BSM Experimental Searches 1

Zach Marshall (LBNL), CERN-Fermilab HCP Summer School, 31 August 2021
A quick word about me

• Brief summer on CMS in 2005
• Working on ATLAS since 2006
• PhD on ATLAS in 2010
  • Jet shape measurements
• Share time between a few areas in ATLAS
  • SUSY (vanilla and weird searches)
  • Jets (response, SM measurements)
  • Software (simulation, generation, analysis)
• Several positions within ATLAS
  • SUSY search group convener (’16-’18)
  • Deputy computing coordinator (’20-’21)
  • Computing co-coordinator (’21-’22)
Before we get too far…

• I’m gonna talk about a whole bunch of new physics searches and techniques
• Please go ahead and send me a note or write in the chat any particular new physics searches / techniques / models that you’re interested in, and I’ll try to be sure they’re covered in the next lectures
Outline

• Starting a search
• Designing a search
• Estimating backgrounds
• Reporting results
• LLP/Unusual searches

Disclaimer: I’m going to show mostly ATLAS results; I know those best. CMS has done much of the same work (and we share many standards)

Note: Most pictures in these talks are links to the paper / source
So Much Data!

- We measure our data set in inverse cross-section
- Multiply by the cross section to get an event count (or rate)
So Much Data!

- Peak: 1 Higgs boson per second
  - Higgs production is an important background for searches!
- Approx. 67k top quark pairs from the Tevatron; we collect more than that every hour
- Sensitive down to quite small cross sections and rare processes with our full Run 2 dataset (about 140/fb)
Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 5,7,8,13$ TeV

LHC pp $\sqrt{s} = 5$ TeV
Data 0.025 fb$^{-1}$

LHC pp $\sqrt{s} = 7$ TeV
Data 4.5 – 4.9 fb$^{-1}$

LHC pp $\sqrt{s} = 8$ TeV
Data 20.2 – 20.3 fb$^{-1}$

LHC pp $\sqrt{s} = 13$ TeV
Data 3.2 – 79.8 fb$^{-1}$

1 event/s
140 events
14 events
Standard Model Production Cross Section Measurements

**ATLAS** Preliminary

Run 1,2 $\sqrt{s} = 5,7,8,13$ TeV

- **LHC pp $\sqrt{s} = 5$ TeV**
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- **LHC pp $\sqrt{s} = 13$ TeV**
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**ME**

**MEASUREMENT**

**IS THIS A SEARCH?**

- 140 events
- 14 events
What is a search?

• Measurements are searches too!
• “Above 160 GeV… a probability of 1% that the excess is due to a fluctuation.”
• “The best agreement with our data is for $\Lambda_C < 1.6$ TeV”
• Unfortunately, we didn’t find quark compositeness, we found the gluon in the proton…
• Small industry now devoted to reinterpretation
• But for now, we’ll talk about intentional searches
Starting a search

- My favorite way to think about a new project is to think about the **paper**
- What is the **title** of the paper?
- What are the sections of the paper?
- What are the **main plots** in the paper?

- Once I can draw those plots with a crayon, I am ready
  - Different people have different ideas of how much prep to do...
Blinding

- Blinding is one of the biggest philosophical discussions in searches
  - Many measurements are not blind
- What it usually means is “don’t look at your signal region data until your background estimation is finalized.”
- In some cases it is very hard to do.
- It is not strictly necessary, and usually is not strictly required, to do good physics
- It is very helpful to avoid biases
  - ALWAYS COMPARE EXPECTED LIMITS
- Do not take blinding as a religion
  - If you look in your SR and see something stupid, go back and try again.
Searching Step 0: What am I Looking For?

• Identifying a *model* or *signature* of interest is a great starting point
Why a signature? Why a model?

