Revisiting the light NMSSM pseudoscalar at the LHC

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In collaboration with N-E Bomark, S Moretti and L Roszkowski, arXiv: 1409.8393

Outline

- The NMSSM
- The singlet-like pseudoscalar
- NMSSM parameter scans
- Signal-to-background analysis
- Expected sensitivities at the 14 TeV LHC
- Summary

The NMSSM

- Additional Higgs singlet superfield $\hat{S}$

$$W_{\text{NMSSM}} = W_{\text{MSSM}}(-\mu \hat{H}_u \hat{H}_d) + \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{1}{3}\kappa \hat{S}^3 + \ldots$$

EWSB -> $\mu_{\text{eff}} = \lambda v_S$

- 5 new parameters (beside 120+ of MSSM): λ, κ, A_λ, A_κ, v_S
- Predicts 5 neutral Higgs boson states, scalars $H_{1,2,3}$ and pseudoscalars $A_{1,2}$, and a charged pair $H^\pm$
- *NUHM*-CNMSSM: Imposing GUT-scale universality reduces the total No. of free parameters to 9

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \lambda,\ \kappa,\ \mu_{\text{eff}},\ A_\lambda{}^*,\ A_\kappa{}^*$$

The pseudoscalar A_1

- Mass of the singlet-like pseudoscalar

$$m_{A_1}^2 \simeq \lambda(A_\lambda + 4\kappa s)\frac{v^2 \sin 2\beta}{2s} - 3\kappa s A_\kappa$$

- Mass of the SM-like Higgs state

$$m_{H_{\rm SM}}^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2 v^2}{\kappa^2}\left[\lambda - \sin 2\beta\left(\kappa + \frac{A_\lambda}{2s}\right)\right]^2$$

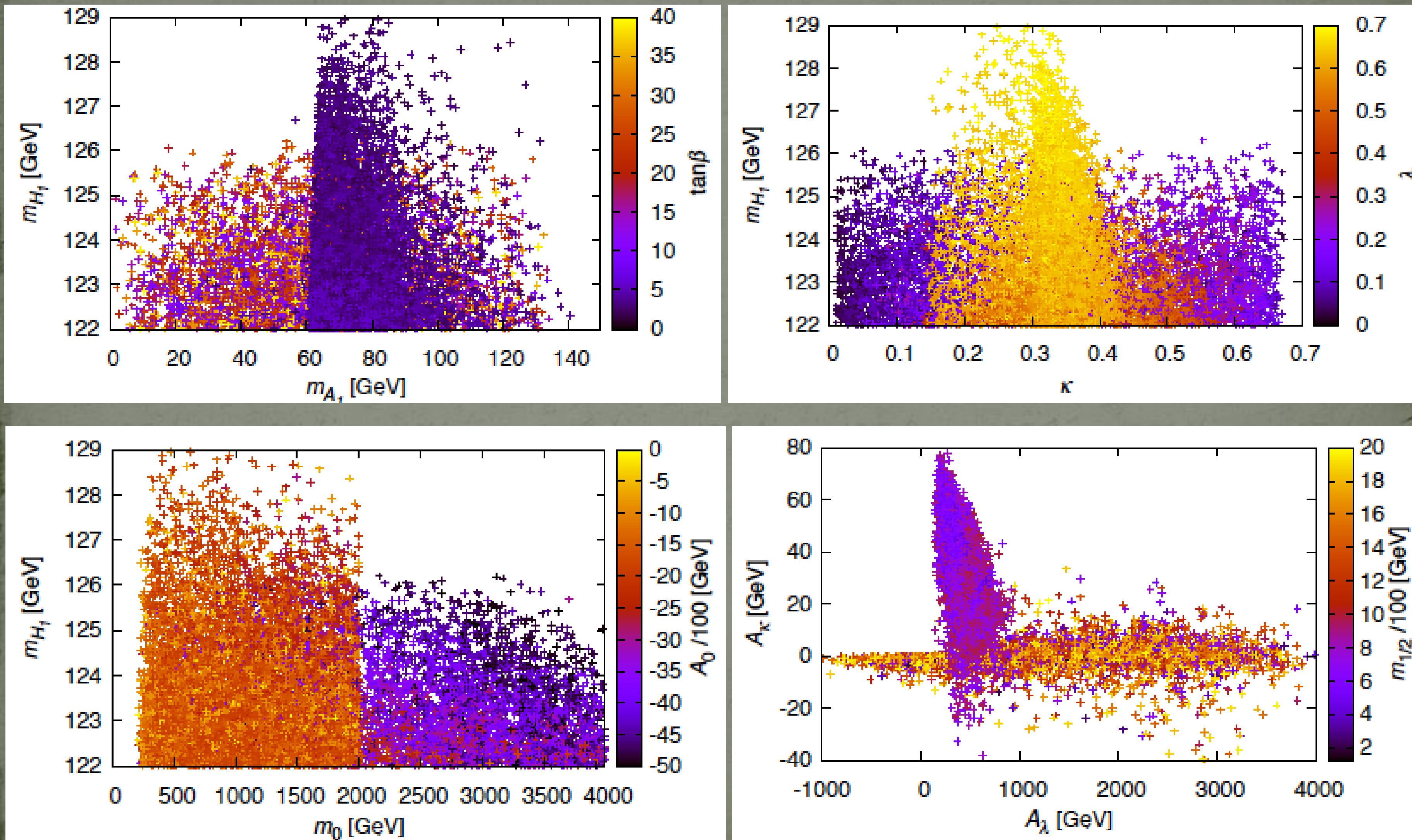
➔ H_{SM} can be either H_1 or H_2 in the NMSSM!

