Exploring the Scalar Sector with Double Higgs Production

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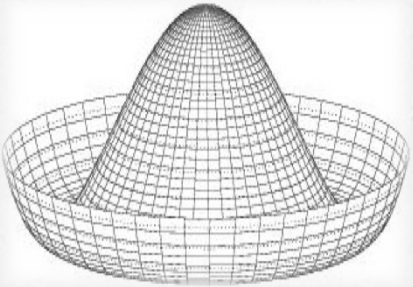
April 12, 2016



Talk based on:

- HH contribution to YR4 Higgs Cross Section Working Group (2016)

  https://svnweb.cern.ch/cern/wsvn/lhchiggsxs/documents/internal/LHCHXSWG-INT-2015-003/HHxIntRep.pdf

- Dawson & Lewis, arXiV: 1508.05397
- Chen, Dawson, & Lewis, 1410.5488; 1406.3349

SM Very Predictive

- Very precise predictions
  - Couplings to fermions proportional to mass $\frac{m_f}{v} h \bar{f} f$
  - Couplings to massive gauge bosons proportional to (mass)^2

$$2m_W^2 \frac{h}{v} W_\mu^+ W^{-\mu} + m_Z^2 \frac{h}{v} Z_\mu Z^\mu$$

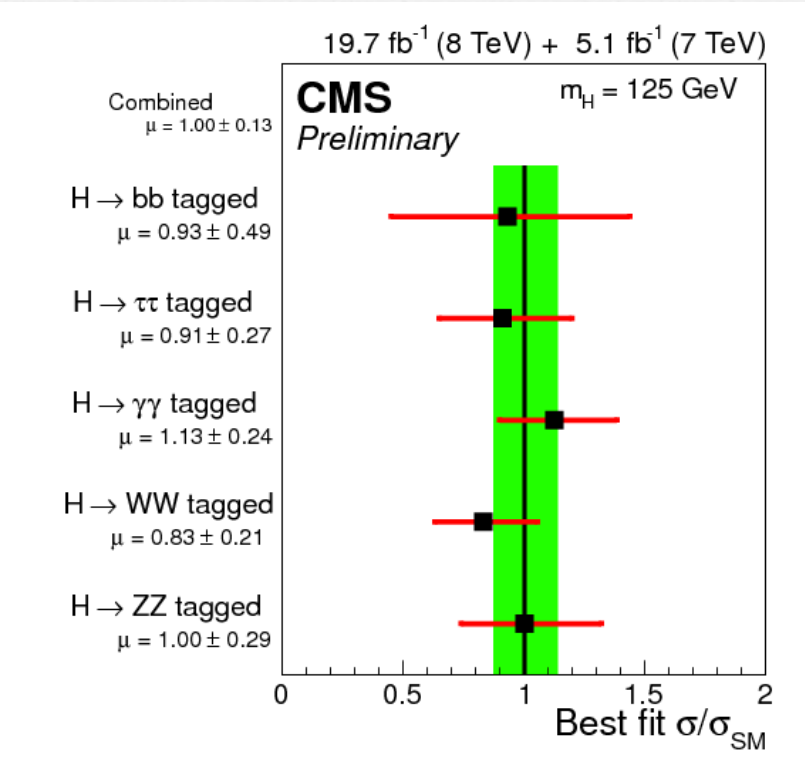
  - Couplings to massless gauge bosons at 1-loop

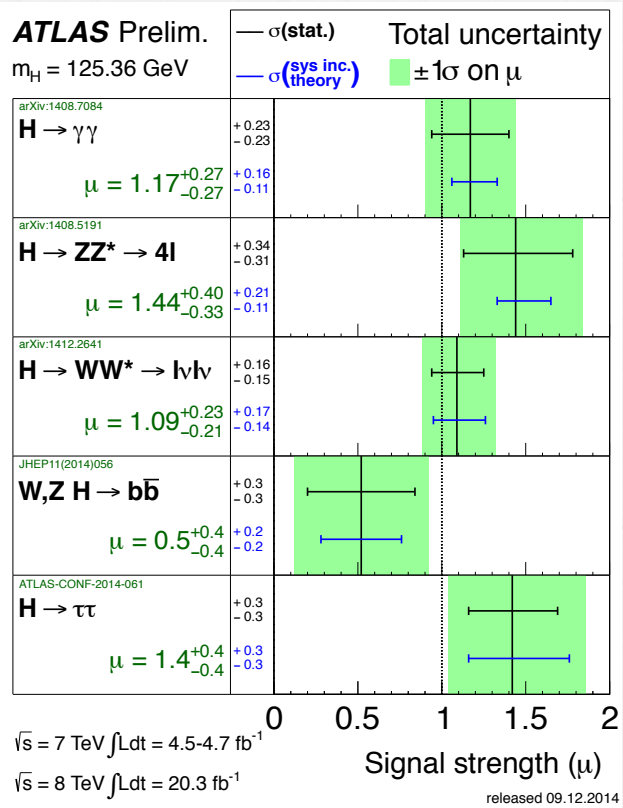
$$\kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^A_{\mu\nu} G^{A,\mu\nu} + \kappa_\gamma \frac{\alpha}{8\pi} \frac{h}{v} F_{\mu\nu} F^{\mu\nu} + \kappa_{Z\gamma} \frac{\alpha}{8\pi s_W} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu}$$

  - Higgs self-couplings proportional to m_h^2

$$\frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

Consistent with SM Hypothesis





Requires theory input!

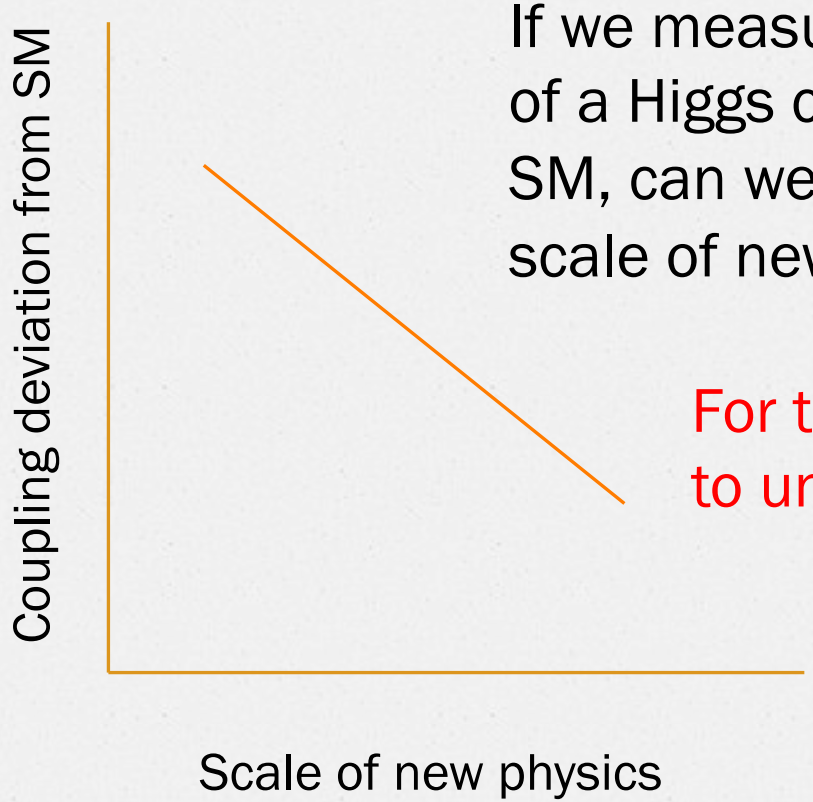
At the 10-30% level:

- Fermion couplings to b, t, τ ✔
- Gauge boson couplings to W/Z/g/γ ✔
- Higgs h^2 coupling ✔
- No information on hZγ, 2nd generation fermions, h^3, h^4 couplings....
- Generically, Higgs coupling deviations in BSM:

$$\mathcal{O}\left(\frac{v^2}{M^2}\right) \sim 5\% \left(\frac{1\ TeV}{M}\right)^2$$

Much work to do!

What we hope for



If we measure a large deviation of a Higgs coupling from the SM, can we associate it with a scale of new physics?

For this to work, we have to understand the SM first

Higgs self-couplings

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

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

- hhh and hhhh couplings predictions of theory
- Perturbative: $\lambda_3 = \frac{m_h^2}{2v} \sim .13v \quad \lambda_4 = \frac{m_h^2}{8v^2} = .03$
- In general: Corrections to relationship between λ_3 and λ_4 of $O(1/\Lambda^2)$

* This is NOT true in models with new light particles

Higgs Production at 13 TeV

	σ(pb) at 13 TeV	σ(pb) at 8 TeV
Gluon Fusion	43.9	19.27
VBF	3.748	1.578
Wh	1.38	.70
Zh	.87	.42
tth	.51	.13
hh	.034	.008

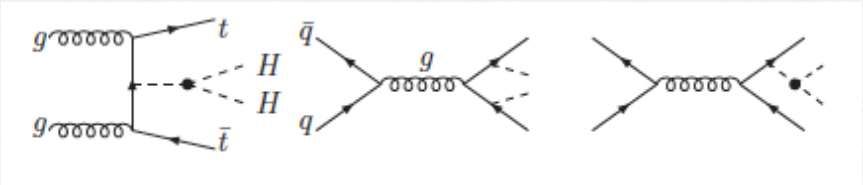
Factors of 2-4 increases in rates

Note large increase in tth and hh rates!

