SUMMARY OF HIGGS-BOSON PROPERTY MEASUREMENTS AT CMS

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ON BEHALF OF THE CMS COLLABORATION

- Higgs analyses and their combination
- Mass and width
- σ/σ_{SM} and p_T distribution
- Couplings to SM particles
- Spin hypotheses

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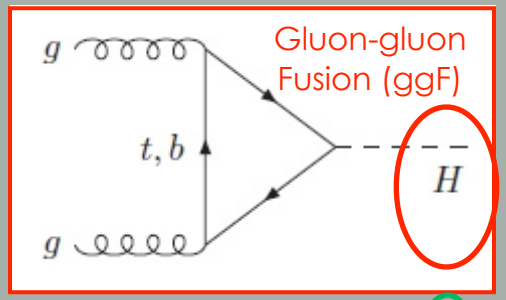
HIGGS ANALYSES IN CMS

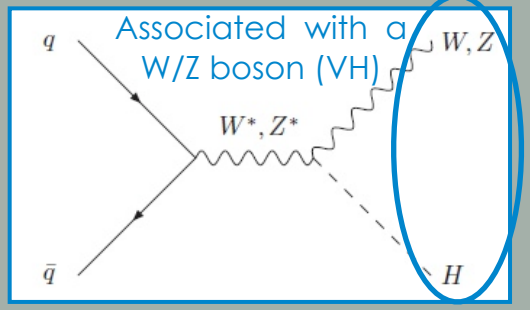
Lot of progress since discovery in July 2012

Searches target different production modes, either by means of separate studies or event categorization

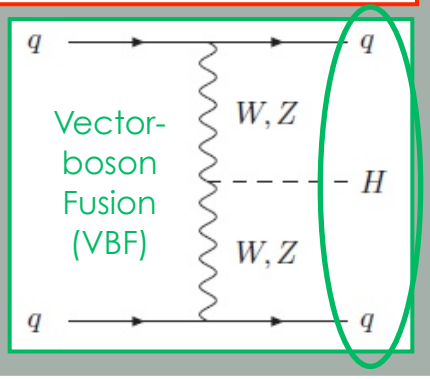
- Selection of best-purity events (becomes necessary for high-background modes like $b\bar{b}$, $\tau\tau$, invisible)
- Measurement of couplings to fermions/vector bosons



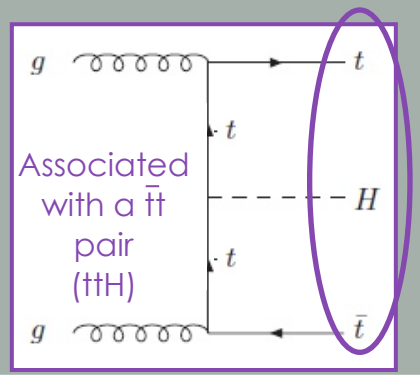
Gluon-gluon Fusion (ggF)



Associated with a W/Z boson (VH)



Vector-boson Fusion (VBF)



Associated with a $t\bar{t}$ pair (ttH)

×

SM decays
- $Z^*Z^{(*)} \rightarrow 2l2l'$
- $W^*W^{(*)} \rightarrow 2l2\nu$
- $\gamma\gamma$
- $\tau\tau$
- $b\bar{b}$

- Suppressed or forbidden in SM
  - $\mu\mu$
  - Invisible … etc.

INPUTS FOR COMBINATION

Input channels and their analysis categories (red = not yet included in combination [1], purple = updated afterwards)

- $Z^*Z^{(*)} \rightarrow 2l2l'$ [2] (obs. significance = 6.7σ)
  - $N_{jets} \geq 2$ (targeting VBF) or < 2 (using $p_T(H)$ to discriminate ggF from other production modes)
- $W^*W^{(*)} \rightarrow 2l2\nu$ [3] (obs. significance = 3.9σ)
  - Same-flavor or different-flavor leptons, $N_{jets} = 0$, 1 or 2 (targeting VBF)
  - ~~3l3ν~~ for WH tagging
- bb [4] (obs. significance = 2.1σ)
  - Boosted VH tag: additional eν, μν, ee, μμ, νν with 2 b-jets, split in low/high $p_T(V)$
  - ttH tag: lepton + n jets (n > 3), of which m b-tagged jets (m > 2) or dilepton with q b-tagged jets (q > 1)
- γγ [5] (obs. significance = 3.2σ)
  - $N_{jets} = 2$ for VBF category, VH tag with an extra e or μ or $E_{T,miss}$, or ttH tag
  - Untagged events in 4 di-photon resolution/purity categories
- ττ [6] (obs. significance = 2.8σ)
  - $N_{jets} = 2$ for VBF category or ttH tag
  - Untagged only if at least one τ decays leptonically, at least 1-jet tag if fully hadronic
  - Split in low/high $p_T(\tau\tau)$

HIGGS MASS

Uses only ZZ* and $\gamma\gamma$ (mass resolution = 1-2%)

