SM & BSM Higgs

Jay Wacker
SLAC

Hadron Collider Physics Symposium
August 25, 2010
Outline

- Where We Stand
- The SM Higgs
- Boosted Higgs
- Novel Higgs Decays
- Looking Forward
The Need for a Higgs Boson

Longitudinal polarization of $W$ & $Z$ badly behaved at large energies

Strong Scattering at High Energies

![Graph showing strong scattering at high energies with a Higgs boson](image-url)
The Need for a Higgs Boson

Longitudinal polarization of $W$ & $Z$ badly behaved at large energies

Strong Scattering at High Energies

Large corrections to observables

$$m_{Z^0} - m_{W^\pm} \sim \left| Z^0 \right| \sim Z^0 - W^\pm \sim \frac{g^2}{16\pi^2} m_{Z^0} \log \Lambda^2$$
Current Limits

Regularization of the radiative corrections depend on Higgs mass

Standard Model Fit without direct searches

Best fits are to 80 GeV, slight tension with direct searches

Standard Model Fit with direct searches

Tevatron searches beginning rewrite fits
Caveats on from Beyond the Standard Model

The minimal SM may not be complete story...

New physics can also contribute to the measurements constraining Higgs mass

Heavy Higgs still feasible without exotic physics
A second Higgs doublet
4th Generation
Technicolor, Randall-Sundrum, Little Higgs
Possible Motivations for a Heavy Higgs

The “Little” Hierarchy Problem is mostly solved

\[ V_{\text{Higgs}} = \lambda |H|^4 + \mu^2 |H|^2 \]
\[ m_{h_0}^2 = 2\lambda v^2 = -2\mu^2 \]

\[ \delta \mu^2 \sim \frac{3y_{\text{top}}^2}{16\pi^2} \Lambda_{\text{top}}^2 \]

Fine Tuning \( \sim \frac{m_{h_0}^2}{\delta \mu_{h_0}^2} \)
Possible Motivations for a Heavy Higgs

The “Little” Hierarchy Problem is mostly solved

\[ V_{\text{Higgs}} = \lambda |H|^4 + \mu^2 |H|^2 \quad m_{h_0}^2 = 2\lambda v^2 = -2\mu^2 \]

Typically 1% to 10% Fine Tuning

Most BSM theories predict a 100 GeV Higgs
Constraints put new physics in the 750 GeV - 2 TeV range

Theories with Higgs masses in the 300 GeV range reduce Fine Tuning by an order of magnitude

Model Builders are short of theories that predict heavy Higgs
Randall-Sundrum Models frequently have Heavy Higgs
Outline

Where We Stand
Standard Model prefers a light Higgs
Tevatron is closing in on SM window
Extensions to the SM can have heavy Higgs

The SM Higgs

Boosted Higgs

Novel Higgs Decays

Looking Forward
Producing the SM Higgs at Hadron Colliders

- **Gluon Fusion**
- **Associated Production**
- **Vector Boson Fusion**
- **Top Higgs Production**
Understanding Higgs Signatures is an Industry

**Tools**

**Cross Section**
- **ggF**
- **HIGLU** (NLO QCD+EW)
- **HPro** (NLO QCD)
- **FEHiPro** (NNLO QCD+EW)
- **HNNLO** (NNLO QCD)
- **ggh@NNLO** (NNLO QCD)
- **VBF**
- **VV2H** (NLO QCD)
- **VBFNLO** (NLO QCD)
- **HAWK** (NLO QCD+EW)
- **VBF@NLO** (NNLO QCD)
- **WH/ZH**
- **V2HV** (NLO)
  ...
- **ttH**
- **HQQ** (QCD LO)
- **bbH**
- **bbH@NNLO** (NNLO)

**Higgs Decay**
- **HDECAY** (NLO)
- **PROPHECY4f** (NLO)
- **FeynHiggs**
- **CPSuperH**

**Kinematics; Higgs p_T**
- **HqT** (NLO+NNLL)
- **ResBos** (NLO+NNLL)

**PDF:** MSTW, CTEQ, NNPDF, etc.

Taken from J. Tanaka at “Higgs Hunting” Orsay, July 29-31, 2010

Higgsa Huntina WS@Orsav
Gluon Fusion Largest Uncertainty

Largest cross section, but arises at loop level

Theoretical uncertainty translates into weakening bounds
Gluon Fusion Largest Uncertainty

Largest cross section, but arises at loop level

Theoretical uncertainty translates into weakening bounds

Beyond the SM Uncertainty

Coupling not directly tied to electroweak symmetry breaking

New particles can contribute in loop

4th Gen (+900%), light top squarks (-50%)
The Rapidly Advancing World of Higgs Calculations