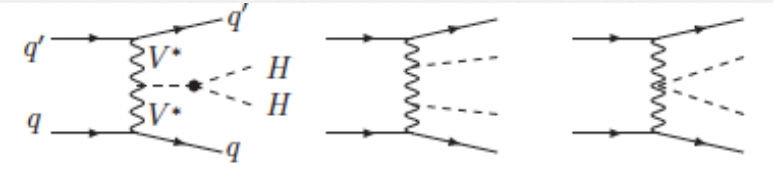
[Higgs Cross Section Working Group]

Production of hh

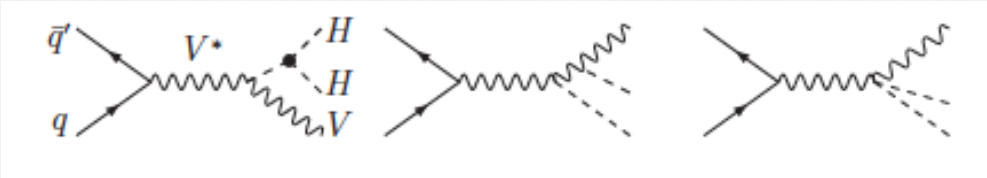
Sensitive to heavy colored particles (eg stops or top partners)



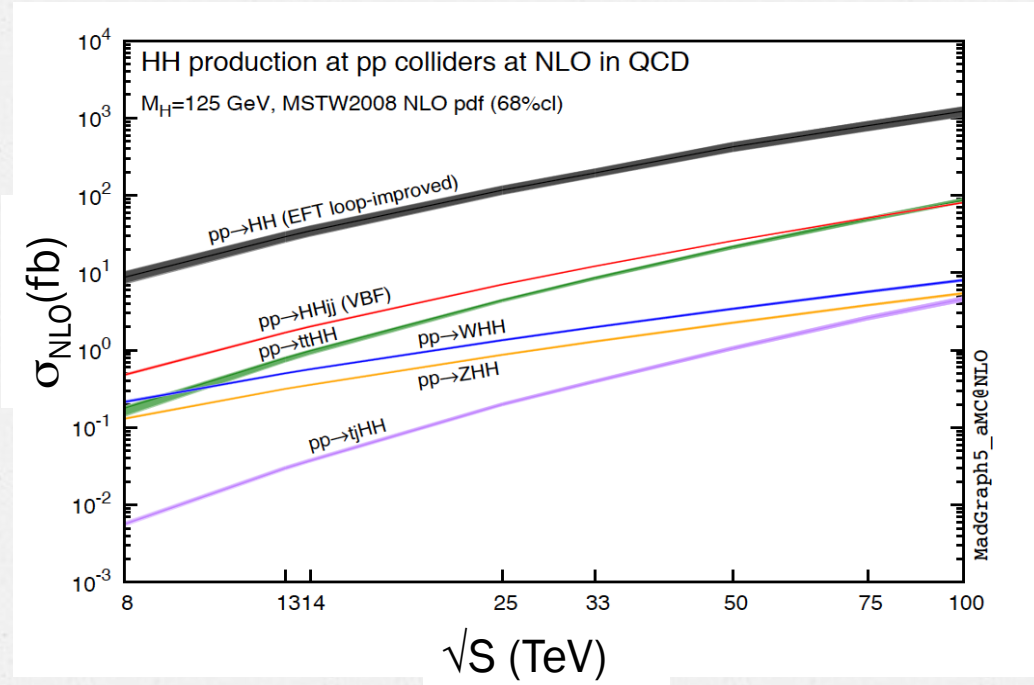
Sensitive to anomalous top-Higgs couplings



Sensitive to anomalous VVhh couplings



Small Rates for hh

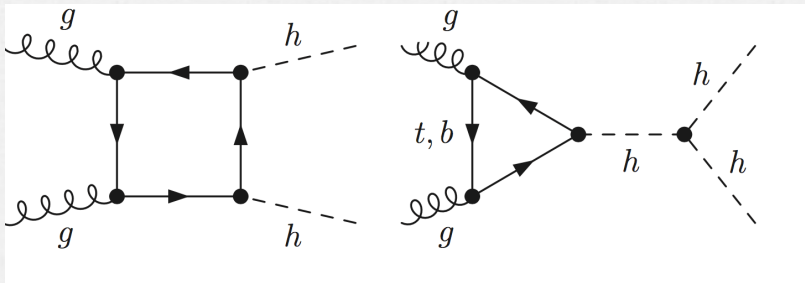


- Only gluon fusion likely to be relevant
- Large increase in hh rate at high energy

* Light bands, LO, Solid bands NLO

[Frederix et al, 1408.5147]

Production of hh



- Dominant production from gluon fusion through top quark loops
- Sensitive to Higgs tri-linear coupling
- Large cancellation between box and triangle (vanishes at threshold) ➡ reduces sensitivity to λ_3

Two Higgs Production at LHC

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

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

- M_t^2>>s, p_T^2 (low energy theorem)

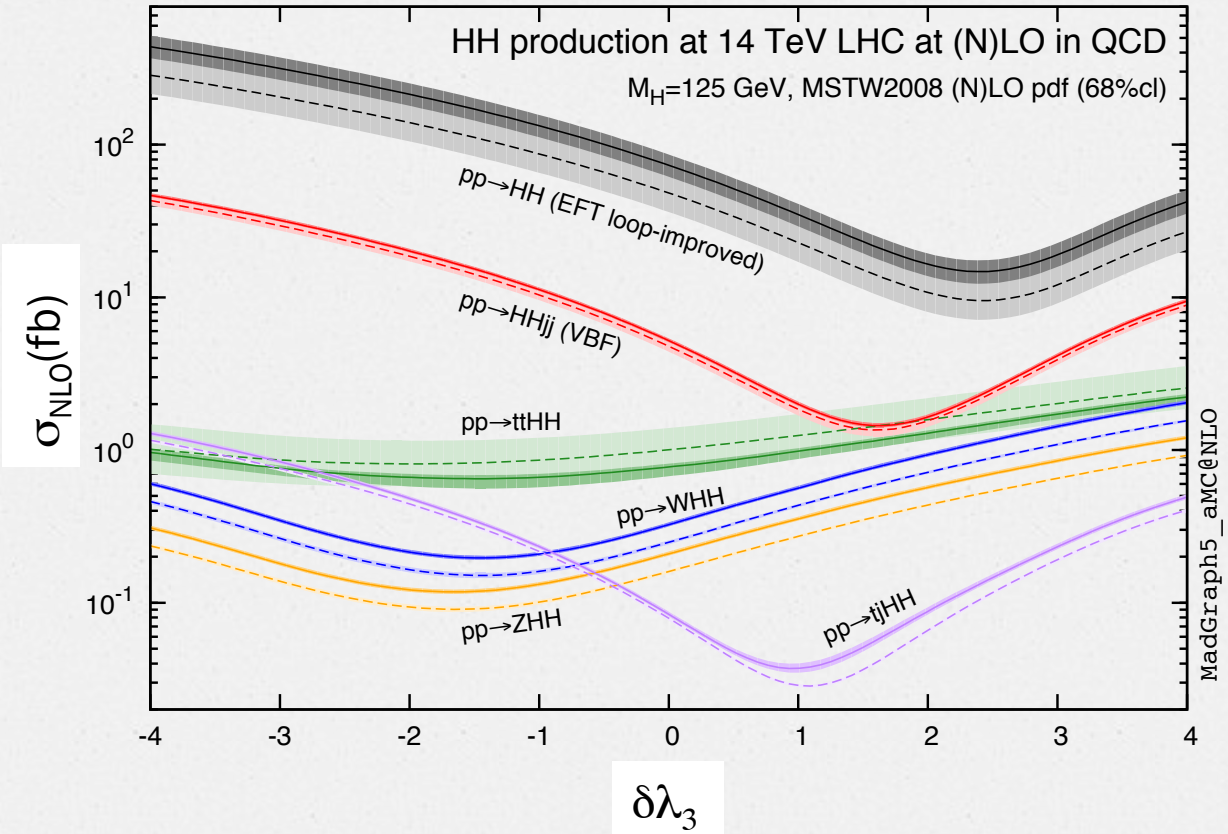
$$F_0 \to -\frac{4}{3} + \frac{4M_h^2}{s - M_h^2}(\lambda_3)$$

$$F_2 \to 0$$

hhh coupling (1 for SM)

- For large s, dependence on λ_3 suppressed
- More sensitivity to negative λ_3
- Exact cancellation at threshold

hhh coupling: λ_3



Current Searches Far from SM

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

Cocktail of channels: $\sigma/\sigma_{SM} < 70$

$$8\ TeV : \sigma = 11.2\ fb^{+4.1\%+4.4\%}_{-5.7\%-4.0\%}$$

$$13\ TeV : \sigma = 37.9\ fb^{+4.3\%+3.1\%}_{-6.0\%-3.1\%}$$

Scale, PDF+α_s uncertainties

A few 13 TeV hh Results

- Not yet competitive with 8 TeV results
- CMS: hh→ bbττ
- $\kappa_\lambda = \lambda_3/\lambda_{3SM}$

k_λ	Observed (expected) upper limits [pb]								Theoretical cross section [pb]
	$bb\mu\tau_h$		$bbe\tau_h$		$bb\tau_h\tau_h$		Combined		
-20	59.6	(49.6)	53.9	(70.4)	20.9	(20.9)	19.8	(19.0)	5.5
-1	38.1	(30.4)	31.3	(42.7)	14.2	(12.8)	13.2	(11.6)	0.146
0	32.2	(25.5)	25.8	(35.4)	12.3	(10.6)	11.3	(9.6)	0.81
1	25.3	(19.6)	19.4	(26.9)	9.8	(8.1)	8.8	(7.2)	0.038
2	21.4	(15.9)	15.4	(21.7)	8.2	(6.5)	7.3	(5.7)	0.018
5	107	(82.7)	85.0	(111)	29.0	(30.1)	28.6	(28.0)	0.089
20	73.5	(62.3)	69.3	(89.0)	24.4	(25.9)	23.4	(23.7)	3.4
30	88.2	(59.7)	85.3	(86.0)	23.7	(24.9)	22.7	(22.8)	8.4