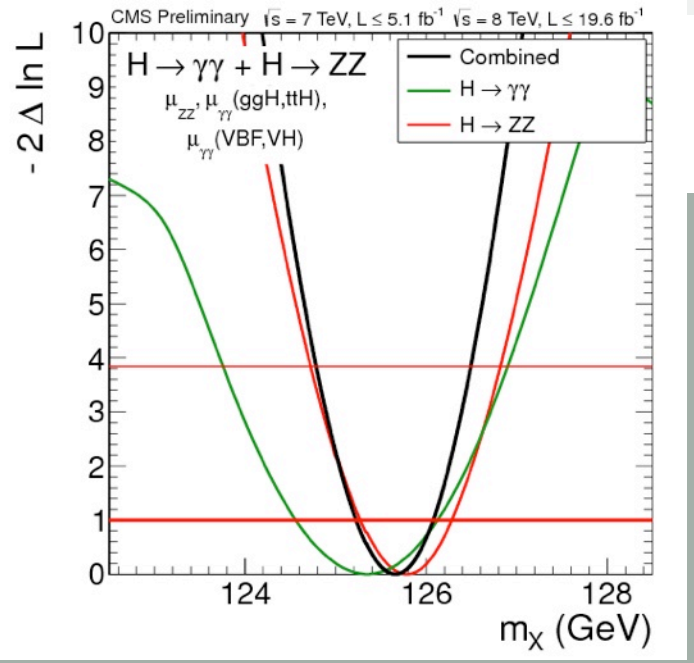
Cross sections of $H \rightarrow ZZ^*$, $gg \rightarrow H \rightarrow \gamma\gamma$, and VBF/VH $H \rightarrow \gamma\gamma$ free in the fit

- Good agreement with result where all cross sections fixed

Good compatibility between the two channels

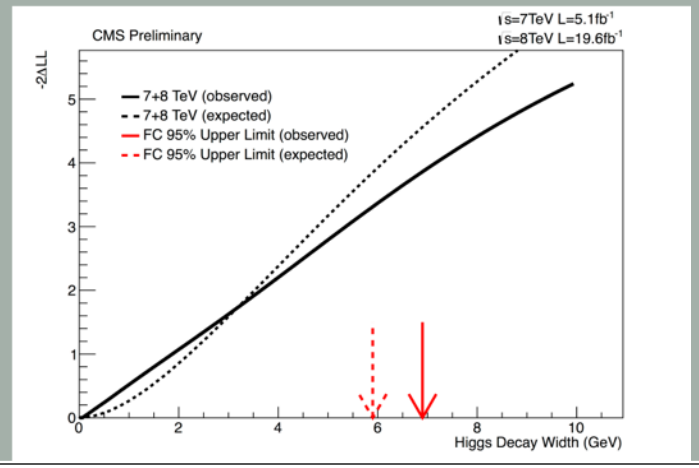
SM expectations of all quantities which follow are computed at the fitted mass

m_X = 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV



Limit on boson width using $H \rightarrow \gamma\gamma$ [7]:

$\Gamma < 6.9$ GeV @95% C.L.



