Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum with the ATLAS experiment

arXiv:2108.07586
public page

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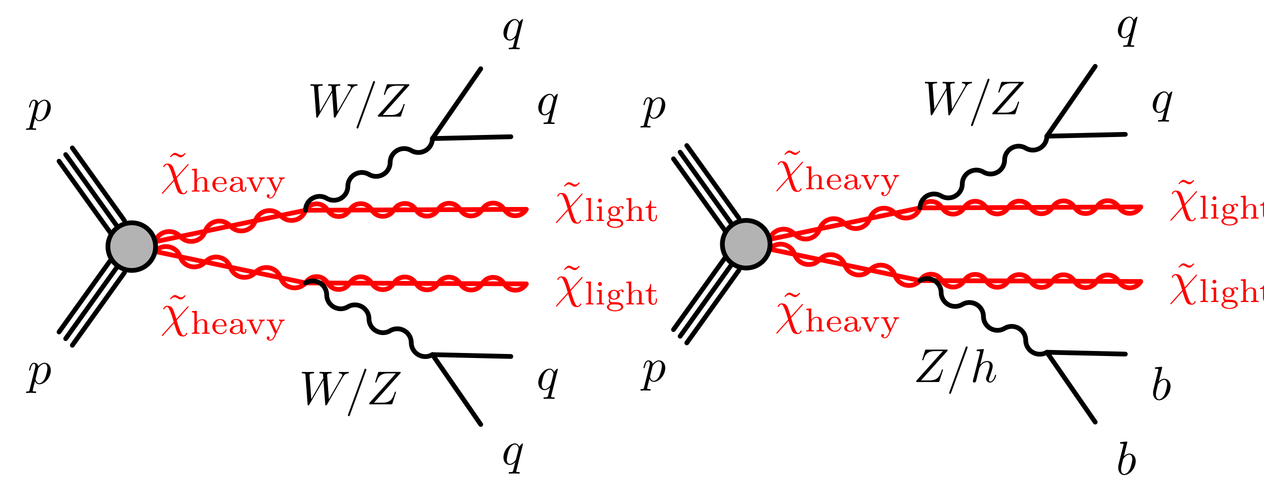
on behalf of the ATLAS collaboration

24 August 2021
The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Introduction

- **Target : EWKinos with Δm > 400GeV**

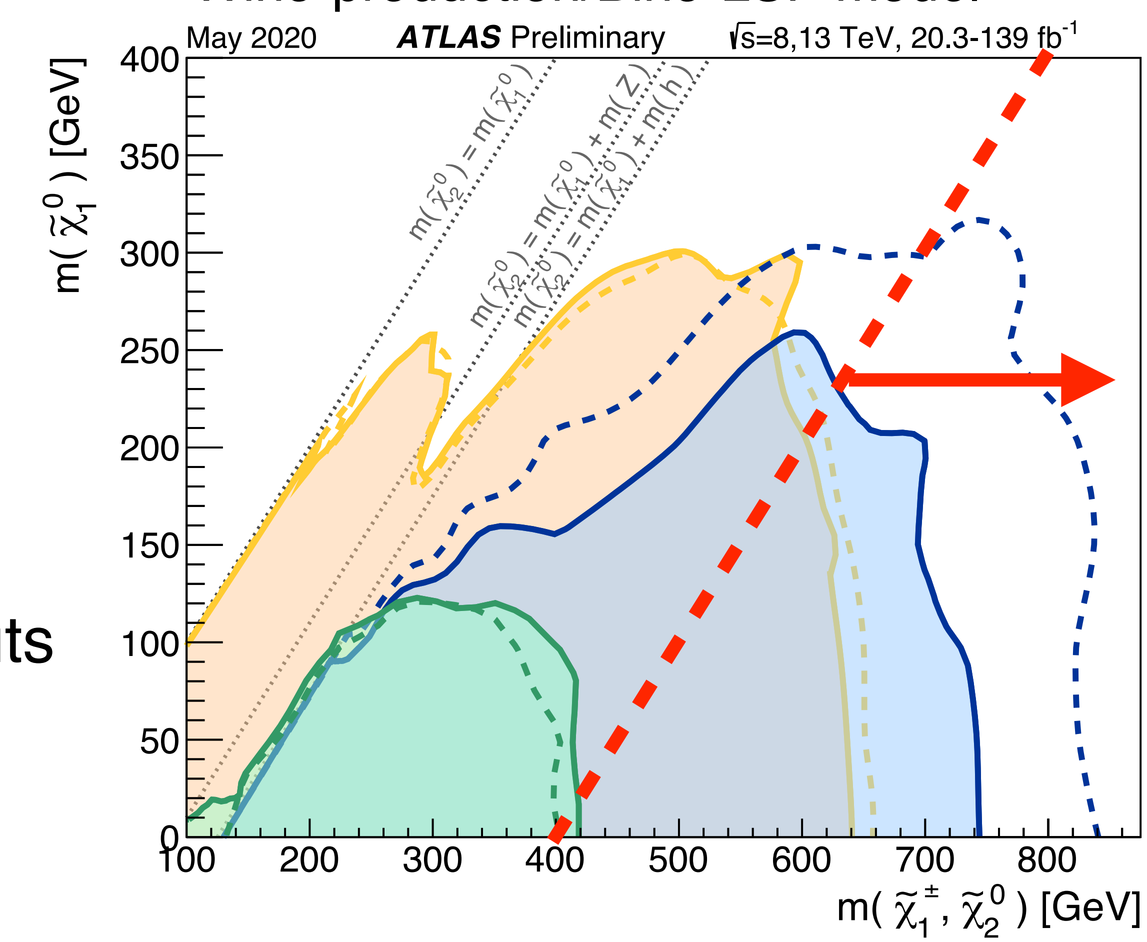
$$\Delta m = m(\tilde{\chi}_{\rm heavy}) - m(\tilde{\chi}_{\rm light})$$



  - Consider wino or higgsino pair-production and various types of LSP (bino/wino/higgsino/gravitino/axino)
  - Focus on the full hadronic decays of W/Z/h.
  - motivation : Dark matter, Naturalness, Muon g-2
  - **qqqq final state is explored for the first time in LHC!**

- Advantages :
  - Large branching ratio
    - Most of the previous searches rely on leptonic final states with W→lν or Z→ll.
    - Increased BGs can be still handled when with large Δm, using tight kinematic cuts and "boosted boson tagging".
  - Small model dependency
    - As W, Z and h are targeted altogether.

Wino-production/Bino-LSP model

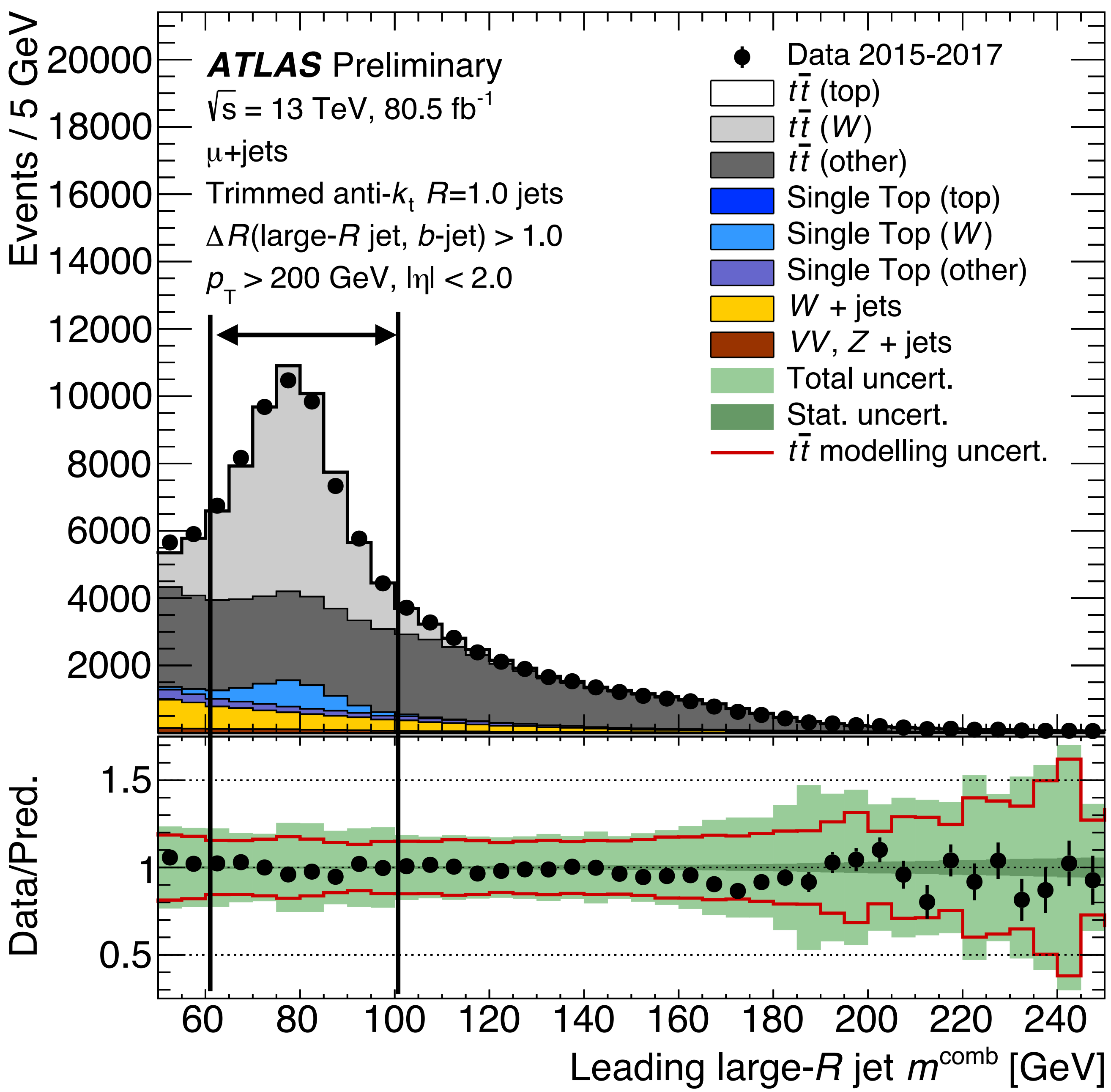


Boson tagging

- **W/Z → qq tagging**
  - 3 variable cuts with p_T-dependent cut values
    - Jet mass window selection
    - Upper cut on D_2 - energy correlation : represent 2-prong substructure
    - Upper cut on n_{trk} - track multiplicity

selection for the W/Z mass peak

Jet mass



(ATL-PHYS-PUB-2020-017)

Boson tagging

- **W/Z → qq tagging**
  - 3 variable cuts with p_T-dependent cut values
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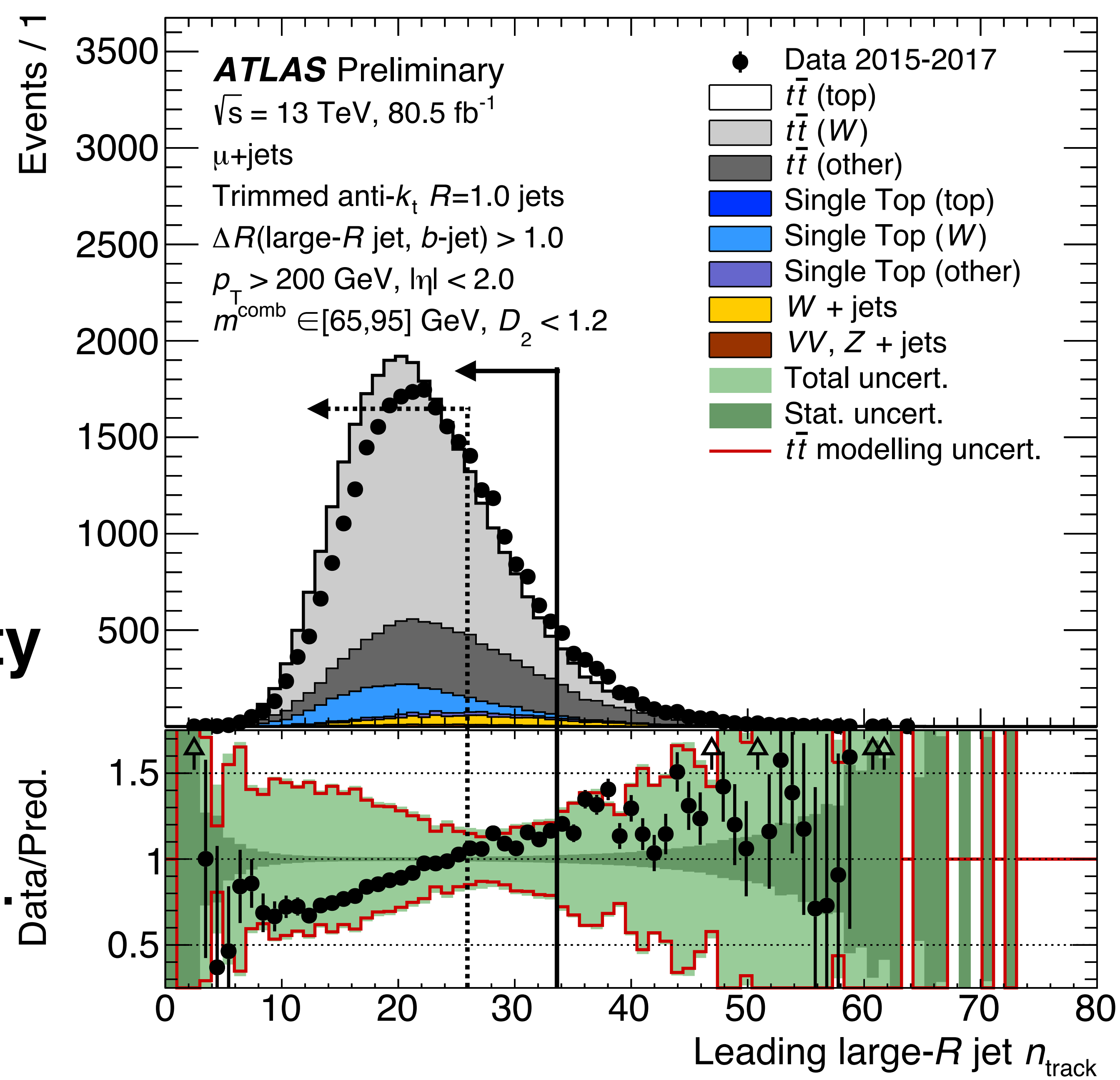
    - Upper cut on D_2 - energy correlation : represent 2-prong substructure
    - Upper cut on n_{trk} - track multiplicity

- **W/Z : color singlet -> particle multiplicity is nearly independent of p_T.**

- **single parton jet : high multiplicity (high p_T jet)**

- n_{trk} cut is optimized for this analysis.

