Direct searches for new particles & resonances @ LHC

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On behalf of CMS & ATLAS Collaborations

ICFA Seminar 2026 - Future Perspectives in HEP

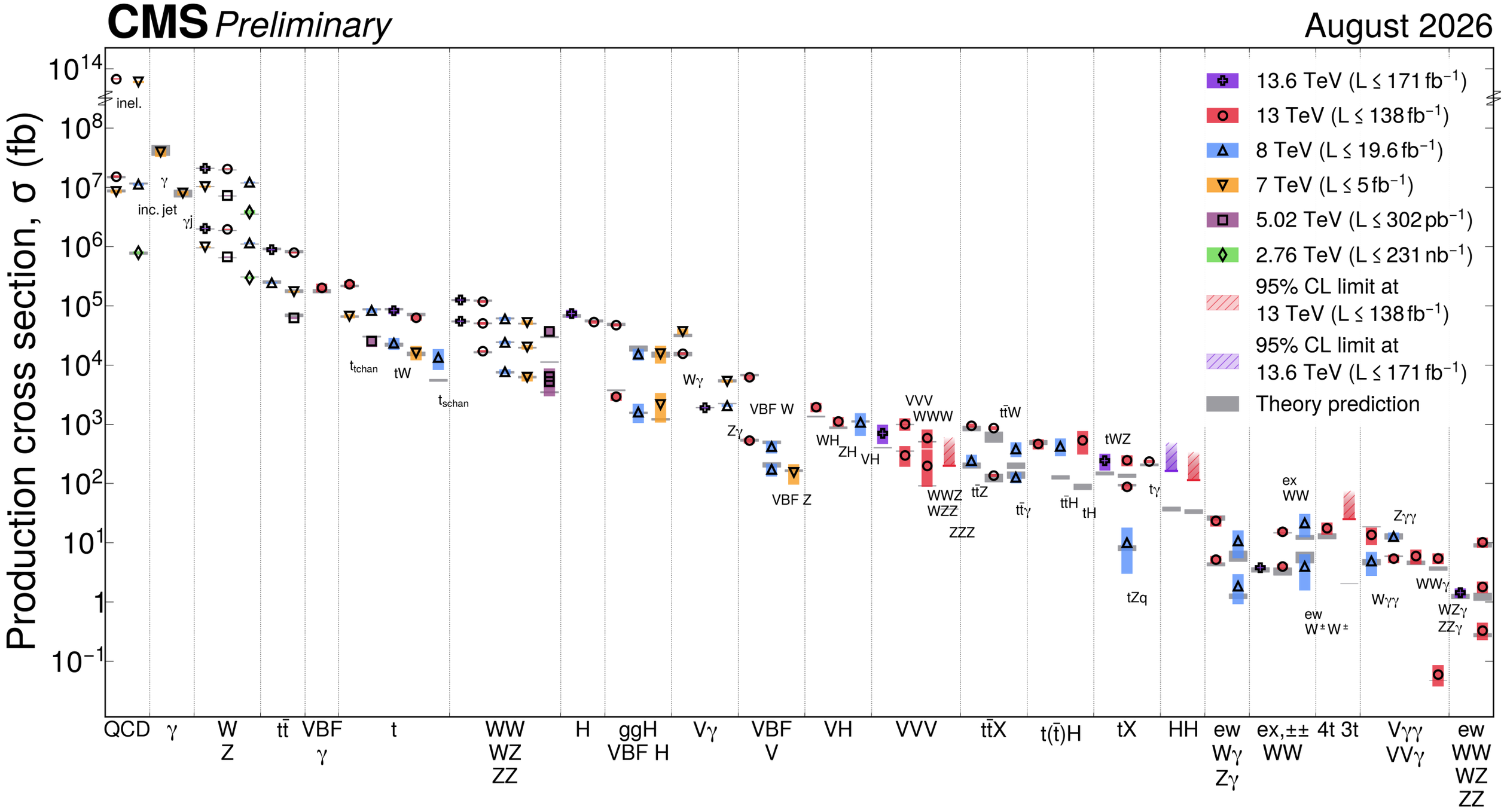
Toyama International Conference Centre, Toyama, Japan

November 2-6, 2026

IISER PUNE

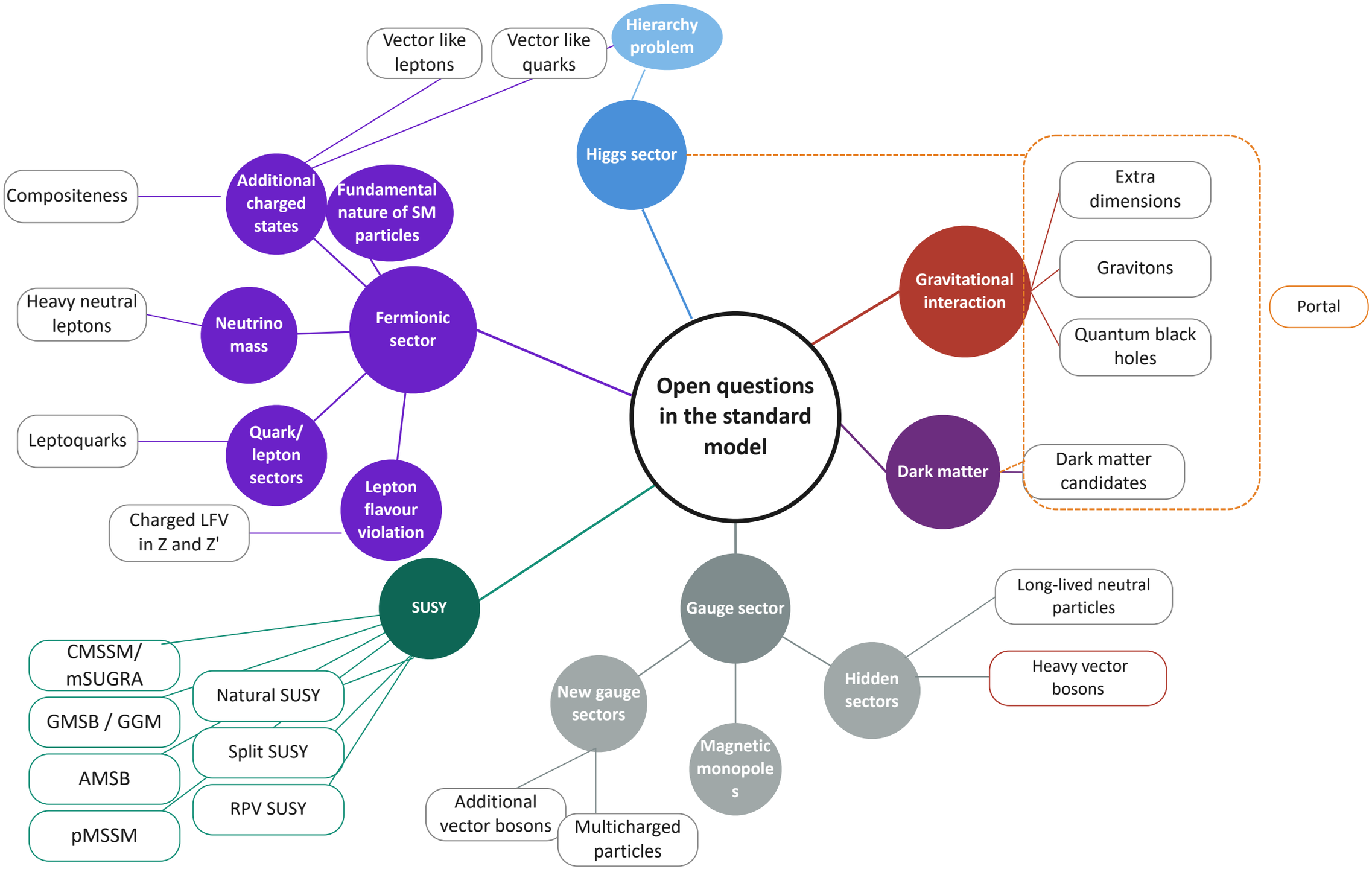
No Cracks in the Standard Model — Yet !

SM Summary
ATLAS & CMS



Despite remarkable agreement across 14-15 orders of magnitude, the Standard Model cannot be the full story — the search for what lies beyond begins here !

Beyond SM at the LHC: A Broad Landscape



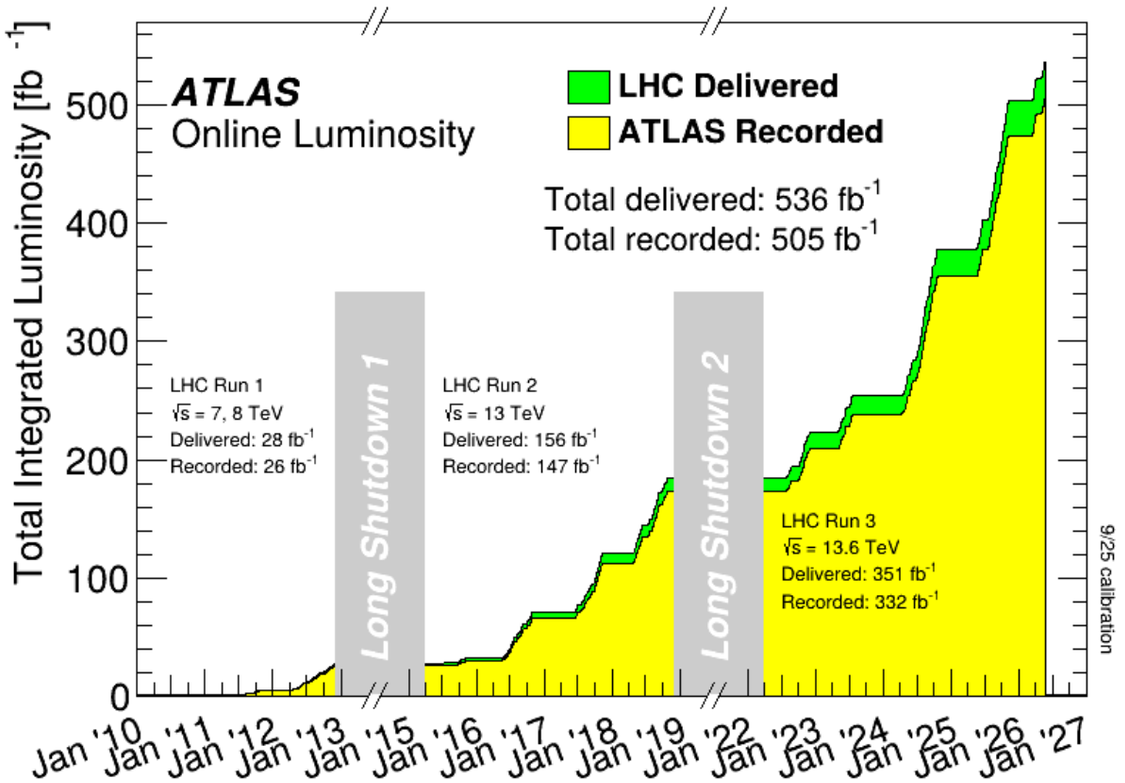
The challenge: each topology demands dedicated triggers, objects, signal regions, and background methods. **O(100) active searches running in parallel —** and anomaly detection to catch what targeted searches miss.

Searches for extended scalar sectors - C. Botta

Searches: hidden sectors, heavy neutral leptons etc. - T. Schroeder

Direct searches for new particles/resonances at LHC - S. Sharma

Luminosity & Datasets



Run-2 (2016-2018) ~130-140 fb^{-1}

&

Run-3 (2022-2026) ~320 fb^{-1}

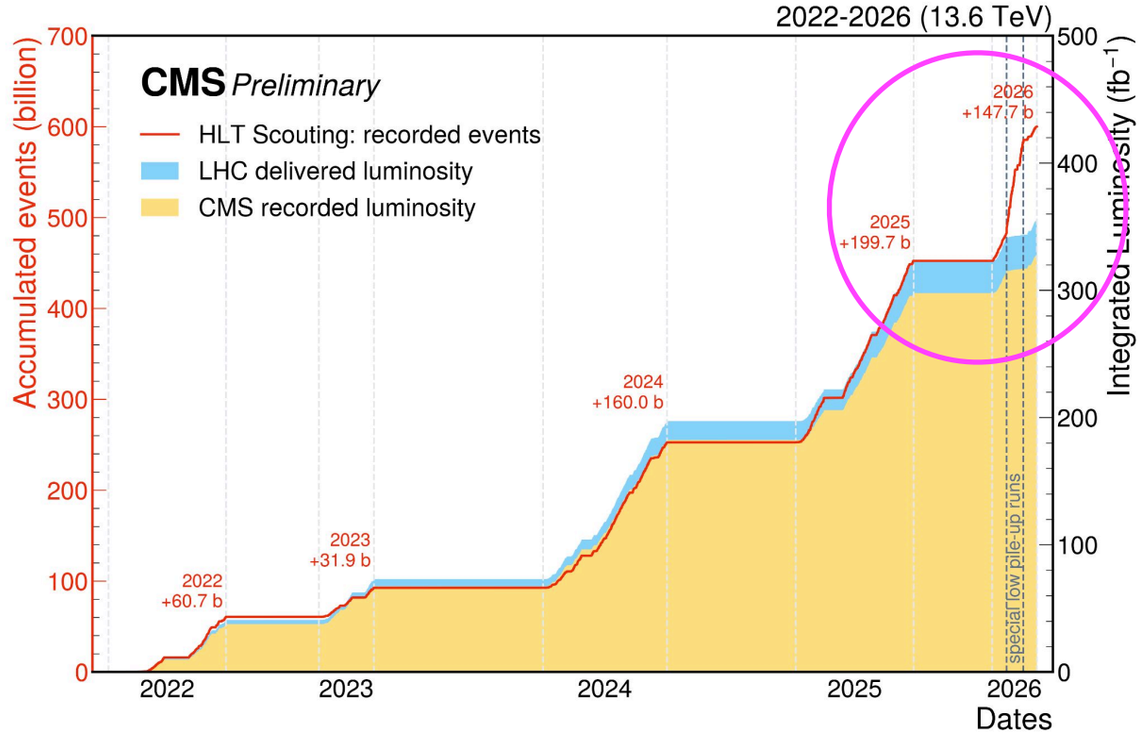
Dedicated data streams (CMS) - Ref-2026

Standard data stream: Prompt offline reconstruction, Full event content ~4 kHz, ~4.5 GB/s

Parking data stream: Delayed offline reconstruction, full event content ~6 kHz, ~6.7 GB/s

HLT scouting data stream: No offline reconstruction, only HLT objects and calibrations ~28 kHz, ~0.8 GB/s

ATLAS and LHCb also have developed similar strategies.

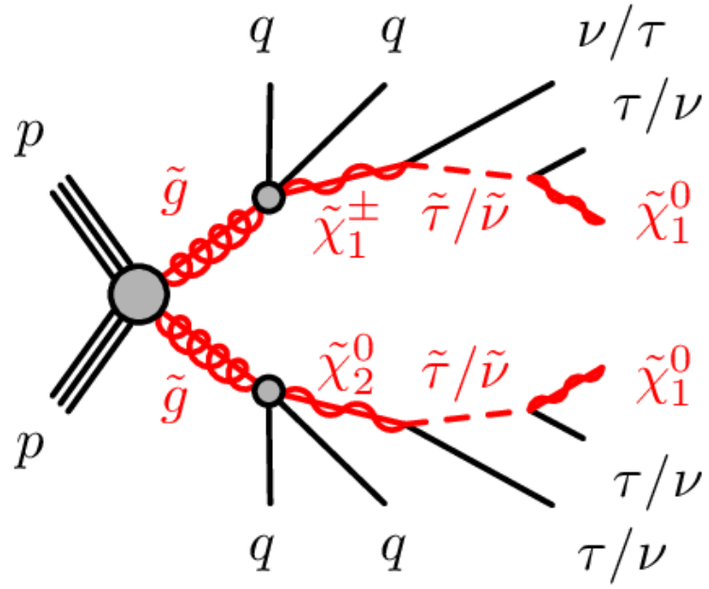


Overcoming the limitations of standard DAQ flows has substantially extended sensitivity to low-mass and rare phenomena!

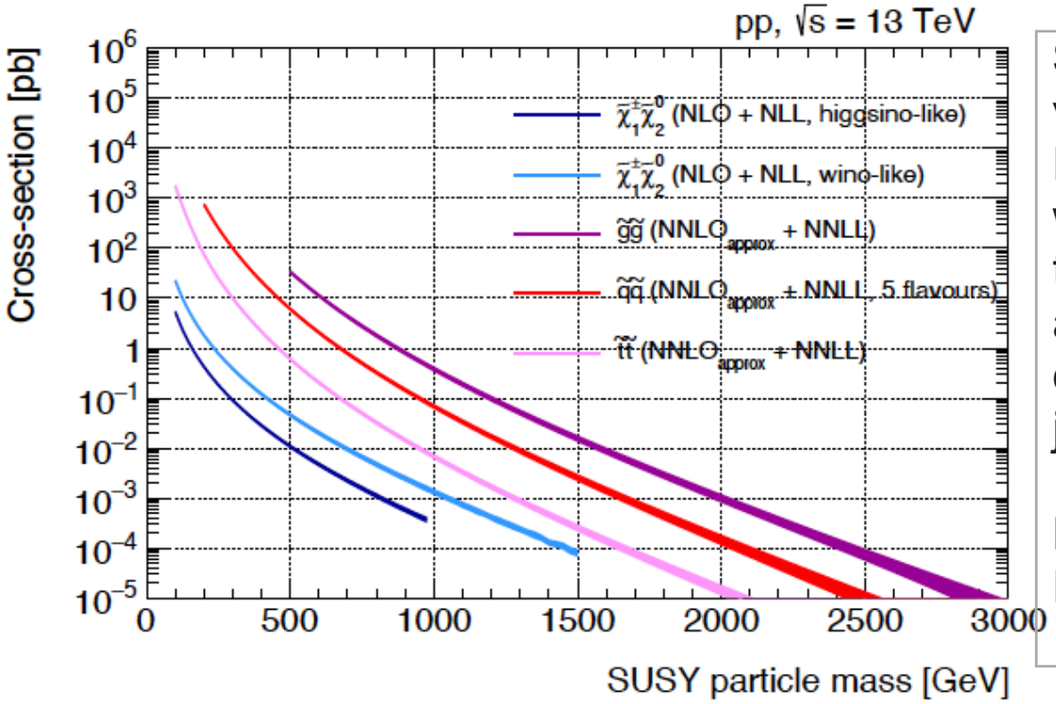
Supersymmetry

General remarks

- Supersymmetry extends the SM particle content with a superpartner differing by spin 1/2 and an additional Higgs doublet.
- Opens a wide range of interactions some of which need to be restricted e.g. proton decay. Enforce R-Parity = $(-1)^{3B+L+2S}$.
- Stabilizes the Higgs mass against radiative corrections (constraints SUSY scale to ~a TeV), provides a potential DM candidate, coupling unification.



SUSY search program at LHC - a bird eye view



Signature based vanilla searches for RPC (RPV) SUSY with (without) missing transverse momentum along with a number of leptons, photons & jets.

Boosted tags for W/Z/H and tops.

Compressed Spectra
$\Delta M \rightarrow 0$ GeV
Soft leptons or jets or disappearing tracks

Long-Lived Particles
Displaced vertices, disappearing tracks, delayed photons.

Modified vertex finders & dedicated ML taggers.

Beyond Simplified Models
pMSSM global Bayesian fit (19 parameters, 10 CMS analyses): maps survival probability across full EWK SUSY parameter space.

Helps identifying blind spots.

SUSY is not yet discovered. We extended "vanilla" inclusive searches to specific, difficult scenarios.

