Recent Beyond the Standard Model Search Results from ATLAS and CMS

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Motivation

- Standard Model (SM) describes many phenomena to astonishing accuracy

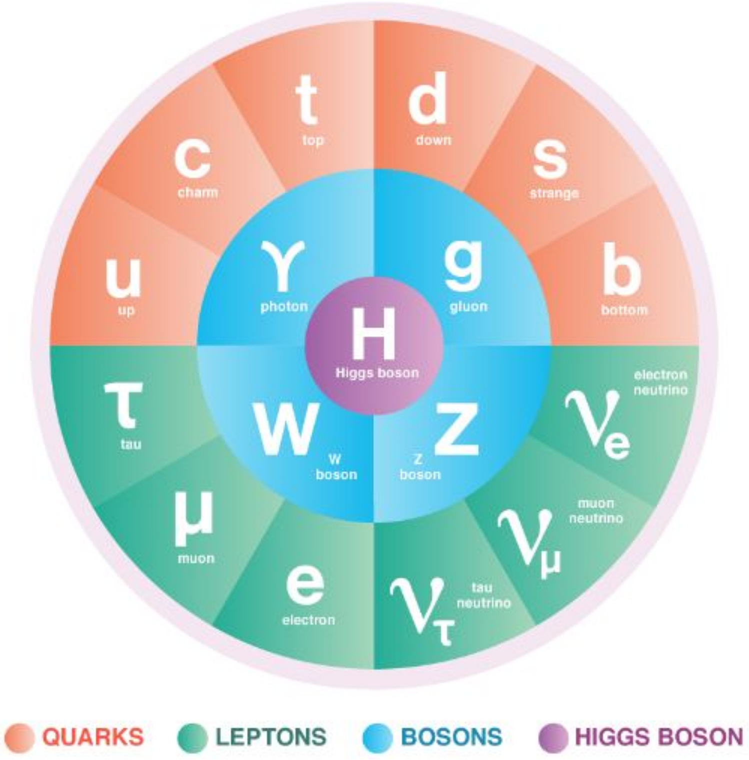

Image Credit

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- Standard Model (SM) describes many phenomena to astonishing accuracy - **but it is incomplete**

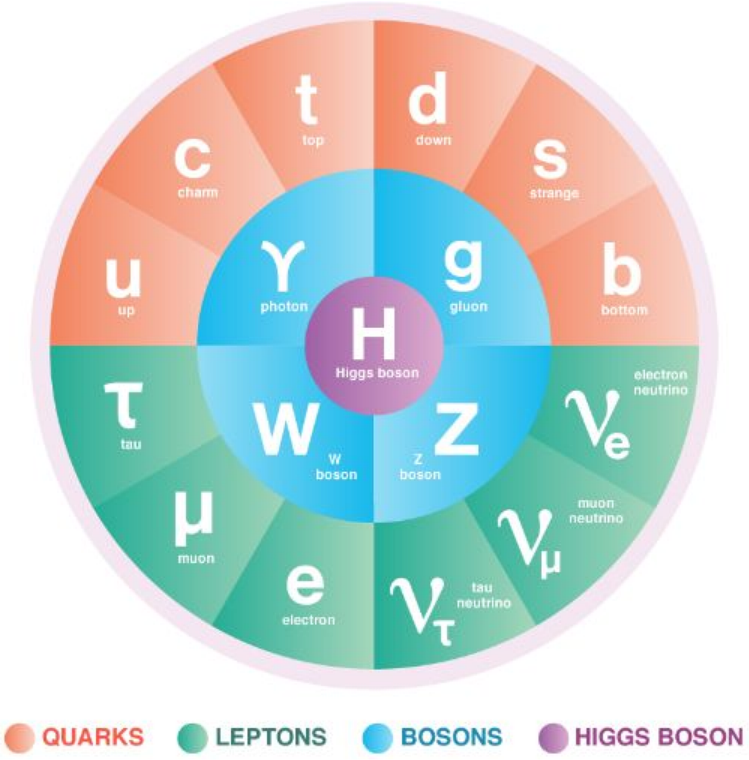
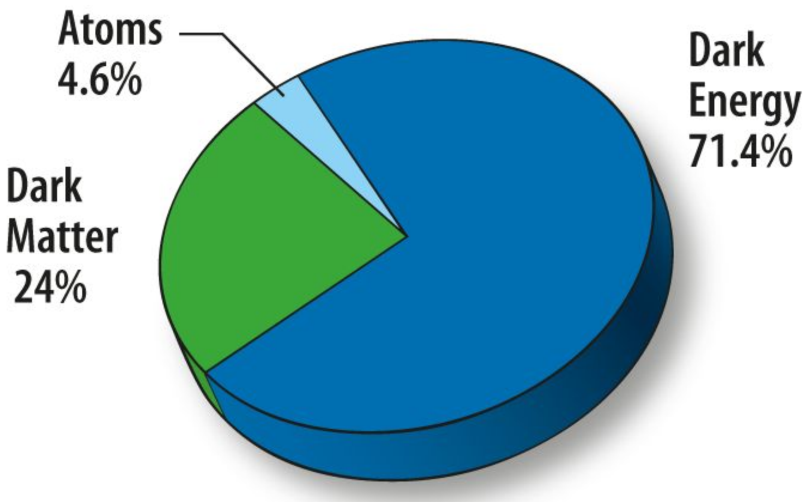


Image Credit

Motivation

- Standard Model (SM) describes many phenomena to astonishing accuracy - **but it is incomplete**
- Standard Model does not account for
  - Dark matter or energy



TODAY
Image Credit

Motivation

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  - Neutrino masses

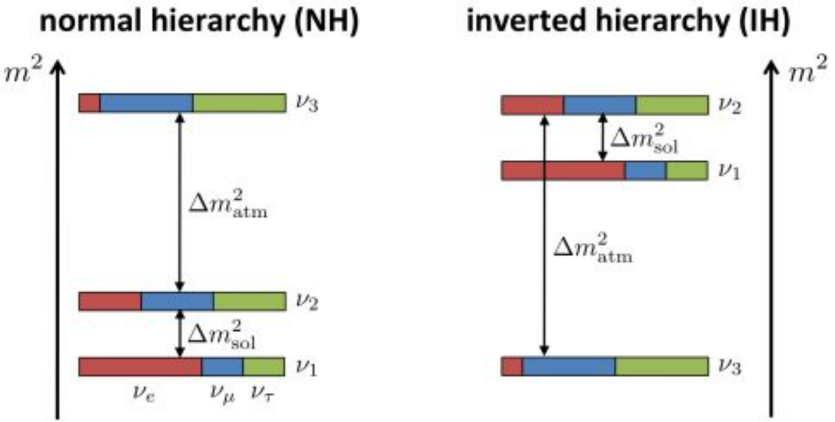

Image Credit

Motivation

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  - Neutrino masses
  - Matter/antimatter asymmetry

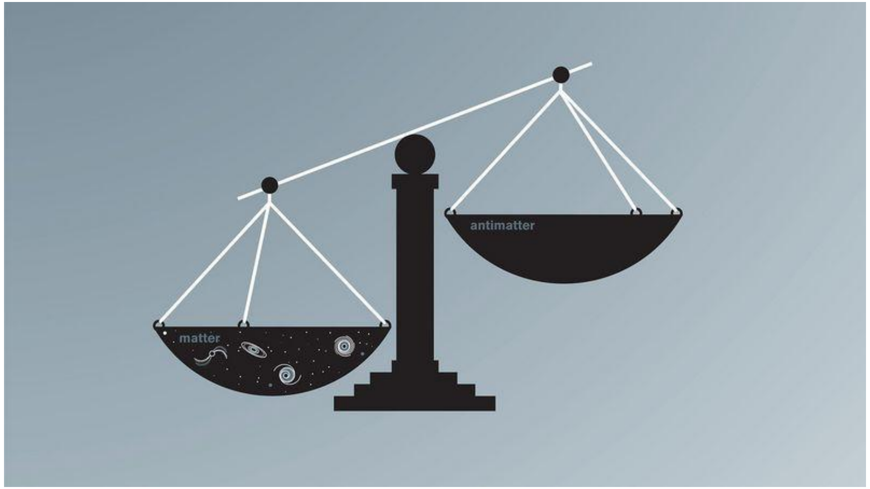

Image Credit

Motivation

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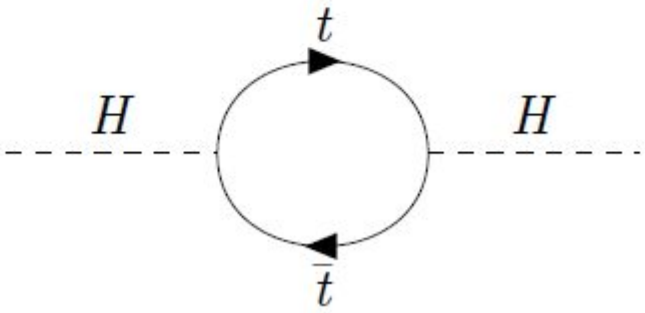
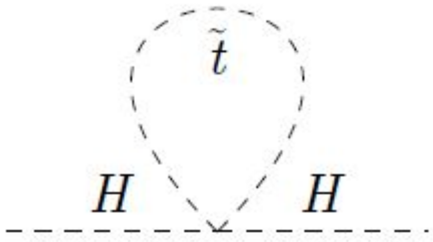
  - Neutrino masses
  - Matter/antimatter asymmetry
  - Naturalness of Higgs mass





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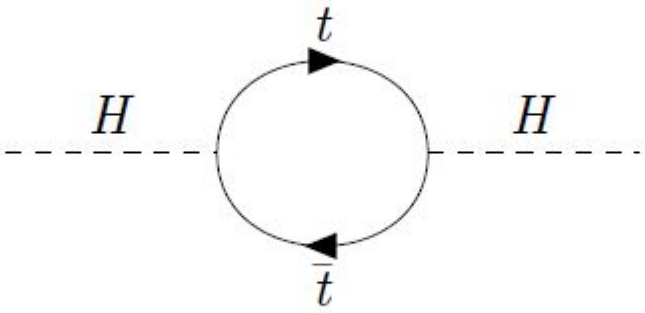
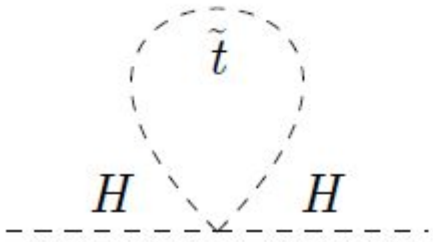
  - Matter/antimatter asymmetry
  - Naturalness of Higgs mass

- Various models have been proposed to address these challenges
  - Supersymmetry (SUSY), two Higgs doublet (2HDM), vector-like quarks (VLQs), majorana neutrinos, and more





Beyond the Standard Model at ATLAS and CMS

- Many searches cover various models
  - Most recent listed in table

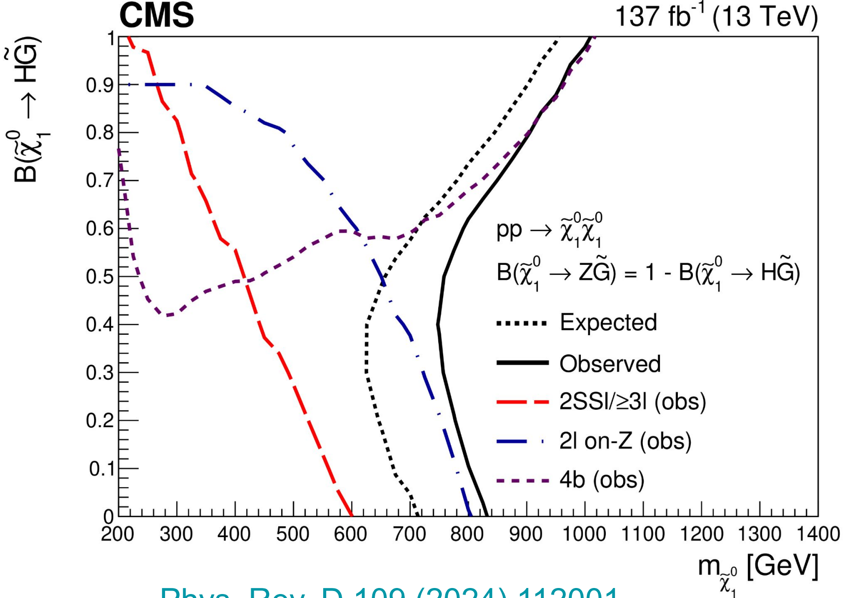
- Will cover
  - Summary Plots
  - Individual Results
    - Compressed Electroweak Supersymmetry
    - Emerging Jets
    - Additional Higgs X→YH searches

ATLAS Results (Full List)	**CMS Results** (Full List)
Search for emerging jets at 13 TeV	Combination of CMS searches for heavy vector boson resonances
Resonant SH→yybb Run2 + partial Run 3 (2022-2023)	Search for resonances decaying to an anomalous jet and a Higgs boson
Low-mass dijet resonance search with trigger-level analysis in full Run 2	Compressed SUSY
Search for heavy neutral leptons (Run-2)	X→YH→bbyy
Multilepton general search using Run2 data	Lepton flavor violating Z and Z' boson decays
Search for resonant leptoquark production in lepton+jet final states	H→aa→ 4τ/ 2μ2τ
Multi-b dark Higgs	Z'→$\tau\tau$/WW
Search for Higgs decays into scalars in ZH (Z→vv/ll & H→aa→4b/6b)	Search for b hadron decays to long-lived particles in the CMS endcap muon detectors
SUSY tau + X	Search for resonant production of pairs of dijet resonances through broad mediators
Single VLQ (T/Y) to Wb search (1L)	Search for heavy pseudoscalar and scalar bosons decaying to a top quark pair
Search for emerging jets at 13.6 TeV	Nonresonant and resonant production of a Higgs boson in association with an additional scalar boson in the $\gamma\gamma\tau\tau$ final state

