ATLAS-CMS discussions on HH event generation

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On behalf of the CMS collaborations
06 Feb 2019

I try to follow the outline asked on the email and describe what CMS is using / have available

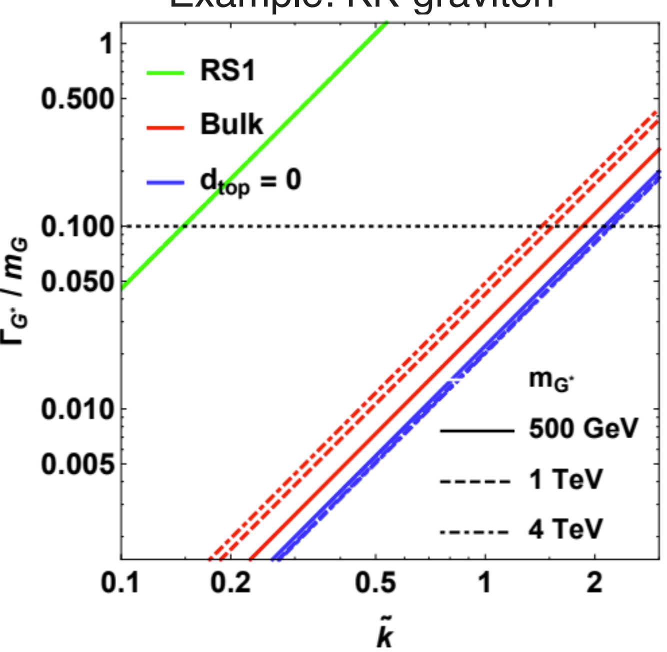
(i) resonant X -> HH - ggF and VBF

aMC@NLO at LO mode for both spin-0 and spin-2 particles, the Lagrangians are revised here and the UFO model is here

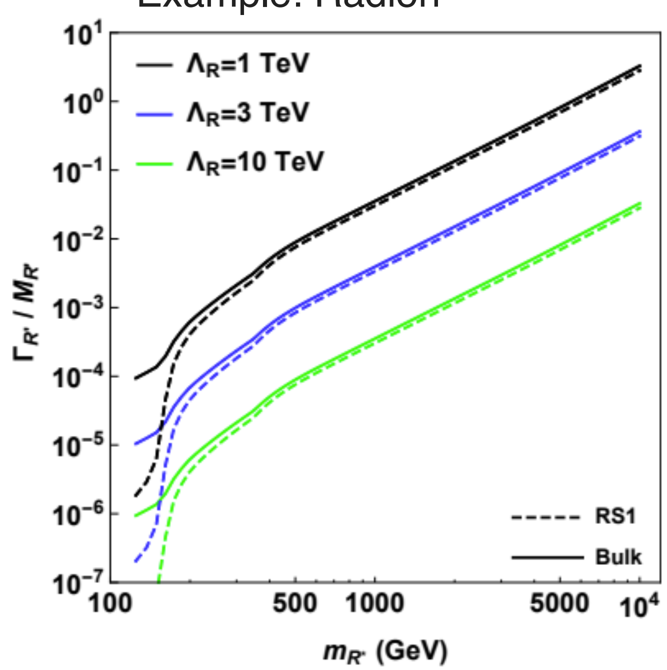
- If the parameter space of the model one will consider is such that the **resonance is narrow** (most of the cases)
  - Spin 0 - can be interpreted as narrow heavy Higgs (2HDM/SUSY) AND Radion
  - Spin-2 - can be interpreted as a bulk KK-graviton (less model independent case than the spin-0)

- To any model there is a part of the parameter space that the **resonance is not expected to be narrow**
  - We have the possibility of scan the width of the resonance in the above mentioned model
    - We do not actually do that yet…
    - We could agree on a grid mass X width grid to scan here

