Color Octet Scalars and the Higgs

Radja Boughezal

Argonne National Laboratory

Implications of EWSB Workshop, Madison, May 2011
Outline

• Motivations: strength of indirect constraints

• Review of Higgs production via gluon fusion

• Looking beyond the Standard Model with the Higgs: colored scalars

• Conclusions
The mass of Charged Higgs boson in type II THDM has the strongest lower bound from $b \rightarrow s \gamma$ for $\tan \beta \leq 40$.

The indirect bound is stronger than the LEP direct bound.
A global fit to EW precision observables provides stronger constraints on various $Z'$ models than the direct search bounds.
New physics and properties of the Higgs

New states can significantly modify the properties of the Higgs

**MSSM**  \[ gg \rightarrow h \rightarrow \gamma \gamma \]  **UED**

![Graph showing Higgs cross section](image)

I. Low, S. Shalgar 2009

F. Petriello 2002

The Higgs cross section is a useful discriminator between models

---

Figure 4: The fractional deviation of \( R = \sigma_{gg\rightarrow h} \times \Gamma_{h \rightarrow \gamma \gamma} \), the \( \gamma \gamma \) production rate, in the UED model as a function of \( m_H \); from top to bottom, the results are for \( m_1 = 500, 750, 1000, 1250, 1500 \) GeV.
Can we use the Higgs boson null search results at Tevatron to indirectly learn about possible new physics?

We need first to understand the Higgs in the SM.
Current Limits on the SM Higgs Mass

Combined efforts from direct searches and theoretical predictions were needed to set tighter limits on $M_H$.

- Current fit of electroweak parameters by LEP EW-working group predicts:

  $M_H = 89^{+35}_{-26} \text{ GeV}$

- Upper bound (from precision EW measurements) and lower bound (direct searches at LEP) at 95% CL (SM Higgs):

  $M_H < 158 \text{ GeV}$
  $M_H > 114 \text{ GeV}$

- Combined results from CDF and D0 excluded $M_H$ in the range $158-173 \text{ GeV}$ and $100-109 \text{ GeV}$ at 95% CL.

  arXiv:1007.4587

LEP EW working group July 2010
Gluon fusion is the dominant production Mode in the SM at both colliders
QCD Corrections to $gg \rightarrow H$

LO is one-loop \(\Rightarrow\) sensitive to new physics
BUT complicated higher order corrections

QCD @ NLO: increase LO cross section by roughly 100%

Full NLO with exact mass dependence known
Djouadi, Graudenz, Spira, Zerwas (1995);

\[ \sigma = \sigma_0 (1 + I + \cdots?) \] convergence an open question

Need NNLO to check convergence of the expansion
3-loop vertex, 2 scales: $m_H, m_T \rightarrow$ untractable
An Effective Theory for Higgs

In the limit where the top-quark is heavier than the Higgs and all other quarks are massless, integrate out the top and couple the gluons to the Higgs through an effective vertex:

\[ 2M_T > M_H \]

\[ C(\alpha_s, M_t) \times \]

\[ \mathcal{L}_{\text{eff}} = -\frac{\alpha_s}{4\pi} C H G^a_{\mu\nu} G^{a\mu\nu} \]

\[ \left( C_0 + \left( \frac{\alpha_s}{\pi} \right) C_1 + \left( \frac{\alpha_s}{\pi} \right)^2 C_2 + \ldots \right) \left( \begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \end{array} \end{array} \end{array} \end{array} \end{array} \end{array} \end{array} \end{array} \end{array} + \ldots \right) \]

Factorization of QCD and model dependent effects

\[ C(\alpha_s) \quad \text{Known in SM through } \alpha_s^5 \quad \text{Schroder, Steinhauser (2006); Chetyrkin , Kuhn, Sturm (2006)} \]
Why is the EFT approach so effective

NLO in the EFT approach: Dawson (1991); Djouadi, Spira, Zerwas (1991)

• Dominant terms to the cross section are the same in the exact and effective theory

very good agreement between $\sigma^{\text{Exact, NLO}}, \sigma^{\text{approximate, NLO}}$
provided we normalize to the exact LO result

- difference < 10% for $m_H$ up to 1 TeV
and < 1% below 200 GeV

$m_H = 2m_T$
Why is the EFT approach so effective?

