Outline

- Review of experiment, theory for SM Higgs
- The very effective Lagrangian for the Higgs
- Electroweak corrections and the Higgs effective theory at 3-loops
  Anastasiou, Boughezal, FP 0811.3458
- Updated numerics, the Tevatron exclusion limit, and fun with PDFs
- Electroweak and quark-mass effects at high Higgs pT
  W.-Y. Keung, FP 0905.2775
Why we expect a TeV scale Higgs

- Last undiscovered particle of the SM
- Many reasons to expect it (or something else) to be observed soon

\[ \alpha_0 \rightarrow -\frac{S}{32\pi v^2} \]
The uncertainty in EWSB mechanism makes Higgs a portal into new physics at the TEV scale

**MSSM**

Low, Shalgar 2009

Hewett, Rizzo 2002
SM Higgs circa 2010

- Precision EW upper bound and direct search lower bound at 95% CL: $114 \text{ GeV} \leq M_H \leq 190 \text{ GeV}$

- **News from the Tevatron**: First exclusion in 2008; new combined results exclude 162-166 GeV SM Higgs at 95% CL
Further improvements

More data, increased acceptances, control over systematics

Can likely exclude entire range $M_H \leq 190$ GeV
Is it the SM Higgs?

Rich experimental program if Higgs is found

\[
\begin{align*}
\frac{\Delta g^2(H,X)}{g^2(H,X)} & \quad \text{g}^2(H,Z) \\
g^2(H,W) & \\
g^2(H,t) & \\
g^2(H,b) & \\
g^2(H,t) & \\
\Gamma_H & \\
\text{without Syst. uncertainty}
\end{align*}
\]

2 Experiments

\[ \int \text{L dt=2*300 fb}^{-1} \]

WBF: 2*100 fb^{-1}

\[
\begin{align*}
\text{CP-even} & \quad A = 0.100 \pm 0.039 \\
\Delta \Phi_{\text{max}} & = 5.8 \pm 15.3
\end{align*}
\]

\[
\begin{align*}
\text{CP-odd} & \quad A = 0.199 \pm 0.034 \\
\Delta \Phi_{\text{max}} & = 93.7 \pm 5.1
\end{align*}
\]

Hankele, Klamke, Zeppenfeld 2006

Couplings to 10%

Is is CP even or odd?
SM Higgs production

Tevatron exclusion limit entirely from $gg \rightarrow H \rightarrow WW$ above 130 GeV
Gluon-fusion at NLO

Top-loop dominant; bottom loop gives $-5\%$ correction from interference

What makes is sensitive to new physics (begins at 1-loop) also makes it tough to calculate...

$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$

Effective interactions

Getting the next terms requires new techniques

*Effective field theory*: exploit heavy mass of virtual particles

Two scales: $M_{Higgs}, m_{top}$

\[
\begin{align*}
\text{Only } M_{Higgs} & \quad \times \quad \left[ \begin{array}{c}
\text{Only } m_{top} \\
\text{O}(M^2_{Higgs}/4m^2_{top})
\end{array} \right]
\end{align*}
\]
The Higgs Lagrangian

Summarized in an “effective Lagrangian” for Higgs-gluon interactions

\[ \mathcal{L}_{\text{eff}} = \alpha_s \frac{C_1}{4v} H G^a_{\mu\nu} G^{\mu\nu}_a \]

\[ C_1 = -\frac{1}{3\pi} \left\{ 1 + \alpha_s C_{1t} + \alpha_s^2 C_{2t} + \lambda_{\text{EW}} [1 + C_{1w}] \right\} \]

Inami, Kubota, Okada 1982
Chetyrkin, Kniehl, Steinhauser 1997
Anastasiou, Boughezal, FP 2009

\[ C_{1q} = \frac{11}{4}, \quad C_{2q} = \frac{2777}{288} + \frac{19}{16} L_t + N_F \left( -\frac{67}{96} + \frac{1}{3} L_t \right) \]
Unreasonably effective EFT

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:

\[ z = \frac{M_H^2}{x_1 x_2 s} \]

Eikonal emission of soft gluons

Identical factors in full theory with \( \sigma_0 \rightarrow \sigma_{LO} \), full theory

Initial NNLO study of \( 1/m_t \)
suppressed operators indicates this persists

Harlander, Mantler, Marzani, Ozeren 2009
NNLO in the EFT

Motivates calculation to NNLO in the EFT

$K(p\bar{p} \rightarrow H + X)$

$\sqrt{s} = 2 \text{ TeV}$

$K$-factor: 2 at LHC, 3.5 at Tevatron

Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven 2002-2003

Anastasiou, Melnikov, FP 2005
Electroweak corrections

Residual QCD uncertainty ~10% $\Rightarrow$ EW corrections potentially important to match QCD and experimental precision

