Search for compressed mass spectra in VBF signatures with the ATLAS detector

$\sqrt{s}$ = 13 TeV, 140 fb^{-1}, Run 2 full dataset

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Chinese High Energy Physics Association · 16th June 2026

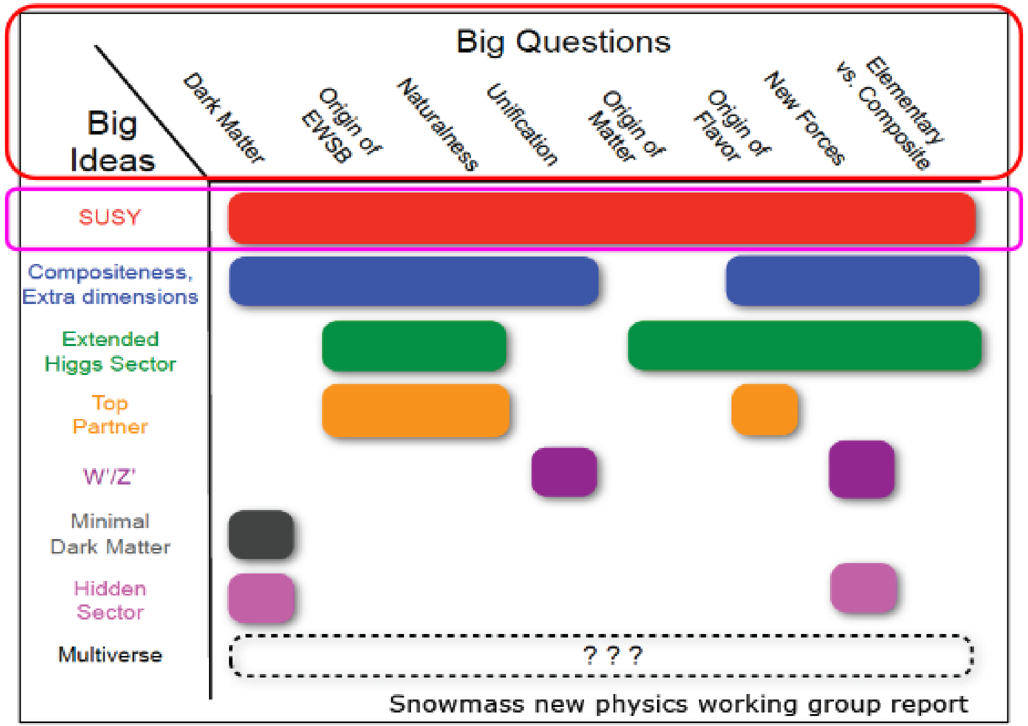
ATLAS Collaboration, JHEP 12 (2024) 116, arXiv:2409.18762

Introduction:

Why SUSY ?

- SM is the most successful framework
  But still harbors **inherent limitations**
- Provide Dark matter candidate
- Have unification of gauge coupling
- Solve the hierarchy problem
- … …

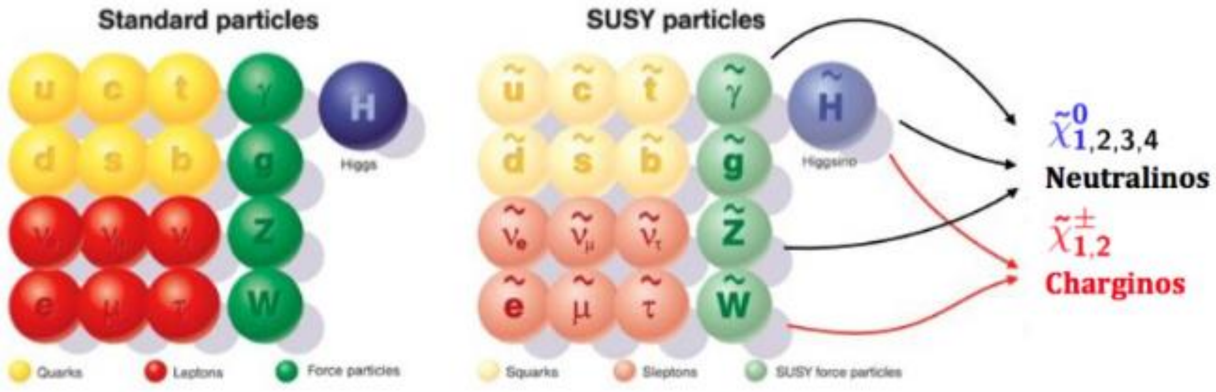
SUSY provides solution for most of the big questions



What is SUSY:

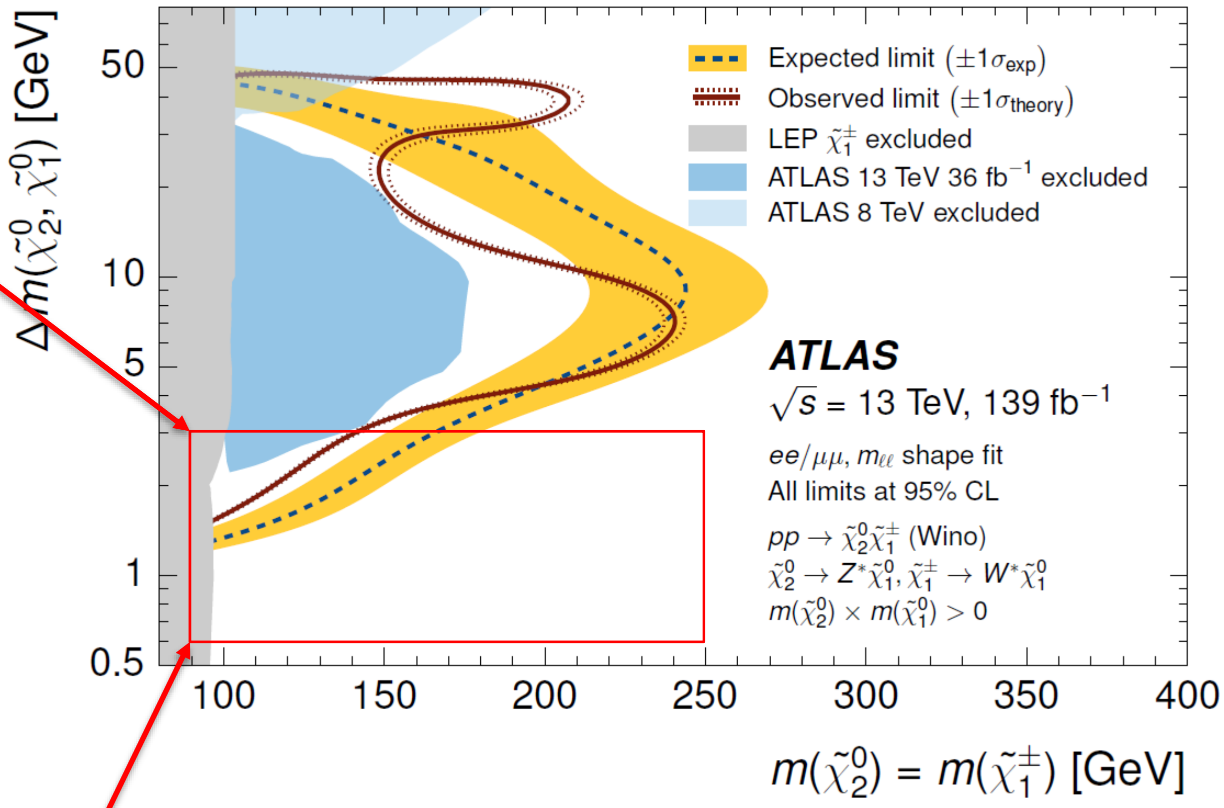
- Introduction of a symmetry between particles:
  $Boson \leftrightarrow Fermion$
- Extension of space and time:
  add fermionic coordinates

$$Q|Fermion\rangle = |Boson\rangle, \qquad Q|Boson\rangle = |Fermion\rangle$$



Physics motivation: naturalness and compressed spectra

- **Naturalness** favors light electroweakinos near the electroweak scale.
- $\Delta m(NLSP, LSP) < 2\ GeV$, decay products **too soft to reconstruct**.
- Existing searches (soft lepton, disappearing track) **lose sensitivity**.
- **VBF production** provides a unique probe — sensitivity from production mode, not decay: forward jets + E_T^{miss} + 0ℓ.
- ATLAS pMSSM scan confirms limited coverage for Δm < 2 GeV.



