$H \rightarrow ZZ \rightarrow 4l$

- VBF+gg: Powheg @ NLO
- Decay simulation: JHUGEN accounting for interference between lepton permutations
- Alternative spin-parity states: JUHGEN
  (spin 0 states: modeled in gluon fusion w/ Powheg @ NLO)
  (spin 1, spin 2: in quark-antiquark and gg production @ LO + PS w/ Pythia)
- Shape: Breit-Wigner (low mass)
  CPS for mH>400 GeV (→ Gamma>70 GeV)
- Interference between gg → H → ZZ → 4l and gg → ZZ → 4l evaluated @ LO →
  → sys due to missing NLO + sys for ewk corrections

Backgrounds:

- Main backgrounds: ZZ(*), Zγ*, Z+light jets, Z+bbar, Z+ccbar, ttbar
- Additional backgrounds: Zγ+jets, WW+jets, WZ+jets, single bosons with hadronic activity
- qqbar → ZZ: Powheg @ NLO
- WW, WZ: MadGraph
- gg → ZZ: GG2ZZ
- Zγ, Z+jets: MadGraph
- Ttbar: Powheg @ NLO
- All samples are processed w/ Pythia for jet fragmentation and showering

- 2 leptons (17, 8 GeV) OR 3 electrons (15, 8, 5 GeV) triggers. Trigger eff > 98%

$H \rightarrow ZZ \rightarrow 4l$

- H(125) → ZZ → 4l has very low BR ~ 10-4
- Very good mass resolution needed → sys unc has to be lower than stat
- Dibosons, ttbar bkgs: suppressed with cuts on # of leptons, MET
- Electron pT > 7 GeV, |η|<2.5; ECAL calibration: with a BDT technique
- Muon pT> 5 GeV, |η|<2.4;
- Leptons are required to be isolated, and to come from the same PV → Z+jets, ttbar bkg suppression
- Presence of jets if production mechanism is VBF or associated production with W,Z decaying hadronically or if production in association with ttbar
- Opposite-sign pair with inv. mass closest to nominal Z mass: Z1
- Required 40 < m(Z1) < 120 GeV
- Z2 with other pair. If ambiguity: chosen the pair of leptons with highest scalar sum of pT
- m(Z2) required to satisfy 12 GeV < m(Z2) < 120 GeV
- Lepton pT thresholds: 20, 10 GeV for first and second leptons
- m(4l) > 110 GeV
- Resolution of the Higgs mass distribution: 2.0, 1.6, 1.2 GeV for 4e, 2e2μ, 4μ respectively (from double-sided Chrystal Ball fit). Full RMS including asym tails: 2.9, 2.3, 1.7 GeV
- Two categories: 0/1 jet + 2 jets
  0/1 jet cat.: pT(4l) used to understand production mechanism
  2 jets cat.: discriminant (|Δη(jj)|+mjj to understand if VBF production

$H \rightarrow ZZ \rightarrow 4l$

BACKGROUNDS:

Irreducible:

- 4 lepton production from non-resonant diboson production:
  qqbar → ZZ → 4l (NLO Xsec w/ MCFM)
  gg → ZZ → 4l (LO Xsec w/ MCFM) (about 2% contribution wrt qqbar, @ 126 GeV)
- The event topology and kinematic is very similar to those of signal events.
- It's the main background (about 95% contribution to total bkg in the range 100-1000 GeV)
  (~58%, 71%, 86% contribution in 4e, 2e2μ, 4μ in the range 121.5-130.5 GeV)
- ZZ bkg normalization and shape directly from MC
- The expected rate of ZZ ( ) continuum in any given mass range [m1 , m2] is obtained directly from the absolute rate predicted by the MC simulation

Reducible:

Z+jets (Z + bbar, Z + ccbar) and ttbar

- 2 leptons from the Z decay + 2 from cascade decays of hadrons (→ non-isolated)
- Reduced by requiring isolated leptons and putting a cut on the IP significance (reducible bkg contains one or more non-prompt leptons)
- Z+X reducible bkg is estimated using data-driven method + knowledge of the shape from MC samples
- Estimated using control regions defined by a Z1 candidate + 2 leptons (OS or SS) with looser constraints. Estrapolation from control region to signal region is made using lepton misidentification probability. 20-40% sys uncertainty on the normalization of reducible bkg

$H \rightarrow ZZ \rightarrow 4l$

BACKGROUNDS:

Inclusive instrumental and Reducible backgrounds estimation

- The reducible backgrounds for the $H \rightarrow ZZ \rightarrow 4l$ analysis are processes which contain one or more non-prompt leptons.
- The main sources of non-prompt leptons are:
  - non-isolated electrons and muons coming from decays of heavy-flavor mesons
  - mis-reconstructed jets (usually originating from light-flavor quarks)
  - electrons from γ conversions.
- Control sample used to evaluate background from data: events that have a pair of same flavour, opposite sign letons satisfying $40 < m(Z1) < 120$ GeV + an additional pair of reconstructed leptons of same sign (to avoid signal contamination) and same flavor satisfying $12 < m(Z2) < 120$ GeV with cut on IP significance but with no requirements on identification and isolation, with additional constraint $m(4l) > 100$ GeV and at least 3 of the 4 combinations of pairs must satisfy $m > 12$ GeV
- From this set of events the inclusive number of reducible background in the signal region is estimated by measuring the probability for the two additional leptons to pass the isolation and identification analysis cuts, obtained from a “fake rate measurement”

$H \rightarrow ZZ \rightarrow 4l$

KINEMATIC DISCRIMINANT (MELA)

- 3 helicity angles + 2 production angles + m1, m2 → KD (independent of prod. mech.)
- KD = Psig/(Psig+Pbkg)
  Psig=Psig(m1,m2,Ω|m4l)
  Pbkg=Pbkg(m1,m2,Ω|m4l)
- Then: 2D fit over (m4l, KD)
- 172 selected events
- Measured distributions are compared with SM background
- (m4l, KD) distributions of the selected events are splitted into 6 categories (3 final states x 2 running periods)
- 183 mass hypotesis (110-600 GeV) (interpolation)
- For each mass hp: simultaneous fit of the 6 2D distributions
- P(m4l) parametrized with empirical functions using MC for ZZ bkg
- P(m4l) is a BWxCB for signal. Template derived from MC
- The upper limit on the ratio of the production cross section to the SM expectation and the local p-value (significance of the local fluctuations wrt the SM expectation) are derived
- Minimum of the local p-value for 125.5 GeV (local significance: 3.2 σ) (expected: 3.8 σ)
- Signal strength modifier and most probable mass: likelihood scan on data in 2D space of mH vs μ → global minimum at 125.5±0.6 GeV and μ=0.7
- Modified MELA dicriminant (pseudoscalar signal hp in placeof bkg hp) to discriminate between scalar and pseudoscalar hypotheses.

$H \to ZZ \to 4l$

RESULTS

- Kinematic discriminants are defined based on the event probabilities depending on the background or signal spin-parity hypotheses under construction
- Signal and background yields, mass, width, spin/parity are obtained with unbinned maximum likelihood fits to the selected events
- SM Higgs boson excluede at 95% C.L. For the mass ranges 114.5-119.0 GeV and 129.5-832.0 GeV for an expected exclusion range 115-740 GeV
- Minimum of local p-value (= significance of a local excess relative to the background expectation) at m(4l)=125.7 GeV and corresponds to a local significance of 6.8 σ (expected sensitivity: 6.7 σ)
- Mass: 125.6 ± 0.4 (stat) ± 0.2 (sys) GeV
- Upper limit on the width: 3.4 GeV at 95% C.L. (expected upper limit: 2.8 GeV)
- Signal strenght: 0.93 +0.26/-0.23 (stat) +0.13/-0.09(sys) at the best fit mass (125.6 GeV)
- For each category, the signal strength is consistent with SM expectations within uncertainties (dominated by statistical ones)
- Two signal-strength modifiers are introduced as scale factors for the fermion and vector-boson induced contribution to the expected SM cross section. A 2D fit is performed for the 2 modifiers, assuming a mH=125.6 GeV. Results consistent with SM. But with the current limited statistics, we cannot establish yet the presence of VBF and VH production (bosonic mu=0 also compatible with data) (bosonic mu>1 for harder pt(4l) spectrum in data wrt SM expectation).

H → ZZ → 4l

RESULTS

- Spin-parity: the 0- model corresponds to a pseudoscalar
  the 0+h is a scalar not participating in the electroweak symmetry breaking
  spin 1: via qqbar production mechanism (gg suppressed)
  not the same resonance as the one observed in H→γγ decay
  1- → vector
  1+ → pseudovector
  spin 2: massive graviton-like boson
  qqbar → 2+m: with minimal couplings
  gg → 2+h
  gg → 2-h
  gg → 2+b
- 1 and 2m spin hypoteses tested in a production-independent way
- For spin and parity studies the event categorization based on the jets is not used in order to reduce the dependence on the production mechanism → 2D Likelihood: L(Dbkg, D_Jp)
- The Higgs boson mass is assumed to be 125.6 GeV
- The 2D probability density functions for signal and bkg are obtained as 2D templates from simulation from the signal and irreducible bkg, and from control regions for the reducible.
- The pseudoscalar (0-) and all spin-1 hp are excluded at 99.9% or higher CL
- All tested spin-2 models are axcluded at the 95% or higher CL
- The 0+h hp is disfavored, with a CLs value of 4.5% (?)
- Also measurement for possible mixture of CP-even and CP-odd states → anomalous couplings in the H→ZZ amplitude

