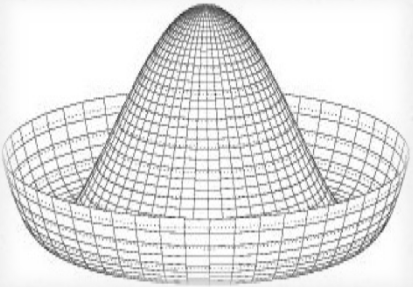
Double Higgs Production

S. Dawson, BNL

Jan 18, 2016



Outline

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

Higgs self-couplings a prediction

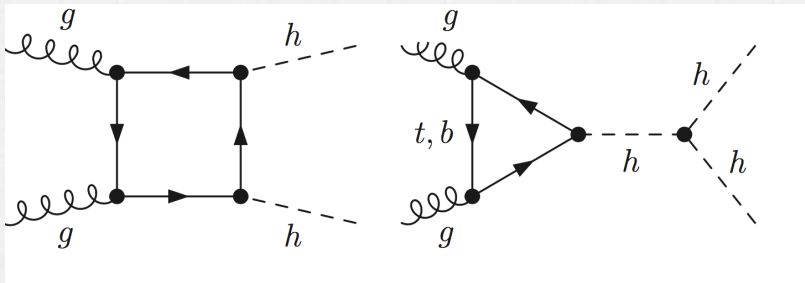
$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

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

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

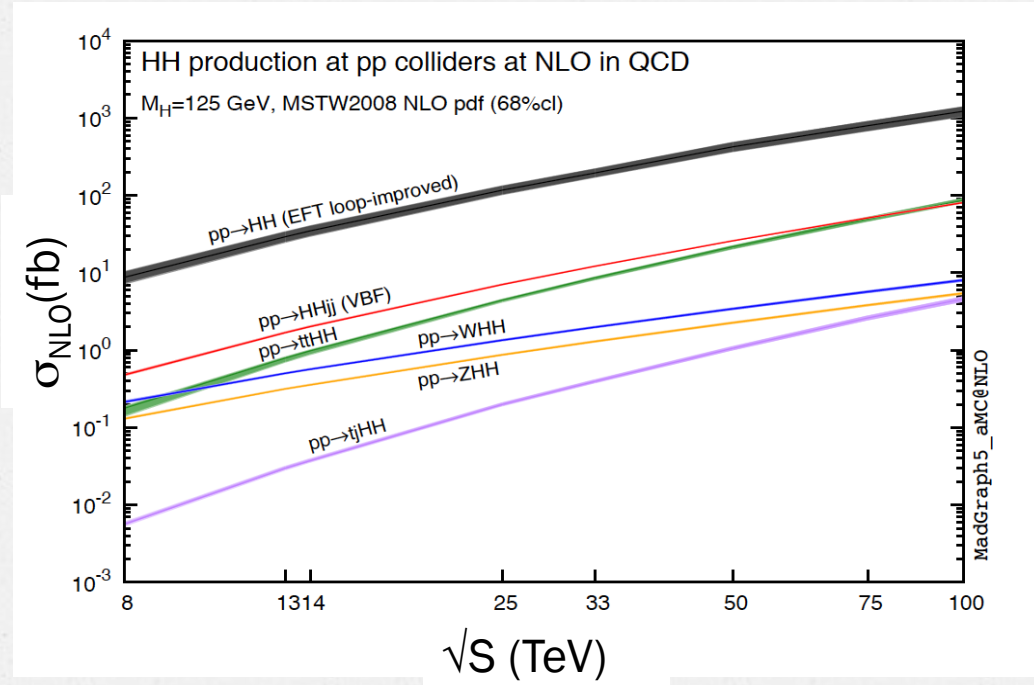
* This is NOT true in models with new light particles

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

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]

Current Searches Far from Observation

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

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

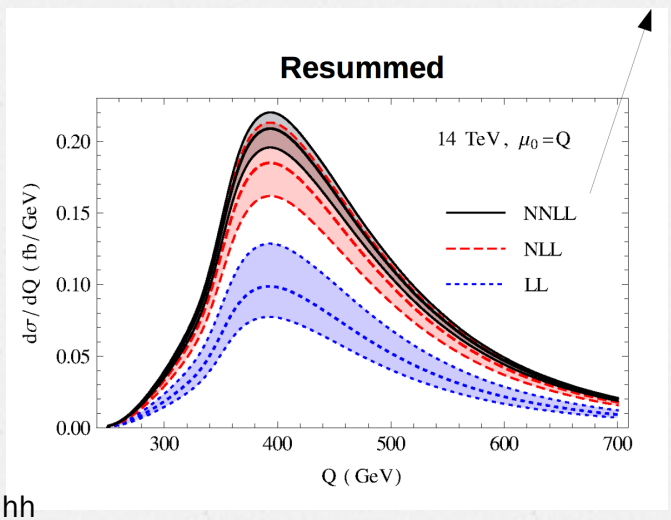
	$\sqrt{s} = 7\ TeV$	$\sqrt{s} = 8\ TeV$	$\sqrt{s} = 13\ TeV$	$\sqrt{s} = 14\ TeV$	$\sqrt{s} = 100\ TeV$
K	1.203	1.200	1.193	1.192	1.195
K'	2.299	2.296	2.301	2.304	2.472

