Hadronic production of a Higgs boson in association with two jets at NLO

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based on work done in collaboration with
John Campbell and Keith Ellis 1001.4495 .

Moriond QCD
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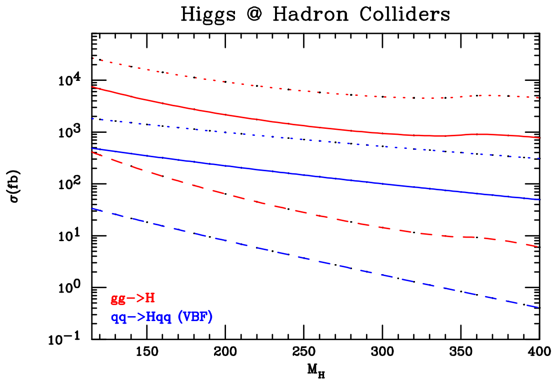
Outline

1. **Motivation: Higgs @ hadron colliders**
2. **Higgs-gluon coupling in the large top-limit**
    - Why use an effective theory?
    - When not to use an effective theory
3. **Higgs plus two jets at the Tevatron**
    - Higgs searches: theoretical uncertainties
    - Cross sections with experimental cuts
4. **Higgs plus two jets at the LHC**
    - Minimal cuts
    - VBF cuts
5. **Conclusions**

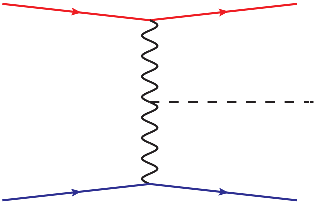
Higgs Production at Hadron Colliders



Higgs Production at the LHC and the Tevatron

- Shown are two of the most important Higgs processes at the LHC (7 TeV solid, 14 TeV dotted) and the Tevatron (dashed) gluon fusion (red) and vector-boson-fusion (blue).
- Gluon fusion dominates at both colliders and is typically an order of magnitude bigger than VBF.
- These plots are at LO are intended to show the order of magnitudes at current c.o.m energies of interest gluon fusion has large K-factors....

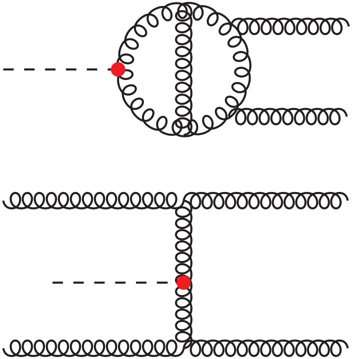
Higgs plus two jets: Signal



Vector-Boson-Fusion

- VBF is an important Higgs discovery channel and is crucial for the measurement of the couplings between the Higgs and the weak vector bosons (W, Z).
- The next-to-leading order QCD corrections are quite small $\sim 5-10\%$ (Han, Valencia, Willenbrock, Figy, Oleari, Zeppenfeld, Berger, Campbell)
  Full EW+QCD corrections (Ciccolini, Denner, Dittmaier)

Higgs production through gluon fusion



gg → *H* @ **NNLO**

- Over the last few years much work has gone into understanding Higgs production at NNLO and beyond. (Anastasiou, Dissertori, Grazzini, Melnikov, Petriello Stöckli, Webber . . .)
- Knowing these amplitudes at NNLO allows up to two jets in the final state.
- The dominant source of theoretical scale dependence enters from these tree-level like pieces. Therefore knowing $H + 2j$ at NLO reduces the overall scale dependence.

Why work in an effective theory?

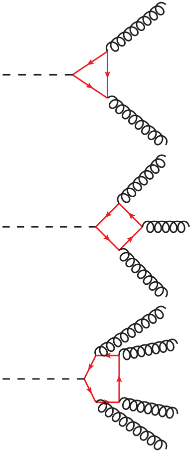
Higgs-Gluon Coupling

In the Standard Model the Higgs couples indirectly to massless gluons.

The only mechanism linking the Higgs to gluons is a fermion loop.

Since the top quark dominates all lighter quarks can be neglected

However, as additional partons are added to the final state calculations become quickly intractable...



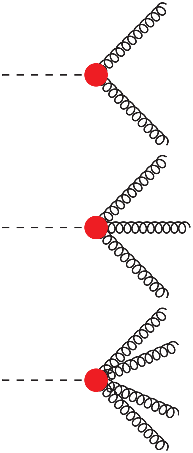
Why work in an effective theory?

