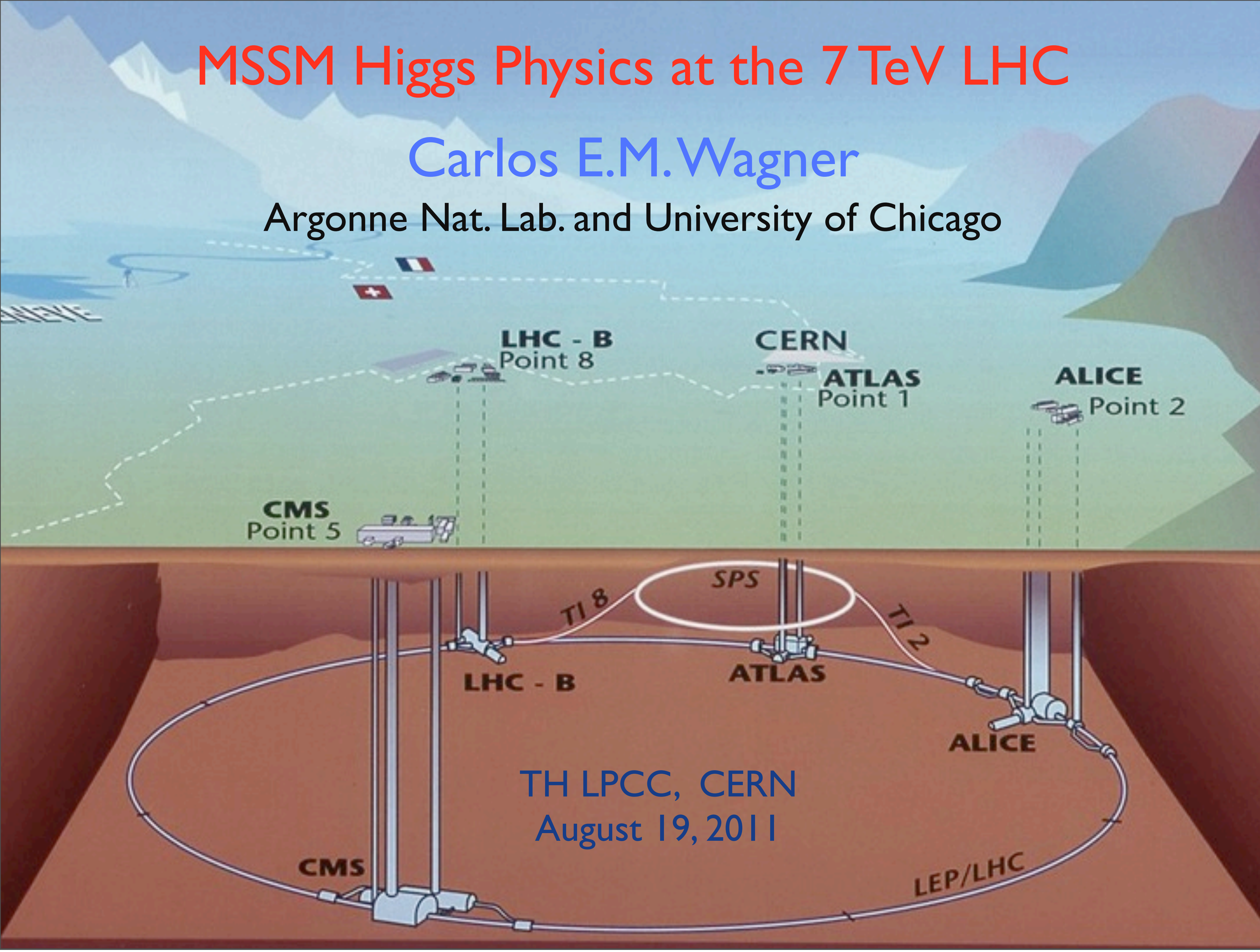
MSSM Higgs Physics at the 7 TeV LHC

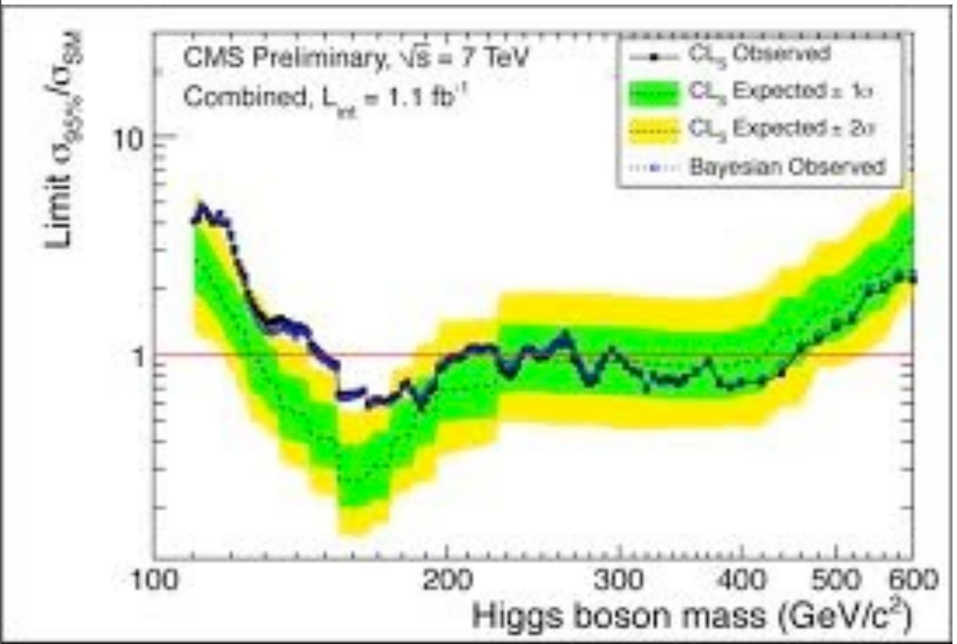
Carlos E.M. Wagner

Argonne Nat. Lab. and University of Chicago



TH LPCC, CERN

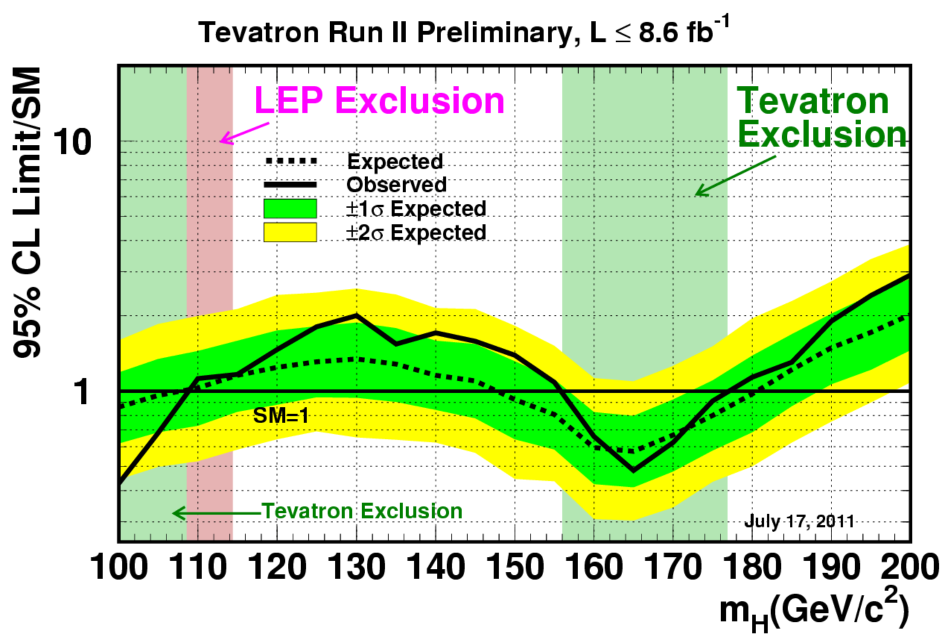
August 19, 2011



We are leaving in exciting times:

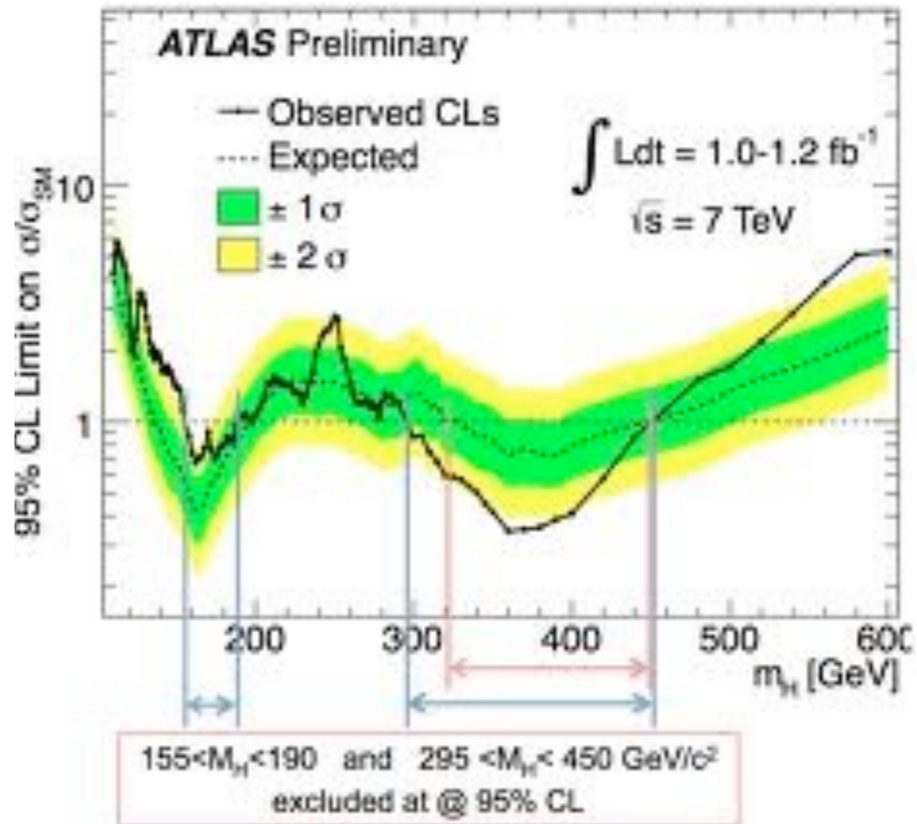
Experiments are starting to test the SM Higgs above the LEP limit, leading to interesting exclusion bounds on its mass.

A light SM-like Higgs, is beginning to be probed by present data. More information from the LHC will be available as early as next week.

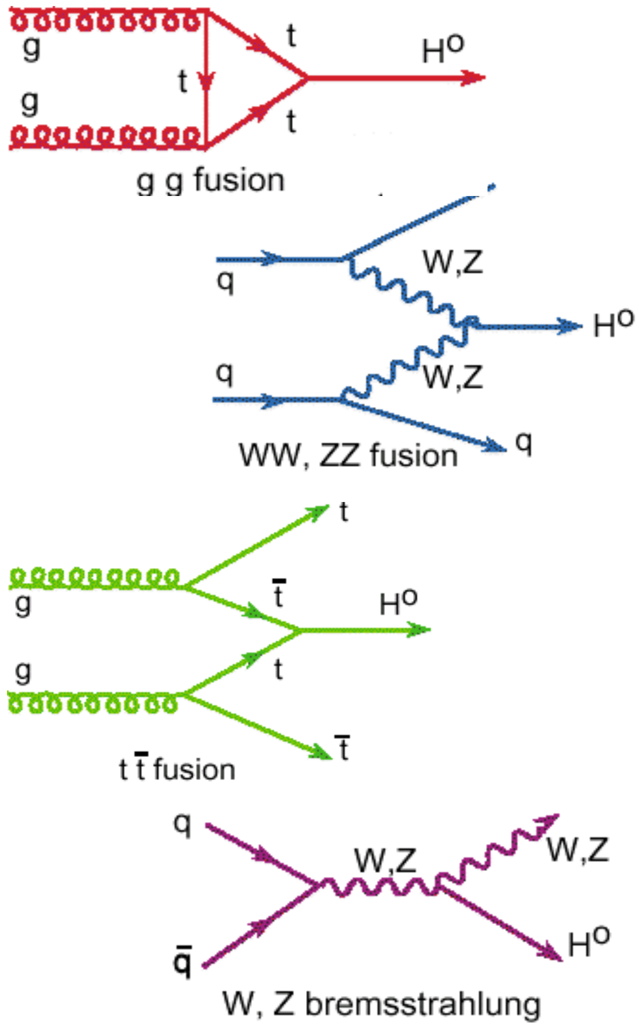


Observed Exclusion : 100-109 and 156-177 GeV/c^2

Expected Exclusion : 100-108 and 148-181 GeV/c^2



The search for the Standard Model Higgs at the LHC

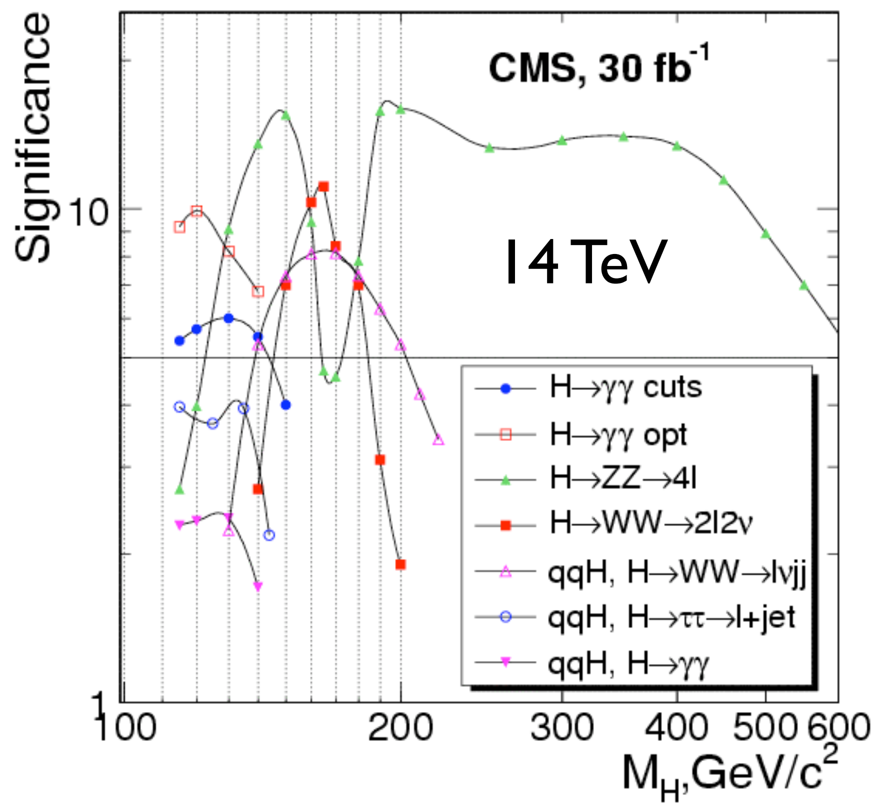


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \rightarrow \gamma\gamma, \tau\tau, bb, WW, ZZ$$

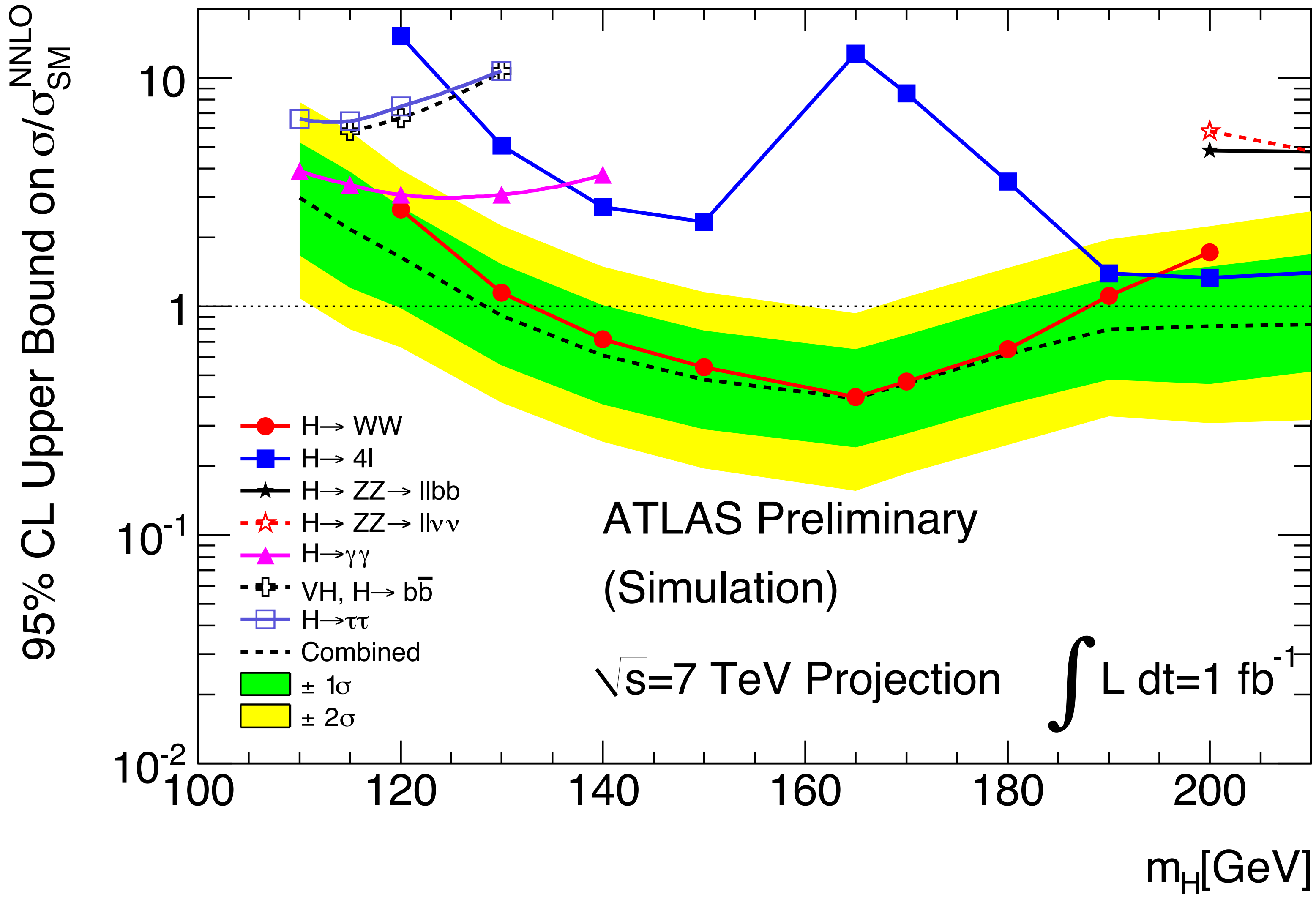
- **High mass range** $m_{H_{SM}} > 200$ GeV

