Non-resonant searches at the TeV scale

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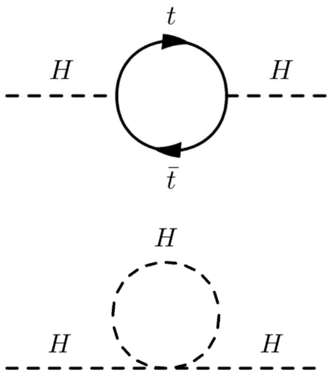
on behalf of the ATLAS and CMS collaborations

LHCP – June 4th 2024

Introduction

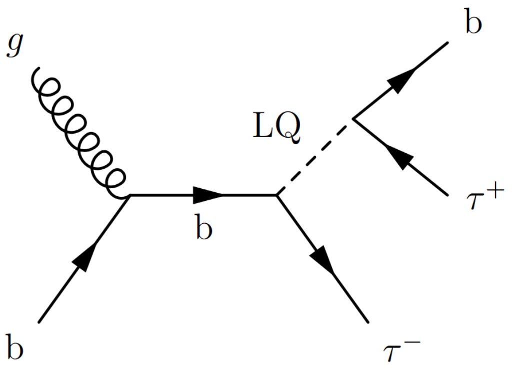


- **Many unresolved questions that the Standard Model cannot answer** (eg. dark matter, Higgs mass fine tuning, baryogenesis, neutrino masses, …)
- **Wide range of new physics searches are conducted at the LHC**, such as for new resonances (Louis' talk), Extended Higgs sector (Shigeki's talk), Long-lived particles (Guglielmo's talk), precision measurements (Andrew's talk)
- Searches that are covered in this talk:
  - **New symmetries giving rise to new particles, eg. Leptoquarks, Supersymmetry, Heavy Neutrinos**
  - **Extra dimensions leading to broad excesses or periodic signals (clockwork), or Quantum Black Holes**
- Can only present a few results ☹ Links to all **CMS Results**, **ATLAS Results**
- Non-resonant Higgs boson pair production not covered in this talk (→ John's talk tomorrow)

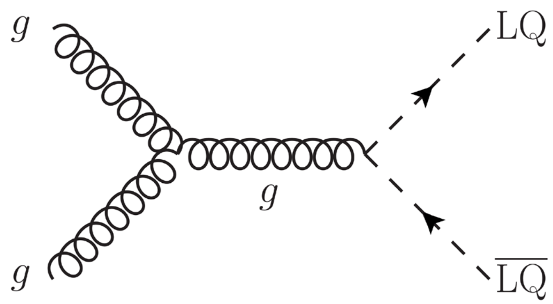
Leptoquarks

- In the SM there are striking similarities between quark and lepton families, but no explanation for it
- **Could there be a deeper symmetry between leptons and quarks?**
- Featured in models like Grand Unified Theories, compositeness, technicolor models, superstrings, R-violating supersymmetry, ...
- **Hypothetical color-triplet bosons carrying both a baryon and a lepton number, with fractional charge**
- Decay to a lepton (or neutrino) and a quark
- Parameters: λ_{LQ} (coupling), β (BR of LQ to charged lepton+quark), **LQ mass**, κ (vector LQs, hep-ph/9610408)
- **Many production modes, for example:**

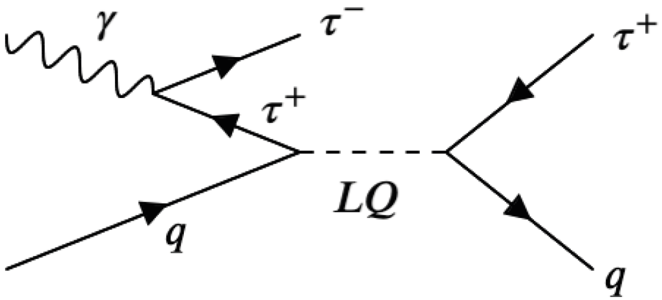
Quark-gluon fusion



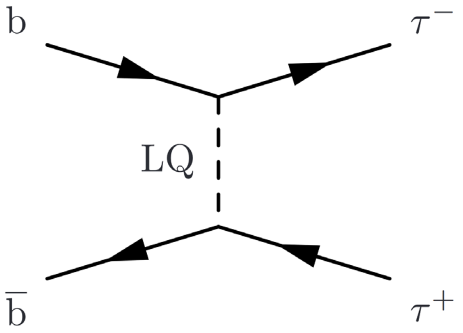
Pair production



τ-quark collision



Non-resonant t-channel



Leptoquarks decaying to μ + b

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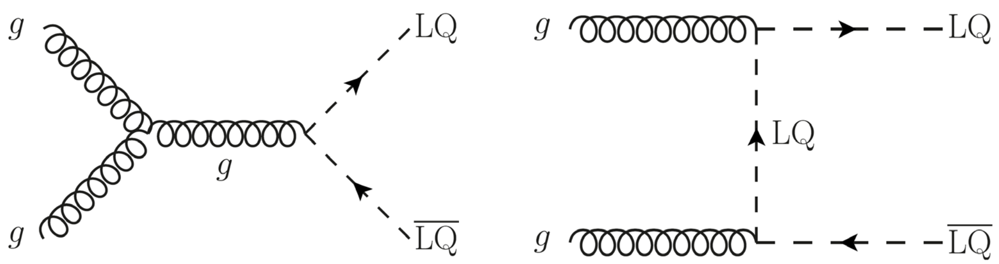
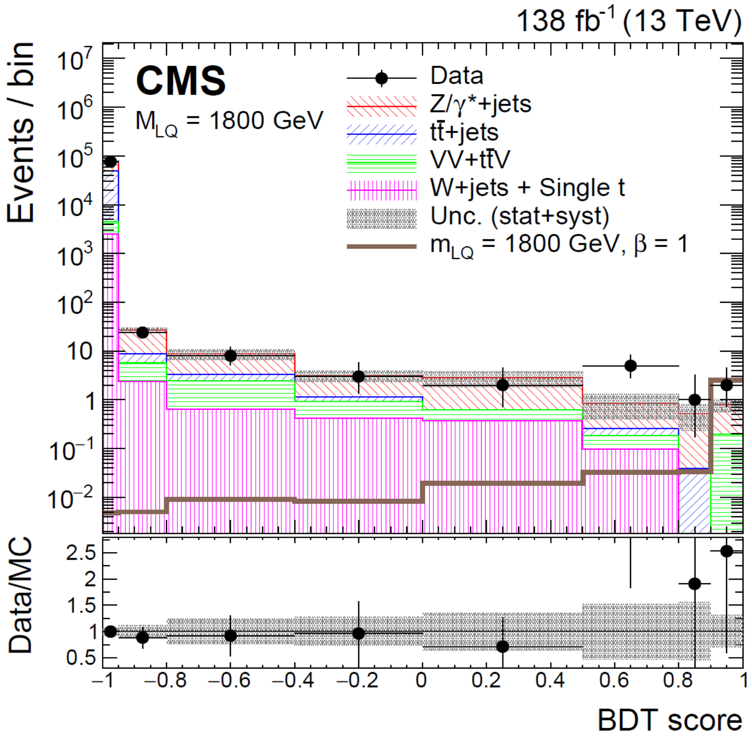
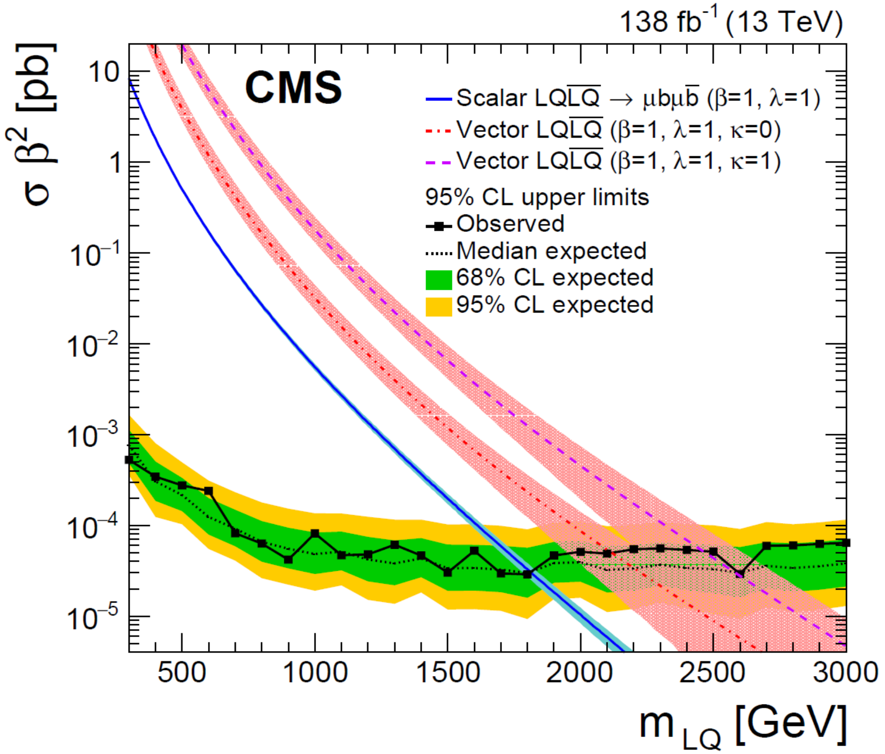
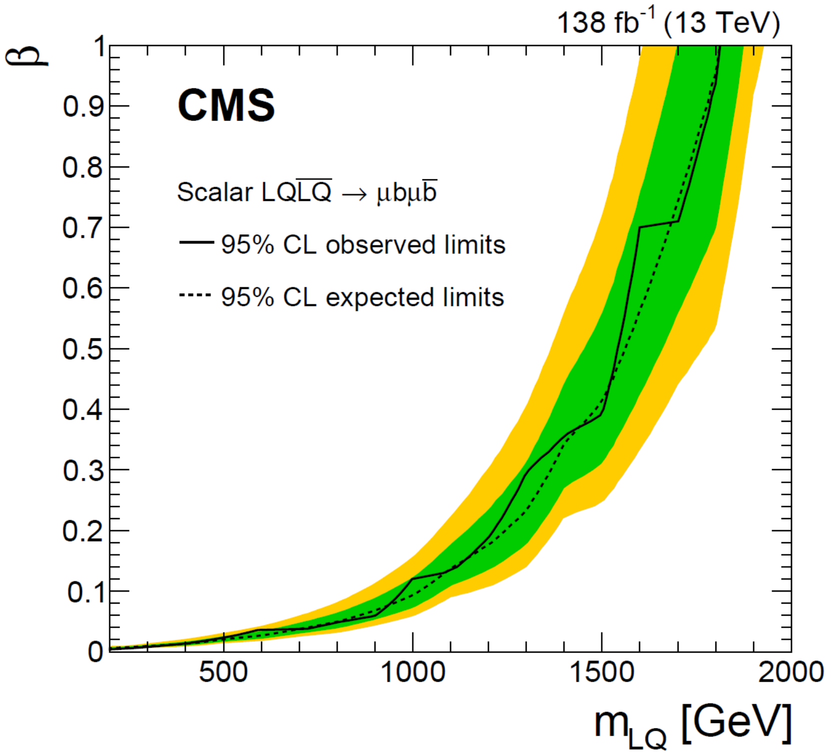


- Only **LQ pair production** considered
- Final state: Two muons (p_T > 53 GeV, $m_{\mu\mu}$>250 GeV), two jets (p_T > 50 GeV) among which at least one is b-tagged
- Two control regions for background estimation (Z, tt; VV, ttV)

- **BDTs** trained on kinematic variables of the muons and jets to enrich a selection in signal events
- BDT cut optimized for each LQ mass hypothesis. **No excess found, but strong limits obtained!**







Leptoquarks via τ + quark collisions

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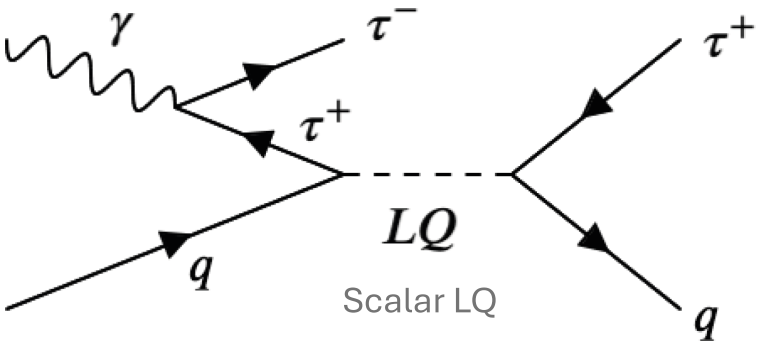
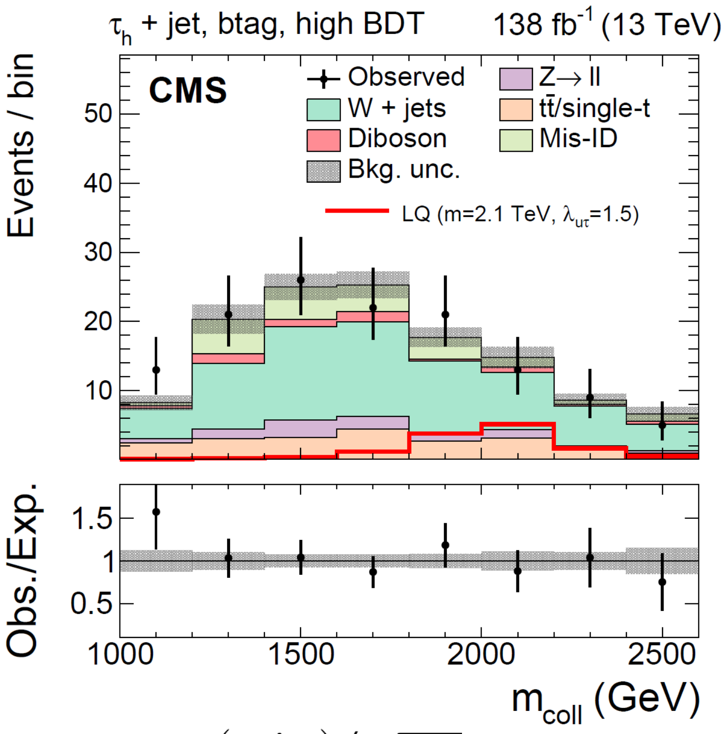


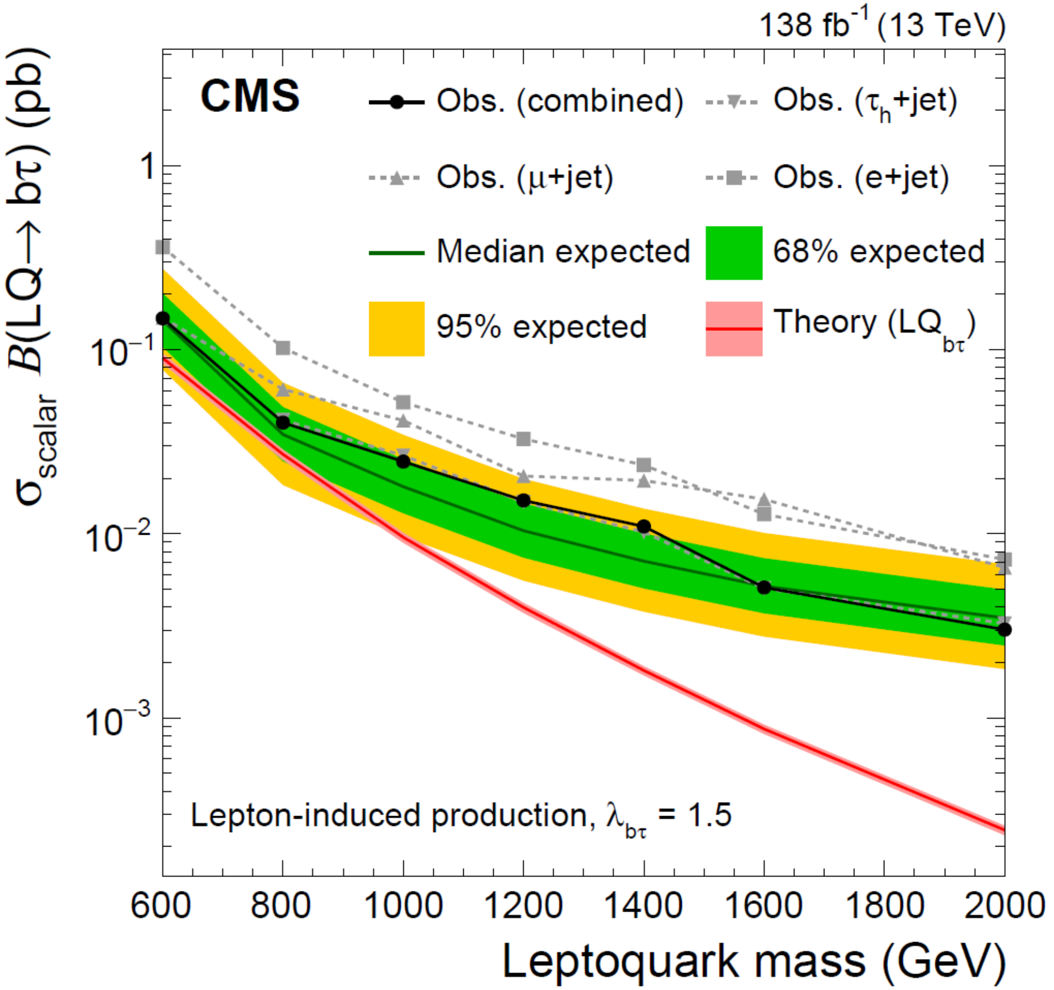
- **Novel production mode**, made possible by advancements in the lepton and photon density functions of the proton
- Exploring three channels: hadronic **τ + jet**, **e + jet**, **μ + jet**, further separated if jet is **b-tagged or not** (different LQ decays)



$$m_{\text{coll}} = m_{\text{vis}}(\tau,\text{jet})/\sqrt{x_{\text{vis}}}$$

$$x_{\text{vis}} = p_T^{\text{vis}}(\tau)/(p_T^{\text{vis}}(\tau) + p_T^{\text{invis}}(\tau))$$

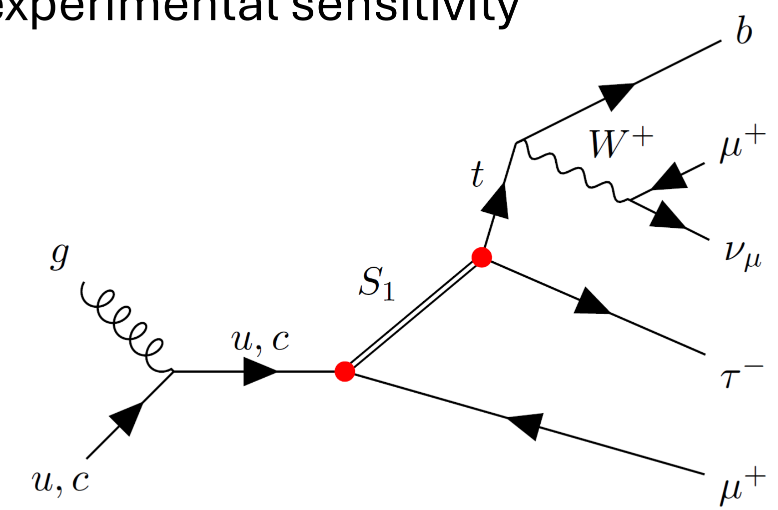
- **BDTs trained in each channel** to separate signal from background
- Categories based on the BDT score → **7 signal-enriched categories**
- Final discriminant: **collinear mass**
- W+jets background normalization estimated from **control region** that is fitted simultaneously

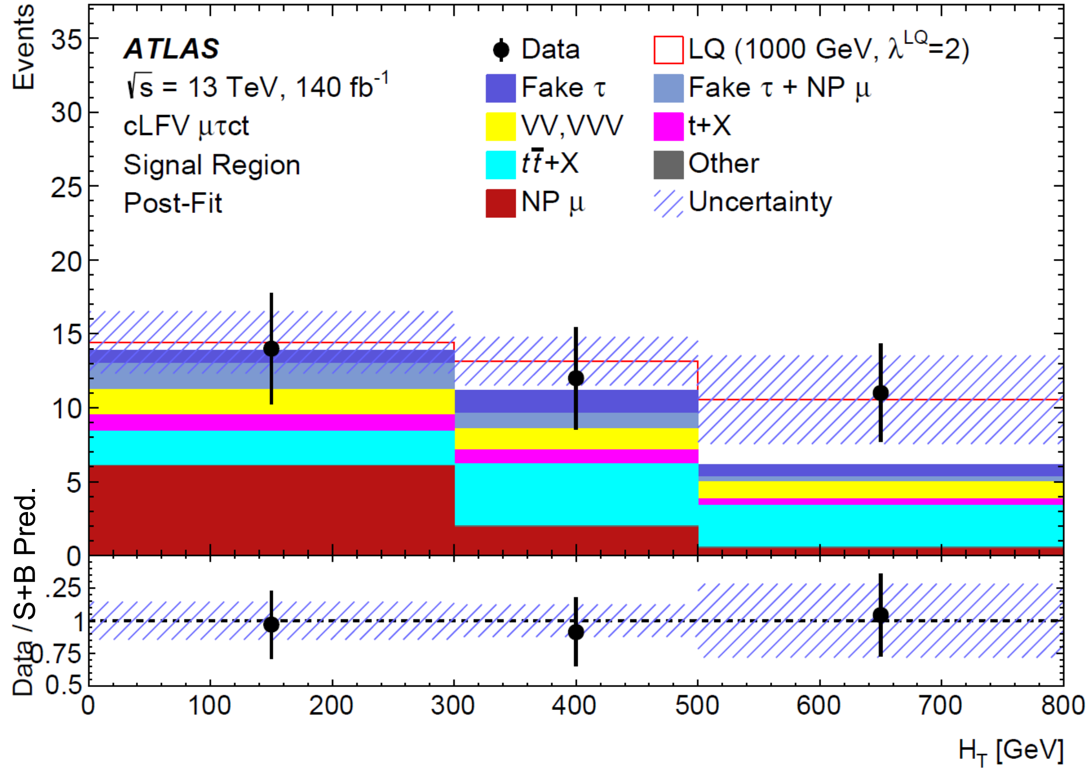


Leptoquarks via charged-lepton-flavor violation 2403.06742

- SM-predicted charged-lepton-flavor violation (cLFV) rates well below experimental sensitivity
- Leptoquarks are a candidate for introducing BSM cLFV interactions, ie. in the **Scalar Leptoquark Model S_1**
- Model introduces couplings between all up-type quarks and all charged leptons (**$\lambda_{t\tau}$ is strongest coupling**)

