TeV4LHC Workshop, Fermilab, 16 - 18 September, 2004

Higgs Boson plus 2 Jet Production: WBF Signal and QCD Background at NLO

Edmond L. Berger

Argonne National Laboratory

1. Introduction & Motivation
2. Production Dynamics and WBF Cuts at the LHC
3. Signal Purity and Coupling Uncertainties at the LHC
4. Summary

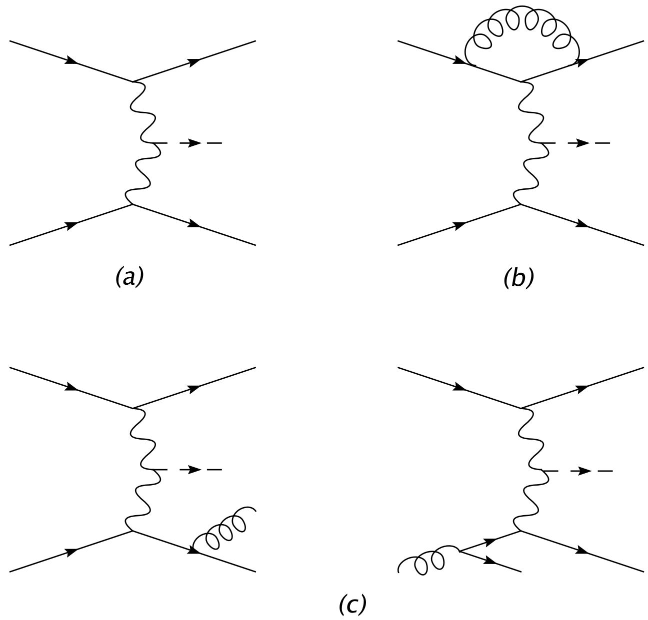
E Berger and John Campbell, hep-ph/0403194, Phys Rev D, in press

Introduction and Motivation

- Assume a SM-like Higgs boson has been discovered, $115 < m_H < 200$ GeV at the Tevatron or the LHC, and that a sample exists of $H + 2$ jet events at the LHC
- Want to use these data to determine the Higgs boson couplings g to weak vector bosons, W and Z
- Focus on two production subprocesses that contribute to $H + 2$ jet events:
  - $W + W \rightarrow H$ and $Z + Z \rightarrow H$ "WBF"
  - $g + g \rightarrow H$ "irreducible QCD background"
- Issues for the determination of couplings:
  - How well can we model the WBF signal and the QCD backgound?
  - How well can we resolve WBF production of H from QCD production of H?
- Independent calculation of $H + 2$ jet processes
  - to gauge the effectiveness of cuts used to select the WBF signal, and
  - to evaluate the accuracy with which coupling g can be determined in experiments at the CERN LHC

$H + 2$ Jet Production – Signal

- Higgs boson H production via WW scattering in NLO QCD. Ex:



- QCD NLO calculation of $H + 2$ jets with CTEQ6M parton densities; renormalization/factorization scale $\mu = m_H$

- Hard perturbative scale μ dependence ~ 2% for $\frac{1}{2}m_H < \mu < 2m_H$, and CTEQ PDF uncertainty ~ 3%, both in the WBF region of phase space
  $\rightarrow$ signal is calculated fairly reliably

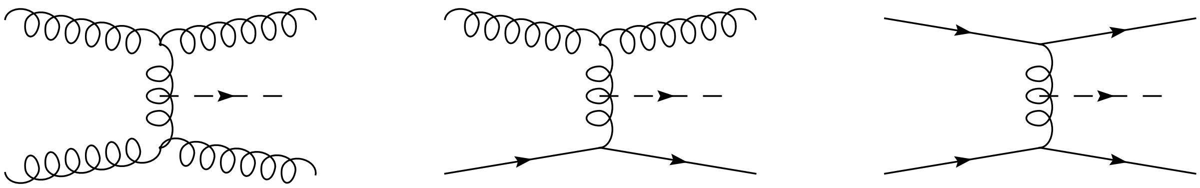
- Events generated with the MCFM code

  J. Campbell & R. K. Ellis PRD65,113007 (2002)

- Independent results (dipole subtraction method) verify the NLO calculation of Figy, Oleari, Zeppenfeld, PRD68, 073005 (2003). K-factor ~ 10%, with small variation over the phase space appropriate for the WBF signal

