## Beyond the Standard Model Higgs Physics using the ATLAS Experiment





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#### on behalf of the ATLAS Collaboration

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# A Higgs! But The Higgs?



ATLAS-CONF-2013-034

- 2012 discovery updated in spring 2013:
  - a Higgs Boson has been observed with mass 125 GeV
- Property measurements ongoing to determine if it is the SM Higgs Boson
  - presently seems pretty SM-like (see eg. <u>A. Mehta</u>, Plenary Higgs 1, and parallel seesion talks)
- Complementary searches for extended Higgs sectors in BSM physics

discover or constrain new BSM physics scenarios
 BSM Higgs Physics using the ATLAS Detector 16/05/13 Matthew Beckingham (Uni Washington)

## Two Higgs Doublet Models

- Extends SM Higgs sector to include two complex Higgs doublets,  $\rm H_{1}$  and  $\rm H_{2}$ 
  - one particular example: MSSM Higgs sector
- Leads to five physical Higgs states: H<sup>+</sup>, H<sup>-</sup>, A(CP-odd), H, h (CP-even)
  - accommodate observed Higgs boson naturally as h=125 GeV
- Additional 2HDM parameters: ratio of doublet vevs tanß, CP-even Higgs mixing angle  $\alpha$  and  $m_{_{\!H}}$
- Two types considered here:
  - Type-I: all fermions couple to  $H_2$
  - Type-II: up-type fermions couple to  $H_2$ , down-type to  $H_1$



# 2HDM: $H \rightarrow WW$



- First dedicated 2HDM search at the LHC
- Search for higher mass CP-even H assuming 125 GeV Higgs is lightest CP-even h of 2HDM
- Preselection based on SM WW analysis: e+µ, high MET
- Split into 0-jet and 2-jet channels
- Final discriminant: neural networks trained separately for each channel at m<sub>H</sub>=150, 180 and 240 GeV BSM Higgs Physics using the ATLAS Detector 16/05/13 Matthew Beckingham (Uni Washington)



# 2HDM: $H \rightarrow WW$

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- No significant excess
- Exclusion limits set separately for Type-I and Type-II 2HDM in cos(α)-m<sub>H</sub> plane at tanβ=1,3,6,20(50)
- Large part of cos(α)-m<sub>H</sub> excluded for Type-I 2HDM in mass range 130<m<sub>H</sub><250 GeV</li>

# **MSSM Higgs Sector**

- MSSM Higgs sector is a constrained Type-II 2HDM at tree level
- Tree level MSSM Higgs sector determined by  $m_{\!_{A}}$  and  $tan\beta$
- Consistent with SM-like h=125 GeV
- Couplings to b-quarks and τ-leptons enhanced for large tanβ
- Neutral Higgs searches focusing on b-associated and gg-fusion production with TT or µµ decays
- Charged Higgs searches focusing on low mass: production in top decays and decay to TV or cs



6 **W** 

# MSSM H→tt/µµ

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- Categorise by final state  $(T_e T_\mu, T_{lep} T_{had}, T_{had} T_{had}, \mu\mu)$ and b-tag/veto
- TT channels: data driven
   T-embedded Z→µµ for
   Z→TT background,
   multijet from same-sign data
- Di-tau invariant mass reconstructed using likelihood based method (Missing Mass Calculator)
- µµ channel: parametrised background fitted to data outside of individual signal mass windows

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# MSSM $H \rightarrow \tau \tau / \mu \mu$



- No significant excess seen above backgrounds
- Set limits on MSSM (m<sub>h</sub><sup>max</sup> scenario) in m<sub>A</sub>-tanβ plane and cross section x branching ratio
- Significant proportion of unexcluded phase space still compatible with interpreting 125 GeV Higgs as one of CP-even MSSM Higgs Bosons

# MSSM H<sup>+</sup>→TV



- Search for H<sup>+</sup> through lepton universality violation in tt events
  - Lepton universality: W decays equally to  $e/\mu/\tau$
  - Light H<sup>+</sup> decays mainly to τ: violation of lepton universality
- Hence consider ratio of lepton+ $T_{had}$  to dilepton final states in tt events •
  - allows for cancelation of major systematics
- Orthogonal direct T+jets search: tau and W decay hadronically •

