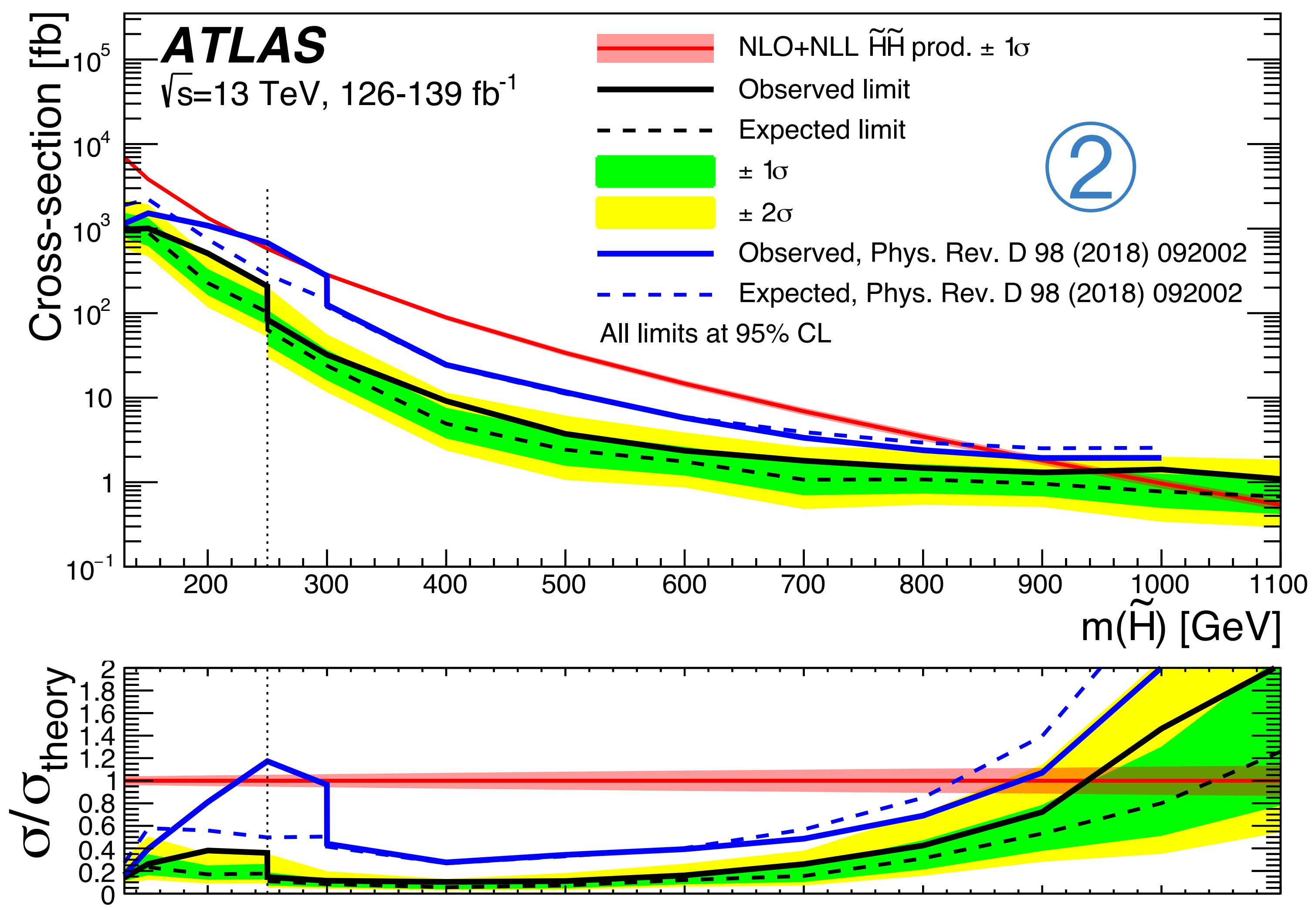


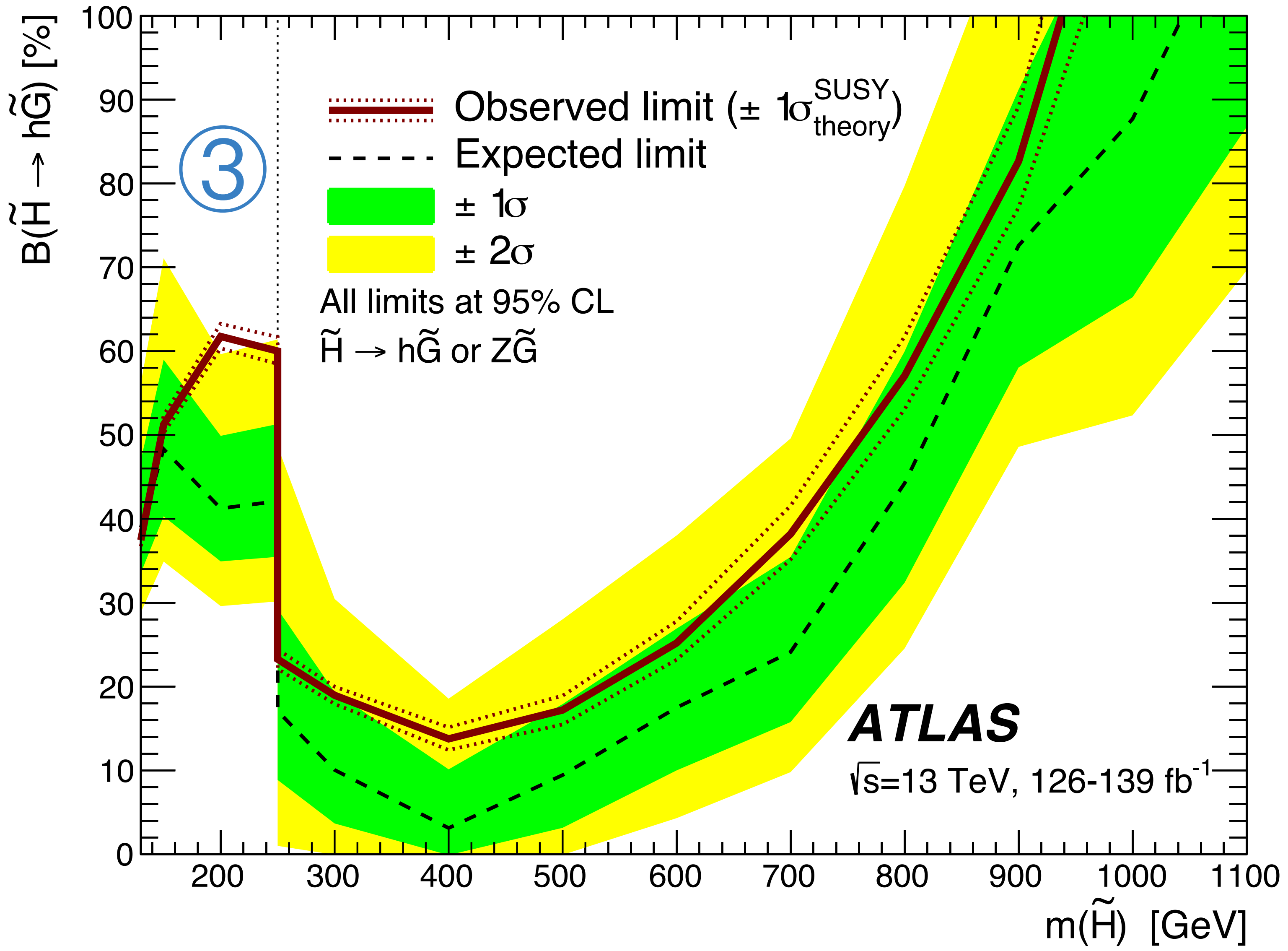


① Largest excess of **1.9σ** (**2.6σ**) local significance in High-Mass (Low-Mass) channel

② Most sensitive limits to date to GMSB simplified models in 130 GeV $< m(\tilde{H}) <$ 800 GeV mass window

