Vector Boson Fusion at the LHC

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Outline

- Weak Boson Fusion and Anomalous Couplings
- Gluon-gluon Fusion
- Higher Order Calculations
- Conclusions

The Higgs Boson at the LHC

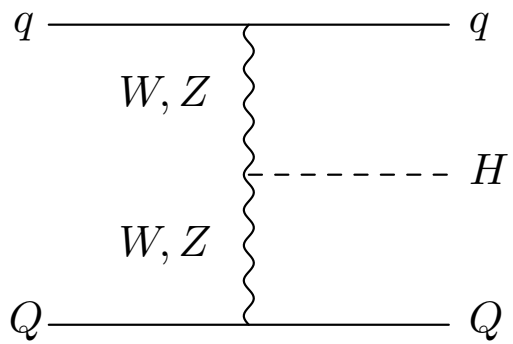
- First need to discover a fundamental scalar.

  If one is found, crucial to test if it is responsible for Electroweak Symmetry Breaking.

- One aspect is the coupling of the Higgs boson to W and Z bosons. Study this by either:
  - Production through a HWW/HZZ vertex & use all decay channels
    or
  - Use all production channels, and study $H \to WW^{(*)}$ / $H \to ZZ^{(*)}$

- Concentrate here on the first option.

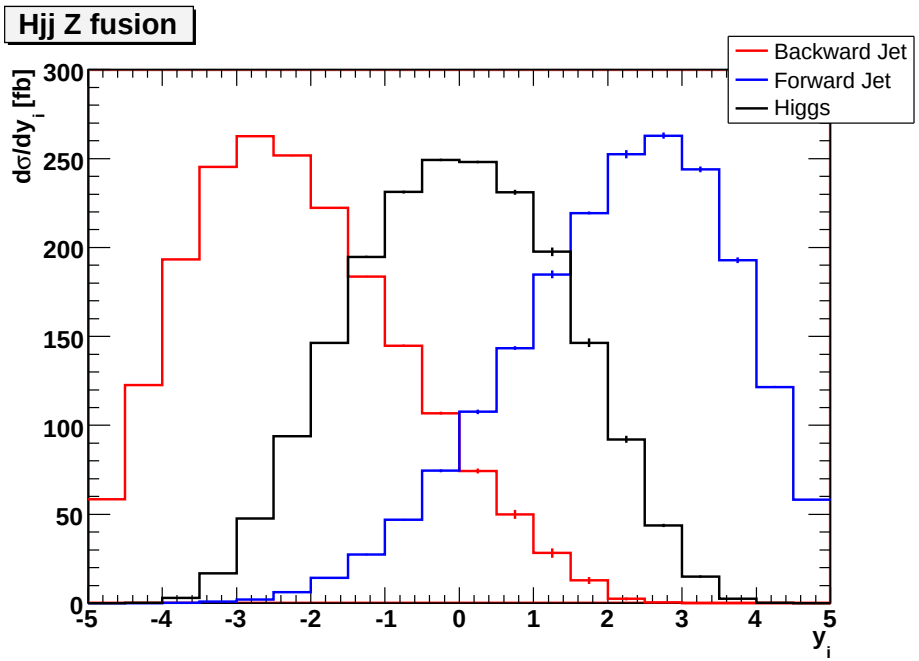
Weak Boson Fusion (WBF)



- Second largest production cross section at LHC
  Few pb depending on Higgs boson mass.
- Ratio of W:Z events about 3:1
- Each jet gets small transverse kick $\sim m_W/2$
- Have 1 forward jet, 1 backward jet & central Higgs boson

Weak Boson Fusion (WBF)