$H \to \gamma\gamma$

- Clean final state → high precision for mass reconstruction
- Decay mediated by a t, W loop
- BR~0.23% @ 125 GeV (max), falling to ~0.1% @ 150 GeV → search in 110 <mH < 150
- Large diphoton continuum background
- Analysis performed with multivariate classifiers
- The signal measurement is performed a simultaneous fit to the diphoton invariant mass distributions in the various event classes
- The signal model is derived from simulation
- The background is obtained by the fit to data
- Z → ee is used to estimate the accuracy of the signal simulation (energy recontruction and selection/classification), treating the electron showers as if they were from photons
- New analysis: improved intercalibration of em calorimeters and improved energy regression algorithm → better energy resolution
- ECAL calibration: exploiting phi symmetry of the energy flow and using $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, $W \to e\nu$, $Z \to ee$
- Continuous laser monitoring of the crystal transparency and consequent correction
- Reconstruction of photons: uses superclustering of ECAL energy

H → γγ

- Diphoton triggers with asymmetric transverse energy thresholds
- One path requiring loose calorimetric ID (shape of em shower) + loose iso on photons
- One path requiring high value for R9 (=shower shape variable)
  R9 = energy sum of 3x3 crystals centered on the most energetic crystal in the supercluster, divided by the energy of the supercluster
  Photons that convert before reaching the calorimeter tend to have wider showers → lower values of R9 than unconverted photons
- 7 TeV: E_T> 26 (18) GeV for the leading (trailing) photon
  8 TeV: E_T> 36 (22) GeV
- Trigger efficiency: 99.4%

- For ggH and VBF: Powheg @ NLO
- ggH cross section reduced by 2.5% to account for interference with non-resonant diphoton production
- VH, ttbarH processes: Pythia alone
- Samples for spin hp testing: Jhugen @ LO + Pythia
- Bkg: diphoton w/ Madgraph + Pythia @ 7 TeV
  w/ Sherpa @ 8 TeV

- ECAL, barrel region: superclustes from 5 crystals in eta (centered on the most energetic one) and with variable extension in phi
- endcap region: 5x5 crystals marices, summed if close in phi
- Half the photons convert before they reach ECAL → tracker information

$H \rightarrow \gamma\gamma$

- Photon candidates are reconstructed from energy deposits in ECAL using algorithms that constrain the supercluster in eta and phi to the shapes expected from electrons and photons with high pT
- An MVA technique is used to correct for:
  - the containment of the shower in the clustered crystals
  - the shower losses for photons that convert upstream of the calorimeter
  - the effects of PU
  (regression MVA)
  The regression provides a per-photon estimate of the parameters of a function that describes the photon energy response (gaussian core +power law tails) and therefore at the end the ratio of the true energy to uncorrected supercluster energy

- The continuum background is due to prompt diphoton production (irreducible), 70% of the total bkg after the complete selection and classification
- The reducible bkg is due to gamma+jet events or dijet events
  (at least one of the objects reconstructed as a photon comes from a jet, typicallly from neutral mesons that take a substantial fraction of the total jet pT and thus are relatively isolated from hadronic activity in the detector)
- Photons from $\pi 0 \rightarrow \gamma\gamma$ give photons rather collimated in the pT range of interest → reconstructed as a single photon
- Selection of photons:
  pT>33 (25) GeV for the leading (second) photon
  cut on the hadronic leakage of the shower
  electron veto to exclude $Z \rightarrow ee$ events

$H \rightarrow \gamma\gamma$

- Efficiency of the photon preselection: using T&P technique on data.
  The eff of all the preselection requirements, but the electron veto, is measured using $Z \rightarrow ee$ events. Electron veto eff: using $Z \rightarrow \mu\mu\gamma$ events (photon produced for FSR)
- Preselection eff: 92-99%
- Boosted Decision Tree (BDT) to separate prompt photons from misidentifications of jet fragments. Variables used in BDT:
  - lateral shower shape variables
  - isolation variables
  - energy median density per unit area in the event (ρ)
  - η, E of the supercluster for the photon
  Data-MC agreement for photon identification: with $Z \rightarrow ee$ and $Z \rightarrow \mu\mu\gamma$ events and the highest pT photon in diphoton events with diphoton energy > 160 GeV

- Diphoton vertex identification:
  no charged particles → identified indirectly
  3 discriminating variables are calculated for each primary vertex:
  - sum of the squared pT's of the charged particle tracks associated to a vertex
  - 2 variables accounting for the vector and scalar balance of pT between the diphoton system and the charged particles tracks associated to the vertex
  Vertex finding efficiency for mH=125 GeV: ~ 80% in 8 TeV dataset
- Second multivariate discriminant to estimate the event-by-event probability for the vertex assignment to be within 10 mm of the diphoton interaction point (vertex probability BDT)

H → γγ

- Event classification:
  - 100 < mγγ < 180 GeV
  - pT1 > mγγ/3, pT2 > mγγ/4
  - If multiple candidates: chosen the one with highest pT1+pT2
  - BDT (photon ID) > -0.2 (for both photons) → retains 99% of simulated signal events and removes about 24% of events in data
  - events classification: 14 (11) classes for 8 (7) TeV data samples