PhysRevD.101.052005

Goal: probe compressed models (Δm ≈ 0.2–3 GeV) via VBF production mode

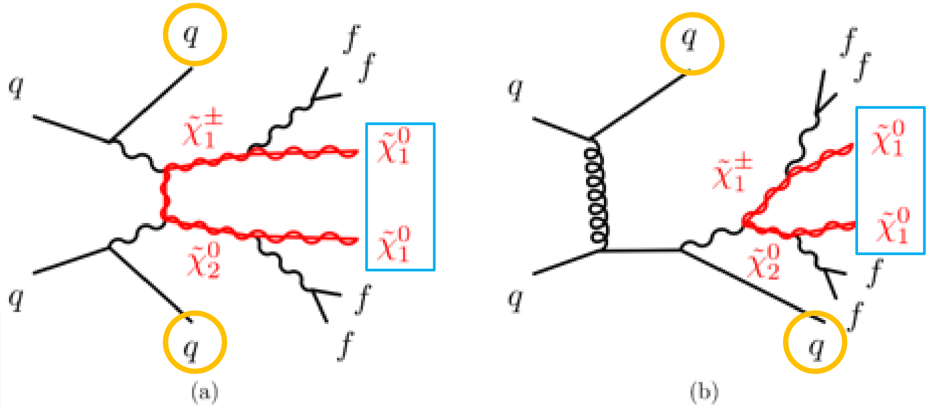
Signal model: bino LSP + wino NLSP

Particle spectrum

$\tilde{\chi}_1^0$ — LSP (DM candidate), **bino-like**

$\tilde{\chi}_2^0$, $\tilde{\chi}_1^+$, $\tilde{\chi}_1^-$ — NLSPs (mass degenerate), **wino-like**

Decay via off-shell W*/Z* → soft fermions (unreconstructable)



m(NLSP): **75–175 GeV**

Δm(NLSP, LSP): **0.2–5 GeV**

Final state:

2 forward VBF tagging jets + $\boxed{\text{large } E_T^{miss}}$ + zero leptons

Decay products too soft to be reconstructed — signature comes entirely from production mode

Pure-EWK and mixed QCD-EWK diagrams share identical initial/final states → Dedicated cross-section estimation

Event selection

Preselection

Selection Type	Selections	Comments
Trigger	Inclusive E_T^{miss}	offline > 200 GeV, >95% eff.
Jet p_T	$p_T(j_1) > 80, p_T(j_2) > 40\ GeV$	$\lvert\eta\rvert < 4.5$
VBF topology	$\lvert\Delta\eta_{jj}\rvert > 3.0, m_{jj} > 600\ GeV$	
Angular	$min[\Delta\varphi(jet, p_T^{miss})] > 0.4$	suppress QCD multijet
Vetoes	zero e/μ, zero b-jets, zero τ_{had}	

Signal region

Selection Name	Cuts	Comments
E_T^{miss}	> 250 GeV	
Jet Number	= 2 jets	enriched in pure-EWK processes
	≥ 3 jets	retain acceptance for SUSY production with QCD vertices
Lepton Number	= 0	
BDT score	[0.60, 1.00]	8 bins
	[0.88, 1.00]	single-bin

BDT Configuration & Variable Importance

Why BDT instead of simple 1D m_{jj} fit?

1D m_{jj} fit: sensitivity worse than LEP limit.

Multivariate BDT exploits VBF kinematic correlations for better S/B separation.

14 Training Variables

Kinematics(8):	$E_T^{miss}, m_{jj}, p_T(j_1), p_T(j_2), \Delta\eta_{jj}, \Delta\varphi_{jj}, p_T(j_1) + p_T(j_2), \frac{pT(j_1) + pT(j_2)}{E_T^{miss}}$
Angular(3):	$\Delta\phi\left(jj, p_T^{miss}\right), \min\left[\Delta\phi\left(j, p_T^{miss}\right)\right], \Delta\phi(p_T^{miss}, jets)$
Transverse mass(3):	$m_T(j_1), m_T(j_2), m_T(j_1) + m_T(j_2), weighted\ sum\ of\ m_{jj}\ and\ E_T^{miss}$

Training Configuration

Validation: k=5 cross-validation, no overtraining

Training signal: m(NLSP)=100 GeV, Δm=1 GeV

Hyperparameters: num_leaves=31, lr=0.05, n_estimators=500

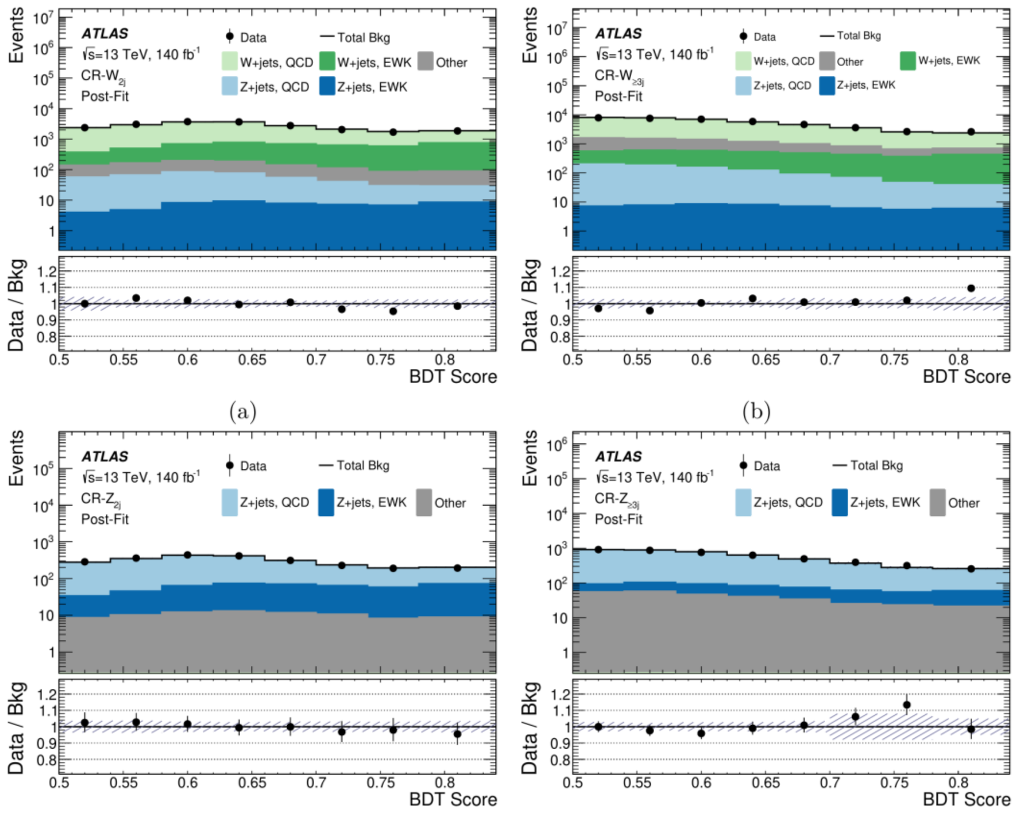
2j / ≥3j: trained and normalised independently

Background Contaminations & Estimation

Z(→νν)+jets and **W(→ℓν)+jets**: Sherpa MC, CR normalised.

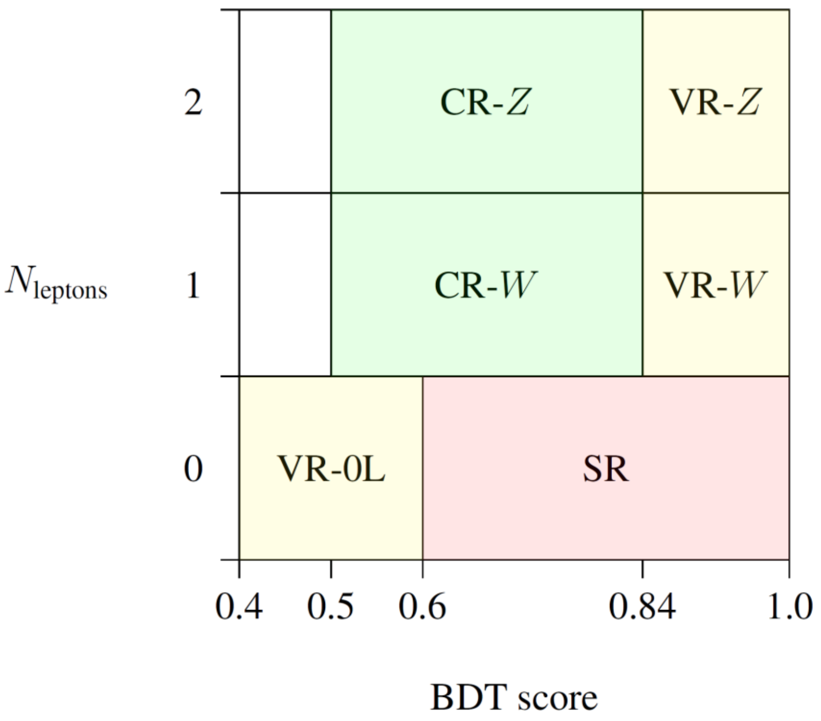
QCD multijet: data-driven ABCD (~few% in SR).

