对撞机上新物理寻找

SUZHOU · 16-20 APR 2026 · TALK ON 18 APR

Experimental overview of

[SU,SY]

and beyond

Yang Liu
School of Science, SYSU · liuy2399@mail.sysu.edu.cn

Outline

Talk structure

1. Overview and search strategy
2. Strong SUSY
3. Electroweak SUSY
4. LLP SUSY
5. Beyond simplified models
6. Summary

Paper cited in this talk

Radiative natural supersymmetry: Reconciling electroweak fine-tuning and the Higgs boson mass
ARXIV:1212.2655

Radiatively-driven natural supersymmetry at the LHC
ARXIV:1310.4858

Search for supersymmetry in final states with missing transverse momentum and three or more b-jets in 139 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
ARXIV:2211.08028

Simple, but not simplified: A new approach for optimising beyond-Standard Model physics searches at the Large Hadron Collider
ARXIV:2305.01835

ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM
ARXIV:2402.01392

A statistical combination of ATLAS Run 2 searches for charginos and neutralinos at the LHC
ARXIV:2402.08347

Search for long-lived charged particles using large specific ionisation loss and time of flight in 140 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
ARXIV:2502.06694

Prospects for supersymmetry at high luminosity LHC
ARXIV:2502.10879

Searches for direct slepton production in the compressed-mass corridor in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector
ARXIV:2503.17186

Search for squarks and gluinos in pp collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV in events with τ-leptons, jets and missing transverse momentum using the ATLAS detector
ARXIV:2507.00296

General search for supersymmetric particles in scenarios with compressed mass spectra using proton-proton collisions at $\sqrt{s} = 13$ TeV
ARXIV:2508.13900

Supersymmetry searches in CMS Run 2: A complete review
ARXIV:2510.17971

Search for Higgsinos in final states with low-momentum lepton-track pairs at 13 TeV
ARXIV:2511.16394

Search for higgsinos in compressed mass spectra using low-momentum tracks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
ARXIV:2511.20042

Search for long-lived particles using displaced vertices of oppositely charged leptons in 140 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
ARXIV:2601.05664

Rare and Experimentally Challenging Supersymmetry Signatures
ARXIV:2601.06358

Search for long-lived charginos and τ-sleptons using final states with a disappearing track in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
ARXIV:2603.08315

Reinterpretation of searches for supersymmetry in models with variable R-parity-violating coupling strength using the full ATLAS Run 2 Dataset
ARXIV:2603.15007

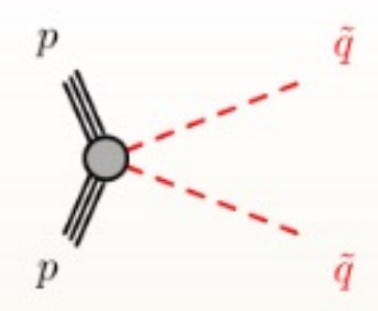
Search for direct pair production of top squarks in pp collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV in events with two oppositely charged leptons using the ATLAS detector
ARXIV:2603.16191

EXPERIMENTAL SUSY SEARCH

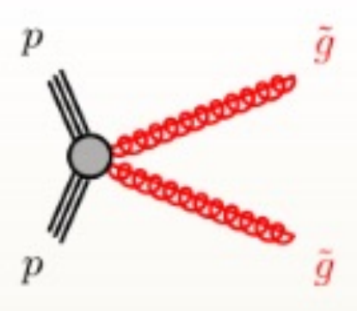
General strategy of searching SUSY

RPC

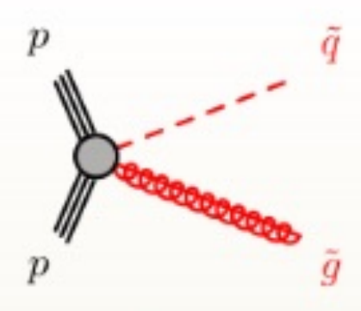
STRONG



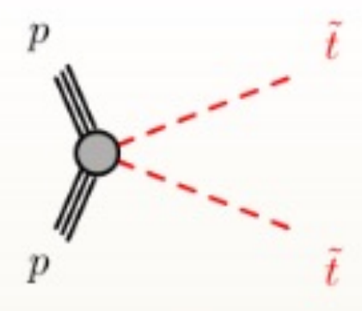
$\tilde{q}\tilde{q}$



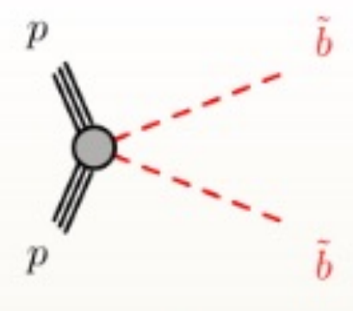
$\tilde{g}\tilde{g}$



$\tilde{q}\tilde{g}$



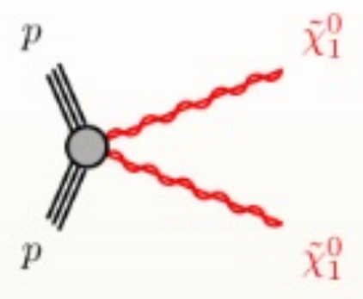
$\tilde{t}\tilde{t}$



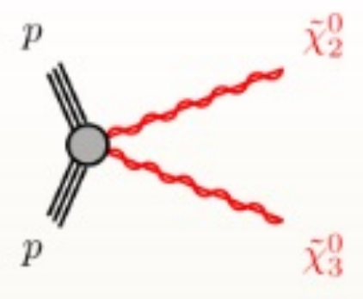
$\tilde{b}\tilde{b}$

EWK

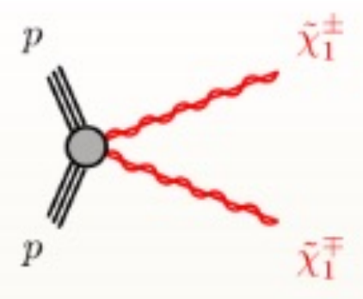
GAUGINO-PAIR



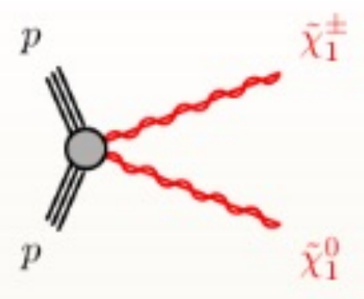
$\tilde{\chi}^0_1\tilde{\chi}^0_1$



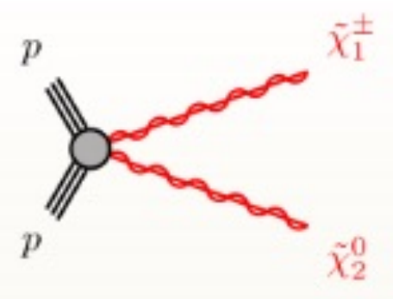
$\tilde{\chi}^0_2\tilde{\chi}^0_3$



$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$

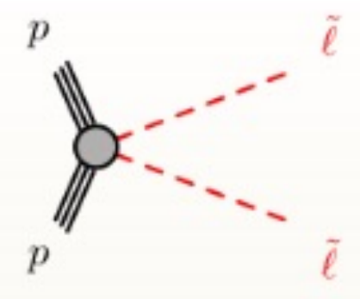


$\tilde{\chi}^\pm_1\tilde{\chi}^0_1$



$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$

SLEPTON-PAIR



$\tilde{\ell}\tilde{\ell}$

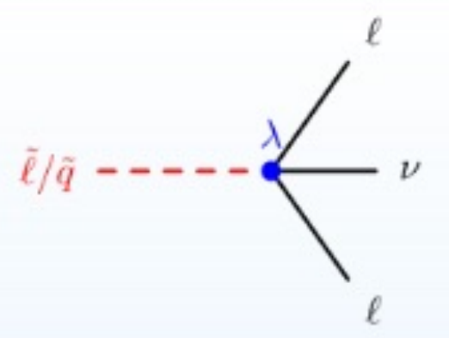
RPC final state: SM particles + large missing energy (MET)

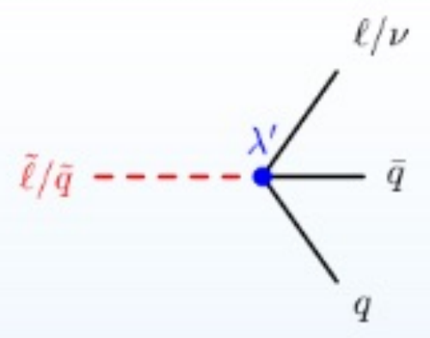
RPV

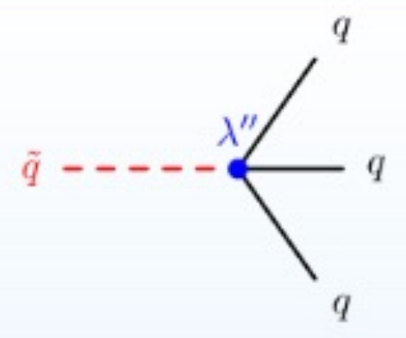
$$W_R = \frac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k + \kappa_iL_iH_u$$

Λ **(LLE)** · Λ' **(LQD)** · Λ'' **(UDD)**

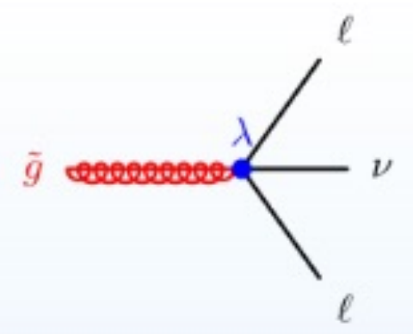
SLEPTON / SQUARK

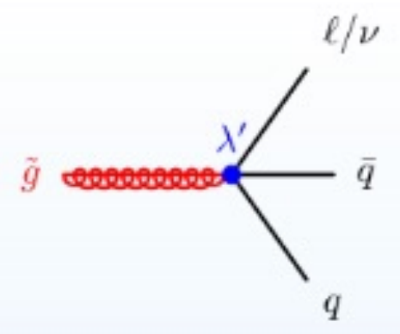


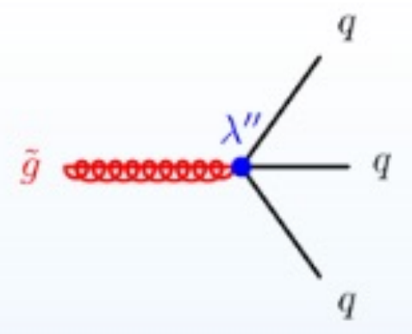




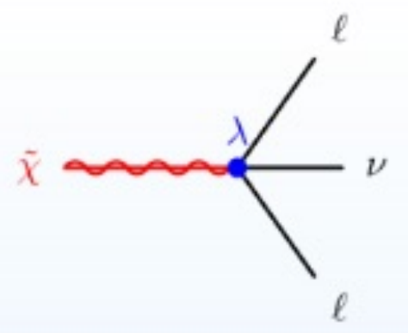
GLUINO

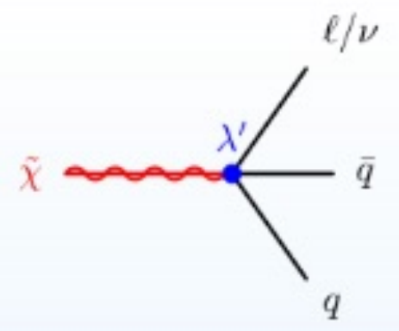


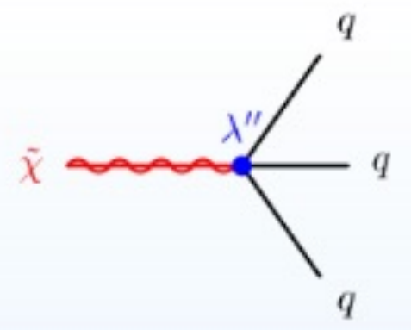




GAUGINO







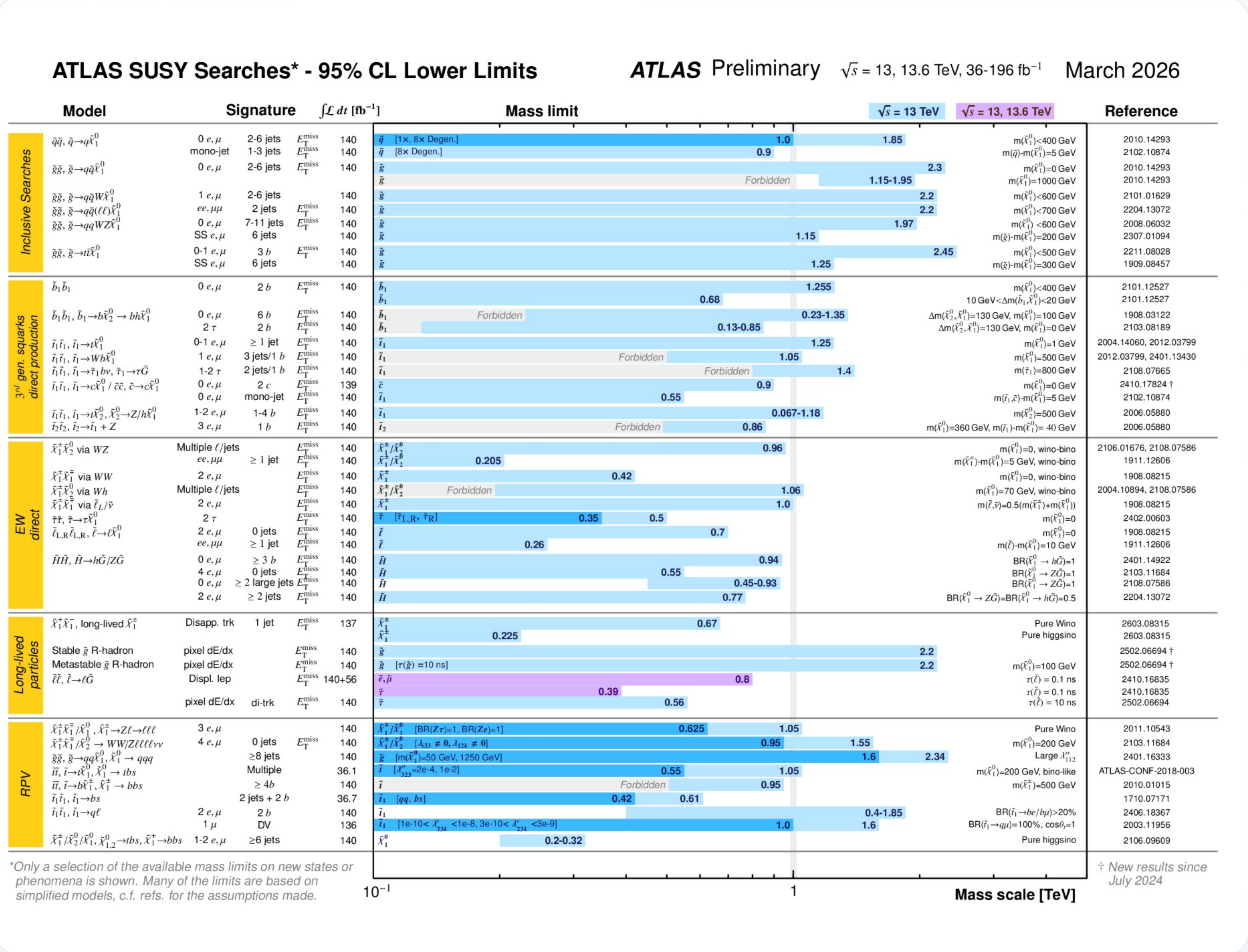
RPV final states: visible SM + less MET (prompt) or unconventional LLP signatures

Overview of Current LHC SUSY Search Results

✓ Full Run 2 · ~140 fb^{-1}

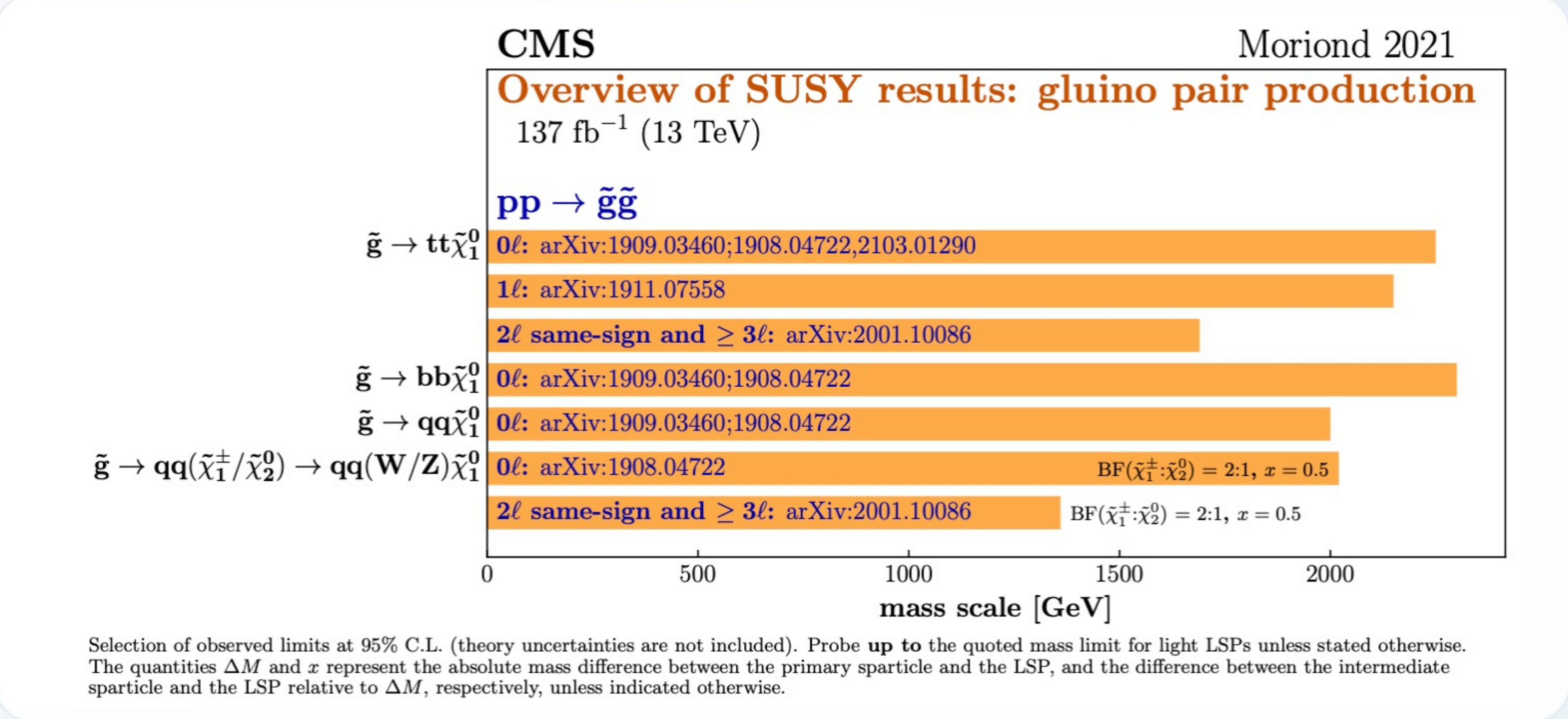
▶ Run 3 Ongoing · 13.6 TeV

● **ATLAS · ALL PROCESSES · ATL-PHYS-PUB-2026-003 (MAR 2026)**

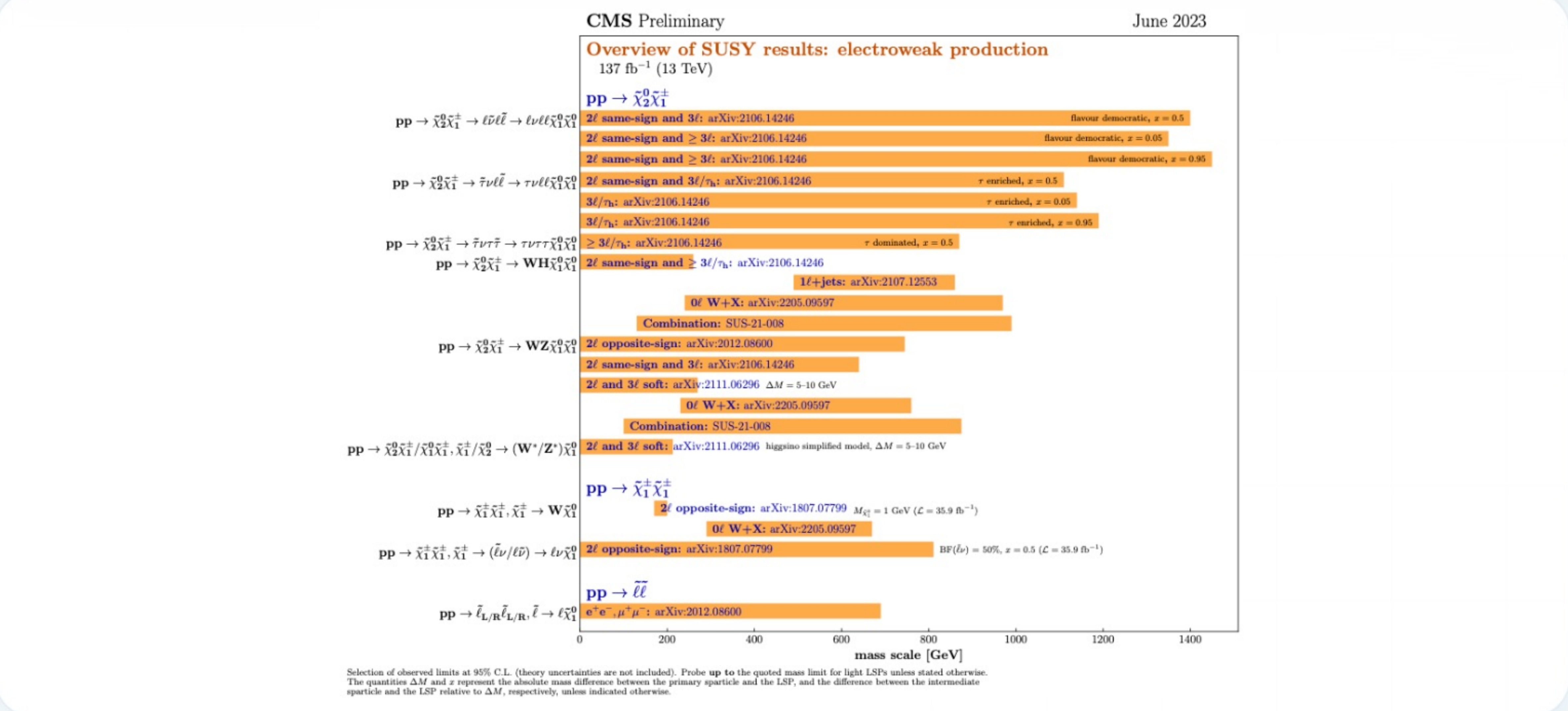


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

● **CMS · STRONG & EWK · CMS-SUMMARY-SEARCHES.DOCS.CERN.CH (APR 2026)**



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



No Significant Excess

All search channels consistent with SM background predictions; no signal excess above significance threshold observed

Strong Mass Exclusions

Gluinos up to **~2.3-2.5 TeV** · Stops **~1.4 TeV** · EWK particles **~1.1 TeV**
(simplified models, 95% CL)

Run 3 Searches Ongoing

Most published results from Full Run 2 (~140 fb^{-1}, 13 TeV) · Run 3 & combined analyses in progress; more sensitivity ahead

