Introduction

- ATLAS has been collecting data since 2010, now nearing end of Run 2
- Searches for new physics have been a primary motivator for LHC physics program
- We haven’t found anything yet
- Should we despair? …

(Spoiler: no!)
Obligatory ATLAS experiment slide
Using simplified models, summaries, and scans to identify research directions
How should we interpret search results so far?

Most important statement in any search: did we find **evidence of new physics**?

- If no, set limits! With limits, analyses prioritise making generalised statements which are as easy as possible to reinterpret in different frameworks.

- Simplified models are just spherical cows but give us a framework to understand how our results relate to one another.

- Summaries in context of various models help us find holes and plan next steps for search program.

All models, and therefore all limits, should be taken with a grain of salt! But they are important to let us **contextualise** our zeros.
Example: simplified dark matter models at ATLAS

What is that?

Range of answers!

Dark Matter Effective Field Theories

Contact Interactions

Dipole Interactions

Less complete

“Sketches of models”

Moving this way

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Run II standard

via DMF
Example: PMSSM scan

- Use simplified “phenomenological” MSSM as a model generator
  - Throw toy universes with different parameters and check exclusion with analyses
  - Results reported as fraction of models excluded
- Advantages: help us find holes! Disadvantages: difficult to make meaningful statements given sparse sampling of the parameter space

ATLAS

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

Highlighting under-covered spots

Best limits exclude 1 TeV stop, but not in all models
Current results in SUSY
SUSY strong production

- High production $\sigma$ with boost from 13 TeV -> strong motivation for early run II searches!
- Squark & gluino production gives final states with lots of hadronic activity + MET
- Strong limits with 36/fb!
Recent highlights: SUSY strong production

Highlight: OS-dilepton update!

arXiv:1805.11381
Recent highlights: EW SUSY

- Production $\sigma$ for EW smaller; benefited less from CME jump
- Signature: leptons/gauge bosons+MET. Clean; main bkgs from diboson, ttbar

Highlight: $2/3l$

$\chi^\pm_1$, $\chi^0_1$, $\chi^0_2$, $\chi^0_3$

$\ell\rightarrow e/\mu$

March 2018 ATLAS Preliminary $\sqrt{s}=8,13$ TeV, 20.3-36.1 fb$^{-1}$

Expected limits Observed limits

All limits at 95% CL

Recent highlights: EW SUSY

Highlight: 2/3l

\[ m_{T2} = \min_{q_T} \left[ \max \left( m_T(p_T^1, q_T), m_T(p_T^2, p_{T\text{miss}} - q_T) \right) \right] \]

Use \( E_{T\text{miss}}, m_{T2}, \) etc to gain info where lots of unmeasured particles

arXiv:1803.02762

+ arXiv:1806.02293 (New!)
Compressed spectra in SUSY

\[ \tilde{t}_1 \) production, \( \tilde{t}_1 \to b f f' \tilde{\chi}_1^0 / \tilde{t}_1 \to c \tilde{\chi}_1^0 / \tilde{t}_1 \to W b \tilde{\chi}_1^0 / \tilde{t}_1 \to t \tilde{\chi}_1^0 \]

May 2018

\[ m(\tilde{\chi}_1^0) \] [GeV] vs \[ m(\tilde{t}_1) \] [GeV]

**ATLAS Preliminary**

- 0L [1709.04183]
- 1L [1711.11520]
- 2L [1708.03247]
- Monojet [1711.03301]
- c0L [1805.01649]
- Run 1 [1506.08616]

Observed limits, Expected limits, All limits at 95% CL
Compressed spectra in SUSY

LSP a lot lighter than stop: nice easy signatures, maybe even boosted
Compressed spectra in SUSY

May 2018

Mass splitting smaller than top mass: decays suppressed
Compressed spectra in SUSY

Mass splitting really small: “compressed”. SM particles so soft they are hard to detect
Compressed spectra in SUSY

May 2018

ATLAS Preliminary

$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \rightarrow W b \tilde{\chi}_1^0$  
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \rightarrow W b \tilde{\chi}_1^0$  
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Observed limits  
Expected limits  
All limits at 95% CL