- Signatures are *general*
- They don’t rely on *biases* of the pheno community
- They let you *explore* interesting detector / detection problems
- **Extremely hard** for ‘vanilla’ signatures (jets+MET)

- Models are (usually) *physical*
- Someone has worked out the *implications* in the real world
- They allow *comparisons* between searches and other experiments
- May allow *detailed optimization* (also *bad*)

- Signatures don’t necessarily have fewer or more parameters than models
- A search for a signature doesn’t necessarily mean interpretation is easier or harder
My Opinion

- Let a good *model* guide you to an interesting *signature*
- Then generalize your search based on that *signature*
Dealing with a model

- This is a(n example of a) simplified model
Dealing with a model

- This is an example of a) simplified model

\[ \tan(\beta) = 30, \ A_0 = -2m_0, \ \mu > 0 \]

**ATLAS**

- $\sqrt{s} = 8$ TeV, $L = 20$ fb$^{-1}$

All limits at 95% CL.
Dealing with a model

• This is a(n example of a) simplified model
Dealing with a model

• This is an example of a) simplified model
• Two new particles

Squark

Neutralino/
LSP/
Dark Matter
Dealing with a model

- This is an example of a simplified model
- Two new particles
- One decay possibility

Jet

$p$

$q$

I can search for that 😊
So many options!
So many options!
Back to our model…

• What are the **free parameters** of our model?
  
  • We have to make the thing: there’s a production cross section.
  