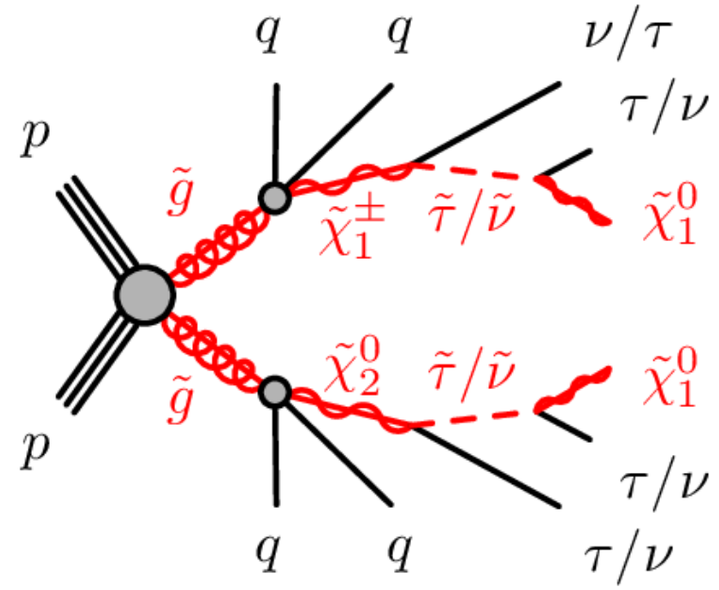
Eur.Phys.J.C 85 (2025) 12, 1437

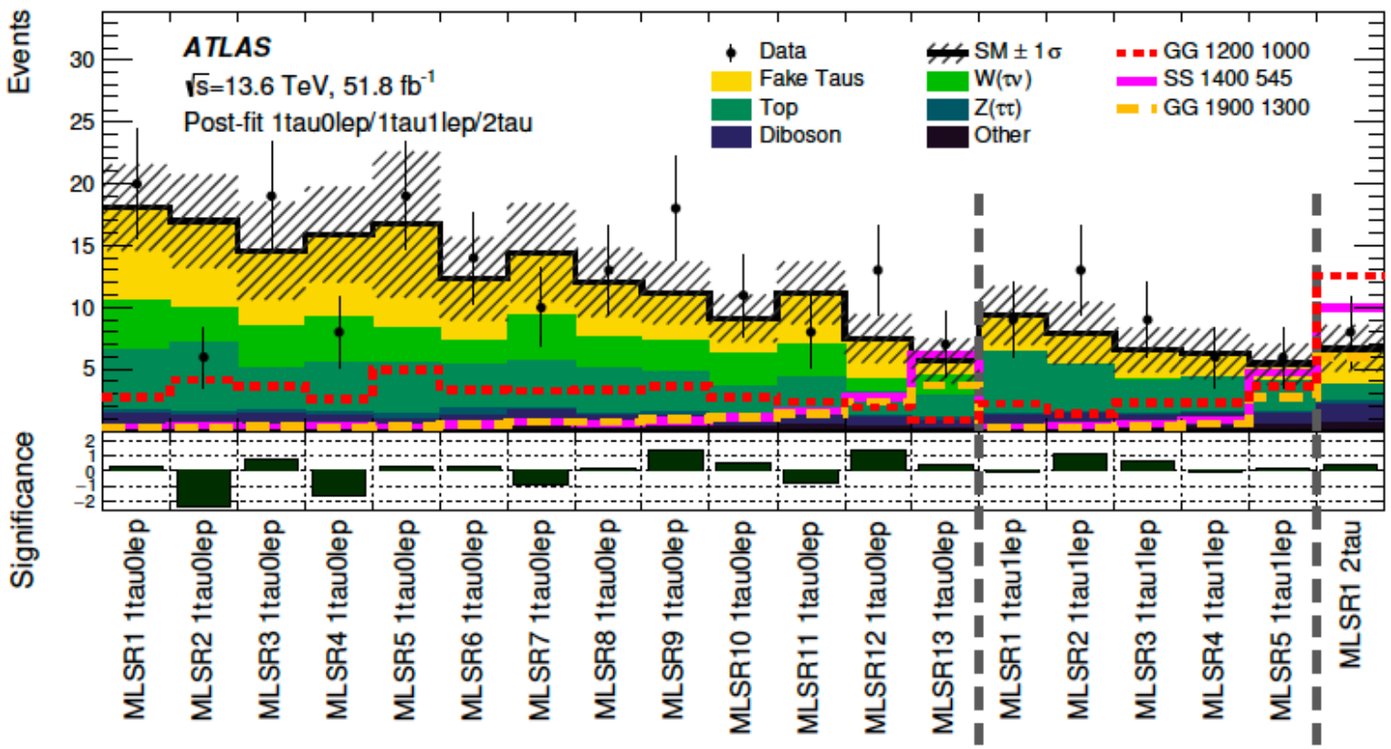
Searches for gluinos and squarks with τ-leptons

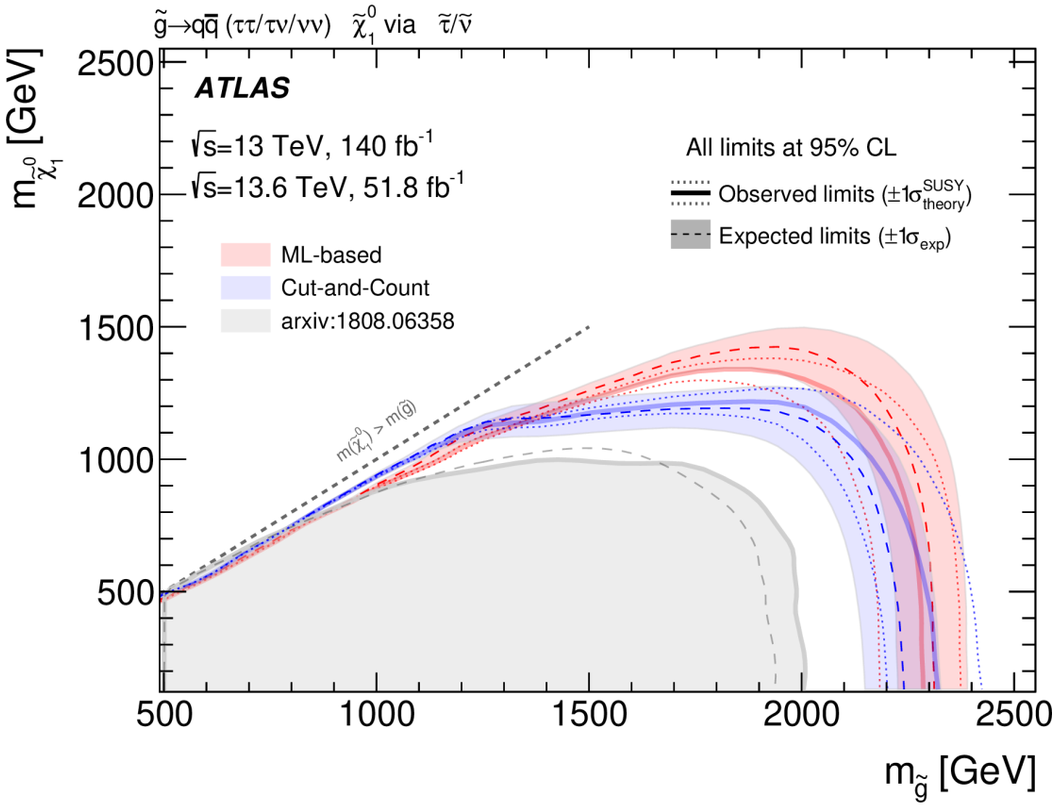
Run-2 + partial Run-3 search (192 fb^{-1}):

Targets pair-production of gluinos and 1st/2nd generation squarks decaying via charginos / neutralinos & staus / sneutrinos.

Uses events with ≥2 jets and MET in three complementary channels: 1τ_h, 1τ_h + 1e/1μ , ≥2 τ_h using a ML based approach.







Dedicated τ channels provide unique sensitivity to high tanβ SUSY scenarios mediated by staus.

Summary - Gluino masses up to 2.4 TeV and squark masses up to 1.8 TeV have been probed @ LHC.

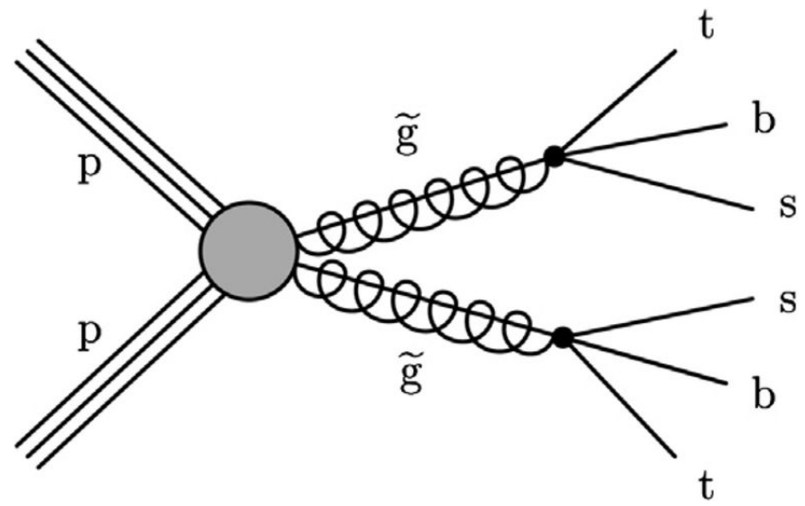
JHEP 10 (2026) 186

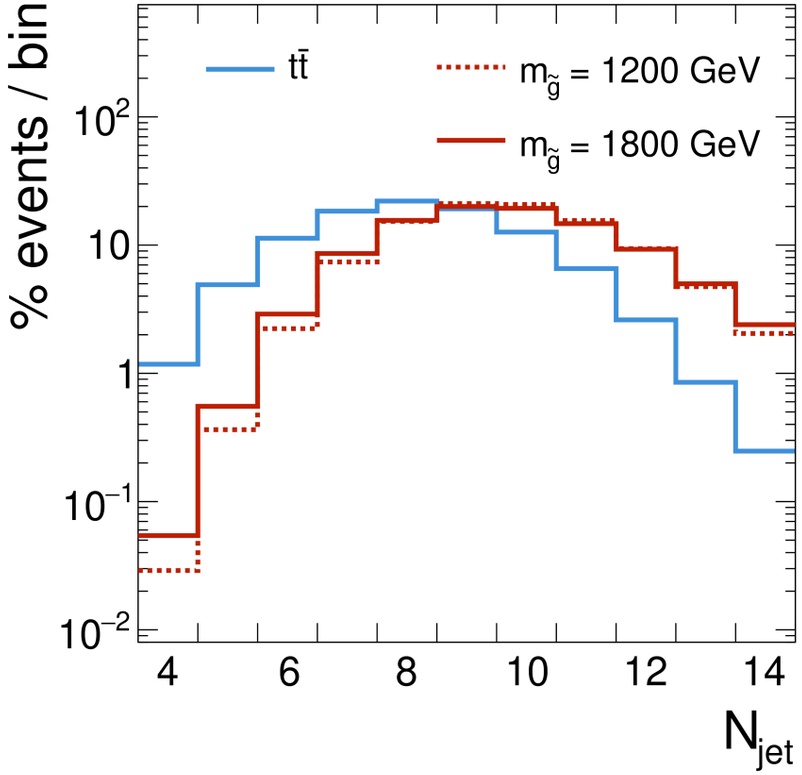
RPV gluinos and squarks - with large radius jets

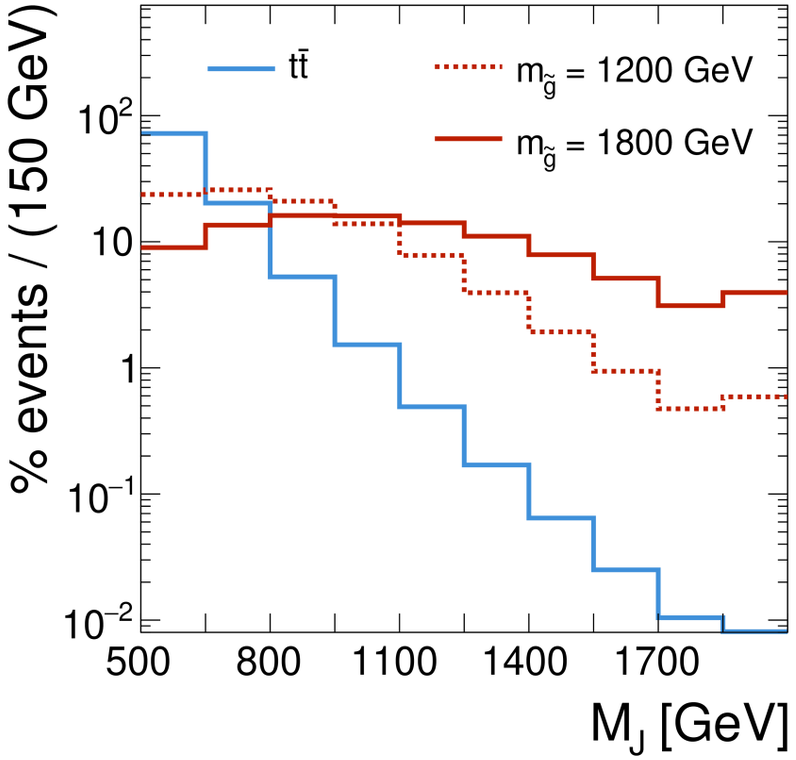
Targeting RPV SUSY via baryon-number violating coupling λ''_{323}

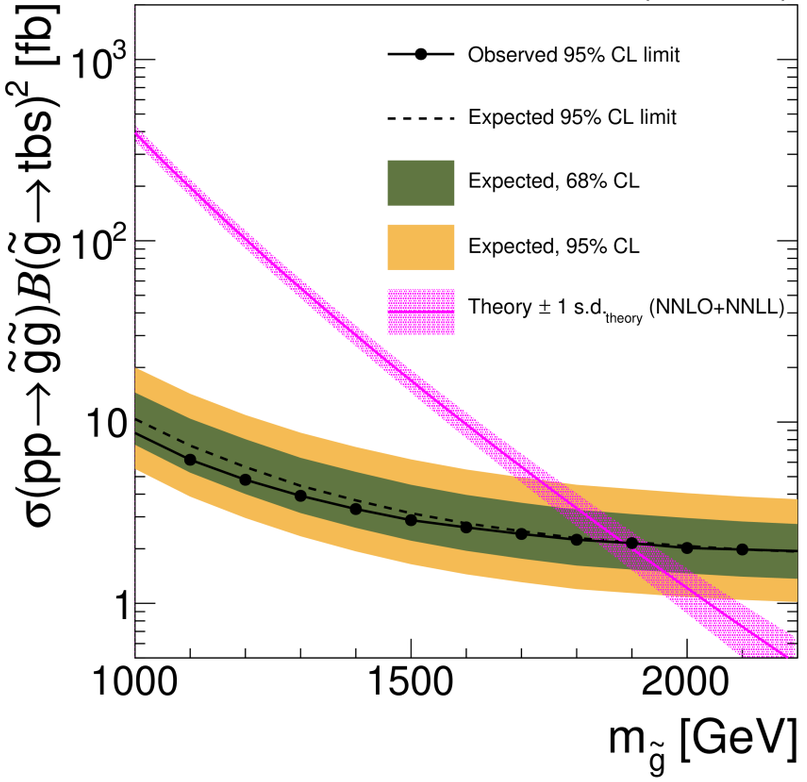
Search using 1-lepton + ≥ 2 b-jets & multijets

- Small-radius jets & lepton clustered into large-radius jets (AK12)
- Sensitive variables number of jets (Njet), b-jets (Nb), and sum of large-radius jet masses (MJ)
- Data-driven background estimation across bins of Njet, Nbjet and MJ









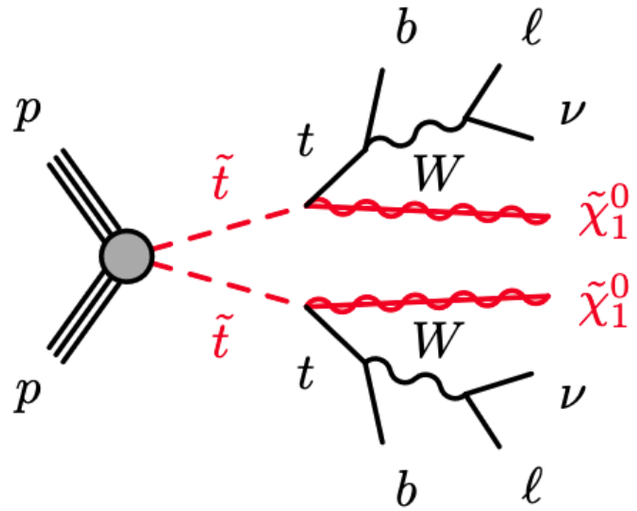
Excluded gluinos models with RPV decay modes up to mass of ~1.9 TeV.

Also refer to CMS-SUS-23-014 for a generic search with large radius jets

arXiv:2603.16191

Pair-production of top-squarks

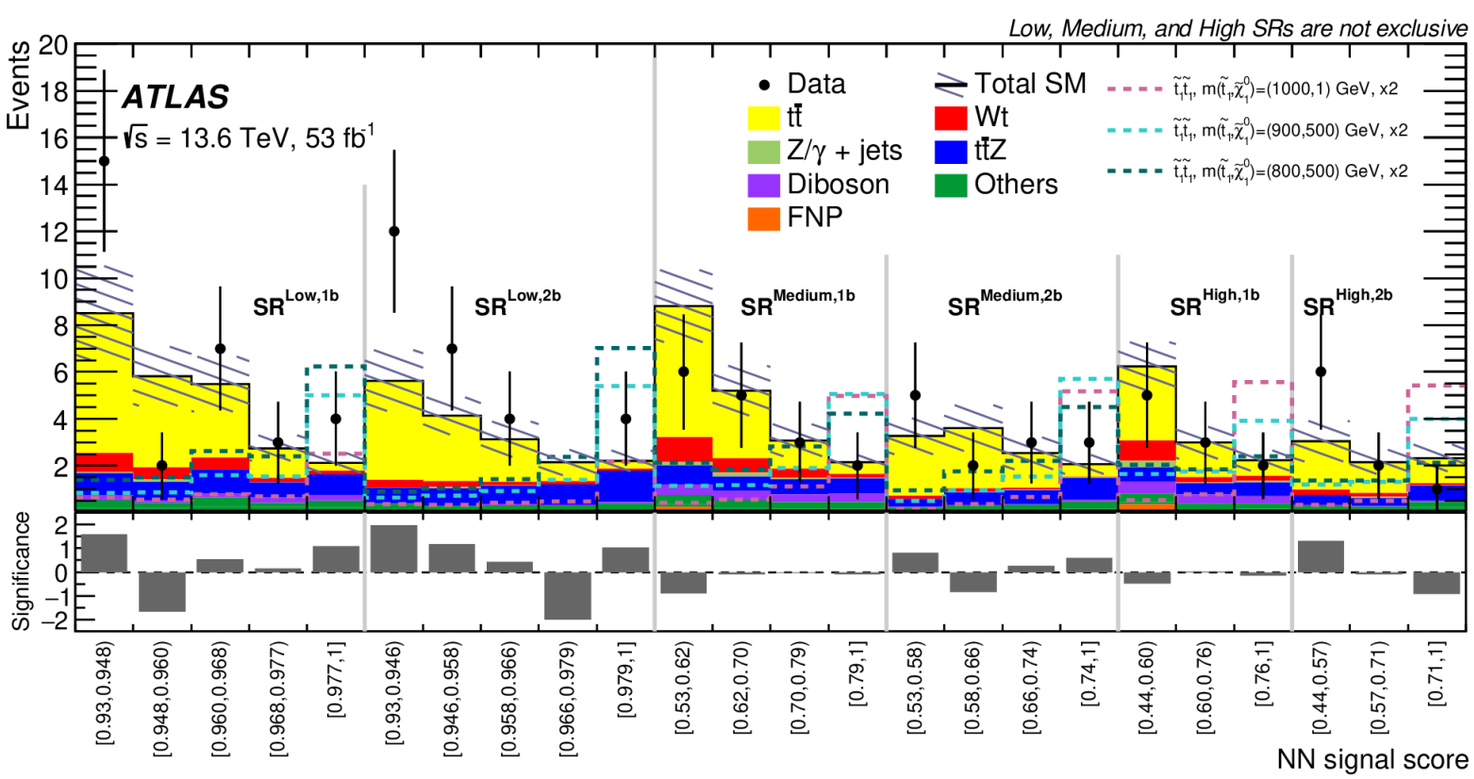
R-parity conserving SUSY using Run 2 + Run 3

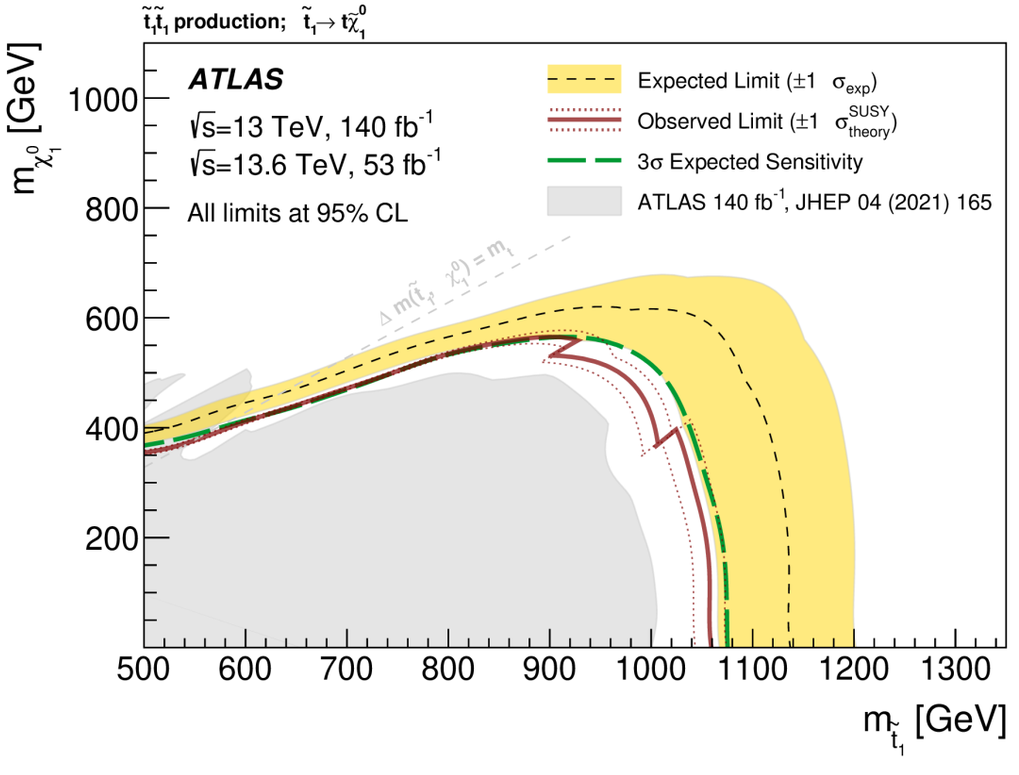


Uses 2ℓ + b-jets + MET final states

Dedicated neural networks for low, medium and high ΔM (stop, LSP)

Up to 50% improvement in expected sensitivity of benchmark point of 1 TeV due to updated analysis strategy and 20% due to addition of Run 3 data.





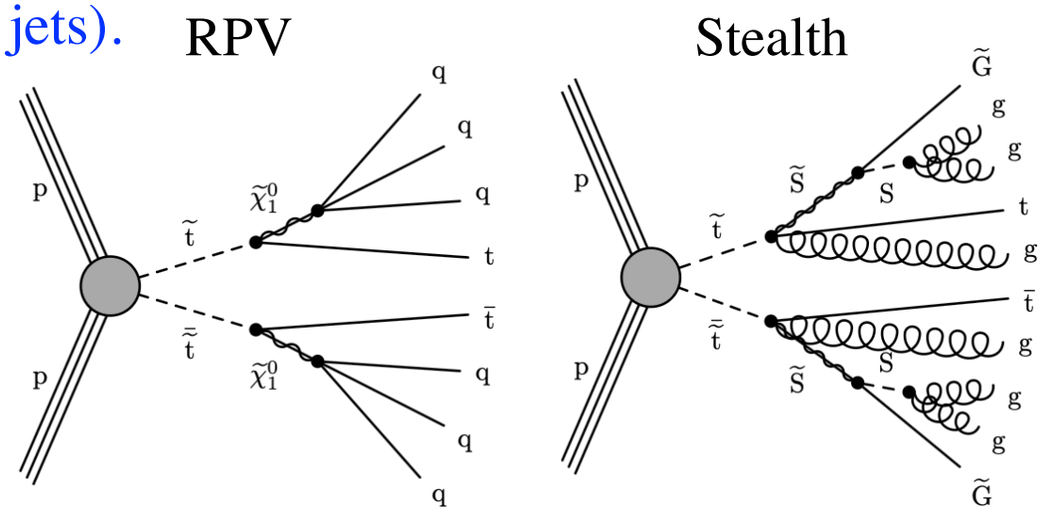
Stops up to the masses of approximately 1060 GeV are excluded for small LSP masses.

