Higher order QCD effects in *WW* production with jets

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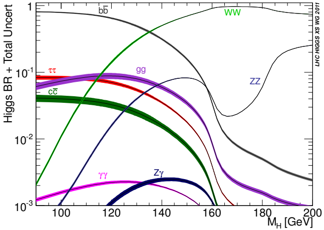
Outline

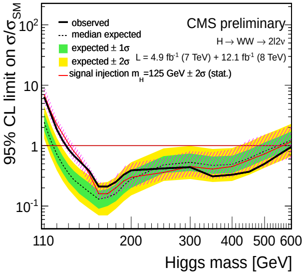
- Motivation
- Brief outline of generalized unitarity
- $WWjj$ to NLO in QCD
- Gluon fusion effects in WW, WWj
- Conclusion

$H \to WW$ decay mode



Higgs searches:

- $H \to WW$ subdominant mode
- Leptonic decay $\to$ mass reconstruction not possible



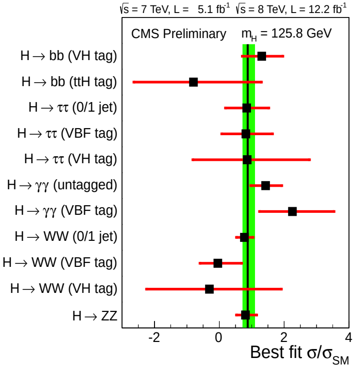
- **Evidence** of Higgs in this channel (3.1 σ)

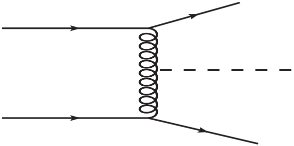
Electroweak-Higgs coupling

- $H \to WW$ probes coupling of Higgs to EW sector
- Tree-level relation between W, Z mass and coupling to Higgs protected by **custodial symmetry**
- Rescaling of W- and Z-coupling to Higgs parametrized by κ_W, κ_z .
- $\lambda_{W,Z} = \kappa_W/\kappa_z = 1$ in SM
- Current CMS value: $\lambda_{W,Z} = [0.57, 1.65]$
- Consistent with SM, but tighter bounds desirable

WW as background to GF and VBF Higgs

- Higgs signals sorted into 0,1,2+ jet bins
  $\rightarrow$ allows identification of backgrounds in each bin
- Around 30% of Higgs created with one jet, around 15% with two (or more) jets
- $H(\rightarrow WW)jj$ created through weak boson fusion (WBF) as well as gluon fusion (GF)
- WBF has characteristic **forward jets** with little hadronic activity between them
- $WW(+$ jets) is irreducible background to all processes





WW production as signal

WW production also interesting in its own right, or as place where New Physics may be found (e.g. in trilinear vector boson couplings)

- Recent CMS result for WW production finds $\sigma = 69.9 \pm 2.8 \pm 5.6 \pm 3.1$ pb
- Prediction: $\sigma = 57.7^{+2.4}_{-1.6}$ pb
- 2σ effect ...

Why NLO?

- Comparisons with Tevatron data show LO is **insufficient** - NLO needed
- NLO corrections can be large ($\sim 60\%$ enhancement for WW production)
- No guarantee that this enhancement will be consistent over phase space or distribution
- Factorization/renormalization scale uncertainty **significantly reduced** at NLO

How NLO?

Three ingredients needed for NLO calculations:

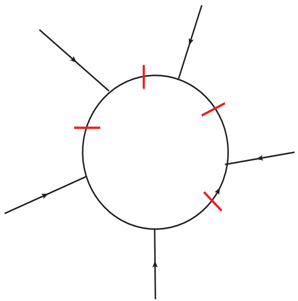
- Real emission correction
- Virtual (one-loop) amplitudes $\rightarrow$ generalized unitarity/OPP procedure
- Matching of IR divergences in real emission corrections to those in virtual amplitudes $\rightarrow$ Catani-Seymour dipoles

Generalized Unitarity method

- Virtual amplitudes stripped of color factors to give partial amplitudes $\rightarrow$ primitive amplitudes
- OPP subtraction: tensor integrals in primitive amplitudes written in terms of **scalar integrals** (known) and **coefficients** $c(l)$
- Analytic form of coefficients known - polynomial in $(l.n_i)$
- By choosing (complex) momenta such that propagators vanish, can solve for coefficients

Generalized Unitarity method

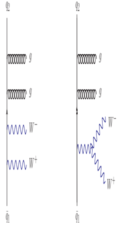
- Equivalent to performing a unitarity cut on the primitive amplitudes, resulting in tree-level helicity amplitudes
- $\rightarrow$ computed with Berends-Giele currents (also used to calculate Born amplitudes and real emission corrections)



