Searches for New Physics at the LHC: an experimentalist's perspective

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What this talk is trying to do

• Aimed at theorists
• Give a sense of how searches for New Physics are carried out
• Give some rules-of-thumb to help think about them
• Point out issues on the theoretical side
Outline

- Cross sections (parton luminosities)
- Ingredients for discoveries
- Different type of searches
  - examples
  - comments on theoretical issues

Parton-Parton luminosities

- LHC opens up new energy regime
  - obvious
- A way to think about this and develop a semi-quantitative intuition:
  Look at parton-parton luminosities
- Hadron collider = collisions of two broadband beams of partons (q, q, and gluons)
- Define "effective luminosity" for parton-parton collisions as a function of the $E_{CM}$ of the parton-parton system
Parton-Parton luminosities (2)

- Parton-parton x-section, $i+j \rightarrow X$:
  \[
  \hat{\sigma}_{ij}(\hat{s}) \text{ at } E_{CM} = \sqrt{\hat{s}}
  \]

- $pp$ (or $pp$) x-section, $pp \rightarrow X$ or $pp \rightarrow X$:
  \[
  \sigma = \sum_i \int dx_i dx_j f_i(x_i) f_j(x_j) \hat{\sigma}_{ij}
  \]
  (the sum is over all the $i$'s and $j$'s that result in $X$)

- Rewrite it as:
  \[
  \frac{d\sigma}{d\tau} = \sum \frac{dL_{ij}}{d\tau} \hat{\sigma}_{ij} \quad \tau \equiv \frac{\hat{s}}{s}
  \]
  \[
  \frac{dL_{ij}}{d\tau} = \frac{1}{1 + \delta_{ij}} \int \frac{dx}{x} \left[ f_i(x) f_j(\frac{\tau}{x}) + f_j(x) f_i(\frac{\tau}{x}) \right]
  \]

Luminosity for parton-parton collisions as a function of parton-parton $E_{CM}$

Parton-Parton luminosities (3)

- $gg$ luminosity @ LHC
- $qq$ luminosity @ LHC
- $gg$ luminosity @ Tevatron
- $qq$ luminosity @ Tevatron

![Graph showing luminosity as a function of $\sqrt{s}$ (GeV)]
Zooming-in on the < 1 TeV region

\[ \sqrt{\hat{s}} \text{ (GeV)} \]

- gg luminosity @ LHC
- qq luminosity @ LHC
- gg luminosity @ Tevatron
- qq luminosity @ Tevatron

LHC vs Tevatron

1st (simplistic) rule of thumb:
- For 1 TeV gg processes, 1 fb\(^{-1}\) at FNAL is like 1 nb\(^{-1}\) at LHC
- For 1 TeV qq processes, 1 fb\(^{-1}\) at FNAL is like 1 pb\(^{-1}\) at LHC
Another rule of thumb:

$\frac{dL}{d\tau}$ falls steeply with $E_{\text{CM}}$

- In multi-TeV region, $\sim$ by factor 10 every 600 GeV
- New states produced near threshold
- Suppose you have a limit on some pair-produced object, $M > 1$ TeV
- How does your sensitivity improve with more data?

**Answer:** by $\sim (600/2)=300$ GeV $= 30\%$ for 10 times more lumi

Improving sensitivity with luminosity is tough...

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SM Cross Sections

Good to keep these in mind when thinking about NP

- $\sigma(\text{bb}, \text{high } P_T) \sim 1 \mu b$
- $\sigma(W \rightarrow \ell \nu) \sim 60 \text{ nb}$
- $\sigma(WW) \sim 200 \text{ pb}$
- $\sigma(tt) \sim 1 \text{ nb}$

Jet rates are enormous

$\sim 10 \mu b/\text{GeV} @ 100 \text{ GeV}$

$\sim 0.1 \text{ pb/GeV} @ 1 \text{ TeV}$

Also, another useful rule of thumb:

$\sigma(X+1\text{jet}) \sim 1/10 \sigma(X)$ for moderate ($\sim 30 \text{ GeV}$) $P_T$ jet
NP discoveries at the LHC

3 + 1 ingredients

0. **Detector and machine:** *If they don't work, forget it*
   - How fast will they come up? Don't know, but probably not fast.

