Modification of Higgs Pair Production at the LHC

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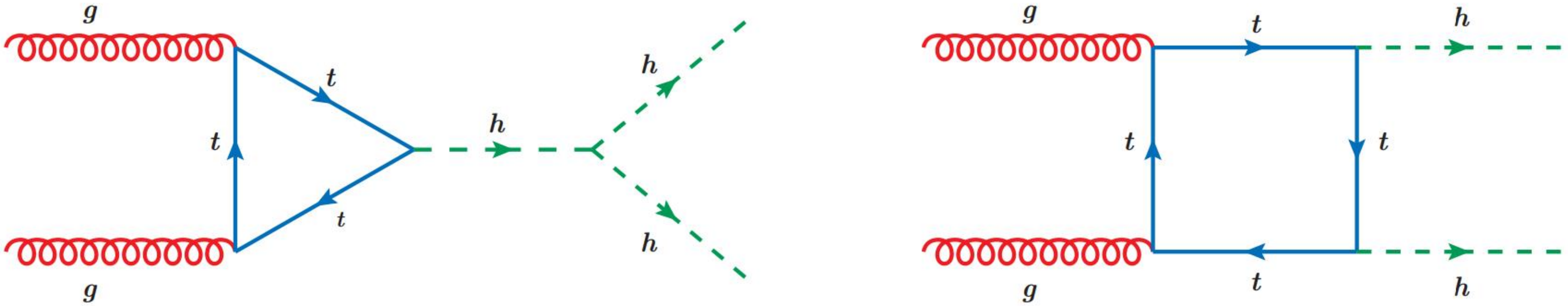
Why Di-Higgs?



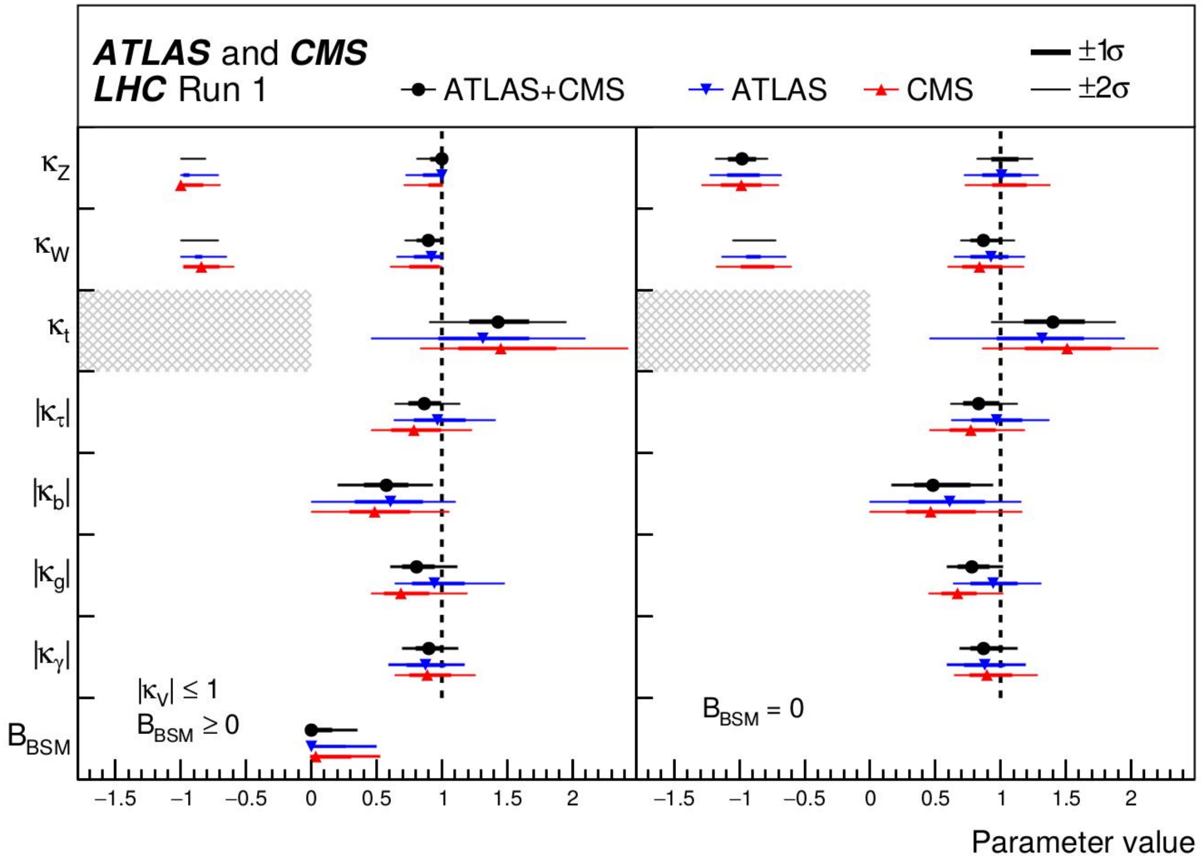
$$\frac{d\hat{\sigma}_{gg\to hh}}{d\hat{t}} = K\frac{G_F^2\alpha_s^2}{256(2\pi)^3} \times \left[\left|(C_\triangle F_\triangle + C_\Box F_\Box)\right|^2 + \left|C_\Box G_\Box\right|^2\right]$$

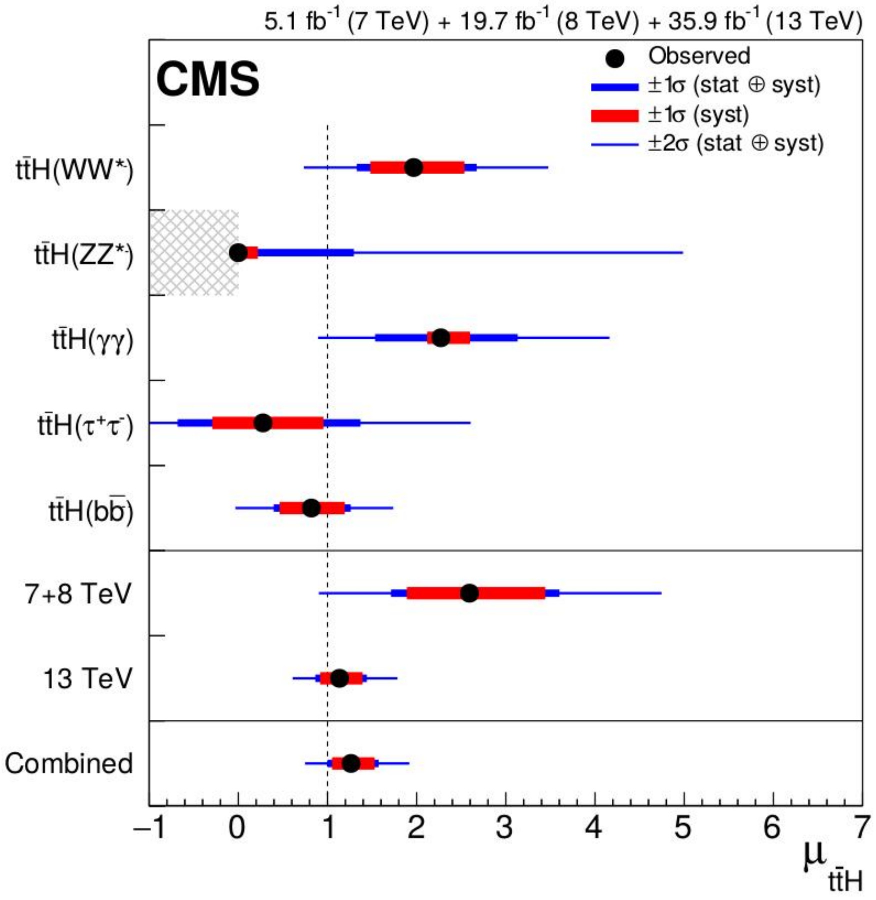
Destructive interference between the triangle and the box

Sensitive to BSM physics : Small changes of the couplings can lead to Large change in production

Direct probe to Higgs self coupling

Higgs Couplings: LHC Results





Outline

- Modifications to Higgs self-coupling
- Enhancing di-Higgs production with light colored states
- Impact of top Higgs coupling modification
- Collider phenomenology

Based on arXiv:1512.00068 and arXiv: 1711.05743

Higgs Self Coupling

$$\mathcal{M}^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{21}^2 & m_{22}^2 \end{pmatrix} = \begin{pmatrix} 2\lambda_h v^2 & 2\left(a_{hs} + \lambda_{hs} v_s\right) v \\ 2\left(a_{hs} + \lambda_{hs} v_s\right) v & m_s^2 + \lambda_{hs} v^2 \end{pmatrix}$$

