Constraints on the Higgs width from off-shell production and decays to Z-boson pairs

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On behalf of the CMS Collaboration

The flavor of Higgs workshop
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Outlines

- Theoretical motivations
- H→ZZ→4l on-shell
- H→ZZ→4l off-shell
- H→ZZ→2l2nu off-shell
- Statistical analysis
- Conclusions

arXiv:1405.3455

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs

The CMS Collaboration*

Abstract

Constraints are presented on the total width of the recently discovered Higgs boson, Γ_H, using its relative on-shell and off-shell production and decay rates to a pair of Z bosons, where one Z boson decays to an electron or muon pair, and the other to an electron, muon, or neutrino pair. The analysis is based on the data collected by the CMS experiment at the LHC in 2011 and 2012, corresponding to integrated luminosities of 5.1 fb^{-1} at a centre-of-mass energy $\sqrt{s} = 7$ TeV and 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV. A simultaneous maximum likelihood fit to the measured kinematic distributions near the resonance peak and above the Z-boson pair production threshold leads to an upper limit on the Higgs boson width of $\Gamma_H < 22$ MeV at a 95% confidence level, which is 5.4 times the expected value in the standard model at the measured mass.

Submitted to Physics Letters B

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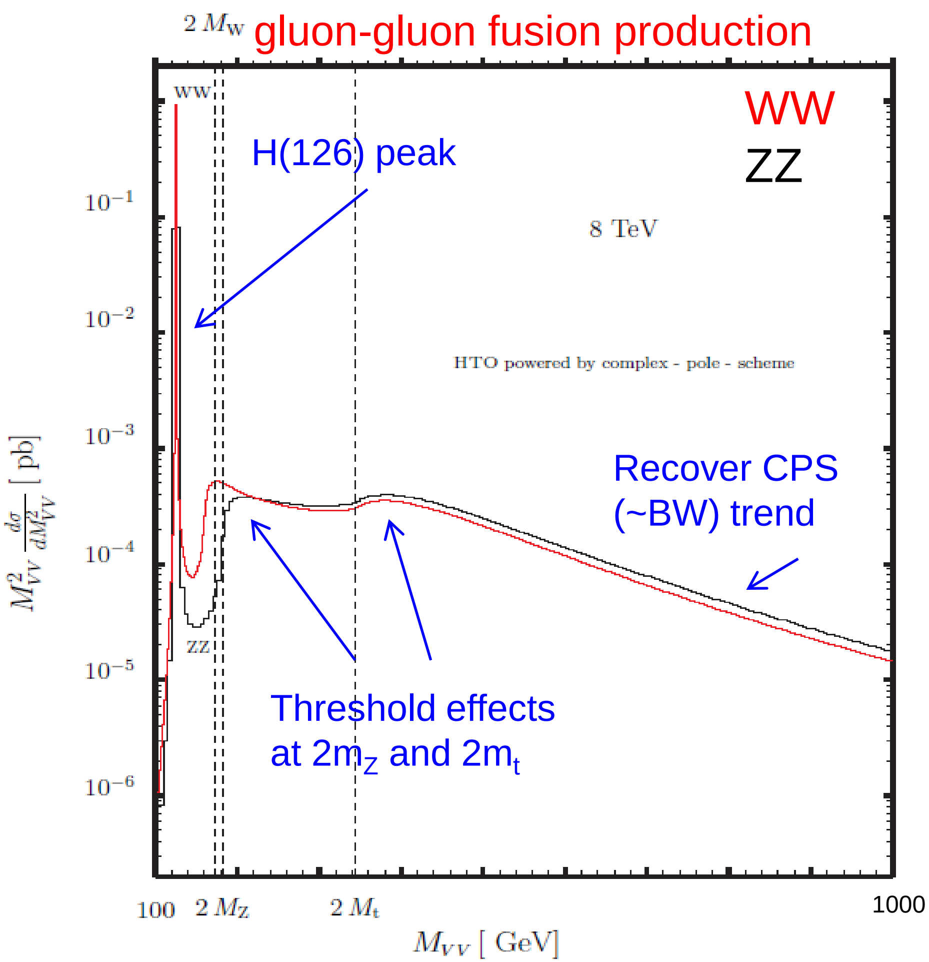
Theoretical background

N. Kauer and G. Passarino, JHEP 08 (2012) 116



$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(m^2_{ZZ}-m^2_{H})^2 + m^2_{H}\Gamma^2_{H}}$$

- **Off-shell H*→VV is not neligible !**

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

- **H*→ZZ account for ~8% of the total cross-section in the ZZ final state**

Theoretical background

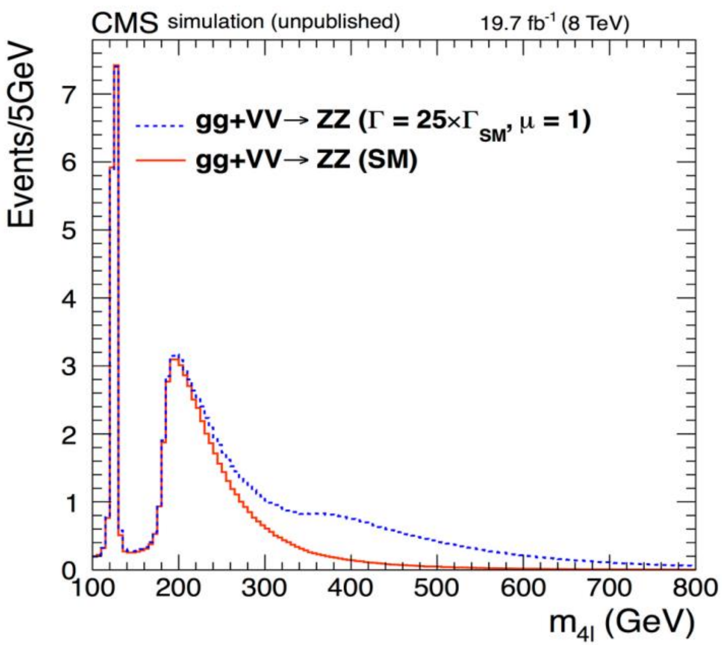
- F. Caola, K. Melnikov (Phys. Rev. D88 2013) and J. Campbell et al. (arXiv:1311.3589)