$$H \rightarrow WW,\ ZZ$$



If there is a Higgs boson, with properties similar to those predicted in the Standard Model, the high energy/luminosity LHC will find it.

$$\text{Expected Significance}(\sigma) = 2/R_{\text{expected}}$$

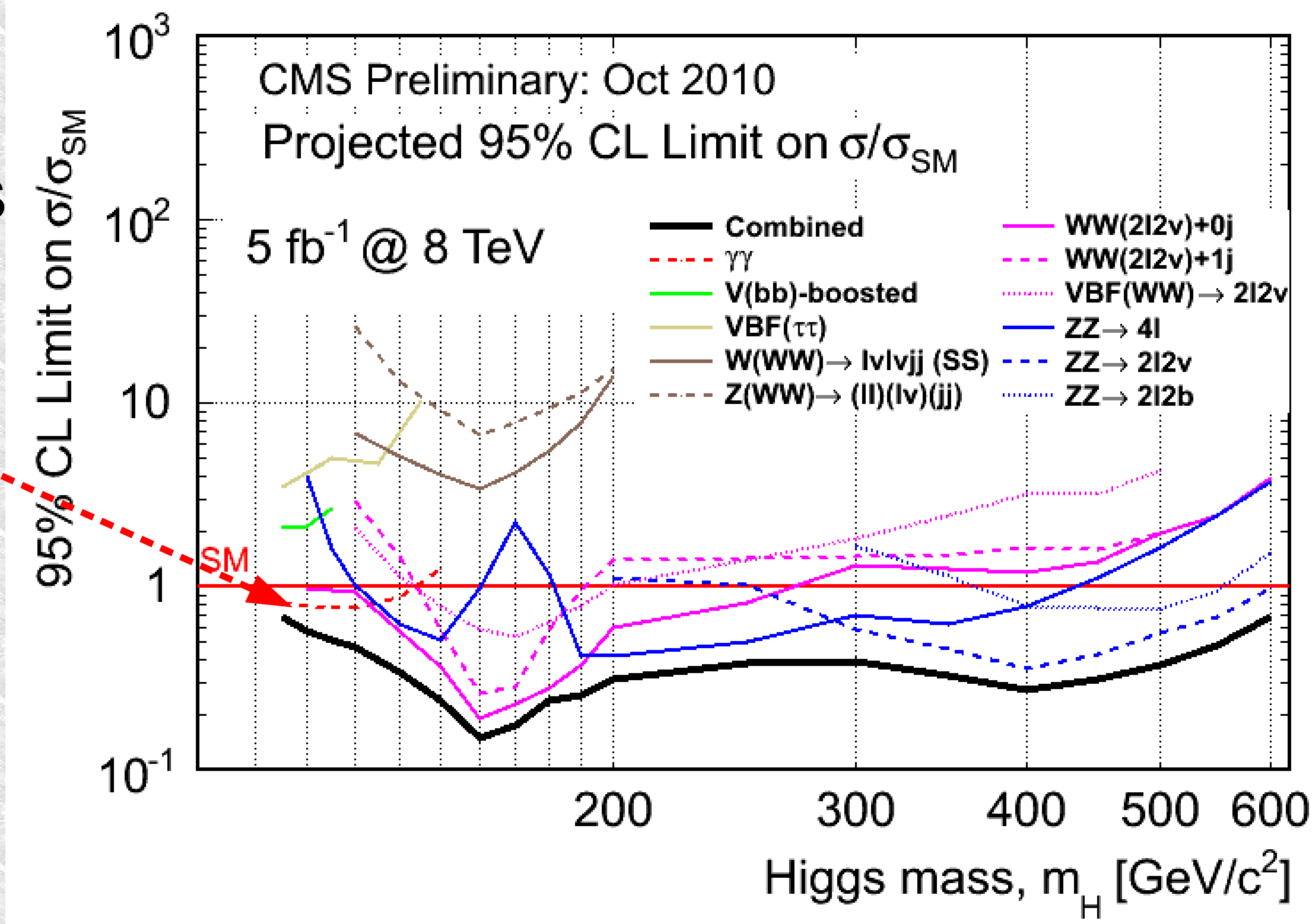


With 5 inverse fb (about the end of this year) each experiment expects to be able to probe a SM Higgs in the whole range above 115 GeV and combination of ATLAS and CMS could lead to evidence on this mass range.

Current 7 TeV LHC Run

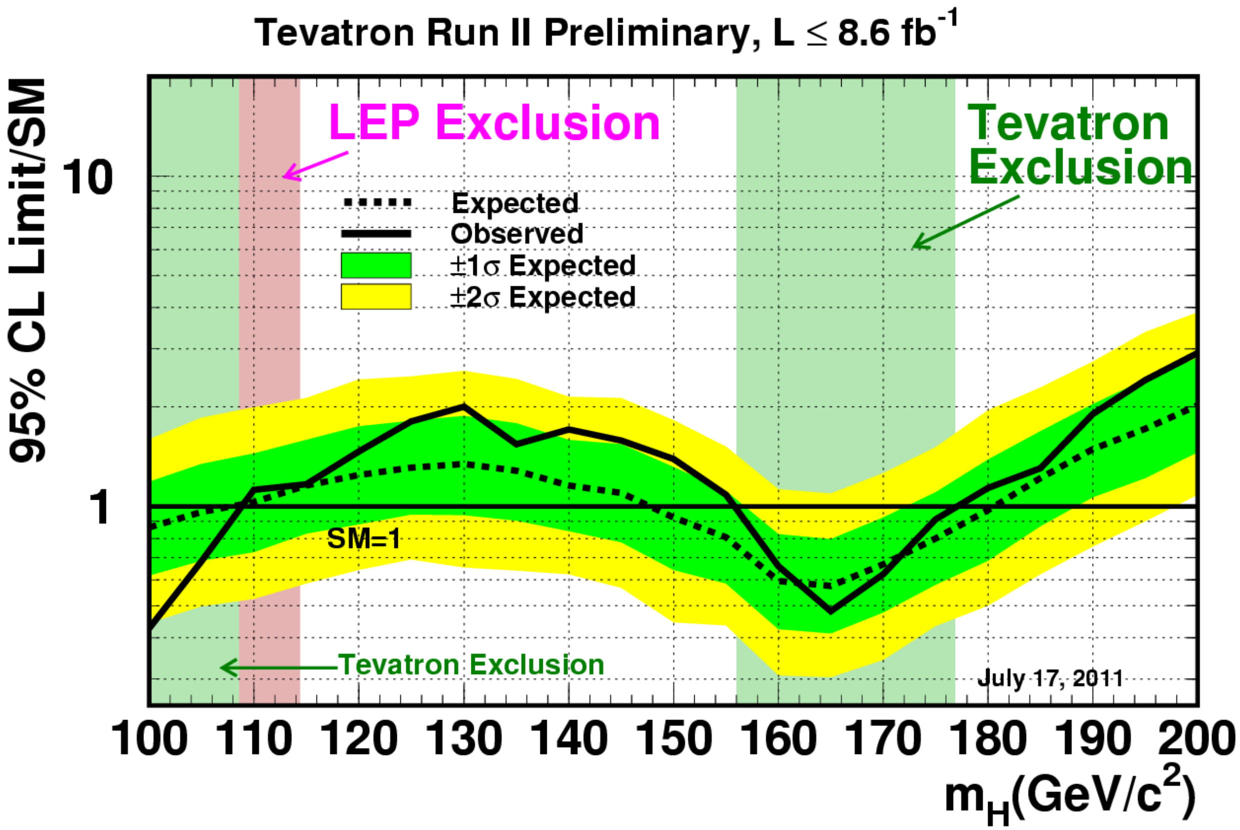
Contributions by channel

- Hardest point is lowest mass
- 5 channels at 120GeV
- H→γγ best




Chicago
Booster
CDF
DØ
Tevatron
p̄ source
Main Injector
(new)

