Prospects and status of next-to-minimal SUSY

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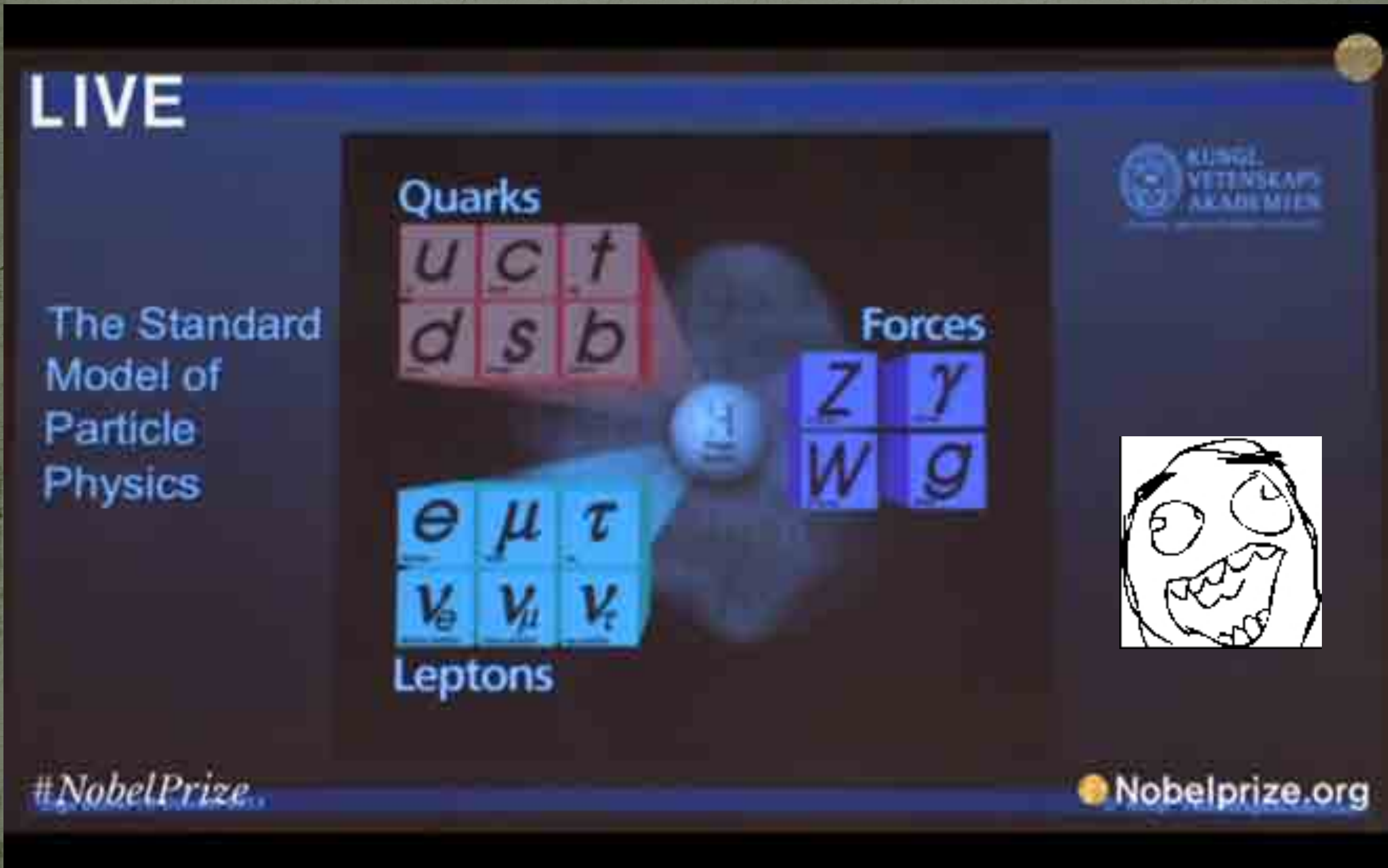
Outline

- Why beyond MSSM?
- NMSSM and its variants
- ~125 GeV Higgs boson(s) in the NMSSM
- Status and collider prospects of the NMSSM
- A pseudoscalar mass-degenerate with SM-like Higgs boson
- A light pseudoscalar via decays of the SM-like Higgs boson
- Novel Higgs-to-Higgs decays in the complex NMSSM
- Summary & outlook

The Standard Model

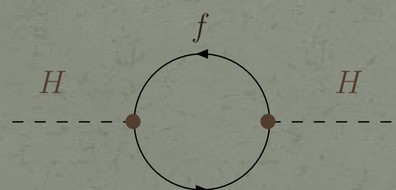


Is the SM complete now?

- Massless neutrinos
- No suitable cold dark matter candidate
- No quantum gravity
- Insufficient CP-Violation for baryon asymmetry

New Physics needed!

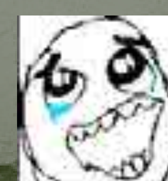
But Higgs boson mass ~ 125 GeV



$$\sim N_f \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6m_f^2\log\frac{\Lambda}{m_f} - 2m_f^2\right] + \cdots$$

$$\sim \frac{\lambda_S N_S}{16\pi^2}\left[-\Lambda^2 + 2m_S^2\log\left(\frac{\Lambda}{m_S}\right)\right] - \frac{\lambda_S^2 N_S}{16\pi^2}v^2\left[-1 + 2\log\left(\frac{\Lambda}{m_S}\right)\right] + \cdots$$

FINE - TUNING!



Supersymmetry

Fermions <-> Bosons: Higgs boson mass regulated!

$$\lambda_f^2 = 2m_f^2/v^2 = -\lambda_S, \quad N_S = 2N_f$$

$$\Delta M_H^2 = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right] + \cdots$$

- Supermultiplets: partners of SM bosons and fermions
- Two higgs doublets with opposite hypercharge
- Minimal manifestation: MSSM
  - 3 neutral Higgs bosons, a charged pair
  - R-parity -> Lightest neutralino as dark matter!

What ails thee, MSSM?

