# Higher order QCD effects in *WW* production with jets

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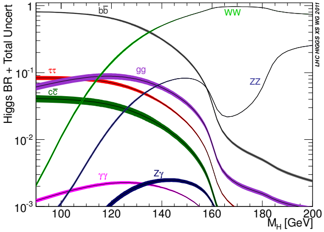
arXiv:hep-ph/1104.2327
arXiv:hep-ph/1205.6987

Fermilab, 17 January 2013

# Outline

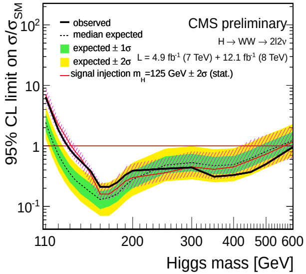
- Motivation
- Brief outline of generalized unitarity
- *WWjj* to NLO in QCD
- Gluon fusion effects in $WW$, $WWj$
- Conclusion

# $H \to WW$ decay mode




**Higgs searches:**

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



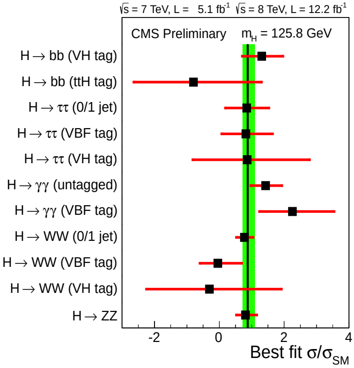

- **Evidence** of Higgs in this channel (3.1 $\sigma$)

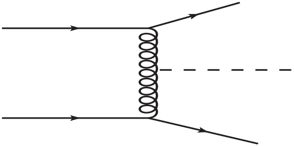
# Electroweak-Higgs coupling

- $H \to WW$ 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 $\kappa_W, \kappa_z$ .
- $\lambda_{W,Z} = \kappa_W/\kappa_z = 1$ 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
- $WW(+\text{ jets})$ 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
- $2\sigma$ 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:

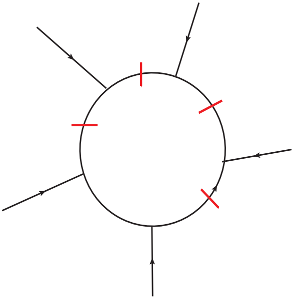
- Real emission correction
- Virtual (one-loop) amplitudes → generalized unitarity/OPP procedure
- Matching of IR divergences in real emission corrections to those in virtual amplitudes → Catani-Seymour dipoles

# 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**
- Analytic form of coefficients known
- By choosing (complex) momenta such that propagators vanish, can solve for coefficients

# Generalized Unitarity method

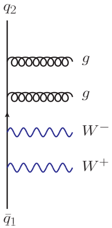
- Equivalent to performing a unitarity cut on the primitive amplitudes, resulting in tree-level helicity amplitudes
- $\rightarrow$ computed with Berends-Giele currents (also used to calculate Born amplitudes and real emission corrections)



# *WWjj* production

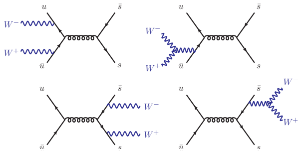
Two distinct **strong** production processes:

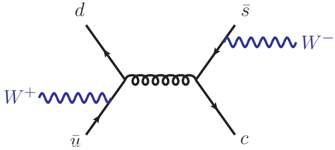
Two quark, two gluon processes:




All permutations of $W$-bosons with gluons

Four quark processes:



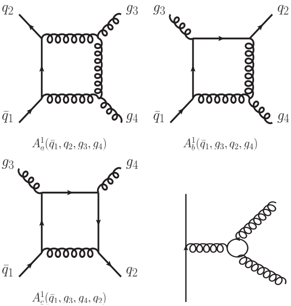


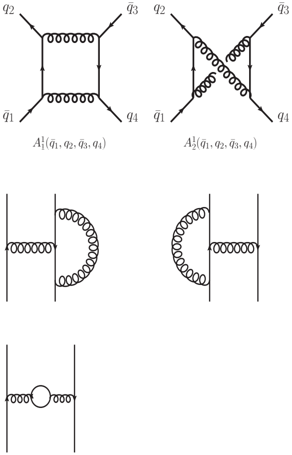

Also $t$-channel contributions → Complicated flavor structure

# Virtual corrections

**Five** primitive amplitudes 4q process:

**Four** primitive amplitudes for 2q,2g process:



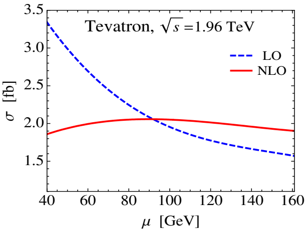
# Parameters for Tevatron

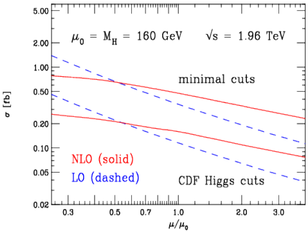
**Signature:** two opposite-sign leptons, missing energy, two or more jets

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

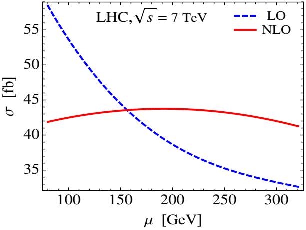
- $\sigma_{LO} = 2.5 \pm 0.9$ fb, $\sigma_{NLO} = 2.0 \pm 0.1$ fb
- At LO, **uncertainty** in background four times larger than **signal**!
- Uncertainty reduced at NLO by order of magnitude, but still **comparable** to signal.

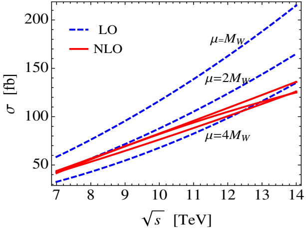
# Parameters for LHC

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: $p_{T,l} > 20$ GeVm $|\eta_j| < 2.4$, $p_{T,\mathrm{miss}} > 30$ GeV

# LHC cross-sections



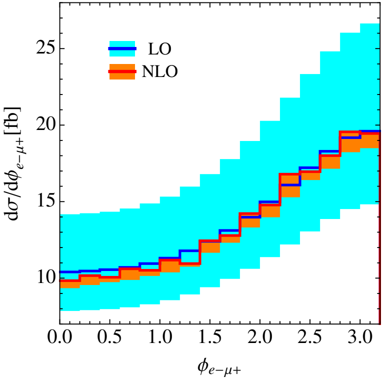




- $\sigma_{LO} = 46 \pm 13$ fb, $\sigma_{NLO} = 42 \pm 1$ fb
- At NLO, approximately linear increase in cross-section as $\sqrt{s}$ increased
- "Optimal" factorization/renormalization scale: $2m_W$ at $\sqrt{s} = 7$ TeV, $4m_W$ at $\sqrt{s} = 14$ TeV

# LHC angular distribution

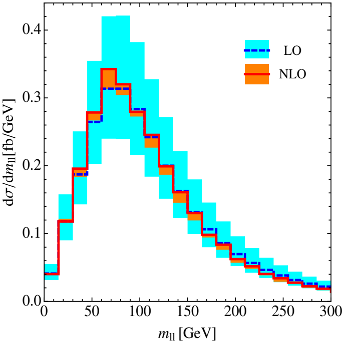
To discriminate between signal and background: **distributions**

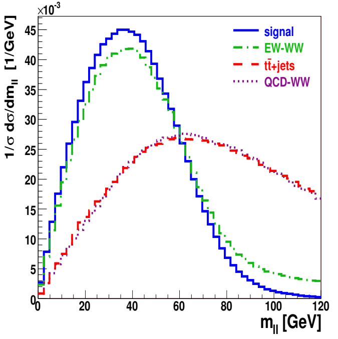
Useful distribution: opening angles between leptons $\phi_{e^- \mu^+}$.
Higgs: **small angle**; background: **back-to-back**



