VBF HH Generation and Benchmarks

Tyler James Burch, on behalf of the ATLAS and CMS collaborations

Double Higgs Production at Colliders Workshop

September 7, 2018

Vector Boson Fusion

Higgs boson production mode:

- Vector bosons radiate from quarks, the quarks in turn result in very forward, high-pT jets
- Bosons collide, resulting in a hard interaction yielding a central Higgs boson

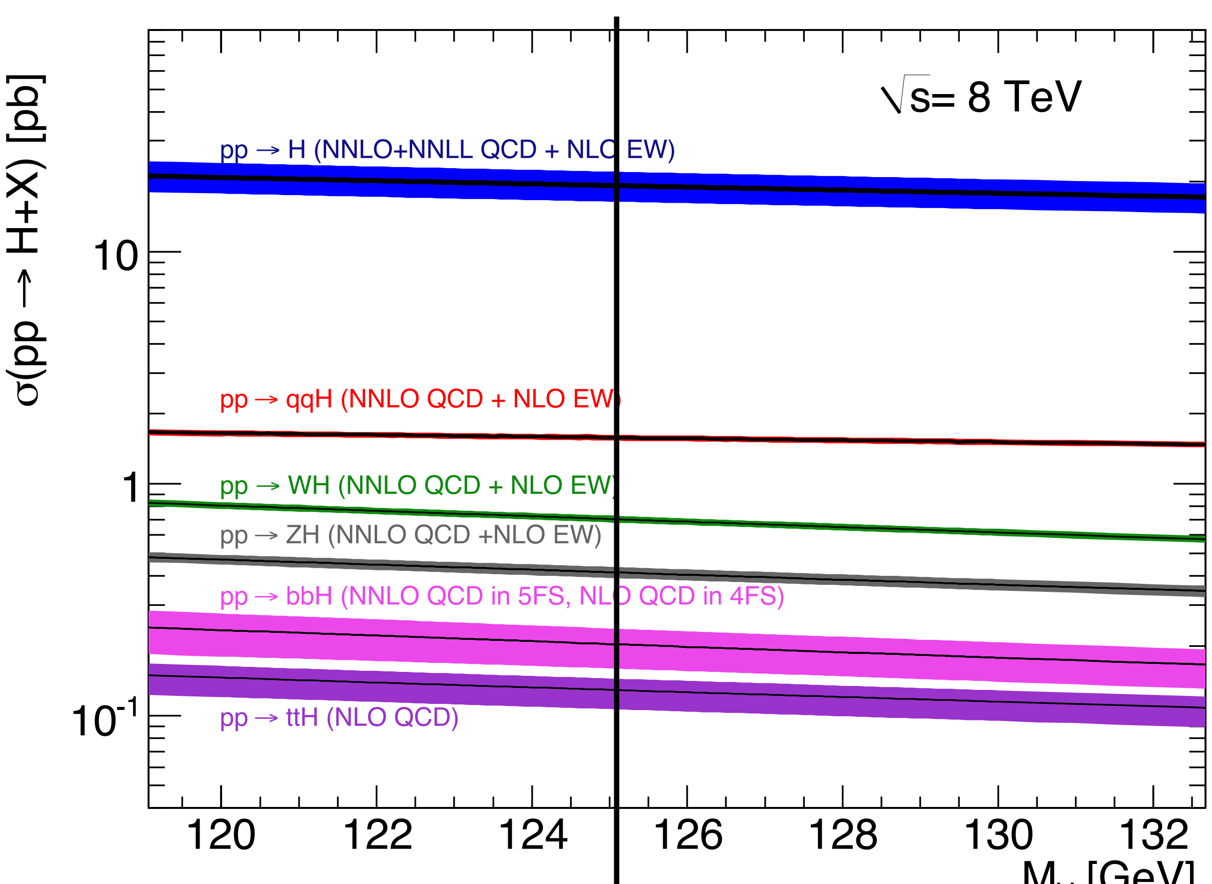
Advantages:

Forward jets, reduced hadronic activity in central region - Unique signature!

Second largest production mode - More signal events than VH, ttH, bbH

Disadvantage:

Still an order of magnitude smaller than ggF production



LHC Higgs XS WG

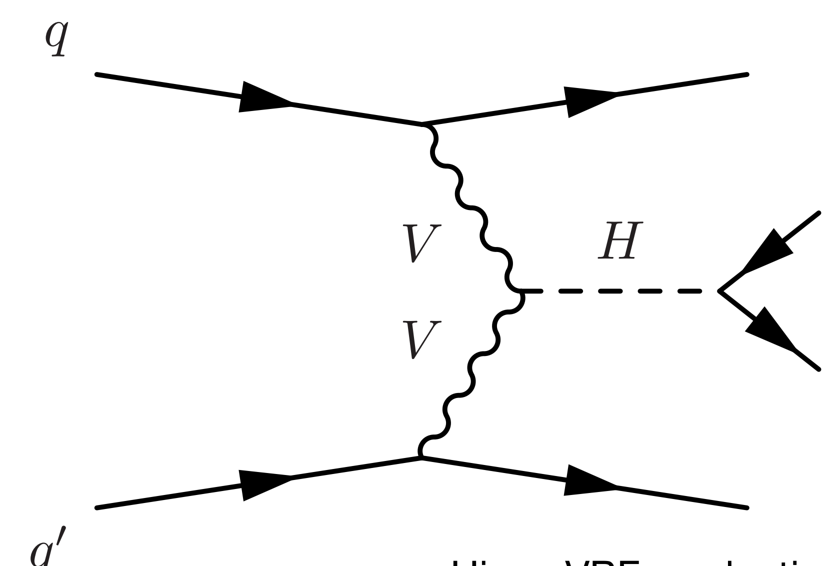
(for 13 TeV)

ggF = 87.3 %

VBF = 6.8%

}VH = 4.1%

}ttH + bbH = 1.8%



mono-Higgs VBF production
arXiv:1807.08639

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Standard Model VBF di-Higgs Production

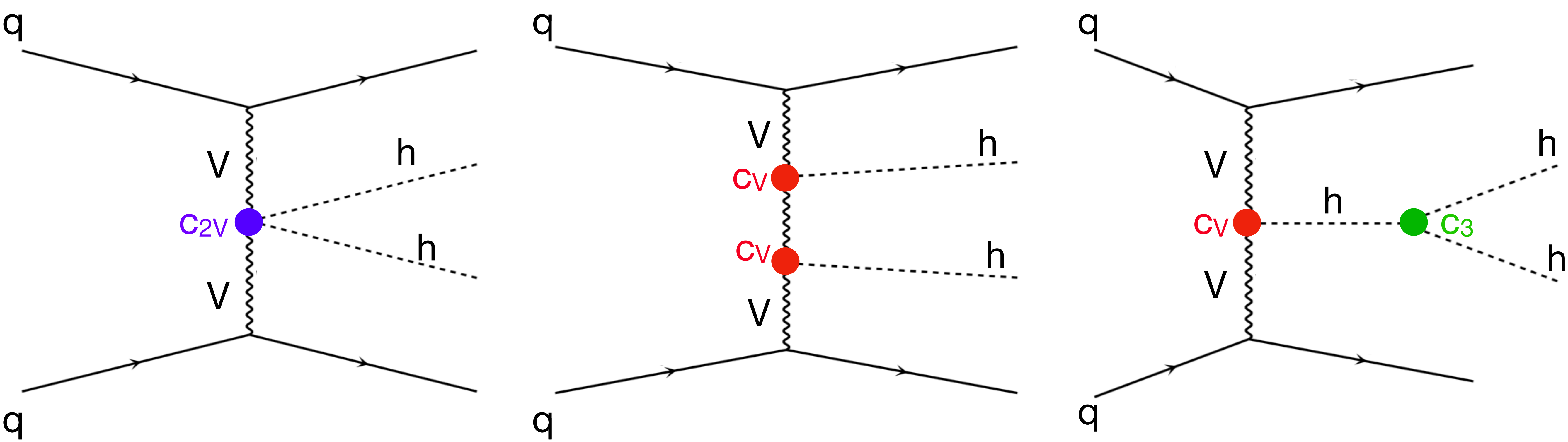
SM VBF di-Higgs Production

Effective Lagrangian

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}Tr(D_\mu\Sigma^\dagger D^\mu\Sigma)[1 + 2c_V\frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \ldots] - m_i\bar{\psi}_{Li}\Sigma(1 + c_\psi\frac{h}{v} + \ldots)\psi_{Ri} + h.c.$$