Other backgrounds: Top, diboson, triboson: MC simulation.



CR-W / CR-Z post-fit BDT

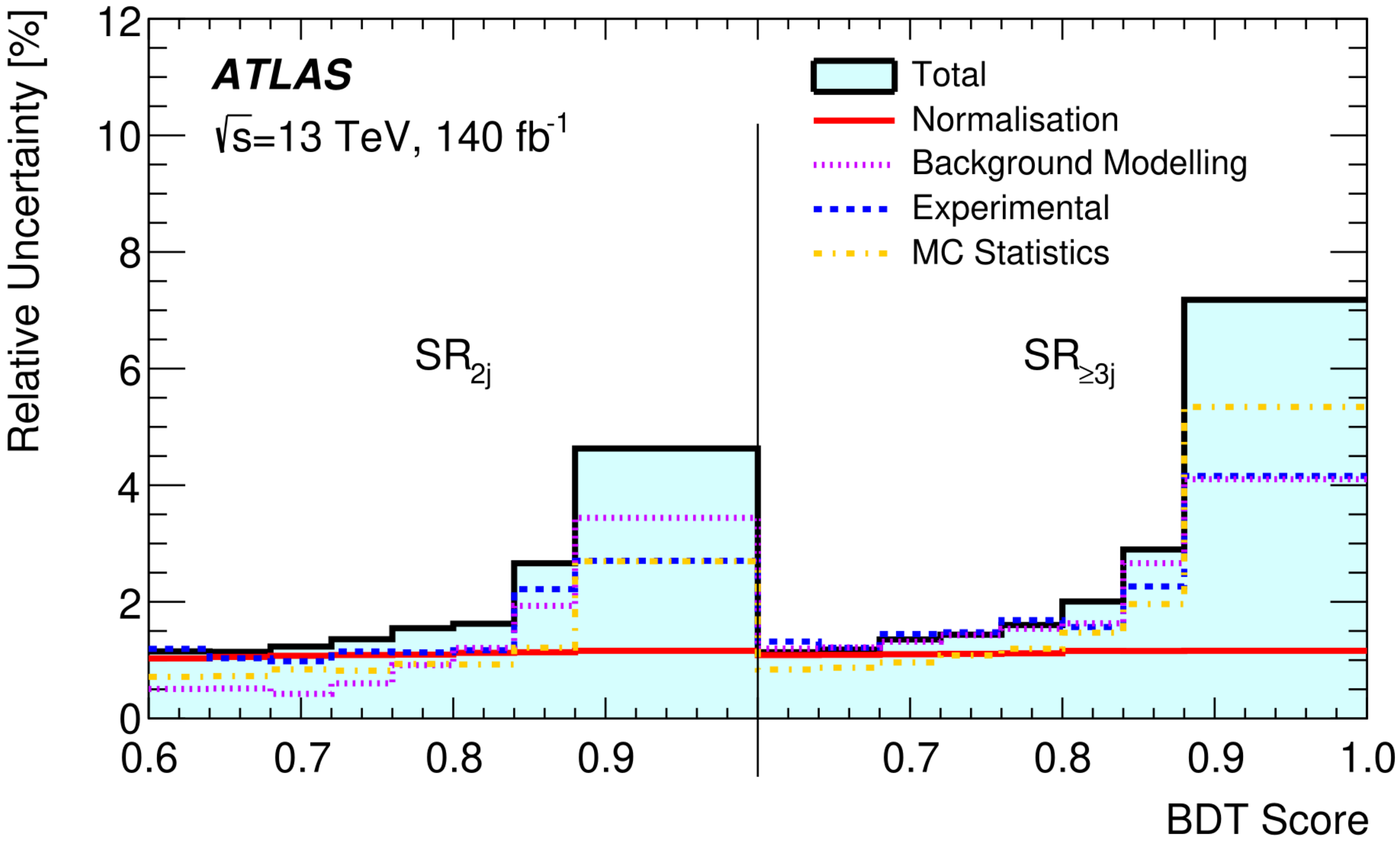
CRs and VR



Region	CR$-W$	CR$-Z$
$2j$	0.800 ± 0.007	0.829 ± 0.018
$\geq 3j$	0.986 ± 0.013	1.046 ± 0.019

Details for ABCD method shown in backup

Systematic uncertainties



Total uncertainty 1–7%.

Comparable contributions:

Normalisation
~2–5%

Bkg modelling
~2–5%

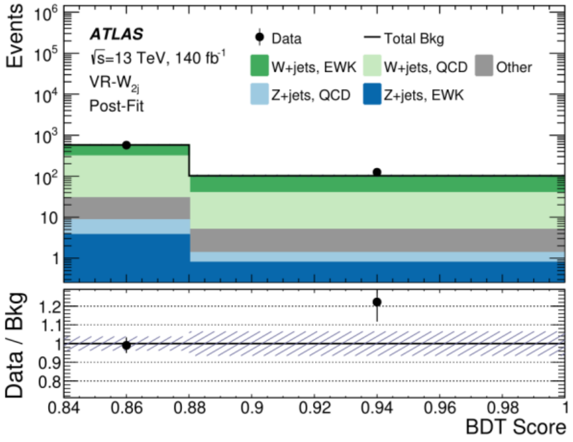
Experimental
~1–3%

MC statistics
~1–2%

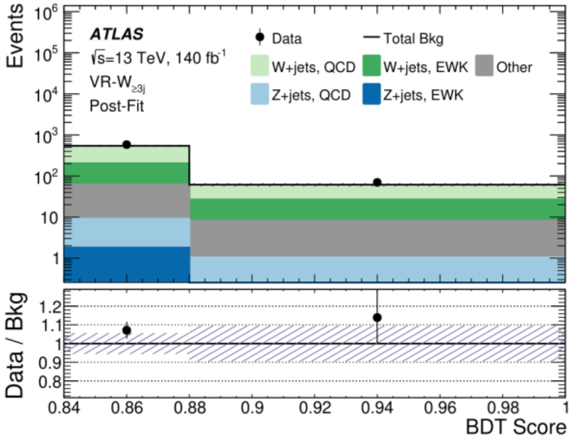
Muon reconstruction efficiency — largest single experimental uncertainty (affects CR-Z normalisation)

Validation regions

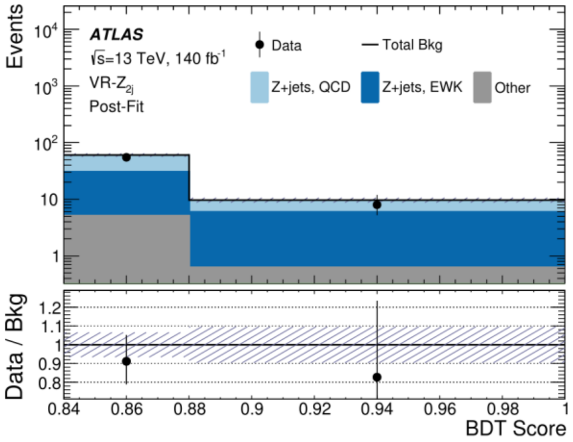
VR-W / VR-Z BDT



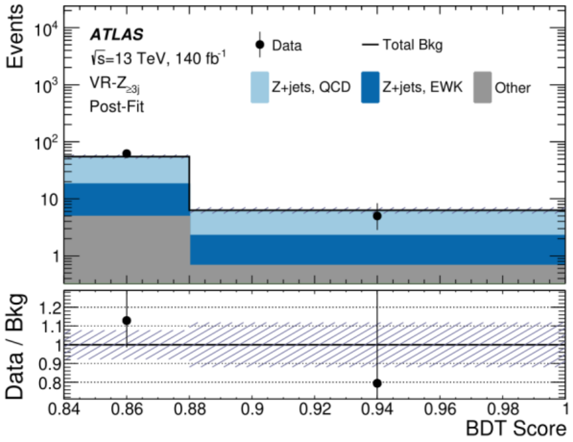
(a)