n_{trk}



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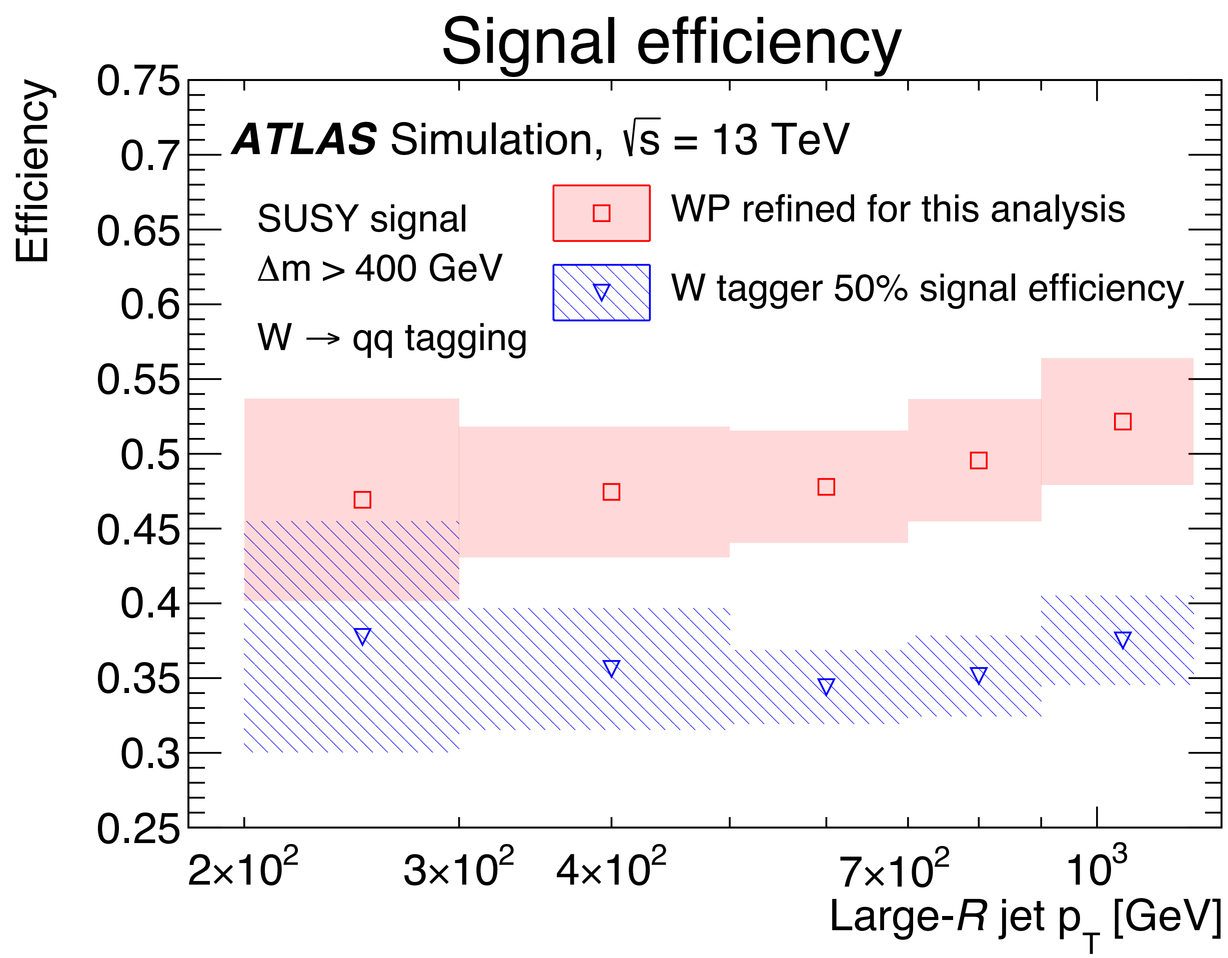
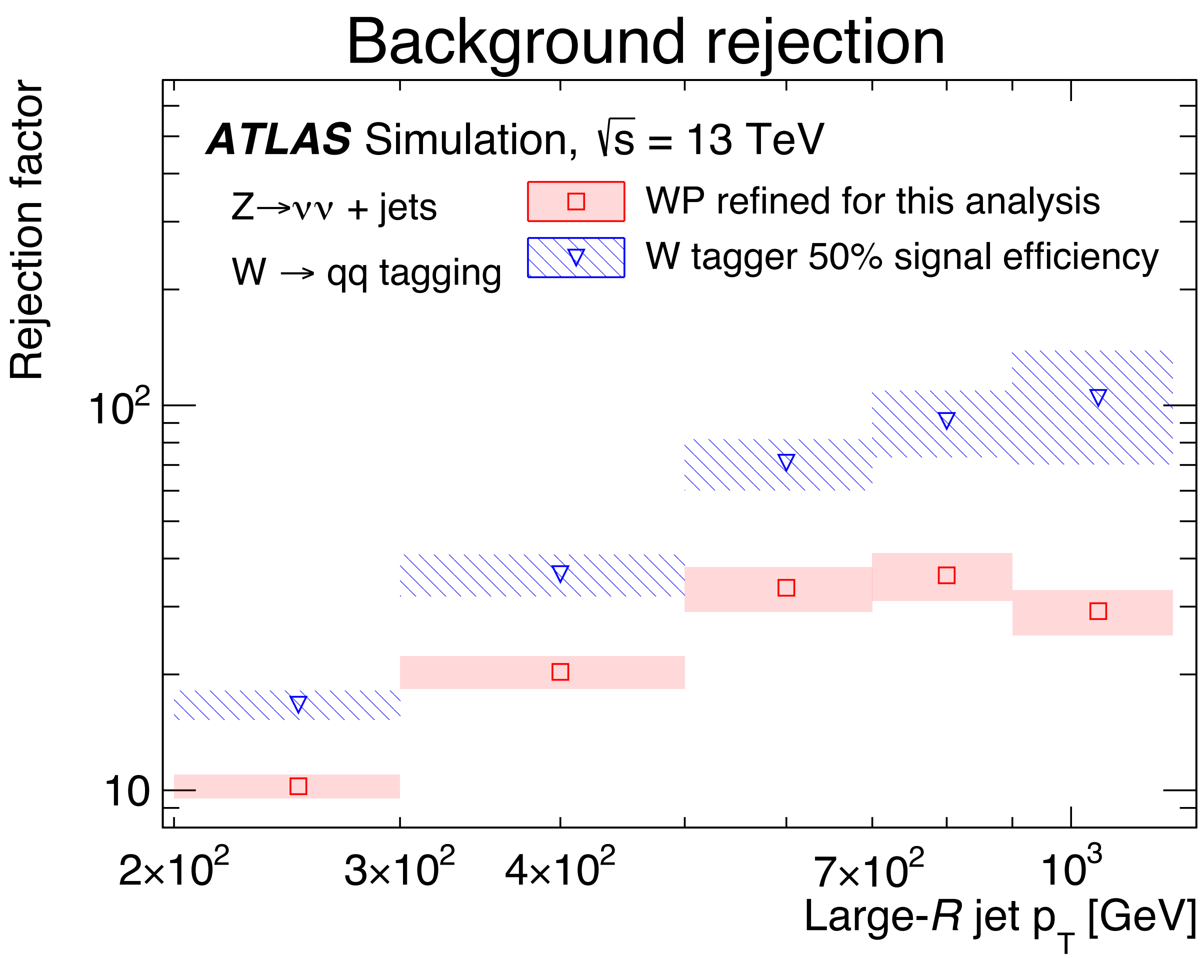
Boson tagging

Official 50% WP vs **redefined WP for this analysis**

- **W → qq tagging**
  - signal boson efficiency : 45 ~ 50% (= 1.3 × Official WP)
  - background rejection (= 1/background efficiency) :
    10 ~ 30 (= 0.5 × Official WP)

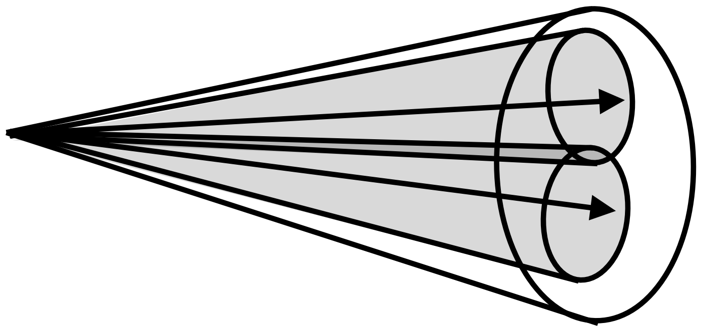
- **Z → qq tagging :** similar with W → qq tagging





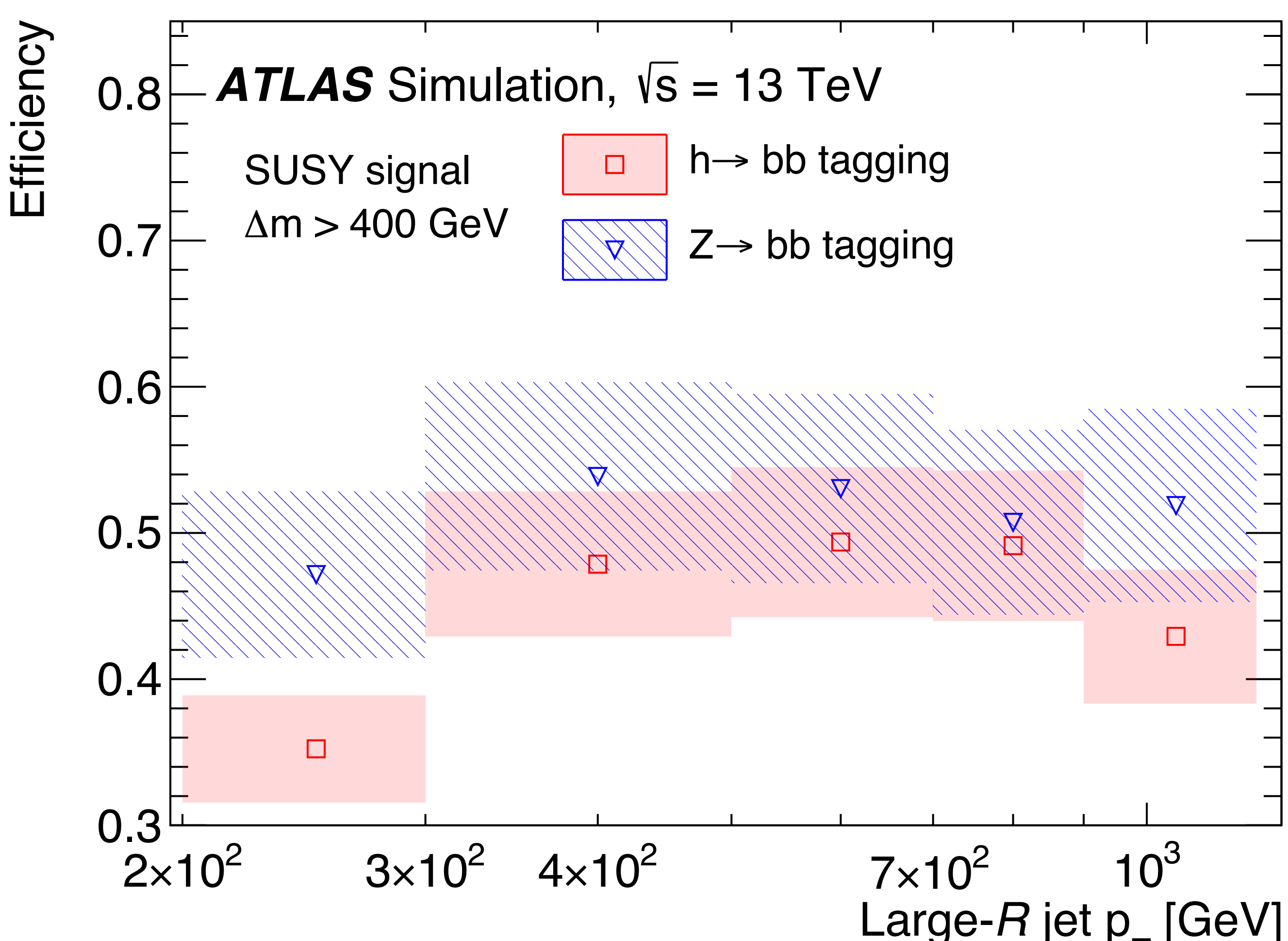
※ Jet mass > 40 GeV cut is already applied.

Boson tagging



- **Z/h → bb tagging**
  - Require 2 small b-tagged sub jets within a large-R jet
  - 2b-tagged large-R jet mass window selection for the Z/h mass peak
    - 70 GeV < m(Jbb) < 100 GeV for Z candidates
    - 100 GeV < m(Jbb) < 135 GeV for h candidates
  - Jet mass corrected for muons from semi-leptonic b-hadron decays
  - Signal efficiency : ~ 50 %
  - background efficiency :
    depends on the origin of sub jets,
    0.1 ~ 10 %

Signal efficiency



※ Jet mass > 40 GeV cut is already applied.

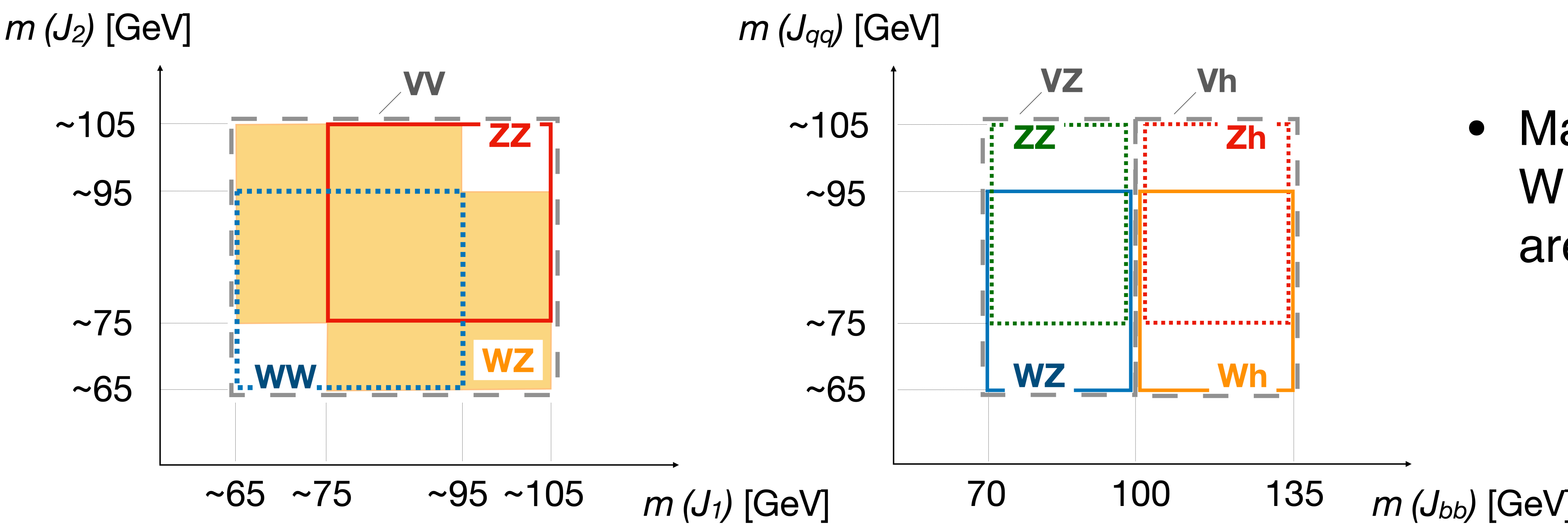
Event selection strategy

- **Preselections for SRs**
  - n(large-R jets) ≥ 2, Lepton-veto, MET > 200 GeV (trigger)

- **2 categories**
  - 4Q : (W/Z)(W/Z) → qqqq
  - 2B2Q : (W/Z)(Z/h) → qqbb
    - Split based on the presence/absence of 2b-tagged large-R jet

- **Boson tagging requirements on the two large-R jets**
  - 10 signal region (SRs) bins to target different bosons from the signals

SR definition



(a) SR-4Q

(b) SR-2B2Q

- Mass cuts of W→qq/Z→qq are overlapped.

Selections

- **Dominant background : Z(→vv) + ISR jets**
- **Further BG rejection cuts**
  - Veto b-jets outside the large-R jets ($n_{b\text{-jet}}^{unmatched}$ = 0)
  - minΔϕ(j,MET)>1.0 to select spherical event topology
  - m_{eff} (scalar sum of MET, J_1 and J_2 p_T) : select events with hard kinematics
  - m_{T2} : stransverse mass with the two large-R jets assigned to the visible particle legs

	SR(CR0L) 4Q	SR(CR0L) 2B2Q
$n_{\text{Large-}R\text{ jets}}$	≥ 2	
n_{lepton}	$= 0$	
$p_{\text{T}}(\ell_1)$ [GeV]	-	
n_{photon}	-	
$n(V_{qq})$	$= 2\ (= 1)$	$= 1\ (= 0)$
$n(!V_{qq})$	$= 0\ (= 1)$	$= 0\ (= 1)$
$n(J_{bb})$	$= 0$	$= 1$
$m(J_{bb})$ [GeV]	-	$\in [70, 135\ (150)]$
$n_{b\text{-jet}}^{\text{unmatched}}$	$= 0$	
$n_{b\text{-jet}}$	≤ 1	-
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 300	> 200
$p_{\text{T}}(W)$ [GeV]	-	
$p_{\text{T}}(\gamma)$ [GeV]	-	
m_{eff} [GeV]	> 1300	$> 1000\ (> 900)$
$\min \Delta\phi(E_{\text{T}}^{\text{miss}}, j)$	> 1.0	
m_{T2} [GeV]	-	> 250

Background estimation

- **V needs to decay leptonically ($W \to l\nu, Z \to \nu\nu$) to create large enough MET**
  - V+jets (50-75%) : **2 ISR jets & 0 real boson jet**
  - VV, ttbar, single-top (~20%) : **1 ISR jet & 1 real boson jet**

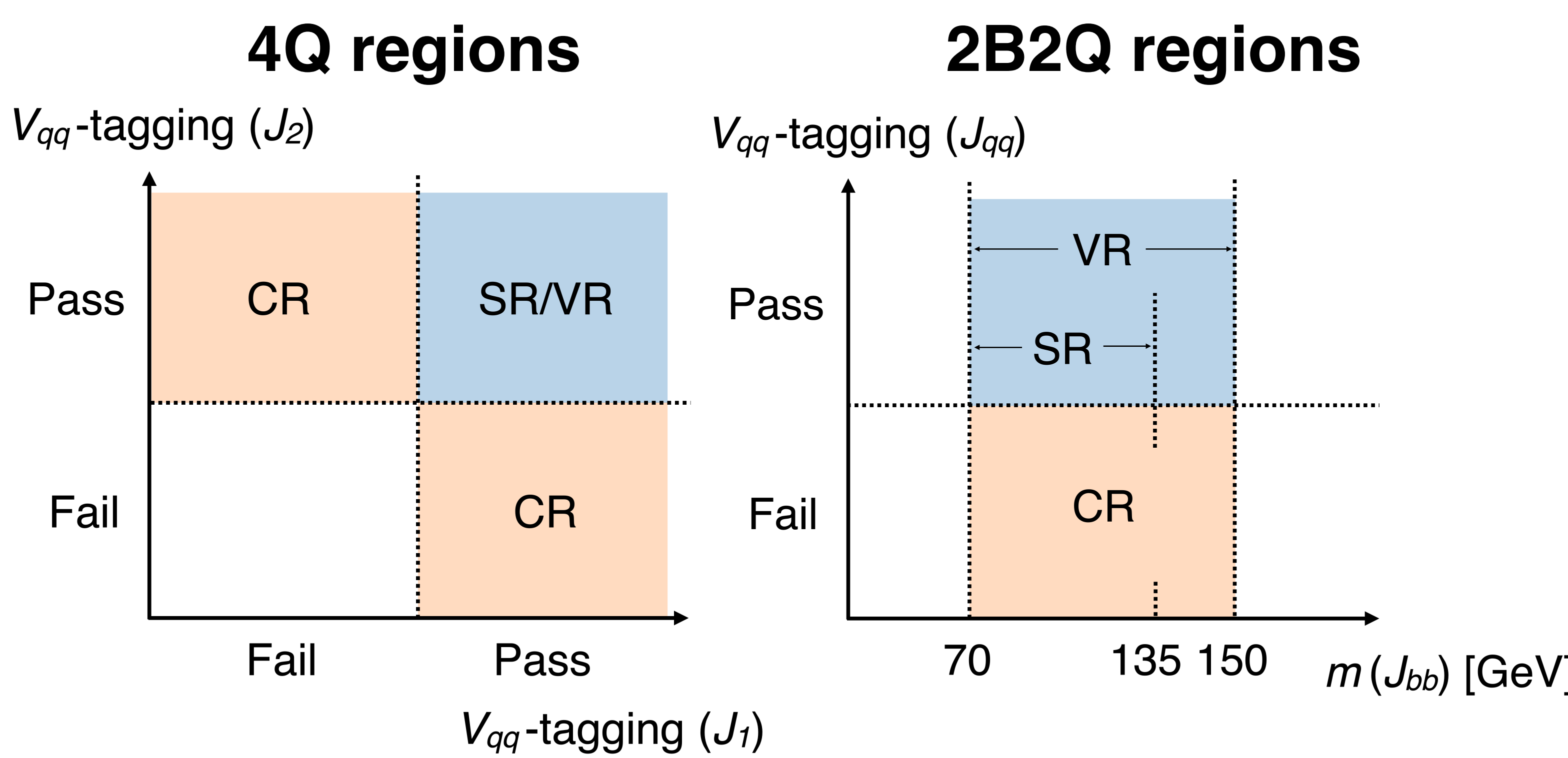
"Reducible BG" (>90%)
→ Semi data-driven method

