Closing the Wedge with 300 and 3000 fb^{-1} at the LHC

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Motivation

- We have discovered a Higgs boson:
  - Couplings to massive bosons.
  - Nonuniversal couplings to fermions.
  - Appears the new boson couples according to mass and is related to EWSB.
- Era of directly probing the mechanism of electroweak symmetry breaking (EWSB) has begun.
- Necessary to investigate if there is more to the EWSB sector.
- One popular beyond the standard model theory that addresses this is the Supersymmetry.
- For studies at the LHC energies it is useful to study the minimal low energy realization, the Minimal Supersymmetric Standard Model (MSSM).

MSSM Higgs Sector

- Due to the need for anomaly cancellation, the MSSM contains two Higgs doublets, H_1, H_2.
- There are five physical Higgs bosons: $h, H, A, H^{\pm}$
- At tree level, Higgs sector described by two parameters, typically chosen to be $\tan\beta = v_1/v_2$ and M_A
- We will consider the scenario where the lightest Higgs boson, h, is identified as the Higgs discovered at $M_h = 125.5$ GeV.

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- We will consider the scenario where the lightest Higgs boson, h, is identified as the Higgs discovered at $M_h = 125.5$ GeV.
- At tree level $M_h \leq M_Z$. Fortunately, stop loops provide considerable correction to the Higgs mass.
- The leading component to the Higgs mass from stop loops:

$$\varepsilon = \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Stop mixing parameter: $X_t = A_t - \mu\cot\beta$
- $M_S = \sqrt{m_{\tilde{t}_1\tilde{t}_2}}$ is the geometric mean of the stop masses.
- This correction is maximized when $X_t = \sqrt{6}M_S$.

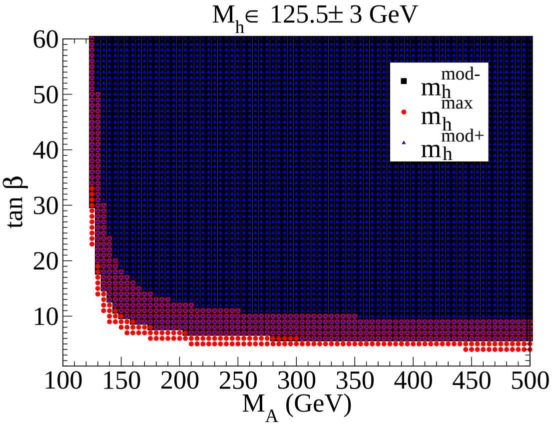
Benchmarks

- Will consider benchmark points from Carena, Heinemeyer, Stål, Wagner, Weiglein, 1302.7033.
- $m_h^{\rm max}$ scenario chosen to maximize one-loop stop correction to Higgs mass
  Carena, Heinemeyer, Wagner, Weiglein, hep-ph/0202167
  - $X_t^{\rm OS} = 2M_{\rm SUSY}$ (on-shell calculation)
  - $X_t^{\overline{\rm MS}} = \sqrt{6}M_{\rm SUSY}$ ($\overline{\rm MS}$ calculation)
- However, $m_h^{\rm max}$ does its job too well... much of $\tan\beta - M_A$ region produces too large a Higgs mass.
- Slightly decrease stop mixing parameter.
- $m_h^{\rm mod+}$:
  - $X_t^{\rm OS} = 1.5M_{\rm SUSY}$
  - $X_t^{\overline{\rm MS}} = 1.6M_{\rm SUSY}$
- $m_h^{\rm mod-}$:
  - $X_t^{\rm OS} = -1.9M_{\rm SUSY}$
  - $X_t^{\overline{\rm MS}} = -2.2M_{\rm SUSY}$
- Third generation squark masses: $M_{\rm SUSY} \equiv M_{\tilde{t}_L} = M_{\tilde{b}_L} = M_{\tilde{t}_R} = M_{\tilde{b}_R}$