1. **Trigger:** *If you didn't trigger on it, it never happened*
   - See next slide

2. **Backgrounds:** *It's the background, stupid*
   - Need to understand SM and instrumental backgrounds
     - Instrumental BG: experimentalists, mostly
     - Physics BG: theorists, mostly
   - There are exceptions....

3. **Searches:** *If you look for something, you may not find it. But if you don't look, you will never find it*
   - Model independent vs model dependent searches

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**Trigger**

- Inelastic cross section $O(100 \text{ mb})$
- For low luminosity $\sim 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, event rate $\sim 100 \text{ MHz}$
- Data Acquisition Capability: $\sim 100 \text{ Hz}$

**Most of the events are thrown away**
Example of possible CMS trigger menu (L=2 x 10^{33})

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV or GeV/c)</th>
<th>Rate (Hz)</th>
<th>Cumulative Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive electron</td>
<td>29</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Di-electrons</td>
<td>17</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Inclusive photons</td>
<td>80</td>
<td>4</td>
<td>38</td>
</tr>
<tr>
<td>Di-photons</td>
<td>40, 25</td>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>Inclusive muon</td>
<td>19</td>
<td>25</td>
<td>68</td>
</tr>
<tr>
<td>Di-muons</td>
<td>7</td>
<td>4</td>
<td>72</td>
</tr>
<tr>
<td>Inclusive τ-jets</td>
<td>86</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>Di-τ-jets</td>
<td>59</td>
<td>1</td>
<td>76</td>
</tr>
<tr>
<td>1-jet * E_T^{miss}</td>
<td>180 * 123</td>
<td>5</td>
<td>81</td>
</tr>
<tr>
<td>1-jet OR 3-jets OR 4-jets</td>
<td>657, 247, 113</td>
<td>9</td>
<td>89</td>
</tr>
<tr>
<td>Electron * Jet</td>
<td>19 * 45</td>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>Inclusive b-jets</td>
<td>237</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Calibration and other events (10%)</td>
<td></td>
<td>10</td>
<td>105</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>105</td>
</tr>
</tbody>
</table>

NP discovery ingredients

- Carefully crafted combinations of
  - photons
  - electrons
  - muons
  - taus
  - jets
  - b-tagged jets
  - missing transverse energy (MET)
- Or, something much more exotic, e.g. CHAMPS
- A quick look at the ingredients to develop intuition about them
  - particularly the questions of BG & fake rates
Jets

- Jets are everywhere
- Jets can fake isolated high $P_T \gamma$, e, $\mu$, $\tau$ signatures
  - Probability of jet faking a $\gamma$: $\sim$ few $10^{-4}$
  - Probability of faking e or $\mu$: $\sim$ 1 order of magnitude smaller
    - But some jets have real lepton, e.g., b-jets
  - Probability of faking a $\tau$: $\sim$ few $10^{-3}$
- Light quark or gluon jets fake b-quark signature at the % level

All of these to be measured on data (not MC)

Missing Transverse Energy

- Fake MET mostly from jets, resolutions and tails
- Also from missed muons
- Also from "underlying event"

Jet $E_T$ Resolution

And the tails don't come without some work....
• A little bit of intuition/knowledge of
  – cross-sections
  – triggers
  – fake rates
  is necessary to estimate whether something is feasible or not
• Hardest intuition is on MET tails

• Have easy to use tools to calculate x-section, kinematical distribution for many LO processes
e.g., COMPHEP

New Physics discoveries @ LHC

Broadly speaking, three possibilities

1. Self Calibrating
   • e.g., a mass peak

2. Counting experiments
   • The number of observed events of some type
     is >> than the SM prediction

3. Distributions
   • The distribution of some kinematical quantity
     is inconsistent with the SM prediction

NB: the distinction is not always clean, but still useful to think in these terms
Self Calibrating Signals (SCS)

- A NP signal that stands out and punches you in the face
  - where you do not need to know the SM BG very precisely
    - or do you?
    - watch out for irrational exuberance
- For example:
  - A mass peak
  - A huge distortion to some kinematical distribution
  - Something truly weird, e.g., a heavy slow particle

SCS example: $Z' \rightarrow \mu\mu$
Another SCS example: di-jet resonances

- If produced strongly, E6 di-quarks, Z', W', ...
- If produced weakly, tougher

Rules of thumb:

- e.g., excited quarks, axigluons, E6 di-quarks, Z', W', ...