$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$





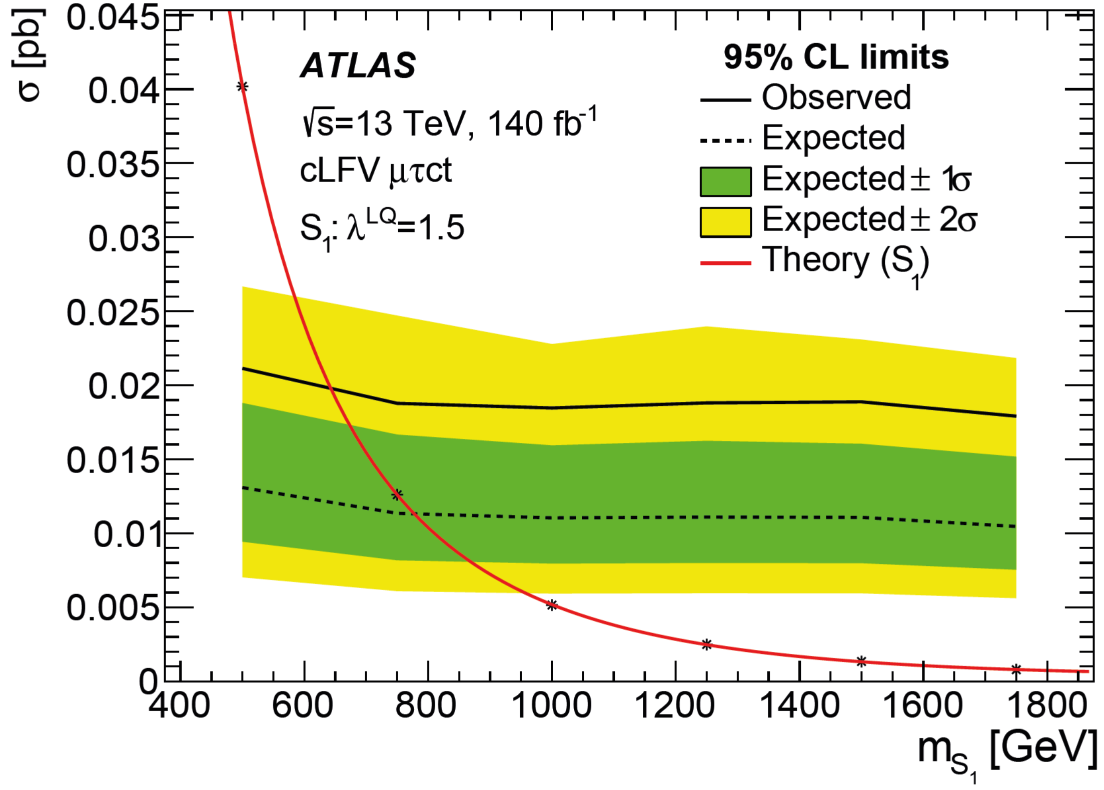
Analysis:

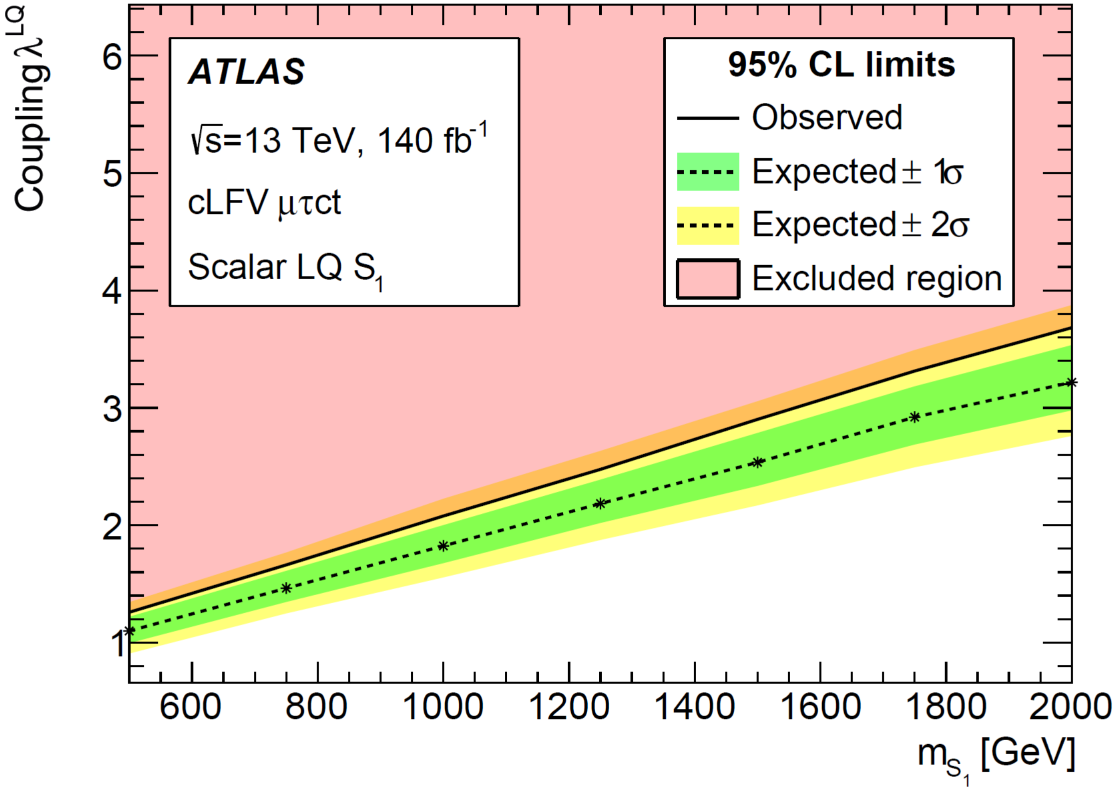
- Final state: 2 μ (same-sign), 1 τ_{had}, ≥ 1 jet (including exactly one b-jet)
- Final discriminant: scalar sum of the lepton and jet transverse momenta H_T
- **Slight excess at high H_T bins (~ 1.6σ)** here shown for m_{S_1}=1 TeV and λ^{LQ}=2.0
- Fit includes SR and a CR enriched in ttbar+μ events

Leptoquarks via charged-lepton-flavor violation

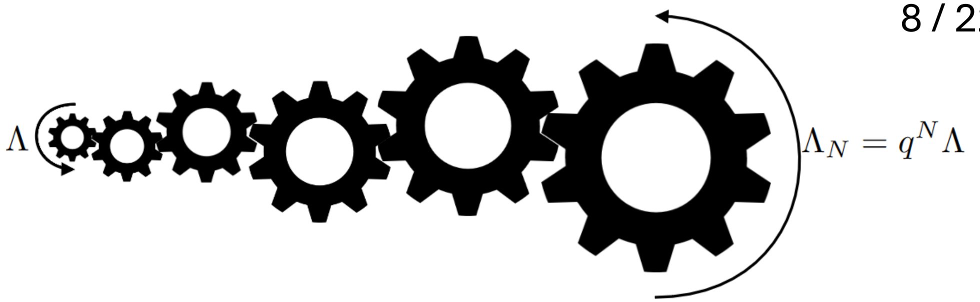
2403.06742

- Excess almost not dependent on the S_1 mass, cross section limits almost flat
- LQ excluded for masses below 620 GeV, assuming λ_{LQ} = 1.5
- Exclusion of coupling values of λ_{LQ} = 1.3 to 3.7 for LQ masses between 0.5 and 2.0 TeV

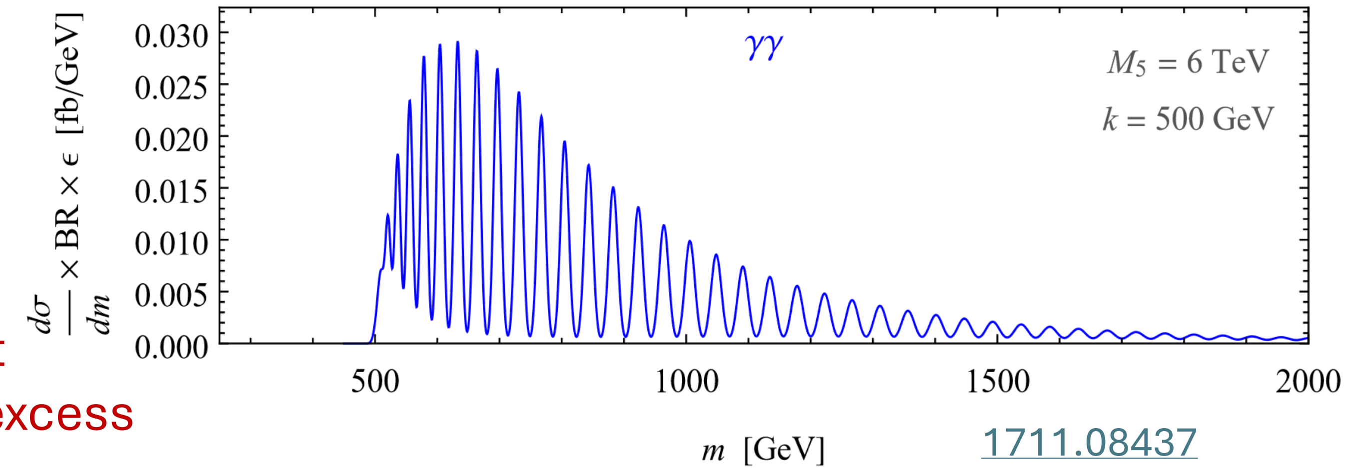




Periodic Signals (Clockwork)



- **Clockwork mechanism can generate large hierarchies with only $\mathcal{O}(1)$ couplings and N fields** 1610.07962
- This concept offers **solutions to hierarchy problems**, such as Higgs boson mass naturalness, why gravity is so weak, or why dark matter is cosmologically stable
- The **clockwork gravity model** assumes extra dimensions and predicts a **narrowly-spaced spectrum of resonances in mass**, such as towers of Kaluza-Klein (KK) gravitons → **periodic signal**
- Mass spacing between signals is a few percent at the onset an falls below 1% at high masses
- **Parameters:** k - onset of the KK graviton spectrum, M_5 - five-dimensional reduced Planck mass
- Signal cross section roughly scales as $\sigma \sim M_5^{-3}$
- Resolution effects can wash out the periodic structure and result in a broad signal shape especially at high masses
- In the **continuum limit**, the KK spacing is so tight that it cannot be resolved anymore → one broad excess

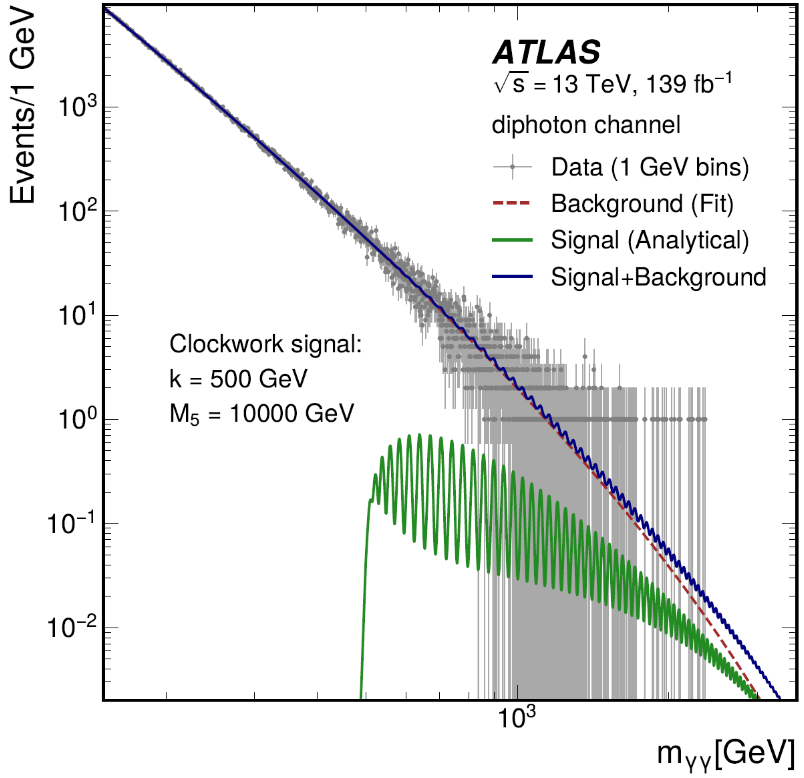


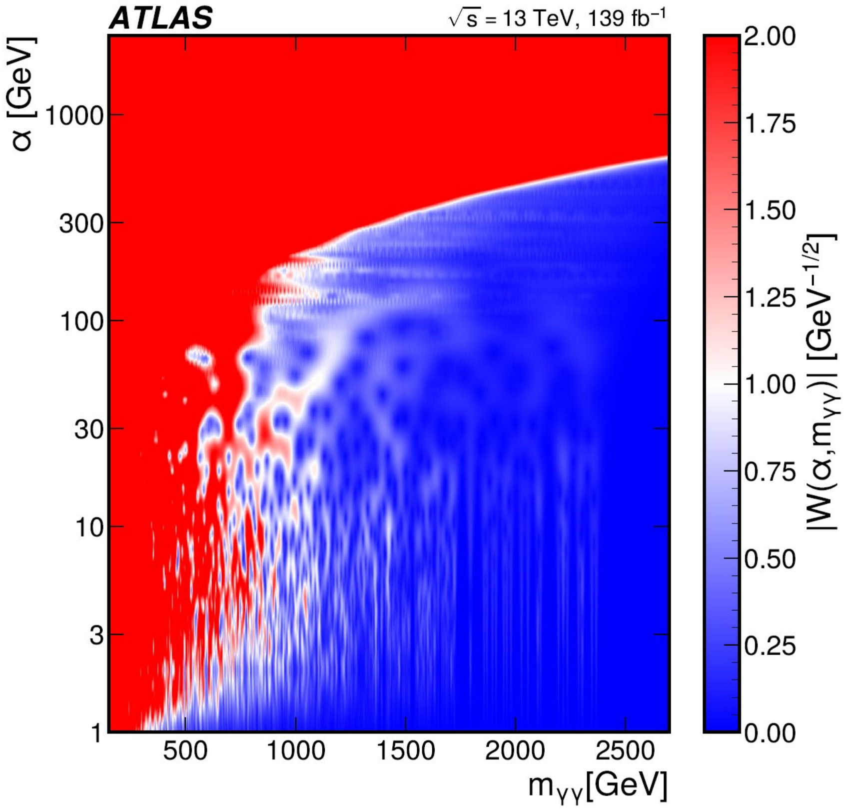
1711.08437

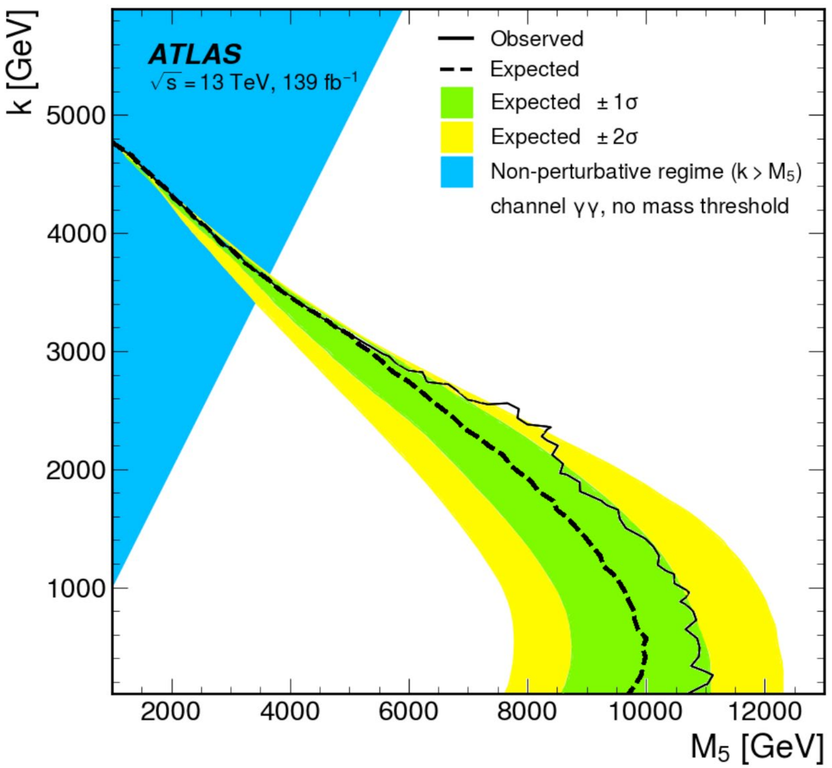
Periodic Signals (Clockwork)

2305.10894

- Search conducted in the invariant mass spectra of **di-photon and di-electron final states**
- **Continuous wavelet transform (CWT)** used to transform the mass spectra into scalograms („image“) of mass vs. frequency. Scaling parameter α either dilates or compresses the signal.
  It is inversely proportional to the frequency (i.e. if α is large, then the signal is „stretched“) .
- **Convolutional neural networks** or **autoencoders** used to search for anomalies („islands“) in the scalogram, but no signal detected in the dataset



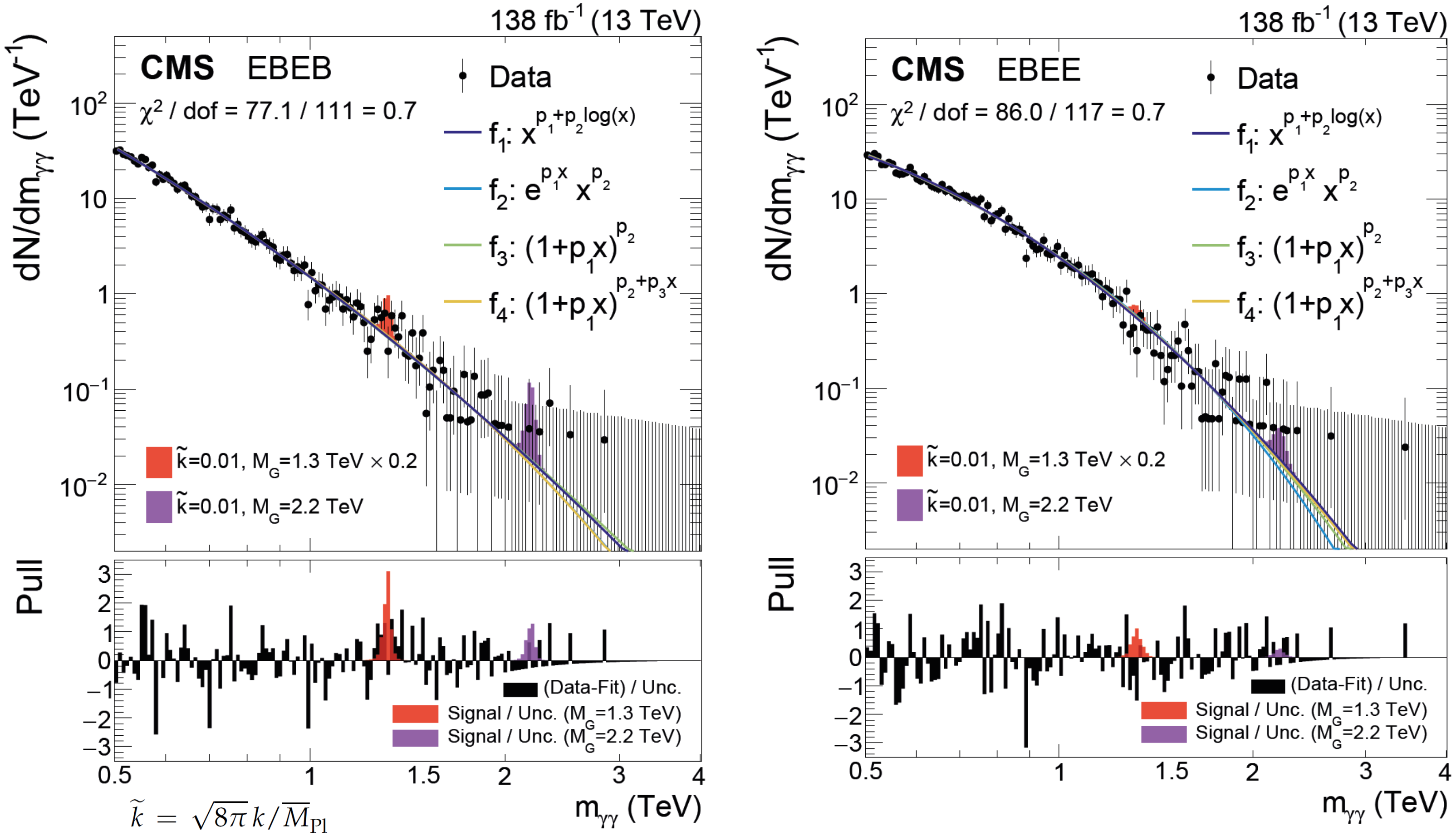




Broad Resonances in Diphoton

2405.09320

- **Arkani-Hamed, Dimopoulos, Dvali (ADD) model** predicts n compactified extra dimensions. Kaluza-Klein modes of the graviton are tightly spaced and result in a broad, non-resonant excess. Interference with the background is considered.
- In the **continuum limit of the clockwork framework**, an infinite tower of very narrow KK graviton modes also leads to a continuous excess in the diphoton mass spectrum. No interference with the background.



