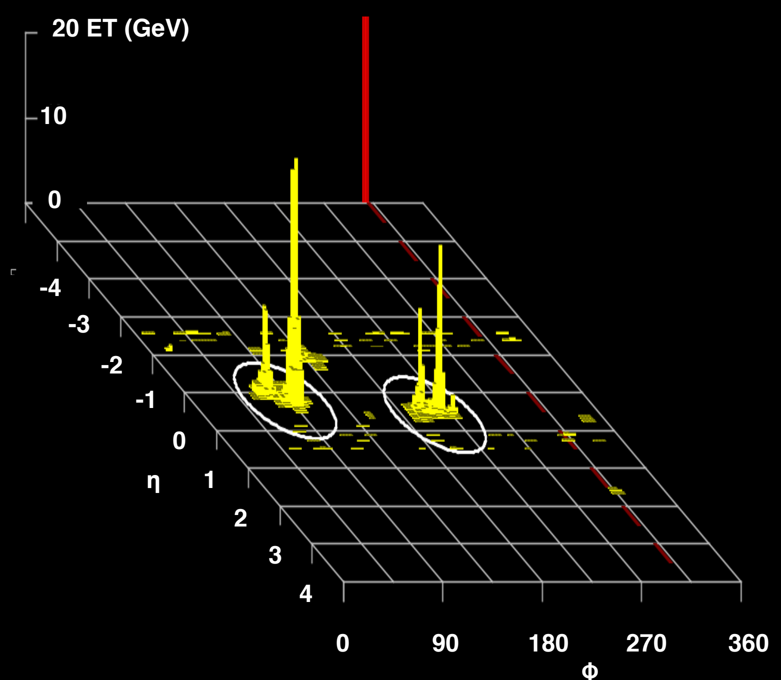
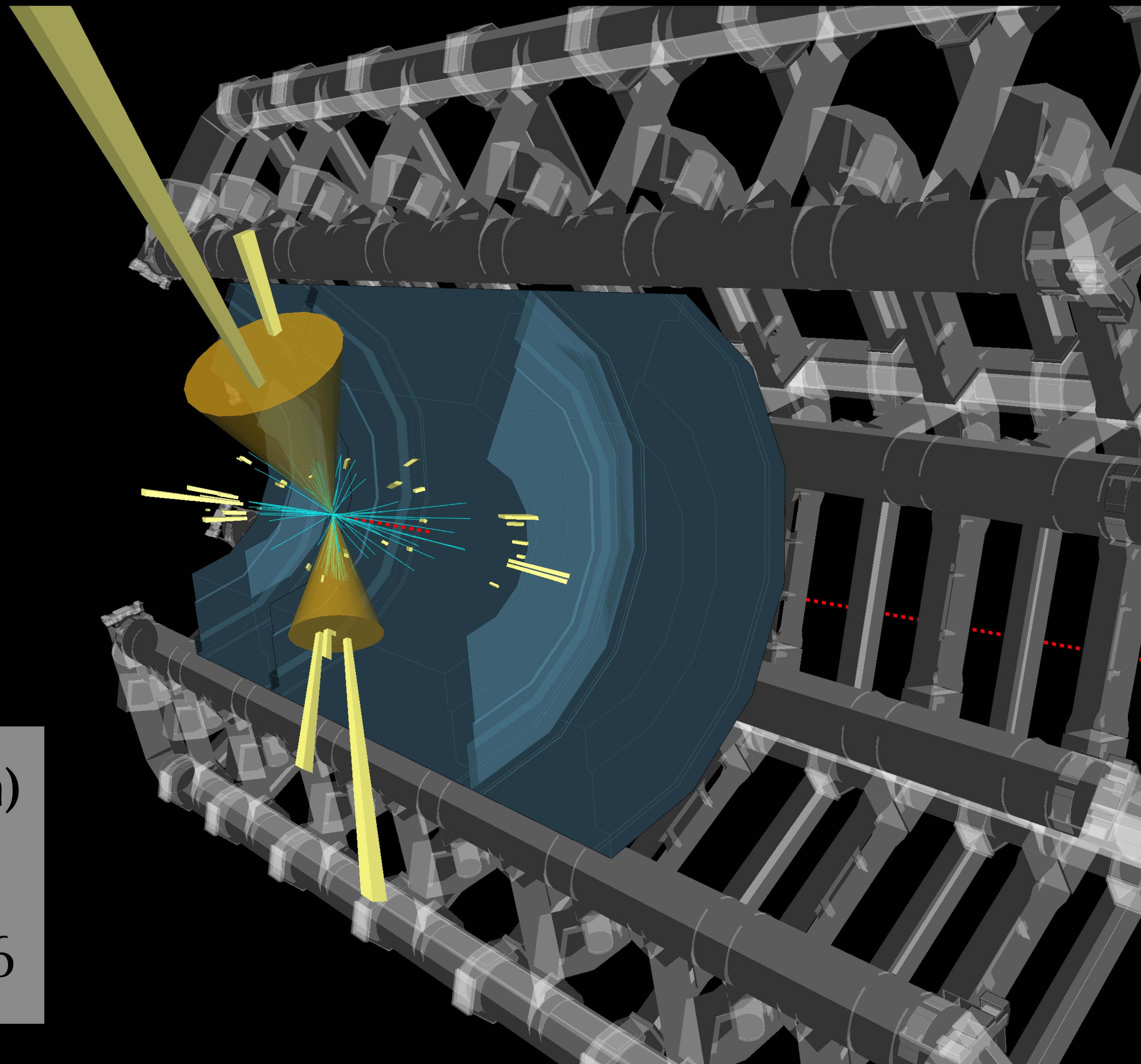
Search for Electroweakinos using Fully-hadronic Final states with Boosted Boson Jets in ATLAS EXPERIMENT





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RAMP Meeting #6

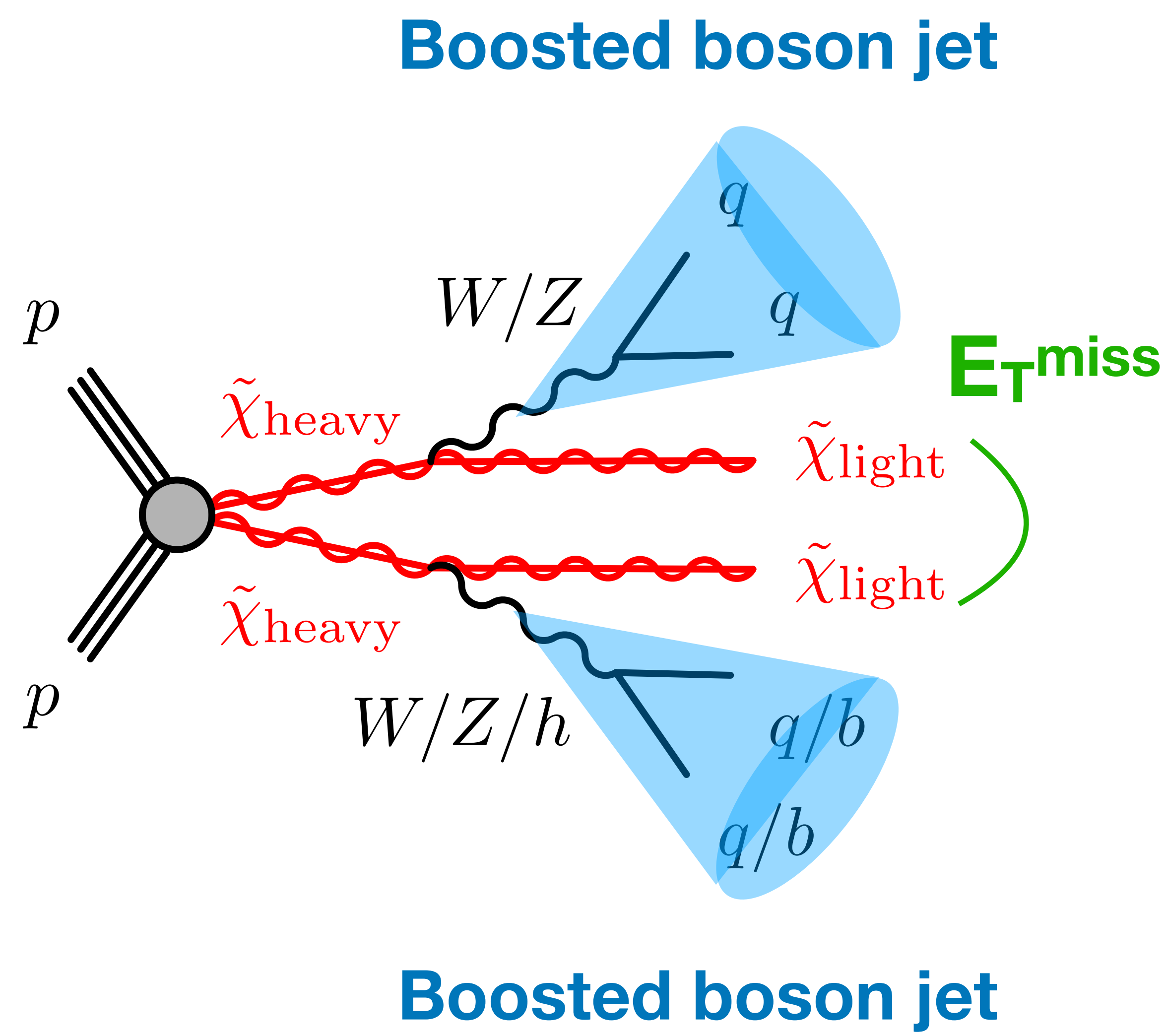
Introduction

Target: **Inclusive EWKino pair production**

- Two 'species' with large mass splitting Δm(heavy, light) > 400GeV.
- R-parity consv. → **Di-boson + E_T^{miss}**

Highlights:

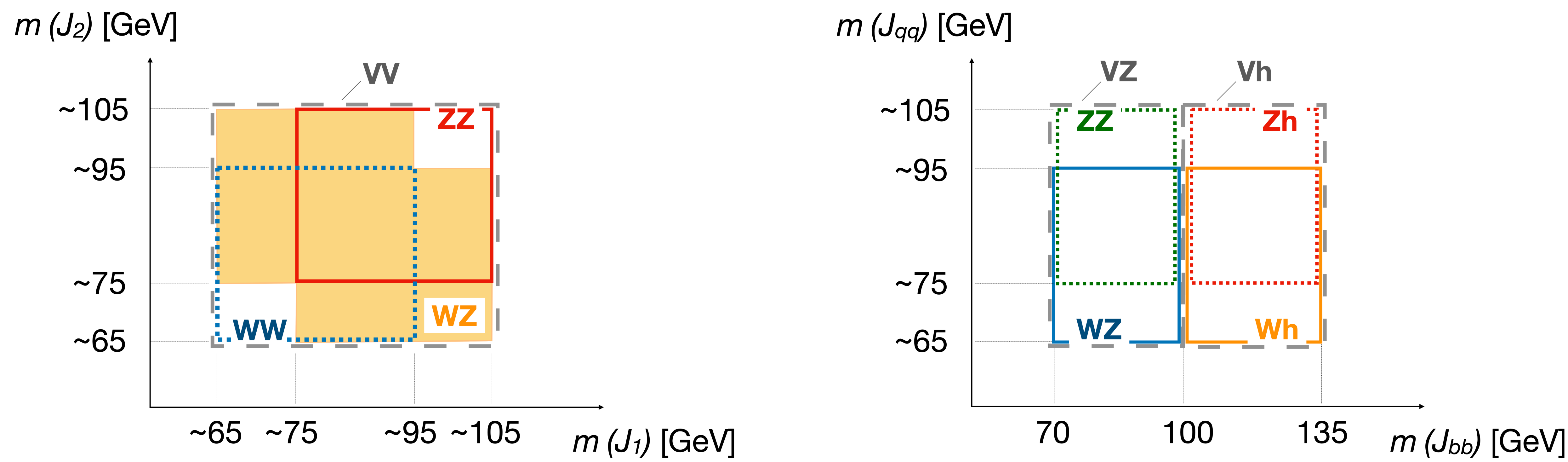
- New fully-had. final states + boosted boson tagging **drastically improved the high mass sensitivity.**
- Event selection / Limit presentation **targeting various realistic models.**



Published materials:

- arXiv: 2108.07586 (accepted by PRD)
- ATLAS publication webpage / HEPData containing the main/auxiliary materials
- Dedicated talk in SUSY2021 (Y. Okazaki)

Analysis Strategy



(a) SR-4Q (b) SR-2B2Q

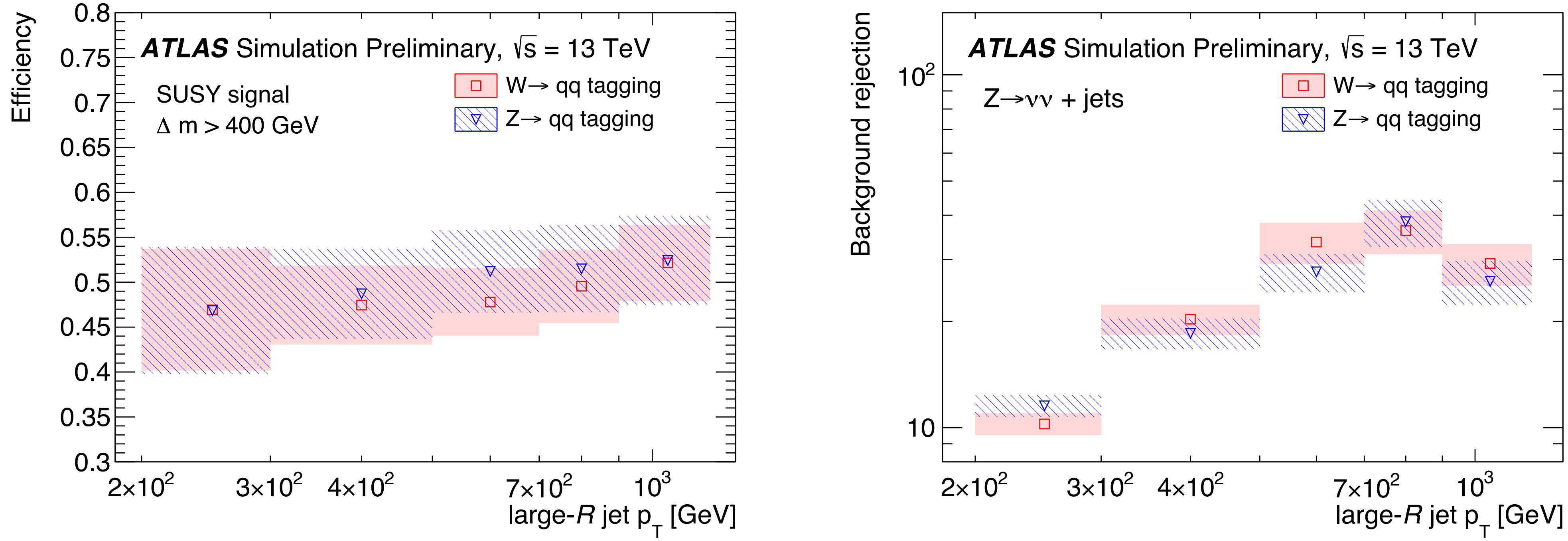
- Six “di-boson types” can be considered in the signals: **WW** / **WZ** / **Wh** / **ZZ** / **Zh** / **hh**
- Using two final state categories: **qqqq** and **bbqq**†
- One signal region (SR) per di-boson type, segmented by different ‘boosted boson tagging’.
- Background rejection cuts:

  Large E_T^{miss}, m_{eff}, min. $\Delta\phi$ (j, E_T^{miss}), veto b-jets outside the jets used for boson tagging etc.

