What should we learn?

ATLAS potential

SM Higgs Properties

Measurement in ATLAS.

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Why believe in a light Higgs?

Electroweak fit (Z properties, W and top mass) give at 95%:

\[ M_H < 163 \text{GeV}/c^2 \]

\[ M_H < 191 \text{GeV}/c^2 \] (with search bound)

Will drop with new D0 m_\text{W}
Likelihoods from EW/LEP/TeV

- Sum of likelihoods: crude but instructive
- Higgs mass 115 to 135 (145)GeV
- Gfitter (gfitter.desy.de) find 150GeV limit.
Rates?

- LHC backgrounds!
  
  Every event at a lepton collider is physics; every event at a hadron collider is background

  Sam Ting

- Need distinctive signatures
Higgs production

- $gg \rightarrow H$
- $q\bar{q} \rightarrow H$
- $W, Z$
- $t\bar{t}H$

Cross-section [pb] vs. $m_H$ [GeV]

- $ATLAS$
  - $gg \rightarrow H$
  - $q\bar{q} \rightarrow H$
  - $W, Z$
  - $t\bar{t}H$
Higgs Decay

Only decays considered for analysis are shown
The Higgs Discovery

If Higgs boson is heavy (>130GeV/c^2)
- Significant decays to WW\(^{*}\), ZZ\(^{*}\)
- These have clear leptonic decay modes
- ZZ\(\rightarrow\)4\(l\) is frankly nicer, but WW\(\rightarrow\)l\(\nu\)l\(\nu\) more common
- Comparable sensitivity
- The discovery is statistically promising

If Higgs boson is light (<130GeV/c^2)
- (and it is)
- Use rare H\(\rightarrow\)\(\gamma\)\(\gamma\)
- Or VBF H\(\rightarrow\)\(\tau\)\(\tau\) – can trigger leptons
- WW and ZZ search for off-shell vector boson

Assume this has been done!
Is this the SM Higgs?

- Higgs mass
- Higgs couplings
  - Lifetime/width
  - Branching ratios
- Higgs charge
- Spin/parity
- Self-coupling
Higgs mass

- Used to test EW fits
  - Precision required in SM is $O(10\%)$
  - SUSY makes absolute prediction, higher precision valuable

- 120GeV
  - Higgs to $\gamma\gamma$ best
  - H to ZZ also useful

- 160GeV
  - Measured by $H \rightarrow ZZ \rightarrow llll$
\[ H \Rightarrow ZZ \Rightarrow l^+l^-l^+l^- \]

- 130 GeV/c²
- 150 GeV/c²
- 180 GeV/c²
- 300 GeV/c²
- 400 GeV/c²
- 600 GeV/c²
Material Distributions

- Complex material distribution complicates electron/photon energy scale
  - CDF 0.2 $X_0$ in silicon
  - D0 4$X_0$ before calorimeter
- Needs to be understood for photon reconstruction
- Electron/photon energy scales are different
- Effect on 120GeV $H \rightarrow \gamma\gamma$
Higgs mass

120GeV
- Higgs to γγ dominates
- Statistical precision 1.4-1.7GeV per event
- ⇒Dominated by photon scale, O(0.5%) or better
- Assumes luminosity $\sim 10^{33}\text{cm}^2\text{s}^{-1}$; pileup degrades vertex reconstruction

160GeV
- Measured by $H\rightarrow ZZ\rightarrow llll$
- Resolution 2-2.5GeV per event
- ⇒Dominated by lepton scale O(0.5-0.2%) or better

Non-SM Higgs may suppress bosonic decays
- $\tau\tau$ has best measurement – outside this scope
Higgs Couplings

- **Lifetime/Width:**
  - Standard Model Higgs < 200GeV
  - Lifetime ~ $10^{-22}$s – decay length not measurable
    - But we must check consistency with zero
  - Width rises with mass
  - <10MeV below 140GeV
  - Measurable from ~200 GeV

- **Branching Ratios:**
  - Much more promising...
  - But without total rate
  - Only relative BR's

Accuracy set by natural width
Higgs rates: $m_H = 120$ GeV

- Cross-section times branching ratio in channels examined
Higgs rates: $m_H = 160\text{GeV}$

- Cross-section times branching ratio in channels examined
  - WW dominates
  - ZZ similar
  - Others fall
Higgs sensitivity: \( m_H = 160 \text{GeV} \)

- '?' : my estimate.
- ZZ VBF surely possible too.
- Cross-sections mimic sensitivity.