  - tt+X, VVV (~10%) : **0 ISR jet & 2 real boson jets**

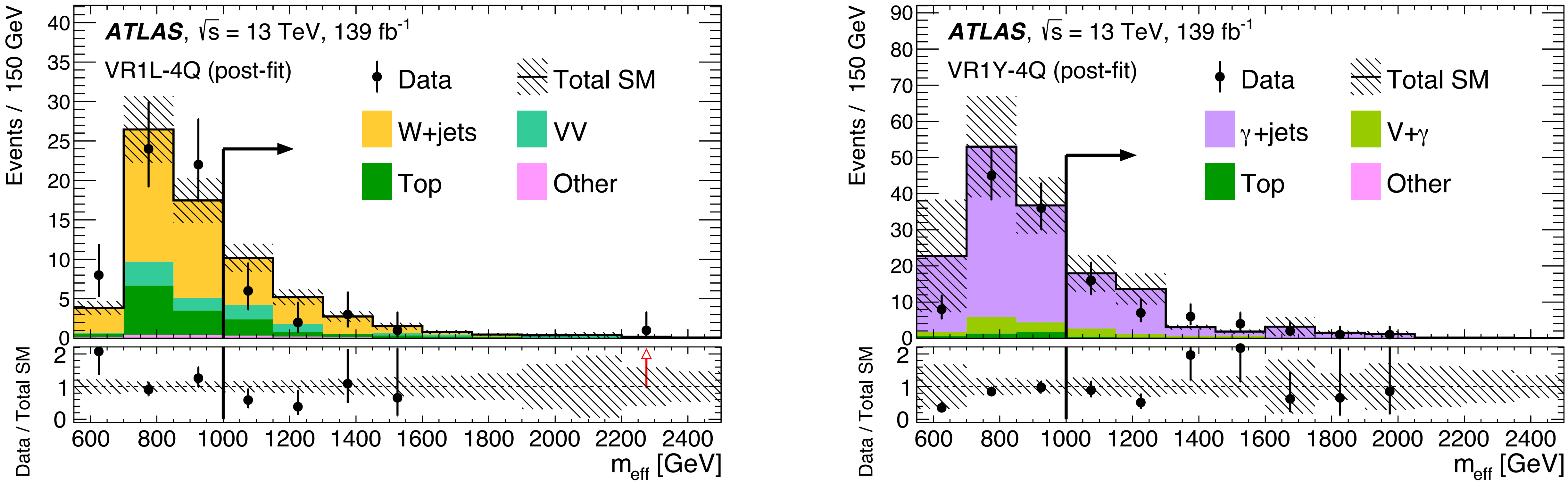
"Irreducible BG" (<10%)
→ Direct from MC

  - "Fake boson" originating from ISR jets.

- **Estimation strategy**
  - Using semi-data driven method
    - Using MC extrapolation
    - MC is normalized by data in Control Region (CR)
    - CR defined by inverting the W/Z-tagging of SR.



Background estimation



- CR→SR extrapolation relies on MC modeling.
  → need to validate using data

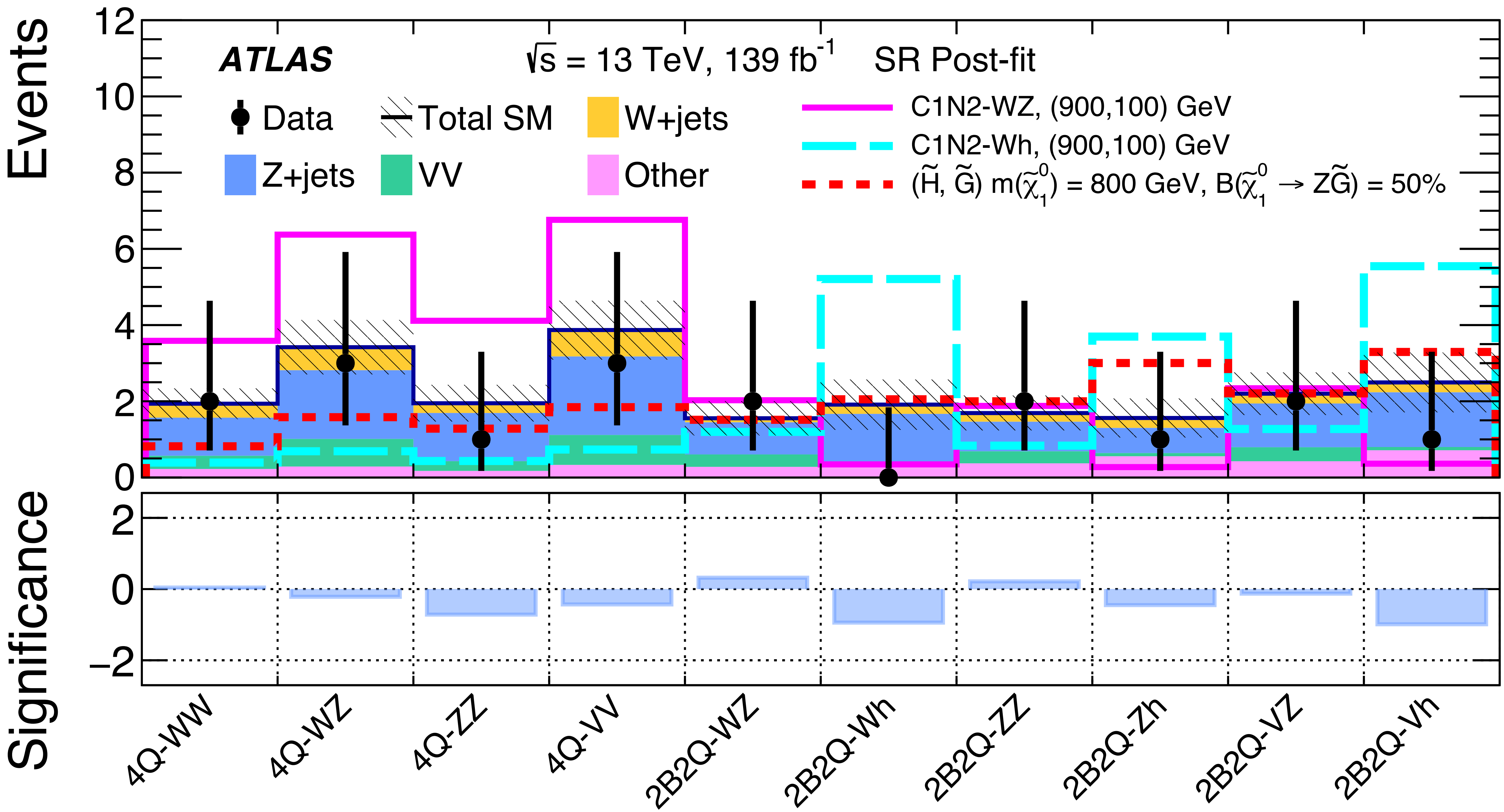
- Validation for reducible background estimation

  - W(→lν)+jets / γ+jets (Similar diagram with dominant BG in SR : Z(→νν)+jets)

    - Define control/validation regions with 1 lepton / 1photon.
    - CR : similar with 0-lepton CR (inverting the W/Z-tagging)
    - VR : similar with 0-lepton SR

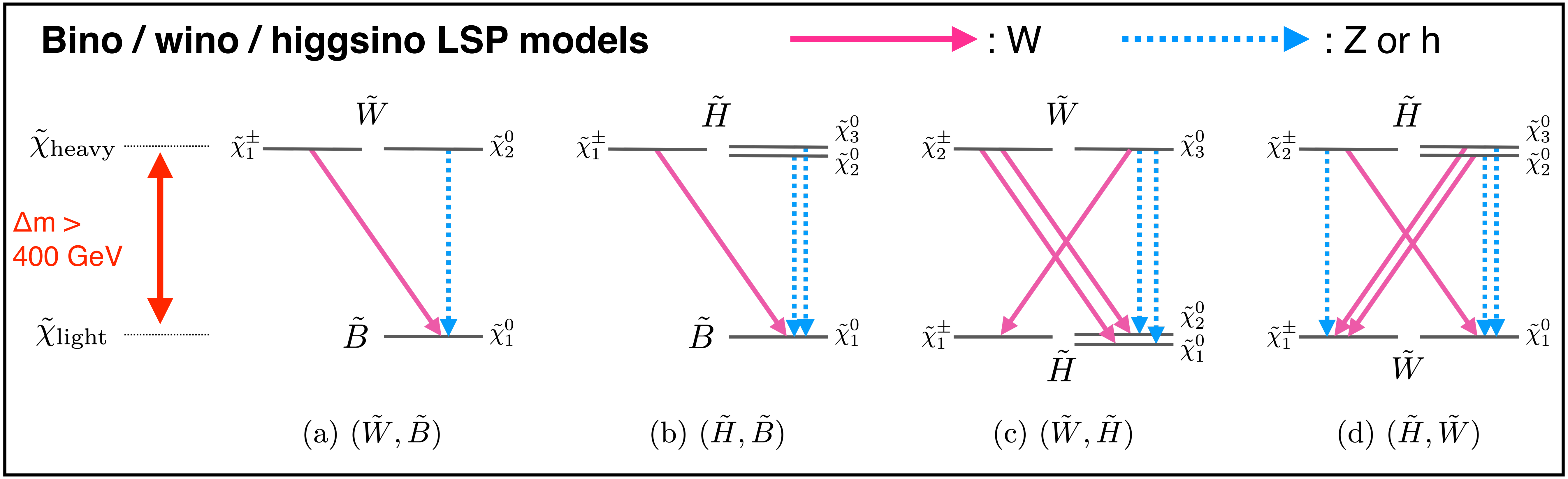
  - Good agreement is found.

Unblinded signal regions



- **No data excess in SR.**

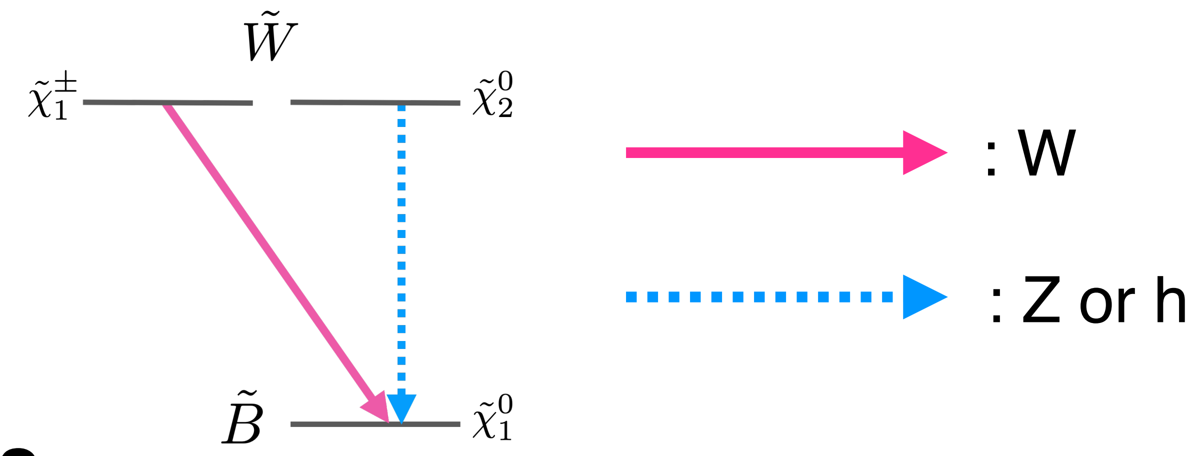
Target models



- Baseline MSSM scenario
- Wino or Higgsino pair-production
- Consider both the simplified models (100% branching ratio) and other interesting MSSM interpretations.

