Maximizing Di-Higgs

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work in progress

Topic of the Week, LHC Physics Center, Fermilab
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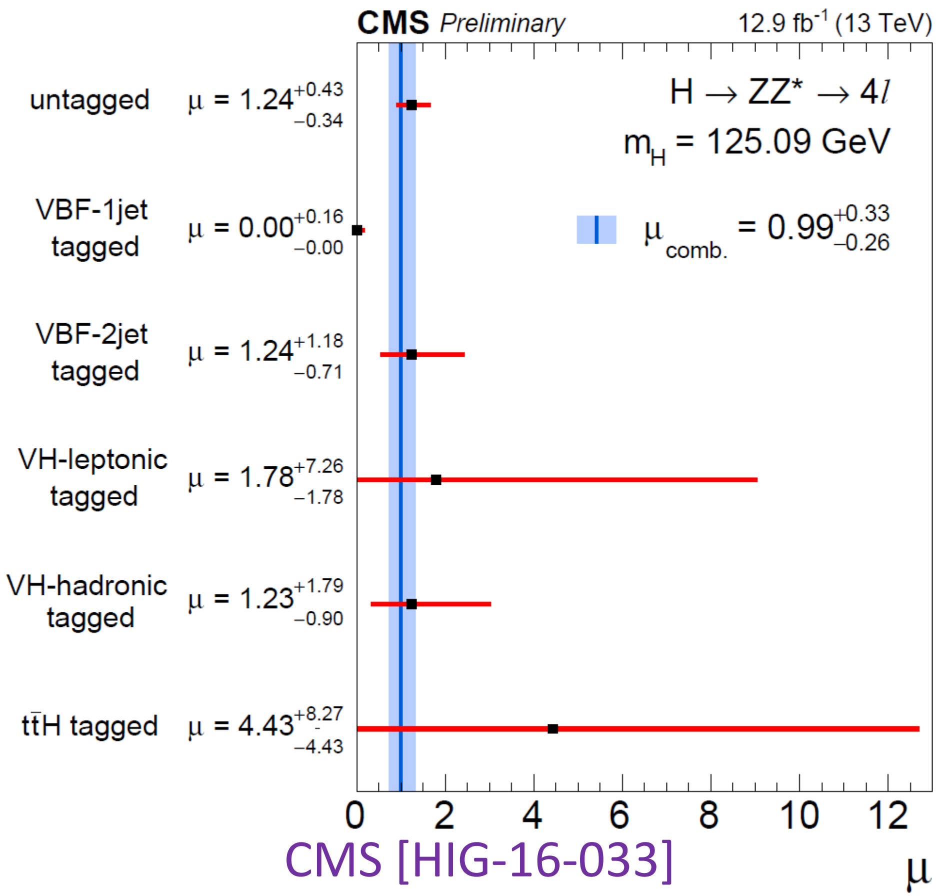
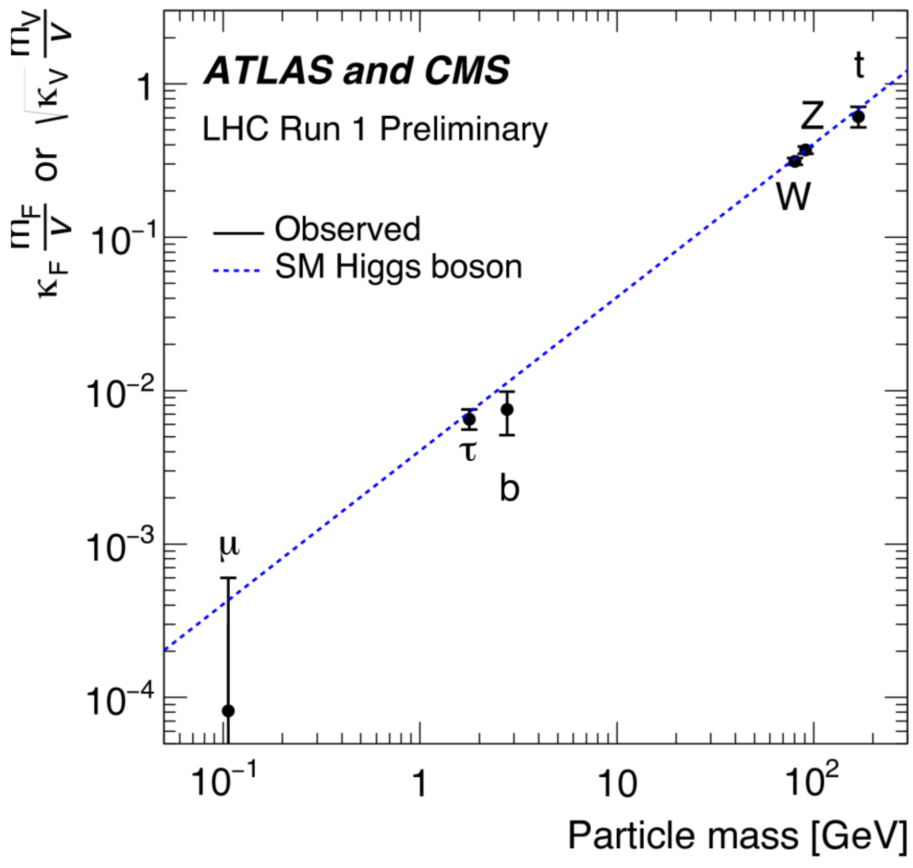
Introduction and Motivation

- The Higgs characterization program at the LHC is well underway

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002



CMS [HIG-16-033]



Introduction and Motivation

- Many more results in Higgs physics expected
  - SM: Possibilities for light quark Yukawa couplings (see FY [1609.06952] and references therein)
  - New physics: Exotic Higgs decays, exotic production, couplings to DM
  - Will focus on (non-resonant) double Higgs production