EXPERIMENTAL SUSY SEARCH

Strong SUSY Searches: Current Landscape

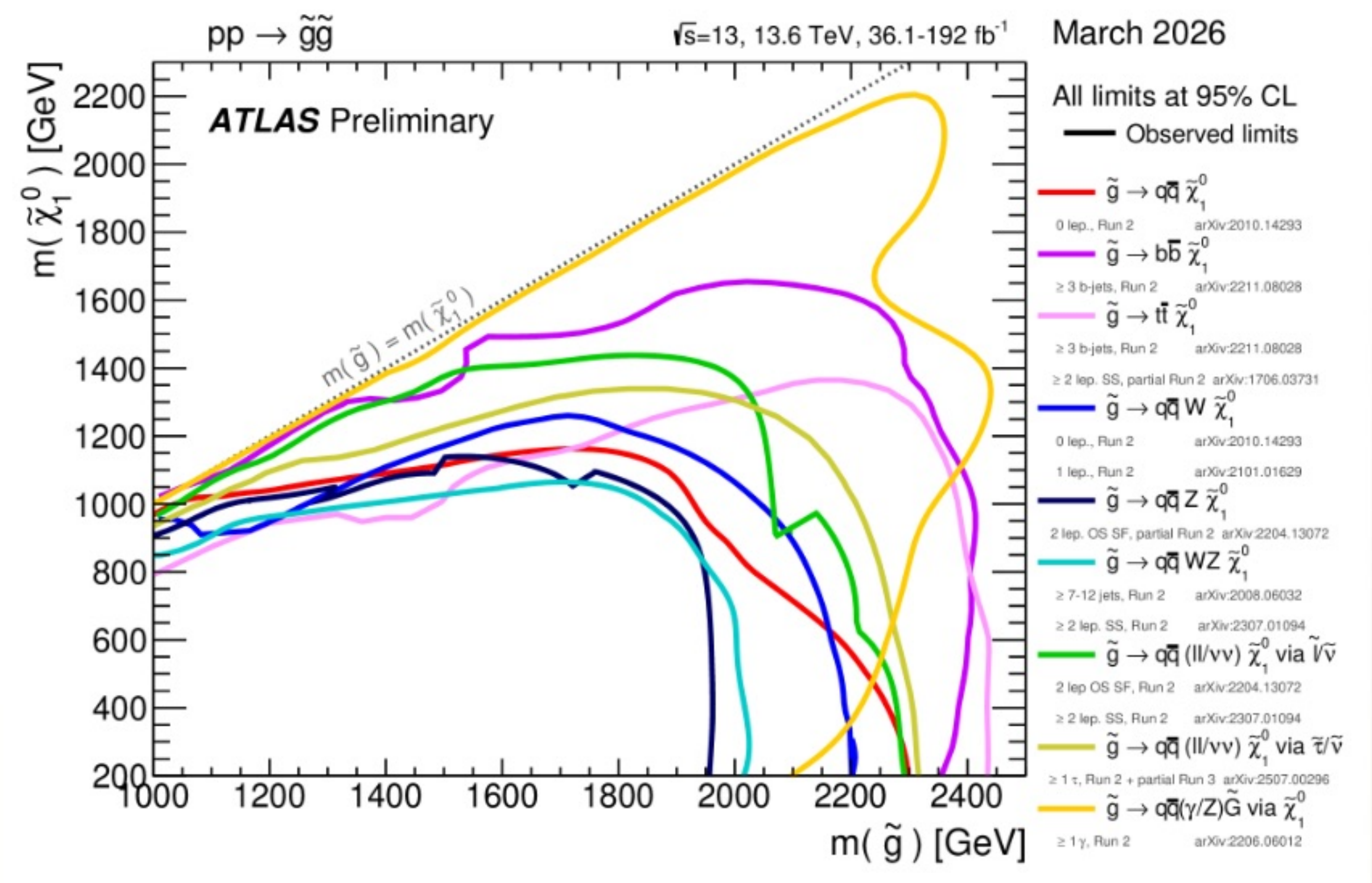
STRONG PRODUCTION

GLUINO / SQUARK / STOP / SBOTTOM

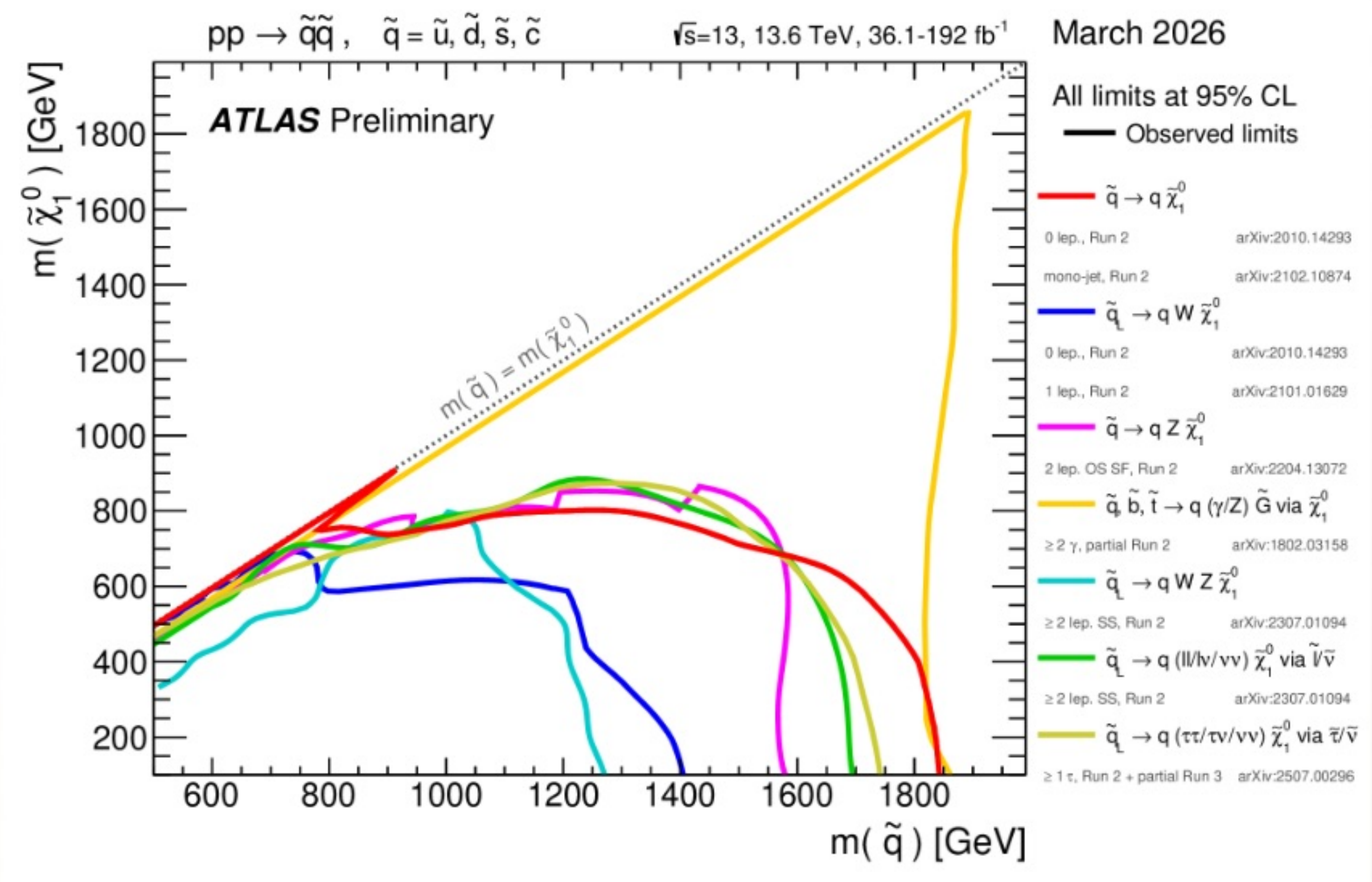
0L, 1L, MULTIJET, B-RICH, COMPRESSED

ATLAS STRONG-SECTOR SUMMARIES FROM ATL-PHYS-PUB-2026-003

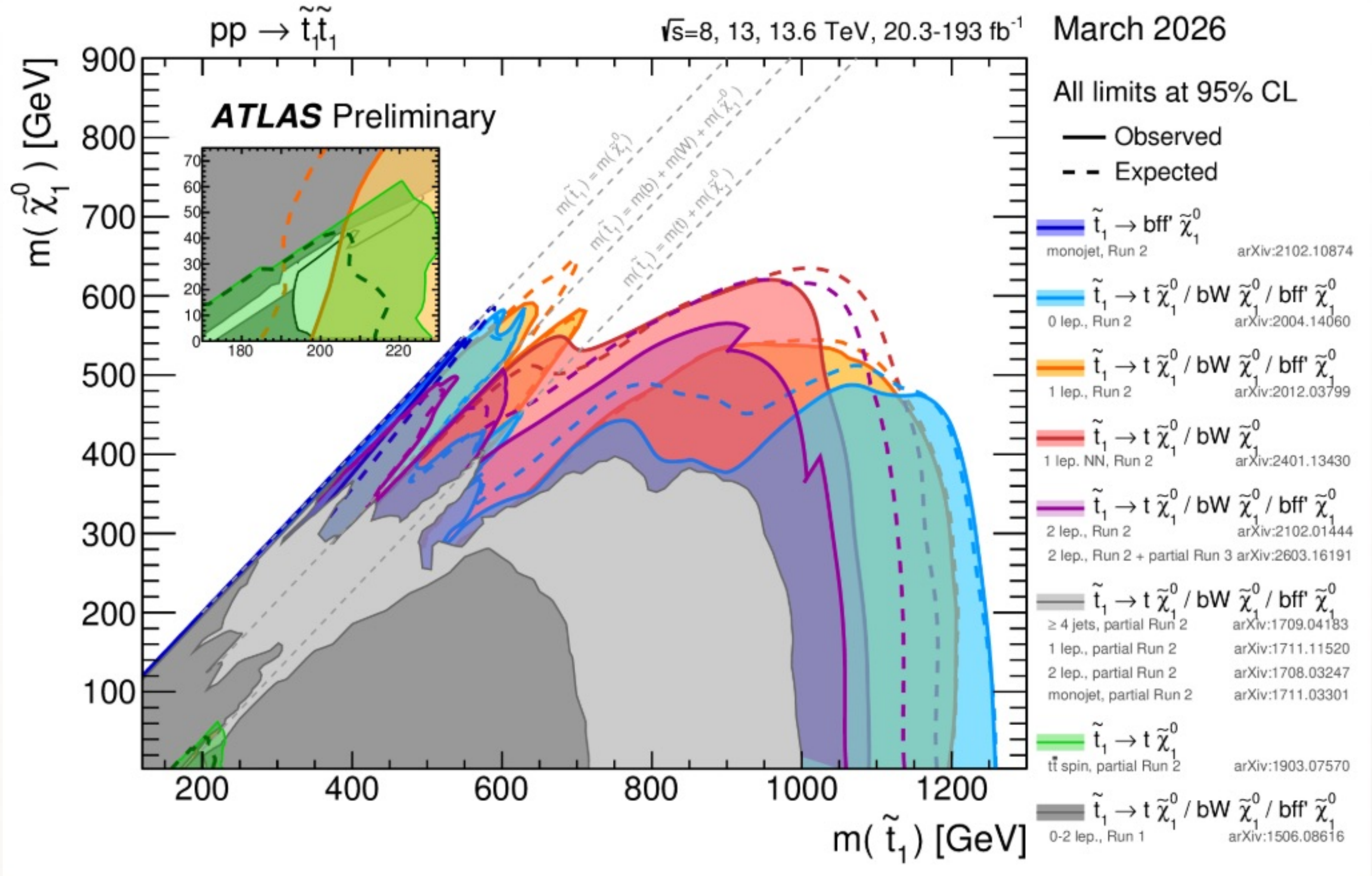
GLUINO



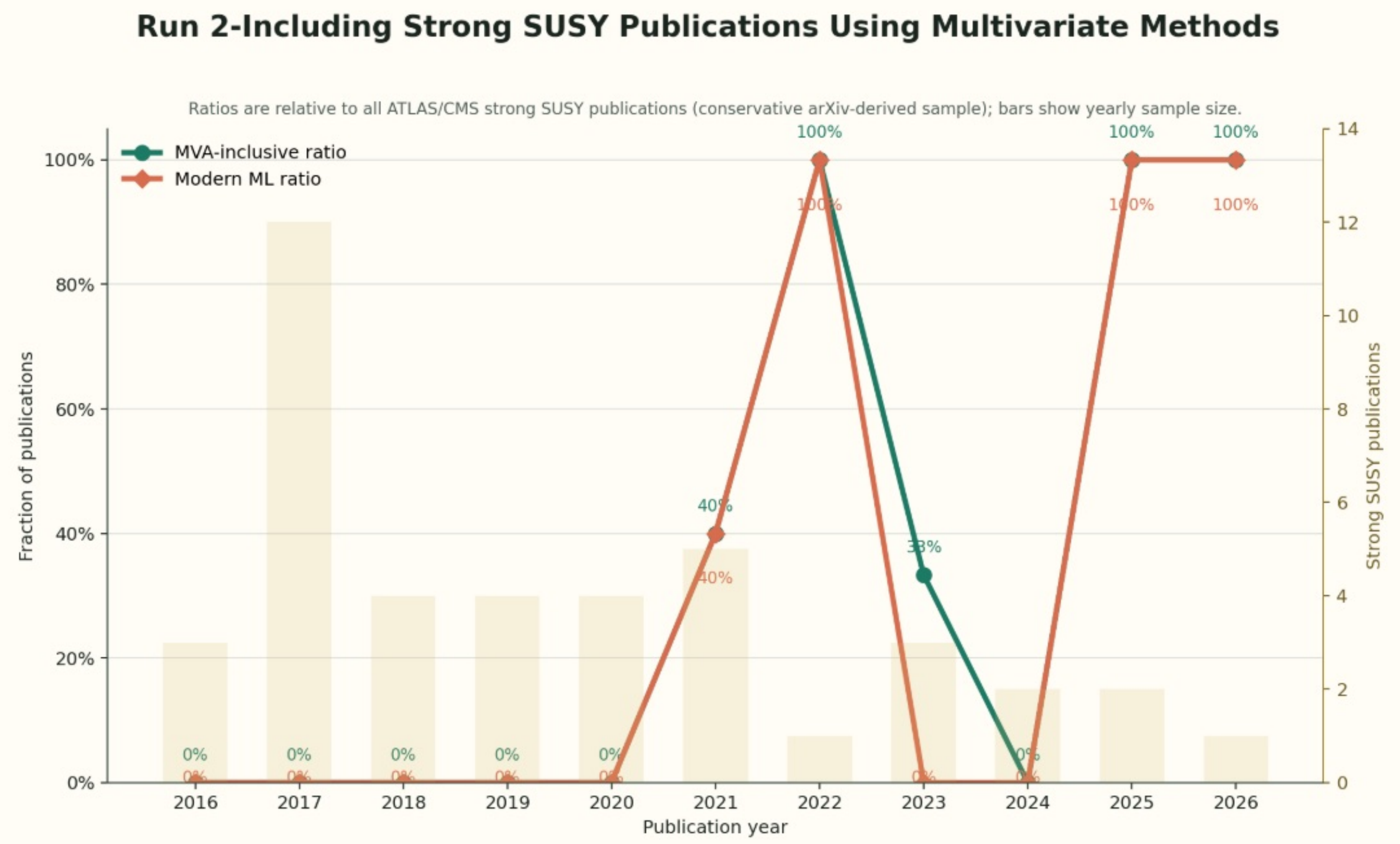
LIGHT-FLAVOR SQUARK



TOP SQUARK



MODERN ML ADOPTION IN STRONG SUSY SEARCHES – ATLAS+CMS (ARXIV-DERIVED SAMPLE)



WHAT THE STRONG PROGRAM IS TELLING US

≥3b-jets, 2 SS-ℓ & τ final states are the most sensitive channels

These channels – alongside GMSB-specific signatures – deliver the strongest per-event discrimination against SM backgrounds.

$m_{\tilde{t}} \lesssim 1.5\,\mathrm{TeV}$: minimal fine-tuning, yet still wide-open

Naturalness favors this region *[arXiv:1212.2655, 1310.4858]*; large stop parameter space remains unconstrained.

The frontier has shifted to difficult corners

Compressed spectra, stealth/RPV topologies, and low-MET signatures now define the hardest regions to probe.

Modern ML is now universal – and delivers real gains

100% of recent strong analyses use deep networks or graph-based methods; sensitivity improvements are measurable.

No significant excess in mainstream strong searches

ATLAS and CMS both see broad consistency with the Standard Model across inclusive and third-generation channels.

Reach extends to multi-TeV gluino scales

Strong production still delivers the highest SUSY mass reach, with the exact limit controlled by decay topology and spectrum assumptions.

Key challenge: from broad coverage to hard regions

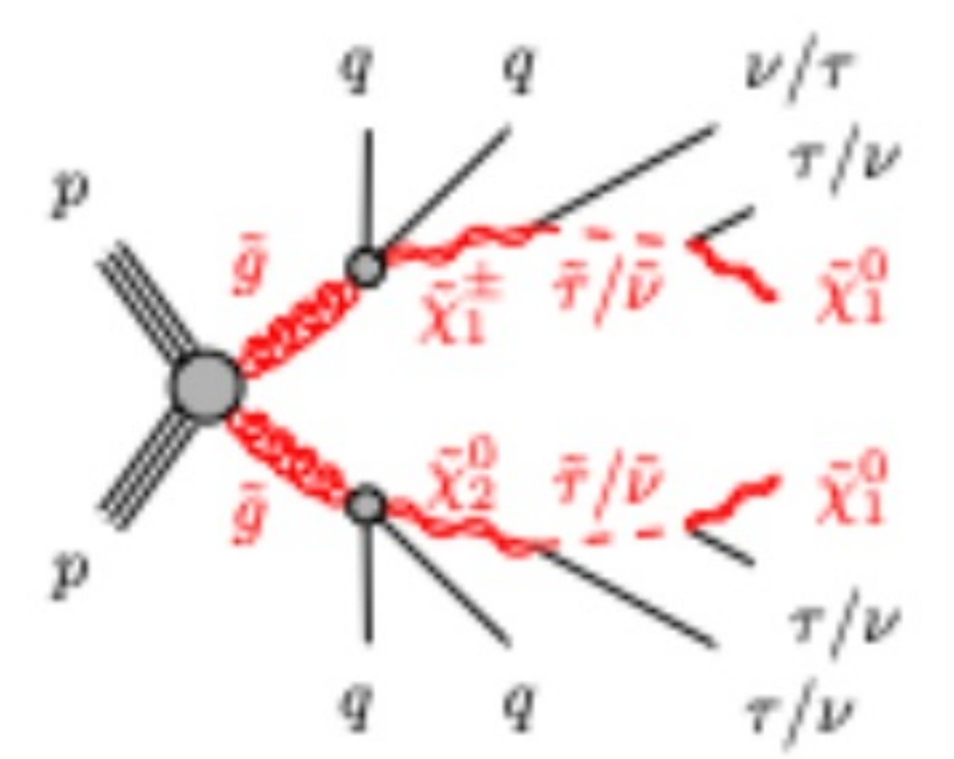
The next gains will come less from generic MET searches and more from compressed, low-MET, and topology-specific analyses.

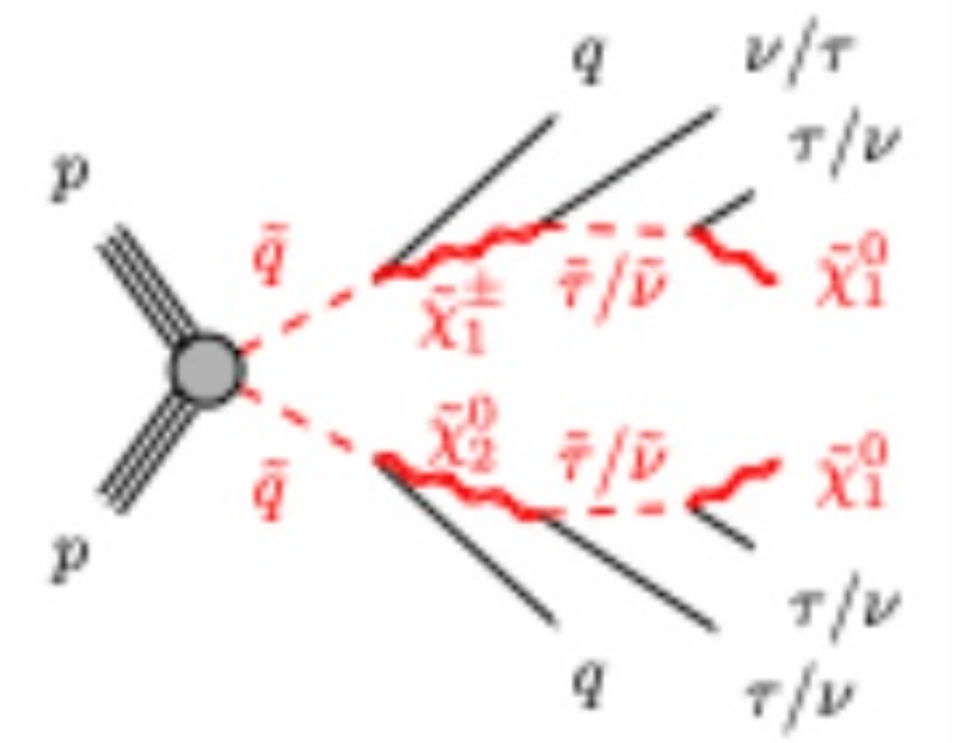
EXPERIMENTAL SUSY SEARCH

Representative Strong Results: τ-jets & OS-Dilepton Channels

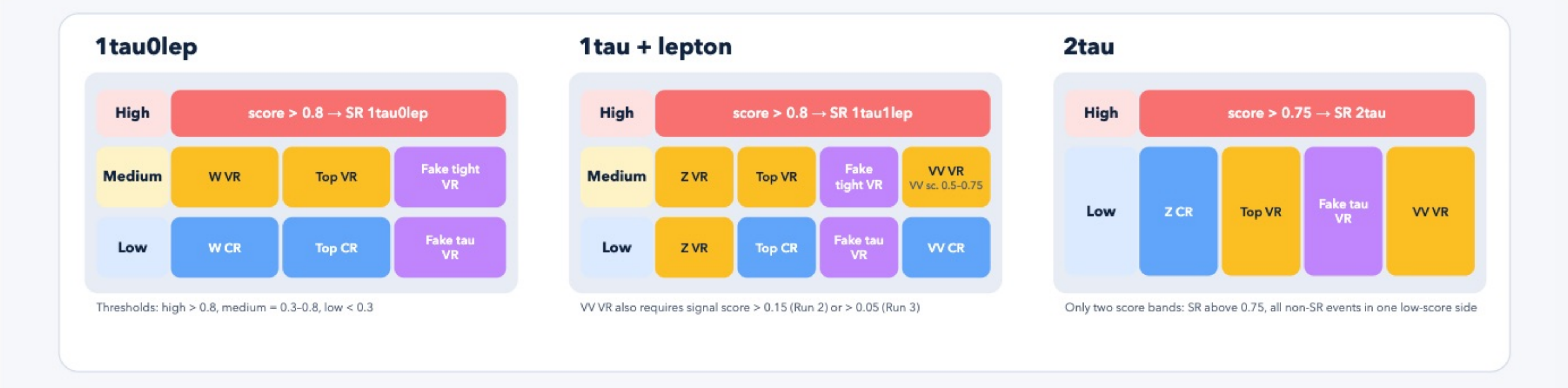
$\tilde{g}/\tilde{q} \to \tilde{\tau}/\tilde{\nu} \to \tau$ + jets + MET

arXiv:2507.00296 (ATLAS, 2025)





ANALYSIS ORGANIZATION



1tau0lep

High	score > 0.8 → SR 1tau0lep		
Medium	W VR	Top VR	Fake tight VR
Low	W CR	Top CR	Fake tau VR

Thresholds: high > 0.8, medium = 0.3–0.8, low < 0.3

1tau + lepton

High	score > 0.8 → SR 1tau1lep			
Medium	Z VR	Top VR	Fake tight VR	VV VR VV sc. 0.5–0.75
Low	Z VR	Top CR	Fake tau VR	VV CR

VV VR also requires signal score > 0.15 (Run 2) or > 0.05 (Run 3)

2tau

High	score > 0.75 → SR 2tau			
Low	Z CR	Top VR	Fake tau VR	VV VR

Only two score bands: SR above 0.75, all non-SR events in one low-score side

Compressed SR

1τ channels – low-Δm target

Applies to: 1τ0ℓ and 1τ+ℓ channels

- Split: pT(τ₁) < 45 GeV – soft-τ regime
- Binned var: MET; SR bins from MET > 400 GeV
- Jet multiplicity: ≥ 2 jets
- 1τ0ℓ: mT(τ₁) > 80 GeV
- 1τ+ℓ: mT(τ₁) + mT(ℓ₁) > 350 GeV

Soft-τ compressed topology.
Cut-and-count often matches or outperforms
ML for soft-object, ISR-boosted topologies
where BDT sculpting can hurt sensitivity.

High Mass SR

1τ channels – large-Δm target

Applies to: 1τ0ℓ and 1τ+ℓ channels

- Split: pT(τ₁) > 45 GeV – hard-τ regime
- Binned var: MET (shared MET axis, harder cuts)
- HT > 1000 GeV; ≥ 3 jets required
- 1τ0ℓ: mT(τ₁) > 250 GeV
- 1τ+ℓ: mT(τ₁) > 120 GeV; ΣmT > 350 GeV

Targets large mass splittings and hard objects.
Strong HT + jet-multiplicity requirements
suppress tt̄ and W+jets backgrounds.
Mirrors classic strong-SUSY high-mass logic.

Two Tau SR

≥2τ channel – inclusive high-mass

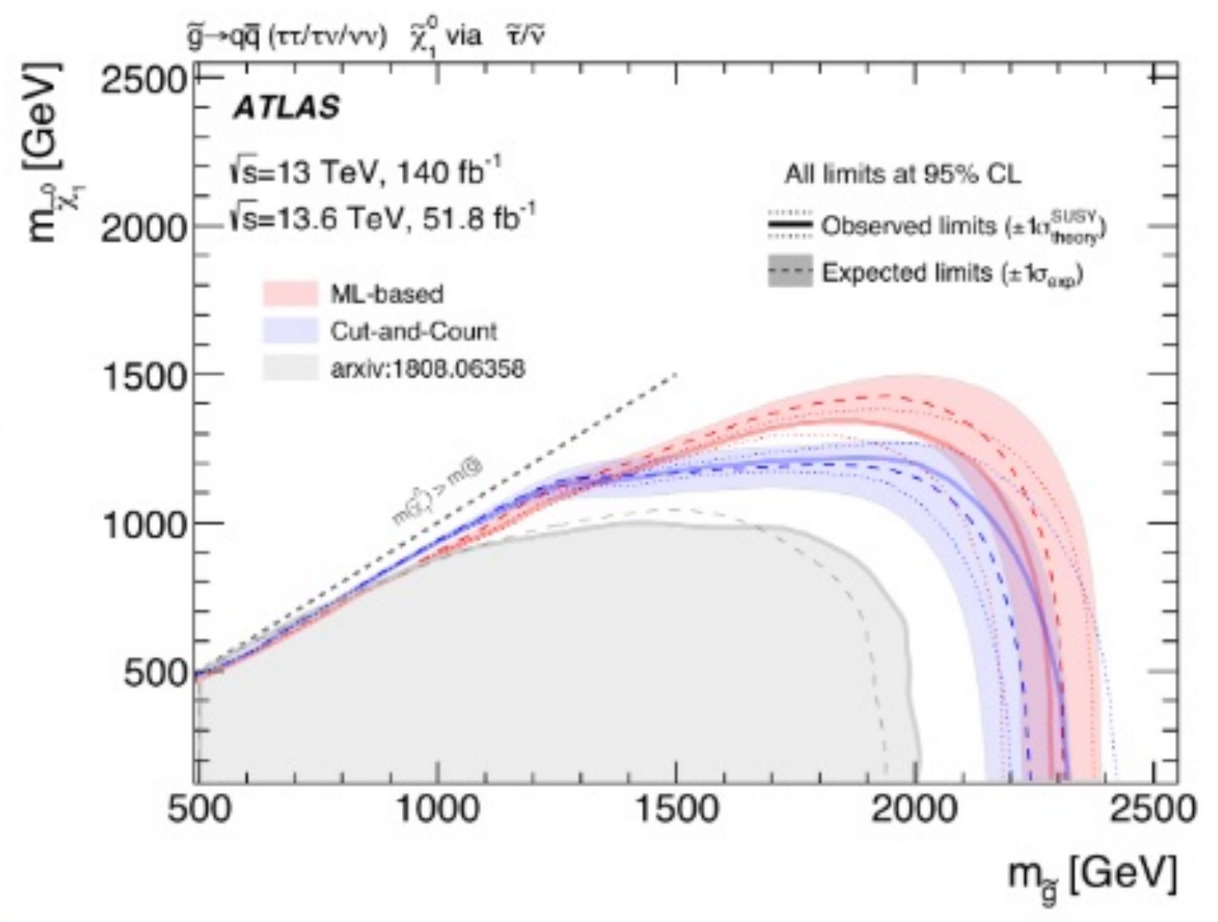
Applies to: ≥2τ analysis branch only

- No compressed/high-mass sub-division here
- Binned var: mT(τ₁) + mT(τ₂) [di-τ mT sum]
- MET > 200 GeV; HT > 800 GeV; ≥ 3 jets
- SR: mT(τ₁) + mT(τ₂) > 150 GeV
- No extra MET cut beyond preselection

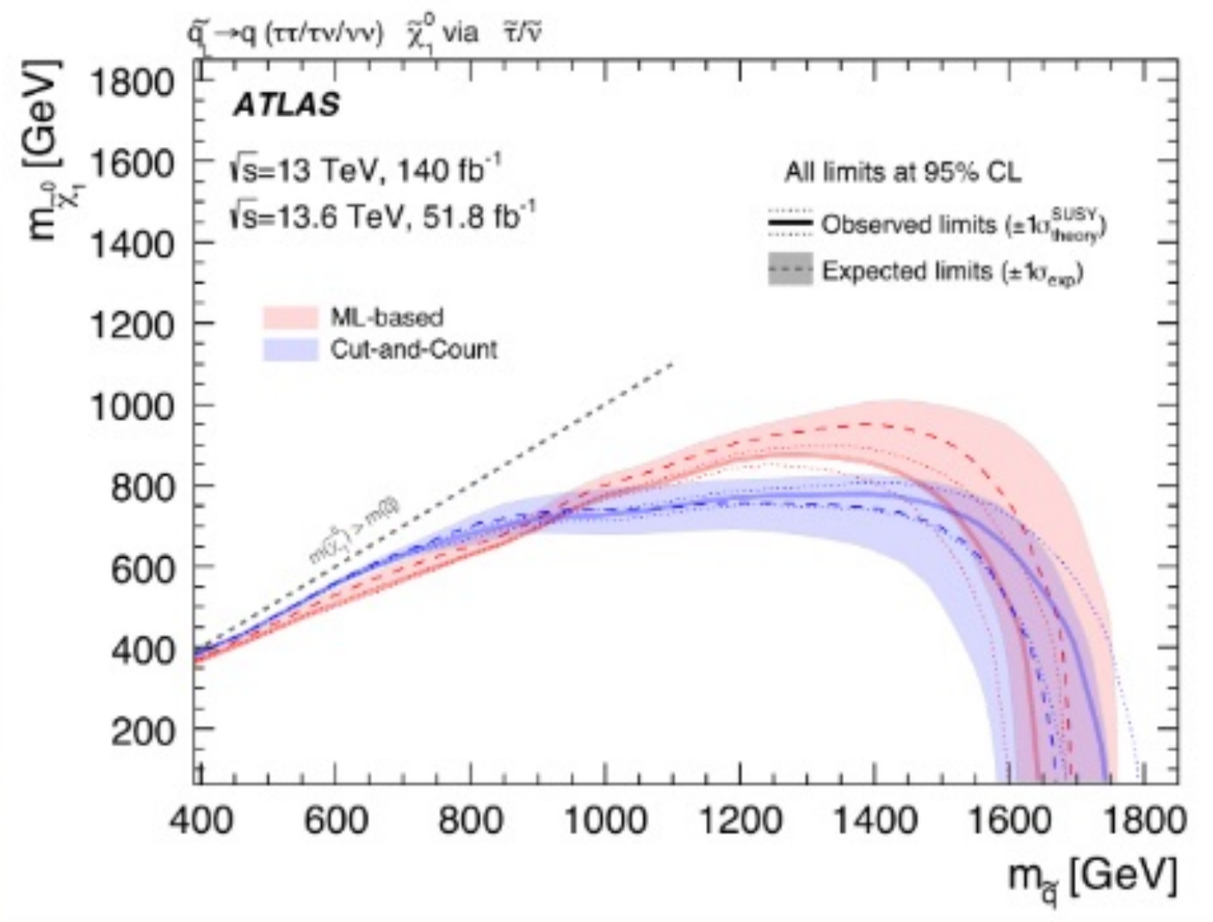
Two reco τs naturally suppress compressed events.
ATLAS uses a single inclusive SR targeting
the hard spectrum – di-τ kinematics already
kill most soft backgrounds without sub-regions.

EXCLUSION LIMITS AT 95% CL

GLUINO



SQUARK



TAU-RICH CASCADE

This is a representative **strong-SUSY tau cascade** search, simultaneously covering both **gluino** and **squark** production. In **pMSSM/MSSM**, this is not a niche corner: if the **stau** or **tau sneutrino** is relatively light, electroweakino cascades from gluinos or squarks naturally leave **multiple τ leptons** in the final state.

TWO COMPLEMENTARY MODES

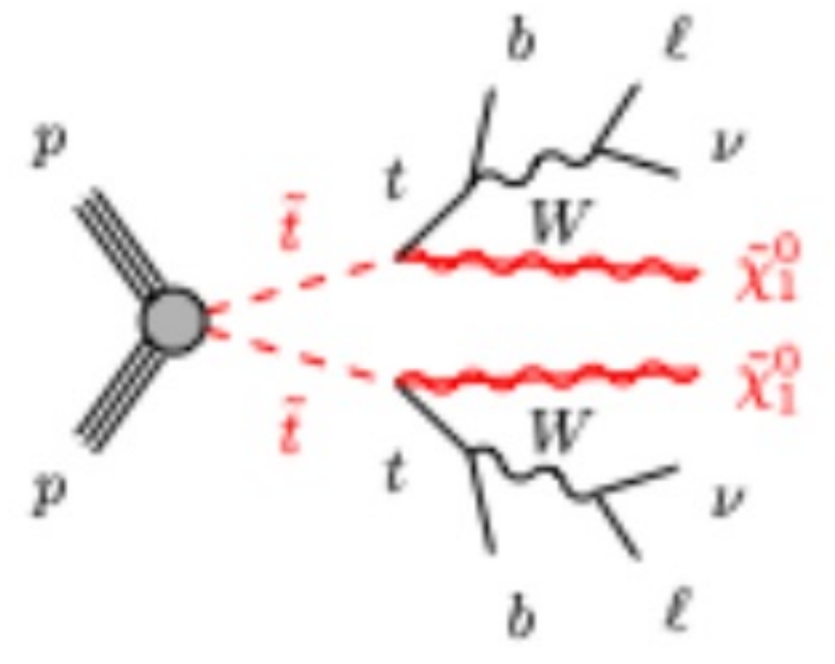
ML and **cut-and-count** are used together, with complementary reach in the **high-mass** and **compressed** regions.

FINAL REACH

The final exclusion pushes to about **$m_{\tilde{g}} \approx$ 2.25 TeV** and **$m_{\tilde{q}} \approx$ 1.7 TeV**.