Initial NNLO study of $1/m_t$ suppressed operators indicates this persists (Harlander et al; Pak et al, 2009)

NLO in the EFT:

\[
\Delta \sigma = \sigma_0 \frac{\alpha_s}{\pi} \left\{ \left( \frac{11}{2} + \pi^2 \right) \delta(1-z) + 12 \left[ \frac{\ln(1-z)}{1-z} \right] - 12z(-z + z^2 + 2)\ln(1-z) \right\}
\]

\[
-6 \frac{(z^2 + 1 - z)^2}{1-z} \ln(z) - \frac{11}{2} (1 - z)^3
\]

Analytic continuation to time-like form factor

\[z = M_H^2/(x_1x_2s)\]

eikonal emission of soft gluons

Identical factors in full theory with $\sigma_0 \to \sigma_{LO}$, full theory
Different theoretical approaches for producing Higgs predictions for \( gg \to H \) were found to agree within a few percents.

Theoretical predictions are well under control.

Can we use these results to indirectly exclude new physics?

- NNLO QCD corrections increase cross-section by 10-15% \( \sigma = \sigma_0 (I + I + 0.15 + \cdots) \)

- Converging perturbative series
- Reduction of renormalization and factorization scale dependence

- EW corrections increase NNLO cross-section by 2-6%
Beyond the Standard Model

- Properties of the Higgs boson can be modified in theories with additional particles
  - need precise predictions of cross sections to detect any deviations from measurements

- Higgs production via Gluon fusion is loop induced very sensitive to new physics

- Lots of new physics to study, which Tevatron is already looking for:
  4th generation, colored scalar particles...

- They can couple to Higgs already at tree level and can modify the gg → H xsection
Example Studies:

heavy Colored scalars effects on the cross section in the $gg \rightarrow H$ process

Details can be found in physrevD81:114033,2010 & arXiv:1101.3769
Color-adjoint scalar @ NLO

\begin{align*}
\text{Tevatron} \\
m_h/4 \leq \mu_R=\mu_F \leq m_h \\
m_h = 165 \text{ GeV} \\
\lambda_1 = 2.5 \\
\text{NLO}
\end{align*}

Diagram:

- SM
- SM+scalar

Graph:

- \( \sigma \) (pb) vs. \( m_S \) (GeV)

- Tevatron conditions

- Mass scale range

- Scale parameter

- SM and SM+scalar contributions

- Diagram with quark and Higgs interactions.
Only at NNLO a precise prediction is obtained \(\rightarrow\) need NNLO for the indirect searches!
- Assuming the existence of a 4\textsuperscript{th} generation of fermions with large masses, a SM-like Higgs boson in the mass range 131-204 GeV is excluded (Anastasiou, R. B., Furlan 2010)
A byproduct of the 4\textsuperscript{th} generation analysis of Tevatron is this interesting table:

the observed 95\% $\text{CL}$ upper limit on

\[
\sigma(g g \rightarrow H) \times Br(H \rightarrow WW)
\]

Various new physics models can be studied using these results
Constraints on heavy colored scalars from Tevatron’s Higgs exclusion limit
Color octet & fundamental scalars in \( gg \to H \)

- Scalars that transform as \((8,1)_0\) and \((3,1)_0\) under \( SU(3) \times SU(2) \times U(1) \)

\[
\mathcal{L}^{adj} = \mathcal{L}_{SM} + \text{Tr} \left[ D_\mu S D^\mu S \right] - m_S'^2 \text{Tr} \left[ S^2 \right] - g_s^2 G_{4S} \text{Tr} \left[ S^2 \right]^2 - \lambda_1 H^\dagger H \text{Tr} \left[ S^2 \right],
\]

\[
\mathcal{L}^{fund} = \mathcal{L}_{SM} + (D_\mu S)^\dagger D^\mu S - m_S'^2 S^\dagger S - \frac{1}{2} g_s^2 G_{4S} (S^\dagger S)^2 - \lambda_1 H^\dagger H S^\dagger S.
\]

\( \lambda_1 \) allowed by all symmetries

\( G_{4S} \) required by renormalizability at NNLO
Color octet scalars in $gg \rightarrow H$

- Color octet scalars arise in theories with universal extra dimensions
- Primary decays expected to be into $tt$ or $bb$ depending on $m_S$
- Can be searched for at Tevatron by looking for four $b$-jet final state, BUT direct search is difficult due to large QCD background
- Search reach at Tevatron estimated to be 280 GeV (Dobrescu, Kong, Mahbubani (2007))
- Can indirectly search for it using the influence of the scalar on Higgs production cross section

