Search for pair production of higgsinos in events with two Higgs bosons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions at the ATLAS experiment

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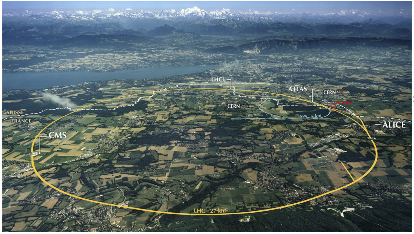
Outline

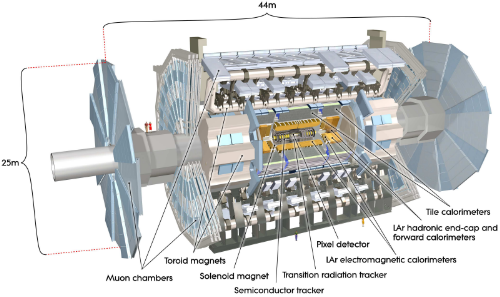
1. Introduction
2. Low-mass Channel
3. High-mass Channel
4. Results

Full paper available at arXiv:2401.14922

The Large Hadron Collider and ATLAS

- The Large Hadron Colldier (LHC) is the world's largest particle accelerator
  - 13 TeV collision energy[1], ≈1 billion proton-proton collisions/second
- ATLAS is a general purpose particle detector



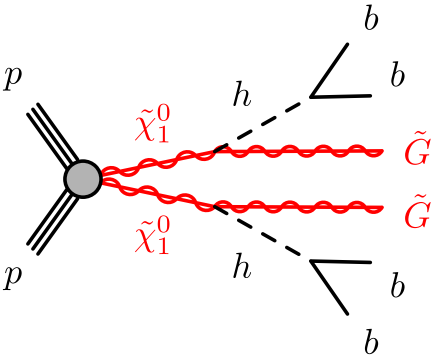


Left: The LHC. Image credit: Maximilien Brice, CERN. Right: The ATLAS detector (JINST 3 (2008) S08003).

[1] 13.6 TeV in Run 3

Signal Model

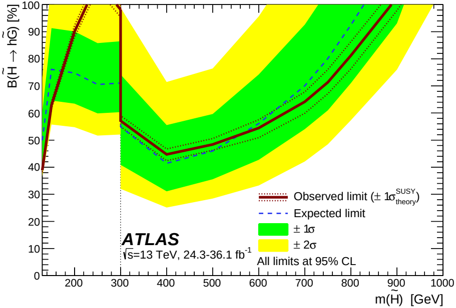
- Look for supersymmetric (SUSY) model
  - Lightest SUSY particle (LSP) is nearly massless gravitino
- Target higgsino-dominated neutralino as next-to-lightest SUSY particle
- Most common predicted decays are $\tilde{\chi}_1^0 \rightarrow h\tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$
  - Target the Higgs decay channel
- $\mathcal{B}(h \rightarrow b\bar{b})$≈58%
  - Look for $hh \rightarrow b\bar{b}b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$



SUSY signal model.

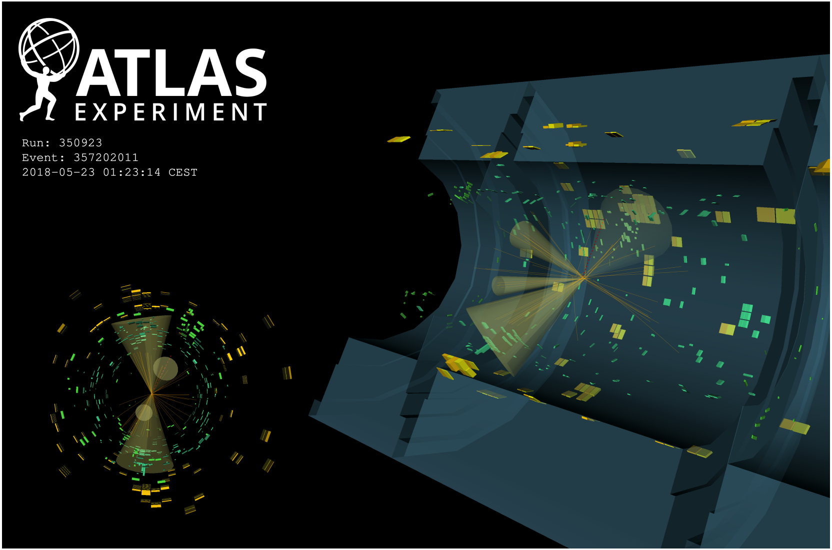
Motivation

- Previous results use 2015-2016 data
  - Small excess at 275 GeV
- Natural SUSY favors light higgsinos
  - Worth investigating excess with more data
  - We now have roughly 5x the data



Exclusion limits on higgsino pair production using 2015-2016 data. Figure from [2].

Low-mass Channel



Candidate event with $E_{\mathrm{T}}^{\mathrm{miss}} = 14.0$ GeV

Trigger Strategy and Event Selection

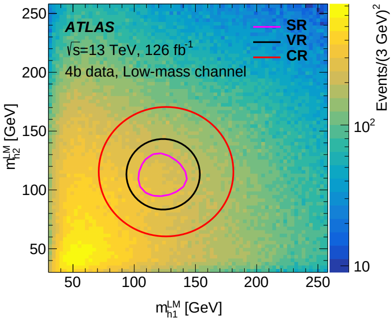
- For low higgsino masses, gravitinos not energetic enough for $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - Using triggers targeting 2 b-jets (p_{T} threshold 35-55 GeV)

- Reduce $t\bar{t}$ by vetoing events with leptons or
  $$X_{Wt} = \sqrt{\left(\frac{m_{jj} - m_W}{0.1 \cdot m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 \cdot m_{jjb}}\right)^2} < 1.8$$

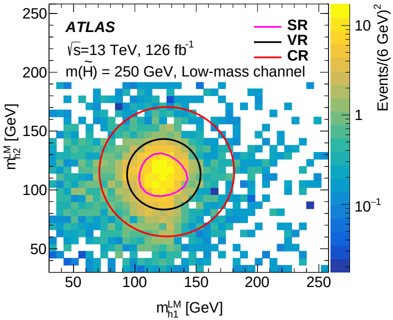
- Reconstruct Higgs bosons from b-jets
  - If < 4 b-jets, use random untagged jets

Region Definitions

- Regions defined using the masses of the reconstructed Higgs bosons
- Signal: $\sqrt{(\frac{m_{h1}-120}{0.1 m_{h1}})^2 + (\frac{m_{h2}-110}{0.1 m_{h2}})^2} < 1.6$



(a) $4b$ data



(b) 250 GeV Signal

Region Definitions

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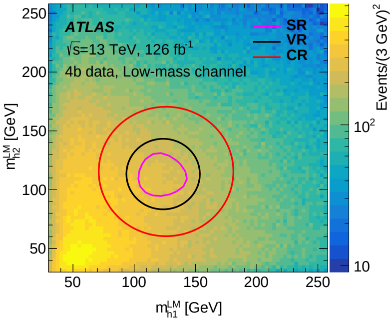
- Validation: $\sqrt{(m_{h1} - 120 * 1.03)^2 + (m_{h2} - 110 * 1.03)^2} < 30$ GeV



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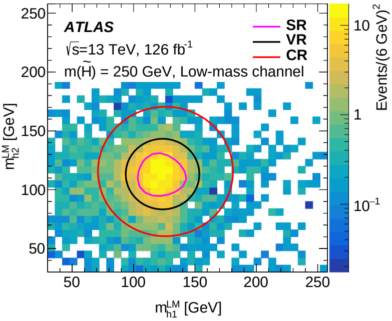

