Beyond Standard Model - Experiment

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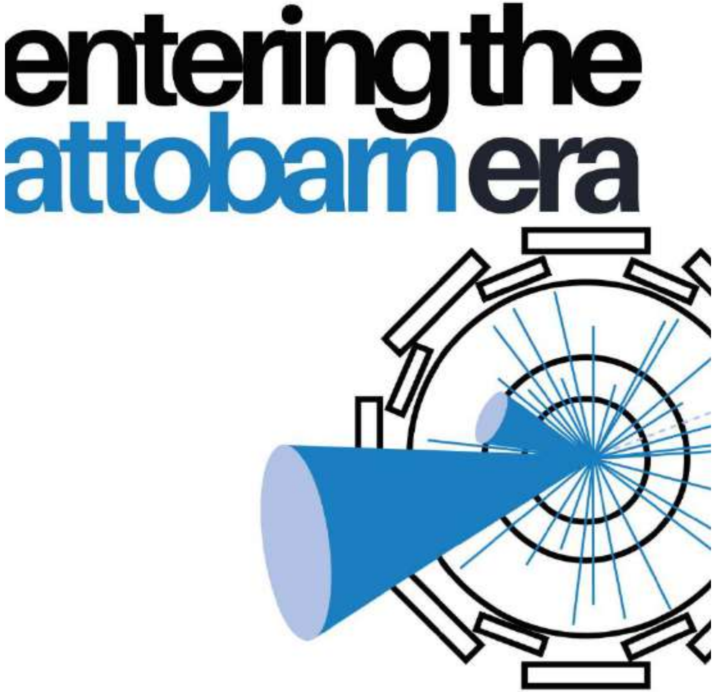
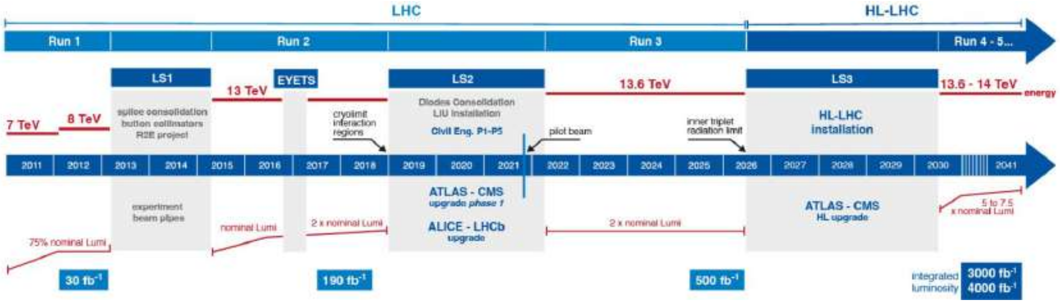
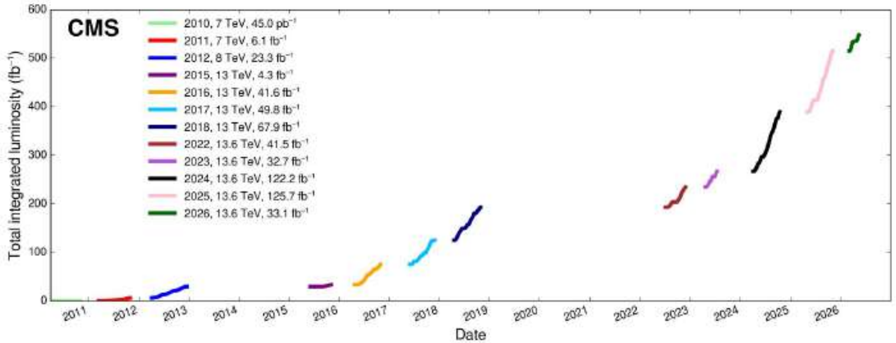
Disclaimer

- I did not select the latest results, but did a personal selection of results that could show the state of the art, overviews or analysis strategies used to get new results in some BSM areas.
- For most of the recent results see ICHEP 2026 BSM program

Energy-frontier physics relies on the LHC



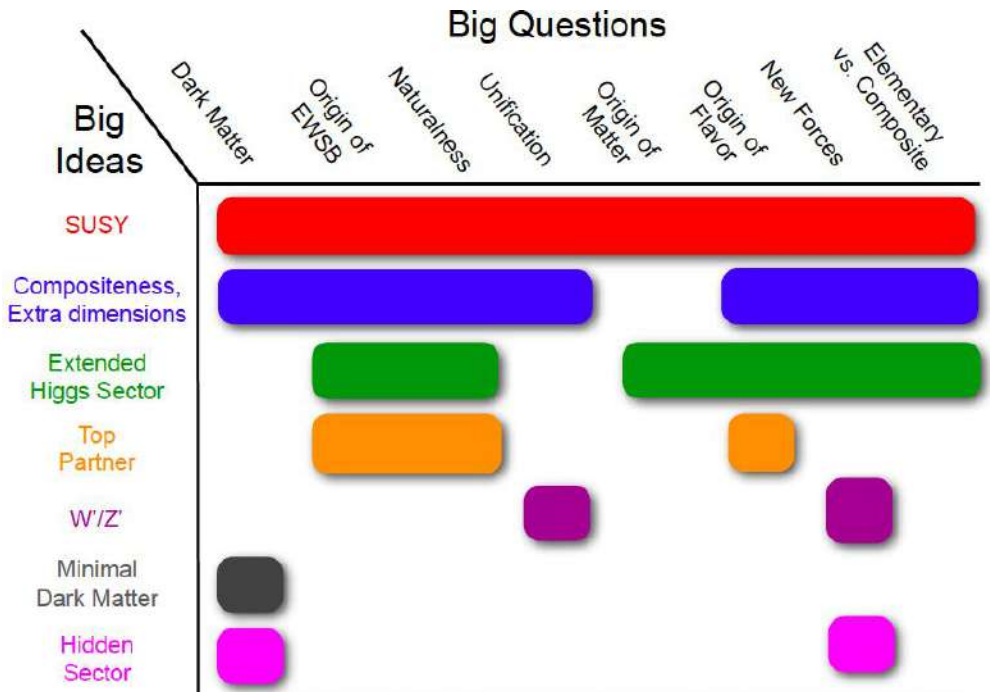




Since the LHC began operations in 2010, it has delivered over 0.5 attobarns (500 fb^{-1}) of proton–proton collisions to the experiments. Many physics targets that were not considered in the original plan are now mainstream.

BSM Physics at LHC

- Natural EWSB: Supersymmetry (SUSY), large/warped extra dimensions
- Neutrino masses/mixing, flavor anomalies: RPV SUSY, scalar di-quarks
- Dynamic explanation of EWSB: New strong dynamics
- Unification of all forces: magnetic monopoles, SUSY
- Dark matter: Axion-Like particles, Dark Sectors, SUSY, scalar mediators



arXiv:1311.0299v1

Guide for New Physics

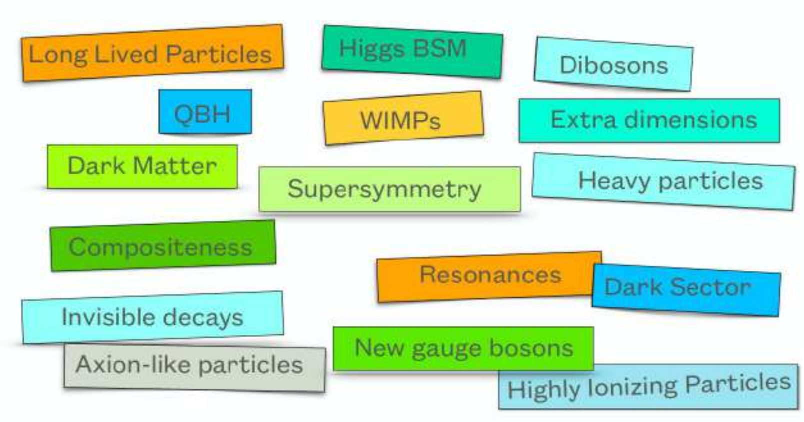
- For the last ~50 years, we've known what to look for at each step: Z boson, W boson, top quark, Higgs boson.
- Many expected SUSY particles to follow shortly after the Higgs, but now increasingly pushed to extreme regions of parameter space.

- Today, we no longer have a single guiding theory to motivate discoveries, but we do have largest HEP dataset ever collected
  - BSM not around the corner → Optimize analysis resources for broad BSM coverage and prioritize well-motivated dedicated searches.

Simplicity

- Effective Theories
- Simplified Models
- Complete Theories

Complexity



BSM at LHC

Searches for deviations from the SM in precision measurements (what is in the loop?) → hints for scale of new physics

- Electroweak physics
  - Higgs boson properties
  - W and Z bosons
  - Multibosons
- Top physics
- Flavor physics

Direct searches for BSM phenomena

→ evidence of new physics

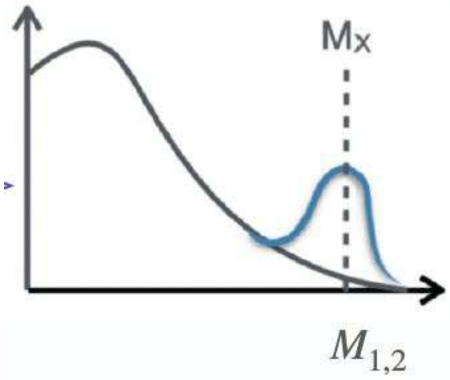
- Resonant searches
- Non-resonant searches
- Unconventional signatures

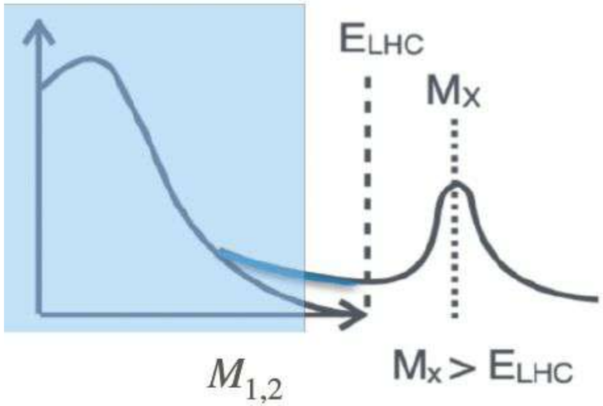
This Talk

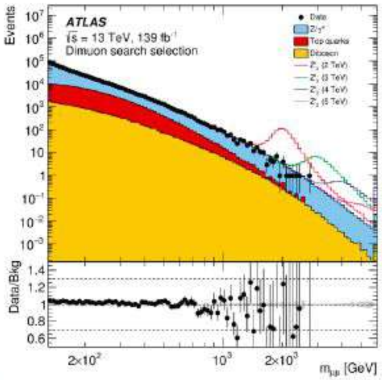
With increasing statistics we could aim for:

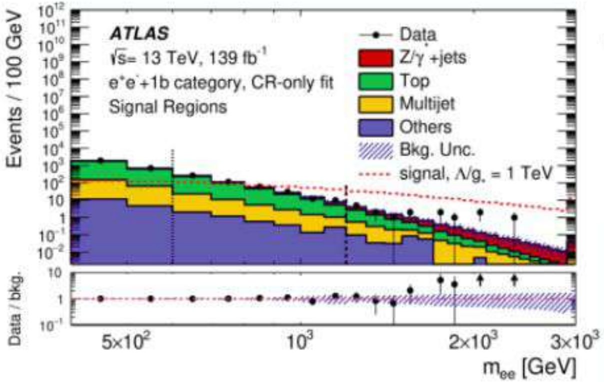
- low-coupling electroweak states (smaller couplings, relatively light)
- high-x (large mass)

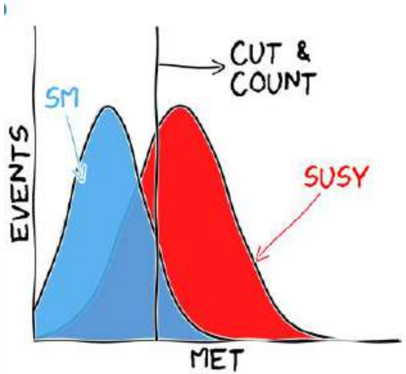
Search for New Particles

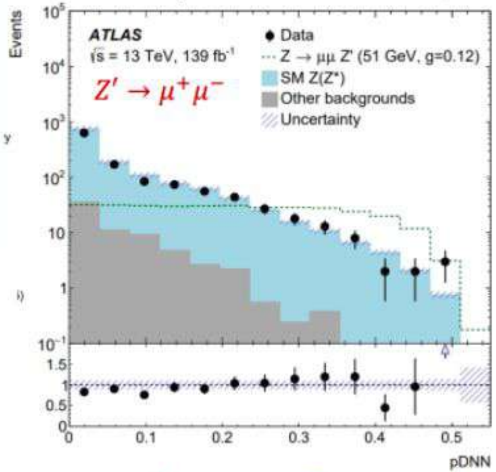


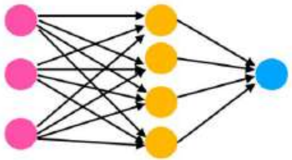




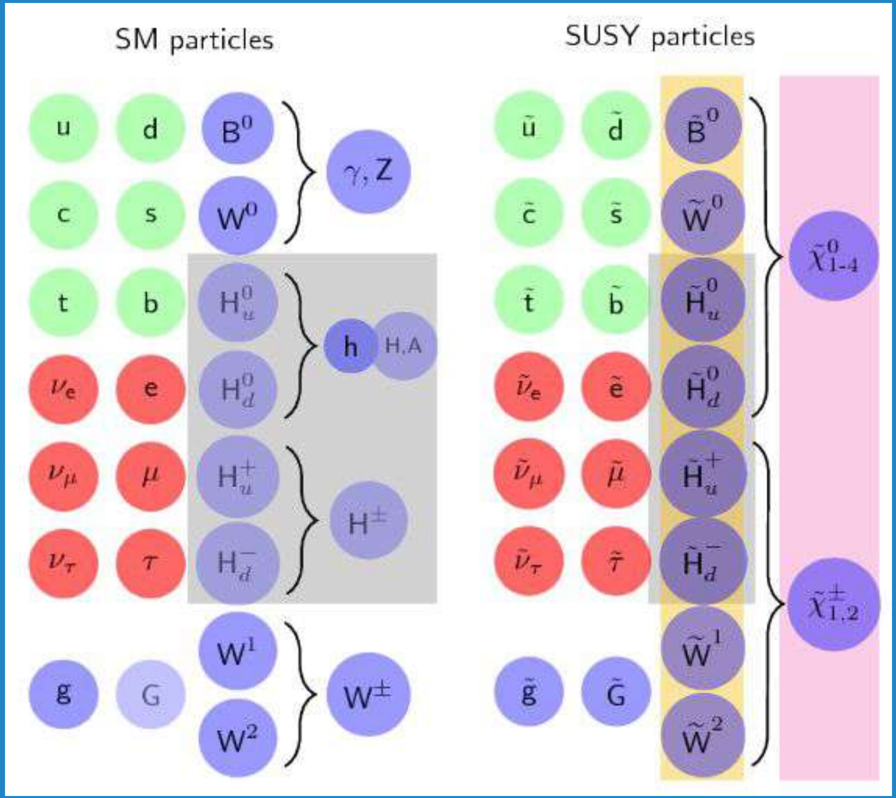




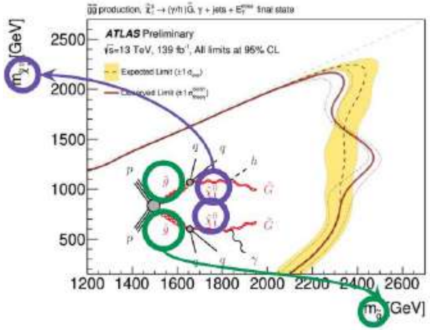




SUSY

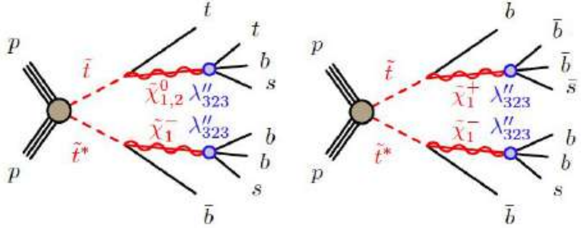


General Scenarios



- **Strong Production**
  - Searches focusing on gluino & squark production
  - Many particles in the final states (jets, leptons, photons)
  - Dedicated 3G SUSY searches (top- and bottom-squarks)
  - Unique phenomenology & final states with heavy fermions
- **Electroweak Production**
  - Rare but clean signatures
  - Less well-constrained than Strong SUSY
  - Sleptons/Neutralinos affect g-2

- **R-Parity Conservation (RPC)**
  - Prevents Proton decay
  - Conserves Baryon & Lepton number
  - Lightest SUSY particle (LSP) is stable and non-interacting (DM candidate)
  - Final states containing large Missing Transverse momentum
- **R-Parity Violation (RPV)**
  - Most general super-potential contains B&L -number violating terms (non-zero lambda terms)
  - Other conditions (not just R-parity) can prevent proton decay
  - More weakly constrained than RPC
  - Very rich phenomenology, final states with many particles (and small missing transverse momentum)



SUSY EWK pMSSM Scan

- **Phenomenological Minimal Supersymmetry (pMSSM)**
  - Number of SUSY parameters reduced from **~100 to 19 and for EWK to some of the main relevant parameters**
  - **N-dimensional scan of the SUSY electroweak sector**
  - LHC and external constraints: LEP, flavor, precision EWK, Dark Matter

M_1	-2 TeV	2 TeV	Bino mass parameter
M_2	-2 TeV	2 TeV	Wino mass parameter
μ	-2 TeV	2 TeV	Bilinear Higgs mass parameter
M_A	0 TeV	5 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