- Superpotential not conformal invariant: `μ-problem´

$$W_{\rm MSSM} = h_u \, \widehat{Q} \cdot \widehat{H}_u \, \widehat{U}^c_R \, + \, h_d \, \widehat{H}_d \cdot \widehat{Q} \, \widehat{D}^c_R \, + \, h_e \, \widehat{H}_d \cdot \widehat{L} \, \widehat{E}^c_R \, + \, \mu \widehat{H}_u \cdot \widehat{H}_d$$

- Higgs @ LHC -> Large M_{SUSY} and/or A_t

$$\Delta m_h^2 = \frac{3 m_t^4}{4\pi^2 v^2} \left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$

- SUSY @ LHC -> Fine-tuning problem reloaded!

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- ~125 new parameters!
  - pMSSM: ~25 SUSY parameters
  - GUT-universality – CMSSM: only 4 SUSY parameters
    - -> severely constrained / fine-tuned

The (Z_3 invariant) NMSSM

- An additional Higgs singlet superfield $\hat{S}$

$$W_{\rm NMSSM} = \text{MSSM Yukawa terms} + \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

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

$$V_{\rm soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right)$$

- 5 new parameters (at low energy): λ, κ, A_λ, A_κ, v_S
- 5 neutral Higgs bosons, 5 neutralinos
- CNMSSM: Impose universality at the GUT-scale

$$p_i = \{ m_0, m_{1/2}, A_0, \lambda, \text{sign}[\mu_{\rm eff}], (A_\kappa) \}$$

- Partially relaxed universality: CNMSSM-NUHM

$$p_i = \{ m_0, m_{1/2}, A_0, \tan\beta, \mu_{\rm eff}, \lambda, \kappa, A_\lambda, A_\kappa \}$$

- cNMSSM: complex Higgs sector

Variants

The most general superpotential with a singlet superfield

$$W = W_{\text{Yukawa}} + (\mu + \lambda S)H_u H_d + \frac{\mu_S}{2}S^2 + \frac{\kappa}{3}S^3 + \xi S$$

- *PQ*-NMSSM [Bae et al., 1208.2555]
- nMSSM [Panagiotakopoulos and Tamvakis, 9908351]: $Z_{5/7}$ – symmetric
- GNMSSM [Ross and Schmidt-Hoberg et al., 1108.1284]: $Z_{4/8}$ – symmetric
- SMSSM [Delgado et al., 1005.1282]: Z_2 – symmetric
- NMSSM with a right-handed neutrino [Wang et al., 1303.6465]
- NMSSM+ [Hall and King, 1209.4657]
- E_6MSSM [King et al., 0510419]: *U(1)'* – symmetric
- DiracNMSSM [Lu et al.,1308.0792] : Two singlets - $M_s S\bar{S}$

…

125 GeV SM-like Higgs boson(s)

- Mass at the tree level

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

- λ , κ -> 0: h_1 very (MS)SM-like (maximal fine-tuning!)
- $\lambda \sim 0.1$, $\tan\beta \sim 10$: h_1 still SM-like (less fine-tuned mass)

[Badziak et al., 1304.5437]

- $\lambda \sim 0.5 - 0.7$, $\tan\beta \sim 2 - 6$: two possibilities
  - $h_2 \sim 125$ GeV: $\sigma_{\gamma\gamma}(h_2) > \sigma_{\gamma\gamma}(h_{SM})$ [Ellwanger, 1112.3548]
  - h_1 , $h_2 \sim 125$ GeV: $\sigma_{\gamma\gamma}(h_1+h_2) > \sigma_{\gamma\gamma}(h_{SM})$

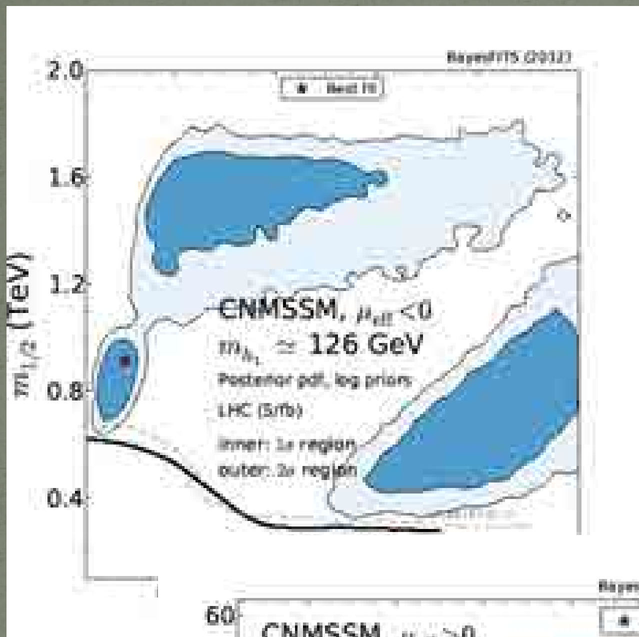
[Gunion et al., 1207.1545]

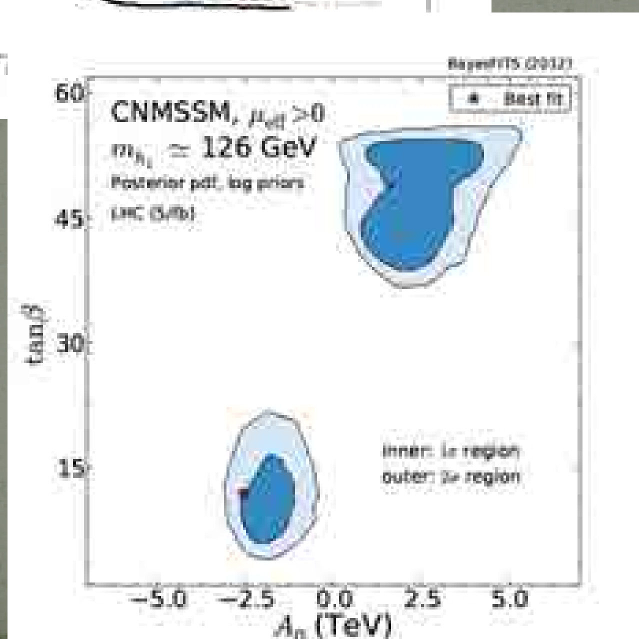
Minimal FINE - TUNING!