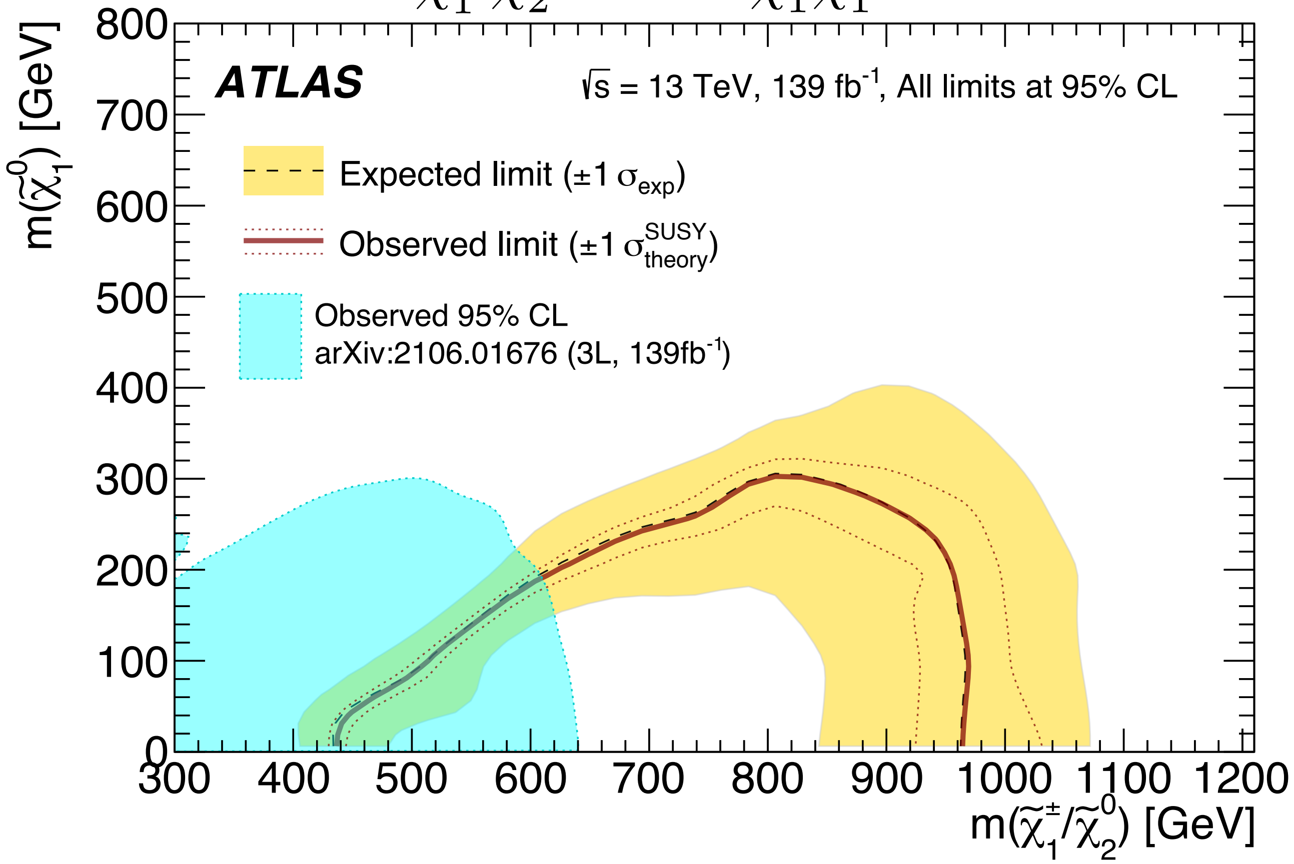
Exclusion limits : Simplified model

$(\tilde{W}, \tilde{B})$ simplified model

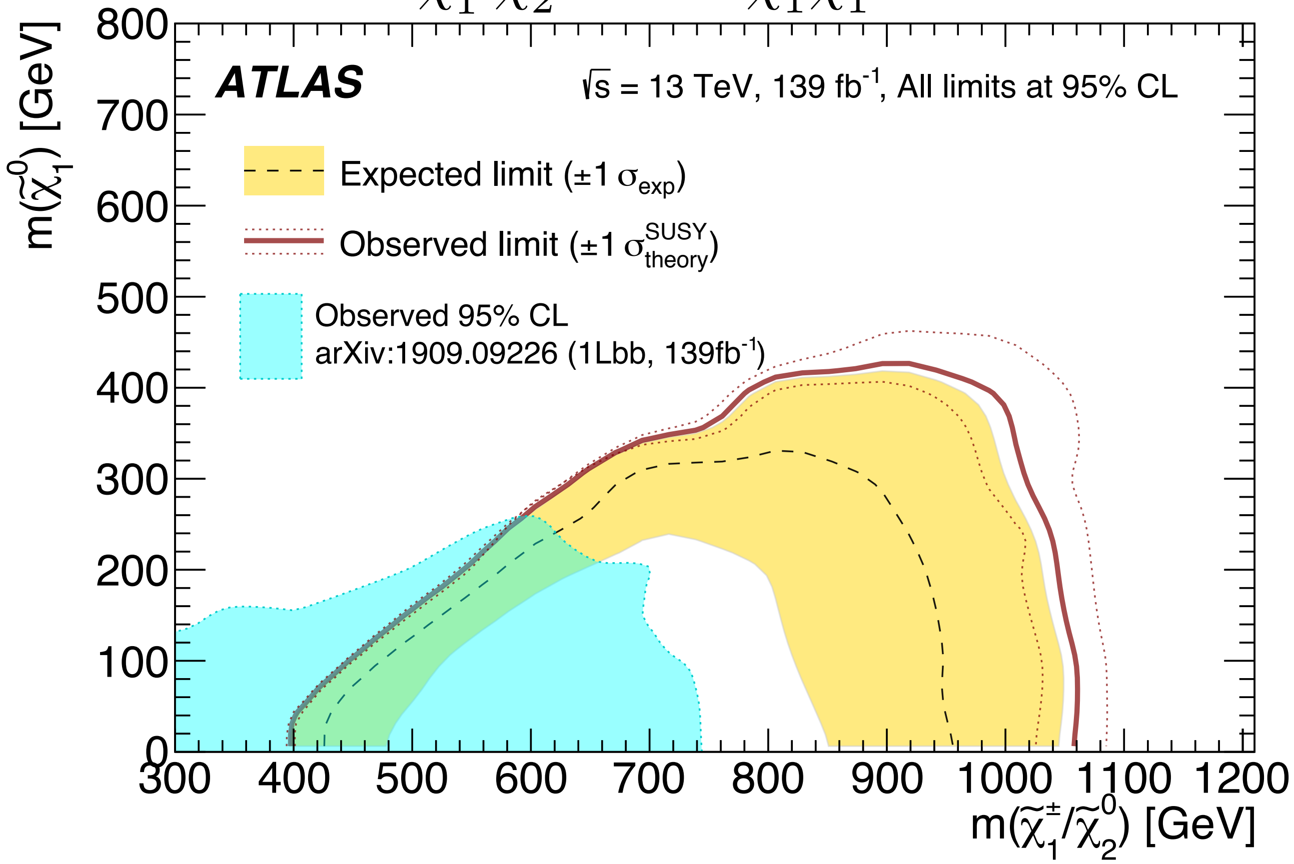


- **300-400 GeV improvement w.r.t. existing best limits by ATLAS/CMS.**

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$



$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to Wh\tilde{\chi}_1^0\tilde{\chi}_1^0$

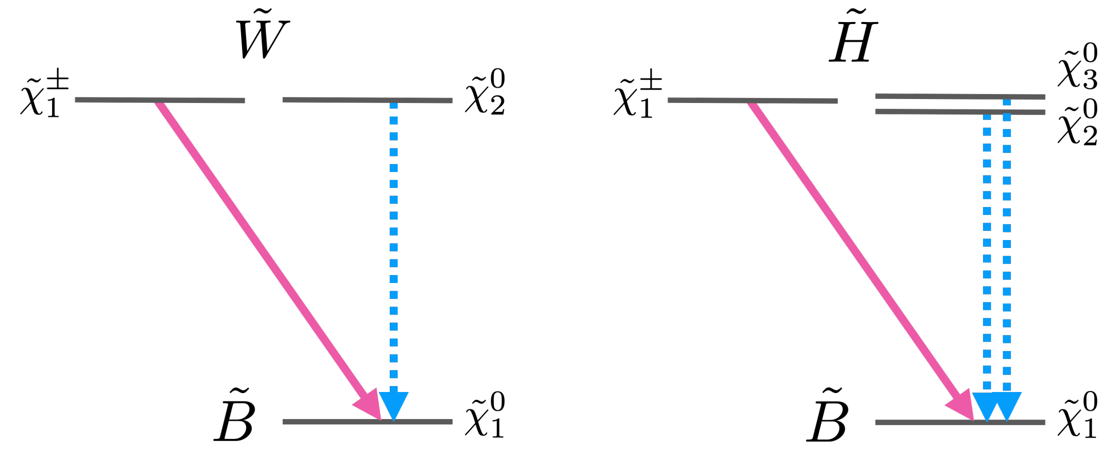


Exclusion limits : Bino-LSP model

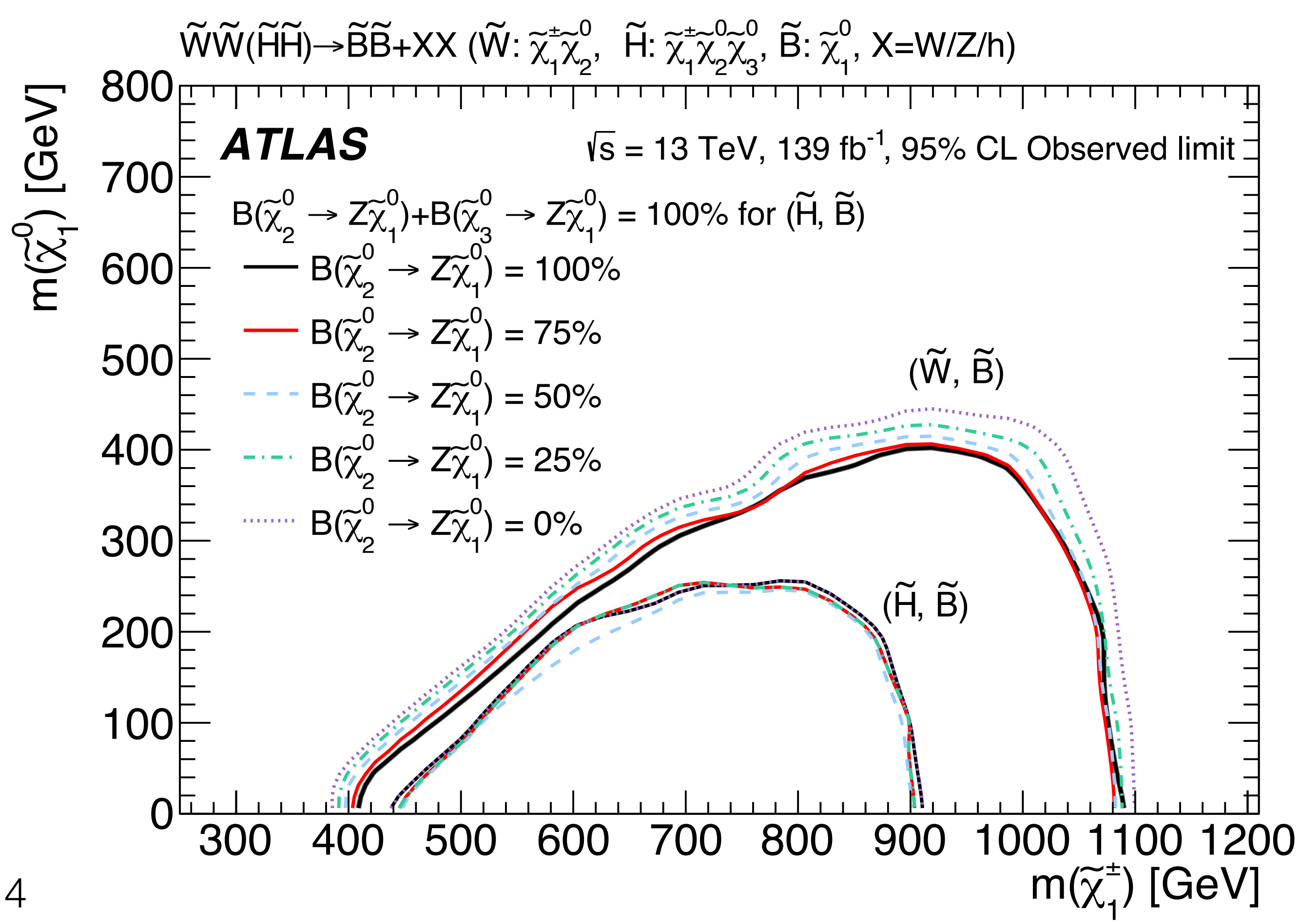
Bino-LSP model : $(\tilde{W}, \tilde{B}), (\tilde{H}, \tilde{B})$

$$\mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1 - \mathcal{B}(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0)$$

$$\mathcal{B}(\tilde{\chi}_3^0 \to Z\tilde{\chi}_1^0) = 1 - \mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)$$



- $\mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)$ is almost free parameter
- Small dependency on the variable branching fraction : $\tilde{\chi}_2^0 \to Z/h\tilde{\chi}_1^0$
- **Up to 1050 (900) GeV for wino (higgsino) production.**

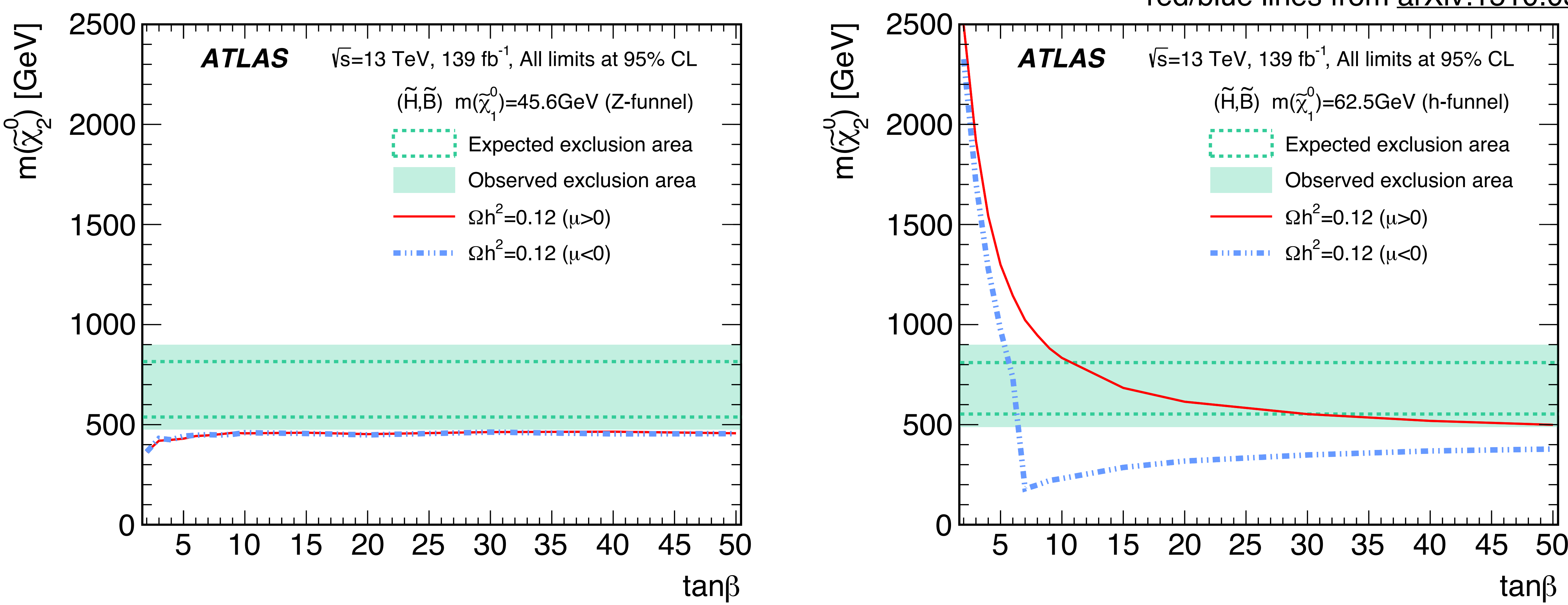


Bino-dominant dark matter scenario

$$(\tilde{H}, \tilde{B})$$

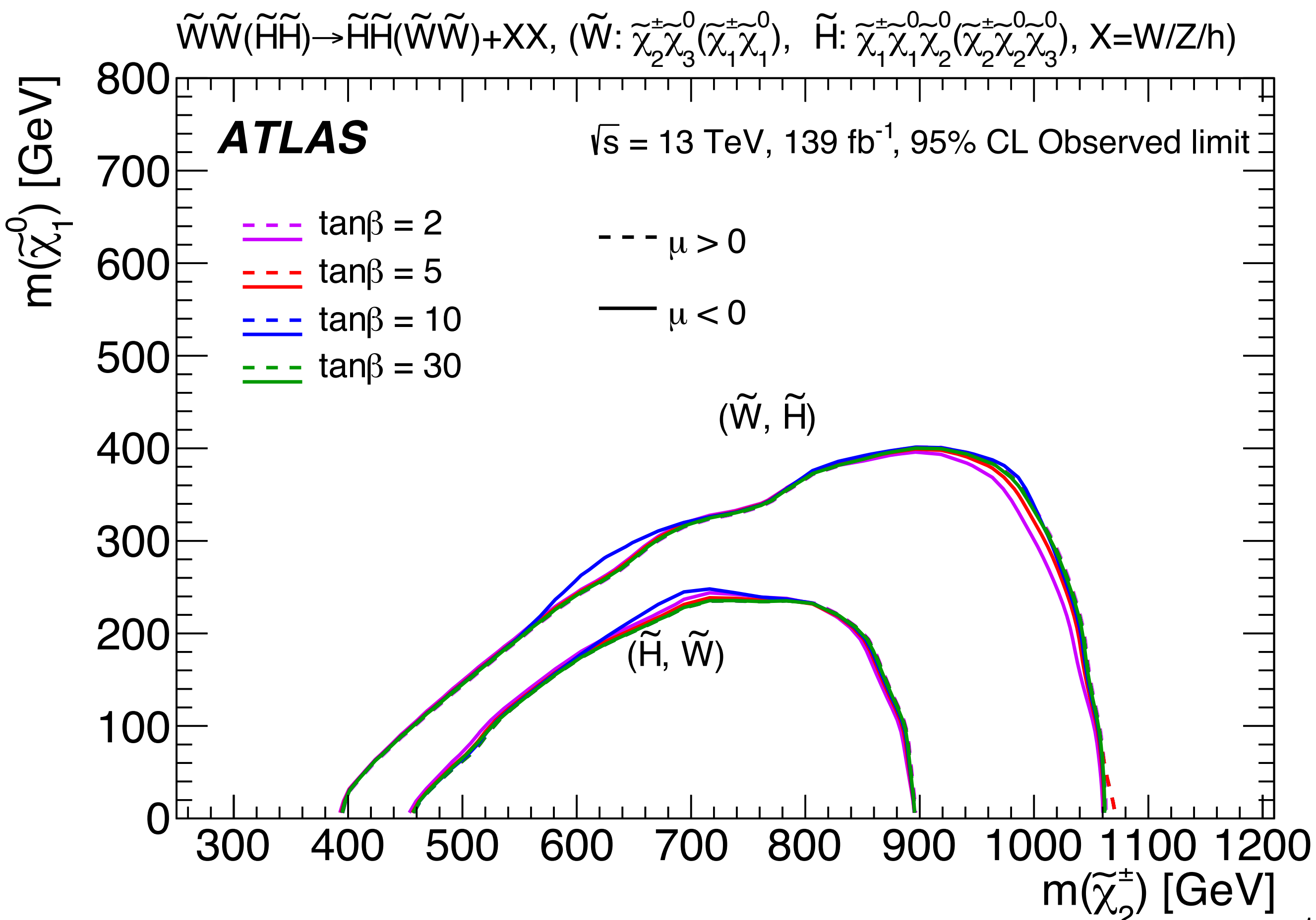
- large Δm is favored by DM relic density when bino LSP mass ~ m(Z)/2 or m(h)/2 ("Z/h funnel scenario")
- Strongest collider constrain obtained by the analysis.

