New physics in double Higgs production

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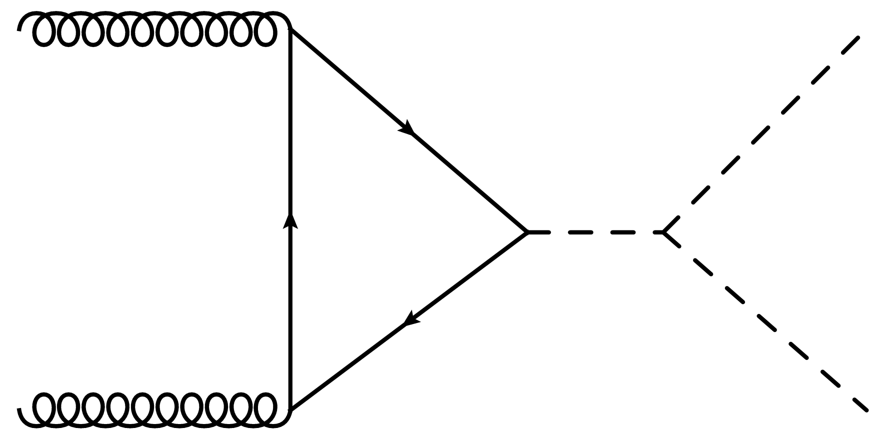
1504.05596, with S. Dawson and I. Low

Double Higgs production

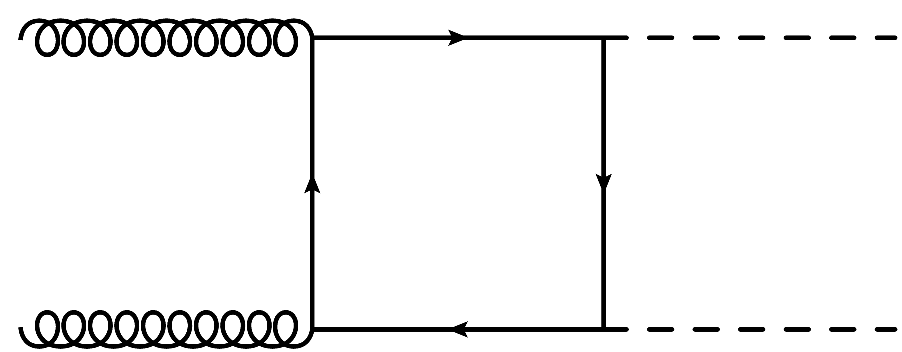
Proceeds through heavy quark loops

Triangle diagram is sensitive to Higgs self-coupling



Box and triangle diagrams exhibit partial cancellation

Cross section is very low: σ(13 TeV LHC) = 34 fb



The Higgs self-coupling

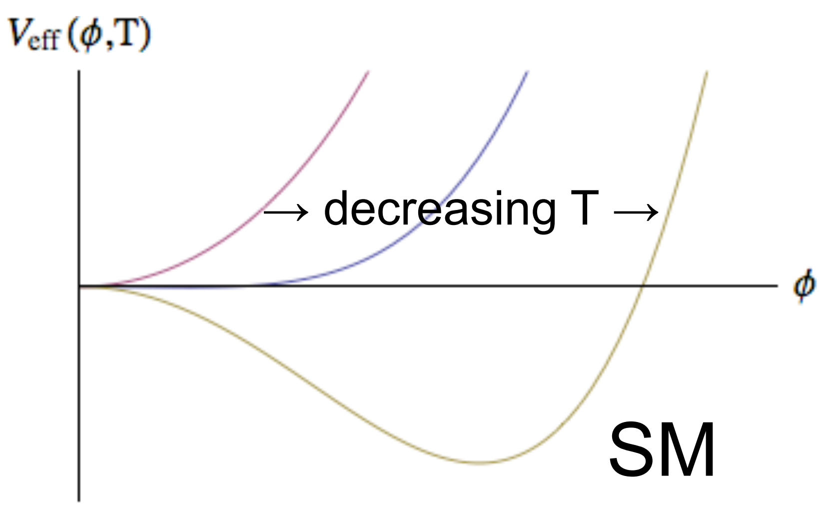
$$V = \mu^2 H^\dagger H + \frac{1}{2}\lambda \left(H^\dagger H\right)^2 \qquad\qquad H \to \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$$

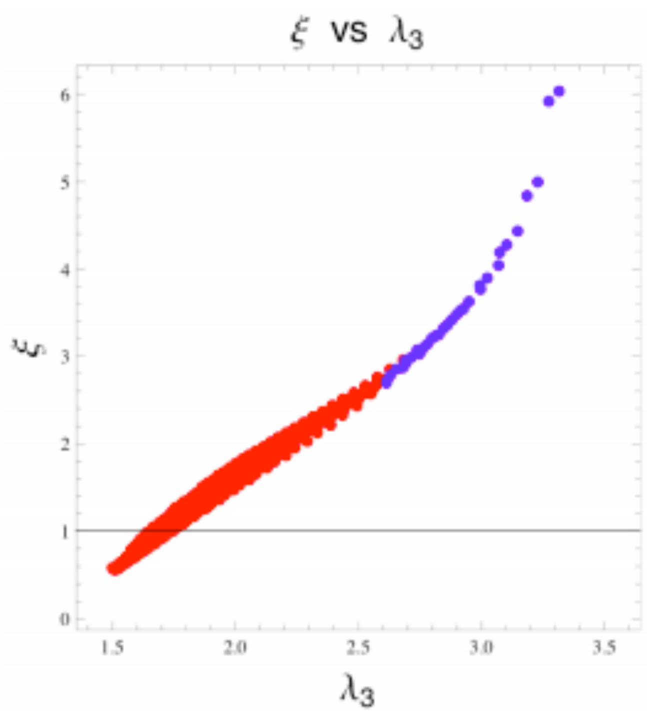
$$\lambda = m_h^2/v^2 \to \lambda_{hhh} = 3m_h^2/v$$

Measurement probes scalar potential, testing the structure of the Standard Model

Double Higgs production is one of the only collider processes that is sensitive to the self-coupling

The Higgs self-coupling





Generically, adding new physics to make the EW phase transition strongly first-order shifts the Higgs self-coupling

