Outline

- Review of experiment, theory for SM Higgs
- The gluon-fusion mechanism: a precision QFT playground
- 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
  Anastasiou, Boughezal, FP 0811.3458
- Electroweak and quark-mass effects at high Higgs pT
  W.-Y. Keung, FP 0905.2775
- Low-pT resummation using soft-collinear effective theory
  S. Mantry, FP, in progress
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

\[ \Lambda_{NP} \leq 1.7 \text{ TeV} \]
Higgs in SM extensions

The uncertainty in EWSB mechanism makes Higgs a portal into new physics at the TEV scale

- Loop-induced gluon, photon modes can have $O(1)$ deviations
- Non-standard decays can drastically change collider signals

Dermisek, Gunion hep-ph/0510322

S. Dawson

Hewett, Rizzo hep-ph/0202155

<table>
<thead>
<tr>
<th>$m_{h_1}/m_{a_1}$ (GeV)</th>
<th>$h_1 \to b\bar{b}$</th>
<th>$h_1 \to a_1 a_1$</th>
<th>$a_1 \to \tau\bar{\tau}$</th>
<th>$\sigma_{obs}/\sigma_{exp}$</th>
<th>$\delta\Phi$</th>
<th>$N_{SD}^{LHC}$</th>
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<td>0.938</td>
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SM Higgs circa 2009

Precision EW upper bound and direct search lower bound at 95% CL:

$$114 < M_H/\text{GeV} < 163$$

**News from the Tevatron**: First exclusion in 2008; new combined results exclude 160-170 GeV SM Higgs at 95% CL arXiv:0903.4001
Discovery program over entire mass range at Tevatron+LHC
Coupling measurements to 10% possible; spin, CP
SM Higgs production

** gg fusion dominant by factor of 10 **

Associated production, WBF essential for light Higgs

Tevatron exclusion limit entirely from gg→H→WW above 130 GeV

BR(H→WW) > 90% for 160-170 GeV Higgs
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...


Can reach $K_{\text{NLO}} = \sigma_{\text{NLO}} / \sigma_{\text{LO}} \approx 2$ at LHC, 3 at Tevatron; why so large?
Effective theory for Higgs

- Difficult to go to NNLO and check convergence of expansion
- NLO analytic expressions unwieldy to study, develop intuition about
- Use EFT instead for top (Shifman et al. 1979; Ellis et al. 1988; S. Dawson; Djouadi, Spira, Zerwas 1991)

Region of validity: $M_H < 2m_t$

Known through $O(\alpha_s^5)$:
Schroder, Steinhauser; Chetyrkin, Kuhn, Sturm hep-ph/0512058, 0512060
NLO in the EFT

\[ \Delta \sigma = \sigma_0 \frac{\alpha_s}{\pi} \left\{ \left( \frac{11}{2} + \pi^2 \right) \delta(1-z) + 12 \left[ \frac{\ln(1-z)}{1-z} \right] \right\} + 12z(-z + z^2 + 2)\ln(1-z) \]
\[ -6\left( \frac{z^2 + 1 - z}{1-z} \right) \ln(z) - \frac{11}{2} (1-z)^3 \} \] (integration over PDFs⇒integration over z)

First source of large correction:
11/2+\pi^2 \Rightarrow 50\% increase (can even resum these corrections Magnea, Sterman 1990; Ahrens, Becher, Neubert, Yang 0808.3008)

Second source: shape of PDFs enhances threshold logarithm
Unreasonably effective EFT

- In the full theory with top quarks, study eikonal approximation for real emission, Sudakov form factor for virtual.

\[
\Delta \sigma_{\text{soft}}^{\text{top}} = \sigma_{\text{top}}^{(0)} C_A \frac{\alpha_s}{\pi} (1 - z)^{-1-2\epsilon} \lambda^{-1-\epsilon} (1 - \lambda)^{-1-\epsilon} \\
\Rightarrow \sigma_{\text{top}}^{(0)} \frac{\alpha_s}{\pi} 12 \left[ \frac{\ln(1 - z)}{1 - z} \right]_+ \\
\Delta \sigma_{\text{Sud}}^{\text{top}} = \sigma_{\text{top}}^{(0)} 2 C_A \frac{\alpha_s}{\pi} \frac{1}{\epsilon^2} \left( \frac{-\mu^2}{\hat{s}} \right)^\epsilon \delta(1 - z) \\
\Rightarrow \sigma_{\text{top}}^{(0)} \frac{\alpha_s}{\pi} \pi^2 \delta(1 - z)
\]

- Dominant corrections in full and EFT differ only by tree-level cross section ⇒ caused by shape of gluon PDF

\[
\sigma_{\text{approx}}^{\text{NLO}} = \left( \frac{\sigma_{\text{EFT}}^{\text{EFT}}}{\sigma_{\text{LO}}^{\text{LO}}} \right) \sigma_{\text{QCD}}^{\text{LO}}
\]