- Diphoton trigger p_T > 60-70 GeV. Offline p_T cut > 125 GeV
- **Two categories**:
  - EBEB (both γ in the barrel)
  - EBEE (one barrel, one endcap)
- **Background model**:
  - Sherpa MC reweighted to NNLO
  - Data-driven estimate of misidentified jets
- Fit to **binned $m_{\gamma\gamma}$ distribution**

Broad Resonances in Diphoton 2405.09320

ADD model:

Lower limits on the mass scale M_S [TeV] for three theory conventions:

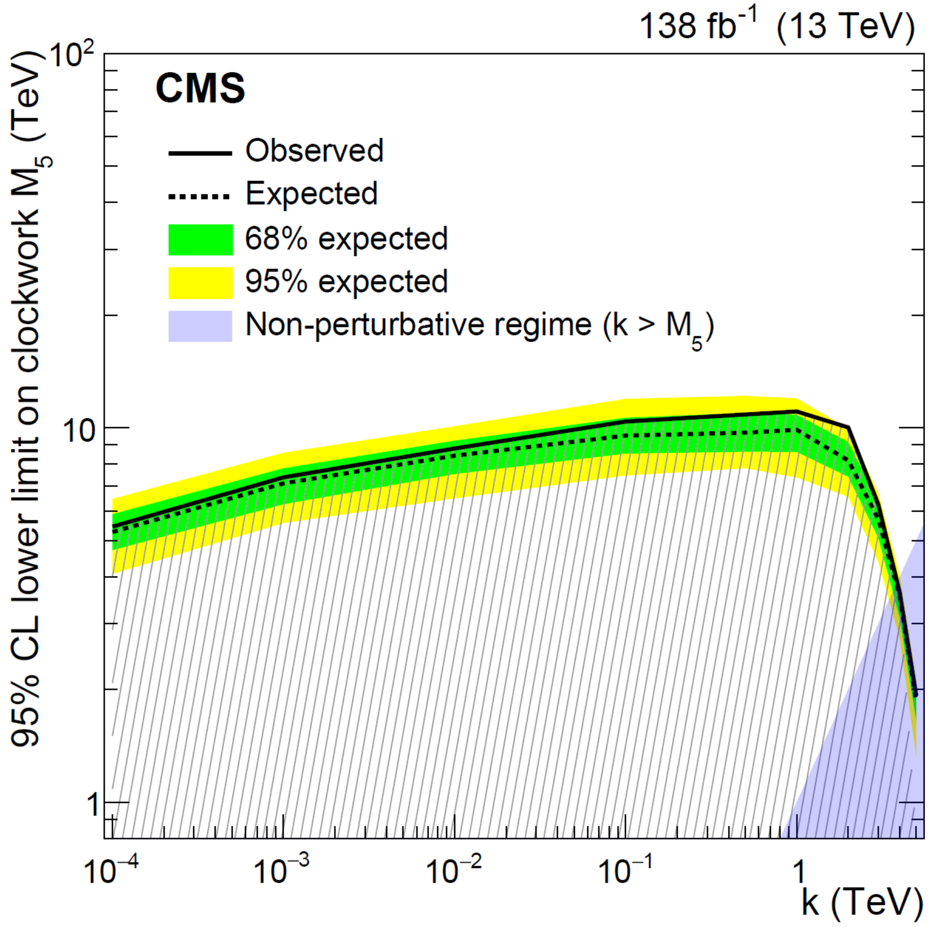
- GRW: Giudice-Rattazzi-Wells hep-ph/9811291
- Hewett: hep-ph/9811356
- HLZ: Han-Lykken-Zhang hep-ph/9811350

Signal:	GRW	Hewett		HLZ				
		negative	positive	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Expected:	$8.7^{+0.7}_{-0.6}$	$7.3^{+0.3}_{-0.3}$	$7.8^{+0.6}_{-0.5}$	$10.3^{+0.8}_{-0.7}$	$8.7^{+0.7}_{-0.6}$	$7.9^{+0.6}_{-0.5}$	$7.3^{+0.6}_{-0.5}$	$6.9^{+0.6}_{-0.5}$
Observed:	9.3	7.1	8.3	11.1	9.3	8.4	7.8	7.4

M_S is the ultraviolet cutoff parameter for the virtual graviton exchange

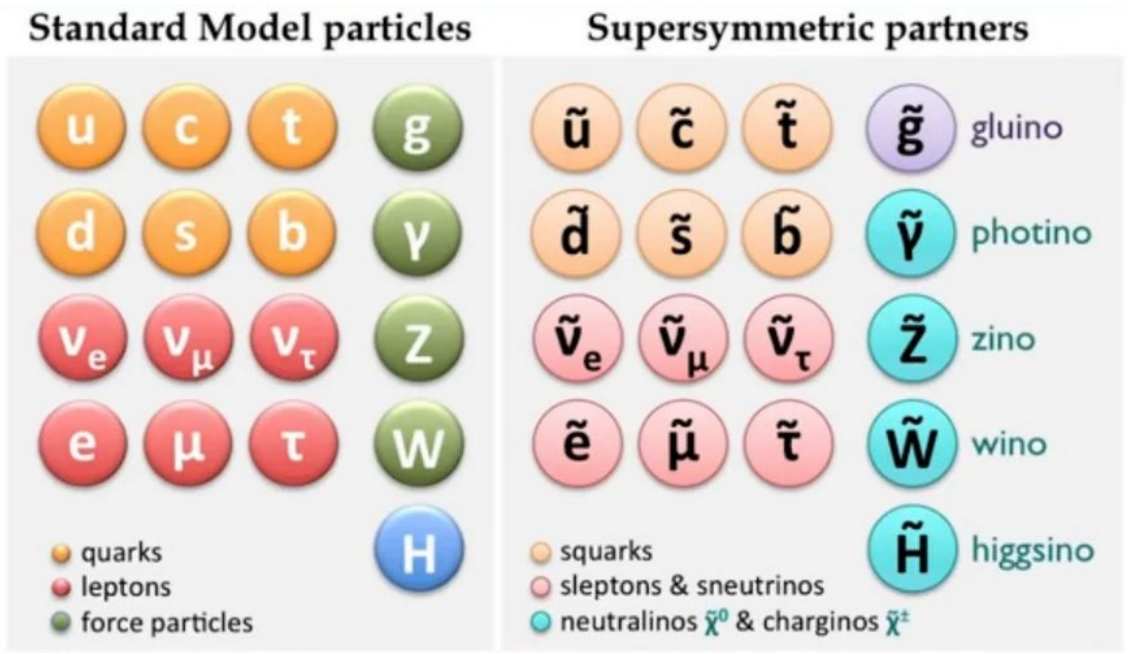
Continous clockwork gravity model: →

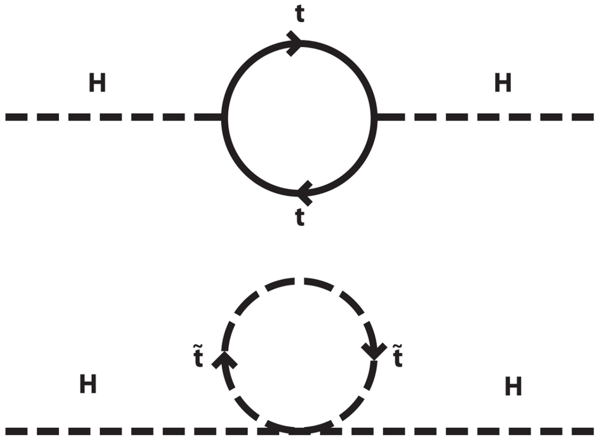
Values of M_5 excluded for k values in the range of 0.2 – 2000 GeV.
Strongest exclusion of M_5 < 11 TeV for k=1 TeV



Supersymmetry

- Fundamental symmetry between fermions (half spin) and bosons (integer spin)
- Can stabilize the Higgs mass up to the Planck scale
- Provides dark matter candidates
- Gauge couplings unify at high energies
- Preserves baryon asymmetry





Sfermion loops cancel divergent corrections to the Higgs boson mass

R-parity:

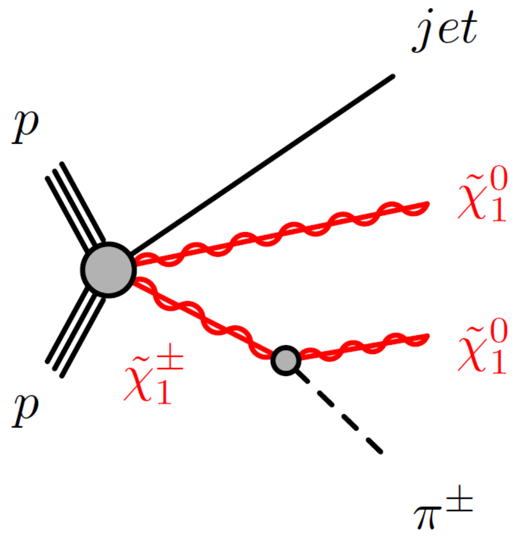
$P_R = (-1)^{3(B-L)+2s}$

+1 for SM, -1 for SUSY partners

In R-violation scenarios the LSP is not stable

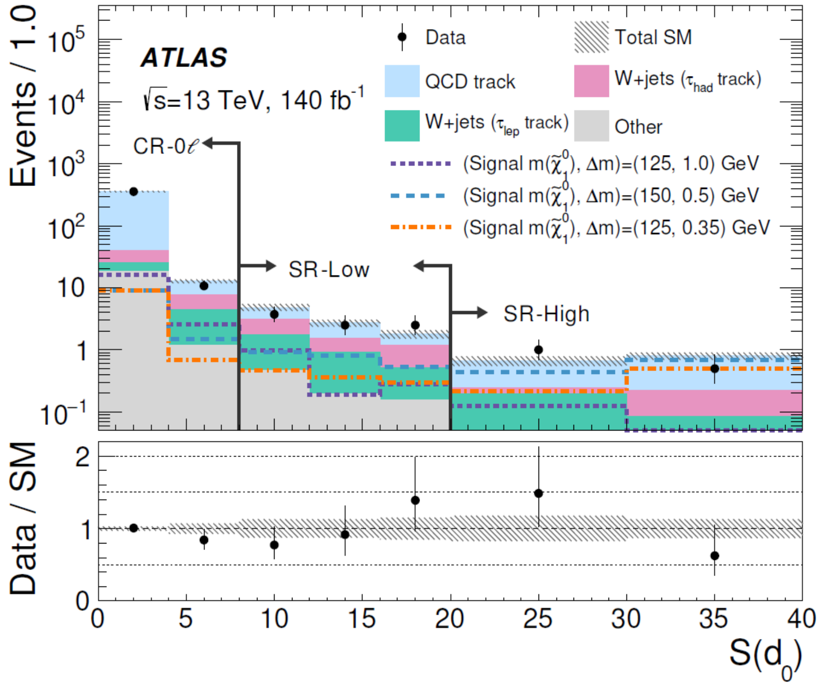
Compressed Higgsinos with mildly-displaced tracks

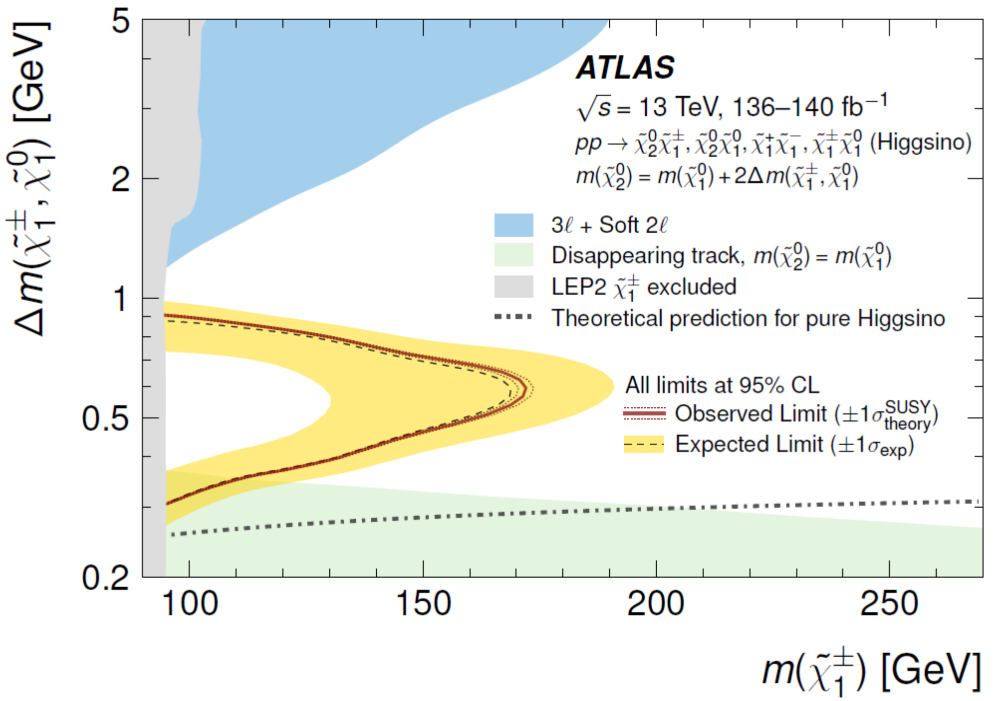
2404.01996



- Higgsinos are the SUSY partners to the Higgs bosons. Mass eigenstates: $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$
- Higgsino masses are connected to the EWSB, favored to be at EW scale $\mathcal{O}$(100 GeV) even if SUSY mass scale is very high (natural SUSY)
- Small mass-splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx 0.3\text{–}1$ GeV
- **Very compressed topology, difficult!** Strongest bounds came from LEP, up to now.
- $\tilde{\chi}_1^\pm$ flight length is $\mathcal{O}$(0.1-1mm).
  Decays dominantly to charged pions with a **mildly-displaced low-p_T track**.

- **Track p_T 2-5 GeV**, aligned with $p_T$miss direction
- Must have a signal in first layer of the inner detector
- High p_T jet (> 250 GeV)
- MET > 600 GeV
- Final discriminant: **S(d0), transverse impact parameter significance**

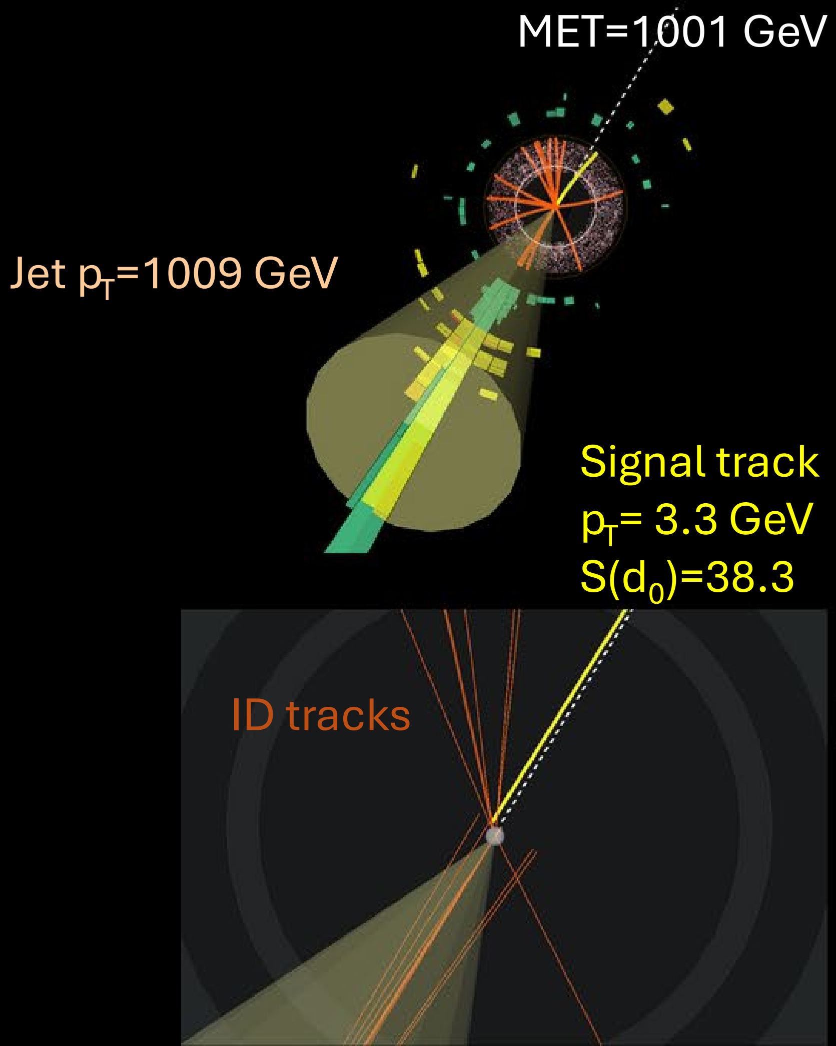


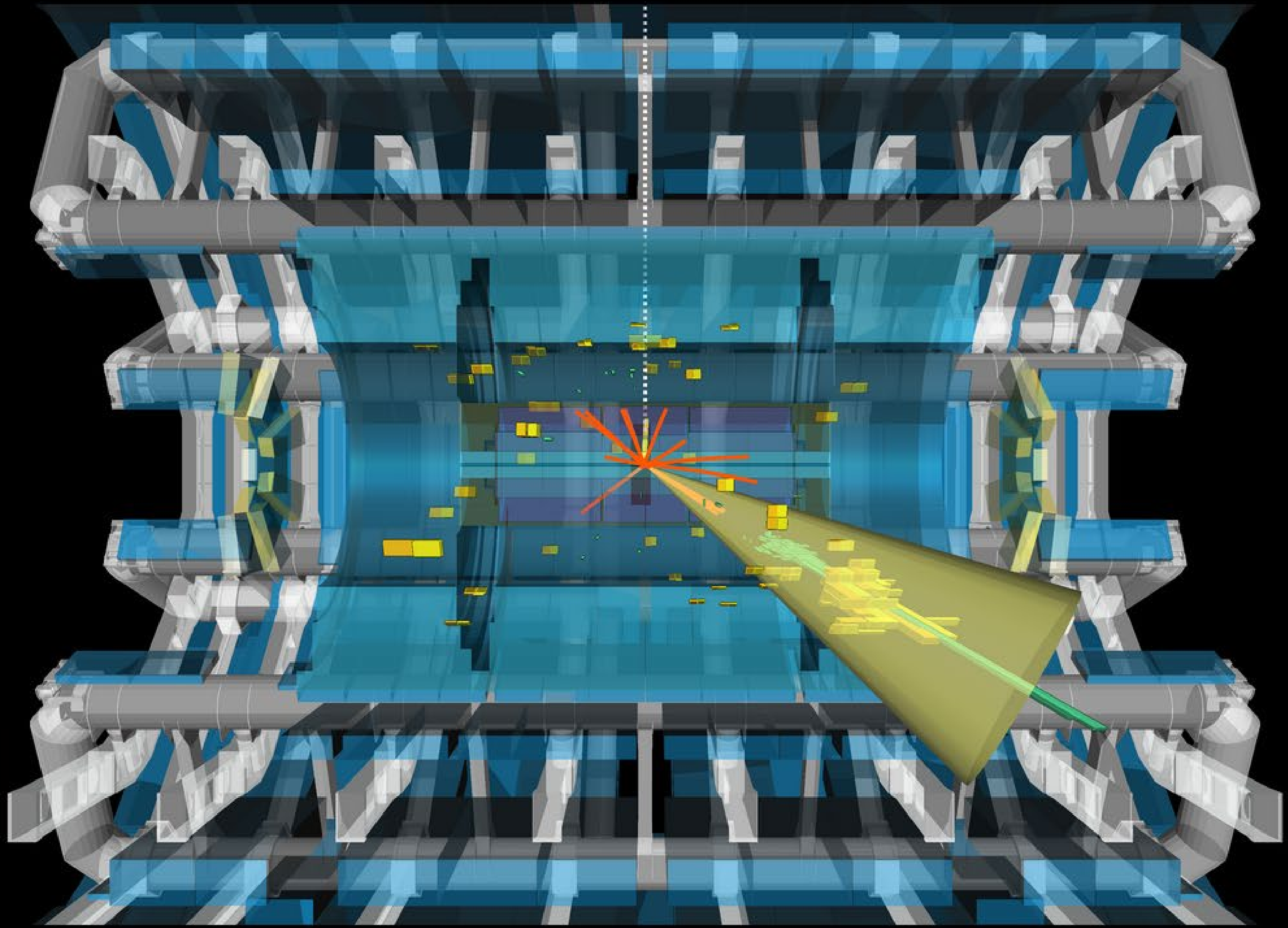


Higgsino decay candidate event from the SR-High

ATLAS EXPERIMENT

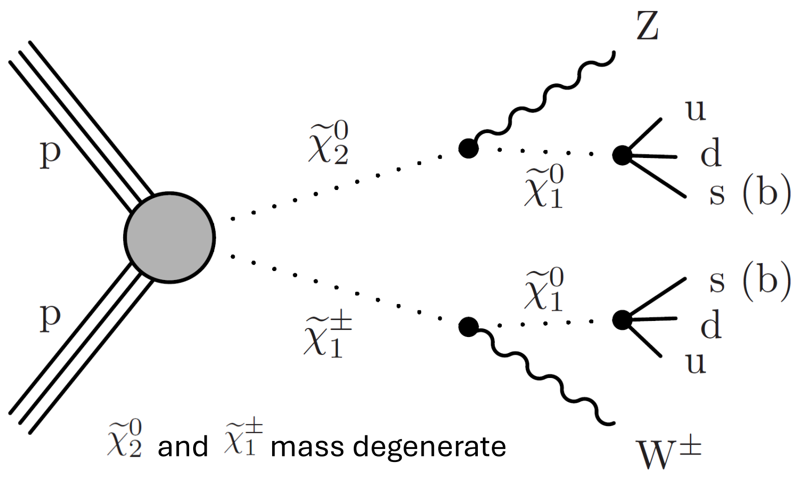
Run: 349309
Event: 1342904905
2018-05-01 16:21:51 CEST