  • Two new particles mean two new masses.
Back to our model…

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  • We have to make the thing: there’s a production cross section.
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```
<table>
<thead>
<tr>
<th>LSP Mass</th>
<th>Squark Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>q</td>
</tr>
<tr>
<td>q</td>
<td>p</td>
</tr>
</tbody>
</table>
```
Back to our model...

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![Diagram showing LSP and squark masses with light and heavy LSP and squark regions](image)

- Lighter Squark
- Heavier LSP
- Low energy jets!
Back to our model…

• What are the **free parameters** of our model?
  • We have to make the thing: there’s a production cross section.
  • Two new particles mean two new masses.
Back to our model…

• What is our **signature**?

• Jets with MET, but how much of each depends on where we are in the **parameter space**
Back to our model…

- What are our **assumptions**?
  - Is this SUSY, so that we know the production cross section?
  - What about the other particles?
    - Do we *really* know the cross section?
    - Could there be other decays?
    - Would they help us or hurt us?
  - Do the squarks have a lifetime?

\[ p \rightarrow \tilde{q} \tilde{q} \tilde{\chi}^0_1 \tilde{\chi}^0_1 \tilde{q} \rightarrow q q \tilde{\chi}^0_1 \tilde{\chi}^0_1 \]
Those Assumptions

• Always keep an eye on those assumptions you’re making!

• Remember, the goal is to **find new physics**, not to search for a diagram.

• A change to your search might make you a bit more sensitive to your particular model, but **at what cost**?

• When reading papers, be very careful with assuming that they have or **do not have** sensitivity to a slightly different model

  • Especially when the slight difference is something like a lifetime
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SURPRISE! It was a leptoquark search the whole time!
Those Assumptions

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- When reading papers, be very careful with assuming that they have or **do not have** sensitivity to a slightly different model
  - Especially when the slight difference is something like a lifetime

SURPRISE!

It was a dark matter search the whole time!
Those Assumptions

- This becomes a big issue when thinking about backgrounds.
Those Assumptions

- This becomes a big issue when thinking about backgrounds.
Those Assumptions

• This becomes a big issue when thinking about backgrounds

• Be extremely careful!
  • Can you use photon+jets to estimate Z+jets? W+jets?
  • Can you use different flavor leptons to estimate same-flavor leptons?

• Very clever data-driven estimates often suffer from model-dependent signal contamination
But what about a signature?

• Commonly overheard: “But I’m searching for a signature, so this is fully general! I have no assumptions!”
But what about a signature?

- If your signal is far easier to find in other ways, your search probably isn’t the right one.
- If I want displaced photons, this model works:

  \[
  \begin{array}{c}
  p \\
  \hline
  LLP \\
  \hline
  p \\
  \hline
  h \\
  \hline
  X \\
  \end{array}
  \]

- But Higgs bosons don’t like to decay to photons. Gonna be way easier to find other ways.
- This doesn’t mean you shouldn’t look for displaced photons!
- It just means you should optimize with a different signal.
But what about a signature?

• If your signal is far easier to find in other ways, your search probably isn’t the right one

• If I want **displaced photons**, this model *actually* works:

![Diagram](image)

• But Higgs bosons *don’t like to decay to photons*. Gonna be way easier to find other ways.

• This *doesn’t mean* you shouldn’t look for displaced photons!

• It just means you should optimize with a different signal.
But what about a signature?

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• If I want **displaced leptons**, this model works:

  ![Diagram](https://example.com/diagram.png)

  - But to avoid the $Z'$ decay to quarks (and a dijet search), I have to reduce the coupling to quarks, which changes the production cross section for the model

  • Doesn’t mean this isn’t worth searching for! Just have to be careful that the model makes sense.
But what about a signature?

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- If I want displaced leptons, this model **actually** works:

  ![Diagram](image)

- But to avoid the $Z'$ decay to quarks (and a dijet search), I have to reduce the coupling to quarks, which changes the production cross section for the model

- Doesn’t mean this isn’t worth searching for! Just have to be careful that the model makes sense.
We’ve done a few searches.

ATLAS Exotics Searches - 95% CL Upper Exclusion Limits

Selected CMS SUSY Results - SMS Interpretation

ATLAS SUSY Searches - 95% CL Lower Limits

CMS Preliminary

L = 13 TeV

L = 12.9 fb⁻¹ L = 35.9 fb⁻¹

*Observed limits at 95% C.L. - theory uncertainties not included.
Only a selection of available mass limits. Probe "up to" the quoted mass limit for m0 → 0 GeV unless stated otherwise.

Selected CMS SUSY Results - SMS Interpretation

