Double Higgs Coupling

The Measurement of Higgs Self-Coupling at the LHC: theoretical staus

J. Baglio, A. Djouadi, R. Grober, M.M. Muhlleitner,
J. Quevillon and M. Spira

Introduction

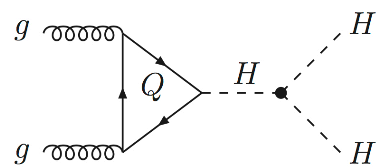
- Need to measure the Higgs self coupling
  - Only way to reconstruct scalar potential of the Higgs field.
  - Trilinear coupling in SM is uniquely related to the mass of the Higgs.

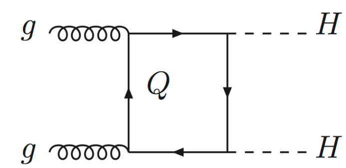
$$\lambda_{HHH} = \frac{3M_H^2}{v}$$

  - Four main classes to measure double Higgs production at colliders
    - Gluon fusion gg->HH
    - VBF
    - Double Higgs-strahlung qq' -> V^* -> VHH
    - pp -> ttHH production with a top quark pair
  - Double production is at least 2 orders of magnitude smaller than single production and not all double Higgs production involves the trilinear coupling.
  - Will look at NLO and NNLO corrections for these processes except: for VBF NNLO is negligible, and pp->ttHH is already complicated at LO.

Higgs Pairs at Higher Orders

- Gluon Fusion
  - Dominant process for pair production
    - ~ order of mag. Larger than VBF
  - LO cross section below





  - NLO calculated using Effective Field Theory by applying low energy theorem
    - Numerical evaluation done with HPAIR
  - K-factor = $\sigma_{LO}/\ \sigma_{NLO}(\ \alpha_{LO}\ /\ \alpha_{NLO}\ )$ ~ 2.0 (1.5) for $\sqrt{s}$ = 8 (100) TeV

$$\hat{\sigma}_{\rm LO}(gg \to HH) = \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t}\, \frac{G_F^2 \alpha_s^2(\mu_R)}{256(2\pi)^3} \left\{ \left| \frac{\lambda_{HHH}\, v}{\hat{s} - M_H^2 + i M_H \Gamma_H} F_\triangle + F_\Box \right|^2 + |G_\Box|^2 \right\},$$

where

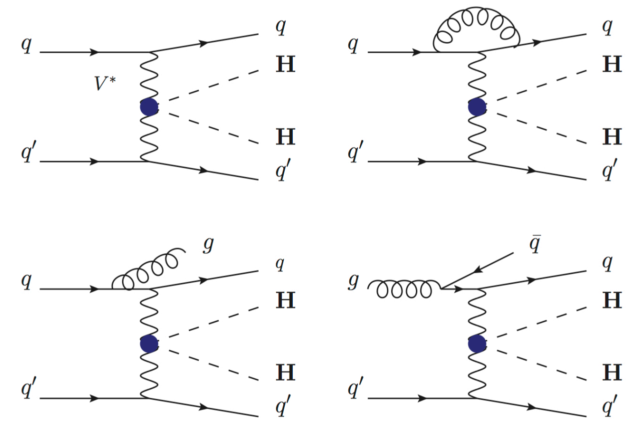
$$\hat{t}_\pm = -\frac{\hat{s}}{2}\left(1 - 2\frac{M_H^2}{\hat{s}} \mp \sqrt{1 - \frac{4M_H^2}{\hat{s}}}\right),$$

$$F_\triangle \to \frac{2}{3}, \quad F_\Box \to -\frac{2}{3}, \quad G_\Box \to 0$$

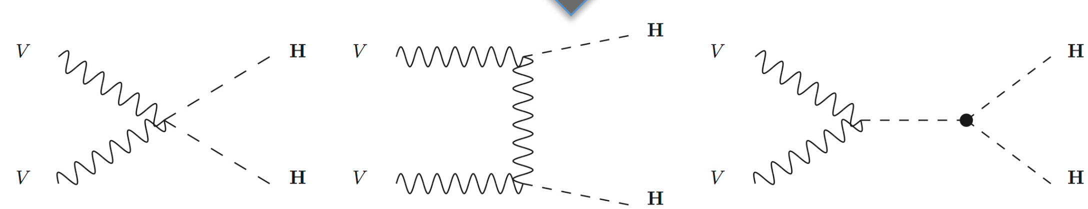
← Form factors approach constant values in the infinite top quark mass limit.

Higgs Pairs at Higher Orders

- Vector Boson Fusion
  - Structure function approach to calculate QCD corrections similar to single Higgs production
  - NLO corrections in analogy to single Higgs VBF
  - Notice only one vertex contributes to the trilinear coupling. Others are irreducible background.