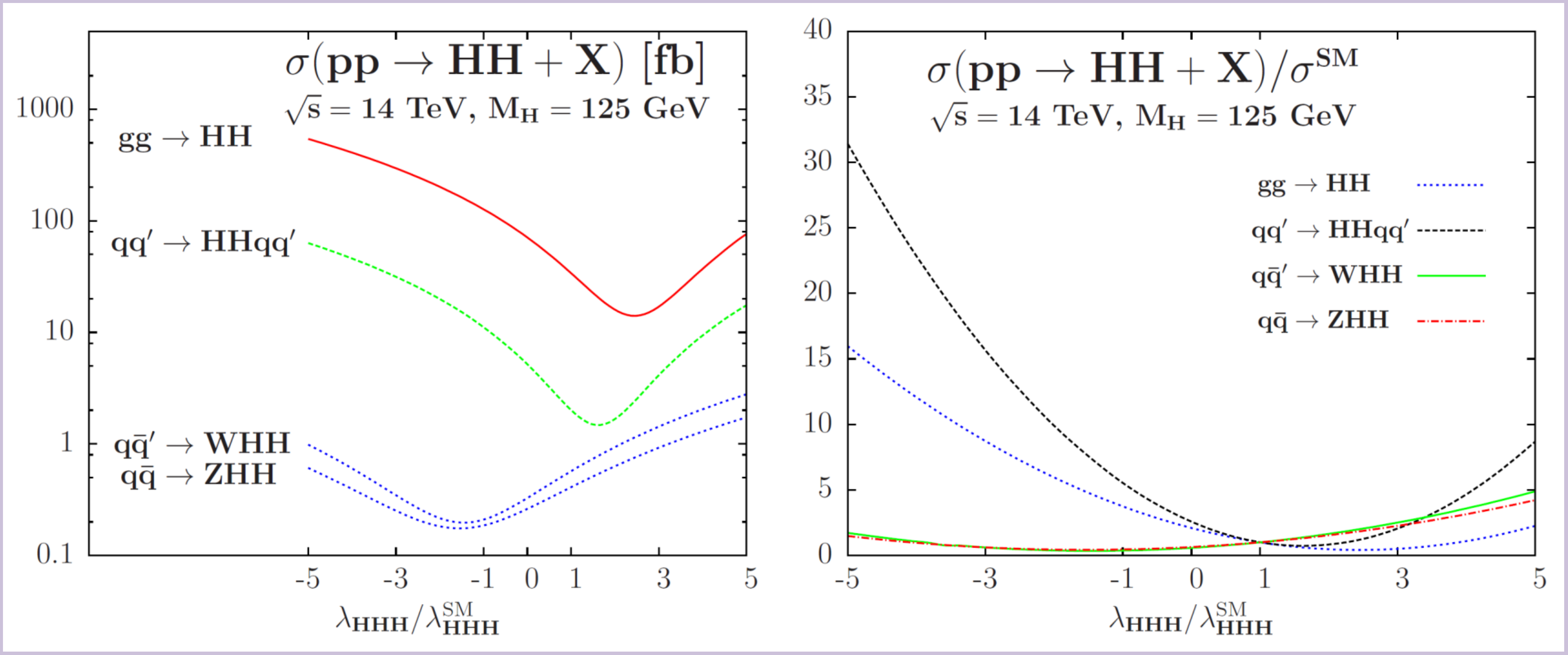
$\sigma(gg \to hh)$	m_h = 125.09 GeV	Scale (%); Theory (%); α_s (%); PDF (%)
7 TeV	7.068 fb	+4.0 (-5.7); ±5; ±2.8; ±3.4
8 TeV	10.15 fb	+4.1 (-5.7); ±5; ±2.6; ±3.1
13 TeV	33.41 fb	+4.3 (-6.0); ±5; ±2.3; ±3.1
14 TeV	39.51 fb	+4.4 (-6.0); ±5; ±2.2; ±2.1

NNLO+NNLL (NLO with top mass dependence)
Borowka, et. al. [1604.06447]

Triple Higgs coupling sensitivity

- Double Higgs production is necessary for extracting the triple Higgs coupling

Baglio, et. al. [1212.5581]



Triple Higgs coupling sensitivity

- Double Higgs production is necessary for extracting the triple Higgs coupling

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

Snowmass Higgs WG report [1310.8361]

- Mild sensitivity, cancellation between box and triangle diagrams
- Improved sensitivity from new channels

Outline

- Review of ggH and ggHH phenomenology
- Models for decorrelating ggH and ggHH
- Numerical results
- Conclusions

Higgs pair production

- Resonant vs. non-resonant
  - 2HDM heavy Higgs decays, gauge singlet phenomenology
  - Resonant structure easier to identify
- Many decay channels
  - 4b: 33.3%
    - CMS [HIG-16-026 [2.32 fb^[-1]]: 3.88 pb (342xSM)
  - 2b2τ: 7.3%
    - CMS [HIG-16-028, HIG-16-029] 508 fb (200xSM)
  - 2b2γ: 0.262%
    - CMS [HIG-16-032] 7.9 fb (91xSM)

Higgs pair production

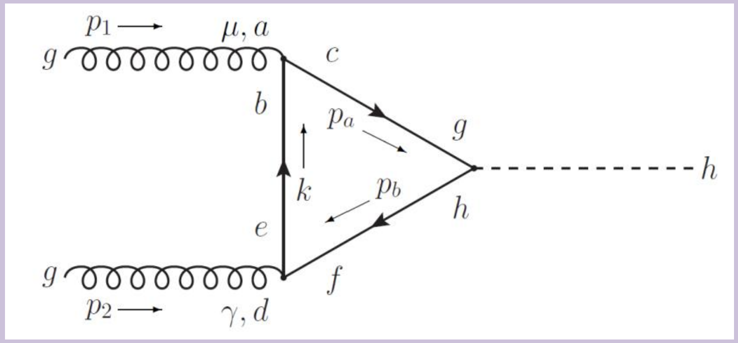
- Non-resonant
  - Colored particles in the loop will generally affect both ggH and ggHH
  - Hard to disentangle loop particle except with high statistics

Dawson, Lewis, Low [1504.05596]

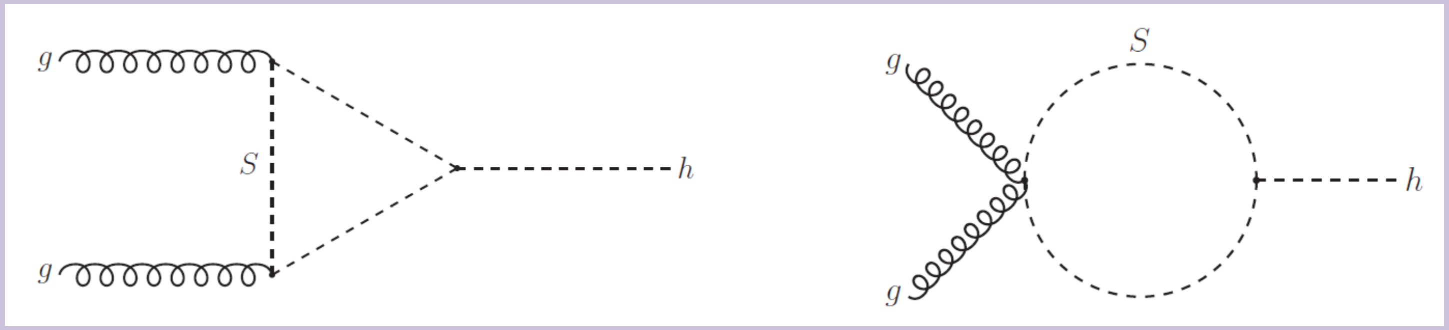
- Higgs low-energy theorem
  - Decoupling (and non-decoupling) nature of new physics leads to important features in ggH and ggHH

