BSM models for Multiboson

COMETA WG1 Kick-Off Meeting

10 November 2023

Jose Miguel No

IFT-UAM/CSIC, Madrid

What BSM?

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... I will focus on **neutral resonances**

(will also comment on charged resonances & multiboson decays)

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... I will focus on **neutral resonances**

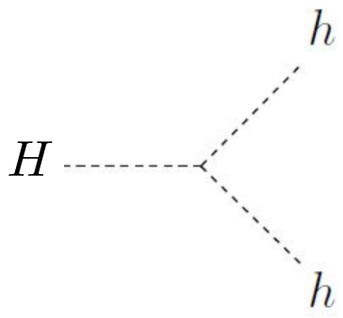
GOAL of this TALK

Discuss/highlight key aspects* for **resonant multiboson LHC signatures** which COMETA can address and/or improve on.

*my own view... discussion very welcome!

1. Di-Higgs & Di-boson interplay

- **Neutral states with $H \to hh$ also feature $H \to VV$**



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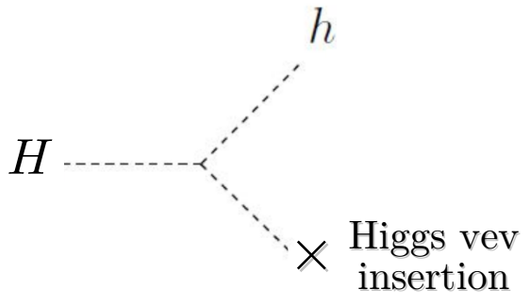
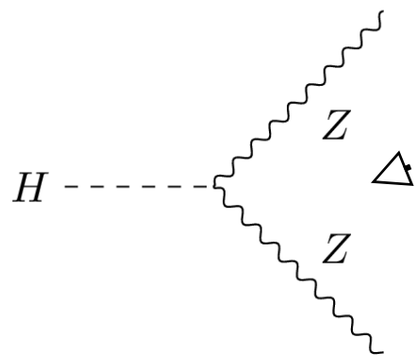


"mixing"

scalar excitation aligned with Higgs vev → not mass eigenstate

$\mathbf{v} + \boldsymbol{\varphi}$

φ = admixture of H and h



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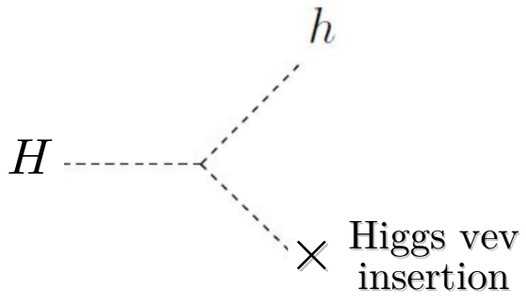

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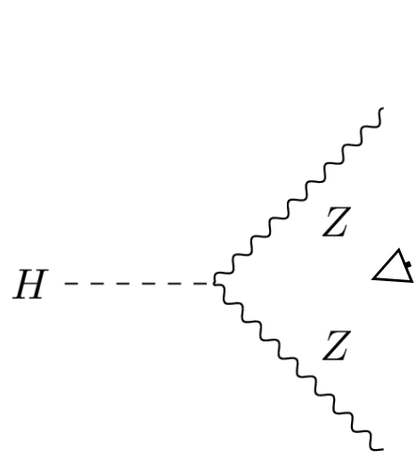


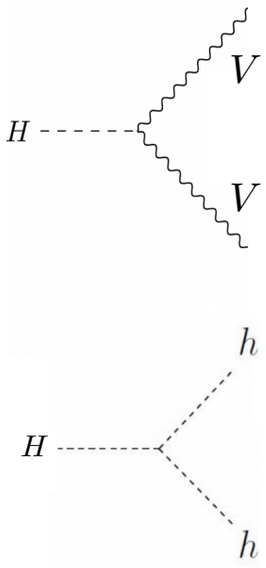
Naive estimate – Goldstone Equivalence Theorem – for $m_H^2 \gg m_W^2$ yields:

$$\mathrm{BR}(H \to W^+W^-) = 0.5, \quad \mathrm{BR}(H \to ZZ) = 0.25, \quad \mathrm{BR}(H \to hh) = 0.25$$

1. Di-Higgs & Di-boson interplay

- Neutral states with $H \to hh$ also feature $H \to VV$
- **Yet, sizable deviations from GET expected in specific models**

  e.g. **2HDM**



$$\sim c_{\beta-\alpha}$$

$$\sim \frac{-c_{\beta-\alpha}}{2v^2}\Big[(2\,m_h^2+m_H^2-4\,M^2)s_{\beta-\alpha}^2+2\,t_{2\beta}^{-1}(2\,m_h^2+m_H^2-3\,M^2)s_{\beta-\alpha}c_{\beta-\alpha} - (2\,m_h^2+m_H^2-2\,M^2)c_{\beta-\alpha}^2\Big]$$

...even possible for Hhh coupling to vanish!