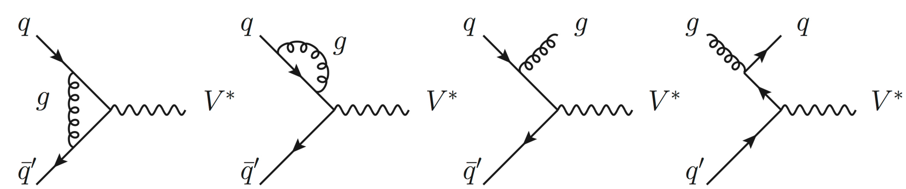
Possible vertex contributions to the blobs above



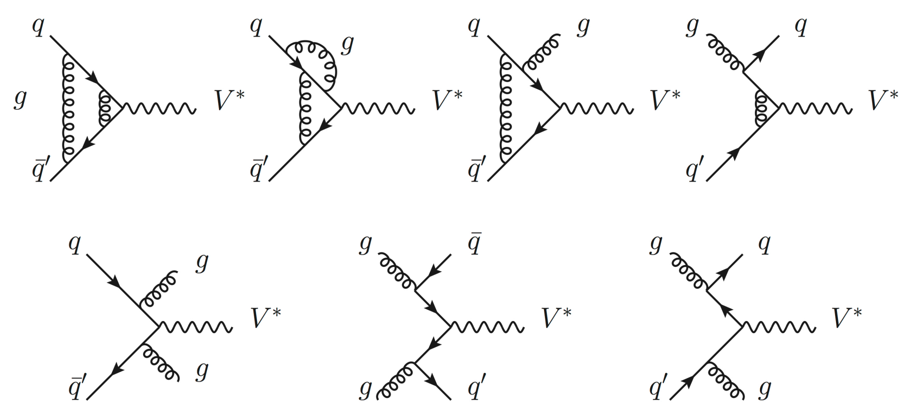
Higgs Pairs at Higher Orders

- Higgs-strahlung
  - Process can be viewed as the Drell-Yan production pp->V* followed by the splitting process V*->VHH.

NLO



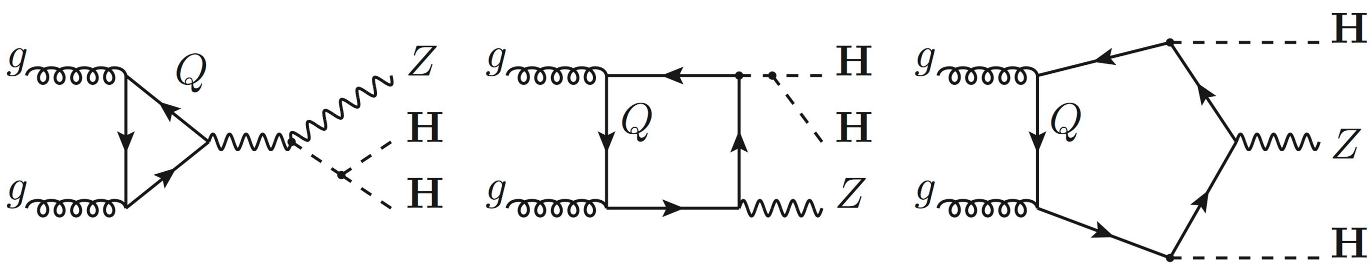
NNLO



$$\sigma^{\rm NNLO}(pp \to VHH) = \sigma^{\rm LO} + \Delta\sigma_{q\bar{q}} + \Delta\sigma_{qg} + \Delta\sigma_{q\bar{q}} + \Delta\sigma_{qg} + \Delta\sigma_{qq'} + \Delta\sigma_{qq} + \Delta\sigma_{gg} + \delta_{VZ}\Delta\sigma_{gg\to ZHH},$$

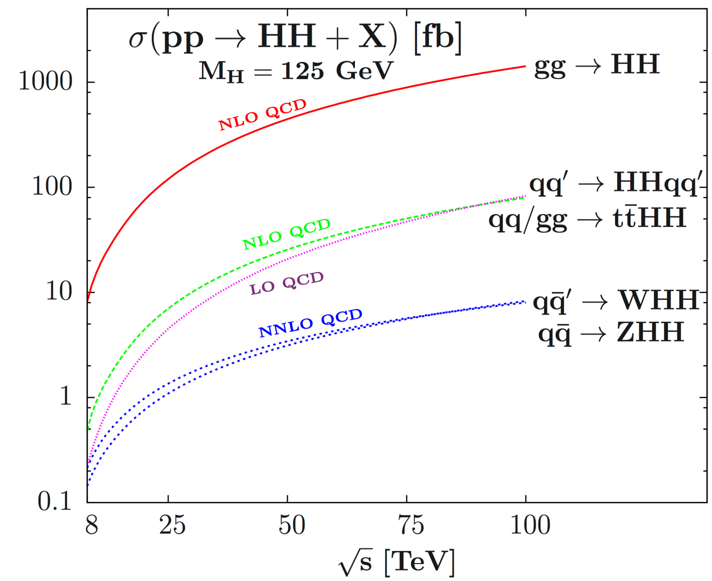
Higgs Pairs at Higher Orders

- Higgs-strahlung
  - The last contribution to the cross section from gg->ZHH adds between +20% - +30%. (In single Higgs production this only adds ~+5%)
    - This is because of the additional pentagon topology which involves two top Yukawa couplings and eliminates some of the interference between the triangle and box topologies.



