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

Marco Vanadia on behalf of the ATLAS Collaboration

Sapienza University of Rome & INFN

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INFN Istituto Nazionale di Fisica Nucleare

SAPIENZA UNIVERSITÀ DI ROMA

ATLAS

The story so far

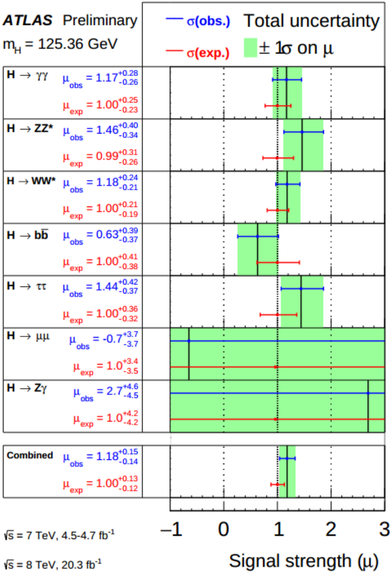
- 2012 discovery by ATLAS & CMS of a new resonance, with properties compatible with that of SM Higgs
- No surprises so far for CP properties and couplings; uncertainties on $\sigma \times BR \approx$20-30%

Run-2

- $\sqrt{s}$: 8 TeV $\rightarrow$ 13 TeV !!!
- $O(10)$ fb^{-1} in 2015

BR($h \rightarrow$non-SM)$_{LHC}$ $\lesssim$30% : lots of space for BSM physics in the Higgs sector!

ATLAS-CONF-2015-007



What are we looking for?

- 2 Higgs Doublets Models (2HDMs): 7 parameters, 4 types depending on structure of the couplings
  - Prediction: 5 particles, CP-even h and H, CP-odd A, $H^{\pm}$
- SUSY: possible solution for hierarchy problem and Dark Matter
  - Prediction of the minimal model (MSSM): Type-2 2HDM-like Higgs sector, 2 free parametrs (e.g. M_A, $tan\beta$) for a given benchmark
- Single additional EW singlet: mixing between Higgs doublet and EW singlet, possible solution for Dark Matter
  - Prediction: 2 CP-even particles h, H
- Higgs portal towards Dark Matter/hidden sectors: Higgs interacting with WIMPs or non-SM sectors
  - Prediction: invisible decays for Higgs, long lived particles...
- Composite Higgs: e.g. MCHMs, naturalness restored by a compositeness scale f
  - Prediction: Higgs couplings $\neq$ SM
- Higgs triplets, next-to-minimal extensions, ...

And how?

SM h constraints	Model-independent	Specific models	Exotic signatures
BSM interpretation of h couplings	SM-like searches $H \to \gamma\gamma$, $H \to VV$, ...	Search for new particles A, $H^{\pm}$, ...	$H \to INV$, LFV, long-lived particles...

ATLAS Run-1: 2 Higgs Doublets Models searches

Charged Higgs

- $H^{\pm} \to W^{\pm}Z$: arXiv:1503.04233
- $H^{\pm} \to \tau^{\pm}\nu$: JHEP03 (2015) 088, JHEP06(2012)039
- $H^{\pm} \to \tau^{\pm}\nu$ in $t\bar{t}$ through lepton universality violation: JHEP03(2013)076
- $H^{\pm} \to c\bar{s}$: EPJC, 73 (2013) 2465

Neutral Higgs

- $A \to Zh$: PLB 744 (2015) 163-183
- $h/A/H \to \tau\tau$: JHEP11(2014)056
- $H \to hh \to \gamma\gamma b\bar{b}$: PRL 114, 081802
- $H \to hh \to b\bar{b}b\bar{b}$: ATLAS-CONF-2014-005, superseeded by ATLAS-EXOT-2014-11
- $H \to ZZ$: PLB 707 (2012)
- $X \to \gamma\gamma$: PRL 113, 171801 (2014)

2HDM cascade

- $H^0 \to W^{\mp}H^{\pm} \to W^{\mp}W^{\pm}h^0 \to W^{\mp}W^{\pm}b\bar{b}$: PRD 89, 032002 (2014)