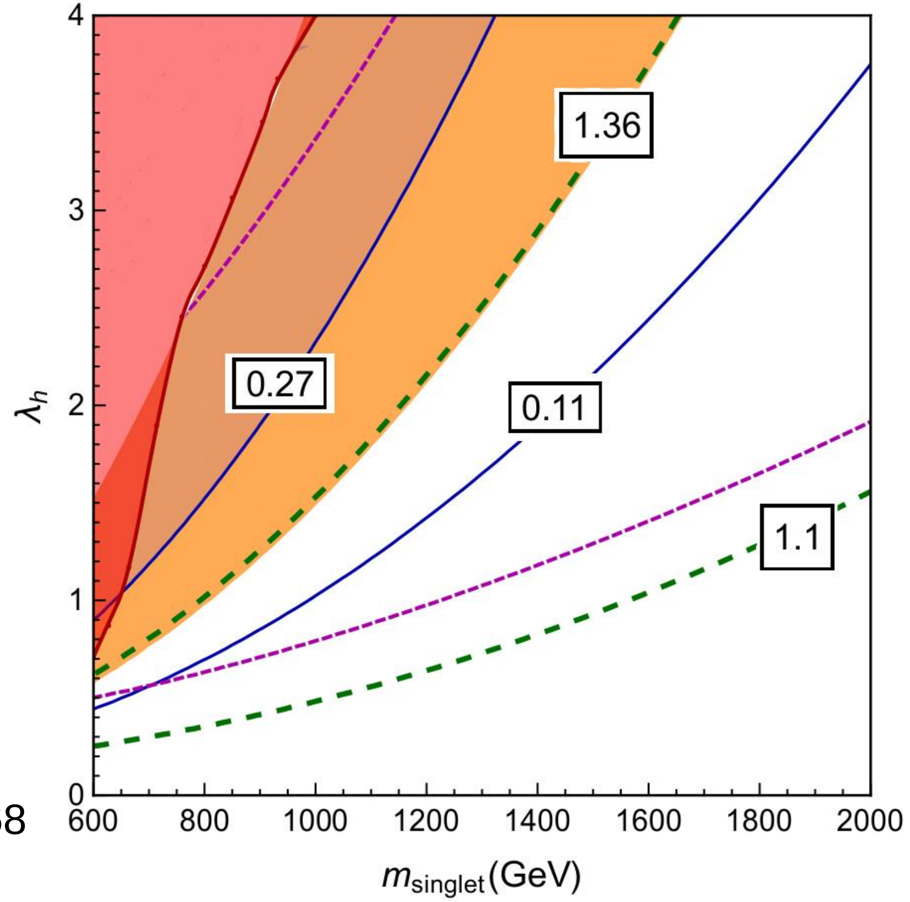
$$V\left(\phi_h, \phi_s, T\right) = \frac{m_0^2 + a_0 T^2}{2} + \phi_h^2 + \frac{\lambda_h}{4}\phi_h^2 + a_{hs}\phi_h\phi_s^2 + \frac{\lambda_{hs}}{2}\phi_h^2\phi_s^2 + \frac{m_s^2}{2}\phi_s^2 + \frac{a_s}{3}\phi_s^3 + \frac{\lambda_s}{4}\phi_s^4$$

Singlet Extension

Orange: First order PT

Green: Enhancement of self coupling

P Huang, AJ, B Li, C Wagner arXiv: 1512.00068



Higgs Self Coupling

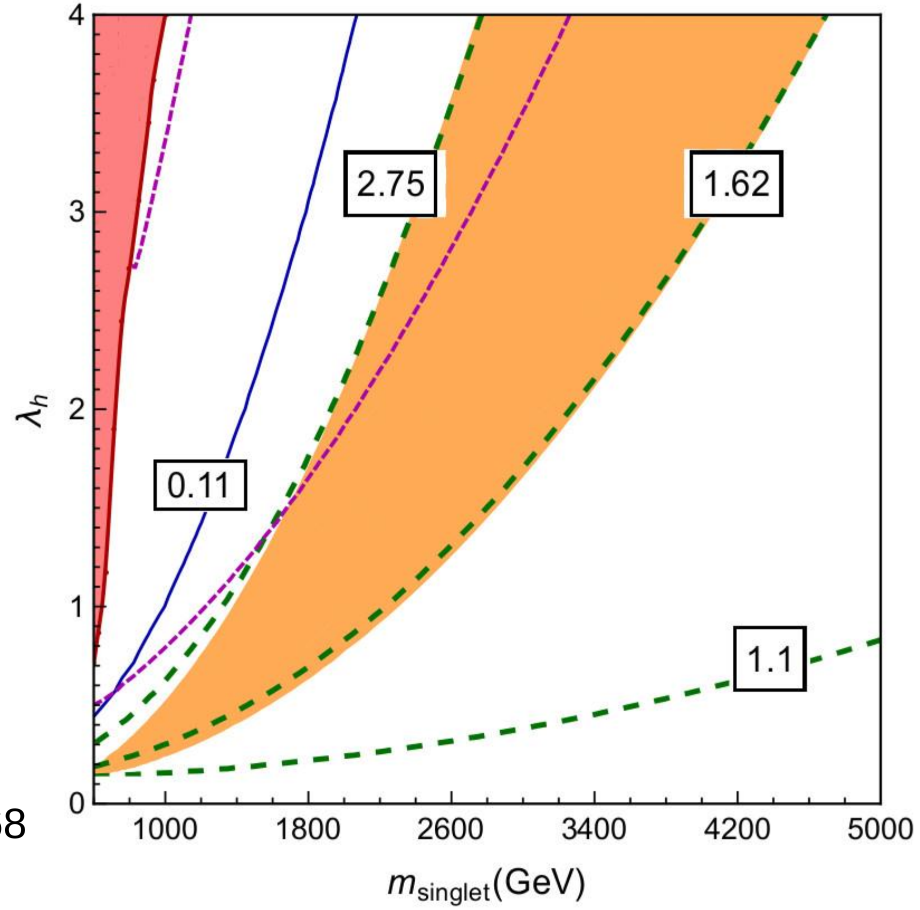
$$\lambda_3 = \frac{3m_h^2}{v}\left[1 + \left(\frac{2\lambda_{hs}v^2}{m_h^2} - \frac{3}{2}\right)\tan^2\theta\right]$$

