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HIGGS BOSON PLUS 2 JET PRODUCTION

WBF SIGNAL AND QCD “BACKGROUNDS”

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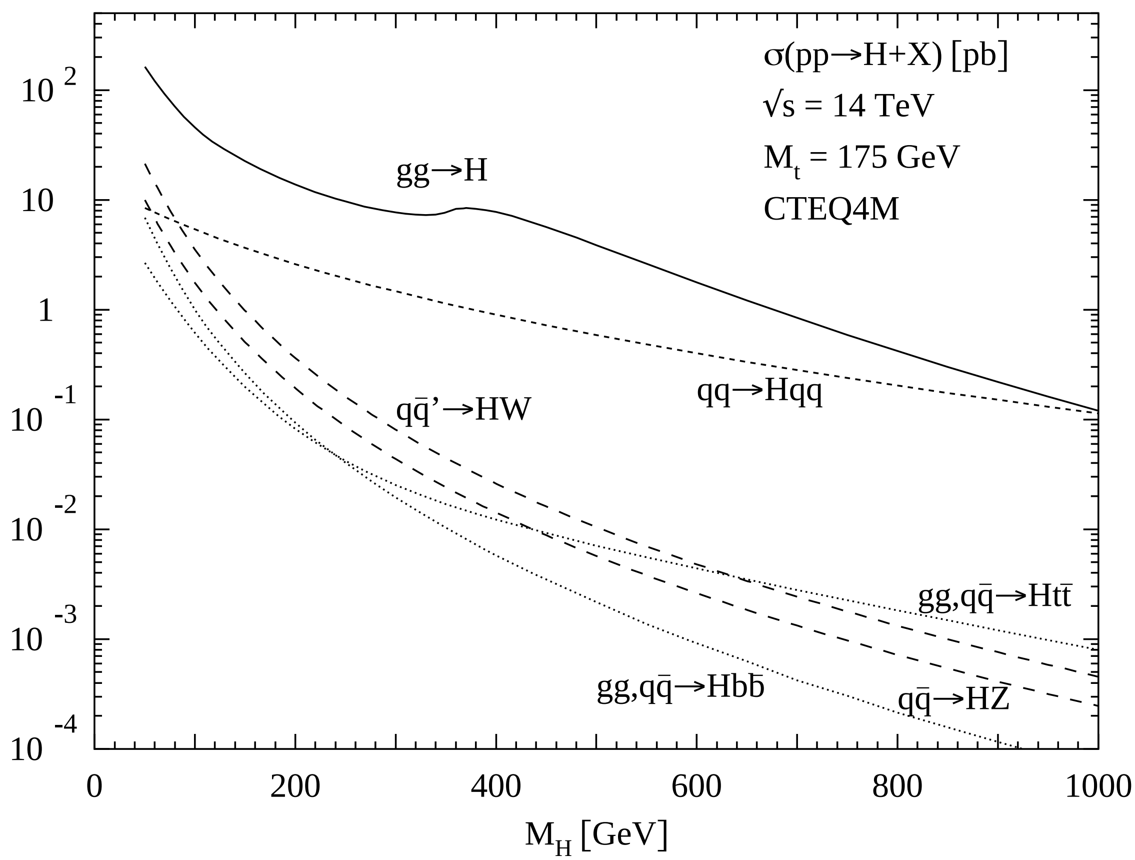
1. Introduction and Motivation

- The Higgs boson is expected to be produced at the LHC through various partonic production processes and observed in its decays to SM particles
  - $gg \to hX$, with $h \to \gamma\gamma$, $h \to WW^*$, ZZ^* ;
  - $gg \to t\bar{t}hX$, with $h \to b\bar{b}$ or $h \to \gamma\gamma$;
  - $qq \to hqqX$ via $W^+W^-(ZZ) \to hX$, with $h \to WW^*$, $h \to \gamma\gamma$, or $h \to \tau^+\tau^-$
- The fully inclusive gluon-gluon fusion subprocess $gg \to hX$ is the dominant production mechanism; $qq \to H + 2$ jets is next in line

(figure from M. Spira)

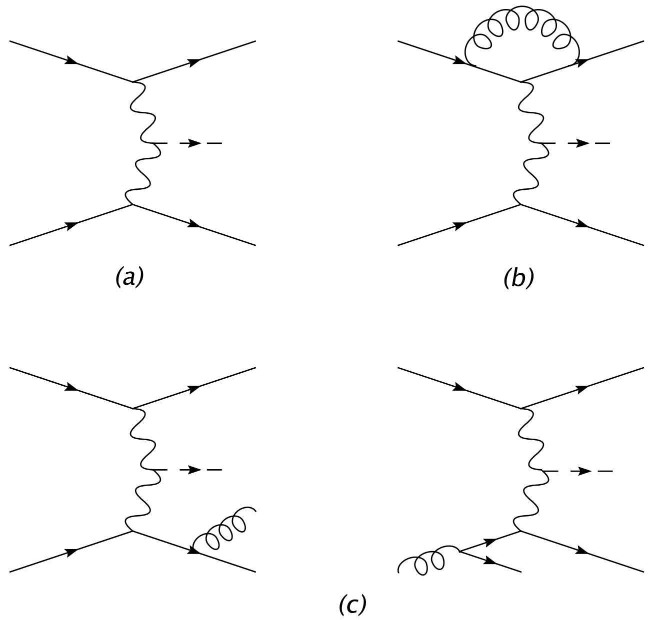


1. Introduction and Motivation

- Assume a SM-like Higgs boson has been discovered, $115 < m_H < 200$ at the Tevatron or 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:
  - $W + W \to H$ and $Z + Z \to H$ "WBF"
  - $g + g \to H$ "QCD background"
- Question: 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
- Define Purity $P = \frac{S}{S+B}$
  Show results on P 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 – Signal

