Searches and constraints on beyond the Standard Model physics with the ATLAS Detector

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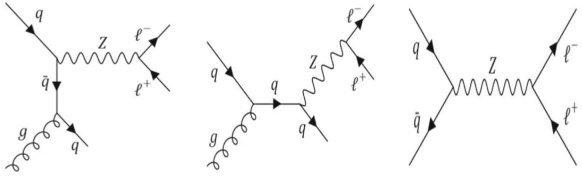
CAP Congress 2026
21-26 June, Ottawa

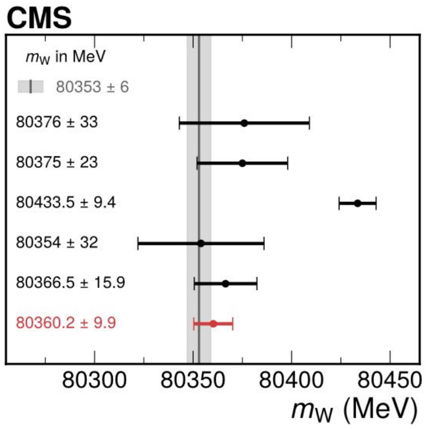
ATLAS EXPERIMENT

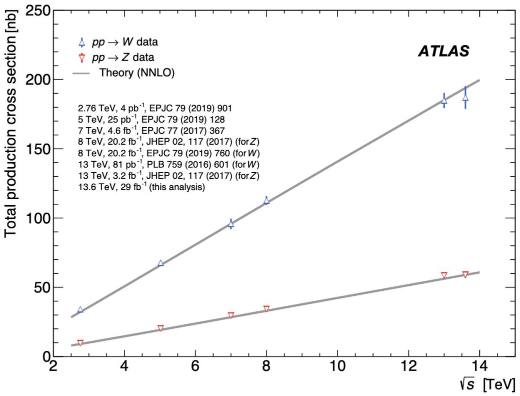
University of Victoria

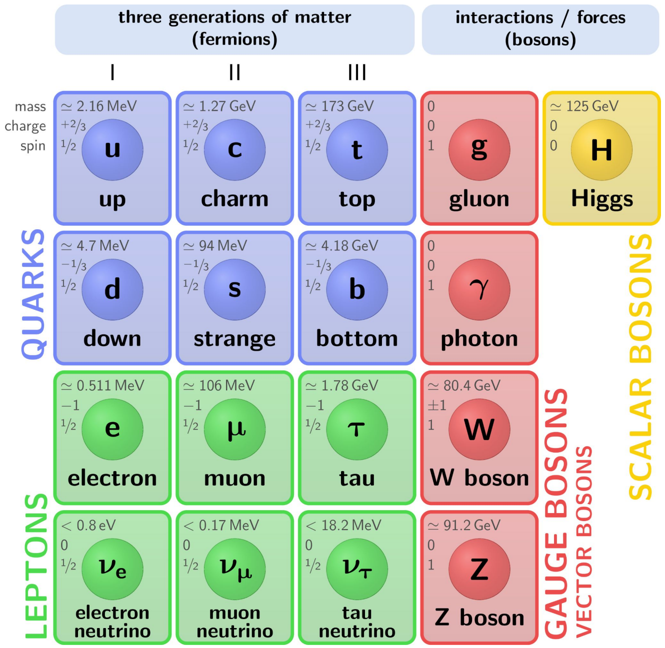
The Standard Model

- Most complete theory of fundamental particles and their interactions.
- Remarkable agreement with existing data



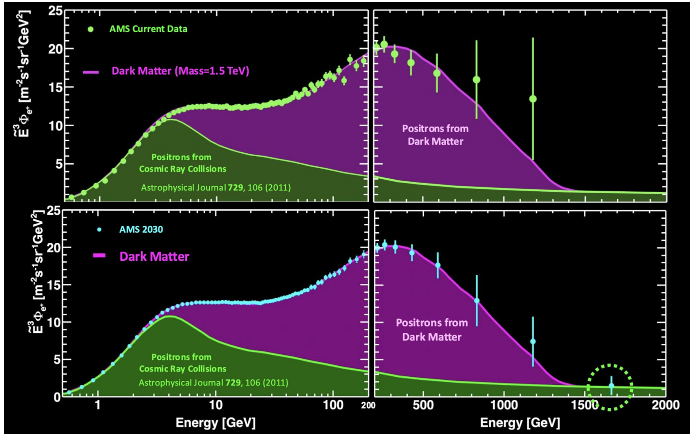






The incompleteness of the Standard Model

- However the Standard model lacks an explanation for known natural phenomena
  - Gravity
  - Dark matter/energy
  - Neutrino mass and oscillations
  - Matter-antimatter asymmetry
- In addition it would be nice if the Standard Model came with
  - An explanation to the hierarchy problem
  - Fewer free parameters, or an explanation as to why there are so many



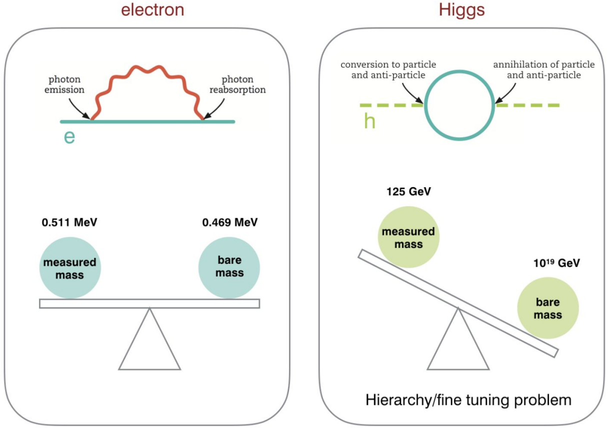
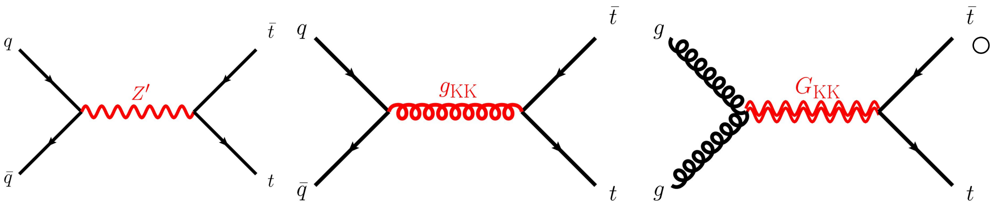


Diagram credit: Flavia De Almeida Dias

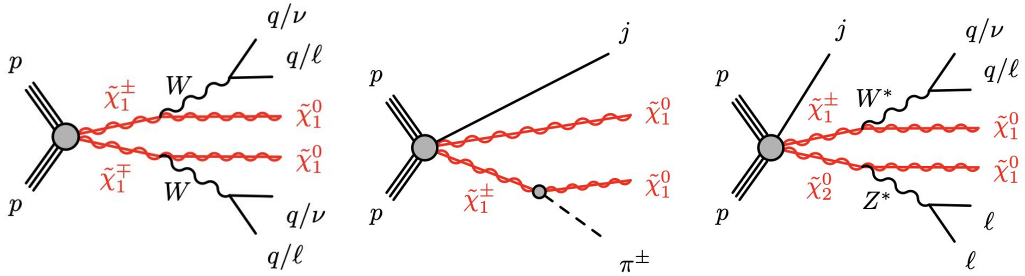
"It is as though we see a pencil standing on its tip in the middle of a table. While this scenario is not impossible, if we were confronted with this sight we would seek an explanation, looking for some mechanism that stabilizes the pencil and prevents it from falling over. For instance, we might look to see if the pencil is secretly hanging from a string attached to the ceiling." - N. Arkani-Hamed (link)

