Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state

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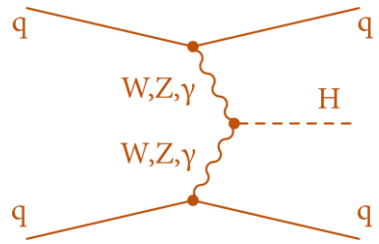
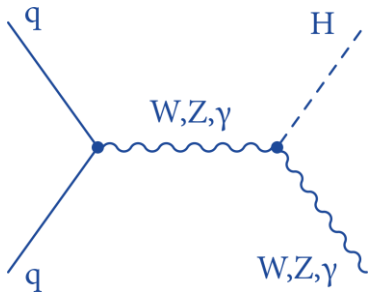
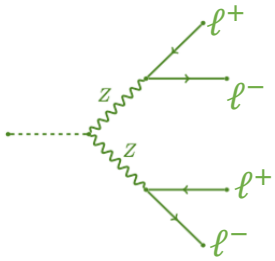
Introduction

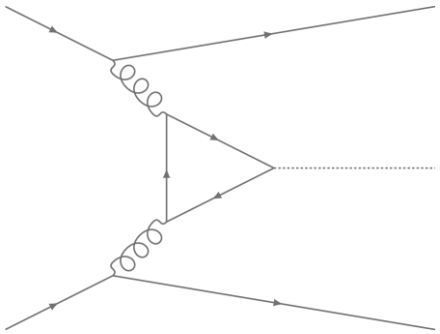
- Search for anomalous HVV couplings
  - Kinematics of jets from VBF and VH production
  - Kinematics of leptons in $H \rightarrow ZZ$ decay

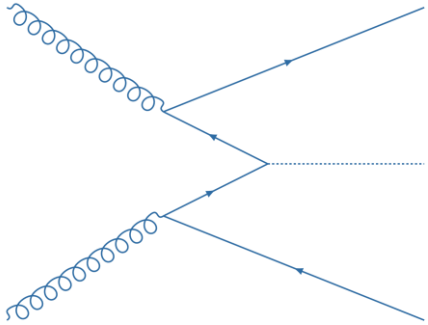




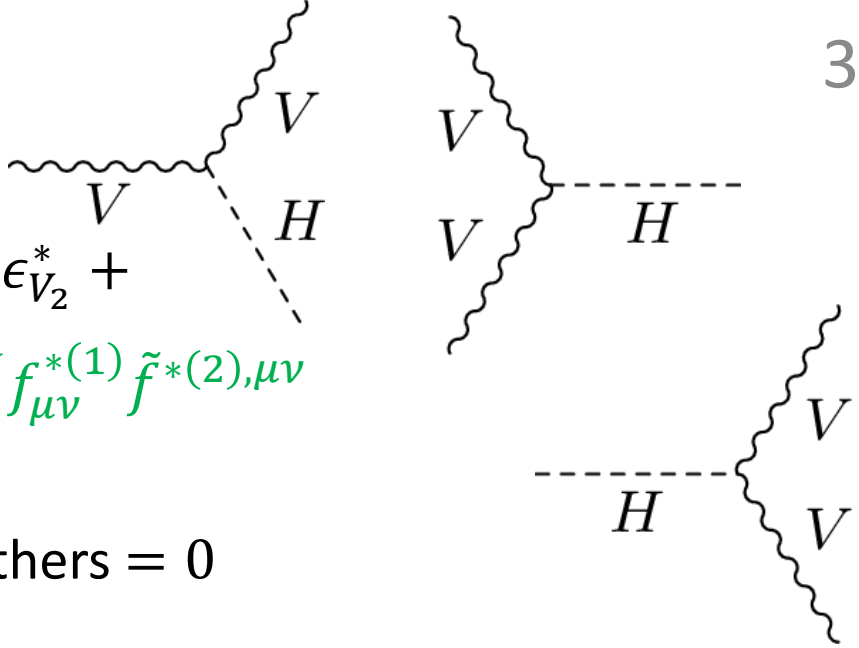


- Search for anomalous Hff couplings
  - Kinematics of jets from gluon fusion with extra jets
  - Kinematics of top decays from ttH





