Double Higgs at the LHC

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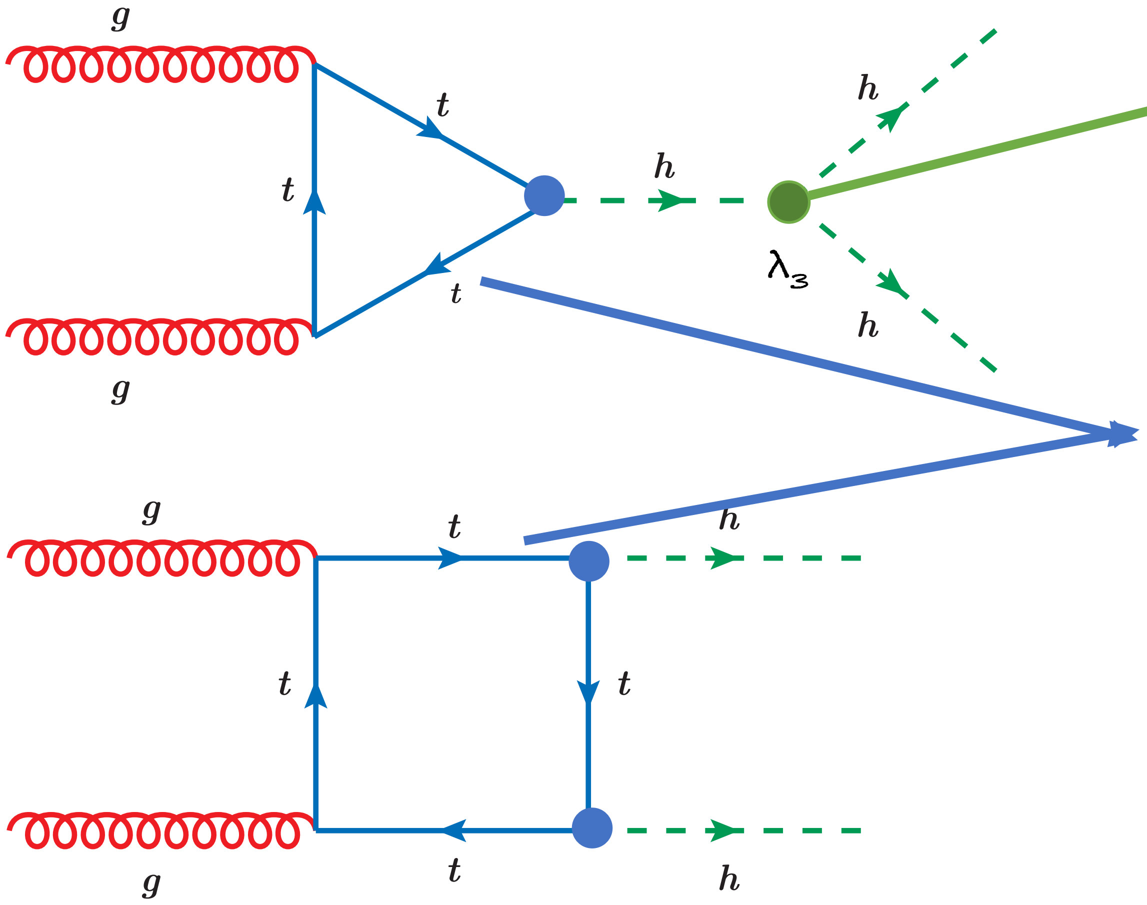
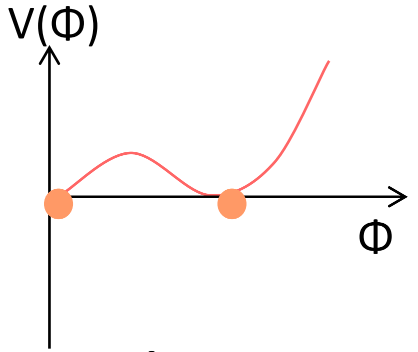
The More The Merrier

PhD Comics



1) Sensitive to the trilinear coupling -- tightly related to the nature of EWPT
2) Sensitive to new loop particles and y_t -- indirect probes of new physics
3) Can we make this measurement?

Electroweak Phase Transition



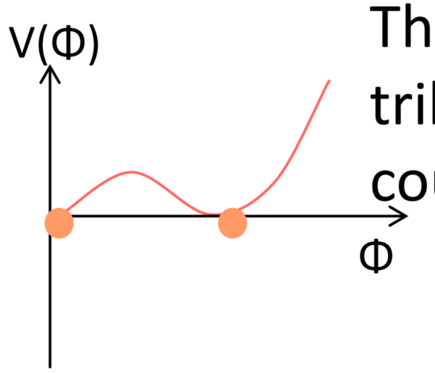
- A strong 1st order EWPT is required for Electroweak Baryogenesis, but is hard study from cosmology (see D. Egana-Ugrinovic's talk yesterday and C. Grojean's talk this morning)
- EWPT in the SM is not first order (unless the $m_h < 40$ GeV)
- New physics is required for a strongly first-order phase transition
- The new physics will alter the finite-temperature Higgs potential
- We can reconstruct the zero temperature Higgs potential by collider measurements!
- After measuring the vev and m_h, the next measurement will be Higgs trilinear coupling, the third derivative of the Higgs potential

Relating the EWPT to the Higgs Trilinear Coupling

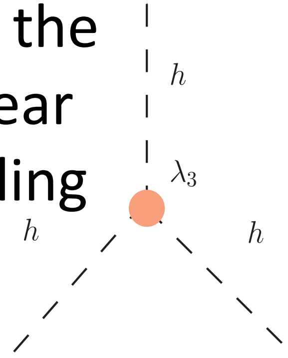
A lot of models can be consistent with a first order EWPT

SM + singlet (more on this in M. Sullivan's talk in 10 min)
SM + scalar doublet (like MSSM stops)
SM + chiral fermion (like MSSM gauginos)
SM + varying Yukawas (like flavons)
…

Calculate T_c and v_C



Then the trilinear coupling

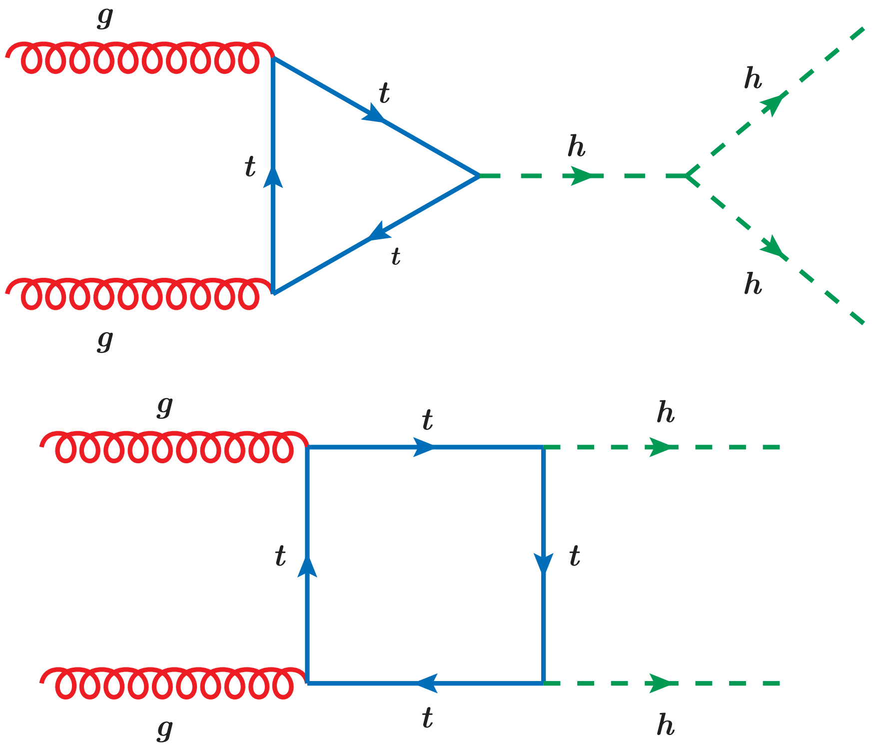


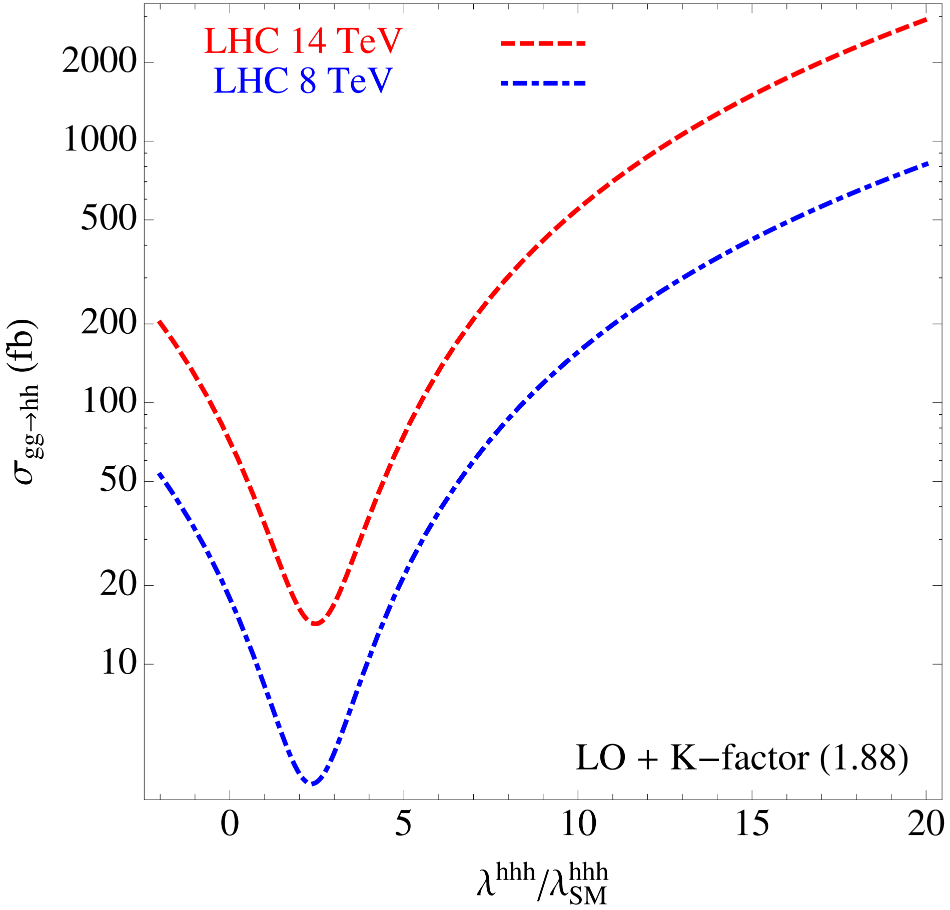
The trilinear coupling could deviate significantly from its SM value in the region consistent with a strong first order EWPT