$\tilde{t}\tilde{t} \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$ OS-ℓℓ + b-jets + MET

arXiv:2603.16191 (ATLAS, 2026)



ANALYSIS ORGANIZATION

Low-Δm

Δm = 200 to 300 GeV

1b category	2b category
Shared threshold: mT2(ll) > 80 GeV	
Shared threshold: NN signal score > 0.93	
nb = 1, nlight > 0	nb > 1, nlight ≥ 0

Medium-Δm

Δm = 300 to 500 GeV

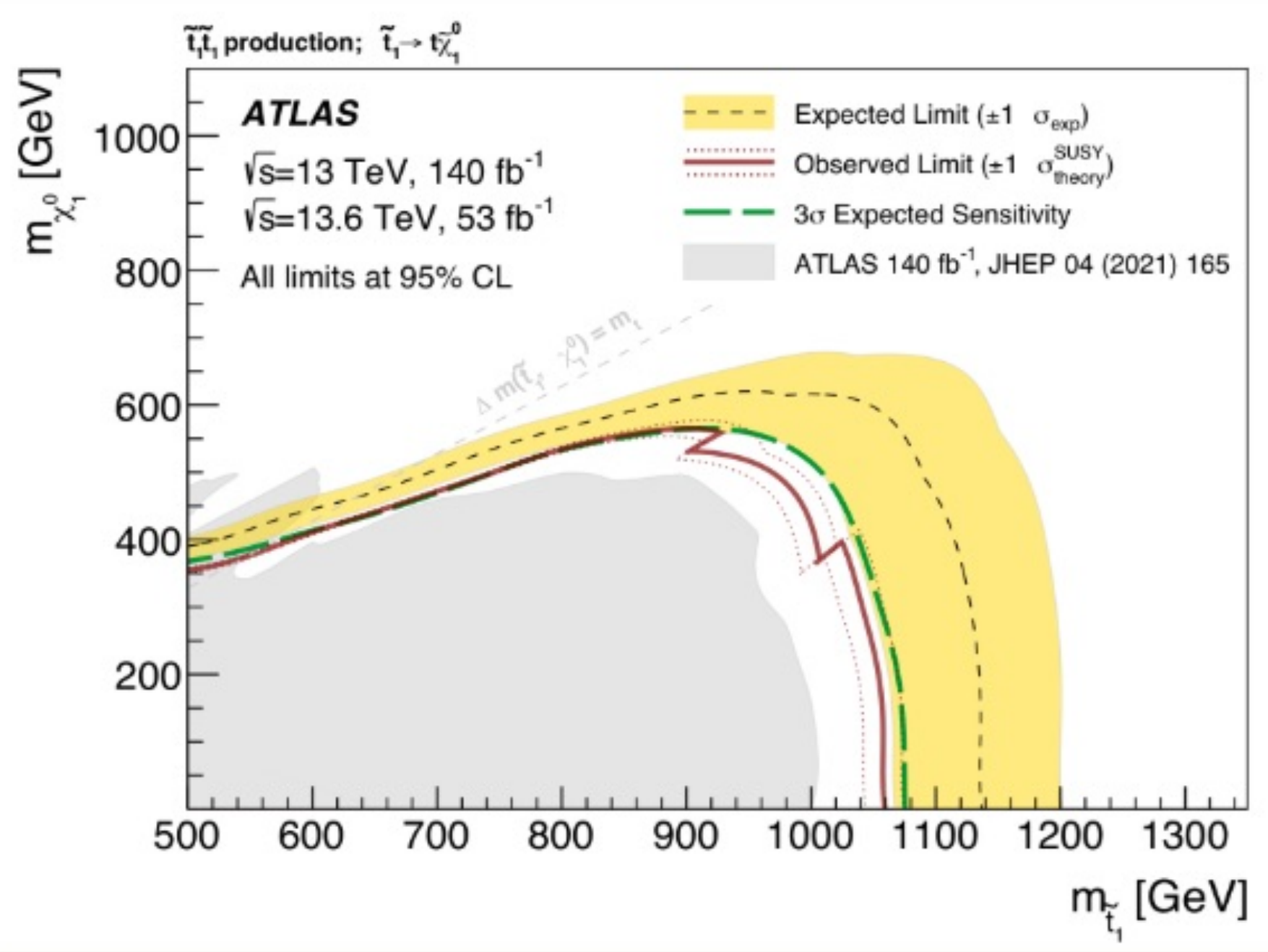
1b category	2b category
Shared threshold: mT2(ll) > 90 GeV	
Shared threshold: NN signal score > 0.53	
nb = 1, nlight > 0	nb > 1, nlight ≥ 0

High-Δm

Δm ≥ 600 GeV

1b category	2b category
Shared threshold: mT2(ll) > 100 GeV	
Shared threshold: NN signal score > 0.44	
nb = 1, nlight > 0	nb > 1, nlight ≥ 0

EXCLUSION LIMITS AT 95% CL



NATURALNESS MOTIVATION

Stop is a first-priority SUSY target for **naturalness**: the large **top Yukawa** makes top loops the dominant correction to the Higgs mass.

CURRENT REACH

Combined Run 2 + early Run 3 excludes stop up to about **1060 GeV** for a light LSP, about **100 GeV** beyond the previous full Run 2 dilepton result.

USEFUL BENCHMARK

For **$m_{\tilde{t}}$ = 1 TeV, $m_{\tilde{\chi}_1^0}$ = 400 GeV**, improved reconstruction plus the new **ML strategy** alone improves the expected upper limit by about **50%**.

OBSERVED VS EXPECTED

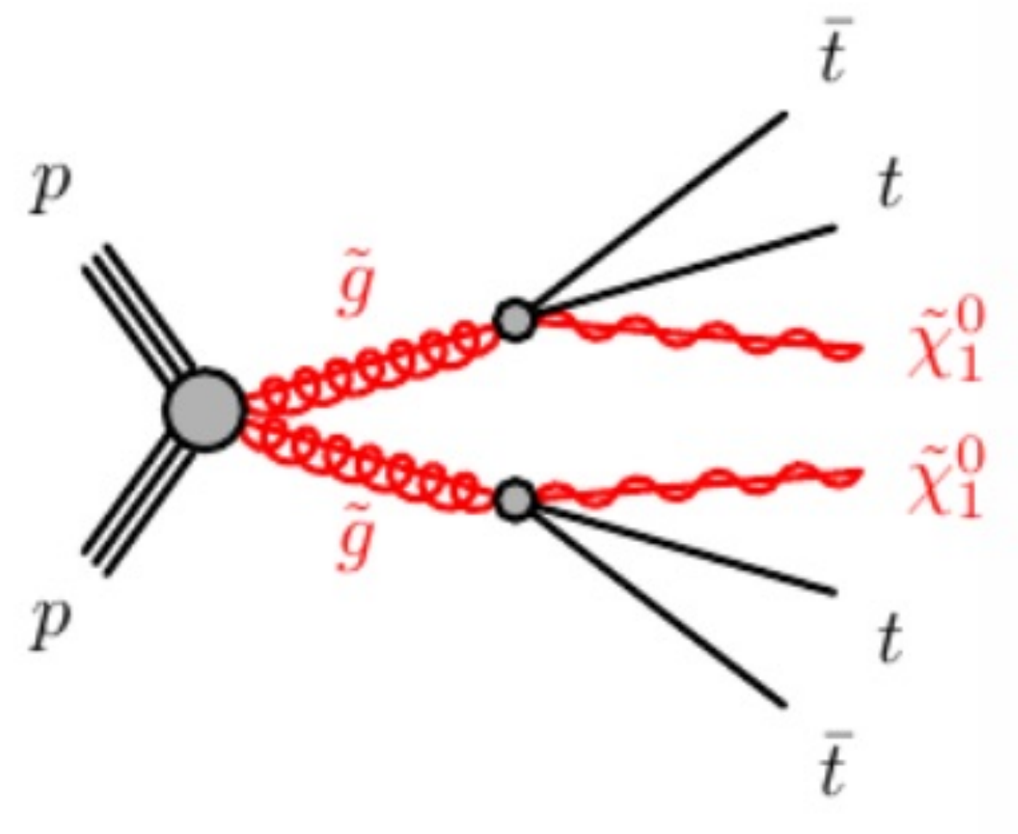
Observed is slightly weaker than expected because Run 2 has small upward fluctuations in the **medium/high-Δm 1b** regions; they are statistically compatible, but make the contour more conservative.

EXPERIMENTAL SUSY SEARCH

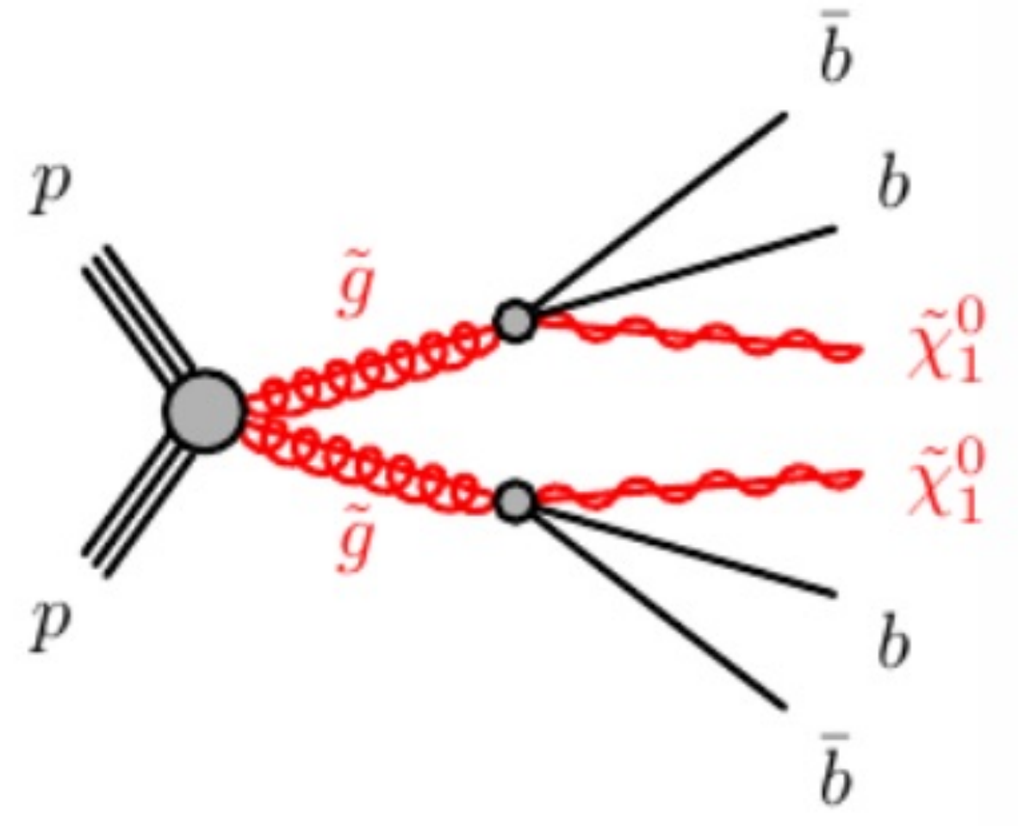
Representative Strong Results: $\geq 3b$ Channels

$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ / $b\bar{b}\tilde{\chi}_1^0$ / Gtb mixed

ATLAS · arXiv:2211.08028 · JHEP 06 (2023) 048



GTT



GBB

ANALYSIS ORGANISATION

Cut-and-count **Parameterised NN** shared preselection: large MET + ≥6 jets + ≥3 b-jets

1 • Re-optimised cut-and-count

Gtt / Gbb / Gtb · reinterpretation-friendly

Gtt **Gbb** **Gtb**

Region B	M1 / M2	Region C
large Δm	moderate Δm	compressed
≥ 1.5 TeV	0.3 – 1.5 TeV	≤ 0.3 TeV

0-lepton branch

zero baseline leptons in the SRs

- **SR · meff / MET / mTmin(b) / MJΣ cuts**
- **CRtt · exactly 1 signal lepton**
- **VR · inverted MJΣ or meff or MET**

SRs defined by 0 baseline leptons;
CRtt introduced by requiring exactly 1 signal lepton.

1-lepton branch

at least 1 signal lepton in the SRs

- **SR · meff / MET / mT / MJΣ cuts**
- **CRtt · inverted mT requirement**
- **VR · high-mT / high-mTmin(b) sidebands**

SR+CRtt orthogonal via mT; VRs probe sidebands of the mT distribution.

Gtt uses only CC SRs for limits (NN not optimised for Gtb).

2 • Parameterised deep neural network

Targeted Gtt / Gbb; one model, all mass points

Inputs: low-level kinematics + model flag
+ (m_g̃, m_χ̃₁⁰) as continuous parameters

Set-cover compression → 8 representative SRs
4 Gtt points + 4 Gbb points; one SR set covers the full grid

Gtt NN family

(2100,1) · (1800,1) · (2300,1200) · (1900,1400) GeV

- **SR · high P(Gtt) cut**
- **CRtt · orthogonal NN output window**
- **VRtt · NN sideband + meff / MJΣ**

CRs and VRs tuned so their kinematics stay close to the targeted SR.

No CRZ for Gtt: final state has no OSSF lepton pairs → Z+jets background negligible.

Gbb NN family

(2800,1400) · (2300,1000) · (2100,1600) · (2000,1800) GeV

- **SR · high P(Gbb) cut**
  - **CRtt** → **VRtt**
  - **CRZ** → **VRZ**

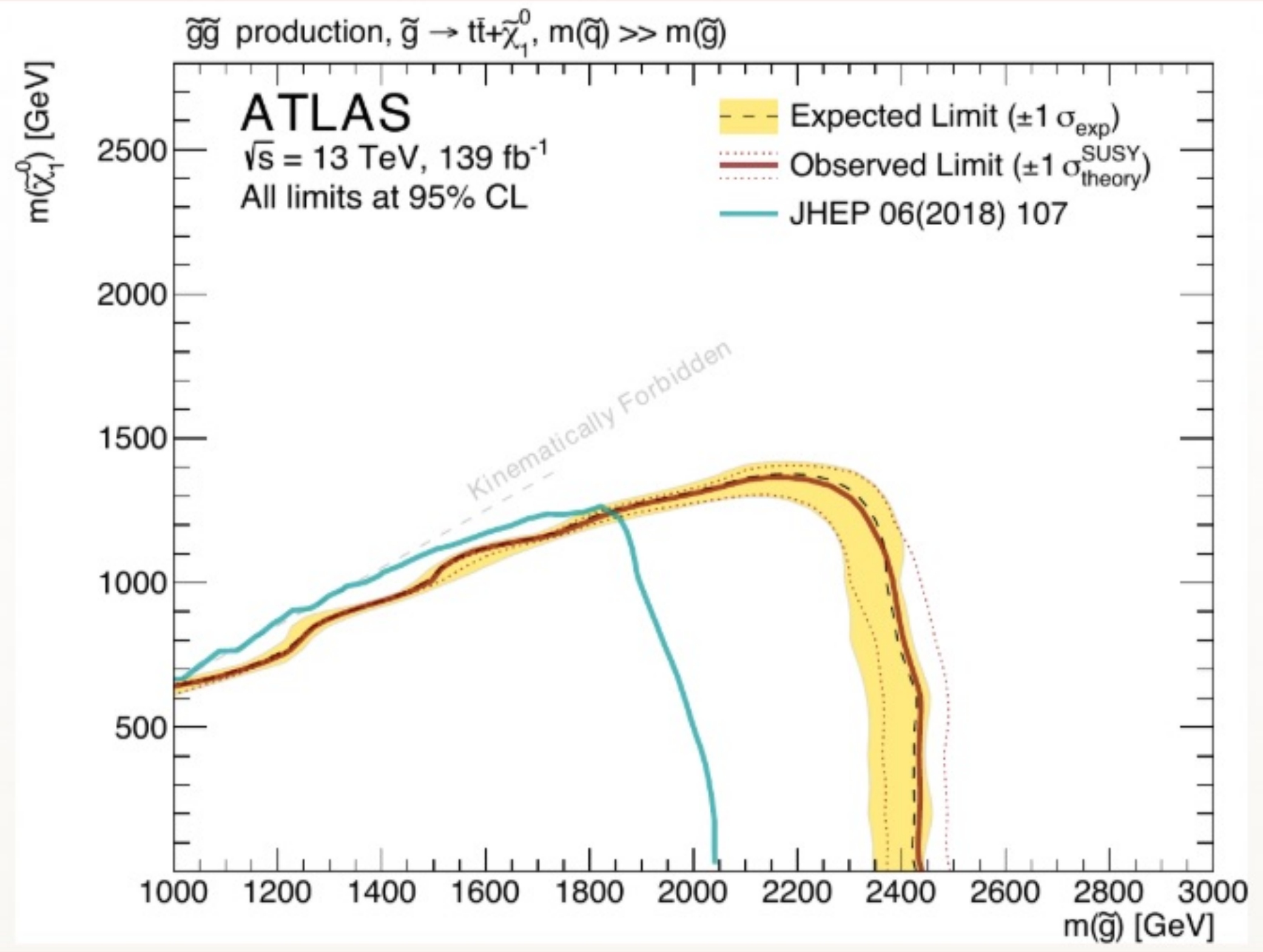
CRZ: 2 OSSF leptons in Z window;
lepton momenta added back to MET.

Gbb → bb̄χ̃: no top quark → extra Z(→ℓℓ)+jets control region needed to constrain Z+jets background.

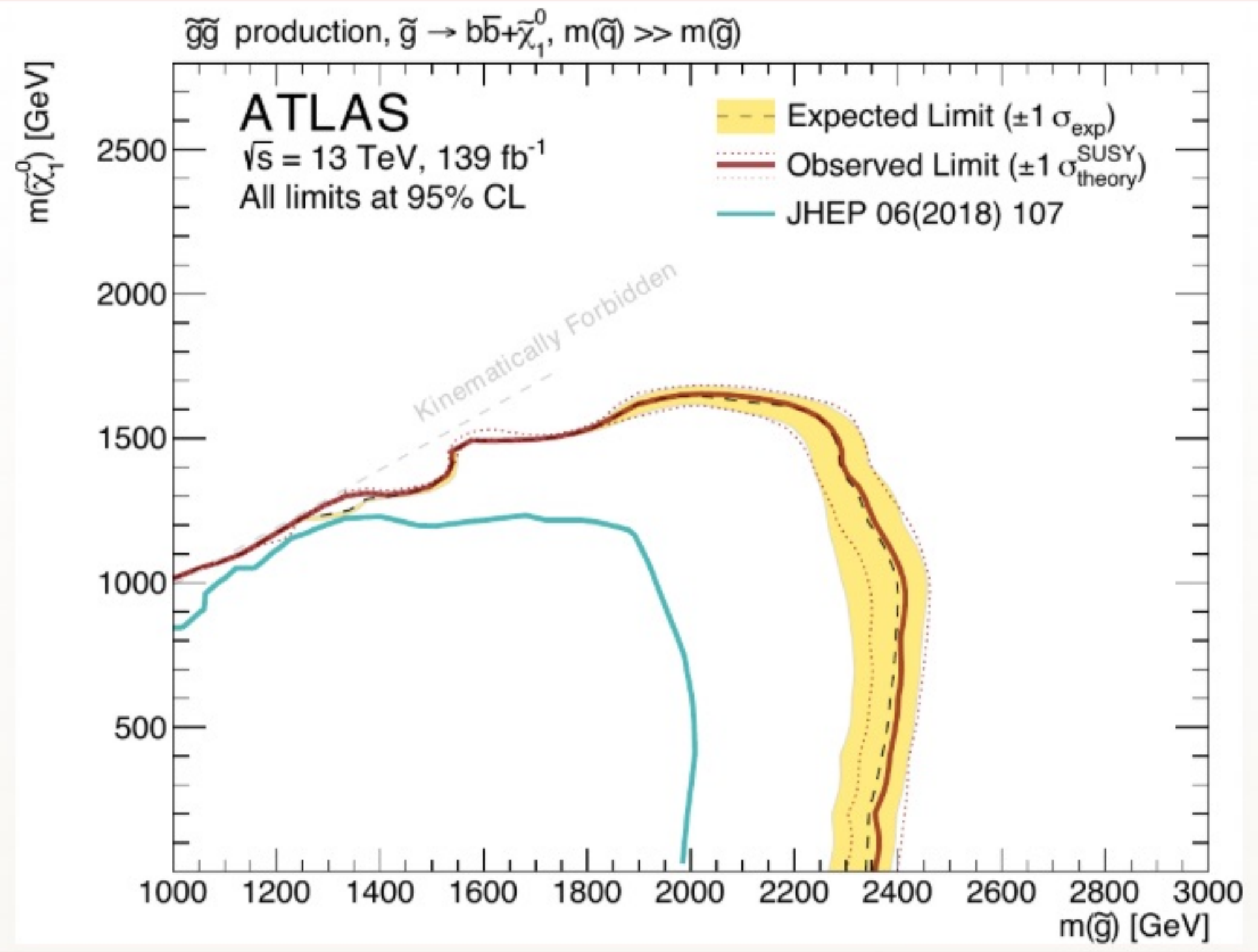
NN SRs used for Gtt/Gbb limits; CC SRs provide higher sensitivity for Gtb.

EXCLUSION LIMITS AT 95% CL

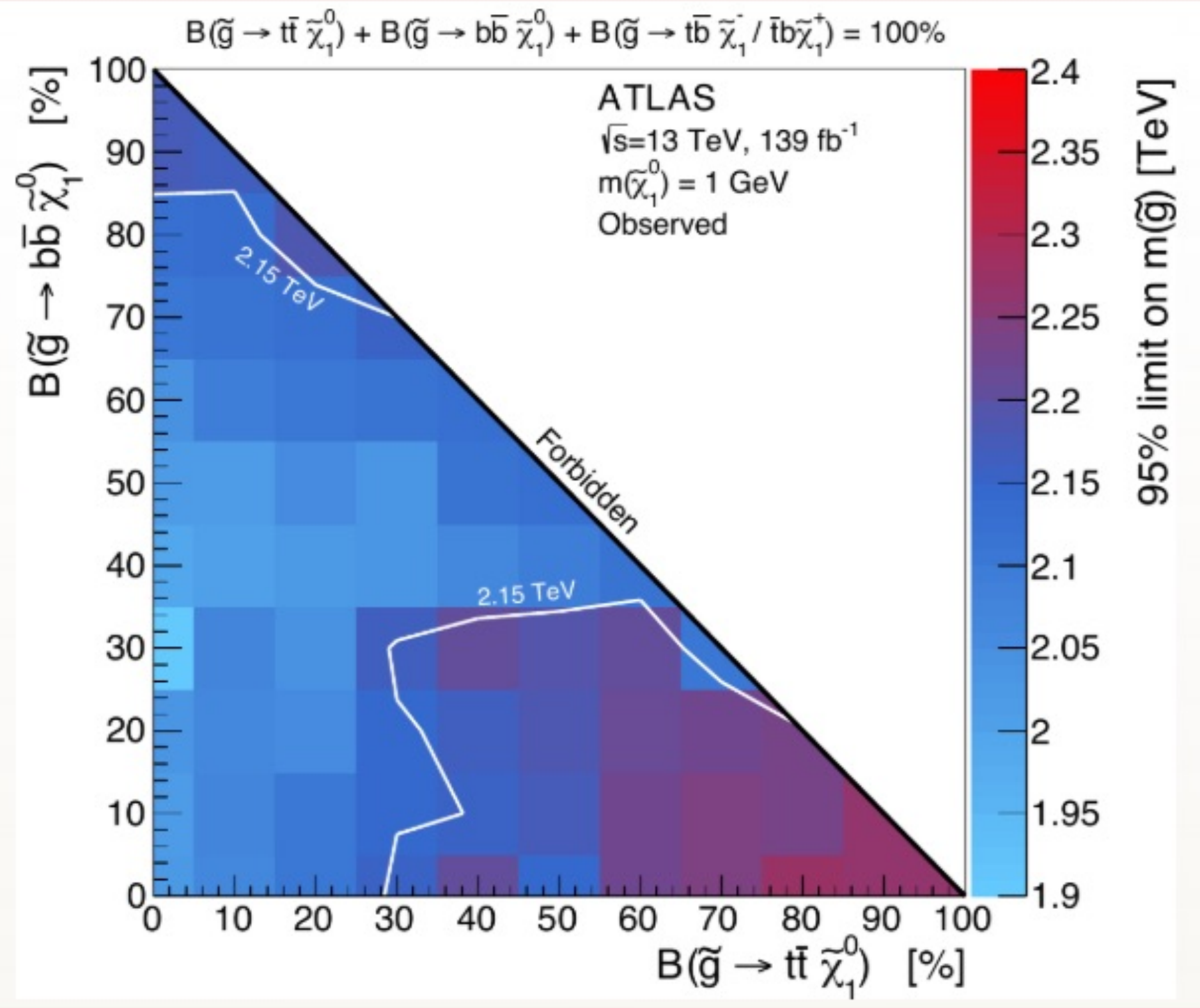
GTT – NN



GBB – NN



GTB BR PLANE (CC)



GTT – 95% CL OBS.

$m_{\tilde{g}} < 2.44\,\mathrm{TeV}$

massless $\tilde{\chi}_1^0$, NN analysis

GBB – 95% CL OBS.

$m_{\tilde{g}} < 2.35\,\mathrm{TeV}$

massless $\tilde{\chi}_1^0$, NN analysis

One of the strongest gluino limits from full Run 2

Exclusion pushed to **2.3–2.4 TeV**, setting the current benchmark for simplified Gtt/Gbb models.

Dual strategy: re-optimised CC + deep NN

CC regions remain reinterpretation-friendly; NN delivers peak sensitivity for specific signal hypotheses.

Parameterised NN: one network across the full mass plane

$(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ fed as continuous inputs – no per-point retraining; exploits interpolation across the grid.

Gtb BR plane: beyond the pure-decay endpoints

Directly shows how the limit varies with mixed decay fractions – intermediate BR scenarios need explicit coverage, not just the Gtt/Gbb pure limits.