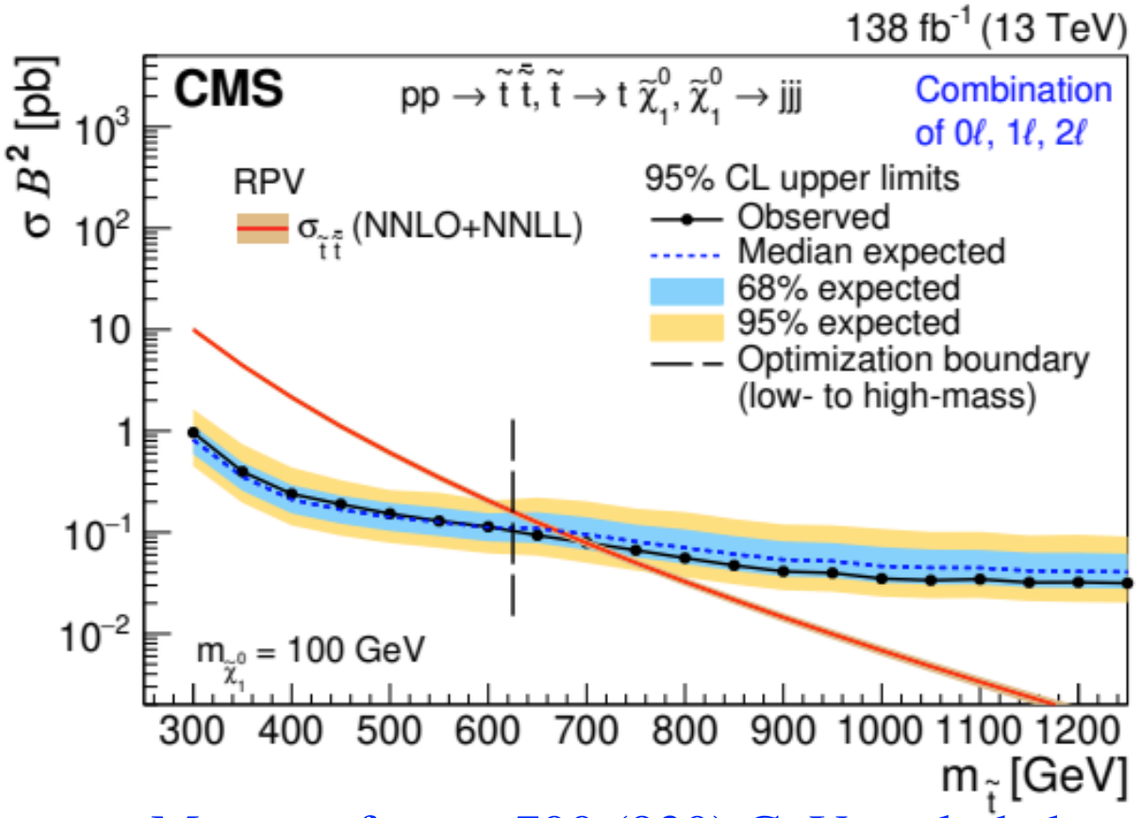
Pair-production of top-squarks

Baryonic R-parity violating SUSY or stealth SUSY

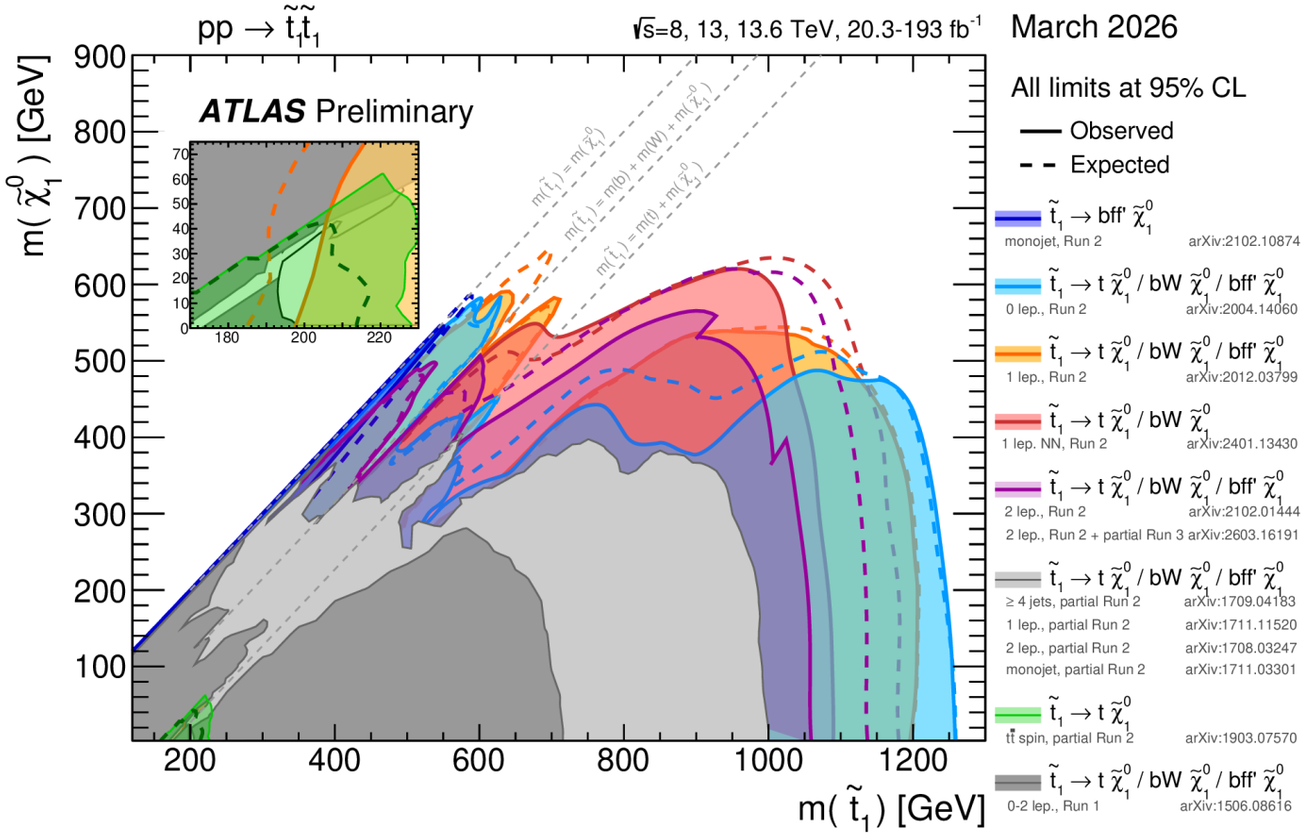
Excess around 400 GeV was reported in Run-2 analysis (1ℓ + jets).

- Current analysis uses 0ℓ / 1ℓ / 2ℓ + ≥ 6 jets.
- Employs improved background estimation methods to better control uncertainties in the modeling of jet multiplicity - uses an distance correlator method to obtain two independent neural network variables.





Masses of up to 700 (930) GeV excluded for RPV (Stealth) SUSY models

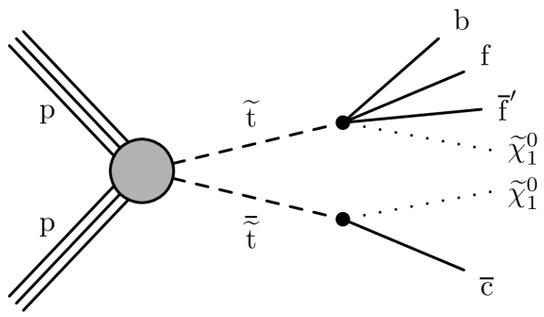


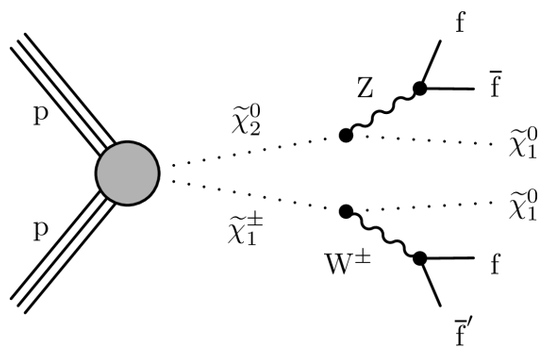
Overall status of stop pair-production searches

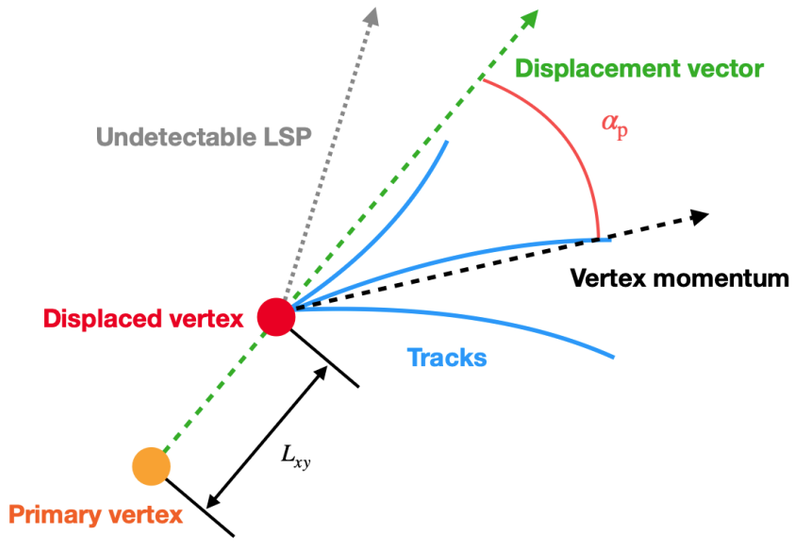
Long lived electroweakinos & top-squarks

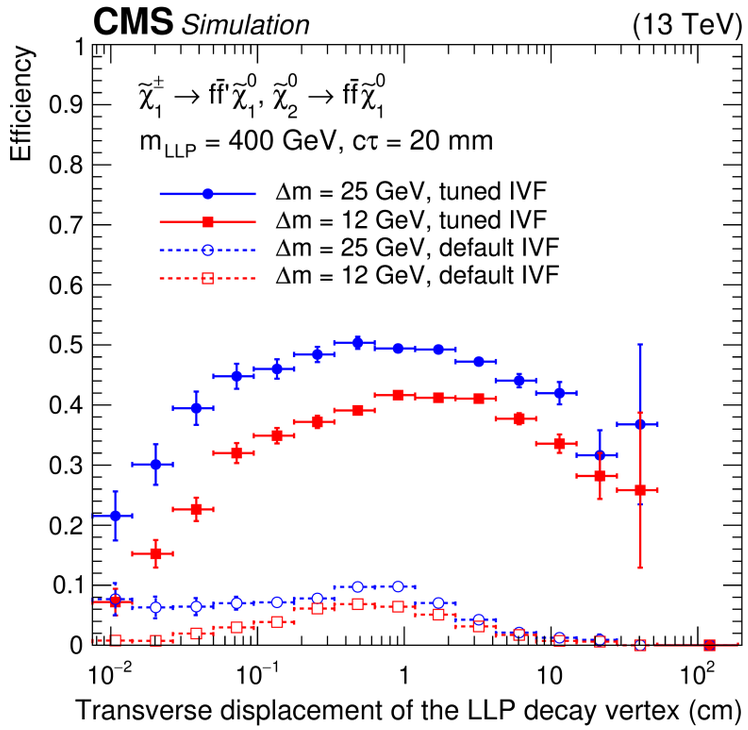
Compressed co-annihilation models

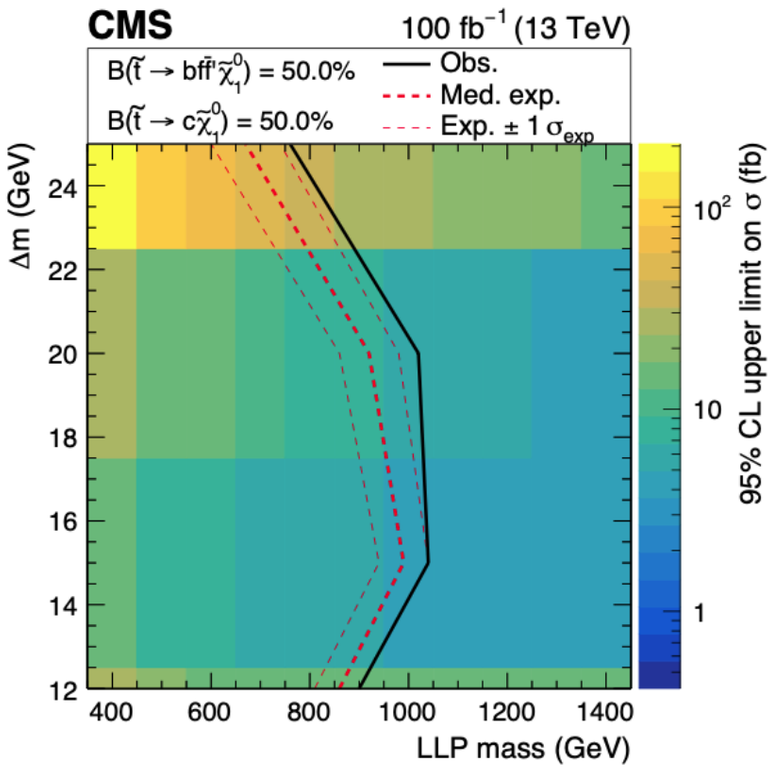
- Small mass splitting - Δm (NLSP, LSP) < 25 GeV
- LLP arises naturally in long-lived stop NLSP & bino-wino annihilation
- If the LLP decays inside the tracker instead of escaping it, the optimal signature becomes a soft displaced vertex - **dedicated vertex reconstruction**.

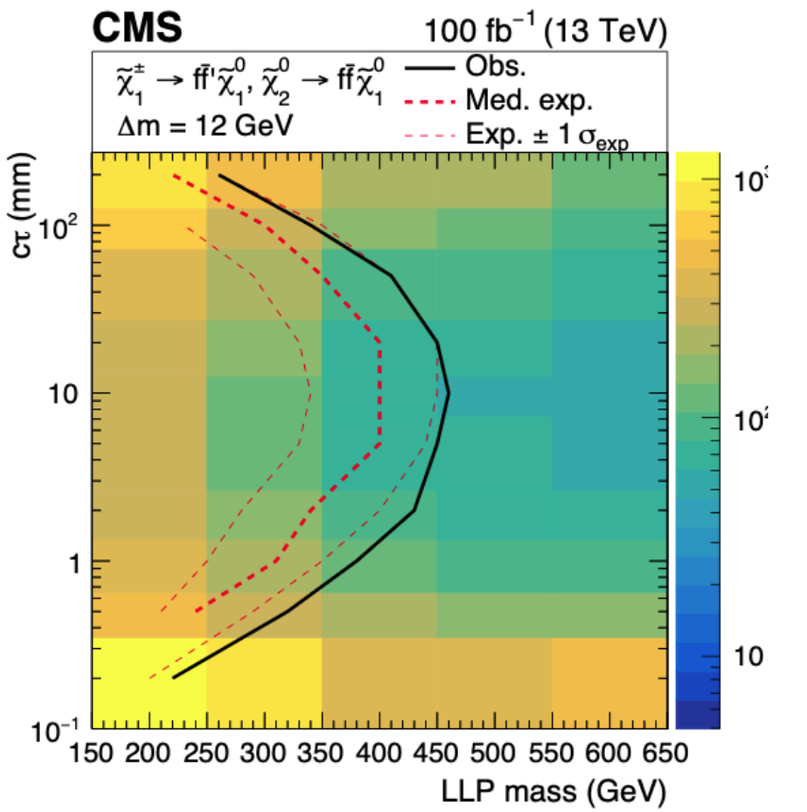








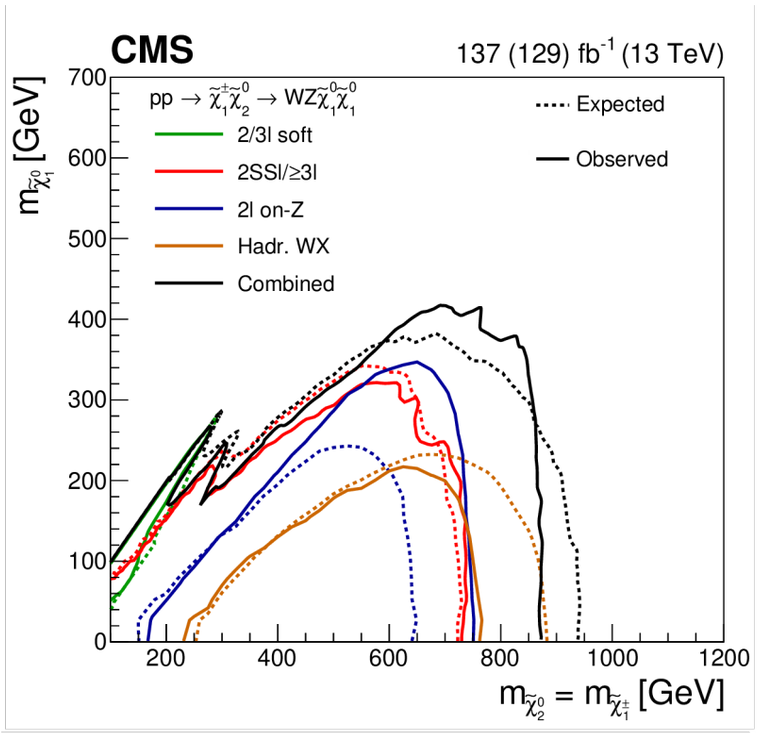


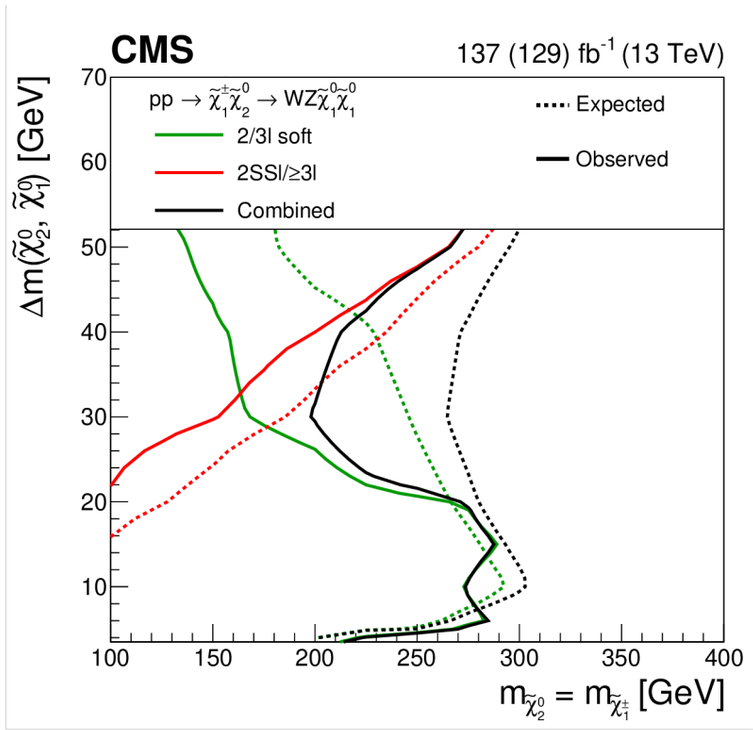


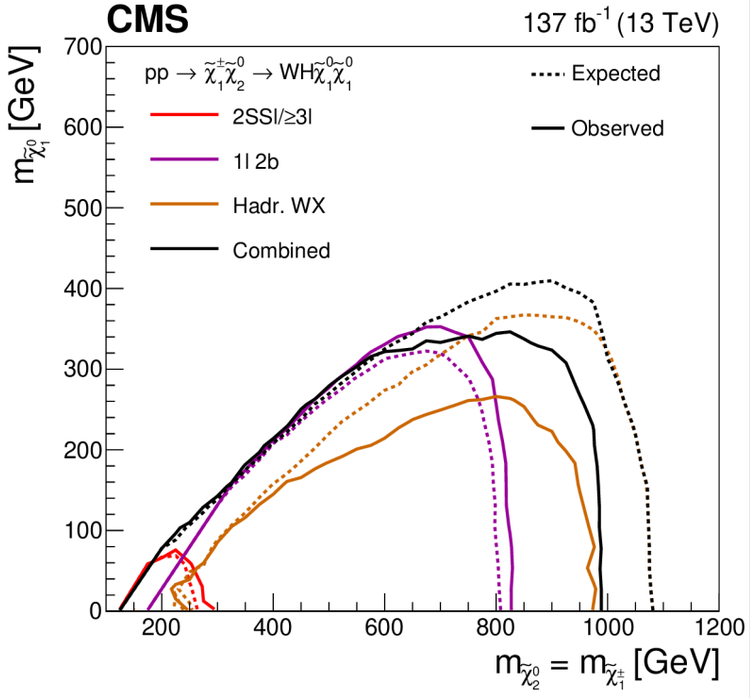
Search excludes top squarks with masses ~ 400–1100 GeV and wino-like neutralinos with masses ~ 220–550 GeV.