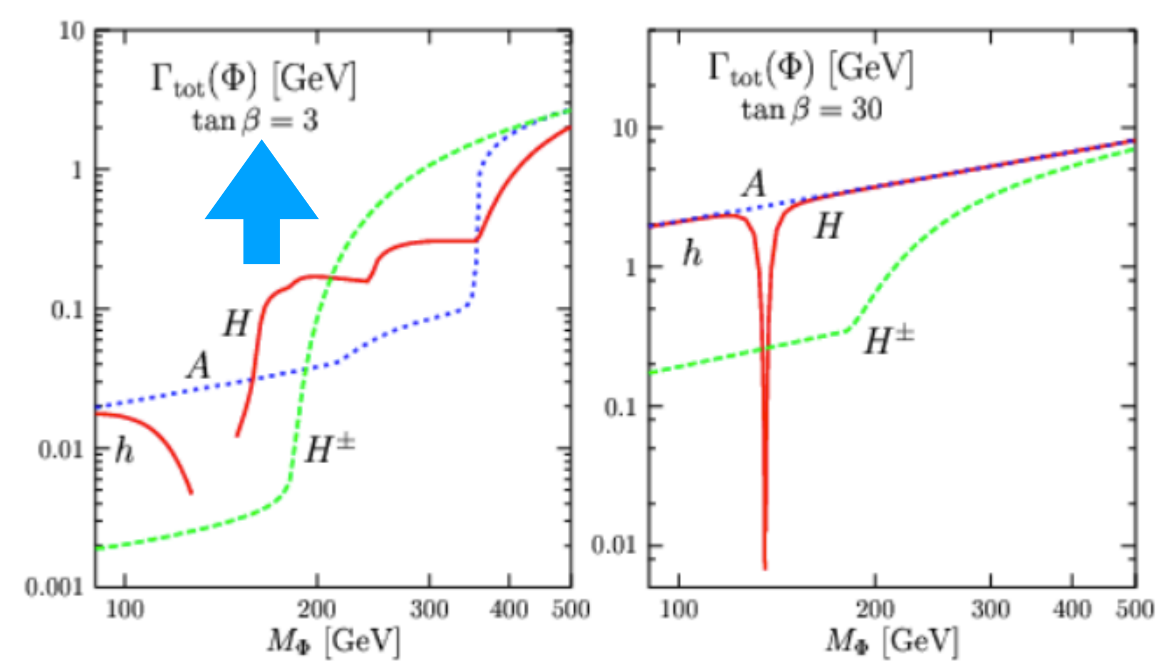
Example: KK-graviton



Example: Radion



Example: MSSM

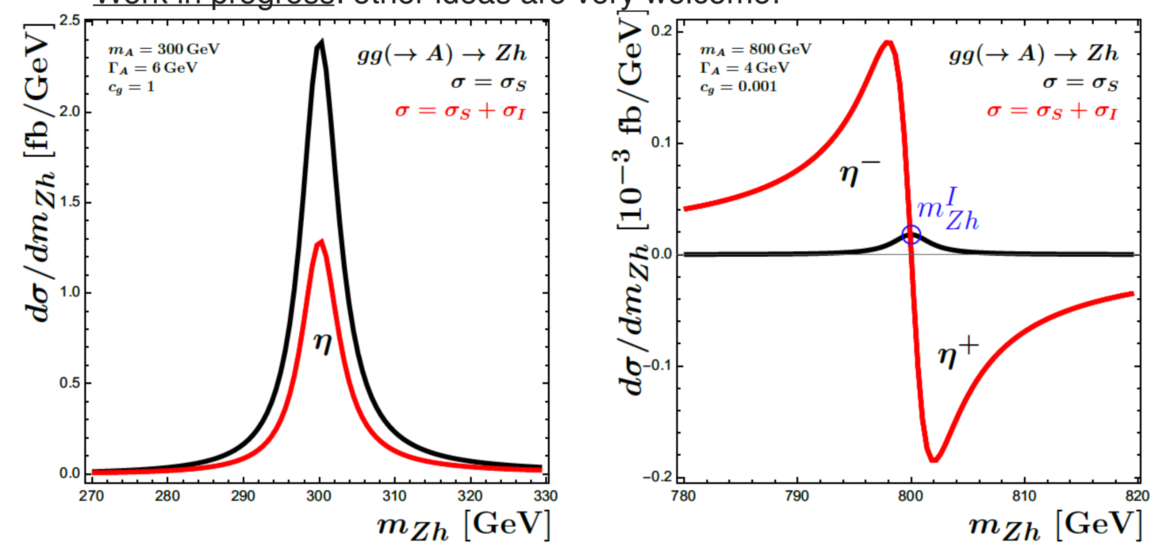


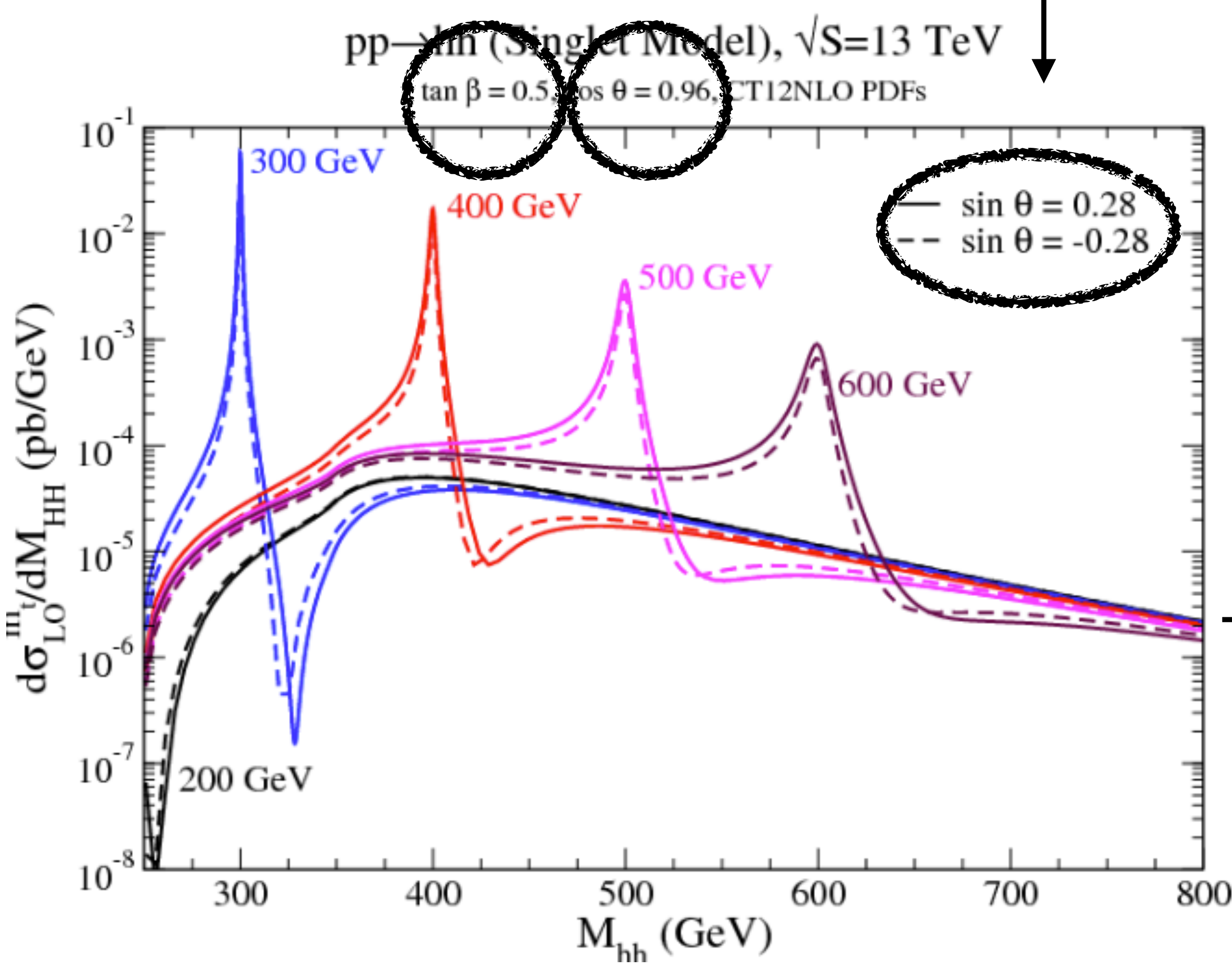
(i) resonant X -> HH - ggF and VBF

- To models of a spin-0 resonance there may be a part of the parameter space (low enough cross section) that the resonance is not expected to **interfere with the non-resonant SM HH production** and produce a weird HH line shape
- We have models easily (aMC@NLO), but we do not have yet not the best way to scan the line shape
  - It would be to nice to devise a minimal set of physical parameters (mass X width X ???)
  - To scan parameters in even one concrete models proves to be difficult task
    - The line shape is extremely model dependent
    - We could anyhow for the time being chose a simplified model that allows for interference (eg singlet model of these authors, also in UFO) and have an first access of the impact of changes on resonance line shape in final limits

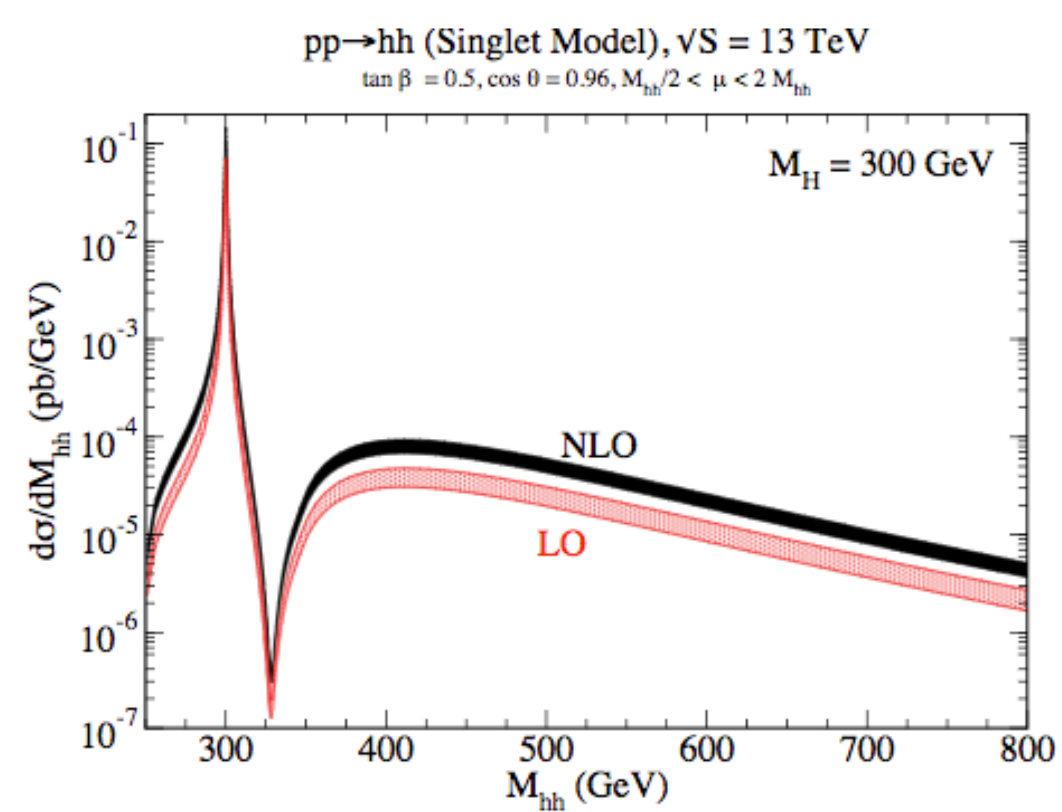
Example done in X -> ZhH but the principle is the same to HH

Work in progress: other ideas are very welcome!





There is also the NLO version



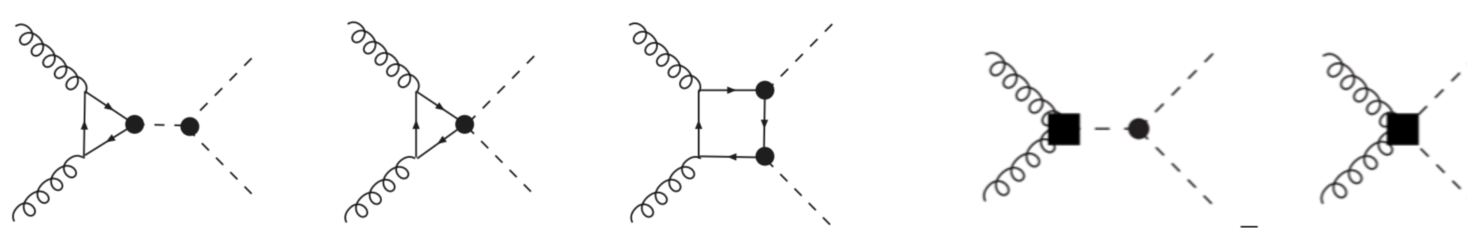
(i) resonant X -> HS and SS

- We did not systematically considered yet such analyses however the most probable is that we use aMC@NLO
  - For the SS case we can use the same as we use fo HH (just changing the “H” mass)
  - For the SH model, in 4b we are investigating X -> YH production with a NMSSM model that experts (Abideh Jafari and Yiming Zhong) privately suggested this model,
    - fully configurable masses and widths of both BSM resonances involved (mX, mY, gammaX, gammaY)
    - it's actually the same model that CMS uses to make H > aa searches, but modified by Zhong to add Higgs-like coupling of the heaviest scalars with the SM particles

non-resonant X HH - ggF

- **EFT ggF - aMC@NLO at LO mode**
  - ggF: privately provided by Eleni Vryonidou in 2014 (here)
    - Change in anomalous couplings -> violent signal shapes changes -> no need that we pass by that point here
    - Five anomalous couplings as described in any reference of non-linear EFT parametrization, see HXSWG.
      - No chromomagnetic operator on it - I asked more than once, the authors do not provide, so they cannot complain that we do not use it…
    - The non-linear parametrization can be mapped to any other parametrization of operators by linear combinations
      - As parametrization for the model the non-linear one is the most general UFO input we could ask for
      - We generate the shape benchmarks and deal with then to any possible interpretation afterwards (see next)

- **EFT ggF NLO + top mass effects**
  - We already have a private version of the Powheg that allows variate kl-kt - in process of being tested on CMSSW (Gundrum Heinrich et all)
    - The prevision is that we will also have a model where we can generate also the sharpe benchmarks (?)
      - I understood that it is difficult to have one that allows all EFT parameters to vary freely (to be confirmed)
  - There is no available model (to our knowledge) from aMC@NLO team that allows variate Higgs couplings



- **SM ggF:**
  - ggF: LO - results up to now - aMC@NLO at LO mode (the same that are respectively used for anomalous couplings)
  - ggF NLO + top mass effects
    - We have (almost) ready samples with Powheg (last available version)
    - We just received the model from aMC@NLO and we are currently integrating to CMSSW

non-resonant HH - ggF - BSM scans (technical)

	Reweighing event by event using representative matrix of events (e.g. the shape benchmarks) + analytical formulas	Treating the parts of the cross section as different samples to be combined (as ATLAS: see Xiaohu Sun presentation)
Use	**EFT (including kl-kt scans)**	**kl-kt scans only (5-6 parameters it would become cumbersome)**
Pros	All the generated event statistics has positive weights = Maximal use of MC stats	More intuitive for setting limits on parameters given the statistical tools available on experiments
Cons	To set limits on parameters themselves one must adapt the limit setting framework for doing limits from scans/shape morphings	Part of the generated MC statistics may have negative weights, according with the point some weights can be large.
How we need the MC	If we can generate samples/shape benchmark we are happy (or at least some anomalous points) - Check if this is possible in Powheg (NLO+top mass)	The best is if we will be able to generate the interference parts separately - It is possible in aMC@NLO in LO mode - Not possible in Powheg (NLO+top mass) (yet?)
	CMS analyses has been doing up to now	We do have this implemented and tested - As we did our MC/shape benchmarks, we first construct the three parts of the cross section with event by event reweighing and then apply the method