Cross Sections and Sensitivity at the LHC

- Total cross sections



$$\mu_0^{gg\to HH} = M_{HH},\ \ \mu_0^{qq'\to Hqq'} = Q_{V^*},\ \ \mu_0^{q\bar{q}'\to VHH} = M_{VHH},\ \ \mu_0^{q\bar{q}/gg\to t\bar{t}HH} = M_t + M_H.$$

$$M_W = 80.398\ \text{GeV},\quad M_Z = 91.1876\ \text{GeV},\quad M_t = 173.1\ \text{GeV},$$

$$\alpha_s^{\text{LO}}(M_Z^2) = 0.13939,\quad \alpha_s^{\text{NLO}}(M_Z^2) = 0.12018,\quad \alpha_s^{\text{NNLO}}(M_Z^2) = 0.11707$$

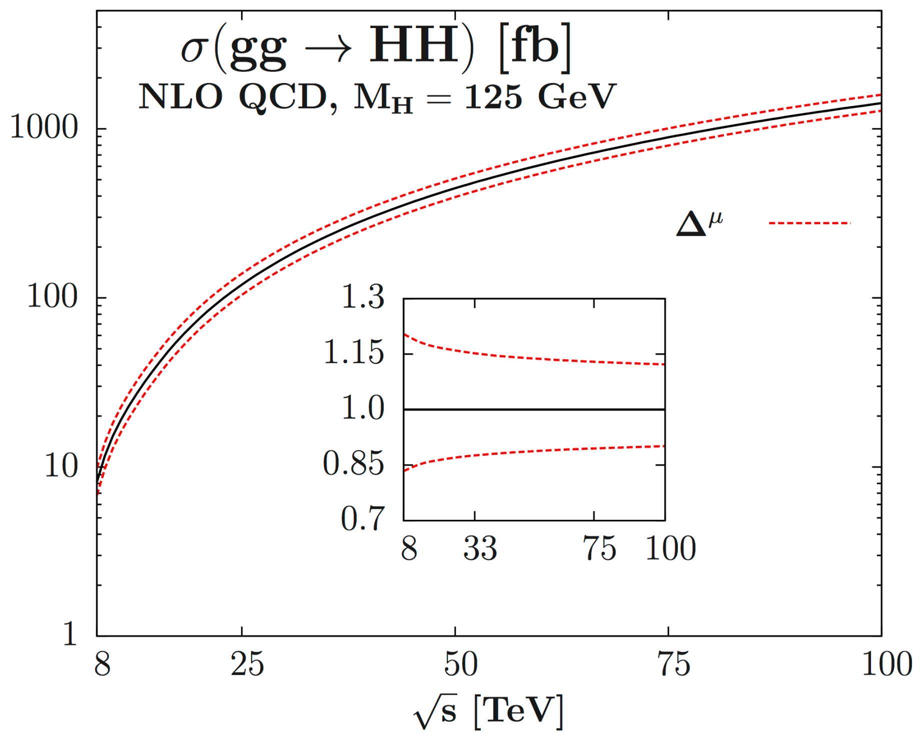
$\sqrt{s}$ [TeV]	$\sigma^{\text{NLO}}_{gg\to HH}$ [fb]	$\sigma^{\text{NLO}}_{qq'\to HHqq'}$ [fb]	$\sigma^{\text{NNLO}}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\text{NNLO}}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\text{LO}}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.22
14	33.89	2.01	0.57	0.42	1.09
33	207.29	12.05	1.99	1.68	8.37
100	1417.83	79.55	8.00	8.27	82.69

Cross Sections and Sensitivity at the LHC

- Theory Uncertainties in gluon fusion
  - Higher order corrections
  - Vary μ_R , μ_F to estimate error

$$\frac{1}{2}\mu_0 \leq \mu_R = \mu_F \leq 2\,\mu_0.$$

Δ^μ of order ~ +20% / -17% at 8 Tev
+12%/ -10% at 100 Tev

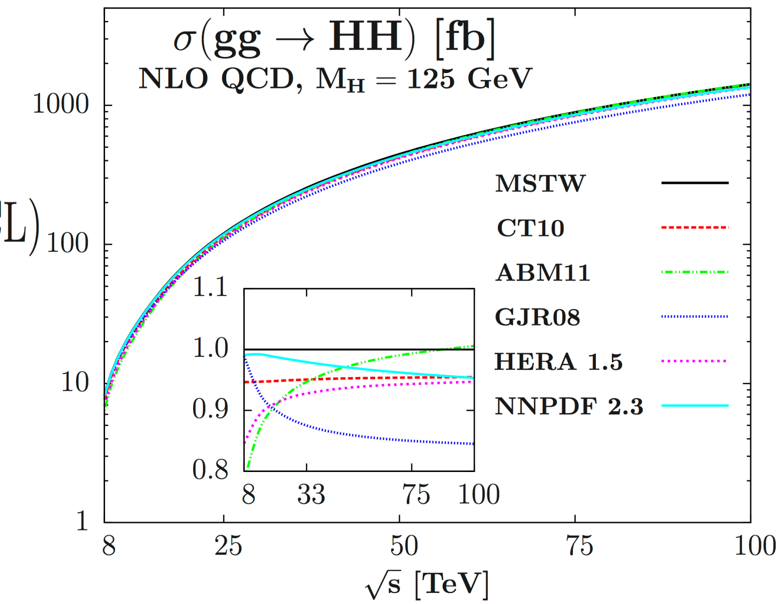


Not surprising because NNLO QCD corrections for the top loop are not known for the gg->HH process