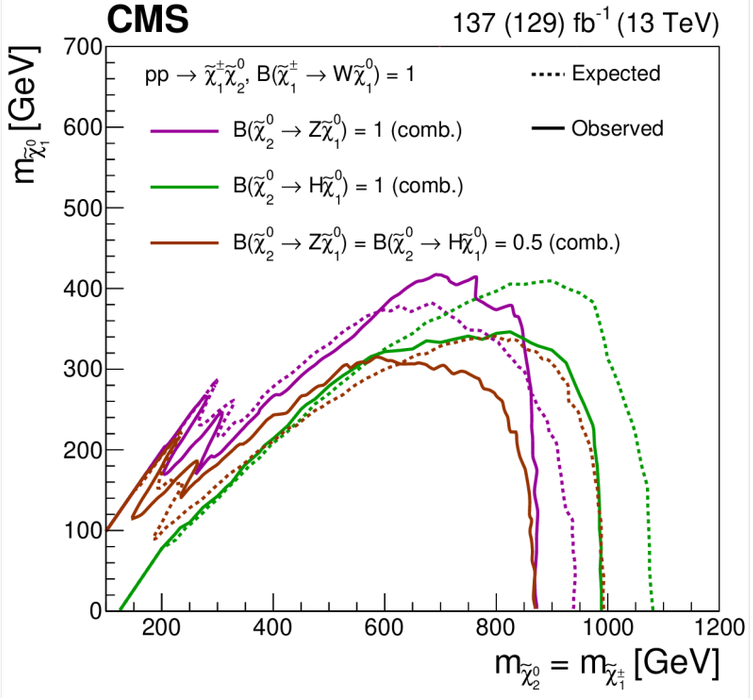
Combination of Electroweakino searches

CMS arXiv:2402.01888
ATLAS arXiv:2402.08347









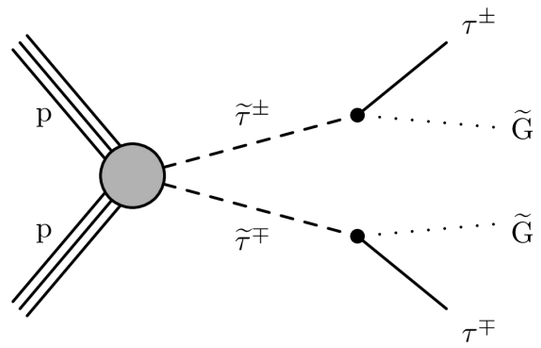
Up to ~300 GeV electroweakinos have been probed in small ΔM scenarios & up to ~1 TeV otherwise).

Pair production of long-lived staus

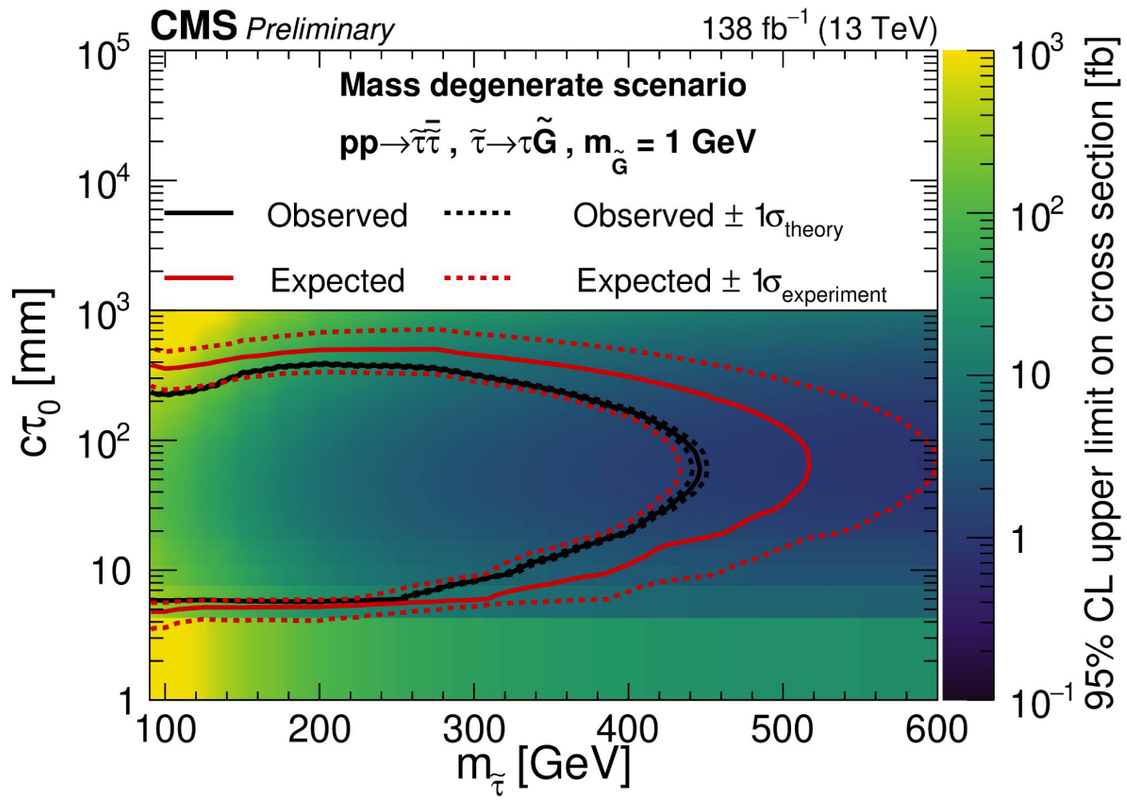
arXiv:2601.17576

Long lived staus in GMSB models - staus become long-lived due to small gravitational coupling to the gravitino.

First application of GNN-based ParticleNet for displaced tau identification- learns both τ decay topology and displaced-track information.



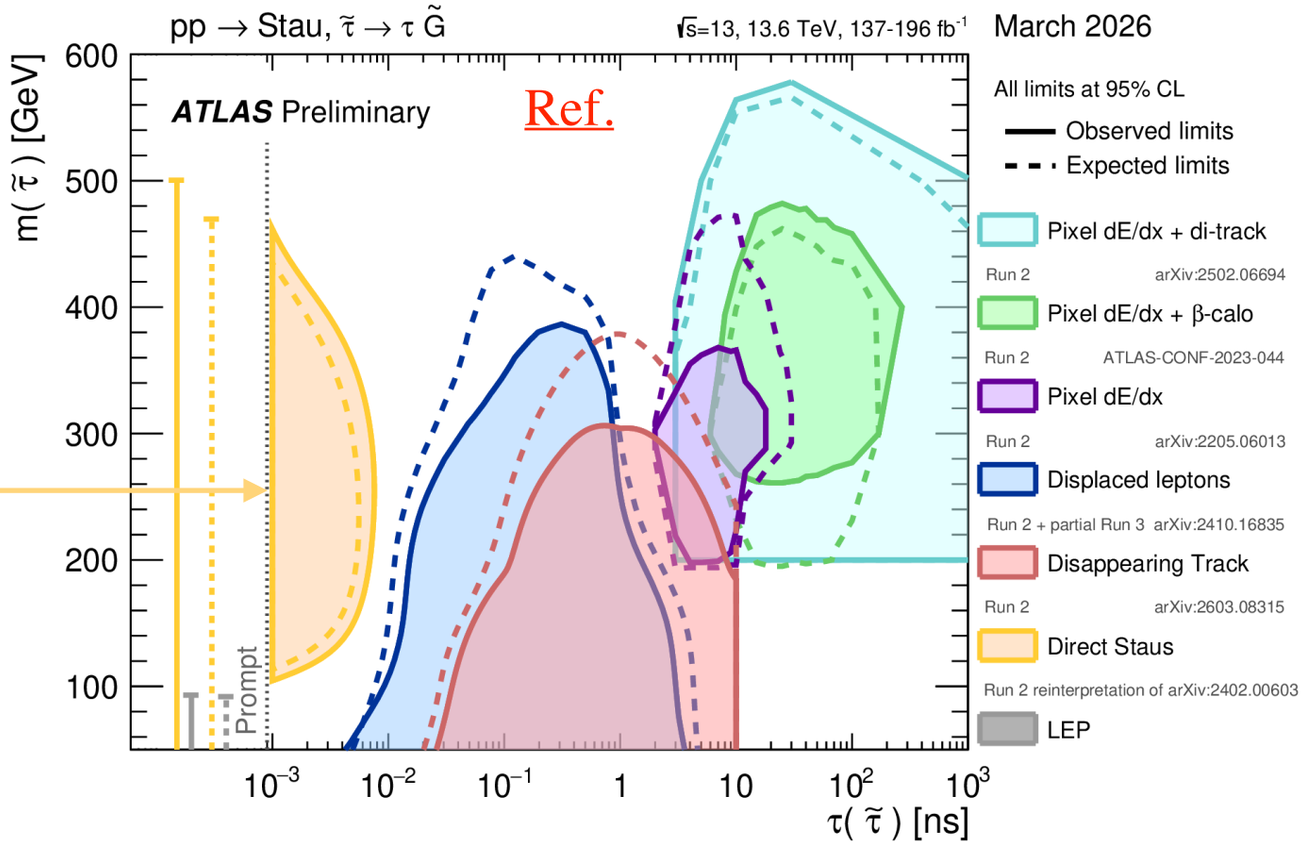
Excludes masses upto 425 GeV for lifetime of 50 mm.



Dedicated displaced-τ reconstruction extends τ-based SUSY searches from prompt to long-lived signatures.

The lower lifetime range is complemented by a reinterpretation of a search originally designed to target stau pair production in prompt scenarios.

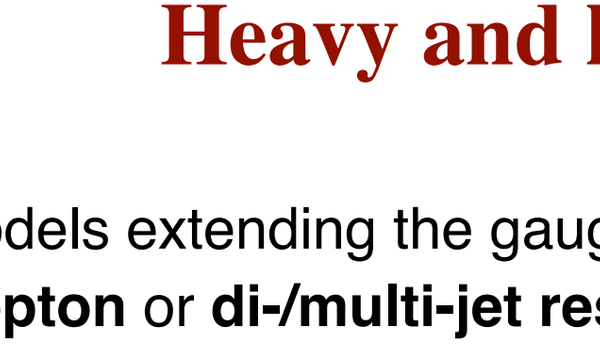
Compressed sleptons (e/μ-flavors) are also probed to ΔM of ~2 GeV in the mass range up to ~200 GeV - JHEP 08 (2025) 053



Heavy and light BSM resonances

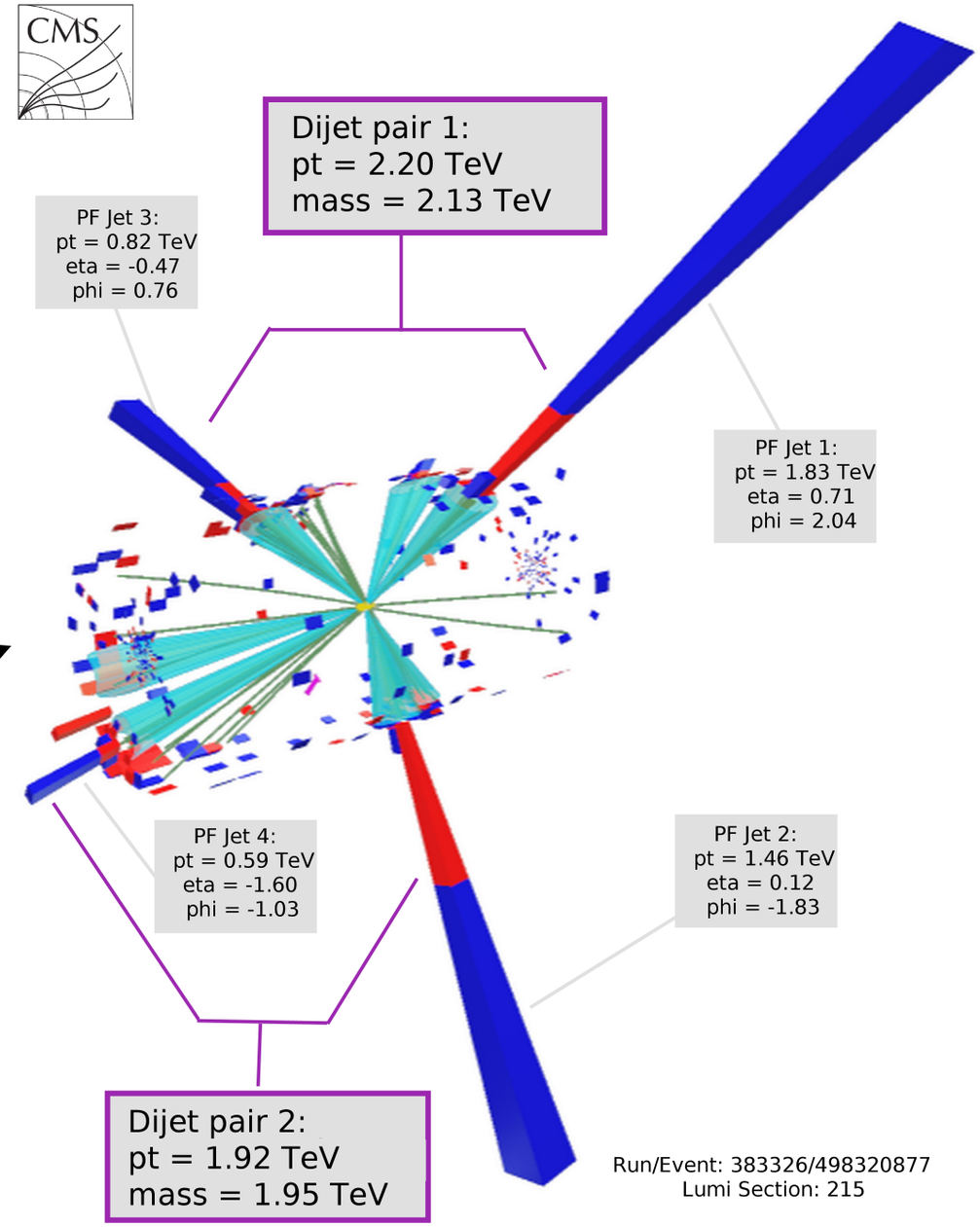
Various BSM models extending the gauge sectors can result in **dilepton** or **di-/multi-jet resonances** or **decays to SM vector bosons**.

- Grand unified theories (GUTs)
- Left-Right Symmetric Model
- Sequential Standard Model
- E_6 gauge group Models extending to additional U(1) gauge symmetries
- Sequential Standard Model (SSM)
- Spin-2 KK Graviton excitations
- ….



Invariant mass of daughter products

CMS-PAS-EXO-25-004



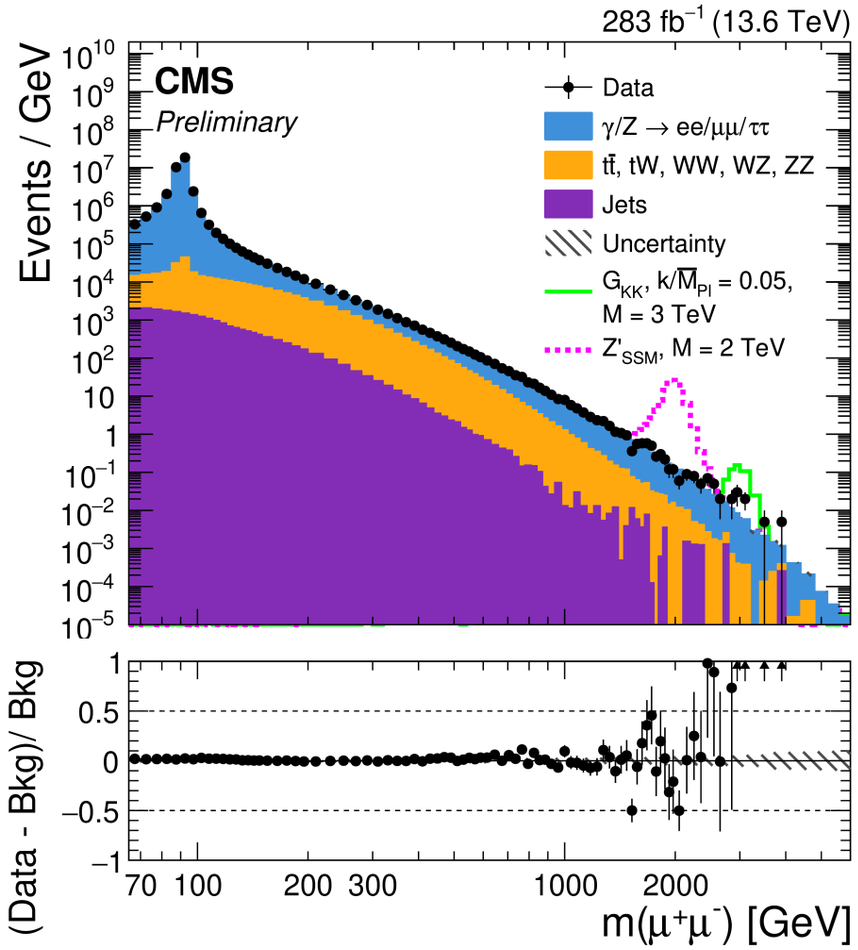
Other handles when neutrinos are present.

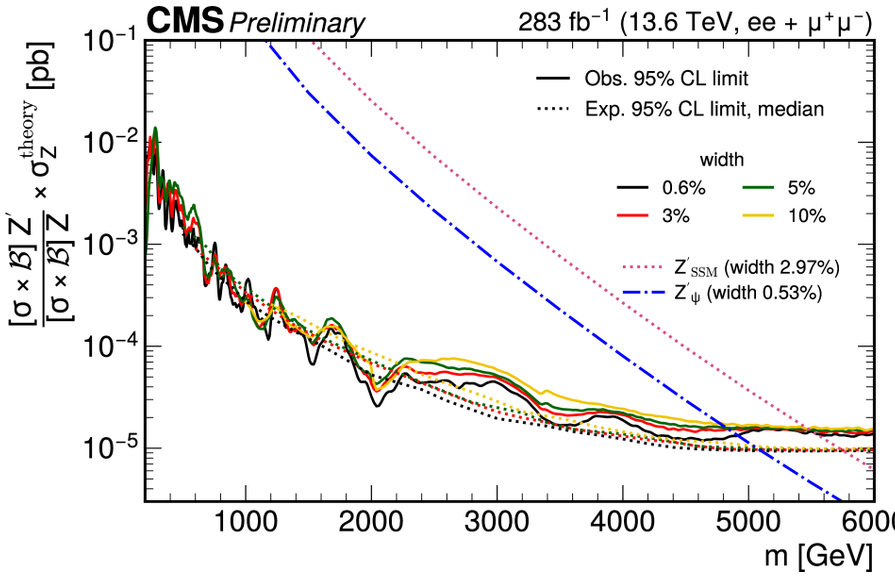
Massive Gauge bosons: Z'→ ee or μμ

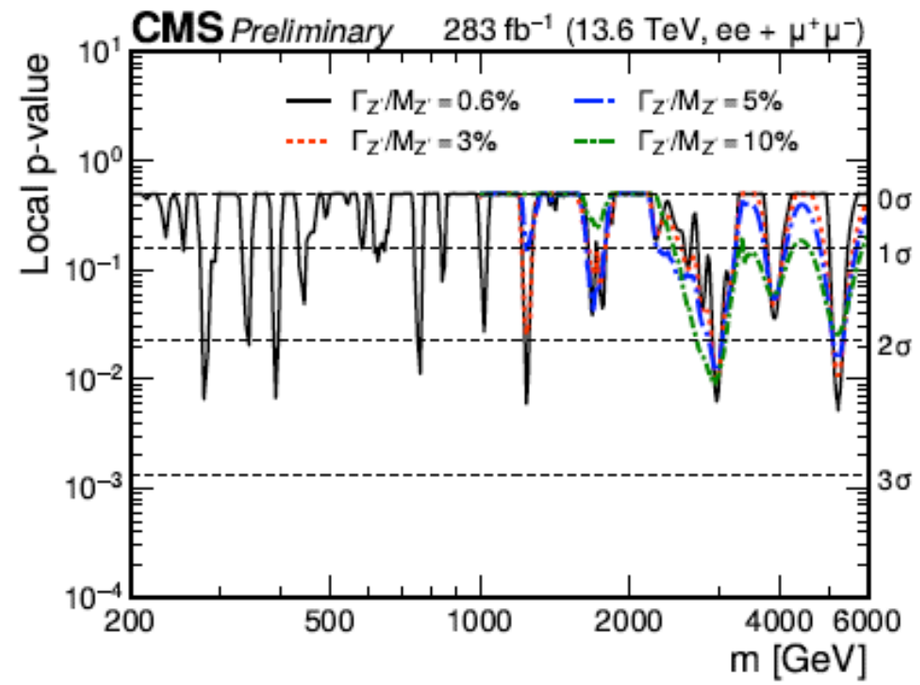
- Classic dilepton search over a smoothly falling dilepton background from the SM processes.
- Results are interpreted in a simplified Z' SSM, superstring-inspired scenarios and RS model spin-2 gravitons.

