Programme of Lectures

- Motivations and introduction
- What we know now
- The future?
  - Supersymmetric Higgses
  - Higgs factories
The Particle Higgsaw Puzzle

Is LHC finding the missing piece?
Is it the right shape?
Is it the right size?
From Discovery to Measurement

- Mass measurements: 125.6 ± 0.3 GeV
- Signal strengths ~ SM in many channels
- Frontiers:
  - VBF significance 2σ in several channels, 3σ combined
  - Decay to \( \tau\tau \) emerging, limits on \( \tau\tau \) (\( \mu\tau, e\tau \))
  - Decay to bbbar emerging (CMS, Tevatron)
  - Indirect evidence for ttbar coupling (search for ttbar + H/W, Z\( \gamma \))
Couplings resemble Higgs of Standard Model

- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879
Some Questions

- What is it?
  - Higgs or …?
- What else is there?
  - Supersymmetry …?
- What next?
  - A Higgs factory or …?
Elementary Higgs or Composite?

- Higgs field: \[ \langle 0 | H | 0 \rangle \neq 0 \]
- Quantum loop problems

Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed \( m_t > 200 \) GeV

New technicolour force?
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Cut-off \( \Lambda \sim 1 \) TeV with Supersymmetry?

Cutoff \( \Lambda = 10 \) TeV
Higgs as a Pseudo-Goldstone Boson

‘Little Higgs’ models (breakdown of larger symmetry)

Loop cancellation mechanism

Little Higgs

Supersymmetry
What is it?

- Does it have spin 0 or 2?
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?
What is the Spin of the ‘Higgs’?

- Decays into $\gamma \gamma$, so cannot have spin 1
- **Spin 0 or 2?**
- Selections of WW and ZZ events are based on spin 0 hypothesis
- Can diagnose spin via
  - production in association with W or Z
  - angular distribution of $\gamma \gamma$
  - angular correlations of leptons in WW, ZZ decays
Does the ‘Higgs’ have Spin Two?

- Would have graviton-like couplings:

  \[ \mathcal{L}_{\text{int}} = -\frac{c_i}{M_{\text{eff}}} G^{\mu\nu} T^{i}_{\mu\nu} \]

- Coefficients somewhat model-dependent

- Warped compactification:

  \[ ds^2 = w^2(z) (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2) \]

- Expect equal couplings for photons, gluons

  \[ \Gamma(X \rightarrow gg) = 8 \Gamma(X \rightarrow \gamma\gamma) \]

  \[ c_{g,\gamma} \approx 1/ \int_{z_{\text{UV}}}^{z_{\text{IR}}} w(z) dz \]

- Larger coefficients for W, Z, b, t

  \[ c_b \simeq c_t \gtrsim c_W \simeq c_Z = \mathcal{O}(35) \times (c_g = c_\gamma > c_u, c_d) \]

- Smaller coefficients for u, d, s, c

  (Also expect vector mass < tensor mass X LHC)

Does the ‘Higgs’ have Spin Two?

- Fit of vector-boson couplings to spin-two model

- Prediction of AdS-type graviton-like model disfavoured by $> 3 \sigma$

Does the ‘Higgs’ have Spin Zero?

Vector boson + ‘Higgs’ combined invariant mass very different for spins 0 and 2

Spin Discriminating Power

Available TeVatron data, 2012 LHC data should be able to distinguish spins 0 and 2

The ‘Higgs’ probably a Scalar

- Pseudoscalar, graviton-like spin-2 disfavoured
The ‘Higgs’ probably a Scalar

- Associated production cross section increases more rapidly with energy for $0^-$, spin 2

- Pseudoscalar, graviton-like spin-2 disfavoured

Does the ‘Higgs’ have Spin Zero?

- Polar angle distribution: $X_2 \rightarrow \gamma\gamma$
  (flat for $X_0$)

- Azimuthal angle distribution: $X_0 \rightarrow WW$
  (flat for $X_2$)

Does the ‘Higgs’ have Spin Two?