(b)

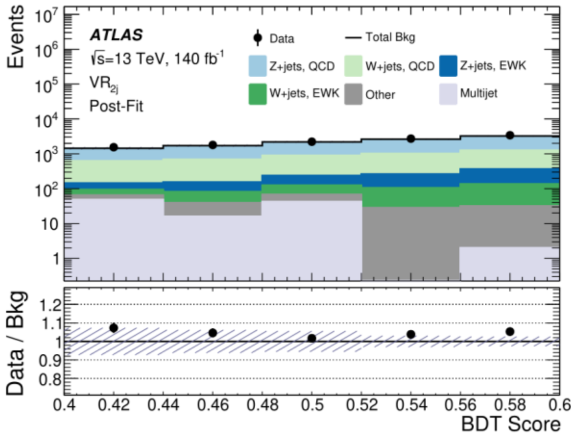


(c)

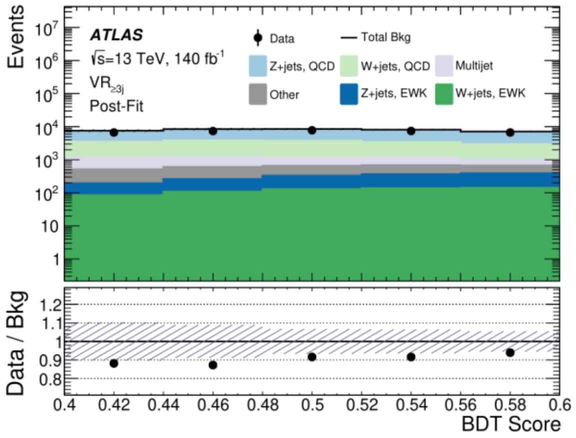


(d)

VR-0L BDT



(a)



(b)

good data/MC agreement

Signal region: single-bin results

Single-bin SR: BDT ∈ $[0.88, 1.00]$. No significant excess observed.

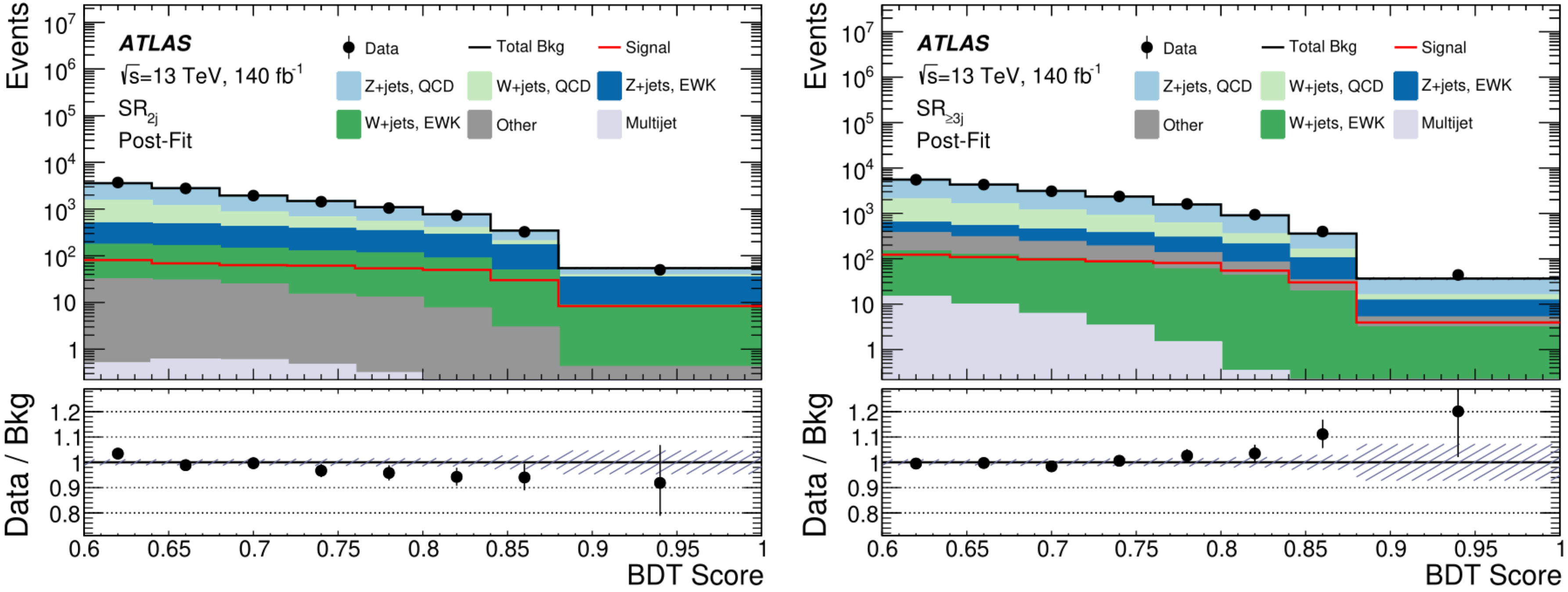
Maximum significance ~0.88σ (p = 0.19, $SR_{\geq 3j}$)

Single-Bin Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
SR_{2j}	50	55.9 ± 3.7	0.09	13.1	$17.7^{+7.3}_{-5.2}$	0.50
$\mathrm{SR}_{\geq 3j}$	44	39.8 ± 4.3	0.18	24.9	$18.5^{+8.6}_{-5.8}$	0.19

$\langle\epsilon\sigma\rangle^{95}_{obs}$: the constraints on contributions from BSM physics to the target phase space
S^{95} : the signal events

Signal region: Multi-bins (post-fit)

- 8 bins in total: 7 equal-width bins + Singal bin SR
- The last bin [0.88, 1.00] is the most sensitive.
- Signal yields shown for $100\ GeV\ \ \tilde{\chi}_2^0$for $\Delta m = 1\ GeV$

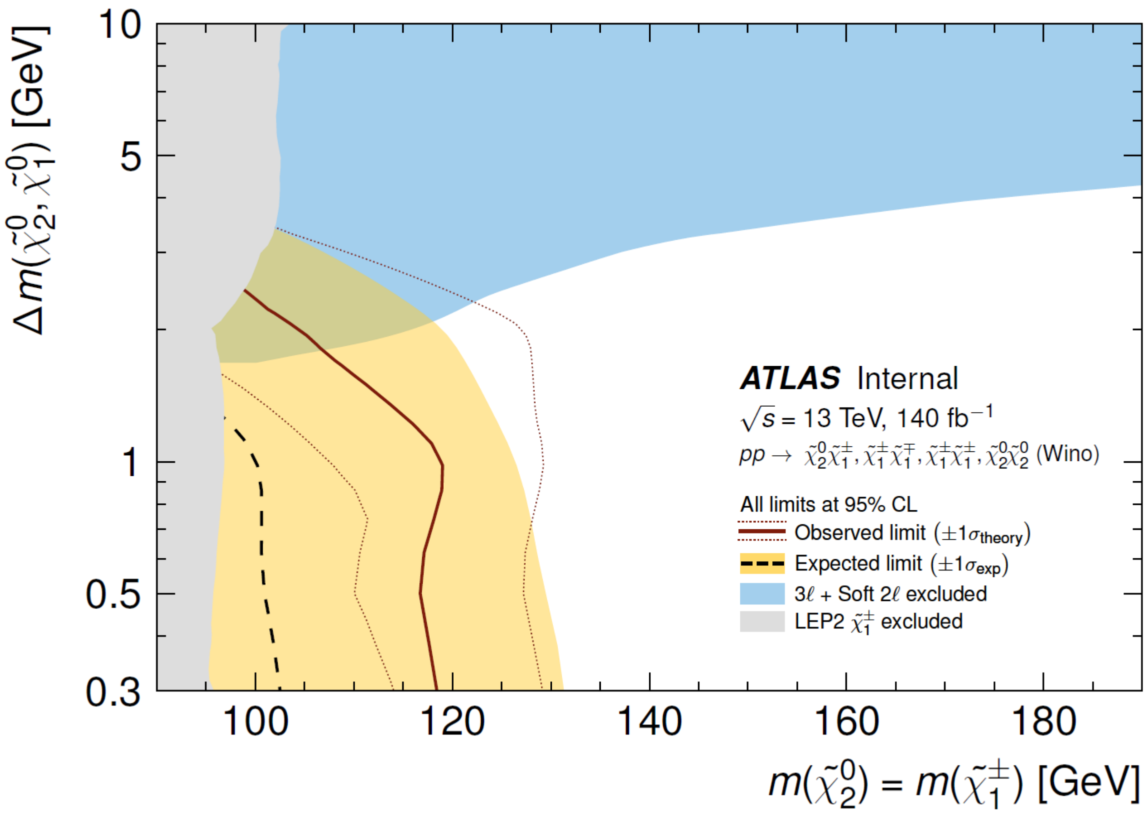


(a) (b)

Profile likelihood fit → CLs method → 95% CL exclusion limits

Exclusion limits: wino NLSP + bino LSP

95% CL exclusion in the $(m(\tilde{\chi}_2^0/\tilde{\chi}_1^\pm), \Delta m)$ plane. Simultaneous fit of CRs and SRs.