The Tevatron is also providing bounds on the Higgs mass



Observed Exclusion : 100-109 and 156-177 GeV/c^2

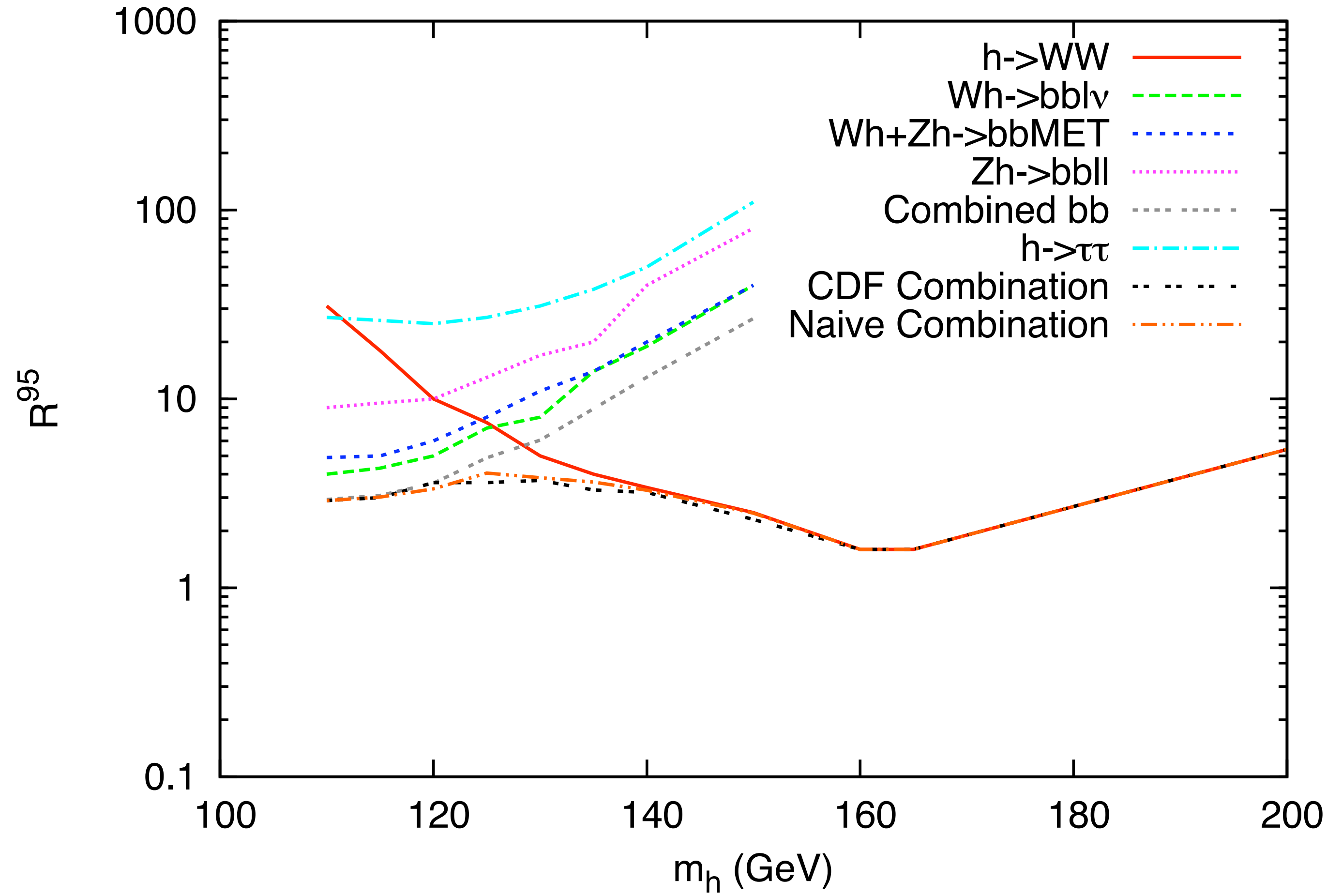
Expected Exclusion : 100-108 and 148-181 GeV/c^2

Interesting enough, if a Higgs were there, one would expect, in average $R_{\rm obs} = R_{\rm exp} + 1$.

The excess statistical significance is, however, $2/R_{\rm exp}$

Comparison of Simple Combination of Channels with CDF Results. Ratio R for exclusion

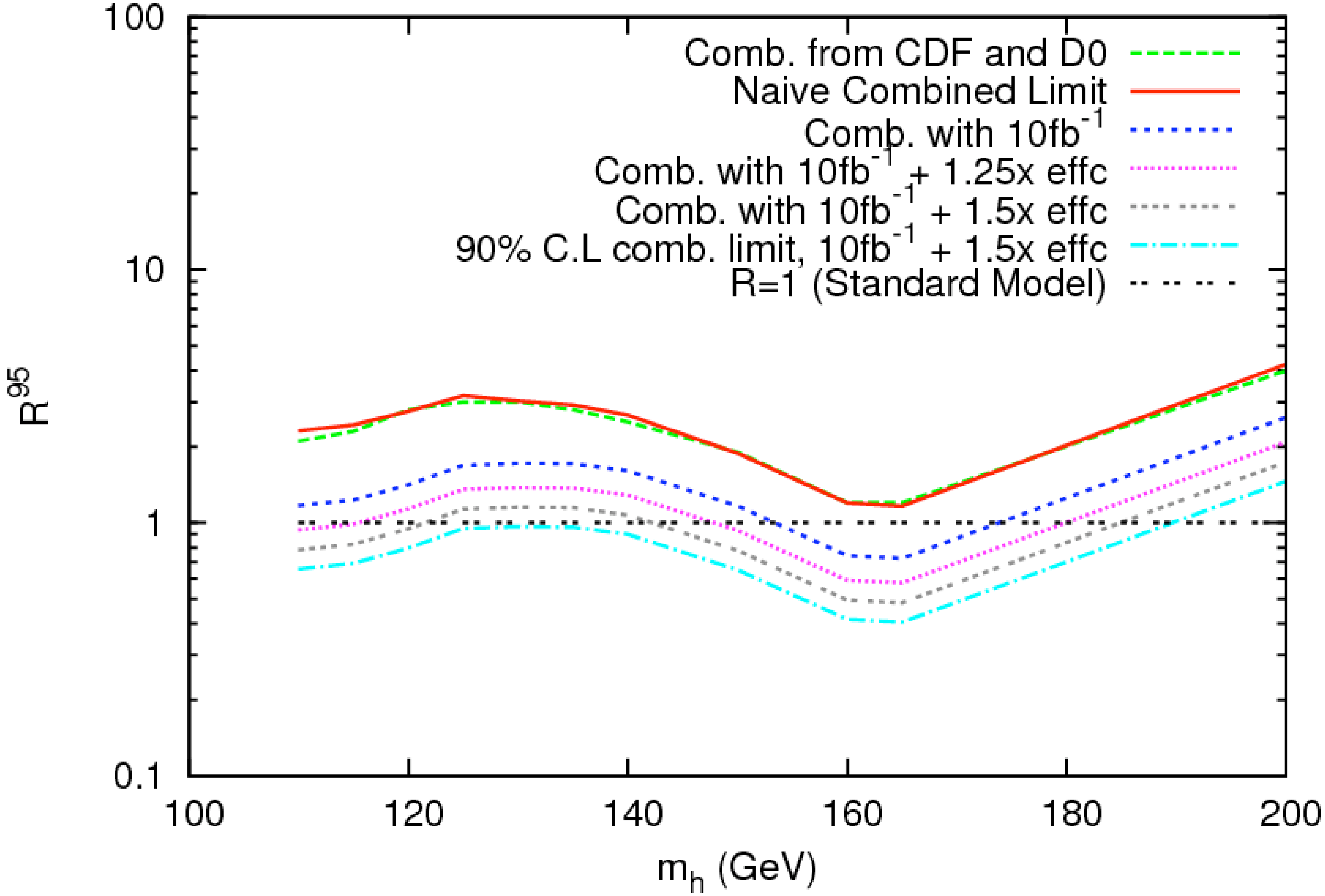
P. Draper, T. Liu and C. Wagner'09



Applicable to new model in which all channels rescale in the same way.
In the MSSM, channels should be considered separately and recombined.