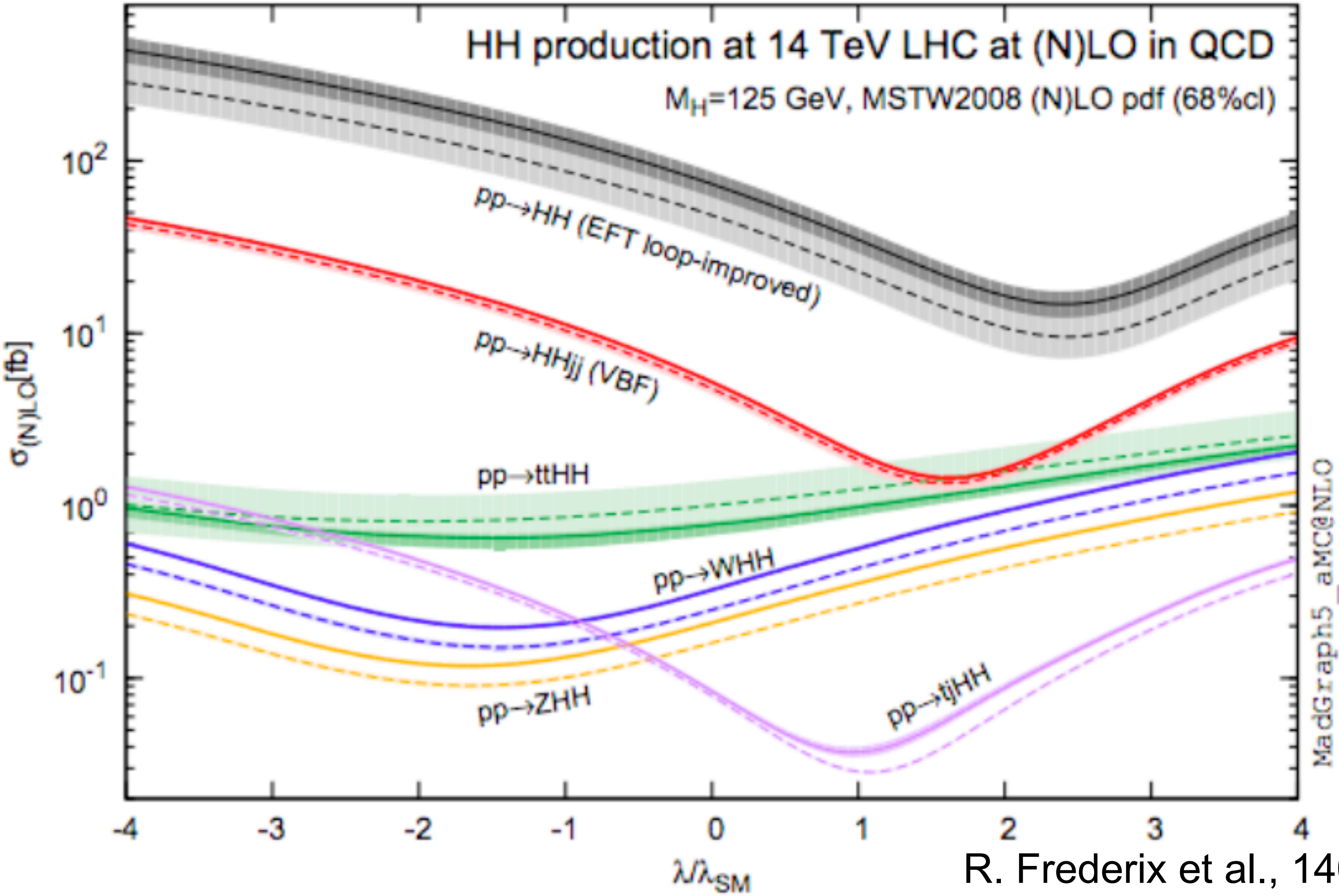
e.g. non-renormalizable H^6 operator

A. Noble and M. Perelstein, 0711.3018

Connection with EW baryogenesis

D. Curtin et al., 1409.0005

The Higgs self-coupling

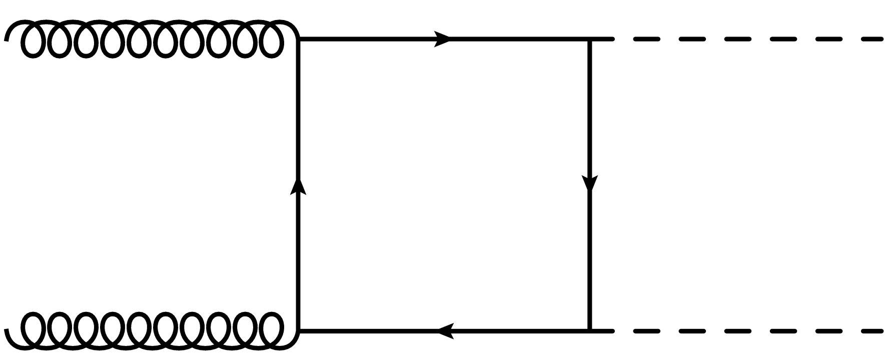


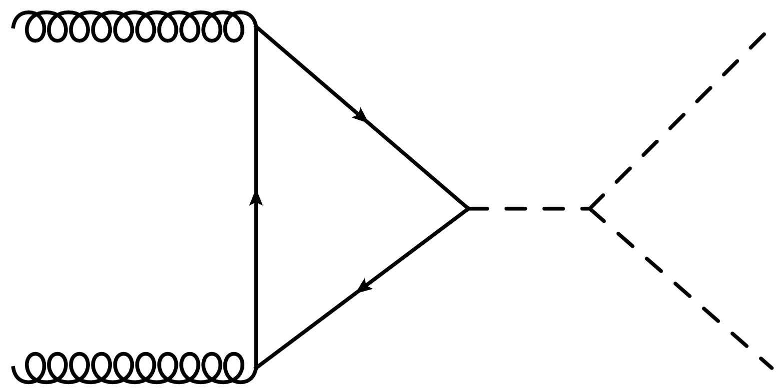
R. Frederix et al., 1401.7340

Overall cross section is sensitive to self-coupling

Note large LO uncertainty; NLO does not always have m_t

Threshold cancellation





SM: perfect cancellation between box and triangle at threshold when quark in loops is heavy

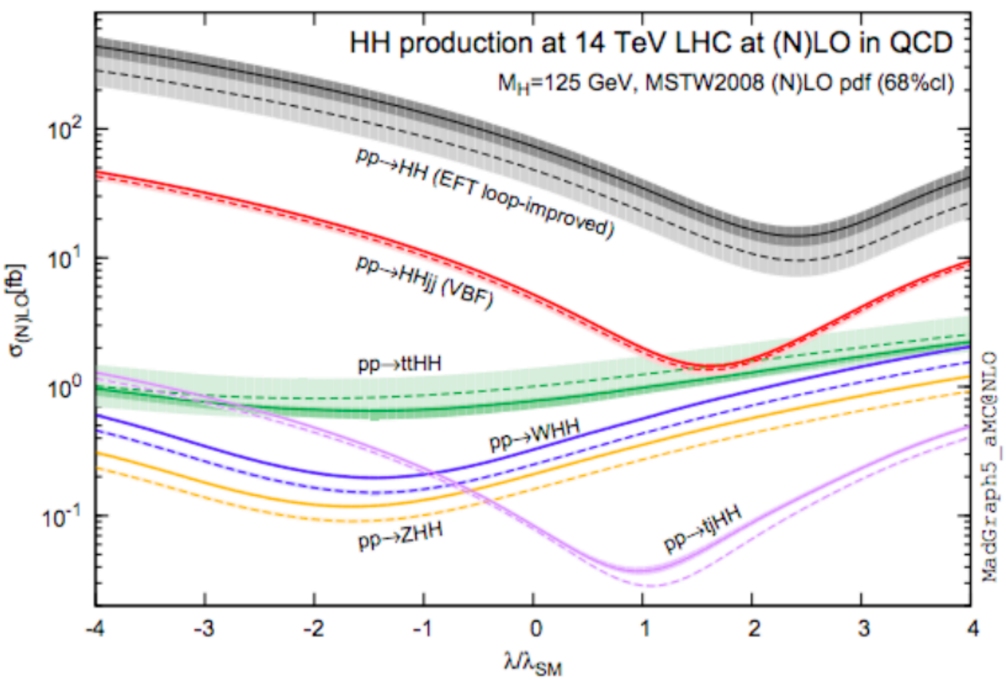
Can be seen via low energy theorem

$$\mathcal{M}_{hh} \propto \langle hh| \log(1+\frac{h}{v})|0\rangle = \langle hh|\frac{h}{v} - \frac{h^2}{2v^2}|0\rangle$$

threshold: $\frac{1}{v}\frac{\lambda_{hhh}}{\hat{s}-m_h^2} = 1/v^2$ $\quad -1/v^2$