- Important production channels of A_1 (< 150 GeV mass)
  - gg ➔ bbA_1 (associated production with b quarks)
  - H'' ➔ A_1 A_1/Z; (H'' produced via *gf*)

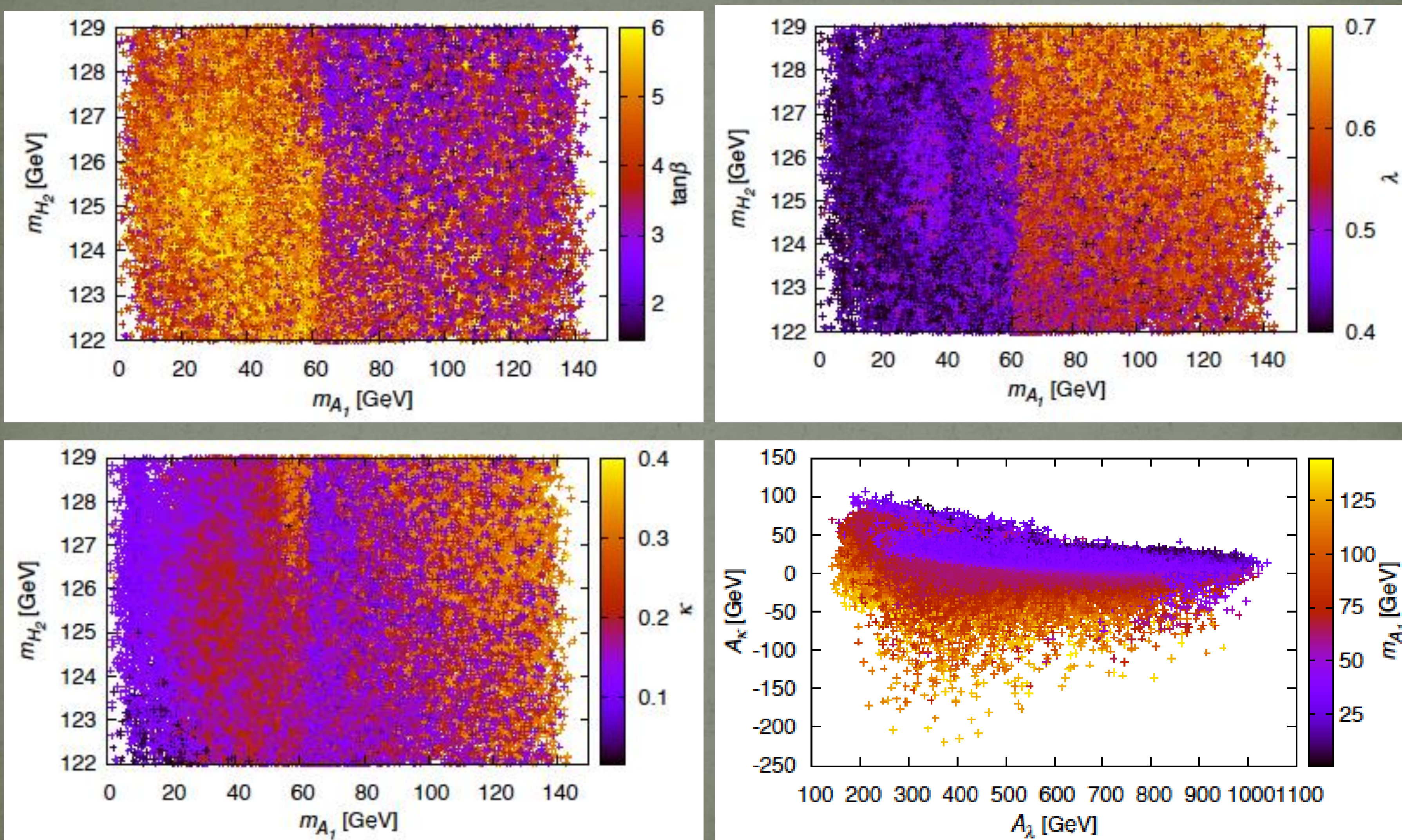
    ➔ $H'' = H_{SM}$ or H'