Result

Observed limit:

m(NLSP) < 117 GeV

for Δm < 1 GeV

Expected: 100–104 GeV

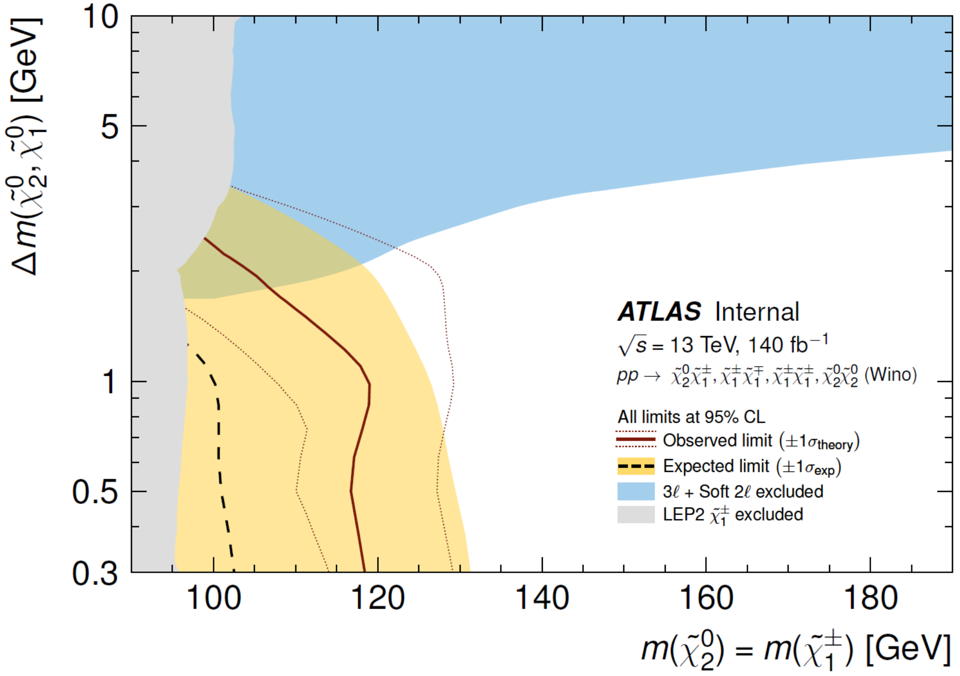
Slightly stronger than expected due to mild deficit in SR_{2j}

LEP: ~92 GeV

→ ~25 GeV beyond LEP

Summary

- **First search** for compressed wino-bino SUSY in VBF final states with the ATLAS detector, using $140\ fb^{-1}$ of Run 2 data.
- No significant excess observed;
  Upper limits are set at 95% CL using the CLs method.
- Fills the $\Delta m\ <\ 2\ GeV$ probe gap
  — complementary to soft lepton and disappearing track searches.
- $\boldsymbol{m(NLSP)\ <\ 117\ GeV}$ excluded for $\Delta m\ <\ 1\ GeV$, extending **~25 GeV beyond LEP**.
- Model-independent limits: $\langle\epsilon\sigma\rangle_{obs}^{95}\ =\ 0.09\text{–}\ 0.18\ fb$
- CMS VBF results shown in backup



[ATLAS Collaboration, JHEP 12 (2024) 116, arXiv:2409.18762]

Thanks

Questions?

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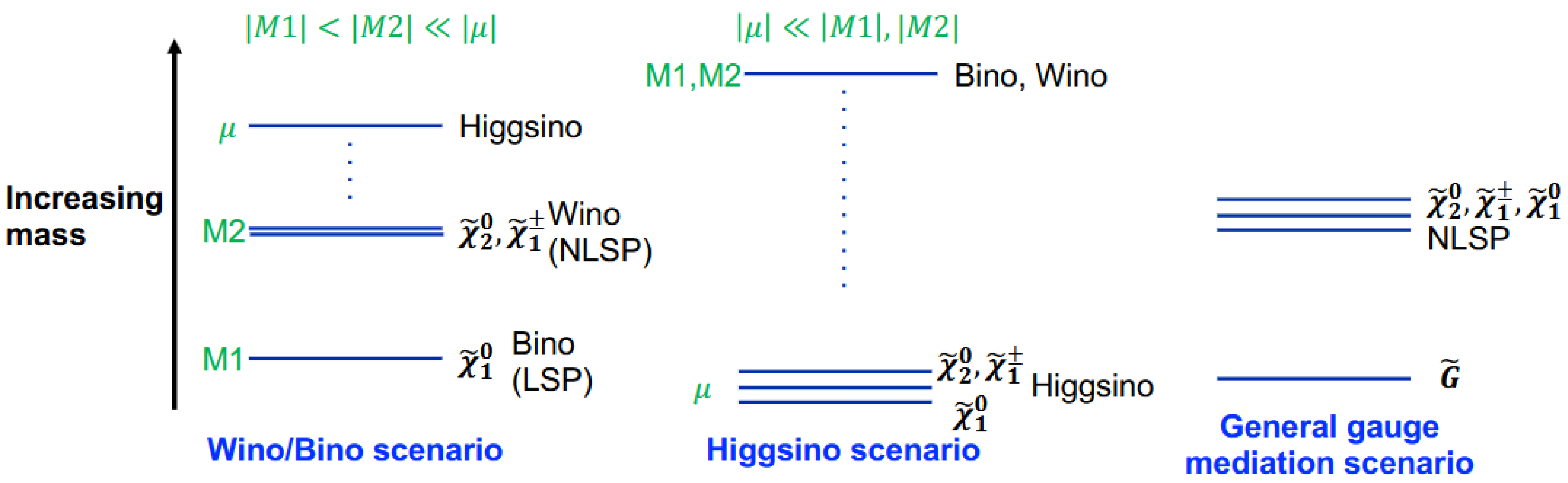
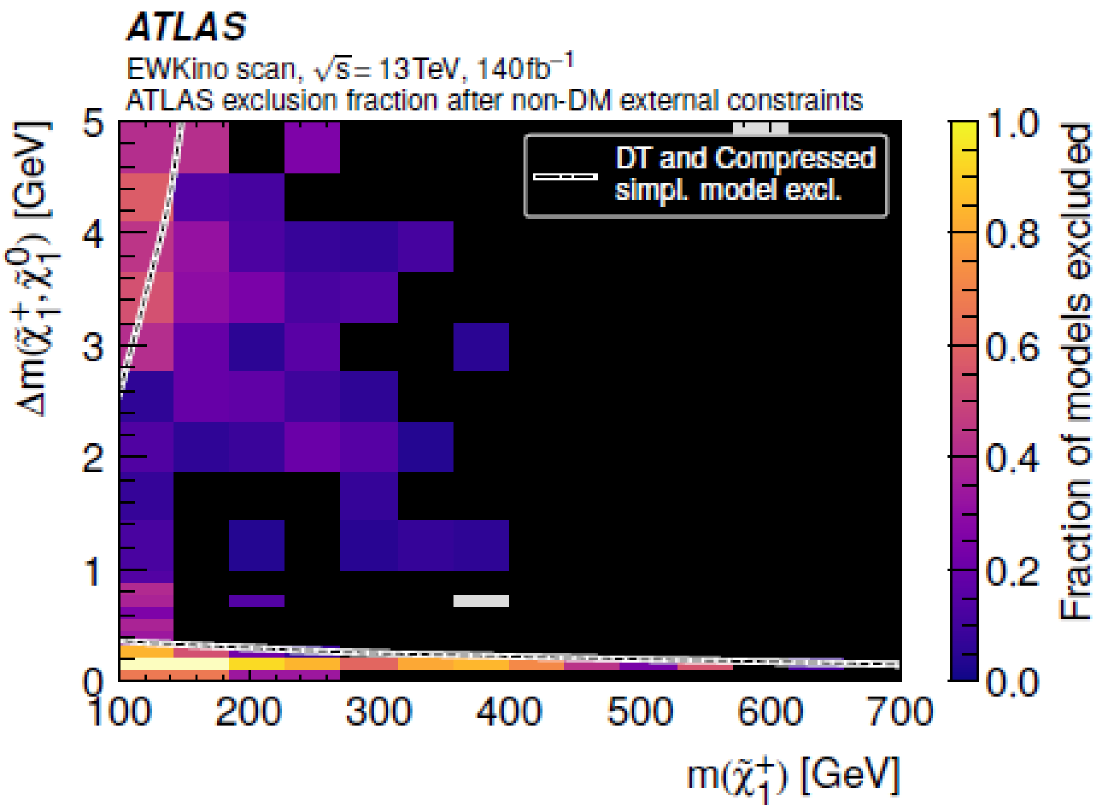
ATLAS Collaboration, JHEP 12 (2024) 116, arXiv:2409.18762