Threshold cancellation

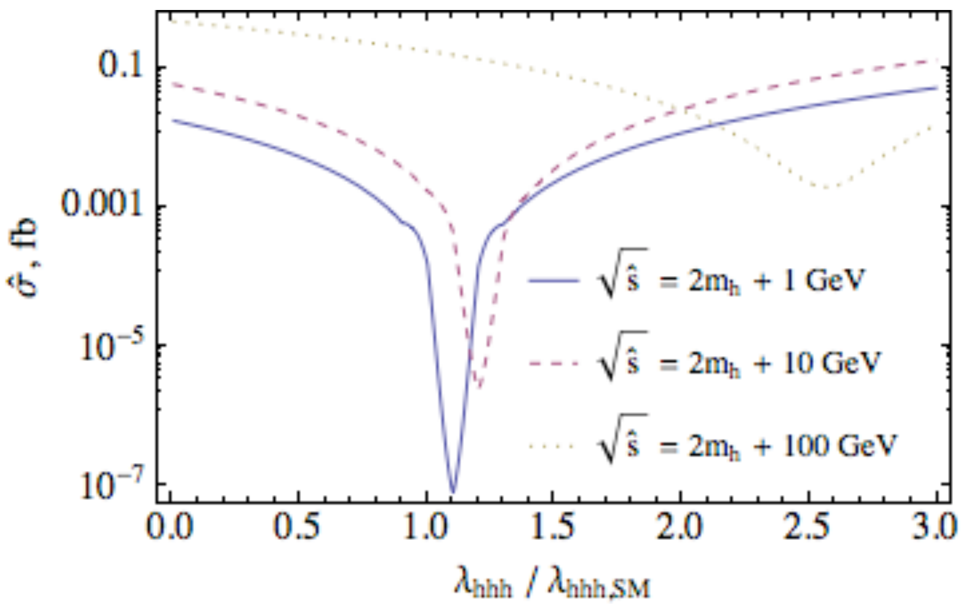
In the SM, the cancellation between the box and triangle diagrams is significant even for the finite top mass

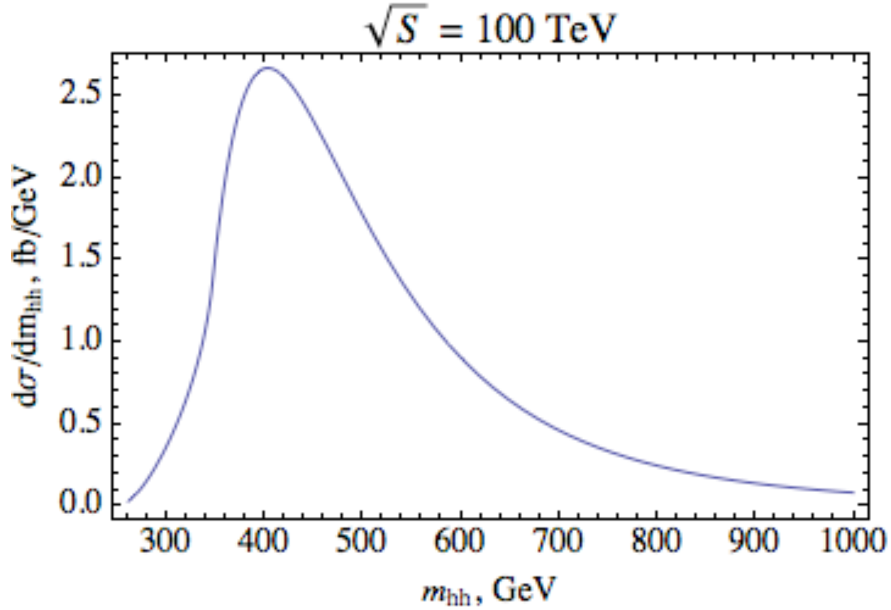


Changing the Higgs triple coupling affects this cancellation, modifying the hh cross section

Production above threshold also affects minimum

Threshold cancellation

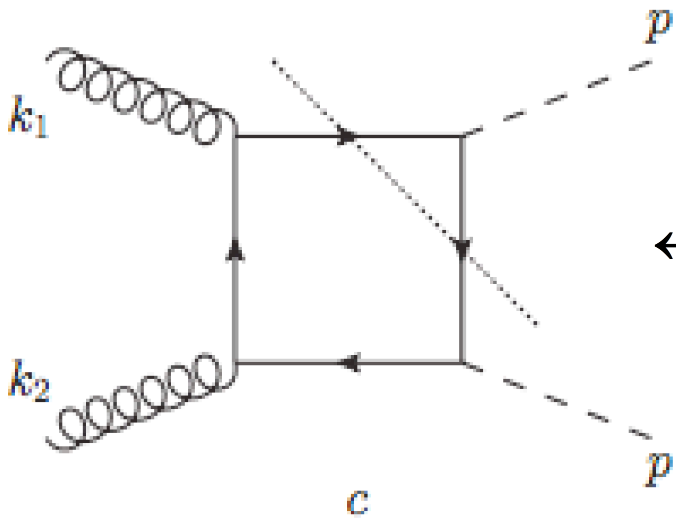




Highest parton luminosity at threshold, but cancellation is strongest there

Look at invariant mass distribution to see how cancellation gets spoiled above threshold

Cut techniques



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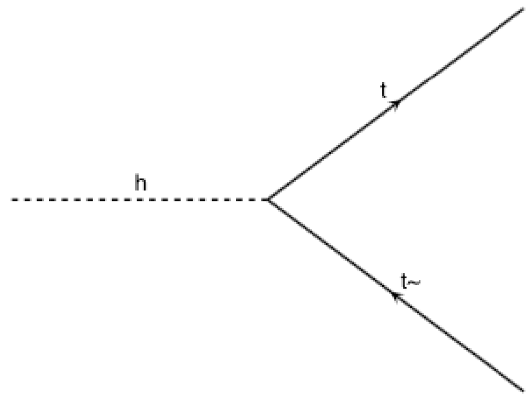
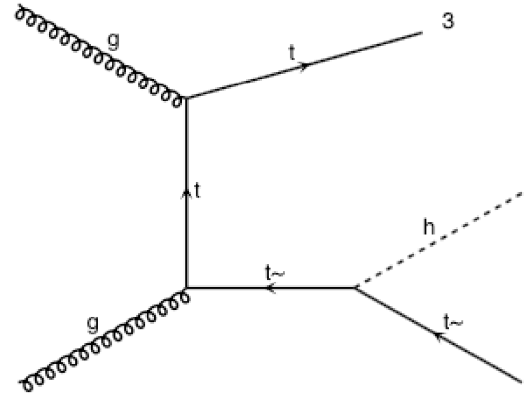


