MELA techniques for EFT measurements

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A simplified picture of experimental analyses

Physics interest
(Discovering BSM physics, measuring particle properties...)

Selection of final state
(Leptons, jets, MET, heavy-flavor objects...)

Detector, trigger, reco.

Background estimation:
(QCD, non-prompt leptons, conversions, instrumental MET etc., often est. data-driven for good reasons)

Sensitive and feasible observables:
- Obtain p_T, ϕ (and η, m) of lower-level physics objects from event reconstruction
- Compute angular and q^2 higher-level observables whenever possible
- Condense the information using MELA and ML techniques

Results could be provided in the form of
- Folded (or unfolded) distributions of observables
- Efficiency/resolution of relevant quantities
- Interpretation of the observation for BSM/EFT/properties

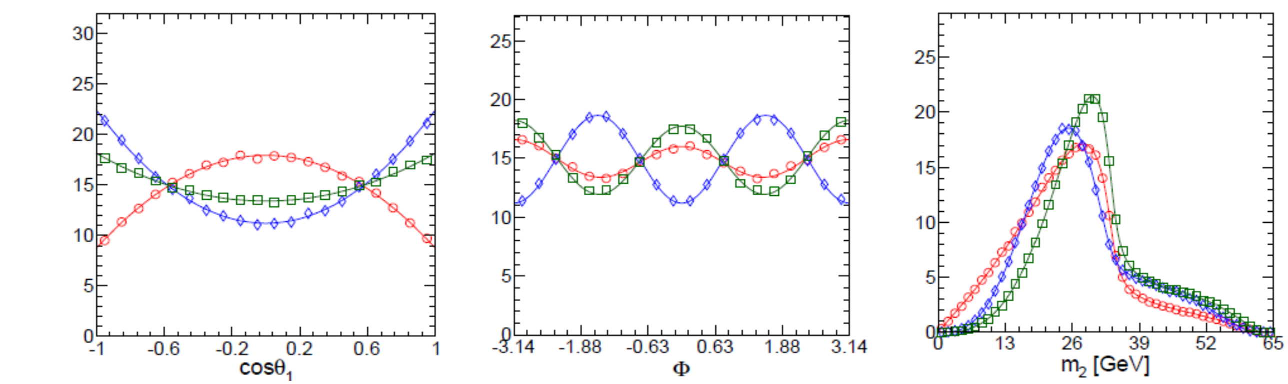
Higher-level observables in EFT measurements

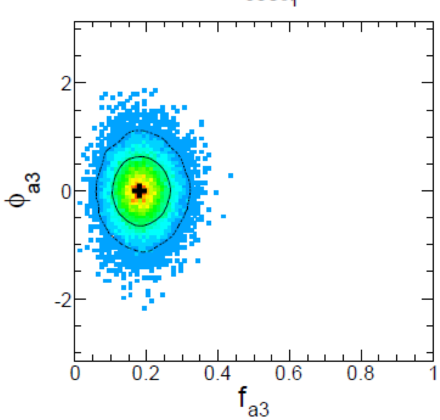
→ Best to use the full set of angular correlations and q^2 observables to measure EFT effects whenever possible:

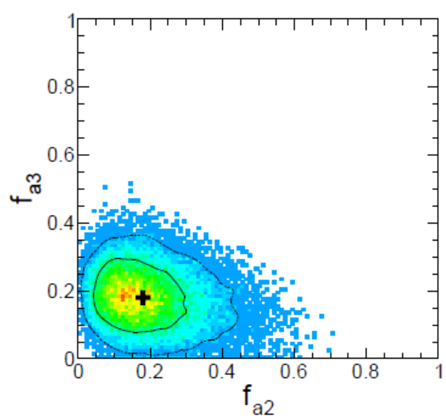
→ Contains the full multi-dimensional information on the kinematics without any dependence on what BSM operators are interesting.

→ EFT effects observable in both decay and production of the final state.