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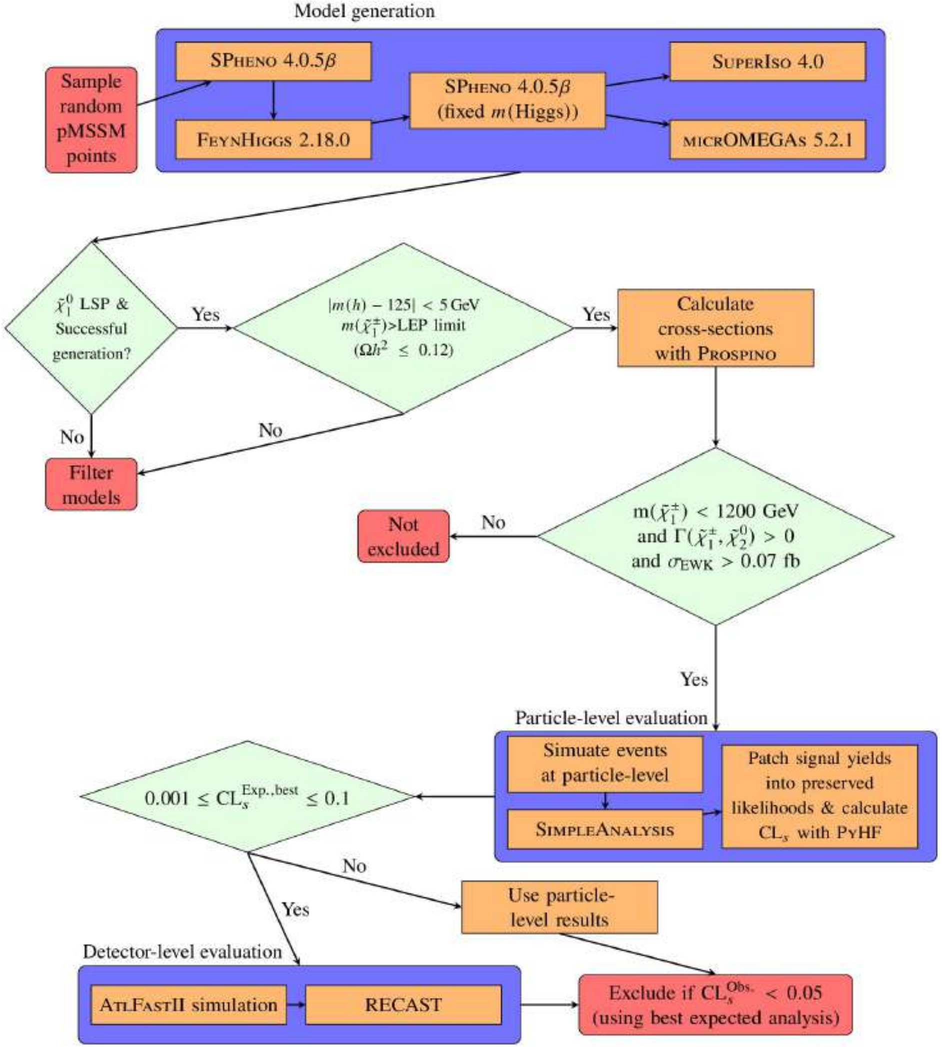
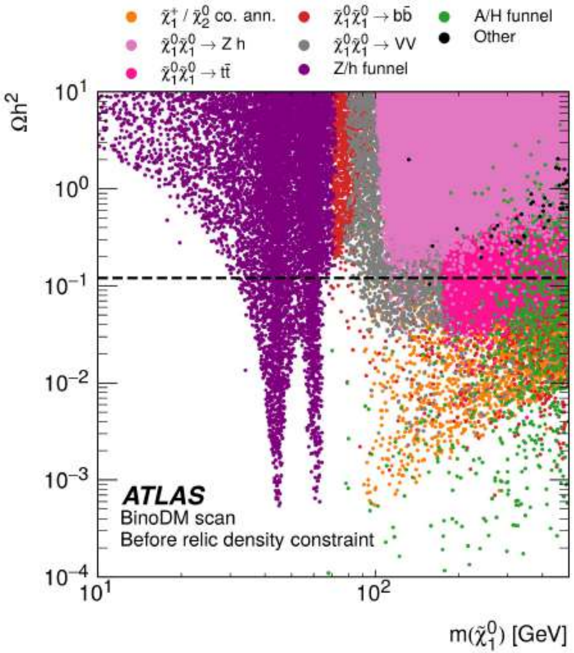
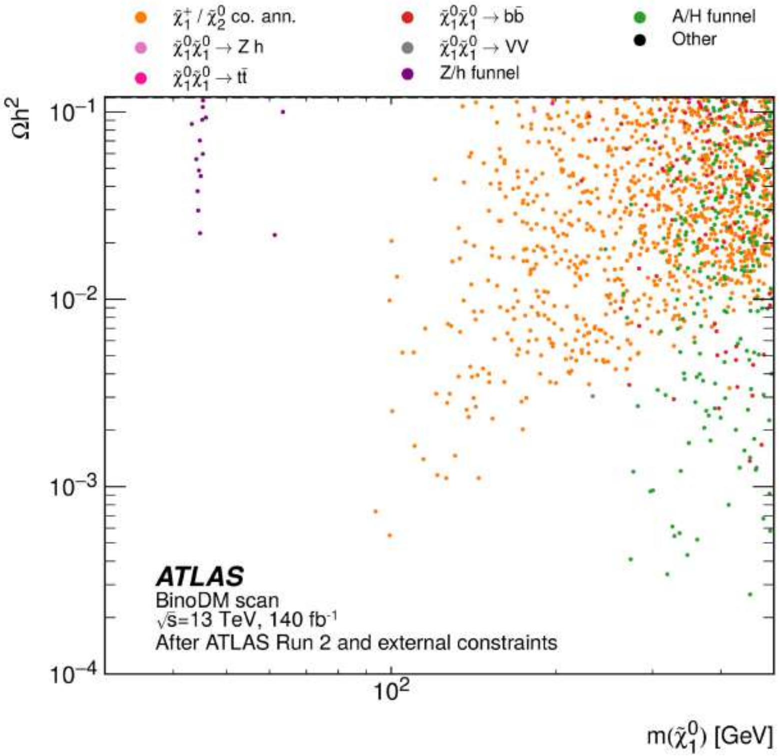


SUSY EWK pMSSM

Impose LHC & external constraints

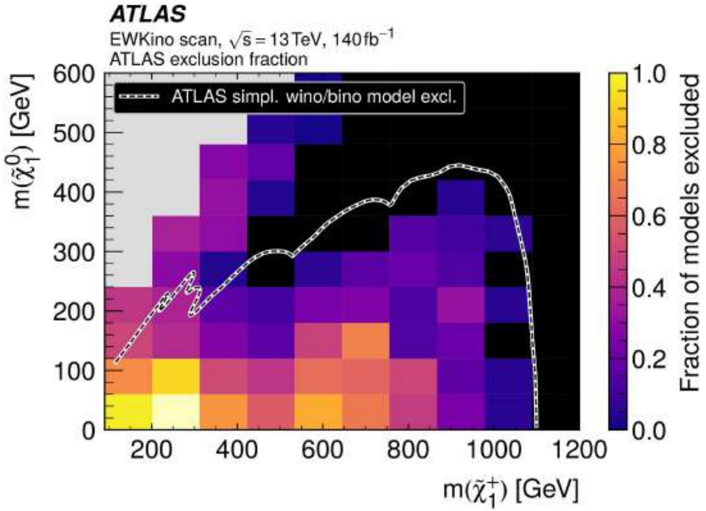


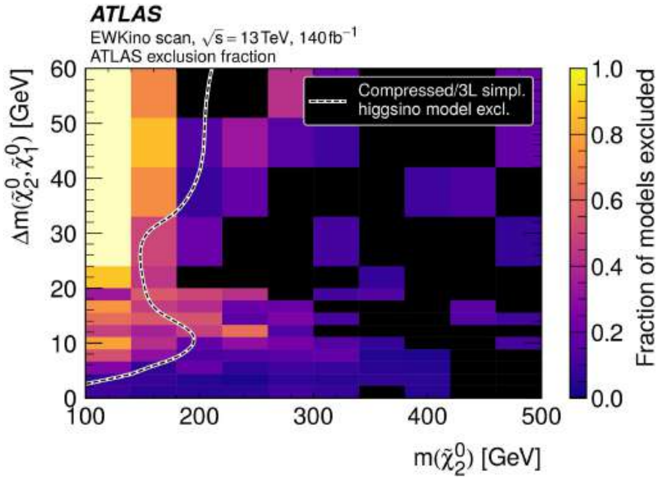


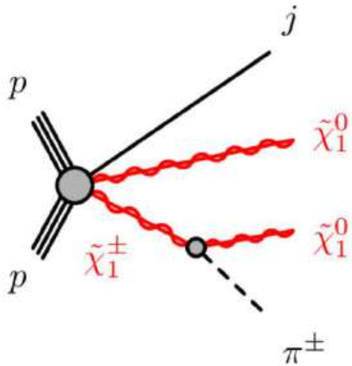
- Previously-favoured regions for masses where the dark-matter particle has about half the mass of the Z boson or the Higgs boson (Z/h funnel) have been almost totally excluded
- Almost full exclusion of low-mass χ_{01} in regions where a low-mass neutralino would not oversaturate the dark matter relic abundance.

SUSY EWK pMSSM

- Only small region of parameters space has ~100% exclusion (yellow bins)
- Exclude at least 50 % of models up to chargino mass of 400 GeV Even outside simplified model contour
- Only up to ~50% of models with compressed spectra is excluded







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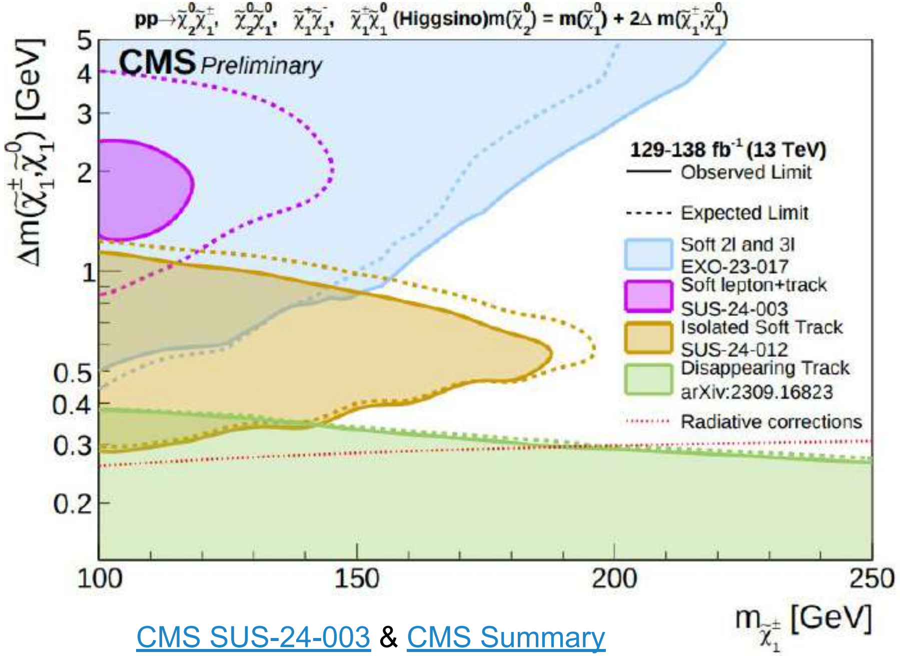
For CMS interpretation see SUS-24-004

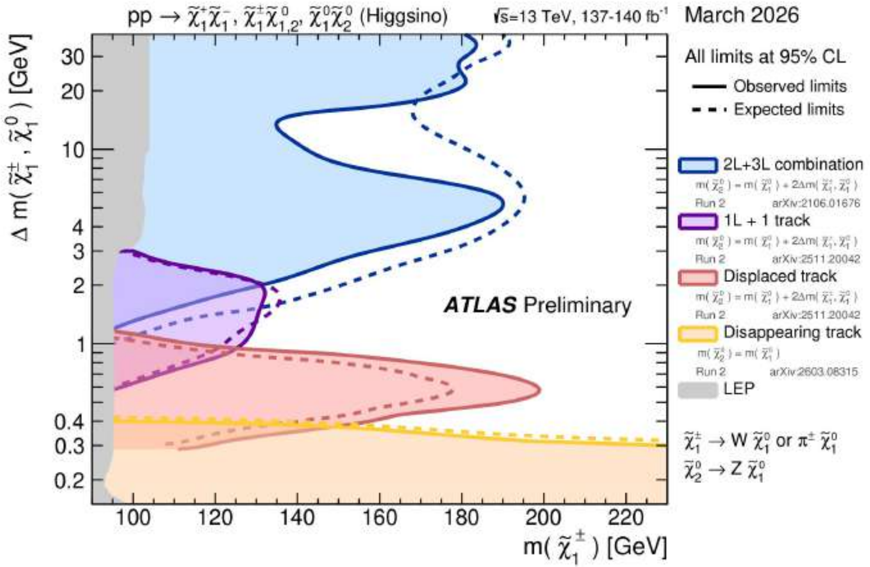
Compressed EWK SUSY

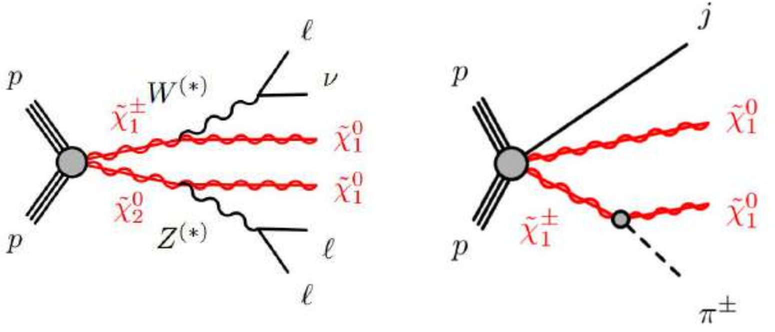
ATL-PHYS-PUB-2026-003

Tackle through dedicated searches

- Soft leptons target higher Δm
- Soft lepton+track target intermediate Δm
- Displaced tracks from $\pi^{\pm}$ target low Δm
- Disappearing tracks target lowest Δm





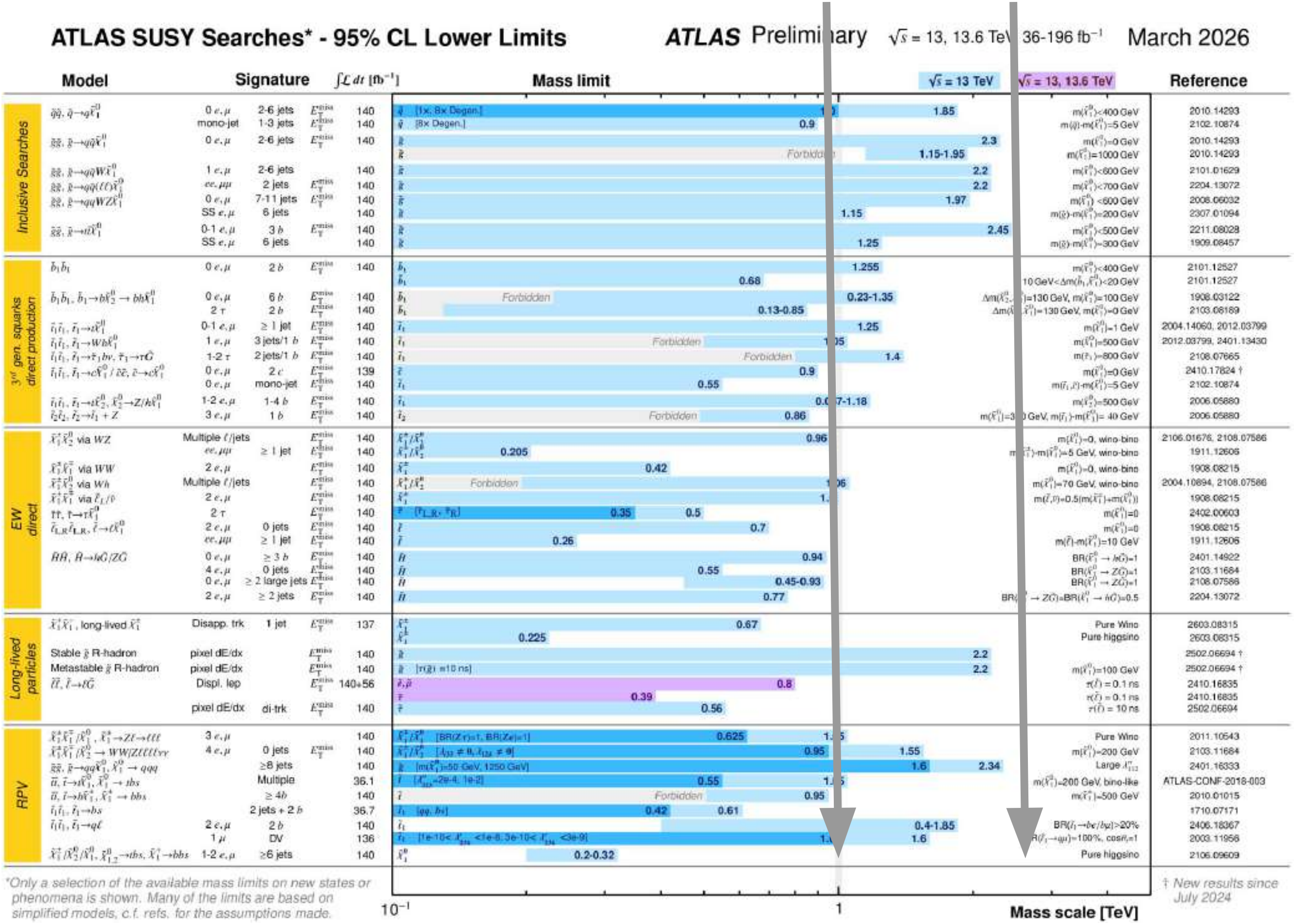


CMS SUS-24-003 & CMS Summary

Mass reach of searches for Supersymmetry

Simplified models limits full Run 2 and preliminar Run 3 dataset

- **Up to ~2.5 TeV exclusion for gluinos at low LSP mass**
- **Up to ~1.85 TeV for squarks (8-fold degeneracy)**
- **Some scenarios excluding ~1.4 TeV stops**
- **Up to ~1 TeV limits for gauginos and ~0.7 TeV for sleptons**

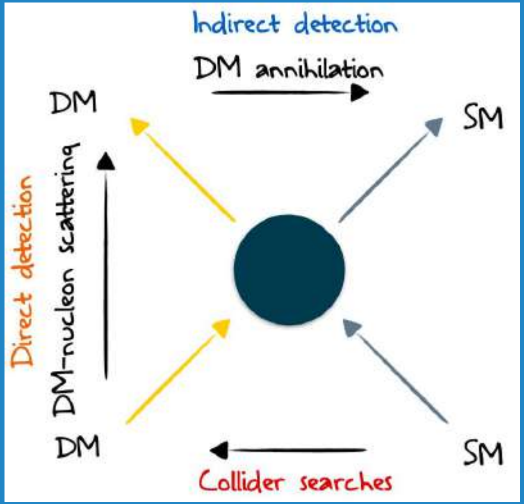


https://atlaspo.cern.ch/public/summary_plots/

HEPData

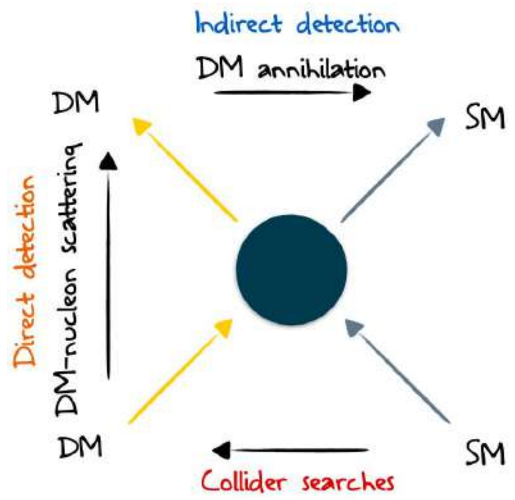
ATL-PHYS-PUB-2026-003

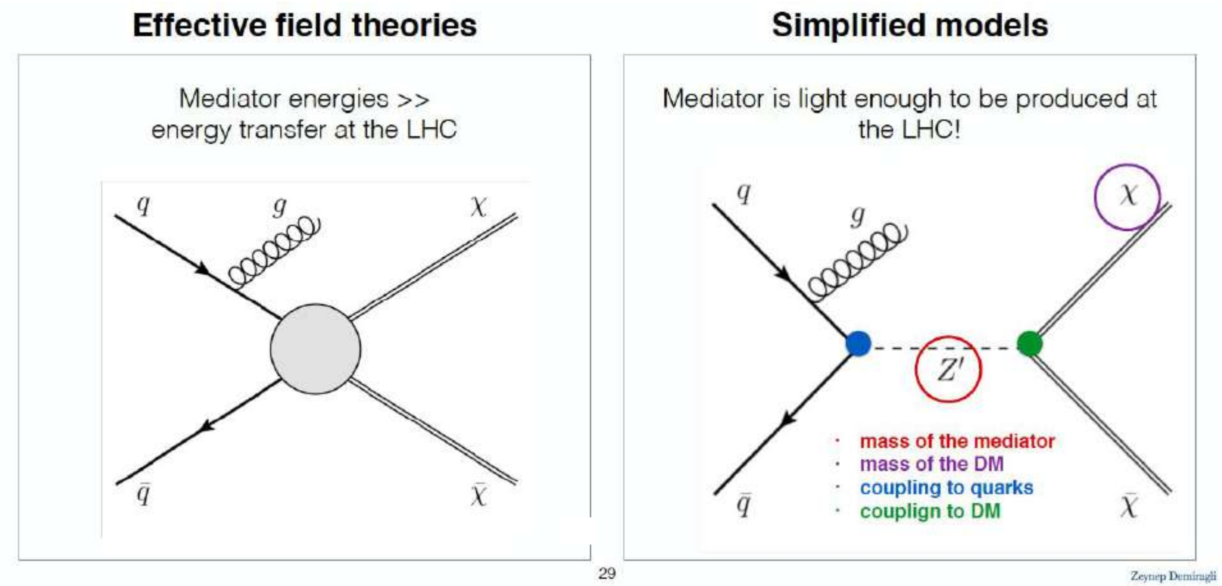
Dark Matter



Indirect detection
DM annihilation
DM
SM
Direct detection
DM-nucleon scattering
DM
SM
Collider searches

Dark Matter





At early Run-2 the ATLAS and CMS experiments made common efforts to set a well-defined simplified models approach.