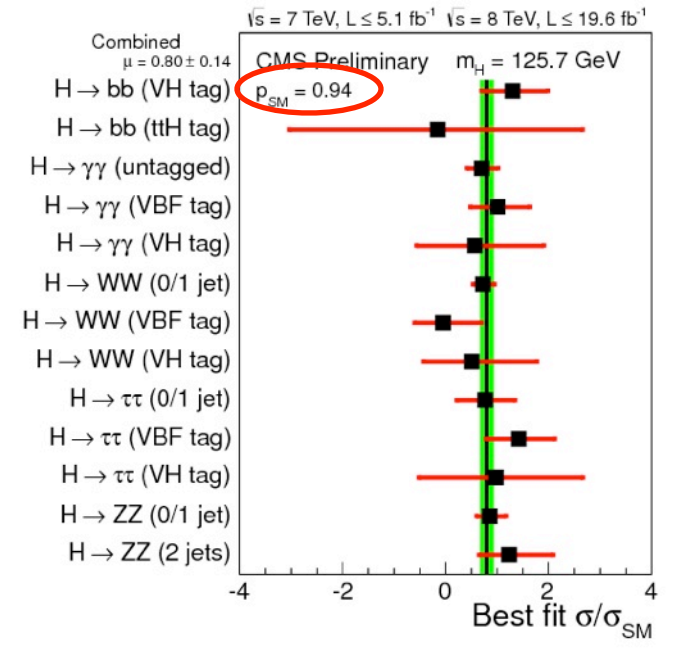
HIGGS CROSS SECTION

Expressed as $\mu = \sigma/\sigma_{SM}$

Combined

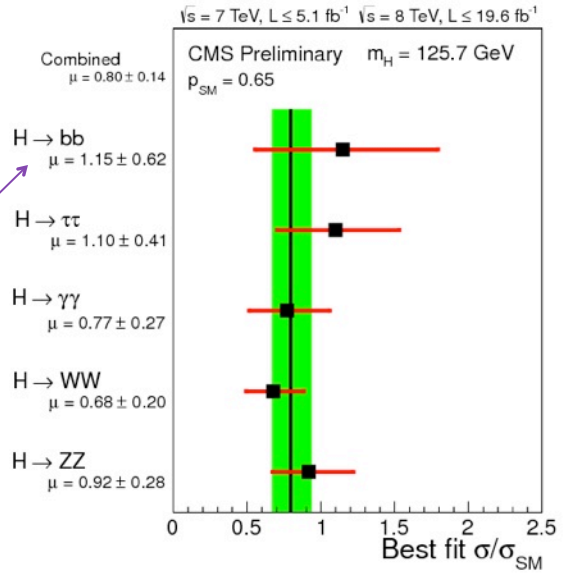
$\mu = 0.80 \pm 0.14$

Split per single inputs

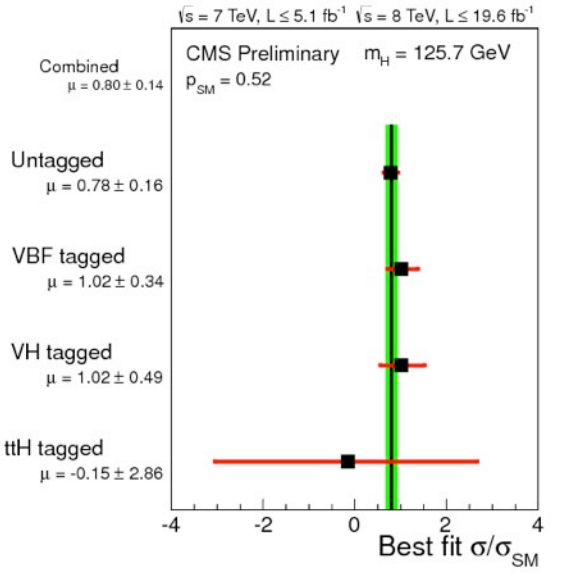


Split per final state

Now updated:
$\mu = 1.0 \pm 0.5$



Split per tagging of production process



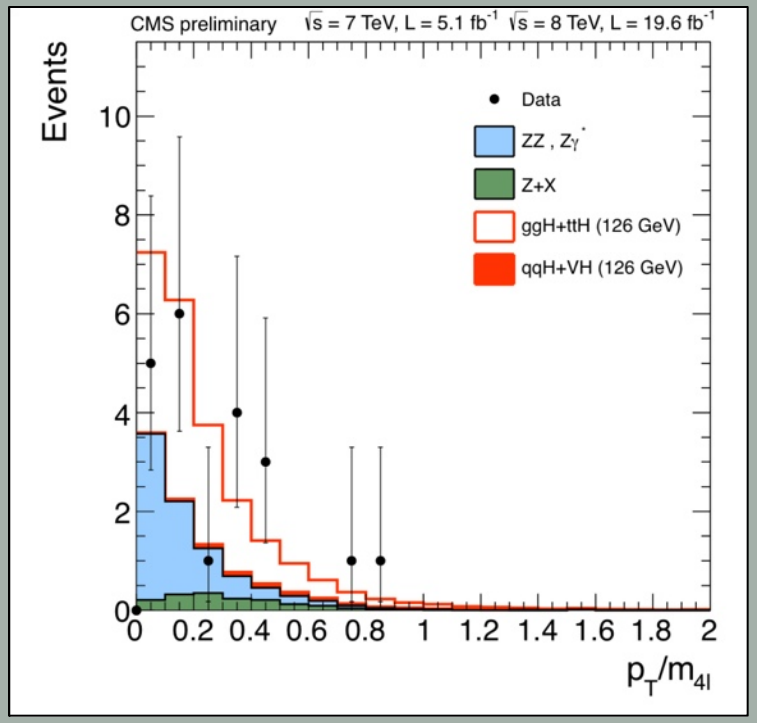
HIGGS P_T DISTRIBUTION

Using the ZZ* channel [2]

Compared with theoretical expectations

- VBF: NLO prediction (POWHEG)
- VH: LO predictions (Pythia6) reweighted to NLO
- ggF: NLO prediction (POWHEG) tuned to NNLO+NNLL spectrum and including top- and bottom quark mass effects

Good agreement, more data will allow measurement of differential cross-section



Events in
$121.5 < m_{4l} < 130.5$ GeV

TESTS OF HIGGS COUPLINGS

Compute all ($\sigma \cdot$ BR)'s, scaling the SM Higgs couplings with free factors $\kappa = c/c_{SM}$

- Most σ's and Γ's depend on corresponding κ^2 (i.e. insensitive to relative signs) but not all, e.g. interference between loops of t and W in $H \rightarrow \gamma\gamma$

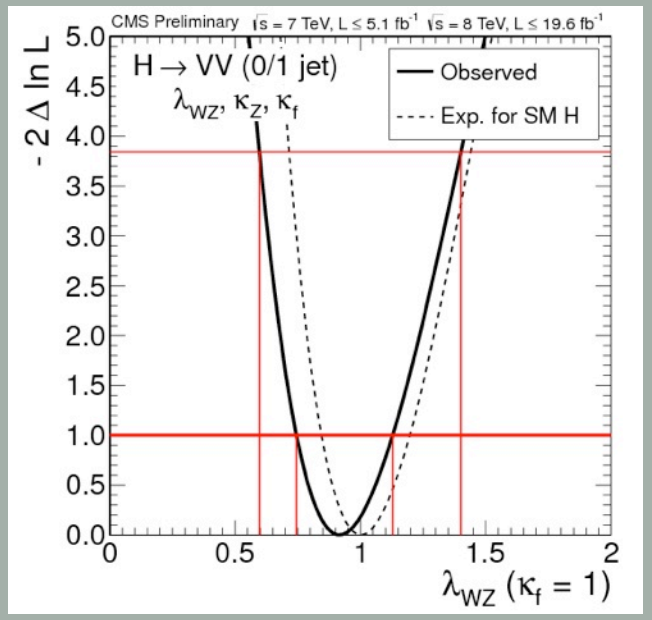
Two scenarios considered

- Sum of BR's constrained to SM ($\Gamma_{tot} = \Sigma_i \Gamma_{SM,i}$)
- Allowing for BSM decays ($\Gamma_{tot} = \Sigma_i \Gamma_{SM,i} + \Gamma_{BSM}$)