Cross Sections and Sensitivity at the LHC

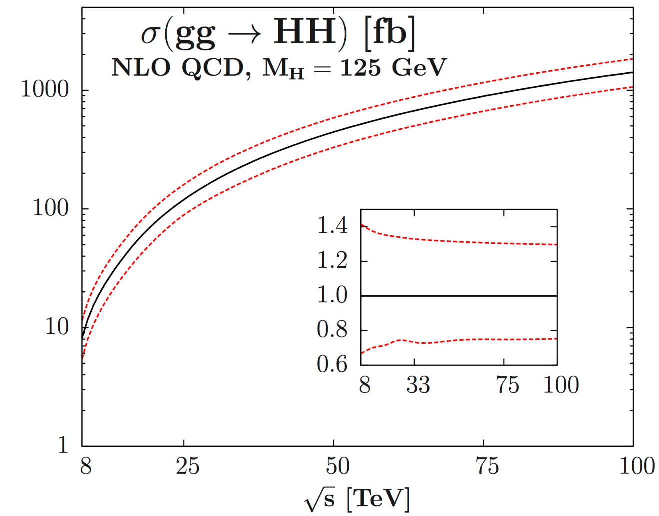
- PDF and α_s error
  - Theoretical uncertainties depending on which PDF is used due to assumptions in parameterization.
  - There is an additional ~6% (8TeV) - ~2% (100TeV) error due to the fits used on the experimental data
  - MSTW also puts errors on α_s

$$\alpha_s(M_Z) = 0.12018^{+0.00122}_{-0.00151}(\text{at } 68\% \text{ CL}) \text{ or } {}^{+0.00317}_{-0.00386} \ (\text{at } 90\% \text{ CL})$$



Cross Sections and Sensitivity at the LHC

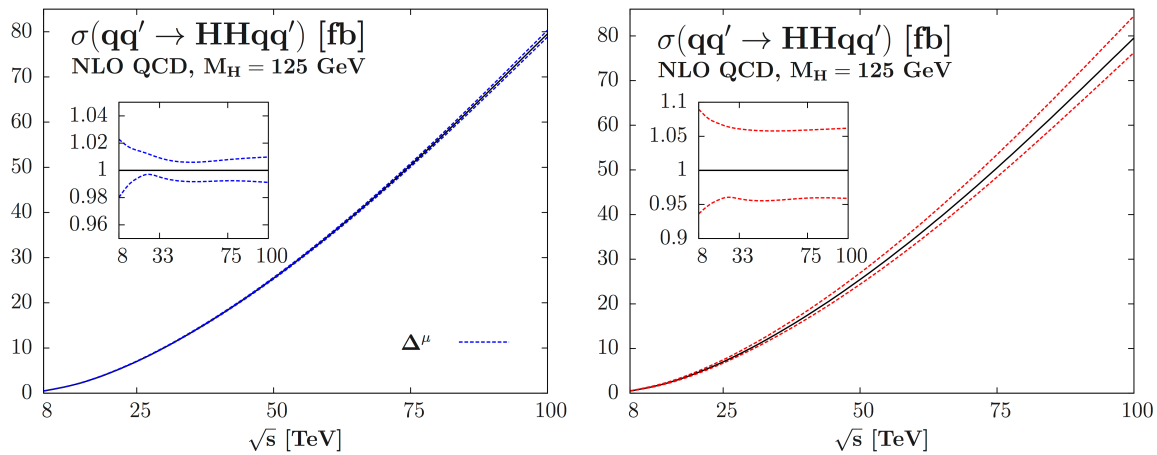
- Total Uncertainties
  - Totals are obtained using a procedure detailed in ref [57]. Adding in quadrature is too optimistic and adding linearly is too conservative so a combination is used.



$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	Scale [%]		PDF [%]		PDF+α_s [%]		EFT [%]	Total [%]	
8	8.16	+20.4	−16.6	+5.8	−6.0	+8.5	−8.3	±10.0	+41.5	−33.3
14	33.89	+18.2	−14.7	+3.9	−4.0	+7.0	−6.2	±10.0	+37.2	−29.8
33	207.29	+15.2	−12.4	+2.5	−2.7	+6.2	−5.4	±10.0	+33.0	−26.7
100	1417.83	+12.2	−9.9	+2.0	−2.7	+6.2	−5.7	±10.0	+29.7	−24.7

Cross Sections and Sensitivity at the LHC

- VBF total uncertainties
  - All calculated in a similar manner to gluon fusion



$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{NLO}}_{qq'HH}$ [fb]	Scale [%]		PDF [%]		PDF+α_s [%]		Total [%]	
8	0.49	+2.3	−2.0	+5.2	−4.4	+6.7	−4.4	+9.0	−6.4
14	2.01	+1.7	−1.1	+4.6	−4.1	+5.9	−4.1	+7.6	−5.1
33	12.05	+0.9	−0.5	+4.0	−3.7	+5.2	−3.7	+6.1	−4.2
100	79.55	+1.0	−0.9	+3.5	−3.2	+5.2	−3.2	+6.2	−4.1

Cross Sections and Sensitivity at the LHC

- Even more tables of errors. This time Higgs pair production with an associated vector boson.

