Pheno 2010 May 10, 2010

The MSSM Higgs Case for Run III at the Tevatron

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Run III at the Tevatron

- Current plan for the Tevatron: shut down at the end of 2011.
- Recent discussion: run through 2014 (“Run III”). Very interesting! Proposal requires among other things a careful analysis of physics potential.
- Many possibilities for what might come out of the Tevatron in 3 extra years. Higgs is the breadwinner and the case for Run III has to be built on the Higgs reach.
- Practically, will need broad support from community outside the Fermilab/Chicago area.
- This talk: Projected Run III Higgs reach of the Tevatron in the SM and MSSM, cf. 2011 reach.

LHC

- Important side question: Why should the Tevatron continue to run through 2014 if the LHC will eventually surpass it?

- Same reason the shutdown was pushed back from 2010 to 2011: it is the conservative approach. As long as the Tevatron is producing superior physics results, use it!

- For low-mass Higgs physics, 2014 is likely the earliest that the LHC can start becoming competitive. May take even longer, particularly those channels that clearly demonstrate relation of Higgs to EWSB (WH and VBF->$\tau\tau$). WH is strong and proven channel at the Tevatron.

Basic Numbers for 2011 Projections

Wade Fisher — Tevatron Low Mass Higgs Searches — 21

Higgs Sensitivity Projections

Moriond EW
March 7th 2010

A few active areas of analysis improvements (not a full list!):

- Demonstrated charm quark discrimination ability: ~30% equiv lumi gain
- Improved usage of b-Tagging information: ~20% equiv lumi gain
- Reduced dijet mass resolution: ~15% equiv lumi gain
  for every 1% absolute gain in σ_{Mbb} for up to ~50-60% possible
- Addition of lower yield final states ($H\rightarrow\tau\tau/\gamma\gamma/ZZ/l\nu jj$, etc): ~5-10% equiv lumi gain
- Improved lepton ID eff & reduced inst. lumi dependence: ~5-10% equiv lumi gain

These factors alone can buy us ~1.4× in the limit (~2× in effective luminosity)

Additional improvements ongoing, eg. ττ channels -> projections typically done with **50%** improvements.
CDF and D0 each have about 7 fb^{-1} of analyzable data at present, and are gaining data at >2fb^{-1}/yr. Expect to have about **10 fb^{-1} apiece** by the end of 2011.

FROM 2011 TO RUN III

- 2011: 10 fb^{-1}/experiment, ~50% analysis improvements in primary search channels w.r.t. March 2009

- 2014: same improvements, possibly more, 16 fb^{-1}/experiment

- Sensitivity scales approximately with Sqrt(L)x(ε)

- ∴ bottom line: Assuming no further analysis improvements, Run III gives Sqrt(16/10) ≈ 27% improvement over 2011.

How far can 27% go?

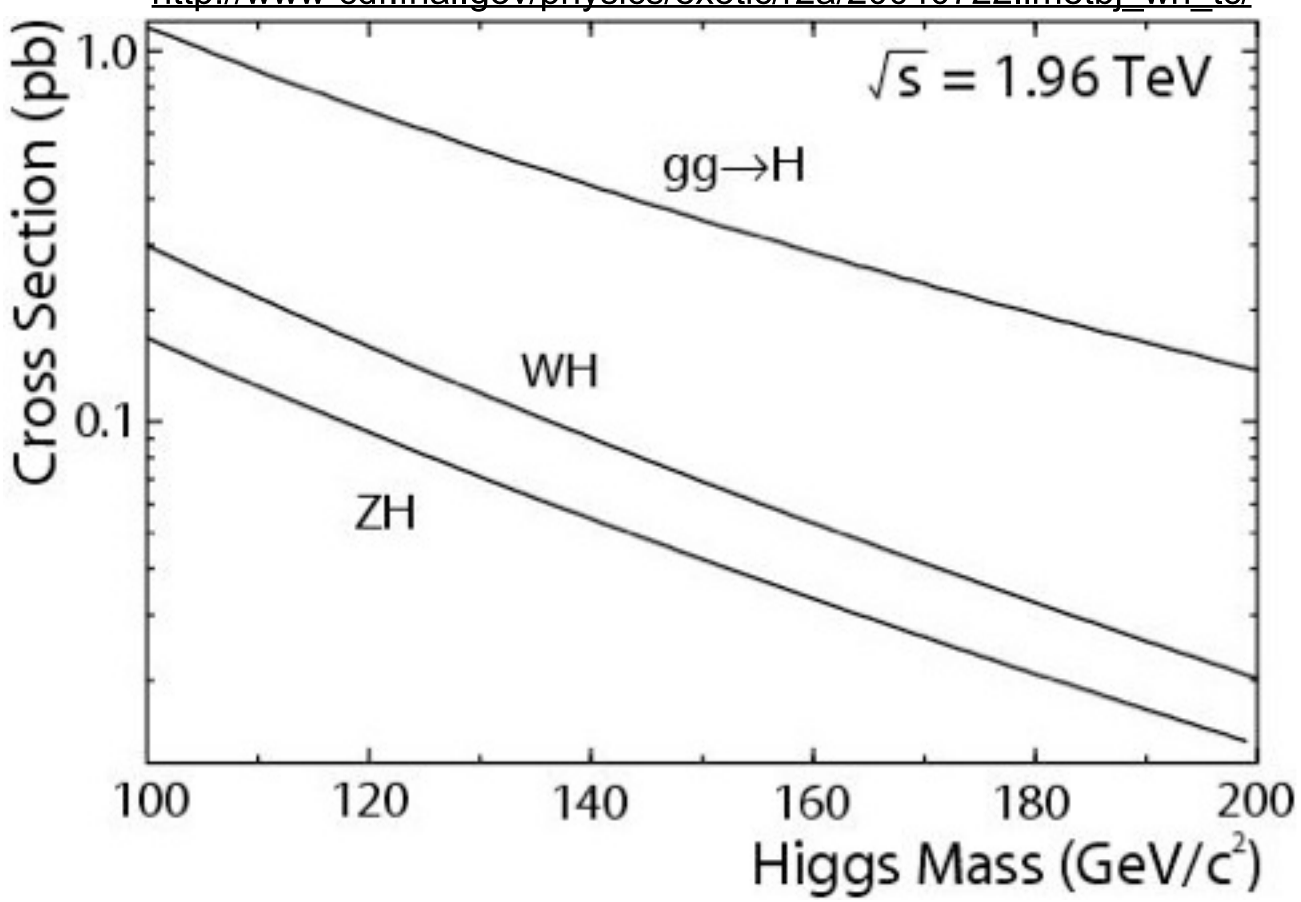
- Standard Model Higgs
  P. Draper, T. Liu, and C.E.M Wagner, Phys.Rev.D80:035025, 2009 (arxiv:0905.4721)

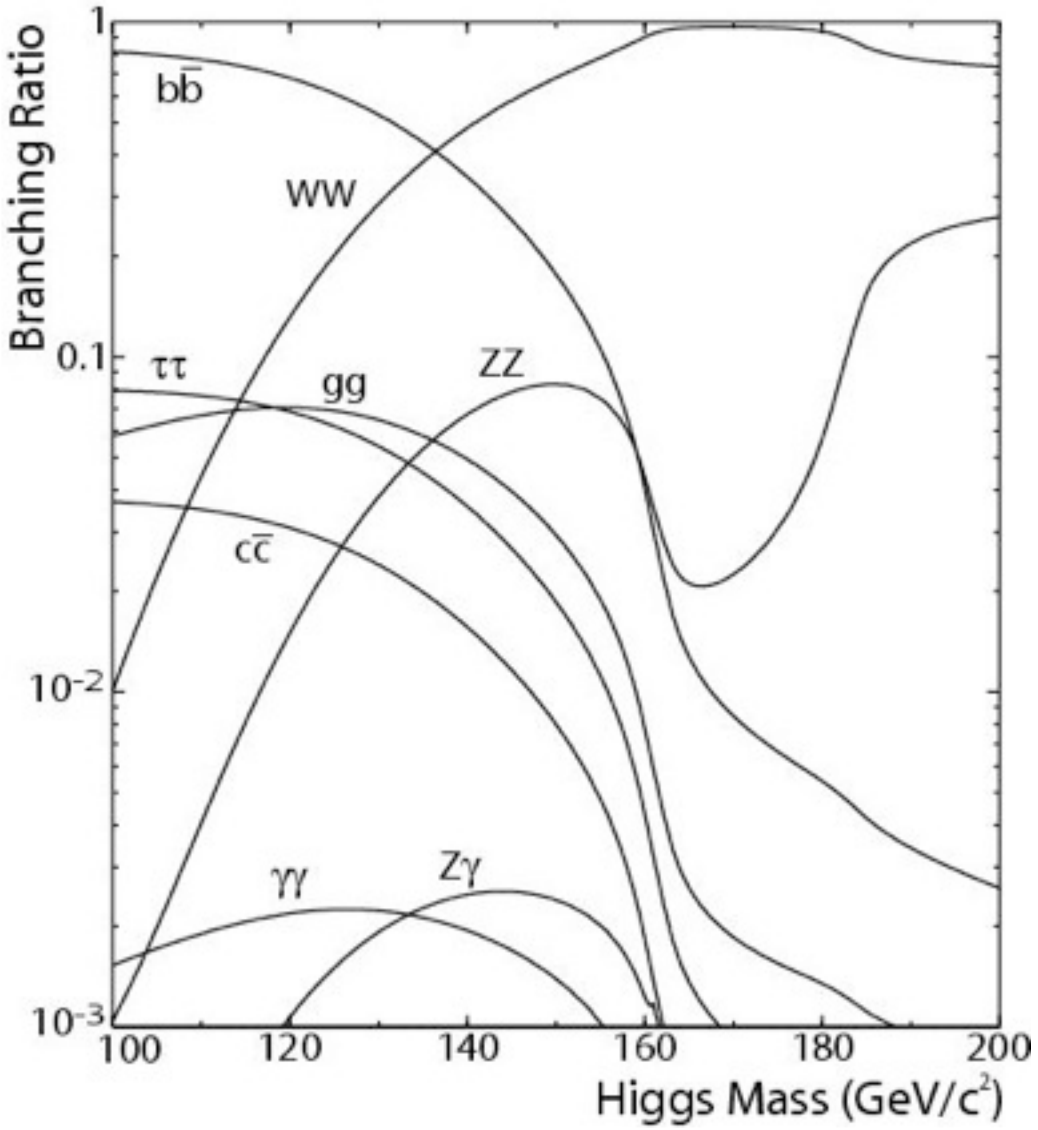
- MSSM: 2 EW-Scale CP-conserving Benchmark Scenarios (Maximal and Minimal Mixing). SM-like searches and searches that target MSSM Higgs with weak gauge boson couplings
  P. Draper, T. Liu, and C.E.M Wagner, Phys.Rev.D80:035025, 2009 (arxiv:0905.4721)
  P. Draper, T. Liu, and C.E.M Wagner, Phys.Rev.D81:015014, 2010 (arxiv:0911.0034) (Also treats MSSM with CP-violating EW-Scale parameters)

- MSSM: High-Scale embeddings (CMSSM, GMSB)
  M. Carena, P. Draper, S. Heinemeyer, T. Liu, C.E.M. Wagner, and G. Weiglein, In Preparation