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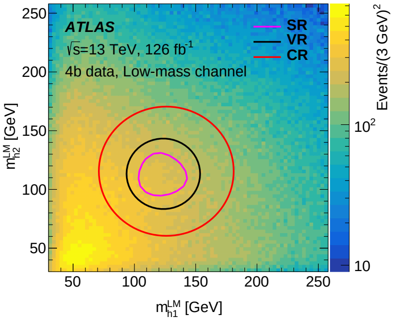

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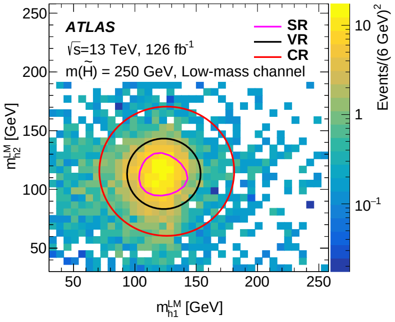

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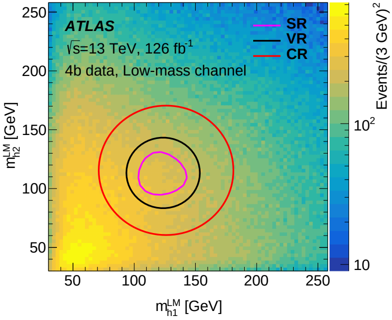
- Control: $\sqrt{(m_{h1} - 120 * 1.05)^2 + (m_{h2} - 110 * 1.05)^2} < 55$ GeV
- Each is split into a 2b sample (=2 b-jets) and a 4b ($\geq$4 b-jets) sample



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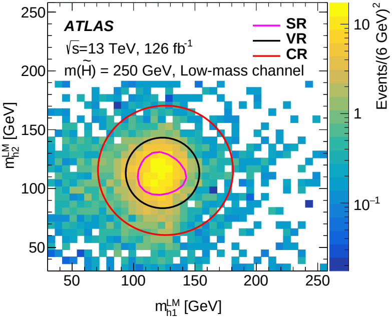

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Background Estimate

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  - Poorly modeled by MC, so use a data-driven method

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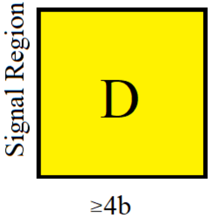

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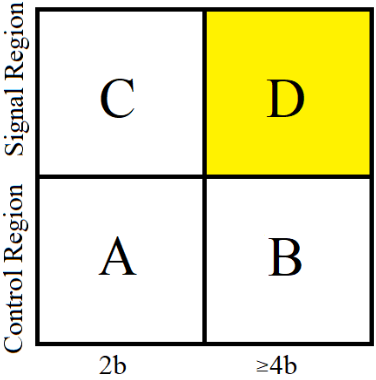
- In each region, make 2b and $\geq$4b sample
  - 2b has low signal contamination
  - Similar backgrounds to 4b



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- In each region, make 2b and $\geq$4b sample
  - 2b has low signal contamination
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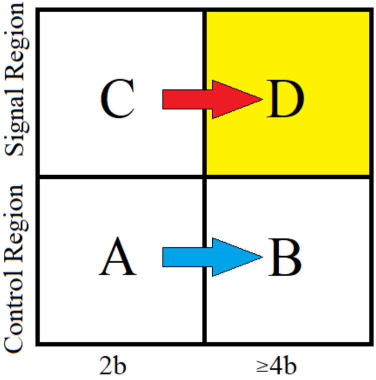
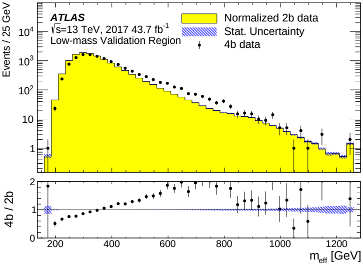
- Transfer factor $\mu_{\text{CR}} = \frac{N_{4b}^{\text{CR}}}{N_{2b}^{\text{CR}}}$ (=B/A)
- $N_{4b,bkg}^{\text{SR}} = \mu_{\text{CR}} N_{2b}^{\text{SR}}$ (D=CB/A)



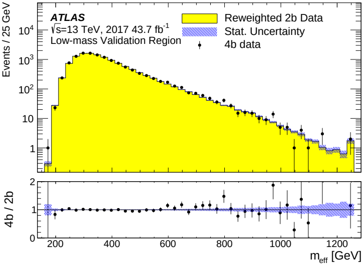
Boosted Decision Tree Reweighting

- Baseline ABCD method only gives us event counts, not distributions
- We bin our data in $E_{\mathrm{T}}^{\mathrm{miss}}$ and $m_{\mathrm{eff}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{i=1}^{4} p_{\mathrm{T}}(\mathrm{jet}_i)$
- Train a Boosted Decision Tree (BDT) to reweight kinematics
  - Train using 2b/4b CRs
  - Apply to 2b SR



(a) Before reweighting

BDT →

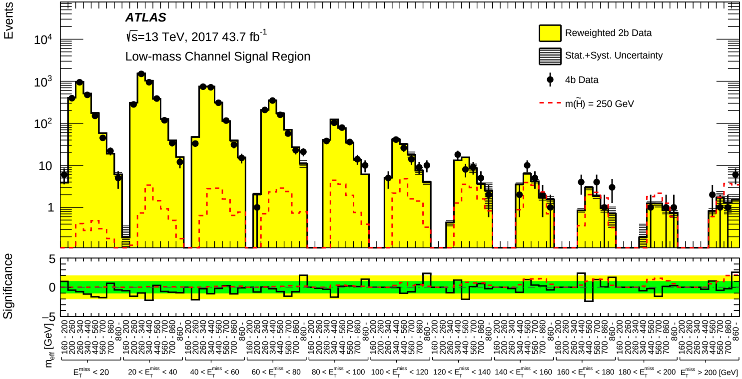


(b) After reweighting

Comparison of 2017 data in the VR.

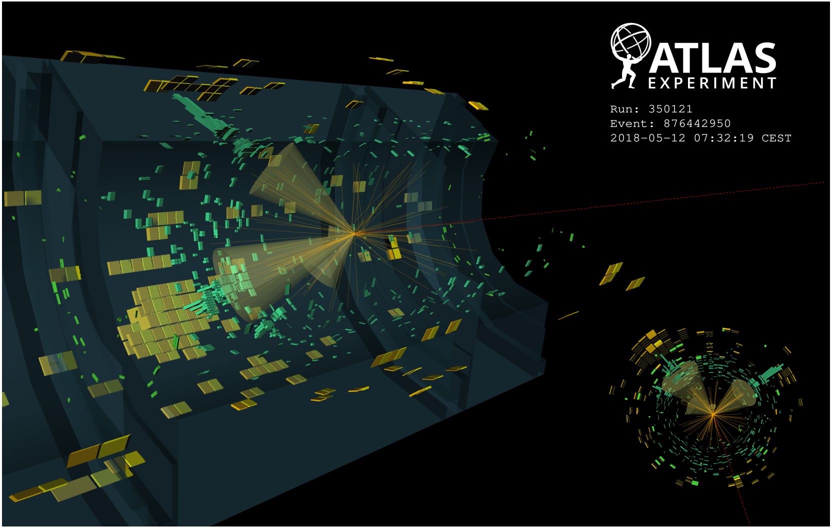
Signal Region Yields

- Largest deviation in final ($E_T^{\text{miss}} > 200$ GeV, $m_{\text{eff}} > 860$ GeV) 2017 bin
  - 6 observed vs. 1.51±0.35 predicted events (2.6σ local)
- Large number of bins means deviations expected; VR modeling shows good agreement



Yields in the 2017 signal region for the low-mass channel.