  First: events tagged for the production process
  Rest (99%): classification according to a variables obtained with a multivariate technique
  Classification based on the value of a multivariate discriminant.
- The discriminant has high value for events with good diphoton mass resolution and high probability of being signal rather than bkg. It is mass independent
  Variables in the discriminant: pT1/mγγ, pT2/mγγ, pseudorapidities of photons, photon ID classifier for both photons, cosine between the 2 photons in the transverse plane, relative mass resolution, probability of selecting the correct vertex
  The S/B ratio increases with increasing the value of the discriminant.
  VBF, VH and ttbar events achieve high values of the BDT.
  Agreement data-MC tested with Z→ee events
- VBF, VH, ttbar production mechanisms → harder Higgs pT spectra
  Dijet discriminant for discriminating VBF signal from diphoton background
  Combined BDT: dijet BDT + diphoton BDT + pT(γγ)/mγγ
  VBF events are selected from the ones satisfying the loose dijet preselection, cutting on the combined BDT.

H → γγ

- For VH production:
  - events with a lepton are separated into 2 classes: significant MET or another lepton (for leptonically decaying Z or W)
  - another class with events with 2 or more jets
  - another class with events with large MET

- For ttbar associated production:
  - small cross section
  - cross section x BR ~ 0.3 fb → leptonic and hadronic top decays collected together
  → lepton-tagged and multijet-tagged category

Classes for the VBF di-jet tagged events and the untagged events are defined using the scores of the classification BDTs:
- the combined BDT score is used to define the dijet-tagged classes
- the diphoton BDT score defines the untagged classes for untagged events

The best untagged class (untagged 0) contains events in which the diphoton system has high pT. The second best class (untagged 1) have mostly events in which both photons are unconverted and situated in the central barrel region of ECAL

$H \rightarrow \gamma\gamma$

- A parametric signal model is constructed separately for each event class and for each production mechanism from a fit of the simulated invariant mass shape (after applying the corrections from comparison data-MC for $Z \rightarrow ee$, $Z \rightarrow \mu\mu\gamma$ samples)
- The bkg estimate is obtained from a fit to the data
- Improved intercalibration of ECAL wrt the previous version
- Improved supercluster energy correction regression

Statistical analysis method

- Simultaneous binned max-likelihood fit to the diphoton invariant mass distribution in all the event classes for 100 GeV < mH < 180 GeV
- Bkg from a fit to the $m_{\gamma\gamma}$ distribution in data, signal from parametric signal model
- The chosen test-statistic, used to determine how signal- or bkg-like the data are, is based on the profile likelihood ratio.
- Sys uncertainties are accounted for as nuisance parameters
- The discrete profiling method has been developed to treat the uncertainty associated with the choice of the function used to fit the bkg (in a similar way to sys unc associated with measurements)

Systematic uncertainties:

- Production cross section: largest contribution to the error on signal strength Coming from missing higher orders and unc on parton distribution functions
- Integrated luminosity, vertex finding efficiency, trigger eff, photon energy scale (from electron vs photon diffs), energy scale non-linearity, photon ID discriminator end per-photon energy resolution (imperfect simulation of the shower shape), ...

H → γγ

Alternative analyses

- Three, to provide verification of different aspects of metodology
  1) Cut-based analysis
  Does not use MVA technique to select or classify events.
  Photon ID is performed by dividing photons into 4 mutually exclusive categories depending on barrel/encap, R9>0.94 or not
  ID: with a subset of the vars used in the MVA analysis; depends on the category
  High R9 values → unconverted photons; good resolution
  Photons in barrel → better energy resolution; likely to be signal photons
  2) Sideband background model analysis
  Same MVAs as the main analysis, but different background modelling
  The bkg is extracted from sidebands in the mass distribution
  3) Dijet 2D analysis
  Uses a different method for extracting the signal produced by VBF: exploits the fact that the invariant mass for VBF jets is larger than for bkg jets or jets produced by the ggH process. The VBF signal is extracted in a parametric 2D fit of signal and background in the (mγγ, mjj) plane.