HIGGS SEARCH CHANNELS AT THE TEVATRON

http://www-cdf.fnal.gov/physics/exotic/r2a/20040722.lmetbj_wh_tc/

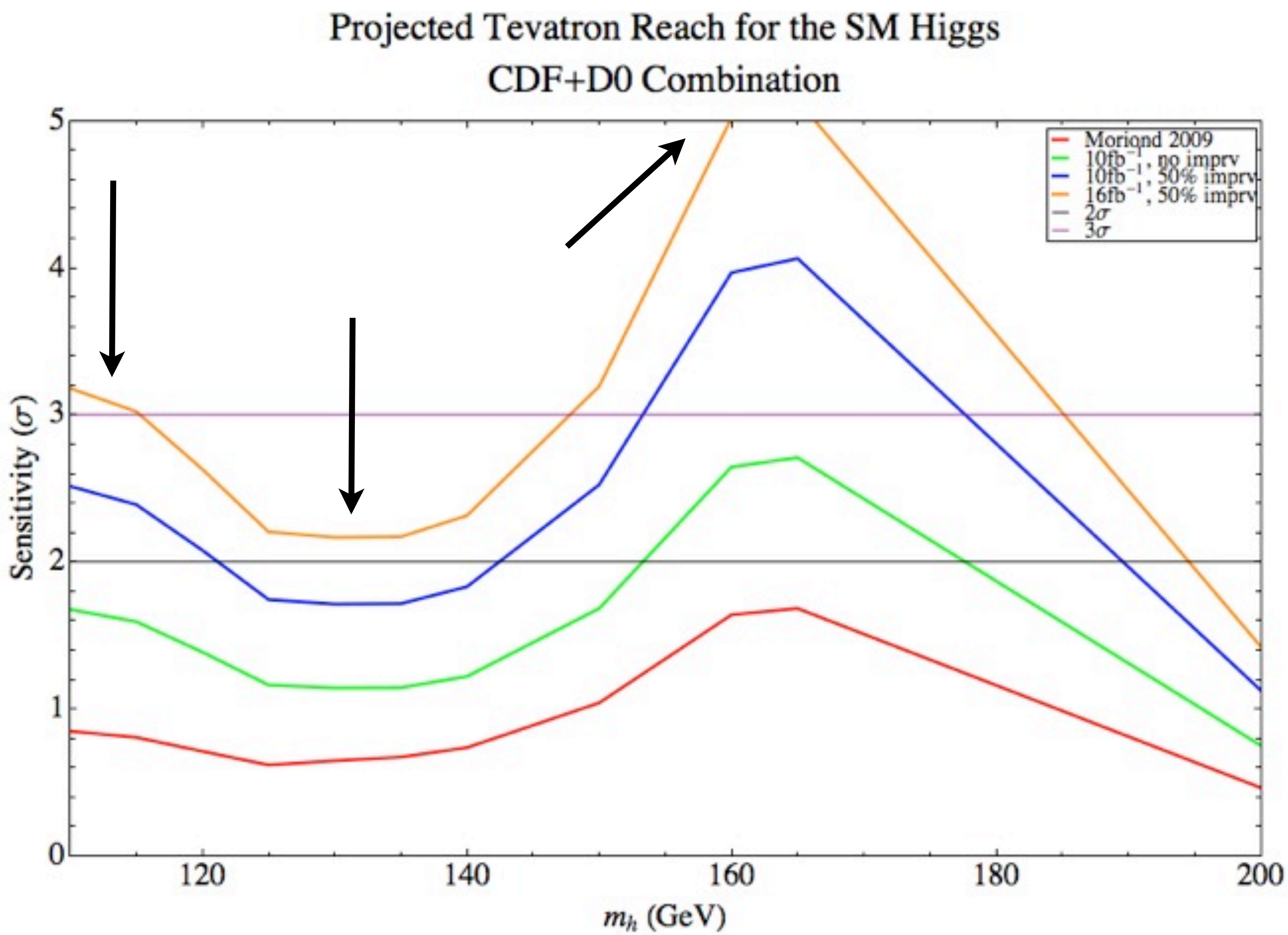




Multiple channels from CDF and DZero can be put together to give a combined sensitivity S in units of Gaussian standard deviations. Approximately add in quadrature.

$$\sum \left(\frac{\epsilon_i}{\epsilon_i^0} \sqrt{\frac{L_i}{L_i^0}} \times \frac{s_i}{\sqrt{b_i}} \right)^2 = S^2$$

Prospects for SM Higgs Searches at the Tevatron



CDF+D0 multi-channel combination. WH->bb dominates at 115 GeV, gg->H->WW dominates at 160 GeV. Both contribute in intermediate range.

OUTLINE

- Standard Model Higgs

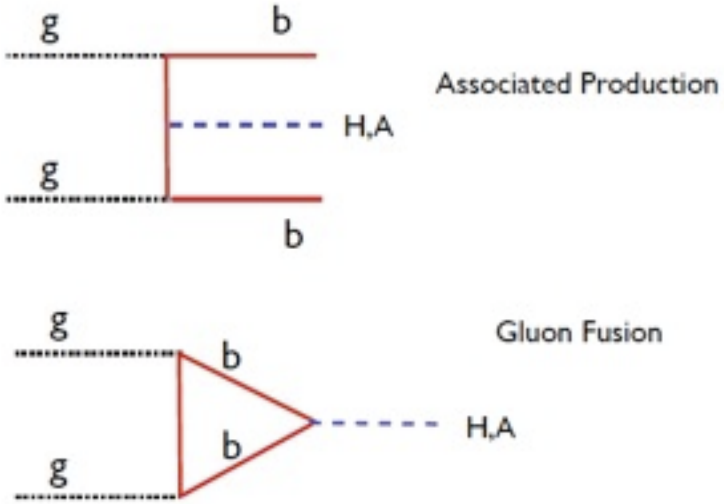
- MSSM: EW-Scale Benchmark Scenarios

  P. Draper, T. Liu, and C.E.M Wagner, Phys.Rev.D80:035025, 2009 (arxiv:0905.4721)
  P. Draper, T. Liu, and C.E.M Wagner, Phys.Rev.D81:015014, 2010 (arxiv:0911.0034)

- MSSM: High-Scale embeddings

CP-conserving MSSM Higgs Sector

- Two CP-even mass eigenstates h, H and one CP-odd mass eigenstate A
- Typically one CP-even Higgs has couplings to gauge bosons similar to those of the SM Higgs ("SM-like"), and one couples very weakly to VV ("Nonstandard")
- At tree level, m_A and $\tan\beta \equiv \langle H_u^0 \rangle / \langle H_d^0 \rangle$ completely determine the Higgs mass spectrum and their couplings to the SM particles.
- $m_{nonstandard} \simeq m_A$
- Nonstandard Higgs has tan β-enhanced couplings to down-type fermions -> new search channels are gluon fusion through a b quark loop and b-associated production, with decay to ττ



$H_i \to \tau\tau$

Procedure

- Choose benchmark values for $A_t, \mu, M_S \ldots$, which represent generic or interesting effects of the radiative corrections
- Study the sensitivity on the m_A - tan β plane in each scenario

$$S_{MSSM,i} = S_{SM,i} \times \frac{\sigma_{MSSM,i} Br_{MSSM,i}}{\sigma_{SM,i} Br_{SM,i}}$$

- Allow each channel to go through any MSSM Higgs state

$$gg \to h \to WW, \quad gg \to H \to WW$$

- Rescale by efficiency and luminosity gains, recombine channels
- Initially look at SM-like search channels only, then combine with Nonstandard search channels to get maximum sensitivity to MSSM Higgs parameter space

Maximal & Minimal Mixing Scenarios

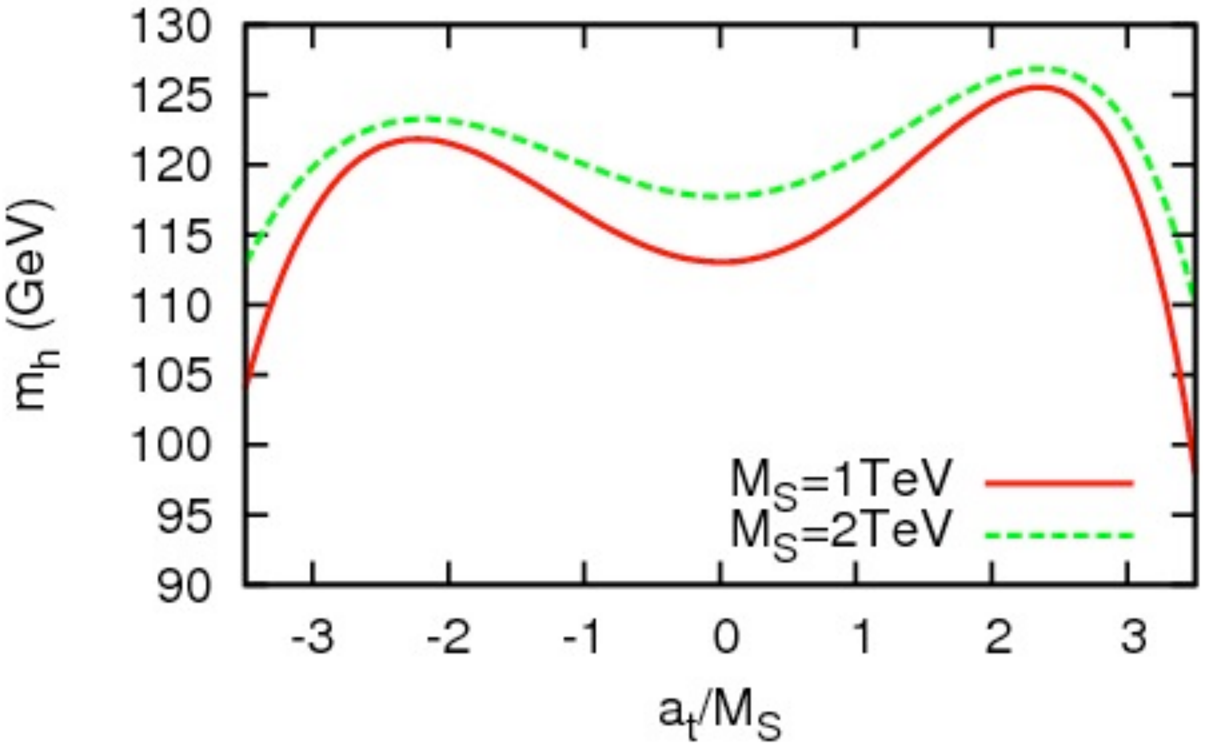
Carena, Quiros, Espinosa, & Wagner '95

(Large m_A limit)

$$m_h^2 = m_Z^2 \cos^2 2\beta \left(1 - \frac{3m_t^2}{8\pi^2 v^2} t\right) + \frac{3m_t^4}{4\pi^2 v^2}\left[\frac{1}{2}X_t + t + \frac{1}{16\pi^2}\left(\frac{3m_t^2}{2v^2} - 32\pi\alpha_3^2\right)(X_t t + t^2)\right]$$

$$X_t \equiv \frac{2a_t^2}{M_S^2}\left(1 - \frac{a_t^2}{12M_S^2}\right), \quad a_t \equiv A_t - \mu/\tan\beta, \quad t \equiv \log\frac{M_S^2}{m_t^2}$$

m_h vs a_t: $\tan\beta=50$, $m_A=300$GeV, $\mu=200$GeV



Maximal Mixing: $a_t = \sqrt{6}M_S$

$M_S = 1$ TeV

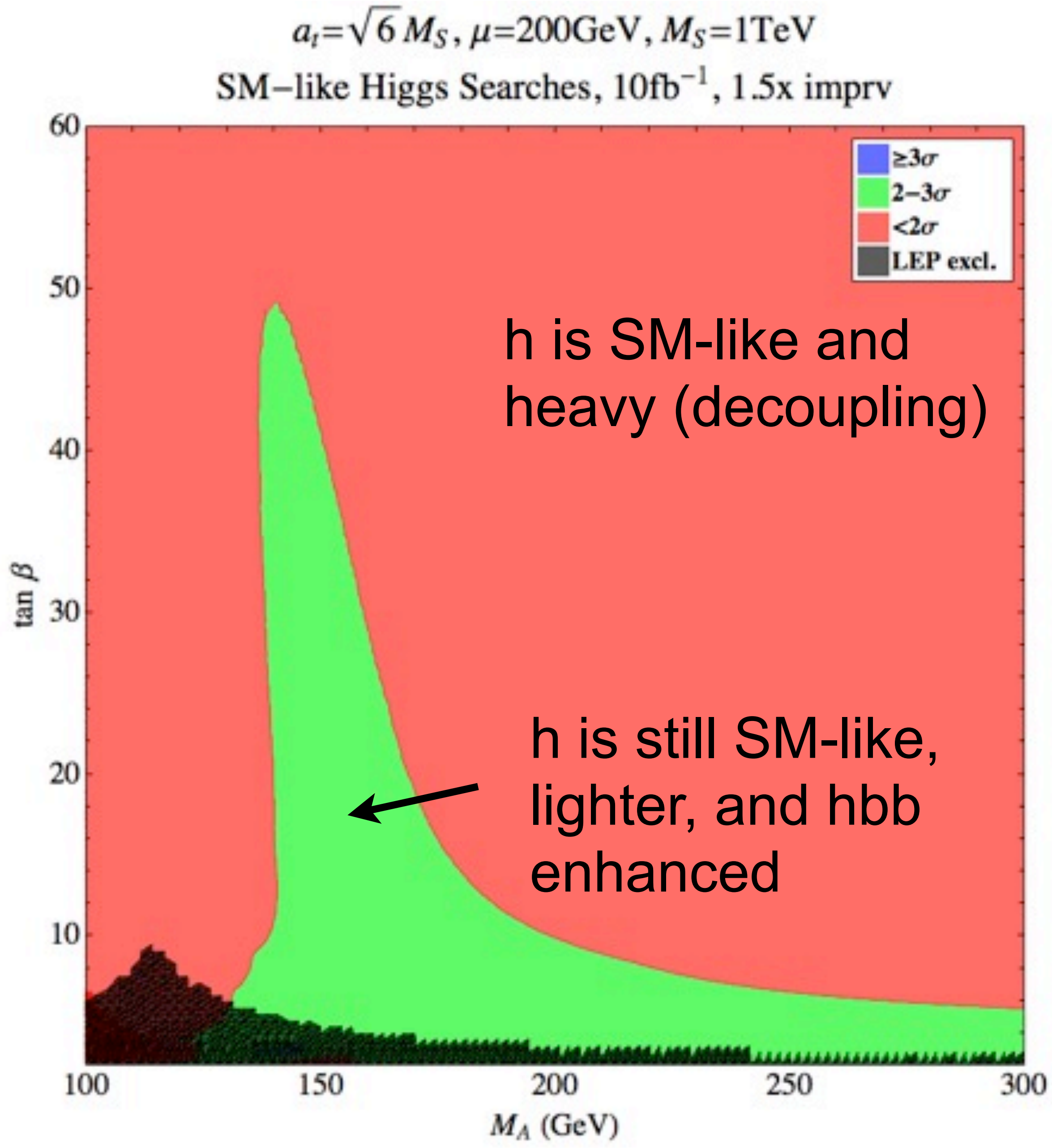
$$125 \text{ GeV} \lesssim m_h \lesssim 130 \text{ GeV}$$