SM

Projections

- Observation of hh production with 3 ab^{-1}: ATLAS, 1.3σ; CMS 2σ
- Measurement of hhh coupling with 3 ab^{-1}: ATLAS, $-1.3 < \lambda_3 < 8.7$

Double Higgs production is strong motivation for 100 TeV collider

- At 100 TeV, rate is (46)* rate at 13 TeV
- Projection is 30% measurement of $\delta\lambda_3$ at 100 TeV

[Arkani-Hamed, Han, Mangano, Wang, arXiv: 1511.06495]

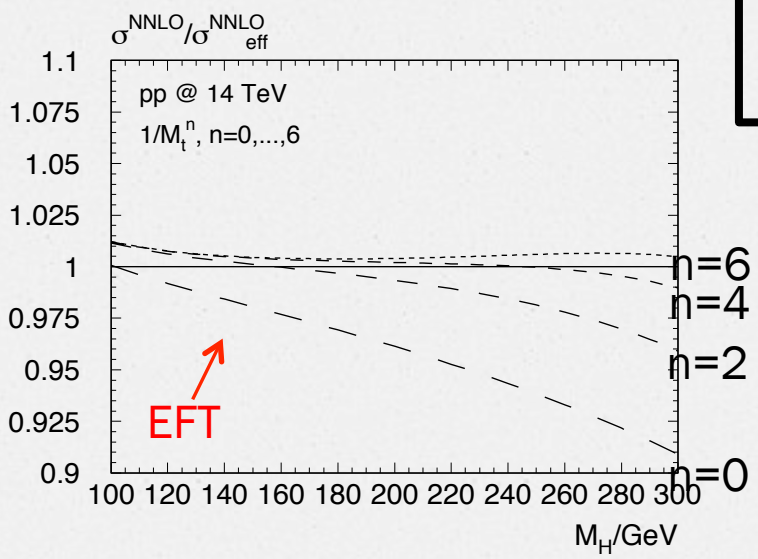
Computing NLO Corrections

- Use effective Lagrangian: $L = \frac{\alpha_s}{12\pi}\frac{h}{v}G^A_{\mu\nu}G^{\mu\nu,A}$

- Used to calculate single Higgs production to NNLO
- Compute K factor and then weight LO (with top mass dependence)
- Know exact NLO result, so can check validity

ggh checked at NNLO

- Top contribution verified by expansion in $(M_h^2/m_t^2)^n$
- EFT (n=0) accurate to ~ 2% for M_h=126 GeV



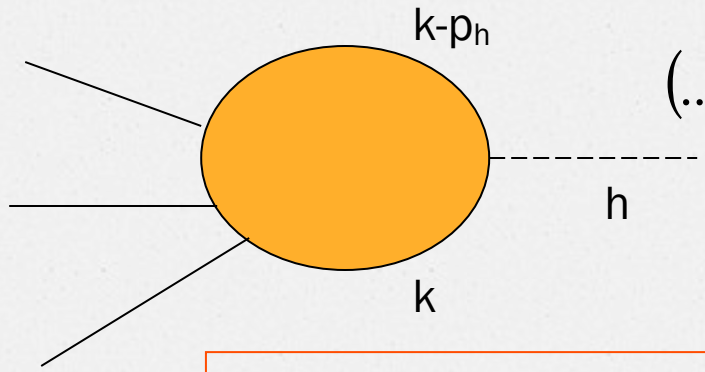
$1/m_t^2$ expansion converges well for gg → h

gg→h is a 1-scale problem (M_h)

[Harlander, Mantler, Marzani, Ozeren, 0912.2104; Pak, Rogel, Steinhauser, 0911.4662]

Effective Theory for Heavy Particles

- Integrate out heavy top, $M_h << m_t$
- Several ways to derive low energy theorems



$$(\ldots\ldots)\frac{i}{k-m}\frac{-im}{v}\frac{i}{(k-p_H)-m}$$

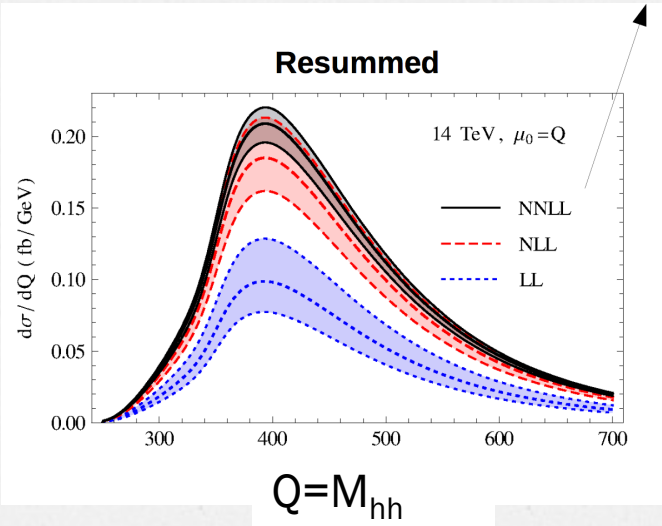
$$\rightarrow \frac{im}{v}\left(\frac{1}{k-m}\right)^2$$

$$\boxed{\lim\ p_H \rightarrow 0\ \ M(XH) = \frac{m^0}{v^0}\frac{\partial}{\partial m^0}M(X)}$$

$$L^n = \frac{\alpha_s}{12\pi}G_{\mu\nu A}G^{A,\mu\nu}\log\left(1+\frac{h}{v}\right)$$

Progress in SM Calculations

- Dominant process is gg → hh
  - Threshold resummation at NNLL matched to NNLO
  - These calculations are in $m_t \to \infty$ limit



Excellent convergence of series

[De Florian, Mazzitelli, 1505.07122]

Double Higgs Production

- QCD corrections computed in $m_t \to$ infinity limit and weighted by exact LO calculation
- Rates known to NNLO-NNLL ➡ large corrections

$$K \equiv \frac{\sigma_{NNLO}}{\sigma_{NLO}}$$

$$K' \equiv \frac{\sigma_{NNLO}}{\sigma_{LO}}$$

Calculated in $m_t \to \infty$ limit

	$\sqrt{s} = 7\ TeV$	$\sqrt{s} = 8\ TeV$	$\sqrt{s} = 13\ TeV$	$\sqrt{s} = 14\ TeV$	$\sqrt{s} = 100\ TeV$
K	1.203	1.200	1.193	1.192	1.195
K'	2.299	2.296	2.301	2.304	2.472

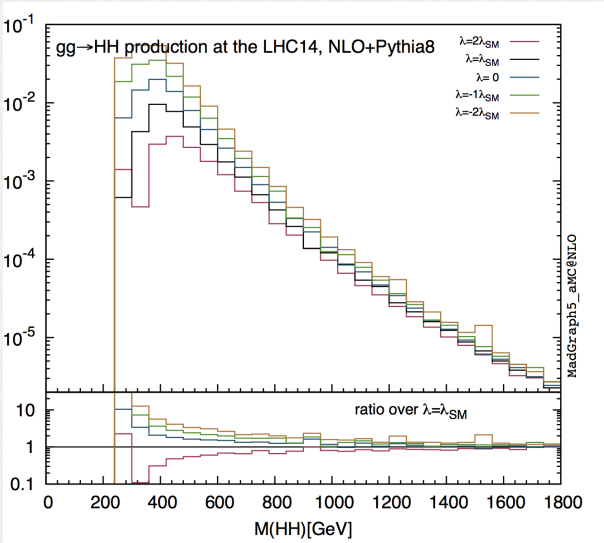
Renormalization/factorization scale choice $\mu_0 = m_{hh}/2$ reduces effects of summing large logarithms

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

Dependence on λ3 at NLO, NNLO

$\delta\lambda_3/\lambda_{SM}$	$\sigma_{NNLL}/\sigma_{NNLL,SM}(\delta\lambda_3)$ -2	-1.5	-1	-0.5	1
$\sqrt{s} = 7$ TeV	4.17	3.12	2.24	1.53	0.452
$\sqrt{s} = 8$ TeV	4.09	3.06	2.21	1.52	0.455
$\sqrt{s} = 13$ TeV	3.85	2.92	2.13	1.49	0.466
$\sqrt{s} = 14$ TeV	3.82	2.90	2.12	1.49	0.467
$\sqrt{s} = 100$ TeV	3.39	2.62	1.97	1.43	0.492

