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

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

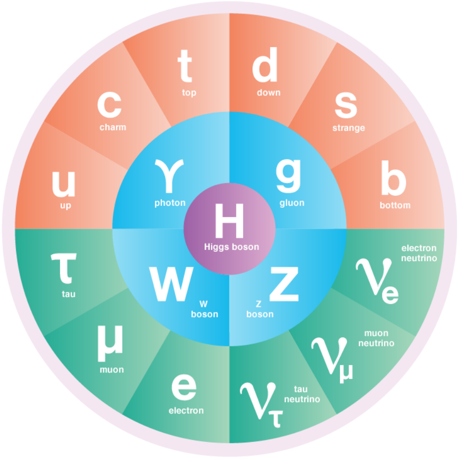


Image credit: Symmetry Magazine.

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

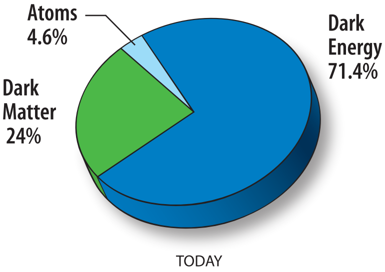
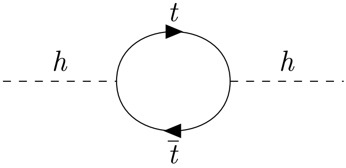


Image credit: NASA/WMAP Science Team.

The Hierarchy Problem

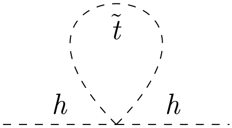
- Observed Higgs mass is 125 GeV $= m_{\text{h}} \approx m_{\text{bare}} + m_{\text{correc}}$
- Fermions (in particular top quark) contribute to m_{correc}
- $\Delta m_{\text{fromtop}} = O(\Lambda_{\text{cutoff}}) \approx 10^{19}$ GeV
- To get observed 125 GeV, need suspiciously neat cancellation
  -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

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

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

- $m_{\mathsf{Z}} = 91.2$ GeV
- For this cancellation to be natural, terms must be of the order of m_{Z}
  - Higgsinos predicted to be relatively light

The Large Hadron Collider

- The Large Hadron Colldier (LHC) is currently the largest particle accelerator
  - 27 km circumference
  - 1 billion proton-proton collisions/second
  - 13 TeV collision energy

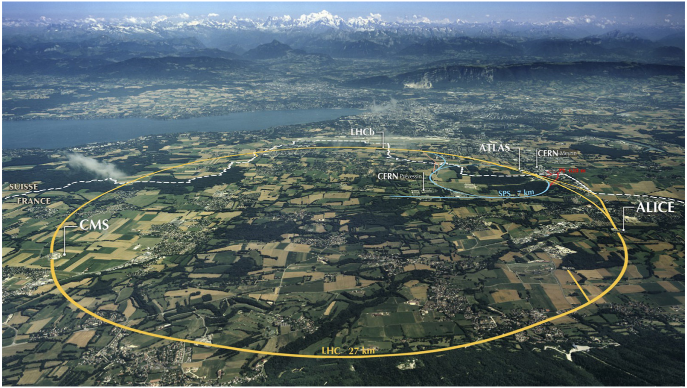
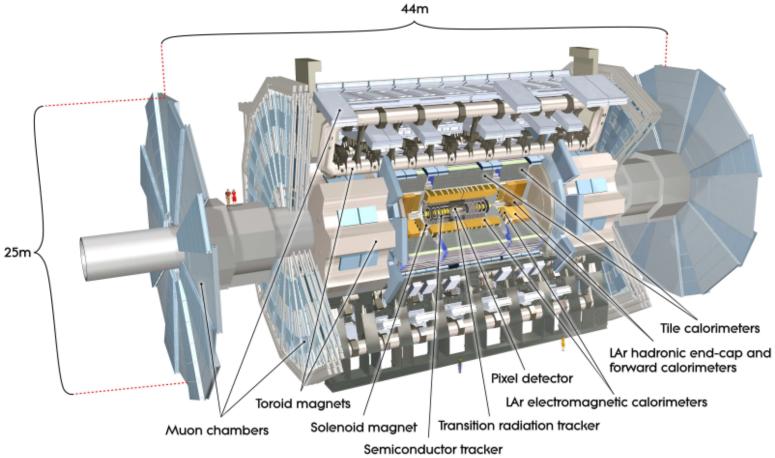


Image credit: Maximilien Brice, CERN

The ATLAS Detector

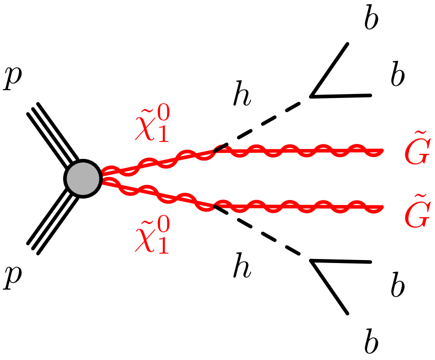
- General purpose particle detector
- Has a series of layers to measure different particles



The ATLAS detector (JINST 3 (2008) S08003)

Signal Model

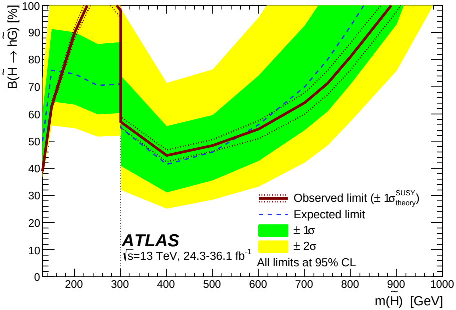
- Look for gauge-mediated supersymmetry breaking (GMSB) model
  - LSP is nearly massless gravitino
- Target higgsino-dominated neutralino as NLSP
- Most common predicted decays are $\tilde{\chi}_1^0 \to h\tilde{G}$ and $\tilde{\chi}_1^0 \to Z\tilde{G}$
  - Target the Higgs decay channel
- $\mathcal{B}(h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



SUSY signal model.