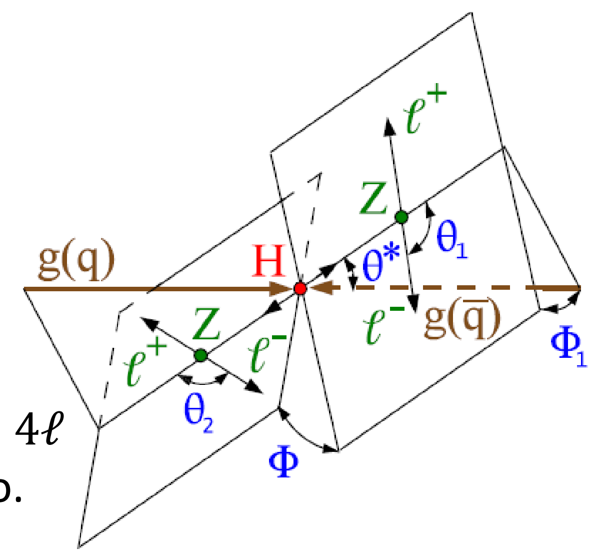
→ Fits can be done based on analytic formulae with detector effects included, or templates from events after full detector simulation if n_{dof} is small enough







Examples from $H \to 4\ell$
See [1] for more info.



Constructing a Matrix Element Likelihood Analysis

→ One can compute the probabilities of the SM and alternative BSM hypothesis, or their amplitude-level mixture to condense the multi-dimensional kinematic information, and extract templates of these distributions from full detector simulation (x number of systematics).

→ The Neyman-Pearson lemma states that the likelihood ratio test is the most powerful test among all statistics. On a per-event basis, the following discriminants constitute likelihood ratios that can be used directly as observables in the analysis:

$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})} \qquad \mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) \times \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}}$$

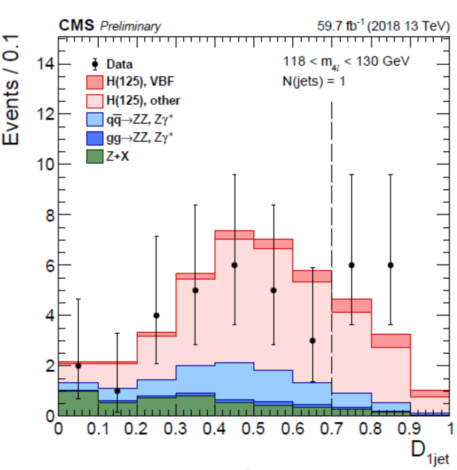
→ The D_{alt}-type discriminants are sensitive to contributions scaling with $|g_{BSM}|^2$, so they are useful in more statistics-limited analyses.
→ Can also be used to distinguish the signal hypotheses from backgrounds.

→ D_{int}-type interference discriminants are sensitive to contributions scaling with g_{BSM} itself, along with its sign, and their importance becomes dominant at high luminosity.
→ Higher-order terms in g_{BSM} in the EFT amplitude are also understood less and likely suppressed, and this construct avoids these problems by construction.
→ This type of discriminant could be for any interference components, so can also be used to measure signal – background interference, not limited to just EFTs.

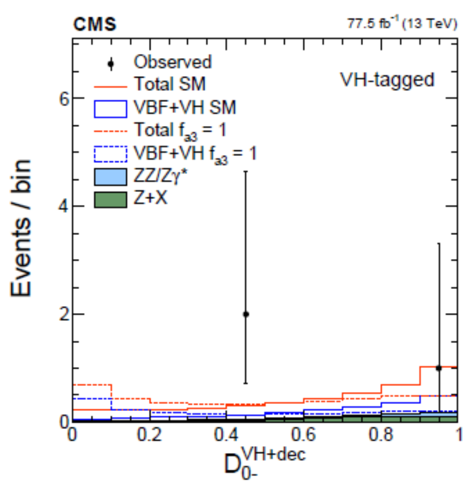
Calculation of the probabilities

→ The probabilities P_i can be calculated using either helicity amplitudes and spherical harmonics for simple amplitudes, or matrix elements directly from the generators (JHUGen, MCFM, MadGraph) for more complicated interactions:
→ Can also integrate missing degrees of freedom where sensitivity is expected
→ For clean detector objects, smearing and correction terms could be introduced to model detector effects and acceptance if there is significant gain (e.g., m_{4l} resolution in Higgs analyses, m_{jj} with certain assumptions)
→ The construction of likelihoods should nevertheless take into account the uncertainties on these physics objects, treating the computation of P_i as a black box.