$O(1)$ deviation is typical can go up to $7\lambda_3^{SM}$

PH, A. Joglekar, B. Li, and C. Wagner, arxiv:1512:00068; PH, A. Long, and L.T. Wang, arxiv:1608.06619

Probe the Trilinear Coupling at the LHC Production Cross Section





At NNLO, 14 TeV

$\lambda_3 = \lambda_3^{SM}$, σ(pp -> hh) = 40 fb

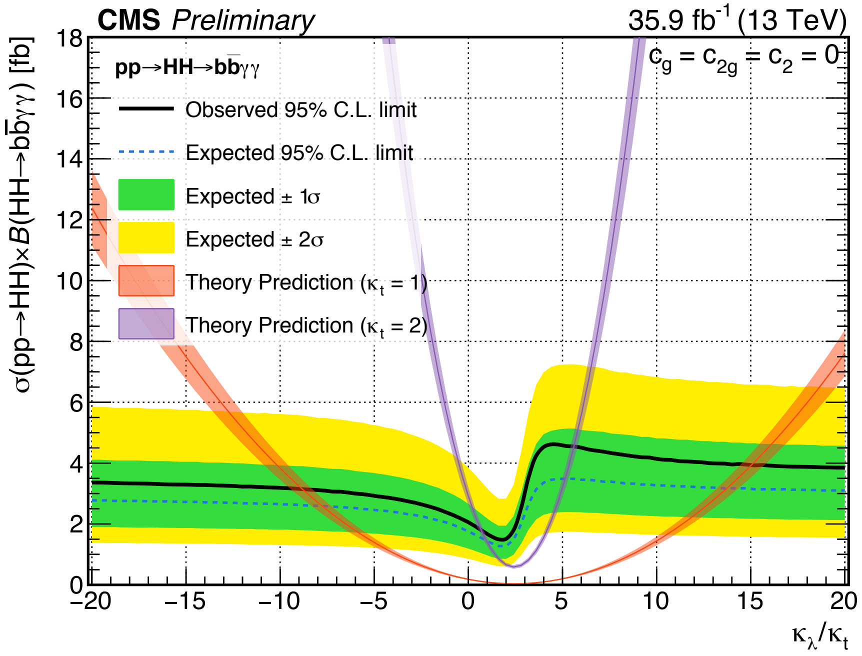
$\lambda_3 = 5\lambda_3^{SM}$, σ(pp -> hh) = 100 fb

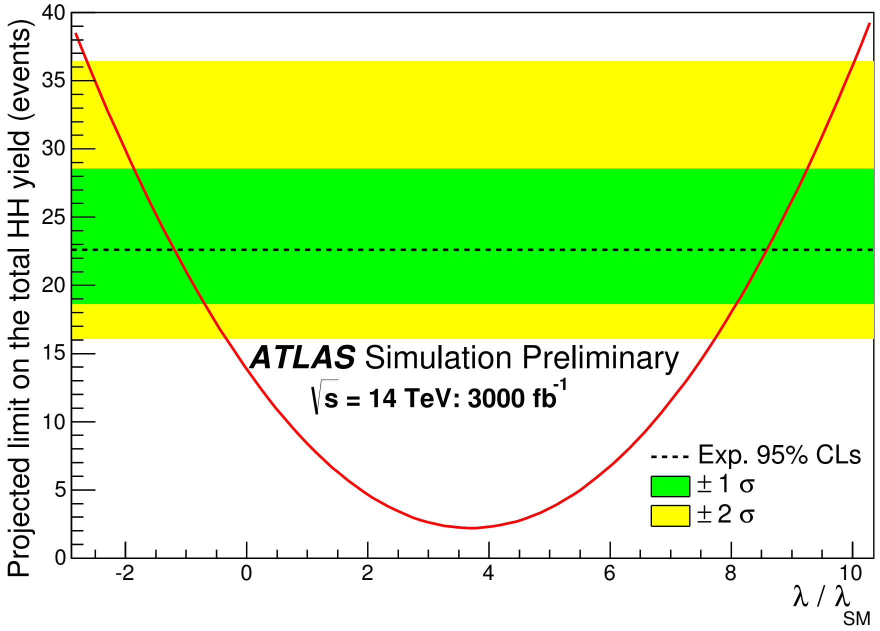
De Florian and Mazzitelli, Grigo, Melnikov, and Steinhauser

Spira, figure from Barger, Everett, Jackson, and Shaughnessy

Probe the Trilinear Coupling at the LHC, $bb\gamma\gamma$

[CMS-PAS-HIG-17-008]





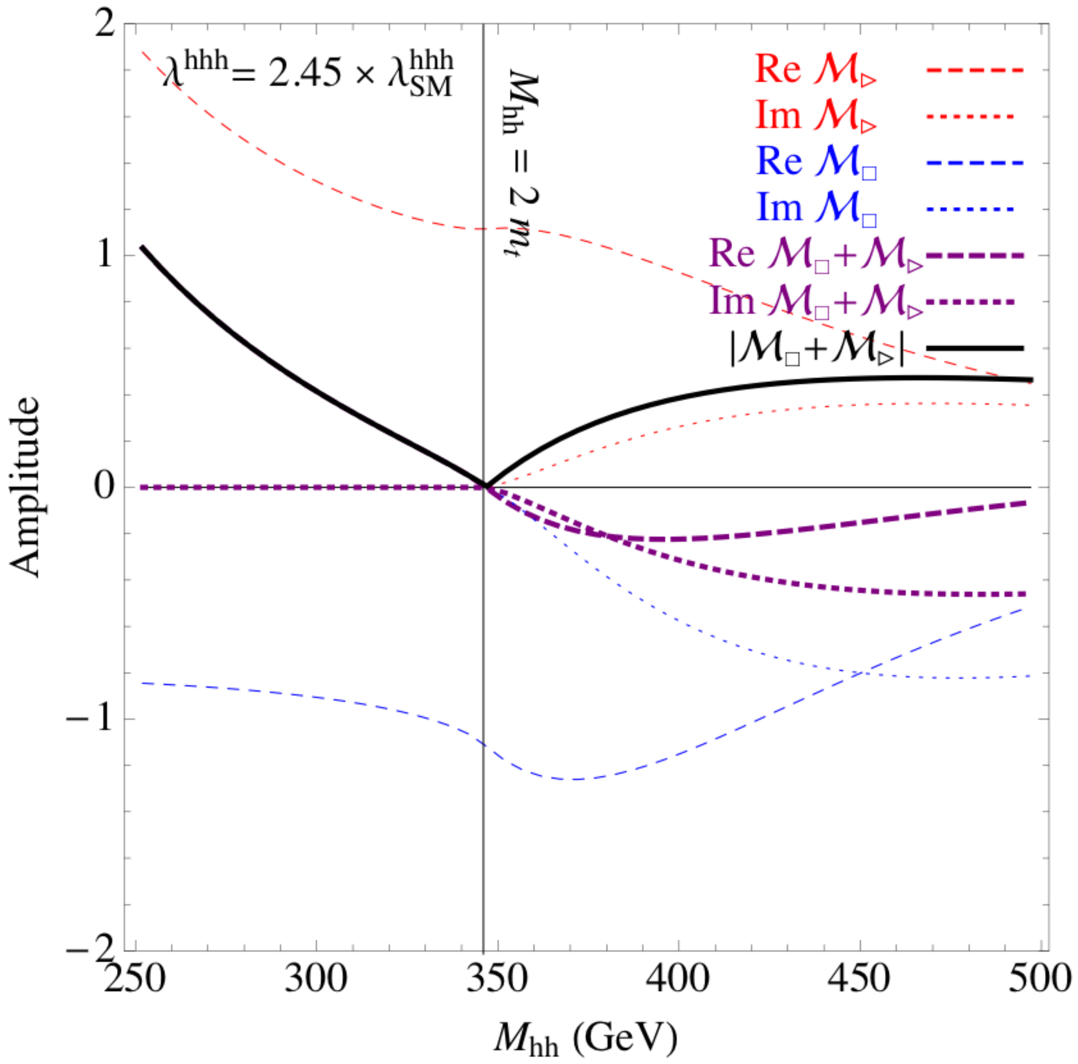
ATL-PHYS-PUB-2014-019

Current projection shows very limited sensitivity, especially in the region can be consistent with a strong 1st order EWPT

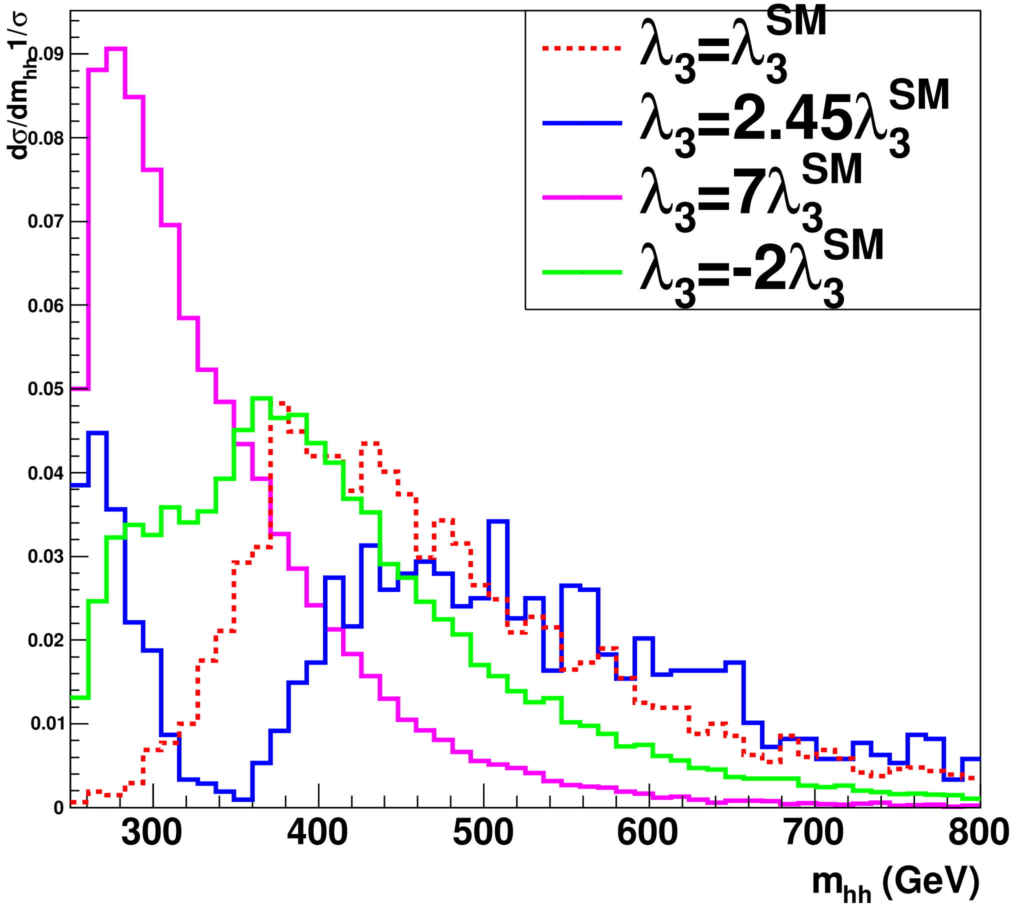
Acceptance goes down significantly for large values of λ_3