ATLAS Run-1: other BSM Higgs searches

NMSSM

- $aa \to \mu\mu\tau\tau$: ATLAS-HIGG-2014-02

Higgs $\to$ invisible

- $VH \to hadronic + INV$: arXiv:1504.04324
- VBF h with $h \to$ $invisible$ ATLAS-CONF-2015-004
- Mono-jet arXiv:1502.01518
- $ZH \to \ell\bar{\ell} + INV$: PRL 112, 201802 (2014)

Exotic Higgs

- Exotic h decays with at least 1 γ, E_T^{miss} and 2 forward jets ATLAS-CONF-2015-001
- $H(narrow\ scalar) \to t\bar{t}$: ATLAS-CONF-2015-009
- $H \to ZZ_{dark}$, $H \to Z_{dark}Z_{dark}$: ATLAS-CONF-2015-003
- Pair produced double-charged $H^{\pm\pm}$: CERN-PH-EP-2014-158
- $h \to$ *long lived particles*: ATLAS-CONF-2014-041, JHEP11(2014)088
- Wh with $h \to$ *hidden sector*: New J. Phys. 15 (2013) 043009
- Search for $W\gamma$ and $Z\gamma$ resonances: PLB 738, 428 (2014)
- ...

Indirect measurements

- $H \to J/\Psi\gamma$ and $H \to \Upsilon\gamma$: arXiv:1501.03276
- Constraints from h couplings: ATLAS-CONF-2014-010, ATLAS-CONF-2015-007

2 Higgs Doublets Models (2HDMs)

- 2 Higgs doublets, 5 particles: h and H CP-even, A CP-odd, $H^{\pm}$
- 7 free parameters (with minimum assumptions: no CP-violation in Higgs sector, no FCNC)
  - 4 masses
  - 1 soft symmetry breaking parameter
  - $\tan\beta = v_2/v_1$, fraction of the vacuum expectation values of the doublets
  - α, mixing angle between h and H. Often $\cos(\beta - \alpha)$ is used as parameter, which controls couplings (in particular of H to VV, if $\rightarrow$0 then 2HDM$\rightarrow$SM)

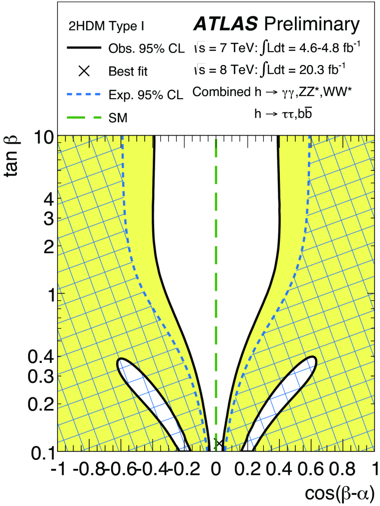
- Classified depending on the structure of the couplings in 4 types
  - Type-I (Fermiophobic in the zero mixing limit)
  - Type-II (MSSM-like)
  - Lepton-specific
  - Flipped

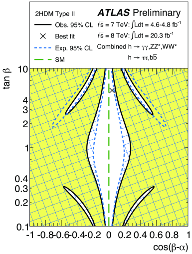
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

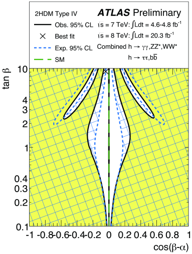
Branco et al, arXiv:1106.0034

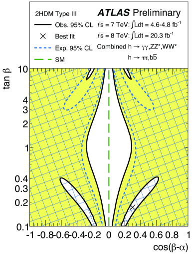
- Only one among the possible models, but an important benchmark for interpreting experimental results
- Type-II is an approximation for SUSY with a high mass scale

Indirect constraints on 2HDMs



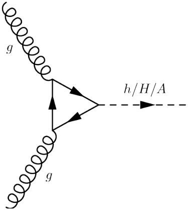






2HDM parameter space is significantly constrained by h^{SM} couplings measurements

Plots from ATLAS-CONF-2014-010



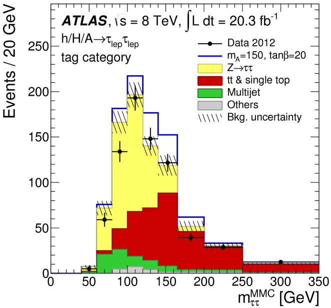
- Model-independent search for scalar resonances
- Key search for high-tan β MSSM
- Search channels:
  - $\tau\tau \to \ell\ell(+neutrinos)$, low mass
  - $\tau\tau \to \ell + hadrons(+neutrinos)$, low/high mass
  - $\tau\tau \to hadrons(+neutrinos)$, high mass