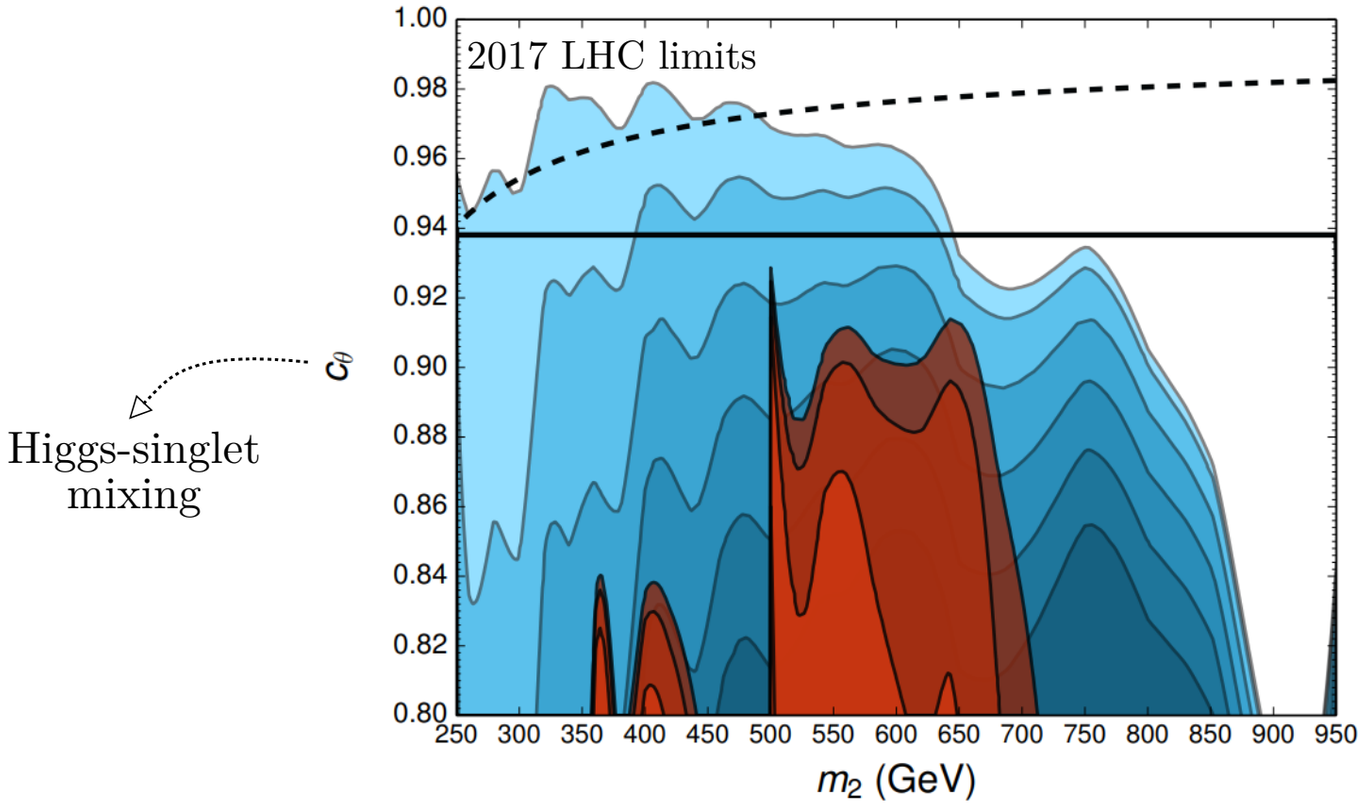
1. Di-Higgs & Di-boson interplay

- Neutral states with $H \to hh$ also feature $H \to VV$
- **Sizable deviations from GET expected in specific models**

di-Higgs vs di-boson BRs: large variation across model parameter space

Impact on LHC limits ...

e.g. Higgs + singlet (**xSM**)



$H \to ZZ$ $H \to hh$

$\lambda_{Hhh}/v = 0, 1, 2, 3, 4, 5$

Lighter $\to$ Darker

Huang, JMN, Pernie, Ramsey-Musolf, Safonov, Spannowsky, Winslow. PRD 96 035007 (2017)

1. Di-Higgs & Di-boson interplay

- Neutral states with $H \to hh$ also feature $H \to VV$
- **Sizable deviations from GET expected in specific models**

di-Higgs vs di-boson BRs: large variation across model parameter space

Strong di-Higgs – di-boson LHC complementarity in BSM

Yet, very few studies in literature*...

Butazzo, Sala Tesi. JHEP 11 158 (2015)

Zhang, Li, Liu, Ramsey-Musolf, Zeng, Arunasalam. arXiv:2303.03612

*There must be more, I just don't know them!

1. Di-Higgs & Di-boson interplay

- Neutral states with $H \to hh$ also feature $H \to VV$
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- **Combining di-Higgs & di-boson data** breaks degeneracies in parameter space of models

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(obvious) e.g.

$pp \to H \to hh$ ➡ degeneracy between $\dfrac{pp \to H}{pp \to H_{\rm SM}}$ and BR($H \to hh$)

Combination with $pp \to H \to VV$ allows to separate both

(at least partially!)

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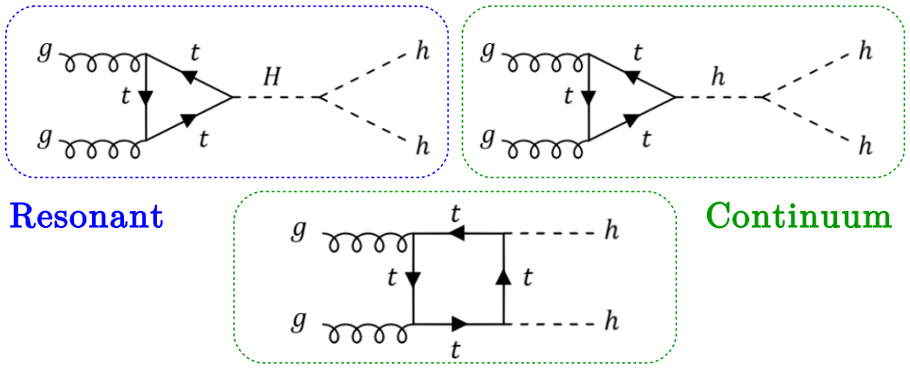
For certain models, combinations of constraints may yield **maximum allowed Cross Sections** (that could well be below experimental limits!)

⬇

Link to **LHC "Inverse problem"**

2. Interference effects in Di-Higgs



courtesy: Alain Verduras

Interference between **resonant** & **non-resonant** di-Higgs could be important...

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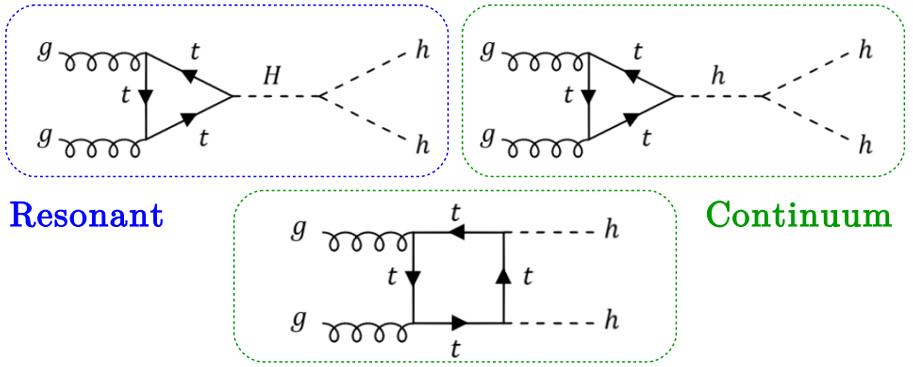

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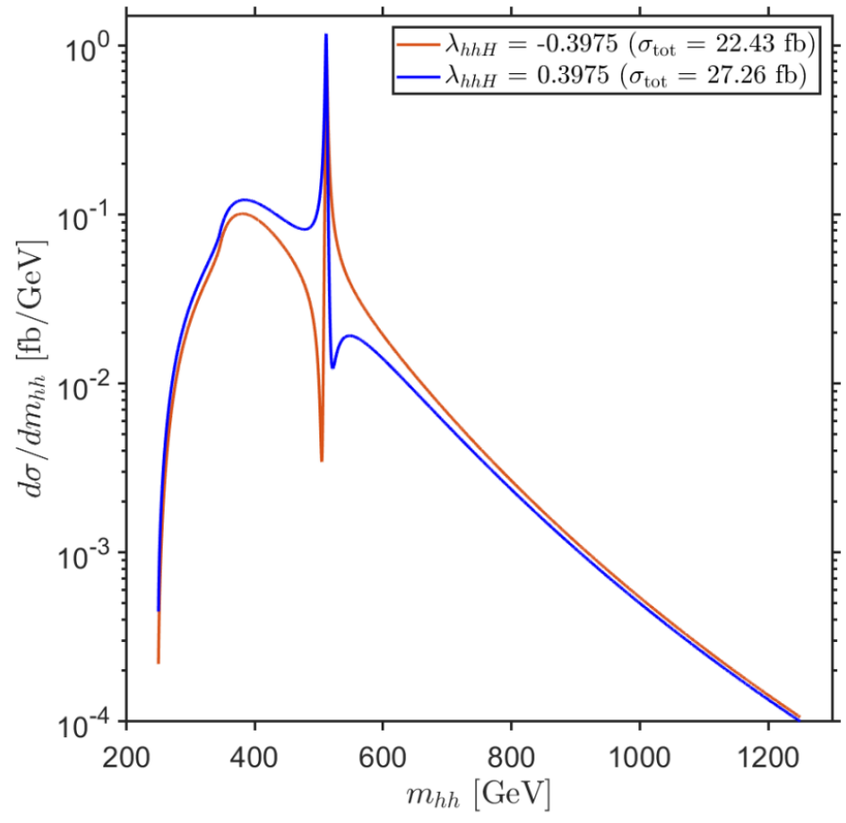
Interference between **resonant** & **non-resonant** di-Higgs could be important...