de Florian, Mazzitelli

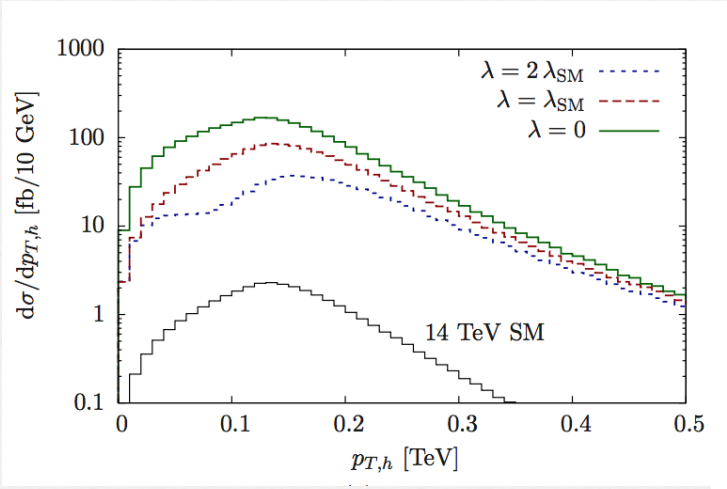


Rates and distributions significantly changed by non-SM λ_3

* Normalization is $\delta\lambda_3$=0 in SM limit

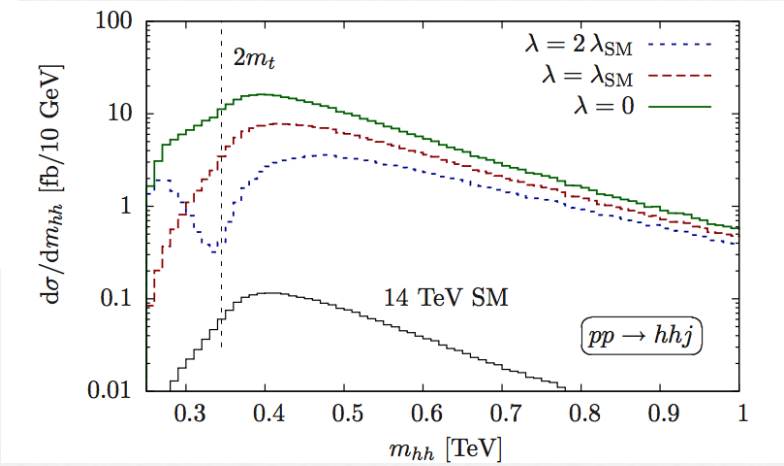
Vryonidou, Zaro

Need to understand Shapes



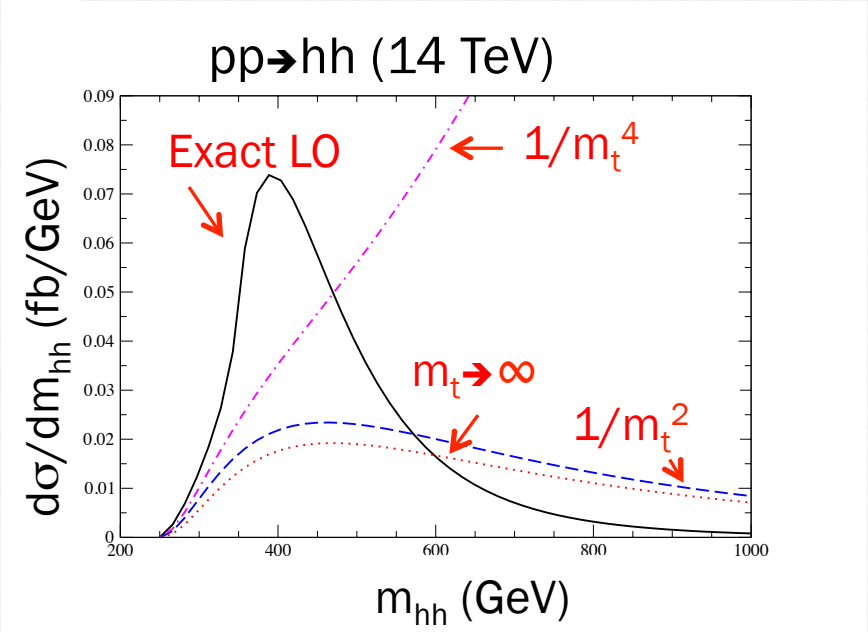
Barr et al, arXiv:1412.7154

LO plots



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 improve distributions

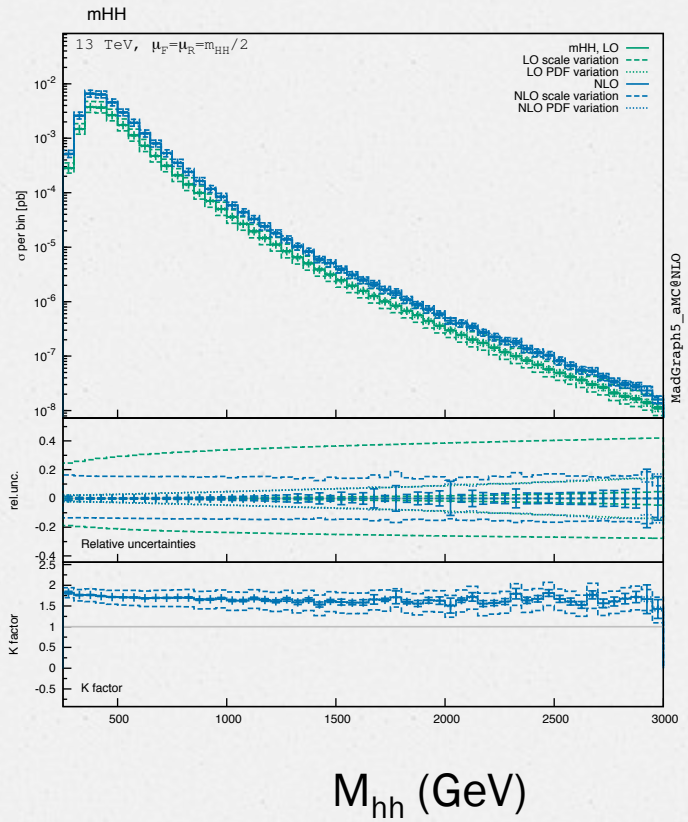
[Dawson, Furlan, and Lewis, arXiv:1210.660]

Towards including m_t effects at NLO

- HOW BIG ARE $1/m_t^2$ CORRECTIONS?
- Compute NLO with virtual corrections in $m_t \to \infty$ limit and real corrections with exact m_t dependence (MadGraph5_aMC@NLO)
- Compute $1/m_t^{2n}$ corrections to NNLO and normalize to exact LO
- Different results from 2 approaches
- Arbitrarily assign ±10% uncertainty from m_t dependence

Distributions at NLO

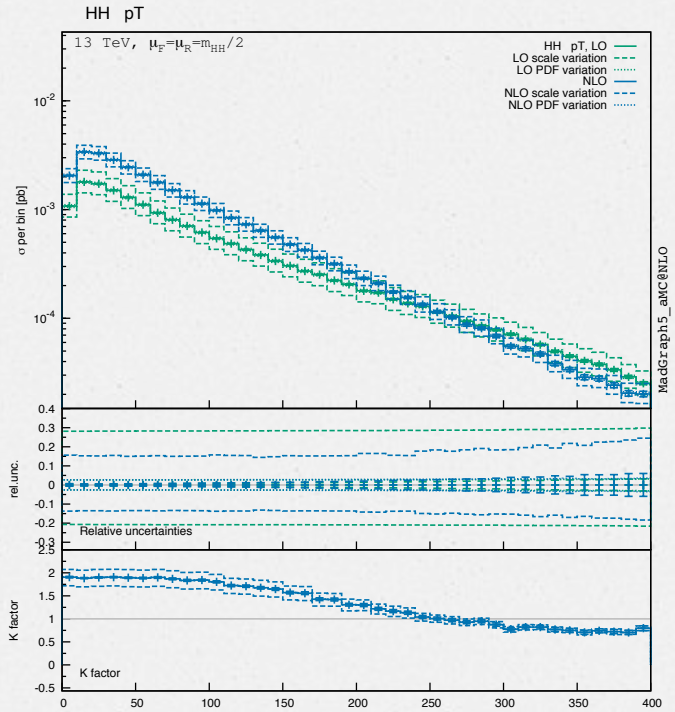
- MadGraph5_aMC@NLO gets m_t dependence in real emission corrections
- Differential uncertainties from scale/PDF~O(30%)
- K factor relatively flat for M_{hh}: LO*K factor ok here



M_{hh} (GeV)

Distributions at NLO

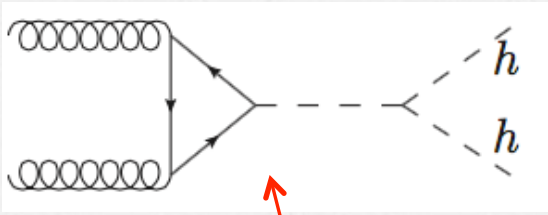
- Not all distributions have flat K factors
- Distributions which are sensitive to hard gluon emission aren't just rescaling of LO
- Assign larger uncertainty

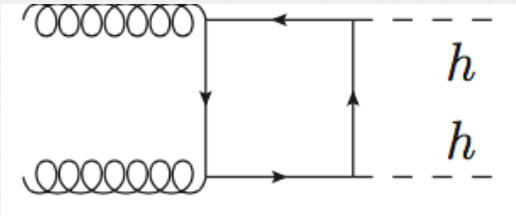


$p_T(hh)$

What is contributing to hh?

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



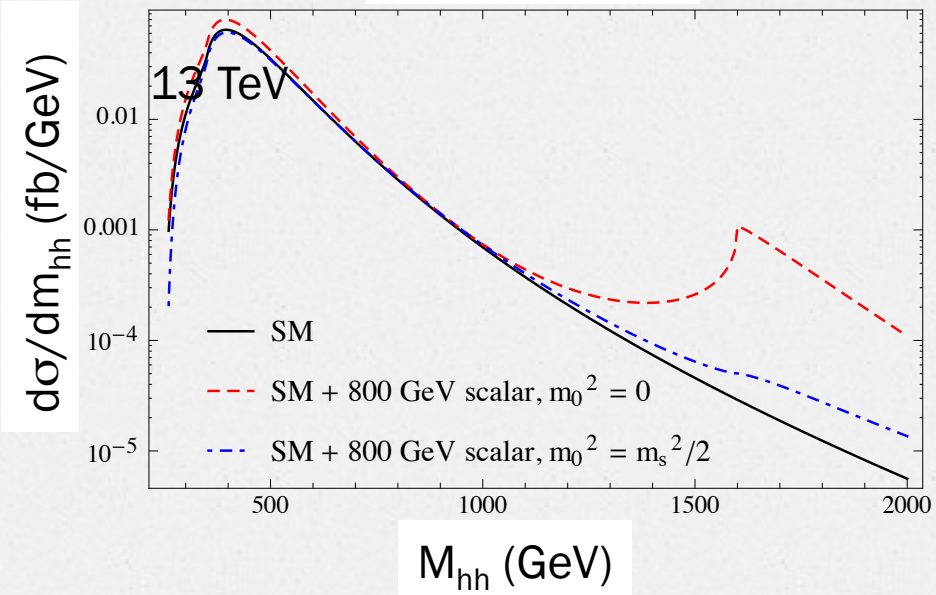


Parameters restricted by requirement that gg→h has SM value

What about adding a scalar?