Both methods can be used @NLO + top mass effects

- Reweighing method:
  - mHH and cost*HH are very resilient against NLO corrections
  - we would need to calculate again the coefficients
  - for the NLO Powheg group already provided to 14 TeV in bins of mHH (NLO + top mass effects)
    - 13 TeV on the way

- Other request to the authors:

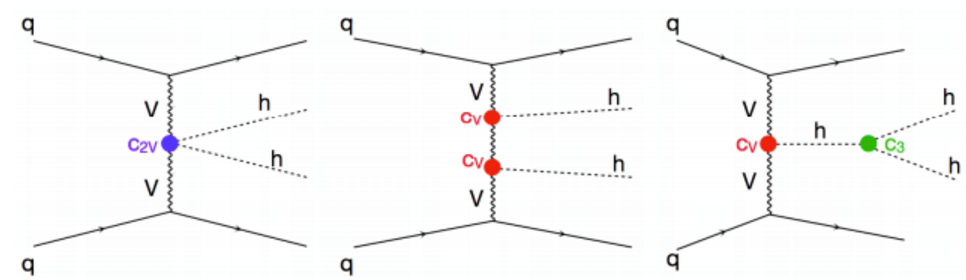
—> Have the coefficients up to higher mhh (~3 TeV?) - to take care of the boosted analyses - now it is up to mhh = 1 TeV

—> Make the coefficients to cover the 3D kinematics of the Higgs pair (do it mhh X cost*HH, now is only on mhh bins)

—> cost*hh is approximately flat, but after analysis selection it is not completely flat

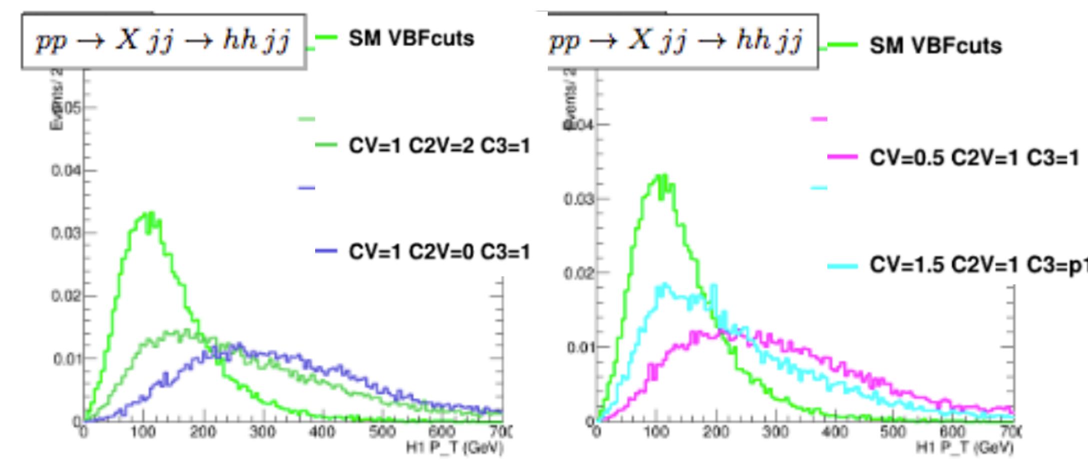
non-resonant X HH - VBF (EFT)

- There are three parameters (see HXSWG) - we use the model privately by R.Contino here, but many more equivalent UFO models for the same physics can be found here
    - We also have the model on the non-linear parameterization



Both SM and EFT are simulated with aMC@NLO in LO mode.

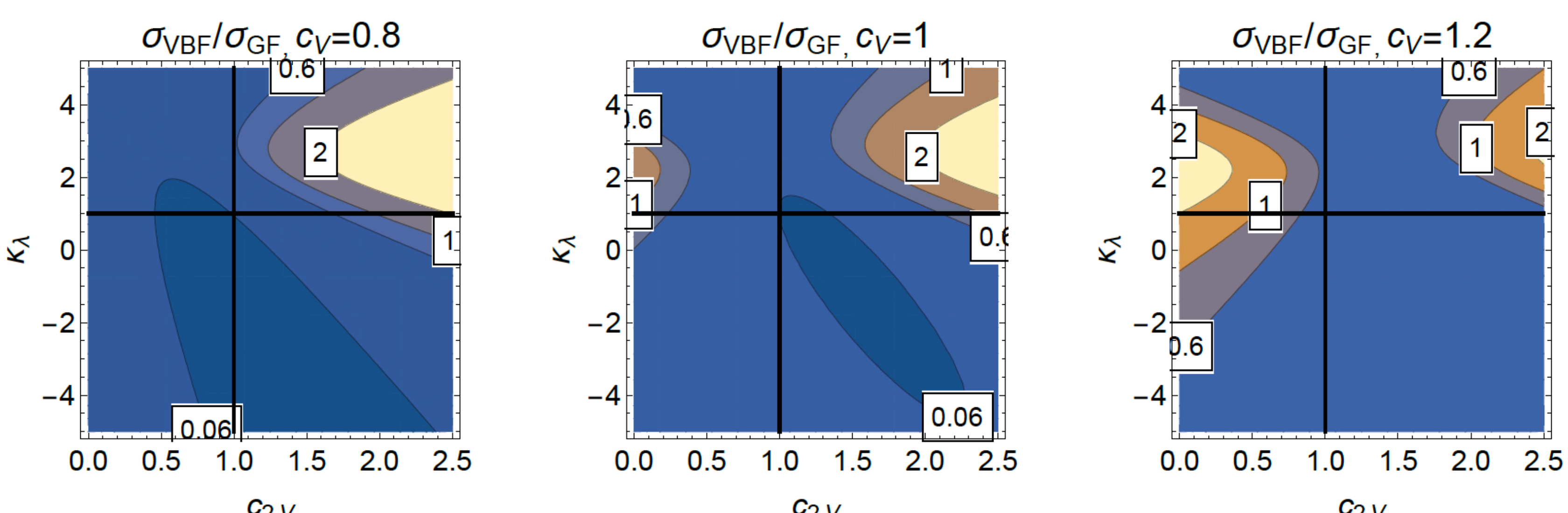
- There is no settled method of how practically scan the parameter space, so we chose 6 random points
    - cards with the parameters we generated can be found here
- Do we want a systematic shape benchmark definition here?
- Do we want analytical reweighing formulas?
- Do we want to agree on a set of points?



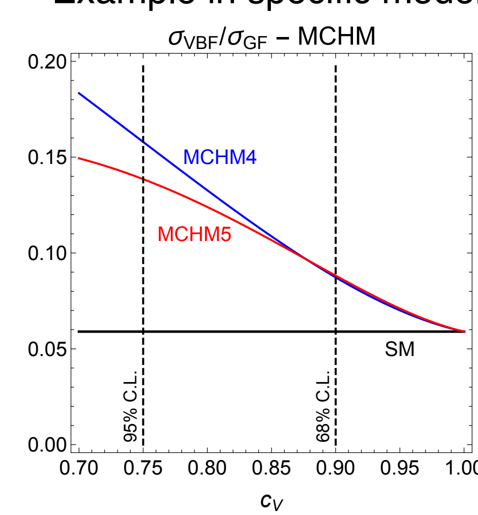
We do have the NLO QCD models to such process, but we know that QCD corrections to VBF are small…

- Need to devise a way to consider the process together with ggF EFT in some scenarios

The second largest production mode of HH is the VBF mode. Though in SM case, the VBF is non-significant compared to GGF but in BSM scenario, the VBF can become quite sizable with respect to GGF



Example in specific model



Work in progress! Anamika Aggarwal, Enrico Bertuzzo, A.C. and Florian Goertz

Parton shower for (i) resonant, (ii) non-resonant HH production;

- We use Pythia8 for all showering
  - To aMC@NLO at LO mode (both ggF and VBF) there is no secret
    - For completeness here there is one example
  - The NLO configs for completeness, here is one example

non-resonant HH - ggF - BSM scans (practical)
(Aka - Usage of EFT frameworks)

1) Shape benchmarks

- Shape benchmarks are designed to facilitate a possible discovery (if there is something to discover)
  - Deliver results (in absence of discovery) on its terms only inform us practical information (not EFT info!):
    - how much an analysis is affected by change of kinematics roughly
    - Which is the phase space it is more sensitive to
    - How channels/experiments compare in different phase space configurations

2) Specific scans and constraints on anomalous couplings / EFT coefficients

- We DO want to do those, but

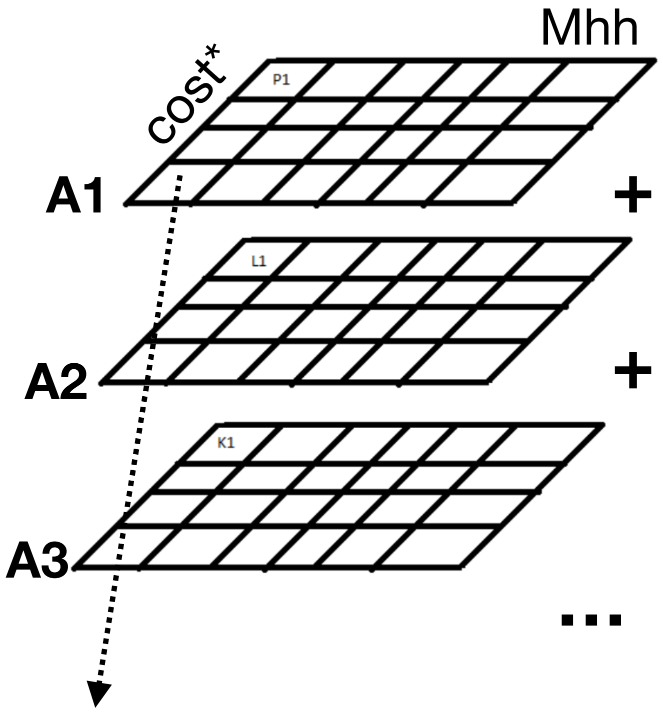
- We do make the kl-kt scan, even if this one make little sense in theory
- we could to agree in some other 2D scans (maybe on some specific model for the correlation of anomalous couplings) as start point/example of a full fledged theory interpretation…
  - To consider:
    - Single H processes that are affected by the same EFT parameters (as ttH) shall be treated consistently
    - How to consider VBF HH (that have additional anomalous couplings) on those scans?