③ Sets upper limit as low as 14% on $B(\tilde{H} \to h\tilde{G})$



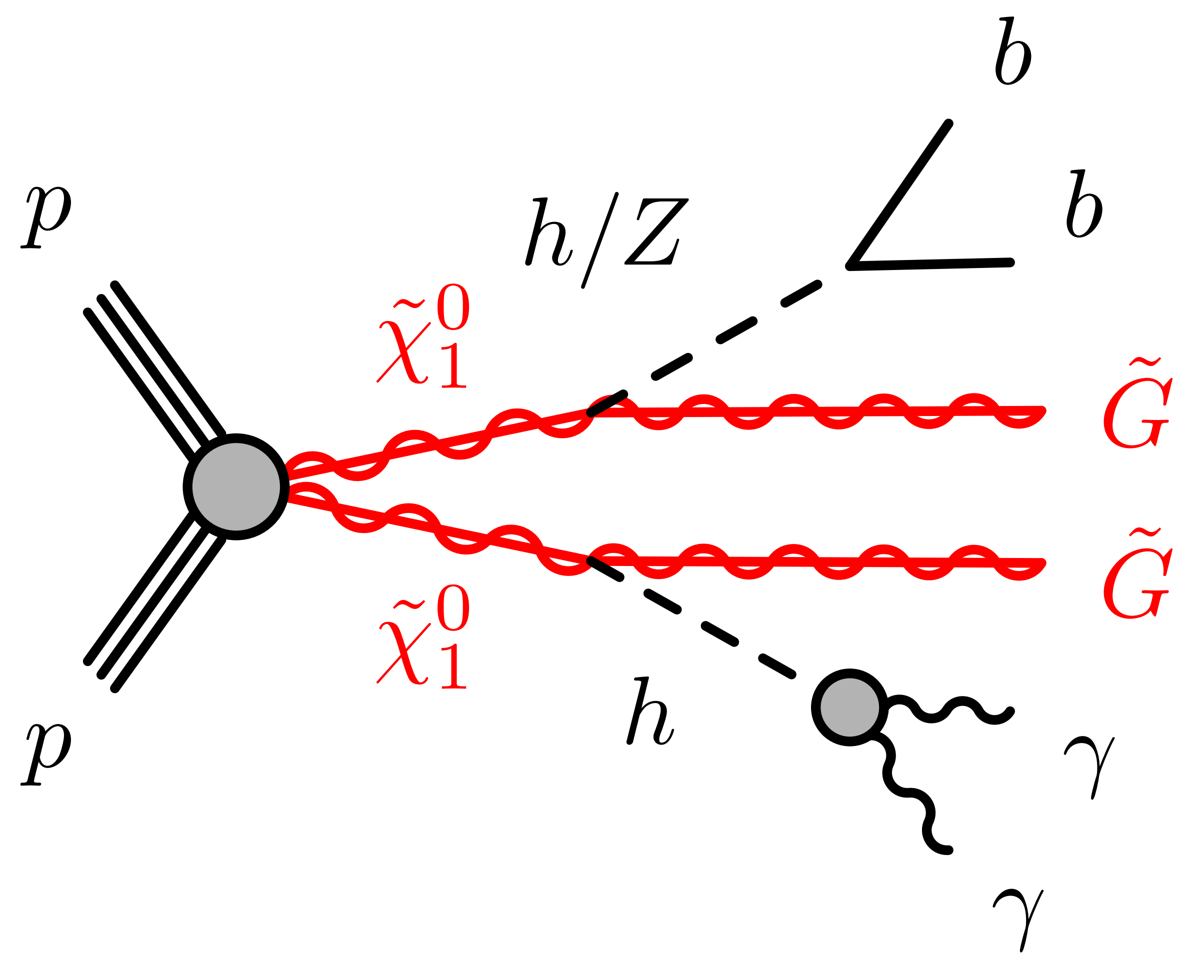


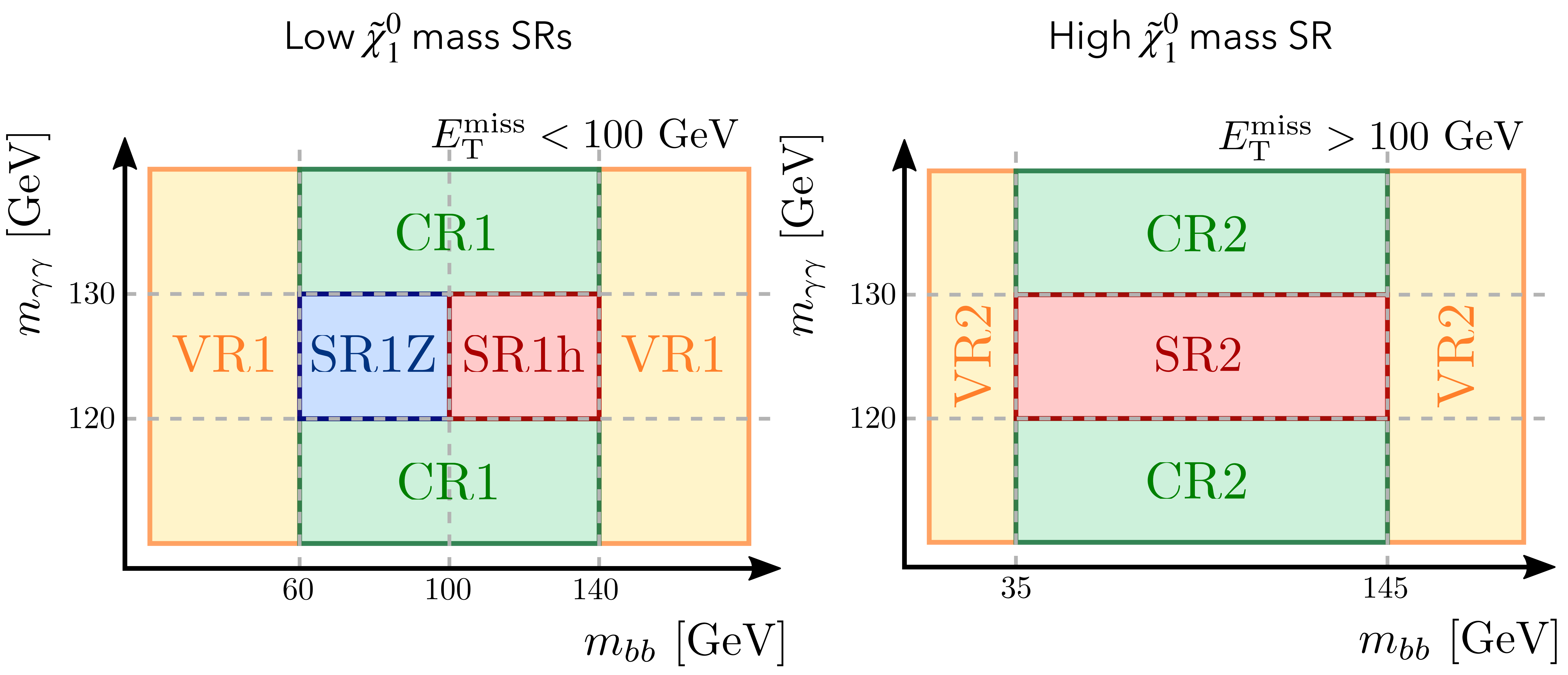
$\gamma\gamma bb$ + MET

arXiv:2404.01996

Provides complementary results to multi-*b* search by targeting different SM boson decays