Benchmarks

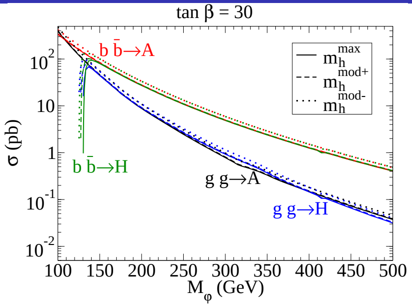
- Common parameters Carena, Heinemeyer, Stål, Wagner, Weiglen, 1302.7033:
  - $M_{\tilde{q}_{1,2}} = 3M_{\tilde{l}_{1,2}} = 1500\ \mathrm{GeV}$
  - $A_f = 0, \quad (f = c, s, u, d, \mu, e)$
  - $m_t = 173.2$ GeV
  - $M_1 = \frac{5}{3}\frac{s_w^2}{c_w^2}M_2$
  - $\mu = M_2 = 200$ GeV
  - $m_{\tilde{g}} = \frac{3}{2}M_{\tilde{l}_3} = 1500$ GeV
  - $A_b = A_\tau = A_t$

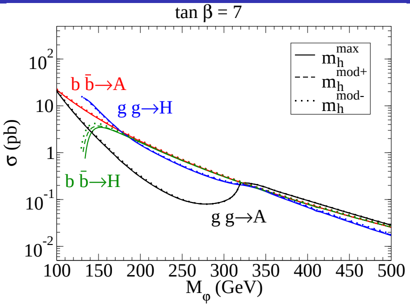
M_h range from benchmarks

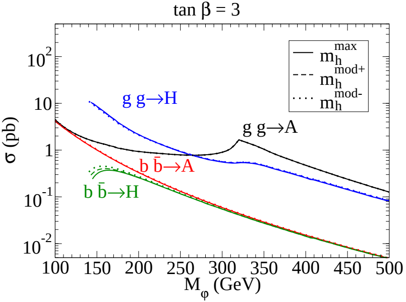


- Band in $\tan\beta - M_A$ plane for which M_h inside 125.5 ± 3 GeV range Carena, Heinemeyer, Stål, Wagner, Weiglen, 1302.7033.
- Decoupling regime $M_A \gg M_Z$: $M_h^2 = M_Z^2 \cos^2 2\beta + \varepsilon \sin^2\beta$
- FeynHiggs Heinemeyer, Hollik, Weiglein, hep-ph/9812320 was used to produce this plot, and it is used extensively in the rest of the presentation.

Production at 7 TeV LHC

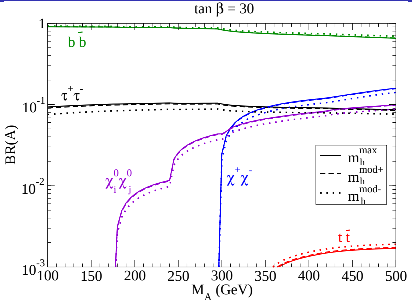


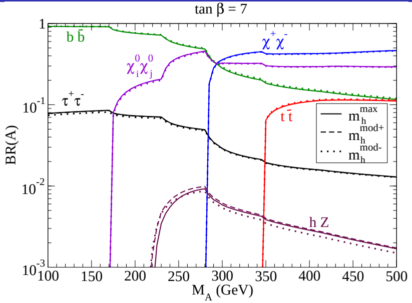


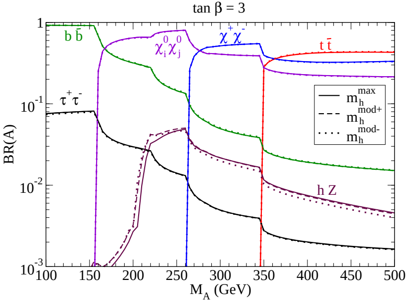


- Kink at $M_\phi \sim 320$ GeV from imaginary part in top loop.
- The $b\bar{b}$ cross section has been rescaled from the SM value produced by bbh@nnlo Harlander, Kilgore, hep-ph/0304035, and the *gg* cross section is rescaled from the values given by the LHC Higgs Cross Section Working Group.