- Discriminate spin 2 vs spin 0 via angular distribution of decays into $\gamma\gamma$

$N_{\text{sig}} = 160$, High S/B

Monte Carlo simulations

JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

JE & Hwang: arXiv:1202.6660

$2^+$ disfavoured @ 99%
Does the ‘Higgs’ have Spin Zero?

- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$
  (for $\phi = \pi$)

The ‘Higgs’ Spin is probably 0

- Graviton-like spin-2 disfavoured at 99.9% CL
What is it?

- Does it have spin 0 or 2?
  - Spin 2 very unlikely
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?
The ‘Higgs’ is probably a scalar

- Pseudoscalar $0^{-}$ disfavoured at $> 99\%$ CL
What is it?

- Does it have spin 0 or 2?
  - Spin 2 seems unlikely, but needs experimental checks
- Is it scalar or pseudoscalar?
  - Pseudoscalar disfavoured by experiment
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?
Phenomenological Framework

- Assume custodial symmetry:
  \[ SU(2) \times SU(2) \rightarrow SU(2)_V \quad (\rho \equiv M_W/M_Z \cos \theta_w \sim 1) \]

- Parameterize gauge bosons by \(2 \times 2\) matrix \(\Sigma\):

\[
\mathcal{L} = \frac{v^2}{4} \text{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) - m_i \psi^i_L \Sigma \left(1 + c \frac{h}{v} + \ldots \right) \psi^i_R + \text{h.c.}
\]
\[+
\frac{1}{2} (\partial_\mu h)^2 + \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left(\frac{3m_h^2}{v}\right) h^3 + d_4 \frac{1}{24} \left(\frac{3m_h^2}{v^2}\right) h^4 + \ldots \]

\[
\Sigma = \exp \left( i \frac{\sigma^a \pi^a}{v} \right) \quad \mathcal{L}_\Delta = - \left[ \frac{\alpha_s}{8\pi} b_s G_{a\mu\nu} G_{a}^{\mu\nu} + \frac{\alpha_{em}}{8\pi} b_{em} F_{\mu\nu} F_{\mu\nu} \right] \left(\frac{h}{V}\right)
\]

- Coefficients \(a = c = 1\) in Standard Model
Phenomenological Framework

• $a$ parametrizes couplings of $h$ to massive gauge bosons

• $c$ parametrizes couplings of $h$ to fermions:
  
  • Standard Model: $a = c = 1$
  
  • Composite Higgs MCHM4: $a = c = \sqrt{1 - \xi} \quad \xi \equiv (v/f)^2$
  
  • Composite Higgs MCHM5: $a = \sqrt{1 - \xi}, \quad c = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$
  
  • Pseudo-Dilaton: $a = c = \frac{v}{V}$
Re-interpreting SM Higgs Searches

\[ R_{gg} = \frac{(-\frac{v}{\sqrt{2}}b_s + cF_t)^2}{F_t^2} \], \quad R_{VBF} = a^2 \quad , \quad R_{ap} = a^2 \quad , \quad R_{hs} = c^2 \]

\[ R_{VV} = a^2 \quad , \quad R_{ff} = c^2 \quad , \quad R_{\gamma\gamma} = \frac{(-\frac{v}{\sqrt{2}}b_{em} - \frac{8}{3}cF_t + aF_w)^2}{(-\frac{8}{3}F_t + F_w)^2} \]

- Only \( R_{\gamma\gamma} \) is sensitive to relative sign of \( a, c \)
Re-Interpreting SM Higgs Searches

- Sensitivities of different experimental search (sub)channels:

<table>
<thead>
<tr>
<th>channel</th>
<th>Production sensitive to</th>
<th>Decay sensitive to</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$c$</td>
</tr>
<tr>
<td>$\gamma \gamma$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\gamma \gamma$ VBF</td>
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<td>×</td>
</tr>
<tr>
<td>WW</td>
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<td>✓</td>
</tr>
<tr>
<td>WW 2-jet</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>WW 0,1-jet</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>$b\bar{b}$ (VH)</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>$b\bar{b}$ ($ttH$)</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>ZZ</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\tau \tau$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\tau \tau$ (VBF, VH)</td>
<td>✓</td>
<td>×</td>
</tr>
</tbody>
</table>
Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by $a$, to fermions by $c$

- Standard Model: $a = c = 1$

No evidence for deviation from SM
Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by $a$, to fermions by $c$

- ‘Wrong’ sign of $c$ disfavoured

JE & Tevong You, arXiv:1303.3879
Single Higgs + Top Production

- Sensitive to sign of H-t coupling
- Sign fixed by renormalizability

Significant measurement possible @ LHC14?
What is it?