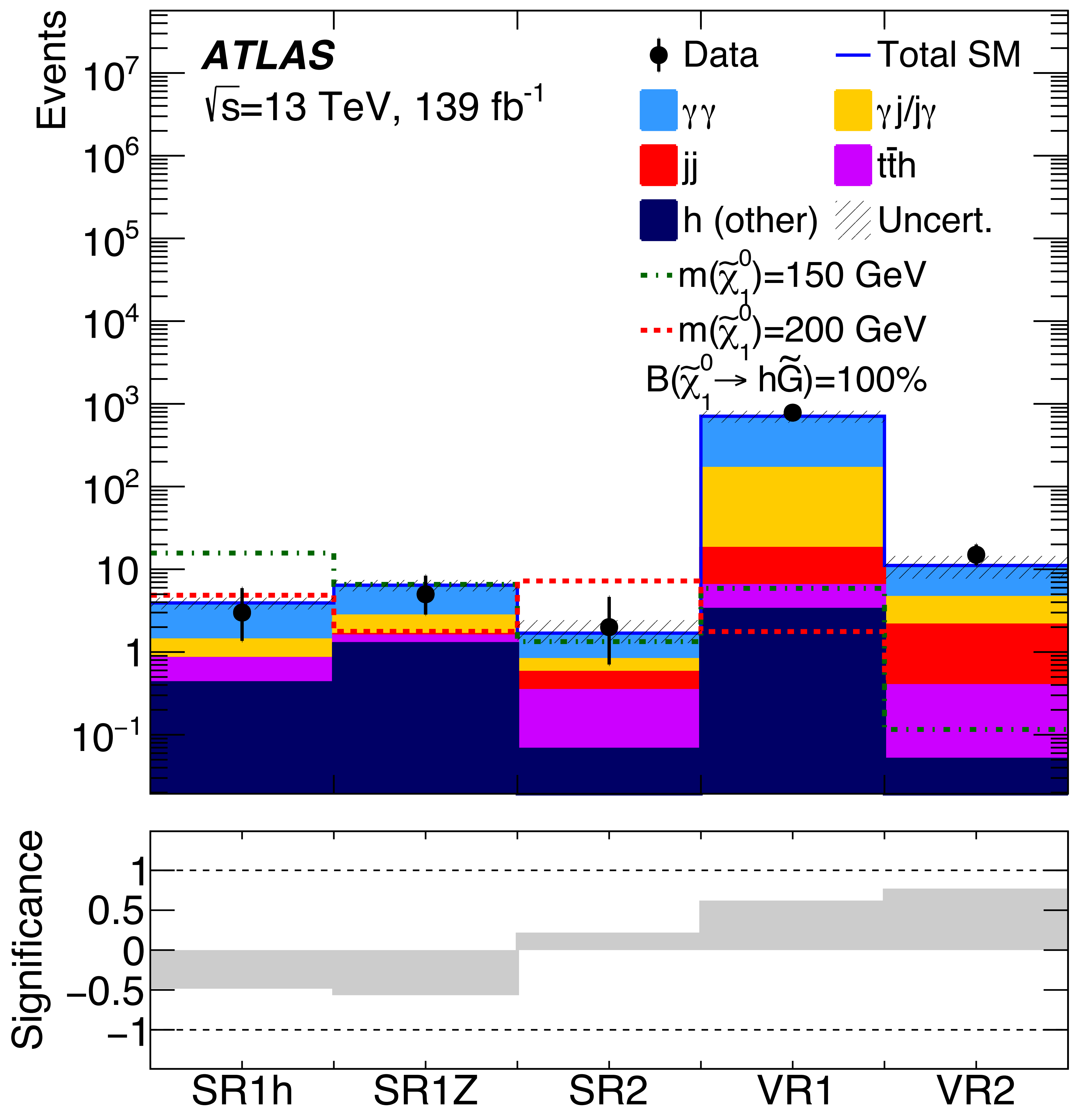
- **GMSB scenario** complementary to previous one, targeting $\tilde{\chi}_1^0$ decays via **SM** $h(\rightarrow \gamma\gamma/b\bar{b})$ or $Z(\rightarrow b\bar{b})$ bosons
- Events selected vetoing leptons and requiring exactly 2γ + $2b$-jets in the h or Z mass windows
- Three non-overlapping signal regions defined to be sensitive to different $\tilde{\chi}_1^0$ masses and decay modes
- Dominant non-resonant backgrounds estimated using sidebands + ABCD methods, others from MC



