Gluon-induced diboson production as background to Higgs, and determining Higgs properties

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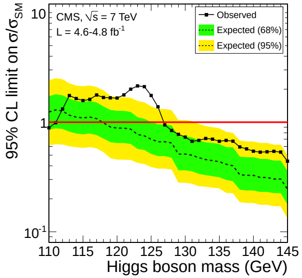
Outline

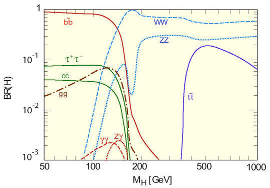
- **Gluon-induced NNLO QCD corrections to W^+W^- (+ jet) as background to Higgs**
  (with Tom Melia, Kirill Melnikov, Markus Schulze and Giulia Zanderighi arXiv:hep-ph/1205.6987)
- **Higgs $\mathcal{CP}$ from distributions**
- **Higgs $\mathcal{CP}$ from event shapes**

Higgs Introduction

- Hints of particle at $124 - 126$ GeV.
- Evidence/discovery rely on precision discrimination between signal and background.
- If discovery confirmed, more questions – SM Higgs? Couplings? $\mathcal{CP}$ properties?



CMS, hep-ex/1202.1488

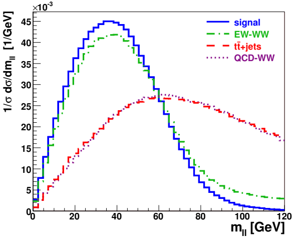


- $H \to WW \to l^+l^-\nu\nu$ important decay (although $H \to b\bar{b}$ is dominant, and $H \to ZZ \to 4l$ nicer signature)
- Signal binned according to number of jets produced – identification of background.

Signal vs Background

- Background from $t\bar{t}$, WW production
- $t\bar{t}$ background removed by b-tagging veto
- $H \to WW$ gives spin anticorrelations between W's $\to$ small angle between emitted leptons
- Background WW production has (relatively) flat distributions
- Cut on relative azimuthal angle $\Delta\Phi_{ll} < 1.8$, invariant mass of lepton $m_{ll} < 50$ GeV

ATLAS-CONF-2012-12



Klämke and Zeppenfeld, hep-ph/0703202

Signal production

- Higgs production without jets known to NNLO in QCD
- *Hj* and *Hjj* production known to NLO in QCD
- All implemented in `MCFM`, and with parton showering in `POWHEG`

  Campbell *et al*, hep-ph/1202.5475

$\Rightarrow$ Signal well understood.

Diboson Production

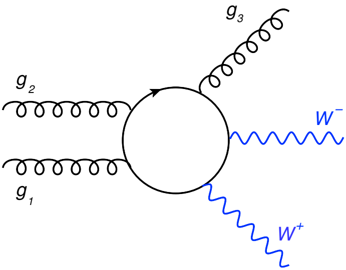
- WW known analytically at LO, NLO and gluon-induced contribution to NNLO in QCD
- Publicly available in `MCFM`, `POWHEG`, `MC@NLO`
- $WW + j$ analytically known at LO and publicly available
- $WW + j$ at NLO known — Ellis, Campbell, Zanderighi; Dittmaier, Kallweit, Uwer
- now public – add-on to `MCFM`
- $WW + 2j$ known at NLO — Melia, Melnikov, RR, Zanderighi; Greiner *et al*

Gluon-induced diboson production

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

No corresponding tree-level amplitude:

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



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

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

Gluon-induced WW production

$gg \to WW$ studied by Binoth *et al* hep-ph/0503094, hep-ph/0611170

Find highly cut dependent contribution to overall signal:

- For generic cuts*, $\sigma_{\rm LO} \simeq 270$ fb, $\sigma_{\rm NLO} \simeq 490$ fb, $\sigma_{gg} \simeq 30$ fb
  $\sigma_{gg+{\rm NLO}}/\sigma_{\rm NLO} = 1.06$
- For "Higgs search cuts"**, $\sigma_{\rm LO} \simeq 4.6$ fb, $\sigma_{\rm NLO} \simeq 4.8$ fb, $\sigma_{gg} \simeq 1.4$ fb
  $\sigma_{gg+{\rm NLO}}/\sigma_{\rm NLO} = 1.30$