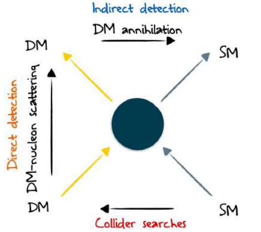
Mostly 4 parameters:

- Mediator mass (M_{Med})
- WIMP mass (m_χ)
- 2 couplings (g_q,g_χ), typically (1, 0.25)

DM as Dirac-fermionic WIMPs
Neutral, stable, weakly interacting particles with mass O(100 GeV)

arXiv:1507.00966v

DM Summary



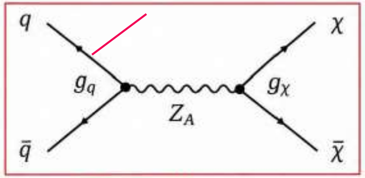
Results translated into **DM-nucleon elastic scattering cross-section limits**

↪Compared to direct searches

↪**Competitive at low DM masses**

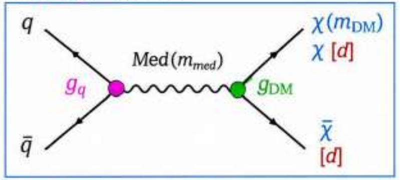
■ **Simplified models:**

(mono-X: E_T^{miss}+X; mediator: resonance)

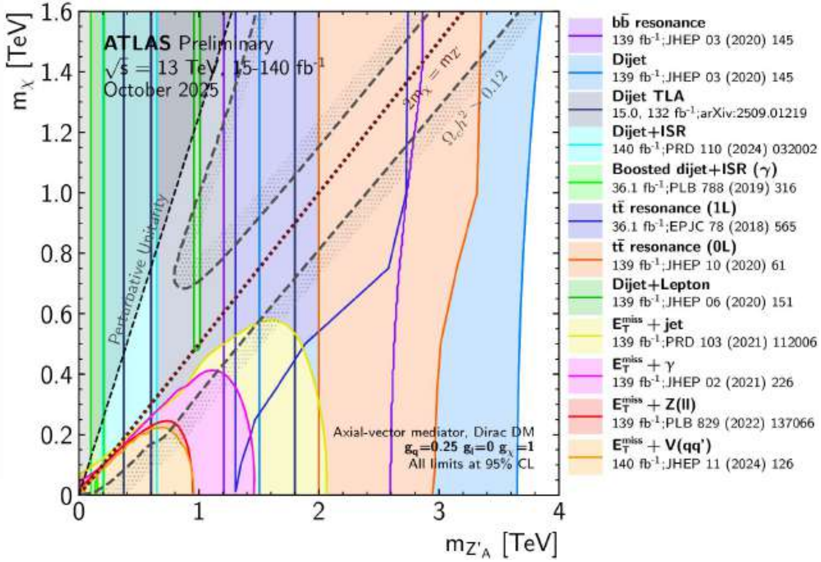


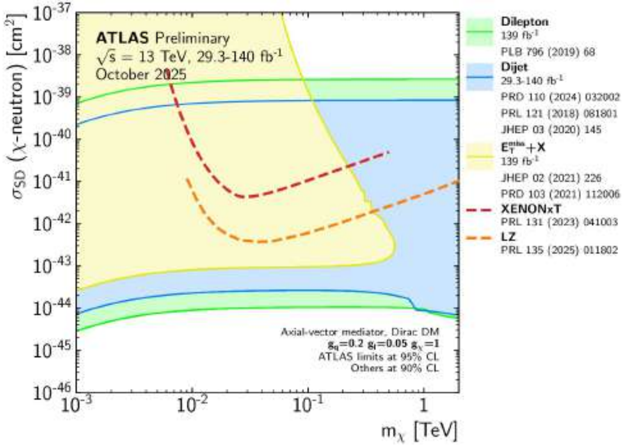
mono-X: E_T^{miss}+X

X: jet, γ, V, H …



mediator: resonance of di-jet, bb, tt





Searches can exclude mediator masses between ~50 GeV and ~3.6 TeV for almost whole DM mass range.

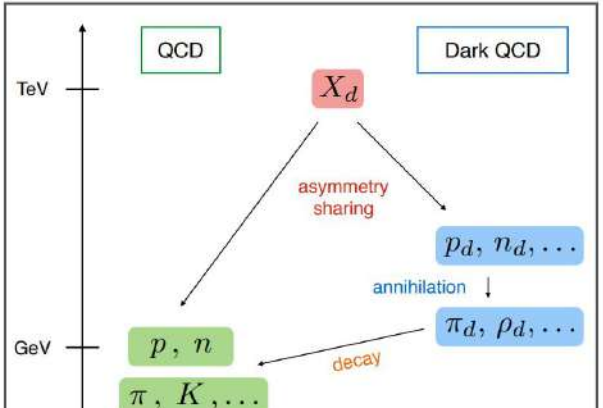
ATL-PHYS-PUB-2025-041

Dark QCD

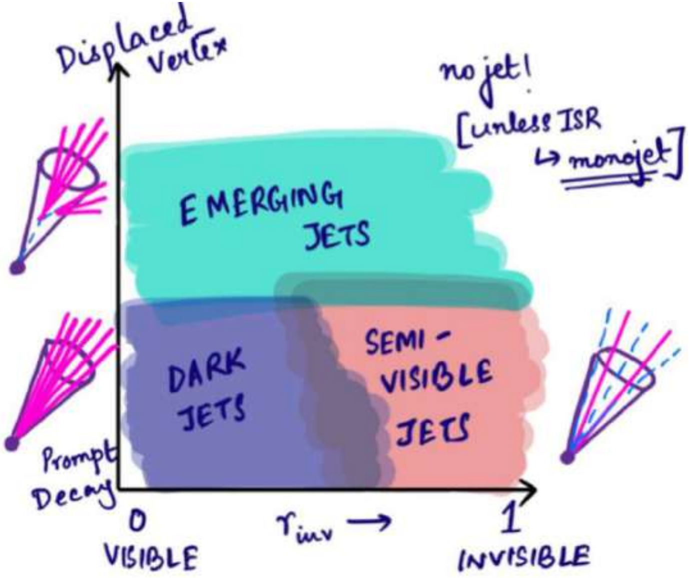
Wide ranging and successful dark matter collider search programme in Run-2. Initially focussed on WIMP hypotheses.

But what if there existed **a force similar to SM strong force (=QCD) but acting on a dark sector**?

- Would **expect dark baryons, and dark mesons** (the lightest of which would be like dark π or ρ and could be DM candidates!)
- Wide range of phenomenology possible depending on coupling strengths to SM and lifetimes of particles:
  - Semi-visible jets
  - Emerging jets
  - Dark jets



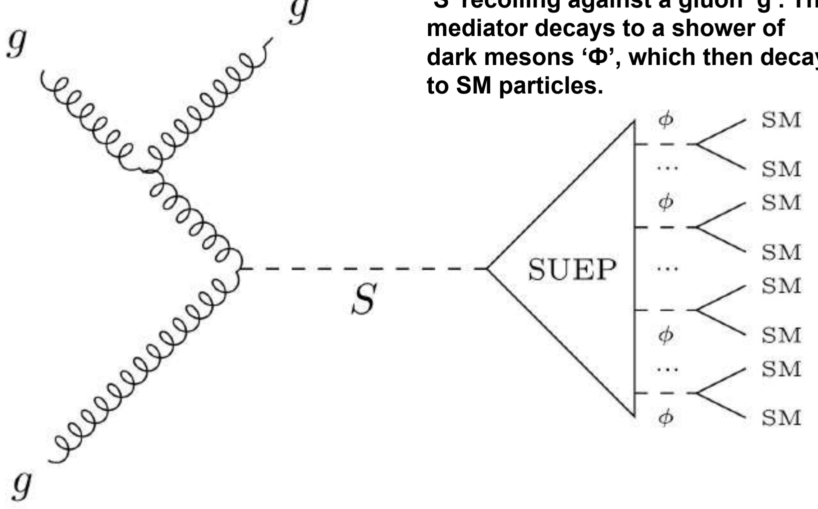
arxiv.1502.05409



Search for Soft Unclustered Energy Patterns (SUEPs)

- Strongly coupled hidden sectors
- Dark shower loses collinear jet structure
  - SUEP phenomenology
  - **Nearly isotropic emission of soft particles**
  - High charged-particle multiplicity
  - Low-p_T tracks distributed throughout detector
  - Absence of conventional jets
- Experimental challenges
  - Soft objects fail standard jet triggers
  - Large QCD and pileup backgrounds
  - Non-standard reconstruction strategies required

production of the mediator particle ‘S’ recoiling against a gluon ‘g’. The mediator decays to a shower of dark mesons ‘Φ’, which then decay to SM particles.



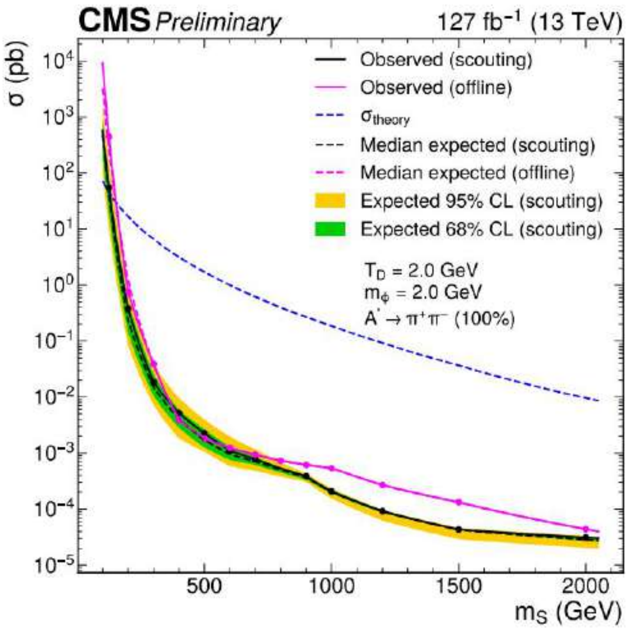
CMS data-scouting stream strategy on data-taking→ records only the results of the trigger-level reconstruction in order to enable a lower threshold on the hadronic activity)
Significant lower threshold on trigger.
Recording only a subset of each event’s data (trigger level)
ATLAS has similar strategy as “TLA stream”. Similar techniques Sphericity & Extended ABCD method.

PhysRevLett.133.191902

CMS-PAS-EXO-23-001

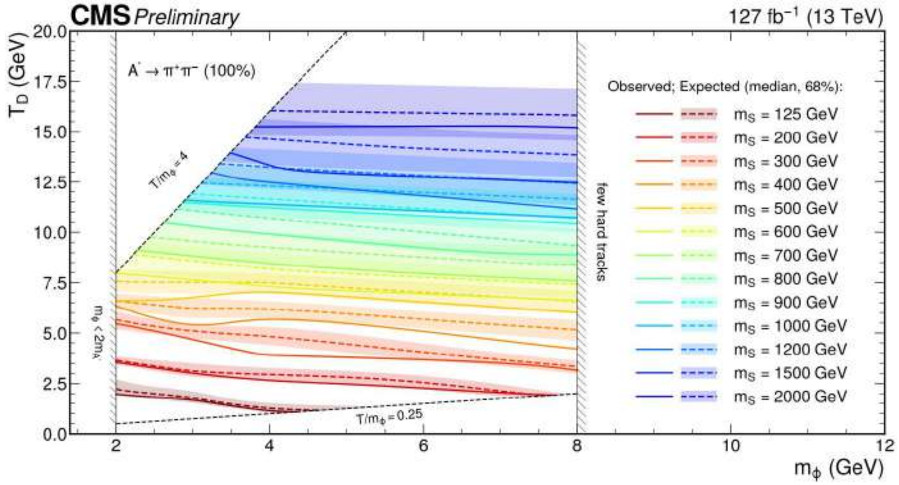
Search for soft unclustered energy patterns (SUEPs)

Data-scouting show decent improvement on limits with more data and higher signal acceptance



CMS-PAS-EXO-23-001

PhysRevLett.133.191902



First dedicated SUEP research provide strong exclusion for thermalized dark showers.
(The regions below the observed limits are excluded)

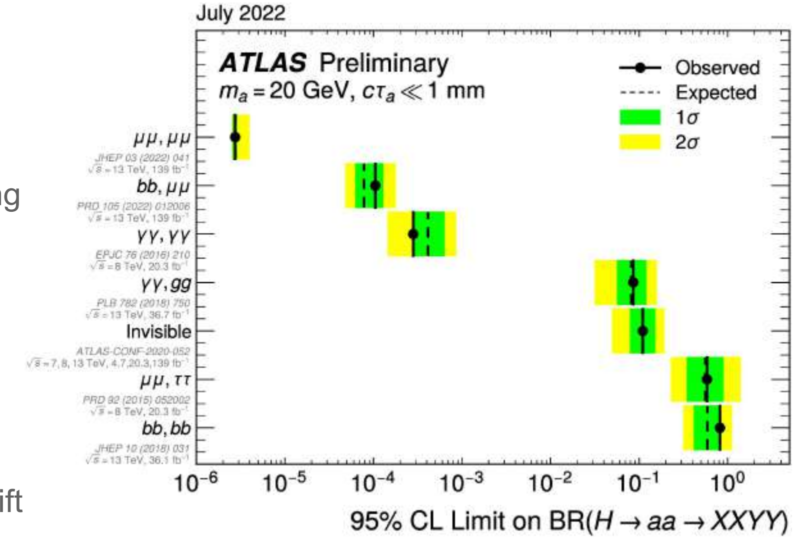
See ATLAS complementary results: arxiv.org:2605.20015

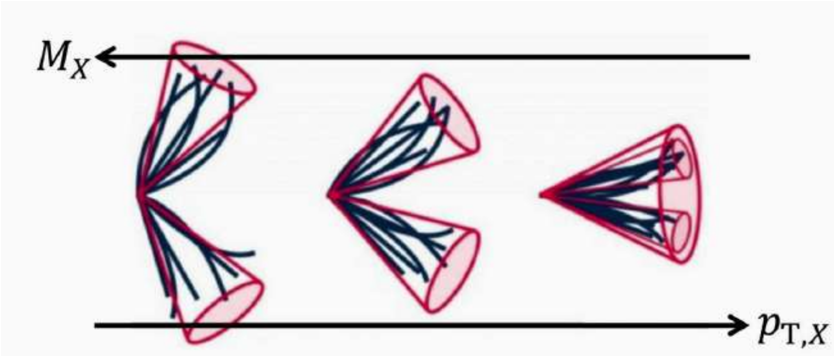
Higgs Portal

Searches for low-mass BSM physics

So far:

- No discovery yet of EW/TeV scale BSM physics
- **Many models well-constrained at high mass**
- **Weaker constraints on low-mass BSM scenarios**
- (Very) broadly-speaking, two main “classes” - whether or not involving Higgs boson decay
- Higgs the only elementary scalar in the SM.
- **Current bounds still allow sizable BSM Higgs BRs**
    - Br(H→undetected) < 12% (2207.00092 & Nature 607)
    - Br(H→invisible) < 10.7% (2301.10731 & PLB 842)
- Many models allow for low-mass new physics:
    - Additional Higgs-like particles, a-la 2HDM(+s)
    - **Axion-like particles** (ALPs) in SM extensions with broken shift symmetry
    - Heavy neutral leptons (HNLs), e.g. in seesaw mechanism