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



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

- μ dependence $\sim 2\%$ for $\frac{1}{2}m_H < \mu < 2m_H$, and CTEQ PDF uncertainty $\sim 3\%$, both in the WBF region of phase space

- Events generated with the MCFM code

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

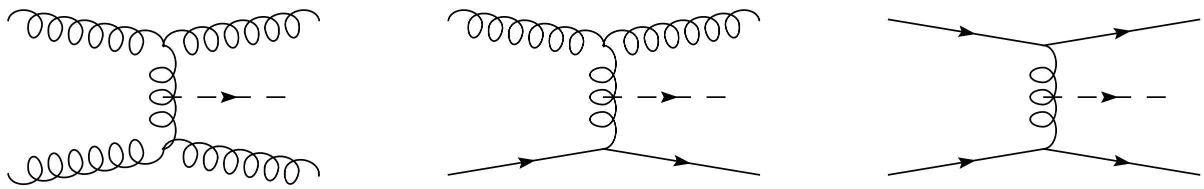
- Independent results (dipole subtraction method) verify the NLO calculation of

  Figy, Oleari, and Zeppenfeld, PRD68, 073005 (2003).

  K-factor $\sim 10\%$, with small variation over the phase space appropriate for the WBF signal

$H + 2$ Jet Production – Background

- Higgs boson H production via gg scattering. Ex:



- Fully differential NLO calculation of $H + 2$ jet production $gg \to H + j + j + X$ 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 $m_H << 2m_t$ (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)
  - or from NLO $pp \to Z + 2$ jets + X, but parton subprocesses are different $\quad K \sim 1 \pm 10\%$

    J. Campbell, R. K. Ellis, & D. Rainwater PRD68, 094021 (2003)

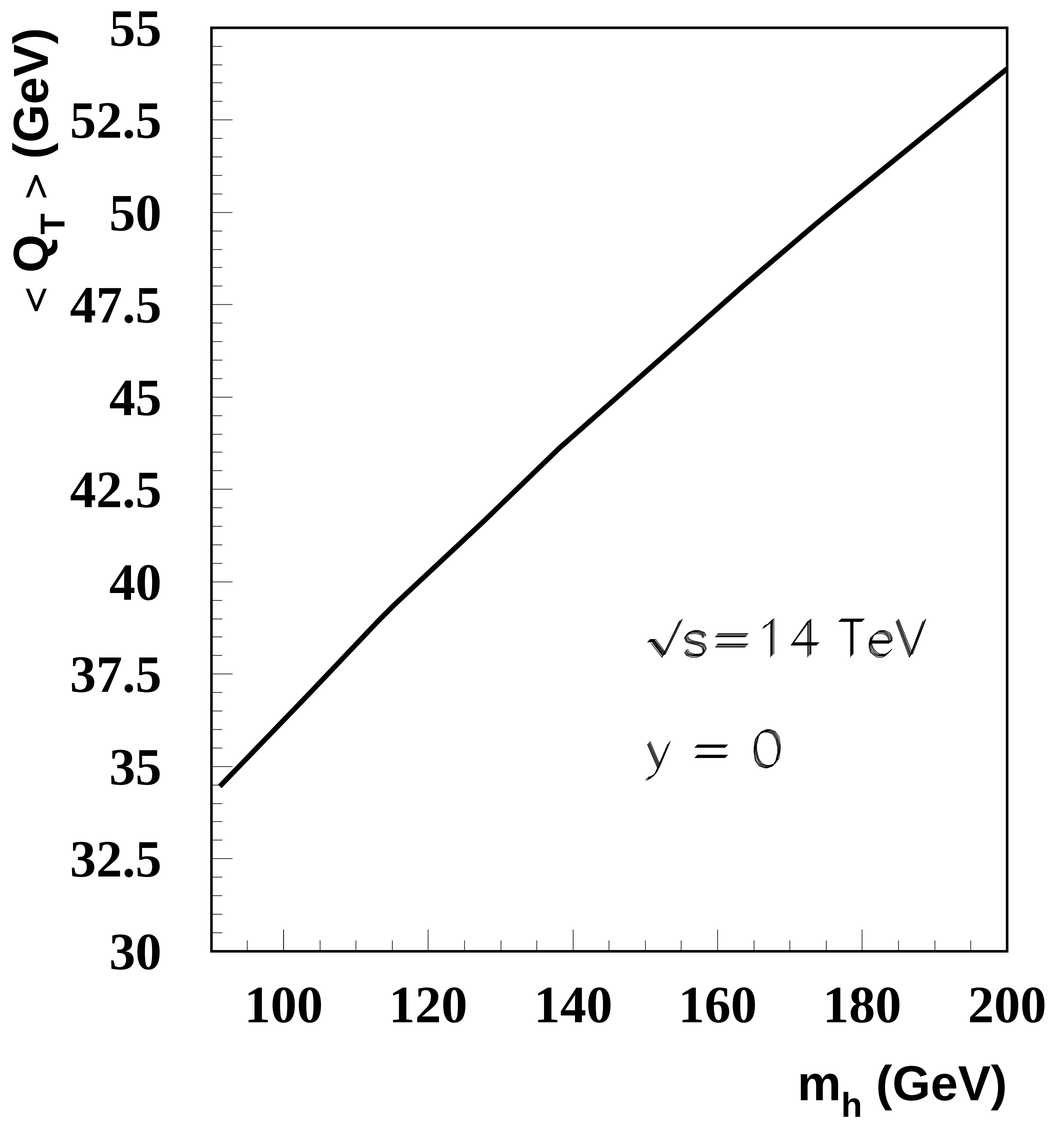
- Fully differential NLO calculation is needed of the QCD process $gg \to H + 2$ jets so that the NLO enhancement can be obtained in the WBF region of phase space

