

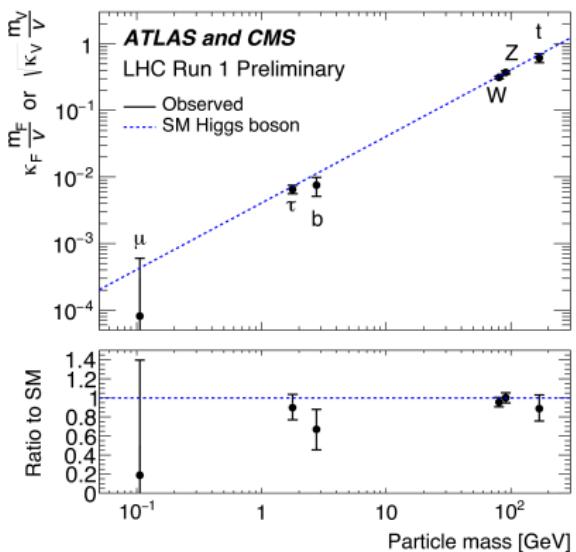
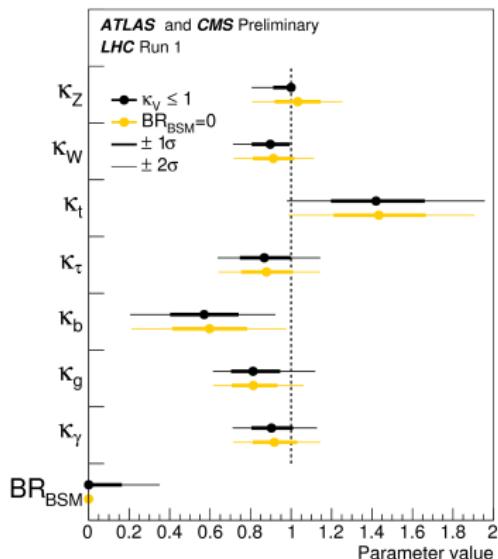
# Higgs Physics in the Singlet Extended Standard Model

Ian Lewis  
University of Kansas

arXiv:1605.04944 S. Dawson, **IL**  
o Phys. Rev. D92 (2015) 094023 S. Dawson, **IL**

August 18, 2016  
Loopfest XV  
University at Buffalo

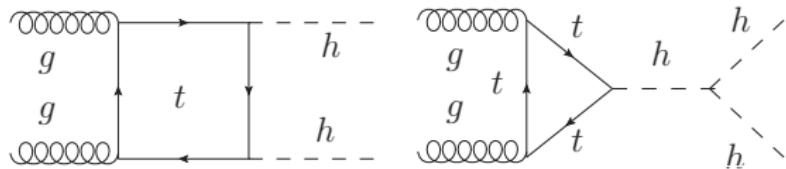
# Observed Scalar Remarkably Standard Model Like



ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

- "κ" scheme:  $\kappa_j^2 = \sigma_j / \sigma_j^{SM}$  or  $\kappa_j^2 = \Gamma_j^j / \Gamma_{SM}^j$
- With Higgs mass known, SM completely predictive.

# Double Higgs Production

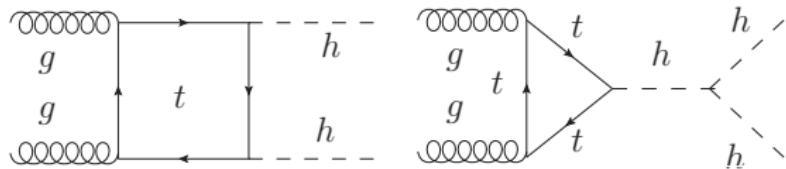


- Higgs potential has two terms:

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- Know mass:  $m_h^2 = 125$  GeV
- Know vev:  $v = 246$  GeV
- Standard Model potential completely determined:  $\mu = 88$  GeV,  $\lambda = 0.13$
- Measuring trilinear coupling tests electroweak symmetry breaking mechanism.

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- Measuring trilinear coupling tests electroweak symmetry breaking mechanism.
- Recently calculated to next-to-leading order in QCD with full top quark mass dependence. Cross sections at 13 TeV:

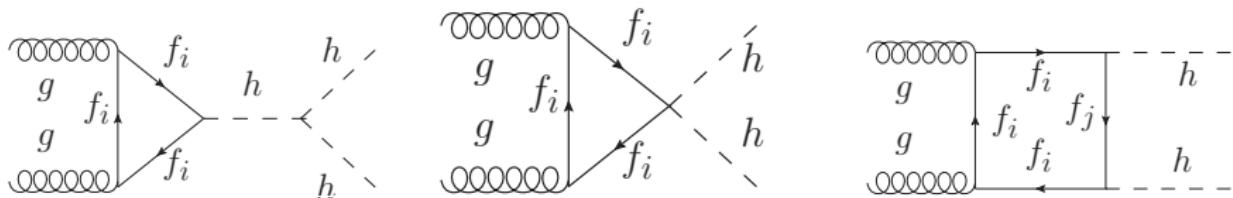
Borowka, *et al.*, PRL 117 (2016) 012001

- $\sigma^{NLO} = 27.80^{+13.8\%}_{-12.8\%} \text{ fb} \pm 0.3\% \text{ (stat.)} \pm 0.1\% \text{ (int.)}$

# New Physics in Double Higgs production

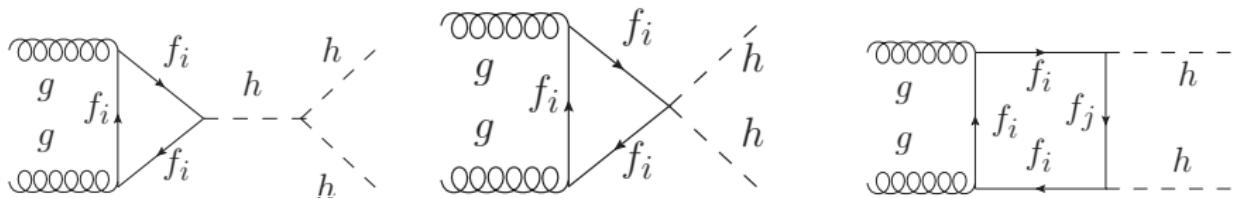
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  - Exact cancellation between box and triangle diagrams at double Higgs threshold.
- Potentially sensitive to new physics.

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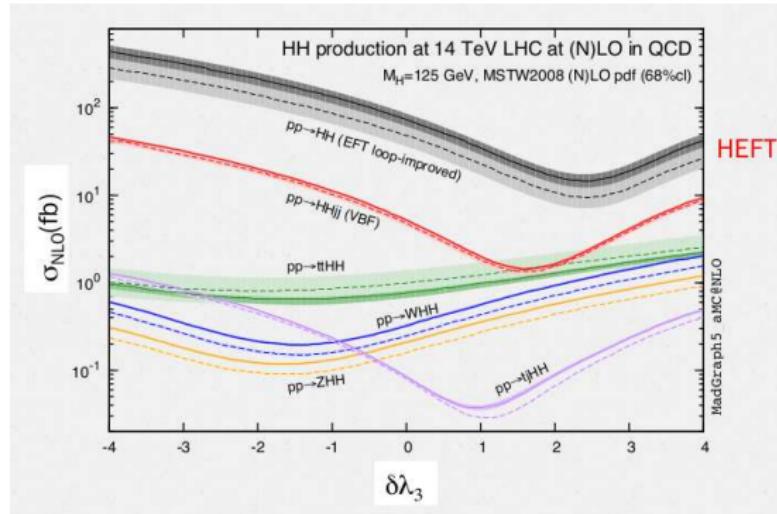
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  - Can have new colored particle couple to Higgs and run in loop.
    - Double Higgs production sensitive to different couplings than single Higgs.
    - For heavy colored states, difficult to have appreciable changes in rate  
[Dawson, Furlan, IL PRD87 \(2013\) 014007](#), [Chen, Dawson, IL PRD90 \(2014\) 035016](#)
  - Maybe have fine-tuned light colored scalars  
[Batell, McCullough, Stolarski, Verhaaren JHEP 1509 \(2015\) 216](#); [Kribs, Martin PRD86 \(2012\) 095023](#).