NF-enhanced sourced of 2-loop light-quark corrections

K-factor? Values between 1-4 assumed in literature; do these get same K-factor of top-quark piece? (Initial Tevatron exclusion limit assumed K=4)

First goal: check with 3-loop calculation in EFT

Aglietti, Bonciani, Degrassi, Vicini 2004
Actis, Passarino, Sturm, Uccirati 2008
EFT formulation

\[ \mathcal{L} = -\alpha_s \frac{C_1}{4v} H G^\alpha_{\mu\nu} G^{\alpha\mu\nu} \]

\[ C_1 = -\frac{1}{3\pi} \left\{ 1 + \lambda_{EW} \left[ 1 + a_s C_{1w} + a_s^2 C_{2w} \right] + a_s C_{1q} + a_s^2 C_{2q} \right\} \]

Radius of convergence: \( M_H \leq M_W \ldots \)

**However**, dominant corrections from threshold logs and analytic continuation identical in full and EFT

Calculate K-factor in EFT, normalize to exact 2-loop EW result
Factorization in the EFT

If the K-factor for light-quark pieces is the same as the top quark, then the Wilson coefficient in the EFT “factorizes”

\[ C_1 = -\frac{1}{3\pi} \left\{ 1 + \lambda_{EW} \left[ 1 + a_s C_{1w} + a_s^2 C_{2w} \right] + a_s C_{1q} + a_s^2 C_{2q} \right\} \]

Factorization holds if \( C_{1w} = C_{1q} \); \( C_{1q} = \pi/4 \)

Calculate \( C_{1w} \) from 3-loop diagrams, check deviation from \( C_{1q} \), study numerical effect
How to derive a higher-order Higgs EFT

Matching at $O(\alpha \alpha_s)$:

\[ = -\frac{1}{3\pi} \frac{\alpha_s}{v} \lambda_{EW} M_0 \]

\[ = A^{(2)}(M^2_H = 0) M_0 + O\left(\frac{M^2_H}{M^2_W}\right) \]

Equate to get $\lambda_{EW}$
How to derive a higher-order Higgs EFT II

Matching at $O(\alpha\alpha_s^2)$:

$\begin{align*}
\lambda_{EW}C_{1w}M_0 & = A^{(3)}(M_H^2 = 0)M_0 + O\left(\frac{M_H^2}{M_W^2}\right), \\
& = -\frac{1}{3\pi} \frac{\alpha_s}{\nu} (\lambda_{EW}C_{1w})M_0
\end{align*}$

(Other EFT graphs scaleless after expansion)

Equate to get $C_{1w}$
Calculation and results

Expansion in mass ratio reduces integrals to 3-loop vacuum bubbles:

$$I(\nu_i) = \int \prod_{j=1}^{3} d^d k_j \frac{1}{k_1^{2\nu_1} k_2^{2\nu_2} (k_3^2 - M_{W,Z}^2)^{\nu_3} (k_1 - k_2)^{2\nu_4} (k_2 - k_3)^{2\nu_5} (k_3 - k_1)^{2\nu_6}}$$

$$= \int \prod_{j=1}^{3} d^d k_j \mathcal{D}$$

Chetyrkin, Tkachov 1981

Use Poincare invariance to reduce ~1000s of these to 2 master integrals:

$$\int \prod_{j=1}^{3} d^d k_j \partial_i [k_k \mathcal{D}] = 0$$

$$\lambda_{EW} = \frac{3\alpha}{16\pi s_W^2} \left\{ \frac{2}{c_W^2} \left[ \frac{5}{4} - \frac{7}{3} s_W^2 + \frac{22}{9} s_W^4 \right] + 4 \right\}$$

$$C_{1w} = \frac{7}{6}$$

$$C_{1w} = \frac{7}{6}$$
Analytical result: $C_{1w} = 7/6$, compared to $C_{1q} = 11/4$

Difference between factorization hypothesis and actual result irreverently small (weak violation)

$$\sigma_{3-loop} = \sigma_{2-loop} \left\{ \frac{\alpha_s}{\pi} C_{1w} + G^{(1)}_{EFT} \right\}$$

$$\alpha_s(C_{1w} - C_{1q})/\pi \approx 5\%$$

$G^{(1)}_{EFT} \approx 100\%$; contains $\pi^2$, $\ln(1-z)/(1-z)$

K-factor of 3.5 at Tevatron appropriate
Combine QCD, EW corrections to derive current best prediction, check what is in Tevatron analysis: Anastasiou, Boughezal, FP 2009