Dobrescu, Kong, Mahbubani (2007)
Extracting bounds on the scalars parameter space

- Use the following LO amplitude and nth order cross section:

\[ A^{LO} = A_t^{LO} + A_b^{LO} + A_S^{LO} \]

\[ \sigma^n = \sigma_{t+S}^{LO}(m_t, m_S) K^n_{EFT} + \sigma_{Sb}^{LO}(m_S, m_b) + \sigma_{tb}^{LO}(m_t, m_b) + \sigma_{bb}^{LO}(m_b) \]

- Use HDECAY to produce the SM partial decay widths of the Higgs

\[ \Gamma_{gg}, \Gamma_{\gamma\gamma}, \Gamma_{Z\gamma}, \Gamma_{WW}, \Gamma_{ZZ}, \ldots \]

- Replace \( \Gamma_{gg}^{SM} \) with the one that includes the scalar contribution \( \Gamma_{gg}^{new} \)

- The scalars increase the Higgs production cross section and the gg partial width

How does this change the BR(H → WW)?
Extracting bounds on the scalars parameter space

Example: \[ \Gamma_{gg}^{new} = 5 \Gamma_{gg}^{SM} \]

\[ \text{MH} = 120 \text{ GeV} \]
\[ Br(H \rightarrow WW)^{SM} = 0.13 \]
\[ Br(H \rightarrow WW)^{new} = 0.099 \]

\[ \text{Roughly 25\% decrease} \]

\[ \text{MH} = 165 \text{ GeV} \]
\[ Br(H \rightarrow WW)^{SM} = 0.9581 \]
\[ Br(H \rightarrow WW)^{new} = 0.946 \]

\[ \text{Roughly 1\% decrease} \]

The branching ratio is mostly affected at low Higgs masses where it decreases significantly.
Extracting bounds on the scalars parameter space

Two competing effects:

- an increasing cross section for all values of $m_H$
- a branching ratio that decreases at low $m_H$ and remains almost unchanged at high $m_H$

Implications:

- the stronger bounds are obtained at higher values of $m_H$
- bounds at low values of $m_S (< 50 \text{ GeV})$ should not be taken seriously due to the limitation of the effective theory

Note: included a constraint $\frac{\Gamma_{\text{tot}}}{m_H} < \frac{1}{5}$ to prevent strong couplings
Extracting bounds on the scalars parameter space

- Strongest bound occurs at $m_H = 165\text{GeV}$
  \[ m_{S^{adj}} \geq 900 \text{ GeV} \]

- Excluded $m_S < 130\text{GeV}$ for $135 < m_H < 250 \text{ GeV}$

- Estimated direct search limit is $280\text{GeV}$ at Tevatron for scalars decaying primarily to $b\bar{b}$

Direct search insensitive to $m_H$ and lambda but depends on the decay mode while indirect search is independent from the decay mode but sensitive to $m_H$ and lambda
- Strongest bound occurs at $m_H = 165$ GeV
  
  $m_{S}^{\text{fin}} \geq 500$ GeV

- Excluded $m_S < 100$ GeV for
  
  $150 < m_H < 190$ GeV

Threshold enhancement for Xsection for $m_H = 2$ mS

Tail comes from constraint

\[ \frac{\Gamma_{\text{tot}}}{m_H} < \frac{1}{5} \]
Summary

- Direct and indirect search techniques are complementary for probing new physics parameter space

- The precision of the $gg \rightarrow H$ prediction in SM reached the level where new physics effects can not be washed out. This has become an additional constraint on physics Beyond the SM

- I have showed two example states that significantly alter the Higgs cross section: color-adjoint and color-fundamental states
  
  - strong constraints on their parameter space were obtained using Tevatron’s exclusion limit for $gg \rightarrow H \rightarrow WW$

  - many other models involving heavy colored particles coupled to Higgs can be studied and constrained in a similar way
Backup Slides
Extracting bounds on the scalars parameter space

- The scalar sector is defined through the parameters $\lambda_1, G_{4S}, m_S$

  - Use RGE to get the allowed values of $G_{4S}$ by demanding absence of Landau pole up to 10 TeV:

    - adjoint scalar $G_{4S}(v) < 1.5$
    - fundamental scalar $G_{4S}(v) < 2.5$

    we chose $G_{4S} = 1$ and checked that other values in the allowed range change the bounds by at most 5%

- There is no symmetry reason to expect $\lambda_1$ to be small.
  we chose $\lambda_1 = 1$ for simplicity