# New Physics in Double Higgs production



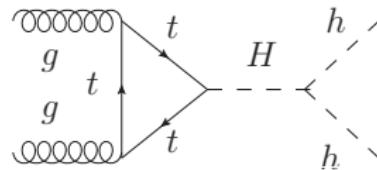
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[Batell, McCullough, Stolarski, Verhaaren JHEP 1509 \(2015\) 216](#); [Kribs, Martin PRD86 \(2012\) 095023](#).
  - New physics in Higgs potential can shift trilinear coupling.
  - Resonant production of double Higgs production.

# Shifted Trilinear Coupling



- ATLAS project  $1.3\sigma$  significance of Higgs pair production with  $3 \text{ ab}^{-1}$  in the  $b\bar{b}\gamma\gamma$  channel [ATL-PHYS-PUB-2014-019](#)
  - Limit  $-1.3 \lesssim \lambda/\lambda_{SM} \lesssim 8.7$
- CMS project  $1.9\sigma$  significance for double Higgs pair production for  $bb\gamma\gamma, bb\tau\tau, bbWW$  [CMS PAS FTR-15-002](#)
- Can maybe do better if optimize for non-SM trilinear couplings or use distributions  
Huang, Joglekar, Li, Wagner PRD93 (2016) 055049; Kling, Plehn, Schichtel arXiv:1607.07441

# Resonant Production



- Resonant production has chance to give a large enhancement to double Higgs production.
- Adding a scalar singlet to the SM is the simplest extension of the SM.
  - Can give rise to this interaction.
- Well-motivated.
  - Can be responsible for a strong first order phase transition.
  - In general, difficult to eliminate Higgs portal:  $\Phi^\dagger \Phi S^2$

# SCALAR SINGLET

# $Z_2$ Symmetric Limit

- Introduce a real scalar  $S$  that is a singlet under the SM gauge group.
- Introduce  $Z_2$  parity:  $S \rightarrow -S$  and  $SM \rightarrow SM$ .
- Renormalizable coupling to SM through Scalar potential:

$$V(\Phi, S) = -\mu^2 \Phi^\dagger \Phi - m^2 S^2 + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_2}{2} \Phi^\dagger \Phi S^2 + \frac{b_4}{4} S^4$$

- $\Phi = (0, \frac{v+h_{SM}}{\sqrt{2}})^T$ : SM Higgs doublet.

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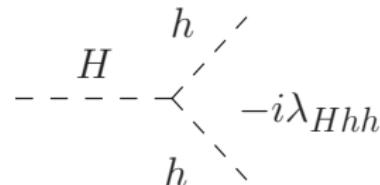
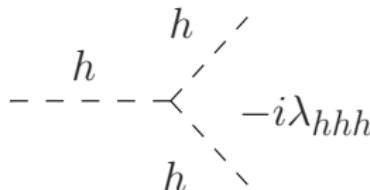
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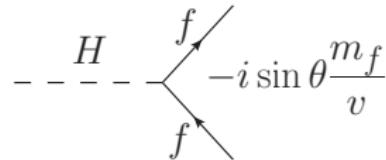
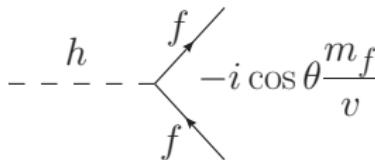
- $\Phi = (0, \frac{v+h_{SM}}{\sqrt{2}})^T$ : SM Higgs doublet.
- Two mass eigenstates:
  - $h$  with mass  $m_h = 125$  GeV
  - $H$  with mass  $M_H > m_h$
- 5 degrees of freedom:
  - Two masses:  $m_h, M_H$
  - Mixing angle between scalars:  $\theta$ :
    - $h = \cos \theta h_{SM} - \sin \theta s$
    - $H = \sin \theta h_{SM} + \cos \theta s$
  - Two vevs:  $v = 246$  GeV,  $\langle S \rangle = x/\sqrt{2}$ , and  $\tan \beta = v/x$ .

# Relevant Feynman Diagrams

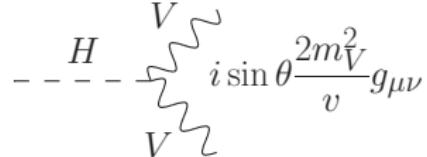
- Trilinear couplings:



- Couplings to fermions:

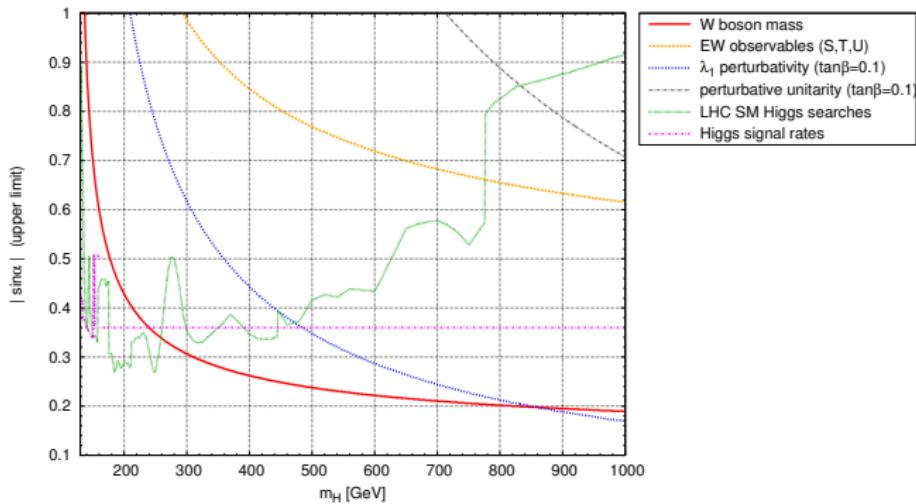


- Couplings to gauge bosons:



- Since  $H$  couplings to fermions and gauge bosons proportional to SM coupling, it is produced through same mechanisms as SM Higgs boson.

# Current Limits



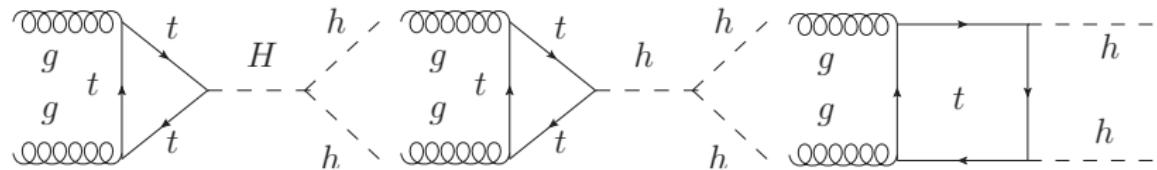
Robens, Stefaniak EPJ C76 (2016) 268

- Limits on  $\tan \beta = \sqrt{2}v/\langle S \rangle$  come from perturbativity ( $\sin \theta = 0.1$ )  
Stefaniak, Robens EPJ C75 (2015) 104
  - for  $M_H = 200$  GeV  $\tan \beta \lesssim 1.5$
  - for  $M_H = 500$  GeV  $\tan \beta \lesssim 0.5$
- See also Falkowski, Gross, Lebedev JHEP 1505 (2015) 057; Buttazzo, Sala, Tesi JHEP 1511 (2015) 158