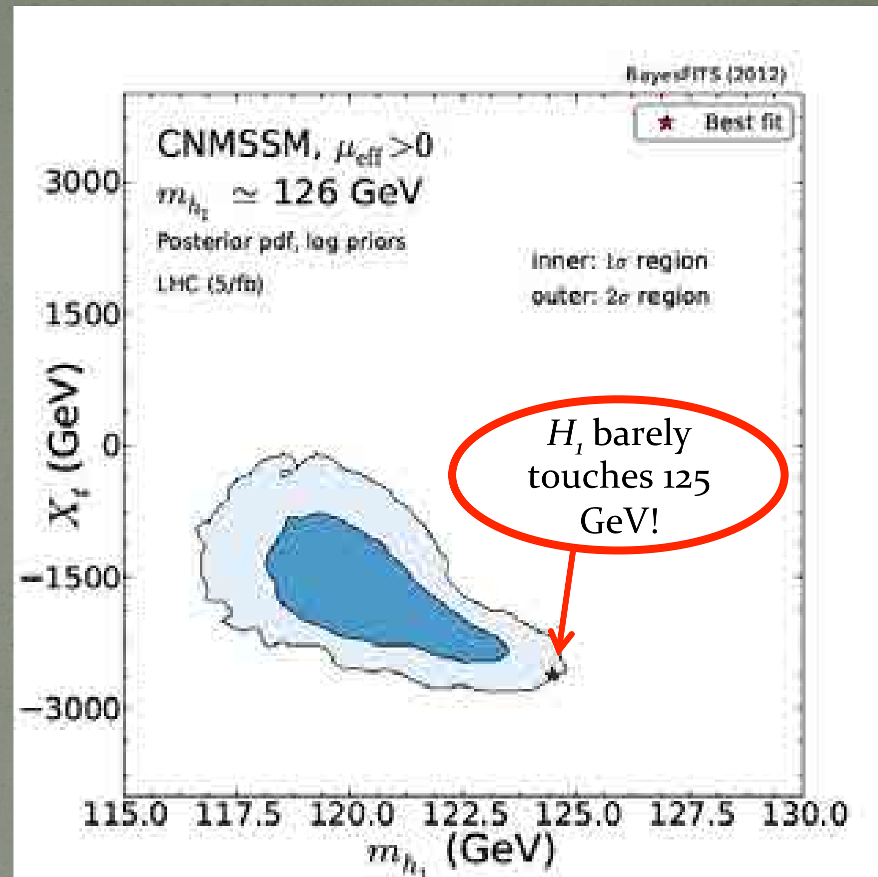
Status of the theory

- Higgs mass matrix:
  - [Ellwanger and Hugonie, 0504269]: Full one-loop in the effective potential approach
  - [Degrassi and Slavich, 0907.4682]: Full one-loop in the Feynman diagrammatic approach + $\mathcal{O}(\alpha_s\alpha_t+\alpha_s\alpha_b)$
  - [Goodsell et al, 1411.4665]: $\mathcal{O}(\alpha_\lambda+\alpha_\kappa)^2$
  - [Muhlleitner et al., 1412.0918]: Full one-loop in the cNMSSM
  - [Muhlleitner et al., 1206.6806]: $\mathcal{O}(\alpha_s\alpha_t+\alpha_s\alpha_b)$ in the cNMSSM
- Most important S-matrix calculations:
  - Gluon fusion production: Up to NNNLO QCD corrections - adopted from the MSSM, no EW corrections for now
  - Fermionic decay widths also generalised from the MSSM
  - [Nhung et al., 1306.3926]: Corrections to the trilinear Higgs boson self-couplings

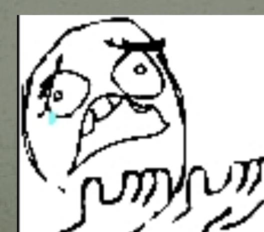
The CNMSSM







[Kowalska et al.,1211.1693]



Experimental signatures

- Mainly low energy
  - A GeV-scale scalar H_1

$$m^2_{h_{1,2}} \approx \frac{1}{2}\left\{M_Z^2 + 4(\kappa s)^2 + \kappa s A_\kappa \mp \sqrt{\left[M_Z^2 - 4(\kappa s)^2 - \kappa s A_\kappa\right]^2 + 4\lambda^2 v^2 \left[2\lambda s - (A_\lambda + \kappa s)\sin 2\beta\right]^2}\right\}$$

(for large-ish *tanβ,* [Miller et al., 0304049])

  - and/or pseudoscalar A_1

$$m^2_{A_1} \simeq \lambda(A_\lambda + 4\kappa s)\frac{v^2 \sin 2\beta}{2s} - 3\kappa s A_\kappa - \frac{M^4_{P,12}}{M^2_{P,11}}$$

  - and/or neutralino LSP

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s \end{pmatrix}$$

~ 125 GeV A_1 and $\gamma\gamma$ rate enhancement

- Light (higgsino) charginos -> enhanced $a_1\gamma\gamma$ coupling

$$C^{\rm eff}_{a_i}(\gamma\gamma) \simeq \frac{g_{a_1\chi_1^\pm\chi_1^\pm}}{\sqrt{\sqrt{2}G_F}\, m_{\chi_1^\pm}} A^{a_i}_{1/2}(\tau_i) \quad \Rightarrow \quad C_{a_1}(\gamma\gamma) \simeq \lambda \times \frac{130\ \rm GeV}{m_{\chi_1^\pm}}$$

- Gluon-fusion suppressed, but not bbA_1

$$R^{bb}_{\gamma\gamma}(a_1) = C^2_{a_1}(dd)\, C^2_{a_1}(\gamma\gamma)\, \frac{\Gamma^{\rm total}_{h_{\rm SM}}}{\Gamma^{\rm total}_{a_1}} \simeq |P''_{11}|^2\, \lambda^2 \left(\frac{130\ \rm GeV}{m_{\chi_1^\pm}}\right)^2 \left(\frac{1}{\Gamma^{\rm total}_{a_1}/\Gamma^{\rm total}_{h_{\rm SM}}}\right)$$