EXO-25-021

Z' → ee / μμ

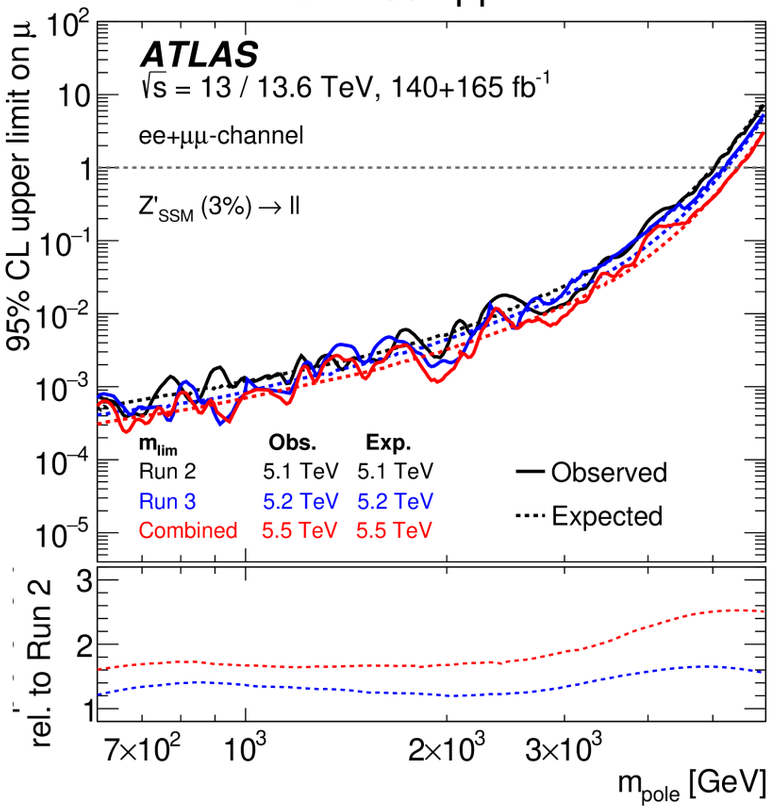






arXiv:2607.28334

Z' → ee / μμ



More details on the EFT interpretation in the talk by Hannes Mildner

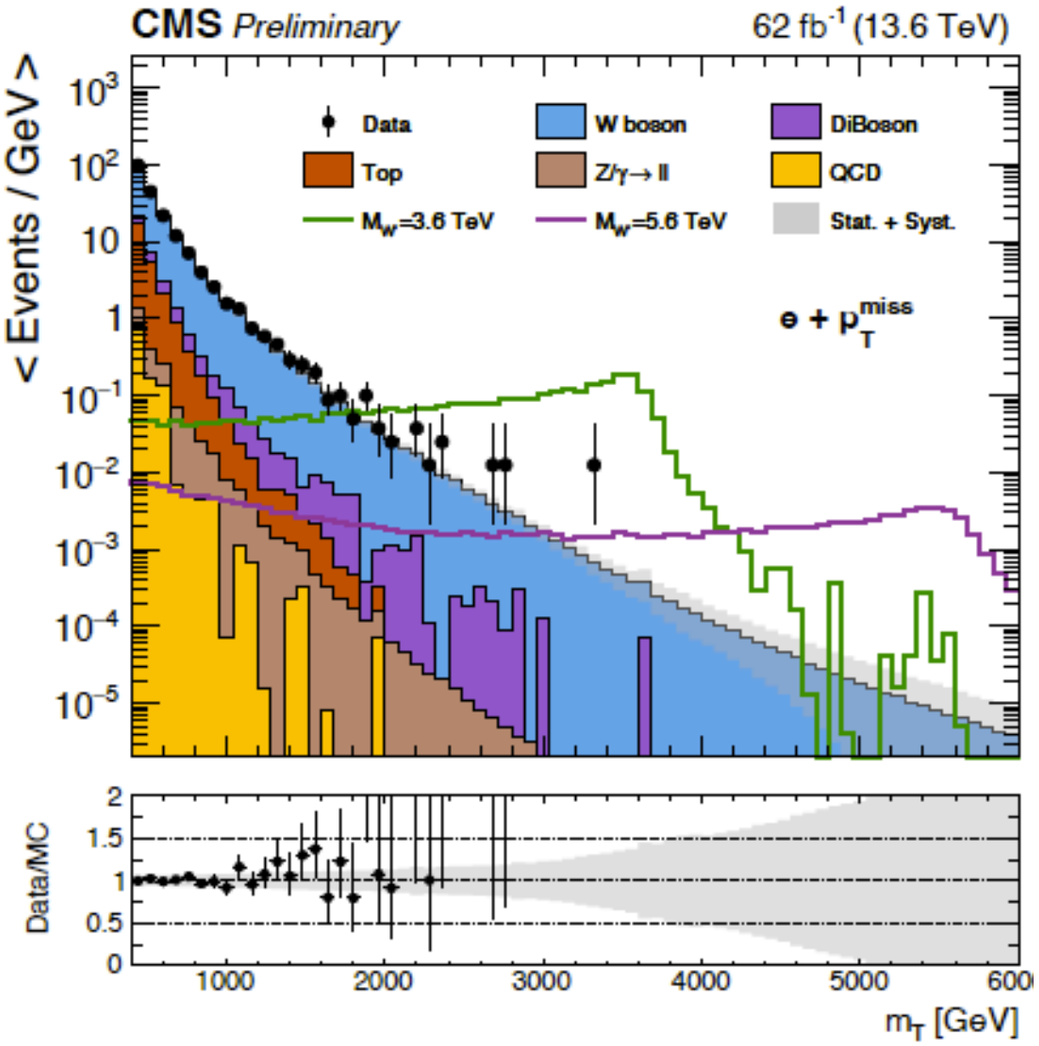
ATLAS and CMS probing masses of new resonances above 5 TeV with unprecedented sensitivity!

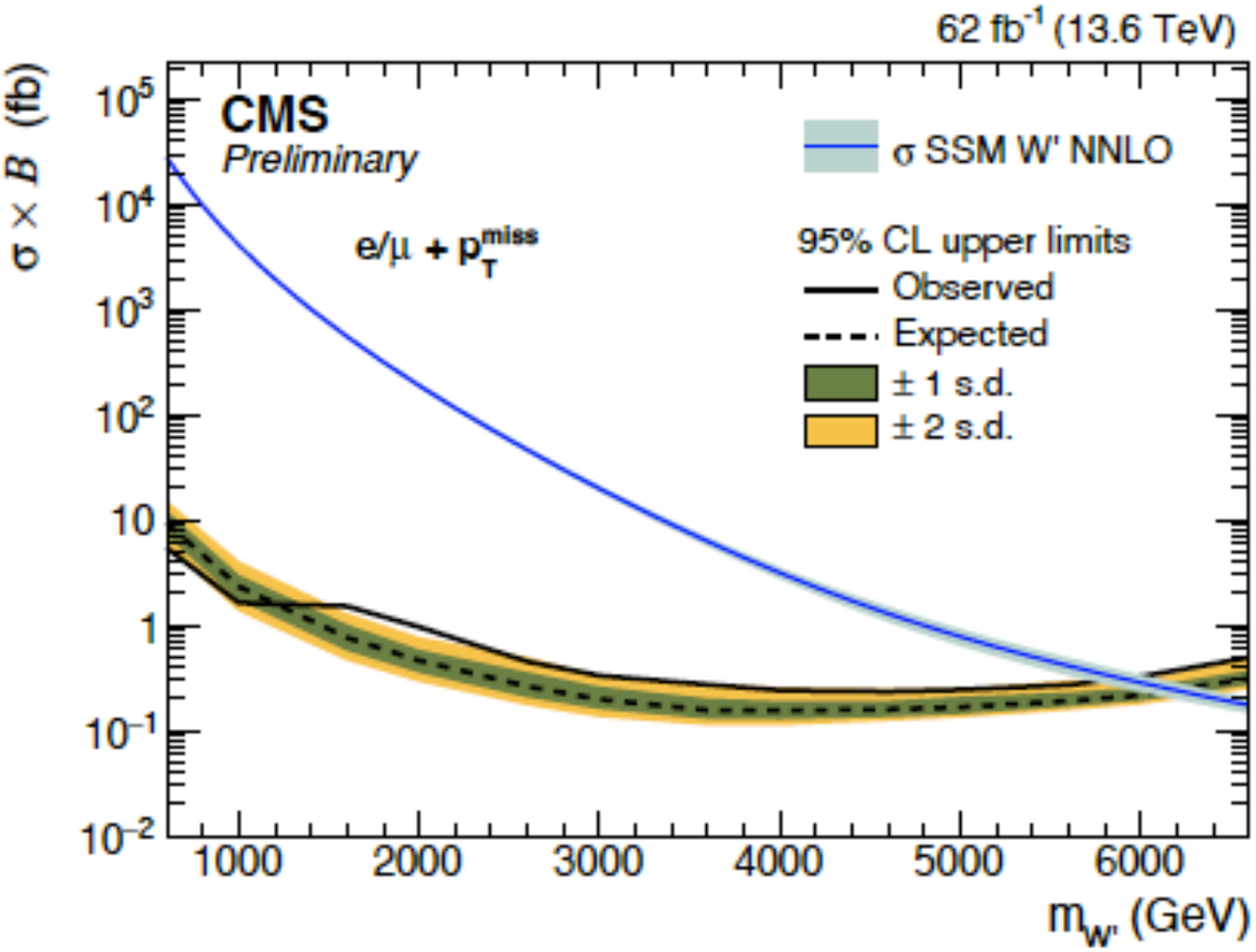
Massive Gauge bosons: W'→ $e\nu_e$ or $\mu\nu_\mu$

- Search for a massive resonant signal in the high mass tail of transverse mass (m_T) distribution.
- Results are interpreted in a simplified sequential standard model (SSM), involving both production and decay modes of W'.

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos[\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})]\right)}$$

SSM W' masses excluded up to 5.7-5.9 TeV





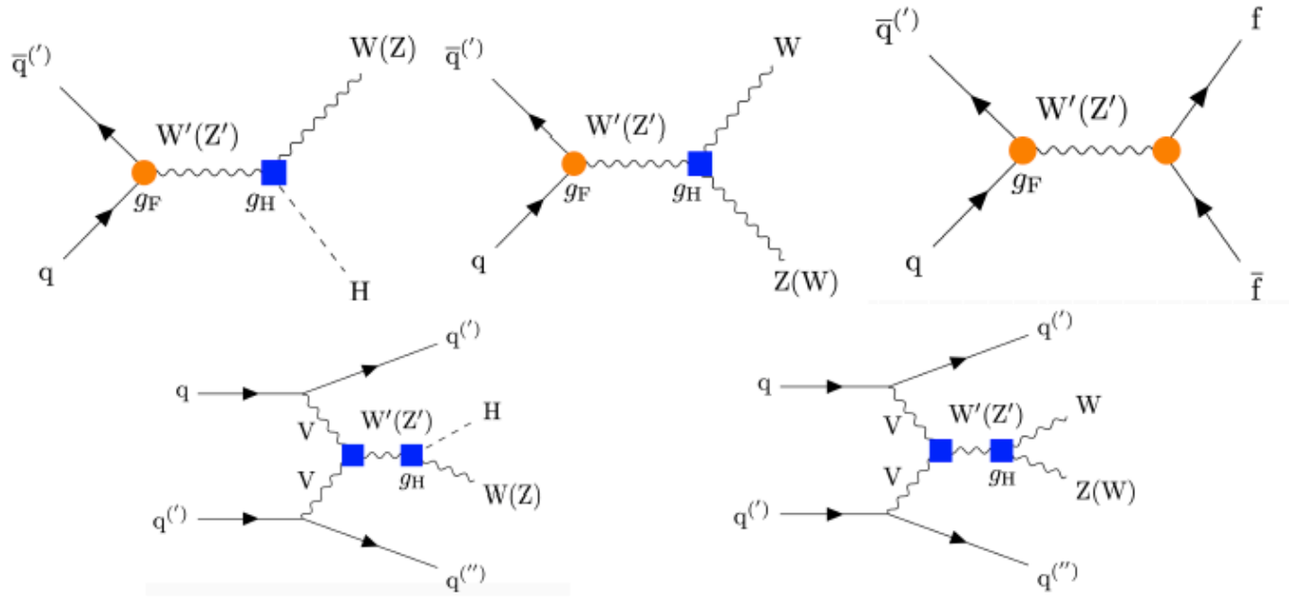
Expected limit extended by 600 GeV wrt Run 2 - 50% increase in W' cross-section in the region of limits for COM energy 13 → 13.6 TeV.

Heavy resonances decaying to multiple SM bosons

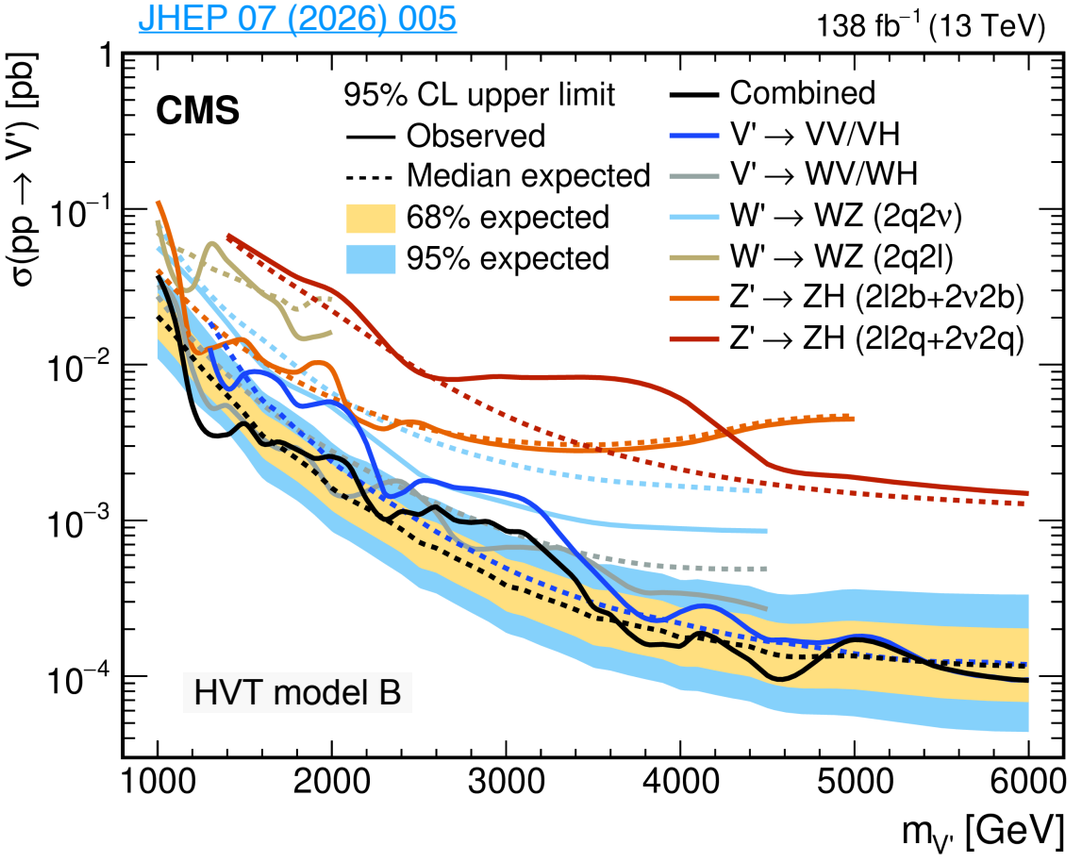
Many BSM frameworks predict a heavy state coupled to electroweak symmetry breaking. Such a state decays preferentially to W, Z, and H bosons.

Several handles — resolved, semi-merged, or merged decay products depending on the masses involved.

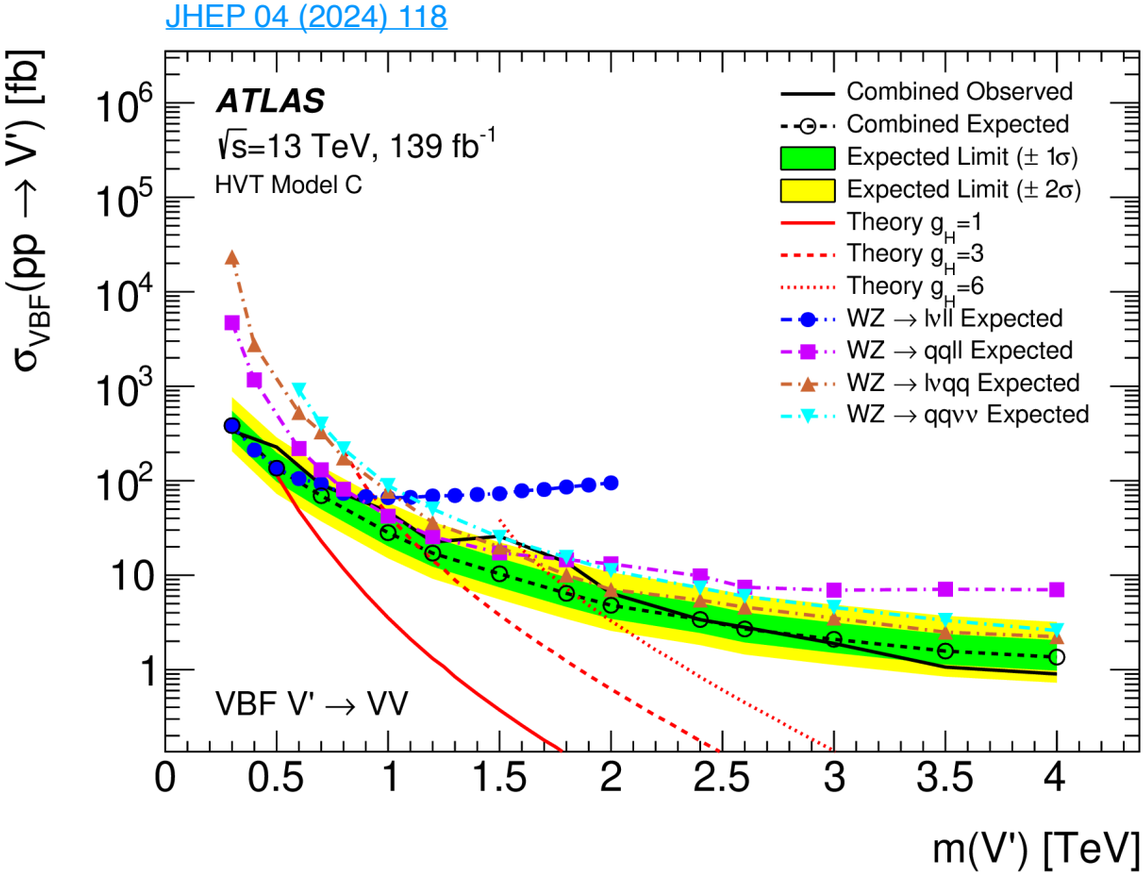
Simplified heavy vector-boson triple (HVT) framework for analysis design & interpretation.



JHEP 07 (2026) 005



JHEP 04 (2024) 118



HVTs with masses below 2 – 5.5 TeV have been excluded depending on the couplings and model assumption.

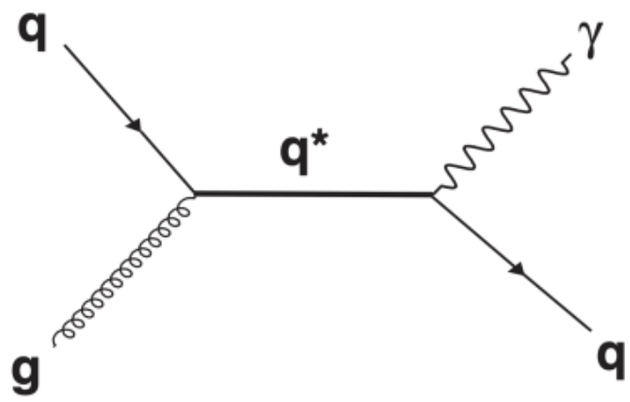
More resonances

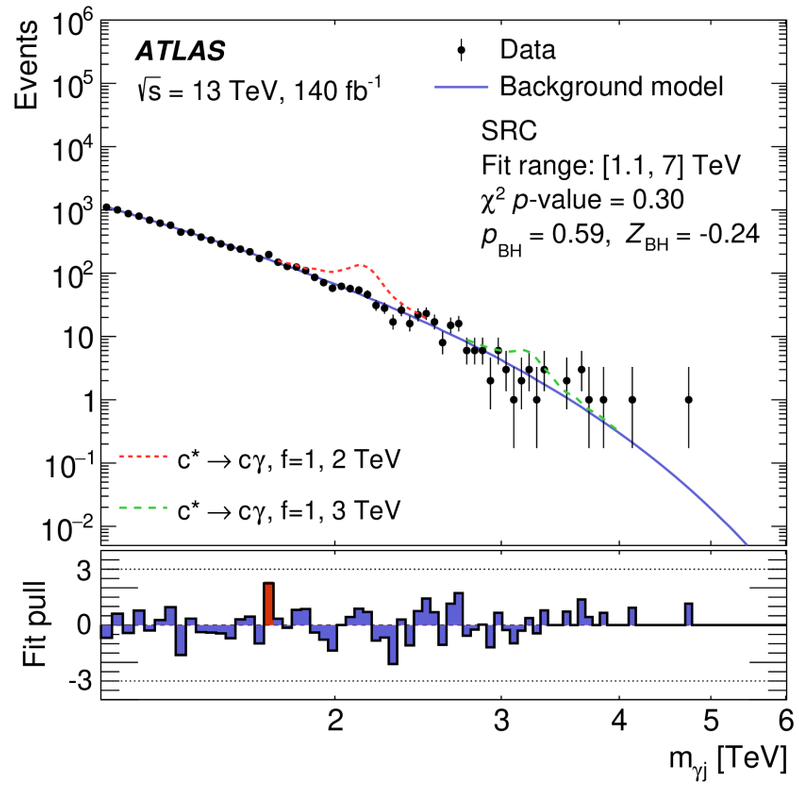
Excited quarks & leptons and Quantum Black Holes

arXiv:2608.26935
CMS-EXO-24-028

First direct constraints on c^* **production** at the LHC.

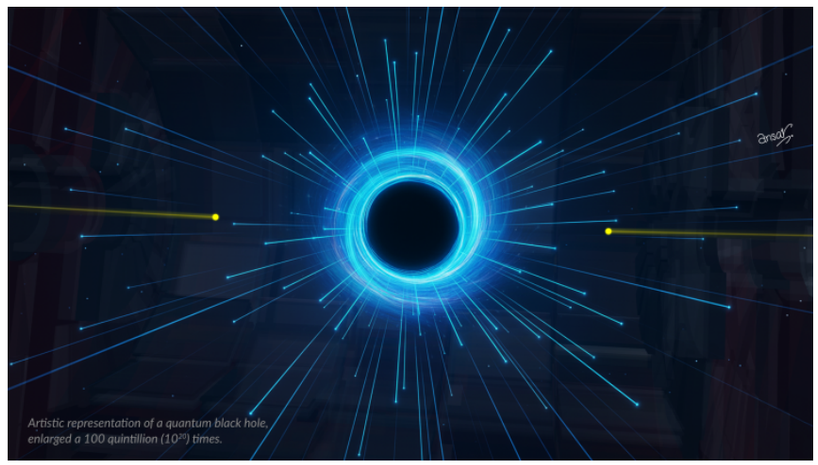
Search for a localized excess in the γ–jet invariant mass spectrum.