ggH and interference from scalars

- Gluon fusion review
  - In SM, dominated by top contribution



  - Colored scalar can constructively or destructively interfere



see Kumar, Vega-Morales, FY [1205.4244] and refs. therein

ggH and interference from scalars

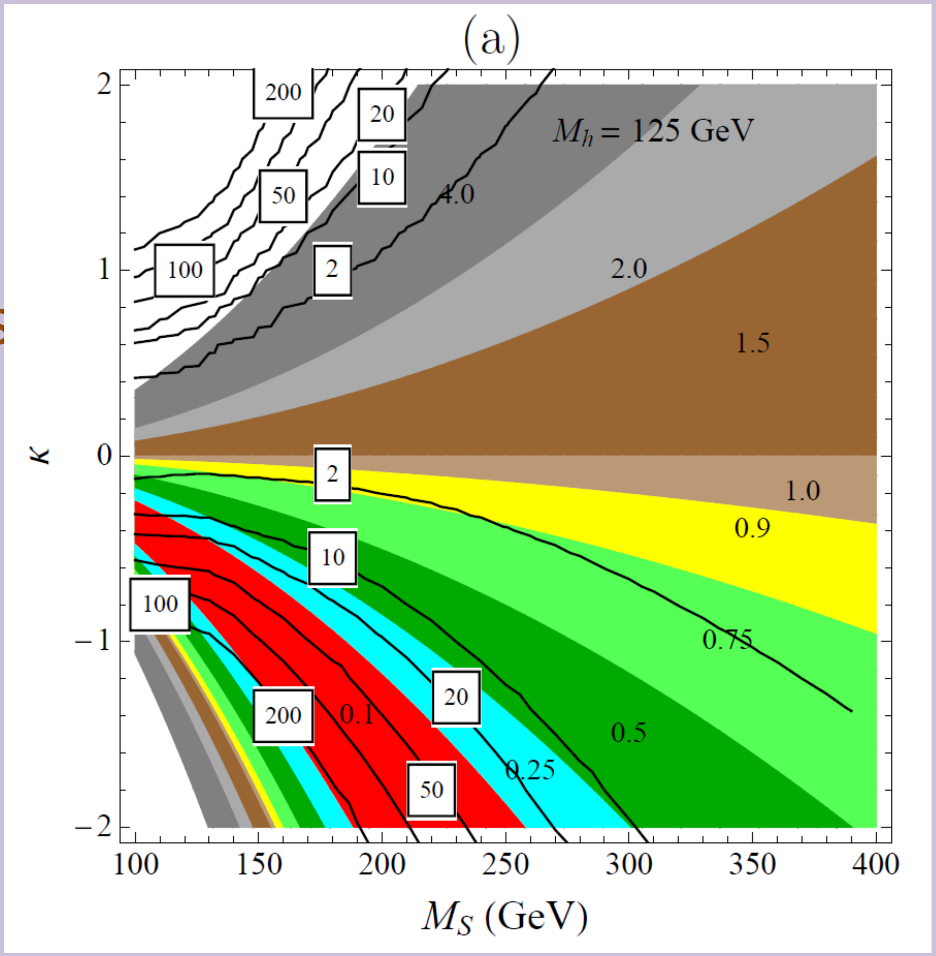
- Gluon fusion review
  - Constructive (destructive) if Higgs portal coupling is negative (positive)
    - As expected from LEH theorem and taking into account fermion loop factor

$$\epsilon_{gg}|_{SM+S} = \frac{\left|\sum_f \left(\frac{C(r_f)}{2v_h} F_F(\tau_f)\right) + \frac{C(r_s)\lambda_{hp} v_h}{4m_S^2} F_S(\tau_S)\right|^2}{\left|\sum_f \left(\frac{C(r_f)}{2v_h} F_F(\tau_f)\right)\right|^2}$$

Kumar, Vega-Morales, FY [1205.4244]

ggHH and interference from scalars

- Similar story for ggHH
  - Color octet scalar in loop
  - Can hide in direct searches
  - Strong effects in ggHH!

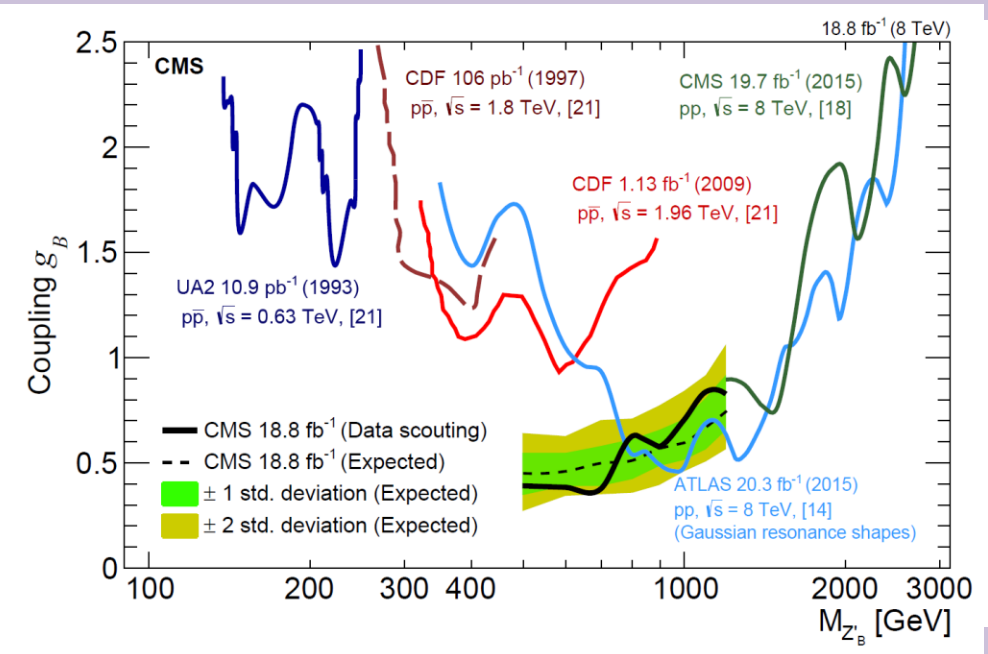


Kribs, Martin [1207.4496]