H → γγ

Results

- Mass distribution in combined data (7 and 8 TeV)
- Sum of the signal-plus-background fits to the 25 event classes in both the 7 and 8 TeV datasets
- Best-fit mass mH=124.7 GeV
- Local p-value: quantifies the probability for the background to produce a fluctuation as large – or larger – than the apparent signal observed, within a specified range and uncorrected for the look elsewhere effect
- The expected significance has been calculated using the bkg expectation obtained from the S+B fit (= the so-called *post-fit* expectation)
- The significance of the minimum of the local p-value (at 124.7 GeV) is 5.7σ, where a local significance of 5.2σ is expected from the SM Higgs boson
- The signal strength is the ratio between the production cross section times the BR over the SM expectation
- Best-fit signal strength in the main analysis (where the value of mH is treated as a nuisance parameter in the fit) is 1.14 +0.26 -0.23 (corresponding best-fit mass: 124.7 GeV) For the cut-based analysis: 1.29 +0.29 -0.26
- It is possible to separate statistical and systematic contributions: (vedi paper)
- Mass measurement: to make it less model-dependent, the signal strenghts of the production processes involving H coupling to fermions (ggH, ttbarH) and H coupling to bosons (VBF, VH) are allowed to vary independently. Negative log-likelihood ratio as a function of the mass hypothesis where the signal strengths are allowed to vary independently gives mH=124.70 +- 0.34 GeV. The mass measure in unchanged even requiring that the two signal strengths to be equal (from the map of the value of q in the (mH, mu) plane).

H → γγ

Results

- Best fit strength for each of the production processes: compatible with SM (Higgs mass: nuisance parameter in the fit)

- Decay width
  It is possible to set a limit on the width of the observed signal (albeit a limit far in excess of the SM expectation of 4 MeV for mH=125 GeV)
  To accomodate the natural width of the Higgs boson, the Gaussian components used in the signal model of the SM analysis, where the signal width is assumed to be negligible as compared to the detector resolution, are replaced by an analytic convolution of a Breit-Wigner distribution (modelling a non-zero decay width) with a Gaussian distribution (modelling the detector resolution).
  A profile likelihood estimator is used to calculate upper limits on the width (mass allowed to vary in the fit). Observed (expected) upper limit: 2.4 (3.1) GeV at 95% CL
  Negative log likelihood ratio as a function of the decay width

- Testing spin hypotheses
  The Landau-Yang theorem forbids the direct decay of a spin-1 particle into a pair of photons
  Spin-2 "graviton-like" model with minimal couplings (2+m) produced by gg, by qqbar and by a mixture of the two processes
  Events divided into 40 classes (4 as in the cut based x binning in costhetastar)
  Separation between the 2 hp: using a test statistic defined as -2log[L(S+B|2+)/L(S+B|0+)] when performing a simultaneous fit of all 40 event classes together.
  The 2+ hp is disfavoured at 94% CL for gg fusion prod, at 85% CL for qqbar production

$H \rightarrow ZZ \rightarrow 2l2\nu$

- Two SF OS leptons compatible with the decay of a Z boson and a large MET from ν's
- Double-muon and double-electron triggers (thresholds: 17 and 8 GeV)
- Single muon triggers: only to recover inefficiencies (thr: 24 GeV)
- Leptons: well identified and isolated with pT> 20 GeV and inv mass w/in 15 GeV of mZ
- pT(ll)>55 GeV. Lepton tracks compatible w/ primary vertex origin hp

Background:

- Z+jets events w/ large mis-measured MET from hadronic recoil (?): rejected requiring MET > 80 GeV and removing events in which the angle in the azimuthal plane between the MET vector and the closest jet is smaller than 0.5 rad (to remove events w/ mismeasurements of the jet energy) Modelled from an orthogonal sample of events of γ+jets

- ttbar→2l2ν2b, tW→2l2νb: suppressed by rejecting events containing a b-tagged jet (w/ impact parameter significance: jet probability algorithm) or a soft muon from leptonic decay of b. Estimated w/ a control sample e+-mu-+ passing all other analysis selections

- Dibosons:
  WZ→3lν : suppressed rejecting events w/ additional (=third) lepton w/ pT>10 GeV
  WZ, ZZ bkg: modelled with MC sim and normalized to their NLO Xsec (w/ MCFM)
  WW bkg: estimated w/ a control sample e+-mu-+ passing all other analysis selections

Event classification according to the number and topology of jets w/ pT>30 GeV:

- VBF category: the two highest-pT jets have |Δη|>4, mass>500 GeV
- 0 jet
- >= 1 jet
  and to the lepton flavour → 6 categories

$H \to ZZ \to 2l2\nu$

BR(ZZ→2l2nu) ~ 6 * BR (ZZ→4l)

Background (*Madgraph*):
- Z+jets (produced w/ Xsec 5 odg larger than signal)
- Top (ttbar, tW (*Powheg*))
- Diboson production (WZ, ZZ, WW)

Signal: generated w/ Powheg

Signal/bkg interference significant for masses higher than 400 GeV (GG2VV @ LO)
Interference: destructive above the mass pole, constructive below the mass pole

Event selection: see previous slide

Analysis strategy

Reconstructed transverse mass (mT) and MET used as final discriminating variables:
MET for the VBF categories, mT for all the other categories
The resolution of the mT is ~7% for mH=200 GeV and ~15% for mH=800 GeV
Both “cut-in-categories” and “shape” analysis
Cut-in-categories analysis optimized in order to obtain the best expected exclusion limit at 95% CL using mT and MET variables. The CLs method is used to compute the expected limit
Shape analysis: by fitting the MET distr in the VBF category and the mT distr in the other 2 categories

