Lifetime and quantum numbers of the Higgs boson using the decay  $H \rightarrow 4\ell$ 

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#### Observables in $H \rightarrow 4\ell$ On-Peak Spin-Parity & Tensor Structure On-Peak Lifetime NEW! Off-Peak Width Off-Peak Spin-Parity NEW! Conclusions



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- Eight independent d.o.f. describe the kinematics in center of mass frame
  - $m_{4\ell}, m_{Z1}, m_{Z2}, \theta^*, \Phi_1, \theta_1, \theta_2, \Phi$
  - Difficult to use all simultaneously







 Transform into Discriminants sensitive to specific pieces of amplitude using MELA method





#### Spin-1

- Excluded from Landau-Yang ( $H \rightarrow \gamma \gamma$ )
- $H \rightarrow ZZ$  kinematics exclude any mixture of  $1^+$  and  $1^-$ , any production

arXiv:1411.3441







- Spin-0 Amplitude
  - Expression to the order of  $q^2$
  - Interpretation only clear for small BSM contributions

$$\begin{split} \mathcal{A}(HVV) \sim & \frac{1}{v} \quad \left( \left[ \mathcal{A}_{1} - e^{i\phi_{\Lambda_{Q}}} \frac{\left(q_{V_{1}} + q_{V_{2}}\right)^{2}}{\left(\Lambda_{Q}\right)^{2}} - e^{i\phi_{\Lambda_{1}}} \frac{q_{V_{1}}^{2} + q_{V_{2}}^{2}}{\left(\Lambda_{1}\right)^{2}} \right] m_{V}^{2} \epsilon_{V_{1}}^{*} \epsilon_{V_{2}}^{*} \\ & + \quad q_{2} f_{\mu\nu}^{*(V_{1})} f^{*(V_{2}),\mu\nu} + a_{3} f_{\mu\nu}^{*(V_{1})} \tilde{f}^{*(V_{2}),\mu\nu} \right) \end{split}$$

- In the SM only the  $a_1$  term is sizable for ZZ and WW ( $a_1 = 2$ )
- Λ<sub>1</sub> is scale of new physics on-peak
- $\Lambda_Q$  is scale of new physics off-peak
- $a_2$  is a CP-even scalar ( $10^{-2} 10^{-3}$  in SM)
- ► *a*<sub>3</sub> is a CP-odd pseudo-scalar (three-loop level in SM)
- $a_2$ ,  $a_3$ ,  $\Lambda_1$ ,  $\Lambda_Q$  (ZZ terms) are tested in  $H \rightarrow 4\ell$
- $a_2^{Z\gamma}$ ,  $a_3^{Z\gamma}$ ,  $\Lambda_1^{Z\gamma}$ ,  $a_2^{\gamma\gamma}$ ,  $a_3^{\gamma\gamma}$  are tested in  $H \to 4\ell$



- To measure HVV anomalous couplings in spin-0, we report effective cross section fractions
  - Invariant under coupling notation and allows for full coverage

$$f_{\alpha 3} = \frac{|\alpha_3|^2 \sigma_3}{|\alpha_1|^2 \sigma_1 + |\alpha_2|^2 \sigma_2 + |\alpha_3|^2 \sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{\alpha 3} = \arg\left(\frac{\alpha_3}{\alpha_1}\right)$$

- ► ZZ,  $Z\gamma^*$ , and  $\gamma^*\gamma^*$  are tested when amplitude ratio is real  $(\phi_{ai} = 0 \text{ or } \pi)$  (e.g.  $\phi_{ai} = 0$  is SM)
- $H \rightarrow 4\ell$  measures ZZ couplings by profiling the phase as well





 $H \rightarrow 4\ell$  lifetime and quantum numbers

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- ► Techniques used to study 11 anomalous couplings HZZ, HZ $\gamma$ , H $\gamma\gamma$ , HWW, HZZ + HWW
  - $HZ\gamma$  ( $H\gamma\gamma$ ) limits are 170(730)× SM expectations

All measurements consistent with the SM Higgs Boson  $J^{CP} = 0^{++}$ 

arXiv:1411.3441





$$\Delta r = \overline{r_{4l}} - \overline{r_{ref}}$$
$$\Delta t \equiv \frac{m_{4l}}{p_T} \left( \overline{\Delta r_\perp} \cdot \widehat{p_T} \right)$$