† bbbb is not considered here since covered by the other analysis to come)

Boosted Boson Tagging

e.g. W/Z→qq tagging efficiency



(a) Efficiency (b) Rejection factor

Common: Large-R jets (R=1.0) with p_T>200GeV and m_J>40GeV

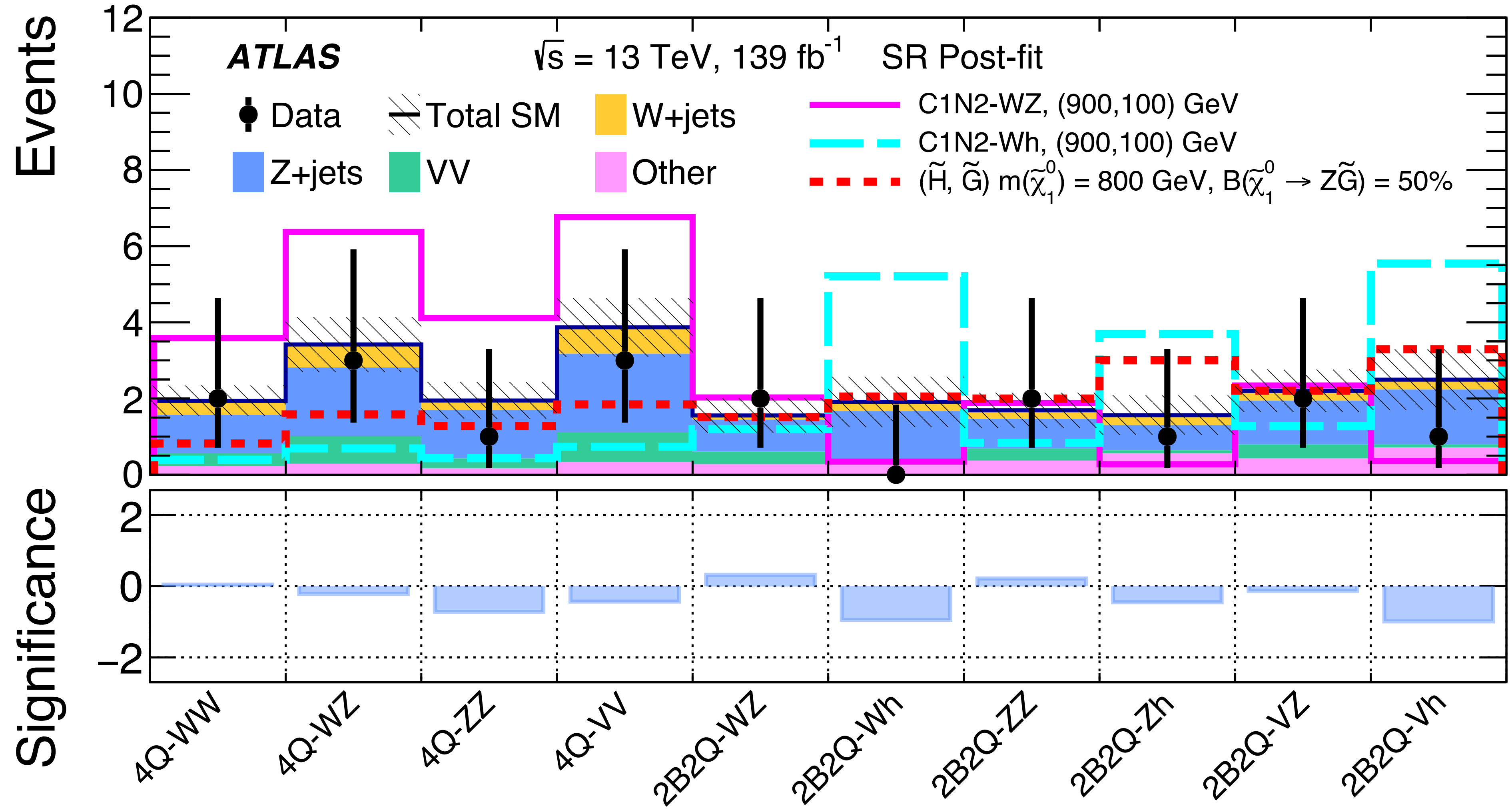
W/Z→qq tagging (see also ATL-PHYS-PUB-2020-017)**:**

- p_T dependent cuts in m_J, D_2 (~two-bodyness), n_{Tracks}

Z/h→bb tagging (see also arXiv 1906.11005)**:**

- Exactly two b-tagged track jets (R=0.05-0.4, p_T dependent) inside the large-R jet radius.
- $m_J \in$ [70,100] GeV ([100, 135] GeV) for Z (h) tagging

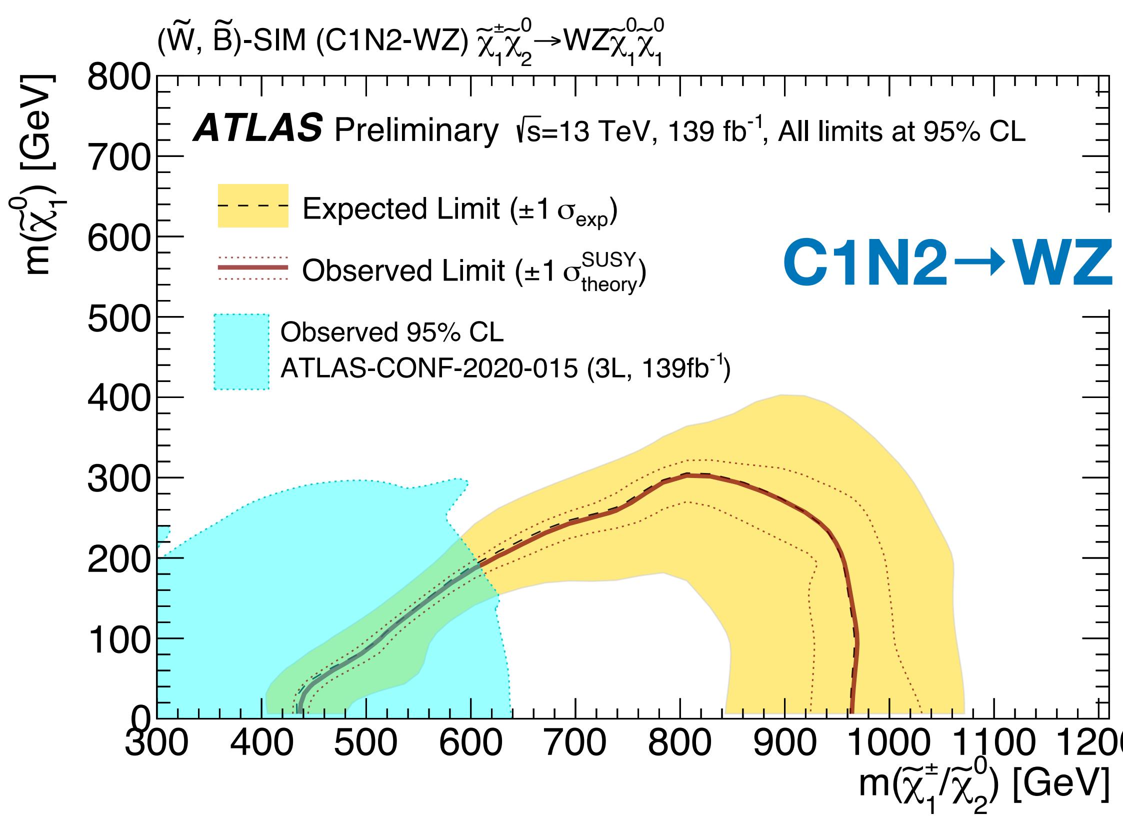
Results - Signal Regions

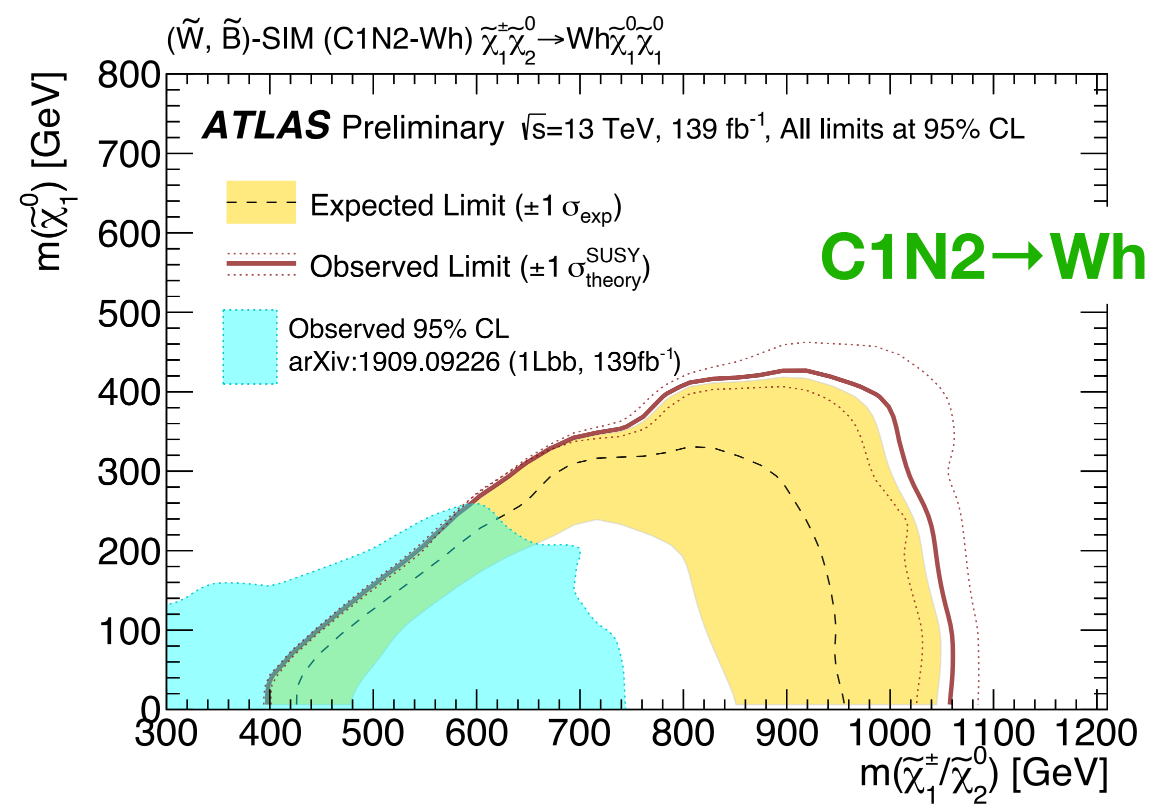


- Main backgrounds: **Z(→νν)+jets**, **W(→ℓν)+jets**, **VV(→ℓνqq)+jets**
- Typical BG yields in the SRs: **a few events**, with 20-30% accuracy for the estimation. Stat. uncertainty dominates (50-100%).
- **No excess beyond the SM.**

Model Interpretation (1) - Wino/Bino simplified models

Model	Production	Final states	SRs simultaneously fitted	Branching ratio
C1C1-WW	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$	WW	4Q-WW	$\mathcal{B}(\tilde{\chi}_1^\pm \to W\tilde{\chi}_1^0) = 1$
C1N2-WZ	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	WZ	4Q-WZ, 2B2Q-WZ	$\mathcal{B}(\tilde{\chi}_1^\pm \to W\tilde{\chi}_1^0) = \mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1$
C1N2-Wh	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	Wh	2B2Q-Wh	$\mathcal{B}(\tilde{\chi}_1^\pm \to W\tilde{\chi}_1^0) = \mathcal{B}(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0) = 1$



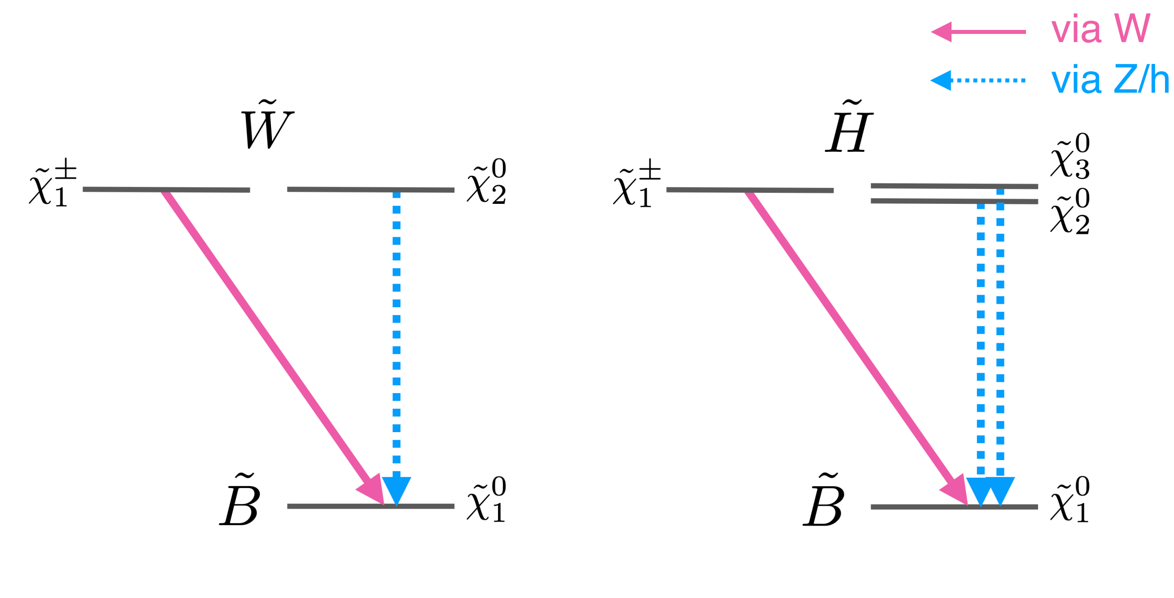


○ **Benchmark models conventionally considered in collider interpretation for decades i.e.**

i.e. bino-like LSP & wino-like degenerate NLSP, single production mode (C1C1 or C1N2), 100% BR.