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]

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



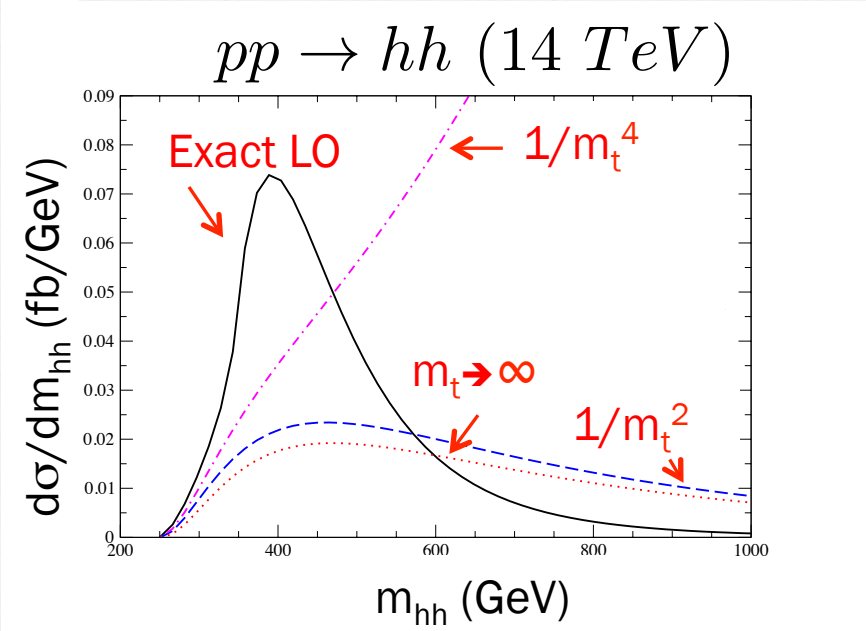
Excellent convergence of series

$Q = m_{hh}$

[De Florian, Mazzitelli, 1505.07122]

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

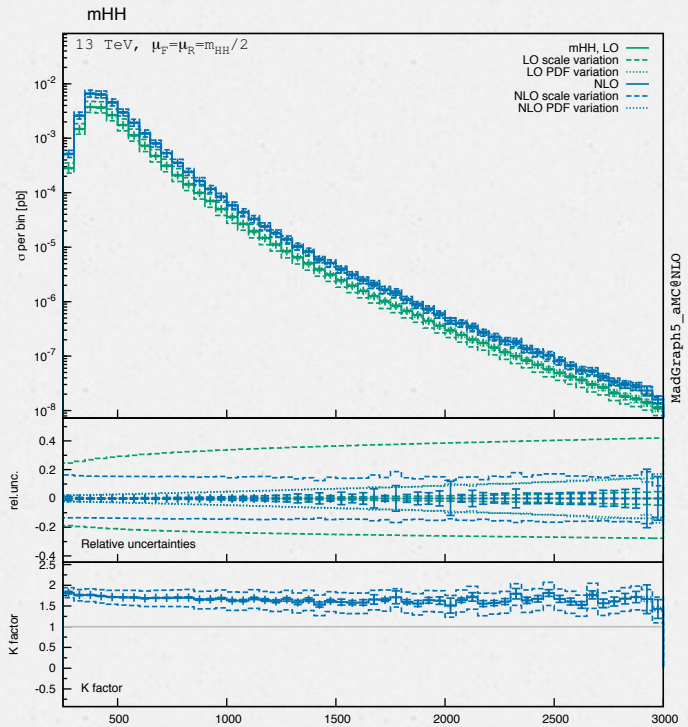
[Dawson, Furlan, and Lewis, arXiv:1210.660]

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 NLO and normalize to exact LO
- Different results from 2 approaches
- Arbitrarily assign ±10% uncertainty from m_t dependence

Distributions at NLO

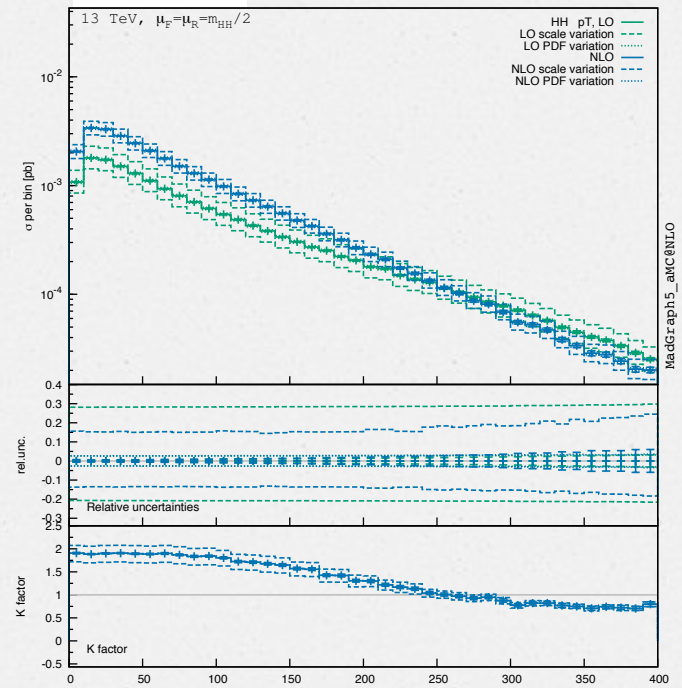
- MadGraph5_aMC@NLO gets m_t dependence in real emission corrections
- Differential uncertainties from scale/PDF~O(30%)
- K factor relatively flat for m_{hh}: LO*K factor ok here



