Non-resonant searches at the TeV scale

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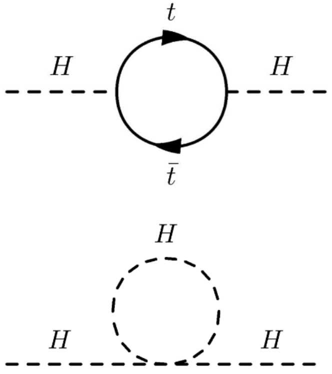
on behalf of the ATLAS and CMS collaborations

LHCP – June 4th 2024

Introduction

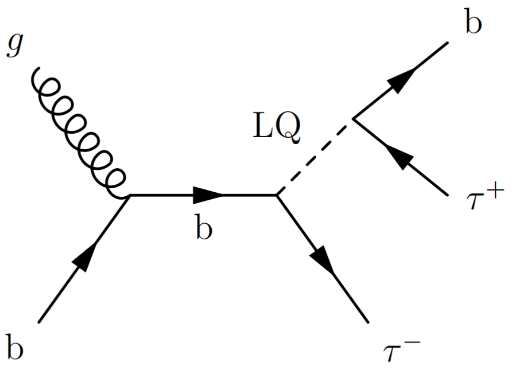


- **Many unresolved questions that the Standard Model cannot answer** (eg. dark matter, Higgs mass fine tuning, baryogenesis, neutrino masses, …)
- **Wide range of new physics searches are conducted at the LHC**, such as for new resonances (Louis' talk), Extended Higgs sector (Shigeki's talk), Long-lived 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)

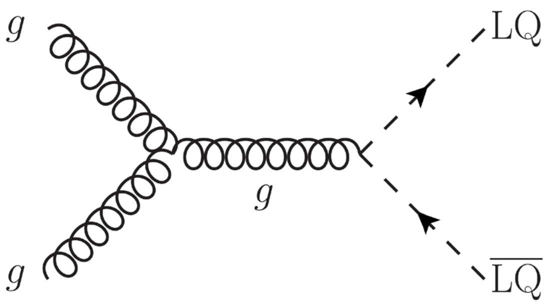
Leptoquarks

- 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:**

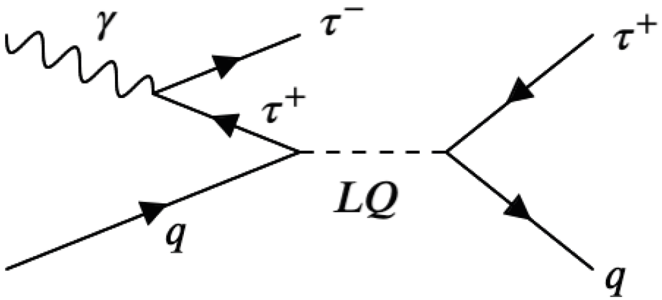
Quark-gluon fusion



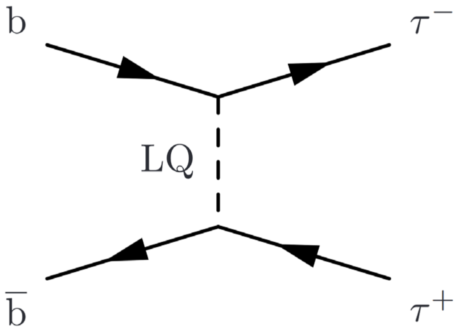
Pair production



τ-quark collision



Non-resonant t-channel



Leptoquarks decaying to μ + b

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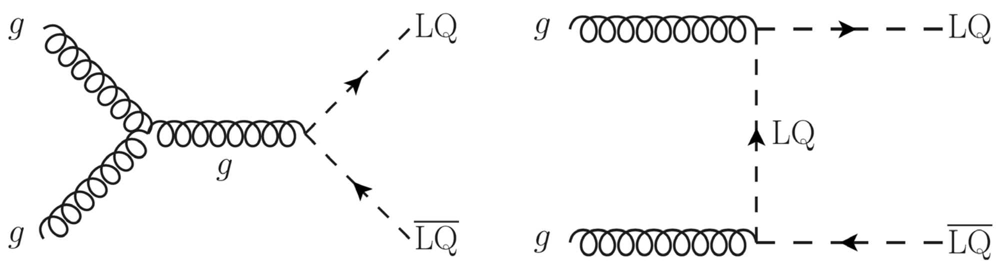
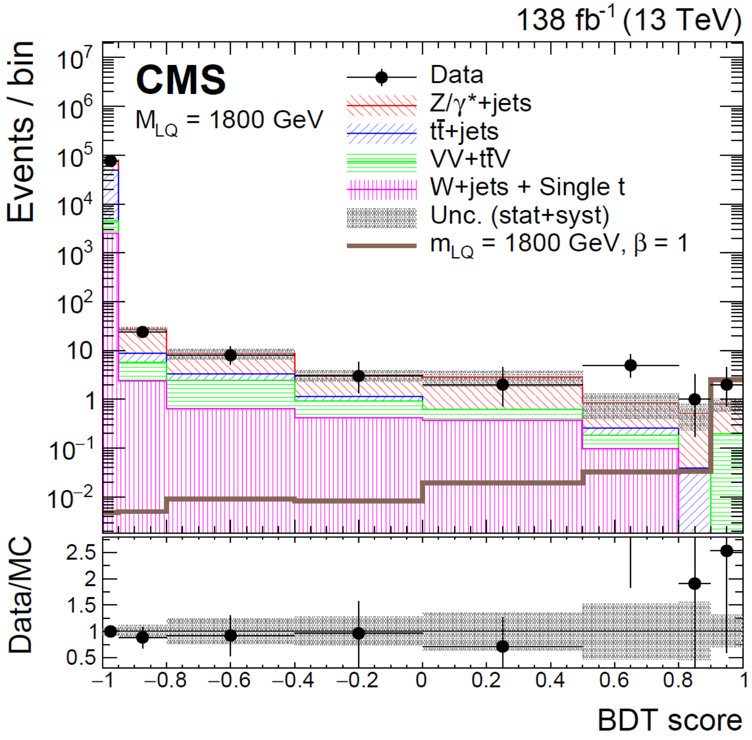
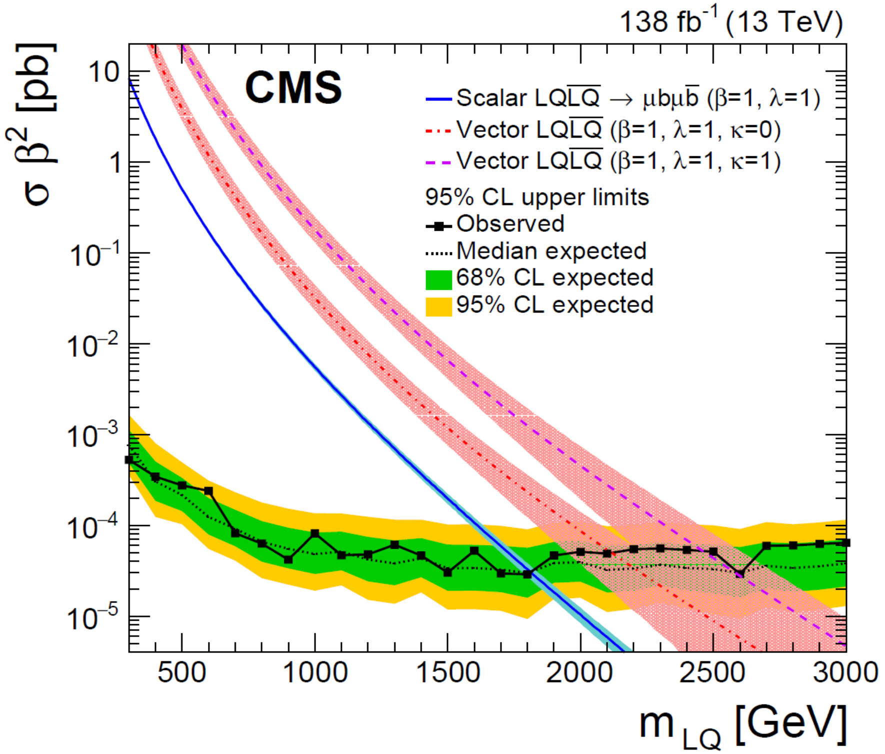
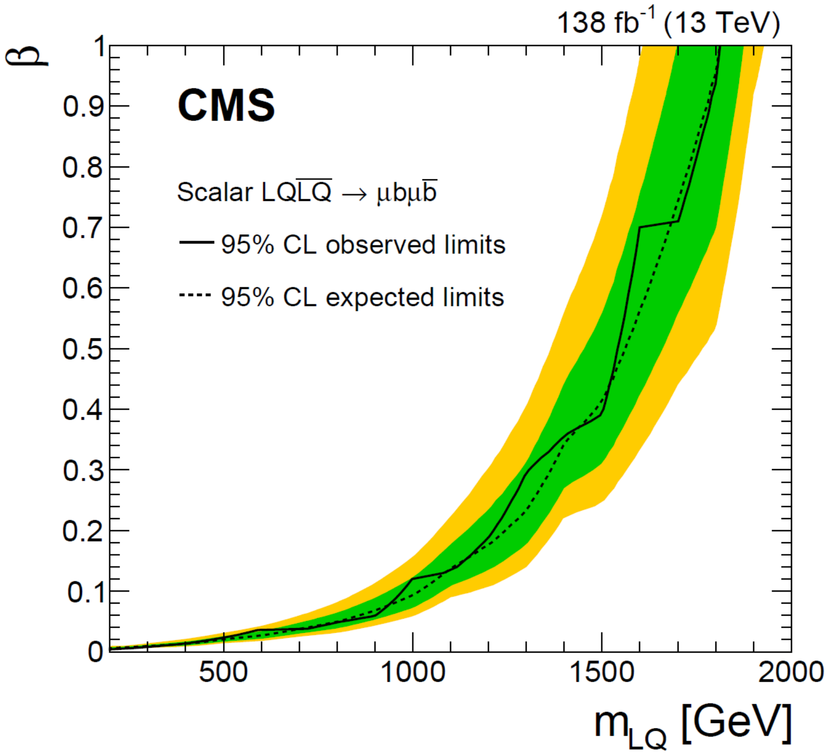


- Only **LQ pair production** considered
- Final state: Two muons (p_T > 53 GeV, $m_{\mu\mu}$>250 GeV), two jets (p_T > 50 GeV) among which at least one is b-tagged
- Two control regions for background estimation (Z, tt; VV, ttV)

- **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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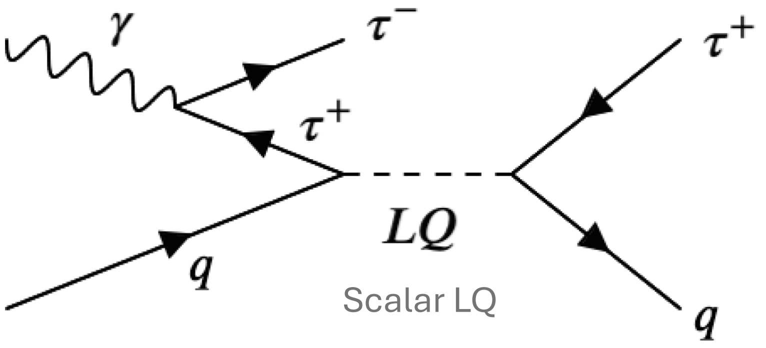
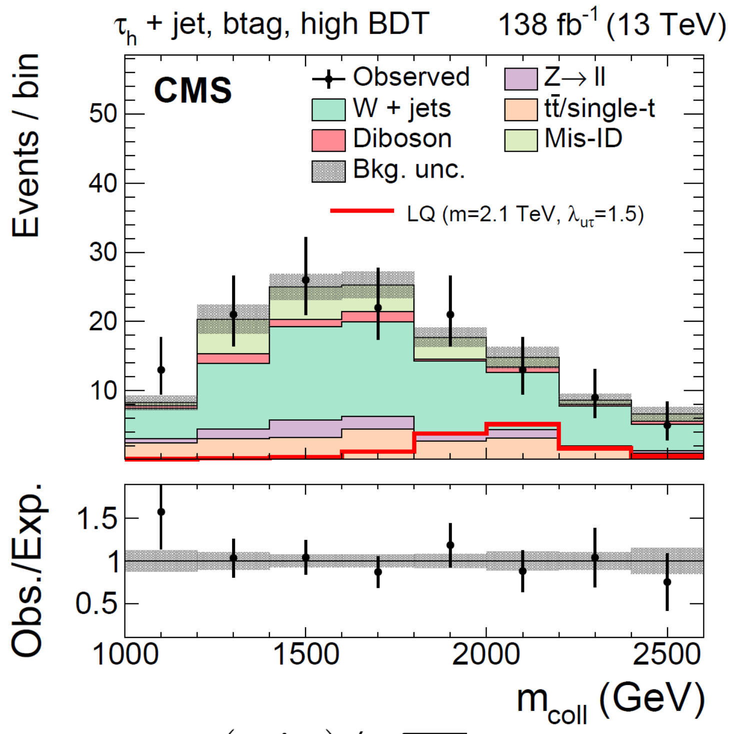


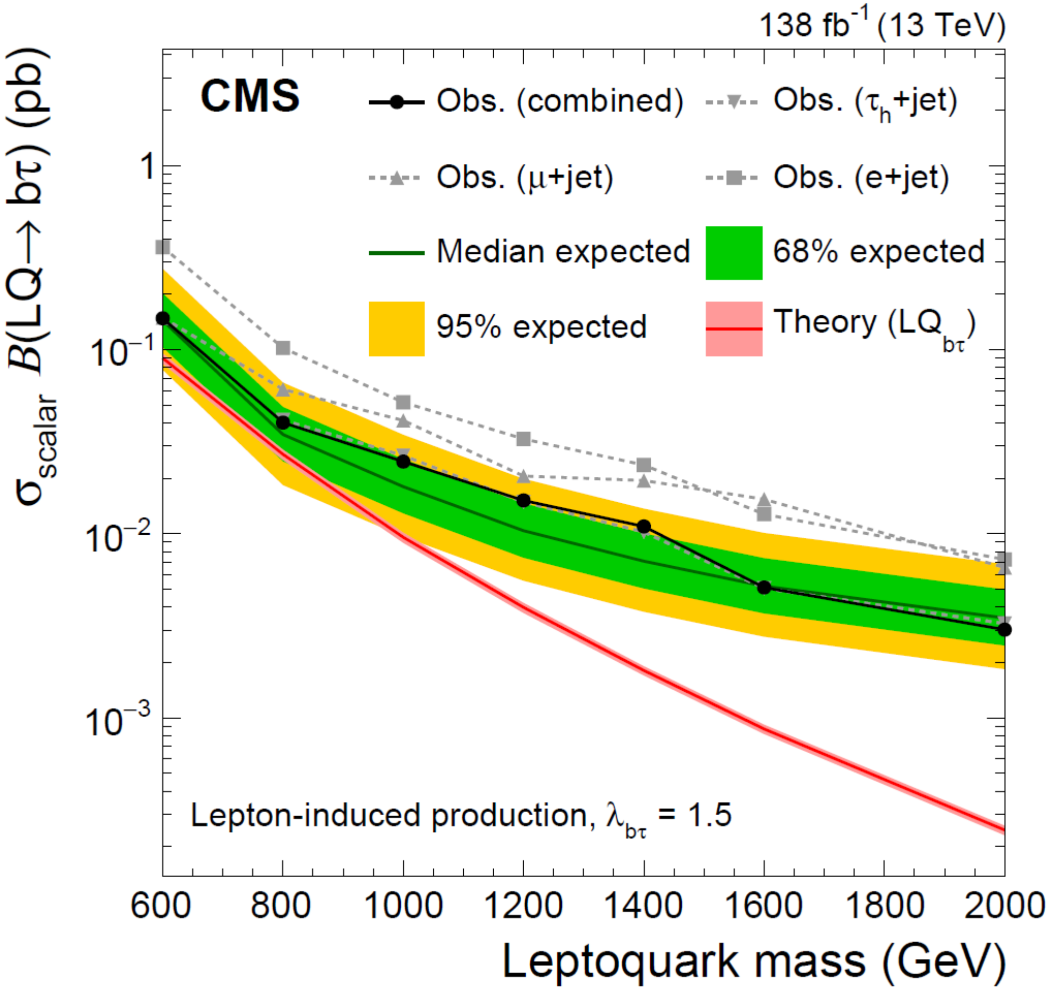
- **Novel production mode**, made possible by advancements in the lepton and photon density functions of the proton
- Exploring three channels: hadronic **τ + jet**, **e + jet**, **μ + jet**, further separated if jet is **b-tagged or not** (different LQ decays)



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

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

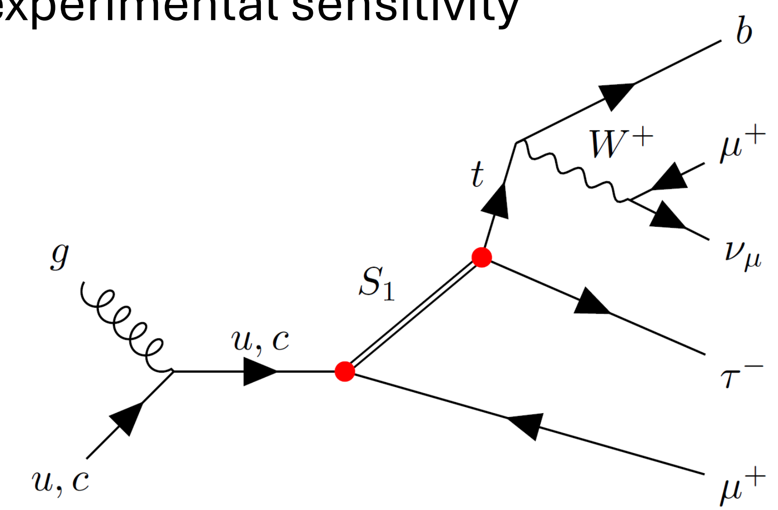
- **BDTs trained in each channel** to separate signal from background
- Categories based on the BDT score → **7 signal-enriched categories**
- Final discriminant: **collinear mass**
- W+jets background normalization estimated from **control region** that is fitted simultaneously

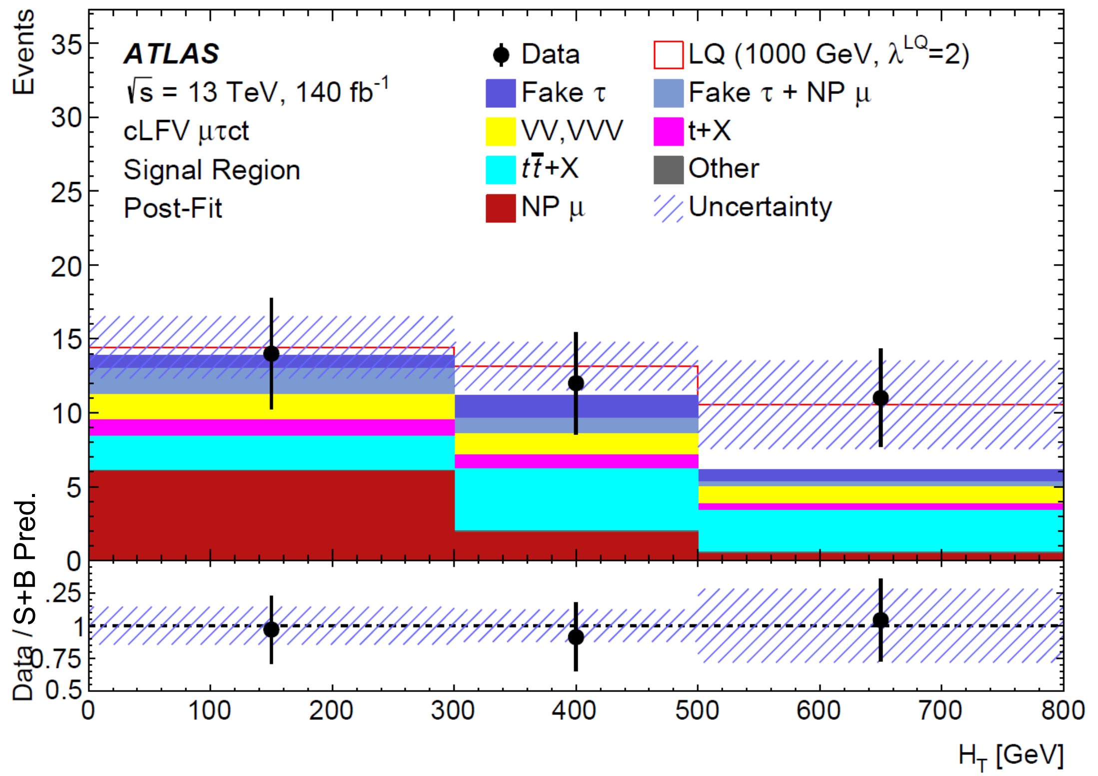


Leptoquarks via charged-lepton-flavor violation 2403.06742

- SM-predicted charged-lepton-flavor violation (cLFV) rates well below experimental sensitivity
- Leptoquarks are a candidate for introducing BSM cLVF 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**)