# Status of Single Production Calculation

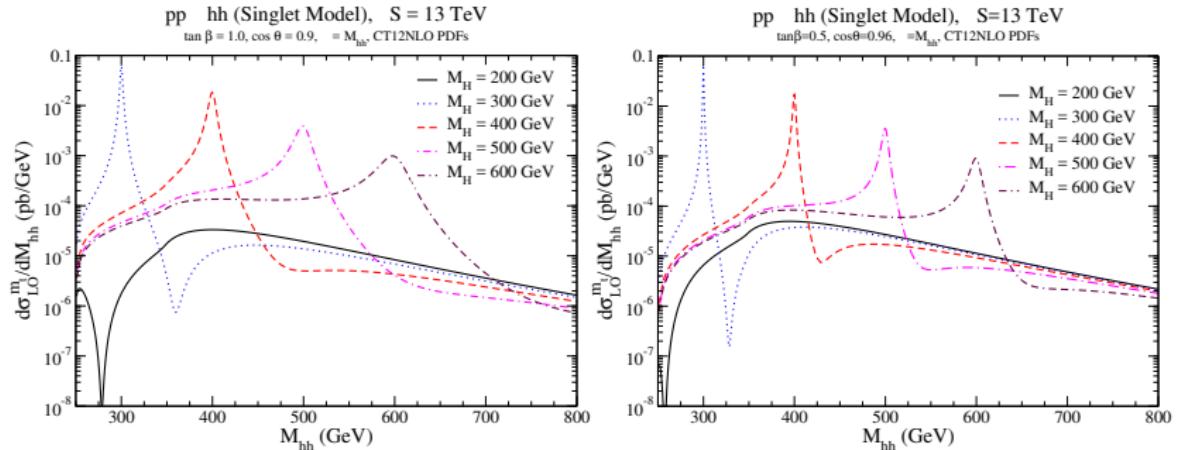
- $N^3LO$  known for gluon fusion  
[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberg, arXiv:1605.05761](#)
  - Scalar production at many different masses.
- $NNLO$  color singlet implemented into MCFM  
[Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams, arXiv:1605.08011](#)
- Heavy to light decays and renormalization calculated at one loop  
[Bojarski, Chalons, Lopez-Val, Robens, JHEP 1602 \(2016\) 147](#)
- Will be interested at NLO for double Higgs production through scalar resonance.
- First leading order...

# Double Higgs Production



- 3-contributions:
  - Heavy resonance production (H-resonance).
  - Light off-shell resonance (h-resonance).
  - Box diagram.
- Refer to box diagram and h-resonance as “SM-like” contribution.

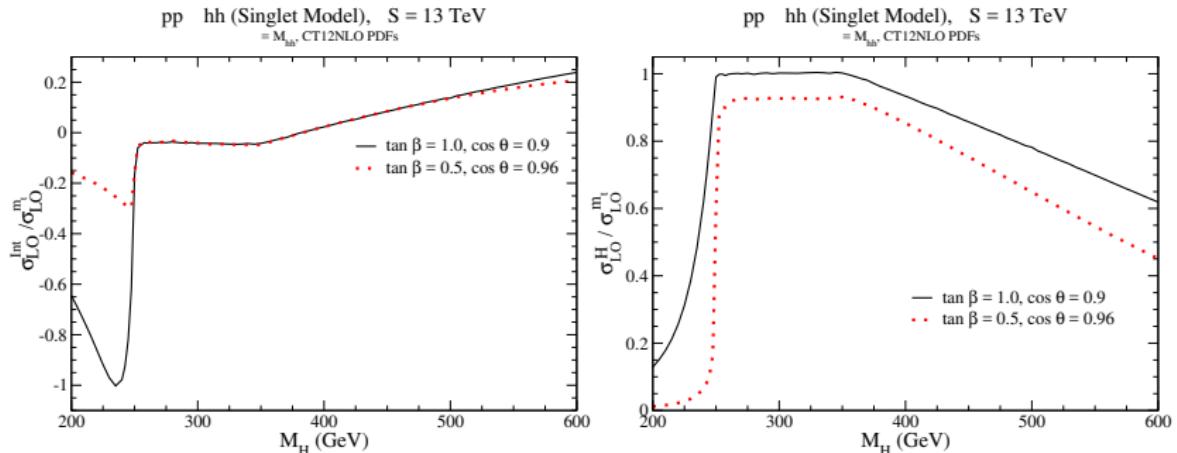
# Invariant Mass Distributions



- In limit  $M_H \gg m_h$ :  $\lambda_{Hhh} \rightarrow \frac{M_H^2}{2v} \sin 2\theta (\cos \theta + \sin \theta \tan \beta)$
- Hence, in limit  $s, m_h^2 \ll M_H^2$  the H-propagator and coupling becomes:

$$\frac{\lambda_{Hhh} v}{s - M_H^2 + i\Gamma_H M_H} \rightarrow -\frac{\sin 2\theta (\cos \theta + \sin \theta \tan \beta)}{2}$$

# Importance of Interference



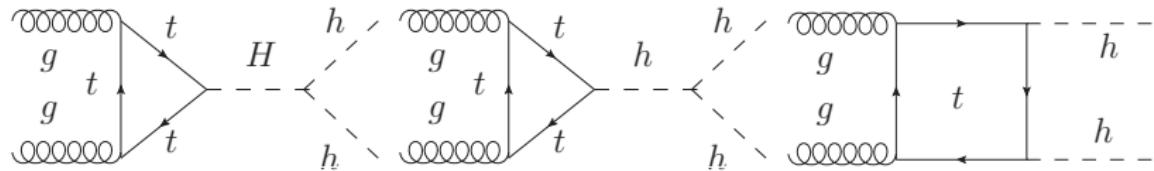
- Interference defined to be:

$$\sigma_{LO}^{Int} = \sigma_{LO} - (\sigma_{LO}^H + \sigma_{LO}^{h+Box})$$

- Can make a substantial contribution to the total cross section.
- Approximating total cross section as resonance breaks down.

# NLO Corrections

# NLO Corrections



- Originally done keeping the form factors of the LO amplitude at LO:

$$g^{A,\mu}(p)g^{B,\nu}(q) \rightarrow h(p')h(q')$$

$$A_{AB}^{\mu\nu} = \frac{\alpha_s}{8\pi v^2} \delta_{AB} \left( P_1^{\mu\nu}(p,q) F_1(s,t,u,m_t^2) + P_2^{\mu\nu}(p,q,p') F_2(s,t,u,m_t^2) \right)$$

- Spin-0 projector:  $P_1^{\mu\nu}$
- Spin-2 projector:  $P_2^{\mu\nu}$

# NLO Corrections

- NLO calculation done treating the form factors  $F_1$  and  $F_2$  at LO  
[Dawson, Dittmaier, Spira, PRD58 \(1995\) 115012](#)
- NNLO results also done in  $m_t \rightarrow \infty$  limit for SM double Higgs production  
[de Florian \*et al\*, arXiv:1606.09519](#)
- Two ideas:
  - Replace SM form factors with form factors in the singlet model.
  - Calculate K-factor in  $m_t \rightarrow \infty$  limit and reweight exact LO cross section calculated in the singlet model.