- In the **on-shell** region ($m_{ZZ} \sim m_H$), we have :

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

- In the **off-shell** region ($m_{ZZ}-m_H >> \Gamma_H$), we have :

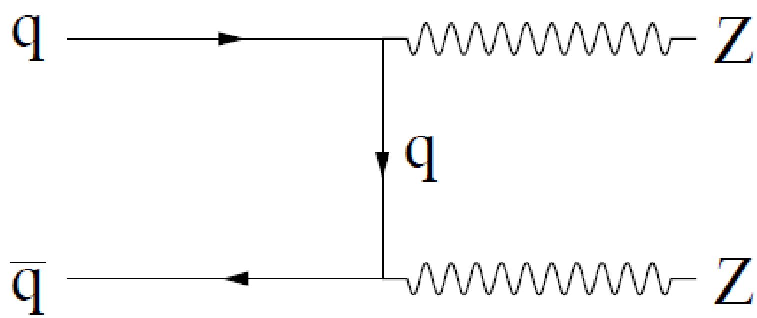
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$



- Taking the ratio of On-shell / off-shell, give us a direct information on Γ_H
  - Valid if the coupling ratio On/Off-shell remains unchanged (i.e. top loop dominates in ggF)

Dominant contributions in ZZ prod.

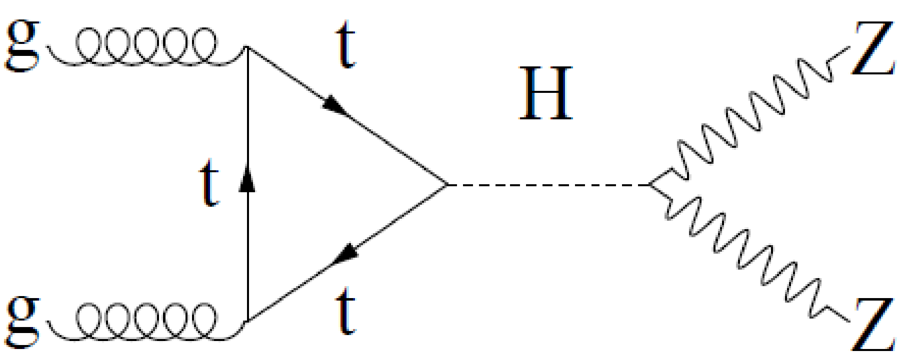
Backgrounds (LO)

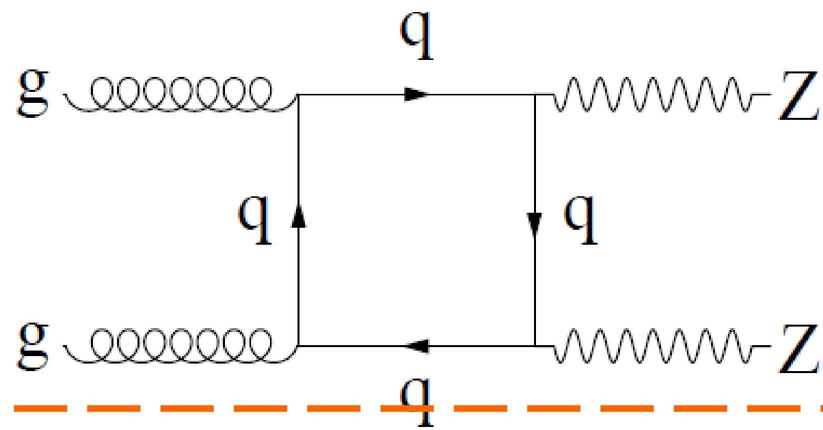


Strong Interferences

Signal

Backgrounds (qq continuum)

