

Double Higgs Production

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Higgs and Beyond Workshop

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Outline

- Why measure the Higgs-self couplings?
- What do we expect?
 - Standard Model
 - Beyond the Standard Model
- Some phenomenology
 - Is double Higgs production observable?

Higgs self-couplings a prediction

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

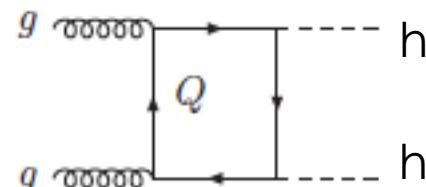
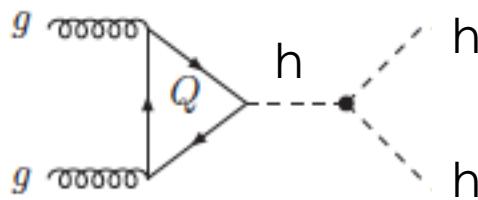
$$V \rightarrow -\frac{M_h^2}{2} h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

- hhh and $hhhh$ couplings predictions of theory
- They are perturbative: $\lambda_3 = \frac{M_h^2}{2v} \sim .13v$ $\lambda_4 = \frac{M_h^2}{8v^2} = .03$
- In general:

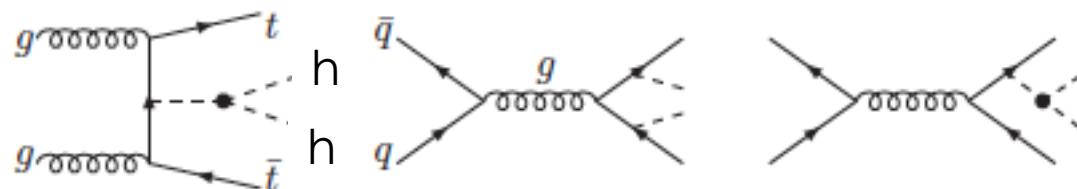
Corrections to relationship between λ_3 and λ_4 of $\mathcal{O}(1/\Lambda^2)$

* This is NOT true in models with new light particles

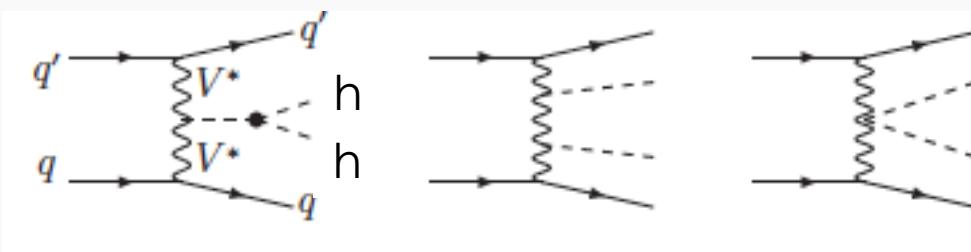
Production of hh



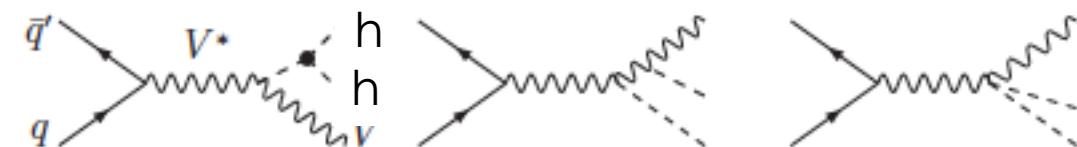
Sensitive to heavy colored particles (eg stops or top partners)



Sensitive to anomalous top-Higgs couplings

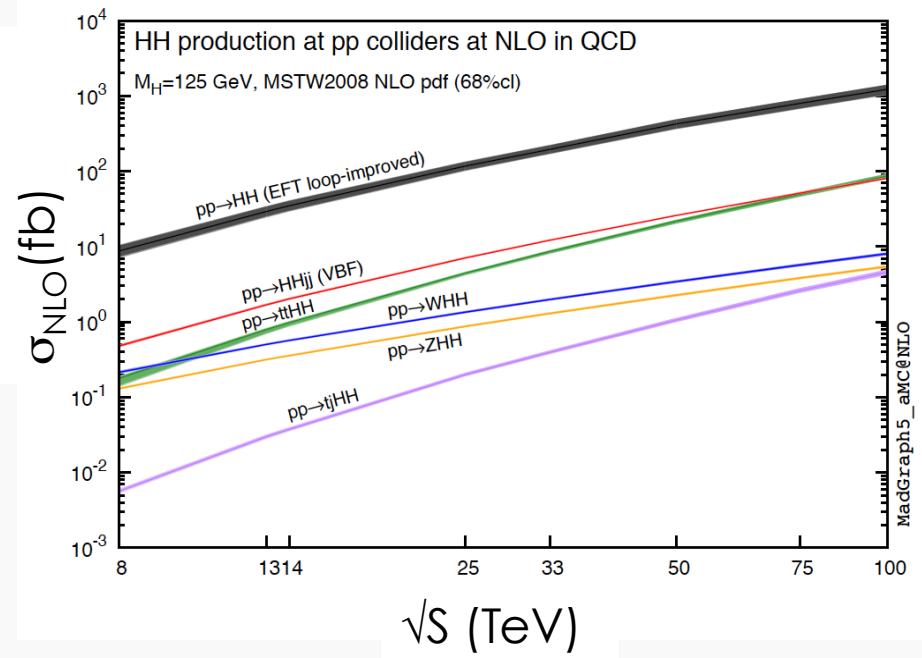
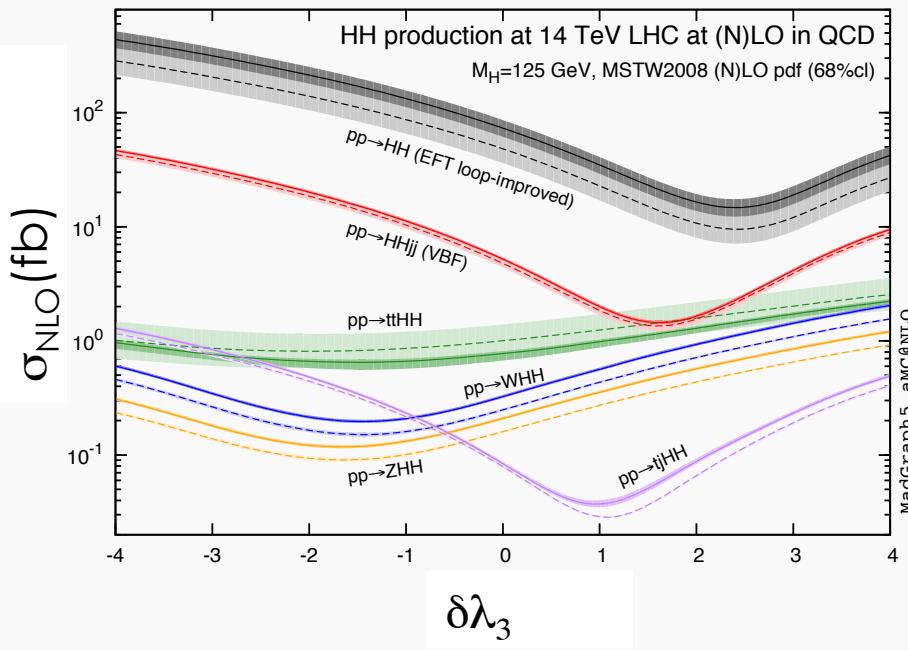


Sensitive to anomalous $VVhh$ couplings



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Small Rates for hh



- Only gluon fusion likely to be relevant
- Large increase in hh rate at high energy

* Light bands, LO, Solid bands NLO

[Frederix et al, 1408.5147]

