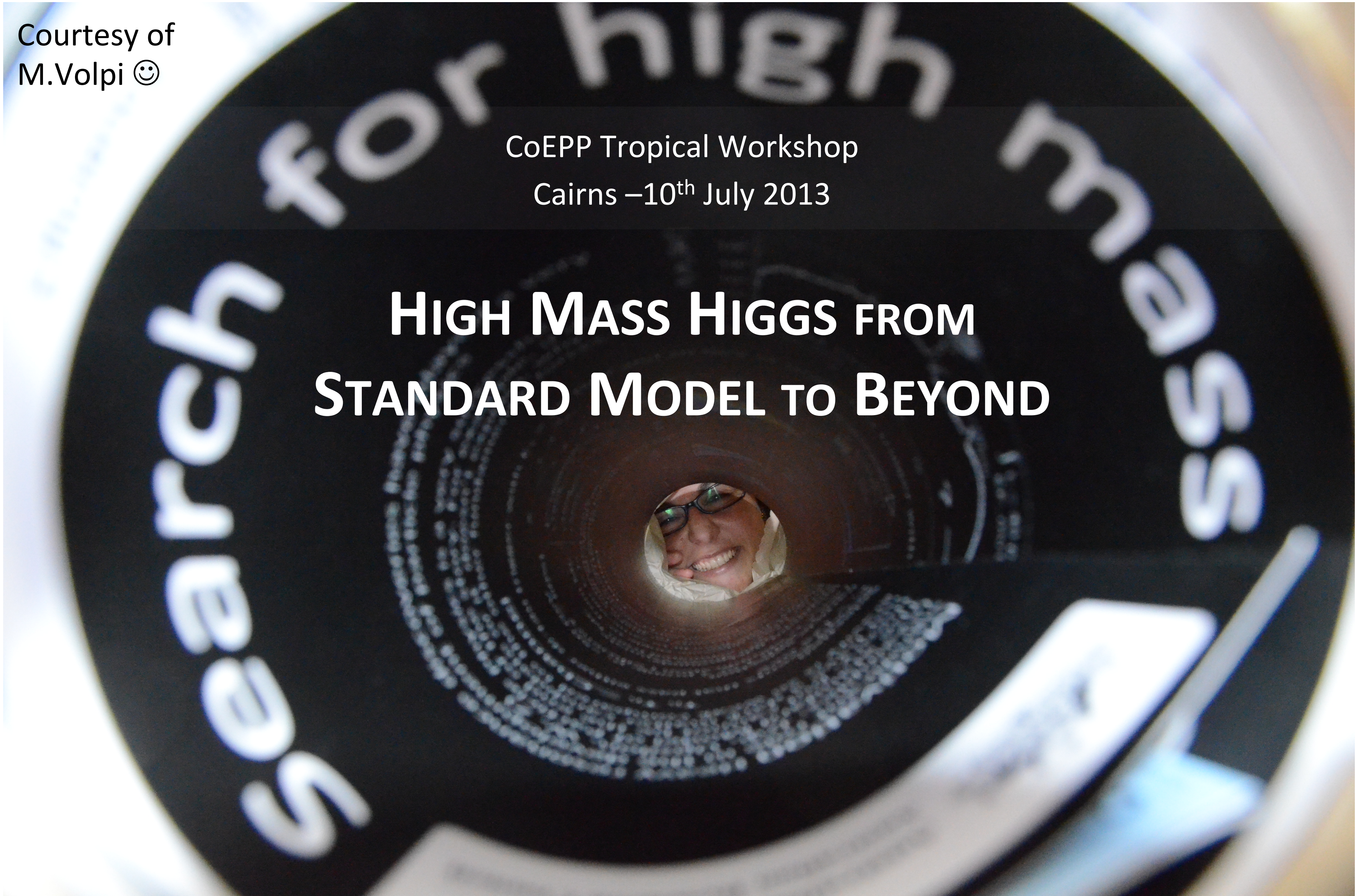
Courtesy of
M.Volpi ☺



CoEPP Tropical Workshop
Cairns –10th July 2013

High Mass Higgs from Standard Model to Beyond

Sara Diglio
The University of Melbourne

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

The University of Melbourne

OUTLINE

- Summary of tests results on the nature of the Higgs boson (→ see also Gui's talk for more details)
- Why high mass Higgs searches?
- BSM benchmark definition and strategy
- Analysis status and future plans
- Conclusions

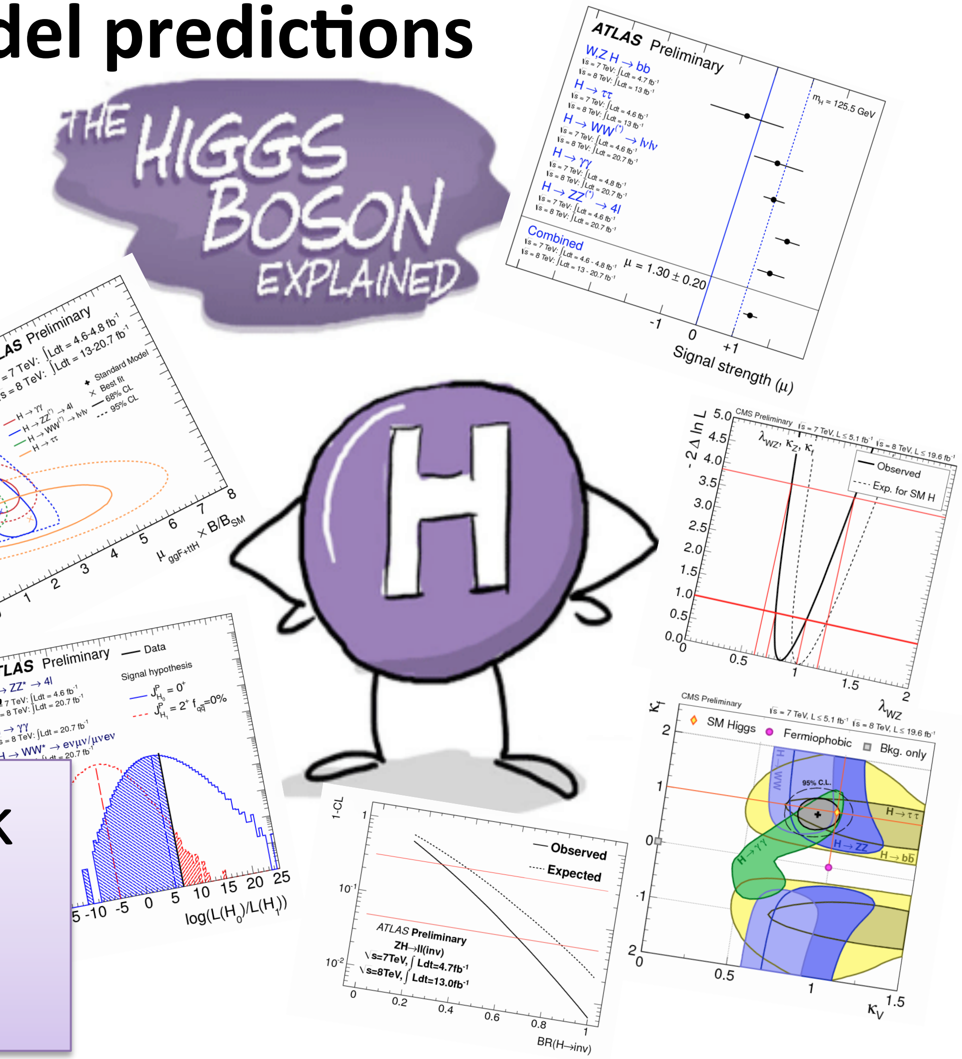
A simple example of
theorists←→ experimentalists link

From the model definition to the analysis search

Since the 4th July 2012 …

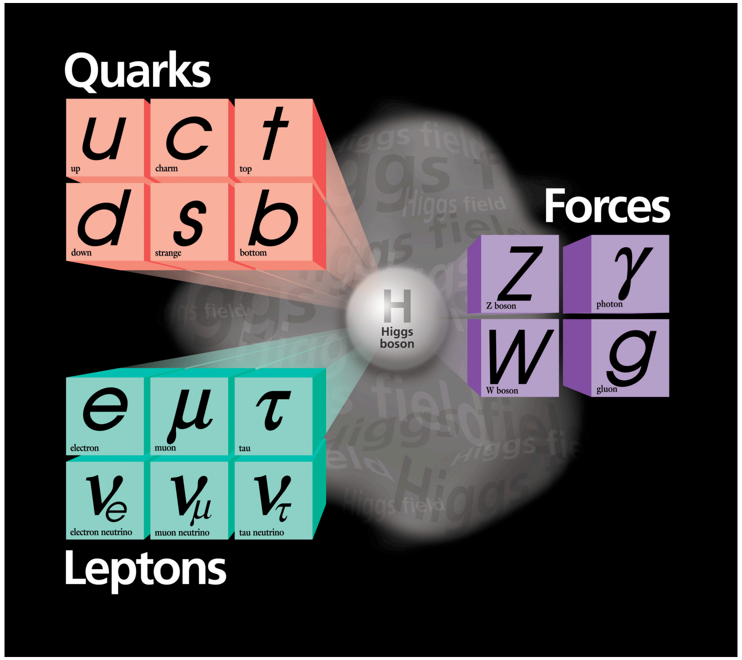
Testing the nature of the Higgs boson wrt Standard Model predictions

- Overall compatibility
- Production modes
- Global fit on Couplings
- Spin 0, mostly CP+
- Custodial W/Z symmetry
- BR(H→inv) < 0.6 @95% CL

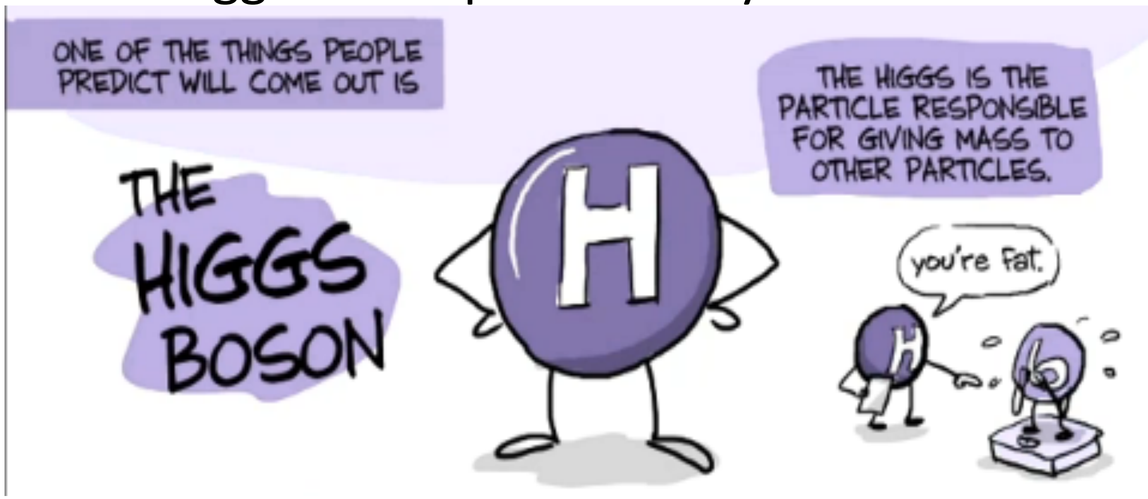


The new boson does not look an impostor ← it closely resembles the SM Higgs

'THE' HIGGS BOSON?