... and might yield valuable physical information!



Arco, Heinemeyer, Muhlleitner, Radchenko. arXiv:2212.11242

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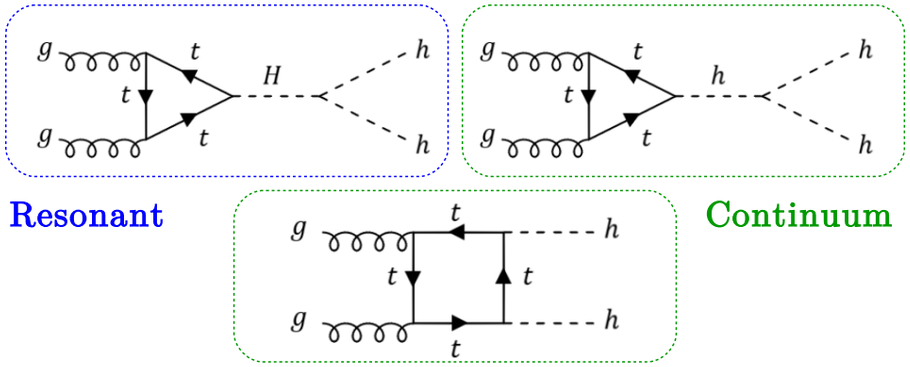

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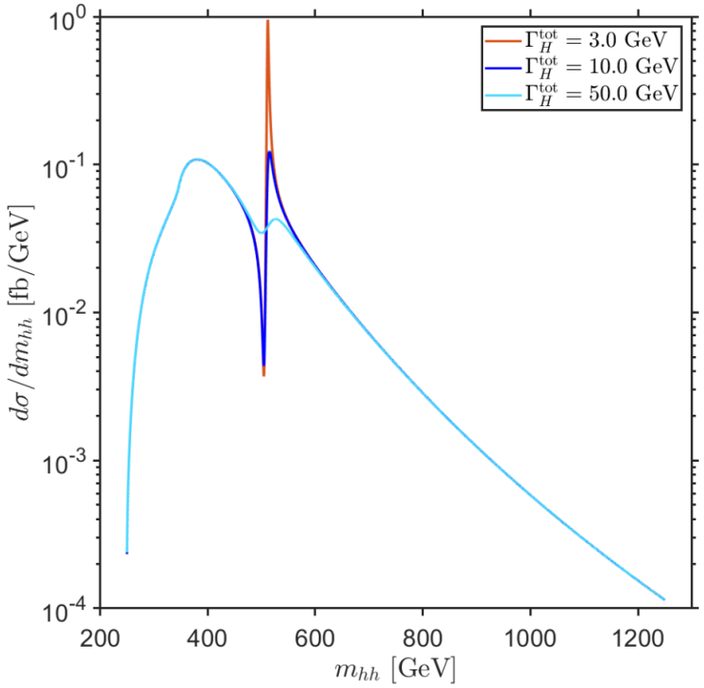
Interference between **resonant** & **non-resonant** di-Higgs could be important...

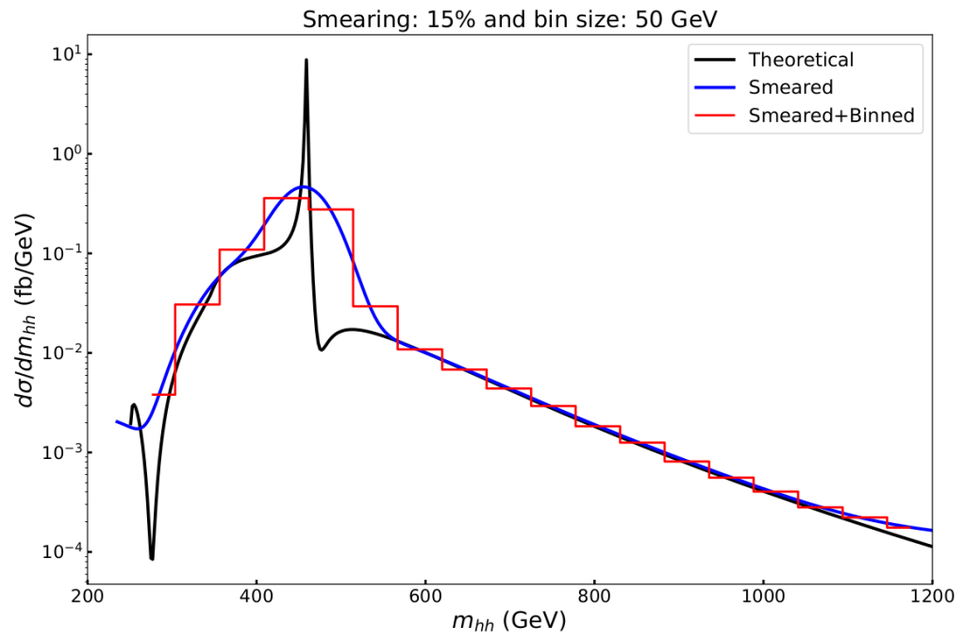
But:

Strong dependence on H-width



Arco, Heinemeyer, Muhlleitner, Radchenko. arXiv:2212.11242

Effect of smearing & binning?



