Higgs-plus-two-jet production at the LHC

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Overview

1) Introduction to standard VBF analysis techniques
2) Reminder: using VBF to extract Higgs quantum numbers and couplings
3) Identification of the H+2j production mechanism using a jet veto

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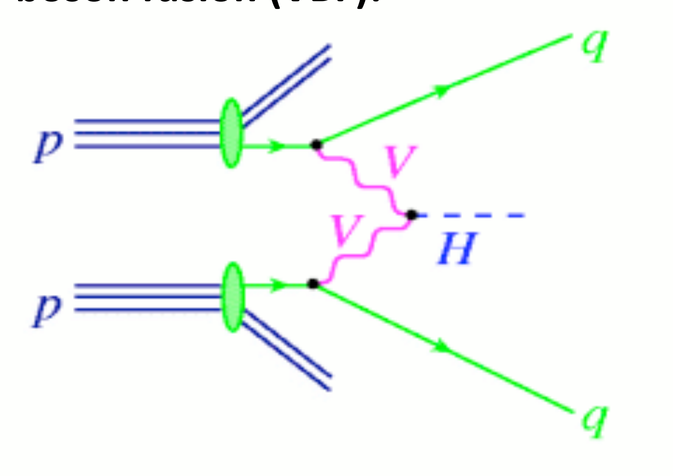
Higgs-plus-two-jet production

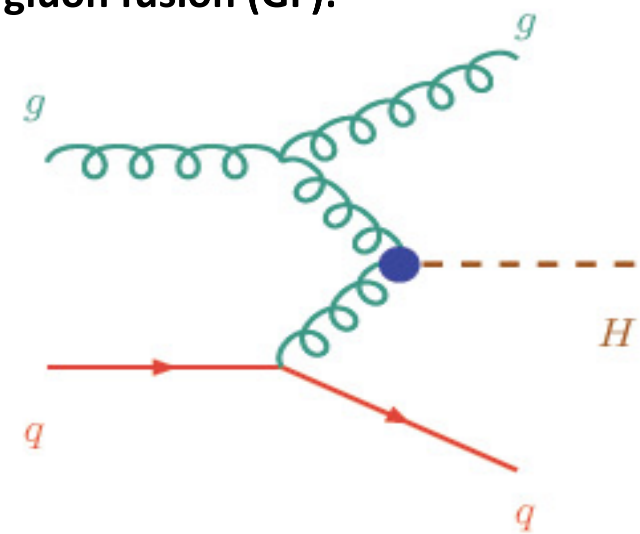
Vector boson fusion (VBF):



Quarks in proton radiate V's. Naturally produces two tag jets with large transverse momentum , $O(M_W)$

No colour flow between quark lines – expect that QCD radiation between quark-jets will be suppressed.

Gluon-gluon fusion (GF):



Higgs production via gluon-gluon fusion (through top quark loop). Tag jet production not 'typical', but does occur. Therefore GF can act as a "background" to VBF

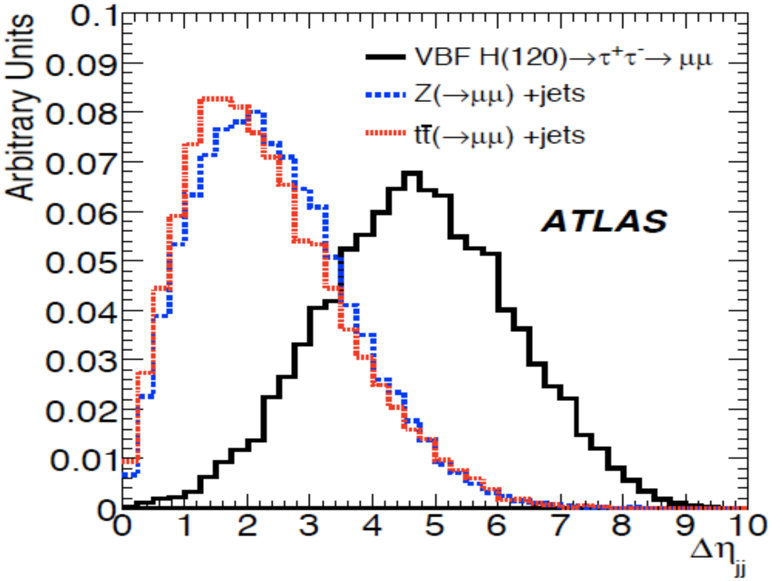
Colour octet flow between tag jets – expect more radiation in the region between the tag jets.