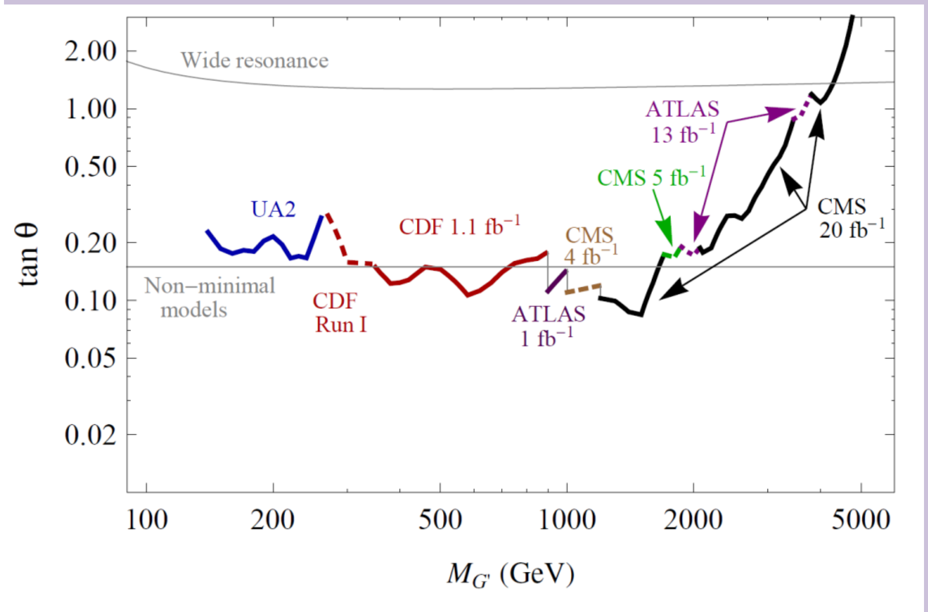
Direct probes for new colored particles

- Colored loop particles can be difficult to detect
  - Dijet resonance searches lose sensitivity at low masses

CMS [1604.08907]

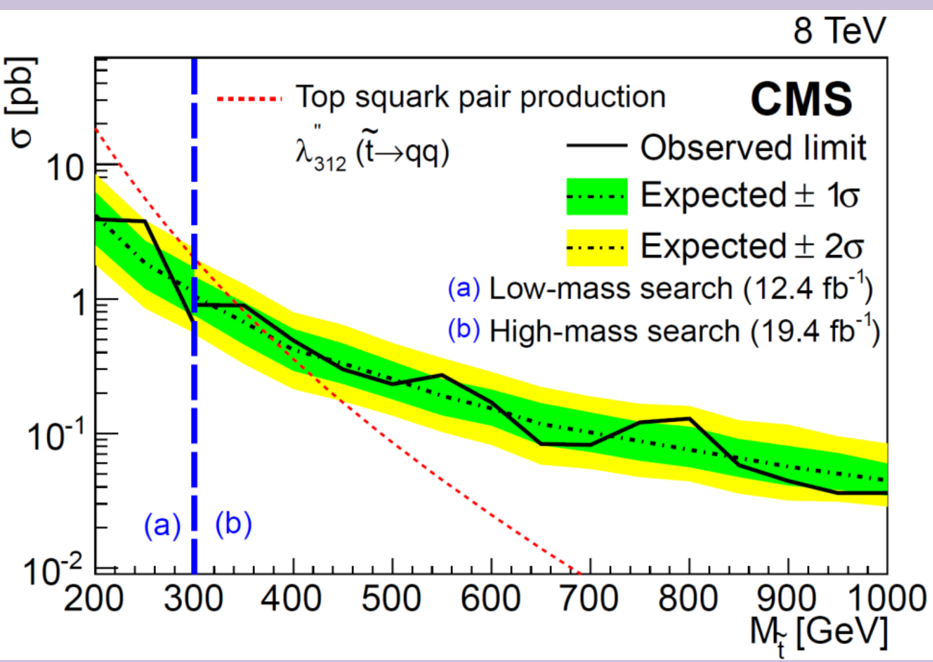


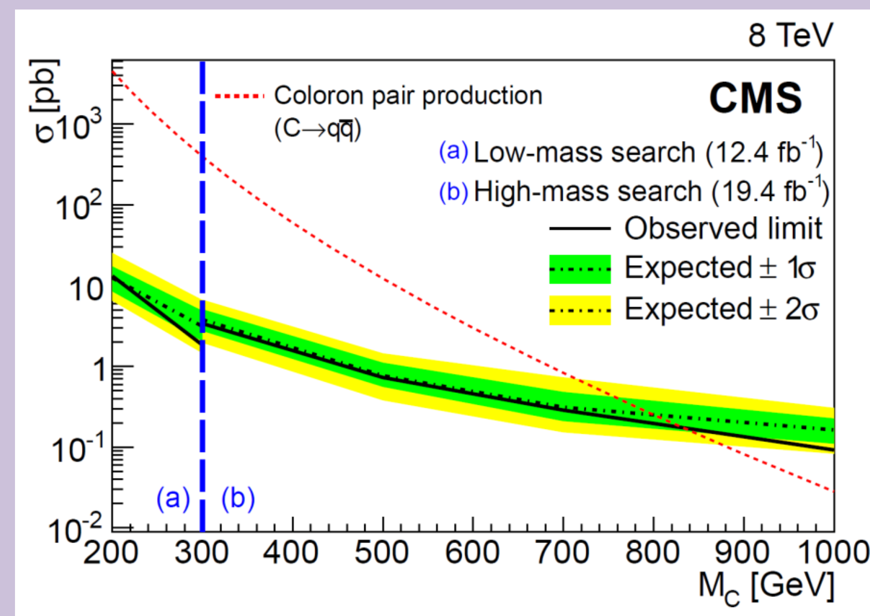
Dobrescu, FY [1306.2629]



Direct probes for new colored particles

- Colored loop particles can be difficult to detect
  - Pair production rates only depend on mass