- Does it have spin 0 or 2?
  - Spin 2 seems unlikely, but needs experimental checks
- Is it scalar or pseudoscalar?
  - Pseudoscalar disfavoured by experiment
- Is it elementary or composite?
  - No significant deviations from Standard Model
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

\[ \lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right)^{1+\epsilon}, \quad g_V = 2 \left( \frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}} \right) \]

Global fit

- Red line = SM, dashed line = best fit

JE & Tevong You, arXiv:1303.3879
It Walks and Quacks like a Higgs

- Do couplings scale \( \sim \) mass? With scale = \( v \)?

\[
\lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right)^{1+\epsilon}, \quad g_V = 2 \left( \frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}} \right)
\]

- Standard Model Higgs: \( \epsilon = 0, \; M = v \)
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

\[ \epsilon = -0.022^{+0.042}_{-0.021} \quad M = 244^{+20}_{-10} \text{ GeV} \]

JE & Tevong You, arXiv:1303.3879
What is it?

- Does it have spin 0 or 2?
  - Spin 2 seems unlikely, but needs experimental checks
- Is it scalar or pseudoscalar?
  - Pseudoscalar disfavoured by experiment
- Is it elementary or composite?
  - No significant deviations from Standard Model
- Does it couple to particle masses?
  - Some \textit{prima facie} evidence that it does
- Quantum (loop) corrections?
- What are its self-couplings?
Loop Corrections?

- ATLAS sees excess in $\gamma\gamma$, CMS sees deficit

- Loop diagrams ~ Standard Model?

JE & Tevong You, arXiv:1303.3879
Loop Corrections?

• Gluon-gluon coupling $\sim 1$ $\sigma$ low?

• $\gamma\gamma$ coupling $\sim 1$ $\sigma$ high?

JE & Tevong You, arXiv:1303.3879
Beyond any Reasonable Doubt

- Does it have spin 0 or 2?
  - Simple spin 2 couplings excluded
- Is it scalar or pseudoscalar?
  - Pseudoscalar strongly disfavoured
- Is it elementary or composite?
  - No significant deviations from Standard Model
- Does it couple to particle masses?
  - Prima facie evidence that it does
- Quantum (loop) corrections?
  - $\gamma\gamma$ coupling $\geq$ Standard Model?
- What are its self-couplings? Hi-lumi LHC or …?
What is its Decay Rate?

- Compared with the Standard Model prediction

- Assuming no non-Standard Model modes
What is its Decay Rate?

- Compared with the Standard Model prediction

- Assuming no non-Standard Model modes

JE & Tevong You, arXiv:1303.3879
Mass Shift sensitive to $\Gamma_H$

- Apparent $m_{\gamma\gamma} \neq m_{ZZ^*}$ due to interference with QCD
  - Depends on kinematics
  - Sensitive to sign and magnitude of Higgs couplings

Dixon & Li, arXiv:1305.3854
The Story so Far

• A new chapter in particle physics is open
• The new particle is a scalar
• Couplings ~ Standard Model Higgs
• Severe constraint on composite models
• Elementary scalar a challenge for theorists
• Fits naturally within supersymmetry
  – Mass, couplings
• But no sign of supersymmetric particles
• On to HE, HL-LHC and beyond
Conversation with Mrs Thatcher: 1982

What do you do?

Think of things for the experiments to look for, and hope they find something different.

Wouldn’t it be better if they found what you predicted?

Then we would not know how to progress!