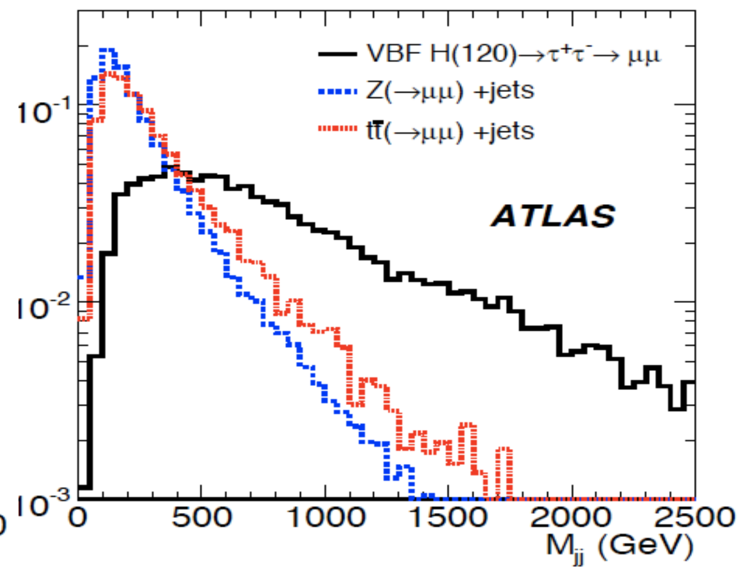
VBF analyses at the LHC (I)

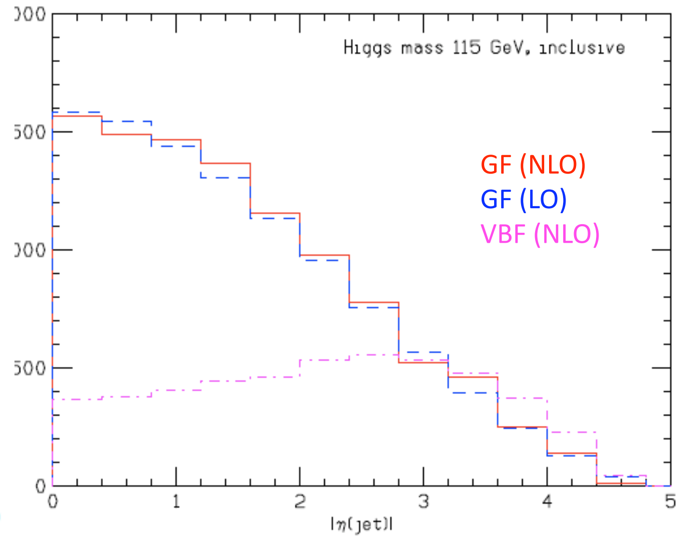
- The Higgs events are selected in two stages:
  - The Higgs is identified by the decay products (i.e. tau reconstruction for $H \rightarrow \tau\tau$)
  - The jet activity in the event is required to be (i) two ‘tagging’ jets (the leading jets in the event, corresponding to the quarks that radiated the vector boson) and (ii) no third jet in the rapidity interval between the tagging jets.

- There are a number of cuts applied to the tag jet system, which enhance the VBF signal over both the background and the GF process.
  - Typical cuts are: $E_{T,1} > 40$ GeV, $E_{T,2} > 20$ GeV, $M_{jj} > 700$ GeV,

$$\Delta\eta > 4.4, \qquad \eta_1 \times \eta_2 < 0,$$

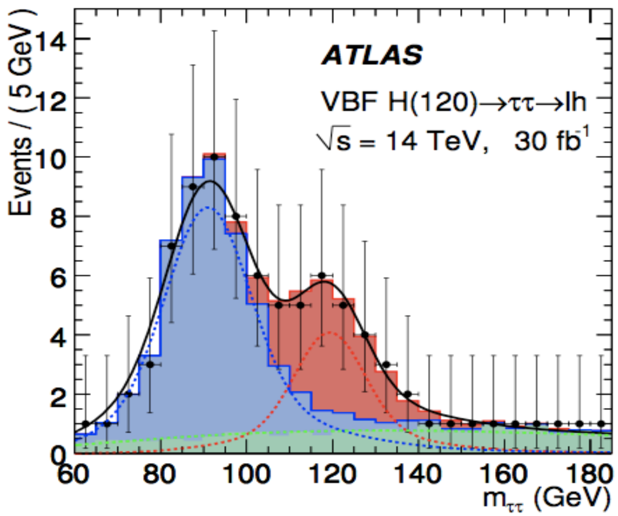






VBF analyses at the LHC (II)

- After main analysis cuts on tag-jets (widely separated, large invariant mass), the analyses typically veto on third jet activity in the central region between the tag jets.
- This veto is set very low, not only to reduce backgrounds, but to suppress Higgs production from gluon-gluon fusion (GF).



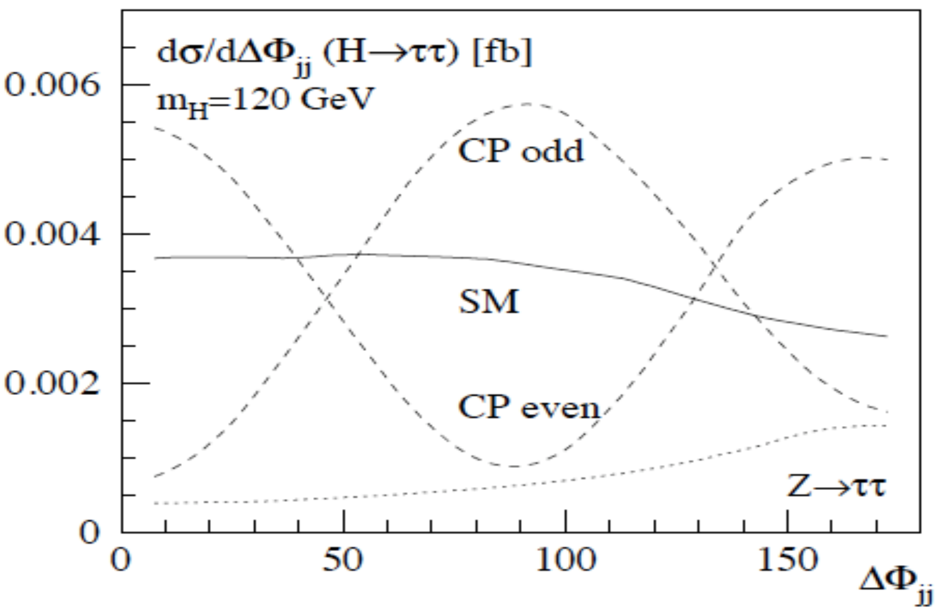
Signal is extracted from the $m_{\tau\tau}$ distribution.