Prospects for Higgs Searches at the Tevatron

P. Draper, T. Liu and C. Wagner'09



Improvements with respect to Winter'09 10 percent already achieved

Tevatron shutdown expected this fall, with about $10\ \mathrm{fb}^{-1}$ of luminosity

With the current run, and expected improvements, the Tevatron should probe the low Higgs mass region up to 185 GeV

Physics Beyond the SM : Supersymmetry

Mass of the SM-like Higgs h

- Most important corrections come from the stop sector,

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

where the off-diagonal term depends on the stop-Higgs trilinear couplings, $X_t = A_t - \mu^* / \tan\beta$

- For large CP-odd Higgs boson masses, and with $M_S = m_Q = m_U$ dominant one-loop corrections are given by,

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right) \right)$$

- After two-loop corrections:

M.Carena, J.R. Espinosa, M. Quiros, C.W. '95
M. Carena, M. Quiros, C.W.'95

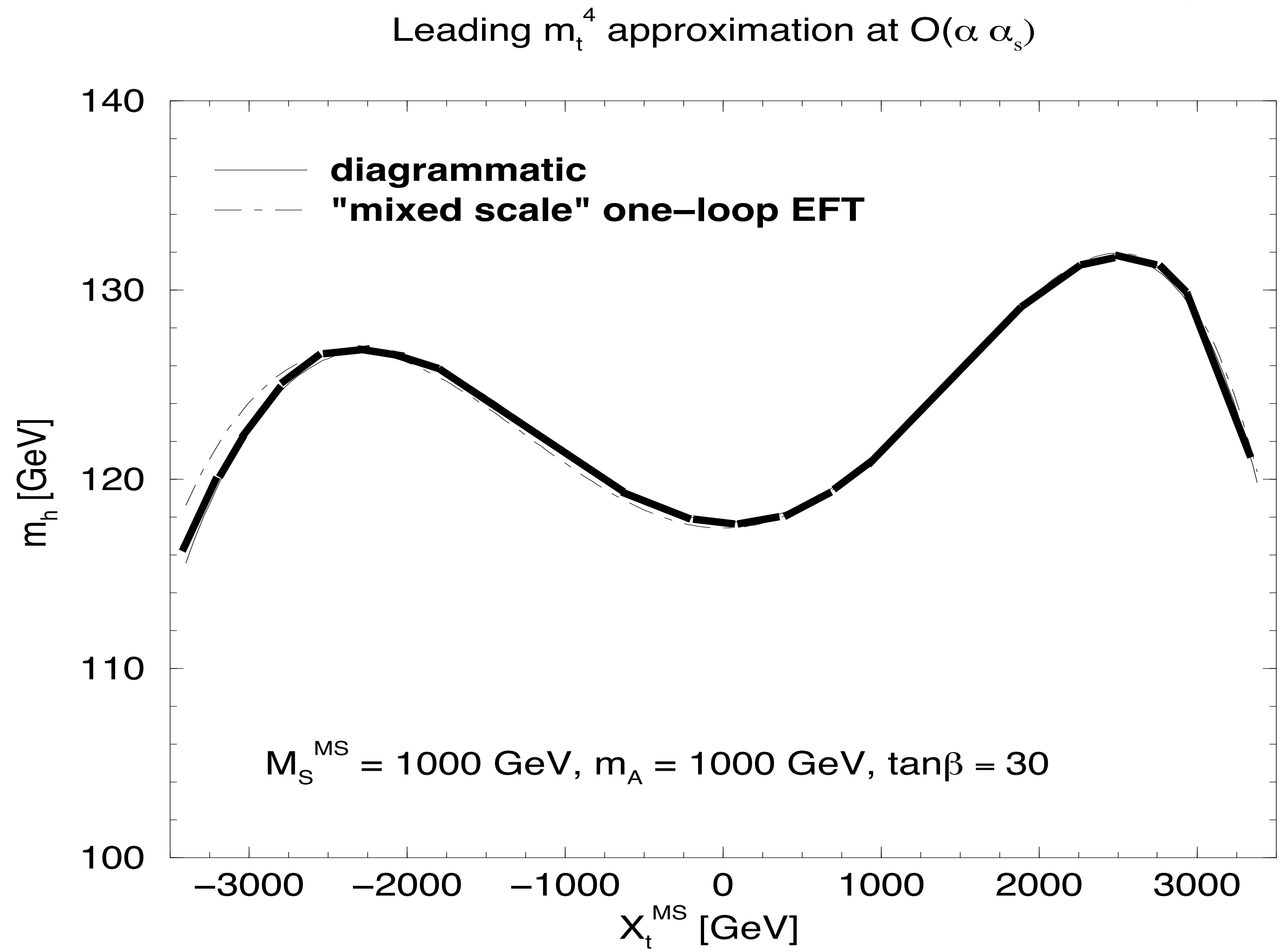
• upper limit on Higgs mass:
$m_h \lesssim 135$ GeV

$$M_S = 1 \to 2\ \text{TeV} \Longrightarrow \Delta m_h \simeq 2 - 5\ \text{GeV}$$
$$\Delta m_t = 1\ \text{GeV} \Longrightarrow \Delta m_h \sim 1\ \text{GeV}$$

Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00



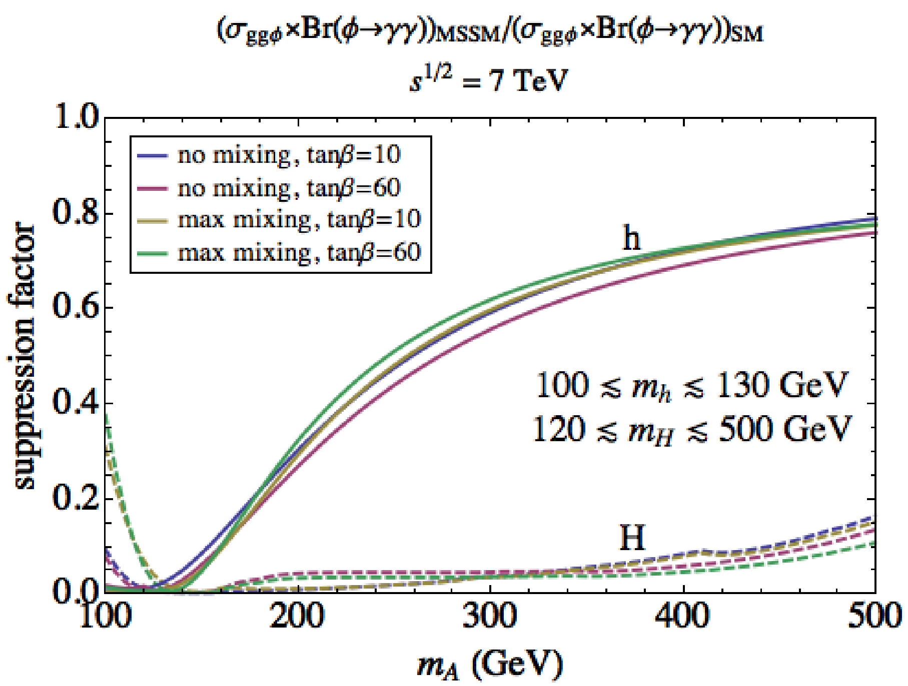
$m_t = 180$ GeV. For $m_t = 173$ GeV, the maximum m_h shifts to 127 GeV.

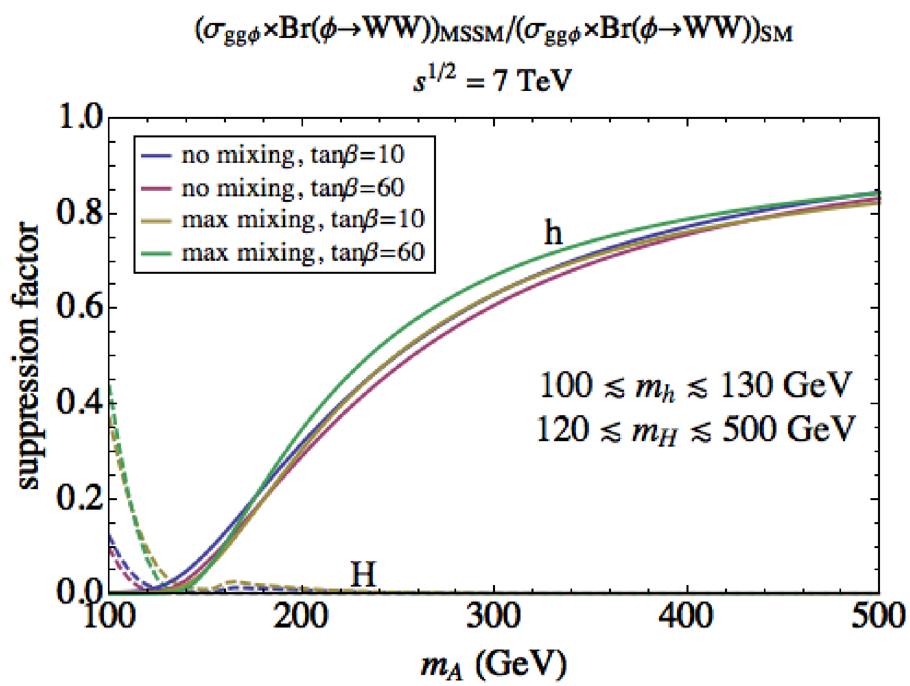
$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing}; \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

