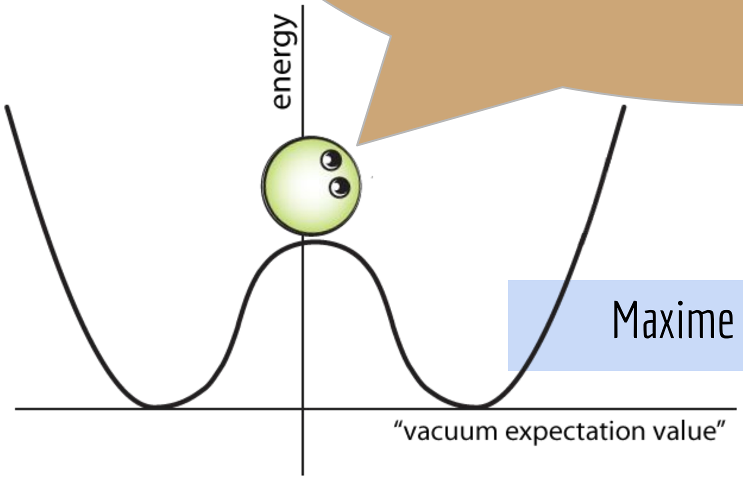
ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

UNIVERSITÉ DE LYON | Lyon 1

Higgs-boson potential at colliders



Maxime Gouzevitch

31/08/2022

Preamble

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

The exploration of significantly higher energies than the LHC will make it possible to study the production of Higgs boson pairs and thus to explore the particle's interaction with itself, which is key to understanding the fabric of the universe.

Roadmap

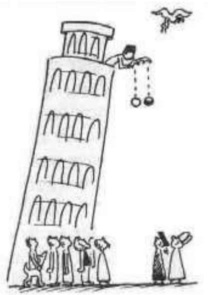
1) Theoretical bases for the BEH potential
2) LHC results
3) Projections for Future colliders

This presentation is based on:

1) The HH white paper: "**Higgs boson potential at colliders: Status and perspectives**": https://arxiv.org/abs/1910.00012 published in REVIP in Nov. 2020.
2) Higgs pair workshop 2022 in Doubrovnik: https://indico.cern.ch/event/1001391/timetable/
3) LHC publications with full Run II dataset including "Jubileum" paper in Nature.

1) Theoretical bases of the BEH potential

1.1) The BEH potential in SM



BEH was introduced in the SM as a minimalistic function (quartic polynomial) with a non-trivial minimum (inspired for example by Landau-Ginzburg potential of Superconductors):

$$V(\mathrm{h}) = -m_{\mathrm{H}}^2 \mathrm{h}^2 + \lambda \mathrm{h}^4$$

before EWSB with "h" an EW doublet

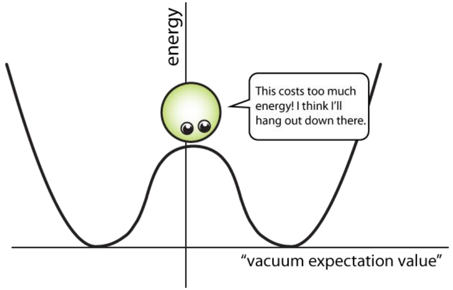
$$V(H) = \frac{1}{2} m_{\mathrm{H}}^2 \mathrm{H}^2 + \lambda v \mathrm{H}^3 + \frac{1}{4} \lambda \mathrm{H}^4 + V_0$$

after EWSB with H physical boson

"h = v+H"

The potential is defined by 3 parameters, 2 being independant:

$$m_{\mathrm{H}},\ \lambda,\ \mathrm{et}\ v = \frac{m_{\mathrm{H}}}{\sqrt{2\lambda}}$$



1.2) Potential parameters within SM paradigma

$$\lambda = \frac{m_{\mathrm{H}}^2}{2v^2}$$

Expérimentalement:

- Vev is measured via muon life time that provides Fermi constant with high precision

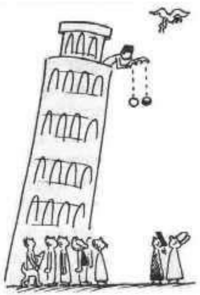
$$v = (\sqrt{2}G_{\mathrm{F}})^{-1/2} \simeq 246.22 \text{ GeV} \qquad \frac{G_{\mathrm{F}}}{(\hbar c)^3} = 1{,}166\,378\,7(6) \times 10^{-5} \text{ GeV}^{-2}$$

- Higgs boson mass is known with 0.1% precision from the LHC:

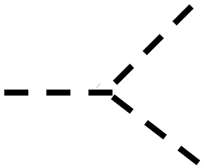
$$m_{\mathrm{H}} = 125.38 \pm 0.14$$

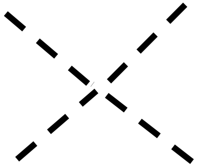
- Self-coupling within SM paradigma is known with precision of 0.2%.

1.3) Higgs Self-coupling: a direct handle



$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2\mathrm{H}^2 + \lambda v\mathrm{H}^3 + \frac{1}{4}\lambda\mathrm{H}^4 + V_0$$





Mass term

Triple self-coupling

Quartic self-coupling

1.4) How potential can be different from SM?

- It is important to remember that BEH potential is a postulate. We need to measure it directly!

- The Higgs boson discovery and it SM-like behaviour in EW sector shows that BEH potential shall be a very good approximation of the real potential.

- The real potential can be written in EFT approach or explicit models as :

$$V = V_{BEH} + \text{Correction}$$

1.5) Example of SM singlet extension

The Model

Extend the SM by a real scalar particle, S

V(H) ⟹ V(H, S)

Study the trilinear interactions

$$V_H(H) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2$$
$$V_{HS}(H,S) = \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2$$
$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

Chen, Dawson, Lewis
arXiv:1410.5488
and many others

$$V_{\rm self} \supset \frac{\lambda_{111}}{3!} h_1^3 + \frac{\lambda_{211}}{2!} h_2 h_1^2 + \frac{\lambda_{221}}{2!} h_2^2 h_1 + \frac{\lambda_{222}}{3!} h_2^3 +$$
$$\frac{\lambda_{1111}}{4!} h_1^4 + \frac{\lambda_{2111}}{3!} h_2 h_1^3 + \frac{\lambda_{2211}}{4} h_2^2 h_1^2 + \frac{\lambda_{2221}}{3!} h_2^3 h_1 + \frac{\lambda_{2222}}{4!} h_2^4.$$

arXiv.22xx.xxxx

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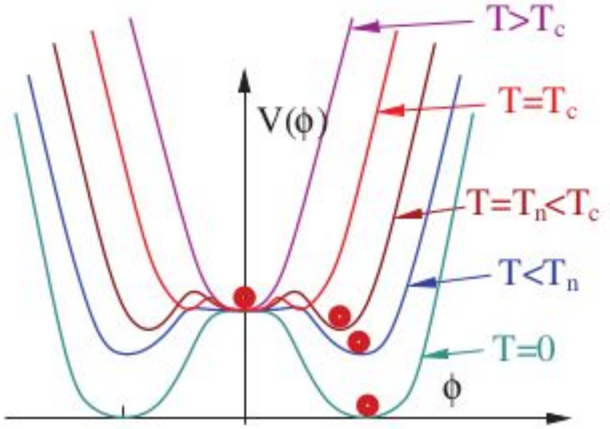
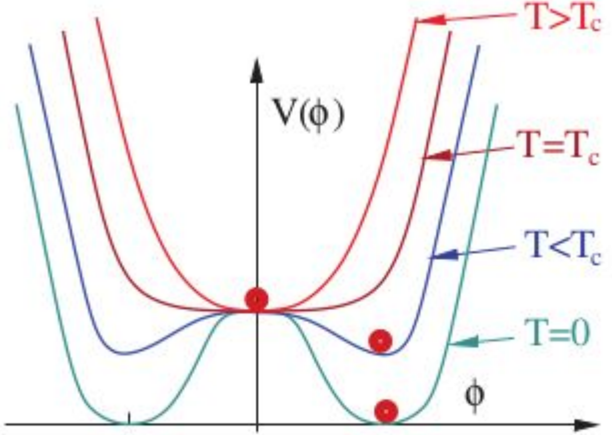
H. Alhazmi

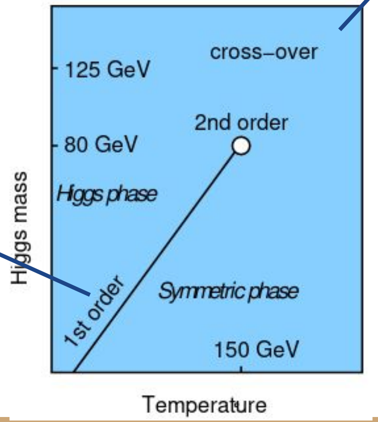
https://indico.cern.ch/event/1001391/contributions/4842692/attachments/2455023/4207706/Haider_Higgs_Pairs_2022.pdf

1.6) Connection to cosmology





- 1st order phase transition can generate baryon asymmetry.
- Requires lighter Higgs boson :(

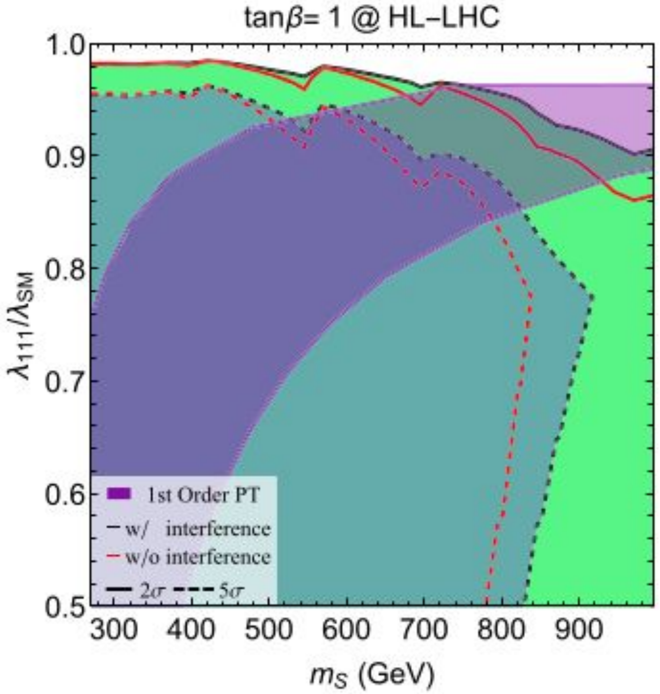


https://arxiv.org/pdf/2008.09136.pdf

1.6) Connection to cosmology

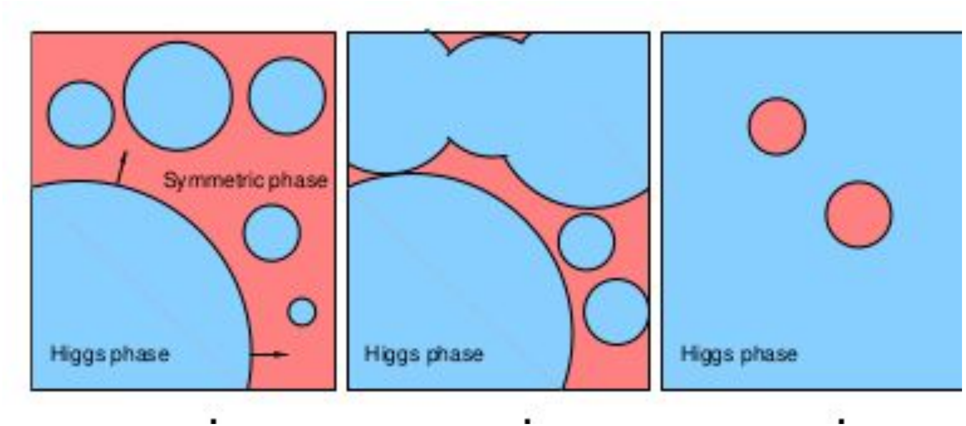
https://doi.org/10.1103/PhysRevD.97.095032.