Ref.: Primary (production) vertex or beam spot

• Average  $\Delta t$  is inversely proportional to the width

$$\langle \Delta t \rangle = \tau_H = \frac{\hbar}{\Gamma_H}$$



- ▶ 105.6 < m<sub>4ℓ</sub> < 140.6 GeV
- D<sub>bkg</sub> as spin-parity

CMS

Events / 0.05

20

15

10

5

- $c \cdot \Delta t$  (Shown for  $D_{bkg} > 0.5$ )
  - $p_T$  an input (Shown  $D_{\rm bkg} > 0.5$ )

19.7 fb<sup>-1</sup> (8 TeV) + 5.1 fb<sup>-1</sup> (7 TeV)

• Fit for direct constraint on  $\tau_H$ 

Observed

SM

lz+x

02

õ 4

0.6

0.8

ZZ/Zγ\*

····· f<sub>a3</sub>=1



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D<sub>bkg</sub>

Events / 40 μm



- Observed(expected) limit on lifetime
  - $c \cdot \tau_H < 57(56) \mu m$  at 95% CL
  - Translates to  $\Gamma_H > 3.5(3.6) \times 10^{-9}$  MeV
- Not sensitive to SM prediction of  $c \cdot \tau_H \sim 48 fm$









$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{On-Peak} = c rac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{O \textit{ff}-Peak} = \textit{C}' g_{ggH}^2 g_{HZZ}^2$$

Measuring width translates to measuring the lifetime

- On-Peak signal scales with  $\mu = \sigma / \sigma_{SM}$
- Off-Peak signal scales with  $\mu * \Gamma_H / \Gamma_H^{SM}$
- Interference scales with  $\sqrt{\mu * \Gamma_H / \Gamma_H^{SM}}$







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- Use Signal Strength and Production Mechanism from 4<sup>l</sup> On-Peak
- Relate Low Mass Results and High Mass results
  - Γ<sub>H</sub> is the only free parameter when On-Peak and Off-Peak are combined
- CMS 19.7 fb<sup>-1</sup> (8 TeV) + 5.1 fb<sup>-1</sup> (7 TeV) <sup>10</sup> -7 ⊓L Off-Peak 41 observed  $\Gamma_H < 33 \text{ MeV}$  at 95% C.L. ----- 4l expected Expected < 42 MeV at 95% C.L.  $H \rightarrow 77$ On-Peak 95% CI  $\Gamma_{H} < 3.4 \text{ GeV}$  at 95% C.L. • Predicted at  $m_H = 125.6 \text{ GeV}$ :  $\Gamma_{\mu}^{SM} = 4.16 MeV$ 68% CI arXiv:1405.3455 30 50 60 Г<sub>н</sub> (MeV)





$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$

# Off-Peak Event Categorization

Category	Mass region	Criterion	Observables $\vec{x}$		
Width, on-shell dijet	$105.6 < m_{4\ell} < 140.6 { m GeV}$	$N_{\rm jet} \ge 2$	$m_{4\ell}$	$\mathcal{D}_{bkg}^{kin}$	$\mathcal{D}_{\text{jet}}$
Width, on-shell nondijet	$105.6 < m_{4\ell} < 140.6 { m GeV}$	$N_{\rm jet} < 2$	$m_{4\ell}$	$\mathcal{D}_{bka}^{kin}$	$p_{\mathrm{T}}$
Width, off-shell dijet	$220 < m_{4\ell} < 1600 { m GeV}$	$\mathcal{D}_{\text{iet}} \ge 0.5$	$m_{4\ell}$	$\mathcal{D}_{gg}$	
Width, off-shell nondijet	$220 < m_{4\ell} < 1600 { m GeV}$	$\dot{\mathcal{D}_{iet}} < 0.5$	$m_{4\ell}$	$\mathcal{D}_{gg}$	

- f<sub>AQ</sub> and Γ<sub>H</sub> have similar off-peak effects
- ► VBF categorization key due to increased  $f_{\Lambda Q}$  contribution
- $\mathcal{D}_{jet}$  untangles VBF from H+jj
  - Kinematics of Jets

$$\mathcal{D}_{jet} = \left[1 + \frac{\mathcal{P}_{HJJ}(\vec{\Omega}^{H+JJ}, m_{4\ell})}{\mathcal{P}_{VBF}(\vec{\Omega}^{H+JJ}, m_{4\ell})}\right]^{-1}$$







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Conclusion: What did we find?