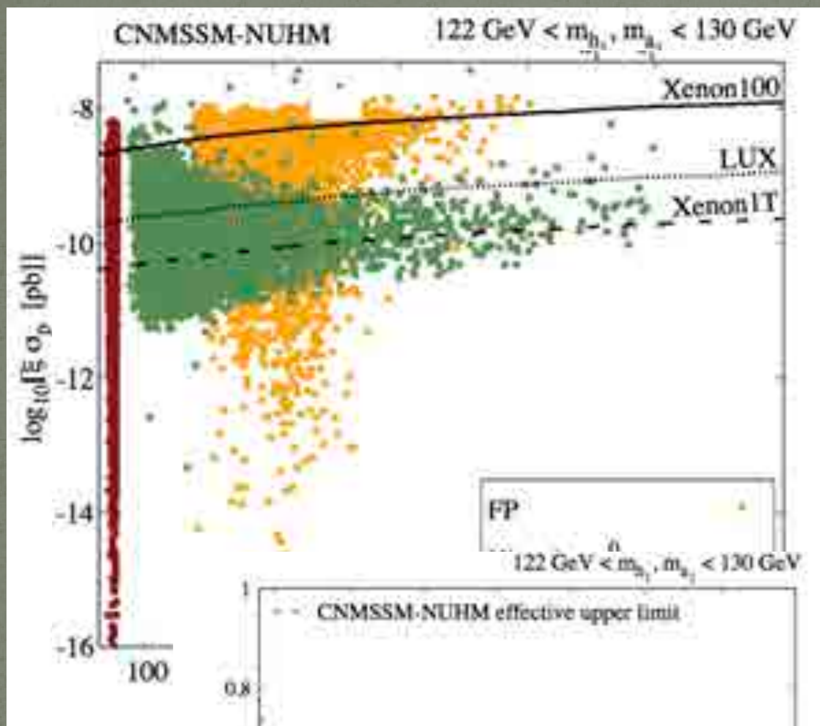
- Enhancement in all *d*-type fermionic channels also!

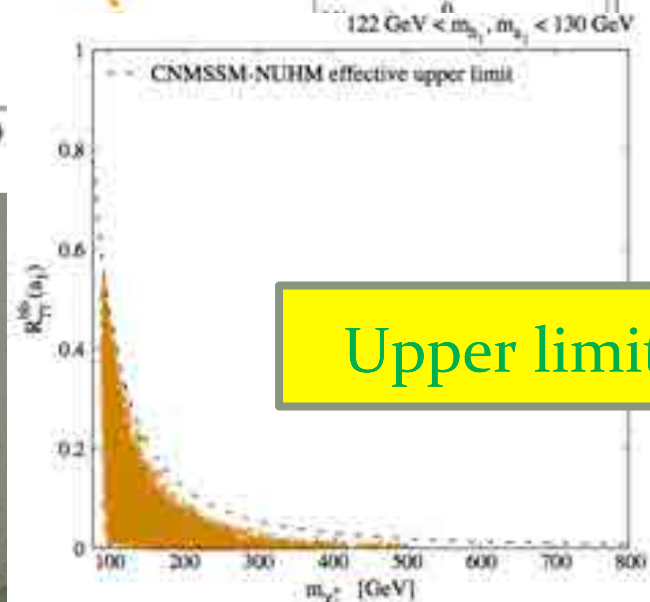
$$R^{bb}_{b\bar{b}/\tau^+\tau^-}(a_1) \simeq \frac{|P''_{11}|^4}{\Gamma^{\rm total}_{a_1}/\Gamma^{\rm total}_{h_{\rm SM}}}, \qquad |P''_{11}| \simeq \left|\frac{\lambda(A^{\rm SUSY}_\lambda - 2\kappa s)v}{\mu(A^{\rm SUSY}_\lambda + \kappa s)}\right|$$

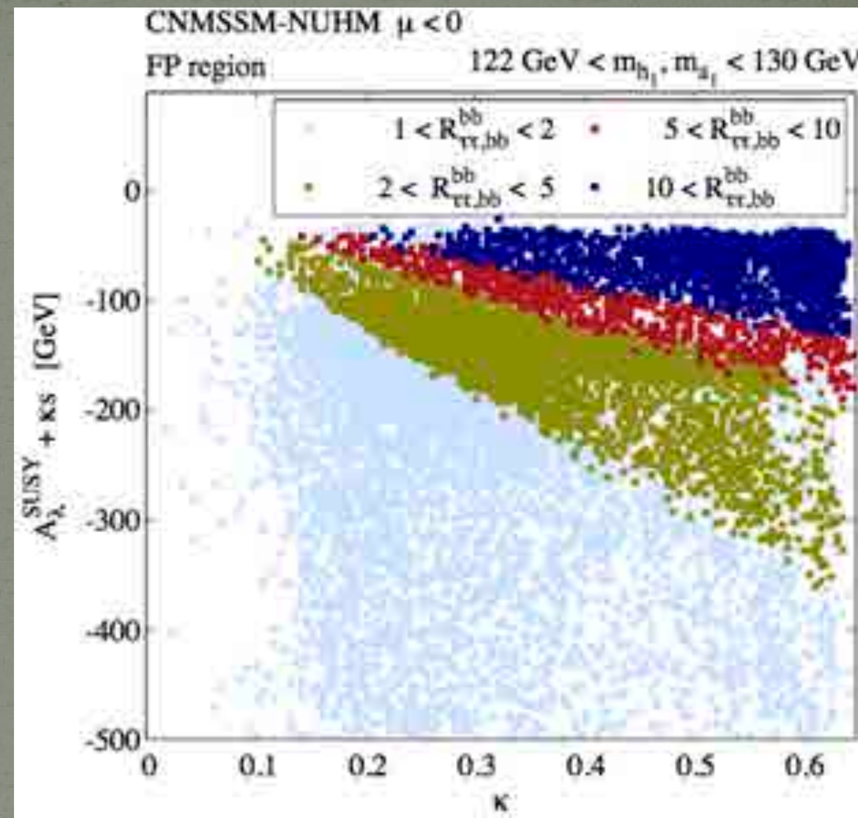
Discrepancy between the $\gamma\gamma$ and ZZ signal rates!