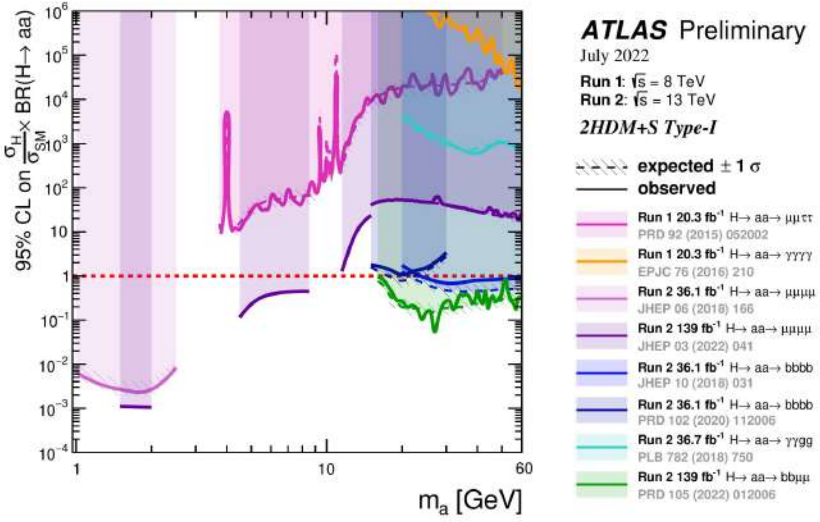


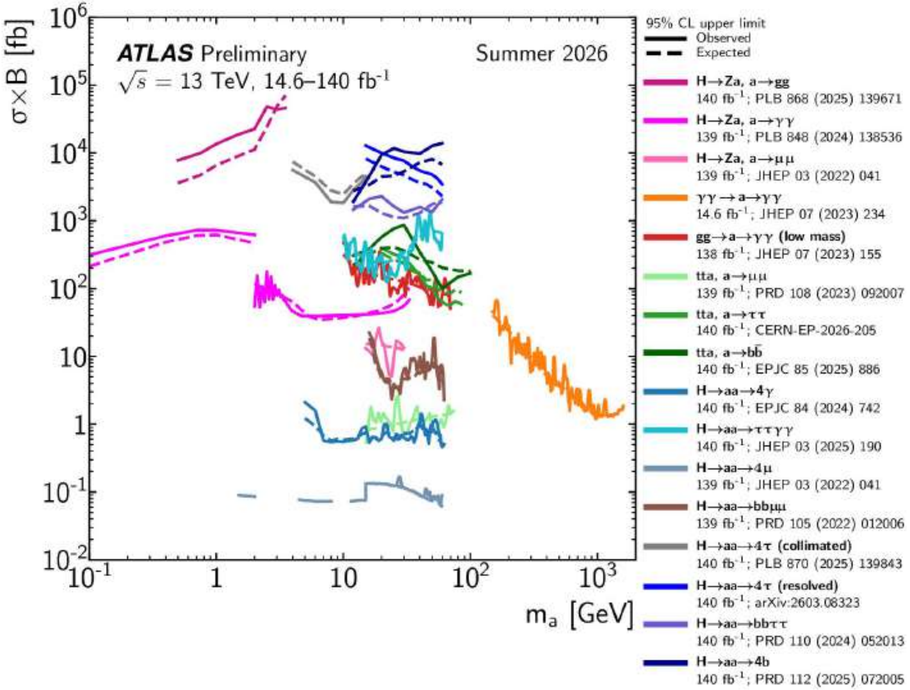
Low-mass BSM searches often quite challenging:

- Collimated decay products → dedicated tagging methods
- Long-lived, weakly coupled → displaced tracking/vertexing
- Background-rich → innovative analysis strategies (+clever ML)

Exotic Higgs Boson Decays

Many searches for anomalous Higgs boson decays into two **axion-like particles (ALPs)** with different decay modes couplings

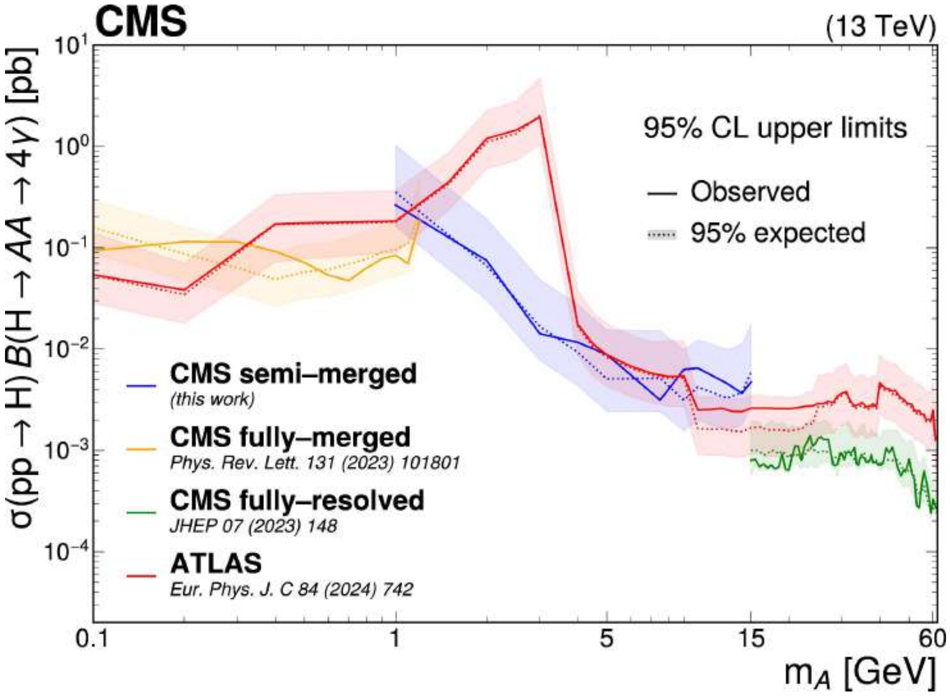




ATL-PHYS-PUB-2025-011 ATL-PHYS-PUB-2026-016

Merged and Semi-merged photons in final state

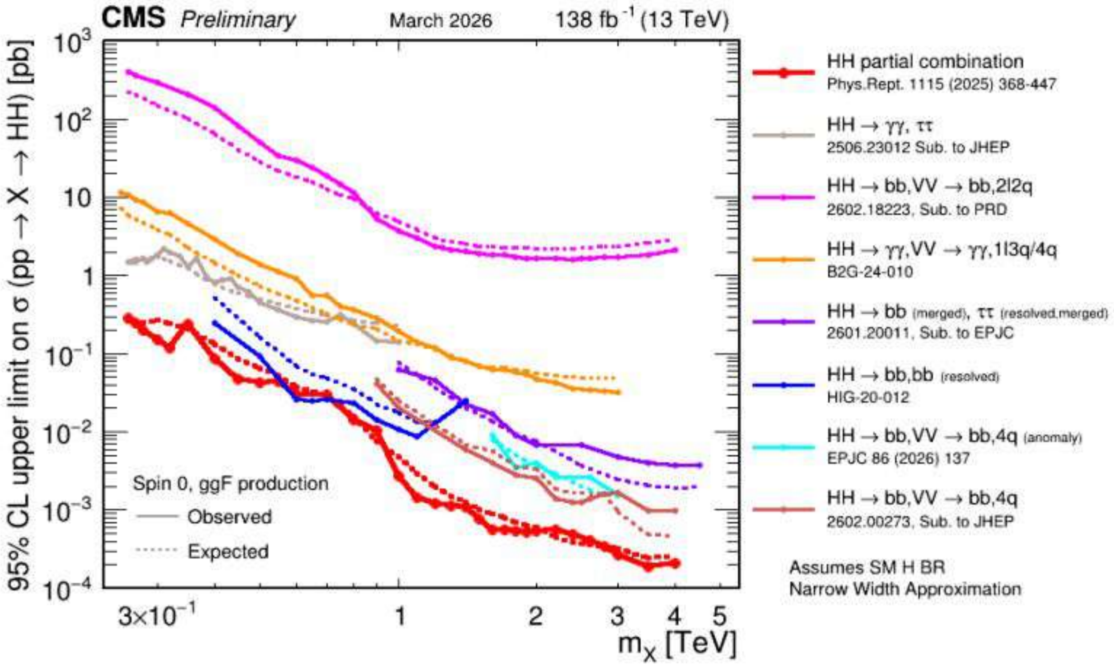
- Model: H → aa → 4γ
- Semi-merged topology:
  - **one a→γγ reconstructed as one photon-like object**
  - **other a→γγ reconstructed as two resolved photons**
- Motivation: bridges the gap between fully merged and fully resolved 4γ searches
- Key technique: merged m_a cannot be built from objects directly →mass regression GNN from ECAL energy-deposit patterns
- Complementary to full-merged/resolved researches



arXiv:2601.00183 (Submitted to the JHEP)

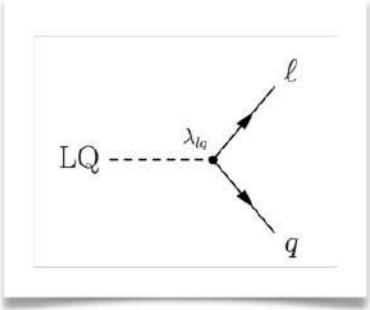
Flip the diagram

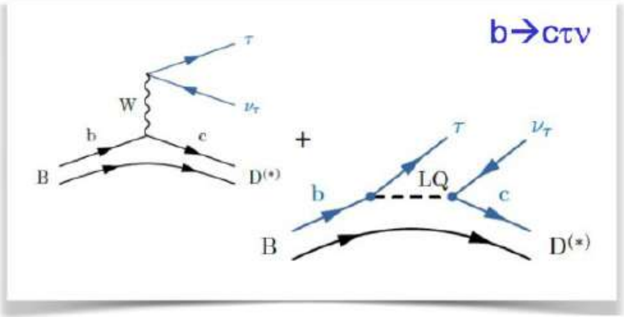
Instead of the Higgs decaying to something new, what if something new decays to a Higgs?
e.g. X → HH, X → SH

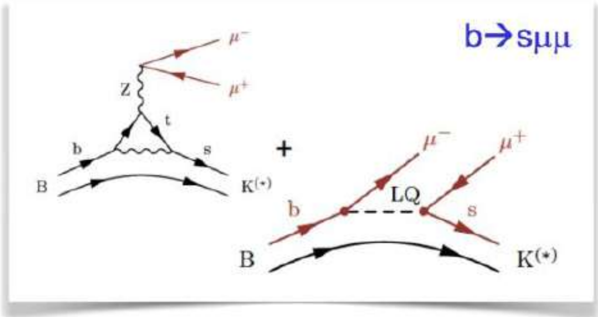


CMSPublic

Leptoquarks





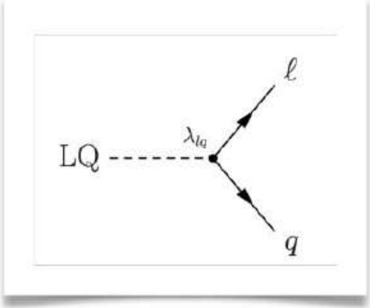


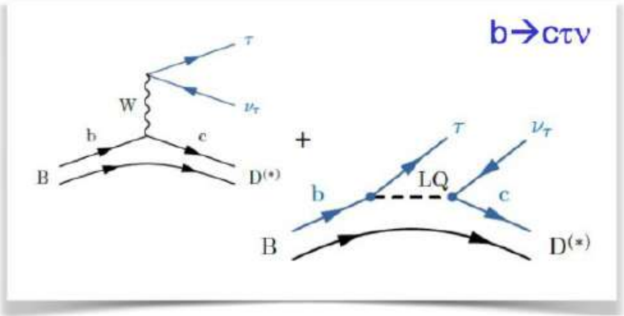
Search for resonant leptoquark production via lepton-jet signatures

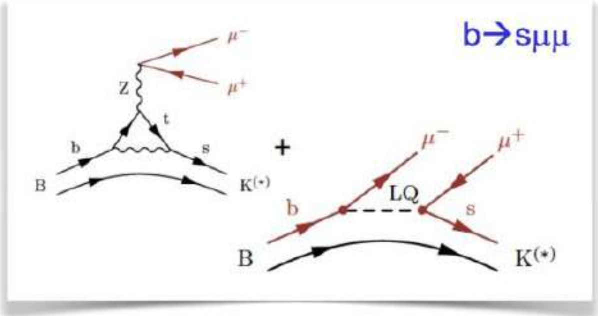
- Several recent results have pointed towards anomalies in the flavour sector
- Even after some excesses disappeared, many tensions remain with the SM.

- Leptoquarks (LQs) represent a prominent category of hypothetical heavy states predicted by various grand unified theories featuring extended gauge groups .

- These colour-charged **particles carry both baryon and lepton numbers, naturally reflecting the underlying symmetry between the two sectors** as predicted by unifying theories and suggested by observed patterns in nature.







Scalar LQ interactions with SM particles are determined by three parameters: the LQ mass m_{LQ}, the LQ branching ratio to a charged lepton and a quark β, and the LQ-quark-leptoquark Yukawa coupling λ

Search for resonant leptoquark production via lepton-jet signatures

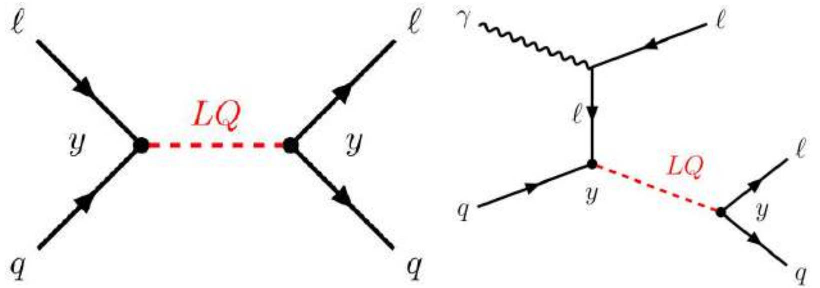
1st ATLAS analysis for LQ production exploiting lepton+photon PDFs

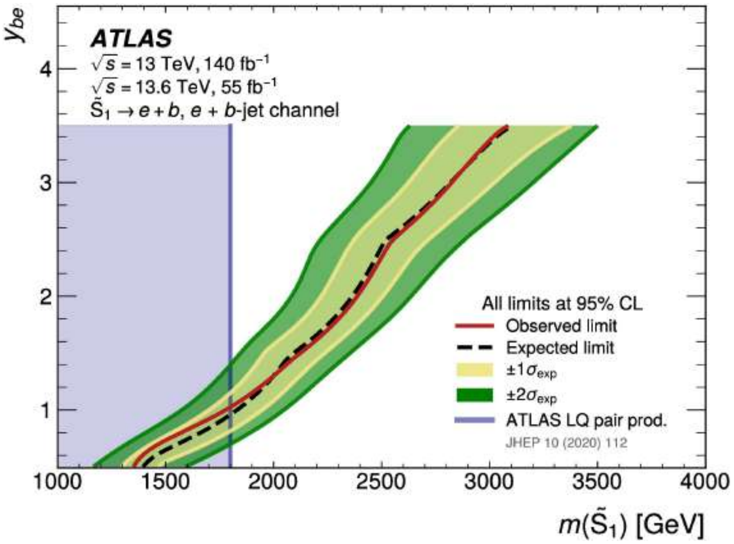
Possible now due to advancements in understanding of lepton content of protons

Photon PDF less suppressed than lepton PDF → contributions roughly on “equal footing”

Search in final states with 1 or 2 leptons and a jet
1e or 1μ + 1 light jet; 1e or 1μ + 1 b-jet
2e or 2μ + 1 light jet; 2e or 2μ + 1 b-jet

LQ sensitivity also from non-resonant production to dilepton production via t-channel (DY)





Derived limits on coupling vs LQ mass

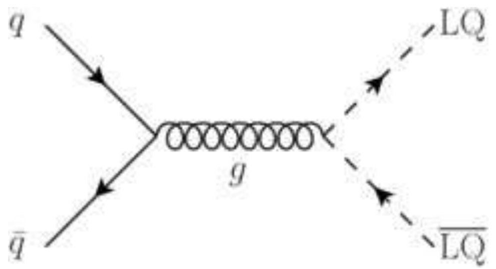
JHEP12(2025)180

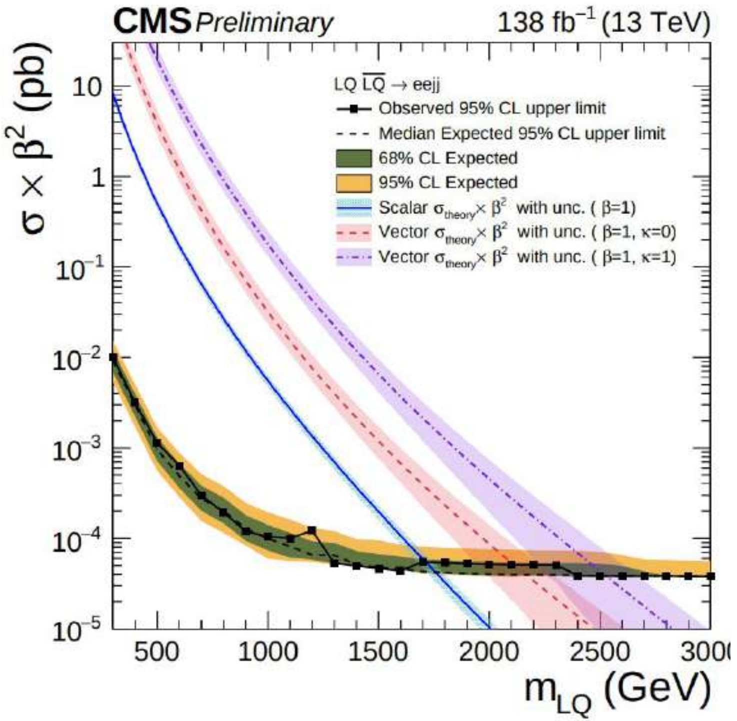
Leptoquark pair-production

The pair production cross section is nearly independent of λ and at the LHC dominates over single production for moderate values of λ.

Scalar leptoquarks decaying to down quarks with β = 1.0 are excluded at the 95% confidence level for masses below 1710 GeV (1755 GeV expected).

Vector leptoquarks are excluded at the 95% confidence level for β = 1 below masses of 2110 GeV (2165 GeV expected) for the minimal coupling scenario, and below 2525 GeV (2525 GeV expected) for the Yang-Mills coupling scenario.