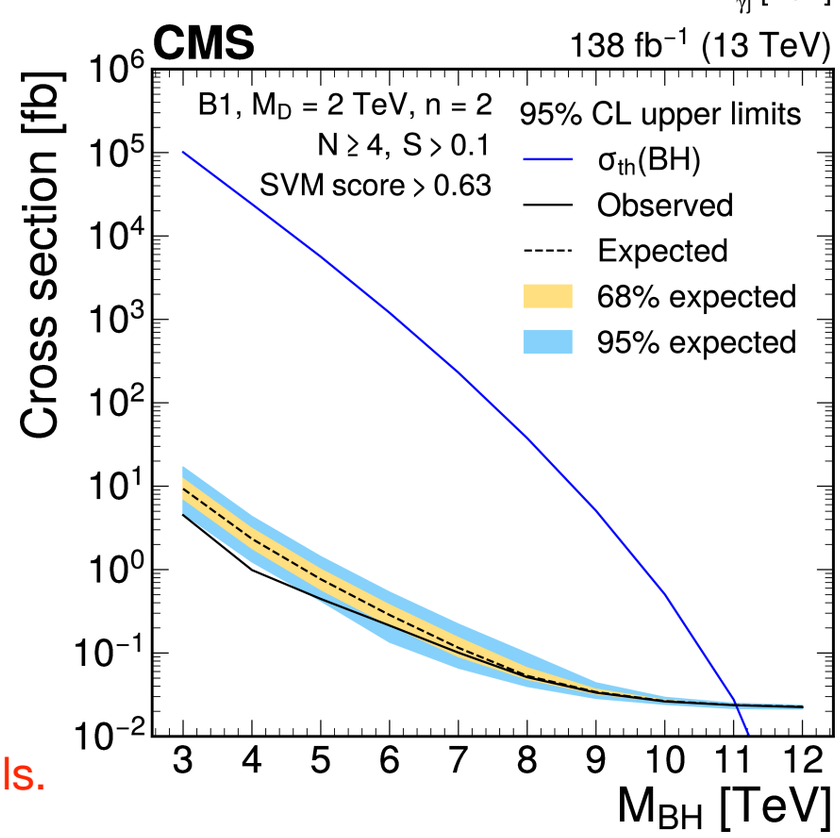




For $f = 1$, masses up to 6.0 TeV (q^*), 3.5 TeV (c^*), and 2.6 TeV (b^*) are excluded. QBH ~5.3 (7.5) RS (ADD) are probed.

Blackholes & sphalerons in events with multiple energetic jets, leptons, and photons using the shape invariance of the scalar sum of the transverse momenta of all objects in the event.





Excluded up to 8.4-11.4 TeV semiclassical BHs & 9.0--10.7 TeV string balls.

Recent result from ATLAS using l+jets (arXiv:2604.19495)

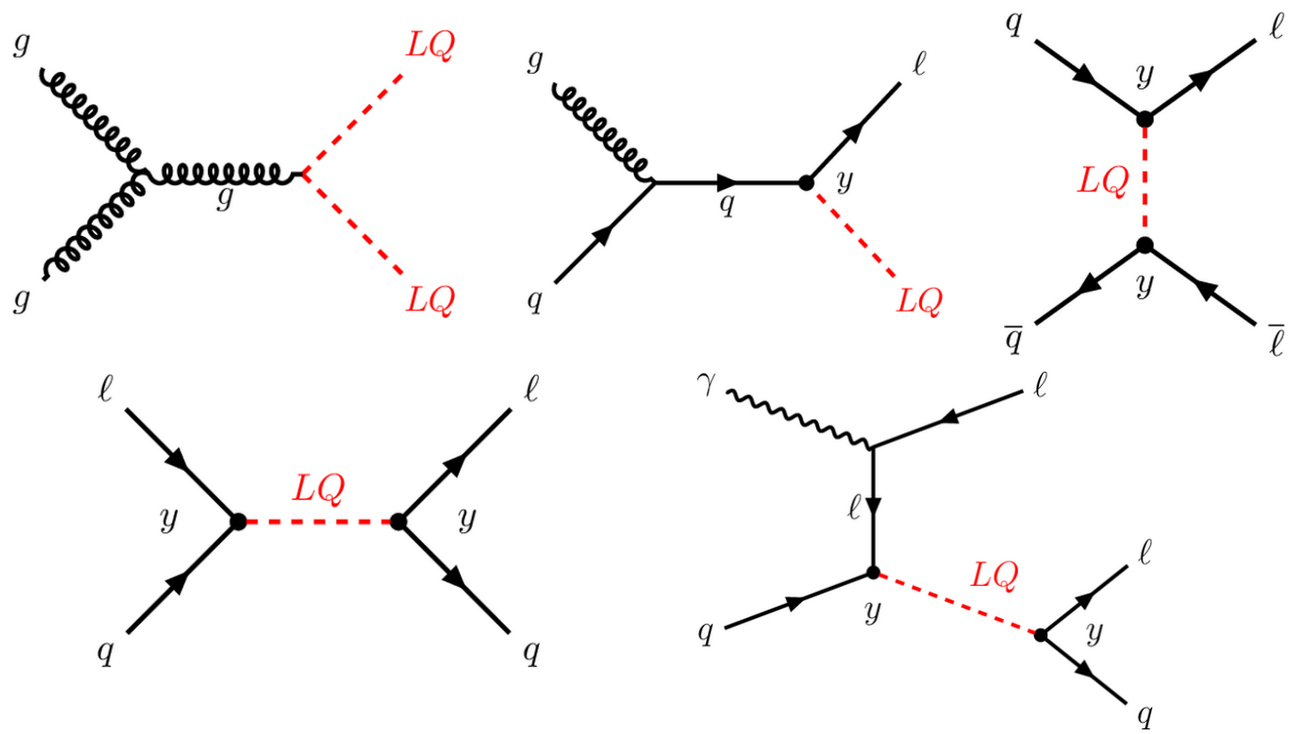
image ref

LeptoQuarks (LQs)

LeptoQuarks - connect lepton and quark sectors

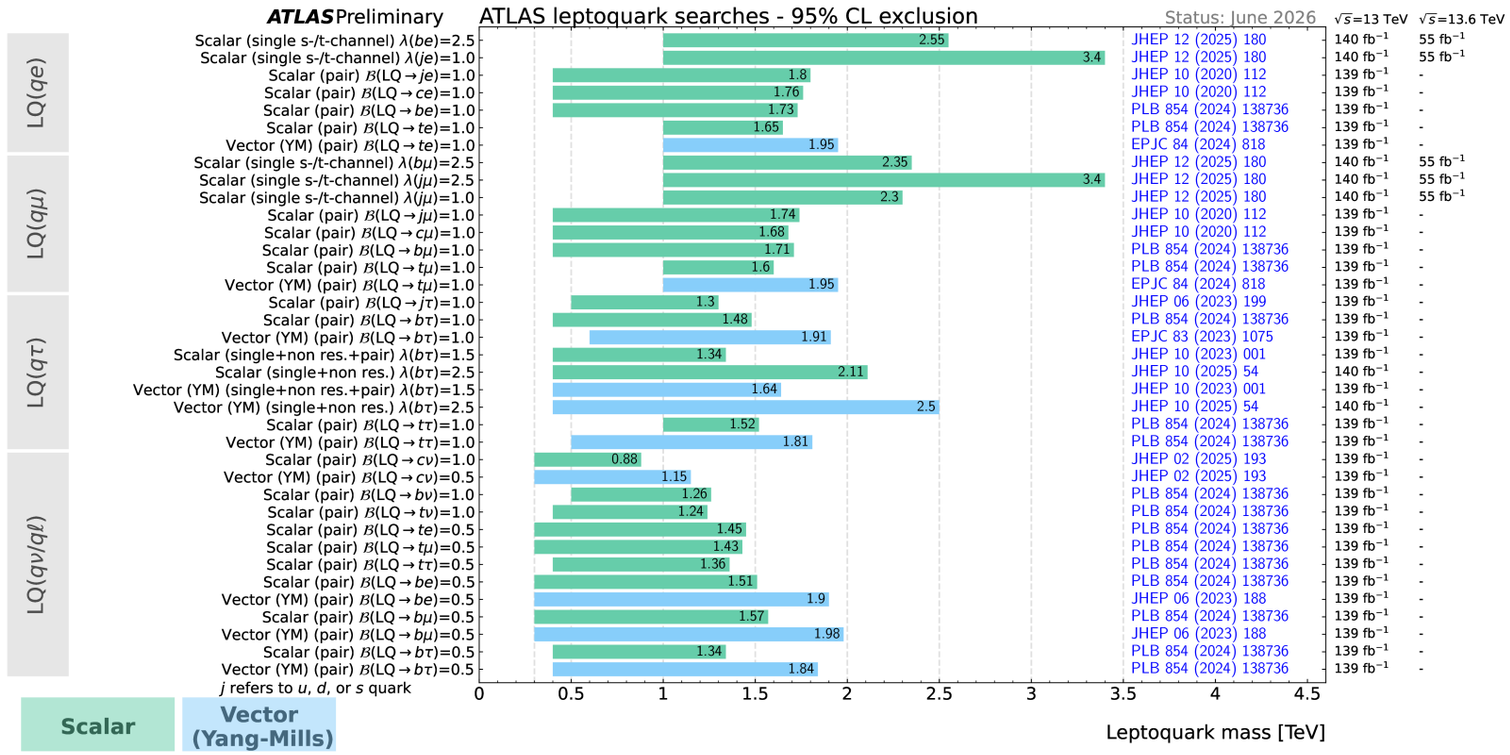
- carry both lepton & baryon quantum numbers
- scalars or vectors
- carry color & fractional electric charge

Motivated naturally in GUT frameworks, composite models where quarks and leptons share substructure, technicolor, RPV SUSY. Interesting in addressing flavour anomalies.

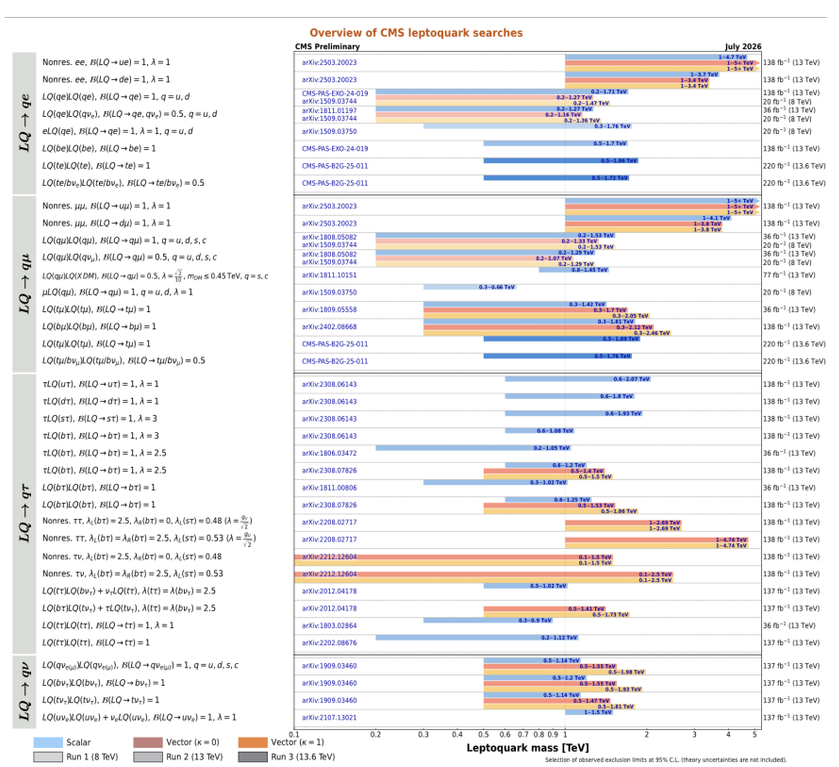


Experimental signature: quark+lepton pair (single production) or di-quark+di-lepton (pair-production).

ATLAS & CMS have probed LQ masses of up to 3.5 TeV (single) & 2.5 TeV (pair-production).



https://cms-summary-searches.docs.cern.ch/lq_bar/



Pair-production of LeptoQuarks ($t\ell$ or $b\nu_\ell$)

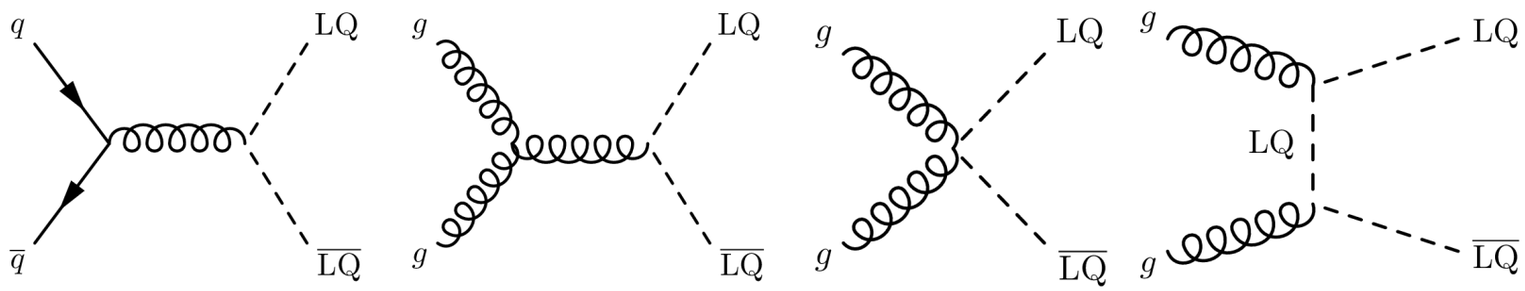
CMS-PAS-B2G-25-011

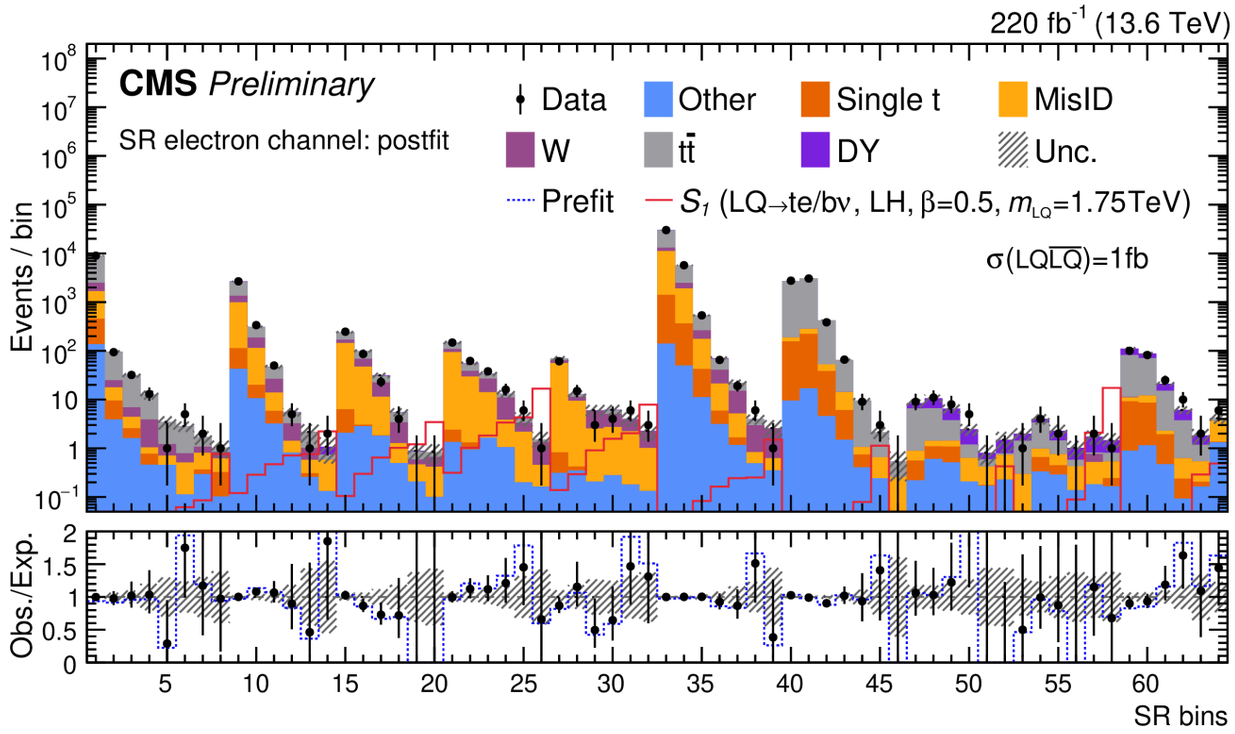
Run-3 result

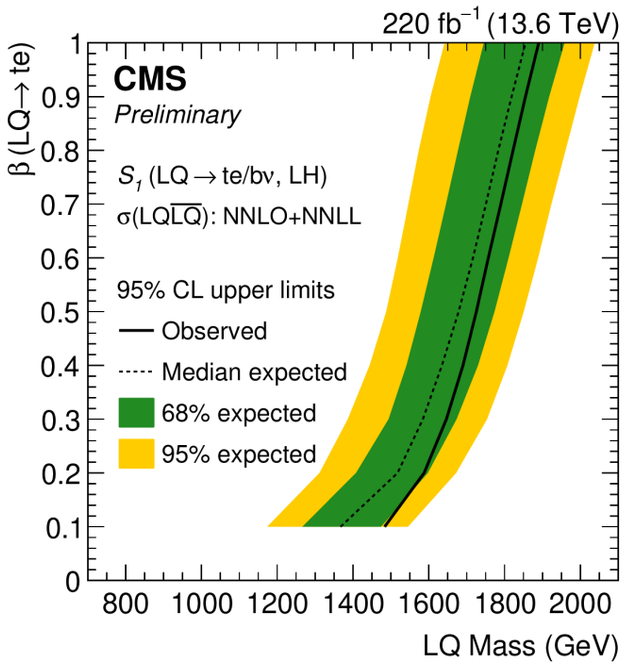
Analysis targets **couplings between 3rd generation quarks and 1st & 2nd generation leptons** - $t\ell\,t\ell$, $t\ell\,b\nu_\ell$, $b\nu_\ell b\nu_\ell$

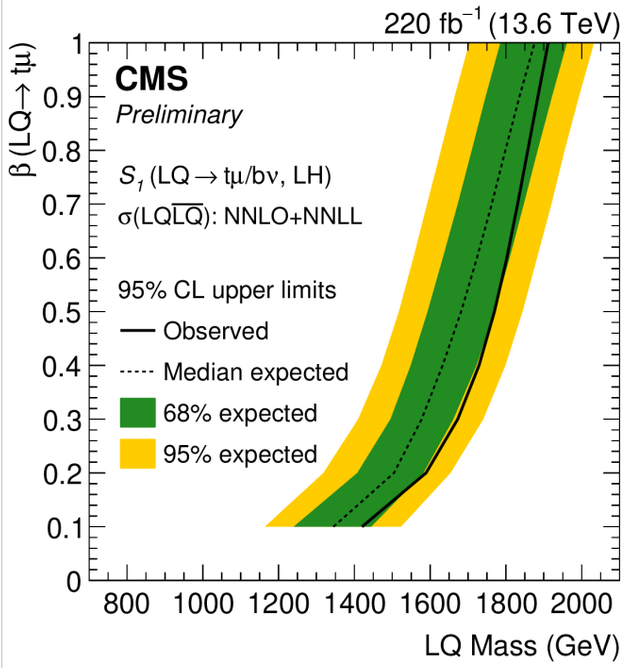
Events with leptons (e & μ) and missing transverse energy along with additional hadronic activity

LO quark- and gluon-initiated pair-production processes









For LH couplings, probed masses up to 1.72 (1.76) TeV for LQs coupling to e (μ).
For RH couplings, probed masses up to 1.86 (1.90) TeV for LQs coupling to e (μ).