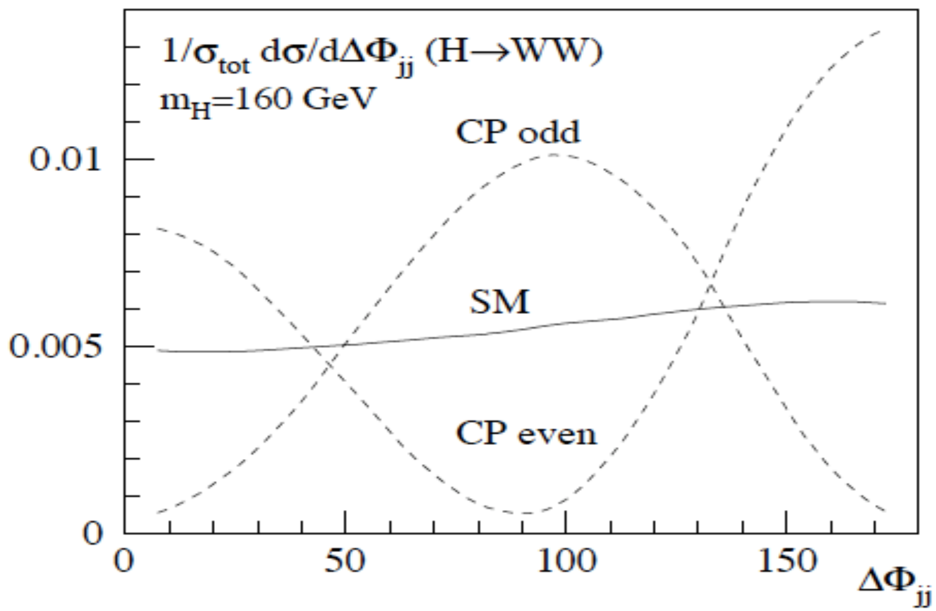
The shape of the background is dominated by instrumental effects and will be determined from in-situ methods.

Once the Higgs has been observed, the VBF events can be used for precision measurements of the Higgs CP, as well as feeding into the global coupling extraction

Higgs CP measurements in VBF

- It was pointed out by Plehn et. al (PRL88:051801,2002) that the tensor structure of the Higgs coupling to weak bosons could be probed by analysis of the azimuthal angle between the tag-jets in VBF.
  - SM term $\mathcal{L}_{\mathrm{SM}} \sim HV_{\mu}V^{\mu}$ can be distinguished from the anomalous CP-even and CP odd couplings couplings, $\mathcal{L}_{\mathrm{eff}} \sim HV_{\mu\nu}V^{\mu\nu}$ and $\mathcal{L}_{\mathrm{eff}} \sim HV_{\mu\nu}\tilde{V}^{\mu\nu}$





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Extraction of Higgs couplings

- The cross-section *x* branching ratio for a Higgs measurement in VBF will eventually be fed into a global analysis of Higgs production channels in order to extract the couplings.
- The ratios of couplings are easily extracted:

$$\frac{\sigma_{\mathrm{WWH}} \times B.R(H \to ZZ)}{\sigma_{\mathrm{ggH}} \times B.R(H \to ZZ)} \propto \frac{\Gamma_{\mathrm{WWH}}\Gamma_{\mathrm{ZZH}}/\Gamma}{\Gamma_{\mathrm{ggH}}\Gamma_{\mathrm{ZZH}}/\Gamma} \propto \frac{\Gamma_{\mathrm{WWH}}}{\Gamma_{\mathrm{ggH}}}$$

- The individual couplings can also be extracted after making some mild assumptions about the Higgs sector (e.g. Phys.Rev.D70:113009,2004)