Amplitudes

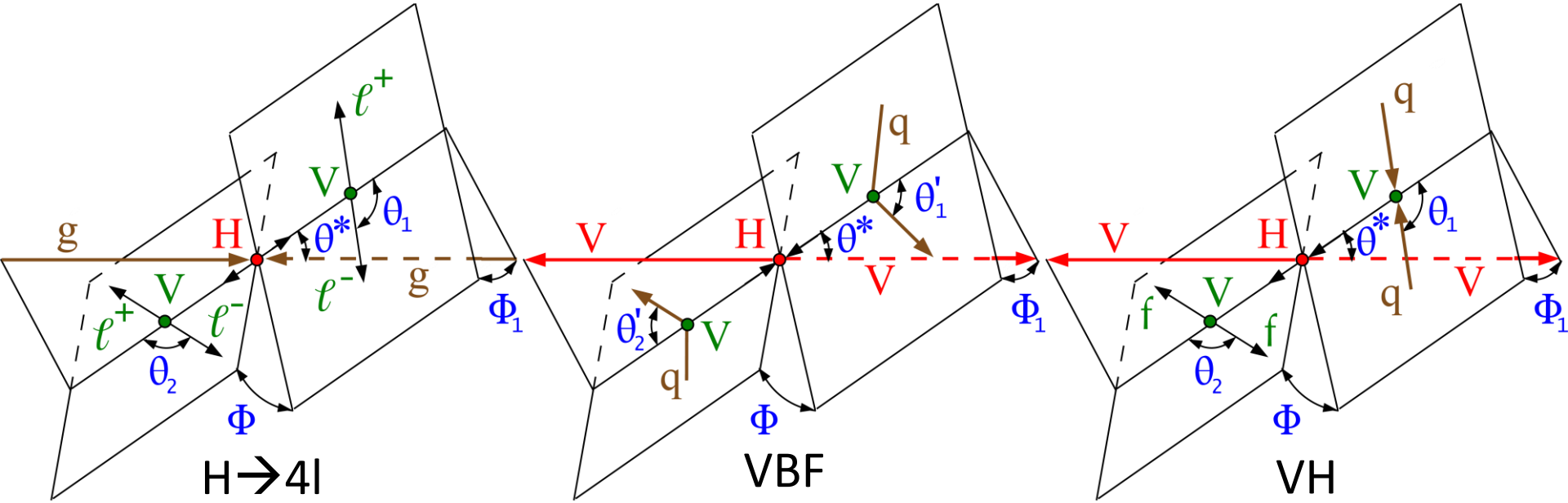


- $A(HVV) \sim \left[a_1^{VV} + \frac{q_{V_1}^2 + q_{V_2}^2}{\left(\Lambda_1^{VV}\right)^2}\right] m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$
- $VV = ZZ, WW, Z\gamma, \gamma\gamma$
- SM, tree level: $a_1^{ZZ} = a_1^{WW} = 2$, others $= 0$
- Assume $a_i^{ZZ} = a_i^{WW}$, call it "a_i"
- Measure $a_2, a_3, \Lambda_1, \Lambda_1^{Z\gamma}$
- Parameterize as fractional cross section $f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}$ and relative phase $\phi_{ai} = \arg\left(\frac{a_i}{a_1}\right)$

- $A(Hff) = -\frac{m_f}{v} \bar{\psi}_f \left(\kappa_f + i\tilde{\kappa}_f \gamma_5\right) \psi_f$
- Fractional cross section: $f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}$

VBF and VH production and H→4l decay

- All three processes have the same dynamics
- Kinematics are completely different
- $H \to ZZ \to 4l$: Z boson masses $m_{Z1} + m_{Z2} \leq 125$ GeV
- $V^* \to VH$: $m_V \approx 91.2$ GeV, $m_{V^*} \geq (91.2 + 125)$ GeV
- VBF: Z bosons are offshell with negative q^2, typically $\sqrt{-q^2}$~few hundred GeV
- All anomalous couplings have an extra power of q^2 in the amplitude →enhanced in VBF and VH



General strategy

Key:
No HVV vertices
1 HVV vertex
2 HVV vertices

- Split events into categories c
- In each category, parameterize p.d.f. for each process p with templates $T^{i}_{c,p}$ describing the most important kinematics for the processes targeted by that category

$$P_c(f_{ai}, \vec{\Omega}) = \sum_p T_{c,p}(\vec{\Omega}) + \sum_{i,j} \mu_p \left(a_i a_j T^{ij}_{c,p}(\vec{\Omega}) \right) + \sum_{i,j,k,l} \mu_p \left(a_i a_j a_k a_l T^{ijkl}_{c,p}(\vec{\Omega}) \right)$$

- For HVV: $a_i = a_1, a_2, a_3, \frac{1}{\Lambda_1^2}, \frac{1}{\left(\Lambda_1^{Z\gamma}\right)^2}$ (15, 70 terms to parameterize!)
- For Hff: $a_i = \kappa_f, \tilde{\kappa}_f$

