Total cross section numbers for the double Higgs production with anomalous Higgs couplings

HH Subgroup Meeting
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Università degli Studi di Padova

CERN

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Outline

We had proposed a method to define benchmarks for GF non-resonant di-Higgs production at LHC, parametrizing the anomalous Higgs couplings.

We then classify representative benchmarks according only with kinematical properties of the signal

Previous talks from this group:

in HH-x meetings: 24/02/15, 17/07/15, 19/11/15

Mainz HH workshop 03/15

Arxiv:1507.02245

This talk:

The cross sections for the di-Higgs production via Higgs anomalous couplings, and the list of the benchmarks we propose.

The Higgs boson anomalous couplings parametrization

Relevant to pp -> HH,
in terms of the physical Higgs excitation

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3$$

pure Higgs → Self couplings, unconstrained

$$-\frac{m_t}{v}(v + \kappa_t h + \frac{c_2}{v} h h)(\bar{t}_L t_R + h.c.)$$

Yukawa type

$$+\frac{1}{4}\frac{\alpha_s}{3\pi v}(c_g h - \frac{c_{2g}}{2v} h h) G^{\mu\nu} G_{\mu\nu}$$

Gluon contact interactions

5 parameters:

$$\kappa_\lambda, \kappa_t, c_2, c_g, c_{2g}$$

neglect light generations, motivated e.g. from smallness of FCNCs see e.g. FG, 1406.0102

We use the most general parametrization => it includes the case the physical Higgs boson is not completely part of a doublet.

The linear case is recovered to particular relations among the parameters: cg = - c2g

The cluster analysis in a concept:

The number of parameters and the nature of the process does not make it easy to connect a particular signal topology to the different regions of parameter space (different interference patterns among different processes)

Parameter space scan in the anomalous couplings (1507 points, see later)

→

MC simulation
(mhh , cosTheta*)
+
Test Statistic classification
+
cluster analysis

→

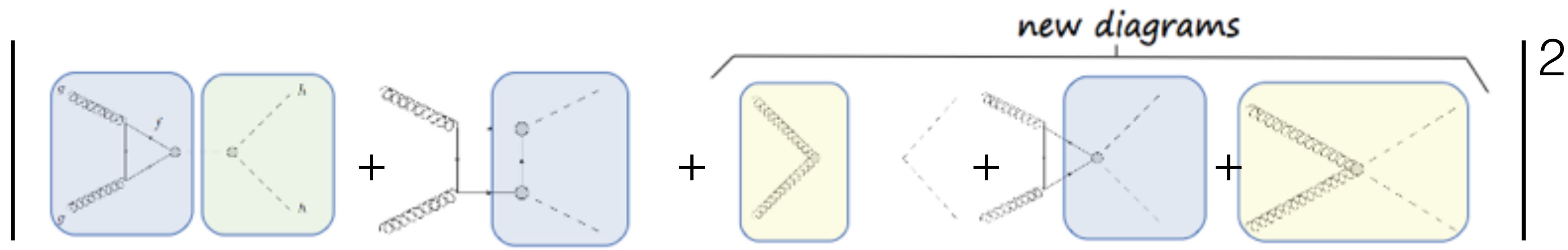
12 benchmark points as representative of signal topologies from a large parameter space scan

Look on the last HH-x meeting 19/11/15 !!!

The results of the parameter space scan also allow us to calculate the enhancement of total cross section for di-Higgs production with respect to the SM benchmark in a principled way.

The non-resonant di-Higgs cross section

$\sigma_{hh} \longrightarrow$



The SM cross section can be factored out from the anomalous total cross section:

$$
\begin{aligned}
\frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = \; & A_1\,\kappa_t^4 + A_2\,c_2^2 + (A_3\,\kappa_t^2 + A_4\,c_g^2)\,\kappa_\lambda^2 + A_5\,c_{2g}^2 + (A_6\,c_2 + A_7\,\kappa_t\kappa_\lambda)\kappa_t^2 \\
& +(A_8\,\kappa_t\kappa_\lambda + A_9\,c_g\kappa_\lambda)c_2 + A_{10}\,c_2c_{2g} + (A_{11}\,c_g\kappa_\lambda + A_{12}\,c_{2g})\,\kappa_t^2 \\
& +(A_{13}\,\kappa_\lambda c_g + A_{14}\,c_{2g})\,\kappa_t\kappa_\lambda + A_{15}\,c_g c_{2g}\kappa_\lambda
\end{aligned}
$$

