

## CMS Searches for Higgs Bosonic

**Decavs** 

#### Alexei Safonov

### Texas A&M University On behalf of CMS Collaboration

@ Michael Kirste



## Winter 2016 CMS Higgs Results

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Muon Resourc	2015 FreeTaxU	CMS-doc-1285	LHC Ski 2016,	https://indico.c	Obergurgl Univ	HL-LHC Upgra	TAMU Muon Tri	PhysicsResults	Preliminary Res	
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							Visit us: CMS Pu	blic website, CMS Physics ; Cor	tact us: CMS Publications	s Commi
Recent	Higgs Physics Prelim	ninary Results								
CMS-PAS	-HIG-16-009	Searc	h for invisible decays of a Higg	gs boson produced via vector b	boson fusion at $\sqrt{s} = 13$ TeV.				March 2016	
CMS-PAS	-HIG-16-007		Summary results of high	mass BSM Higgs searches usin	ng CMS run-I data				March 2016	
CMS-PAS	-HIG-16-011	Sea	rch for resonant Higgs boson	pair production in the $b\overline{b}\ell_{\nu}\ell_{\nu}$	final state at $\sqrt{s} = 13 \text{ TeV}$				March 2016	
CMS-PAS	-HIG-15-008		Search for tH produc	tion in multilepton final states a	at √5 = 13 TeV				March 2016	
CMS-PAS	-HIG-16-002	Search for resonant pair p	roduction of Higgs bosons de	caying to two bottom quark-ant	iquark pairs in proton-proton	collisions at 13 TeV			March 2016	
CMS-PAS	-HIG-15-005		First results on Higgs to $\gamma\gamma$ at 13 TeV						March 2016	
CMS-PAS	-HIG-16-010		Search for H to Z(II)+A(bb) with 2015 data						March 2016	
CMS-PAS	-HIG-16-014	Search for scalar res	or scalar resonances in the 200-1200 GeV mass range decaying into a Z and a photon in pp collisions at $\sqrt{s}=8$ TeV						March 2016	
CMS-PAS	-HIG-16-001	Se	Search for a heavy scalar boson decaying into a pair of Z bosons in the $2\ell' 2\nu$ final state						March 2016	
CMS-PAS	-HIG-15-004		Studies of Higgs boson production in the four-lepton final state at $\sqrt{s}=-$ 13 TeV						March 2016	
CMS-PAS	-HIG-16-004	Search for till	Search for $\vec{\mathfrak{ti}} H$ production in the $H \to b\bar{b}$ decay channel with $\sqrt{s}=~$ 13 TeV pp collisions at the CMS experiment						March 2016	
CMS-PAS	-HIG-15-013	1	Model independent search for Higgs boson pair production in the $b\overline{br}^+ t^-$ final state					March 2016		
CMS-PAS	-HIG-16-012	Search for non-resonant Higgs boson pair production in the $b\bar{b}\bar{r}^+r^-$ final state						March 2016		
CMS-PAS	-HIG-16-013	Search for resonant Higgs boson pair production in the $b\bar{b}r^+r^-$ final state						March 2016		
CMS-PAS	-HIG-16-008	Se	arch for invisible Higgs bosor	is in pp $\rightarrow$ ZH $\rightarrow 2\ell' + E_1^{mass}$	channels at $\sqrt{s} = 13 \text{ TeV}$				March 2016	
CMS-PAS	-HIG-14-041	Search for exotic	decays of the Higgs boson to	a pair of new light bosons with	two muon and two b jets in fi	nal states			March 2016	
CMS-HI	IG-14-035	Combin	ed search for anomalous pseu	doscalar HVV couplings in VH	production and H $\rightarrow$ VV decay	1	Submitted to PLB		13 February 2016	
CMS-PAS	-HIG-15-011	Search for the exotic decay of	f the Higgs boson to two light	pseudoscalar bosons with two	taus and two muons in the fin	al state at $\sqrt{s} = 8 \text{ TeV}$			February 2016	
CMS-PAS	-HIG-14-039	Search	n for a doubly-charged Higgs t	boson with $\sqrt{s} = 8$ TeV pp colli	sions at the CMS experiment				January 2016	
CMS-PAS	-HIG-15-010	Measurement of the transvers	e momentum spectrum of the	Higgs boson produced in pp c	ollisions at $\sqrt{s} = 8$ TeV using	the $H \rightarrow WW$ decays			December 2015	
CMS-H	IG-14-033	Search for a low-n	nass pseudoscalar Higgs boso	on produced in association with	a bb pair in pp collisions at ,	/s = 8 TeV	Submitted to PLB		11 November 2015	

- About 20 new analyses approved since the beginning of the year
  - Roughly half are based on the 13 TeV data (2015)