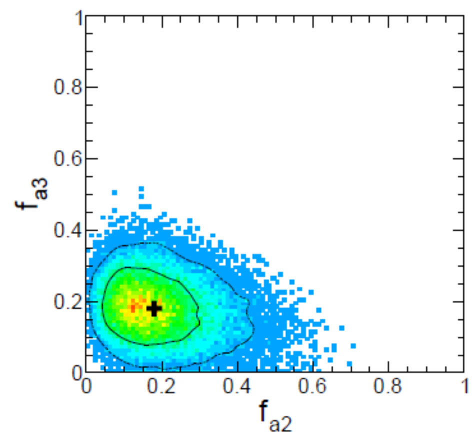
→ The performance from constructing dedicated discriminants is very similar to using the full information.

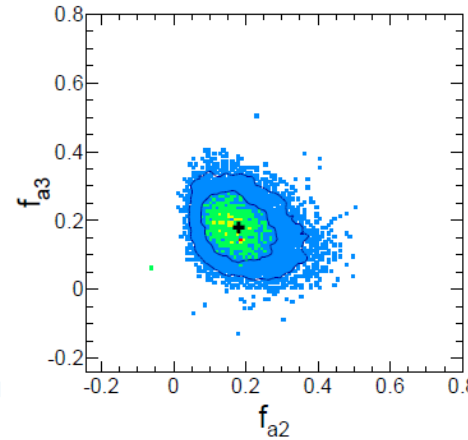


D_{1jet} for VBF [1, 2]



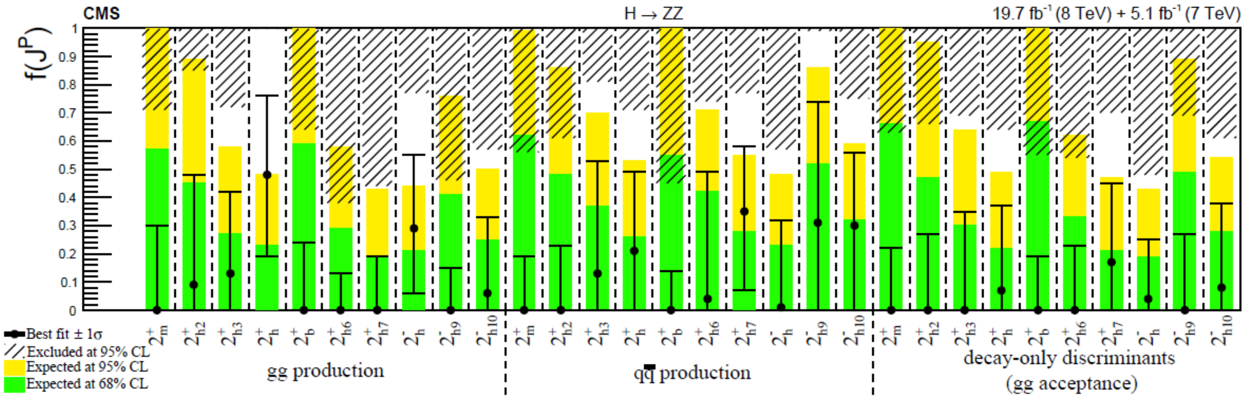
D^{VH} with m_{jj} res. corr. [3]



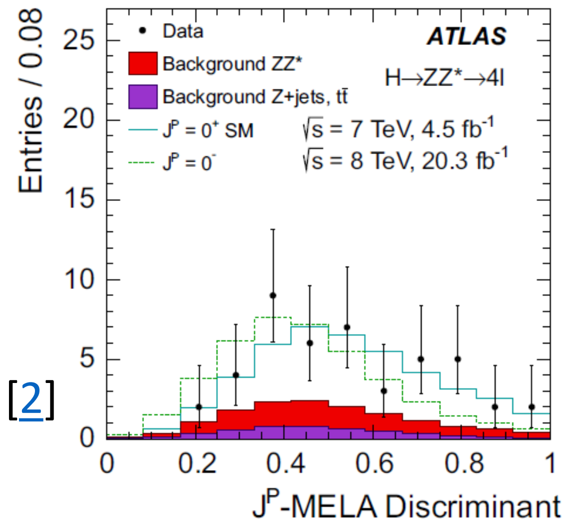


Full 7D vs 3D with MELA KDs [4]

