SIGNAL SIGNIFICANCE IN THE IDEAL LHC WORLD

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– What the problem with significance is
– How we can try to solve it
– Where it seems to work

in collaboration with Kyle Cranmer [he did all the statistics]
Haven’t we all had this problem?

- some new BSM model predicts a crazy new particle
- extraction from backgrounds at LHC  [LHC physics is statistics]
- parton-level signal/background analysis  [all of the U.S. can do that now]
- cuts analysis an art, not a science  [know-how got people like me a job]
- experimentalist reluctant to invest time  [no trust because they know phenomenologists]
- yes: neural net with hugely improved significance  [my papers]
- yes: parton level analysis proven completely wrong  [everyone else’s papers]
- no: idea forever lost

How to solve it in the ideal world?

- (1) predict significance which can be obtained
- (2) check if experimental analysis is optimal

⇒ emulate the perfect experimentalist on a laptop  [to take him home or to workshops]
The Problem with LHC Searches: 2

An example from real life [TP, Rainwater, Zeppenfeld vs. Cranmer, Quayle, Wu]

- WBF $H \rightarrow \tau\tau$ in Standard Model
- cut analysis promising, experimentalists convinced [after years of convincing]
- neural net even better with LEP-type events weighting
- new Higgs discovery channel

⇒ could we have predicted this?

<table>
<thead>
<tr>
<th>Higgs Mass</th>
<th>Cut Analysis (Pet.%)</th>
<th>Cut on NN</th>
<th>NN Sig. w/cut</th>
<th>NN Sig. w/LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>2.95</td>
<td>0.89</td>
<td>3.71</td>
<td>4.68</td>
</tr>
<tr>
<td>120</td>
<td>3.09</td>
<td>0.93</td>
<td>3.97</td>
<td>4.88</td>
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<tr>
<td>125</td>
<td>3.06</td>
<td>0.92</td>
<td>3.93</td>
<td>4.75</td>
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<tr>
<td>130</td>
<td>2.72</td>
<td>0.94</td>
<td>3.70</td>
<td>4.49</td>
</tr>
<tr>
<td>135</td>
<td>2.56</td>
<td>0.96</td>
<td>3.36</td>
<td>4.02</td>
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<tr>
<td>140</td>
<td>1.86</td>
<td>0.97</td>
<td>2.85</td>
<td>3.38</td>
</tr>
</tbody>
</table>

- Improvement of ~30% from Neural Nets
- Improvement of ~60% with Likelihood Ratio

[B. Quayle, ATLAS Higgs meeting, 2003]
Likelihood ratio

\[ L_b = \frac{e^{-b} b^N}{N} \quad \quad L_{s+b} = \frac{e^{-(s+b)} (s + b)^N}{N} \]

\[ q = \log \frac{L_{s+b}}{L_b} = -s + N \left( 1 + \frac{s}{b} \right) \rightarrow - \sum_j s_j + \sum_j N_j \left( 1 + \frac{s_j}{b_j} \right) \]

– remember: Gaussian significance approximately \( n_\sigma \sim -2q \)

→ inspiration by LEP-Higgs analyses:
   integration over all possible p.s. points by replacing \( s, b \rightarrow |\mathcal{M}_{s,b}|^2 \)

\[ q(x) = \left( 1 + \frac{|\mathcal{M}_s|^2}{|\mathcal{M}_b|^2} \right)_x \]

→ treatment of log likelihood as measurement function

→ extraction of probability distribution function more involved: \( \rho_{s,b}(n) \)

→ integrate over background pdf \( CL_b = \int_N^{\infty} dn \rho_b(n) \) \([5\sigma \text{ with probability } 2.85 \times 10^{-7}\])
Beyond naive phase space integration

- irreducible & unsmeared: signal and background phase space identical

$$\sigma_{\text{tot}} = \int dPS \, M_{PS} \, d\sigma_{PS} = \int d\vec{r} \, M(\vec{r}) \, d\sigma(\vec{r})$$

→ same random numbers for S and B, all phase space info included [over-all \( \phi \)?]