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- Two ideas:

- Replace SM form factors with form factors in the singlet model.
- Calculate K-factor in  $m_t \rightarrow \infty$  limit and reweight exact LO cross section calculated in the singlet model.

$$\sigma_{\text{NLO}}^{m_t}(pp \rightarrow hh) = \sigma_{\text{LO}}^{m_t} + \sigma_{\text{virt}}^{m_t} + \sigma_{gg}^{m_t} + \sigma_{gq}^{m_t} + \sigma_{q\bar{q}}^{m_t}$$

- Most pieces proportional to LO cross section:

$$\begin{aligned}\sigma_{gg}^{m_t} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^1 \frac{dz}{z} \hat{\sigma}_{\text{LO}}^{m_t}(s=z\tau S) \left\{ -z P_{gg}(z) \log \frac{\mu_F^2}{\tau s} \right. \\ &\quad \left. - \frac{11}{2}(1-z)^3 + 6[1+z^4+(1-z)^4] \left( \frac{\log(1-z)}{1-z} \right)_+ \right\}, \\ \sigma_{gq}^{m_t} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^1 \frac{dz}{z} \hat{\sigma}_{\text{LO}}^{m_t}(s=z\tau S) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{\mu_F^2}{\tau s(1-z)^2} \right. \\ &\quad \left. + \frac{2}{3} z^2 - (1-z)^2 \right\}, \\ \sigma_{q\bar{q}}^{m_t} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^1 d\tau \sum_q \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^1 \frac{dz}{z} \hat{\sigma}_{\text{LO}}^{m_t}(s=z\tau S) \frac{32}{27}(1-z)^3.\end{aligned}$$

# NLO Corrections

- However,  $\sigma_{virt}$  not proportional to LO:

$$\sigma_{\text{virt}}^{m_t} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}^{m_t}(s = \tau S) C^{m_t},$$

$$C^{m_t} = \pi^2 + \frac{11}{2} + \frac{33 - 2n_{lf}}{6} \log \frac{\mu_R^2}{s}$$

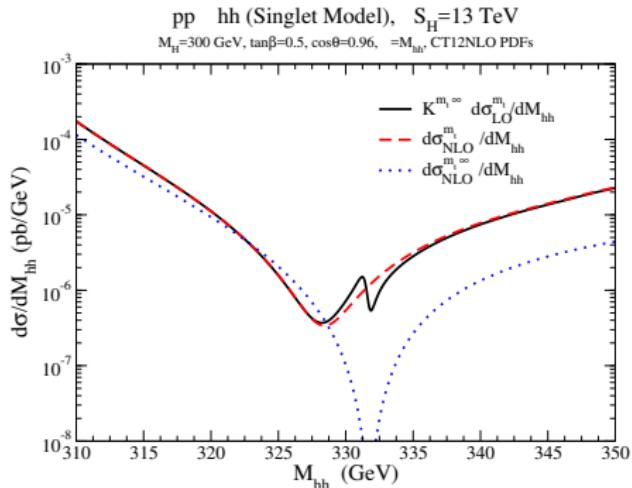
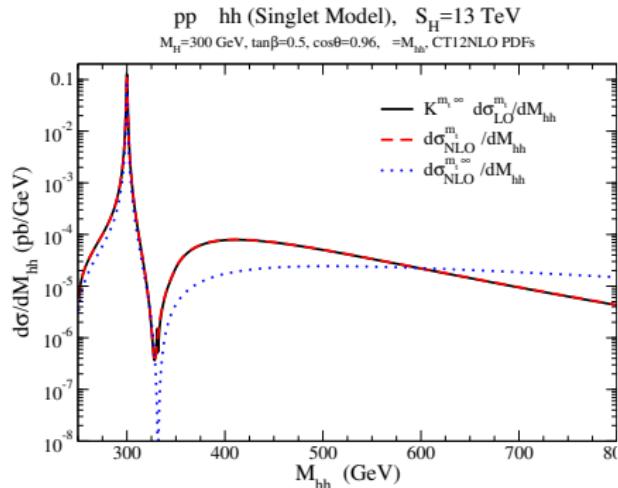
$$+ \frac{8s}{9} \cos^2 \theta \text{Real} \left( \frac{\int_{-\frac{s}{4}(\beta+1)^2}^{-\frac{s}{4}(\beta-1)^2} dt \left\{ F_1(s, t, u, m_t^2) - \frac{p_T^2}{2tu} (s - 2m_h^2) F_2(s, t, u, m_t^2) \right\}}{\int_{-\frac{s}{4}(\beta+1)^2}^{-\frac{s}{4}(\beta-1)^2} dt \left\{ |F_1(s, t, u, m_t^2)|^2 + |F_2(s, t, u, m_t^2)|^2 \right\}} \right)$$

- Possible issues with reweighting:

$$K^{m_t \rightarrow \infty} \frac{d\sigma_{LO}^{m_t}}{dM_{hh}} = \left( \frac{d\sigma_{NLO}^{m_t \rightarrow \infty}}{dM_{hh}} \Big/ \frac{d\sigma_{LO}^{m_t \rightarrow \infty}}{dM_{hh}} \right) \frac{d\sigma_{LO}^{m_t}}{dM_{hh}}$$

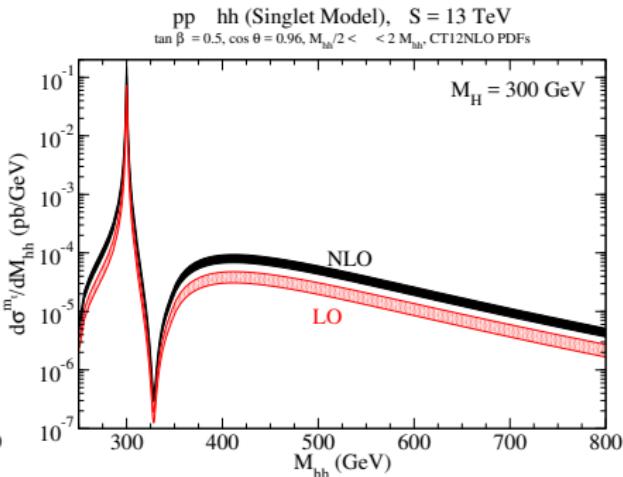
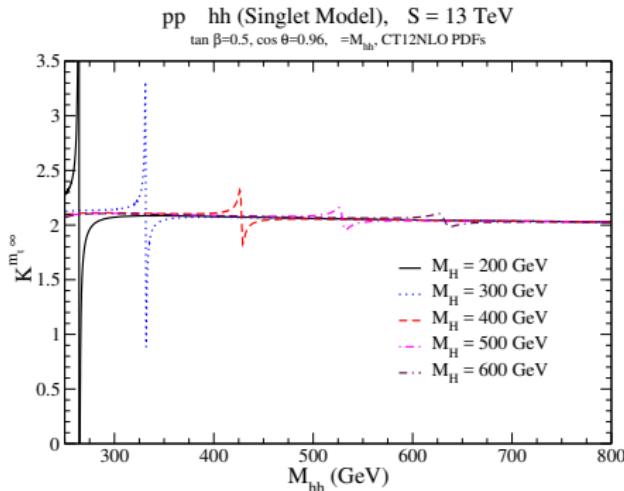
- Location of strong destructive interference is different for finite and infinite top quark mass.

# Comparison of Schemes



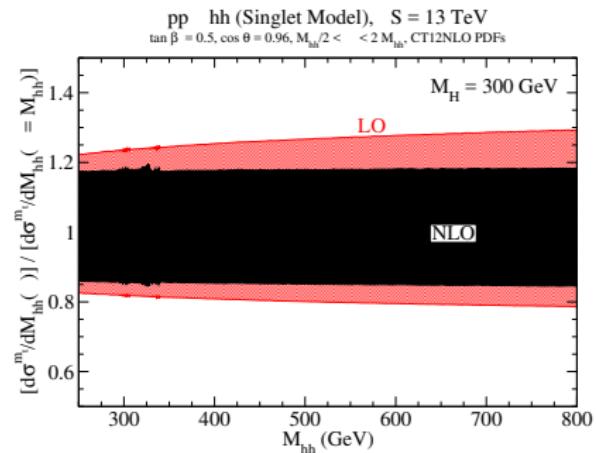
- Good agreement, except in destructive interference regime.

