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

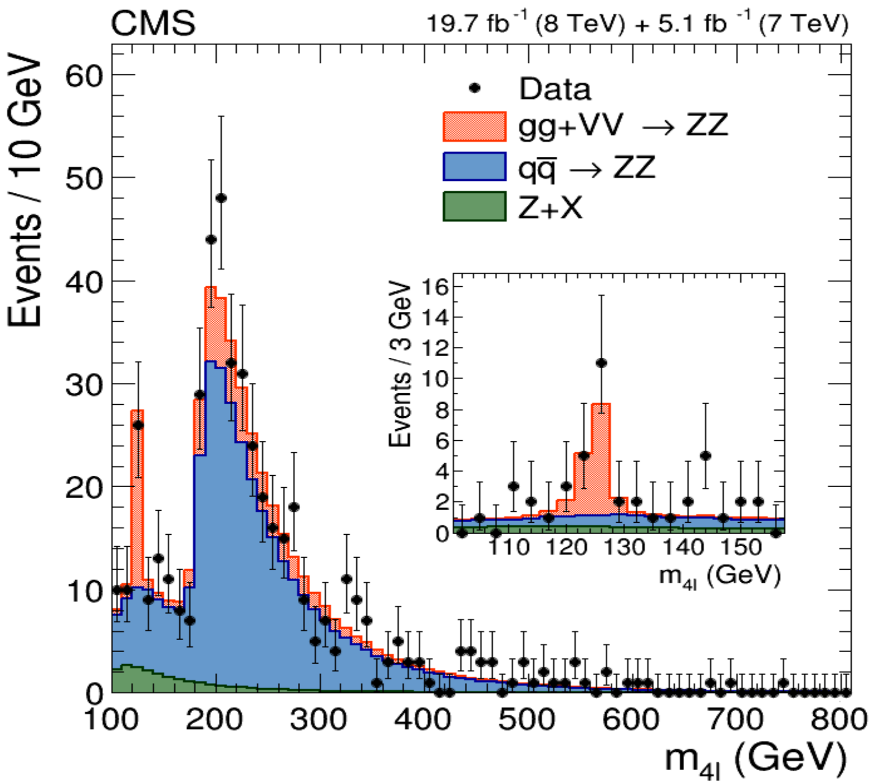
arXiv:1405.3455 (Accepted by Physics Letters B)

Loïc Quertenmont

On behalf of the CMS Collaboration

ICHEP2014, Valencia,
03 July 2014

Introduction



- H→ZZ→4l analysis in a nutshell
  - 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

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

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

- **Standard Model predicts a width that is 3 order of magnitude smaller :**

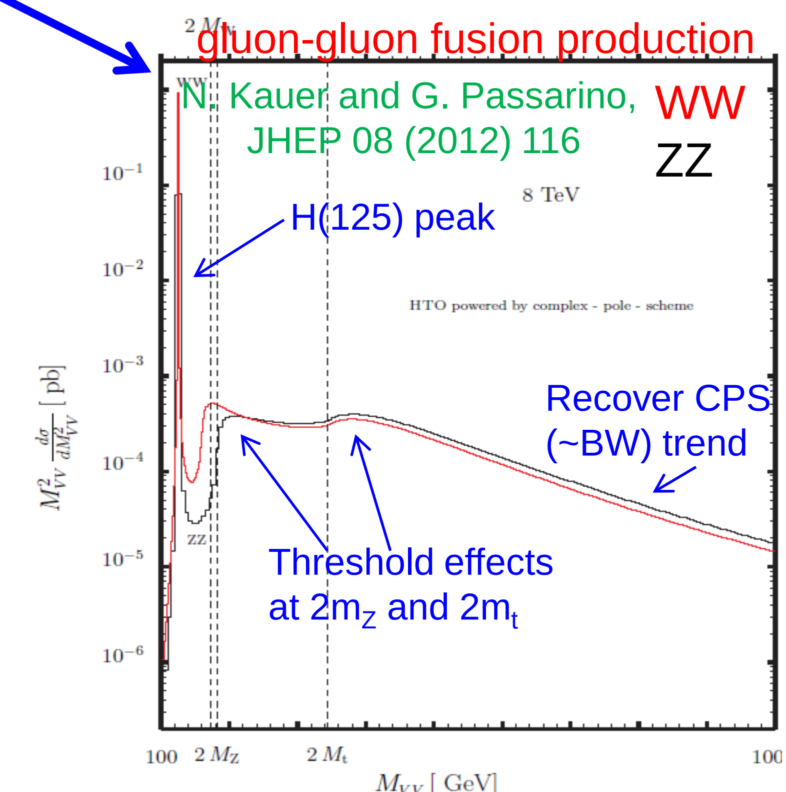
$$\Gamma_{tot} = 4.2 \text{ MeV}$$

- **Indirect measurements based on off-shell higgs production can be used to constraint further the Higgs width**