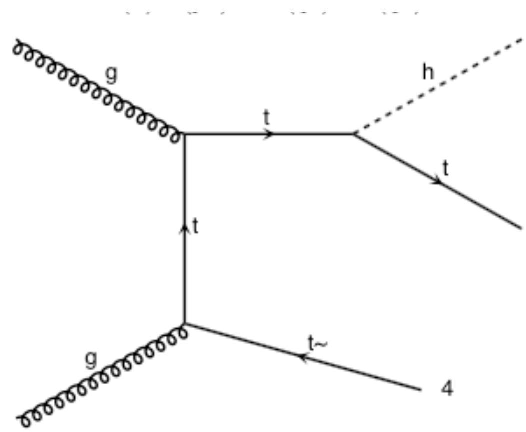
(a) $h(p_1) \to t(q_1) + \bar{t}(q_2)$



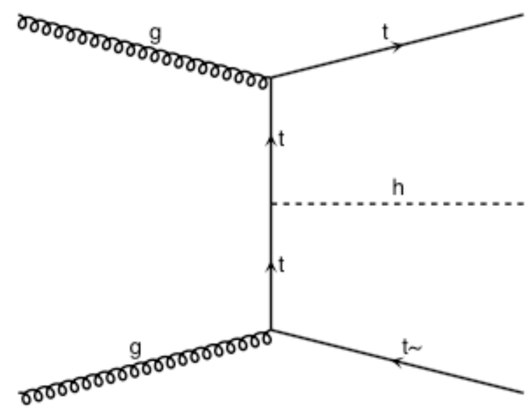
(b) $g(k_1) + g(k_2) \to t(q_1) + \bar{t}(q_2) + h(p_2)$

Optical theorem: cut diagrams = Im full loop diagram with two propagators going on-shell

→ complete analytic understanding of amplitude cancellation



(c) $g(k_1) + g(k_2) \to t(q_1) + \bar{t}(q_2) + h(p_2)$



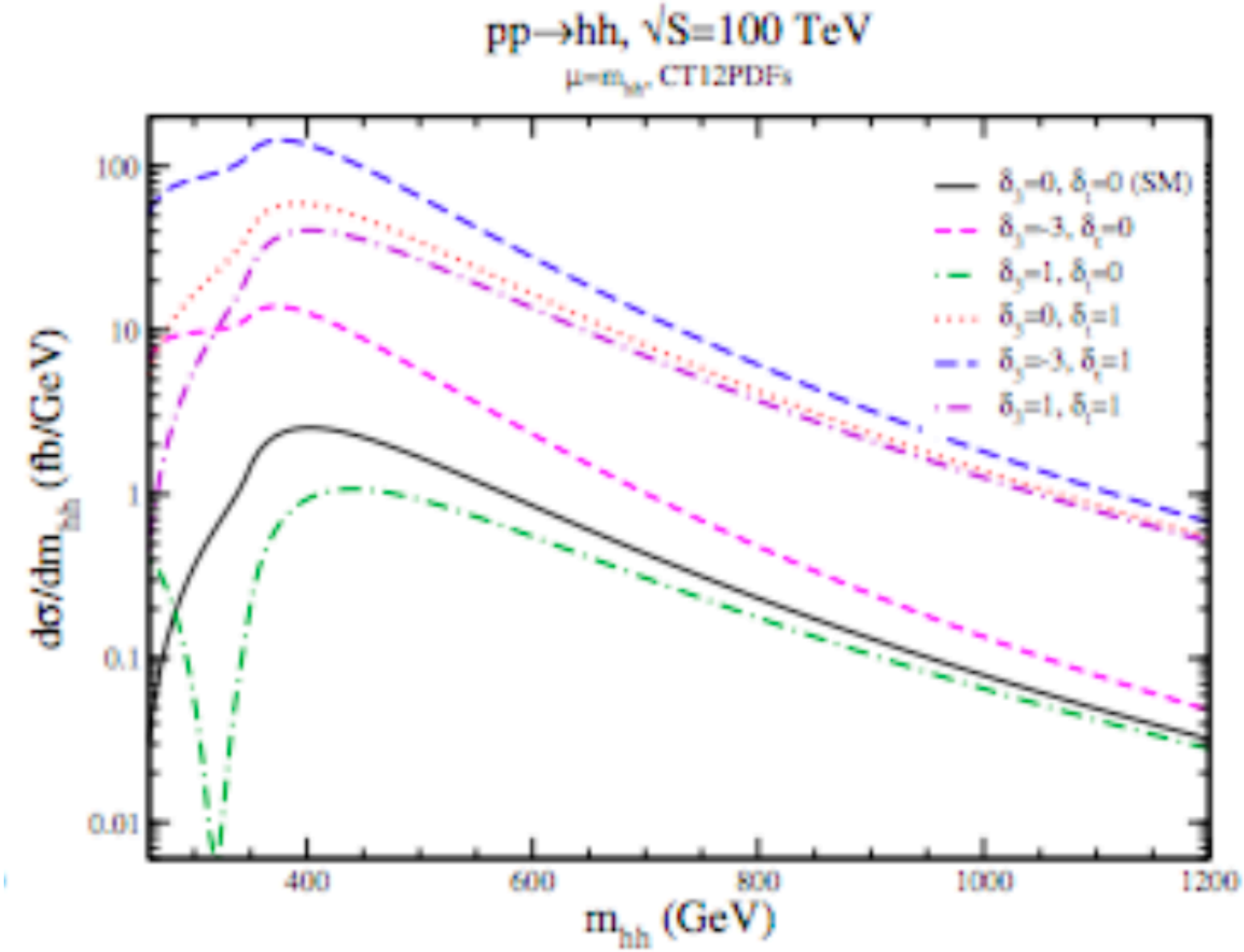
(d) $g(k_1) + g(k_2) \to t(q_1) + \bar{t}(q_2) + h(p_2)$

see also Li and Voloshin, 1311.5156

Explicit models

Modified top Yukawa

Combination of non-SM top Yukawa (δ_t) and Higgs self-coupling (δ_3) shifts distributions considerably