Probe the Trilinear Coupling at the LHC Acceptance goes down for large λ_3

- In most of the analysis, m_{hh} > 350 GeV, or something equivalent is required.
- The destructive interference occurs between the real part of the triangle and the box diagrams
- Above the tt threshold, the amplitudes develop imaginary parts, the cancellation does not occur
- When λ_3 increases, the amplitudes increases more below the tt threshold than above the threshold
- m_{hh} shifts to smaller value for large λ_3



Probe the Trilinear Coupling at the LHC
Acceptance goes down with λ_3



Parton level, MCFM

$\lambda_3 < 3\lambda_3^{SM}$, $m_{hh} > 350$ GeV

$\lambda_3 < 3\lambda_3^{SM}$, 250 GeV $< m_{hh} <$ 350 GeV

λ_3	λ_3^{SM}	$5\lambda_3^{SM}$	$7\lambda_3^{SM}$	$9\lambda_3^{SM}$	0	$-\lambda_3^{SM}$	$-2\ \lambda_3^{SM}$
$S/\sqrt{B}$	3.3	2.1	6.0	11	4.4	7.5	9.8

14 TeV and 3000 fb^{-1}

0.7 σ for $\lambda_3 \sim 5\lambda_3^{SM}$ if using the cut $m_{hh} > 350$ GeV

Big Improvement!

arxiv:1512.00068 PH, A. Joglekar, B. Li, and C. Wagner

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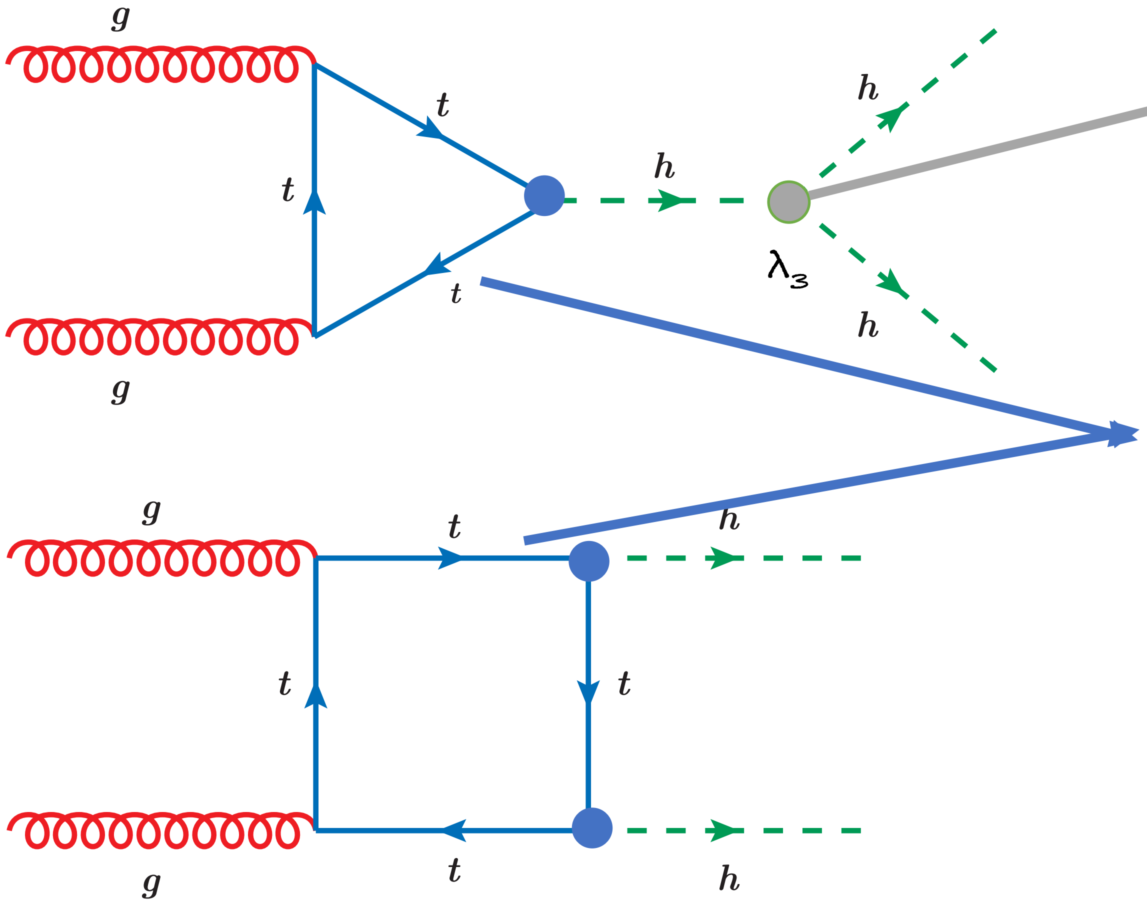
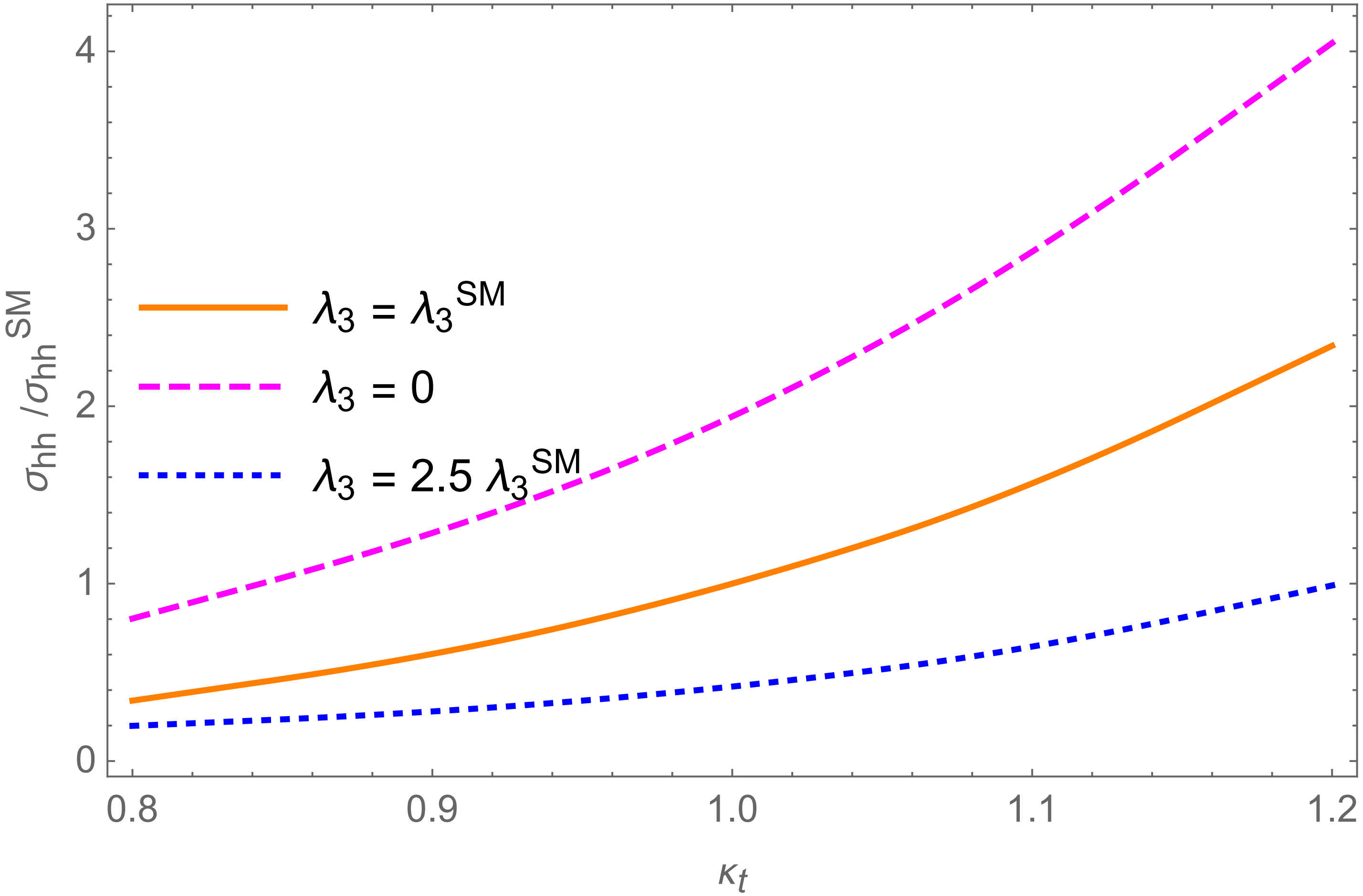


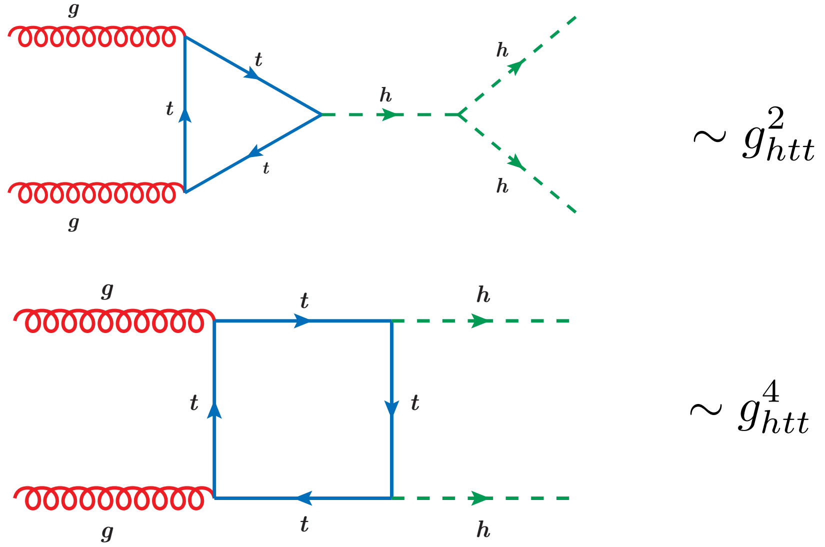
1) Sensitive to the trilinear coupling -- tightly related to the nature of EWPT
2) Sensitive to new loop particles and y_t -- indirect probes of new physics