# K-factor

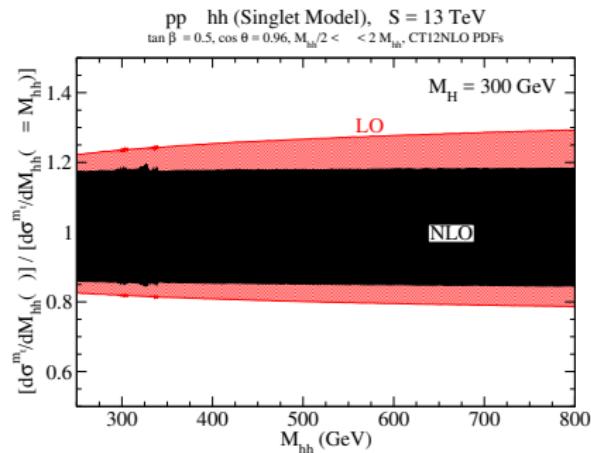


- NLO corrections increase rate by around a factor of two.
- Kinks come from very small LO cross section.

# Scale Uncertainty

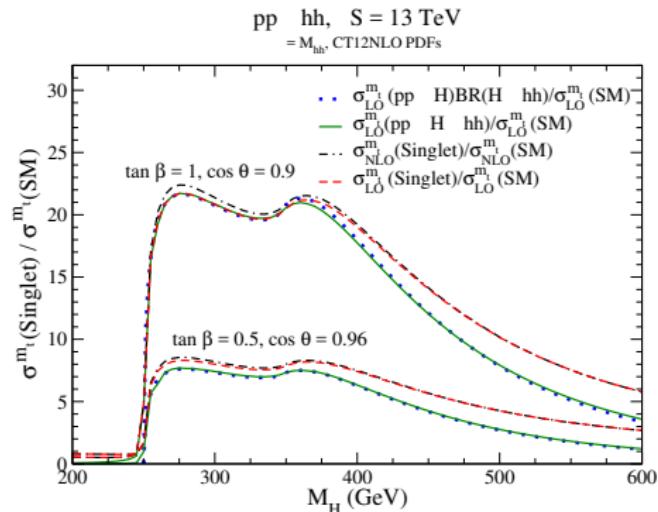


# Scale Uncertainty



- Are conclusions about importance of interference robust against NLO corrections?

# Enhancement of SM Cross Section

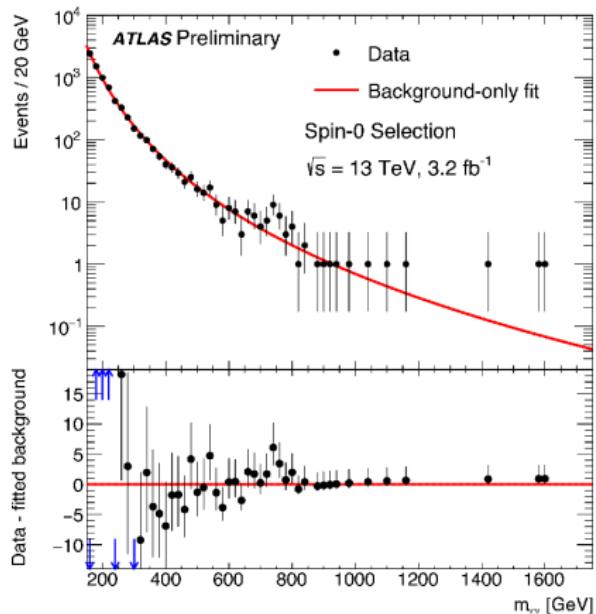


- Conclusions about interference robust against NLO corrections.

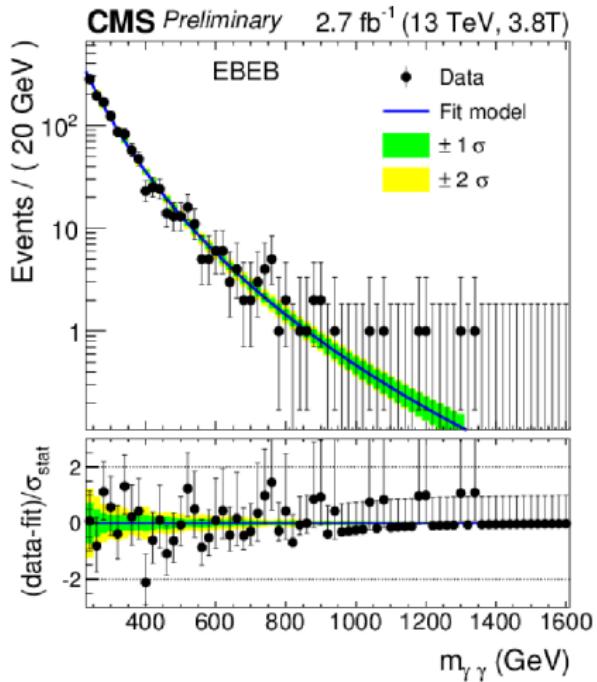
~~The 750 GeV Gorilla in the Room~~

Dearly Departed Friends

# Excess of Diphoton Events



ATLAS-CONF-2016-018



CMS-PAS-EXO-16-018

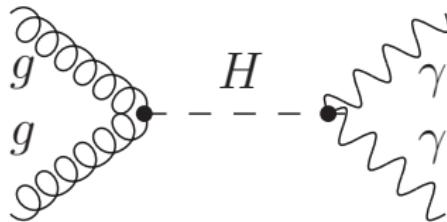
- Both ATLAS and CMS have an excess of di-photon events at 750 GeV.
  - Around  $3.9\sigma$  local significance for ATLAS,  $3.4\sigma$  for CMS

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# EFT Singlet Model



- Add additional EFT interactions into the singlet model:

$$\mathcal{L} = g_s^2 \frac{c_{gg}}{\Lambda} SG^{\mu\nu,a}G_{\mu\nu}^a + \frac{c_{BB}}{\Lambda} g'^2 SB^{\mu\nu}B_{\mu\nu} + \frac{c_{WW}}{\Lambda} g^2 SW^{\mu\nu,a}W_{\mu\nu}^a.$$

- Allow  $S$  to mix with the SM Higgs.

# $WW$ and $ZZ$ Couplings

- New terms in Feynman Rules of observed Higgs boson:

$$-\overline{h} \begin{array}{c} \diagdown \\[-10pt] \text{---} \\[-10pt] \diagup \end{array} V \begin{array}{c} \diagup \\[-10pt] \text{---} \\[-10pt] \diagdown \end{array} V i \cos \theta \frac{2m_V^2}{v} g_{\mu_1 \mu_2} + 16i \sin \theta \frac{m_V^2}{\Lambda v^2} c_{VV} (p_{1,\mu_2} p_{2,\mu_1} - g_{\mu_1 \mu_2} p_1 \cdot p_2)$$

- $c_{ZZ} = c_{WW} \cos^4 \theta_W + c_{BB} \sin^4 \theta_W$

- Since original term is large, expect new EFT terms to make a small difference.