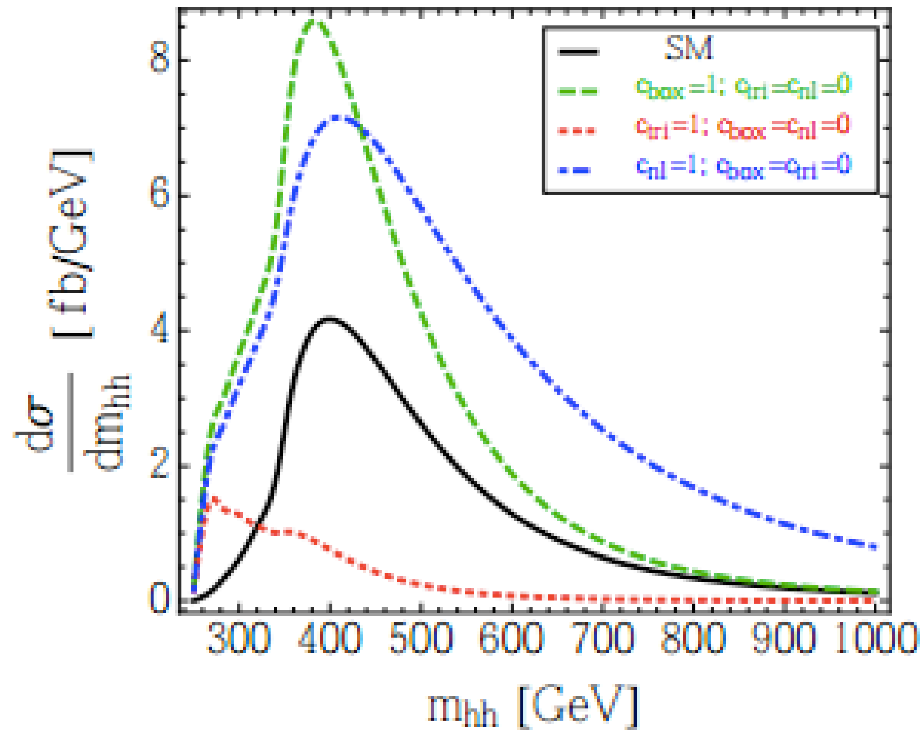


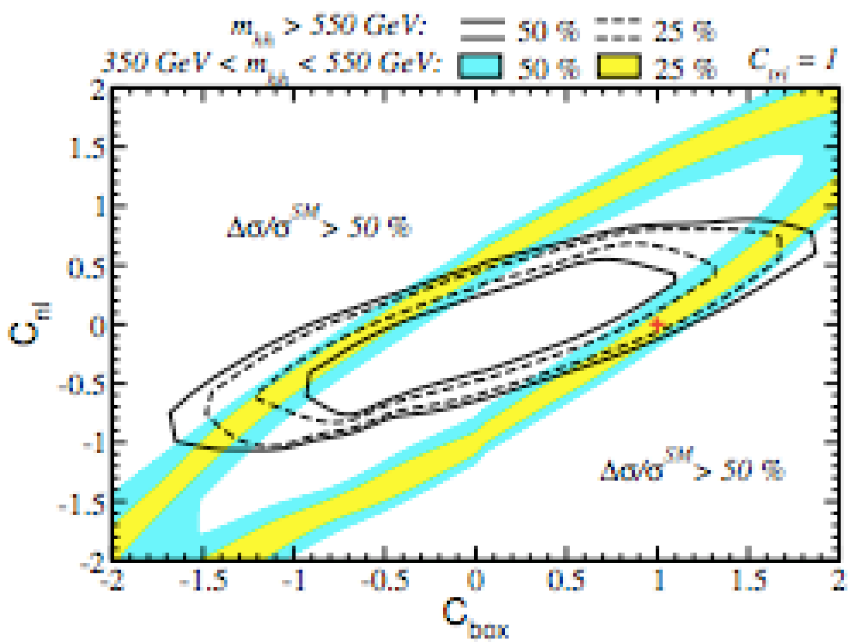
Threshold cancellation spoiled away from SM (black)

Anomalous tthh coupling

Next simplest is to add a tthh coupling with strength $c_{nl}\ m_t\ /\ v^2$

Challenging to discriminate, even at 100 TeV CM energy





Can break much of the degeneracy in potential BSM effects by using bins of invariant mass

C.-R. Chen and I. Low, 1405.7040

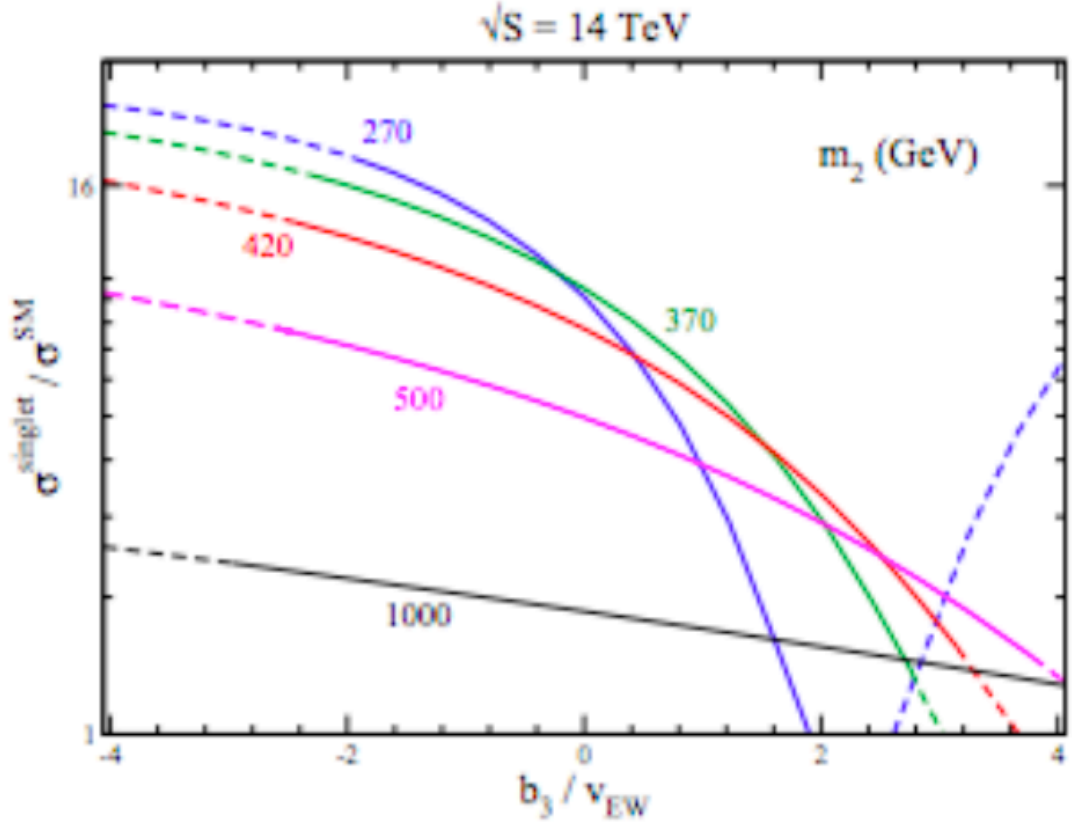
Resonant production

Production of resonance that decays to hh

Works for getting hh without causing extra single Higgs production

e.g. Higgs mixing with a heavy singlet, NMSSM, general 2HDM

hh distribution is peaked at resonance



C.-Y. Chen et al., 1410.5488

see also:
J.M. No and M. Ramsey-Musolf, 1310.6035

New loop particles: fermions

New colored particles can run in hh loop diagrams if they couple to the Higgs

Fermions: must be vector-like to avoid spoiling gluon fusion rate for single Higgs

see also:
A. Pierce et al., hep-ph/0609049
S. Dawson et al., 1210.6663
...