Higgs-Gluon Coupling

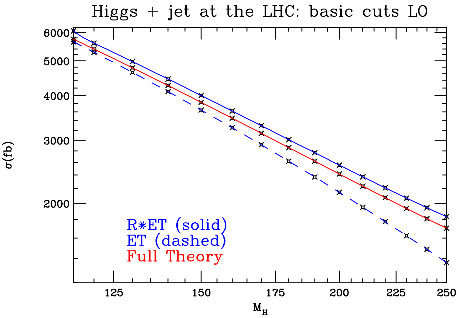
To reduce the complexity the top-quark can been integrated out resulting in an effective-vertex

This results in tree-level like (massless) complexity for Leading Order amplitudes

Compared to massive one-loop amplitudes at Leading Order in the full theory.



Estimating the mass effects



One can estimate the effect of the top-mass by multiplying the effective theory result by the following quantity

$$R = \frac{\sigma_{finite\ m_t}(gg \to H)}{\sigma_{m_t\ \infty}(gg \to H)}$$

Which in the region where $x > 1$ can be expressed as,

$$R = \left[\frac{3x}{2}\left(1 - (x-1)\left[\sin^{-1}\frac{1}{\sqrt{x}}\right]^2\right)\right]^2$$

Here $x = 4m_t^2/m_h^2$.

Effective theory Breakdown

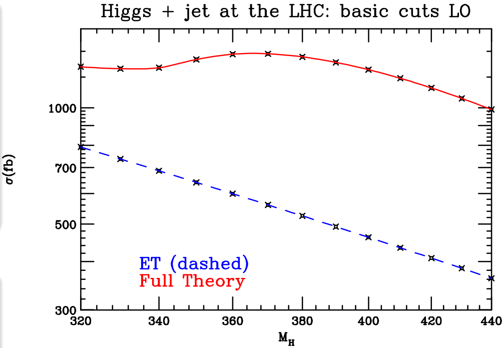
When should the effective theory not be trusted?

When $m_h > 2m_t$

Here the effective theory does a rather poor job of reproducing the full theory. This is due to the resonance-like behaviour when the Higgs can produce two tops on-shell.

What happens to R?

For $x < 1$ R becomes a complex function....



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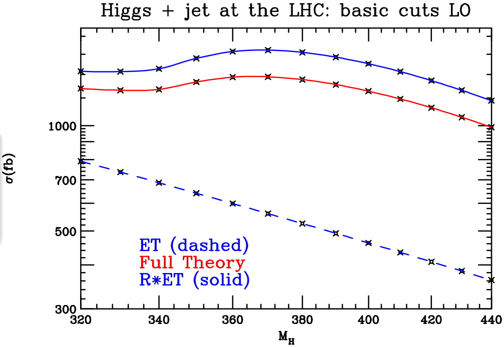
Saving the Effective theory

So we multiply by $|R|$ to restore the full theory shape.



Effective theory Breakdown

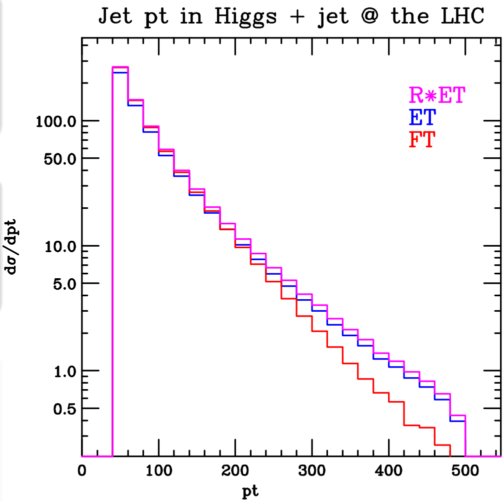
When jet $p_t > m_t$

Jet p_t distributions are not accurately described when $p_t > m_t$.

Shown here for $pp \to H + j$ at the LHC with $\sqrt{s} = 10 TeV$ and basic cuts on the jets $p_t > 40 GeV$ and $|\eta| < 4.5$ and $m_H = 160$ GeV

Need for NLO

K factors around 1.2- 1.3 for $H + 2j$ show that NLO is more important than mass effects in the mid-p_t range.