Modifications to Double Higgs Production
Modified y_t



PH, A. Joglekar, M.Li, C. Wagner, appear soon

κ_t (g_{htt} / g_{htt}^{SM})= 1.1 leads to a 50% increase in the cross section



Destructive Interference

Box dominates in the SM

New particles, stops as an example, Constraints

- modification in gluon fusion

compensated by the mixing between the two stops

$$\frac{c_g}{c_g^{\rm SM}} = \frac{c_\gamma}{c_\gamma^{\rm SM}} = c_t + \frac{m_t^2}{4}\left[c_t\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2}\right) - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$

enhanced from an enhanced tth coupling

$$\tilde{X}_t^2 = X_t(A_t + \mu \sin\alpha/\cos\alpha)$$

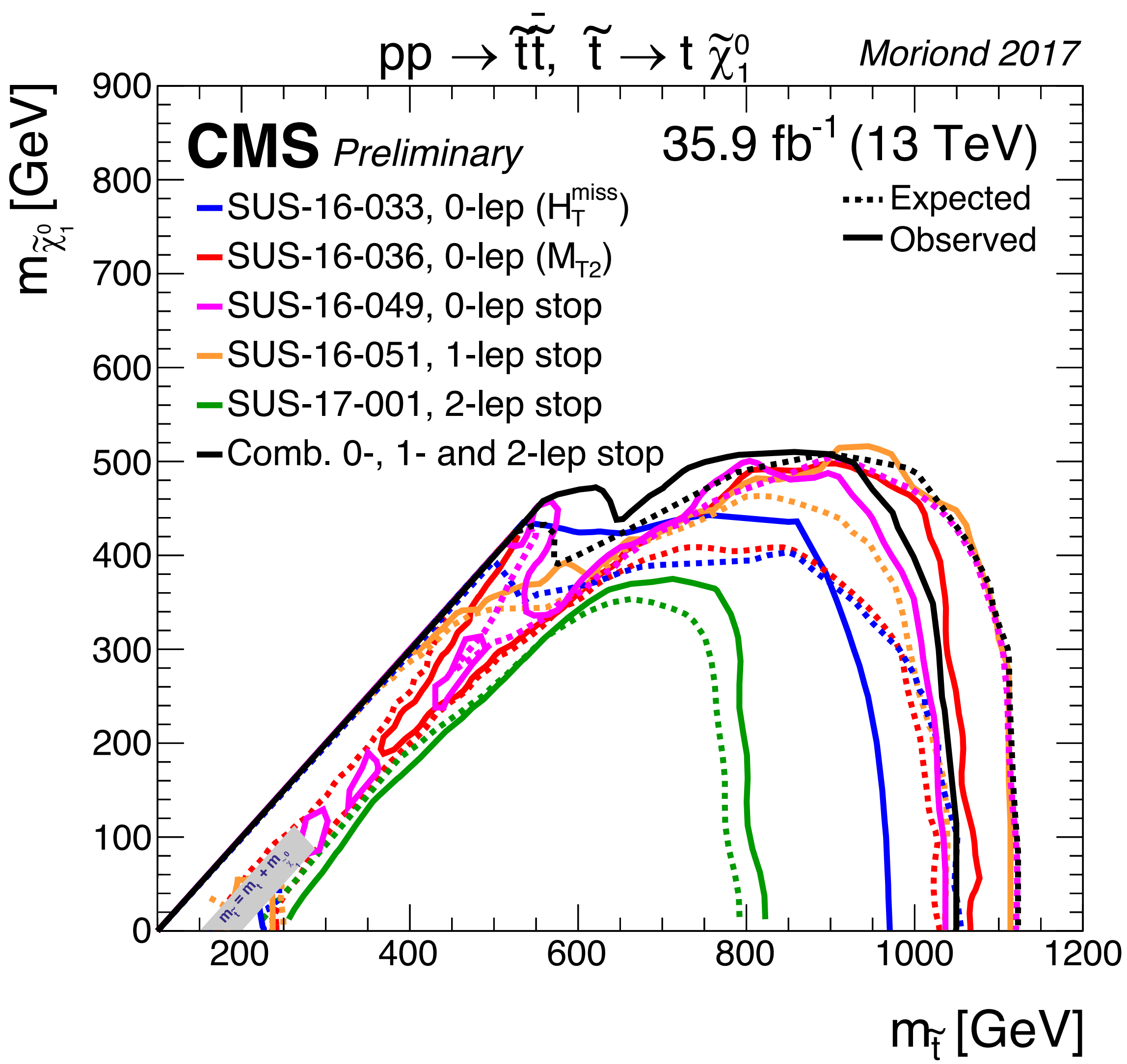
- Vacuum stability

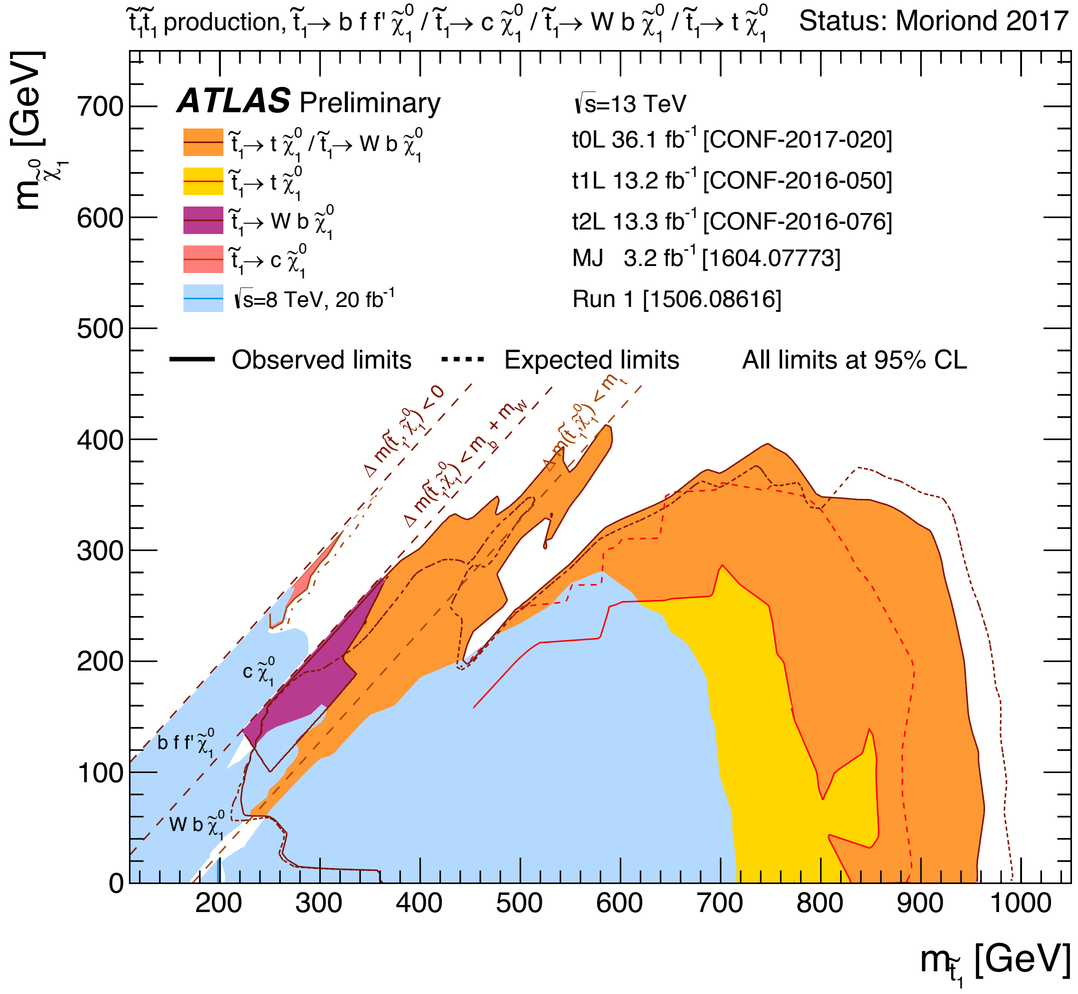
$$A_t^2 \leq \left(3.4 + 0.5\frac{|1-r|}{1+r}\right)(m_Q^2 + m_U^2) + 60\left(\frac{m_Z^2}{2}\cos(2\beta) + m_A^2\cos^2\beta\right) \quad r = m_{U_3}^2/m_{Q_3}^2$$

Blinov, and Morrissey, 2014

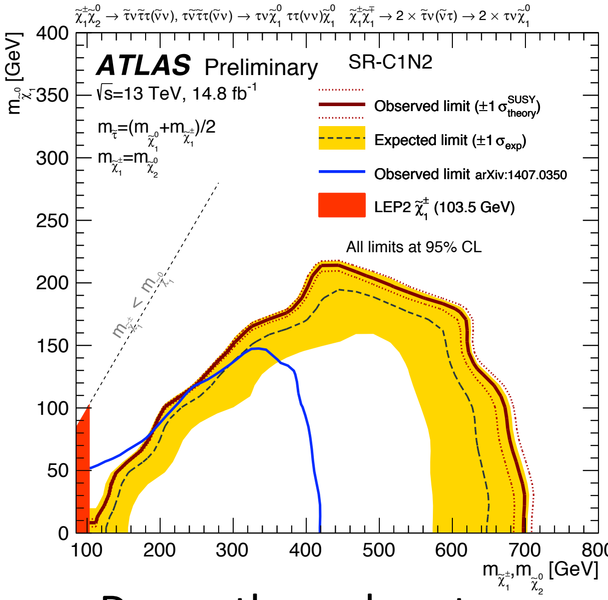
Constraints : Stop Direct Limit

Weak constraints when stops are heavier than 500 GeV



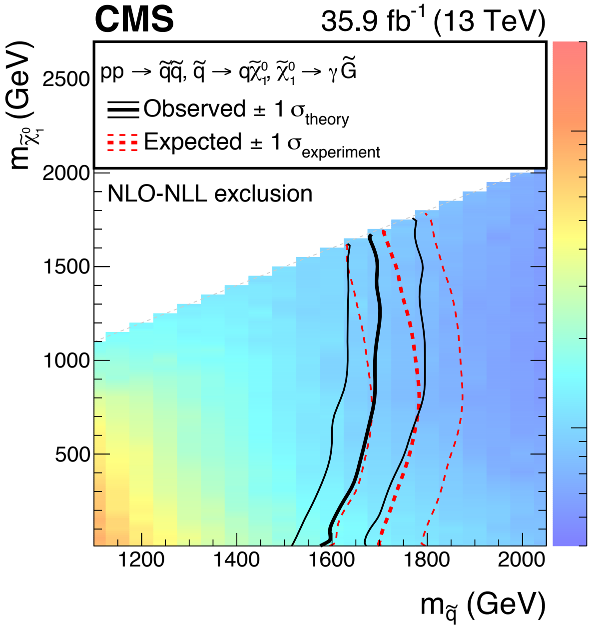


Possibly Ways to Hide the Light Stops?