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





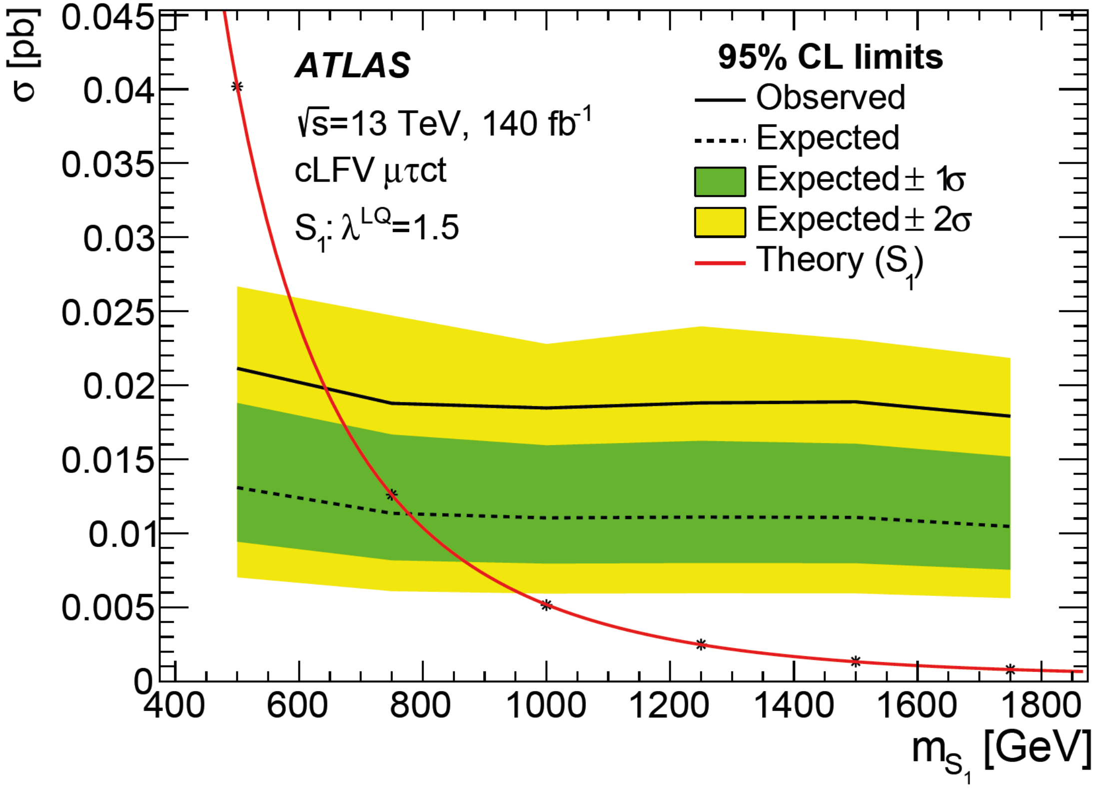
Analysis:

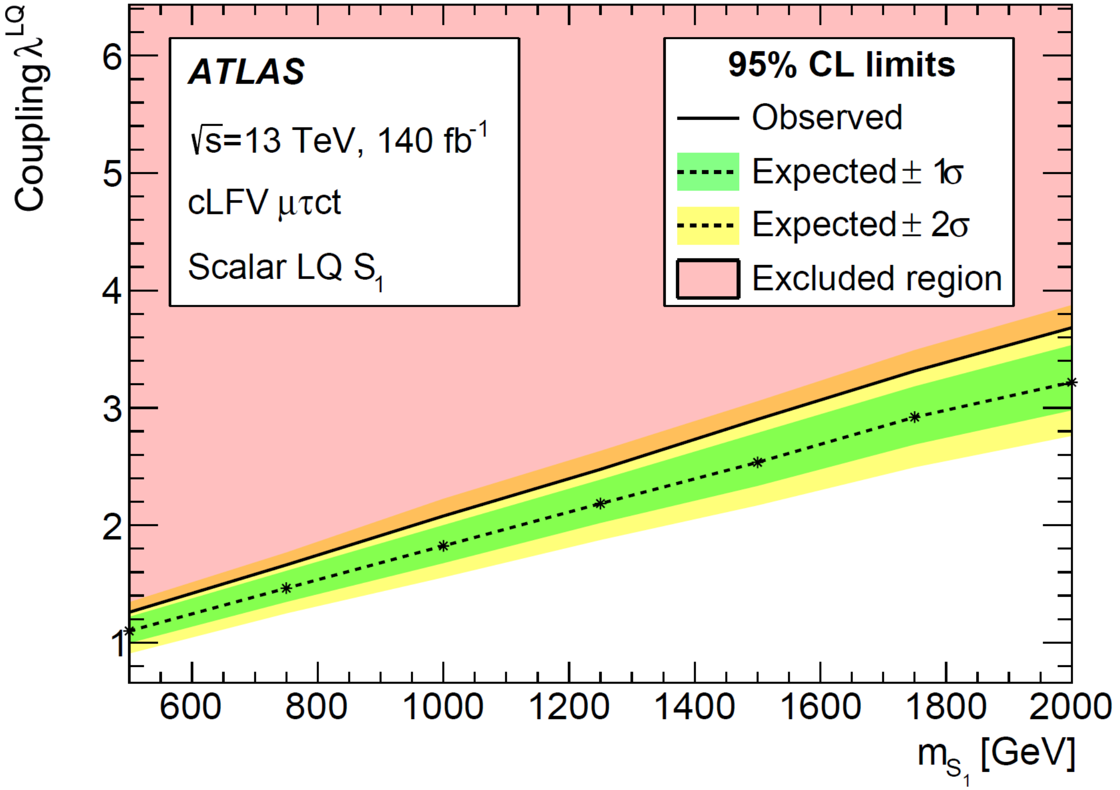
- Final state: 2 μ (same-sign), 1 τ_{had}, ≥ 1 jet (including exactly one b-jet)
- Final discriminant: scalar sum of the lepton and jet transverse momenta H_T
- **Slight excess at high H_T bins (~ 1.6σ)** here shown for m_{S_1}=1 TeV and λ^{LQ}=2.0
- Fit includes SR and a CR enriched in ttbar+μ events

Leptoquarks via charged-lepton-flavor violation

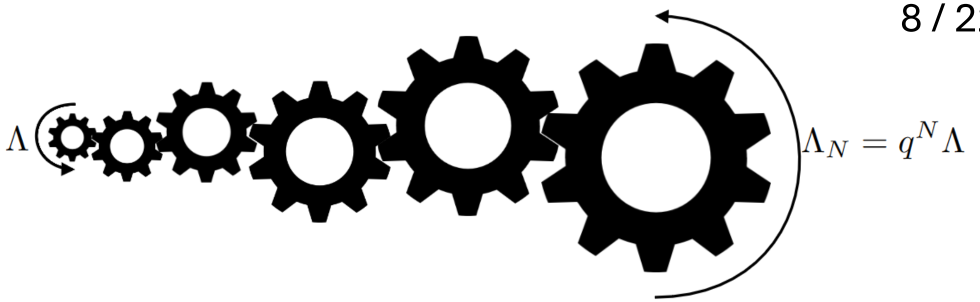
2403.06742

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

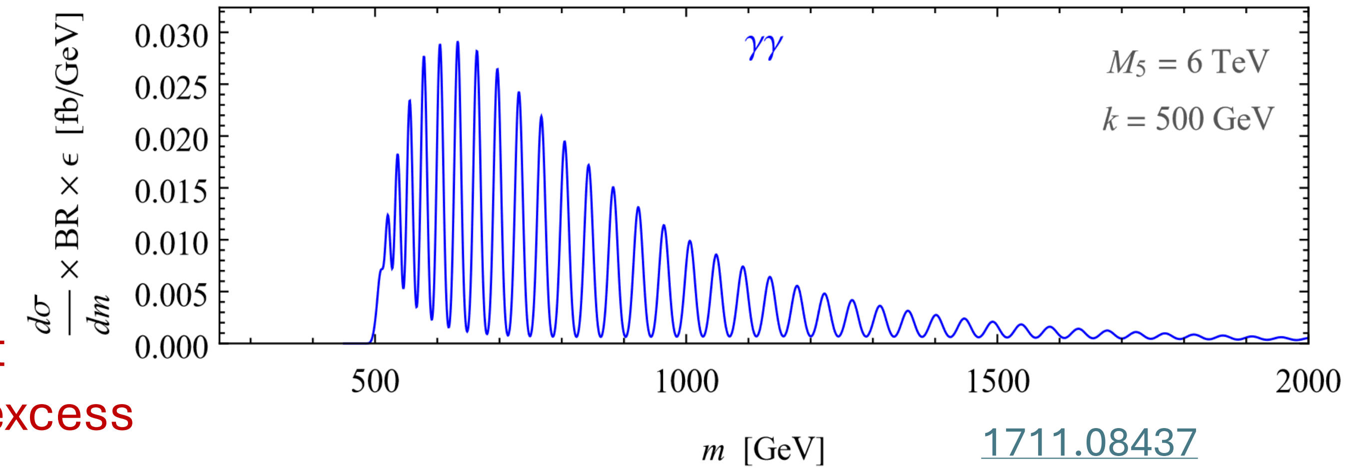




Periodic Signals (Clockwork)



- **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

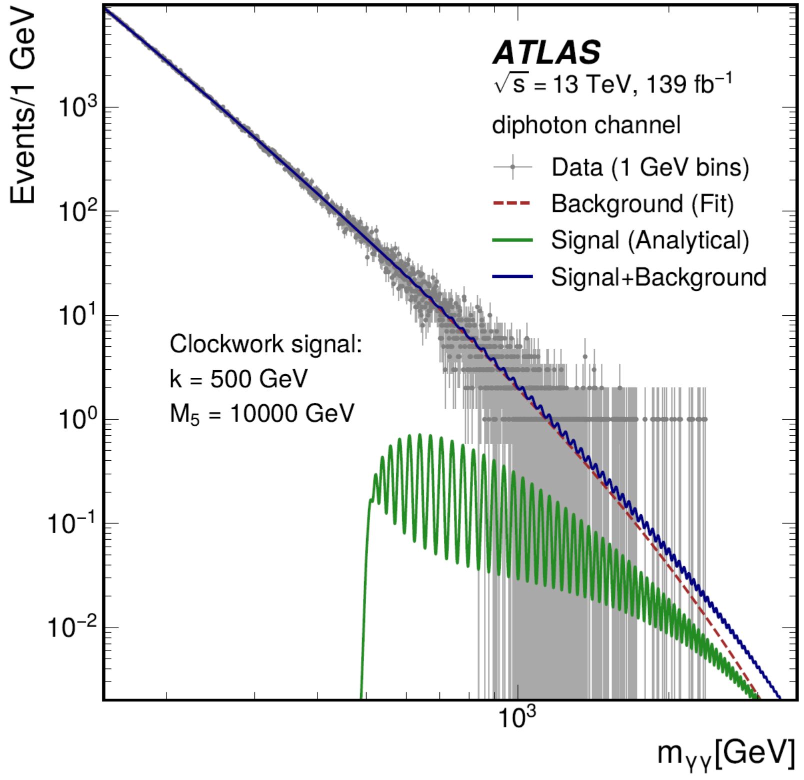


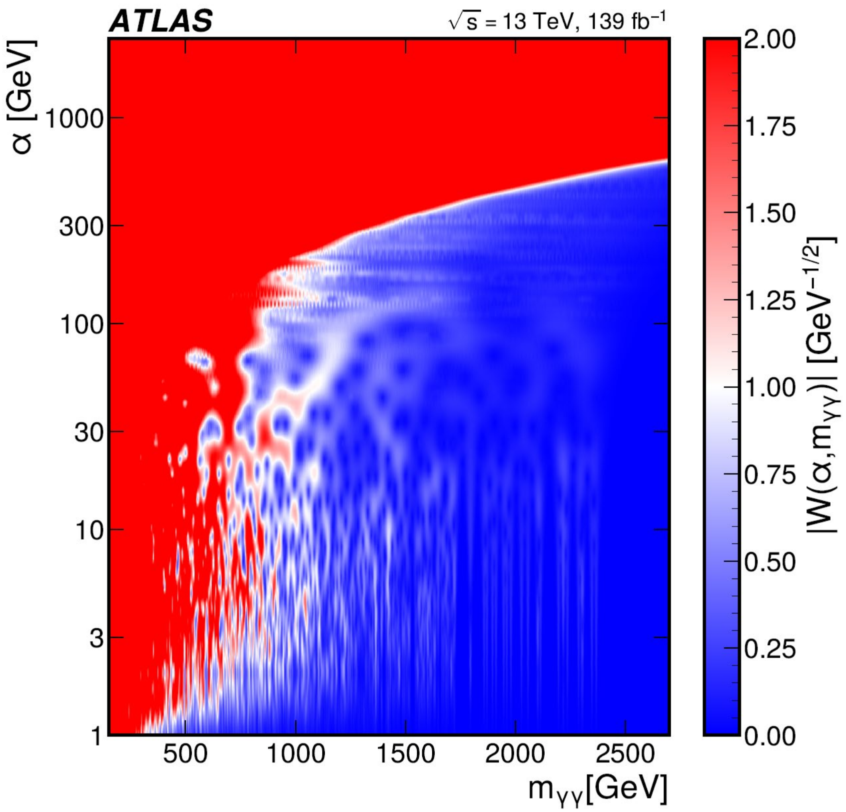
1711.08437

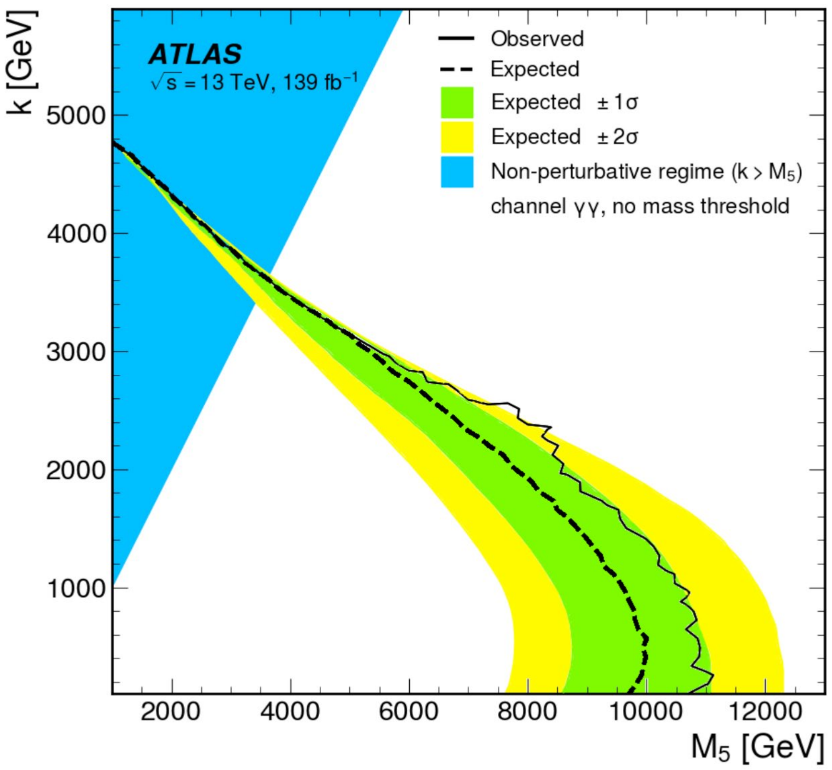
Periodic Signals (Clockwork)

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



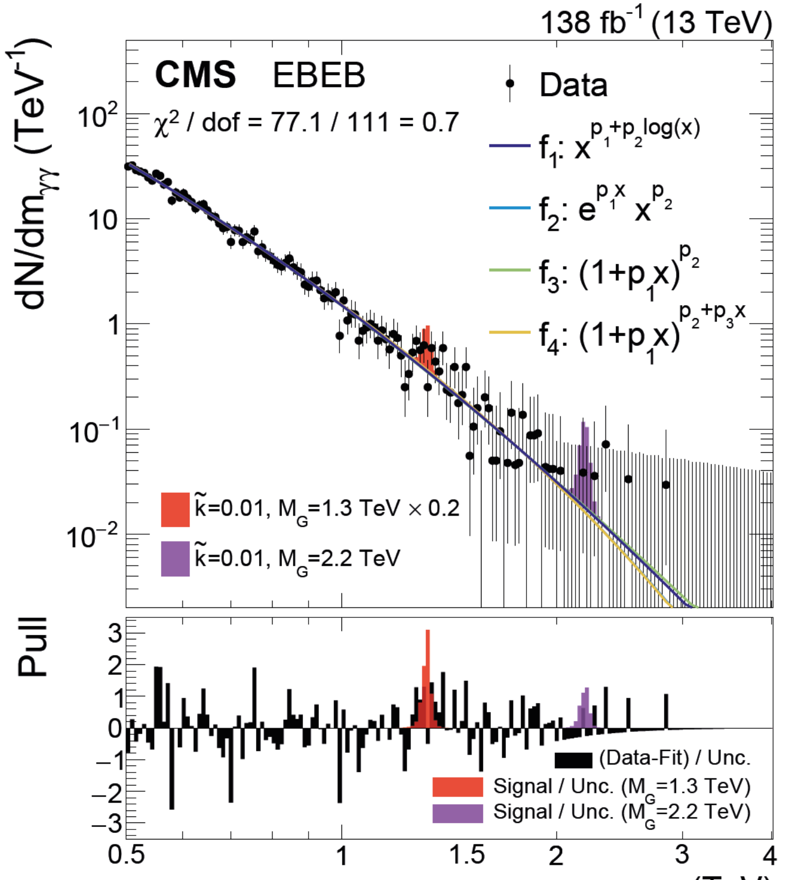




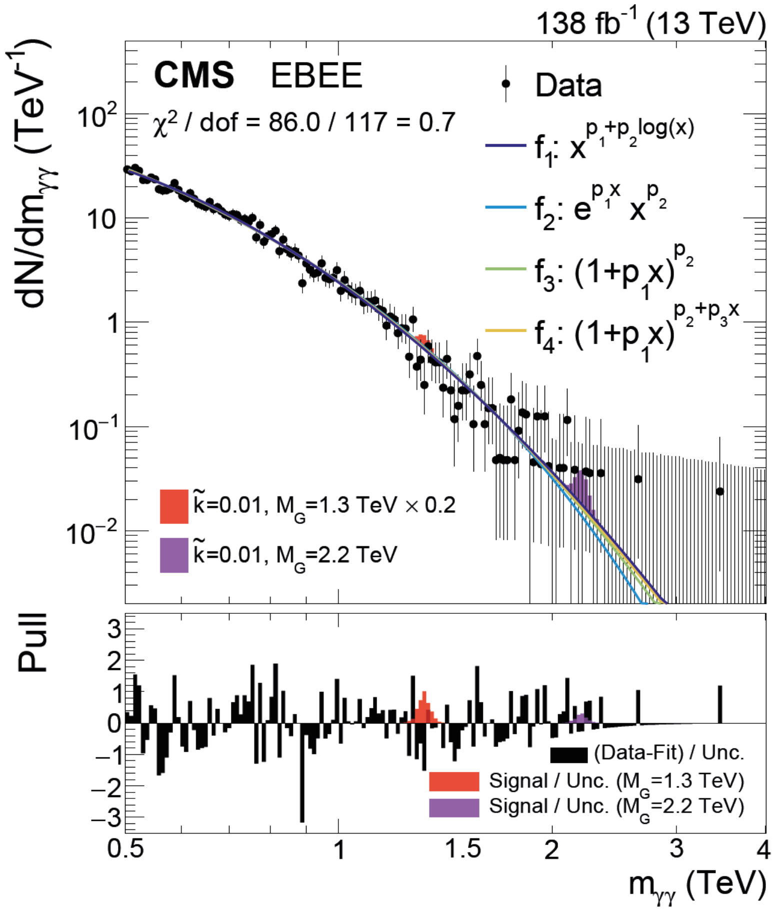
Broad Resonances in Diphoton

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.