Event Characteristics

- Hallmark of WBF events 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 will generate a softer p_T spectrum
- The rapidity spectra also differ figures later
- 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

Mean Transverse Momentum of H Production

- All orders resummation for H production via gg scattering



$$< p_T^H > \simeq 0.18 m_H + 18GeV$$

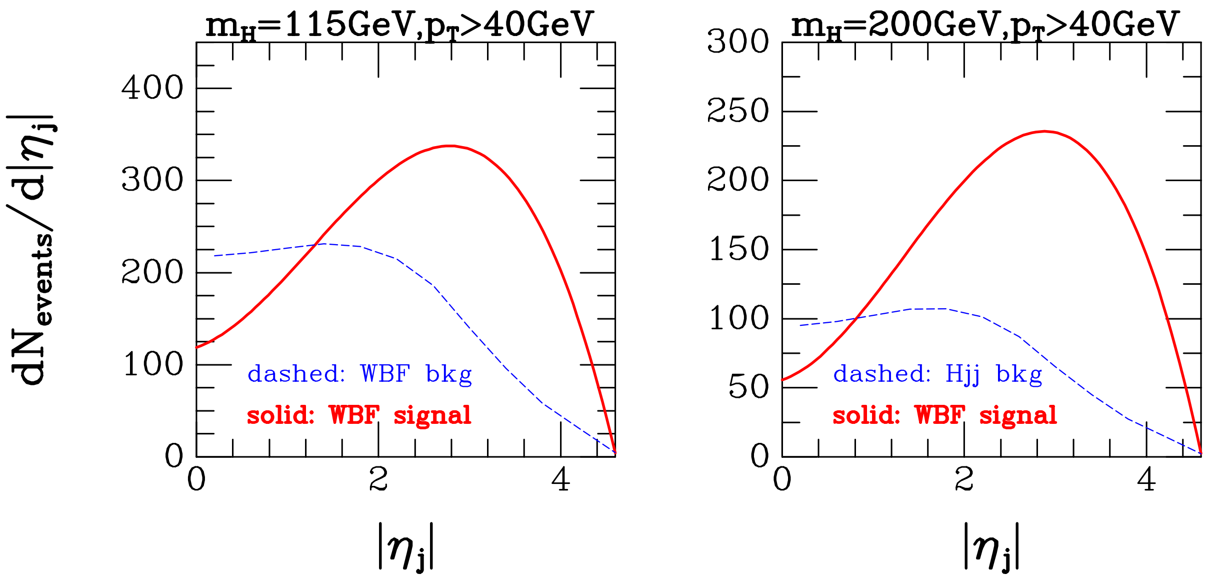
Berger and Qiu Phys Rev D 67, 034026 (2003)

Generic Cuts

- Generic cuts Figy et al. Jets from the Monte Carlo runs are clustered according to the k_T algorithm with
  - $p_T^{\rm jet} > 20$ GeV, to be raised
  - jet pseudo-rapidity $|\eta^{\rm jet}| < 4.5$, and
  - jet separation $\Delta R_{jj} = \sqrt{\Delta\eta_{jj}^2 + \Delta\phi_{jj}^2} > 0.8$
- The two jets with the highest p_T are chosen as the tagging jets and ordered in rapidity, $\eta_{j_1} < \eta_{j_2}$
- To approximate the acceptance for the Higgs boson decay products imagine a Higgs boson decay to two charged particles, denoted "leptons"
  - Require $p_T^{\rm lept} > 20\ {\rm GeV}$, $|\eta^{\rm lept}| < 2.5$, $\Delta R_{j\ell} > 0.6, \eta_{j_1} < \eta_{\rm lept} < \eta_{j_2}$
- Higgs decay products lie between the tagging jets

$H + 2$ Jet Production – Jet Rapidity Distribution

- Higgs boson H production via WW 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:

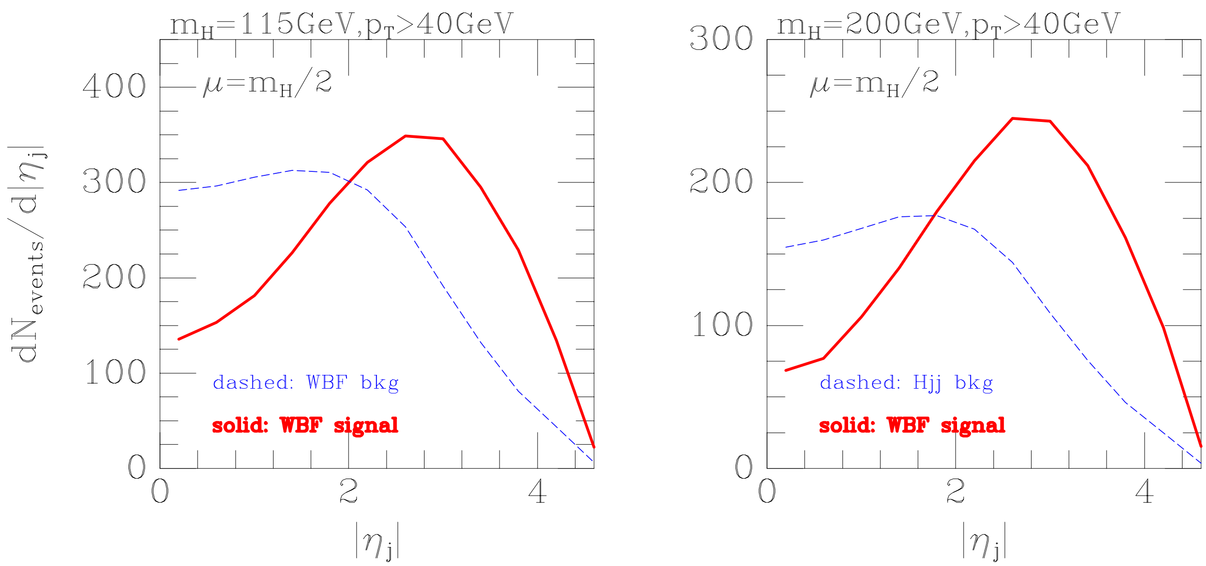
$$\eta_{\rm peak} - \eta_{\rm width}/2 < |\eta_j| < \eta_{\rm peak} + \eta_{\rm width}/2$$

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

- 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) (for 1 fb^{-1}, no BR included) $\mu = m_H/2$:



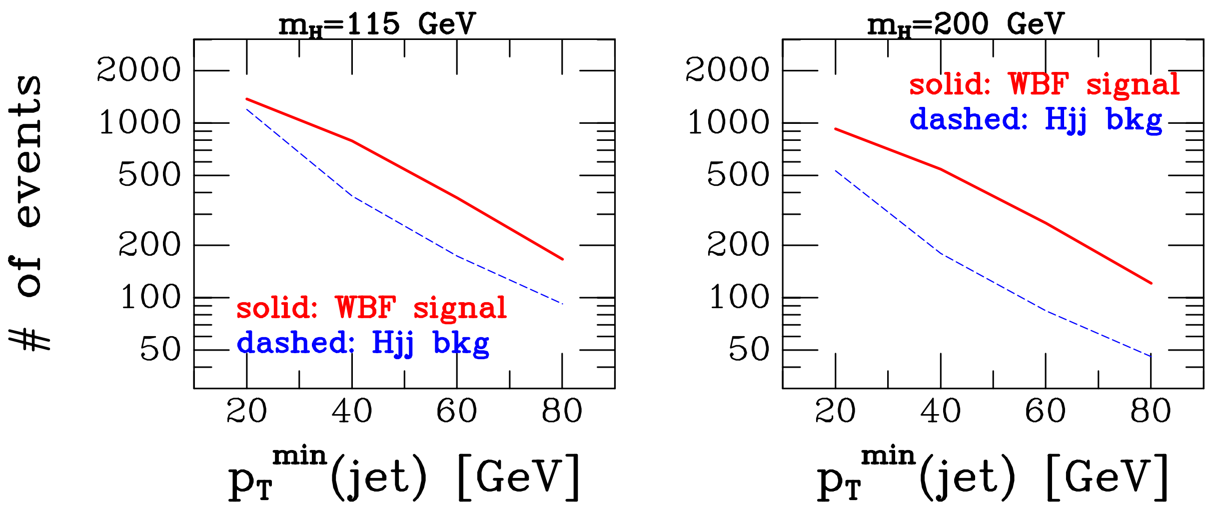
- Magnitude and shape of the signal distribution depend very little on μ

- Magnitude of the background is much greater at $\mu = m_H/2$. Not much effect on the shape

- Not much question that a differential NLO calculation is needed for the background process $H + 2$ jets

$H + 2$ 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
$$P = S/(S+B)$$

- 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

$H + 2$ Jets – Derivation of Coupling Uncertainty

- Both the signal and the background have $H + 2$ jets
- Want the uncertainty $\delta g/g$ on the coupling of the Higgs boson to vector bosons
- Define $r = g^2_{\mathrm{observed}}/g^2_{\mathrm{predicted}}$
- Assume deviation in the expected total number of events arises from the effective coupling $\rightarrow r = \frac{(N-B)}{S}$
- Uncertainty in r:

$$\delta r/r = \sqrt{(\delta S/S)^2 + ((\delta N)^2 + (\delta B)^2)/(N - B)^2}$$

- In terms of purity P = S/(S + B)

$$\frac{\delta g}{g} = \frac{1}{2}\sqrt{(\frac{\delta S}{S})^2 + \frac{1}{P^2}(\frac{\delta N}{N})^2 + \frac{(1 - P)^2}{P^2}(\frac{\delta B}{B})^2}$$