If κ for every fermion and boson left independently free, limited constraining power with current Higgs data

→ consider "reasonable" BSM hypotheses

- e.g. test of "custodial symmetry"
  - Use ZZ* and WW* data
  - fermions couplings fixed to SM



FERMIONS AND BOSONS

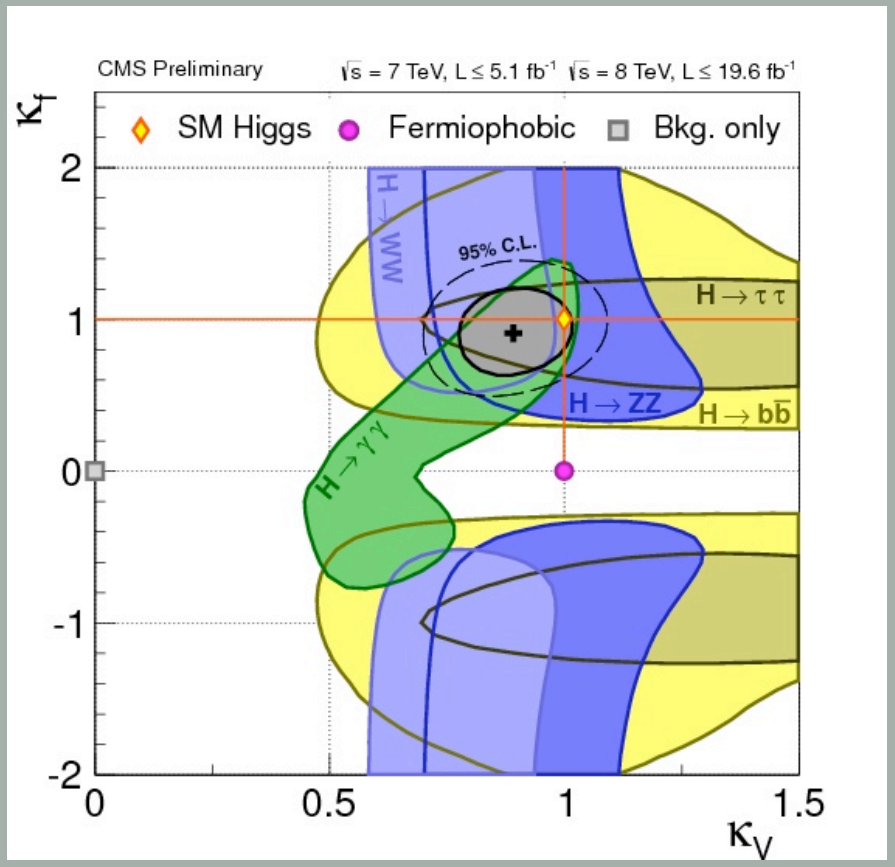
Consider common scale factors for all fermions and all bosons (κ_V, κ_f)

Most important inputs: relative abundance of Higgs production in VBF/VH tagged modes vs. ttH and untagged

SM within the 68% confidence level

- κ_V in [0.74, 1.06] @ 95% C.L.
- κ_f in [0.61, 1.33] @ 95% C.L.