Singlet Extension

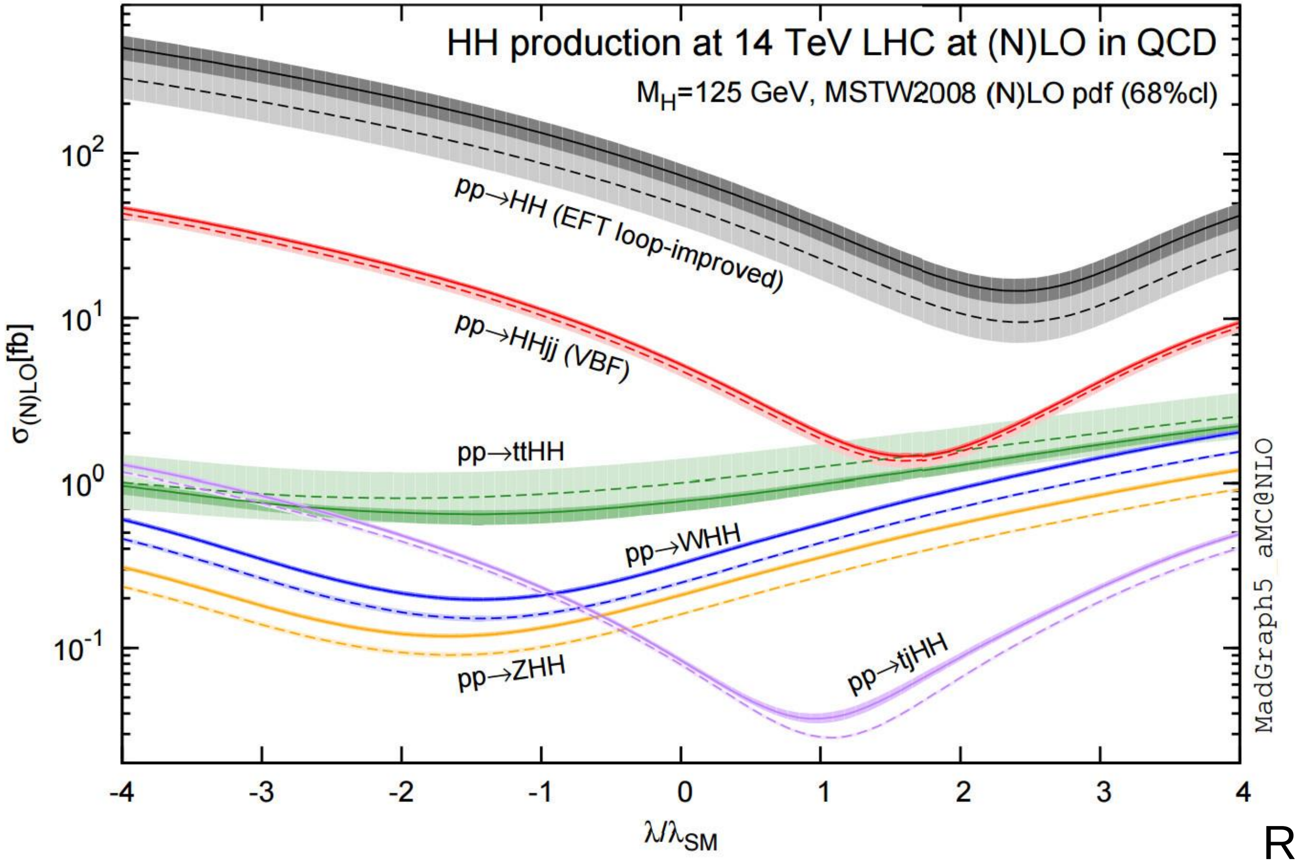
range: First order PT

Green: Enhancement of self coupling

P Huang, AJ, B Li, C Wagner arXiv: 1512.00068



Higgs Pair Production σ



Small production cross section at the LHC

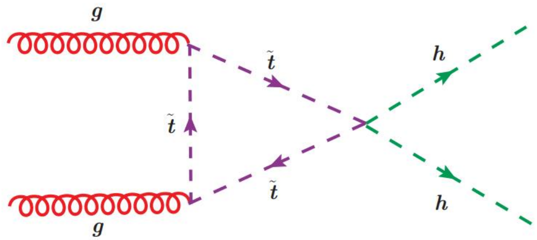
About 30 fb in SM

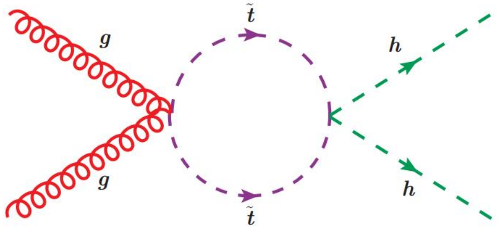
About 60 ab in hh→ $bb\gamma\gamma$

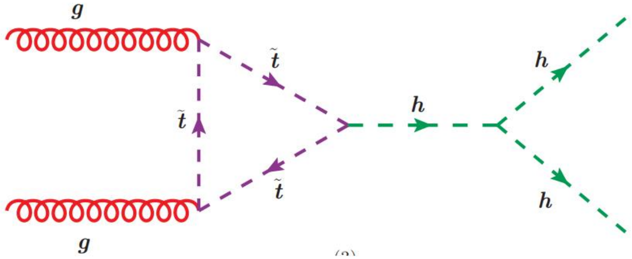
R.Federix et al arXiv: 1401.7340

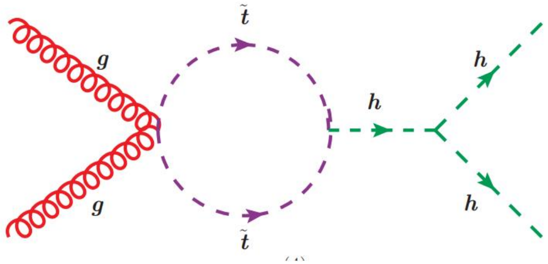
Light Colored Scalars

Example: Stops in SUSY models



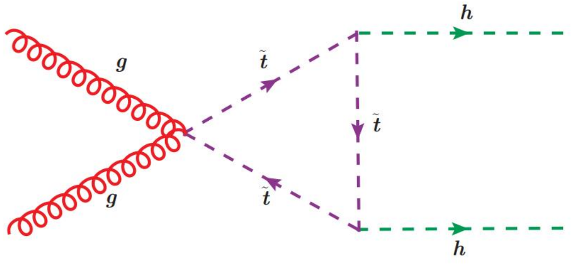


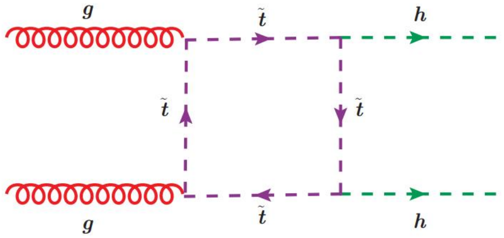




No parametric enhancement

Trilinear Coupling Enh



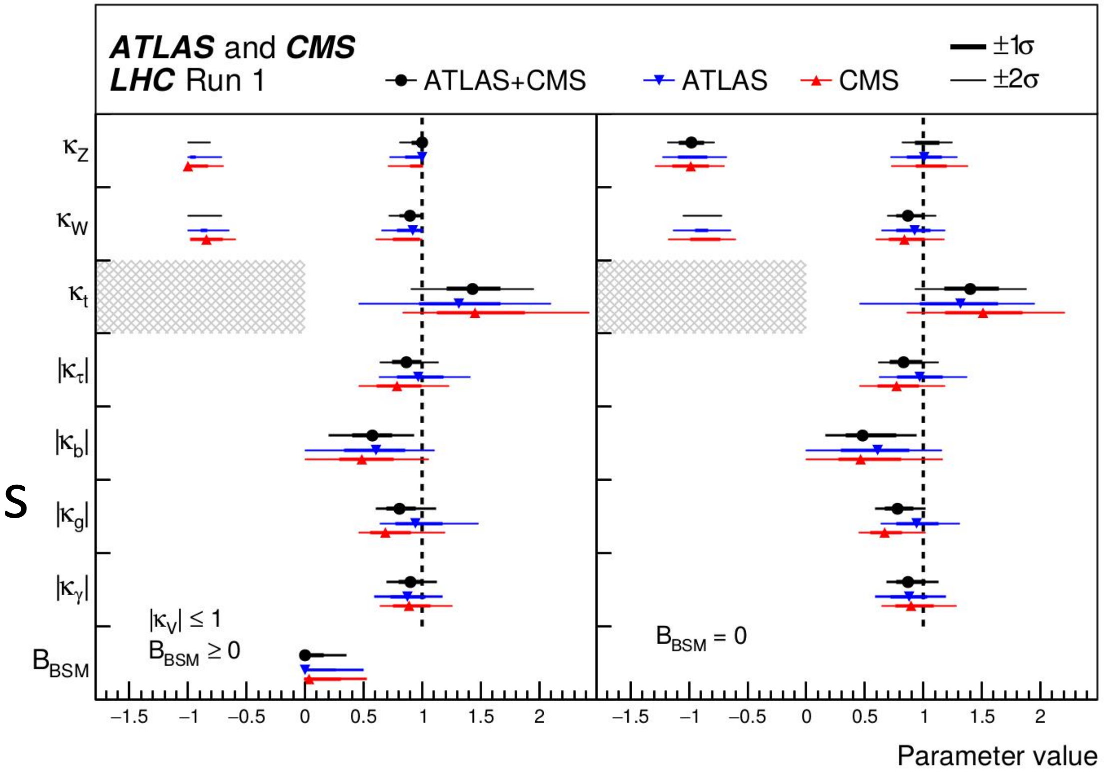


$$\mathbf{M}^{\mathbf{2}}_{\tilde{\mathbf{t}}} = \begin{pmatrix} m_Q^2 + m_t^2 & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 \end{pmatrix}$$

Mixing

Higgs Couplings: Status

- Best fit Run I : top Yukawa ~ 1.4,
  bottom Yukawa ~0.6
- About 2σ away from the SM values
- BR for h → bb is ~ 0.58
- Change in decay width to b will drastically modify other branching ratios
- Signal strength measured is roughly SM therefore need to reduce production
- ggh coupling best fit ~0.8



2HDM modification of Higgs Couplings

2HDM are well motivated;
Appear in MSSM, NMSSM

$$\kappa_t = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha)\left[1+\cot\beta\cot(\beta-\alpha)\right],$$