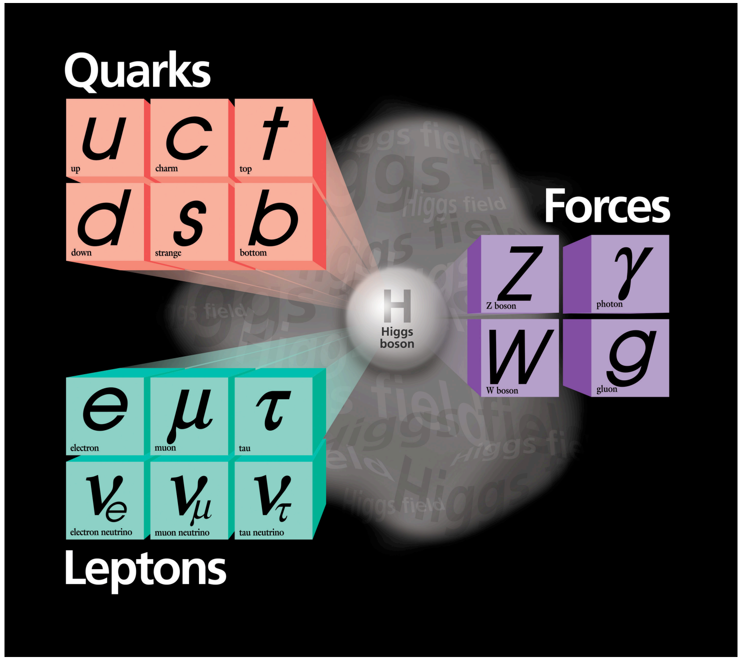
- According to the current results the 125 GeV discovered particle closely resembles the Higgs boson predicted by the SM



OPEN QUESTIONS :

- Is it fully responsible for the generation of the masses of other SM particles ?
- Or is it part of a more extended sector with **more 'Higgs-like' particles**?

‘A’ Higgs Boson?



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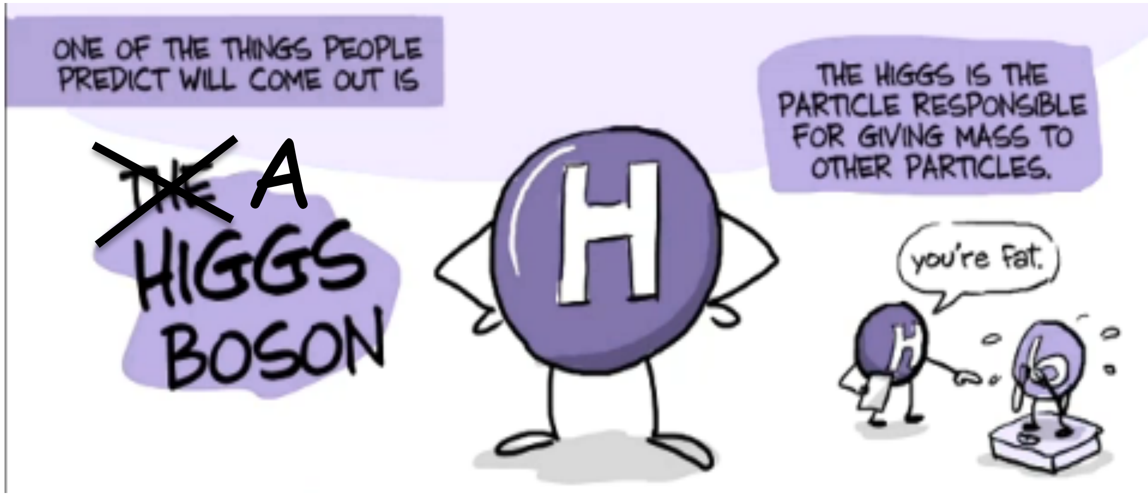

OPEN QUESTIONS : → **‘The’ or ‘A’ Higgs boson?**

- Is it fully responsible for the generation of the masses of other SM particles ?
- Or is it part of a more extended sector with **more ‘Higgs-like’ particles**?

Need to investigate
Beyond SM scenarios

BEYOND THE STANDARD MODEL SCENARIO

Is a completely model independent analysis possible?
→ **NOT enough data yet to have a model independent conclusion**

Even with a few reasonable assumptions

- spin-0 + CP-even
- custodial W/Z symmetry
- No FCNC

still the parameter space is large →**need to consider benchmark models**

The SM is one specific point in the wide parameter space available in more generic benchmark models
→ reinterpretation and extension of SM analysis

Strategies developed for SM searches will be extended to Beyond SM (BSM) 'SM-like'

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I will focus on a quite generic BSM benchmark which:

- **is consistent with ~125 GeV observation**
- contains a **second heavier Higgs-like state**
- is compatible with EW precision data

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125 GeV Higgs + Real Singlet

C. Grojean, K. Kumar, H. E. Logan et al.

Model discussion and strategy building within the Heavy Higgs and BSM LHC HXS WG

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→ reinterpretation and extension of SM analysis

I will focus on a quite generic BSM benchmark which:

- **is consistent with ~125 GeV observation**
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- is compatible with EW precision data

Heavy Higgs and BSM subgroup

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSM

Contacts: ATLAS: K. Peters, **SD**
CMS : M. Kadastik, S. Bolognesi
TH : M.Muehlleitner, H.Logan

- **LHC Higgs Cross section working group** (LHC HXSWG):
  Joint effort between LHC experimental and theory communities
- The **main scope of the subgroup** is to
  - provide **theoretical guidelines** in common between ATLAS and CMS to characterize properly the **Heavy Higgs searches in the SM case**
  - Since we don't yet have enough date to perform a completely model independent analysis → **define/choose** quite generic **BSM benchmarks** to perform the corresponding analyses within the ATLAS and CMS experiments
- **Current status**
  - Theoretical guidelines have been used to perform **SM Heavy Higgs analysis**
  - A minimal extensions of the SM scenario have been chosen to start with : **125 GeV Higgs + Real Singlet**
- Guidelines, implementations, tests and BSM scenarios have been documented in the YR3 (sessions 12 and 13): http://arxiv.org/pdf/1307.1347v1.pdf

BEYOND THE STANDARD MODEL SEARCHES

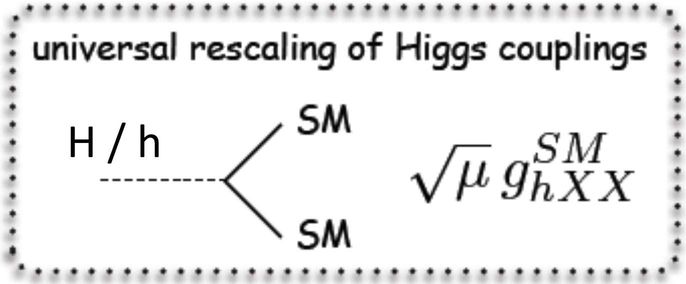
These searches will allow to

- **either** ***provide a further confirmation of the SM nature of the Higgs boson at ~125 GeV*** by excluding the existence of other Higgs-like particles in the high mass regime

- **or** ***find new Higgs-like particles in the high mass regime*** which might be co-responsible for the generation of the masses of other SM particles

125 GeV Higgs + real singlet

- 2 Higgses with couplings rescaled wrt SM
1. h125 (h) coupling = κ
2. Heavy Higgs (H) coupling= κ'
- **H** constrained by h → $\kappa_V^2 + \kappa_V'^2 = 1. \quad \kappa \equiv \kappa_V = \kappa_f.$
- considering **H→h h decay** **(BR_{new})**



$\sqrt{\mu}\, g_{hXX}^{SM}$

By C. Grojean, K. Kumar, H. E. Logan

125 GeV Higgs + real singlet

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- **H** constrained by h →
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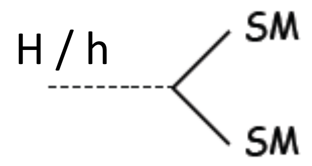
universal rescaling of Higgs couplings



$$\sqrt{\mu}\, g_{hXX}^{SM}$$

$$\kappa_V^2 + \kappa_V'^2 = 1. \qquad \kappa \equiv \kappa_V = \kappa_f.$$

- **Heavy Higgs search in 2 parameters space for each M_H hypotesis**

$$\mu' = \frac{\sigma' \times BR'}{\sigma_{SM} \times BR_{SM}} = \kappa'^2 (1 - BR_{new}).$$

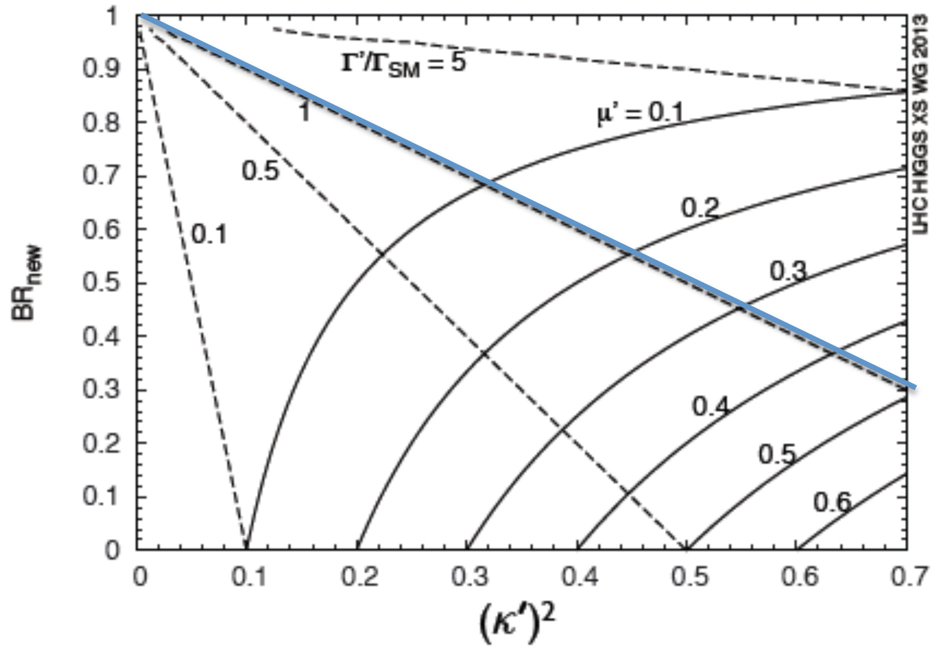
$$\sigma' = \kappa'^2 \sigma_{SM},$$

$$\Gamma' = \frac{\kappa'^2}{(1 - BR_{new})} \Gamma_{SM},$$

$$BR' = (1 - BR_{new}) BR_{SM},$$

width may be narrower or larger than SM

By C. Grojean, K. Kumar, H. E. Logan



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- Constraining the parameters space by using current measurements on h