Neutrinos in the final state, thus complete kinematics reconstruction is not possible

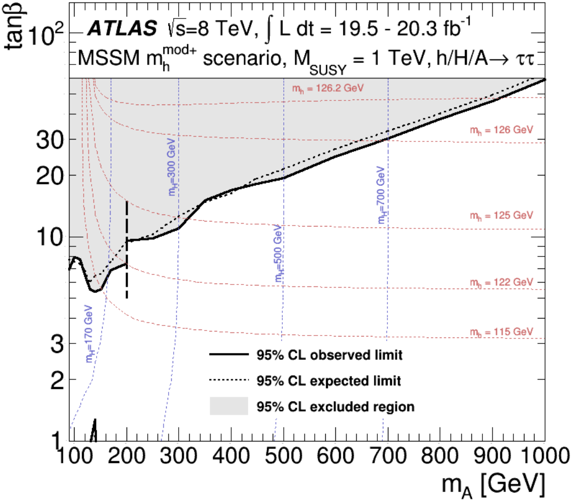
Missing Mass Calculator

Missing Mass Calculator used for the reconstruction (MMC, NIM A 654 (2011) 481–489):

- E_T^{miss} and 4-momenta of all visible objects are used
- $m_{\tau\tau}$ most probable value is calculated with a likelihood

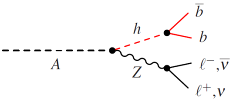


MMC mass in the $\ell\ell$ channel, b — *tagged* category



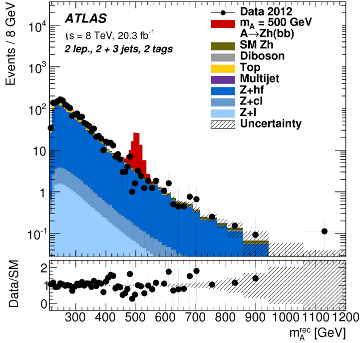
- High $\tan\beta$ 2HDMs significanlty constrained for $m_A \ll 1$ TeV
- High $\tan\beta$, $m_A \approx 1$ TeV region is a target for very early Run-2 measurements
- Low $\tan\beta$, $m_A \approx 300$ GeV region explored by other Run-1 searches

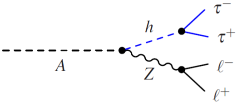
  $\rightarrow$ focus of the following slides



$A \to Zh \to (\ell\ell/\nu\nu)b\bar{b}$

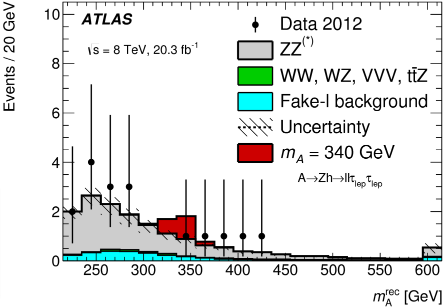
- $\ell\ell$: 2 b−jets selected, >2 vetoed, $105 < m_{bb} < 145$ GeV. $\sigma(m_A)/m_A \approx$ 2-3%
- $\nu\nu$: discriminant variable $m_A^{rec} = \sqrt{(E_T^{bb} + E_T^{miss})^2 + (\vec{p}_T^{bb} + \vec{E}_T^{miss})^2}$