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}
  - "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

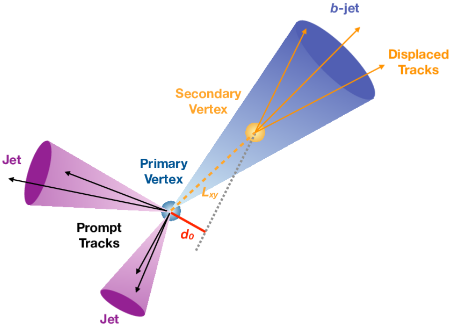
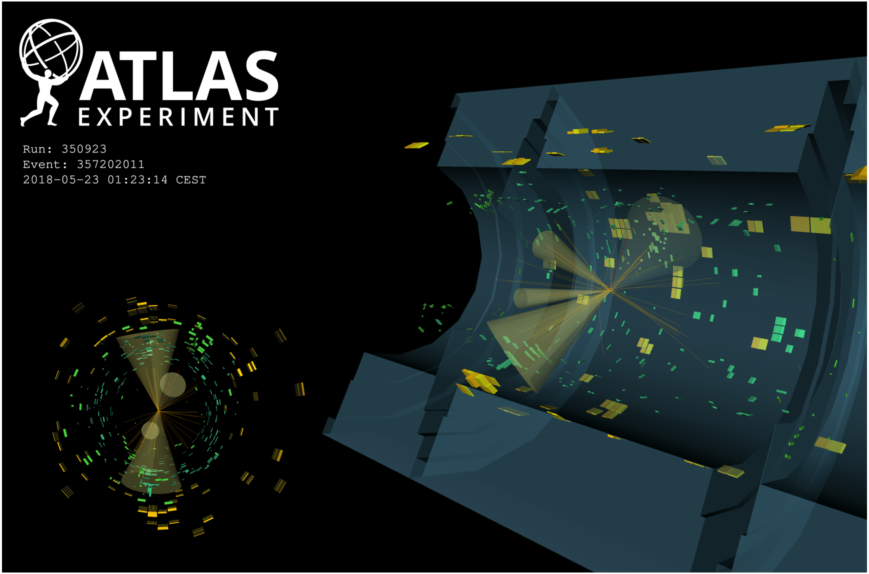


Image credit: 2106.03584

Low-mass Channel

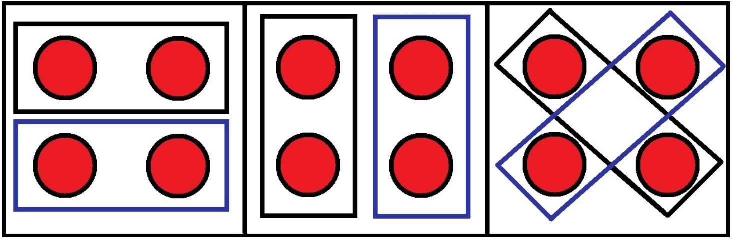


Trigger Strategy

- For low higgsino masses, gravitinos not energetic enough for $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
- Instead, we use a combination of triggers targeting 2 b-jets plus
  - High p_{T} jet for initial state radiation (ISR)
  - High H_{T} ($\sum_{\mathrm{jets}} p_{\mathrm{T}}$)
  - 2 other jets
- Different triggers require each year to be treated separately

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



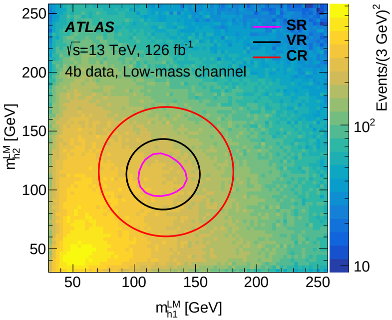
Event Selection

- Want to reduce background from $t\bar{t}$

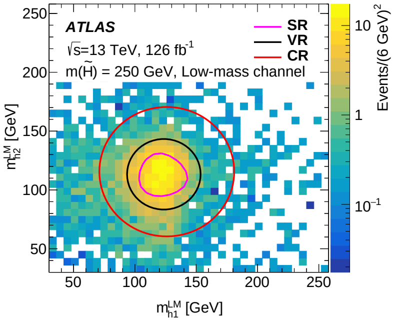
1. Veto events with leptons
2. Top consistency $X_{Wt} = \sqrt{\left(\frac{m_{jj}-m_W}{0.1 \cdot m_{jj}}\right)^2 + \left(\frac{m_{jjb}-m_t}{0.1 \cdot m_{jjb}}\right)^2}$
    - Construct W candidate using two jets
    - Construct top candidate using two W jets plus one other jet
    - Events with $X_{Wt} < 1.8$ for any combination vetoed

Region Definitions

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



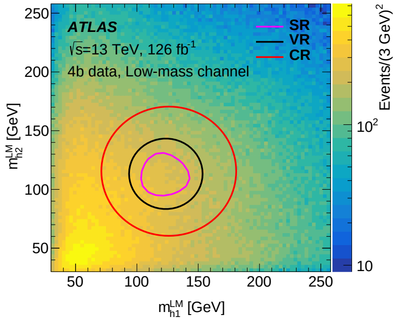
(a) $4b$ data



(b) 250 GeV Signal

Region Definitions

- Regions defined using the masses of the reconstructed Higgs bosons
- Signal: $\sqrt{(\frac{m_{h1}-120}{0.1m_{h1}})^2 + (\frac{m_{h2}-110}{0.1m_{h2}})^2} < 1.6$
- Validation: $\sqrt{(m_{h1} - 120 * 1.03)^2 + (m_{h2} - 110 * 1.03)^2} < 30$ GeV



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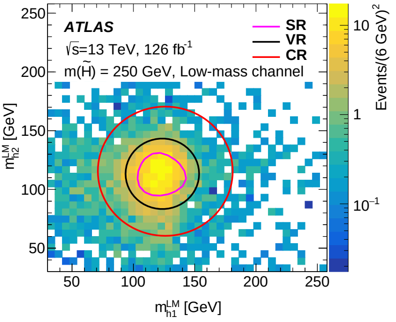