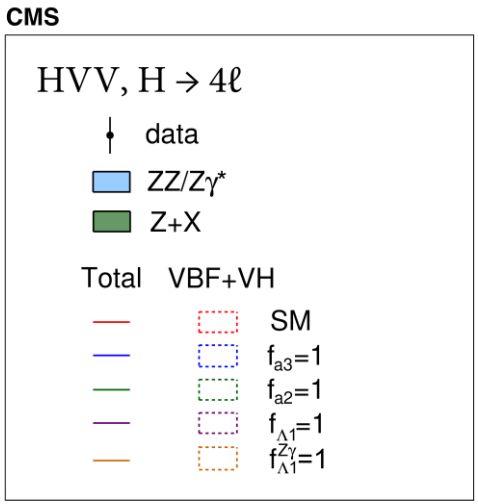
Categories and discriminants

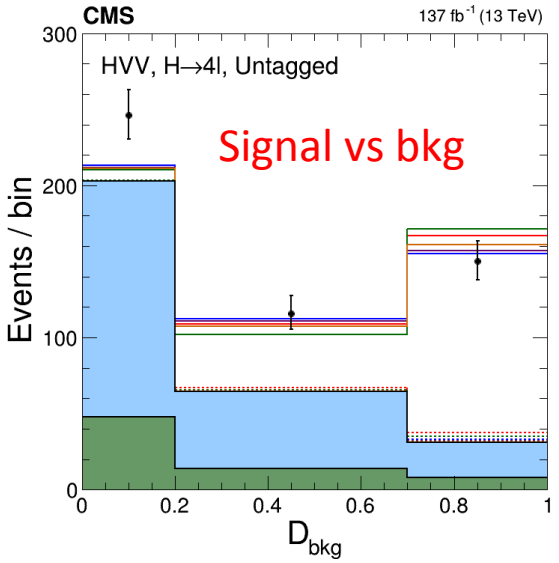
- In principle, want to distinguish all of the components (background, SM and anomalous signal for various processes, various interferences)
- In practice, divide into categories to isolate processes, then use discriminants within each category to separate hypotheses

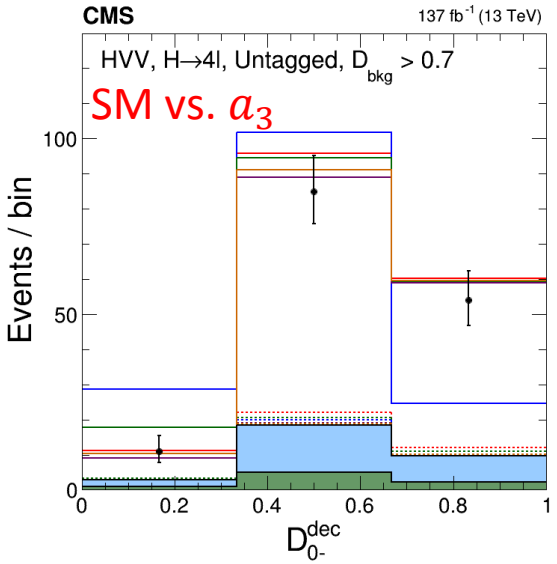
Category	HVV	Hff
VBF-2jet	Cut on discriminant to select VBF from ggH+jets Discriminants: MELA VBF+decay	Cut on discriminant to select VBF from ggH+jets Discriminants: MELA ggH+jets in VBF topology
VH-hadronic	Cut on discriminant to select VH from ggH+jets Discriminants: MELA VH+decay	Cut on discriminant to select VBF from ggH+jets Discriminants: MELA signal vs. bkg
VH-leptonic	Extra leptons Discriminants: pT and MELA signal vs. bkg	Extra leptons Discriminants: MELA signal vs. bkg
ttH-hadronic	N/A	Extra jets and b-jets Discriminants: MELA+BDT ttH kinematics
ttH-leptonic	N/A	Extra leptons, jets, and b-jets Discrimiannts: MELA+BDT ttH kinematics
VBF-1jet	Cut on discriminant to select VBF from ggH+jets, integrating over missing DOF Discriminants: pT and MELA signal vs. bkg	Cut on discriminant to select VBF from ggH+jets, integrating over missing DOF Discriminants: MELA signal vs. bkg
Boosted	High pT Discriminants: pT and MELA signal vs. bkg	N/A
Untagged	All other events Discriminants: MELA decay kinematics	All other events Discriminants: MELA signal vs. bkg

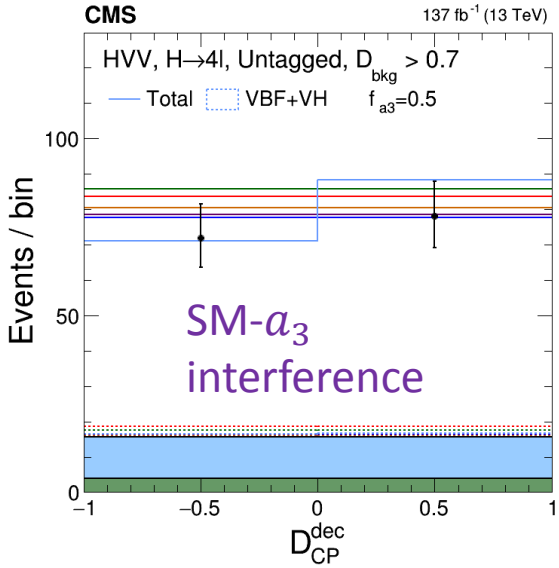
Discriminants – HVV untagged and boosted