- ≥4 jets (1 b-jet) + tau, high MET cut + m<sub>iib</sub> mass window BSM Higgs Physics using the ATLAS Detector 16/05/13 Matthew Beckingham (Uni Washington)

### MSSM H⁺→TV



- No significant excess seen above backgrounds
- Combine limits from ratio method and tau+jets using  $R_{e+\mu}$  and  $m_{\tau}(\tau,MET)$  as discriminants, respectively
- Upper limit (95% CL) on B(t $\rightarrow$ bH<sup>+</sup>): 0.8%-3.4% for 90<m<sub>H+</sub><160 GeV
- Large H<sup>+</sup> phase space ruled out by direct search



120

100

140

Dijet mass [GeV]

160



80

Events / 6 GeV

2500

2000

1500

1000

500

**4**0

60

#### Significant H<sup>+</sup>→cs BR at low tanβ in MSSM

- Search in semi-leptonic tt channel
  - 1 e/µ and ≥4 jets (2 b-jet)
  - high MET and  $m_{\tau}(I, MET)$
- Fully reconstruct tī system using kinematic fitter
- Dijet invariant mass used as discriminating variable
  - no significant excess seen
- Upper limit (95% CL) on B(t→bH<sup>+</sup>): 5%-1% for 90<m<sub>H+</sub><150 GeV assuming B(H<sup>+</sup>→cs) = 100%

#### arXiv:1302.3694

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# **Invisible Higgs Decays**



#### ATLAS-CONF-2013-011

- ZH→II+invisible: direct search for BSM enhancement of invisible decays
- Select opposite sign lepton pairs with Z mass constraint, balanced by high MET

**ATLAS** Preliminary

0.2

 $\sqrt{s} = 7 \text{ TeV}, \int \text{Ldt} = 4.6-4.8 \text{ fb}^{-1}$ 

 $\sqrt{s} = 8 \text{ TeV}, \int Ldt = 13-20.7 \text{ fb}^{-1}$ 

 $[\kappa_{\gamma}, \kappa_{q}, B_{i}]$ 

SM expected

- Observed

 No significant excess: set limit assuming SM ZH production BR<sub>inv,undet</sub> < 0.65 (95% CL)</li>

2 In A(B<sub>i,u</sub>)

- Complementary measurement using combined Higgs coupling
- Assume all couplings are SM-like ( $\kappa_i$ =1)
- Modify total width  $BR_{inv,undet} = 1 \frac{\kappa_H^-}{\Gamma_H / \Gamma_H^{SM}}$ and profile  $\kappa_g$  and  $\kappa_\gamma$
- BR<sub>inv,undet</sub> < 0.6 (95% CL)

0.4

0.5

ATLAS-CONF-2013-034

0.6

0.7

B<sub>i.u</sub>

0.3

# Summary

- A Higgs Boson has been observed at the LHC with mass m=125 GeV and properties currently consistent with SM
- Still needs to be determined if this is the only Higgs Boson which is responsible for EWSB
- Many direct searches for extended BSM Higgs sector by ATLAS
  - including some not shown here
- However, no evidence found for extended Higgs sector in ATLAS searches
- Further analyses for full LHC run 1 datasets still progressing:
  - keep 'em peeled for updates!

For more details and other results see <u>ATLAS Higgs Public Results</u> page



#### Backup



## **Backup: References**

- Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb-1 of proton-proton collision data (<u>ATLAS-CONF-2013-034</u>)
- Search for Higgs bosons in Two-Higgs-Doublet models in the H  $\rightarrow$  WW  $\rightarrow$  evµv channel with the ATLAS detector (<u>ATLAS-CONF-2013-027</u>)
- Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector (JHEP02(2013)095)
- Search for charged Higgs bosons through the violation of lepton universality in ttbar events using pp collision data at sqrt(s) = 7 TeV with the ATLAS experiment (JHEP03(2013)076)
- Search for a Light Charged Higgs Boson in the decay channel H+→cs<sup>-</sup> using 4.7 fb-1 of pp collisions at √s=7~TeV with the ATLAS detector (arXiv:1302.3694)
- Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS (<u>ATLAS-CONF-2013-011</u>)