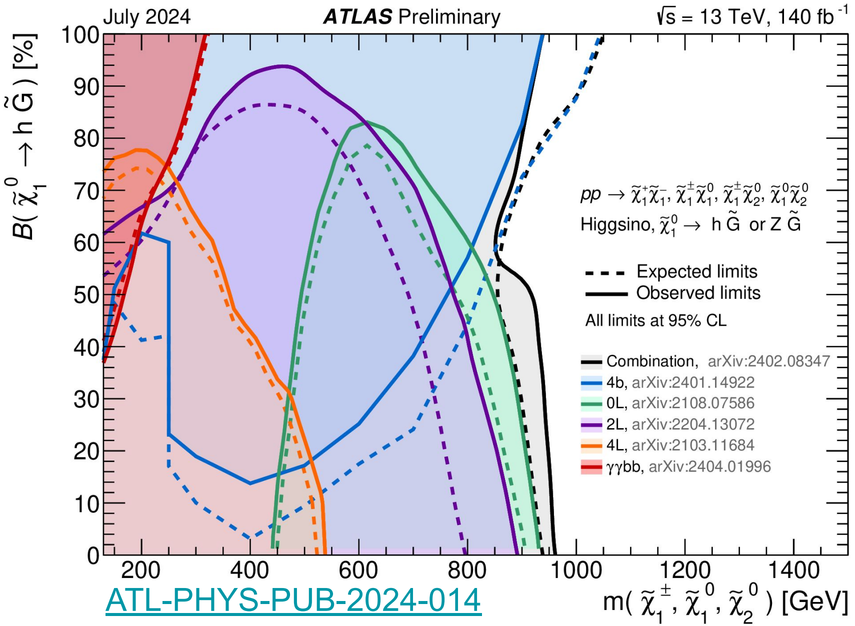
Summary Plots

Electroweak SUSY with Gravitinos

- Small cross sections
  - But masses expected to be light due to naturalness



Phys. Rev. D 109 (2024) 112001

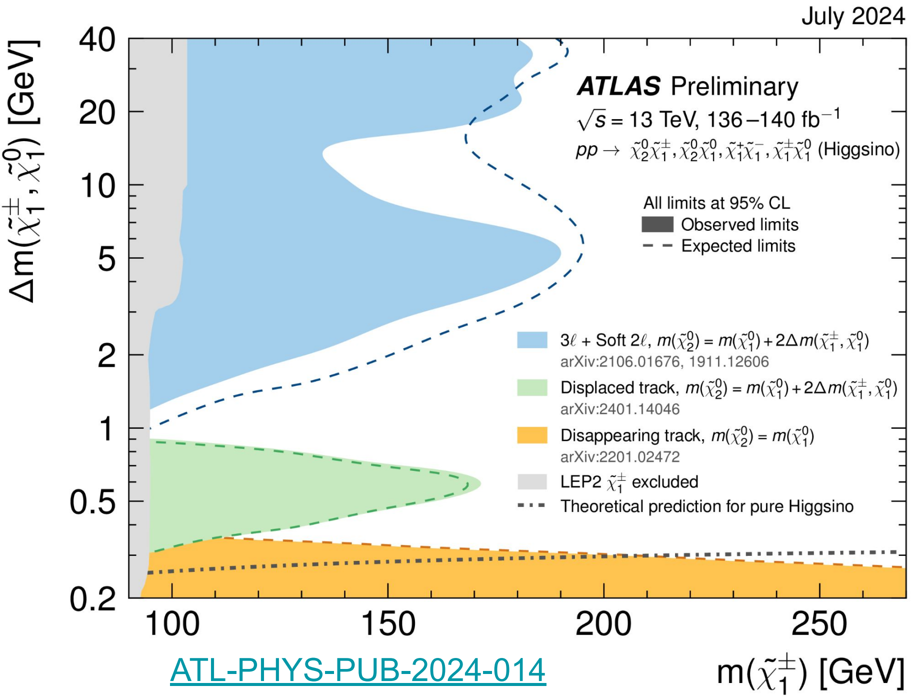


ATL-PHYS-PUB-2024-014

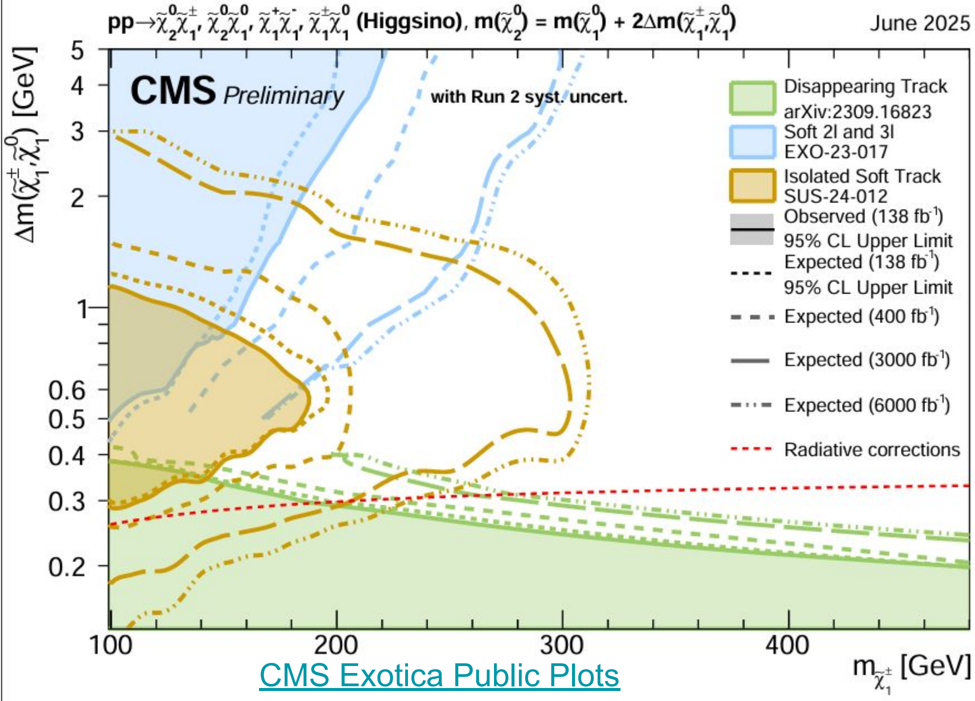
- Gauge-mediated supersymmetry breaking (GMSB) models benefit from **combinations** of complementary analyses

Compressed Electroweak SUSY with Higgsinos

- Triplet of higgsino states: Small mass splittings give difficult to detect signatures
- **Closing the gap** with innovative analysis techniques - will discuss latest results



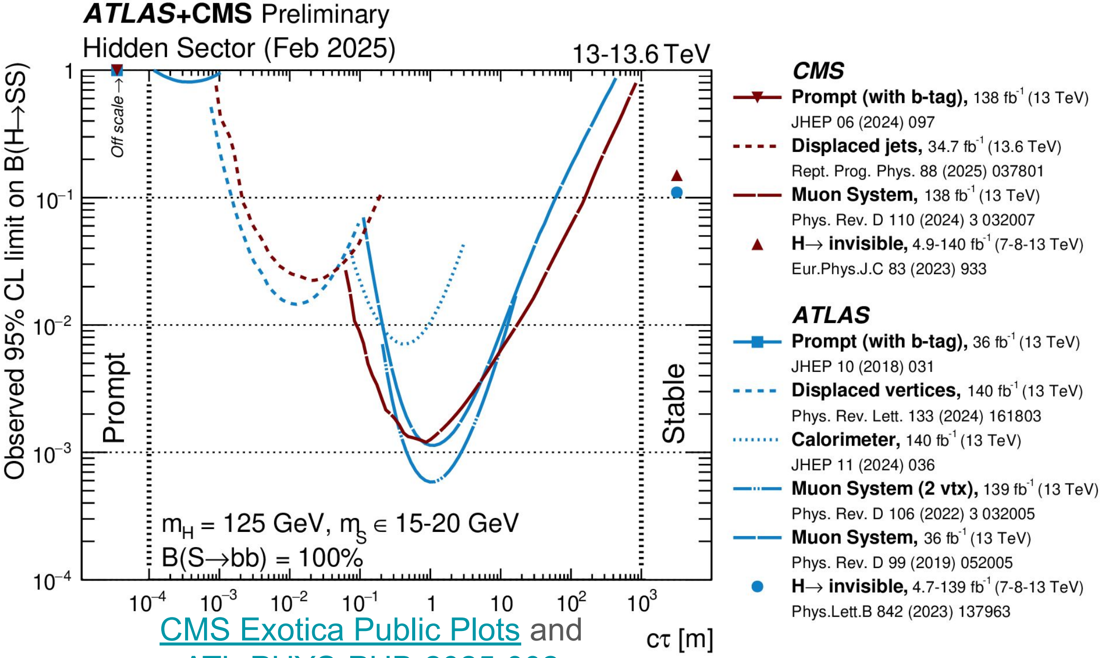
ATL-PHYS-PUB-2024-014



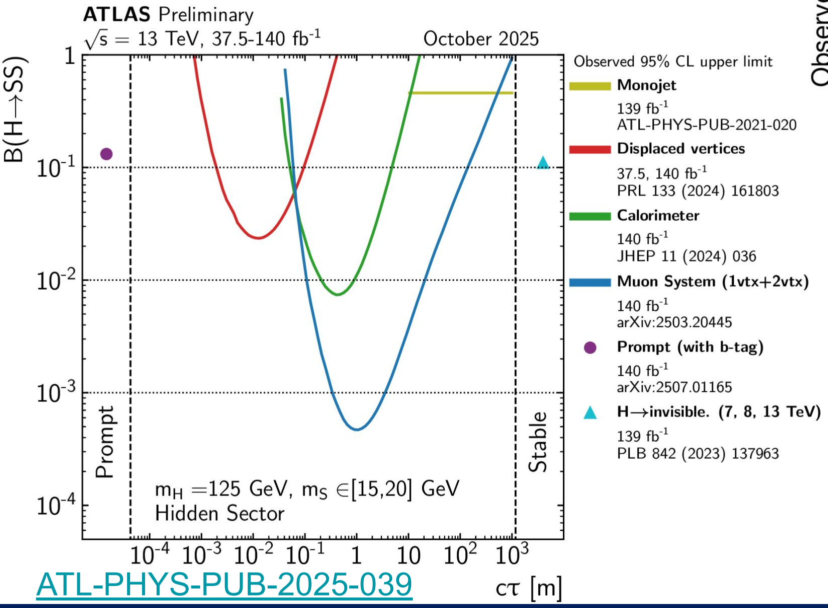
CMS Exotica Public Plots

Long-Lived Particles

- **Long-Lived Particles** could evade constraints from standard searches



CMS Exotica Public Plots and ATL-PHYS-PUB-2025-002

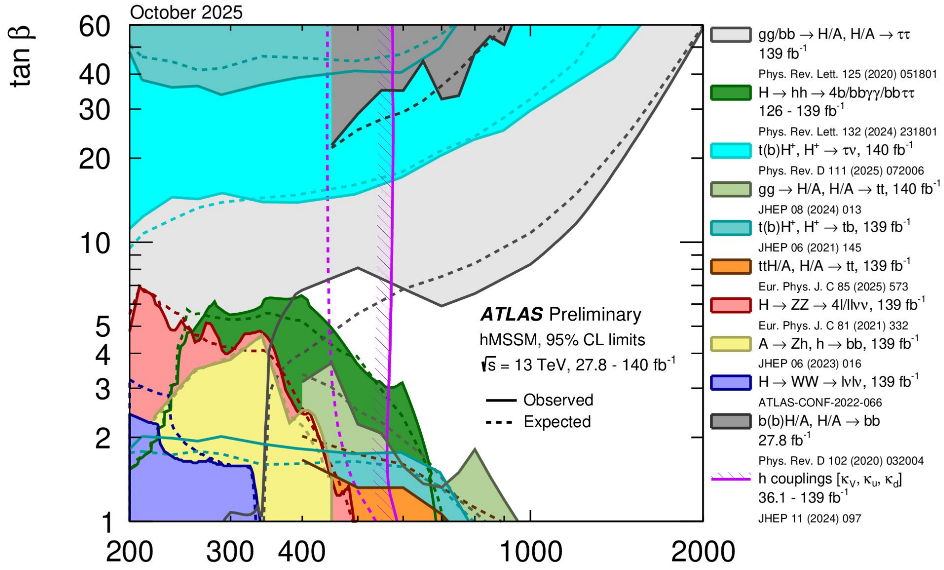


ATL-PHYS-PUB-2025-039

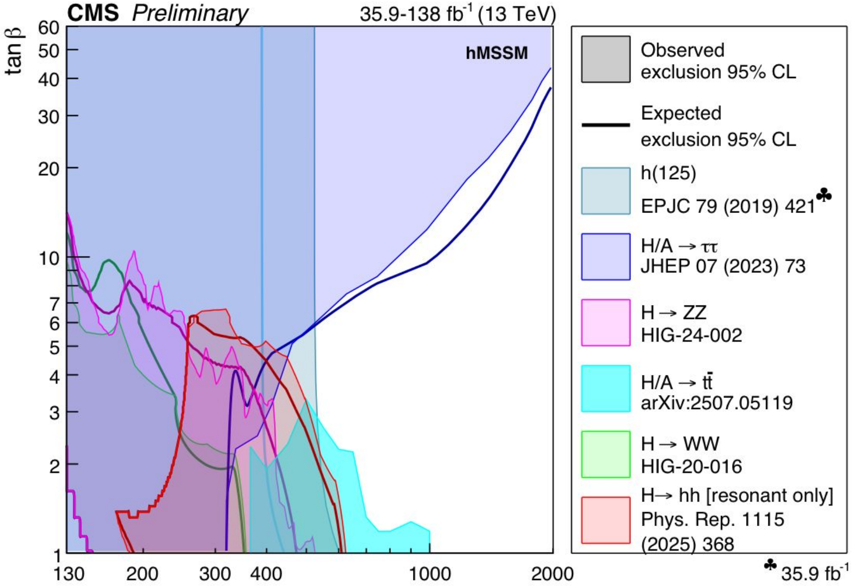
- Requires dedicated reconstruction and analysis techniques
- Will discuss other new long-lived results in more detail

Searches for Additional Higgs Bosons

- Many dedicated analyses explore Minimal Supersymmetric SM
- Other additional Higgs searches will be discussed