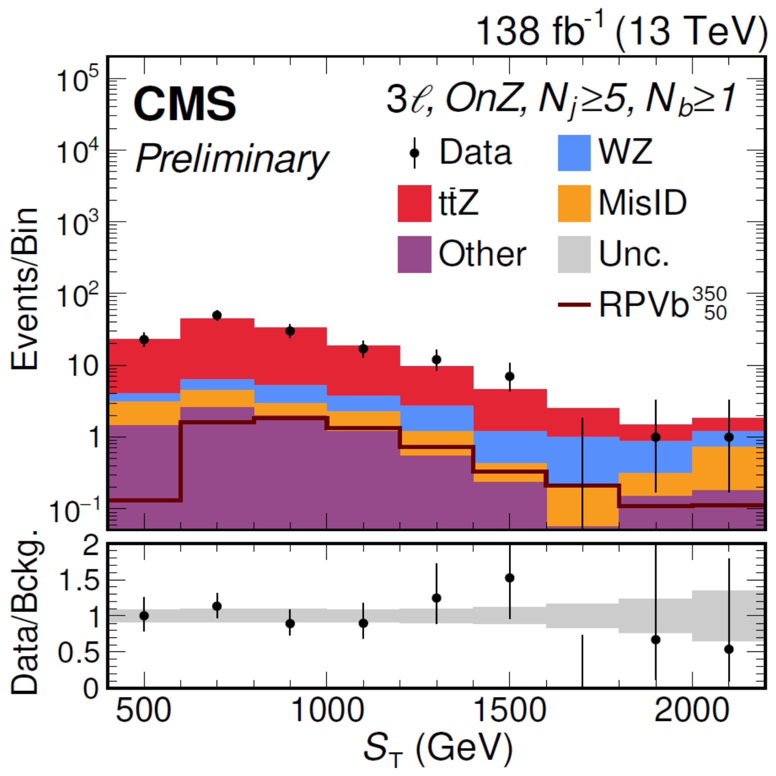
Hadronic R-parity violating SUSY decays

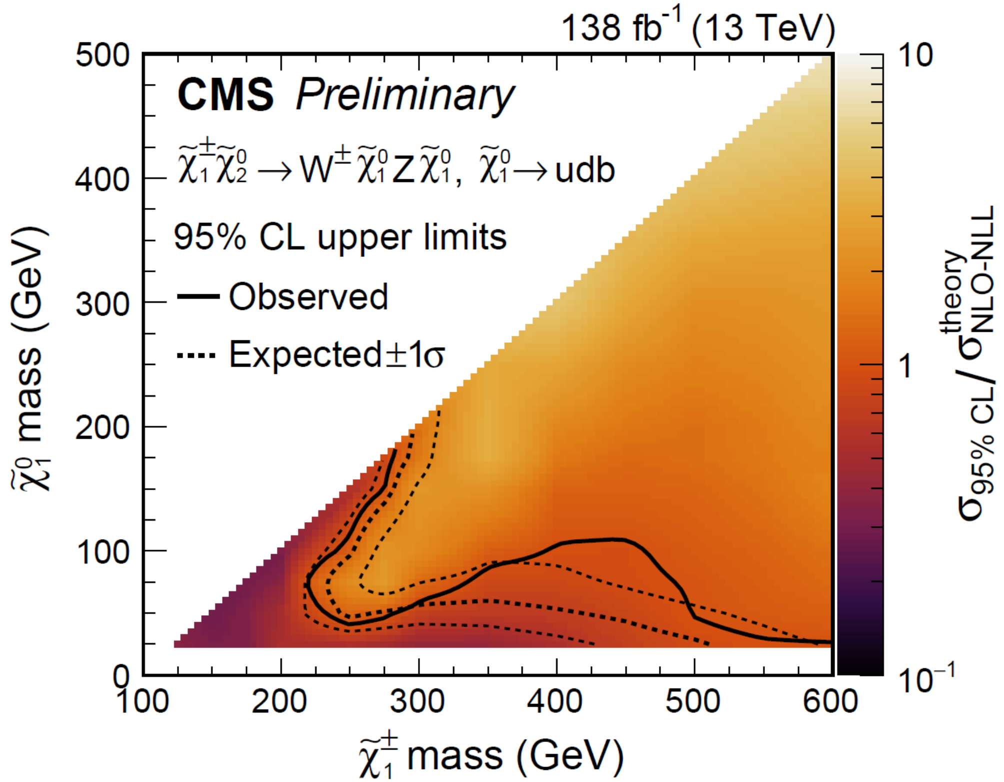
CMS-PAS-SUS-23-015



- Production of **chargino-neutralino pair** through electroweak process
- **Cascade decays to $\tilde{\chi}_1^0$ and a vector boson (Z or W),** followed by hadronic R-parity violating prompt decays of the LSP
- $W \to l\nu$, $Z \to ll$. LSP → uds or **LSP → udb** (shown here)
- Final state consists of **3 leptons and up to 6 jets**
- Control regions with 4 or 5 leptons enriched in bkg

- Lepton pair consistent with Z mass („OnZ“)
- **Effective mass S_T:** Scalar p_T sum of charged leptons, jets, and $p_T$miss → No combinatorics
- **Wide excess expected**
- **Related RPV-SUSY search by ATLAS:** 2401.16333





ATLAS combination of charginos and neutralinos

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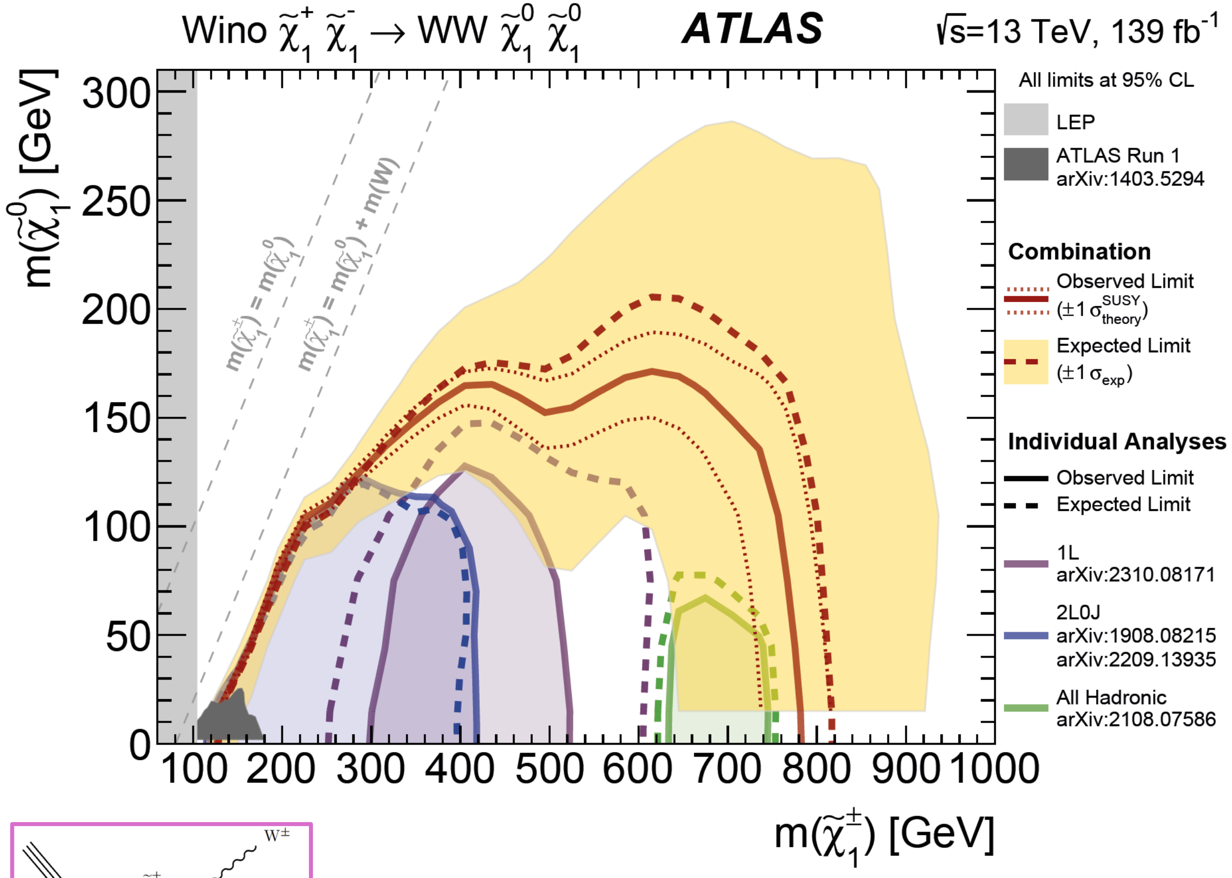
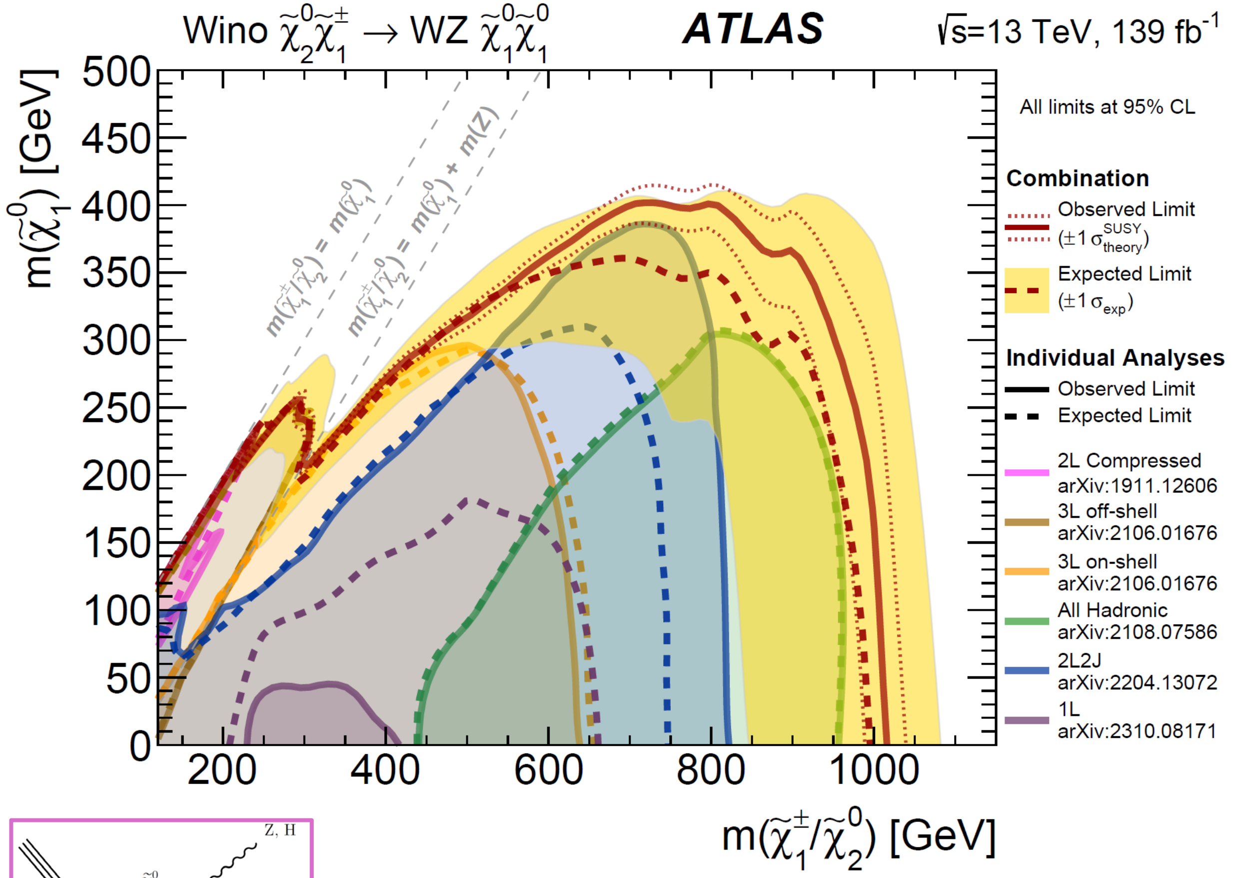
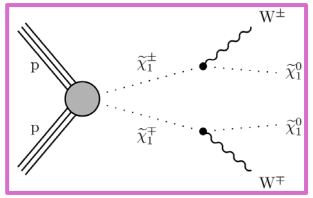
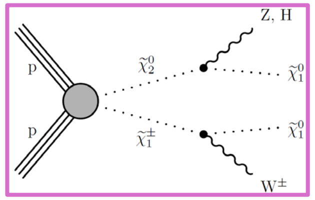






Pure-wino **chargino-pair production** decaying to W bosons and the LSP.



Pure-wino **mass-degenerate chargino-neutralino production**.

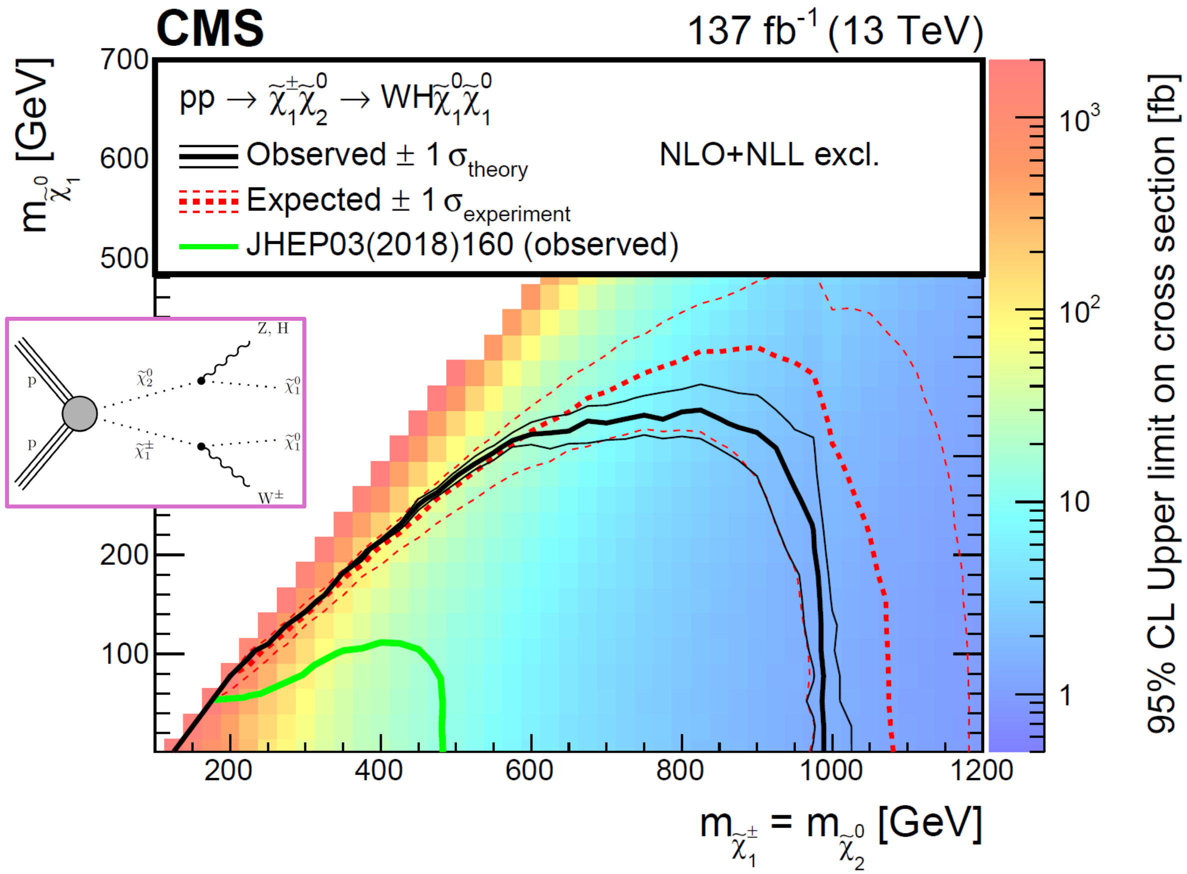
Limits on $\tilde{\chi}^\pm_1$ mass reach up to ~800 GeV for light LSP.

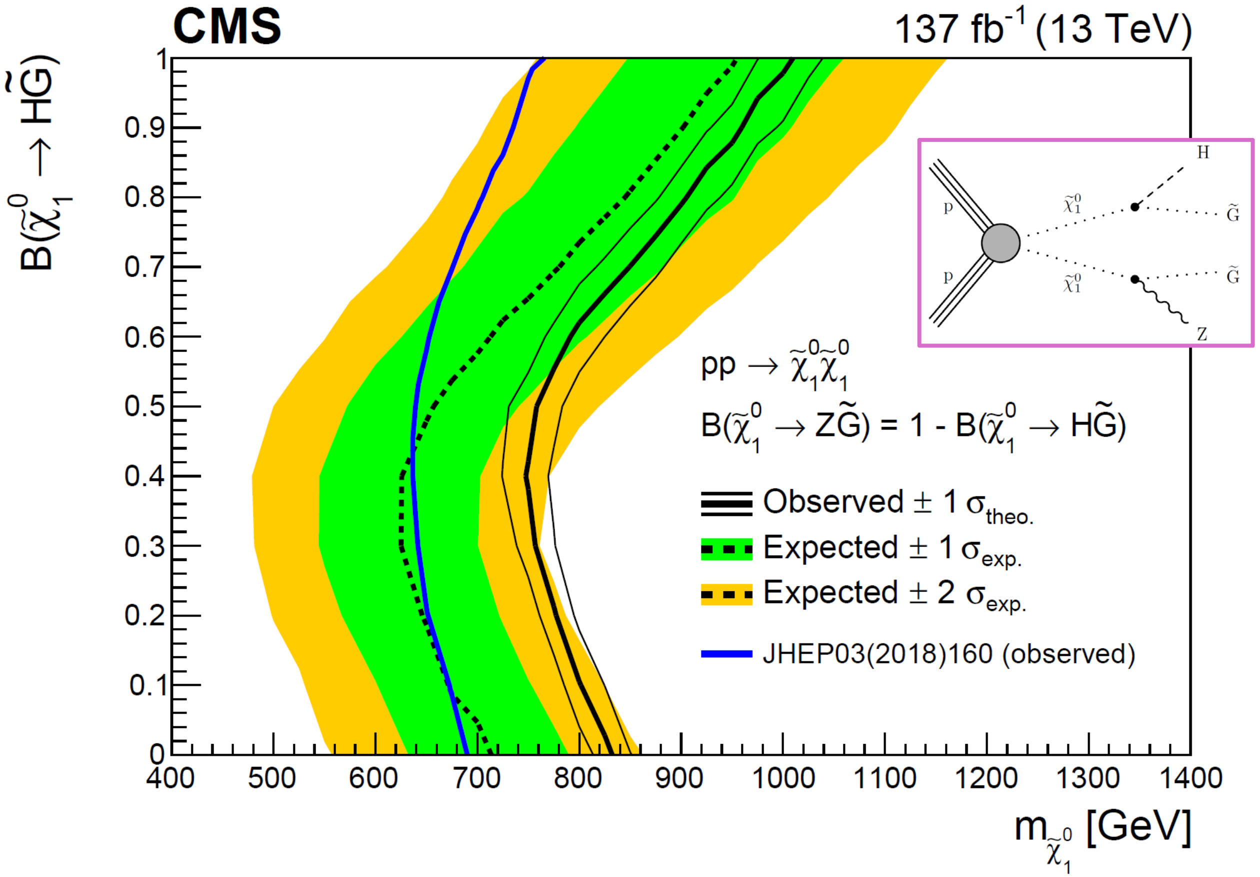
Decays to W/Z and the LSP. Limits reach up to 1 TeV.

Combinations extend sensitivity to SUSY production up to 100 GeV in (N)LSP masses, sensitivity to SUSY production cross-sections increased by up to 40%

CMS combination of charginos and neutralinos

2402.01888





Wino-bino model: **Mass-degenerate chargino-neutralino production**, decays to W, H and the LSP.

1σ excess driven by Hadronic WW/WZ/WH search 2205.09597

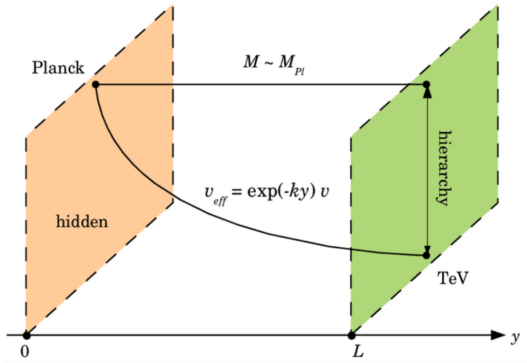
For LSP mass of 50 GeV, $\tilde{\chi}_1^{\pm}$ below 990 GeV excluded.

Gauge mediated SUSY breaking: **Neutralino-pair production** with decays to H or Z and Gravitino

Exclusion ranges between 750 GeV and 1 TeV depending on $\mathcal{B}(\tilde{\chi}_1^0 \to H\tilde{G})$

Quantum Black Holes

- Predicted in **theories with low scale of quantum gravity** M_D (order of **1-10 TeV**)



Randall-Sundrum

- **Models considered**:
  - Large extra dimensions (Arkani-Hamed-Dimopoulos-Dvali, ADD)
  - Warped extra dimensions (Randall-Sundrum, RS1)

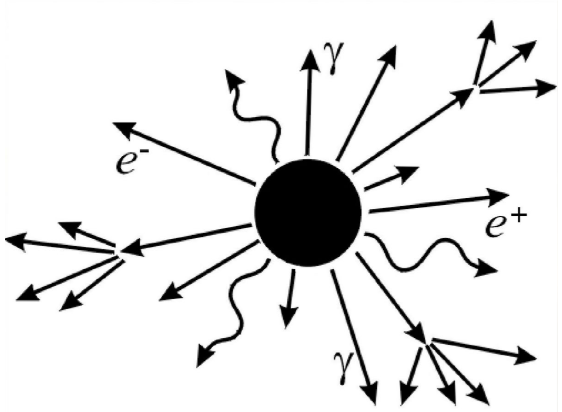
- **Global symmetries** such as baryon or lepton number may not be conserved in strong-gravity interactions

- QBH production in pp collisions via **2-to-2 scattering** , for example:

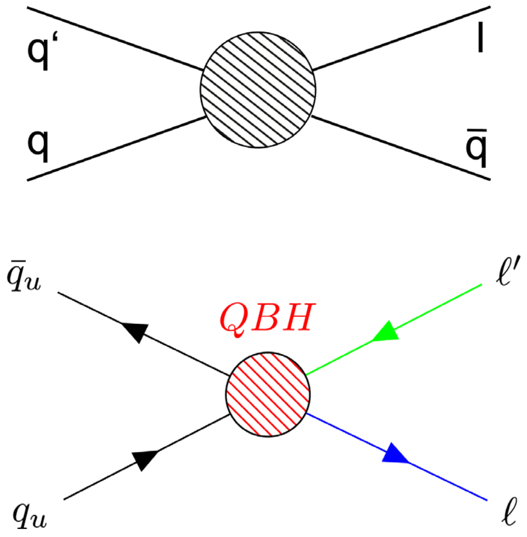
$$uu \to \bar{d}\ell^+, \quad ud \to \bar{u}\ell^+, \quad \bar{d}\bar{d} \to d\ell^+$$

- **QBH decay to two-particle final states with large branching fraction (51-74% in ADD or RS1).**

In contrary, semi-classical BH decay into multi-particle final states via Hawking radiation.