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Two Higgs Production at LHC

- Cross section has spin-0 and spin-2 contributions

$$\frac{d\sigma(gg \rightarrow hh)}{dt} = \frac{\alpha_s^2}{32768\pi^3 v^4} \left(|F_0|^2 + |F_2|^2 \right)$$

- $m_t^2 \gg s, p_T^2$ (low energy theorem)

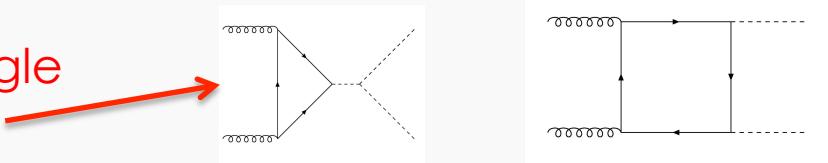
$$F_0 \rightarrow -\frac{4}{3} + \frac{4M_h^2}{s - M_h^2} (\delta\lambda_3) \quad \text{(hhh coupling/hhh}_{\text{SM}}\text{)}$$
$$F_2 \rightarrow 0$$

- For large s , dependence on $\delta\lambda_3$ suppressed
- More sensitivity to negative $\delta\lambda_3$
- Exact cancellation in SM at threshold

Double Higgs Production

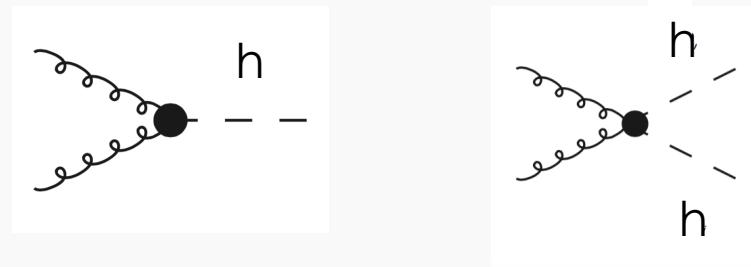
- Cancellation in large m_t limit between box and triangle diagrams

Greatly restricted by single
Higgs production



- QCD corrections computed in $m_t \rightarrow \infty$ limit and weighted by exact LO

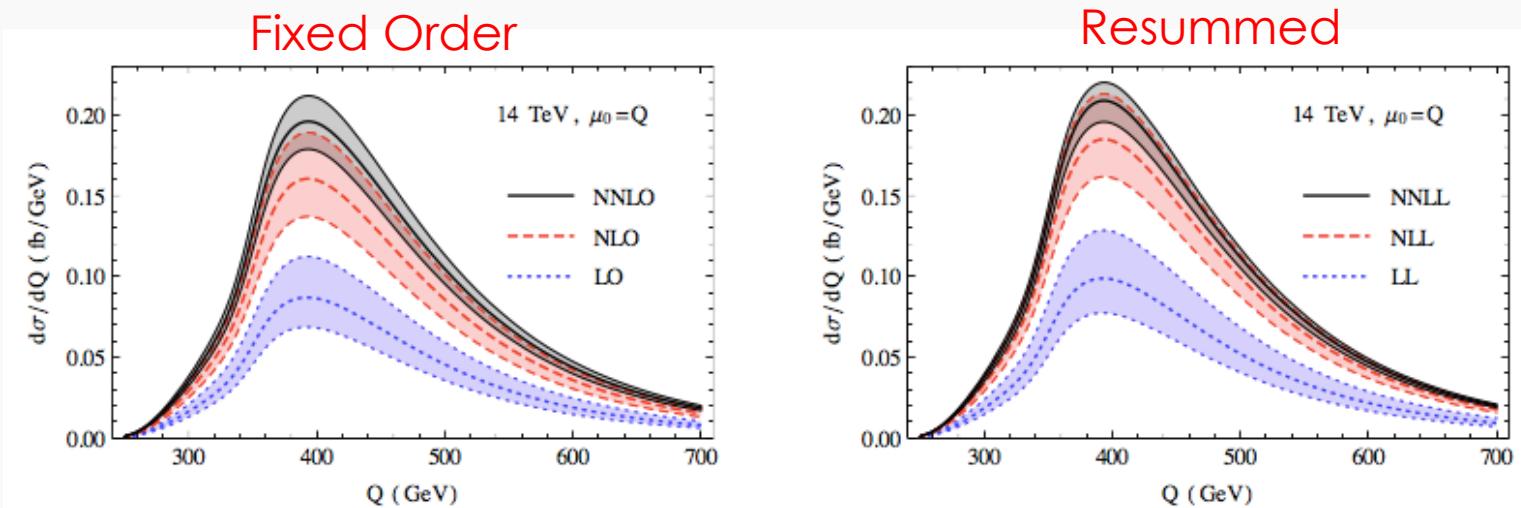
$$L \sim \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu}^A G^{A,\mu\nu}$$



[Dawson, Dittmaier, Spira, hep-ph/9805244]

Progress in SM Calculations

- Dominant process is $gg \rightarrow hh$
 - Threshold resummation at NNLL matched to NNLO
 - Scale uncertainty reduced at NNLL
 - Good convergence
 - These calculations are in $m_t \rightarrow \infty$ limit



[De Florian, Mazzitelli, 1505.07122]

*MSTW2008 PDFs

Using newest NNLO PDFs

$\mu_0 = Q$	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+ α_S unc. (%)
7 TeV	7.61	+5.6 – 6.0	± 3.3	± 4.3
8 TeV	11.0	+5.5 – 6.0	± 3.0	± 4.0
13 TeV	37.3	+5.1 – 6.1	± 2.1	± 3.1
14 TeV	44.2	+5.2 – 6.1	± 2.0	± 3.0
100 TeV	1712	+5.2 – 6.2	± 1.7	± 2.6

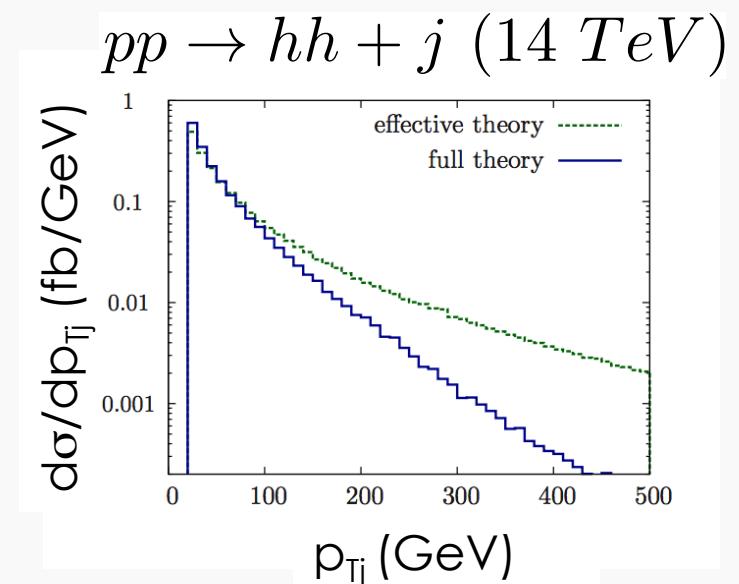
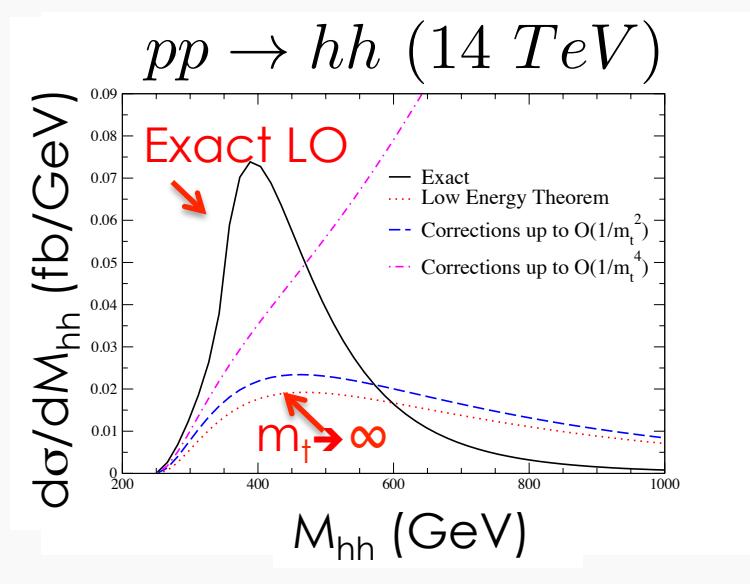
$\mu_0 = Q/2$	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+ α_S unc. (%)
7 TeV	7.72	+4.0 – 5.7	± 3.4	± 4.4
8 TeV	11.2	+4.1 – 5.7	± 3.1	± 4.0
13 TeV	38.0	+4.3 – 6.0	± 2.1	± 3.1
14 TeV	45.1	+4.4 – 6.0	± 2.1	± 3.0
100 TeV	1749	+5.1 – 6.6	± 1.7	± 2.7