$\tilde{k} = \sqrt{8\pi}\, k/\overline{M}_{\rm Pl}$



- 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:

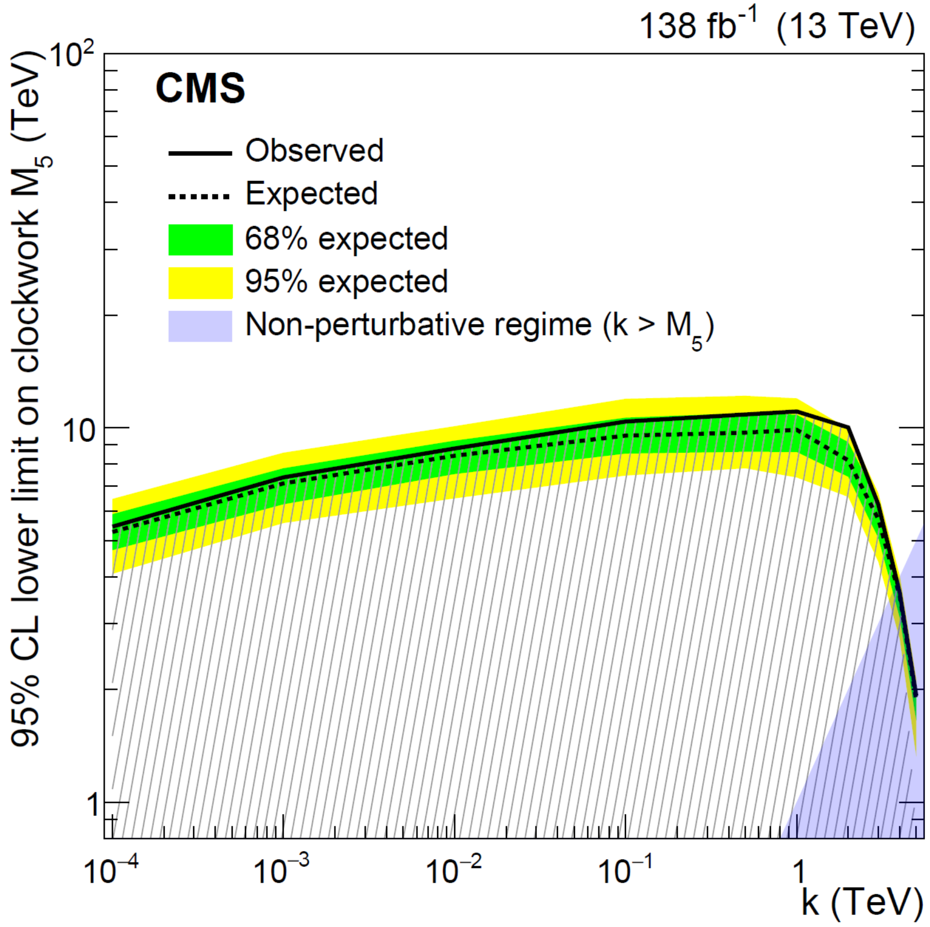
Lower limits on the mass scale M_S [TeV] for three theory conventions:

- 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

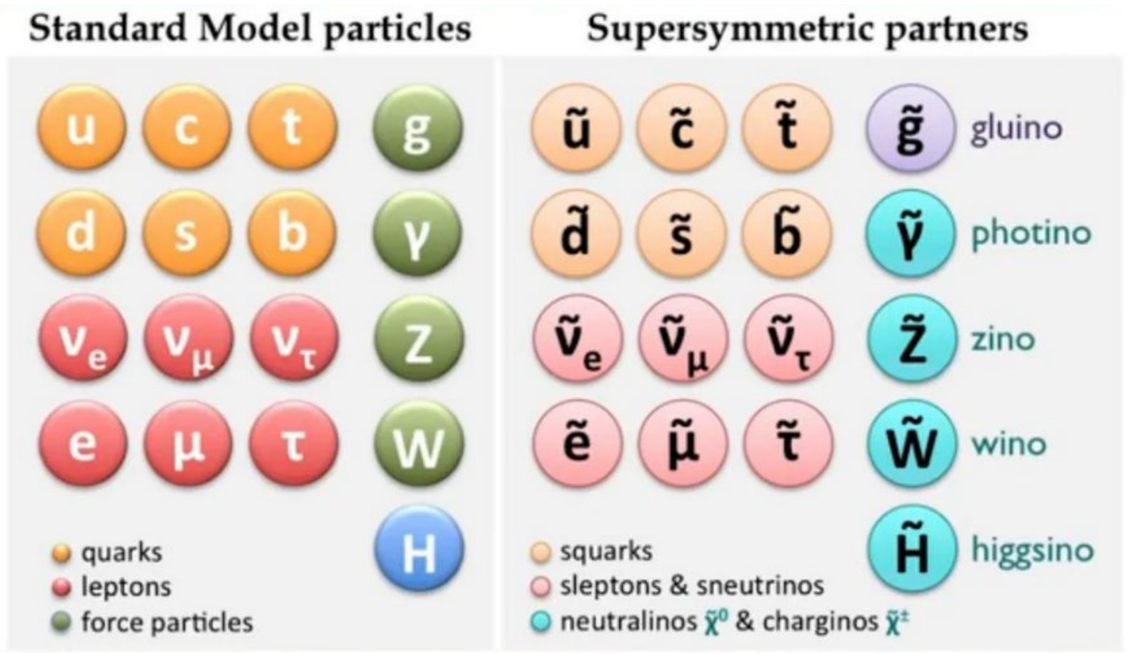
Continous clockwork gravity model: →

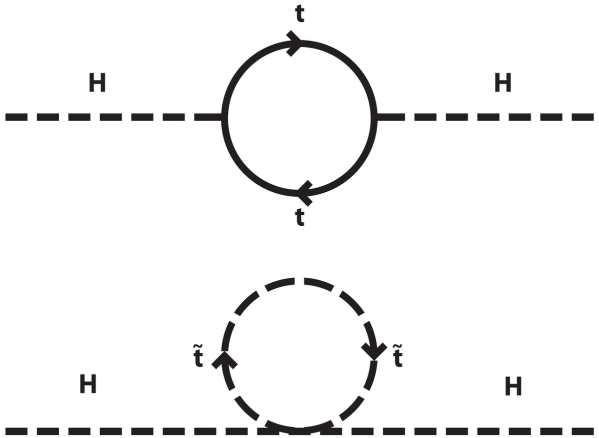


Values of M_5 excluded for k values in the range of 0.2 – 2000 GeV.
Strongest exclusion of M_5 < 11 TeV for k=1 TeV

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

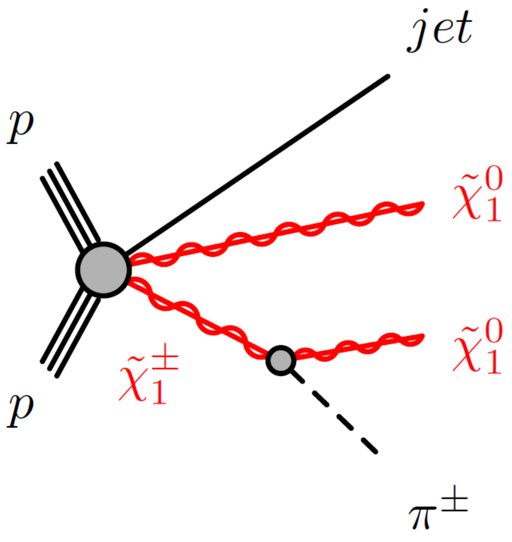
R-parity:

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

+1 for SM, -1 for SUSY partners

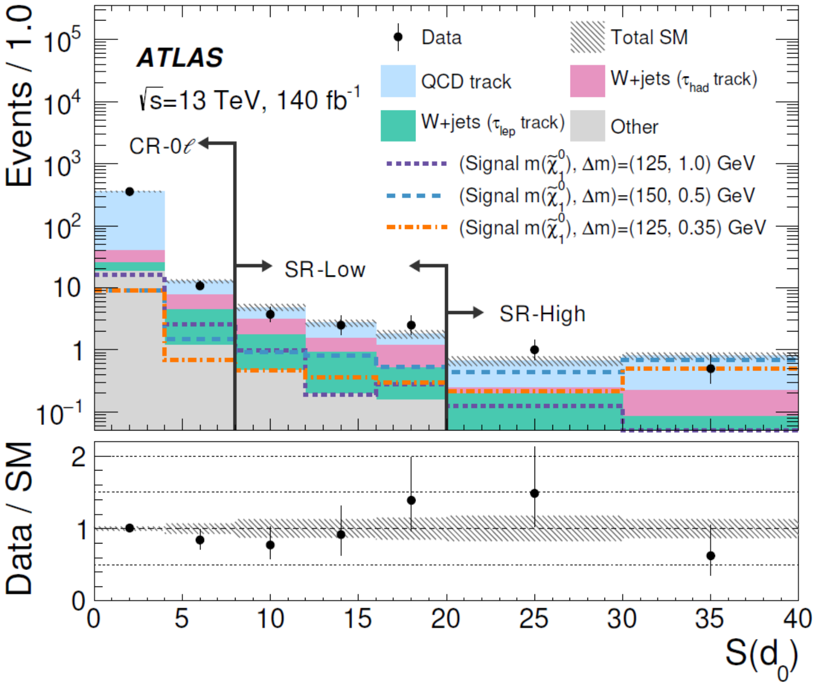
In R-violation scenarios the LSP is not stable

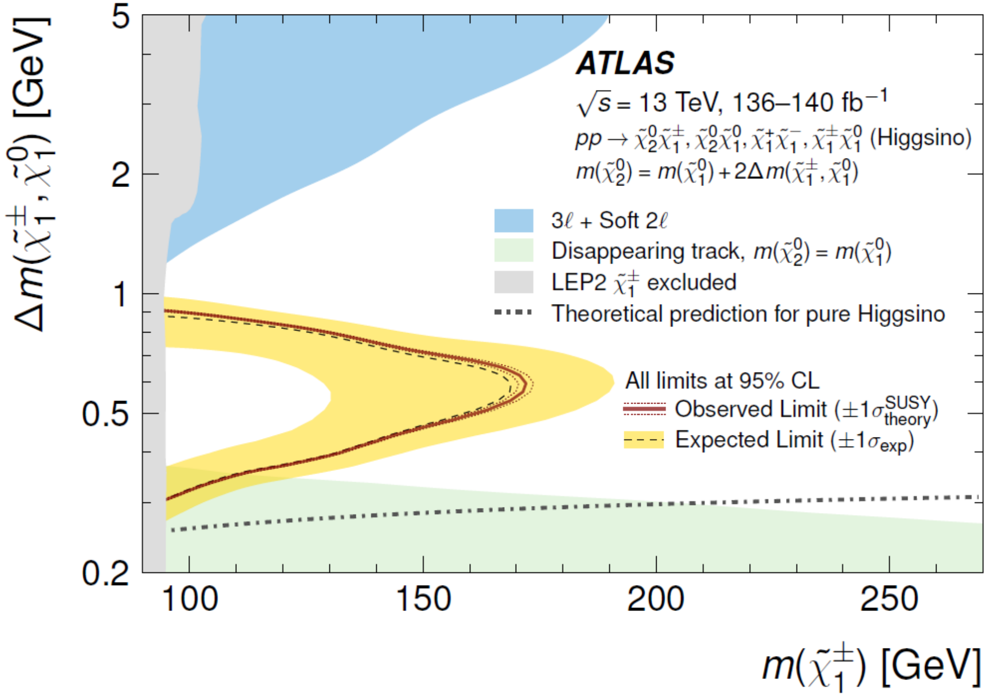
Compressed Higgsinos with mildly-displaced tracks 2404.01996



- 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**

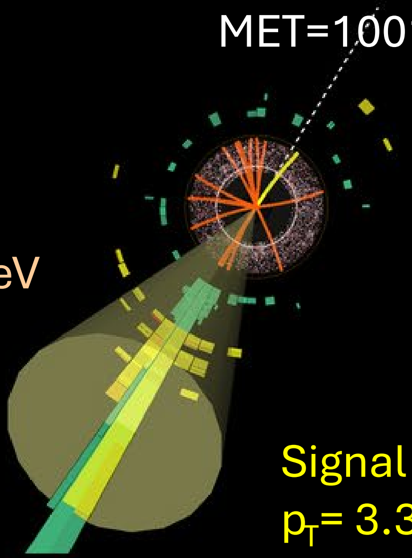




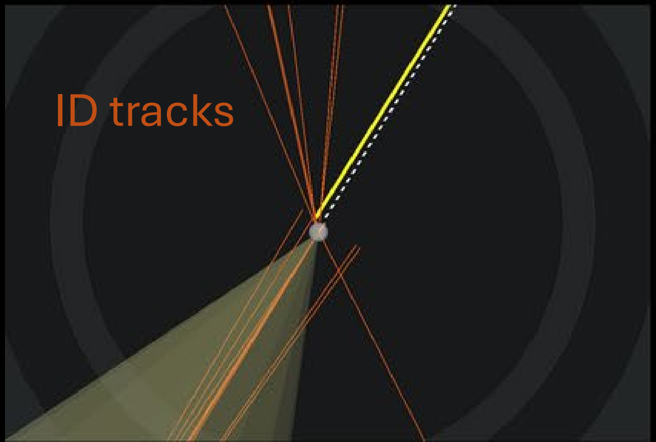
Higgsino decay candidate event from the SR-High