WWjj production

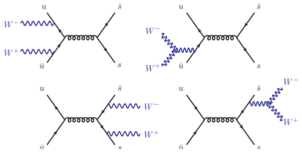
Two distinct **strong** production processes:

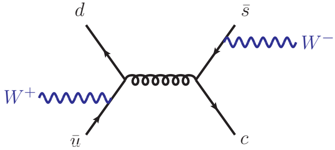
Two quark, two gluon processes:



All permutations of W-bosons with gluons

Four quark processes:

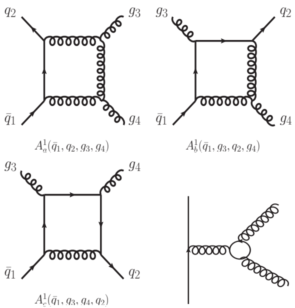




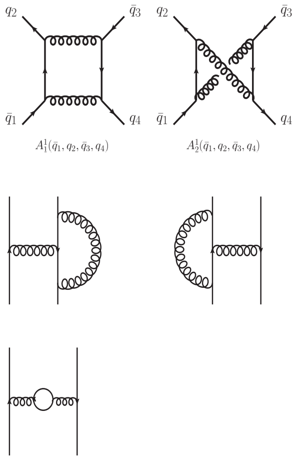
Also t-channel contributions $\rightarrow$ Complicated flavor structure

Virtual corrections

Four primitive amplitudes for 2q,2g process:



Five primitive amplitudes 4q process:



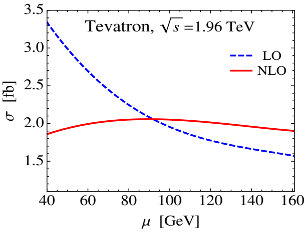
Parameters for Tevatron

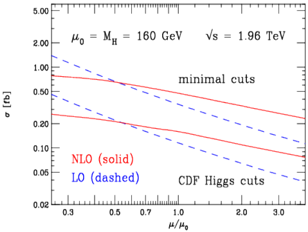
Signature: two opposite-sign leptons, missing energy, two or more jets

Cuts used similar to CDF in Higgs searches:

- Jets defined using k_T-algorithm with $\Delta R_{j1j2} > 0.4$
- Jet cuts: $p_{T,j} > 15$ GeV and $|\eta_j| < 2.5$
- Lepton cuts: $p_{T,l1} > 20$ GeV, $|\eta_{l1}| < 0.8$; $p_{T,l2} > 10$ GeV, $|\eta_{l2}| < 1.1$
- Lepton isolation: jets within $\Delta R = 0.4$ of a lepton must have $p_{T,j} < 0.1 p_{T,l}$.
- Lepton cuts: $m_{ll} > 16$ GeV and $p_{T,\mathrm{miss}}^{\mathrm{spec}} \equiv p_{T,\mathrm{miss}} \sin\left[\min\left(\Delta\phi, \pi/2\right)\right] > 25$ GeV

Tevatron Results





From Campbell, Ellis, Williams, hep-ph:1001.4495

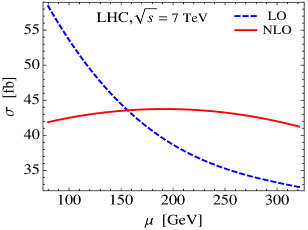
- $\sigma_{LO} = 2.5 \pm 0.9$ fb, $\sigma_{NLO} = 2.0 \pm 0.1$ fb
- At LO, **uncertainty** in background four times larger than **signal**!
- Uncertainty reduced at NLO by order of magnitude, but still **comparable** to signal.

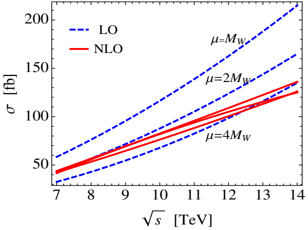
Parameters for LHC

Look at $WWjj$ as **signal**:

- Center-of-mass energy $\sqrt{s} = 7$ TeV
- Jets defined with anti-k_t algorithm with $\Delta R_{jj} = 0.4$
- Jets cuts: $p_{T,j} > 30$ GeV and $|\eta_j| < 3.2$
- Lepton cuts: $p_{T,l} > 20$ GeV, $|\eta_l| < 2.4$, $p_{T,\mathrm{miss}} > 30$ GeV

LHC cross-sections



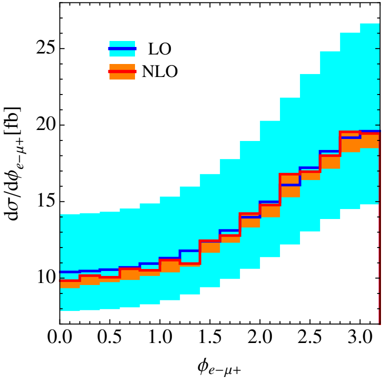


- $\sigma_{LO} = 46 \pm 13$ fb, $\sigma_{NLO} = 42 \pm 1$ fb
- At NLO, approximately linear increase in cross-section as $\sqrt{s}$ increased
- "Optimal" factorization/renormalization scale: $2m_W$ at $\sqrt{s} = 7$ TeV, $4m_W$ at $\sqrt{s} = 14$ TeV