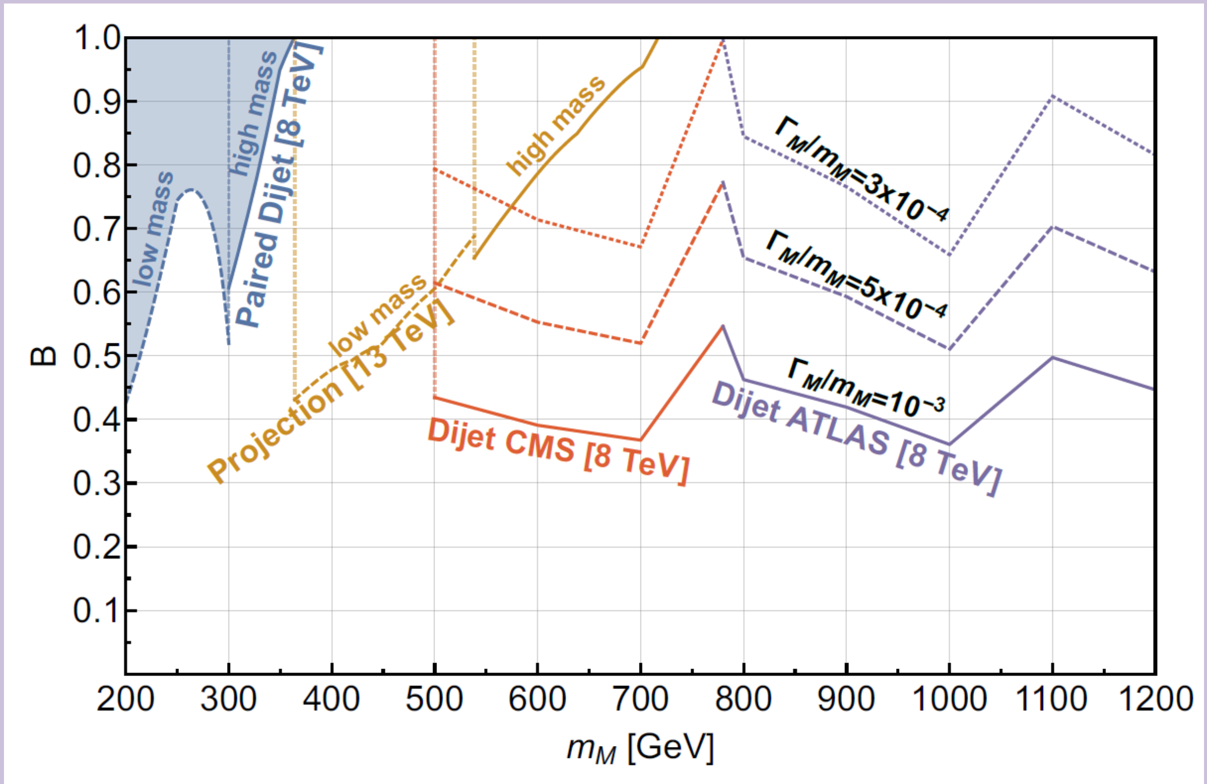




CMS [1412.7706]

Introduction and Motivation

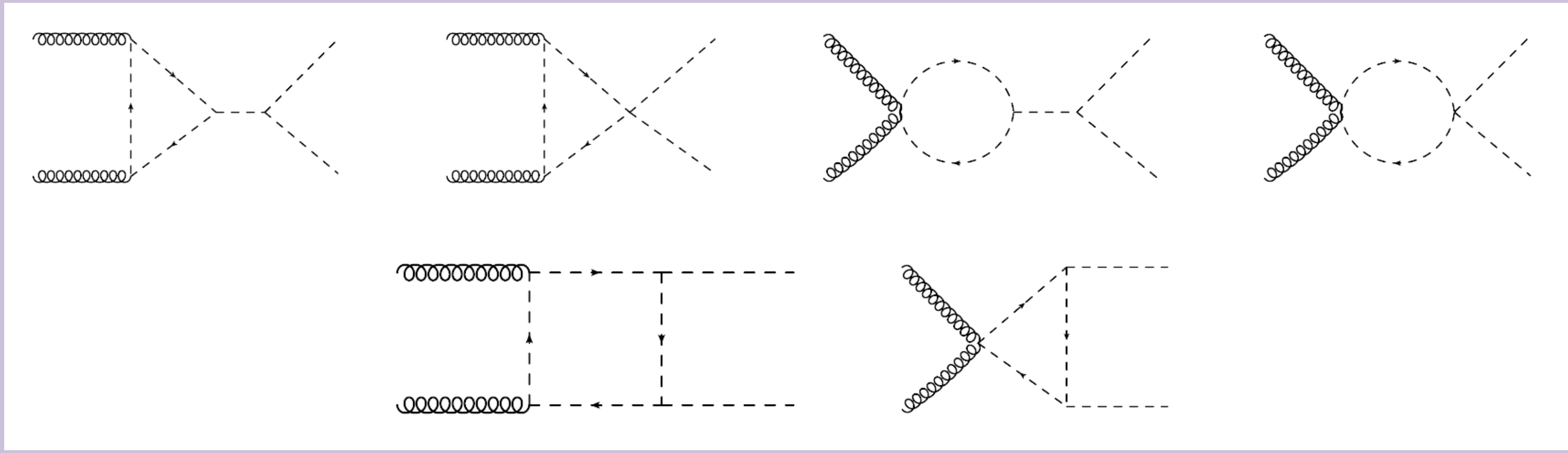
- Colored loop particles can be difficult to detect
  - Pair production rates only depend on mass
  - But additional decays (SUSY-like) can weaken direct constraints



Buschmann, El Hedri, Kaminska, Liu, de Vries, Wang, FY, Zurita [1605.08056]

Decorrelating ggH and ggHH

- Decorrelating ggH and ggHH necessarily relies on cancelling contribution to ggH
- Top diagrams proportional to quartic coupling (or Higgs cubic coupling)
- Bottom coupling proportional to quartic coupling squared (once Higgs gets its vev)



Lagrangian 1

- Consider two colored scalars
  - Focus on λ_{1H} and λ_{2H} couplings
    - Will not deviate cubic Higgs coupling

$$\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - V(\phi_1, \phi_2, H)$$

$$\begin{aligned} V(\phi_1, \phi_2, H) &= -\mu^2 |H|^2 + \lambda_H |H|^4 \\ &+ m_1^2 |\phi_1|^2 + m_2^2 |\phi_2|^2 + \lambda_1 |\phi_1|^4 + \lambda_2 |\phi_2|^4 + \lambda_{12} |\phi_1|^2 |\phi_2|^2 \\ &+ \lambda_{1H} |\phi_1|^2 (|H|^2 - v^2/2) + \lambda_{2H} |\phi_2|^2 (|H|^2 - v^2/2) \end{aligned}$$