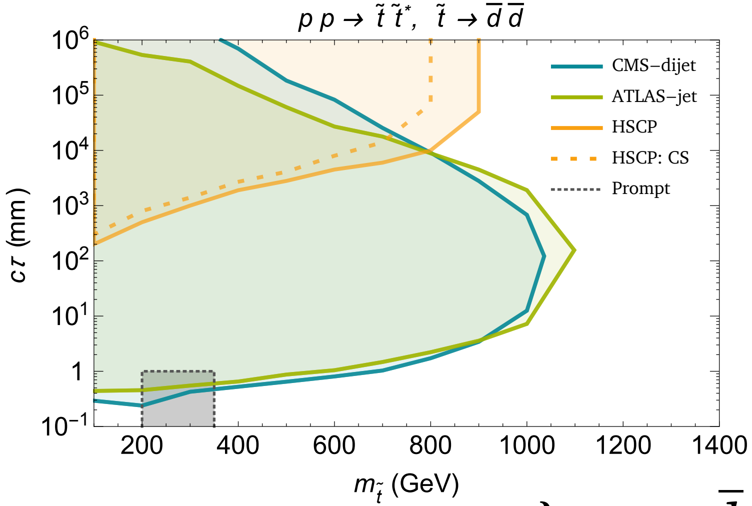
Decay through a stau

M. Carena et al, 1303.4414



Gauge Mediation Models

diphoton + missing energy final state

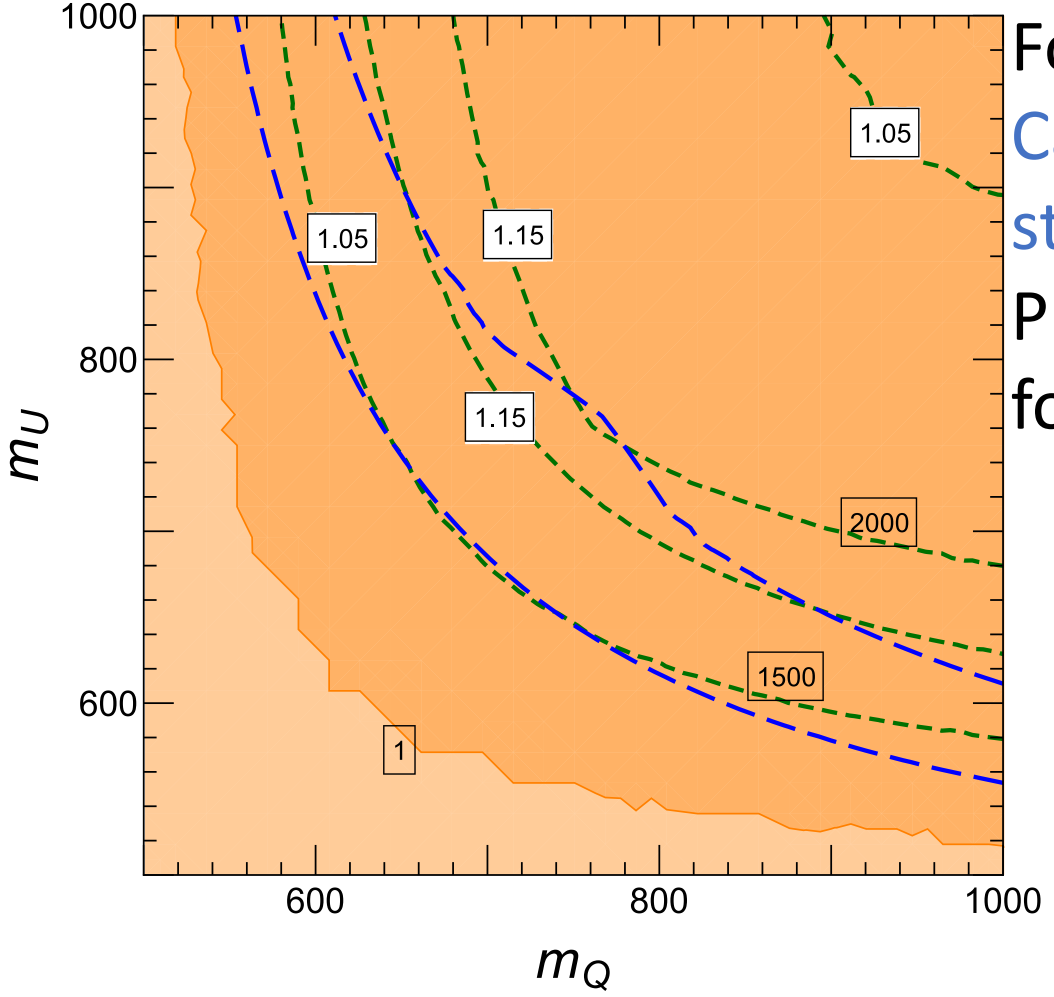


Long-Lived RPV stops $\lambda_{ijk}\bar{u}_i\bar{d}_j\bar{d}_k$

C. Csaki et al, 1505.00784

In all three cases, the exact limit should be obtained by recasting the current data.
Double Higgs provides a model independent probe for stops
Will consider light stops as light as 300 GeV

Modifications to Double Higgs Production



500 GeV stops, all couplings SM-like

For each value of m_Q and m_U,
Calculate the largest X_t allowed for the lightest stop > 500 GeV, and Vacuum stability

Plot $\sigma_{hh} / \sigma_{hh}^{SM}$, by modifying MCFM and region for $0.8 < \kappa_g < 0.9$ (darker), and $0.9 < \kappa_g < 1$ (lighter)

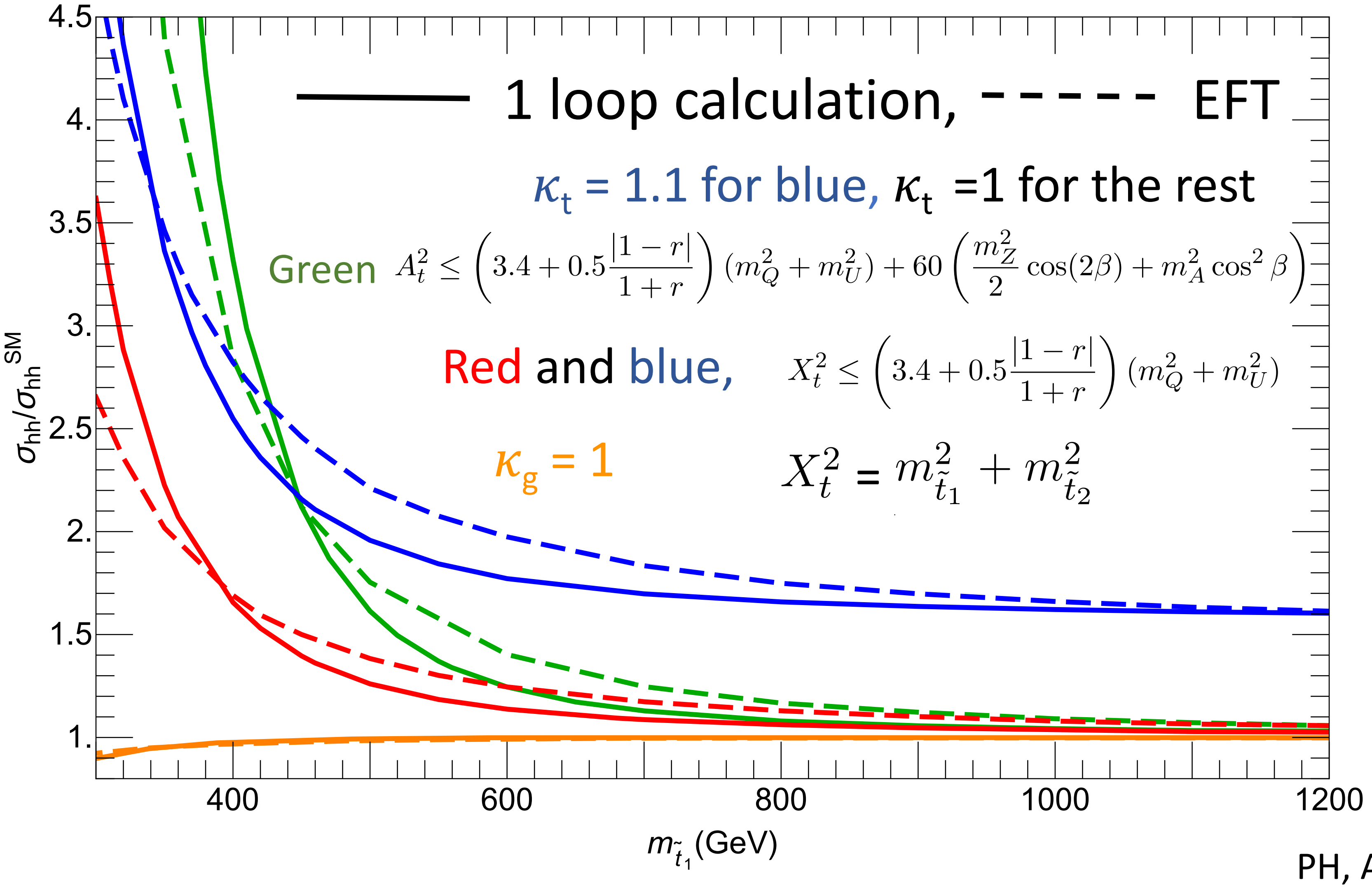
15% enhancement for a conservative choice of the vacuum stability constraint $X_t^2 \leq \left(3.4 + 0.5\frac{|1-r|}{1+r}\right)(m_Q^2 + m_U^2)$

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

with m_A = 350 GeV, $\tan\beta$ =1, 60% enhancement

PH, A. Joglekar, M.Li, C. Wagner, appear soon

Modifications to Double Higgs Production



Larger modifications for lighter stops

Larger modifications for larger X_t (Green vs Red)

Larger modification with an enhanced top coupling(Red vs Blue)