- All measurements consistent with the SM Higgs Boson
  - $J^{CP} = 0^{++}$
  - $\Gamma_H \sim 4 \text{ MeV}$
- CMS produced most comprehensive set of HVV coupling (& tensor structure) measurements to date.
- New Results on lifetime/width
  - CMS shows:  $26MeV > \Gamma_H > 3.5 \times 10^{-9} \text{ MeV}$
  - Interplay of Off-Peak and & On-Peak measurements fruitfull
- $\blacktriangleright$  Many results are stat. limited  $\rightarrow$  promising for Run-2 & beyond
  - ▶ Will the new boson tell us something about *CP* violation?
  - Is this THE HIGGS BOSON or something else?



- "Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV", CMS collaboration, doi = "10.1103/PhysRevD.92.012004", arXiv:1411.3441 (hep-ex)
- "Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs", CMS collaboration, doi = "10.1016/j.physletb.2014.06.077", arXiv:1405.3455 (hep-ex)
- "Limits on the Higgs boson lifetime and width from its decay to four charged leptons", CMS collaboration, Submitted to PRD, arXiv: 1507.06656 (hep-ex)



### 🎇 Spin-0 HZZ Constraints (2/2)



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- $\blacktriangleright~H \rightarrow WW \rightarrow \ell \nu \ell \nu$  kinematics described by lepton momenta and MET
  - Build 2D p.d.f. of  $[M_T, m_{\ell\ell}]$
  - Fit spin-0 HVV anomalous couplings
  - Spin-2 Example shown here for demonstration purposes.



## Spin-0 Constraints (ZZ+WW)



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- $H \rightarrow ZZ \rightarrow 4\ell$  at CMS
  - The most sensitive at 125 GeV
  - High Signal to Background ratio (1 : 1)
  - No Missing Energy
  - Well understood backgrounds





#### Muons

- Muon Spectrometer: muon track identification
- Silicon tracker: inner track identification

- Electrons
  - Electromagnetic Calorimeter: energy deposit
  - Silicon tracker: inner track identification



## ${ ightarrow} H o Z\!Z o 4\ell$ Analysis at CMS

- Triggers: dilepton & tri-electron
- Analysis Region:
   m<sub>4l</sub> > 110 GeV
- Z candidates
  - Z<sub>1</sub> candidate: 40 < m<sub>Z1</sub> < 120 GeV
     </p>
  - Z<sub>2</sub> candidate:
     12 < m<sub>Z2</sub> < 120 GeV</li>
- Backgrounds
  - $q\bar{q} \rightarrow ZZ \& gg \rightarrow ZZ$ from Monte Carlo
  - Reducible from Data
     (Z + bb, Z + tt̄,
     Z + Jets, WZ + Jets)





 $g(\overline{q})$ 

- 5 angles +  $m_{Z_1}$  +  $m_{Z_2}$ 
  - Fully describes the decay kinematics in center of mass frame
  - Create MELA (Matrix Element Likelihood Approach) discriminant to determine signal from background
  - JHUGen, analytical Signal, MCFM - Background



g(q)

 $\mathcal{D}_{bkg}^{kin}$ 

## 🎇 The Compact Muon Solenoid





- ► Triggers:
  - 2 Electrons  $p_T > 17, 8 \text{ GeV}$
  - 2 Muons  $p_T > 17, 8 \, \text{GeV}$
  - Electron + Muon  $p_T > 17, 8 \text{ GeV}$
  - 3 Electrons  $p_T > 17, 8, 5 \text{ GeV}$
- Leptons
  - Electrons: Particle Flow Identification
    - Clusters of Energy in ECAL + Track in Silicon Tracker
    - $p_T^e > 7 \text{ GeV } \& |\eta^e| < 2.5$
  - Muons: Particle Flow Identification
    - ► Track in Muon Spectrometer + Track in Silicon Tracker
    - $p_T^{\mu} > 5 \, \text{GeV} \& |\eta^{\mu}| < 2.4$
  - Well Isolated ( $\Delta R < 0.4$ ) & from Primary Vertex (SIP<sub>3D</sub> < 4)
  - Final State Radiation merged back into leptons
- Jets: Particle Flow
  - Anti- $k_T$  clustering algorithm, D = 0.5
  - $p_{T}^{jet} > 30 \, {
    m GeV} \, \& \, |\eta^{jet}| \, < \, 4.7$