With

$$V(h) = \frac{1}{2}m_h^2h^2 + c_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + c_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$



c_V (hVV coupling)

c_{2V} (hhVV coupling)

c_3 (Higgs trilinear coupling, λ)

c_4 (Higgs quartic coupling)

c_ψ (Higgs coupling to fermions) } do not significantly affect VBF hh production

(all values normalized to 1 in SM)

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SM VBF di-Higgs Production

di-Higgs production has generally very small cross sections
Underscores need for investigating channels other than ggF to improve sensitivity

di-Higgs searches motivated by sensitivity to the Higgs trilinear coupling
- Gives insight into electroweak symmetry breaking
- di-Higgs is the only channel with direct sensitivity to this coupling

VBF production is also sensitive to the trilinear coupling!
- Parton level study by Arganda, Garcia-Garcia, Herrero projects VBF production to have **similar sensitivity to λ as ggF, even at current luminosities** [arxiv:1807.09736]

Gives access to additional coupling c_{2V}
If di-Higgs production is observed, provides additional tests of the Standard Model

$$\sigma_{HH}^{vbf} = 1.64 \text{ fb}$$

$$\sigma_{HH}^{ggF} = 33.4 \text{ fb}$$

Luminosity (fb^{-1})	Expected VBF HH Events Produced	bbbb	bbtt	$\gamma\gamma$bb
150 (Expected Run 2)	240	82	18	0.6
300 (Expected LHC 13 TeV)	490	163	36	1.3
3000 (Expected HL-LHC)	4900	1630	360	13

(Not accounting for acceptance or efficiency)

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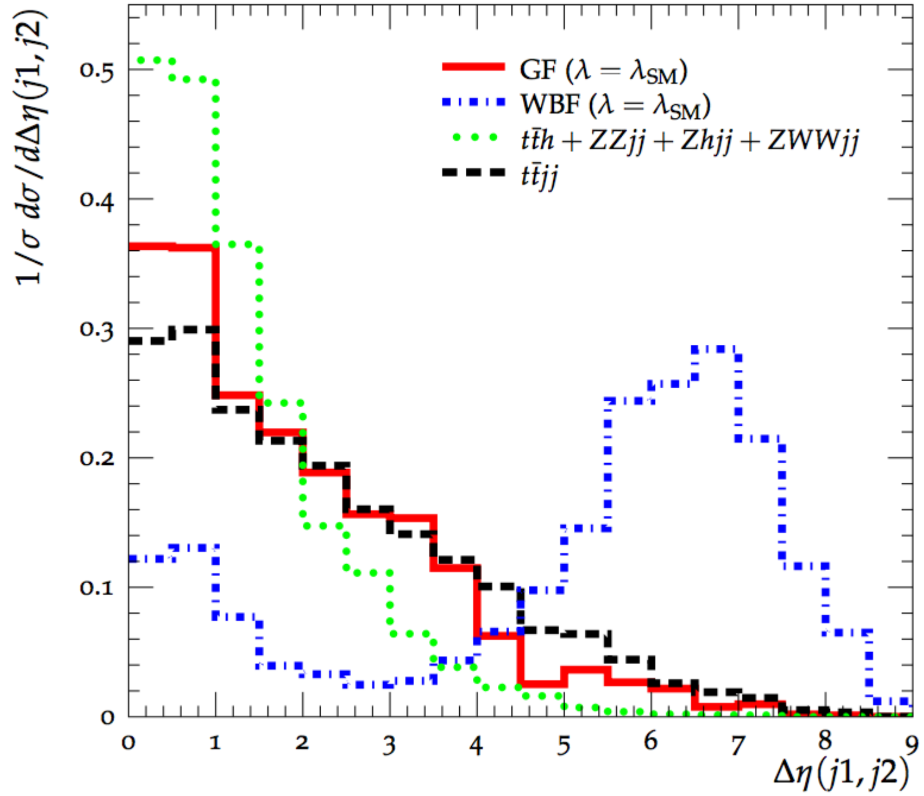
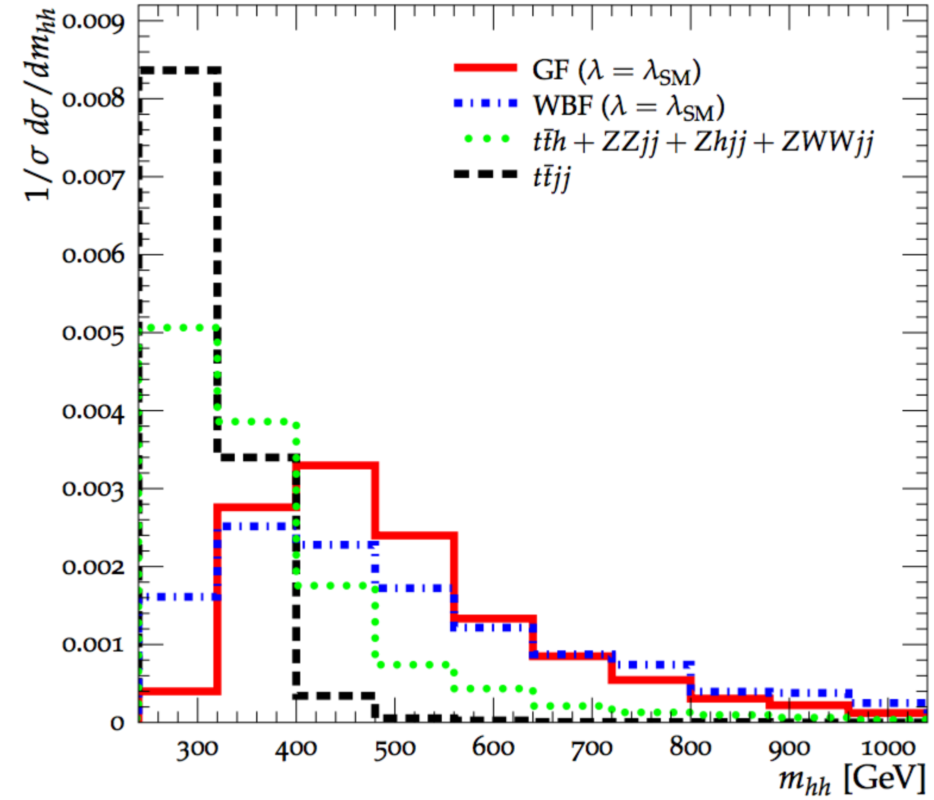
SM VBF HH in bbττ Channel





Hadron-level analysis (in Rivet) performed to optimize signal to background looking at bbττ final state

- Requirement of central b-tagged jets and central taus near Higgs mass applied

Due to low production rate, need careful optimization cuts to retain sensitivity

However, the **unique VBF topology** makes this manageable:
Targeting VBF only: require **$m_{hh} \geq$ 400 GeV** and **$\Delta\eta(j_1, j_2) \geq 5$**

- Reduces background by factor of ~300
- $S/\sqrt{B}$ ~ 0.8

Dolan, Englert, et al.
Eur.Phys.J. C75 (2015) no.8, 387

Interesting study - encourage taking a look! [arxiv:1506.08008]

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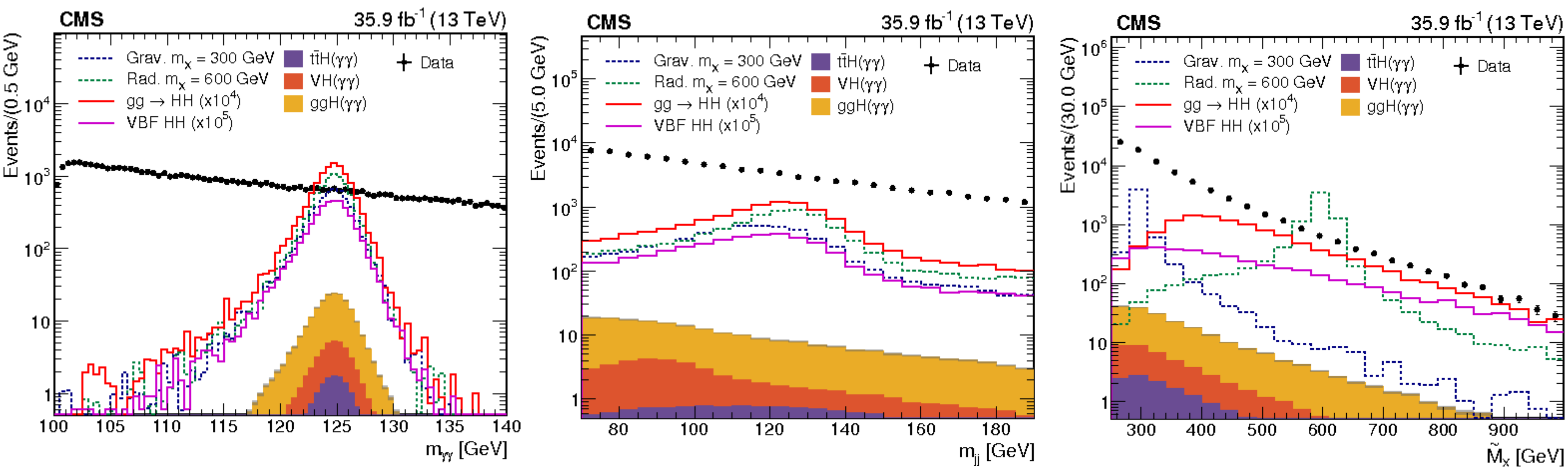
VBF HH at the LHC