Theoretical background

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

F. Caola, K. Melnikov (Phys. Rev. D88 2013)
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 :

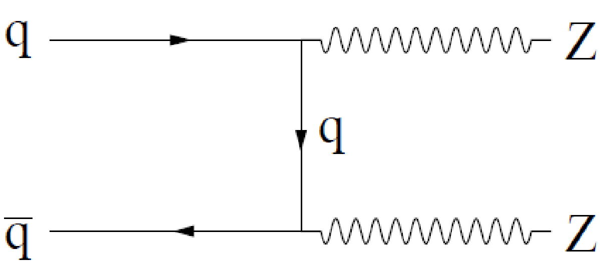
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

- **Γ_H can be extracted from the ratio On/Off-shell**

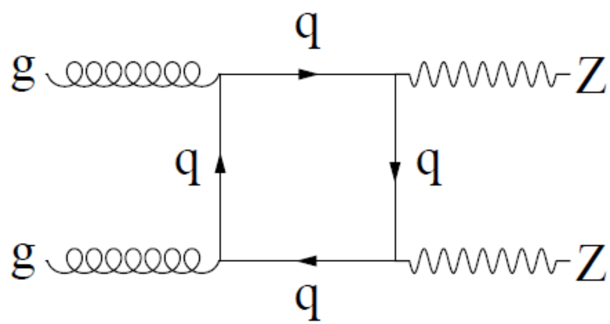
- Mild-model dependence : The method works for BSM models if this ratio is not modified by new physics (i.e. top loop still dominates in ggF)

ZZ production and KFactors

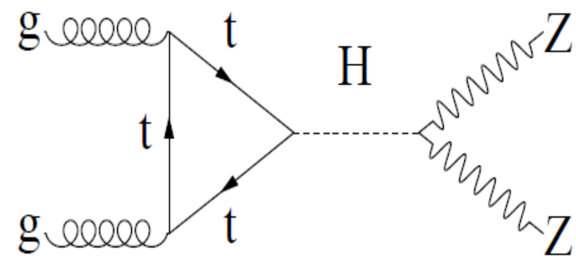
Backgrounds (LO)



Backgrounds(qq continuum)



Signal



Strong Interference

- Signal / background / interference
- NNLO/LO kFactors depend on mZZ

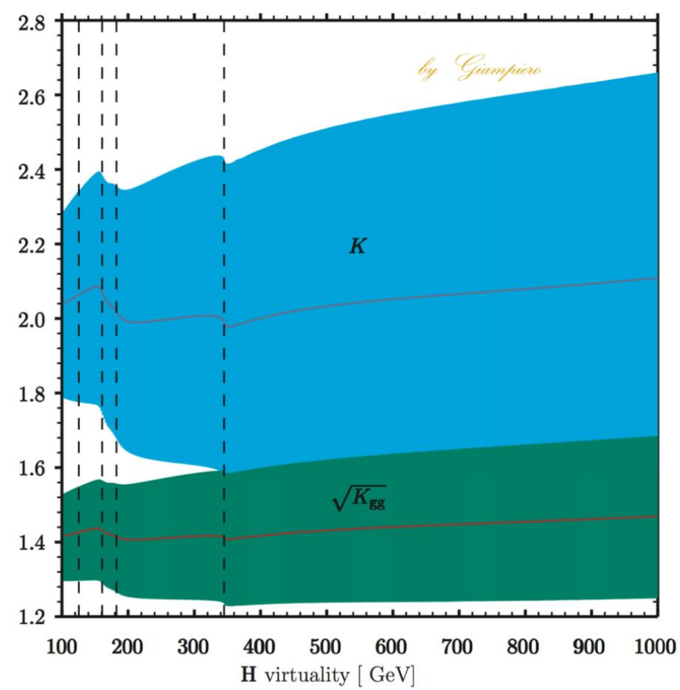
  G. Passarino (arXiv:1312.2397)
- Use the same kFactors for signal and gg continuum