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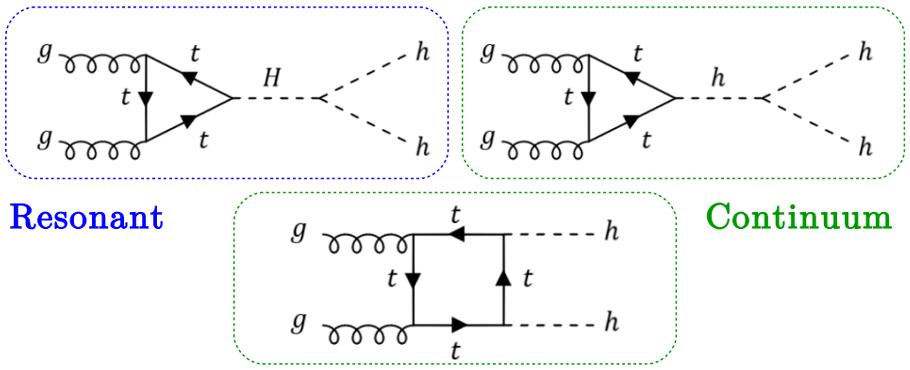
2. Interference effects in Di-Higgs

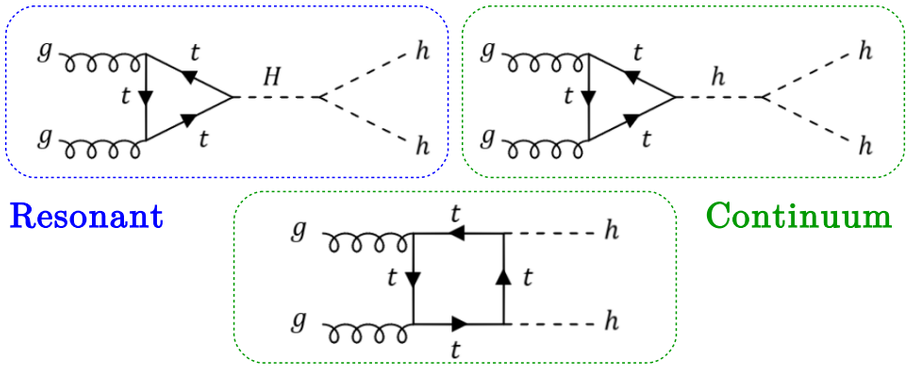


courtesy: Alain Verduras

Still:

Interference effects will become very relevant when LHC sensitivity to resonant di-Higgs signal will become **comparable** to LHC sensitivity to SM di-Higgs continuum

2. Interference effects in Di-Higgs



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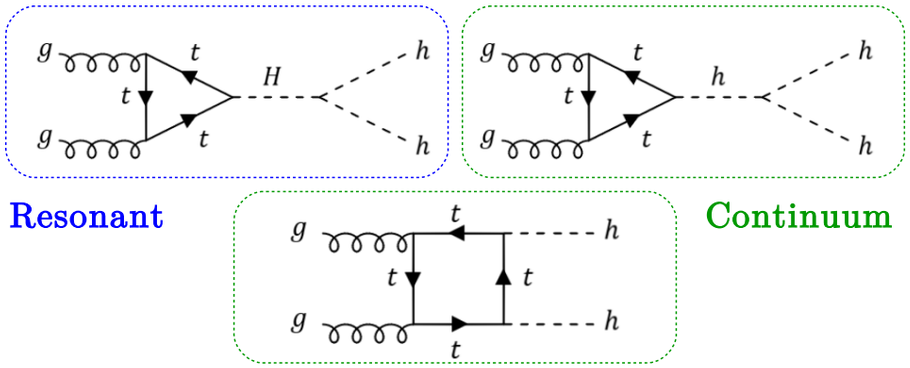
Accounting for **interference is standard** in ATLAS/CMS resonant **di-boson** searches

Shouldn't it become so for resonant di-Higgs? *

* Of course, non-resonant (SM) di-boson is well-measured,
whereas non-resonant di-Higgs is yet to be!
(+ depends on unknown $\boldsymbol{\lambda_{hhh}}$)

2. Interference effects in Di-Higgs



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Accounting for **interference is standard** in ATLAS/CMS resonant **di-boson** searches

Could *it become so for resonant di-Higgs?* ***How****?*

3. New (**resonant**) multiboson LHC searches

Are there multiboson searches not currently performed but useful?

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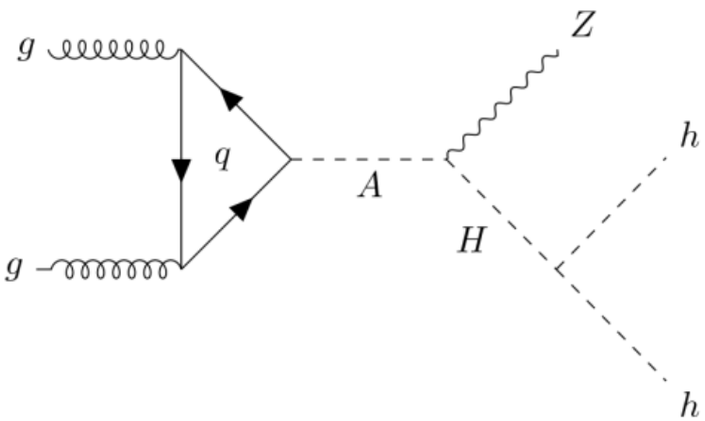
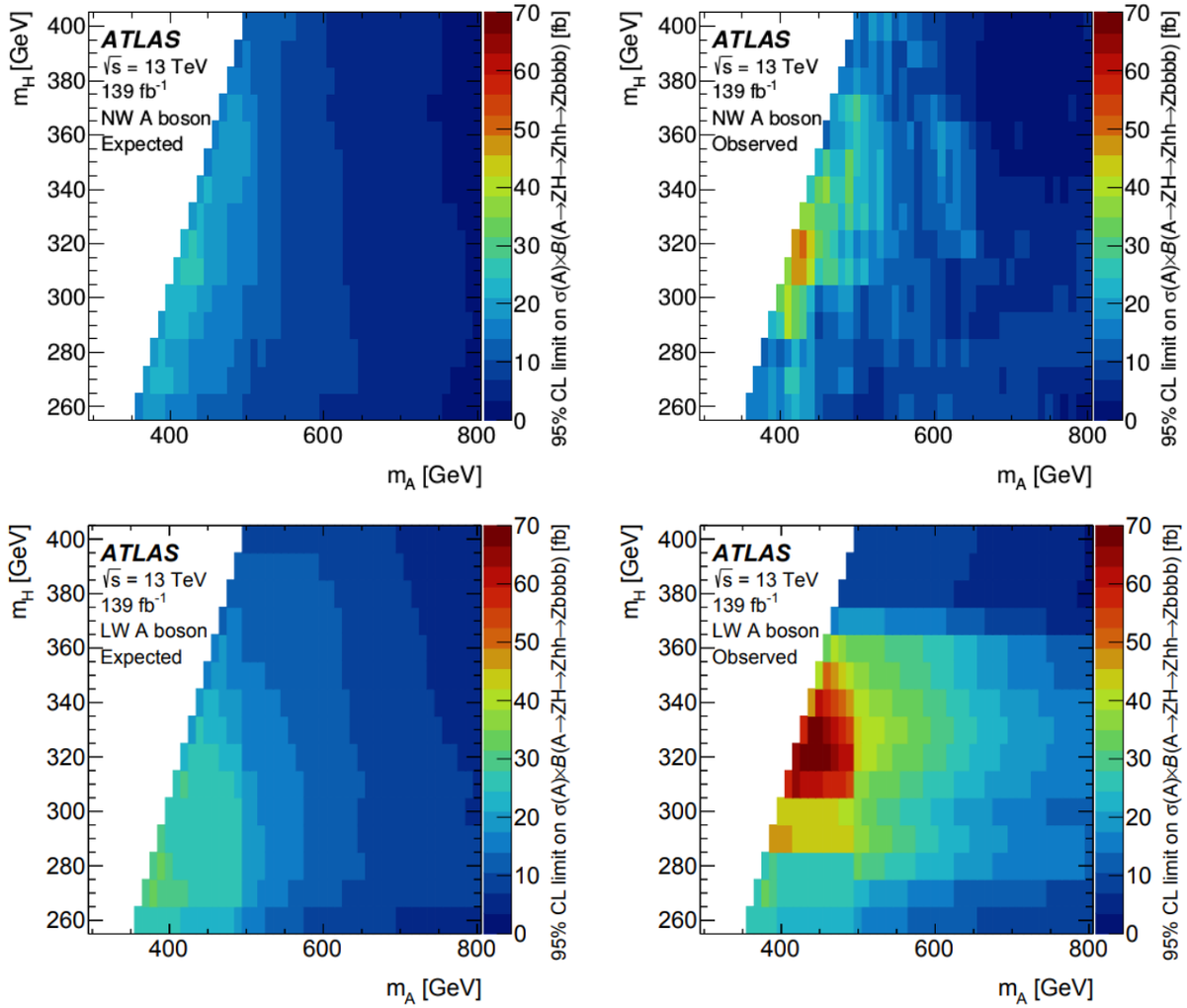
- Cascade decays leading to multiboson: ***Zhh***