(b) 250 GeV Signal

Region Definitions

- Regions defined using the masses of the reconstructed Higgs bosons
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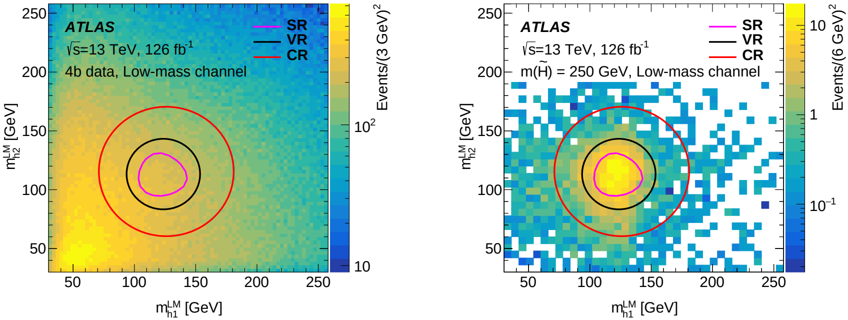
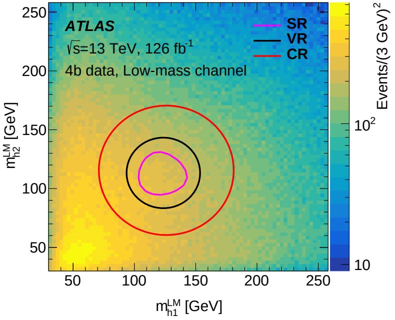
- Validation: $\sqrt{(m_{h1} - 120 * 1.03)^2 + (m_{h2} - 110 * 1.03)^2} < 30$ GeV
- Control: $\sqrt{(m_{h1} - 120 * 1.05)^2 + (m_{h2} - 110 * 1.05)^2} < 55$ GeV



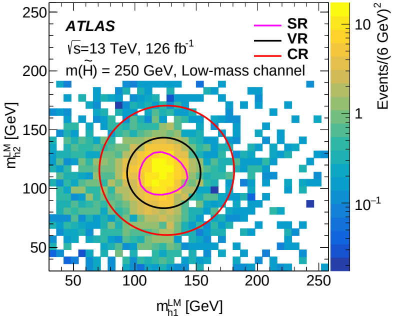
(a) $4b$ data (b) 250 GeV Signal

Region Definitions

- Regions defined using the masses of the reconstructed Higgs bosons
- Signal: $\sqrt{(\frac{m_{h1}-120}{0.1m_{h1}})^2 + (\frac{m_{h2}-110}{0.1m_{h2}})^2} < 1.6$
- Validation: $\sqrt{(m_{h1} - 120 * 1.03)^2 + (m_{h2} - 110 * 1.03)^2} < 30$ GeV
- 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 (≥4 b-jets) sample



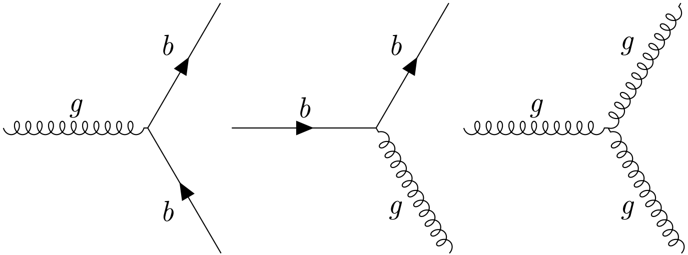
(a) $4b$ data



(b) 250 GeV Signal

Background Estimation

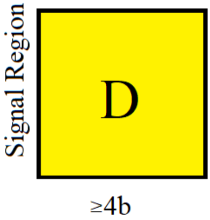
- Background mainly QCD multijet
  - Large cross section
  - Large cross section theory uncertainty
- Avoid these problems by using a **purely data-driven** method called the ABCD method



Selected fundamental QCD multijet processes.

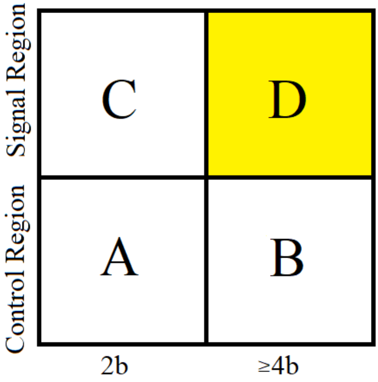
Data-Driven Background Modeling

- We want to estimate background in $\geq$4b signal region "D"



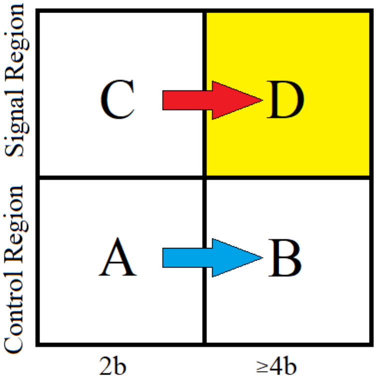
Data-Driven Background Modeling

- We want to estimate background in $\geq$4b signal region “D”
- In each region, make 2b and $\geq$4b sample
  - 2b has low signal contamination
  - Similar backgrounds to 4b



Data-Driven Background Modeling

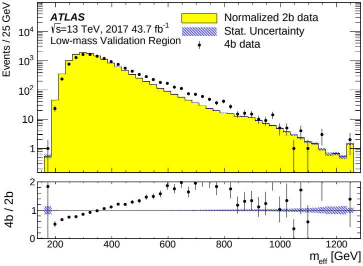
- We want to estimate background in $\geq$4b signal region "D"
- In each region, make 2b and $\geq$4b sample
  - 2b has low signal contamination
  - Similar backgrounds to 4b
- Transfer factor $\mu_{\text{CR}} = \frac{N_{4b}^{\text{CR}}}{N_{2b}^{\text{CR}}}$ (=B/A)
- $N_{4b,bkg}^{\text{SR}} = \mu_{\text{CR}}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



Boosted Decision Tree Reweighting

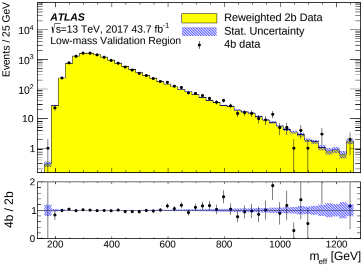
- Baseline ABCD method only gives us event counts, not distributions
- We bin our data in $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{eff}
- Train a Boosted Decision Tree (BDT) to reweight kinematics
  - Train using 2b/4b CRs
  - Apply to 2b SR
- At each node, BDT splits events into 2 bins
  - Maximize 2b/4b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

- CR-derived weights applied in VR
- Excellent agreement



(a) Before reweighting

BDT



(b) After reweighting

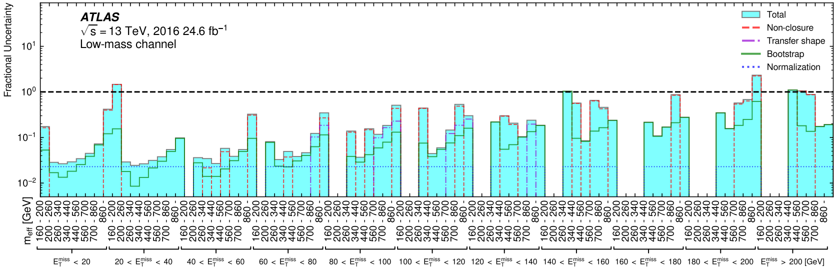
Comparison of 2017 data in the VR.