### The ATLAS Detector



- Muon spectrometer |η|<2.4 (air core toroids + muon chambers)
- Hadronic Calorimeter |η|<5 (Fe+scintillator tiles or LAr+W/Cu)

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- EM calorimeter |η|<3.2 (Pb/LAr accordion)
- Inner detector |η|<2.5
   <ul>
   (2 Tesla solenoid, Si pixels, Si strips + TRT)
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# Backup: 2HDM H→WW

- Selection
  - Exactly two leptons of different flavour and charge, p<sub>T,1</sub>>25 GeV, p<sub>T,2</sub>>15 GeV

$$-$$
 m<sub>II</sub>>10 GeV, MET<sub>rel</sub>>25 GeV

• 0-jet:

 $- \Delta \phi_{\parallel} < 2.4, m_{\parallel} < 75 \text{ GeV}$ 

• 2-jet:

η<sub>j1</sub>xη<sub>j2</sub><0, m<sub>II</sub><80 GeV,</li>
 m<sub>T</sub>(II,MET)<180 GeV</li>



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# Backup: 2HDM H→WW

#### 0 Jet NN @ 180 GeV

$ \eta(\ell_1) $ $m_{\rm T}$ $m(\ell_1\ell_2)$	Variables used in the 0-jet channel and the 2-jet channelThe absolute value of the pseudorapidity of the leading lepton.The transverse mass of the lepton- $E_{\rm T}^{\rm miss}$ system, as defined in Equation 2.The invariant mass of the dilepton system.	ent fraction / 0.07	0.3	ATLAS Preliminary H→WW→evµν + 0 jets NN @180GeV	$\sqrt{S} = 8 \text{ TeV}$ 2HDM $m_{H}$ =180 GeV 2HDM $m_{h}$ =125 GeV Total background
$p_{\mathrm{T}}(\ell_1 \ell_2)$	The transverse momentum of the dilepton system.	Щ	0.1-		╼╤╾╴│╴╴┤
$E_{\mathrm{T,rel}}^{\mathrm{miss}}$	The projection of the calorimeter-based missing transverse momentum.		Ę		
$ \Delta Y(\ell_1 \ell_2) $	The absolute value of the rapidity differences of the two charged leptons.		٥f		
	Variables used in the 2-jet channel only		U	0.2 0.4	NN output
$p_{\mathrm{T}}(\ell_2)$	The transverse momentum of the second-leading lepton.			2 Jet NN	@ 180 GeV
$p_{\mathrm{T}}(j_1)$	The transverse momentum of the leading jet.		_		
$m(j_1)$	The mass of the leading jet.	.07	F	ATLAS Preliminary	√s = 8 TeV
$\cos\theta(\ell_1,\ell_2)$	The cosine of the angle between the two charged leptons.	0 /	0.4	$H \rightarrow WW \rightarrow ev\mu v + 2 jets$	2HDM <i>m</i> <sub>H</sub> =180 GeV
$m(j_1j_2)$	The invariant mass of the dijet system.	u	ŧ		- 2HDM m <sub>h</sub> =125 GeV
$p_{\mathrm{T}}^{\mathrm{tot}}$	The total transverse momentum, defined as the magnitude of the vector sum of the tra	ctio	0.3	-	
	momenta of the two jets, the two leptons and the missing transverse momentum:	fra	E E		1
	$p_{\rm T}^{\rm tot} =  \mathbf{p}_{\rm T}^{\rm tot}  =  \mathbf{p}_{\rm T}^{\ell 1} + \mathbf{p}_{\rm T}^{\ell 2} + \mathbf{p}_{\rm T}^{j 1} + \mathbf{p}_{\rm T}^{j 2} + \mathbf{p}_{\rm T}^{\rm miss} .$	ant	0.2	- 5	
		Eve	0.1		



0.4

0.2

0.6

0.8

NN output

W

# Backup: High Mass $H \rightarrow ZZ$



- H→ZZ(\*)→4I search reaches up to m=1 TeV
- 4e, 2e2µ, 2µ2e and 4µ channels
- VBF (Δη<sub>jj</sub>>3, m<sub>jj</sub>>350 GeV),
   VH (additional light lepton), and ggH exclusive channels
- Consider m<sub>H</sub>>200 GeV
- Assume SM-like width for high masses using Complex Pole Scheme