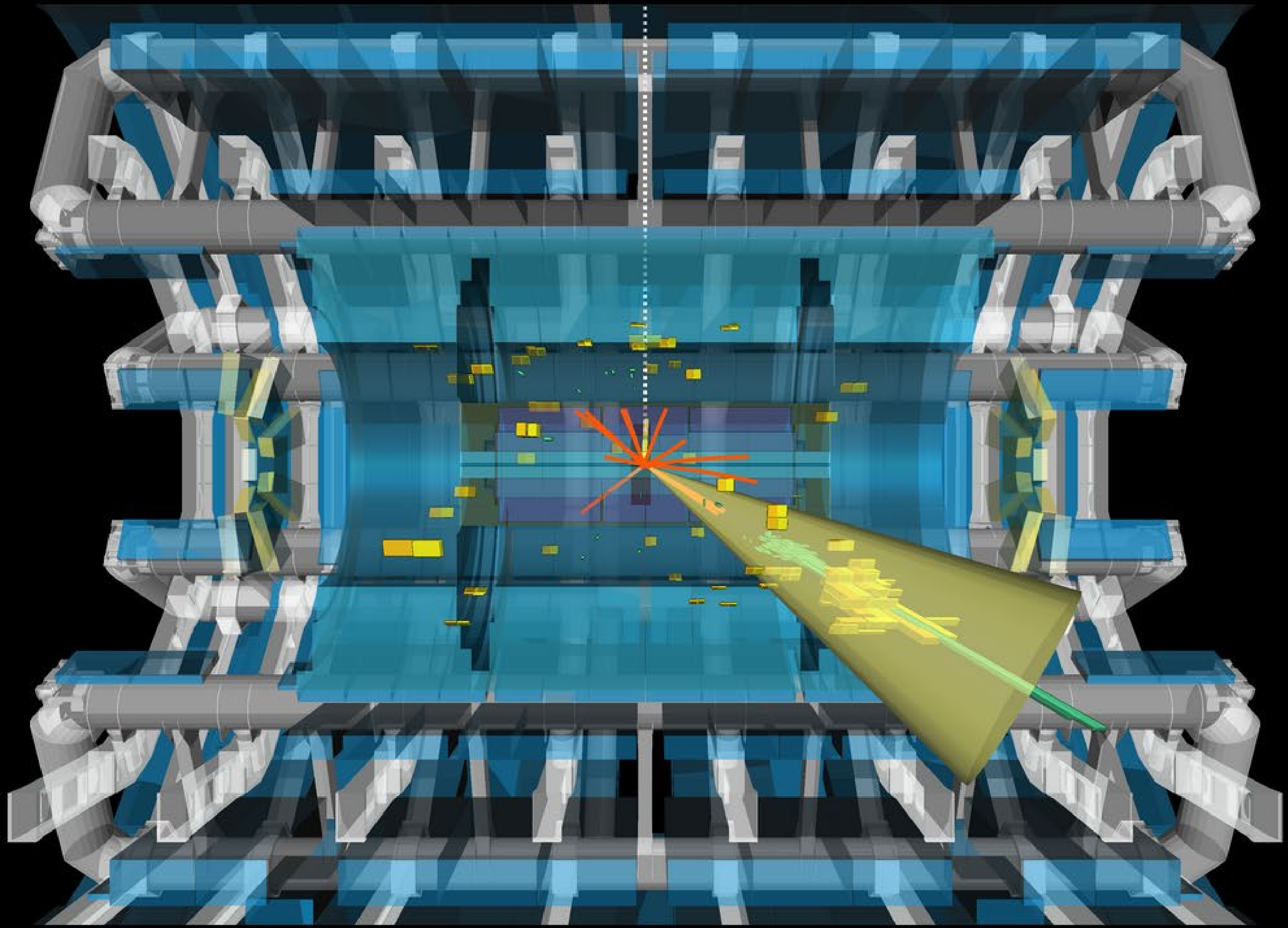
ATLAS EXPERIMENT

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



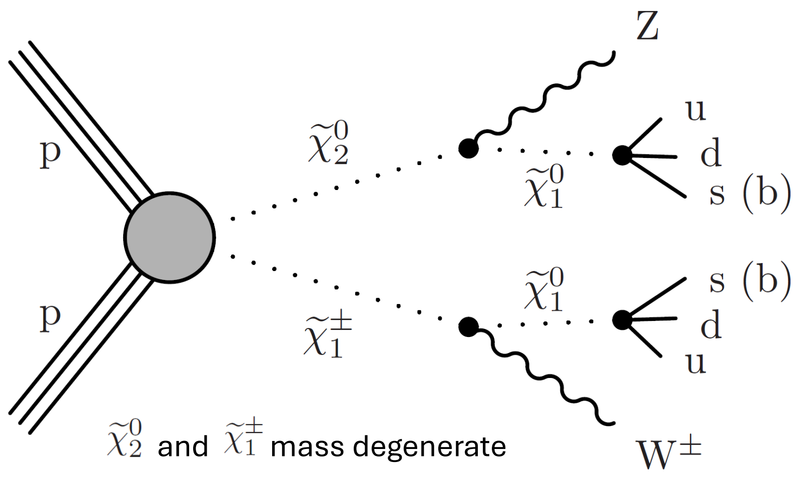
Signal track
p_T= 3.3 GeV
$S(d_0)$=38.3





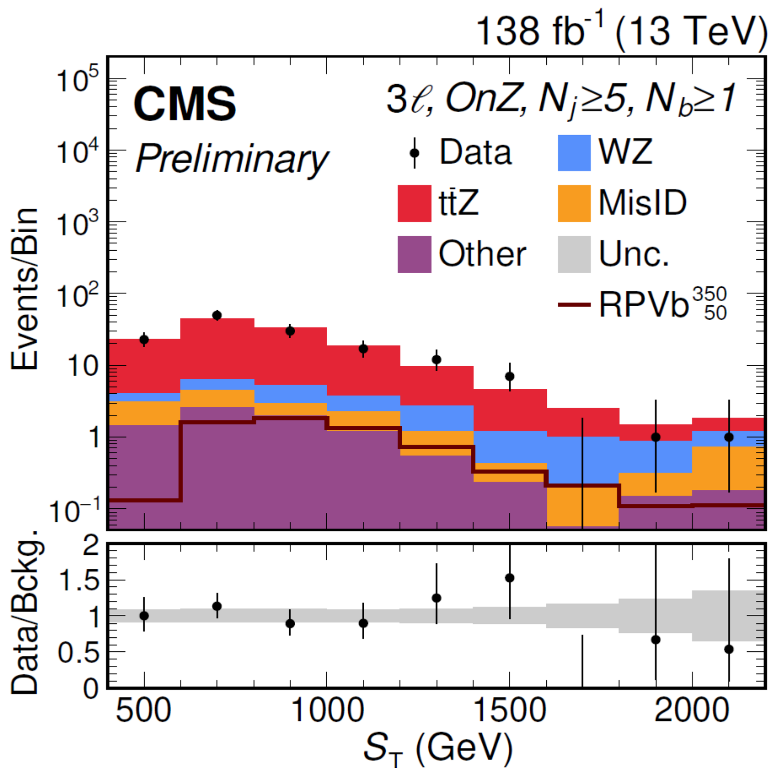
Hadronic R-parity violating SUSY decays

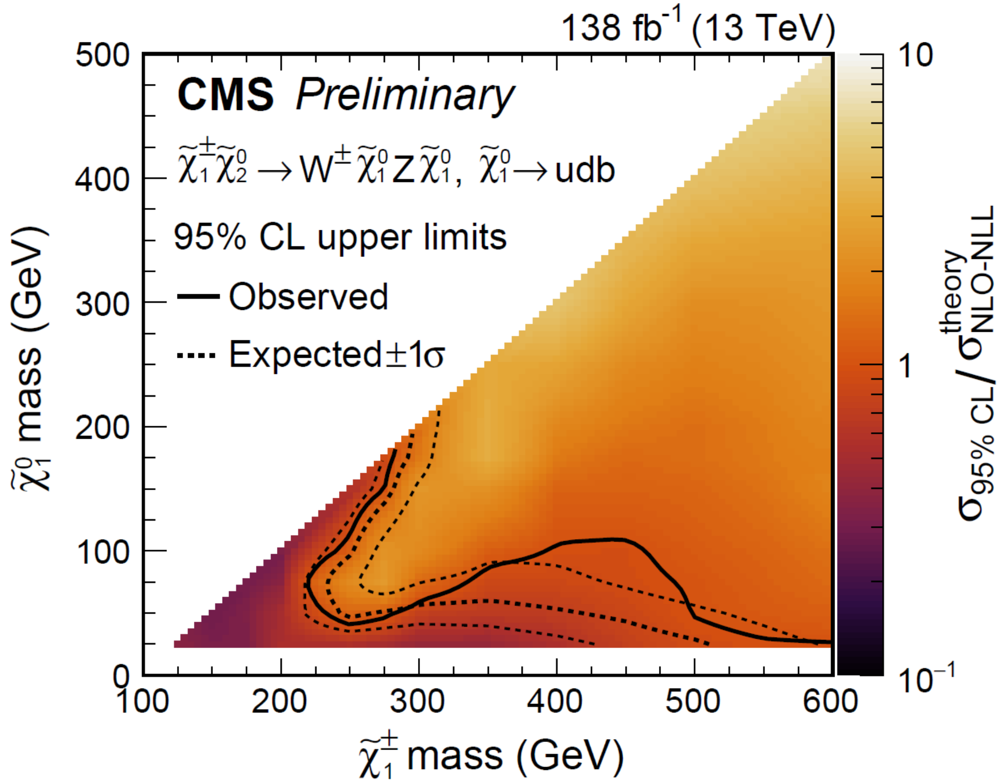
CMS-PAS-SUS-23-015



- 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
- $W \rightarrow l\nu$, $Z \rightarrow ll$. 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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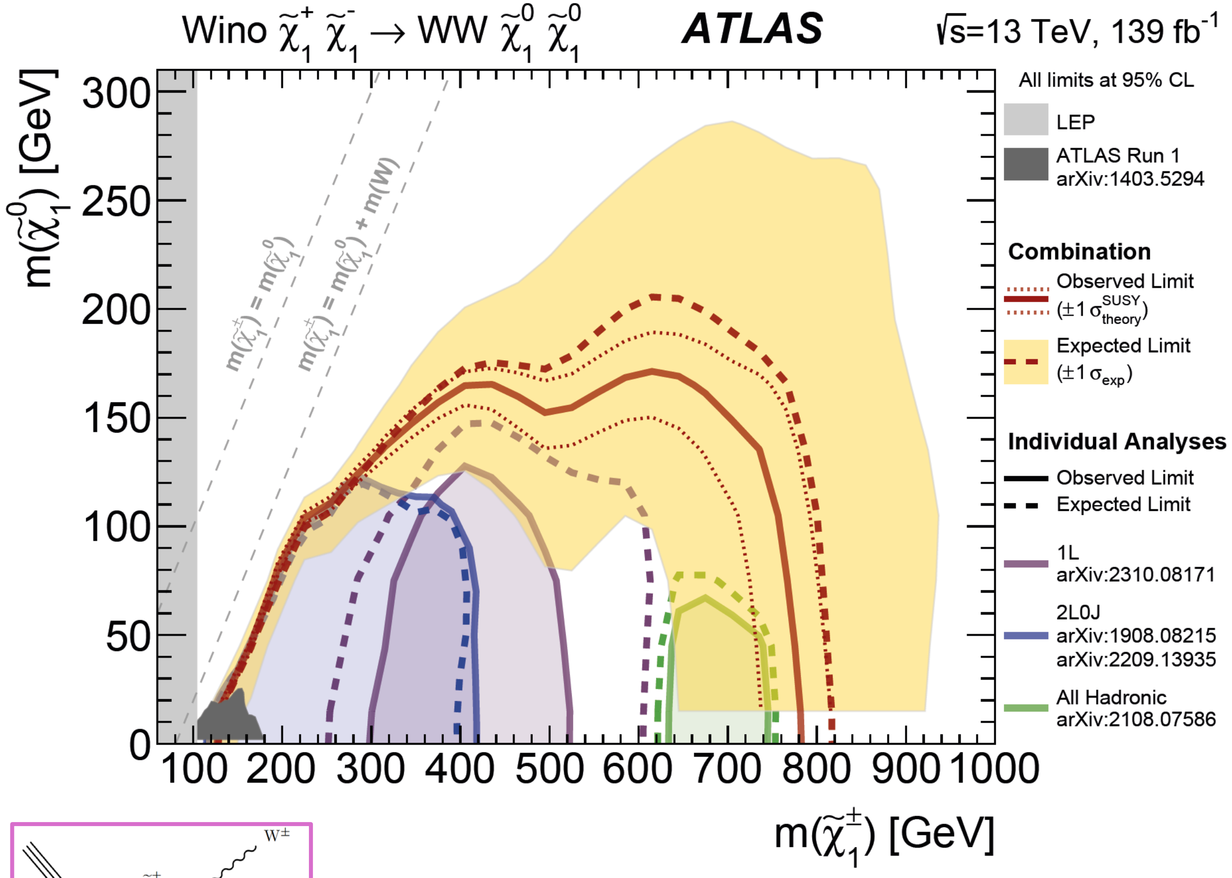
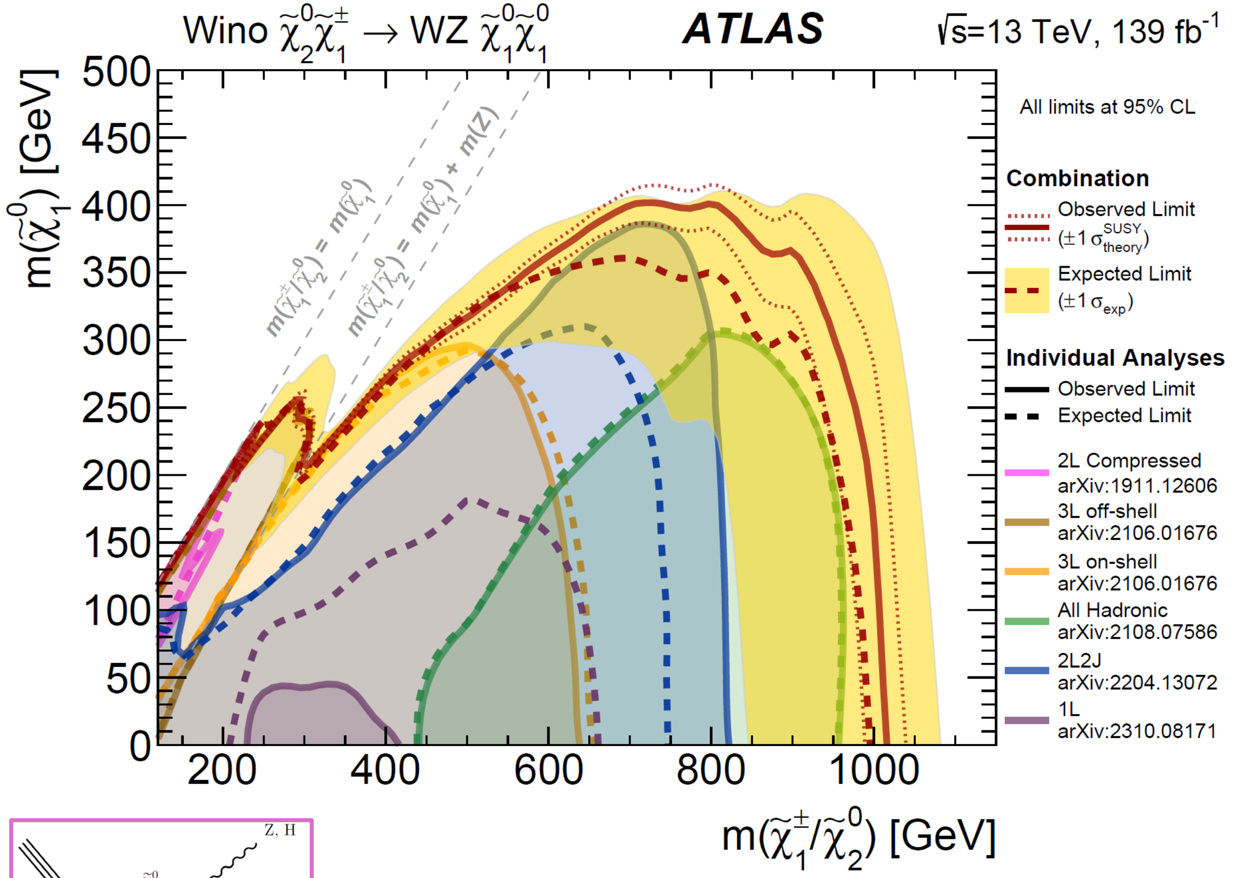
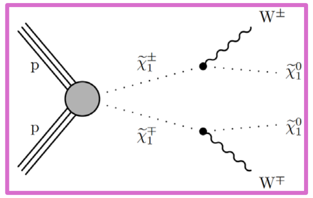
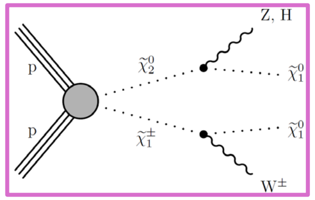






Pure-wino **chargino-pair production** decaying to W bosons and the LSP.

Limits on $\tilde{\chi}_1^\pm$ mass reach up to ~800 GeV for light LSP.



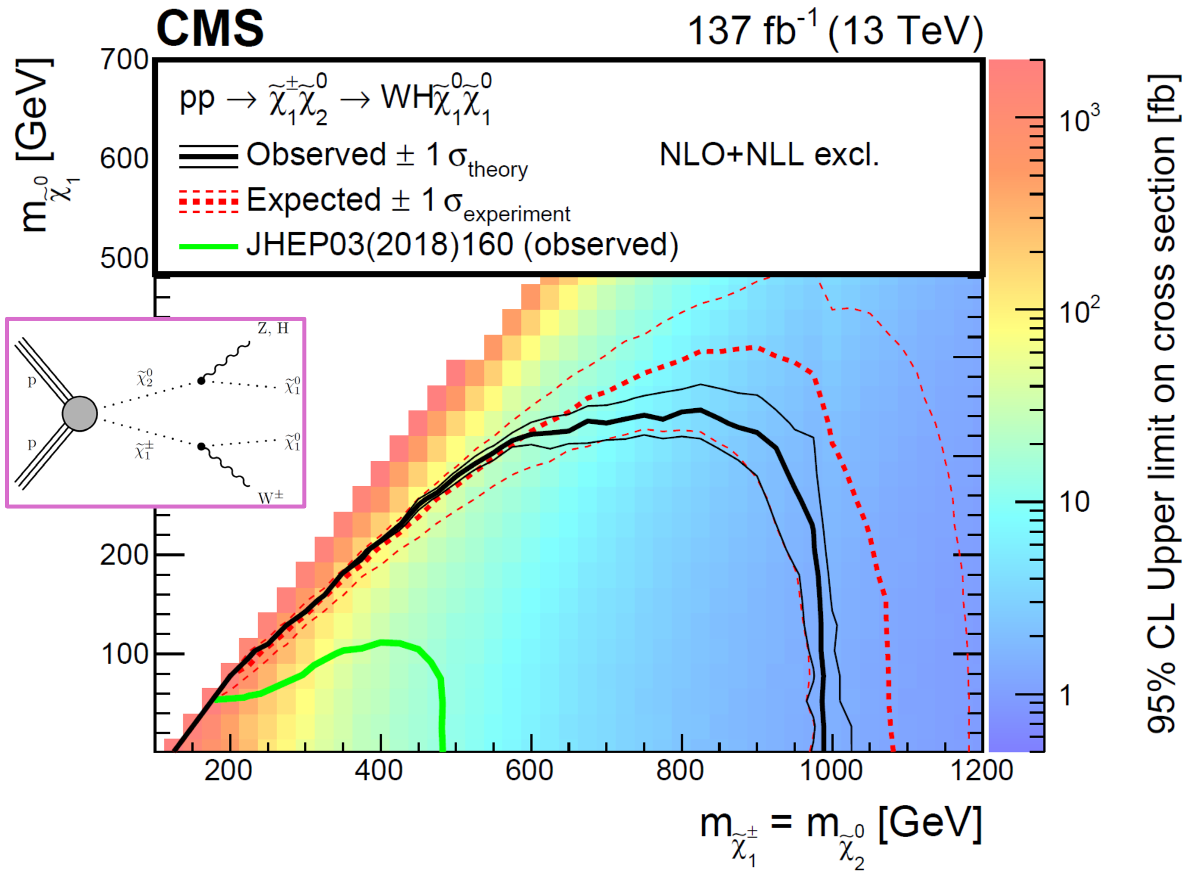
Pure-wino **mass-degenerate chargino-neutralino production**.

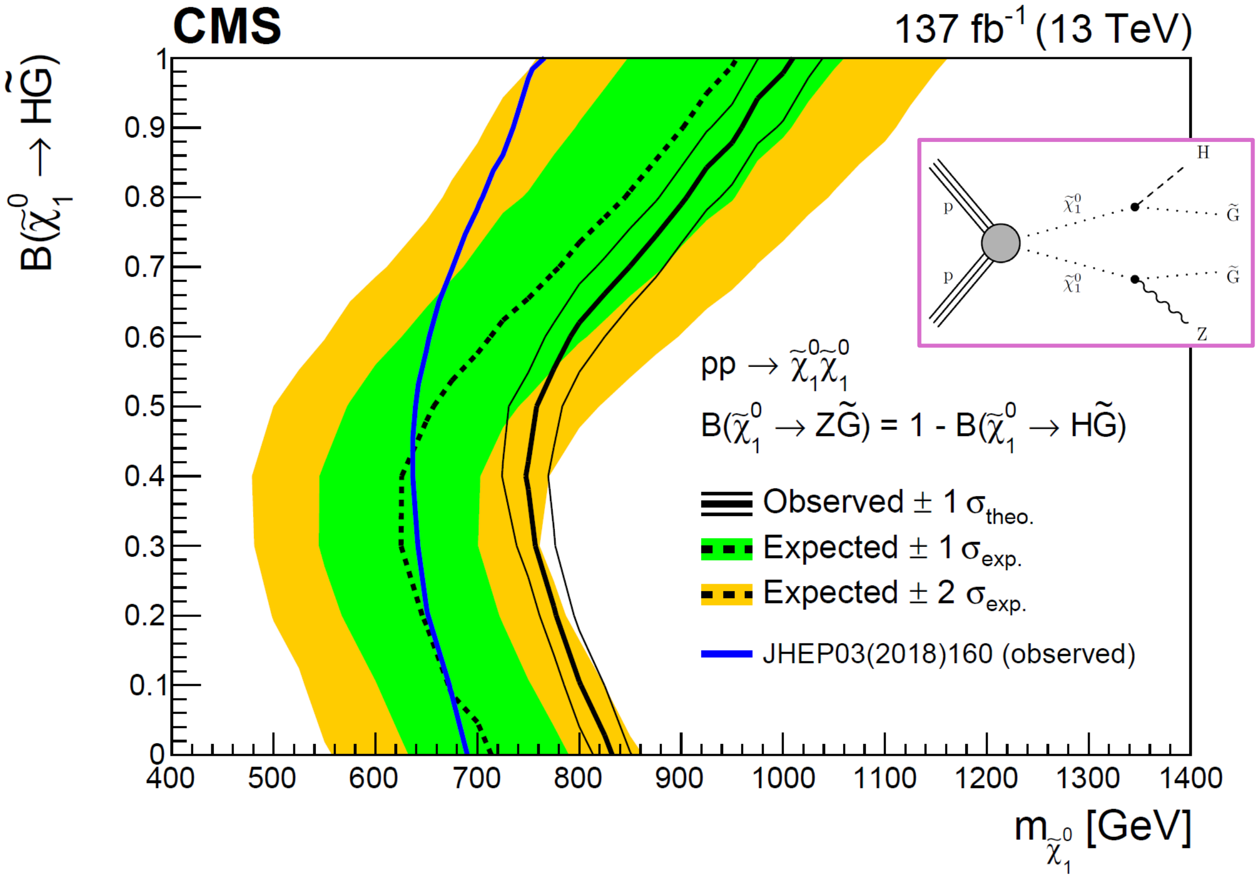
Decays to W/Z and the LSP. Limits reach up to 1 TeV.

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

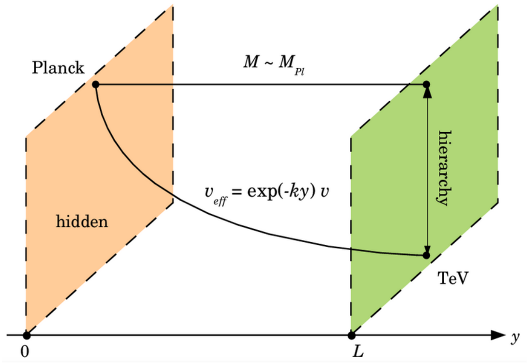
For LSP mass of 50 GeV, $\tilde{\chi}_1^{\pm}$ below 990 GeV excluded.

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 $\mathcal{B}(\tilde{\chi}_1^0 \to \mathrm{H}\tilde{\mathrm{G}})$

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)

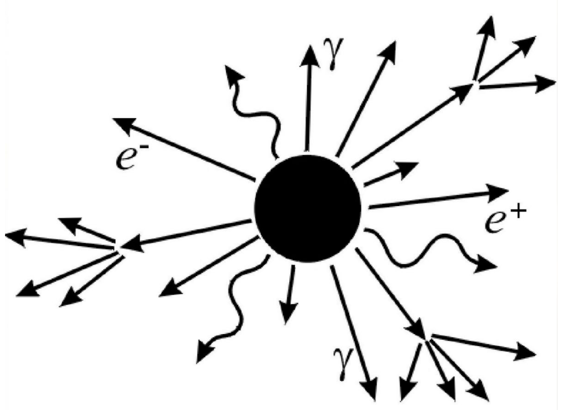
- **Global symmetries** such as baryon or lepton number may not be conserved in strong-gravity interactions

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

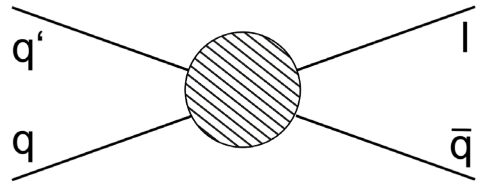
$$uu \to \bar{d}\ell^+, \quad ud \to \bar{u}\ell^+, \quad \bar{d}\bar{d} \to d\ell^+$$

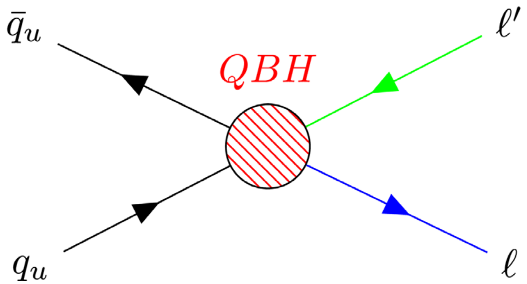
- **QBH decay to two-particle final states with large branching fraction (51-74% in ADD or RS1).**