Cuts:
$p_{T_j} > 20$ GeV,
$|\eta_j| \leq 5$,
$R_{jj} > 0.6$

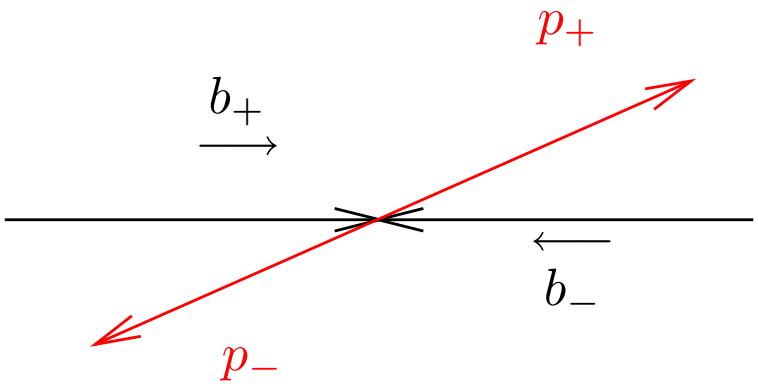


In general, use the following 'WBF cuts' to get a purer sample:

generic: $p_{T_j} > 20$ GeV, $|\eta_j| \leq 5$
plus: $s_{jj} > (600\ \text{GeV})^2$, $\eta_{j_1}\eta_{j_2} < 0$, $|\eta_{j_1} - \eta_{j_2}| > 4.2$

The $\Delta\phi_{jj}$ Distribution

Instead, to study the HVV coupling, can study Lorentz structure through azimuthal angles of the jets:



Distinguish jets as imposed opposite sign rapidities.

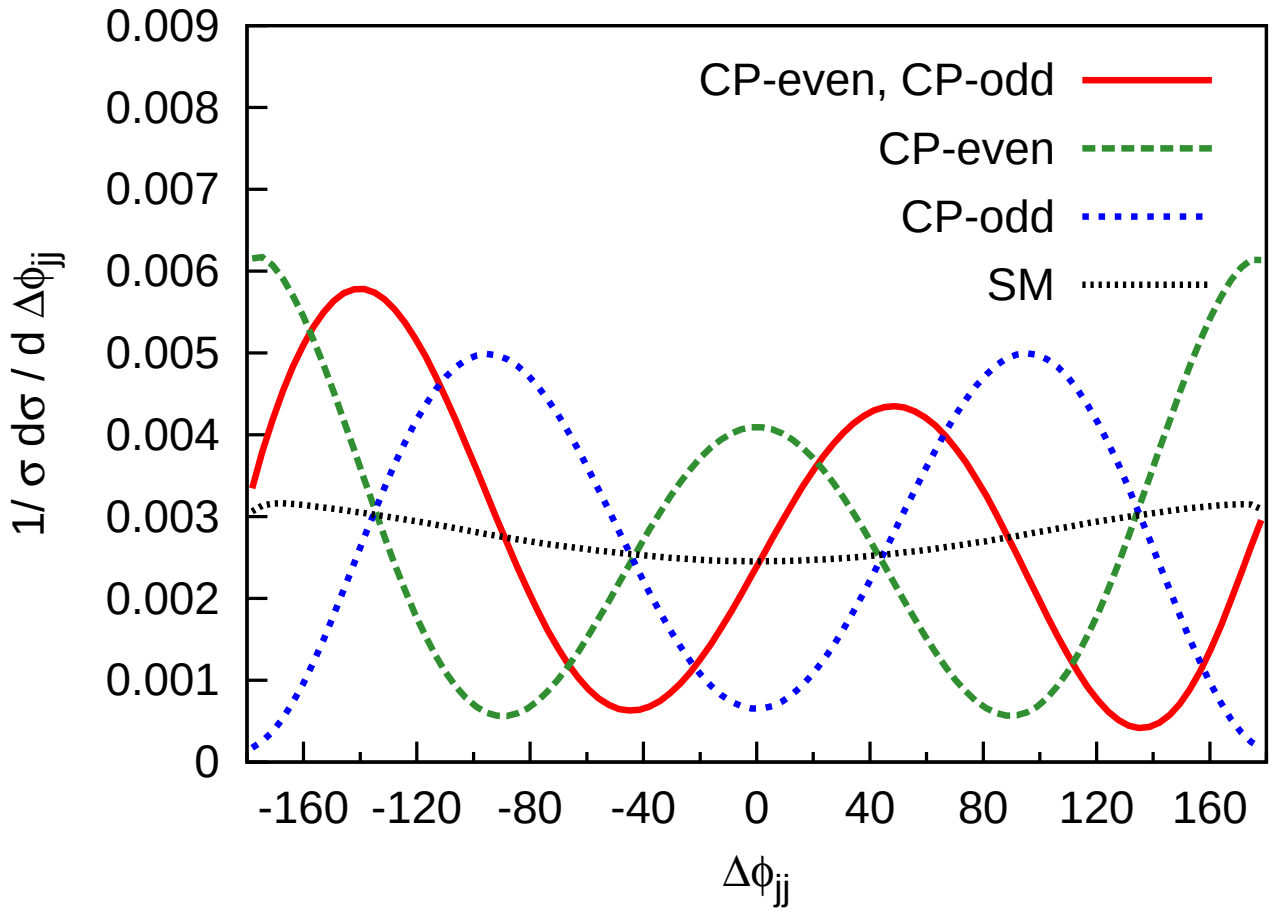
Therefore, can distinguish the full range of $\Delta\phi_{jj} \in [-\pi, \pi]$.