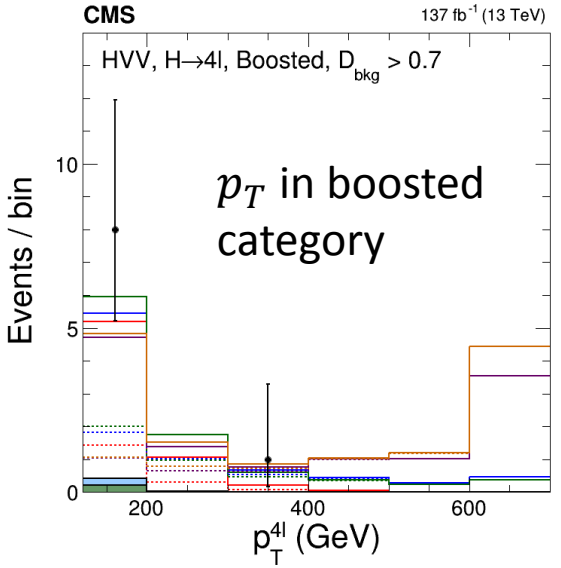
- Matrix element discriminants (via MELA) for two interfering processes:
  - $D_{alt} = \frac{p_{sig}}{p_{sig}+p_{alt}}$
  - $D_{int} = \frac{p_{int}}{2\sqrt{p_{sig}p_{alt}}}$
    - optimal to distinguish sig, alt, and their interference