* $p_{T,l} > 20{\rm GeV}$, $|\eta_l| < 2.5$, $p_{T,{\rm miss}} > 25{\rm GeV}$
** $35{\rm GeV} < p_{T,l,{\rm max}} < 50{\rm GeV}$, $p_{T,l,{\rm min}} > 25{\rm GeV}$, $\Delta\Phi_{ll} < 0.78$, $m_{ll} < 35{\rm GeV}$,
$p_{T,j} > 20{\rm GeV}$, $|\eta_j| < 3$

This 30% contribution is used by experimentalists.

BUT cuts used by CMS, ATLAS much looser:

$p_{T,l,{\rm max}} > 25$ GeV, $p_{T,l,{\rm min}} > 15$ GeV, $\Delta\Phi_{ll} < 1.8$, $m_{ll} < 50$ GeV

Gluon induced $WW(+j)$ production

Looked at $gg \to gWW$ and relooked at $gg \to WW$

Standard Cuts

		σ_{LO}	$\sigma_{\mathrm{NLO}}^{\mathrm{incl}}$	$\delta\sigma_{\mathrm{NNLO}}$	$\delta\sigma_{\mathrm{NNLO}}/\sigma_{\mathrm{NLO}}^{\mathrm{incl}}$
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%

Higgs search cuts, cf. ATLAS-CONF-2012-12

		σ_{LO}	$\sigma_{\mathrm{NLO}}^{\mathrm{excl}}$	$\delta\sigma_{\mathrm{NNLO}}$	$\delta\sigma_{\mathrm{NNLO}}/\sigma_{\mathrm{NLO}}^{\mathrm{excl}}$
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%

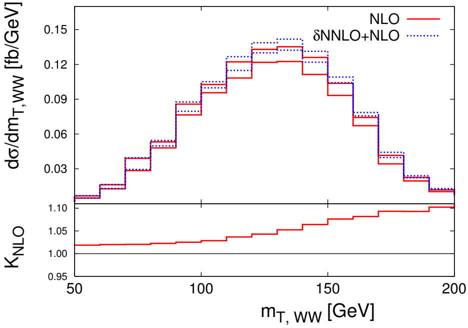
Gluon-induced WW production

- For WW, standard cuts give similar result to Binoth *et al.*
- Gluon-induced production slightly smaller for $WW + j$ with standard cuts.
- For Higgs cuts, important contribution to WW and $WW + j$ production (comparable to NLO scale uncertainty)
- **But** much smaller than 30% estimate
- $H + j$ production has cross-section 2 fb at 8 TeV, 5 fb at 14 TeV – gluon-induced NNLO contribution to background about half signal.

K-factor Distribution

Define

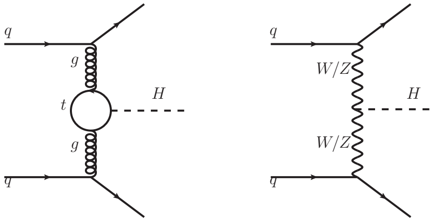
$$K_{\mathrm{NLO}} = \left. \frac{\mathrm{d}\sigma_{\mathrm{NLO}+\delta\mathrm{NNLO}}}{\mathrm{d}\sigma_{\mathrm{NLO}}} \right|_{\mu=2m_W} .$$