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

Systematic Uncertainties

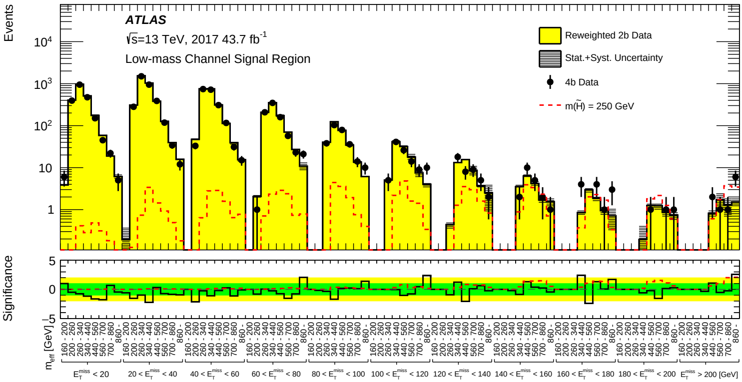
- Three systematic uncertainties on the background estimate
  1. Non-closure uncertainty
     - Reweighting in CR is imperfect
     - Set bin-by-bin fractional difference between 4b CR and reweighted 2b CR as shape systematic
  2. Transfer shape uncertainty
     - Validity of weight extrapolation from 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

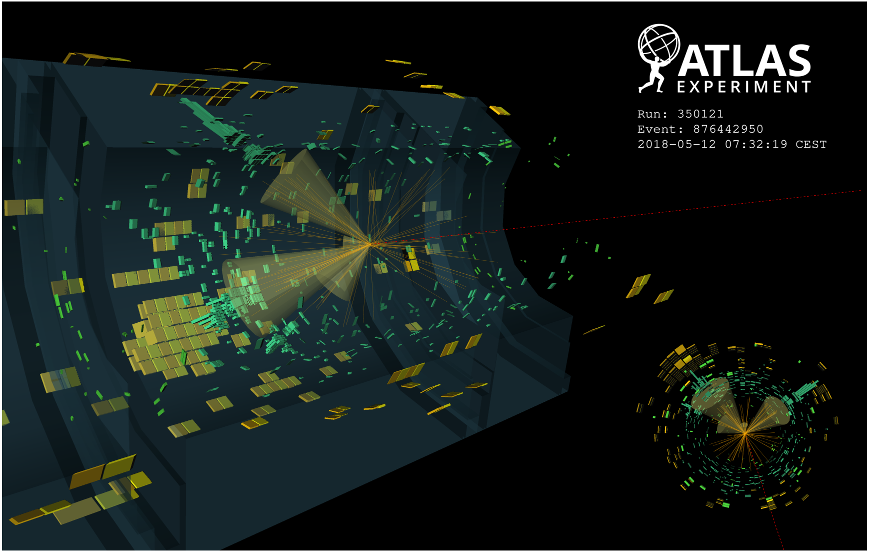
Signal Region Yields

- Largest deviation in final ($E_{\mathrm{T}}^{\text{miss}} > 200$ 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



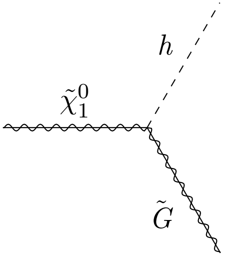
Yields in the 2017 signal region for the low-mass channel.

High-mass Channel



Trigger Strategy

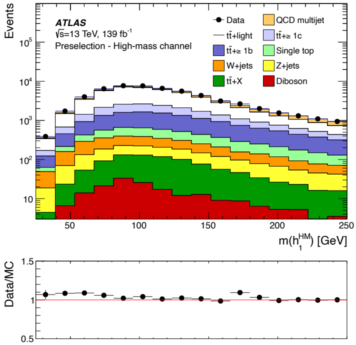
- High-mass higgsino decays leave significant $E_{\mathrm{T}}^{\mathrm{miss}}$ in the detector
  $\rightarrow$ Use the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger!
- Trigger fully efficient for $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
  - Derive scale factors to correct MC for 150 GeV< $E_{\mathrm{T}}^{\mathrm{miss}}$ <200 GeV



Higgsino decay vertex

Object Definitions

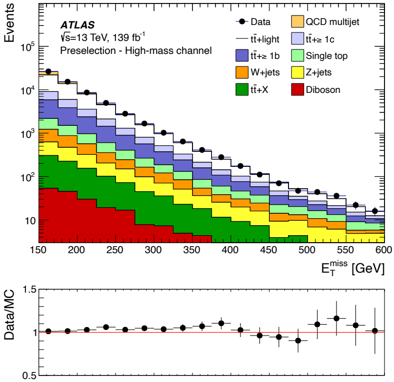
- Need to select b-jets and pair into Higgs bosons
  - Allow $3b$ events by treating untagged jet as b-jet
  - Pair same way as low-mass
- $\Delta\phi^{4j}_{\text{min}}$ is the minimum angle between $E_{\text{T}}^{\text{miss}}$ and any of the 4 leading jets
  - Useful for rejecting fake $E_{\text{T}}^{\text{miss}}$ 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 $m(h_1)$

Event Selection

- Preselections:
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
  - ≥ 3 b-jets, 4-7 total jets
  - $\Delta\phi_{\mathrm{min}}^{4j} > 0.4$
  - Veto leptons
- Train a BDT to distinguish signal from background
  - Inputs: 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}, $m(h_1)$, $m(h_2)$, $\Delta R(h_1)$, $\Delta R(h_2)$, $\Delta R_{\mathrm{min}}^{bb}$
  - Parameterize with truth higgsino mass



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

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 $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 1c$

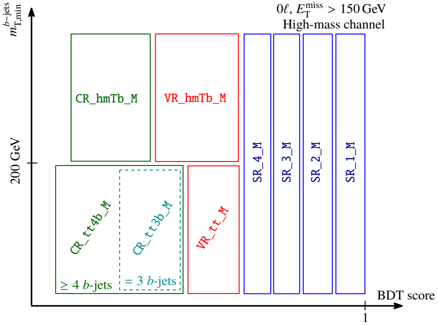


Diagram of high-mass regions.