Signal strenght

$\mu = 1.3 \pm 0.2$

Taking the uncertainty to be Gaussian→ **2σ** lower bound on μ and hence an upper bound on **μ'**

$\mu > 0.9 \rightarrow \mu' < 0.1$

Higgs Coupling

$\kappa = 1.11 \pm 0.08$

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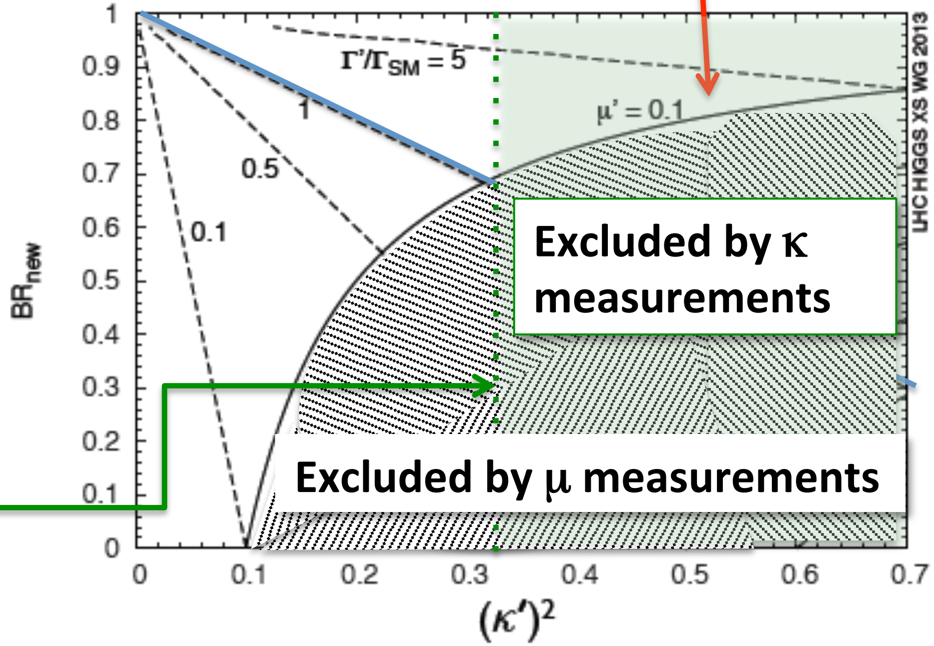

125 GeV Higgs + real singlet

Research strategy

ATLAS-CONF-2013-034

- Constraining the parameters space by using current measurements on h
- Scan over M_H vs Γ' on the available parameter space (being Γ' linked to κ' and BR_{new})
- *Starting from:*
  - $\Gamma' = \Gamma_{SM}$
  - $\Gamma' = \Gamma_{Narrow\ Width}$

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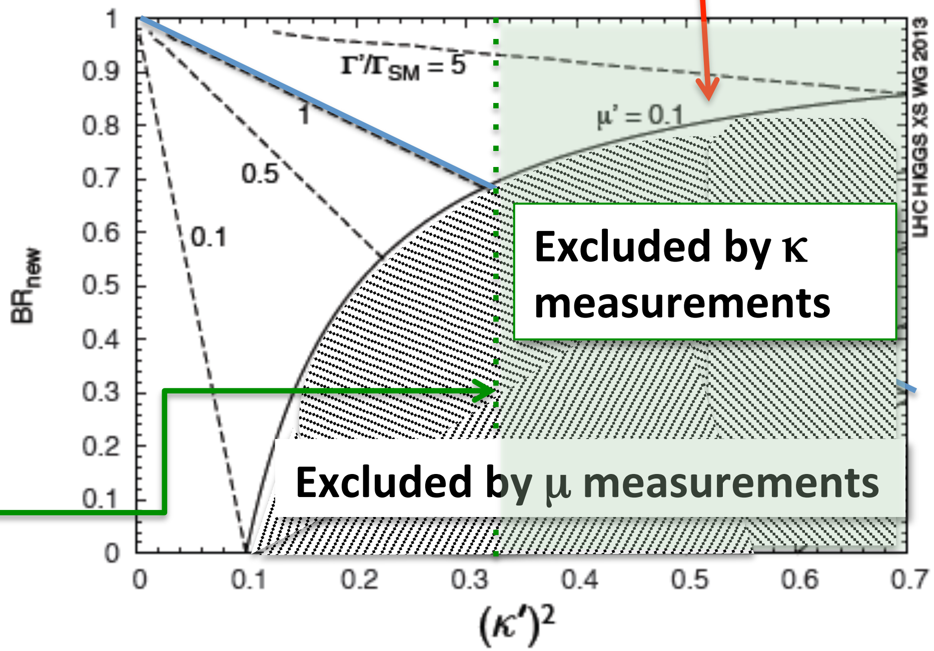

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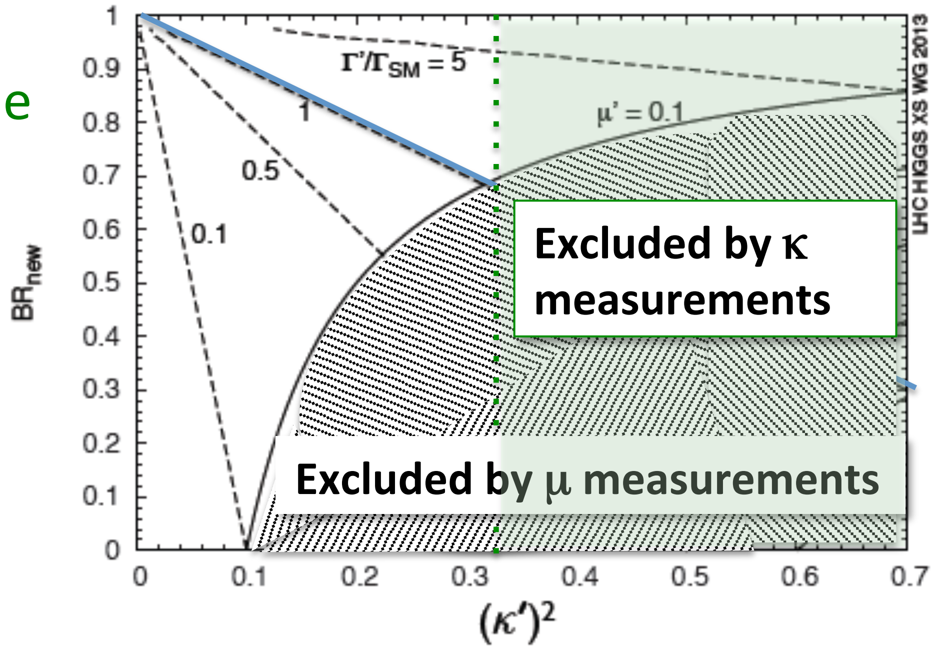
- *Starting from:*
  - $\Gamma' = \Gamma_{SM}$
  - $\Gamma' = \Gamma_{Narrow\ Width}$

  Results for the H→WW→ lnln channel will be presented at EPS

- **Near Future**: explore the full available parameter space
  - Extend tool and techniques developed for SM search
  - Using same SM MC signal samples by rescaling them to account for width-change related effects

These searches will allow to

- **either** ***provide a further confirmation of the SM nature of the Higgs boson at 125 GeV*** by excluding the existence of other Higgs-like particles in the high mass range
- **or** ***find a new Higgs-like particles in the high mass range***



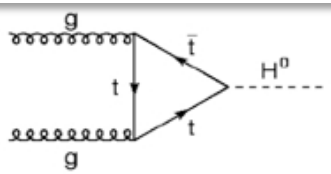
THE STANDARD MODEL CASE

DIFFERENCES WRT LOW MASS REGION

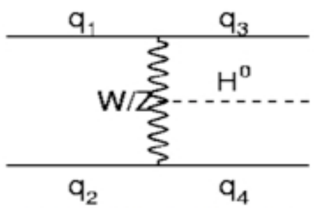
- Theoretical issues
  - related to the Higgs width → see next slides
- Experimental issues
  - Depending from the final state → see from slide 29

THEORETICAL ISSUES RELATED TO HIGH MASS

The Standard Model

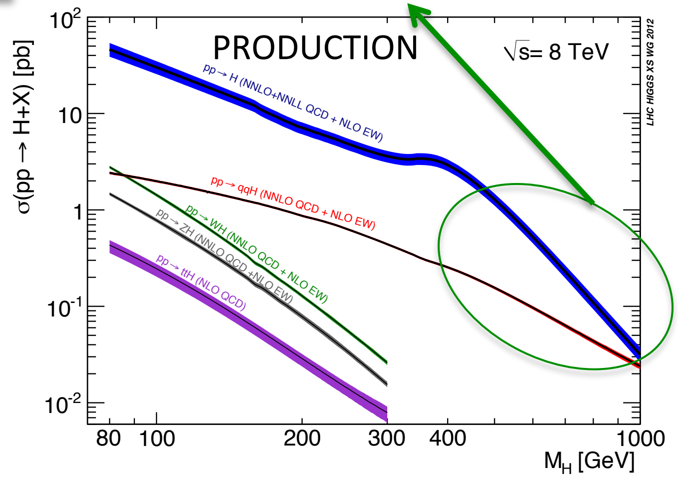


Gluon Fusion (GF)