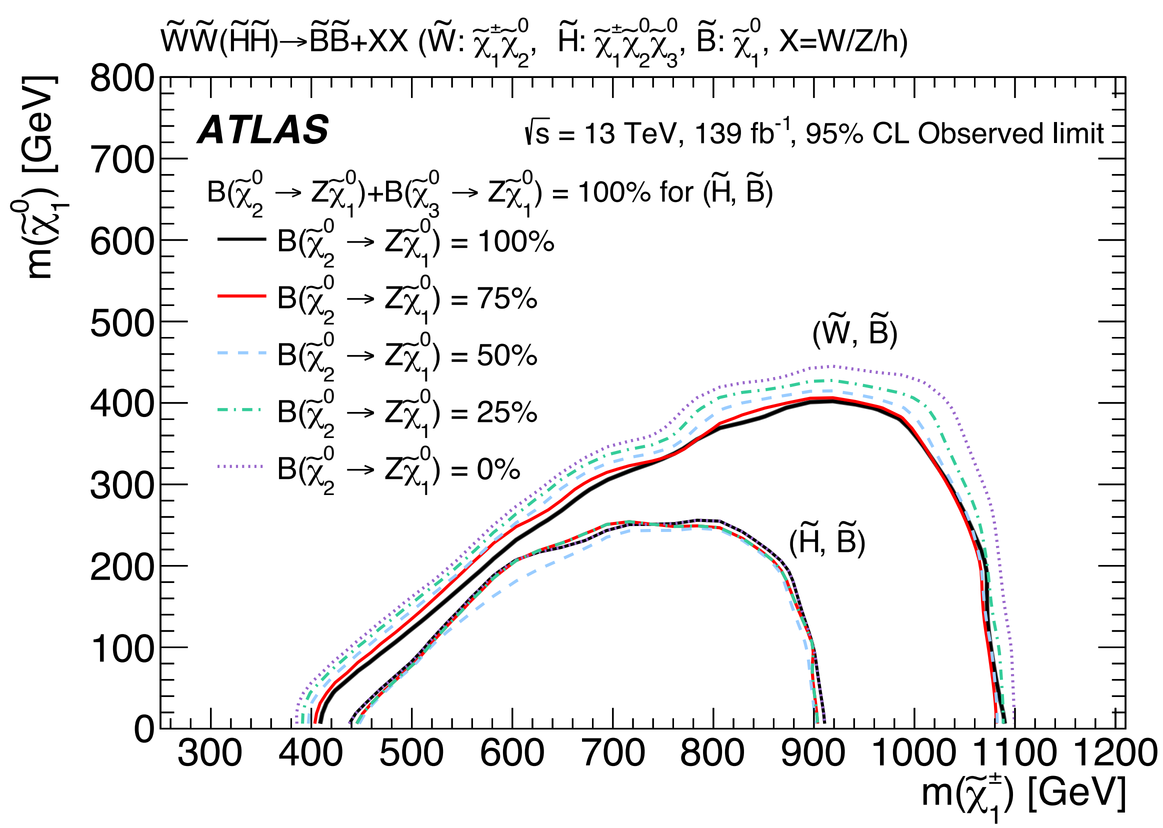
Model Interpretation (2) - 'Realistic' Bino-LSP models

Model	Production	Branching ratio
$(\widetilde{W},\widetilde{B})$	$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$	$\mathcal{B}(\widetilde{\chi}_1^{\pm} \to W\widetilde{\chi}_1^0) = 1$ $\mathcal{B}(\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0)$ scanned
$(\widetilde{H},\widetilde{B})$	$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_3^0$, $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$	$\mathcal{B}(\widetilde{\chi}_1^{\pm} \to W\widetilde{\chi}_1^0) = 1$ $\mathcal{B}(\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0)$ scanned $\mathcal{B}(\widetilde{\chi}_3^0 \to Z\widetilde{\chi}_1^0) = 1 - \mathcal{B}(\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0)$

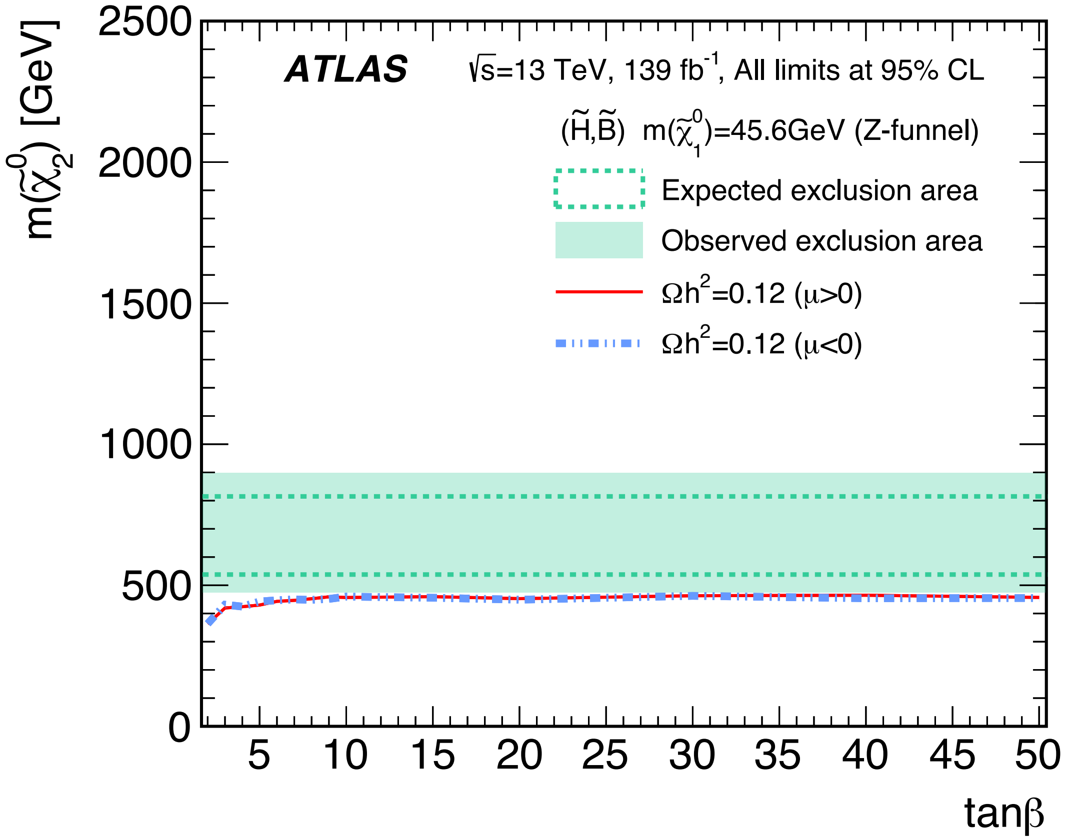


(a) $(\tilde{W}, \tilde{B})$ (b) $(\tilde{H}, \tilde{B})$

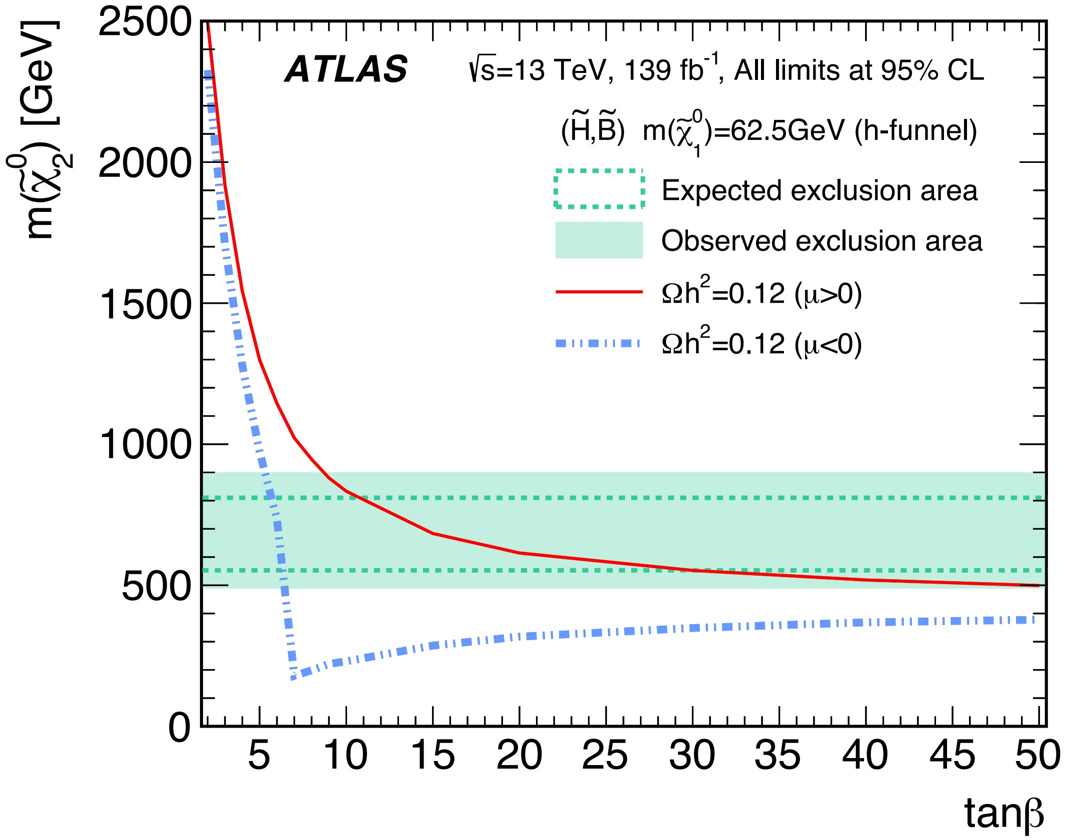
- **Consider all possible production/decay modes at once.** Simultaneously fit multiple SRs to avoid the sensitivity to varying branching ratios.
- **Neutralino (N_2, N_3) branching ratio is scanned** accounting for the significant dependency on the decoupled higgsinos.
  → All yields the same results.
- For $(\tilde{\chi}_{heavy}, \tilde{\chi}_{light}) = (\tilde{H},\tilde{B})$, the limits are also interpreted into the **resonant DM scenario ('funnel').**



Model Interpretation (2) - 'Realistic' Bino-LSP models



(a) $m(\tilde{\chi}_1^0) = m_Z/2$ (Z-funnel)

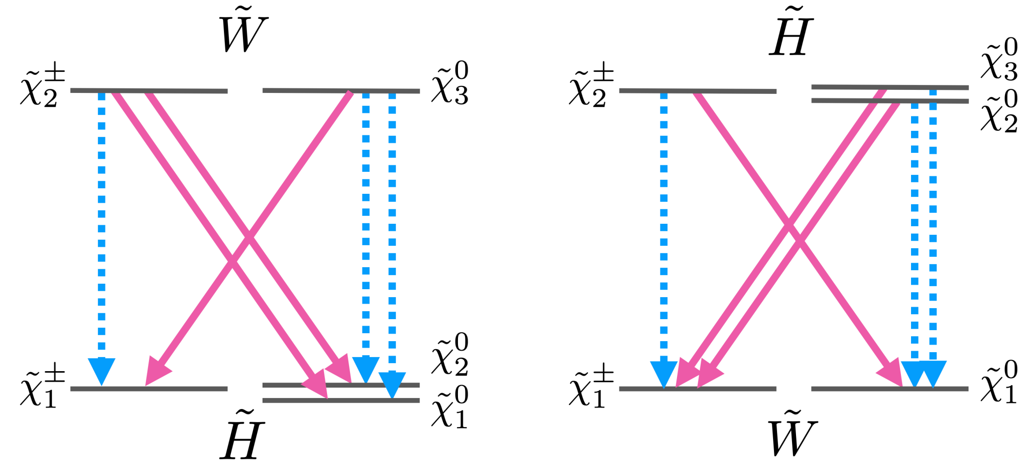


(b) $m(\tilde{\chi}_1^0) = m_h/2$ (h-funnel)

- For ($\tilde{\chi}_{heavy}$, $\tilde{\chi}_{light}$) = ($\tilde{H}$,$\tilde{B}$), the limits are also interpreted into the **resonant DM scenario ('funnel').**
- Strongest limit ever obtained in the collier experiments.

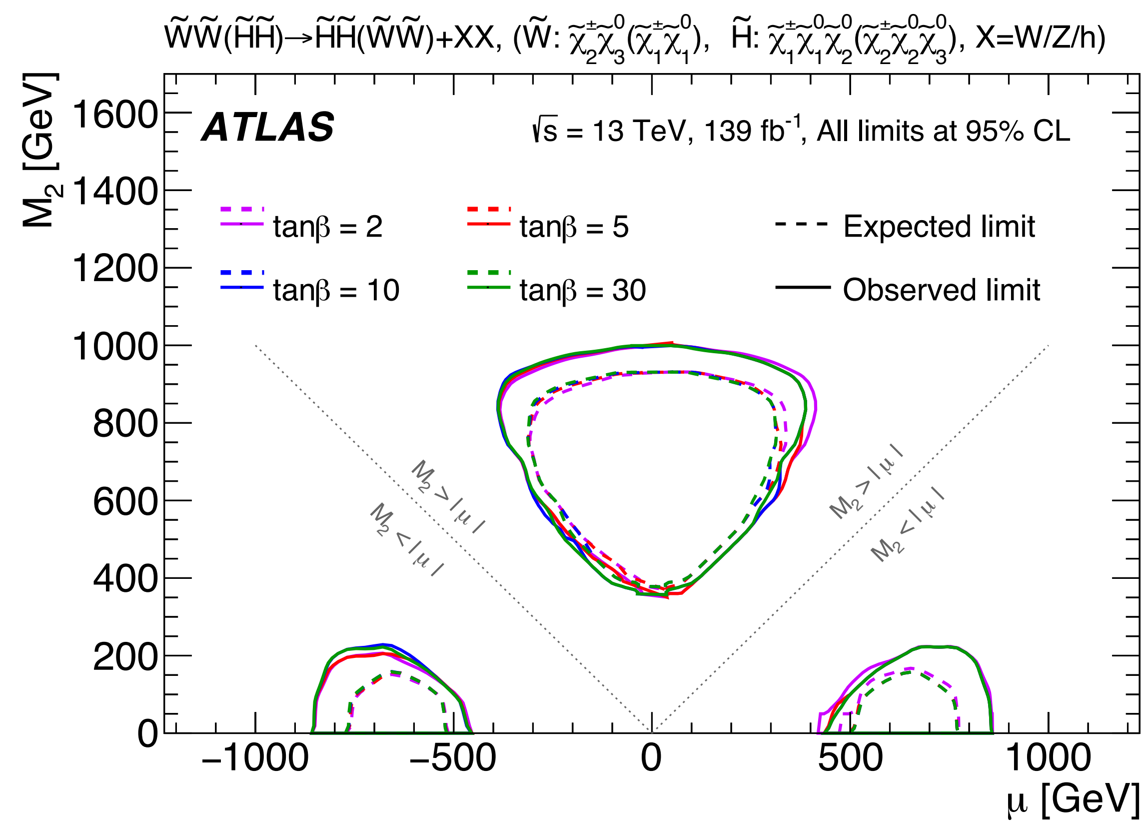
Model Interpretation (3) - ‘Realistic’ Wino/Higgsino-LSP models

Model	Production	Branching ratio
$(\widetilde{W},\widetilde{H})$	$\widetilde{\chi}_2^{\pm}\widetilde{\chi}_2^{\mp}$, $\widetilde{\chi}_2^{\pm}\widetilde{\chi}_3^{0}$	Determined from $(M_2, \mu, \tan\beta)$
$(\widetilde{H},\widetilde{W})$	$\widetilde{\chi}_2^{\pm}\widetilde{\chi}_2^{\mp}$, $\widetilde{\chi}_2^{\pm}\widetilde{\chi}_2^{0}$, $\widetilde{\chi}_2^{\pm}\widetilde{\chi}_3^{0}$, $\widetilde{\chi}_2^{0}\widetilde{\chi}_3^{0}$	Determined from $(M_2, \mu, \tan\beta)$



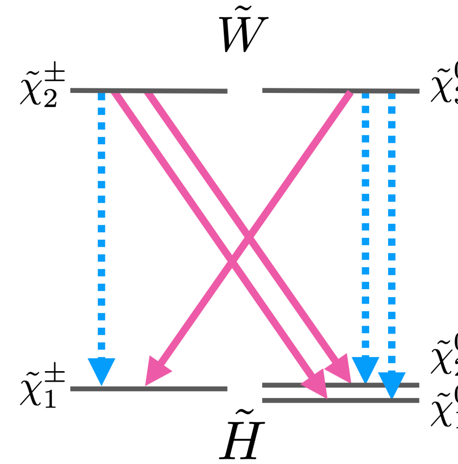
(c) $(\tilde{W},\tilde{H})$ (d) $(\tilde{H},\tilde{W})$

- Again, all production modes with non-100% BRs.
- Wino doublet / higgsino triplet are treated as fully-degenerate. Soft particles from the small splitting are not considered.
- **Start with the (M_2, μ) space for interpretation.**
  i.e. Compute the BRs for each point in (M_2, μ) with
  various tanβ assumption + decoupled scalar SUSYs.