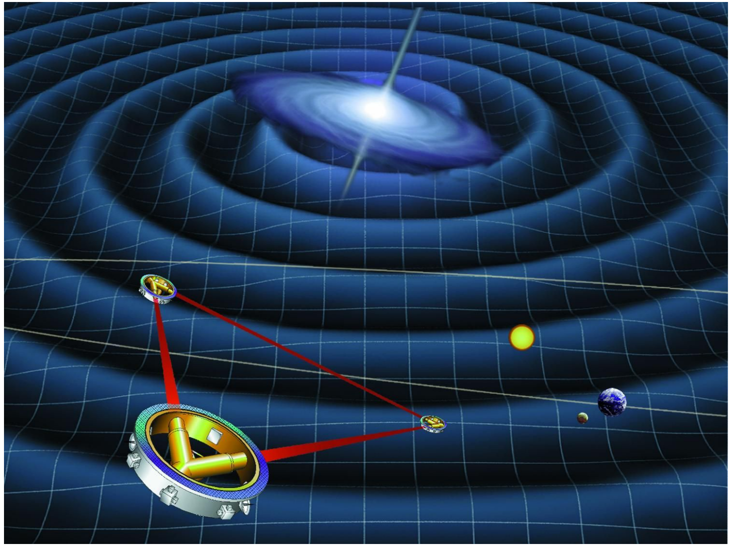
- Singlet extension can preserve the 1st order phase transition.
- It leads also to a different effective k_λ parameter of BEH potential.



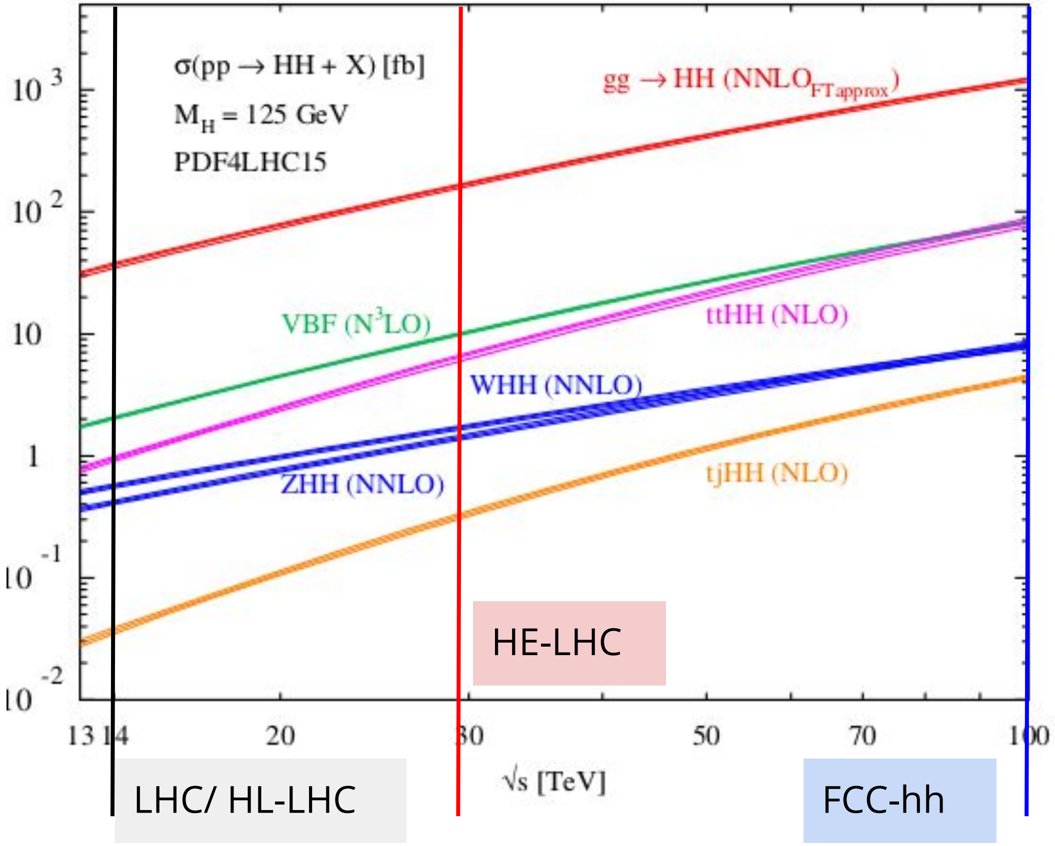
1.6) Connection to cosmology

- 1^{st} order phase transition can be also observed in large scale primary gravitational waves.

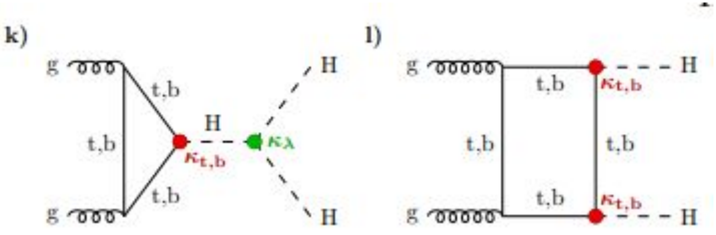




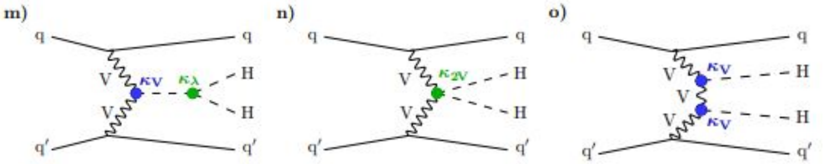
1.7) Production cross sections



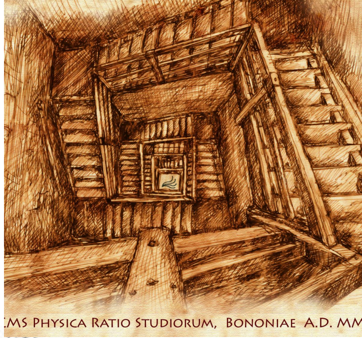
- Cross section rises as power law with √S
- Dominant production mode: gg → HH



- - Subdominant O(5%): VBF HH

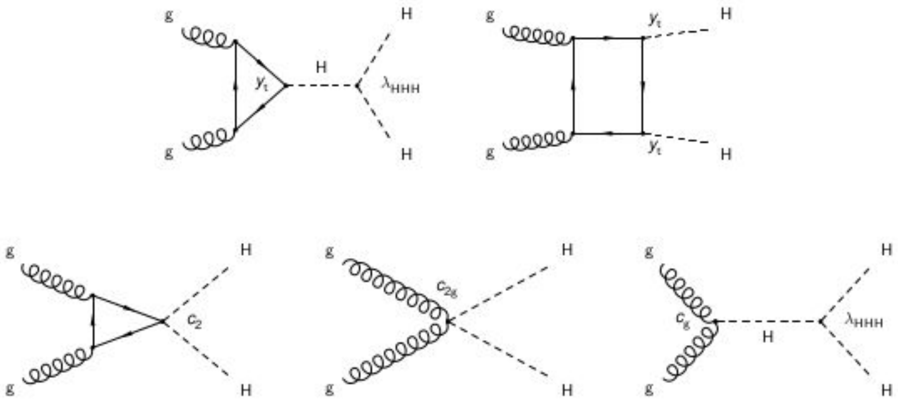


1.8) HH in HEFT



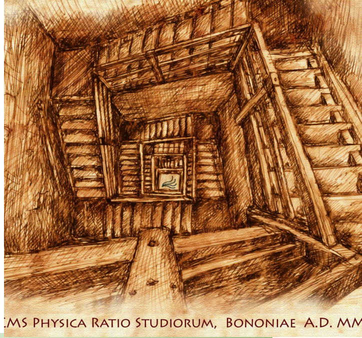
Potential part related to HH production* in gluon-gluon fusion:

$$\mathcal{L}_{\mathrm{HH}} = \kappa_\lambda \, \lambda^{\mathrm{SM}}_{\mathrm{HHH}} v \, H^3 - \frac{\mathrm{m_t}}{v}\left(\kappa_\mathrm{t} H + \frac{c_2}{v} H^2\right)\left(\bar{\mathrm{t}}_\mathrm{L} \mathrm{t}_\mathrm{R} + \mathrm{h.c.}\right) + \frac{1}{4}\frac{\alpha_\mathrm{s}}{3\pi v}\left(c_\mathrm{g} H - \frac{c_{2\mathrm{g}}}{2v} H^2\right) G^{\mu\nu} G_{\mu\nu}$$



* Neglecting some operators there : chromomagnetic, coupling to b quark. More details in J. Lang talk https://indico.cern.ch/event/1001391/contributions/4842688/attachments/2454956/4207582/JannisLang_HiggsPairs2022.pdf

1.9) Analytical parametrization



- One can build an analytical parametrization of HH production as function of these parameters.