MSSM Higgs Searches at the LHC

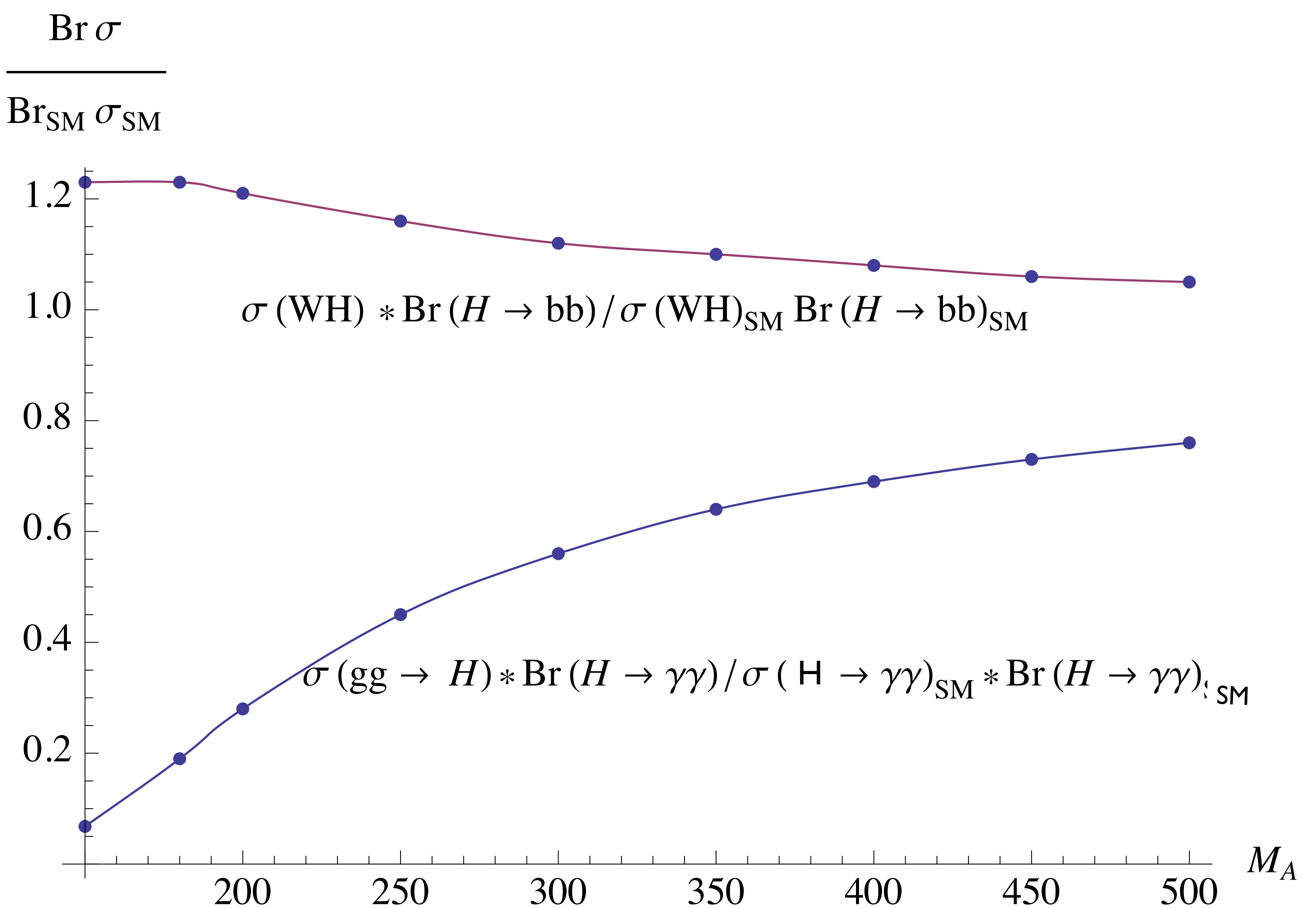
P. Draper, T. Liu, C. Wagner, **Phys.Rev.D81:015014,2010**; M. Carena, P. Draper, T. Liu, C. Wagner, arXiv:1107.4354

- In the MSSM, one of the Higgs bosons has standard model like couplings to the top and gauge bosons
- Relevant SM-like channels of production and/or decay are induced by loops, which are affected by new physics (mainly stops). We shall assume all relevant supersymmetric particles to be heavy, with masses of order 1 TeV.
- Moreover, the dominant width of Higgs decay into bottom quarks is enhanced due to mixing with non-standard Higgs bosons. Top Yukawa tend to be somewhat reduced by same effect. This affects the main production and decay channels.





Suppression factor in the LHC channels at the 2012--2013 run

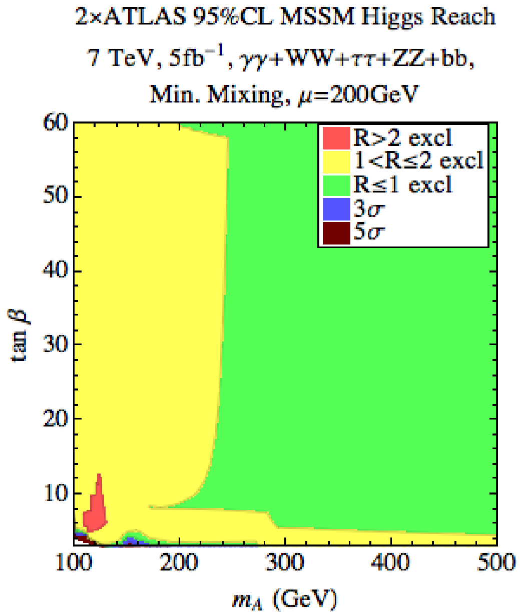


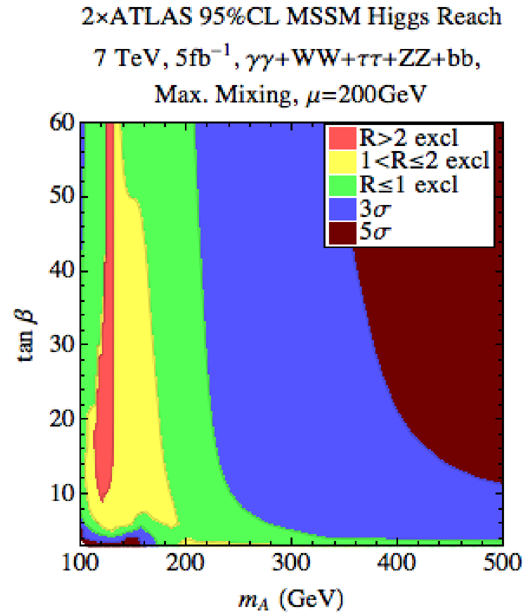
Even for a CP-odd Higgs mass of 500 GeV, since necessary luminosity to probe a Higgs signal is proportional to the inverse square of the rate, suppression is relevant.

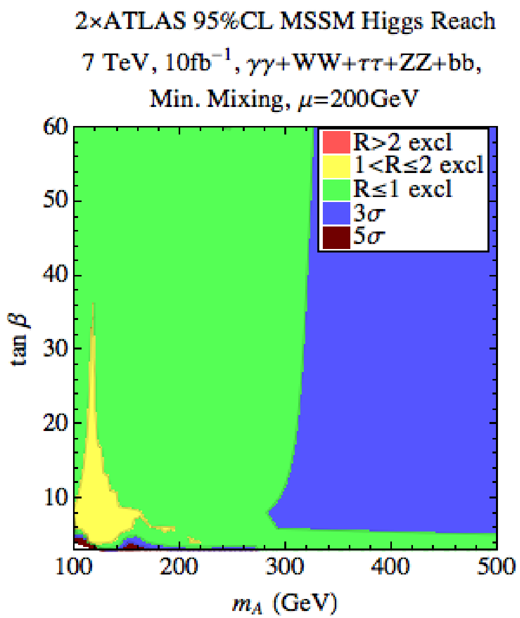
7 TeV LHC MSSM Higgs Reach

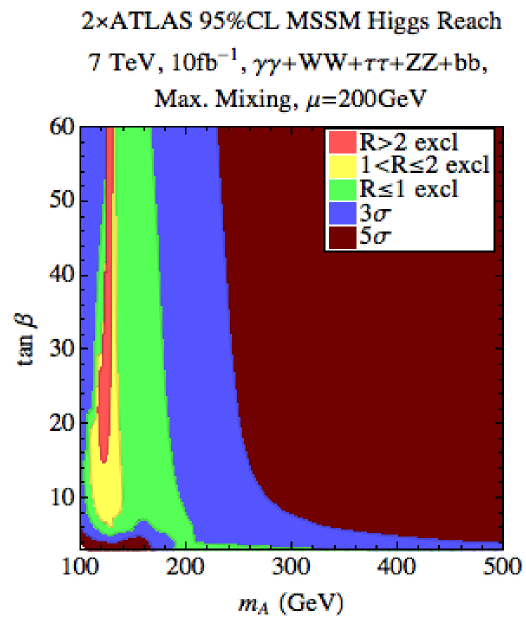
P. Draper, T. Liu, C. Wagner, **Phys.Rev.D81:015014,2010**; M. Carena, P. Draper, T. Liu, C. Wagner, arXiv:1107.4354