Minimal Mixing: $a_t = 0$

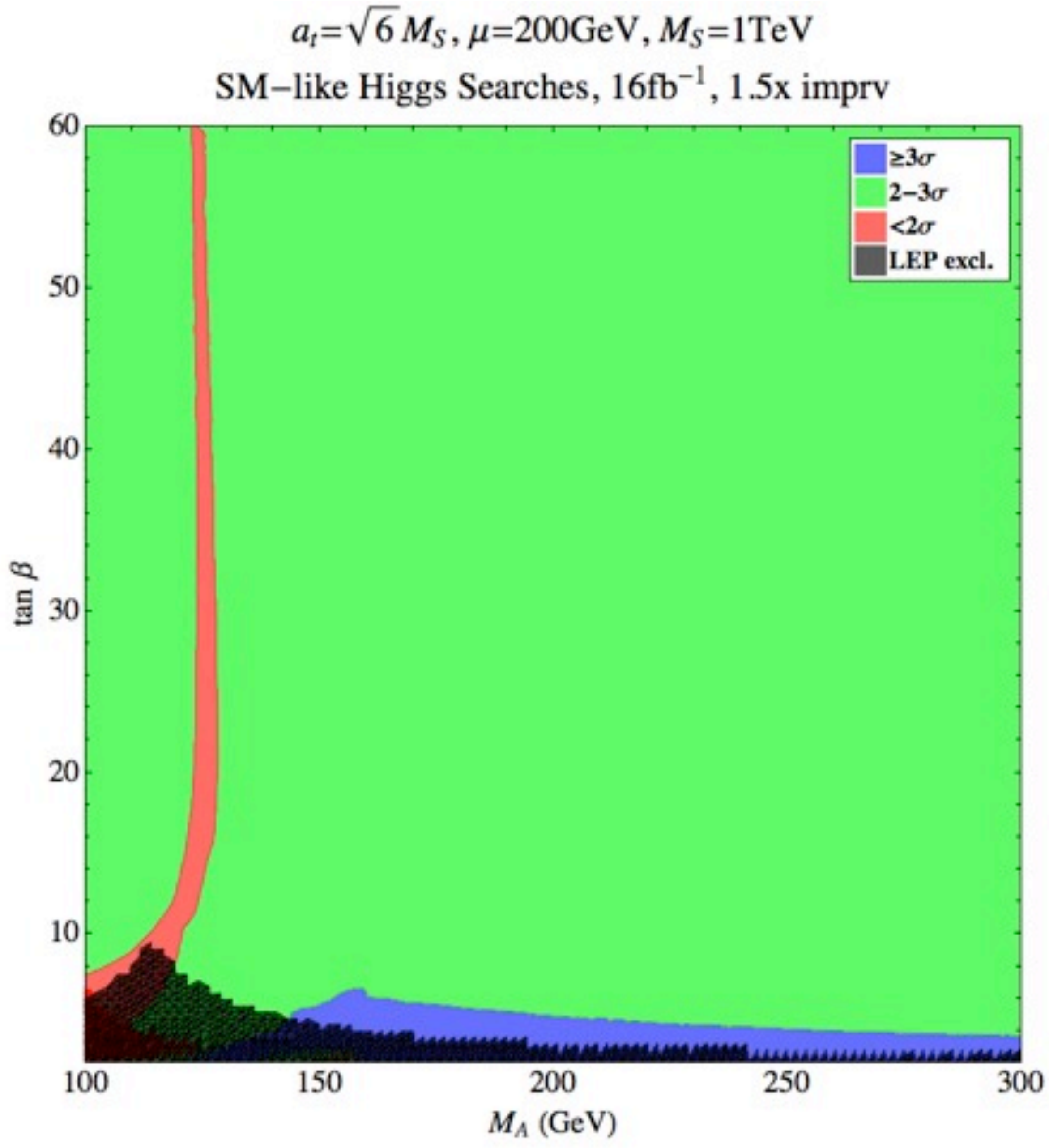
$M_S = 2$ TeV

$$111 \text{ GeV} \lesssim m_h \lesssim 116 \text{ GeV}$$

Maximal Mixing Scenario (SM-like Higgs Searches)

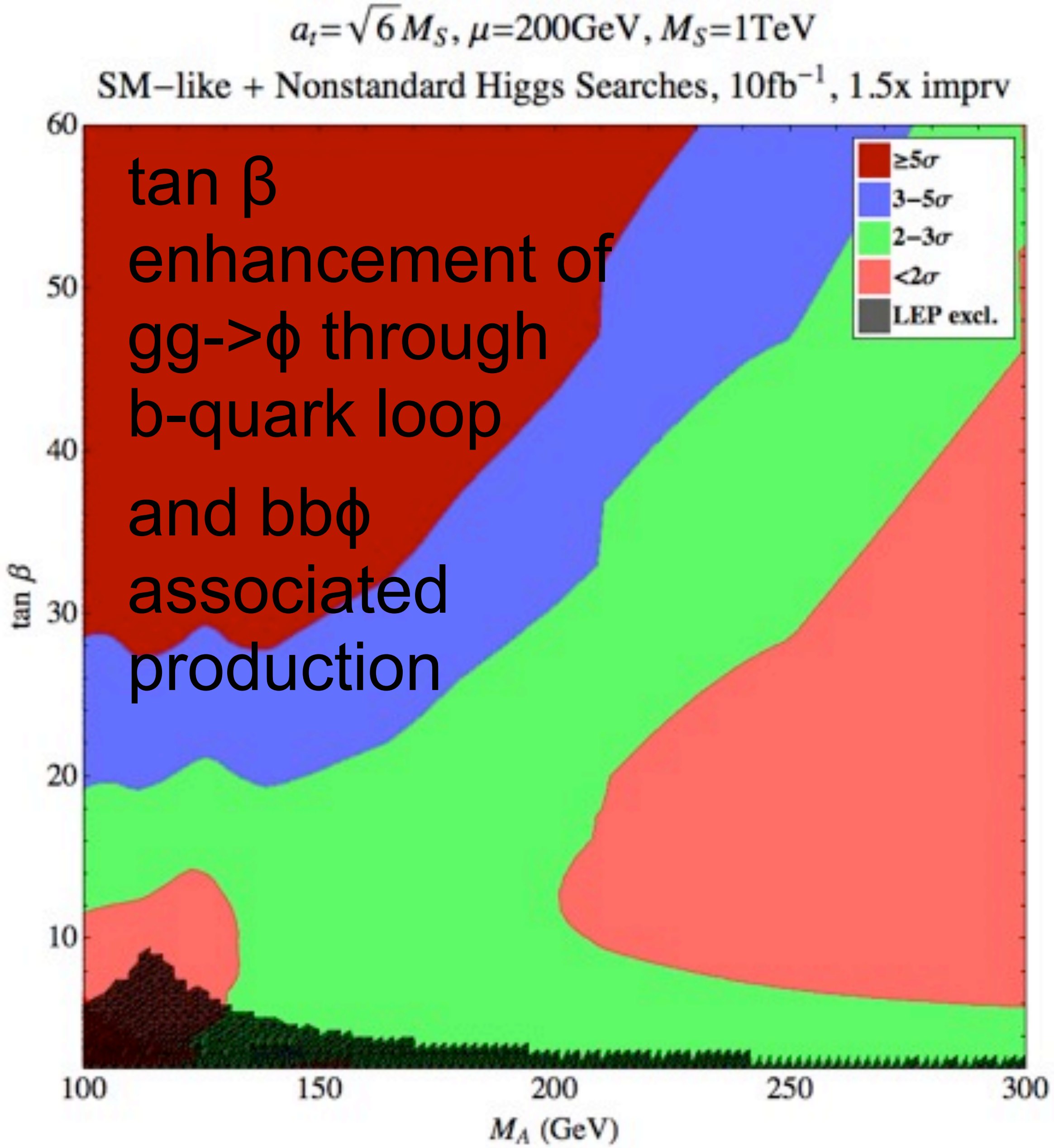


2011

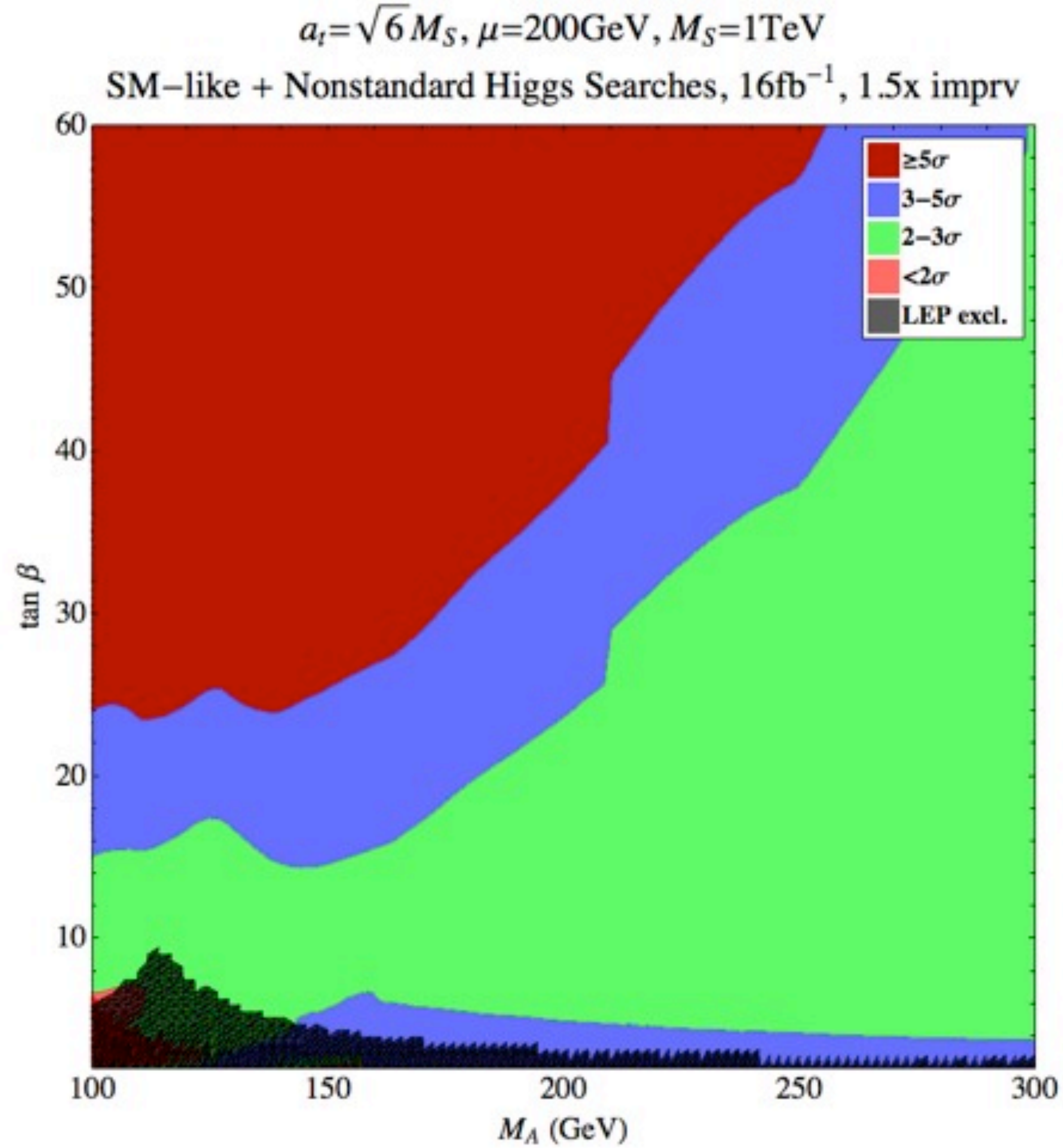


Run III

Maximal Mixing (Nonstandard + SM-like Higgs Combined Reach)