Decays of Pseudoscalar

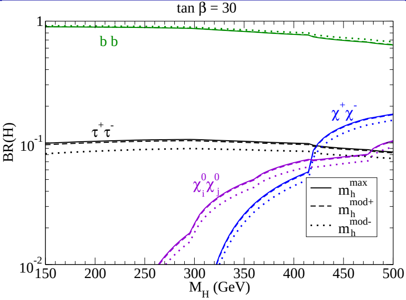


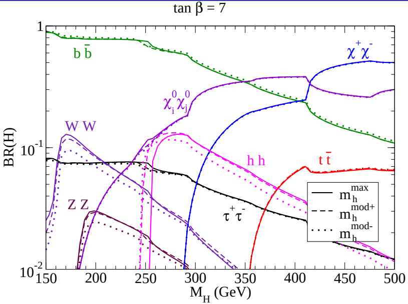


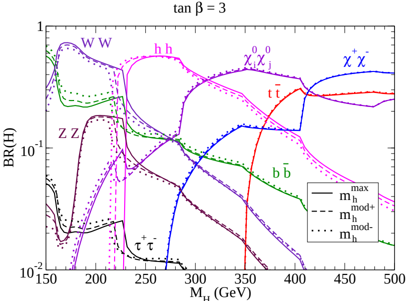


- At high $\tan\beta$, $b\bar{b}$ and $\tau^+\tau^-$ dominate.
- At lower $\tan\beta$, neutralino and chargino decays much more important.

Decays of Heavy Scalar

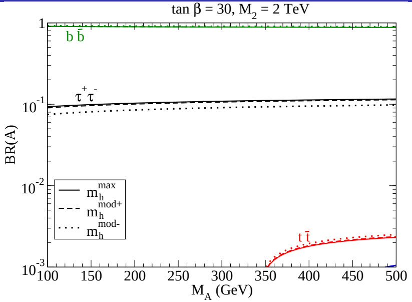


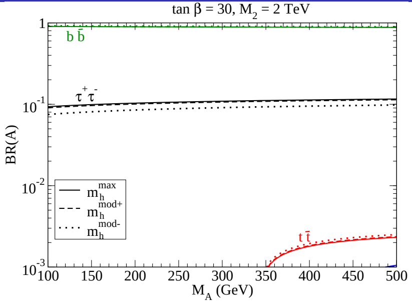


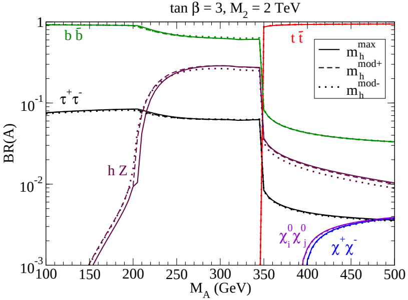


- At high $\tan\beta$, $b\bar{b}$ and $\tau^+\tau^-$ dominate.
- More complicated at lower $\tan\beta$, depends on mass range.

Decays of Pseudoscalar With $M_2 = 2$ TeV





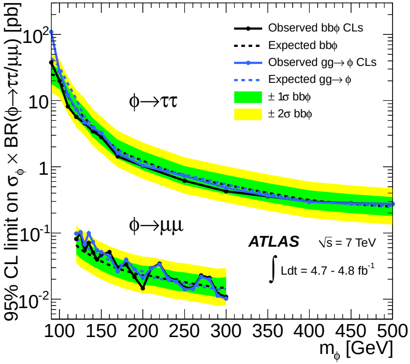


- $M_2 = 2$ TeV alters neutralino mass spectrum and branching ratios of heavy Higgs.
- $A \to \tau^+\tau^-$ more viable for all $\tan\beta$.
- $A \to hZ$ more important at low $\tan\beta$
- Extends range for $H \to hh$