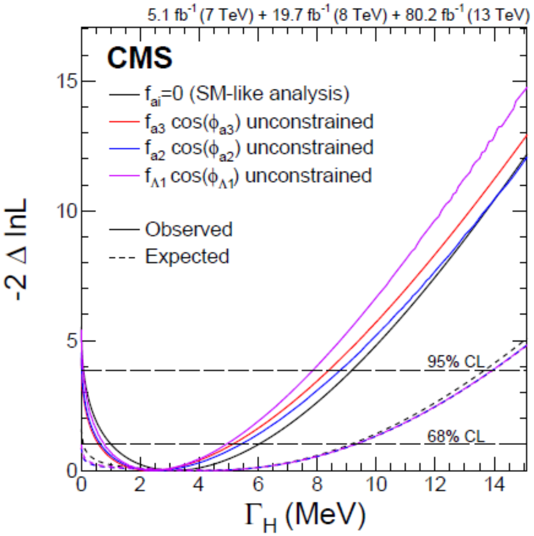
More examples of uses of MELA in analyses



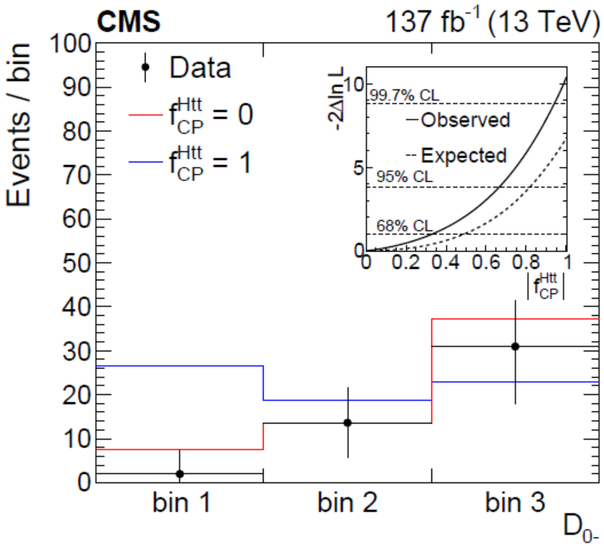
[1]



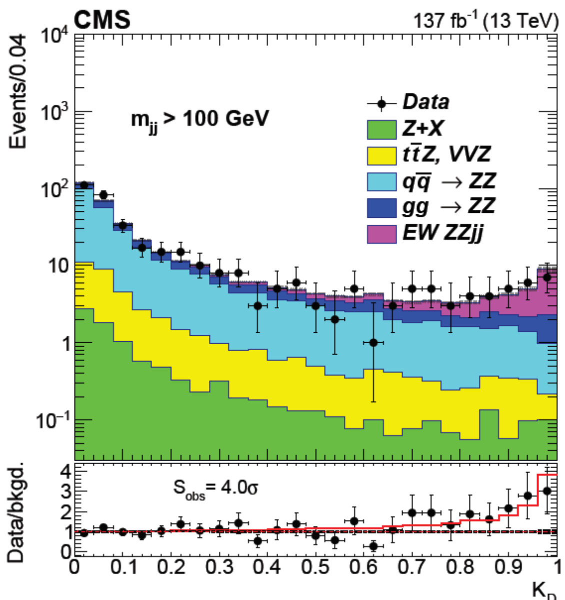
[2]



[3]

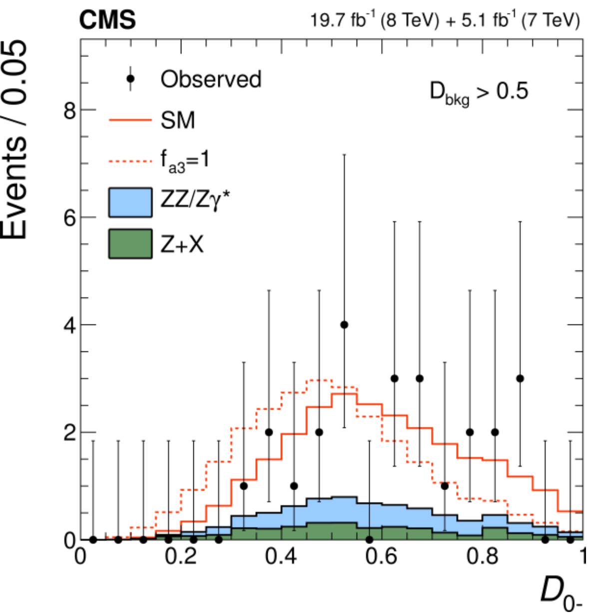


[4]