- Do not forget: to assure re-usage of the data in a model independent fashion and with maximal precision there are some suggestions as deliver the <u>complete likelihood in terms of HH</u>
  - This is not the scope of this talk

Backup

Analytical parametrization of shapes
Reweighing event by event shape benchmarks

[3]



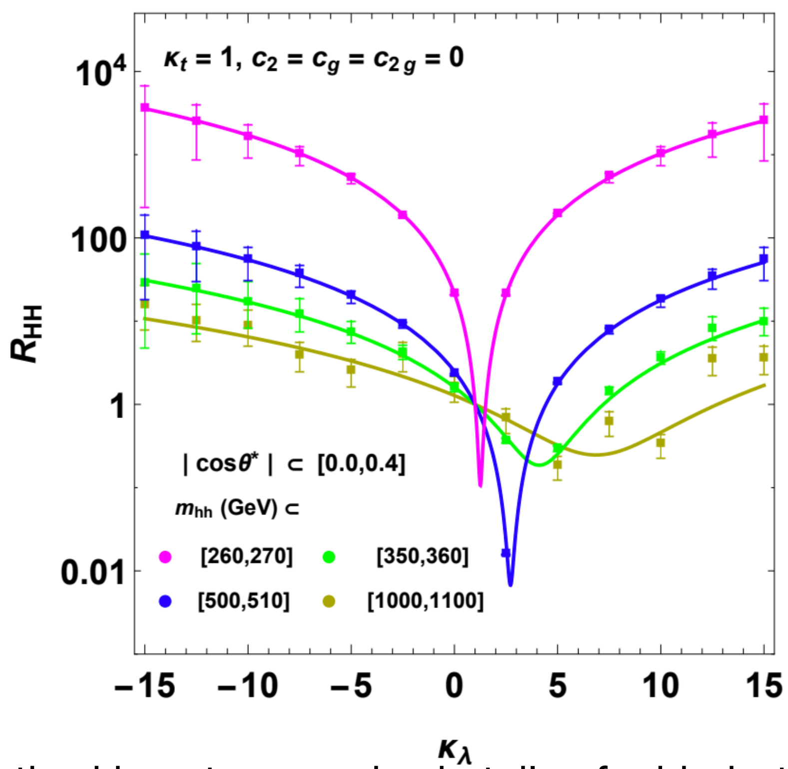
$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}}$$

There are 2 practical ways to get the coefficients/bin:

1) Using an MC model that allow simulation of different parts of the matrix element squared and binning it
   - in MG_MC@NLO it means using coupling orders
   - There is model ready @5D

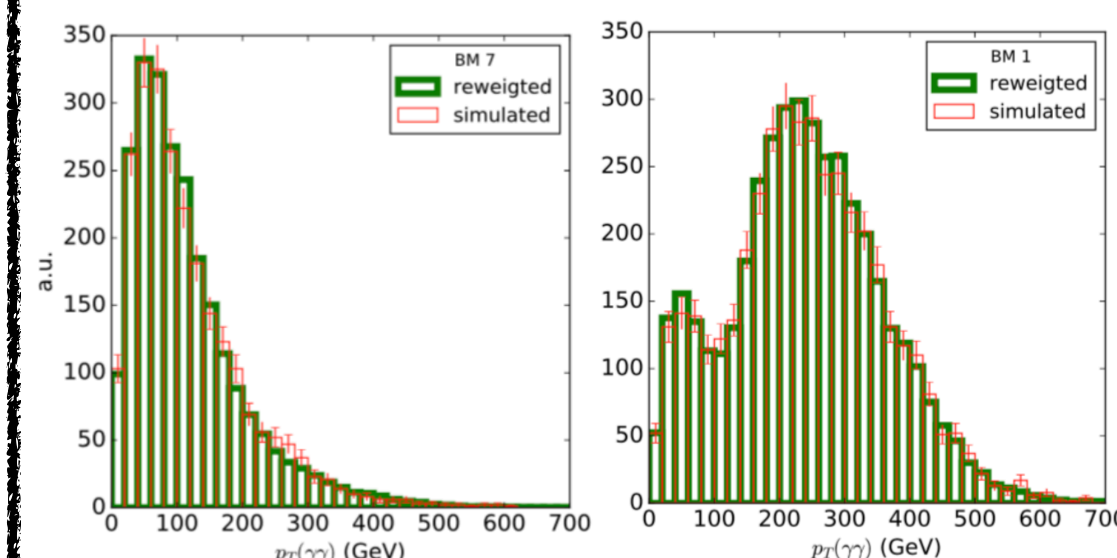
2) Brute force: generating a large grid of parameter space and fitting the above formula in each kinematical bin
   - This was done when the tools (1) were not available
   - MC simulations do have statistical uncertainties

=> The more number of samples on a scan more precise the fit, e.g.



=> This method is not so precise in tails of mhh, but for the kinematics space of resolved analyses it was well validated and used on all CMS analyzes (but bbWW)

Example of validation on signal region of CMS ggbb 2015 recast (Anamika's talk)



Reweighing 12M MC events (sum of BM)

Treating pieces of cross section as different samples to be combined

Total shape = all the interference parts summed up, with proper coefficients

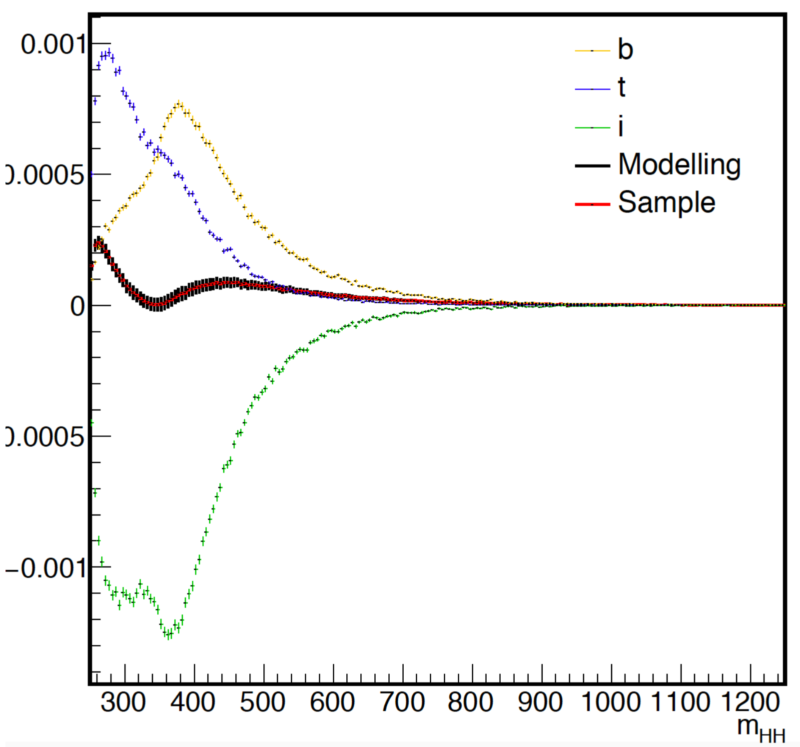
There are 2 practical ways to get the shape parts:

1) Using analytical formulas to isolate them from few simulations on different points (see P. Bokan talk)
2) Using an MC model that allow simulation of different parts of the matrix element squared

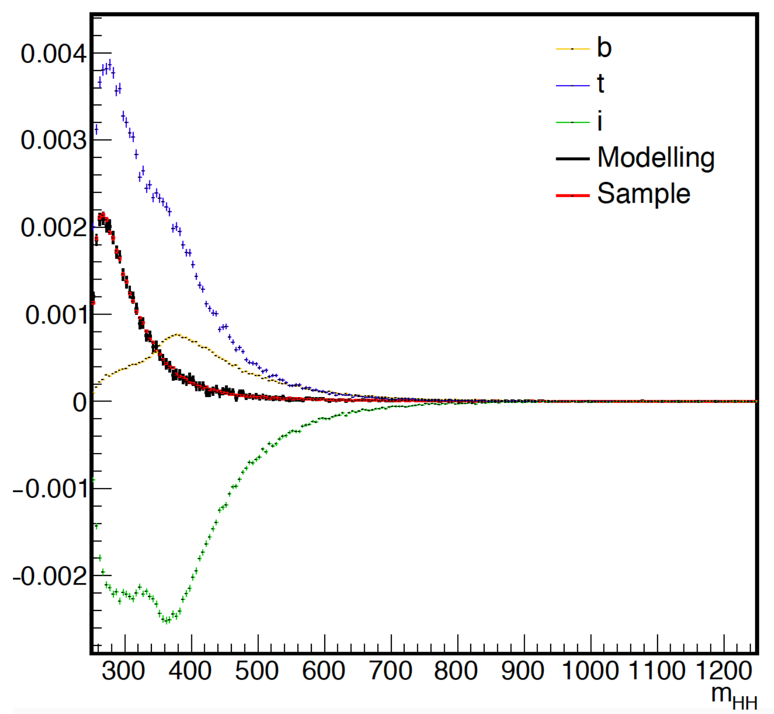
Validation done by L. Cadamuro

Only the model with kt-kl animals couplings were available at the time of validation (LO)
=> triangle (t) + box (b) + interference (i)