$H + 2$ Jet Production – Irreducible Background

- Higgs boson H production via gg scattering. Ex:



- Fully differential NLO calculation of $H + 2$ jet production does not exist; contribution computed at LO Kauffman Desai and Risal, PRD55, 4005 (1997); PRD58, 119901 (1998)

- Effective ggH coupling included in the limit of $m_H \ll 2m_t$ and $p_T^H < m_t$ (c.f. Del Duca et al NP B616, 367 (2001))

- NLO enhancement (K) factor is needed in the region of the WBF cuts. It can be estimated from
  - inclusive NLO $gg \to H$ $\quad K \sim 1.7 - 1.8$

    Harlander & Kilgore PRD64, 013015 (2001); Anastasiou & Melnikov, NP B646, 220 (2002)
  - NLO $gg \to H + 1$ jet $\quad K \sim 1.3 - 1.5$

    Ravindran, Smith, van Neerven NP B665, 325 (2003)

- Uncertainty: hard scale μ dependence ....

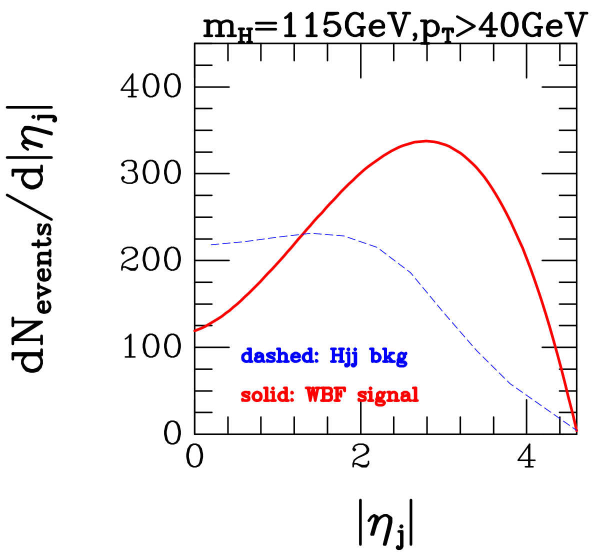
Event Characteristics

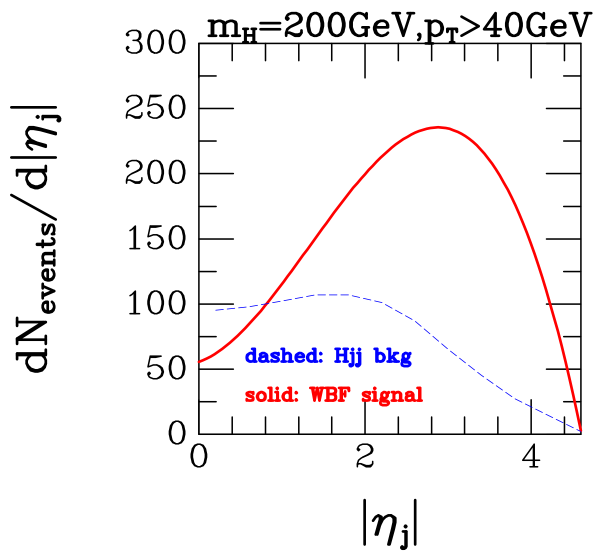
- Hallmark of WBF events in hadron reactions is a Higgs boson accompanied by two “tagging” jets having large $p_T \sim \mathcal{O}(\frac{1}{2}M_W)$
- QCD $gg \to H + 2$ jets generate a softer p_T spectrum
- The rapidity spectra for the WBF and QCD production mechanisms also differ, related to the fact that the gluon parton density (that plays a dominant role in the background) is softer than the quark density; figures shown on next slide
- The p_T spectrum of the Higgs boson is also relatively hard. All-orders resummed calculation Berger and Qiu PRD 67, 034026 (2003) provides $< p_T^H >\sim 35$ GeV at $m_H = M_Z$, growing to $< p_T^H >\sim 54$ GeV at $m_H = 200$ GeV
- Require reliable QCD representation of Hjj for jets at large p_T. Hard matrix elements are needed. A showering approach for generating the momentum distributions of the jets would not suffice; showering yields softer jets and overestimates signal purity