Plehn, Rainwater, Zeppenfeld: `hep-ph/0105325`
Figy, Hankele, Klämke, Zeppenfeld: `hep-ph/0609075`

Look for anomalous HWW/HZZ couplings of the form:

$$V_{HWW}(p^\mu, q^\nu) = g_W M_W (a_1 g^{\mu\nu} + a_2 (g^{\mu\nu} p\cdot q - p^\nu q^\mu) + a_3 \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma).$$

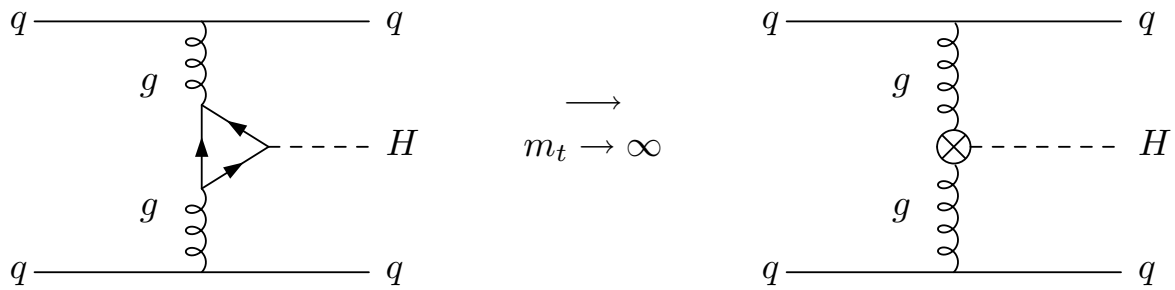
The $\Delta\phi_{jj}$ Distribution



Plot from Figy et al, hep-ph/0609075

Gluon-Gluon Fusion

- Consider the following process:



- In heavy m_t limit treat as effective vertex (for $m_H \lesssim 200$ GeV).

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{4}\left(1 - \frac{\alpha_s H}{3\pi v}\right) G^a_{\mu\nu} G^{a\mu\nu} + \mathcal{O}(\alpha_s^2)$$

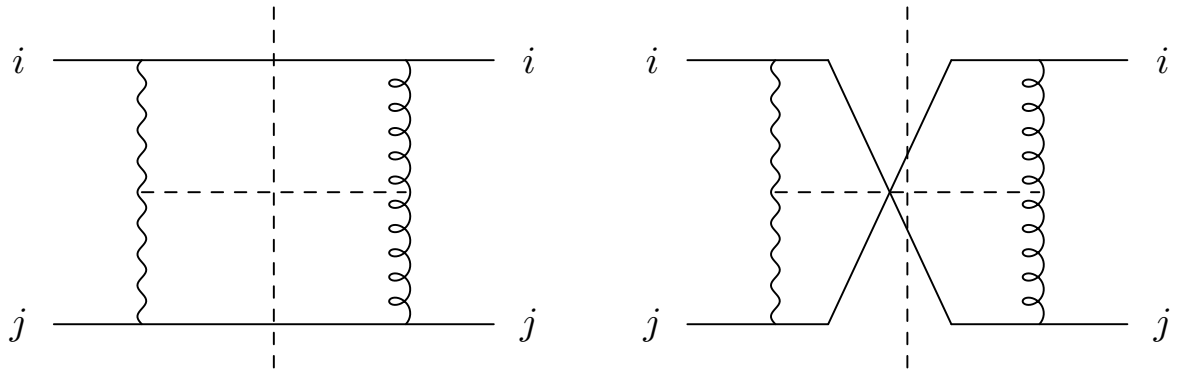
  which gives

$$V_{Hgg}(p^\mu, q^\nu) = \frac{i\alpha_s}{3\pi v}(p \cdot q g^{\mu\nu} - p^\nu q^\mu) \ .$$

- Not the same form as the HWW/HZZ couplings, so must be suppressed.