$\sqrt{s}$=13 TeV, 36.1 fb$^{-1}$

0L [1709.04183]  
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2L [1708.03247]  
Monojet [1711.03301]  
c0L [1805.01649]  
Run 1 [1506.08616]

arXiv:1708.08232

+ ISR jet for boost!
A challenging corner: Higgsinos

Dedicated search for compressed EW scenarios (arxiv: 1712.08119) handles mid-range

When sufficiently compressed, decays suppressed and Higgsino becomes long-lived: search via disappearing tracks (arxiv:1712.02118)
A challenging corner: Higgsinos

Dedicated search for compressed EW scenarios [arxiv:1712.08119] handles mid-range

Not currently accessed!

When sufficiently compressed, decays suppressed and Higgsino becomes long-lived: search via disappearing tracks [arxiv:1712.02118]
RPC meets RPV: Long-lived charginos

Short lifetimes are more difficult

Decay lengths outside the detector = stable for us
RPC meets RPV: Stops

\[ \tilde{\chi}_1^0 \rightarrow \chi_1^0 \rightarrow t \tilde{b}_s \]

\[ m(\tilde{t}_1) \leq 200 \text{ GeV}, \text{ bino-like} \]

\[ \lambda'' \leq 13 \text{ TeV} \]

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \text{Expected} \]

\[ \text{Observed} \]

\[ \text{95\% CL limits} \]

\[ \text{RPC meets RPV: Stops} \]

\[ \text{More RPC-like} \quad \leftrightarrow \quad \text{More RPV-like} \]
RPC meets RPV: Stops

\[ m(t_{\tilde{t}}) \text{ [GeV]} \]

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV} \)

- **RPC Stop 0L (36.1 fb\(^{-1}\))**
- **RPC Stop 1L (36.1 fb\(^{-1}\))**
- **RPV 1L (36.1 fb\(^{-1}\))**
- **Dijet (37 fb\(^{-1}\)), TLA (3.2 fb\(^{-1}\))**
- **Dijet pairs (36.7 fb\(^{-1}\))**

95\% CL limits

**Forbidden by RGE:** Phys. Rev. D60 (1999) 056002

More RPC-like \[ \rightarrow \] More RPV-like

**RPC-RPV Combination:** \( \tilde{t} \rightarrow t\tilde{\chi}_1^0 (\rightarrow tbs) / \tilde{t} \rightarrow bs, m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{ bino-like} \tilde{\chi}_1^0 \)**
RPC meets RPV: **Stops**

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV} \]

- Blue: RPC Stop 0L (36.1 fb\(^{-1}\))
- Light Blue: RPC Stop 1L (36.1 fb\(^{-1}\))
- Green: RPV 1L (36.1 fb\(^{-1}\))
- Red: Dijet (37 fb\(^{-1}\)), TLA (3.2 fb\(^{-1}\))
- Black: Dijet pairs (36.7 fb\(^{-1}\))

95% CL limits

\[ m(\tilde{t}_1) [\text{GeV}] \]

\[ \lambda'' \]

More RPC-like \arrow{<} More RPV-like

"or here!"

So don’t let this scare you:

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\int F d\tau$(fb$^{-1}$)</th>
<th>Mass limit</th>
<th>$\sqrt{s}$ = 7, 8 TeV</th>
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**Inclusive Searches**

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**Other**

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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
These are ideal-case limits intended for reinterpretation: simple BR assumptions, straightforward parameter choices... there is still space for a <2 TeV gluino, just in more complicated scenarios!

So don’t let this scare you:

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
BSM Higgs
The BSM Higgs program

Additional Higgses

• Many models (incl. 2HDM) postulate additional Higgs bosons

• Charged higgses or heavier equivalents of SM Higgs

Higgs to Invisible

• Look for production of DM particles by decays of SM Higgs

• Uncertainty on SM Higgs production $\sigma$ is $\sim 30\%$, so sufficient “wiggle room” to allow this
Recent highlights:
Heavy Higgs to ZH

- Search in Z→ll, (another non-SM) H→bb. Possible additional b-jets in association with A.