Distributions at NLO

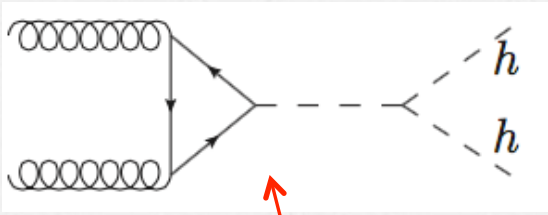
- Not all distributions have flat K factors
- Distributions which are sensitive to hard gluon emission aren't just rescaling of LO

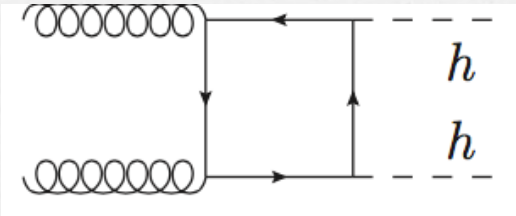
$p_T(hh)$



What is contributing to hh?

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



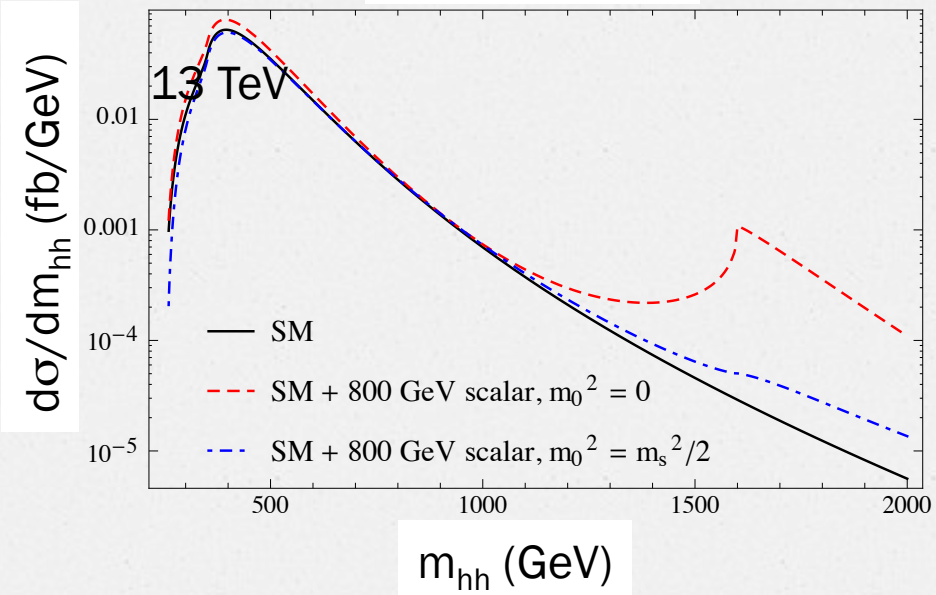


Parameters restricted by requirement that gg→h has SM value

What about adding a scalar?

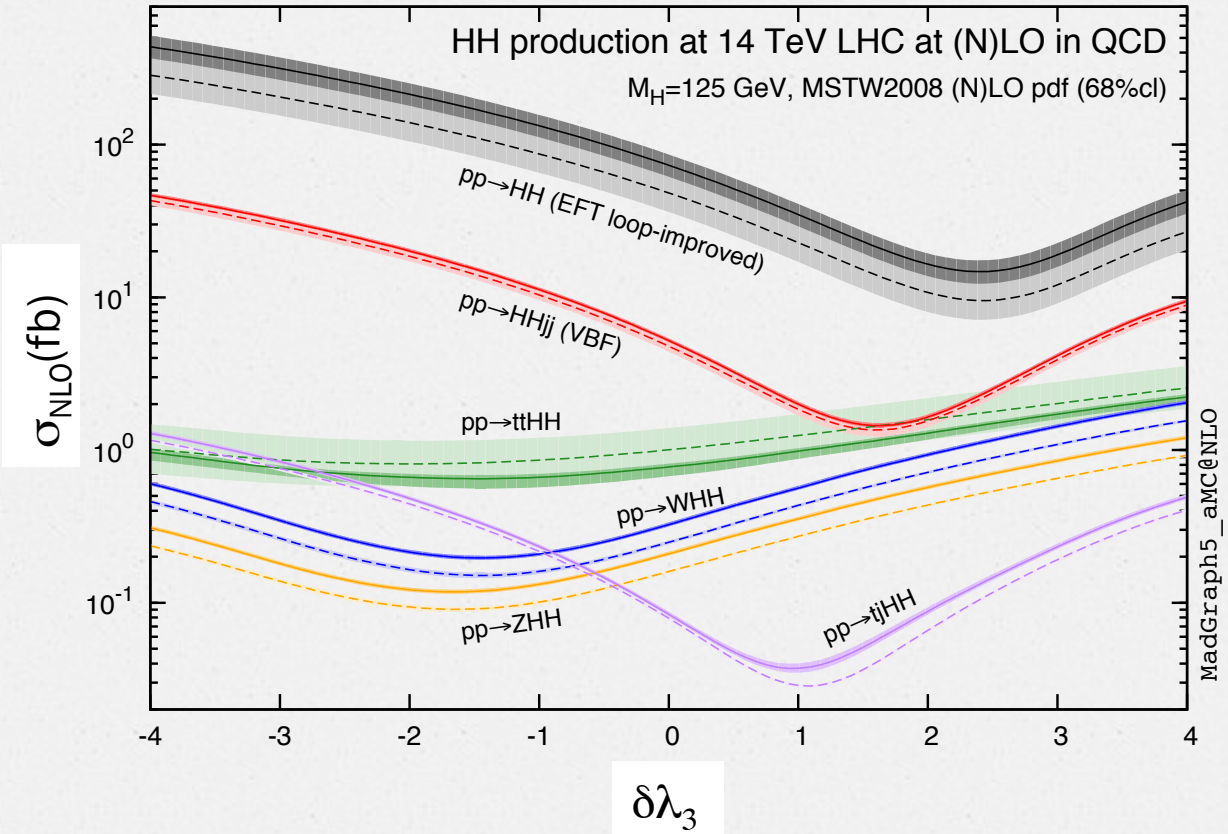
- At high invariant mass, distributions different in presence of color triplet scalar