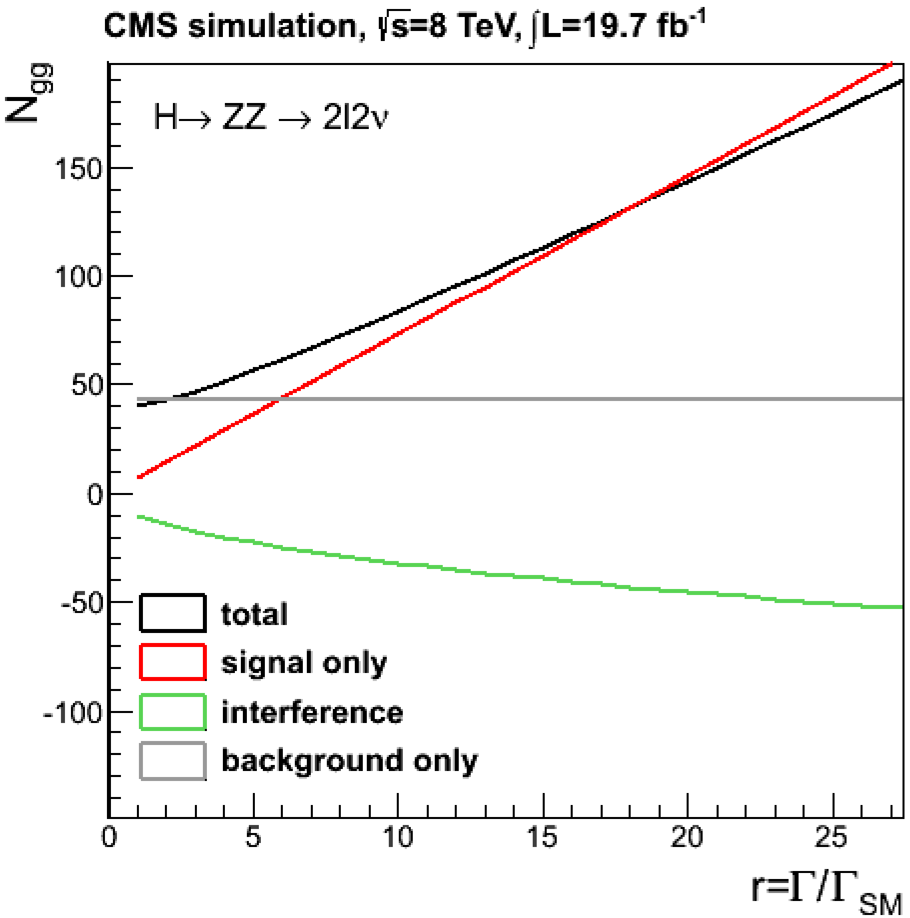




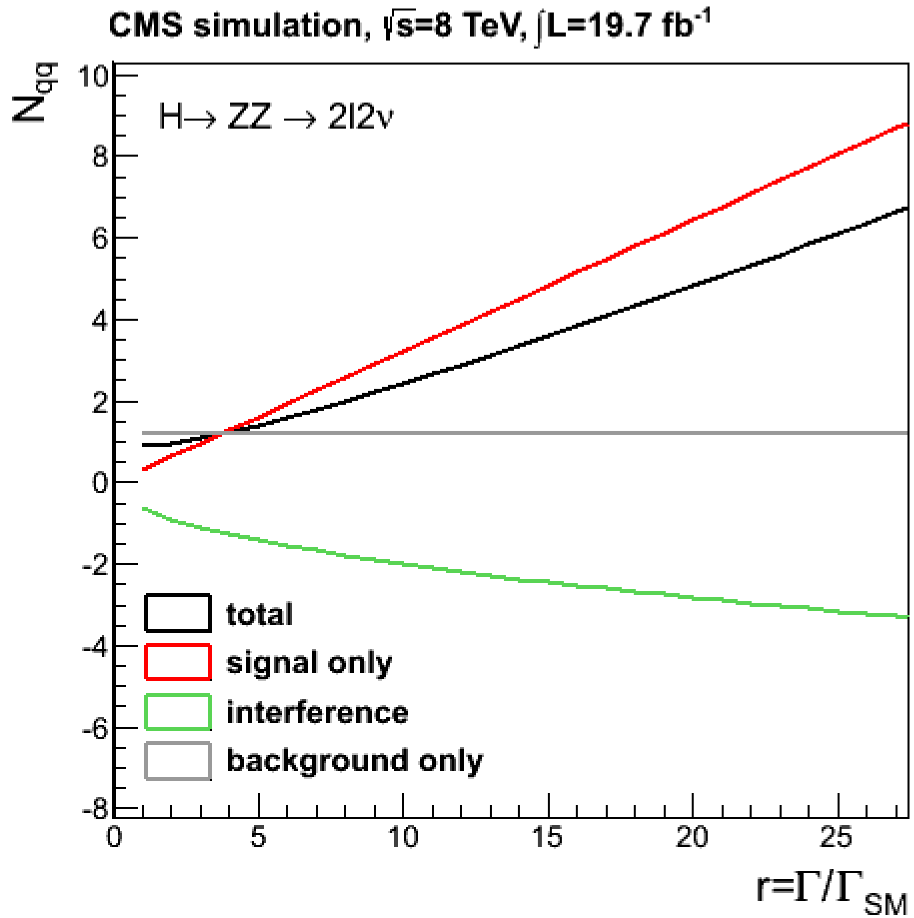
- Similar kind of interference also exist in VBF prod. channel

Yields vs Γ_H

ggF



VBF



Off-shell MC Simulation

- **M_H = 125.6GeV & Γ_H = 4.15MeV**

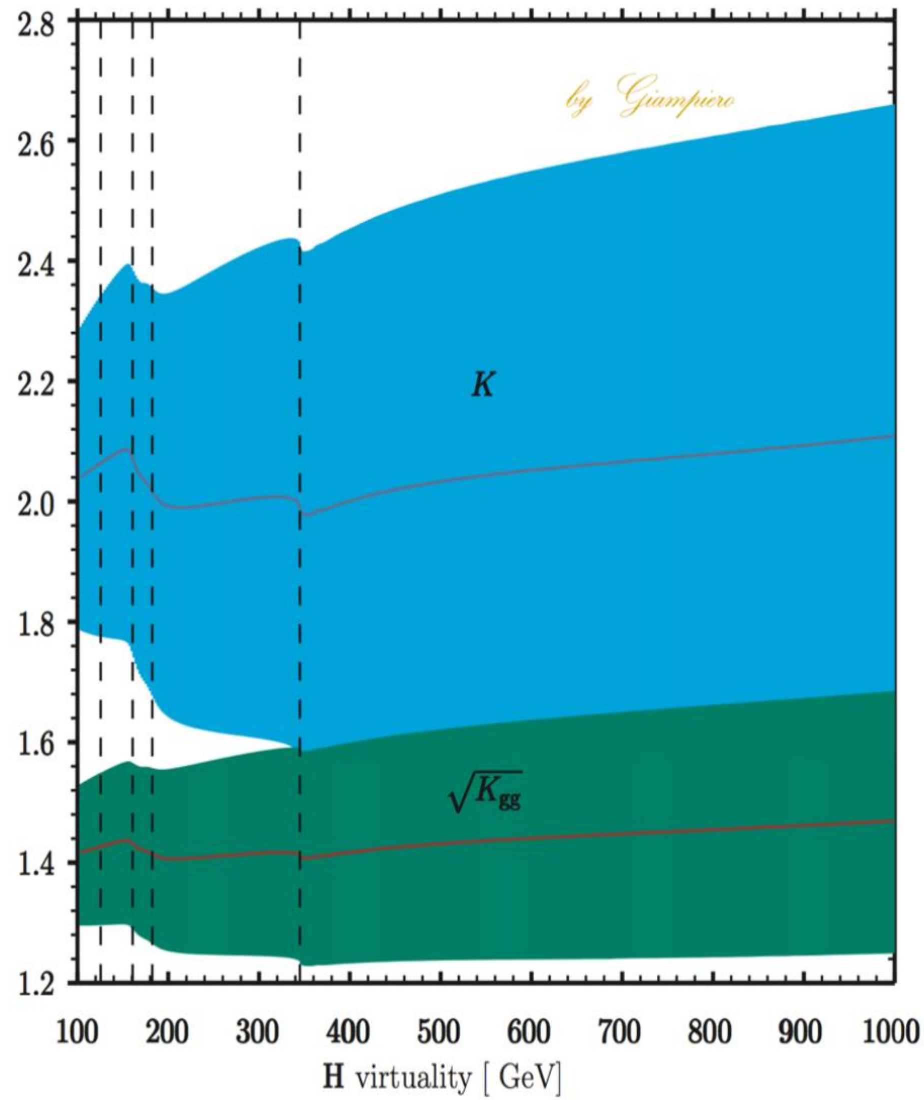
- **Gluon-gluon fusion (gg2VV / MCFM) :**
  - Signal/background/interference
  - NNLO/LO kFactors depend on mZZ