qq->WHH

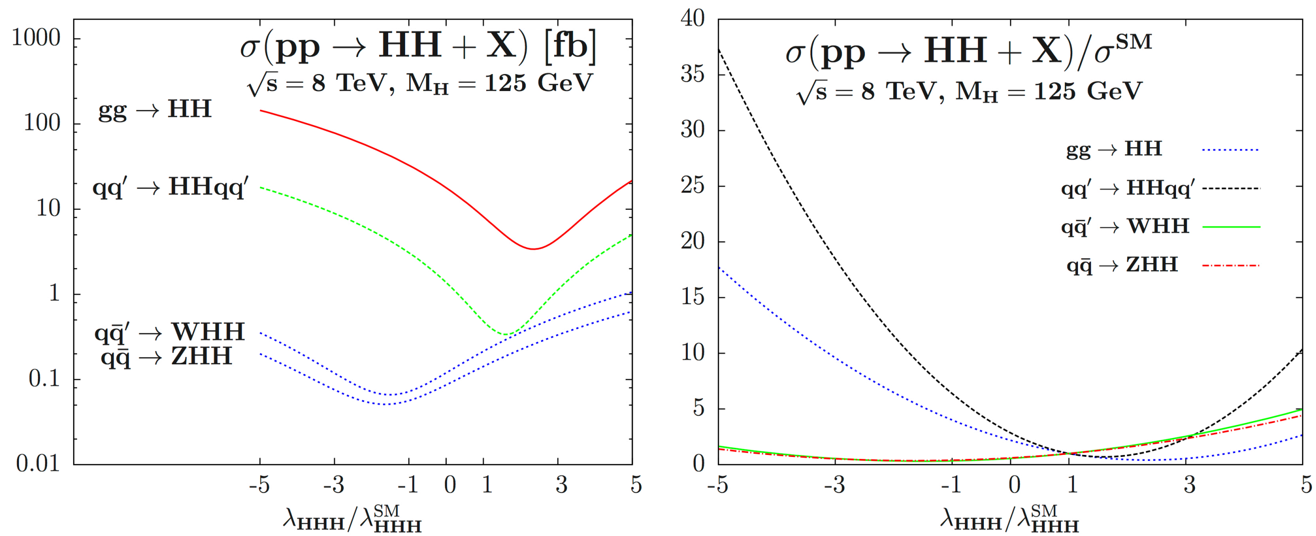
$\sqrt{s}$ [TeV]	σ_{WHH}^{NNLO} [fb]	Scale [%]		PDF [%]		PDF+α_s [%]		Total [%]	
8	0.21	+0.4	−0.5	+4.3	−3.4	+4.3	−3.4	+4.7	−4.0
14	0.57	+0.1	−0.3	+3.6	−2.9	+3.6	−3.0	+3.7	−3.3
33	1.99	+0.1	−0.1	+2.9	−2.5	+3.4	−3.0	+3.5	−3.1
100	8.00	+0.3	−0.3	+2.7	−2.7	+3.8	−3.4	+4.2	−3.7

qq->ZHH

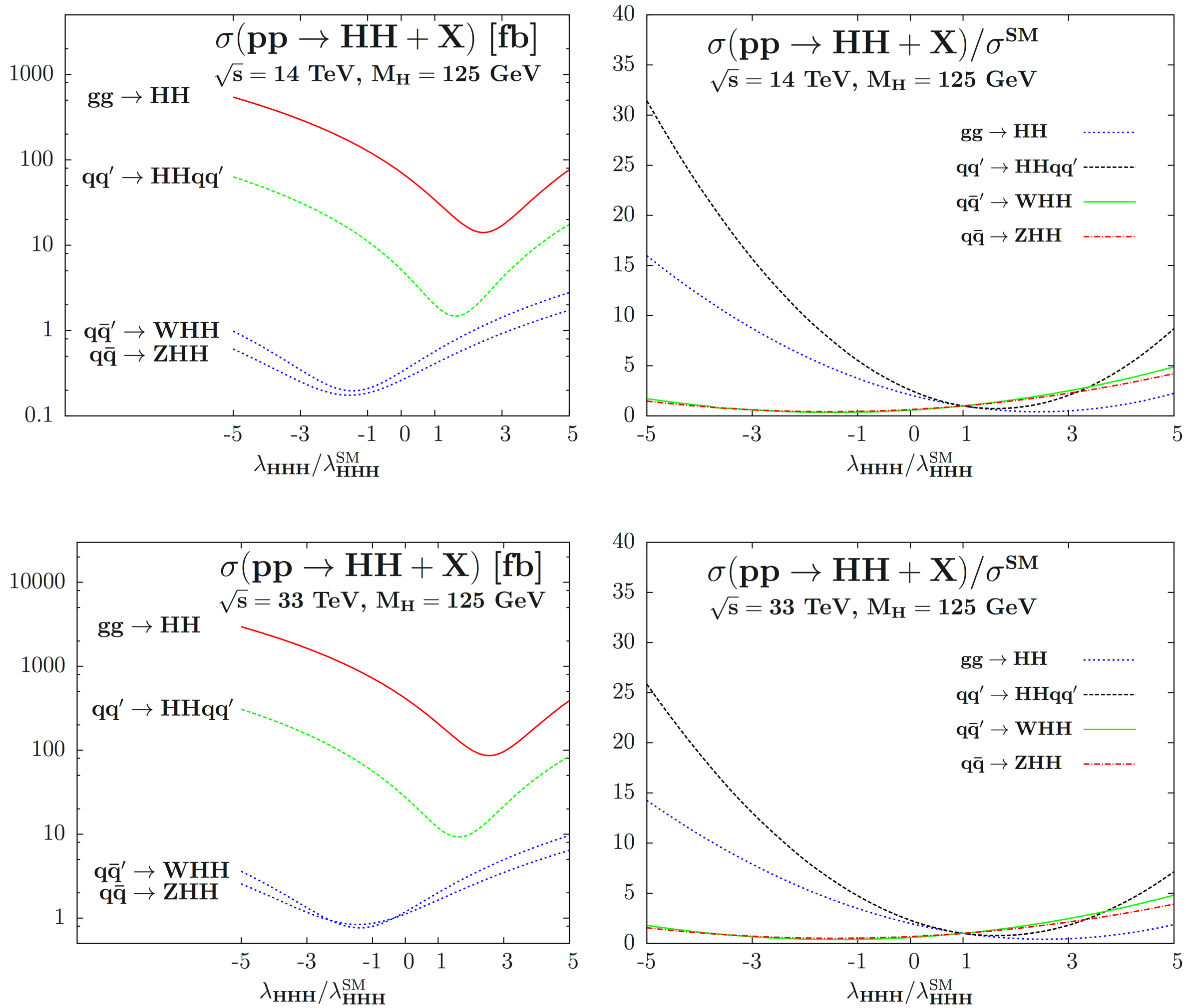
$\sqrt{s}$ [TeV]	σ_{ZHH}^{NNLO} [fb]	Scale [%]		PDF [%]		PDF+α_s [%]		Total [%]	
8	0.14	+3.0	−2.2	+3.8	−3.0	+3.8	−3.0	+6.8	−5.3
14	0.42	+4.0	−2.9	+2.8	−2.3	+3.0	−2.6	+7.0	−5.5
33	1.68	+5.1	−4.1	+1.9	−1.5	+2.7	−2.6	+7.9	−6.7
100	8.27	+5.2	−4.7	+1.9	−2.1	+3.2	−3.2	+8.4	−8.0