"Fermiophobic Higgs" hypothesis excluded



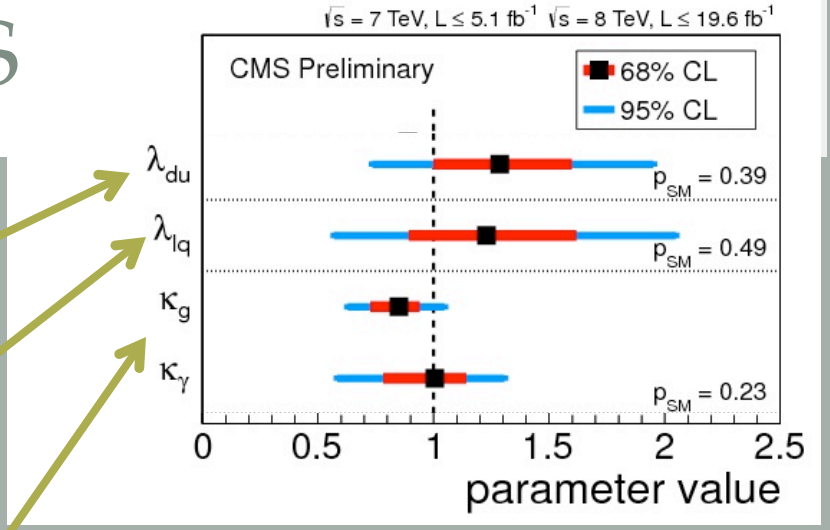
OTHER SCENARIOS

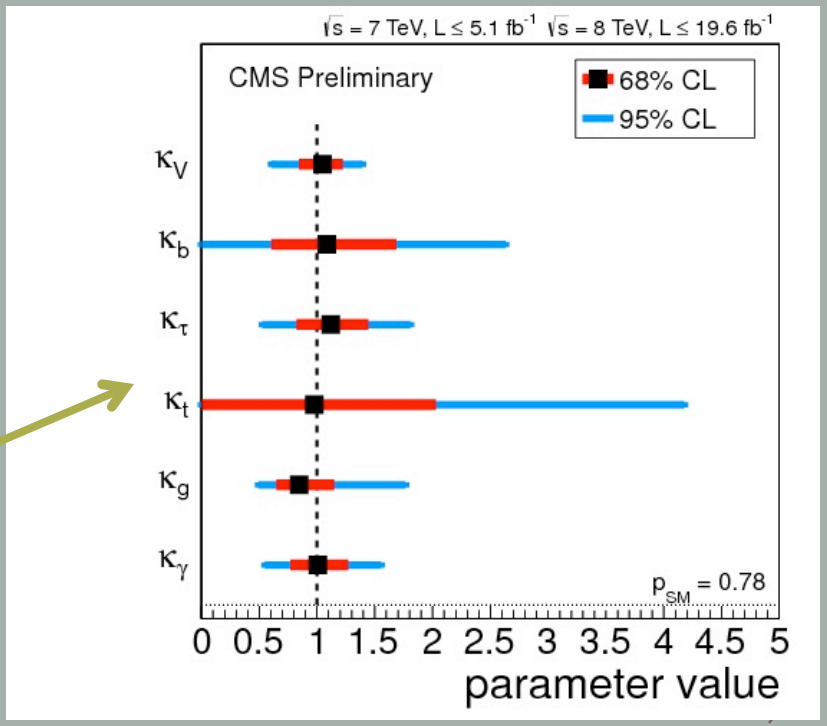
Ratio between couplings to up and down-type quarks, $\lambda_{du} = \kappa_d/\kappa_u$, left free (common to all generations, e.g. in MSSM)

Ratio between couplings to leptons and quarks, $\lambda_{lq} = \kappa_l/\kappa_q$, left free (common to all generations, e.g. in general 2HDMs)

κ_g and κ_γ left free (without resolving the loops, sensitive to presence of NP particles in them)

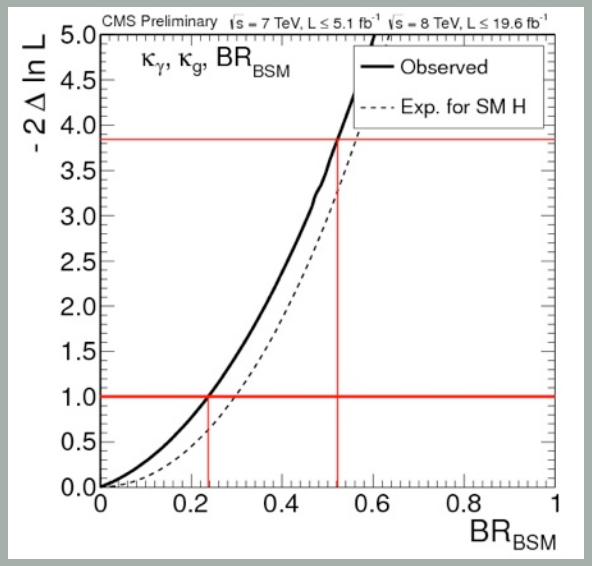
6 free coefficients (κ_V, common to W and Z, κ_γ, κ_g and κ_l κ_u, κ_d common to the 3 generations)





BSM DECAYS

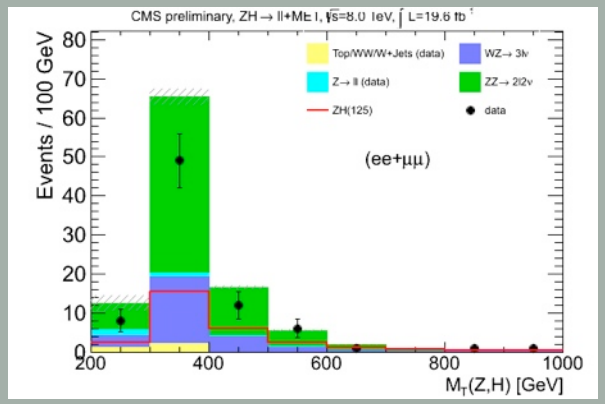
Constrained indirectly using all observed modes (profiling κ_γ and κ_g)

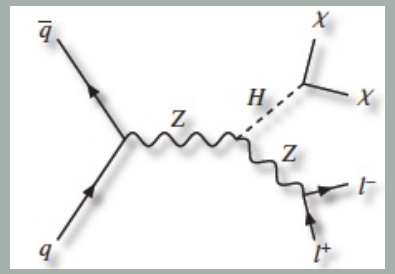


$BR_{BSM} < 0.52$ @ 95% C.L.