- A_1 further decays into *bb* or $\tau^+\tau^-$, Z to l^+l^-

Parameter scans for $H_{SM} = H_1$ case



Parameter scans for $H_{SM} = H_2$ case

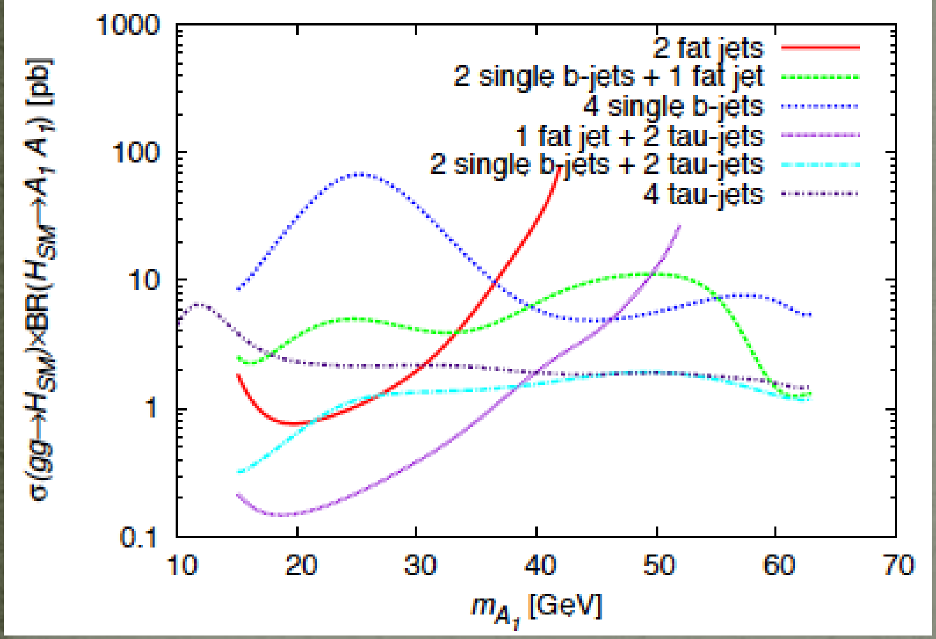


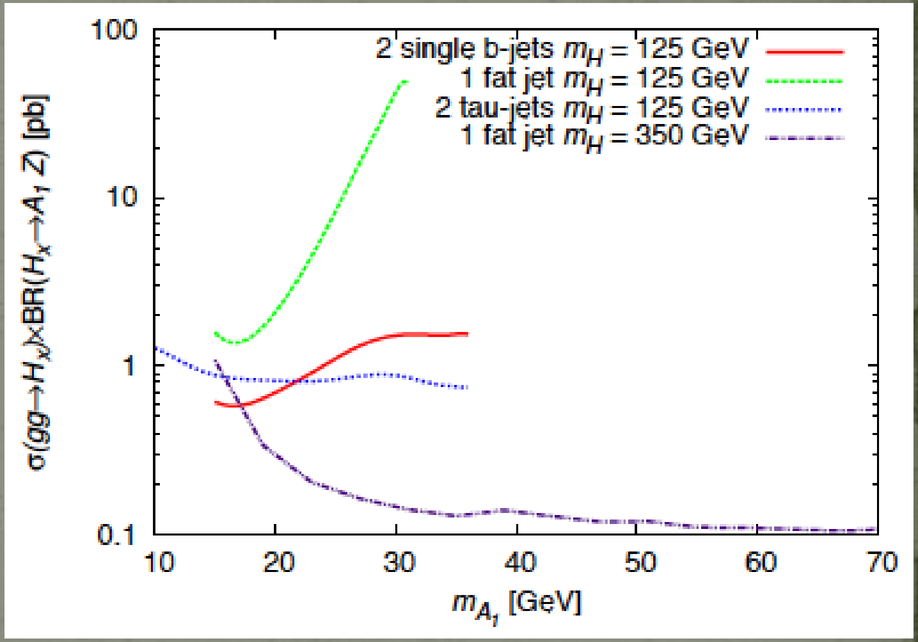
Event analysis

- *Tools*
  - Sushi v1.1.1 for *gf* and *bbh* signal cross sections
  - MadGraph 5 for the BGs
  - Pythia 8.18 interfaced with FastJet 3.0.6 for hadronisation
  - Mass spectra and BRs calculated using NMSSMTools 4.2.1
- Jet substructure method (*Butterwotrth et al.*, 0802.4270) used