$$pp \to hh$$



[Dawson, Ismail, Low, arXiv:1504.05596]

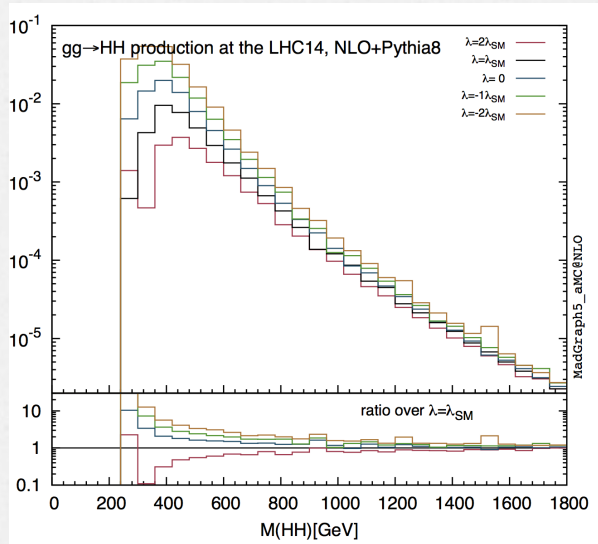
Interest is in hhh coupling: λ3



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

It's not just λ3

- Construct consistent effective field theory: EFT

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

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

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

- 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, $\delta\lambda_3$

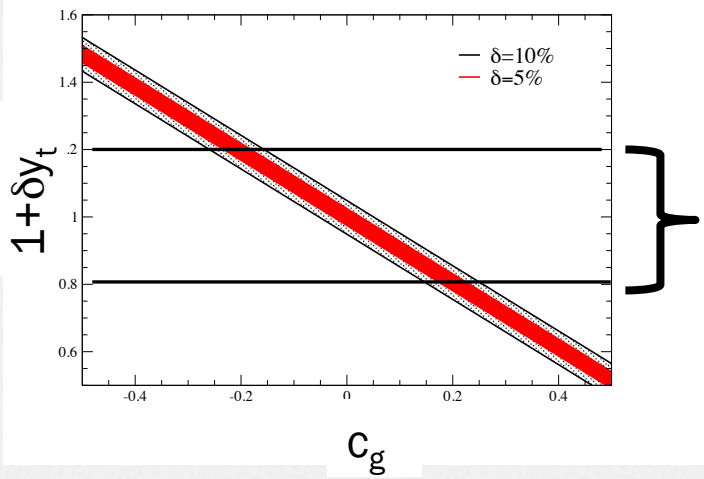
Linear EFT assumes Higgs is a doublet

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



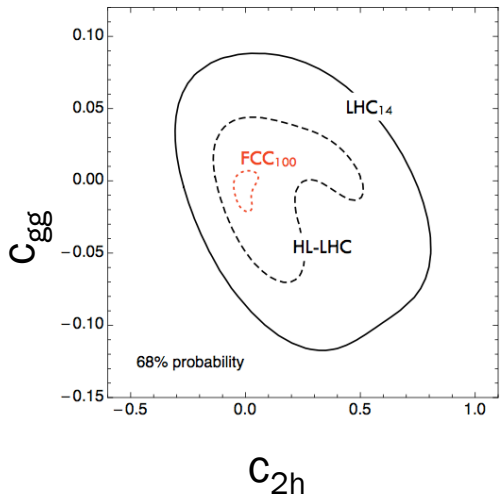
Excluded by 20% measurement of tth

Fits to EFT Coefficients

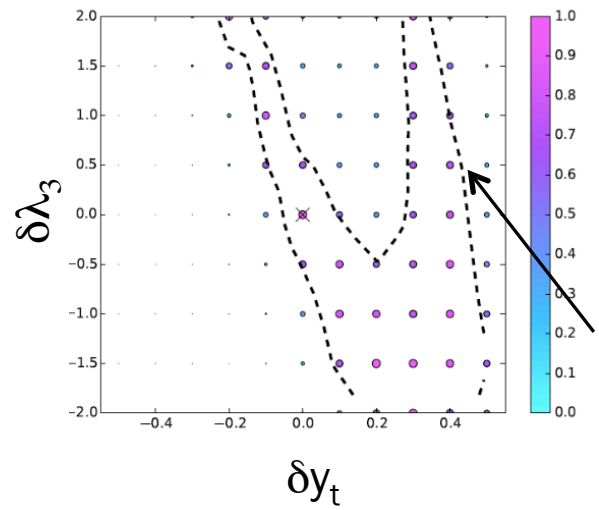
c_{2h}, $\delta\lambda_3$ only probed in hh production

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

300, 3000 fb-^{1}, bbγγ



14 TeV, 600 fb^{-1}, bbττ