- Results framed in 2HDM model with various parameter choices for generality.
(Other) exotics searches
Exotics search methodology

- Largely signature driven
- Each signature open to range of BSM models
- Various dedicated summary or combination efforts in Run II
Exotics search methodology

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- Various dedicated summary or combination efforts in Run II

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

95% C.L. exclusion limits

- HVT model B \( g_v = 3 \)
- Observed
- Expected
- \( q\bar{q}q \)
- \( l\nu qq \)
- \( l\bar{l}qq \)
- \( v\bar{v}qq \)

**MET+X**

- Diboson
- Heavy scalars
- New (spin-1 or 2) bosons
- Black holes
- Dark matter
- Jet pairs
- Compositeness
- Heavy flavour
Recent highlights: lepton+MET

\[ m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \phi_{\ell\nu})} \]

- Search for heavy resonances decaying to e/μ + ν
- W’ boson used as benchmark model to define limits
- One of first 80/fb “intermediate” ATLAS results
Recent highlights: TLA

- Dijet final state open to many models. Here, look for $Z'$ mediator

- Use jets at trigger level to access low cross section, low mass signals

ATLAS

- Data, 29.3 fb$^{-1}$, $|y^*| < 0.6$
- Background fit
- BumpHunter interval
- $Z'$, $\sigma \times 500$
  
  $m_Z = 750$ GeV, $g_q = 0.1$
  
  BH $p$-value = 0.44
  
  $\chi^2$ $p$-value = 0.13

- Data, 3.6 fb$^{-1}$, $|y^*| < 0.3$
- Background fit
- BumpHunter interval
- $Z'$, $\sigma \times 500$
  
  $m_Z = 550$ GeV, $g_q = 0.1$
  
  BH $p$-value = 0.6
  
  $\chi^2$ $p$-value = 0.42

ATLAS

95% CL upper limits

- Observed
  
  $\sigma / m_G = 0.05$
  
  $\sigma / m_G = 0.07$
  
  $\sigma / m_G = 0.10$

- Expected
  
  $\sigma / m_G = 0.05$ ($\pm 1-2\sigma$)
  
  $\sigma / m_G = 0.07$
  
  $\sigma / m_G = 0.10$
Recent highlights: vector-like quarks

- Example of increasing usage of machine learning in ATLAS: one signal region defined via a BDT!
- Only events not in traditional SR considered in BDT selection
Exotics constraints on dark matter

**Z’ simplified model**
- Assume vector or axial-vector mediator
- Strong constraints from mono-X, dijet(+X), dilepton analysis families
- Public plots out now, see next page!

**2-Higgs doublet model**
- More realistic benchmark
- Still simplified, but UV-complete
- Strong constraints from mono-X, heavy flavour analyses
- Summary in whitepaper

[arxiv:1507.00966](https://arxiv.org/abs/1507.00966)
[arxiv:1701.07427](https://arxiv.org/abs/1701.07427)
Dark matter: Z’ mediator summary

- Results still depend a lot on the assumptions we make, even with just 5 free parameters!
- Plots: axial-vector mediator (vector mediator in backup)
  - Top: \( g_L = 0.1, \ g_q = 0.1 \)
  - Bottom: \( g_L = 0, \ g_q = 0.25 \)
Comparing collider DM limits to the rest of the field

DM Simplified Model Exclusions

Spin-independent DM-nucleon $\sigma$

$\sigma_{SI}$ (DM-nucleon) $[cm^2]$

$10^{-37}$

$10^{-38}$

$10^{-39}$

$10^{-40}$

$10^{-41}$

$10^{-42}$

$10^{-43}$

$10^{-44}$

$10^{-45}$

$10^{-46}$

$10^{-47}$

$10^{-48}$

1

10

100

1000

DM Mass [GeV]

Dijet

Dijet 8 TeV $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$


Dijet $\sqrt{s} = 13$ TeV, 37.0 fb$^{-1}$

arXiv:1703.09127 [hep-ex]