## Outline

- SM(-like) Higgs measurements:
   − H→γγ, H→WW, H→ZZ
- Heavish Higgs searches:
   − H→γγ, H→ZZ, H→Zγ
- Lightish Higgs searches:

— H**→**aa

- This talk is only a glimpse at select CMS Winter 2016 results
  - See CMS Higgs public results page for more: <u>https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG</u>



# SM(-like?) H→ZZ→4l at 13 TeV

- Essentially the same analysis as with 7 and 8 TeV
  - 4 $\mu$ , 4e, and 2e2 $\mu$  final states
- The good news is that the 125 GeV Higgs is still there





- Significance of the excess at 125 GeV is 2.5σ (the expectation is 3.4σ)
- Consistent with the 7 TeV and 8 TeV results

# SM(-like?) H→ZZ→4l at 13 TeV

- Good agreement within 118<m<130 GeV range
- Fiducial x-section measurement cuts:
  - P<sub>T1</sub>>20, P<sub>T2</sub>>10 GeV
  - $P_{T3/4} > 7/5 \text{ GeV} (e/\mu)$
  - Isolations, kinematic selections
  - 105<M(4l)<140 GeV
- Nice agreement with the SM and previous measurements at 7 and 8 TeV

$\sigma_{\rm fid.}$	$= 2.48^{+1.46}_{-1.13}$ (stat.)	$^{+0.28}_{-0.18}( m sys.)^{+0}_{-0}$	).01 ).04(model d	ep.) fb
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Channel	4e	$4\mu$	2e2µ	$4\ell$
$q\bar{q} \rightarrow ZZ$	$0.33\pm0.03$	$0.75\pm0.05$	$0.92\pm0.07$	$2.00\pm0.14$
$gg \rightarrow ZZ$	$0.04\pm0.01$	$0.08\pm0.01$	$0.07\pm0.01$	$0.18\substack{+0.03\\-0.02}$
Z+X	$0.17\substack{+0.15\\-0.09}$	$0.19\pm0.08$	$0.26\pm0.10$	$0.62_{-0.16}^{+0.20}$
Sum of backgrounds	$0.54^{+0.16}_{-0.10}$	$1.02\pm0.09$	$1.25\pm0.13$	$2.80^{+0.25}_{-0.22}$
Signal ( $m_{\rm H} = 125 \text{ GeV}$ )	$0.91^{+0.11}_{-0.10}$	$1.70\pm0.15$	$2.21\pm0.22$	$4.82^{+0.44}_{-0.45}$
Total expected	$1.45^{+0.21}_{-0.16}$	$2.72\pm0.20$	$3.45\pm0.29$	$7.62^{+0.58}_{-0.56}$
Observed	1	3	4	8



 $2.39 \pm 0.25$  fb.



# Search for Heavy H→ZZ→4l

- Same analysis, but taking advantage of higher center or mass energy to look into the high mass domain
  - Signal and background treated in a consistent fashion, including interferences and the H(125 GeV) tail
  - MCFM+JHUGen+HNNLO within MELA framework
- Observed limits compatible with the expectation for null hypothesis





### CMS CMS

# Search for Heavy $H \rightarrow ZZ \rightarrow 2I2v$

- Another new 13 TeV analysis
- Leptons can be electrons or muons
  - P<sub>T1/2</sub>>25 GeV
  - $P_T(II)>55 \text{ GeV}$
  - |M(II)-M(Z)|<30 GeV
  - MET>125 GeV
  - b-veto to suppress tt-bar
- Exclusive categories for ee and  $\mu\mu$  channels:
  - 0 jet, 1+ jets, and VBF
- Data consistent with the expectation
  - Limits require explicit assumptions on the width of the new boson



# Search for Heavy $H \rightarrow ZZ \rightarrow 2I2v$

- Generic limits in the plane of  $\Gamma$ /  $\Gamma_{\rm SM}$  vs m<sub>H</sub>
  - For mH>1 TeV, take  $\Gamma_{\rm SM}$ =m<sub>H</sub>
  - Separate for gg and VBF



- Combination in assumption that gg/VBF follows the SM ratio
- Same results interpreted in the context of 2HDM
  - See CMS-PAS-HIG-16-001 for details



# Search for Heavy Higgs $A \rightarrow Z\gamma$

- Selections:
  - Two leptons (e or  $\mu$ ) with P<sub>T1/2</sub>>10/20 GeV
  - Photon with
     P<sub>T</sub>>40 GeV



- M(II)>50 GeV, M(IIg)>150 GeV
- Data and SM expectation statistically compatible
  - 95% C.L. upper limit set assuming narrow width signal
    - In generator set width  $\Gamma_A$  to 1% of the m(A)



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# Higgs in Di-Photons at 13 TeV