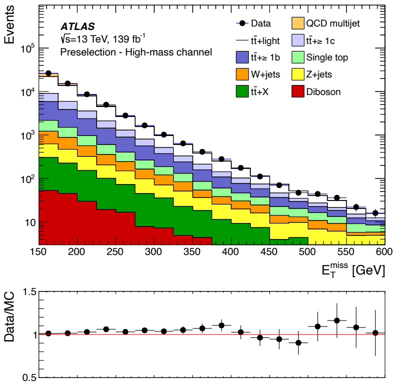
High-mass Channel



Candidate event with $E_{\mathrm{T}}^{\mathrm{miss}} = 550.3$ GeV

Trigger Strategy and Event Selection

- Select events using the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
- Require
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV[1]
  - ≥ 3 b-jets, 4-7 total jets
  - $\Delta\phi_{\mathrm{min}}^{4j} > 0.4$
  - Veto leptons
- Train a BDT to distinguish signal from background
  - Parameterize with truth higgsino mass
  - Input variables: N_{jets}, $N_{b\text{-jets}}$, H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance, $m_{\mathrm{T,min}}^{b\text{-jets}}$, M_J^{Σ}, $m(h_1)$, $m(h_2)$, $\Delta R(h_1)$, $\Delta R(h_2)$, $\Delta R_{\mathrm{min}}^{bb}$



Preselection $E_{\mathrm{T}}^{\mathrm{miss}}$

[1] Built with track-based soft term

Region Definitions

- Signal, Validation, and Control Regions defined using BDT scores
  - Split using $N_{b\text{-jets}}$, $m_{\mathrm{T,min}}^{b\text{-jets}}$ to handle different backgrounds
  - Nb: Separate for each mass point: SR_1_M means SR_1 for M GeV higgsino
- Use CRs to normalize $t\bar{t}$, single top, and Z+jets[2] background Monte Carlo

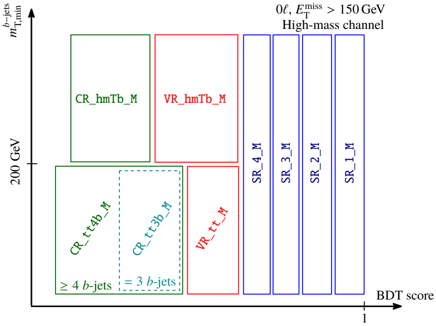
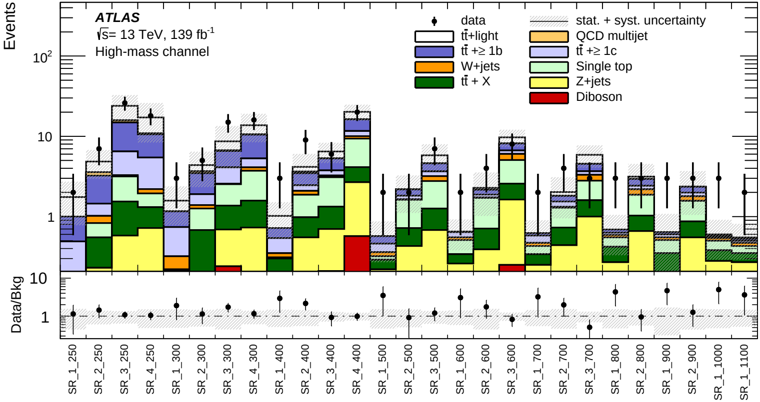


Diagram of high-mass regions.

[2] Special regions used to model $Z \to \nu\nu$ using $Z \to \mu\mu$

Signal Region Yields

- Largest excess is 1.9σ (local) in SR_1_1000
  - Excesses in SR_1_900, SR_1_1000, and SR_1_1100 highly correlated

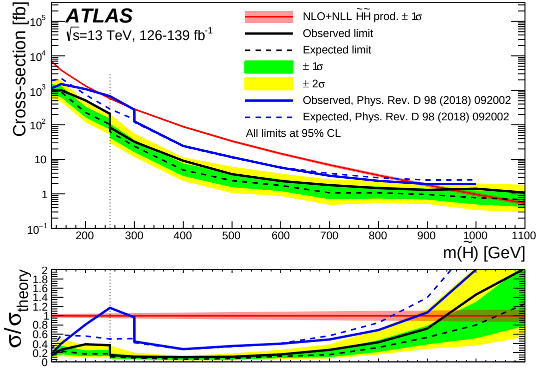


Yields in the signal regions for the high-mass channel

Results

Exclusion Limits

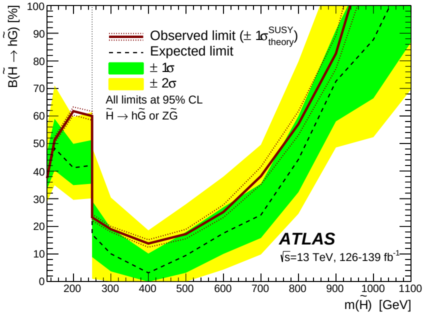
- Use low-mass channel below 250 GeV, high-mass above
- Exclude up to 940 GeV (≈ 1040 GeV expected)
    - Most sensitive analysis to-date
    - Most stringent constraints from 130-800 GeV

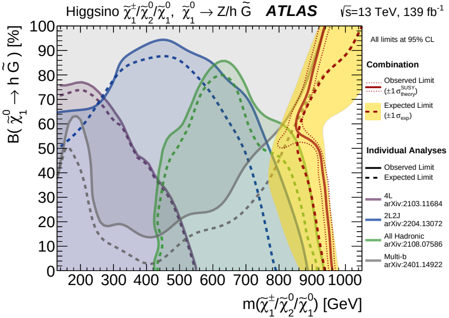


Limits for $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$=100%

Branching Ratio Limits

- Relax assumption on $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$=100%
  - Allow for Higgs or Z decays
  - Assume theory cross section
- Combine with other analyses to achieve strong exclusion across the BR plane





Left: Limits on $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$. Right: EWK Combination results [3].

Conclusion

- Presented a search for higgsinos decaying to Higgs bosons and gravitinos
- Used two complementary channels to target low and high higgsino masses
- Improved significantly over previous analyses, placing strong constraints on the SUSY model

Thank you for listening!

arXiv:2401.14922

References

1. ATLAS Collaboration, "Search for pair production of higgsinos in events with two Higgs bosons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions at the ATLAS experiment," submitted to PRD, [arXiv:2401.14922 [hep-ex]].
2. ATLAS Collaboration, "Search for pair production of higgsinos in final states with at least three b-tagged jets in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector," Phys. Rev. D **98**, no.9, 092002 (2018) doi:10.1103/PhysRevD.98.092002 [arXiv:1806.04030 [hep-ex]].
3. ATLAS Collaboration, "A statistical combination of ATLAS Run 2 searches for charginos and neutralinos at the LHC," submitted to PRL, [arXiv:2402.08347 [hep-ex]].
4. CMS Collaboration, "Search for higgsinos decaying to two Higgs bosons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV," JHEP **05** 014 (2022) doi:10.1007/JHEP05(2022)014 [arxiv:2201.04206 [hep-ex]].

