QCD–EW Effects in Higgs Production and a New Prediction for $gg \rightarrow H$ in SM

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In collaboration with:
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What we know about the SM Higgs Boson Mass today

- Current fit of electroweak parameters by LEP EW-working group predicts:
  \[ M_H = 90^{+36}_{-27} \text{ GeV} \]

- Upper bound (from precision EW measurements) and lower bound (direct searches at LEP) at 95% CL:
  \[ M_H < 163 \text{ GeV} \]
  \[ M_H > 114.4 \text{ GeV} \]

- News from the Tevatron: Combined results from CDF and D0 excluded a Higgs Boson mass of 170 GeV at 95% CL
  \[ \text{arXiv:0808.0534} \]
  Extended recently to the range \[160 < M_H < 170 \text{ GeV} \]
  \[ \text{arXiv:0903.4001} \]
Gluon fusion

**gg → H:** largest cross section at Tevatron and LHC

LO is already 1-loop \(\Rightarrow\) complicated higher order corrections

QCD corrections at NLO: increase LO cross section by 80-100%

available in full and effective theory: Graudenz @ al 93; Dawson @ al 91; Djouadi @ al 91

\[
\sigma^\infty \equiv \sigma^{LO}(m_t, m_b) \frac{\sigma(m_t \to \infty)}{\sigma^{LO}(m_t \to \infty)}
\]

difference between \(\sigma^{Exact \ NLO}, \sigma^\infty \ NLO\)

< 10% for up to 1 TeV and < 1% below 200 GeV
Inclusive $x$-section of $gg \rightarrow H$ at NNLO in QCD

NNLO QCD contributions calculated in the large $M_T$ limit: increase $x$-section by 10-15%.

NNLO Corrections are significantly smaller than NLO contributions ⇒ converging perturbative series

Harlander @ al (2002); Anastasiou @ al (2002); Ravindran @ al (2003)

Resummation of soft gluon effects at NNLL: an additional 6% to total $x$-section

Catani, de Florian, Grazzini, Nason (2003)
NLO Electroweak Corrections to $gg \to H$

Residual uncertainty from QCD: 9–11%

EW Corrections could be important for matching precision of QCD predictions

\[ \sigma_{EW} = \sigma_0 (1 + \delta_{EW}) \]

• Light quarks (analytically): real $M_w, M_z \to \delta_{EW}$ up to 9%
• Top quark: Taylor expansion for $M_H < 2M_W$

Aglietti, Bonciani, Degrassi, Vicini (2004); Degrassi, Maltoni (2004)

• Light quarks: complex $M_w, M_z$ everywhere
• Top quark: extend calculation to $M_H > 2M_W$

Actis, Passarino, Sturm, Uccirati (2008)

Light quarks do not dominate above 180 GeV

Light quarks + top:
\[ \delta_{EW} : (+4) - (+6)\% \]
\[ 115 \text{ GeV} \leq M_H \leq 160 \text{ GeV} \]
\[ \delta_{EW} : (-4) - (+4)\% \]
\[ 160 \text{ GeV} \leq M_H \leq 400 \text{ GeV} \]
What about mixed EW-QCD effects?

At LHC QCD corrections to

\[ \sigma(gg \rightarrow H) \approx \sigma_{LO}(1 + 0.7 + 0.3 + \ldots) \approx 2\sigma_{LO} \]

\[ O(\alpha) \text{ up to } 6\% \text{ of LO} \]

\[ O(\alpha \alpha_s) ? \]

What we need:

several loops & several scales \[ M_W / M_Z, M_H \]

Quite hard with the current computational capabilities!

Can we just assume the mixed EW-QCD is the same as EW x QCD (complete factorisation)?

We need to check that... possible if we use an effective field theory approach again
Two assumptions were made:

- **No QCD enhancement to light quarks**
  
  \[ \hat{\sigma}_{ij} = \sigma^{(0)}_{\text{EW}} G_{ij}^{(0)} (z) + \sigma^{(0)} \sum_{n=1}^{\infty} \left( \frac{\alpha_s}{\pi} \right)^n G_{ij}^{(n)} (z) \]

  1-2\% increase in total xsection

- **QCD enhancement to light quarks = QCD enhancement to top quark**

  \[ \hat{\sigma}_{ij}^{\text{CF}} = \sigma^{(0)}_{\text{EW}} G_{ij} (z; \alpha_s) \]

  5-6\% increase in total xsection

Complete Factorization assumption used in the Tevatron exclusion limits!
The Tevatron observed 95% CL upper limit on the cross section vs the predicted SM cross section

\[ M_H = 170\,\text{GeV} \] is excluded!