From CERN-OPEN-2008-020
Higgs sensitivity: $m_H = 120 \text{GeV}$

- '?' : my estimate.
- '??' for VBF $H \rightarrow bb$, currently under study.
- $\tau\tau$ VBF isolated
- Several weak channels

From CERN-OPEN-2008-020
H to $\text{llll}$

- Good channel for $>130\text{GeV}$
- Need $Z\text{bb}$ background below $ZZ$ threshold
- Ten sigma discovery for $150\text{GeV}$
  - $\Rightarrow$ Order 10% rate

- Production sums gluon fusion and VBF
  - It must be possible to separate these to learn more
H to WW\(^(*)\)

- Analysis needs good background model
  - Spin correlation help
- Signal rates relatively large

\[
\int L \ dt = 10 \text{ fb}^{-1}
\]

10\(\sigma\) for 160GeV using 10fb\(^{-1}\)
10% in both VBF and gluon fusion
Inclusive analysis (gluon fusion)

Higgs plus 1 jet analysis (gluon fusion + VBF)

Higgs plus 2 jet analysis (80% VBF, 20% gluon)

Sensitive to all production processes!

3.8σ for 10fb⁻¹ and 120GeV

Higgs plus missing energy (ZH+WH)
H to tau tau

- Signal should give good s/b
- Needs jet veto to work
- Also good modelling of Z background

- Sensitivity over 4σ below 135GeV for 30fb⁻¹
  - Should give 25% measurement of σ x br
ttH, H to bb

s/b poor

Improving simulations always seems to add complication

'Dead';
S. Heinemeyer,
Seattle, Jan 2009

ArXiV: 0905:0110
ttbb k-factor 1.8
Increases the background
[Signal too, by 1.25]
ttH, H to bb: Doesn't lie down

- Looks not much worse than Wbb at D0 to me
- Wait – TeVatron plot has signal shown times 10!
Other access to Hbb coupling:

- WH/ZH at LHC being revived via subjet analysis
  - Butterworth et al., PRL 100:242001 (2008)
  - Use boosted ($p_T > 200\text{GeV}$)
  - Higgs
  - Decompose merged jets
  - Now being fully analysed in ATLAS
  - Also NN etc. approaches being pursued again

- Also VBF $H\gamma$ production unexpectedly promising
- Yukawa Hbb coupling important to measure.
Couplings Extraction

- Only relative rates can be measured
  - More assumptions needed
  - Here HWW/HZZ couplings forced <= SM values
- Find couplings squared for 30fb$^{-1}$, 2 expts, to:
  - 40% W, Z, τ, and t
  - 60% for b
- Will improve with more data
In many cases several MSSM Higgs bosons can be found.
If only one, can we distinguish from SM?
Use Br. $h \rightarrow \tau \tau / h \rightarrow WW$ in VBF production, c/f SM $\rightarrow \Delta$
Ratio cancels production effects
$\Delta > 2$ in black region is two-sigma separation

Charges

- Electric charge explicitly zero through discovery modes
- Also must be colourless
Spin Measurement

- All channels naturally exclude fermionic source
- $H \rightarrow \gamma \gamma$ observation excludes spin 1.
- ZZ angular distributions will confirm spin 0
  - Low mass: $Z^*$ mass distribution

- High mass: ZZ decay correlations
- Also $H \rightarrow WW$ $l^{-}l^{-}$ mass
Parity Extraction

- Using ZZ angles above, extract
  
  \[ R = \frac{L_{\text{Longitudinal}} - T_{\text{Transverse}}}{L_{\text{Longitudinal}} + T_{\text{Transverse}}} \]
  
  - 100fb\(^{-1}\) clearly gives parity

- VBF angles also sensitive.
Anomalous couplings

- CPO (odd) and CPE (even) anomalous WWH couplings could exist in addition to SM ones.
- H to WW decay gives a test
- The VBF $H \rightarrow \tau\tau$ also:
  - Interjet angle
  - High statistics
  - 10 fb$^{-1}$ in ATLAS
  - CPE ~ distinguishable with this dataset

Higgs self-coupling

- Very desirable test of the theory
  - Quartic self-coupling drives VeV

- Extremely challenging
  - SLHC required, plus luck
  - hep-ph/0304015 finds 160-180GeV plausible
  - No pileup, fast-sim, backgrounds look low
  - Now ~ excluded!
Conclusions

- We are ringing Peter's doorbell
- It will be ~2013 before we know who answers