So far, only the CMS $\gamma\gamma$bb analysis has considered VBF as a signal model in their published analysis, though no dedicated VBF categories to-date

Mass spectra from the analysis shown - VBF contributions in pink (normalized to 10^5 times its cross section)



CMS-HIG-17-008-004

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VBF HH at the LHC

Signal events are chosen via a BDT, which is trained on ggHH samples.

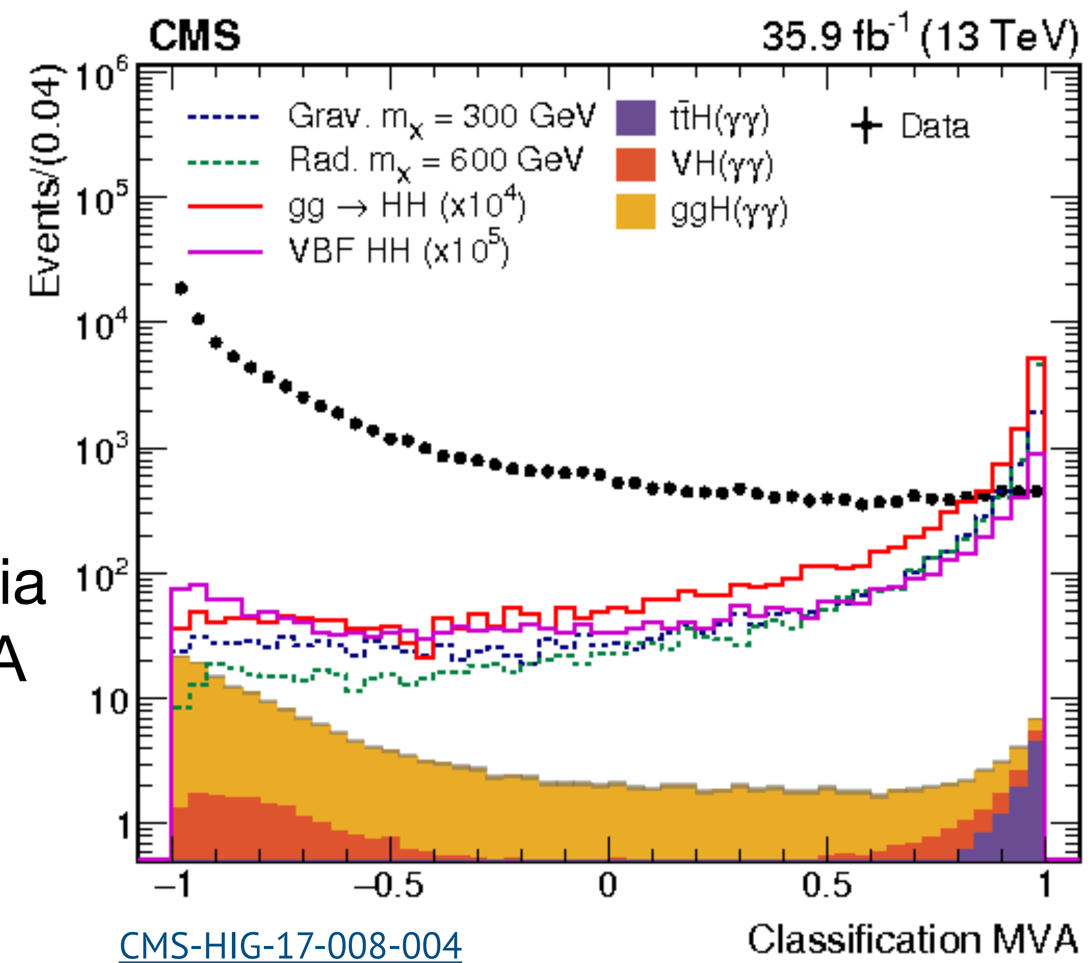
- Efficiency times acceptance is 13% for SM-like VBF HH due to training on ggHH (30% for ggHH)
  - 10% in high-mass region (> 350 GeV)
  - 3% in low-mass region (< 350 GeV)

Including VBF production improves sensitivity by 1.3%

Future:

Introduce an independent VBF category, select signal via cuts on distinct VBF variables, or even a dedicated MVA trained on VBF events

- Ongoing investigations in ATLAS toward dedicated VBF categories in full Run-2 HH analyses for several channels



CMS-HIG-17-008-004

VBF contribution in pink (normalized to 10^5 times its cross section)

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BSM Non-Resonant VBF di-Higgs Production

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SM VBF di-Higgs Production

Effective Lagrangian

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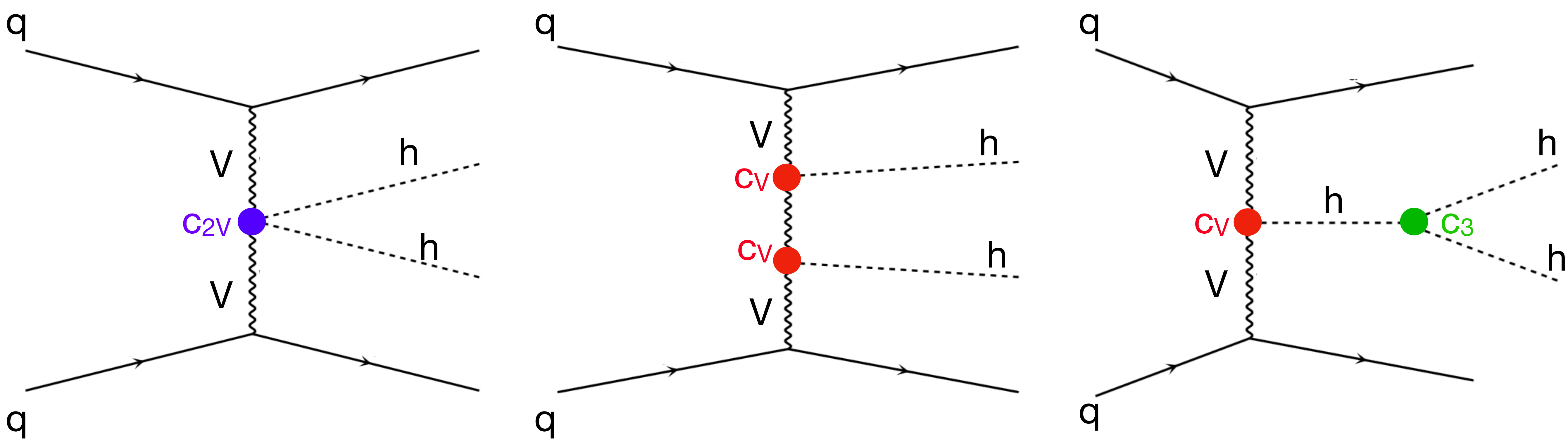

- c_V (hVV coupling)
- c_{2V} (hhVV coupling)
- c_3 (Higgs trilinear coupling, λ)
- c_4 (Higgs quartic coupling)
- c_ψ (Higgs coupling to fermions)

All values normalized to 1 in SM, but **can probe BSM models where these vary from SM value**