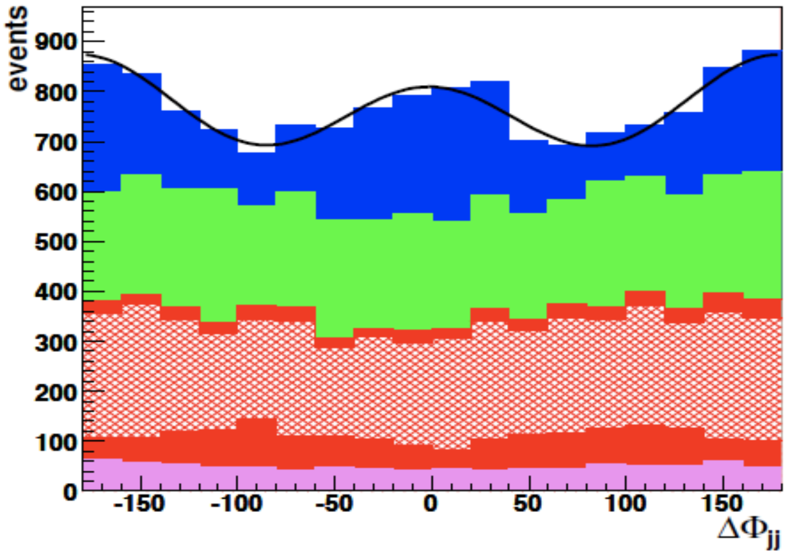
A recent evaluation such a global analysis was done by Lafaye et. al. (JHEP 0908:009,2009)

Note that the GF and VBF production channels are not independent. Need to suppress one channel w.r.t the other.

	σ_{symm}	σ_{neg}	σ_{pos}
$\Delta_{ZZH/WWH}$	± 0.41	-0.40	$+0.41$
$\Delta_{ttH/WWH}$	± 0.51	-0.54	$+0.48$
$\Delta_{bbH/WWH}$	± 0.31	-0.24	$+0.38$
$\Delta_{\tau\tau H/WWH}$	± 0.28	-0.16	$+0.40$
$\Delta_{\gamma\gamma H/WWH}$	± 0.30	-0.27	$+0.33$
$\Delta_{ggH/WWH}$	± 0.61	-0.71	$+0.46$

Production of H+2j events via gluon fusion

- In general, production of H+2j by GF is considered to be a bit of a nuisance as it contaminates the VBF channel
- H+2j via GF has been studied in its own right by Klamke et. al. (JHEP 0704:052,2007).



- CP nature of effective gluon coupling can be probed in H+2j events produced by GF

$$\mathcal{L}_{\text{eff}} \sim H G_{a,\mu\nu} G^{a,\mu\nu}$$

- Different cuts are proposed to enhance GF instead of VBF
- First studies indicated that SM H➔WW was feasible, but probably not lower masses with H➔ττ

- In BSM models, the Higgs couplings are typically different than the SM Higgs couplings:
  - GF could be very important if the couplings to vector bosons are heavily suppressed
  - It would be good to have a handle on the 'contamination' between GF and VBF channels

Measuring VBF and GF at the same time?

- Crucial component is the veto on additional jets above Q_0 in the central region between the two tag jets.
- The excess of events in the di-tau invariant mass spectrum contains contributions from both GF and VBF:

$$\sigma(Q_0) = \Lambda_{\rm g}\sigma_{\rm g}^{\rm SM}(Q_0) + \Lambda_{\rm V}\sigma_{\rm V}^{\rm SM}(Q_0)$$

here, Λ_i is the ratio of the actual Higgs coupling to 'i' to the SM value, i.e. $\Lambda_g = \Lambda_V = 1$ in the SM.

- Instead of cutting at low veto-scales, to suppress GF contribution, can in principle measure the size of the Higgs cross-section as a function of Q_0 and extract contributions for GF and VBF separately. [PLB 696 (2011) 87-91]
  - Advantage that it does not assume a SM-like coupling to vector bosons, applicable to BSM Higgs
  - Can we do this in practice, given the likely event rate at LHC and the theory/experimental uncertainties?

First estimate of the feasibility: H→ττ

MC samples

1) SHERPA 1.2 used to generate samples of GF and VBF Higgs events at √s=14TeV. Specifically generate H+nj, with n=2,3. Higgs mass chosen to be 120GeV.
2) K-factors invoked to account for missing virtual corrections by normalizing dedicated samples to the NLO calculation of Campbell, Ellis & Zanderighi (2006). This is needed to get the ratio of GF and VBF events correct.

VBF analysis cuts

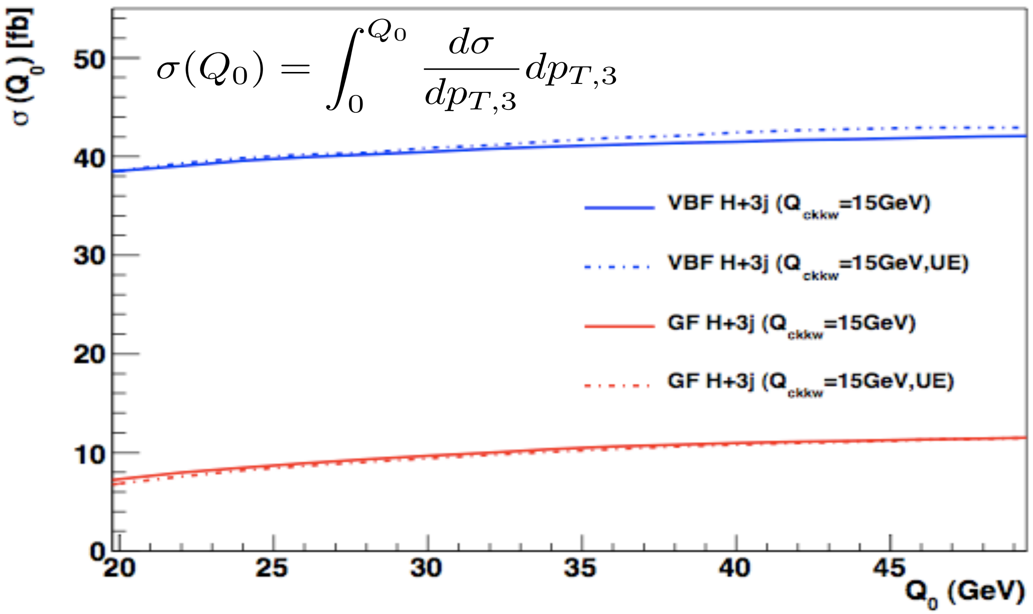
Jets found using Anti-k_T algorithm with R=0.4.