ATL-PHYS-PUB-2025-042

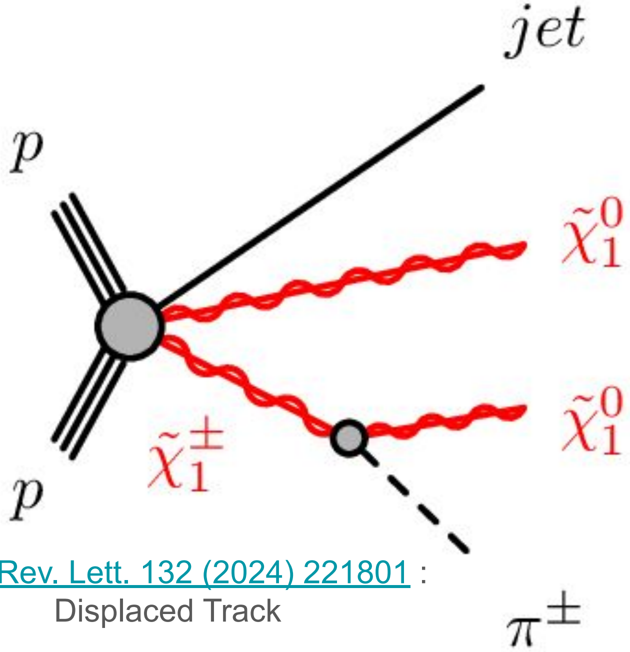


CMS Higgs Public Plots

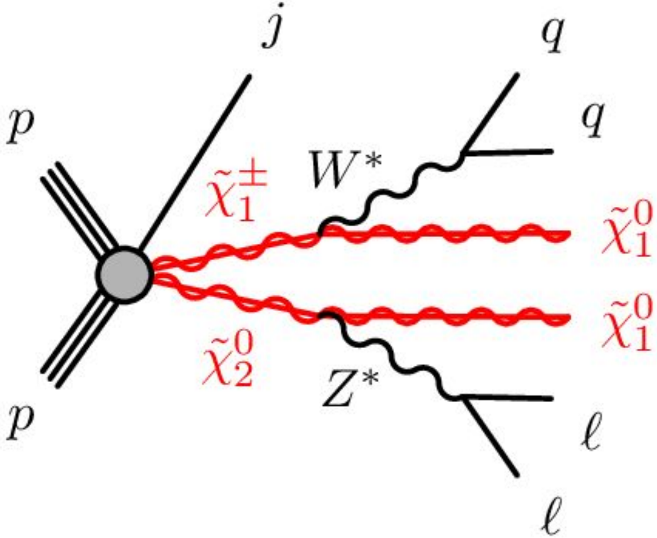
Individual Results

Compressed EWK SUSY

- Naturalness favors light higgsinos
- New results cover gap for $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$
    - Gap in coverage at Δm~0.3-1.5 GeV



Phys. Rev. Lett. 132 (2024) 221801 : Displaced Track



Phys. Rev. D 97 (2018) 052010 : Leptons

- 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

Compressed EWK SUSY

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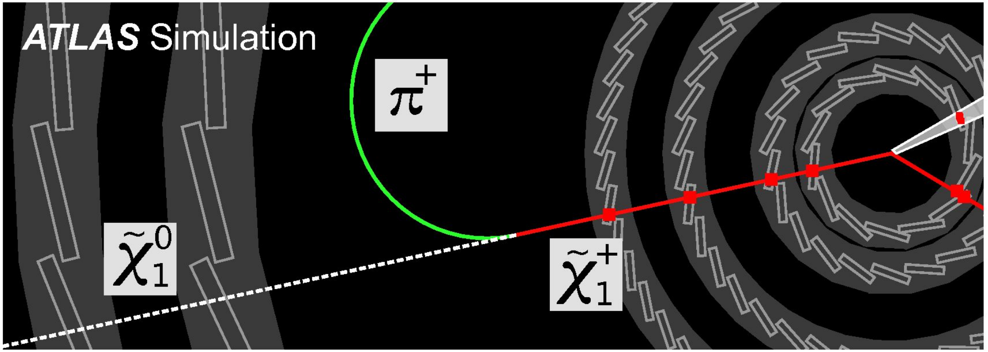
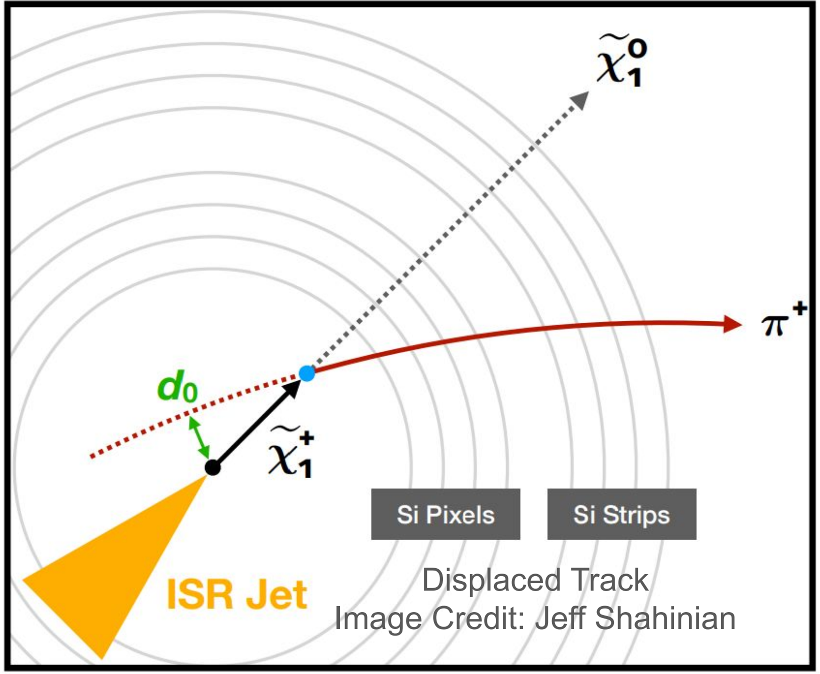


JHEP 06 (2018) 022 : Disappearing Track



Displaced Track
Image Credit: Jeff Shahinian

- Tackle through dedicated searches
  - Soft leptons target higher Δm
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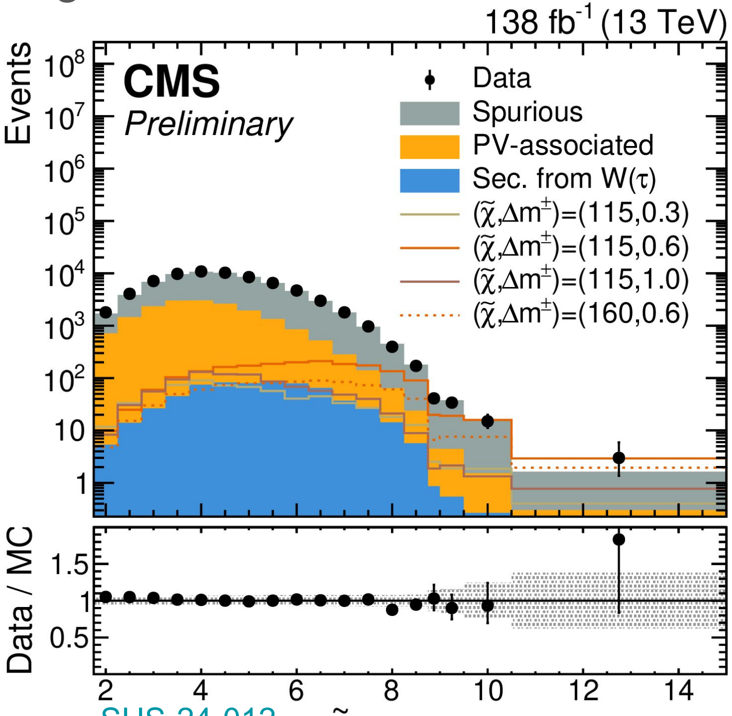
  - Disappearing tracks target lowest Δm

Compressed EWK SUSY: Displaced Track

- Look for mildly displaced, low-momentum pions
- Different strategies to distinguish signal vs. background

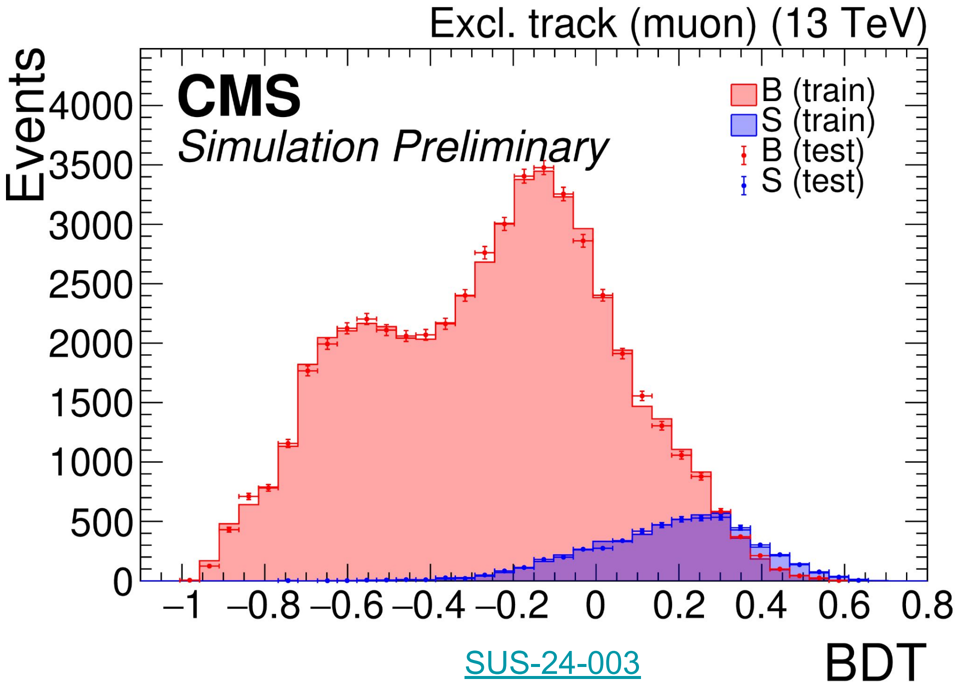
- **ATLAS:** Cut on event kinematics Phys. Rev. Lett. 132 (2024) 221801
  - Look for pion tracks displaced from collision vertex
  - Require high p_T^{miss}
- **CMS:** Train a parametrized Neural Network (PNN) SUS-24-012
  - Parameterized in terms of Δm
  - Sort into orthogonal Signal Regions (SRs) by max PNN score



SUS-24-012

Compressed EWK SUSY: CMS Soft Leptons

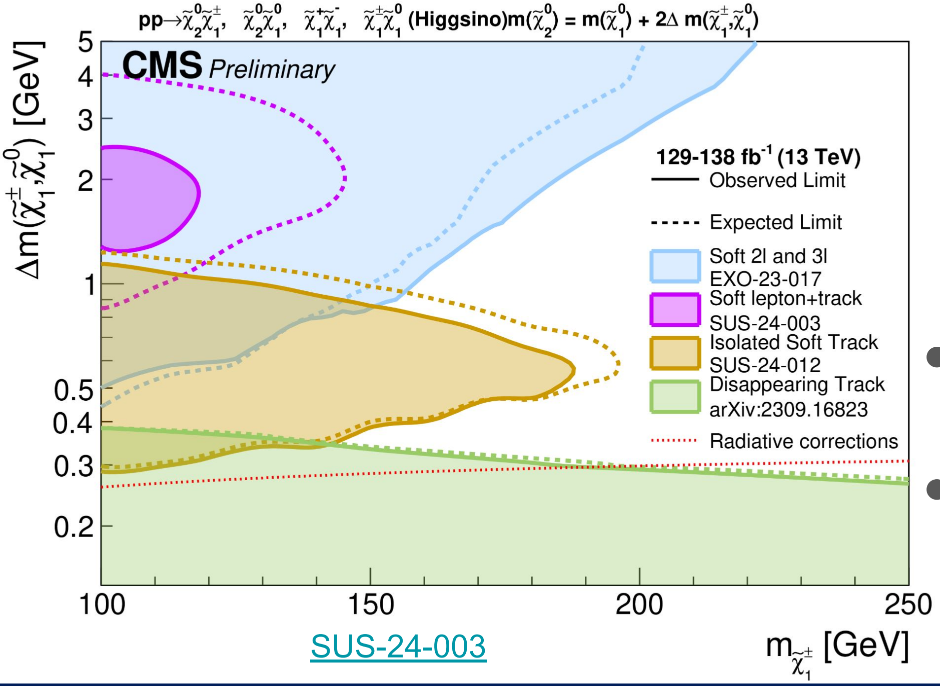
- 2/3 lepton search EXO-23-017
  - Dedicated algorithm adds low-p_T electrons
  - Select events using $m_{\ell\ell}$, p_T^{miss}, other kinematics
- 1 lepton + 1 track search SUS-24-003
  - Use tracks for leptons below p_T threshold
  - Uses Boosted Decision Trees (BDTs) to distinguish S vs. B



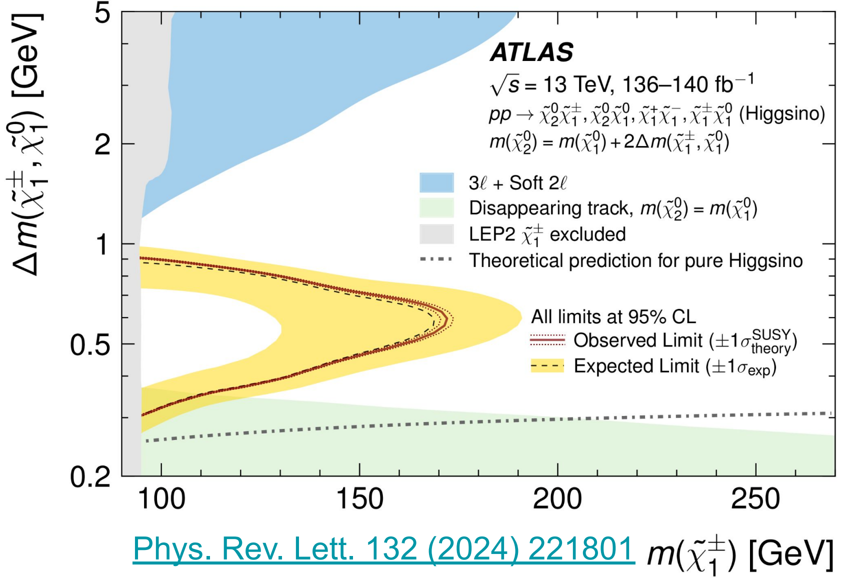
SUS-24-003

Compressed EWK SUSY: Results

- Soft lepton signatures Δm ~1 GeV+
  - Benefits from low lepton/track thresholds



SUS-24-003

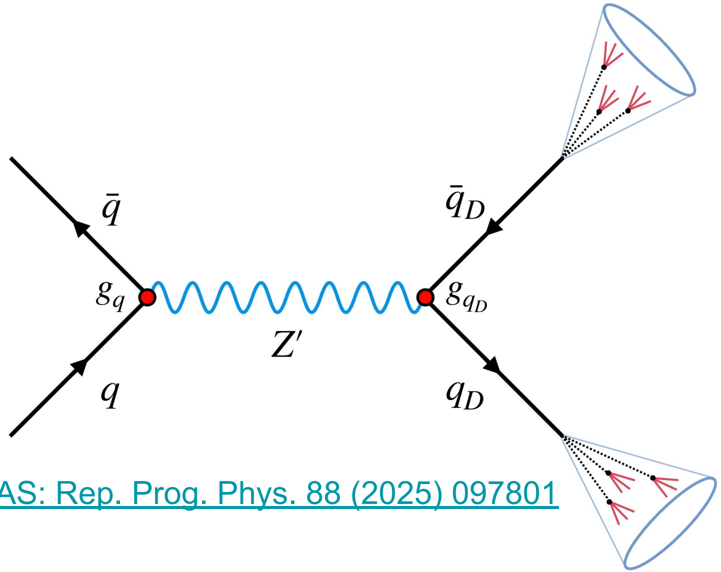


Phys. Rev. Lett. 132 (2024) 221801

- Displaced track signatures set constraints from Δm ~0.3-1.0 GeV
- Covers parameter space not probed since LEP