- Composite Higgs model where Higgs is a pseudo-Nambu-Goldstone Boson

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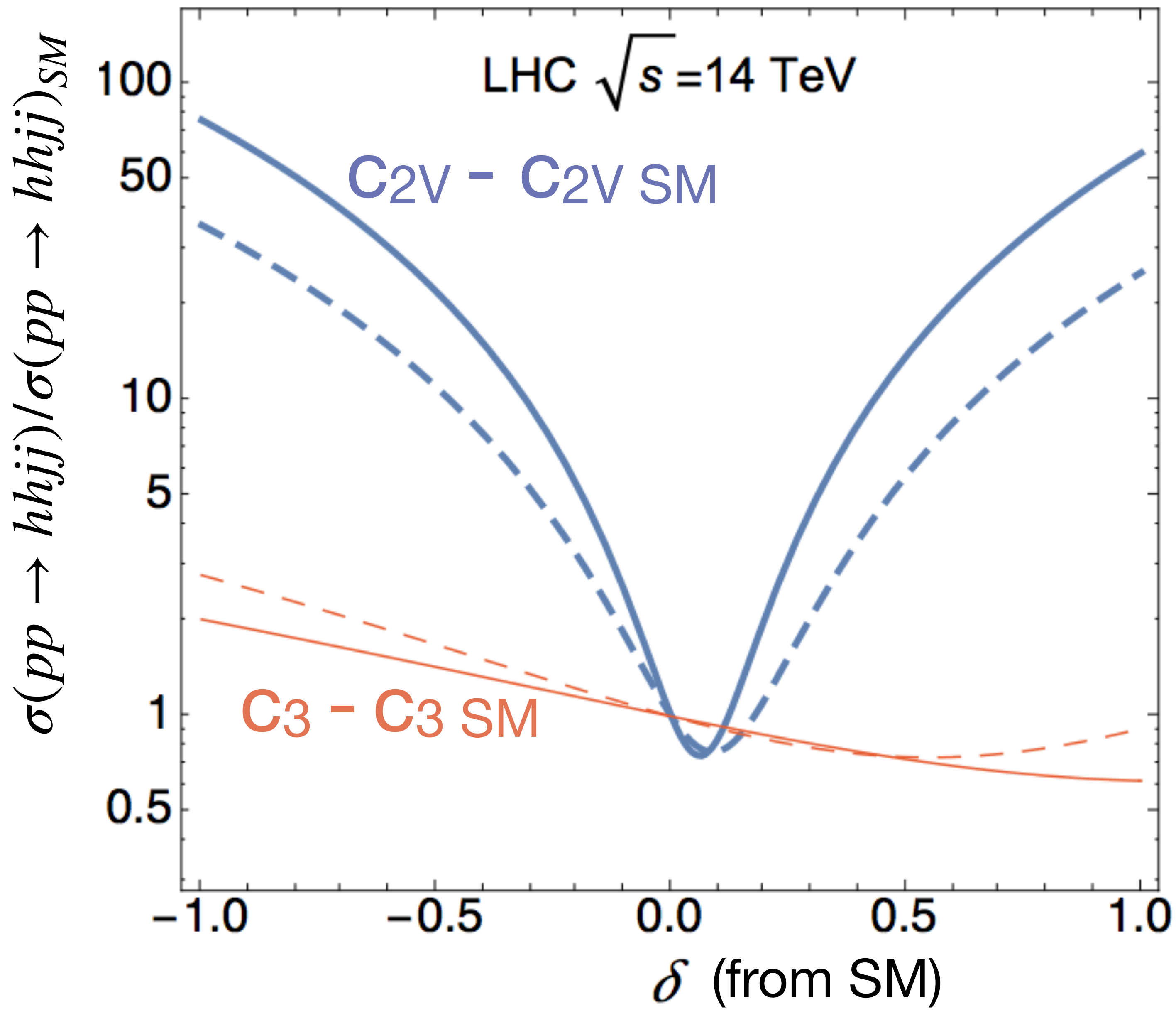
BSM Non-Resonant Production

Bishara, Contino, Rojo
Eur. Phys. J. C 77 (2017) 481



VBF di-Higgs cross section as a function of c_{2V} and c_3 from the SM value

Solid: Acceptance cuts (study on 4b events)

- $pT_j \geq 25$ GeV
- $pT_b \geq 25$ GeV
- $|\eta_j| \leq 4.5$
- $|\eta_b| \leq 4.5$

Dashed: Analysis cuts

- $|\Delta y_{jj}| \geq 5$
- $m_{jj} \geq 700$ GeV
- Central jet veto: $pT_{j3} \leq 45$ GeV for j_3 lying between the VBF jets in η

Even small deviations from the SM on vector boson couplings to the Higgs can result in very large changes in production rate

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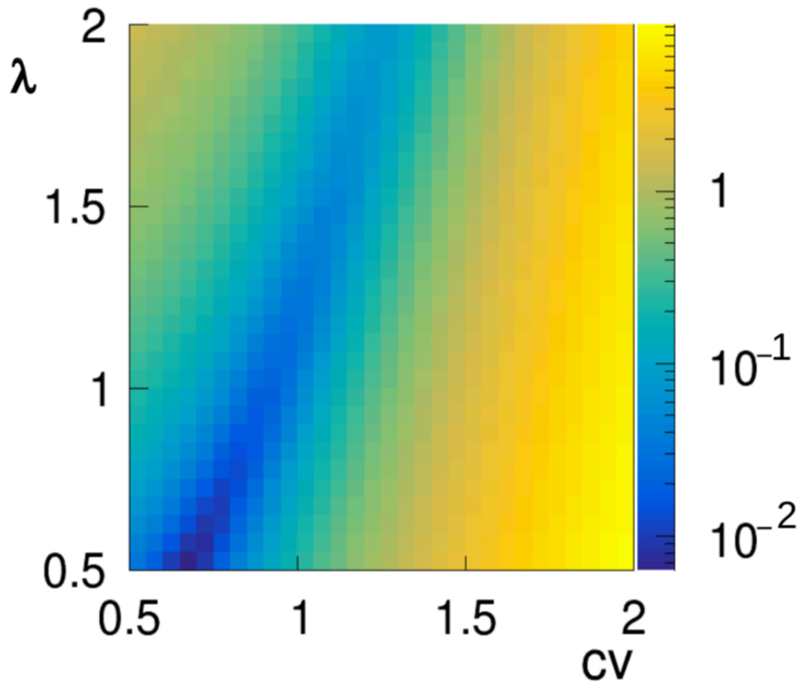
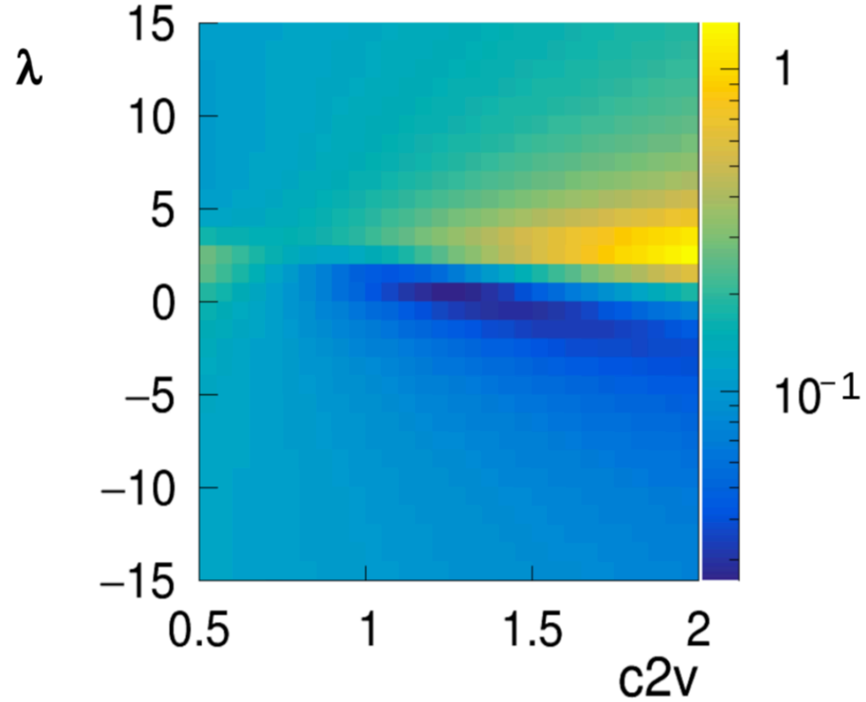
BSM Non-Resonant Production

Given the drastic effects of varying the vector boson couplings, one can parametrize $\sigma_{VBF}/\sigma_{ggF}$, VBF becoming the dominant production mode when > 1