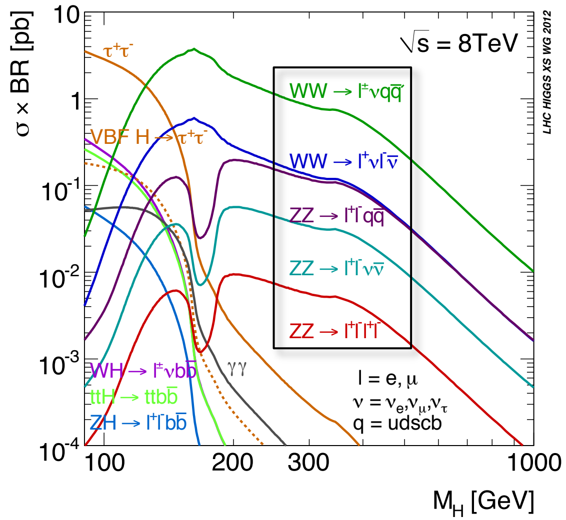


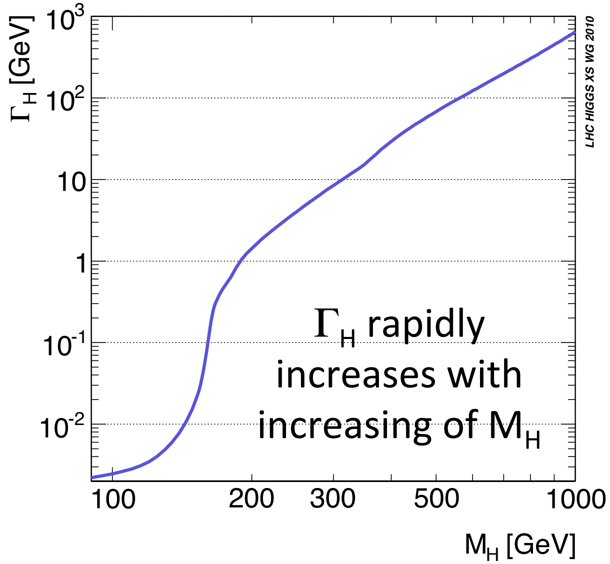
Vector-Boson-Fusion (VBF)

ggF and **VBF** comparable



DECAY





With the **increasing of the <u>Higgs width</u>** we must account for:

- Lineshape effect → Higgs propagator
- Signal-continuum Background interference effect

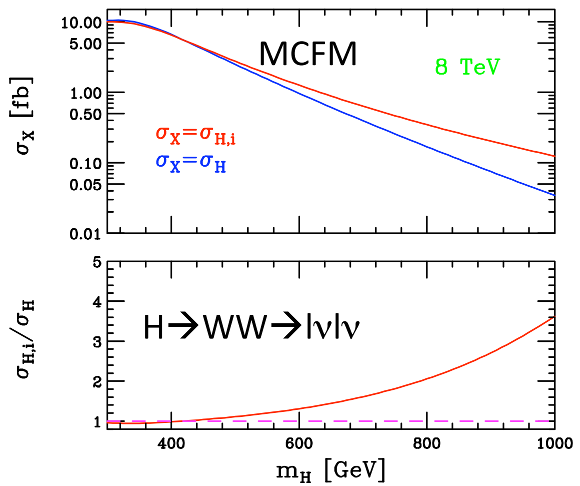
These effects can be neglected for $\Gamma_H \ll M_H$

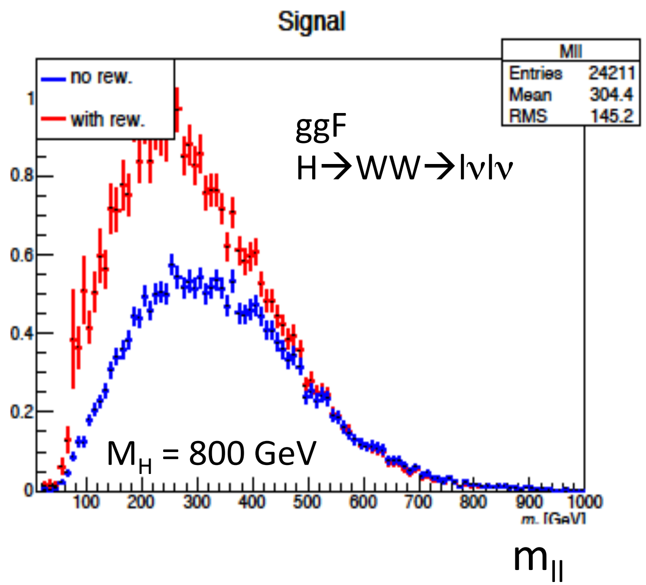
HEAVY HIGGS SEARCHES: SM

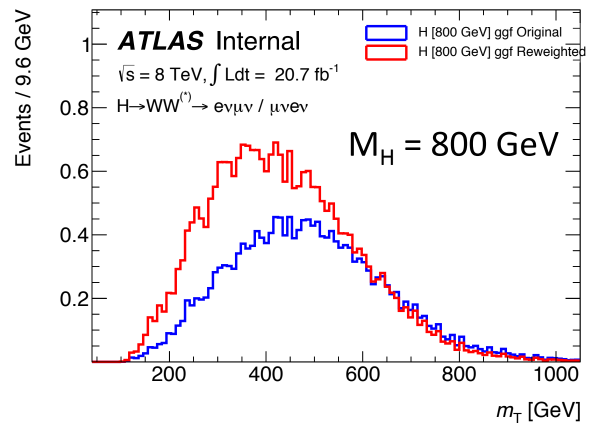
THEORETICAL ISSUES

- **$400 \le M_H \le 1000$ GeV**
  - Lineshape effect: redefinition of the Higgs propagator
    → use **Complex Pole Scheme (CPS) PowHeg** signal samples
  - Signal- VV (ZZ or WW) continuum background **interference effect**
    - It affects both the total X sec and distributions
    - Effect increase with the increasing of Γ_H
    - **Interference is NOT included in PowHeg CPS samples:**

    → **Weighting MC signal samples to account for the interference effect** *







$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}}\right|^2},$$

* Recipe from the LHC HXSWG

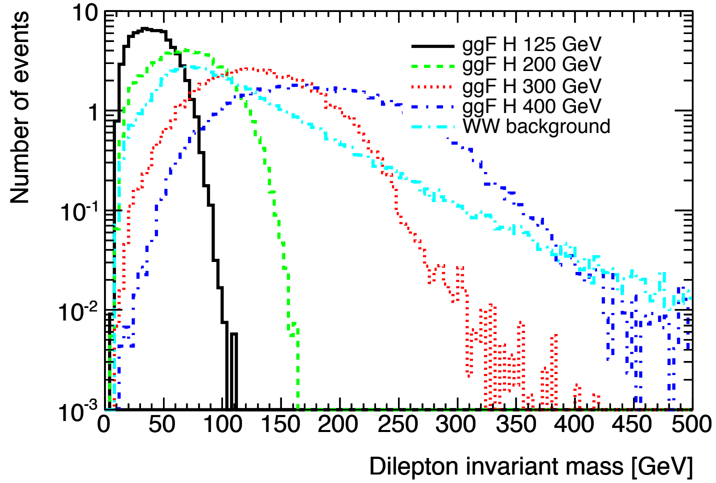
EXPERIMENTAL ISSUES RELATED TO HIGH MASS

Example on H→WW channels

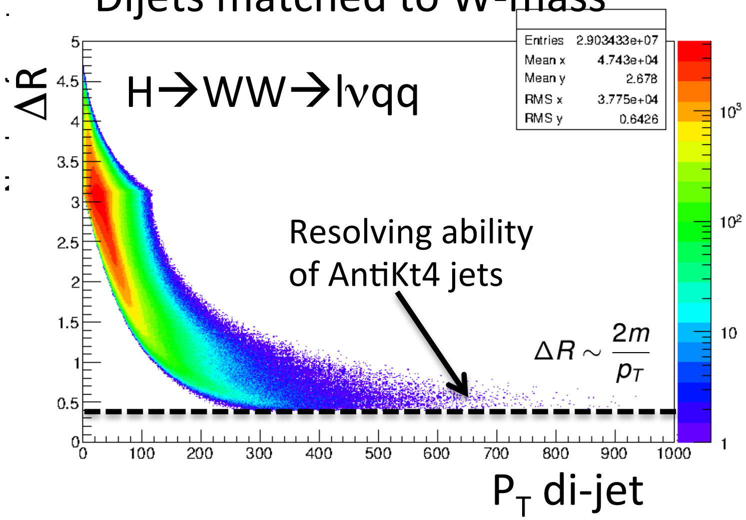
- **Different event topology**
  - Larger m_H →
  - →more difficult to disentangle signal from dominant bkg
  - →study variables correlations
  - Re-optimization of Signal Region (SR*)
  - Re-optimization of Control Regions (CR**)
  - **Jet merging**
  - → larger boost to V (W or Z) : larger p^V_T
  - → ΔR of V decay products gets smaller:
  - → **Lost ability to resolve jets with ΔR < 0.4**
  - Possible solution under investigation:

    Fat Jets + jet substructure techniques

H→WW→lνlν



Dijets matched to W-mass



*SR: region where the signal is enhanced wrt bkg **CR: bkg region where the contamination of the signal is negligible

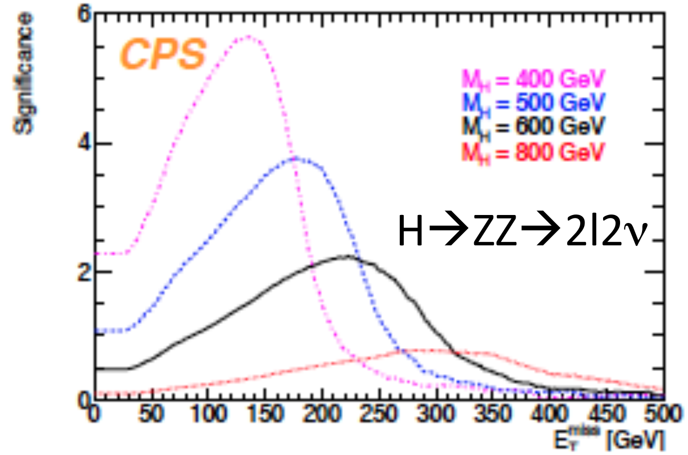
Experimental Issues related to High mass

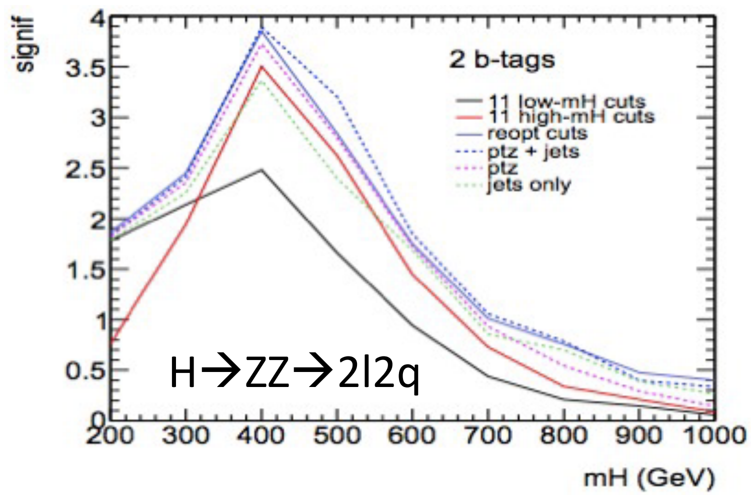
Examples on H→ZZ channels

- **Different event topology**
  - Optimization studies for the event selection
    - E^{t}_{miss}, $\Delta\phi_{ll}$, jet veto
    - **Significance:** $Z_{LLR} = \sqrt{2\left((S+B)\ln[1+\frac{S}{B}]-S\right)}$
  - **Jet merging**
    - In very high-mass region (mH > 600 GeV) the Z→jj is boosted and the two jets may overlap
    - Dedicated category to recovery efficiency loss