p values

1σ contours

S. Dawson, BNL, Jan 18, 2016

[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]

Projections

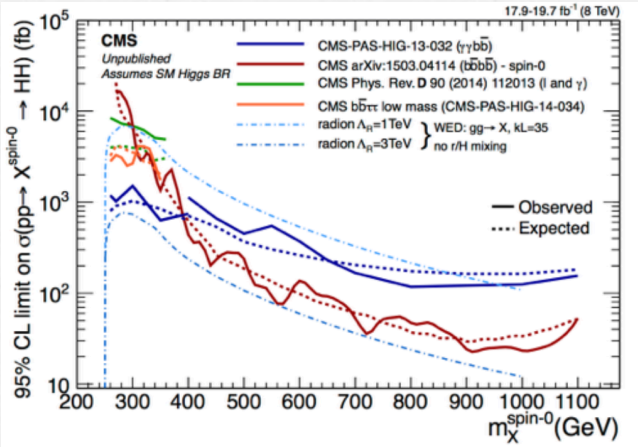
- Observation of hh production with 3 ab^{-1}: ATLAS, 1.3σ; CMS 2σ
- Measurement of hhh coupling with 3 ab^{-1}: ATLAS, $-1.3 < \lambda_3 < 8.7$

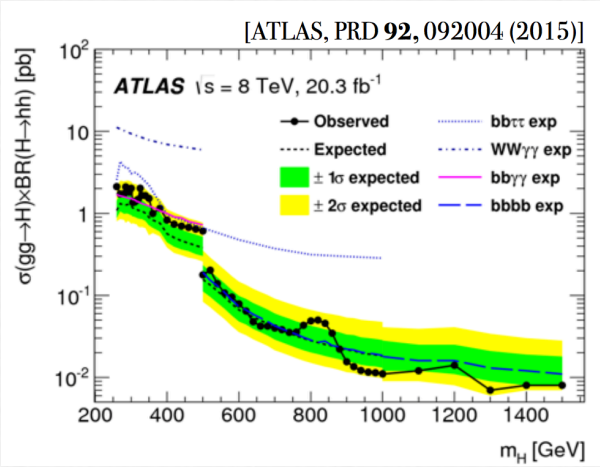
Double Higgs production is strong motivation for 100 TeV collider

- 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]

hh sensitive to new resonances



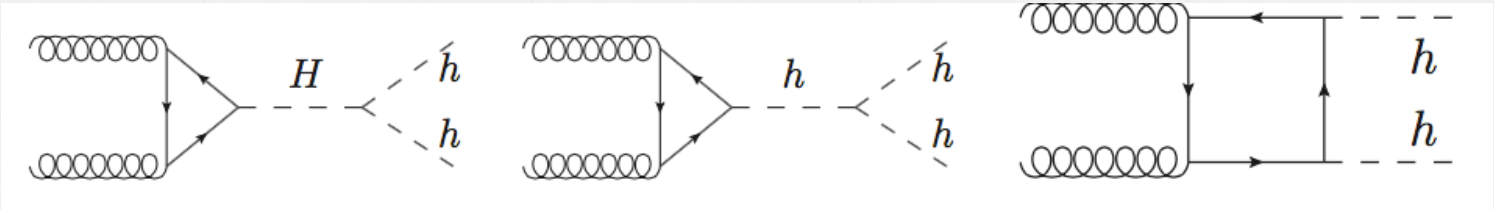


hh production is ideal place to look for new physics

* σ_{SM}=11 fb at 8 TeV

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



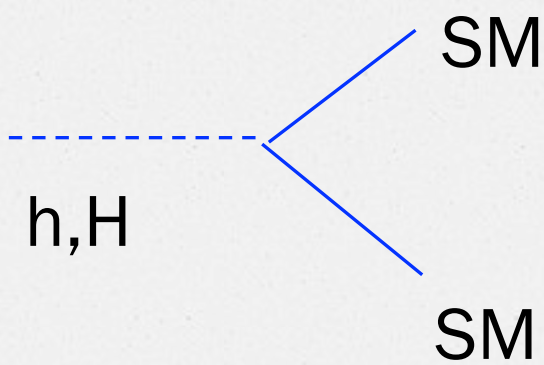
- Model can be dark matter portal

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: $$M_h, M_H, v, tan\beta = \frac{v}{\langle S \rangle}, \theta$$
- |cos α| >.92 from Higgs couplings, heavy Higgs searches, M_W