LHC angular distribution

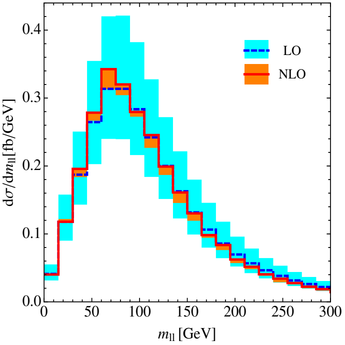
To discriminate between signal and background: **distributions**

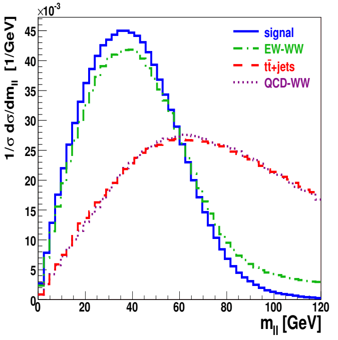
Useful distribution: opening angles between leptons $\phi_{e^-\mu^+}$.
Higgs: **small angle**; background: **back-to-back**



LHC mass distribution

Linked to $\phi_{e^- \mu^+}$ is mass of lepton system m_{ll}

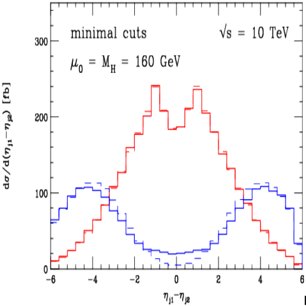




From Klämke and Zeppenfeld, hep-ph:0703202

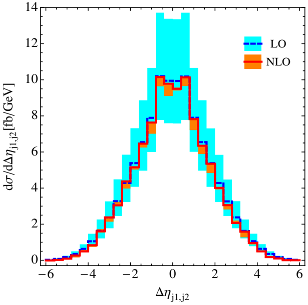
Today's signal is tomorrow's background

Higgs created through GF has central jets;
through VBF has forward jets



From Campbell, Ellis, Williams, hep-ph:1001.4495

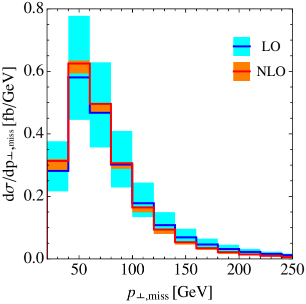
Background jets **central**

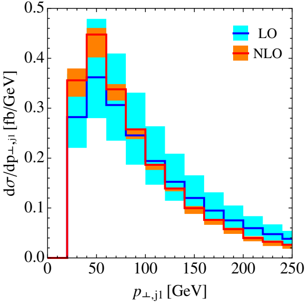


Cut on central jets removes both *WWjj* and GF background

NLO results **greatly reduce scale uncertainty** → improved reliability

LHC distributions

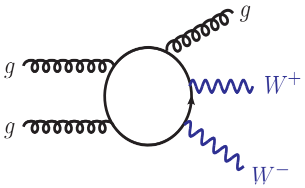




- Mild softening at high scales - indication that fixed scale is too small, and **dynamic scale** would be better
- Reduced scale uncertainty again apparent

Gluon fusion in WW production

$WW + n$ jets with no external quarks - only gluons - through a fermion loop



No corresponding tree-level amplitude:

- One-loop amplitude is finite
- Enters as a NNLO correction to $pp \to WW + n$ jets

Finite, gauge invariant, self-contained contribution to NNLO correction.

Additional factors of α_s $\leftrightarrow$ Large gluon flux at LHC

Gluon-induced *WW* production

$gg \to WW$ studied by Binoth, Ciccolini, Kauer, Krämer

hep-ph:0503094, hep-ph:0611170

Find highly **cut-dependent** contribution to overall cross-section:

- For generic cuts*, $\sigma_{gg+NLO}/\sigma_{NLO} = 1.06$
- For Higgs search cuts**, $\sigma_{gg+NLO}/\sigma_{NLO} = 1.30$

$^{*}p_{T,l} > 20$ GeV, $|\eta_l| < 2.5$, $p_{T,\mathrm{miss}} > 25$ GeV

$^{**}35\mathrm{GeV} < p_{T,l\mathrm{max}} < 50$ GeV, $p_{T,l\mathrm{min}} > 25$ GeV, $\Delta\phi_{ll} < 0.78$, $m_{ll} < 35$ GeV, $p_{T,j} > 20 GeV$, $|\eta_j| < 3$