=> 15 coefficients appearing in different combinations define **the cross section enhancement** with respect to the SM benchmark

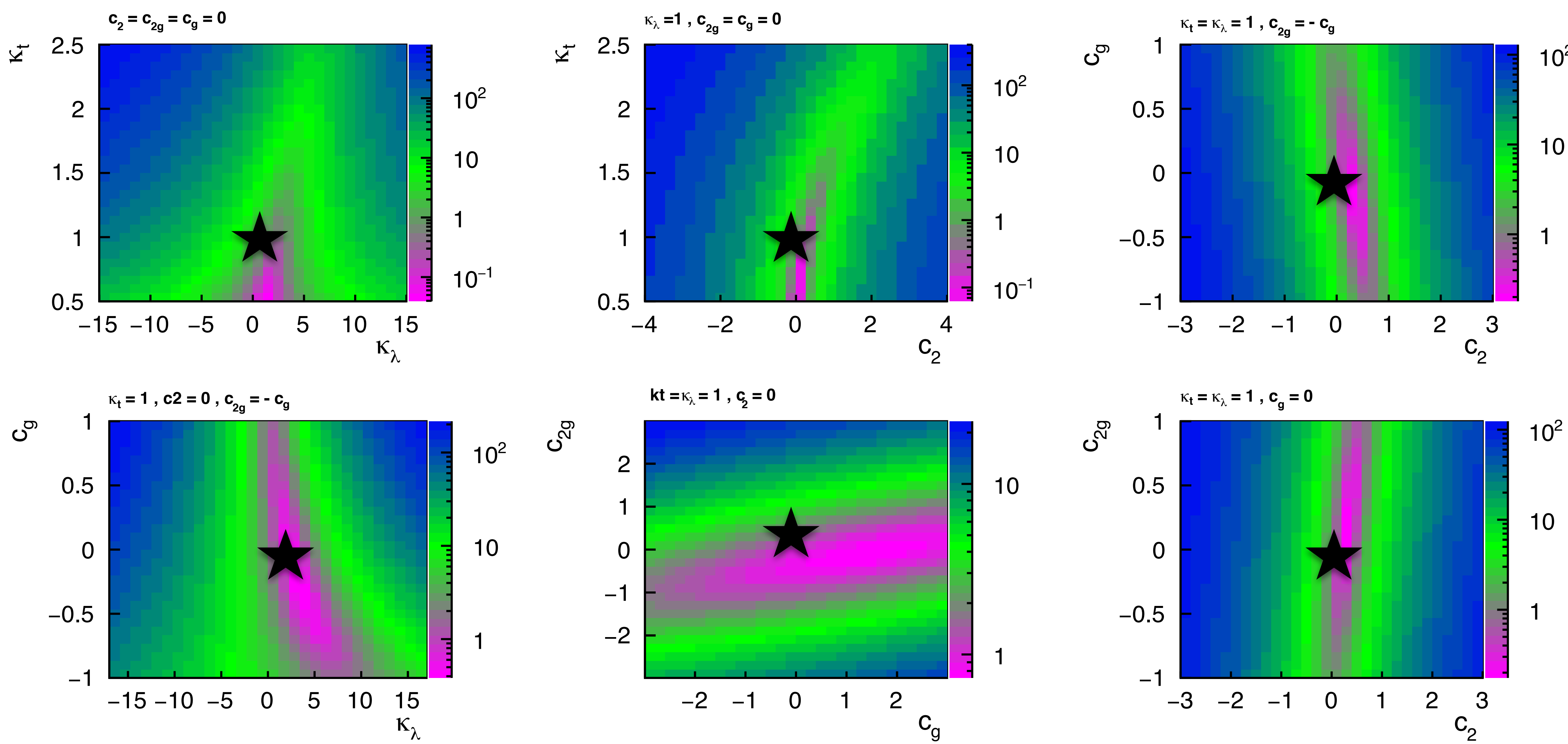
Ideally all the coefficients can be fixed recursively, calculating individually each coefficient, smartly setting some of the parameters to zero.
=> only 15 points are necessary to fix the enhancement formula

However cross section calculations have associated **uncertainties**,
=> Result unstable, depending on the selected points.
=> It is not trivial to the estimate uncertainties of the coefficients.