ATLAS. Eur. Phys. J. C 83 519 (2023)



$\sigma(A) \times B(A \to ZH \to Zhh \to Zbbbb)$



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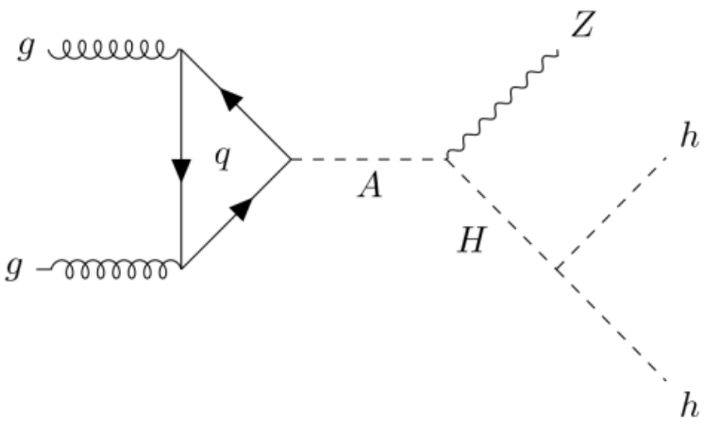
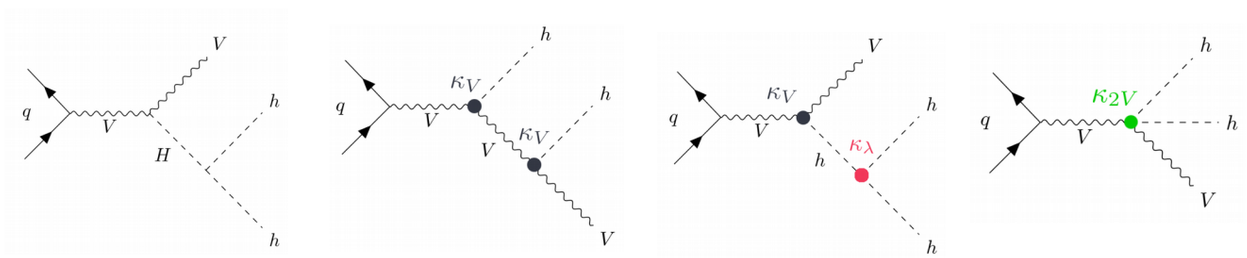


(also non-resonant & κ- interpretations...)



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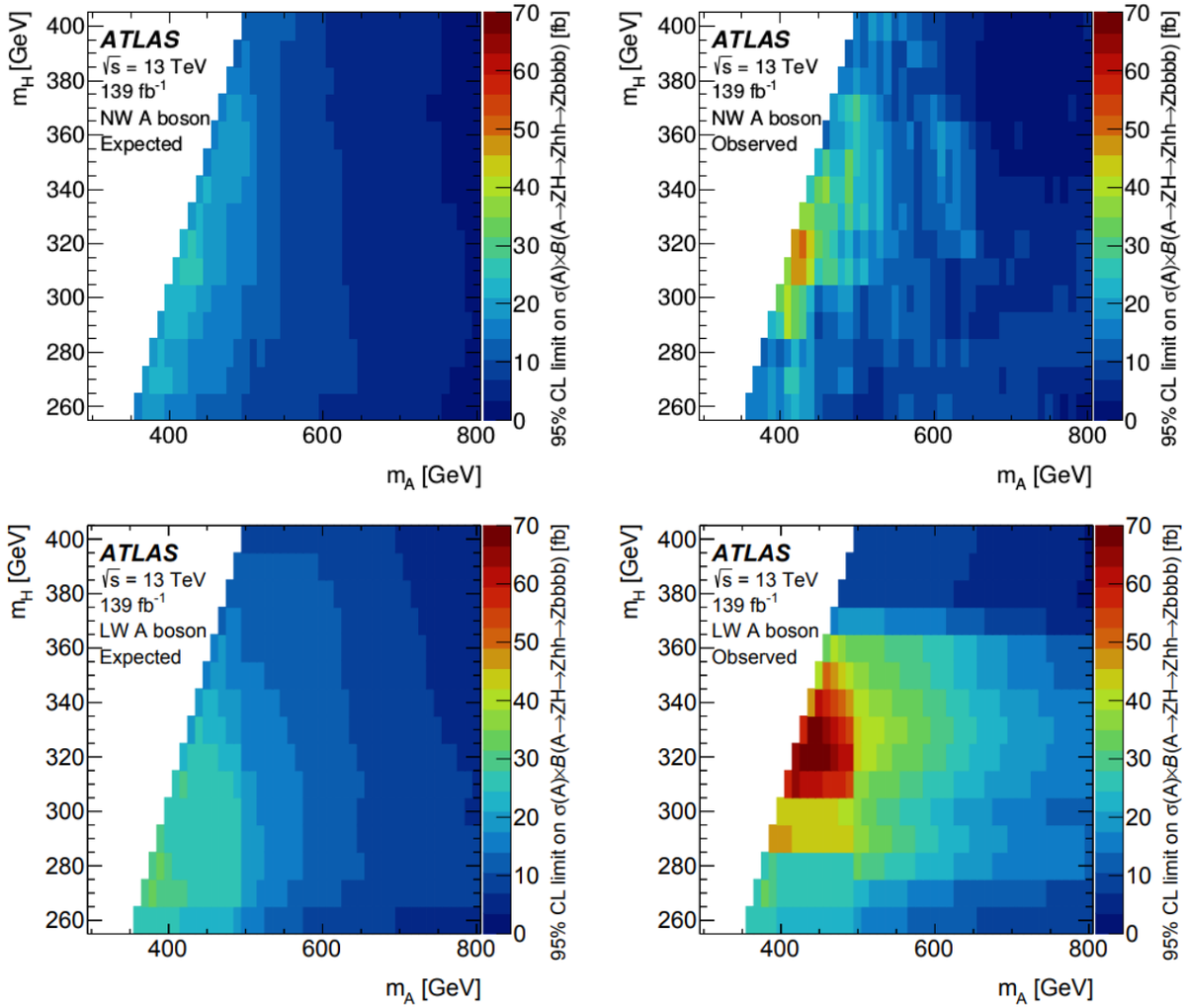