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

- NLO EWK corrections

  $q\bar{q} \rightarrow ZZ/WZ$ (5% decrease @700GeV)

  up to 10% uncertainty



Statistical analysis

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

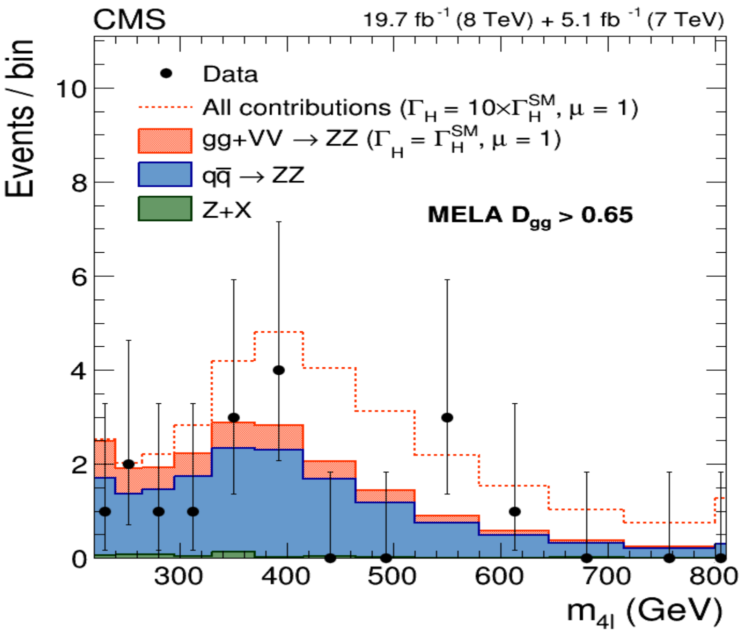
$$\mathcal{P}_{\rm tot}^{\text{on-shell}}(\vec{x}) = \mu_{\rm ggH} \times \left[\mathcal{P}_{\rm sig}^{\rm gg}(\vec{x}) + \mathcal{P}_{\rm sig}^{\rm t\bar{t}H}(\vec{x})\right] + \mu_{\rm VBF} \times \left[\mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm sig}^{\rm VH}(\vec{x})\right] + \mathcal{P}_{\rm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

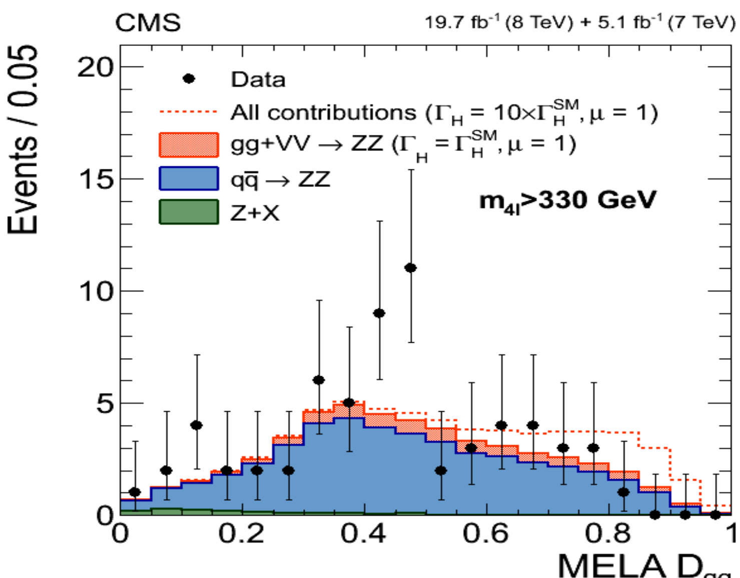
$$\mathcal{P}_{\rm tot}^{\text{off-shell}}(\vec{x}) = \left[\mu_{\rm ggH} \times (\Gamma_{\rm H}/\Gamma_0) \times \mathcal{P}_{\rm sig}^{\rm gg}(\vec{x}) + \sqrt{\mu_{\rm ggH} \times (\Gamma_{\rm H}/\Gamma_0)} \times \mathcal{P}_{\rm int}^{\rm gg}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm gg}(\vec{x})\right]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