Significance M_H=800 GeV	
4-bodies	0.13
3-bodies	0.24

Significance w/o BG uncertainty





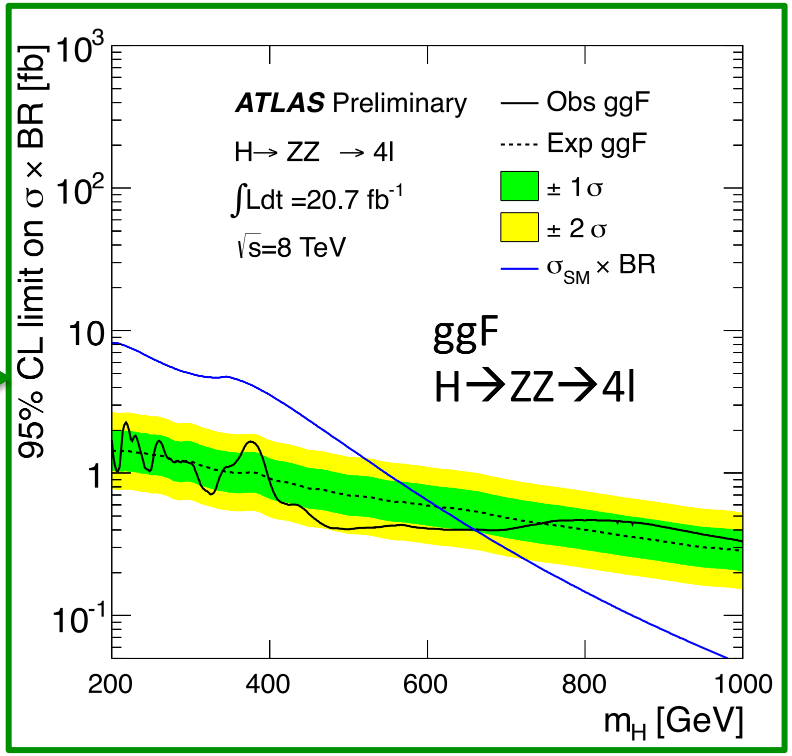
SM RESULTS: INTERPRETATION

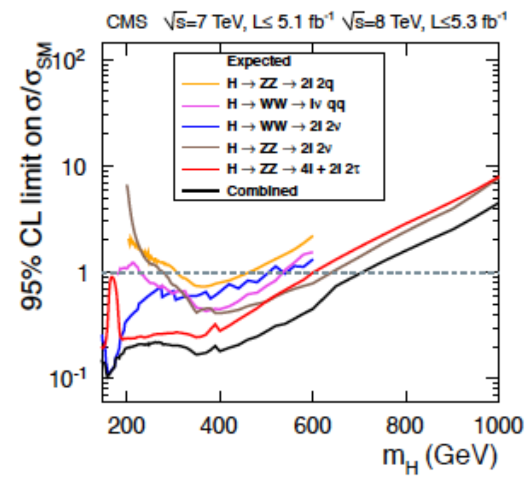
BSM interpretation: σ x BR

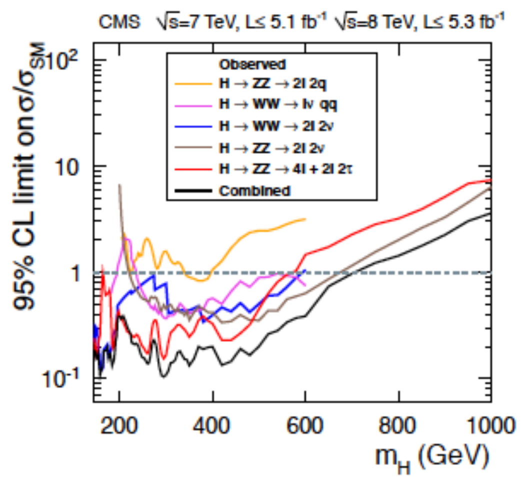
Advantage of σ x BR

Every model (compatible with the generic assumptions made to perform the analysis) can extract its own limit by including the correspondent theory prediction curves into the plane and obtain

the upper limits on σ x BR at 95% CL







SM interpretation σ/σ_{SM}

Exclusion limit only SM prediction

BEYOND THE STANDARD MODEL REGION $\Gamma' \neq \Gamma_{SM}$

What we learned from SM searches

A lot of work has been done from both theoretical and experimental side to perform the analysis in the high mass region

- Theoretical issues
  - Higgs lineshape propagator
  - Interference between signal and continuum bkg
- Experimental issues
  - Different topology

All the analysis techniques and tools developed for SM will be used for BSM

WHAT WE LEARNED FROM SM SEARCHES

A lot of work has been done from both theoretical and experimental side to perform the analysis in the high mass region

- Theoretical issues
  - Higgs lineshape propagator
    - The correct propagator is a complex function (CPS)
    - Breit-Wigner (BW) approximation used in the low mass region is not valid
    - → CPS implemented in new PowHeg MC
  - Interference between signal and continuum bkg
    - Bigger effect for larger Γ_H
    - Need to weight PowHeg MC samples to account for the effect

      → estimation by using MC which include I_{LO} : MCFM and gg2VV
- Experimental issues
  - Different topology
    - Re-optimization studies specific for each final state

All the analysis techniques and tools developed for SM will be used for BSM

H CONSTRAINED BY

ATLAS-CONF-2013-034

- Constraining the parameters space by using current measurements on h
- Scan over M_H vs Γ' on the available parameter space (being Γ' linked to κ' and BR_{new})

$$\mu' = \frac{\sigma' \times \mathrm{BR}'}{\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}} = \kappa'^2(1 - \mathrm{BR}_{new}).$$

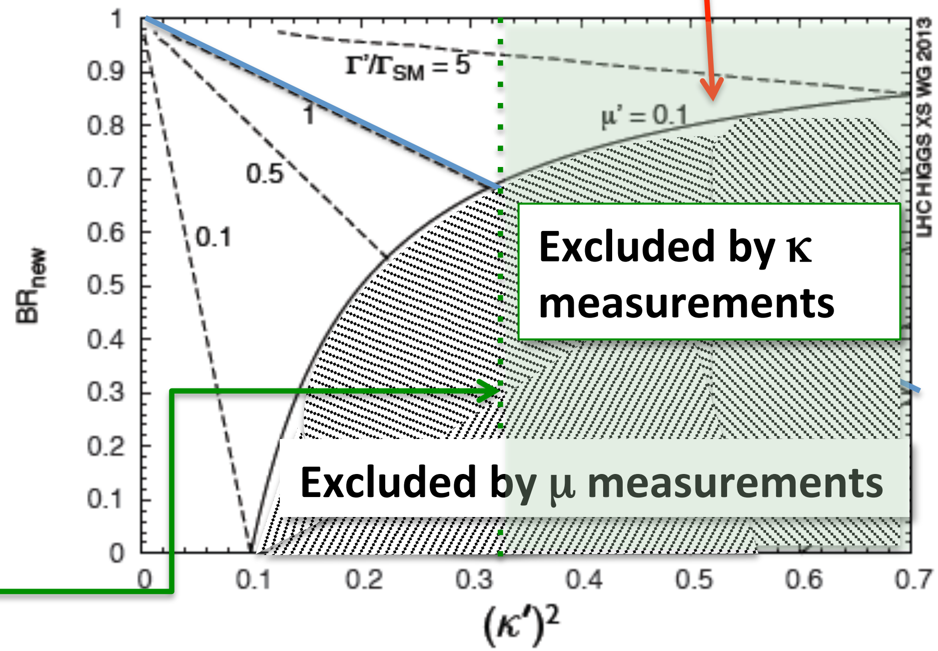
$$\begin{aligned} \sigma' &= \kappa'^2 \sigma_{\mathrm{SM}}, \\ \Gamma' &= \frac{\kappa'^2}{(1-\mathrm{BR}_{new})}\Gamma_{\mathrm{SM}}, \\ \mathrm{BR}' &= (1-\mathrm{BR}_{new})\mathrm{BR}_{\mathrm{SM}}, \end{aligned}$$

Signal strenght

$\mu = 1.3 \pm 0.2$

Taking the uncertainty to be Gaussian→ **2σ** lower bound on μ and hence an upper bound on **μ'**

μ > 0.9 → μ' < 0.1



Higgs Coupling

$\kappa = 1.11 \pm 0.08$

Taking the uncertainty to be Gaussian→**2σ** lower bound on κ and hence an upper bound on **κ'**

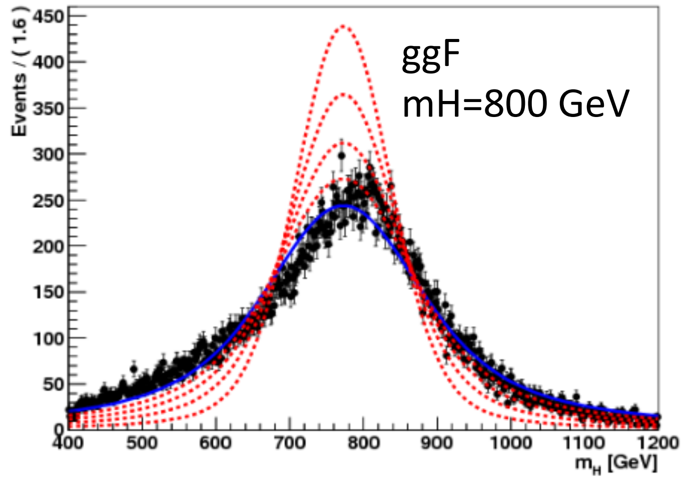
κ > 0.95 → κ' < 0.31

From SM to BSM

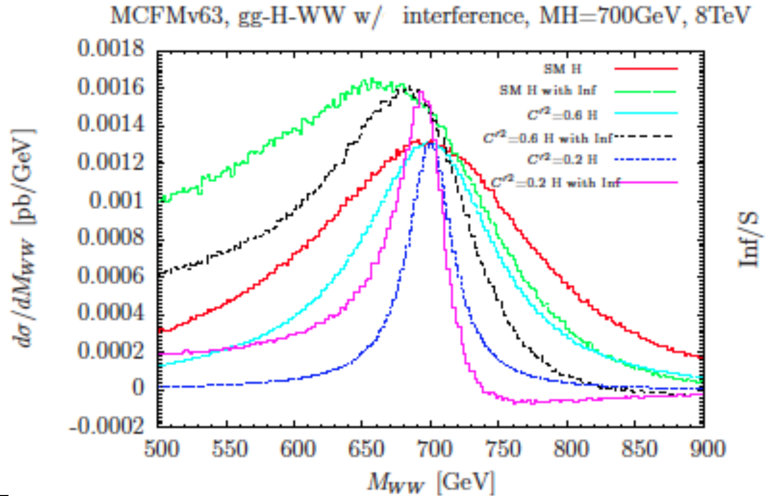
Goal: reweight the heavy Higgs width Γ'_H
by some factor $\Gamma'_H = K' \times \Gamma_{SM}$ where $K' = (\kappa'^2/(1-BR_{new}))$