  - Factor $1/P$ that multiplies $\delta N/N \rightarrow$ $P < 1$ dilutes statistical power of data
  - Factor $(1 - P)/P$ that multiplies $\delta B/B \rightarrow$ $P \rightarrow 1$ reduces role of uncertainty in B
  - Size of background is included in P

Estimates of Uncertainties in S, B, and N

- Let $\delta S/S = 10\%$

  NLO effects are known; μ dep and PDF uncert are estimated

- Let $\delta B/B = 30\%$

  NLO effects not calculated yet for $H + 2$ jets; μ dep of the NLO inclusive process is $\sim 20\%$ for $\frac{1}{2}m_H < \mu < 2m_H$; PDF another $\sim 5\%$

- For N and $\delta N/N$, we must specify decay modes of H
  - for $m_H = 115$ GeV, pick $H \to \tau^+\tau^-$
    with one τ decaying to hadrons and one to leptons
    combined branching ratio 0.033
    tagging efficiency 0.26; net reduction factor $\epsilon \sim 0.01$
  - for $m_H = 200$ GeV, pick $H \to W^+W^-$; if both decay to leptons, $\epsilon \sim 0.036$

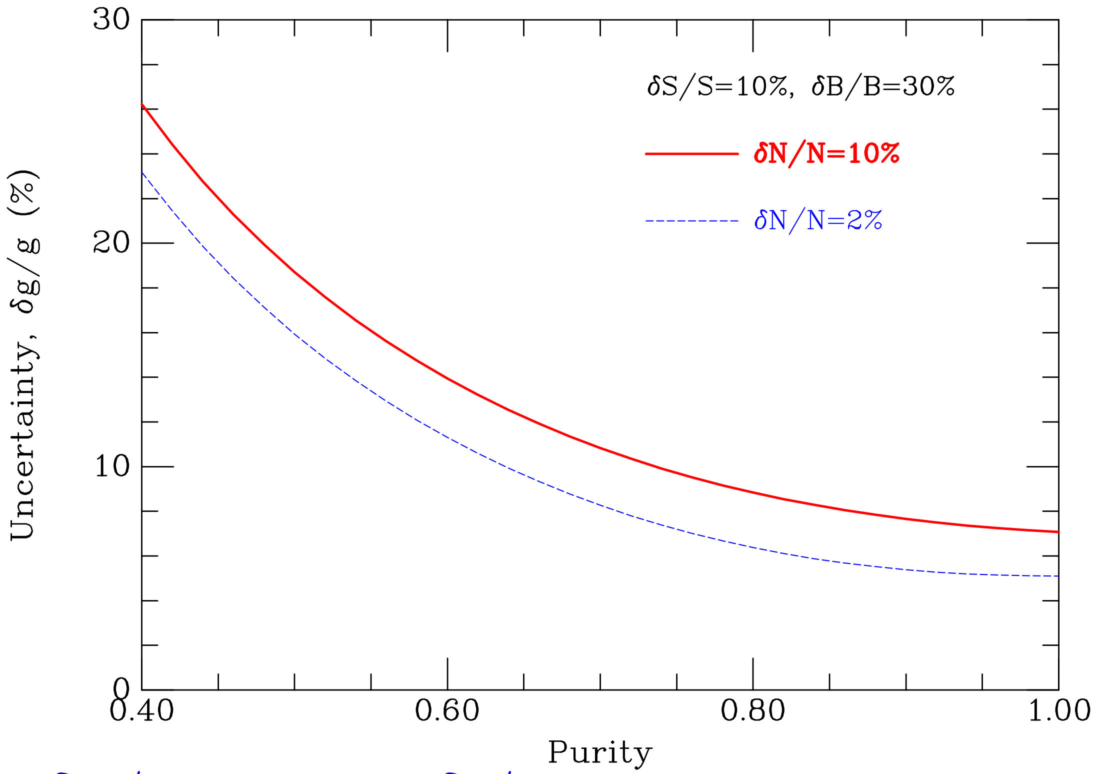
- "Low luminosity" minimum of ~ 10 fb^{-1} integrated luminosity is needed to discover H in the WBF process

  ATLAS, S. Asai et al hep-ph/0402254 one (good) year of LHC operation at 10^{33} cm^{-2}s^{-1}
  - $(S + B) \sim 12000 \times 0.01 = 120$ events at $m_H = 115$ GeV and $p_T^{\rm cut} = 40$ GeV;
    $\delta N/N \sim 10\%$
  - $(S + B) \sim 7000 \times 0.036 \sim 250$ events at $m_H = 200$ GeV and $p_T^{\rm cut} = 40$ GeV; $\delta N/N \sim 6\%$

Estimates of Uncertainties in S, B, and N

- "High luminosity" after 5 years of LHC operation, anticipate an integrated luminosity of ~ 200 fb^{-1}
  - at $m_H = 115$ GeV and $p_T^{\rm cut} = 40$ GeV;
    $\delta N/N \sim 2$%
  - at $m_H = 200$ GeV and $p_T^{\rm cut} = 40$ GeV;
    $\delta N/N \sim 1.5$%