Backup

The Triumph of the Standard Model

- The Standard Model (SM) provides an excellent description of many phenomena
  - 17 particles (+anti-particles)
  - 3 fundamental forces (excluding gravity)
- Withstood numerous tests
- Astonishing accuracy

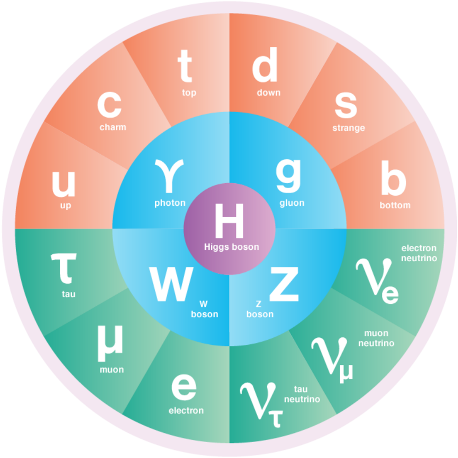


Image credit: Symmetry Magazine.

Breaking the Standard Model

- However, the SM suffers from several problems
  - Requires **fine-tuning** to explain the Higgs boson mass (hierarchy problem)
  - Does **not** account for dark matter nor dark energy
  - Does **not** explain dominance of matter over antimatter (baryon asymmetry)
  - Does **not** explain neutrino masses

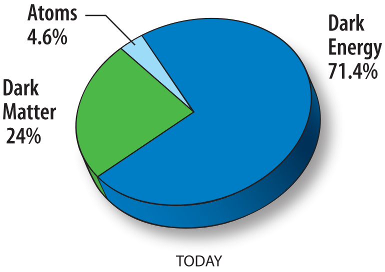
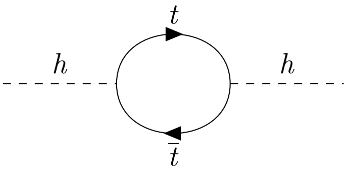


Image credit: NASA/WMAP Science Team.

The Hierarchy Problem

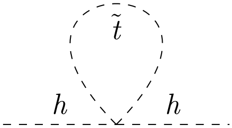
- Observed Higgs mass is 125 GeV $= m_{\text{h}} \approx m_{\text{bare}} + m_{\text{correc}}$
- Fermions (in particular top quark) contribute to m_{correc}
- $\Delta m_{\text{fromtop}} = O(\Lambda_{\text{cutoff}}) \approx 10^{19}$ GeV
- To get observed 125 GeV, need suspiciously neat cancellation
  - In principle, m_{bare} should be free parameter



Higgs self-energy top quark loop.

Supersymmetry

- Theory of supersymmetry (SUSY) can solve this
- Introduce a bosonic partner for every fermion (and vice versa)
- Corrections similar in magnitude but opposite sign
- $\Delta m_{\text{toploop}} + \Delta m_{\text{stoploop}} \approx 0$



Higgs self-energy stop quark loop.

- Similar considerations require other SUSY particles
- Bonus: Lightest supersymmetric particle (LSP) could be dark matter!

SUSY and the Higgs boson

- SUSY requires separate Higgs doublets for up-type, down-type quarks
- 3 degrees of freedom provide masses for $W^{\pm}$, Z
  - 5 Higgs bosons: h, H, A, H^{+}, and H^{-}
  - Superpartners of Higgs called "higgsinos"
- Higgsinos mix with binos and winos
  - 4 neutralinos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$
  - 2 charginos: $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$

Higgsino Mass Scales

- To obtain the correct Higgs vacuum expectation values, need

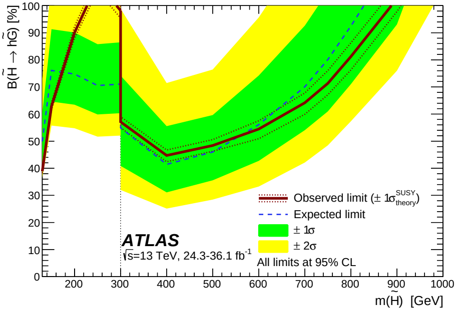
$$\frac{m_Z^2}{2} \approx -\mu^2 - m_{H_u}^2 - \text{loop corrections}$$

where μ is the higgsino mass term and m_{H_u} is SUSY-breaking term

- $m_Z = 91.2$ GeV
- For this cancellation to be natural, terms must be of the order of m_Z
  - Higgsinos predicted to be relatively light

Prior Results

- Previous results use 2015-2016 data
  - Small excess at 275 GeV
- Split into two channels
  - **Low-mass** and **high-mass**
- We made many improvements, including:
  - Roughly 5 times the stats (2015-2018)
  - Improved jet reconstruction and b-tagging
  - Implementing a BDT for the high-mass channel
  - Significant reoptimization



Exclusion limits on higgsino pair production using 2015-2016 data. Figure from [2].

Glossary

- Jets are streams of particles from hadronization of quarks and gluons
- b-jets are jets tagged as containing bottom quarks
  - Optimal working point for this analysis has 77% efficiency
- $E_{\mathrm{T}}^{\mathrm{miss}}$ is the negative vector sum of all objects' p_{T} with a track-based soft term
  - "Missing energy" of the event
- m_{eff} is the $E_{\mathrm{T}}^{\mathrm{miss}}$ plus the sum of p_{T} of jets from Higgs boson decays

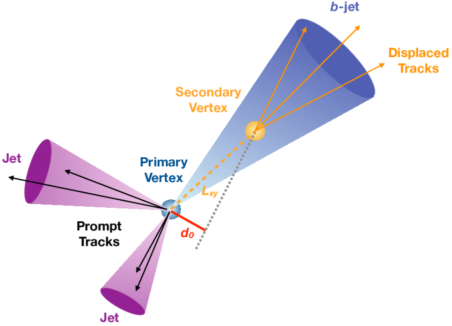


Image credit: 2106.03584

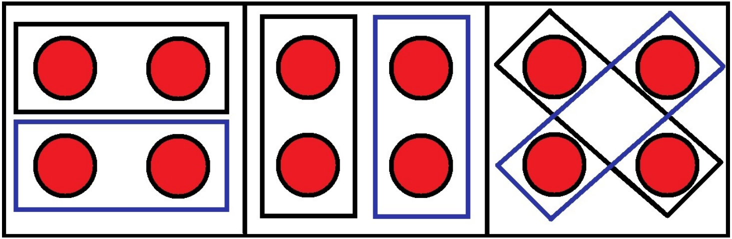
Low-mass Trigger Strategy

- Need to decorrelate scale factors for each trigger
- Create orthogonal offline selections:
  1. If leading jet p_{T} above threshold, use 2b1j trigger
  2. Else, if H_{T} above threshold, use 2bH_{T} trigger
  3. Else, use 2b2j trigger