  - $A_1 \rightarrow bb$: one fat jet or two single *b*-jets
  - $A_1 \rightarrow \tau^+\tau^-$: two τ-jets
- (Conservative) 50% *b*, τ-tagging efficiency assumed
- 6 possible final state combinations for $H'' \rightarrow A_1 A_1$
- 3 possible final state combinations for $H'' \rightarrow A_1 Z$
- For $H''=H_{SM}$ an A_1 candidate should have invariant mass 125±20 GeV in case of A_1A_1, 125±10 in case of A_1Z

Sensitivity at the LHC

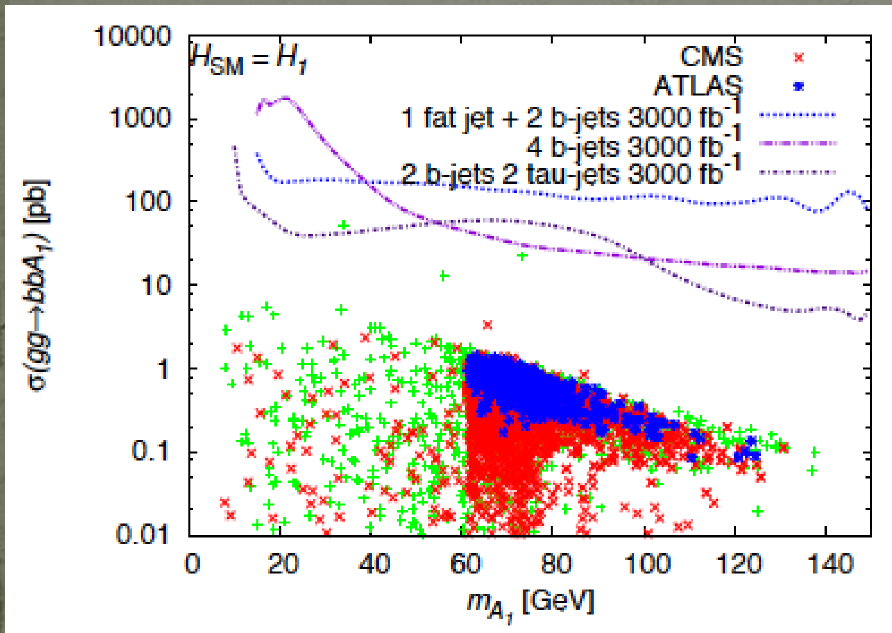
- Discovery reach: $S/\sqrt{B} > 5$ at 30/fb, 300/fb and 3000/fb for LHC run-II with $\sqrt{s} = 14$ TeV

