Finding the Source of Electroweak Symmetry Breaking: Theoretical Summary

S. Dawson, BNL, July 31, 2010

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Higgs Hunting

Discussions on Tevatron and first LHC results
What are the criteria?

- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W and Z gauge bosons
  - Non-zero mass of fermions
  - Unitarity at 1 TeV

- Must be consistent with all data
  - Precision electroweak data
  - Tevatron searches
  - Flavor changing neutral currents
  - Little hierarchy
    - Much possible physics required to be at $>>$ TeV
Unitarity

- Massive W and Z’s have longitudinal polarizations
- Longitudinal interactions spoil nice properties of gauge theories:
  - Loops are not finite without Higgs
  - Scattering amplitudes grow with energy
What unitarizes WW scattering?

- Symmetry breaking could be weakly coupled
  - SUSY, Higgs Portal (lots of singlets), Extra-D with multiple vector bosons.....

- Symmetry breaking could be strongly coupled
  - Technicolor, QCD like models, Higgsless, composite Higgs.....
The TeV Scale

- We expect the Higgs or unitarity restoring action to be around 1 TeV

- Symmetry breaking mechanism must:
  - Give mass to vector bosons
  - Not have massless Goldstone boson
  - Be part of a renormalizable quantum field theory
  - History: Zinn-Justin

Simplest possibility is weakly coupled Higgs boson
Allowed parameter space shrinking

Search for the Higgs Particle

Status as of July 2010

Excluded by
LEP Experiments
95% confidence level

Excluded by
Tevatron
Experiments

Excluded by
Indirect Measurements
95% confidence level

Higgs mass values

100 114 120 140 158 175 185 200 GeV/c^2

95% confidence level
Precision EW Data

- Prefer light ($M_h < 158$ GeV) SM Higgs
- Quality of fit is good—doesn’t require new physics

Includes direct search limits

[Hoecker]

Not updated
Understanding Statistics....

- 2-sided confidence level of direct search limits from LEP & Tevatron
- Log likelihood interpretation of experiments

Updated from ICHEP

[Hoecker]  S. Dawson  8
Precision data restrict BSM scenarios

- General 2 Higgs doublet
- Kaluza Klein particles
- Little Higgs with T parity
- MSSM
- 4 generations

Can accommodate heavy Higgs with some types of new physics

[Image: Diagram showing 4th generation particles]
Higgs at the LHC

Goal: Update with comparison of PDFs and reliable estimates of uncertainties
Do we need update of Tev4LHC plots?
Higgs Searches

Updated

Need reliable predictions for many channels
Many tools available

- gg→h
  - NNLO QCD + EW
  - Resummation (threshold)
- Vector Boson Fusion
  - NLO QCD + EW with decays, NNLO QCD
- Vh
  - NLO + EW, NNLO QCD
- tth
  - NLO
- NLO event generators
  - MC@NLO, POWHEG
- Decays
  - NLO QCD+EW

Plea to experimentalists: Help theorists make their tools useful!
SM calculations in great shape

- Dominant production mode is $gg \rightarrow h$
- NNLO in heavy $M_{\text{top}}$ limit
- Exact $t, b$ loops at NLO
- $N^3LL$ resummation
- EW and mixed EW/QCD corrections

Precise predictions needed for error estimates

[Anastasiou]
gg → h

- Fully differential NNLO rates

Anastasiou, Melnikov, Petriello

The issues:
- How to chose central scale / scale variation?
- How to combine PDF & scale uncertainties?

\[ \sigma(M_h = 165 \text{ GeV})_{\text{Tevatron}} = 389.0 \text{ fb} \pm 8.1\% \quad \text{(scale)} \pm 13.6\% \quad (\alpha_s + \text{PDF}) \]

Similar size
Small scale gives better convergence

Moch and Vogt

Anastasiou, Lazopoulos

Average pt @ LHC 7 TeV

M_{higgs} = 120 GeV
How big is uncertainty on $gg \rightarrow h$?