Recent searches in *eqeq* CMS-PAS-EXO-24-019 , lepton induced CMS-PAS-EXO-24-005

Phys. Lett. B 882 (2026) 141033

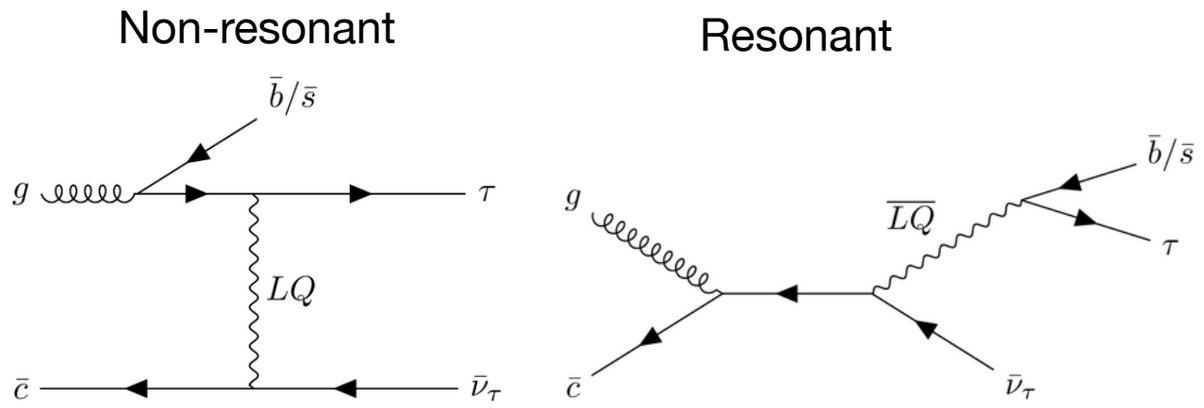
Search for LQ with τ and MET

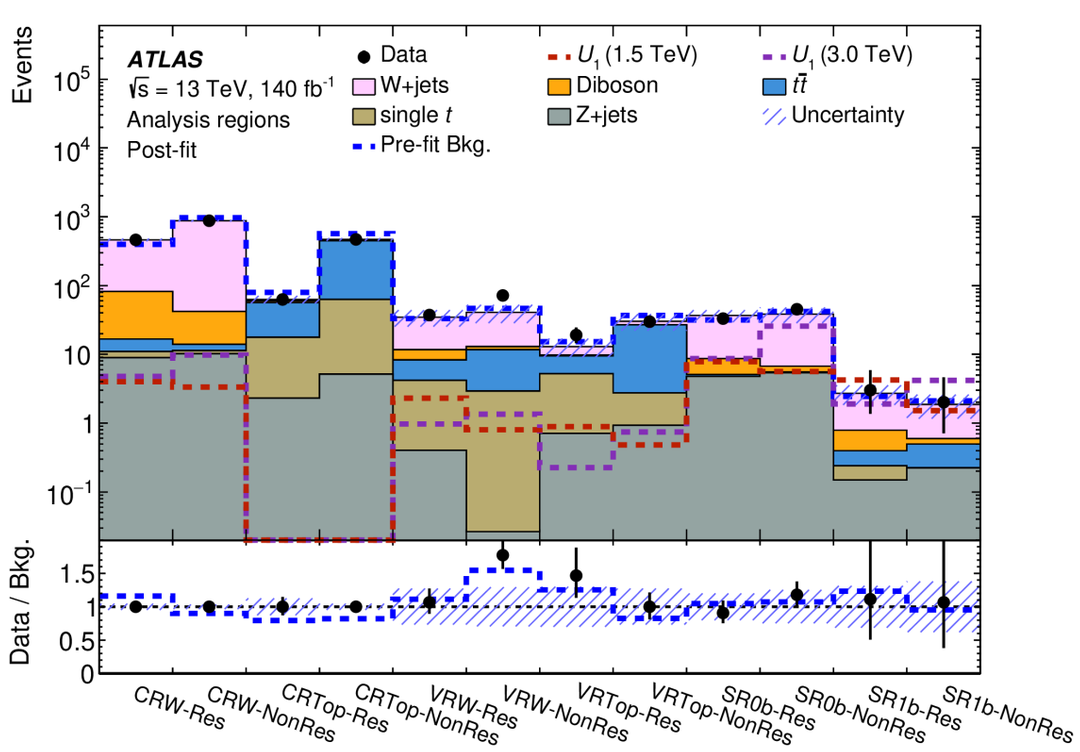
First ATLAS LQ search in τν+b final state

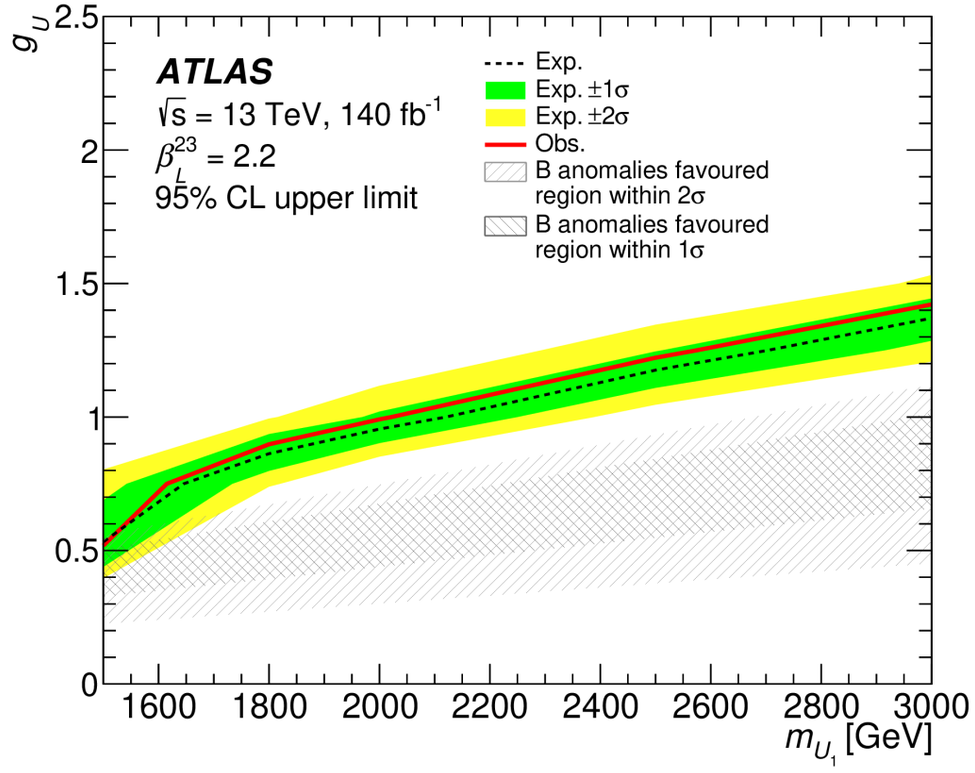
Motivated by explanation to the $R(D(*))$ anomaly via a non-zero $c\nu$ coupling (otherwise flavor-suppressed in SM).

Analysis targets non-resonant t-channel (high mass) & resonant (low-mass) production, in events split by 0 or 1 b-jet.

Requires a high-pT τ_h and large MET.





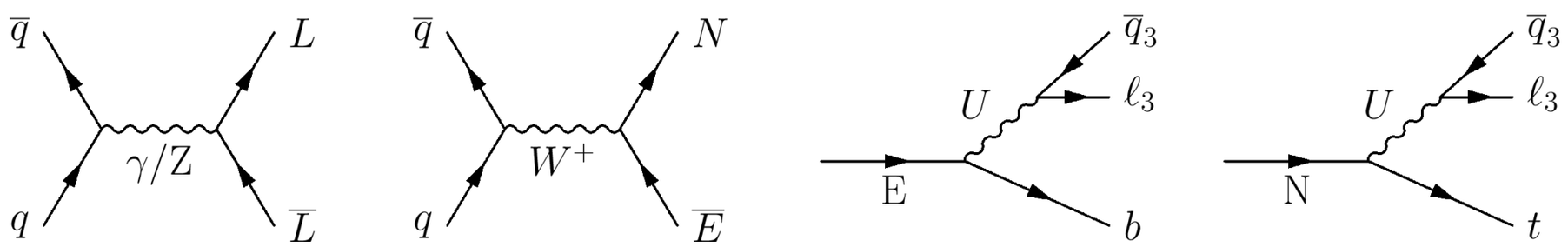


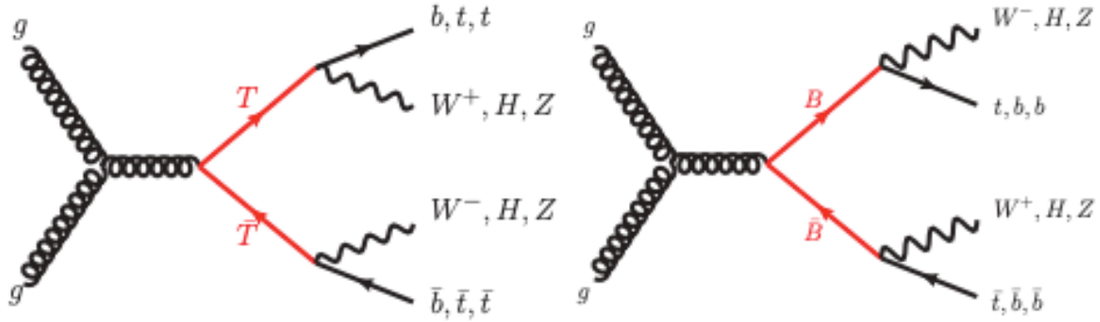
Probes the parameter space **at high β^{23}_L values**, not covered by the previous $\tau\tau$ searches.

Upper limits are established on the $U1$ vector-LQ couplings for masses between 1.5 TeV and 3.0 TeV.

Vector-like quarks & Vector-like leptons

- Vector-like fermions arise in composite Higgs models (Higgs as pseudo-Nambu–Goldstone boson), string theory, large extra dimensions, and weak-scale SUSY
- Not constrained by SM precision measurements as bare mass terms are allowed.
- Potentially address the hierarchy & fine-tuning problem by acting as top-quark partners





- VLLs - colour-singlet fermions, L = (ν'_τ, τ'), rich decay $\nu'_\tau \rightarrow W\tau$; $\tau' \rightarrow Z\tau$ or $H\tau$
- VLQs - colored fermions with spin-half & some may have non-SM isospins
  - Singlets: T (charge 2/3), B (charge −1/3)
  - Doublets: ($X_{5/3}$, T), (T, B), (B, $Y_{-4/3}$)
  - Triplets: (X, T, B) or (T, B, Y)
- Each VLQ decays via W, Z, or H + 3rd generation quark → enormous variety of final states

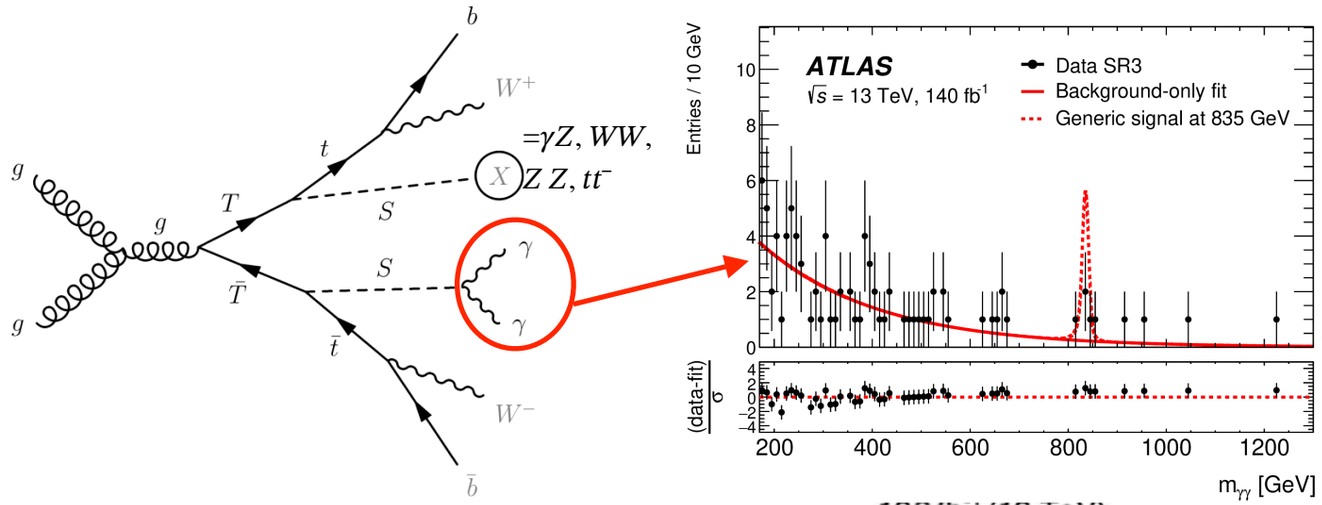
Exotic VLQ decays T → St

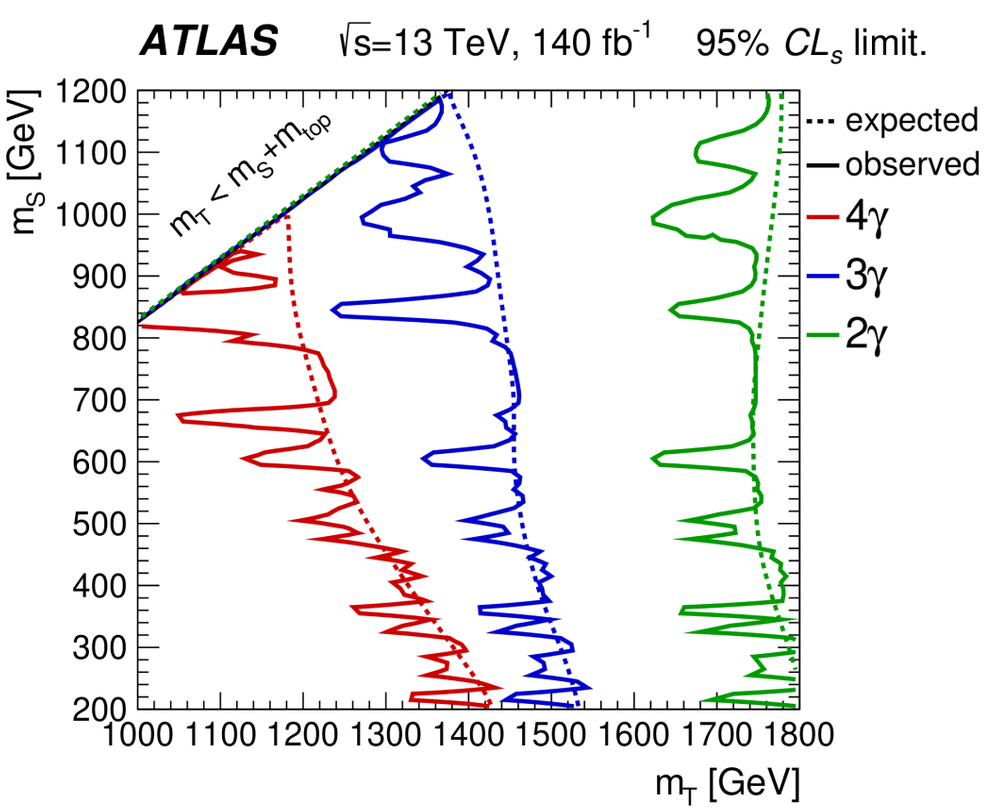
CERN-EP-2026-225
CMS-PAS-B2G-24-016

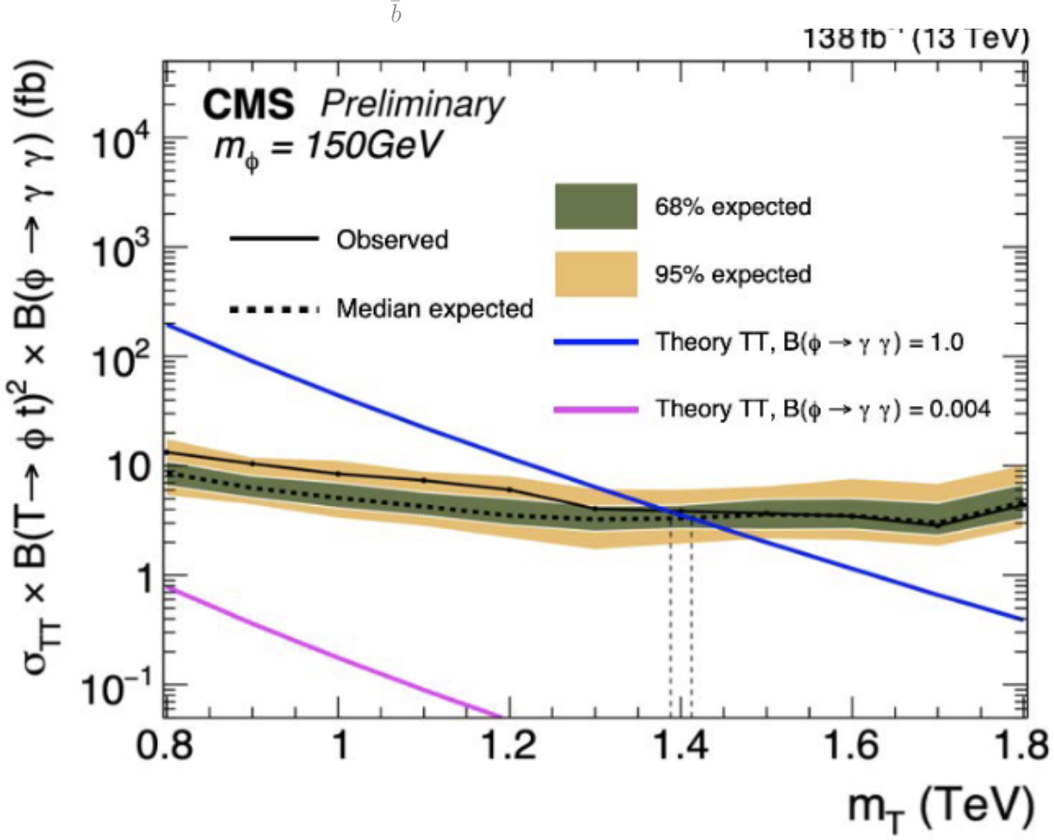
Search for VLQs arising as a consequence of compositeness motivated potential existence of additional exotic scalars or pseudoscalars, called *S* or Φ. First search at LHC targeting T →t Φ(γ γ).

One Φ→ γ γ (clean signature)
Other Φ can decay to: Zγ, ZZ, WW, γγ, tt
Uses diphoton events with b-jets ≥ 2, high MET and visible pT, $m_{\gamma\gamma}$>150 GeV

Look for an excess in $m_{\gamma\gamma}$ spectrum.







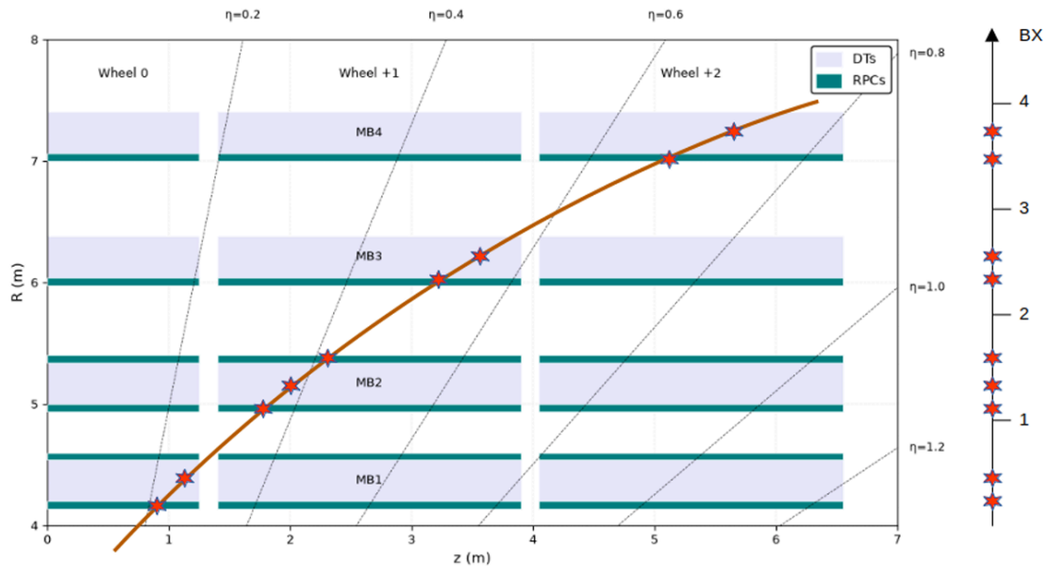
Vector-like Top quarks masses less than up 1.6 TeV are excluded for all S masses assuming for 100% S→2γ.

VLLs with multileptons (arXiv:2508.19778), VLQs with lepton+jets (arXiv:2605.28538), Heavy top quark X5/3 (CMS-PAS-B2G-24-005), Vector-like T → tH(→ WW) (CMS-B2G-24-020), B2G-24-013 (VLQ B -> tW)

Phys. Lett. B 878 (2026) 140498

Search for Heavy Stable Charged Particles (HSCPs)

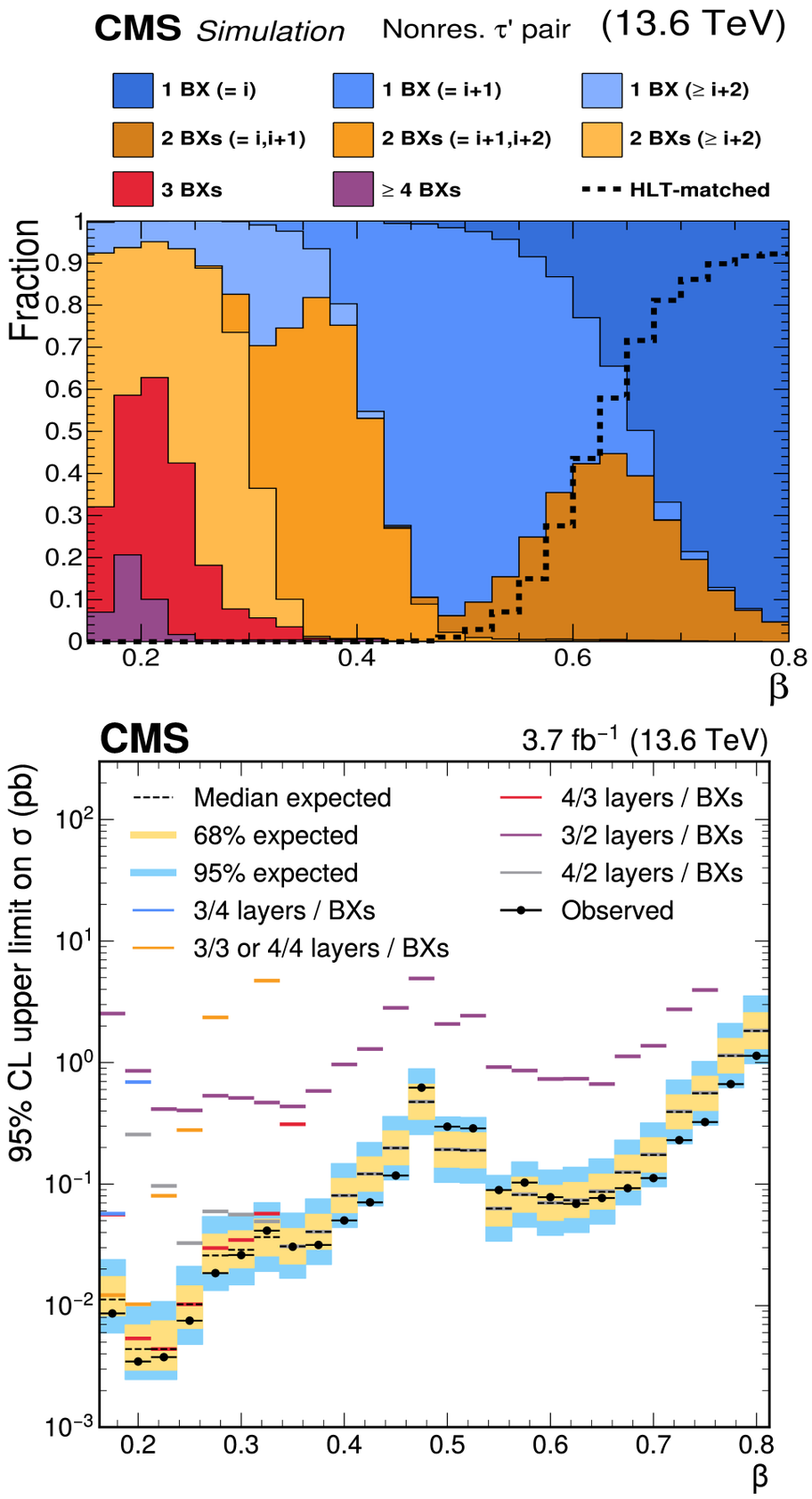
HSCPs - massive charged particles with long lifetime, moving slowly resulting in large ionization energy losses → can produce stubs in muon chambers over several bunch crossings : missed by standard triggers.