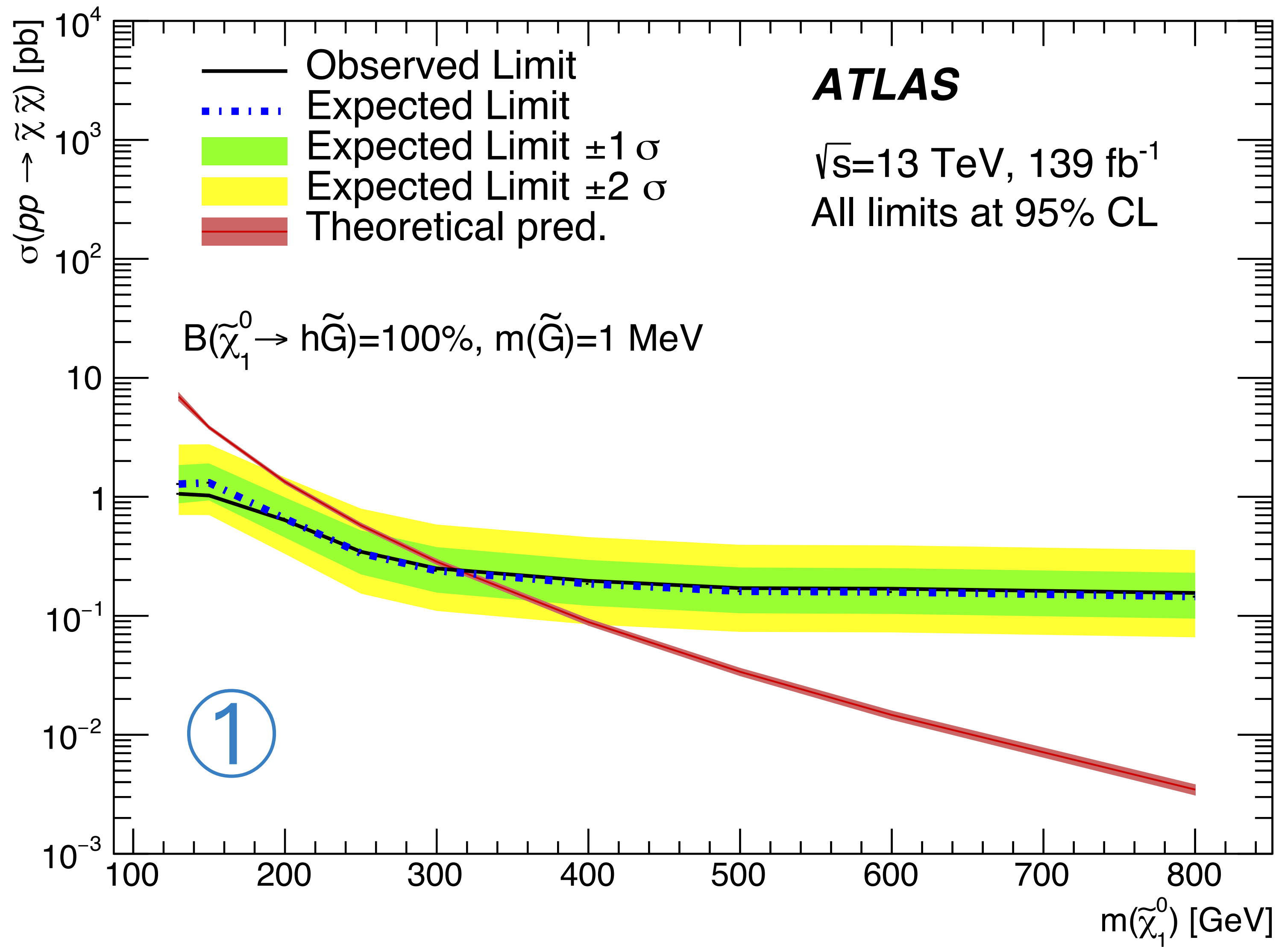


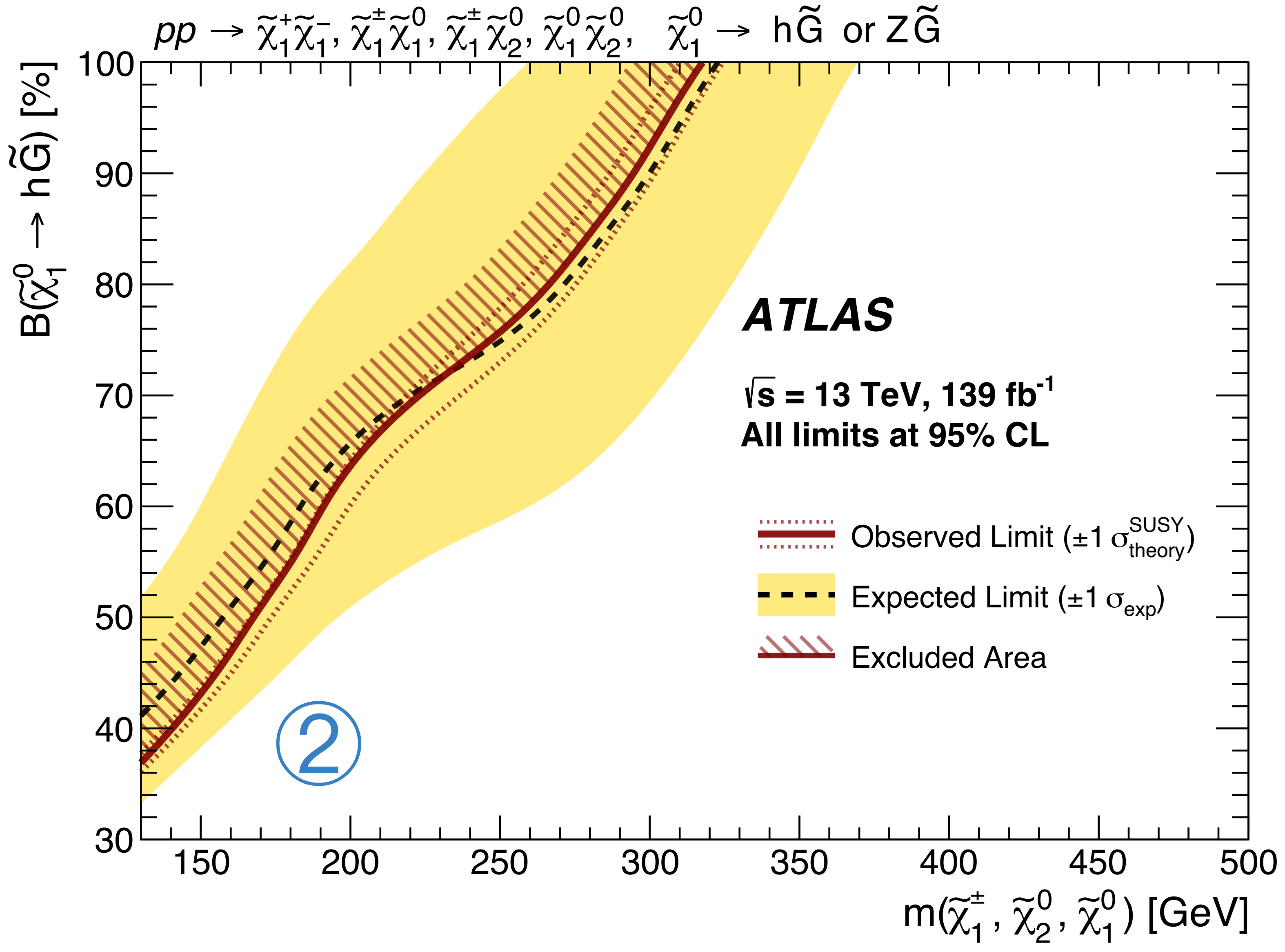
$\gamma\gamma bb$ + MET

arXiv:2404.01996



- Very good agreement between data and SM predictions
- SRs statistically combined to improve individual limits
  ① Pure higgsino cross-section excluded for $m(\tilde{\chi}_1^0) < 320$ GeV
  ② Excluded BRs as low as 36%, improvements w.r.t. multi-b search for $m(\tilde{\chi}_1^0) \lesssim 320$ GeV





Summary

- Overview of some of the most recent electroweak SUSY searches with ATLAS
  - Large improvements in analysis techniques w.r.t. partial Run-2 results
  - Extension to higher (lower) masses (mass-splittings)
  - Large ongoing effort of analyses preservation and combination
- **With LHC Run-3 in full swing many more exciting results are coming…stay tuned!**
- And don't miss other ATLAS EW-SUSY results:
  - SUSY searches at ATLAS by Joaquin Hoya
  - Search for electroweak supersymmetry with compressed spectra by Jeff Shahinian
  - Searches for supersymmetry in non-minimal models by Ying Wun Yvonne Ng

BACKUP

Some variables used in SUSY searches

- The *transverse mass* is defined as

$$m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2(|\mathbf{p}_{\mathrm{T}}||\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}| - \mathbf{p}_{\mathrm{T}} \cdot \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})}$$

- The *stransverse mass* is defined as

$$m_{\mathrm{T2}} = \min_{\mathbf{q}_{\mathrm{T}}} \left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T1}}, \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T2}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}})\right)\right]$$

  and shows an endpoint for events where two massive particles each decays into detected + undetected objects ($\mathbf{q}_{\mathrm{T}}$ is chosen as the transverse vector minimising the larger of the two transverse masses)

- The *effective mass* is defined as the following scalar sum

$$m_{\mathrm{eff}} = p_{\mathrm{T}}^{\ell} + \sum_{\mathrm{jets}} p_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

- The $E_{\mathrm{T}}^{\mathrm{miss}}$ *significance* is defined as the log-likelihood ratio of measuring the total observed transverse momentum to the likelihood of the null hypothesis, i.e.