What *could* lie beyond the Standard Model

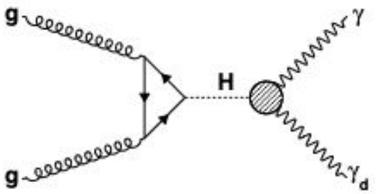
- New models predicting heavy vector particles

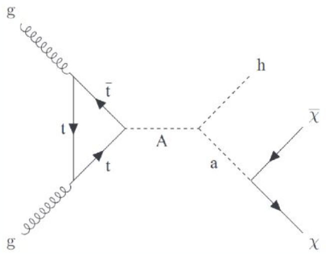


- Supersymmetry



- Dark matter candidates
  - WIMPs (fermiphobic Z', SUSY neutralino, higgsino, etc.)
  - Higgs as a portal connecting SM to dark matter (2HDM+a, dark photons, more)





- Many more*

*Standard disclaimer: this talk will not be a comprehensive review of constraints from ATLAS on all BSM models explored across the ATLAS search program, rather a few highlights from the past year, with preference given to searches employing novel techniques

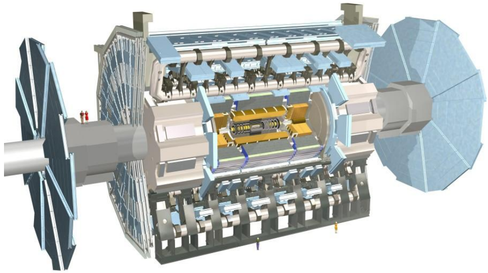
Where can we look beyond the SM*

Neutrino and Cosmic Ray Observatories

- Understand origin and spectra of cosmic rays
- Their interactions in the atmosphere

Collider Experiments

- "Factories" for heavy particles - W, Z, t, H, BSM(?)
- ATLAS, CMS, LHCb, ALICE, Belle II, FASER …



Others

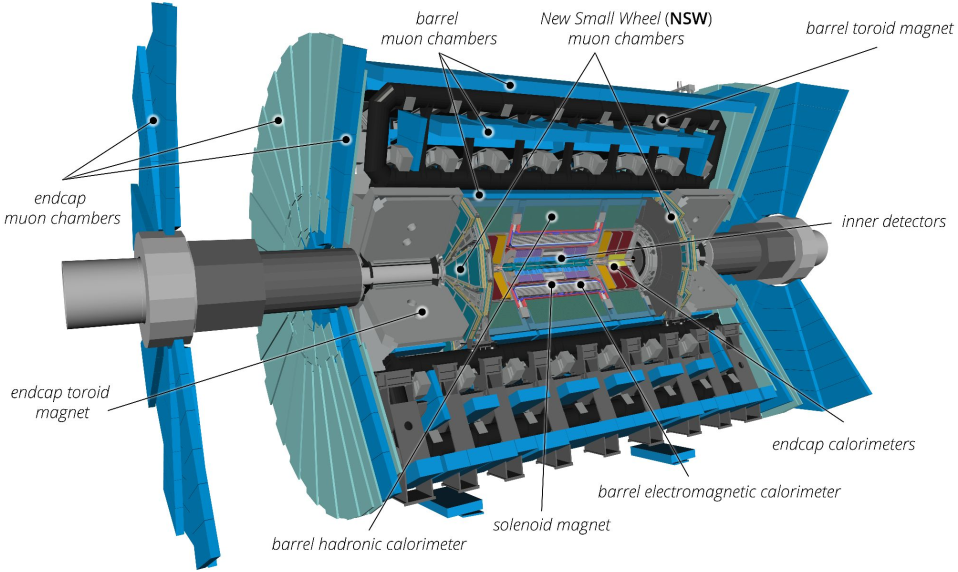
- Dark matter observatories (LZ, DEAP, etc)
- Many more

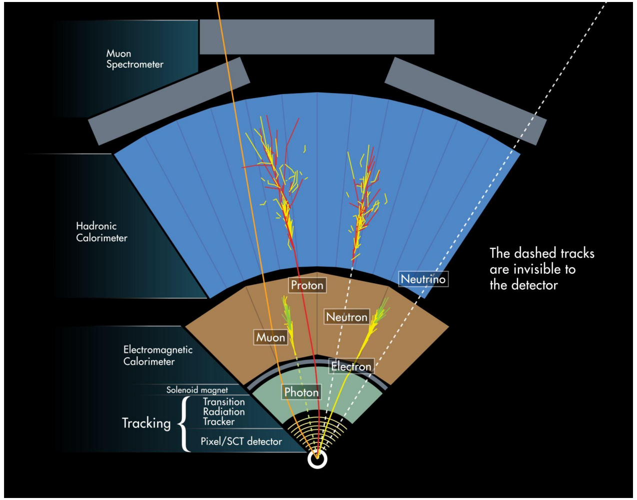
*a few examples, with overlap

The ATLAS Detector

General purpose

- Inner detector: charged particle tracks+momentum measurement
- Hadronic and electromagnetic calorimeters: energy measurement
- Muon spectrometer: muon momentum measurement
- Solenoid and toroid magnets: track curvature for momentum measurement





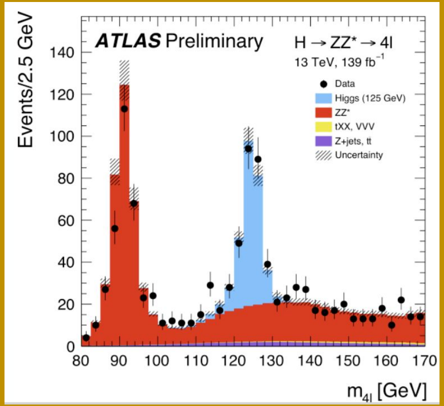
Two-tiered trigger system

- 40 kHz collisions*
- L1: hardware based, input from calorimeter and muon spectrometer. 100kHz rate
- HLT: Full detector granularity. 1.7 kHz rate

*40kHz bunch crossing rate - not every bc has protons

Avenues to new physics in ATLAS

Resonant Searches



- Target specific, well motivated theoretical model

Unconventional Signatures

- Typically uncovered phase space
- Multiple model interpretations

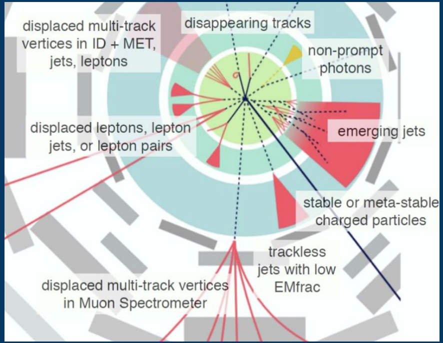
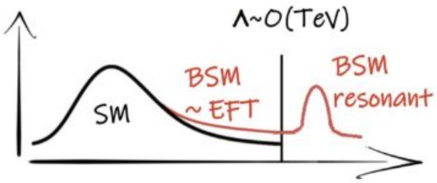