Z_2 symmetric singlet model

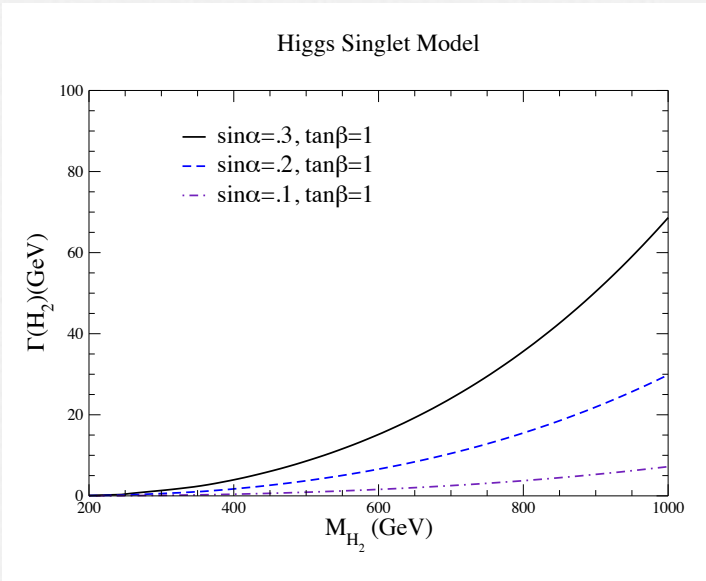
- If kinematically allowed, H → hh

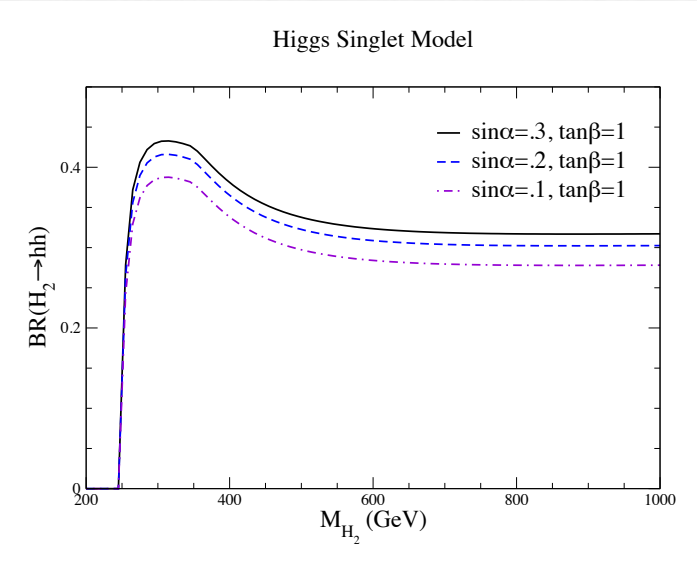


Coupling to light Higgs ~ cos θ
Coupling to heavy Higgs ~ sin θ

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

Branching ratio $H \to hh$ can be significant





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

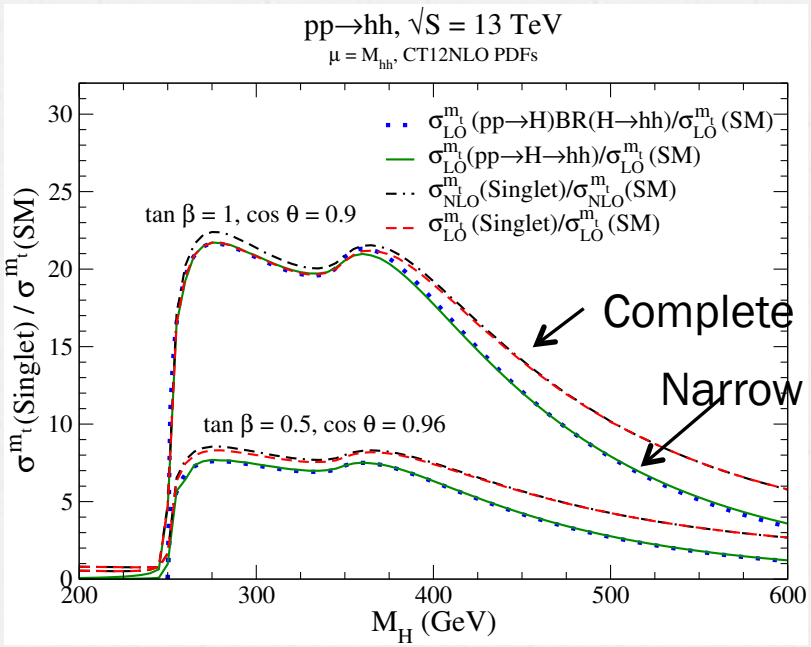
$$\tan\beta < 1.3\left(\frac{600\ GeV}{M_H}\right)$$