Directly, searching for "invisible" decay modes [8]

- ZH, H → invisible, Z → l^+l^-



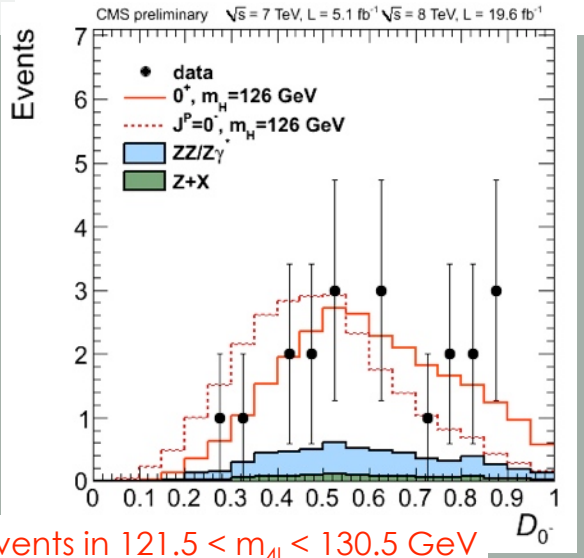


$BR_{H(125)\to invisible} < 0.75$ @ 95% C.L.

- VBF, H → invisible

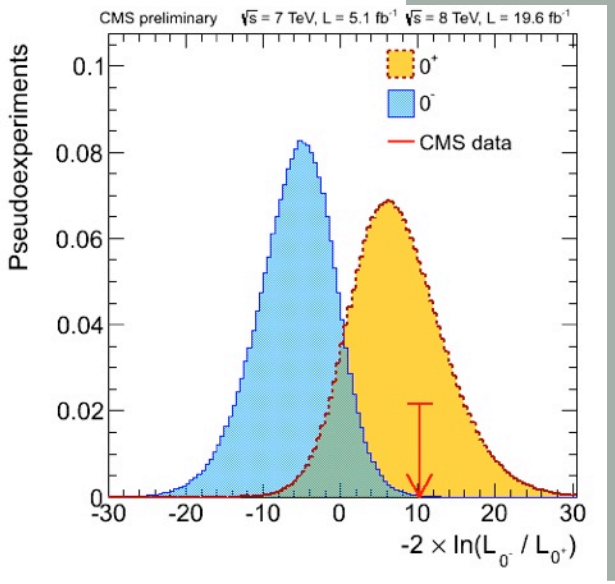
See S. Dasu's talk tomorrow

SPIN: 0^+ VS. 0^-



Events in $121.5 < m_{4l} < 130.5$ GeV

$D_{bkg} > 0.5$



Using the ZZ* channel [2]

Likelihood discriminant based on the LO decay matrix elements expected for scalar and pseudoscalar boson

- Variables: 2 di-lepton invariant masses + 5 decay angles in different rest frames

$$D_{J^P} = \left[1 + \frac{P(\boldsymbol{\Omega}, m_{ll}, m_{l'l'} | J^P)}{P(\boldsymbol{\Omega}, m_{ll}, m_{l'l'} | 0^+)}\right]^{-1}$$

Confidence level estimated via pseudo-experiments with templates from simulation

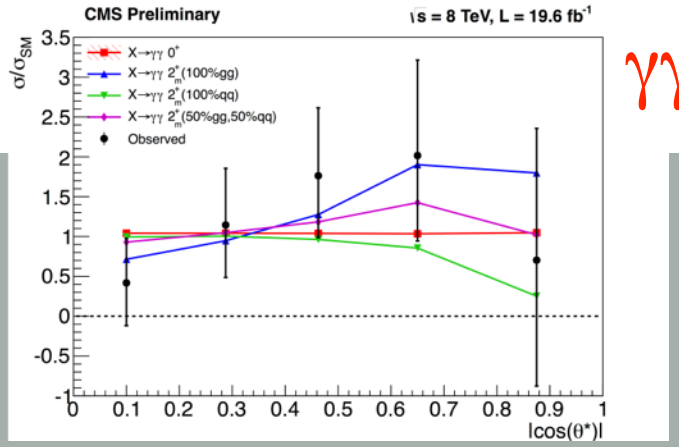
- Fully compatible with SM hypothesis
- 0^- hypothesis excluded at 3.3σ level
- Other "exotic" hypotheses tested (0^+_h, 1^-, 1^+), most ruled out at $\geq 3\sigma$

SPIN: 0^+ VS. 2^+

Performed in the ZZ* analysis with an analogous technique but also in WW* and γγ [7] (using the cosθ* angle only)

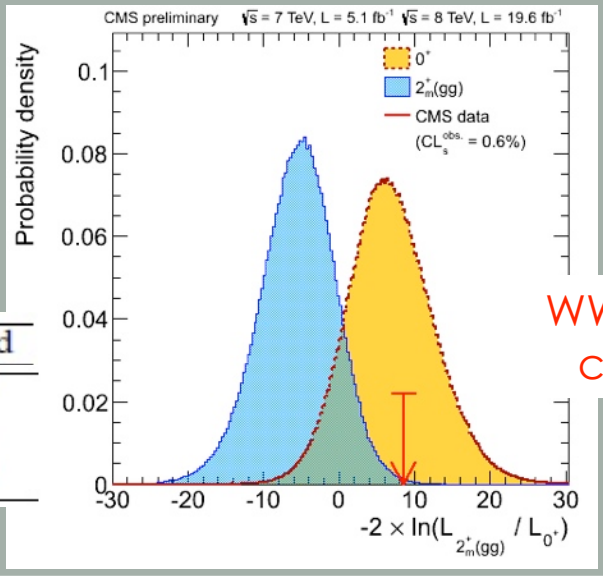
Not a single matrix element, depends on (unknown) spin-2 particle couplings. A few hypotheses chosen:

- Production 100% from gg or 100% from qq, or mixed
- "Minimal" couplings to SM fields (e.g. RS graviton)



γγ

Source	χ^2 p-value
Data vs. 0^+	0.68
Data vs. 2^+_m (100% gg)	0.91
Data vs. 2^+_m (100% $q\bar{q}$)	0.51
Data vs. 2^+_m (50% gg, 50% qq)	0.81



WW* and ZZ* combined

	$ZZ \to 4\ell$	$WW \to \ell\nu\ell\nu$	Combined
$P(q \le q^{obs.} \mid 0^+)$	-0.90σ	0.44σ	-0.34σ
$P(q \ge q^{obs.} \mid 2^+_m(gg))$	2.81σ	1.32σ	2.84σ
$1 - CL_s^{obs.}$	98.6%	86.0%	99.4%

CONCLUSIONS

Combining the 5 main Higgs search modes ($Z^*Z^{(*)} \rightarrow 2l2l'$, $W^*W^{(*)} \rightarrow 2l2\nu$, $\gamma\gamma$, $\tau\tau$, $b\bar{b}$) with full statistics (~5 fb^{-1} at 7 TeV and ~19 fb^{-1} at 8 TeV) CMS performed a wide range of property measurements of the newly discovered boson

- Mass measurement with 0.3% total uncertainty
- Excluded broad resonance with $\Gamma > 6.9$ GeV
- Found total cross-sections compatible with SM Higgs boson within uncertainties ($\sigma/\sigma_{SM} = 0.80 \pm 0.14$)
- Separation using tagging of production modes allowed quite precise measurement of couplings
  - No significant deviations from SM observed, uncertainties vary from ~30% to 50-400% depending on the BSM scenario considered
- SM spin-parity has been tested against several alternative hypotheses
  - 0^- disfavored at 3.3σ
  - 2^+ disfavored at 2.8σ assuming 100% gg production