Cross Sections and Sensitivity at the LHC

- Sensitivity to the trilinear Higgs coupling
  - Rescale the λ_{HHH} coupling in terms of the SM coupling
    - $\lambda_{HHH} = \kappa\lambda^{SM}_{HHH}$
  - Most sensitive channel is VBF through most of the κ range



Cross Sections and Sensitivity at the LHC



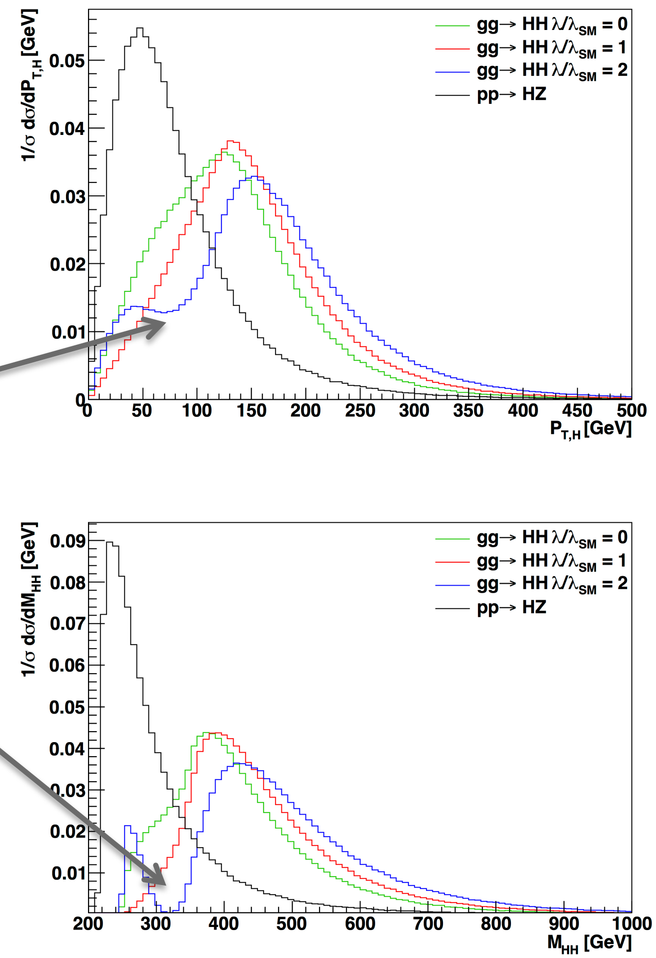
Prospects at the LHC

- Since it is the dominant process, focus on gluon fusion.
  - Examine channels $gg \to HH \to b\overline{b\gamma\gamma}$, $gg \to HH \to b\bar{b}\tau^+\tau^-$, $gg \to HH \to b\bar{b}W^*W^*$
  - Assume branching ratios of 57.7% for H to b quarks, 0.228% for H to photon pair, 6.12% for H to tau pair, 21.5% for H to W^*W^*