→ smearing! otherwise e.g. \( m_{\mu\mu}^{\text{real}} \neq m_{\mu\mu}^{\text{meas}} \) too distinctive

→ smear small number of observables/random numbers with Gaussian G

$$\sigma_{\text{tot}} = \int d\vec{r}_{\perp} \, dr_{m}^{*} \int_{-\infty}^{\infty} dr_{m} \, M(\vec{r}) \, d\sigma(\vec{r}) \, G(r_{m}, r_{m}^{*})$$

→ modified random number vector \( \vec{r} = \{\vec{r}_{\perp}, r_{m}\} \) without back door

→ complete smearing?!

→ have to replace phase space by spectrum of set of distributions (can be large and overlapping)

→ about to be be implemented in Whizard [Cranmer, TP, Reuter]
WBF Higgs with decay $H \rightarrow \mu\mu$  [TP & Rainwater, 0107180]

- number of signal events small  [$\sigma \cdot \text{BR} \sim 0.25\text{fb}$]
- no distribution with golden cut

$\rightarrow$ perfect for neural net analysis
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Old results [leading (irreducible) backgrounds]

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>$M_H$ [GeV]</th>
<th>$\sigma_H$ [fb]</th>
<th>$\sigma_{Z_{\text{QCD}}}$ [fb]</th>
<th>$\sigma_{Z_{\text{ew}}}$ [fb]</th>
<th>S/B</th>
<th>significance $\sigma$</th>
<th>$\Delta \sigma / \sigma$</th>
<th>$L_{5\sigma}$ [fb$^{-1}$]</th>
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<tbody>
<tr>
<td>14</td>
<td>115</td>
<td>0.25</td>
<td>3.57</td>
<td>0.40</td>
<td>1/9.1</td>
<td>1.7</td>
<td>60%</td>
<td>2600</td>
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<tr>
<td>14</td>
<td>120</td>
<td>0.22</td>
<td>2.60</td>
<td>0.33</td>
<td>1/7.5</td>
<td>1.8</td>
<td>60%</td>
<td>2300</td>
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<td>0.17</td>
<td>1.61</td>
<td>0.24</td>
<td>1/6.5</td>
<td>1.7</td>
<td>65%</td>
<td>2700</td>
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<td>0.10</td>
<td>1.11</td>
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<td>5.3</td>
<td>20%</td>
<td>270</td>
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<tr>
<td>200</td>
<td>120</td>
<td>2.36</td>
<td>29.2</td>
<td>4.0</td>
<td>1/8.0</td>
<td>5.7</td>
<td>20%</td>
<td>230</td>
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<tr>
<td>200</td>
<td>130</td>
<td>1.80</td>
<td>18.7</td>
<td>2.7</td>
<td>1/6.9</td>
<td>5.3</td>
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<td>260</td>
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<tr>
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<td>140</td>
<td>1.14</td>
<td>13.4</td>
<td>2.0</td>
<td>1/7.9</td>
<td>4.0</td>
<td>27%</td>
<td>500</td>
</tr>
</tbody>
</table>
Statistical promise of WBF $H \rightarrow \mu\mu$

- relevant for physics: confirm Yukawa coupling to 2nd generation
- gluon–fusion channel helpful? [Han & McElrath, Boos etal.]
  - better try WBF alone

- cut analysis impossible
- event weighting in neural net promising
- only irreducible backgrounds
- smearing only relevant for $m_{\mu\mu}$ [mimick by $\Gamma'_H$]

  - compute likelyhood for each event
  - upper limit on parton level significance

  $\Rightarrow$ WBF $H \rightarrow \mu\mu$: 3.7 sigma in 300 fb$^{-1}$
  
  [4.2$\sigma$ with jet veto; 5.2$\sigma$ for Atlas+CMS]

  $\Rightarrow$ see if we can find an experimental group now
Higgs/BSM news for LHC

- we can emulate the perfect experimentalist!
- another cool tool in the pipeline
- concept and feasibility shown
- incorporation into Whizard over summer