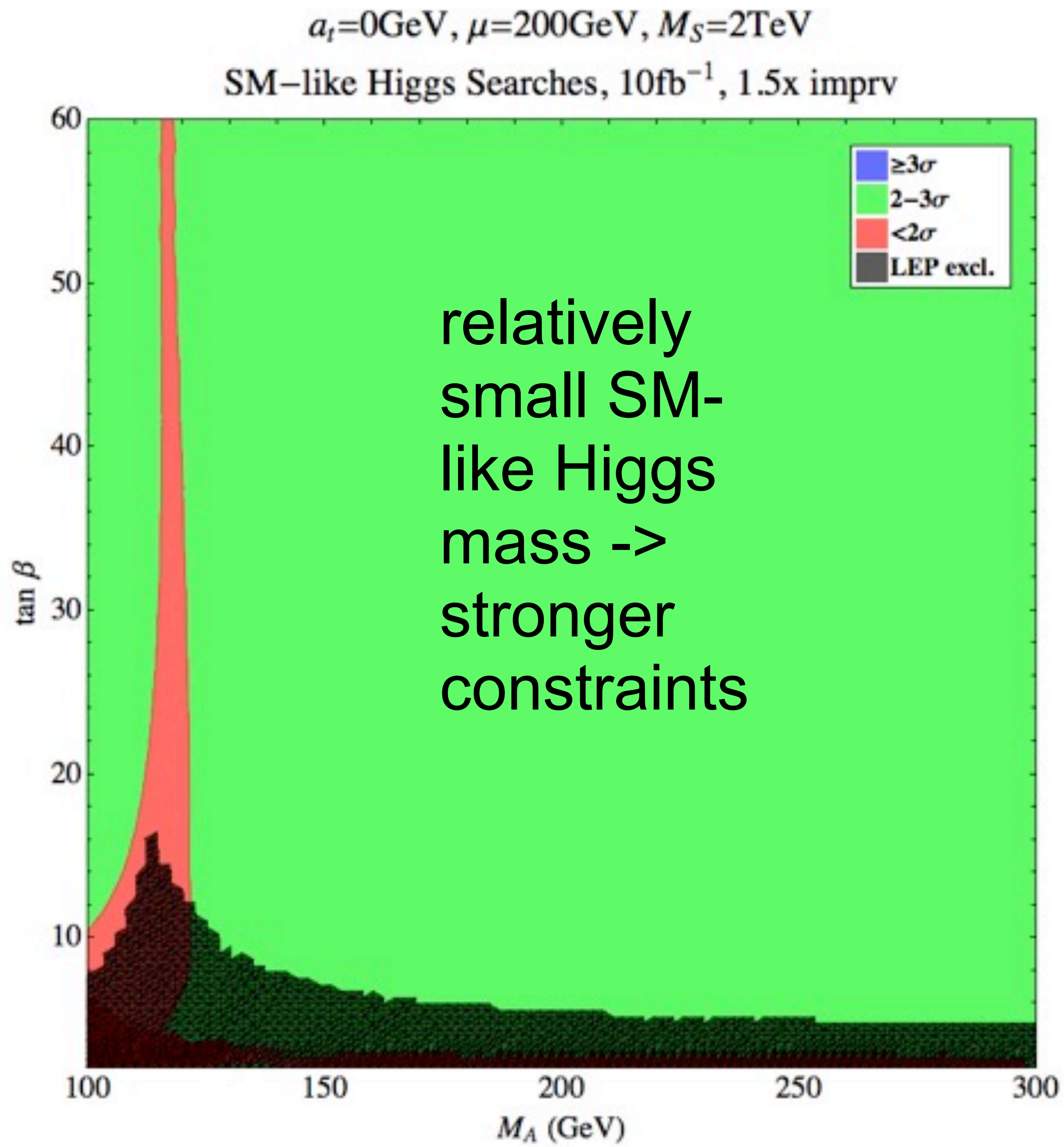


2011



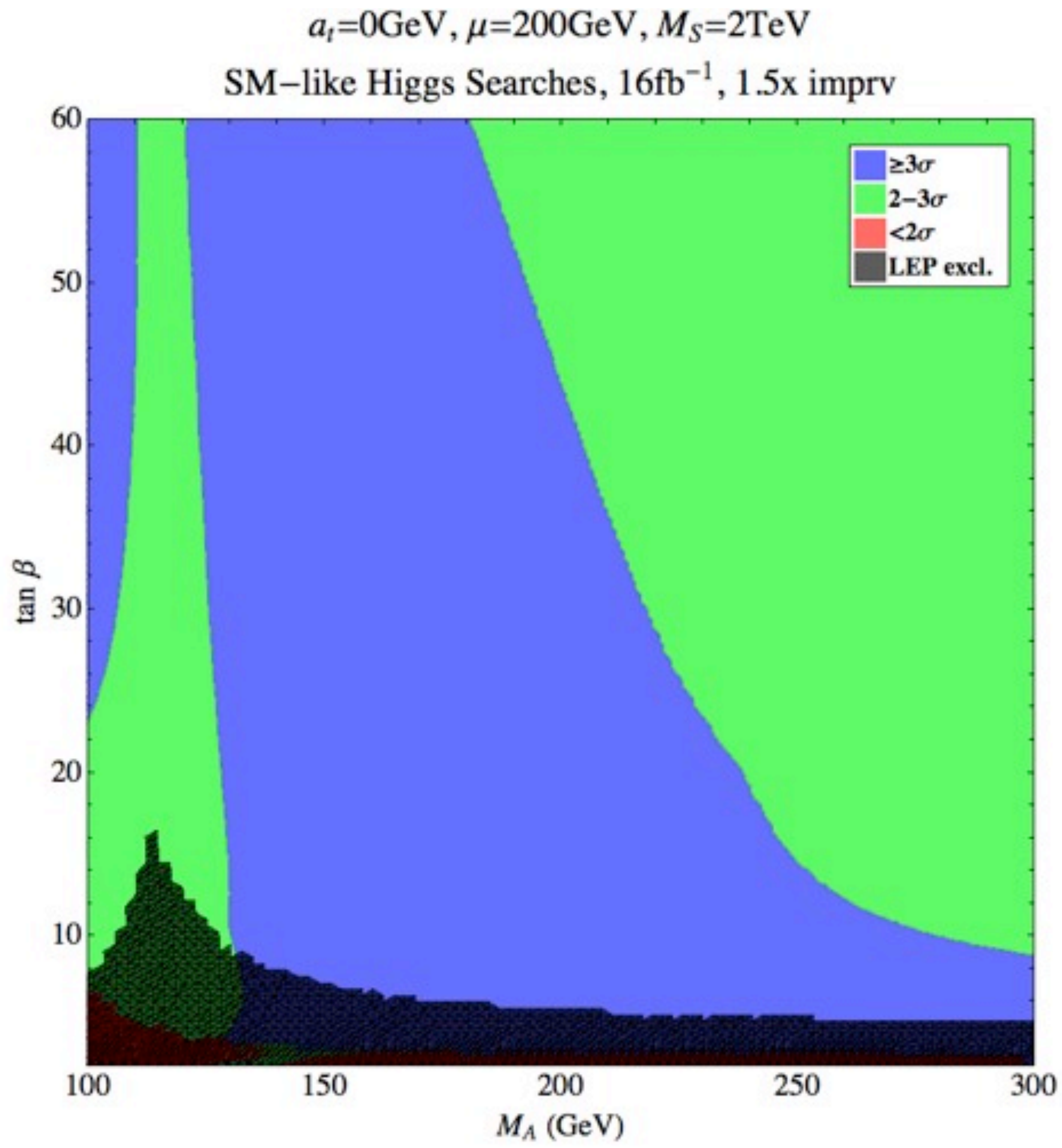
Run III

Minimal Mixing Scenario (SM-like Higgs Searches)



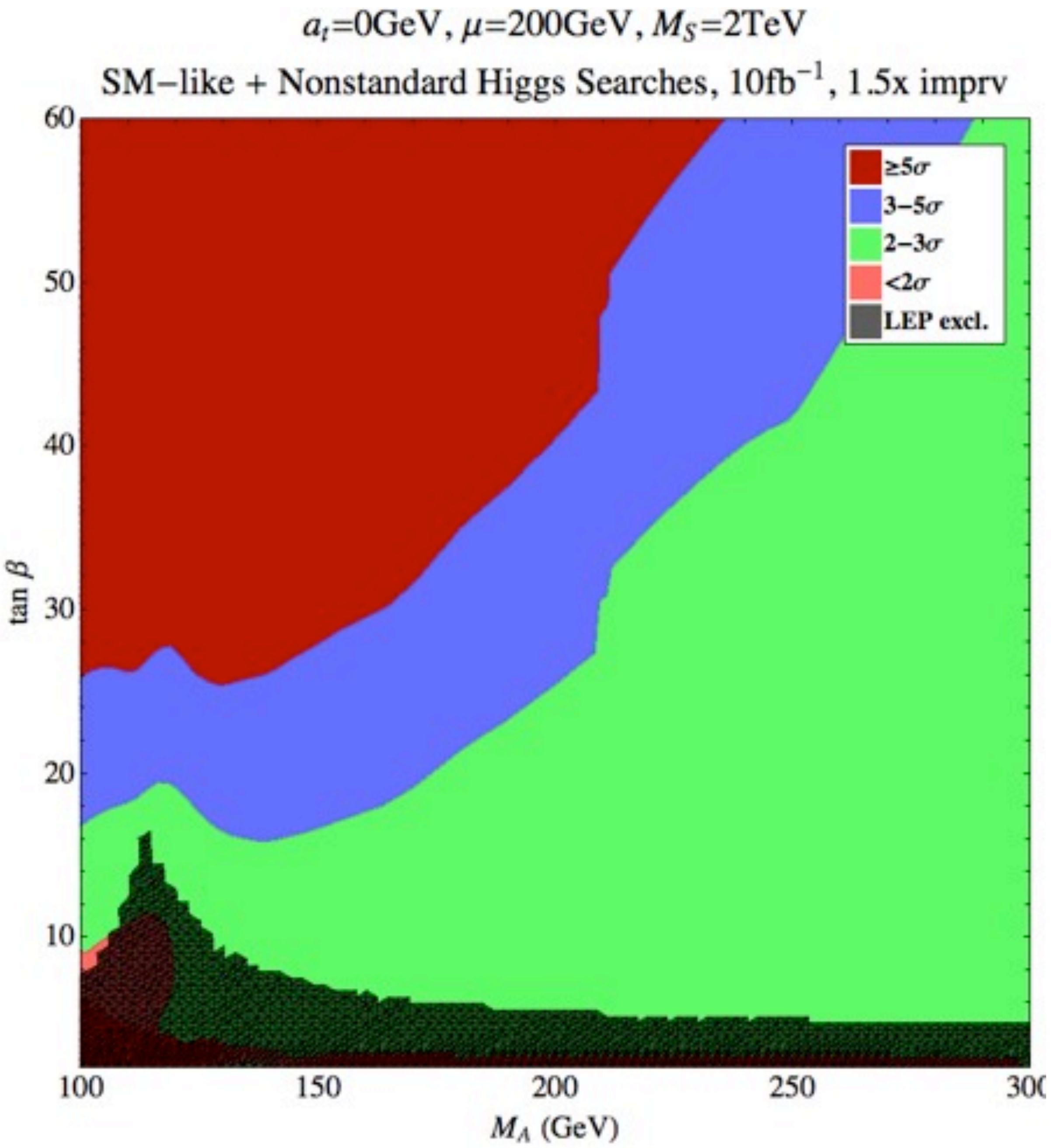
relatively small SM-like Higgs mass -> stronger constraints

2011

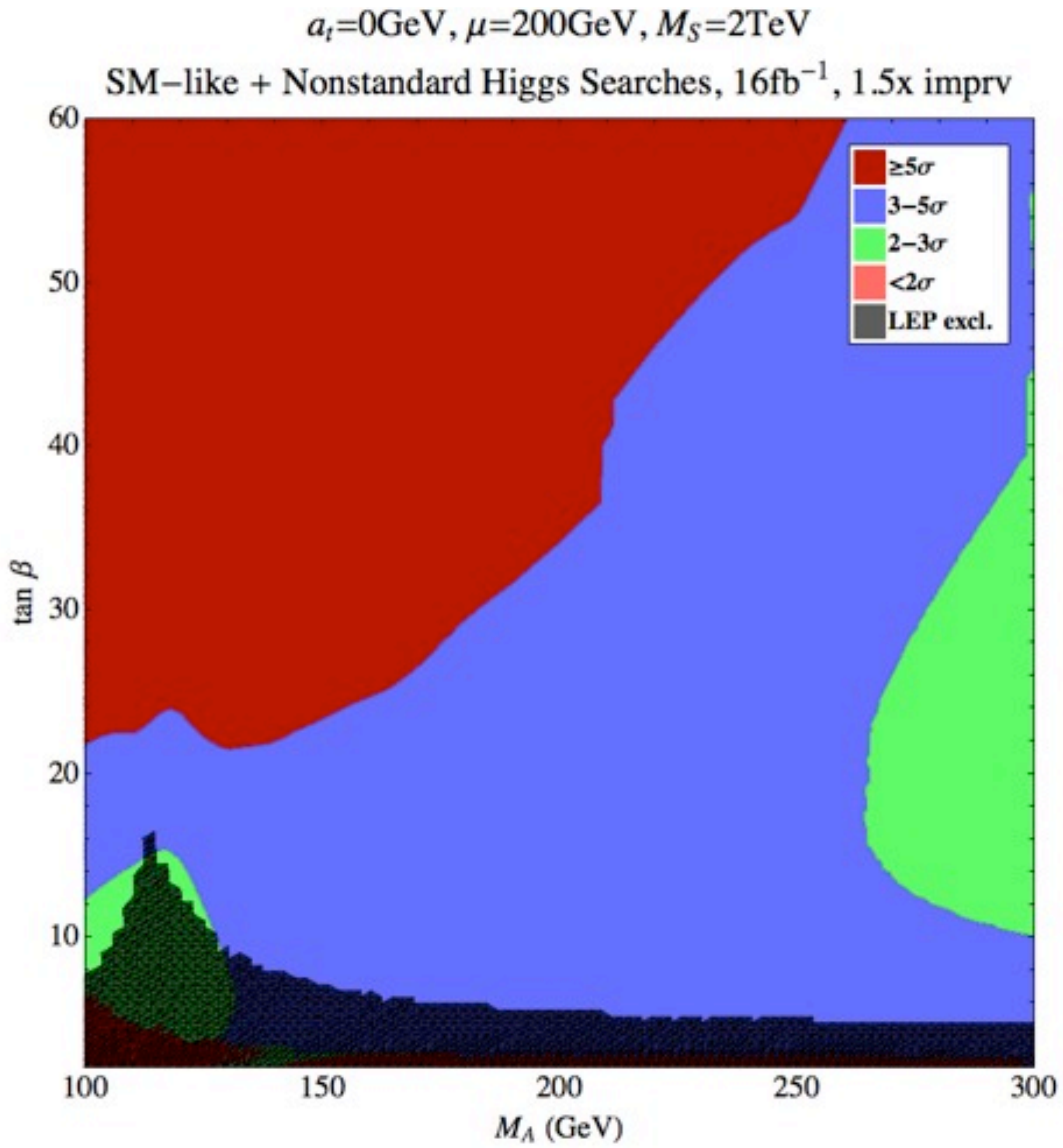


Run III

Minimal Mixing (Nonstandard + SM-like Higgs Combined Reach)