    G. Passarino (arXiv:1312.2397)
  - Use the same kFactors for signal and gg continuum

    M. Bonvini et al.(Phys.Rev.D 88 2013)

- **Vector boson fusion (Phantom) :**
  - Represent 7% under the peak
  - Grows to ~10% for mZZ ~ 300-600GeV

- **VH and ttH production :**
  - Negligible in the high mass region

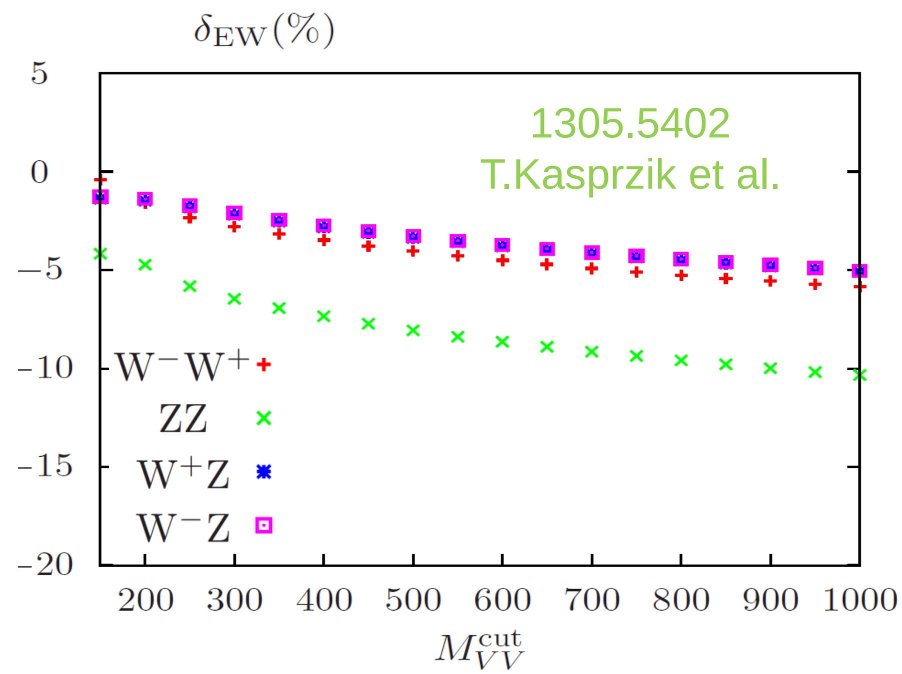


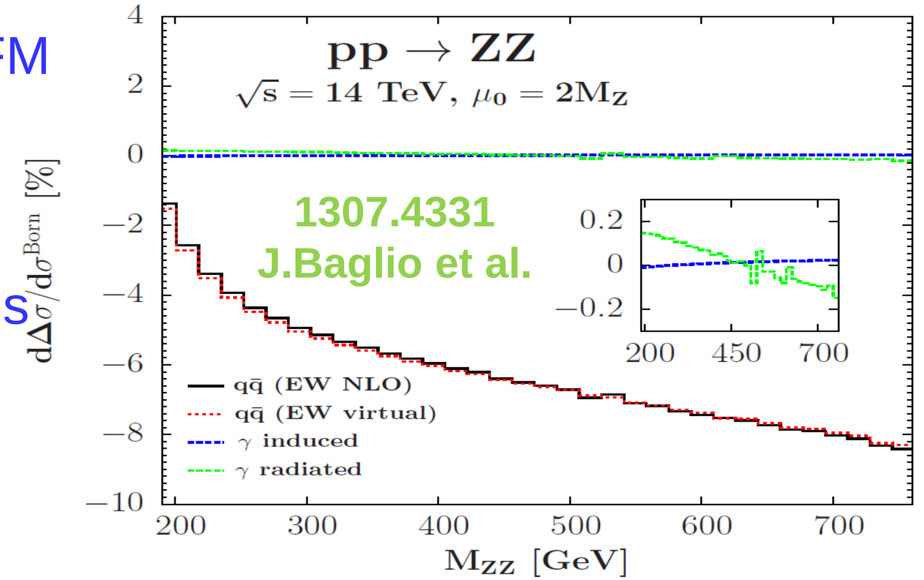
NLO EWK corrections

- Corrections to $q\bar{q} \rightarrow ZZ/WZ$ backgrounds
- Adopting the work from:
  - Baglio et al. (arXiv 1307.4331)
  - Bierweiler et al. (arXiv 1305.5402)
  - Gieseke (arXiv 1401.3964)

- Uncertainty on the correction assigned as $\delta_{NLO\ QCD}$ x $\delta_{NLO\ EWK}$ where $\delta_{NLO\ QCD}$ is derived from MCFM → up to 10% at the end.