ICHEP ’16 + Moriond ’17
Splitting Things Up

- A search can be sensitive to **many** signals

- ATLAS divides searches into
  - SUSY: *primarily* SUSY-motivated models
  - HDBS: *primarily* Higgs BSM models
  - Exotics: everything else

- CMS divides searches into
  - SUSY: *primarily* light-flavor SUSY
  - B2G: *primarily* models with heavy flavor
  - Exotica: everything else, including *all* LLPs

- LHCb has one group with most searches

- ALICE has no search group that I know of
Searching Step 1: Designing a Search

• Now that we have a model, we have to go look for it!

• Pro Tip: For most searches, aim to do one or two difficult things.
  • If you’re a phenomenologist: find that difficult thing they did.
  • If you’re watching a talk: ask about that difficult thing they did.
Back to our model

• What are the characteristics of your signature?
• What makes this different from the Standard Model and how can you isolate those?

[Diagram with symbols for particle interactions and missing transverse momentum]
Back to our model

- What are the characteristics of your signature?
- What makes this different from the Standard Model and how can you isolate those?

(Now would be a good time to run off and generate some events to play with)
First and Foremost: The Trigger

- All experiments have a complex, multi-level trigger system to identify events to read out
- If it doesn’t pass the trigger, it’s gone forever
- Two stages:
  - Coarse, fast (µs), hardware-based (Level 1)
  - Detailed, slow (s), software-based (HLT)
- For most searches, the Level 1 trigger is the hard part
- In a nutshell: there had better be something interesting / different about your signal!
- There is a cottage industry devoted to pointing out novel signatures that could be missed, and then finding other cool ways to pick out the events
# Trigger: Keep it Simple

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Typical offline selection</th>
<th>Trigger Selection</th>
<th>L1 Peak Rate [kHz]</th>
<th>HLT Peak Rate [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L1 [GeV]</td>
<td>HLT [GeV]</td>
<td>L=2.0x10^{24} cm^{-2} s^{-1}</td>
</tr>
<tr>
<td>Single leptons</td>
<td>Single isolated $\mu$, $p_T &gt; 27$ GeV</td>
<td>20</td>
<td>26 (i)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Single isolated tight $e$, $p_T &gt; 27$ GeV</td>
<td>22 (i)</td>
<td>26 (i)</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Single $\mu$, $p_T &gt; 52$ GeV</td>
<td>50</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Single $e$, $p_T &gt; 61$ GeV</td>
<td>60</td>
<td>22 (i)</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Single $\tau$, $p_T &gt; 170$ GeV</td>
<td>160</td>
<td>100</td>
<td>1.4</td>
</tr>
<tr>
<td>Two leptons</td>
<td>Two $\mu$, each $p_T &gt; 15$ GeV</td>
<td>2 x 10</td>
<td>2 x 14</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Two $\mu$, each $p_T &gt; 23$, 9 GeV</td>
<td>20</td>
<td>22.8</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Two very loose $e$, each $p_T &gt; 18$ GeV</td>
<td>2 x 15 (i)</td>
<td>2 x 17</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>One $e$ &amp; one $\mu$, $p_T &gt; 8$, 25 GeV</td>
<td>20 ($\mu$)</td>
<td>7, 24</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>One loose $e$ &amp; one $\mu$, $p_T &gt; 18$, 15 GeV</td>
<td>15, 10</td>
<td>17, 14</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>One $e$ &amp; one $\mu$, $p_T &gt; 27$, 9 GeV</td>
<td>22, (c, i)</td>
<td>26, 8</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Two $\tau$, $p_T &gt; 40$, 30 GeV</td>
<td>20 (i), 12 (+jets, topo)</td>
<td>35, 25</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>One $\tau$ &amp; one isolated $\mu$, $p_T &gt; 30$, 15 GeV</td>
<td>12 (i), 10 (+jets)</td>
<td>25, 14 (i)</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>One $\tau$ &amp; one isolated $e$, $p_T &gt; 30$, 18 GeV</td>
<td>12 (i), 15 (i) (+jets)</td>
<td>25, 17 (i)</td>
<td>4.6</td>
</tr>
<tr>
<td>Three leptons</td>
<td>Three very loose $e$, $p_T &gt; 25$, 13, 13 GeV</td>
<td>20, 2 x 10</td>
<td>24, 2 x 12</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Three $\mu$, each $p_T &gt; 7$ GeV</td>
<td>3 x 6</td>
<td>3 x 6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Three $\mu$, $p_T &gt; 21$, 2 x 5 GeV</td>
<td>20</td>
<td>20, 2 x 4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Two $\mu$ &amp; one loose $e$, $p_T &gt; 2 x 11$, 13 GeV</td>
<td>2 x 10 ($\mu$)</td>
<td>2 x 10, 12</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Two loose $e$ &amp; one $\mu$, $p_T &gt; 2 x 13$, 11 GeV</td>
<td>2 x 8, 10</td>
<td>2 x 12, 10</td>
<td>2.3</td>
</tr>
<tr>
<td>Signle photon</td>
<td>One loose $\gamma$, $p_T &gt; 145$ GeV</td>
<td>24 (i)</td>
<td>140</td>
<td>24</td>
</tr>
<tr>
<td>Two photons</td>
<td>Two loose $\gamma$, each $p_T &gt; 55$ GeV</td>
<td>2 x 20</td>
<td>2 x 50</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Two $\gamma$, $p_T &gt; 40$, 30 GeV</td>
<td>2 x 20</td>
<td>35, 25</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Two isolated tight $\gamma$, each $p_T &gt; 25$ GeV</td>
<td>2 x 15 (i)</td>