2011



Run III

OUTLINE

- Standard Model Higgs
- MSSM: EW-Scale Benchmark Scenarios
- MSSM: High-Scale embeddings

  M. Carena, P. Draper, S. Heinemeyer, T. Liu, C.E.M. Wagner, and G. Weiglein, In Preparation

Scans in High-Scale Models: CMSSM & GMSB

Constrained MSSM: Scan over GUT-scale values for common soft scalar mass m_0, gaugino mass $m_{1/2}$, trilinear coupling A_0, and tan beta.

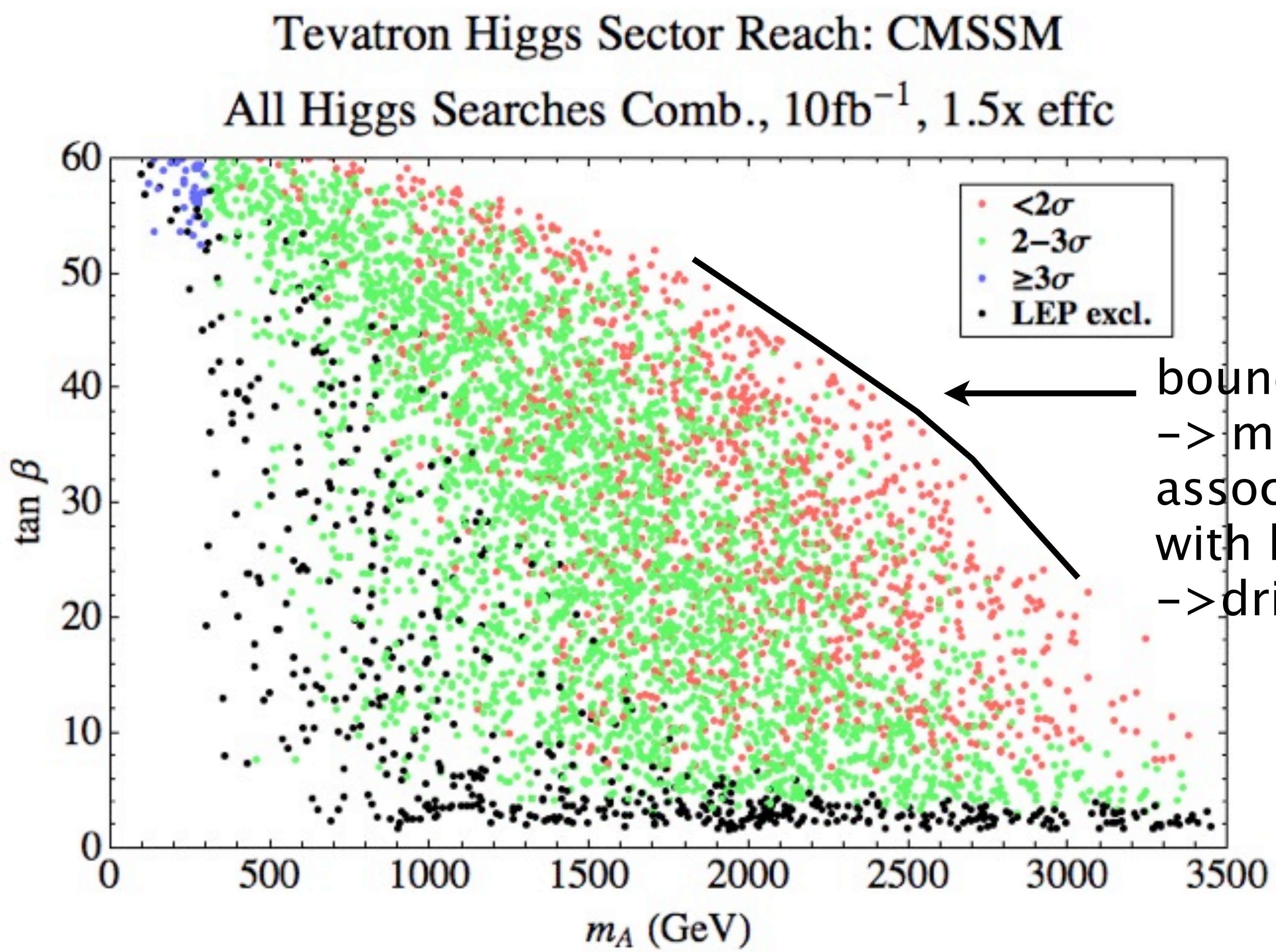
$$
\begin{gathered}
50\ \text{GeV} < m_0 < 2\ \text{TeV} \\
50\ \text{GeV} < m_{1/2} < 2\ \text{TeV} \\
-3\ \text{TeV} < A_0 < 3\ \text{TeV} \\
1.5 < \tan\beta < 60
\end{gathered}
$$

Minimal Gauge Mediation: Scan over...
-messenger scale M_{mess} where SUSY-breaking is communicated to the MSSM
-SUSY-breaking vev scale $\Lambda \sim \langle F \rangle / \langle S \rangle$ (soft masses ~ $\alpha\Lambda/4\pi$)
-number of messengers N_{mess} in complete SU(5) $5+\bar{5}$ reps
-tan beta

$$
\begin{gathered}
10^4\ \text{GeV} < \Lambda < 2 \times 10^5\ \text{GeV} \\
\Lambda < M_{mess} < 10^4 \times \Lambda \\
1 \leq N_{mess} \leq 8 \\
1.5 < \tan\beta < 60
\end{gathered}
$$

Run to EW scale and look at Higgs sector reach.

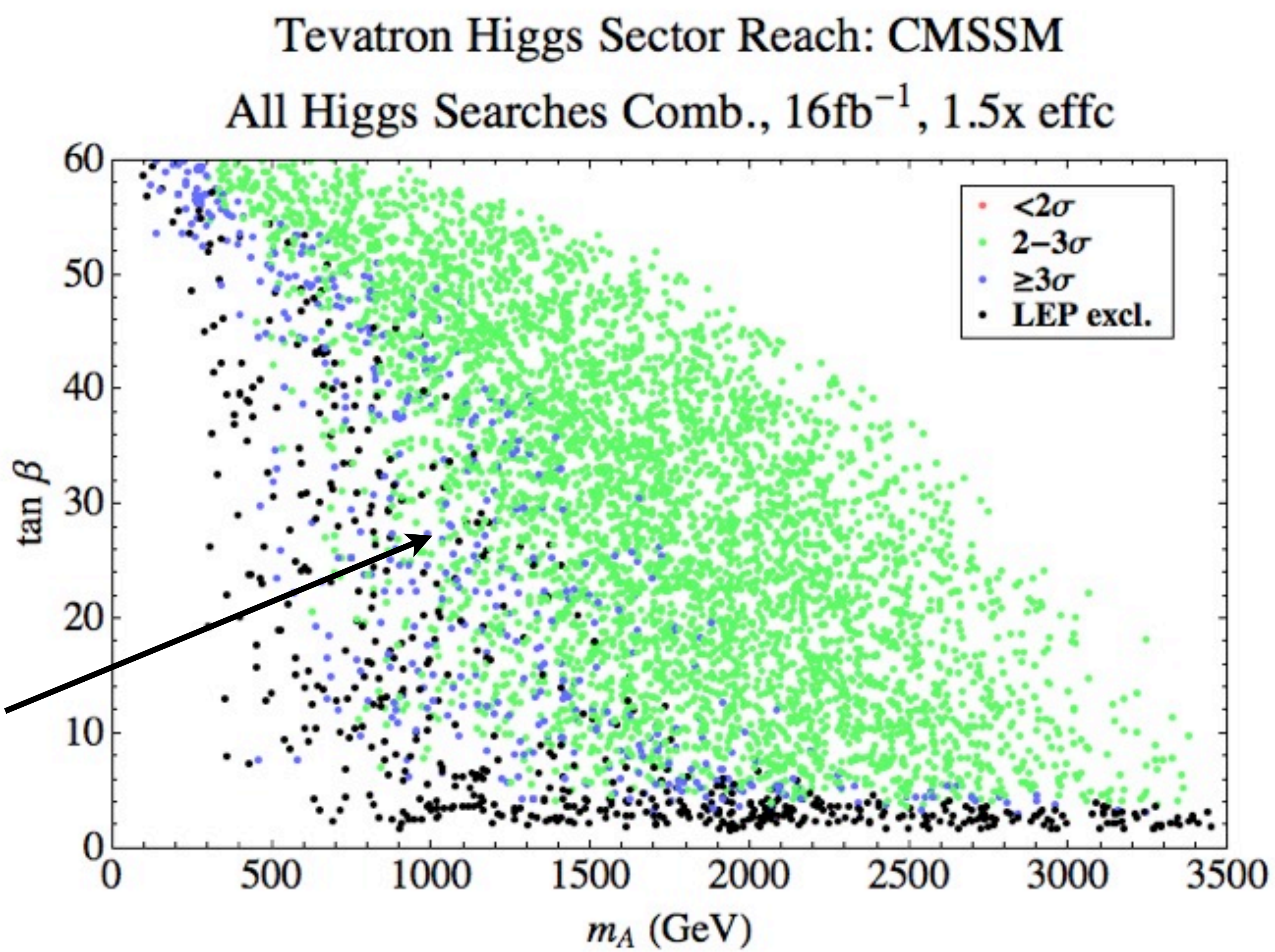
CMSSM 10fb^{-1}



boundary saturation
-> $m_{Hu}-m_{Hd}$ larger,
associated by RG
with heavy squarks
->drives up m_h