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

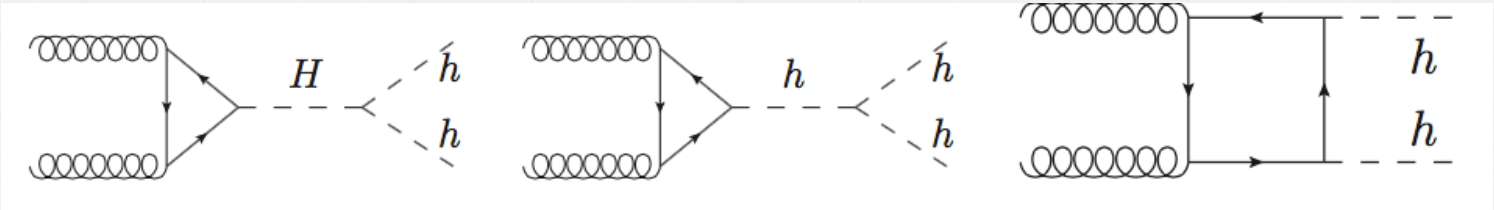
$$pp \to hh$$



[Dawson, Ismail, Low, arXiv:1504.05596]

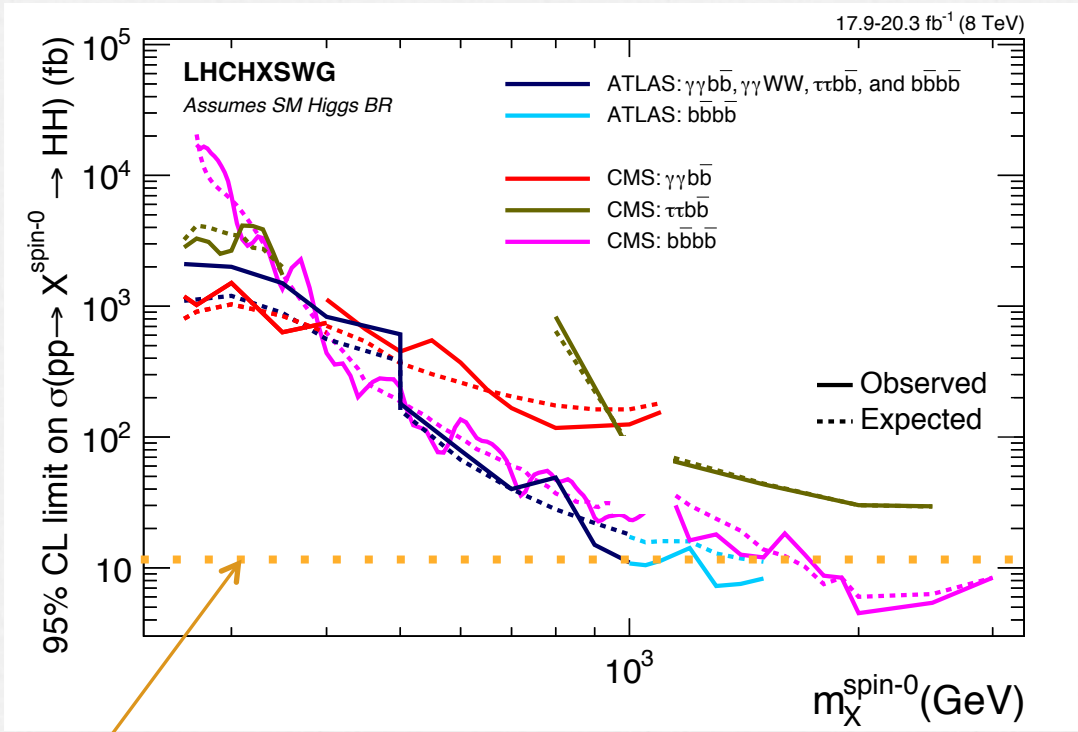
Resonances Can Increase Rate

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



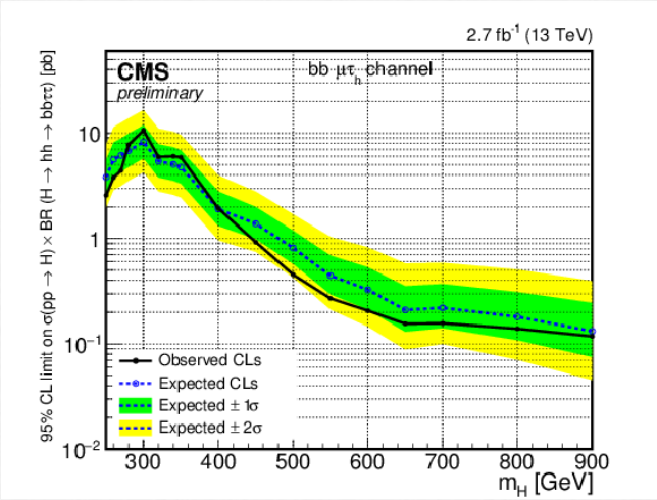
- Model can be dark matter portal
- (Simple explanation for 750 GeV $\gamma\gamma$ excess)
- Similar results in MSSM, NMSSM,2HDM…

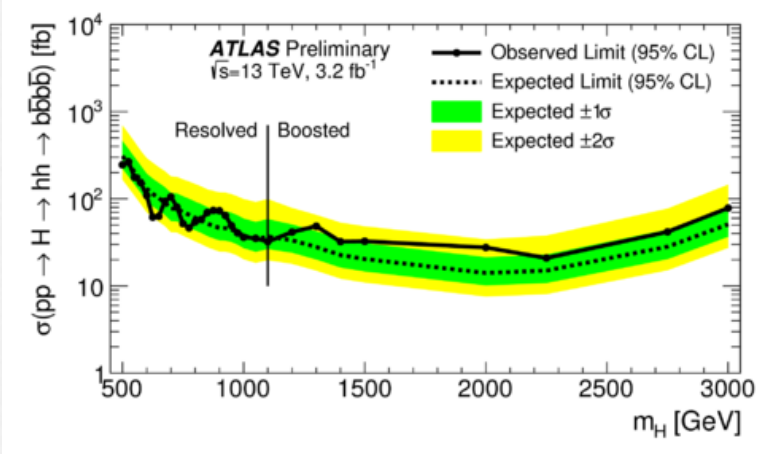
hh Sensitive to New Resonances



* σ_{SM}=11 fb at 8 TeV

Resonance Searches at 13 TeV





Not yet competitive with 8 TeV limits

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:

$$h = \cos\alpha h_{SM} - \sin\alpha S$$

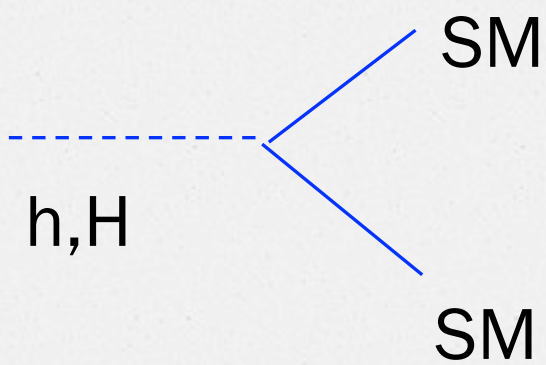
$$H = \sin\alpha h_{SM} + \cos\alpha S$$

- Physical parameters:

$$\boxed{M_h = 125\ GeV, M_H, v = 246\ GeV, tan\beta = \frac{v}{\langle S \rangle}, \theta}$$