Category	Year	Online selections	Offline selections
Low-mass channel			
$2b1$j	2016	1 jet ($p_{\mathrm{T}} > 100$ GeV), 2 b-jets (60% b-jet efficiency, $p_{\mathrm{T}} > 55$ GeV)	$p_{\mathrm{T},j1} > 150$ GeV
	2017	1 jet ($p_{\mathrm{T}} > 150$ GeV), 2 b-jets (70% b-jet efficiency, $p_{\mathrm{T}} > 55$ GeV)	$p_{\mathrm{T},j1} > 350$ GeV
	2018		$p_{\mathrm{T},j1} > 500$ GeV
$2bH_{\mathrm{T}}$	2017	$H_{\mathrm{T}} > 300$ GeV, 2 b-jets (50% b-jet efficiency, $p_{\mathrm{T}} > 55$ GeV)	$p_{\mathrm{T},j1} < 350$ GeV, $H_{\mathrm{T}} > 850$ GeV
	2018		$p_{\mathrm{T},j1} < 500$ GeV, $H_{\mathrm{T}} > 700$ GeV
$2b2$j	2016	2 jets ($p_{\mathrm{T}} > 35$ GeV), 2 b-jets (60% b-jet efficiency, $p_{\mathrm{T}} > 35$ GeV)	$p_{\mathrm{T},j1} < 150$ GeV
	2017	2 jets ($p_{\mathrm{T}} > 35$ GeV), 2 b-jets (40% b-jet efficiency, $p_{\mathrm{T}} > 35$ GeV)	$p_{\mathrm{T},j1} < 350$ GeV, $H_{\mathrm{T}} < 850$ GeV
	2018	2 jets ($p_{\mathrm{T}} > 35$ GeV), 2 b-jets (60% b-jet efficiency, $p_{\mathrm{T}} > 35$ GeV)	$p_{\mathrm{T},j1} < 500$ GeV, $H_{\mathrm{T}} < 700$ GeV
High-mass channel			
$E_{\mathrm{T}}^{\mathrm{miss}}$	2015	$E_{\mathrm{T}}^{\mathrm{miss}}(\mu$ inv.$) > 70$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
	2016	$E_{\mathrm{T}}^{\mathrm{miss}}(\mu$ inv.$) > 90$ GeV	
	2017	$E_{\mathrm{T}}^{\mathrm{miss}}(\mu$ inv.$) > 100$ GeV	
	2018	$E_{\mathrm{T}}^{\mathrm{miss}}(\mu$ inv.$) > 110$ GeV	

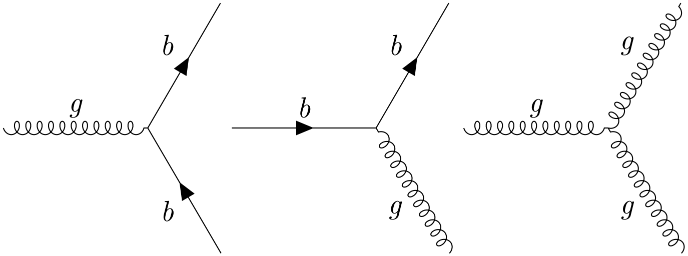
Low-mass Higgs Boson Reconstruction

- Each Higgs boson decays to 2 b-jets
  - Select 4 b-jets with highest p_{T}
  - If fewer than 4 exist, select remainder randomly
- 3 ways to pair 4 jets
  - Pair such that $\max(\Delta R_{jj}(h1), \Delta R_{jj}(h2))$ is minimized



Low-mass Background Estimation

- Background mainly QCD multijet
  - Large cross section
  - Large cross section theory uncertainty
- Avoid these problems by using a **purely data-driven** method called the ABCD method



Selected fundamental QCD multijet processes.

Low-mass Boosted Decision Tree Reweighting

- Baseline ABCD method only gives us event counts, not distributions
- We bin our data in $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{eff}
- Train a Boosted Decision Tree (BDT) to reweight kinematics
  - Train using 2b/4b CRs
  - Apply to 2b SR
- At each node, BDT splits events into 2 bins
  - Maximize 2b/4b difference
  - End up with many bins
  - Instead of using to discriminate, calculate weight to make 2b match 4b
- Use large set of 51 variables

Low-mass BDT

- Train to reweight from $2b$ CR$\rightarrow 4b$ CR
- 51 input variables
  - Mass, energy, p_{T}, η, ϕ of each Higgs boson candidate and Higgs boson candidate jet
  - Mass and p_{T} of the di-Higgs system
  - N_{jets}, $E_{\mathrm{T}}^{\mathrm{miss}}$, a modified X_{Wt}
  - Number of track-jets associated to each Higgs candidate
  - 14 angular variables
- Hyperparameters:
  - Learning rate: 0.3
  - Maximum number of layers: 5
  - Minimum number of events per node: 250
  - Sampling fraction: 0.4
  - Number of trees: 50/75/100 for 2016/2017/2018

Low-mass Bootstraps

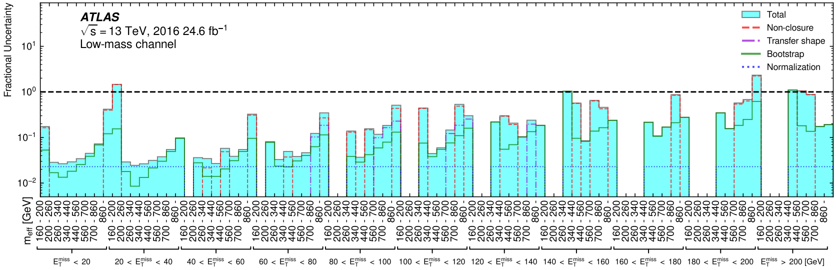
- Need statistical uncertainty of BDT-reweighted background
- Use a bootstrap method:
  1. Apply random Poisson weights ($\mu = 1$) to each input event
  2. Retrain BDT using weighted events
  3. Repeat 100 times ($+1$ unweighted)
  4. Set nominal estimate to median of 100$+$1 variations
  5. Set uncertainty using percentiles of variations, (84%-16%)$/2$

Low-mass Binning

- Discovery: Single-bins
  - Optimized for 150 GeV higgsinos: $E_{\mathrm{T}}^{\mathrm{miss}} > 20$, $m_{\mathrm{eff}} > 560$ GeV
  - Optimized for 300 GeV higgsinos: $E_{\mathrm{T}}^{\mathrm{miss}} > 150$, $m_{\mathrm{eff}} > 340$ GeV
- Exclusions: 2-dimensional fit
  - $E_{\mathrm{T}}^{\mathrm{miss}}$: $\{0,20,40,60,80,100,120,140,160,180,200,13000\}$ GeV
  - m_{eff}: $\{160,200,260,340,440,560,700,860,13000\}$ GeV

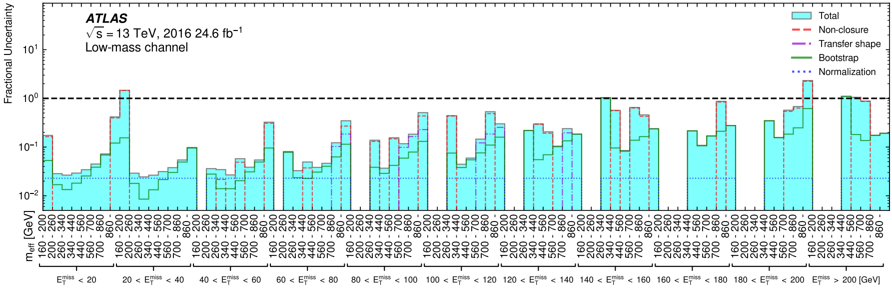
Low-mass Systematic Uncertainties

- Three systematic uncertainties on the background estimate
  1. Non-closure uncertainty
     - Reweighting in CR is imperfect
     - Set bin-by-bin fractional difference between 4b CR and reweighted 2b CR as shape systematic
  2. Transfer shape uncertainty
     - Validity of weight extrapolation from CR→SR
     - Re-train BDT in VR, take difference between predictions
  3. Transfer normalization uncertainty
     - Change in 2b/4b ratio from CR→SR