- ~5% reduction in the expected yields at 700 GeV





Statistical analysis

- **Build the probability density function and use it to perform a likelihood fit:**

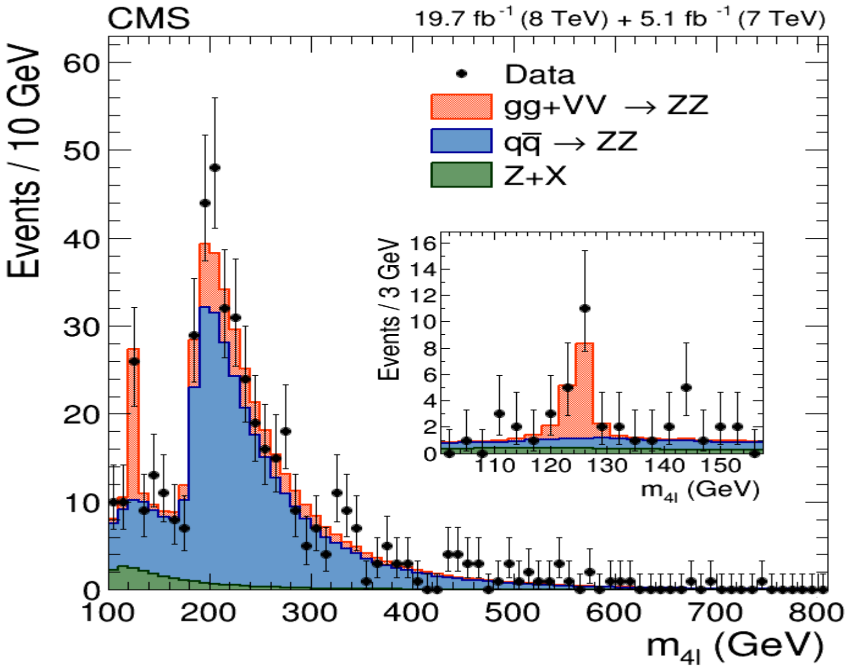
$$\mathcal{P}_{\rm tot}^{\rm on\text{-}shell}(\vec{x}) = \mu_{\rm ggH} \times \left[\mathcal{P}_{\rm sig}^{\rm gg}(\vec{x}) + \mathcal{P}_{\rm sig}^{\rm t\bar{t}H}(\vec{x})\right] + \mu_{\rm VBF} \times \left[\mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm sig}^{\rm VH}(\vec{x})\right]$$
$$+ \mathcal{P}_{\rm bkg}^{\rm q\bar{q}}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm gg}(\vec{x}) + \ldots$$

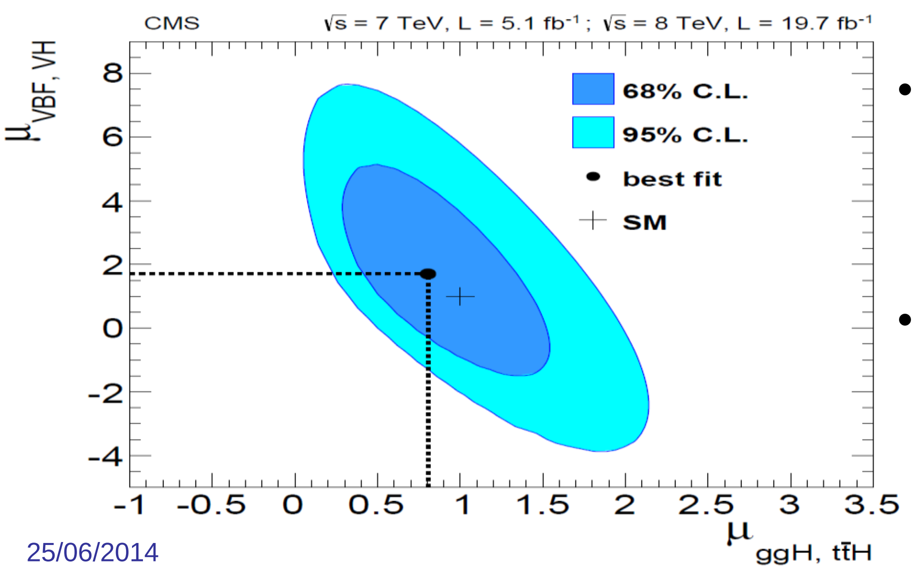
$$\mathcal{P}_{\rm tot}^{\rm off\text{-}shell}(\vec{x}) = \left[\mu_{\rm ggH} \times (\Gamma_{\rm H}/\Gamma_0) \times \mathcal{P}_{\rm sig}^{\rm gg}(\vec{x}) + \sqrt{\mu_{\rm ggH} \times (\Gamma_{\rm H}/\Gamma_0)} \times \mathcal{P}_{\rm int}^{\rm gg}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm gg}(\vec{x})\right]$$
$$+ \left[\mu_{\rm VBF} \times (\Gamma_{\rm H}/\Gamma_0) \times \mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \sqrt{\mu_{\rm VBF} \times (\Gamma_{\rm H}/\Gamma_0)} \times \mathcal{P}_{\rm int}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm VBF}(\vec{x})\right]$$
$$+ \mathcal{P}_{\rm bkg}^{\rm q\bar{q}}(\vec{x}) + \ldots$$ *(Backgrounds w/o interf.)*

- **3 parameters are unconstrained in the likelihood fit**
  - **μ_{ggF} and μ_{VBF} : Signal strength scaling w.r.t SM prediction**
    → totally driven by the “on-shell” analysis
  - **Γ_H/Γ_0 : Higgs width scaling w.r.t SM prediction**
    → Γ_H is extracted from the off-shell analysis

- **The ZZ→4l channel is used to constrain the on-shell part.**
- **The 4l and 2l2v decay channels are used to constrain the off-shell part**

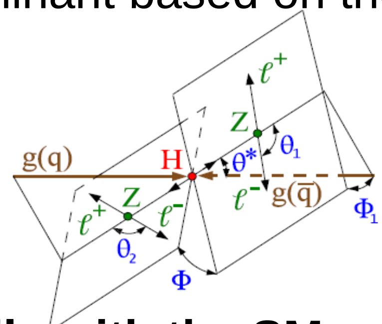
4l on-shell (summary)





- Analysis is unchanged w.r.t H→ZZ→4l paper **(arXiv:1312.5353)**

- 4 isolated leptons
- Lepton pT>20, 10, 5, 5 GeV
- 2 OS / SF pairs with M_{ll}>4 GeV
- 105.6 < M_{4l} < 140.6 GeV
- Matrix Element Discriminant based on the system kinematics (m_{Z1}, m_{Z2}, 5 angles)