- 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

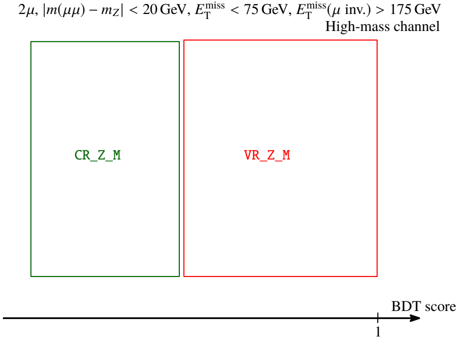
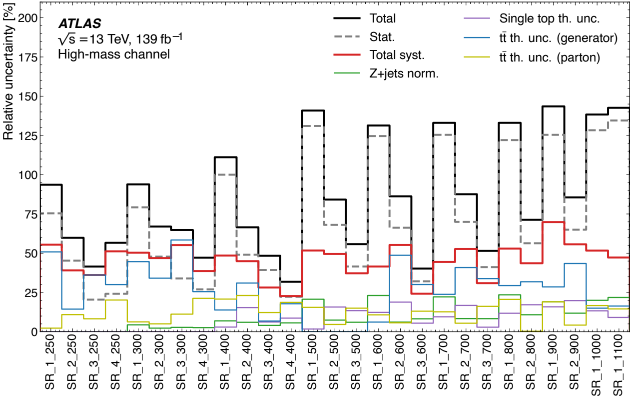


Diagram of high-mass Z CRs and VRs.

Uncertainties

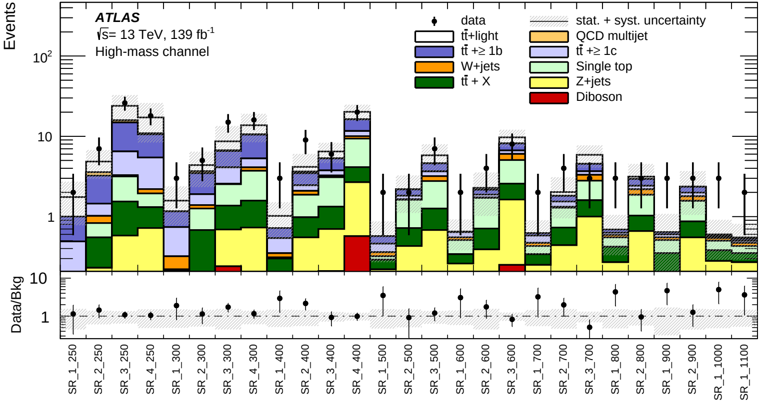
- Experimental and modeling uncertainties on signal and background MC
  - Jet energy scale and resolution, jet mass scale, soft $E_{\mathrm{T}}^{\mathrm{miss}}$ terms, flavor-tagging, pile-up, trigger, luminosity
  - Also on low-mass signals



Uncertainties for the high-mass channel.

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

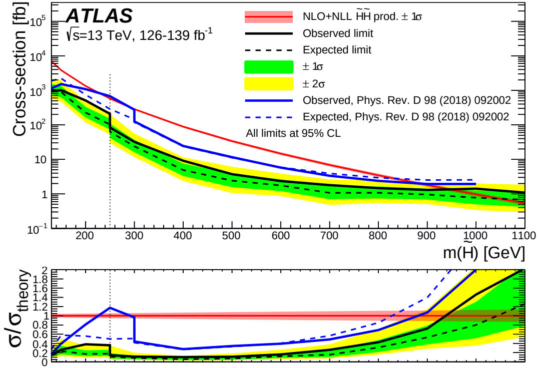
Discovery Regions

- Create model-independent regions to search for excesses
  - Low-mass:
    - SR_LM_150: $E_T^{miss} > 20$, $m_{eff} > 560$ GeV
    - SR_LM_300: $E_T^{miss} > 150$, $m_{eff} > 340$ 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}	$\langle\epsilon\sigma\rangle_{obs}^{95}$ [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)

Exclusion Limits

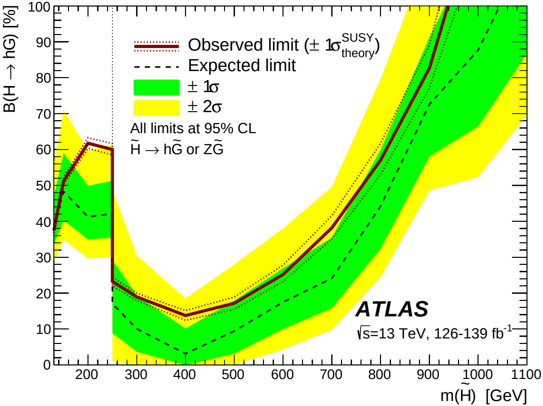
- Use low-mass channel below 250 GeV, high-mass above
- Exclude up to 940 GeV (≈ 1040 GeV expected)
    - Most sensitive analysis to-date
    - Most stringent constraints from 130-800 GeV



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

Branching Ratio Limits

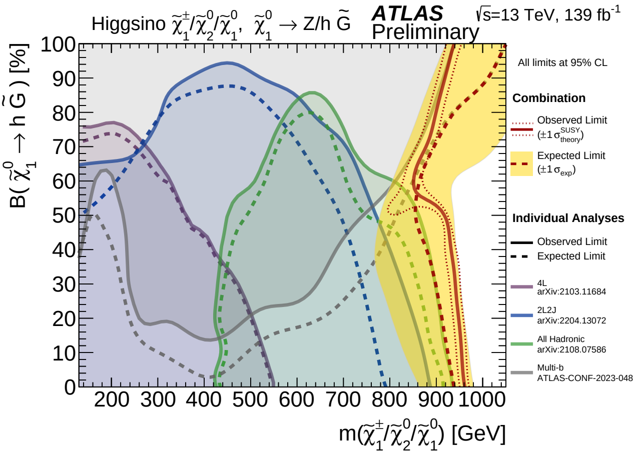
- Relax assumption on $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$=100%
  - Allow for Higgs or Z decays
  - Assume theory cross section
- Ruled out excess from prior analysis



Limits on $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$

Combination Results

- Highly complementary with leptonic and all-hadronic analyses
- Combine with other analyses to achieve strong exclusion across the BR plane



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 GMSB SUSY models

Thank you for listening!