LHCHXSWG-2016-001 and CERN YR4

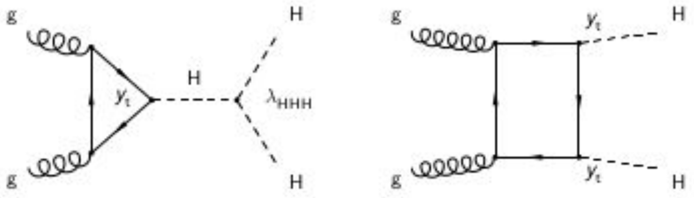
$$R_{\mathrm{HH}} \equiv \frac{\sigma_{gg\to\mathrm{HH}}}{\sigma^{\mathrm{SM}}_{gg\to\mathrm{HH}}} \stackrel{LO}{=} A_1\,\kappa_t^4 + A_2\,c_2^2 + (A_3\,\kappa_t^2 + A_4\,c_g^2)\,\kappa_\lambda^2 + A_5\,c_{2g}^2$$
$$+ (A_6\,c_2 + A_7\,\kappa_t\kappa_\lambda)\kappa_t^2 + (A_8\,\kappa_t\kappa_\lambda + A_9\,c_g\kappa_\lambda)c_2$$
$$+ A_{10}\,c_2c_{2g} + (A_{11}\,c_g\kappa_\lambda + A_{12}\,c_{2g})\,\kappa_t^2$$
$$+ (A_{13}\,\kappa_\lambda c_g + A_{14}\,c_{2g})\,\kappa_t\kappa_\lambda + A_{15}\,c_gc_{2g}\kappa_\lambda\,.$$

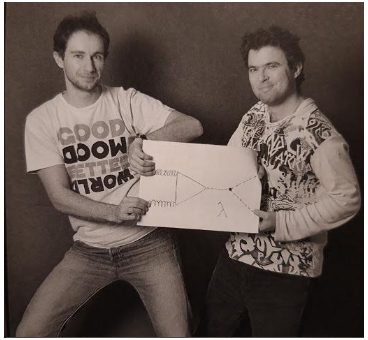
$$\sigma_{gg\to\mathrm{HH}} = \sigma^{\mathrm{SM}}_{\mathrm{HH,NNLO+NNLL}} \cdot R_{\mathrm{HH}}\,,$$

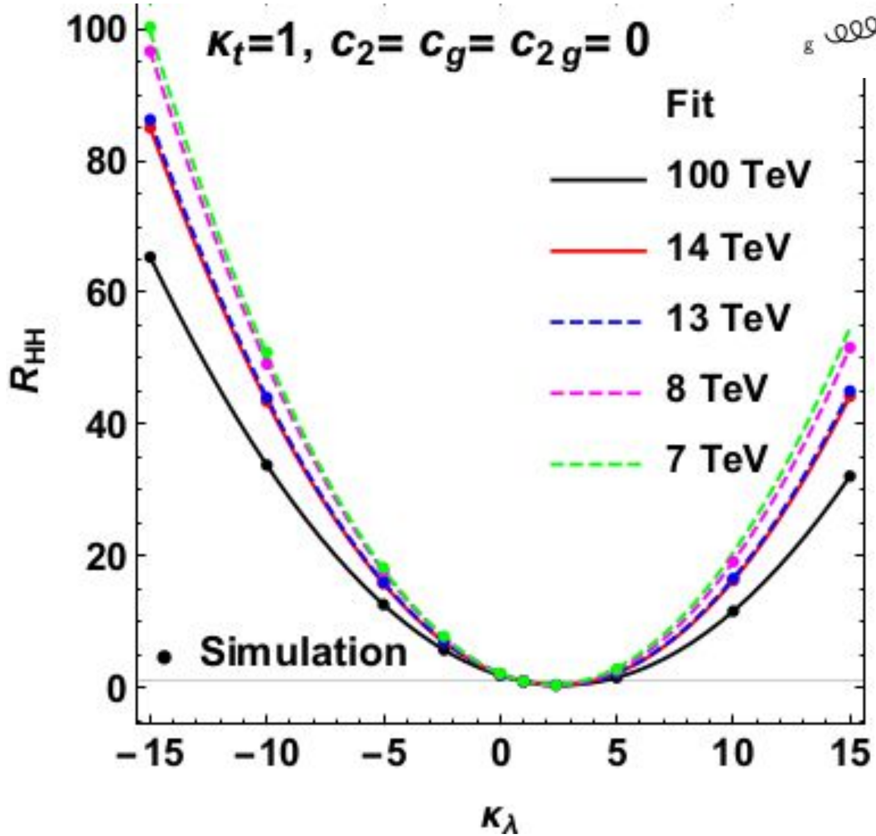
$\sqrt{s}$	7 TeV	8 TeV	13 TeV	14 TeV	100 TeV
A_1	2.21	2.18	2.09	2.08	1.90
A_2	9.82	9.88	10.15	10.20	11.57
A_3	0.33	0.32	0.28	0.28	0.21
A_4	0.12	0.12	0.10	0.10	0.07
A_5	1.14	1.17	1.33	1.37	3.28
A_6	-8.77	-8.70	-8.51	-8.49	-8.23
A_7	-1.54	-1.50	-1.37	-1.36	-1.11
A_8	3.09	3.02	2.83	2.80	2.43
A_9	1.65	1.60	1.46	1.44	3.65
A_{10}	-5.15	-5.09	-4.92	-4.90	-1.65
A_{11}	-0.79	-0.76	-0.68	-0.66	-0.50
A_{12}	2.13	2.06	1.86	1.84	1.30
A_{13}	0.39	0.37	0.32	0.32	0.23
A_{14}	-0.95	-0.92	-0.84	-0.83	-0.66
A_{15}	-0.62	-0.60	-0.57	-0.56	-0.53

For NLO parameterization have a look at L. Skyboz talk:
https://indico.cern.ch/event/1001391/contributions/4827320/attachments/2453035/4203719/HiggsPairs-2022_Scyboz.pdf

1.10) HH "SM"-like



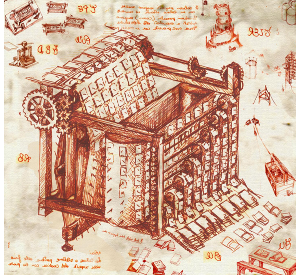




- Strong dependence on κ_λ with an interference minimum at κ_λ^{min} = 2.2.
- Strong interference and symmetry around κ_λ^{min}:

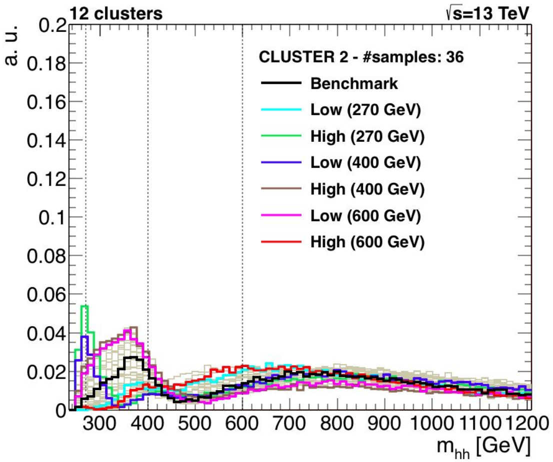
$$R_{HH} = A_1(2.09)\,\kappa_t^4 + A_3(1.33)\,\kappa_t^2\,\kappa_\lambda^2 + A_7(-1.37)\,\kappa_t^3\kappa_\lambda$$

1.11) Shape benchmarks: how to distinguish between different EFT parameters

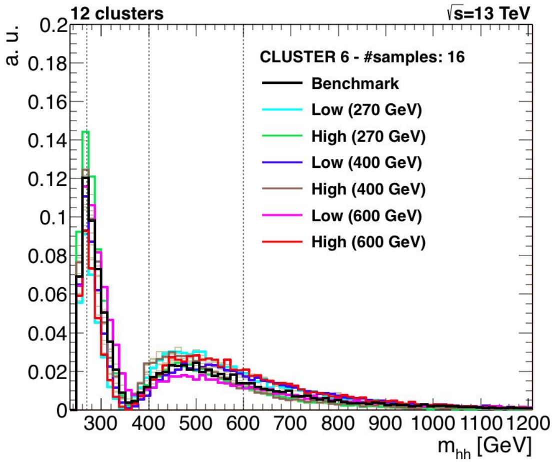


- Different operators have different mHH spectra -> Many operators complex interference patterns.
- At LO 12 typical benchmarks (arXiv:1507.02245, LHCHXSWG-2016-001, CERN YR4).
  More recently 7 BM an NLO including experimental constraints (arXiv:2204.13045).
- Any BSM point shape can be mapped to one of the benchmarks.

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	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
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	-1.0	1.0
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	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

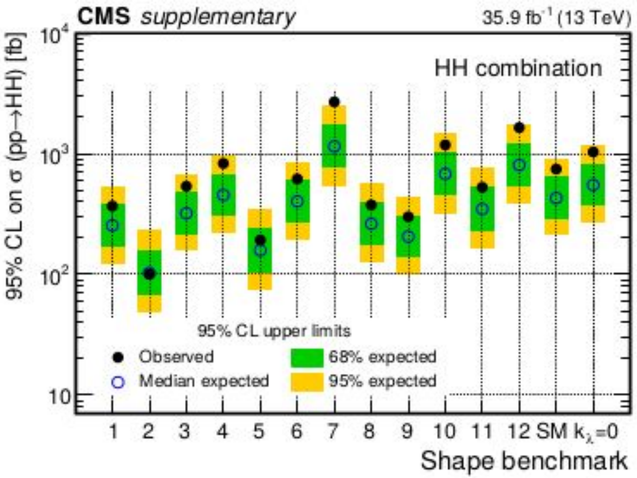


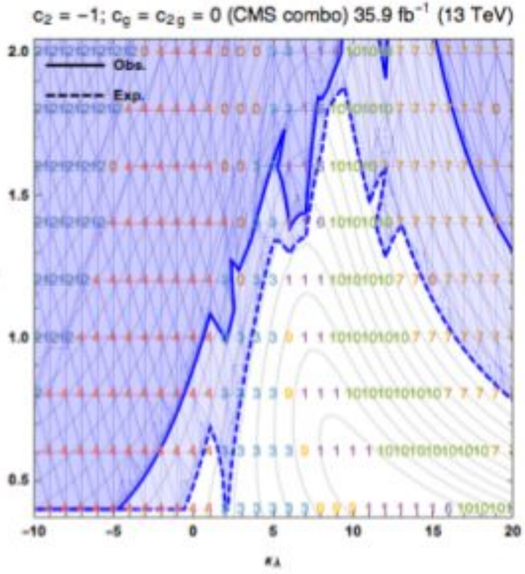
BSM with long UV tail



Maximal interference

1.12) How to use benchmarks

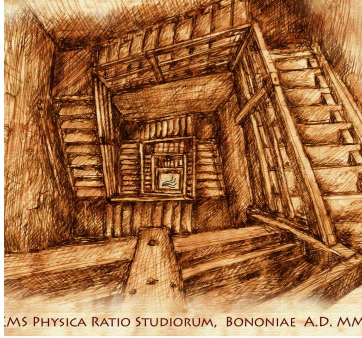




EFT parameter	Method	allowed interval at 95% CL	
		observed	expected
κ_λ	Benchmarks	-11 –20	-6 – 12
	CMS	-12 – 19	-7.1 – 14
κ_t	Benchmarks	-2.05 –2.3	
c_2	Benchmarks	-1.35 –1.45	

- Experiments provides limits on benchmarks. They can be mapped into EFT spaces or into explicit theories.