$H + 2$ Jet Production – Jet Rapidity Distribution

- Higgs boson H production via WW and ZZ scattering in NLO and via gg QCD processes (LO)

  (for 1 fb^{-1}, no BR included):





- Shape of the signal distribution depends very little on the Higgs boson mass or on the p_T cut for the tagging jets. Peak at $|\eta| \sim 3$. Full width at half-max ~ 2.8
- Background falls off sharply beyond $|\eta| \sim 2$
- Motivates a simple WBF prescription:

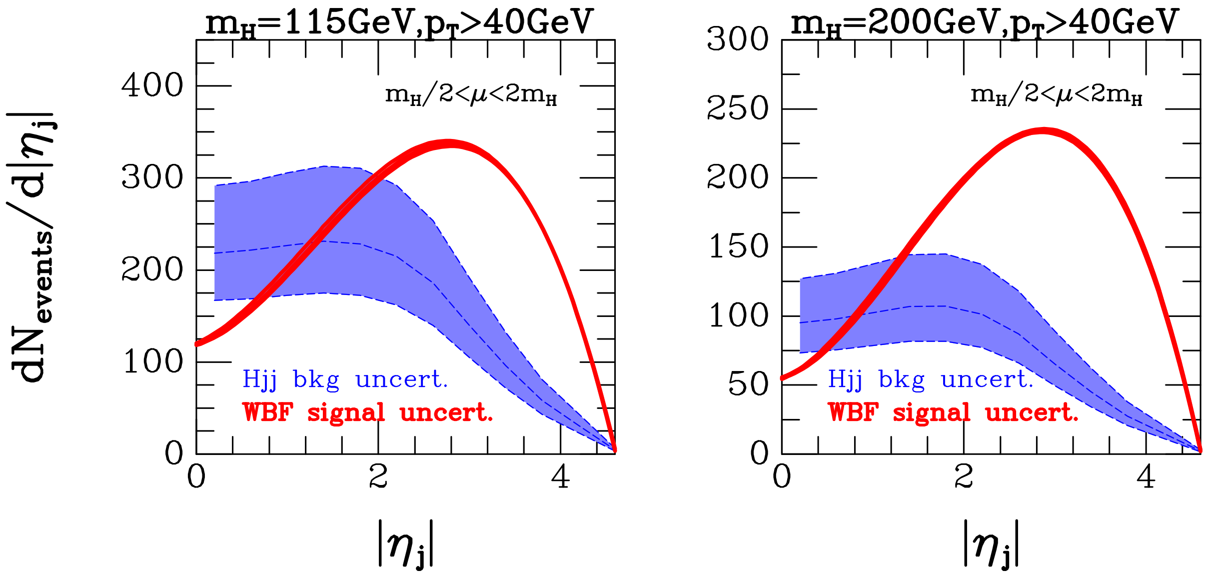
$$\eta_{\rm peak} - \eta_{\rm width}/2 < |\eta_j| < \eta_{\rm peak} + \eta_{\rm width}/2$$

$j = j_1$ or $j = j_2$, $\eta_{\rm peak}$=3, and $\eta_{\rm width}$=2.8

- This is our working definition of the WBF region

$H + 2$ Jet Production – μ dependence

- Higgs boson H production via WW scattering in NLO and via gg QCD processes (LO)
  hard-scale μ variation from $\mu = m_H/2$ to $\mu = 2m_H$:



- Magnitude and shape of the signal distribution depend very little on μ: $\pm 2\%$

- Magnitude of the background shows significant uncertainty at LO; it is 70% greater at $\mu = m_H/2$, and 40% less at $\mu = 2m_H$

- This uncertainty in the irreducible background translates into uncertainty in the extraction of the coupling strenghts. To reduce the uncertainty, a differential NLO calculation is needed for the QCD background process $H + 2$ jets

Steps toward $H + 2$ jets NLO QCD Background

- The tree-level matrix elements for $H + 3$ jets are computed

  Del Duca, Frizzo, Maltoni hep-ph/0404013; JHEP 0405, 064 (2004)

- Loop processes remain; appropriate NLO subtractions; soft and collinear singularities

- Extend the NLO study of $gg \to H + 1$ jet

  Ravindran, Smith, van Neerven NP B665, 325 (2003)

  to one additional jet in fully differential fashion

- Equivalent calculation for $W + 2$ jets and $Z + 2$ jets done and implemented in MCFM J. Campbell and R. K. Ellis

- Full NLO calculation of $H + 2$ jets would be similar; the LO process involves 3 independent matrix elements: $g + g \to H + g + g$; $g + g \to H + q + \bar{q}$; and $q + \bar{q} \to H + q + \bar{q}$

- Anyone already doing this?

Signal Purity

- Define Purity $P = \frac{S}{S+B}$
  S is the number of signal $H + 2$ jet events and
  B is the number of $H + 2$ jet QCD background events
  both in the WBF region of phase space
- Study Purity P of the signal vs p_T of the jets
- Evaluate uncertainty $\frac{\delta g}{g}$ of the coupling in terms of
  P $\frac{\delta N}{N}$ $\frac{\delta S}{S}$ and $\frac{\delta B}{B}$

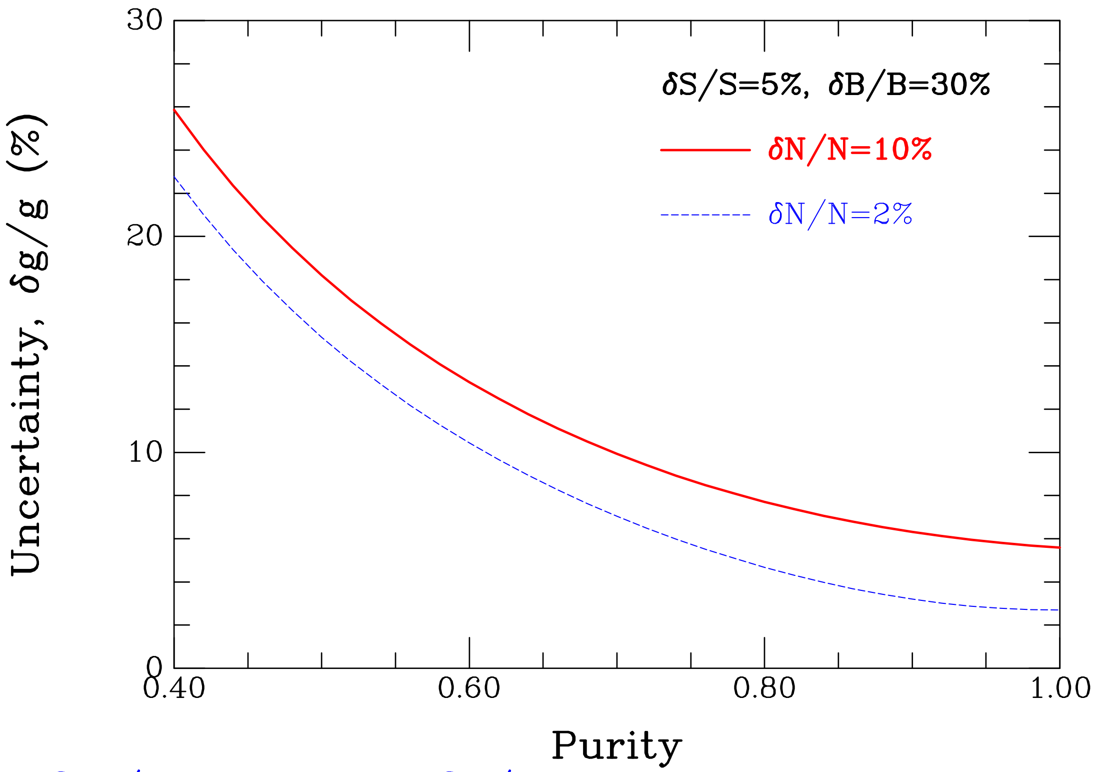
$H + 2$ Jet Production – Event Rates for 1 fb^{-1}