Inclusive production cross sections down to 10% uncertainties dominated by PDFs

NNLO+N^3LL+EW

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>1.215+0.031+0.070</td>
</tr>
<tr>
<td>120</td>
<td>1.073+0.026+0.064</td>
</tr>
<tr>
<td>125</td>
<td>0.950+0.022+0.059</td>
</tr>
<tr>
<td>130</td>
<td>0.844+0.019+0.054</td>
</tr>
<tr>
<td>135</td>
<td>0.752+0.016+0.050</td>
</tr>
<tr>
<td>140</td>
<td>0.673+0.014+0.046</td>
</tr>
<tr>
<td>145</td>
<td>0.602+0.012+0.043</td>
</tr>
<tr>
<td>150</td>
<td>0.541+0.010+0.039</td>
</tr>
<tr>
<td>155</td>
<td>0.486+0.009+0.036</td>
</tr>
<tr>
<td>160</td>
<td>0.433+0.008+0.033</td>
</tr>
<tr>
<td>165</td>
<td>0.385+0.006+0.030</td>
</tr>
<tr>
<td>170</td>
<td>0.345+0.005+0.028</td>
</tr>
<tr>
<td>175</td>
<td>0.310+0.005+0.026</td>
</tr>
<tr>
<td>180</td>
<td>0.280+0.004+0.024</td>
</tr>
<tr>
<td>185</td>
<td>0.252+0.003+0.022</td>
</tr>
<tr>
<td>190</td>
<td>0.228+0.003+0.020</td>
</tr>
<tr>
<td>195</td>
<td>0.207+0.002+0.019</td>
</tr>
<tr>
<td>200</td>
<td>0.189+0.002+0.018</td>
</tr>
</tbody>
</table>

Ahrens, Becher, Neubert, Yang 1008.3162

http://wwwthep.physik.uni-mainz.de/~llyang/RGHiggs/
LO, NLO, NNLO for Gluon Fusion

Many generators now:

Leading order (w/ PS/ME Matching)

Next to Leading Order

Next to Next to Leading Order

Broad agreement except for MC@NLO

\[ \alpha_s^3(\mu) |_{\mu=m_{h^0}+p_{T_{h^0}}} \]

vs

\[ \alpha_s^2(\mu) |_{\mu=m_{h^0}} \quad \alpha_s(\mu) |_{\mu=p_{T_{h^0}}} \]

NNLO indicates the later
LO, NLO, NNLO MC’s and Jet $P_T$S

Frequently divide up searches into different jet multiplicities

Larger uncertainties in higher multiplicities
still good relative agreement
Outline

Where We Stand

The SM Higgs
Calculations are rapidly advancing, PS/ME Matching offers good estimates of additional jets

Boosted Higgs

Novel Higgs Decays

Looking Forward
Boosted Higgs
Recent progress in using jet substructure to
distinguish resonances with high $p_T$ from ordinary jets

$\rho_T h^0 \approx 0$

Boost

$\rho_T h^0 \sim \text{few } m_{h^0}$

Reduces combinatorics
Makes Higgs resonance visible in invariant masses

Butterworth, Davison, Rubin, Salam 0809.2530
Boosted Higgs
Several Similar Procedures

One fat jet
Decluster
Filtered

Identify 3 hardest subjets
Removes extraneous energy

Doesn’t shape the background
A previously abandoned channel
Huge combinatorics, boosted topologies help

Higgs typically has high $p_T$

Top and Higgs are boosted!

Can discover the Higgs with 30 fb$^{-1}$
Higgs from Beyond the SM

Kribs, Martin, Roy, Spannowsky 0912.4731

Can have QCD production of new particles

\[ \tilde{q} \rightarrow q\chi_2 \rightarrow q(\chi_1 h) \]

Branching ratios into Higgs can be up to 25%

Need a widely spaced spectrum

\[ \chi_0^0 \rightarrow h^0 Z^0 \]

Can have QCD production of new particles

\[ L = 10 \text{ fb}^{-1}, \sqrt{s} = 14 \text{ TeV} \]
Heavy SM Higgs

For $m_{h^0} > 300$ GeV

Higgs decay products are boosted

5σ discovery for 10 fb$^{-1}$
Jet Pull

Gallichio, Schwartz 1001.5027

Shapes of dijet resonances different for color singlets vs color octets

Parton showering between color connections

Pull: angle between the major axes of the jets

D0 begun using in Higgs searches: 10% additional discrimination
Outline

Where We Stand

The SM Higgs

Boosted Higgs
Advancing techniques are opening up many new channels to discover the Higgs
Offers many new channels to measure properties of the Higgs