Dijet TLA $\sqrt{s} = 13$ TeV, 3.4 fb$^{-1}$

ATLAS-CONF-2016-030

Dijet + ISR $\sqrt{s} = 13$ TeV, 15.5 fb$^{-1}$

ATLAS-CONF-2016-070

$E_T^{miss} + X$

$E_T^{miss} + \gamma$ $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$


$E_T^{miss} + $ jet $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

ATLAS-CONF-2017-060

$E_T^{miss} + Z$ $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

ATLAS-CONF-2017-040

CRESST II

arXiv:1509.01515v1

XENON1T

arXiv:1705.06655v2

PandaX

arXiv:1607.07400

LUX


Vector mediator, Dirac DM

$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$

ATLAS limits at 95% CL, direct detection limits at 90% CL
Comparing collider DM limits to the rest of the field

- Axial vector mediators, spin dependent limits

Important to place collider results in wider context!
Now what?
Search program in early Run II focused on low-hanging fruit: strongly produced signatures, simple final states, simple detector needs
Up and out

Now working up the tree: EW SUSY, low mass or low cross section signals are still benefitting from increasing luminosity
Up and out

Lots left to do which is hard to see or hard to access! Really compressed states, long lived particles, signatures with interference…
Improving performance improves analyses!

- Instead of sitting and waiting for a slow accumulation of luminosity, push performance improvements and analysis reach improves.

\[ ATLAS \text{ Simulation Preliminary} \]
\[ \sqrt{s} = 13 \text{ TeV} \]
\[ \text{anti } k_T \text{ R=1.0, WZ } \rightarrow \text{qqqq} \]
\[ p_T^{\text{jet}} < 2.0, \ p_T^{\text{jet}} > 200 \text{ GeV} \]

**Example:** new jet inputs in VVJJ improve resolution!

**Example:** improving b-tagging efficiency would benefit searches!
The search and measurement lifecycle
The search and measurement lifecycle

Search becomes limited by SM prediction accuracy/uncertainties

NNPDF 3.1 NNLO Q= 2.0 GeV

\( \chi^2/N \) dN/dx vs. x

\( 10^{-5} \to 10^0 \)

\( 10^{-4} \to 10^{-3} \)

\( 10^{-2} \to 10^{-1} \)

\( 10^0 \)

\( 3.4 < m_{jj} < 3.7 \) TeV

\( 3.4 < m_{jj} < 4.0 \) TeV

\( 4.3 < m_{jj} < 4.6 \) TeV

\( \geq 4.9 \) TeV

\( \geq 5.4 \) TeV

\( \geq 4.6 \) TeV

\( \geq 4.0 \) TeV

\( \geq 3.7 \) TeV

\( \geq 3.4 \) TeV

\( \geq 3.0 \) TeV

\( \geq 2.5 \) TeV

\( \geq 2.0 \) TeV

\( \geq 1.5 \) TeV

\( \geq 1.0 \) TeV

\( \geq 0.5 \) TeV

Data

SM ±22 TeV

ATLAS

L=81 nb⁻¹ - 3.2 fb

\( \sqrt{s} = 13 \) TeV

anti-\( k_T \) \( R=0.4 \)

NLO QCD

\( k_{EW} \otimes k_{NP} \)

\( H_{R} = \mu_{F} = P_{T}^{\text{max}} \)

CT14

\( \text{HERAPDF 2.0} \)

\( \text{ABMP16} \)

arxiv:1703.09127

Theoretical uncert.

Total uncertainty

The search becomes limited by SM prediction accuracy/uncertainties.
The search and measurement lifecycle

Search becomes limited by SM prediction accuracy/uncertainties

Measurement provides new input for theory predictions

ATLAS

$\sqrt{s} = 13$ TeV

anti-$k_T$ $R=0.4$

$L = 81 \text{nb}^{-1}$ - 3.2 fb

$\chi^2/N_dN/d$
The search and measurement lifecycle

Predictions improve

Search becomes limited by SM prediction accuracy/uncertainties

Measurement provides new input for theory predictions

ATLAS

\( L = 81 \text{nb}^{-1} \cdot 3.2 \text{fb}^{-1} \)