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, "Run 2 results of searches for charginos and neutralinos at the ATLAS experiment using statistical combination," ATLAS-CONF-2023-046 (2023). (preliminary)
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

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

<table>
<tr><th>Category</th><th>Year</th><th>Online selections</th><th>Offline selections</th></tr>
<tr><td colspan="4">Low-mass channel</td></tr>
<tr><td rowspan="3">$2b1j$</td><td>2016</td><td>1 jet (p_T > 100 GeV),
2 b-jets (60% b-jet efficiency, p_T > 55 GeV)</td><td>$p_{T,j1} > 150$ GeV</td></tr>
<tr><td>2017</td><td rowspan="2">1 jet (p_T > 150 GeV),
2 b-jets (70% b-jet efficiency, p_T > 55 GeV)</td><td>$p_{T,j1} > 350$ GeV</td></tr>
<tr><td>2018</td><td>$p_{T,j1} > 500$ GeV</td></tr>
<tr><td rowspan="2">$2bH_T$</td><td>2017</td><td rowspan="2">H_T > 300 GeV,
2 b-jets (50% b-jet efficiency, p_T > 55 GeV)</td><td>$p_{T,j1} < 350$ GeV, $H_T > 850$ GeV</td></tr>
<tr><td>2018</td><td>$p_{T,j1} < 500$ GeV, $H_T > 700$ GeV</td></tr>
<tr><td rowspan="3">$2b2j$</td><td>2016</td><td>2 jets (p_T > 35 GeV),
2 b-jets (60% b-jet efficiency, p_T > 35 GeV)</td><td>$p_{T,j1} < 150$ GeV</td></tr>
<tr><td>2017</td><td>2 jets (p_T > 35 GeV),
2 b-jets (40% b-jet efficiency, p_T > 35 GeV)</td><td>$p_{T,j1} < 350$ GeV, $H_T < 850$ GeV</td></tr>
<tr><td>2018</td><td>2 jets (p_T > 35 GeV),
2 b-jets (60% b-jet efficiency, p_T > 35 GeV)</td><td>$p_{T,j1} < 500$ GeV, $H_T < 700$ GeV</td></tr>
<tr><td colspan="4">High-mass channel</td></tr>
<tr><td rowspan="4">E_T^{miss}</td><td>2015</td><td>$E_T^{miss}(\mu \text{ inv.}) > 70$ GeV</td><td rowspan="4">$E_T^{miss} > 150$ GeV</td></tr>
<tr><td>2016</td><td>$E_T^{miss}(\mu \text{ inv.}) > 90$ GeV</td></tr>
<tr><td>2017</td><td>$E_T^{miss}(\mu \text{ inv.}) > 100$ GeV</td></tr>
<tr><td>2018</td><td>$E_T^{miss}(\mu \text{ inv.}) > 110$ GeV</td></tr>
</table>

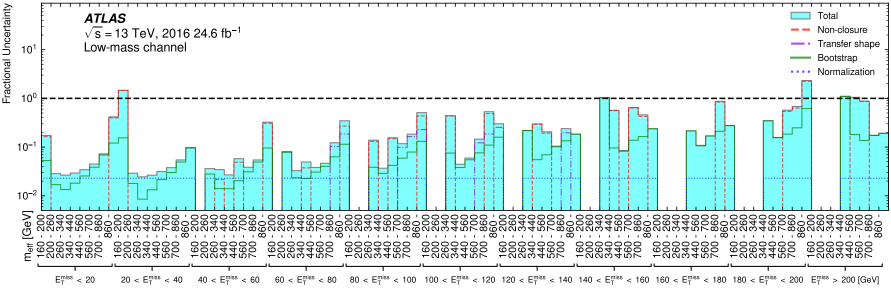
Low-mass BDT

- 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

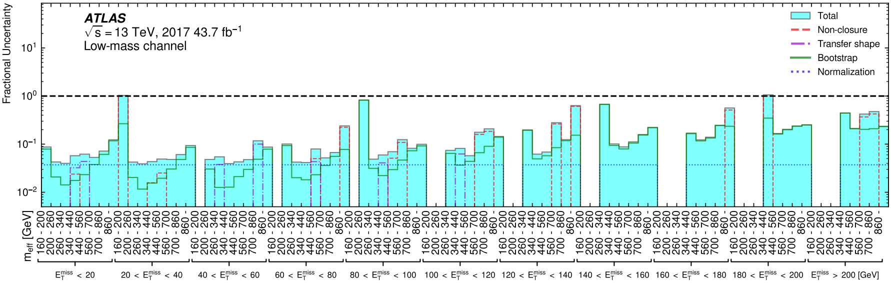
- Need statistical uncertainty of BDT-reweighted background
- Use a bootstrap method:
  1. Apply random Poisson weights ($\mu = 1$) to each input event
  2. Retrain BDT using weighted events
  3. Repeat 100 times ($+1$ unweighted)
  4. Set nominal estimate to median of 100$+$1 variations
  5. Set uncertainty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