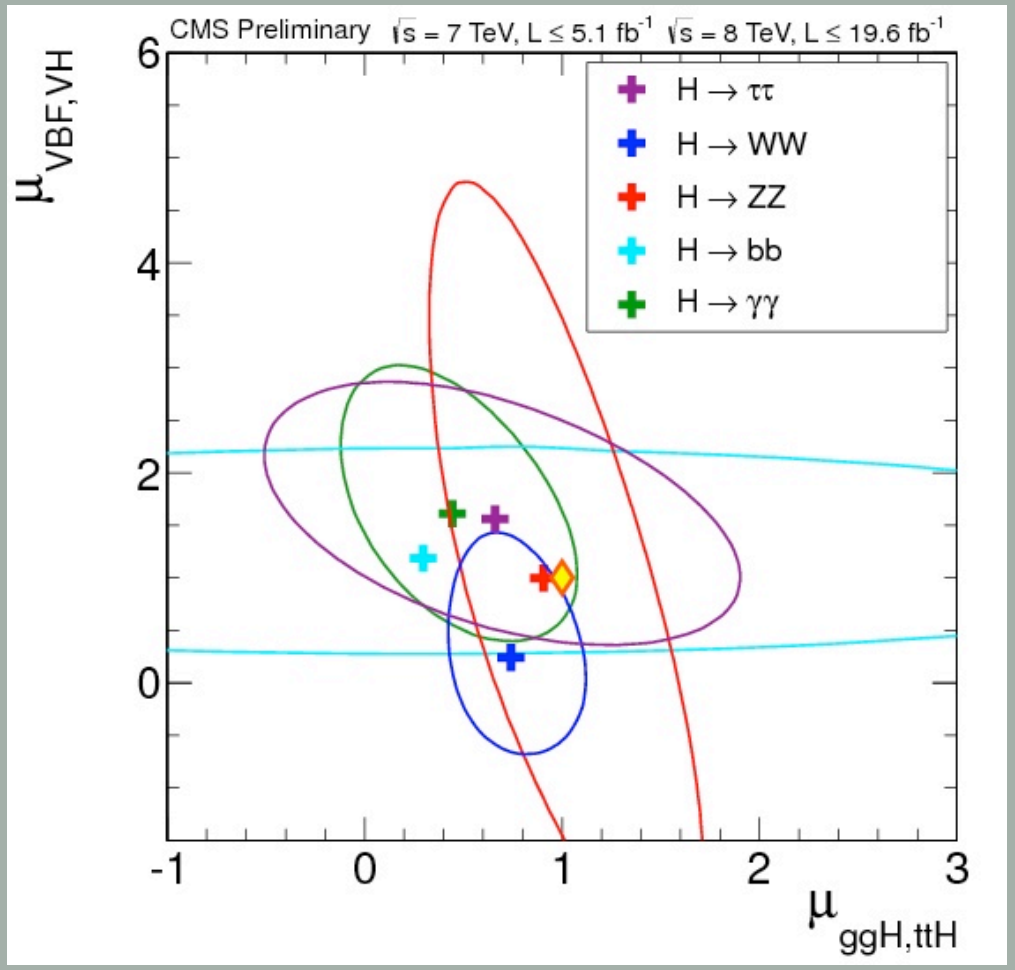
REFERENCES

All to be found in: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

[1] The CMS Collaboration, CMS-PAS-HIG-13-005 (2013)
[2] The CMS Collaboration, CMS-PAS-HIG-13-003 (2013)
[3] The CMS Collaboration, CMS-PAS-HIG-13-002 (2013)
[4] The CMS Collaboration, CMS-PAS-HIG-12-044 (2012)
updated, *ibid*. CMS-PAS-HIG-13-012 (2013)
[5] The CMS Collaboration, CMS-PAS-HIG-13-001(2013)
[6] The CMS Collaboration, CMS-PAS-HIG-13-004 (2013)
[7] The CMS Collaboration, CMS-PAS-HIG-13-016 (2013)
[8] The CMS Collaboration, CMS-PAS-HIG-13-018 (2013)

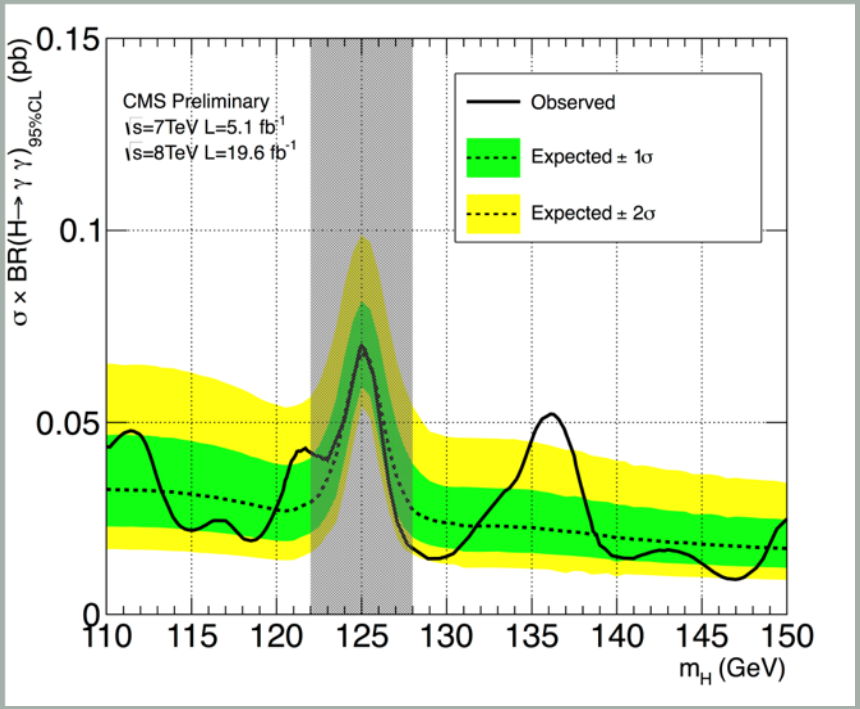
BACKUP

μV, μF

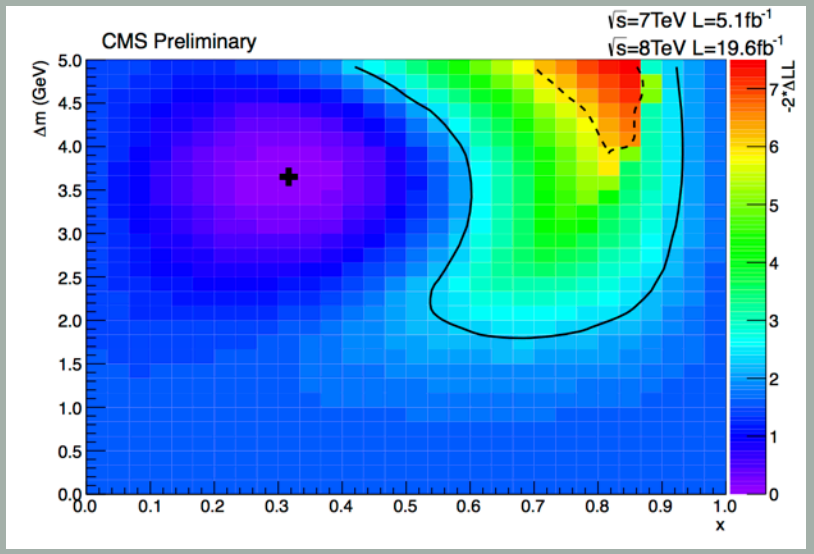

CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
H → ττ
H → WW
H → ZZ
H → bb
H → γγ
μVBF,VH
μggH,ttH
6
4
2
0
-1
0
1
2
3

EXCLUSION LIMITS FOR 2ND RESONANCE

Somewhere else in the γγ mass spectrum



Degenerate with 1st resonance (fraction x of 2nd resonance, mass difference Δm)



SPIN-0-TO-2 SEPARATION AS A FUNCTION