2011

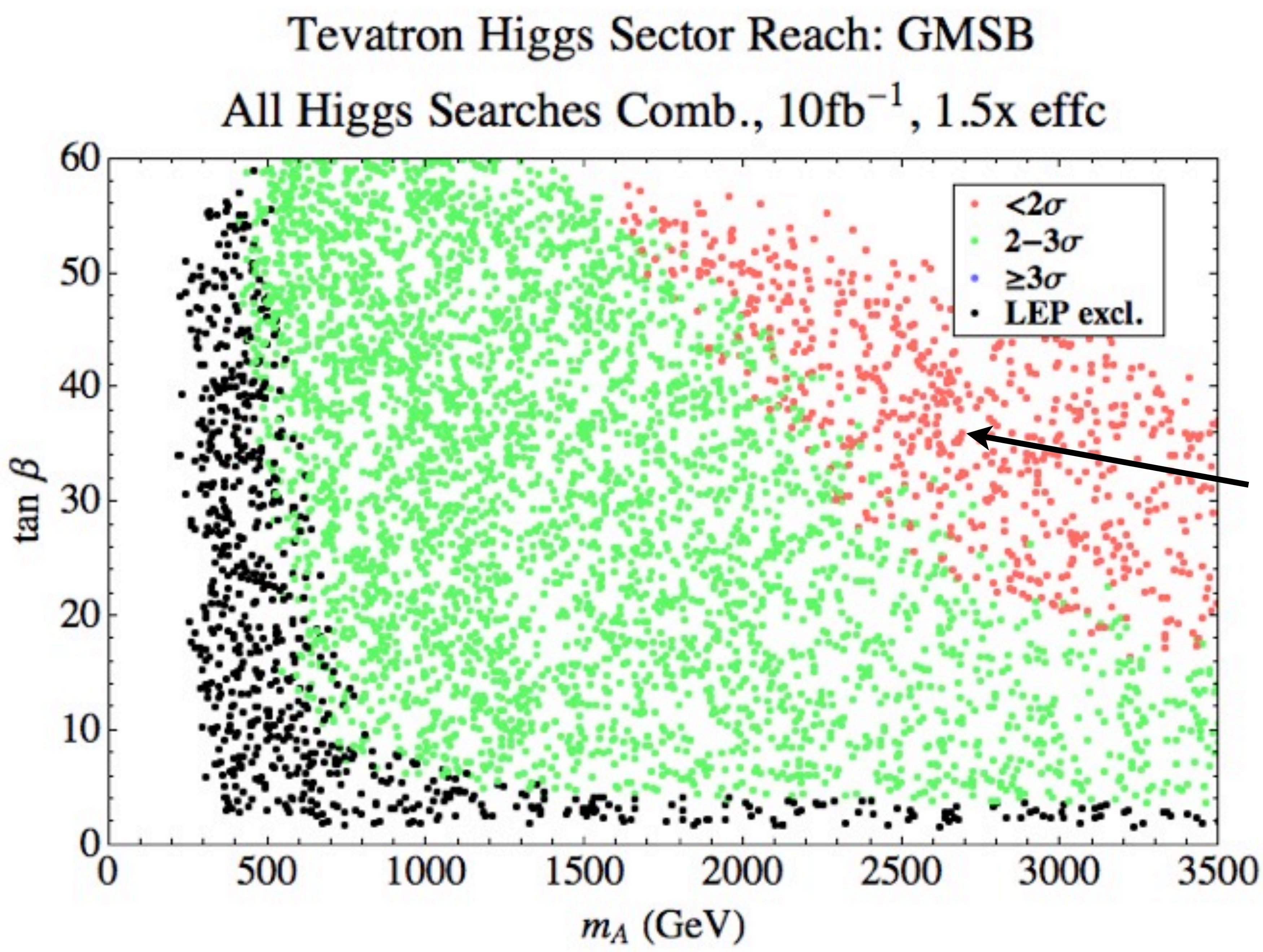
CMSSM 16fb^{-1}



lower m_A -> m_{Hu}–m_{Hd} smaller associated with lighter squarks -> lower m_h

Run III

GMSB 10fb^{-1}

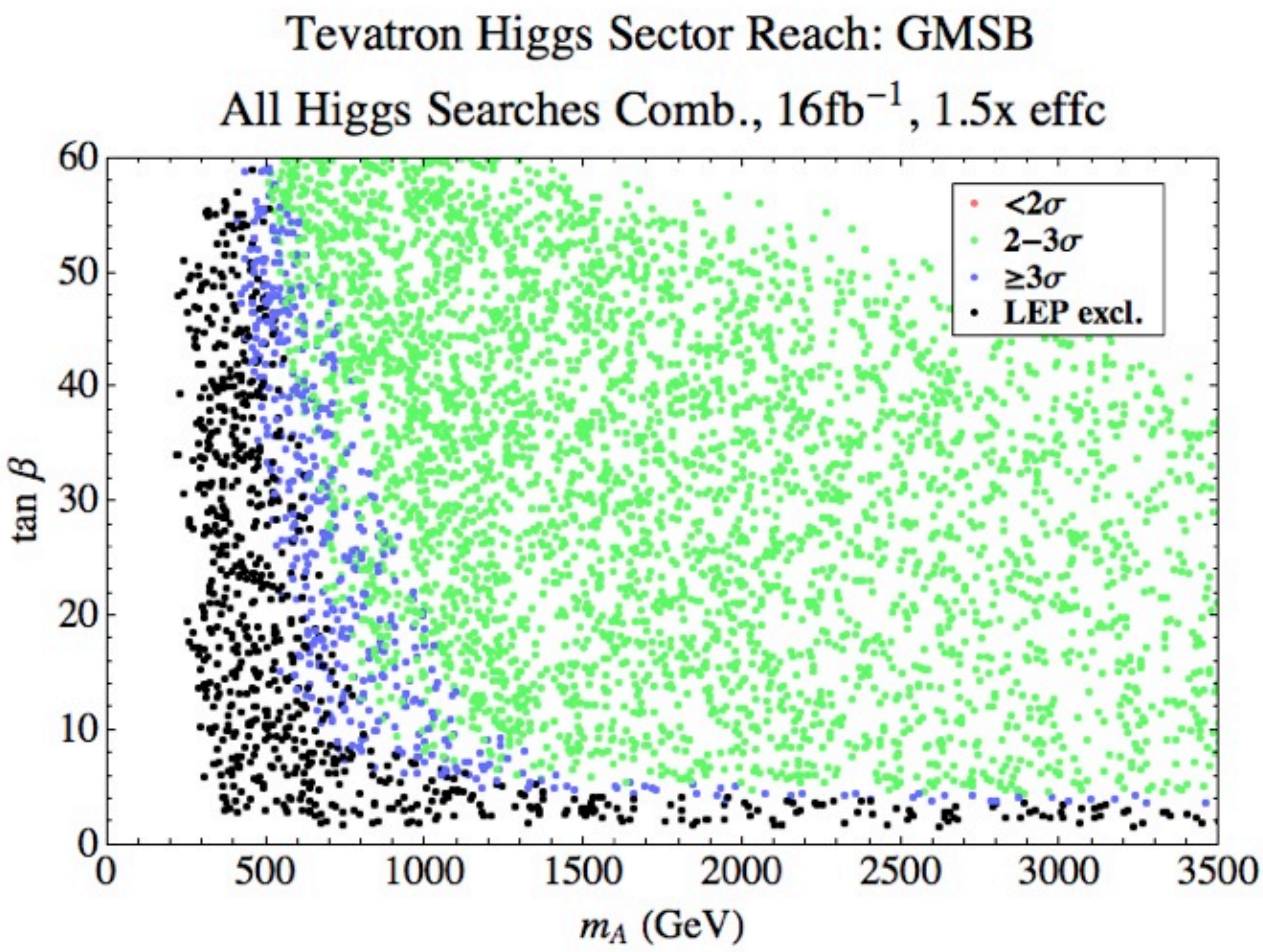


small A terms, light h

All very near 2σ

2011

GMSB 16fb^{-1}



Run III

Conclusions

SM Higgs: Run III can offer 3σ sensitivity in the low mass range, 5σ sensitivity around WW threshold, and full 2σ exclusion coverage over the whole mass range. None of these are projected with a 2011 shutdown.

MSSM Higgs: With a combination of SM-like and nonstandard Higgs searches, Run III gives the Tevatron exclusion power over the whole parameter space of standard benchmark scenarios at the 2σ level and offers 3σ evidence in many cases.

Also: CDF currently circulating a white paper with even stronger reach than what we predict (3σ over whole SM Higgs mass range)

http://home.uchicago.edu/~pdraper/MSSMHiggs/MSSMHiggs.html

http://home.uchicago.edu/~pdraper/MSSMHiggsCPV/MSSMHiggsCPV.html

Backup Slides

Higgs Sector of the MSSM (No CP Violation)

- Two Higgs Doublets H_d and H_u coupling to down-type and up-type fermions, respectively
- Two CP-even mass eigenstates h, H and one CP-odd mass eigenstate A

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix}$$

- m_h bounded by m_Z, lifted to ~ 125-130 GeV by radiative corrections and TeV-scale superpartners
- At tree level, m_A and $\tan\beta \equiv \langle H_u^0 \rangle / \langle H_d^0 \rangle$ completely determine the Higgs mass spectrum and their couplings to the SM particles.

(Continued)

$$-\pi/2 \le \alpha \le 0 \qquad \frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}(\cot\alpha - \tan\alpha) = (\cot\beta - \tan\beta)$$

- Relative to the SM, tree-level couplings to fermions rescaled by

$$g_{hdd} = -\frac{m_d}{v}\frac{\sin\alpha}{\cos\beta}, \qquad g_{huu} = \frac{m_u}{v}\frac{\cos\alpha}{\sin\beta}$$
$$g_{Hdd} = \frac{m_d}{v}\frac{\cos\alpha}{\cos\beta}, \qquad g_{Huu} = \frac{m_u}{v}\frac{\sin\alpha}{\sin\beta}$$
$$g_{Add} = \frac{m_d}{v}\gamma_5\tan\beta, \quad g_{Auu} = \frac{m_u}{v}\gamma_5\cot\beta$$

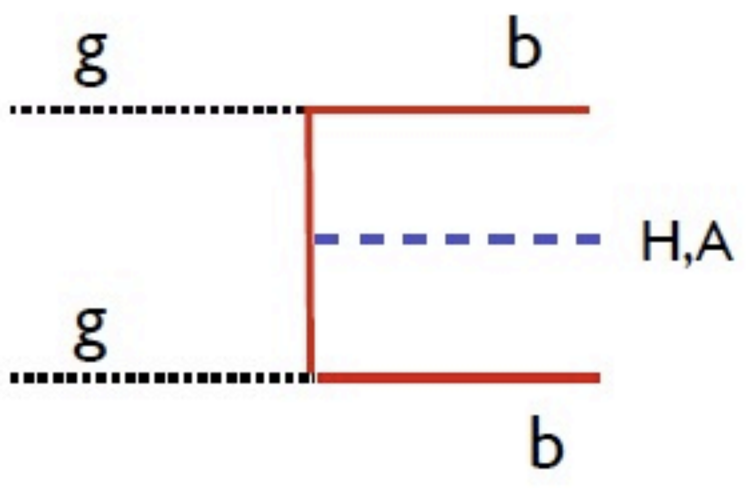
- The tree-level couplings to VV rescaled by $\sin(\beta-\alpha)$ and $\cos(\beta-\alpha)$ for h and H. A doesn't couple to VV by CP.

  - In the large m_A region $\alpha \to \beta - \pi/2$, VVh coupling is SM-like and H doesn't couple to VV: "decoupling limit"
  - In the small m_A region $\alpha \to -\beta$, VVH coupling is SM-like and h doesn't couple to VV: "antidecoupling limit"

- At loop level, more parameters are involved: $A_t, \mu, M_S \ldots$

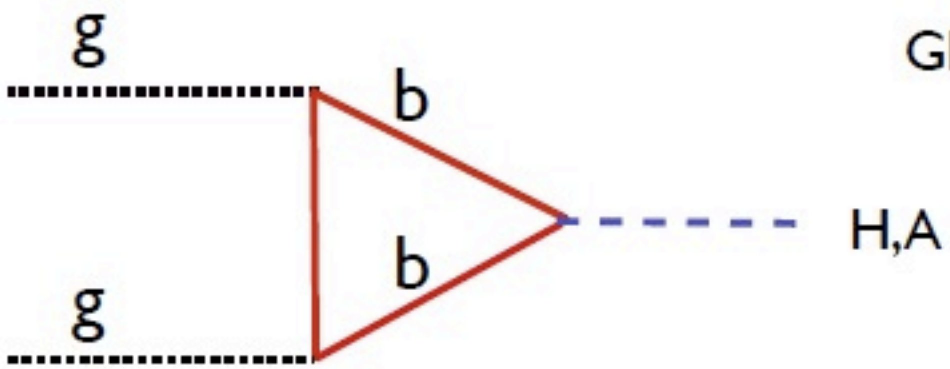
Tevatron MSSM Higgs channels

- SM-like Higgs (dominated) searches: $(W,Z)H_i \rightarrow bb$ (occasionally $gg \rightarrow H_i \rightarrow WW$)
- Nonstandard Higgs (dominated) searches:



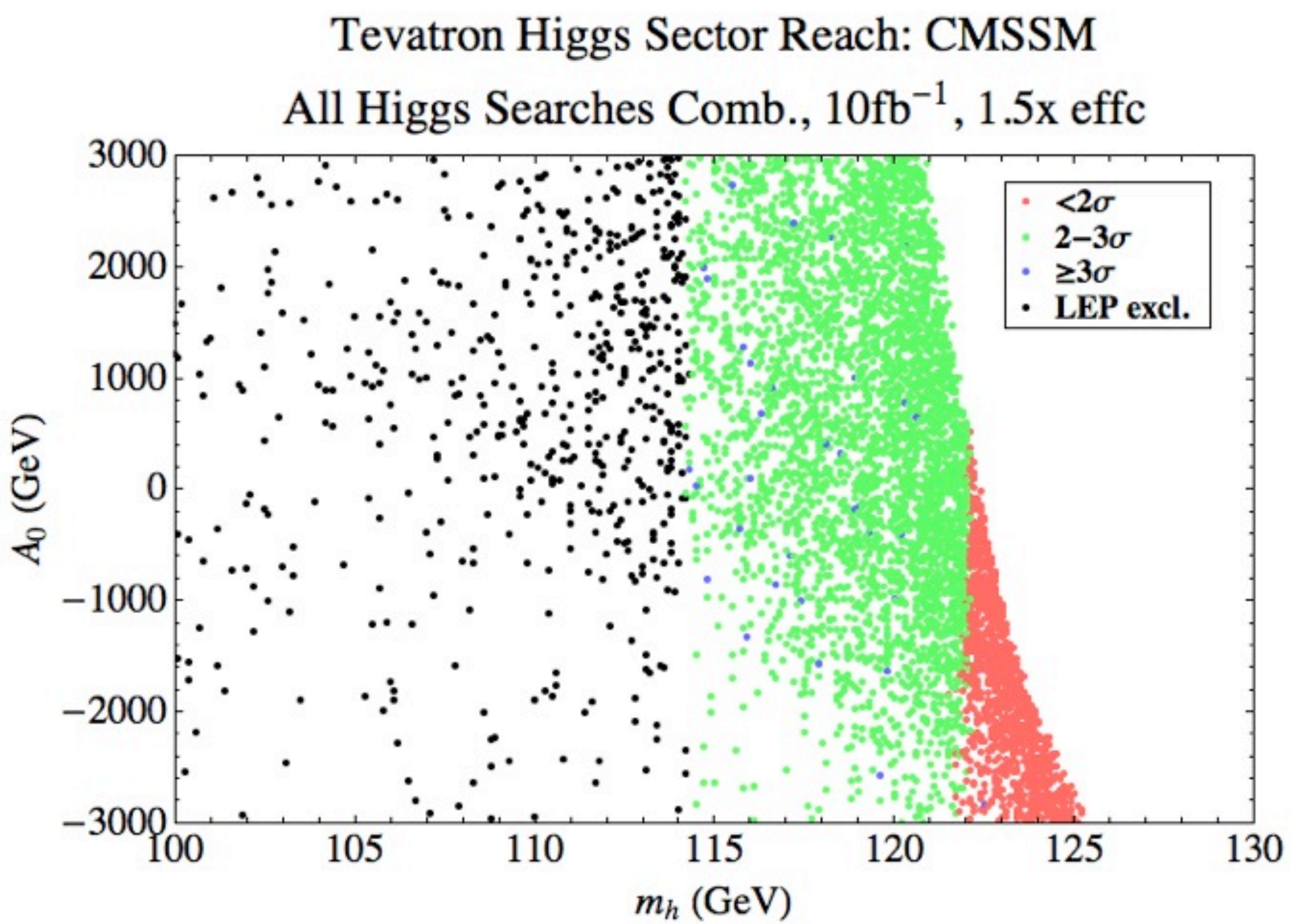
Associated Production

$H_i \rightarrow \tau\tau$



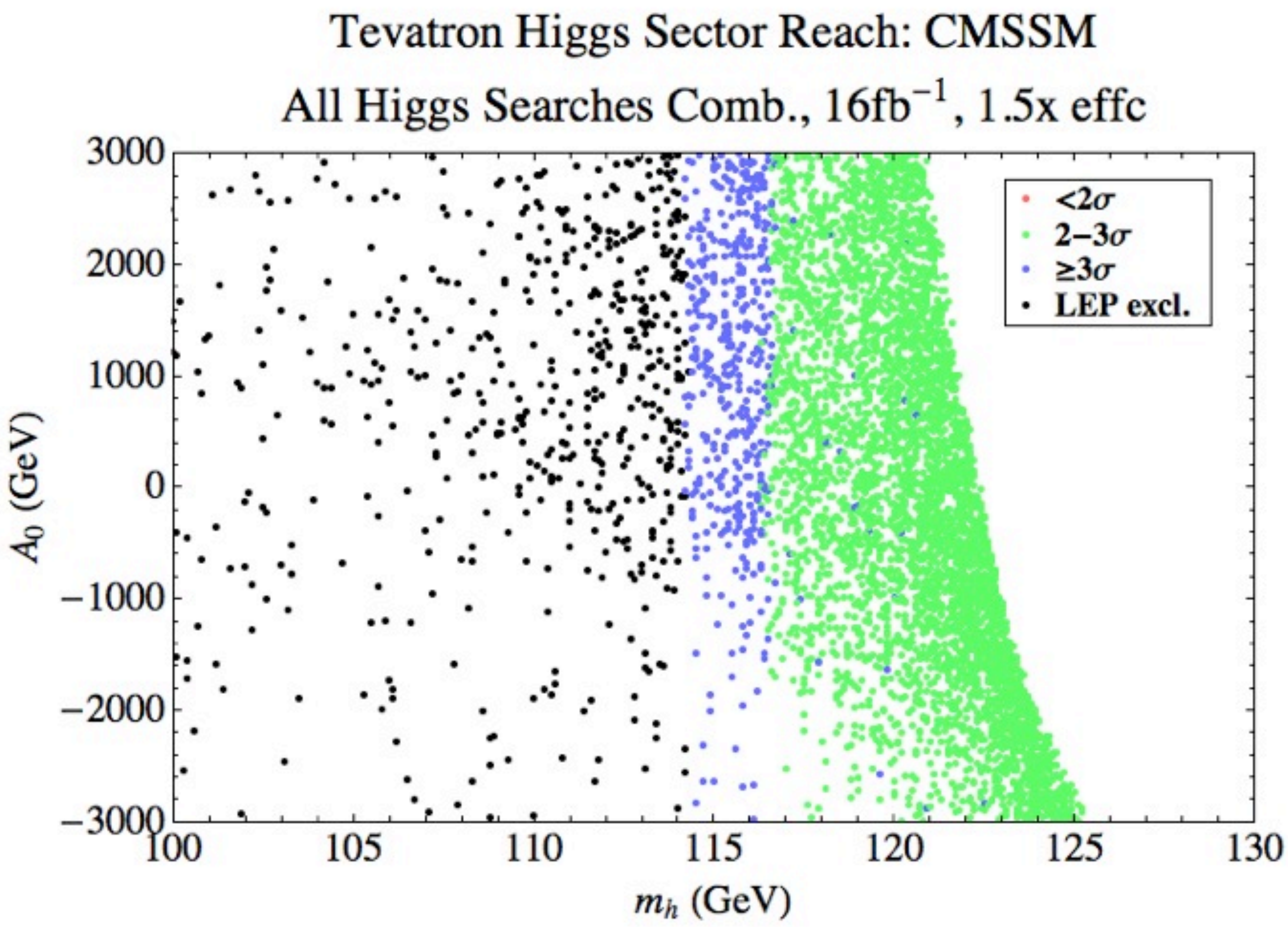
Gluon Fusion

CMSSM $10fb^{-1}$



2011

CMSSM 16fb^{-1}



Run III

OUTLINE

- Standard Model Higgs
- MSSM: EW-Scale CP-conserving Benchmark Scenarios
- MSSM: EW-Scale CP-violating scenario
  P. Draper, T. Liu, and C.E.M Wagner, Phys.Rev.D81:015014, 2010 (arxiv:0911.0034)
- MSSM: High-Scale embeddings

CPX Scenario: Large μ and CP Violation

- A large Higgsino mass parameter μ and CP-violating phases both affect the Higgs sector in the MSSM at loop level

  a) Large μ may strongly alter the tree-level coupling to down-type fermions at large tan β

  b) Arg(A_t) and Arg(M_3) alter the effective $\phi b\bar{b}$ couplings and mix H_u,H_d,A into three states of indefinite CP: H_1,H_2,H_3 with mixing matrix O_{ij}

  ➔ Use m_{H^+} instead of m_A as an input parameter

  (in the CP–conserving limit, $m_{H^+}^2 = m_A^2 + m_W^2$)

Effective Yukawa Couplings

$$y_{H_i b\bar{b}} \equiv \left(\frac{m_b}{174\ \mathrm{GeV}}\right) g^S_{H_i b\bar{b}}$$

correction to the SM

$$g^S_{H_i \bar{d}d} = \mathrm{Re}\left(\frac{1}{1+\kappa_d\tan\beta}\right)\frac{O_{1i}}{\cos\beta} + \mathrm{Re}\left(\frac{\kappa_d}{1+\kappa_d\tan\beta}\right)\frac{O_{2i}}{\cos\beta} + \mathrm{Im}\left[\frac{\kappa_d\left(\tan^2\beta+1\right)}{1+\kappa_d\tan\beta}\right] O_{3i}$$

CP-violating term

$$\kappa_d \simeq \frac{2\alpha_s}{3\pi}\frac{M^*_{\tilde{g}}\mu^*}{\max(m^2_{\tilde{d}}, M^2_{\tilde{g}})} + \frac{|h_u|^2}{16\pi^2}\frac{A^*_u\mu^*}{\max(m^2_{\tilde{u}}, M^2_{\tilde{g}})}$$

Effective Yukawa Couplings

$$y_{H_i b\bar{b}} \equiv \left(\frac{m_b}{174\ \mathrm{GeV}}\right) g^S_{H_i b\bar{b}}$$

correction to the SM

Neglecting Phases:

$$g^S_{hb\bar{b}} = \left(\frac{-\sin\alpha}{\cos\beta}\right)\left(\frac{1-\kappa_b\cot\alpha}{1+\kappa_b\tan\beta}\right)$$

MSSM Tree

Threshold correction

$$\kappa_d \simeq \frac{2\alpha_s}{3\pi}\frac{M^*_{\tilde{g}}\mu^*}{\max(m^2_{\tilde{d}}, M^2_{\tilde{g}})} + \frac{|h_u|^2}{16\pi^2}\frac{A^*_u\mu^*}{\max(m^2_{\tilde{u}}, M^2_{\tilde{g}})}$$

Nonstandard Limit: $g^S_{hb\bar{b}} = -\tan\beta\left(\frac{1}{1+\kappa_b\tan\beta}\right)$ (large tan β)

Far SM-like Limit: $g^S_{hb\bar{b}} \rightarrow 1$, but convergence is somewhat slow.

-> Regions where SM-like and NS Higgs couplings to b quarks are suppressed relative to tree-level MSSM

CPX Scenario

- CPX benchmark scenario (M. Carena et. al '00):

$$M_S = 500 \text{ GeV}, \quad |A_t| = 1 \text{ TeV},$$
$$\mu = 2 \text{ TeV}, \quad M_{1,2} = 200 \text{ GeV},$$
$$A_{b,\tau} = A_t, \quad |M_3| = 1 \text{ TeV}.$$

- Three representative cases (M_3 = soft mass of gluino):

a. $\mathrm{Arg} M_3 = 0^\circ, \quad \mathrm{Arg} A_{t,b,\tau} = 0^\circ$

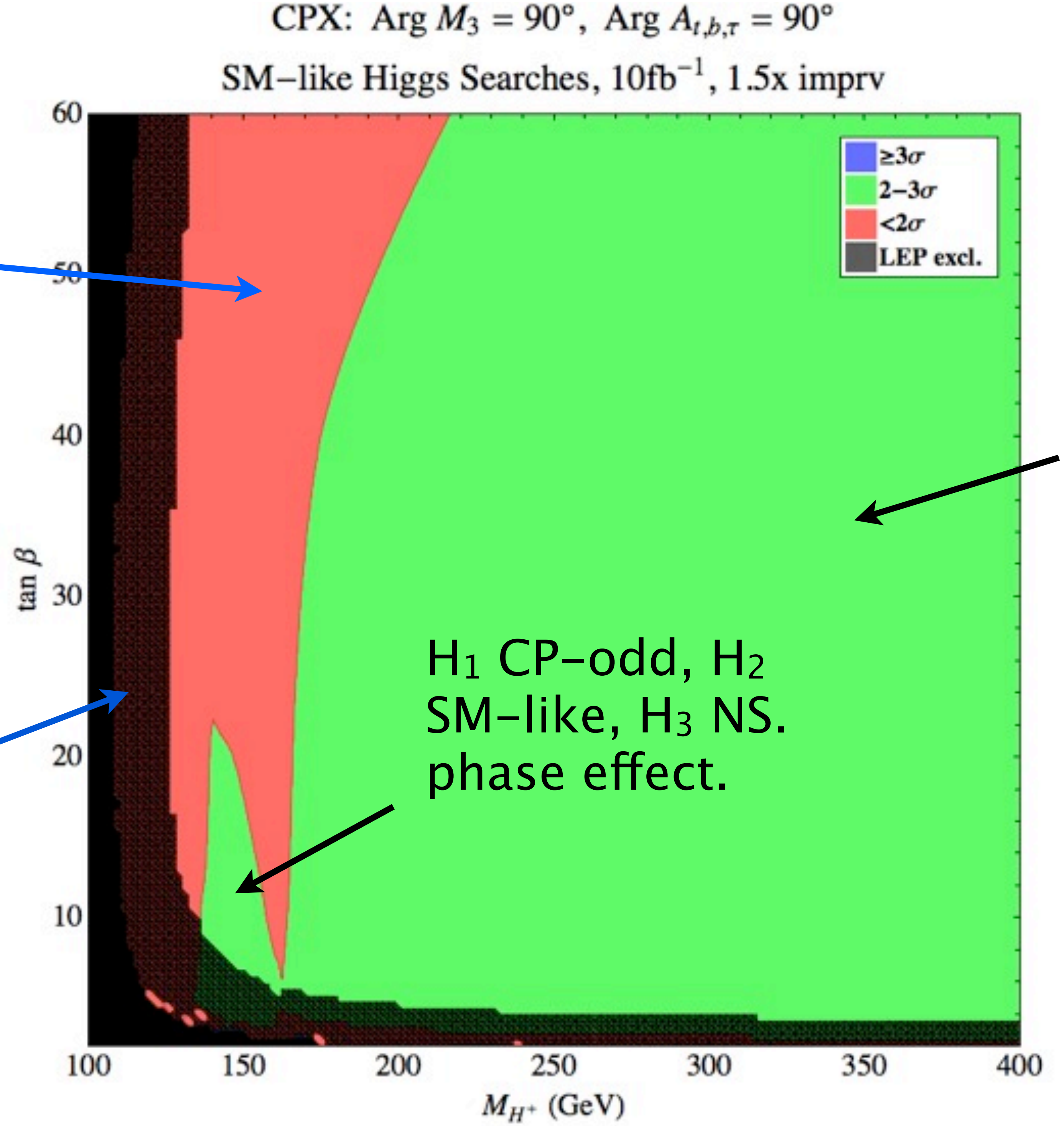
b. $\mathrm{Arg} M_3 = 90^\circ, \quad \mathrm{Arg} A_{t,b,\tau} = 90^\circ$

c. $\mathrm{Arg} M_3 = 140^\circ, \quad \mathrm{Arg} A_{t,b,\tau} = 140^\circ$

CPX Scenario: SM-like Higgs Searches

P.D., T. Liu, C. Wagner, arXiv: 0911.0034

Weak due to the large tan β loop suppression of the H_2bb coupling. Large μ effect.