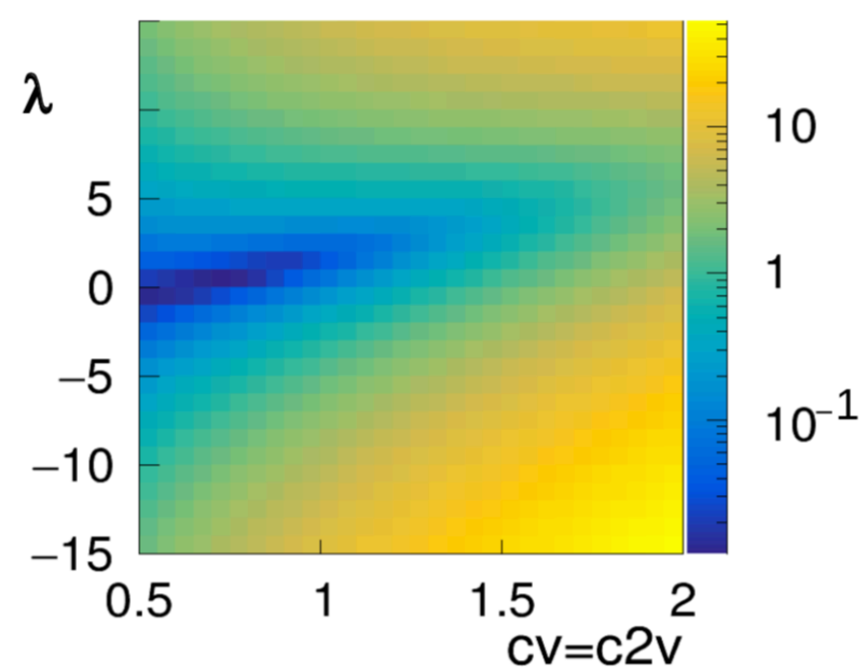
($K_\lambda = \lambda/\lambda_{SM} = c_3$)



varying just c_V



varying just c_{2V}



varying both c_V and c_{2V}

Anamika Aggarwal (Masters Thesis) and Alexandra Carvalho

This underscores the **parameter space still to be studied**

In many of those regimes, **VBF HH production contributes significantly**

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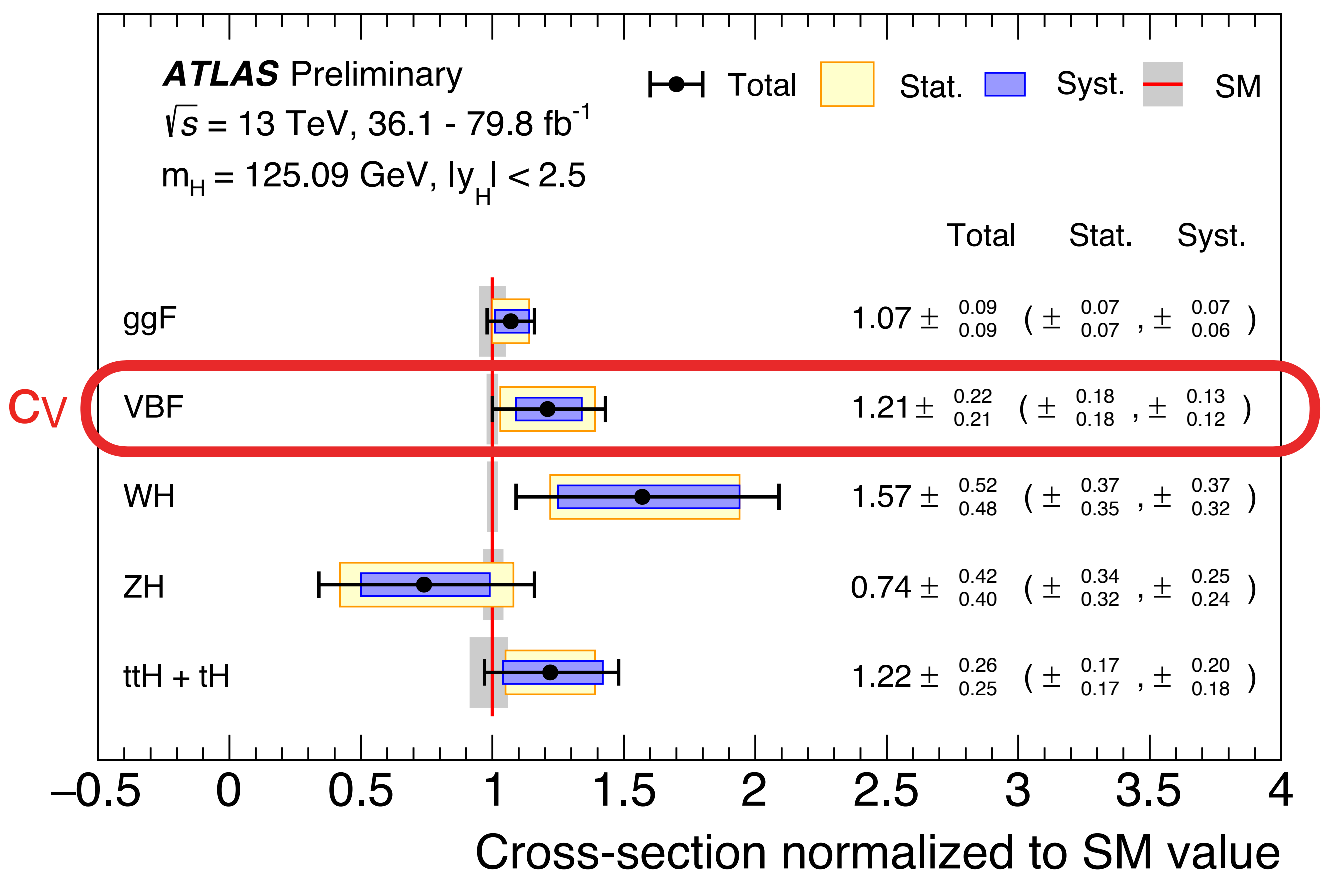
BSM Non-Resonant Production

Current Experimental Constraints:

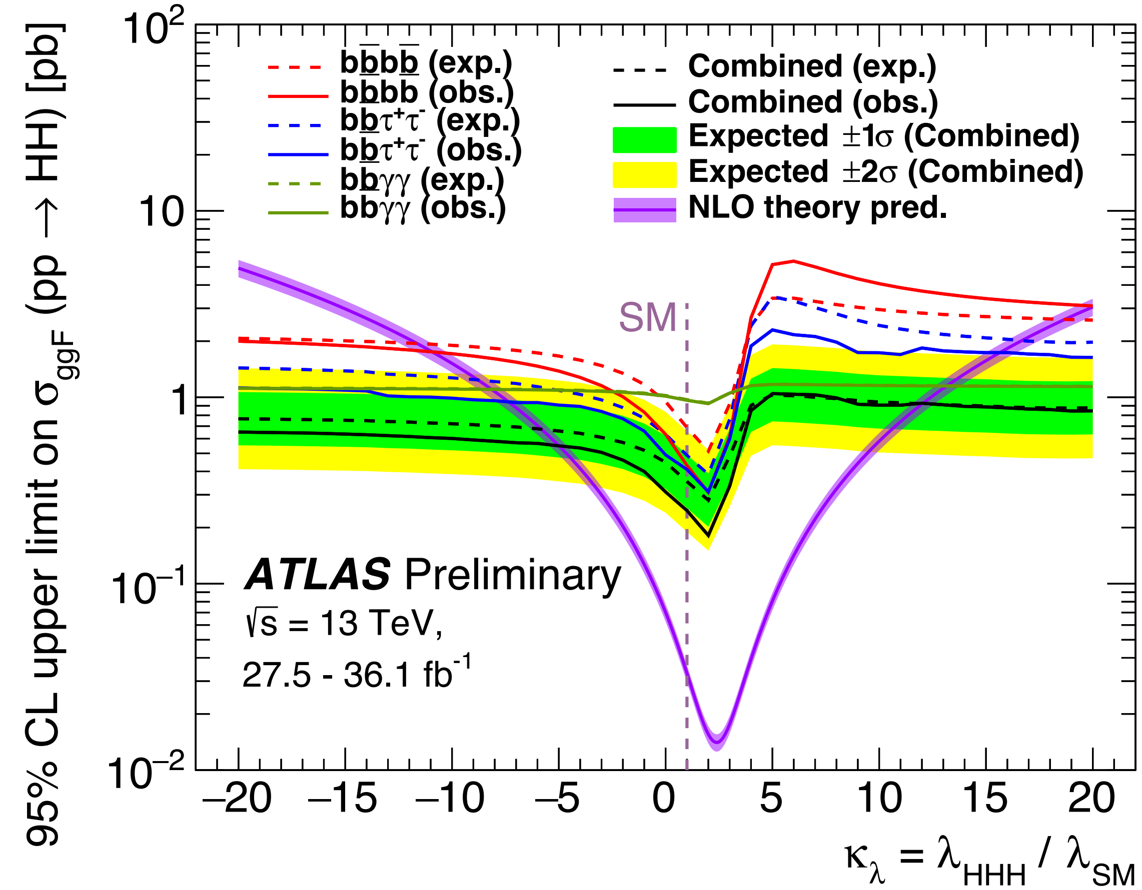
c_V - Limits from mono-Higgs production

c_3 - Best limits from ATLAS combination

c_{2V} - No existing experimental limits. Mono-Higgs searches do not probe this vertex



ATLAS-CONF-2018-031



-5.0 < c_3 (K_λ) < 12.1

Untouched parameter space with potential for interesting physics!