- Baglio & Djouadi uncertainty on $gg \rightarrow h$: $\sim \pm 38\%$
- Roughly 2x’s Anastasiou uncertainty: mainly due to method of combining scale and PDF/$\alpha_s$ uncertainty, along with larger variation of scale, $m_h/3 < \mu < 3m_h$

Tevatron assumes $\pm 17.5\%$ theory uncertainty on $gg \rightarrow h$
PDF errors are complicated....

- Prescription for PDF errors:
  - Errors quoted by PDF fitters typically smaller than variations between sets
  - PDF4LHC: Use envelope of MSTW, CTEQ, NNPDF predictions
- Effectively amounts to doubling MSTW error

Differences not just $\alpha_s$
Higgs Cross Section Working Group

- Attempt to clarify uncertainties on Higgs rates
- Total rates now; differential rates with cuts coming
- Working towards ATLAS/CMS combination

PDF4LHC recipe for NLO gg→h
Compare theory/experiment

- Experiments separate Higgs rate into 0, 1, 2 jet bins
- Theory precision degrades from 0 to 1 to 2 jet bins

Theory uncertainties depend on cuts & binning

[Anastasiou]
$h \rightarrow \gamma\gamma$: Discovery channel for light Higgs

- Single $\gamma$ production: experiment/theory differences seem to be sorted out
- Understanding double photon production necessary before Higgs discovery
  - Low $\gamma\gamma$ differences could be theory/experiment miscommunication about isolation cuts

[Guillet]
Vector Boson Fusion

- Discovery channel
  - 2nd largest cross section over entire $M_h$ range
- VBF: $h \rightarrow \tau^+\tau^-$ and $h \rightarrow WW$ useful for $h$ couplings
- Probes new vector boson interactions
VBF with NLO QCD + EW

- Electroweak corrections to vector boson fusion are of similar size as QCD corrections (-4%, -7%)
- QCD contributions very sensitive to cuts
- Partial cancellation between EW & QCD

[Ciccolini, Denner, Dittmaier]
VBF at (partial) NNLO

- NNLO corrections in DIS approximation
  - Prediction for total rate under excellent control

Bolzoni, Maltoni, Moch, Zaro

Scale uncertainty ~ PDF uncertainty ~ 2%
Interface with NLO Monte Carlos

- Only 2 NLO MCs: **POWHEG & MC@NLO**
  - Hardest jet with LO accuracy, other jets generated by shower in collinear/soft approximations

- **MC@NLO tied to HERWIG**

- **POWHEG**
  - Can switch shower models
  - No issues with incomplete cancellations of higher order effects
  - Automation: new processes should be faster

[Nason]
gg→h in MC@NLO & POWHEG

- Harder $p_T$ spectrum in POWHEG than MC@NLO
  - (large) K factor multiplies all $p_T$ in POWHEG, not in MC@NLO
- Dip in MC@NLO understood
  - Incomplete cancellation (NNLO effect)

Differences understood

[Nason]
VBF in POWHEG

- 3rd jet generated by shower
  - Not accurate in central region as needed for $p_T$ veto
- As $p_T$ veto gets smaller, shower/hadronization as important as NLO scale variation

[Nason]
Step 2: Extract parameters

- Measure couplings to fermions & gauge bosons
  \[
  \frac{\Gamma(h \rightarrow b\bar{b})}{\Gamma(h \rightarrow \tau^+\tau^-)} \approx 3 \frac{m_b^2}{m_\tau^2}
  \]

- Measure spin/parity
  \[J^{PC} = 0^{++}\]

- Measure self interactions
  \[V = \frac{M_h^2}{2} h^2 + \frac{M_h^2}{2\nu} h^3 + \frac{M_h^2}{8\nu^2} h^4\]

Need good ideas here!
CP Higgs Studies

- Study CP of spin-0 particle in model independent way
- Simple observables sensitive to spin
  - Differential width for $h \rightarrow ZZ \rightarrow 4f$
  - Depending on parameters need $\sim 100 \text{ fb}^{-1}$

[Godbole]
Determining Spin/Parity

- Suppose we find a resonance $X \rightarrow ZZ \rightarrow l^+l^-l^+l^-$
  - What is it?
- Helicity amplitudes with most general ZZX couplings for $X = \text{spin } 0, 1, 2$
- Amplitude depends on 5 angular variables
- Can distinguish between various spin parity assumptions with small number of events

- Monte Carlo simulation of signal/background with detector effects
- For $M_h = 250 \text{ GeV}$ and 30 signal events (corresponds to 5 fb$^{-1}$ for SM rate), have $4\sigma$ discrimination between $0^+$ and $0^-$
Is the Higgs a Scalar?