NEW: PDF uncertainty significantly reduced from MSTW PDFs

[De Florian, Mazzitelli, 1505.07122; Contribution to LHC Higgs Cross Section Working Group]

Radiative corrections in large m_t limit?

- Large m_t limit known to poorly reproduce distributions at LO



Adding extra powers of $1/m_t^2$ doesn't help distributions

[Dawson, Furlan, and Lewis, arXiv:1210.6603; Dolan, Englert, and Spannowsky, arXiv:1206.5001]

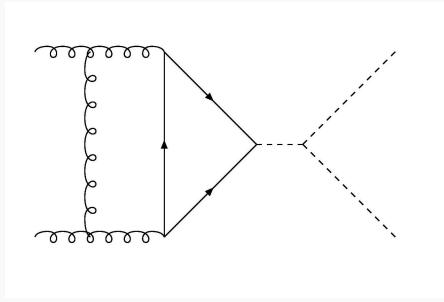
Towards including m_t effects at NLO, NNLO

- HOW BIG ARE $1/m_t^2$ CORRECTIONS?
- Compute NLO with virtual corrections in $m_t \rightarrow \infty$ limit and real corrections with exact m_t dependence (improved HEFT)
- Compute $1/m_t^{2n}$ corrections to NLO and normalize to exact LO
- Different results from 2 approaches
- Arbitrarily assign $\pm 10\%$ uncertainty from m_t dependence

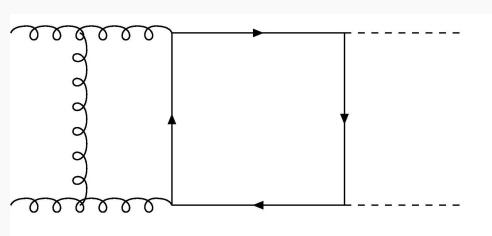
[$1/m_t^2$ corrections: Grigo, Hoff, Melnikov, Steinhauser, arXiv:1305.7340; Grigo, Melnikov, Steinhauser, arXiv: 1408.2422; Grigo, Hoff, Steinhauser, arXiv: 1508.00909;
HEFT: Maltoni, Vryonidou, Zaro, arXiv: 1408.6542; Frederix et al, arXiv:1401.7340]

Compute NLO corrections to hh production

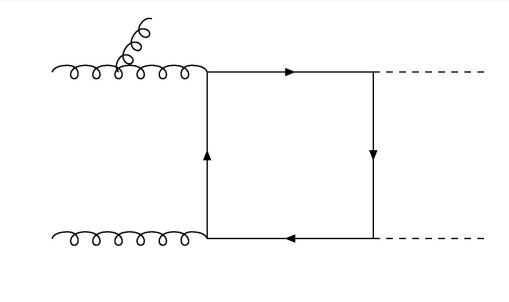
- $\mathcal{O}(\alpha_s^3)$ contributions
- Compute as expansion in small external momentum
 - Can keep as many terms in expansion as desired
- Need 2 loop box integrals with m_t , M_h



Known



New

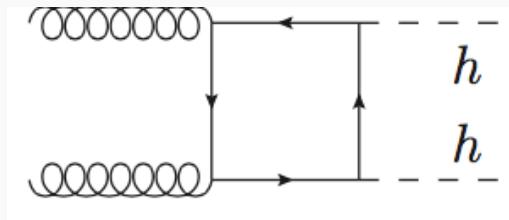
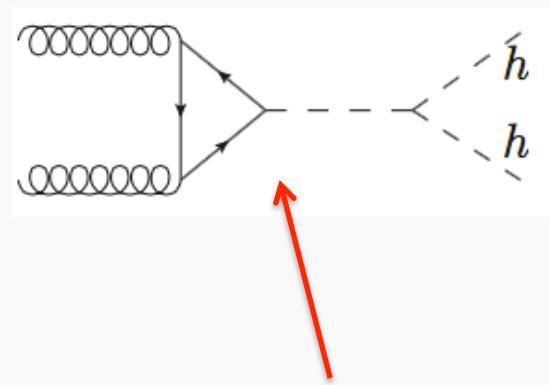


Easy

[Borowka, Di VitaGreiner, Heinrich, Jones, Kerner, Luisoni, Mastrolia, Schlenk, Schubert, Zirke]

What is contributing to hh?

- Do we know it's a top quark?
- Could it be a stop? Or other colored scalar?



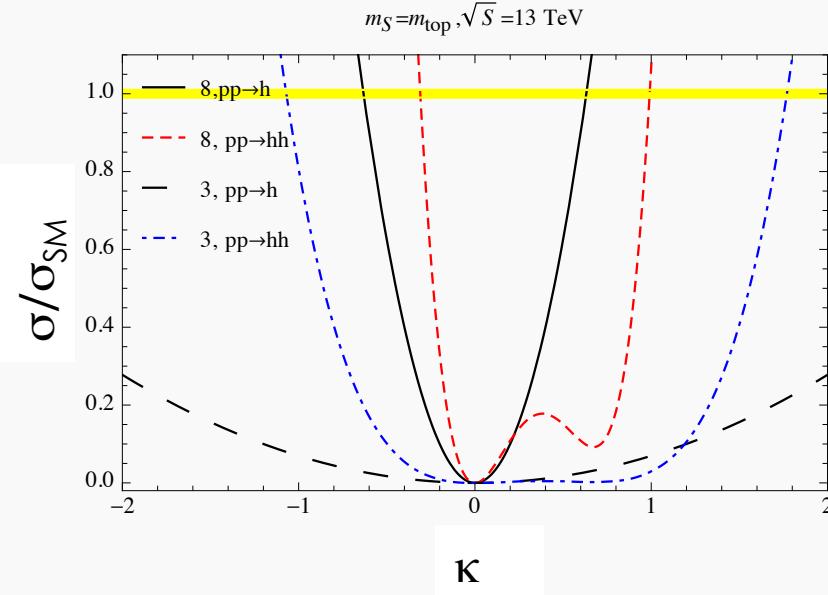
Parameters restricted by requirement
that $gg \rightarrow h$ has SM value

Colored scalar in loop?