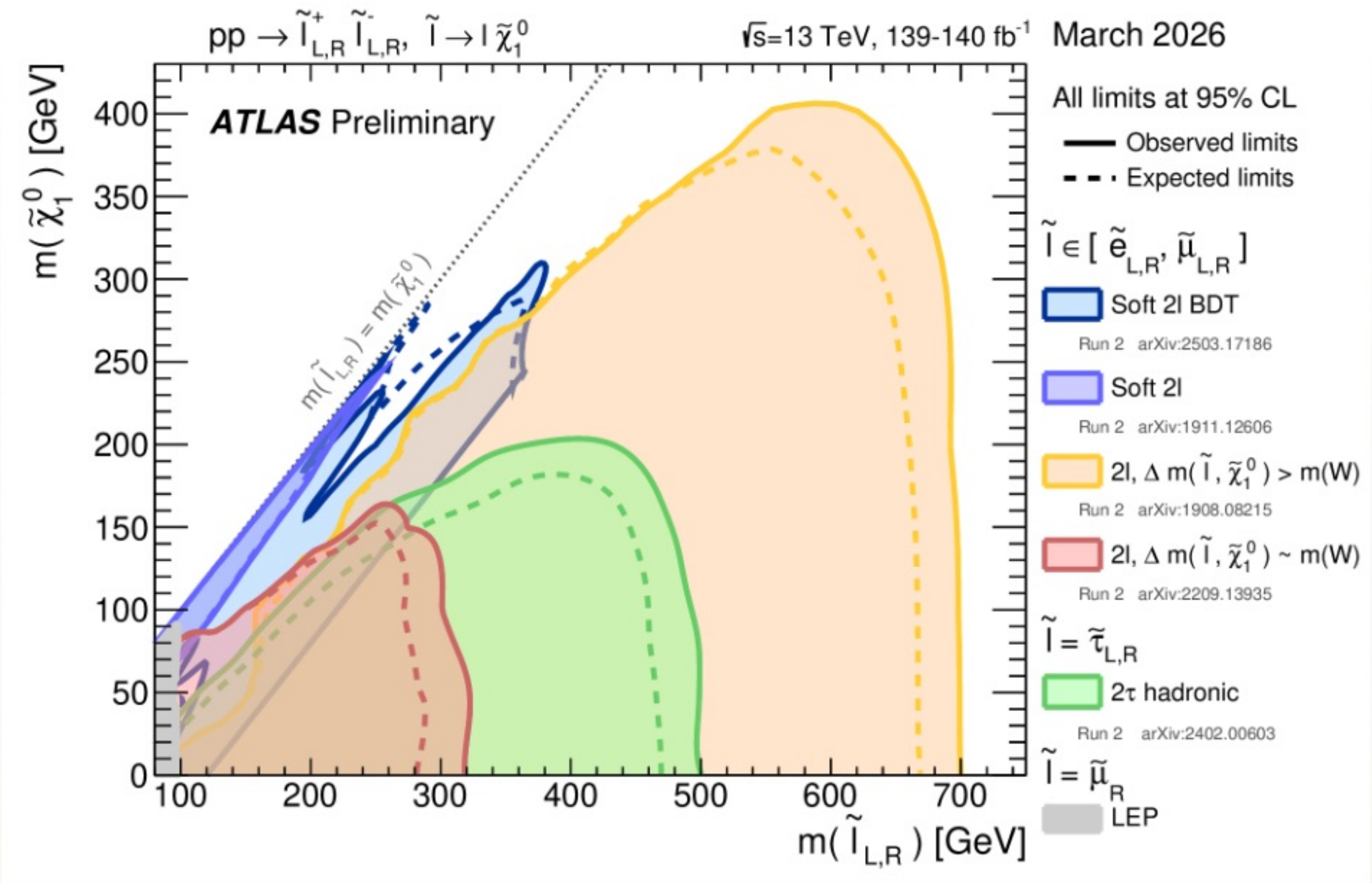
EXPERIMENTAL SUSY SEARCH

EWK SUSY Searches: Current Landscape

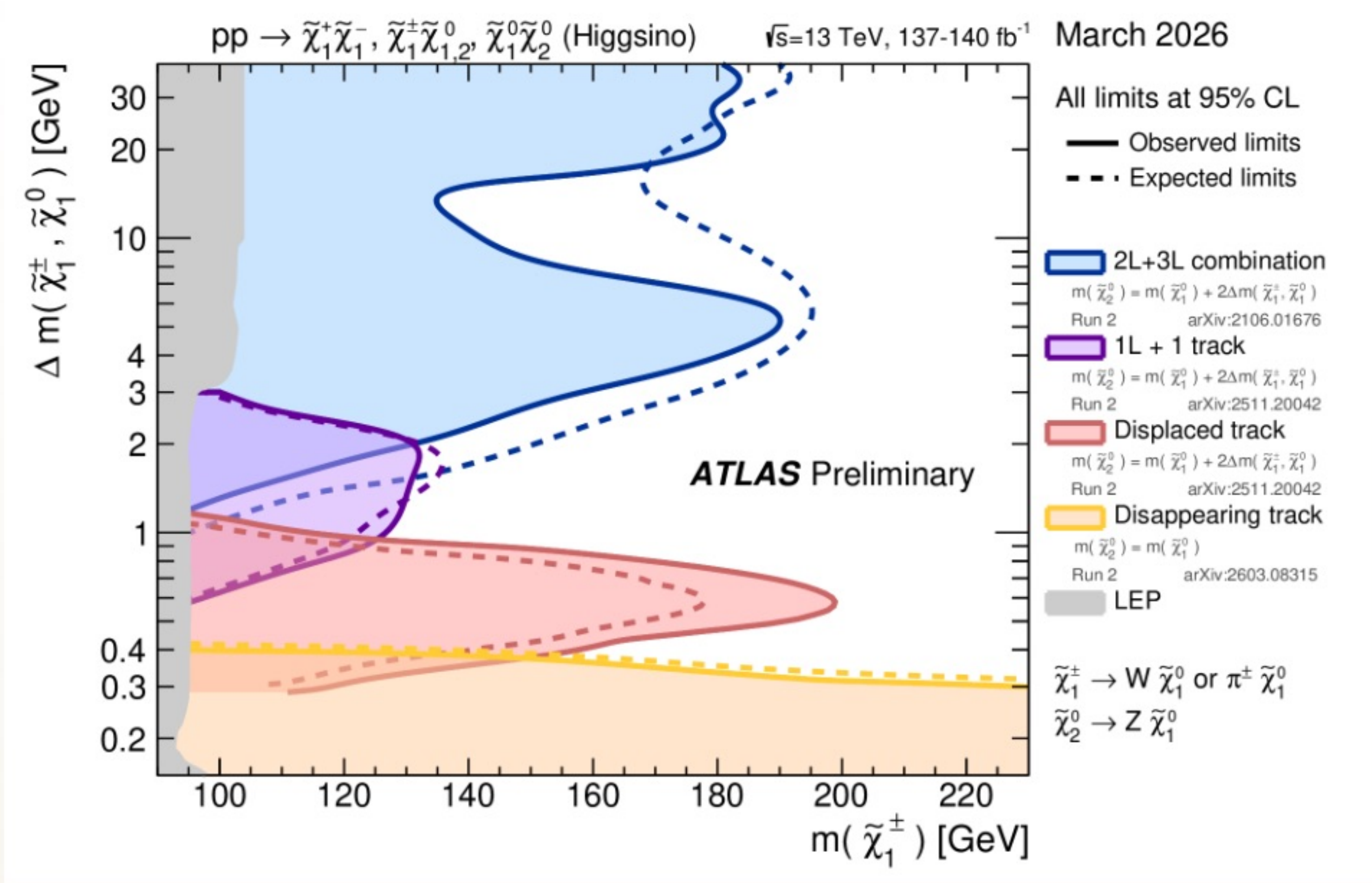
ATLAS SUMMARY PLOTS

Source: ATL-PHYS-PUB-2026-003

SLEPTON AND STAU SUMMARY



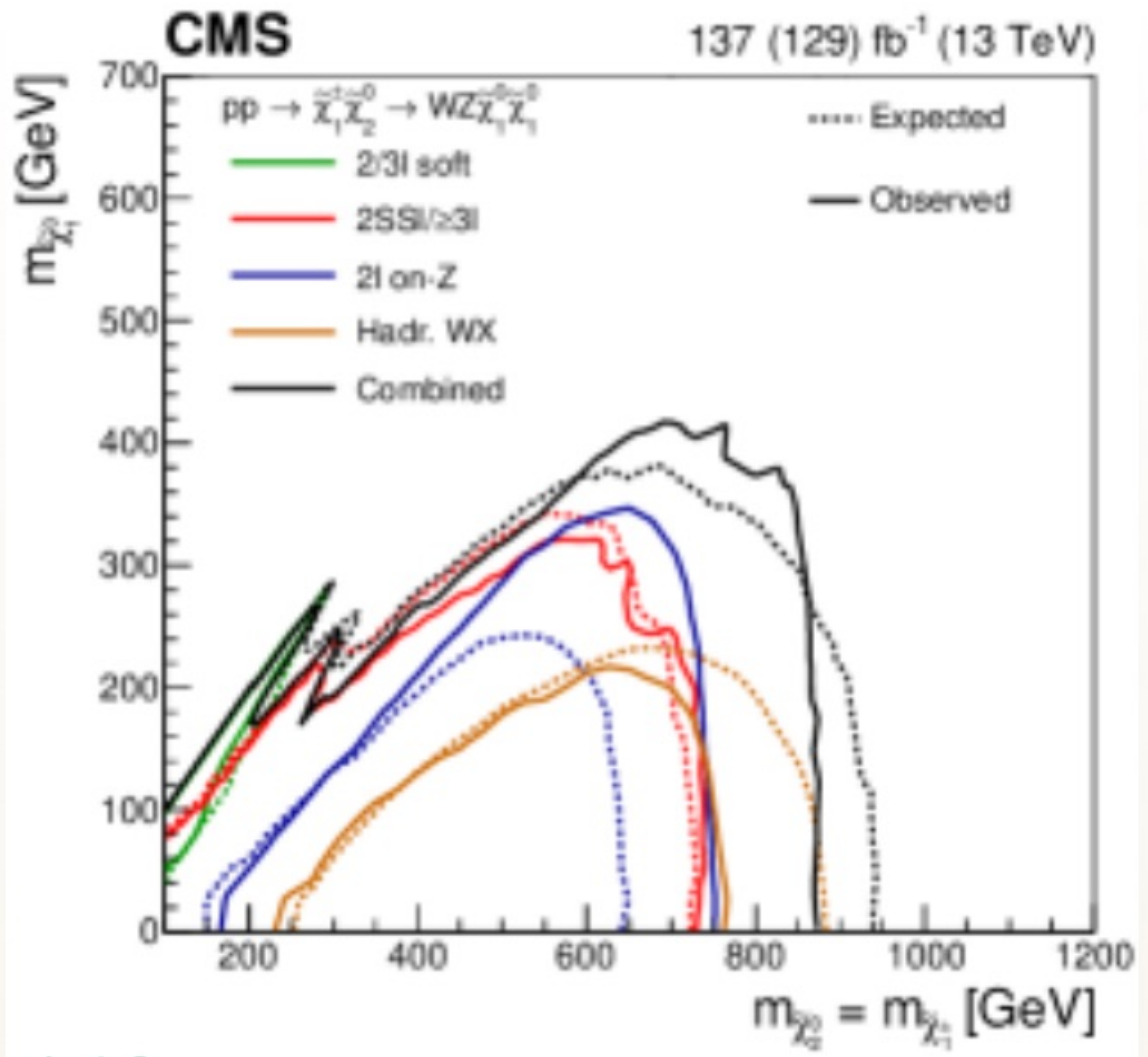
COMPRESSED HIGGSINO SUMMARY



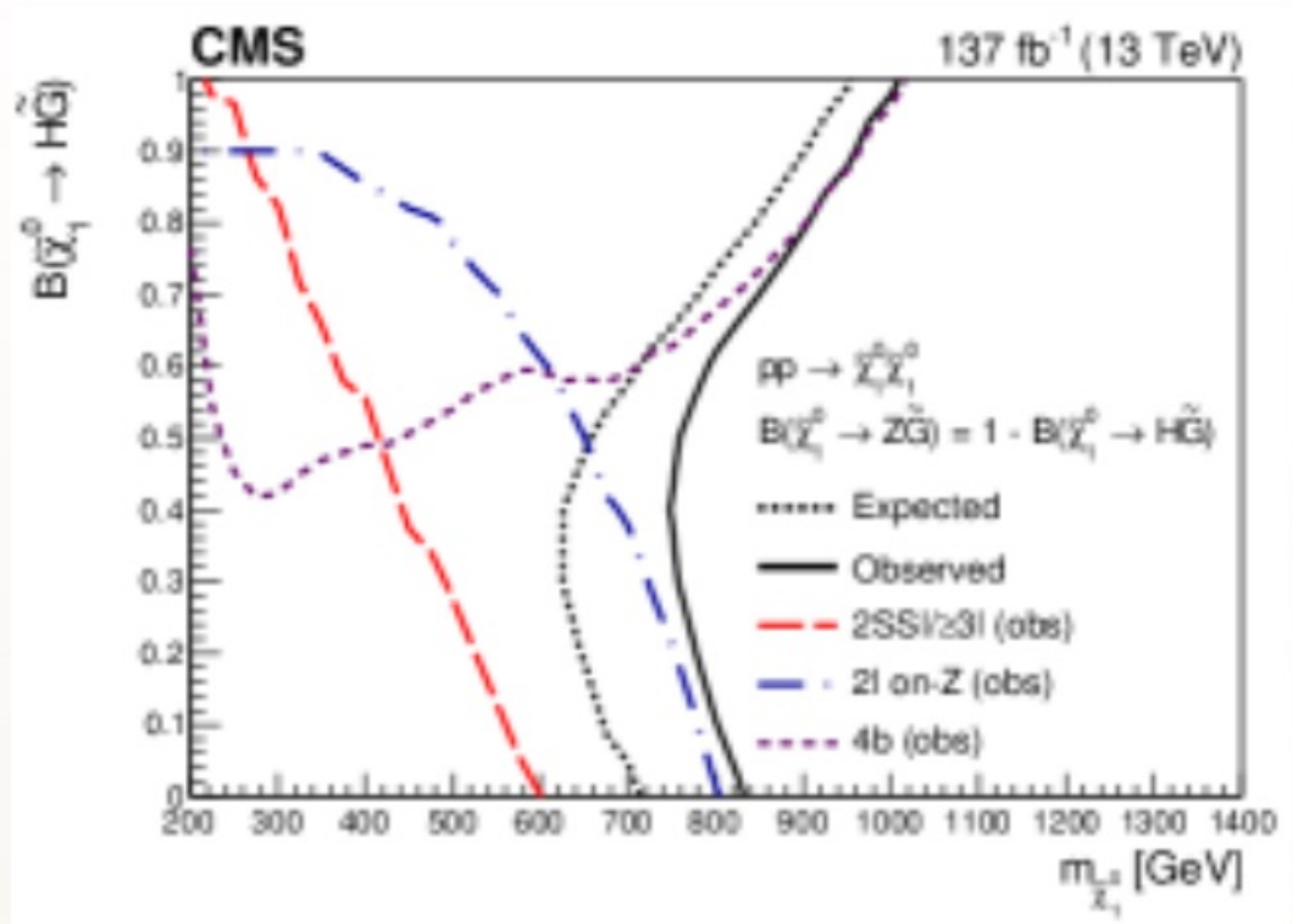
CMS SUMMARY PLOTS

Source: arXiv:2510.17971

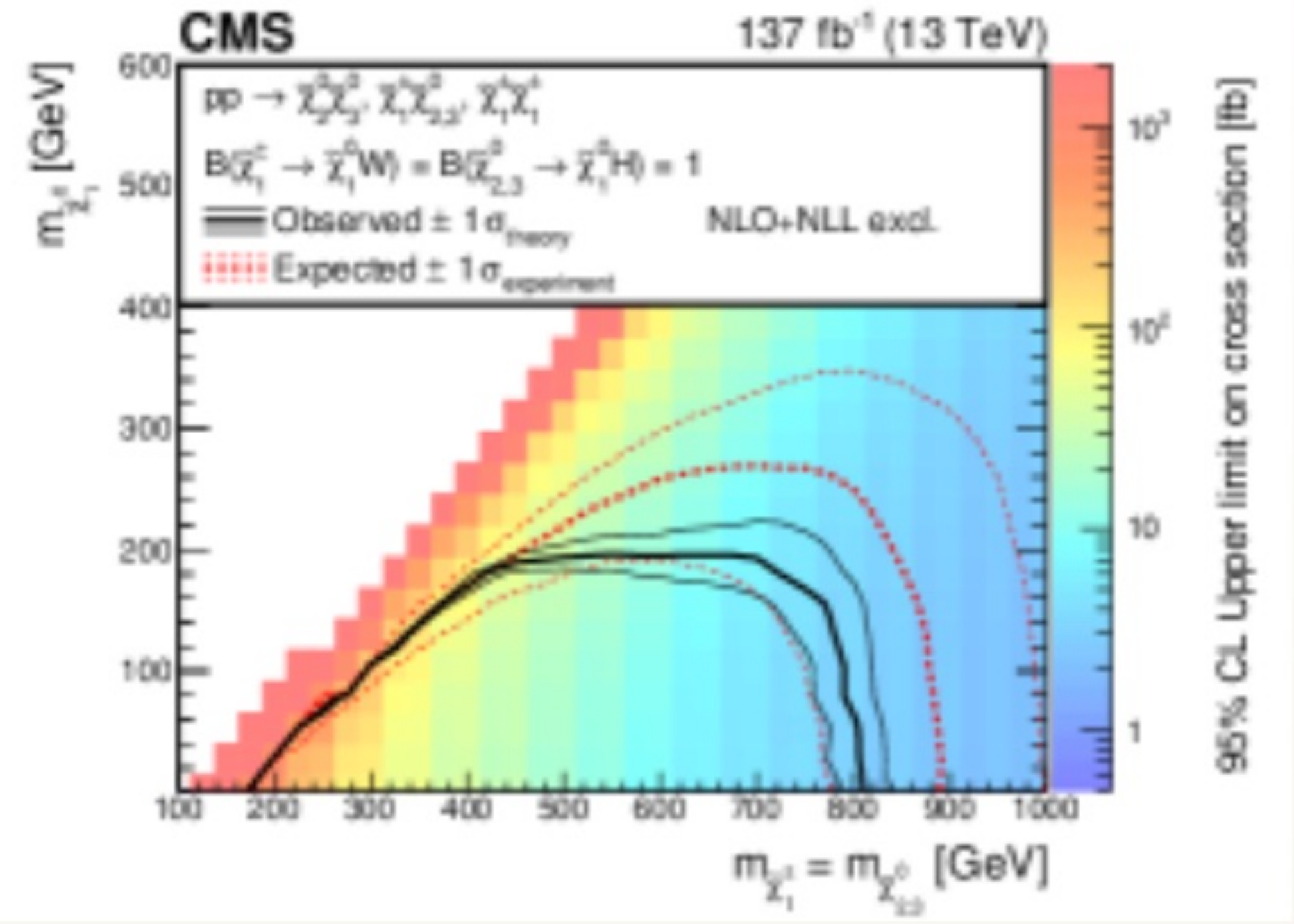
WINO-BINO, WZ



GMSB-HIGGSINO

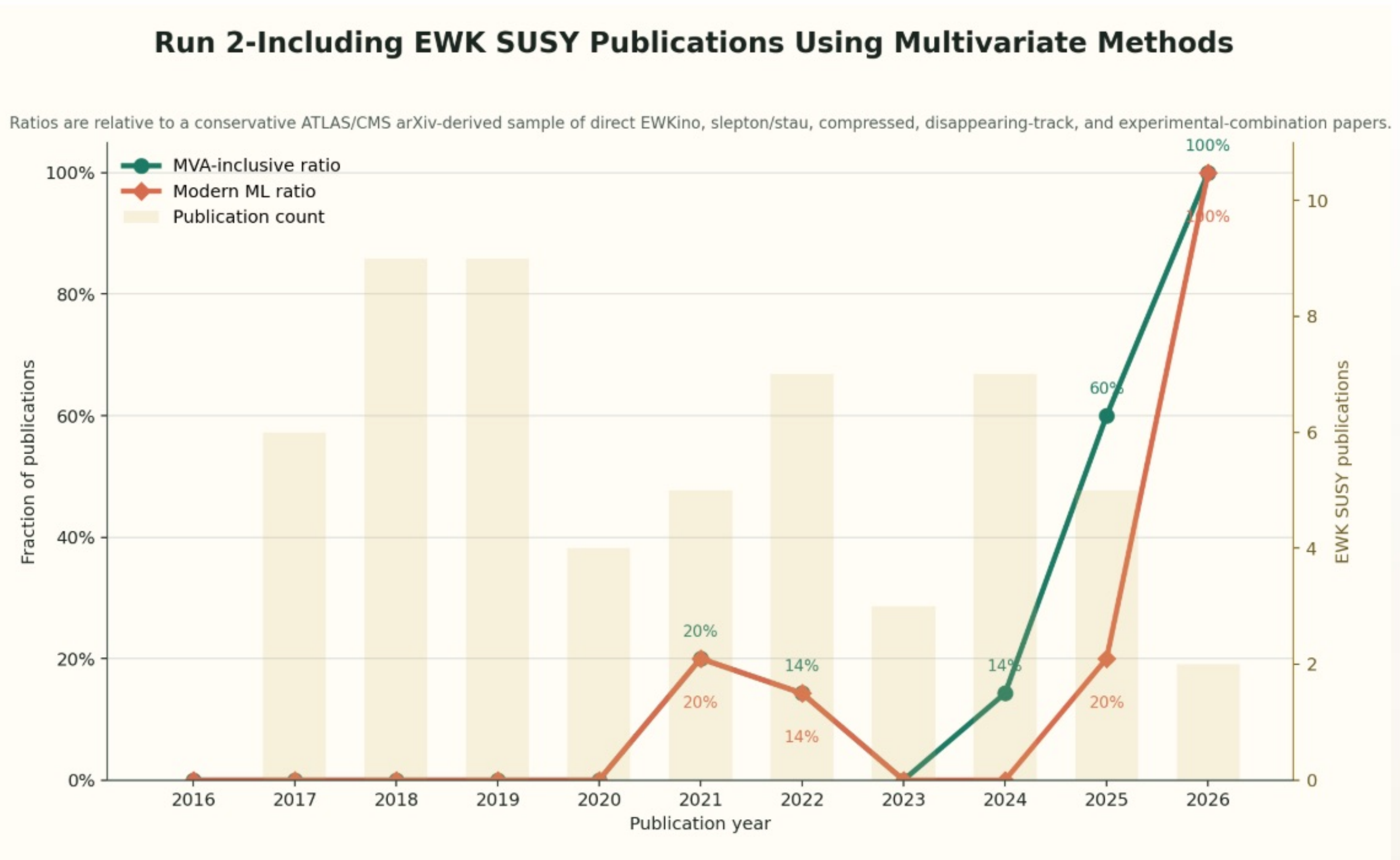


HIGGSINO-BINO



ML USAGE IN EWK SUSY SEARCHES

ML has become a mainstream choice, with tangible gains in sensitivity already visible in the current EWK SUSY program.



Run 2-Including EWK SUSY Publications Using Multivariate Methods

Ratios are relative to a conservative ATLAS/CMS arXiv-derived sample of direct EWKino, slepton/stau, compressed, disappearing-track, and experimental-combination papers.

WHAT THE EWK PROGRAM IS TELLING US

Bino-like
prompt reach to ~0.9-1.1 TeV

Higgsino-like
typically few 100 GeV

Sleptons / staus
~700 GeV / few 100 GeV

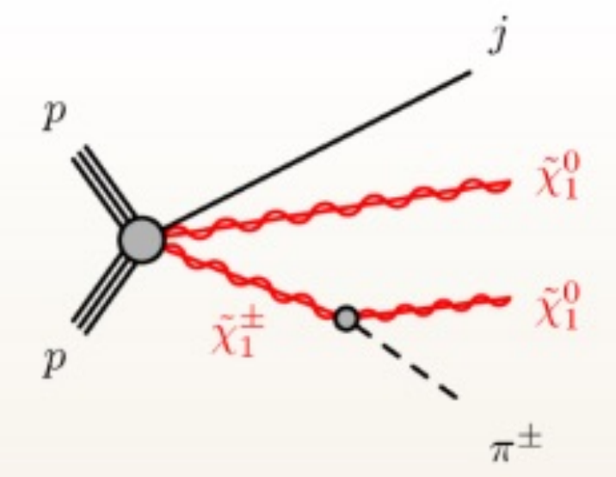
- More physical configurations make EWK SUSY searches intrinsically more complex, but the present experimental coverage is already fairly broad.
- The main emphasis now shifts to compressed spectra, where soft-object and ISR-assisted strategies are essential.

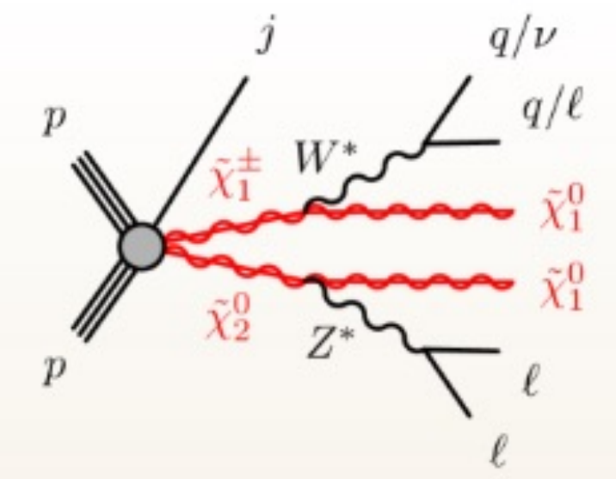
EXPERIMENTAL SUSY SEARCH

Representative Strong Results: Compressed Higgsino Search

ATLAS 2511.20042

displaced-track + 1l1T





TARGET FINAL STATES

- ISR JET + MET
- SOFT DISPLACED TRACK
- 1 PROMPT SOFT ℓ
- 1 LOW-P_T TRACK

EVENT LOGIC

ISR recoil
monojet-like trigger and large missing momentum

Visible system turns ultra-soft
Δm and lifetime decide what can still be reconstructed

Analysis hand-off
displaced-track at very small Δm, 1l1T once the decay is prompt

HAND-OFF MAP

DT

DISPLACED-TRACK

For the sub-GeV regime, the visible decay product is effectively pion-like and displaced.

Event NN
ISR recoil and MET define the event-level search regions

Track NN
keeps the soft displaced track usable against detector backgrounds

1l1T

PROMPT HAND-OFF

Once the chargino decay is prompt enough, ATLAS switches to a soft lepton plus low-p_T track topology.

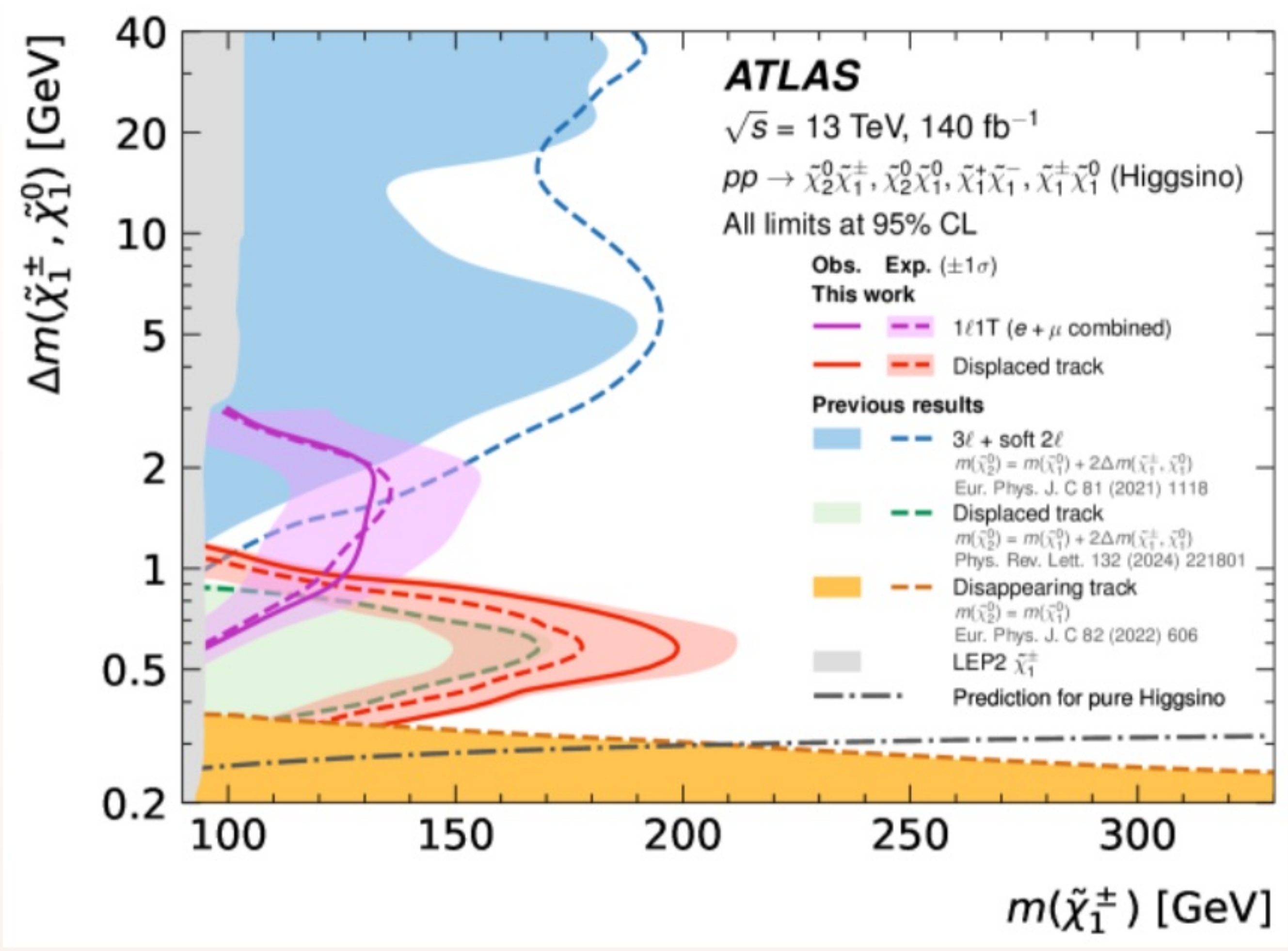
Soft-lepton taggers
recover the prompt low-momentum lepton candidate

pNN(Δm)
specialized bins match the changing prompt spectrum across Δm

ATLAS RESULT

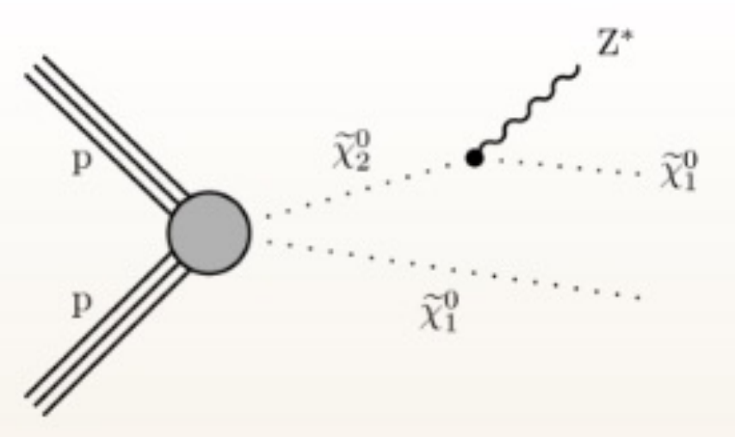
continuous coverage from 0.3 to 3 GeV

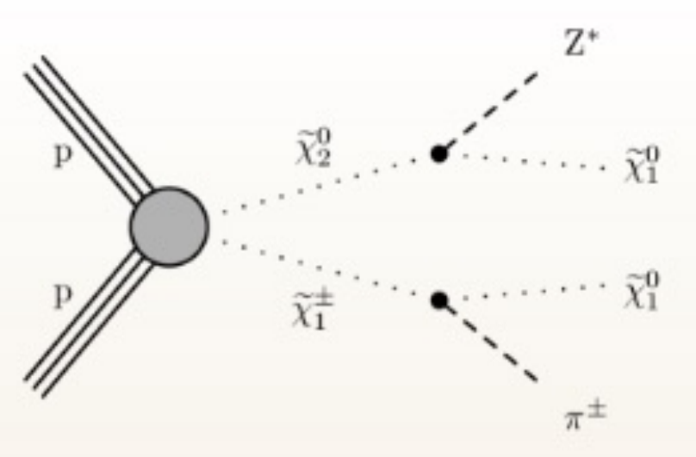
The displaced-track and 1l1T contours complement each other and together remove the old LEP gap over most of the targeted strip.



