Bounding the Higgs boson width from off-shell production and decay to $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$

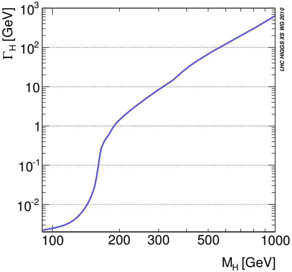
Mykhailo Dalchenko
on behalf of the CMS Collaboration

LLR, Ecole Polytechnique

21 July, 2014

The Higgs boson width

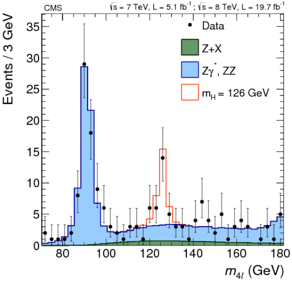
LHCXSWG



The total decay width is a *fundamental* parameter

- Relates to the couplings to all massive particles $\Rightarrow$ sensitive to the BSM physics
- Hard to measure: $\Gamma_H \simeq 4$ MeV @ $m_H \simeq 126$ GeV

PRD 89 (2014) 092007



Direct constraints

- Current (excellent) experimental resolution is too large for direct measurements: $\sigma_m \sim \mathcal{O}(1)$ GeV
- Constraint from the resonance width in $H \to ZZ \to 4\ell$: $\Gamma_H < 3.4$ GeV @ 95% CL
- Constraint from the resonance width in $H \to \gamma\gamma$: $\Gamma_H < 2.4$ GeV @ 95% CL

(see S. Chhibra and C. Martin talks)

Width constraints from off-shell Higgs

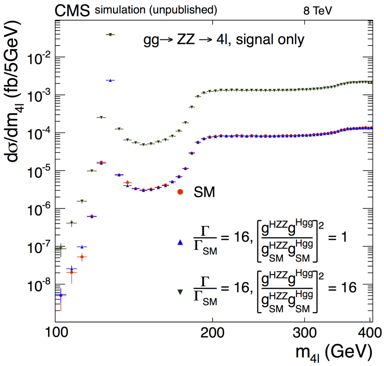
- Off-shell Higgs boson production is small but the *BR* to 2 real *Z* is large above $2m_Z$
- Under change of width, peak yield remains constant if we scale the couplings in appropriate way

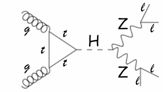
$$\sigma_{pp\to H\to ZZ} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{\Gamma}$$

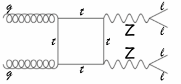
- Off-shell Higgs yield is proportional to this scale

$$\sigma_{pp\to H\to ZZ} \sim g^2_{Hgg}g^2_{HZZ}$$

- Interference between the signal and background is sizeable and must be accounted for







(see D. de Florian talk)

Analysis overview

- Use $gg \to 4\ell$ (GG2VV and MCFM for $ZZ \to 4\ell$, GG2VV only for $ZZ \to 2\ell 2\nu$) and $VV \to 4\ell,\ 2\ell 2\nu$ (Phantom) MC samples
- Build probability templates for signal, background and interference using $m_{4\ell}$ and a kinematic discriminant D_{gg} in case of $ZZ \to 4\ell$
  $P_{\text{total}} = \mu r P_{gg\to H\to 4\ell} + \sqrt{\mu r} P_{\text{interference}} + P_{gg\to 4\ell}$
  $r = \Gamma/\Gamma_{\text{SM}}$, μ - signal strength
- Build similar probability templates for VBF
- Build similar probability templates for signal, background and interference using m_{ll}^{T} in case of $ZZ \to 2\ell 2\nu$
- Perform a combined fit of the off-shell and on-shell regions

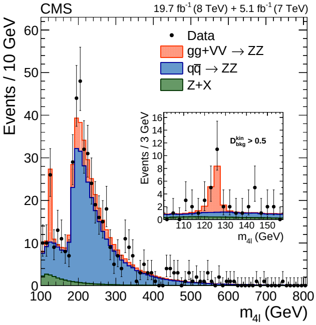
4ℓ analysis

Selection settings and reconstruction are identical to
PRD 89 (2014) 092007

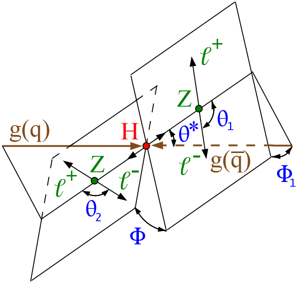
- Two pairs of OS/SF leptons. Z_1 closest to the Z mass, Z_2 the remaining with highest sum of p_t
- $40 < m_{Z_1} < 120$GeV $12 < m_{Z_2} < 120$GeV
- One lepton with $p_t > 20$ GeV/c, another with $p_t > 10$ GeV/c.
- $m_{4\ell} > 100$ GeV, $m_{l^+l^-} > 4$ GeV