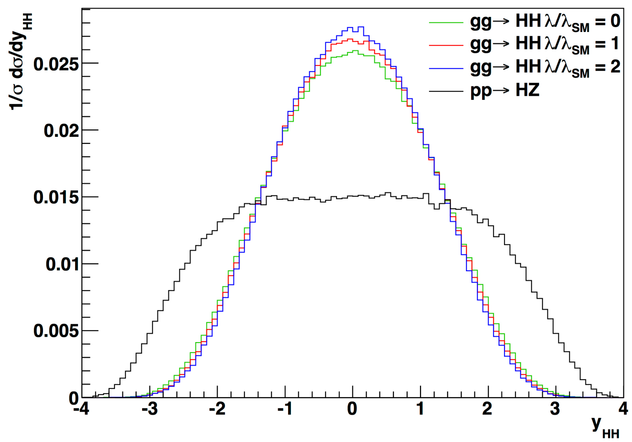
Prospects at the LHC

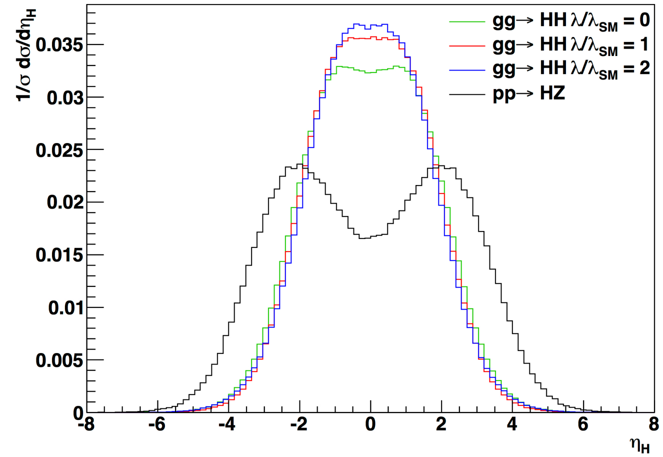
- Kinematical distributions of gg->HH

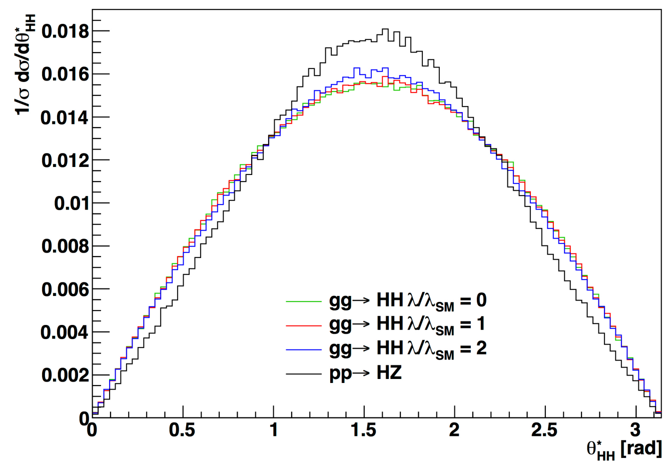
Interference between box and triangle topologies



Prospects at the LHC







Prospects at the LHC

- $bb\gamma\gamma$ channel
  - Include NLO QCD corrections on signal by multiplicative factor K=1.88
  - Veto on events with soft leptons (< 20 GeV) and $|\eta| < 2.4$ to reduce the ttH background. Also require exactly one b and photon pair with the b's having P_T > 30 GeV and isolation > 0.4 (in $\eta-\phi$). Same for photons.

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	ZH	S/B	$S/\sqrt{B}$
Cross-section NLO [fb]	8.92×10^{-2}	5.05×10^{3}	1.39	3.33×10^{-1}	1.77×10^{-5}	6.87×10^{-2}
Reconstructed Higgs from bs	4.37×10^{-2}	4.01×10^{2}	8.70×10^{-2}	1.24×10^{-3}	1.09×10^{-4}	1.20×10^{-1}
Reconstructed Higgs from γs	3.05×10^{-2}	1.78	2.48×10^{-2}	3.73×10^{-4}	1.69×10^{-2}	1.24
Cut on M_{HH}	2.73×10^{-2}	3.74×10^{-2}	7.45×10^{-3}	1.28×10^{-4}	6.07×10^{-1}	7.05
Cut on $P_{T,H}$	2.33×10^{-2}	3.74×10^{-2}	5.33×10^{-3}	1.18×10^{-4}	5.44×10^{-1}	6.17
Cut on η_H	2.04×10^{-2}	1.87×10^{-2}	3.72×10^{-3}	9.02×10^{-5}	9.06×10^{-1}	7.45
Cut on $\Delta R(b,b)$	1.71×10^{-2}	0.00	3.21×10^{-3}	7.44×10^{-5}	5.21	16.34
"Detector level"	1.56×10^{-2}	0.00	8.75×10^{-3}	8.74×10^{-3}	8.92×10^{-1}	6.46

Cross-section at 14TeV c.m.e. for 3000 fb^{-1} int. luminosity

Prospects at the LHC

Bbττ Channel

- Similar cuts to the last slide plus P_T of the Higgs must be > 100 GeV. Also require that M_{bb} be within 25 GeV of the Higgs mass, $M_{\tau\tau}$ be within 50 GeV (25 GeV optimistic). In addition, apply more advanced cuts based on kinematic distributions.