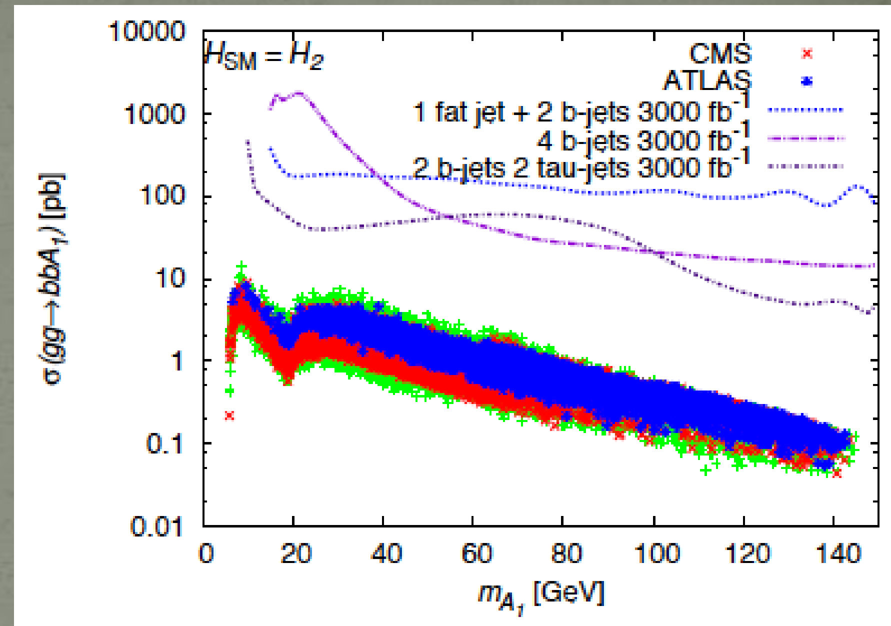




- Multiplied by 0.9 for $A_1 \rightarrow bb$ and by 0.1 for $A_1 \rightarrow \tau^+\tau^-$