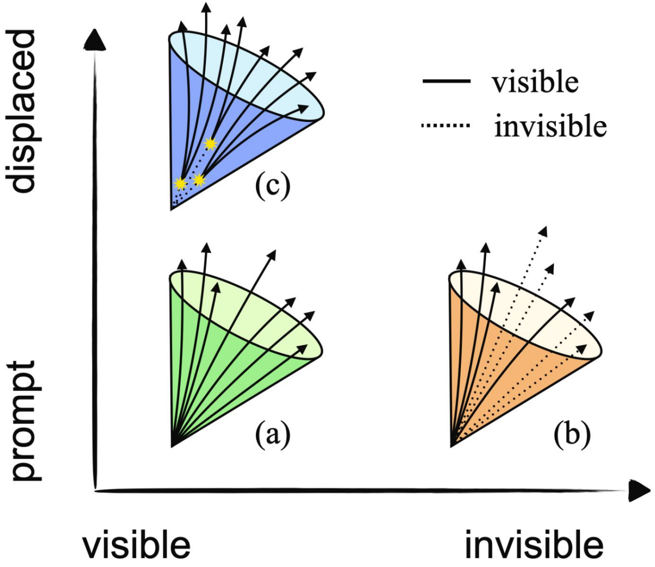
Emerging Jets

- "Dark sector" (DS) models can provide potential dark matter candidates
  - "Dark QCD" provides analogue for jets and hadrons
  - Can connect via mediator (e.g. Z') or Higgs portal
  - Dark bound states can decay back to SM



ATLAS: Rep. Prog. Phys. 88 (2025) 097801

Image Credit

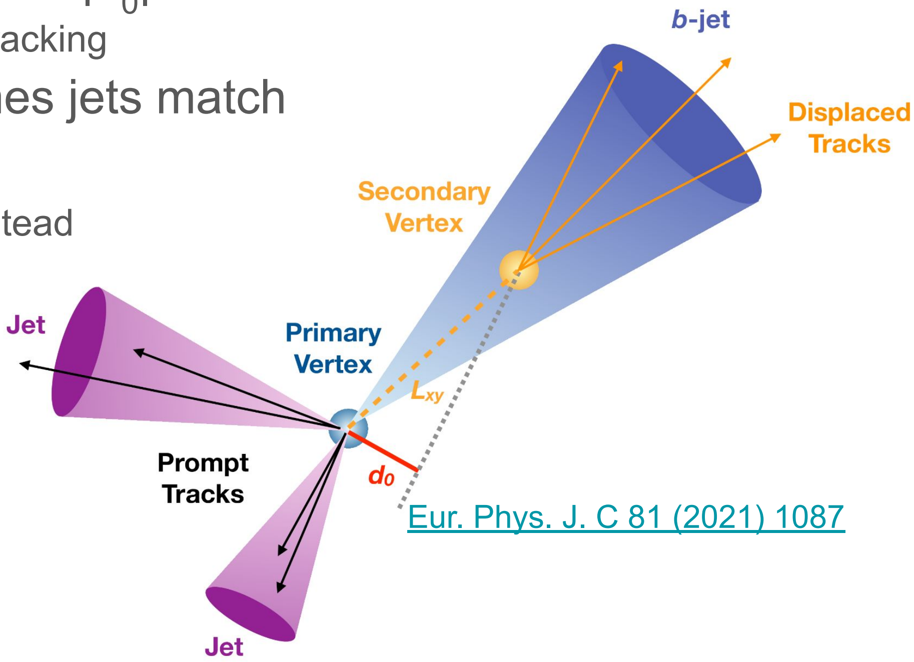


- Small couplings give "emerging/displaced jets"
  - Longer lifetimes give displaced vertices (DVs) as DS particles decay to SM
  - Tackle through **dedicated reconstruction**
  - Classified as a "long-lived particle" (LLP)

Emerging Jets: ATLAS Analysis Techniques

- New Run 3 emerging jet trigger adds LLP sensitivity
  - Requires low "prompt track fraction" of p_T from prompt tracks
- Standard tracking reconstructs tracks with $|d_0|<5$mm
  - Extend to $|d_0|<300$mm with dedicated LLP tracking
- Standard particle flow algorithm assumes jets match primary vertex
  - Use calorimeter-based jet reconstruction instead

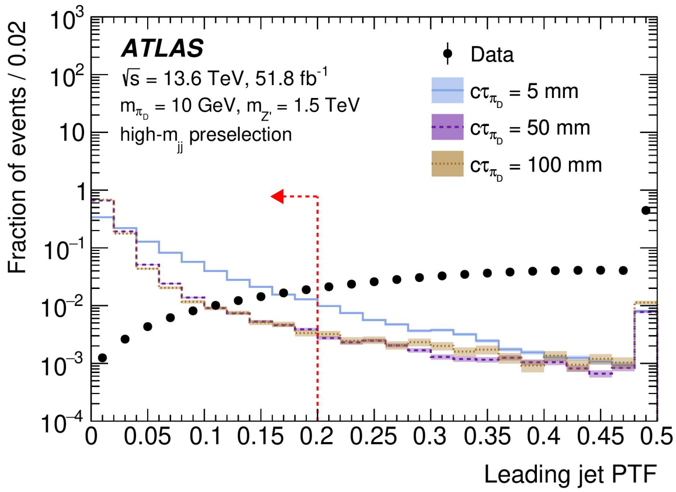
$$\mathrm{PTF} = \frac{\sum_{\mathrm{trk} \subseteq \Delta R < 1.2} p_{\mathrm{T}}^{\mathrm{trk}}}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

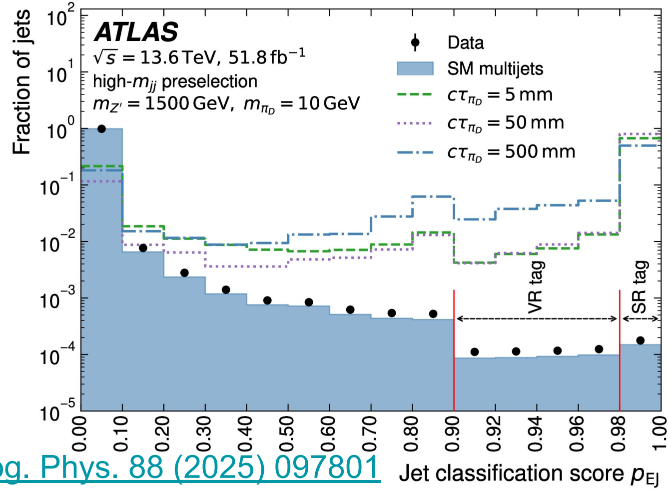


[Eur. Phys. J. C 81 (2021) 1087]

Emerging Jets: ATLAS Analysis

- Two strategies: Cut & Count and Machine Learning (ML)
- Cut & Count
  - Suppress background with Prompt Track Fraction
- Machine learning
  - Use a transformer jet tagging algorithm based on GN2
  - Classifies jets and track origin, and measures track-pair compatibility to give probability of emerging jet

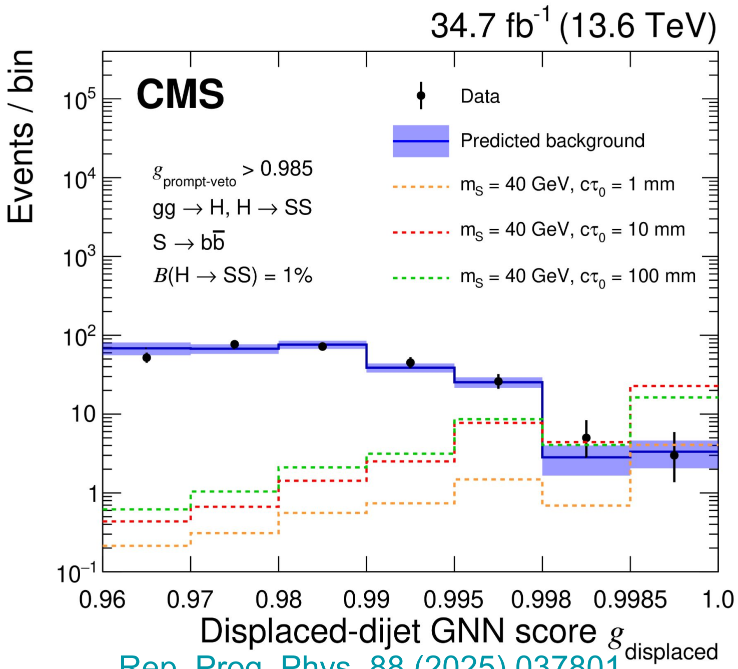




[Rep. Prog. Phys. 88 (2025) 097801]

Emerging Jets: CMS Analysis

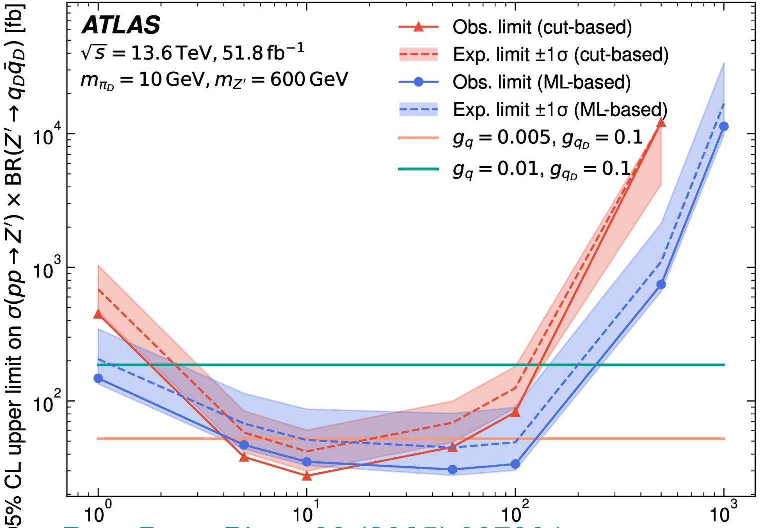
- New displaced jet triggers introduced in Run 3
  - Require jets with displaced tracks, few prompt tracks
  - Trigger efficiencies 4-17x higher than 2017-2018 counterparts!
- Reconstruct displaced vertices from pairs of displaced tracks
- Use Graph NNs (GNNs) to identify which dijets from LLP decays
  - Tracks and DVs are nodes, while relations are edges
  - Two taggers: “displaced” and “prompt veto”
- Select DV with good χ^2/dof



Rep. Prog. Phys. 88 (2025) 037801

Emerging Jets: Results

- Limits on Z' mediators to dark pions
- Makes use of Run 3 data
  - 2022 for CMS, 2022+2023 for ATLAS
- Benefits from innovative triggers, reconstruction, and ML techniques



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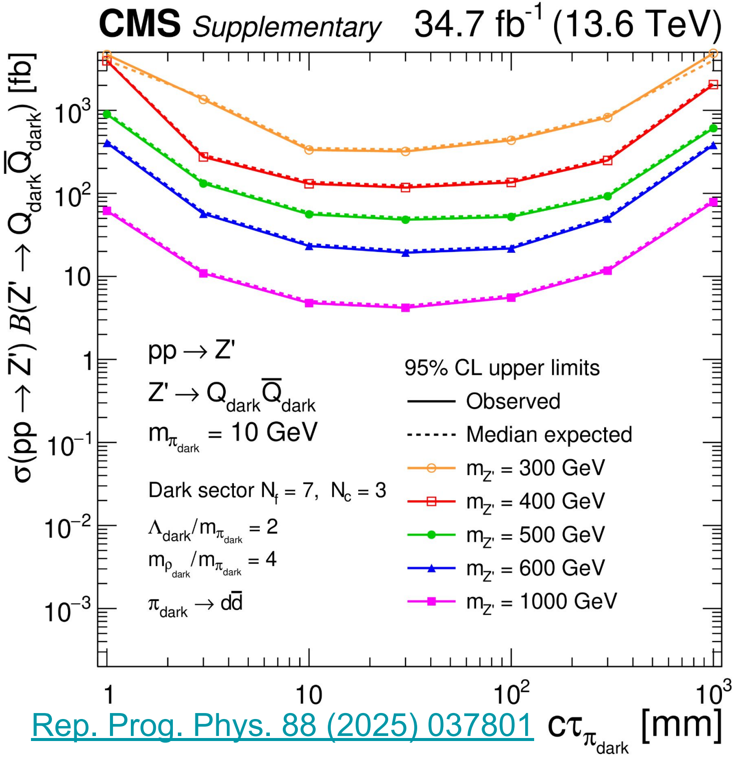
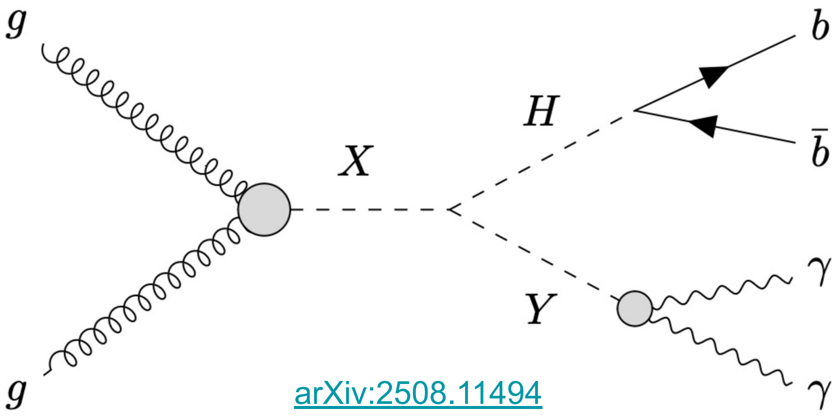


Rep. Prog. Phys. 88 (2025) 037801

- CMS also has limits on Higgs portals, ATLAS on scalar mediators arxiv:2510.12347