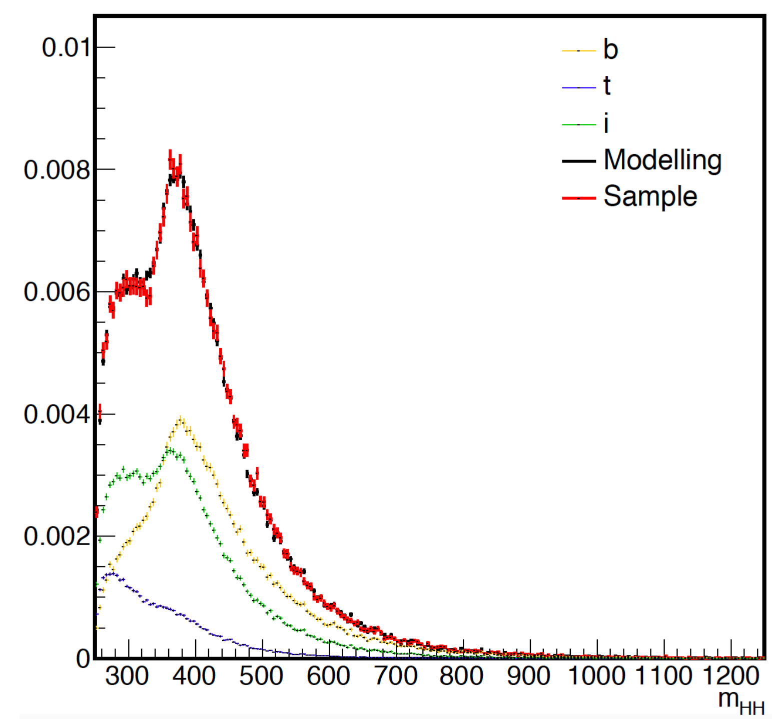
k_λ = 2.5, k_t = 1



k_λ = 5, k_t = 1



k_λ = -2, k_t = 1.5

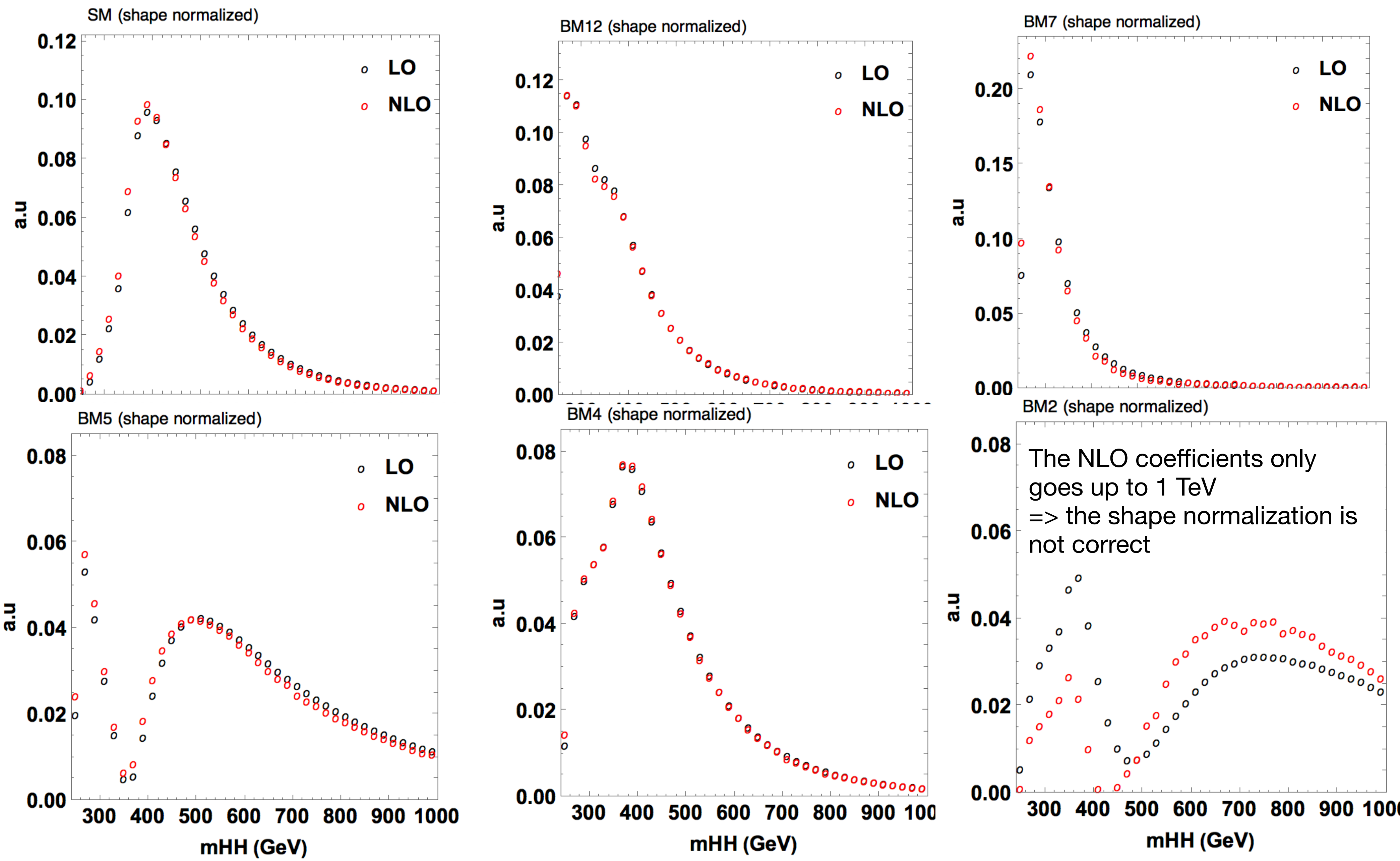


Made with the default MGaMC@NLO SM loop model + coupling orders (kindly done by Eleni Vryonidou)
The 5D version (LO) is done (see backup), just ask me out

Shape EFT @ QCD NLO with top mass effects

The authors of [1] calculated reweighing coefficients to QCD NLO (parametrized only by mhh)

- Testing on the shape benchmarks:



Request to the authors (see part II of this talk)
—> Have the coefficients up to higher mhh (~3 TeV?)
—> Make the coefficients to cover the 3D kinematics of the Higgs pair
    —> cost*hh is approximately flat, but after analysis selection it is not completely flat — see backup
    —> mhh cost* can still be a good approximation to reconstruct the hh system, one can add thought pz(hh) to complete the 3D
—> have the same result at 13TeV = future studies

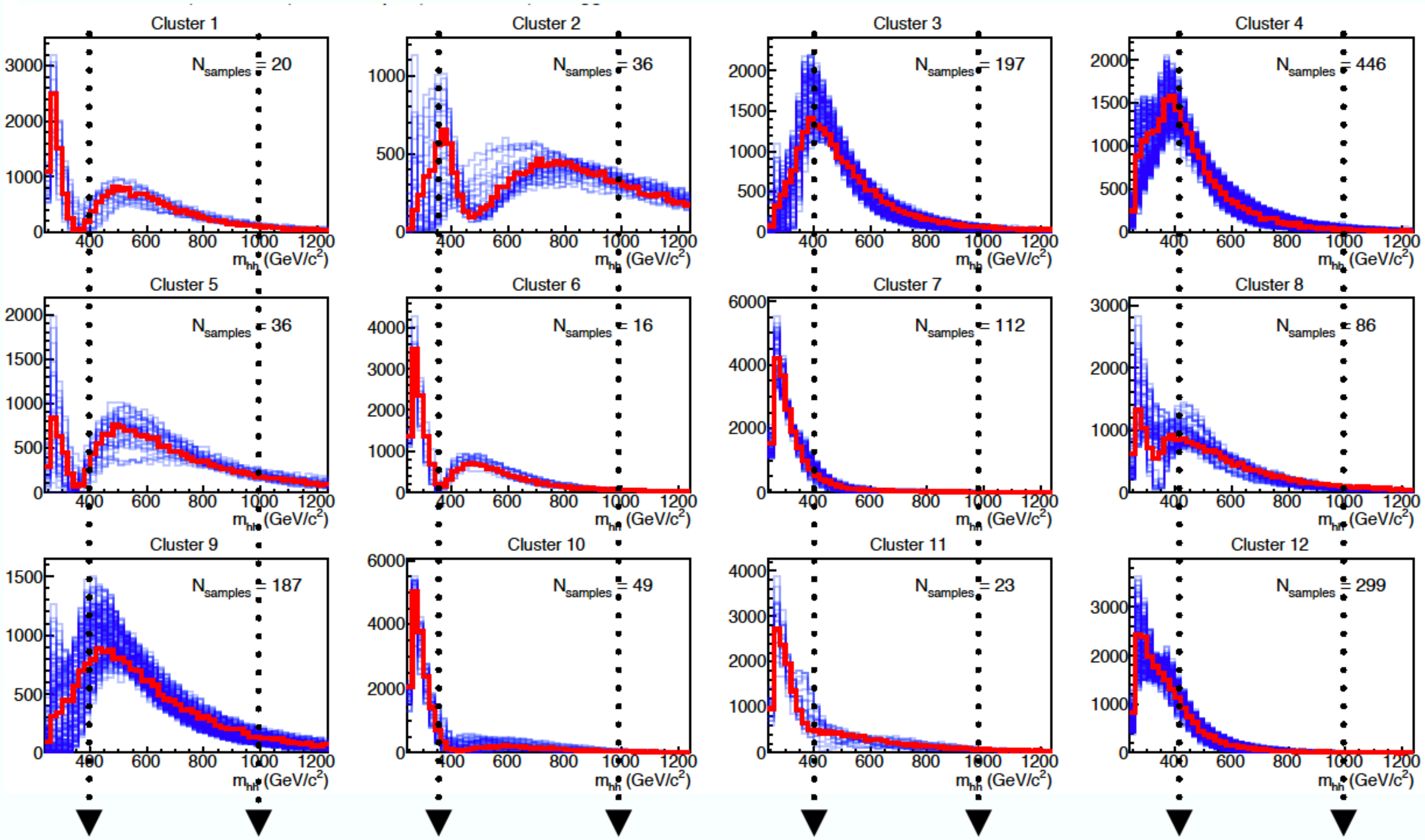
[5] HH production in non-linear EFT with full mt-dependence at NLO QCD. G. Buchalla, M. Capozi A. Celis G. Heinrich L. Scybozb

Resulting shape benchmarks

[1]

From a scan of 1507 parameter space points smartly chosen to spam the 5D parameter space, and using LO MC simulations we arrive in automated way to a kinematic classification to define benchmark points.