  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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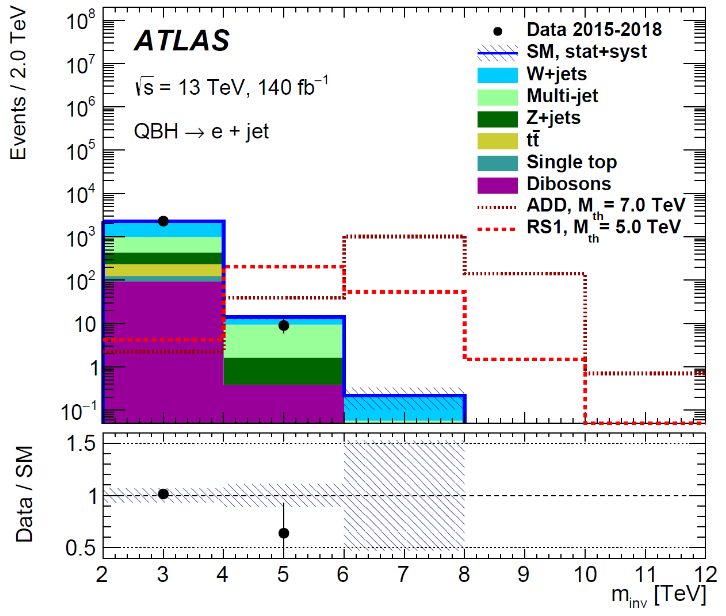
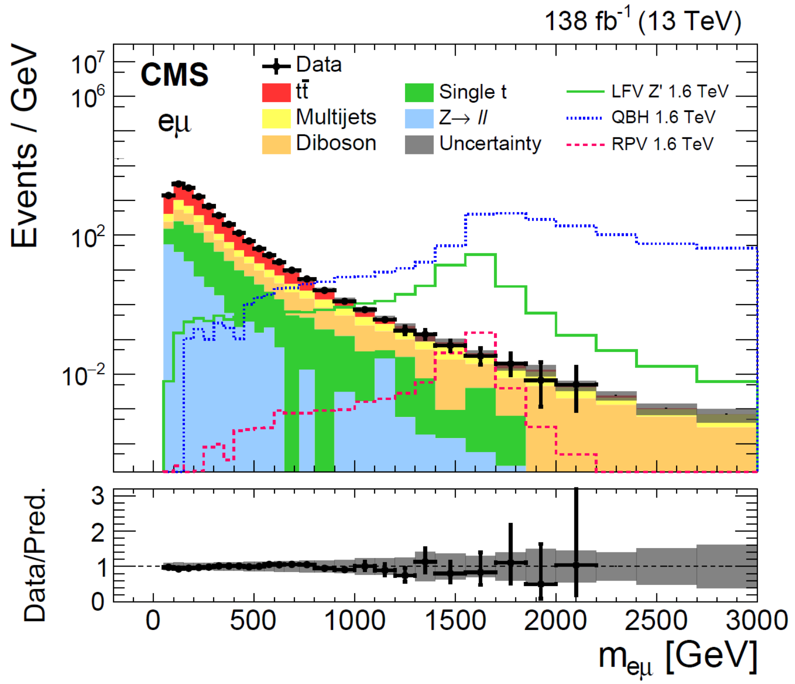
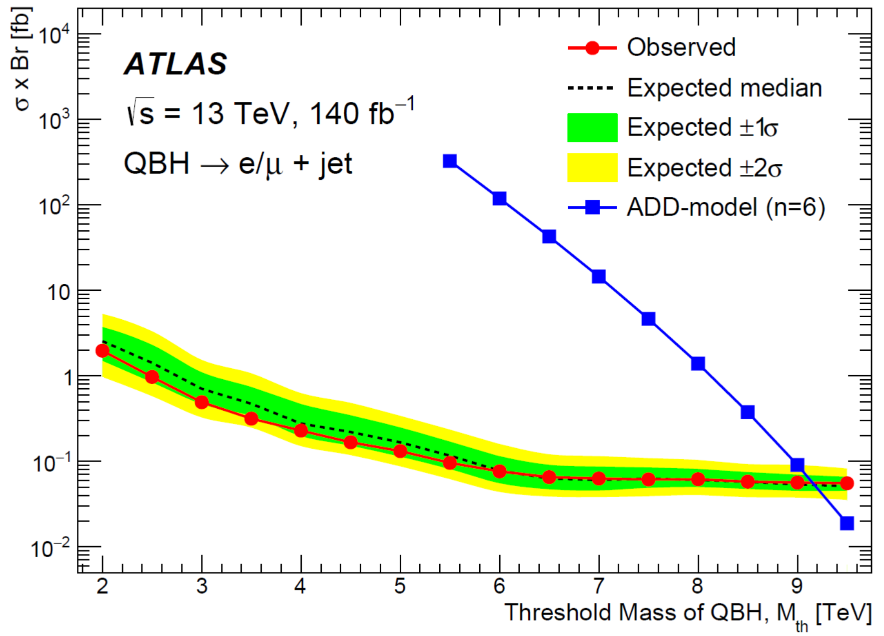
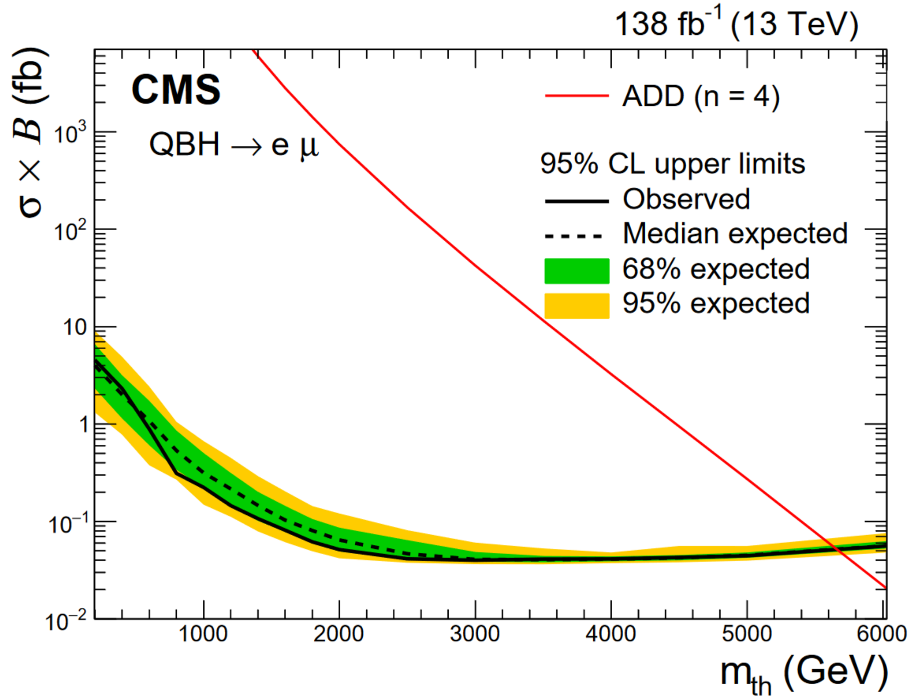








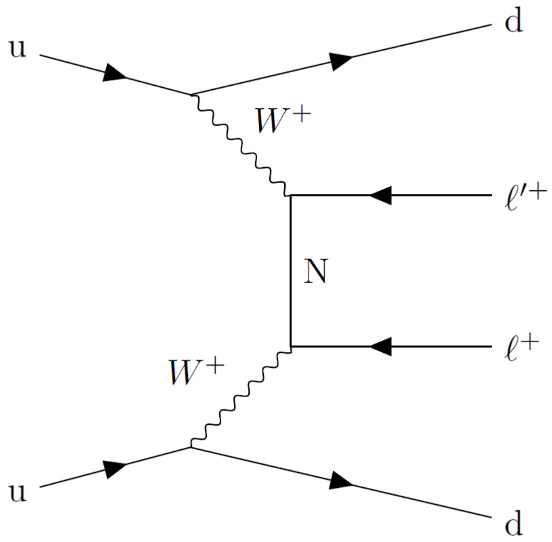
ATLAS result:

- **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



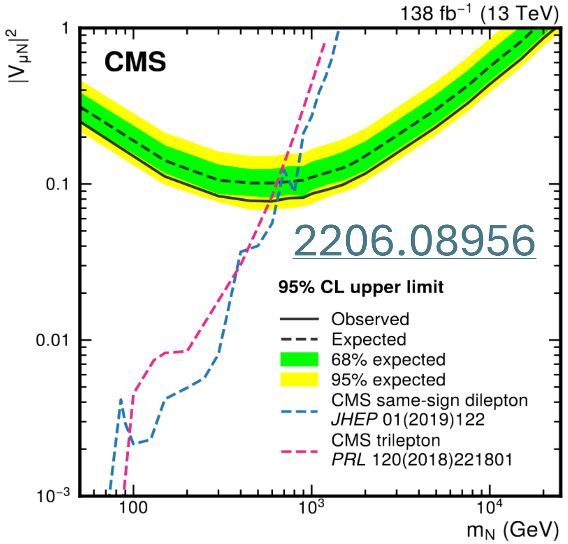
- VBF same-sign W boson scattering
- Final state: two leptons + two jets

- **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 **$m_\nu \sim \mathcal{O}(vev^2/m_N)$**
  (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 ~ $|V_{eN} V_{\mu N}|^2$

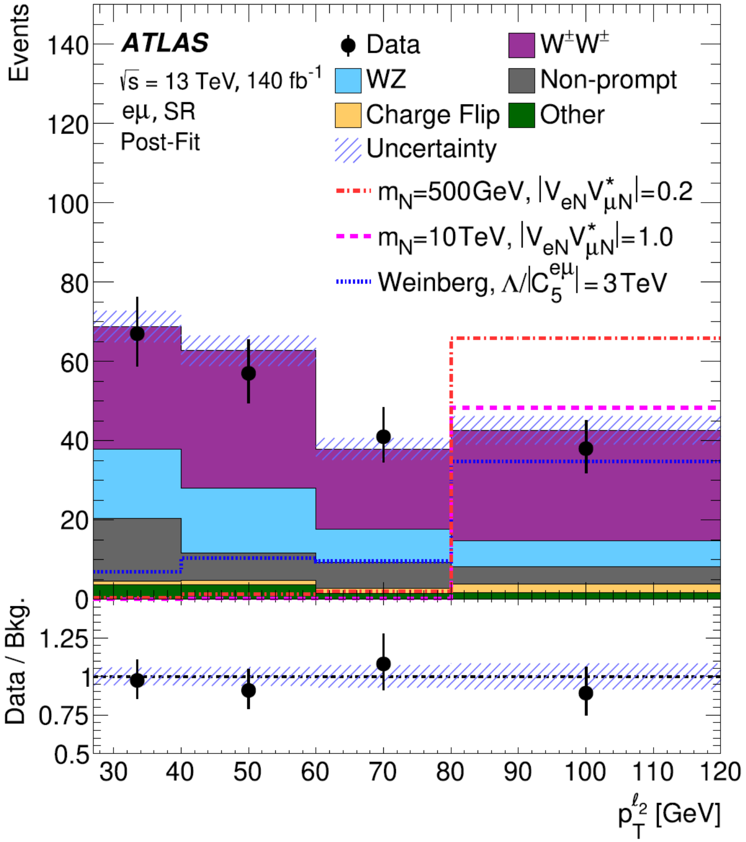
Heavy Majorana Neutrinos

2403.15016

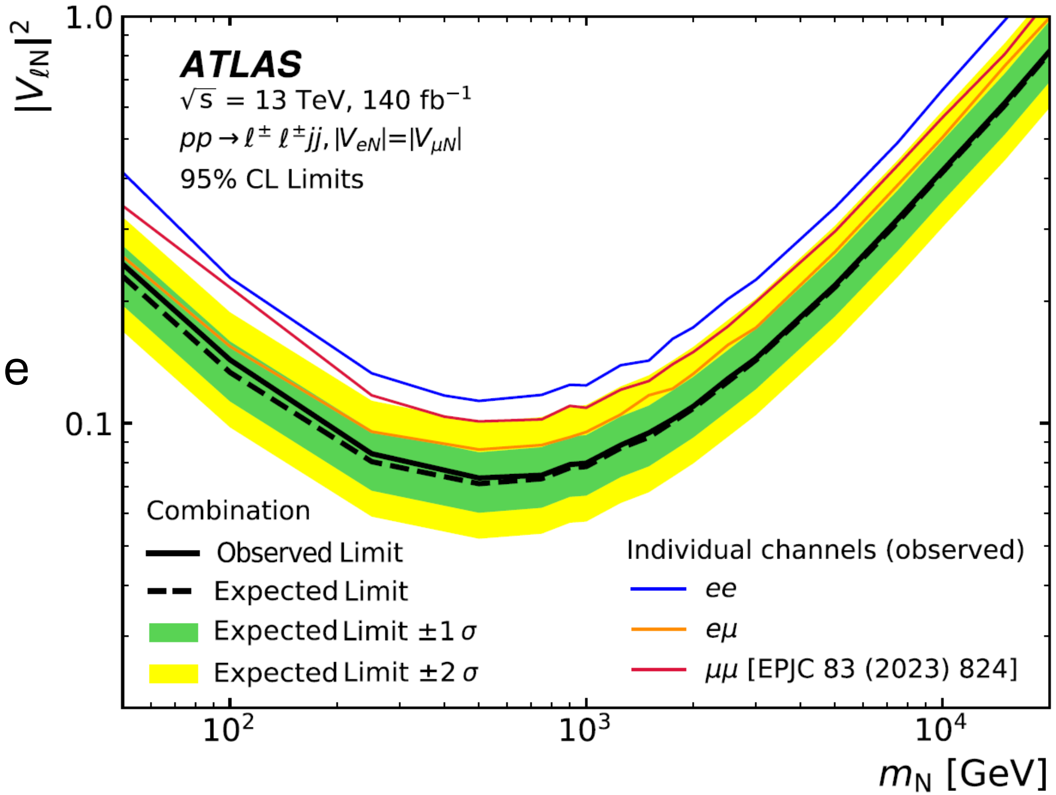
- Two channels: **ee or eμ (+ two jets)**, that are then statistically combined
- Jets have a large rapidity gap ($|\Delta y|>2$) and large invariant mass (m_{jj} > 500 GeV)
- **Most discriminating variable: p_T of the subleading lepton**
- WW and WZ control region for background estimation



2206.08956



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



Summary

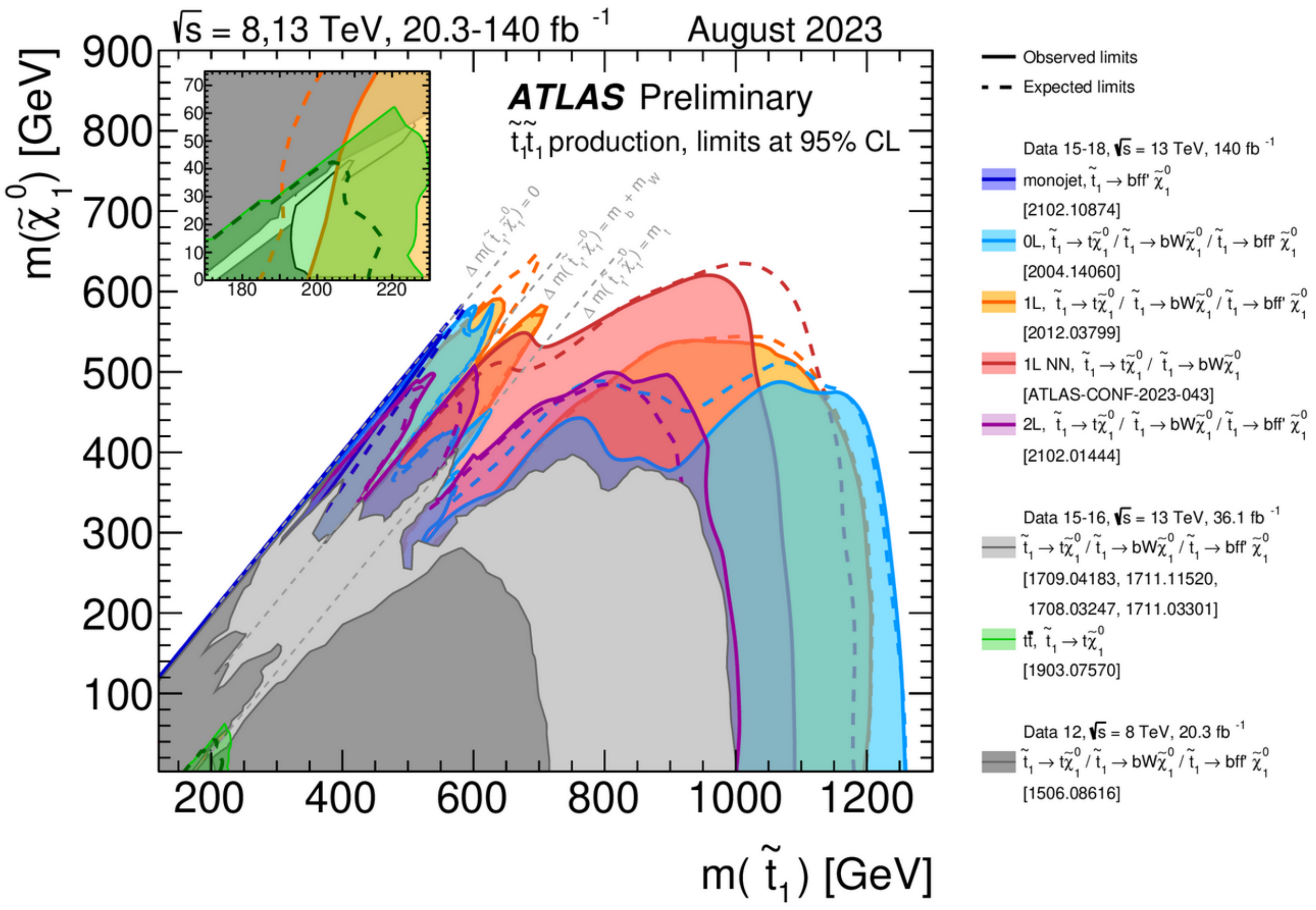
- Diverse set of searches presented with the full Run 2 dataset from ATLAS and CMS, non-resonant searches complementary to resonance and other searches.

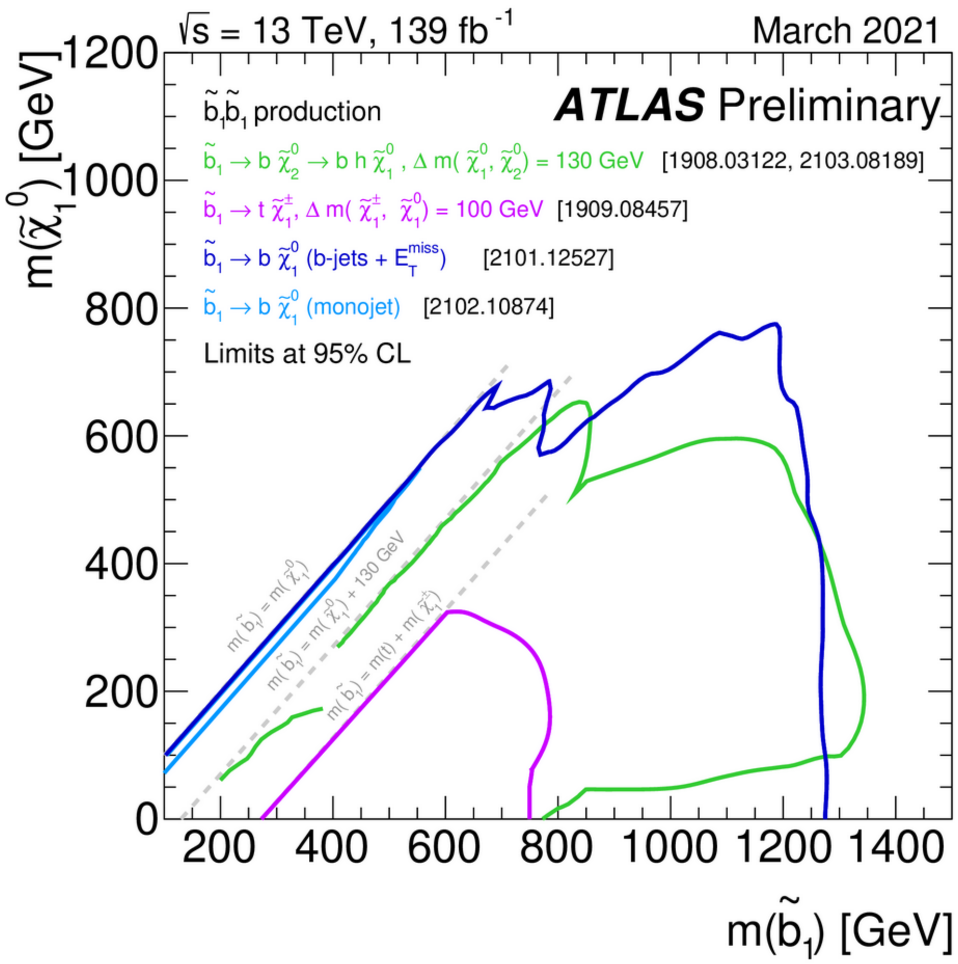
- **No significant excess found, stringent limits in various models set**:
  - Vector LQ decays to μ+b for λ=1, β=1 and κ=1 excluded for masses up to 2.6 TeV
  - Scalar LQ excluded for masses below 620 GeV, assuming λ_{LQ} = 1.5 in cLFV interactions
  - M_5 up to 11 TeV excluded for k=1 TeV in extra-dimensional 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)