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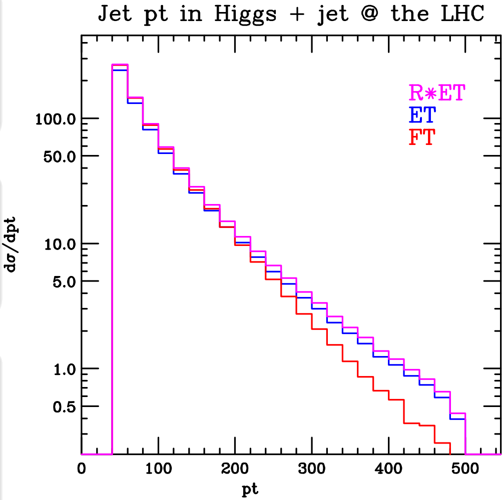

Recent developments

- $pp \rightarrow H + 2j$ was first calculated in 2006 using a semi-numerical approach (Campbell, Eliis, Giele, Zangerighi)
- Since 2006 the individual helicity amplitudes for Higgs + jets have been calculated by several groups (Badger, Berger, Campbell, Del Duca, Dixon, Eliis, Glover, Mastrolia, Risager, Sofiantaos, CW)
- Culminating in complete analytic control (of H+2 jets) in Autumn 2009, these amplitudes have since been implemented in MCFM v5.7 leading to the following improvements
  - Computation speed greatly improved which allows decays of Higgs bosons to be included
  - Differential cross-sections much quicker to compute
  - Code is now public

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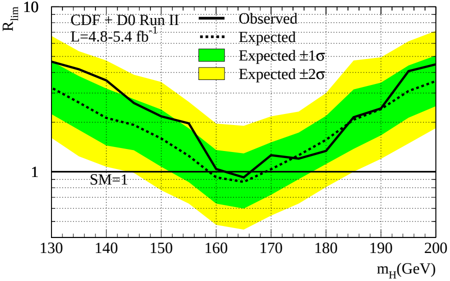

Higgs seraches at the the Tevatron
1001.4162

CDF and DO Higgs searches are beginning to suggest exclusion regions of Higgs masses.

However, sensitivity to theoretical predictions of Higgs production can shift SM expectations, increasing or decreasing exclusion limits

NNLO Higgs production known (Anastasiou, Dissertori, Grazzini Stöckli, Webber) how does perturbative scale variation combine?

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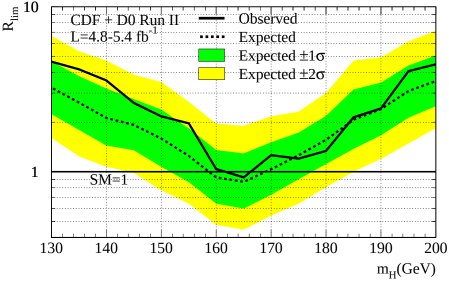

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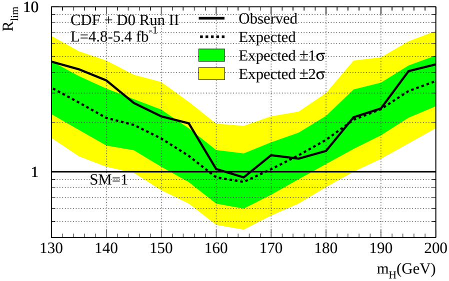

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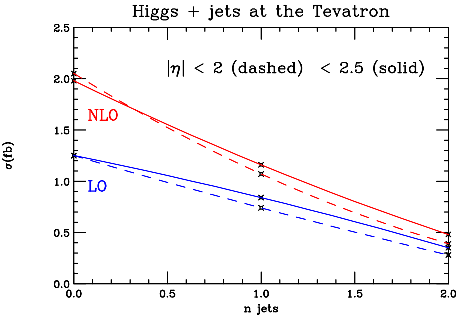
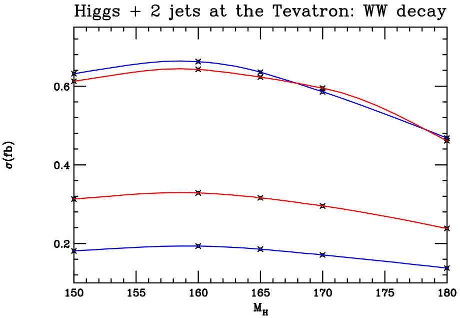
Higgs + jets @ NLO : Tevatron

Cross sections for $pp \to H(\to W^+(\to e^+\nu)W^-(\to \mu^-\overline{\nu}))+$ jets with a basic set of cuts $p_t(jet) > 15$ GeV, $R_{jet,jet} > 0.4$

Scale variation between $m_H/2 \leq \mu \leq 2m_H$ shows improvement from around
$+90\% - 44\%$ at LO to
$+35\% - 30\%$ at NLO.