The Mhh distributions in the clusters:



Mhh = 400, 1000, 400, 1000, 400, 1000, 400, 1000, GeV

Red: the benchmark
Blue: the other samples in the cluster

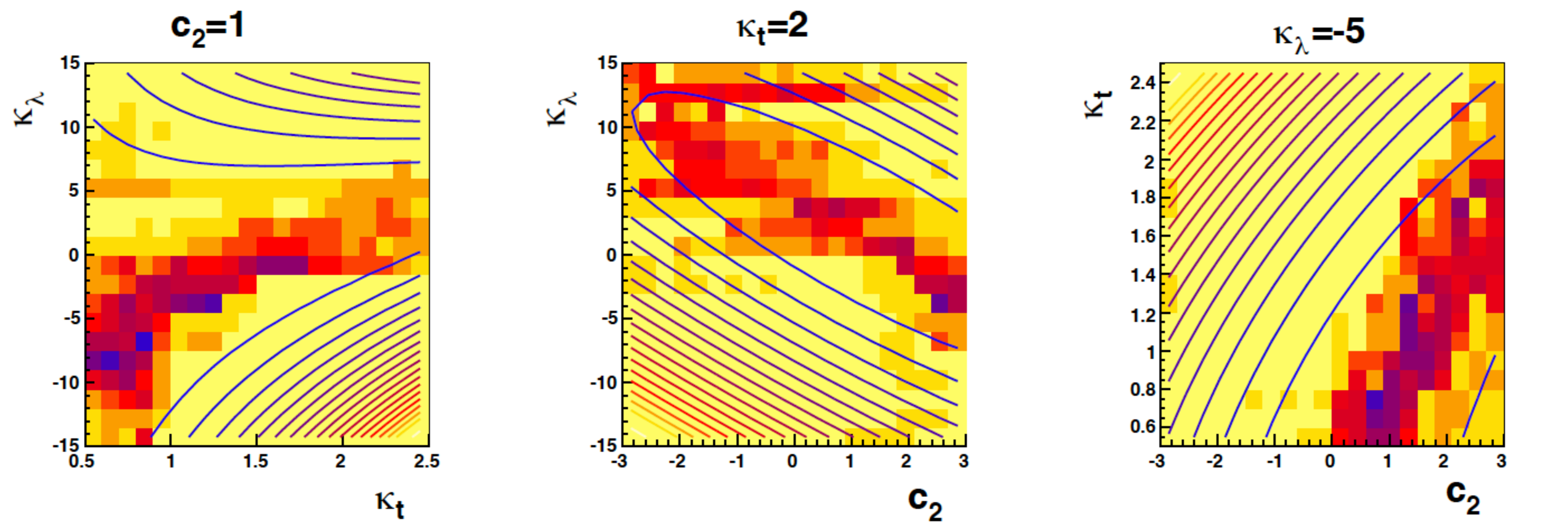
The benchmarks are part of the LHCXSWG YR4

Shape benchmarks distributions on parameter space

[1]

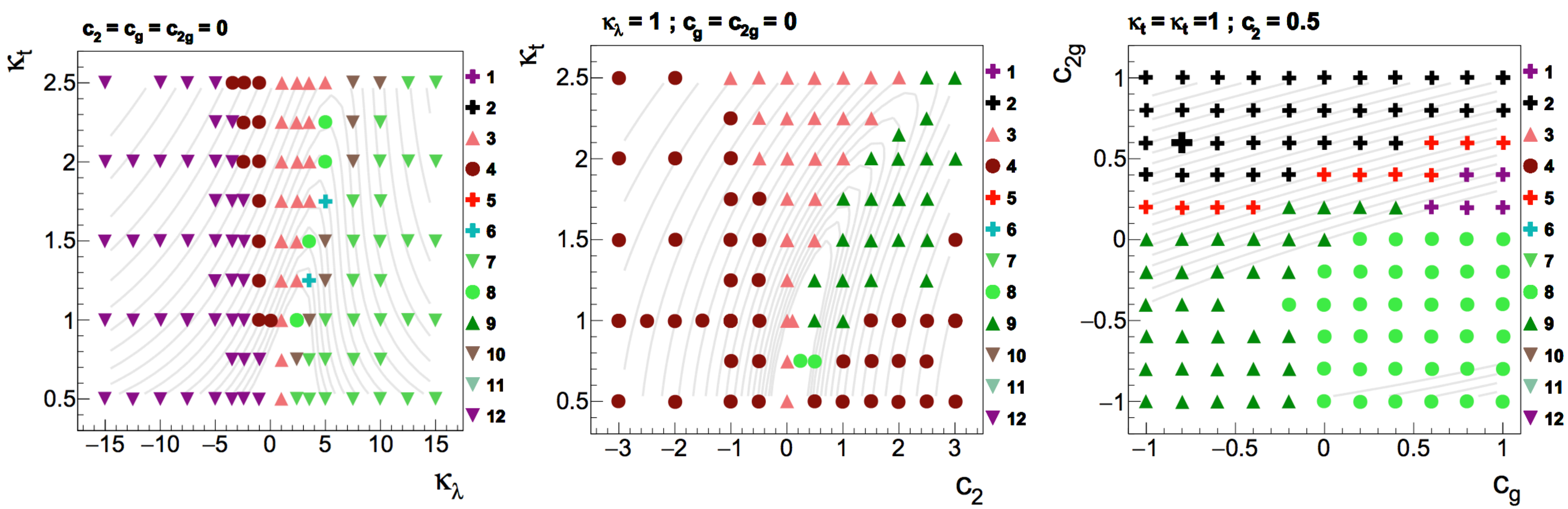
A larger variability in kinematic topologies is correlated with local minima of cross sections (where apparent cancelations among different processes holds)

When we overlap the values of the TS between two nearest neighbors samples with the isolines of cross section we directly see the correlation



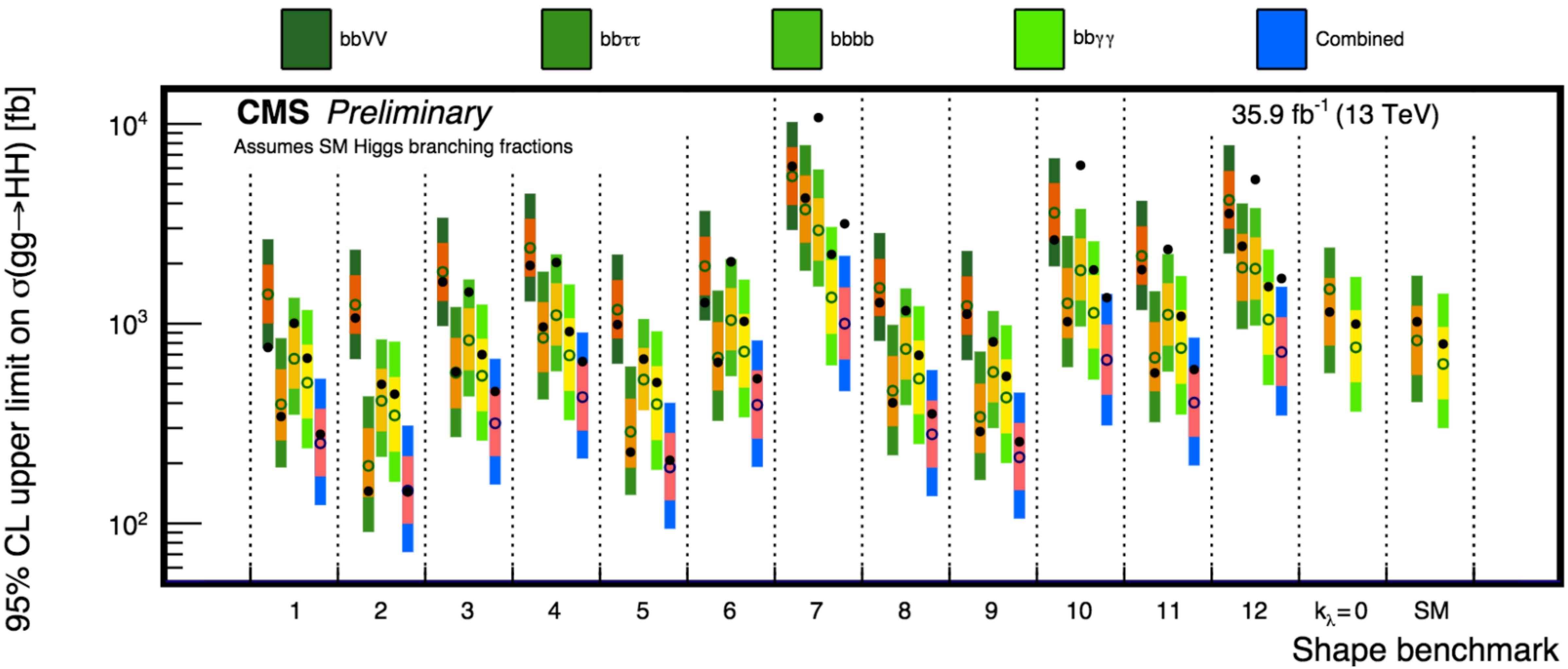
Blue/Red stand for higher values of the TS between nearest neighbors

As result, the distributions of benchmarks usually enclose simply connected regions of couplings