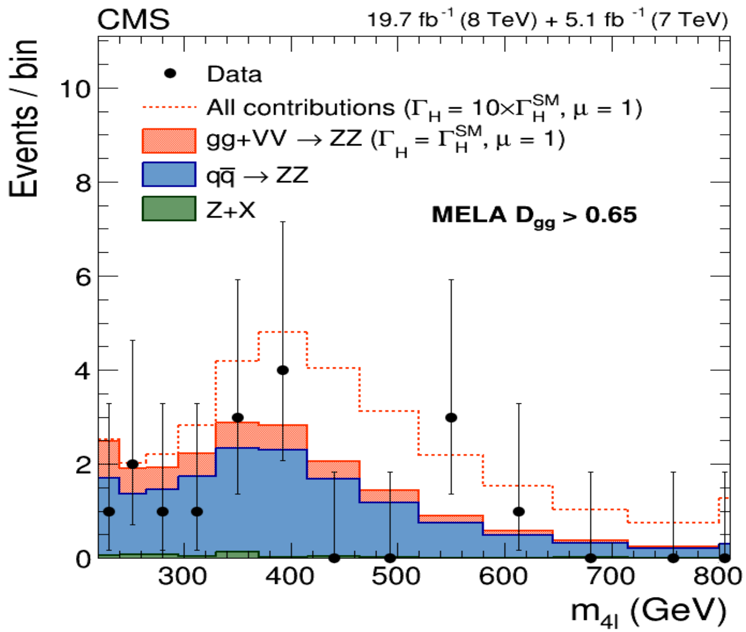
- **Results are comptabile with the SM:**

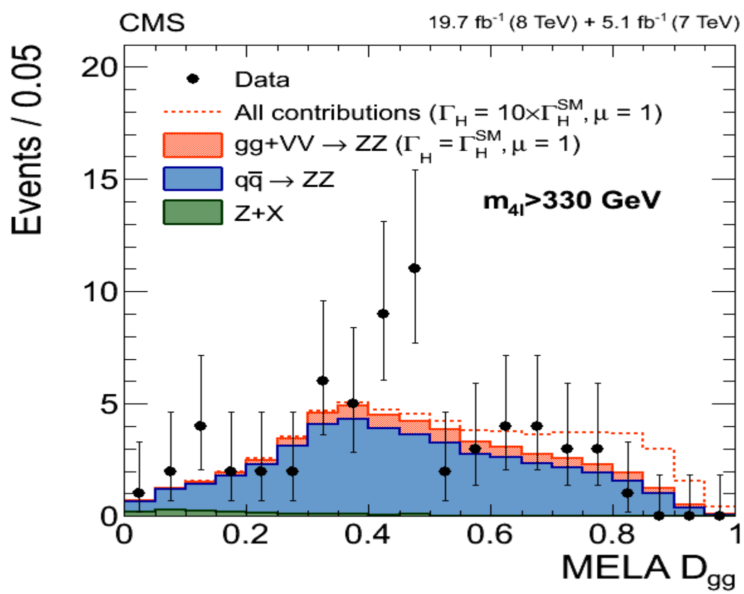
$$\mu_F = 0.81^{+0.49}_{-0.38}$$
$$\mu_V = 1.7^{+2.2}_{-1.7}$$

- **Direct measurement of the higgs width in M_{4l} distribution lead to :**

$$\Gamma_{tot} \leq 3.4 \text{ GeV}$$

4l off-shell



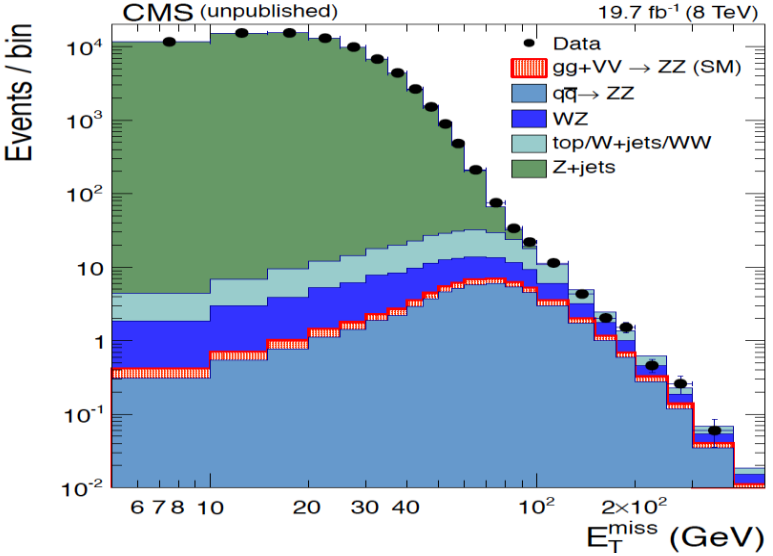


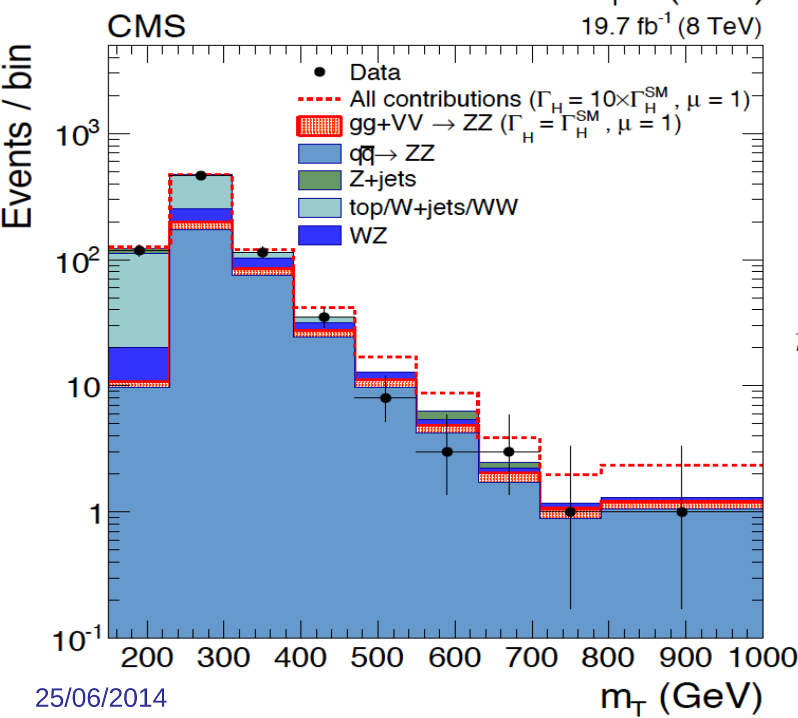
- **Based on two variables :**
- **Matrix Element based discriminant :**