Common strategy ATLAS-CMS

1. **Rescaling the width of SM PowHeg signal samples**
   - Generate a set of weights from a fit for ggF and VBF
   - Multiply the fitted width by a factor
   - Keep normalisation



2. **Scaling for the signal-continuum bkg interference effects**
   - **Weights depending from the width→ bigger effect for larger Γ'_H**



TOWARDS RESULTS

ATLAS approach

- Constraining the parameters space by using current measurements on the 125 GeV particle

Signal strength:
$\mu > 0.95 \rightarrow \mu' < 0.05$
Higgs Coupling:
$\kappa > 0.95 \rightarrow \kappa' < 0.31$

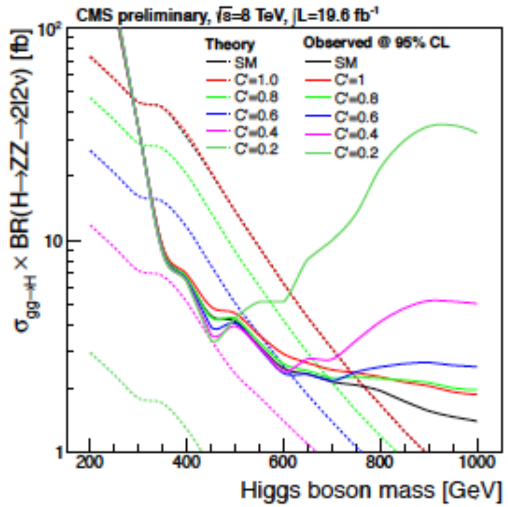
- **FUTURE:**
  - Approach as from previous slide in the available parameters space
  - scan over M_H vs Γ' for $\Gamma' \neq \Gamma_{SM}$

CMS approach

- Start exploring the parameters space region for $\Gamma' < \Gamma_{SM}$ regardless of constraints from existing data
- Already published for H→ZZ→lnln and H→WW→lνqq final states, plan to extend to other channels too

H→ZZ→2l2ν

scan over the range
$0.2 \leq \kappa' \leq 1.0$



CONCLUSIONS

- **The discovery era is just started…**
- Experimental measurements confirm the ~125 GeV particle looks more and more consistent to "the/a" SM Higgs
- There are natural extensions to the SM which are compatible with the current results and which predict the existence of an additional neutral Higgs-like resonance in the high-mass regime
- **An example of search from the model definition to the strategy and experimental search has been provided**

↓

- **Collaboration between theory and experimental communities is fundamental to reach the common goal to contribute to the discovery era**

BACKUP

125 GeV Higgs + real singlet (I)

The most general gauge-invariant potential can be written as [615,617]

$$V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 + \lambda_2 s^2\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) + \mu_1 s^3 + \mu_2 s\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right), \quad (316)$$

where s is the real singlet scalar and in the unitary gauge the SM Higgs doublet can be written as

$$\Phi = \begin{pmatrix} 0 \\ (\phi + v)/\sqrt{2} \end{pmatrix} \quad (317)$$

with $v \simeq 246$ GeV. We have already used the freedom to shift the value of s so that s does not get a vacuum expectation value. As a result, M^2 must be chosen positive in Eq. (316).

To prevent the potential from being unbounded from below, the quartic couplings must satisfy the conditions:

$$\lambda > 0, \qquad \lambda_1 > 0, \qquad \lambda_2 > -2\sqrt{\lambda\lambda_1}. \quad (318)$$

The terms quadratic in the fields (that give rise to the mass matrix) are

$$V_2 = \lambda v^2\phi^2 + \frac{1}{2}M^2 s^2 + \mu_2 v\,\phi s. \quad (320)$$

In particular, the mixing between ϕ and the singlet field s is controlled by the coupling μ_2. The mass eigenvalues are then given by

$$M^2_{h_1,h_2} = \lambda v^2 + \frac{1}{2}M^2 \mp \sqrt{\left(\lambda v^2 - \frac{1}{2}M^2\right)^2 + \mu_2^2 v^2}\,, \quad (321)$$

125 GeV Higgs + real singlet (II)

where we have defined the mass eigenstates $\mathrm{h}_1, \mathrm{h}_2$ as

$$\begin{aligned} \mathrm{h}_1 &= \phi \cos\theta - s \sin\theta \\ \mathrm{h}_2 &= \phi \sin\theta + s \cos\theta, \end{aligned} \tag{322}$$

with the mixing angle θ which can be written as

$$\tan 2\theta = \frac{-\mu_2 v}{\lambda v^2 - \frac{1}{2} M^2} \,. \tag{323}$$

In order to find the domain of θ we can rewrite the masses as follows:

$$M^2_{\mathrm{h}_1,\mathrm{h}_2} = \left(\lambda v^2 + \frac{1}{2} M^2\right) \mp \left(\frac{1}{2} M^2 - \lambda v^2\right) \sec 2\theta \tag{324}$$

If we require h_1 to be the lighter mass eigenstate and choose $M^2 > 2\lambda v^2$, then $\sec 2\theta > 0$, and hence $\theta \in (-\frac{\pi}{4}, \frac{\pi}{4})$.

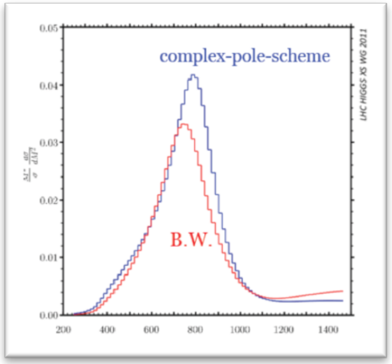
Note that in the notation of Eq. (309) and (310) we have in particular

$$\kappa \equiv \kappa_{\mathrm{V}} = \kappa_{\mathrm{f}} = \cos\theta \tag{325}$$

$$\kappa' \equiv \kappa'_{\mathrm{V}} = \kappa'_{\mathrm{f}} = \sin\theta \,. \tag{326}$$

THEORETICAL ISSUES RELATED TO HIGH MASS

Lineshape effect: Higgs propagator

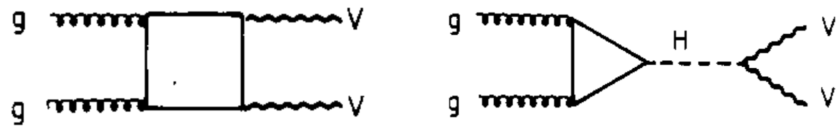


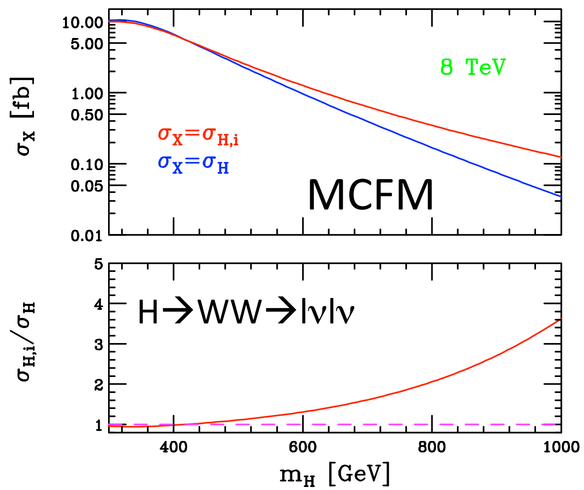
$$\delta\left(\hat{s}-M_H^2\right) \rightarrow \begin{cases} \text{Fixed width: } \dfrac{1}{\pi}\dfrac{M_H\Gamma_H}{\left(\hat{s}-M_H^2\right)^2+\left(M_H\Gamma_H\right)^2} \\ \text{Running width: } \dfrac{1}{\pi}\dfrac{\hat{s}\Gamma_H/M_H}{\left(\hat{s}-M_H^2\right)^2+\left(\hat{s}\Gamma_H/M_H\right)^2} \end{cases}$$

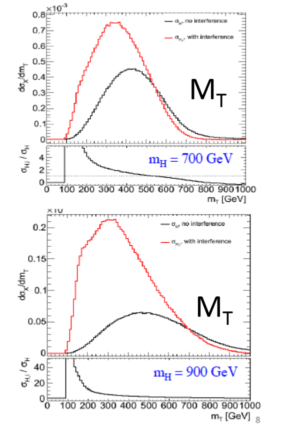
- The propagator affects both
  - the total X sec
  - the mass shape
- The effect increase with the increasing of M_H
- The BW propagator is **NOT valid** anymore in the **heavy mass region** ($M_H \geq 400$ GeV) → **The correct propagator is a complex function**
- Solution: **COMPLEX POLE SCHEME (CPS)**

NEW **CPS PowHeg samples** (ggF and VBF) available for all the **WW** and **ZZ** final states for **$400 \leq M_H \leq 1000$ GeV**

interference sig-continuum bkg







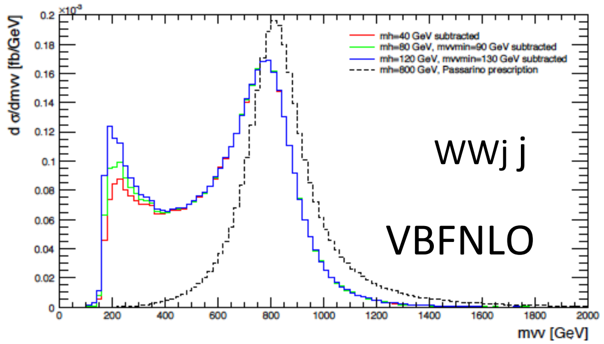
$$m_T = \sqrt{\left(E_T^{\ell\ell}+E_T^{miss}\right)^2 - \left|\mathbf{p}_T^{\ell\ell}+\mathbf{p}_T^{miss}\right|^2},$$