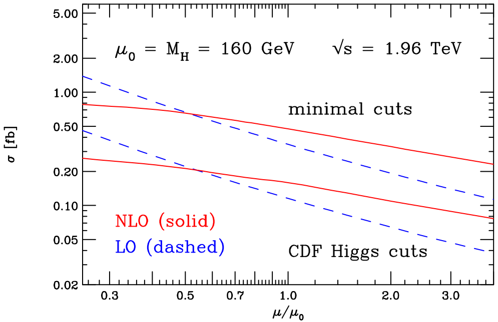
Cross sections with experimental cuts

Lepton cuts

- $p_t^{\ell_1} > 20\ \mathrm{GeV}$, $|\eta^{\ell_1}| < 0.8$
  $p_t^{\ell_2} > 10\ \mathrm{GeV}$, $|\eta^{\ell_2}| < 1.1$.
  $m_{\ell_1 \ell_2} > 16\ \mathrm{GeV}$.
- Each lepton must be isolated. Any jet found by the algorithm that lies within a $\eta - \phi$ distance of 0.4 from a lepton should have a transverse momentum less than 10% of that of the lepton itself.
- The missing transverse momentum the sum of the two neutrino momenta – is constrained using

$$\not{E}_t^{\,\mathrm{spec}} = \not{E}_t \sin\left[\mathrm{min}\left(\Delta\phi, \frac{\pi}{2}\right)\right] .$$

with $\not{E}_t^{\,\mathrm{spec}} > 25\ \mathrm{GeV}$.



Scale uncertainties at the Tevatron : analysis of 0905.3529 (Anastasiou, Dissertori, Grazzini, Stöckli, Webber)

Estimate the total scale uncertainty of the NNLO inclusive cross section (using NNLO pdfs) by varying the scale for the 0-,1- and 2-jet bins

$$\frac{\Delta N_{\text{signal}}(\text{scale})}{N_{\text{signal}}} = 66.5\% \cdot \begin{pmatrix} +5\% \\ -9\% \end{pmatrix} + 28.6\% \cdot \begin{pmatrix} +24\% \\ -22\% \end{pmatrix} + 4.9\% \cdot \begin{pmatrix} +78\% \\ -41\% \end{pmatrix} = \begin{pmatrix} +14.0\% \\ -14.3\% \end{pmatrix}$$

Apply Experimental cuts, which modifies the jet-multiplicities. CDF note 9500

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Conclusions: Theoretical error for the numbers of events at various jet mulitplicities should not be estimated collectively from the scale variation of the total cross-section. Errors from *LO* effects are large.

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Scale uncertainties at the Tevatron : MCFM analysis @ NLO

Evaluating everything at NLO yields bin fractions of around 58 % (0-jet) 30 % (1-jet) and 11 % (2-jet) . Including NNLO (0-jet) effects will push the (1-jet) and (2-jet) bins down, increasing the (0-jet) bin.

As a result of our NLO calculation we can update the result of 0905.3529 and improve the overall scale uncertainty

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Higgs at the LHC: minimal cuts

Minimal Cuts

We impose a minimal set of cuts such that

$p_t > 40$ GeV, $|\eta| < 4.5$, $R_{j,j} > 0.8$

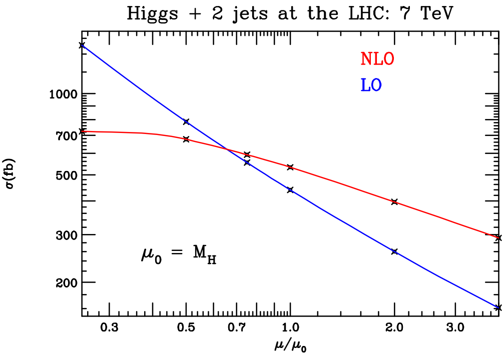
Scale uncertainties

We find typical scale uncertainties of around $\pm 24\%$ at NLO (compared to around $+75\%, -40\%$ at LO)