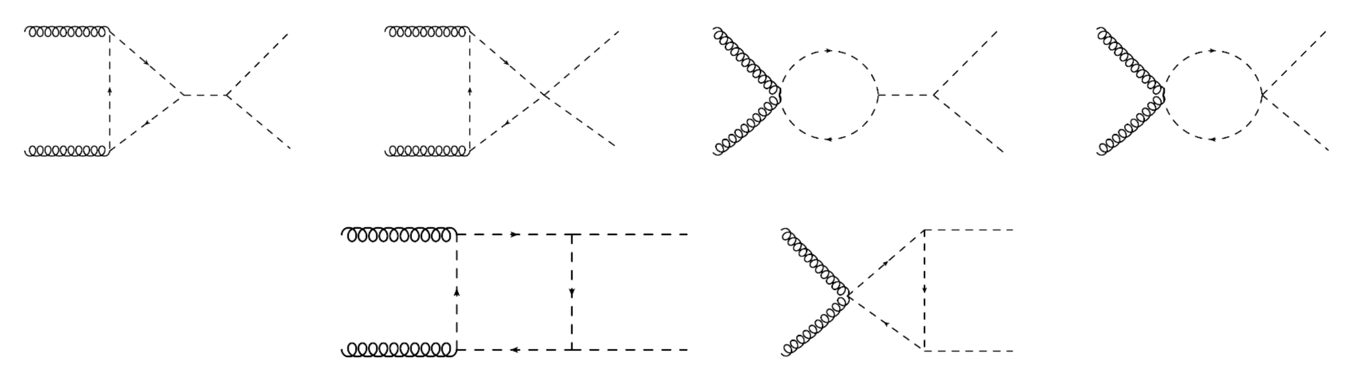
  - Vacuum stability requirements constrain mixed quartics λ_{1H} and λ_{2H} in competition with on λ_1, λ_2, and λ_H

Lagrangian 2

- Consider two colored scalars, one is SU(2) doublet
  - Additional A term beyond λ_{1H} and λ_{2H} couplings
    - A term causes mixing between scalars

$$\mathcal{L} = |D_\mu \phi_L|^2 + |D_\mu \phi_R|^2 - V(\phi_L, \phi_R, H)$$

$$\begin{aligned} V(\phi_L, \phi_R, H) = &-\mu^2 |H|^2 + \lambda_H |H|^4 \\ &+ m_L^2 |\phi_L|^2 + m_R^2 |\phi_R|^2 + \lambda_L |\phi_L|^4 + \lambda_R |\phi_R|^4 + \lambda_{LR} |\phi_L|^2 |\phi_R|^2 \\ &+ \lambda_{LH} |\phi_L|^2 (|H|^2 - v^2/2) + \lambda_{RH} |\phi_R|^2 (|H|^2 - v^2/2) \\ &+ A \phi_L \phi_R^* H + \text{ c.c.} \end{aligned}$$