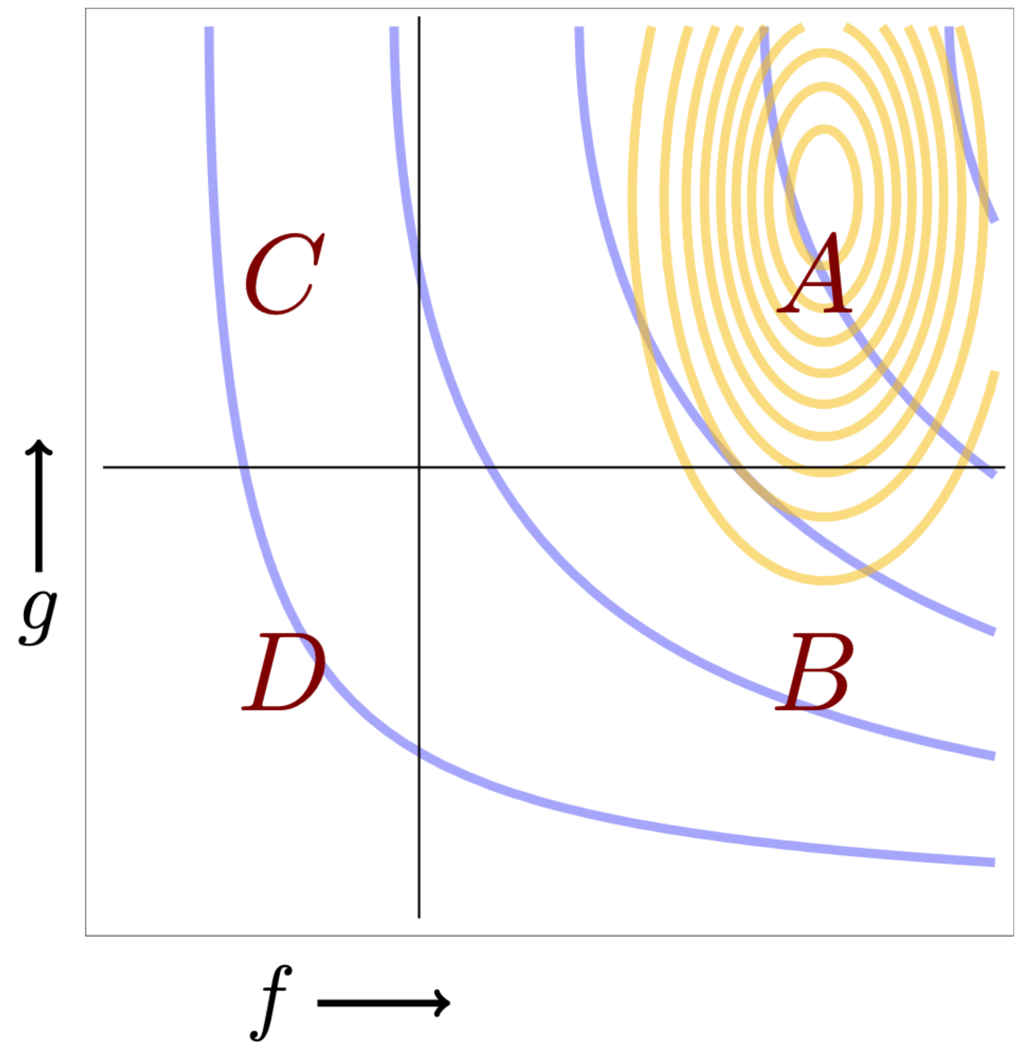
$$\sigma_{E_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2\ln\left[\frac{\max_{\mathbf{p}_{\mathrm{T}}^{\mathrm{inv}} \neq 0} \mathscr{L}(E_{\mathrm{T}}^{\mathrm{miss}} \,|\, \mathbf{p}_{\mathrm{T}}^{\mathrm{inv}})}{\max_{\mathbf{p}_{\mathrm{T}}^{\mathrm{inv}} = 0} \mathscr{L}(E_{\mathrm{T}}^{\mathrm{miss}} \,|\, \mathbf{p}_{\mathrm{T}}^{\mathrm{inv}})}\right]}$$

  where high values indicate $E_{\mathrm{T}}^{\mathrm{miss}}$ is due to particles escaping detection