What went into the predicted cross section:

- the complete factorization assumption was used
- \( b \)-quark contributions with the same QCD enhancement as top (Catani et al, 2003)
- old PDFs (MRST2002)

2009: the exclusion extended to the range 160-170 GeV
Our Goals (Anastasiou, RB, Petriello (2008)):

- Check the validity of complete factorization assumption
- Provide most up-to-date QCD prediction of $\sigma(gg \rightarrow H)$ with best current estimates of $K$-factors and newest PDFs
EFT formulation (Anastasiou, R.B, Petriello 2008)

\[ L_{\text{eff}} = -\alpha_s \frac{C_1}{4\pi} H G^a_{\mu\nu} G^{a\mu\nu} \]

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

Radius of convergence \( M_h \leq M_w \); however top-quark EFT valid up to \( 1 \text{ TeV} > 2M_t \), reason to expect similarity here

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

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

Complete Factorization holds if \( C_{1w} = C_{1q} \) \& \( C_{2w} = C_{2q} \)

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

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


\[
C_{1w} = \frac{7}{6}
\]

to be compared with

\[
C_{1w}^{fac} = C_{1q} = 11/4
\]

Violation of Factorization assumption!

Numerical effect on cross section?
Results 2

\[ \sigma_{QCD}^{NNLO} = \sigma^{(0)} G_{ij}(z; \alpha_s) + \sigma^{(0)}_b G_{ij}^{(0)}(z) K_{bb} + \sigma^{(0)}_{t,b} G_{ij}^{(0)}(z) K_{tb} \]

\[ \sigma_{EW}^{NNLO} = \sigma_{t,lf}^{(0)} \left\{ G_{ij}^{(0)}(z) \left[ 1 + a_s(C_{1w} - C_{1q}) + a_s^2(C_{2w} - C_{2q} + C_{1q}(C_{1q} - C_{1w})) \right] 
+ a_s G_{ij}^{(1)}(z) \left[ 1 + a_s(C_{1w} - C_{1q}) + a_s^2 G_{ij}^{(2)} \right] \right\} . \]

\[ \sigma_{best} = \sigma_{QCD}^{NNLO} + \sigma_{EW}^{NNLO} \]

\[ \sigma_{EW}^{NNLO \, CF} = \sigma_{t,lf}^{(0)} G_{ij}(z; \alpha_s) \]

\[ a_s = \frac{\alpha_s}{\pi} \]

\[ \sigma^{(0)}_b = \frac{G_F \alpha_s^2}{512 \sqrt{2 \pi}} |G_b|^2, \]

\[ \sigma^{(0)}_{t,b} = \frac{G_F \alpha_s^2}{512 \sqrt{2 \pi}} \left[ 2 \text{Re} \left( G_t G_b^* \right) \right], \]

\[ \sigma^{(0)}_{t,lf} = \frac{G_F \alpha_s^2}{512 \sqrt{2 \pi}} \left[ 2 \text{Re} \left( G_t G_{lf}^* \right) \right] \]

\[ G_{ij}(z; \alpha_s) = \sum_{n=0}^{\infty} \left( \frac{\alpha_s}{\pi} \right)^n G_{ij}^{(n)}(z) \]

\[ G_{ij}^{(0)}(z) = \delta_{ig} \delta_{jq} \delta(1-z) \]

**Note:** tb-interference is negative.

QCD corrections to top for large \( M_t \)
Results 2

\[ \sigma_{QCD}^{\text{NNLO}} = \sigma_{QCD}^{(0)} G_{ij}(z; \alpha_s) + \sigma_b^{(0)} G_{ij}(z) K_{bb} + \sigma_{t,b}^{(0)} G_{ij}(z) K_{tb} \]

\[ \sigma_{\text{EW}}^{\text{NNLO}} = \sigma_{t,lf}^{(0)} \left\{ G_{ij}^{(0)}(z) \left[ 1 + a_s (C_{1w} - C_{1q}) + a_s^2 (C_{2w} - C_{2q} + C_{1q} (C_{1q} - C_{1w})) \right] 
+ a_s G_{ij}^{(1)}(z) \left[ 1 + a_s (C_{1w} - C_{1q}) + a_s^2 G_{ij}^{(2)} \right] \right\}, \]

\[ \sigma_{\text{best}} = \sigma_{QCD}^{\text{NNLO}} + \sigma_{\text{EW}}^{\text{NNLO}} \]

\[ \sigma_{\text{EW}}^{\text{NNLO CF}} = \sigma_{t,lf}^{(0)} G_{ij}(z; \alpha_s) \]