# LHC mass distribution

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

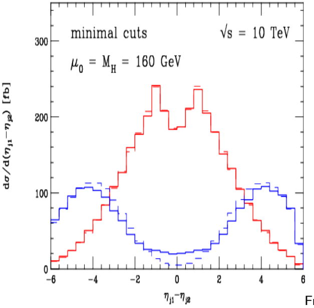



From Klämke and Zeppenfeld, hep-ph:0703202

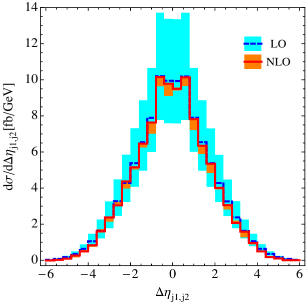
# Today's signal is tomorrow's background

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




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

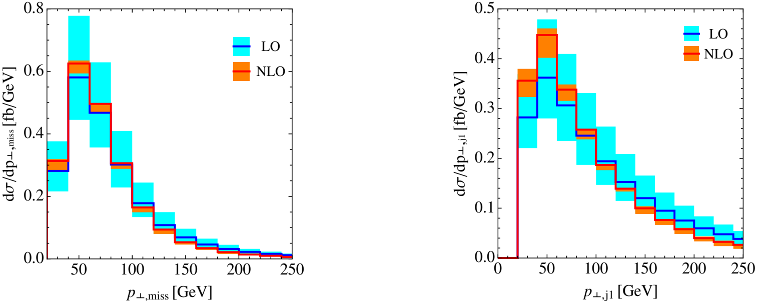
Background jets **central**




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

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

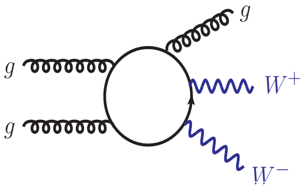
# LHC distributions




- 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 $\alpha_s$ $\leftrightarrow$ 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

| | | $\sigma_{\mathrm{LO}}$ (fb) | $\sigma^{\mathrm{incl}}_{\mathrm{NLO}}$ (fb) | $\delta\sigma_{\mathrm{NNLO}}$ (fb) | $\delta\sigma_{\mathrm{NNLO}}/\sigma^{\mathrm{incl}}_{\mathrm{NLO}}$ |
|---|---|---|---|---|---|
| 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% |
| | $WW$j | $87.8(1)^{-10.9}_{+13.5}$ | $111.3(2)^{-5.5}_{+4.9}$ | $3.4(1)^{-1.0}_{+1.6}$ | 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% |
| | $WW$j | $203.4(1)^{-19.9}_{+22.9}$ | $254.5(4)^{-10.2}_{+9.0}$ | $11.8(4)^{-3.2}_{+4.7}$ | 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

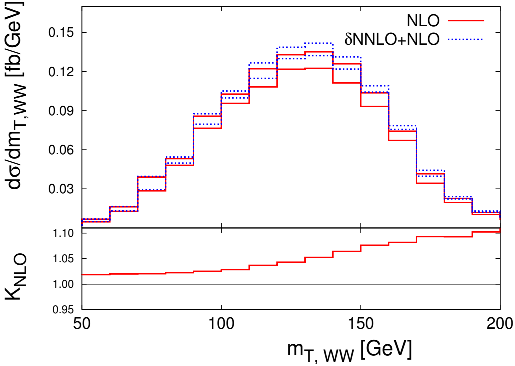
| | | $\sigma_{\rm LO}$ (fb) | $\sigma^{\rm excl}_{\rm NLO}$ (fb) | $\delta\sigma_{\rm NNLO}$ (fb) | $\delta\sigma_{\rm NNLO}/\sigma^{\rm excl}_{\rm NLO}$ |
|---|---|---|---|---|---|
| 8 TeV | $WW$ | $35.6(1)^{+0.9}_{-1.3}$ | $38.8(1)^{+1.0}_{-0.8}$ | $2.7(1)^{-0.5}_{+0.7}$ | 7.0% |
| | $WW$j | $12.6(1)^{-1.5}_{+1.8}$ | $10.6(1)^{+0.3}_{-0.9}$ | $0.6(1)^{-0.2}_{+0.2}$ | 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% |
| | $WW$j | $28.7(1)^{-2.6}_{+2.9}$ | $20.5(1)^{+1.7}_{-2.2}$ | $1.8(2)^{-0.5}_{+0.7}$ | 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

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




$K$-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: $\phi_{ll}$, $m_{ll}$, $\Delta\eta_{jj}$
  $\rightarrow$ 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