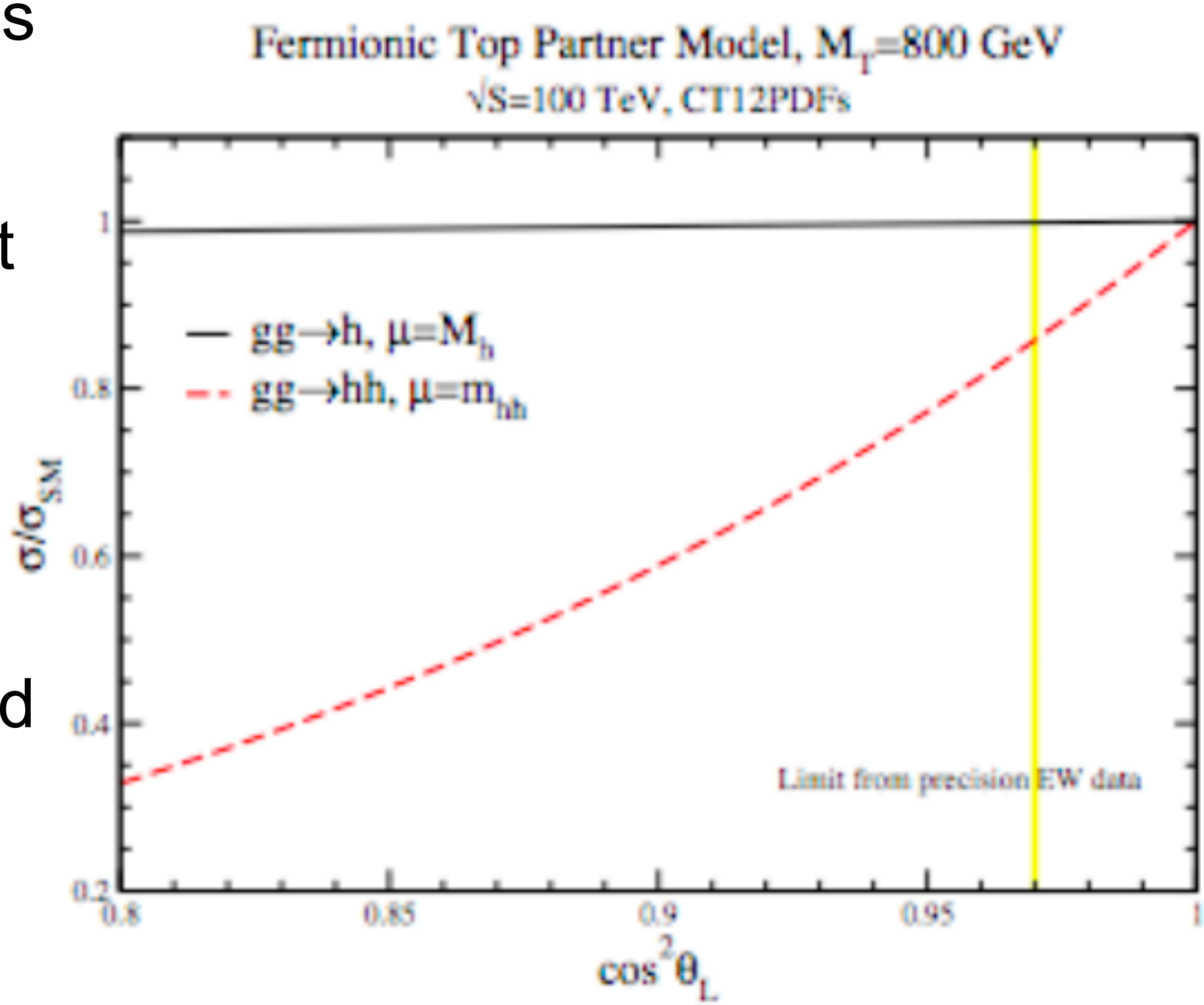
Consider vector-like partner that mixes with the SM top, as in e.g. Little Higgs

Must choose mass, mixing of partner that satisfy precision electroweak measurements as well as direct searches

New loop particles: fermions

Single Higgs rate is ~SM, and double Higgs is between 80-100% of SM at 100 TeV

Invariant mass distribution is virtually unchanged upon inclusion of fermionic top partner



New loop particles: scalars

Scalars: similar to stops in SUSY, but amount of mass coming from electroweak symmetry breaking is not fixed in general

Consider most general renormalizable Lagrangian for colored scalar interacting with Higgs doublet

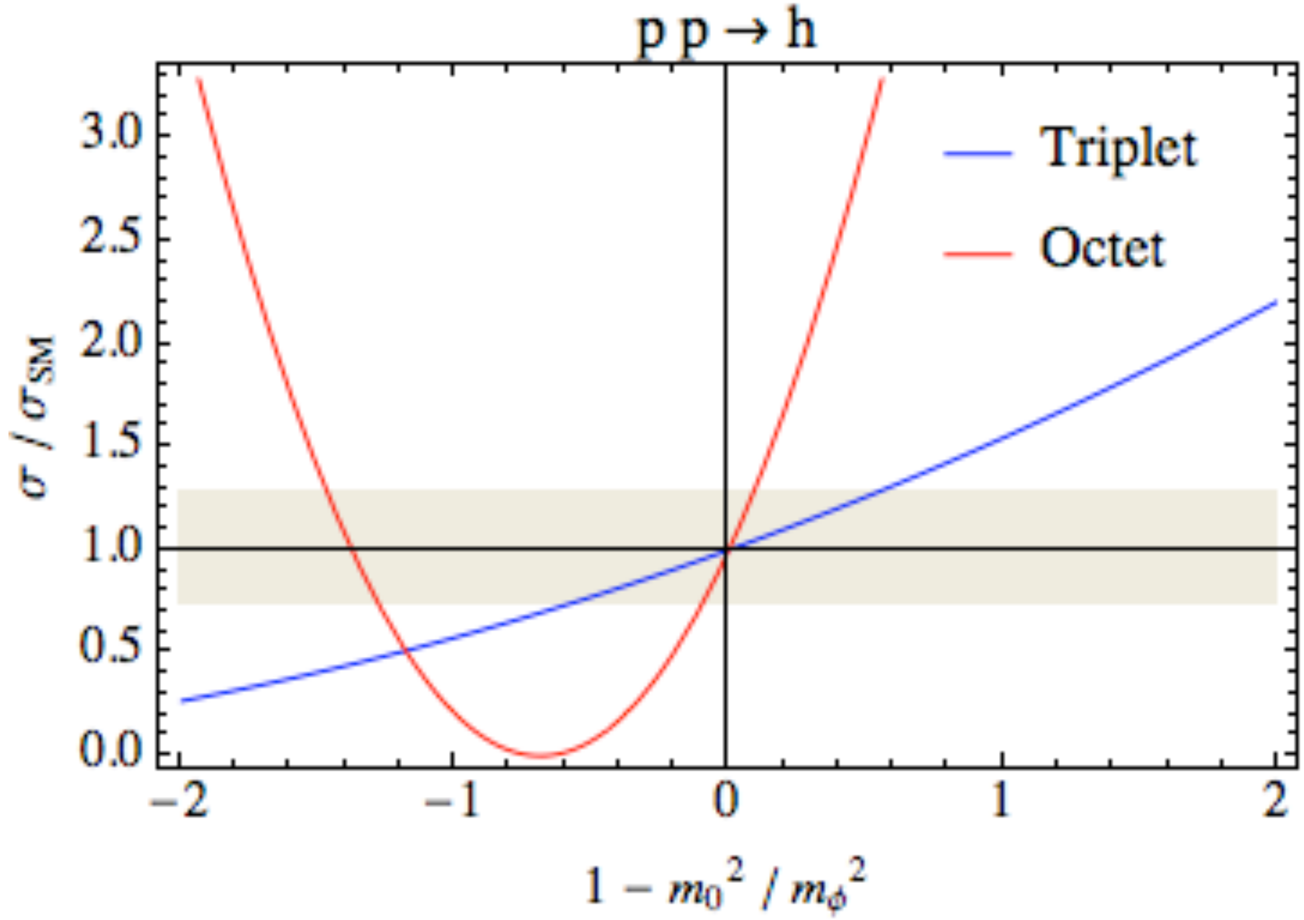
$$\mathcal{L} \supset D^\mu \phi^* D_\mu \phi - m_0^2 \phi^* \phi - \kappa \phi^* \phi H^\dagger H$$

$$m_\phi^2 = m_0^2 + \frac{\kappa v^2}{2}$$

see also:
E. Asakawa et al., 1009.4670
G. Kribs and A. Martin, 1207.4496
...