- VBF sensitive to HVV tensor structure

\[ T^{\mu\nu} = c_1 g^{\mu\nu} + c_2 \left( p_1 \cdot p_2 g^{\mu\nu} - p_1^\mu p_2^\nu \right) + c_3 \epsilon^{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta \]

SM  \hspace{1cm} CP even  \hspace{1cm} CP odd

Hankele, Klamke, Zeppenfeld, Figy

Azimuthal angle between tagging jets

[Dittmaier]
Higgs couplings from VBF

- Signal: VBF, $h \rightarrow \tau \tau$
- Idea: vary central jet veto scale to extract gg and VBF separately
- Large theoretical uncertainty in normalization & shape of gg rate

60 fb$^{-1}$ gives $\sim$ 30% measurement of VBF couplings

[Pilkington]
Jet Substructure

- At LHC energy, electroweak scale physics (W, Z, h, t) inside jets
  - Distinguish between QCD generated jets and those due to heavy object decays
  - Algorithms for unclustering jets
  - Apply technique to Wh, Zh, h → bb
    - Important to get y_b
  - Require h & V have high p_T (>200 GeV)
  - Decay products collimated, subjet techniques useful

[Butterworth]
Subjets and $Vh, h \rightarrow bb$

Butterworth, Davison, Rubin, Salam

$d)$

$S\sqrt{B} = 5.9$
in 112-128 GeV

Events / 8 GeV / 30 fb$^{-1}$

$q\bar{q}$

$V+\text{jets}$

$VV$

$V+\text{Higgs}$

$3.5 \sigma$, 30 fb$^{-1}$, 14 TeV
Many alternatives to SM

- MSSM
  - A favorite
  - Still a lot of work to do to have reliable predictions

- Multi-Higgs
  - NMSSM has 1 extra chiral superfield

- Higgsless

- Composite Higgs

- TBD....

\[ \text{Requires } > 100 \text{ fb}^{-1} \]
MSSM

- 5 Higgs bosons. h, H, A, H^±
- Rates affected by change in couplings
  - For $\tan \beta > 10$, largest rate is $b\bar{b}\phi$ at LHC
  - Need NLO generator for $b\bar{b}\phi$
  - $h$ decays 90% to $b\bar{b}$, 10% to $\tau^+\tau^-$

[Spira]
MSSM & Tevatron Limits

- **bb→φ→τ⁺τ⁺** (NNLO QCD)
  - MSSM corrections included using Δm_b approximation
  - Resums large effects to get effective couplings
  - Accurate to < 1%

- **bg→φb→τ⁺τ⁻b, bbb** (NLO QCD)
  - bbφ vertex corrections included in Δm_b approximation
  - Remaining squark/gluon loop contributions neglected in limits
  - O(±20%) for m_{SUSY}~500 GeV

[Spira]
MSSM Higgs production rates

- Squark/gluino loops important for $gg \rightarrow \phi$
  - Rate significantly reduced

SQCD corrections
(relative to LO b loop)

Mühlleitner, Rzehak, Spira

Anastasiou, Beerli, Daleo

$\tan \beta = 20$
NMSSM

- Add gauge singlet superfield
  - Rich phenomenology: 3 neutral Higgs, 2 pseudoscalars, 5 neutralinos

- Severely limited by ALEPH/B physics/Tevatron Higgs limits
  - Some regions allowed where lightest neutralino can be dark matter
  - New signature: $h \rightarrow aa$
Conclusions

- Thanks to the organizers!
  - Theory/experimental dialog critical
  - Theory calculations for Higgs signal under excellent control for SM
    - Still need work on theoretical uncertainties on background
  - Need to come to consensus about treatment of theoretical uncertainties
    - Higgs cross section working group can do this!
  - BSM scenarios need more work