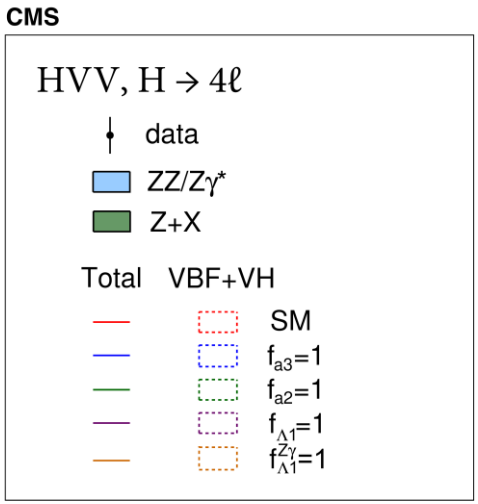


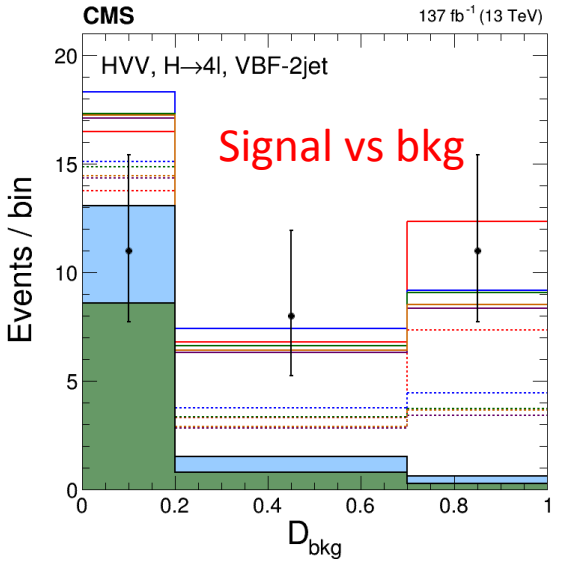


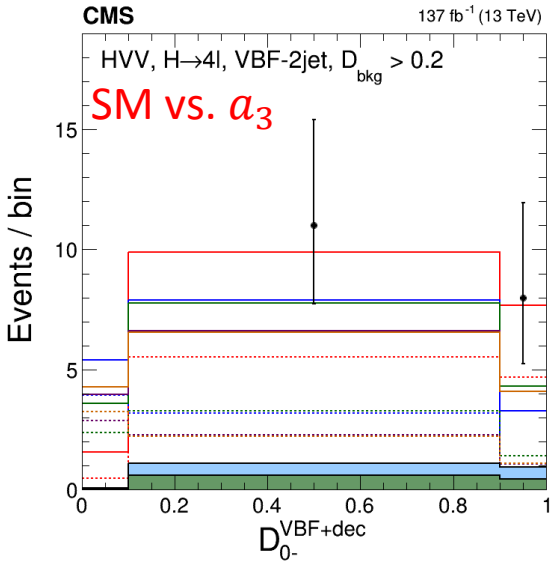


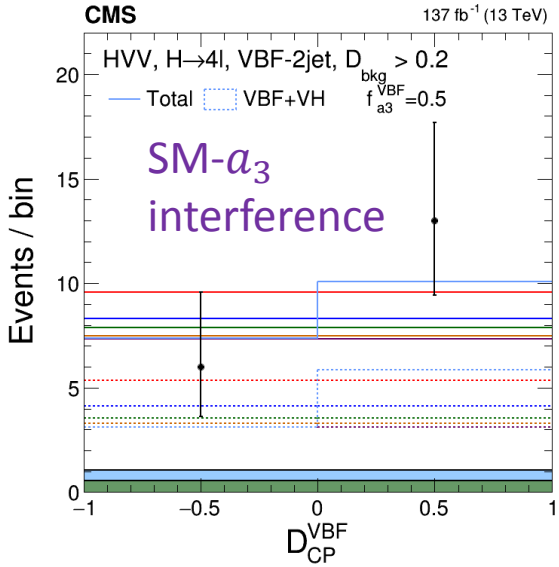
Discriminants – HVV VBF

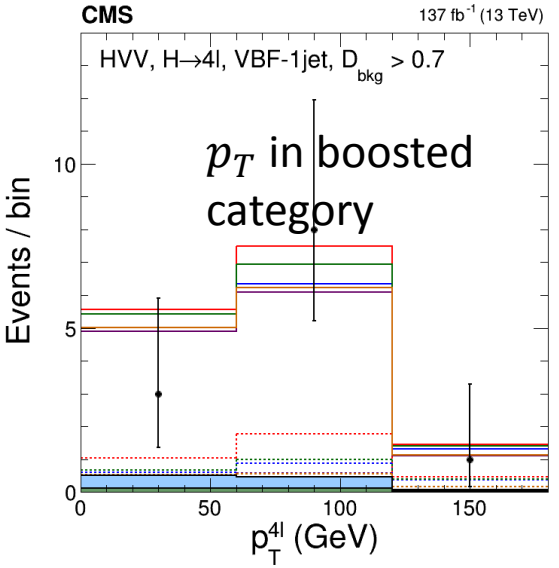
- Matrix element discriminants (via MELA) for two interfering processes:
  - $D_{alt} = \frac{p_{sig}}{p_{sig}+p_{alt}}$
  - $D_{int} = \frac{p_{int}}{2\sqrt{p_{sig}p_{alt}}}$
    - optimal to distinguish sig, alt, and their interference