Main systematics:
- Experimental unc on selection/measurement of reconstructed objects
- Theoretical unc on the signal and bkg processes derived from MC (ZZ interference...)
- Unc on bkg's determined from control samples in data (100% unc on Z+jets estimation from data) (25% unc on non-resonant bkg estimation from data)

$H \rightarrow ZZ \rightarrow 2l2\nu$

Results:

- No significant excess of events is observed over the expectation from the SM bkg → we set un upper limit on the production cross section of a SM-like Higgs boson
- The limits are set for different mH hypotheses using a modified frequentist method (CLs method)
- A profile likelihood ratio test statistics is used. In the likelohood the total number of events observed is compared w/ the predictions from bkg and signal by means of a product of Poisson probabilities
  Uncertainties are handled by introducing nuisance parameters with a probability density function
  The nuisance parameters modify parametrically the expectiations for both signal and bkg processes
- The procedure summarised above is generalised for the shape-based analysis in order to parametrize each bin of the shape distribution used
- Ratio of 95% CL cross section upper limit relative to the SM theoretical expectation
- With the shape analysis (most sensitive): a SM-like Higgs boson is excluded at 95% CL in the mass range 248-930 GeV (expected exclusion range: 254-898 GeV) (EXPECTED PIÙ STRETTO DELL'OBSERVED – QUINDI NON ESCLUSIONE IN TUTTO IL RANGE OBS, NO?)
- This result extends the ones obtained with the other ZZ channels, and with WW channel
- Reinterpretation of the result as a search for an electroweak singlet scalar mixing with the 125 GeV Higgs boson: the couplings of the two gauge eigenstates become inter-related by unitarity → the original coupling strength of the light Higgs boson is reduced wrt the SM case.
  We use the C'2 definition to generate different widths of the siglet scalar boson. The generated SM signal mass line shape generated by Powheg is re-weighted in order to simulate the singlet scalar line shape. In the re-weighting procedure we set as target line shape a relativistic Breit Wigner with a narrower signal width. The new narrower resonance is excluded for various widths and branching ratios to new particles.

Higgs boson width from off-shell production and decay to 4l and 2l2ν

Idea to constrain the Higgs boson width using the off-shell Higgs boson production and decay in ZZ away from the resonance.
In gg production mechanism: the off-shell production cross section is ~8% of the on-peak one (at 8 TeV) and it is enhanced up to 20% when in the resonant region (2mZ), or higher in the region near 2m(top) = 2 * 173 GeV
The ratio of off-shell and on-shell production and decay rates in the ZZ channel leads to a direct measurement of ΓH (as long as the ratio of the coupling costants remains invariant, e.g. if there are no new light particles in the gluon fusion loop which would affect the coupling constants differently at the low and high mZZ values).
The upper bound is obtained from the ratio of off-shell production and decay rates in 4l and 2l2ν channels to the on-shell rate (from 4l channel).
Analysis at 8 TeV, with 19.7 fb-1.
ΓH(SM)=4.15 MeV for mH=125.6 GeV (theoretical prediction according to SM)
VBF production mechanism component also taken into account (~10% effect)
Need to take into account the bkg interference with signal for the processes with the same initial and final states. Non resonant gg→ZZ (via a fermion box) leads to negative interf w/ the signal and leads to a decrease of signal yield in the off-peak region (the effect is negligible in the on-peak region due to the narrow signal peak).
Probability distribution functions are constructed for each event to be either signal or background. N is the expected number of events, P the pdf's.
Off-shell → μr (if r=Γ/Γ(SM)); on-shell in 4l → μ
Cancellation of sys uncertainties common to the on-peak and off-peak analyses, in the combined analysis. Other approach: to constrain μ=1 w/ assoc sys from theoretical calc

Higgs boson width from off-shell production and decay to 4l and 2l2ν

Constraints are set on the Higgs boson decay width using off-shell production and decay to ZZ in the 4 lepton or 2l 2nu final states.

A maximum likelihood fit of invariant mass and the dedicated Dgg kinematic discriminant distributions for the 4l analysis and the transverse mass or missing energy distributions in the 2l2nu case is performed. The result of this, combined w/ the 4l measurement near the resonance peak, leads to un upper limit on the Higgs boson width of 4.2 Γ(SM) at 95% CL, assuming Γ(SM)=4.15 MeV.
We obtain un upper bound on ΓH from the comparison of off-shell production and decay distribution in the 4l and 2l2nu channels, and the 4l on-shell rate.