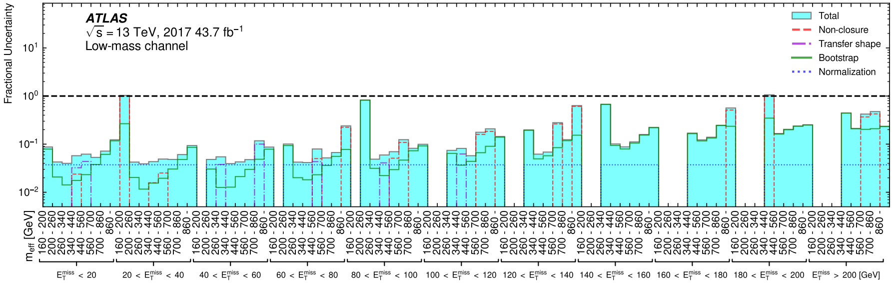
2016 fractional background systematics

Low-mass Channel 2016 Systematics



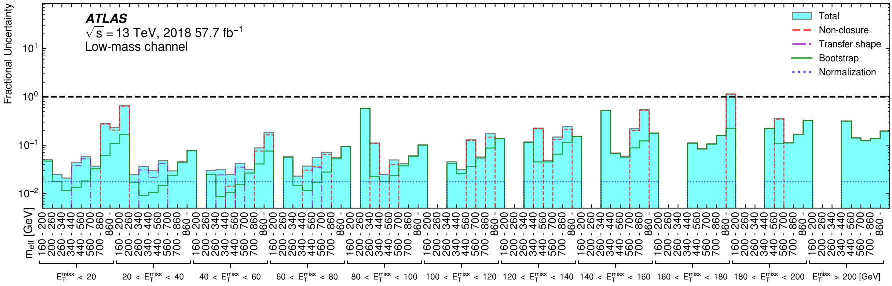
2016 fractional background systematics

Low-mass Channel 2017 Systematics



2017 fractional background systematics

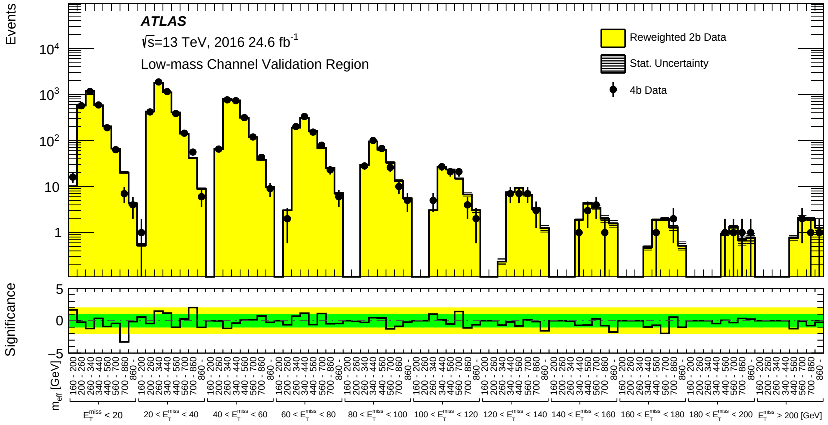
Low-mass Channel 2018 Systematics



2018 fractional background systematics

Low-mass Channel 2016 VR Yields

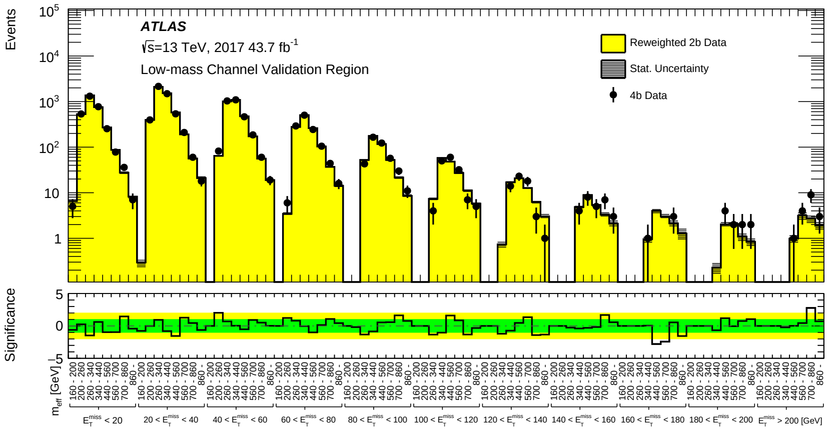
- Modeling looks good in validation regions



Yields in the 2016 validation region for the low-mass channel.

Low-mass Channel 2017 VR Yields

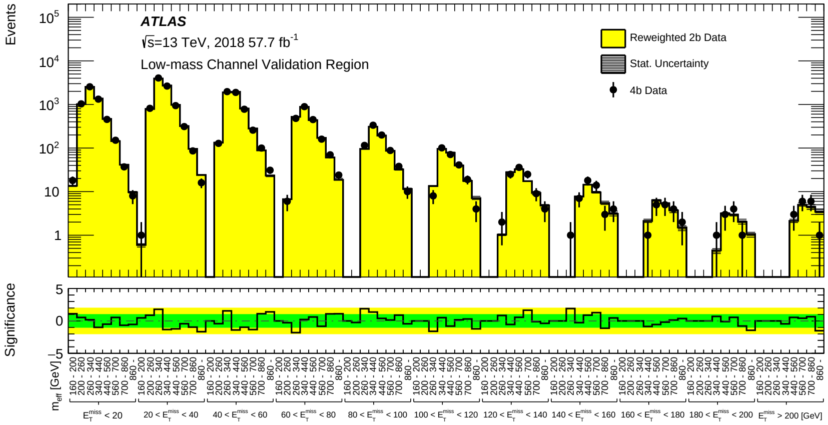
- Modeling looks good in validation regions



Yields in the 2017 validation region for the low-mass channel.

Low-mass Channel 2018 VR Yields

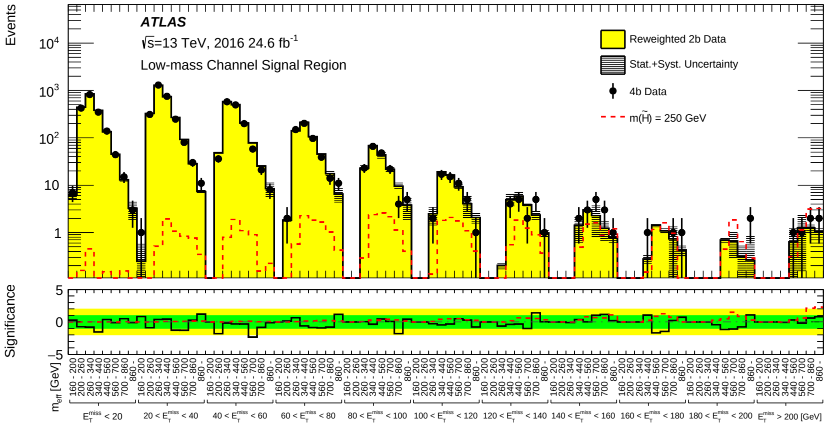
- Modeling looks good in validation regions



Yields in the 2018 validation region for the low-mass channel.