Z_2 symmetric singlet model

- If kinematically allowed, H ➔ hh

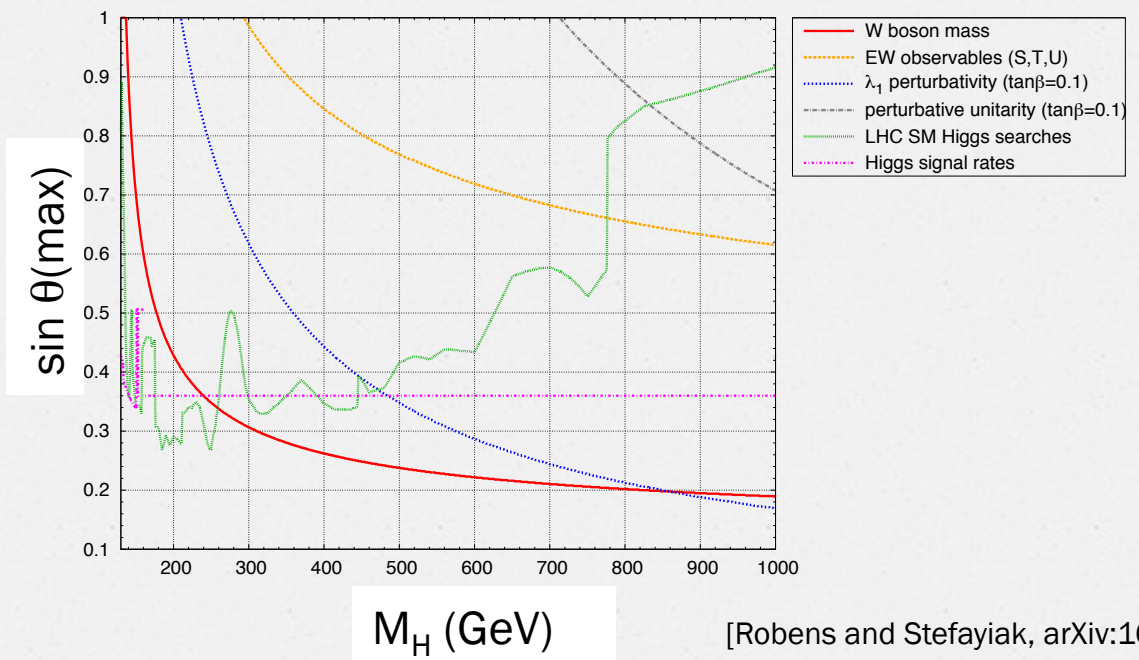


Coupling to light Higgs ~ cos θ
Coupling to heavy Higgs ~ sin θ

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

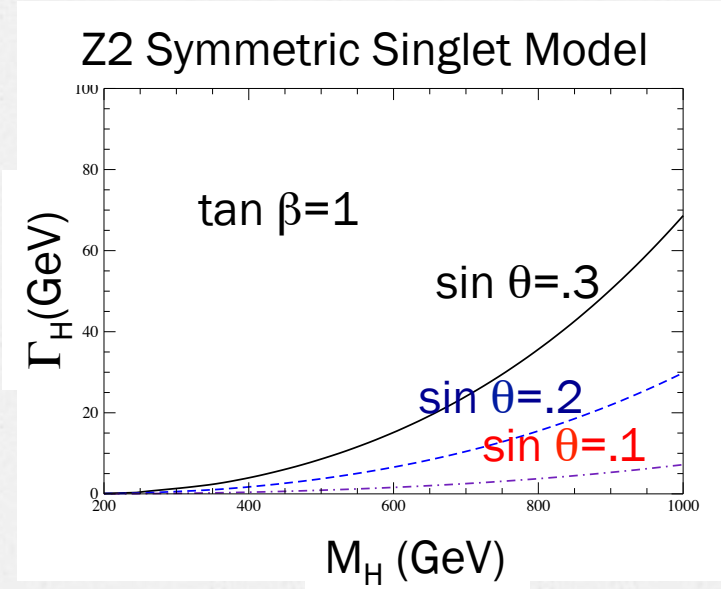
Limits on Singlet Model

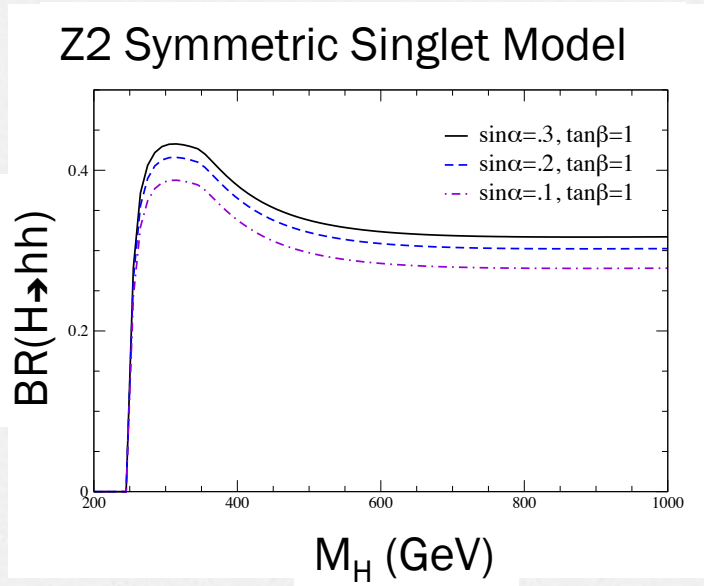
- SM Higgs couplings restrict cos θ<.94 (ATLAS)
- Heavy H contributes to W mass



[Robens and Stefayiak, arXiv:1601.07880]

Branching ratio $H \to hh$





Large tan β gives problems with perturbative unitarity of hh→hh

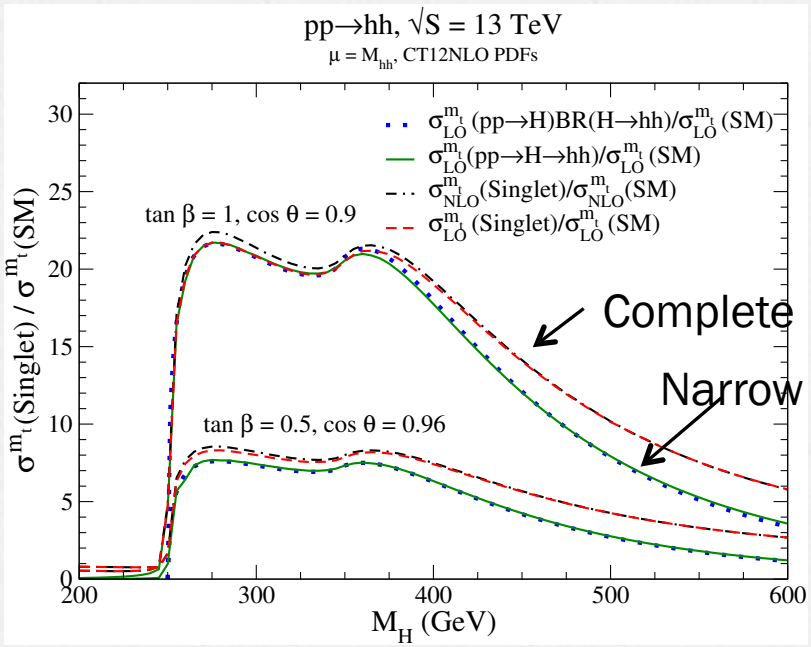
$$\tan\beta < 1.3\left(\frac{600\ GeV}{M_H}\right)$$

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

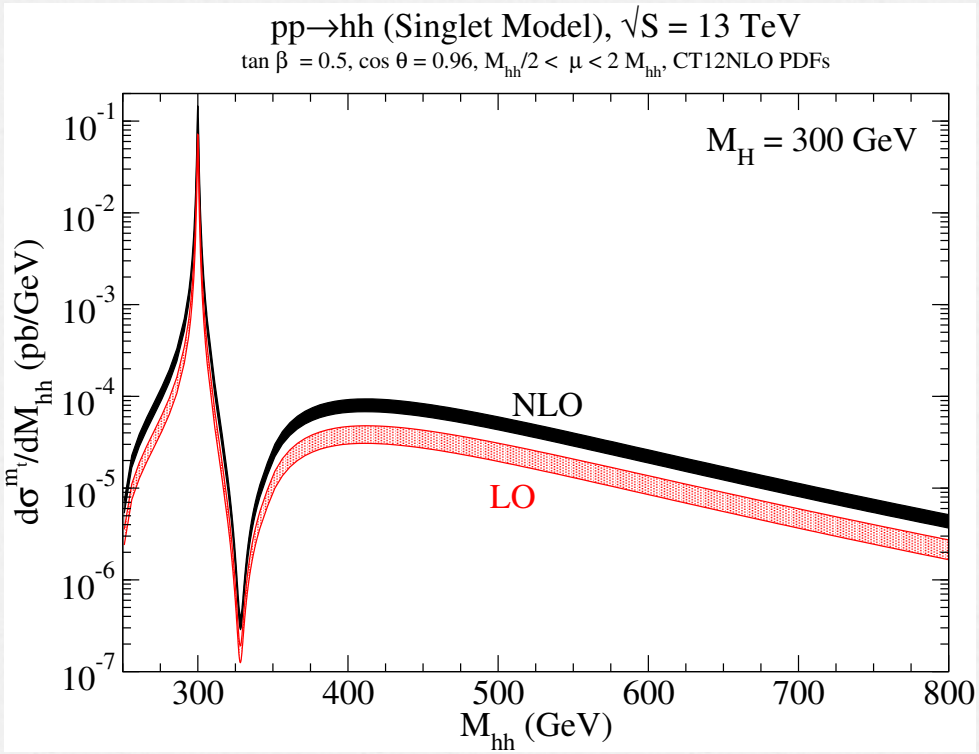


[Dawson, Lewis, arXiv:1508.05397]

NLO corrections to singlet model

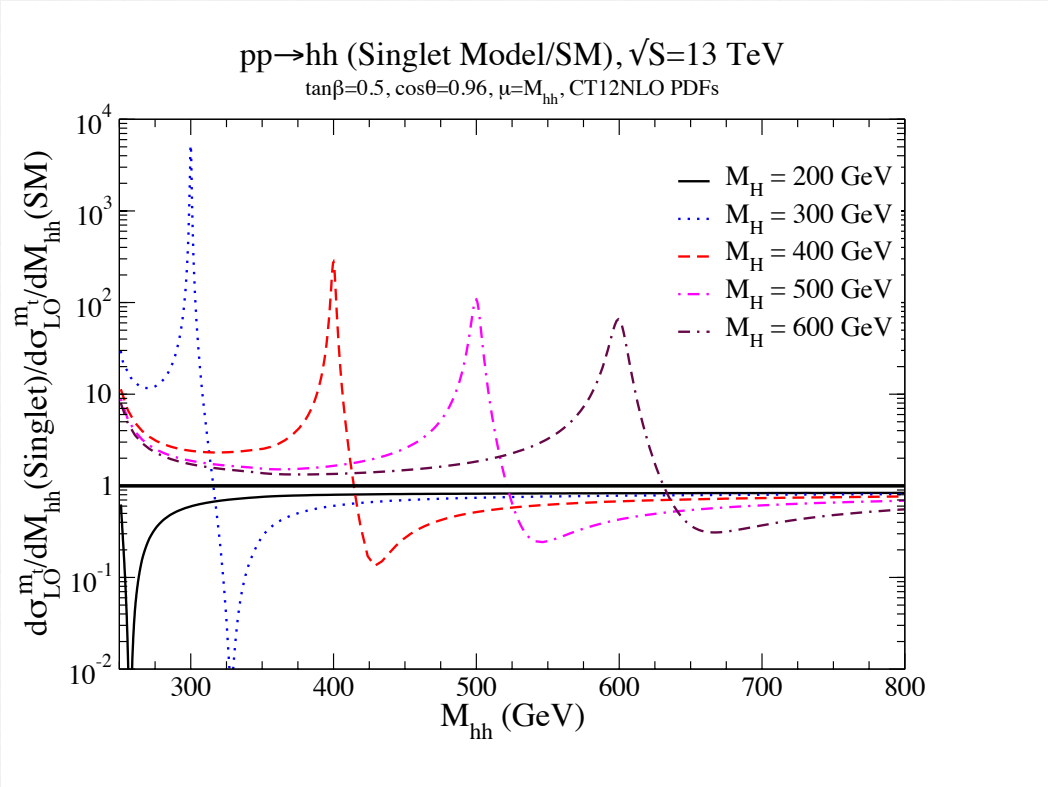
- Computed in $m_t \to \infty$ limit

K factor ~ 2
(as in SM)