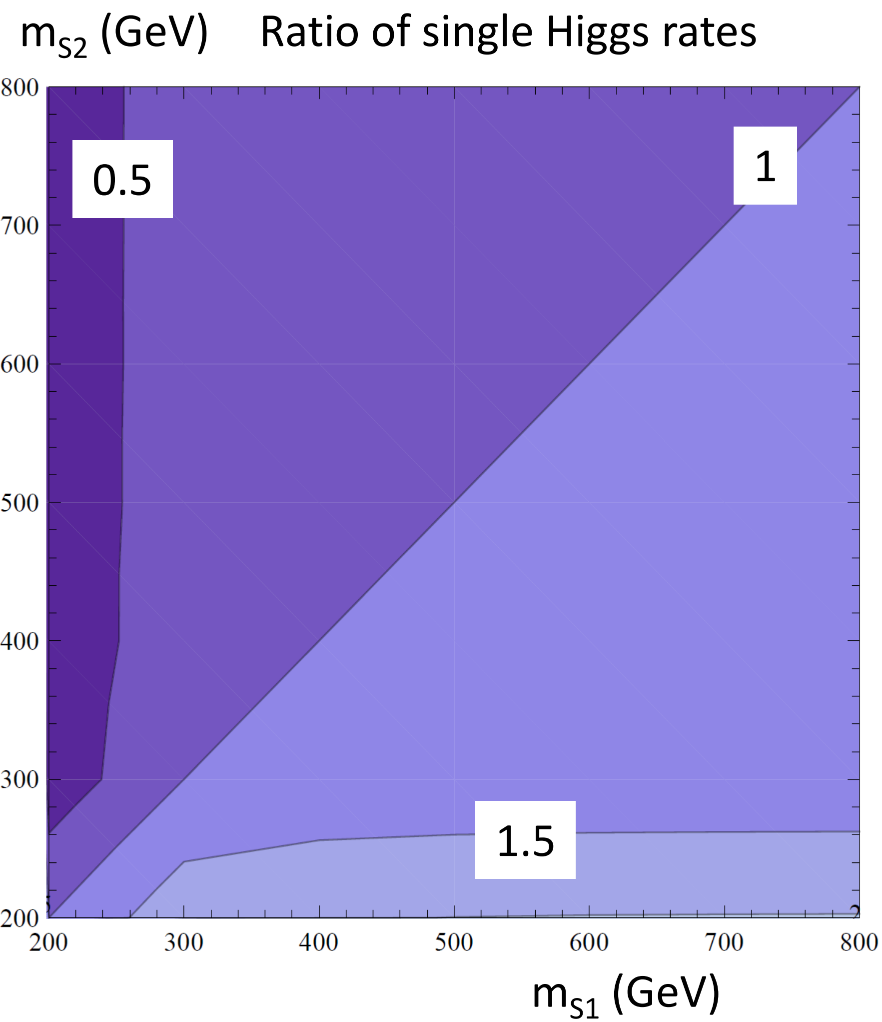


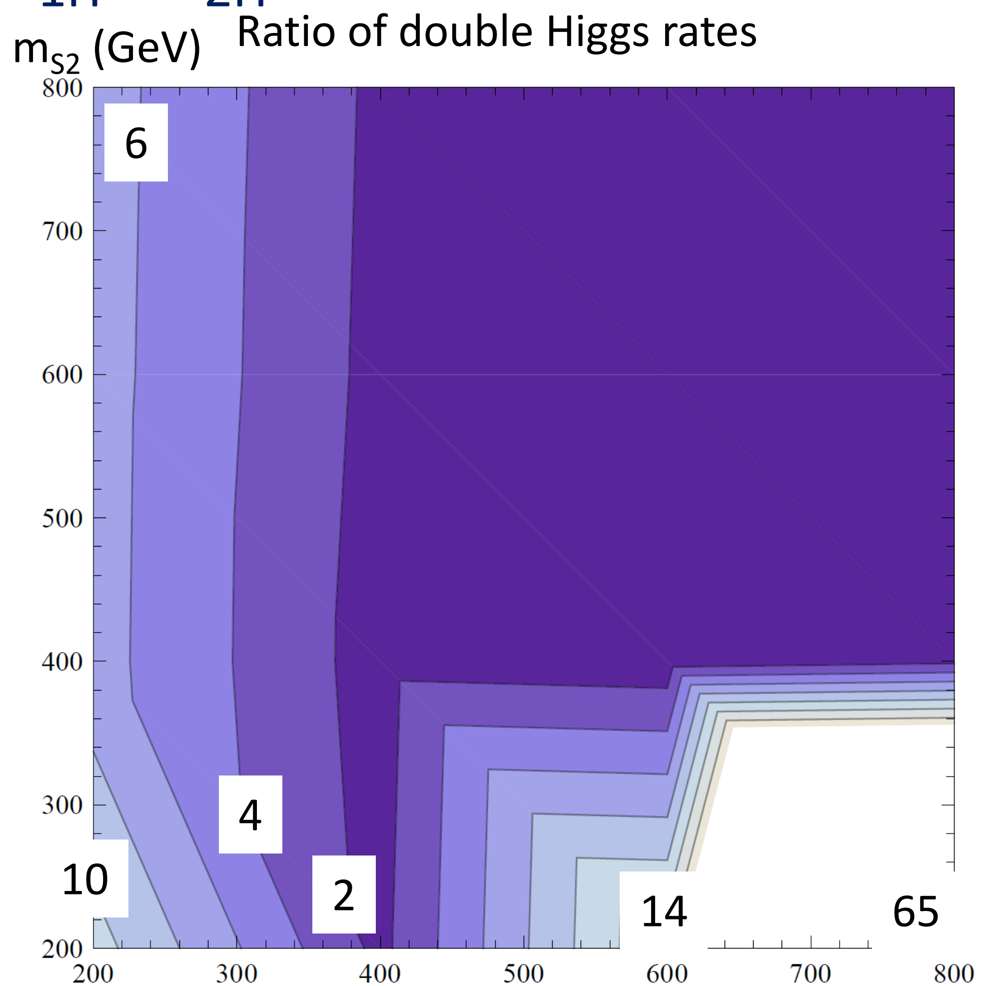
Work in progress

- Have analytic expressions for leading order gg -> hh production
  - Closed form expression for propagator structures with different masses attaching to Higgs vertices
- Implemented expressions in MCFM v8
  - Analyze Higgs field-dependent thermal potential for vacuum stability
  - Impose direct searches

Numerical results

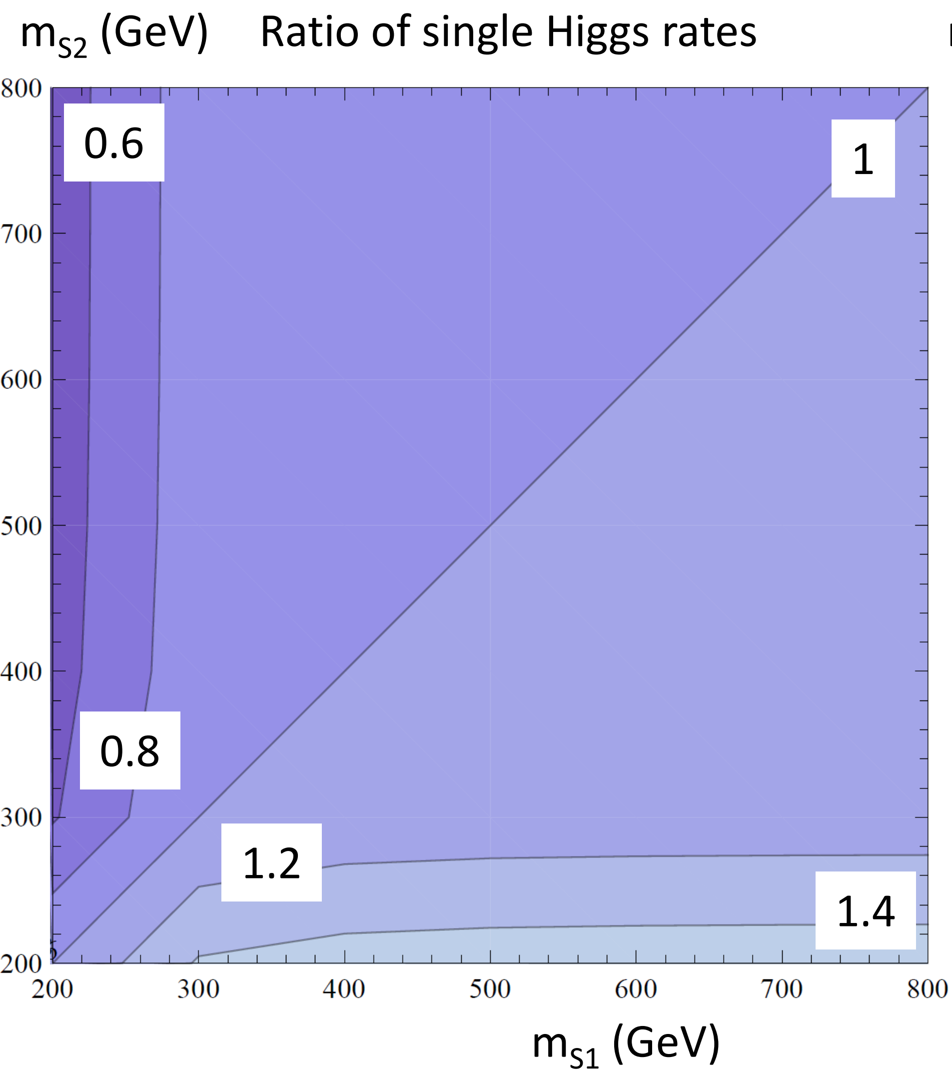
- Model 1 (color triplets, $-\lambda_{1H}= \lambda_{2H}=4$