Low-mass Channel 2016 SR Yields

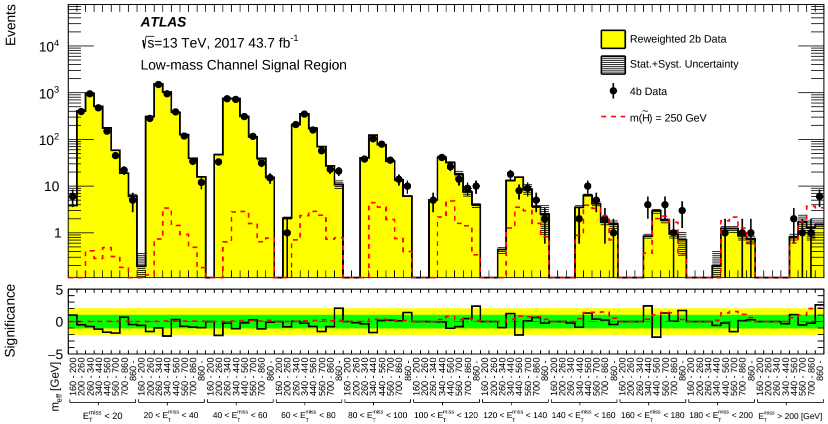
- Good agreement between observations and background
- Some small excesses (and deficits)



Yields in the 2016 signal region for the low-mass channel.

Low-mass Channel 2017 SR Yields

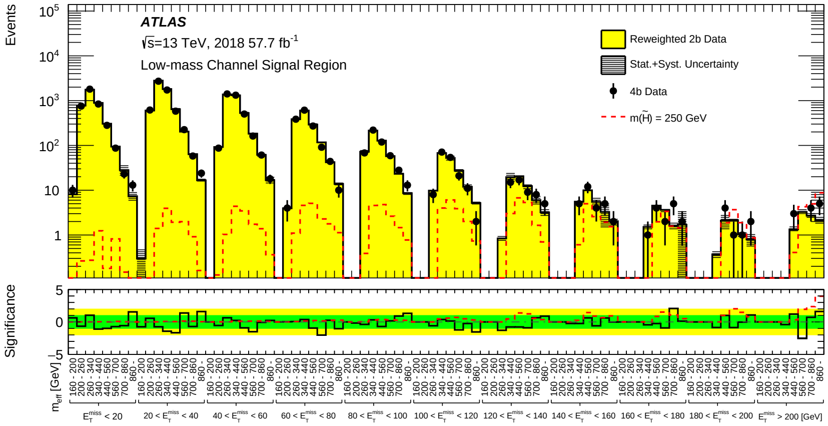
- Largest deviation in final ($E_T^{miss} > 200$ GeV, $m_{eff} > 860$ GeV) bin
- 6 observed vs. 1.51±0.35 predicted events (2.6σ local)



Yields in the 2017 signal region for the low-mass channel.

Low-mass Channel 2018 SR Yields

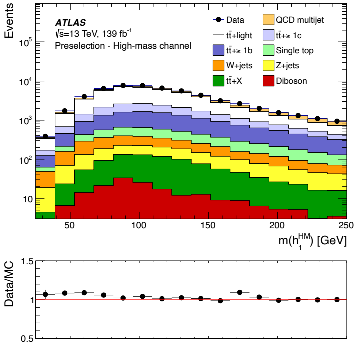
- Good agreement between observations and background
- Some small excesses (and deficits)



Yields in the 2018 signal region for the low-mass channel.

High-mass Object Definitions

- Need to select b-jets and pair into Higgs bosons
  - Allow $3b$ events by treating untagged jet as b-jet
  - Pair same way as low-mass
- $\Delta\phi^{4j}_{\text{min}}$ is the minimum angle between $E_{\text{T}}^{\text{miss}}$ and any of the 4 leading jets
  - Useful for rejecting fake $E_{\text{T}}^{\text{miss}}$ from jet mismeasurement
- $m_{\text{T,min}}^{b\text{-jets}}$ is the minimum transverse mass of $E_{\text{T}}^{\text{miss}}$ and the 3 leading b-jets
- M_J^{Σ} is the scalar sum of large-radius jet masses



Preselection $m(h_1)$

High-mass Trigger Scale Factors

- Uses $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger down to 150 GeV
- Only fully efficient for $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
- Derive SF by comparing data, $t\bar{t}$ with muon trigger
  - ≥ 4 jets, ≥ 2 b-jets, $= 1$ μ
  - 6 H_{T} bins: [0, 250, 300, 400, 600, 800, 999999] GeV
  - Smooth turn-on curves by fitting data and MC each to

$$f(x) = \frac{p_2}{\left[1 + (2^{p_3} - 1)e^{-p_0(x-p_1)}\right]^{\frac{1}{p_3}}}$$

  - SF=$f_{\mathrm{data}}(x)/f_{\mathrm{mc}}(x)$

High-mass Region Definitions

- Define SRs, VRs, and CRs iteratively using BDT scores
  - Define up to 4 SRs by maximizing significance
  - VRs require $\geq$25 events, S/B<20%
  - CRs require $\geq$100 events, S/B<10%
  - Nb: Separate for each mass point
  - SR_1_M means SR_1 for M GeV higgsino
- Separate VRs/CRs for $t\bar{t}$ and high $m_{\mathrm{T,min}}^{b\text{-jets}}$
- Split $t\bar{t}$ CR to measure $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 1c$

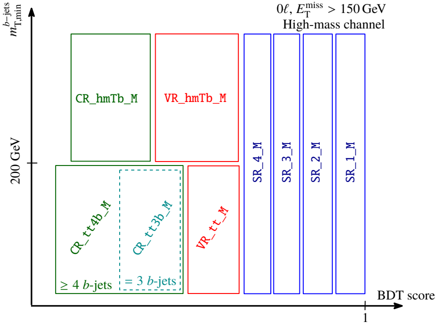


Diagram of high-mass regions.

High-mass Background Estimation

- Main backgrounds are $t\bar{t}$, single top, Z+jets, and QCD multijet
- $t\bar{t}$, single top, and Z+jets are estimated with MC + CRs and SRs
- Z+jets CRs and VRs use 2μ events to model $Z \to \nu\nu$
  - Treat μ as invisible
- Data-driven estimate for QCD multijet
  - Reweight $\Delta\phi^{4j}_{\text{min}} < 0.2$ to $\Delta\phi^{4j}_{\text{min}} > 0.4$ using a Neural Network

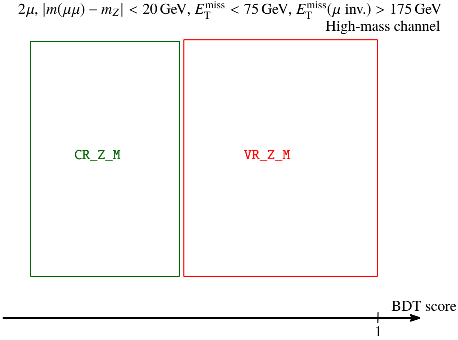


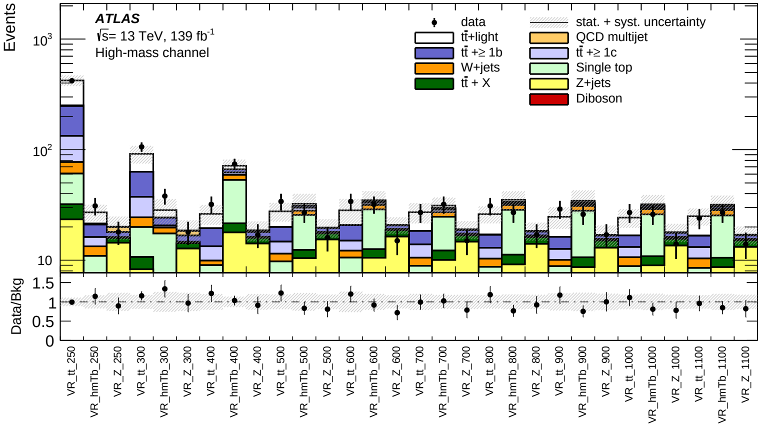
Diagram of high-mass Z CRs and VRs.