SUSY

- **Progressively stringent constraints on strong-production SUSY** (upper limits on masses up to ~ TeV)
  - **Electroweak-production SUSY** are **key analyses** to search for SUSY
- Wino, Bino, Higgsino mixing → **2 charginos $\tilde{\chi}_i^{\pm}$** + **4 neutralinos $\tilde{\chi}_i^0$** → different possible mass spectrum in different scenarios



ATLAS pMSSM Scan



CMS Partial Run 2 Result (35.9 fb^{-1})

CMS initially reported unexpectedly strong limits for VBF compressed SUSY — far stronger than theoretical expectations for the Run 2 partial dataset.

Root cause: CMS neglected QCD-EW interference

→ Over a year of discussions to identify the issue

ATLAS Treatment (This Analysis)

MadGraph5_aMC@NLO generates pure EW VBF and mixed QCD-EW processes separately, combined with proper quantum mechanical interference.

Gauge invariance & PDF convolution preserved

Theory uncertainty: pure EW ~10%, mixed ~25%

At high mjj (> 5 TeV), interference can change σ by factor ~2 — proper treatment essential

Three complementary searches cover the full compressed Δm range

Soft lepton (3ℓ+2ℓ)

Δm > a few GeV · Limited by lepton pT

Disappearing track

Δm ~ 0.3 to few GeV · Requires long-lived $\tilde{\chi}_1^+$

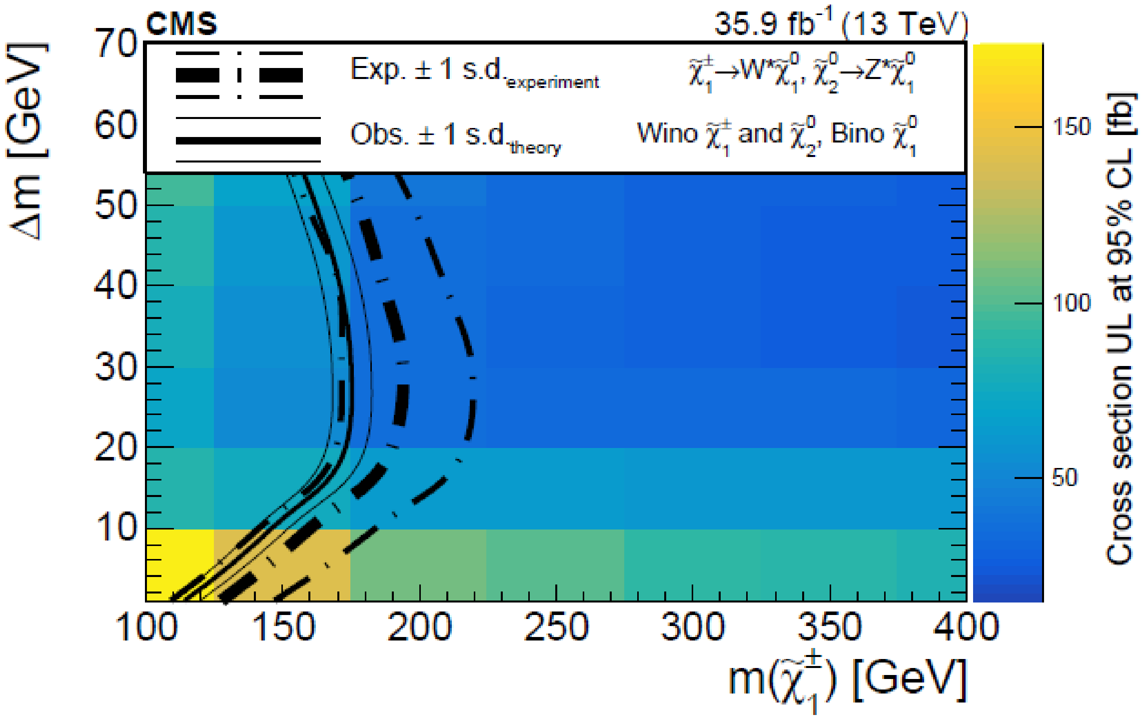
This analysis (VBF)

Δm ~ 0.2–3 GeV · Independent of decays

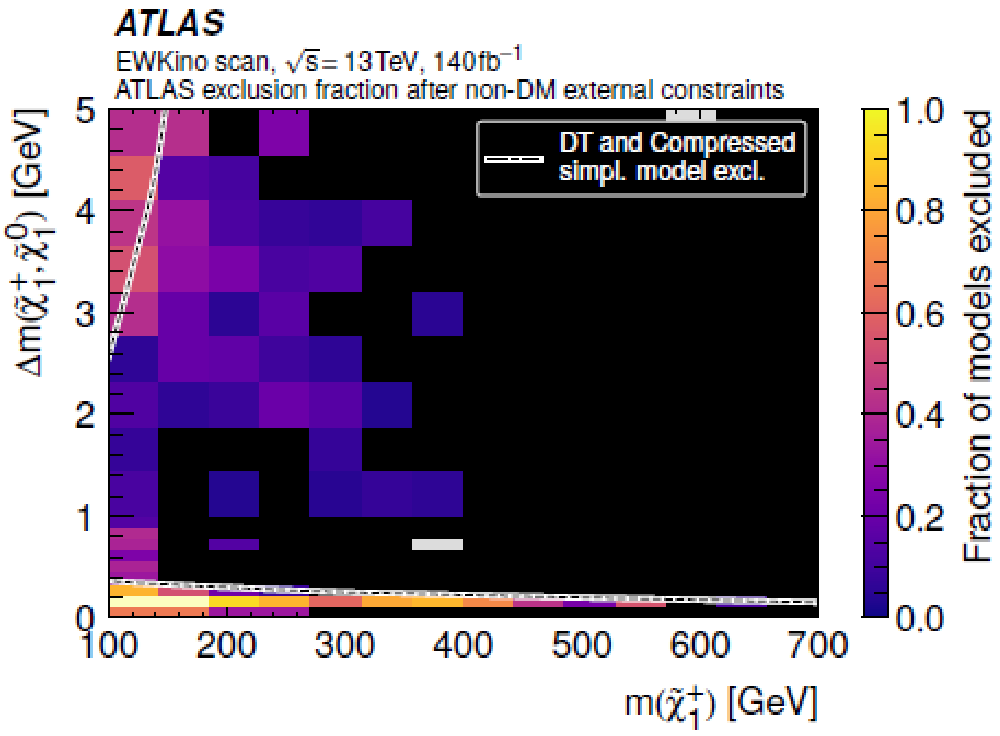
Proper interference treatment + VBF production mode → reliable exclusion limits filling the Δm gap