1.13) HEFT reinterpretation with explicit models



- SM-like: κ_λ et κ_t
- 2HDM, Vector Like Quarks... : κ_λ, κ_t et c_2
- Colored fermions in loops: c_g, c_{2g}.

  Linear EFT realisation (Higgs doublet of EW): $c_g = c_{2g}$

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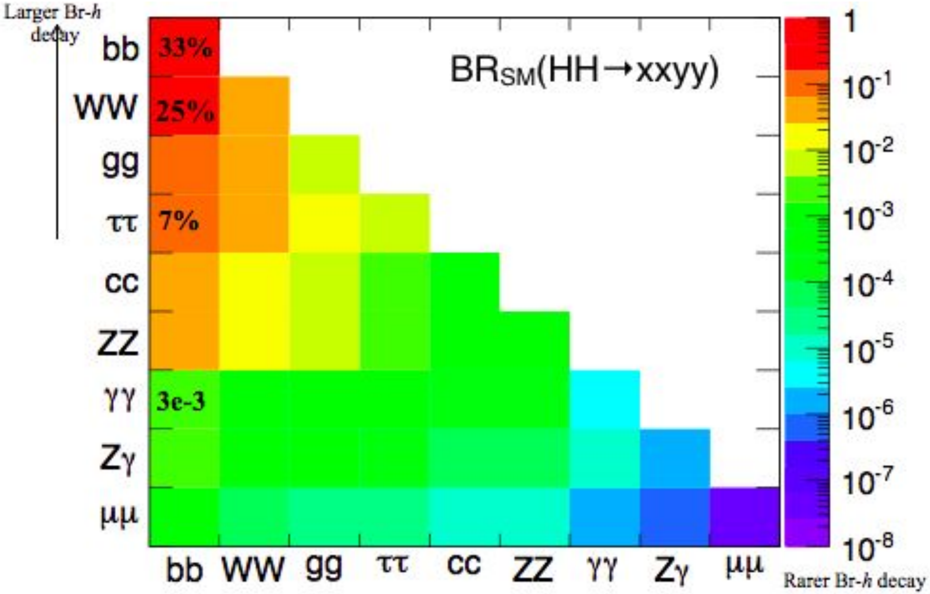
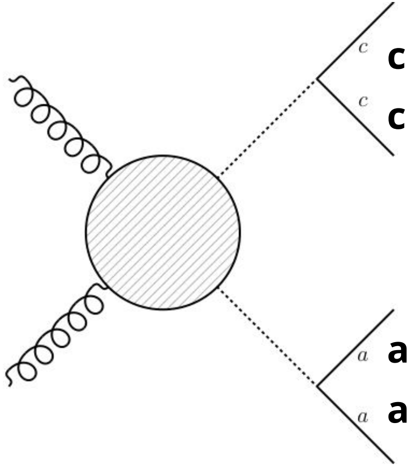
Fund. Parameters	κ_λ	κ_t	c_2
	real scalar singlet with explicit Z_2 breaking [73, 74]		
$\alpha, m_2, \lambda_\alpha$	$1 - \frac{3}{2}t_\alpha^2 + t_\alpha^2\left(\lambda_\alpha - t_\alpha \frac{m_2}{v}\right)/\lambda_{SM}$	$1 - \frac{t_\alpha^2}{2}$	$-\frac{t_\alpha^2}{2}$
	real scalar singlet with spontaneous Z_2 breaking [73]		
α	$1 - \frac{3}{2}t_\alpha^2$	$1 - \frac{t_\alpha^2}{2}$	$-\frac{t_\alpha^2}{2}$
	2HDM (addtl. scalars heavy + Z_2) [75]		
β, Z_6, m_H	$1 - \frac{3Z_6^2}{2\lambda_{SM}}\frac{v^2}{m_H^2}$	$1 - \frac{Z_6}{t_\beta}\frac{v^2}{m_H^2}$	$-\frac{3Z_6}{2t_\beta}\frac{v^2}{m_H^2}$

LHC results and HL-LHC projections

Danielle Monico, 2021

2.1) Higgs - squared

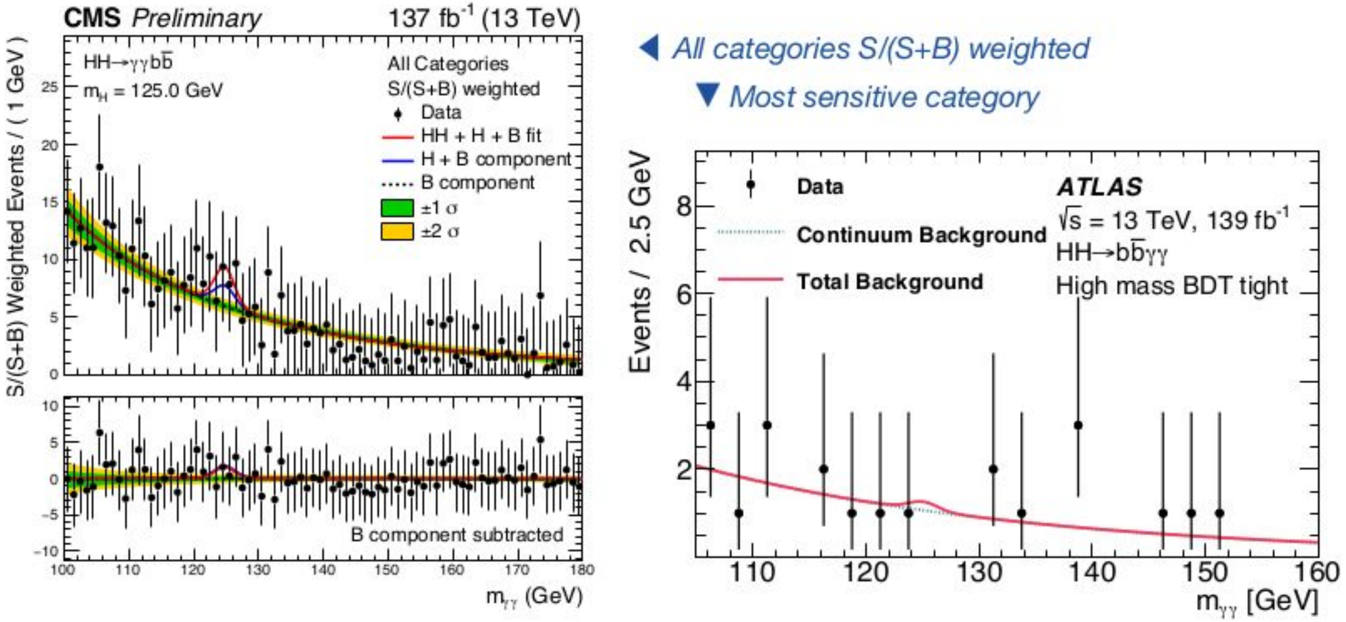




- Very challenging search:
  $\sigma_{HH} < \sigma_H/1000$
- Golden channels
  - **cc = bb** ⟶ BR(H->bb) = 57%
  - **aa = γγ, ττ, WW/ZZ** ⟶trigger and QCD background reduction.
  - **aa = bb** ⟶highest rate, but large background.
- Second level channels:
  - **γγWW, multileptons**: lower sensitivity, but many of them combined can bring some info.

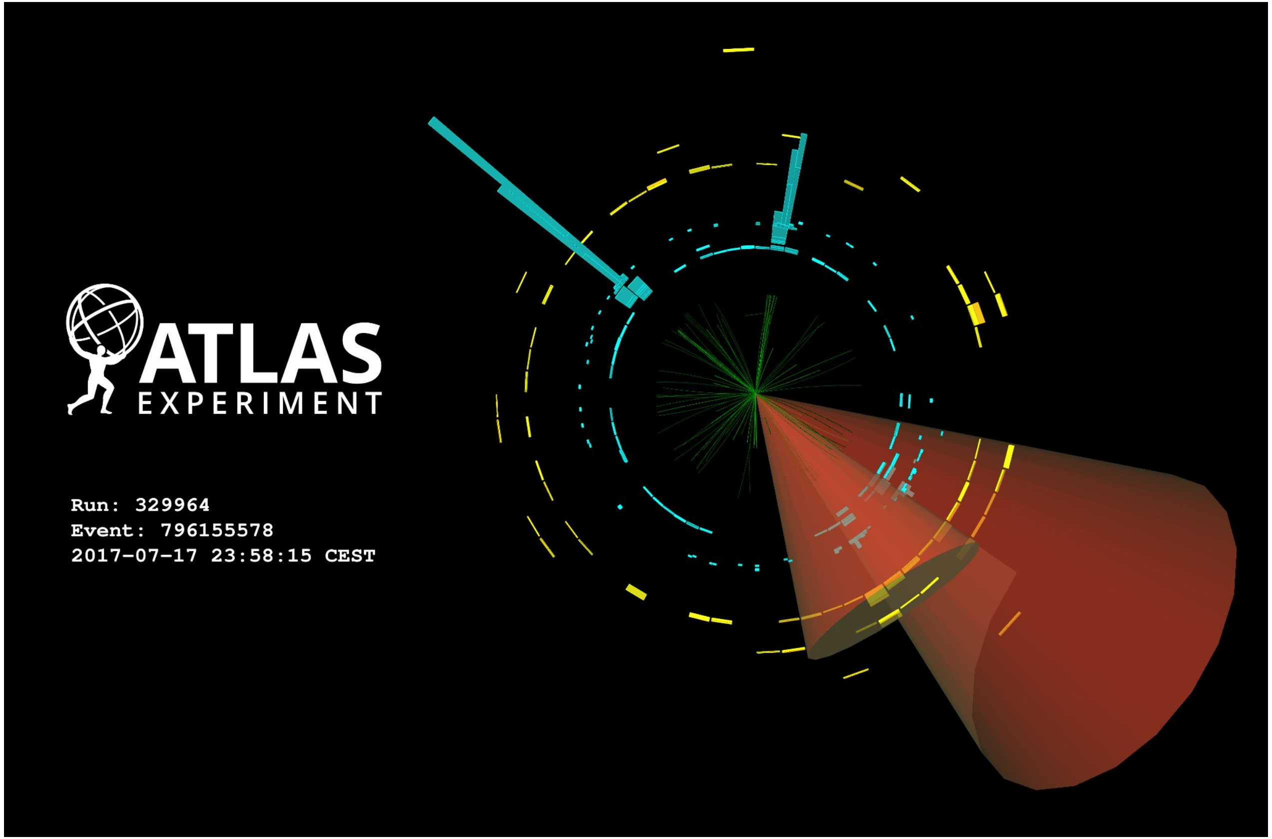
Nice experimental summary of HH production from L. Cadamuro
https://indico.cern.ch/event/1001391/contributions/4842925/attachments/2455652/4208916/HH_experimental_summary.pdf