In addition to the reconstruction, selection and analysis methods used in the standard analysis, the 4l off-shell an uses a dedicated kinematic discriminant Dgg which is a matrix element likelihood discriminant to separate the ZZ components originating from gluon- and quark-initiated processes. Dgg = Pgg/ (Pgg+Pqqbar) where Pgg is the probbility for an event to come from gg→ZZ and Pqqbar is the probability for it to come from qqbar→ZZ

For the 2l2nu analysis, the mT (trasnverse mass) distribution is used as a discriminant for the 0 and >=1 jets categories, while the MET distribution is used for the VBF category

Higgs boson width from off-shell production and decay to 4l and 2l2ν

Data and bkg MC: same used in the H → ZZ → 4l and H → ZZ → 2l2ν
In addition: gg → 4l and 2l2ν events: generated @ LO including the Higgs boson signal as well the bkg and their interference usgin GG2VV and MCFM (the LO is necessary because no NLO available for the fermion box gg→ZZ).
Unphysical samples containing signal only and bkg only components have been generated to model the corresponding pdf.
Even if for the continuum bkg no exact calculation exists for any higher order than LO, the soft collinear approximation can describe the bkg cross section - and therefore the interference - at NNLO with good precision
VBF events: generated with PHANTOM. Off-shell and interference effects are included at LO in these samples.
Both ttbarH and VH productions are not expected to produce a significant off-shell tail, as these mechanisms are suppressed at high mass.
The dominant qqbar → ZZ bkg is evaluated from Powheg and Madgraph while its cross section is obtained from MCFM

Theoretical systematic uncertainties:

- The main sys unc comes from the measured value of μ: the expected (observed) value is 1.00 +0.27 -0.24 (0.93 +0.26 -0.24)
- On the normalization of the main (for both analyses) qqbar→ZZ bkg contribution: 4-10%
- All signal sys for the 4l final state depending only on its total normalization cancel when using the measured on-peak signal strenght as a reference.
- Limited knowledge of the gg → ZZ continuum bkg Xsec

Higgs boson width from off-shell production and decay to 4l and 2l2ν

Results:

Unbinned maximum likelihood fit of data is performed, using sys unc as nuisance parameters

The combined analysis (two channels) gives an observed (expected) exclusion of $\Gamma H <= 4.2$ (8.5) $\Gamma(SM)$ at 95% CL → $\Gamma H <= 17.4$ (35.3) MeV

The observed limit is tighter than the the expected due to a deficit of 4l events in the high m(4l) and high Dgg region, and a deficit in the 2e2nu channel.

The compatibility of the observed results w/ the expectation of the SM Hp is statistically consistent w/ a p-value of 0.02

$H \rightarrow WW$ (leptonic final states)

Selected events with 2 or 3 charged leptons
A complete reconstruction of all the final state particles is not possible because of the presence of neutrinos which are not directly detected.
Variables used: opening angle between the leptons in the transverse plane
dilepton mass
transverse mass of the systems of the 2 leptons and neutrinos
to distinguish between signal and bkg and between SM and exotic resonances w/ different spin/parity
Good discriminating power btw spin 0+ hp and spin 2+m hp(=resonance which couples to bosons through minimal couplings)

BR($H \rightarrow WW$) ~ 22% @ 125 GeV
Production mechanisms investigated: gg, VBF, VH
5 exclusive event categories:
1) $2l2\nu$ + 0/1 jet (targeting the ggH production – additional jet from ISR) $\rightarrow$ dominates the overall sensitivity
2) $2l2\nu$ + 2 jets (VBF production)
3) $2l2\nu$ + 2 jets (VH production)
4) $3l3\nu$ (WH production)
5) $3l\ \nu$ + 2 jets (ZH production with one W decaying hadronically)

Search in the mass range 110-600 GeV
The search range stops at 200 GeV for the analyses targeting the VH production since for larger masses the expected VH Xsec becomes negligible

Background:
- In the dilepton category: non-resonant WW production gives the largest bkg contribution (est from data)
- In events with high jet multiplicity: top-quark production is the main bkg source (from data)
- Trilepton categories: WZ, ZZ production are the main bkg (estimated partly from sim samples)
- Instrumental bkg's from W and Z + jets or photons (from data)

H→WW (leptonic final states)

Data samples from 2011 (7 TeV, 4.9 fb-1) and 2012 (8 TeV, 19.4 fb-1)
Trigger paths used: single-lepton triggers w/ tight lepton ID
dilepton triggers (17, 8 GeV thresholds)
MC samples: signal from gg and VBF with Powheg
alternative spin/parity Hp with Jhugen (LO)
signal from VH production with Pythia
mass lineshape corrected using the complex-pole mass scheme
interference between the gg signal and the gg→WW bkg included
WZ, ZZ, VVV, DY of Z,gamma,W+jets, qqbar→WW with Madgraph
gg→WW using GG2WW
ttbar, tW with Powheg
Z/γ*→ττ and Wγ* bkg: w/ combination of MC and data samples

Event selection: 2 or 3 high-pT lepton candidates originating from the same primary vertex
(the vertex with higher ΣpT2 is chosen as the primary vertex)
jets: pT > 30 GeV, |η|<4.7
b-tagging: w/ Track Counting High Efficiency algorithm
Missing transverse energy vector: negative vector sum of the transverse momenta of all reconstructed particles (charged or neutral) in the event