% - level or better for \( M_H < 2m_t \), even gets >90% of correction above Threshold structure preserved

Initial NNLO study of \( \frac{1}{m_t} \) suppressed operators indicates this persists Harlander, Ozeren 0909.3420
Motivates calculation to NNLO in the EFT

K-factor: 2 at LHC, 3.5 at Tevatron
Electroweak corrections

- Residual QCD uncertainty ≈ 10% ⇒ EW corrections potentially important to match QCD and experimental precision
- \( N_F \)-enhanced sourced of 2-loop light-quark corrections

⇒ Up to ~8-9% at threshold relative to LO QCD

Aglieetti, Bonciani, Degrassi, Vicini hep-ph/0404071; Actis, Passarino, Sturm, Uccirati 0809.1301

- K-factor? Values between 1-4 assumed in literature; do these get same K-factor of top-quark piece?
- First goal: check with 3-loop calculation in EFT
EFT formulation

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

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

However, dominant corrections from threshold logs and analytic continuation of Sudakov form factor 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”

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

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

- 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
Matching to the EFT I

Matching at $\mathcal{O}(\alpha\alpha_s)$:

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

\[ = A^{(2)}(M_H^2 = 0) M_0 + \mathcal{O} \left( \frac{M_H^2}{M_W^2, Z} \right) \]

Equate to get $\lambda_{EW}$
Matching to the EFT II

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

\[ = - \frac{1}{3\pi} \frac{\alpha_s}{v} \lambda_{EW} (\alpha_s C_{1w}) \mathcal{M}_0 \]

\[ = \mathcal{A}^{(3)}(M_H^2 = 0) \mathcal{M}_0 + \mathcal{O}(M_H^2/M_W^2, Z) \]

Equate to get $C_{1W}$
Calculational strategy

- Expansion in $M_H/M_W$ reduces diagrams to 3-loop vacuum bubbles

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

- Use Poincare invariance of loop integrals to facilitate calculation
  K. Chetyrkin, F. Tkachov 1981 \(\Rightarrow\) left with two such integrals to evaluate

\[ \int \prod_{j=1}^{3} d^d k_j \partial_i [k_k D] = 0 \]
Analytical result: $C_{1W} = 7/6$, compared to $C_{1q} = 11/4$

Difference between factorization hypothesis and actual result irrelevantly 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 $\pi^2$, $\ln(1-z)$, the large corrections to HGG operator

K-factor of 3.5 at Tevatron appropriate
Circa December 2008

- Combine QCD, EW corrections to derive current best prediction, check what is in Tevatron analysis
- First limit: $M_H = 170$ GeV excluded

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

What they used

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<tr>
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<th>MRST 2006 PDFs</th>
<th>$K_{tb}, K_{bb}$</th>
<th>EW effects</th>
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<td>original</td>
<td>0.3542</td>
<td>0.3650</td>
<td>0.3868</td>
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<tr>
<td>$M_H = 170$ GeV</td>
<td>0.3943</td>
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10% increase

Update #1
Circa January 2009

- **MSTW 2008 PDF release** arXiv:0901.0002
- Run II inclusive jet data
- Decrease of $\alpha_s(M_Z)$ from $0.119 \rightarrow 0.117$
- Gluon density decreased at $x \sim 0.1$
- $gg$ luminosity error increased from $5\% \Rightarrow 10\%$

$M_H=170$ GeV:

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<tbody>
<tr>
<td>0.3833</td>
<td>0.3988</td>
<td>0.3943</td>
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</table>

$\sim 15\%$ decrease in predicted cross section!

$\sigma \sim \alpha_s^3 f_g^2 \Rightarrow$ very sensitive to these changes!

- Central value, but not increased error, accounted for in 2009 analysis
- LHC: $25\%$ increase in cross sections at $M_H=120$ GeV, $10\%$ at 200 GeV after changing PDFs, bottom-quark description, EW effects

Changes in relevant region for Tevatron analyses

Keep in mind for LHC analyses...
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 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. hep-ph/9805341; Mellado, Quayle, Wu hep-ph/0406095

Color-octet scalar induced deviation in integrated ratio Arnesen, Rothstein, Zupan 0809.1429

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

\[ O_{EW} = \frac{H^\dagger D_\mu H}{v^2} \frac{\bar{q} G^{\mu\nu} \gamma_\nu q}{M_{W,Z}^2} \]

\[ \Rightarrow \]

- Vanishes for $p_g \sim p_1, p_2 \Rightarrow$ 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 at Tevatron

- Reaches $-8\%$ at Tevatron

- $-20\rightarrow 30\%$ at LHC

- All effects being included in updated analysis code FEHiP

Anastasiou, Boughezal, Bucherer, FP, Stoeckli, in progress
Low $p_T$ Higgs production