2.2) Example of HH search: HH→ 2b2γ



- Similar flows of ATLAS and CMS analyses
- Purity and m_{HH} categories for maximal sensitivity
- Powerful signature from the $H\rightarrow\gamma\gamma$ decay used to search for a signal
- Sensitivity limited by stat. uncertainty

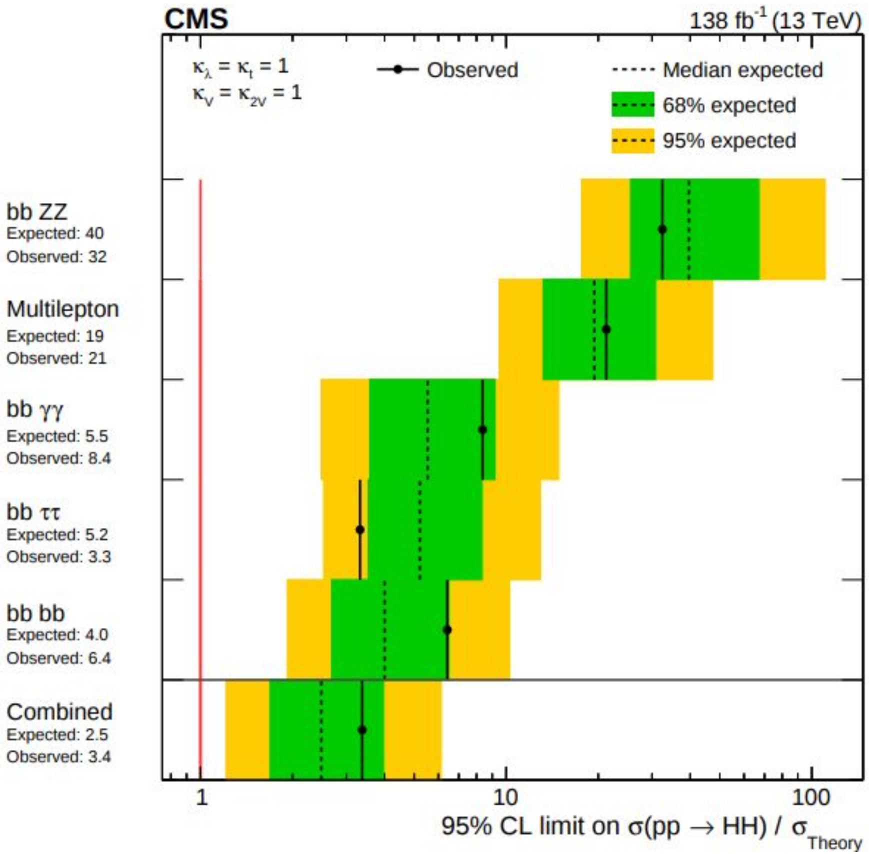
2.2) Example of HH search: HH$\longrightarrow$ 2b2γ



2.3) Information provided by the LHC analyses

1) Limit on total gg → HH cross section assuming SM-like combination of kL and kT
2) Exclusion rangle for kL (gg→HH and VBF HH)
3) Exclusion range for kL x kT
4) Exclusion range for BSM operators: c2
5) Exclusion / gg → HH BSM benchmark
6) Exclusion range: c2v - cv (VBF HH)
7) Limits on resonant production: gg->X->HH or gg → X → YH

2.4) Higgs Jubilee paper in Nature: SM HH

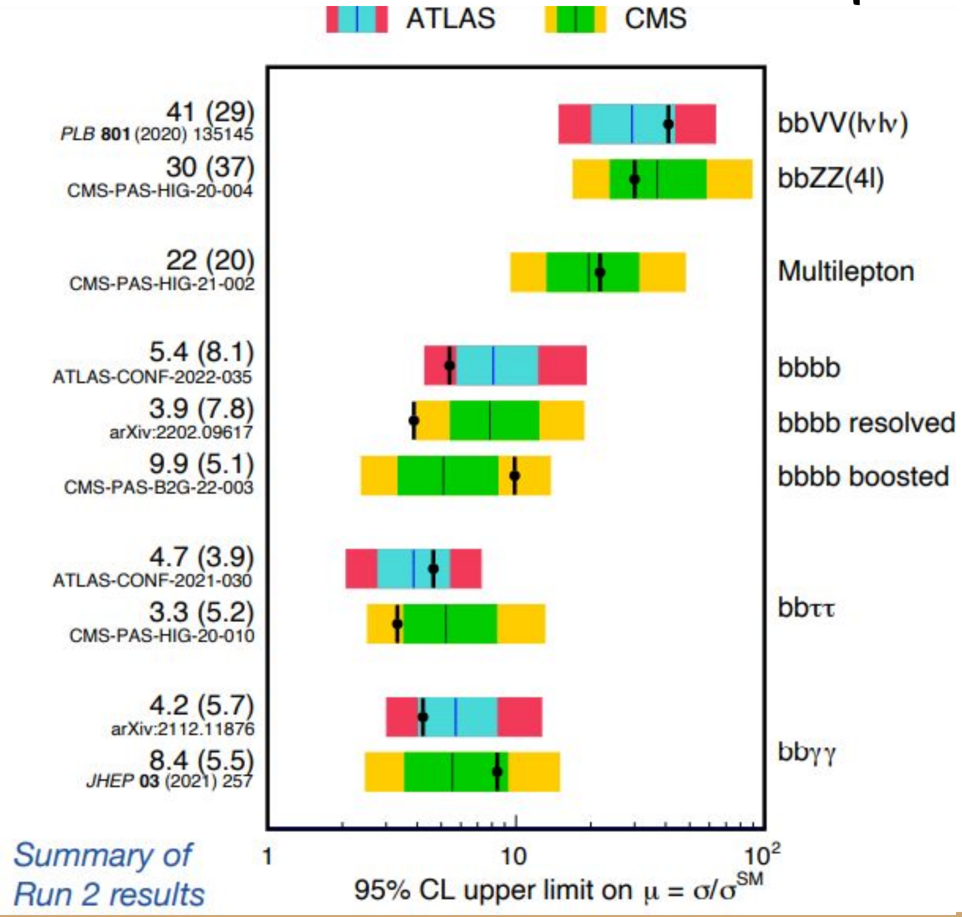


- ATLAS and CMS published in Nature 2 papers describing the portrait of the Higgs boson.
- CMS included part of the HH results with full Run II (138 fb-1) and their combination.

→We are getting closer and closer to SM HH.

[Nature 607 (2022) 60-68]()

2.5) ATLAS vs CMS comparison



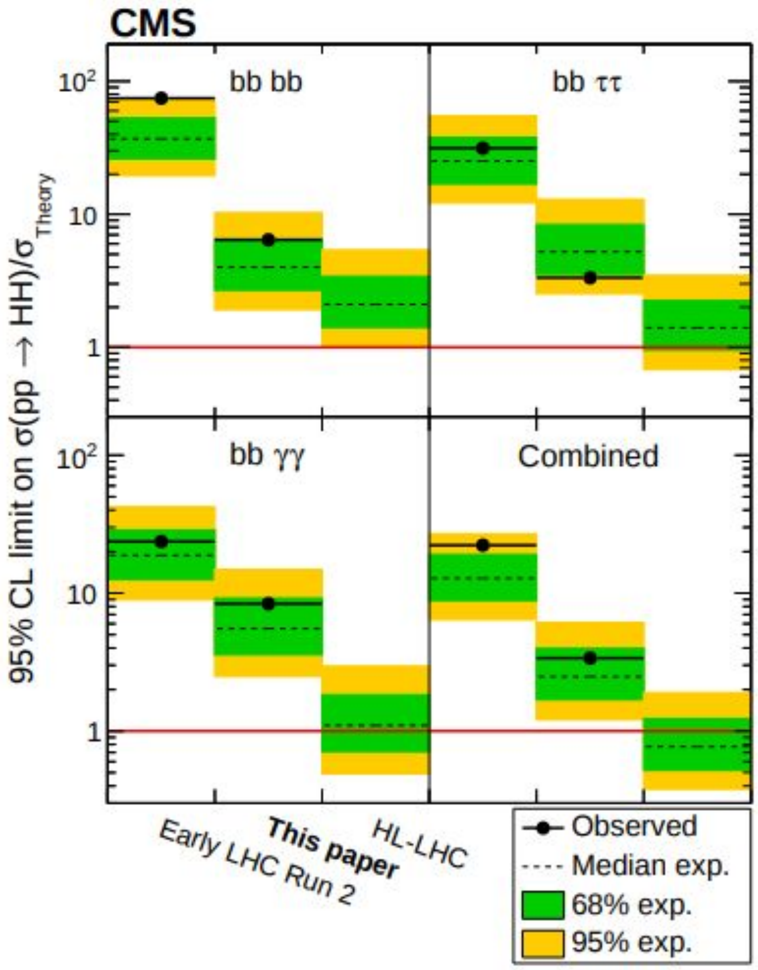
- CMS and ATLAS results for different channels are comparables.

→Including more channels and combining between collaborations the limit < 2 SM is within the reach of Run II.

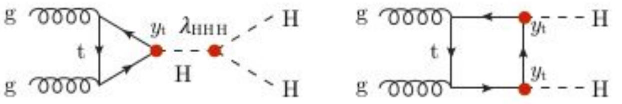
2.6) Improvements over time

	Early anal.	Run II	Run III + Run II	HL-LHC
Lumi	36	138	400	3000
sqrt (S) scaling wrt to early analysis	1	2	3.3	10

Run II analysis is improving much faster than simple luminosity scaling.
Run III + Run II may tackle SM HH once combining ATLAS + CMS.