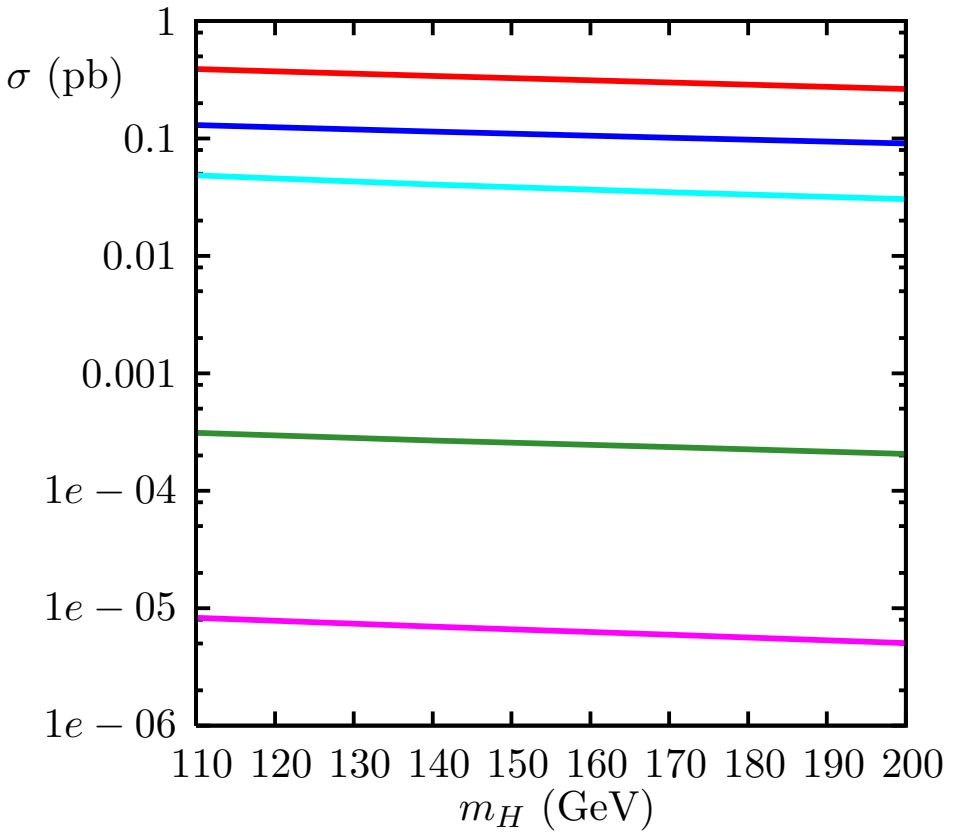
Interference

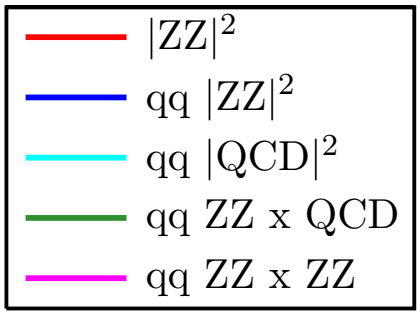
- There are contributions at tree level from cross terms



- Left diagram is zero from colour trace.
  Right diagram contributes.
- Requires identical flavour and colour quarks,
- $t \leftrightarrow u$-channel crossing forces at least one propagator far off-shell

Suppression





Interference term does not have noticeable effect on the cross section.