- Reducible background ("$Z + X$") estimated from data in control regions with Z_1 + at least 1 loose lepton.
- Irreducible bkg calculated from MC, $q\bar{q}$ annihilation from POWHEG
- Phenomenological model for the qq→ZZ shape

PLB 736 (2014) 64



ggMELA



- ggMELA discriminant was developed in the context of the PRD 89 (2014) 092007
- High performances for separating gg→ZZ from qq→ZZ where gg→ZZ includes signal, continuum and their interference for any relative signal strength *a*.

Built from signal and background probabilities: $D_{gg,a} = \frac{P_{gg,a}}{P_{gg,a}+P_{q\bar{q},a}}$, where $P_{gg,a} = a \times P^{gg}_{\text{sig}} + \sqrt{a} \times P^{gg}_{\text{int}} + P^{gg}_{\text{bkg}}$ and $P_{q\bar{q},a} = P^{q\bar{q}}_{\text{bkg}}$

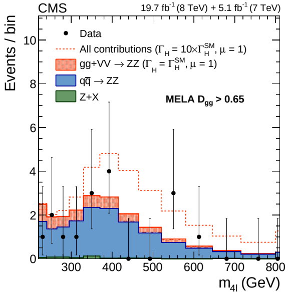
- Signal strength *a* must be chosen when building the discriminant.
- From preliminary studies we expected sensitivity for run 1 data to be around 10×SM, so we chose $D_{gg,10}$.

About 30% improvement when including it in the fit procedure

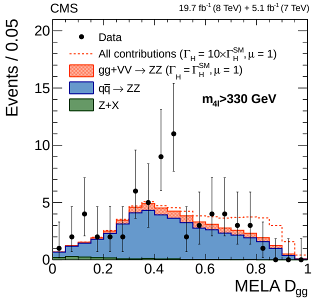
Distributions of selected events

$H \to ZZ \to 4\ell$

PLB 736 (2014) 64



PLB 736 (2014) 64



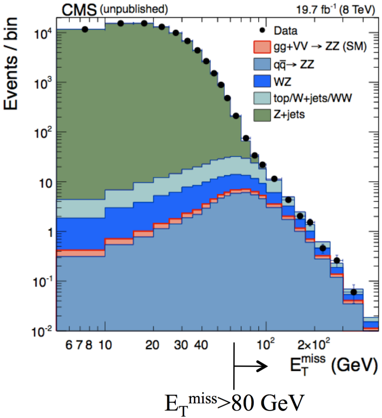
signal-enriched region

- $m_{4\ell} > 330$ GeV
- $D_{gg} > 0.65$

		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

$2\ell 2\nu$ analysis

- 6 times higher branching ratio w.r.t. 4ℓ final state
- Use 4ℓ results in the on-shell region
- High $Z + jets$ background (fake E_T^{miss} from hadronic energy mismeasurement)
- Other backgrounds:
  - Irreducible: ZZ, WZ (from MC)
  - Non-resonant: top, WW
- Analysis variable: transverse mass

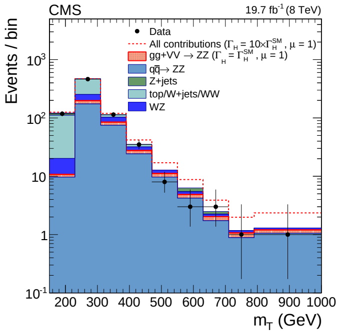


$$M_T^2 = \left[\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_{miss,T}^2 + m_{\ell\ell}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_{miss,T}\right]^2$$

Distributions of selected events

$H \to ZZ \to 2\ell 2\nu$

PLB 736 (2014) 64



signal-enriched region

- $m_T > 350$ 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

Systematic uncertainties

- $gg \to ZZ$
  - Part of cross section uncertainties cancel in the ratio between off-shell and on-shell
  - Shape uncertainties obtained varying PDFs: CT10, MSTW and NNPDF
  - Correlated shape-yield uncertainties produced varying the scales and applying corresponding K-factor
  - $K_{bkg} = K_{sig} \times (1.0 \pm 0.1)$
- $q\bar{q} \to ZZ$
  - QCD scale: correlate shape and yield uncertainties
  - PDFs: constant 4%
  - $q\bar{q} \to ZZ$ EWK corrections (2-7%)
- Lepton efficiency for the trigger, reconstruction and selection
- Background estimation from data (mostly $2\ell 2\nu$, up to 25%)