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

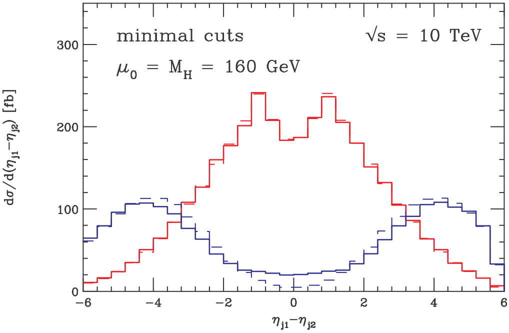
Investigating the Higgs

- Imagine that Higgs is found and mass is known – now investigate its couplings and $\mathcal{CP}$ properties.
- In $H \to WW$ decay mode, best to do so in production with 2 associated jets.
- This can be created in gluon fusion or through weak boson fusion (WBF)
- Former probes Yukawa couplings to quarks, latter probes couplings to EW bosons



$H \to WW + 2j$: GF vs WBF

Difference in jet rapidity $\Delta\eta_{j1j2} = \eta_{j1} - \eta_{j2}$ used to distinguish gluon fusion from WBF.



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

Background has same shape as gluon fusion distribution.

Azimuthal angle between jets

Following Klämke and Zeppenfeld, hep-ph/0703202; Hankele, Klämke, Zeppenfeld, hep-ph/0609075

Have proton beams with four-momenta b_+ and b_-, jets with four-momenta p_+ and p_-.

Define azimuthal angle between jets as

$$\epsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2 p_{T,+} p_{T,-} \sin \Delta\Phi_{jj}$$

- Sign of $\Delta\Phi_{jj}$ defined, invariant under change of beam direction $b_+ \leftrightarrow b_-$, $p_+ \leftrightarrow p_-$
- $\Delta\Phi_{jj}$ is parity odd

Hjj production through gluon fusion

Effective coupling to gluons (integrate out top loop, $m_H < m_t$) given by

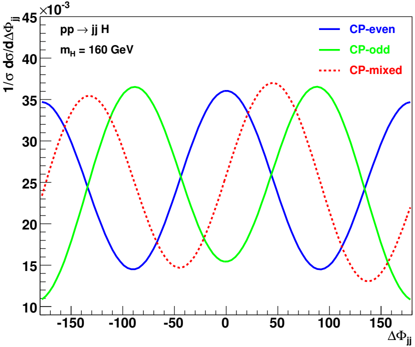
$$\mathcal{L}_{\rm eff} = \frac{y_t}{y_t^{\rm SM}} \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\tilde{y}_t}{y_t^{\rm SM}} \frac{\alpha_s}{16\pi v} H G^a_{\mu\nu} G^a_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}.$$

$\mathcal{CP}$-even and $\mathcal{CP}$-odd couplings y_t and $\tilde{y}_t$ parametrised by

$$\begin{aligned} a_2 &= \frac{y_t}{y_t^{\rm SM}} \frac{\alpha_s}{3\pi v} \\ a_3 &= \frac{\tilde{y}_t}{y_t^{\rm SM}} \frac{\alpha_s}{2\pi v} \end{aligned} \qquad (1)$$

Distributions for $\mathcal{CP}$-even and $\mathcal{CP}$-odd couplings

Differential cross-section has maxima at different values of $\Delta\Phi_{jj}$.



Distributions for $\mathcal{CP}$-even and $\mathcal{CP}$-odd couplings

Difference noticeable even when including backgrounds and mixed $\mathcal{CP}$ states:

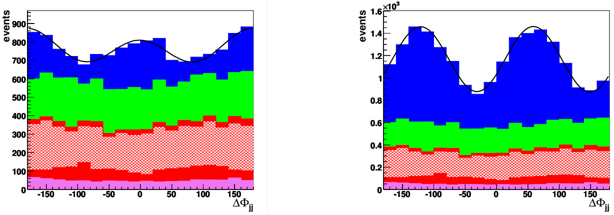


Figure: Events with $\mathcal{L}_{\rm int} = 300{\rm fb}^{-1}$. Left: pure $\mathcal{CP}$-even coupling. Right: mixed coupling with $y_t = \tilde{y}_t = y_t^{\rm SM}$. GF signal (blue); EW WW background (green); $t\bar{t}$ background (red); QCD WW background (purple).