- 13 TeV data update of the diphoton analysis:
  - The Higgs signal is still there
  - 1.7 $\sigma$  signal significance (2.7 $\sigma$  expected)







# Lightish Higgs in Di-Photon Channel

- A spin-off of the 8 TeV SM Higgs search targets 80-110 GeV range
  - E.g. in NMSSM, if h<sub>2</sub>
     is the 125 GeV Higgs,
     we are searching
     here for h<sub>1</sub>
- Selections:
  - $p_{T1(2)}/m_{\gamma\gamma}>28(20)/80$
  - Enhanced electron
     veto to suppress
     Z→ee



# Lightish Higgs in Di-Photon Channel

- Data in statistical agreement with the background only hypothesis
- 95% C.L. upper limits on the production rate
  - Combine all 4 categories
  - Limits range from50 to 150 fb





# Searches for Light Higgses

- Several 8 TeV analyses targeting NMSSM-like scenarios
  - e.g. h<sub>1/2</sub>->a<sub>1</sub>a<sub>1</sub> where a<sub>1</sub> is a light CP-odd Higgs boson
- Final states targeting different m(a<sub>1</sub>) ranges:
   (2b)(2μ): 2m(b)<m(a)</li>
  - $-(2\tau)(2\tau): 2m(\tau) < m(a) < 2m(b)$
  - $-(2\mu)(2\mu): 2m(\mu) < m(a) < 2m(\tau)$

# Search for H(125)→aa→µµbb

- Selections:
  - Muons w/ P<sub>T1/2</sub>>24/9 GeV
  - Two b-tagged jets w/ P<sub>T</sub>>15
     GeV
    - "Medium" b-tag working point
  - |m(μμbb)-125|<25 GeV
- Target range of m(a):
  - 25-65 GeV
- Backgrounds dominated by Z+jets
  - Generally a good agreement with simulation predictions in control regions





# Search for H(125)→aa→µµbb

- No statistically significant excess
- Signal search & limit setting based on fitting for a smooth shape plus a bump
  - No input from simulation for backgrounds
- Limits on the production rate and on B(h→aa→µµbb)







# Search for H(125)→aa→μμττ

- Assume two muons come directly from the decay of a
  - Hit in BR, but signal becomes a narrow bump
- Final states considered:  $\mu\mu\tau_{e}\tau_{h}$ ,  $\mu\mu\tau_{\mu}\tau_{e}$ ,  $\mu\mu\tau_{e}\tau_{e}$
- Selections:
  - Two muons w/ P<sub>T1/2</sub>>18/9 GeV to trigger
  - Additional objects thresholds of 5( $\tau_{\mu}$ ), 7( $\tau_{e}$ ), 15( $\tau_{h}$ ) GeV
  - |m(μμττ)-125 GeV|< 25 GeV
  - |m(μμ)-m(ττ)|<0.8 m (μμ)







# Search for H(125)→aa→μμττ

	Sig	nal		Obs.		
	$m_a = 20 \mathrm{GeV}$	$m_a = 60 \mathrm{GeV}$	ZZ	Reducible	Total	
μμτ <sub>e</sub> τ <sub>e</sub>	$0.20 \pm 0.02$	$0.58 \pm 0.06$	$4.64 \pm 0.39$	$2.49 \pm 1.03$	7.13±1.10	8
μμτ <sub>e</sub> τ <sub>μ</sub>	$0.58 \pm 0.08$	$1.42 \pm 0.16$	$0.10 \pm 0.01$	$1.70 \pm 0.74$	$1.80 \pm 0.74$	2
μμτετh	$0.74 \pm 0.08$	$2.02 \pm 0.20$	$0.16 \pm 0.02$	$5.65 \pm 1.77$	$5.81 \pm 1.77$	5
$\mu\mu\tau_{\mu}\tau_{h}$	0.96±0.10	$2.30 \pm 0.22$	$0.13 \pm 0.02$	0.99±0.31	$1.12 \pm 0.31$	1
$\mu\mu\eta_h\eta_h$	$0.60 \pm 0.06$	$1.90 \pm 0.18$	$0.06 \pm 0.01$	$4.64 \pm 0.98$	$4.70 \pm 0.98$	3
Combined	$3.08 \pm 0.31$	$8.22 \pm 0.82$	5.09±0.39	$15.47 \pm 2.41$	$20.56 \pm 2.44$	19

- Data compatible with background only hypothesis
  - No excess exceeds 2σ global significance
- Set 95% C.L. upper limits on signal event rate
- Also limits in the context of 2 HDM+S models





# Search for H(125)→aa→ττττ

- Target m(a) range between  $2m_{\tau}$  and  $2m_{b}$
- Mass resolution is not great, but large BR