$m_h \simeq 115\text{GeV}$ | $m_h \simeq 130\ \text{GeV}$









Suppression of

$$BR(h \to \gamma\gamma)$$

leads to reduced reach at low values of the CP-odd Higgs mass

$$\text{Significance}(\sigma) = 2/R$$

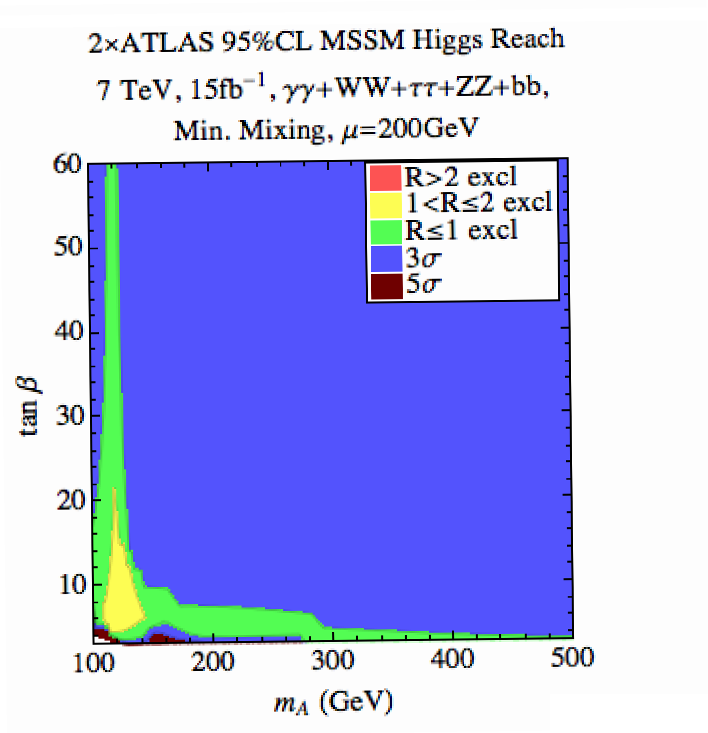
At sufficiently large luminosity

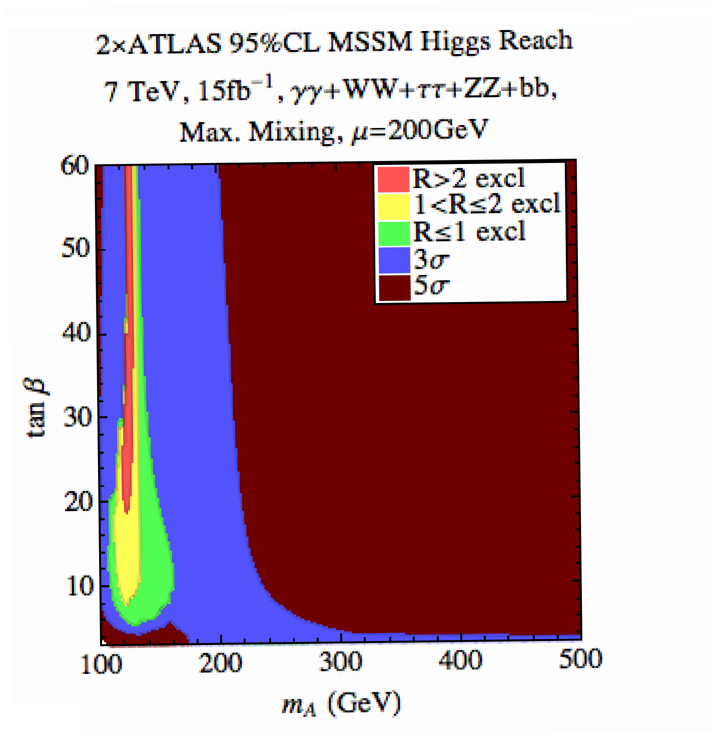
$$Vh, h \to bb$$

$$\text{WBF}, h \to \tau\tau$$

are helpful in partially reducing the reach suppression

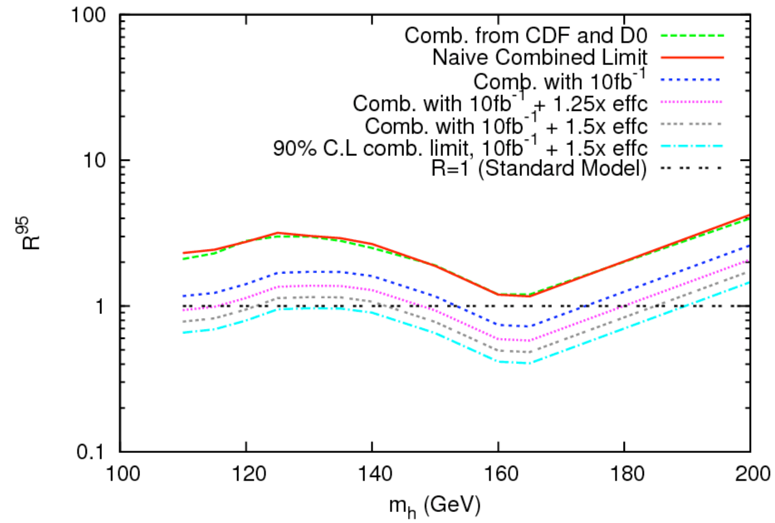
It takes 15 inverse fb and the combination of both experiments to find evidence of the Higgs in most of the parameter space in the minimal mixing scenario.



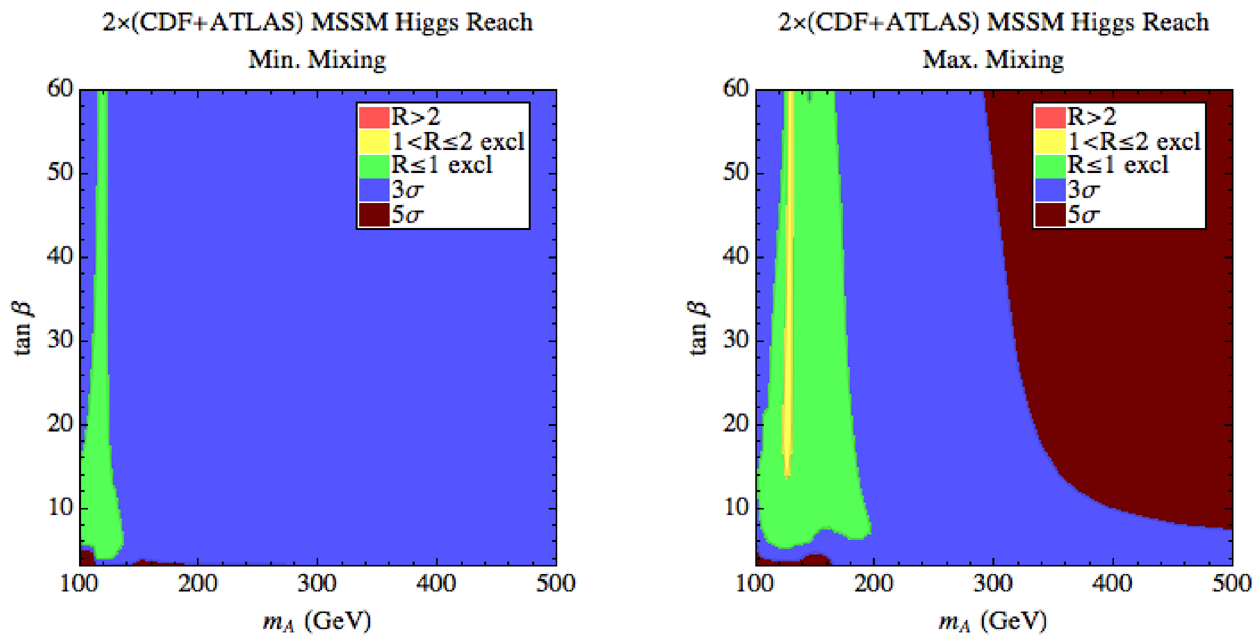


The LHC sensitivity is somewhat complementary to that of the Tevatron, which becomes more sensitive for low Higgs masses.

Combination of data from experiments at the end of 2011 may be useful to find evidence for Higgs at an early stage.