40 MHz scouting demonstrator data: provides reduced L1 muon information bypassing trigger acceptance requirement.

Upper limits as low as 3.5 fb lepton-like charged particles with $|\eta| < 0.83$ and $pT > 500$ GeV.

Extends the sensitivity to HSCPs as slow as β= 0.15 since - proof of concept for L1 trigger data scouting system and complementarity to existing searches.

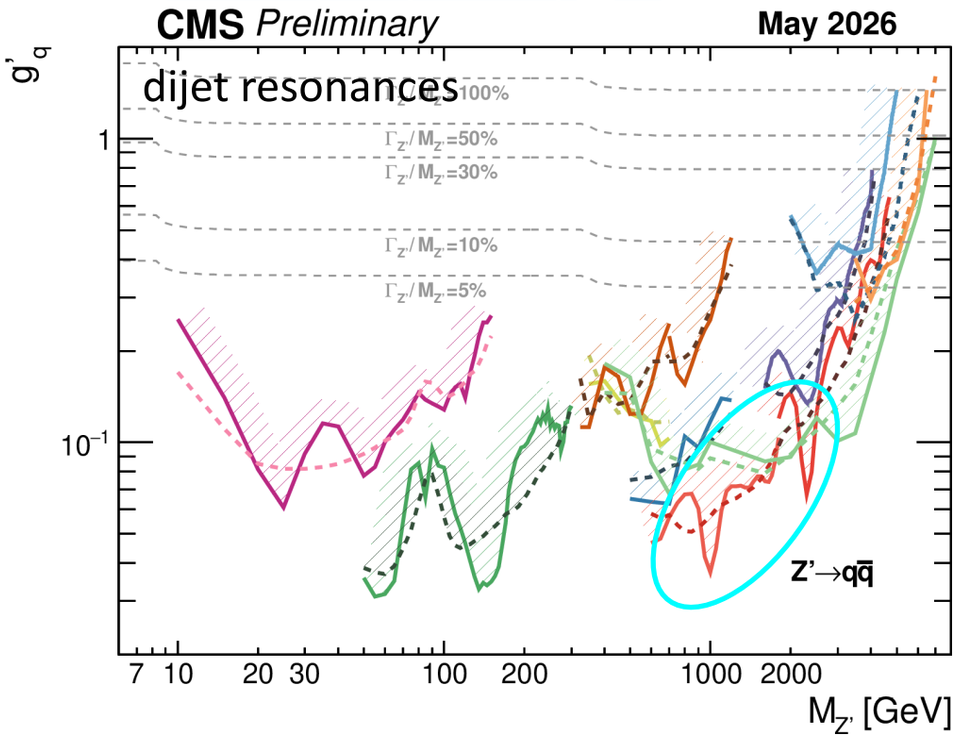


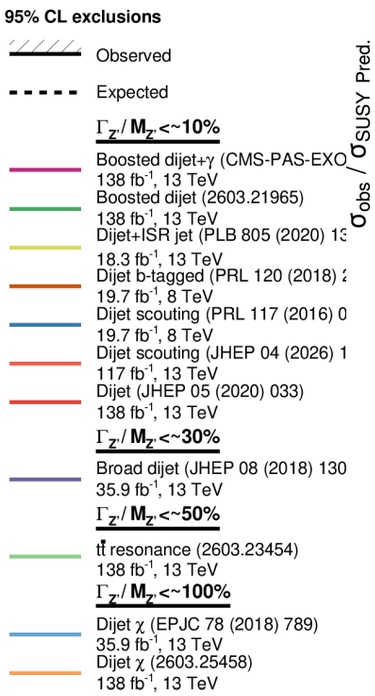
More results using scouting or parked or pileup data

Testing and benchmarking new ideas towards HL-LHC

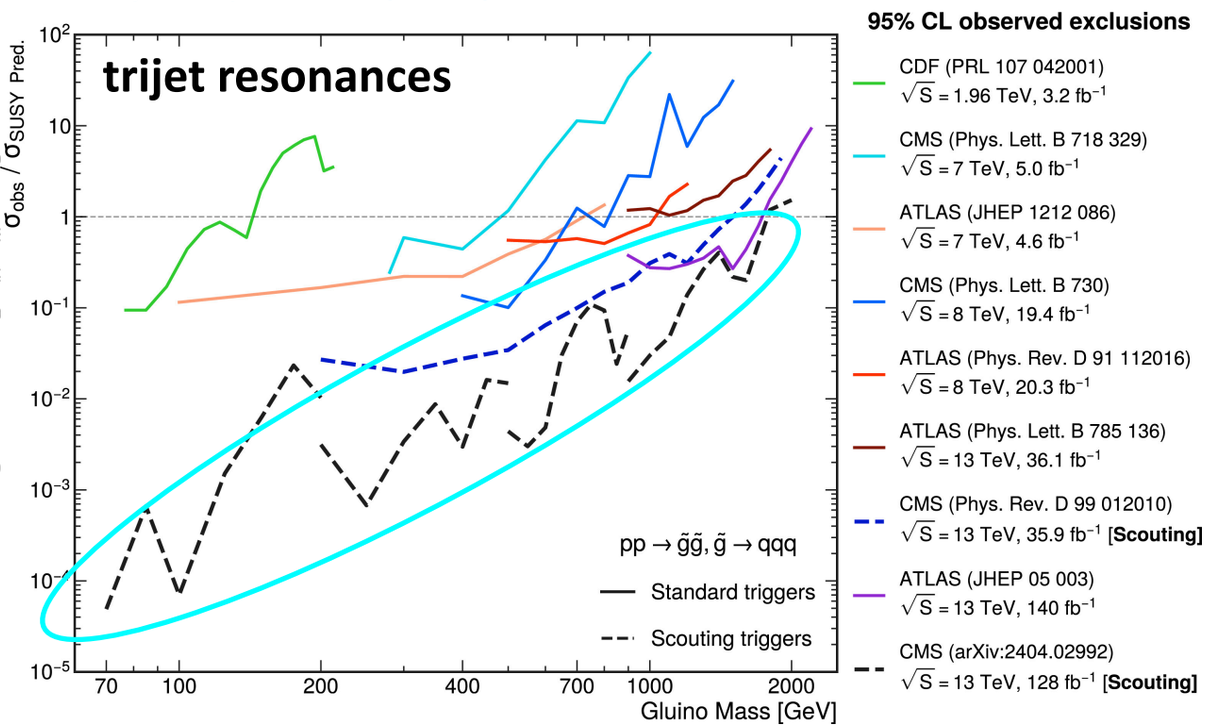
IISER PUNE

PRL 133 (2024) 201803) & ref



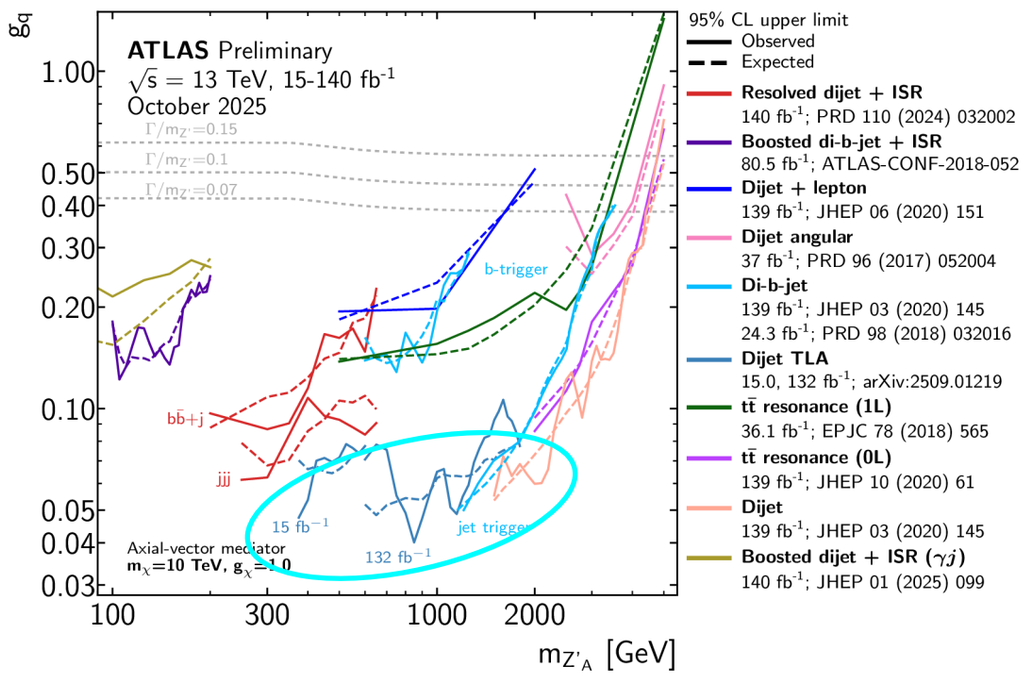


Phys. Rept. 1115 (2025) 678 & ref

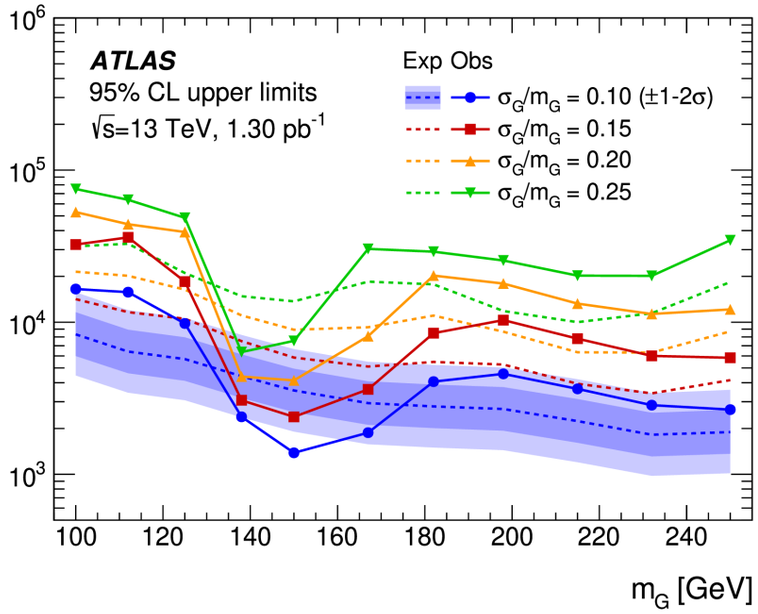


dijet resonances

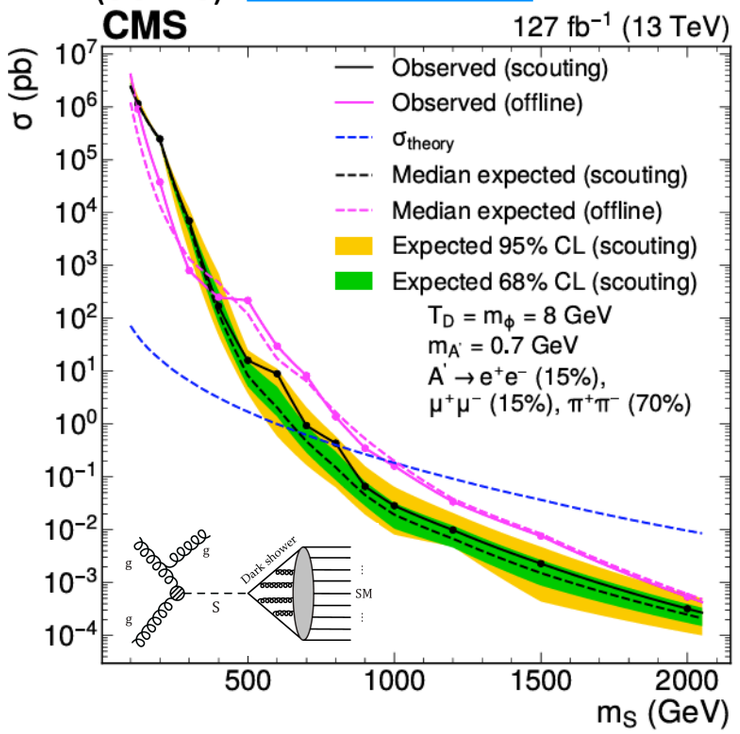
Phys. Rev. D 112 (2025) 092015 & ref



Pileup events from e/μ triggered events arXiv:2606.03222v1



Soft unclustered energy patterns (SUEPs) arXiv:2607.09621



Summary

- No significant excess observed — but many corners of BSM space remain open or only lightly constrained.
- The combination of targeted searches, anomaly detection & global fits is closing blind spots systematically.
- Run 3 brings us ~300 fb^{-1} at 13.6 TeV & HL-LHC > ~3000 fb^{-1} will push sensitivity by another order of magnitude.

The question is not whether BSM physics exists — but whether we are bold enough to look in the right places. We are checking every corner !

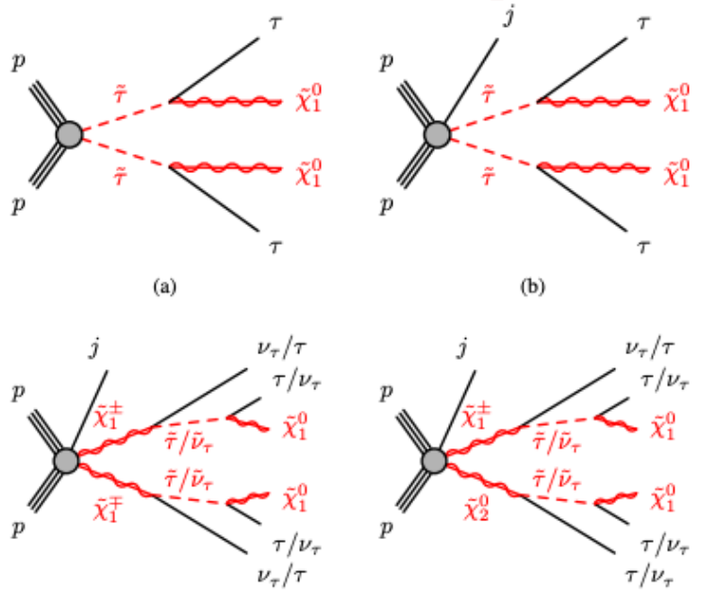
arXiv:2609.37215

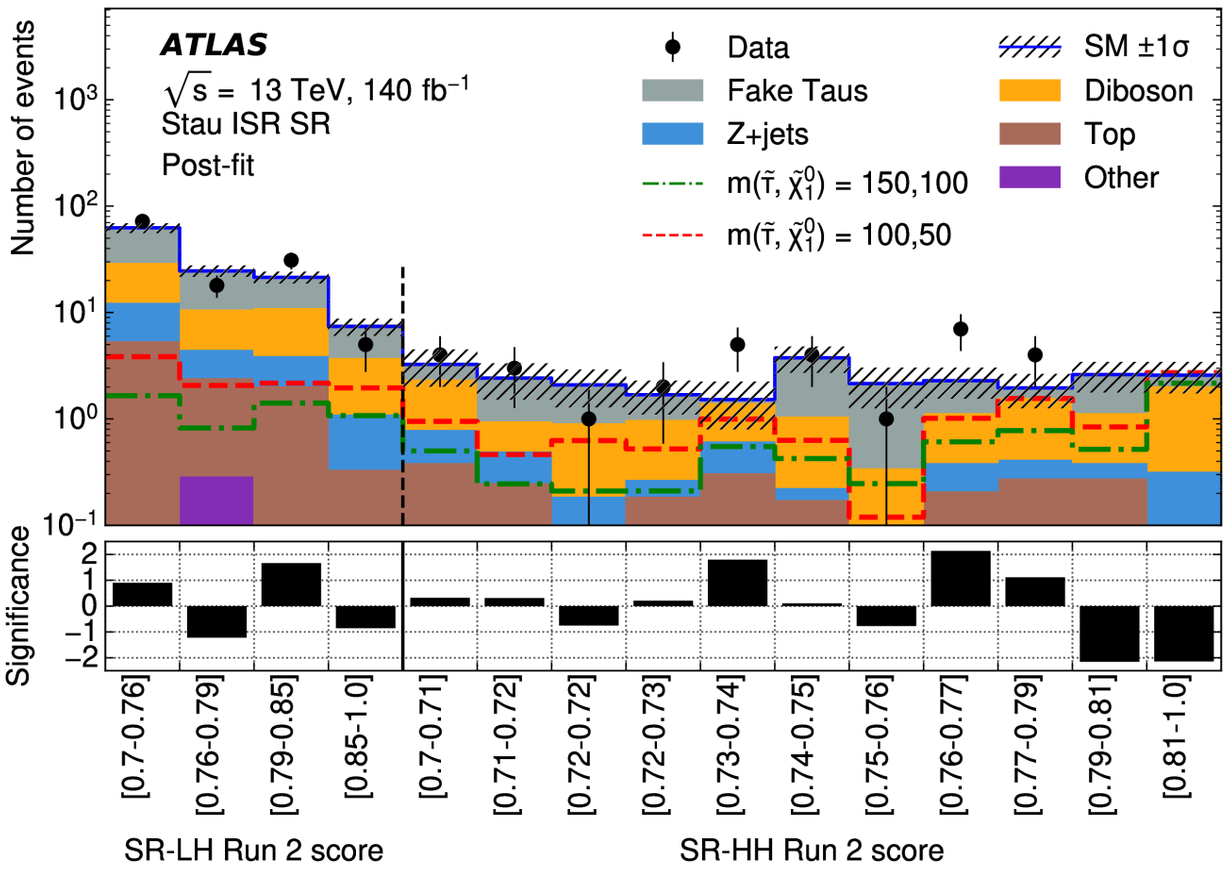
Compressed EWK SUSY production with τ-leptons

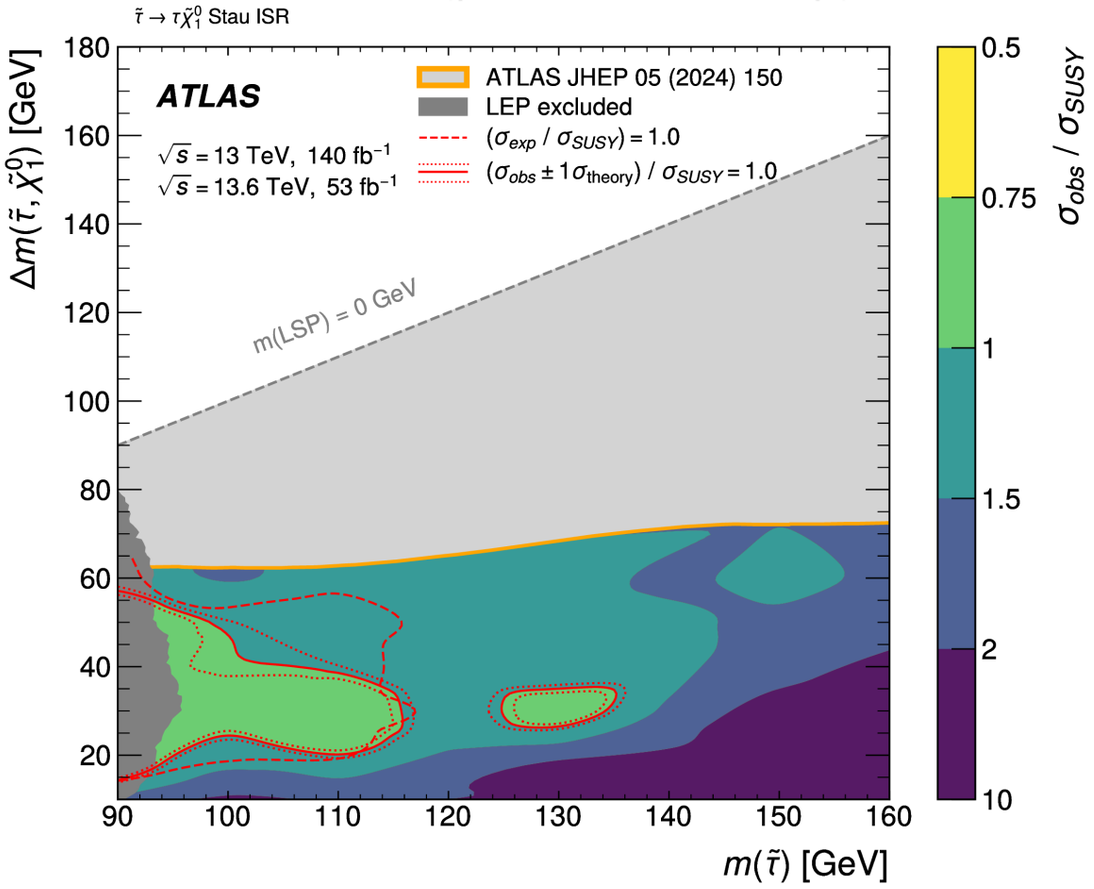
Targets ΔM (NLSP, LSP) < 50 GeV

- Soft e (μ), pT > 4.5 GeV (3 GeV), τ pT > 20 GeV
- with or without an ISR jet
- large missing transverse momentum

Uses a parameterised neural network.







In the individual stau ISR channel, τ-sleptons with masses up to 115 GeV are excluded for ΔM=30 GeV.

Summary - up to ~300 GeV electroweakinos have been probed in small ΔM scenarios (~1 TeV otherwise).