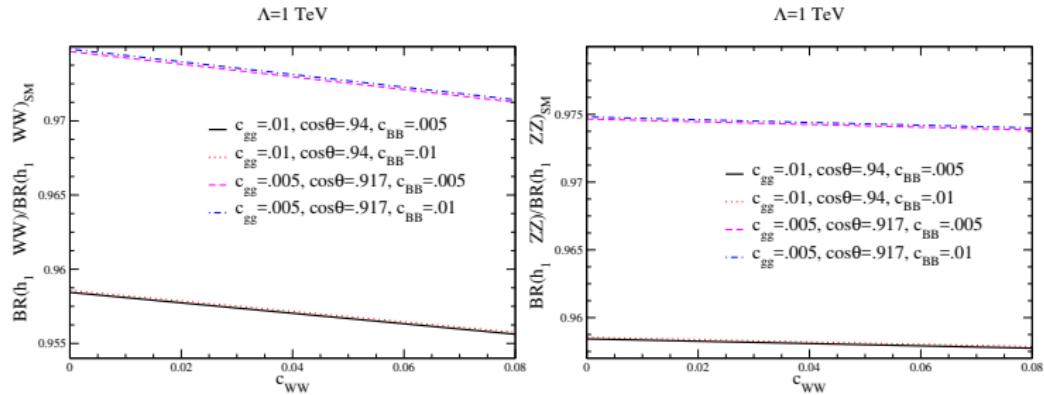
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# $\gamma\gamma$ , $Z\gamma$ , $gg$ couplings

- Now have “tree-level” couplings to  $\gamma\gamma$ ,  $Z\gamma$ , and  $gg$ :

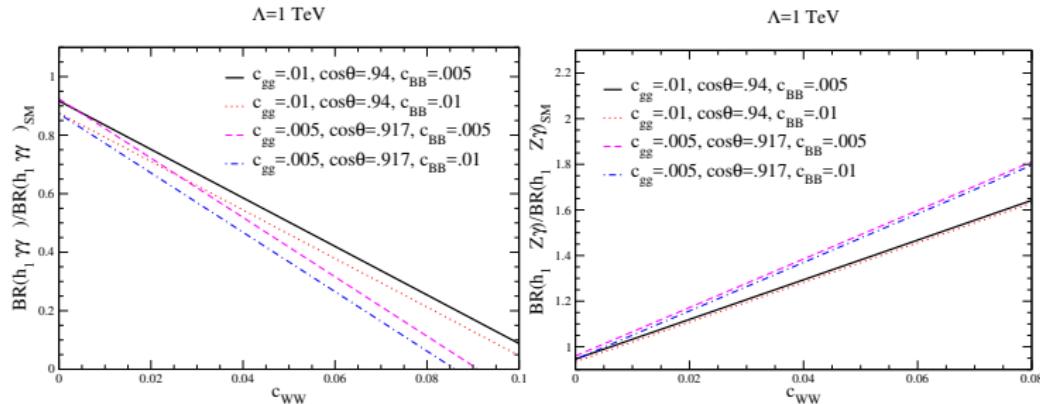
$$h \text{---} \begin{array}{c} \gamma \\ \gamma \end{array} 4i \sin \theta e^2 \frac{c_{BB} + c_{WW}}{\Lambda} (p_{1,\mu_2} p_{2,\mu_1} - g_{\mu_1 \mu_2} p_1 \cdot p_2)$$

$$h \text{---} \begin{array}{c} g \\ g \end{array} 4i \sin \theta g_s^2 \frac{c_{gg}}{\Lambda} (p_{1,\mu_2} p_{2,\mu_1} - g_{\mu_1 \mu_2} p_1 \cdot p_2)$$

$$h \text{---} \begin{array}{c} Z \\ \gamma \end{array} 4i \sin \theta e^2 \frac{c_{WW} \cos^2 \theta_W - c_{BB} \sin^2 \theta_W}{\cos \theta_W \sin \theta_W \Lambda} (p_{1,\mu_2} p_{2,\mu_1} - g_{\mu_1 \mu_2} p_1 \cdot p_2)$$

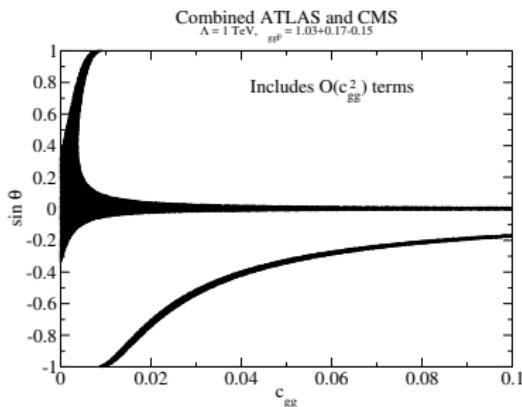
- These were originally loop induced couplings.

# Branching ratios of Observed Higgs



- New interactions can significantly effect the  $\gamma\gamma$  and  $Z\gamma$  decays of the observed Higgs boson.

# Additional EFT on overall signal strength



- Similarly new interaction with  $gg$  can significantly effect production rate.
- Fit to the combined gluon fusion signal strength  $\mu_{ggF} = 1.03^{+0.17}_{-0.15}$ .
  - $\mu_{ggF} = \frac{\sigma_{ggF}}{(\sigma_{ggF})_{SM}}$
- Additional EFT coupling to the gluon field strength greatly changes fit.
  - At  $c_{gg} = 0$  get usual limits on  $\sin \theta$  from signal strength measurements.
  - Away from  $c_{gg} = 0$ , can get very different allowed values for  $\sin \theta$
  - Also important to carefully count EFT.

# Parameter Scan

- Scan over parameters of the model:

$$\begin{aligned}-1 < \sin \theta < 1, \quad 0 < c_{gg} < 0.2, \quad 0 < c_{WW} < 0.2, \quad 0 < c_{BB} < 0.2 \\ -10 \text{ GeV} < b_3 < 10 \text{ GeV}, \quad -3 < a_2 < 10\end{aligned}$$

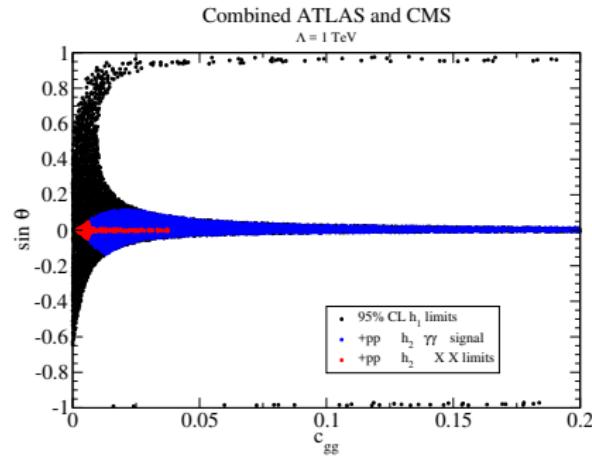
- Do 95% CL fit to the observed Higgs boson signal strengths at 8 TeV:

$$\begin{aligned}\mu_F^{\gamma\gamma} = 1.13^{+0.24}_{-0.21} \quad \mu_F^{WW} = 1.08^{+0.22}_{-0.19} \quad \mu_F^{ZZ} = 1.29^{+0.29}_{-0.25} \\ \mu_F^{bb} = 0.66^{+0.37}_{-0.28} \quad \mu_F^{\tau\tau} = 1.07^{+0.35}_{-0.28}\end{aligned}$$

- Where

$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}}$$

# All Constraints



- Additional operators change Higgs fits.