Additional Higgs X→YH

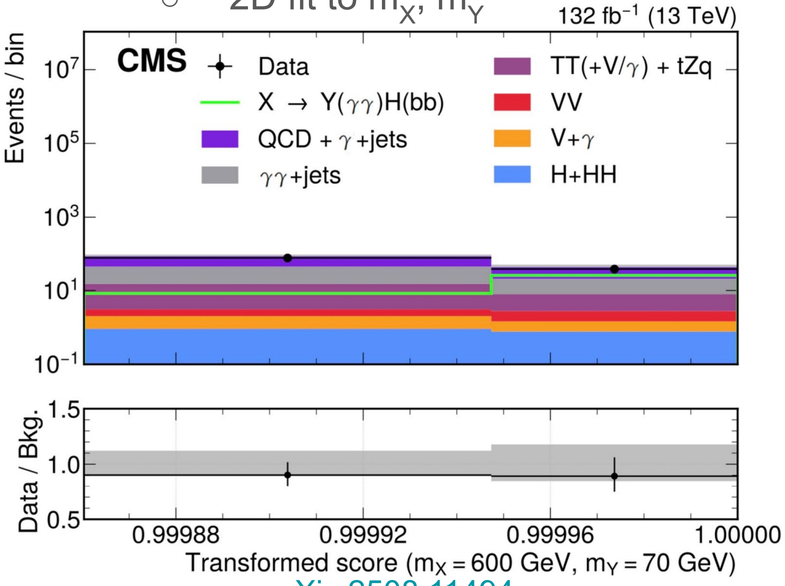
- Additional heavy scalars predicted by NMSSM, two real singlet models, warped extra dimensions
- Look for heavy scalar X decaying to Y/S + Higgs
- Many previous searches in various final states
  - CMS Y(bb)H(γγ) saw excess of 3.8σ local (2.6σ global) for (m_X, m_Y) = (650, 90) GeV [1]
  - ATLAS Y(bb)H(γγ) saw excess of 3.5σ local (2.0σ global) at (m_X, m_Y) = (575, 200) GeV [2]
- Four recent additions
  - Run 2:
    - CMS Y(bb)H(bb) HIG-20-012
    - CMS Y(γγ)H(bb) arXiv:2508.11494
    - CMS Y(VV)H(bb) B2G-23-007
  - Run 2 + partial Run 3:
    - ATLAS Y(bb)H(γγ) arxiv:2510.02857



arXiv:2508.11494

Additional Higgs X→YH

- CMS Y(bb)H(bb)
    - Select events with reconstructed Higgs mass consistent with true value
    - Background estimated by reweighting data with BDT
    - 2D fit to m_X, m_Y



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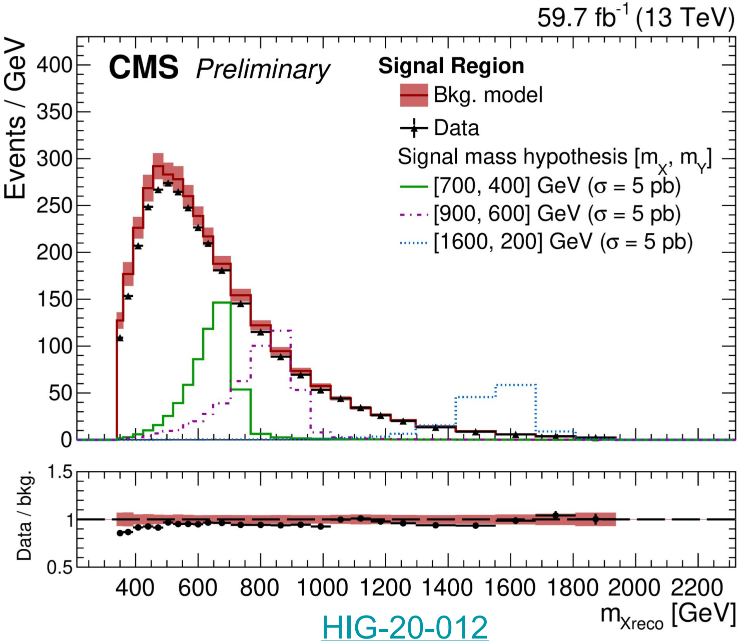
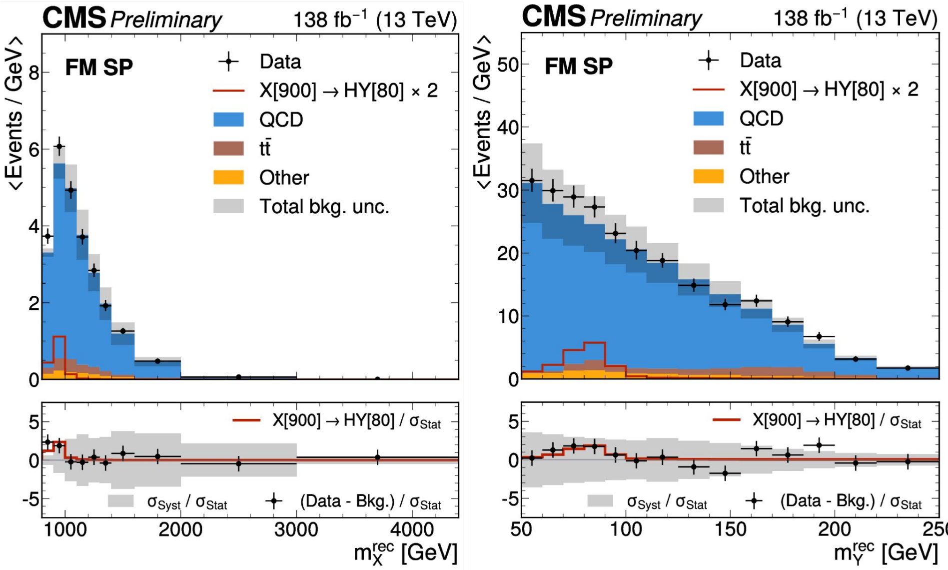


HIG-20-012

- CMS Y(γγ)H(bb)
    - Switch of previous Y(bb)H(γγ) search with excess
    - Train a PNN to gain sensitivity to wide range of signal masses
    - Search for $m_{\gamma\gamma}$ resonance

Additional Higgs X→YH

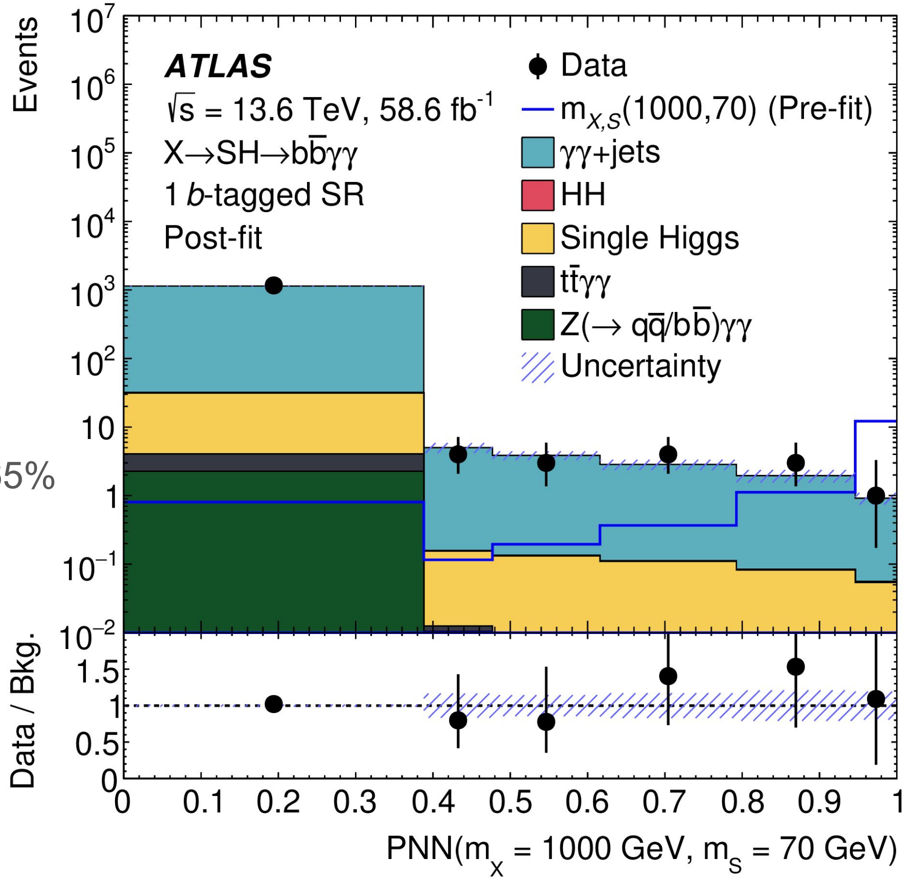
- CMS Y(VV)H(bb)
  - First X→YH to target bbVV→bb4q
  - Two regimes: fully-merged and sermi-merged
    - 1 large-R jet for H, 1-2 for Y
  - PARTICLENET used for H→bb identification
  - Attention-based Neural Network “ParT” used to identify fully-merged Y→VV→4q
  - Require reconstructed Higgs, W/Z to be near true masses
  - Bin in m_X, m_Y



B2G-23-007

Additional Higgs X→YH

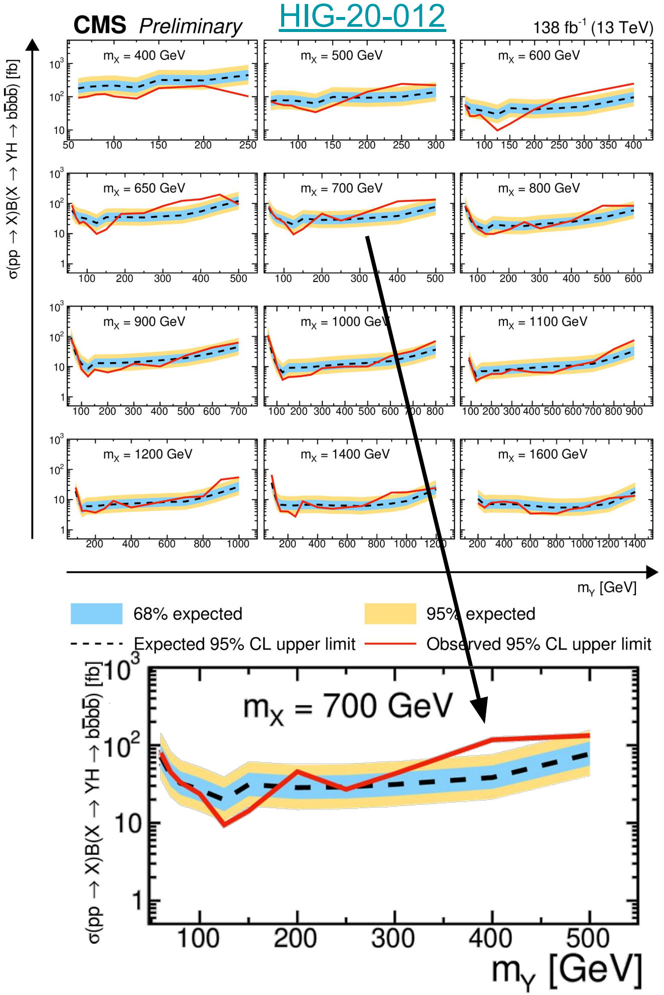
- ATLAS Y(bb)H(γγ)
  - Includes Run 2+partial Run 3 (2022-2023)
  - Use PNN to separate signal from background
  - Fit to PNN score distribution
  - Improved GN2 b-tagger improves limit by 10-65%



arxiv:2510.02857

X→YH: Results

- CMS Y(bb)H(bb)
  - Largest excess 4.1σ local (2.8σ global) for $(m_X, m_Y) = (700, 400)$ GeV
- CMS Y(γγ)H(bb)
  - Y(bb)H(γγ) excess not confirmed
  - Largest excess 3.33σ local (0.65σ global) for $(m_X, m_Y) = (300, 77)$ GeV
- CMS Y(VV)H(bb)
  - Largest excess 3.3σ local (<1σ global) for $(m_X, m_Y) = (900, 80)$ GeV
- ATLAS Y(bb)H(γγ)
  - No significant excess - previous ATLAS and CMS excesses not confirmed



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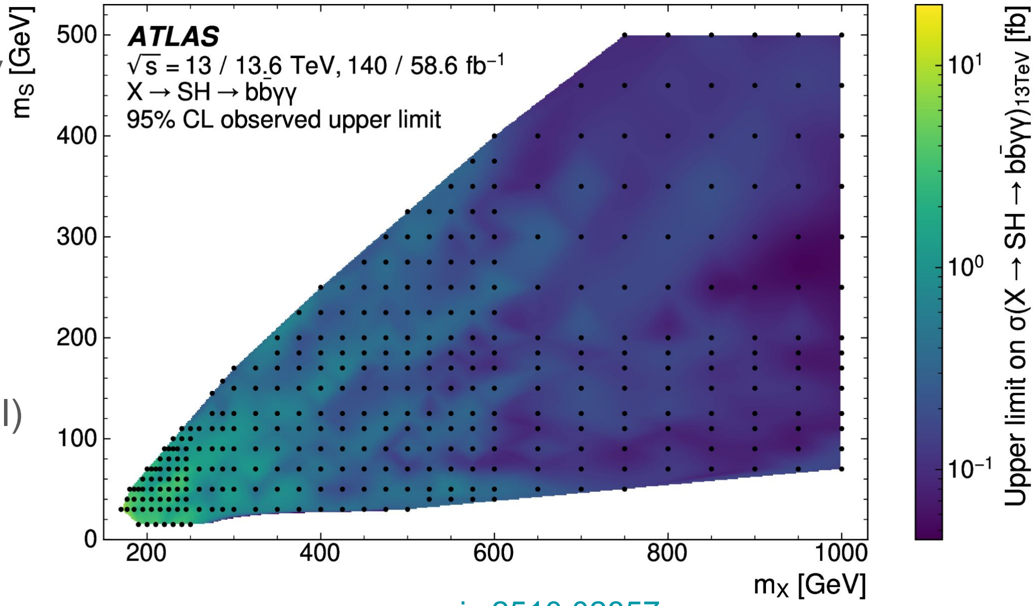


arxiv:2510.02857

Conclusion

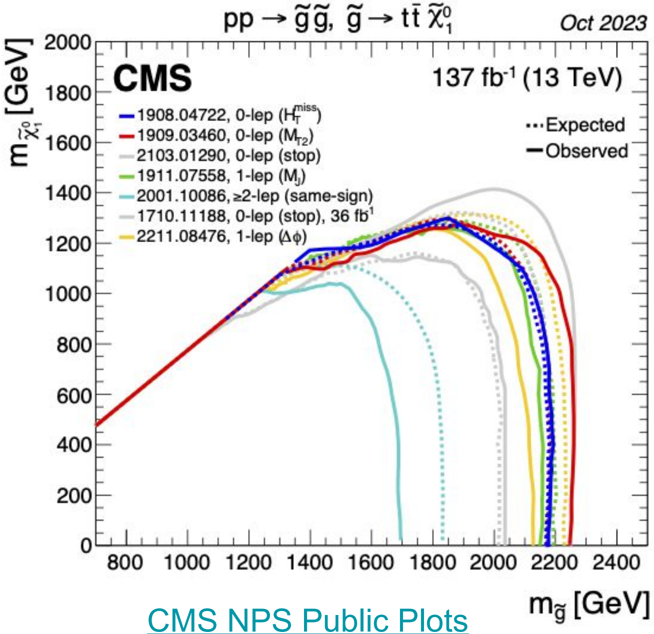
- An overview of the search programs at ATLAS and CMS has been presented
- We continue to search for new physics with
  - A **broad search program** targeting diverse physics models
  - **Innovative techniques** to investigate hard-to-reach phase space
  - And **new ideas** to catch physics we may have missed!