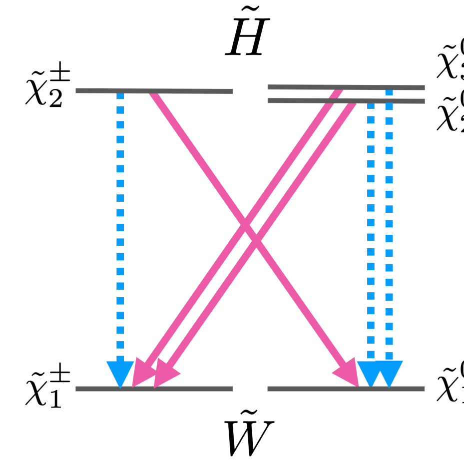


Model Interpretation (3) - ‘Realistic’ Wino/Higgsino-LSP models

Model	Production	Branching ratio
$(\widetilde{W},\widetilde{H})$	$\widetilde{\chi}_2^{\pm}\widetilde{\chi}_2^{\mp}$, $\widetilde{\chi}_2^{\pm}\widetilde{\chi}_3^{0}$	Determined from $(M_2, \mu, \tan\beta)$
$(\widetilde{H},\widetilde{W})$	$\widetilde{\chi}_2^{\pm}\widetilde{\chi}_2^{\mp}$, $\widetilde{\chi}_2^{\pm}\widetilde{\chi}_2^{0}$, $\widetilde{\chi}_2^{\pm}\widetilde{\chi}_3^{0}$, $\widetilde{\chi}_2^{0}\widetilde{\chi}_3^{0}$	Determined from $(M_2, \mu, \tan\beta)$

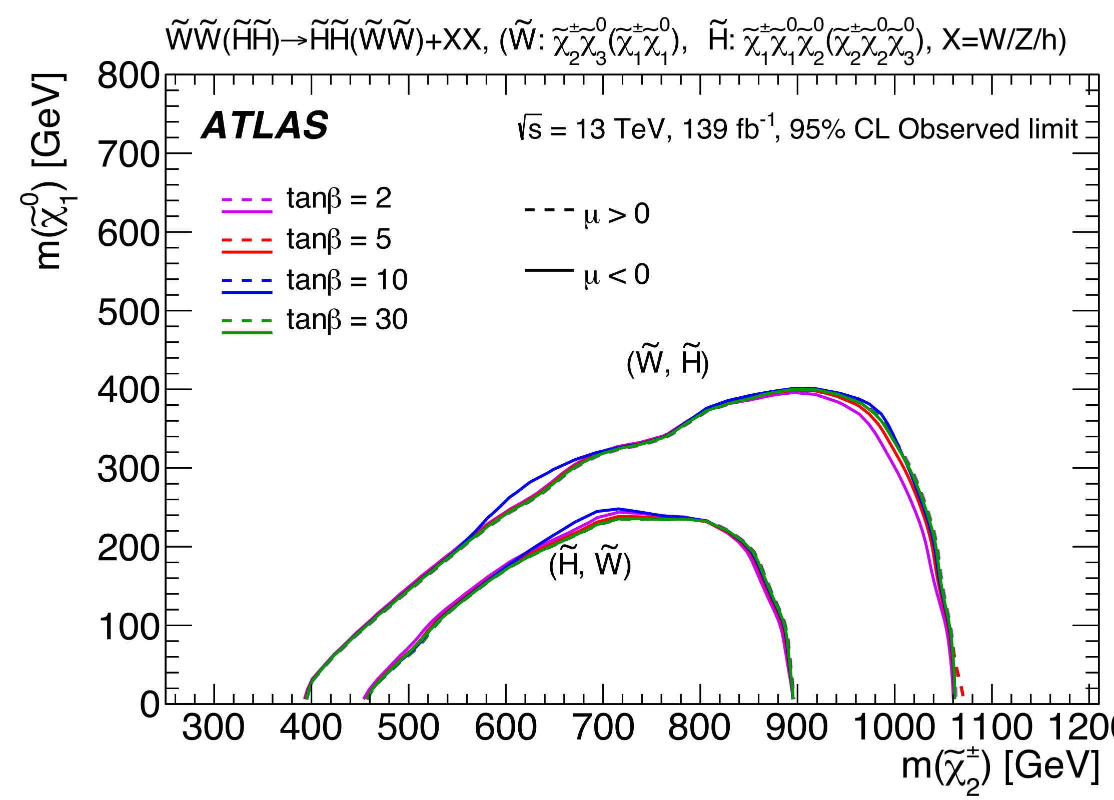


(c) $(\tilde{W}, \tilde{H})$

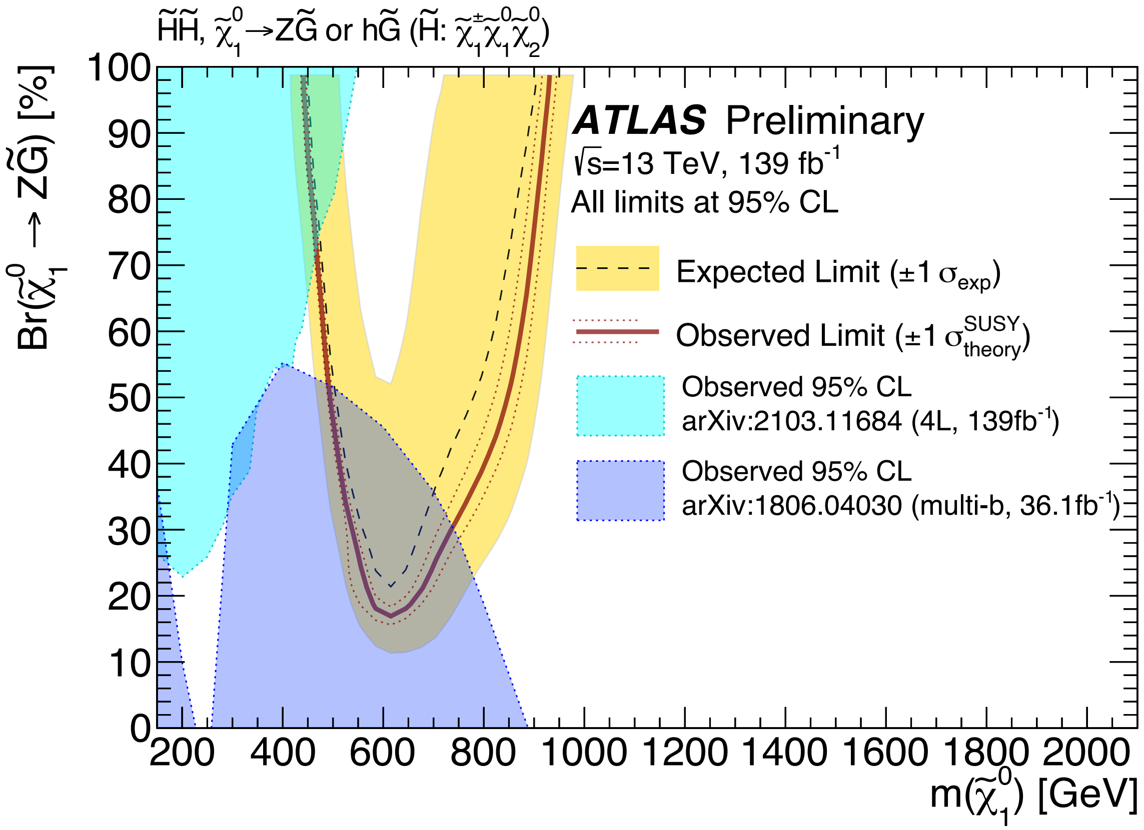


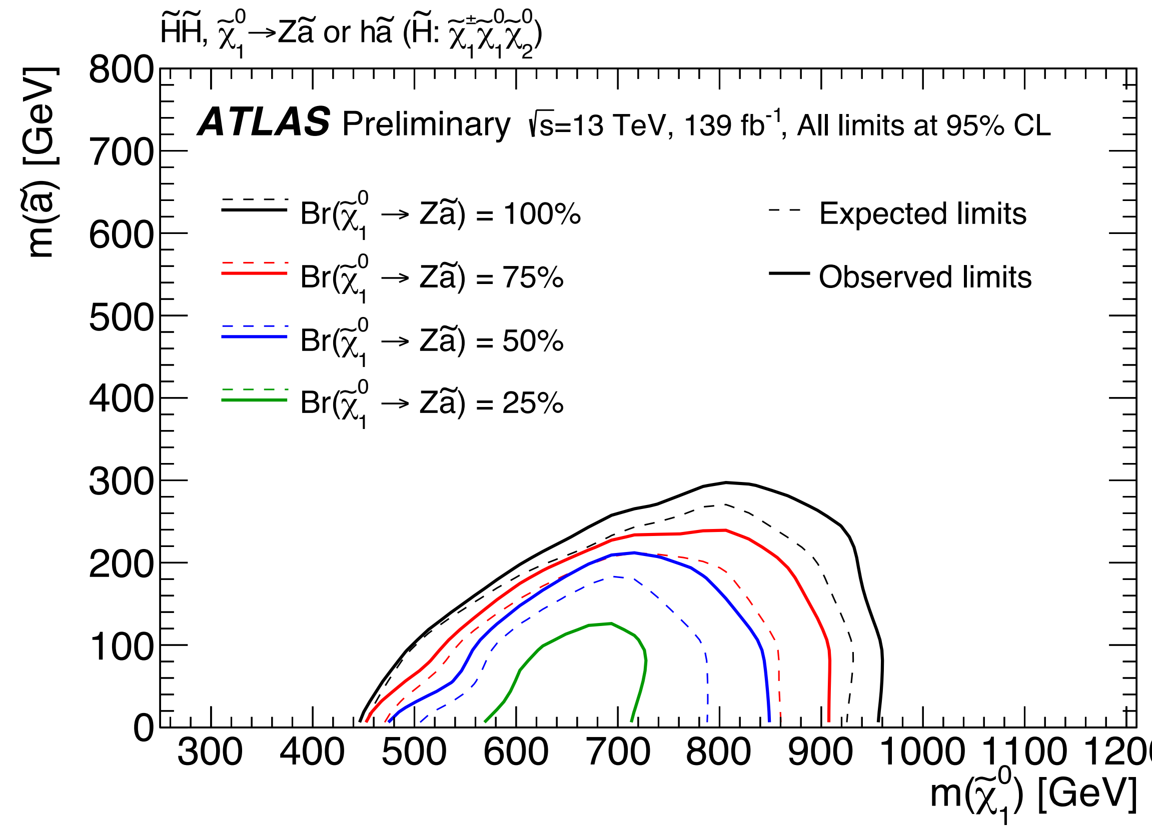
(d) $(\tilde{H}, \tilde{W})$

- Again, all production modes with non-100% BRs.
- Wino doublet / higgsino triplet are treated as fully-degenerate. Soft particles from the small splitting are not considered.
- **Start with the (M_2, μ) space for interpretation.**
  i.e. Compute the BRs for each point in (M_2, μ) with
  various tanβ assumption + decoupled scalar SUSYs.
- **Limits also obtained by transforming (M_2, μ) → (m_{heavy}, m_{light})**
  “Up to 1060GeV is excluded for m_{LSP}<400GeV”

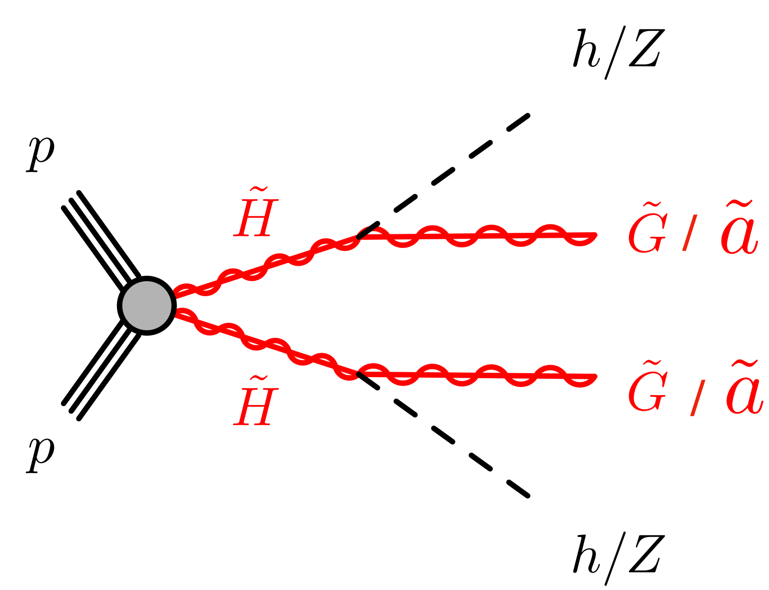


Model Interpretation (4) - Higgsino→gravitino/axino models





- **Sprit of naturalness → light higgsino / QCD axion**
  GGM-like scenarios → massless gravitino LSP
  Axion+SUSY → massless or massive axino LSP
- **Assuming moderate higgsino-gravitino/axino coupling**
  Produced Higgsino decays 100% to the lightest neutral higgsino (N_1) but N_1 still decays promptly.

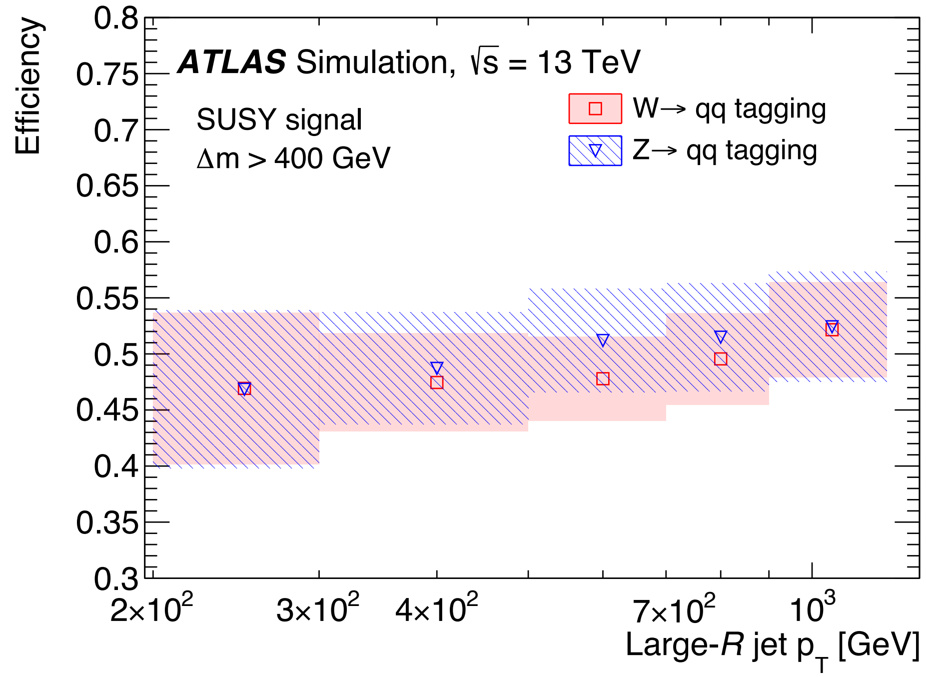


Discussion on published materials

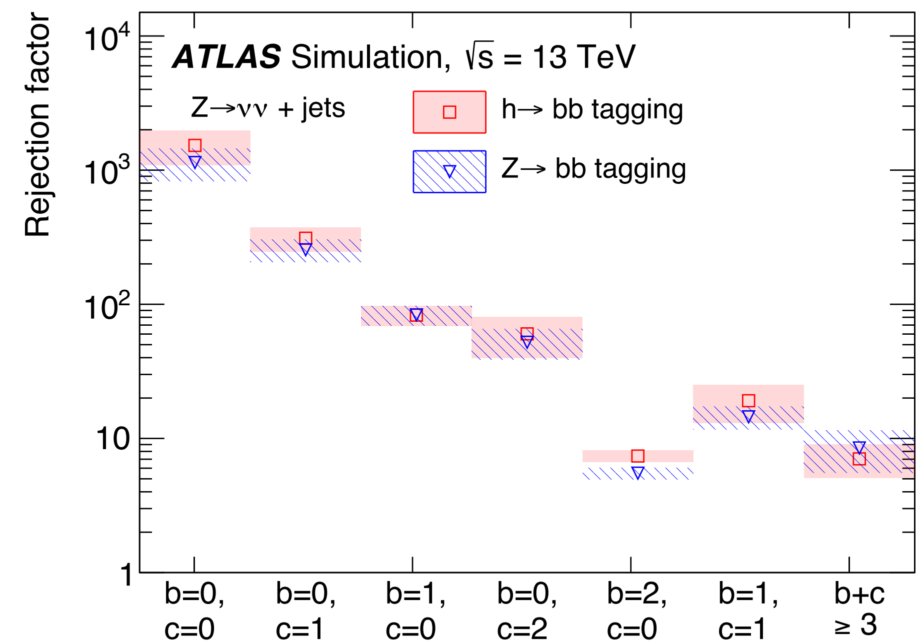
The exhausted list can be found in the backup

Note on the boson tagging efficiency plots

Main Fig 4
Aux. Fig 4



(a) W_{qq}/Z_{qq}-tagging efficiency



(d) Z_{bb}/h_{bb}-tagging rejection

- **m_J>40GeV is always applied for the evaluation**
  - To avoid the QCD modeling uncertainty.
  - The raw BG rejection out of all jets will be much higher (typically ×2-10)
- For signal efficiencies, **ΔR-matching between truth W/Z/h and the jets are also required** for the sample evaluated.
- **BG efficiency generally has significant dependency on the jet components** e.g. single parton jet vs “two-prong” due to gluon splitting.