$$R^{bb}_X(\rm obs) = R^{bb}_X(h_1) + R^{bb}_X(a_1) \simeq 1 + R^{bb}_X(a_1) \quad \text{and} \quad R^{bb}_V(\rm obs) = R^{bb}_V(h_1) \simeq 1$$

CNMSSM-NUHM scan







Upper limit on $m_{\chi^\pm}$

[SM et al., 1305.0591]

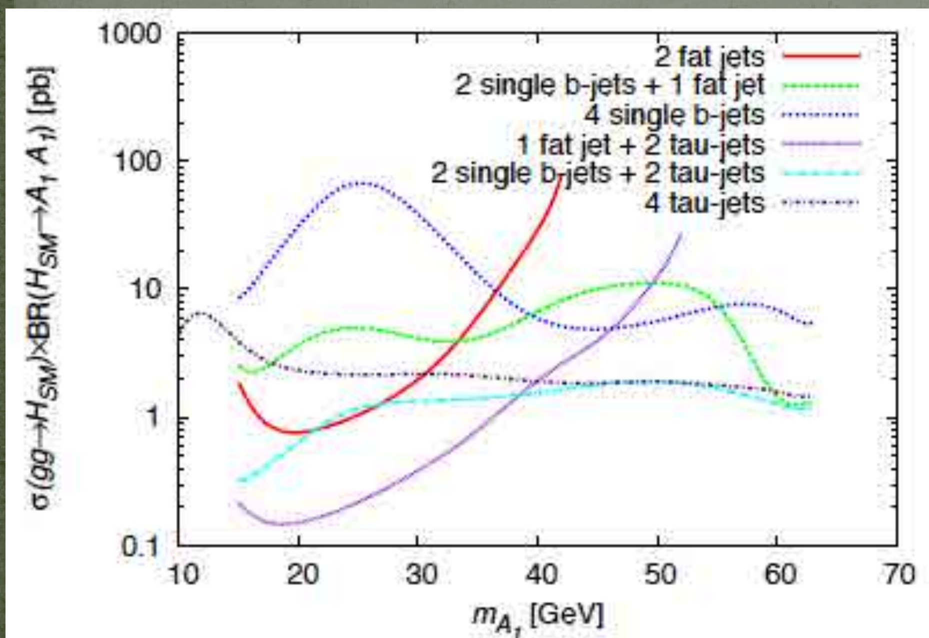
Only in non-minimal SUSY!

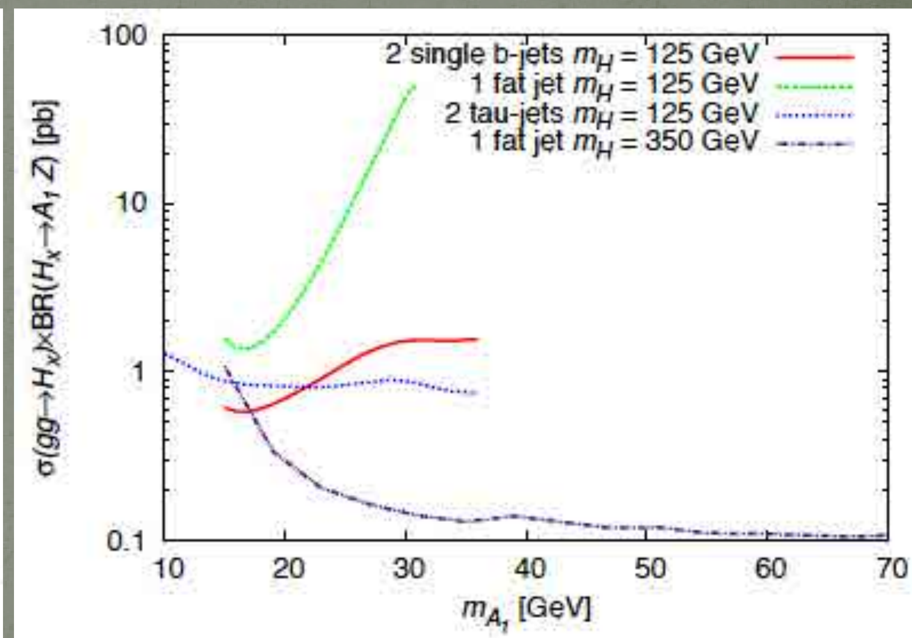
Light A_1 via decays of heavy scalars

- NUHM-CNMSSM scans followed by event analysis
  - Sushi v1.1.1 for *gf* and *bbh* signal cross sections
  - MadGraph 5 for the backgrounds
  - Pythia 8.18 interfaced with FastJet 3.0.6 for hadronisation
  - Mass spectra and BRs calculated using NMSSMTools 4.2.1
- A jet substructure method [Butterworth 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