Resonant production of hh

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

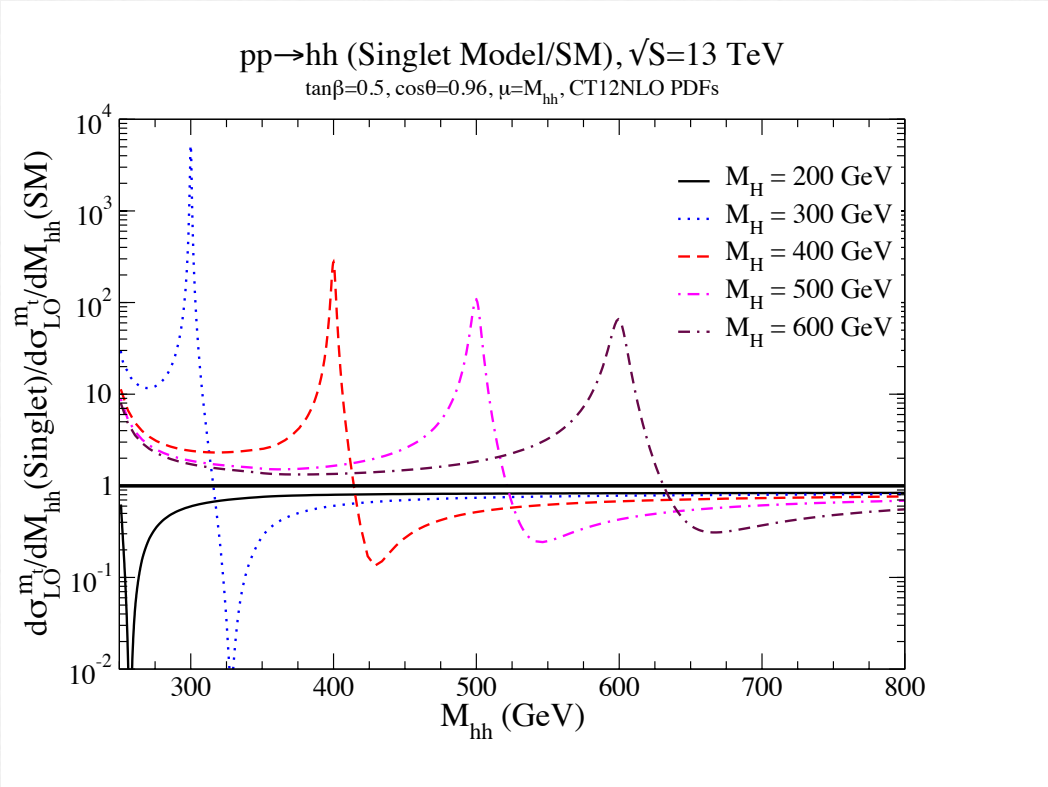
Can get factor of 20 enhancements

*Similar effects in MSSM, NMSSM models



[Dawson, Lewis, arXiv:1508.05397]

Large resonance/interference effects

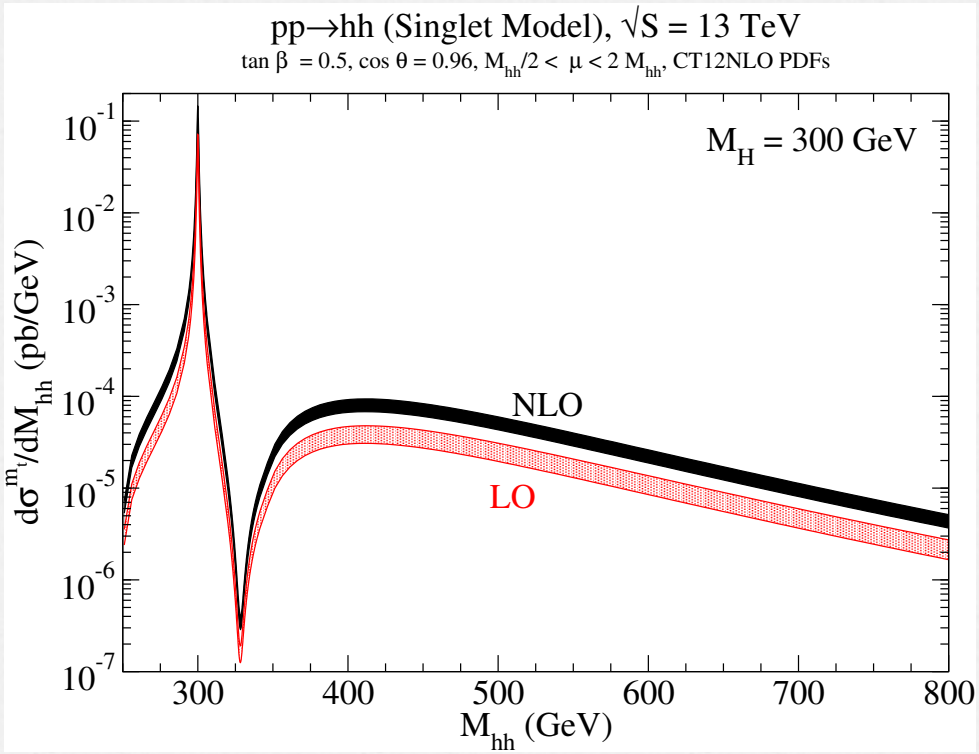


[Dawson, Lewis, arXiv:1508.05397]