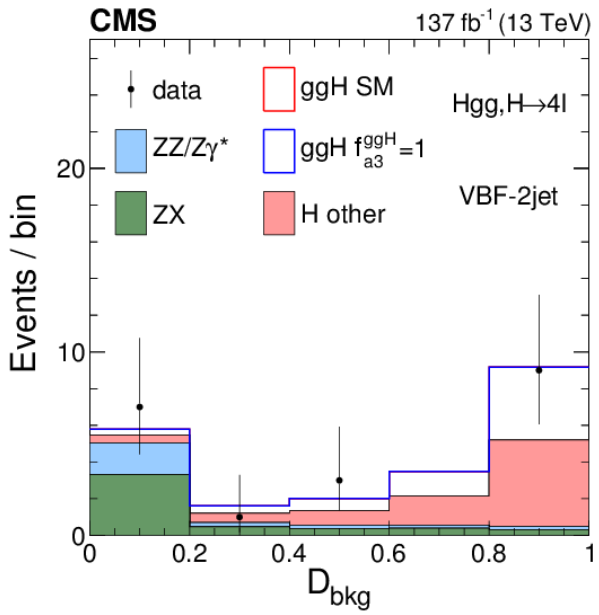


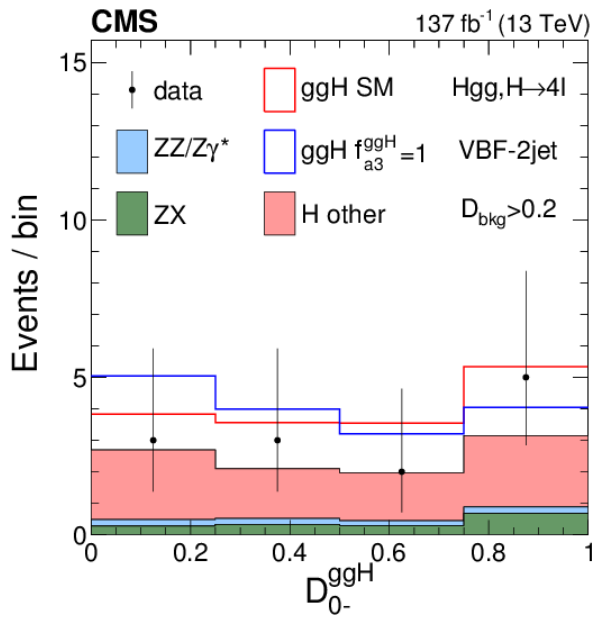


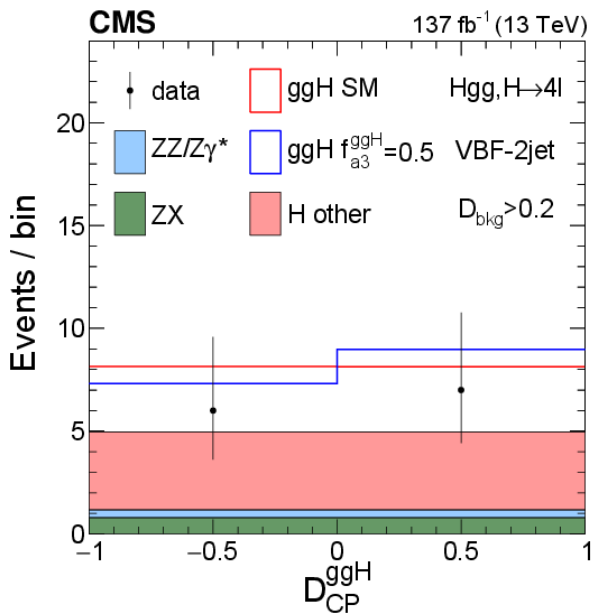


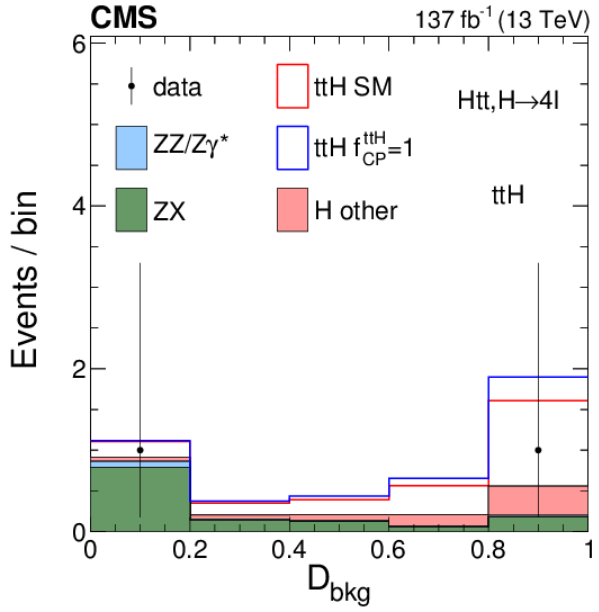


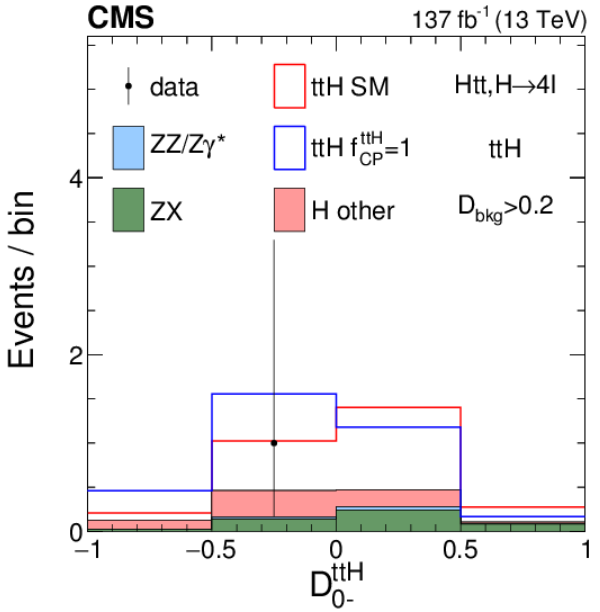
Discriminants - Hff









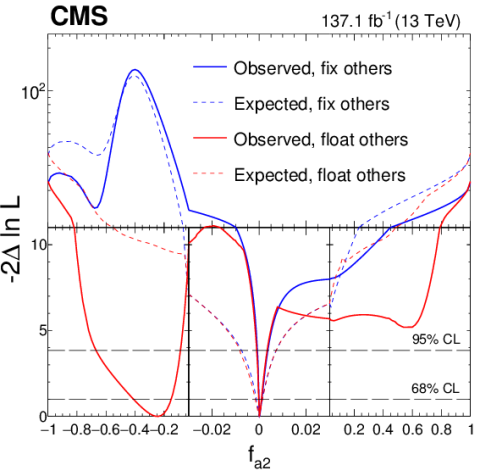


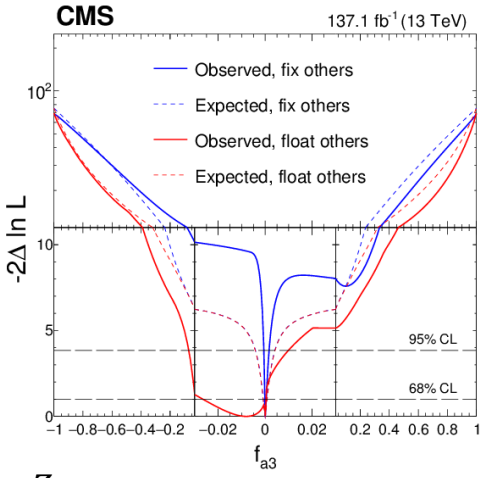
- ggH: ME discriminants just like in HVV, use qq->qq
- ttH: complicated topology, use machine learning discriminant trained by ME generated samples