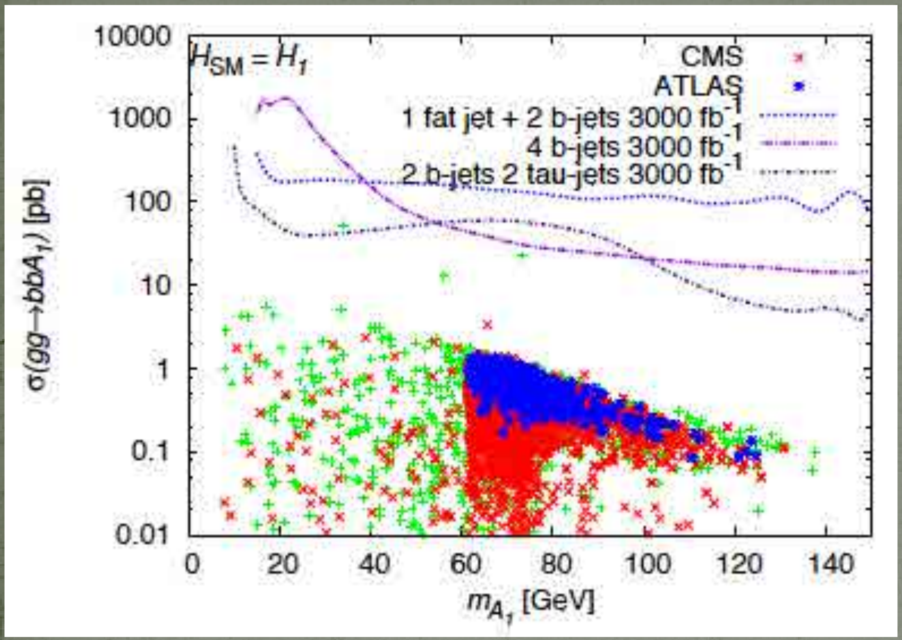


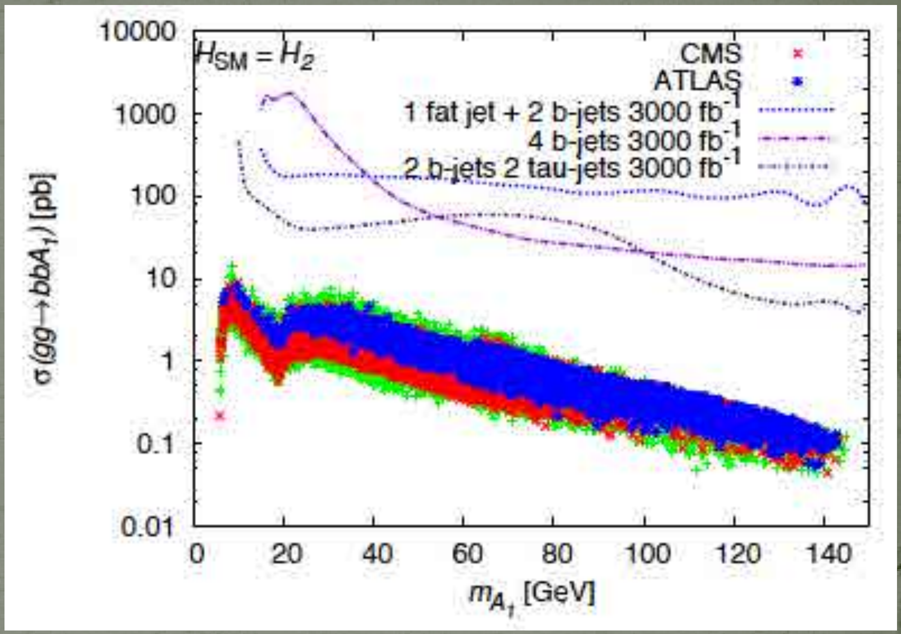


[Bomark et al., 1409.8393]

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

The bbA_1 production process



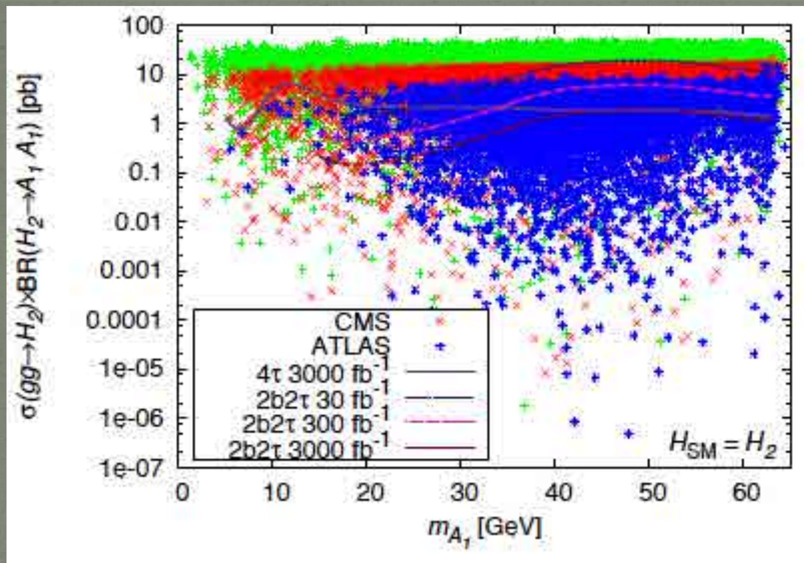


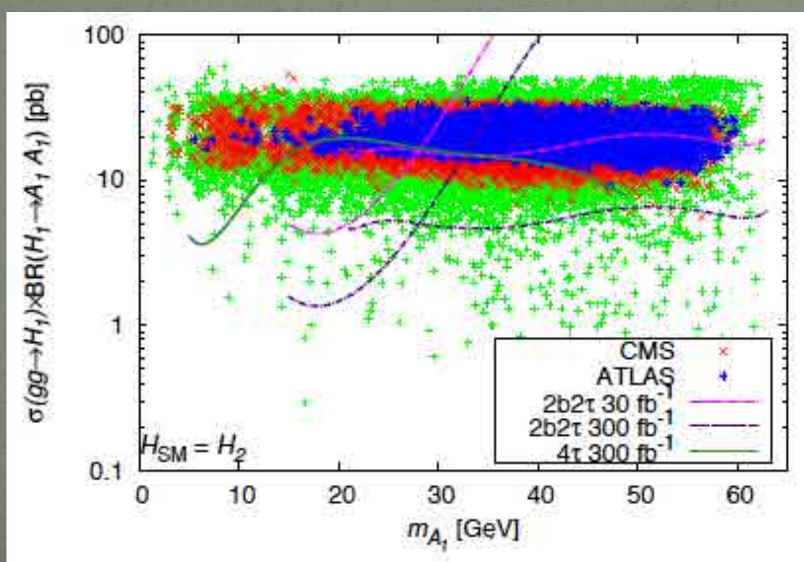
[Bomark et al., 1409.8393]

- 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

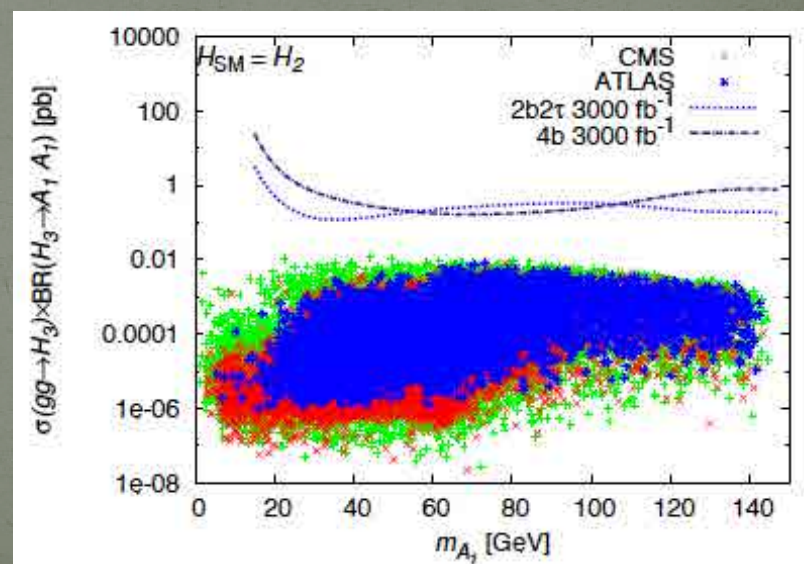
Not accessible for any final state combination!