Coupling Uncertainty *vs* Signal Purity



- If $\delta N/N \sim 10\%$ $\quad \delta g/g \sim 11\%$ $\quad$ for $P = 0.7$
- If $\delta N/N \sim 2\%$ $\quad \delta g/g \sim 8\%$ $\quad$ 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}

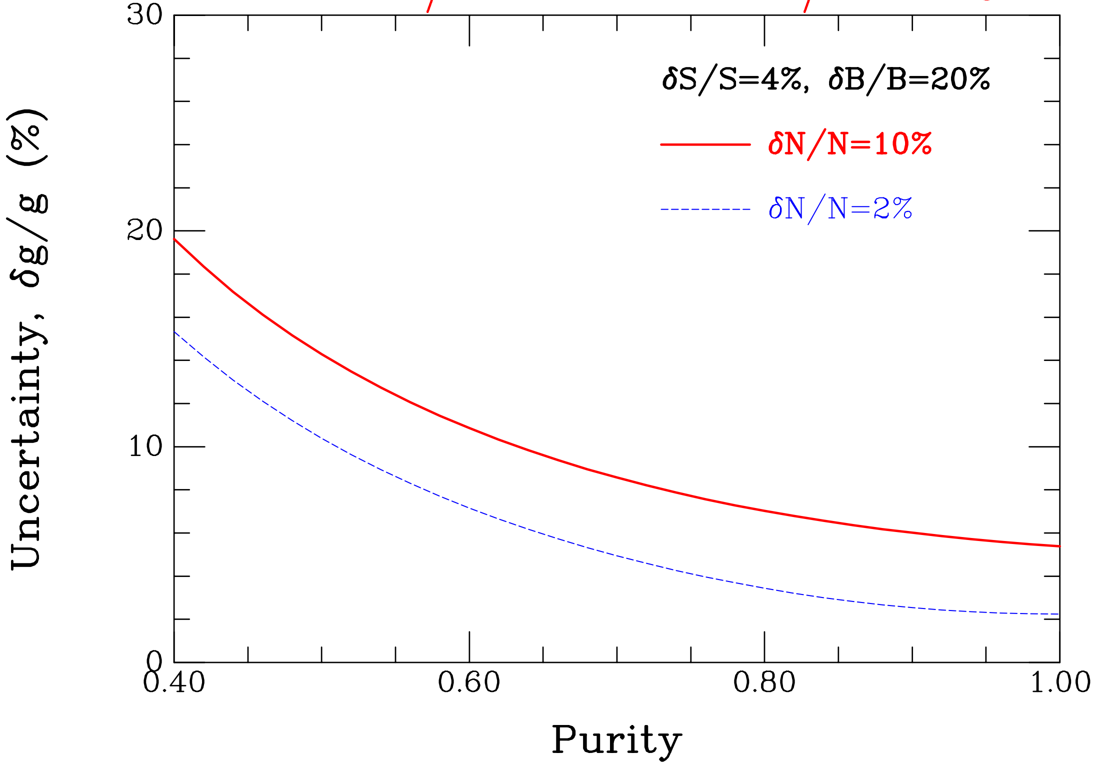
  Obtained for $p_T^{\rm cut} > 40$ GeV at $m_H = 115$ GeV and for $p_T^{\rm cut} > 20$ GeV at $m_H = 200$ GeV
- Suppose $K^{\rm NLO}_{\rm background} \sim 1.6$

  $P = 0.56$ 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 $\rightarrow$ $\delta g/g = 15\%$