The non-resonant di-Higgs cross section

$$\frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = A_1\,\kappa_t^4 + A_2\,c_2^2 + (A_3\,\kappa_t^2 + A_4\,c_g^2)\,\kappa_\lambda^2 + A_5\,c_{2g}^2 + (A_6\,c_2 + A_7\,\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\,\kappa_t\kappa_\lambda + A_9\,c_g\kappa_\lambda)c_2 + A_{10}\,c_2c_{2g} + (A_{11}\,c_g\kappa_\lambda + A_{12}\,c_{2g})\,\kappa_t^2$$
$$+(A_{13}\,\kappa_\lambda c_g + A_{14}\,c_{2g})\,\kappa_t\kappa_\lambda + A_{15}\,c_g c_{2g}\kappa_\lambda$$

Six perpendicular slices of parameter space are sufficient to cover all the parameters combinations that define the cross section enhancement



For concreteness we choose 2D parameter slices that contain the SM point ★

The non-resonant di-Higgs cross section

We calculated the di-Higgs total cross sections to LHC at different CM energies with Monte Carlo technique

- Madgraph5_aMC@NLO simulations to pp -> hh (no generation cuts applied)
- model from E.Vryonidou et all (1401.7340) it contains exact form factors at LO (based in M. Spira et all 9603205)
- PDF: NN23LO1. Scale: mhh. Mh = 125 GeV, Mtop = 173 GeV

The 15 cross section coefficients are found with a simultaneous fit in all the scanned parameter space points using MINUIT

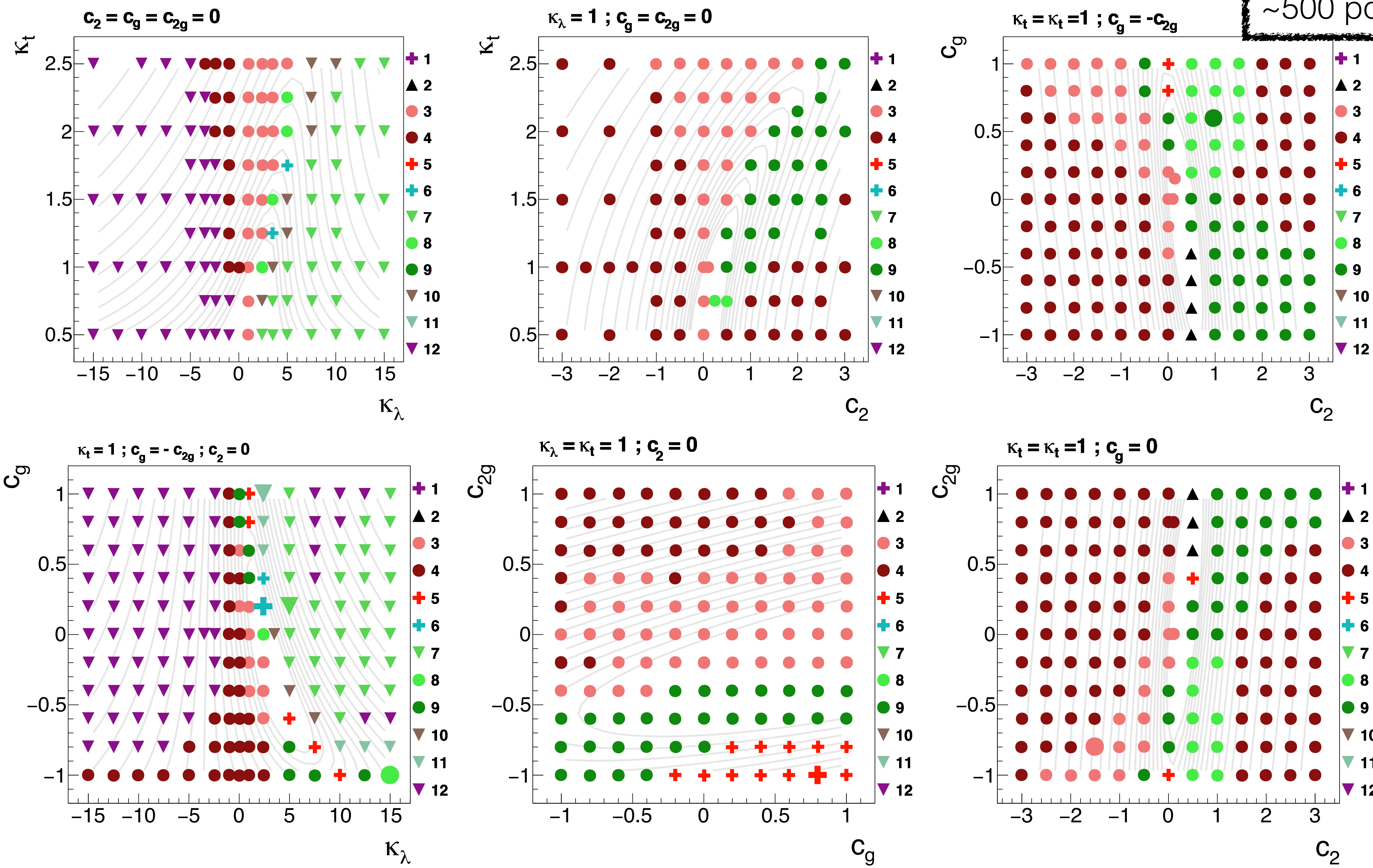
- We allow 10% uncertainty to each input point, emulating the effect of add uncertainties in the coefficients fit for cross section enhancement induced by a more precise calculation.