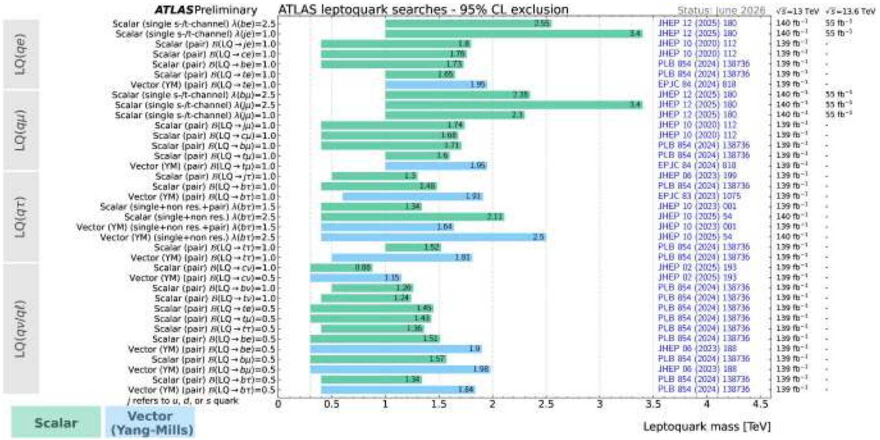


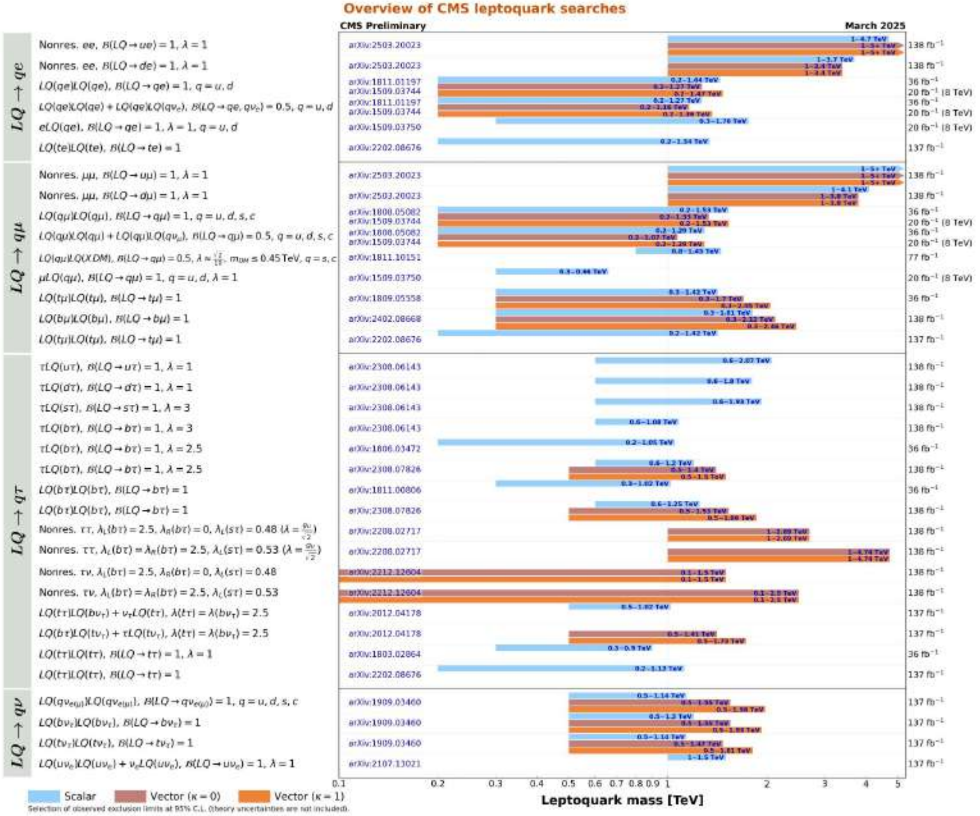


https://cds.cern.ch/record/2957050

Overview on LQ

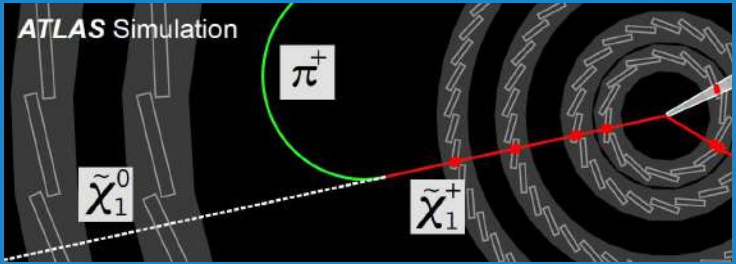
Most of the limits on for several models **exclude masses up to 1700-2500 GeV**





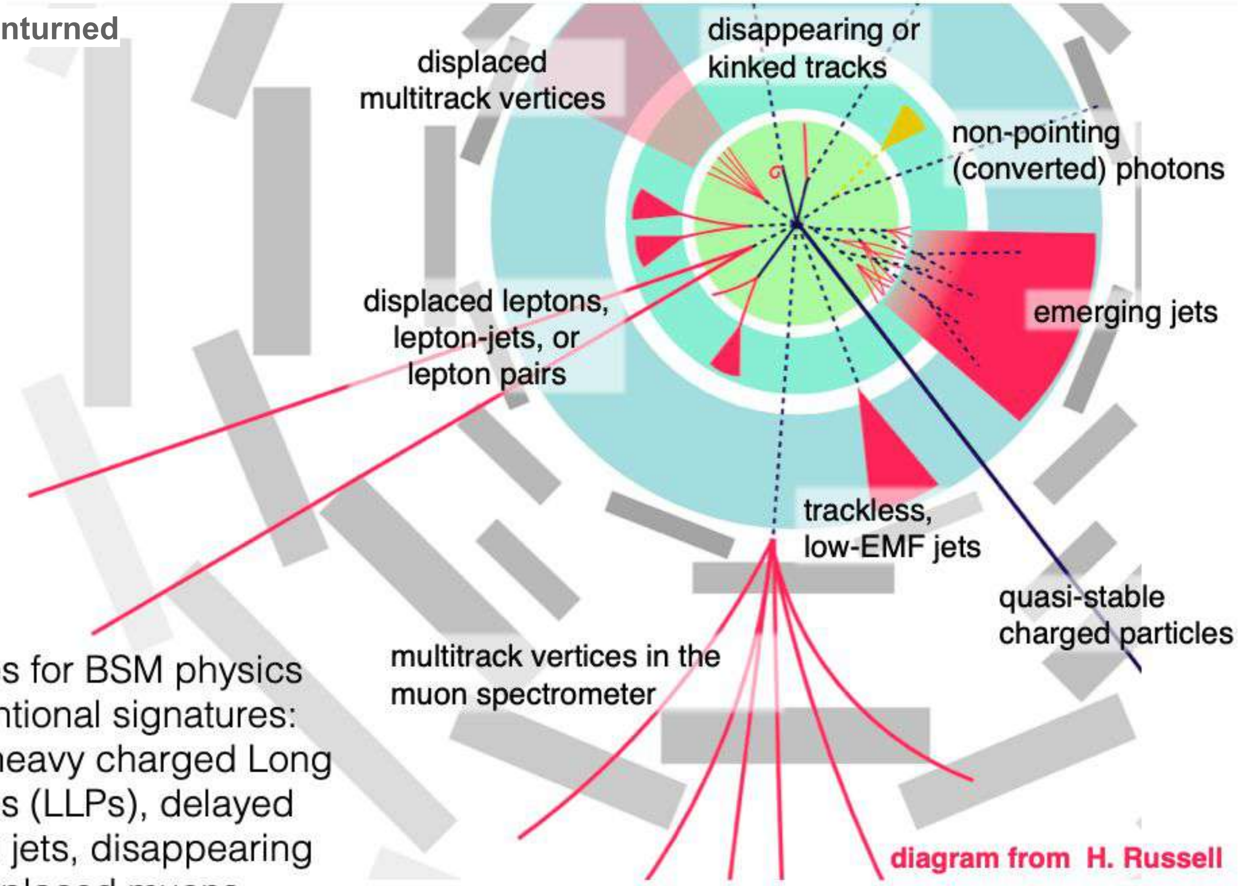
[ATLAS Summary](#) [CMS Summary](#)

Unconventional Signatures



Unconventional Signatures

…ensure no stone is left unturned



Many searches for BSM physics with unconventional signatures: emerging jets, heavy charged Long Lived Particles (LLPs), delayed jets, displaced jets, disappearing tracks, displaced muons

Trigger on Long Lived Particles

arxiv:1810.12602

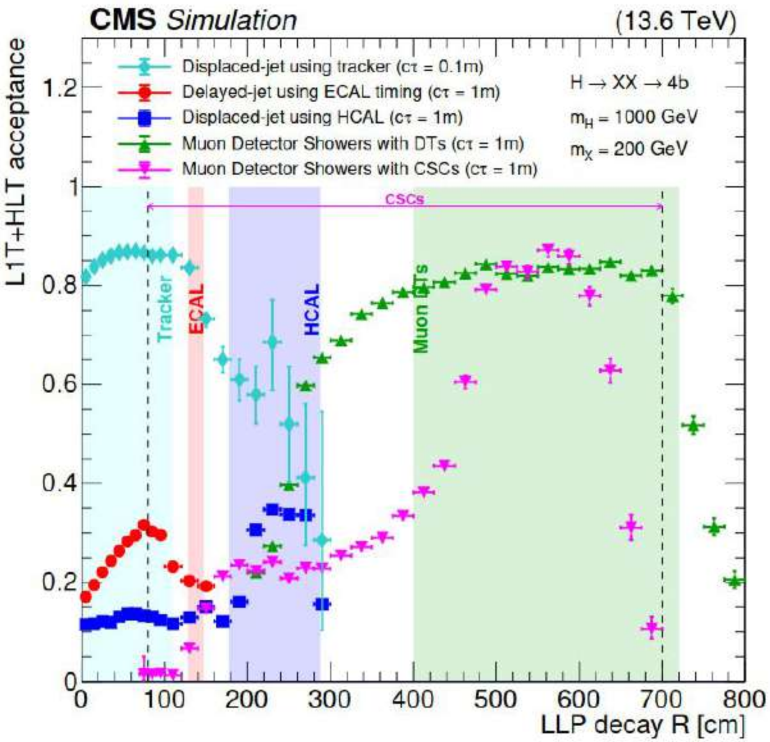
$$\tau^{-1} = \Gamma \sim y^2 \left(\frac{m}{\Lambda}\right)^n \Phi$$

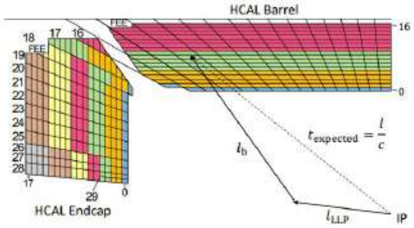
y – small coupling
$m \ll \Lambda$ – scale suppression
Φ – small phase space

Standard algorithms developed to trigger on and reconstruct "physics objects", are usually not optimal for LLP searches because they are designed for promptly decaying particles, thus alternative techniques are often needed.

First comprehensive review of the CMS dedicated LLP trigger program in Run 3:

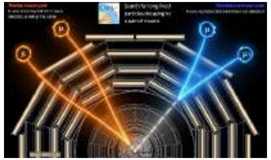
- Diversity and Complementarity
- Total of 15 dedicated LLP triggers
  - Tracker: displaced jets and τ, disappearing tracks
  - ECAL/HCAL: delayed jets, delayed photons
  - Muon: displaced muons, showers, muon + photon
  - Other: Dimuon scouting, jet/muon no-bunch crossing.

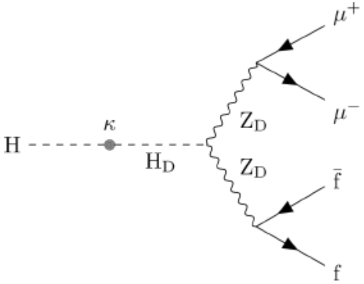


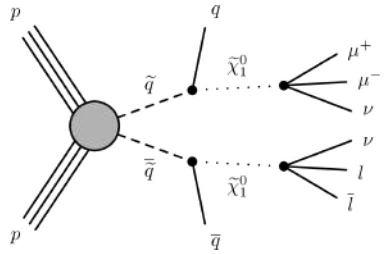


The search for displaced-muons

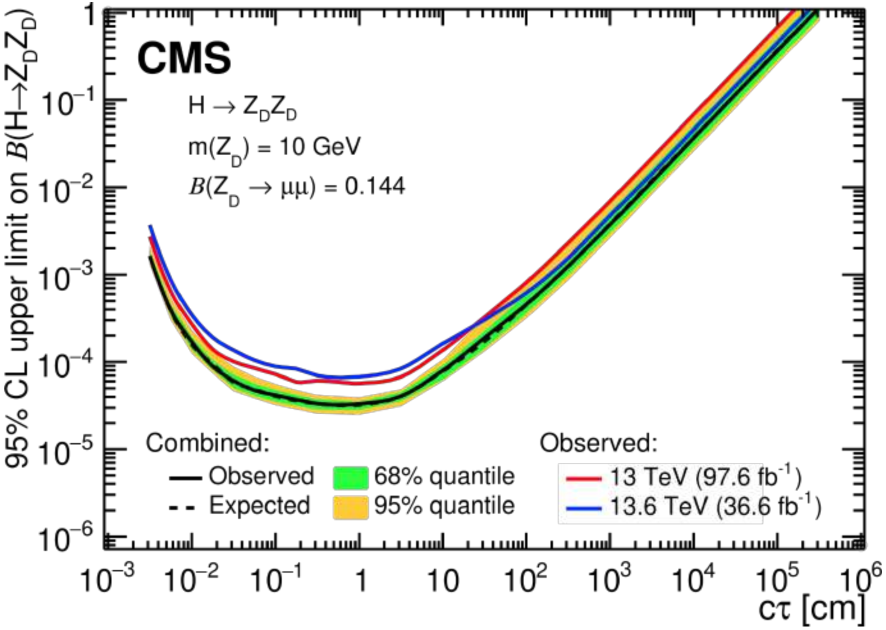
Inclusive search in a pair of displaced muons







- Target: **LLP decays to a pair of displaced muons**
  - Inclusive search over a broad kinematic range
  - **Tracker-muon and muon-system only categories**
- Benchmark models:
  - **Dark photon** and RPV SUSY interpretations
- Run 3 Trigger Improvements:
  - New L1 seeds and HLT paths for soft and displaced muons;
  - Factor of 2 to 4 gain in signal efficiency



Observation consistent with SM expectation.

ATLAS Run 3 result: [Phys. Lett B 878 (2026) 140509]

CMS-EXO-23-014

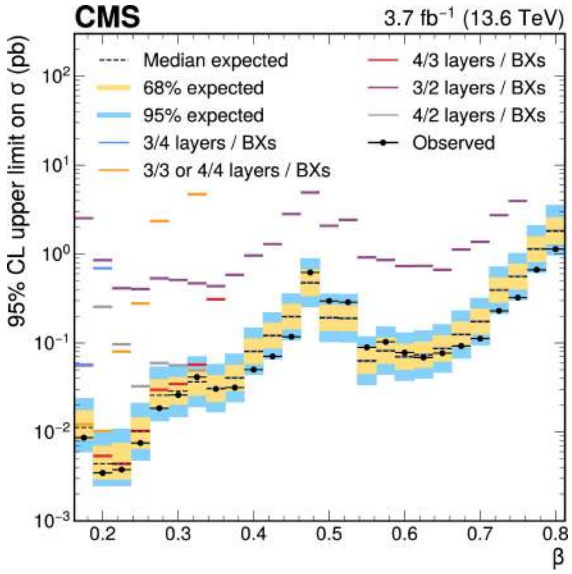
JHEP05(2024)047

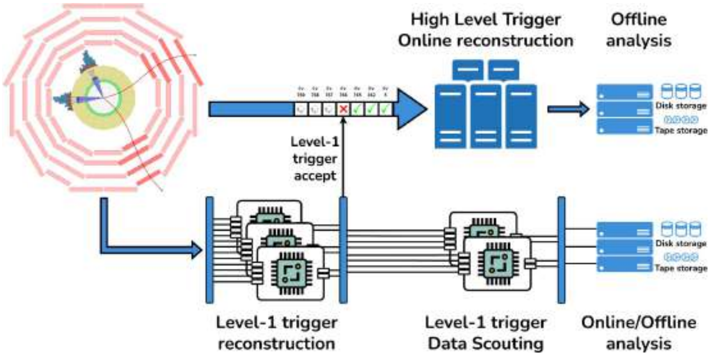
Long Lived Heavy Particles

- Heavy stable charged particles (HSCP) would travel much slower, depositing much more energy per unit distance (dE/dx)
- Rare opportunity to spot new particle directly instead of via decay products.
- **Late arrival in the muon system, multiple Bunch Crossings (BXs)**
- Challenges for standard triggering:
  - Conventional L1 trigger assumes single-BX objects;
  - Targets high-mass, slow HSCPs: m < 6.5 TeV, β ~ 0.3-0.6;
  - Reconstruct tracks across multiple bunch crossings;
  - Categories based on muon layers and BX patterns probe different β regimes;

- **L1 Data Scouting Strategy**:
  - Record all the data at 40MHz in a reduced data format.
  - Store L1 trigger primitives without of trigger decision;
  - Reconstruction of slow muon-like objects from RPC+DT;
  - Access signatures missed by standard L1/HLT paths;

CMS-EXO-25-010

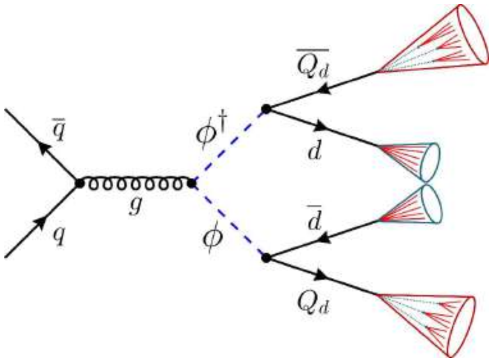


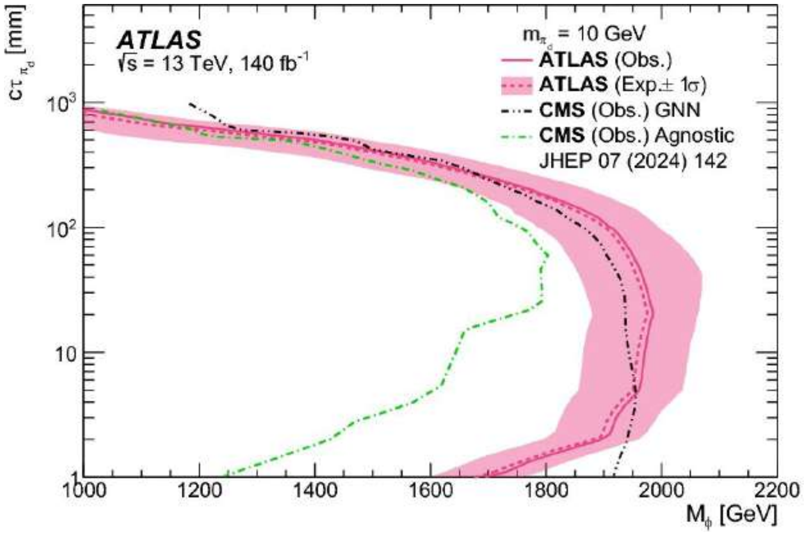


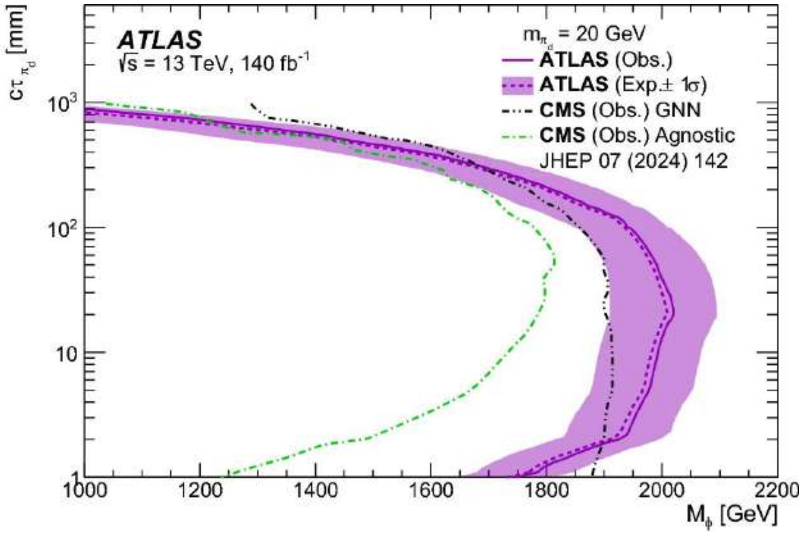
https://arxiv.org/abs/2601.20063

Emerging jets

- Macroscopic displacement of unstable dark particles
- No stable dark particles lead to emerging jets
  - jet with many DVs within jet cone
- Pair-produced 4-jet signature
  - 2 emerging jets with many Displaced Vertices (DV) + 2 SM jets







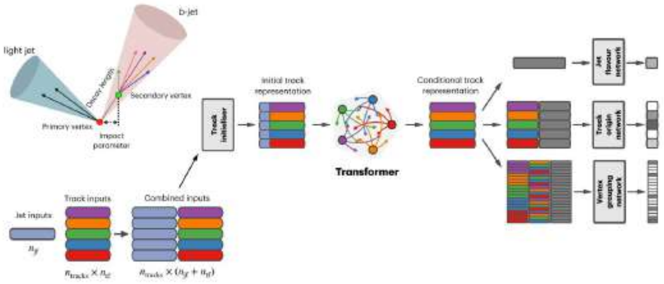
Run-2 limits for different signal models, mass of mediator and decay length of dark pions.