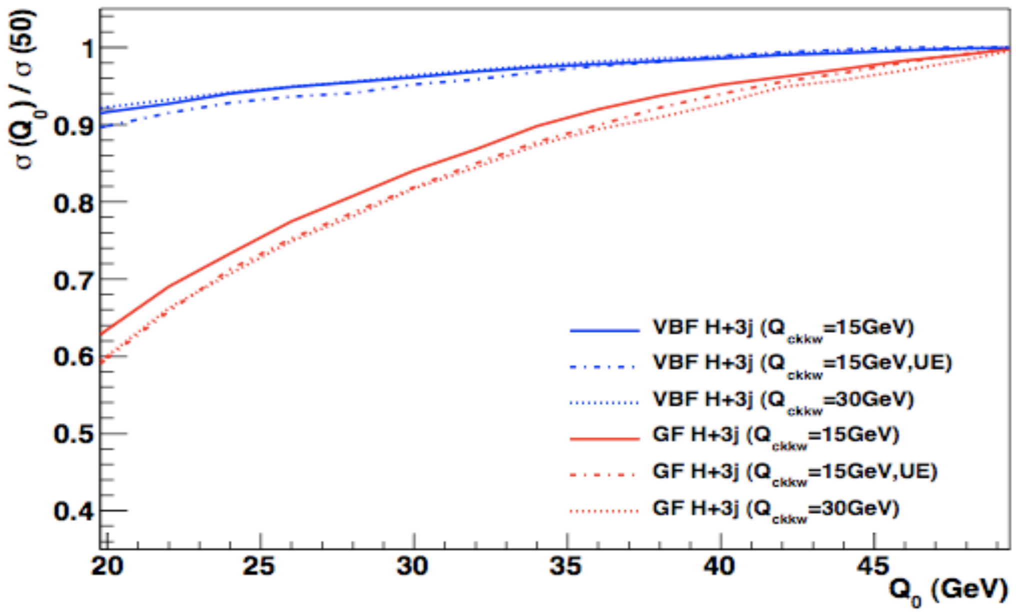
Then, follow explicitly the ATLAS standard VBF analysis [outlined in arXiv:0901.0512]

1) Tag jets: $E_{T,1} > 40$GeV and $E_{T,2} > 20$GeV
2) Tag jets: $M_{jj} > 700$GeV, $\Delta\eta_{jj} > 4.4$ and $\eta_1.\eta_2 < 0$
3) Tau candidates: $\cos(\Delta\phi) > -0.9$
4) Missing $E_T > 30$GeV

After these kinematic cuts, we have a reasonable jet/Higgs topology that mimics a realistic search at the LHC.

The jet veto dependence





- Left plot shows the size of the VBF and GF cross-section as a function of Q_0 after the kinematic cuts (still missing experimental efficiencies for taus, such as trigger, reconstruction…)
- Right plot highlights the different Q_0 dependence of VBF and GF events.
  - CKKW matching scale in SHERPA is important in GF shape – in a way this reflects the large theory uncertainty in the prediction, will return to this later.
  - Underlying event also cause a shape uncertainty between Q_0=20 and Q_0=50 for GF and VBF