Diagram credit: Heather Russell

Measurements of SM processes + Effective Field Theory interpretations

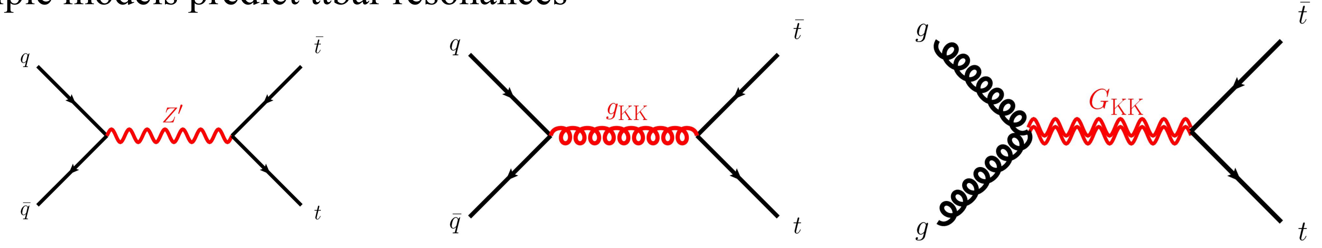


- Covered in Matthew's talk

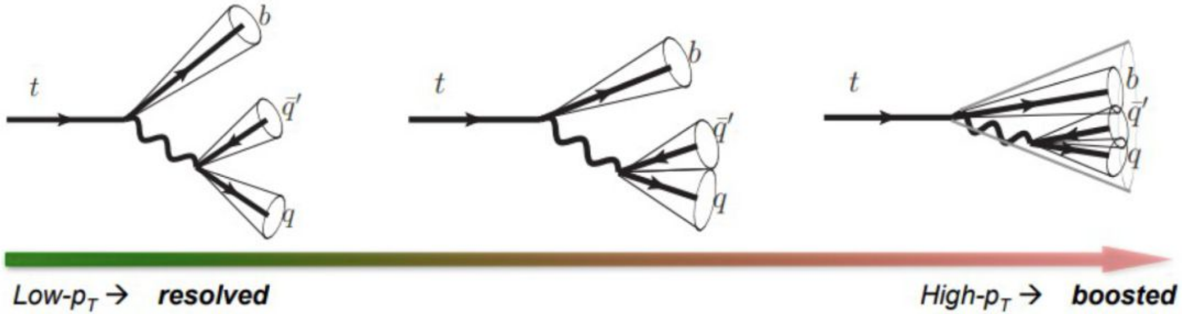
Search for ttbar resonances

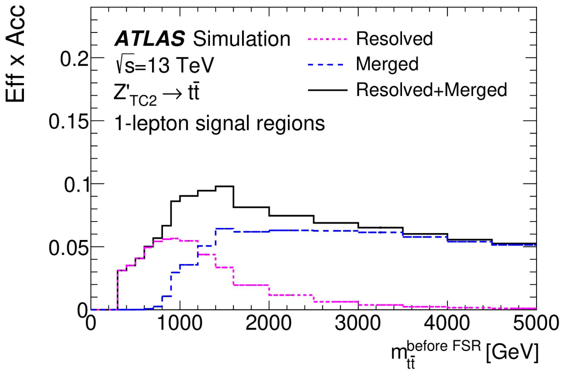
CERN-EP-2025-281

- Multiple models predict ttbar resonances



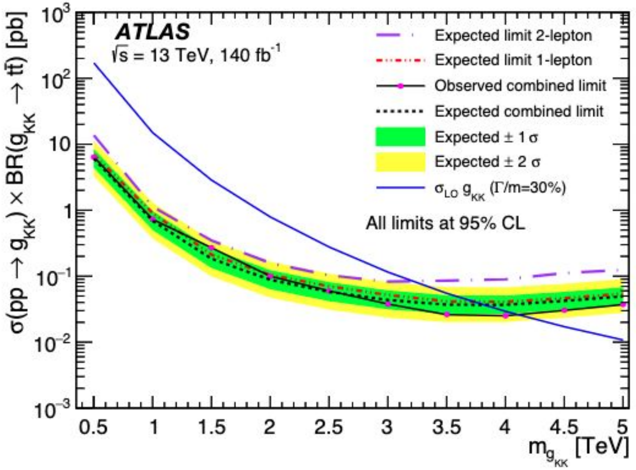
- Search in 1 and 2 lepton final states completes the run 2 Z' search program
- Include boosted ("merged") topology to increase sensitivity
  - Use machine learning to identify jets from high p^T top quarks
  - Use 1 and 2 lepton signal regions, further divided by presence of resolved or merged jets

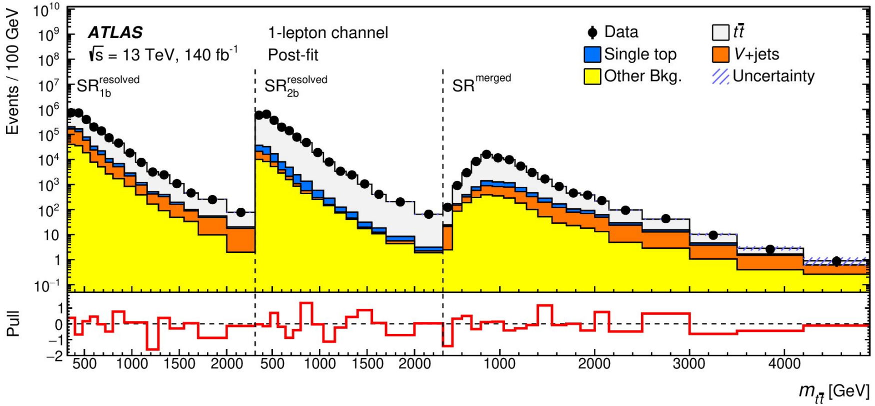




Search for ttbar resonances

- Complementary sensitivity to all hadronic search
- Limits shown for g_{KK} but also set for G_{KK} and Z’
- Potential to combine channels across multiple analyses with full run 2 data → further constrain BSM



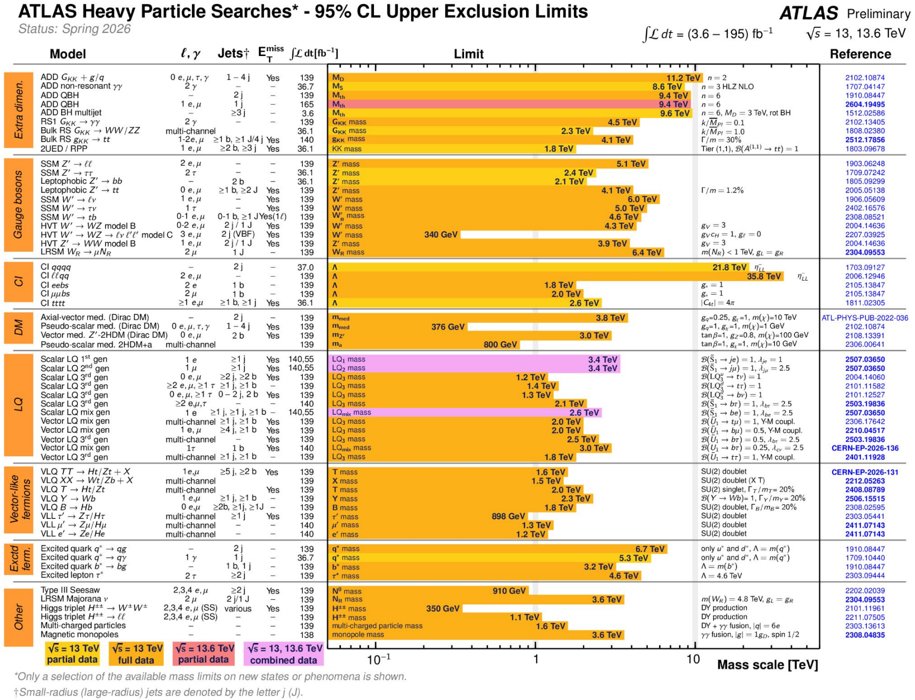


CERN-EP-2025-281

- Define signal regions for resolved different decays
- Define orthogonal validation and control regions to validate modelling
- Fit value of BSM cross section