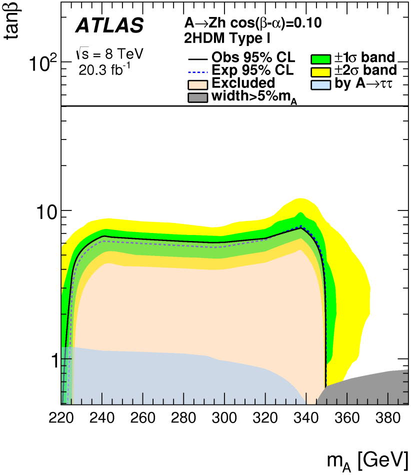


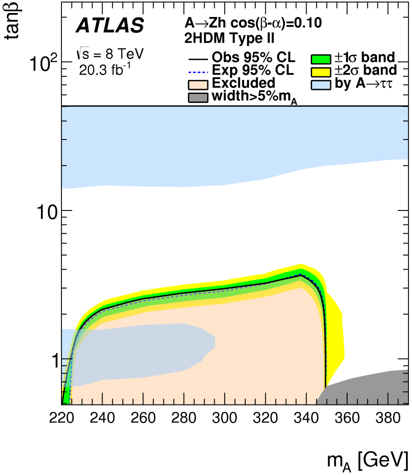
$A \to Zh \to \ell\ell\tau\tau$

- $\tau\tau$ decay reconstructed with MMC
- Constraints to $m_{\ell\ell}$ and $m_{\tau\tau}$: $m_A^{rec} = m_{\ell\ell\tau\tau} - m_{\ell\ell} - m_{\tau\tau} + m_Z + m_h$
- $\sigma(m_A)/m_A \approx$3-5%

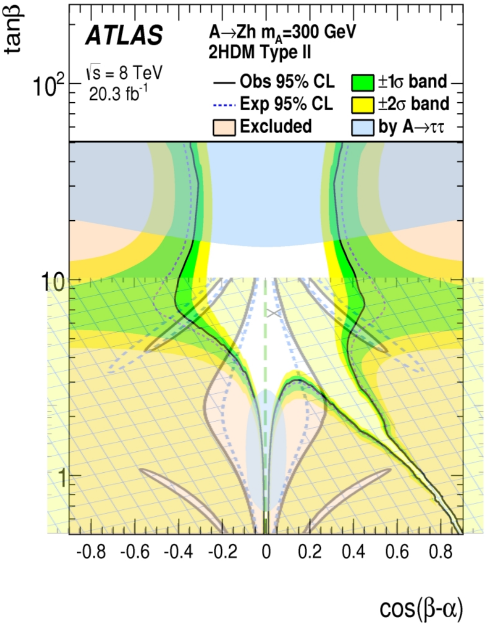


$A \to Zh$: PLB 744 (2015) 163-183





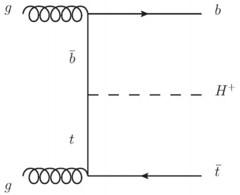
Sensitive up to tan $\beta \approx$5-7, complementary to $A \to \tau\tau$



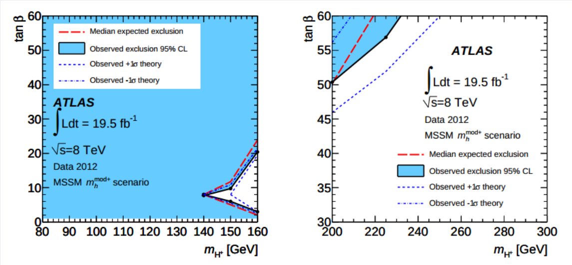
- Here shown a "quick-and-dirty" overlay of the exclusion plot in the $\tan\beta$ vs $\cos(\beta-\alpha)$ space of $A \to Zh$ and $A \to \tau\tau$ searches, assuming m_A =300 GeV, and the one obatined by indirect constraints produced measuring h couplings, for 2HDM Type II models

2HDMs with $m_A \approx 300$ GeV are significantly constrained

$H^{\pm}$ ATLAS searches

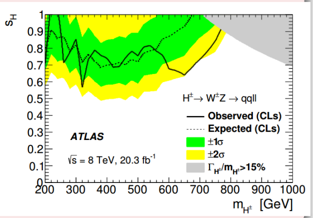


- *tb* decays dominating BR for high mass, but $\tau\nu$ decays have cleaner signature



ATLAS $H^+ \to \tau\nu + jets$ [JHEP03 (2015) 088]: most of the $m_{H\pm} \lesssim m_{top}$ region excluded

- Recently published search for VBF $H^{\pm} \to W^{\pm}Z$ [ATLAS-HIGG-2014-13]
- $H^{\pm} \to W^{\pm}Z$ appears at loop level in 2HDMs, but at tree level in Higgs Triplet Model
- Limits are set for 2HDM and for the Georgi-Machacek HTM
- Plot on the right is the limit for s_H, fraction of m_W^2 and m_Z^2 due to the triplet, in GMHTM