Thermal decay of a BH



QBH

Quantum Black Holes

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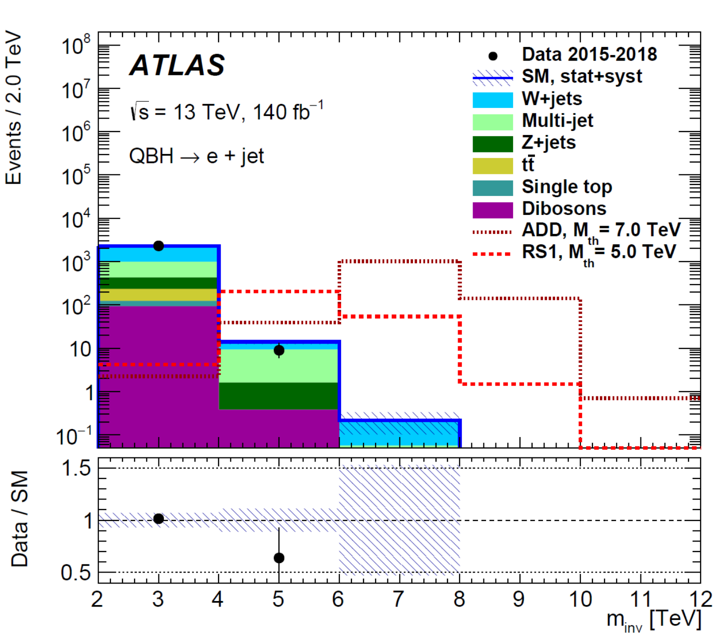
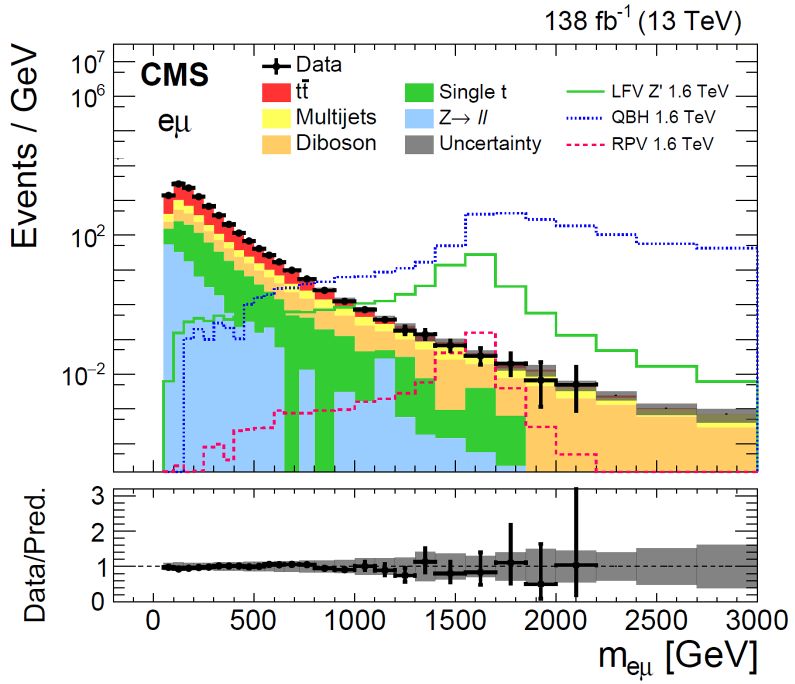
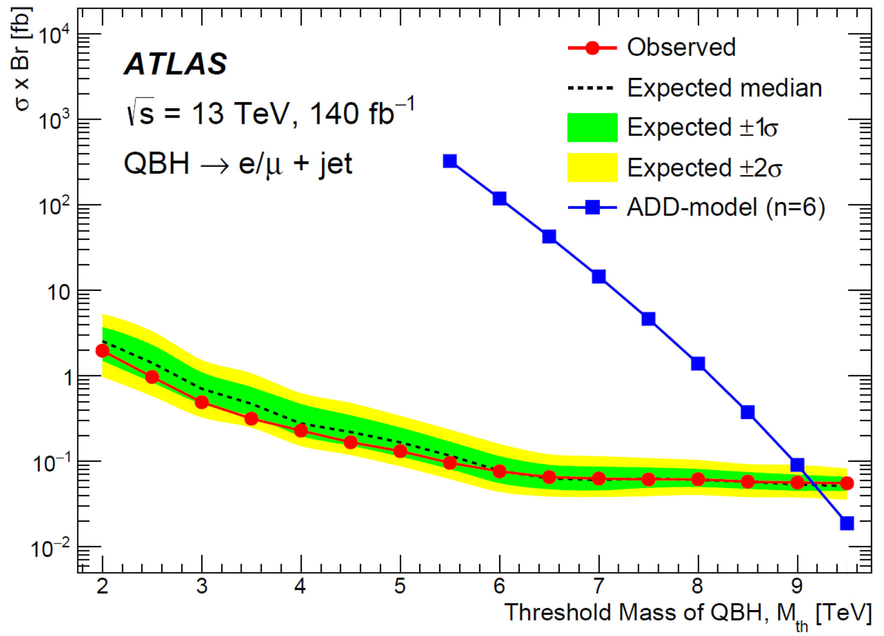
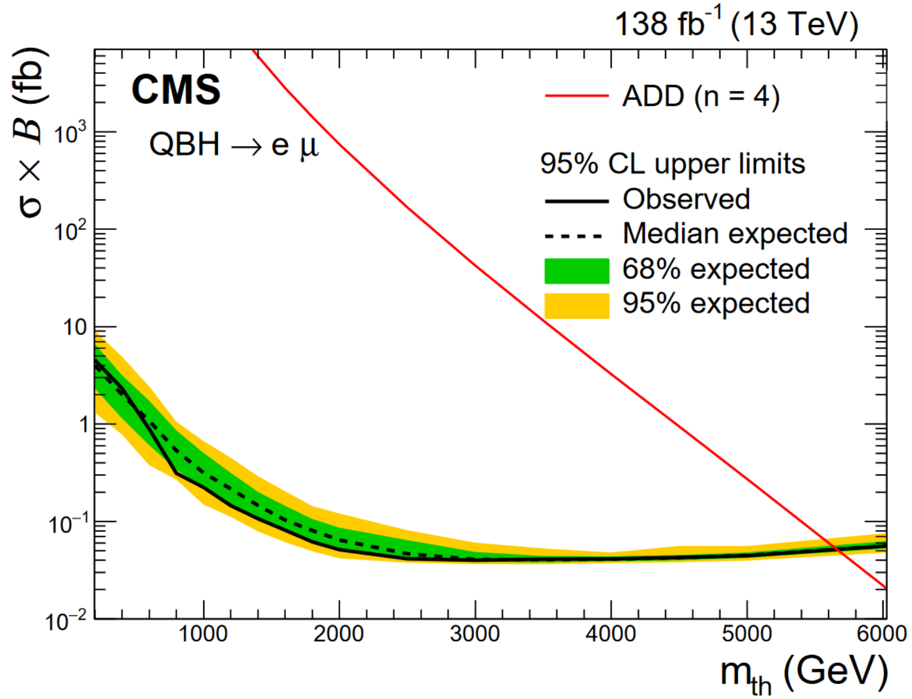








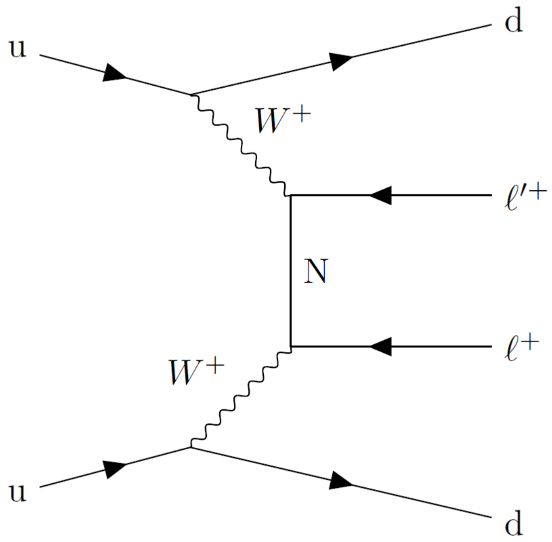
ATLAS result:

- **electron+jet** and **muon+jet** final states
- Fit to SR and three CRs (W, Z, top) using m_{inv} of lepton and jet
- QBH in ADD model with n=6 excluded for M_{th}<9.2 TeV

CMS result:

- **eμ, eτ** and **μτ** channels, separate limits obtained
- Jets faking leptons is estimated from data in control samples
- Best channel: eμ, QBH in ADD with n=4 excluded for M_{th} <5.6 TeV

Heavy Majorana Neutrinos

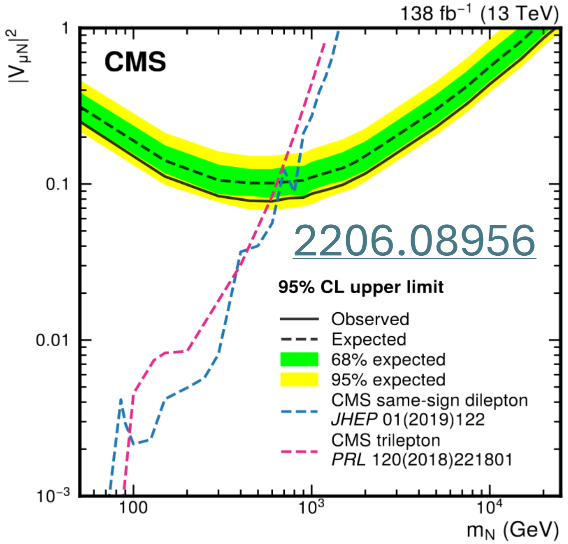


- VBF same-sign W boson scattering
- Final state: two leptons + two jets

- **Neutrinos masses** implied by the observation of neutrino oscillations
- Majorana nature means that these neutrinos are their own anti-particles
- Heavy leptons and extended scalar sectors present in **Seesaw, Left-Right Symmetric** or **GUT models**
- **Phenomenological Type-I Seesaw model**:
  Introduces a new heavy Majorana neutrino N, that generates the small neutrino masses $\mathbf{m_\nu \sim \mathcal{O}(vev^2/m_N)}$
  (vev is the vacuum expectation value 246 GeV, m_N is the mass of the heavy Majorana neutrino)
- Heavy neutrino mass-mixes with SM neutrinos, **mixing parameters V_{eN} and $V_{\mu N}$**
- Cross section ~ $|V_{eN}\, V_{\mu N}|^2$

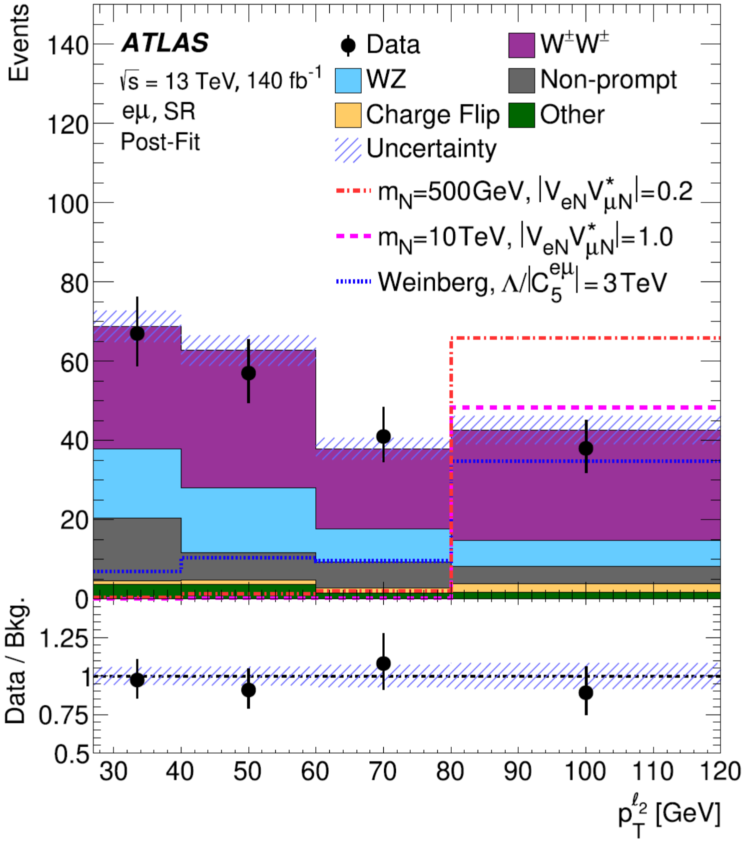
Heavy Majorana Neutrinos

2403.15016

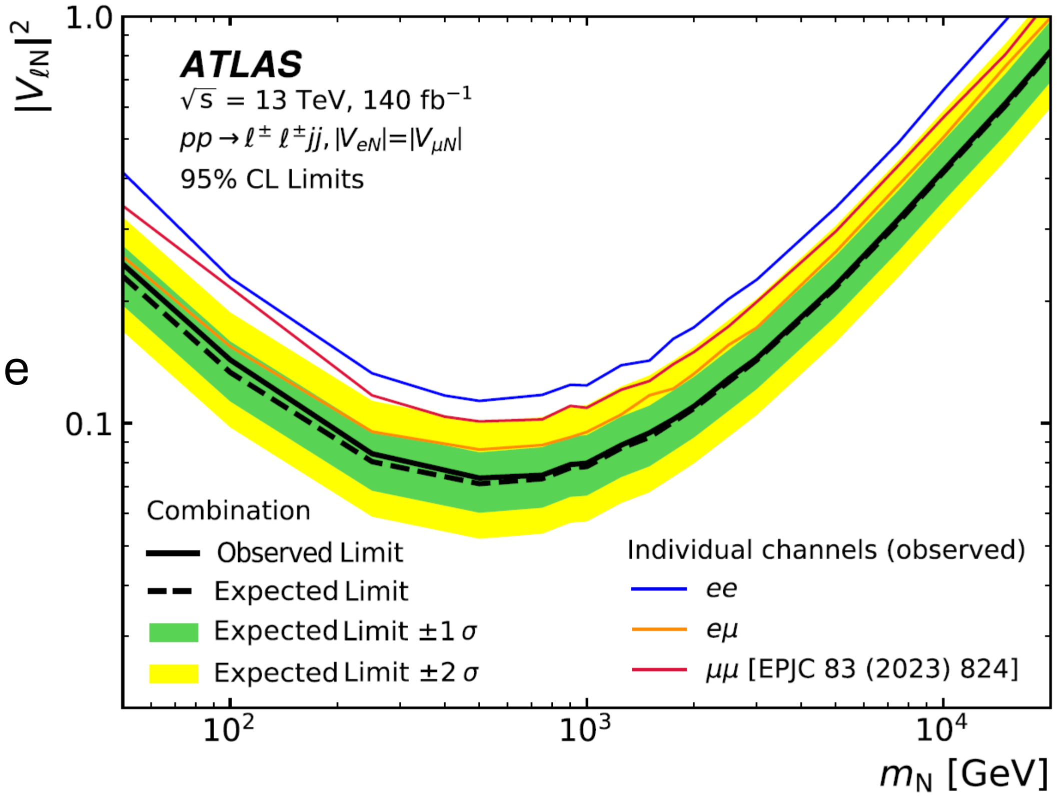


2206.08956

- Two channels: **ee or eμ (+ two jets)**, that are then statistically combined
- Jets have a large rapidity gap (|Δy|>2) and large invariant mass (m_{jj} > 500 GeV)
- **Most discriminating variable: p_T of the subleading lepton**
- WW and WZ control region for background estimation



- Limits set on the mixing parameter value as a function of the neutrino mass within 50 GeV to 20 TeV
- **No excess found**



Summary

- Diverse set of searches presented with the full Run 2 dataset from ATLAS and CMS, non-resonant searches complementary to resonance and other searches.

- **No significant excess found, stringent limits in various models set**:
  - Vector LQ decays to μ+b for λ=1, β=1 and κ=1 excluded for masses up to 2.6 TeV
  - Scalar LQ excluded for masses below 620 GeV, assuming λ_{LQ} = 1.5 in cLFV interactions
  - M_5 up to 11 TeV excluded for k=1 TeV in extra-dimensional clockwork models
  - Natural SUSY Higgsinos with small mass-splitting excluded up to 170 GeV
  - Chargino/neutralino masses up to 1 TeV excluded in SUSY combinations
  - QBH in ADD model with n_D=4 (6) excluded for masses up to 5.6 (9.2) TeV
  - Neutrino mass-mixing parameter values excluded for heavy neutrinos up to 20 TeV

- **Searches with Run 3 data in progress! Some expected improvements:**
  - Larger luminosity increases sensitivity for many searches, eg. EW SUSY, high-mass tails
  - Cross sections for TeV-scale processes profit from increased beam energy (e.g. QBH cross section at 9 TeV doubles, strong SUSY production also gains)

Backup

ATLAS SUSY Searches* - 95% CL Lower Limits

August 2023

ATLAS Preliminary

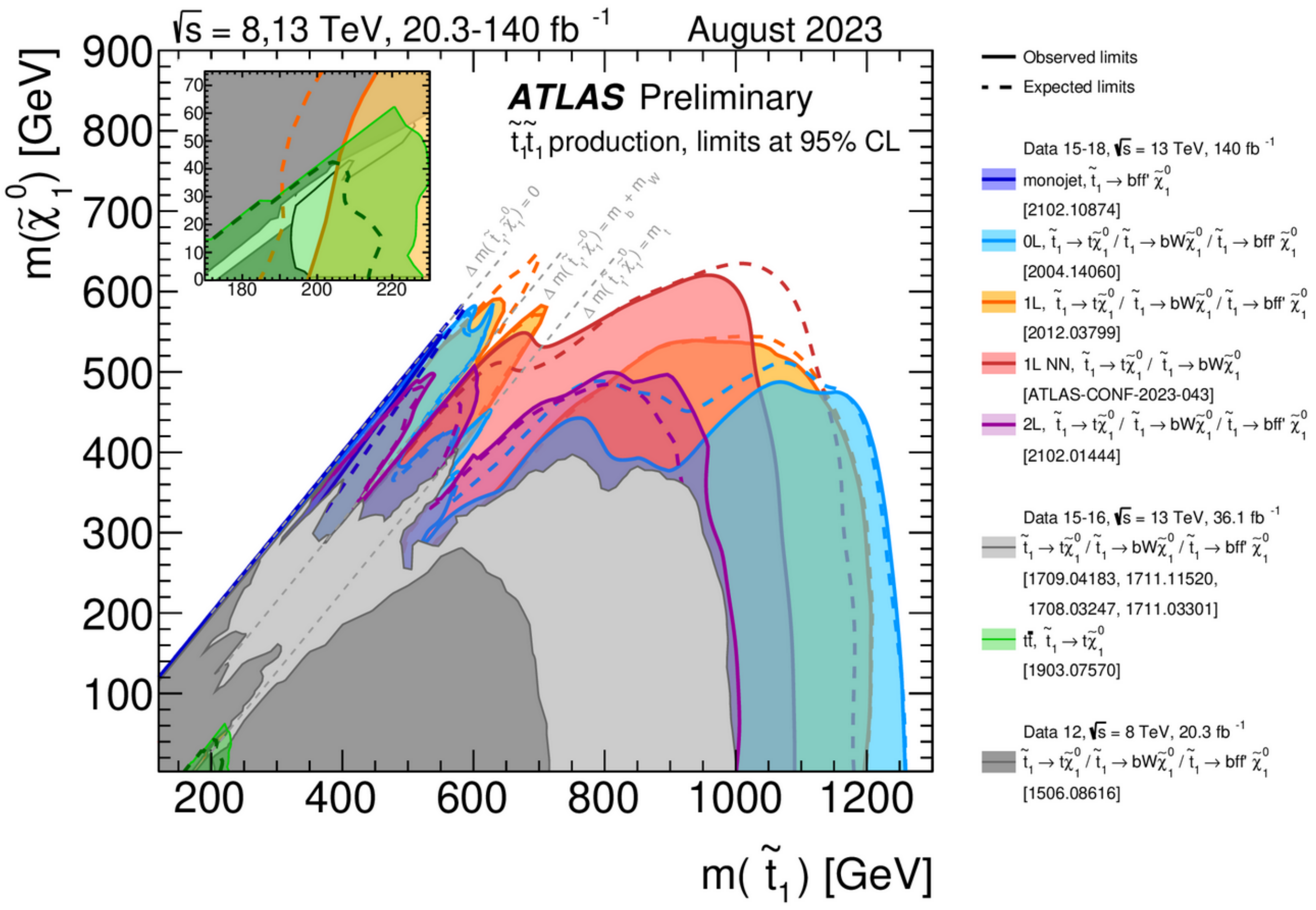
$\sqrt{s}$ = 13 TeV

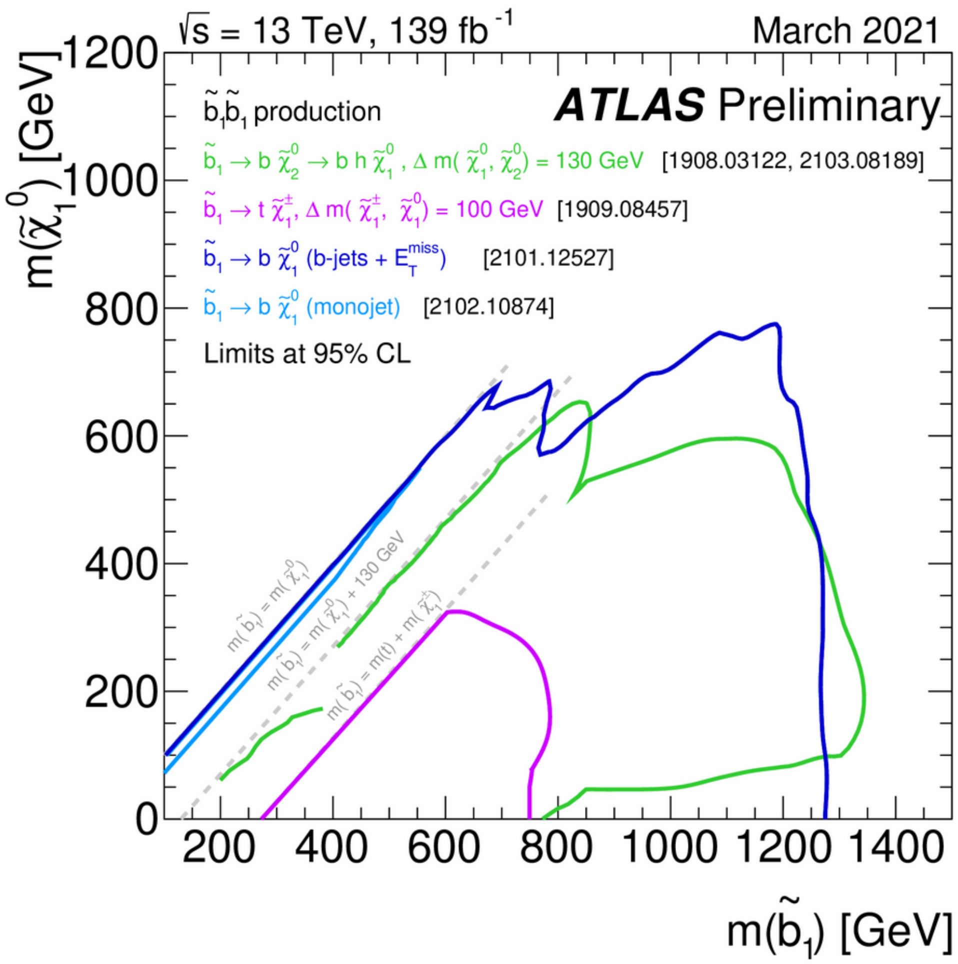
	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Conditions	Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$ [1x, 8x Degen.]	1.0 / 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$ [8x Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$	2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden; 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		140	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$	1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$	2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$	1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$	Forbidden; 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	≥ 1 jet	E_T^{miss}	140	$\tilde{t}_1$	1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden; 1.05	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799, ATLAS-CONF-2023-043
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden; 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$	Forbidden; 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden; 1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_R$, $\tilde{\tau}_{R,L}$]	0.34 / 0.48	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2023-029
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	140	$\tilde{\ell}$	0.26	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	140	$\tilde{H}$	0.94	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	To appear
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$	0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	≥ 2 large jets	E_T^{miss}	140	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	≥ 2 jets	E_T^{miss}	140	$\tilde{H}$	0.77	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=BR($\tilde{\chi}_1^0\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^{\pm}$	0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e},\tilde{\mu}$	0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$	0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 / 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$]	0.95 / 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		≥8 jets		140	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=50 GeV, 1250 GeV]	1.6 / 2.25	Large λ''_{112}	To appear
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 / 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm}\to bbs$		≥ 4b		140	$\tilde{t}$	Forbidden; 0.95	m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 / 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 / 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^+\to bbs$	1-2 e,μ	≥6 jets		140	$\tilde{\chi}_1^0$	0.2-0.32	Pure higgsino	2106.09609