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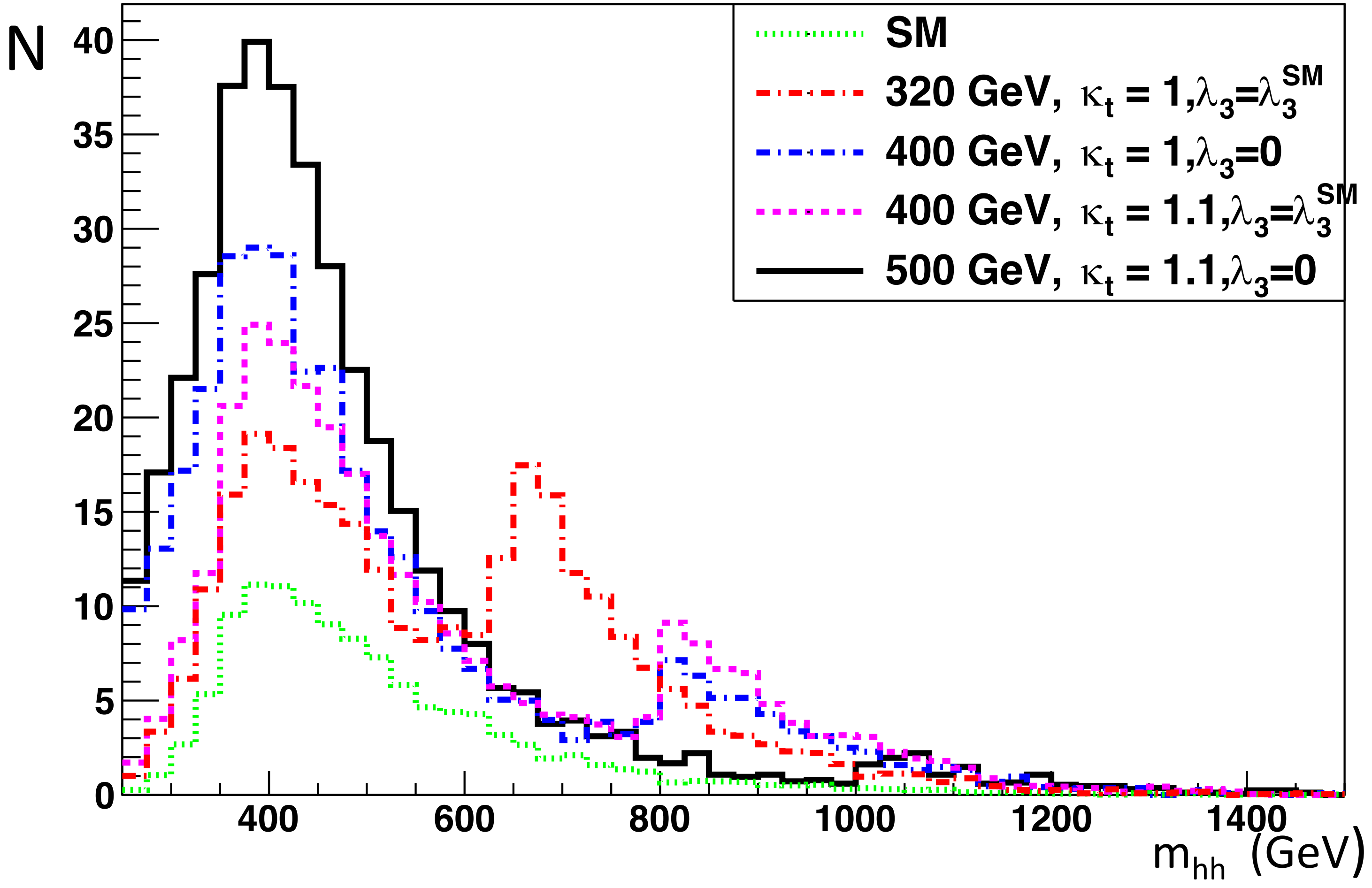
Collider Searches



Number of events for HL-LHC, 3000 fb^{-1}

- expect a second peak at $2m_{stop}$
- exact location depends on m_{stop}, κ_t and λ_3, but it is hard to see
- 500 GeV stops will be hard, unless with large modifications in y_t and λ_3

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Collider Searches

	$m_U(GeV)$	m_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	450	1000	2000	1	1	0.83	320	2.4
BMB	537	1048	2262	0	1	0.87	400	2.9
BMC	537	1048	2262	1	1.1	0.97	400	2.5
BMD	634	1072	2375	0	1.1	1.0	500	3.5

Assume the ATLAS projected sensitivities

$S/\sqrt{B}$	SM	BMA	BMB	BMC	BMD
	1.05	2.52	3.05	2.63	3.68

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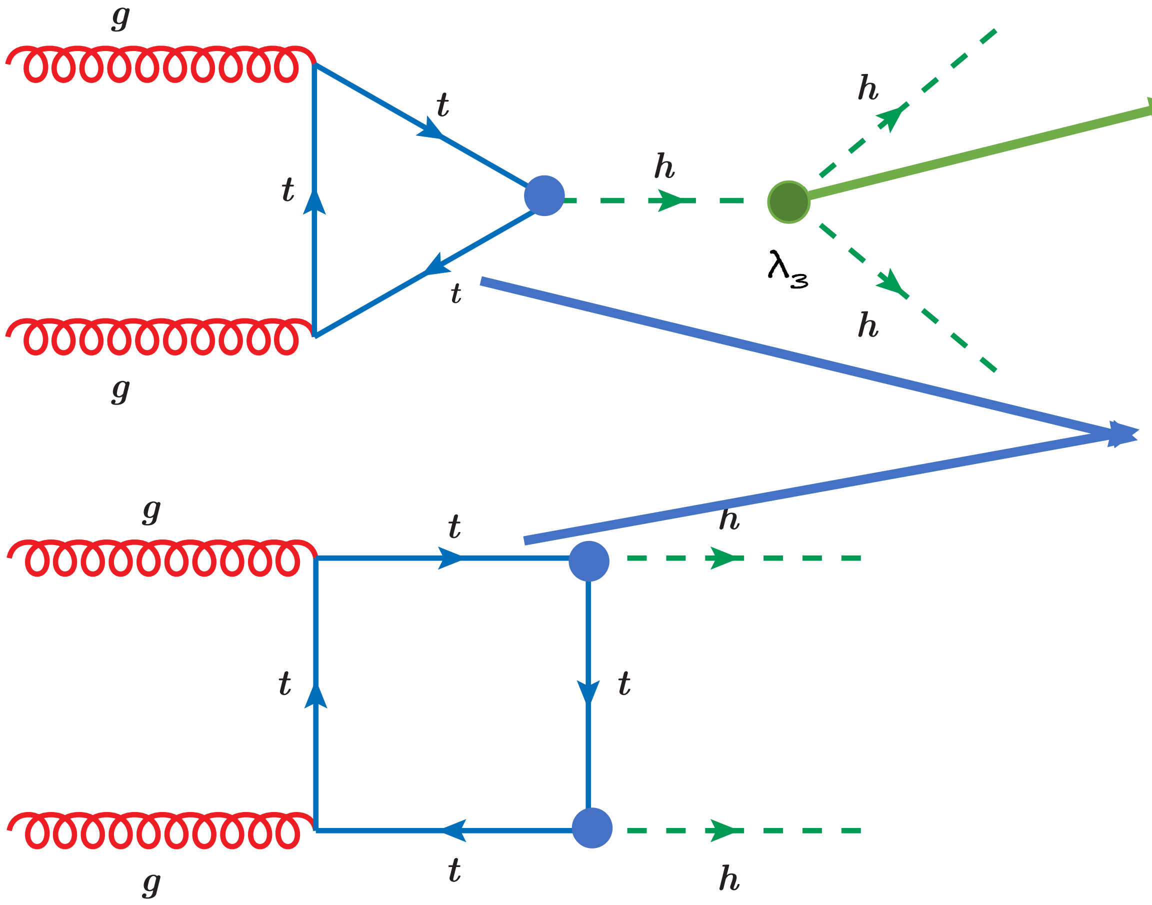

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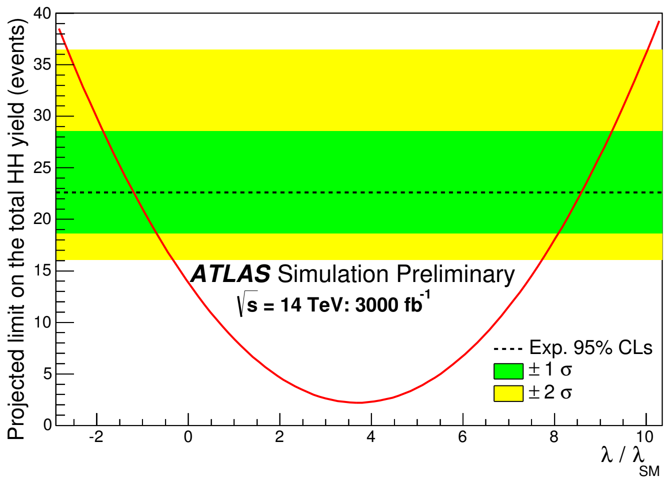
3) We can make this measurement with new physics

Back Up Slides

Probe the Trilinear Coupling at the LHC
Acceptance goes down with λ_3

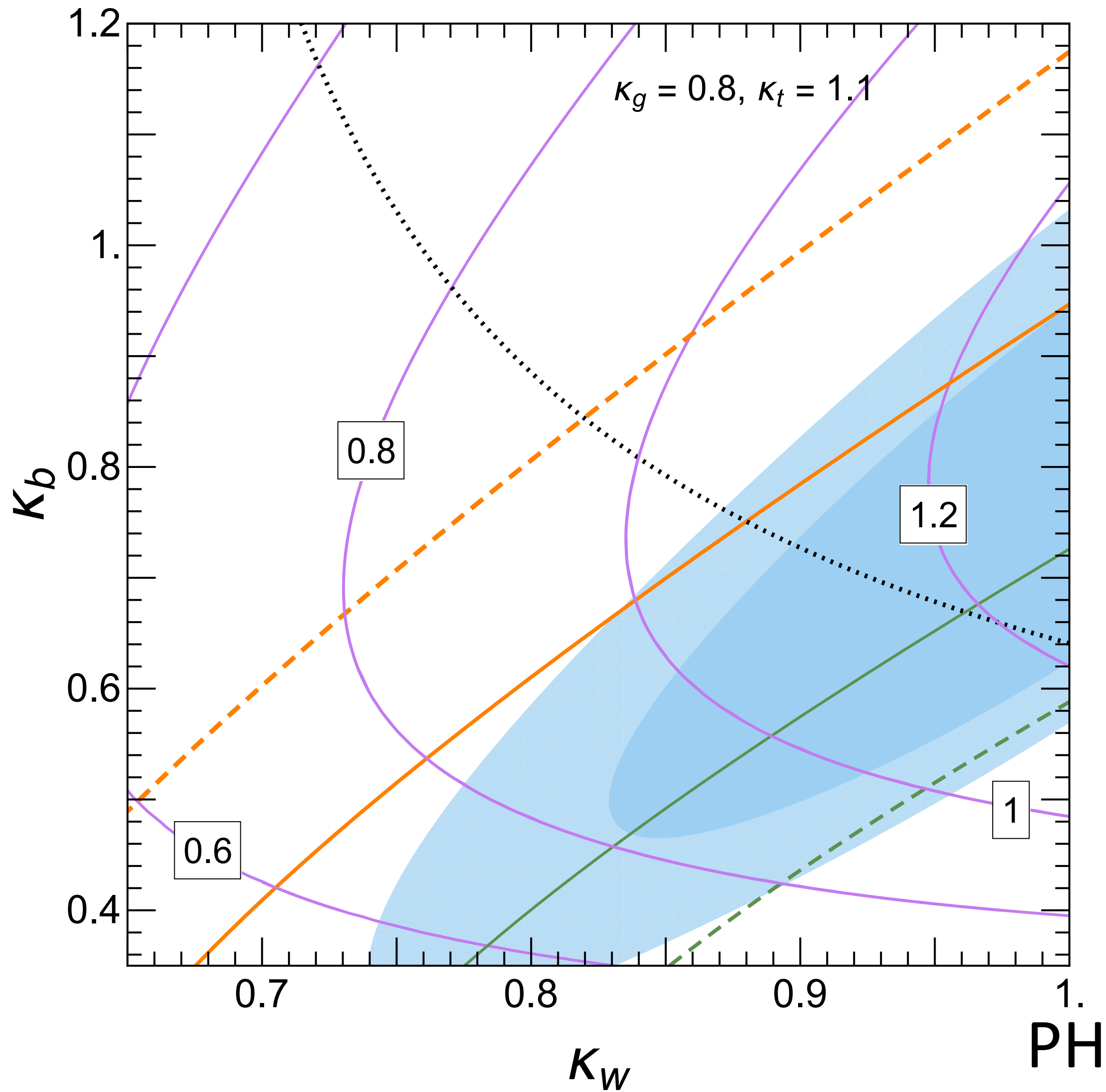
Event Selection Criteria
$\geq$ 2 isolated photons, with $p_T > 30$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$
$\geq$ 2 jets identified as *b*-jets with leading/subleading $p_T > 40/25$ GeV, $\|\eta\| < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\|\eta\| < 2.5$
< 6 jets with $p_T > 25$ GeV, $\|\eta\| < 2.5$
$0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}, p_T^{b\bar{b}} > 110$ GeV