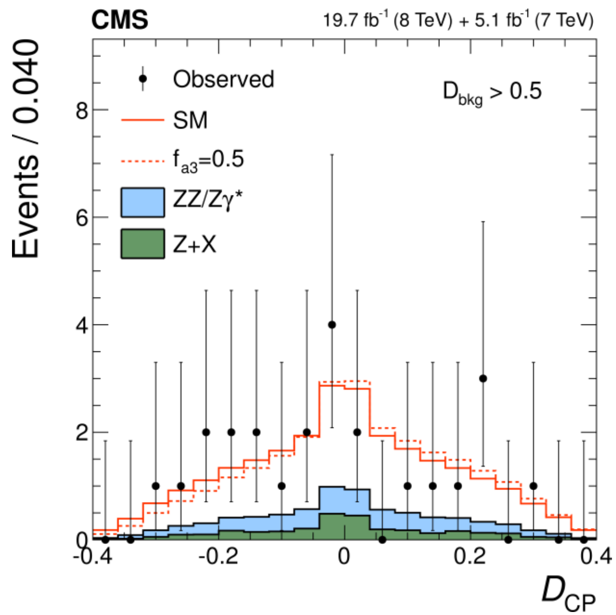


[5]

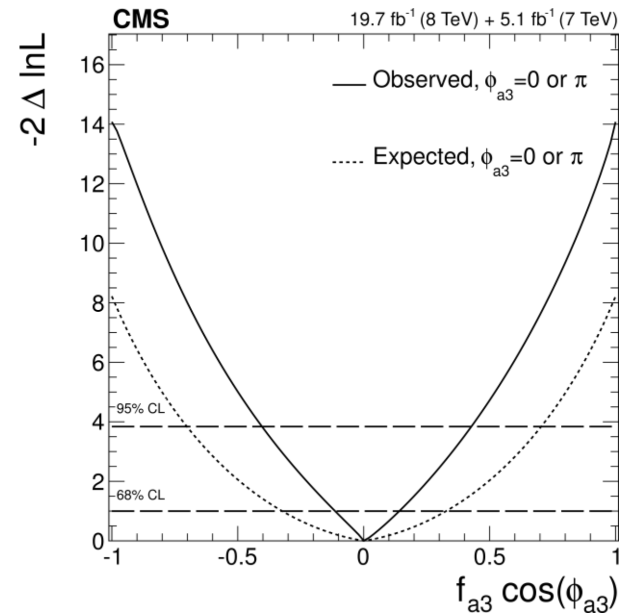
Expanding examples in Higgs measurements: CPV in $H \rightarrow 4\ell$



D_{alt}



D_{int}



Constraint in the form of fractional cross section contribution, f_{a3}

→ Plots are taken from the CMS Run 1 spin-parity analysis [1]:

→ Statistics-limited, so measurement is dominated by the sensitivity of D_{0-}.

→ Constraint can be presented in the form of a fractional contribution, or couplings/coupling ratios themselves (depending on what are the POIs of the likelihood)

How to do a BSM analysis using Higgs production information

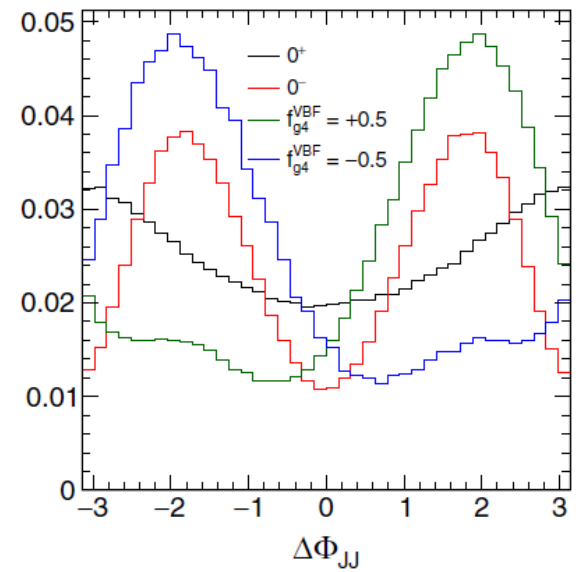
→ One could examine a simple collection of observables (signed $\Delta\phi_{JJ}$ in this example)