The non-resonant di-Higgs cross section

A fine scan in the chosen slices of parameter space is performed:

~500 points

Map of the clusters in the scanned points



For LHC @13 TeV those are used both for calculate cross section and to apply the cluster analysis

Look on the last HH-x meeting 19/11/15 !!!

The non-resonant di-Higgs cross section

The coefficients of the cross section enhancement at different LHC CM energies

$$\frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = A_1\,\kappa_t^4 + A_2\,c_2^2 + (A_3\,\kappa_t^2 + A_4\,c_g^2)\,\kappa_\lambda^2 + A_5\,c_{2g}^2 + (A_6\,c_2 + A_7\,\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\,\kappa_t\kappa_\lambda + A_9\,c_g\kappa_\lambda)c_2 + A_{10}\,c_2c_{2g} + (A_{11}\,c_g\kappa_\lambda + A_{12}\,c_{2g})\,\kappa_t^2$$
$$+(A_{13}\,\kappa_\lambda c_g + A_{14}\,c_{2g})\,\kappa_t\kappa_\lambda + A_{15}\,c_g c_{2g}\kappa_\lambda$$

New!

$\sqrt{s}$	8 TeV	13 TeV	14 TeV	100 TeV
A_1	2.188 ± 0.029	2.210 ± 0.016	2.10 ± 0.027	1.941 ± 0.042
A_2	9.914 ± 0.090	10.598 ± 0.060	10.187 ± 0.094	11.27 ± 0.18
A_3	0.3242 ± 0.0062	0.3046 ± 0.0022	0.2872 ± 0.0052	0.224 ± 0.0063
A_4	0.118 ± 0.014	0.109 ± 0.015	0.103 ± 0.015	0.080 ± 0.021
A_5	1.179 ± 0.041	1.467 ± 0.044	1.360 ± 0.046	2.818 ± 0.068
A_6	-8.73 ± 0.13	-8.968 ± 0.054	-8.54 ± 0.15	-8.29 ± 0.20
A_7	-1.512 ± 0.027	-1.471 ± 0.010	-1.388 ± 0.024	-1.165 ± 0.033
A_8	3.04 ± 0.15	3.017 ± 0.020	2.85 ± 0.16	2.51 ± 0.19
A_9	1.61 ± 0.11	1.56 ± 0.13	1.48 ± 0.15	1.23 ± 0.15
A_{10}	-5.11 ± 0.13	-5.23 ± 0.12	-4.93 ± 0.15	-4.32 ± 0.17
A_{11}	-0.770 ± 0.029	-0.707 ± 0.029	-0.685 ± 0.029	-0.533 ± 0.084
A_{12}	2.074 ± 0.063	1.989 ± 0.066	1.876 ± 0.064	1.43 ± 0.16
A_{13}	0.374 ± 0.016	0.342 ± 0.015	0.328 ± 0.015	0.25 ± 0.033
A_{14}	-0.932 ± 0.056	-0.887 ± 0.057	-0.847 ± 0.056	-0.70 ± 0.16
A_{15}	-0.611 ± 0.038	-0.595 ± 0.041	-0.576 ± 0.041	-0.541 ± 0.060