The Wedge

- Different search modes at LHC relevant for high and low $\tan\beta$.
- Since production cross sections and branching ratios similar in three benchmarks, will focus on $m_h^{\rm max}$
- Focus on $\Phi \to \tau^+\tau^-$ searches, extending current LHC limits.
- Also investigate $A \to hZ$ to open lower $\tan\beta$ regime.
- All cross section bounds assumed to scale as $1/\sqrt{Luminosity}$

Current bounds on $\sigma(pp \to \phi) \times \mathrm{BR}(\phi \to \tau^+\tau^-)$



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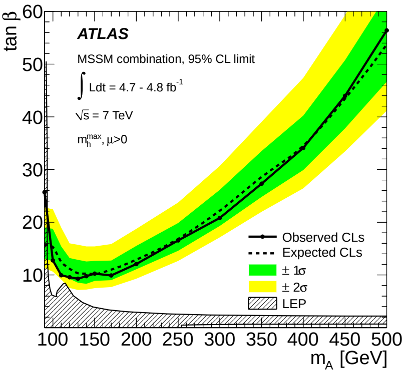
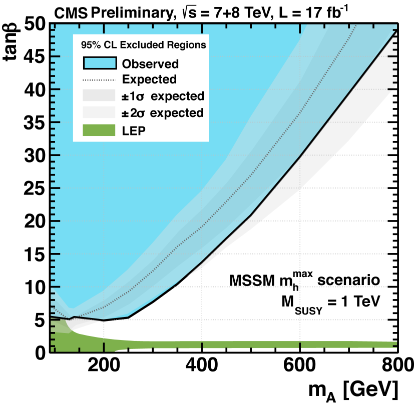
Current bounds





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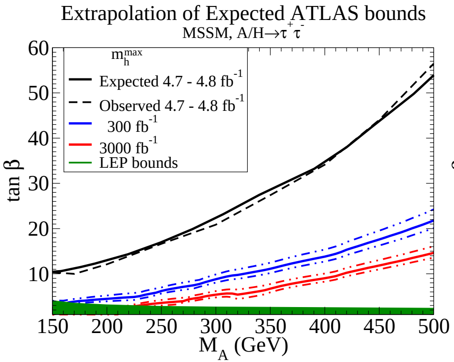
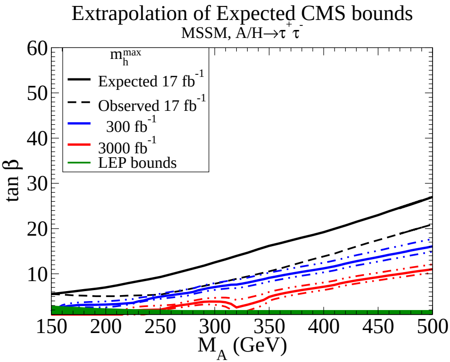
CMS-PAS-HIG-12-050

Projection of bounds to 300 and 3000 fb^{-1}

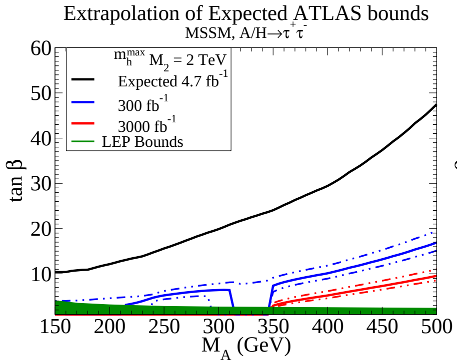


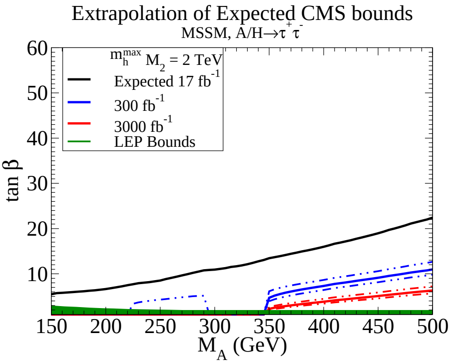


- Included conservative error bands of $\Delta\sigma(\Phi) \times \mathrm{BR}(\Phi \to \tau^+\tau^-) = \pm 25\%$