CMS 2511.16394

dimuon + lepton-track





TARGET FINAL STATES

- ISR JET + HARD MET
- SOFT MM
- M+ EXCLUSIVE TRACK
- E+ EXCLUSIVE TRACK

BLIND SPOT TARGET

Below 3 GeV
standard soft leptons lose efficiency

Target window
$\Delta m_0 = 1$ to 10 GeV

Recover the lost lepton
ultra-soft dilepton or lepton + track

COMMON EVENT SKELETON AND CATEGORY SPLIT

Common preselection
ISR jet, large MET, low-mass window

Category A
dimuon branch

Category B
muon + exclusive track

Category C
electron + exclusive track

Region Definitions

DIMUON BRANCH

Extra cuts
very soft or collimated OS muons

Signal regions
event-BDT bins and low-mass slices

Background control
jetty sideband and prompt-dilepton correction

Output
cleanest ultra-soft dilepton category

Region Definitions

EXCLUSIVE TRACK BRANCHES

Track recovery
highest-score track replaces the lost lepton

Extra cuts
analysis lepton plus max-track BDT

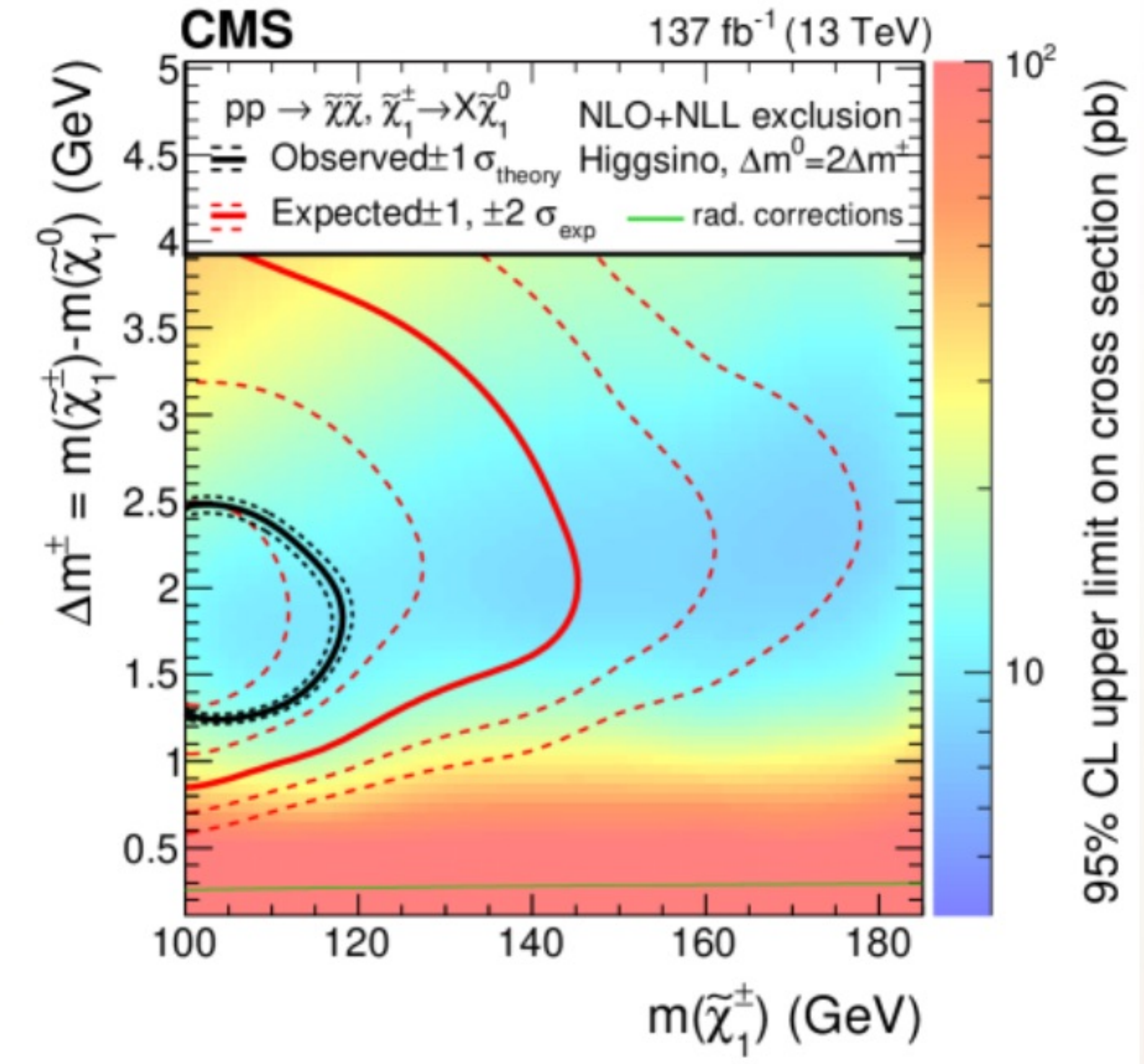
Signal regions
flavor and detector-phase bins

Background method
same-charge control then transfer to OS bins

CMS RESULT

best sensitivity near prompt small-Δm

The exclusive-track recovery channel extends prompt compressed sensitivity below the usual soft-lepton boundary.

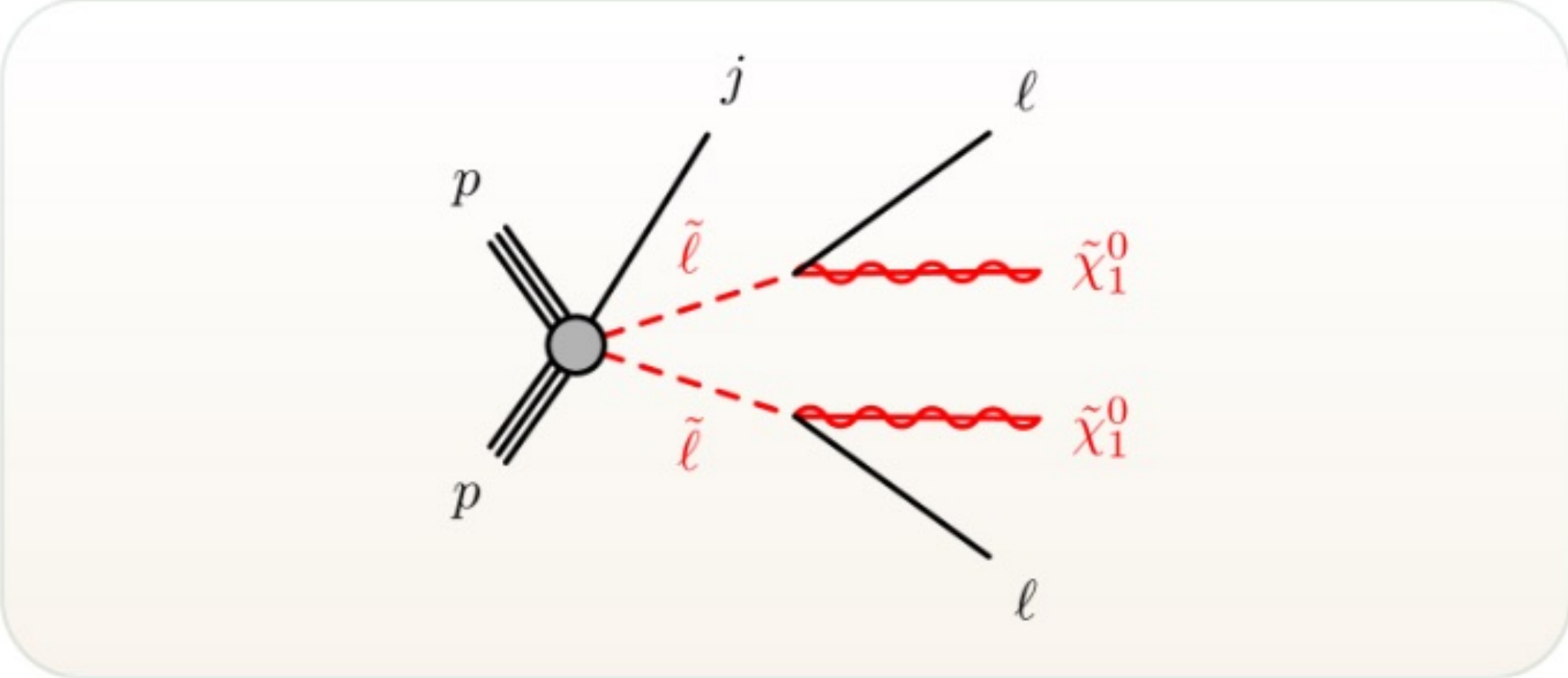


EXPERIMENTAL SUSY SEARCH

Representative EWK Result: Compressed Slepton Corridor

ATLAS 2503.17186

direct slepton pair + ISR recoil



TARGET FINAL STATES

ISR JET + MET
SFOS EE/MM
SOFT LEPTONS
CORRIDOR $\Delta M \lesssim M_W$

CORRIDOR LOGIC

direct slepton pairs
clean SFOS topology still exists underneath the compression

small Δm
both leptons rapidly become soft as the corridor is approached

legacy searches lose power
fixed hard-lepton logic cannot cover the full strip continuously

ATLAS closes the gap
ISR recoil plus dedicated SR design restores sensitivity across the corridor

EVENT SKELETON

ISR jet + MET backbone
recoil makes the event triggerable and anchors the whole strategy

›

compressed SFOS dileptons
ee or $\mu\mu$, but soft enough that Δm binning becomes central

›

two SR constructions
cut-and-count for interpretability, BDTs for continuous corridor reach

Cut-and-count branch
Tighter lepton thresholds and explicit low/high-Δm partitions keep the analysis model transparent.
2 inclusive SRs **split to ee and $\mu\mu$**

BDT corridor branch
Looser entry and five dedicated Δm experts turn the strip into a nearly continuous search space.
5 BDT families **3 bins each**

Cut-and-count SRs
2 inclusive branches, both ending in ee and $\mu\mu$ bins.
SR-low-Δm **SR-high-Δm**

BDT SRs
Five dedicated experts tile the corridor from the softest to the widest mass gaps.
target 5+10 GeV **20 GeV** **30 GeV** **40+50 GeV** **60+75 GeV**

CUT-AND-COUNT MAP

SR-low-Δm
Lower-gap corridor entry with harder control of recoil and lepton softness.
ee **$\mu\mu$**

SR-high-Δm
Higher-gap branch that stays interpretable while keeping the same flavor split.
ee **$\mu\mu$**

BDT TILING OF THE CORRIDOR

target Δm 5+10
lowest-gap expert
bin 1 **ee** **$\mu\mu$**
bin 2 **ee** **$\mu\mu$**
bin 3 **ee** **$\mu\mu$**

target Δm 20
soft-to-intermediate gap
bin 1 **ee** **$\mu\mu$**
bin 2 **ee** **$\mu\mu$**
bin 3 **ee** **$\mu\mu$**

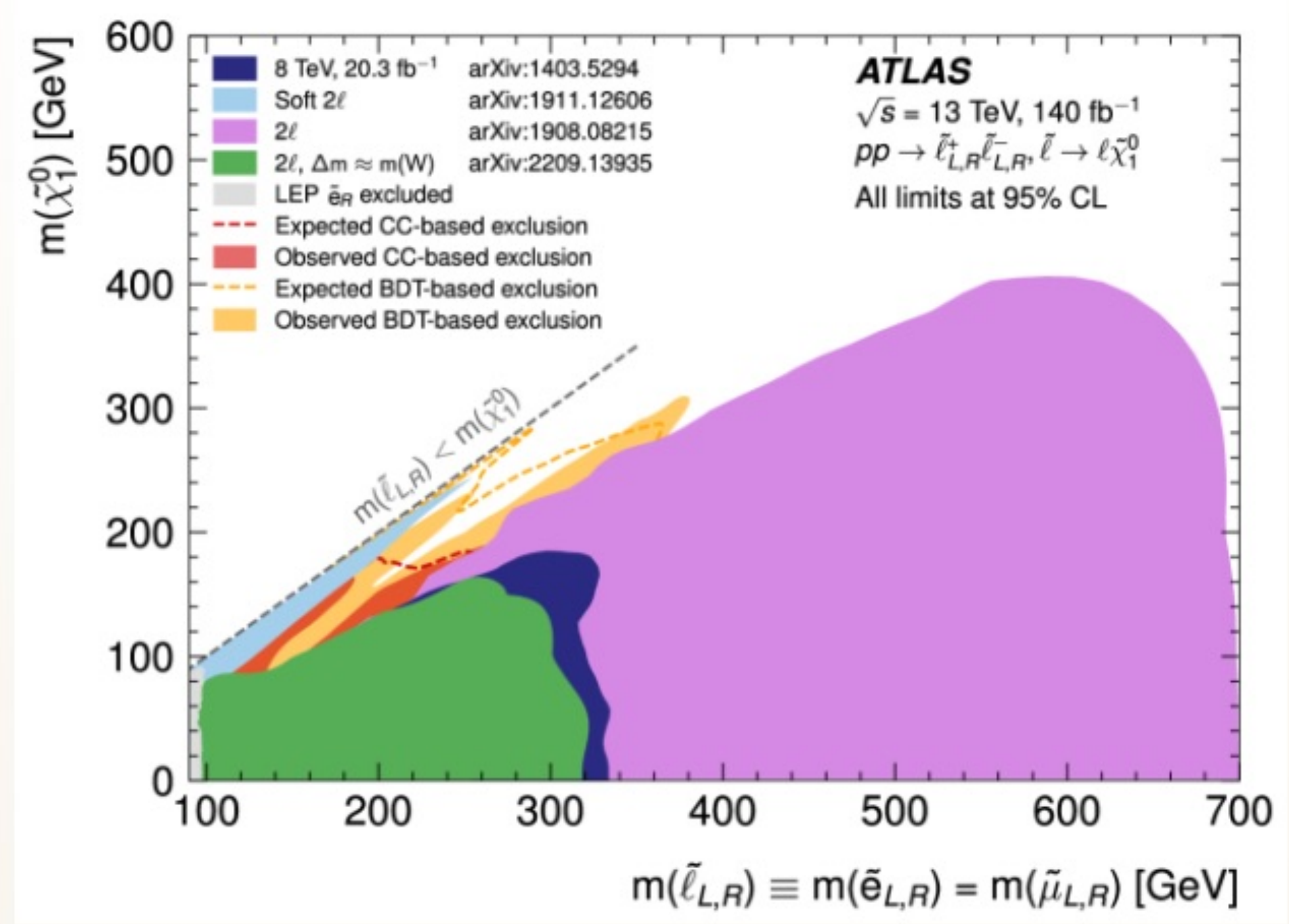
target Δm 30
mid-corridor coverage
bin 1 **ee** **$\mu\mu$**
bin 2 **ee** **$\mu\mu$**
bin 3 **ee** **$\mu\mu$**

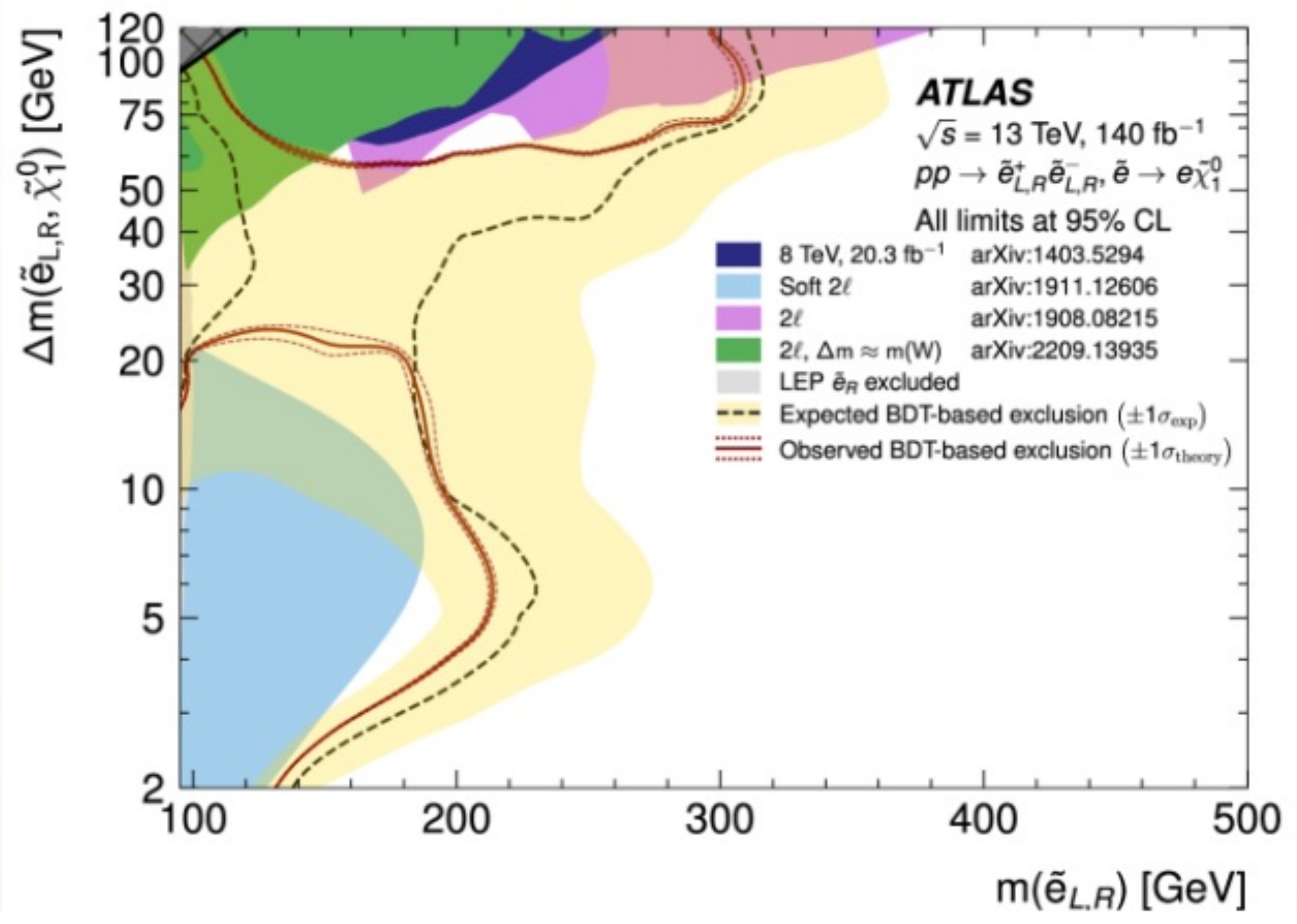
target Δm 40+50
upper-middle corridor
bin 1 **ee** **$\mu\mu$**
bin 2 **ee** **$\mu\mu$**
bin 3 **ee** **$\mu\mu$**

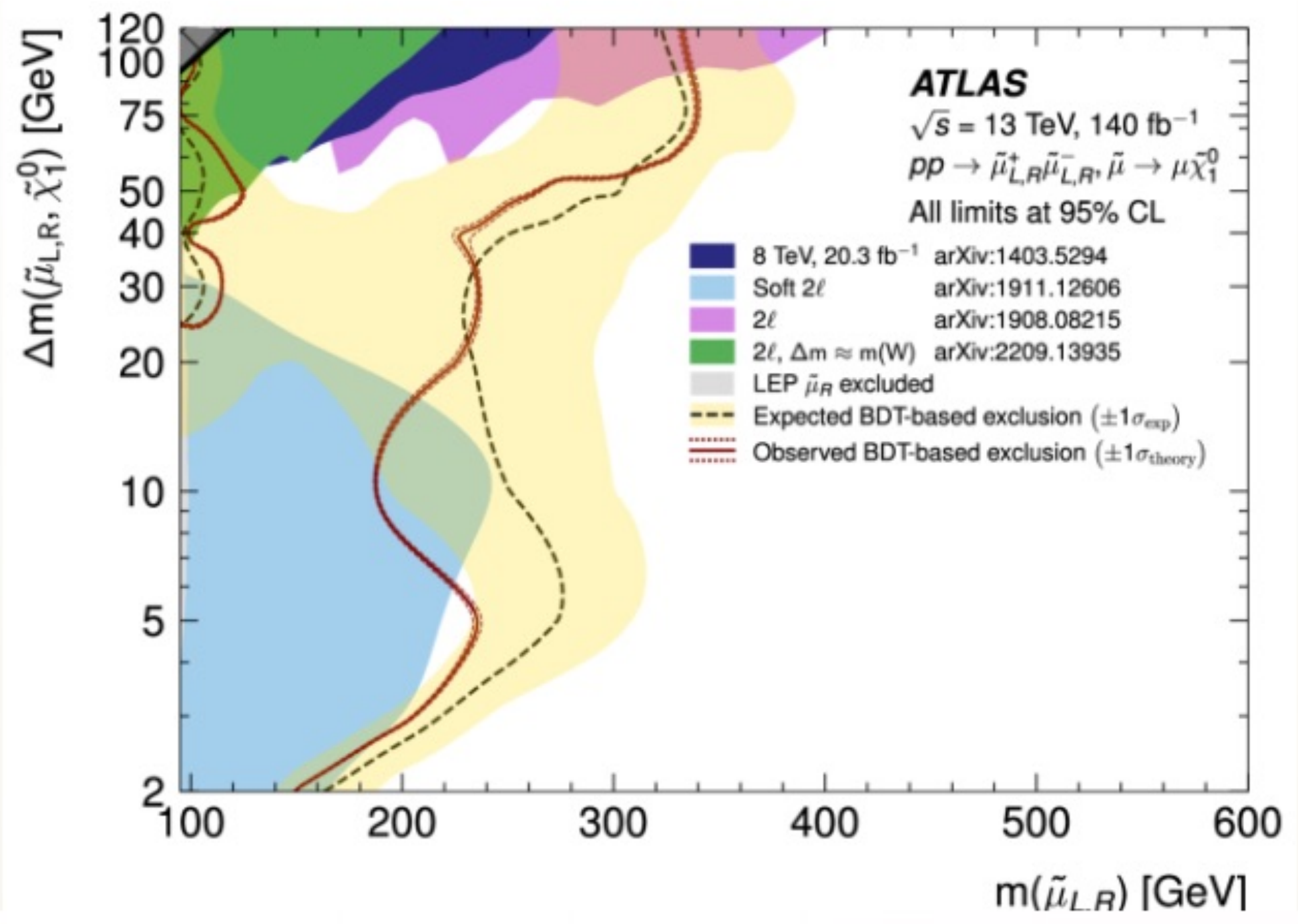
target Δm 60+75
widest gap in the BDT strip
bin 1 **ee** **$\mu\mu$**
bin 2 **ee** **$\mu\mu$**
bin 3 **ee** **$\mu\mu$**

ATLAS RESULT

BDT closes the corridor, with small local ripples







Compressed gap covered

BDT-based search fills the slepton corridor inaccessible to cut-and-count – $\Delta m \approx 10$–50 GeV continuously excluded for the first time.

BDT excesses

Local excesses in BDT regions: **2.0σ** for selectrons ($\Delta m \approx 40$ GeV) and **2.4σ** for smuons ($\Delta m \approx 10$ GeV).

Best-fit signal models

Max discovery significance: **2.1σ** for smuon at $(150,\ 140)$ GeV; **1.9** σ for selectron at $(375,\ 335)$ GeV.

Outlook: jet & $E_{\mathrm{T}}^{\mathrm{miss}}$ systematics

Current jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ correlations dominate the systematic budget. Precise jet energy scale and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction at the HL-LHC will be the decisive factor in confirming or ruling out these excesses.

— EXPERIMENTAL SUSY SEARCH

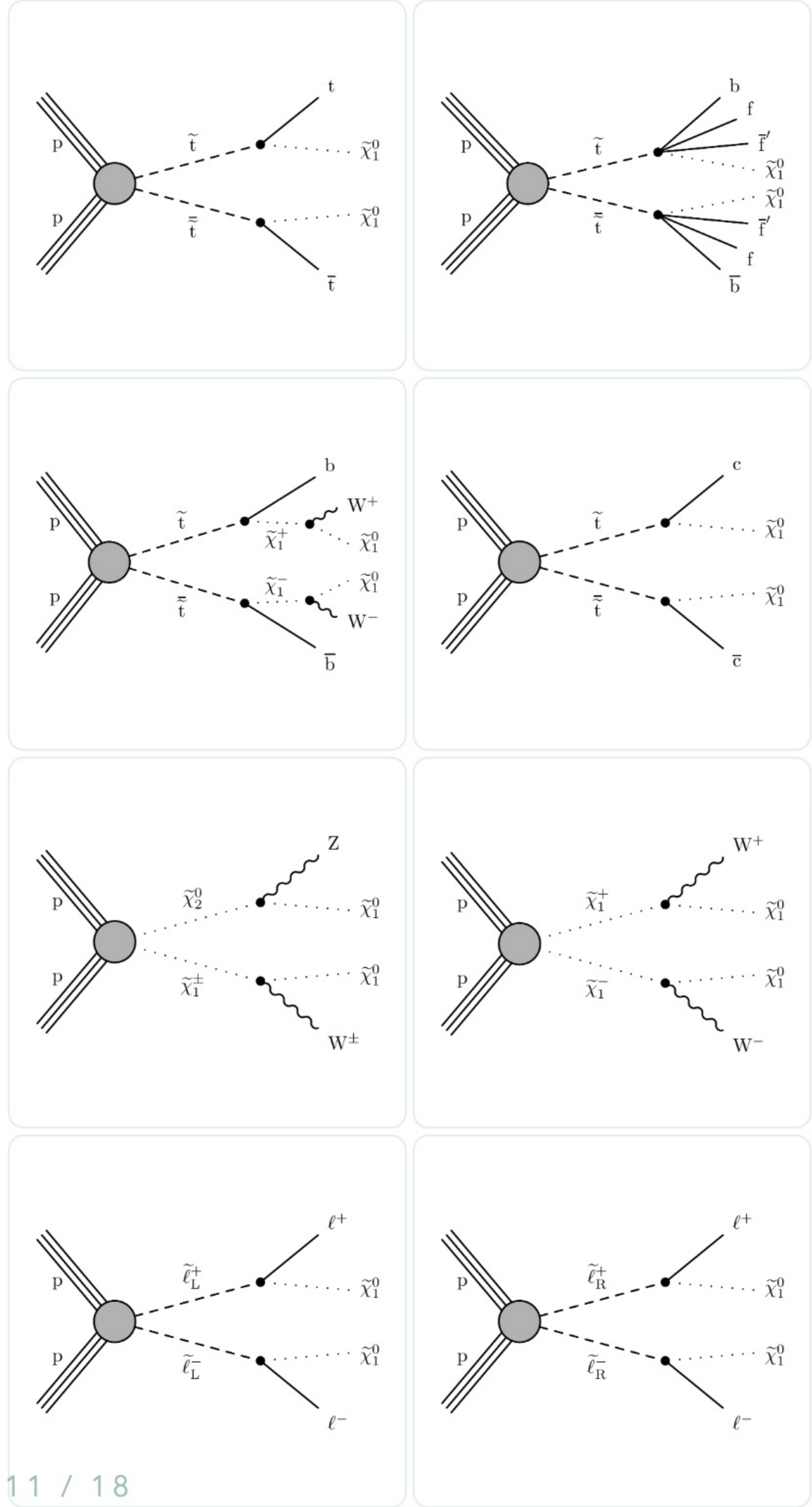
CMS General Search: Compressed Mass Spectra

ARXIV:2508.13900 · CMS SUS-23-003 · 138 FB^{-1}

8 Simplified Models

COMMON FINAL STATE

ISR JET + E_T^{MISS}



ANALYSIS STRATEGY

Region definition

Top layer
ISR tags the compressed recoil.

MET ISR
R_{ISR} and p_T^{ISR} define the SRs.

Lepton content
Exclusive 0L, 1L, and 2L branches.

Soft topology
Bin in N_{jet}^S, SV, and $m_\perp$.

0L

hadronic stop corridor

Split ISR-only and heavy-flavor bins before the final fit.

0 SV
ISR + MET core

$\geq$ 1 SV
Heavy-flavor branch

1J-5J
N_{jet}^S split

CR at low R_{ISR}
Low-R_{ISR} control bins

1L

soft-lepton stop / chargino

One soft lepton plus $m_\perp$ isolates signal from top and W.

1 soft ℓ
Loose low-p_T lepton

$m_\perp$ bins
Suppress W-like backgrounds

1J-4J
Exclusive jet bins

R_{ISR} map
SR and CR in one map

2L / 3L

EWkino / slepton

Compact bins target the clean electroweak channels.