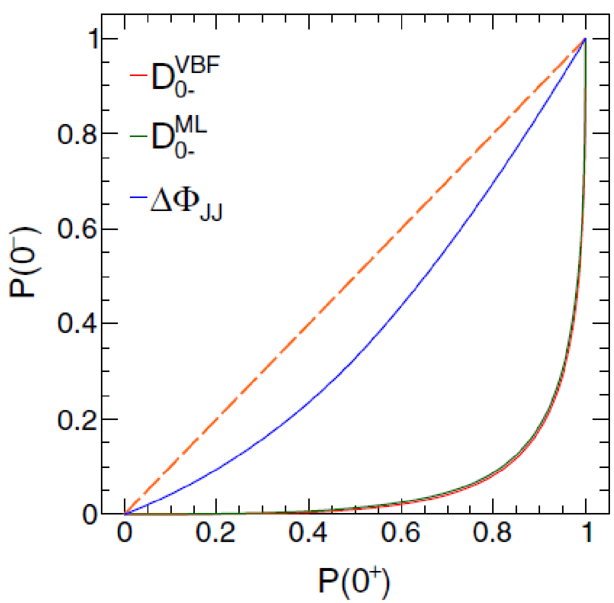
→ For optimal analysis, can construct MELA discriminants, but for the VBF production instead, using the information from the Higgs + 2 jets (or for QCD H+2 jets for quark-initial states) if analyzing CP in gluon fusion).

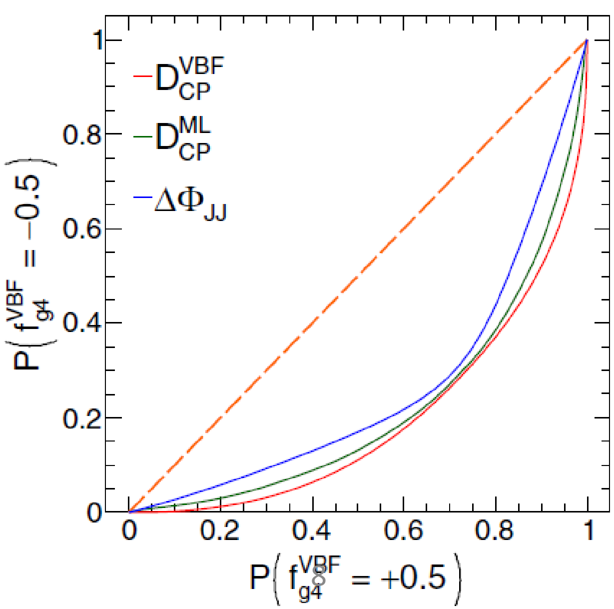
→ Multivariate techniques can be constructed when full information is not available:

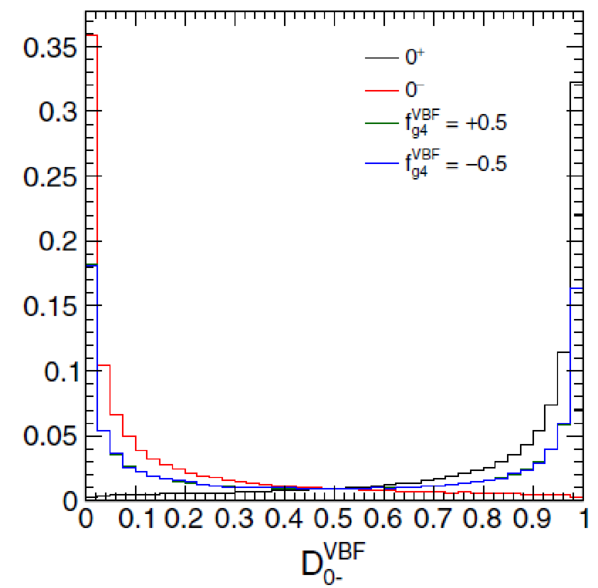
→ Training something in place of D_{alt} is straightforward, pure SM vs pure BSM

→ Training in place of D_{int} should be done with equal mixtures of $(g_{SM}, g_{BSM}) = (+,+)$ vs $(+,-)$