# Backup: MMC

- 6-8 unknowns when reconstructing mass of di-tau invariant mass spectrum, depending on tau decays (depending on number of neutrinos in final state)
- Four constraints: METx, METy, M<sub>tau1</sub>, M<sub>tau2</sub>
- Scan parameter space, calculate di-tau invariant mass at each point and weight by tau decay likelihood distribution
- Most probable value of mass used as estimator for di-tau mass



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A.Elagin, P.Murat, A.Pranko, A.Safonov NIM. A654 (2011) 481

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#### Backup: MSSM H→TT/µµ



# Backup: MSSM H→ττ/µµ

	$ au  o e\mu$	тт $\rightarrow$ eтh / µтh	au  o  au thth
Pre-selection	OS e and $\mu$ m(e, $\mu$ ) > 30 GeV $\Delta \phi(e,\mu) > 2.0$ MET+pT(e)+pT( $\mu$ ) < 125 GeV $\Sigma cos \Delta \phi(I,MET) > -0.2$	OS I and th -No additional leptons -mT(I,MET) < 30 GeV	Two OS th No light leptons MET > 25 GeV
b-tagged	Exactly 1 b-jet ΣpT(jets) < 100 GeV	Leading jet b-tagged pT(b-jet) < 50 GeV	Leading jet b-tagged pT(b-jet) < 50 GeV
b-veto	0 b-tagged jets ΣpT(jets) < 150 GeV	Lead jet fails b-tag MET > 20 GeV	Lead jet fails b-tag Lead th pT > 60 GeV
		$ \begin{array}{c}                                     $	Observed CLs $\pm 1\sigma$ $\pm 2\sigma$ LEP 0 400 450 500
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# Backup: H<sup>+</sup> Ratio Method

- Selection
  - Single electron/muon trigger
  - One trigger matched lepton (p<sub>T</sub>>25 GeV)
  - One additional e/μ/τ (p<sub>T</sub>>25 GeV)
     with no additional lepton
  - At least 2 jets (p<sub>T</sub> > 25 GeV) with at least 2 b-tags
  - MET > 40 GeV
- Event yield ratios

$$R_e = rac{\mathcal{N}(e+ au_{ ext{had}})}{\mathcal{N}(e+\mu)} \quad ext{and} \quad R_\mu = rac{\mathcal{N}(\mu+ au_{ ext{had}})}{\mathcal{N}(\mu+e)}.$$





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# Backup: $H^+ \rightarrow cs$

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- Selection
  - One trigger matched e(μ),
     p<sub>T</sub>>25(20) GeV
  - At least four jets p<sub>T</sub>>25 GeV with at least two b-tags
  - MET>20(30) GeV e(µ) channel
  - $m_{T}$ >30 GeV (e channel)
  - (MET+m<sub>T</sub>)>60 GeV (µ channel)
- Kinematic fit to jjbbl final state

$$egin{aligned} \chi^2 &= \sum_{i=\ell,4 ext{jets}} rac{(p_{ ext{T}}^{i, ext{fit}} - p_{ ext{T}}^{i, ext{meas}})^2}{\sigma_i^2} \ &+ \sum_{j=x,y} rac{(p_j^{ ext{SEJ,fit}} - p_j^{ ext{SEJ,meas}})^2}{\sigma_{ ext{SEJ}}^2} \ &+ \sum_{k=jjb,b\ell
u} rac{(m_k - m_{ ext{t}})^2}{\Gamma_t^2} \ . \end{aligned}$$



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# Backup: Invisible Higgs

- ZH→II+invisible: direct search for BSM enhancement of invisible decays
- Selection:
  - oppositely charged e/µ pair with 76<m<sub>µ</sub><106 GeV</li>
  - jet veto
  - MET>90 GeV
  - Δφ(MET, p<sub>T</sub>miss)<0.2, Δφ(Ζ, MET)>2.6<sup>ξ</sup>

- 
$$\Delta \phi_{\parallel} < 1.7$$
, |MET- $p_{T,\parallel}$ |/ $p_{T,\parallel} < 0.2$ 







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