10^{-1} — 1 — Mass scale [TeV]

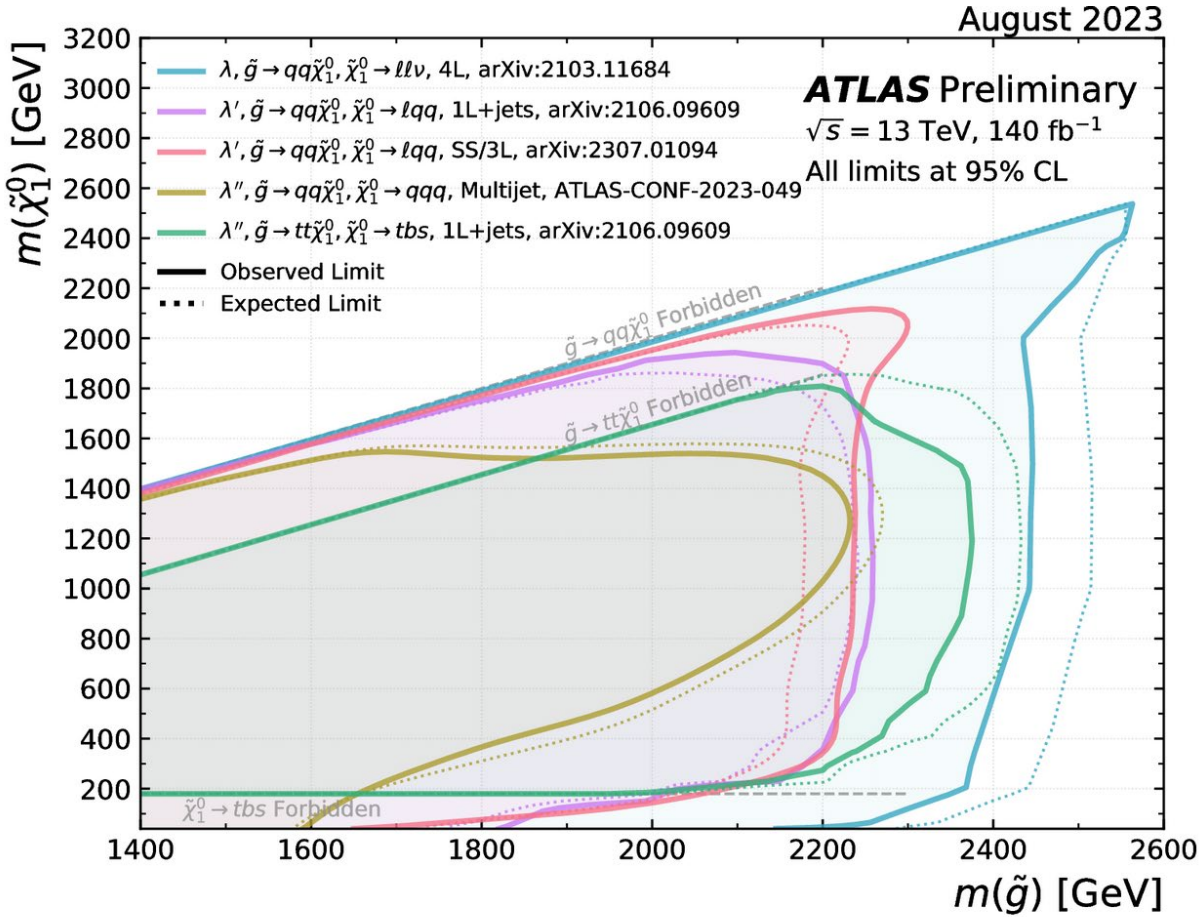
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

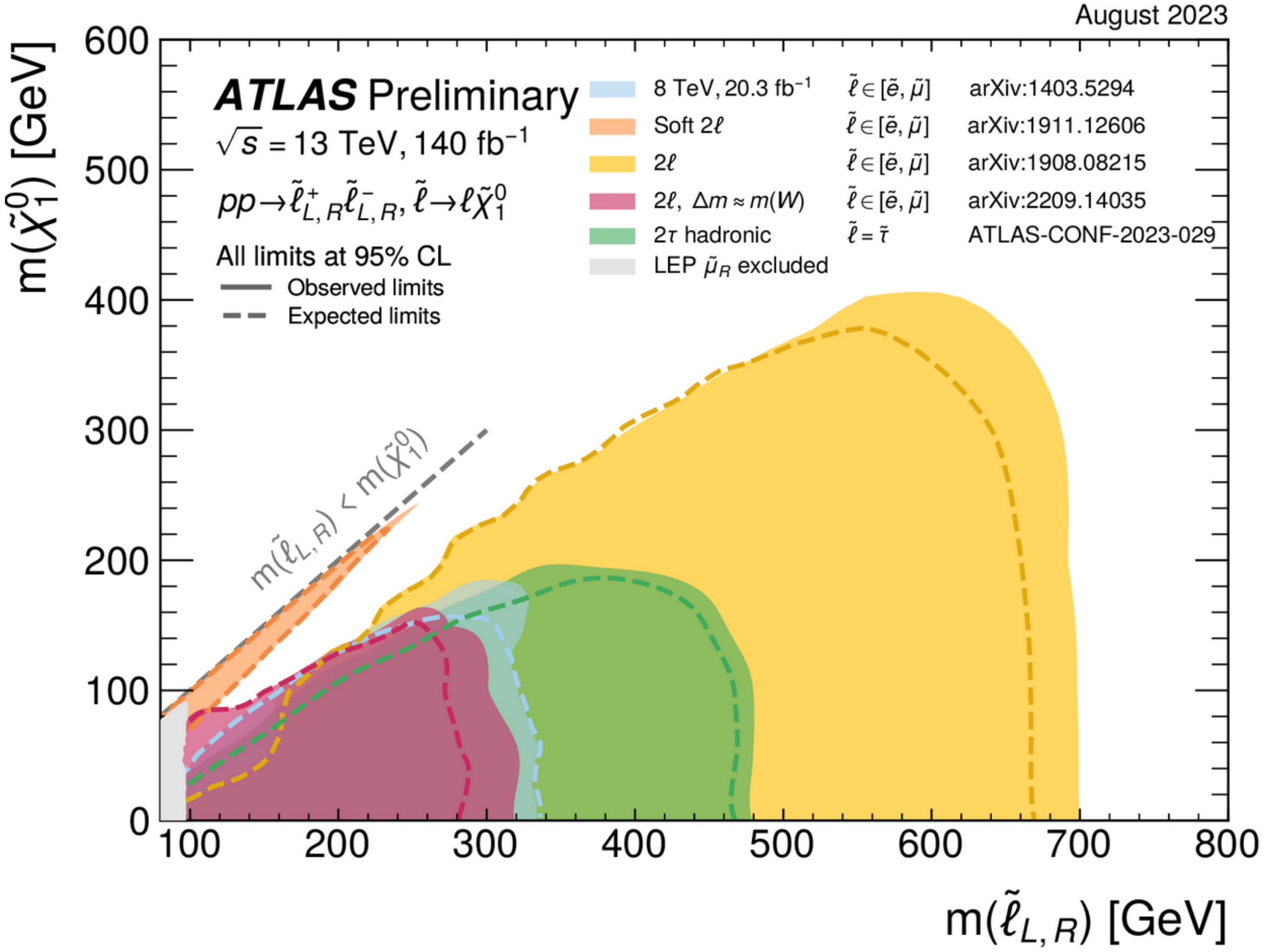
SUSY Summary Plots





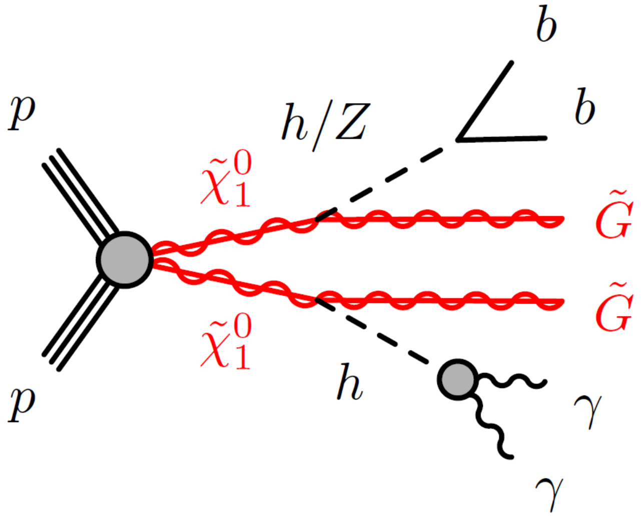
SUSY Summary Plots



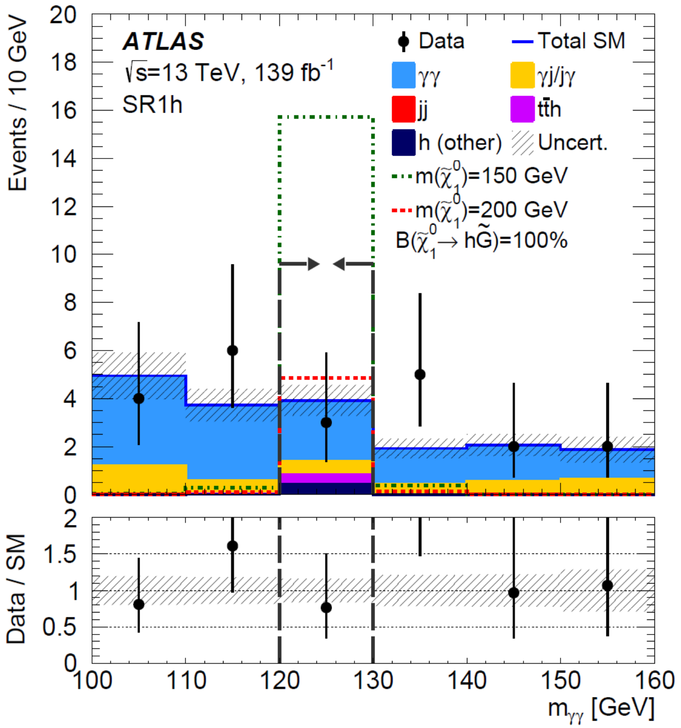


Pair-produced Higgsinos

2404.01996

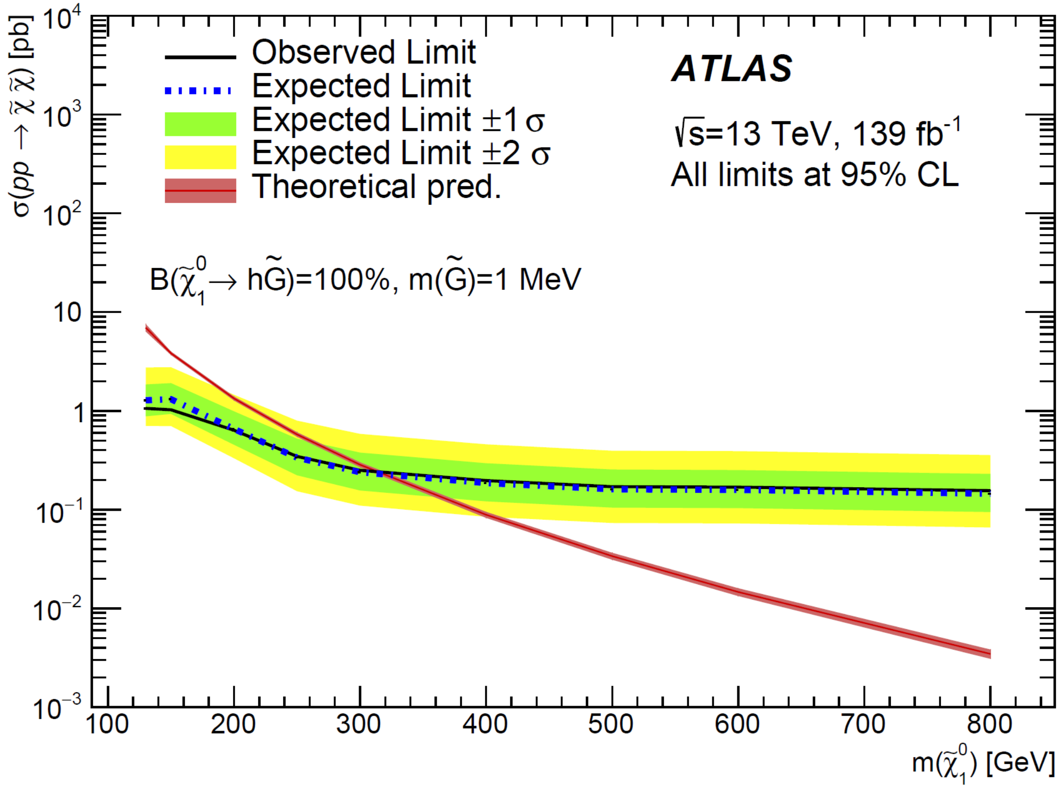


- **Neutralinos $\tilde{\chi}_1^0$ decay to a light Gravitino $\tilde{G}$ and a Higgs or Z boson**
- Neutralino masses at EW scale, even if SUSY mass scale is very high
- **Final state: Missing energy, two photons and two b-jets**
- Selection requires 120 GeV < $m_{\gamma\gamma}$ < 130 GeV



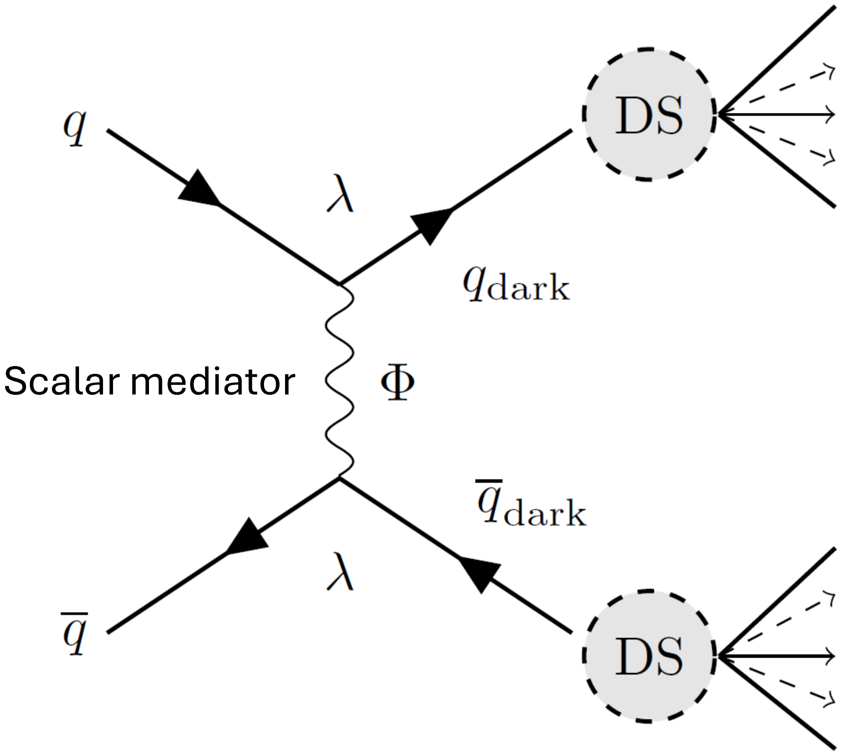
Three signal regions:

- SR1h:
  MET < 100 GeV
  100 GeV < m_{bb} <140 GeV
- SR1Z:
  MET < 100 GeV
  60 GeV < m_{bb} <100 GeV
- SR2 (targets heavy $\tilde{\chi}_1^0$):
  MET > 100 GeV
  35 GeV < m_{bb} <145 GeV

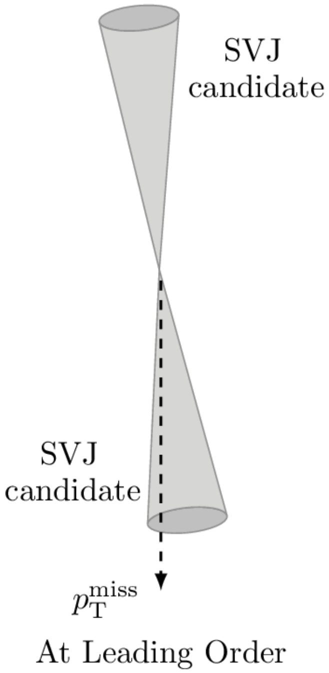


Semi-visible Jets

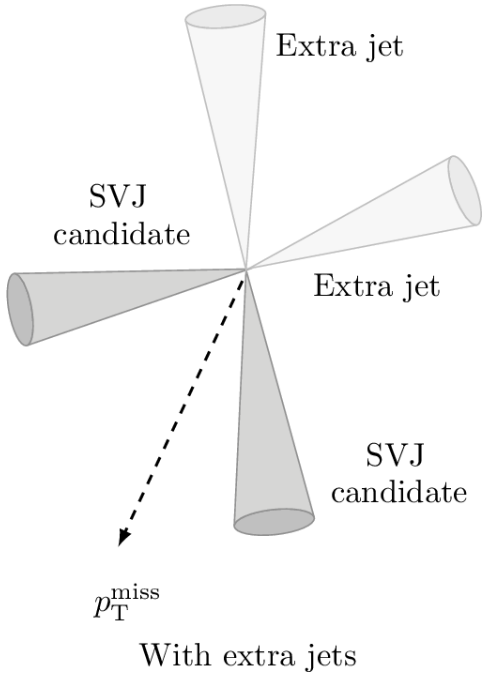
- **Strongly-coupled dark sector featuring a dark shower** (DS) including dark hadrons
- **These dark hadrons may or may not be stable**:
  - If all dark hadrons are stable → missing energy signature.
  - If all dark hadrons decay to SM particles → multijet signature
- „Semi-visible“ means the **fraction of stable hadrons (R_{inv})** has intermediate values