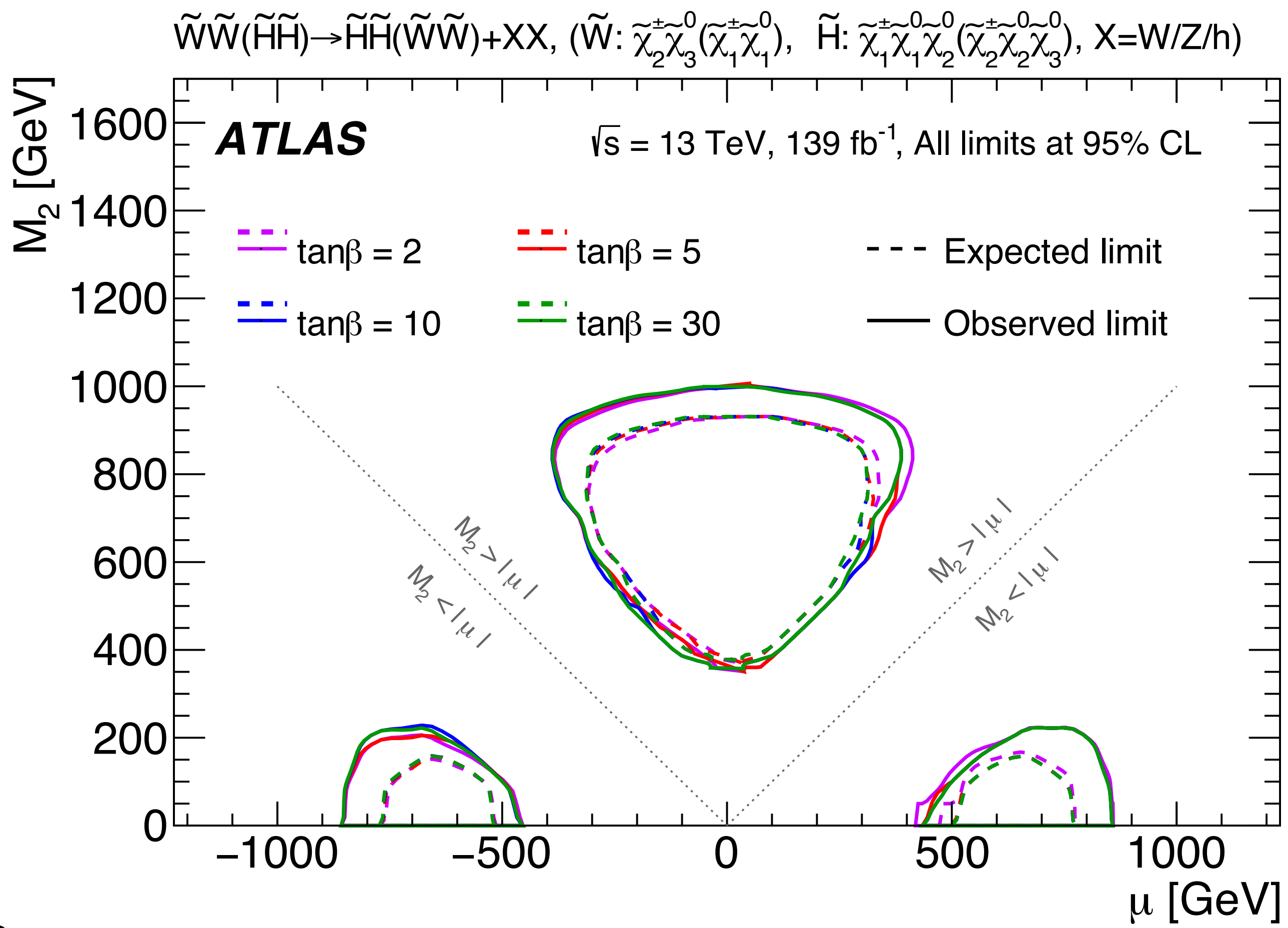
red/blue lines from arXiv:1510.05378



Exclusion limits : $(\tilde{W},\ \tilde{H}),\ (\tilde{H},\ \tilde{W})$

- Scanned over the MSSM parameter (M_2, μ, tanβ) which dedicates the branching ratios of $\tilde{\chi}_{\text{heavy}}$
- Small dependency on variable tanβ and the sign of μ.
- Limits are also interpreted in the (m_{Heavy}, m_{LSP}) plane for a given tanβ.
- **Up to 1050 (900) GeV for wino (higgsino) production.**
  - **Similar to Bino-LSP model.**





Summary

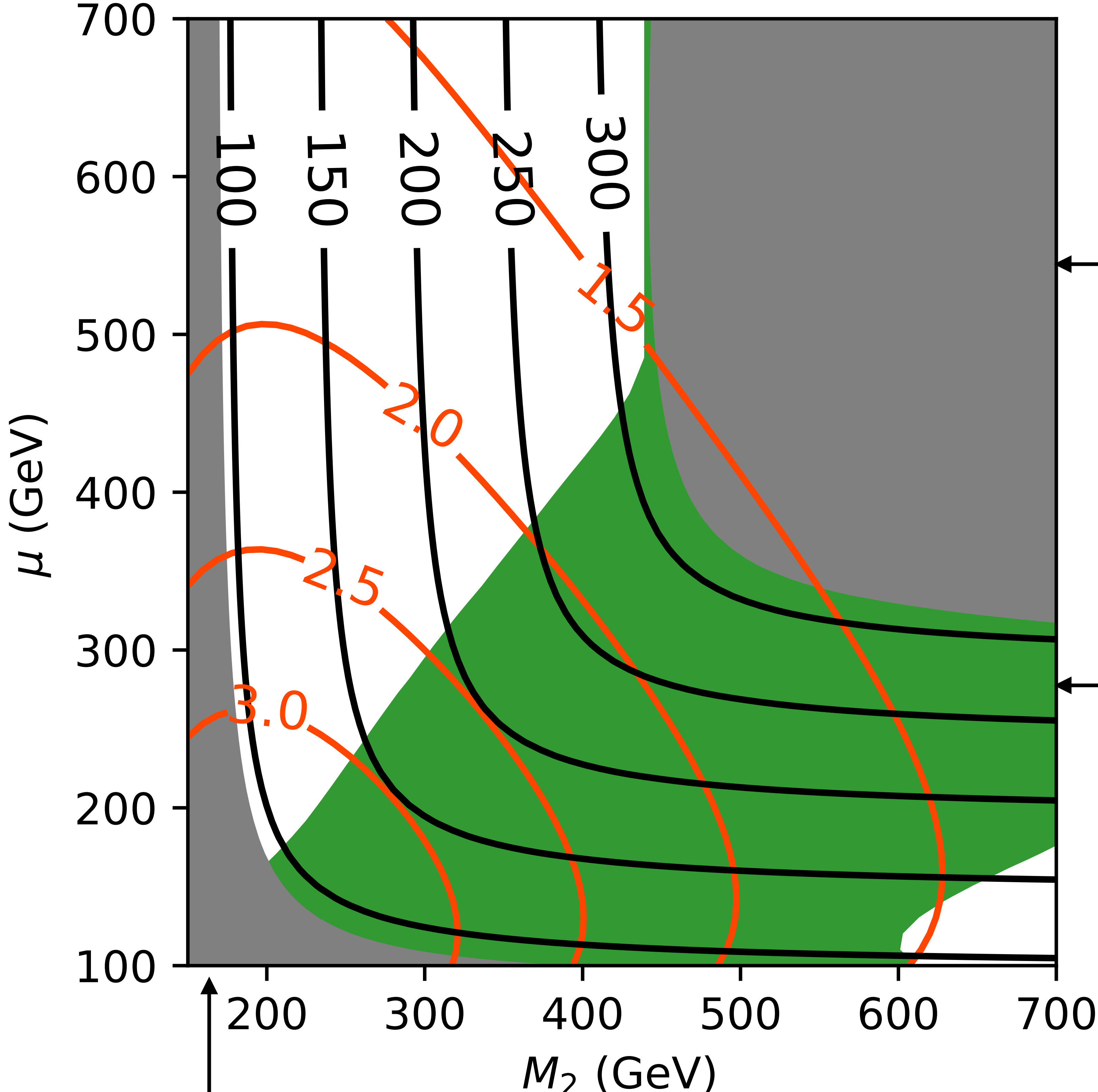
- A new inclusive EWKino search done using fully-hadronic final states.
  - Benefitted by the large branching ratio.
  - Excellent BG rejection with the boosted W/Z/h reconstruction using large-radius jets and the substructure
  - New signature in ATLAS/CMS SUSY search
- Confirmed with various branching ratio hypotheses and LSP types.
- No data excess in the SRs
- **Most stringent limits set for scenarios with large Δm**
  - **300-400 GeV** improvement in the exclusion on the benchmark simplified models w.r.t. existing best limits by ATLAS/CMS.
  - **Up to 1050 (900) GeV is excluded in the wino (higgsino) mass.**

Back up

Muon g-2 motivated scenario

orange contours : Δa_μ^{SUSY} black contours : LSP mass

arXiv:2104.03223



excluded by stat LSP

excluded by XENON-1T

excluded by LEP

Boson tagging

- **W/Z → qq tagging**
    - 3 variable cuts with p_T-dependent cut values
        - Jet mass window selection
        - Upper cut on D_2 - energy correlation
        - Upper cut on n_{trk} - track multiplicity

2-prong -> small D_2
1-prong -> large D_2

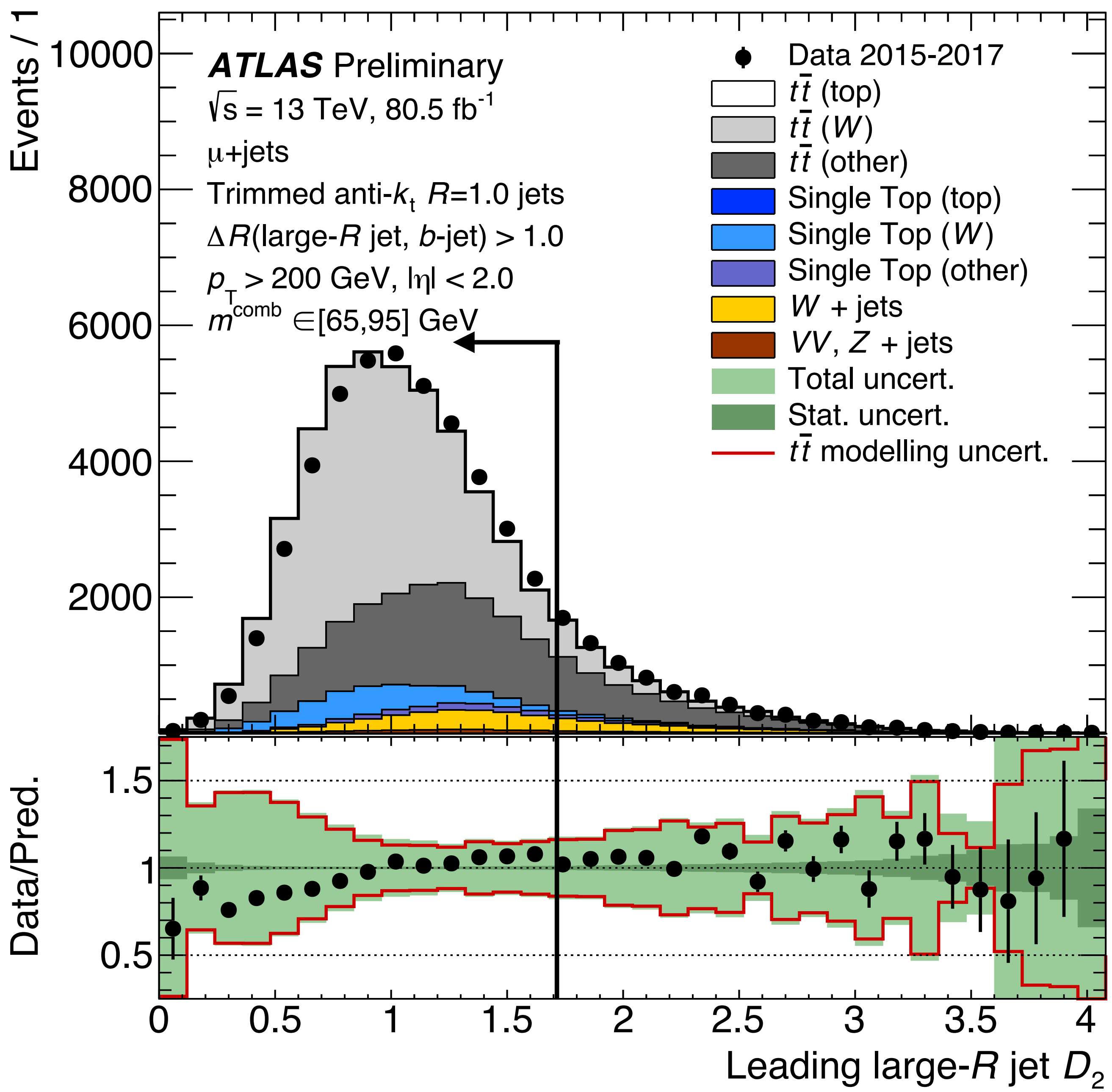
$$\mathrm{ECF}(1,\beta) = \sum_{i\in J} p_{\mathrm{T}i}$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j\in J} p_{\mathrm{T}i}p_{\mathrm{T}j}(\Delta R_{ij})^\beta$$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in J} p_{\mathrm{T}i}p_{\mathrm{T}j}p_{\mathrm{T}k}(\Delta R_{ij}\Delta R_{ik}\Delta R_{jk})^\beta$$

$$D_2^{\beta=1} = \frac{\mathrm{ECF}(3,\beta)(\mathrm{ECF}(1,\beta))^3}{(\mathrm{ECF}(2,\beta))^2}$$

D2



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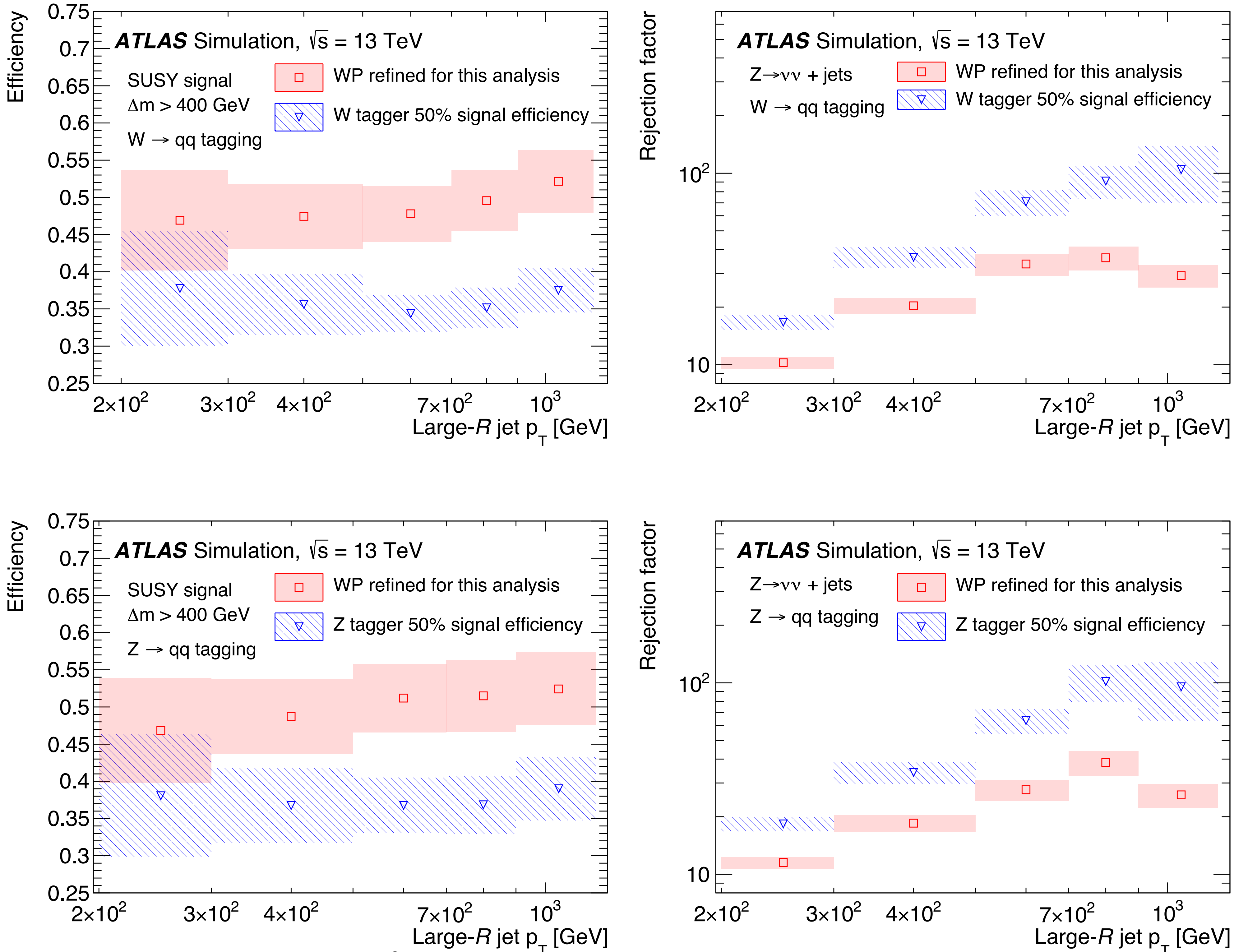
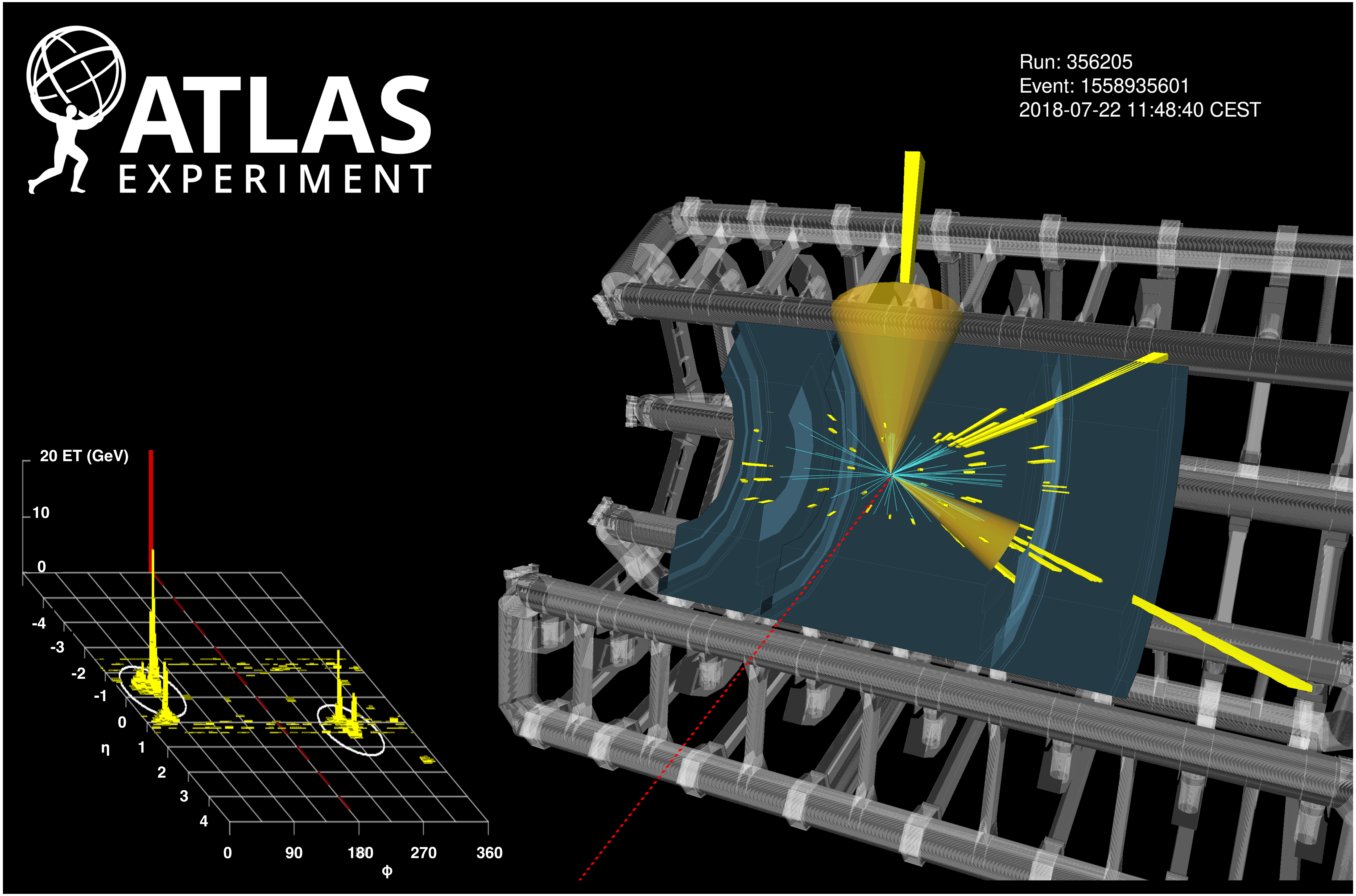
W/Z→qq tagging performance