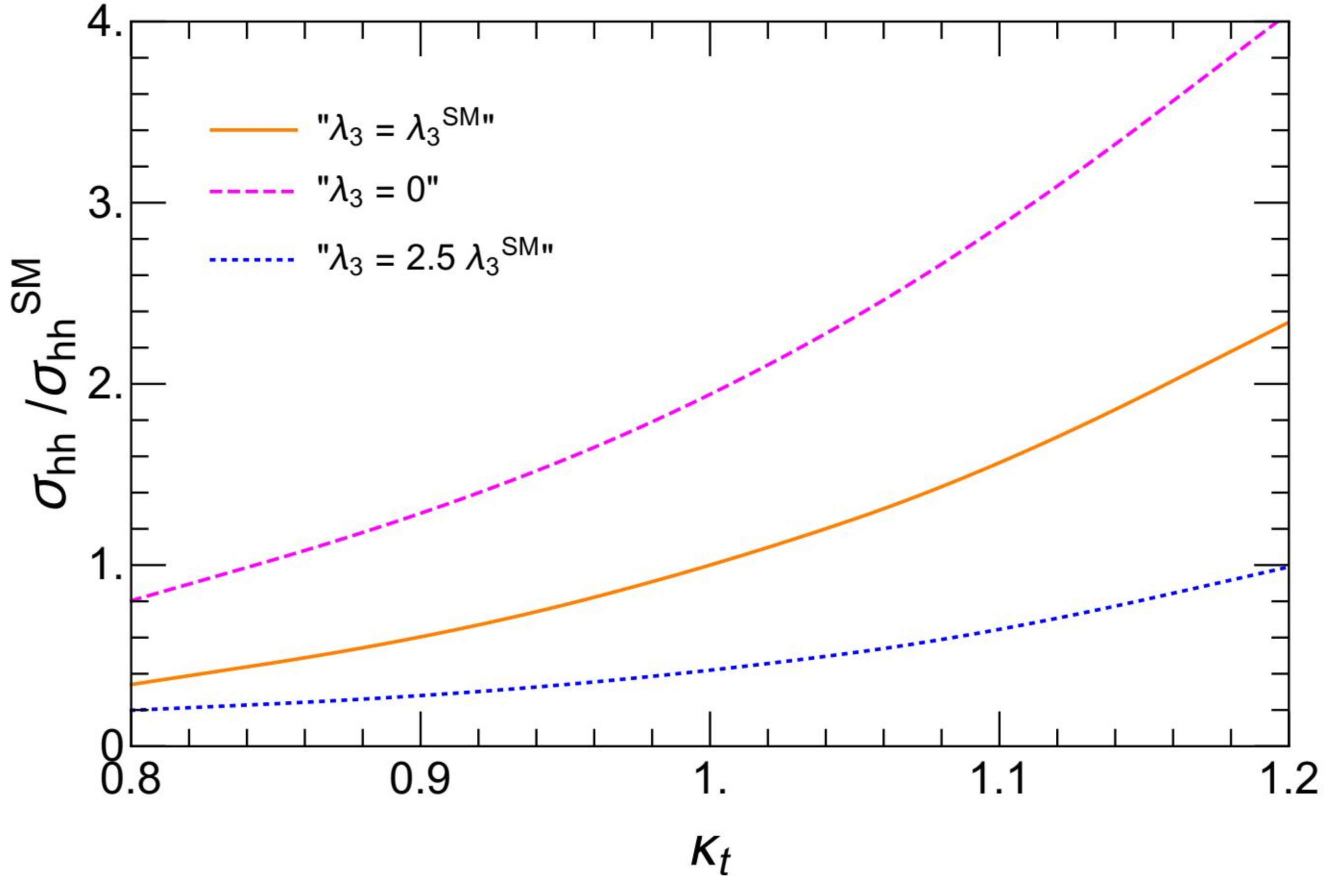
$$\kappa_b = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha)\left[1-\tan\beta\cos(\beta-\alpha)\right]$$

Easily accommodate best fits to top and bottom Yukawa

$$\kappa_g = \kappa_t + \frac{\kappa_t}{4} m_t^2 \left[\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$

κ_g is modified as gluon fusion has tops in loop

Yukawa Modification

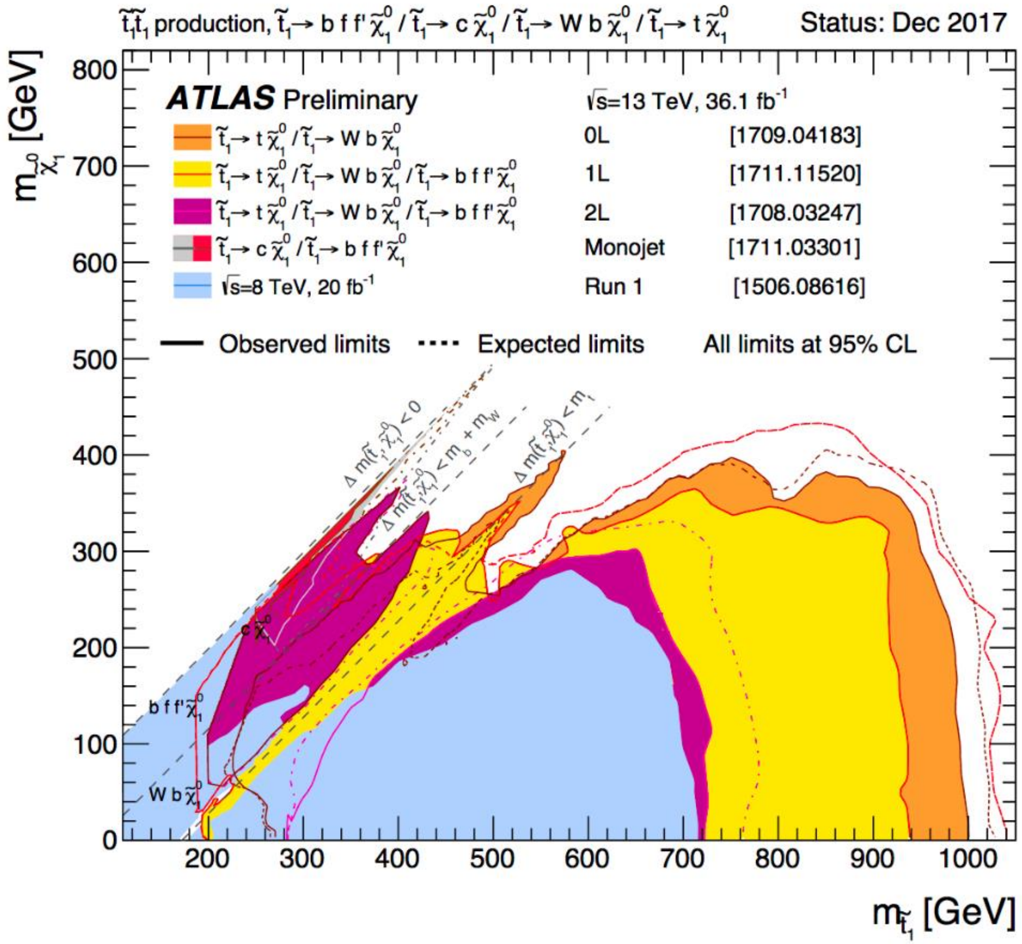


$$\kappa_g = \kappa_t$$

No Stops

λ_3 values correspond to SM, slight enhancement in singlet models and max destructive interference

Stop Mass Bounds



Conservative lower bounds on lightest stop mass are about 500 GeV

Can be somewhat lowered by going to compressed scenarios with light stau where dominant decay channel is stop -> stau -> neutralino