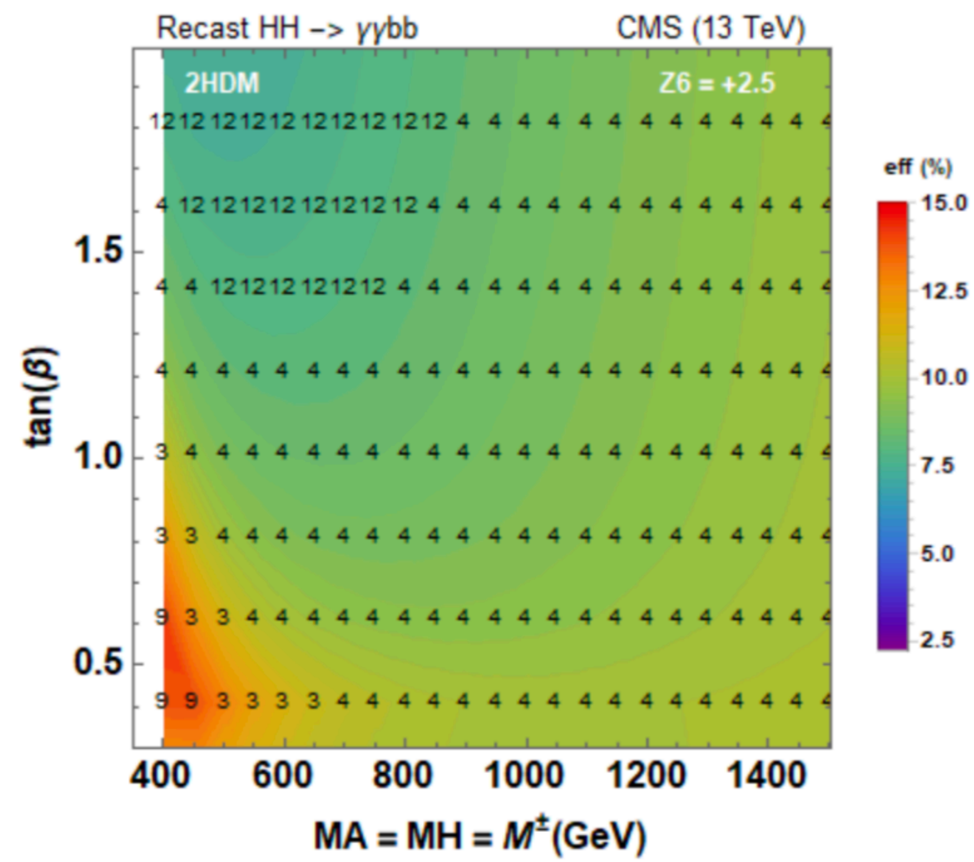
Using CMS combo

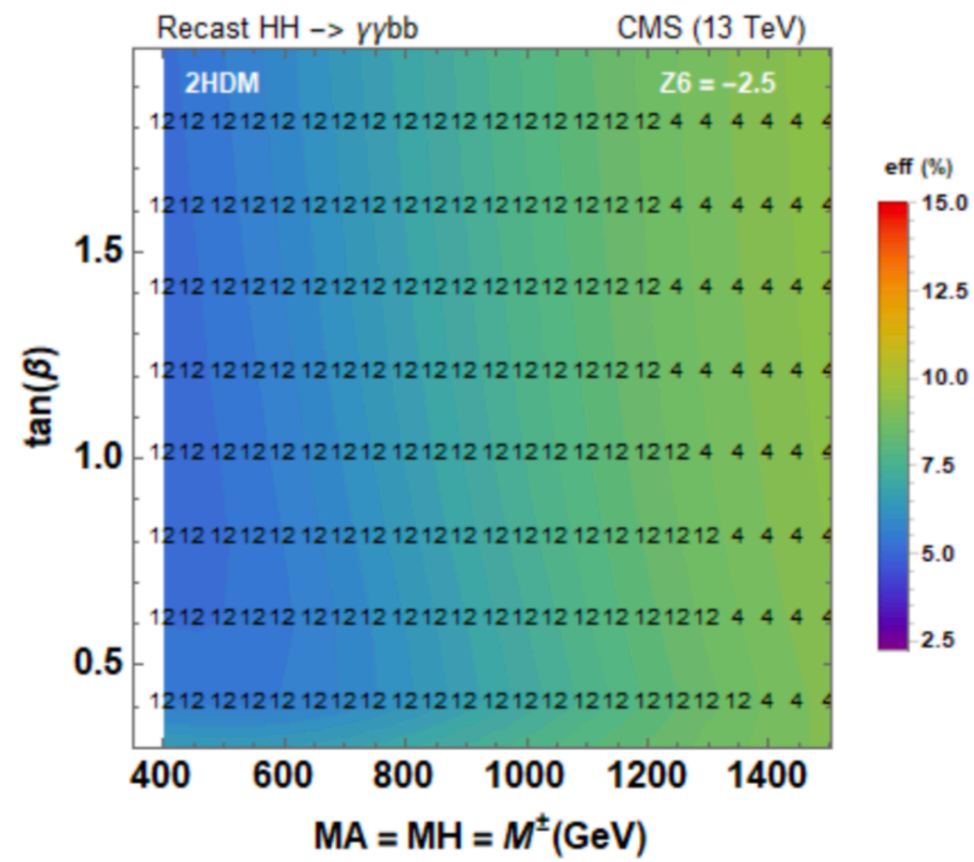
CMS released a limits from the combination of the hh-channels calculated on the shape benchmarks (see L. Cadamuro talk)

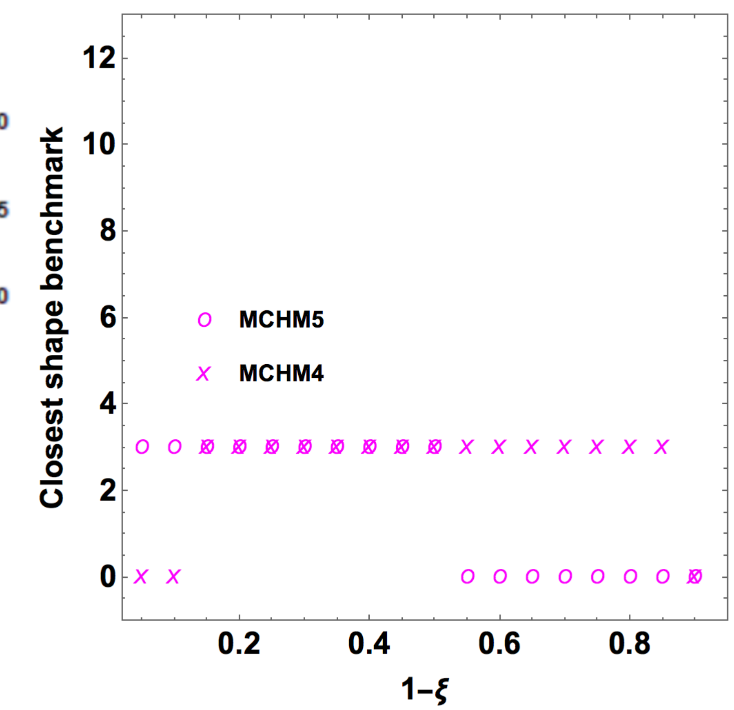


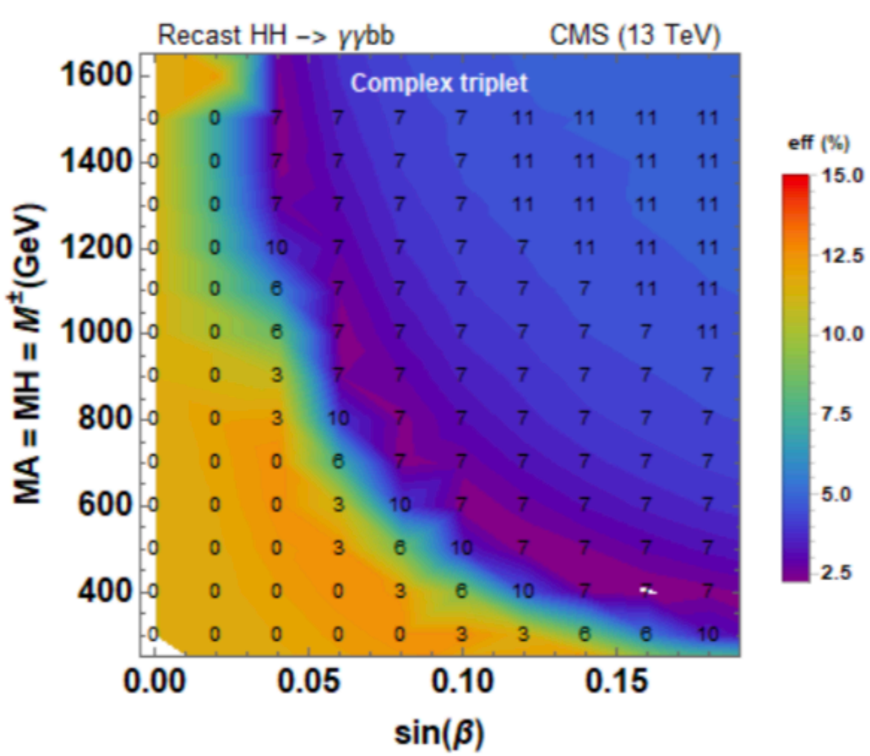
It is clear that the relative impact of each channel for different signal topologies changes
=> They are complimentary on the parameter space of anomalous couplings