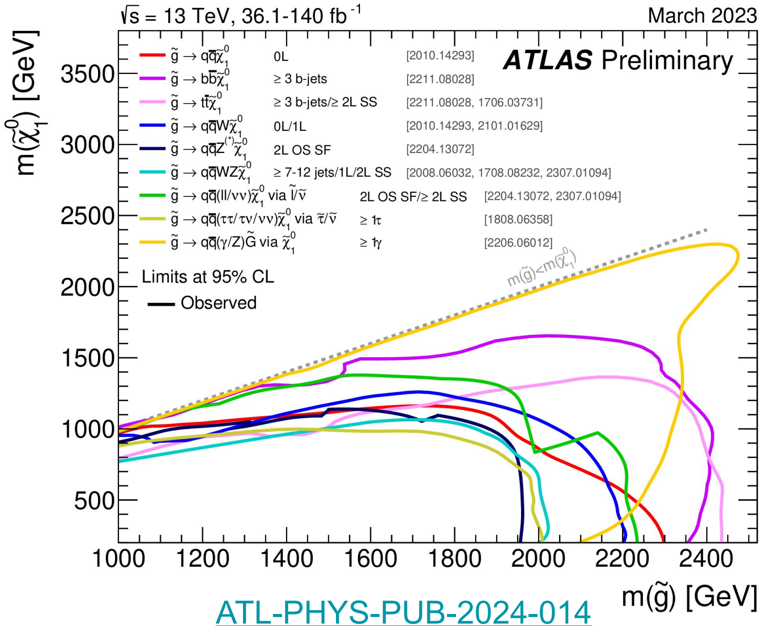
Thank you for listening!

Backup

Strong SUSY

- **Strongly produced** SUSY has high cross sections
- Exclusions over 2 TeV



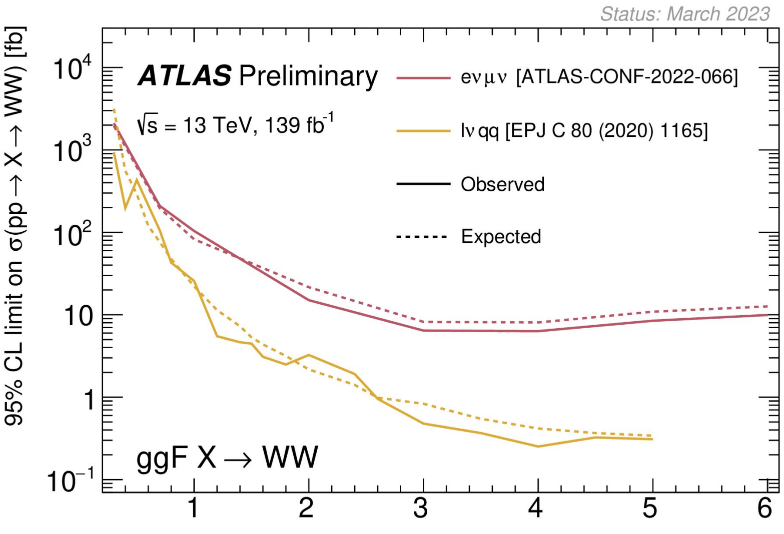


CMS NPS Public Plots

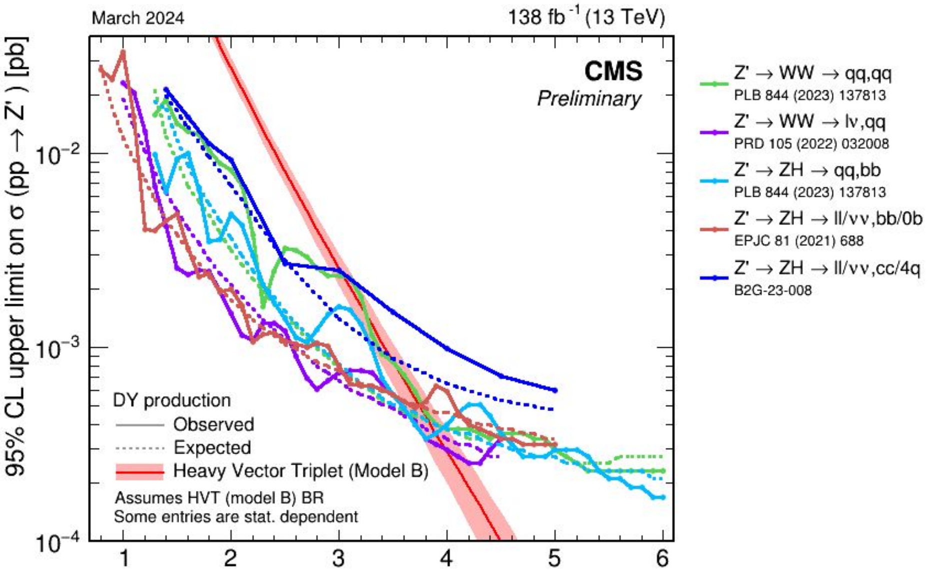
ATL-PHYS-PUB-2024-014

Diboson Resonances

- Heavy Vector Triplet (**HVT**) model yields spin-1 V’ bosons
- Resonances decaying to diboson final states



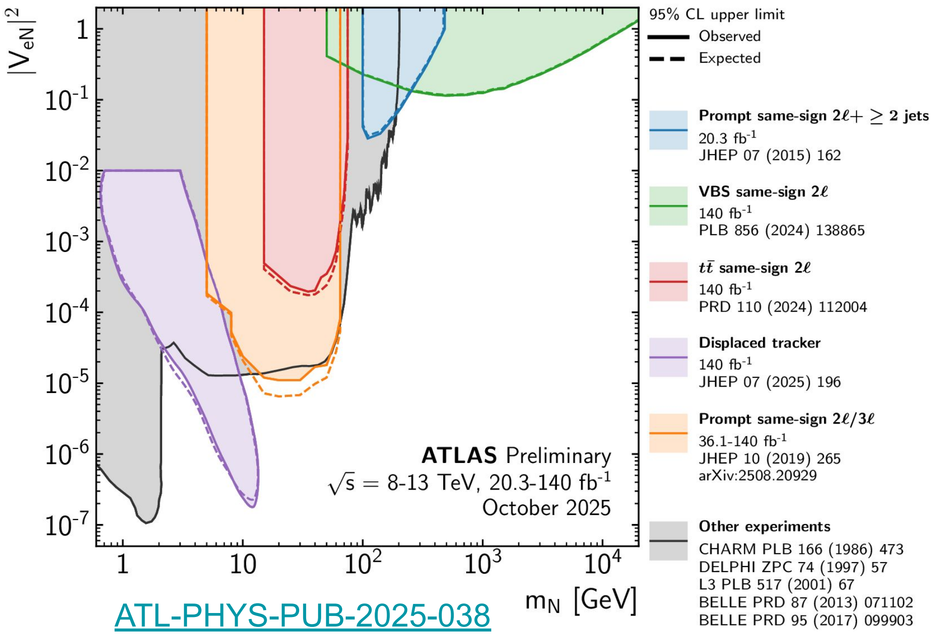
ATL-PHYS-PUB-2023-007



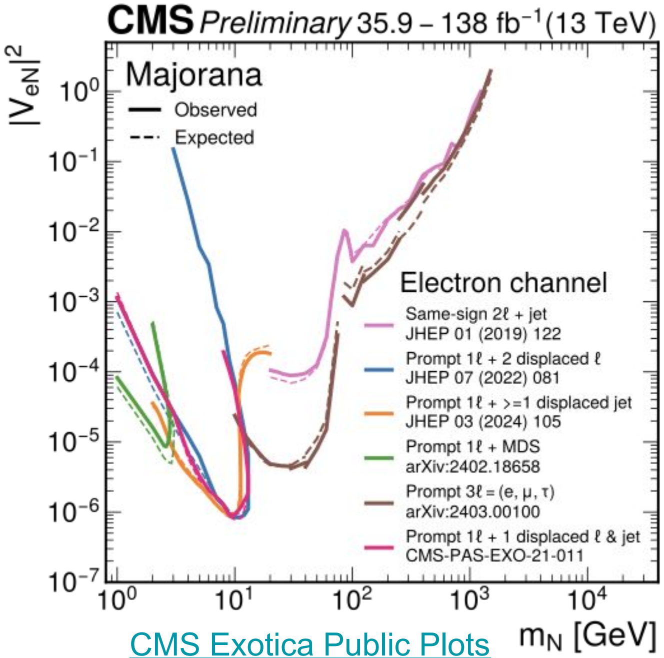
CMS B2G Public Plots

Heavy Neutral Leptons

- Heavy majorana neutrinos
- Recent vector-boson fusion (VBF) analysis covers new high-mass parameter space



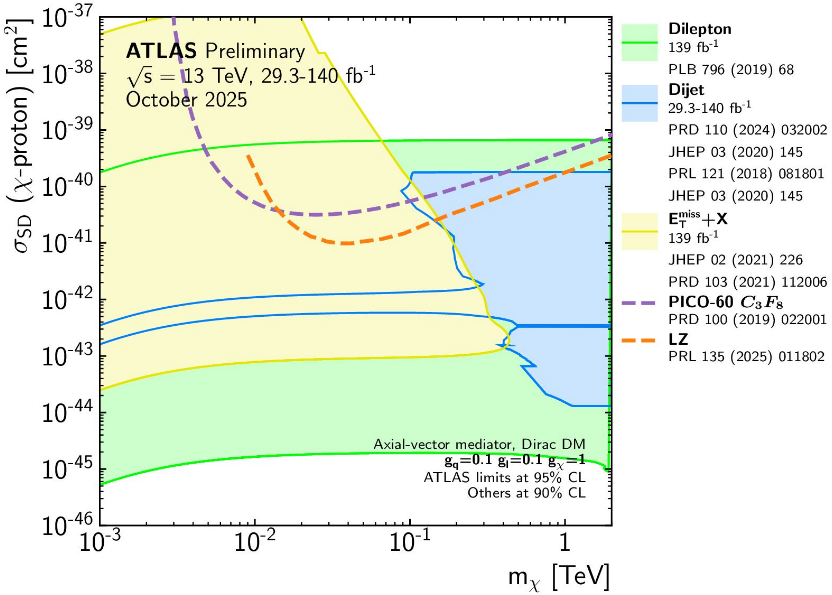
ATL-PHYS-PUB-2025-038



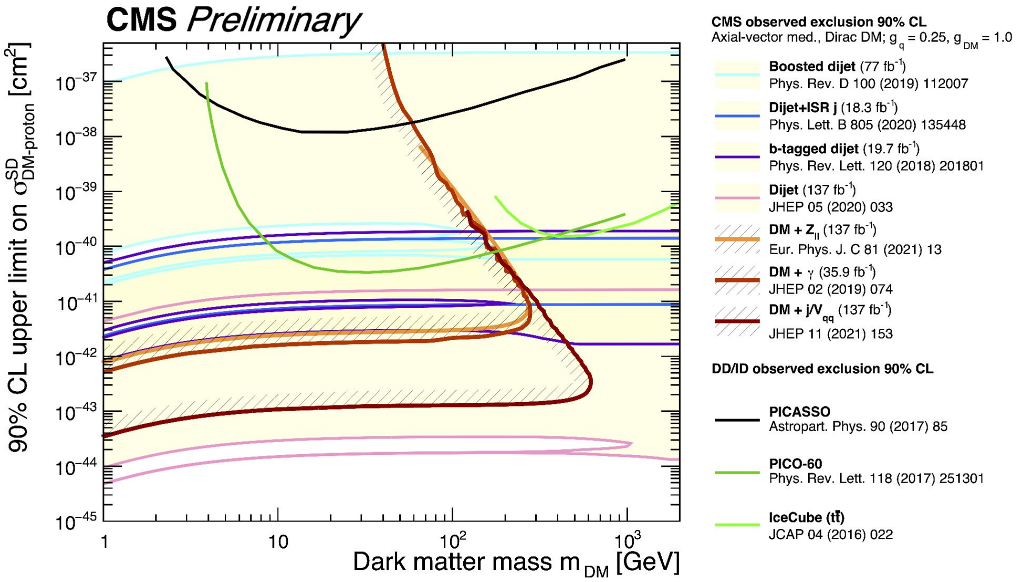
CMS Exotica Public Plots

Dark Matter: Spin-Dependent

- Collider experiments set powerful constraints on axial-vector dark matter interactions

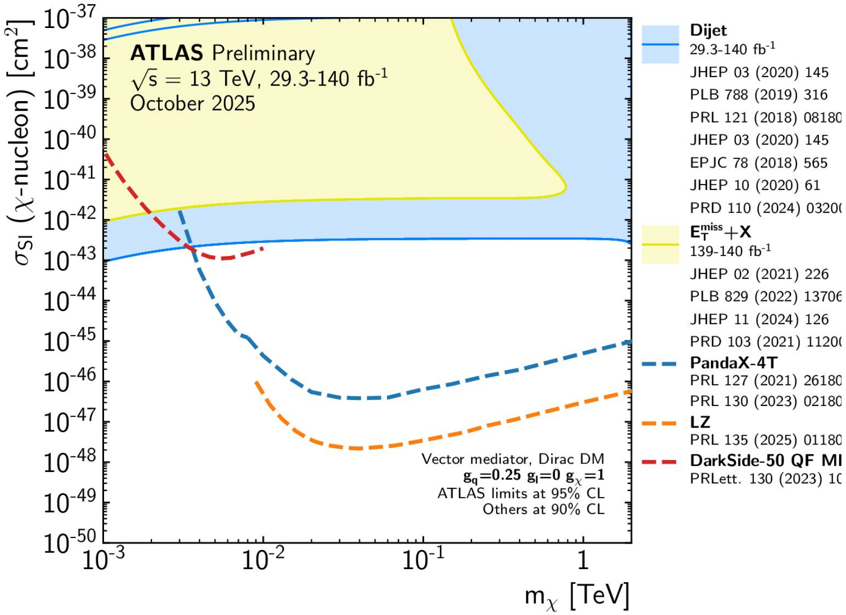


[ATL-PHYS-PUB-2024-041]