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



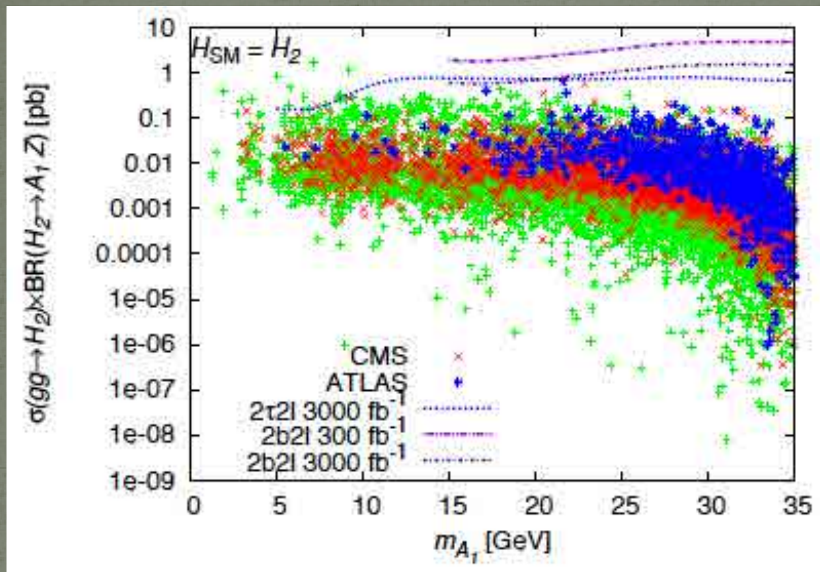


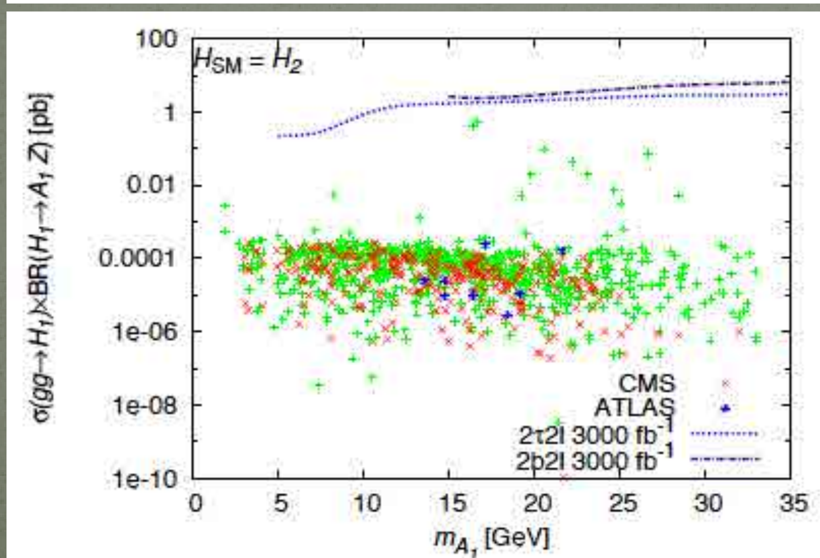
- Should be accessible at as low as 30/fb for H_{SM} and H_1 decays in the $bb\tau^+\tau^-$ final state
- But only if m_{A_1} ~< 62 GeV



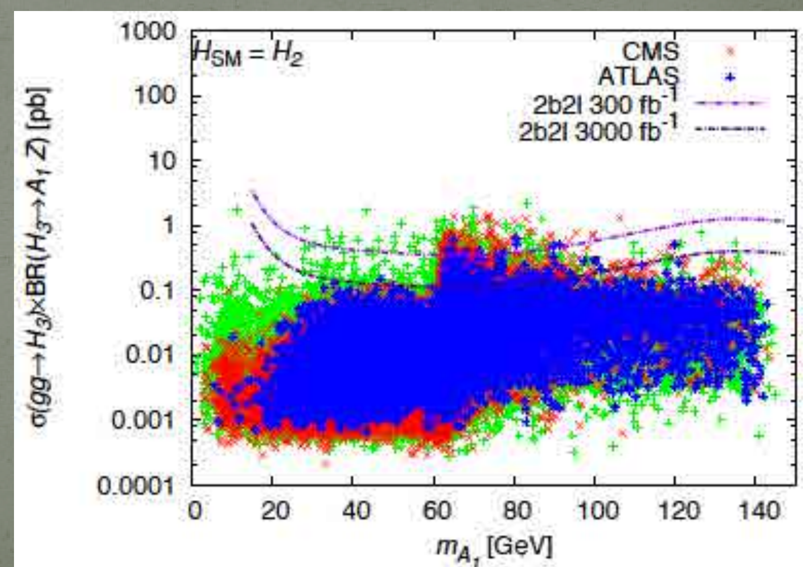
[Bomark et al., 1409.8393]

Production via H" ➔ $A_1 Z$ (for $H_{SM} = H_2$)





- Not accessible even at 3000/fb for H_{SM} decay
- H_3 decay carries promise!
- Supplements the H_{SM} ➔ $A_1 A_1$ channel well for m_{A1} ~> 62 GeV



[Bomark et al., 1409.8393]

The cNMSSM

- CP-violation necessary to explain baryon asymmetry
- MSSM: CPV possible only beyond born approximation