$$\mathcal{D}_{gg} = \frac{\mathcal{P}_{tot}^{gg}}{\mathcal{P}_{tot}^{gg} + \mathcal{P}_{bkg}^{q\bar{q}}} = \left[1 + \frac{\mathcal{P}_{bkg}^{q\bar{q}}}{a \times \mathcal{P}_{sig}^{gg} + \sqrt{a} \times \mathcal{P}_{int}^{gg} + \mathcal{P}_{bkg}^{gg}}\right]^{-1}$$

  - Based on probabilities $\mathcal{P}_{tot}^{gg}$ / $\mathcal{P}_{bkg}^{q\bar{q}}$ that an event originates from qq→4l or gg→4l (includes signal, bckg and interf.)
  - *a* is the strength modificator due to a change of the width. (*a*=10 was chosen for $\mathcal{D}_{gg}$ definition)
- **4l invariant mass : M_{4l} > 220GeV**
- **2 dimensional pdfs are used in the likelihood fit**

2l2nu off-shell





- Analysis technique as in high mass Higgs search(**arXiv:1304.0213**)

- Only the 8TeV dataset is considered for this final state
- BR(ZZ→2l2nu) = ~6x BR(ZZ→4l)
- Larger backgrounds compared to 4l channel
  → Data-driven estimation

- 2 isolated leptons (pT>20GeV)
- OS / SF lepton pair (compatible with a Z)
- E_T^{miss} > 80 GEV (from neutrinos)
- Transverse mass : mT>180 GeV

$$m_T^2 = \left[\sqrt{p_{T,2\ell}{}^2 + m_{2\ell}{}^2} + \sqrt{E_T^{miss\,2} + m_{2\ell}{}^2}\right]^2 - \left[\vec{p}_{T,2\ell} + \vec{E}_T^{miss}\right]^2$$

- **mT distribution is used as the final variable entering the likelihood fit**

Event yields in off-shell region

Off-shell enriched region :

4l channel req.
m_{4l} > 330 GeV
D_{gg} > 0.65

2l2nu channel req.
m_T > 350 GeV
E_T^{miss} > 100 GeV

		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ±0.01	0.90 ±0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ±0.01	0.32 ±0.02
	VBF background component	0.35±0.02	1.22 ±0.07
(e)	$q\bar{q}$ background	9.3 ±0.7	47.6 ±4.0
(f)	other backgrounds	0.05 ±0.02	35.1 ±4.2
(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8	93.2 ±6.0
	observed	11	91

Event yields in off-shell region

$\Gamma_H = 10x\ \Gamma_H^{SM}$

4l channel req.
$m_{4l} > 330$ GeV
$D_{gg} > 0.65$

2l2nu channel req.
$m_T > 350$ GeV
$E_T^{miss} > 100$ GeV

		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2	39.8 ±5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ±0.01	0.90 ±0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ±0.01	0.32 ±0.02
	VBF background component	0.35±0.02	1.22 ±0.07
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	0.77 ±0.04	2.40 ±0.14
(e)	$q\bar{q}$ background	9.3 ±0.7	47.6 ±4.0
(f)	other backgrounds	0.05 ±0.02	35.1 ±4.2
(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8	93.2 ±6.0
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4	124.9 ±7.8
	observed	11	91