[CMS Exotica Public Plots]

Dark Matter: Spin-Independent



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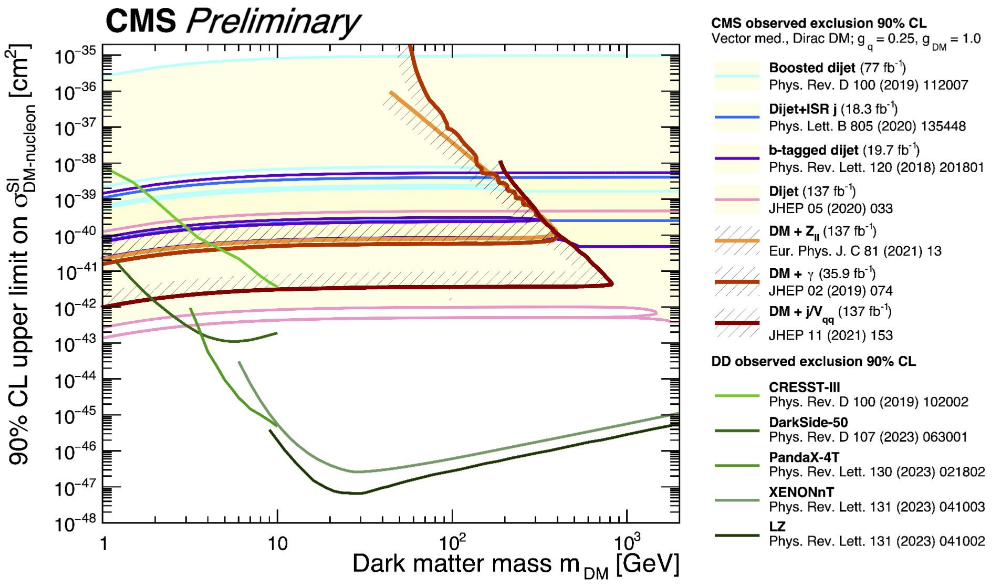
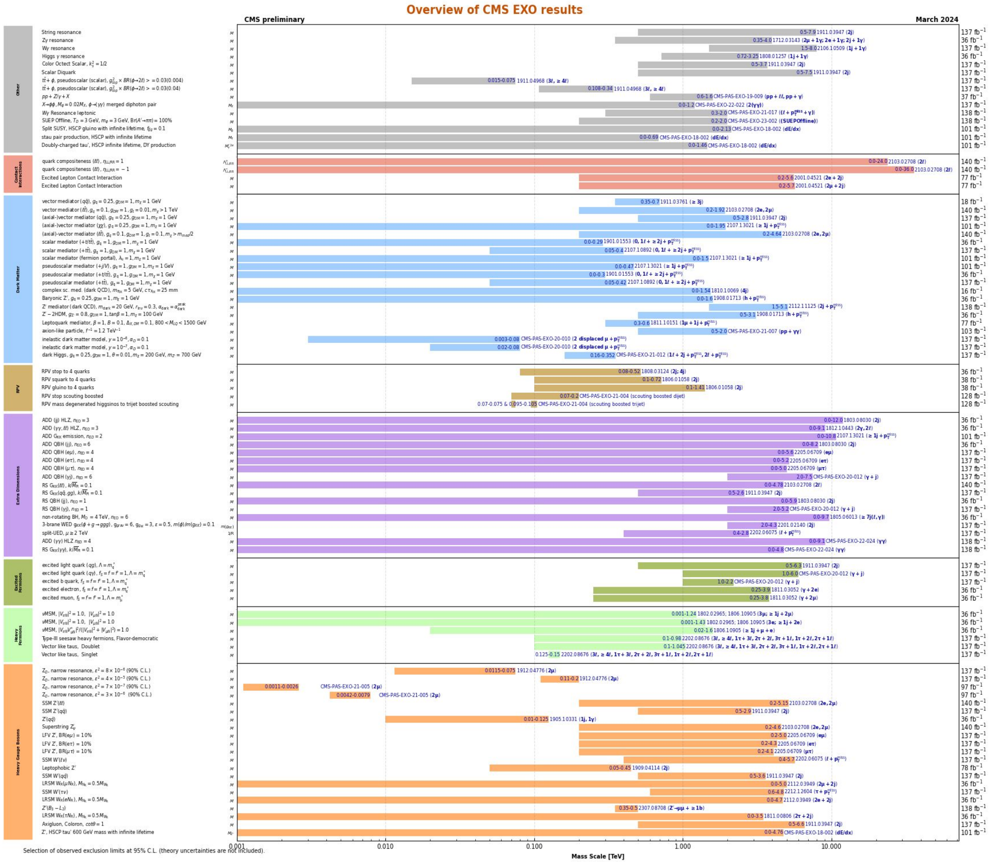


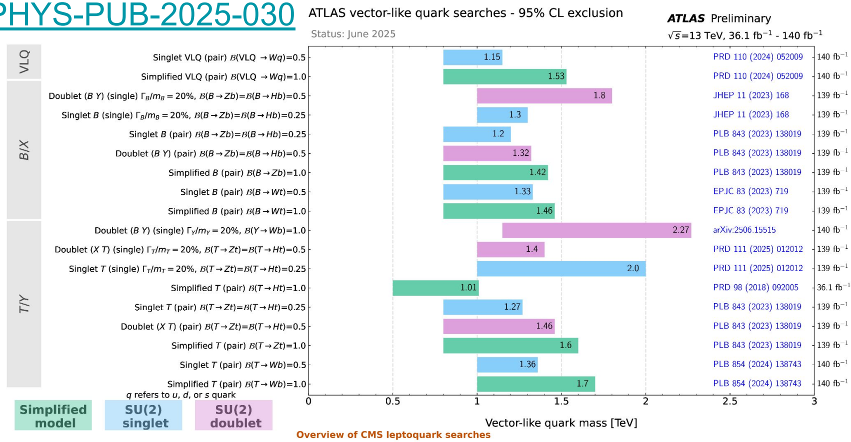
[CMS Exotica Public Plots]

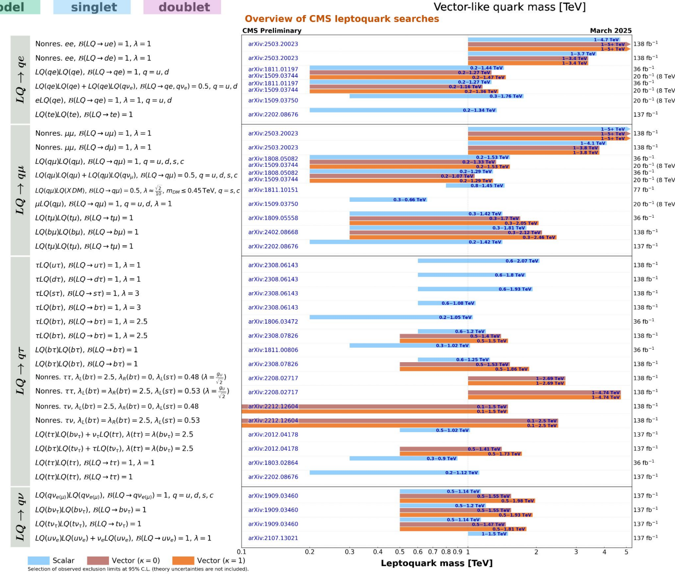
And more…

[CMS Exotica Public Plots](#)

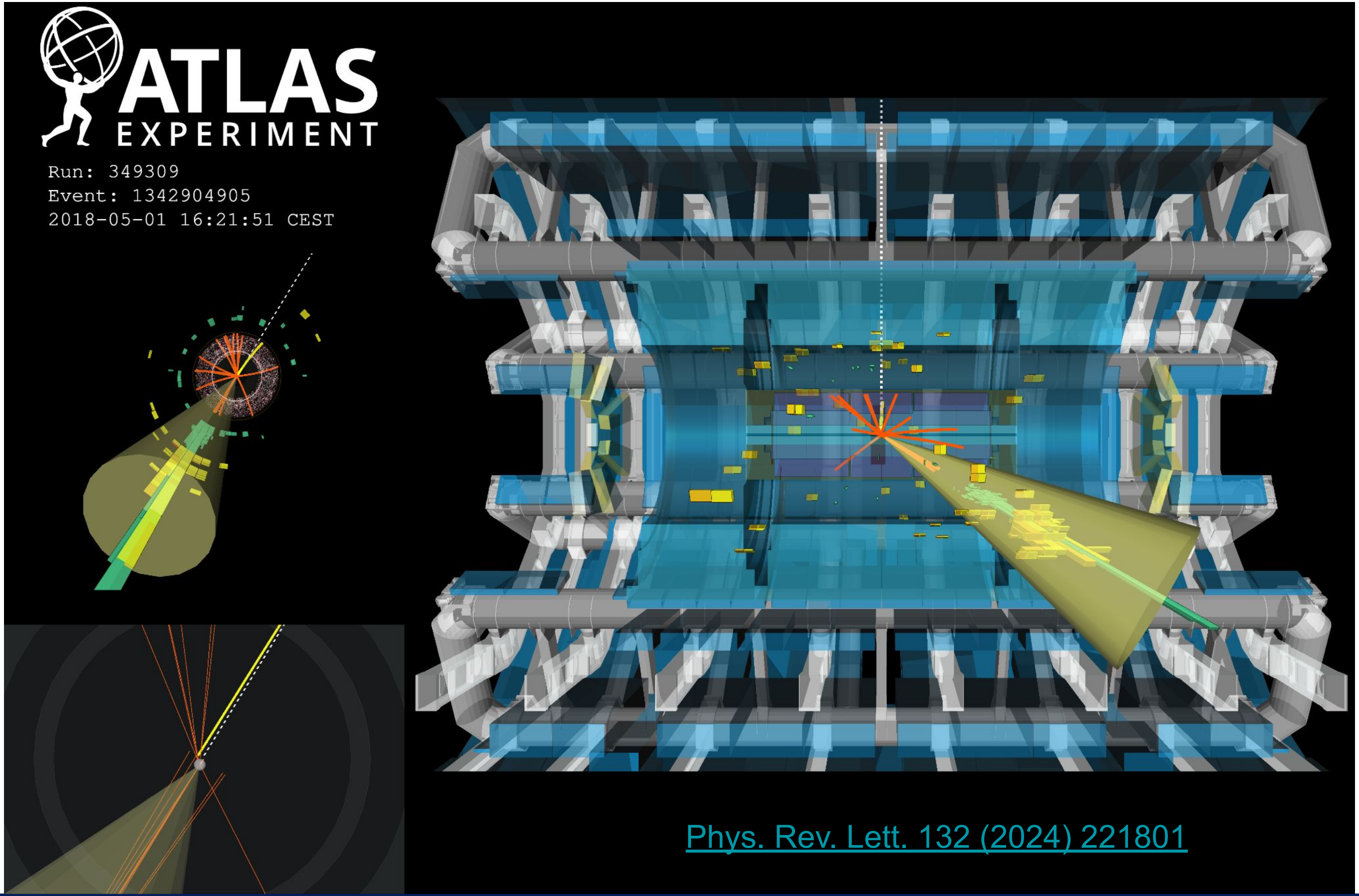


[ATL-PHYS-PUB-2025-030](#)





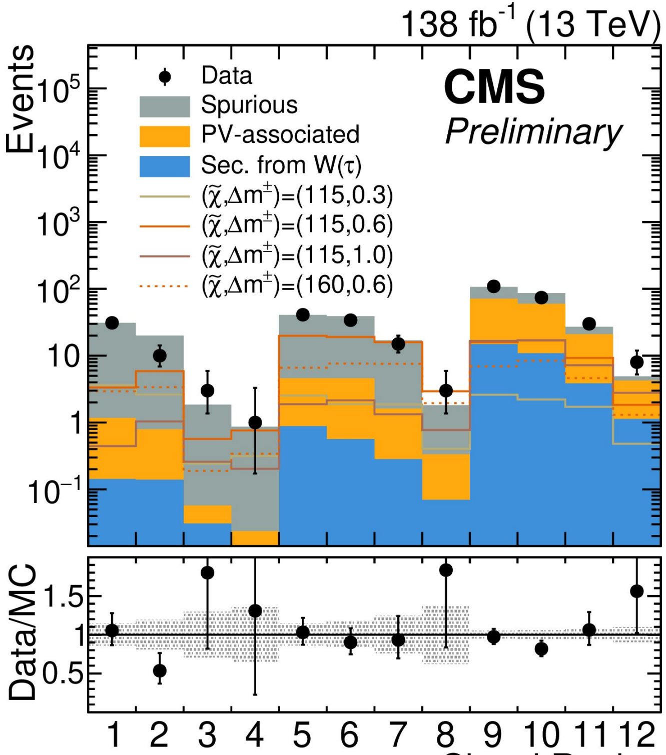
Compressed EWK SUSY: Displaced Track Event Display



Phys. Rev. Lett. 132 (2024) 221801

Compressed EWK SUSY: CMS Displaced Track

- Look for "mildly displaced, low-momentum" pions
- CMS trains a parameterized Neural Network (pNN) to distinguish signal vs. background tracks
  - Parameterized in terms of Δm=0.3,0.6,1.0
- Orthogonal SRs constructed by sorting events based on Δm for max-scoring track, split into 4 bins each
- Primary backgrounds are $Z \rightarrow \nu\nu$, $W \rightarrow l\nu$



SUS-24-012

Compressed EWK SUSY: CMS Soft Leptons

- 2/3 lepton search
  - p_T>1 GeV (3.5 GeV) for electrons (muons)
    - Dedicated algorithm for 1-3 GeV electrons
  - Select events using m_{ll}, p_T^{miss}, other kinematics
  - Dominant background W+jets, ttbar with fake leptons from data-driven techniques
- 1 lepton + 1 track search
  - p_T>5 GeV (2 GeV) for electrons (muons), tracks >1.9 GeV
  - Uses BDTs to distinguish S vs. B