Di-jet resonances (cont.)
(Yet) Another SCS example: di-jet mass distribution

- Distorts angular distributions
- More scatters at high angles
  - More jets at high $P_T$
  - More di-jets at high mass
- Like Rutherford scattering, but with quarks!

If the "edge" is low enough, this could be a relatively easy discovery (Self-calibrating variety)

Di-jet mass distribution distortion

- Ratio of events at high-low $\eta$ is a sensitive variable that eliminates many syst uncertainites

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>CMS</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>OCD</td>
<td>OCD</td>
</tr>
<tr>
<td></td>
<td>$\Lambda^* &lt; 5$ TeV</td>
<td>$\Lambda^* &gt; 10$ TeV</td>
</tr>
<tr>
<td></td>
<td>$\Lambda^* &gt; 15$ TeV</td>
<td>$\Lambda^* &gt; 15$ TeV</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>1.5</td>
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<tr>
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<td>1.0</td>
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<tr>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Stats. Err. for 100 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>Left-Handed Quark Contact Interaction</th>
<th>Left-Handed Quark Contact Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Lambda^*$ for 100 pb$^{-1}$ (TeV)</td>
<td>$\Lambda^*$ for 1 fb$^{-1}$ (TeV)</td>
</tr>
<tr>
<td></td>
<td>$\Lambda^*$ for 10 fb$^{-1}$ (TeV)</td>
<td>$\Lambda^*$ for 10 fb$^{-1}$ (TeV)</td>
</tr>
<tr>
<td></td>
<td>95% CL Exclusion</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>5$\sigma$ Discovery</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Esen and Harris (FNAL)
Gumus and Akchurin (Texas Tech)
Not all that glitters is gold.

 Especially in the tails of distributions.
An aside

Tail of the jet $E_T$ distribution. Definitely not a self calibrating signal (SCS)

- Data in the tail not consistent with QCD + (then) existing sets of parton distribution functions (PDFs)
- Looks like contact term $\Lambda \sim 1.6$ TeV
- Further PDF analysis found that the discrepancy could be absorbed by modifying gluon distribution
  - without conflicting with other data
  - even though all existing PDF fits were "low"
- Modern PDFs include uncertainties
- A great step forward

Example of careful, not-so-glamarous, phenomenological work that has a major impact

Counting experiments, distributions

- Not all NP signals are as dramatic as a mass peak
- Need to establish whether data is or is not compatible with SM
  -> Need the SM prediction
- In some cases the SM prediction can come entirely from the experiment (data driven)
  - Robust
- In other cases the SM prediction relies heavily on theory
  - Not so robust
- A couple of examples to understand typical issues
Example 1: CDF search for NP in lep + \(\gamma\) + MET

- www-cdf.fnal.gov/physics/exotic/r2a/20050714.loginovLepPhotonX/
- A fairly simple final state
- Motivated by a few weird events in Run 1
- Select events, then compare with SM
  - both number of events and kinematical distributions
- Requires careful accounting of SM sources
- A lot of work!
  - typical for this type of searches
  - painstaking accounting of many BG sources
  - you don't just "run the Monte Carlo"

SM contributions to lep+\(\gamma\)+MET (1)

- \(pp \rightarrow W+\text{jet}, \ W\rightarrow\text{lep}\ \nu, \ \text{jet fakes } \gamma\)
  - estimated from observed rate of \(W+\text{jet}\) and measured probability for jet to fake a \(\gamma\)
  - difficult (100% uncertainty), but data driven
- Drell-Yan \(e^+e^-\) pairs with hard brehmstrahlung, where the electron is lost and looks like a \(\gamma\) and the MET fluctuates high
  - estimated from observed rate of \(Z\rightarrow ee\) and \(Z\rightarrow e^+\gamma^-\) and observed MET distribution
  - data driven
- \(pp \rightarrow \text{jets}, \ \text{jets fake leptons}\)
  - estimated from data by relaxing the lepton quality requirements, and extrapolating
SM contributions to lep+γ+MET (2)