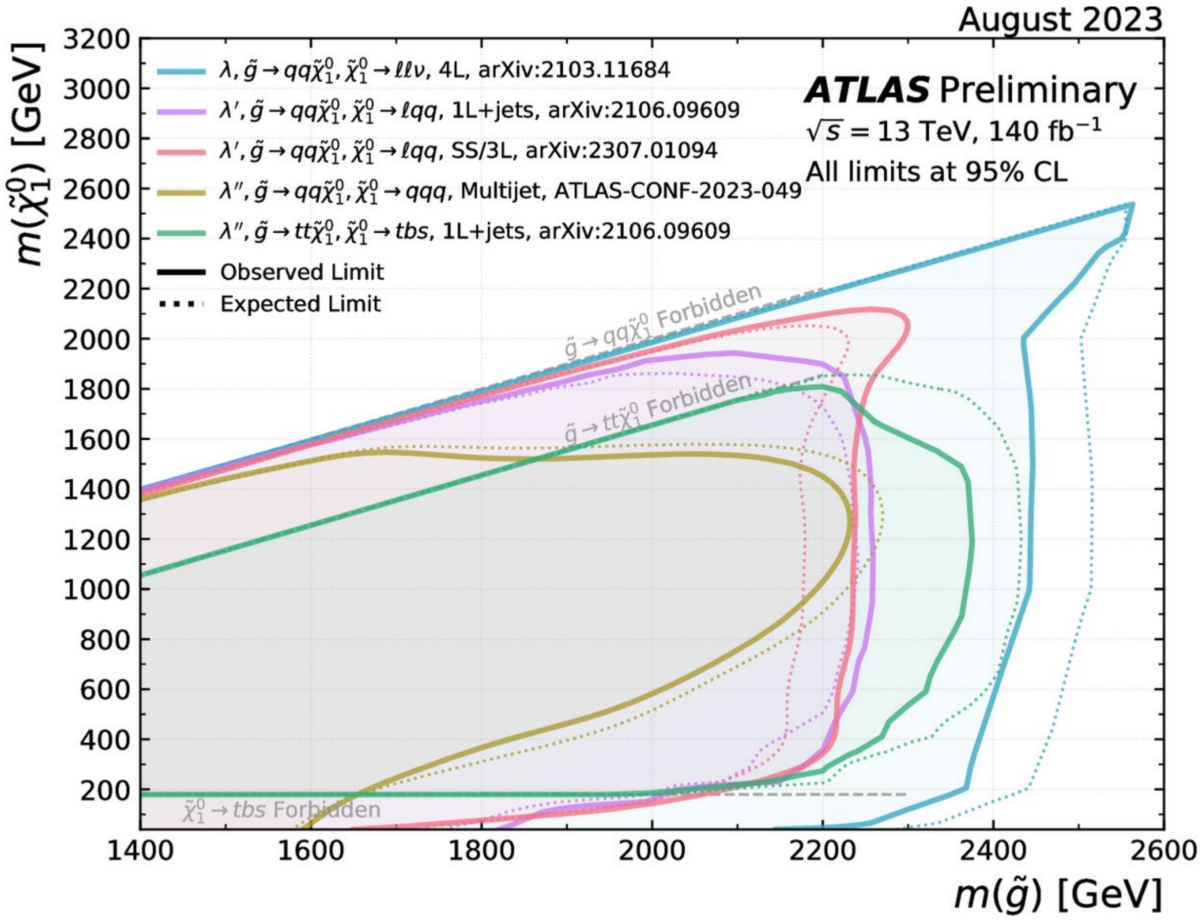
Backup

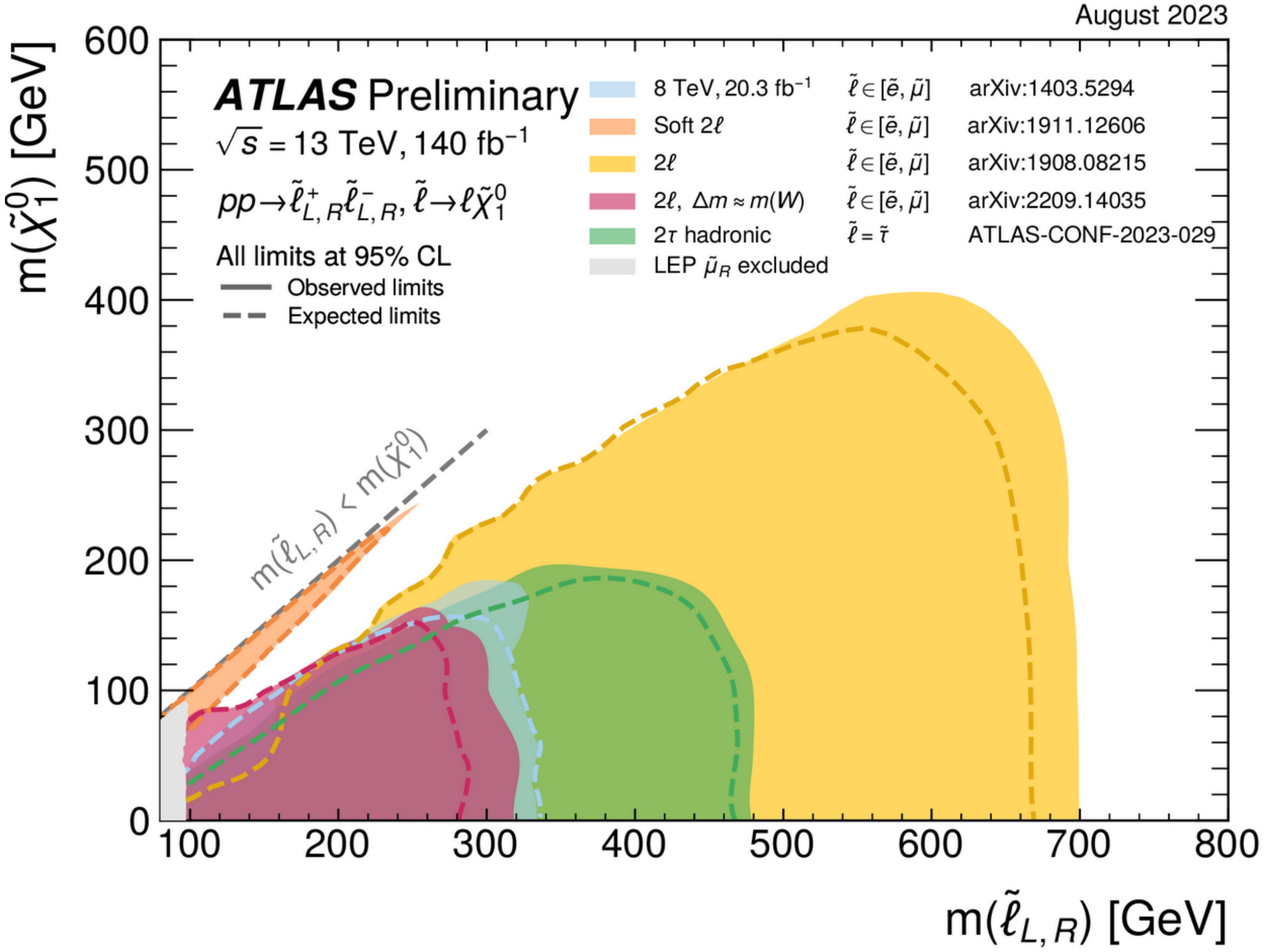
SUSY Summary Plots





SUSY Summary Plots





Pair-produced Higgsinos

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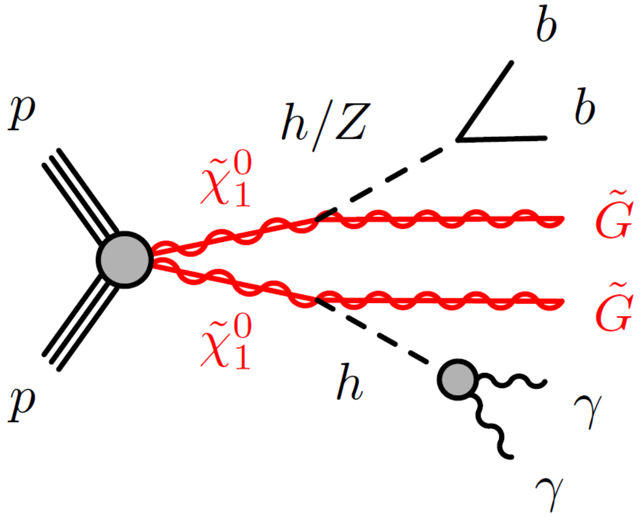
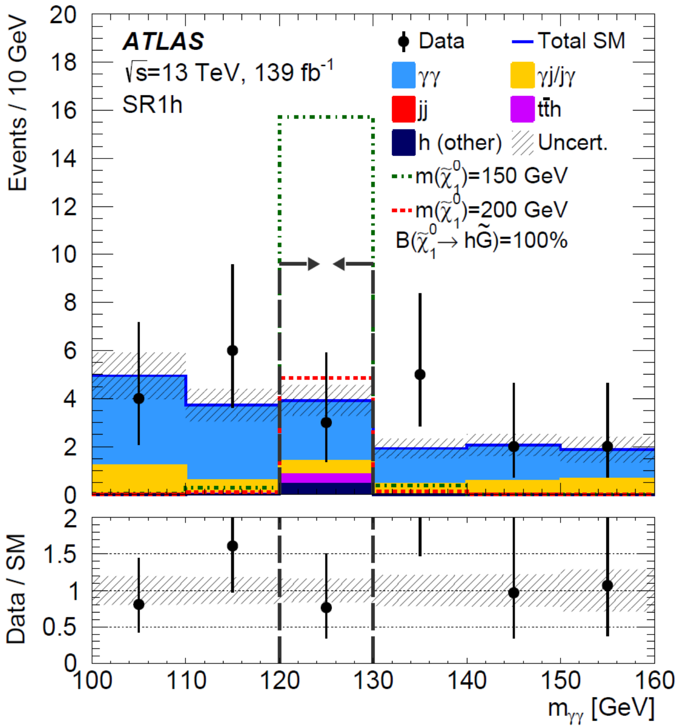
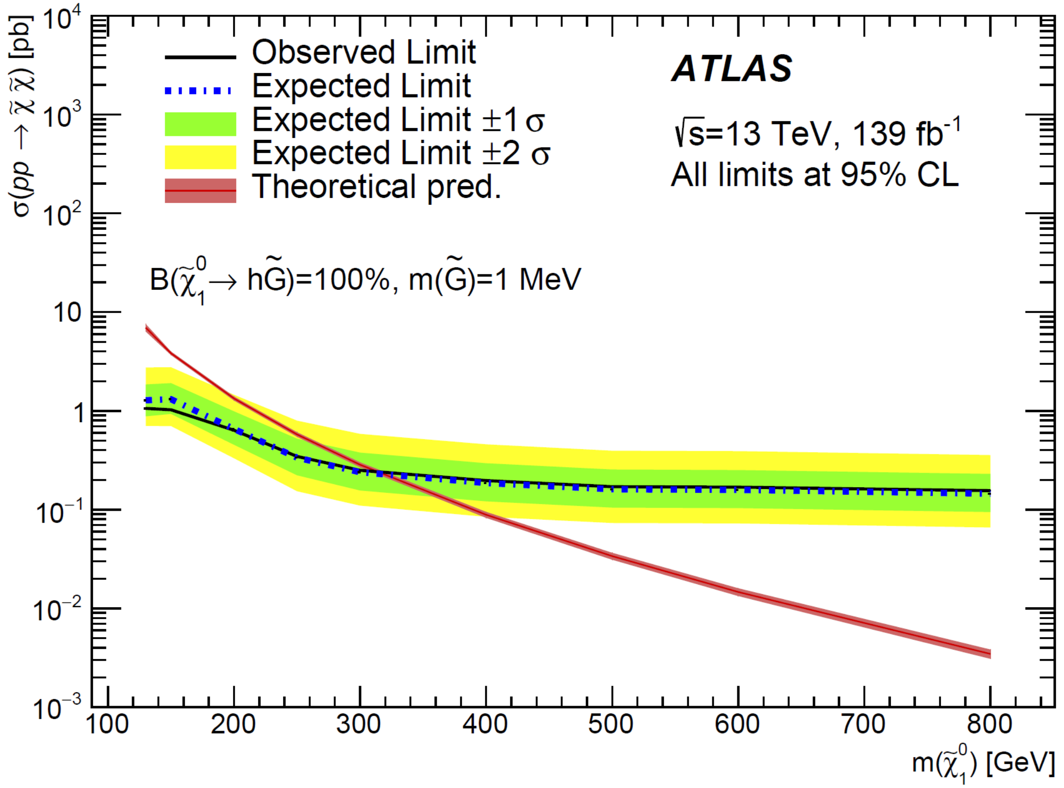


- **Neutralinos $\tilde{\chi}_1^0$ decay to a light Gravitino $\tilde{G}$ and a Higgs or Z boson**
- Neutralino masses at EW scale, even if SUSY mass scale is very high
- **Final state: Missing energy, two photons and two b-jets**
- Selection requires 120 GeV < $m_{\gamma\gamma}$ < 130 GeV



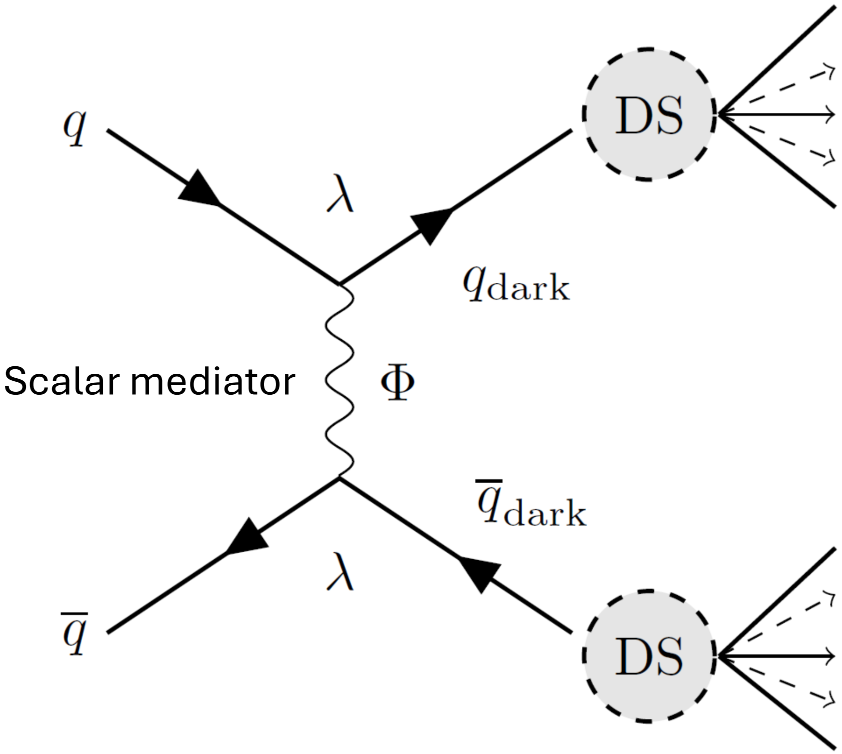
Three signal regions:

- 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

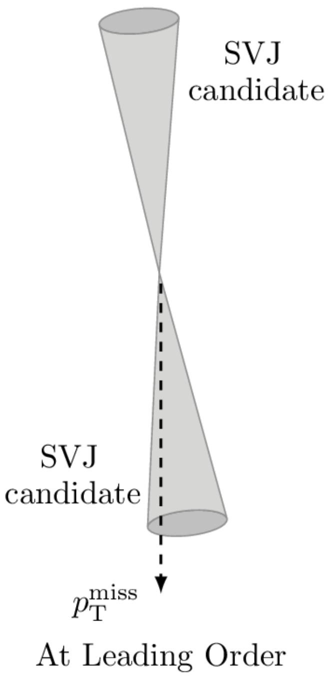


Semi-visible Jets

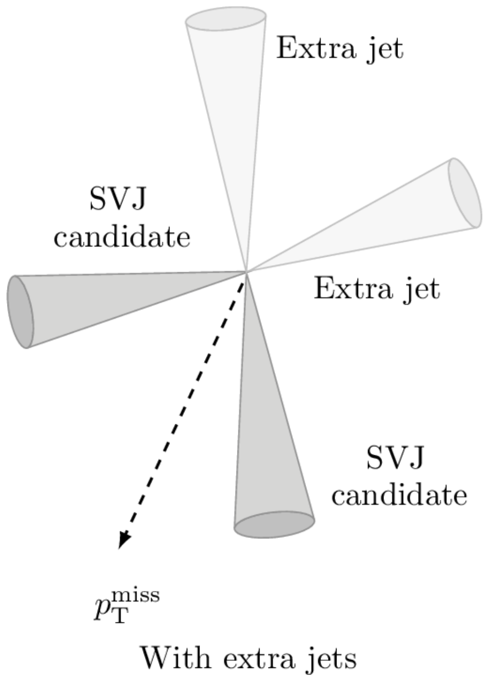
- **Strongly-coupled dark sector featuring a dark shower** (DS) including dark hadrons
- **These dark hadrons may or may not be stable**:
  - If all dark hadrons are stable → missing energy signature.
  - If all dark hadrons decay to SM particles → multijet signature
- „Semi-visible“ means the **fraction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