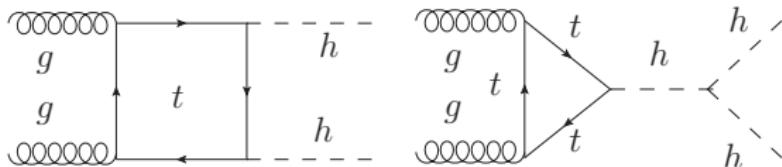
# Conclusions

- Studied resonant double Higgs production in the  $Z_2$  Singlet extended SM.
  - Found significant interference effects between the resonance and the SM-like contributions.
  - Up to  $\sim 20\%$  for resonance masses of 600 GeV.
  - NLO corrections were significant, roughly a factor of 2.
  - Need to be careful reweighting the exact LO result by the  $m_t \rightarrow \infty$  K-factor in the destructive interference region.
  - The conclusions about interference and a factor of 10 enhancements over SM rate was robust against the NLO corrections.
- Explored the singlet model with dimension-5 operators coupling to gluon,  $SU(2)$ , and hypercharge field strengths.
  - With scalar mixing, obtained important corrections to loop induced Higgs couplings.
  - Can be important in fits to observed Higgs data.



# EXTRA SLIDES

# Standard Model



- Parameterize amplitude for  $g^{a,\mu}(p_1)g^{b,\nu}(p_2) \rightarrow H(p_3)H(p_4)$  [Glover, van der Bij, NPB309 \(1988\) 282](#):

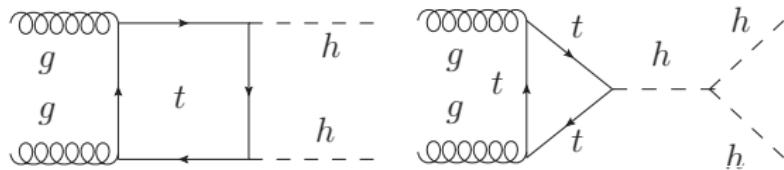
$$A_{ab}^{\mu\nu} = \frac{\alpha_s}{8\pi v^2} \delta_{ab} \left[ P_1^{\mu\nu}(p_1, p_2) F_1(s, t, u, m_t^2) + P_2^{\mu\nu}(p_1, p_2, p_3) F_2(s, t, u, m_t^2) \right]$$

- $P_1$  and  $P_2$  are orthogonal spin-0 and spin-2 projectors.
- Partonic cross section:

$$\frac{d\hat{\sigma}(gg \rightarrow HH)}{dt} = \frac{\alpha_s^2}{2^{15}\pi^3 v^4} \frac{|F_1(s, t, u, m_t^2)|^2 + |F_2(s, t, u, m_t^2)|^2}{s^2}$$

- Can directly expand function in  $1/m_t^2$  to see convergence of series.
- LET corresponds to LO piece.

# Standard Model



- Partonic cross section:

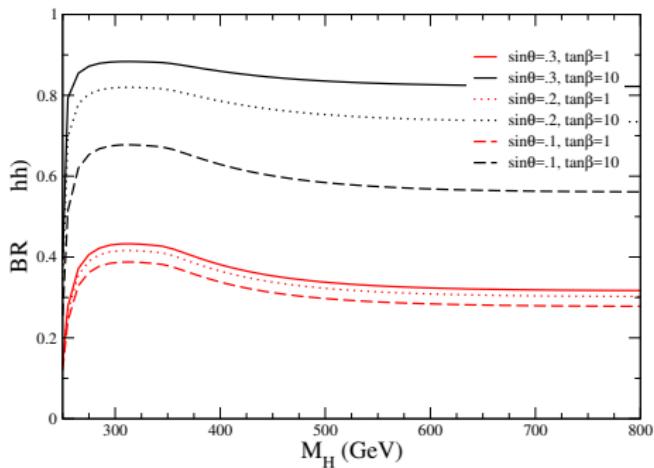
$$\frac{d\hat{\sigma}(gg \rightarrow HH)}{dt} = \frac{\alpha_s^2}{2^{15}\pi^3 v^4} \frac{|F_1(s, t, u, m_t^2)|^2 + |F_2(s, t, u, m_t^2)|^2}{s^2}$$

- In low energy limit  $c_H = 1$        $c_{HH} = -1$ :

$$F_1(s, t, u, m_t^2) \mid_{LET} \rightarrow \left( -\frac{4}{3} + \frac{4m_H^2}{s - m_H^2} \right) s \quad F_2(s, t, u, m_t^2) \mid_{LET} \rightarrow 0$$

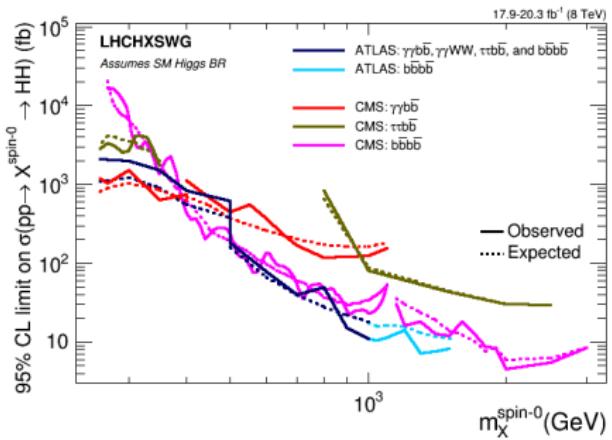
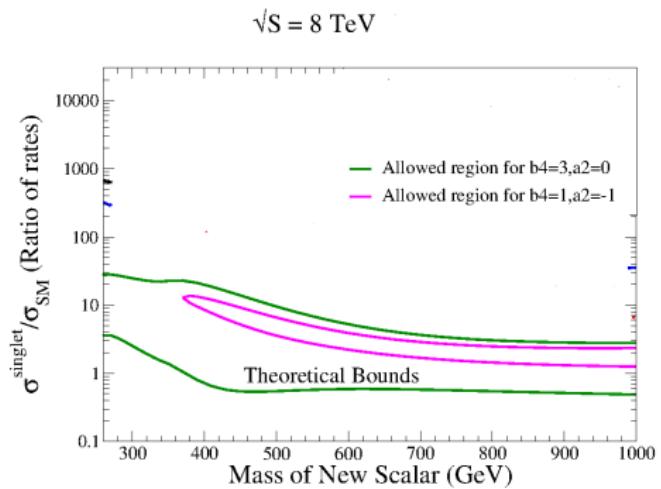
- At threshold  $s = 4m_H$ ,  $F_1 \rightarrow 0$ .

# Branching Ratios Into Double Higgs



- Black:  $\tan\beta = \sqrt{2}v/\langle S \rangle = 10$
- Red:  $\tan\beta = \sqrt{2}v/\langle S \rangle = 1$
- Triple coupling:  $\lambda_{Hhh} = \frac{M_H^2}{2v} \sin 2\theta (\cos \theta + \sin \theta \tan \beta) \left(1 + \frac{2m_h^2}{M_H^2}\right)$

# Current Constraints



- $\sigma_{SM} = 11 \text{ fb}$  at 8 TeV.