- $pp \rightarrow W_{\gamma} \text{ or } Z_{\gamma}$
- Need theoretical input
- LO parton level event generators, interfaced to Pythia
- NLO calculation
- Good case because the NLO calculation exist
- Often it doesn't
- The NLO/LO K-factor is ~1.5, but it varies across phase space
- The LO MC is then "fudged" to account for that

![NLO changes shape of distributions](image)
Results of CDF lep + γ + MET search

Decent agreement in shape and normalization

Lepton+Photon+\text{E}_T Predicted Events

<table>
<thead>
<tr>
<th>SM Source</th>
<th>µγ\text{E}_T \ (90\text{ GeV})</th>
<th>µγ\text{E}_T \ (90\text{ GeV})</th>
<th>(e + µ)γ\text{E}_T</th>
</tr>
</thead>
<tbody>
<tr>
<td>W^±γ</td>
<td>11.9 ±2.0</td>
<td>9.0 ±1.4</td>
<td>20.9 ±2.8</td>
</tr>
<tr>
<td>Z^0γ</td>
<td>1.2±0.3</td>
<td>4.2±0.7</td>
<td>5.4±1.0</td>
</tr>
<tr>
<td>W^±γ, Z^0γ + γγ</td>
<td>0.14±0.02</td>
<td>0.18±0.02</td>
<td>0.32±0.04</td>
</tr>
<tr>
<td>τγγ</td>
<td>0.7±0.2</td>
<td>0.3±0.1</td>
<td>1.0±0.2</td>
</tr>
<tr>
<td>W^±γ+jet faking γ</td>
<td>2.8±2.8</td>
<td>1.6±1.6</td>
<td>4.4±4.4</td>
</tr>
<tr>
<td>Z^0γ → e^+e^−, eγγ</td>
<td>2.5±0.2</td>
<td>-</td>
<td>2.5±0.2</td>
</tr>
<tr>
<td>Jets faking ℓ + \text{E}_T</td>
<td>0.6±0.1</td>
<td>&lt; 0.1</td>
<td>0.6±0.1</td>
</tr>
</tbody>
</table>

Total SM Prediction: 19.8±3.2, 15.3±2.2, 35.1±3.3

Observed in Data: 25, 18, 43

Without NLO, SM prediction ~ 26 ± ?
What would you have concluded?


- Ancient, but an example of a search based on a shape analysis that is independent of theoretical assumptions
  - yes, sometimes this happens!
- Signal is W→tb, t→eνb
  - M(ν) < M_W
- BG is W+jets, W→eν
  - M(ν) = M_W

Z. Phys. C46, 179 1990
Example 3: CDF $t\bar{t}$ evidence (1994)

- Also ancient, but example of counting expt independent of theoretical assumptions
- Signal: lep + MET + $\geq 3$ jets ($\geq 1$ of them b-tagged)
- Background: W+jets (fake b-tag), or Wbb (real b-tag)
- Background estimate, entirely data-driven:
  - measure b-tagging rate per jet in $pp\rightarrow$jets
    - includes fake and real tags
  - apply to jets in $W$ + jets sample
    - conservative
    - b-content of $pp\rightarrow$jets $\gg pp\rightarrow W$+jets

Comments

- Often purely data driven BG estimates do not work
- SM BG to LO have large normalization uncertainties
  - Makes counting experiments difficult
- SM LO event generators can have large shape uncertainties
  - Makes shape analyses difficult
- What are the uncertainties at LO? at NLO?
  - Often can get handle from data, e.g., W+jets vs Z+jets
- **Where is the smoking gun?**
  - As an experimentalist, more comfortable if uncertainties are under my control 😊
  - A theorist might feel differently 😞
  - Should you ask how sausages are made?
What can theorists do for experiments?