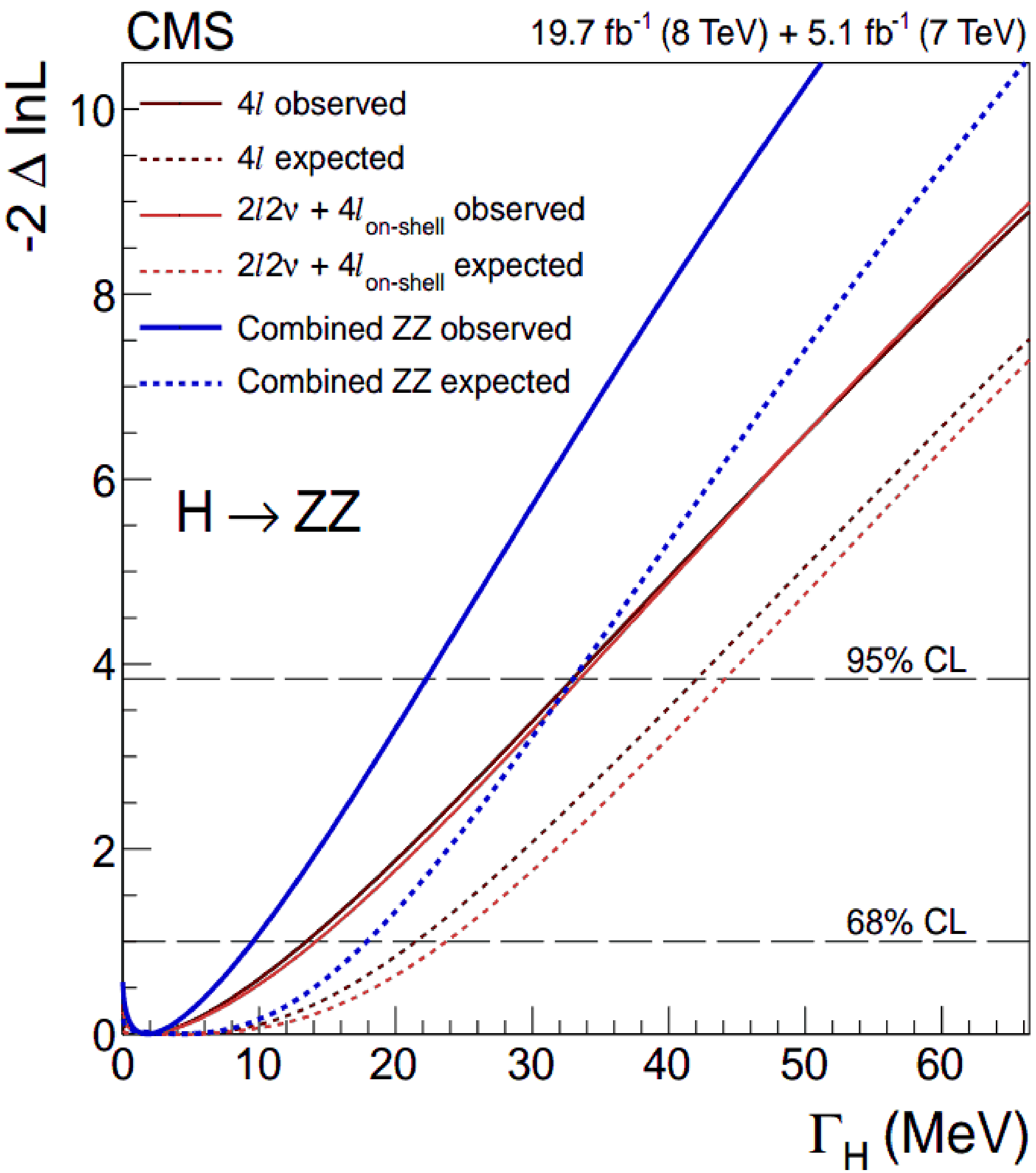
Relevant uncertainties

- **Signal uncertainties:**
  - Trigger Eff. 5%
  - Reco+ID+Iso Eff. (muons) 3-4%
  - Reco+ID+Iso Eff. (elec.) 5-11%
  - Lep & Jet energy scale ~2%
  - 2l2nu • B-Jet veto 1-3%
  - 2l2nu • PS and UE effects on MET 6%

- **Background uncertainties**
  - 2l2nu • tT, tW, WW 15% on ~8% total bckg
  - 2l2nu • Z+Jets 25% on ~3% total bckg

- **Theoretical uncertainties.**
  - qq bckg. 4-10% depending on mZZ
  - gg→ZZ continuum (+int.) 12-14% (kFactors)
  - pdf 1%

Results of the Likelihood fit



- Signal strength measurement
  - $\mu_{ggF} = 0.81^{+0.47}_{-0.37}$
  - $\mu_{VBF} = 1.7^{+2.2}_{-1.7}$
  - ~ Identical to 4l only
- **95% C.L. Limits on Γ_H :**
  - Expected : 33MeV
  - Observed : 22MeV
- **Γ_H Measurement :**
  - Expected : $4.2^{+13.5}_{-4.2}$ MeV
  - Observed : $1.8^{+7.7}_{-1.8}$ MeV
- **Reminder : SM predicts :**
  - Γ_H = 4.2MeV

Results by channels

Analysis	Observed/ Expected	95% CL limit on Γ_H (MeV)	95% CL limit on Γ_H/Γ_H^{SM}	Γ_H (MeV)	Γ_H/Γ_H^{SM}
4ℓ	Expected	42	10.1	$4.2^{+17.3}_{-4.2}$	$1.0^{+4.2}_{-1.0}$
	Expected (no syst.)	41	10.0	$4.2^{+17.1}_{-4.2}$	$1.0^{+4.1}_{-1.0}$
	Observed	33	8.0	$1.9^{+11.7}_{-1.9}$	$0.5^{+2.8}_{-0.5}$
$4\ell_{on-shell} + 2\ell 2\nu$	Expected	44	10.6	$4.2^{+19.3}_{-4.2}$	$1.0^{+4.7}_{-1.0}$
	Expected (no syst.)	34	8.3	$4.2^{+14.1}_{-4.2}$	$1.0^{+3.4}_{-1.0}$
	Observed	33	8.1	$1.8^{+12.4}_{-1.8}$	$0.4^{+3.0}_{-0.4}$
Combined	Expected	33	8.0	$4.2^{+13.5}_{-4.2}$	$1.0^{+3.2}_{-1.0}$
	Expected (no syst.)	28	6.8	$4.2^{+11.3}_{-4.2}$	$1.0^{+2.7}_{-1.0}$
	Observed	22	5.4	$1.8^{+7.7}_{-1.8}$	$0.4^{+1.8}_{-0.4}$

The ZZ→2l2v channel improves the limits by ~20% w.r.t 4l only

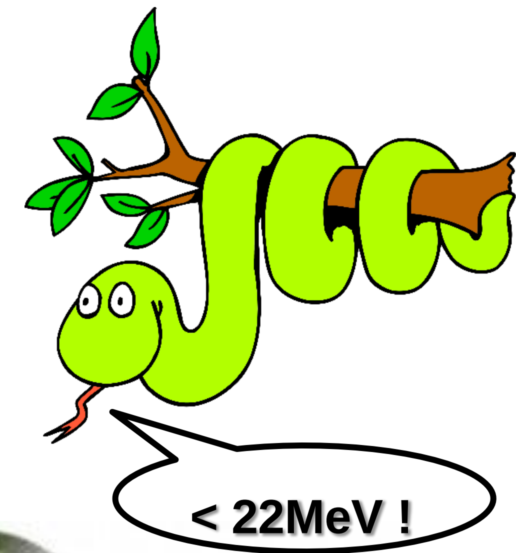
→ Looking forward to had more final states into the game :

ZZ→2l2q? WW→lvlv ? WW→lvjj ?

Compatibility between the observed results and the SM hypothesis lead to a **p-value of 0.24**

Summary

- **Experimental (indirect) constraint on Higgs total width using off-shell H(125.6) production**



- Combined ZZ→4l and 2l2n final states
- Mild model-dependence
  - Assuming that coupling ratio on/off-shell is not not modified by new physics
- Combination results:
  - **$\Gamma/\Gamma_{SM} < 5.4$** (8.0 expected) @ 95% CL
  - **$\Gamma < 22$ MeV** (33 expected) @ 95% CL
  - Measurement → $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV
    (expected: $\Gamma_H = 4.2^{+13.5}_{-4.2}$ MeV)