New loop particles: scalars

Bounds from single Higgs production *regardless* of direct searches for colored scalars



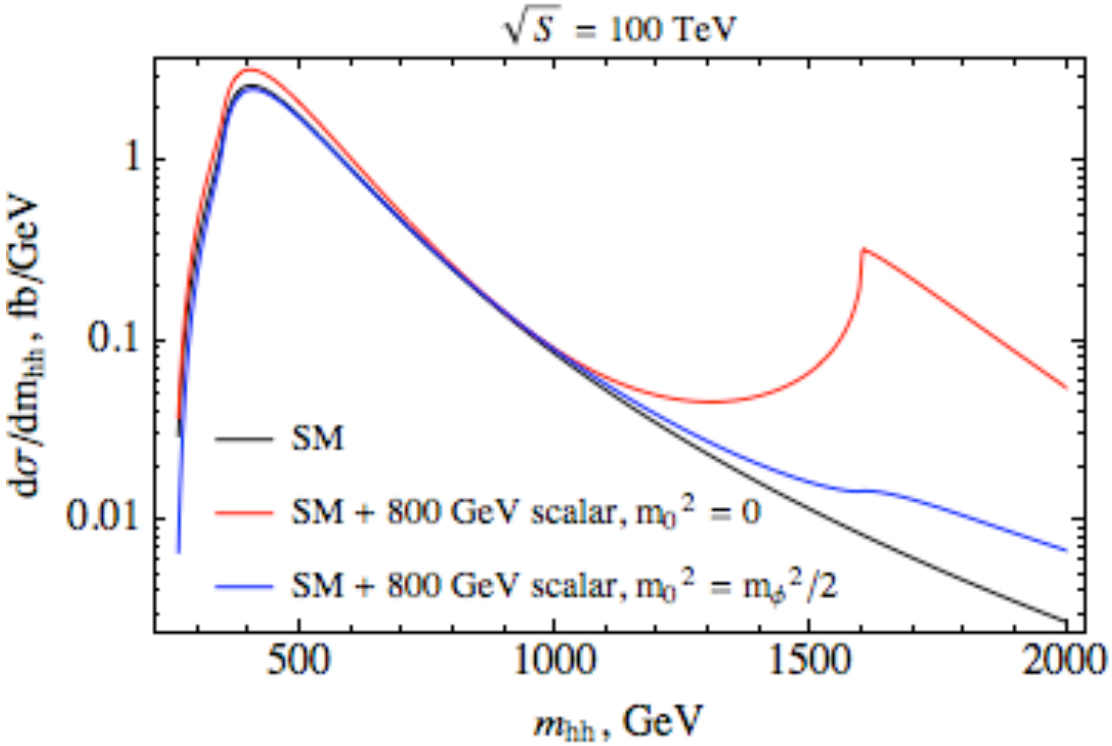
For arbitrarily heavy scalars, fraction of mass coming from EWSB already constrained

New loop particles: scalars

Double Higgs mass distributions offer complementary observation of new colored particles coupling to Higgs

Expect peak in invariant mass distribution when loop propagators go on shell

Less pronounced for large soft scalar masses



Strong constraints from single Higgs; observing deviation in double Higgs from a new particle will be challenging but still useful

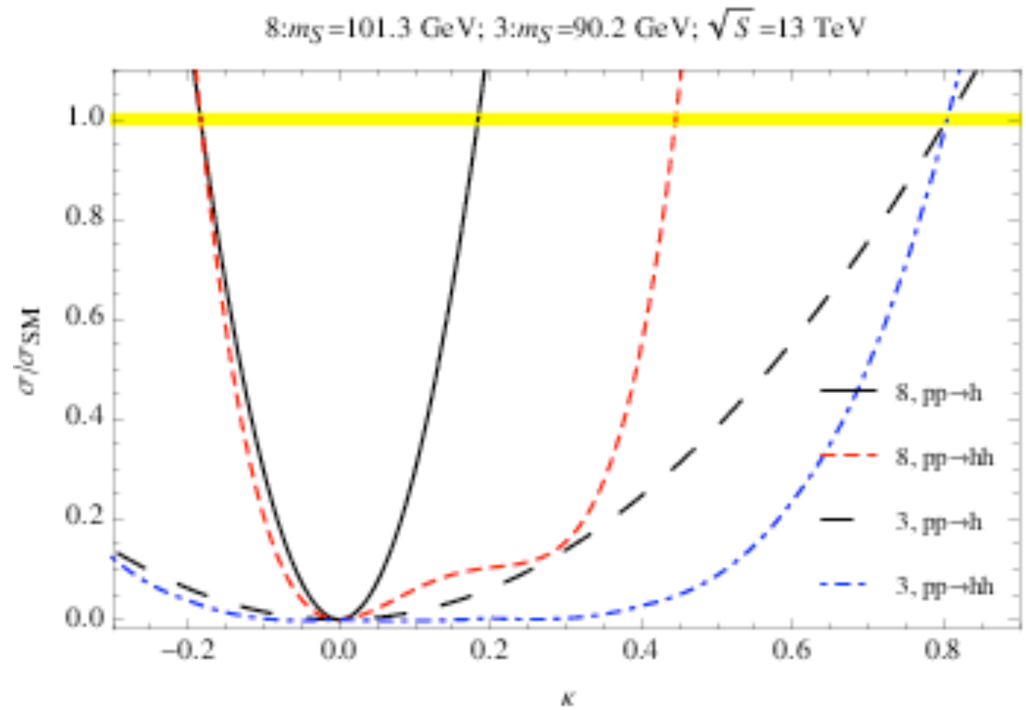
New loop particles: scalars

Finally: try scalar *instead* of top in Higgs production

Tune mass and coupling to reproduce SM single and double Higgs cross sections

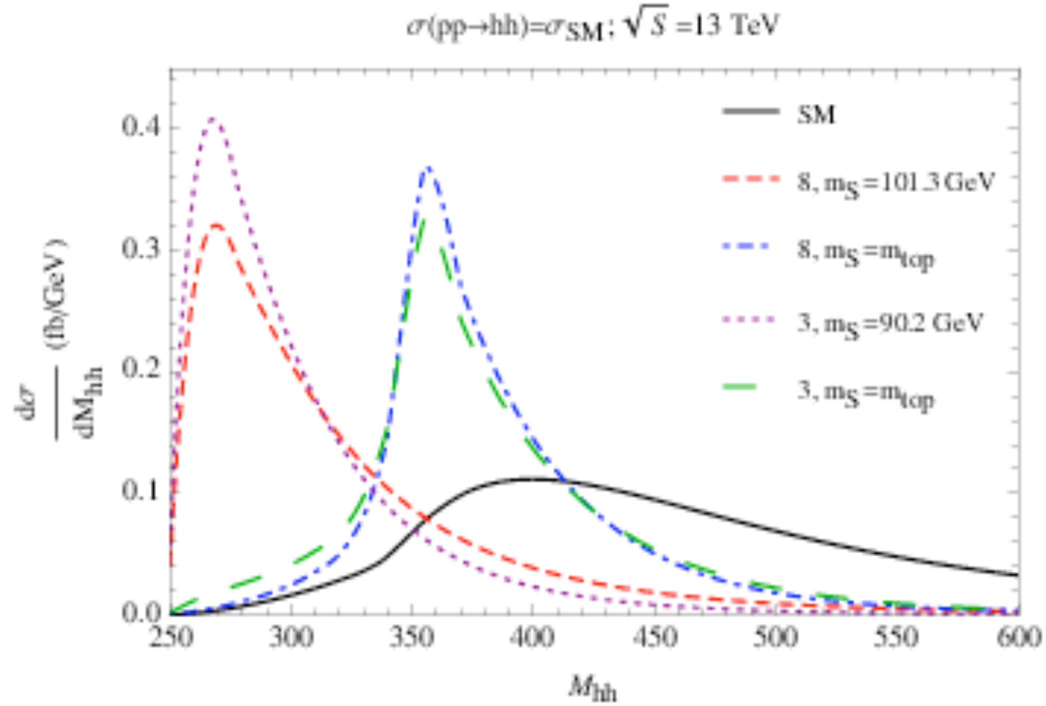
tth will directly probe the top-Higgs coupling, but use scalar instead as playground for spin discrimination

Exact mass and coupling to reproduce SM Higgs cross sections depends on color representation of scalar particle



New loop particles: scalars

Coupling/mass ratio tuned → no threshold cancellation between triangle and box diagrams, for scalars which reproduce SM Higgs cross sections



Without amplitude cancellations, the double Higgs invariant mass distributions for scalars posing as tops are much more peaked near threshold

Generally, efforts to reduce low-mass background to double Higgs searches would be useful to identify any physics that destroys the cancellation

Summary

Higgs pair production provides us with *the* way of measuring the self-coupling of the Higgs, and hence the shape of the Higgs potential

...but it's also sensitive to other forms of new physics!