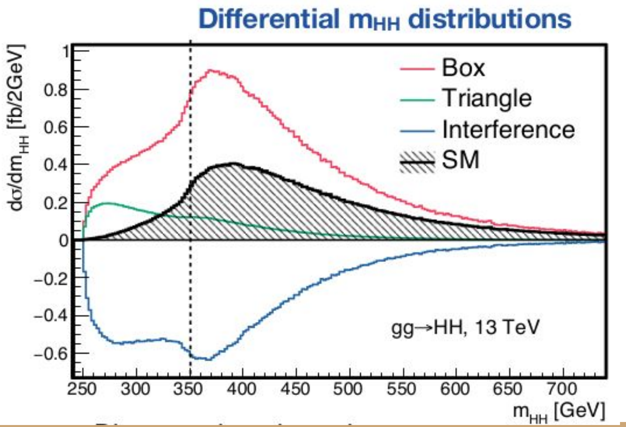
2.7) Self-coupling extraction Run II: k_λ

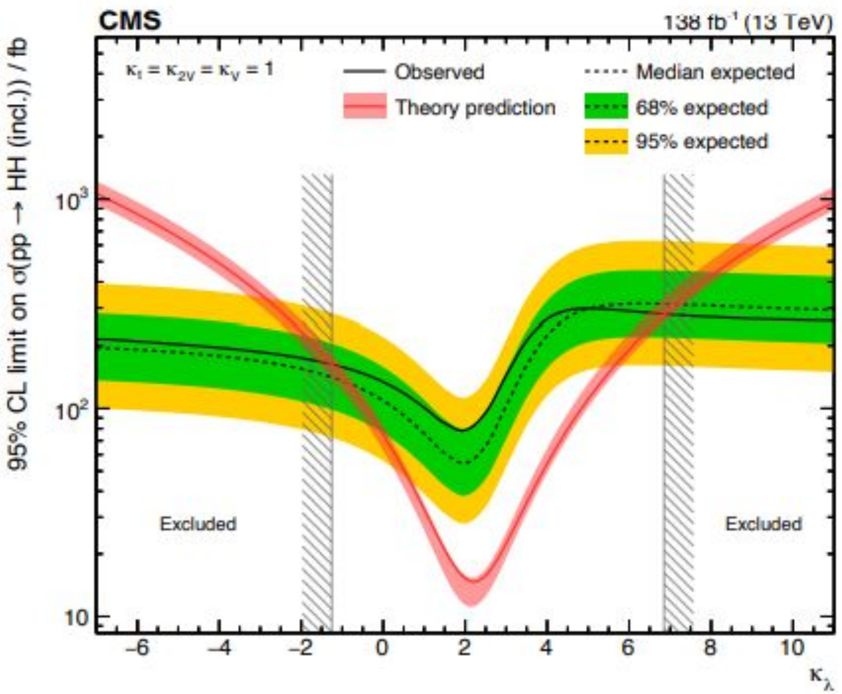


SM k_λ is complicated to measure:

- HH production is dominated by top box diagram: 90% of the total
- Softer spectrum for k_λ >> |1|
  - → lower reconstruction efficiency,
  - → larger cross section.
- Very strong negative interference for $0 < k_\lambda < 4$
  - → harder spectrum
  - → smaller cross section

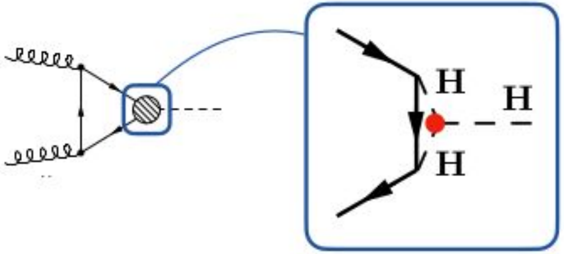
$$R_{HH} = A_1(2.09)\,\kappa_t^4 + A_3(1.33)\,\kappa_t^2\,\kappa_\lambda^2 + A_7(-1.37)\,\kappa_t^3\kappa_\lambda$$





2.8) "Global fit"

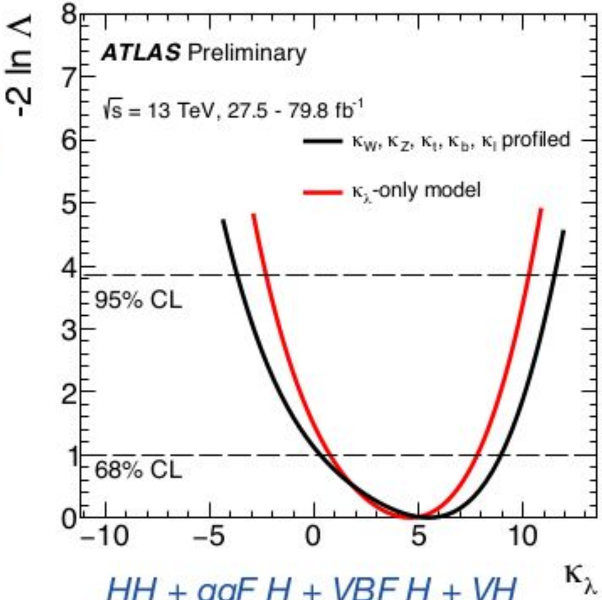
$$R_{HH} = A_1(2.09)\,\kappa_t^4 + A_3(1.33)\,\kappa_t^2\kappa_\lambda^2 + A_7(-1.37)\,\kappa_t^3\kappa_\lambda$$



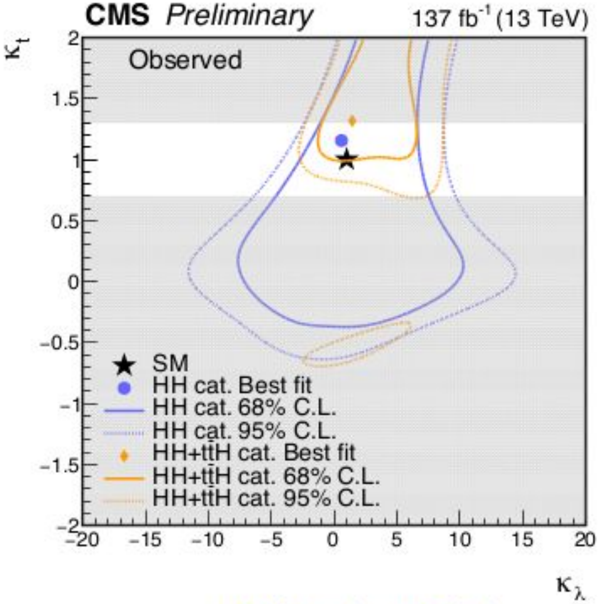
Sensitivity to λ_{HHH} from loop-level effects

- Experimental challenges from channel overlap
- Strong assumptions in the interpretation (κ framework + NLO effects)
- A global model-independent EFT fit as the next step

Global view of λ_{HHH} effects in Higgs physics



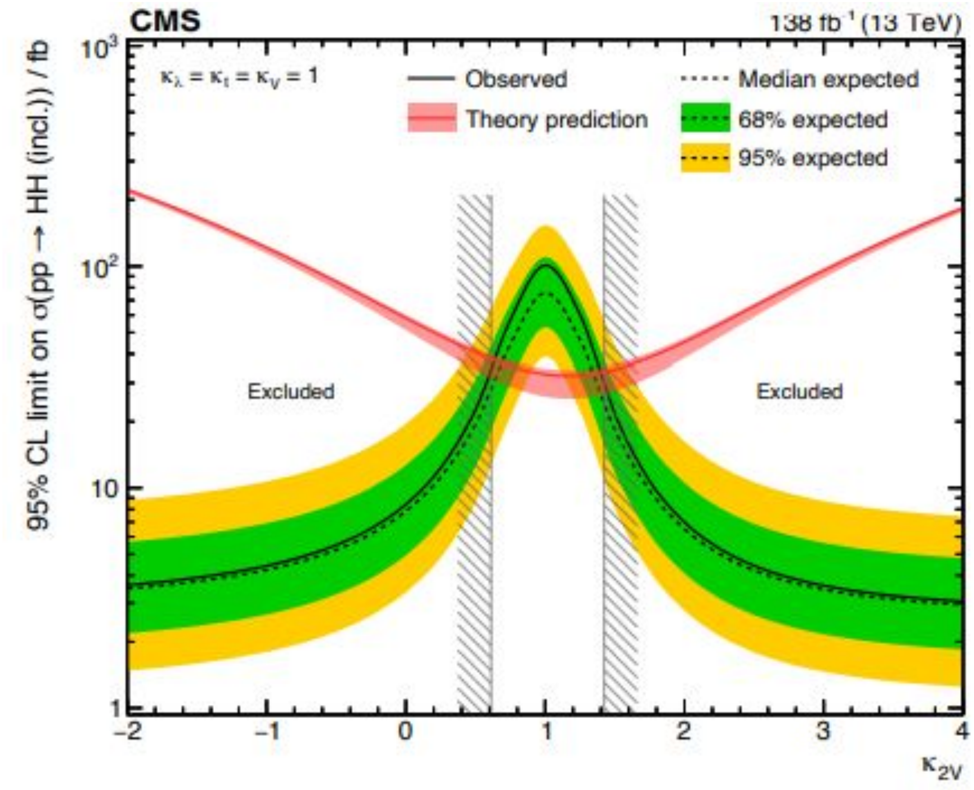
HH + ggF H + VBF H + VH + ttH (excl ttH(γγ))



HH(bbγγ) + ttH(γγ)

Slide from https://indico.cern.ch/event/1001391/contributions/4842925/attachments/2455652/4208916/HH_experimental_summary.pdf

2.9) First “measured” HH coupling: k_{2V}



- Sensitivity to k_{2V} is obtained through the unitarisation constraint.

$$\mathcal{A}(V_L V_L \to \mathrm{HH}) \simeq \frac{\hat{s}}{v^2}\left(C_{2V} - C_V^2\right)$$

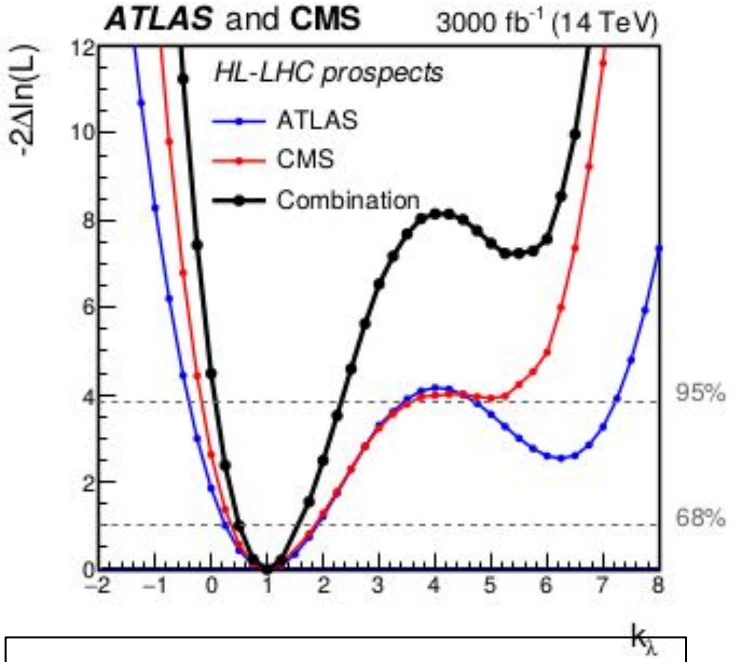
- We observe this operator! Significance > 5σ is already reached.