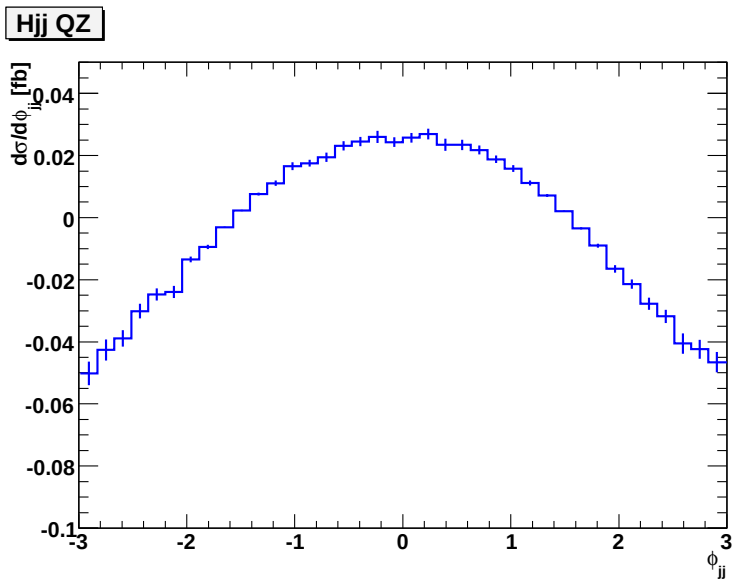
BUT interference is not positive definite.

Must check distributions.

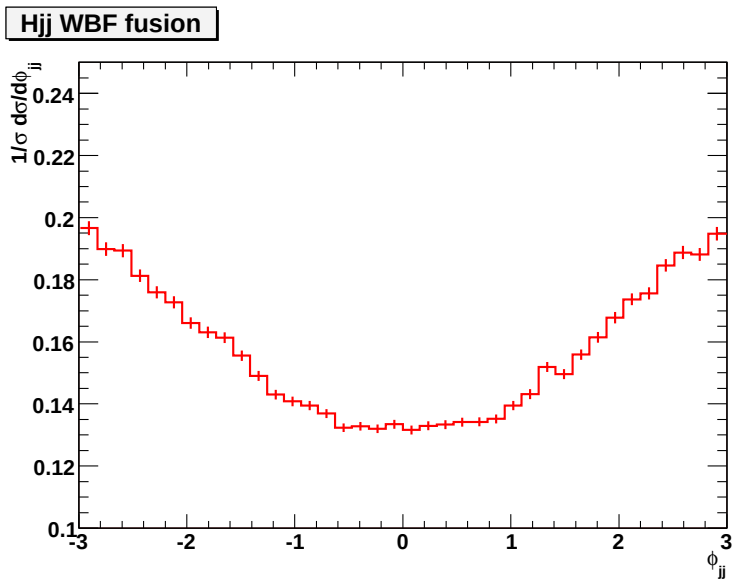
Andersen & JS hep-ph/0611281

Effect on the $\Delta\phi_{jj}$ Distribution

To study coupling, more interested in the $\Delta\phi_{jj}$ distribution.



Total Interference



Normalised WBF

This would be normalised by $(1.5\text{ pb})^{-1}$, so has a negligible effect.

Recap

- So far, have discussed Weak Boson Fusion and its use in the study of the HVV coupling.

- In order to do this, need precision calculations:
  - Weak Boson Fusion
  - Gluon-Gluon Fusion

    and
  - Interference between the two

One-Loop Accuracy

- Calculations to date:

Weak Boson Fusion:

QCD corrections	Djouadi, Spira, Zerwas	PLB 264:440-446
	Han, Valencia, Willenbrock	hep-ph/9206246
	Figy, Oleari, Zeppenfeld	hep-ph/0306109
	Berger, Campbell	hep-ph/0403194
EW corrections	Ciccolini, Denner, Dittmaier	arXiv:0710.4749

Gluon Gluon Fusion:

QCD corrections	Del Duca, Frizzo, Maltoni*	hep-ph/0404013
	Campbell, Ellis, Zanderighi*	hep-ph/0608194

* in heavy m_t limit.