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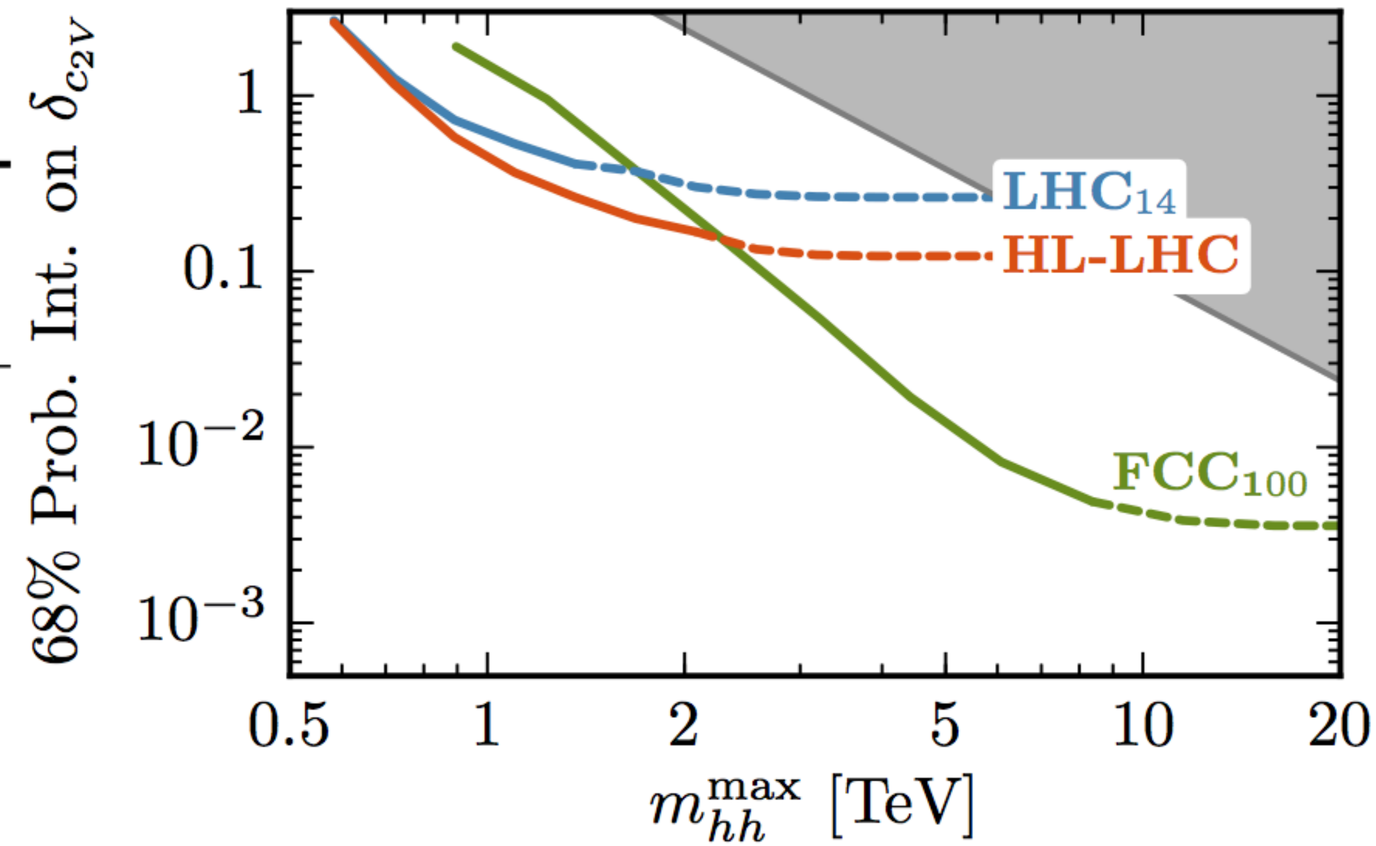
BSM Non-Resonant Production

Bishara, Contino, Rojo
Eur. Phys. J. C 77 (2017) 481

		68% probability interval on $\delta_{c_{2V}}$	
		$1 \times \sigma_{\text{bkg}}$	$3 \times \sigma_{\text{bkg}}$
300 fb^{-1}	LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
3.0 ab^{-1}	HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$



If no resonances, c_{2V} can be constrained to 45% of it's SM value at 300 fb^{-1} before the HL-LHC - motivates VBF analysis even before HL-LHC dataset

Better sensitivity at higher m_{hh}
- Important to study using channels with high mass sensitivity (bbbb, bbττ)

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Couplings to Probe

Grid of coupling variations to be investigated by ATLAS shown

Motivation:

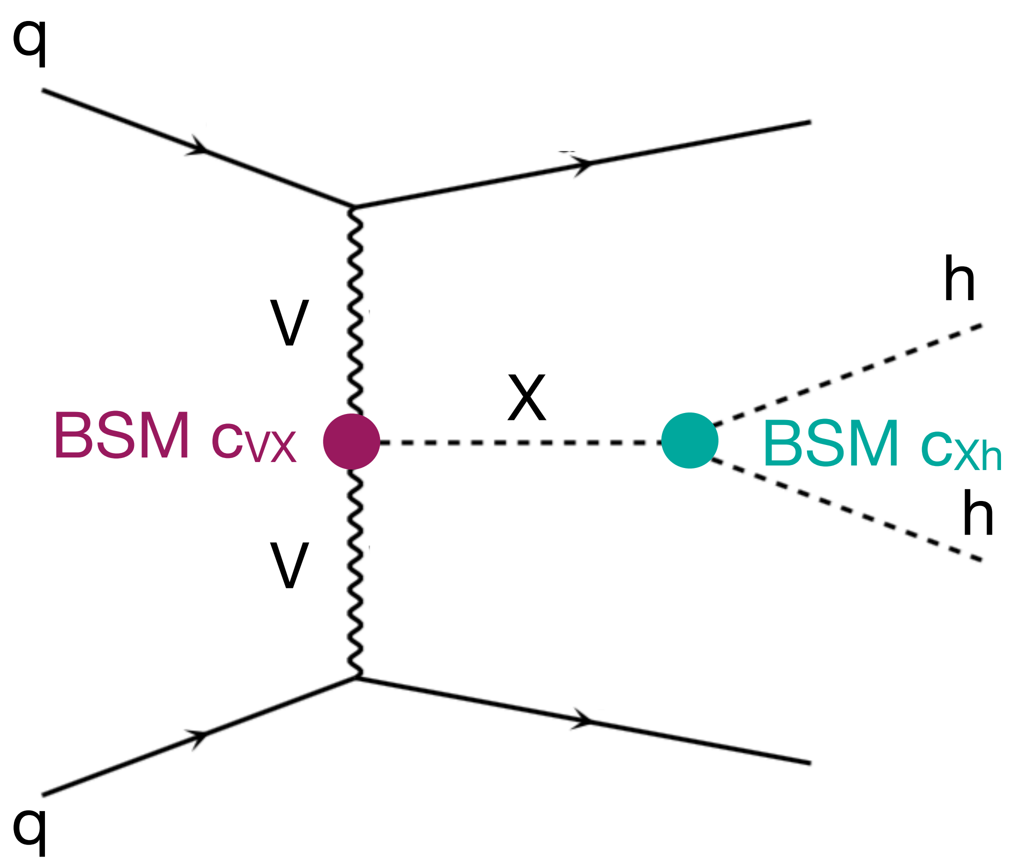
- Want set of variations for interpolation, focus on c_{2V} due to largest sensitivity
- Less sensitive to c_3, so fewer points for interpolation, but include both c_3 and c_{2V} to check correlation
- c_V already fairly constrained, but want to check for c_{2V} dependence