<td>2 x 20 (i)</td>
<td>2.0</td>
</tr>
<tr>
<td>Single jet</td>
<td>Jet ($R = 0.4$), $p_T &gt; 435$ GeV</td>
<td>100</td>
<td>420</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Jet ($R = 1.0$), $p_T &gt; 480$ GeV</td>
<td>2.6</td>
<td>460</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Jet ($R = 1.0$, $p_T &gt; 450$ GeV, $m_{jets} &gt; 45$ GeV)</td>
<td>111 (topo: $R = 1.0$)</td>
<td>420, $m_{jets} &gt; 35$</td>
<td>2.6</td>
</tr>
<tr>
<td>$b$-jets</td>
<td>One $b$ ($e = 60%$), $p_T &gt; 285$ GeV</td>
<td>100</td>
<td>275</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Two $b$ ($e = 60%$), $p_T &gt; 185, 70$ GeV</td>
<td>100</td>
<td>175, 60</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>One $b$ ($e = 40%$) &amp; three jets, each $p_T &gt; 85$ GeV</td>
<td>4 x 15</td>
<td>4 x 75</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Two $b$ ($e = 70%$) &amp; one jet, $p_T &gt; 65, 65, 160$ GeV</td>
<td>2 x 30, 85</td>
<td>2 x 55, 150</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Two $b$ ($e = 60%$) &amp; two jets, each $p_T &gt; 65$ GeV</td>
<td>4 x 15, $</td>
<td>y</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>Multijets</td>
<td>Four jets, each $p_T &gt; 125$ GeV</td>
<td>3 x 50</td>
<td>4 x 115</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Five jets, each $p_T &gt; 95$ GeV</td>
<td>4 x 15</td>
<td>5 x 85</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Six jets, each $p_T &gt; 80$ GeV</td>
<td>4 x 15</td>
<td>6 x 70</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Six jets, each $p_T &gt; 60$ GeV, $</td>
<td>y</td>
<td>&lt; 2.0$</td>
<td>4 x 15</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>$E_T^{miss} &gt; 200$ GeV</td>
<td>50</td>
<td>110</td>
<td>5.1</td>
</tr>
<tr>
<td>$B$-physics</td>
<td>Two $\mu$, $p_T &gt; 11, 6$ GeV, $0.1 &lt; m(\mu, \mu) &lt; 14$ GeV</td>
<td>11, 6</td>
<td>11, 6 (di-$\mu$)</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Two $\mu$, $p_T &gt; 6, 6$ GeV, $2.5 &lt; m(\mu, \mu) &lt; 4.0$ GeV</td>
<td>2 x 6 ($\mu$-$\mu$, topo)</td>
<td>2 x 6 ($\mu$-$\mu$)</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Two $\mu$, $p_T &gt; 6, 6$ GeV, $4.7 &lt; m(\mu, \mu) &lt; 5.9$ GeV</td>
<td>2 x 6 (B, topo)</td>
<td>2 x 6 (B)</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Two $\mu$, $p_T &gt; 6, 6$ GeV, $7 &lt; m(\mu, \mu) &lt; 12$ GeV</td>
<td>2 x 6 ($\mu$, topo)</td>
<td>2 x 6 ($\mu$, topo)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Main Rate: 86

$B$-physics and Light States Rate: 1750

200
Trigger: Keep it Simple

• Most searches rely on *simple triggers* like MET or single-lepton.
• Complexity is an enemy in the trigger! Require ≤ what you have.
  • For multi-lepton signals: can you require only *one* lepton in the trigger?
  • Do you *need* to require a b-tagged jet? If not, then don’t!
• Very high *efficiency* is the name of the game here.
  • You can always remove it later, if you *want to*, but keep as much as possible in the recorded data!

<table>
<thead>
<tr>
<th>Type</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Lepton</td>
<td>545 (mostly e/µ)</td>
</tr>
<tr>
<td>Multi-lepton</td>
<td>251 (mostly tau)</td>
</tr>
<tr>
<td>Photon(s)</td>
<td>90 (half 1 photon)</td>
</tr>
<tr>
<td>Jet(s)</td>
<td>158 (75% 1 jet)</td>
</tr>
<tr>
<td>b-Jets</td>
<td>72</td>
</tr>
<tr>
<td>MET</td>
<td>94</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1750</strong></td>
</tr>
</tbody>
</table>
Trigger: It’s there when you need it

- When you can’t keep it simple, the trigger can quickly get very complex
- There are many one-analysis triggers out there!
  - Triggers with very unusual configurations of objects
  - Triggers for large energy deposits in the muon system or inner detector
  - Triggers for late particles
- This can get extremely sticky
  - Befriend someone who built the hardware if you want something really complicated!
- Lots of talk of track-based triggers for LHC Run 3 – let’s see what happens!
Reconstruction

- After we **record** the data, we need to **reconstruct** the objects.
- Searches often push objects to their limits in every direction:
  - Low momentum, high momentum, far forward, disappearing, re-appearing, displaced, delayed, non-pointing…
- There’s not a lot to say about this except: 1) this is a **lot of hard work**; 2) this is best done **for the experiment**; 3) we can go **much further than we thought**.
Reconstruction

• One of the big pushes in recent years has been for large radius tracking, for long-lived particles

• Tracking is very CPU-hungry, but both experiments work on neat tricks to keep it feasible

• The other key ingredient for many of these searches is detailed understanding of the detector – we’re able to do more than we could at the start up!
Non-Reconstruction

- Remember that sometimes you needn’t reconstruct everything.
- If I can’t reconstruct the quarks on the left, then the diagram is the same as the Dark Matter search on the right.
- If I can’t reconstruct a long-lived (weirdly behaving) particle, then often it “appears” as missing transverse momentum and I can still set a limit on the process!