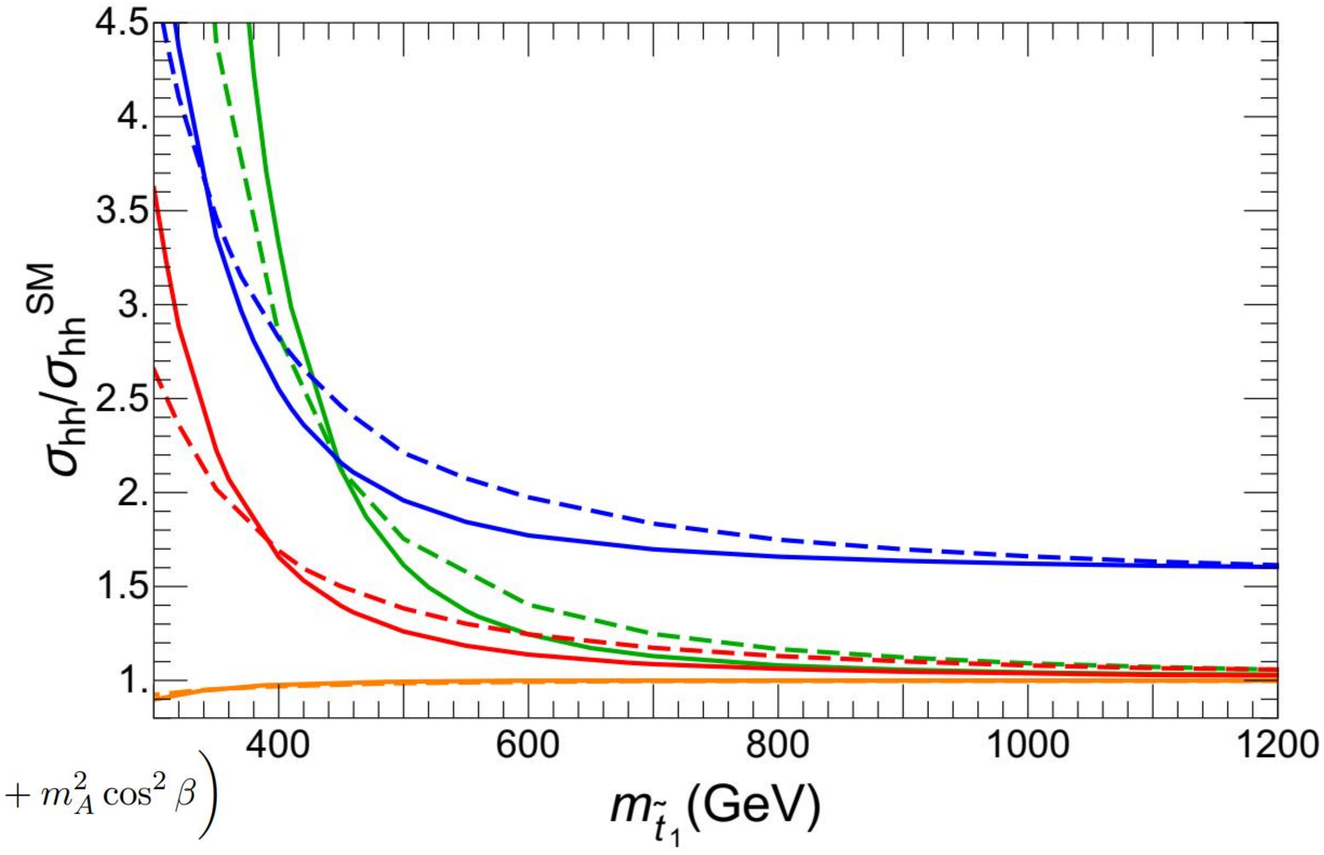
We consider masses of 400 and 500 GeV

One Loop vs. EFT

Blue: $\kappa_t = 1.1$
Others: $\kappa_t = 1.0$

RGB: X_t^2 chosen to saturate Vacuum stability constraint

Orange : X_t^2 chosen to keep $\kappa_g = 1$



$$A_t^2 \leq \left(3.4 + 0.5\frac{|1-r|}{1+r}\right)(m_Q^2 + m_U^2) + 60\left(\frac{m_z^2}{2}\cos(2\beta) + m_A^2\cos^2\beta\right)$$

Mixing Effect

Red: $m_{\tilde{t}} = 300\,\mathrm{GeV}$

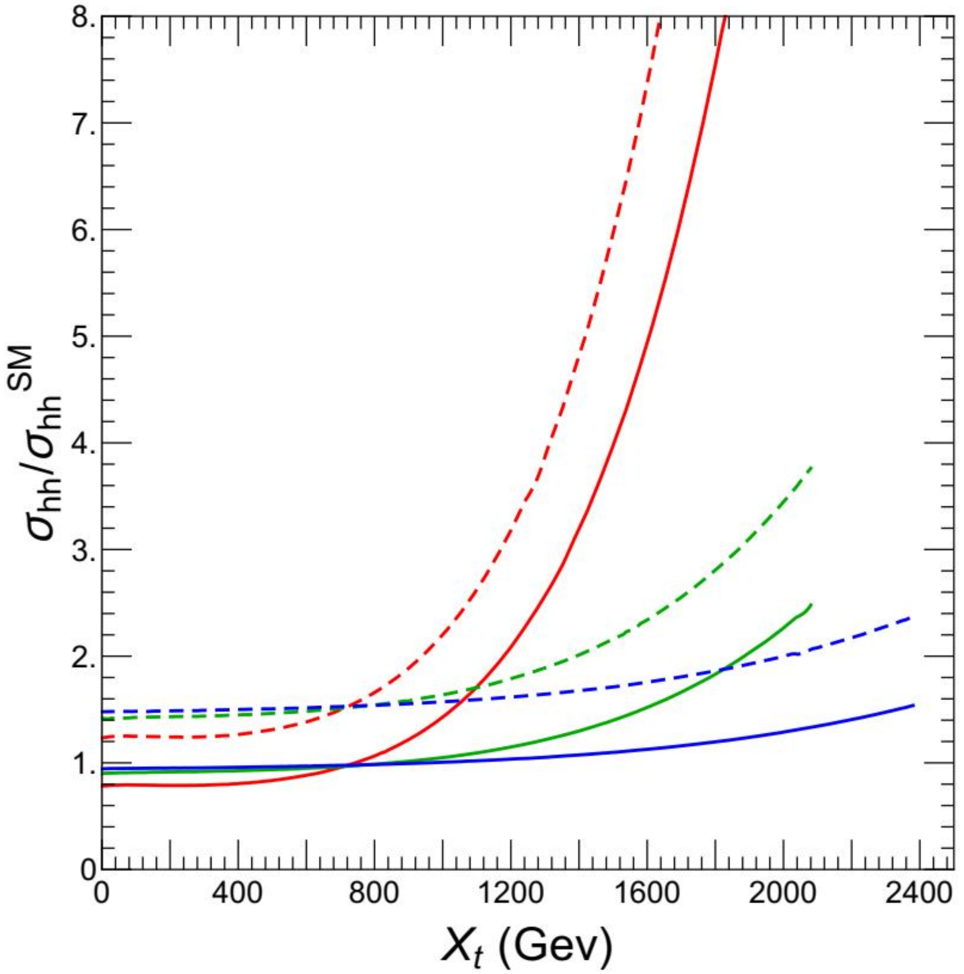
Green: $m_{\tilde{t}} = 400\,\mathrm{GeV}$ $X_t < 3m_Q$

Blue: $m_{\tilde{t}} = 500\,\mathrm{GeV}$

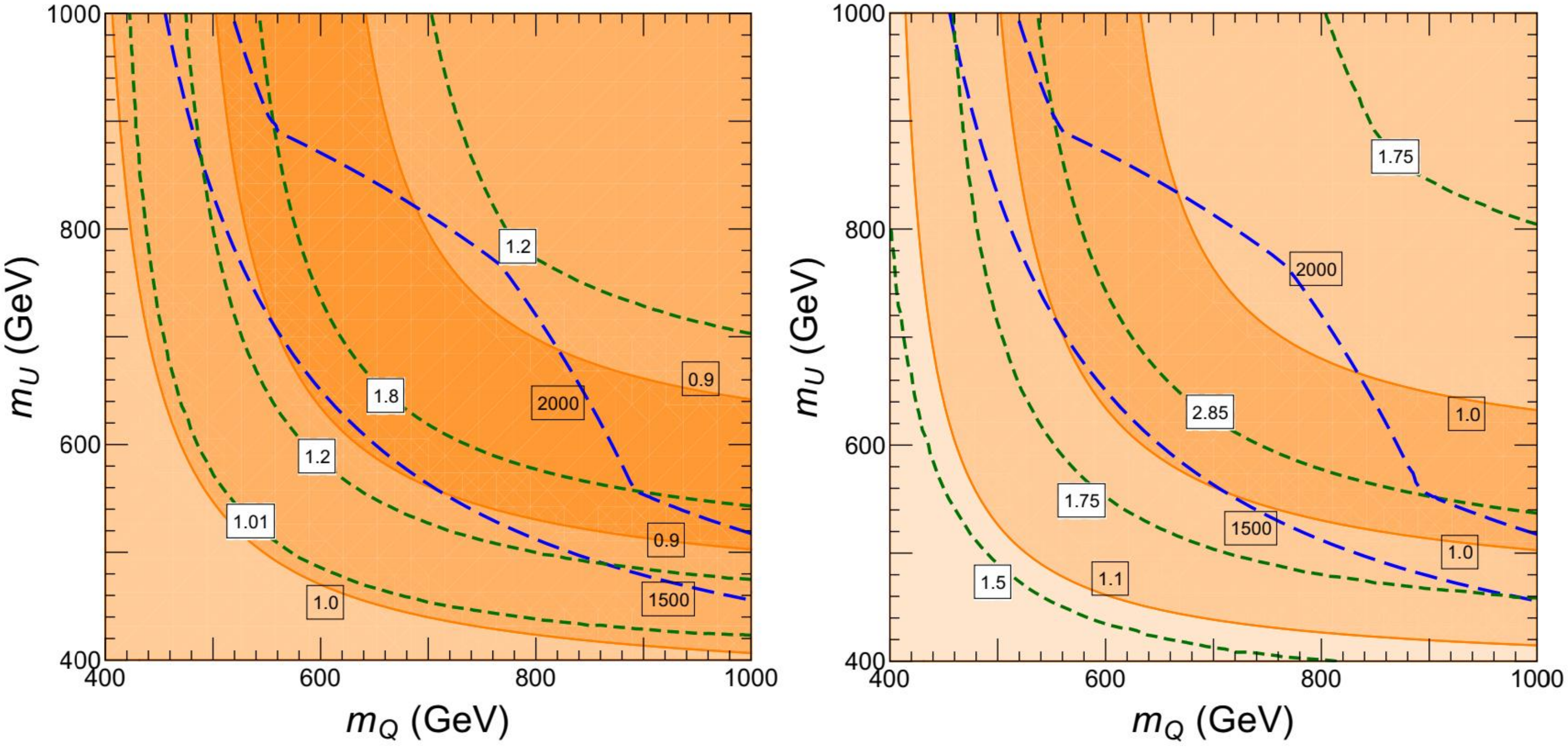
For low mixing Di-Higgs production cross section becomes smaller than the SM