2L: 0J / 1J / 2J
Jet bins with R_{ISR} windows

3L: 0J / 1J
High-purity WZ-like branch

Common fit axes
Shared R_{ISR} and $m_\perp$ axes

Exclusive final states

Low-R_{ISR} CRs embedded

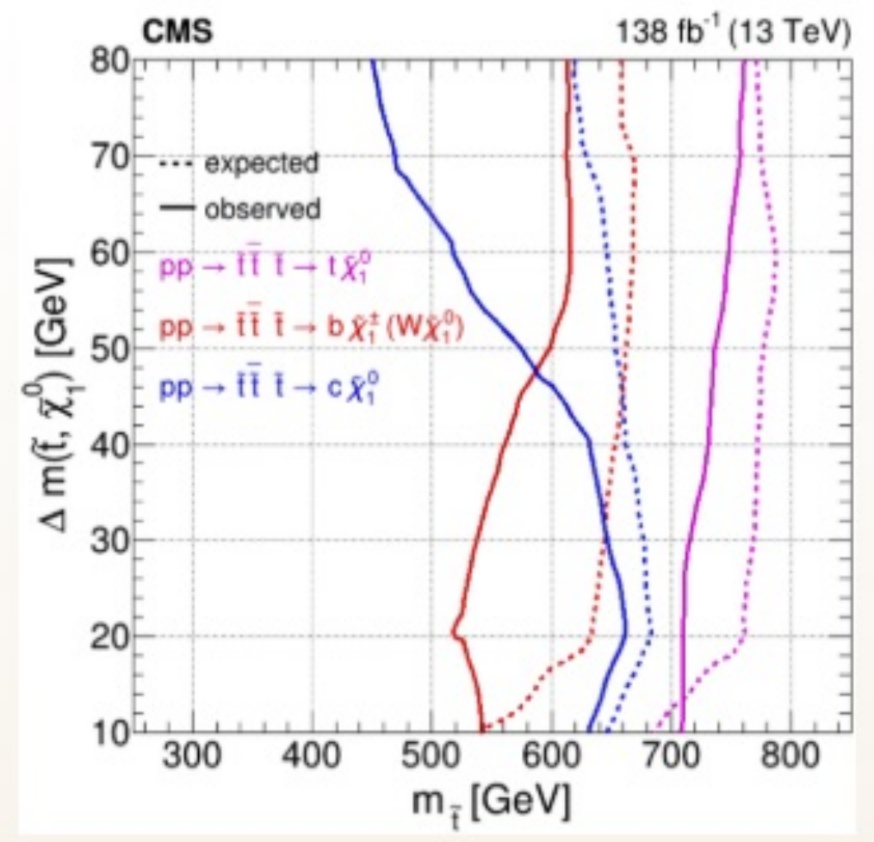
Unified compressed fit

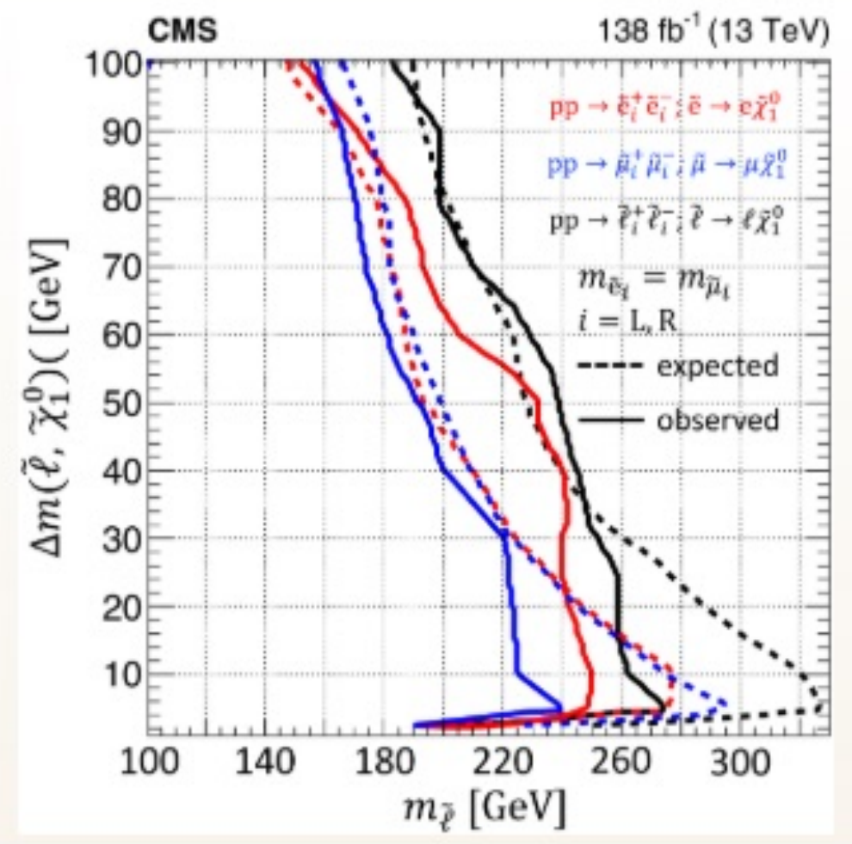
Background estimation: MC-first
WZ/ZZ, top, and DY start from simulation.

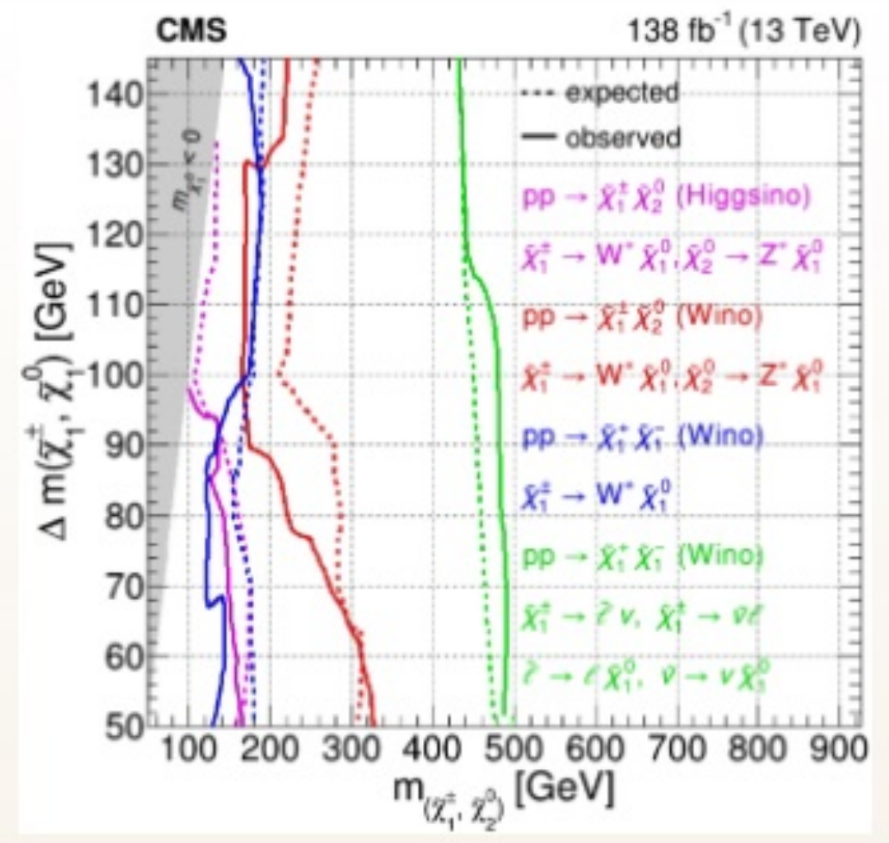
Background estimation: CR correction
Data control bins correct the main normalizations.

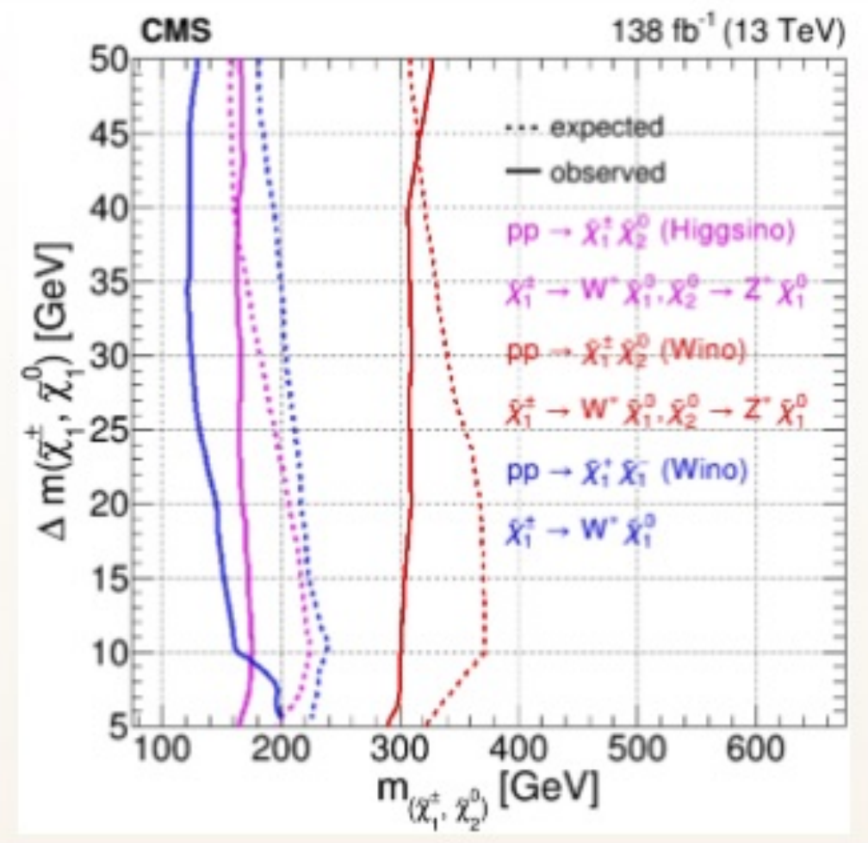
EXCLUSION RESULTS · 13 TEV · 138 FB^{-1}

Representative limits









Exclusion summary

- Stops: $m_{\tilde{t}} \lesssim 680$ GeV in the compressed corridor.
- EWkinos: $m_{\tilde{\chi}_1^\pm} \lesssim 350$ GeV with the combined 0L-3L strategy.
- Sleptons: $m_{\tilde{\ell}} \lesssim 260$ GeV for $\Delta m \lesssim 80$ GeV.

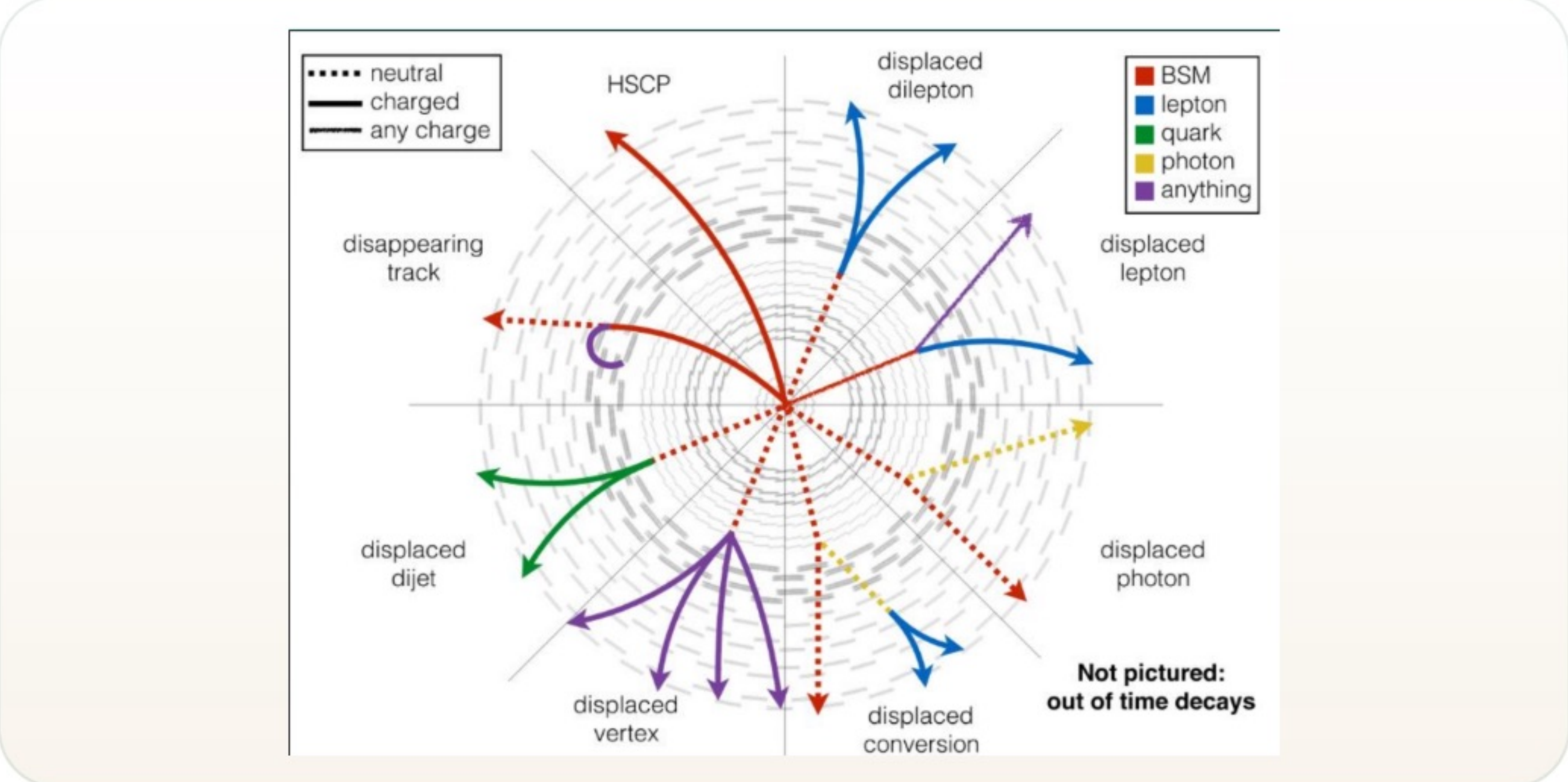
Key features

One unified ISR-based search covers compressed stop, EWkino, and slepton scenarios together.

EXPERIMENTAL SUSY SEARCH

LLP SUSY Searches: Current Landscape

WHY SUSY BECOMES LONG-LIVED AND DETECTOR SIGNATURE MAP



WHY SUSY BECOMES LONG-LIVED

CAUSE A
Compressed spectrum

CAUSE B
Supersymmetry breaking

CAUSE C
Small RPV coupling

Disappearing / displaced tracks
Short charged LLP trajectories inside the tracker, often seeded by compressed chargino-like spectra.

Displaced objects
Displaced tracks, vertices, leptons, taus, and hadronic objects from delayed visible decays.

HSCP-like observables
Meta-stable charged particles reaching outer detectors with TOF and anomalous dE/dx information.

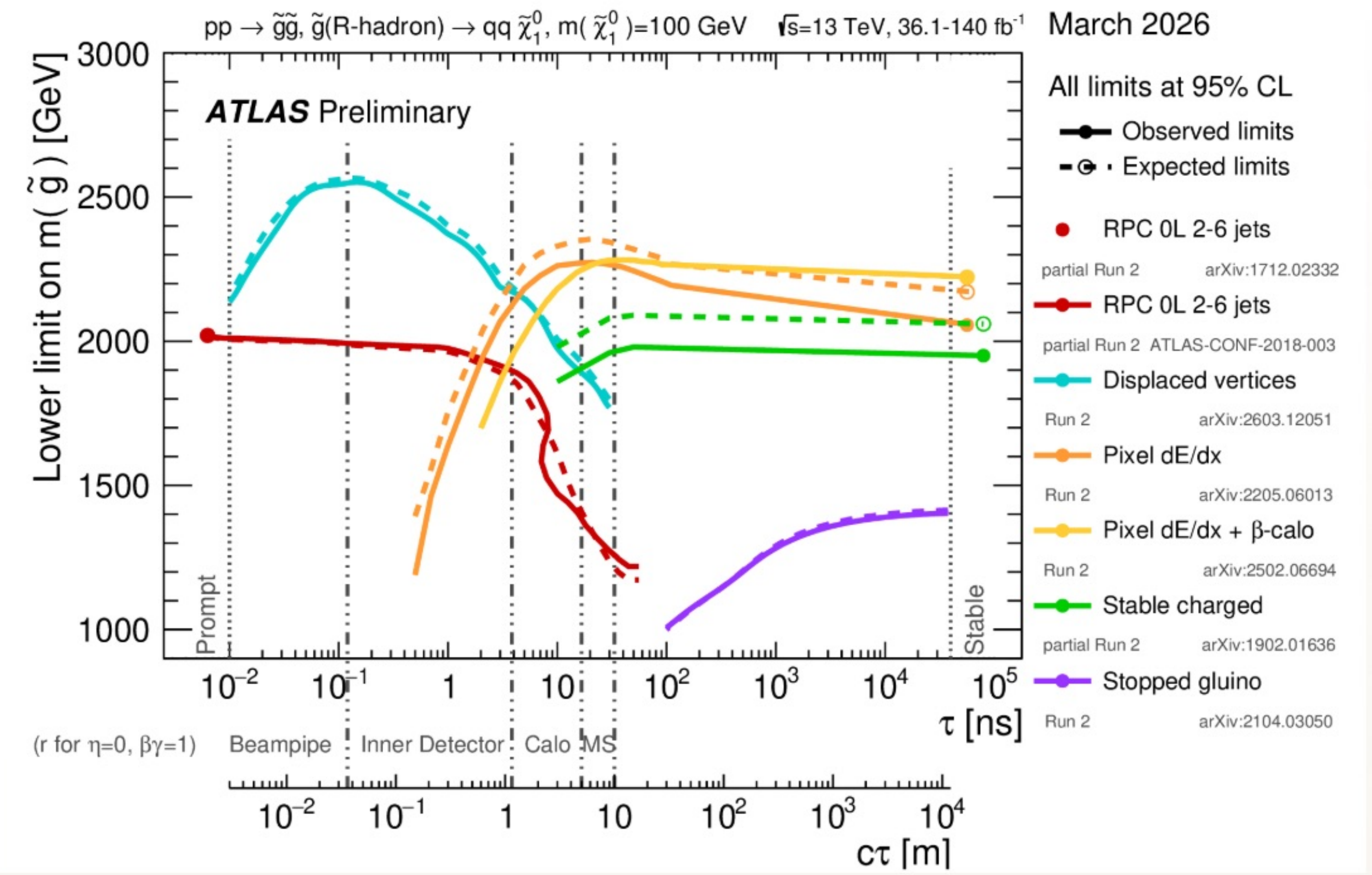
ML USAGE IN LLP SUSY

Publications keep increasing, and LLP-targeted analyses increasingly inherit advanced reconstruction and classification tools.

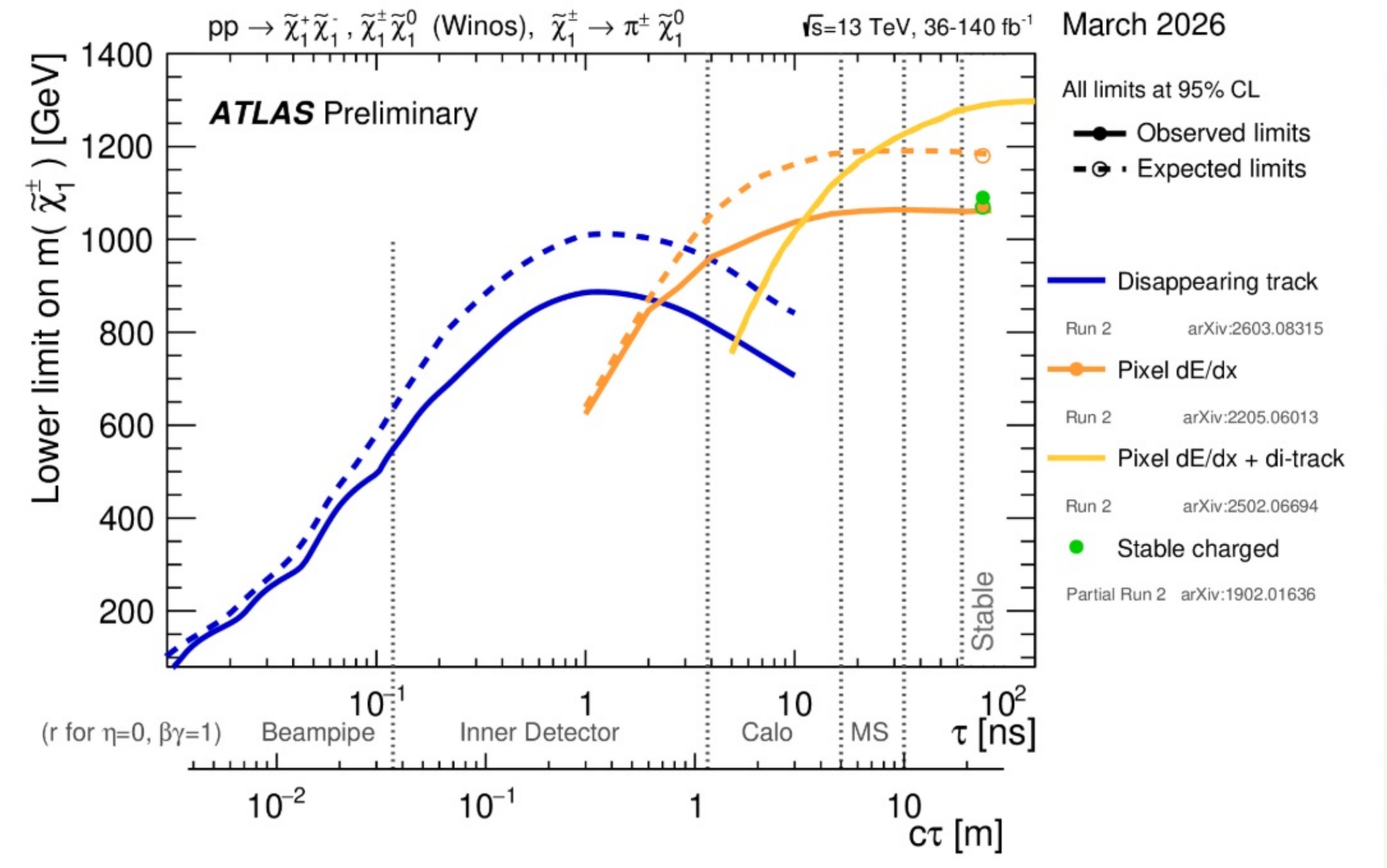
CURRENT ATLAS LLP SUMMARY REACH

Source: ATL-PHYS-PUB-2026-003

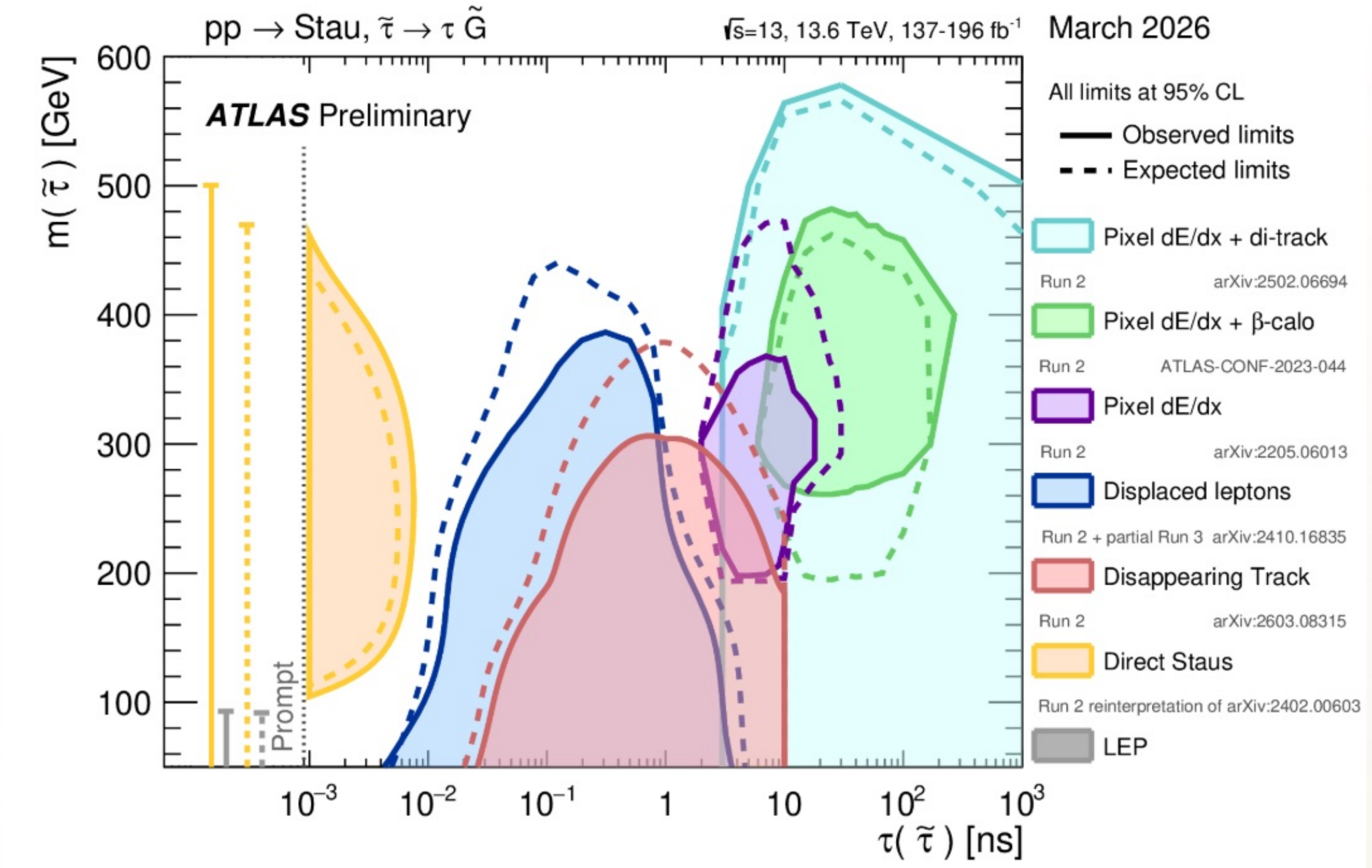
SPLIT SUSY GLUINO



AMSB CHARGINO



GMSB STAU



EXPERIMENTAL SUSY SEARCH

LLP SUSY Representative Search: Searching for $\tilde{\chi}_1^{\pm}$ and $\tilde{\tau}$ Using Disappearing Tracks

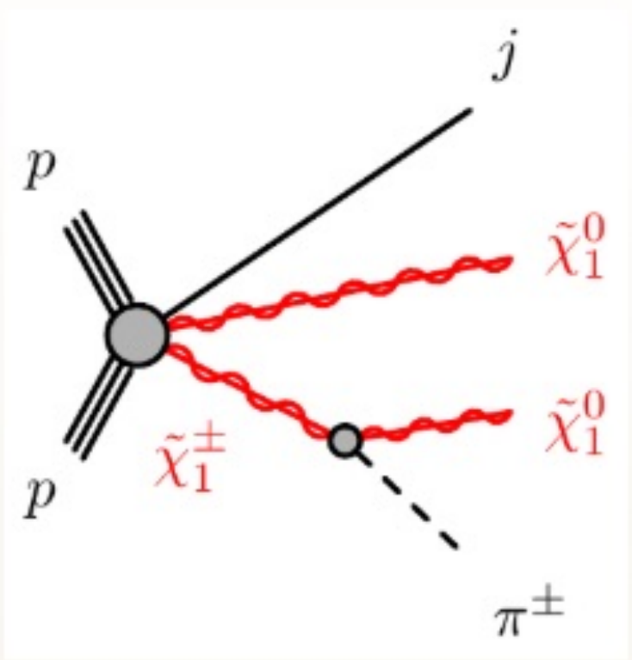
ARXIV:2603.08315 · ATLAS · 137 FB^{-1}

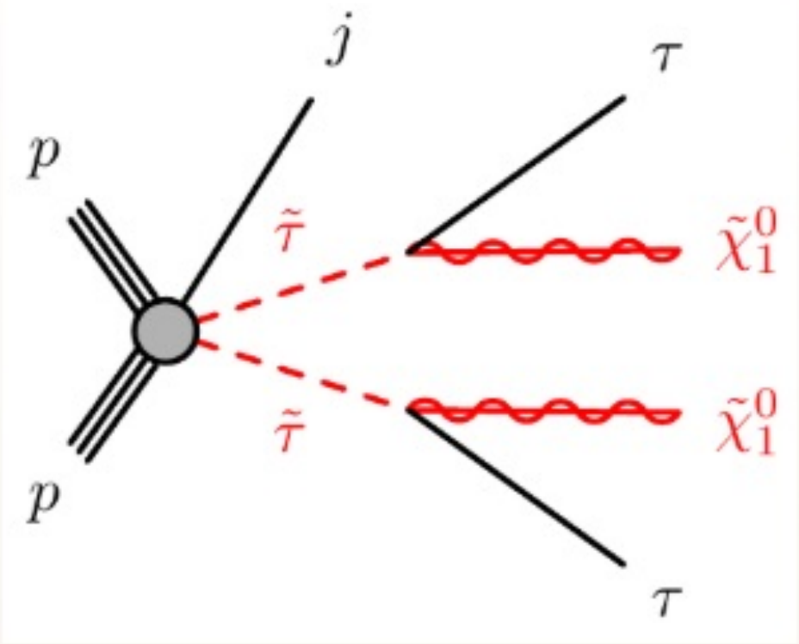
Chargino / Stau Disappearing Track

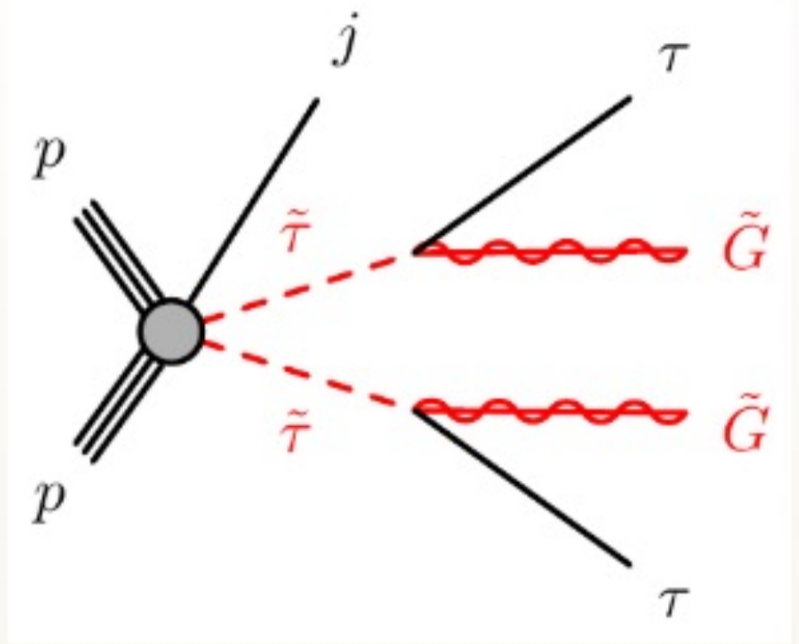
Near-degenerate electroweak states are tagged by ISR recoil, large missing transverse momentum, and a short 3-hit or 4-hit tracklet.

COMMON FINAL STATE

ISR JET · **E_T^{miss}** · **SHORT DISAPPEARING TRACK**







ANALYSIS STRATEGY

Region definition

STEP 1

ISR + E_T^{miss}

Event entry from trigger and hard recoil.

→

STEP 2

Tracklet gate

One disappearing-track candidate required.