Coupling strength λ is a parameter



Missing momentum aligned with one of the jets

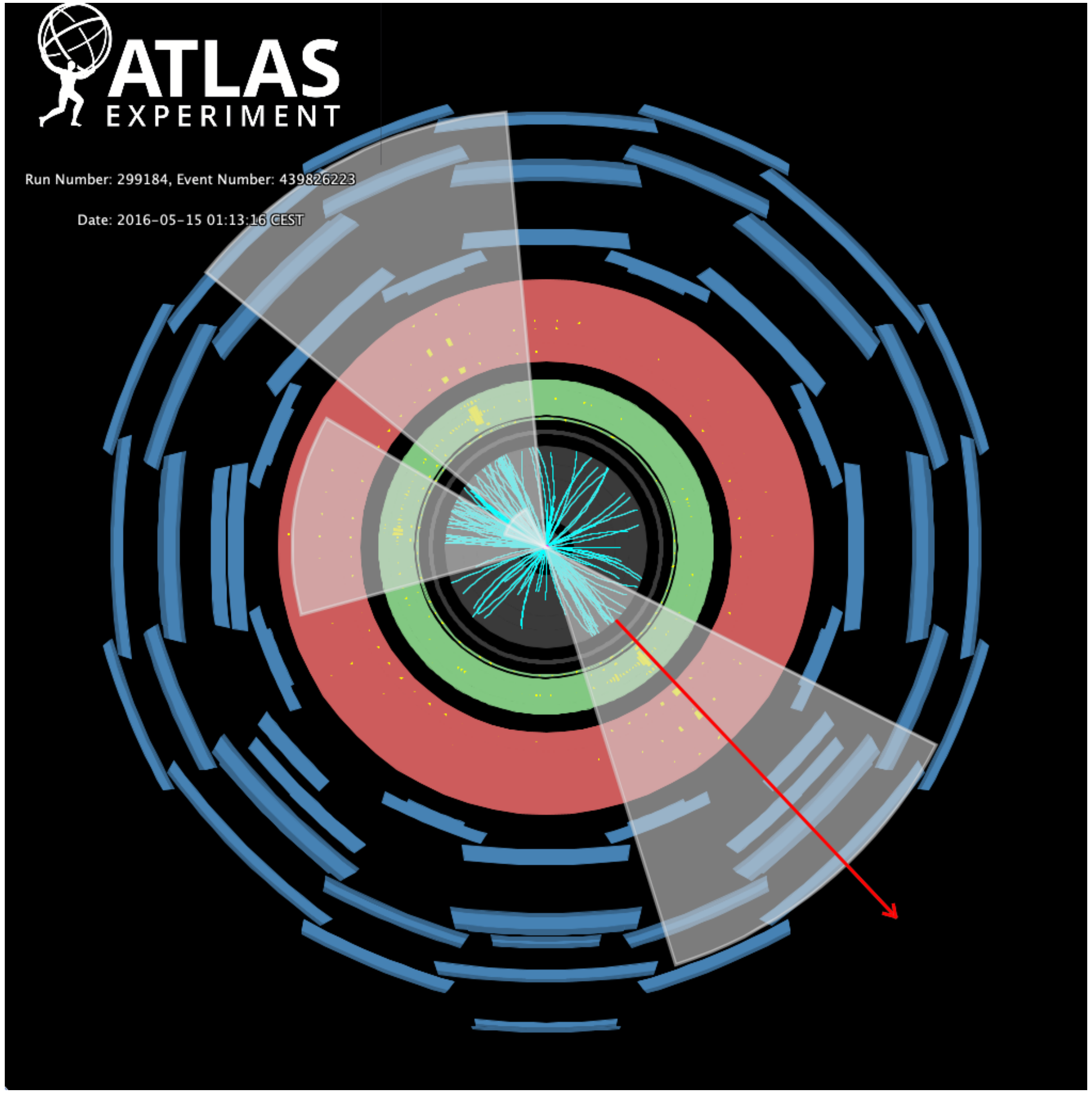


Missing momentum direction distorted by presence of extra jets

Semi-visible Jets

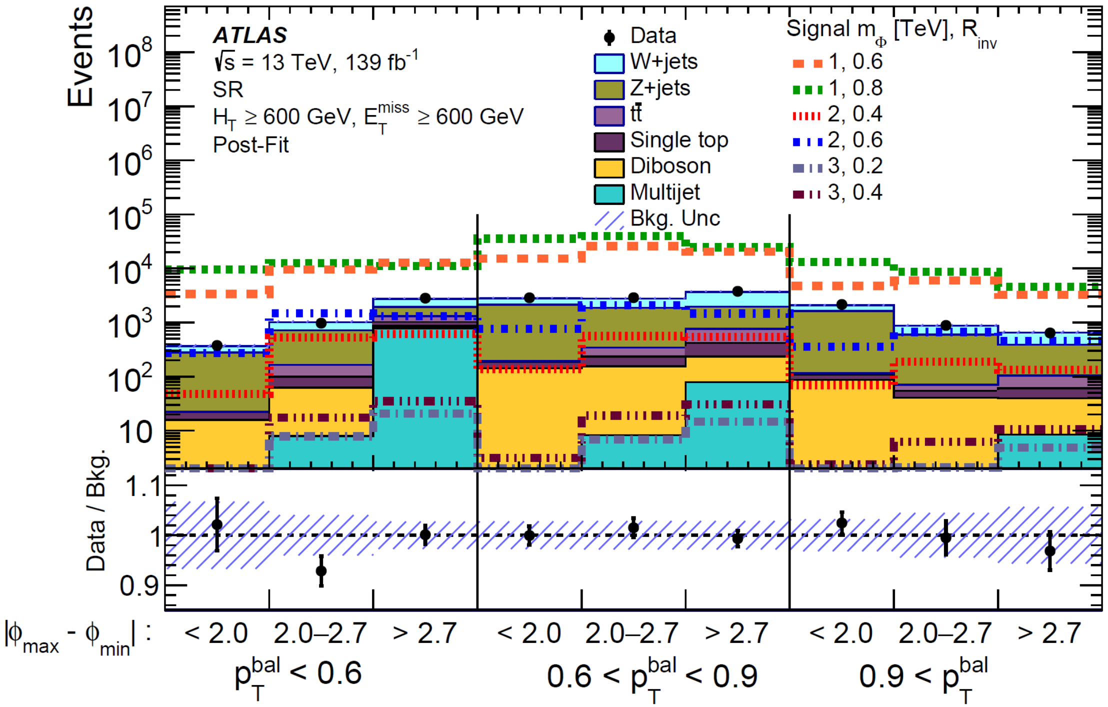
2305.18037

2305.18037



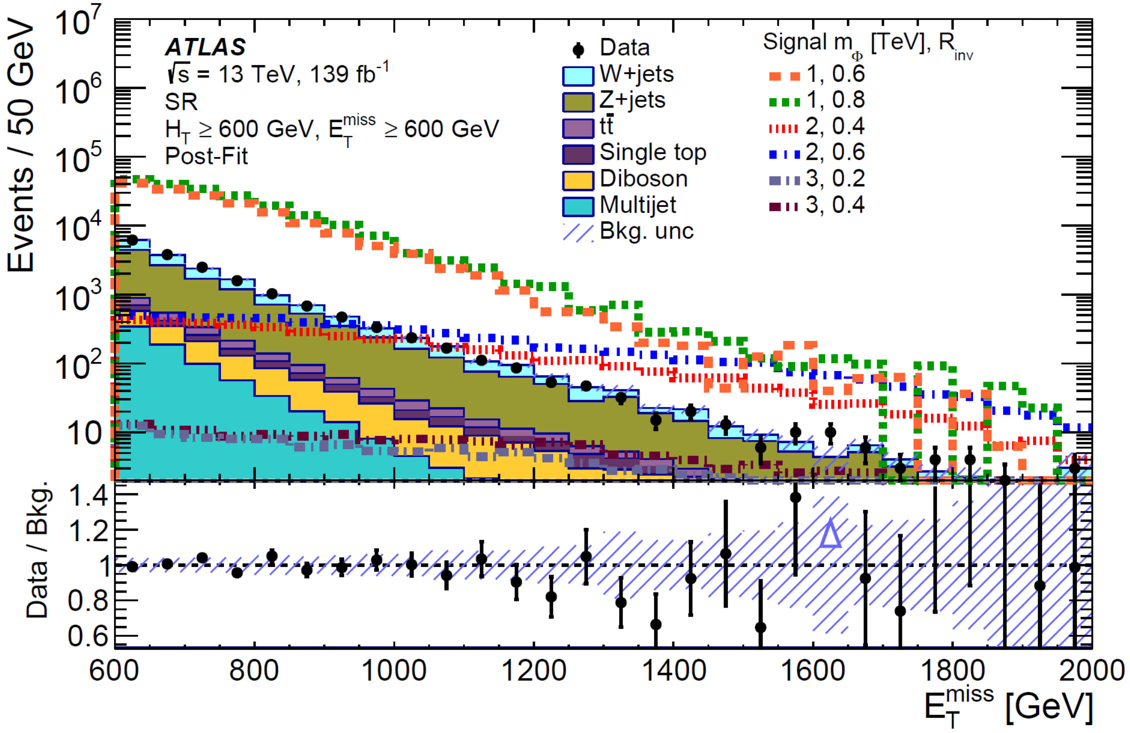
- Missing E_T trigger with online MET >70-110 GeV

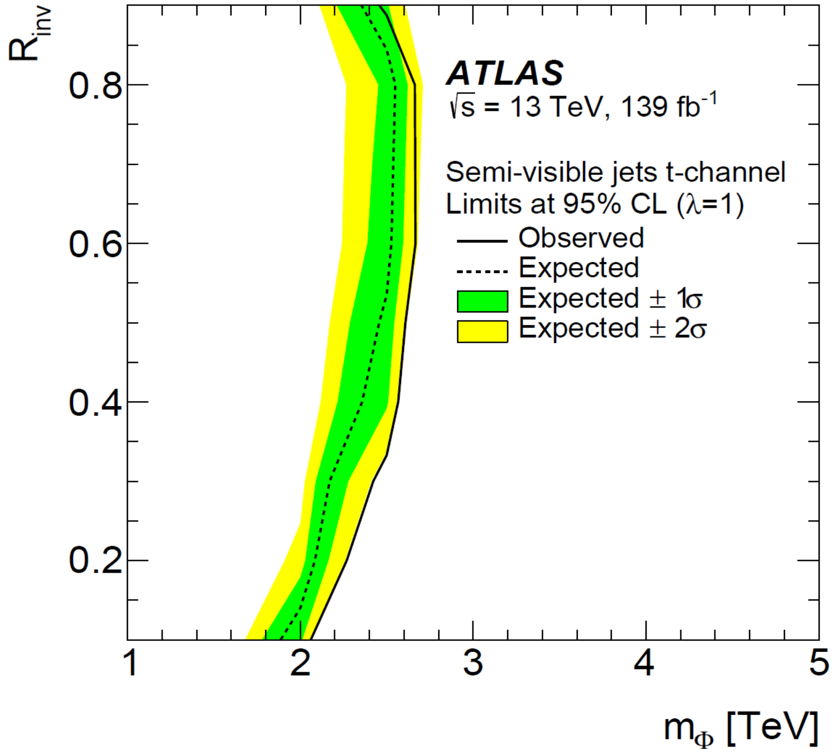
- Events with at least two jets, leading jet p_T > 250 GeV, one jet close to the missing p_T direction
- Events with at leptons or at least two b-jets vetoed in the SR. Three control regions with leptons used for background estimation.
- In the SR: MET > 600 GeV, H_T> 600 GeV
- p_T balance $p_T^{bal} = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$ and azimuthal separation between jets for final discrimination and fit

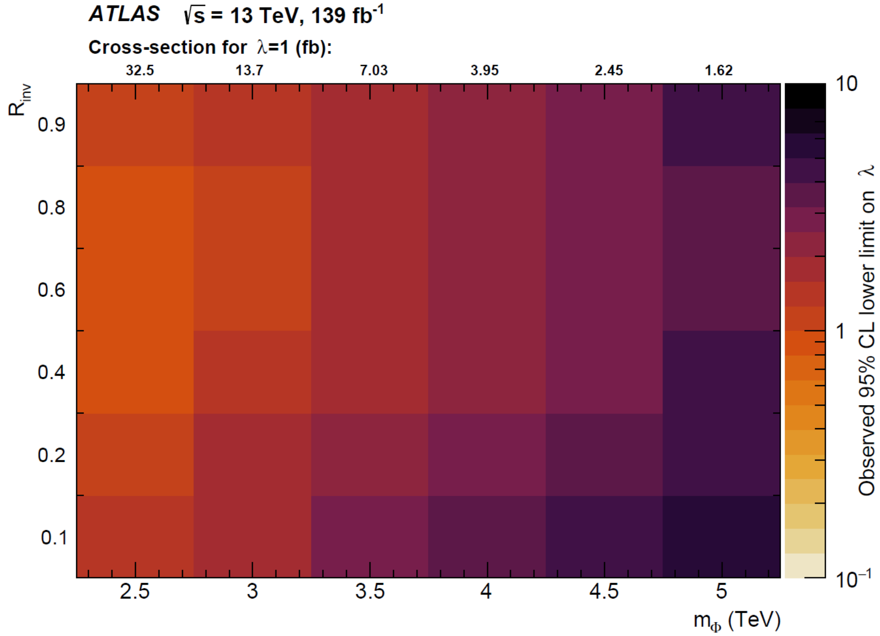


Semi-visible Jets

2305.18037







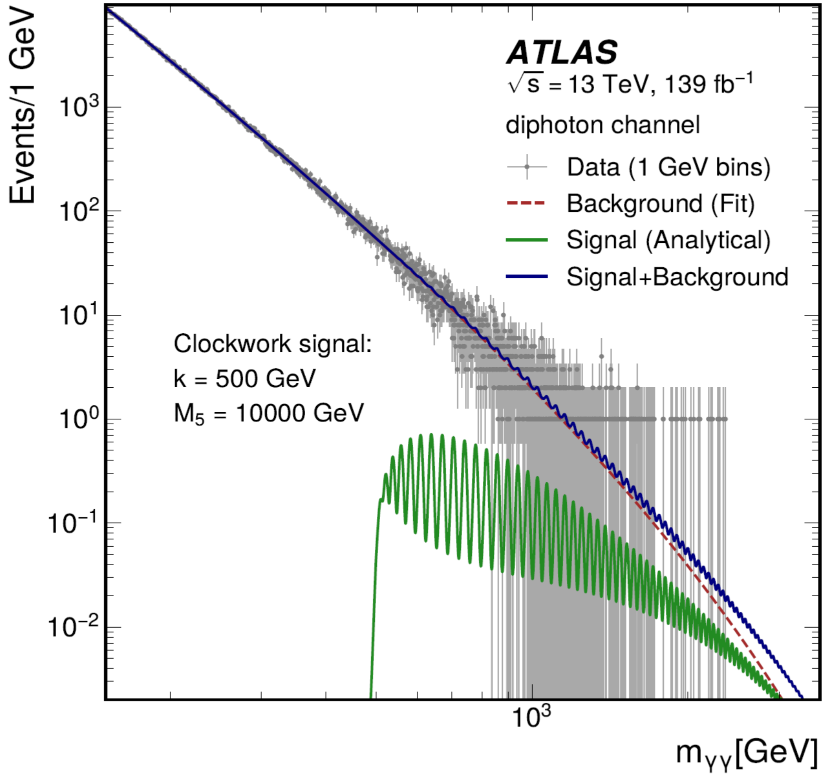
- **No excess found**
- Upper limits on the mediator mass between 2.4 - 2.7 TeV, depending on R_{inv}
- Limits on coupling strength λ set (for m_Φ > 2.5 TeV)

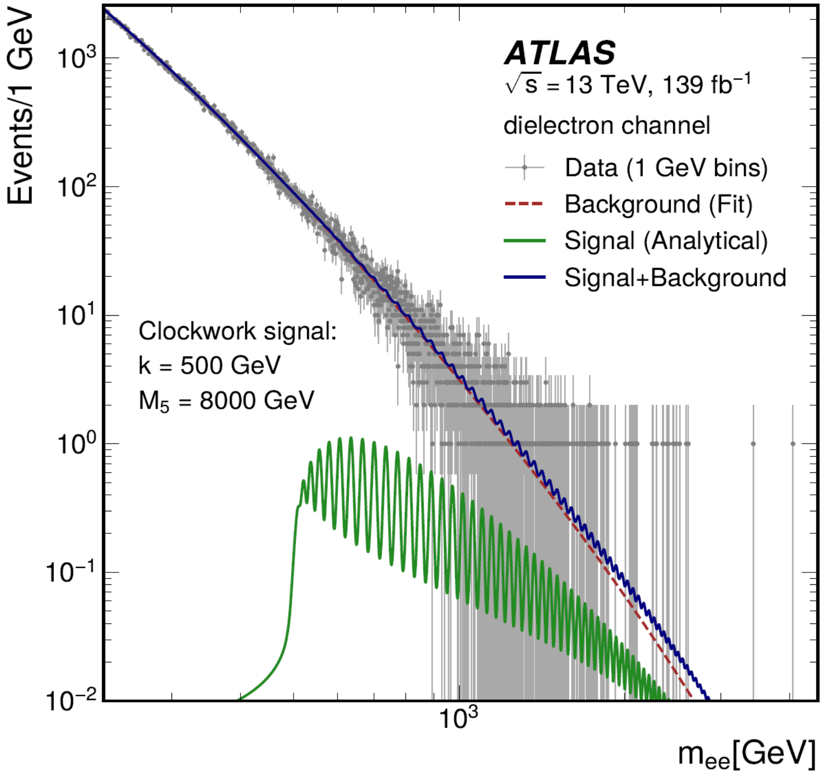
Periodic Signals (Clockwork): Analysis

2305.10894

- Search conducted in **di-photon and di-electron final states**
- Di-photon: Tight ID, photon $E_T > 25$ GeV, $E_T/m_{\gamma\gamma} > 0.35$ (0.25), $m_{\gamma\gamma} > 150$ GeV
- Di-electron: Medium ID, $E_T > 30$ GeV, $m_{ee} > 225$ GeV
- Background modelled with **fit function** determined from simulated mass distributions:

$$f_{\gamma\gamma}(x; b, a_0, a_1) = (1 - x^{1/3})^b x^{a_0 + a_1 \log(x)} \qquad f_{ee}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1-x)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}$$

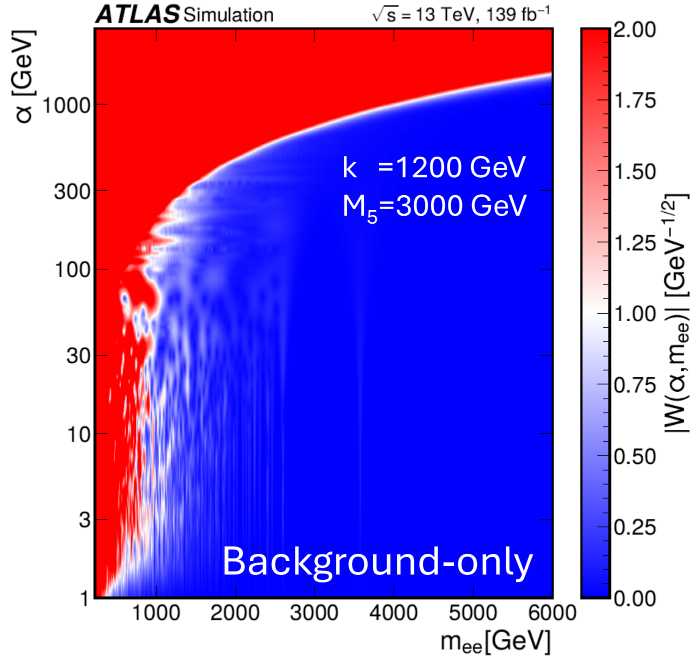


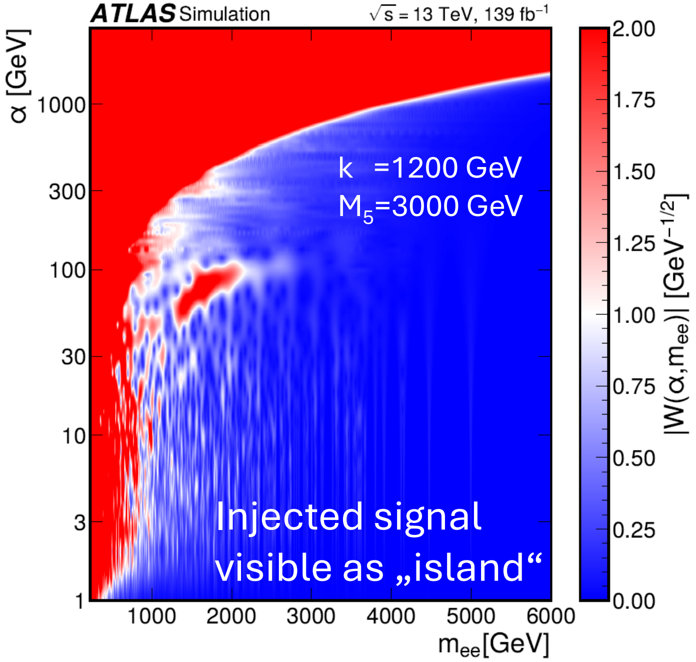


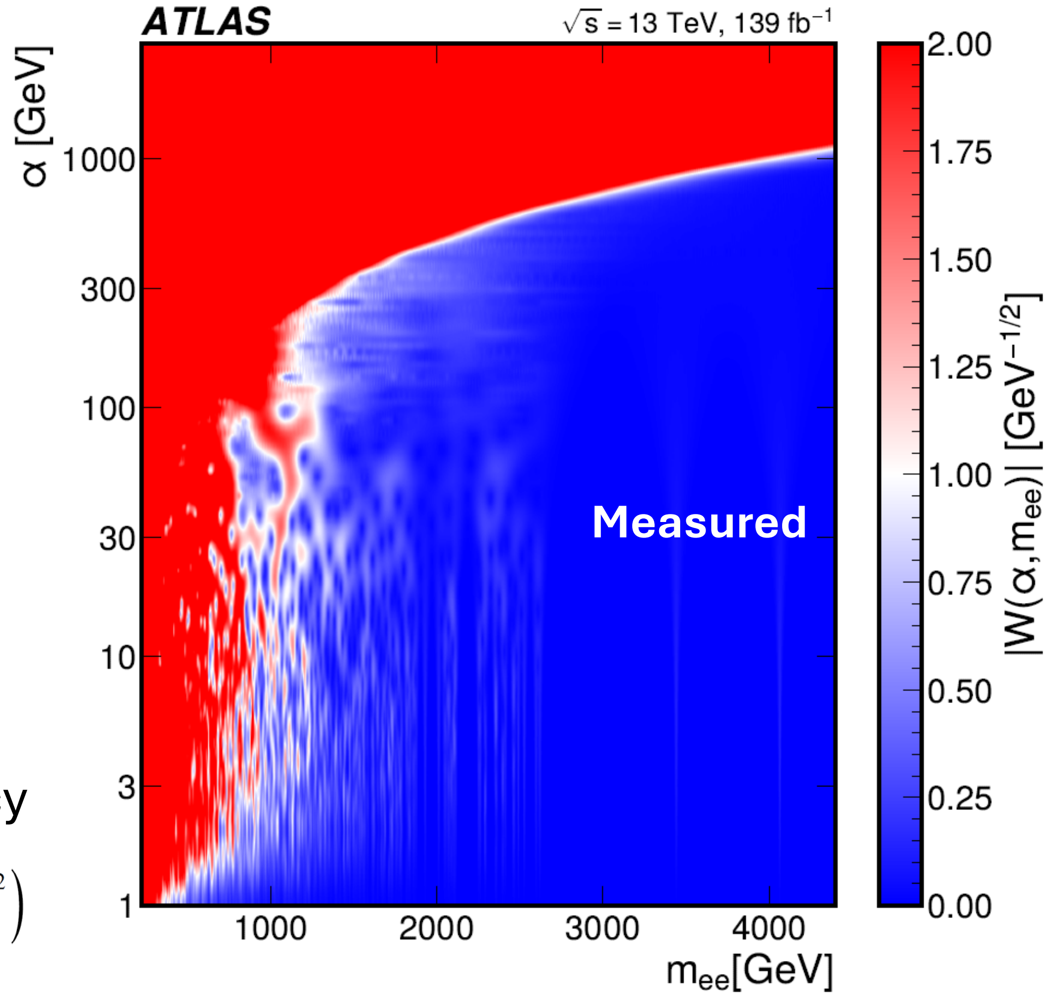
- **Signals also modelled with analytical functions** created for any point in the k-M_5 plane
- Validated with MC samples at specific parameter points

Periodic Signals (Clockwork): Analysis

2305.10894







- **Continuous wavelet transform (CWT)** used to transform the mass spectra into scalograms („image“) of mass vs. frequency

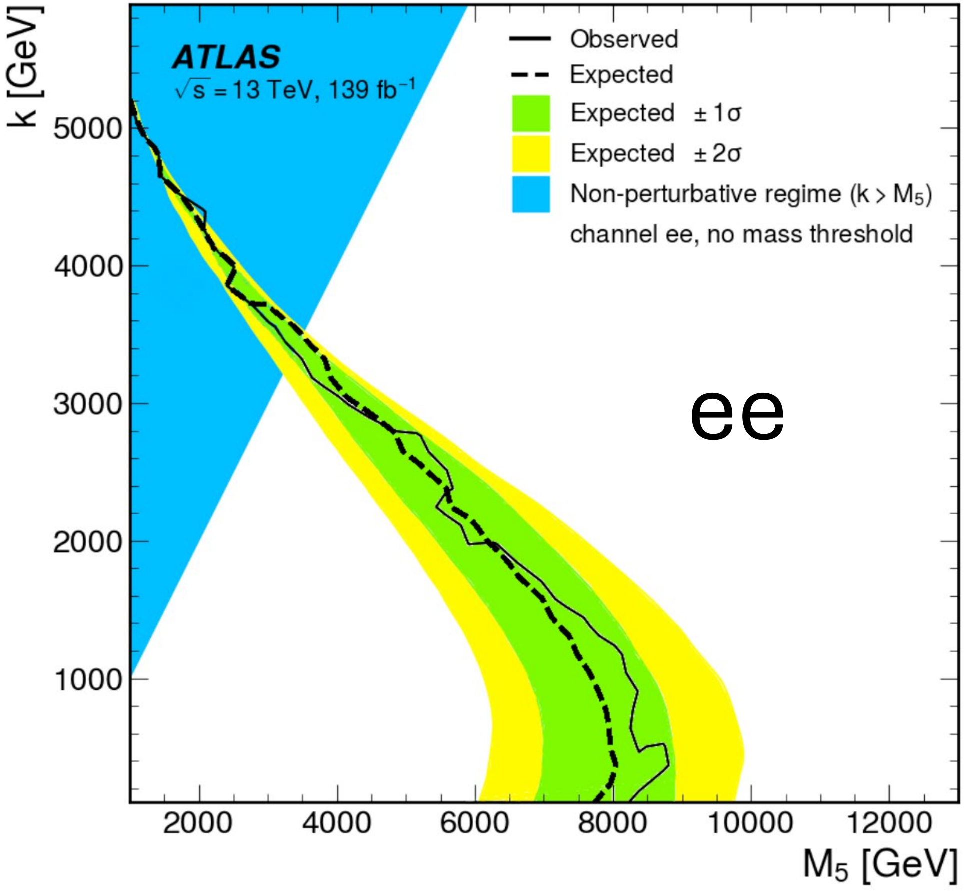
$$W(\alpha,\beta) = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{+\infty} f(m)\, \psi^* \left(\frac{m-\beta}{\alpha}\right) dm \qquad \psi(x) \equiv \frac{1}{\sqrt{B\pi}} e^{-x^2/B} \left(e^{i2\pi Cx} - e^{-\pi^2 BC^2}\right)$$