- Selections:
  - Require a muon in each boosted object, the two muons should have the same charge to reduce backgrounds
  - Muon thresholds  $p_{T1/2}$ >17/10 GeV
  - Exactly one extra track with  $p_T>2.5$  GeV near muon and no other tracks w/  $P_T>1$  GeV
- Background shape modeled using QCD enriched samples – good agreement





# Search for H(125)→aa→ττττ

 Data compatible with background only expectation at the level of statistics

			Expected signal for $(\sigma B)_{sig} = 5 \text{ pb}, m_{\phi_1} \text{ [GeV]} =$				
Bin	Data	Bkg.	4	5	6	7	8
(1,1)	124	$116 \pm 7$	$9.7 \pm 1.5$	$1.9 \pm 0.5$	< 0.1	$0.1 \pm 0.1$	< 0.1
(1,2)	231	$247 \pm 10$	$21.6 \pm 2.9$	$6.8 \pm 1.1$	$1.9 \pm 0.5$	$0.3 \pm 0.2$	$0.1 \pm 0.1$
(1,3)	91	$98 \pm 6$	$3.8 \pm 0.8$	$4.9 \pm 0.9$	$2.4 \pm 0.6$	$0.9 \pm 0.3$	$0.2 \pm 0.2$
(1,4)	64	$60 \pm 5$	$0.1 \pm 0.1$	$1.5 \pm 0.4$	$1.8 \pm 0.5$	$0.8 \pm 0.3$	$0.5 \pm 0.2$
(2,2)	137	$142 \pm 8$	$14.2 \pm 2.0$	$8.2 \pm 1.3$	$2.8 \pm 0.6$	$1.5 \pm 0.4$	$0.8 \pm 0.3$
(2,3)	112	$104 \pm 6$	$3.7 \pm 0.7$	$10.4 \pm 1.6$	$9.2 \pm 1.4$	$4.4 \pm 0.8$	$2.3 \pm 0.6$
(2,4)	61	$59 \pm 5$	< 0.1	$2.6 \pm 0.6$	$5.6 \pm 1.0$	$8.1 \pm 1.3$	4.0±0.8
(3,3)	16	$19 \pm 2$	< 0.1	$4.8 \pm 0.9$	$4.8 \pm 0.9$	$3.7 \pm 0.7$	$2.2 \pm 0.5$
(3,4)	29	$23 \pm 3$	< 0.1	$1.9 \pm 0.5$	$8.0 \pm 0.9$	11.1 ± 1.5	$9.4 \pm 1.4$
(4,4)	8	7±1	< 0.1	< 0.1	$3.1 \pm 0.6$	9.1 ± 1.4	$11.2\pm1.7$

- Interpretation from the fit for signal+background shapes to the data in selected bins
  - 95% C.L. upper limit set on the production rate of signal events
  - Rates in excess of a few pb are excluded



# Search for H→aa→μμμμ

- Selections:
  - P<sub>T1</sub>>17 GeV, P<sub>T2/3/4</sub>>8 GeV
  - 2 pairs of close-by muons
  - No requirement on  $4\mu$  mass
    - E.g. in NMSSM, it can be "the other" CP-even Higgs that has strong coupling to a<sub>1</sub> if a<sub>1</sub> has large singlet component
- Search for the excess on the diagonal of m<sub>1</sub> vs m<sub>2</sub>
  - Model independent results, also benchmark using NMSSM
  - Assume SM-like production x-sections for  $h_{1/2}$  to simplify interpretation



# Higgs Decay to Dark Photons

- Spin the same  $4\mu$  analysis as  $H \rightarrow \gamma_D \gamma_D + X$ 
  - H could be the 125 GeV Higgs or could be something else
- Dark photons could have an appreciable lifetime before decay
  - Depends on the strength of the mixing with the SM sector (SM photon)
- Benchmark using  $h(125) \rightarrow n_1 n_1 \rightarrow (\gamma_D n_D)$  $(\gamma_D n_D)$ 
  - Limits in  $\epsilon_{mix}$  versus m( $\gamma_{\text{D}}$ ) for a range of values for BR of SM-like Higgs to these states
    - Implies model dependence when comparing to low energy results
  - Nice complementarity with ATLAS analysis searching for decays far from the interaction point





## Summary

- SM(-like?) Higgs boson studies start moving towards the era of precision measurements
  - Kinematics, properties, production cross-sections
  - Only a small 13 TeV dataset, but things look consistent with what we saw at 7 and 8 TeV
- Searches for new physics in Higgs sector
  - NMSSM, 2HDMs, heavy and light
  - Becoming more systematic, combinations are in works
- Expect more exciting news over this year
  - 13 TeV data has just started coming in 2015, expect ~30 fb<sup>-1</sup> by the end of 2016
  - Troops are standing by as evidenced by many Higgs results this winter