CMS Displaced Track Training Variables

- CMS PNN variables

SUS-24-012

Variable	Description
$\Delta m^{\pm}$	Model mass splitting.
p_{T}	Transverse momentum of the track.
$\|\eta\|$	Pseudorapidity of the track.
$\|\Delta\varphi(\text{Track}, \vec{p}_{\mathrm{T}}^{\text{miss}})\|$	Azimuthal angle between the track and the $p_{\mathrm{T}}^{\text{miss}}$ vector.
$\|\Delta\varphi(\text{Track, Leading Jet})\|$, $\|\Delta\eta(\text{Track, Leading Jet})\|$	Azimuthal angle and distance in pseudorapidity between the track and the leading jet.
$\log_{10}(\text{dxy})$, $\log_{10}(\text{dz})$	Transverse and longitudinal impact parameters (standard straight line approximation) with respect to (a) the leading primary vertex and (b) the closest primary vertex from pileup interactions.
$\log_{10}(\text{dxy}^{\text{Error}})$, $\log_{10}(\text{dz}^{\text{Error}})$	Error on the transverse and longitudinal impact parameters (standard straight line approximation).
$\log_{10}(\text{IPxy})$, $\log_{10}(\text{IPz})$, $\log_{10}(\text{IPxy Significance})$, $\log_{10}(\text{IPz Significance})$	Transverse and longitudinal impact parameters and impact parameter significances (custom helix extrapolation) with respect to (a) the leading primary vertex, (b) the closest primary vertex from pileup interactions, (c) the primary vertex associated to the track during reconstruction, and (d) the closest primary vertex excluding the associated vertex.
$\Delta\text{xy}(\text{PV, ass. PV})$, $\Delta\text{z}(\text{PV, ass. PV})$	Distance in the transverse plane and along the z-axis between the leading primary vertex and the primary vertex associated to the track (if assigned).
$\Delta\text{xy}(\text{PV, ass. SV})$, $\Delta\text{z}(\text{PV, ass. SV})$	Distance in the transverse plane and along the z-axis between the leading primary vertex and the secondary vertex associated to the track (if assigned).
Abs. Iso PF	Sum of transverse momenta of PF candidates within a cone of $\Delta R < 0.3$ around the track.
ΔR_{min}	Distances to the (a) closest jet with $p_{\mathrm{T}} > 30\,\text{GeV}$, (b) closest jet with $p_{\mathrm{T}} > 15\,\text{GeV}$, (c) closest track with $p_{\mathrm{T}} > 5\,\text{GeV}$, and (d) second closest track with $p_{\mathrm{T}} > 5\,\text{GeV}$.
$p_{\mathrm{T}}^{\text{miss}}$	Event-level magnitude of $p_{\mathrm{T}}^{\text{miss}}$.

CMS 1L1T Training Variables

- CMS BDT variables

SUS-24-012

Rank	Variable
1	$\Delta R\,(t,\ell)$
2	$\|\Delta\eta\,(t,\ell)\|$
3	$p_{\mathrm{T}}(\ell)$
4	$\|\Delta\phi\,(t,\text{hard }\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\|$
5	$\|\Delta\eta\,(t,j_1)\|$
6	$\|\Delta\phi\,(t,\ell)\|$
7	$\|\eta\,(t)\|$
8	$\|\eta\,(\ell)\|$
9	$\Delta R\,(\ell,j_1)$
10	$m_{t\ell}$

ATLAS Emerging Jet Training Variables

Rep. Prog. Phys. 88 (2025) 097801

- Training variables for ATLAS emerging jet transformer

Input	Description
Jet η	Jet pseudorapidity
d_0	Track closest distance to PV in transverse plane
$z_0 \sin(\theta)$	Track closest distance to PV in longitudinal plane
$\Delta\phi$	Azimuthal angle of the track, relative to the jet ϕ
$\Delta\eta$	Track pseudorapidity, relative to jet η
q/p	Track charge over momentum
$\sigma(\phi)$	Uncertainty in track ϕ
$\sigma(\theta)$	Uncertainty in track θ
$\sigma(q/p)$	Uncertainty in track q/p
$d_0/\sigma(d_0)$	signed d_0 significance
$z_0/\sigma(z_0)$	signed z_0 significance
$N_{\text{PIX hits}}$	Number of Pixel hits per track
$N_{\text{SCT hits}}$	Number of SCT hits per track
$N_{\text{IBL hits}}$	Number of innermost pixel layer hits
$N_{\text{PIX shared}}$	Number of Pixel shared hits
$N_{\text{SCT shared}}$	Number of SCT shared hits

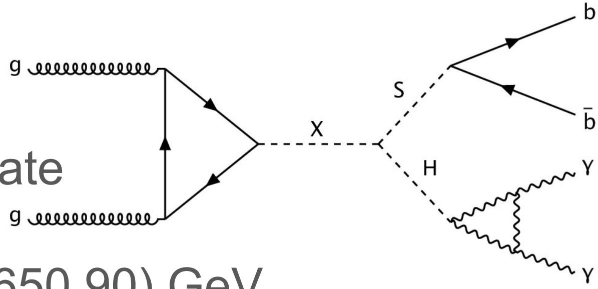
CMS Emerging Jet Training Variables

- Displaced tagger
  - d_{xy}/σ_{xy}
  - d_{xyz}/σ_{xyz}
  - Distance from the PV to the crossing point of the track helix
  - Dijet direction in the transverse plane
  - Whether the track is associated with the jet with a larger p_T
  - Ratio between the track energy and the energy sum of the tracks associated with the dijet
  - Vertex invariant mass and p_T
  - Vertex track multiplicity
  - Transverse decay length significance
  - χ^2/dof of the vertex fit
  - The angles between the vertex momentum vector
  - The direction from the PV to DV
  - The dijet candidate momentum direction
  - Track-to-DV association
  - d_{xyz} and d_{xyz}/σ_{xyz} between the track and the DV
  - Angle between the track direction and the direction of the DV displacement from the PV

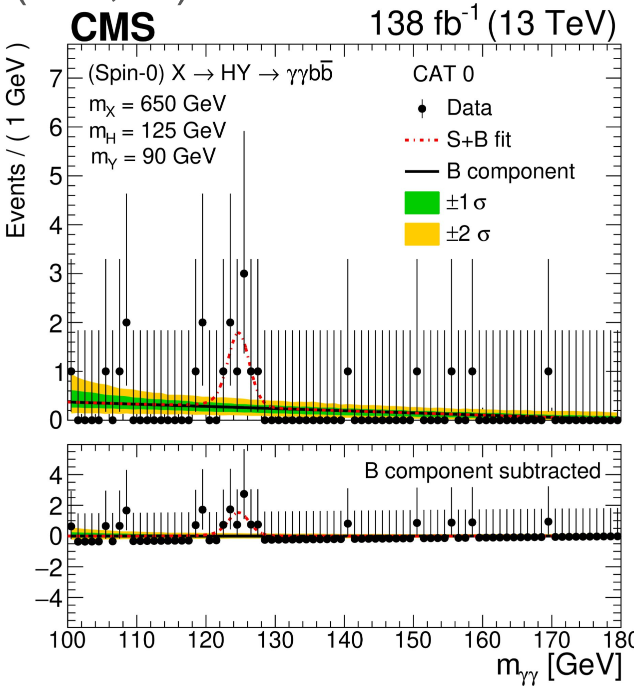
- Prompt-veto tagger
  - d_{xy} and d_{xy}/σ_{xy}
  - Track-to-PV associations for the leading PV and pileup vertices
  - Track-to-jet associations
  - Ratio between the track energy and the total energy of the dijet candidate
  - Whether the two tracks are associated with the same PV

Rep. Prog. Phys. 88 (2025) 037801

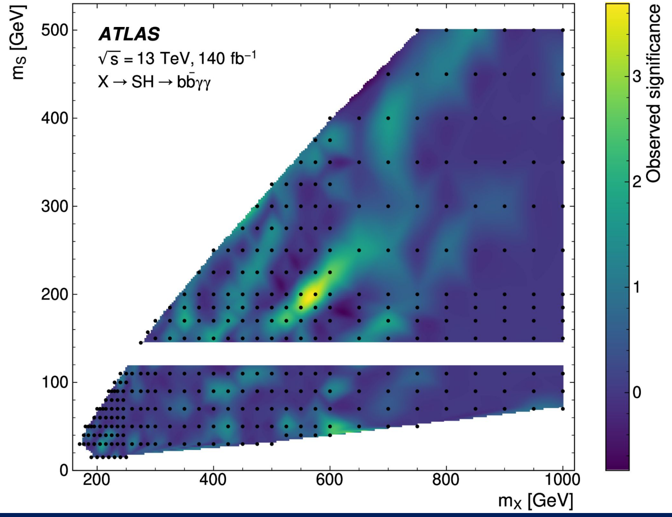
X→SH→bb$\gamma\gamma$ (ATLAS [1] and CMS [2])



- Search for two extra scalars X and S/Y in bb$\gamma\gamma$ final state
  - Can occur in NMSSM, 2HDM extensions
- CMS sees 3.8σ (<2.8σ global) excess at (m_X, $m_{S/Y}$)= (650,90) GeV
  - Global significance is upper bound
  - CMS does not see this excess in bb$\tau\tau$ [3], $\gamma\gamma\tau\tau$ [4][1]



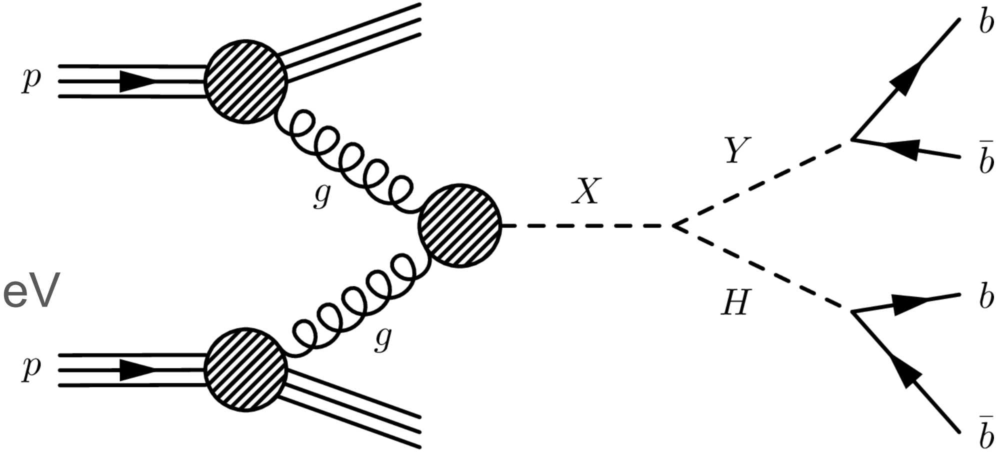
- ATLAS instead sees 3.5σ (2.0σ global) excess at (575, 200) GeV

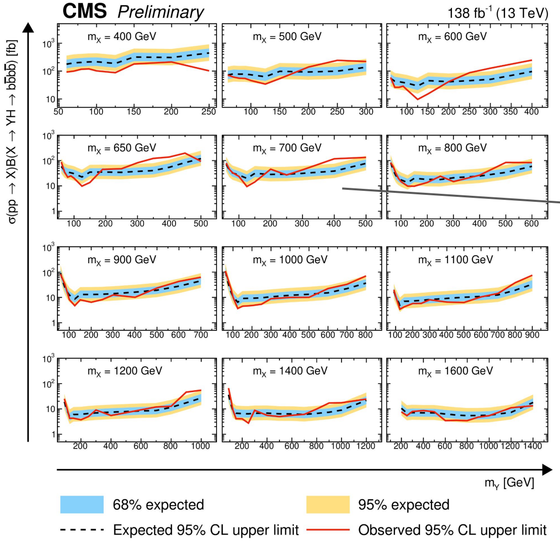


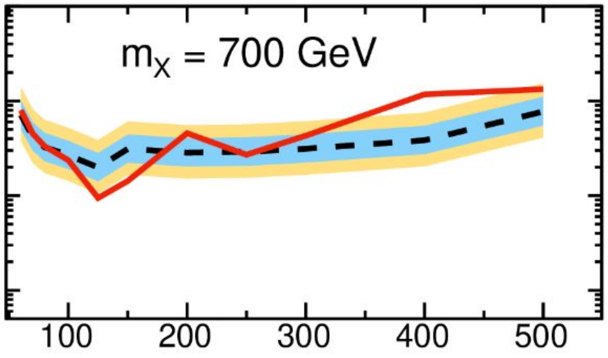
[1] $\gamma\gamma\tau\tau$ does see some different excesses

X→SH→4b (CMS) [5]

- Same model as previous slide
- Looking at 4b final state
- Excess at (m_X, $m_{S/Y}$)= (700,400) GeV
  - 4.1**σ** (2.8**σ** global)







CMS Y(γγ)H(bb) Training Variables

- Variables for PNN training

Category	Variables
Photon-related	$p_\mathrm{T}(\gamma\gamma)/m_{\gamma\gamma}$, $p_\mathrm{T}(\gamma_1)/m_{\gamma\gamma}$, $p_\mathrm{T}(\gamma_2)/m_{\gamma\gamma}$, $\Delta R(\gamma\gamma)$, $\Delta\eta(\gamma\gamma)$
Jet-related	$p_\mathrm{T}(j_1)$, $p_\mathrm{T}(jj)$, $m(jj)$, $\Delta R(jj)$, $m(j_1)$, b tagging score(j_1), b tagging score(j_2), $\Delta R(\gamma_1, j_1)$, $\Delta R(\gamma_1, j_2)$, $\Delta R(\gamma_2, j_1)$, $\Delta R(\gamma_2, j_2)$
Photon-jet combinations	$\Delta R(\gamma_1, jj)$, $\Delta R(\gamma_2, jj)$, $\Delta R(\gamma\gamma, j_1)$, $\Delta R(\gamma\gamma, j_2)$, $\Delta R(\gamma\gamma, jj)$, $\Delta\eta(\gamma\gamma, jj)$, $\Delta\eta(\gamma\gamma, j_1)$, $\Delta\eta(\gamma_1, j_2)$, $\Delta\phi(\gamma\gamma, jj)$, $\Delta\phi(\gamma\gamma, j_1)$, $\Delta\phi(\gamma\gamma, j_2)$

arXiv:2508.11494

CMS Y(bb)H(bb) Training Variables

- Variables for BDT background reweighting
  - p_T of four b-jet candidates
  - p_T and η of H and Y candidates
  - Angular separation ΔR between the two jets that form the reconstructed H candidate
  - ΔR between the two jets that form the reconstructed Y candidate
  - Orthogonal distance of the event from the diagonal defined by $m_{Xreco} - m_{Yreco} = 125$ GeV

HIG-20-012

ATLAS Y(bb)H(γγ) Training Variables

- Most powerful variables for PNN training are:
  - Invariant masses of photon/b-jet combinations
  - p_T of b-jets

arxiv:2510.02857