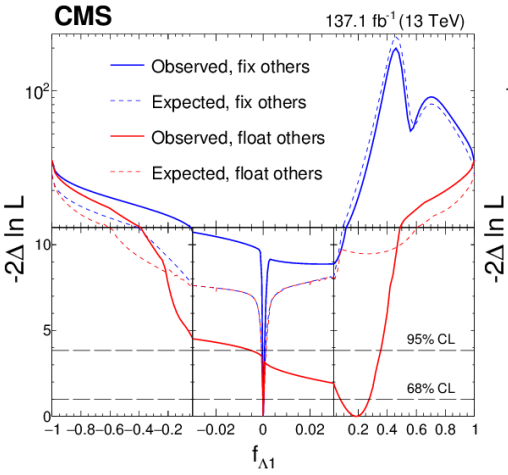
Results - HVV

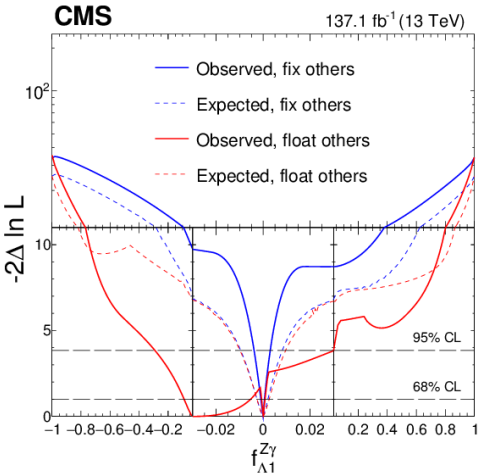
Many more plots in the paper!

- Floating other couplings has small effect on expected narrow minimum, larger effect on outer part
- Observed: VBF minimizes at 0, but decay minimizes at (0.01, -0.30, 0.12, -0.05)

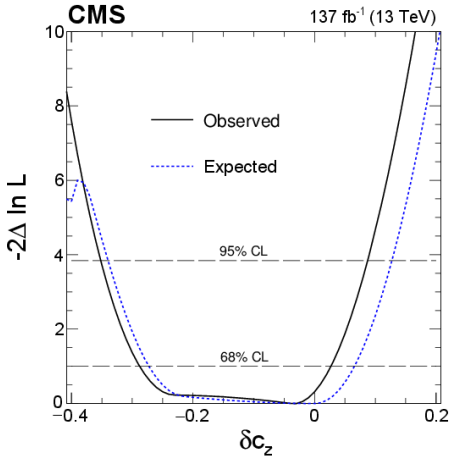


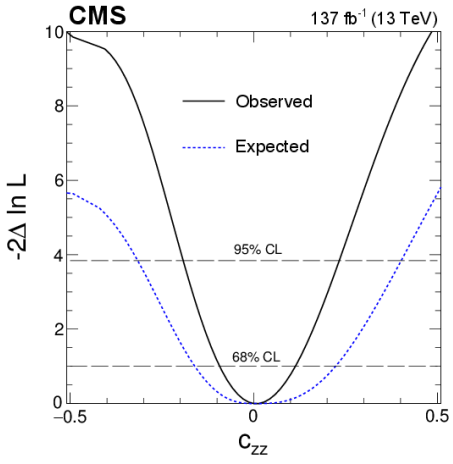


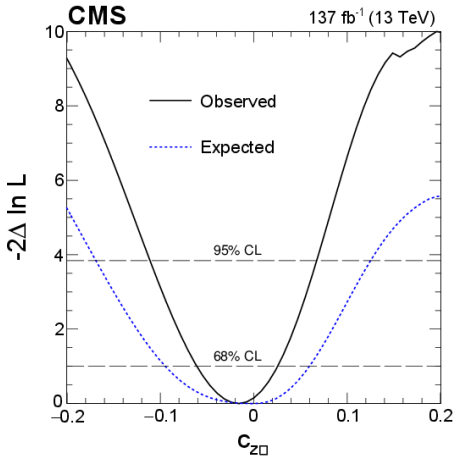


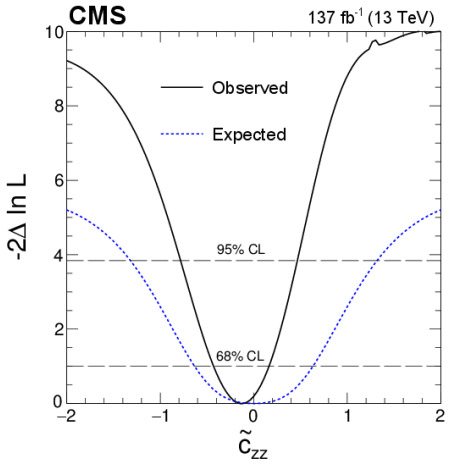


- SMEFT framework: $f_{\Lambda 1}^{Z\gamma}$ is a function of the other couplings
- Constraints on EFT couplings