Starts increasing due to the sign flip for the trilinear coupling of lighter stops with the Higgs boson, which becomes linearly dependent on X_t

Quartic growth in cross section leads to large change



Di-Higgs σ Enhancement



Left: $\kappa_t = 1.0$

Right: $\kappa_t = 1.1$

$\lambda_3 = \lambda_3^{SM}$

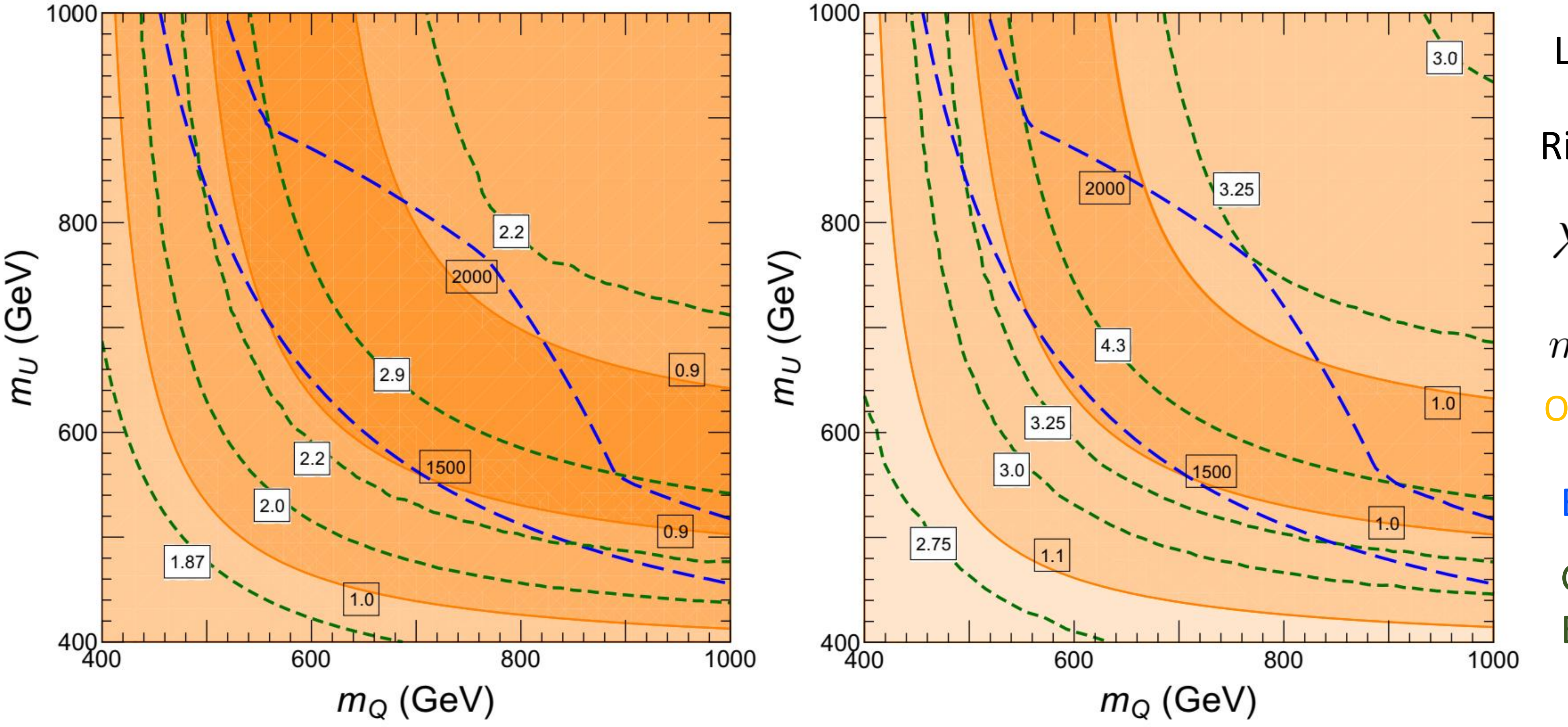
$m_{\tilde{t}_1} = 400\,\mathrm{GeV}$

Orange: κ_g

Blue : $\tilde{X}_t$

Green: σ Enhancement

Di-Higgs σ Enhancement



Left: $\kappa_t = 1.0$

Right: $\kappa_t = 1.1$

$\lambda_3 = 0$

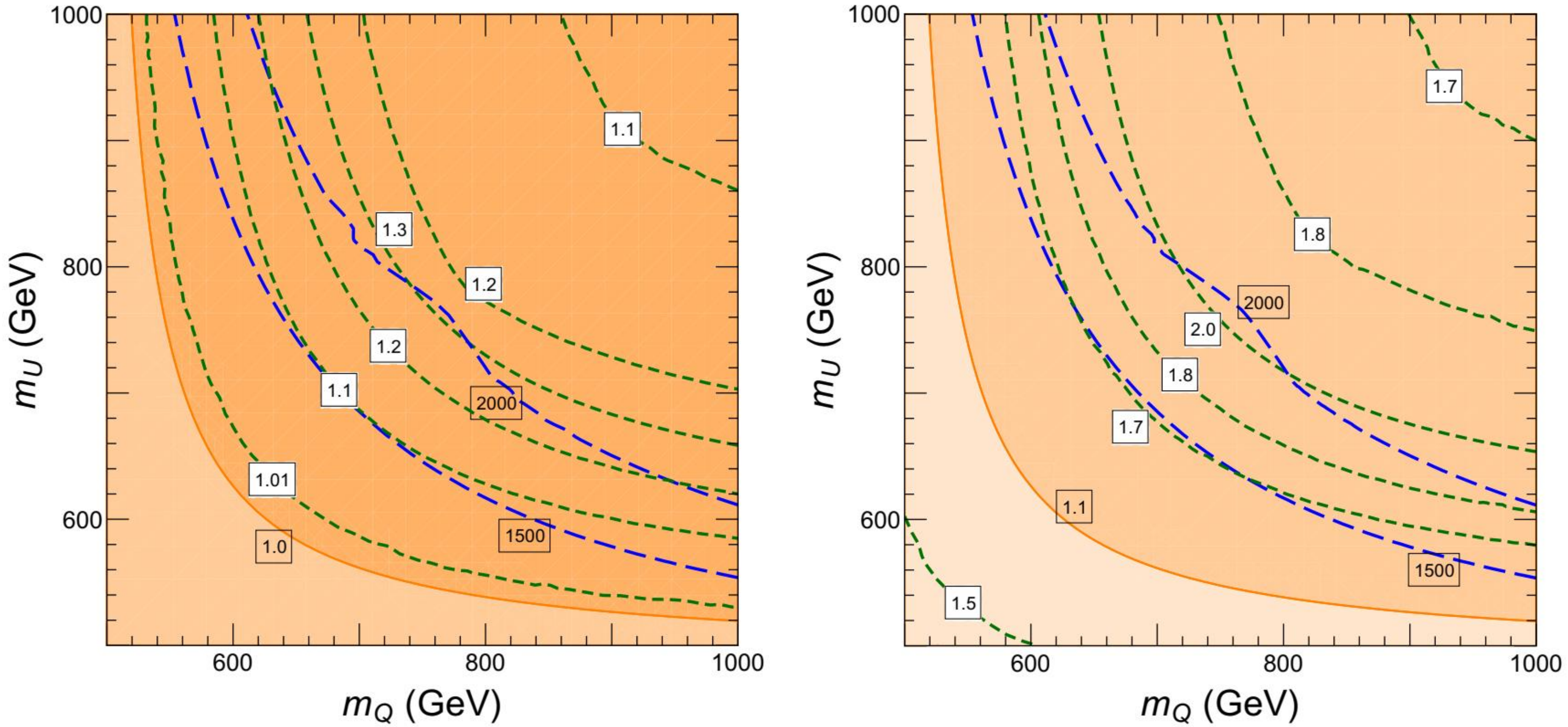
$m_{\tilde{t}_1} = 400\,\mathrm{GeV}$

Orange: κ_g

Blue : $\tilde{X}_t$

Green: σ Enhancement

Di-Higgs σ Enhancement



Left: $\kappa_t = 1.0$

Right: $\kappa_t = 1.1$

$\lambda_3 = \lambda_3^{SM}$

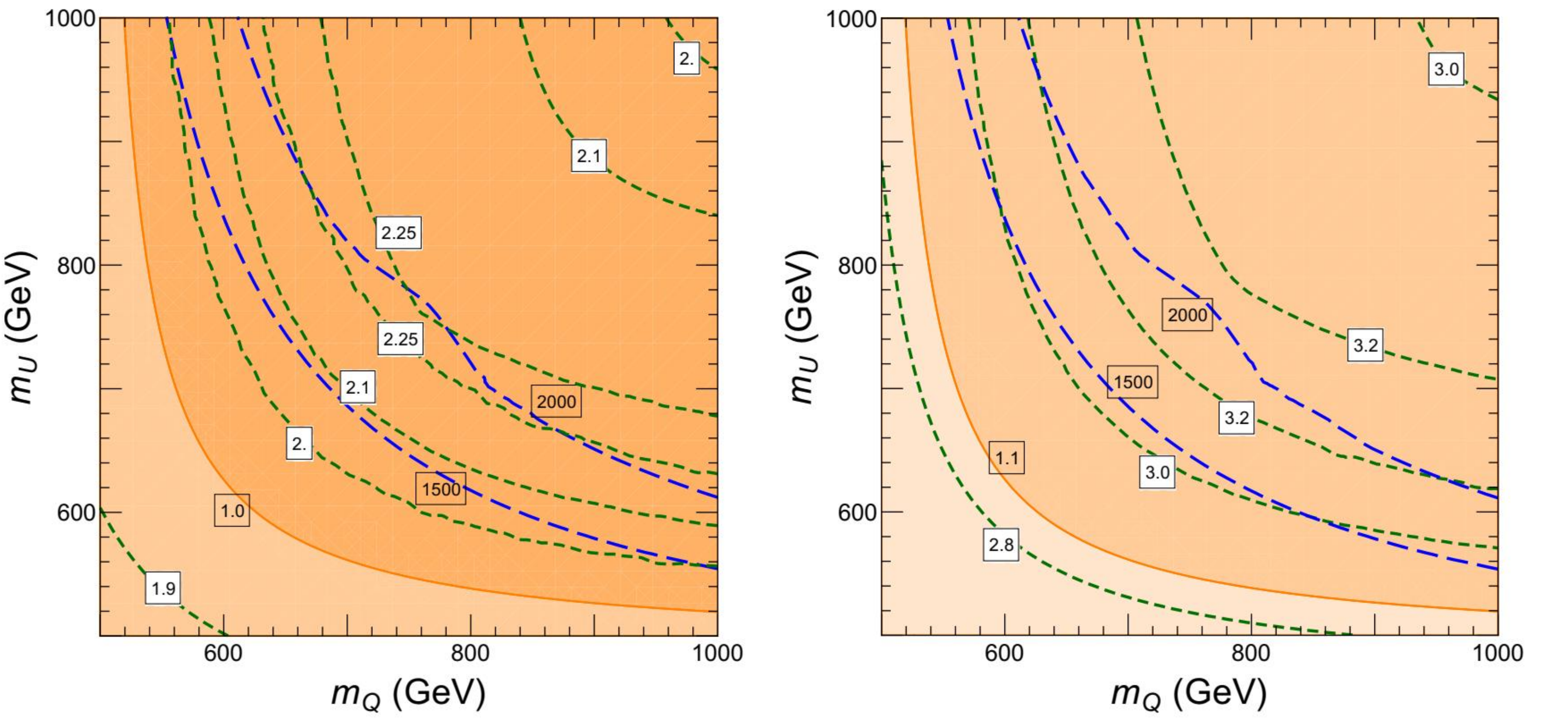
$m_{\tilde{t}_1} = 500\,\mathrm{GeV}$

Orange: κ_g