Low-mass Channel 2016 Systematics



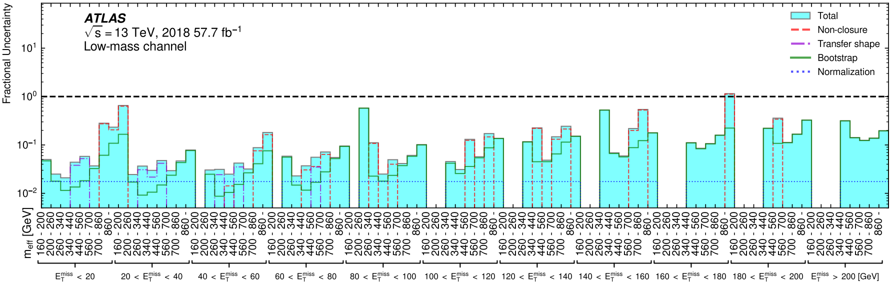
2016 fractional background systematics

Low-mass Channel 2017 Systematics



2017 fractional background systematics

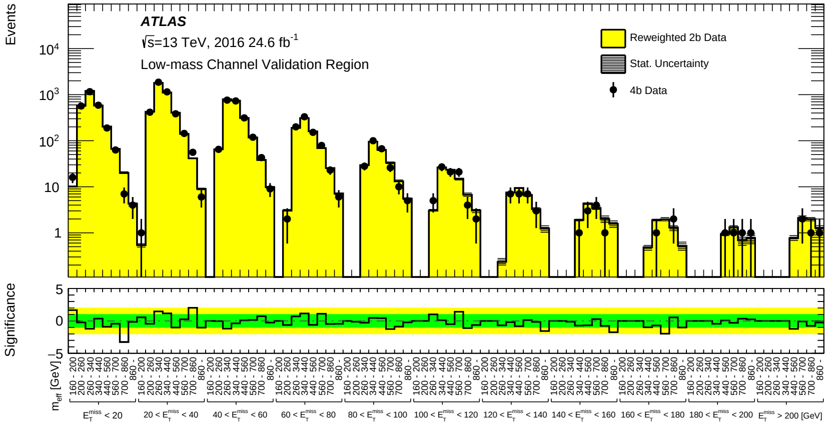
Low-mass Channel 2018 Systematics



2018 fractional background systematics

Low-mass Channel 2016 VR Yields

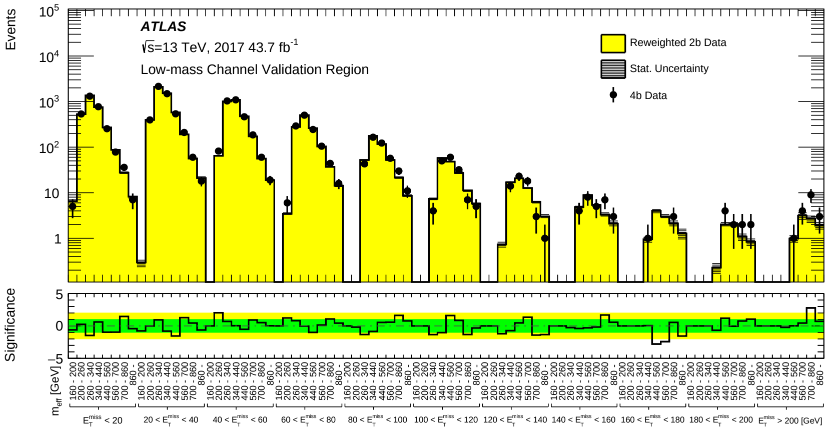
- Modeling looks good in validation regions



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

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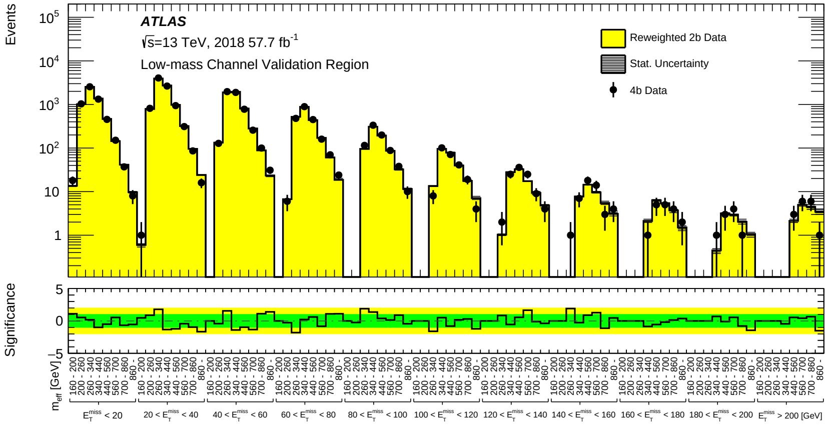
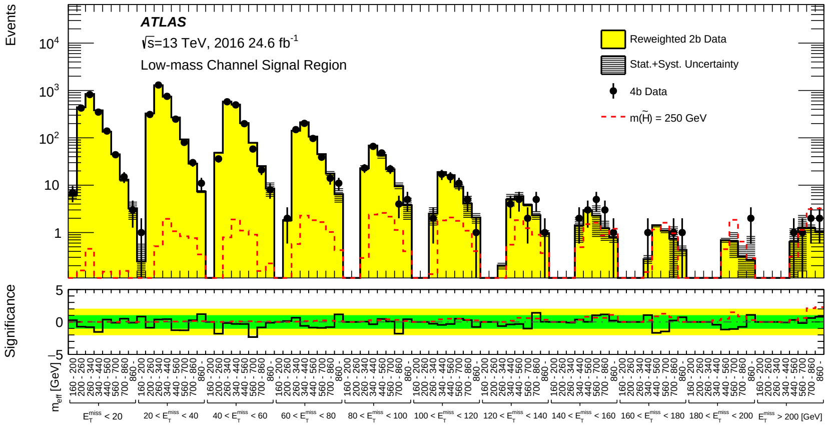


Yields in the 2018 validation region for the low-mass channel.

Low-mass Channel 2016 SR Yields

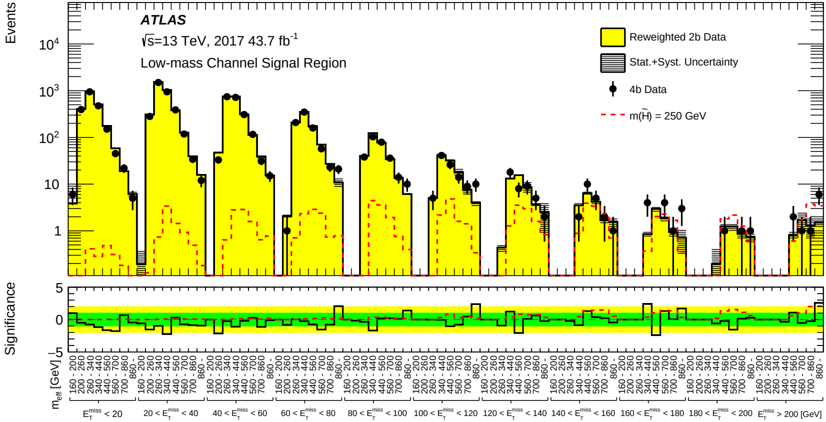
- Good agreement between observations and background
- Some small excesses (and deficits)