In any case, should harmonize approach between experiments and theoretical motivation
- Discussion section afterwards

$c_3 \equiv \lambda/\lambda_{SM}$	c_{2V}	c_V
1	1	1
1	0	1
1	0.5	1
1	1.5	1
1	2	1
0	1	1
2	1	1
1	1	0
0	1	0
1	0	0
1	0	0.5

BSM Resonant VBF di-Higgs Production

BSM Resonant Production



Similar to ongoing ggF searches, can also imagine a BSM scenario with a resonance that couples to the vector bosons

However, not particularly well studied:
- CMS-PAS-FTR-18-003 study of $Xjj \to hhjj \to b\bar{b}b\bar{b}jj$, projects 2-4σ for bulk graviton with full HL-LHC 3 ab^{-1}, assuming cross section of 1 fb
- Not much other work out there out there - worth thinking about, but concerns whether signals in these models are practically viable

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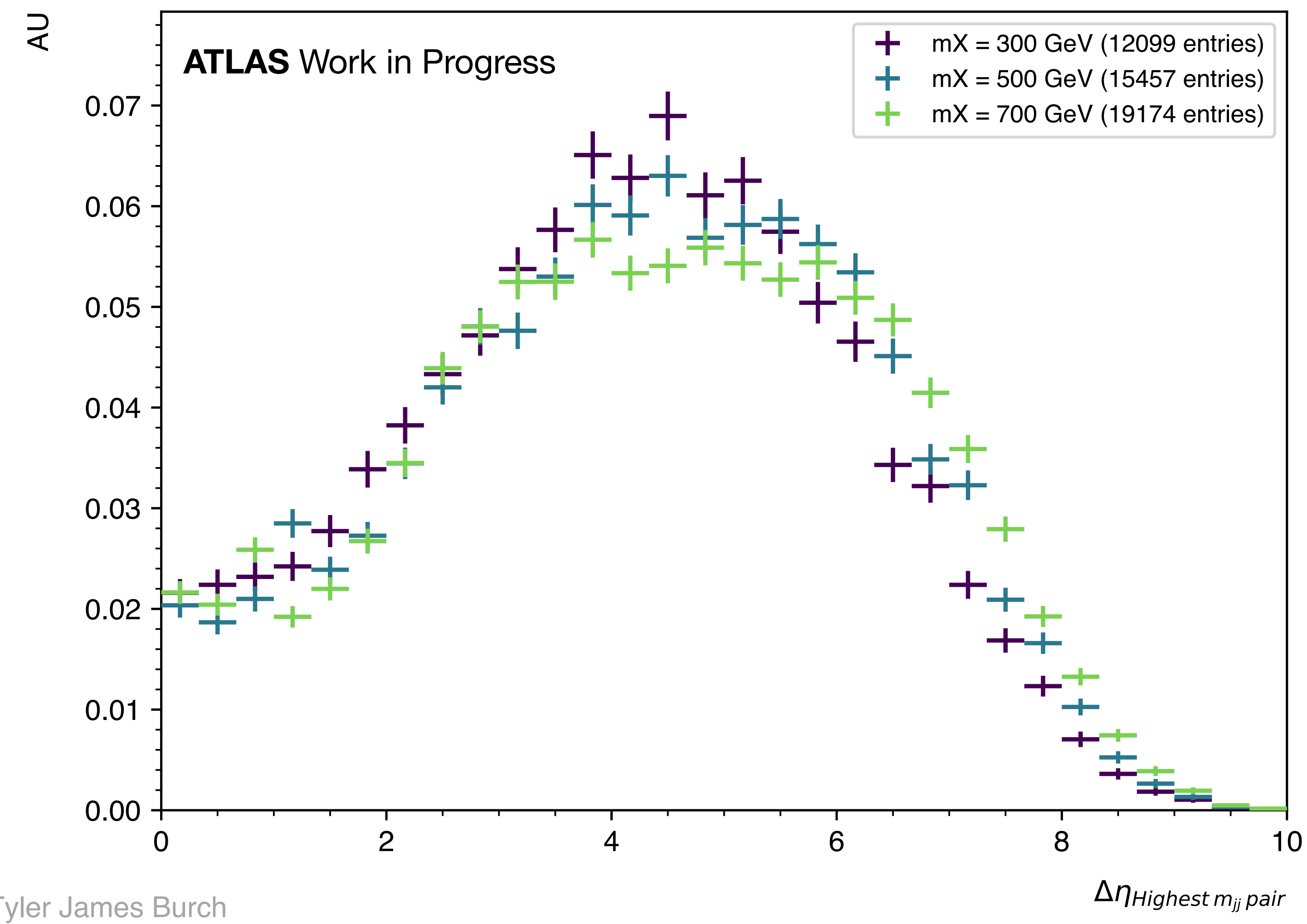
BSM Resonant Production

ATLAS work-in-progress, conducted at truth level in the $\gamma\gamma$bb channel



Tyler James Burch

VBF jets kinematically very similar to non-resonant VBF production, so similar **Δη cuts can be used** to target resonant and non-resonant production

Planned resonance mass simulation grid (GeV): 260, 280, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000