- Event rates for the Hjj WBF signal(NLO) and Hjj background(LO), including our WBF requirement that at least one jet have $1.6 < |\eta| < 4.4$ (no BR included)

p_T cut [GeV]	20	40	80
Signal ($m_H = 115$)	1374	789	166
Bkg	1196	382	92
Purity	0.53	0.67	0.64
Signal ($m_H = 200$)	928	545	121
Bkg	534	179	46
Purity	0.63	0.75	0.72

- Recall $$P = S/(S+B)$$
  - Purity is independent of total integrated luminosity
- p_T cut of 40 GeV yields a good S/B across the range $m_H = 115$–200 GeV. p_T cut of 20 GeV is marginal
- Signal purities of $\sim 65\%$ for p_T cut $\gtrsim 40$ GeV; purity is greater at the larger values of m_H

Coupling Uncertainty *vs* Signal Purity



- If $\delta N/N \sim 10\%$ $\delta g/g \sim 10\%$ for $P = 0.7$
- If $\delta N/N \sim 2\%$ $\delta g/g \sim 7\%$ for $P = 0.7$
- Uncertainties in S and in B dominate uncertainty in g.
  With $P = 0.7$ and $\delta N/N = 2\%$, then $\delta S/S$ and $\delta B/B$ have to be reduced to 3% and 6% before statistics control the answer
- $P > 0.65$ permits $\delta g/g \sim 10\%$ after 200 fb^{-1}
  Obtained for $p_T^{\rm cut} > 40$ GeV at $m_H = 115$ GeV and for $p_T^{\rm cut} > 20$ GeV at $m_H = 200$ GeV
- Suppose $K^{\rm NLO}_{\rm background} \sim 1.6$
  $P = 0.56$ for $p_T^{\rm cut} > 40$ GeV at $m_H = 115$ GeV $\rightarrow$
  $\delta g/g = 13\%$
  $P = 0.52$ for $p_T^{\rm cut} > 20$ GeV at $m_H = 200$ GeV $\rightarrow$
  $\delta g/g = 15\%$

Summary

- Studied $H + 2$ jet production at the energy of the LHC. Fully differential hard matrix elements used to generate p_T spectra
- Evaluated the signal purity P (fraction of real H events produced by WBF) in each case as a function of the transverse momentum cut used to define the tagging jets
- A fully differential NLO calculation of the $H + 2$ jet QCD background distributions is needed, applicable in the WBF region of phase space, so that P and $\delta g/g$ can be determined more accurately
- After 200 fb^{-1} are accumulated at the LHC, it may be possible to achieve an accuracy $\delta g/g \sim 10\%$ in the effective coupling (combination of HWW and HZZ) of the Higgs boson to weak bosons. (These estimates are less optimistic than those in the Les Houches 2003 study)
- With a 500 GeV LC and 500fb^{-1}, the expected accuracies are $\delta g_{ZZH}/g_{ZZH} \simeq 3\%$ for $120 < m_H < 200$ GeV and $\delta g_{WWH}/g_{WWH} \simeq 3\%$ to $\simeq 7\%$ for $120 < m_H < 160$ GeV