Official 50% WP vs redefined WP for this analysis

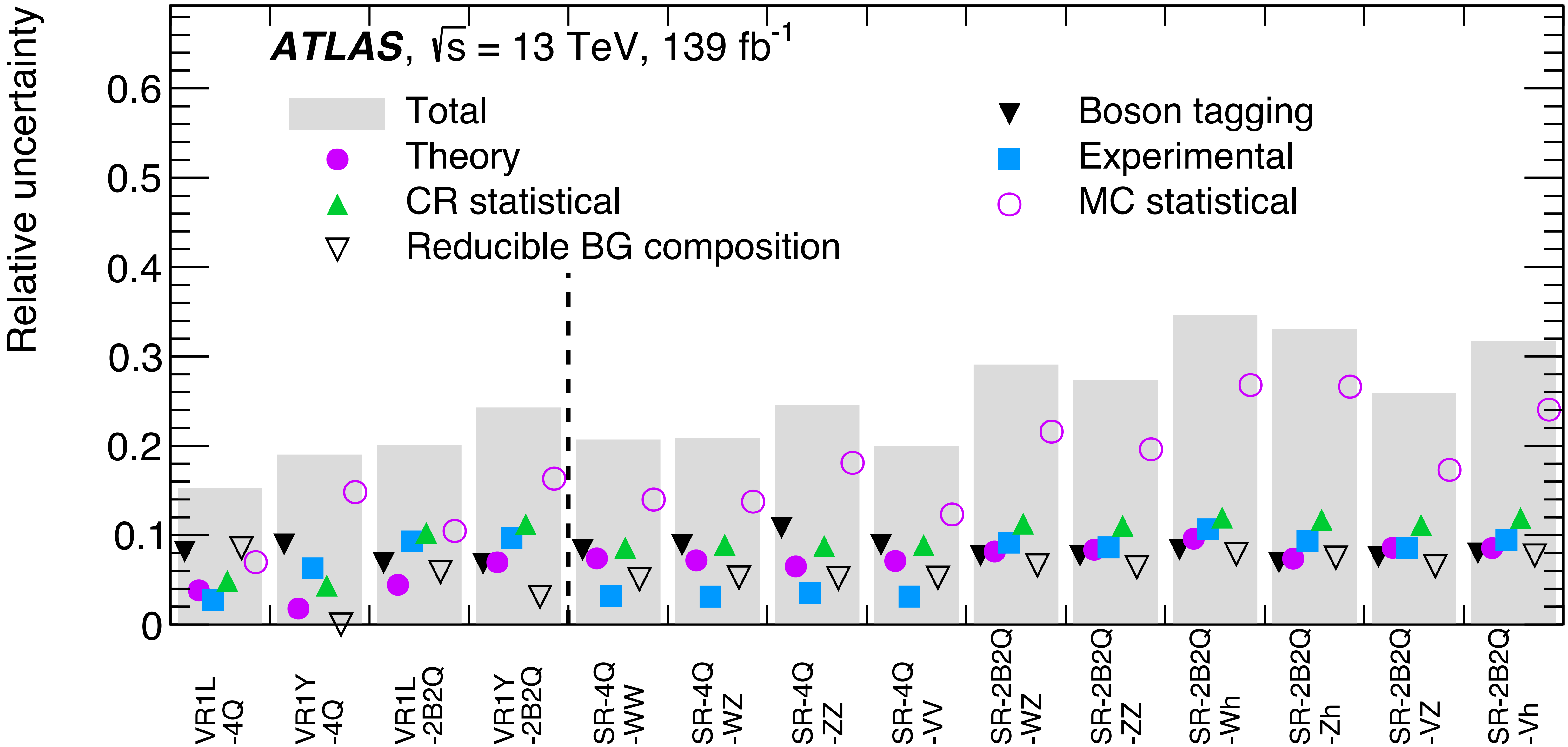
- n_{trk} cut of redefined WP is loosened.
- efficiency
  - 35 ~ 40 % (Official WP)
  - 45 ~ 50 % (Redefined WP)
- background rejection
  - (Official WP) = (Redefined WP) × 2



Event display



Systematic uncertainty



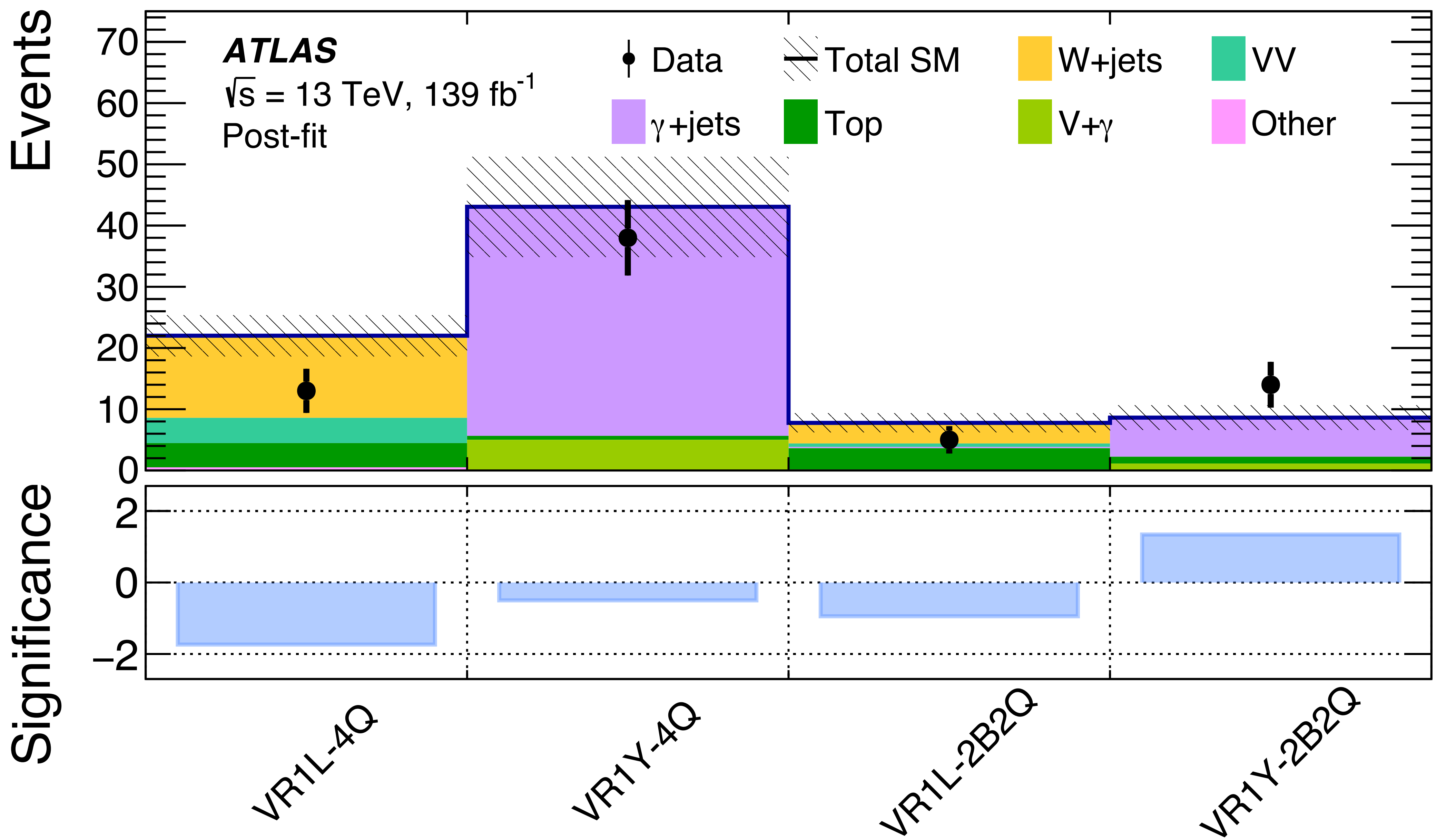
- **Dominant systematic uncertainty is MC stats.**
  - Experimental/Theory uncertainty are used in accordance with the recommendation.
  - Uncertainties for reducible backgrounds are evaluated as the extrapolation uncertainty.
  - Boson tagging uncertainty is the largest of the experimental uncertainties.
- **Still smaller than data stat. uncertainty(70~100%) in SR.**

CR/VR yields in 1L/1Y regions

Region	CR1L-4Q	VR1L-4Q	CR1L-2B2Q	VR1L-2B2Q
Observed	439	13	96	5
Post-fit	439 ± 21	22.0 ± 3.4	96 ± 10	7.8 ± 1.5
W+jets	325 ± 16	13.4 ± 2.2	48 ± 5	3.4 ± 0.7
Z+jets	4.45 ± 0.21	0.198 ± 0.035	0.58 ± 0.06	0.044 ± 0.012
γ+jets	< 1	-	0.57 ± 0.06	0.22 ± 0.10
VV	65.4 ± 3.1	4.1 ± 0.8	6.9 ± 0.7	0.55 ± 0.15
$V\gamma$	< 1	-	< 0.1	-
VVV	1.3 ± 0.6	0.52 ± 0.28	0.14 ± 0.08	0.09 ± 0.05
$t\bar{t}$	30.4 ± 1.5	2.7 ± 0.4	24.0 ± 2.5	1.8 ± 0.4
t+X	11.0 ± 0.5	0.91 ± 0.21	13.2 ± 1.4	1.27 ± 0.34
$t\bar{t}$+X	1.5 ± 1.2	0.16 ± 0.12	1.5 ± 1.1	0.4 ± 0.4
Vh	< 0.1	< 0.001	0.69 ± 0.07	0.046 ± 0.009

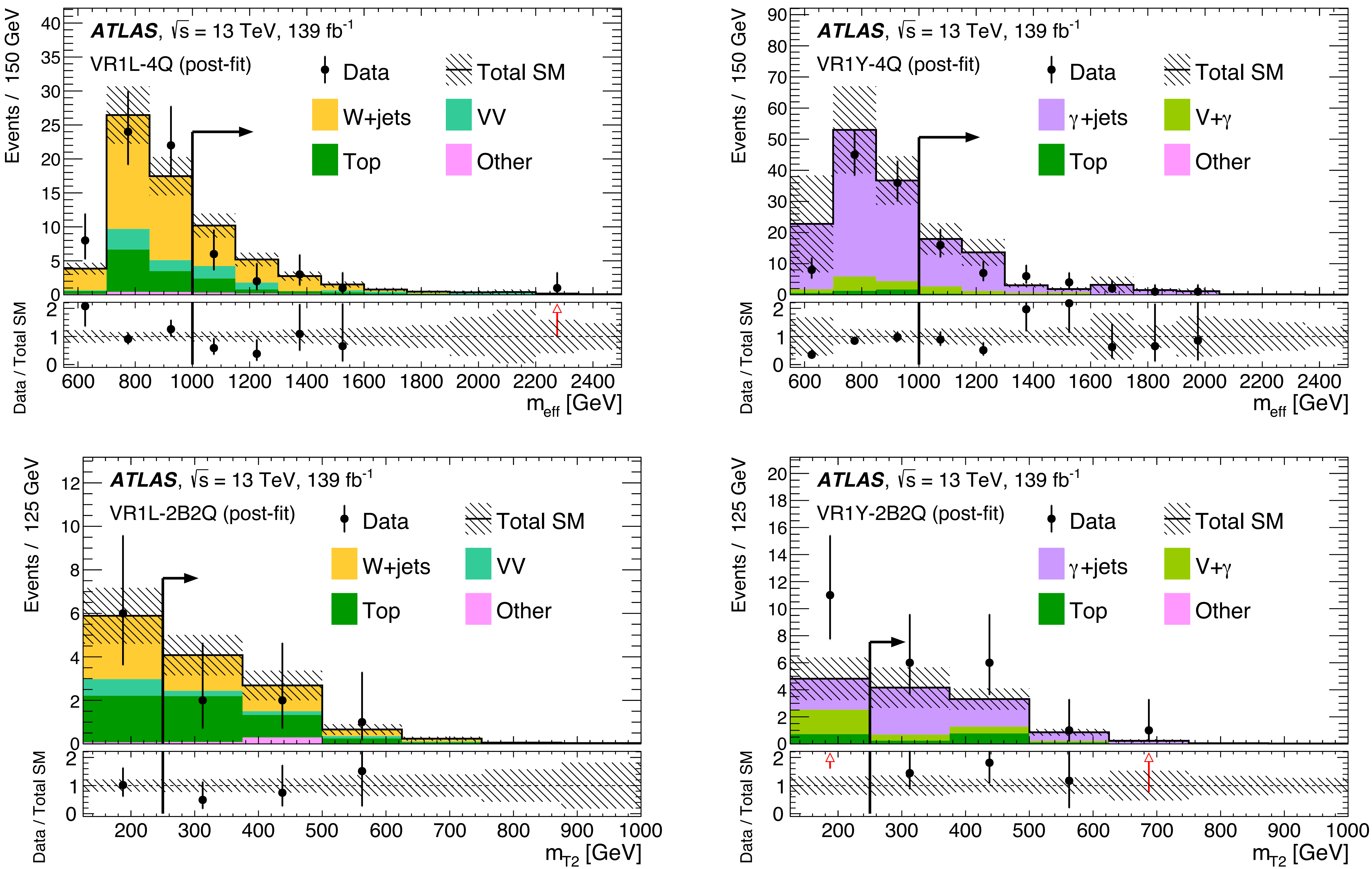
Region	CR1Y-4Q	VR1Y-4Q	CR1Y-2B2Q	VR1Y-2B2Q
Observed	1001	38	127	14
Post-fit	1001 ± 32	43 ± 8	127 ± 11	8.6 ± 2.0
W+jets	2.59 ± 0.08	< 0.1	< 0.1	-
Z+jets	< 1	-	< 0.01	-
γ+jets	856 ± 28	37 ± 7	107 ± 11	6.4 ± 1.6
VV	< 1	-	-	-
$V\gamma$	131 ± 4	5.0 ± 0.9	12.6 ± 1.3	1.13 ± 0.27
VVV	< 0.1	< 0.01	-	-
$t\bar{t}$	1.28 ± 0.04	-	0.57 ± 0.06	0.28 ± 0.18
t+X	< 1	-	< 0.1	-
$t\bar{t}$+X	9 ± 6	0.6 ± 0.5	7 ± 5	0.8 ± 0.6
Vh	< 0.001	-	< 0.01	-