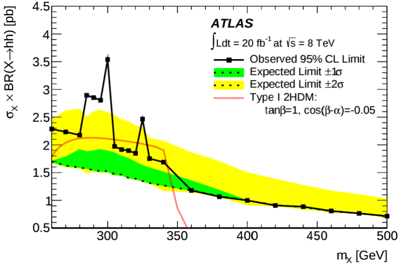
hh searches in Run-1

$H \to hh$ searches already sensitive to BSM models in Run-1, and important for preparation to long-term non-resonant *hh* measurements

- resonant: 2HDMs, hidden sectors, exotic models (e.g. gravitons), …
- non-resonant enhancement: compositeness, colored scalars, 4^{th} generation, …

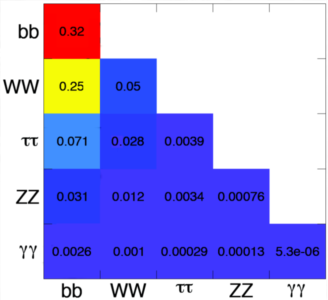
ATLAS publications

$hh \to bb\gamma\gamma$, $hh \to 4b$



plot from PRL 114, 081802

BR *hh* decay



$hh \to bb\gamma\gamma$ PRL 114, 081802

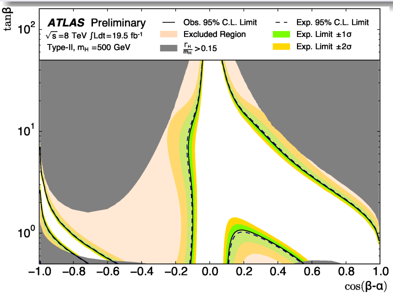
- Non-resonant: fit of continuum + SM h + BSM to $m_{\gamma\gamma}$
- Resonant: counting analysis cutting on $m_{\gamma\gamma}$ and $m_{bb\gamma\gamma}$
- Sensitive for $\tan\beta \approx 1$
- Observed (expected) for non-resonant production: 2.2 pb ($1.0^{+0.5}_{-0.2}$ pb)

$H \to hh$ searches already sensitive to BSM models in Run-1, and important for preparation to long-term non-resonant hh measurements

- resonant: 2HDMs, hidden sectors, exotic models (e.g. gravitons), ...
- non-resonant enhancement: compositeness, colored scalars, 4^{th} generation, ...

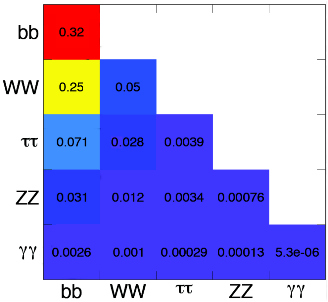
ATLAS publications

$hh \to bb\gamma\gamma$, $hh \to 4b$



plot from ATLAS-EXOT-2014-11

BR *hh* decay

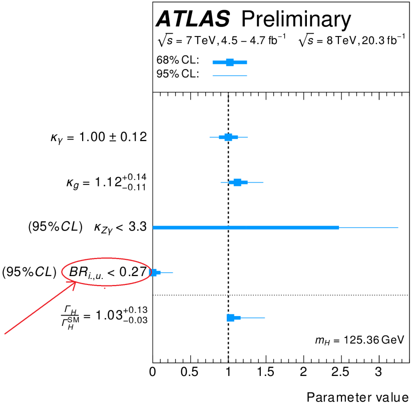


$hh \to 4b$ ATLAS-EXOT-2014-11

- $hh \to 4b$ new paper soon in arXiv (preliminary results were in ATLAS-CONF-2014-005)
- Analysis performed both with resolved jets and for "fat"-jets, for boosted topologies (i.e. high mass)
- Limits set for resonances, e.g. KK graviton or additional Higgs in 2HDM, non-resonant limits set too

- Many BSM models predict invisible h decays
  - SUSY
  - extra-dimensions
  - 4th generation ν
  - ...
- Indirect measurement constraint $BR(h \to invisible)$ to less than 30% (but with assumptions on other h couplings...)