Reference: CMS SUS-16-047; ATLAS JHEP 12 (2024) 116, arXiv:2409.18762

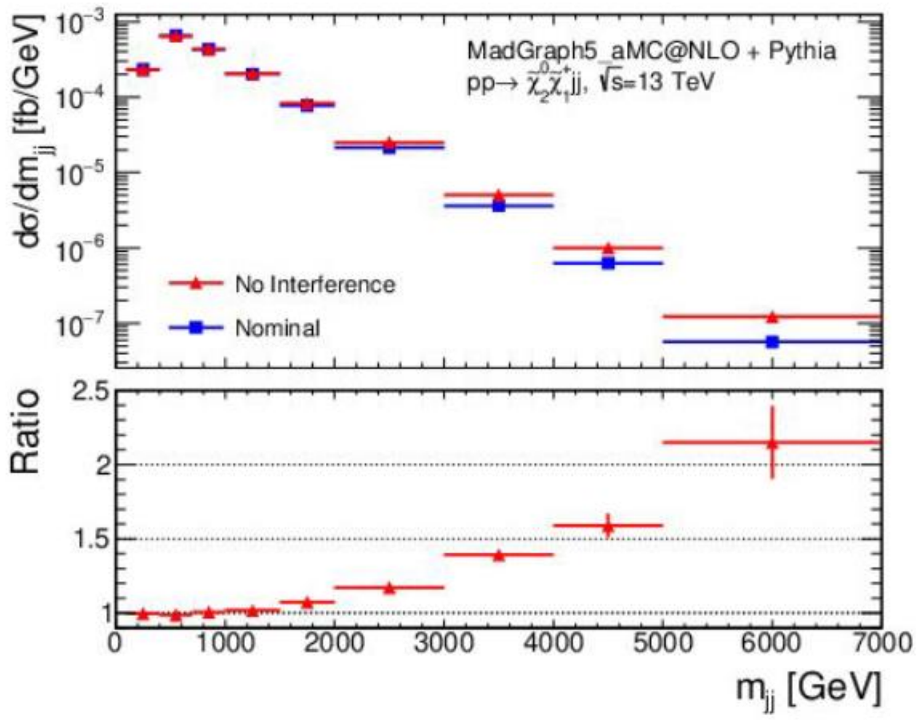
Cross-Checks: CMS Interference



ATLAS pMSSM Scan



VBF tag: a pair of jets with largest value of m_{jj} and opposite signed pseudo-rapidity

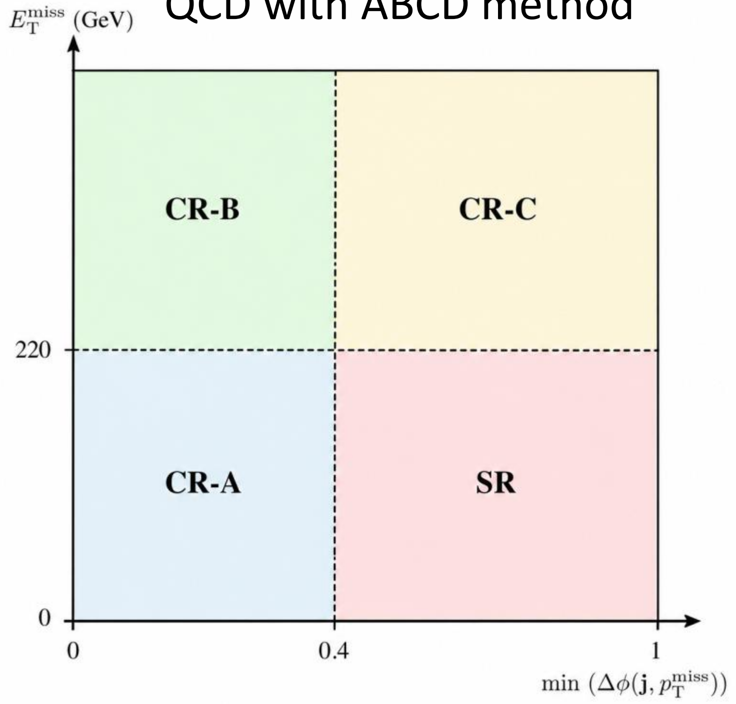


Background Estimation: QCD Multijet (ABCD Method)

ABCD Region Definitions and Transfer Factor

$$N_{\mathrm{SR}} = \frac{N_{\text{CR-C}}^{\text{data}} - N_{\text{CR-C}}^{\text{MC}}}{N_{\text{CR-B}}^{\text{data}} - N_{\text{CR-B}}^{\text{MC}}} \left(N_{\text{CR-A}}^{\text{data}} - N_{\text{CR-A}}^{\text{MC}}\right)$$

QCD with ABCD method



Key Points

QCD contribution in SR: **~few %**

Very small compared to V+jets backgrounds

Large uncertainties: **~100%**

Dominated by V+jets MC subtraction

Validated in 220 < ETmiss < 250 GeV region

ABCD significantly improves on MC-only estimates

Post-Fit Yields in Signal Regions

SR_{2j}

BDT Score	[0.60, 0.64)	[0.64, 0.68)	[0.68, 0.72)	[0.72, 0.76)	[0.76, 0.80)	[0.80, 0.84)	[0.84, 0.88)	[0.88, 1.0]
Observed events	3712	2774	1946	1441	1054	729	326	50
Fitted SM events	3590 ± 40	2806 ± 32	1953 ± 24	1490 ± 20	1100 ± 17	774 ± 13	347 ± 9	54.4 ± 2.5
Z + jets, QCD	2104 ± 34	1648 ± 28	1117 ± 22	826 ± 15	576 ± 12	387 ± 10	145 ± 6	16.8 ± 1.1
W + jets, QCD	993 ± 30	691 ± 23	422 ± 18	292 ± 11	190 ± 10	108 ± 7	36.6 ± 3.4	3.7 ± 0.7
Z + jets, EWK	322 ± 8	307 ± 6	273 ± 5	249 ± 5	224 ± 6	192 ± 6	117 ± 5	25.4 ± 1.9
W + jets, EWK	139 ± 3	131 ± 3	117 ± 3	109 ± 3	98 ± 3	79 ± 3	45 ± 2	8.1 ± 0.6
Other	30 ± 7	28 ± 7	23 ± 5	14.0 ± 3.2	12.3 ± 3.0	7.2 ± 1.6	2.8 ± 0.7	0.4 ± 0.1
Multijet	$0.5^{+1.6}_{-0.5}$	$0.6^{+1.9}_{-0.6}$	$0.6^{+1.8}_{-0.6}$	$0.5^{+1.4}_{-0.5}$	$0.3^{+1.0}_{-0.3}$	$0.2^{+0.5}_{-0.2}$	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.1}_{-0.0}$

$\mathrm{SR}_{\geq 3j}$

BDT Score	[0.60, 0.64)	[0.64, 0.68)	[0.68, 0.72)	[0.72, 0.76)	[0.76, 0.80)	[0.80, 0.84)	[0.84, 0.88)	[0.88, 1.0]
Observed events	5504	4295	3068	2358	1611	936	398	44
Fitted SM events	5530 ± 60	4310 ± 50	3120 ± 40	2344 ± 34	1570 ± 25	904 ± 18	358 ± 10	36.6 ± 2.6
Z + jets, QCD	3530 ± 80	2740 ± 60	1980 ± 40	1481 ± 33	974 ± 24	564 ± 18	202 ± 10	21.3 ± 2.1
W + jets, QCD	1390 ± 60	1050 ± 40	708 ± 29	503 ± 21	310 ± 17	138 ± 8	55 ± 5	3.6 ± 0.7
Z + jets, EWK	249 ± 5	226 ± 4	204 ± 5	177 ± 4	154 ± 4	121 ± 4	68 ± 3	6.7 ± 0.8
W + jets, EWK	129 ± 5	111 ± 4	93 ± 3	77 ± 2	56 ± 2	42 ± 2	19 ± 1	2.9 ± 0.4
Other	220 ± 50	170 ± 40	131 ± 30	103 ± 24	74 ± 18	40 ± 10	14 ± 4	2.0 ± 0.5
Multijet	10^{+50}_{-10}	10^{+31}_{-10}	6^{+19}_{-6}	3^{+10}_{-3}	1^{+4}_{-1}	$0.3^{+1.1}_{-0.3}$	$0.0^{+0.0}_{-0.0}$	$0.1^{+0.4}_{-0.1}$

Key Observations

Z+jets (QCD) dominant background in all bins
~60% of total in 2j, ~65% in ≥3j

QCD multijet contribution: ~few % at most
Negligible compared to V+jets backgrounds

Highest BDT bin [0.88, 1.0] is most sensitive
Used as single-bin "discovery" region

SR_2j: mild deficit in highest bin (50 obs vs 54.4 exp), p(s=0)=0.50
SR_≥3j: mild excess in highest bin (44 obs vs 36.6 exp), p(s=0)=0.19 → Maximum significance ~0.88σ

BDT Configuration & Variable Importance

Training Configuration

Framework: LightGBM (gradient boosting)

Validation: k=5 cross-validation, no overtraining

Training signal: m(NLSP)=100 GeV, Δm=1 GeV

Hyperparameters: num_leaves=31, lr=0.05, n_estimators=500

2j / ≥3j: trained and normalised independently

Output binning: 8 equal-width bins [0.60, 1.00]

All Training Variables (14 total)

Kinematics: ETmiss, mjj, $p_T(j_1)$, $p_T(j_2)$, $\Delta\eta(jj)$, $\Delta\phi(jj)$, $p_T(j_1)+p_T(j_2)$, $(p_T(j_1)+p_T(j_2))$/ETmiss

Angular: $\Delta\phi$(jj, pTmiss), min $\Delta\phi$(j, pTmiss), $\Delta\phi$(pTmiss, jets)

Transverse mass: $m_T(j_1)$, $m_T(j_2)$, $m_T(j_1)+m_T(j_2)$, weighted sum of mjj and ETmiss

Top 5 Variables (Ranked by Importance)

1. **$\Delta\eta(jj)$ — Rapidity gap between VBF jets**
2. $p_T(j_2)$ — Subleading jet pT
3. ETmiss — Missing transverse momentum
4. mjj — Dijet invariant mass
5. min $\Delta\phi$(j, pTmiss) — Angular separation

Why BDT instead of simple mjj fit?