Slides from Z. Bern at LBNL LHC West Coast Theory Network meeting

Experimenters to theorists: *Please calculate the following at NLO*

<table>
<thead>
<tr>
<th>Single boson</th>
<th>Diboson</th>
<th>Triboson</th>
<th>Heavy flavour</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \pm \leq 5$</td>
<td>$WW \pm \leq 5$</td>
<td>$WWW \pm \leq 5$</td>
<td>$t \pm \leq 5$</td>
</tr>
<tr>
<td>$W + \ell \ell + \leq 3$</td>
<td>$WW + \ell \ell + \leq 3$</td>
<td>$WWW + \ell \ell + \leq 3$</td>
<td>$t + W + \leq 2$</td>
</tr>
<tr>
<td>$Z \pm \leq 5$</td>
<td>$ZZ \pm \leq 5$</td>
<td>$ZZZ \pm \leq 5$</td>
<td>$t + Z + \leq 2$</td>
</tr>
<tr>
<td>$Z + \ell \ell + \leq 3$</td>
<td>$ZZ + \ell \ell + \leq 3$</td>
<td>$ZZZ + \ell \ell + \leq 3$</td>
<td>$t + Z + \leq 2$</td>
</tr>
<tr>
<td>$\gamma + \leq 5$</td>
<td>$\gamma + \leq 5$</td>
<td>$\gamma + \gamma + \leq 5$</td>
<td>$t + h + \leq 2$</td>
</tr>
<tr>
<td>$\gamma + \ell \ell + \leq 3$</td>
<td>$\gamma + \ell \ell + \leq 3$</td>
<td>$\gamma + \gamma + \ell \ell + \leq 3$</td>
<td>$t + Z + \leq 2$</td>
</tr>
</tbody>
</table>

**More Realistic Experimenter’s Wish List**

**Let Houckes 2005**

<table>
<thead>
<tr>
<th>process</th>
<th>background to</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$, new physics</td>
<td>$H\gamma$, new physics</td>
</tr>
<tr>
<td>production by vector boson fusion (VBF)</td>
<td>$t\bar{t}H$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$VBF=H \rightarrow t\bar{t}H$, new physics</td>
</tr>
<tr>
<td>$VBF=H \rightarrow V\gamma$, new physics</td>
<td>$VBF \rightarrow V\gamma$, various new physics signatures</td>
</tr>
<tr>
<td>SUSY: Higgs</td>
<td>SUSY: Higgs</td>
</tr>
</tbody>
</table>

Theorists to experimenters: *in your dreams*

**Also: implement calculation in a MC so that they can be used easily 😊**

Now that we are about to get data, nuts-and-bolts contributions can be more useful than suggestions for yet another beyond the SM theory

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Model dependent vs. model independent searches

- Can search for generic NP signatures  
  e.g., the lep + $\gamma +$ MET CDF search described earlier
- Or, for very specific, complicated signatures  
  e.g., $pp \rightarrow$ TT, $T \rightarrow Z \rightarrow bW$, $t \rightarrow evb Z \rightarrow \mu\mu$, $W \rightarrow \mu\nu$
- Because we do not know what the NP is, generic searches are very powerful
- But in a generic search worry about missing complicated signature
- With O(1000) physicists both approaches will be pursued
This huge signal had been in various data sets for many years.

- What is hiding in the Tevatron data sets?
- What was missed by the Tevatron triggers?

A case study: \( t\bar{t} \) at the Tevatron

- The high \( P_T \) discovery at Tevatron
- Not NP, the ultimate known unknown
- Complicated signature, search narrowly focused on expected SM properties

**Would it have been seen in generic search?**

- In the high statistics lep+jets channel probably not for a long time
  - Lots of BG, theoretical tools (W+multijet & Wbb calculations/MC), analysis techniques developed specifically for the search
- In the dilepton channel would have slowly emerged as excess of events with jets (and eventually, b-jets)

Power of multi-lepton searches
If we see NP, can we tell what it is?

- Great question, great fun
  - Supersymmetry and the LHC inverse problem (hep-ph/0512190)
  - Olympics.....

- Emphasis shifts to "Given that you see X, if the NP is Y, you should see Z"
  - suggestions with Z experimentally impossible not very useful 😒
    - but do not underestimate your experimental colleagues!
  - a well developed feel for experimental issues could make a difference

Conclusion

- After a long wait, exploration of the TeV scale is about to start in earnest

- There are many ideas about NP, but we don't know what it is

- Nuts-and-bolts contributions from theory community extremely important and perhaps underappreciated