- Could we replace the top with a scalar?

$$L = (D_\mu s)^*(D^\mu s) - m_0^2 s^* s - \frac{\lambda_s}{2} (s^* s)^2 - \kappa s^* s |\Phi^\dagger \Phi|$$

- Physical mass $m_s^2 = m_0^2 + \frac{\kappa v^2}{2}$ ($m_0=0$ all mass from EWSB)

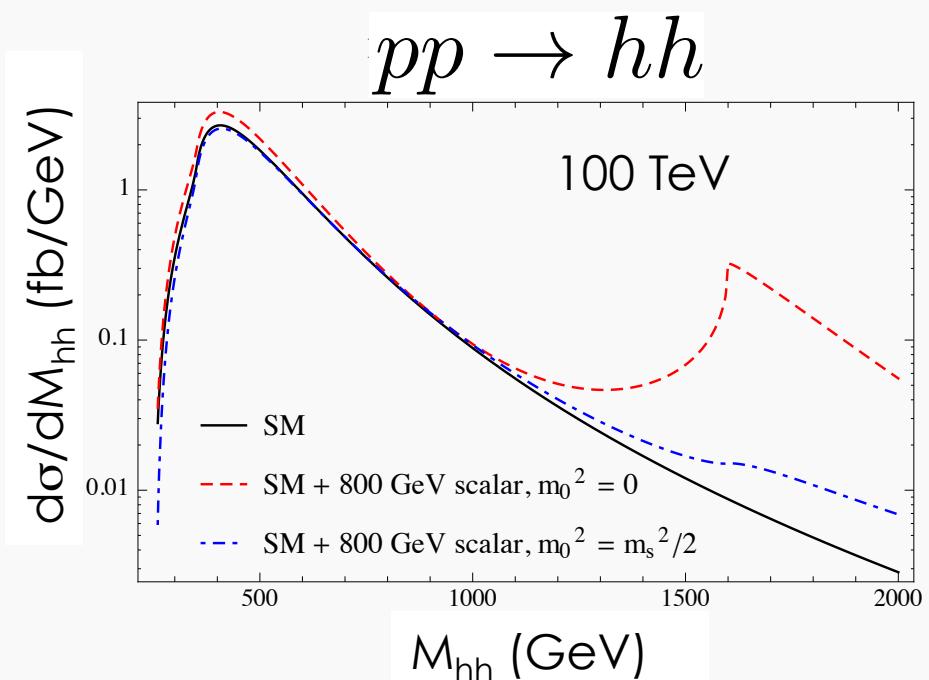
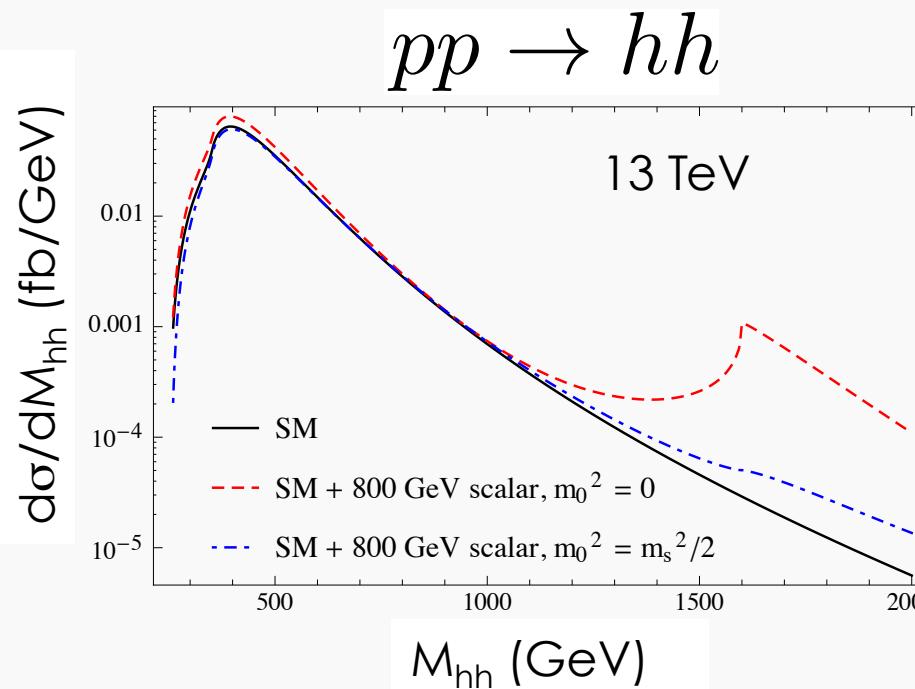


Color octet: SM 1h rate predicts highly suppressed 2h rate

Color triplet: SM 1h rate obtained for $\kappa = \pm 3.7$

What about adding a scalar?

- At **high invariant mass**, distributions different in presence of color triplet scalar



[Dawson, Ismail, Low, arXiv:1504.05596]

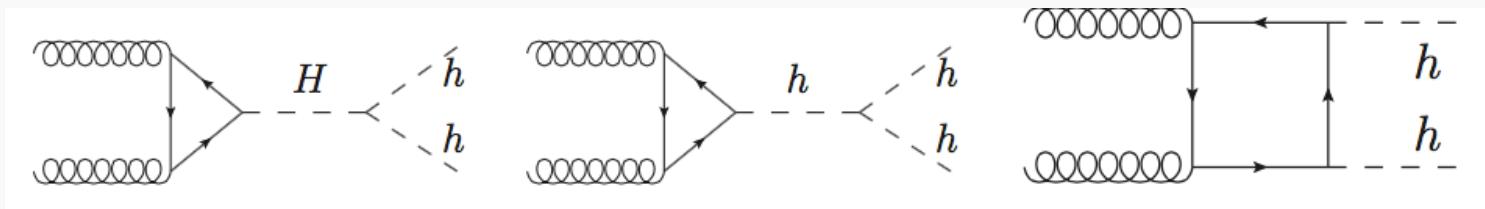
[See also, Batell, McCullough, Stolarski, Verhaaren, arXiv: 1508.01208]

Need a resonance to increase rate!

- Simplest example: Add a scalar singlet, S
- Before EWSB, singlet only couples to Higgs doublet
- After EWSB, singlet mixes with SM Higgs boson
- For simplicity, impose Z_2 symmetry:

$$SM \rightarrow SM$$

$$S \rightarrow -S$$



Singlet Model

- Very predictive:

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

- Physical fields: $h = \cos \theta h_{SM} - \sin \theta S$

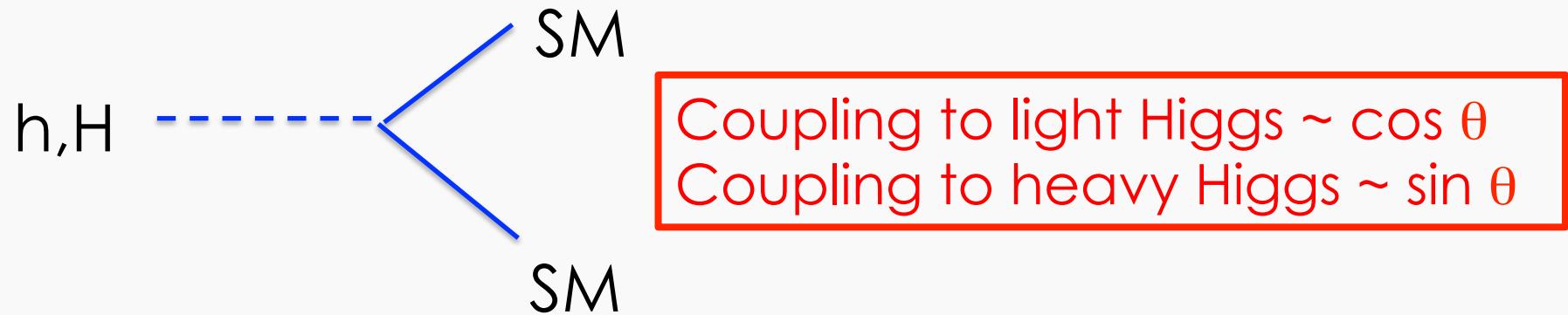
$$H = \sin \theta h_{SM} + \cos \theta S$$

- Physical parameters:

$$M_h, M_H, v, \tan \beta = \frac{v}{\langle S \rangle}, \theta$$

Z_2 symmetric singlet model

- Very simple model:

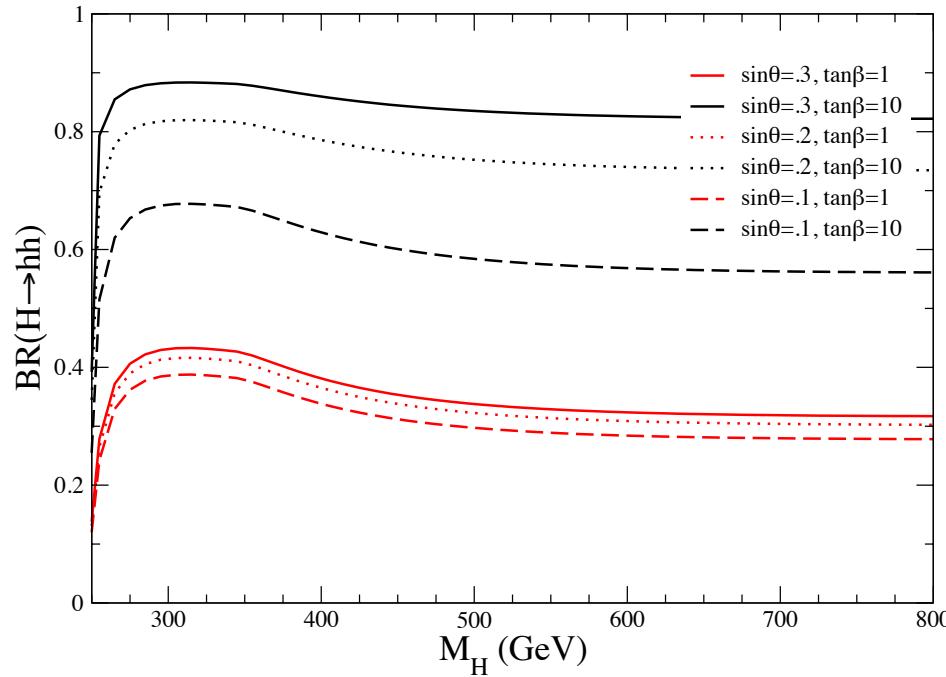


- If kinematically allowed, $H \rightarrow hh$

$$\Gamma(h) = \cos^2 \theta \Gamma_{SM}$$

$$\Gamma(H) = \sin^2 \theta \Gamma_{SM} + \Gamma(H \rightarrow hh)$$

Branching ratio $H \rightarrow hh$ can be significant

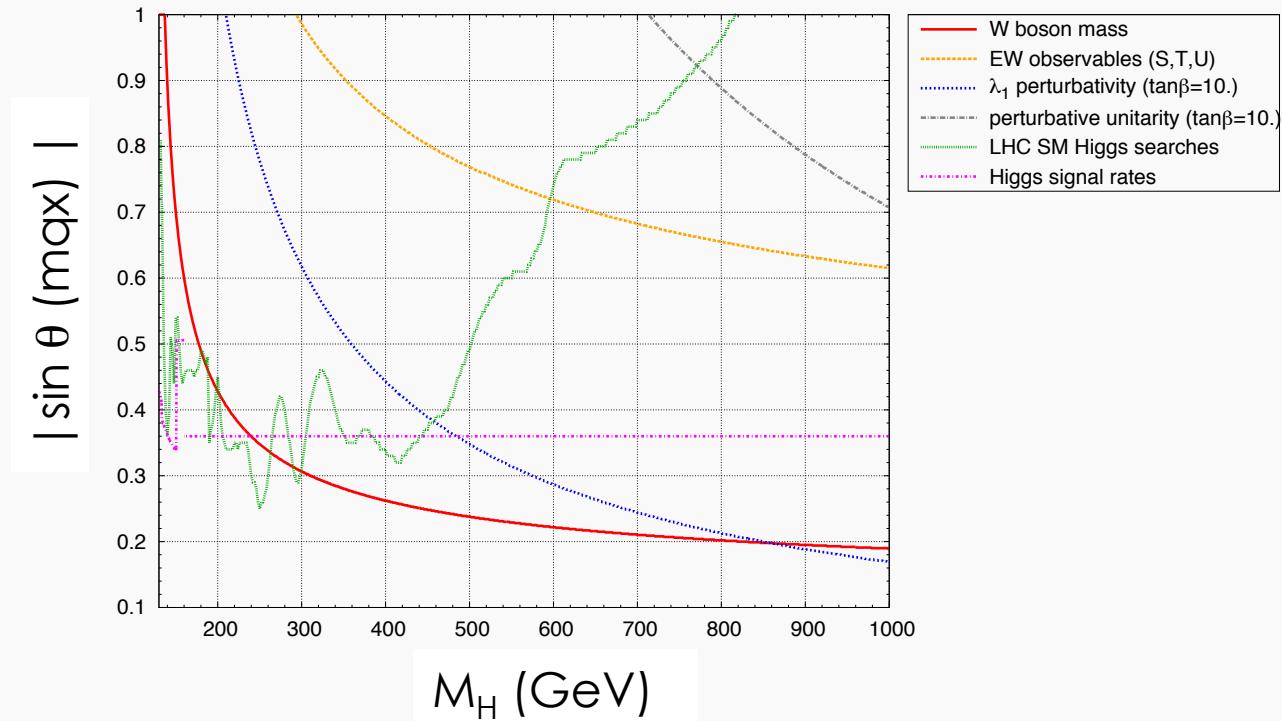


Large $\tan \beta$ gives problems with perturbative unitarity of $hh \rightarrow hh$

$$\tan \beta < 1.3 \left(\frac{600 \text{ GeV}}{M_H} \right)$$

Limits on singlet model

- Limits from M_W , Higgs coupling measurements, direct searches for heavy Higgs bosons



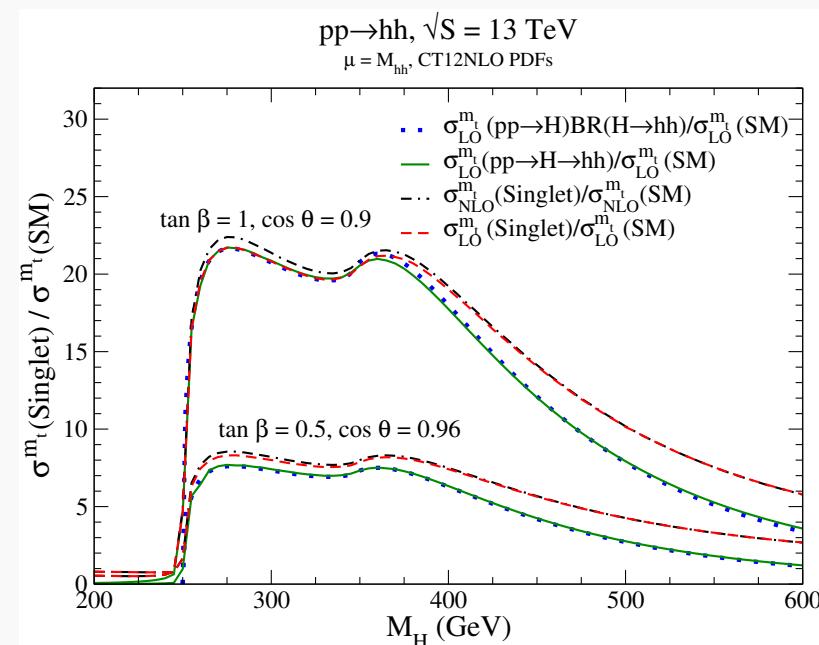
[Bojarski, Chalons, Lopex-Val, Robens, arXiv:1511.08120]

Resonant production of hh

- Large resonant effects when $M_H \sim 2M_h$
- NWA approximation accurate for $M_H < 400$ GeV