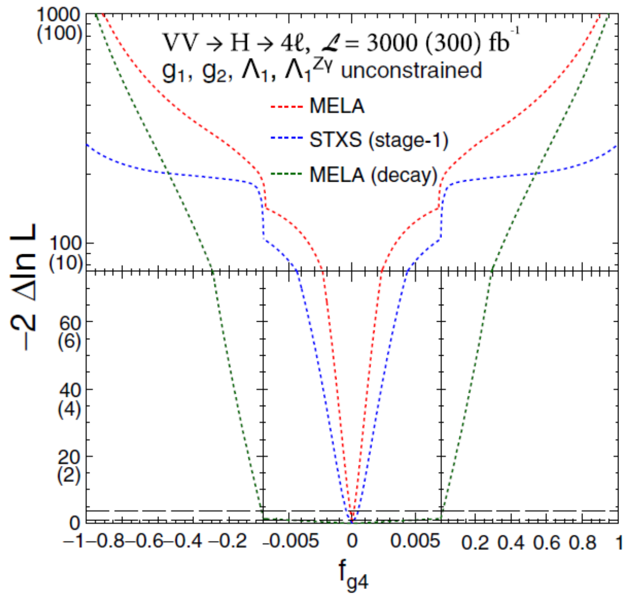


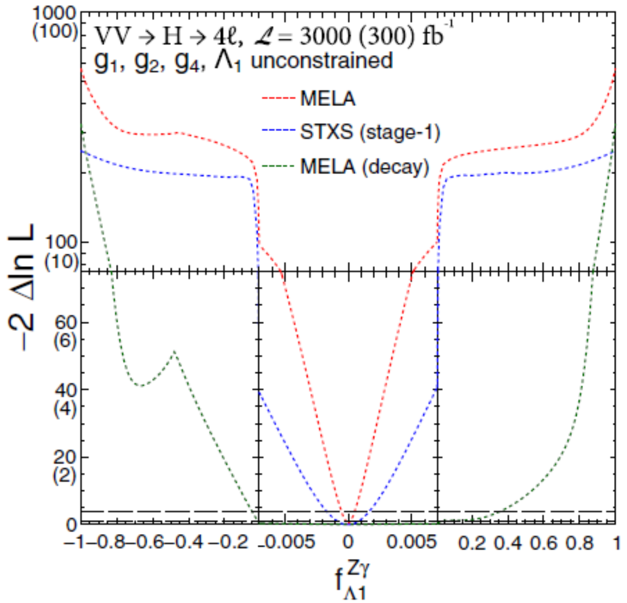






HVV coupling constraints from 4ℓ using production and decay together





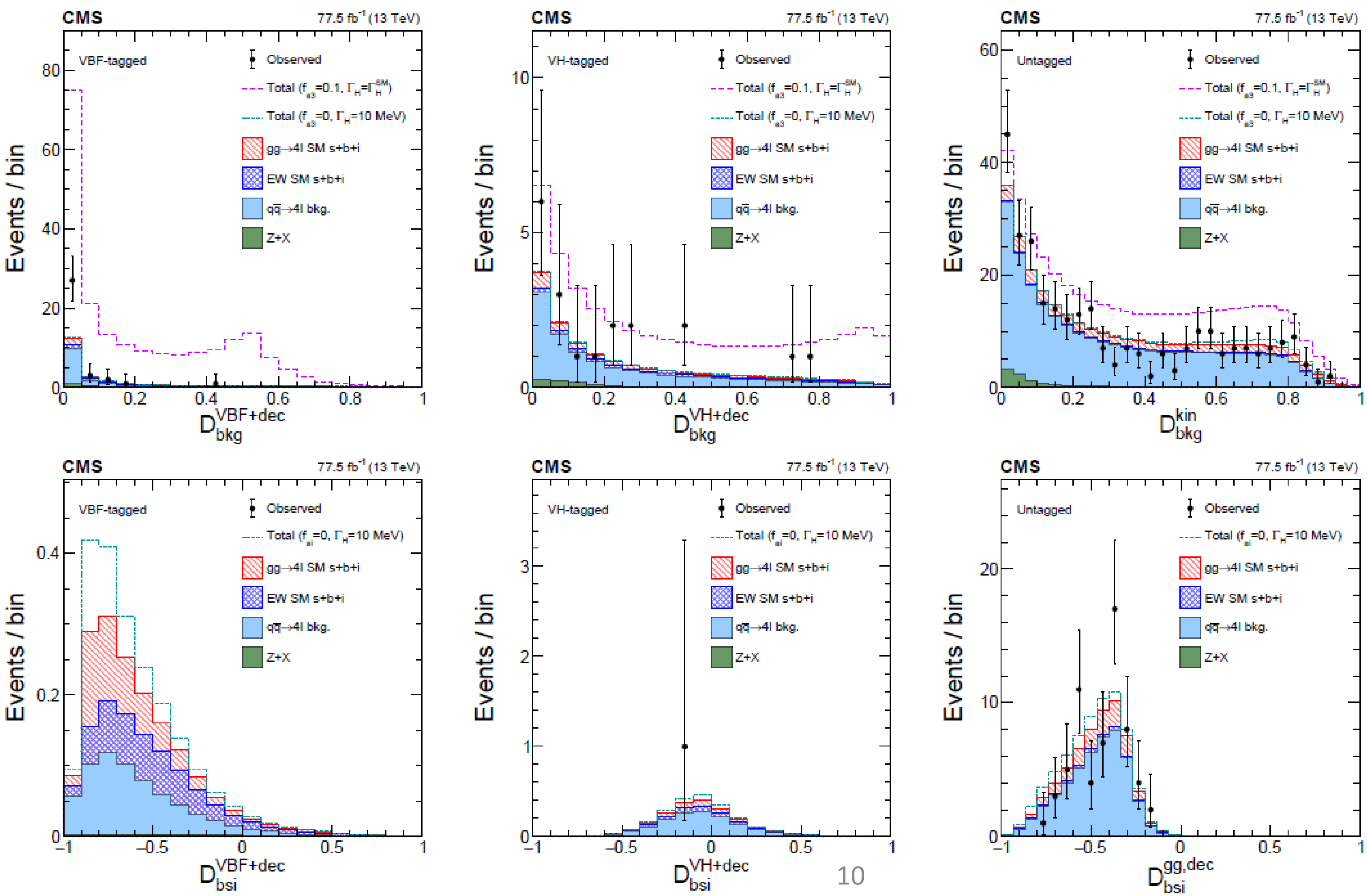
→ Different interference components can be obtained via dedicated simulation or reweighting existing simulated events