- The interference affects both the total X sec and distributions → different effect **depending from the final state**
- **Interference is NOT included in PowHeg CPS samples**

Need to rescale MC signal samples using other MCs (MCFM or gg2VV) with I_{LO}

SIG-BKG INTERFERENCE EFFECT

Vector Boson Fusion

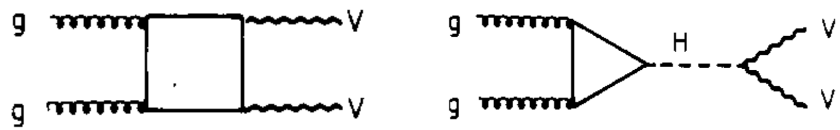


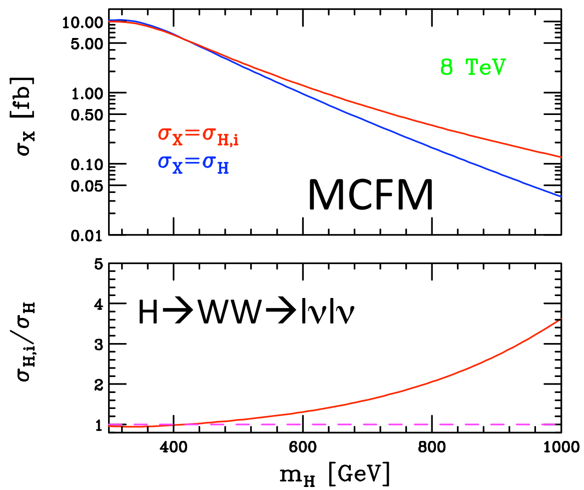
Some light-Higgs mass dependence in threshold region around m_{VV} = 200 ⇒ eliminate by cuts

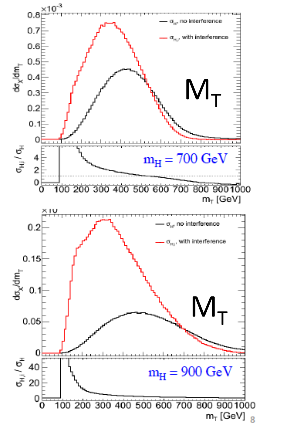
- Define $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_H(m_H)|^2 - B$ where $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$
- Integrate over suitable mass range $[m_H - \Gamma_1, m_H + \Gamma_2]$
- ⇒ S and B well defined and do not violate unitarity
- **Interference is NOT included in PowHeg CPS samples:**

→ **Need to correct MC signal samples using other MCs (VBFNLO) with I_{LO}**

Gluon gluon fusion







$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss}|^2}$,

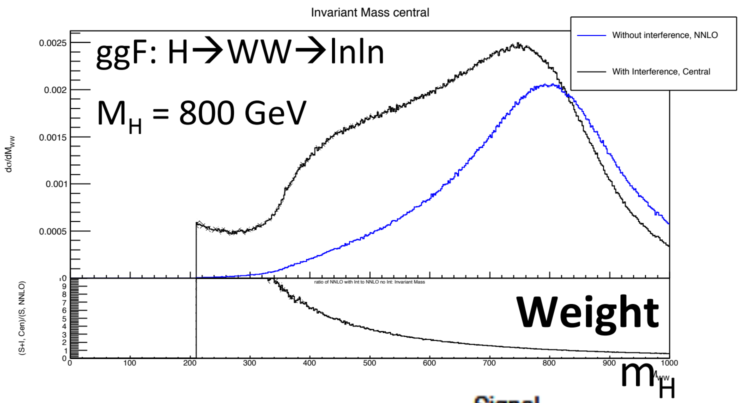
- The interference affects both the total X sec and distributions
- Effect increase with the increasing of m_H
- **Interference is NOT included in PowHeg CPS samples:**

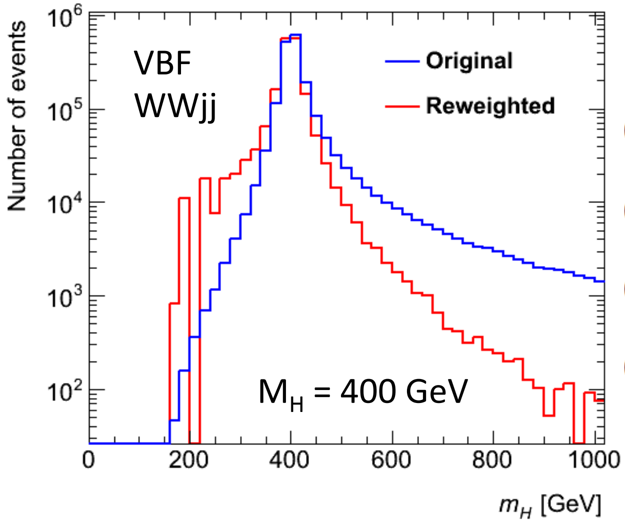
→ **Need to rescale MC signal samples using other MCs (MCFM or gg2VV) with I_{LO}**

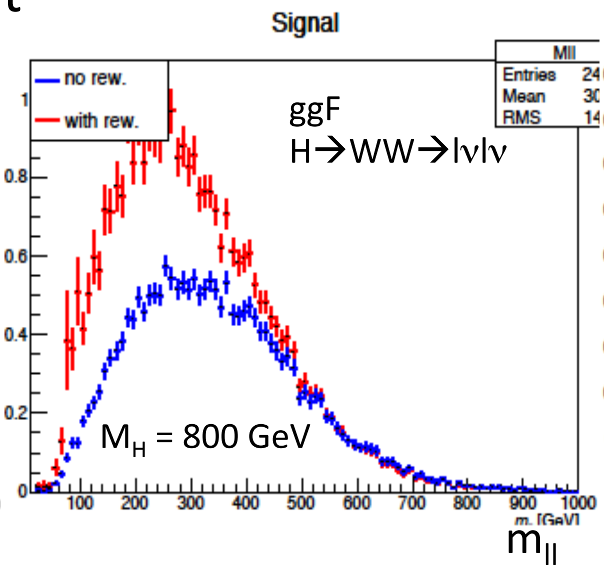
INTERFERENCE RESCALING TOOLS

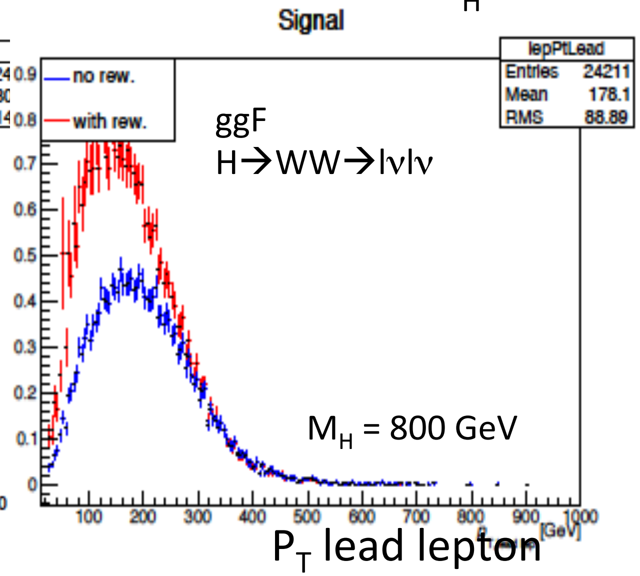
Different tools (depending from the final states) developed to reweight the MC signal samples to account for the interference effect

- **Weight** calculated as the ratio between m_H distribution with and without the interference effect
- Rescale MC signal samples on an event by event weight





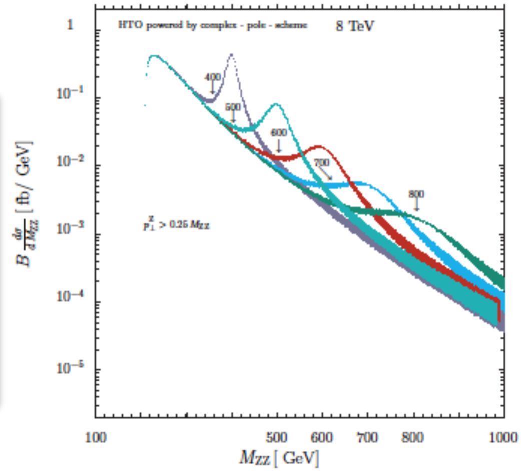


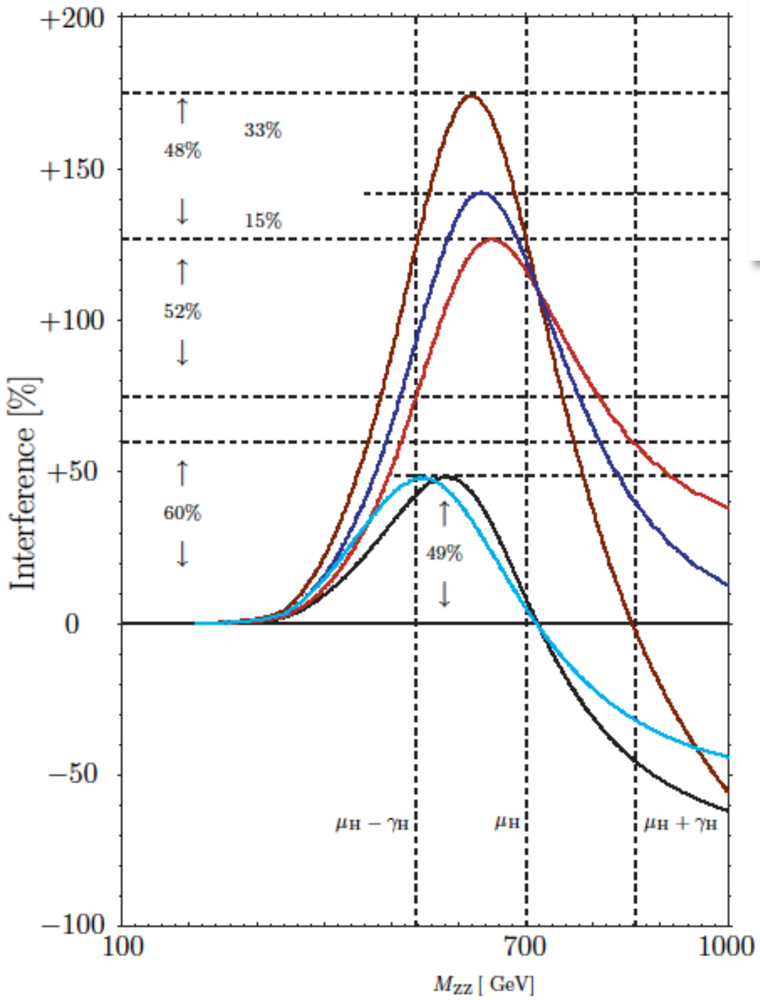


GGF INTERFERENCE RESCALING LO → NNLO

How does the interference scale from LO to NNLO?