All systematic uncertainties
correlated between the on-shell and off-shell regions affect μ
but not Γ_H in the combined measurement

Results

Joint unbinned likelyhood fit

- Perform fit simultaneously on-shell (4ℓ) and off-shell ($4\ell + 2\ell 2\nu$)
- Fitted parameters: $\mu_F, \mu_V, \Gamma_H/\Gamma_H^{SM}$ ($\Gamma_H^{SM} = 4.15$ MeV)

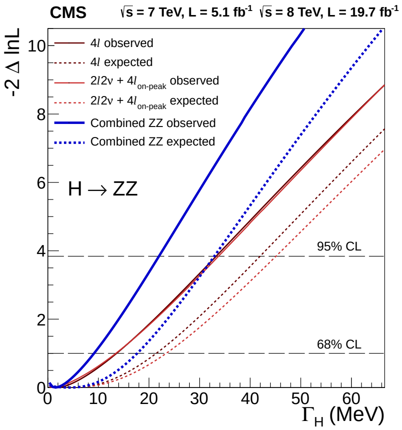
95% CL exclusion limit

- Observed: 22 MeV
- Expected: 33 MeV

Best fit Γ_H

- Observed: $1.8^{+7.7}_{-1.8}$ MeV
- Expected: $4.2^{+13.5}_{-4.2}$ MeV

PLB 736 (2014) 64



Conclusions

First experimental constraint on the Higgs width using $H^* \to ZZ$ events

- $\Gamma_H < 22$ MeV @95% CL
- More than 2 order of magnitude improvement w.r.t. direct on-peak measurement

Mild model dependency

- Assume essentially no new particles in the gluon fusion loop
- Assume no contribution from BSM physics in the background

Perspectives

- The expected tail/peak cross-sections ratio is ~ 2 times higher @13 TeV than @8 TeV
- The measurement may become limited by systematic uncertainties
- Improved determination of theory cross sections, in particular for the gg background is needed

Cross sections and events generation

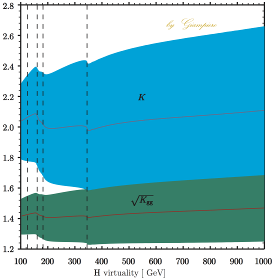
Gluon fusion, GG2VV and MCFM

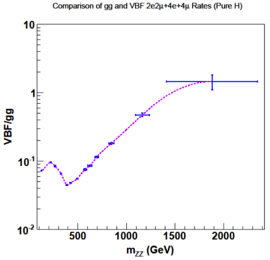
- Latest versions of generators include signal, background and interference
- Assume $m_H = 125.6$ and $\Gamma_{SM} = 4.15$ MeV for generations as in PRD 89 (2014) 092007
- Set factorization and renormalization running scale of $m_{4\ell}/2$
- Apply $m_{4\ell}$-dependent K-factor (NNLO/LO) for signal from G. Passarino (Eur. Phys. J. C74 (2014) 2866)
- Use $K_{background} = K_{signal}$ assigning a 10% uncertainty on this assumption following M. Bonvini et al. (Phys. Rev. D88 (2013) 034032)

Vector boson fusion, PHANTOM

- VBF production is 7% of the total at H(125.6) peak
- Fraction of VBF increases with $m_{4\ell}$
- Same settings, similar lineshape except second enhancement due to $t\bar{t}$ in the $gg \to H$