→

STEP 3

Exclusive SR buckets

Split by layer, MET, and soft-pion logic.

Shared Baseline

Applied once before SR assignment.

- **Trigger** MET passed
- **Leptons** $N_\ell = 0$
- **Jets** at least one jet, $p_T^{j_1} > 100$ GeV
- **Tracklet** $p_T > 60$ GeV
- **Topology** $|\Delta\phi(j_1, \text{MET})| > 1.0$

SR4High hard recoil

4-layer, high-MET

LAYER LOGIC	MET
at least one 4-layer tracklet	> 300 GeV

No soft-pion handle.

SR4Mid lower recoil

4-layer, mid-MET

LAYER LOGIC	MET
at least one 4-layer tracklet	150 to 300 GeV

Same layer category, softer MET window.

SR3High1pi soft-pion tagged

3-layer, with soft pion

LAYER LOGIC	EXTRA HANDLE
3-layer only, no 4-layer tracklet	require a charged-pion candidate

3-layer branch with pion requirement.

SR3High0pi pion veto

3-layer, pion veto

LAYER LOGIC	EXTRA HANDLE
3-layer only, no 4-layer tracklet	charged-pion veto, MET > 280 GeV

Complementary 3-layer branch with tighter MET.

BACKGROUND ESTIMATION

Control and validation regions

Shared Workflow Templates → CRs / VRs → Feed to SR

FAKE TRACKLETS

Data-driven combinatorial estimate

Random hit combinations dominate, so the estimate is anchored in data.

Template	Fake-enriched events provide the tracklet p_T shape.
Transfer	Impact-parameter and MET factors move the template to the SR.
Checks	Dedicated CRs and VRs validate the SR-like extrapolation.

PHYSICS BACKGROUND

Lepton and hadron mis-reconstruction

Electrons, muons, and hadrons can fake short tracklets and are constrained with sideband data.

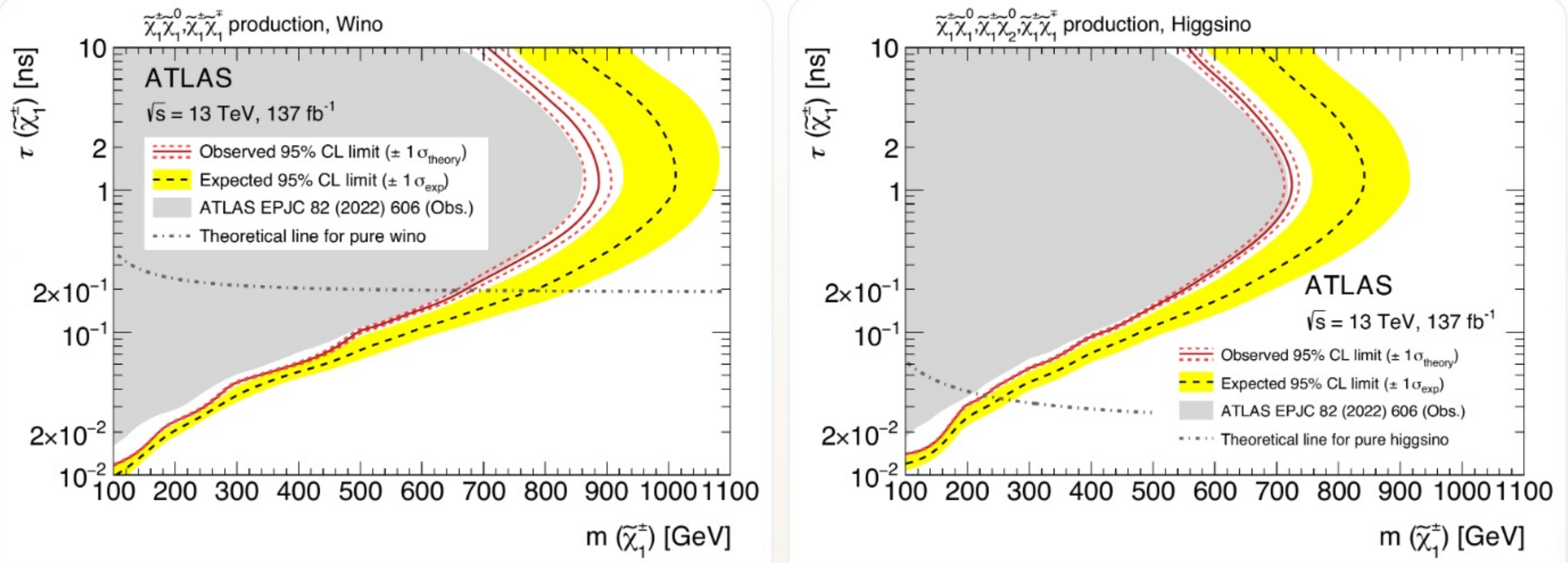
Templates	Separate object templates for electron, muon, and hadron sources.
CRs	Lepton-rich and hadron-sideband CRs float the mis-ID normalisation.
Checks	VRs test transfer to the disappearing-track phase space.

EXCLUSION RESULTS · 13 TEV · 137 FB^{-1}

Representative limits

Chargino lifetime limits

Observed reach at ~ 1 ns: wino 880 GeV, higgsino 720 GeV.

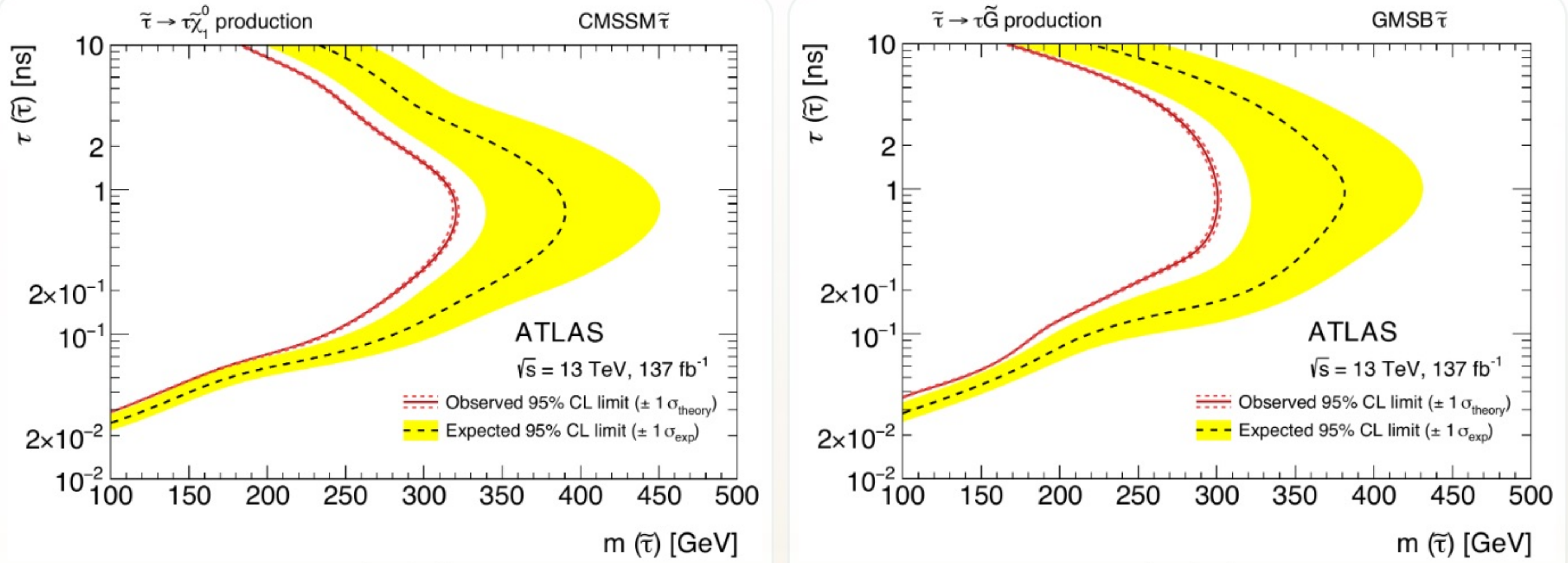


Wino

Higgsino

Stau lifetime limits

Observed reach at ~ 1 ns: CMSSM 320 GeV, GMSB 300 GeV.



CMSSM-inspired stau

GMSB-inspired stau

Headline message

One ISR + MET + tracklet analysis covers both long-lived chargino and long-lived stau interpretations.

Wino / higgsino chargino

Around 1 ns, the reach extends to about 880 GeV for wino-like and 720 GeV for higgsino-like charginos.

Very short lifetime higgsino

For lifetimes below about 0.03 ns, higgsino-like charginos remain excluded up to about 225 GeV.

Long-lived stau

At about 1 ns, stau limits reach roughly 320 GeV in CMSSM and 300 GeV in GMSB interpretations.

EXPERIMENTAL SUSY SEARCH

LLP SUSY Representative Search: Displaced Opposite-Sign Leptons

ARXIV:2601.05664 · ATLAS · 140 FB^{-1}

RPV Neutralino to Displaced Dileptons

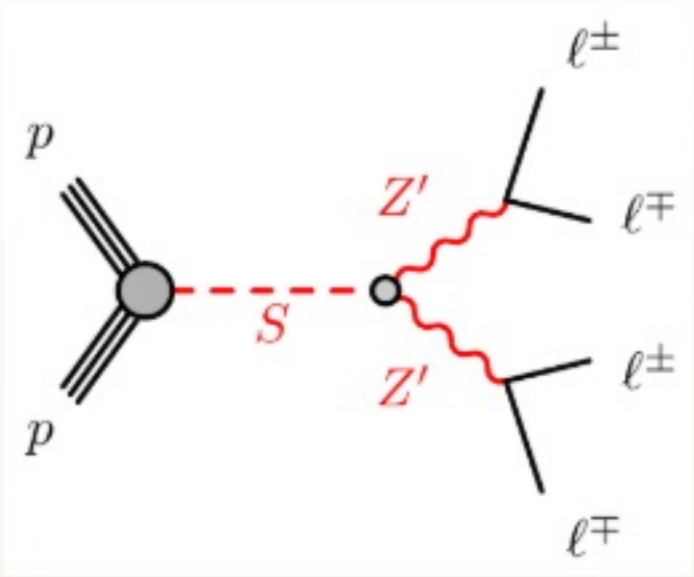
Small RPV couplings keep the LSP neutralino long-lived enough to decay inside the inner detector as a clean displaced ee, $e\mu$, or $\mu\mu$ vertex.

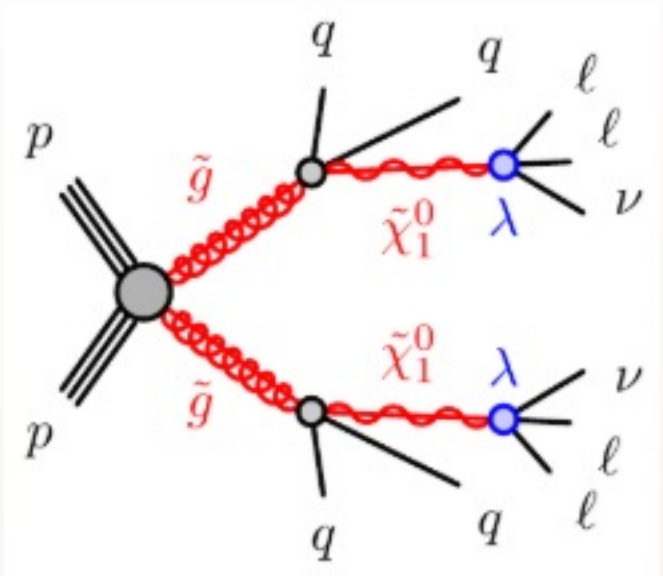
COMMON FINAL STATE

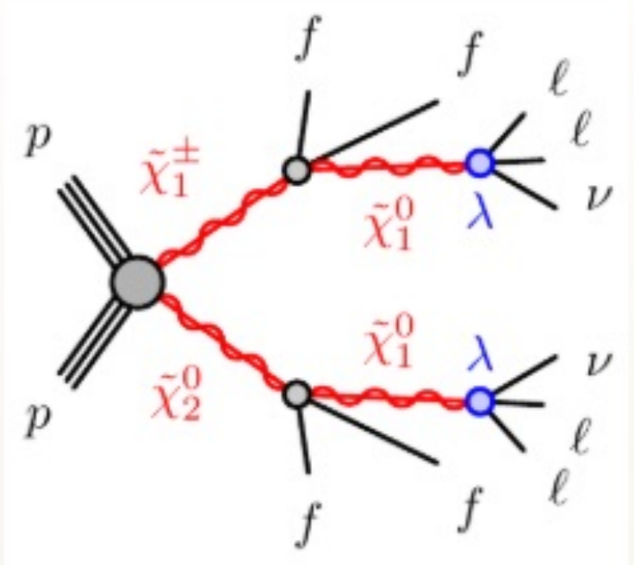
DISPLACED $EE/EM/MM$ VERTEX

SINGLE DV REQUIRED

LONG-LIVED $\tilde{\chi}_1^0$







ANALYSIS STRATEGY

Object-driven displaced-vertex selection

STEP 1

Displaced-friendly trigger

Avoid prompt-like ID-track requirements at trigger level.

→

STEP 2

Modified lepton ID

Use LRT tracks and remove the prompt-biased pixel and d_0 cuts.

→

STEP 3

High-quality DV

Demand a well-fit displaced opposite-sign dilepton vertex.

Shared Baseline

Designed around the DV object rather than a hard event topology.

- **PV** one primary vertex with at least two tracks
- **Tracks** displaced-lepton ID tracks with $p_{\mathrm{T}} > 10$ GeV
- **Match** at least one trigger-matched signal lepton
- **Model scope** no jet or MET requirement
- **Cosmics** veto on $\mu\mu$ and $e\mu$ back-to-back pairs

Muon trigger for displaced μ

MS-only path

OBJECT	THRESHOLD
MS-only muon	$p_{\mathrm{T}} > 60$ GeV, $\lvert\eta\rvert < 1.05$

Electron trigger for displaced e

Photon-based path

SINGLE-OBJECT	TWO-OBJECT
photon $p_{\mathrm{T}} > 140$ GeV	diphoton $50 + 50$ GeV

DV fiducial geometry + quality

Tracker-barrel decay

DISPLACEMENT	FIDUCIAL
$R_{xy} > 2$ mm	$r < 300$ mm, $\lvert z\rvert < 300$ mm

Signal DV final SR object

Clean dilepton vertex

CORE CUTS	REJECTION
OS leptons, $\chi^2/\mathrm{dof} < 5$	$m_{DV} > 12$ GeV + material veto

BACKGROUND ESTIMATION

Two residual background sources

Shared Workflow Data CR → Extrapolate / Mix → Single DV SR

COSMIC BACKGROUND

Inverted-cosmic-veto control region

Dimuon DVs that pass all SR cuts except the cosmic veto anchor the residual cosmic prediction.

CR	Use the $\Delta R_{\cos} < 0.01$ region with the veto inverted.
Transfer	Fit the tail and extrapolate to the SR requirement $\Delta R_{\cos} > 0.01$.
Yield	Tiny prediction: about 8.3×10^{-3} for $\mu\mu$ and 1.2×10^{-5} for $e\mu$.

CROSSING TRACKS

Data-driven toy event mixing

The dominant non-cosmic residual comes from two unrelated leptons accidentally forming a fake signal DV.

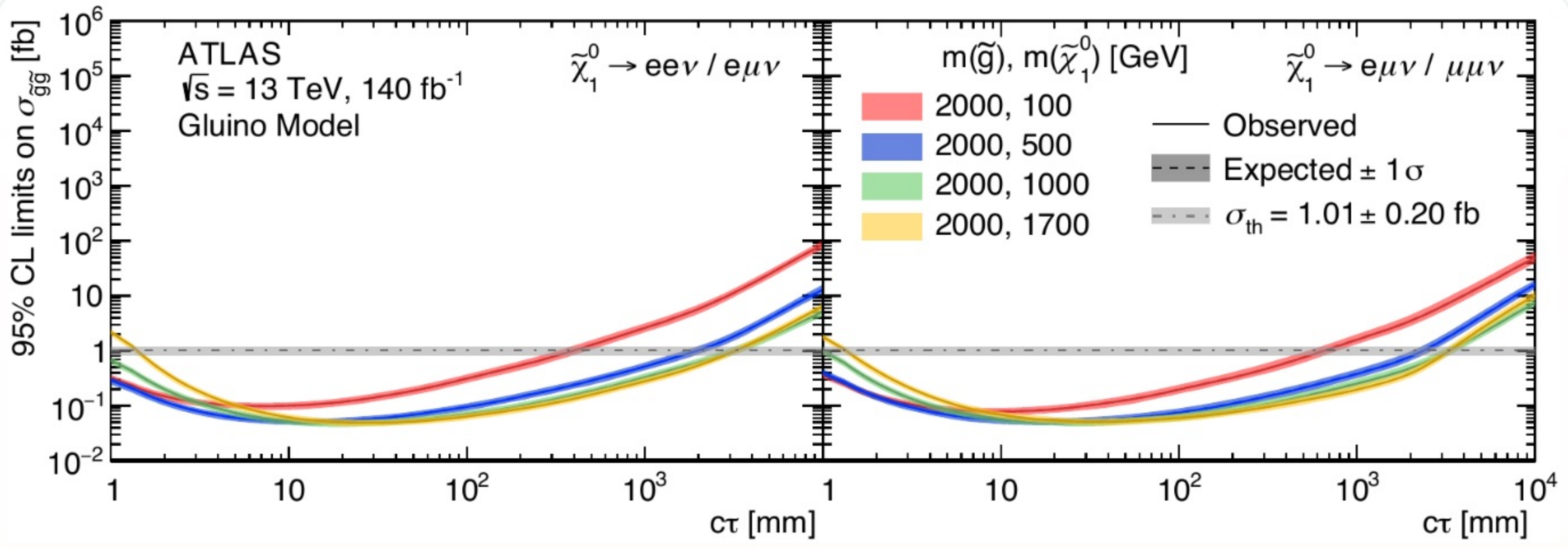
Inputs	Pick opposite-sign signal leptons from different data events plus a random PV.
Method	Shift tracks around the new PV and rerun the full DV reconstruction algorithm.
Output	Apply the measured crossing probability to candidate pairs in data to predict the SR yield.

EXCLUSION RESULTS · 13 TEV · 140 FB^{-1}

Representative limits

Gluino-fed long-lived $\tilde{\chi}_1^0$

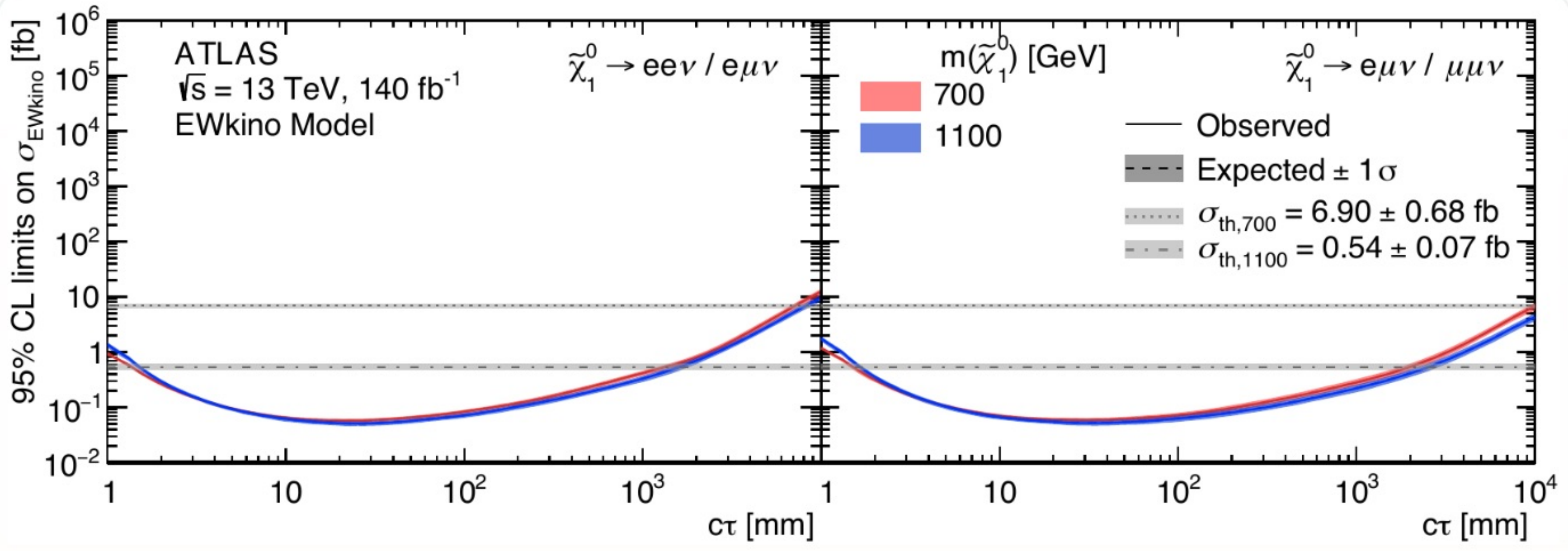
For $m(\tilde{g}) = 2000$ GeV, the excluded $c\tau$ range grows to about 3.2–3.3 m for $m(\tilde{\chi}_1^0) = 1000$ GeV.



Left: λ_{121} ($ee/e\mu$), right: λ_{122} ($e\mu/\mu\mu$)

EWkino-fed long-lived $\tilde{\chi}_1^0$

For $m(\tilde{\chi}_1^0) = 1100$ GeV, the excluded lifetime reaches about 1.6 m for λ_{121} and 2.6 m for λ_{122}.



Lower masses go much further: 700 **GeV reaches** 7.2 **m or the edge of the scanned range.**

Headline message

A single displaced-dilepton DV analysis gives a direct, dedicated experimental anchor for small-RPV long-lived neutralinos.

Observed events

No displaced opposite-sign dilepton vertex candidate is observed after the full selection.

Strong production

For lighter gluinos around 1.5 TeV, most of the scanned 1–10^4 mm lifetime range is excluded for $m(\tilde{\chi}_1^0) \geq 500$ GeV.

Electroweak production

For $m(\tilde{\chi}_1^0) \leq 500$ GeV, the full scanned lifetime range is excluded in the EWkino interpretation.

EXPERIMENTAL SUSY SEARCH

LLP SUSY Representative Search: HSCP with dE/dx and TOF

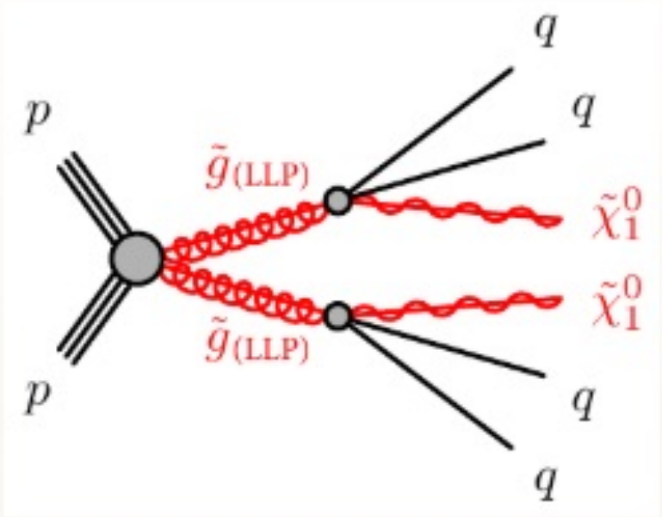
ARXIV:2502.06694 · ATLAS · 140 FB^{-1}

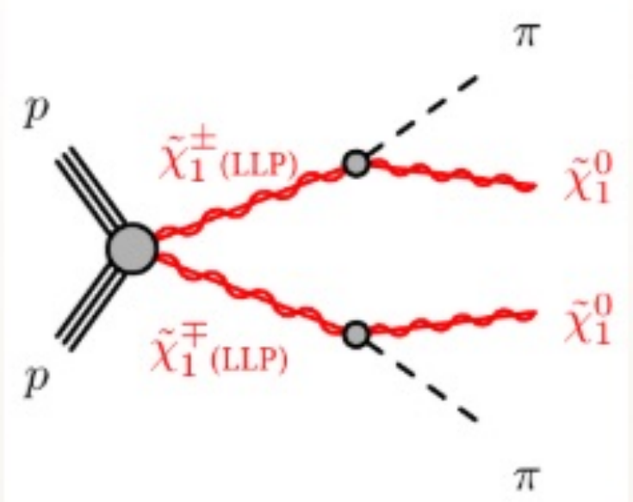
Slow charged LLPs from propagation observables

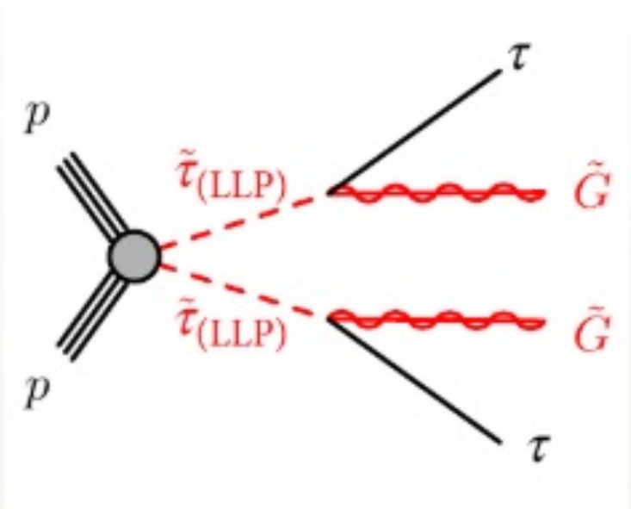
The signal object is the heavy charged track itself: anomalously large pixel dE/dx plus delayed TileCal TOF, with SUSY interpretations for R-hadrons, $\tilde{\chi}_1^{\pm}$, and $\tilde{\tau}$.

COMMON FINAL STATE

- SLOW CHARGED TRACK
- LARGE PIXEL DE/DX
- DELAYED TILECAL TOF







ANALYSIS STRATEGY

Propagation-driven charged-track selection

STEP 1

MET trigger + hard track

Calorimetric MET plus an isolated central track with $p_{\mathrm{T}} > 120$ GeV.

→

STEP 2

Two complementary SRs

One-track β SR for heavy LLPs, two-track ionisation SR for lighter pair production.

→

STEP 3

2D mass compatibility

Require trapezoidal mass compatibility from independent $\beta\gamma$ measurements.

Shared Baseline

The track response is the signal object.

- **Trigger** Run-2 calorimetric MET
- **PV** hard-scatter vertex
- **Track** isolated central track, $p_{\mathrm{T}} > 120$ GeV
- **Ionisation** large pixel dE/dx
- **Lifetime** starts at $\tau \gtrsim 3$ ns

β search heavy slow LLPs

Single-track + TOF

EVENT
offline MET > 170 GeV

TRACK SR
dE/d$x > 1.8$ and $\beta_{\mathrm{calo}} < \beta_{\mathrm{cut}}$

Di-track search lighter pair-produced states

Opposite-sign pair

EVENT
offline MET > 20 GeV

PAIR SR
OS tracks, $m_{\mathrm{inv}} > 200$ GeV

Mass reconstruction 2D compatibility

Independent $\beta\gamma$ handles

B-SR PLANE
$[m_{dE/dx}, m_{\mathrm{TOF}}]$

DI-TRACK PLANE
$[m_{A,dE/dx}, m_{B,dE/dx}]$

Model focus benchmark split

Which SR wins

B-SEARCH
best for $\tilde{\chi}_1^{\pm}$ and R-hadrons

DI-TRACK
best for pair-produced $\tilde{\tau}$

BACKGROUND ESTIMATION

Response-tail pseudo-data prediction

Shared Workflow Control regions → Sample templates → 2D mass SR

B-SEARCH BACKGROUND

Sidebands for kinematics and slow-particle response

Sample momentum from a kinematic CR and combine it with dE/dx and β_{calo} templates to predict $[m_{dE/dx}, m_{\mathrm{TOF}}]$.

kin-CR	Invert dE/dx, relax β_{calo}.
$\beta\gamma$-CR	Invert MET; use it for dE/dx and TOF templates.
Validation	Low-dE/dx and high-β_{calo} VRs test closure.

DI-TRACK BACKGROUND

Same-event pair templates keep correlations

Reuse two-track kinematics from inverted-dE/dx events, then resample the two dE/dx values in $|\eta|$ bins.