Cut on m_{hh}



$m_{hh} > 350$ GeV is required in most theory studies

Modifications to Higgs Decays



The decay branching ratios of h->bb, and h->$\gamma\gamma$ depend strongly on κ_w and κ_b

For given value of κ_g and κ_t, show the region consistent with the Run1 data within 1σ and 2σ

BR(h->bb)×BR(h-> $\gamma\gamma$) normalized to SM

$\kappa_\gamma = 1.28\ \kappa_w - 0.28\ \kappa_g$ to account for the top and stop contributions

Run 2 data, central value in solid, 1 σ in dashed, for h-> $\gamma\gamma$ in ATLAS and CMS, h->bb in dotted

Largest modification ~ 20%

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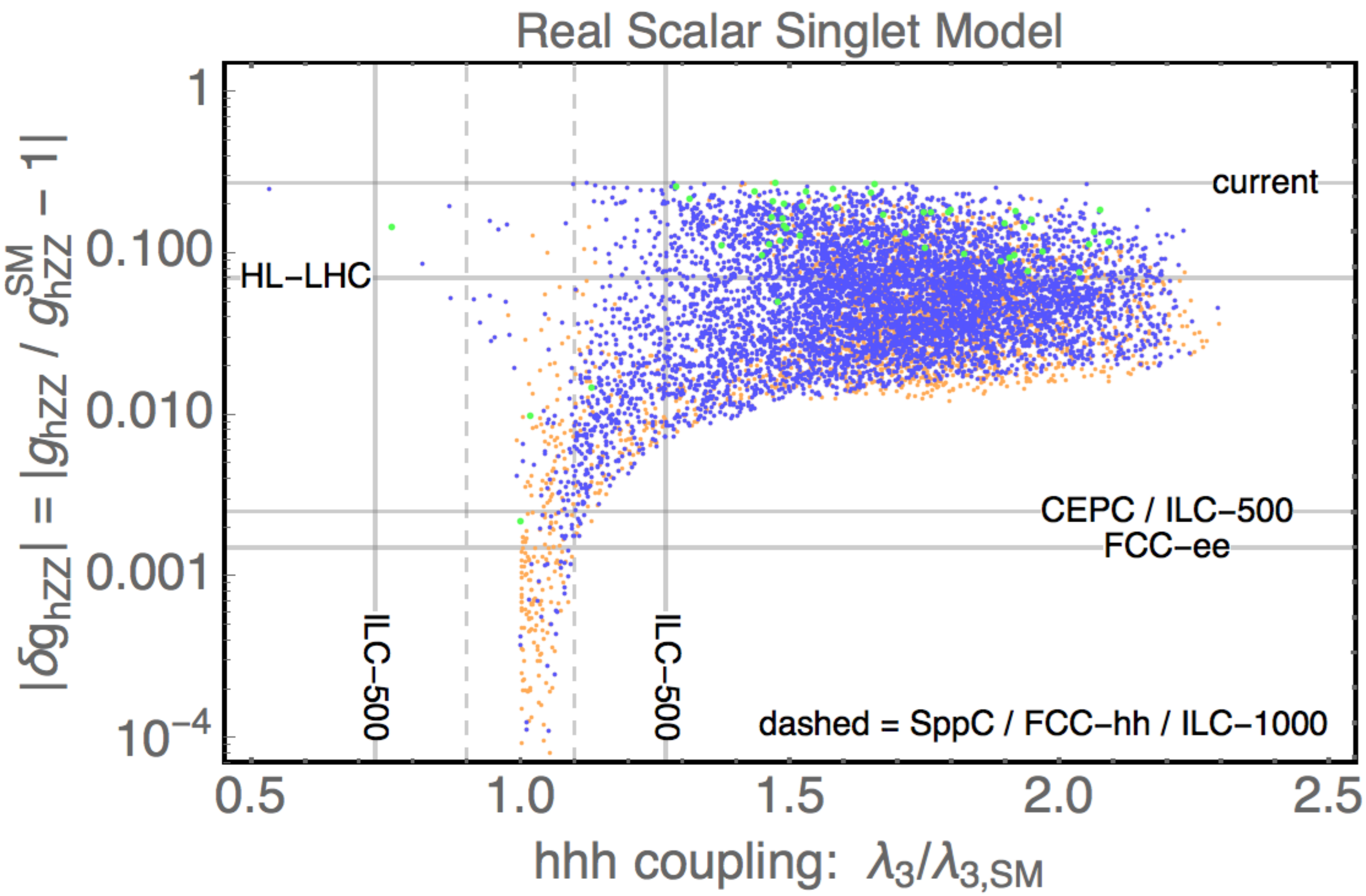
Complimentary to lepton colliders and gravitational wave detections