CR/VR yields in 1L/1Y regions

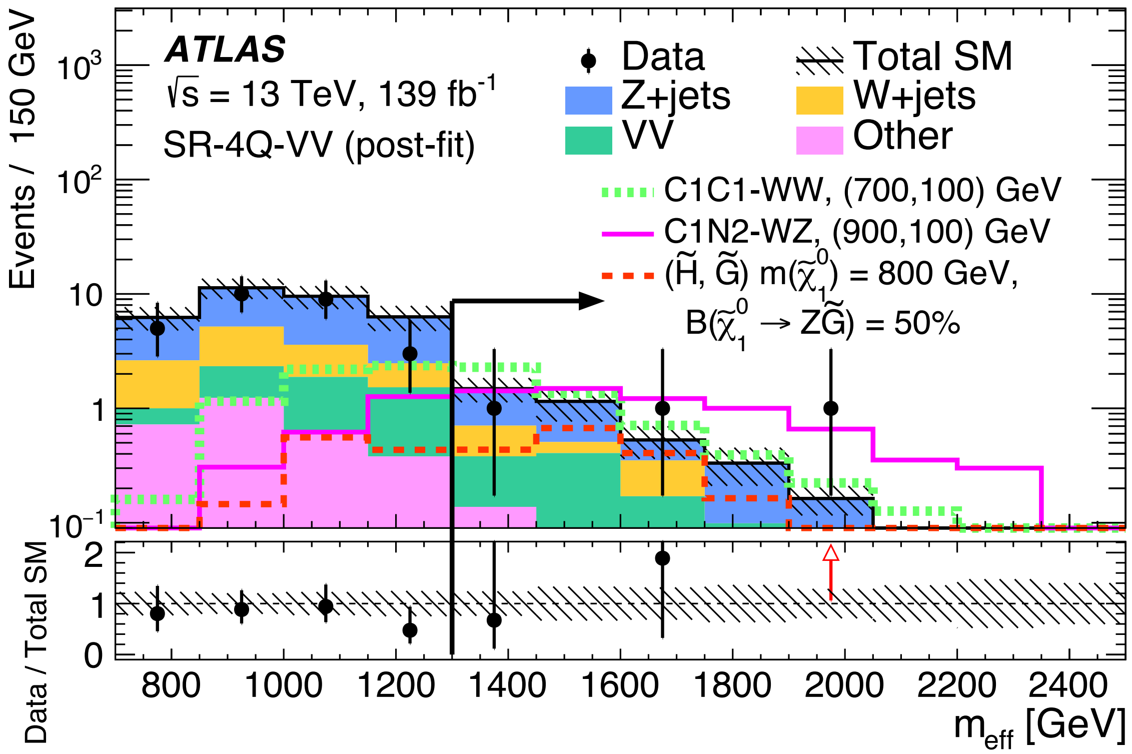


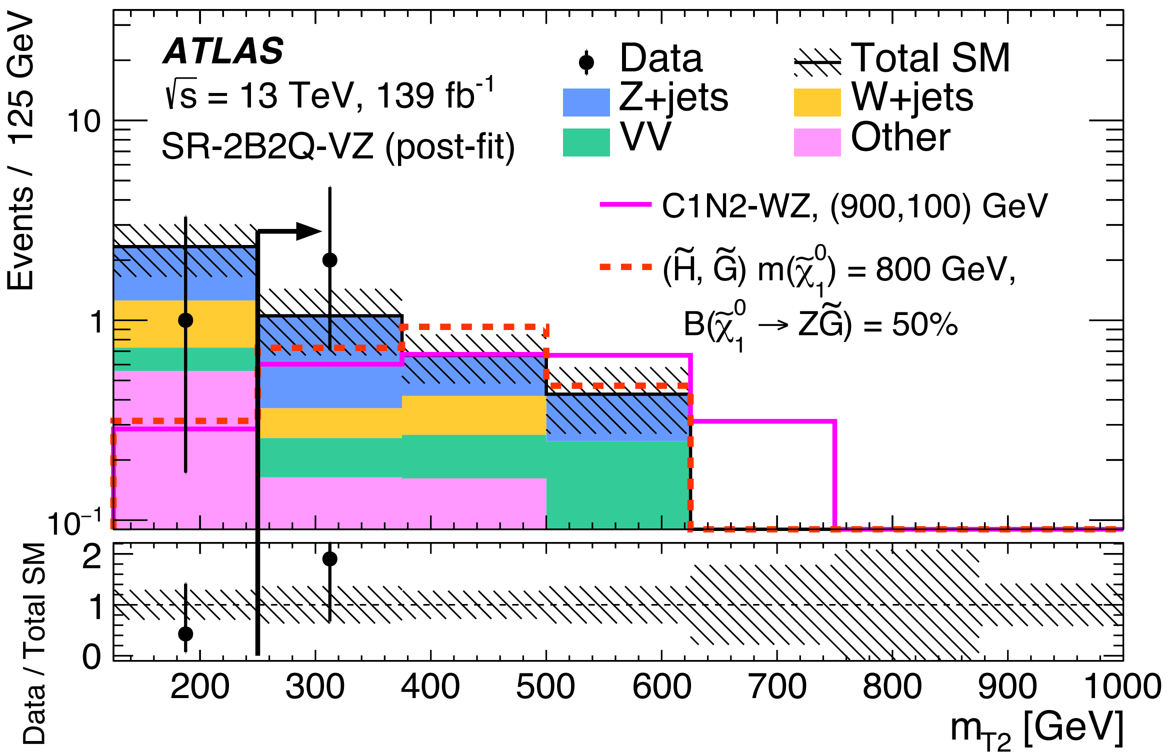
- 6 independent fits done in 0L4Q, 1L4Q, 1Y4Q, 0L2B2Q, 1L2B2Q, 1Y2B2Q category separately.
- A common NF assigned on the sum of reducible BGs in each fit.
- Uncertainty assigned per BG separately.
- Good agreement is found. Max deviation: 1.8σ deficit in VR1L-4Q, most likely due to the fluctuation.

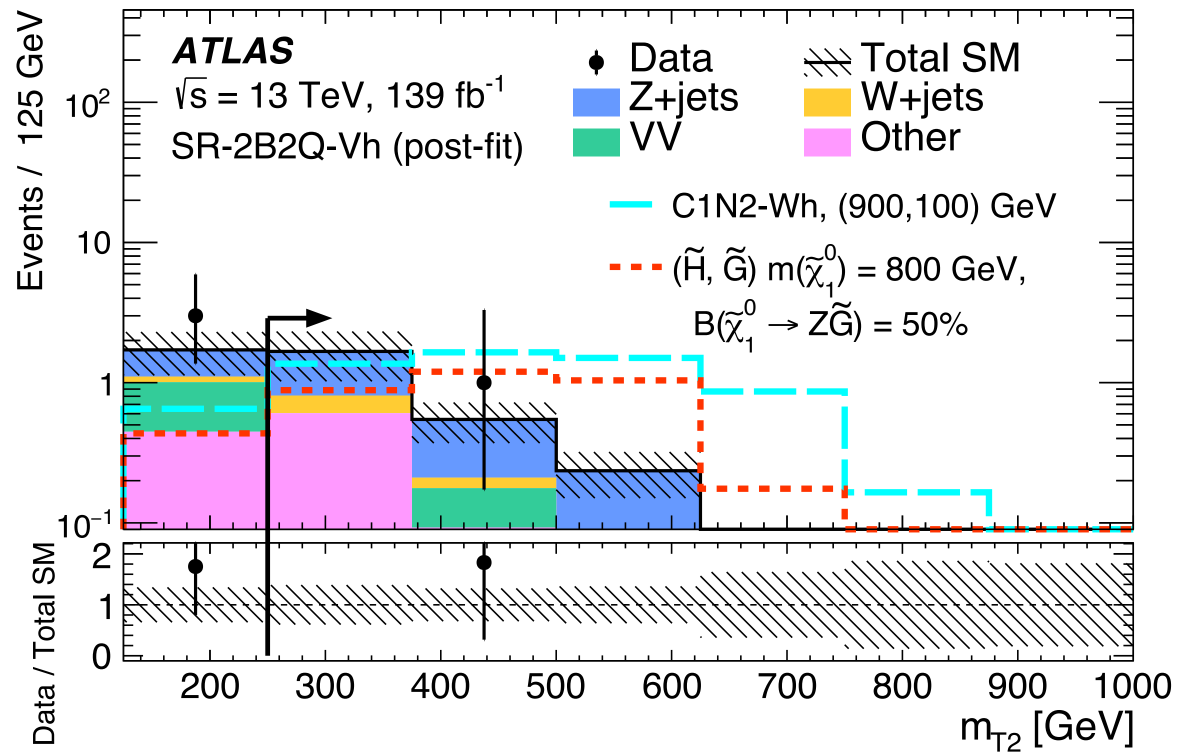
Kinematic distributions in VRs



Kinematic distributions in SRs







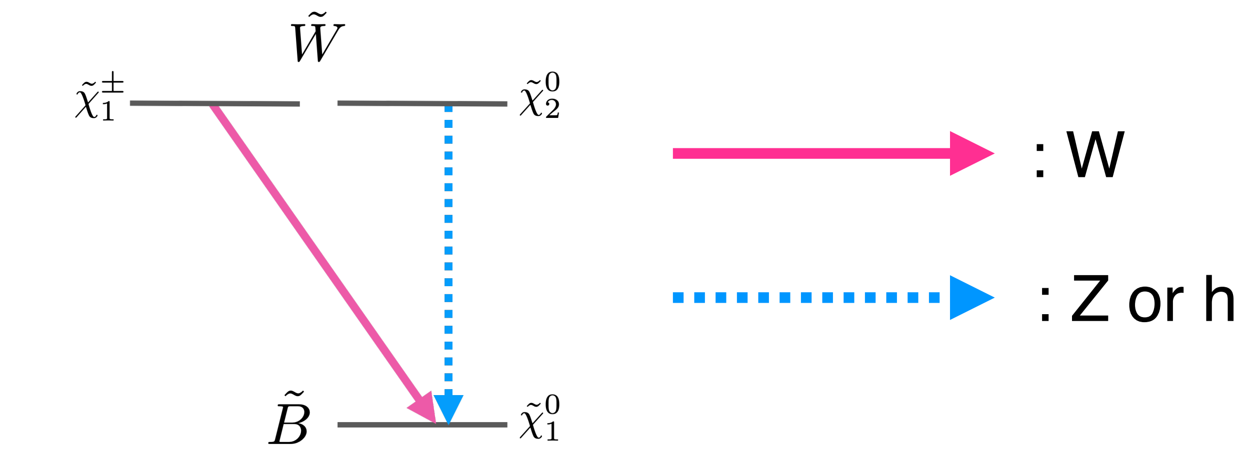
CR/SR yields in 0L regions

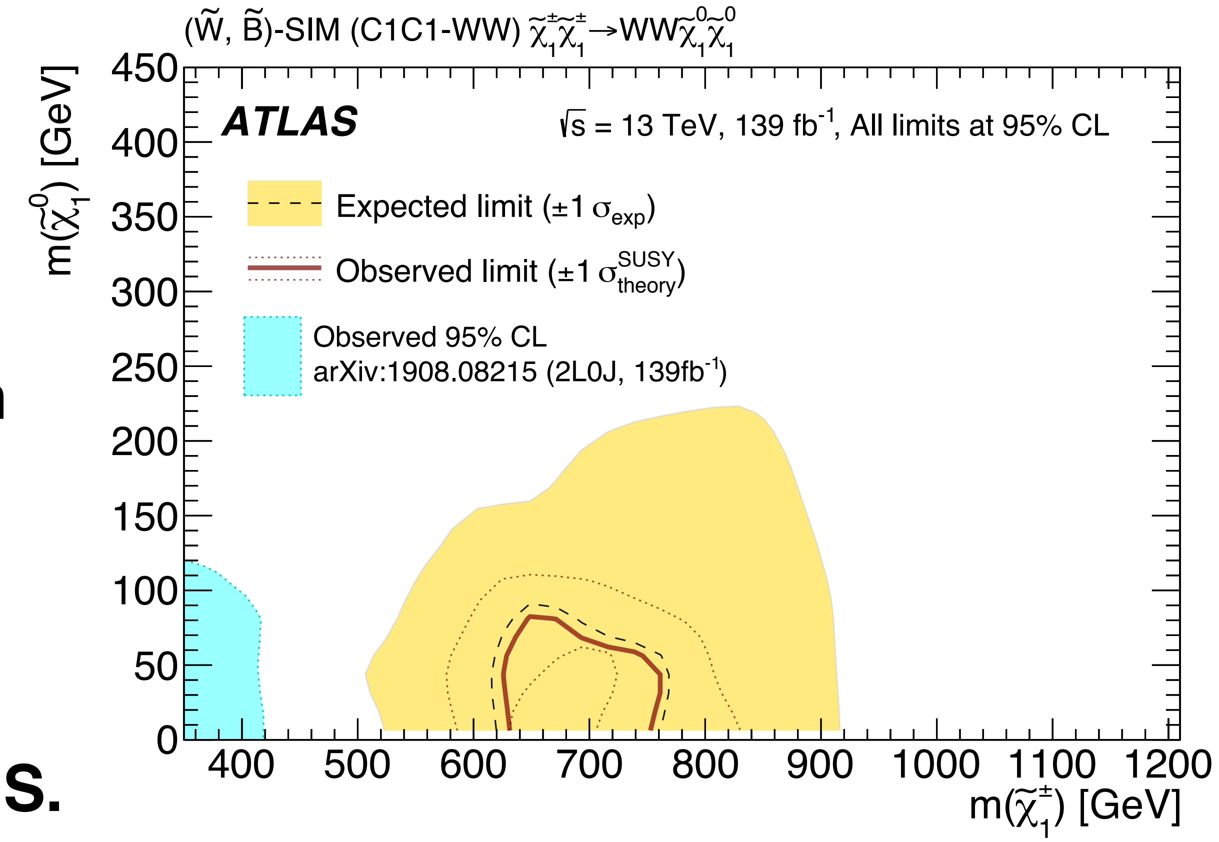
Region	CR0L-4Q	CR0L-2B2Q	SR-4Q-WW	SR-4Q-WZ	SR-4Q-ZZ	SR-4Q-VV
Observed	129	83	2	3	1	3
Post-fit	129 ± 11	83 ± 9	1.9 ± 0.4	3.4 ± 0.7	1.9 ± 0.5	3.9 ± 0.8
W+jets	24.2 ± 2.2	16.6 ± 2.0	0.37 ± 0.08	0.60 ± 0.13	0.26 ± 0.07	0.69 ± 0.15
Z+jets	78 ± 7	44 ± 5	1.0 ± 0.21	1.8 ± 0.4	1.26 ± 0.32	2.1 ± 0.4
VV	21.5 ± 1.9	7.1 ± 0.9	0.35 ± 0.11	0.73 ± 0.24	0.26 ± 0.09	0.79 ± 0.25
VVV	0.9 ± 0.4	0.10 ± 0.05	0.17 ± 0.09	0.19 ± 0.10	0.11 ± 0.07	0.23 ± 0.12
$t\bar{t}$	1.38 ± 0.12	7.8 ± 0.9	0.039 ± 0.009	0.060 ± 0.018	0.025 ± 0.010	0.063 ± 0.018
$t+X$	1.32 ± 0.12	2.87 ± 0.34	0.015 ± 0.006	0.039 ± 0.016	0.012 ± 0.005	0.039 ± 0.016
$t\bar{t}+X$	1.3 ± 0.9	3.7 ± 2.6	-	-	-	-
Other	< 0.1	0.95 ± 0.11	< 0.001	< 0.001	< 0.001	< 0.001

Region	SR-2B2Q-WZ	SR-2B2Q-Wh	SR-2B2Q-ZZ	SR-2B2Q-Zh	SR-2B2Q-VZ	SR-2B2Q-Vh
Observed	2	0	2	1	2	1
Post-fit	1.6 ± 0.4	1.9 ± 0.7	1.7 ± 0.5	1.6 ± 0.5	2.2 ± 0.6	2.5 ± 0.8
W+jets	0.11 ± 0.06	0.24 ± 0.09	0.23 ± 0.08	0.26 ± 0.10	0.26 ± 0.09	0.26 ± 0.09
Z+jets	0.84 ± 0.27	1.3 ± 0.5	0.78 ± 0.23	0.66 ± 0.24	1.15 ± 0.33	1.4 ± 0.5
VV	0.33 ± 0.11	0.09 ± 0.03	0.32 ± 0.10	0.085 ± 0.032	0.37 ± 0.11	0.085 ± 0.030
VVV	0.047 ± 0.027	< 0.01	0.051 ± 0.032	0.011 ± 0.007	0.06 ± 0.04	0.011 ± 0.007
$t\bar{t}$	0.016 ± 0.006	0.13 ± 0.04	0.064 ± 0.019	0.40 ± 0.16	0.072 ± 0.021	0.46 ± 0.18
$t+X$	0.11 ± 0.05	0.07 ± 0.04	0.11 ± 0.05	0.041 ± 0.022	0.11 ± 0.05	0.10 ± 0.05
$t\bar{t}+X$	0.10 ± 0.08	$0.07^{+0.10}_{-0.07}$	0.14 ± 0.12	$0.08^{+0.09}_{-0.08}$	0.18 ± 0.14	$0.10^{+0.11}_{-0.10}$
Other	< 0.01	0.03 ± 0.01	< 0.01	0.024 ± 0.008	< 0.01	0.037 ± 0.011