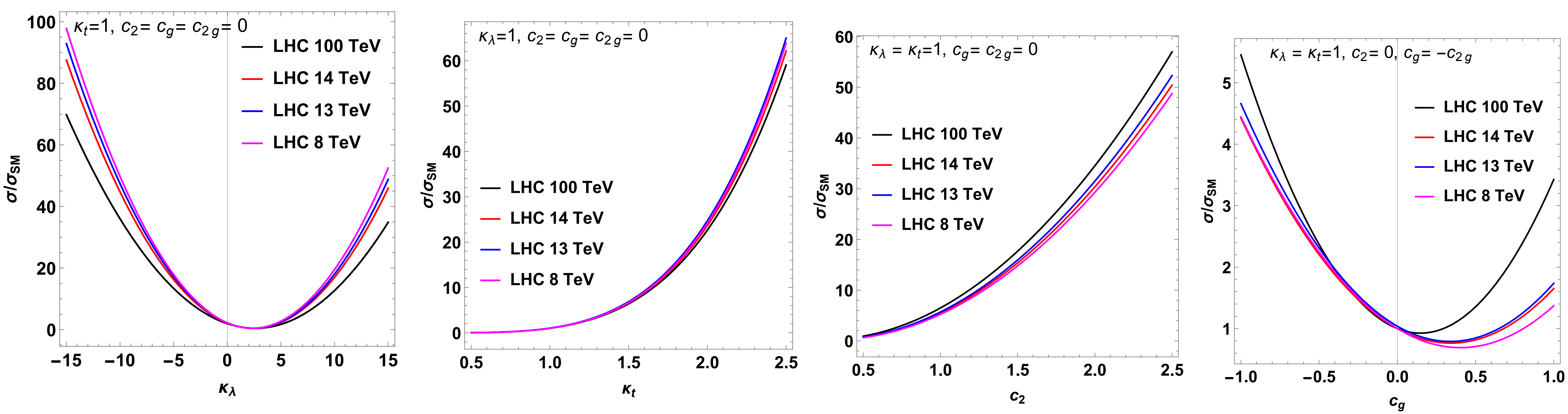
The PDF choice, scale and mass effects are expected to be secondary effects for the ratio of total cross sections.

Preliminary studies points that k-factors tend to be flat with the anomalous couplings M.Spira et all (1504.06577)

The cross section can be normalized to the state of the order SM HH cross section or as well to the LO HH cross section.

The non-resonant di-Higgs cross section

Difference of the enhancement among CM energies when variating only one parameter



Same order of magnitude for the enhancement in the inspected parameter space range

less than 10% variation among predicted enhancements when changing the CM energy from 8 TeV to 14 TeV and variating the parameters $\kappa_\lambda, \kappa_t, c_2$

(up to 20% when large Higgs-gluons contact interactions)

Additional material to be inserted in the report

The list of benchmarks points:

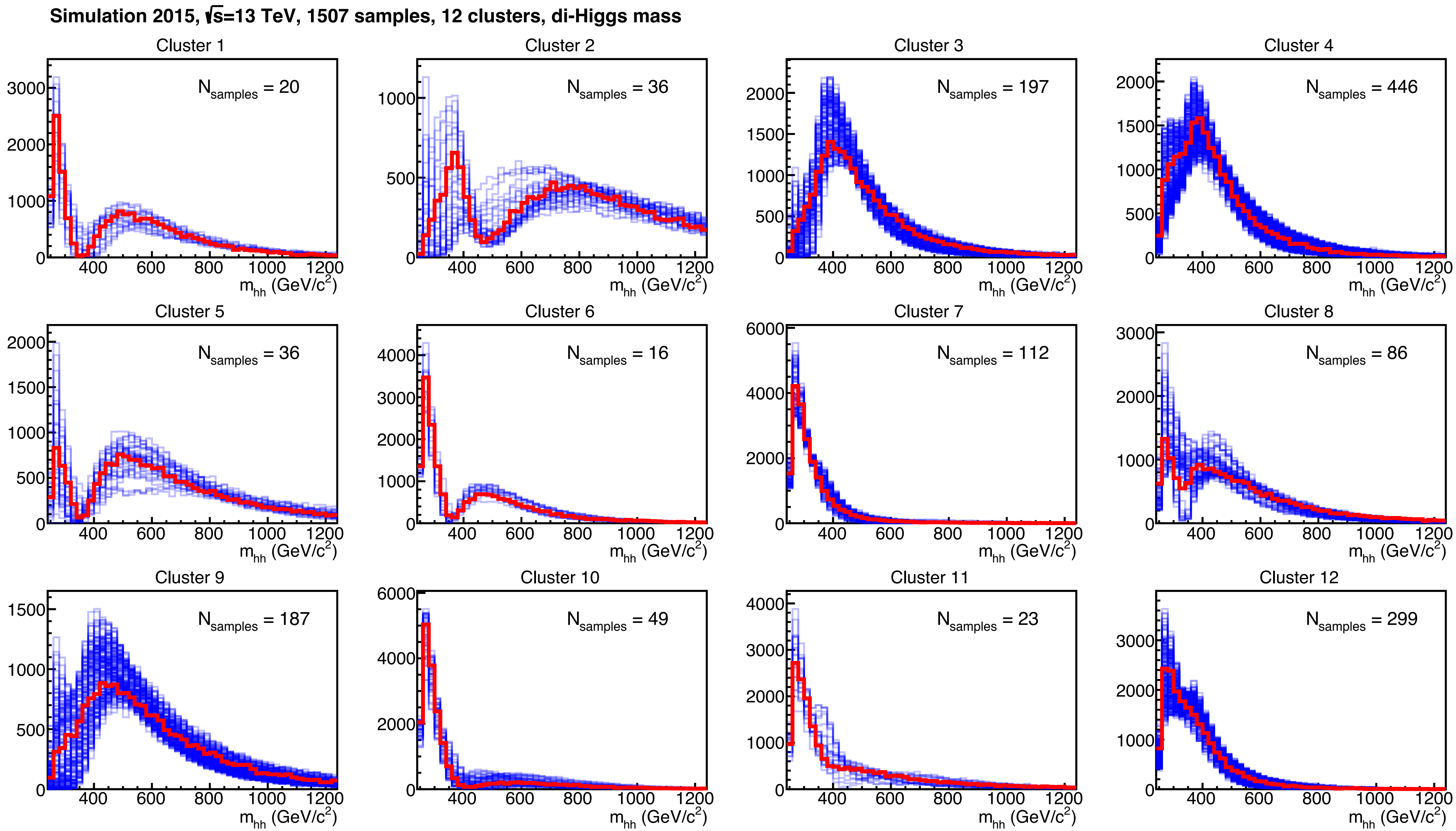
1507 points were clustered in 12 clusters:

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.55	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