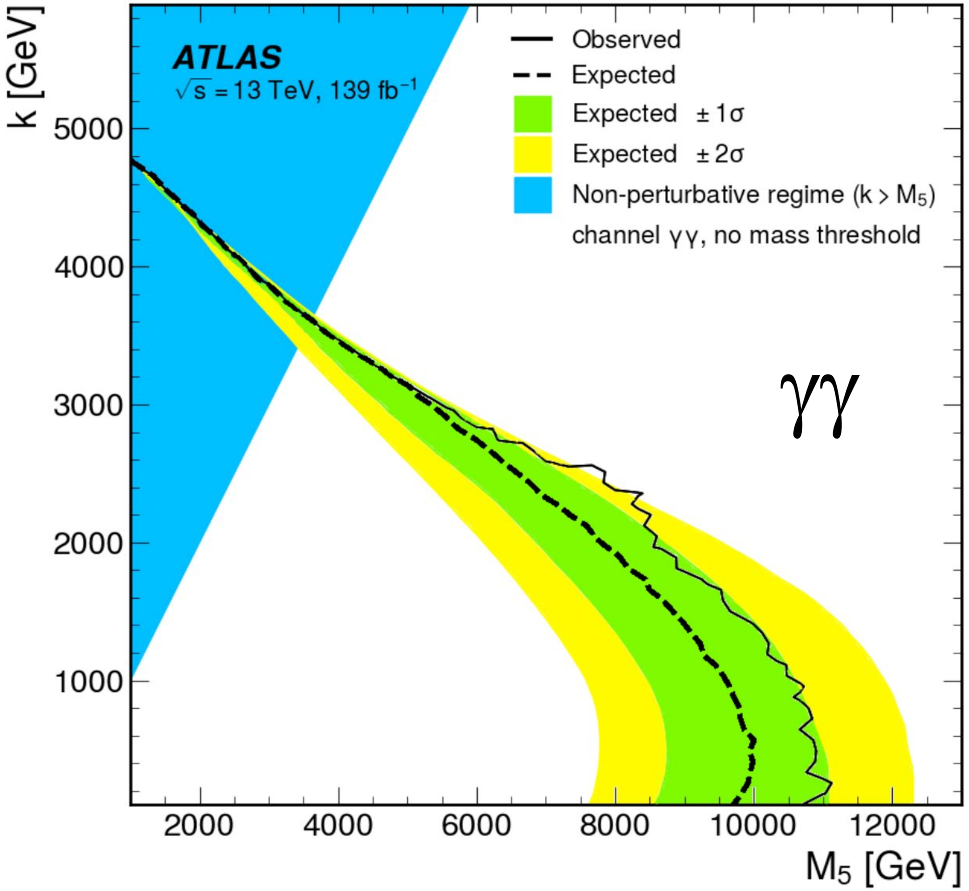
Morlet wavelet. B=2, C=1

- Scaling parameter α either dilates or compresses the signal. It is inversely proportional to the frequency (meaning if α is large, then the signal is „stretched“)
- **Convolutional neural networks** or **Autoencoder** used to search for anomalies („islands“) in the scalogram

Periodic Signals (Clockwork): Results

2305.10894





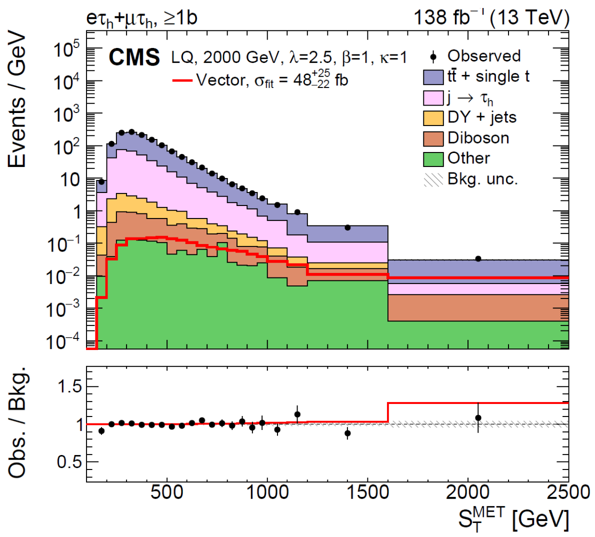
- No significant excess found, largest significance 1.5σ in the dielectron channel for **model-independent** AE analysis
- **Model-dependent limits in k-M_5 plane** derived, obtained from the classifier NN analysis.
- **Maximum excluded M_5 value is 11 TeV (8 TeV) for the $\gamma\gamma$ (ee) channel.**

Leptoquarks decaying to τ + b: 2308.07826

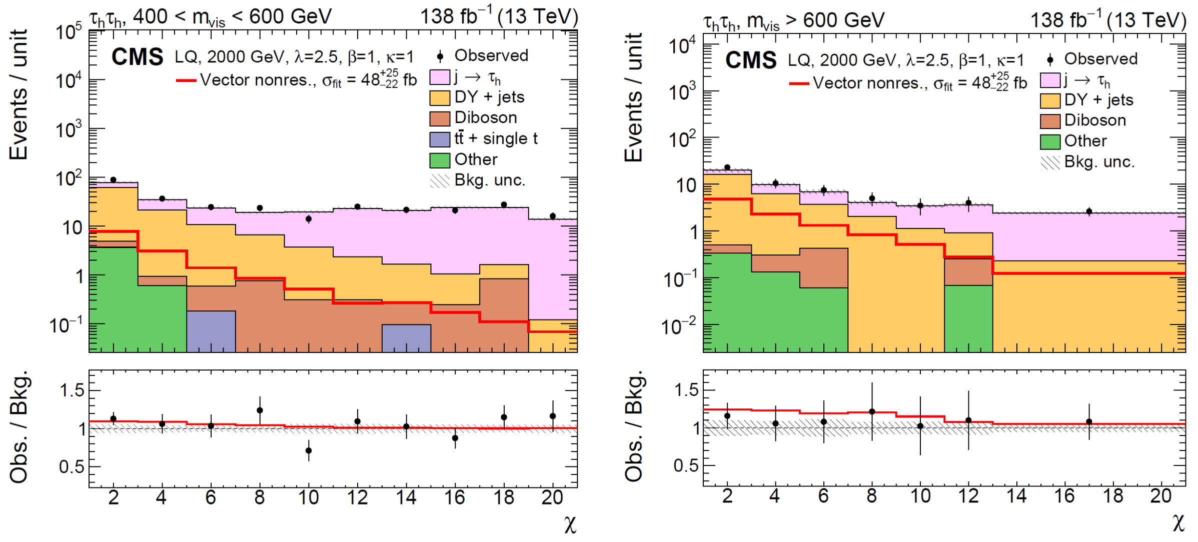
(Result from 2023)

- Produced singly resonant or nonresonant, and pair-produced.
  Non-resonant dominates cross section for large values of λ, scales with λ^4
- Analysis selects events with two leptonicaly or hadronicaly decaying taus ($e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$, $e\mu$, $\mu\mu$)
- Resonant: 0 or ≥1 b-jet, non-resonant: veto of high-pT jets
- Final discriminants: for non-resonant the angular separation of the taus $\chi = \exp(|\Delta\eta|)$,
  for resonant the scalar p_T sum $S_T^{MET} = p_T^1+p_T^2+p_T^3+p_T^{miss}$

Resonant

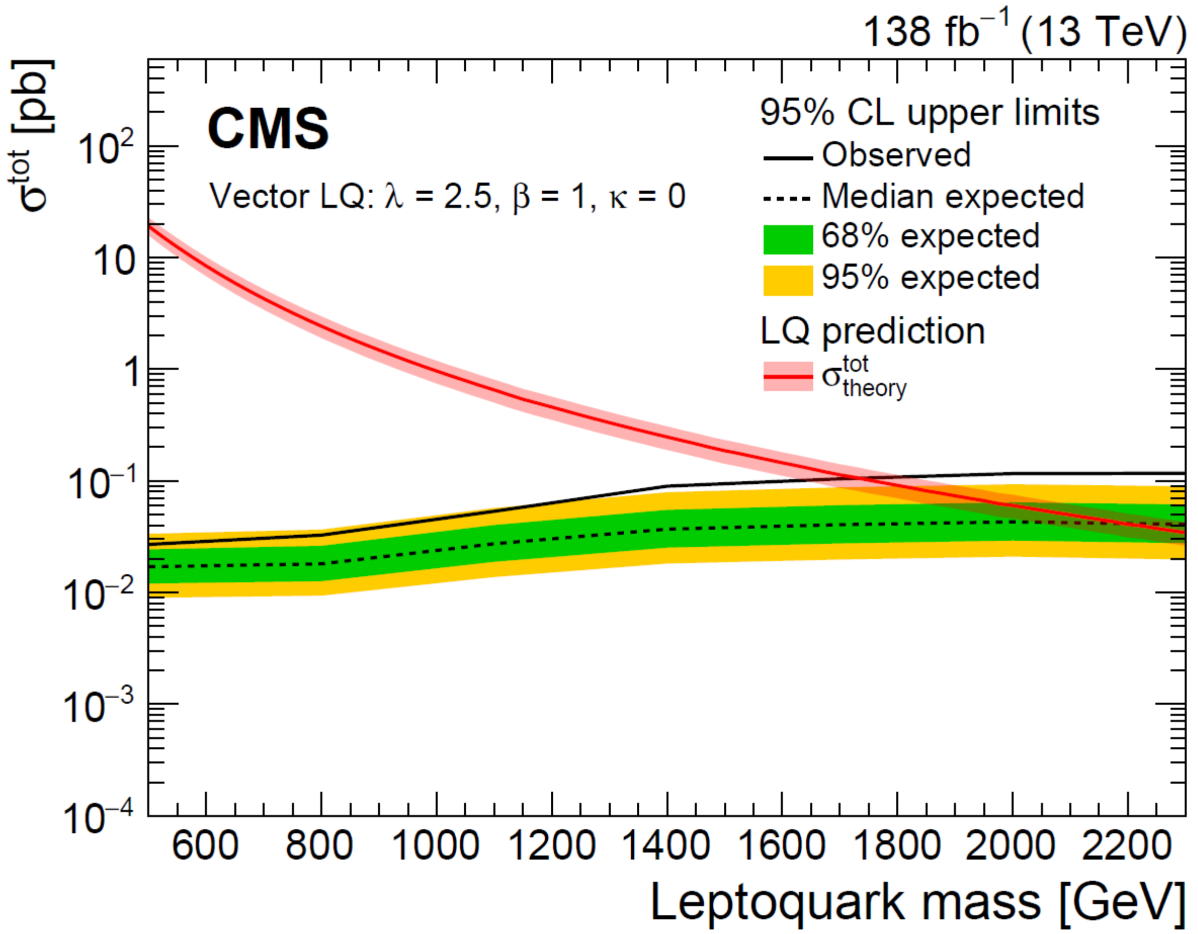


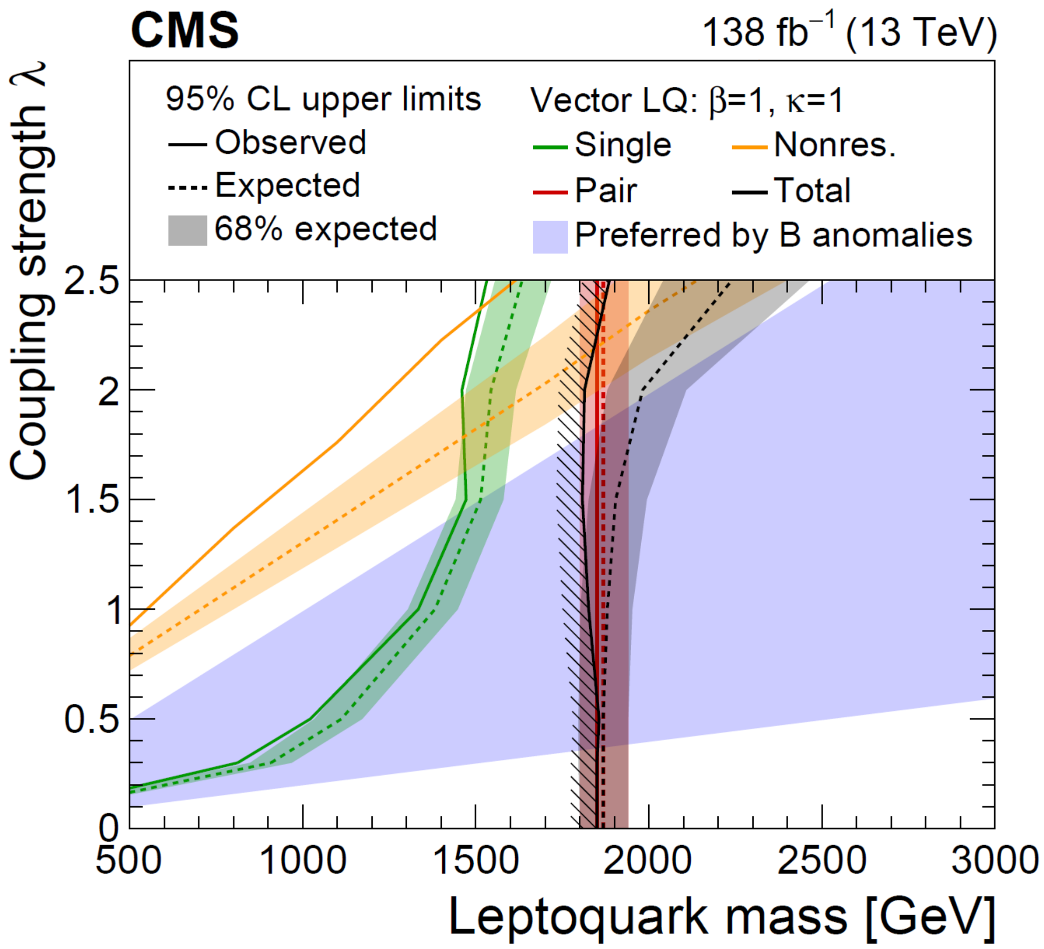
Non-resonant



Leptoquarks decaying to τ + b: 2308.07826

(Result from 2023)





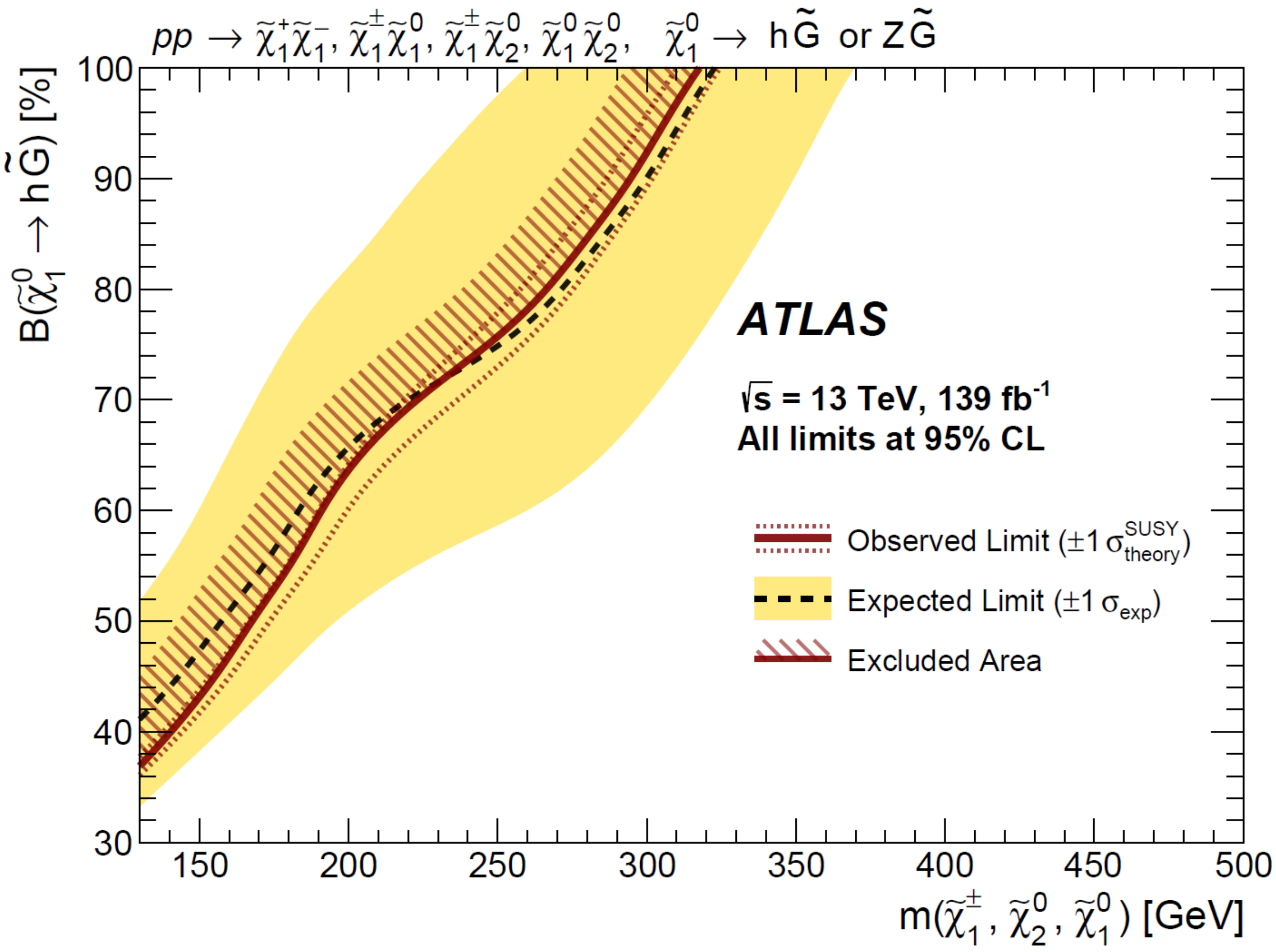
Vector LQ for λ=2.5, β=1 and κ=1 excluded for masses below 1.7 TeV

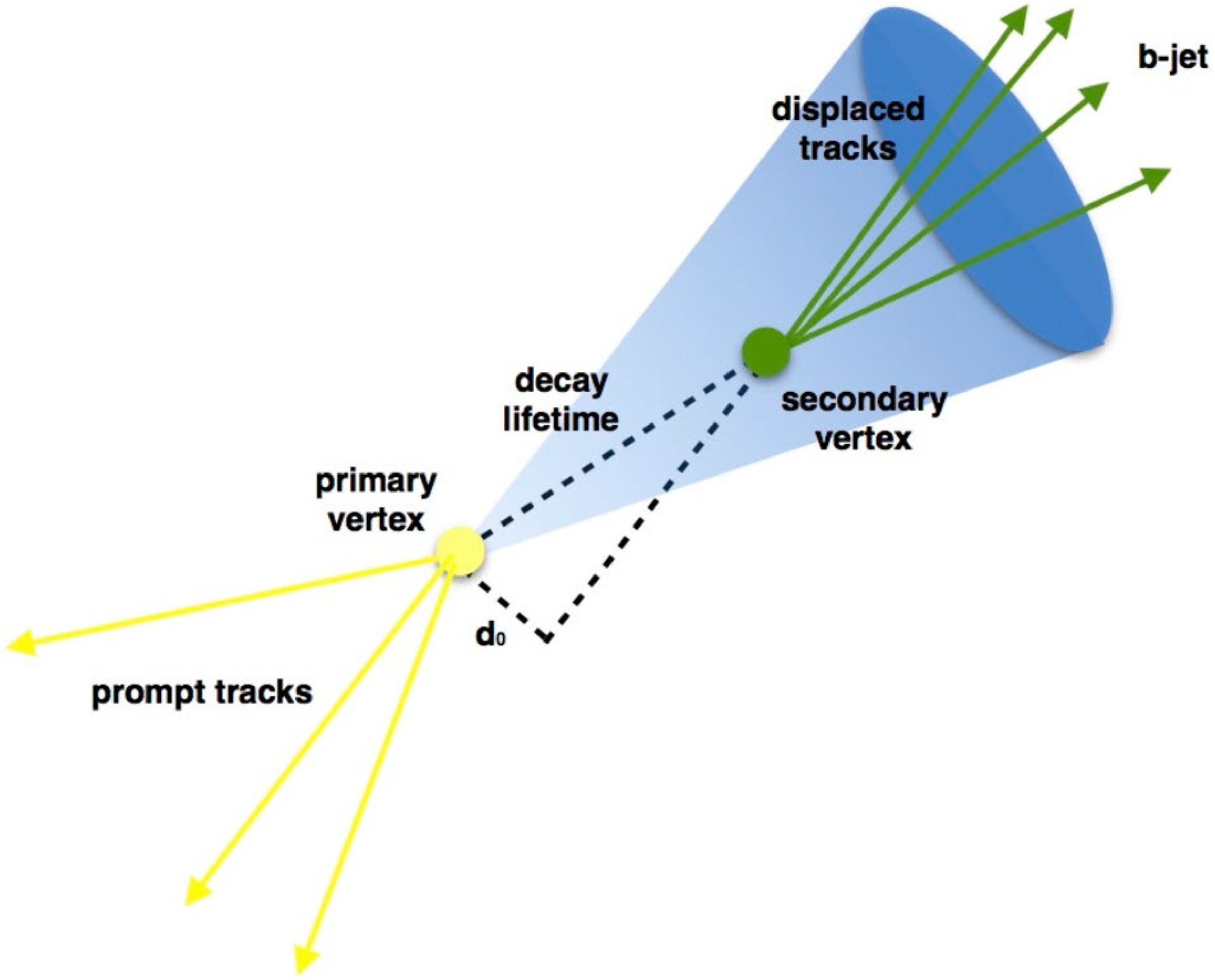
Broad excess found

2.8σ local significance for 2 TeV LQ mass at λ=2.5

Pair-produced Higgsinos

2404.01996




b-jet
displaced
tracks
decay
lifetime
secondary
vertex
primary
vertex
d0
prompt tracks