→ Our ignorance is transferred in the uncertainties →





A reweighting procedure to rescale MC samples for the interference effect has been set up, based on invariant mass

LO
- S+B (LO)
- S+B+I (LO)

NNLO
- multiplicative
  (S+I)*K +B
- additive
  (S*K) + I + B

  (multiplicative and additive: **UNCERTAINTY BAND**)
- intermediate: **CENTRAL VALUE**
  S*K + I*K' + B

where **K = S_{NNLO}/S_{LO}** while K' just include gg initiated diagrams

INTERFERENCE RESCALING PROCEDURE

Is the reweighting on the mass shape enough to catch the distortion of kinematics due to interference ?

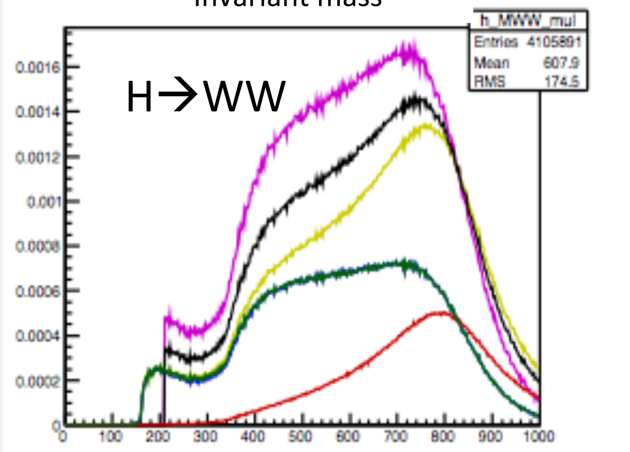
Without interference
With Interference
Reweighted

} MCFM generated - LO

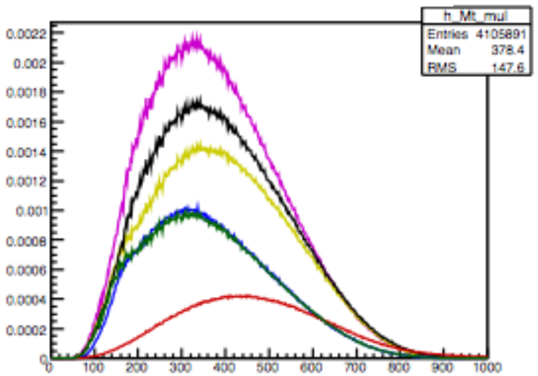
Additive
Multiplicative
Intermediate

} MCFM reweighted- NNLO

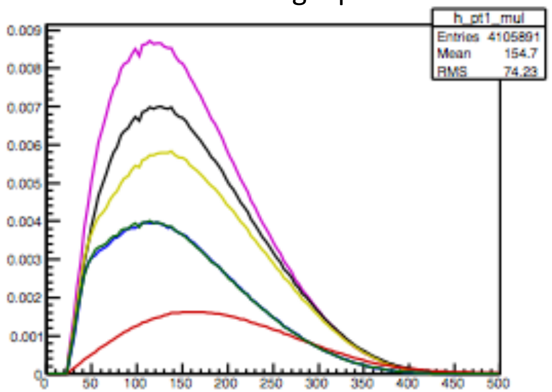
Invariant mass



Transverse mass



Pt leading lepton



Yes!
We can reweight our MC samples to account for the signal-background interference effect and the LO→NNLO effect

CMS RESULTS

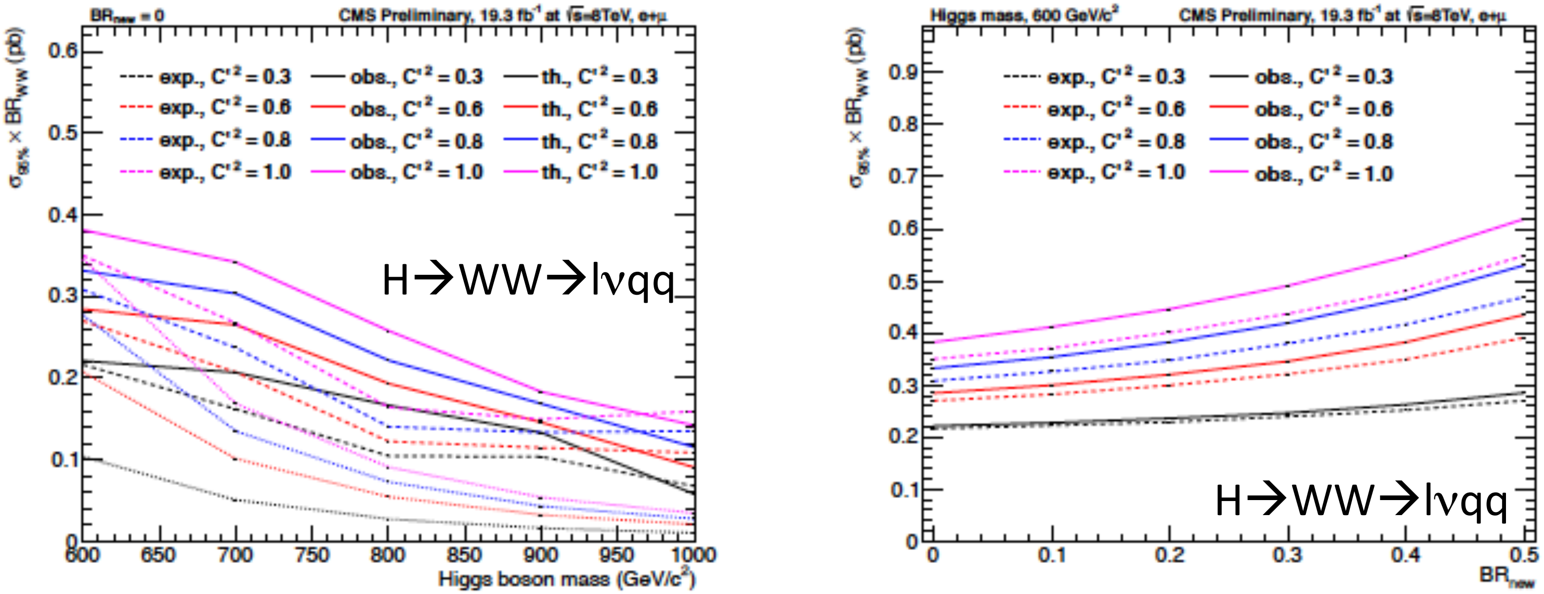
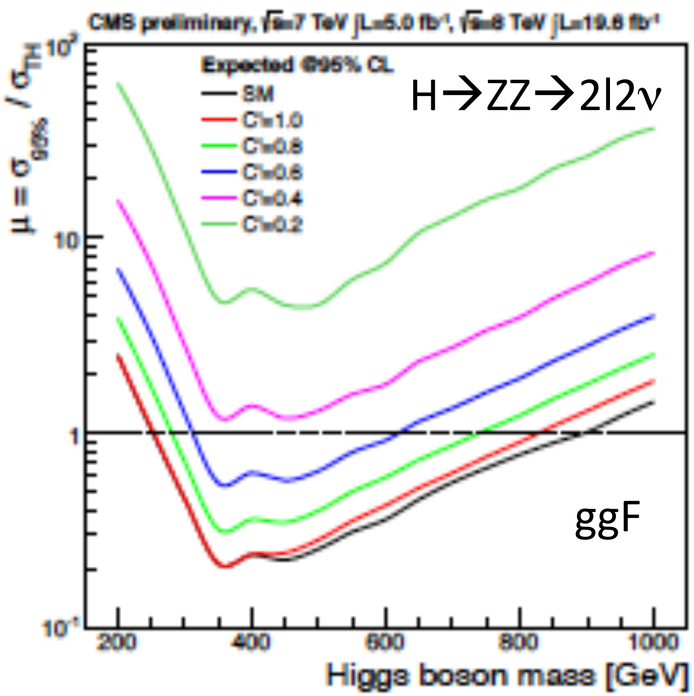
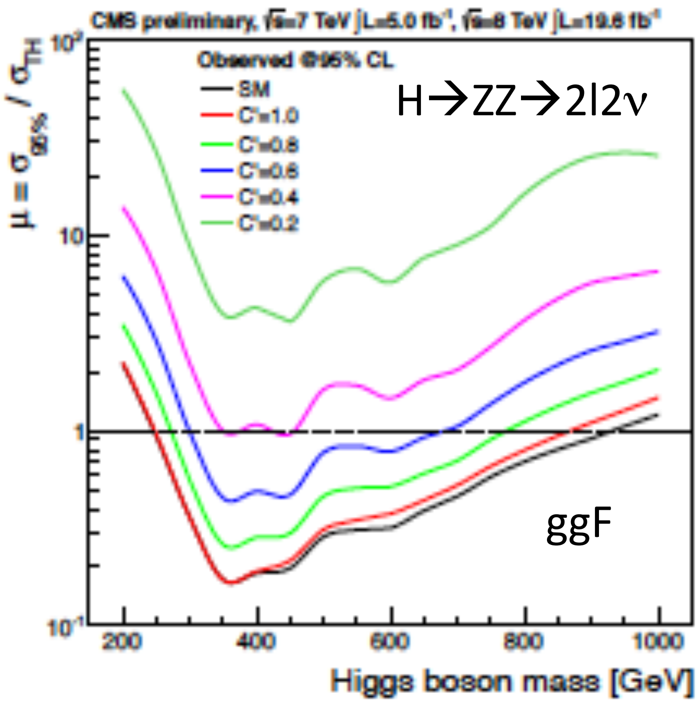


Figure 7: On the left, BSM exclusion limits for a signal mass hypothesis of 600 GeV as a function of mass for various values of C'^2 where $BR_{new} = 0$. On the right, BSM exclusion limits for a signal mass hypothesis of 600 GeV as a function of BR_{new} for various values of C'^2 where $m_H = 600\,\mathrm{GeV}$.

- BSM interpretation limits
- Performed in the region $\Gamma_H' \leq \Gamma_{SM}$
- **No constraints from existing data** taken into account: scan over the range 0.3 ≤ C' ≤ 1.0
- **Only gluon gluon fusion**

CMS RESULTS





- Reference benchmarks σ_{TH}: SM and **125 GeV Higgs + real singlet**
- Performed in the region $\Gamma_H' \leq \Gamma_{SM}$
- **No constraints from existing data** taken into account: scan over the range $0.2 \leq C' \leq 1.0$
- Assuming **no decay of the new scalar into new particles**: $BR_{new} = 0$