ATLAS-CONF-2015-007

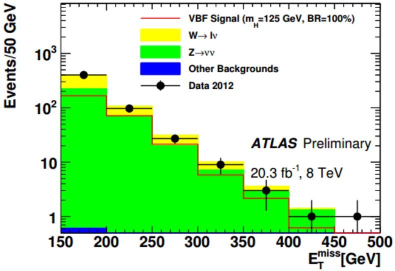


Direct measurements by ATLAS

- Vh with $V \to hadrons$, $h \to invisible$ (arXiv:1504.04324)
- VBF h with $h \to invisible$ ATLAS-CONF-2015-004
- Zh with $Z \to \ell\ell$, $h \to invisible$ PRL 112, 201802 (2014)
- Mono-jet general search, with $h \to invisible$ results arXiv:1502.01518

- 2 jets with $p_T^1 > 75$ GeV, $p_T^2 > 50$ GeV
- Veto for b/τ-tagging, veto for e/μ inside jets, veto for third jet
- $E_T^{miss} > 150$ GeV, $\Delta\eta_{jj} < 2.5$, $\Delta\eta_{jE_T^{\rm miss}} > 1$ to suppress QCD multi-jet
- Jets with big rapidity gap $\Delta\eta_{jj}$ >4.8, and $m_{jj} > 1$ TeV

- $Z \to \ell\ell$ and $W \to \ell\nu$ measured in data control samples
- Extrapolated to signal sample with correction factors evaluated with simulations
- Combined fit to event yields in signal and control samples



- Observed (expcted) BR limit **29% (35%)** $\to$ comparable with indirect limit
- New result for *VH* with $V \to$ *hadrons*: **78% (86%)** [arXiv:1504.04324]
- Result from *Zh* with $Z \to \ell\ell$, $h \to$ *invisible*: **75% (63%)** [PRL 112, 201802 (2014)]

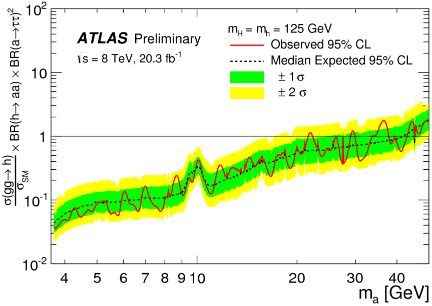
NMSSM $h \to aa$

Many BSM models introduce new scalar or pseudoscalar particles, e.g. NMSSM

- m_h =125 GeV creates a small hierarchy problem for MSSM
- This is solved in NMSSM with the introduction of light pseudoscalar Higgs particles a ($m_a < m_h$)

Scenarios for searches: either SM $h \to aa$ or additional H decaying in aa
Signatures strongly depending on m_a: decay channels are $ee/\mu\mu$, $\tau\tau$ if $m_a > 2m_\tau$, bb if $m_b > 2m_b$

New ATLAS results for $aa \to \mu\mu\tau\tau$ shown @ Moriond: Limit for h_{SM} decay to aa vs m_a

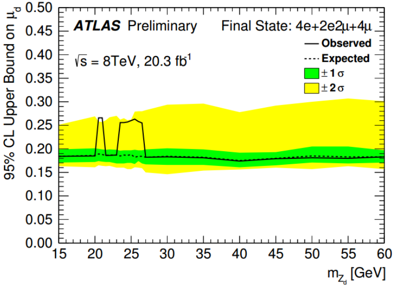


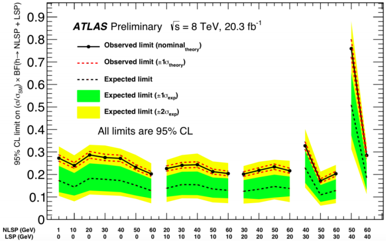
- Request of $a \to \mu\mu$ decay costs factor 100 due to BR (wrt $a \to \tau\tau$) but still beneficial due to cleanness and trigger
- Current lower limit by ALEPH, $m_H > 107$ GeV with $a \to 4\tau$ for BR($H \to aa$)=1
- @LEP: ZH production, coupling could be small in NMSSM, important to expolit gg fusion @ LHC
- Mass region explored complementary to CMS measurements $a \to \mu\mu$, $h \to 4\mu$, $a \to bb$