NLO corrections to singlet model

- Computed in $m_t \to \infty$ limit

K factor ~ 2
(as in SM)



[Dawson, Lewis, arXiv:1508.05397]

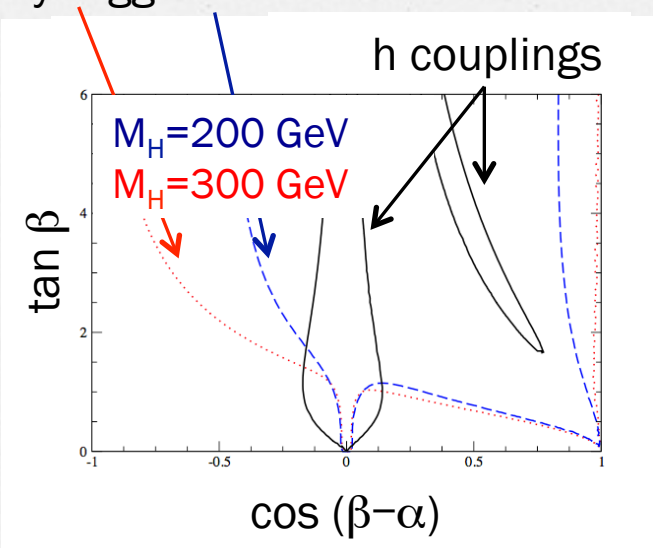
Slightly more complicated: 2HDM

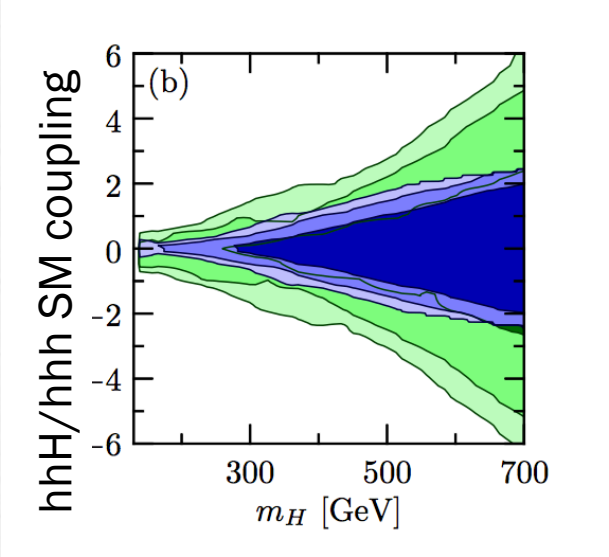
- 2HDM has 5 Higgs particles: h,H,A,H±
- Described by masses, couplings, $\cos(\alpha-\beta)=0$ is SM limit, and $\tan\beta$
- 4 possibilities for Higgs coupling assignments which conserve flavor
  - Decoupling: M_A, M_{H2}, $M_{H+} \to \infty$, couplings $\to$SM
  - Alignment: ***A,H_2,H+ can be light, $\cos(\beta-\alpha) \to 0$***

Limits on 2HDM

- Limits on 2HDM from heavy Higgs searches, Higgs couplings

heavy Higgs searches

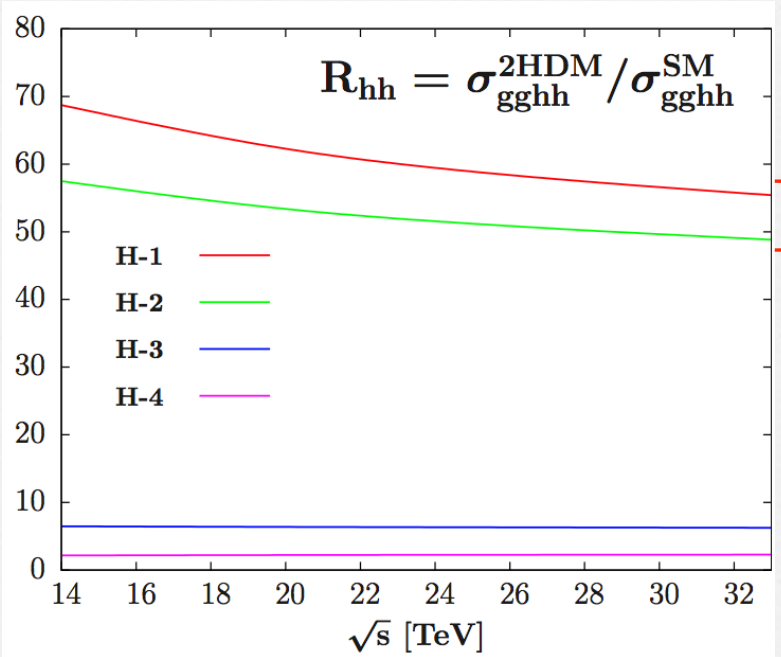




[Dawson, Sher, 1305.1624; Baglio et al, arXiv:1264]

Resonant effects in 2hdm

- Benchmark scenarios see large enhancements



tan β ~2,
m_H~300 GeV

Smaller enhancements as m_H increases

[Baglio et al, arXiv:1264]

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