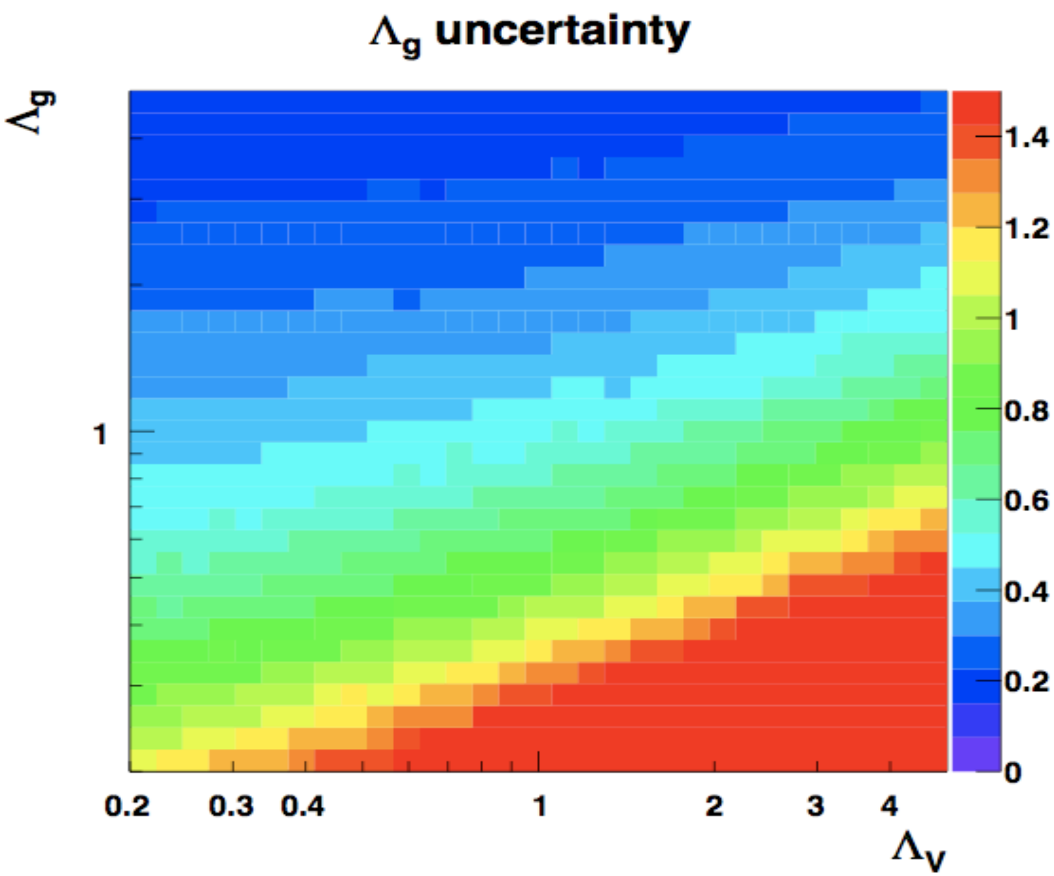
Extracting the GF and VBF components

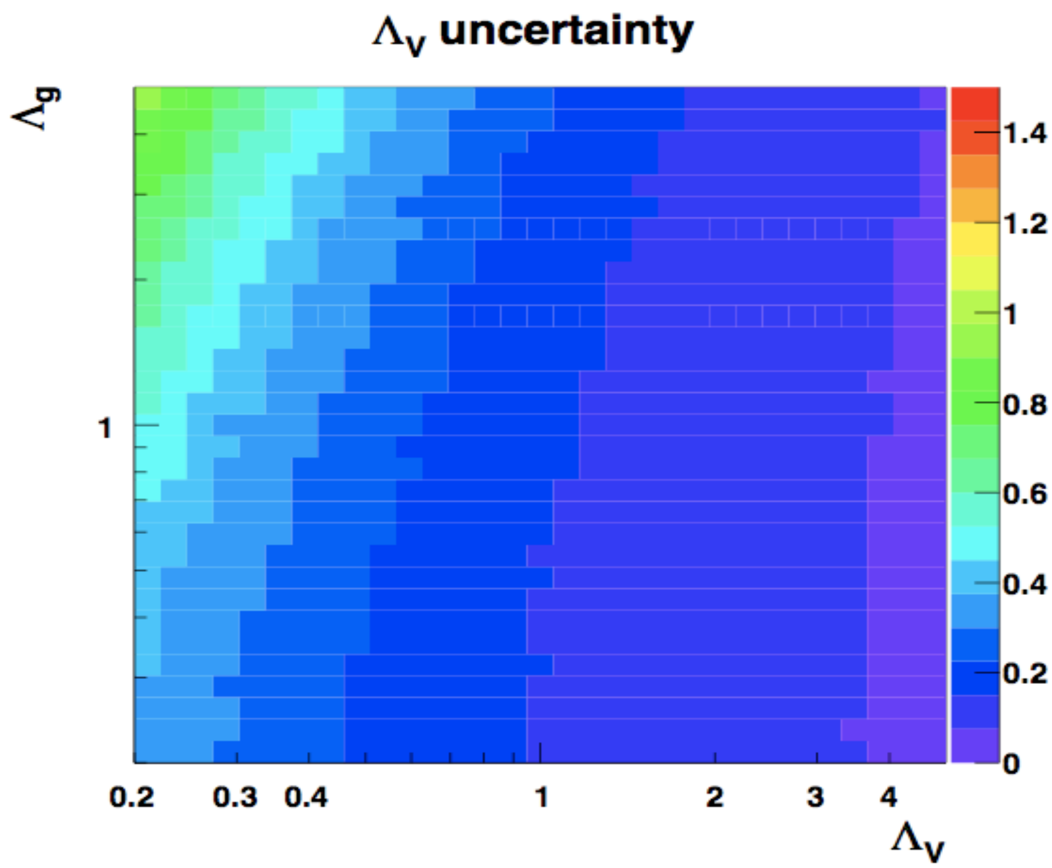
- We need to account for experimental efficiency, ε, for tau-tau measurements (trigger, reconstruction, id…..)
  - Efficiency will be similar for GF and VBF events because we have already cut on the topology of the H+2j system. Take ε=0.036 (corresponds to all decay channels).