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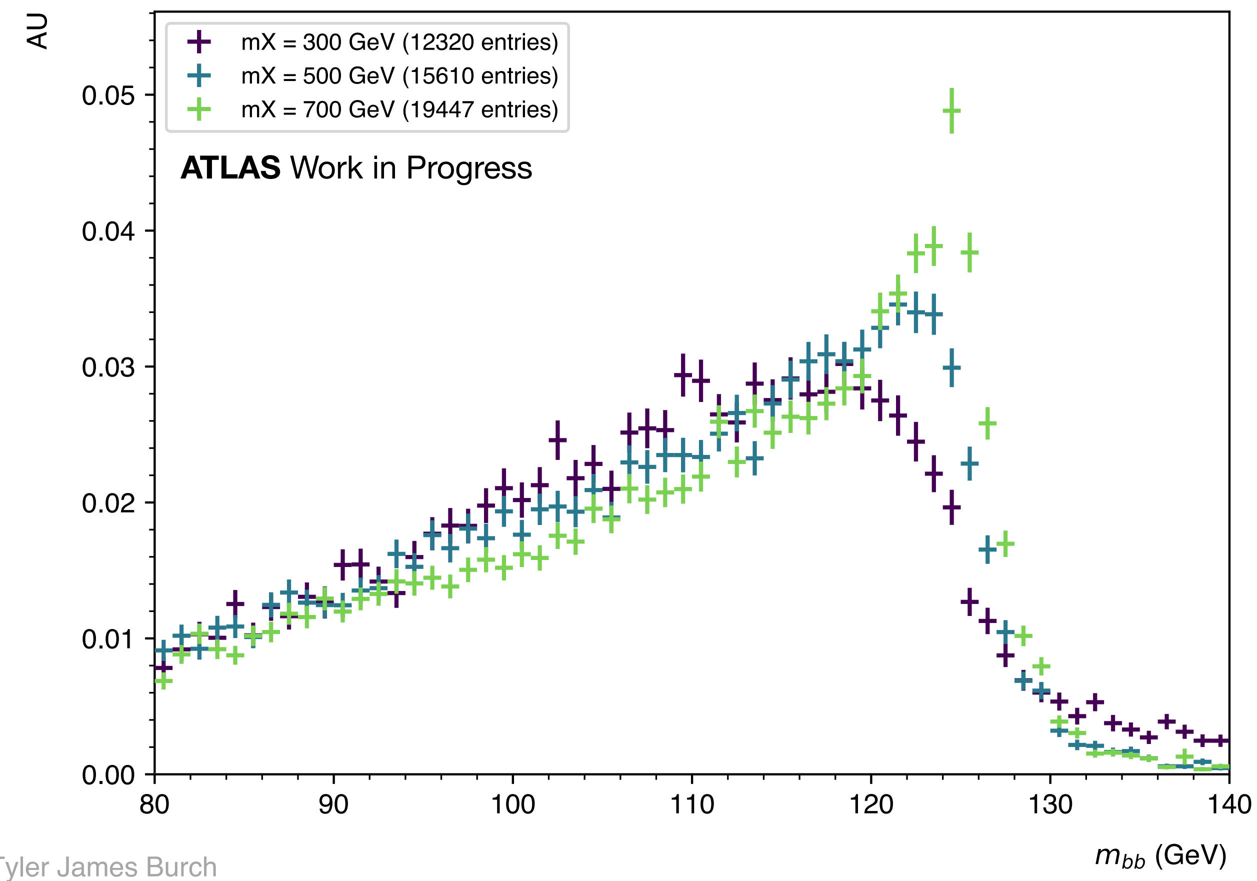
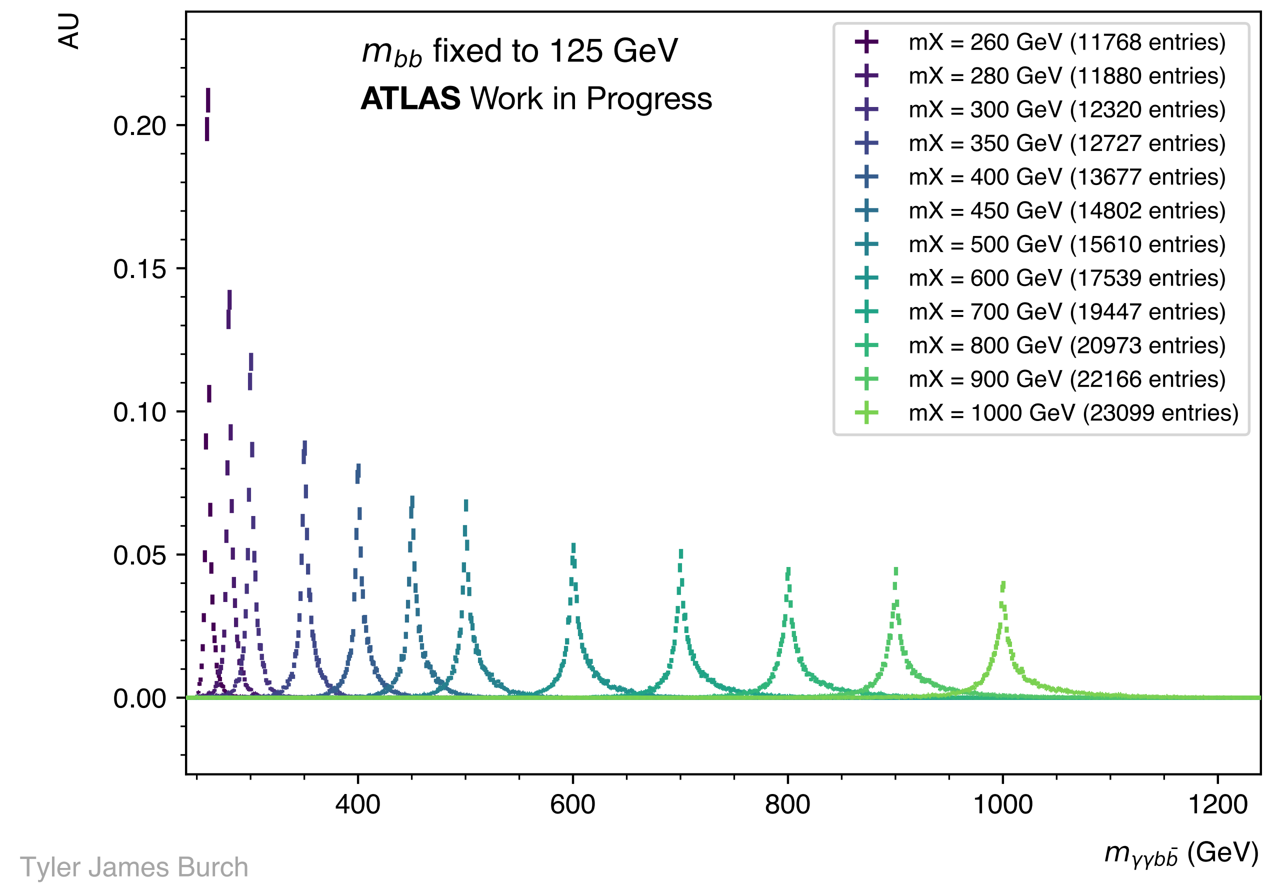
BSM Resonant Production

ATLAS works-in-progress, conducted at truth level in the $\gamma\gamma$bb channel





Higgs kinematics sensitive to resonant mass as expected, so
same analysis approach as ggF production can be taken with resonant VBF

Experimental work on resonant production just getting started! Plenty to think about, certainly worth discussion going forward

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Conclusion

VBF topology has a unique signature that is easy to target

- Very pure signal regions possible with just a few cuts
- Adding a VBF category to HH analyses can increase sensitivity

Provides insight into interesting couplings

- c_{2V} (hhVV coupling) is interesting and currently has no limits set on it
- Sensitive to c_3 (Higgs trilinear coupling), which provides insight into EWSB, makes di-Higgs uniquely interesting

BSM scenarios make VBF HH already interesting

- Deviations on vector boson couplings will already be interesting with current LHC data, due to the drastic increase in production rate for small variations of c_{2V}

Much to be gained from starting to look at VBF HH production!

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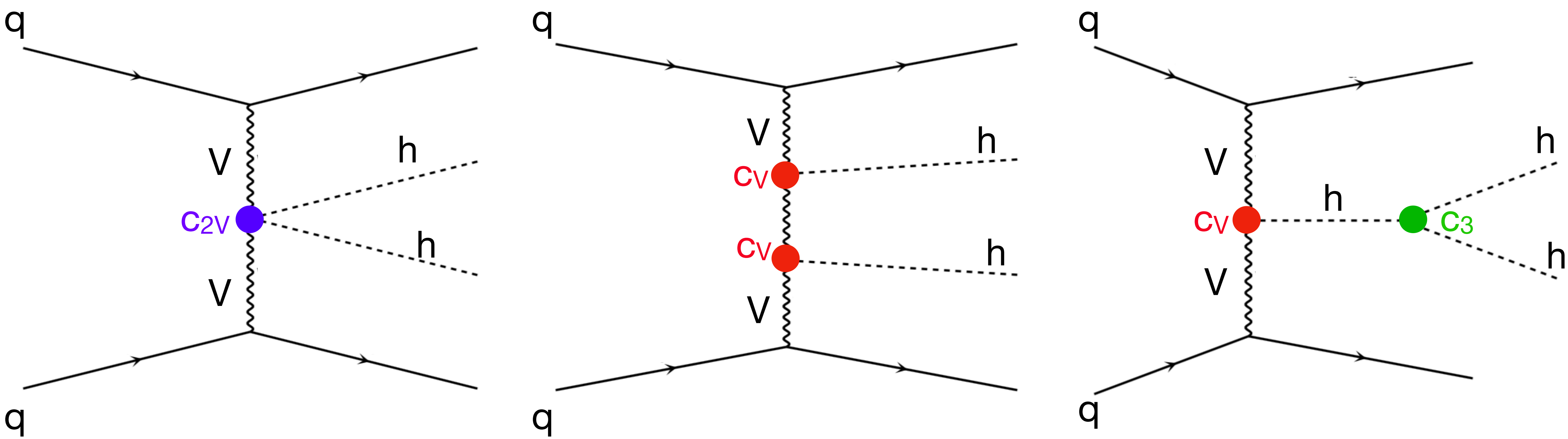
Thank You!

Models and Constraints



Composite Higgs theories where Higgs interactions controlled by $\xi \equiv v^2/f^2$

- v = vev, f = pNGB decay constant
- Minimal SO(5)/SO(4) models predict c_V and c_{2V} relations

$$c_V = \sqrt{1-\xi}$$

$$c_{2V} = 1 - 2\xi$$

Trilinear coupling depends on how the Higgs potential is generated

- e.g. in MCHM5 model, trilinear coupling is predicted as c_{2V}/c_V
- So model-independent **limits on c_{2V} can provide constraints on various BSM scenarios**

$$c_3 = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Correlations in these couplings exist for various models, e.g.

- Higgs belongs to an EW doublet ($\delta_{c_{2V}} \simeq 2\delta_{c_V^2}$)
- Higgs plays no role in EWSB, e.g. Light Dilation Scenario ($\delta_{c_{2V}} = \delta_{c_V^2}$)

$$\delta_{c_V^2} \equiv c_V^2 - 1$$

Bishara, Contino, Rojo
Eur. Phys. J. C 77 (2017) 481

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