→ Comparison of constraints at 300 and 3000 fb^{-1} made using
a) full set of MELA discriminants D_{alt} and D_{int} with production and decay information combined optimally to use the 13 degrees of freedom
b) set of MELA discriminants D_{alt} and D_{int} with decay information only
c) Binning of observables following the STXS 1.1 binning

→ Analysis with a MELA-based binning in 4ℓ with production and decay information combined can be more sensitive to couplings than a decay-only analysis or STXS 1.1 binning

Extending to off-shell studies

→ This extension was investigated in the CMS off-shell width-anomalous couplings analysis [1], where discriminants sensitive to signal – background interference were also used in addition to increase sensitivity to the destructive interference:



D_{bkg} (D_{alt})

D_{bsi} (D_{int})

Summary

→ Explored methods to use matrix elements in analyses
→ Best to use full kinematic information as observables
→ If likelihood ratios can be constructed, they would be optimal observables when interpreting the data in terms the examined BSM contributions
→ Possible to split MELA discriminants into two classes:
D_{alt}: Sensitive to pure SM and pure BSM contributions (second-order in g_{BSM}); signal vs background
D_{int}: Sensitive to interference effects (leading-order in g_{BSM}, signal-bkg. interference)
→ Acceptance, efficiency and resolution could be folded into the observables where significant gain is expected. Integration for missing degrees of freedom are also possible.

→ Explored example analysis elements
→ MELA can be used for both production and decay of resonances
→ Possible to use MELA for continuum contributions (backgrounds, off-shell etc.)
→ When full kinematic information is not available, it is also possible to construct discriminants similar to D_{alt} and D_{int} using ML approaches:
→ Training something in place of D_{alt} is straightforward using pure SM vs pure BSM
→ Training in place of D_{int} should be done with equal mixtures of $(g_{SM}, g_{BSM}) = (+,+)$ vs $(+,-)$

Thank you!

Available MELA packages from JHUGen

→ JHUGenMELA: Matrix element library with an object-oriented C++/Python interface and related numerical convenience tools for analysis, usable for
 → Constructing discriminants for the analysis of couplings and background suppression
 → Reweighting of existing simulation via ratios of $|M|^2$.
 → Includes interface to MCFM/JHUGen matrix elements for background, or signal-background interference computations
 → More details on tool availability and versions: https://spin.pha.jhu.edu
 → References:

Phys.Rev. D81 (2010) 075022, arXiv:1001.3396
Phys.Rev. D86 (2012) 095031, arXiv:1208.4018
Phys.Rev. D89 (2014) 035007, arXiv:1309.4819
Phys.Rev. D94 (2016) 055023, arXiv:1606.03107
Phys.Rev. D102 (2020) 056022, arXiv:2002.09888

→ MelaAnalytics: Package to automate and standardize the computation of large numbers of matrix elements
 → Features event interpretation and approximation tools for NLO VBF/VH topology cases
 → Please contact the author for the most up-to-date distribution.