Model-independent Upper limits

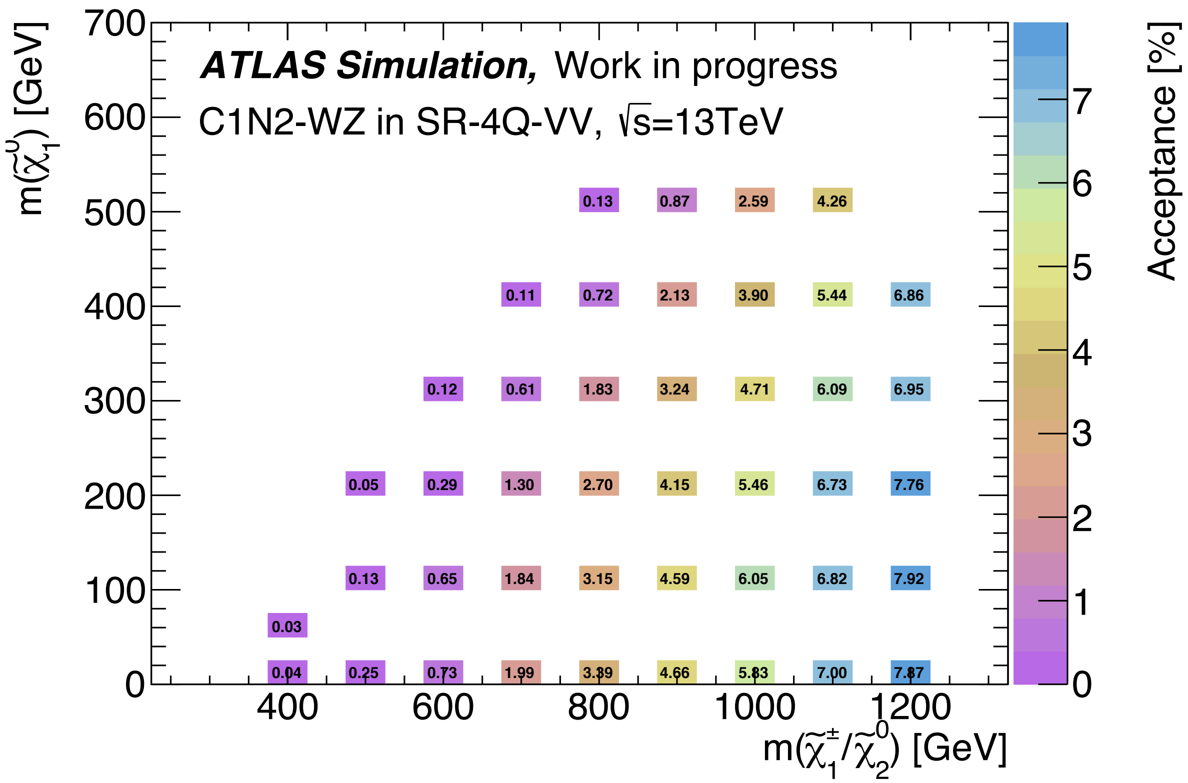
Signal region	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$ [fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$ $(\pm1\sigma)$	$\mathrm{CL_b}$	$p(s=0)$ (Z)
SR-4Q-WW	0.032	4.5	$4.2^{+1.8}_{-1.0}$	0.55	0.44 (0.15)
SR-4Q-WZ	0.036	5.0	$5.1^{+2.1}_{-1.3}$	0.46	-
SR-4Q-ZZ	0.025	3.6	$4.1^{+1.8}_{-1.0}$	0.30	-
SR-4Q-VV	0.034	4.7	$5.3^{+2.3}_{-1.5}$	0.38	-
SR-2B2Q-WZ	0.033	4.7	$4.0^{+1.7}_{-0.7}$	0.66	0.33 (0.44)
SR-2B2Q-Wh	0.022	3.1	$3.9^{+1.3}_{-0.7}$	0.28	-
SR-2B2Q-ZZ	0.033	4.5	$4.1^{+1.7}_{-0.9}$	0.63	0.37 (0.32)
SR-2B2Q-Zh	0.026	3.6	$3.9^{+1.4}_{-0.7}$	0.38	-
SR-2B2Q-VZ	0.032	4.4	$4.4^{+1.8}_{-1.0}$	0.50	-
SR-2B2Q-Vh	0.026	3.6	$4.4^{+1.7}_{-1.0}$	0.24	-
Disc-SR-2B2Q	0.034	4.8	$5.6^{+2.4}_{-1.6}$	0.30	-
Disc-SR-Incl	0.042	5.9	$7.2^{+2.2}_{-2.0}$	0.27	-

- **Two additional "discovery SRs" ORing the nominal SRs**
  - Can give an idea of what if we combine the multiple SRs in case of quick re-interpretation.

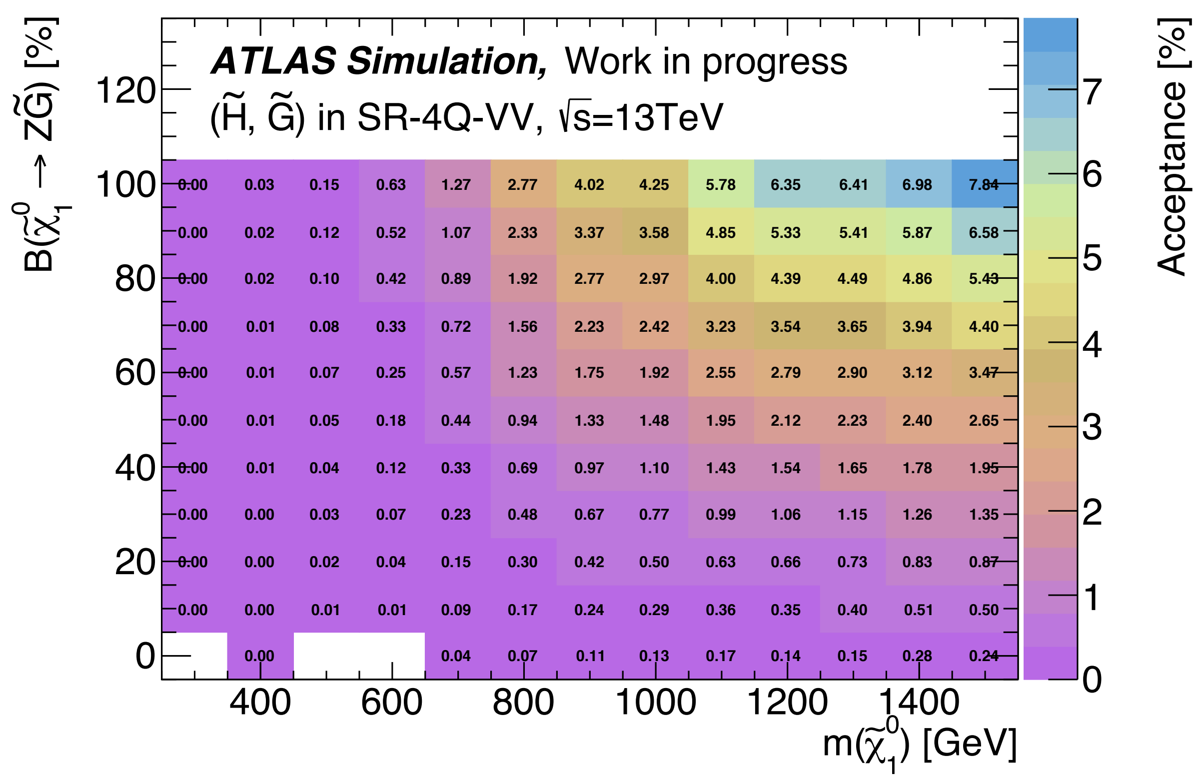
Signal “Acceptance”

Aux. Fig 9-11

Aux. Fig4



(b) C1N2-WZ in SR-4Q-VV

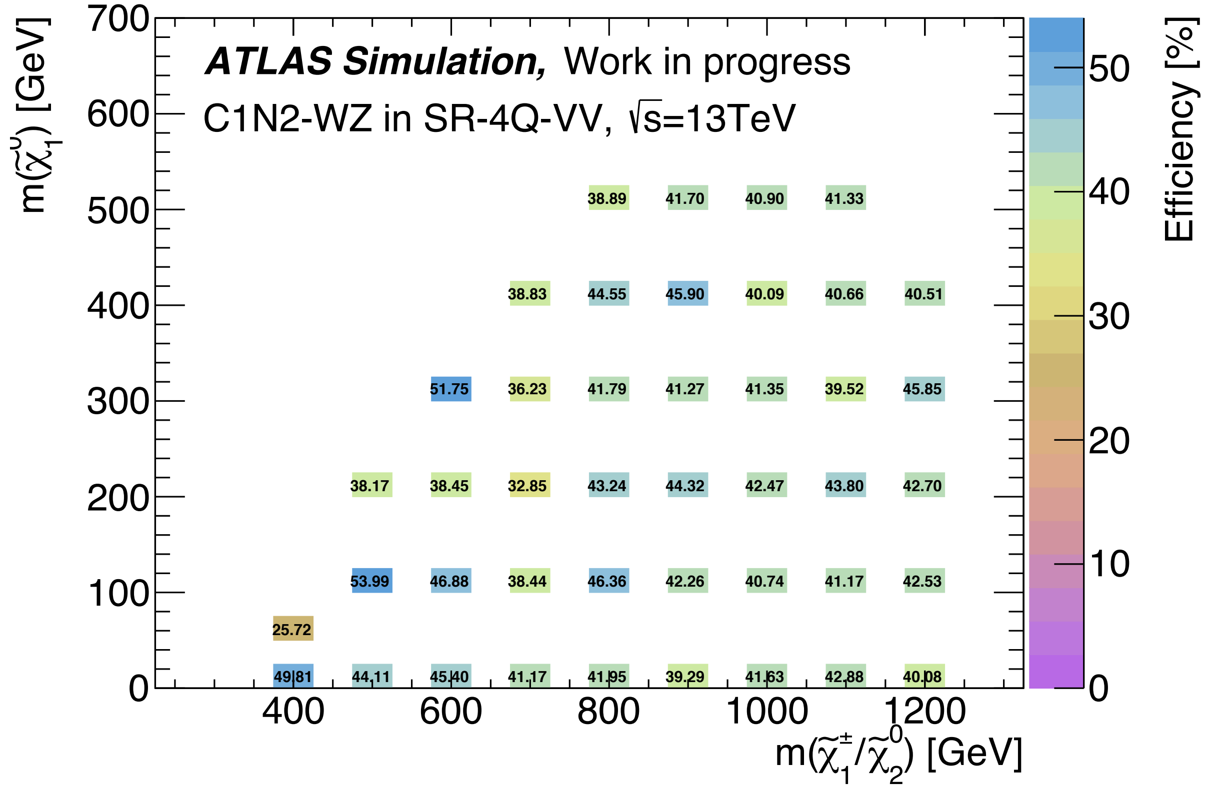


(a) $(\widetilde{H}, \widetilde{G})$ in SR-4Q-VV

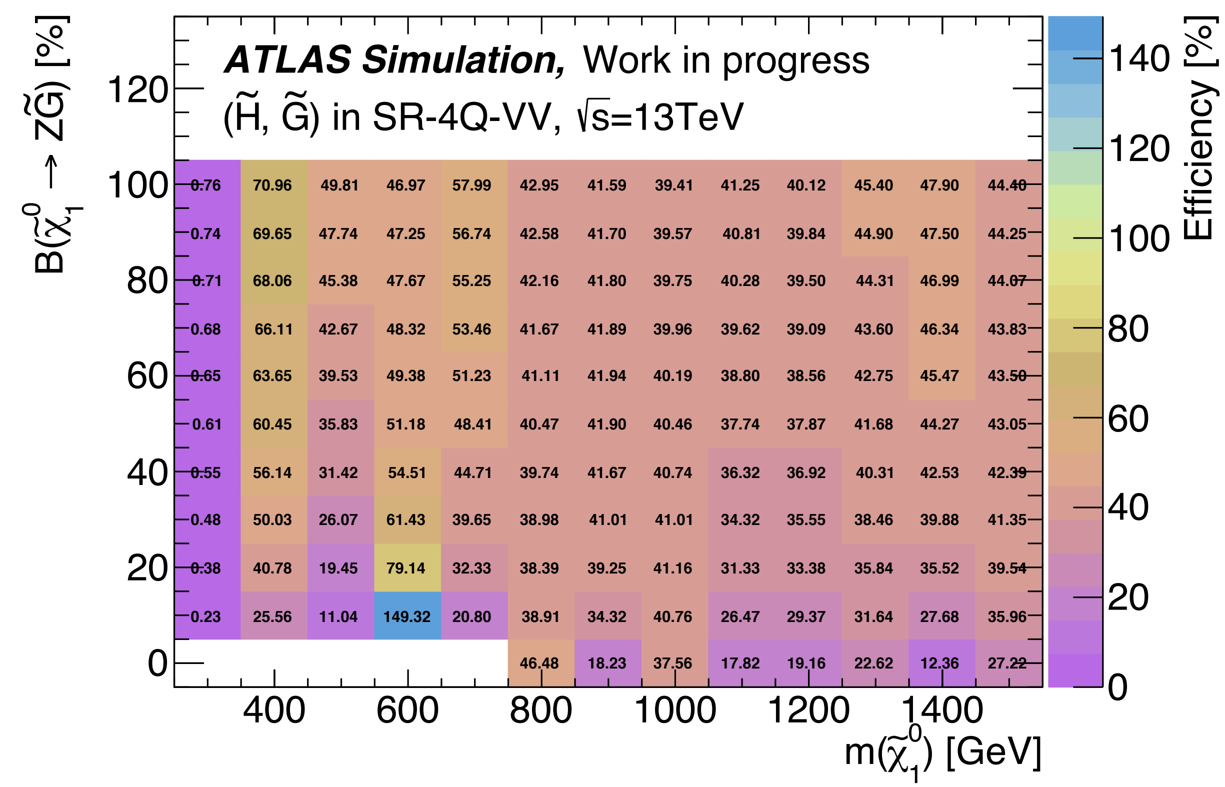
- **Acceptance := (all SR selection except for D2, nTrack cuts in the W/Z→qq tagging) / (all events)**
  - Lepton veto and b-tagging is assumed to be 100% efficient.
  - Reflecting the efficiency of kinematic selections and jet mass cuts in the boson tagging.
  - Branching ratios of W/Z/h are included in the numbers.
- **3 (W~,B~) simplified models + 3 (H~,B~) simplified models + (H~,G~) are considered**

  Only representative SR for each grid is shown.

Signal “Efficiency”



(b) $(\widetilde{W}, \widetilde{B})$ C1N2-WZ in SR-4Q-VV



(a) $(\widetilde{H}, \widetilde{G})$ in SR-4Q-VV

- **Eff := Reco sample yields / truth sample yields**
  - Reflecting eff. of lepton reco/ID, b-tagging, D_2/n_{Track} cuts in the W/Z→qq tagging and the jet mass resolution effect.
  - xsec × Luminosity × Acceptance × Efficiency should agree with the reco sample yield.
  - Very mild dependency across the mass grids.
- **3 (W~,B~) simplified models + 3 (H~,B~) simplified models + (H~,G~) are considered**

  Only representative SR for each grid is shown.