New Heavy Resonances

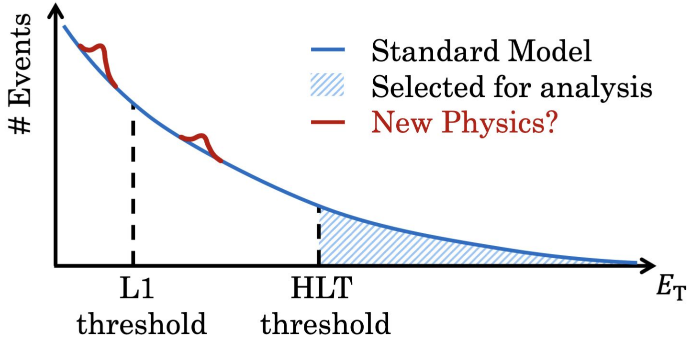
- Broad ATLAS heavy particle search program covering many models predicting heavy particles
  - Extra dimensions
  - Heavy Vector Triplet
  - Contact interactions
  - Dark Matter
  - Leptoquarks
  - …many more
- Updated summary including run 2 and partial run3 results (140 fb^{-1}, 55fb^{-1},165fb^{-1})
- Full Run 3 dataset recorded (300 fb^{-1}): exciting results to come!

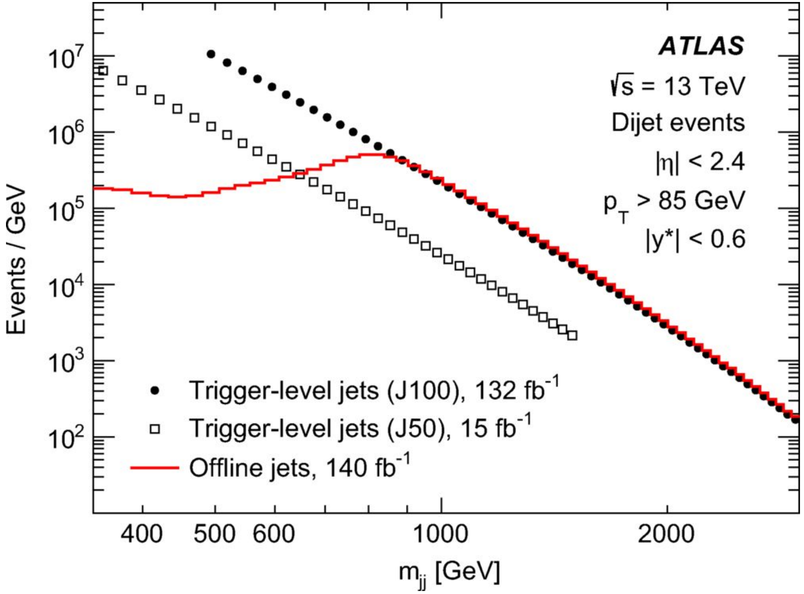


New summary plots

Dijet resonant search with Trigger Level Analysis

- Reach of dijet resonance search is limited by the HLT threshold: below 500 GeV dijet mass, rate + event size exceeds HLT bandwidth





- Trigger Level Analysis (TLA): limit event size to readout at lower threshold
  - Full event size: ~1MB
  - Partial event with limited jet info: ~6kB

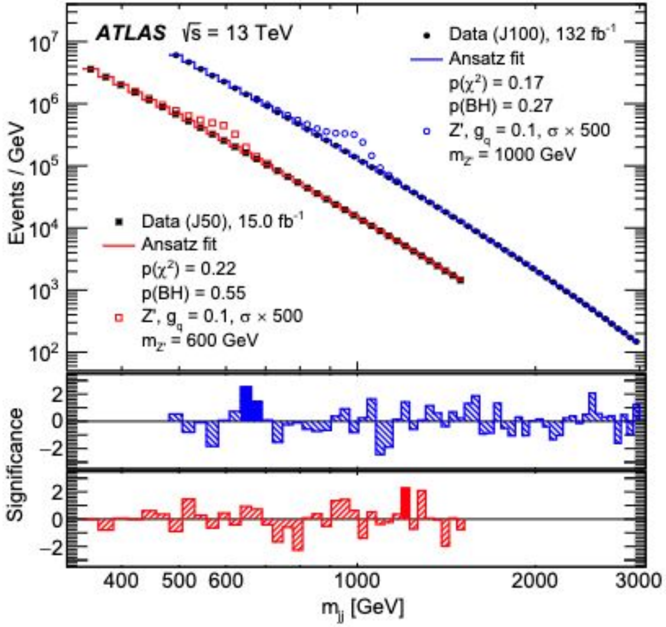
Challenge:
- Statistical precision not matched by simulation
- Limited information for jet calibration

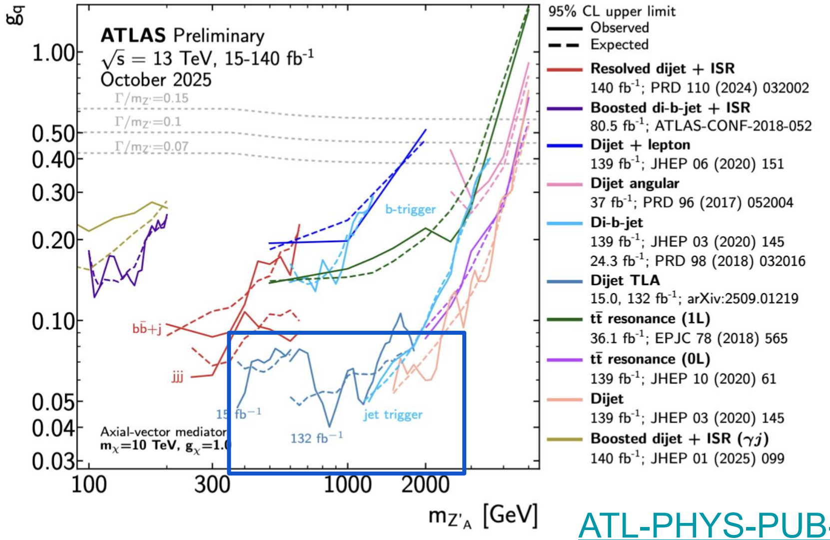
Phys. Rev. D **112**, 092015

Dijet resonant search with Trigger Level Analysis

Solution:
- Custom jet calibration
- Data driven background estimate: 6 degree polynomial in dijet mass

Results:
- Z’ limits: 0.4-0.11: improvement over existing limits in mass range
- Model independent limits on cross section x acceptance x branching ratio to jets





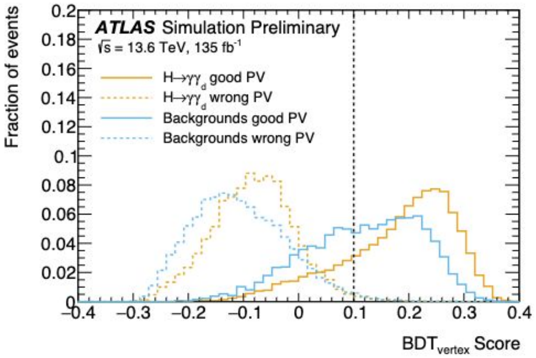
ATL-PHYS-PUB-2025-041

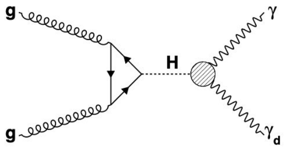
See also: di-jet resonant search using pileup collisions