(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**





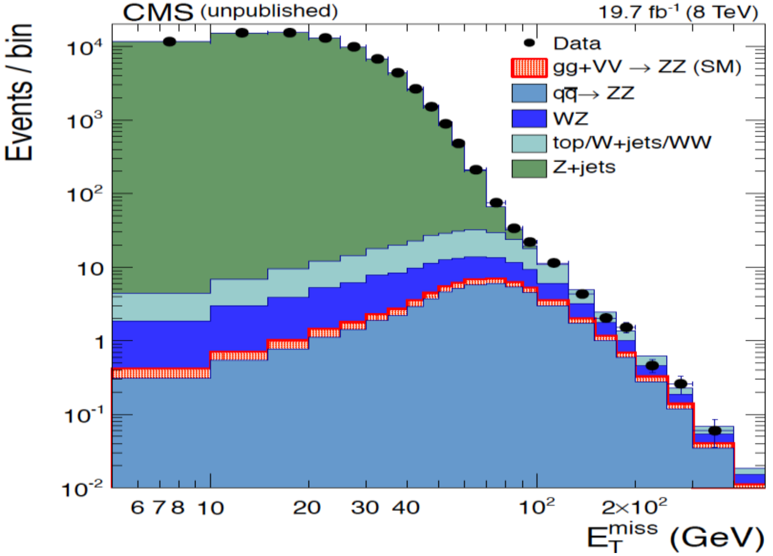
- **On-shell :**
- Analysis is unchanged w.r.t H→ZZ→4l paper (10.1103/PhysRevD.89.092007)

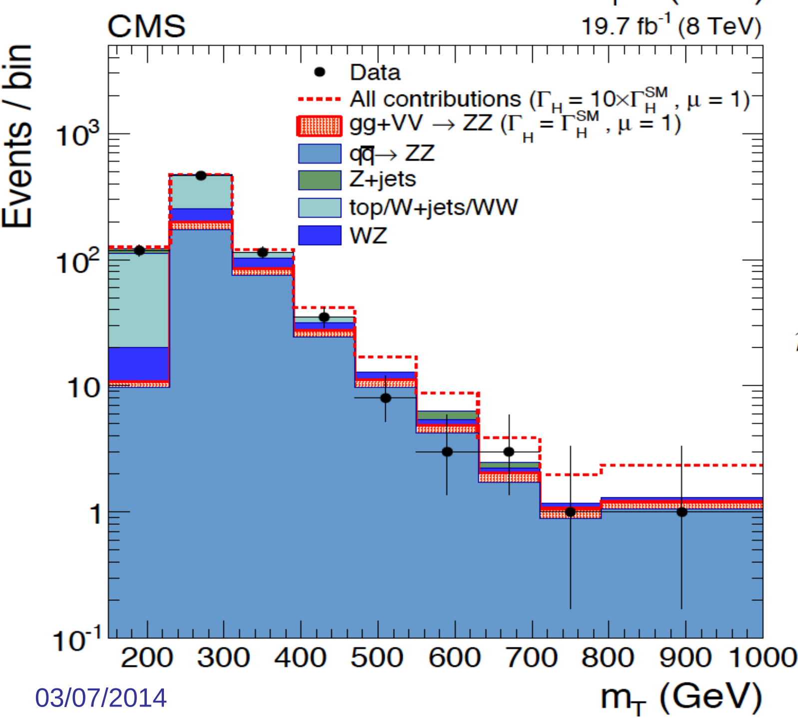
- **Off- shell :**
  - **2 dimensional shapes are used in the likelihood fit**
  - **4l invariant mass : M_{4l} > 220GeV**
  - **Matrix Element based discriminant :**

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

  - Based on probabilities $\mathcal{P}^{gg}_{\rm tot}$ / $\mathcal{P}^{q\bar{q}}_{\rm bkg}$ that an event originates from qq→4l or gg→4l (includes signal, bckg and interf.)
  - *a* is the strength modifier due to a change of the width. (*a*=10 was chosen for $\mathcal{D}_{gg}$ definition)

ZZ→2l2nu off-shell





- Analysis technique as in high mass Higgs search (10.1140/epjc/s10052-013-2469-8)

- Only the 8TeV dataset is used for this channel
- 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 (inclusive in #Jets) is used as the final variable entering the likelihood fit**