# Constraints on Resonance

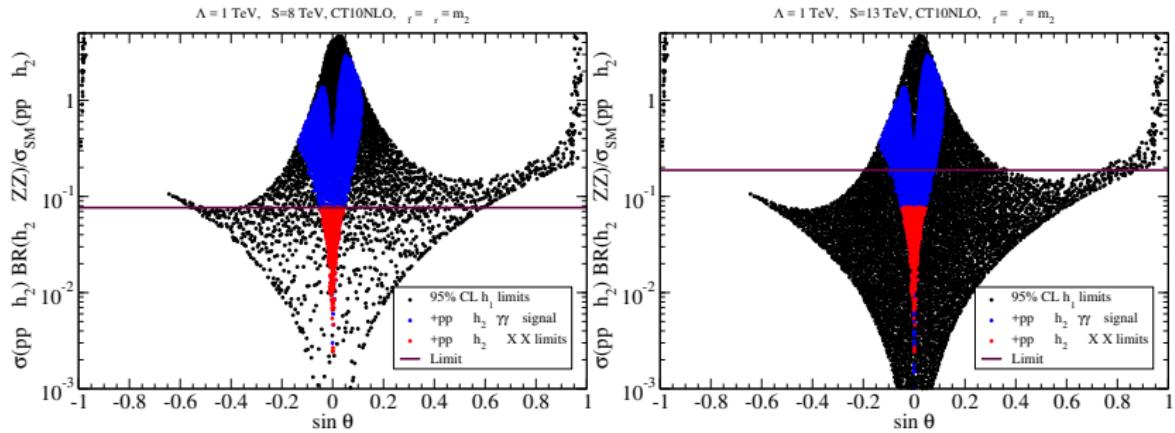
- Require that we reproduce the cross section for the 750 GeV resonance at 13 TeV:

$$\sigma(pp \rightarrow H \rightarrow \gamma\gamma) = 5.2 \pm 2.6 \text{ fb}$$

- Also require that we satisfy the other bounds:

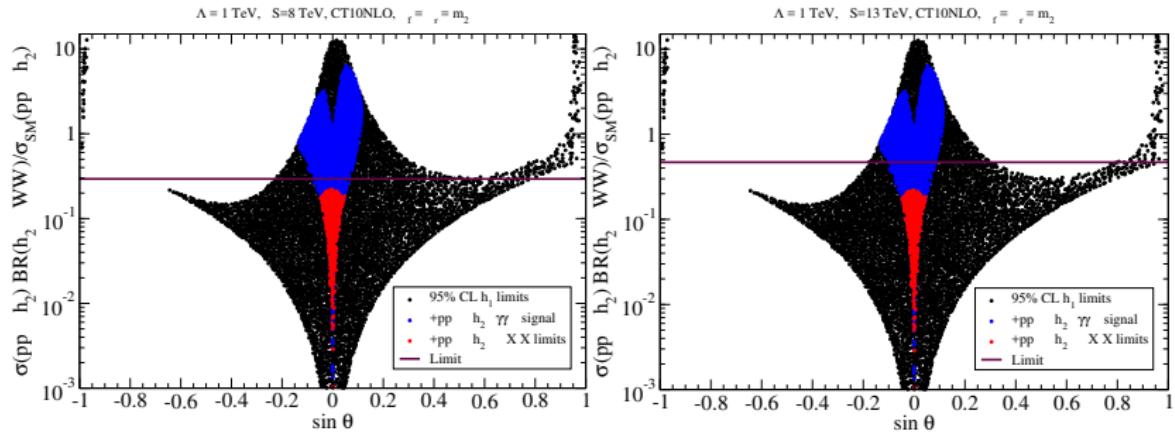
Channel	8 TeV, $\sigma_{max}$	13 TeV, $\sigma_{max}$
WW	46 fb	300 fb
ZZ	12 fb	120 fb
t̄t	700 fb	
Zγ	3.5 fb	30 fb
τ <sup>+</sup> τ <sup>-</sup>	14 fb	60 fb
jj	2100 fb	
hh	41 fb	154 fb

# Constraints from ZZ Rates



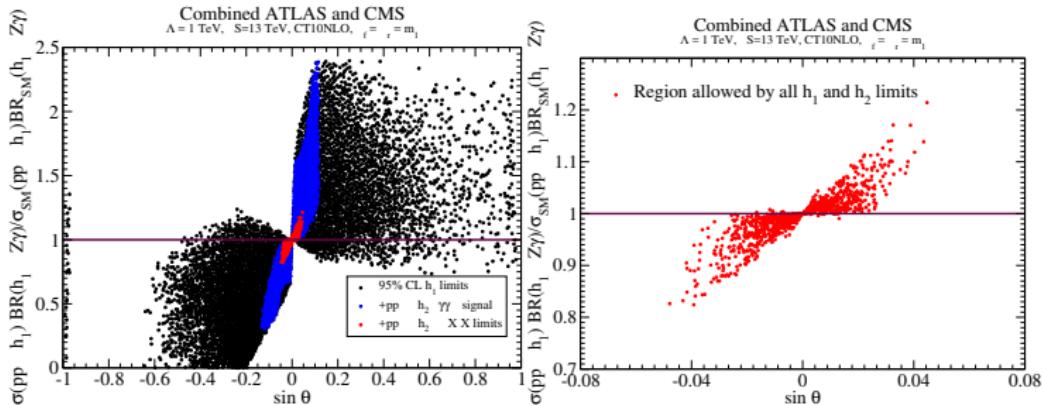
- 8 TeV more constraining than 13 TeV.
- Can already see that this is what constrains  $\sin \theta$ .

# WW Constraints



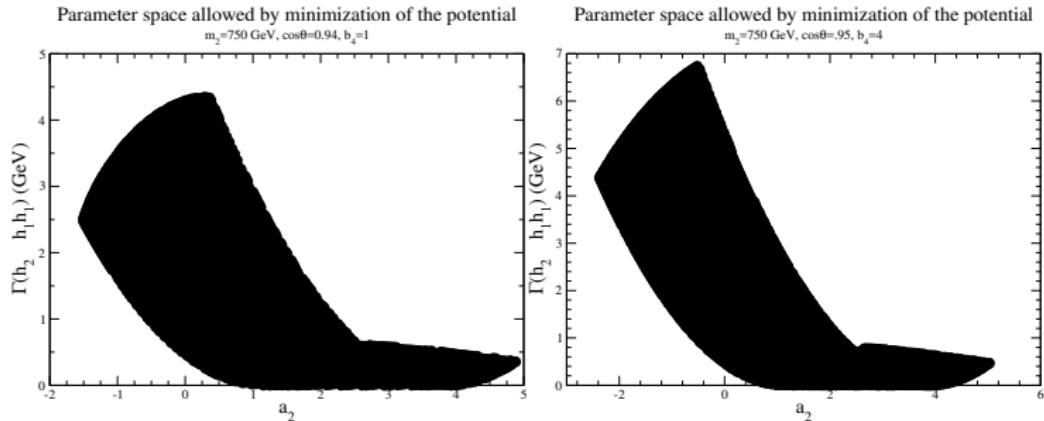
- 8 TeV more constraining than 13 TeV.
- Less constraining than ZZ at the moment.

# SM-like Higgs $Z\gamma$ rate



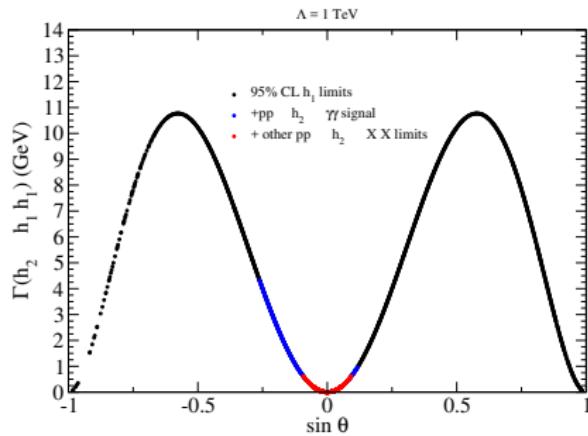
- Can at most change  $h \rightarrow Z\gamma$  rate by 15%

# Partial width to Double Higgs



- Important to measure  $H \rightarrow hh$  if available.
  - Directly depends on parameters in the potential.
  - Maimum partial width depends on  $b_4$ , the  $S^4$  coupling.

# $H \rightarrow hh$ width



- Set  $S^4$  parameter to be maximum allowed for perturbative unitarity of  $SS \rightarrow SS$  scattering.
- After all constraints taken into account, cannot be too big.
- Maximum  $BR(H \rightarrow hh)$  is  $\sim 0.25$ .
  - Total width is not too large.
- Need non-zero mixing to have  $H \rightarrow hh$