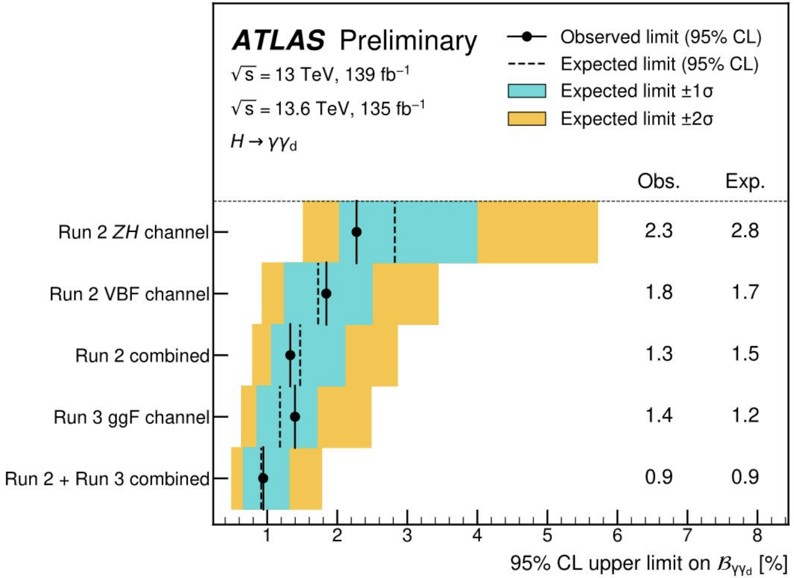
Search for Dark Photons ($H \to \gamma\gamma_d$)

ATL-COM-PHYS-2026-083

- γ_d: gauge boson of an additional $U(1)_D$ gauge group in dark sector
  - Potential candidate for positron anomaly (a la AMS)
- γ_d: escapes the detector undetected:
  - Uncovered phase space: γ + missing transverse momentum signature
  - Signature of multiple BSM models
- ATLAS search enabled by new topological trigger
  - $p^T_\gamma > 50$ GeV, $E^T_{miss} > 70$ GeV, $M^T > 80$ GeV
  - 2x increase in signal acceptance
- Background from incorrect vertex identification
  - Suppress with BDT





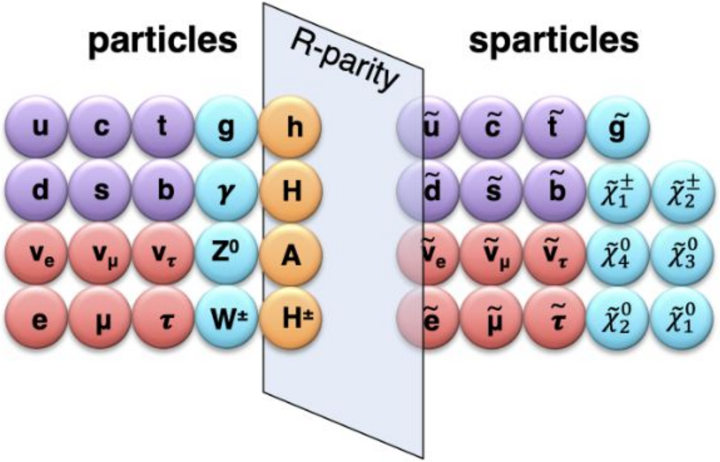


Results:

- $BR(H \to \gamma\gamma_d) < 1.4\%$ at 95% CL
- Run2 + Run3 combination: $BR(H \to \gamma\gamma_d) < 0.9\%$ at 95% CL

Supersymmetry

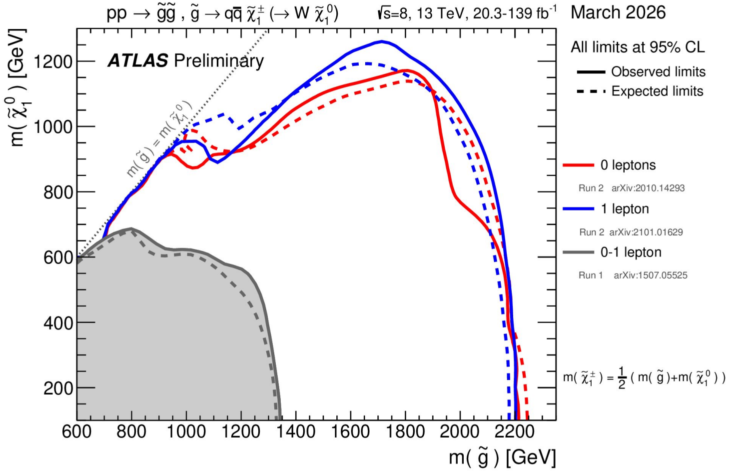
- SUSY is a *strongly* motivated BSM model
- Connects SM fermions and bosons with “super partners”



ATL-PHYS-PROC-2022-030

- Neutralinos and charginos formed from mixing of SUSY partners of W, H and B fields

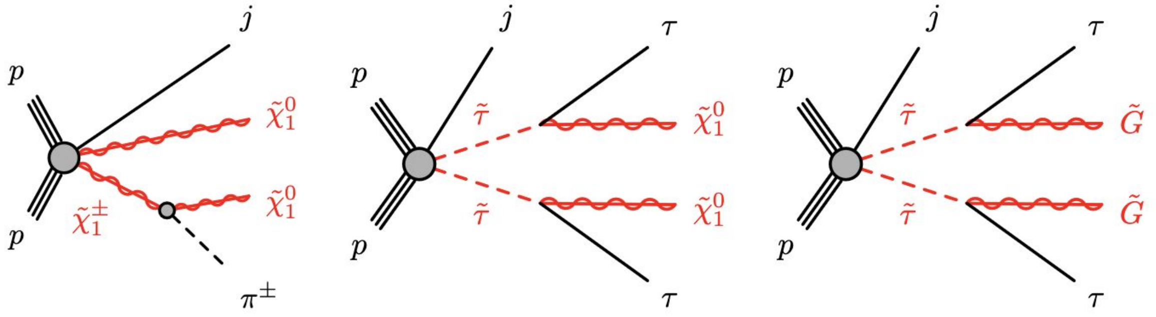
- Solves hierarchy problem
- Lightest SUSY particle is a candidate for dark matter
- Interested in plane of M(LSP) and M(NLSP)