The bbA_1 production process

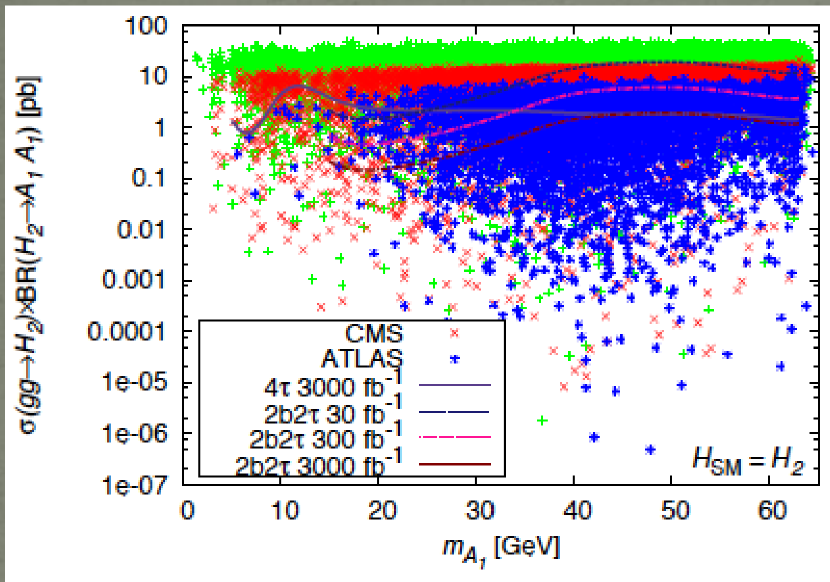




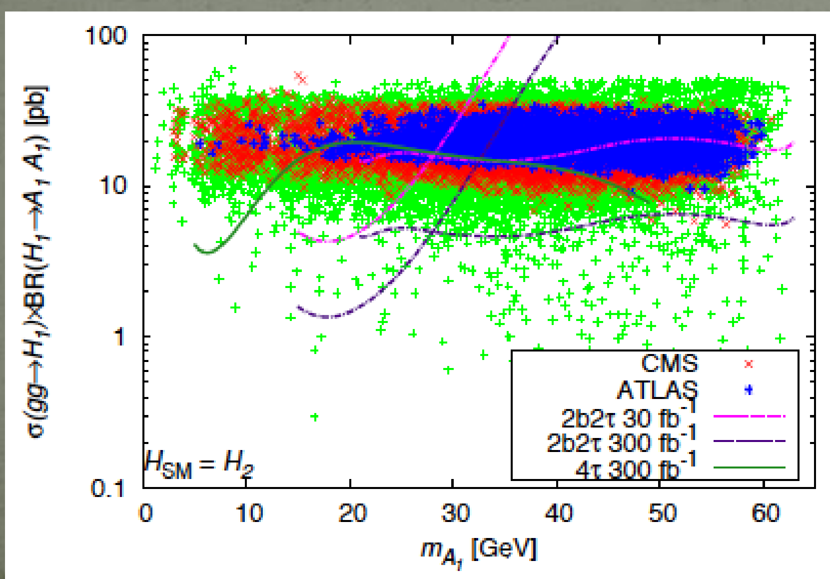
- CMS: [CMS-PAS-HIG-14-009] $\mu^{\gamma\gamma} = 1.13 \pm 0.24\,, \quad \mu^{ZZ} = 1.0 \pm 0.29$
- ATLAS: [ATLAS-CONF-2014-009] $\mu^{\gamma\gamma} = 1.57^{+0.33}_{-0.28}\,, \quad \mu^{ZZ} = 1.44^{+0.40}_{-0.35}$
- Green: *b*-physics, relic density and HiggsBounds only

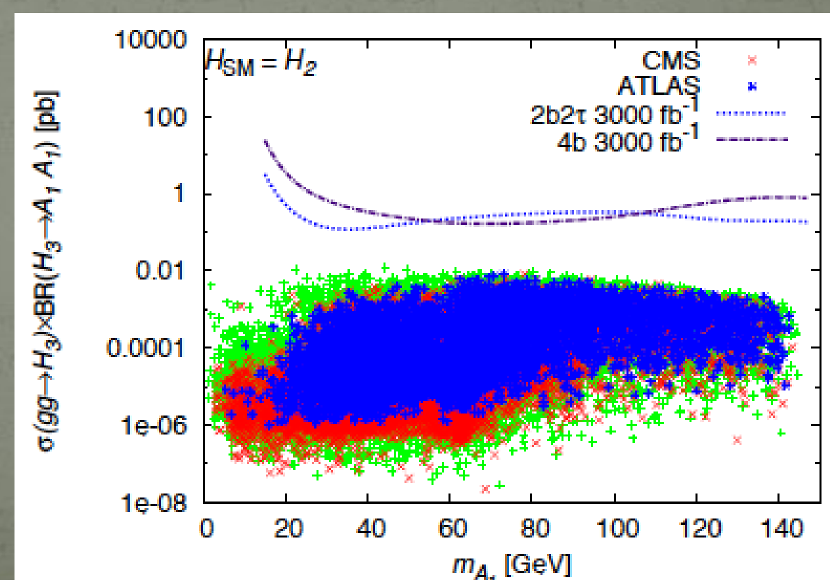
Not accessible for any final state combination!