[Dawson, Lewis, arXiv:1508.05397]

Large resonance/interference effects



[Dawson, Lewis, arXiv:1508.05397]

Relax Z_2 Assumption

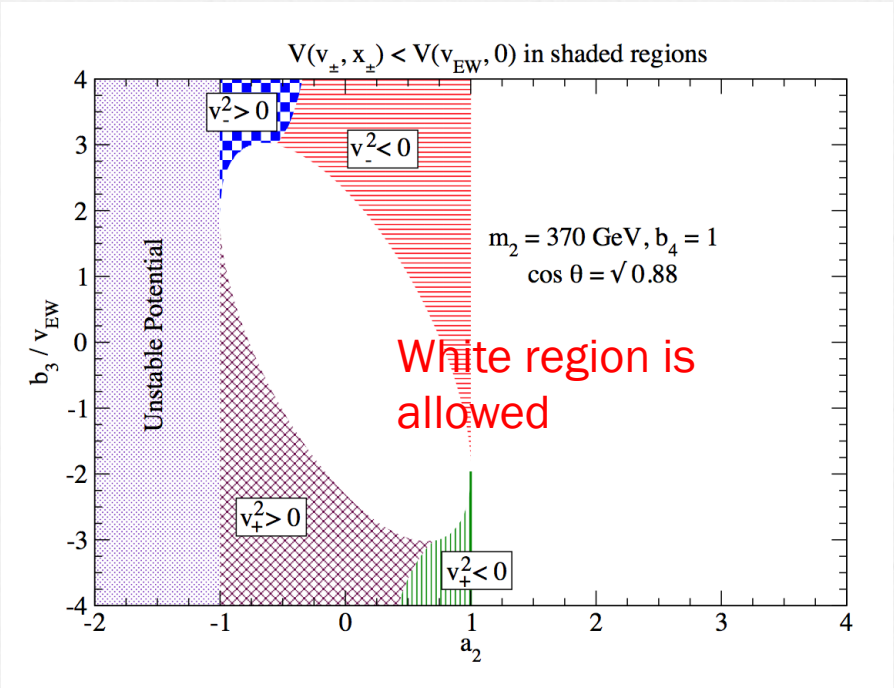
$$
\begin{aligned}
V_H(H) &= -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \\
V_{HS}(H,S) &= \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2 \\
V_S(S) &= b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4
\end{aligned}
$$

Motivated by possibility of 1st order EWPT (Occurs for specific values of parameters; wants negative a_1)

Free parameters:
m_h, M_H, θ ,v=246 GeV, x=0, a_2,b_3,b_4

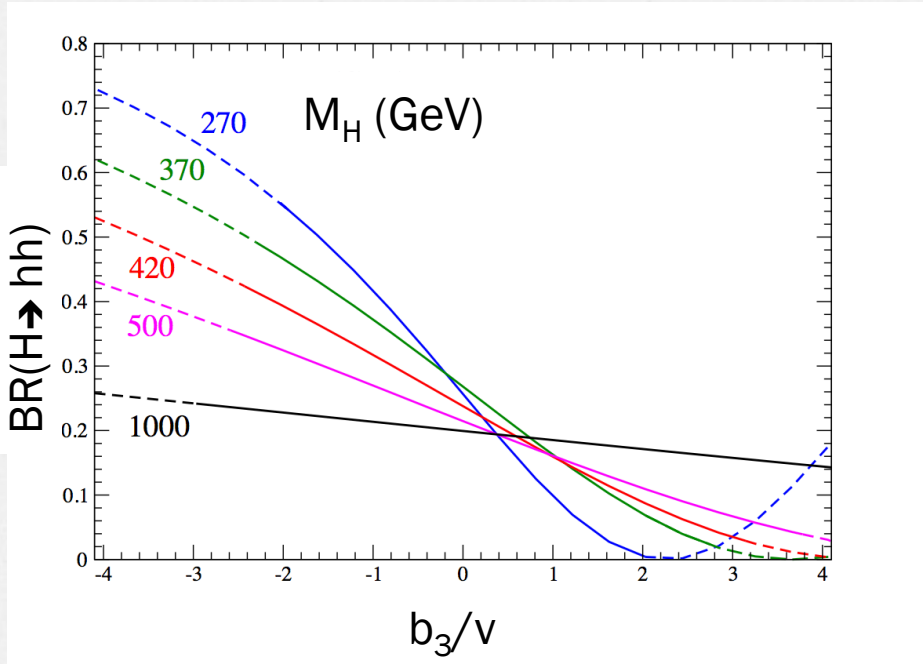
Minimizing potential

- EW minimum must be lowest minimum
- Can always redefine parameters so <S>=x=0

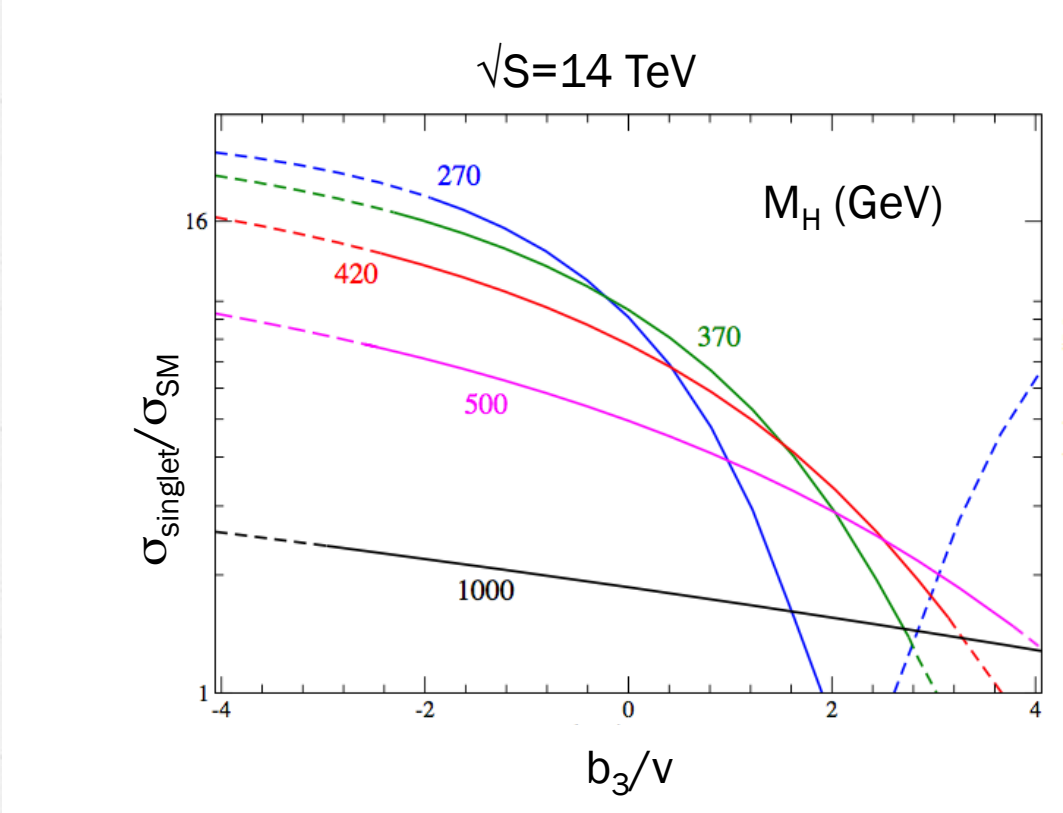


Large BR(H → hh)

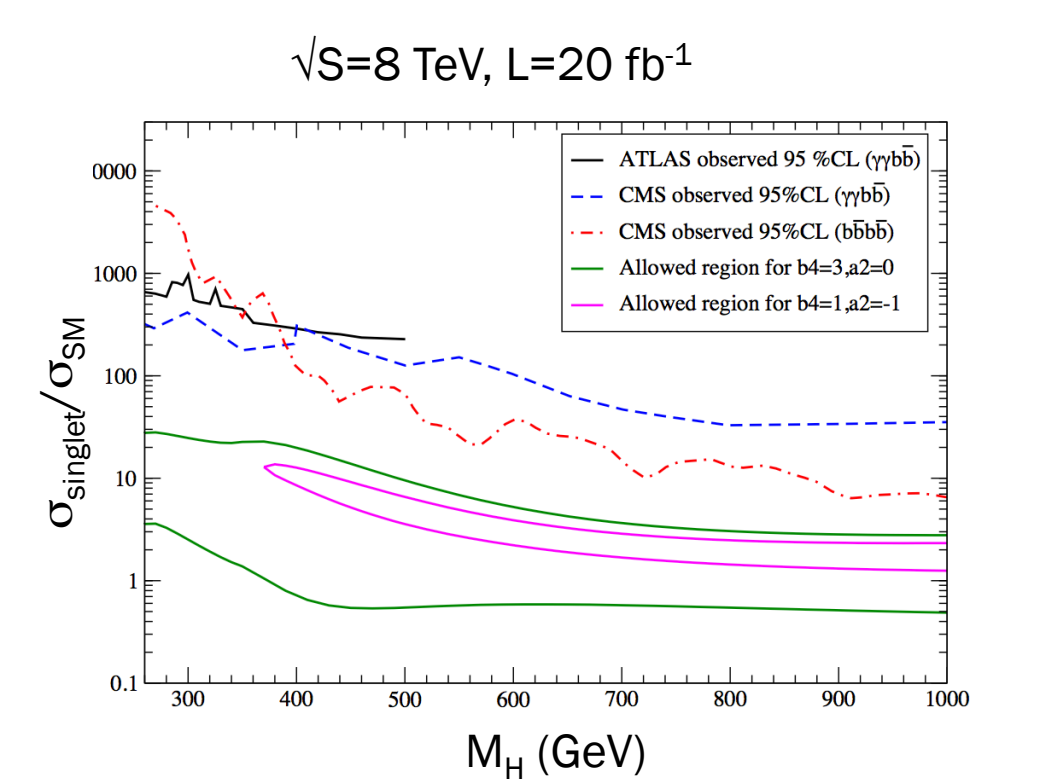
- Dashed regions excluded by vacuum stability