Included are:

- NNLO K-factor computed in large \( M_t \) and normalized to exact LO top-result
- \( O(\alpha) \) (exact results by Actis et al (2008)) & new \( O(\alpha \alpha_s) \) light-quark results
- \( b \)-quark results with exact NLO \( K_{tb}, K_{bb} \)

Note for

\[ 120 \text{GeV} \leq M_H \leq 180 \text{GeV} : 1.2 \leq K_{tb}^{\text{NLO}}, K_{bb}^{\text{NLO}} \leq 1.5 \]

to be compared with \( K_t^{\text{NNLO}} \sim 3.5 \) used by Catani et al (2003) & Tevatron
We use: $G_F, M_W, M_Z$ as input parameters

pole $M_t = 170.9 \text{ GeV}$

$\overline{\text{MS}}$ $m_b$ with $\overline{m}_b(10 \text{ GeV}) = 3.609 \text{ GeV}$

Kuhn et al (2007)

Plotted is $\delta_{EW}^x = 100 \frac{\sigma_{EW}^x}{\sigma_{\text{NNLO}}^{QCD}}$

pure QCD-contributions dominate:

$\alpha_s(C_{1W} - C_{1q}), \alpha_s^2(C_{2W} - C_{2q})$ Smaller than $\alpha_s G_{ij}^{(1)}, \alpha_s^2 G_{ij}^{(2)}$

$\sigma(g g \rightarrow H)$ receives almost the entire 5-6% shift indicated by Complete Factorization
Results 2

New predicted xsection based on the following changes wrt old one (Catani et al 2003):

- Exact NLO \( K_{tb}, K_{bb} \) instead of NNLO \( K_t \) for b-contributions
- Msbar mb instead of pole mass (results only 1.5% larger than with pole mass)
- The new \( \delta_{EW} \) (4-6% instead of the old 5-8%)
- MSTW 2008 PDFs instead of MRST2002

Resummation effects accounted for approximately by choosing \( \mu_F = \mu_R = M_H/2 \)
reproduces central value to better than 1%  

Catani et al 2003

An example: \( M_H = 170 \text{GeV} \) (\( \sigma \) in pb)

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<th>EW effects</th>
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To be compared with old prediction (Catani et al 2003) enhanced by the shift of Aglietti et al: 0.3652

A decrease of 6% in xsection!
Results 2: New Prediction

Tevatron

<table>
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<tr>
<th>$m_H$ [GeV]</th>
<th>$\sigma_{\text{best}}$ [pb]</th>
<th>$m_H$ [GeV]</th>
<th>$\sigma_{\text{best}}$ [pb]</th>
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<tr>
<td>110</td>
<td>1.417 (±7% pdf)</td>
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<tr>
<td>155</td>
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- Values for xsection are 4-6% lower than used in 2008 exclusion by Tevatron for $M_H = 150-170$ GeV
- Theoretical uncertainty from scale dependence obtained by varying $\mu \in [\frac{M_H}{4}, M_H]$ $\rightarrow$$[-11\%, +7\%]$
- PDF errors estimated using error eigenvectors provided with MRST2008 fit

New results accounted for in new Tevatron analysis: extended exclusion range to 160-170 GeV
Summary

1) While QCD and EW corrections don't factorise, numerical effect on cross section is small

2) Provided an updated theoretical prediction for inclusive $\sigma(gg \rightarrow H)$ with best current estimates of K-factors and newest PDFs (MRST2008)

Updated prediction is 4-6% lower than what was previously used by Tevatron in 2008 exclusion

Our new results accounted for in new Tevatron analysis in addition to their new data: extended exclusion range to $160-170\text{GeV}$ arXiv:0903.4001 [hep-exp]