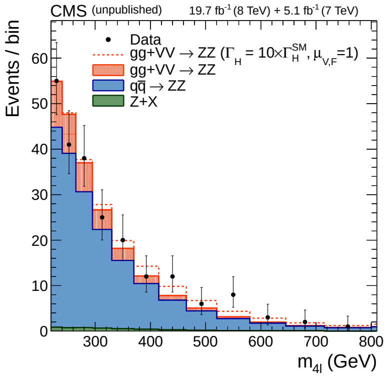
Eur. Phys. J. C74 (2014) 2866

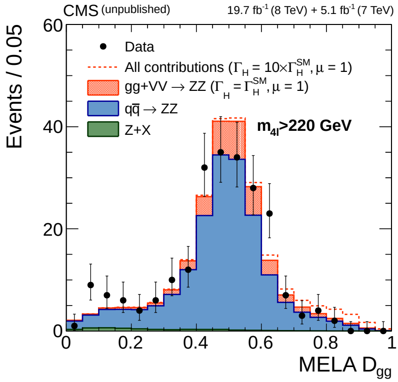




$H \to ZZ \to 4\ell$

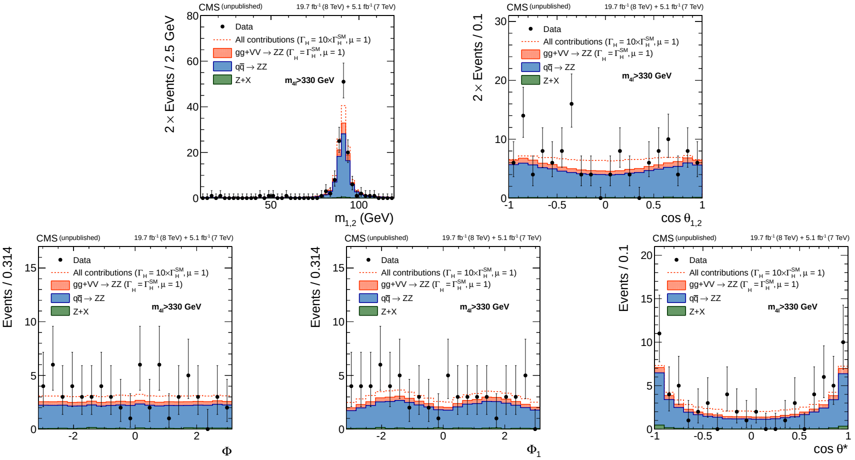
1D distributions in the full analysis range





$H \to ZZ \to 4\ell$

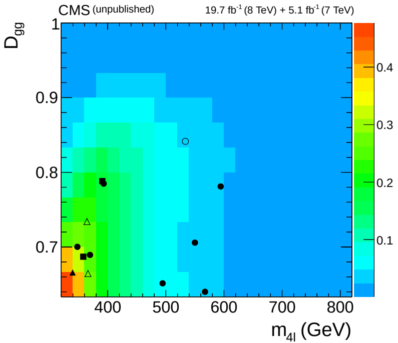
ggMELA inputs, signal-enriched



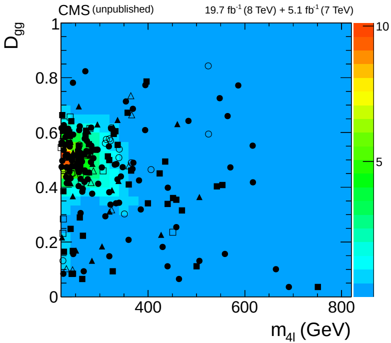
$H \to ZZ \to 4\ell$

2D templates

Signal-enriched



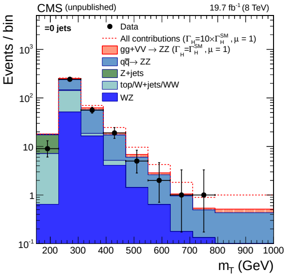
All analysis range



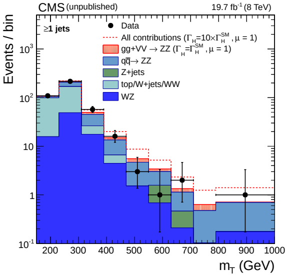
$H \to ZZ \to 2\ell 2\nu$

$m_{\ell\ell}^T$ and E_T^{miss}

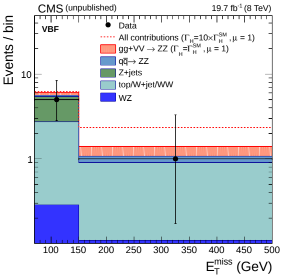
0 jets



≥ 1 jet



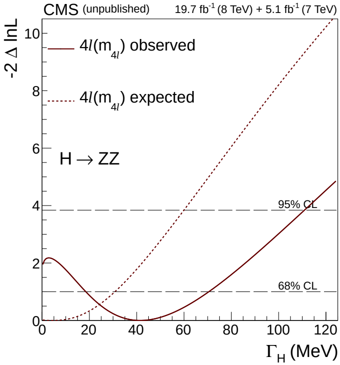
VBF-type



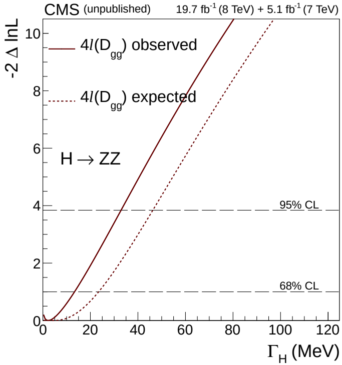
$H \to ZZ \to 4\ell$

1D likelihood scans

1D $m_{4\ell}$



1D D_{gg}



$H \to ZZ \to 2\ell 2\nu$

1D likelihood scan, on-shell measurements from 4ℓ

1D $m_{\ell\ell}^{T}$