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%

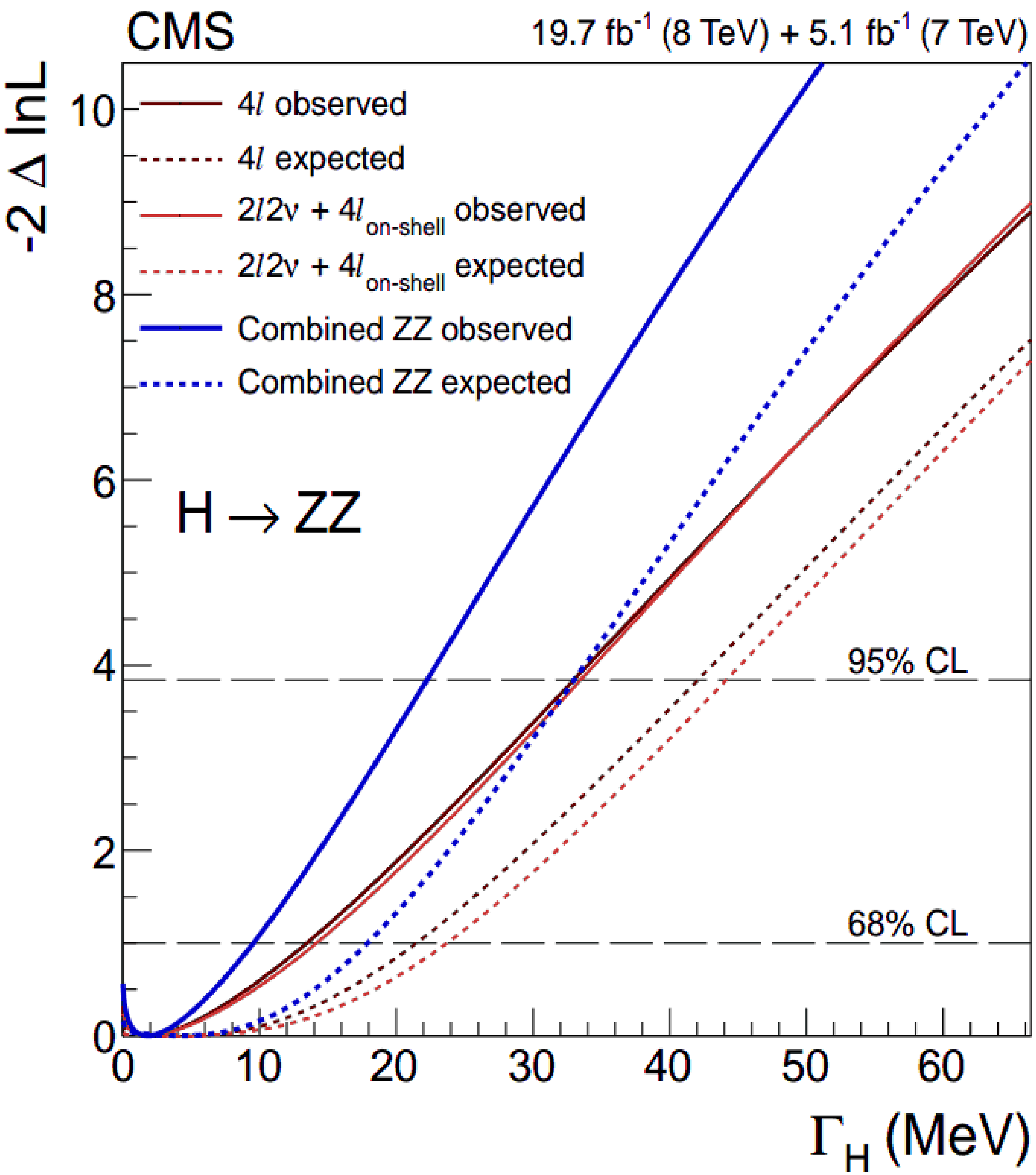
- **Background uncertainties**

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)
NLO pdf	1%	

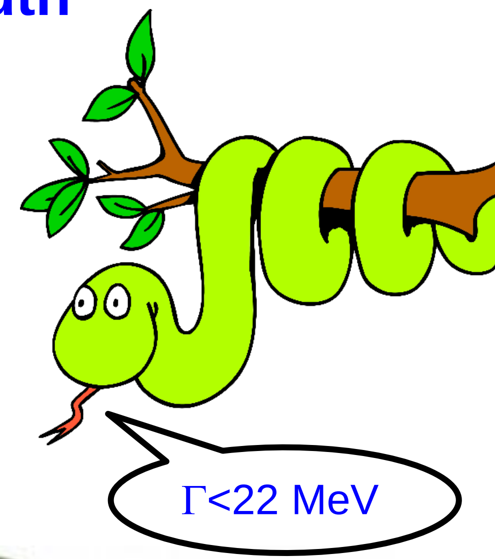
Likelihood profiling



- **Reminder : SM predicts :**
  - $\Gamma_H = 4.2$MeV
- **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
- **Combination** improves the individual limits by ~20%
- Compatibility between the observed results and the SM hypothesis lead to a **p-value of 0.24**

Summary

- **First experimental constraint on Higgs total width using off-shell H(125) production**
- ZZ→4l and ZZ→2l2nu channels considered
- Mild model-dependence
- 95% C.L. Limit:
  - **Γ/Γ_{SM} < 5.4** (8.0 expected)
  - **Γ < 22 MeV** (33 expected)
- Measurement :
  - $\Gamma_H = 4.2^{+13.5}_{-4.2}$ MeV (expected)
  - $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV (observed)
- **Accepted for publication in PLB**



Backups

Results Summary (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	$1.8^{+7.7}_{-1.8}$	$0.4^{+1.8}_{-0.4}$