Any asymmetry in $\Delta\Phi_{jj}$ distribution must be due to $\mathcal{CP}$-odd coupling a_3, since a_2 is parity-even $\rightarrow$ $\mathcal{CP}$-violation in Higgs sector

Hjj production through WBF

Parametrise non-SM couplings between EW bosons and H by effective Lagrangian with dimension-6 operators

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f^i}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots \qquad (2)$$

$\rightarrow$ seven $\mathcal{CP}$-even dimension-6 couplings, four $\mathcal{CP}$-odd dimension-6 couplings.

All constrained by L3 data; three of the $\mathcal{CP}$-even couplings very stringently.

Remaining couplings can be parametrised by d and d_B for $\mathcal{CP}$-even; $\tilde{d}$ and $\tilde{d}_B$ for $\mathcal{CP}$-odd, where

$$d = -\frac{m_W^2}{\Lambda^2} f_{WW} \qquad\qquad d_B = \frac{m_W^2}{\Lambda^2} \tan^2 \theta_w f_{BB}$$

Hjj production through WBF

Couplings are

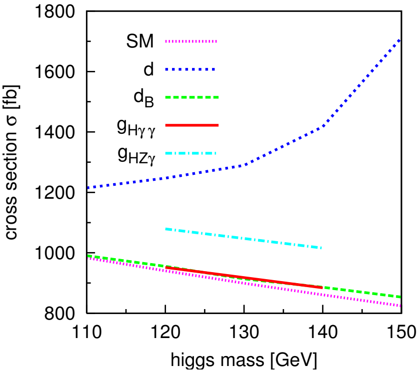
$$\begin{aligned} g_{H\gamma\gamma} &= \frac{g}{2m_W}(d\sin^2\theta_w + d_B\cos^2\theta_w) \\ g^{(2)}_{HZ\gamma} &= \frac{g}{2m_W}\sin 2\theta_w(d - d_B) \\ g^{(2)}_{HZZ} &= \frac{g}{2m_W}(d\cos^2\theta_w + d_B\sin^2\theta_w) \\ g^{(2)}_{HWW} &= \frac{g}{m_W}d. \end{aligned} \tag{3}$$

with L3 constraints

$$|g_{H\gamma\gamma}| < 0.16 \qquad |g^{(2)}_{HZ\gamma}| < 0.59 \qquad |g^{(2)}_{HZZ}| < 0.54 \qquad |g^{(2)}_{HWW}| < 1.41$$

Effects of anomalous couplings on cross-sections

- Saturating L3 bound for $g_{H\gamma\gamma}$ results in **very small cross-section** change.
- Translates into stringent bound on d_B
- Bound on $g^{(2)}_{HZ\gamma}$ and d much looser



Distributions for $\mathcal{CP}$-even and $\mathcal{CP}$-odd couplings

Again, $\Delta\Phi_{jj}$ distribution can be used to probe the $\mathcal{CP}$ nature of the couplings

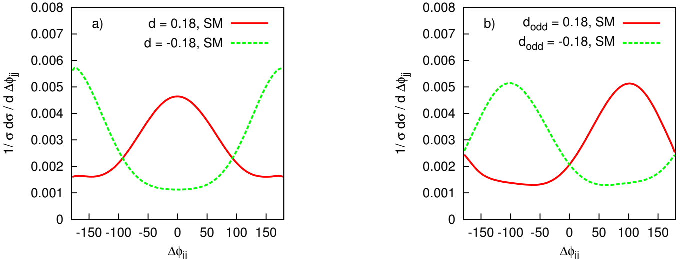


Figure: Normalised distribution for $\mathcal{CP}$-even couplings $d = \pm 0.18$ (left) and for $\mathcal{CP}$-odd couplings $\tilde{d} = \pm 0.18$ (right), with $d_B = \tilde{d}_B = 0$.

Figures include effects of interference between SM and anomalous terms.

Again, any asymmetry in $\Delta\Phi_{jj}$ points to a $\mathcal{CP}$-violating interaction in the Higgs sector.