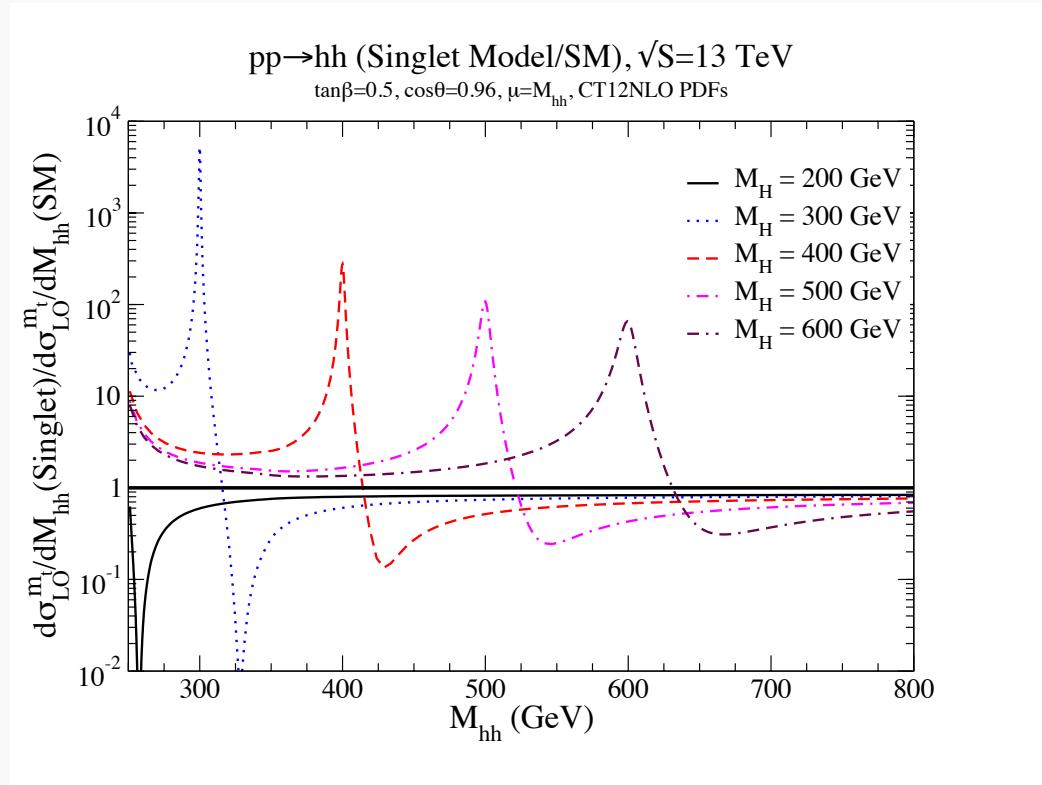
Can get factor of 20 enhancements

*Similar effects in MSSM,
NMSSM models



[Dawson, Lewis, arXiv:1508.05397]

Large resonance/interference effects

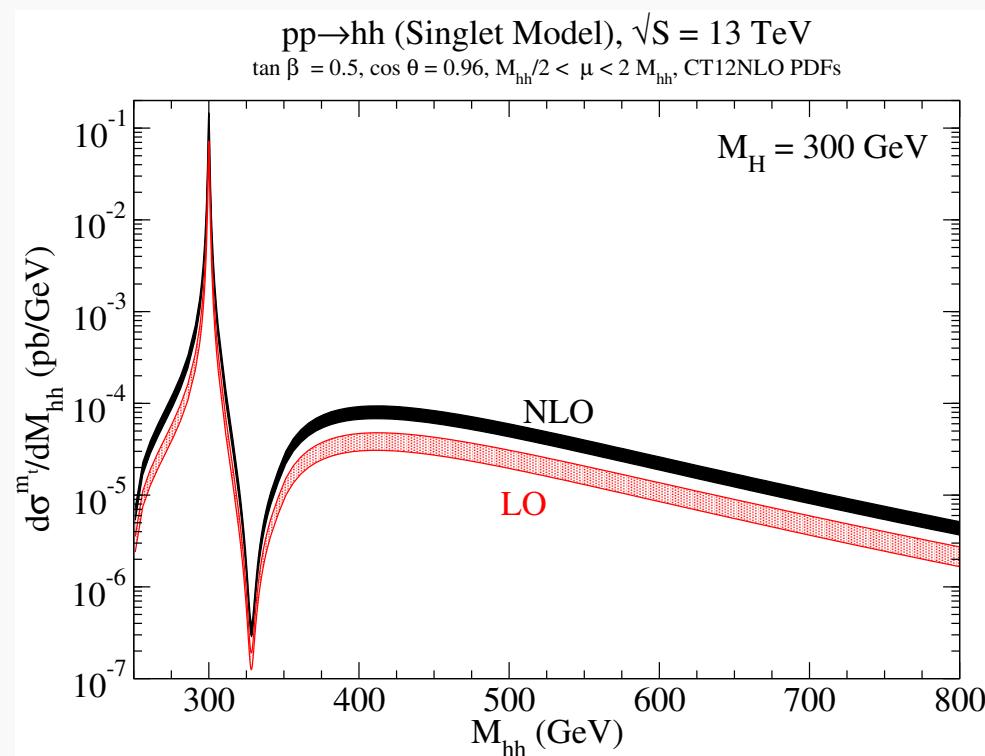


[Dawson, Lewis, arXiv:1508.05397]

NLO corrections to singlet model

- Computed in $m_t \rightarrow \infty$ limit

K factor ~ 2
(as in SM)



Higgs singlet model without Z_2

$$V(\Phi, S) = V_{SM}(\Phi) + V_{\Phi S}(\Phi, S) + V_S(S)$$

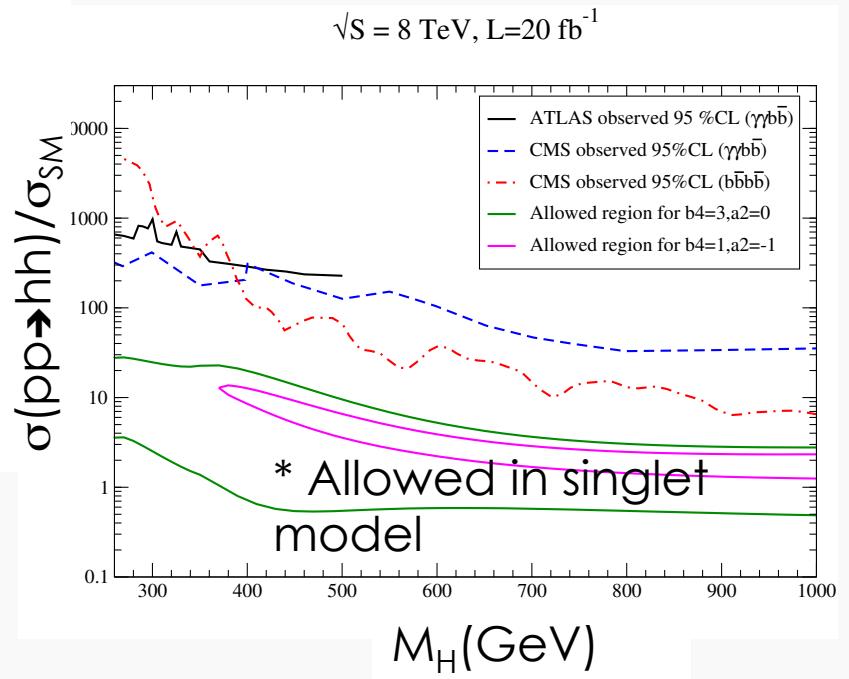
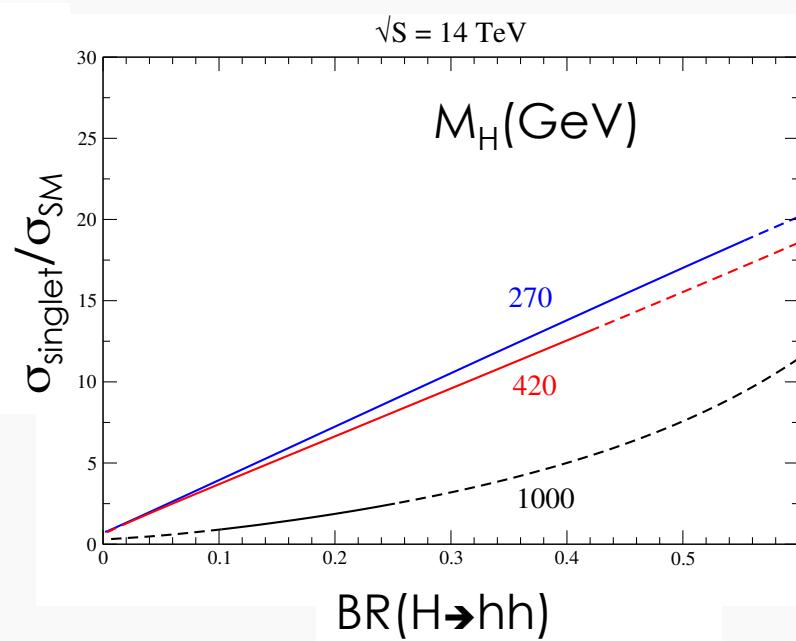
$$V_{\Phi S}(\Phi, S) = \frac{a_1}{2} \Phi^\dagger \Phi S + \frac{a_2}{2} \Phi^\dagger \Phi S^2$$