Combination improves the individual limits by ~20%

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

Strength measurements

- **4l on-shell only**

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

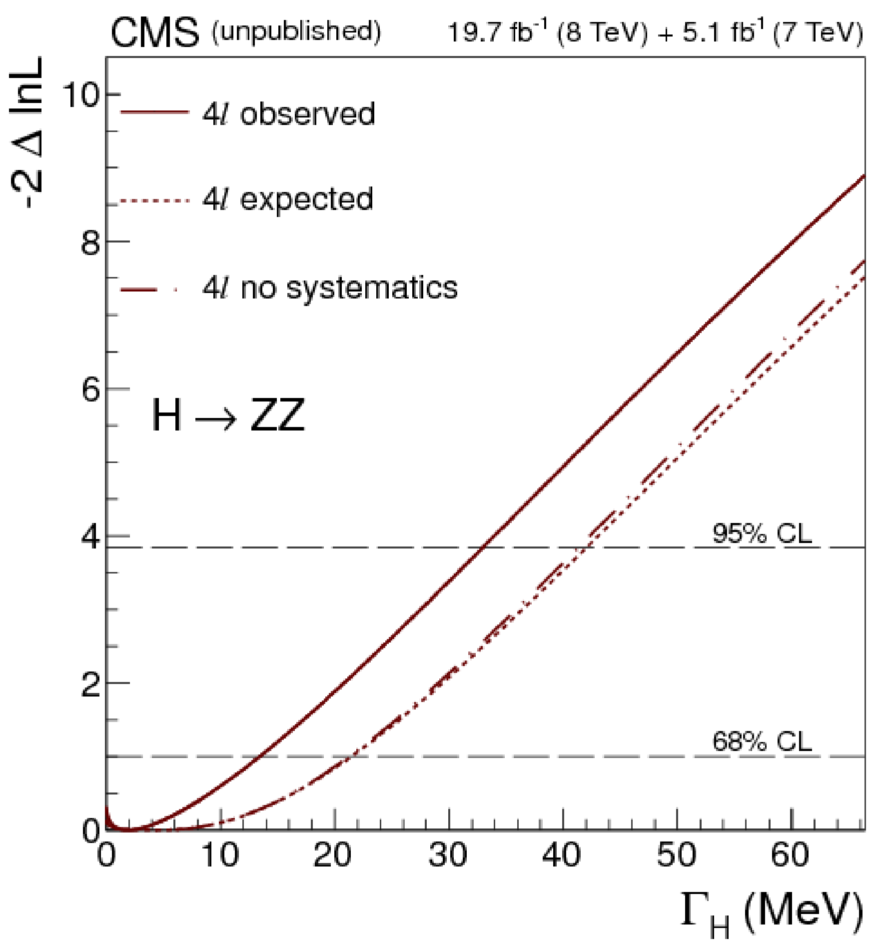
- **4l on-shell / off-shell and 2l2nu**

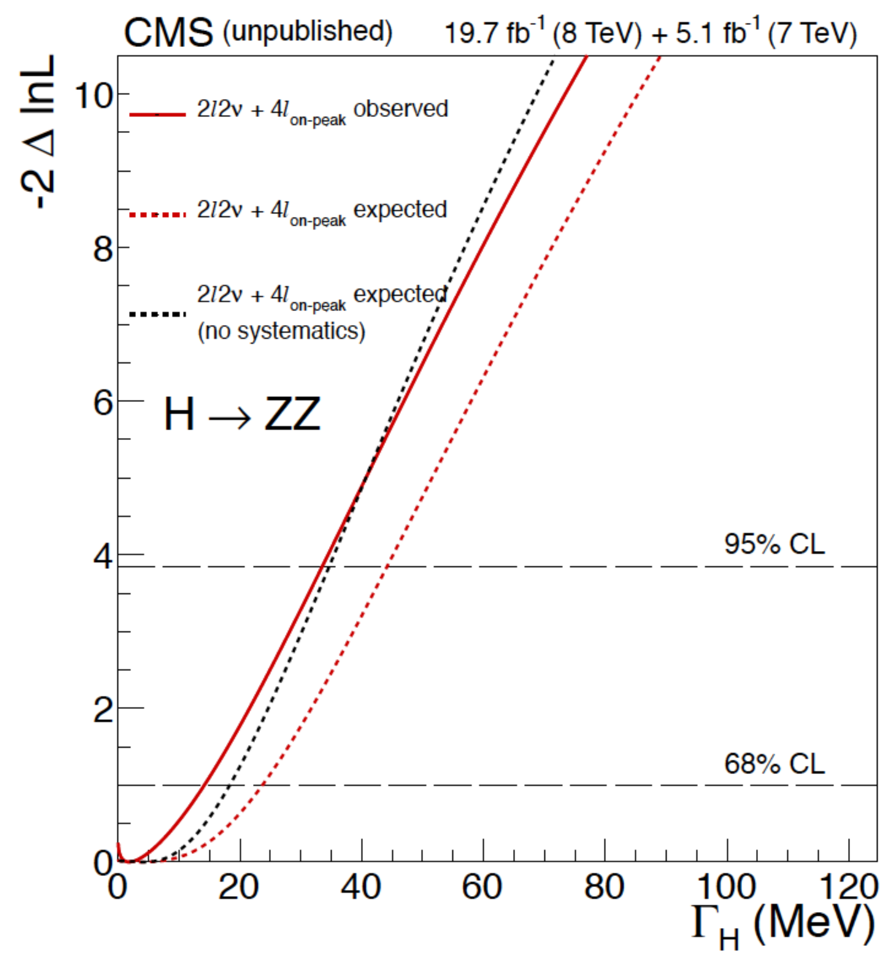
$$\mu_{ggF} = 0.81^{+0.47}_{-0.37}$$

$$\mu_{VBF} = 1.7^{+2.2}_{-1.7}$$

Effect of the systematics

4l not very sensitive to the systematic uncertainties contrary to 2l2nu





Simple cut and count

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	Exp.(Γ_H=Γ_H^{SM})
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4	124.9 ±7.8	Exp.(Γ_H=10xΓ_H^{SM})
	observed	11	91	Observed

Kappa Frame work

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa^2_{\mathrm{g}}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa^2_{\mathrm{g}} \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa^2_{\mathrm{t}}$$

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa^2_{\tau}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa^2_{\gamma}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{\gamma} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{t\bar{t}}}} = \kappa^2_{\mathrm{t}}$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma^{\mathrm{SM}}_{\mathrm{gg}}} : \text{see Section 10.2.2}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{c\bar{c}}}} = \kappa^2_{\mathrm{t}}$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{s\bar{s}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa^2_{\tau}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa^2_{(\mathrm{Z}\gamma)}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{(\mathrm{Z}\gamma)} \end{cases}$$

Total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma^{\mathrm{SM}}_{\mathrm{H}}} = \begin{cases} \kappa^2_{\mathrm{H}}(\kappa_i, m_{\mathrm{H}}) \\ \kappa^2_{\mathrm{H}} \end{cases}$$