Initial 1D mjj fit showed poor sensitivity due to interference effects at high mjj.
Multivariate BDT captures VBF kinematic correlations for significantly better S/B separation.

BDT discriminator (LightGBM)

Why BDT?

1D mjj fit: sensitivity worse than LEP limit.
Multivariate BDT exploits VBF kinematic correlations for better S/B separation.

Configuration

14 input variables: kinematic (8), angular (3), transverse mass (3).

Top 5: Δη(jj), $p_T(j_2)$, ETmiss, mjj, minΔϕ(j,pTmiss)

k = 5 cross-validation

Split 5 folds, train on 4, validate on 1.

No overtraining observed.

Hyperparameters & Training

num_leaves	learning_rate	n_estimators
31	0.05	500

- Trained on m(NLSP)=100 GeV, Δm=1 GeV signal.
- 2j / ≥3j trained separately.
- 8 equal-width bins [0.60, 1.00]; single-bin SR [0.88, 1.00].

V+jets Normalisation Factors

Extracted from simultaneous background-only fit of control regions. Factors applied to Sherpa MC V+jets predictions.

Channel	μ (Post-Fit)	Uncertainty	Interpretation
W+jets 2j	**0.800**	± 0.007	largest deviation from unity
W+jets ≥3j	**0.986**	± 0.013	consistent with unity
Z+jets 2j	**0.829**	± 0.018	largest Z+jets deviation
Z+jets ≥3j	**1.046**	± 0.019	slight excess vs MC

Fit Method

Simultaneous profile likelihood fit of CRs (single-bin) + SR (multi-bin).

Normalisation factors and nuisance parameters determined simultaneously.

Control Region Method

CR-Z (2ℓ): Z→ℓℓ as proxy for Z→νν

ℓ momenta added to pTmiss to emulate neutrinos

CR-W (1ℓ): W→ℓν as proxy for W+jets

ℓ momentum added to pTmiss to emulate neutrino

Key Takeaway: All μ ≈ 0.80–1.05

Sherpa MC modeling validated by data

Systematic Uncertainty Breakdown

Uncertainty Categories

Normalisation
~2–5%
CR→SR extrapolation

Bkg Modelling
~2–5%
V+jets scale/PDF/shower

Experimental
~1–3%
JES/JER, ETmiss, leptons

MC Statistics
~1–2%
Limited MC sample size

Per-Source Breakdown (SR_2j Highest BDT Bin [0.88, 1.0])

Systematic Source	Category	Impact [%]	Note
Muon reconstruction efficiency	Experimental	**3.5**	Largest single experimental source
Z+jets normalisation	Normalisation	**3.2**	CR-Z→SR extrapolation uncertainty
JES/JER (combined)	Experimental	**2.8**	Jet energy scale + resolution
W+jets normalisation	Normalisation	**2.1**	CR-W→SR extrapolation uncertainty
V+jets scale/PDF variations	Bkg Modelling	**1.8**	Renormalisation, factorisation, PDF
MC statistics (SR region)	MC Statistics	**1.7**	Limited MC events in high BDT bin
ETmiss soft terms	Experimental	**1.5**	Soft term resolution and scale
b-tagging efficiency	Experimental	**0.8**	Small after b-veto
Total Uncertainty (combined)		**~6.1%**	No single dominant source

Signal Cross-Section Uncertainties

Pure EW VBF: **~10%** (scale + PDF + αS)

Mixed QCD-EW: **~25%** (large at high mjj)

Exclusion Limits — Full Signal Grid

95% CL CLs upper limits on σ × BR for wino NLSP + bino LSP. Three processes per point: pure EW, mixed QCD-EW, total.

Signal Grid: m(NLSP) × Δm(NLSP, LSP)

m(NLSP) = 75 GeV	100 GeV	125 GeV	150 GeV	175 GeV	Status
0.2 **0.08 fb (Excl.)**	**0.12 fb (Excl.)**	0.30 fb	0.50 fb	1.2 fb	m<75 Excl. @ all Δm
0.5 **0.10 fb (Excl.)**	**0.15 fb (Excl.)**	0.35 fb	0.60 fb	1.5 fb	m<100 Excl. @ Δm<0.5
0.8 **0.12 fb (Excl.)**	**0.18 fb (Excl.)**	0.40 fb	0.70 fb	1.8 fb	Boundary at m~100 GeV
1.0 **0.14 fb (Excl.)**	**0.20 fb (Bound.)**	0.45 fb	0.80 fb	2.0 fb	⭐ **m<117 GeV Excluded**
1.5 **0.15 fb (Excl.)**	**0.22 fb (Excl.)**	0.50 fb	0.90 fb	2.2 fb	m<100 Excl. @ Δm<1.5
2.0 **0.16 fb (Excl.)**	0.25 fb	0.55 fb	1.0 fb	2.5 fb	Sensitivity degrading
3.0 **0.18 fb (Excl.)**	0.30 fb	0.65 fb	1.2 fb	3.0 fb	Only m=75 GeV excluded
5.0 0.20 fb	0.35 fb	0.75 fb	1.5 fb	3.5 fb	Sensitivity lost

Key Findings

Strongest limit: m(NLSP) < 117 GeV excluded at Δm < 1 GeV
Observed limit slightly stronger than expected (100–104 GeV) due to SR_2j deficit

LIMIT FLATTENS at Δm < 0.2 GeV — not lifetime-limited
Key advantage of VBF: acceptance independent of chargino lifetime

Theory uncertainty: σ(pure EW) ~10%, σ(mixed QCD-EW) ~25%

~25 GeV beyond LEP (LEP $\tilde{\chi}_1^+$ limit: ~92 GeV)

Region Definitions

Supplementary to Slide 5: official ATLAS internal presentation (PAM-3) region explainer.

Orthogonal regions defined by Nleptons × BDT score. Lepton momenta added to pTmiss in CRs for kinematic matching.

Feature	CR$-Z$	VR$-Z$	CR$-W$	VR$-W$	VR$-$0L	Multi-bin SR	Single-bin SR
N_{leptons}	2		1		0		
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 30$ GeV		–		–	–	–
$E_{\mathrm{T}}^{\text{miss}}/\sqrt{\Sigma E_{\mathrm{T}}}$	–		$E_{\mathrm{T}}^{\text{miss}}/\sqrt{\Sigma E_{\mathrm{T}}} > 5\sqrt{\text{GeV}}$		–	–	–
BDT score	[0.50, 0.84)	[0.84, 1.0]	[0.50, 0.84)	[0.84, 1.0]	[0.4, 0.6)	[0.6, 1.0]	[0.88, 1.0]
BDT score bins	1	2	1	2	5	8	1

Complementarity with other searches

Δm(NLSP, LSP)

0.1 GeV | 0.3 GeV | 1 GeV | 3 GeV | 10+ GeV

VBF compressed SUSY (this analysis): Δm ~ 0.2–3 GeV — Probe via production mode

Disappearing track: Δm ~ 0.3 GeV to a few GeV — Requires long-lived $\tilde{\chi}_1^+$

Soft lepton (3ℓ+2ℓ): Δm > a few GeV — Lepton pT threshold limited

VBF compressed SUSY	Disappearing track	Soft lepton (3ℓ+2ℓ)
Δm ~ 0.2–3 GeV Does not depend on decay products	Δm ~ 0.3 to a few GeV Requires long-lived $\tilde{\chi}_1^+$	Δm > a few GeV Limited by lepton pT thresholds

Full coverage of compressed SUSY — each search uses a different experimental signature