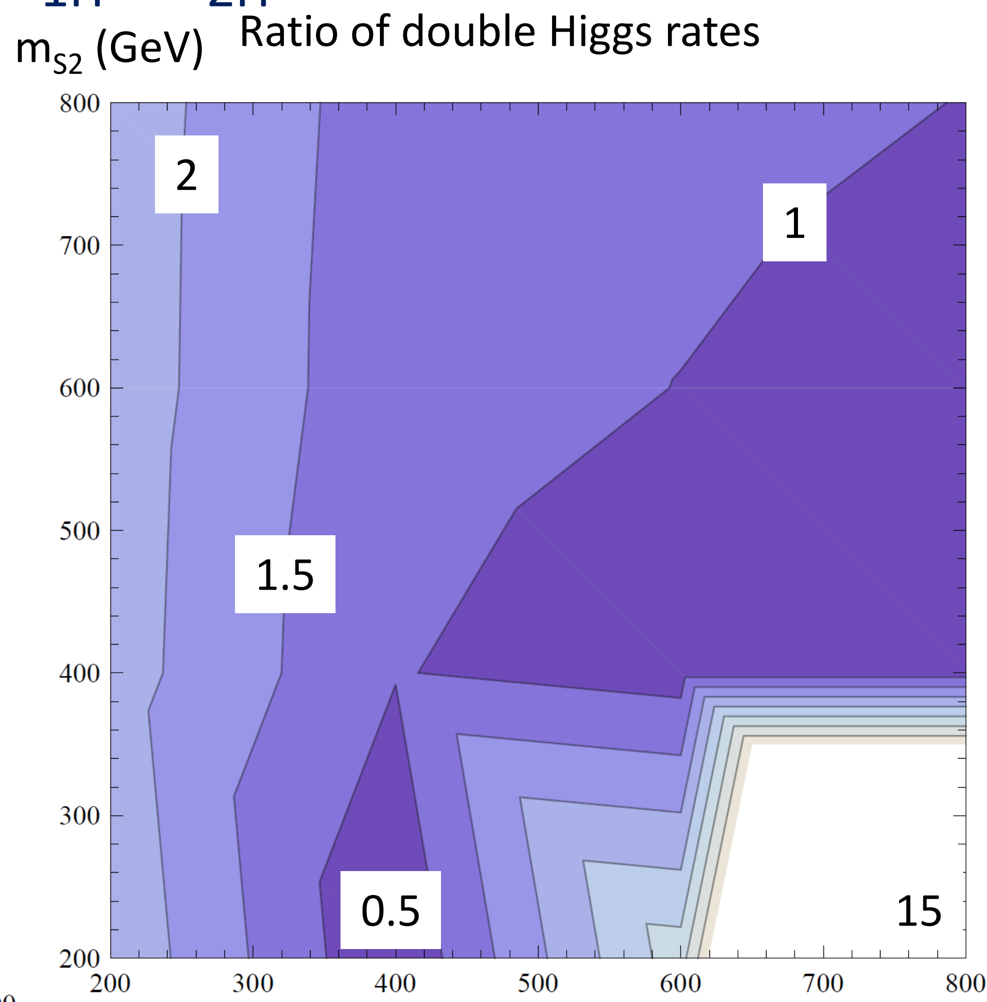




Numerical results

- Model 1 (color triplets, $-\lambda_{1H} = \lambda_{2H} = 2$



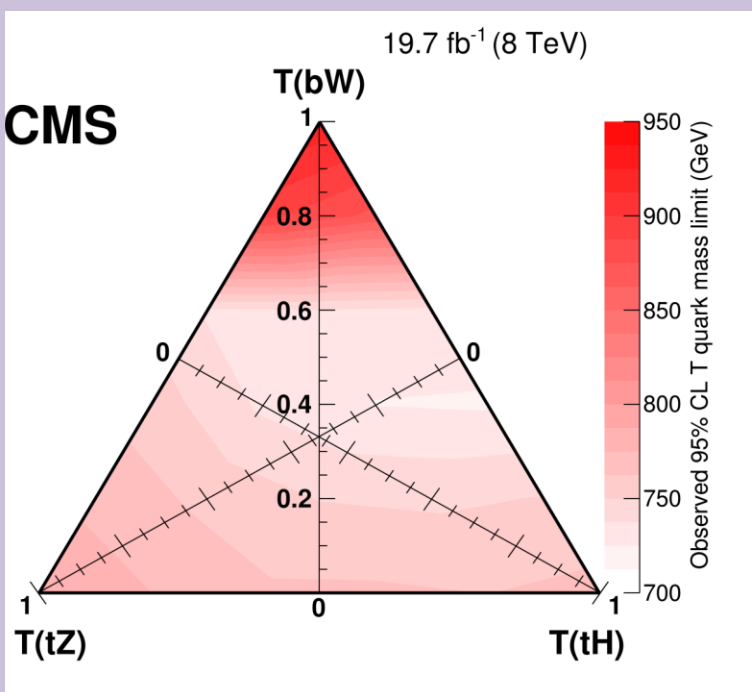


Conclusions

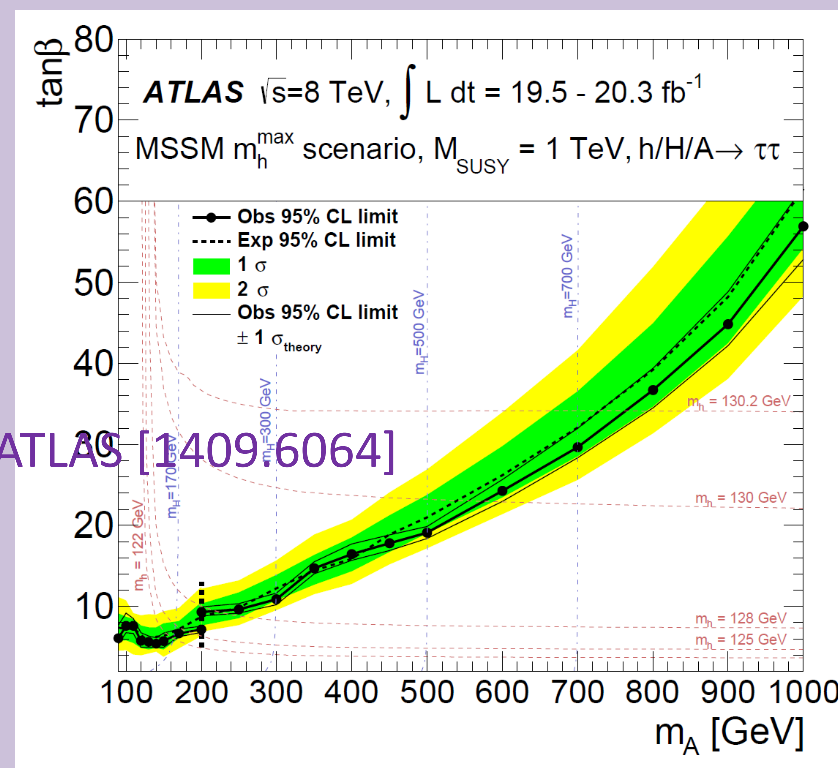
- Decorrelating double Higgs rates and single Higgs rates is interesting avenue for NP
  - Provides only strong motivation for continued results on non-resonant HH production
- Interplay with Higgs potential provides theoretical cutoff of strength of deviation

Outline

- At threshold, exact cancellation in SM



CMS [1509.04177]



ATLAS [1409.6064]