- Using NLO cross-sections and experimental efficiency, predict number of Higgs events for $60fb^{-1}$ of data. Find N_{GF}=25 and N_{VBF}=90 for Q_0=50.

- Perform 2000 pseudo-experiments for a specific choice of Λ_g and Λ_V [SM is $\Lambda_{g,V}$=1].
  - (Poisson distributed) GF and VBF events chosen at random from reduced MC samples (i.e. samples after kinematic cuts),
  - Smear/shift Q_0 distribution by systematic uncertainties (expt and theory)
  - Fit each pseudo-data with theory prediction to extract Λ_g and Λ_V
  - Take uncertainty in method to be the RMS of fit values.

Results without systematic uncertainties





- Colours represent the fractional uncertainty in the fit, across BSM parameter space.
  - Yellow, orange, red mean a very large final uncertainty on Λ
  - Dark blue represents a very well measured uncertainty.

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Impact of systematic uncertainties

What we are trying to measure: $\sigma(Q_0) = \sigma_{jj}(1 - P_{veto}(Q_0))$

H+2j cross-section (after cuts on tag jets)
i.e. A normalization uncertainty

Probability of additional jet above Q_0
i.e. a shape dependence

Take all theory/experimental uncertainties from literature:

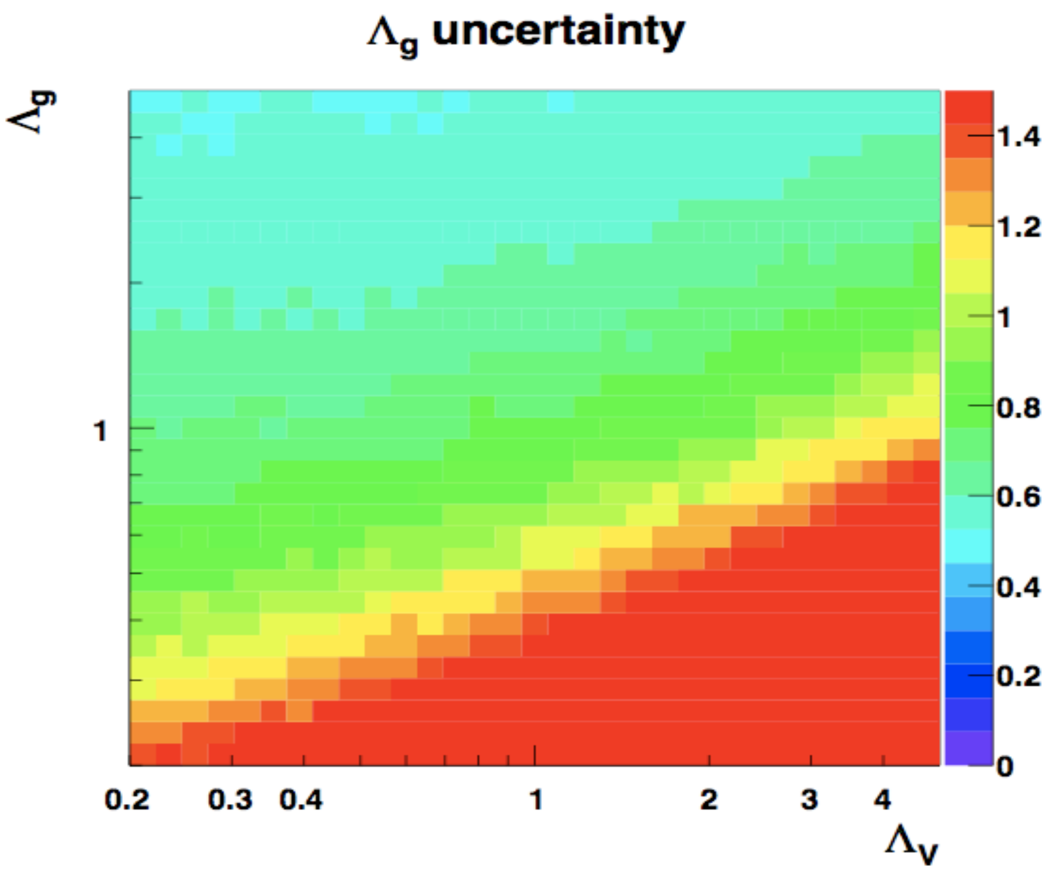
Uncertainties in theoretical prediction:

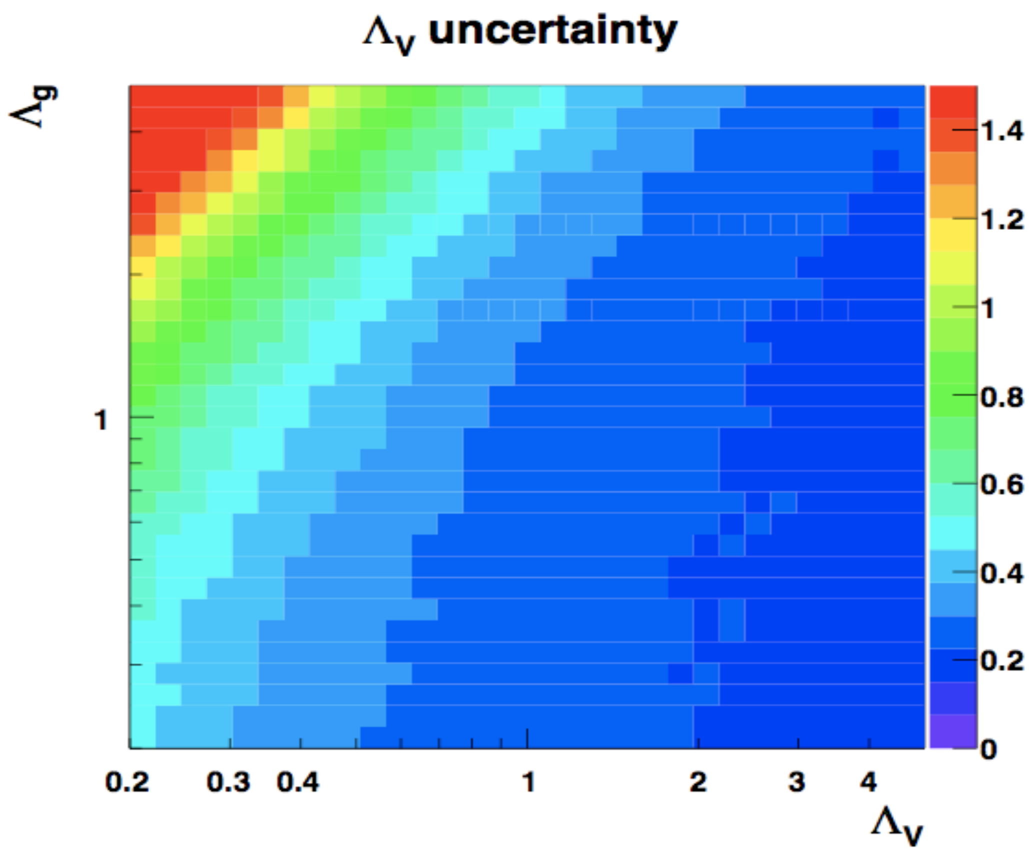
1) VBF: Normalization of H+2j is known to about ±4% and (1-P_{veto}) is known to ±1% at all Q_0.
2) GF: Normalization of H+2j is known to about ±20%. Additional uncertainty from (1-P_{veto}) is not well known. Assign additional, uncorrelated, uncertainty of ±20% at Q_0=20 and 50 GeV.
3) Add in UE uncertainty in (1-P_{veto}), found from SHERPA after turning UE on/off.

Uncertainties from experimental measurement:

1) VBF systematic (20%) on acceptance/normalization is mainly from JES. We find that corresponding systematic for GF is larger (~30%), due to steeper tag-jet distributions.
2) Find mild effect of JES on (1-P_{veto}) -- 0% for VBF and (max) ±3% for GF.
3) Background fluctuations affecting signal extraction is taken into account across Q_0 distribution by adding/removing events based on poisson fluctuation of background.

Results with systematic uncertainties included





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Breakdown of systematic uncertainty

Error	SM ($\Lambda_{g,V} = 1$)		BSM ($\Lambda_g = 4,\ \Lambda_V = 1/4$)	
	$\sigma_{\Lambda_g}/\Lambda_g$	$\sigma_{\Lambda_V}/\Lambda_V$	$\sigma_{\Lambda_g}/\Lambda_g$	$\sigma_{\Lambda_V}/\Lambda_V$
Stat. only	0.51 [0.23]	0.16 [0.07]	0.19 [0.08]	0.72 [0.33]
Backgd.	0.56 [0.25]	0.18 [0.08]	0.20 [0.09]	0.79 [0.35]
VBF	0.52 [0.25]	0.17 [0.08]	0.19 [0.08]	0.75 [0.33]
GF	0.65 [0.45]	0.19 [0.11]	0.43 [0.40]	1.56 [1.40]
Expt.	0.62 [0.39]	0.26 [0.21]	0.35 [0.31]	0.89 [0.52]
All	0.77 [0.57]	0.28 [0.23]	0.53 [0.50]	1.66 [1.49]

Largest uncertainty arises from the theoretical modelling of the GF cross-section and kinematics.

Experimental uncertainty mainly due to JES.
- Overestimated: the current JES@ATLAS is about 1.5x smaller than the values used in this analysis.

Represent the uncertainty given 60 [300] fb^{-1} of data.
Middle rows show effect of statistical uncertainty + specific systematic
- statistical uncertainty in fitting procedure is always present.

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Summary

Higgs-plus-two-jet at the LHC

- VBF measurements are well established as LHC search channels.
- VBF measurements allows the CP nature of the Higgs to be determined, and feed into global extraction of Higgs couplings
- BSM Higgs production changes the relative size of GF and VBF couplings.

The role of the central jet veto

- Dependence of the signal on the jet veto scale can be used to extract the different mechanisms of Higgs production.
  - Contamination of GF in VBF studied in-situ.
  - Simultaneous extraction of effective coupling of Higgs to gluons and vector bosons
- Large uncertainty in both the normalization and shape of the GF cross-section.
- Understanding the central jet veto in the presence of pile-up will be
  - Early measurements of central jet veto in dijet production and W/Z+2jet production is crucial to pin down both the theory and experimental uncertainties