	HH	$b\bar{b}\tau^+\tau^-$	$b\bar{b}\tau^+\tau^-\nu_\tau\bar{\nu}_\tau$	ZH	S/B	$S/\sqrt{B}$
Cross-section NLO [fb]	2.47	2.99×10^4	8.17×10^3	2.46×10^1	6.48×10^{-5}	6.93×10^{-1}
Reconstructed Higgs from τs	2.09×10^{-1}	8.35×10^1	1.58×10^2	5.70×10^{-1}	8.63×10^{-4}	7.36×10^{-1}
Reconstructed Higgs from bs	1.46×10^{-1}	6.34×10^{-1}	1.43×10^1	3.75×10^{-2}	9.75×10^{-3}	2.07
Cut on M_{HH}	1.30×10^{-1}	1.37×10^{-1}	1.74	1.26×10^{-2}	6.88×10^{-2}	5.18
Cut on $P_{T,H}$	1.10×10^{-1}	7.80×10^{-2}	7.17×10^{-1}	1.15×10^{-2}	1.36×10^{-1}	6.71
With $112.5 < M_{\tau\tau} < 137.5$	1.10×10^{-1}	3.41×10^{-2}	3.76×10^{-1}	3.15×10^{-3}	2.67×10^{-1}	9.37

25 GeV Optimistic case

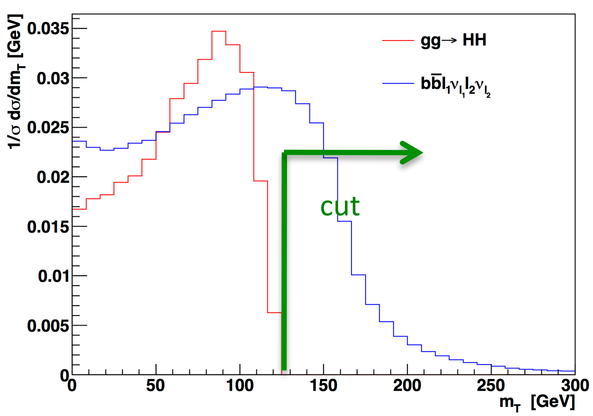
At 300 fb^{-1} 14 TeV, expect 33 events with significance 2.96 in the optimistic case

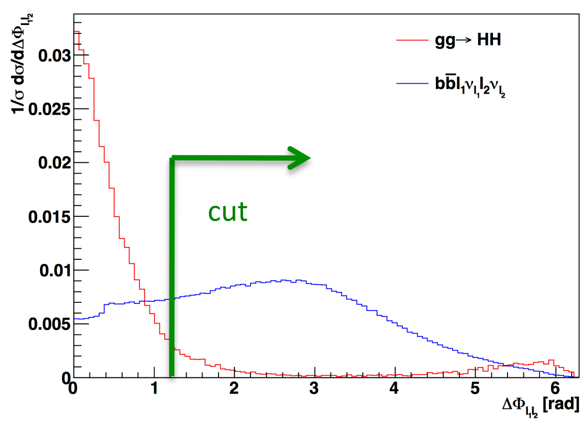
Prospects at the LHC

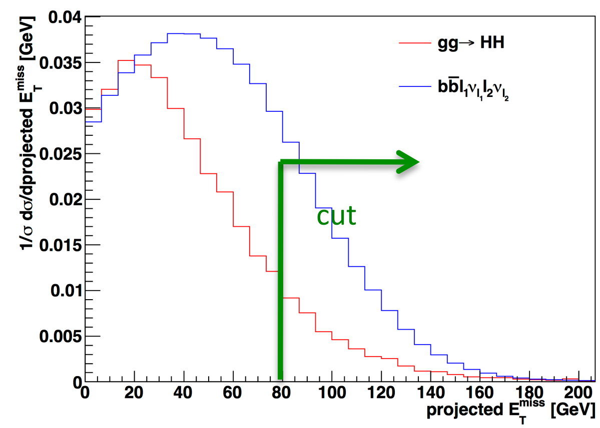
- bbWW channel
  - Only consider W-> $l\nu_l$ with a BR of 10.8%
  - Again similar cuts now with E_t^{miss} > 20 GeV and kinematic cuts.

$$M_T = \sqrt{2p_T^{\ell\ell}E_T^{miss}(1-\cos\Delta\phi(E_T^{miss},\ell\ell))}$$

$$\tilde{E}_T^{miss} = E_T^{miss}\sin\Delta\phi(E_T^{miss},\ell)$$







Prospects at the LHC

- bbWW channel

	HH	$b\bar{b}l_1\nu_{l_1}l_2\nu_{l_2}$	S/B	$S/\sqrt{B}$
Cross-section NLO [fb]	3.92×10^{-1}	2.41×10^{4}	1.63×10^{-5}	1.38×10^{-1}
Reconstructed Higgs from bs	6.18×10^{-2}	1.89×10^{2}	3.27×10^{-4}	2.46×10^{-1}
Cut on M_T	$6.18. \times 10^{-2}$	1.19×10^{2}	5.19×10^{-4}	3.10×10^{-1}
Cut on $\Delta\phi_{\ell_1\ell_2}$	5.37×10^{-2}	6.96×10^{1}	7.72×10^{-4}	3.53×10^{-1}
Cut on $\Delta\theta_{\ell_1\ell_2}$	5.17×10^{-2}	5.65×10^{1}	9.15×10^{-4}	3.77×10^{-1}
Cut on E_T^{miss}	8.41×10^{-3}	3.77×10^{-1}	2.22×10^{-2}	7.50×10^{-1}
Cut on $\tilde{E}_T^{miss}$	4.59×10^{-3}	2.70×10^{-2}	1.70×10^{-1}	1.53

Not great