- $Z_1$  pair of OS SF leptons with mass closest to  $m_Z$ (  $40 < m_{\ell\ell} < 120 \,\text{GeV}$  )
- Remaining pair of OS SF with highest sum of  $p_T$  becomes  $Z_2$  (12 <  $m_{\ell\ell}$  < 120 GeV )
- $\blacktriangleright$  At least one lepton with  $p_T > 20 \, \text{GeV}$  and another with  $p_T > 10 \, \text{GeV}$
- Any OS pair must have  $m_{\ell\ell} > 4 \, {
  m GeV}$





- $Zb\bar{b}$ ,  $Zt\bar{t}$ , Z + Jets, WZ + Jets
- Estimate from control regions
  - ► *Z* + 2*SS* 
    - $Z_1$  and 2 SS,SF both fail
    - Correct for e's from γ conversion



 $\blacktriangleright Z + 2OS$ 

- Z<sub>1</sub> and 2 OS, SF both fail
- Z1 and 2 OS, SF with one pass and one fail







# 🎇 Alternative Spin-1 & 2 Boson

Spin-1 Amplitude

 $A(X_{J=1} \rightarrow V_1 V_2) \sim b_1 \left[ \left( \epsilon_{V_1}^* q \right) \left( \epsilon_{V_2}^* \epsilon_X \right) + \left( \epsilon_{V_2}^* q \right) \left( \epsilon_{V_1}^* \epsilon_X \right) \right] + b_2 \epsilon_{\alpha \mu \nu \beta} \epsilon_X^\alpha \epsilon_{V_1}^{*\mu} \epsilon_{V_2}^{*\nu} \tilde{q}^\beta$ 

- > ZZ tests any fraction of vector( $b_1$ ) & pseudo-vector( $b_2$ ) for  $q\bar{q}$  production and prod. indep.
- WW tests pure states with qq
   production
- Spin-2 Amplitude

$$\begin{split} & A(X_{J=2} \rightarrow V_1 V_2) \sim \Lambda^{-1} \left[ 2c_1 t_{\mu\nu} t^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} t^{*1,\mu\alpha} f^{*2,\nu\beta} \right. \\ & \left. + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (t^{*1,\mu\nu} t^{*2}_{\mu\alpha} + t^{*2,\mu\nu} t^{*1}_{\mu\alpha}) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} t^{*1,\alpha\beta} t^{*(2)}_{\alpha\beta} \right. \\ & \left. + m_V^2 \left( 2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left( \epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^{*}_{V_1} \epsilon^{*}_{V_2} \right) \right. \\ & \left. + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} t^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \right. \\ & \left. + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left( \epsilon^{*\nu}_{V_1} (q\epsilon^{*}_{V_2}) + \epsilon^{*\nu}_{V_2} (q\epsilon^{*\nu}_{V_1}) \right) \right] \end{split}$$

- ZZ tests three production modes (gg,  $q\bar{q}$ , prod. indep.)
- WW tests as a function of  $q\bar{q}$  contribution
- $\gamma\gamma$  tests  $2_m^+$  (c<sub>1</sub> = c<sub>5</sub>) as a function of  $q\bar{q}$  contribution





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- ► Events < 2 jets
  - Use p<sub>1</sub><sup>4ℓ</sup> to discriminate VBF, ggH, ZZ



Events > 2 jets

Discriminant from m<sub>ii</sub> &

 $\Delta \eta_{ii}$  to separate



- We found a particle!
- At  $m_H = 125.7 \text{ GeV}$  local significance
- local signif. =  $6.8\sigma$
- Expected:  $6.7\sigma$



- Full search excludes a wide range
- Expected: 115 740 GeV

114.5 – 119.0 GeV U

Observed:





Other final states much more constraining. All measurements consistent with the Higgs Boson

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