Di-Higgs a "Smoking Gun"

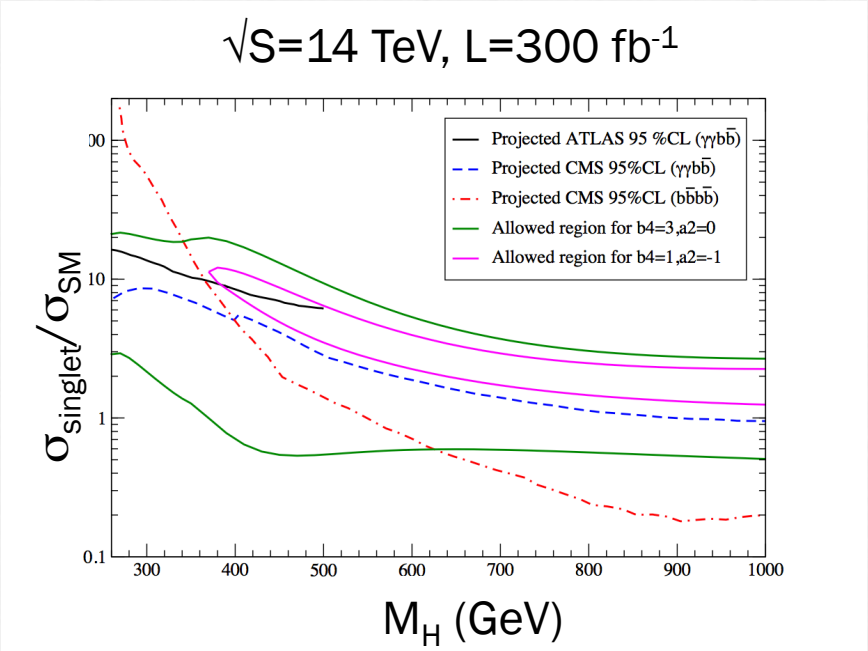


Di-Higgs Rate



Theory Projection

- Scale 8 TeV numbers by cross section/ luminosity ratio



S. Dawson, BNL, April 12, 2016

It's not just λ3

- Construct consistent effective field theory: EFT

$$L \sim L_{SM} + \Sigma_i \frac{C_i}{\Lambda^{n-4}} O_n$$

- Assume new physics decouples at high scales
  - *No new light particles*
  - Λ is scale of new physics >> v
  - EFT valid at E << Λ
  - *No unique operator basis*

Not just λ_3

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

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

  In general, contributions highly correlated

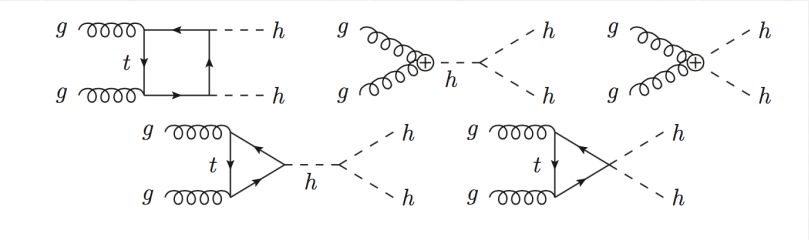
- Non-linear EFT relevant parameters for hh:

  c_g, c_{gg}, c_t, c_{2h}, $\delta\lambda_3$

- Linear EFT, $c_g = c_{gg}$, $c_{2h} = -(3m_t/2v)c_t$,
  relevant parameters for hh: c_g, c_t, $\delta\lambda_3$

Linear EFT assumes Higgs is a doublet

Double Higgs Production in EFT



δy_t, c_g constrained by single Higgs production

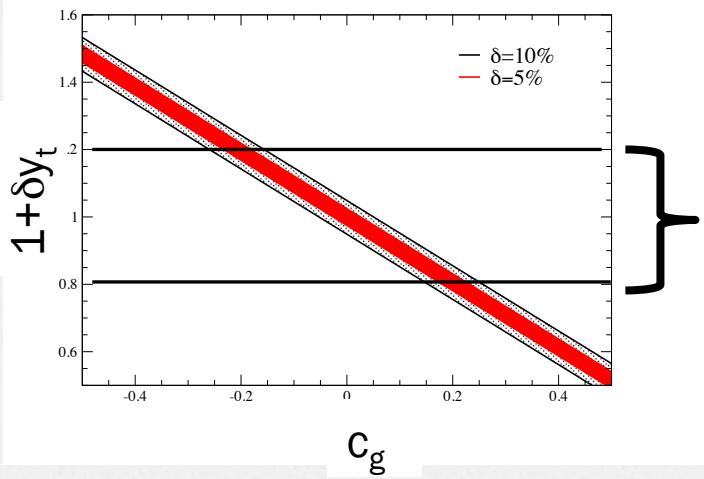
$\delta\lambda_3$, c_{gg} and c_{2h} can only be constrained by 2 Higgs production

Some EFT Parameters Restricted

- Single Higgs production close to SM value

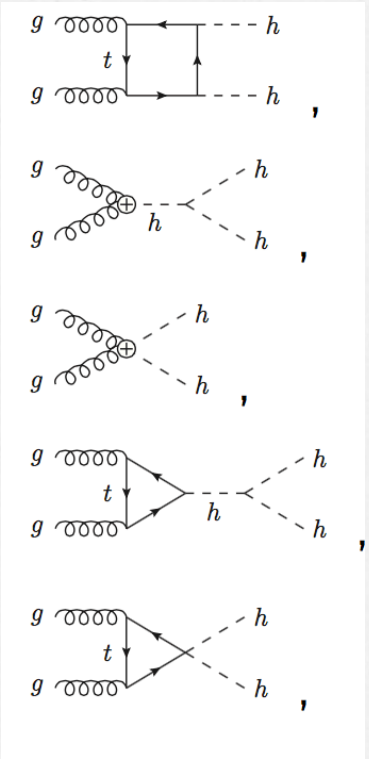
$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{SM}} \sim | c_g + \delta y_t |^2$$

gg→ h rate within δ of SM



Excluded by 20% measurement of tth

Operators have different kinematic dependences



$$y_t^2$$

$$c_g \lambda_3 \frac{m_h^2}{v^2}$$

$$c_{gg} \frac{s}{v^2}$$

$$y_t \lambda_3 \frac{m_h^2}{s} \log^2\left(\frac{m_t^2}{s}\right)$$

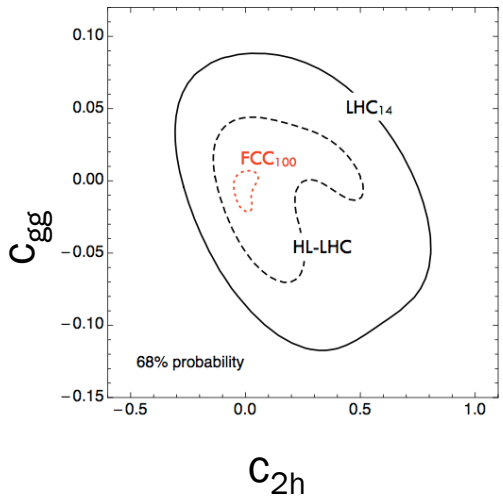
$$c_{2h} \log^2\left(\frac{m_t^2}{s}\right)$$

Fits to EFT Coefficients

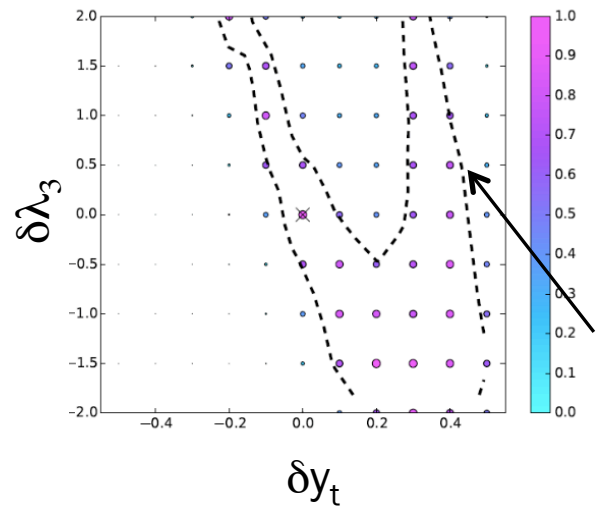
c_{2h}, $\delta\lambda_3$, c_{gg} only probed in hh production

- Use kinematics of signal to improve fits *(Correlations!)*

300, 3000 fb-^{1}, bbγγ



14 TeV, 600 fb^{-1}, bbττ



p values

1σ contours

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

How big are EFT coefficients?

- Singlet model only generates $\delta\lambda_3$

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

- 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

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

These estimated coefficients are much smaller than projected experimental sensitivities

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

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

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