Production via $H" \rightarrow A_1 A_1$ (for $H_{SM} = H_2$)

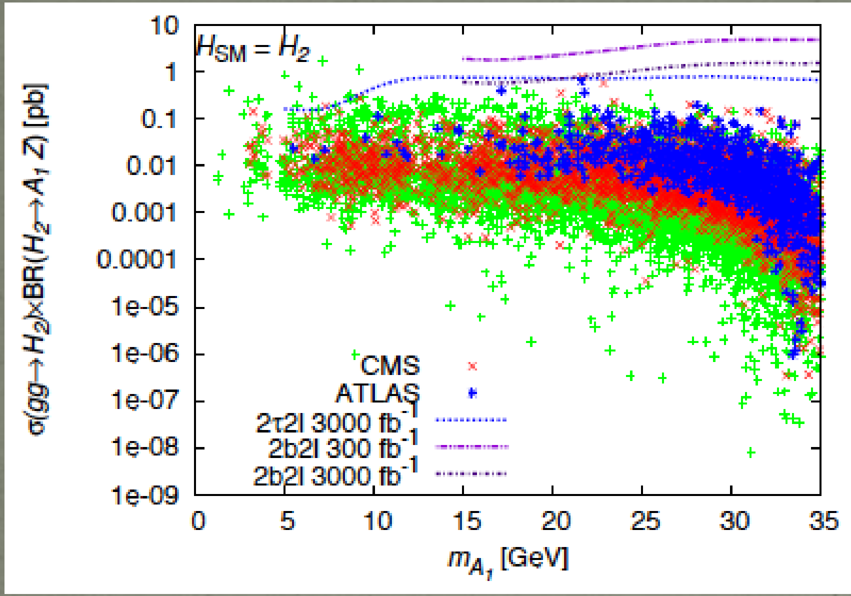


- Should be accessible at as low as 30/fb for H_{SM} and H_1 decays in the $bb\tau^+\tau$ final state
- But only if m_{A1} ~< 62 GeV