New results for "exotic" Higgs decays searches

$h \to ZZ_d \to 4\ell$ and $h \to Z_d Z_d$ 4ℓ ATLAS-CONF-2015-003

- Models with dark gauge symmetry mediated by vector boson Z_d
- ZZ_d : same selection as $h \to 4\ell$, search excess in $m_{\ell\ell}$
- $Z_d Z_d$: search in m_{Zd} for both pairs, 2 candidates found (both have local sign. $< 2\sigma$)





SUSY: h decays with ≥ 1 γ, E_T^{miss} and 2 forward jets ATLAS-CONF-2015-001

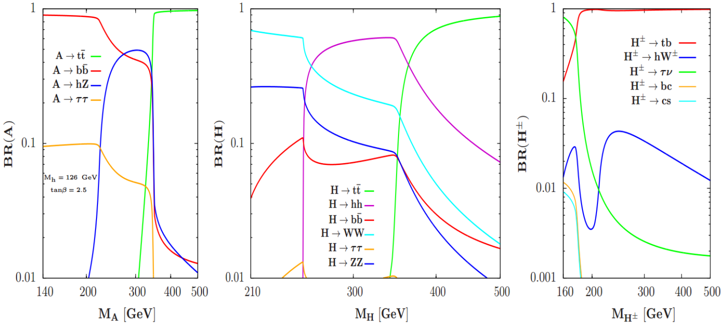
- Gauge mediated symmetry breaking (GMSB) models predict h decays to $\tilde{G}$ and $\tilde{\chi}_0$, with $\tilde{\chi}_0 \to \gamma + \tilde{G}$
- VBF production used to enhance sensitivity
- More stringent limits obtained for di-γ final states

Conclusion and outlook

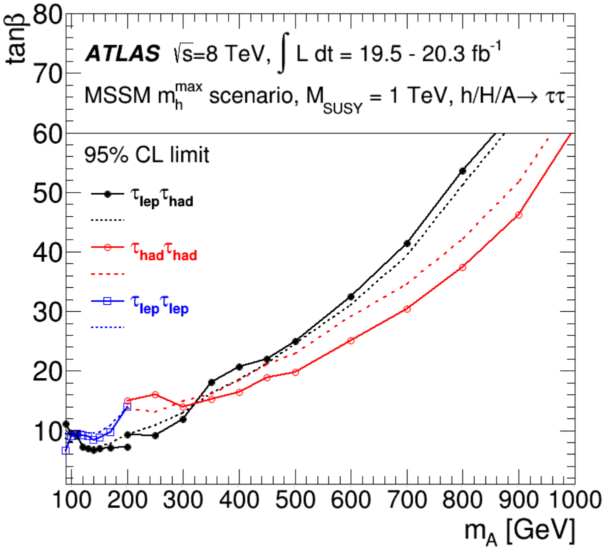
- New ATLAS results for Higgs BSM searches have been presented
  - Searches of resonances compatible with 2HDMs
  - Search for di-Higgs production resonant and non-resonant enhancement (2HDMs, KK graviton, ...)
  - Search for invisible decays of the SM Higgs
  - Search for additional light Higgs particles (NMSSM, ...)
  - Search for “exotic” Higgs decays (dark sector, SUSY...)
- No BSM physics discovery, but we have Run-2 for this!
- 8 TeV $\rightarrow$ 13 TeV: high priority to $\approx$model independent resonance searches for early Run-2
- Early searches will be analogous to Run-1 h_{SM} ones, and will be interesting already with very few fb^{-1}
  - $H/A \rightarrow \tau\tau$
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4\ell$
  - $H^{+} \rightarrow \tau\nu + jets$
  - ...