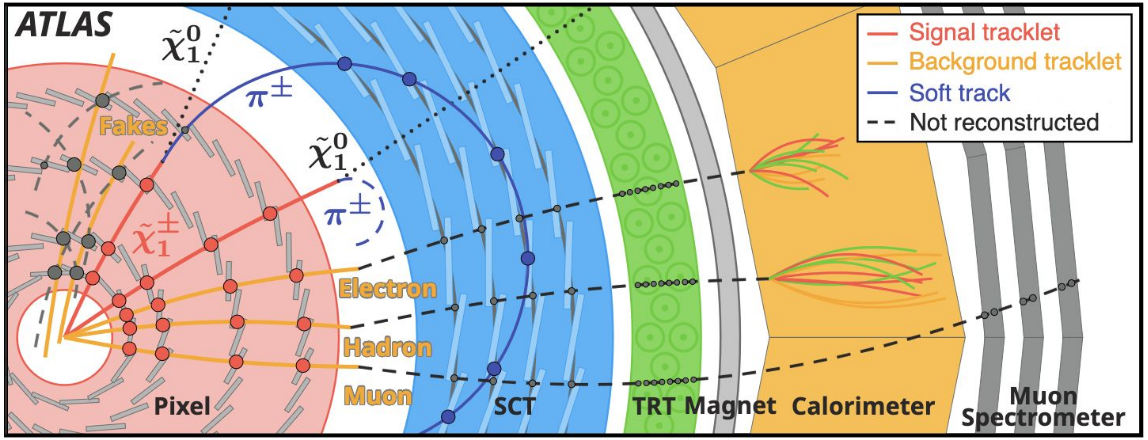


SUSY Summary plots: 2026

Looking for Supersymmetry Via Disappearing Tracks

- Disappearing tracks motivated in multiple BSM models
  - SUSY
  - Minimal dark matter models
- Signature
  - ISR Jet
  - Soft pion or lepton
  - BSM disappearing track!
- Challenge:
  - Large background from fake tracks

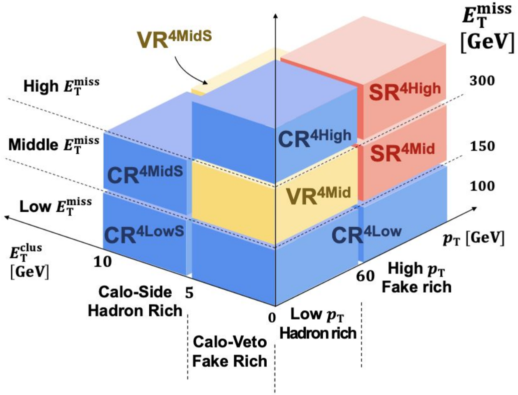


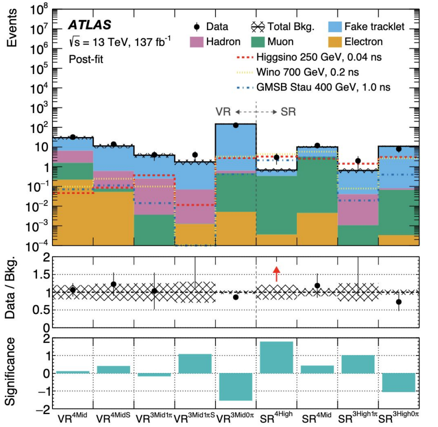


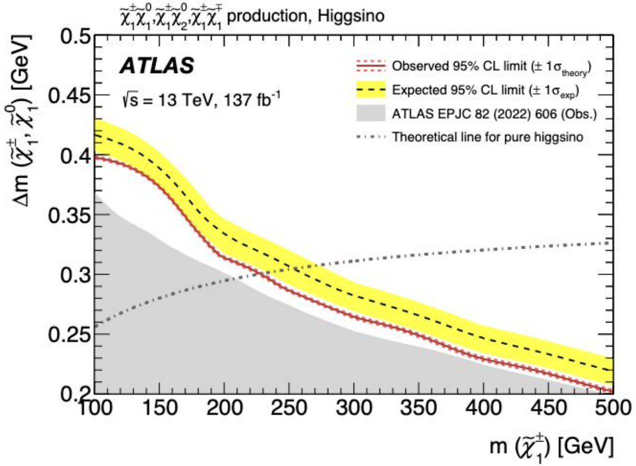
arXiv:2603.08315

Looking for Supersymmetry Via Disappearing Tracks

- Better signal efficiency vs. background rejection by
  - Veto tracklets in nearest strip layers
  - Veto tracklets matched to energy deposits in calorimeter
  - Add 3-hit tracklets and soft-pion tagging
- Complex data driven background estimate (12 control regions in E^{T}_{miss}, tracklet p^{T} and tracklet $E^{T}_{cluster}$ plane)





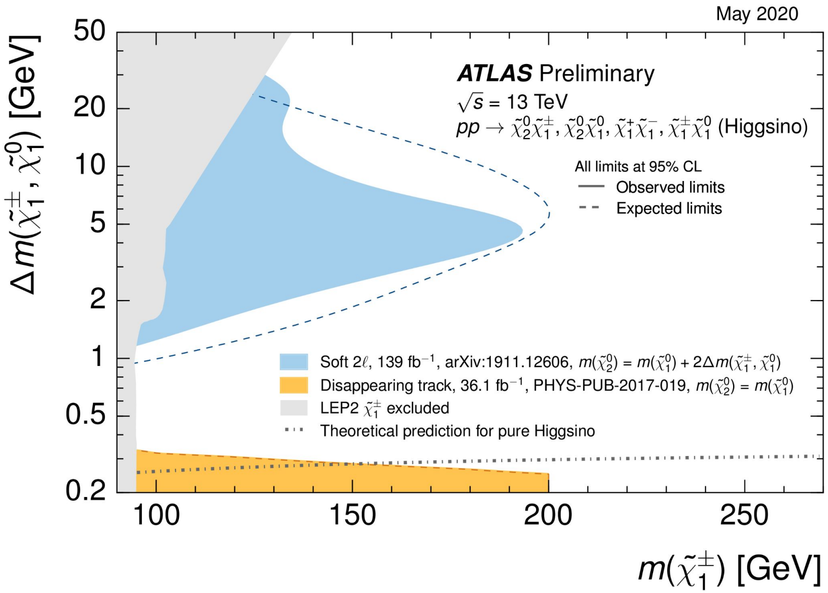


Results:
- Best sensitivity for pure-higgsino mass exclusions
- 225 (250) GeV observed (expected)

Outlook:
- Larger pixel radii and pixel separation in run 4 - diminished sensitivity for shorter lifetime BSM
- Need creative use of the new detector!

Closing the Compressed SUSY Gap

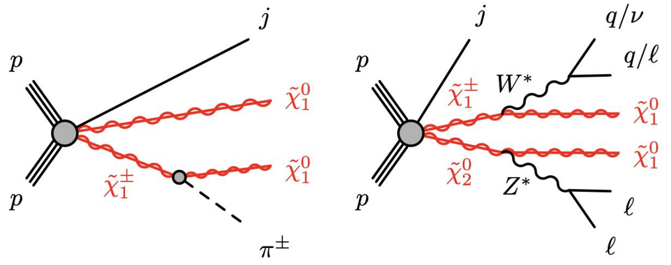
- Consider lightest SUSY particles are a triplet of higgsino-like states with mass splittings Δm ~ 300 MeV (“compressed mass spectra”)
- Mass splittings < 400 MeV: disappearing track
- Mass splittings 300-1500 MeV: displaced track searches
  - Still constrained by LEP [1]
  - Leptons too low-p^T for inner detector (p_T ~ Δm)
  - Higgsino too short lived for disappearing track
- Possible to close the gap?