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
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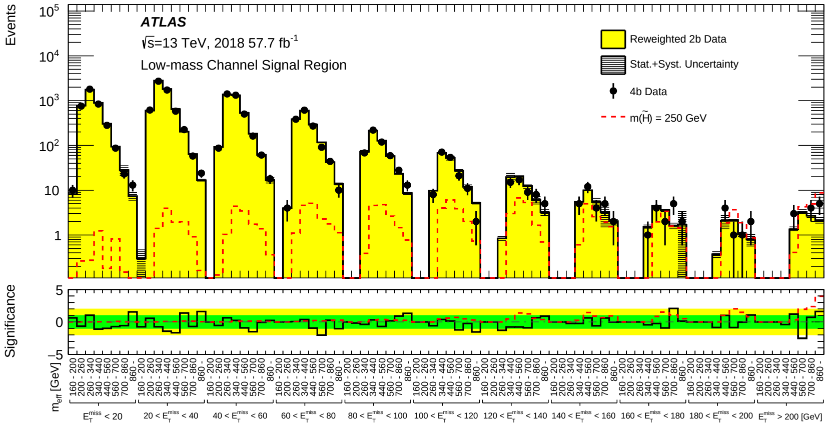


Yields in the 2018 signal region for the low-mass channel.

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

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

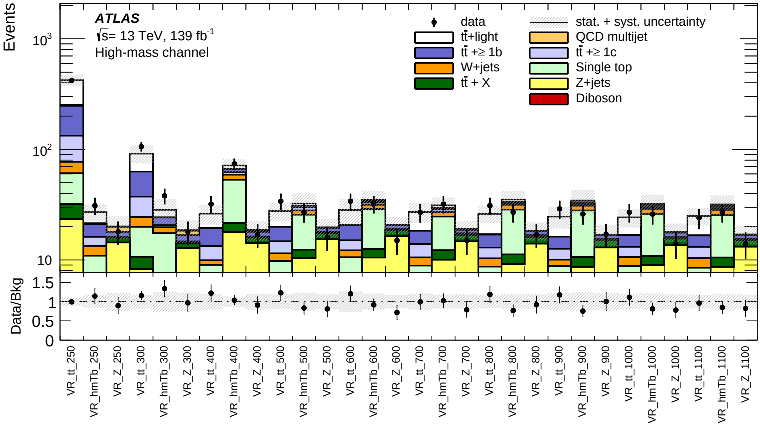
  - SF=$f_{\mathrm{data}}(x)/f_{\mathrm{mc}}(x)$

High-mass 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

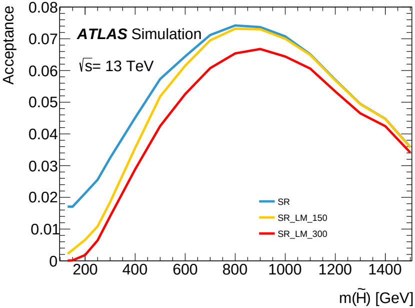
High-mass Channel VR Yields

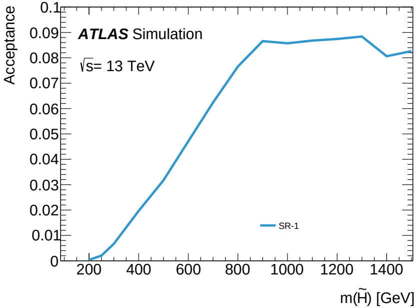
- Modeling looks good in validation regions



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

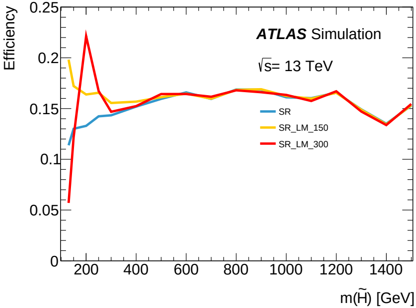
Acceptance

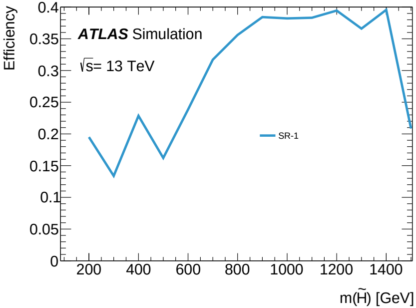




Acceptances for the low-mass (left) and high-mass (right) channels.

Efficiency

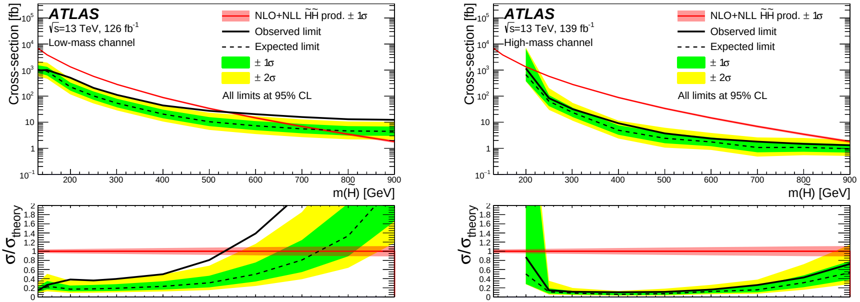




Efficiencies for the low-mass (left) and high-mass (right) channels.

Individual Channel Results

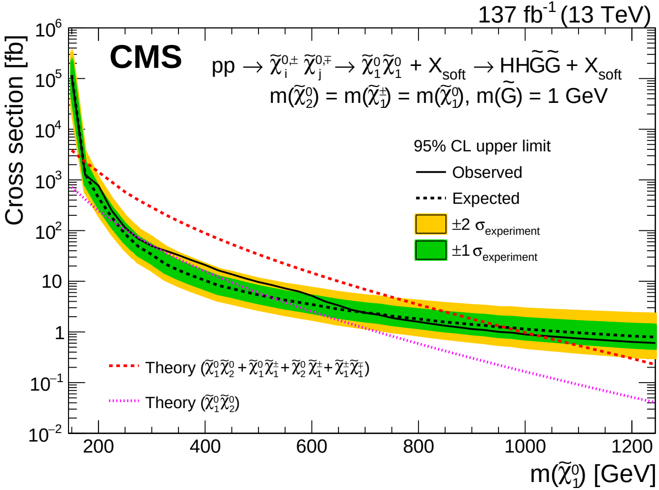
- Low-mass more sensitive from 130-200 GeV, high-mass 250 GeV+



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

CMS Results

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



CMS results [4]