Interference

- Calculations to date:

Crossed term interferences in:

Large m_t limit	Andersen, JS	hep-ph/0611281
Full theory (1-loop)	Ciccolini, Denner, Dittmaier	arXiv:0710.4749

Uncrossed terms:

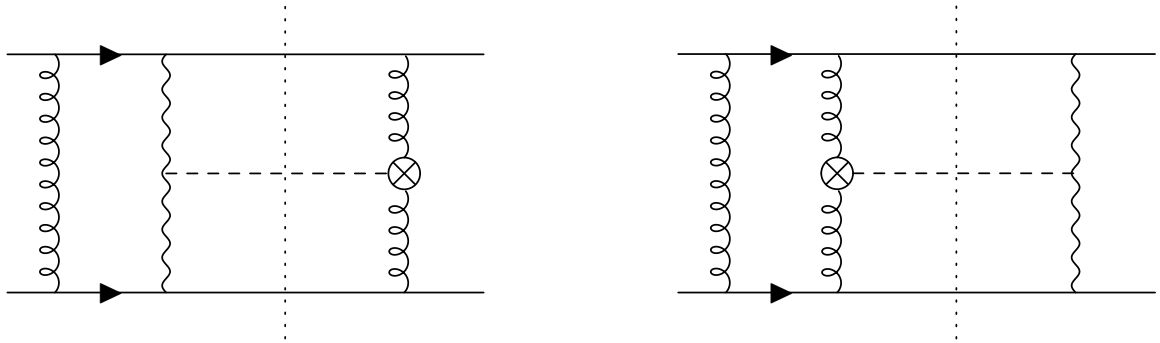
Large m_t limit (1-loop)	Andersen, Binoth, Heinrich, JS	arXiv:0709.3513
	Bredenstein, Hagiwara, Jäger	arXiv:0801.4231

Two completely different sets of diagrams:

Tree-level in large m_t limit is one-loop in full theory.

One Loop Interference

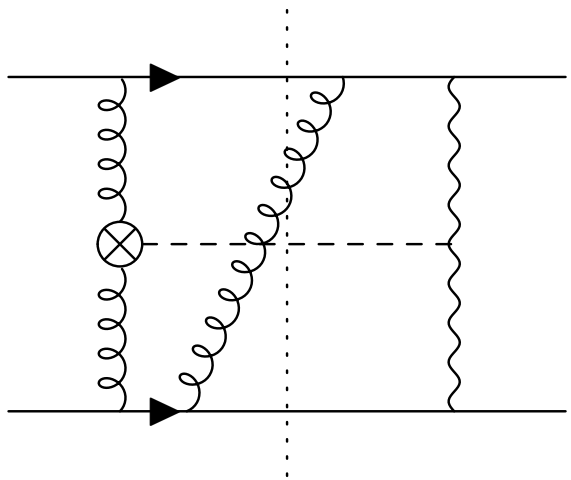
- We calculate diagrams of the form:



- There are four of each as each end of the 'extra' gluon can be attached on either side of the Z/g line.
- Notice that now we do not require identical quarks *or* a $t \leftrightarrow u$-channel crossing .
  This is leading order for non-identical quarks.