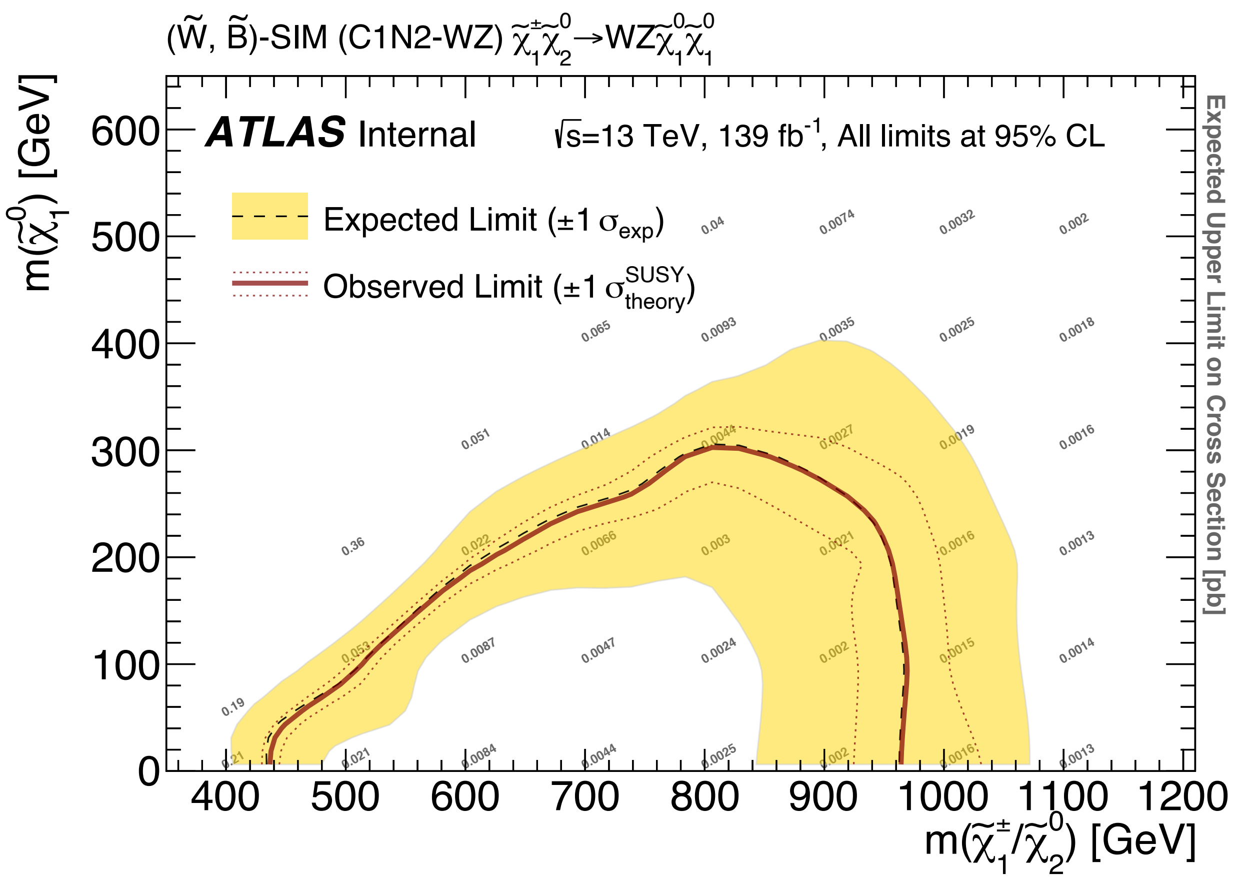
Cut flow

One mass point from the 3 wino/bino simplified models and the (H~,G~) model, up to the respective representative SR

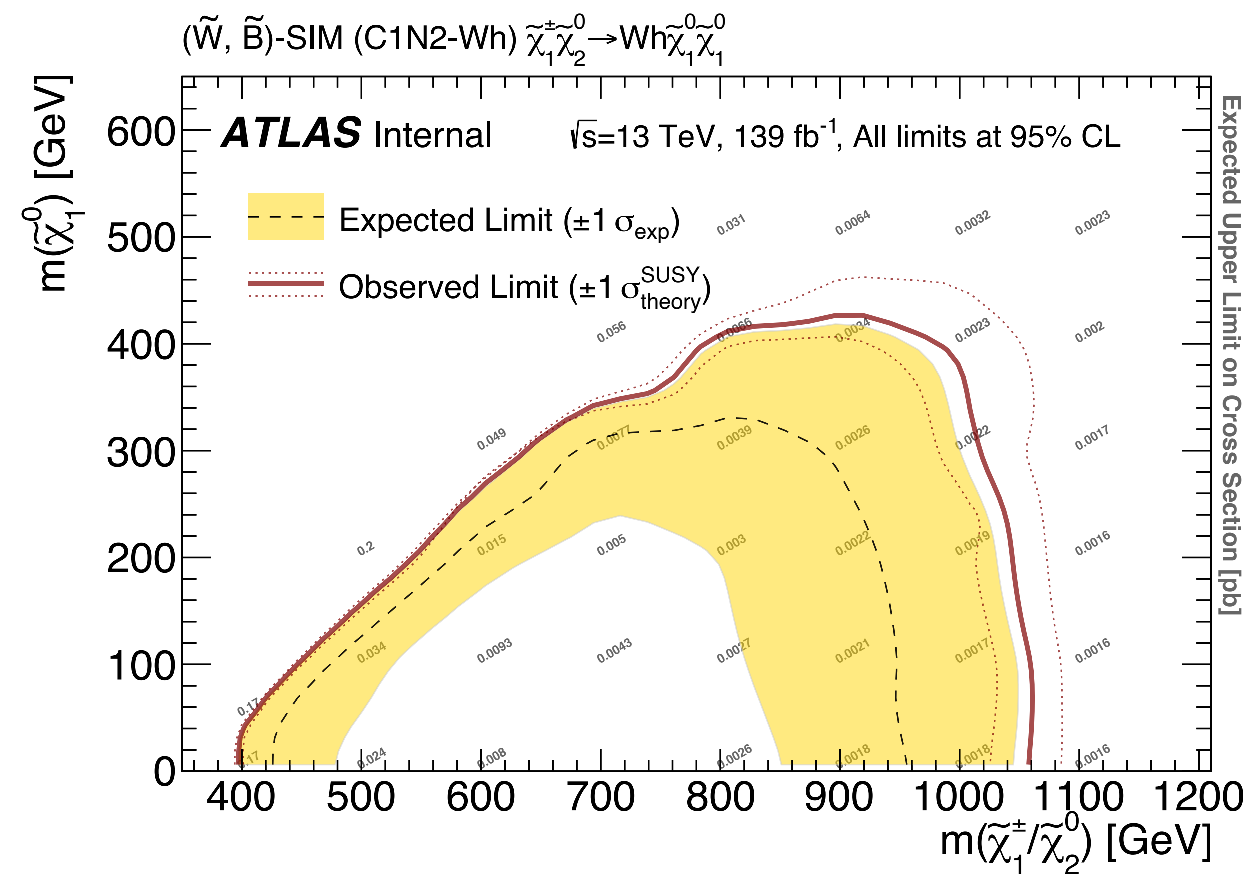
	C1C1-WW $m(\widetilde{\chi}_1^{\pm}/,\widetilde{\chi}_1^0) =$ (700, 100) GeV	C1N2-WZ $m(\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_2^0,\widetilde{\chi}_1^0) =$ (900, 100) GeV	C1N2-Wh $m(\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_2^0,\widetilde{\chi}_1^0) =$ (900, 100) GeV	$(\tilde{H},\tilde{G})$ $m(\widetilde{\chi}_1^0) = 800$ GeV $(\widetilde{\chi}_1^0 \to Z\widetilde{G}) = 50\%$
Initial number of events ($\mathcal{L} \times \sigma$)	619.20	348.29	348.29	482.87
Preliminary event reduction	589.57	330.51	275.97	463.29
Trigger selection and $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV	466.99	287.73	244.06	395.66
Event cleaning	395.78	245.63	207.07	336.46
Lepton veto	241.87	172.60	156.57	259.61
$n_{\mathrm{Large-}R\ \mathrm{jets}} \geq 2$	85.18	68.52	67.95	85.00
$n_{b\mathrm{-jet}}^{\mathrm{unmatched}} = 0$	81.22	64.64	62.74	76.52
$\min \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j) > 1.0$	58.13	44.91	42.83	53.05
SR-4Q-VV				
$n_{b\mathrm{-jet}} \leq 1$	52.01	35.02	19.83	22.99
$E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV	42.78	31.90	17.67	19.99
$m_{\mathrm{eff}} > 1300$ GeV	20.11	23.74	12.66	12.20
$n(V_{qq}) = 2$	6.21	8.00	0.78	2.08
MC-to-data eff. weights	5.28	6.76	0.73	1.85
SR-2B2Q				
$n(J_{bb}) = 1$	2.06	7.65	19.23	26.28
$m_{\mathrm{T2}} > 250$ GeV	1.60	6.60	16.67	21.97
$m_{\mathrm{eff}} > 1000$ GeV	1.57	6.35	16.08	20.47
$n(V_{qq}) = 1$	0.68	3.61	8.80	8.10
SR-2B2Q-VZ				
$m(J_{bb}) \in [70, 100]$ GeV	0.40	2.65	1.40	2.55
MC-to-data eff. weights	0.34	2.34	1.27	2.21
SR-2B2Q-Vh				
$m(J_{bb}) \in [100, 135]$ GeV	0.02	0.39	6.03	3.75
MC-to-data eff. weights	0.02	0.36	5.54	3.29

Table 7: Cut flows of some representative signals up to SR-4Q-VV, SR-2B2Q-VZ, and SR-2B2Q-Vh. One signal point from the $(\widetilde{W},\widetilde{B})$ simplified models (C1C1-WW, C1N2-WZ, and C1N2-Wh) and $(\widetilde{H},\widetilde{G})$ is chosen.

Model-dependent cross-section upper limit



(b) C1N2-WZ

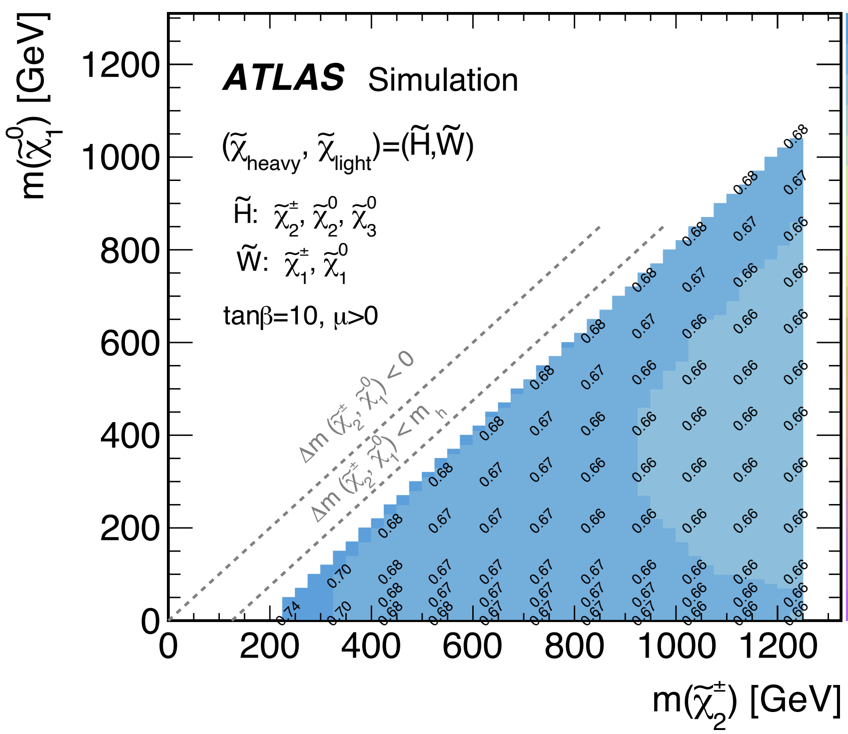


(c) C1N2-Wh

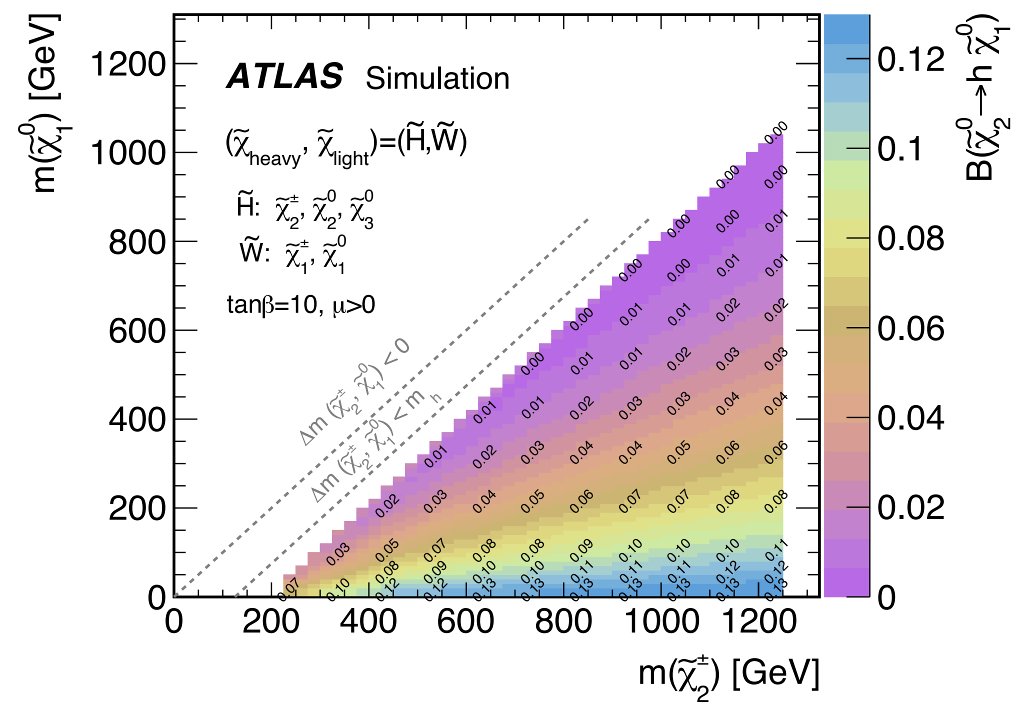
- **Grey numbers: xsec upper limit**
  - Separate plots between the exp. and obs. (limits are the same)
  - Useful to re-derive the limits with different xsec and BR assumptions.
- **3 wino/bino simplified models and the (H~,G~) model are considered**