BACKUP

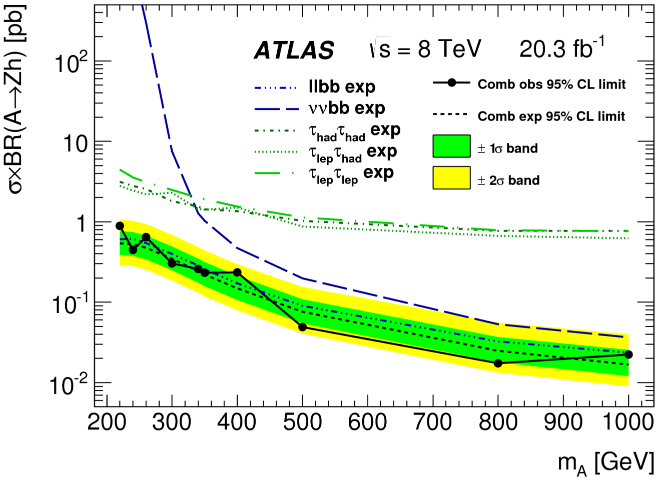
Plots from 1304.1787, Djouadi



- For low $\tan\beta$ and $m_X < 2m_{top}$ most sensitive channels:
  - $H \to hh$, $H \to ZZ$, $H \to WW$, $H \to \tau\tau$
  - $A \to \tau\tau$, $A \to Zh$
- For high $\tan\beta$ both are completely dominated by $b\bar{b}$ (search with associated production) and $\tau\tau$
- H^+ most relevant search channels are tb (dominant BR) and $\tau\nu$ (cleaner)

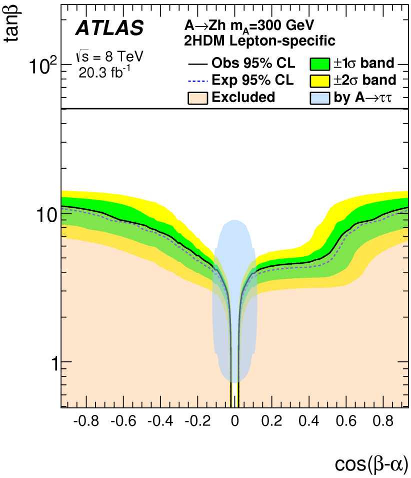

tanβ
80
70
60
50
40
30
20
10
ATLAS √s=8 TeV, ∫ L dt = 19.5 - 20.3 fb⁻¹
MSSM m_h^max scenario, M_SUSY = 1 TeV, h/H/A→ ττ
95% CL limit
τ_lep τ_had
τ_had τ_had
τ_lep τ_lep
100
200
300
400
500
600
700
800
900
1000
m_A [GeV]

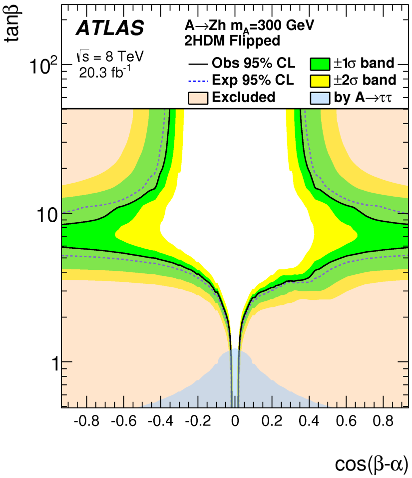
$A \to Zh$: PLB 744 (2015) 163-183



- Dominant channel is $h \to bb$
- $\tau\tau$ channel ensures sensitivity to lepton-specific models, and improves the measured limit @ 300 GeV by 18%

$A \to Zh$: PLB 744 (2015) 163-183





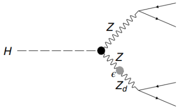
Sensitivity to 2HDM lepton-specific and flipped models thanks to $h \to \tau\tau$

$h \to ZZ_d \to 4\ell$ and $h \to Z_d Z_d$ 4ℓ ATLAS-CONF-2015-003

Hidden or dark sectors included in many BSM models, they provide for example a candidate for DM

- This analyis takes into account models with dark gauge symmetry mediated by a vector boson Z_d
- ZZ_d: same selection as $h \to 4\ell$, search for excesses in dilepton mass m_{34} (pair farthest from m_Z)

  $\to$ per BR($h \to ZZ_d$ 4ℓ)/BR(h 4ℓ) > 0.4 excluded range 15 $< m_{Zd} <$55 GeV



- $Z_d Z_d$: dilepton pairs chosen to minimize $|m_{12} - m_{34}|$, Z and J/Ψ veto, search in m_{Zd} with $|m_{Zd} - m_{12}|$ and $|m_{Zd} - m_{34}| <$ 3-5 GeV (depending on channel)
  - 1 event $4e$ ($m_{12} = 28$ and $m_{34} = 22$ GeV, loc. sig. 1.7σ) and 1 event 4μ ($m_{12} = 23$ e $m_{34} = 18$ GeV, loc. sig. 1.7σ), limits calculated in 15 $< m_{Zd} <$60 GeV range