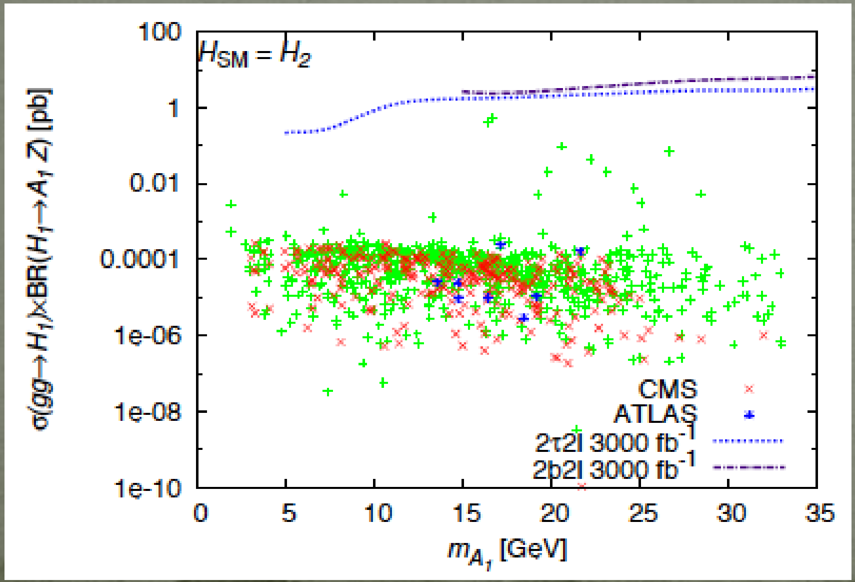


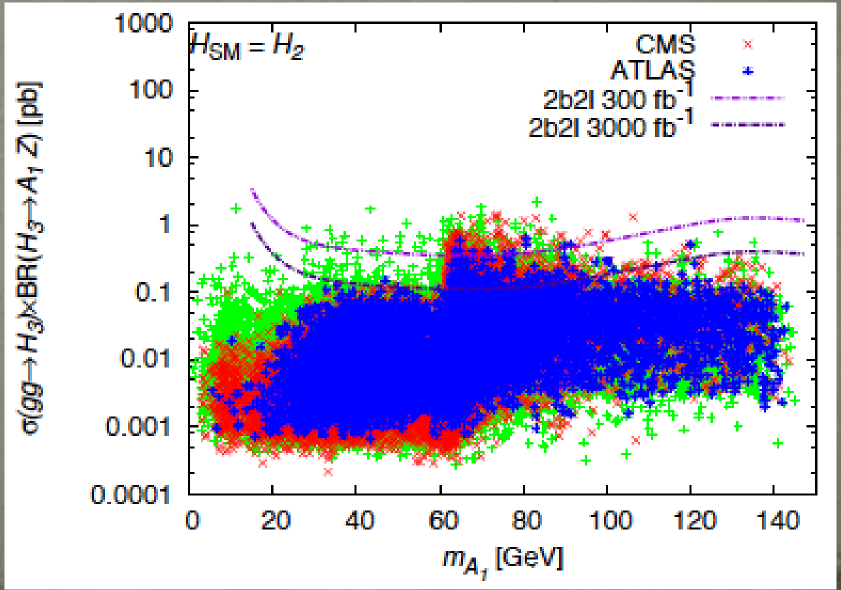


Production via $H'' \rightarrow A_1 Z$ (for $H_{SM} = H_2$)



- Not accessible even at 3000/fb for H_{SM} decay
- H_3 decay carries promise!
- Supplements the $H_{SM} \rightarrow A_1A_1$ channel well for m_{A1} ~> 62 GeV





Conclusions

- The NMSSM parameter space where a < 150 GeV pseudoscalar can be obtained is tightly constrained by the Higgs boson data from the LHC
- The discovery prospects for an A_1 produced in association with *b*-pair are extremely poor
- However, A_1 produced via decays of the heavier CP-even Higgs bosons could be detectable even at 30/fb
- When $H_{SM} \rightarrow A_1 A_1$ is kinematically forbidden, the $A_1 Z$ production channel, which has hitherto not been explored in detail, carries promise

Backup: Jet substructure method

- Cluster all final state visible particles using Cambridge-Aachen algorithm with $R = 1.2$
- For jets with $p_T > 30$ GeV and invariant mass > 12 GeV, go back in the clustering sequence until a relatively symmetric mass drop is achieved: $m_{j_1}, m_{j_2}/m_j < 0.67$ and

$$\frac{\min(p_{T j_1}^2, p_{T j_2}^2)}{m_j^2} \Delta R^2(j_1, j_2) > 0.09\,, \quad \Delta R(j_1, j_2) \equiv \sqrt{(\eta(j_1) - \eta(j_2))^2 + (\phi(j_1) - \phi(j_2))^2}$$

- These two jets clustered using CA with

$$R = \max(\min(\Delta R(j_1, j_2)/2, 0.3), 0.2)$$

- Fat jet: If two hardest jets are b-tagged and the three hardest jets together have an invariant mass > 12 GeV, they are coming from an A_1
- Remaining particles reclustered using antikT algorithm with $R = 0.4$, in order to find single *b*-jets

Backup: Constraints

$$\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-) = (3.2 \pm 1.35 \pm 0.32) \times 10^{-9}$$

$$\mathrm{BR}\,(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma) = (3.43 \pm 0.22 \pm 0.21) \times 10^{-4}$$

$$\mathrm{BR}\,(\mathrm{B_u} \to \tau\nu) = (1.66 \pm 0.66 \pm 0.38) \times 10^{-4}$$

Higgs boson signal rates

$$R_Y^X = \frac{\Gamma(Y \to H_i) \times \mathrm{BR}(H_i \to X)}{\Gamma(Y \to h_{\mathrm{SM}}) \times \mathrm{BR}(h_{\mathrm{SM}} \to X)}$$

$$R^X = 0.895 R^X_{\mathrm{GF}} + 0.073 R^X_{\mathrm{VBF}} + 0.032 R^X_{\mathrm{VH}}$$

gg ->bbA₁ reduced rate

$$R^{bb}_{b\bar{b}/\tau^+\tau^-}(a_1) \simeq \frac{|P''_{11}|^4}{\Gamma^{\mathrm{total}}_{a_1}/\Gamma^{\mathrm{total}}_{h_{\mathrm{SM}}}}\,, \qquad |P''_{11}| \simeq \left|\frac{\lambda(A_\lambda^{\mathrm{SUSY}} - 2\kappa s)v}{\mu(A_\lambda^{\mathrm{SUSY}} + \kappa s)}\right|$$