$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

- Models without Z_2 symmetry motivated by desire to explain electroweak baryogenesis
- (They typically prefer negative a_1 , b_3 and heavier H)

[Profumo, Ramsey-Musolf, Wainwright, Winslow, arXiv:1407.5342; Curtin, Meade, Yu, 1409.0005]

Enhanced hh in singlet model without Z_2



- Enhancements of hh by factors 10-15 if $M_H < 400 \text{ GeV}$
- Easy to arrange in many models.... Major constraint is $gg \rightarrow h$ needs to have observed rate
- Minimum of potential must give $v=246 \text{ GeV}$

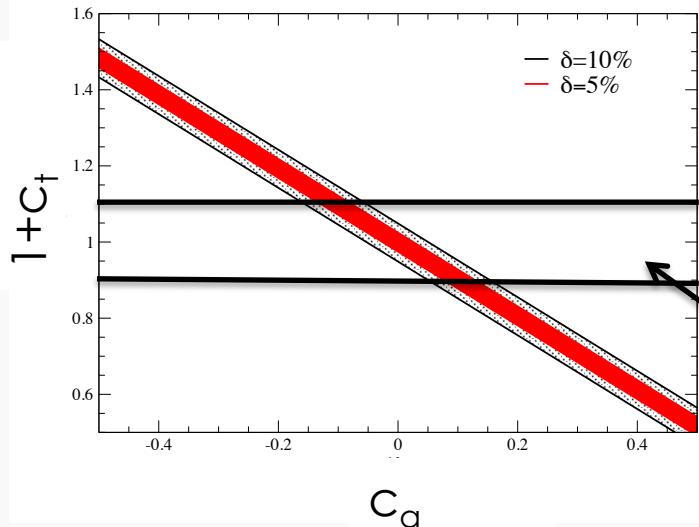
No resonance: Use EFT

- Very simple EFT:

$$L \sim L_{SM} + \frac{\alpha_s}{12\pi} \left(c_g \frac{h}{v} - \frac{c_{gg}}{2} \frac{h^2}{v^2} \right) G^{\mu\nu,A} G_{\mu\nu}^A$$

$$- c_t \frac{m_t}{v} \bar{t} t h + \frac{c_{2h}}{v} \bar{t} t h^2 - \delta \lambda_3 \frac{M_h^2}{2v} h^3$$

$gg \rightarrow h$ rate within δ of SM prediction



*Neglecting some derivative operators

$$A(gg \rightarrow h) = A^{SM} \left(\frac{M_h^2}{m_t^2} \right) [1 + c_t]$$

$$+ A^{SM}(0) c_g$$

Would be excluded by 20% measurement of $t\bar{t}h$

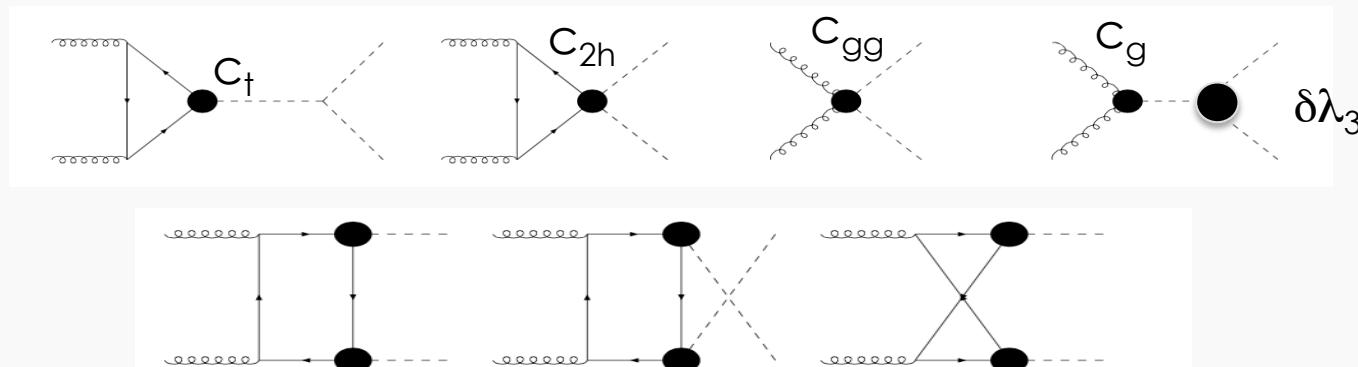
hh production breaks EFT degeneracy

- Single Higgs: $\frac{\sigma(gg \rightarrow h)}{\sigma(gg \rightarrow h)_{SM}} \sim 1 + 2(c_t + c_g)$
- If Higgs arises from a doublet, only $(\Phi^+\Phi)$ combination:

$$c_{gg} = c_g$$

$$c_{2h} = -\frac{3}{2} \frac{m_t}{v} c_t$$

Double Higgs rate not proportional to $c_t + c_g$



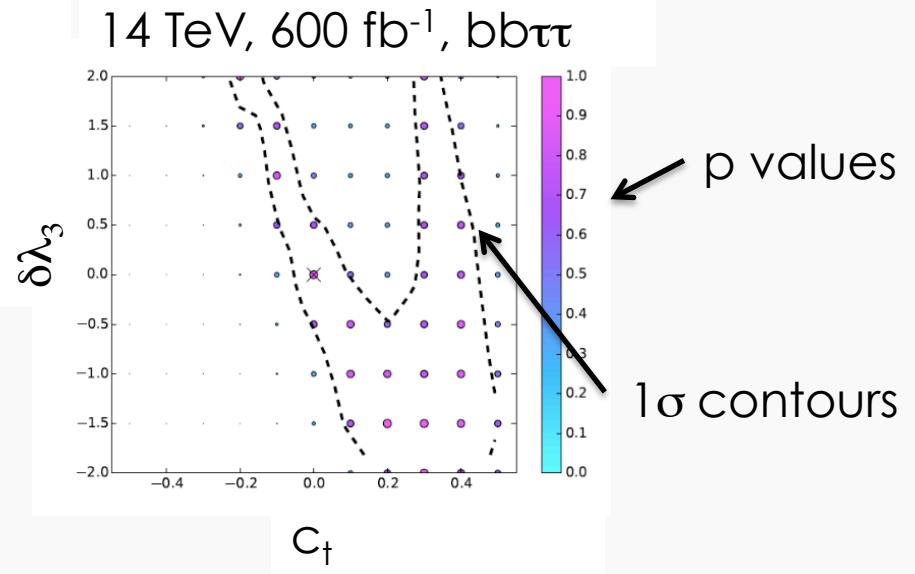
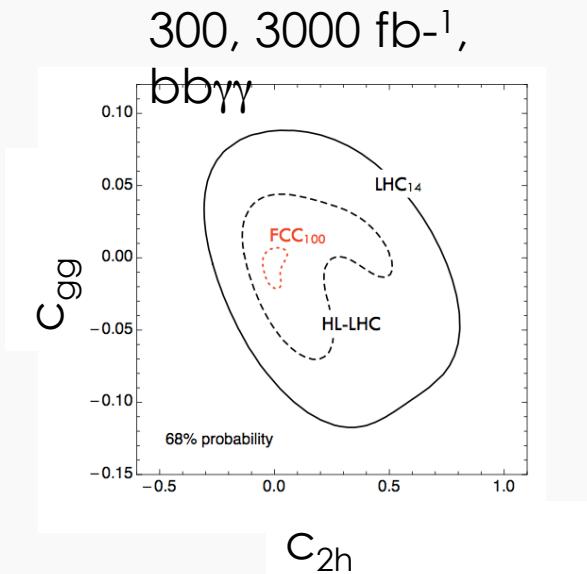
[Chen, Dawson, Lewis, arXiv:1410.5488]