Eur. Phys. J. C 86 (2026) 808

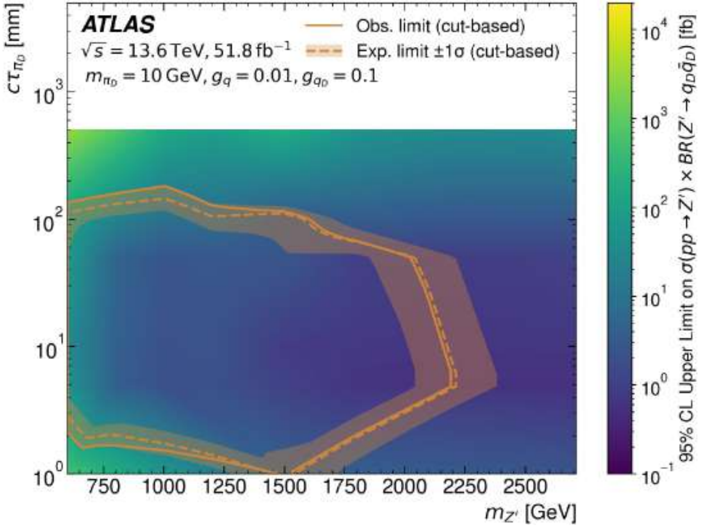
Emerging jets Run-3

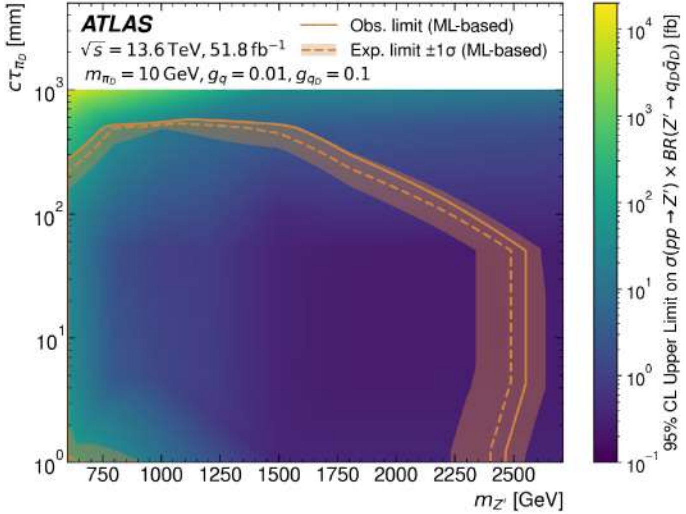
- Two separate signal regions
  - low-m_{jj}: Dedicated Run-3 trigger for displaced-track jet topologies using prompt track fraction.
  - high-m_{jj} regions: Single-jet Trigger.

- Two complementary strategy
  - Cut-based: hand-designed observables, explicit selection cuts, fully data-driven ABCD method for background.
  - ML-based: ATLAS GN2 flavour tagging algorithm transformer, bkg template with shape fit.



ML-based selection provides the best sensitivity, while the cut-based selection is retained for simpler reinterpretation and a more transparent selection.



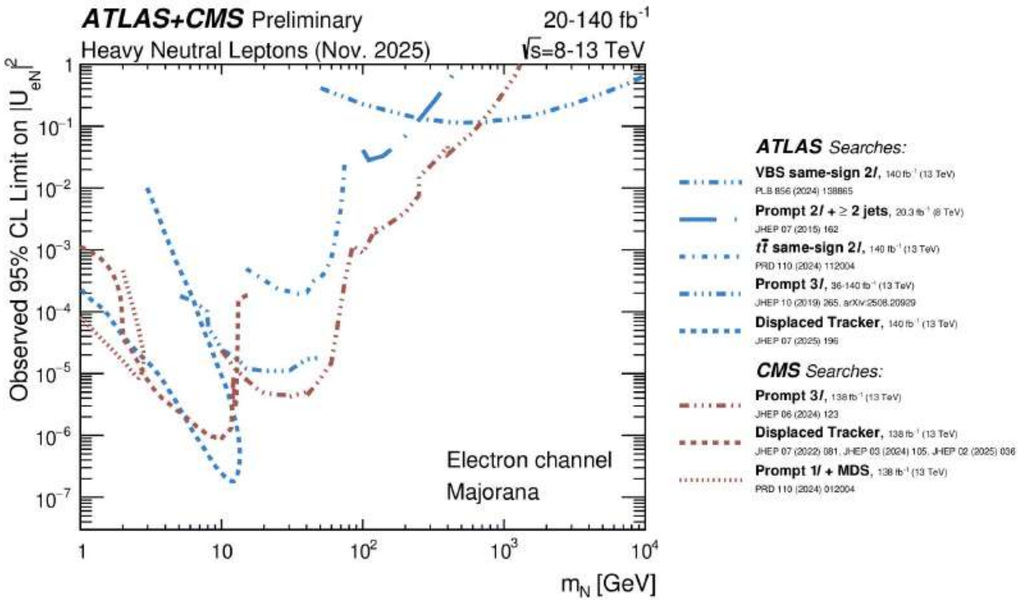


https://arxiv.org/abs/2505.02429

…and many more Searches on new Models

Heavy Neutral Lepton summary plots

- Heavy neutral leptons are primarily motivated by theories aiming to explain SM neutrino masses.
- The type-I seesaw model introduce right-handed neutrino states that carry no SM gauge charges, thus allowing them to have Majorana masses.
- The model explains the light neutrino masses and predicts the existence of heavy mass eigenstates known as “heavy neutral leptons” (HNLs, also denoted N).
- The HNLs can also account for baryon asymmetry via leptogenesis, and models with three HNLs can provide a dark matter candidate.
- The HNL states experience mixing with SM left-handed neutrinos allowing them to undergo weak interactions.
- HNLs have been searched for in a wide range of mixing, mass, and lifetime scenarios.



The 95% confidence level exclusion limits as a function of HNL mass for the HNL mixing to the first generation lepton.

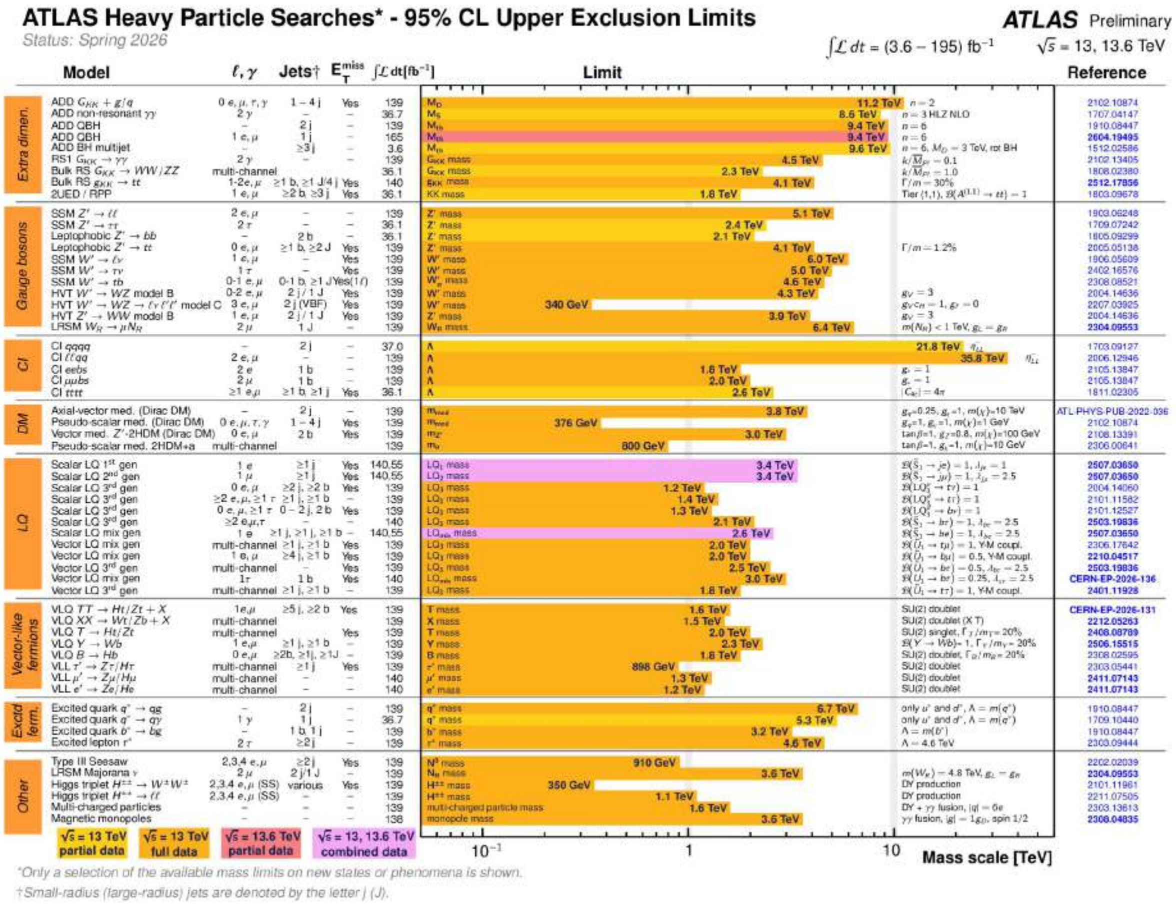
cms-summary

Heavy Particles

From top to bottom, the results cover models with extra dimensions, heavy gauge bosons, contact interactions (CI), dark matter (DM), leptoquarks (LQ), vector-like fermions, excited fermions, and other scenarios.

Different colors indicate the dataset and corresponding integrated luminosity used in each analysis; for results based on combined datasets, the individual luminosity contributions are indicated.

Boldfaced references indicate new searches that extend the mass reach relative to previous summary (Spring 2023), through new channels and/or an updated dataset.



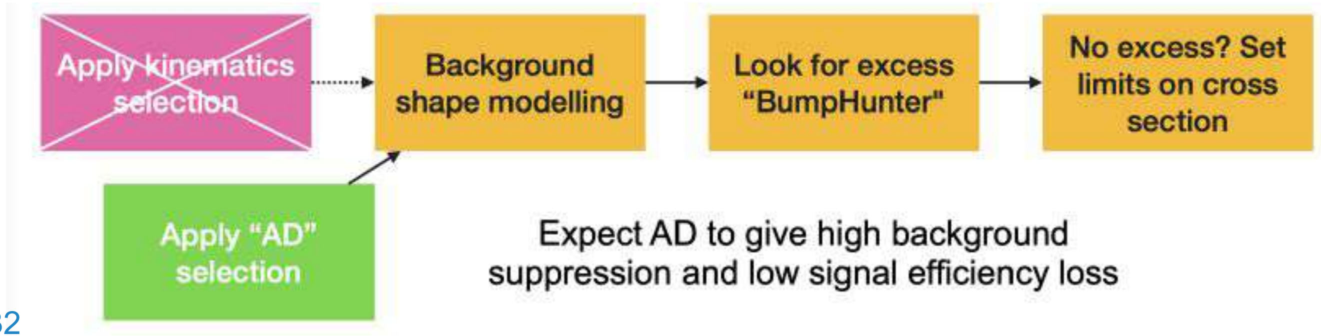
ATL-PHYS-PUB-2026-004

Model Independent Searches

Anomaly Detection for New Physics

Unsupervised machine learning can offer a new style of analyses which is completely agnostic to types of new-physics models. **One of the flagship strategy for unsupervised ML searches**.

- Traditional studies optimize signal regions using BSM Monte Carlo
- **Anomaly detection (AD) is used as a new strategy that defines outlier events to look for new phenomena in two body invariant masses**
- Advantage of using Anomaly Detection
  - Not relying on specific signal hypothesis – Model independent
  - **Unsupervised training on data** (1% randomly-chosen) – no MC modelling required
  - Full exploitation of event topologies on the standard reconstructed objects (jet, b-jet, e, μ, γ, met)



Phys. Rev. Lett. 132 (2024)

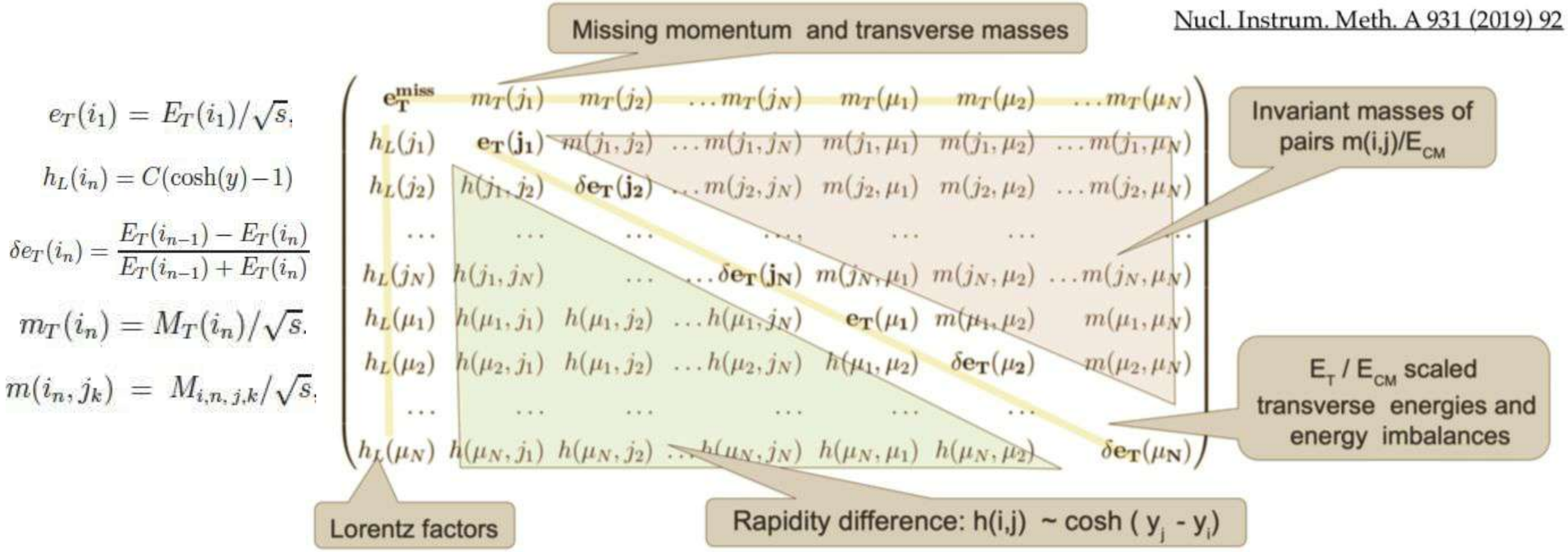
One lepton trigger and pre-selection: $p_{l\,T}$ > 60 GeV, $p_{jet\,T}$ > 30 GeV

Anomaly Detection

Kinematic features of the final-state objects in the preselected events are structured in a matrix called the **rapidity–mass matrix (RMM)** which is proposed as an input for machine learning.

The RMM is a square matrix employed to represent a comprehensive picture of the event in terms of popular variables used for BSM searches, such as E_T^{miss}, transverse energies, transverse masses, Lorentz factors, two-particle invariant masses, and two-particle rapidity differences.