Example of branching ratios derived from the (M₂, μ) scan

Aux. Fig 4-5



(d) $\mathcal{B}(\tilde{\chi}^0_2 \rightarrow W^{\pm}\tilde{\chi}^{\mp}_1)$

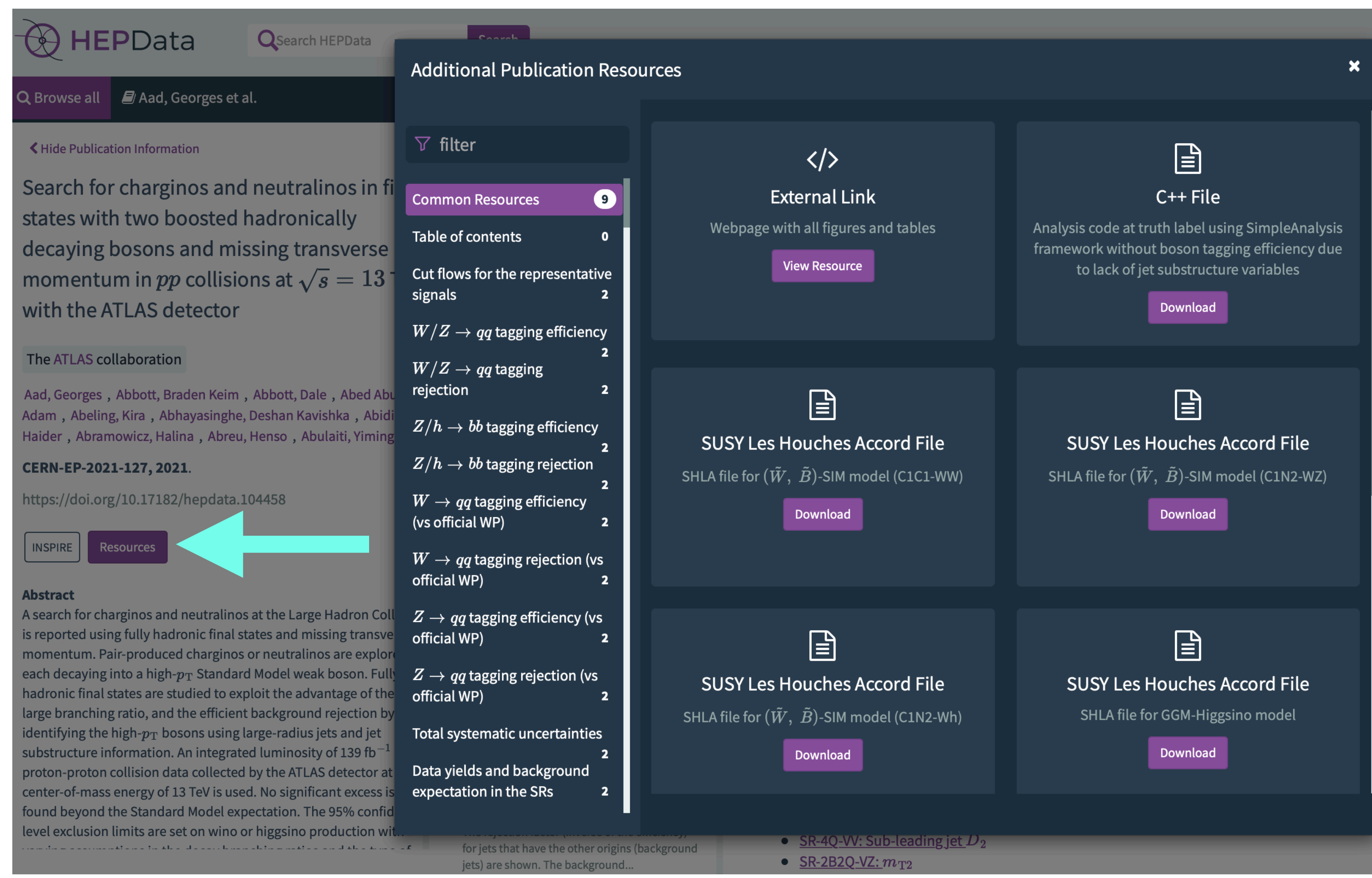


(f) $\mathcal{B}(\tilde{\chi}^0_2 \rightarrow h\tilde{\chi}^0_1)$

- **$\tilde{\chi}_{heavy}$ branching ratio into W, Z or h vs masses.**
  Used for evaluate the limits on the (W~,H~) and (H~,W~) model
- The case tanβ=10 is shown.
- Generally modes with large BR have very mild dependency over the mass and tanβ.
  Some minor modes have drastic dependency.

Materials available in HEP Data

- All the main/aux figures and tables for the paper.
- **Code snipet to illustrate the selection**
  that runs on the SimpleAnalysis framework.
- **SLHA config files**
  For the representative mass point for the 3 wino/bino simplified models and the (H~,G~) model.
- **Full likelihoods (to come soon)**
  Signal/BG yields in all the SRs with all the systematic variations.
  JSON format that runs on pyhf.



Aux materials

Models	Acceptance/Efficiency	σ upper limit	Full likelihood
($\tilde{W}$,$\tilde{B}$) B(N2→ZN1)=50%			✓
($\tilde{H}$,$\tilde{B}$) B(N2→ZN1)=50%			✓
($\tilde{W}$,$\tilde{H}$) tanβ=10, μ>0			✓
($\tilde{H}$,$\tilde{W}$) tanβ=10, μ>0			✓
($\tilde{H}$,$\tilde{G}$)	✓	✓	✓
($\tilde{H}$,$\tilde{a}$) B(N1→Z$\tilde{a}$)=100%			✓
Wino/Bino simplified models			
C1C1-WW	✓	✓	✓
C1N2-WZ	✓	✓	✓
C1N2-Wh	✓	✓	✓

Potential Ideas of Re-interpretation

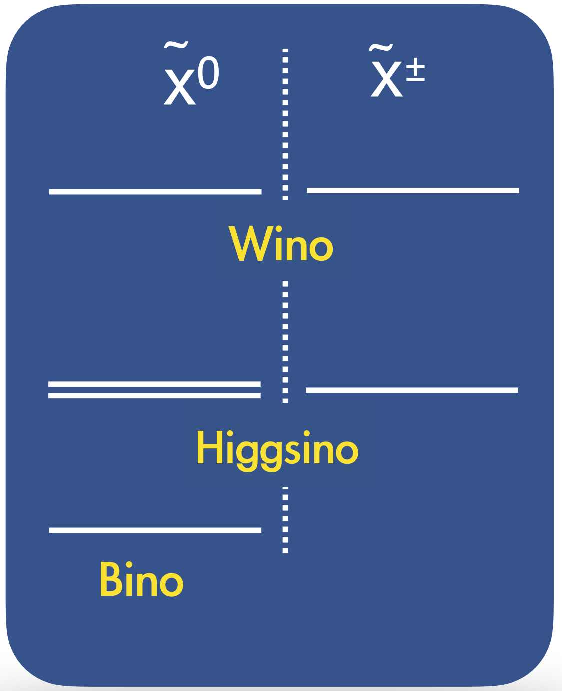
- **Models involving more (moderately) light SUSY particles**
  - Something in between the considered the EWKinos

    e.g. 3rd EWKino

    Sleptons (motivated by muon g-2)

    → Smaller expected signals due to the possible 1-step decays.
  - Case with moderately decoupled squarks

    → Smaller prod. xsec due to the negative interference.
- **Non-prompt higgsino decays for (H~,G~) and (H~,a~) models**

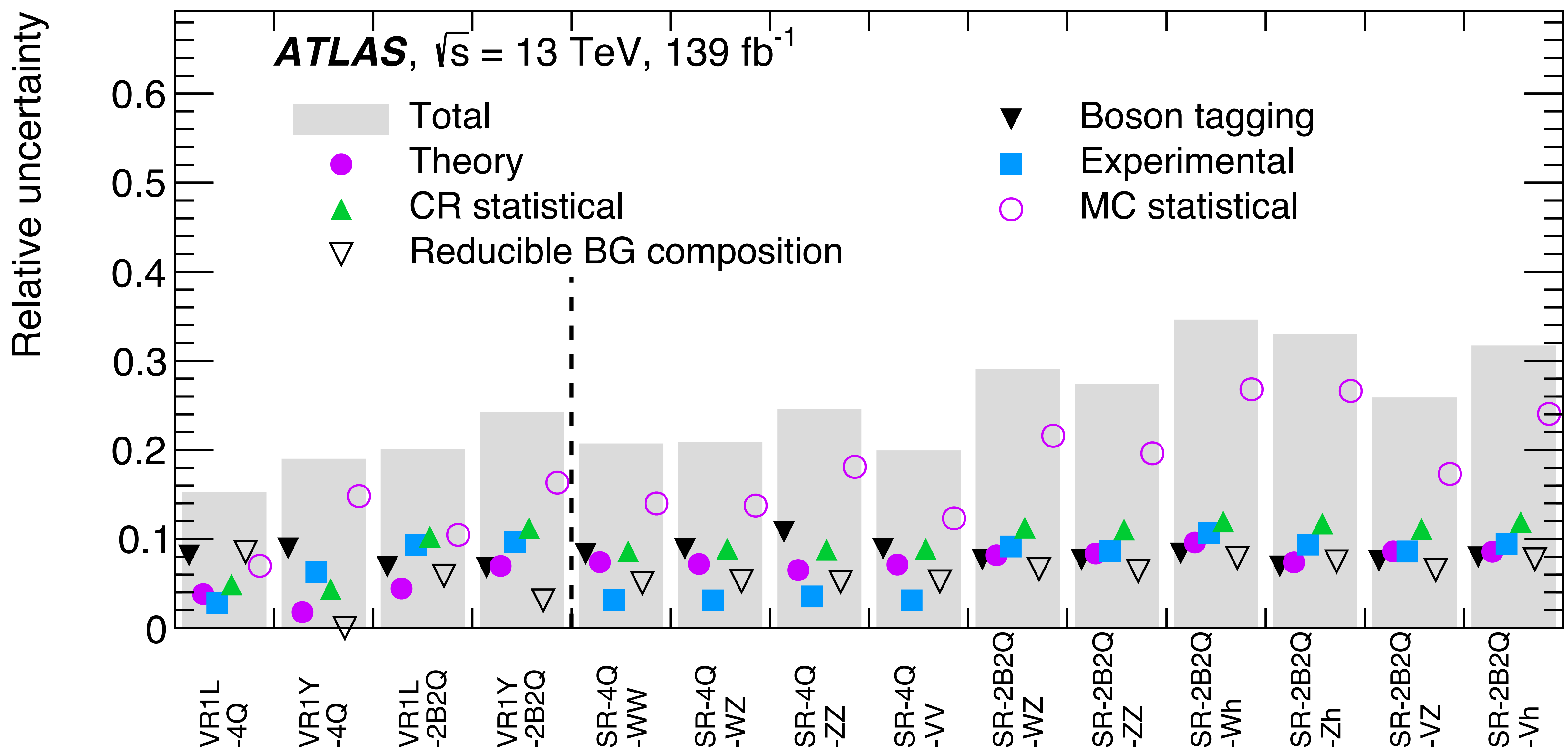


Both can be easily done by scaling down the expected SR yields in the JSON workspace and re-fit using the pyhf.