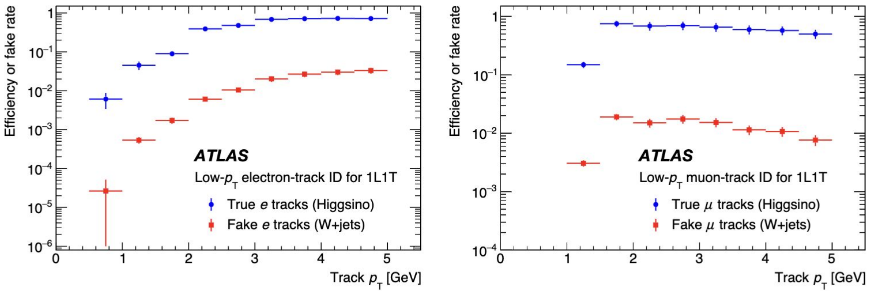


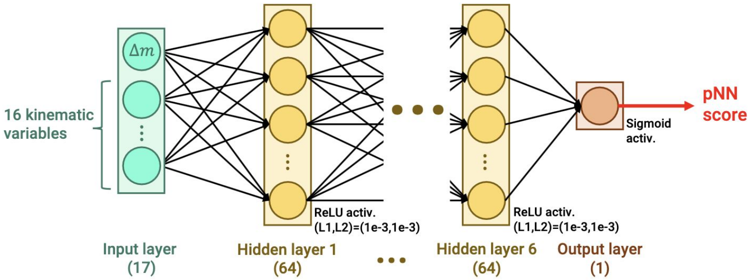
SUSY Summary plots: 2020

Closing the Compressed SUSY Gap

- Search for electroweak higgsino pair production
  - Decay to stable neutralino (LSP) and SM particles
- Δm ~ 1-3 GeV: neural network electron and muon "taggers" (1L + 1 Track)
  - ELectron p^T thresholds: 4.5 GeV → 0.5 GeV
  - Muon p^T thresholds: 3 GeV → 1 GeV
  - Both Dedicated calibration!
- Δm ~ 0.3-1 GeV: neural network to identify track from soft pion (displaced track)
- Require one jet: increase MET for trigger
- Data driven background estimate
  - $Z(\nu\nu)$ + jets
  - $W^{\pm}(\tau^{\pm}\nu)$ + jets
- Use machine learning (pNN) for signal vs background



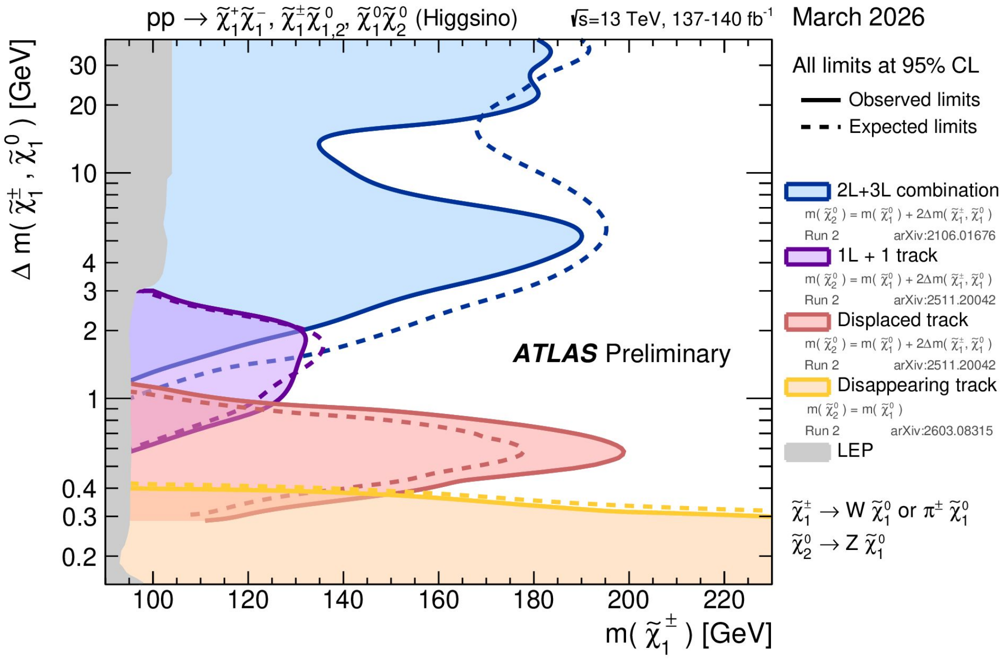




arXiv:2511.20042

Closing the Compressed SUSY Gap

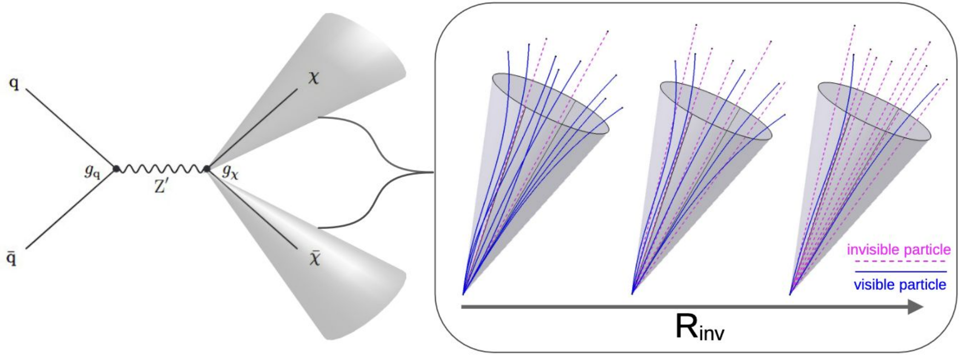
- ATLAS overcomes LEP limits for all values of Δm!

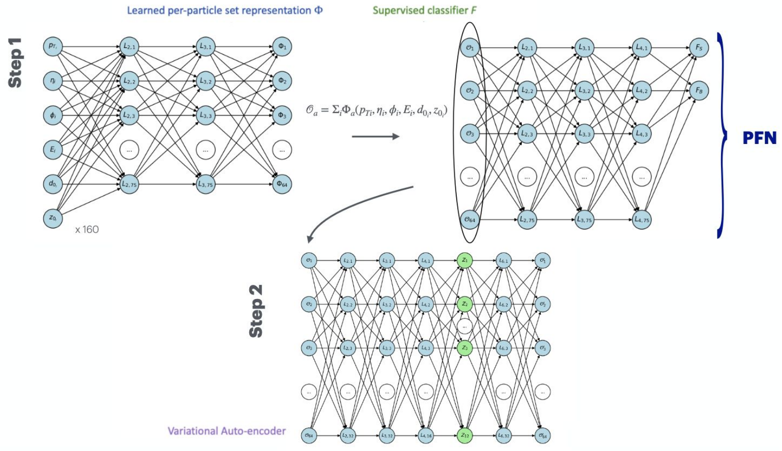


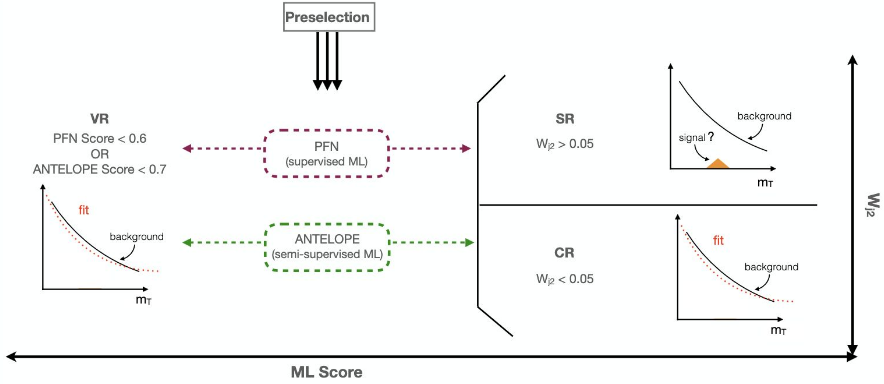
SUSY Summary plots: 2026

Beyond Model Dependent Searches: Anomaly Detection for Semi-visible jets

- Data driven way to explore the unknown unknowns in BSM searches
- Trade off in performance in dedicated search to sensitivity across wider range of models
- In this paper: supervised ML (model dependent) and semi-supervised (model dependent)