Nucl. Instrum. Meth. A 931 (2019) 92

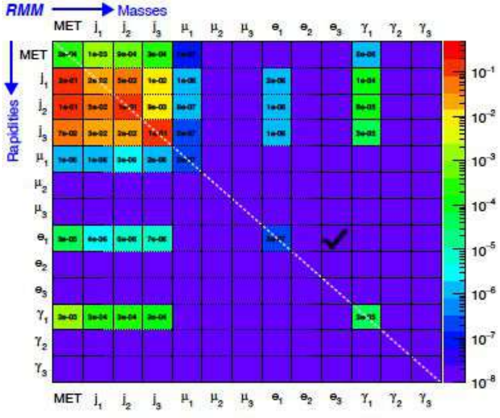


arXiv:1805.11650

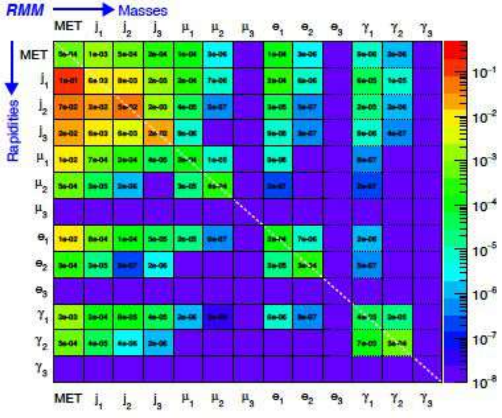
Anomaly Detection

All the input values range of [0,1] fixed by the definitions

No challenge to discriminate

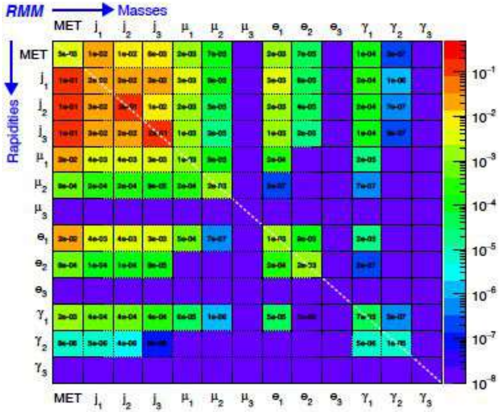


(a)Multi-jets QCD

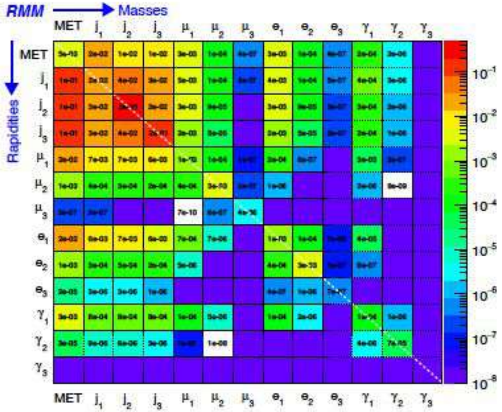


(b)Higgs processes

Challenging to discriminate



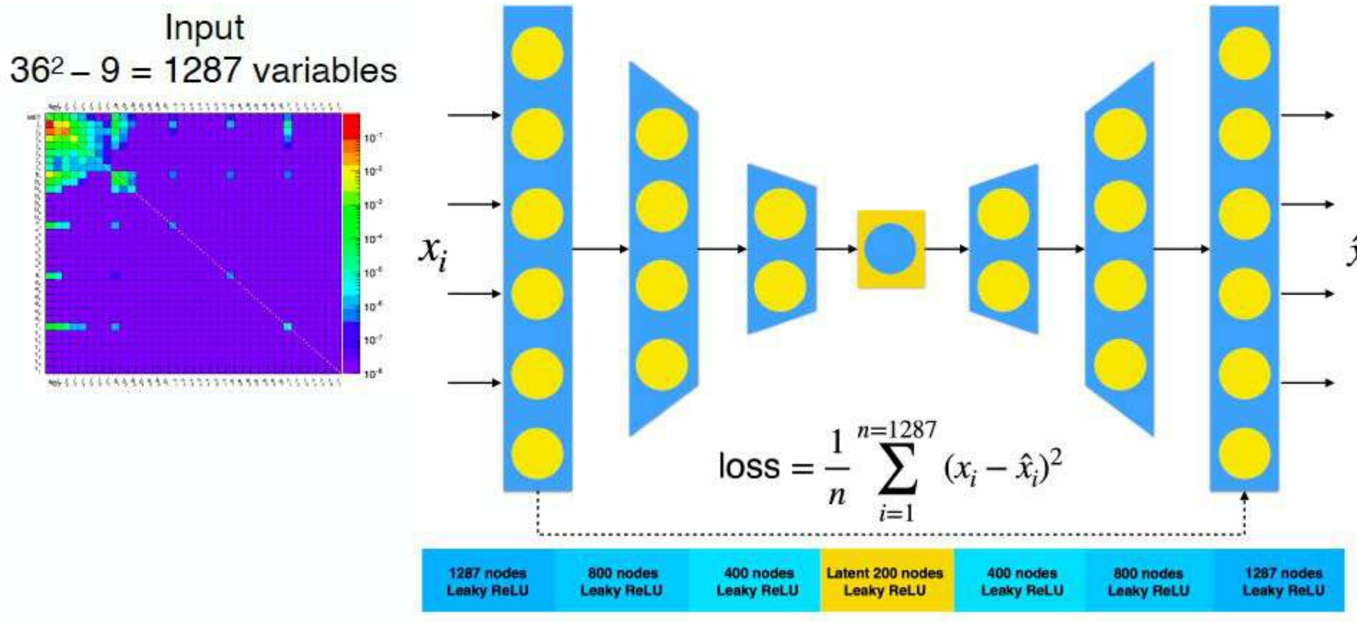
(c)Top ($t\bar{t}$) production



(d)H^+t production

Anomaly Detection

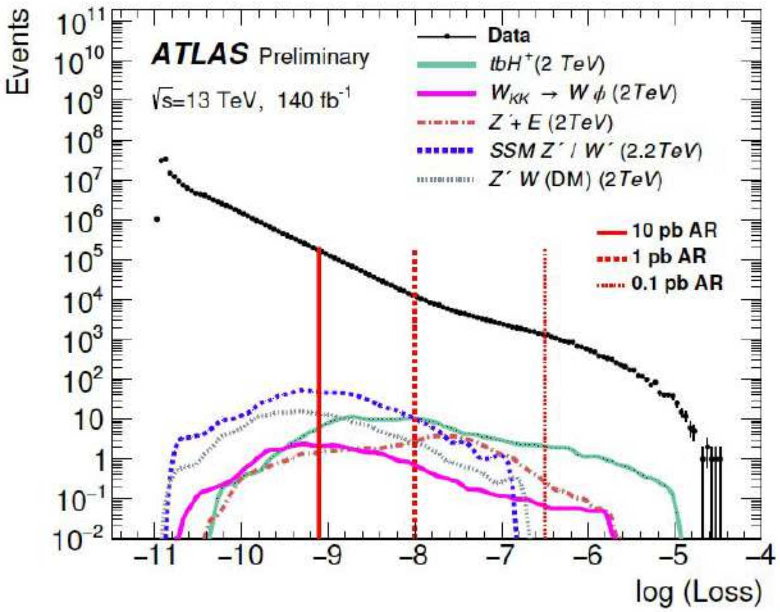
Autoencoder (AE) architecture used to train select anomaly regions using 1% of randomly chosen collision data triggered with an isolated lepton. T**he AE comprises two sections, an encoder and a decoder**. The encoder compresses the input to a latent dimensional space, whereas the decoder takes the data in the latent layer and decompresses it back to its original size. **Events with large reconstruction differences ("loss") are called an "anomaly"**



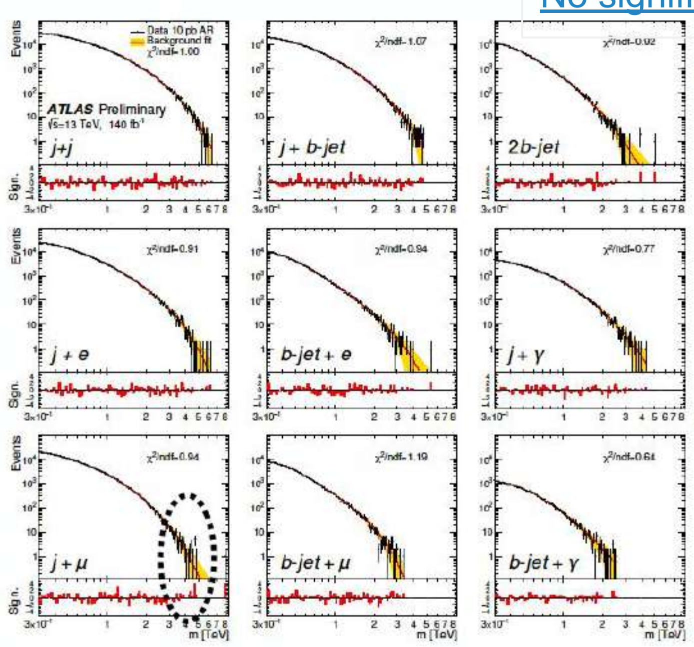
Anomaly Detection

Once Anomaly Regions are selected, two-body invariant mass spectra are inspected

Anomaly score distribution for data & anomaly scenarios



[No significant excess found]()



- Tests of normality on pulls passed for all masses passed
- Background shape uncertainty shown in yellow

- Largest deviation reported by BumpHunter is $m_{j\mu}$ at ~4.8 TeV

Similar strategies for a recent search on multi lepton in final state ([Eur. Phys. J. C 86 (2026)]())

Model-agnostic search for dijet resonances with anomalous jet substructure at CMS

Unsupervised method: Anomaly detection and Autoencoders. Implemented also at Trigger Level (AXOL1TL and CICADA).

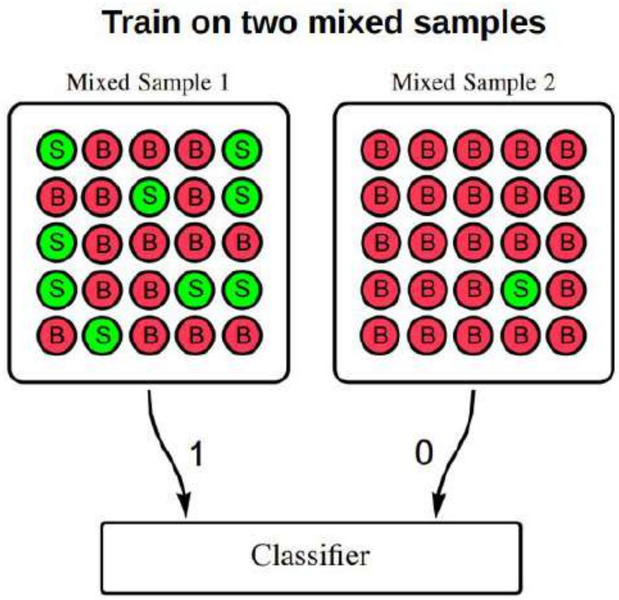
Weakly supervised methods: This paradigm requires two mixed samples of data events, chosen such that one is a mixture of potential signal events and background events, and the other is nearly pure background. For example, construct the first sample so that it consists of data events within the mass peak of a hypothetical resonance, and the second sample consists of background events from the sidebands. The classifier is trained to distinguish between events in these two samples. If sufficient signal is present in the data set, the classifier will learn to distinguish the signal from background, provided that the background composition in the two samples is the same.

Semi Supervised method: Quasi-Anomalous Knowledge, based on a combination of Variational Autoencoders.

CMS-EXO-22-026
CMS-PAS-MLG-23-002

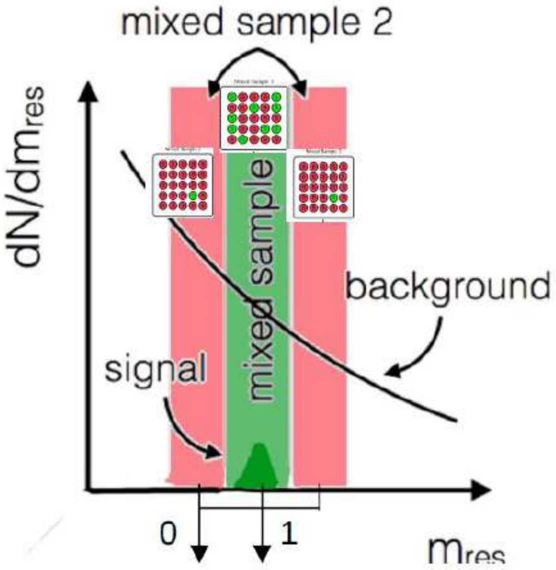
Weak Supervision Classification Without Labels (CWoLa)

Train a classifier (NN) between signal-rich and background rich mixed samples→Learns to identify signal vs. bkg



Classification is performed on NN between two groups of data events rather than relying on individual event labels

[Metodiev, Nachman, Thaler, 1708.02949]



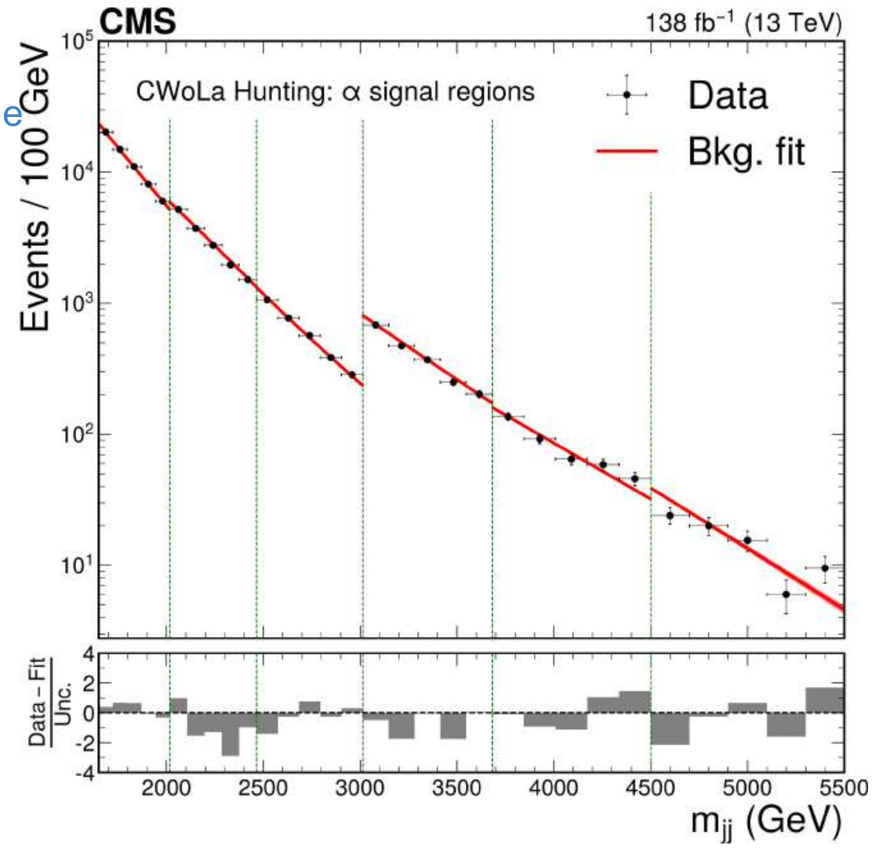
If a narrow resonance exists inside the hypothesized region in sufficient abundance, the weakly supervised training procedure will produce a classifier able to discriminate between it and the QCD background. In the absence of a signal, the two samples will both consist solely of background events, and therefore be indistinguishable in the training procedure.

- Assume signal is a narrow resonance.
- Train signal window vs. narrow sidebands using weak supervision.
- Repeat procedure, scanning over different mass windows
- Need to be careful about correlations between feats & mass

Weak Supervision Classification Without Labels' (CWoLa)

- Train a NN classifier on jets from signal-rich sample vs. background-rich sample
- Must ensure NN classifier does not learn mjj
- Event anomaly score: max(score j1, score j2)
- Keep ~1% most anomalous events
- After cut on NN score, perform bump hunt on remaining events → No clear excess found

- Many other strategies also investigated:
  - Tag N' Train (TNT)
  - Classifying anomalies through outer density estimation (CATHODE)



CMS-EXO-22-026

ATLAS complementary results on Phys. Rev. D 112 (2025)

Summary

- Overview results include setting increasingly strong exclusions on the production of additional scalars, vector-like quarks, vector resonances, supersymmetric particles and long lived particle with unconventional signals, within others.

- No probe of new physics yet, but we have learned a lot of what it is not.

- Improved and novel techniques deployed in searches will be built upon in the coming years, as we continue search with full LHC Run-3 dataset!

Backup slides

Anomaly Detection

Kinematic features of the final-state objects in the preselected events are structured in a matrix called the **rapidity–mass matrix (RMM)** which is proposed as an input for machine learning.

The RMM is a square matrix employed to represent a comprehensive picture of the event in terms of popular variables used for BSM searches, such as E_T^{miss}, transverse energies, transverse masses, Lorentz factors, two-particle invariant masses, and two-particle rapidity differences.

Nucl. Instrum. Meth. A 931 (2019) 92

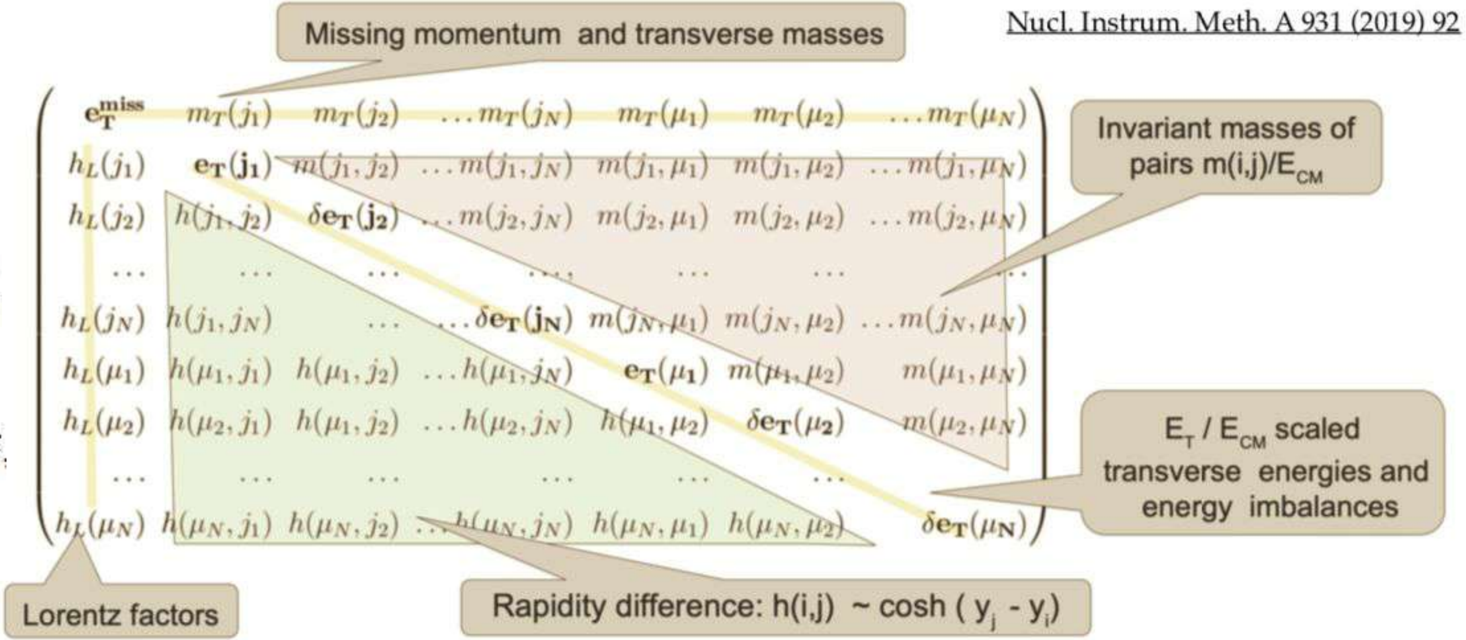
$$e_T(i_1) = E_T(i_1)/\sqrt{s}.$$

$$h_L(i_n) = C(\cosh(y)-1)$$

$$\delta e_T(i_n) = \frac{E_T(i_{n-1}) - E_T(i_n)}{E_T(i_{n-1}) + E_T(i_n)}$$

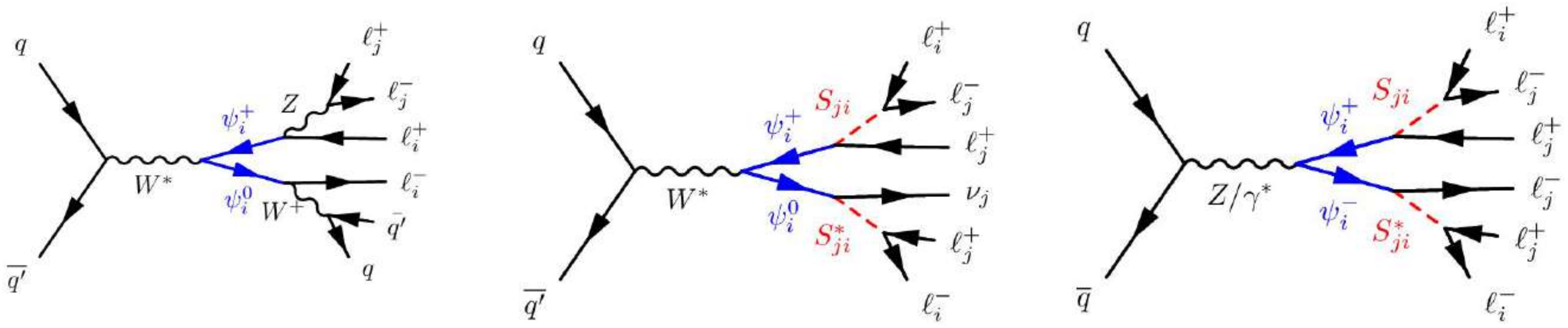
$$m_T(i_n) = M_T(i_n)/\sqrt{s}.$$

$$m(i_n, j_k) = M_{i,n,j,k}/\sqrt{s}.$$



arXiv:1805.11650

Anomaly Detection in multi leptonic final states (ATLAS)