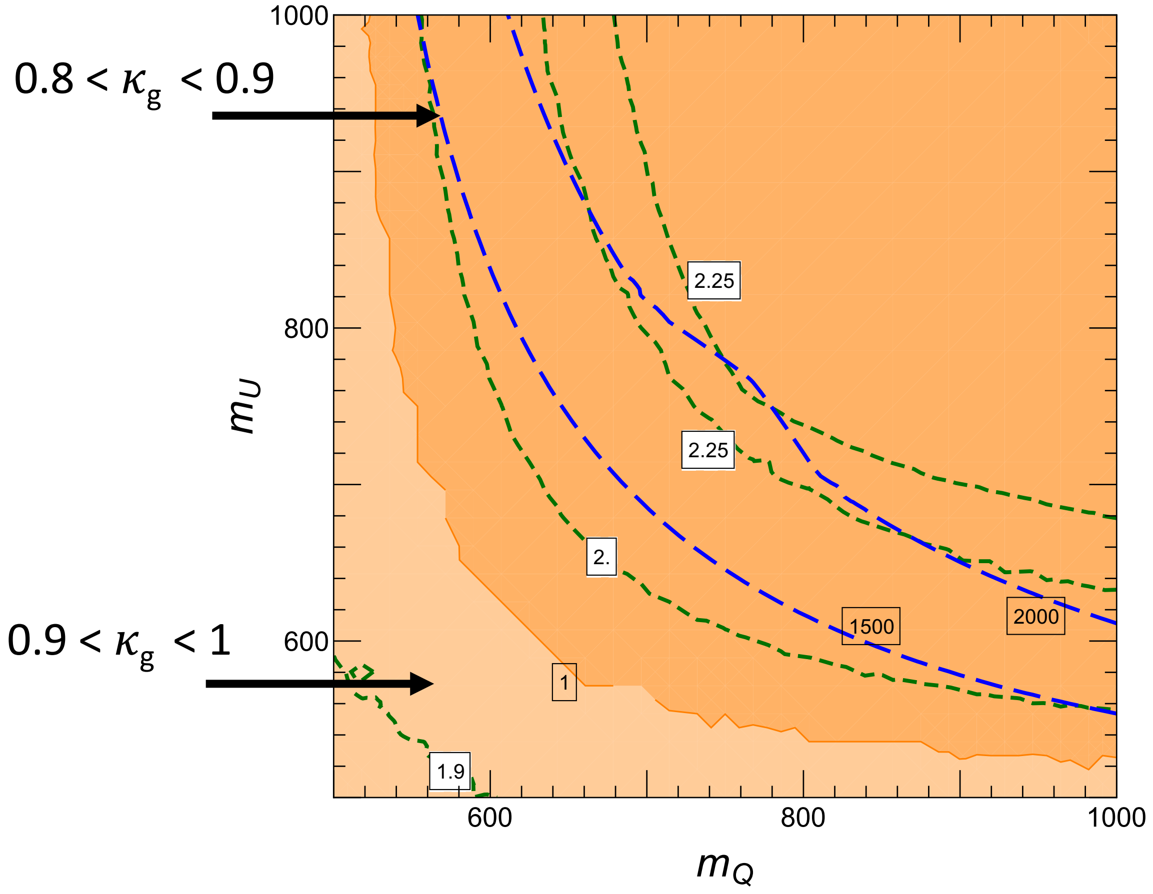


First order phase transition

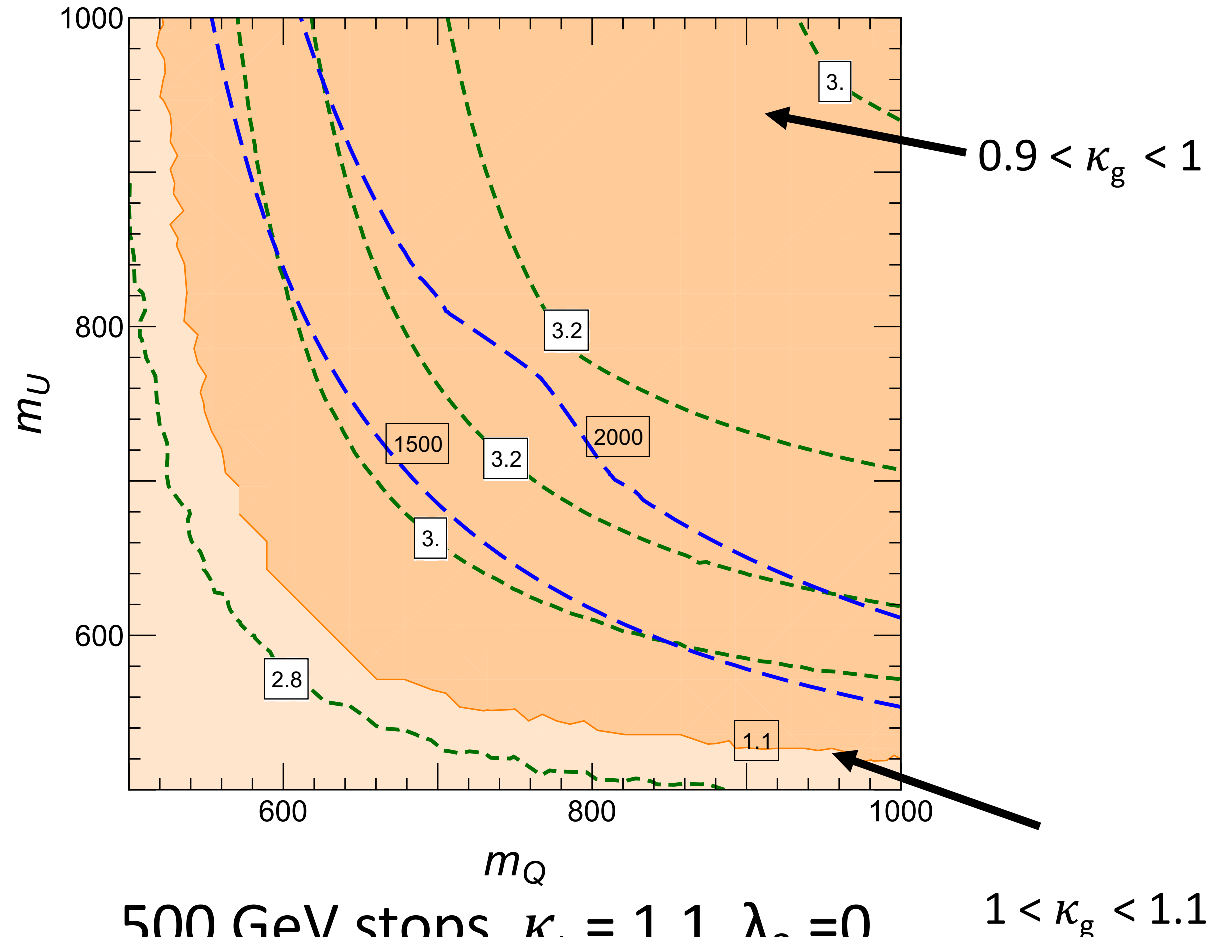
Strongly first order phase transition

very strong first order phase transition, could detect GWs at (e)Lisa

Modifications to Double Higgs Production



500 GeV stops, $\kappa_t = 1$, $\lambda_3 = 0$



500 GeV stops, $\kappa_t = 1.1$, $\lambda_3 = 0$

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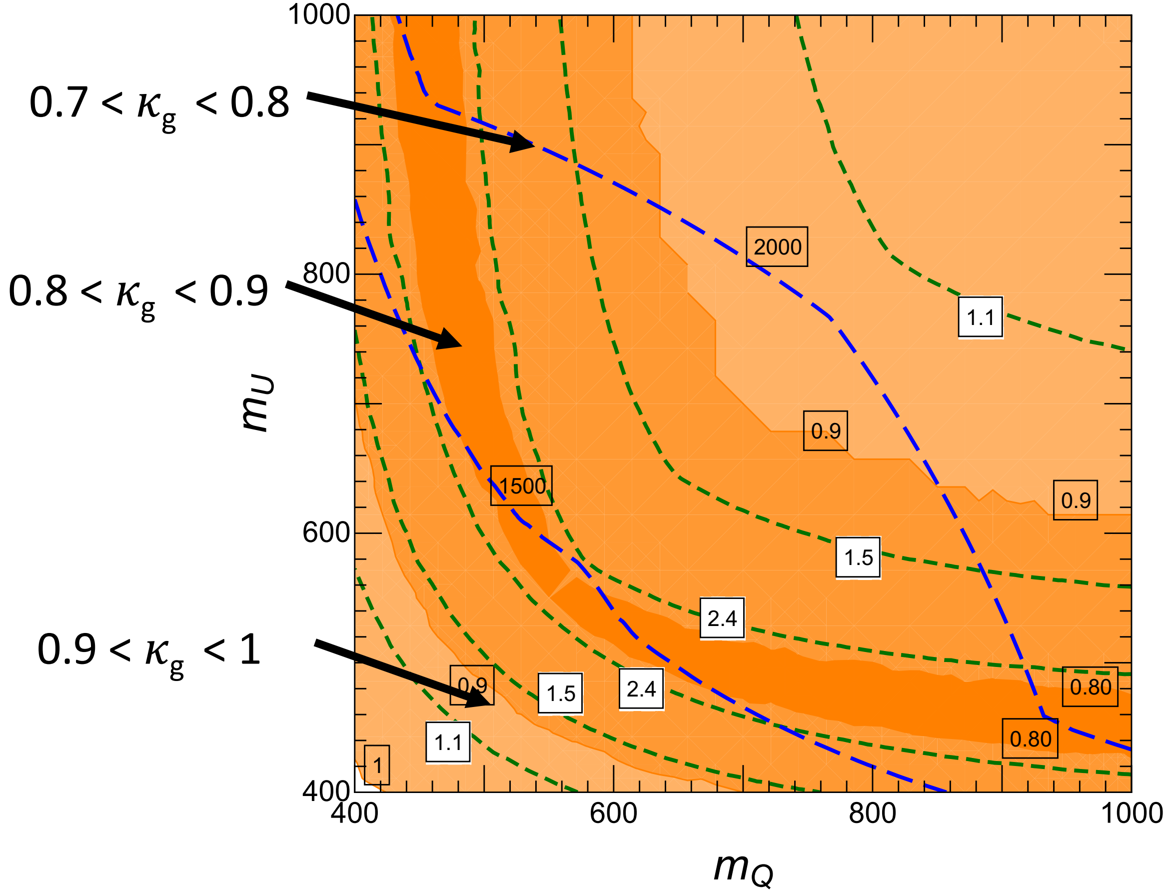
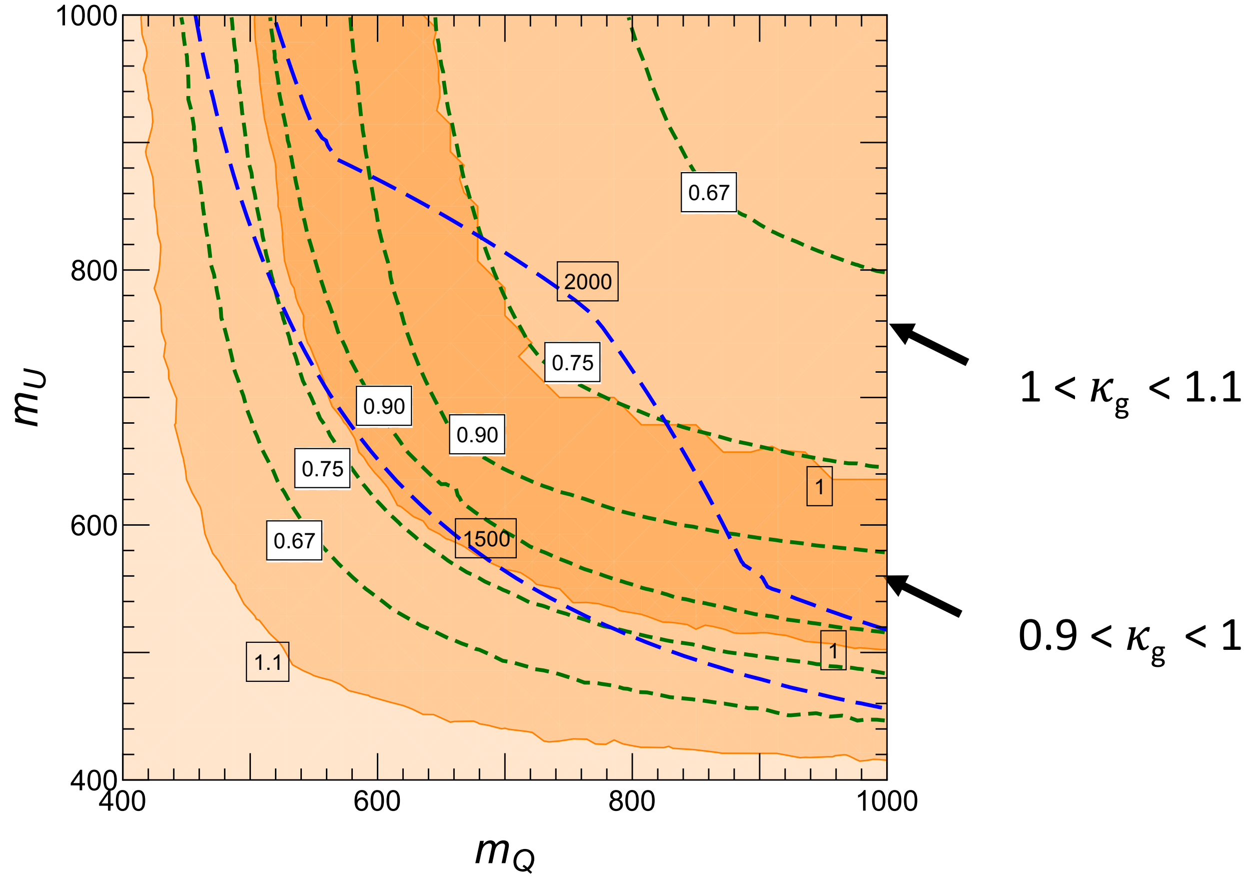
Modifications to Double Higgs Production



300 GeV stops, κ_t = 1, $\lambda_3 = \lambda_3^{SM}$



400 GeV stops, κ_t = 1.1, $\lambda_3 = 2.5\,\lambda_3^{SM}$

Almost recover SM rate even with the strongest cancellation

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EFT for stops

$$|\mathcal{M}|^2 = \frac{\alpha_s^2 G_F^2 \hat{s}^2}{2^{17}\pi^2} \,\Big| \sum_i \beta_i \big(g_h^{(i)} C_\triangle + (-g_h^{(i)} + g_{hh}^{(i)}) C_\Box\big) \Big|^2$$

$$g_h^{\tilde{t}} = \frac{\partial \log(\det M_{\tilde{t}}^2)}{\partial \log v}\Big|_{M_i = M_i(v)} = 2m_t^2 \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}$$

$$g_{hh}^{\tilde{t}} = \frac{\partial^2 \log(\det M_{\tilde{t}}^2)}{\partial(\log v)^2}\Big|_{M_i = M_i(v)} = 2g_h^{\tilde{t}} - {g_h^{\tilde{t}}}^2 + \frac{8m_t^4}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2},$$

$$C_\triangle = \frac{3m_h^2}{\hat{s} - m_h^2}$$