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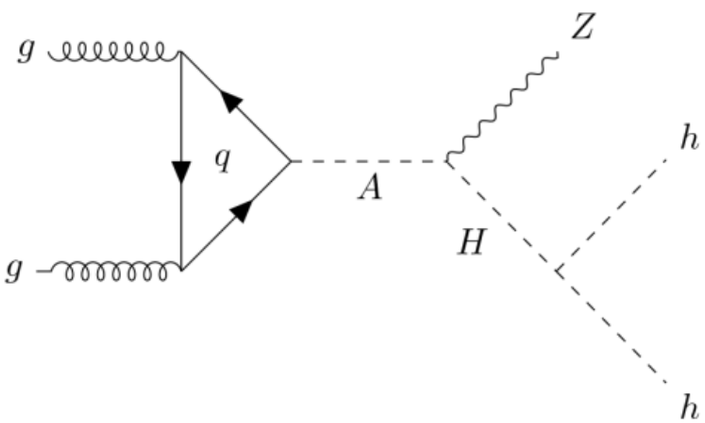

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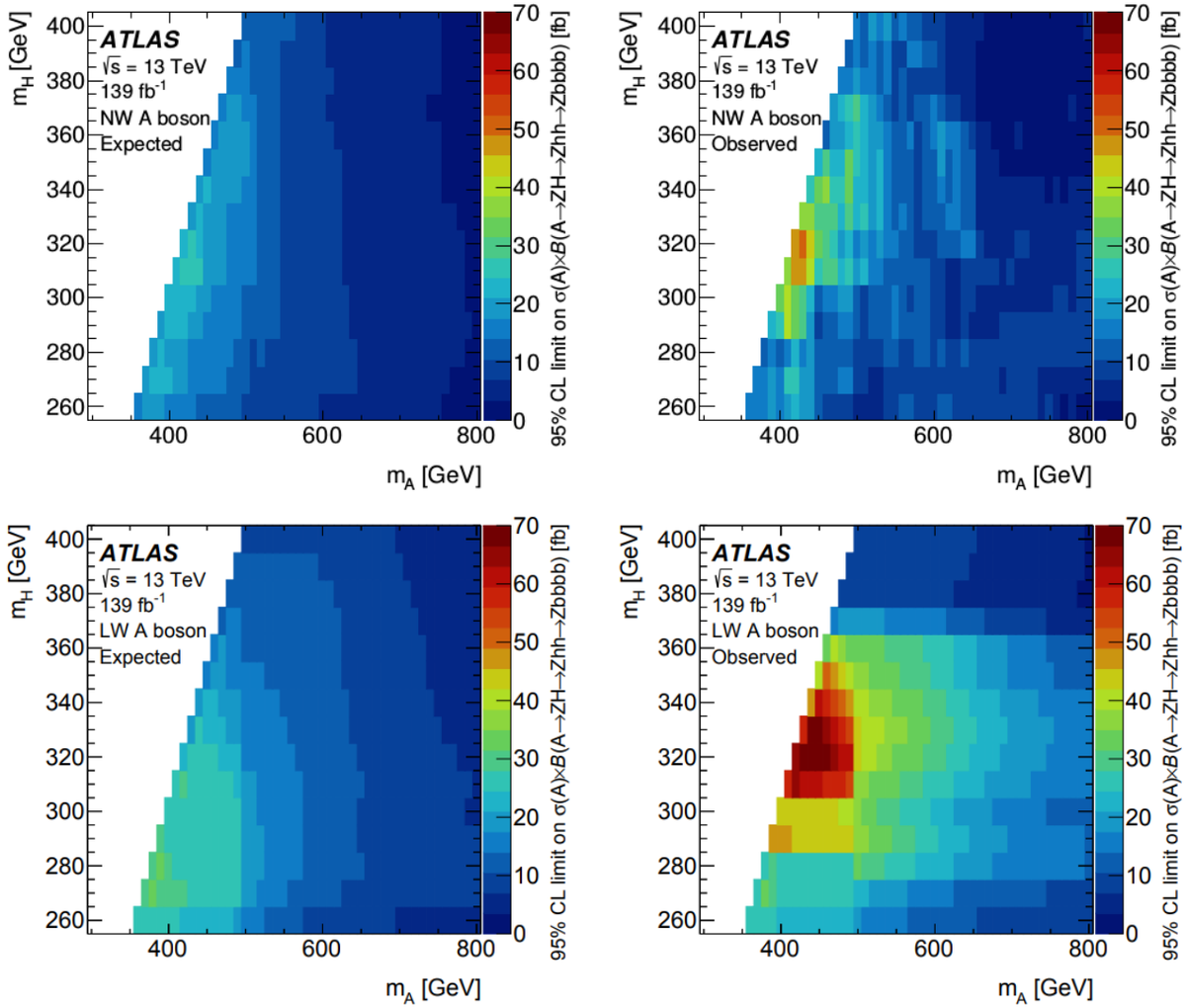

Can this be a BSM discovery search?

i.e. would it cover parameter space not constrained by other searches?

$pp \to H \to hh$ $\qquad$ $pp \to A \to ZH\ (H \to b\bar{b},\ t\bar{t},\ \tau\tau)$

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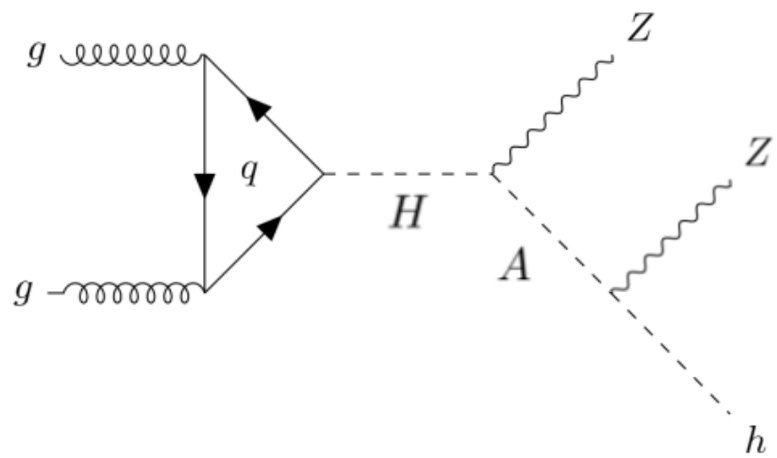