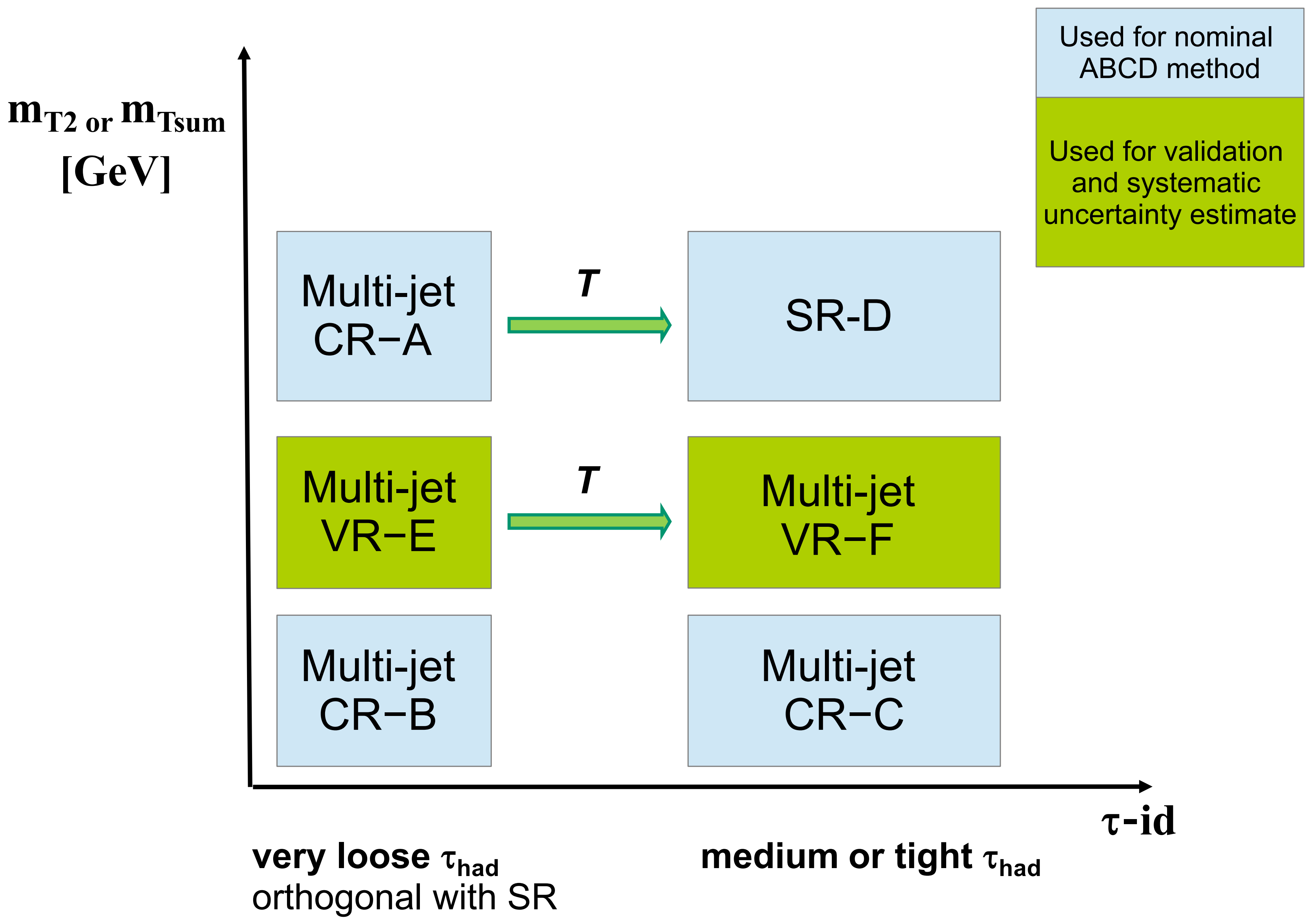
Data-driven ABCD method

- Assumption: f and g as kinematic variables are independent (i.e. statistically uncorrelated)
- If signal is almost entirely located in region A, counting background events in regions B, C and D one can estimate background events in SR via

$$N_A = \frac{N_B \cdot N_C}{N_D}$$



arXiv:2007.14400



- Above an example taken from multi-jet estimation for the direct staus channel of JHEP05(2024)150

b-jets pairing to Higgs boson

- To reconstruct Higgs boson masses $m(h_1^{\rm HM})$ and $m(h_2^{\rm HM})$, jets originating from Higgs candidates are first **identified**:
  - If there are exactly four *b*-jets, use those four
  - If there are more than four *b*-jets, use the four with the highest momenta
  - If there are three *b*-jets only...
    - ...and one has mass larger than 100 GeV, no additional jets are considered (boosted Higgs)
    - ...and none has mass larger than 100 GeV, select fourth jet as the untagged one that minimises $m(h_1^{\rm HM})$ in pairing algorithm below

- Jets are then **paired**:
  - If three jets only are selected, take the heaviest to be a Higgs candidate and pair the remaining two to form the second jet
  - If four jets are selected compute for each of the three possible pairing the quantity

$$\Delta R_{\rm max}^{bb}(h_1^{\rm HM}, h_2^{\rm HM}) = \max(\Delta R(h_1^{\rm HM}), \Delta R(h_2^{\rm HM}))$$

    where $\Delta R(h)$ is the separation of jets coming from the same Higgs candidate
  - Use the pairing that minimises $\Delta R_{\rm max}^{bb}$, since jets are more collimated for signal than for background