Coupling Uncertainty *vs* Signal Purity

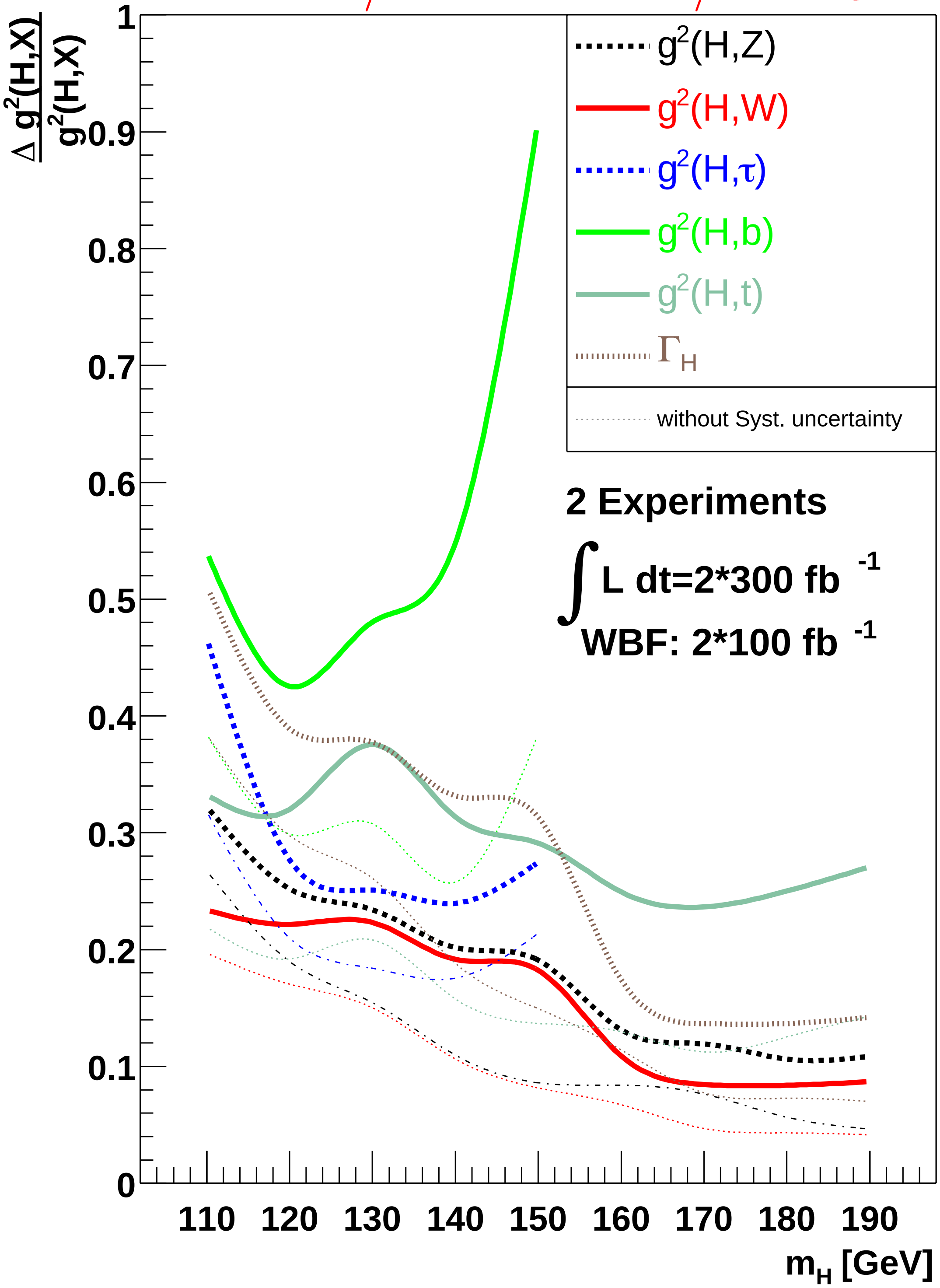
- Smaller values of $\delta S/S = 4\%$ and $\delta B/B = 20\%$



- If $\delta N/N \sim 10\%$ $\delta g/g \sim 9\%$ for $P = 0.7$
- If $\delta N/N \sim 2\%$ $\delta g/g \sim 5\%$ for $P = 0.7$
- New lower values of $\delta g/g$ are very similar to Düehrssen et al, Les Houches 2003 for comparable luminosity
- Not evident from these figures that there is much to gain from $P > 0.7$

Coupling Uncertainty vs Les Houches Results

- Smaller values of $\delta S/S = 4\%$ and $\delta B/B = 20\%$



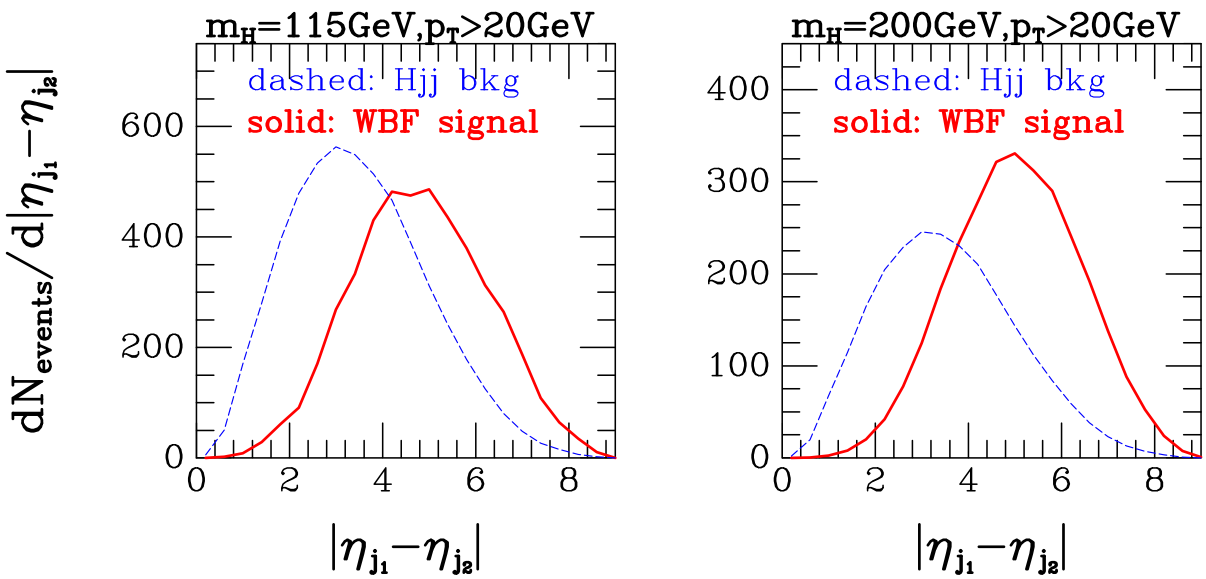
- Scope of the Les Houches study is more ambitious, but the WBF results at high luminosity are quite similar