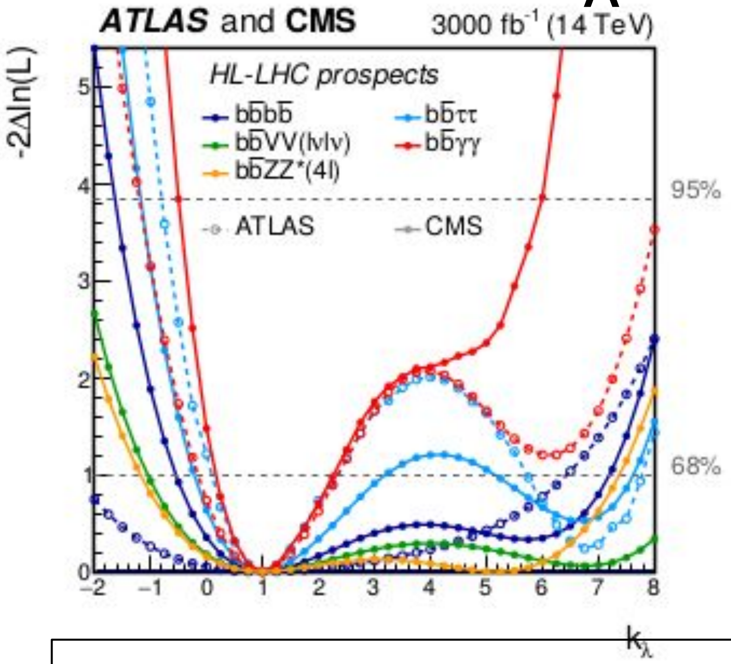
- The specificity there is that we claim the observation by “negative result”, that is less valuable than a

Projections for future colliders

A bit of dream

3.1) Self-coupling extraction HL-LHC: k_λ





k_λ = 1+- 50% is expected.

30% precision may be reached with analysis improvements.

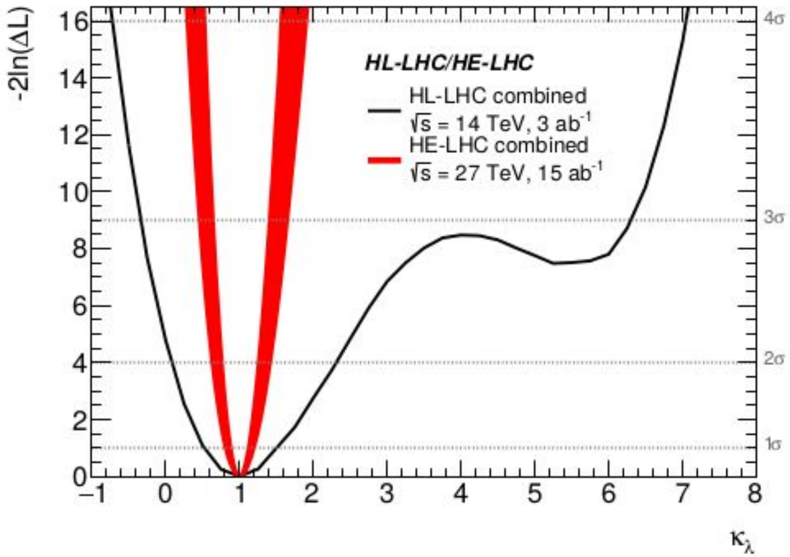
Best channels for self-coupling HH→bbγγ et HH→bbττ sensibles at low m_{HH} : low background and good low p_T trigger.

3.2) Constraints from future pp colliders

Table 23

Expected precision on the direct Higgs self-coupling measurement at future 27 and 100 TeV $p-p$ colliders.

	HE-LHC (27 TeV, $\mathcal{L}$ = 15 ab^{-1})	FCC-hh (100 TeV, $\mathcal{L}$ = 30 ab^{-1})
$\delta\kappa_\lambda$	10–20%	5–7%

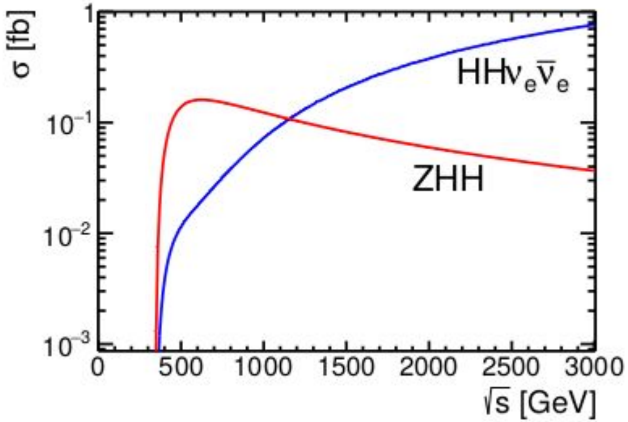


- Higgs self-coupling can be measured with high precision in future pp colliders.

"Higgs Physics at the HL-LHC and HE-LHC", CERN Yellow Report, https://arxiv.org/abs/1902.00134

3.3) Constraints from future ee colliders

- The direct HH production in ee colliders require quite high √S



collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

- kλ can be extracted from EW corrections to single Higgs production in ee colliders.
- Best contraint expected from combination with HL-LHC at least.

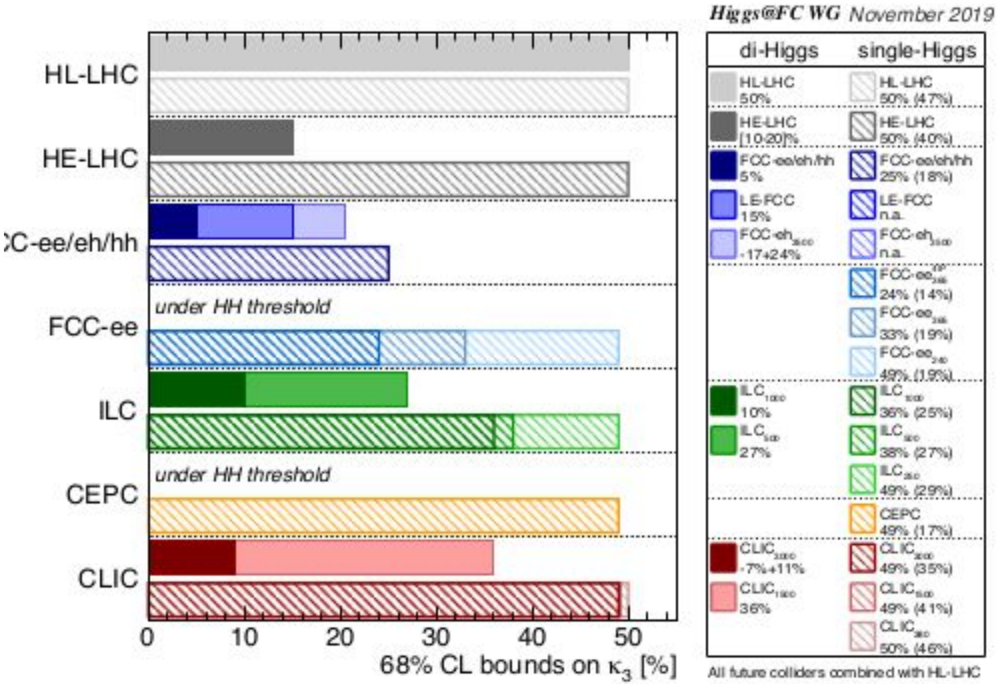
Conclusion

- The LHC program is slowly getting into the BEH potential constraints
- It is a very large scale project O(300) people including experimentalists and theoreticians comparable to the Higgs boson discovery effort.
- BEH potential constraint is the guaranteed and wanted output of any future collider project.

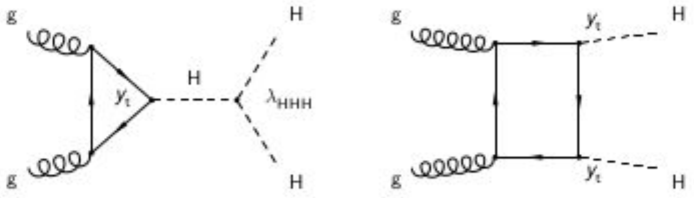
BACKUP

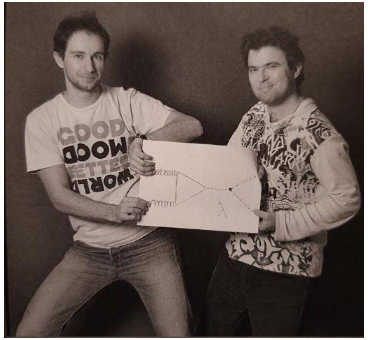
Danielle Monico, 2021

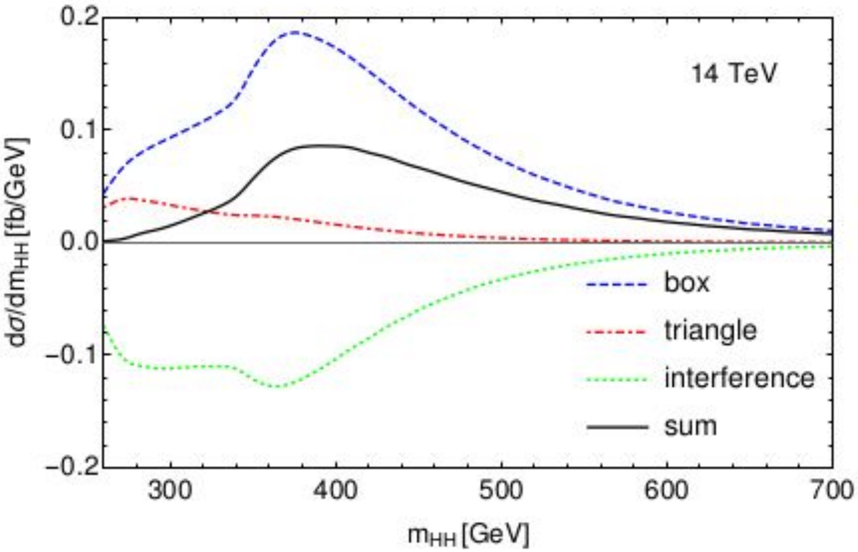
collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-