Comparisons at difference c.o.m

$$\sigma^{NLO}_{(14TeV)} = 2.83\,\mathrm{pb} = 5.3\sigma^{NLO}_{(7TeV)}$$

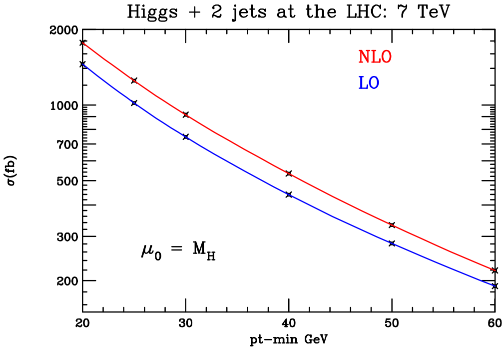
$$\sigma^{NLO}_{(10TeV)} = 1.36\,\mathrm{pb} = 2.6\sigma^{NLO}_{(7TeV)}$$



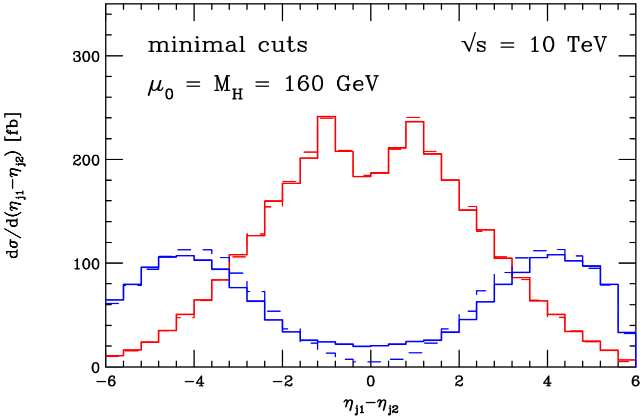
Higgs at the LHC: dependence on min-p_t

$p_t(min)$ dependence

The cross section shows a strong dependence on $p_t(min)$, at NLO $\sigma(p_t > 25) = 8 * \sigma(p_t > 60)$.



Effect of VBF cuts



Shown are the jet pseudorapidity differences for gluon fusion (red) and VBF (blue), dashed lines indicate the LO expressions scaled by the corresponding NLO cross section.

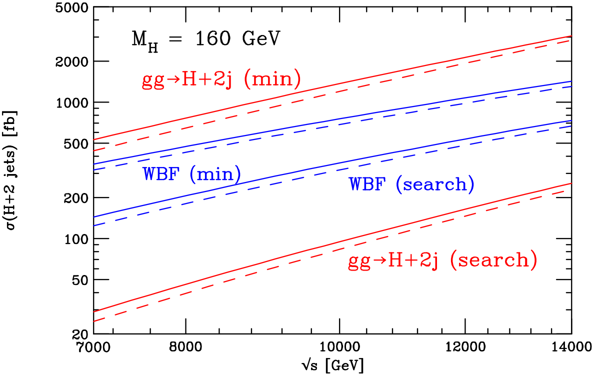
Comparisons between gluon fusion and VBF

Search Cuts

Basic VBF cuts
$|\eta_1 - \eta_2| < 4.2$,
and $\eta_1 \cdot \eta_2 < 0$

Higgs Searches at the LHC

The dashed lines here indicate the LO order result, whilst the solid lines are NLO. We see that the ratio between VBF and Gluon fusion is largest at lower centres of mass energies.



Conclusions

- Higgs + 2 jets calculated analytically in the large top limit, greatly improving speed of code in MCFM which is now publicly available (MCFMv5.7)
- Effective theory valid for Higgs masses $< 2m_t$ and for distributions provided $p_t < m_t$. Although size of NLO effects is greater than m_t ones in these regions.
- Theoretical uncertainty due to scale variation in $gg \to H(\to WW^*)$ at the the Tevatron can be improved by considering 1- and 2-jet bins at NLO.
- At the LHC gluon fusion initiated Higgs + 2 jet events form the background to VBF which can be suppressed by rapidity cuts, the ratio of which is actually larger at lower center of mass energies.

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Conclusions

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