4. Alternative WBF Prescriptions

- We use the requirement that at least one jet have $1.6 < |\eta| < 4.4$
- A different prescription requires instead a rapidity separation requirement $|\eta_{j1} - \eta_{j2}| > 4$
- Another requires an invariant mass cut $M_{jj} > 800$ GeV $\rightarrow$ Figures and Tables
- With these alternatives, there is a significant gain in P for $p_T^{\rm cut} = 20$ GeV, but not for larger values. The gain is accompanied by loss in signal rate at all p_T
- Potential advantages of simple cut on $|\eta|$ of one jet in a high luminosity environment
  - In data (and at higher orders in QCD) there are several jets; our prescription may be easier to implement
  - In a high luminosity environment, with more than one event per beam crossing, selection on only one jet (plus the H) reduces chance that jets from different events are used
- Full experimental simulation would be useful. One could begin with hard QCD LO $H + 2$ jet matrix elements plus Pythia showering – improvement over current ATLAS studies (c.f., S. Asai et al hep-ph/0402254)

$H + 2$ Jet Production – Jet Rapidity Separation

- Higgs boson H production via WW scattering in NLO and via gg QCD processes (LO) (for 1 fb^{-1})



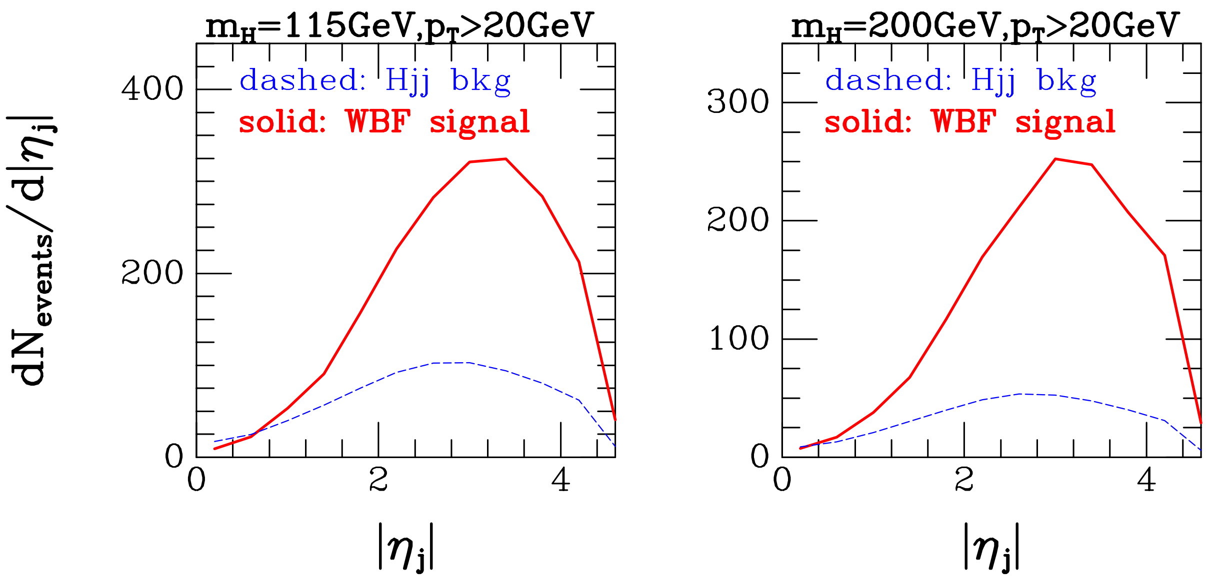
- Shape motivates a rapidity separation cut

$$|\eta_{j1} - \eta_{j2}| > 4$$

p_T cut [GeV]	20	40	80
Signal ($m_H = 115$)	1297	718	137
Bkg	758	207	38
Purity	0.63	0.78	0.78
Signal ($m_H = 200$)	911	521	106
Bkg	349	102	20
Purity	0.72	0.84	0.84

$H + 2$ Jet Production – Jet Rapidity with Mass Cut

- Higgs boson H production via WW scattering in NLO and via gg QCD processes (LO) (for 1 fb^{-1})



- Alternative WBF prescription:

$$M_{jj} > 800 GeV$$

p_T cut [GeV]	20	40	80
Signal ($m_H = 115$)	808	561	158
Bkg	304	183	82
Purity	0.73	0.75	0.66
Signal ($m_H = 200$)	617	428	121
Bkg	157	95	43
Purity	0.80	0.82	0.74

5. Summary

- Studied $H + 2$ jet production at the energy of the LHC. WBF signal at NLO; QCD background at LO with estimates of NLO effects. Fully differential hard matrix elements used to generate p_T spectra
- Investigated effectiveness of 3 different prescriptions to separate/enhance the WBF signal with respect to the *irreducible* QCD background
- 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
- All 3 methods work about equally well in the high-luminosity environment where a large value of the p_T cut is needed
- After 200 fb^{-1} are accumulated, it should be possible to achieve an accuracy $\delta g/g \sim 10$% in the effective coupling of the Higgs boson to weak bosons
- A fully differential NLO calculation of the $H + 2$ jet distributions is needed, applicable in the WBF region of phase space, so that P and $\delta g/g$ can be determined more accurately