High-mass QCD Estimation

- Estimated with data-driven technique
- Replace $\Delta\phi^{4j}_{\text{min}} > 0.4$ with $\Delta\phi^{4j}_{\text{min}} < 0.2$ to get QCD-dominated region
- Subtract non-QCD MC backgrounds from data to get QCD estimate
- Generate a fake $\Delta\phi^{4j}_{\text{min}}$ distribution for use in the BDT using information from dijet MC samples
- Reweight the template with a Neural Network to reproduce correct correlations and normalization

High-mass Channel VR Yields

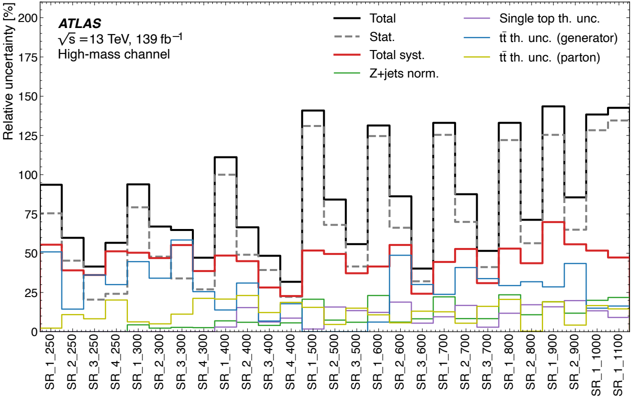
- Modeling looks good in validation regions



Yields in the validation regions for the high-mass channel.

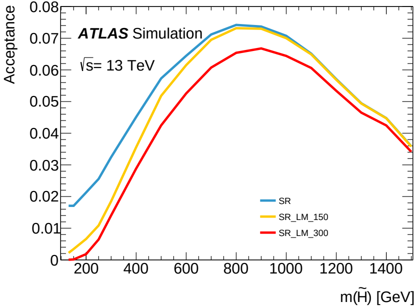
High-mass Uncertainties

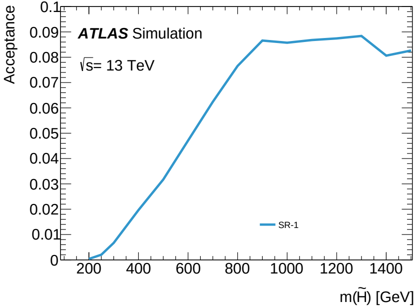
- Experimental and modeling uncertainties on signal and background MC
  - Jet energy scale and resolution, jet mass scale, soft $E_{\mathrm{T}}^{\mathrm{miss}}$ terms, flavor-tagging, pile-up, trigger, luminosity
  - Also on low-mass signals



Uncertainties for the high-mass channel.

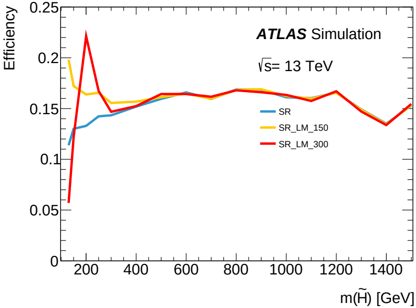
Acceptance

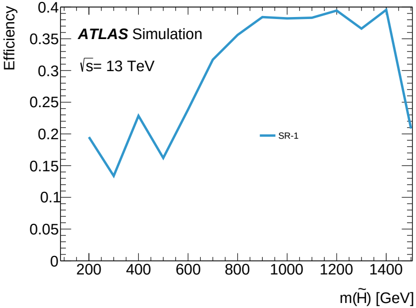




Acceptances for the low-mass (left) and high-mass (right) channels.

Efficiency





Efficiencies for the low-mass (left) and high-mass (right) channels.

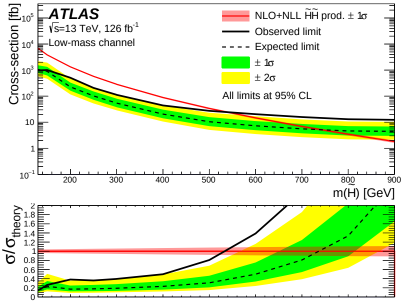
Discovery Region Results

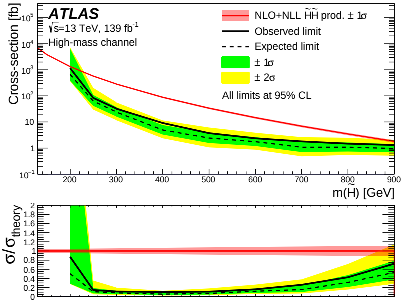
- Create model-independent regions to search for excesses
  - Low-mass:
    - SR_LM_150: $E_{\mathrm{T}}^{\mathrm{miss}} > 20$, $m_{\mathrm{eff}} > 560$ GeV
    - SR_LM_300: $E_{\mathrm{T}}^{\mathrm{miss}} > 150$, $m_{\mathrm{eff}} > 340$ GeV
  - High-mass: Using SR_1 from 250, 500, and 1000 GeV
- Excellent precision on low-mass backgrounds
- Mild excesses ($< 2\sigma$ local)

Signal channel	N_{obs}	N_{pred}	$\langle\epsilon\sigma\rangle_{\mathrm{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	$p(s=0)$
SR_1_250	2	1.8 ± 1.0	0.04	6.2	$5.9^{+1.7}_{-0.9}$	0.48 (0.05)
SR_1_500	2	0.58 ± 0.30	0.04	5.5	$4.0^{+1.7}_{-0.6}$	0.18 (0.92)
SR_1_1000	3	0.60 ± 0.31	0.05	6.7	$4.3^{+0.9}_{-0.9}$	0.03 (1.9)
SR_LM_150	1790	1860 ± 50	0.73	92	127^{+48}_{-34}	0.5 (0.00)
SR_LM_300	97	77.0 ± 5.3	0.31	39	22^{+9}_{-6}	0.03 (1.8)

Individual Channel Results

- Low-mass more sensitive from 130-200 GeV, high-mass 250 GeV+

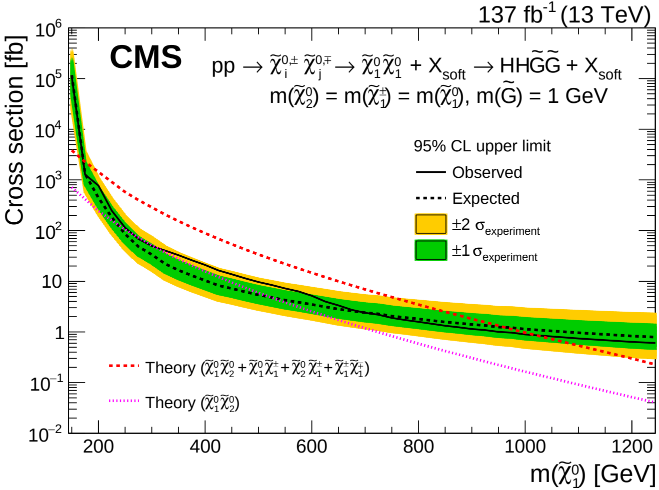




Results for the low-mass (left) and high-mass (right) channels.

CMS Results

- Exclude up to 1025 GeV (≈ 950 GeV expected)



CMS results [4]