Other searches restrict the $p_T$ to low values

LHC $H \rightarrow WW$ jet veto: $p_TJ < 20$ GeV

Dittmar, Dreiner hep-ph/9608317

Leading order prediction for $p_T$ spectrum:

$$\frac{d\sigma}{d{p_T}^2} \sim \sigma_0 \frac{C_A \alpha_s}{\pi} \frac{1}{p_T^2} \ln \frac{s}{p_T^2}$$

must resum to all orders

<table>
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<tr>
<th>Reaction</th>
<th>$\sigma \times BR^2$ [pb]</th>
<th>cut 1-3</th>
<th>cut 4-6</th>
<th>cut 7</th>
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</thead>
<tbody>
<tr>
<td>$pp \rightarrow H \rightarrow W^+W^- (m_H = 170$ GeV)</td>
<td>1.24</td>
<td>0.21</td>
<td>0.18</td>
<td>0.080</td>
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<td>$pp \rightarrow W^+W^-$</td>
<td>7.4</td>
<td>0.14</td>
<td>0.055</td>
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<td>$pp \rightarrow t\bar{t} (m_t = 175$ GeV)</td>
<td>62.0</td>
<td>0.17</td>
<td>0.070</td>
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<td>$pp \rightarrow Wtb (m_t = 175$ GeV)</td>
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<td>0.13</td>
<td>0.016</td>
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Impact-parameter formalism

Classic analysis of Collins, Soper, Sterman NPB250 199 (1985)

As $b \to \infty$, hit Landau pole of QCD coupling; non-perturbative physics enters (why for $p_T > \Lambda_{QCD}$?)

A typical approach; others exist ($W$ is the integrand):

$$W(b) \to W(b_*) \exp \left[ -b^2 g_1 - b^2 g_2 \ln \frac{b_{\text{max}} m_D}{2} \right], \quad b_* = \frac{b}{\sqrt{1 + b^2/b_{\text{max}}^2}}.$$
Other issues occur, in the combination with fixed order

\[ \Delta \equiv \left[ \frac{d\sigma_{\text{fixed}}}{dQ_T} - \frac{d\sigma_{\text{exp}}}{dQ_T} \right] / \frac{d\sigma_{\text{fixed}}}{dQ_T} \]

Large deviation of expanded b-space result from fixed-order complicates combining phase-space regions

"Joint resummation" Kulesza, Sterman, Vogelsang hep-ph/0309264

Claim: more convenient framework to formulate low-\( p_T \) resummation is soft-collinear effective theory
Overview of SCET

Lightning overview of SCET: split QCD gluon field into several fields with definite momentum scalings \( (\eta \sim p_T/M_H) \) and their own gauge transformations

\[ A = A_H + A_{c1} + A_{c2} + A_{us} \]

- \( A_H \sim (p^- , p^+ , p_T) \sim M_H(1,1,1) \) “hard”
- \( A_{c1} \sim M_H(\eta^2,1,\eta) \) “collinear”
- \( A_{c2} \sim M_H(1,\eta^2,\eta) \) “collinear”
- \( A_{us} \sim M_H(\eta^2,\eta^2,\eta^2) \) “ultrasoft”

Integrate out hard modes, match to collinear-invariant operators
At leading-power, can decouple u-soft and collinear gluons

\[ A_c = Y A_c^{(0)} Y^\dagger \]

\[ Y_c = P \exp \left\{ ig \int_{-\infty}^{x} ds \, n \cdot A_{us}(sn) \right\} \]

\( A^{(0)} \) has no u-soft couplings; factorize matrix element into u-soft and collinear components
Low $p_T$ in SCET

- Sequence of effective field theories: $\text{QCD} \rightarrow \text{SCET}_{p_T} \rightarrow \text{SCET}_{\Lambda_{\text{QCD}}}$
- Structure after matching to $\text{SCET}_{p_T}$:

$$\frac{d^2\sigma}{dp_T dY} \sim \int dx_1 dx_2 |C(x_1, x_2; \mu_Q, \mu_T)|^2 \int dk^+\bar{k}_n^- d^2k^+ \bar{d}^2k^\perp \bar{k}_n^- \times J_n^{\alpha\beta}(x_1, k^+_{\parallel}, k^-_{\parallel}, \mu_T) J_{\bar{n}\alpha\beta}(x_2, k^-_{\parallel}, k^+_{\parallel}, \mu_T) S(x_1, x_2, k_{\parallel\bar{n}}, \mu_T)$$

$$|C|^2 \sim \exp \left\{ -\int_{\mu_T^2}^{\mu_Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \gamma_0(\bar{\mu}^2) \right\}$$

- Lower limit of evolution set by matching scale $\mu_T \sim p_T$
- Exact momentum conservation still implemented
- Non-perturbative effects in power-suppressed operators
- Collinear gluon-jet functions valid for other LHC processes; some interesting differences from previous SCET studies...

(Sonny Mantry, FP: soon...)
Conclusions

- Intricate and large quantum effects on 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
- Framework for low-\(p_T\) resummation in SCET that should make fixed-order matching more convenient