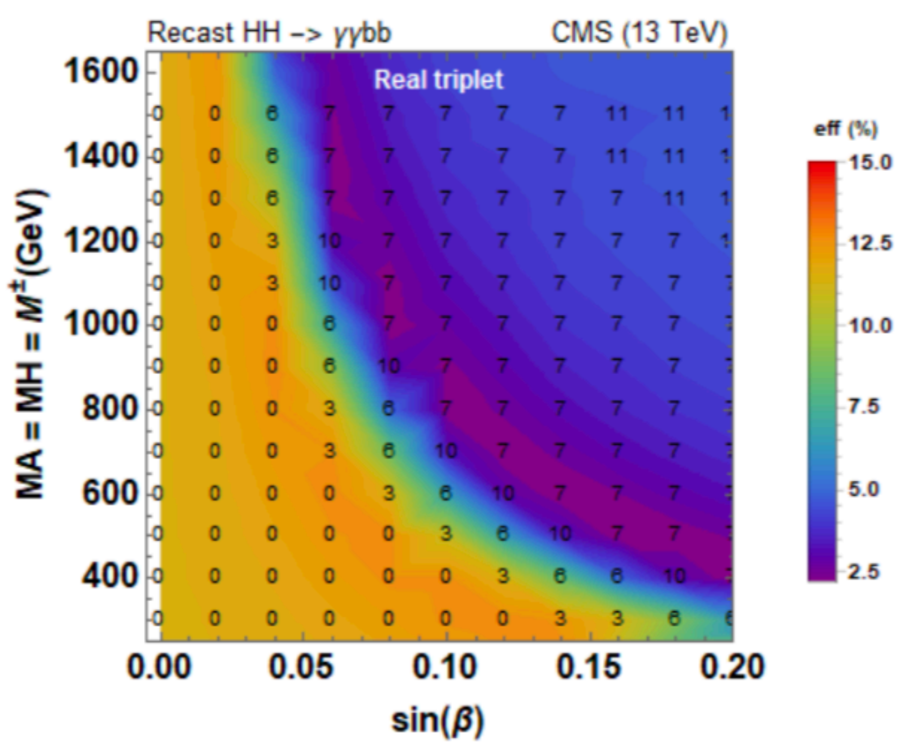
Reweighing event by event shape benchmarks - some validation

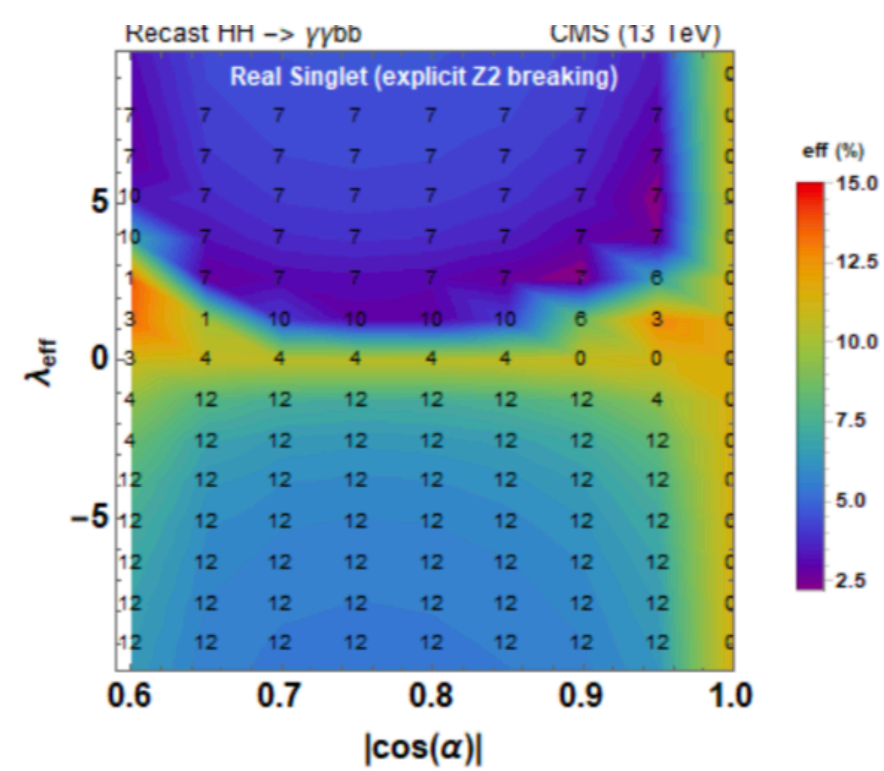




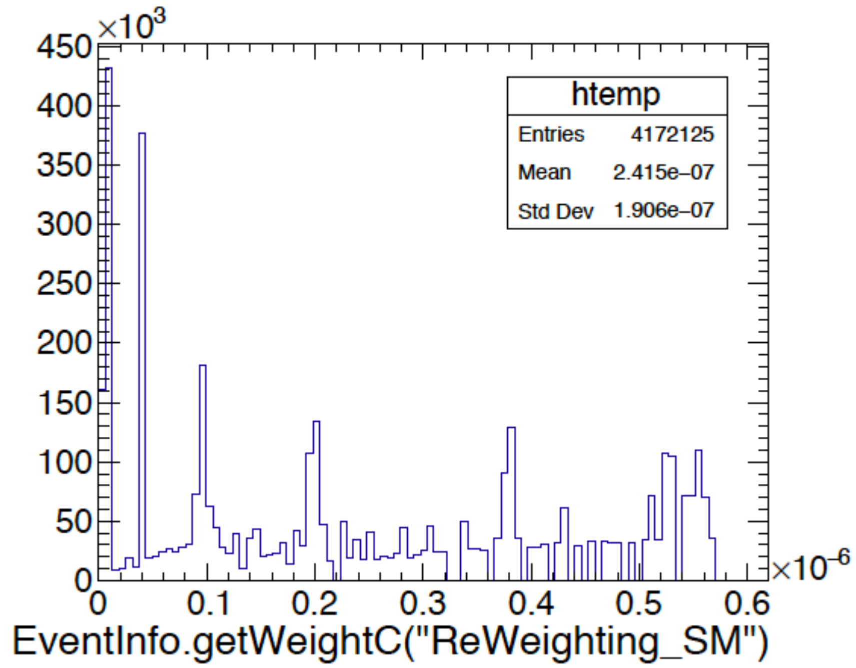


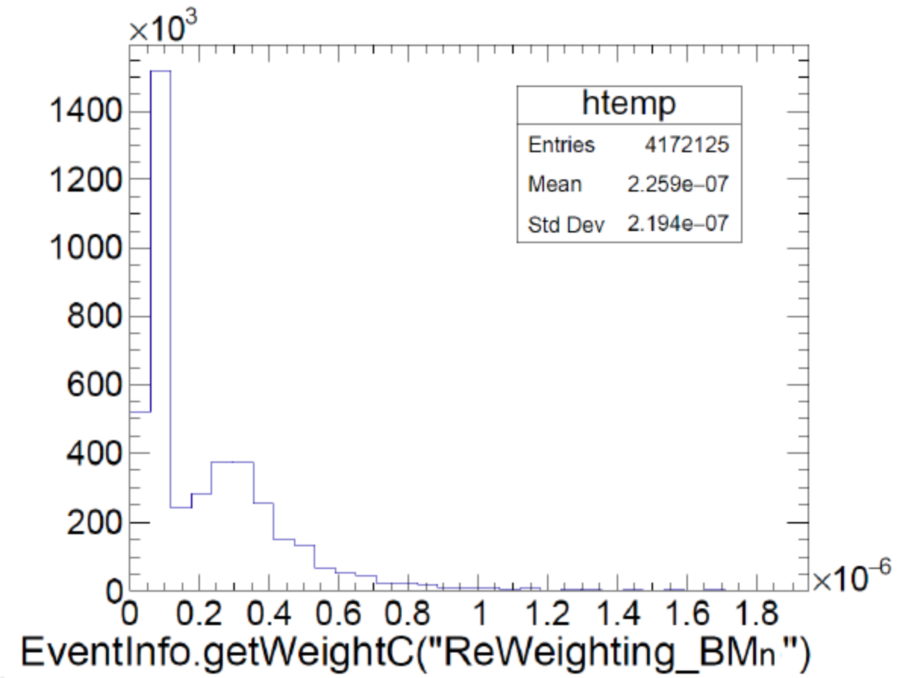


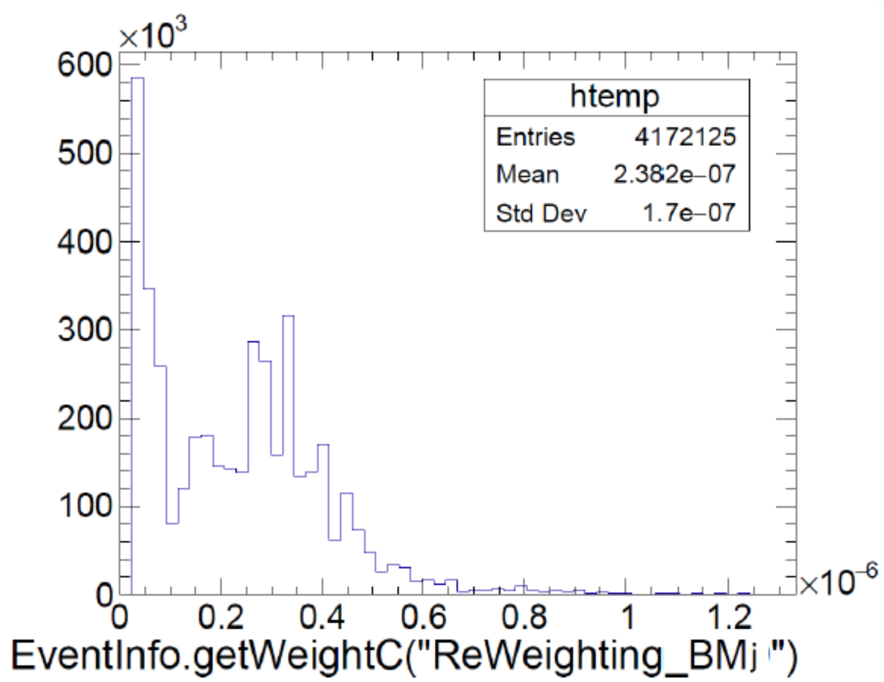




Examples of size of weights







~400k events/sample

Similar weights distributions to all BMs