Blue : $\tilde{X}_t$

Green: σ Enhancement

Di-Higgs σ Enhancement



Left: $\kappa_t = 1.0$

Right: $\kappa_t = 1.1$

$\lambda_3 = 0$

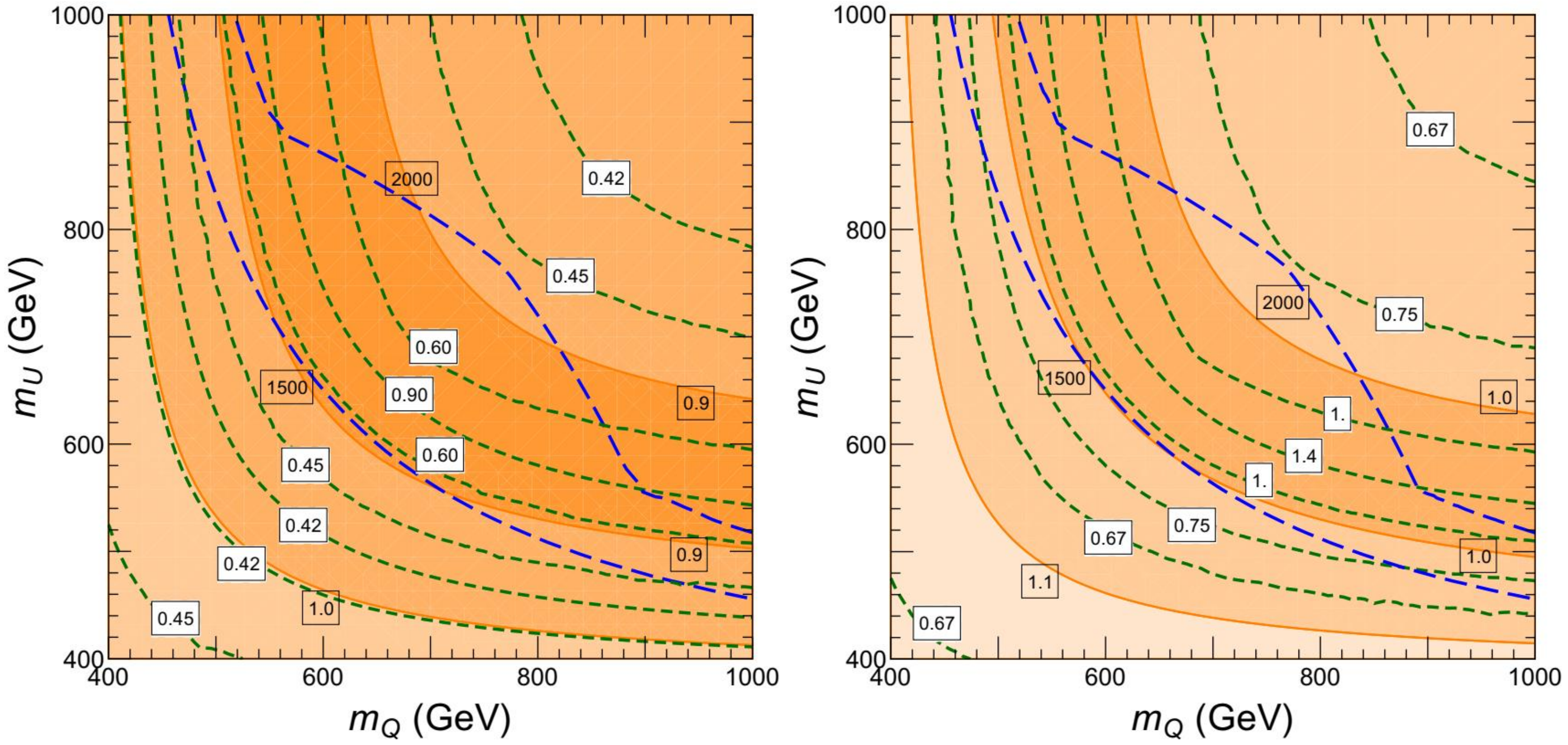
$m_{\tilde{t}_1} = 500\,\mathrm{GeV}$

Orange: κ_g

Blue : $\tilde{X}_t$

Green: σ Enhancement

Di-Higgs σ Enhancement



Left: $\kappa_t = 1.0$

Right: $\kappa_t = 1.1$

$\lambda_3 = 2.5\lambda_3^{SM}$

$m_{\tilde{t}_1} = 400\,\mathrm{GeV}$

Orange: κ_g

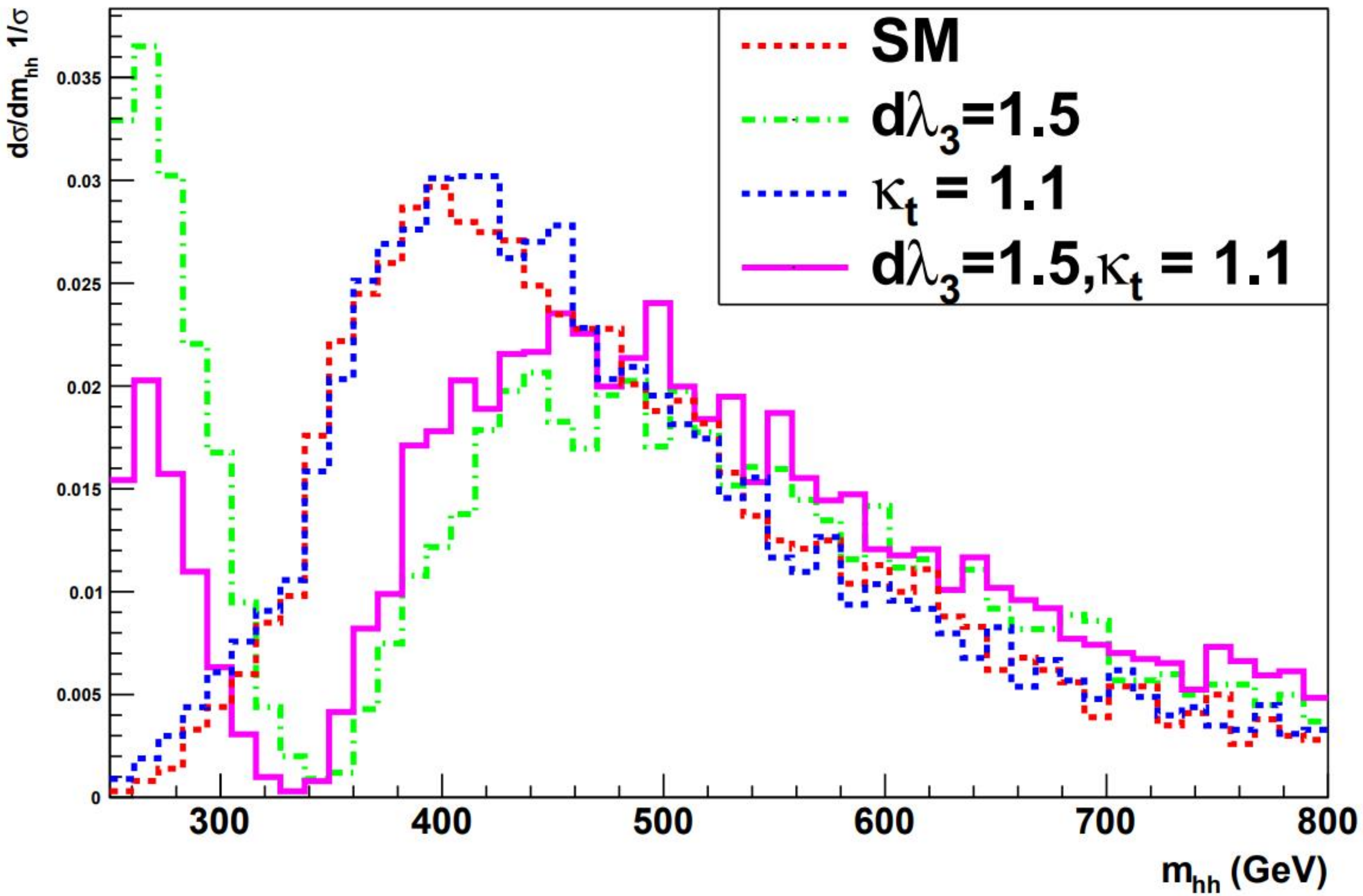
Blue : $\tilde{X}_t$

Green: σ Enhancement

Invariant Mass Distribution

Maximal destructive interference at $\lambda_3 = 2.5\lambda_3^{SM}$

Modification of κ_t can shift the weight of triangle vs. box diagrams as seen by the magenta line



Invariant Mass Distribution

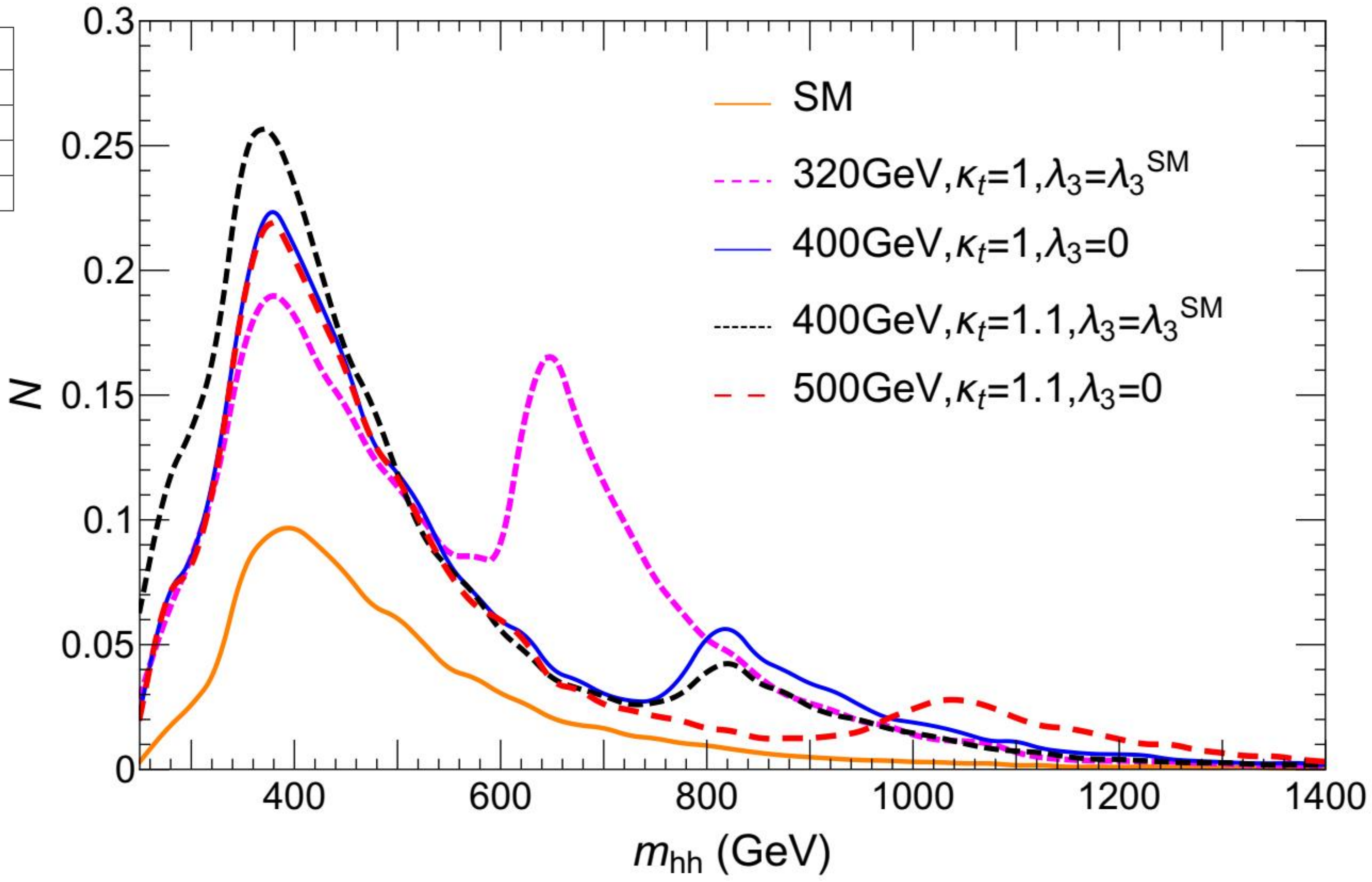
	$m_{U,Q}$ (GeV)	X_t (GeV)	$\frac{\lambda_3}{\lambda_3^{SM}}$	κ_t	κ_g	$m_{\tilde{t}_1}$ (GeV)	$\frac{\sigma_{hh}}{\sigma_{hh}^{SM}}$
BMA	575	1495	1	1	0.82	320	2.87
BMB	650	1690	0	1	0.88	400	2.73
BMC	650	1690	1	1.1	0.96	400	2.53
BMD	795	2385	0	1.1	0.97	500	2.4

$S/\sqrt{B}$	SM	BMA	BMB	BMC	BMD
	1.1	3.0	2.9	2.7	2.5

Somewhat sensitive to light stops with large mixing

Indirect probe independent of the decay

Heavier stops: sensitivity limited to large mixing, negative correction to trilinear coupling



Summary

- Di-Higgs is an important channel sensitive to BSM
- Higgs pair production in gluon fusion channel is strongly correlated with single Higgs production in gluon fusion channel
- Measurements of Higgs couplings at the LHC are in good agreement with the SM
- Yet, varying κ_g, κ_t within allowed uncertainties along with variation in λ_3 can lead to significant deviation in the di-Higgs cross section which can be a probe to underlying interesting physics