First limit: $M_H=170$ GeV excluded 0808.0534

- Same K-factors assumed for top, EW contributions ✓
- Same K-factor assumed for top, bottom quarks $K_{tb} \sim 1.5$, $K_{tt} \sim 3.5 \Rightarrow$ needed updating
- MRST 2002 PDFs used
- Significant changes in heavy-quark threshold treatment

<table>
<thead>
<tr>
<th>Original</th>
<th>MRST 2006 PDFs</th>
<th>$K_{tb}$, $K_{bb}$</th>
<th>EW effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3542</td>
<td>0.3650</td>
<td>0.3868</td>
<td>0.3943</td>
</tr>
</tbody>
</table>

What they used

$M_H=170$ GeV 10% increase

Update #1 December 2008
MSTW 2008 PDF release arXiv:0901.0002

Run II inclusive jet data
Decrease of $\alpha_s(M_Z)$ from 0.119 → 0.117
Gluon density decreased at $x \sim 0.1$
$gg$ luminosity error increased from 5% ⇒ 10%

$M_H=170$ GeV:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3833</td>
<td>0.3988</td>
<td>0.3943</td>
<td>0.3444</td>
</tr>
</tbody>
</table>

$\sim 15\%$ decrease in predicted cross section
$\sigma \sim \alpha_s^3 f_g^2 \Rightarrow$ very sensitive to these changes!

Keep PDF errors in mind for LHC analyses...

Increased error only accounted for in latest 2009 analysis
LHC: 25% increase in cross sections at $M_H=120$ GeV, 10% at 200 GeV
The Higgs $p_T$ spectrum

- Other surprises, perhaps in differential distributions?
- Many studies of $p_T$ spectrum as probe of new physics

Roughly 45\% of Tevatron exclusion from 1,2 jet bins (from M. Herndon)

Some LHC analyses in $\tau\tau$, $\gamma\gamma$ select high $p_T$ to remove background; $p_T > 100$ GeV typical Abdullin et al.1998; Mellado, Quayle, Wu 2004

Color-octet scalar induced deviation in integrated ratio Arnesen, Rothstein, Zupan 2008

Motivational region for precision study; new physics or QCD?
**EW, quark-mass effects**

One possible problem: $p_T^2/m_t^2$ effects from other EFT operators

Effects missed previously that contribute to $qg$, $qq$ channels

Same loop-order as previously included effects

Not useful to compute, but think in terms of operators

\[
O_{EW} = \frac{\partial_{\nu} H}{\nu} \frac{G_{\mu\nu} \bar{q} \gamma_{\nu} q}{M_{W,Z}^2} \quad \Rightarrow \quad \frac{p_H \cdot p_g \bar{u} \not{g} u - p_H \cdot \epsilon_g \bar{u} \not{g} u}{\nu M_{W,Z}^2}
\]

- Vanishes for $p_g \cdot p_1, p_2 \Rightarrow$ hard $p_T$ spectrum
- Interferes, destructively, with EFT contributions
Numerical results

Both $W/Z$ and $p_T^2/m_t^2$ act destructively to reduce EFT prediction.

- Rate too small to be relevant
- Reaches $-8\%$ at Tevatron

$-20 \rightarrow 30\%$ at LHC

W.-Y. Keung, FP 2009
FEHiP

If you want to run your own Higgs simulations...

**Fully Exclusive Higgs Production:**
http://www.phys.hawaii.edu/~kirill/FEHiP.htm

Anastasiou, Melnikov FP

- Fully differential, NNLO QCD in EFT framework

New!

**FEHiPro** Anastasiou, Boughezal, Bucherer, FP, Stoeckli

- Additional electroweak effects in 1-jet bin W.-Y Keung, FP 2009
- Exact bottom/top mass dependence through NLO W.-Y Keung, FP 2009; Anastasiou, Bucherer, Kunszt 2009
- Arbitrary new physics Wilson coefficients in progress
Conclusions

- Intricate and large quantum effects to Higgs production
- Effective theory for gluon-fusion valid over a larger range than naively expected, excellent framework for pheno studies
- Combination of 3-loop light-quark terms, PDFs have significant effect on Tevatron exclusion limits
- Previously neglected high-$p_T$ effects calculated
- All result being implemented in up-to-date analysis code FEHiP