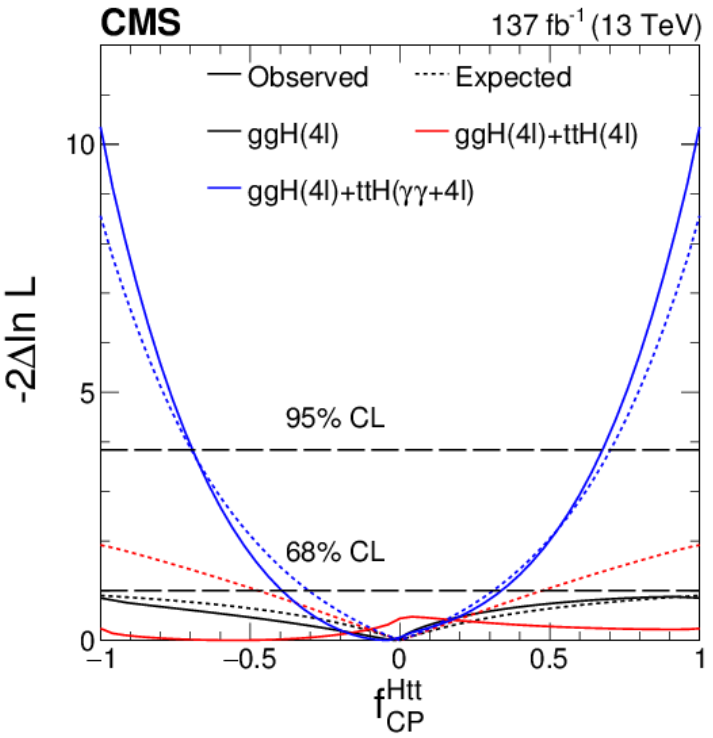




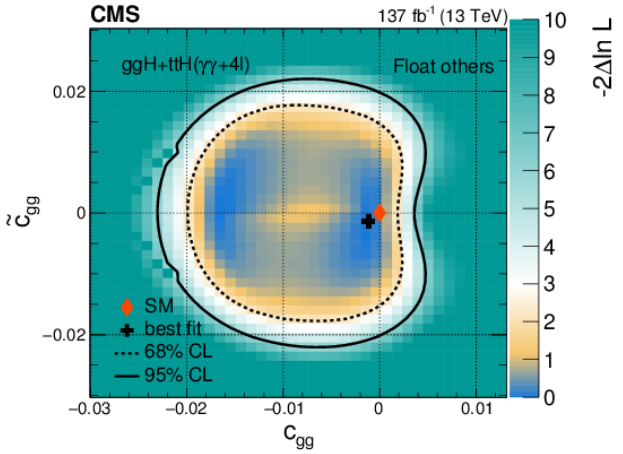
Results - Hff

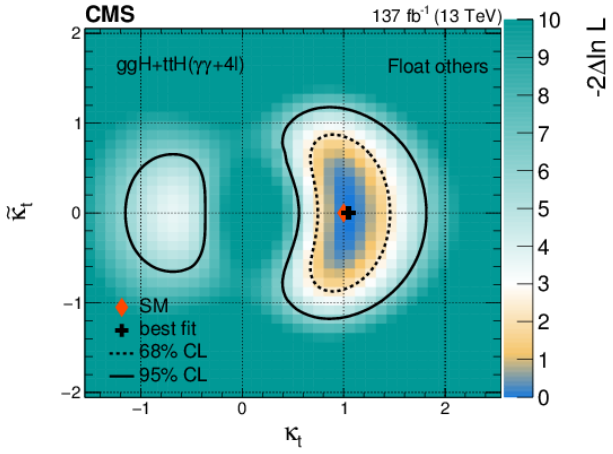
- Relate ggH to ttH couplings (assumptions about gluon loop), combine with $H \rightarrow \gamma\gamma$

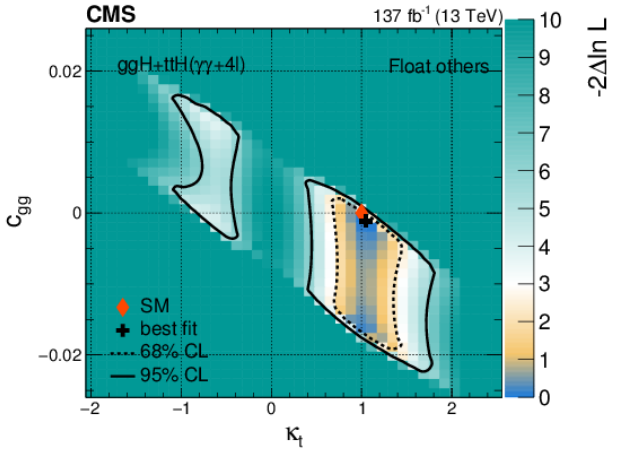
Many more plots in the paper!



- Allow gluon and top couplings to float separately







Summary

- Search for anomalous HVV and Hff couplings in $H \to 4\ell$ with the full Run 2 dataset
- HVV: first simultaneous constraint on 4 anomalous couplings
  - Production and decay minimize in different places
  - Different results from different q^2 ranges worth further study
- Hff: combine with $H \to \gamma\gamma$
  - First combined analysis in ggH and ttH
- Interpret as constraints on EFT parameters, under assumptions on the Higgs boson's width