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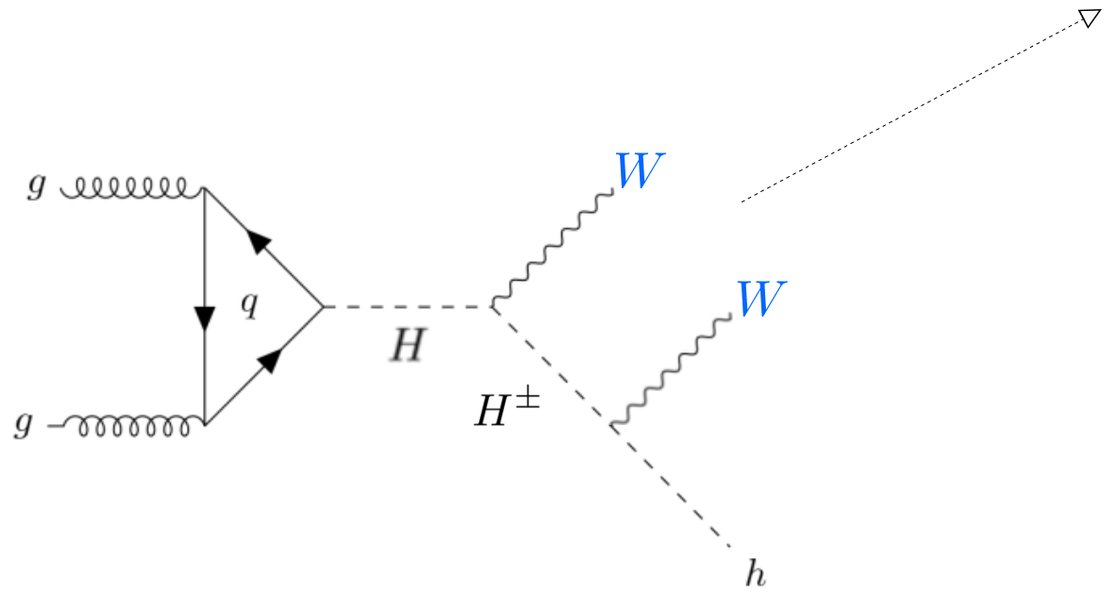
- Cascade decays leading to multiboson: *Zhh* , *ZZh* , ***WWh*** , ***Whh****?*



Consider also charged scalar decays?

3. New (**resonant**) multiboson LHC searches

Are there multiboson searches not currently performed but useful?

- Cascade decays leading to multiboson: Zhh , ZZh , WWh , Whh
- **Extend scope** of current searches**?** (e.g. resonant di-Higgs)

$H \to hX$ with $m_X \neq 125$ GeV

$H \to hh$

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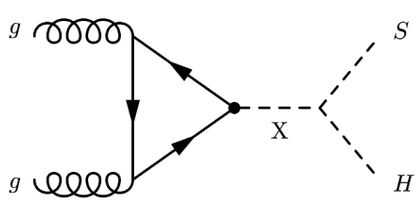
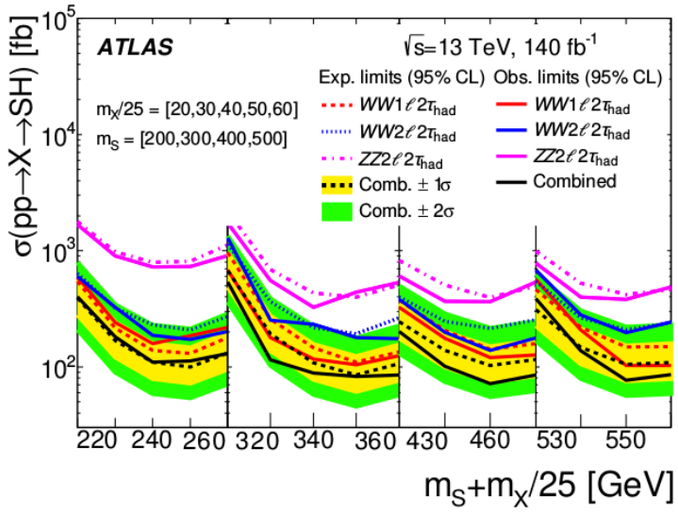
ATLAS. JHEP 10 009 (2023)





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- $H \to XX$ with $m_X \neq 125$ GeV

(this experimental search does not exist)

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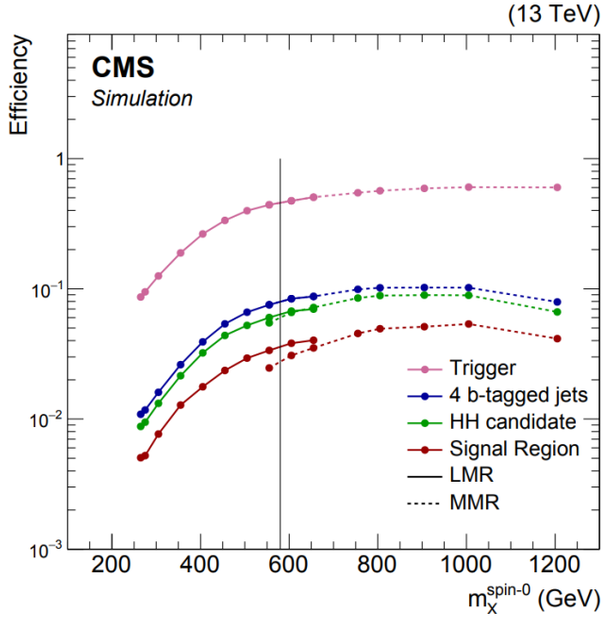
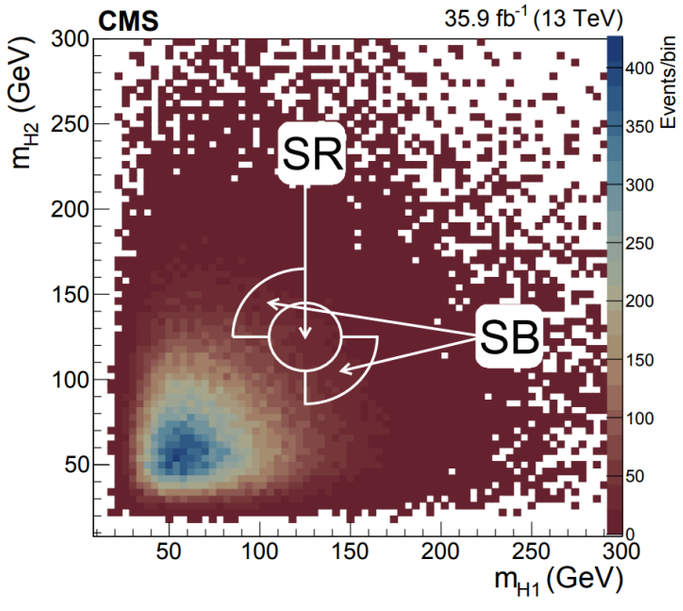
Recast of *CMS, JHEP 08 (2018), 152* ($H \to hh \to b\bar{b}b\bar{b}$)