- Final state w/ 2 leptons: main variables: ΔΦ(ll) → correlated w/ Higgs spin
  m(ll) → discriminating var against Z/γ*→ll bkg
  mT which scales w/ the Higgs mass
  categorization in lepton flavour and jet multiplicity

H → WW (leptonic final states)

Bkg suppression:

- Non-prompt lepton bkg (leptonic decays of heavy quarks, hadrons misid as leptons, electrons from photon conversions in W+jets): suppressed w/ ID and ISO requirements
- Drell-Yan Z/γ* production → high production of same flavour lepton pairs (large Xsec of DY and finite res of MET measurement). The resonant component of DY prod is rejected by requiring m(ll) to be more than 15 GeV away from the Z boson mass. To suppress the remaining off-peak contribution: multivariate selection (MET, kinematic, topological variables)
- Top-quark production: rejection based on soft-muon and b-jet identification
- Non-resonant WW events: normalized to data

1/0 jets gg fusion category:
- a counting analysis is performed in each final state and category using a selection optimized for each mH hp using pT(ll), mll, ΔΦ(ll), mT (Table 4 for cuts)
- 2D (mll, mT) shape analysis for OF final state (both to discriminate signal from bkg and to test spin parity Hp's) (more sensitive than the counting analysis) → binned template fit
- a dedicated analysis to probe the Higgs boson mass is performed using a 2D unbinned parametric ML fit to variables computed in the estimated decay frame of the Higgs boson candidate ("razor frame"): an estimator of the Higgs mass and the opening angle of the 2 leptons in the razor frame (for the different flavour final states)

About 100 total signal events expected
Overall signal eff uncertainty: ~20% (dominated by theoretical unc due to missing high-order corrections and PDF unc)
Sys on bkg estimation: ~15% (dominated by stat unc and by theoretical unc on non-res WW prod)
The sensitivity is limited by the sys unc for the counting analysis
Excess of events observed for low Higgs boson mass Hp's → observed limit weaker than expected
Observed (expected) significance @ 125 GeV: 4 (5.2) σ

$H \rightarrow WW$ (leptonic final states)

2 jets VBF category:
$|\Delta\eta| > 3.5$, inv mass >500 GeV
Template fit to a single kinematic variable: m(ll)
Counting analysis for the same flavour category, and as a cross check for different flavour categories
For mH=125 GeV, a few signal events are expected, with S/B~1

2 jets VH category:
Two centrally-produced jets: $|\eta|<2.5$ from the decay of the associated vector boson
Dijet mass: has to be consistent with the parent boson mass (65-105 GeV)
Separation: $|\Delta\eta|<1.5$
If mH < 180 GeV → 60 GeV < mT < mH
If mH > 180 GeV → 70 GeV < mT < mH
Counting analysis.
Few signal events are expected, with a S/B ~0.08

3 leptons final states

Total charge +-1. pT> 20, 10, 10
WH → 3l3ν:
Main analysis: shape-based analysis using as discriminating variable ΔR(l+l-)
Bkg's: dibosons, tribosons, Zγ
No significant excess of events is observed wrt the bkg prediction
ZH → 3lν + 2 jets:
|mll-mZ| < 15 GeV, m(l+l-)> 12 GeV to reject Vγ*, |mlll-mZ|>10 GeV to reject Z→4l; # jets>=2
mT of the leptonically decaying W less than 85 GeV
|mjj-mW| < 60 GeV to be compatible with a W decay
Shape analysis with mT(lν2j)
No significant excess of events is observed wrt the bkg prediction

$H \to WW$ (leptonic final states)

Combined results
Fig. 21: combined observed and expected 95% CL upper limits on the production cross section of the $H \to WW$ process wrt the SM prediction without assumption of the presence of a SM Higgs boson (left) and considering the SM Higgs boson at 125.6 GeV as part of the bkg processes.
Left: excess of events observed at low mass → observed limits much weaker than the expected ones
SM Higgs boson excluded in the mass range 127-600 GeV at 95% CL (expected exclusion range: 115-600 GeV)
Right: in order to search for another excess, but no significant excess is found anywhere → additional Higgs bosons with SM-like properties excluded in 114-600 GeV at 95% CL

Fig. 22: expected and observed significance
Observed (expected) significance of the signal: 4.3 (5.8) σ for mH=125.6 GeV
Signal strength: 0.72 +0.20 -0.18

Fig. 25: signal strength modifiers

Spin and parity: with 2D shape analysis of (mT, mll): the distribution of the two variables and the correlation between them clearly separates the 2 spin Hp's (0+, 2+min)
Test statistic: q = -2 ln(L(JP)/L0+), L likelihoods
2+min excluded at 83.7% CL (Fig. 28)
Fig. 30: ~1σ separation between 0+ and 0- (pseudoscalar) hp's