\( \sqrt{s} = 13 \text{TeV} \)

anti-\( k_T \) \( R = 0.4 \)

Data

NLO QCD

\( k_{\text{EW}} \otimes k_{\text{NP}} \)

\( R_\mu = r_\mu = \rho_{\mu}^{\text{max}} \)

\( \mu \)

CT14

HERAPDF 2.0

ABMP16

arXiv:1703.09127
The BSM landscape at 13 TeV

Looked under most of the obvious rocks …

… time to start getting more complex!
Thanks! Any questions?
Backup
Additional info: SUSY opposite sign dilepton

- “High-pT lepton search” addresses non-compressed cases where kinematic edge near the Z peak
- “Low-pT lepton search” addresses small Δm between two lightest neutralinos: compressed scenario
- Simplified model: set masses of all not-relevant particles very high so they decouple
- Key backgrounds: Z/γ* + jets, fake leptons, diboson and rare top processes
Additional info: SUSY 2/3 lepton EW search

- The idea: if squarks & gluinos are a lot heavier than sleptons/charginos/neutralinos, then higher cross sections doesn’t benefit them in search.

- Simplified model: take mass-degenerate, pure wino chargino1 & neutralino2; mass-degenerate sleptons.

- Many individual signal regions defined by $m_{\text{ll}}$, $m_{T2}$, number of jets, MET, … Just a few sample distributions shown here!

And go look up the RJR analysis!
Additional info: SUSY stop to charm

- Model: stop pair production with flavour violation, allowing decay to charm + LSP, or flavour-conserving charm squark pair production. Assume 100% BR to c+LSP in both.

- Require 2j, >= 1 c-tagged jets, MET, lepton veto. SR’s further cut on cjet+MET transverse mass to reduce τ contamination

- Separate signal regions with softer/harder, more/fewer jets for various levels of compression
Additional info: Exotics VLQs

- Vector-like quarks couple preferentially to 3rd generation and allow flavour-changing neutral currents as well as regular quark-like charged current decays
  - E.g. T VLQ can give $T \rightarrow (W_b, Z_t, H_t)$
- Classify events by number of jets, b-jets, leptons.
- RECOSR: 3 large-R jets, one W-tagged. b-jet not near lepton. $S_T$ (scalar sum of MET, lepton, small-R jet pTs) must be large. BDTSR: trained and used on events which do not pass RECOSR.

$S_T$, large-R jet mass best BDT variables
Vector mediator DM summary plots: leptophobic

DM Simplified Model Exclusions

ATLAS Preliminary July 2017

DM Mass [TeV]

Mediator Mass [TeV]

Vector mediator, Dirac DM

\( g_q = 0.25, g_l = 0, g_{DM} = 1 \)

All limits at 95% CL

\[ 2 \times \text{DM Mass} = \text{Mediator Mass} \]

\[ \Omega h^2 = 0.12 \]

\[ \sum_\text{Thermal Relic} \]

\[ \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \]

arXiv:1703.09127 [hep-ex]

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]


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ATLAS-CONF-2016-030

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ATLAS-CONF-2017-060

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ATLAS-CONF-2017-040

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arXiv:1703.09127 [hep-ex]
Vector mediator DM summary plots: leptophilic

DM Mass [TeV] vs Mediator Mass [TeV] with exclusions and limits from various ATLAS analyses:

- Dijet: $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$ (Phys. Rev. D. 91 052007 (2015))
- Dijet: $\sqrt{s} = 13$ TeV, 37.0 fb$^{-1}$ (arXiv:1703.09127 [hep-ex])
- Dijet: $\sqrt{s} = 13$ TeV, 3.4 fb$^{-1}$ (ATLAS-CONF-2016-030)
- Dijet + ISR: $\sqrt{s} = 13$ TeV, 15.5 fb$^{-1}$ (ATLAS-CONF-2016-070)

DM Mass = Mediator Mass $\times 2$

Thermal Relic $\Omega h^2 = 0.12$

Vector mediator, Dirac DM
$g_{\rho} = 0.1$, $g_{\rho q} = 0.01$, $g_{\rho DM} = 1$

All limits at 95% CL