Coupling strength λ is a parameter



Missing momentum aligned with one of the jets

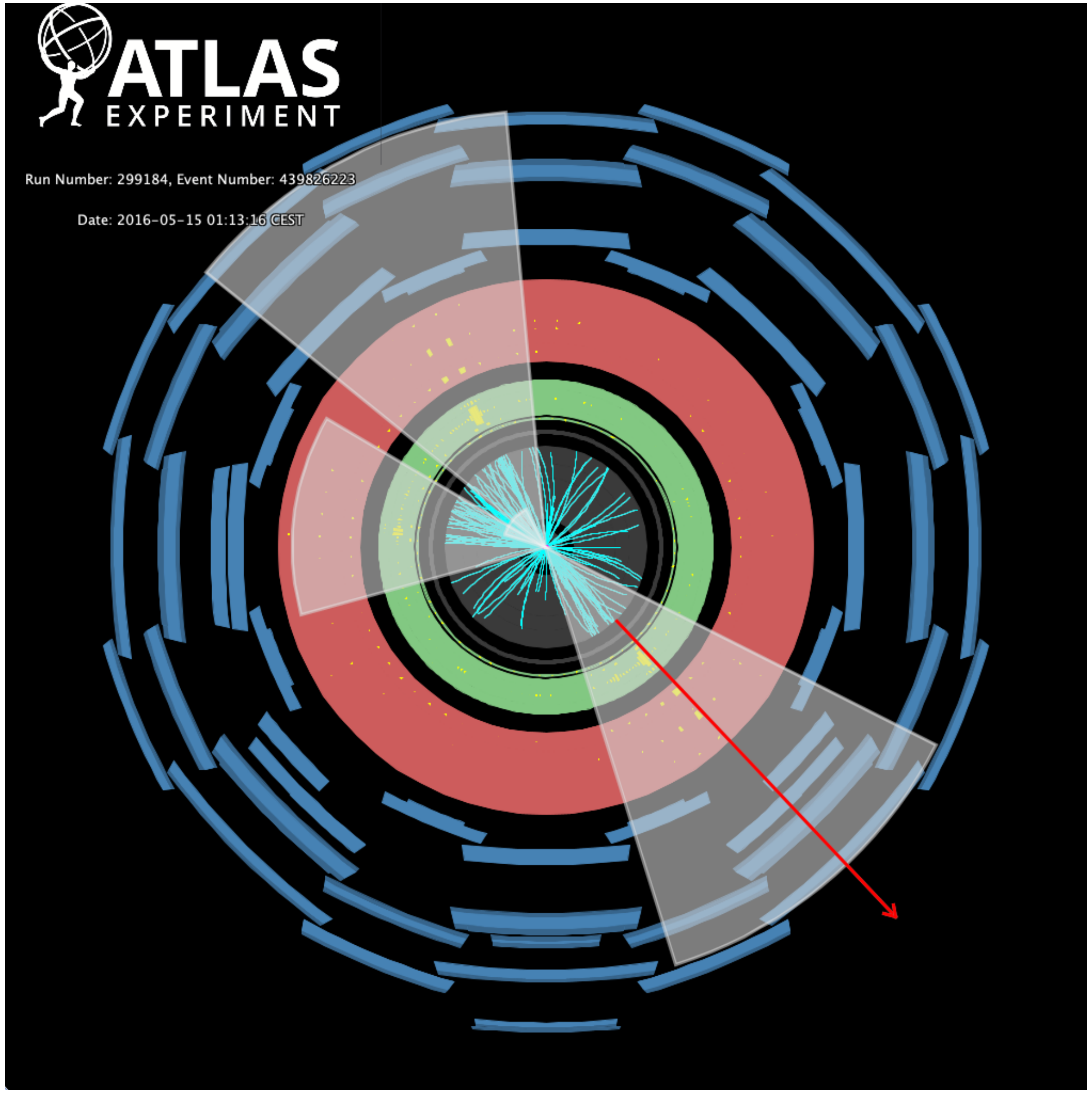


Missing momentum direction distorted by presence of extra jets

Semi-visible Jets

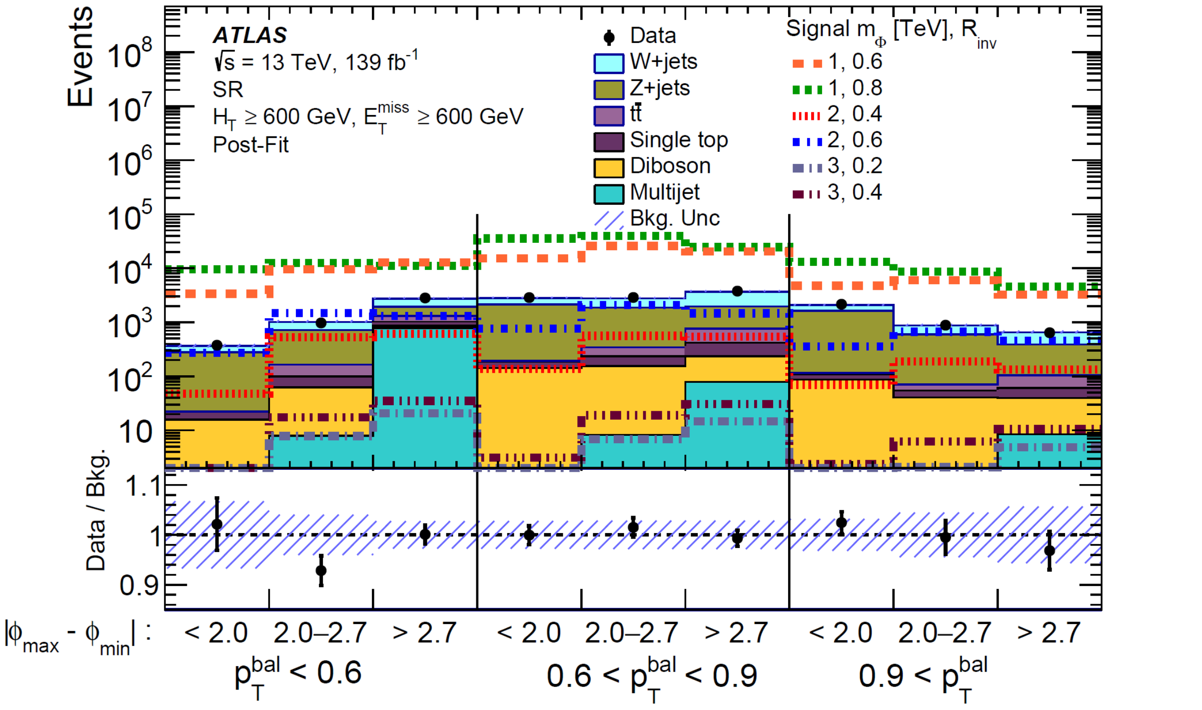
2305.18037

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

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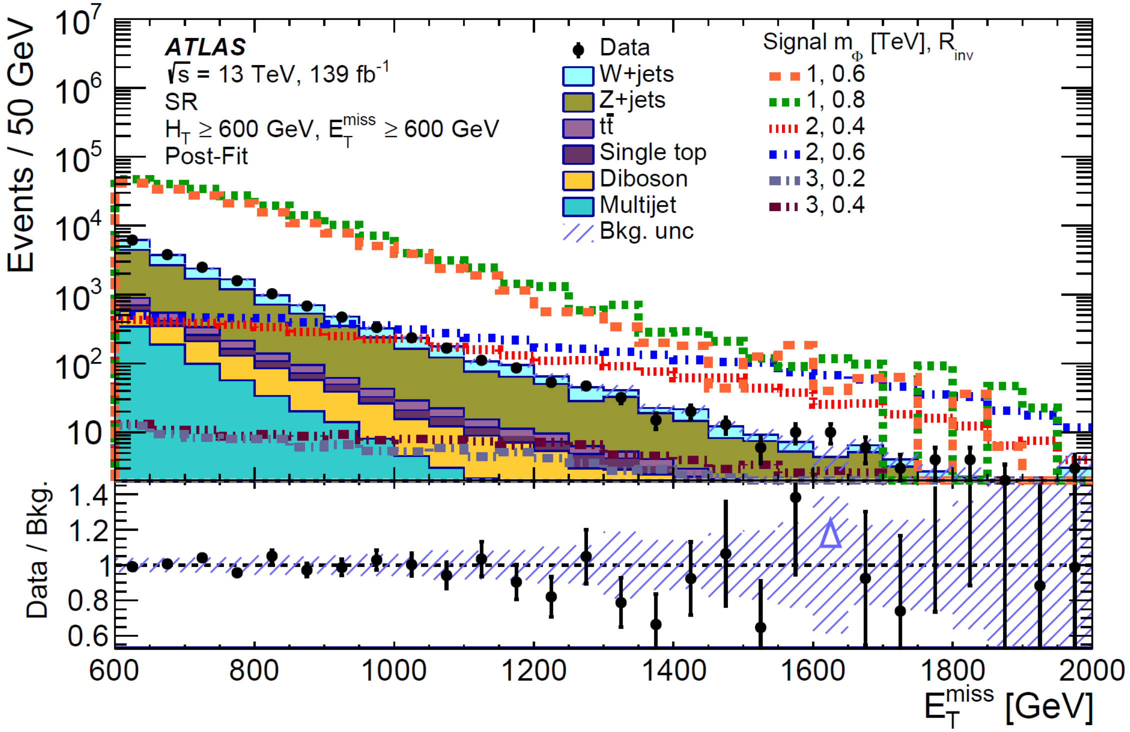
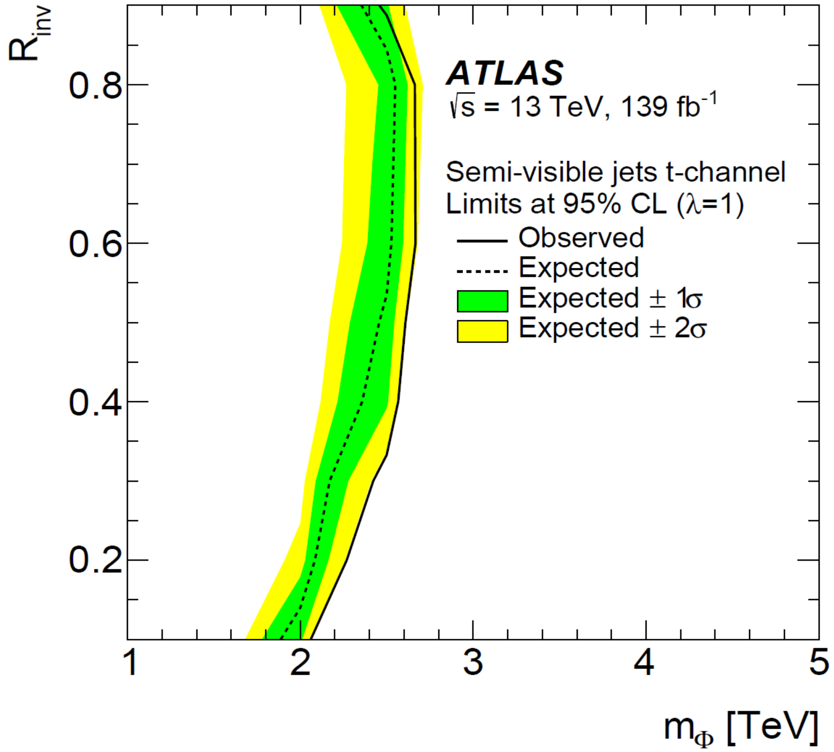
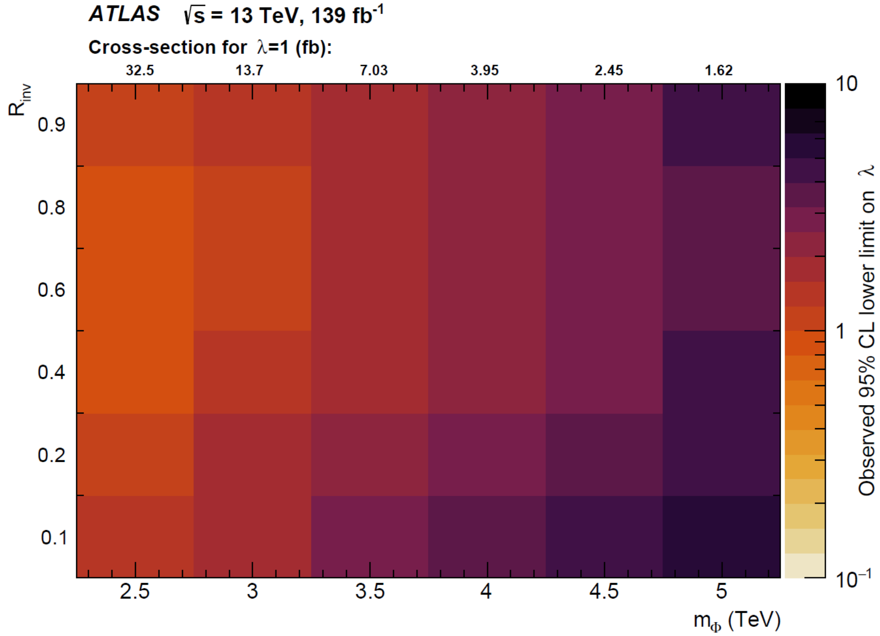






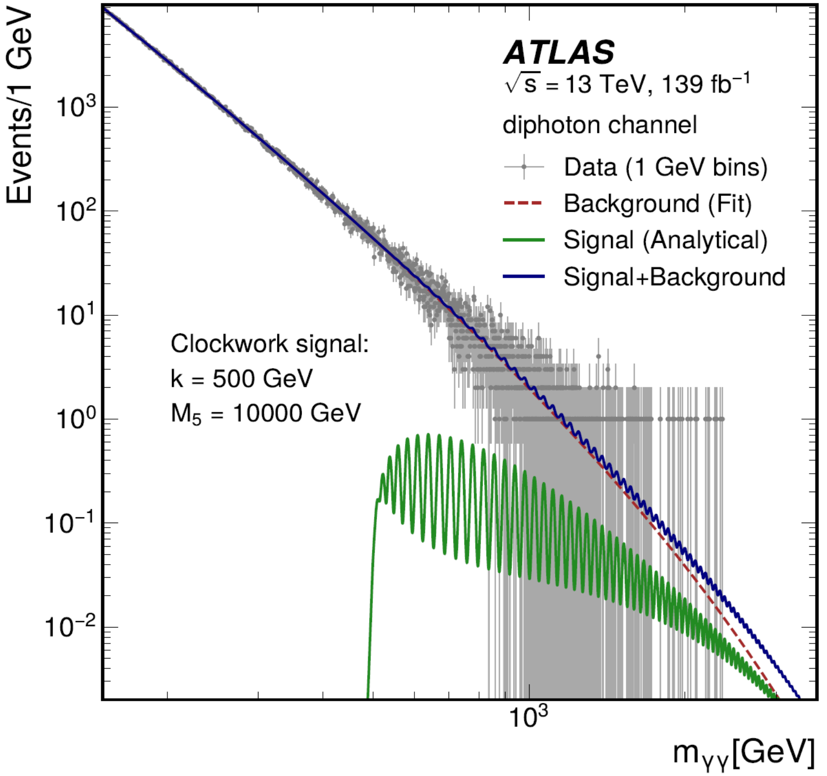
- **No excess found**
- Upper limits on the mediator mass between 2.4 - 2.7 TeV, depending on R_{inv}
- Limits on coupling strength λ set (for $m_{\Phi} > 2.5$ TeV)

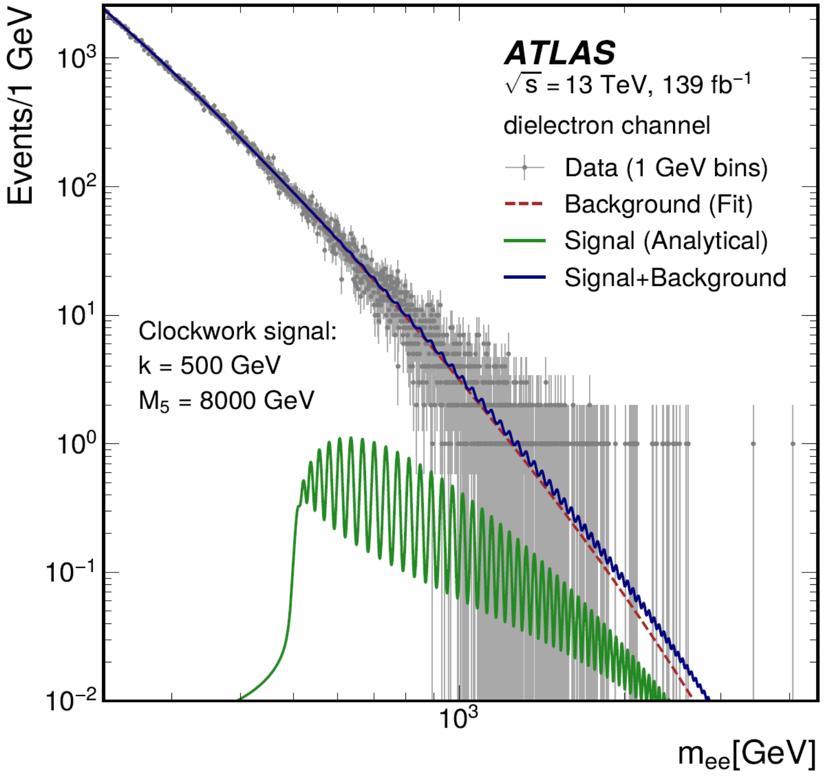
Periodic Signals (Clockwork): Analysis

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

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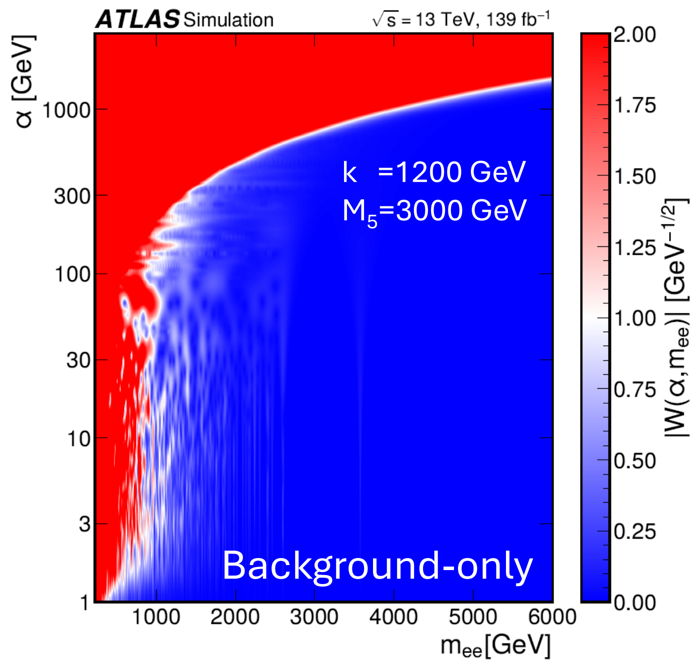
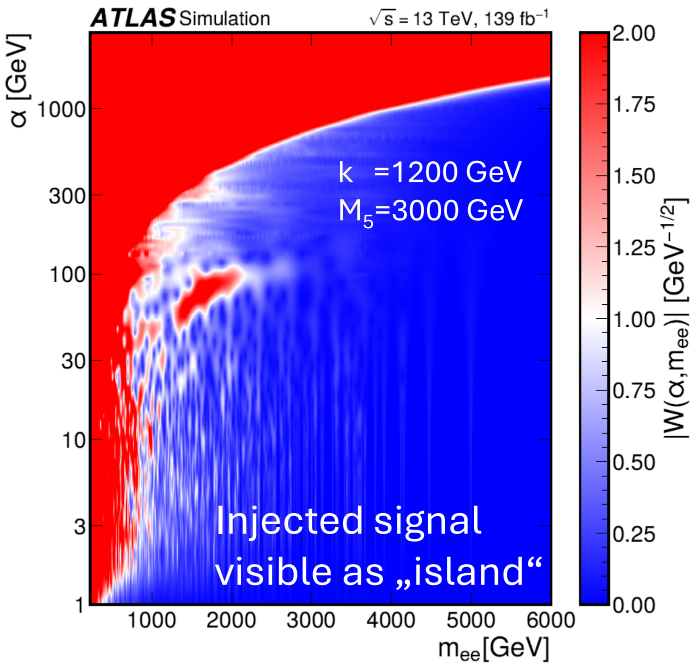
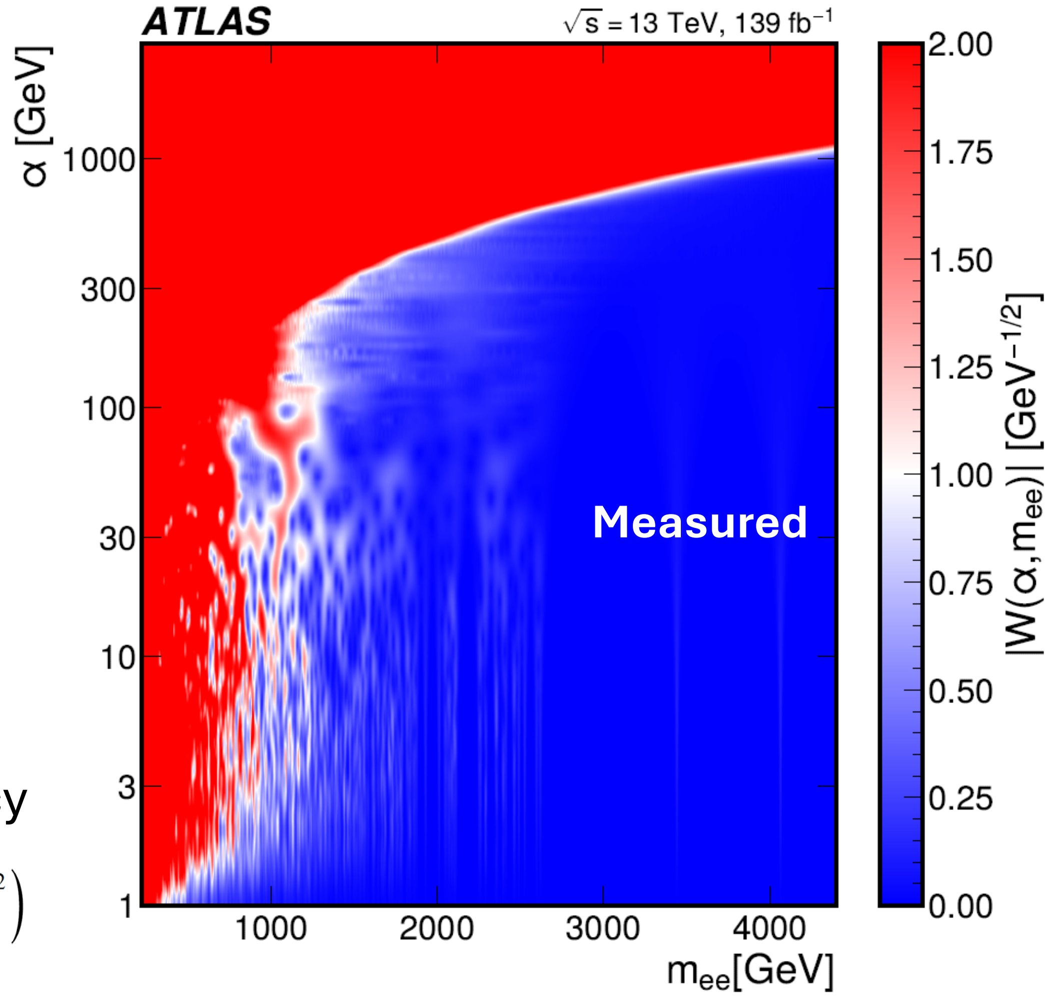






- **Continuous wavelet transform (CWT)** used to transform the mass spectra into scalograms („image“) of mass vs. frequency

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

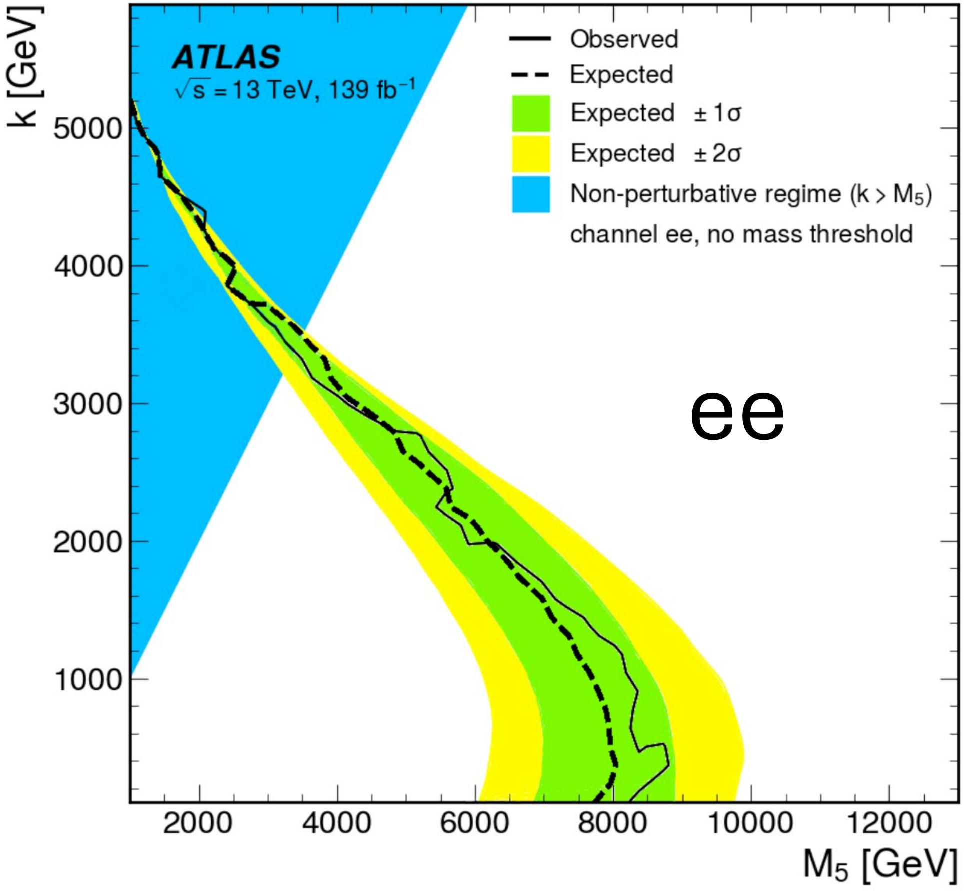
Morlet wavelet. B=2, C=1

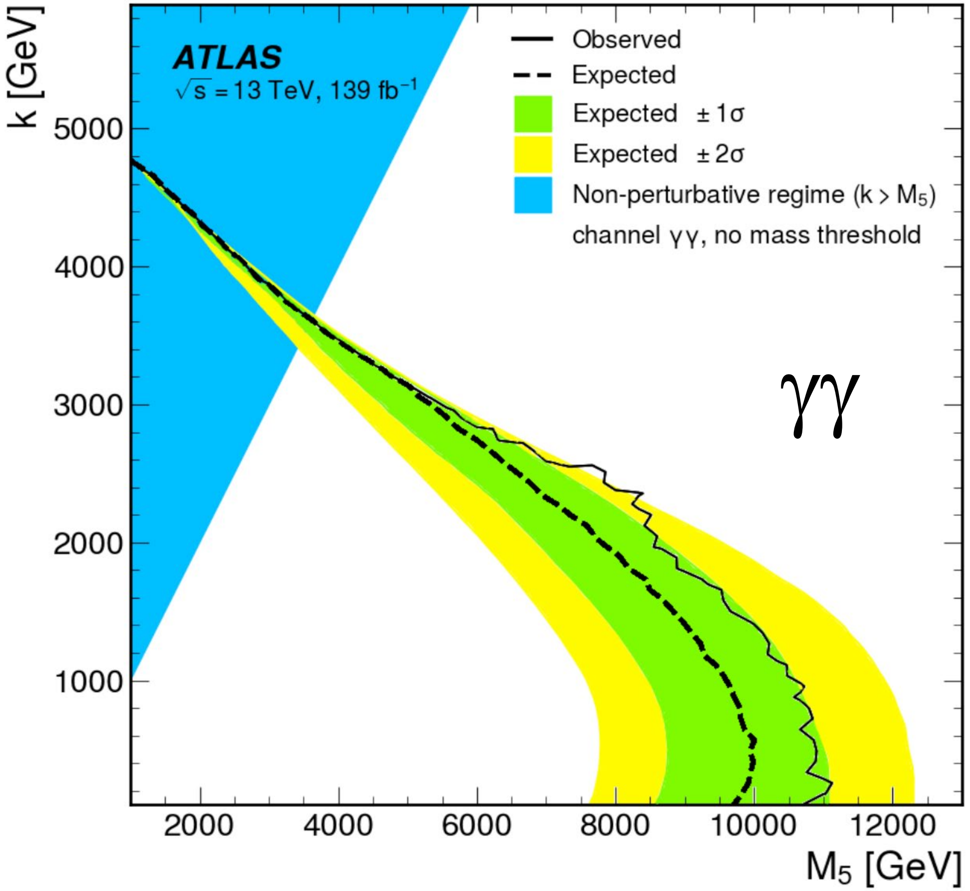
- Scaling parameter α either dilates or compresses the signal. It is inversely proportional to the frequency (meaning if α is large, then the signal is „stretched“)