- Targets high-multiplicity lepton final states due to low SM background rates
- Analysis follows two different channels:
  - Model-independent search for unknown BSM signatures
  - Model-dependent search for benchmarks against previous dedicated searches
- Normalizing flows trained to identify anomalous events compared to bulk SM background

ATLAS: EPJC 86 (2026) 247 - https://arxiv.org/pdf/2502.09770

Model-agnostic search for dijet resonances with anomalous jet substructure (CMS)

- **Background sculpting:**
  - **Correlation between anomaly score and variable of interest**
  - **Artificial bumps introduced**
- **Proper decorrelation is necessary**
- **CMS-MLG-23-002 : Used a quantile regression (QR)**
  - **Many more alternatives ..**

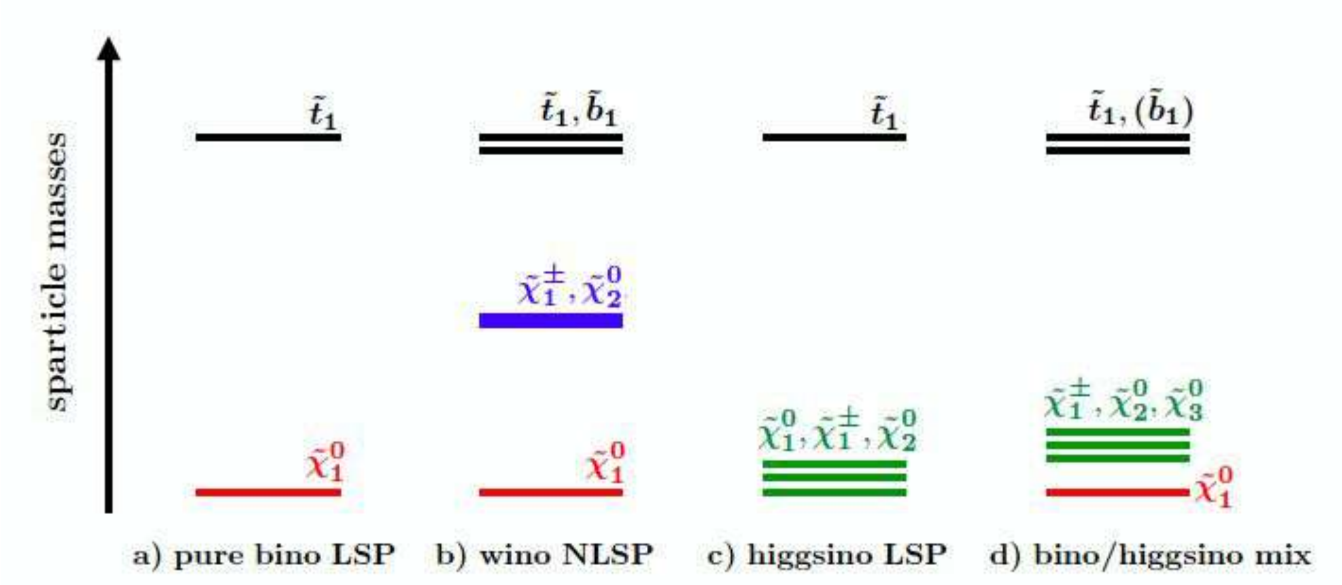
https://arxiv.org/pdf/2412.03747

Model-agnostic search for dijet resonances with anomalous jet substructure (CMS)

Search regions are obtained by utilizing multivariate machine learning methods to select jets with anomalous substructure. A collection of complementary anomaly detection methods—based on unsupervised, weakly supervised, and semi supervised algorithms—are used in order to maximize the sensitivity to unknown new physics signatures. https://cds.cern.ch/record/2938054/

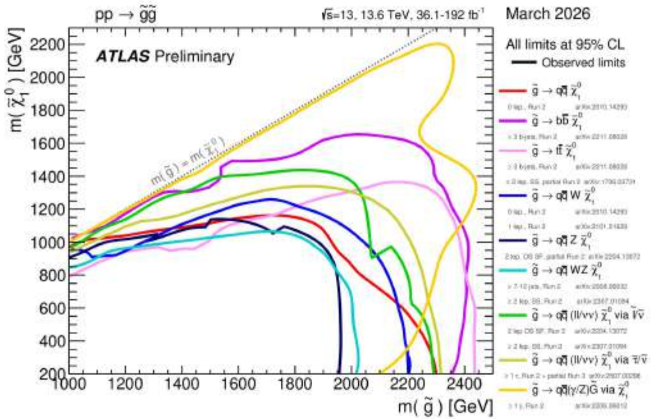
Will show as example CMS-EXO-22-026: Model-agnostic search for dijet resonances with anomalous jet substructure in proton-proton collisions at $\sqrt{s}$ = 13 TeV (2024)

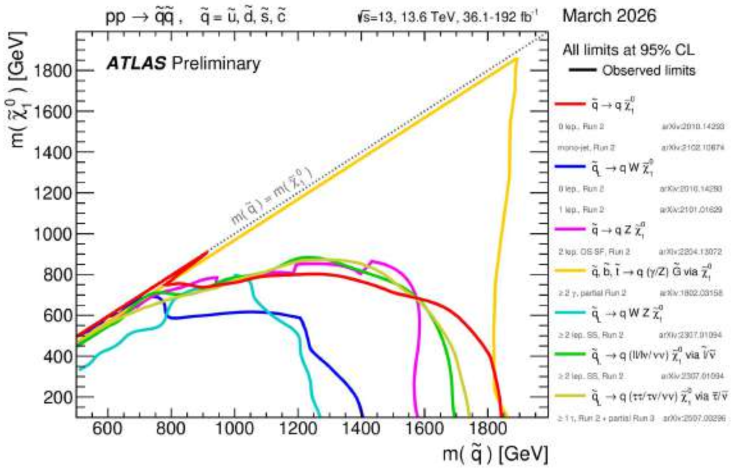
SUSY

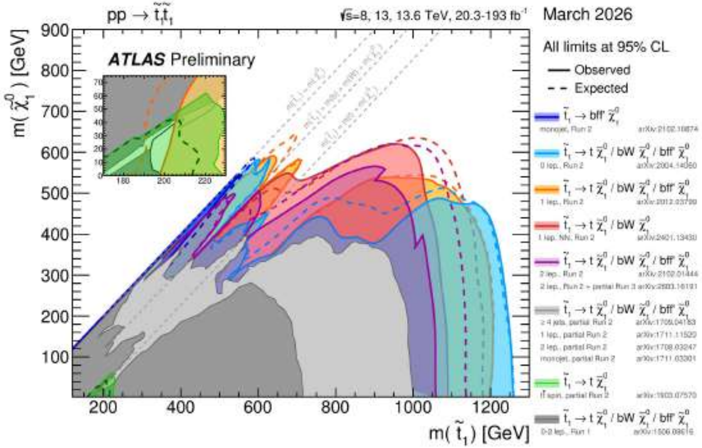

sparticle masses
$\tilde{t}_1$
$\tilde{\chi}_1^0$
$\tilde{t}_1, \tilde{b}_1$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{t}_1$
$\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$
$\tilde{t}_1, (\tilde{b}_1)$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_3^0$
$\tilde{\chi}_1^0$
a) pure bino LSP
b) wino NLSP
c) higgsino LSP
d) bino/higgsino mix

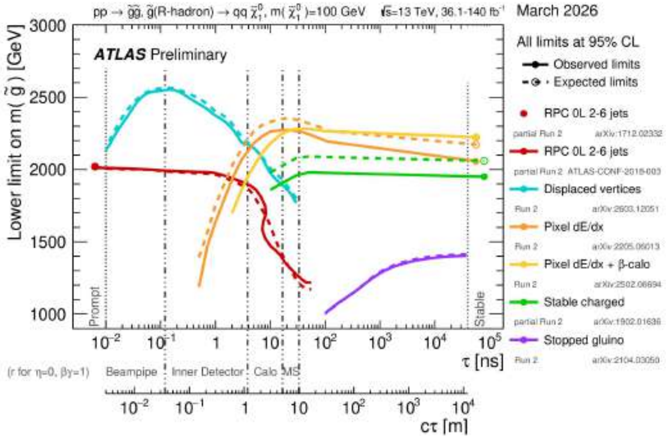
SUSY Strong Summary

Supersymmetry Summary Plot



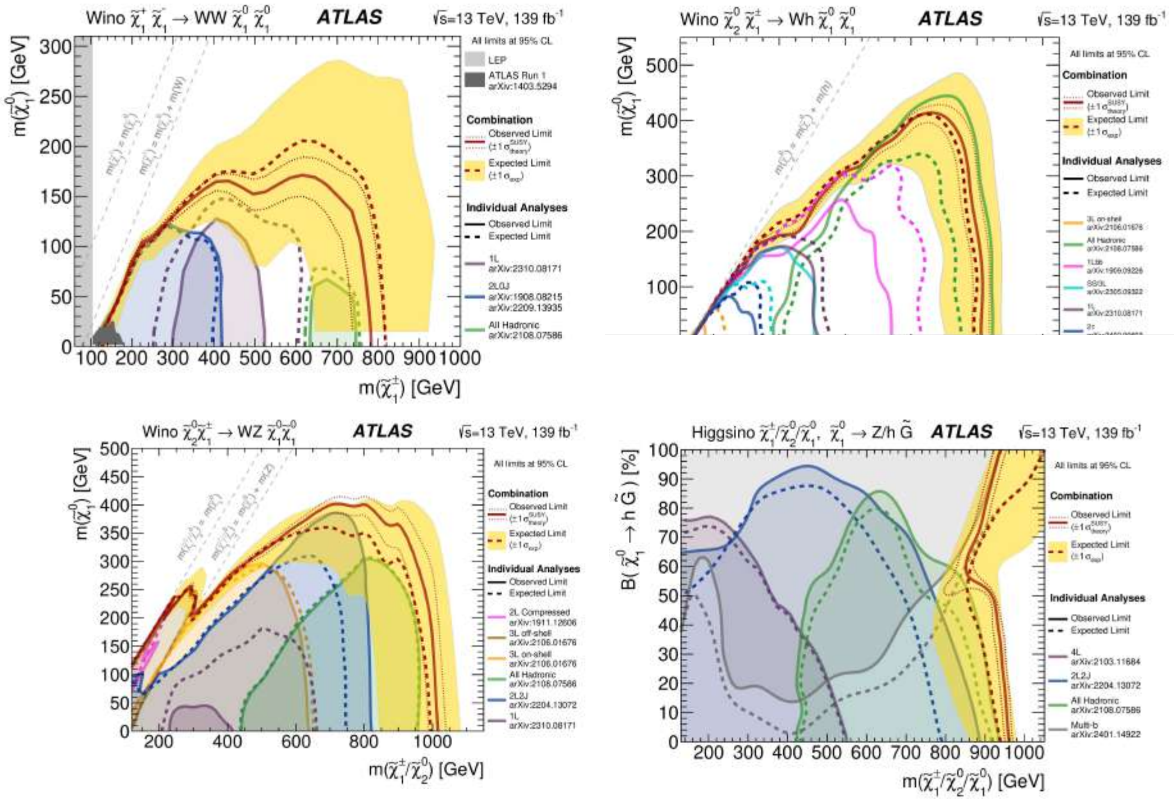






SUSY Electroweak Combination

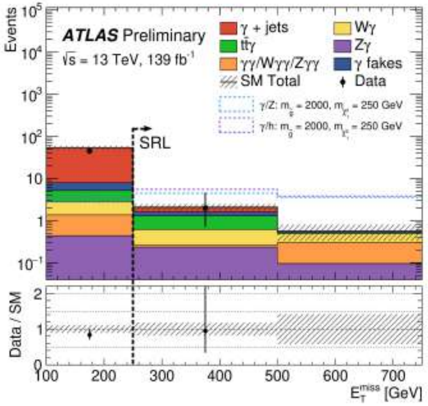
Combination of searches for **chargino/ neutralino production decaying via Higgs, W and Z.**
These **searches are harmonized to allow for the statistical combination** of the results, extending the breadth and depth of the experiment’s sensitivity. Combining results can be particularly powerful when the searches have different, but complementary, sensitivity to the same SUSY models.



extended exclusion limits

[Phys. Rev. Lett. 133, 031802](https://doi.org/10.1103/PhysRevLett.133.031802)

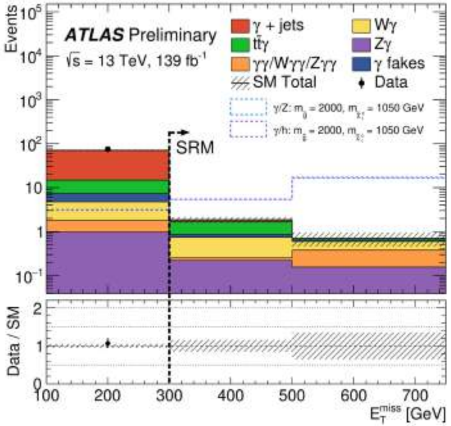
Photon(s) + jets + MET

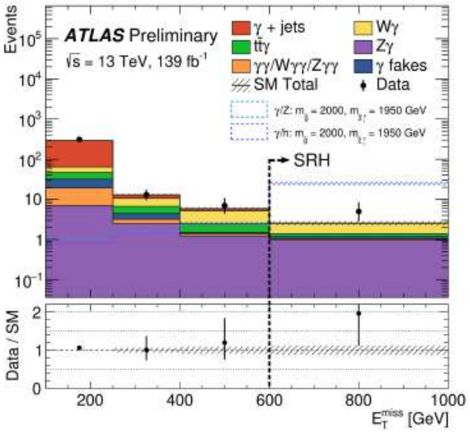


SRL

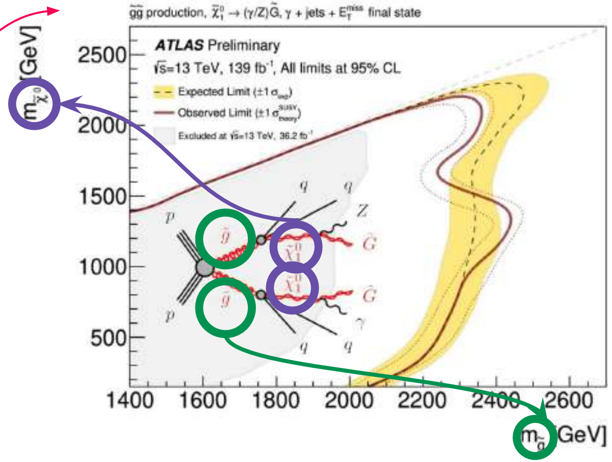
SRM

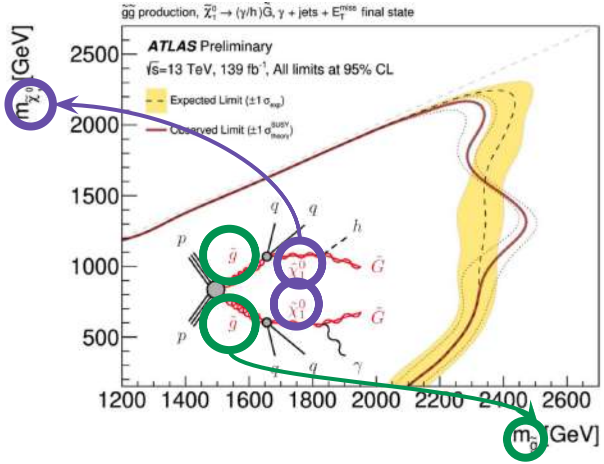
SRH





Result: no significant excess observed. Combined limits with best SR for each model

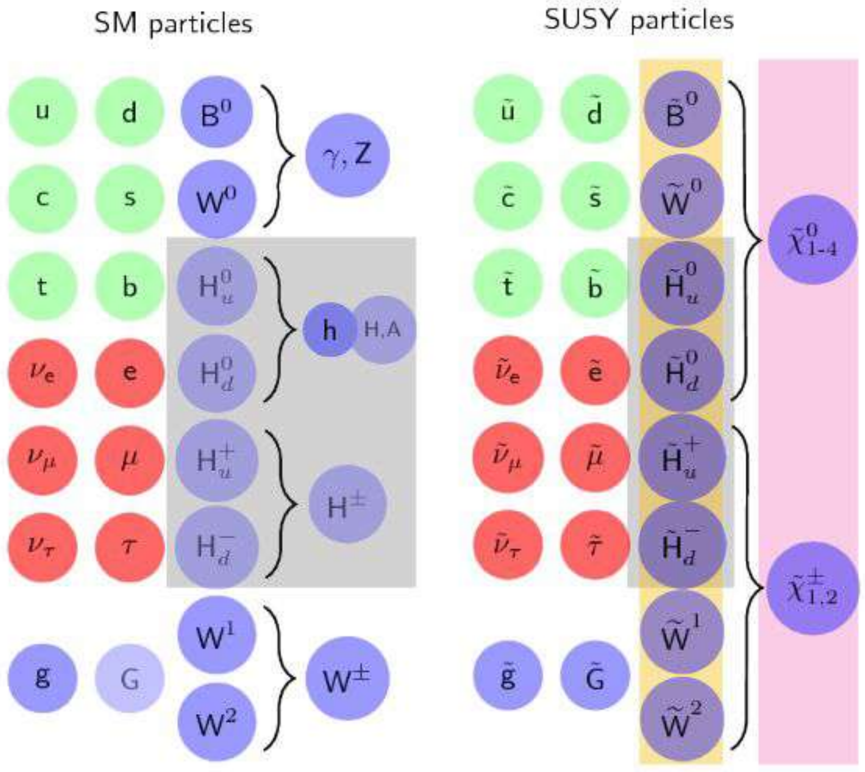




Supersymmetry

SUSY: additional symmetry between fermions and bosons on top of SM

- Supersymmetric partner for every SM particle including an extended Higgs sector
- Results in many partner particles, ideally at an LHC-reachable scale
- Many desirable properties, can provide solutions to the open problems:
    - R-parity conserving SUSY→ LSP is a dark matter candidate*
    - Stops cancel divergences in Higgs boson mass loops
    - High scale gauge coupling unification
- LHC is the only place for direct searches for new heavy particles



Neutralinos χ^0 / Charginos $\chi^\pm$, are mass eigenstates with a mixture of Bino/ Wino/ Higgsino.

* See Steven Lowette this conference for other DM scenarios at LHC