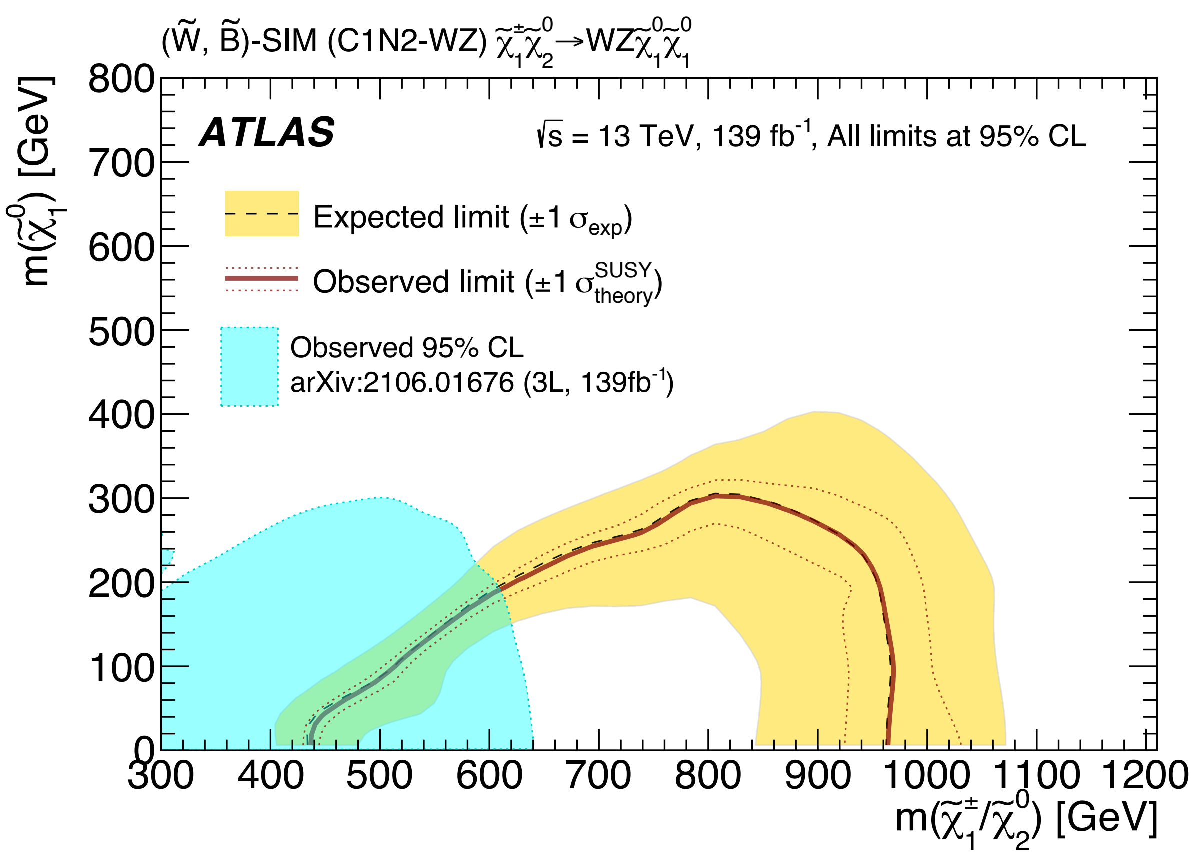
Exclusion limits : Simplified model

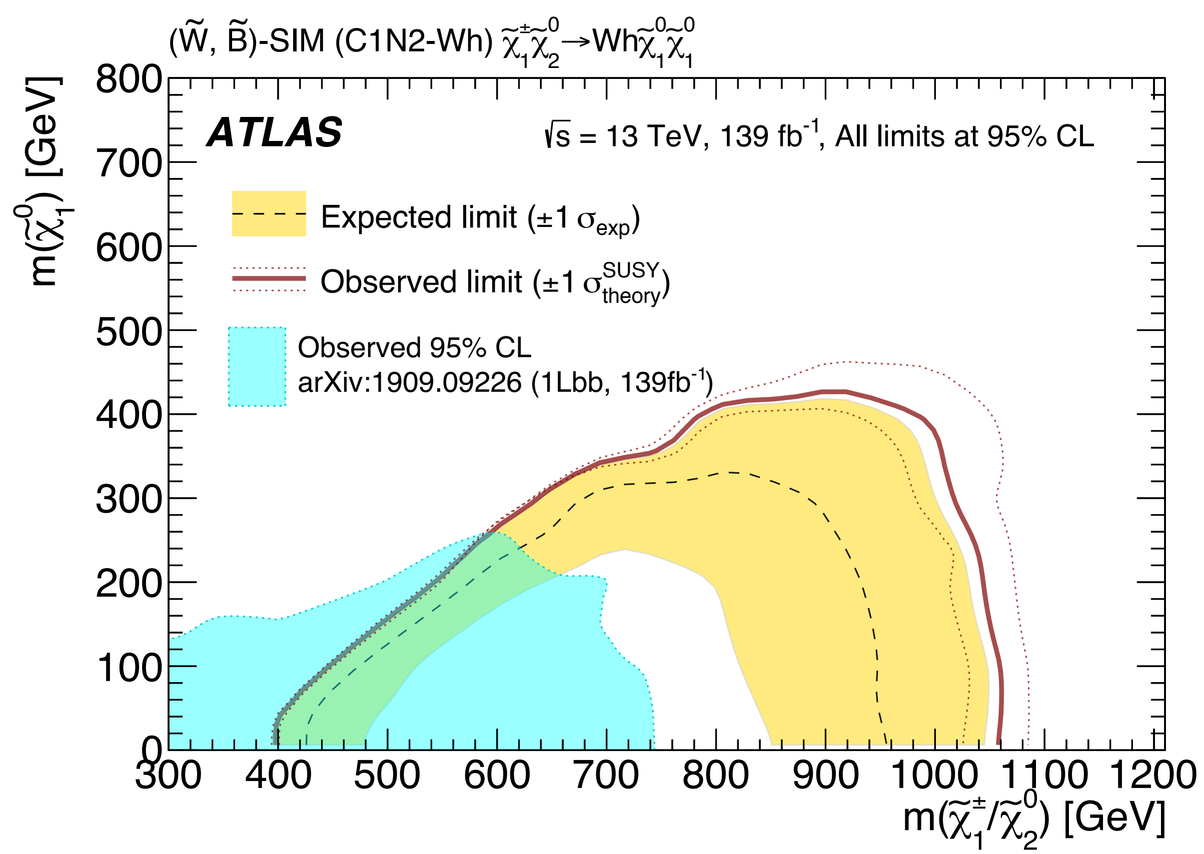
$(\tilde{W}, \tilde{B})$ simplified model





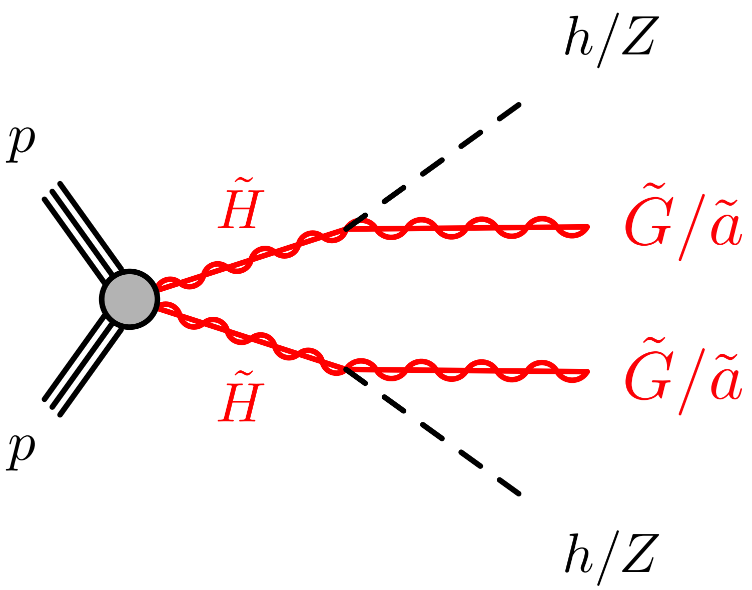
- **300-400 GeV improvement w.r.t. existing best limits by ATLAS/CMS.**



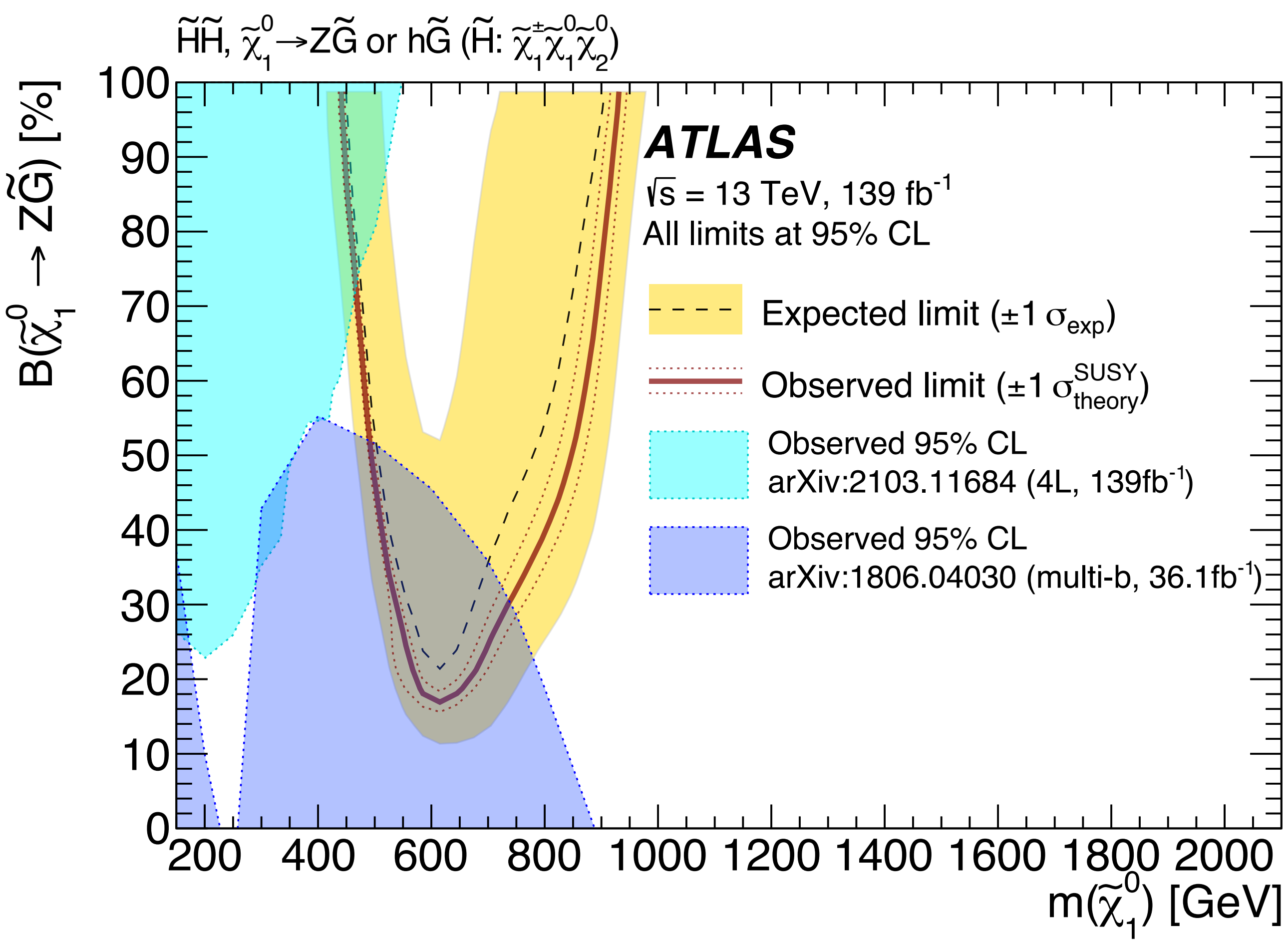


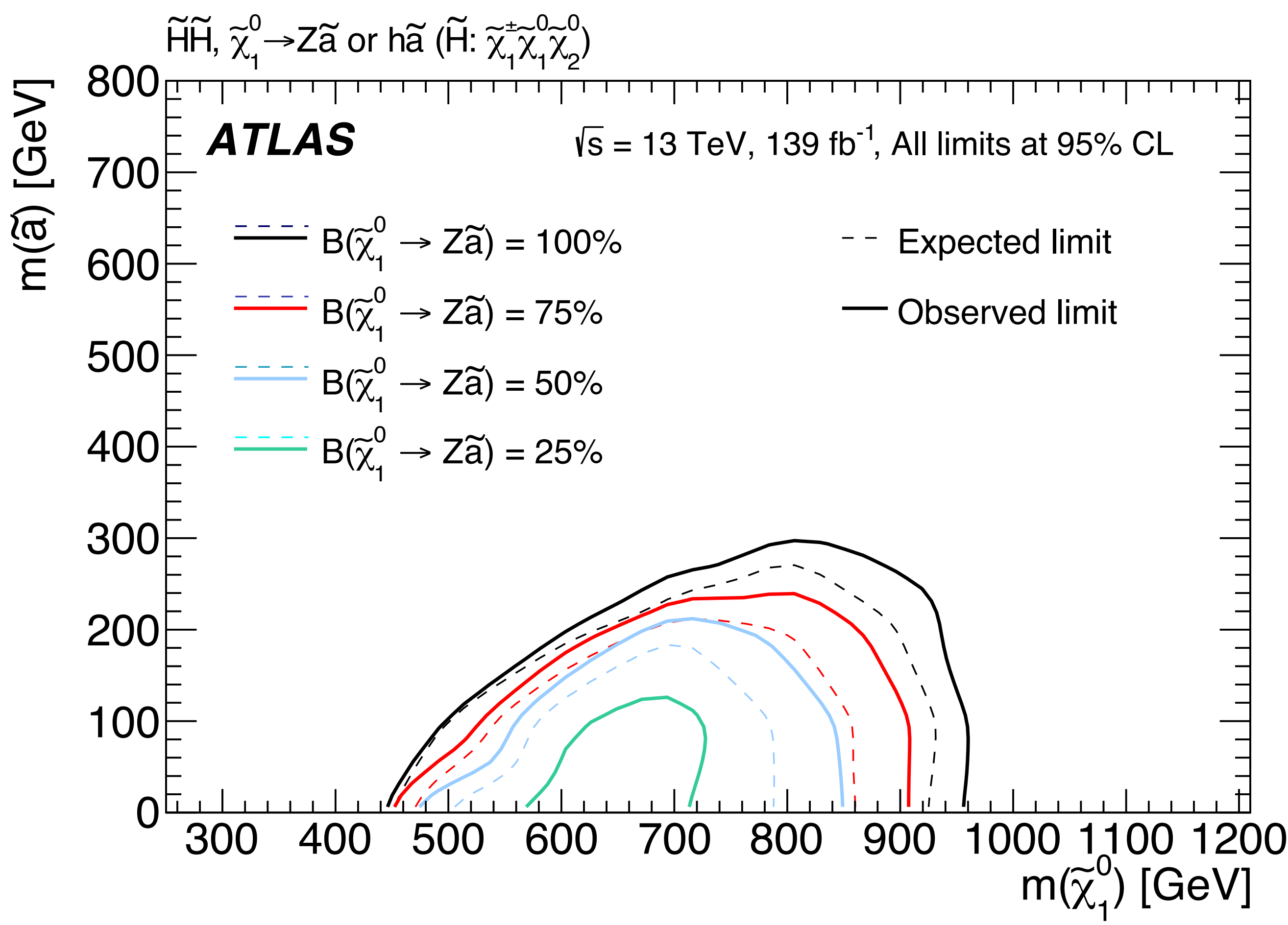
Exclusion limits : $(\tilde{H},\ \tilde{G}),\ (\tilde{H},\ \tilde{a})$

Naturalness driven GGM gravitino-LSP model / **Naturalness driven axino-LSP model**



- Light higgsino motivated by naturalness
- Considering small higgsino-gravitino (axino) coupling
  $\rightarrow \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ decays into $\tilde{\chi}_1^0$, then $\tilde{\chi}_1^0$ decays into $Z/h + \tilde{G}($
- Massless gravitino-LSP or massive axino-LSP
- Branching ratio to Z vs h is a free parameter





Upper limits on BSM signal cross sections

Model independent fit (calculated using toy MC)

Signal region	$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	S^{95}_{obs}	S^{95}_{exp}	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	0.50 (0.00)
SR-4Q-ZZ	0.025	3.6	$4.1^{+1.8}_{-1.0}$	0.30	0.50 (0.00)
SR-4Q-VV	0.034	4.7	$5.3^{+2.3}_{-1.5}$	0.38	0.50 (0.00)
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	0.50 (0.00)
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	0.50 (0.00)
SR-2B2Q-VZ	0.032	4.4	$4.4^{+1.8}_{-1.0}$	0.50	0.50 (0.00)
SR-2B2Q-Vh	0.026	3.6	$4.4^{+1.7}_{-1.0}$	0.24	0.50 (0.00)
Disc-SR-2B2Q	0.034	4.8	$5.6^{+2.4}_{-1.6}$	0.30	0.50 (0.00)
Disc-SR-Incl	0.042	5.9	$7.2^{+2.2}_{-2.0}$	0.27	0.50 (0.00)

Disc-SR-2B2Q : the logical union of SR-2B2Q-VZ and SR-2B2Q-Vh
Disc-SR-Incl : the logical union of SR-4Q-VV and Disc-SR-2B2Q