  Baglio, Djouadi, 1012.0530; Djouadi, Quevillon, 1304.1787

Projection of bounds to 300 and 3000 fb^{-1} with $M_2 = 2$ TeV





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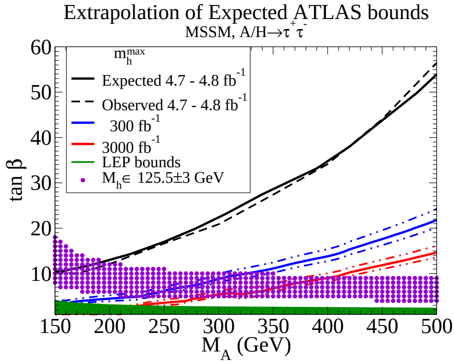
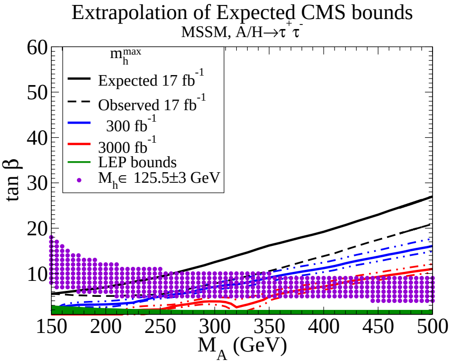
Projection of bounds to 300 and 3000 fb^{-1}





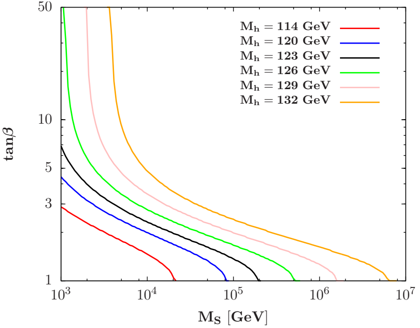
Bounds on M_A in $m_h^{\max}$ scenario:

Luminosity	ATLAS	CMS
300 fb^{-1}	210-240 GeV	230-260 GeV
3000 fb^{-1}	260-290 GeV	290-360 GeV

Low $\tan\beta$

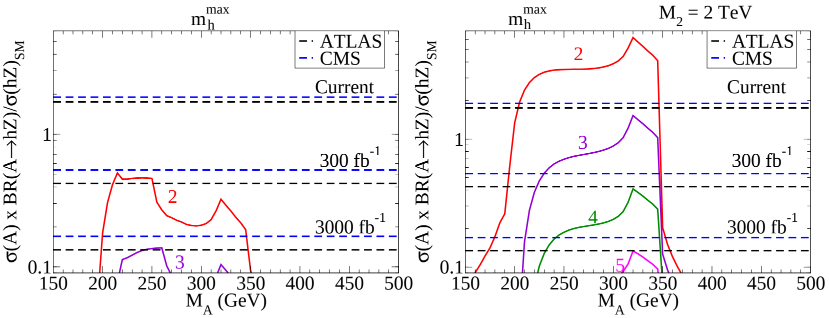
- Although benchmarks considered here do not reproduce correct Higgs mass at low $\tan\beta$, it is possible to reproduce Higgs mass by increasing M_{SUSY} considerably

  Djouadi, Quevillon, 1304.1787



- Search strategy largely depends on neutralino and chargino spectrum.
- Additional signals of additional interest are $A \to hZ$, $H \to hh$, and $H \to WW$.