Novel Higgs Decays

Looking Forward
Novel Higgs Decays

If there is BSM Physics, Higgs discovery can be easily altered

$$\Gamma_{h^0 \rightarrow SM} = \frac{3m_b^2}{4\pi v^2} \sim 10^{-4}$$

New physics could open up unsuppressed decay channels

$$\Gamma_{h^0 \rightarrow BSM} = \frac{g^2_{hX\bar{X}}}{4\pi} \sim 10^{-2}$$

$$\text{Br}(h^0 \rightarrow SM) \sim 10^{-2}$$

Existing search strategies could be ineffective
A concern up to $WW$ threshold
The Classic New Decay

Higgs sector is extended

\[ V = V(H_1, H_2, S_1, \ldots) \]

Additional approximate symmetries

\[ H_i \rightarrow e^{iq_i \alpha} H_i \]

Light Goldstone Bosons (few GeV)

New Higgs decay modes

Not a complicated story!
Fraction of Higgs width that could be altered:

120 GeV: 98%  
150 GeV: 90%  
175 GeV: 50%

Two couplings

\[ \lambda m_{a^0} h^0 (a^0)^2 \]

\[ \frac{1}{f_{a^0}} h^0 (\partial a^0)^2 \]
Buried Higgs of Various Flavors

Three rough classifications

\[(m_{h^0}, m_{a^0})\]

<table>
<thead>
<tr>
<th>(m_{a^0})</th>
<th>Large tan (b)</th>
<th>Democratic</th>
<th>Fermiophobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>(b\bar{b})</td>
<td>(b\bar{b})</td>
<td>(gg)</td>
</tr>
<tr>
<td>4 GeV</td>
<td>(\tau^+\tau^-)</td>
<td>(c\bar{c})</td>
<td>(gg)</td>
</tr>
<tr>
<td>1 GeV</td>
<td>(\mu^+\mu^-)</td>
<td>(\mu^+\mu^-)</td>
<td>(gg)</td>
</tr>
<tr>
<td>0.2 GeV</td>
<td>(e^+e^-)</td>
<td>(\gamma\gamma)</td>
<td>(\gamma\gamma)</td>
</tr>
</tbody>
</table>

Many additional searches necessary
MET

JHEP 1005:049, 2010

Z

0

+ 0

h

−

at the LHC with 5 fb⁻¹

Extending other reach

Reaches up to 200 GeV

at the LHC with 5 fb⁻¹

Lisanti, Wacker 0903.1377

D0 Result

PRL 103:061801, 2009

Di-Muon Peak

Br(a⁰ → 2µ) ~ 1%

mₜ = 100 GeV

ALEPH Result

JHEP 1005:049, 2010

Z

0

→ 2τ

→ 2µ

Extending other reach

in other channels (4g, 4c)

ALEPH
Other Higgs Decay modes

Decays into fermions

\[ h^0 \rightarrow \chi \chi \rightarrow (qqq)(\bar{q}\bar{q}\bar{q}) \quad h^0 \rightarrow \chi \chi \rightarrow (qqq)(qqq) \]

i.e. Baryon number violating R-parity violation

Carpenter, Kaplan, Rhee hep-ph/0607204

\[ h^0 \rightarrow \chi \chi \rightarrow (q\bar{q}' \ell^\pm)(q\bar{q}' \ell^\mp) \quad h^0 \rightarrow \chi \chi \rightarrow (q\bar{q}' \ell^\pm)(q\bar{q}' \ell^\pm) \]

i.e. Lepton number violating R-parity violation

Decay products could be boosted

Two step cascades

\[ h^0 \rightarrow s^0 s^0 \rightarrow (a^0 a^0)(a^0 a^0) \rightarrow \cdots \]

Chang, Fox, Weiner hep-ph/0511250
Outline

Where We Stand

The SM Higgs

Boosted Higgs

Novel Higgs Decays
Signatures of light Higgs bosons easily altered
A new program of Higgs searches necessary

Looking Forward
Implications of the Higgs Mass

Learning the Higgs Mass has profound implications for high scale physics

\[ m_{h^0}^2 = 2\lambda v^2 \quad \lambda = \lambda(m_{h^0}) \]

RG Running concentrates the Higgs mass

\[ \lambda(M_{\text{GUT}}) \]

Most parameter space in minimal SM has Higgs masses ~145 - 175 GeV

![Graph showing the behavior of the quartic Higgs couplings as a function of the cut-off scale.](image)
Conclusion

Rapidly closing in on a SM Higgs boson
Many new calculations and MC tools available

Physics Beyond the Standard Model alter predictions
Mass range, cross sections, decay modes

New searches for the Higgs are possible/necessary
Exotic decays - Some are spectacular, others are a mess
Higgs may be boosted at the LHC
New techniques can revive old search channels

The properties of the LHC have profound implications for the interpretation of the Standard Model