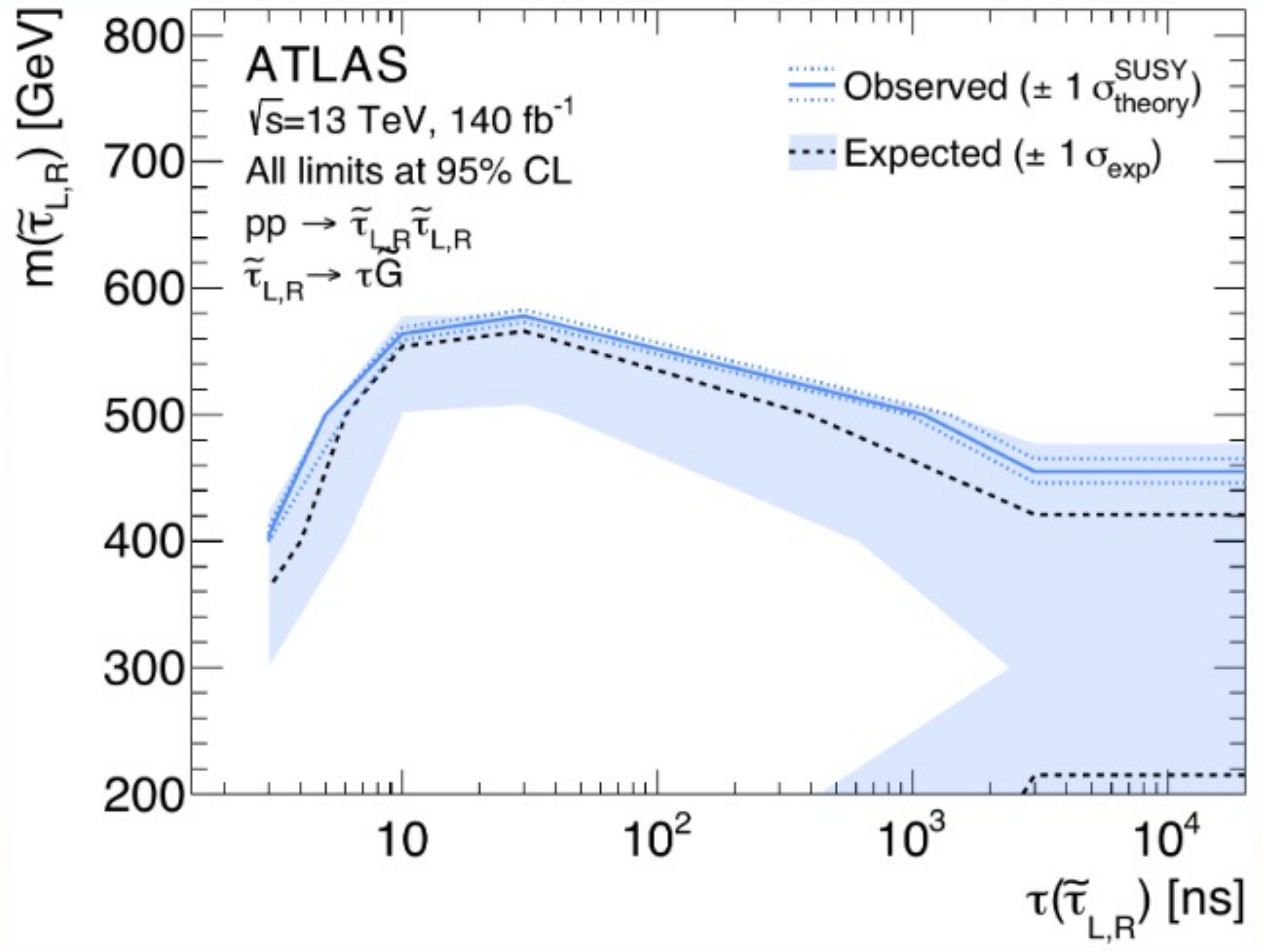
kin-CR	Two same-event tracks with inverted dE/dx.
dE/dx-CR	Require a low-p_{T} track to suppress signal.
Validation	Low-p_{T}, inverted-mass, and W/Z VRs close well.

EXCLUSION RESULTS · 13 TEV · 140 FB^{-1}

Representative limits

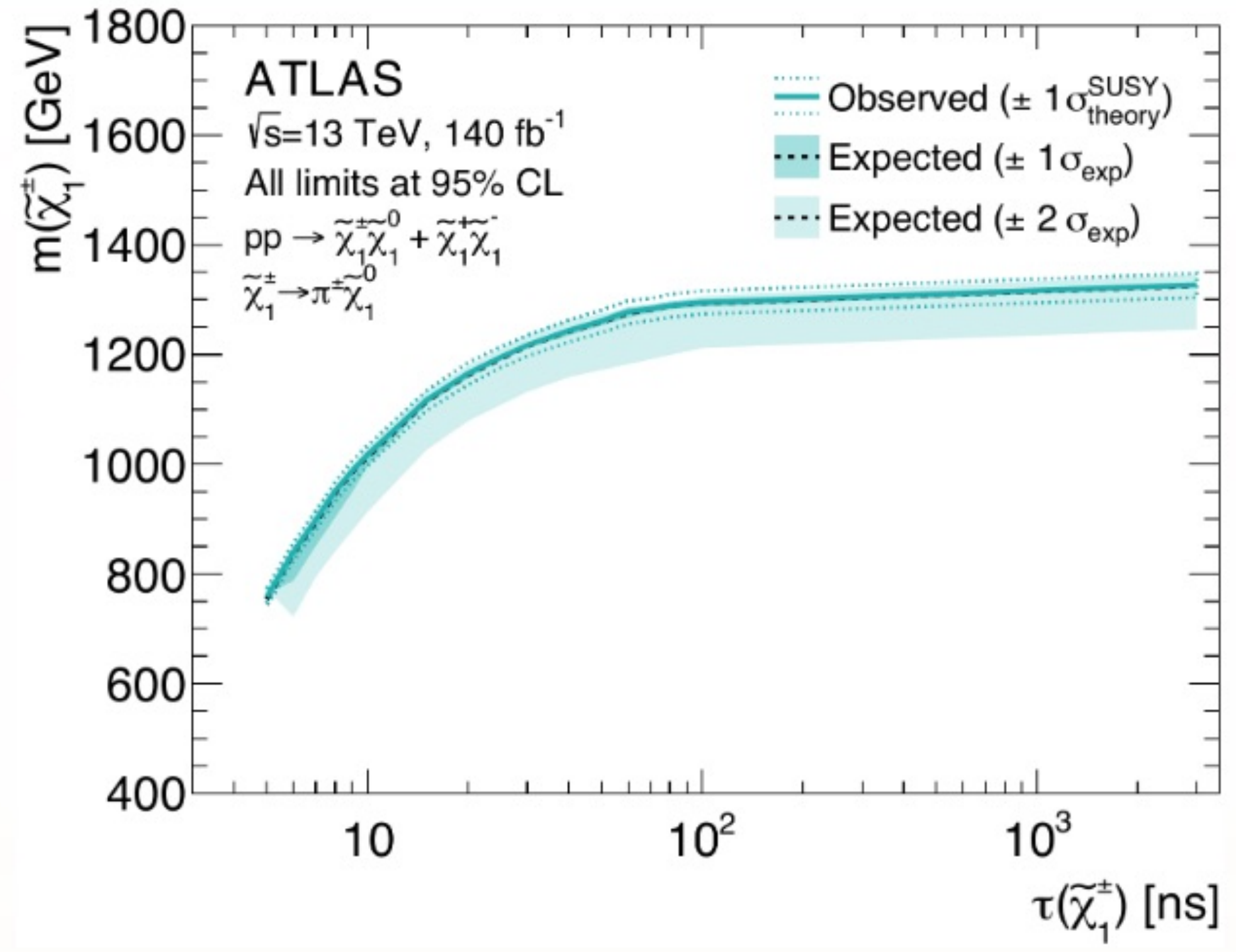
Long-lived $\tilde{\tau}$ from the di-track search

Observed exclusion peaks around 570 GeV near $\mathcal{O}(10)$ ns and remains close to 450 GeV even for detector-stable lifetimes.



Long-lived $\tilde{\chi}_1^{\pm}$ from the β-search

The observed chargino limit climbs from roughly 0.8 TeV at a few ns to above 1.3 TeV for lifetimes beyond about 100 ns.



Headline message

ATLAS turns ionisation and timing into a mature HSCP-like SUSY search language, covering charged LLPs well beyond displaced-decay topologies.

Observed events

No excess is seen; the high-purity di-track Discovery-SR contains zero observed events for an expected background of 0.79 ± 0.19.

Lifetime regime

The analysis is designed for heavy charged LLPs with $\tau \gtrsim 3$ ns, with the strongest TOF gain appearing once tracks live long enough to reach the calorimeter.

Model coverage

One detector-response analysis simultaneously constrains staus, charginos, and also much heavier gluino R-hadron interpretations up to the multi-TeV scale.

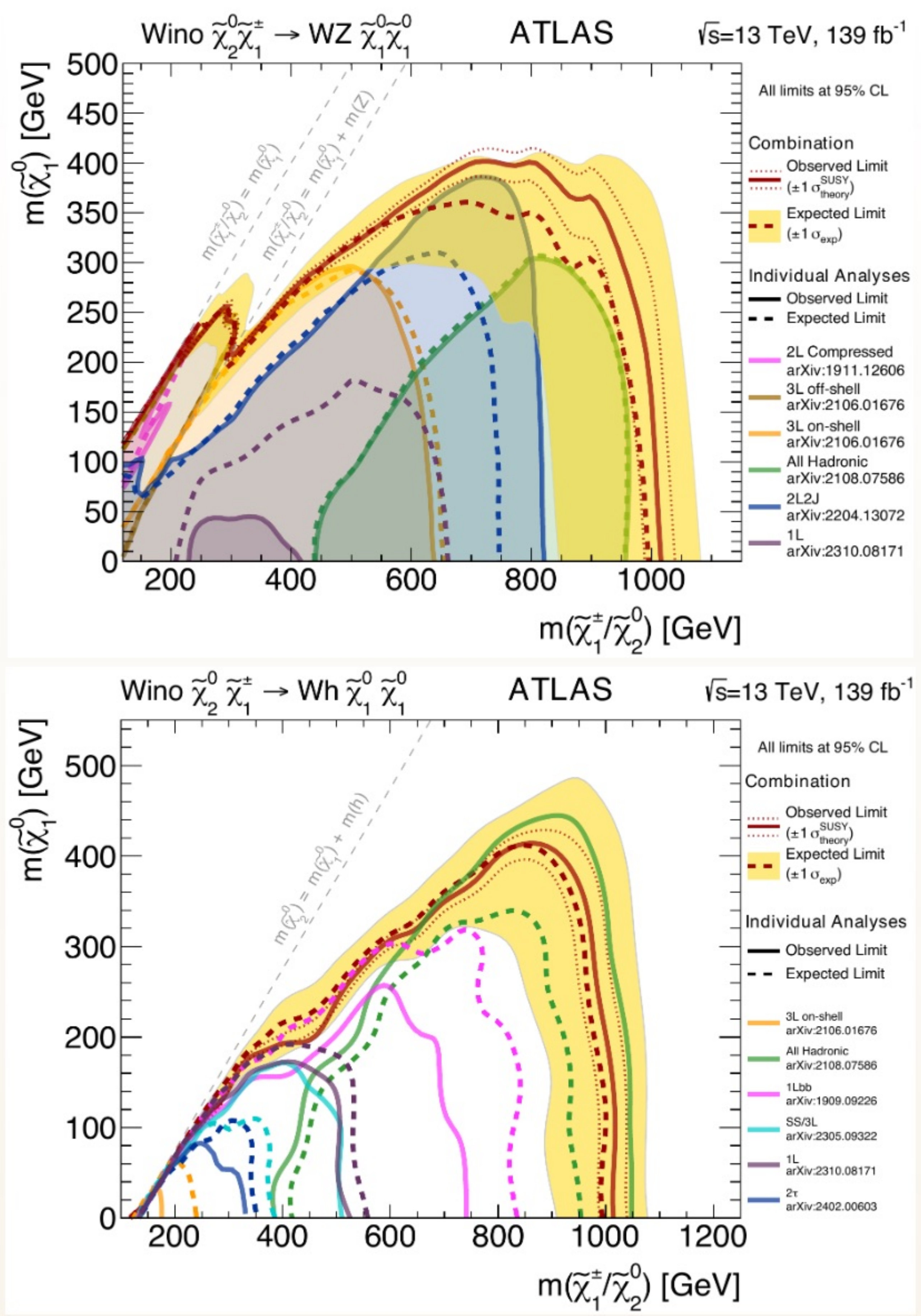
EXPERIMENTAL SUSY SEARCH

SUSY Summary Studies: Beyond Single-Analysis Limits

ATLAS ELECTROWEAKINO STATISTICAL COMBINATION · ARXIV:2402.08347

Combination Study

Run 2 electroweakino exclusions after combining multiple chargino and neutralino channels in a common statistical model.



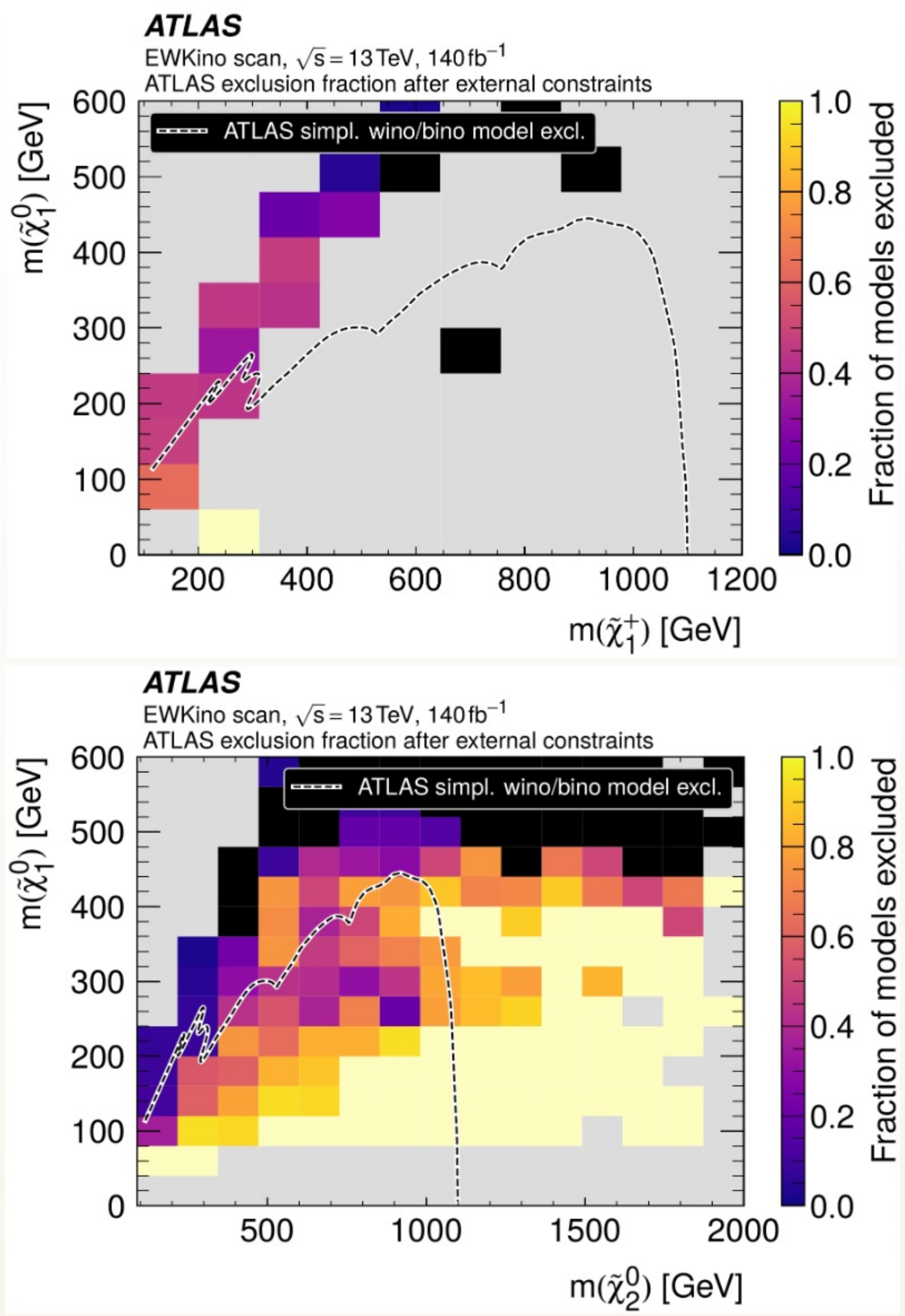
Conclusion
The combination improves the SUSY mass reach by about 30 to 100 GeV and lowers the 95% CL cross-section limits by roughly 15% to 40% relative to the best single analysis.

Why it matters
This is the clean experimental proof that modern SUSY coverage should be judged at the programme level: isolated headline plots understate the real electroweak reach.

ATLAS PMSSM INTERPRETATION · ARXIV:2402.01392

High-Dimensional Scan

Eight Run 2 electroweak searches interpreted in a 19-parameter pMSSM framework together with flavor and dark-matter constraints.



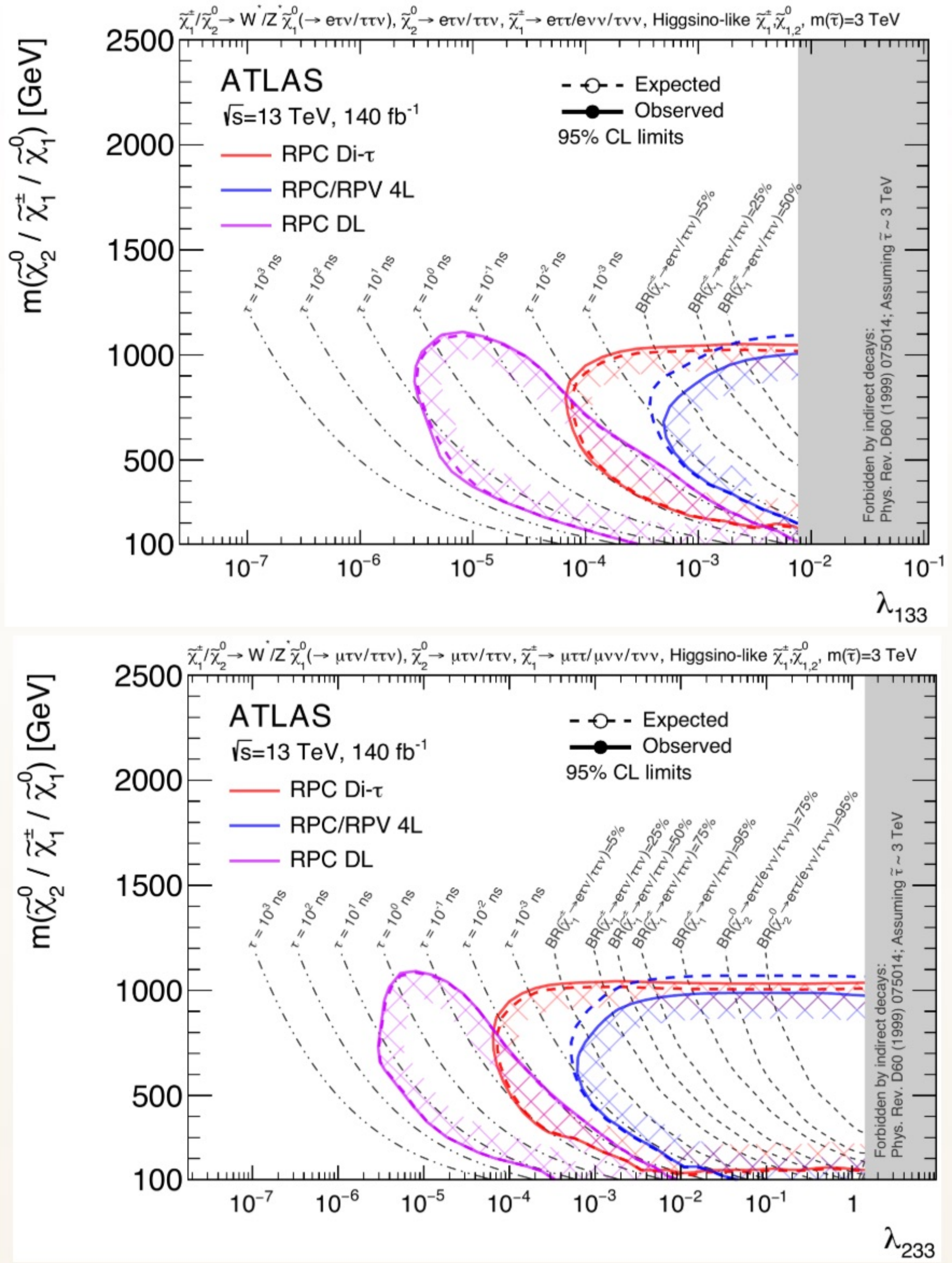
Conclusion
Most low-mass neutralino funnel regions are strongly depleted, while the surviving models cluster in irregular spectra and mixed branching-ratio patterns that do not map cleanly onto simplified benchmarks.

Why it matters
The real experimental question is no longer just "which mass plane is excluded", but "which viable full-model structures remain". That is exactly what a pMSSM-level study reveals.

ATLAS RPC-RPV REINTERPRETATION WITH VARIABLE COUPLING · ARXIV:2603.15007

Variable-Coupling Reinterpretation

A unified reinterpretation across prompt, LLP-like, and effectively stable regimes as the RPV coupling is continuously varied.



Conclusion
The reinterpretation links RPC-like, prompt-RPV, and LLP-like behaviour within one parameter scan; for large couplings, higgsino masses around 0.8 to 1.0 TeV remain excluded across the combined production channels.

Why it matters
This reframes SUSY search strategy as a continuum problem. Future programmes should connect RPC, RPV, and LLP searches instead of treating them as disconnected families.

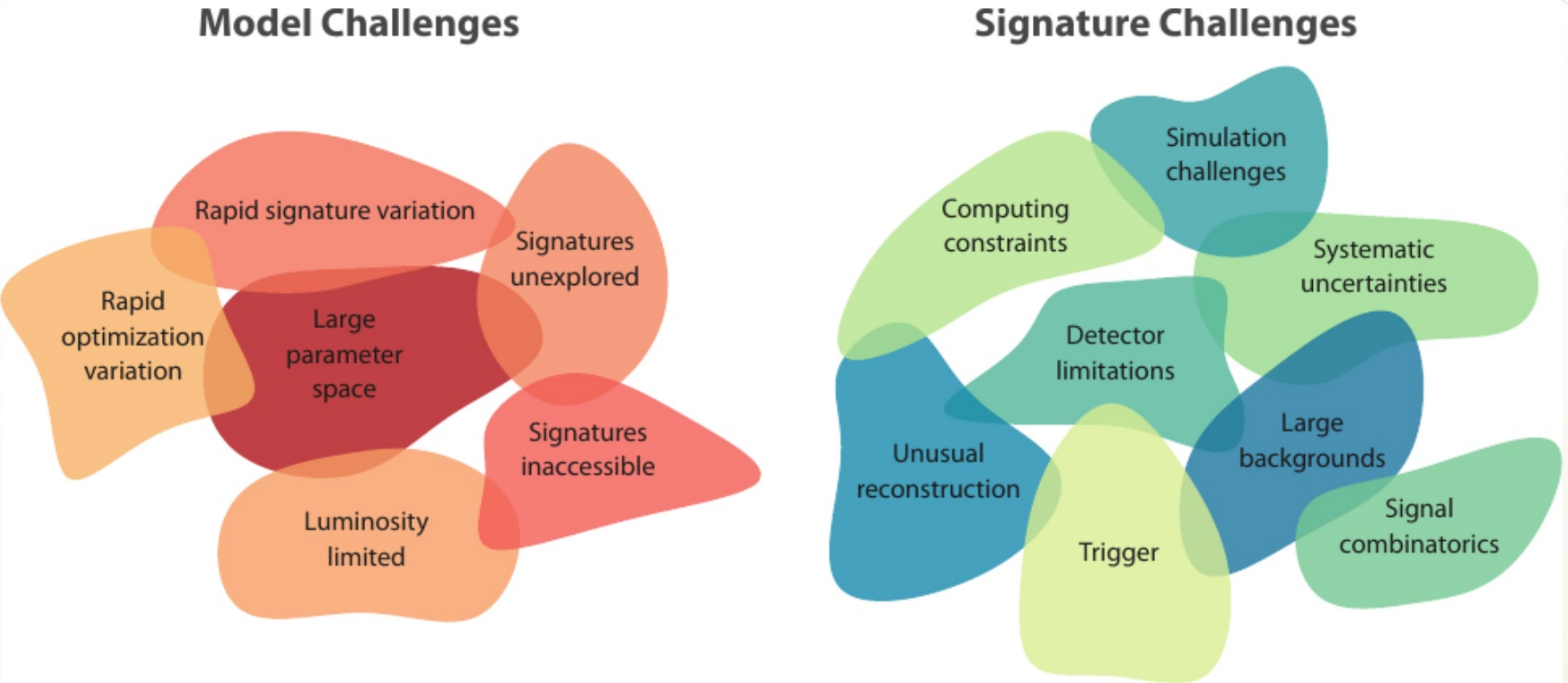
— EXPERIMENTAL SUSY SEARCH

Beyond

PROGRAM-LEVEL FRAMING · ARXIV:2601.06358 · FIG. 2

Why SUSY is hard to find

Each label in Fig. 2 points to a concrete failure mode for standard search design, optimisation, or interpretation.



Large parameter space: Too many masses, mixings, and branching ratios to cover with a few fixed benchmark lines.

Rapid optimisation variation: The best SR or reconstruction strategy changes quickly across parameter space, so one analysis setup stops being close to optimal.

Luminosity-limited: Rare production or tiny acceptance means even the full dataset may still leave only a handful of events.

Trigger challenges: Signals that are soft, delayed, low-multiplicity, or non-isolated may fail to enter the recorded sample at all.

Large backgrounds: Instrumental backgrounds, heavy-flavour decays, pileup, or fake objects can dominate exactly where the signal becomes subtle.

Simulation and computing: Rare detector responses and broad model scans are expensive to simulate well, so coverage itself becomes a resource problem.

Rapid signature variation: Small spectrum changes can move the same model from prompt to soft, displaced, invisible, or mixed final states.

Unexplored or inaccessible signatures: Some signals fall outside what standard prompt-object analyses were originally designed to reconstruct.

Detector limitations: Finite granularity, timing, material effects, and acceptance can directly erase or distort unusual signatures.

Unusual reconstruction: Displaced tracks, disappearing tracks, anomalous ionisation, and timing-heavy objects often break standard reconstruction assumptions.

Signal combinatorics and systematics: Complex cascades make object assignment ambiguous, while detector and theory uncertainties limit the final sensitivity.

FUTURE DIRECTION 1

Unconventional Signatures

The basic point is simple: many remaining SUSY signals do not look like standard prompt high-pT objects, so we need to look in less conventional ways.

Soft objects
We target compressed spectra or low visible-energy decays, where the leptons, jets, or tracks are simply too soft for standard thresholds. So we need lower-threshold triggers, more detailed tracker activity, and smaller calorimeter deposits.

Displaced objects
We target long-lived particles that decay away from the primary vertex, giving displaced tracks, vertices, leptons, or jets. That means impact parameters, secondary vertices, tracker hit patterns, and displaced-trigger logic become essential.

Time of flight (TOF)
Here the target is slow heavy particles that arrive later than ordinary relativistic objects. To see them, we need precise timing from the calorimeter or muon system, correct bunch-crossing assignment, and timing-aware reconstruction.

d*E*/dx
Here we target heavy charged particles that lose energy in an unusual way while crossing the tracker. So the important inputs are charge deposition in the tracker, cluster-level ionisation response, track quality, and careful detector calibration.

What this means experimentally
So the message is that detector-level information has to move closer to the center of the analysis: trigger, tracker, timing, and calorimeter information are no longer just support tools, they become part of the signal definition itself.

FUTURE DIRECTION 2

Go beyond simplified models

The model-benchmark direction is to start from realistic high-dimensional SUSY models, compress them into a low-dimensional latent space, and then build useful benchmark models there.

(a) Use complex models whenever possible
We should not start only from overly clean simplified models. Instead, benchmark studies should use richer spectra, realistic branching structures, and genuinely high-dimensional SUSY parameter spaces whenever possible.

(b) Compress the high-dimensional space into a latent space
The next step is to use some technique, for example machine learning, to map the relevant structure of a high-dimensional model space into a lower-dimensional latent space that we can actually study and visualise.

(c) Build benchmark models in the latent space
Then we can combine this with what we learn from pMSSM scanning, especially the still-open or especially meaningful high-dimensional regions, and create interesting low-dimensional benchmark models in latent space for later studies.

Existing work already shows this can be done · arXiv:2305.01835
This paper is a separate piece of evidence: it shows that machine-learning methods can capture the structure of a high-dimensional SUSY parameter space in a low-dimensional latent space. That gives us a practical route to define benchmark models in latent space and use them in future optimisation and reinterpretation studies.

Summary

- **1. We have already carried out systematic searches using simplified models**
  Experimental SUSY searches have already covered a broad and coherent set of simplified benchmark models across strong, electroweak, prompt, and LLP scenarios.

- **2. No significant excess found so far**
  Up to now, we do not see a clear and convincing deviation that can be interpreted as a SUSY signal.

- **3. A large and still attractive subspace remains unexplored experimentally**
  The open phase space is not just leftover territory. It remains physically interesting and experimentally motivated.
  - Compressed, long-lived, and detector-limited scenarios are still far from fully covered.
  - As emphasized in Prospects for supersymmetry at high luminosity LHC, Run 2 null results do not automatically eliminate the most plausible weak-scale SUSY pictures; they mainly remove older, more naive benchmark expectations.
  - From the theorist-side naturalness re-evaluation, light higgsinos can still be well motivated even when stops and gluinos are heavier than many older natural-SUSY cartoons assumed.
  - The same review argues that surviving SUSY frameworks are often richer than simplified-model language suggests: dark matter may be multi-component, mediation patterns matter, and the most plausible spectra need not look like the cleanest textbook signals.
  - HL-LHC is therefore testing an important and still well-motivated subspace, but not exhausting it. What remains should be treated as a serious target rather than as residual leftover parameter space.

- **4. Looking forward, we should focus on several directions**
  - Focus more on difficult phase space and difficult physics scenarios, such as compressed, long-lived, and other weird cases. This means using unconventional signatures and using more detector-level information directly.
  - Benchmark models should go beyond simplified models, moving from high-dimensional realistic model spaces to lower-dimensional latent-space benchmarks.
  - We need to preserve analyses better, so that future summary studies and statistical combinations can become stronger and more informative.
  - We need better recast technology and better platforms, so that we can fully use the potential of published results and really make every effort count.

- **Machine learning is already helping, and should help even more in the future**
  ML is already useful for tagging, reconstruction, anomaly-sensitive exploration, latent-space model compression, and interpretation. Looking forward, it should continue to help us across many different parts of experimental SUSY searches rather than in only one narrow task.