BUT these cuts are not what LHC uses:

- Initially proposed: $\Delta\phi_{ll} < 1.8$, $m_{ll} < 50$ GeV ATLAS-CONF-2012-012
- End 2012 analysis: $\Delta\phi_{ll} < 0.87$, $m_{ll} < 43$ GeV (m_H dependent cuts)

Standard cuts

Looked at $gg \to WW$ and $gg \to WWg$:

Standard Cuts

		$\sigma_{\rm LO}$ (fb)	$\sigma^{\rm incl}_{\rm NLO}$ (fb)	$\delta\sigma_{\rm NNLO}$ (fb)	$\delta\sigma_{\rm NNLO}/\sigma^{\rm incl}_{\rm NLO}$
8 TeV	WW	$141.0(1)^{+2.8}_{-4.0}$	$232.0(4)^{-5.8}_{+7.5}$	$8.1(1)^{-1.7}_{+2.2}$	3.5%
	WWj	$87.8(1)^{-10.9}_{+13.5}$	$111.3(2)^{-5.5}_{+4.9}$	$3.4(1)^{-1.0}_{+1.6}$	3.1%
14 TeV	WW	$259.6(2)^{+14.2}_{-17.2}$	$448.3(5)^{-7.4}_{+11.6}$	$23.6(1)^{-4.1}_{+5.2}$	5.3%
	WWj	$203.4(1)^{-19.9}_{+22.9}$	$254.5(4)^{-10.2}_{+9.0}$	$11.8(4)^{-3.2}_{+4.7}$	4.6%

- For WW production, results similar to Binoth *et al.*
- Gluon-induced production more important at $\sqrt{s} = 14$ TeV
- Gluon-induced production less important for WWj production

Higgs cuts

Higgs search cuts

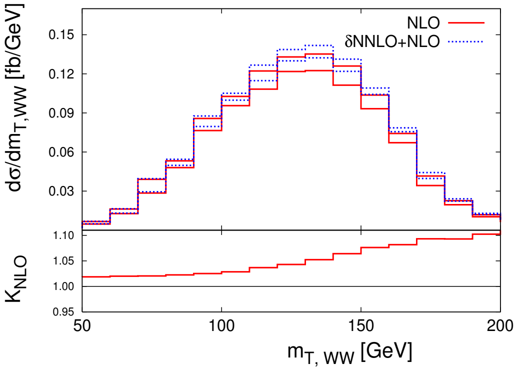
		$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}^{\rm excl}$ (fb)	$\delta\sigma_{\rm NNLO}$ (fb)	$\delta\sigma_{\rm NNLO}/\sigma_{\rm NLO}^{\rm excl}$
8 TeV	WW	$35.6(1)^{+0.9}_{-1.3}$	$38.8(1)^{+1.0}_{-0.8}$	$2.7(1)^{-0.5}_{+0.7}$	7.0%
	WWj	$12.6(1)^{-1.5}_{+1.8}$	$10.6(1)^{+0.3}_{-0.9}$	$0.6(1)^{-0.2}_{+0.2}$	5.7%
14 TeV	WW	$63.4(1)^{+3.9}_{-4.7}$	$63.4(2)^{+2.1}_{-2.0}$	$7.5(1)^{-1.2}_{+1.5}$	11.8%
	WWj	$28.7(1)^{-2.6}_{+2.9}$	$20.5(1)^{+1.7}_{-2.2}$	$1.8(2)^{-0.5}_{+0.7}$	8.8%

- Important contribution to overall cross-section (comparable to NLO scale uncertainty)
- **BUT** not as large as 30% contribution
- Hj production: $\sigma \approx 2$ fb at $\sqrt{s} = 8$ TeV, 5 fb at $\sqrt{s} = 14$ TeV
  $\rightarrow$ gluon-induced NNLO contribution to background **third** of signal cross-section

NNLO K-factor

Define

$$K_{NNLO} = \frac{d\sigma_{NLO+\delta NNLO}}{d\sigma_{NLO}}$$



K-factor is not uniform over phase space and its distribution can be cut-dependent

Conclusions

- NLO QCD corrections to strong production of $WWjj$ computed.
- Moderate (10-20%) change in cross-section compared to LO, but scale uncertainty reduced by up to order of magnitude.
- Improves reliability of distributions aiding discrimination between Higgs signal and WW background: ϕ_{ll}, m_{ll}, $\Delta\eta_{jj}$
  $\rightarrow$ allow discovery in this channel; study Higgs-EW couplings
- NNLO gluon-induced corrections to WW and WWj production computed
- These are **cut-dependent**, more important as cuts become more aggressive
- May be as large as NLO scale uncertainty, and factor 2-3 smaller than signal