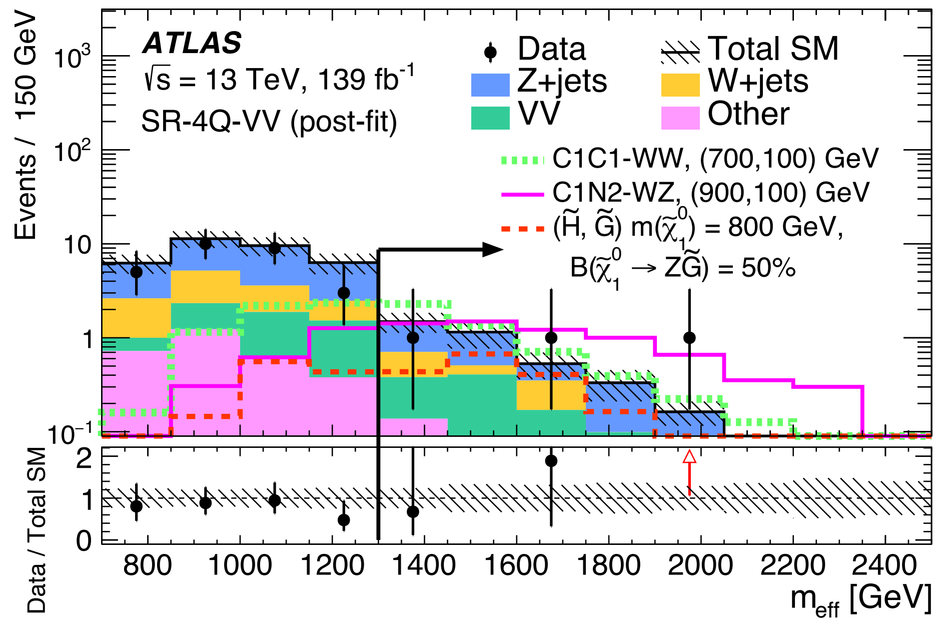

Backup

Summary of Systematics

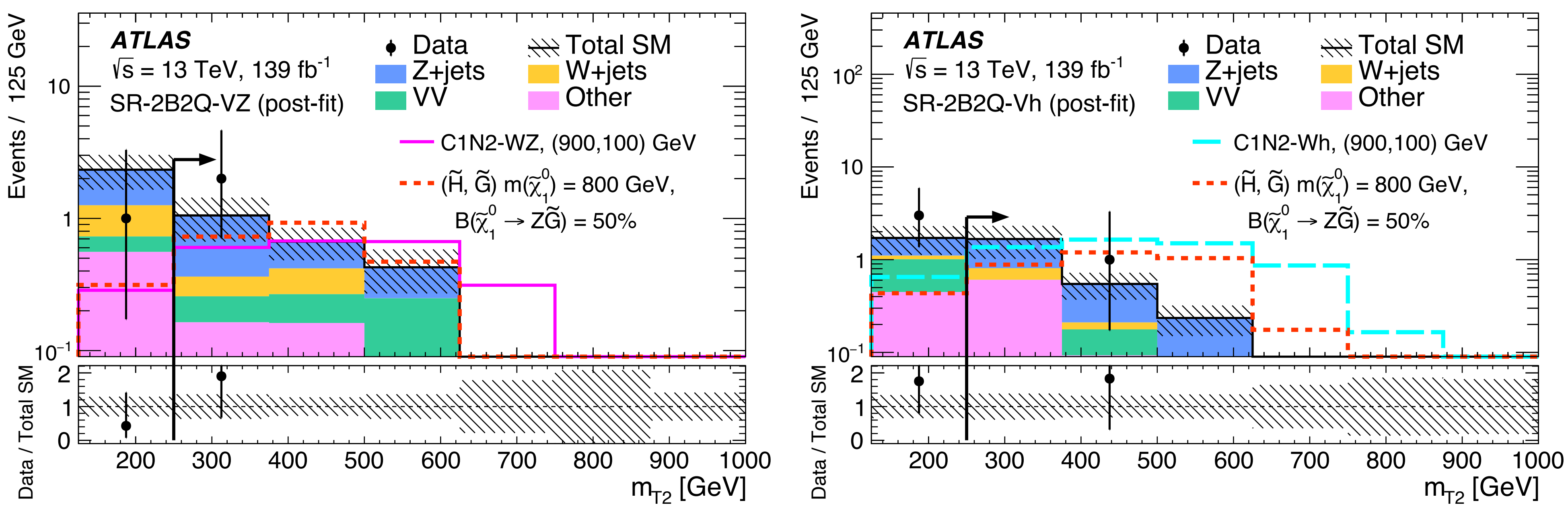
Main Fig 9



SR “N-1” plots



(a) SR-4Q-VV

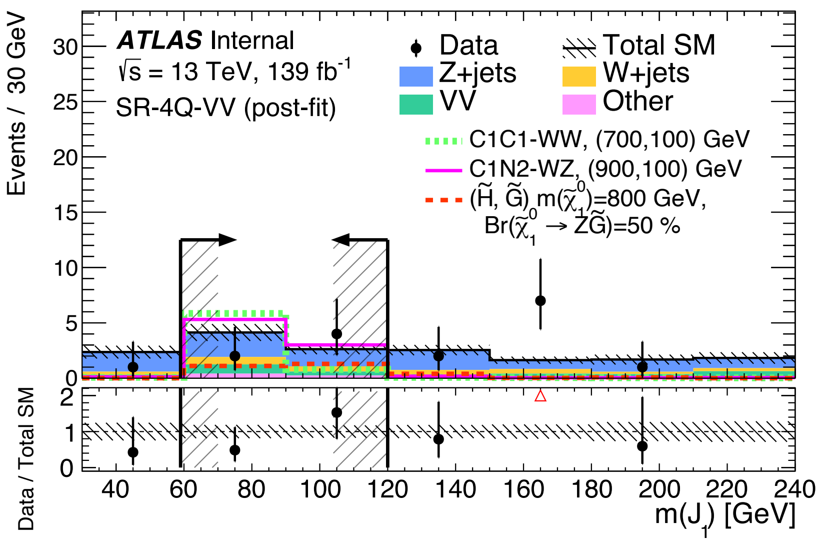


(b) SR-2B2Q-VZ

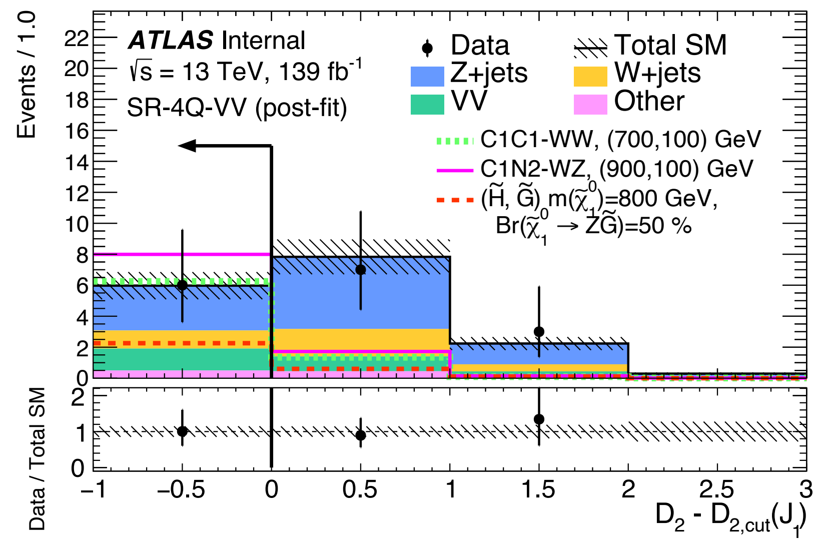
(c) SR-2B2Q-Vh

Additional SR "N-1" plots

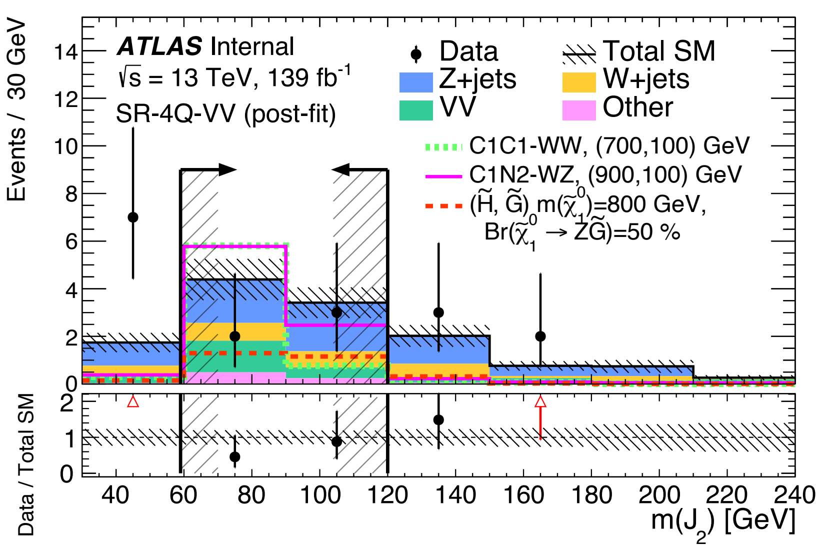
Aux. Fig 2-3



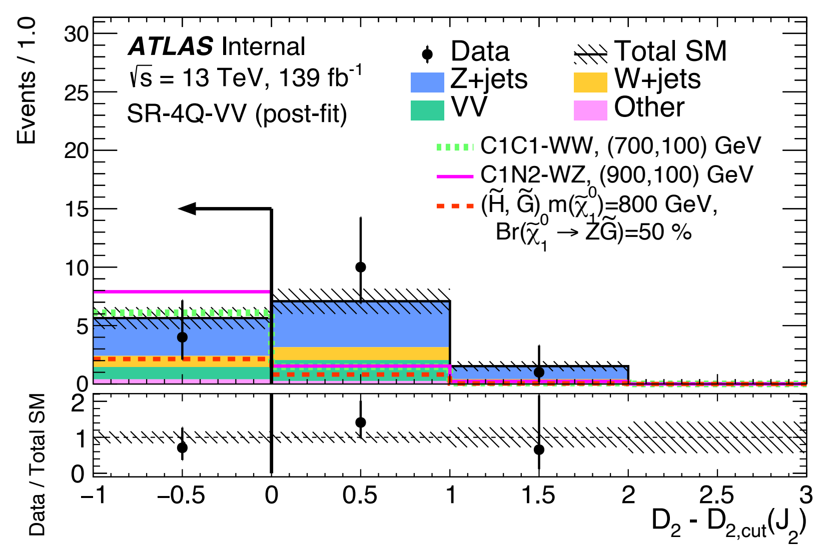
(a) $m(J_1)$



(b) $D_2 - D_{2,\mathrm{cut}}(J_1)$



(c) $m(J_2)$



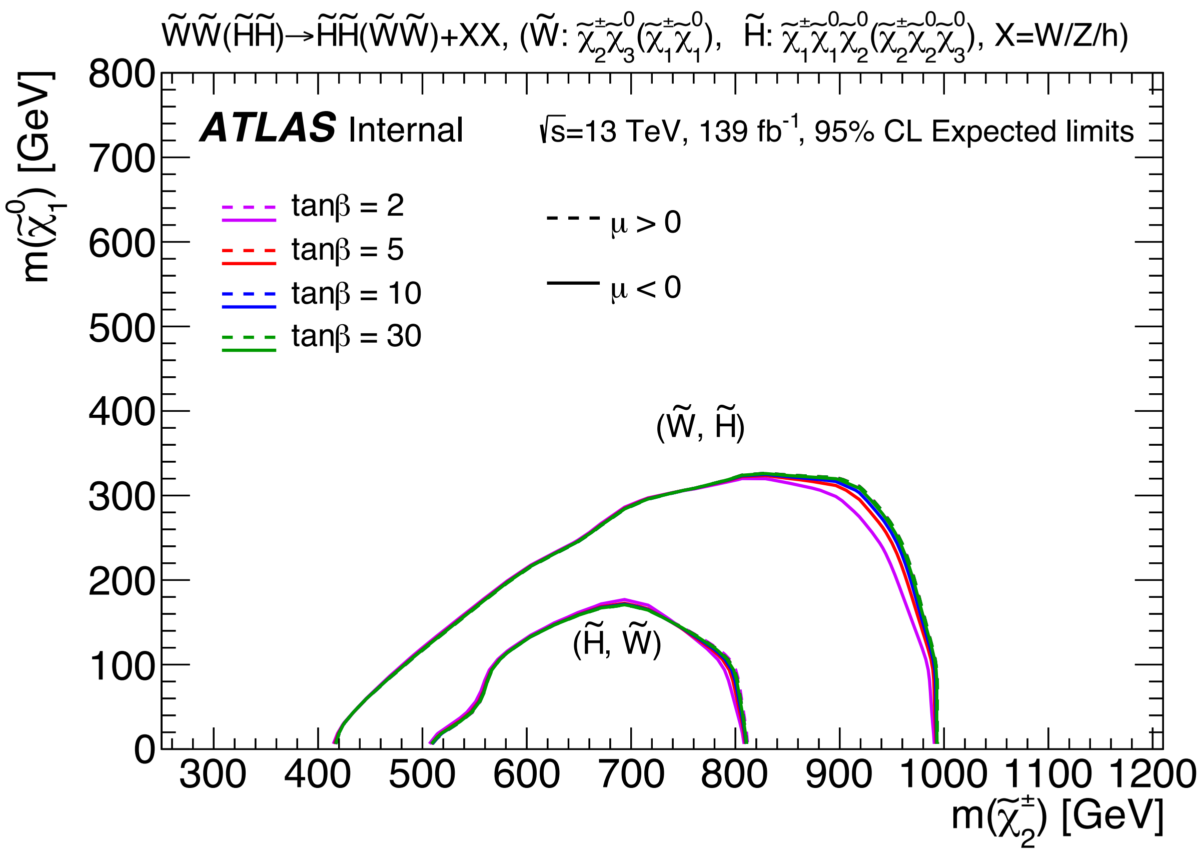
(d) $D_2 - D_{2,\mathrm{cut}}(J_2)$

Jet mass/D2 cuts are not a fixed values but variable vs pT

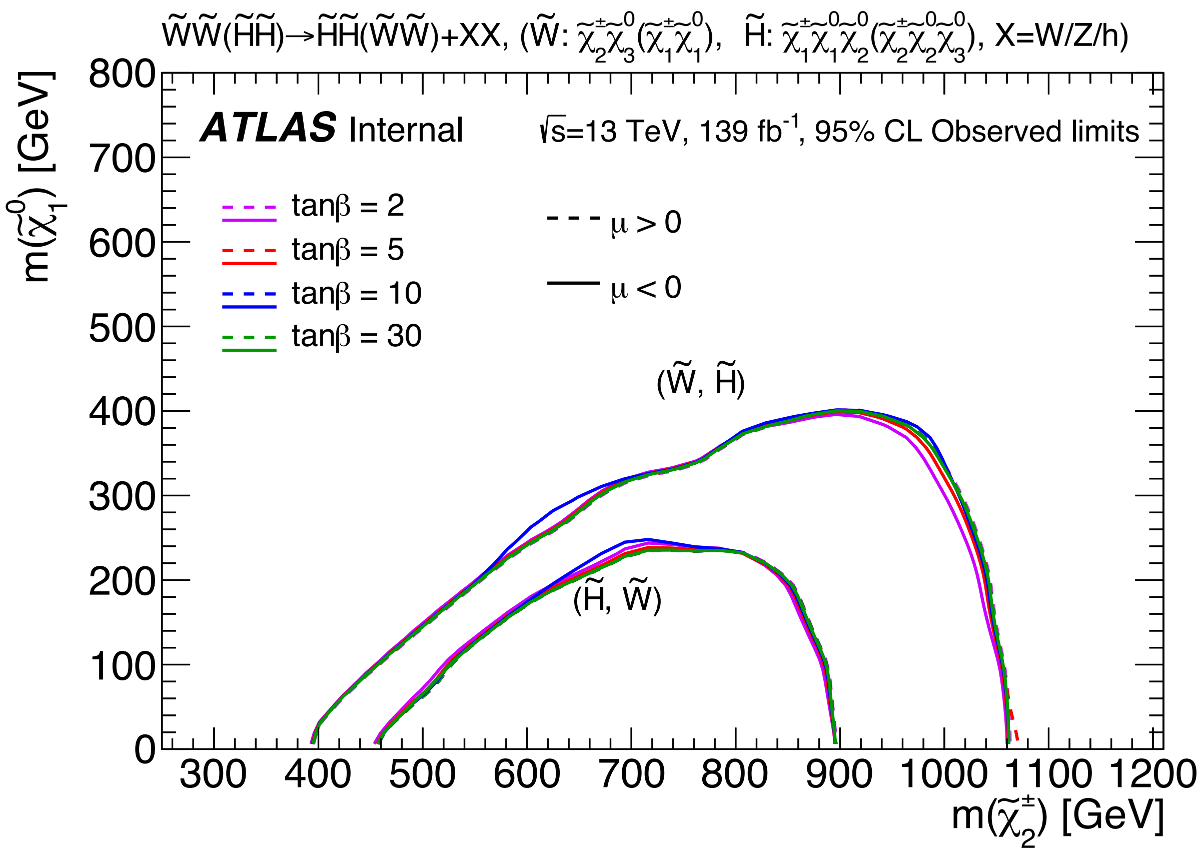
→ Ranges expressed by the vertical hash bands

Summary plots for the (W~,H~) & (H~,W~) models in the physical mass plane

Aux. Fig 6



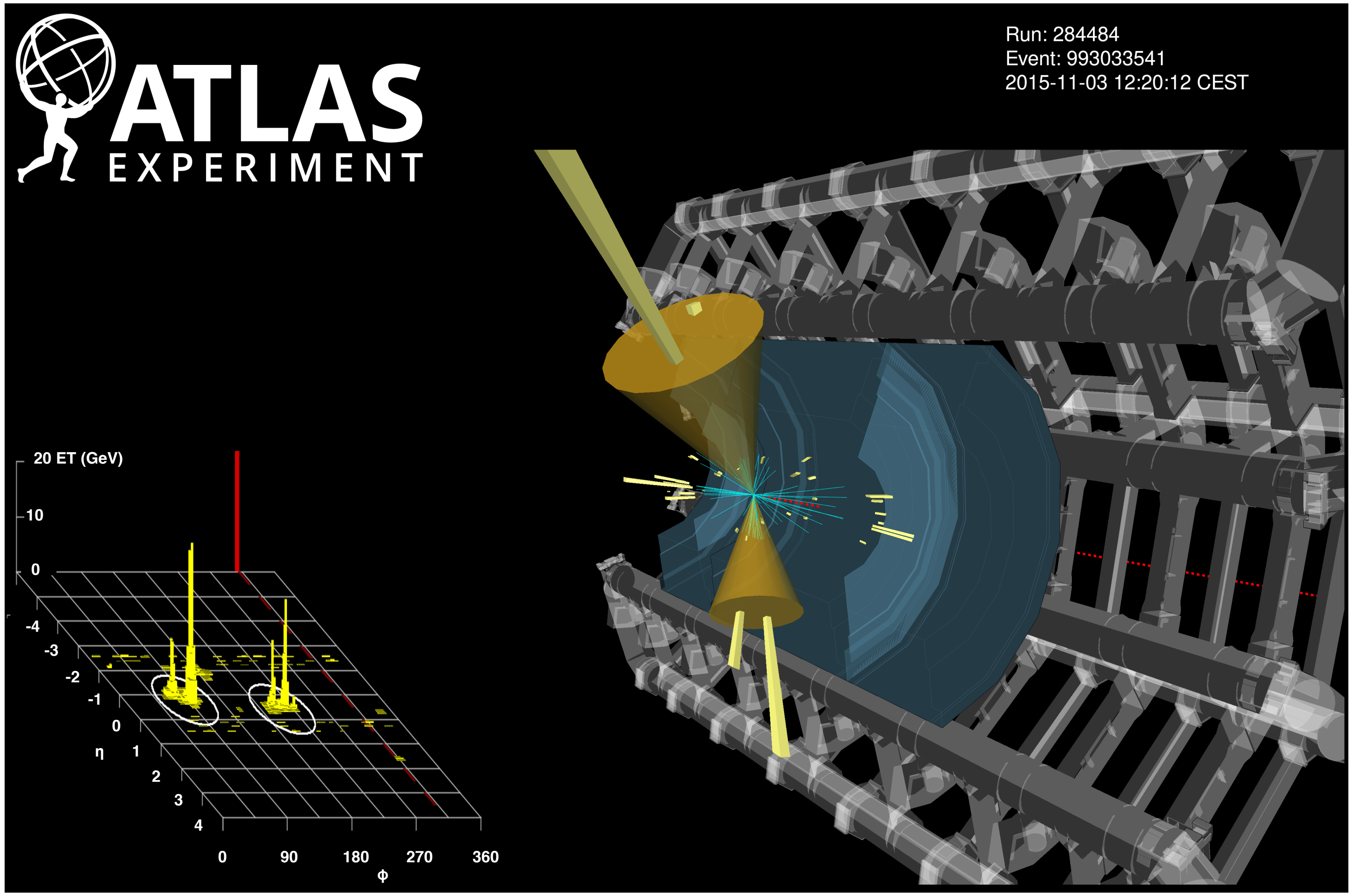
(a) Expected limits



(b) Observed limits

- Main body: Limits as function of (M_2, μ)
- One for the exp., the other for the obs.

Event displays for a few SR events



- **Main display (right):**

  Calo cluster (yellow squares), E_T^{miss} (red), large-R jets (yellow cones), tracks (blue strings)

- **Energy profile (left bottom):**

  Write circles: large-R jets