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Fits to EFT Coefficients

- Many fits in literature
 C_{2h} , $\delta\lambda_3$ only probed in hh production
- Use kinematics of signal to improve fits (*Correlations!*)



[Azatov, Contino, Panico, Son, Arxiv: 1502.00539; Goertz, Papaefstathiou, Yang, Zurita, arXiv:1410.3471]

How big do you expect EFT coefficients to be?

- Singlet model only generates $\delta\lambda_3$

$$\delta\lambda_3 - 1 \sim \pm \left(\frac{v}{M_H} \right)^2 \sim .06 \left(\frac{1 \text{ TeV}}{M_H} \right)^2$$

* \mathbb{Z}_2 symmetry assumed

- Top partner model

$$c_g = c_{gg} \sim \left(\frac{\alpha_s \sin^2 \theta_t}{12\pi} \right) \sim \sin^2 \theta_t (.003)$$

- Colored scalar triplet

$$c_g = c_{gg} \sim - \left(\frac{\alpha_s \kappa}{96\pi} \right) \left(\frac{v}{m_s} \right)^2 \sim -2 \times 10^{-5} \kappa \left(\frac{1 \text{ TeV}}{m_s} \right)^2$$

These estimated coefficients are much smaller than projected sensitivities

[Dawson, Lewis, Zeng, arXiv:1501.04103 ; Chen, Dawson, Lewis, arXiv:1410.5488]

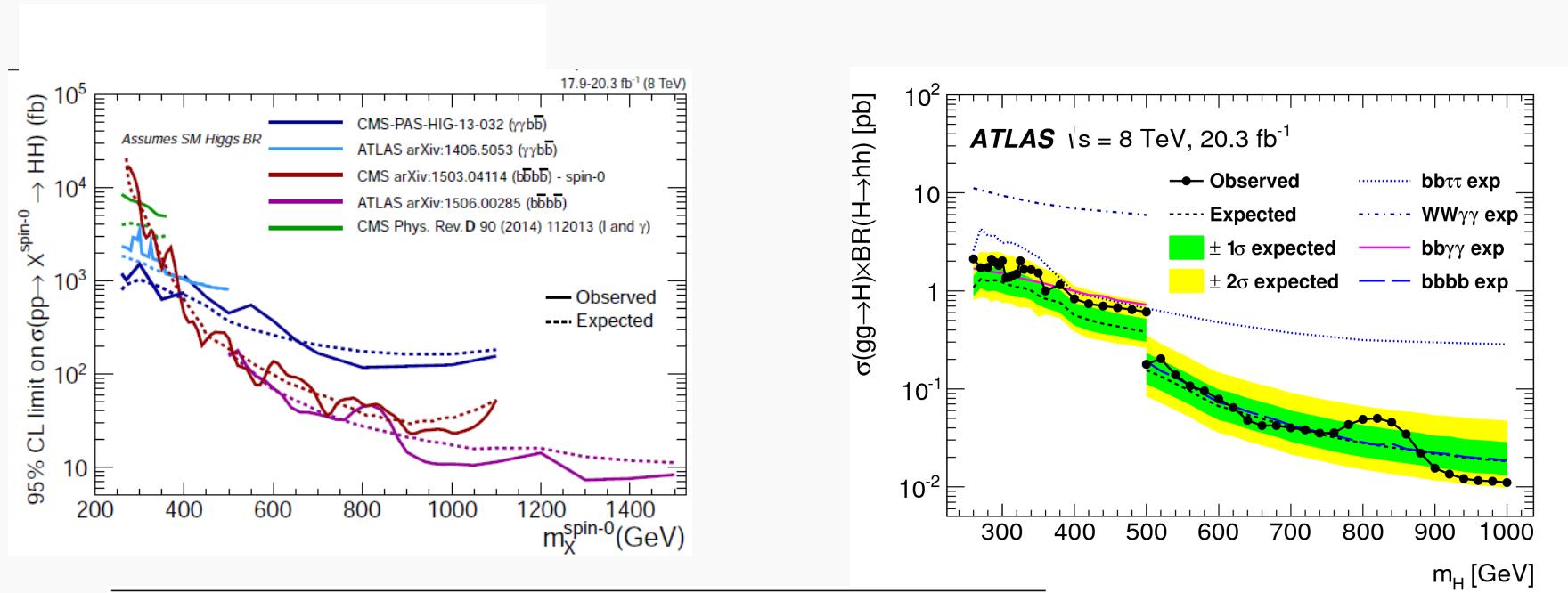
[See also, Brehmer, Freitas, Lopez-Val, Plehn, arXiv:1510.03443]

Observing hh production

- Small number of events:

Channel	BR[%]	Expected Events 8 TeV 20 fb-1	Expected Events 14 TeV 3 ab-1
bbbb	33	66	~40000
bb $\tau\tau$	7.3	15	~9000
bb $\gamma\gamma$	0.26	0.52	317
bbWW \rightarrow bblvjj	7.3	15	~9000
bbWW \rightarrow bblvlv	1.2	2.4	~1500
bbZZ \rightarrow bblljj	0.29	0.58	354
bbZZ \rightarrow bbllll	0.014	0.027	17

Searches



Non-
Resonant
Search

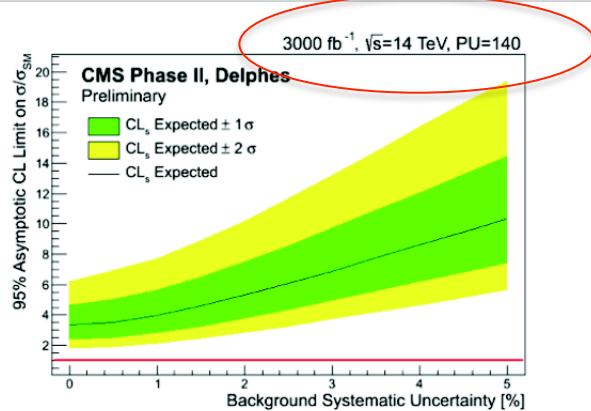
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Upper limit on the cross section [pb]					
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
Upper limit on the cross section relative to the SM prediction					
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

ATLAS, 8 TeV,
95% CL limits
from non-
resonant search

Cocktail of channels

Projections

hh \rightarrow bbWW (95%CL)



Observation of hh production with 3 ab $^{-1}$:
ATLAS, 1.3σ ; CMS 2σ

Measurement of hh coupling with 3 ab $^{-1}$:
ATLAS, $-1.3 < \delta\lambda_3 < 8.7$

Conclusions

- Measuring hh production required to understand Higgs potential
- Difficult to make hh rate much different from SM rate without resonant enhancement because of constraints from single Higgs production and electroweak measurements
- Small rates....serious study of experimental possibilities just beginning