How to distinguish different







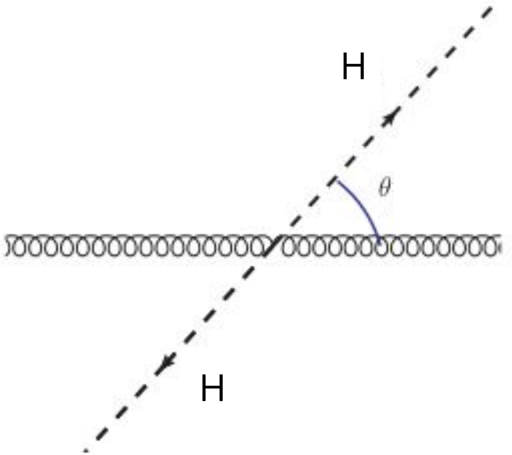
- A 13 TeV: $\sigma_{SM}(HH)$ ~ 31 fb
  - 1000 fois moins que $\sigma_{SM}(H)$!

$$\sigma_{hh} = \sigma_T + \sigma_B + 2\cos(\alpha_I)\sqrt{\sigma_T \sigma_B}$$

avec $\cos \alpha_I$ ~ - 0.9

- Très forte dépendance de m_{HH} = s_hat

Considérations cinématiques simples

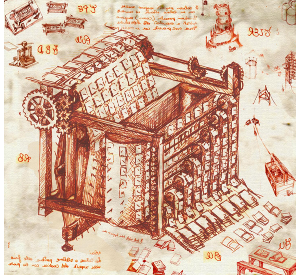


- Etat final gg → HH décrit par 8 variables:
  - 2 Higgs sur couche de masse.
  - 2 lois de conservation pTx, pTy.
  - 1 Invariance en Phi
  - PzHH → caractéristique des PDFs
  - 2 Inv. de Lorentz:
    - $\cos\theta^*_{HH}$ → La production HH est dominée par la S-wave → uniforme en $\cos\theta^*_{HH}$
    - m_{HH} → s_hat

Analyse en cluster

arXiv:1507.02245, LHCHXSWG-2016-001, CERN YR4

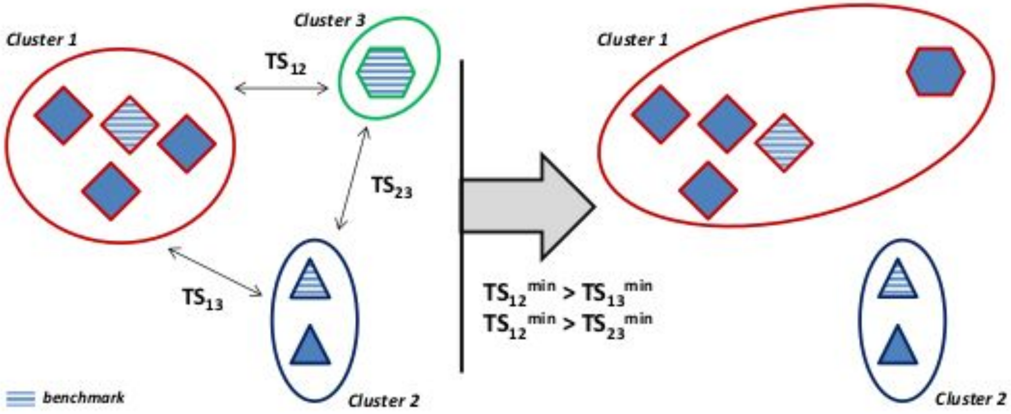
Travail effectué avec U. Padova et ma thésarde A. Oliveira



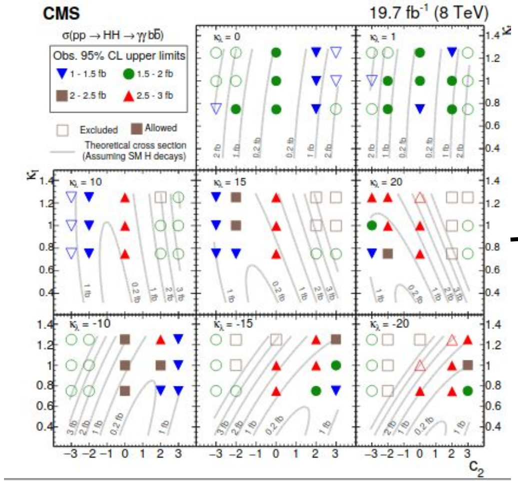
- Généré 1507 points qui maillent l'espace en LO
- Construit une Statistique des test qui sert de "distance" sur l'espace des spectres $\sigma= f(m_{HH}, \cos\theta^*)$

$$TS = 2\,log\left(\frac{L}{L_S}\right) = -2\sum_{i=1}^{N_{bins}}\left[log(n_{i,1}!) + log(n_{i,2}!) - 2log\left(\frac{n_{i,1}+n_{i,2}}{2}!\right)\right]$$

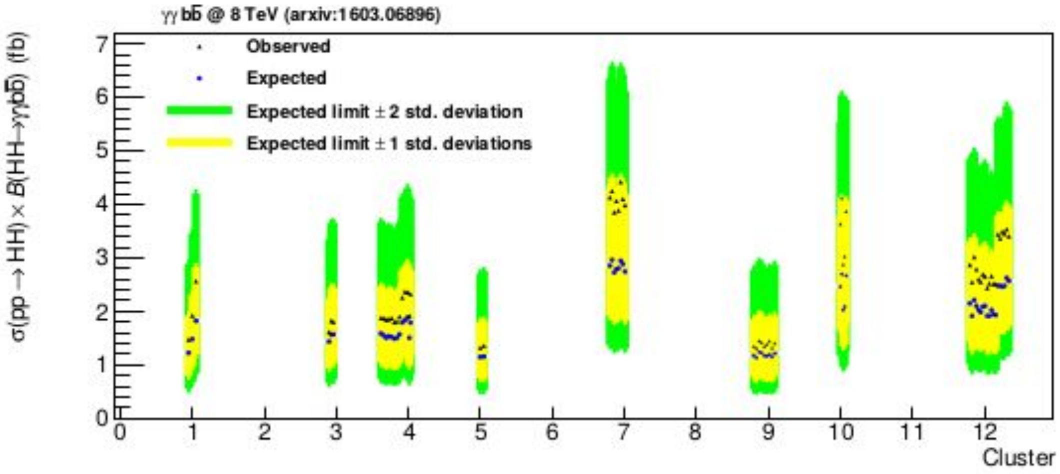
- Tourné un algorithme de partition de l'espace en un nombre prédéfini de clusters



Preuve du principe



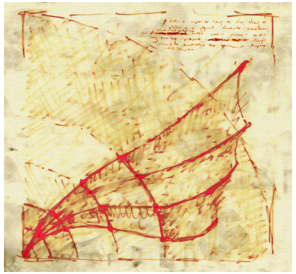
PRD 94, 052012 (2016)

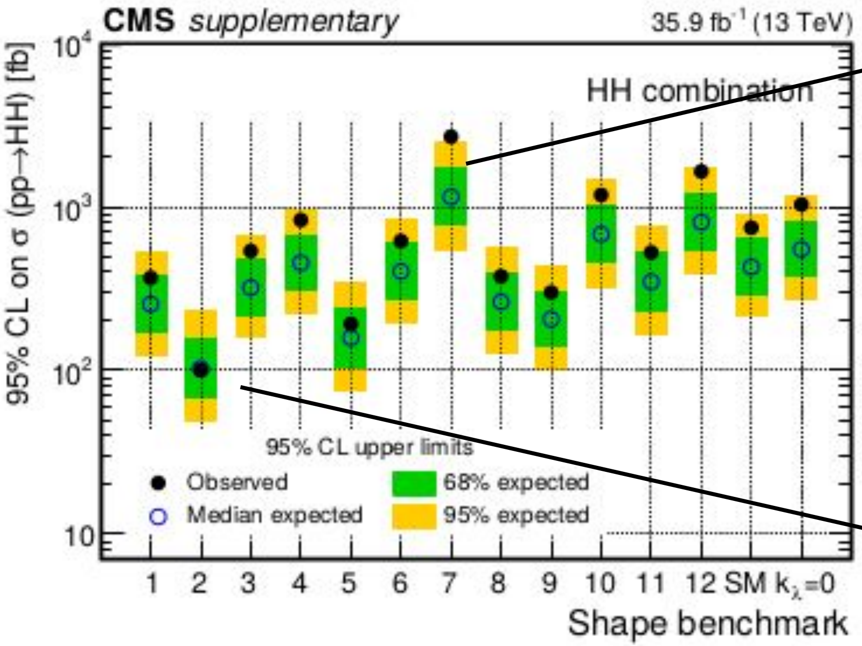


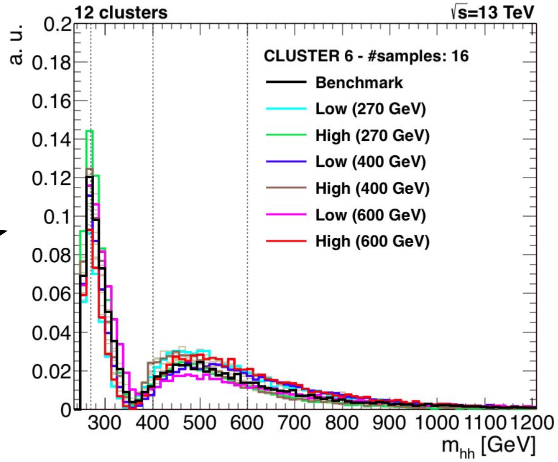
- Preuve expérimentale avec 120 limites obtenus avec de vrai échantillons générés.
- Puis répartis en 12 clusters

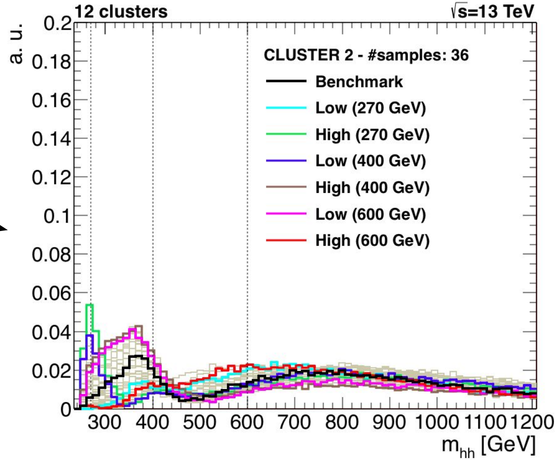
  Variance intra clusters (~20%) << Variance extra-cluster (Fisher-Snedecor)
- La limite entre clusters peut varier d’un facteur 3!!!

Utilisation 1/2









- Repérage d’excès possibles