Event shape variables

- $\mathcal{CP}$-properties of Higgs correlated with energy flow in jets
- Also correlated with energy flow in soft QCD radiation – overall energy flow of event
- To quantify, use event shape variables

Banfi, Salam, Zanderighi, hep-ph/0112156, hep-ph/0407287, hep-ph/1001.4082.

- **transverse thrust**

$$T_{T,g} = \max\{\mathbf{n}_T\} \frac{\sum_i |\mathbf{p}_{T,i}.\mathbf{n}_T|}{\sum_i |\mathbf{p}_{T,i}|} \tag{4}$$

- **thrust minor**

$$T_{m,g} = \frac{\sum_i |\mathbf{p}_{T,i} \times \mathbf{n}_T|}{\sum_i |\mathbf{p}_{T,i}|} \tag{5}$$

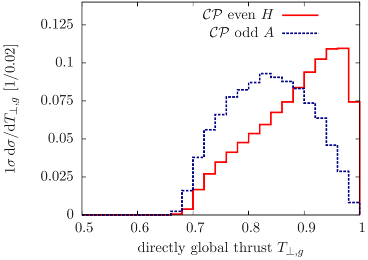
- Cone thrust minor, central total broadening, wide broadening,...

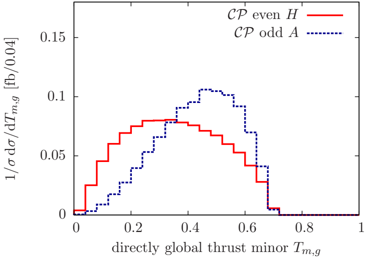
Event shapes in *Hjj*

"Orthogonal" to use of jet distributions

Following Englert, Spannowsky, Takeuch, hep-ph/1203.5788

Hjj with $H \to \tau\tau$

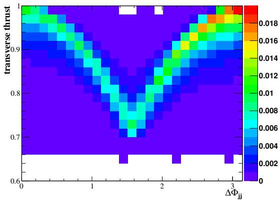




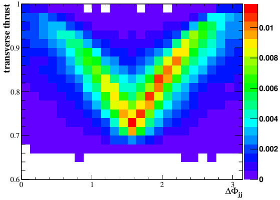
$\mathcal{CP}$-even Higgs has more pencil-like distribution (back-to-back jets)
$\mathcal{CP}$-even Higgs has rounder distribution

Event shapes in Hjj

Thrust then highly correlated with $\Delta\Phi_{jj}$ for $\mathcal{CP}$-even Higgs



Lighter correlation for $\mathcal{CP}$-odd Higgs



Correlation stronger if use **cone thrust minor**.

Event shapes in Hjj

- Claim that a 5-σ discrimination between $\mathcal{CP}$-even and -odd Higgs possible with $\simeq 25\mathrm{fb}^{-1}$ luminosity at 14 TeV LHC...
- as opposed to $\simeq 40\mathrm{fb}^{-1}$ for $\Delta\Phi_{jj}$
- However, sensitive to soft QCD radiation:
  - high pileup at LHC
  - QCD radiative effects: parton showering, hadronisation

Conclusions

- Highly cut dependent NNLO QCD contribution to diboson production from gluon fusion.
- For cuts used at LHC for Higgs searches, contribution is $\simeq 7\%$ at 8 TeV, $\simeq 12\%$ at 14 TeV for WW
- For WWj, contribution is $\simeq 6\%$ at 8 TeV, $\simeq 9\%$ at 14 TeV
- Comparable with NLO QCD scale uncertainty, and about half size of **signal**
- But much smaller than previous result, due to less stringent cuts
- Distributions of $\Delta\Phi_{jj}$ useful for analysing couplings, $\mathcal{CP}$ properties of Higgs for both GF and WBF
- Event shape variables thrust, minor thrust, cone minor thrust also can be used to discover $\mathcal{CP}$ properties of Higgs
- If Higgs discovery is around the corner, there is still lots to be investigated.