- **Convolutional neural networks** or **Autoencoder** used to search for anomalies („islands“) in the scalogram

Periodic Signals (Clockwork): Results

2305.10894





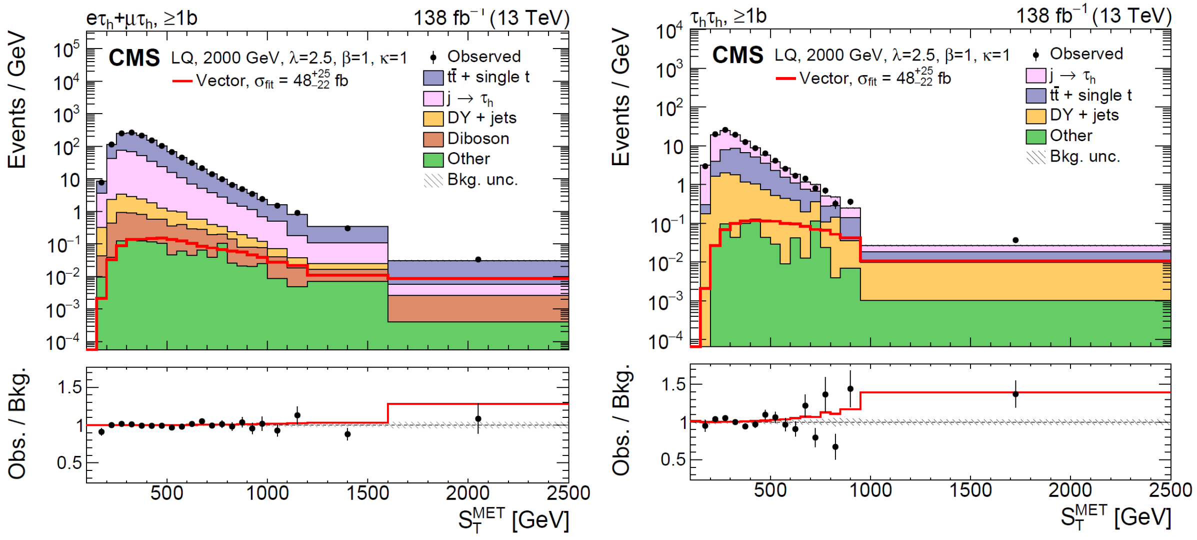
- No significant excess found, largest significance 1.5σ in the dielectron channel for **model-independent** AE analysis
- **Model-dependent limits in k-M_5 plane** derived, obtained from the classifier NN analysis.
- **Maximum excluded M_5 value is 11 TeV (8 TeV) for the $\gamma\gamma$ (ee) channel.**

Leptoquarks decaying to τ + b: 2308.07826

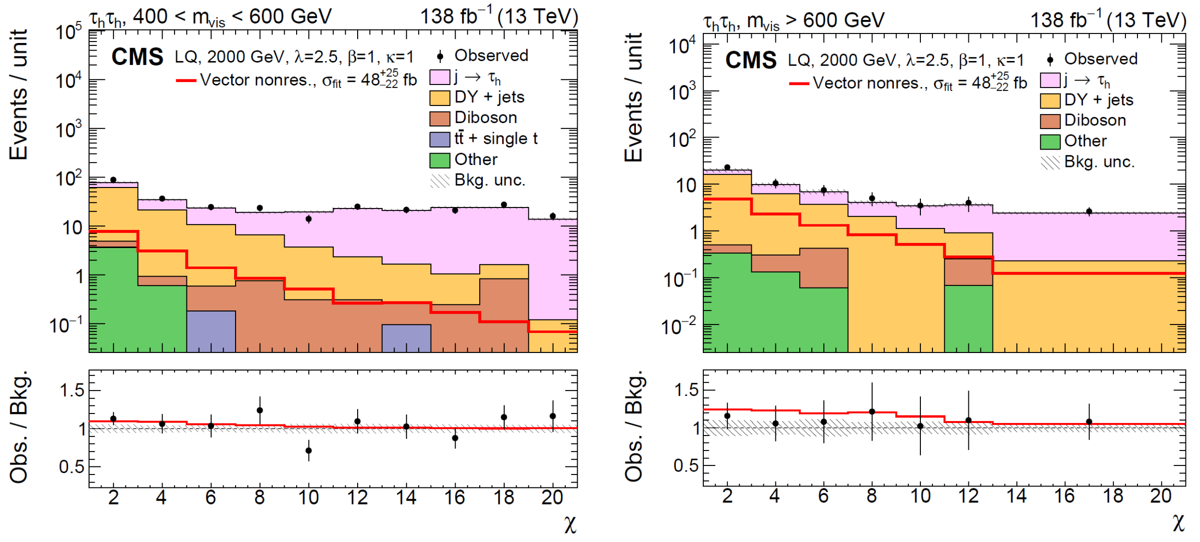
(Result from 2023)

- 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

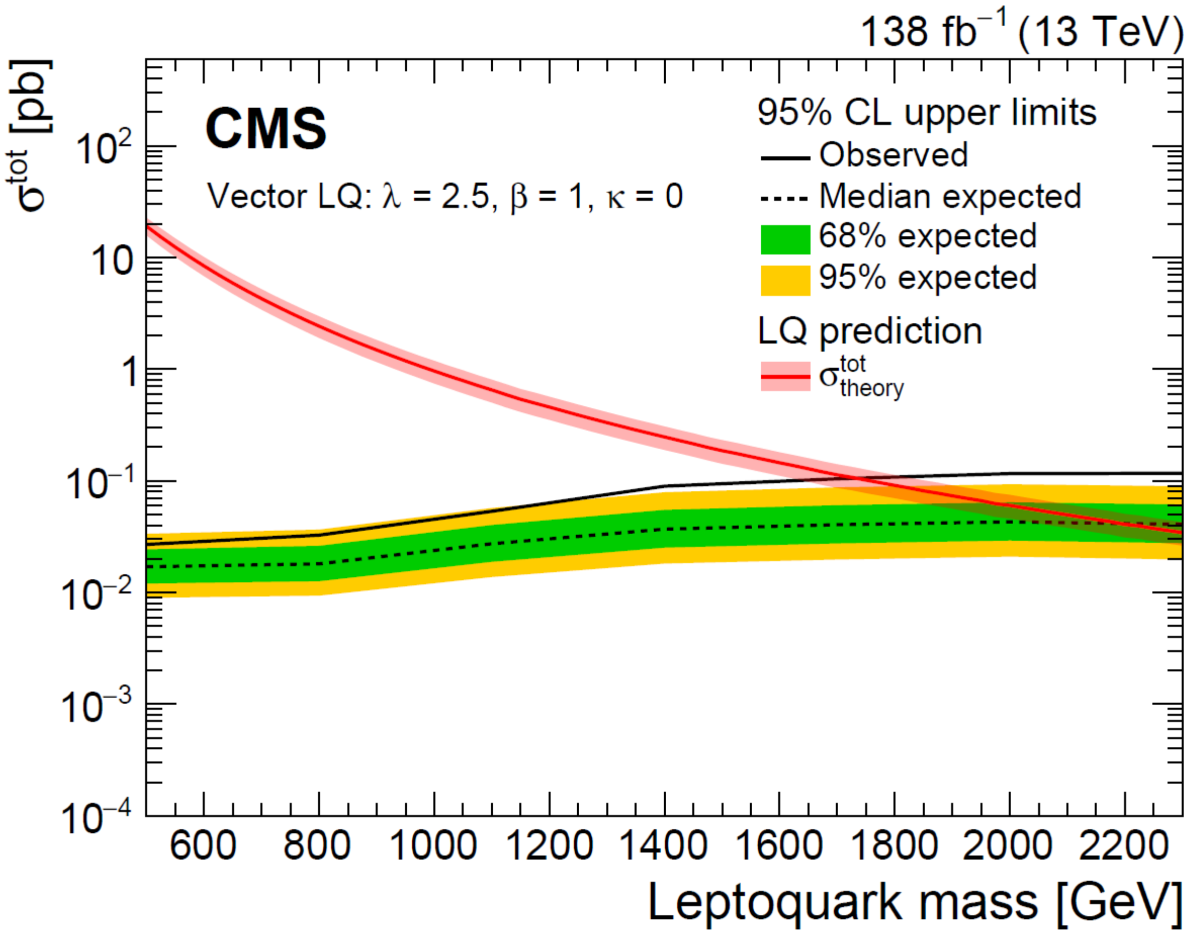


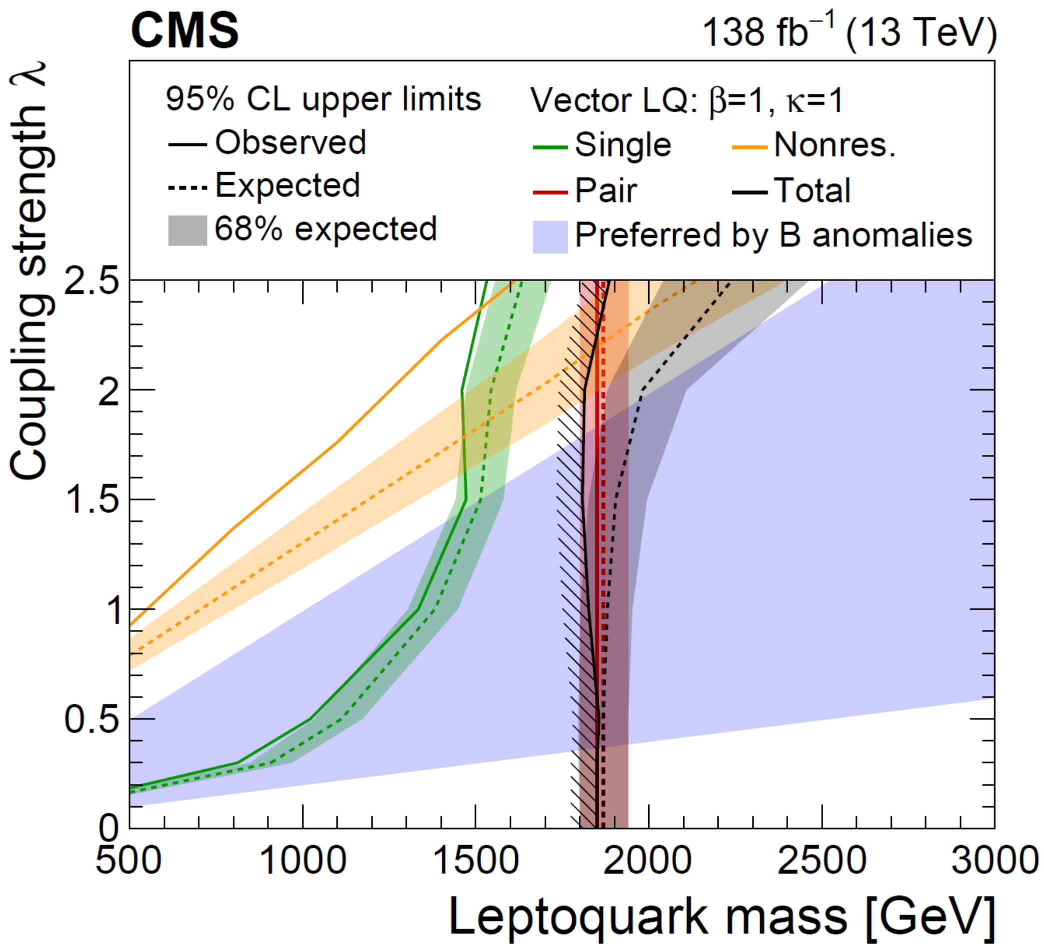
Non-resonant



Leptoquarks decaying to τ + b: 2308.07826

(Result from 2023)





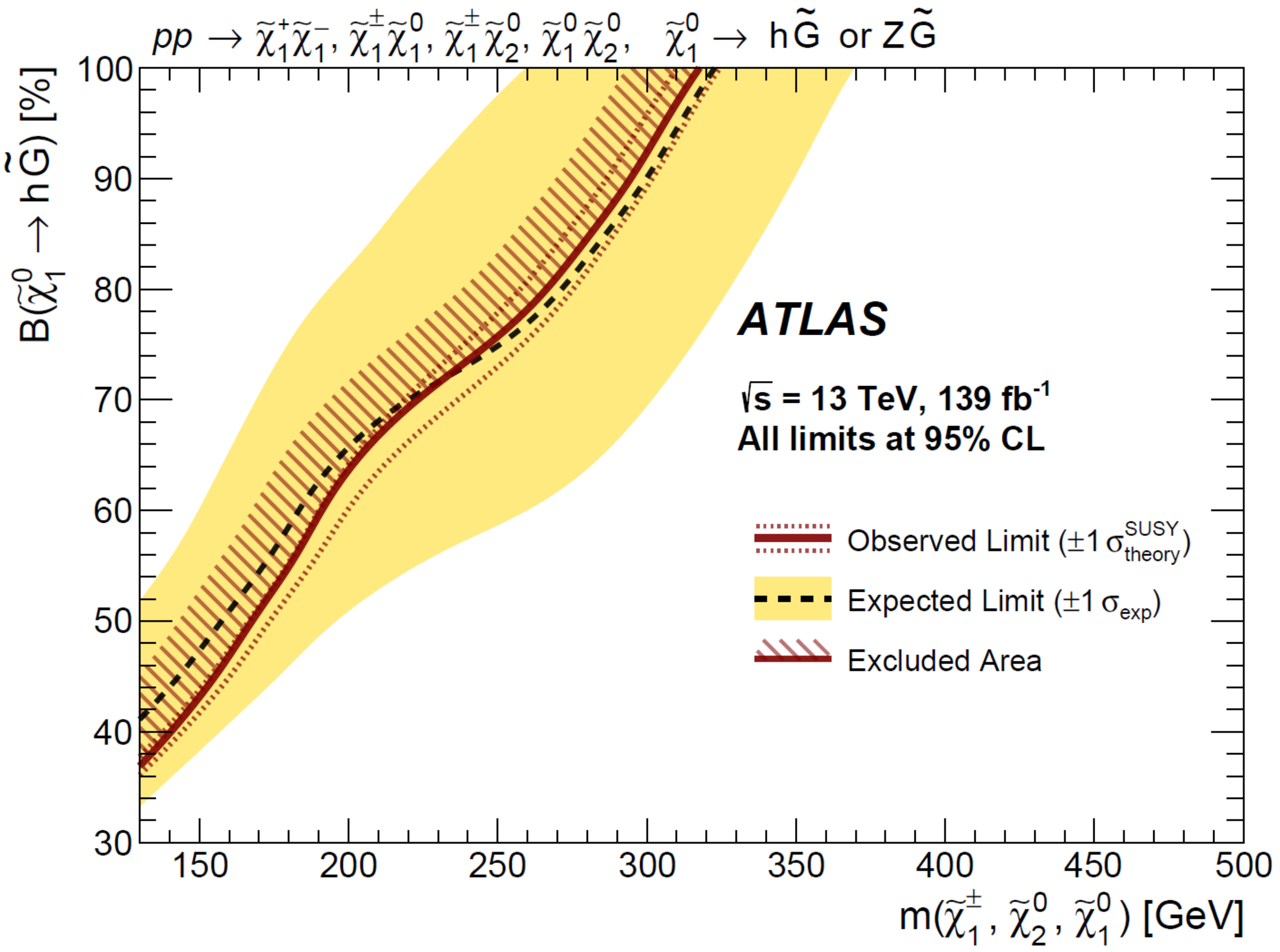
Vector LQ for λ=2.5, β=1 and κ=1 excluded for masses below 1.7 TeV

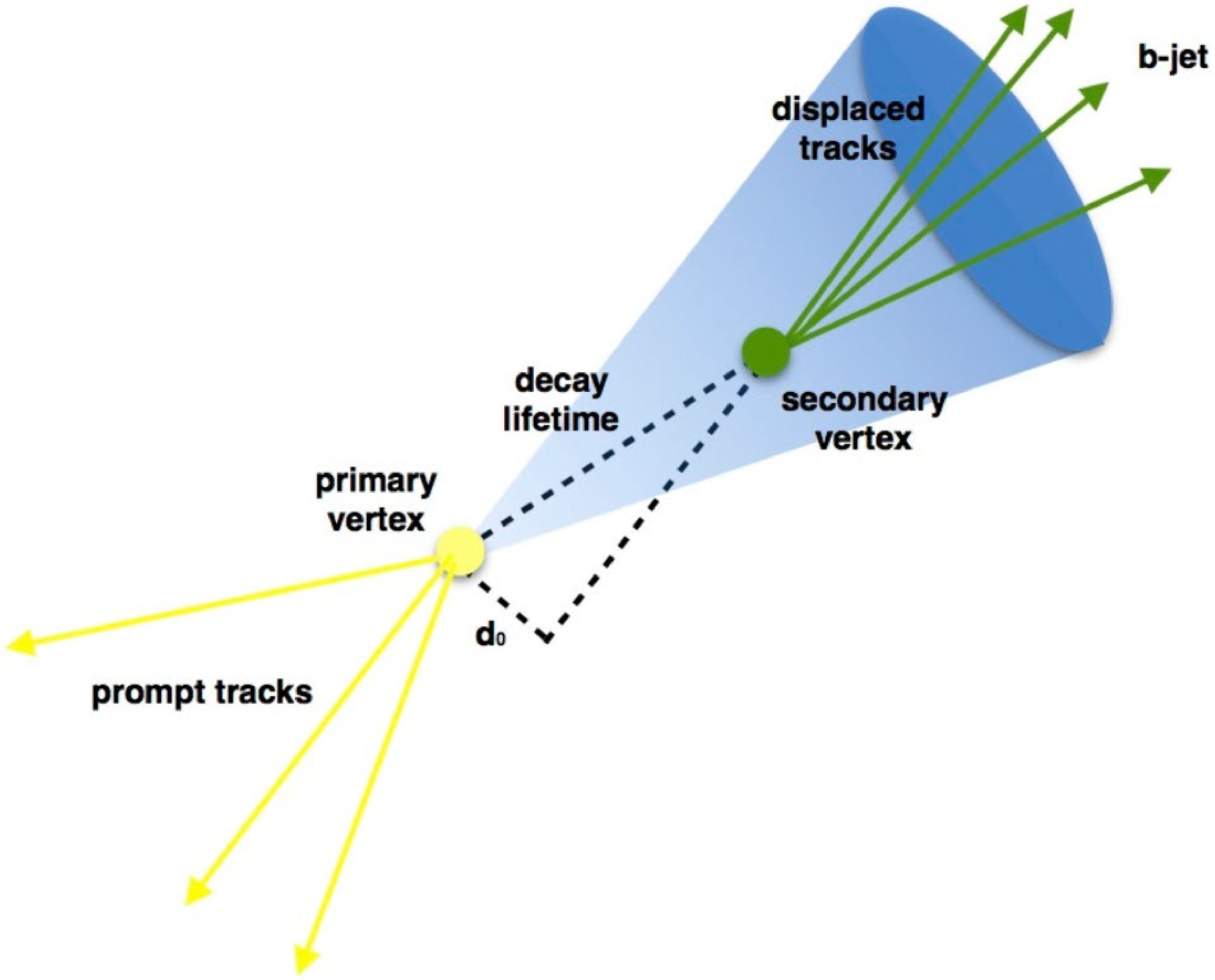
Broad excess found

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
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vertex
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prompt tracks