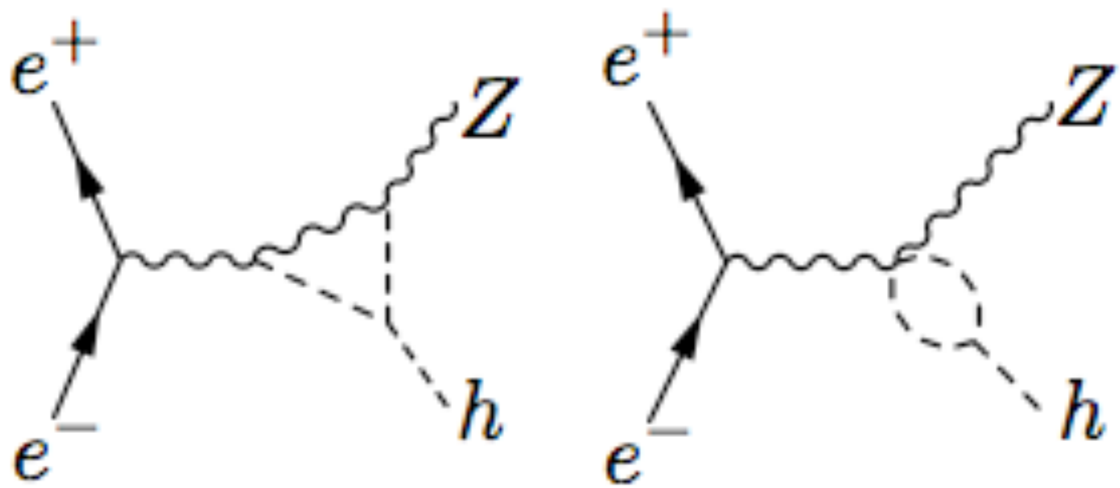
The hh amplitude vanishes at threshold in the limit of an infinitely heavy loop particle with a standard Yukawa coupling, and this cancellation can be understood analytically

Double Higgs can help identify the spin of loop particles, and measuring distributions one day could be particularly interesting

Backup

Higgs self-coupling

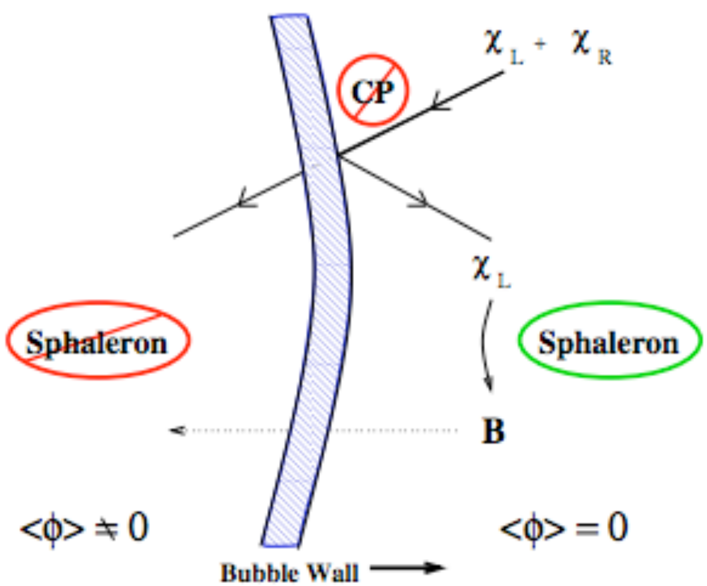
“Loop”hole: Can also measure Higgs self-coupling VH at NLO at ee colliders, albeit model-dependent



M. McCullough, 1312.3322

Electroweak baryogenesis

One reason knowing the structure of the Higgs potential is important is to help determine whether the baryon-antibaryon asymmetry of the universe was generated during the electroweak phase transition



During EWPT, bubbles of broken phase expand

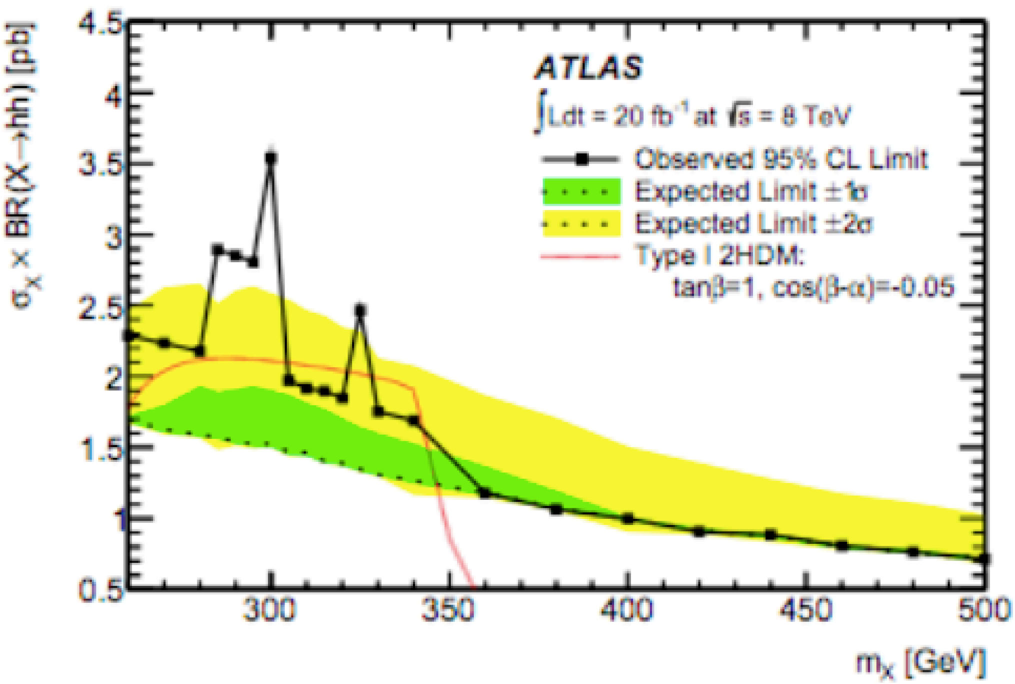
CP-violating interactions near rapidly expanding bubble walls create asymmetries which are converted to B by electroweak sphalerons

D. Morrissey and M. Ramsey-Musolf, 1206.2942

Experimental searches

Most existing limits are on resonances decaying to Higgs pairs, since SM hh cross section is so small

bbγγ and 4b: most promising final states



ATLAS, 1406.5053

CMS-PAS-HIG-14-013