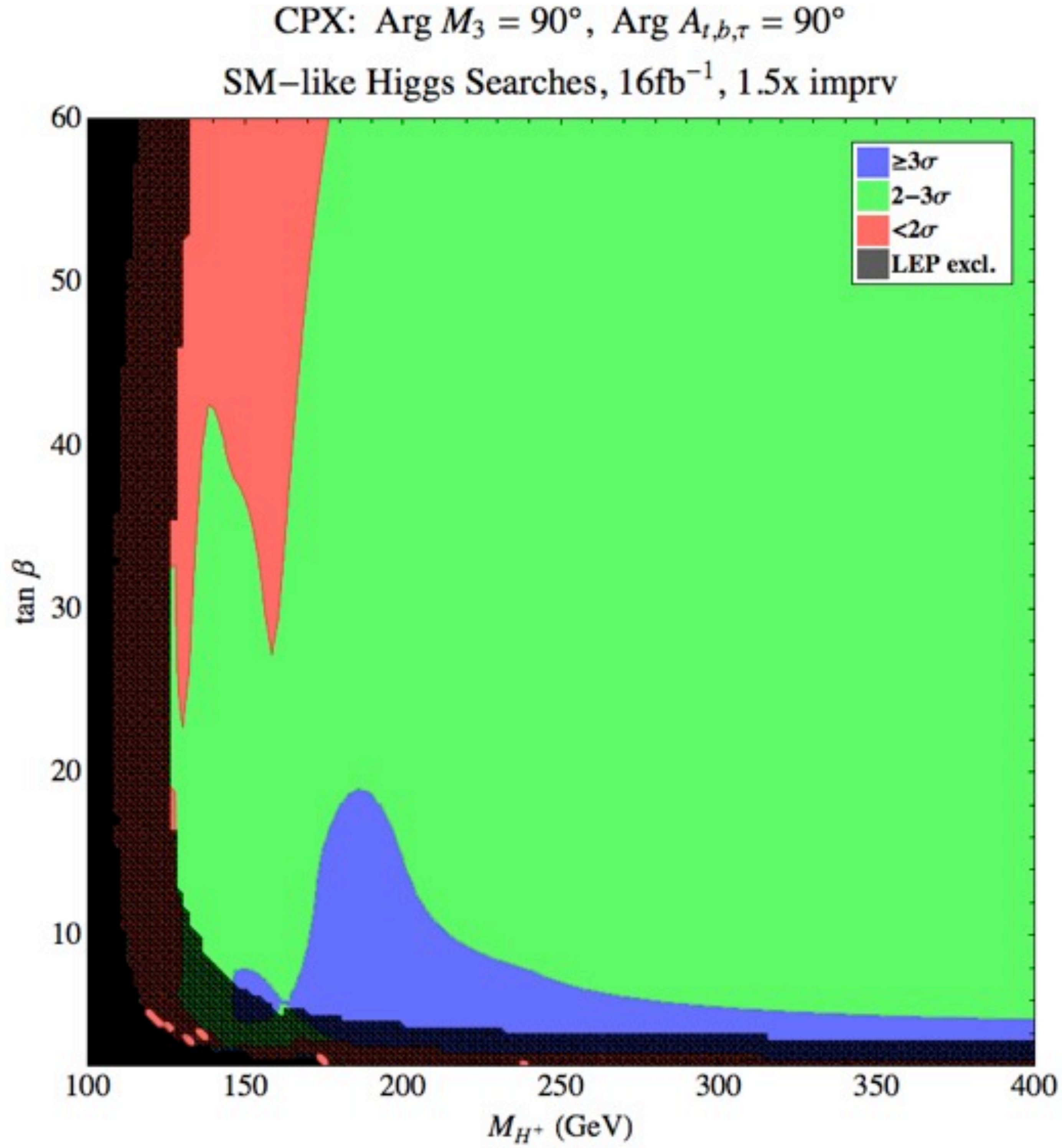
H_1 SM-like, H_2 mostly CP-odd, H_3 mostly NS CP-even

H_1 CP-odd, H_2 SM-like, H_3 NS. phase effect.

H_1 NS, H_2 CP-odd, H_3 SM-like. Weak due to the opening of $H_3 \to H_1H_1$

2011

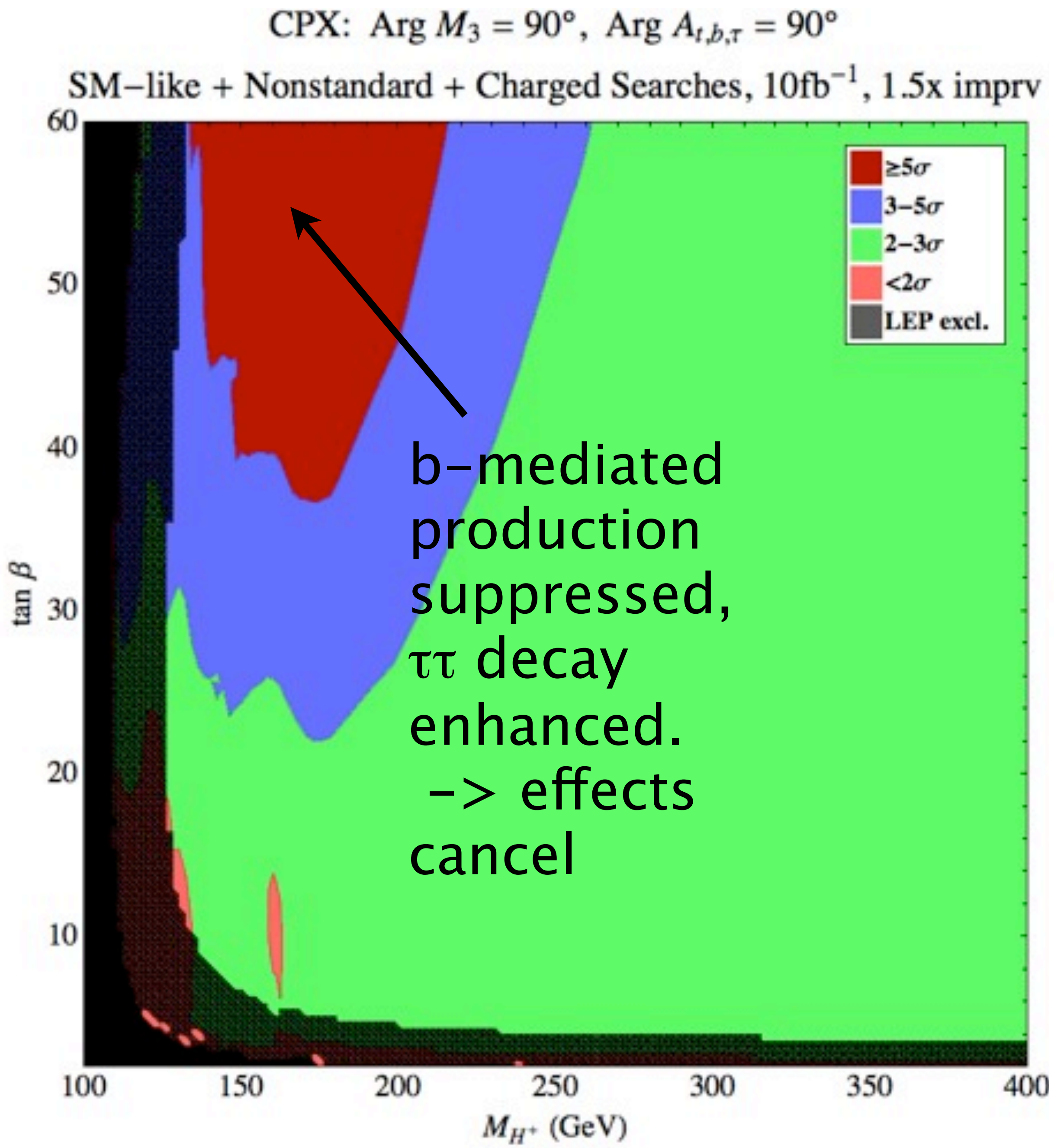
CPX Scenario: SM-like Higgs Searches



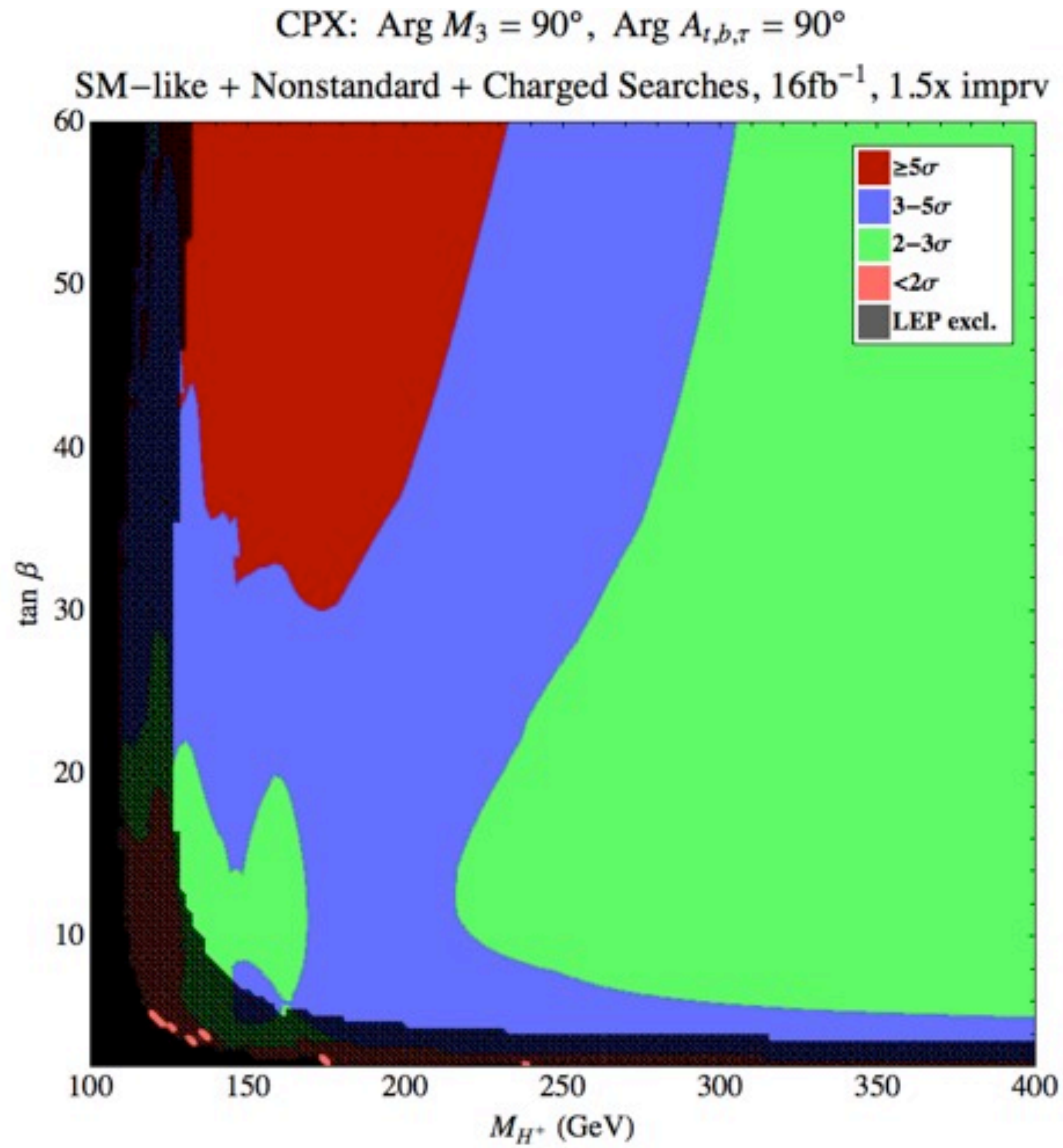
P.D., T. Liu, C. Wagner, arXiv: 0911.0034

Run III

CPX Scenario: Combined Sensitivity



2011



Run III