→ The SM is part of the cluster 2.

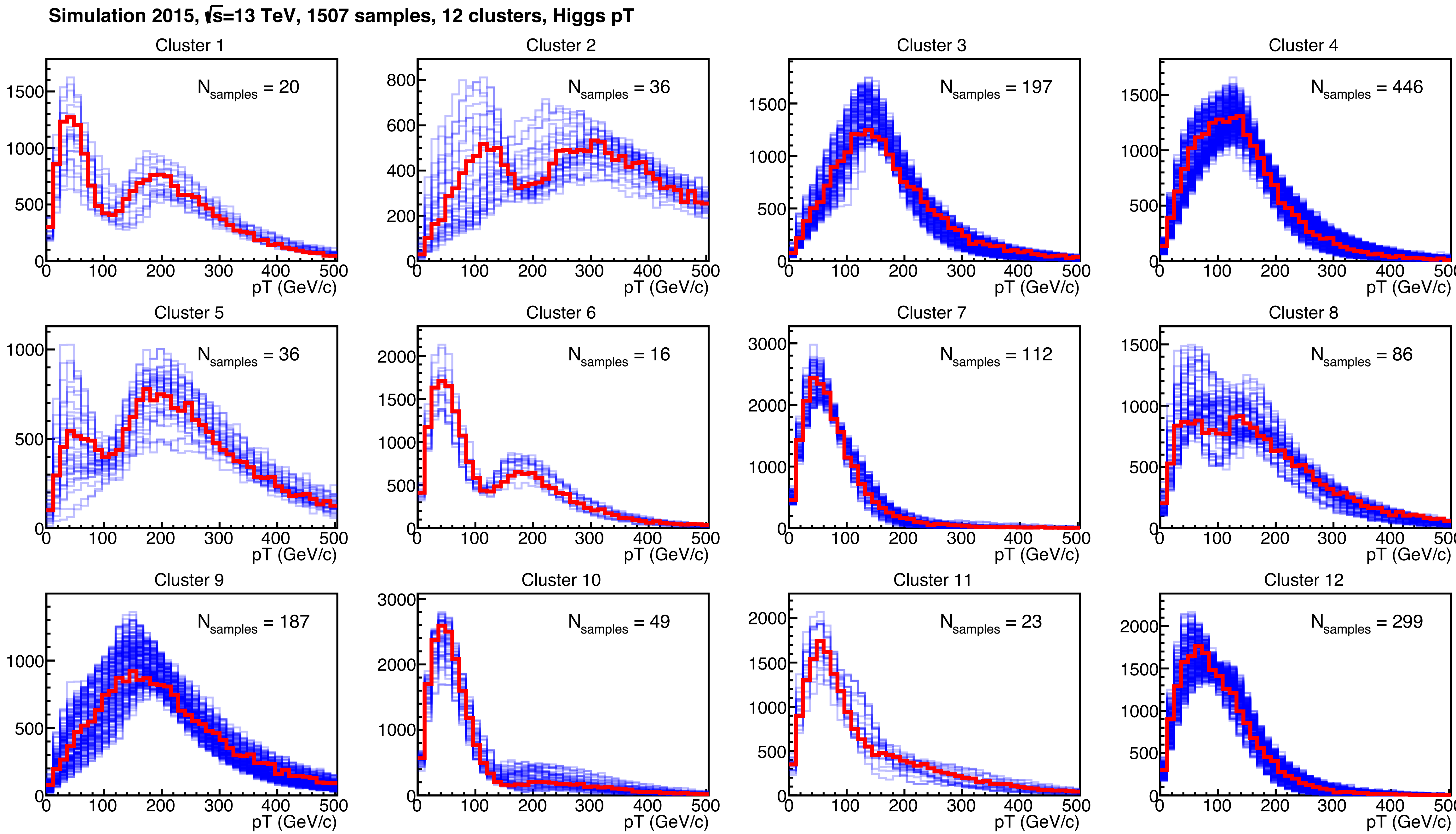
The12 benchmarks as representative of a large parameter space scan