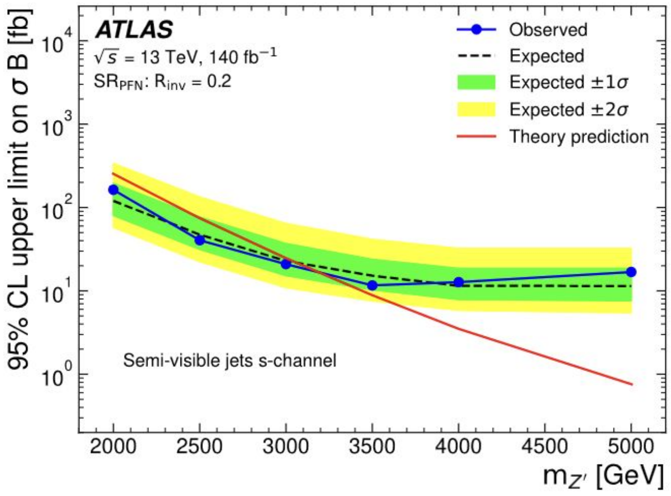


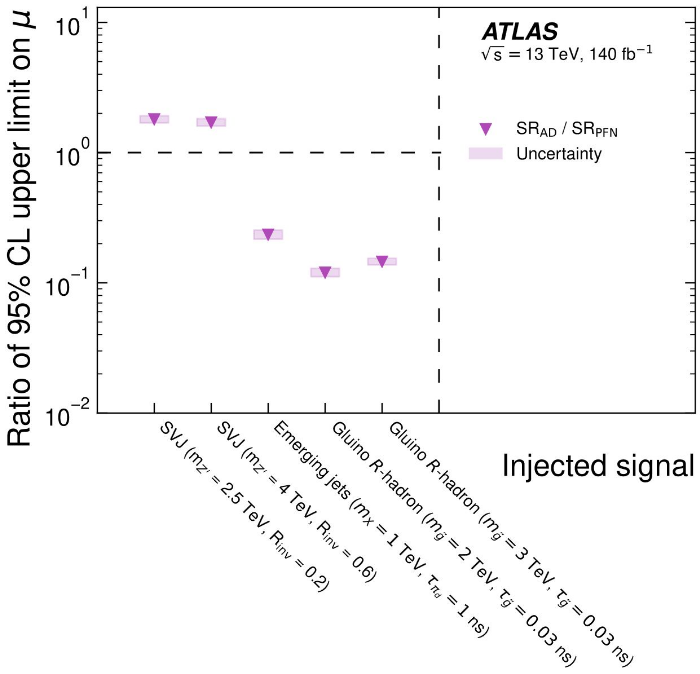


arXiv:2505.01634

Beyond Model Dependent Searches: Anomaly Detection for Semi-visible jets

- Model dependent search: best limits on semi-visible jets signal
- Model independent search: diminished performance on SVJ signal, better performance on similar signatures
  - Emerging jets
  - SUSY gluinos





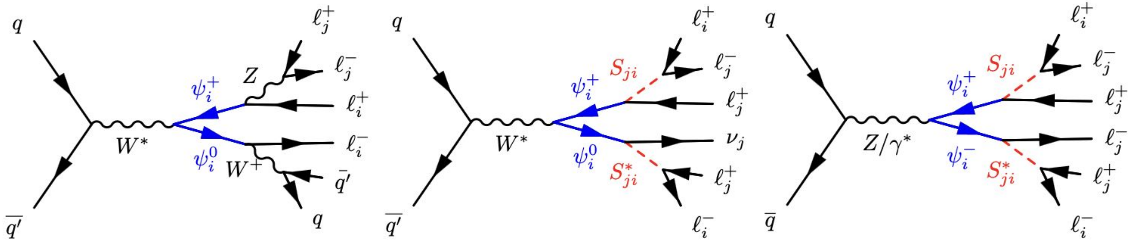
arXiv:2505.01634

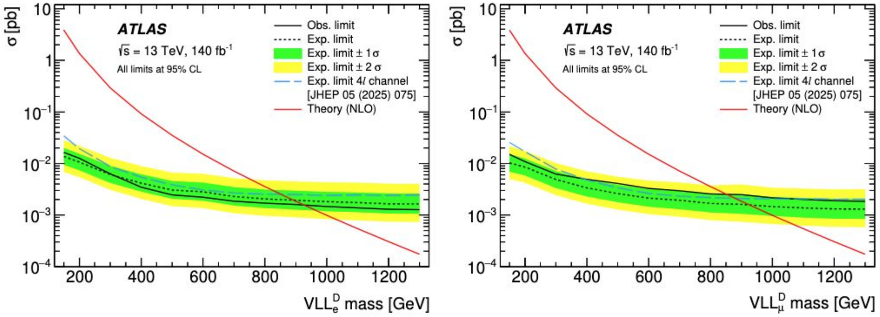
Looking Ahead

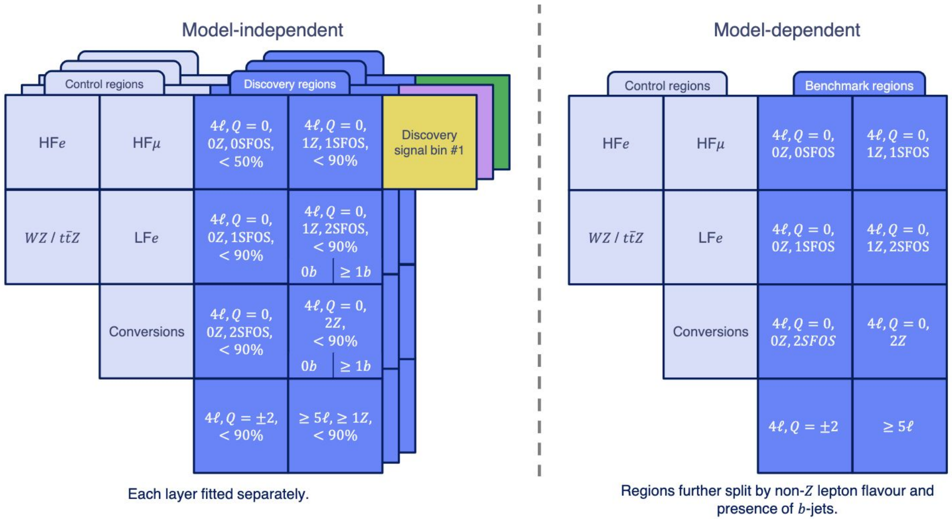
- Presented a small selection of searches for and constraints on BSM physics from ATLAS
- In coming years we'll have the full run2+run3 dataset (450 fb^{-1}) and the beginning of run 4 with a very new detector!
- Perhaps even more exciting is the wealth of new creativity and techniques in the ATLAS collaboration
    - Creative ways to reach new phase space
        - Topological triggers
        - TLA
        - Dedicated object and event reconstruction
    - Novel approaches in machine learning, including anomaly detection
- While BSM physics is elusive, there are plenty of excesses to follow up
- Goal of the ATLAS search program: leave no stone unturned

Beyond Model Dependent Searches: Anomaly Detection in multilepton final states

- Many BSM models produce multilepton final states
  - Vector-like leptons (VLLs)
  - SUSY
- Anomaly detection outperforms dedicated search for some models!







arXiv:2508.19778

Backup: The inner detector