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_{\widetilde{Q}}^2 + m_t^2 - \frac{1}{8}\left(g^2 - \frac{g'^2}{3}\right)\mathcal{D} & -h_t^*\left[A_t^*\left(H_2^0\right)^* + \mu H_1^0\right] \\ -h_t\left[A_t H_2^0 + \mu^*\left(H_1^0\right)^*\right] & m_{\widetilde{U}}^2 + m_t^2 - \frac{g'^2}{6}\mathcal{D} \end{pmatrix}$$

- Tree-level CPV possible in the NMSSM

$$\lambda \equiv |\lambda| e^{i\phi_\lambda} \text{ and } \kappa \equiv |\kappa| e^{i\phi_\kappa} \Longrightarrow \mathcal{M}_0^2 = \begin{pmatrix} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ (\mathcal{M}_{SP}^2)^T & \mathcal{M}_P^2 \end{pmatrix}$$

- Non-zero phases -> CP-mixed mass eigenstates

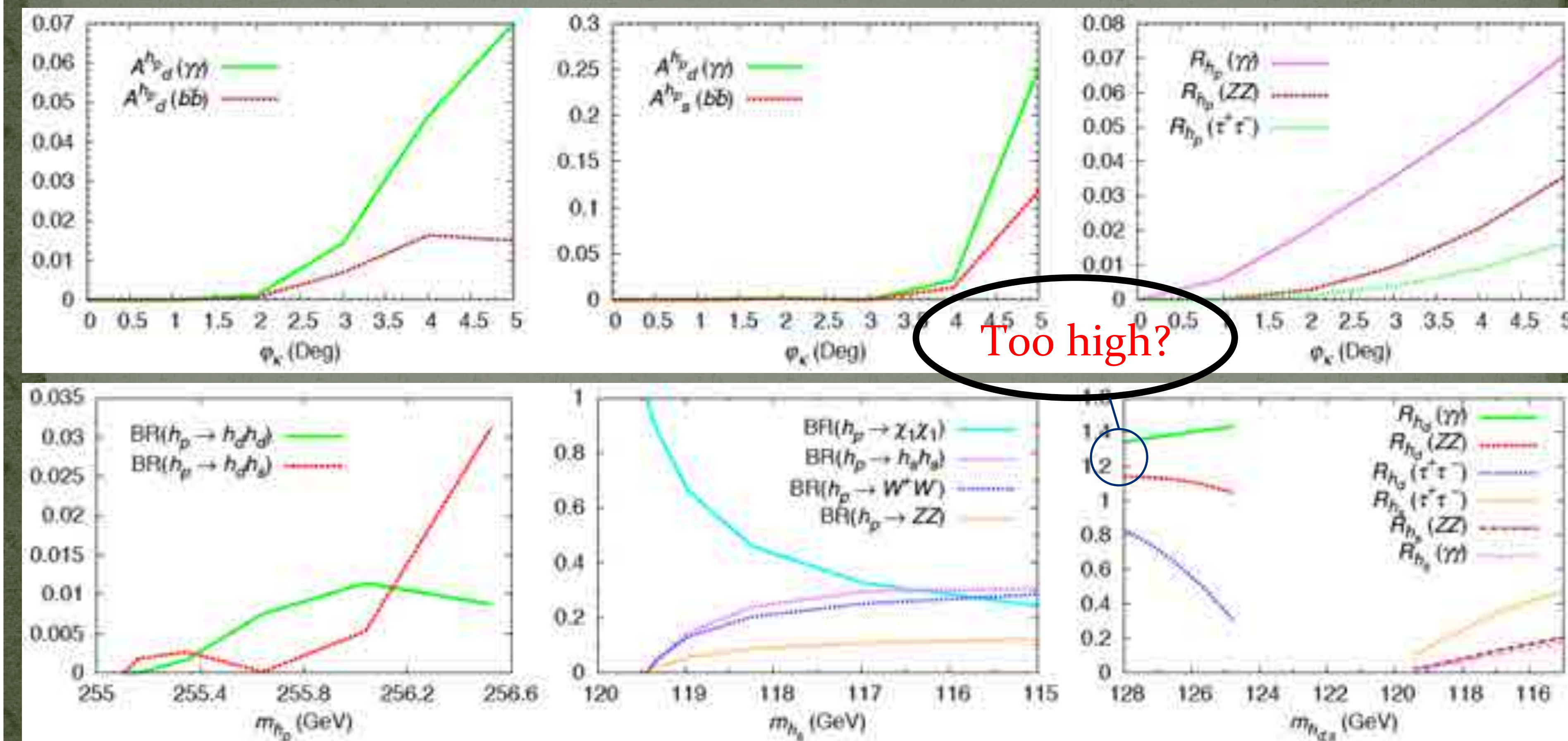
$$(H_1, H_2, H_3, H_4, H_5, H_6)_a^T = O_{ai}\left(H_{dR}, H_{uR}, S_R, H_{dI}, H_{uI}, S_I\right)_i^T$$

- Constrained by fermion EDMs

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} M_W \cos\beta \\ \sqrt{2} M_W \sin\beta & \frac{|\lambda| v_S}{\sqrt{2}} e^{i\phi'_\lambda} \end{pmatrix}$$

Scenario: $h_s = H_1, h_d = H_2, h_p = H_3$

$$A_i^{h_p}(\gamma\gamma) \equiv \frac{\Gamma(h_p \to gg)}{\Gamma(h_{\rm SM} \to gg)} \times {\rm BR}(h_p \to h_d h_i) \times \frac{{\rm BR}(h_d \to \gamma\gamma)}{{\rm BR}(h_{\rm SM} \to \gamma\gamma)}$$



[SM,1310.8129]

Summary & outlook

- The NMSSM offers a vareity of new Higgs boson signatures precluded in the MSSM
- A singlet-like pseudoscalar Higgs boson, A_1, could be degenerate in mass with the SM-like Higgs boson, H_{SM}
- Or, when lighter, A_1 could be produced via decays of the H_{SM}
- In the presence of complex phases in the Higgs sector, a ~ 250 GeV A_1-like CP-mixed state can, alternatively, decay into the SM-like Higgs boson
- Such scenarios, if experimentally observed, could serve as clear indications of non-minimal SUSY

Thank you!

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: $m_{j1}, m_{j2}/m_j < 0.67$ 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