1507 points were clustered in 12 clusters, we show the mhh distribution.



The12 benchmarks as representative of a large parameter space scan

1507 points were clustered in 12 clusters, we show the Higgs pt distribution.



Thank you for attention!

All the material of the talk can be found at:
NonResonantHHAtLHC

The Higgs boson anomalous couplings parametrization relevant to pp -> HH !!!

Self couplings, unconstrained

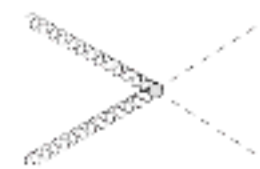
Pure Higgs

Yukawa type

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6$$

$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.} \right)$$

$$+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G_a^{\mu\nu} + \frac{\alpha' c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu}$$

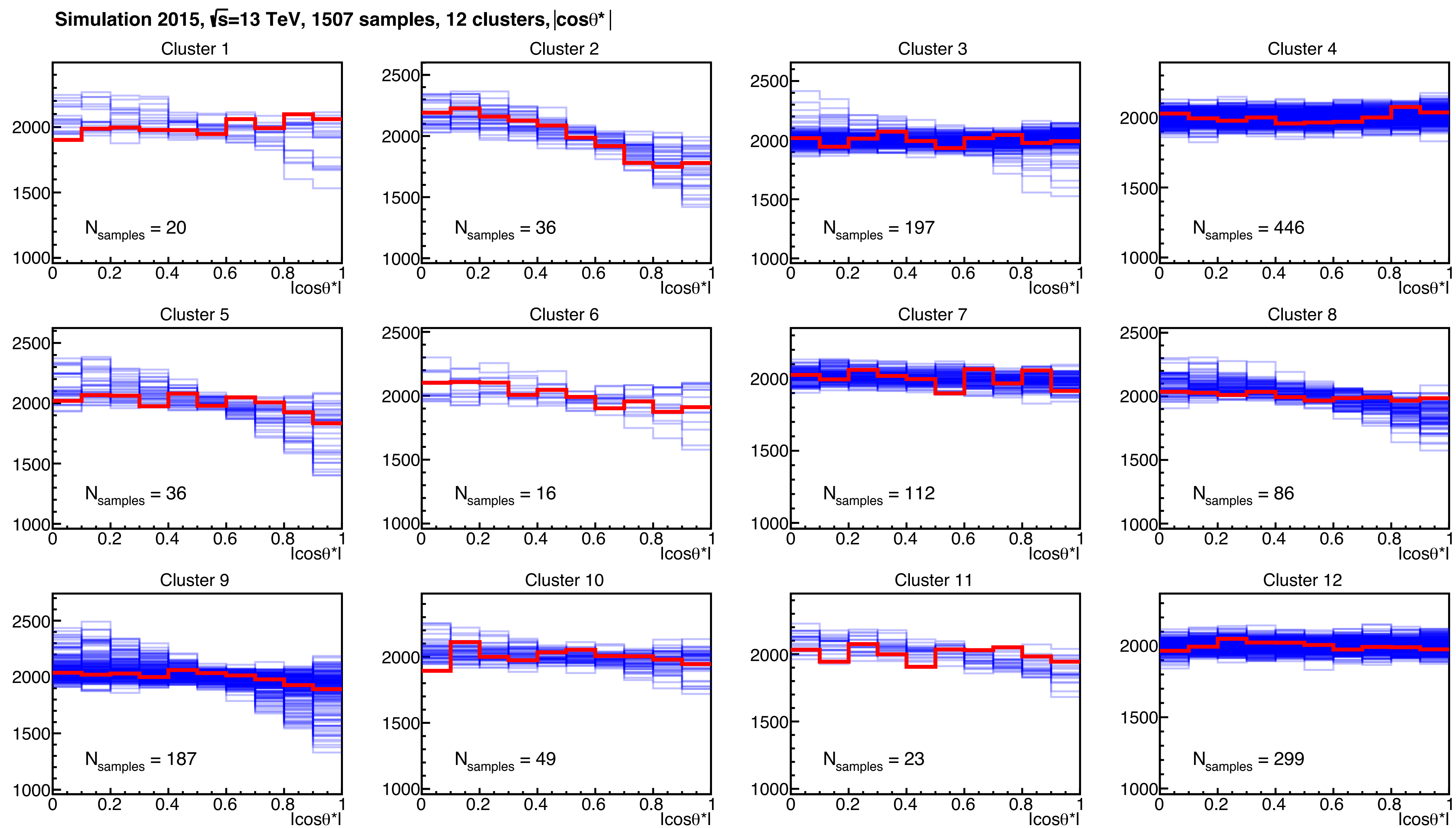


$$+ \frac{i c_{WW}}{16\pi^2\Lambda^2} \mathcal{O}_{WW} \; (+\mathcal{L}_{\rm CP} + \mathcal{L}_{\rm 4f})$$

See e.g.: Elias-Miro, Espinosa, Masso, Pomarol, 1308.1879; Pomarol, Riva, 1308.2803; Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia 1207.1344, 1211.4580, 1304.1151; Falkowski, Riva, Urbano, 1303.1812; Contino, Ghezzi, Grojean, Muhlleitner, Spira, 1303.3876; Dumont, Fichet, von Gersdorff 1304.3369; Trott 1409.7605; Falkowski, Riva, 1411.0669; Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn, Rauch 1505.05516; HXSWG;

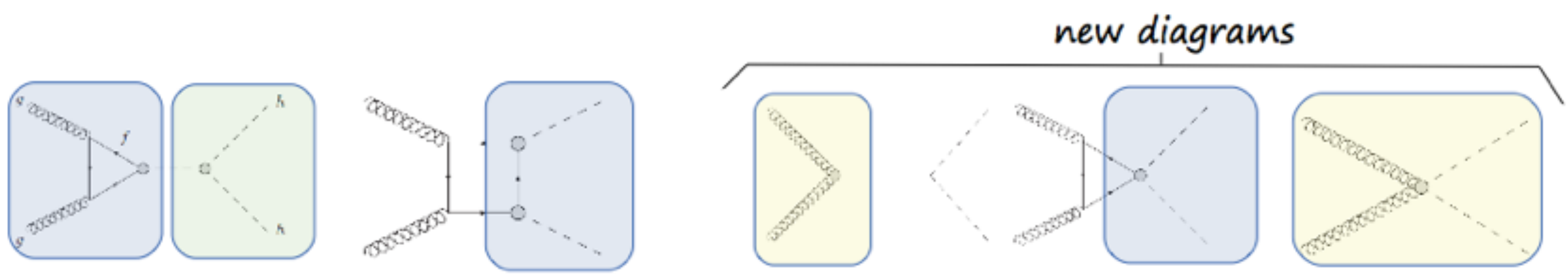
The12 benchmarks as representative of a large parameter space scan

1507 points were clustered in 12 clusters, we show the cosTheta* distribution.



The cluster analysis in concept:

The number of parameters and the nature of the process does not make easy to connect a particular signal topology with the different regions of parameter space (different interference patterns among different processes)



From other side, what we have in hands is a 2 -> 2 process (at LO)