$X \to H(b\bar{b})H(b\bar{b})$





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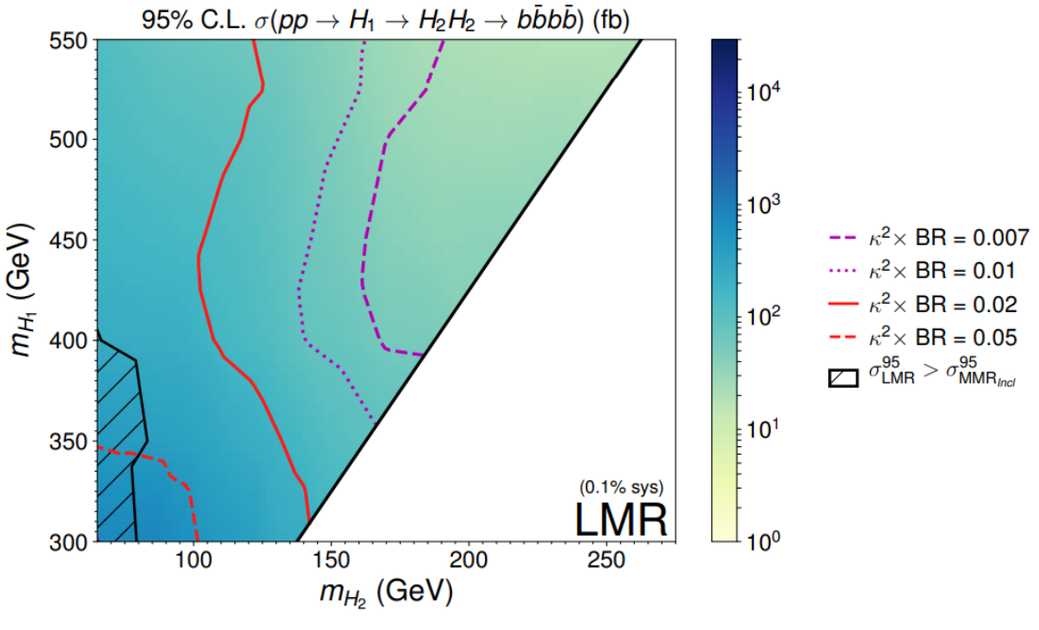


Barducci, Mimasu, JMN, Vernieri, Zurita, JHEP 02 (2020), 002

4. Mass Regions

"Not many" di-boson analyses below 200 GeV...

Only **one** 13 TeV analysis!

CMS, JHEP 06 (2018), 127 (**35.9 fb^{-1}**)

CMS-HIG-17-012

CERN-EP-2018-009
2018/07/05

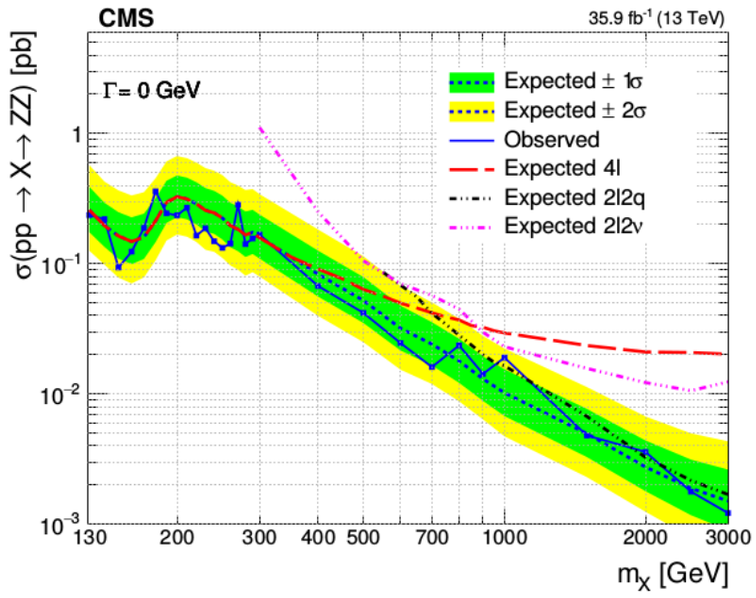
Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

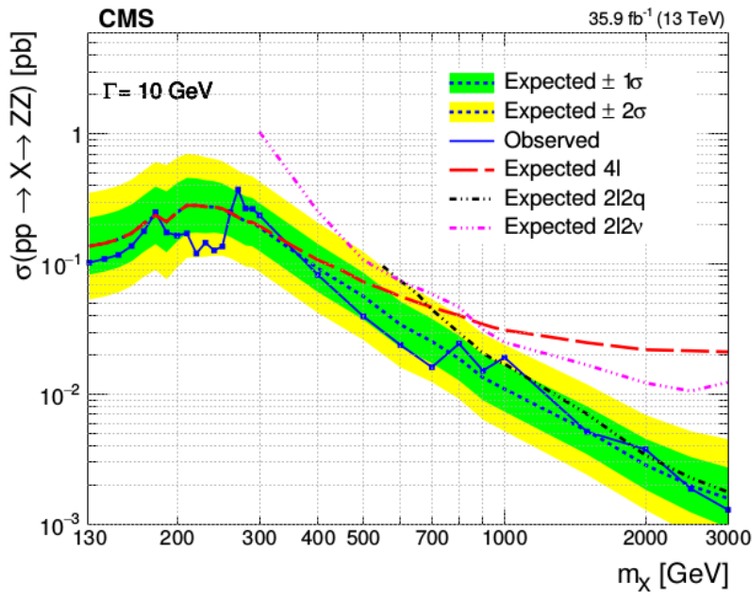
The CMS Collaboration*

Abstract

A search for a new scalar resonance decaying to a pair of Z bosons is performed in the mass range from 130 GeV to 3 TeV, and for various width scenarios. The analysis is based on proton-proton collisions recorded by the CMS experiment at the LHC in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} at a center-of-mass energy of 13 TeV. The Z boson pair decays are reconstructed using the 4ℓ, $2\ell 2q$, and $2\ell 2\nu$ final states, where ℓ = e or μ. Both gluon fusion and electroweak production of the scalar resonance are considered, with a free parameter describing their relative cross sections. A dedicated categorization of events, based on the kinematic properties of associated jets, and matrix element techniques are employed for an optimal signal and background separation. A description of the interference between signal and background amplitudes for a resonance of an arbitrary width is included. No significant excess of events with respect to the standard model expectation is observed and limits are set on the product of the cross section for a new scalar boson and the branching fraction for its decay to ZZ for a large range of masses and widths.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP06(2018)127.





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"Not many" di-boson analyses below 200 GeV...

Only **one** 13 TeV analysis!

CMS, JHEP 06 (2018), 127 (**35.9 fb^{-1}**)

Yet, mass range above 125 GeV but still "light" (< 200 GeV) is phenomenologically interesting...

5. Resonances vs EFT

Are they orthogonal? Probably not...

Worth exploring potential interplay between the two![*]

6. Precision in BSM scalar production & decay

What is the state-of-art for different BSM models? [*]

[*] I leave it fully open to discussion

Summary

- Resonant di-Higgs – di-boson interplay
- Interference in (resonant) di-Higgs
- New BSM (resonant) multi-boson searches
- “Low” mass regions
- Resonant vs EFT
- Precision in BSM scalar production & decay

Thank you!


KEEP
CALM
AND
BACKUP
YOUR
WORK