Real Emission Diagrams

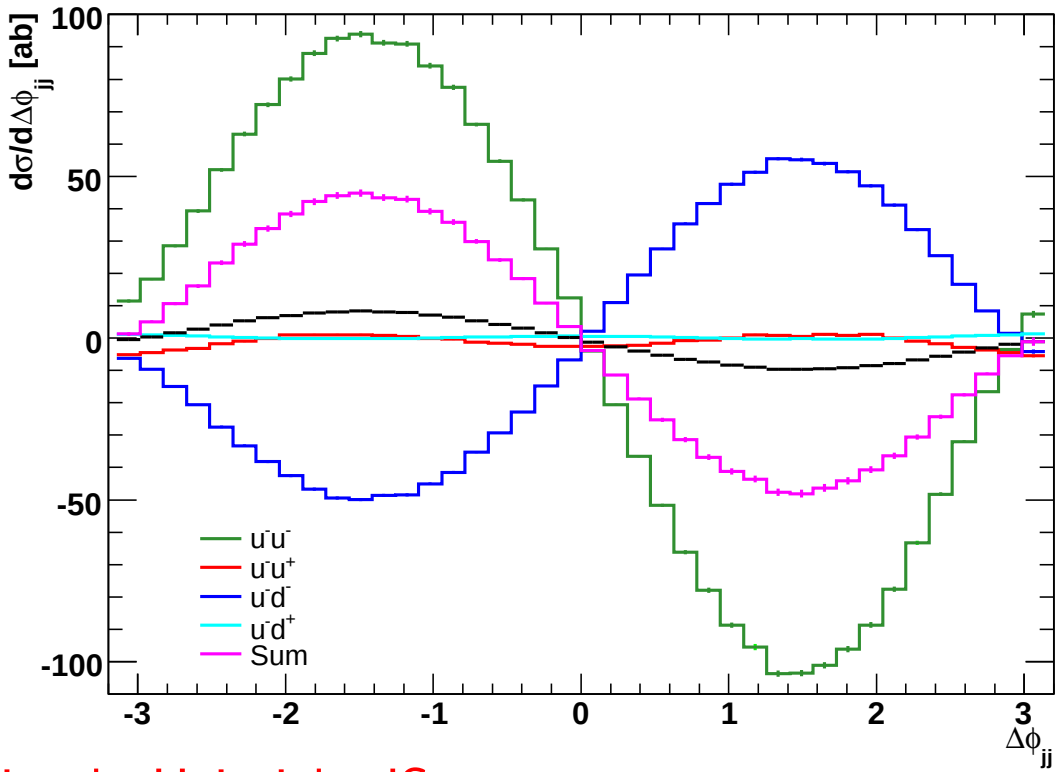
- Our leading poles (ϵ^{-2}) sum to zero but are left with poles in ϵ^{-1} which we must cancel with real emission diagrams:



- Note that the emitted gluon must join the upper and lower quark line to get non-zero colour factor.

Results

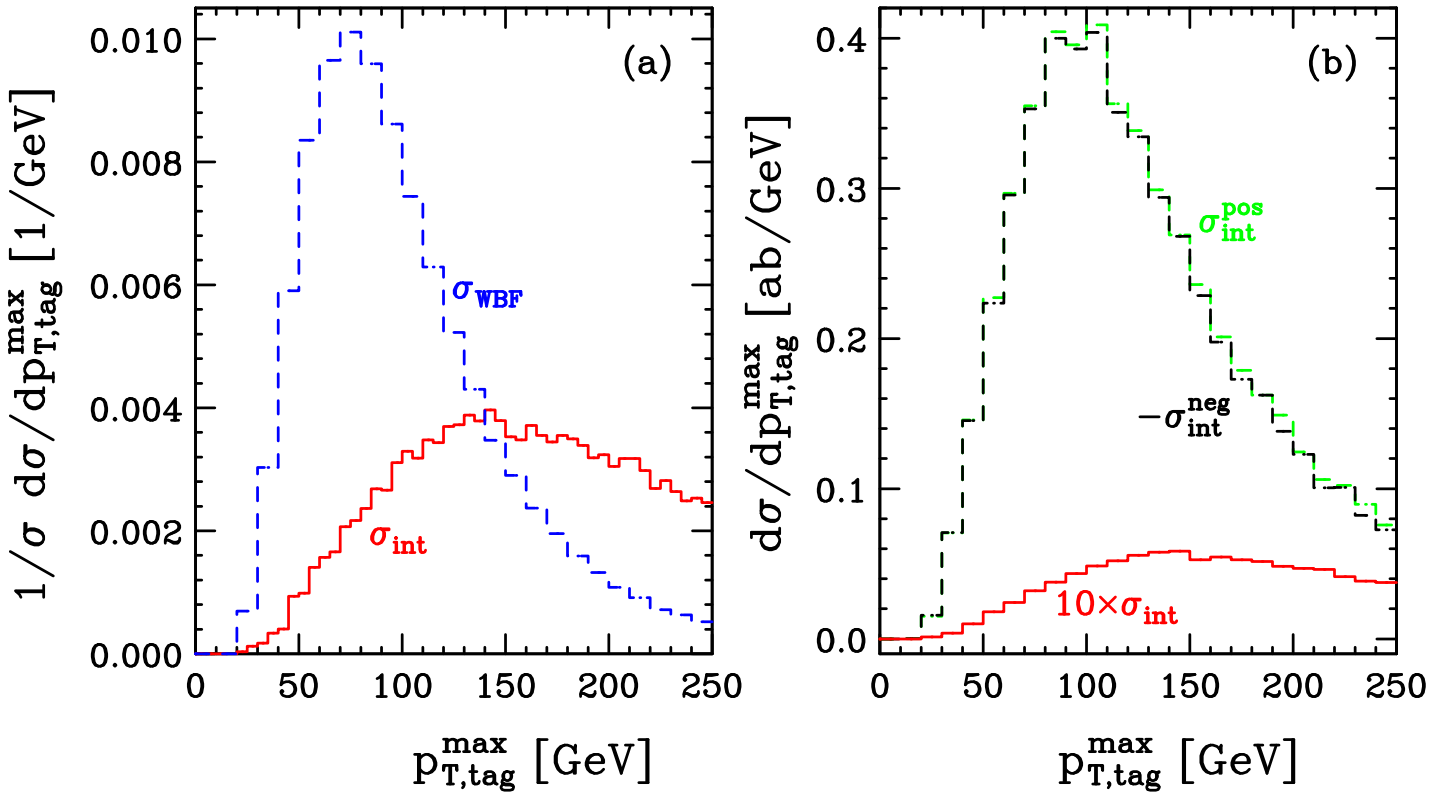
We find a small cross section, 1.19 ± 0.07 ab, but again the $\Delta\phi_{jj}$ distribution is more important, but still negligible:



Andersen, Binoth, Heinrich, JS: arXiv:0709.3513

Results

Similarly, the p_T distribution of the hardest jet for the interference contributions have a different shape, but negligible effect.



Bredenstein, Hagiwara, Jäger arXiv:0801.4231

Cancellations

- The cancellation between quark flavours occurs because the qqZ vertex has different sign for different quark flavours.

  Couplings are not always squared in interference effects.

- 20% suppression from each quark line.

- Additional cancellations between
  - helicity configurations
  - sea quark and valence quark contributions
  - phases from different diagrams

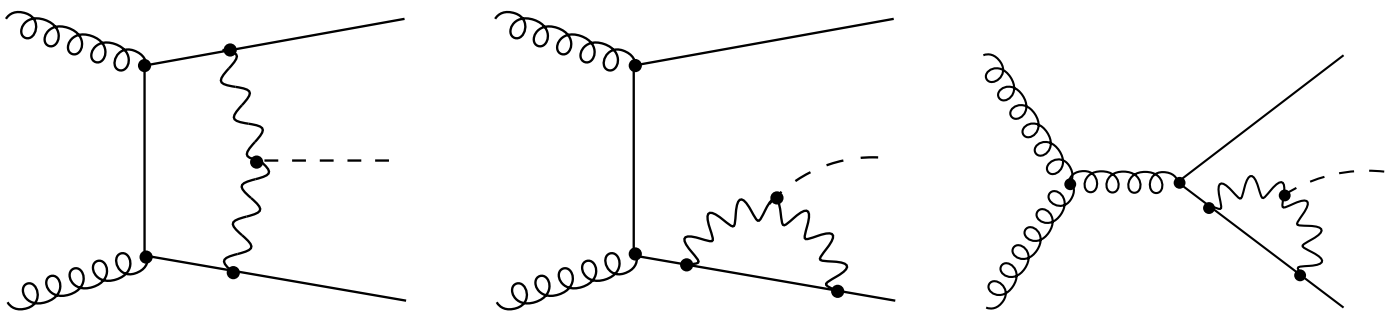
- Couldn't predict the weight of these effects without doing the calculation.

Towards NNLO

Part of the next-to-next-to leading order process has been calculated:

- $H + 3j$ at NLO — Figy, Hankele, Zeppenfeld arXiv:0710.5621
- 1-loop $\times$ 1-loop colour exchange diagrams with 1 quark line.

  E. g.,



Confirmed that all are suppressed by cuts.

Harlander, Vollinga, Weber arXiv:0801.3355

Conclusions

- Higgs boson production through Weak Boson Fusion will be an important channel to study electroweak symmetry breaking.
- Gluon-gluon fusion diagrams individually suppressed by cuts.
- The QCD-EW interference contributions do not affect the overall cross section or important distributions.
- Many higher order calculations of all these processes have been calculated.
- Can now be confident of the clean extraction of the HZZ/HWW vertex.