Projection for $A \to hZ$



- For a 125 GeV Higgs, current bounds on associated productions are
  - ATLAS: $\sigma(VH) < 1.75 \times \sigma(VH)_{SM}$ with 17.7 fb^{-1} ATLAS-CONF-2012-161
  - CMS: $\sigma(VH) < 1.9 \times \sigma(VH)_{SM}$ with 24 fb^{-1} CMS-PAS-HIG-13-012
- No dedicated resonance search, so apply these upper bounds on $\sigma(A \to hZ)$
- With 200 GeV $\lesssim M_A \lesssim$ 250 GeV, sensitive to $\tan\beta \lesssim 2$ with 300 fb^{-1} and $\tan\beta \lesssim 3$ with 3000 fb^{-1}

ILC

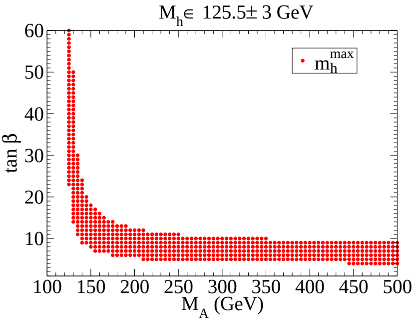
- Search for Higgs-strahlung, $e^+e^- \to Z^* \to Z\Phi$, or pair production $e^+e^- \to Z^* \to \Phi A$
- For $M_A \gtrsim 200$ GeV
  - $Z-Z-H$ and $Z-h-A$ couplings suppressed
  - $Z-Z-h$ and $Z-H-A$ coupling nearly maximal.
- For direct production, if have sufficient energy can have unsuppressed production of $e^+e^- \to Z^* \to HA$.
- Substantial decay channels such as $A/H \to b\bar{b}$, $A/H \to t\bar{t}$, $H \to hh \to 4b$, and $A \to Zh \to Zb\bar{b}$ easier to detect than LHC.
- Not as much uncertainty as LHC in production cross section.
- Should be able to close out wedge without as much ambiguity about theory errors.

Conclusions

- Higgs discovery just beginning of the exploration of EWSB.
- One popular alternative to the SM EWSB scenario is the MSSM.
- Contains 5 Higgs bosons: $h, H, A, H^{\pm}$
- We used current constraints from ATLAS and CMS on $\sigma(pp \to H/A \to \tau^+\tau^-)$ to explore high $\tan\beta$ regime and extrapolate bounds on the $M_A - \tan\beta$ plane at 300 and 3000 fb^{-1}
- Found with 300 fb^{-1}
  - ATLAS can exclude $m_h^{\max}$ benchmark for $M_A \lesssim 210 - 240$ GeV
  - CMS can exclude $m_h^{\max}$ benchmark for $M_A \lesssim 230 - 260$ GeV
- Found with 3000 fb^{-1}
  - ATLAS can exclude $m_h^{\max}$ benchmark for $M_A \lesssim 260 - 290$ GeV
  - CMS can exclude $m_h^{\max}$ benchmark for $M_A \lesssim 290 - 360$ GeV
- To examine low $\tan\beta$ regime, also placed bounds on $A \to Zh$ production via the bound on SM Vh production with $M_h = 125$ GeV.
- In the $m_h^{\max}$ scenario with $200\text{ GeV} \lesssim M_A \lesssim 250\text{ GeV}$, LHC is sensitive to $\tan\beta \lesssim 2$ with 300 fb^{-1} and $\tan\beta \lesssim 3$ with 3000 fb^{-1}
- Increasing M_2 can substantially strengthen all bounds.

EXTRA SLIDES

M_h in the m_h^{max} scheme



- Now know $M_h \sim 125.5$
- Band in $\tan\beta - M_A$ plane for which M_h inside 125.5 ± 3 GeV range.