P. Draper, T. Liu and C. Wagner'09



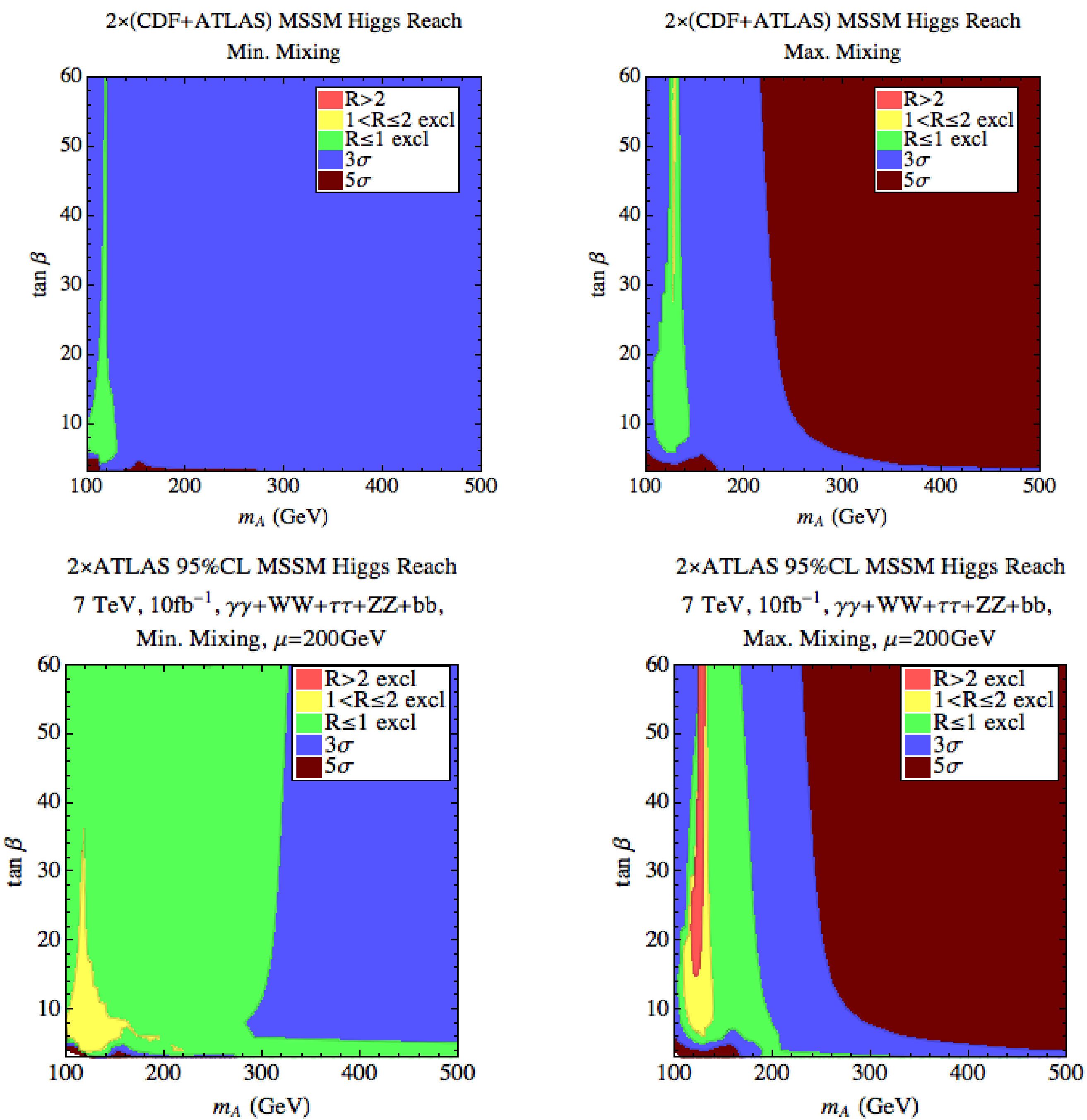
Combination of 5 inverse fb LHC with 10 inverse fb Tevatron data :
Evidence of SM-like Higgs presence in almost all parameter space

M. Carena, P. Draper, T. Liu, C.W.'11

Prospects for 10 inverse fb for each experiment.

LHC + Tevatron

LHC



At maximal mixing, LHC is predominant.

Tevatron remains useful for relatively lo values of the CP-od Higgs mass in the minimal mixin scenario.

M. Carena, P. Draper, T. Liu, C.W.' 11

Higgs Mixing Cancellation

- For large values of the Higgsino mass and (negative) stop mixing parameters, the off-diagonal element of the CP-even Higgs boson mass matrix is suppressed at low values of mA and tanbeta.

- Specifically, this happens when

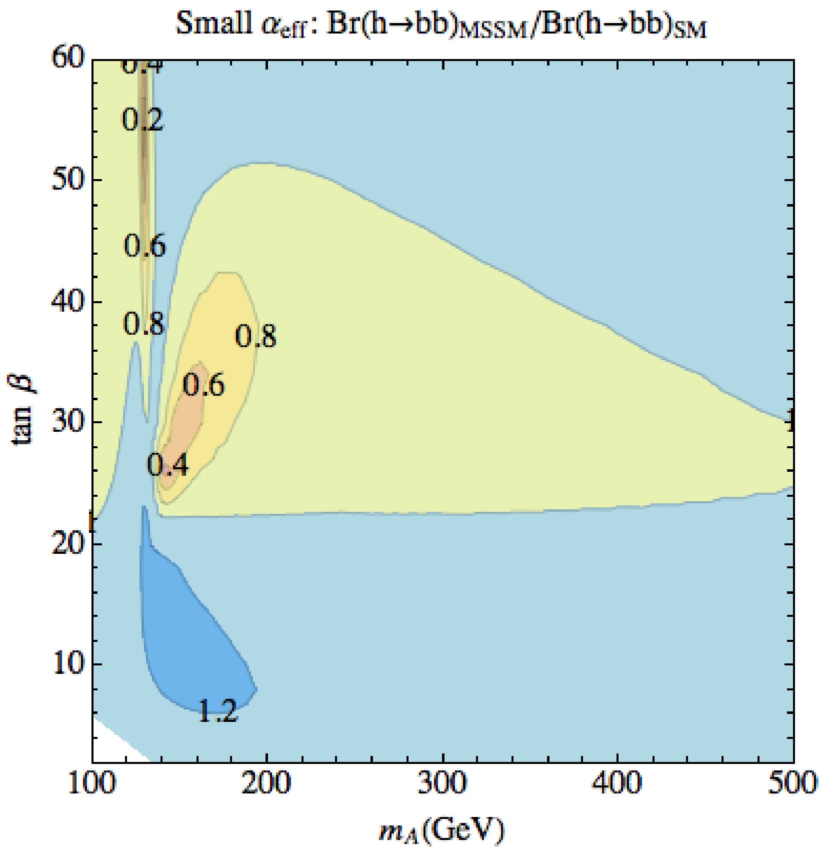
$$\frac{m_A^2}{M_Z^2} + \mathcal{O}(1) \simeq \tan\beta \frac{h_t^4 v^2}{16\pi^2 M_Z^2} \frac{\mu\, X_t}{M_S^2} \left(\frac{X_t^2}{6M_S^2} - 1 \right)$$

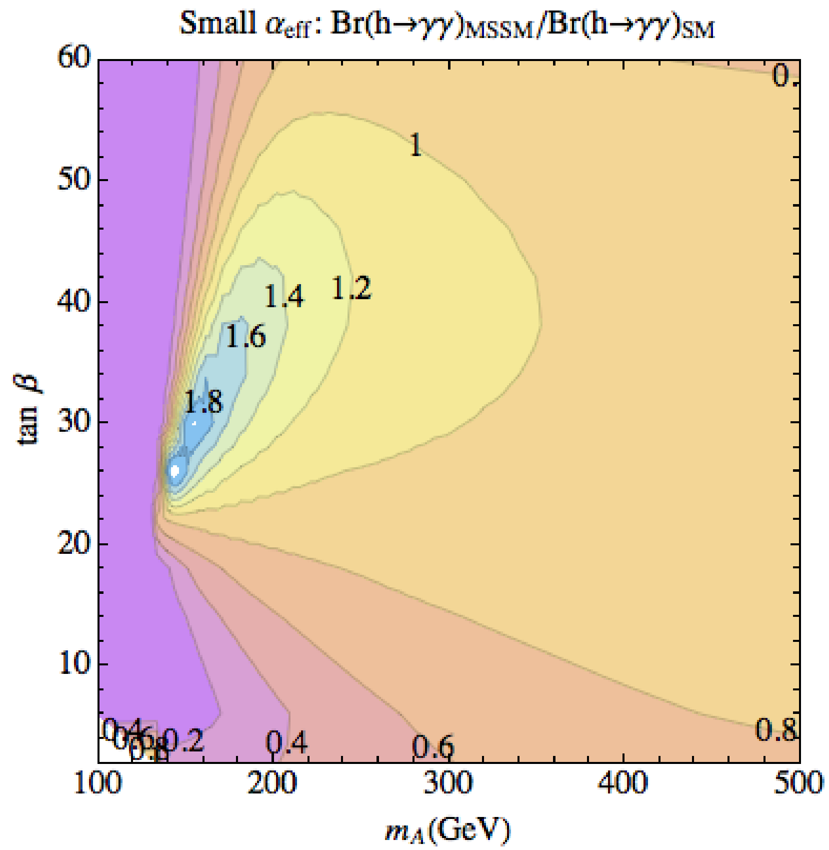
- This means that the mass eigenstate couples has reduced couplings to the down sector (taus and bottoms).

- We shall take $\mu = 2.5 M_S \quad \text{and} \quad X_t = -1.5 M_S$

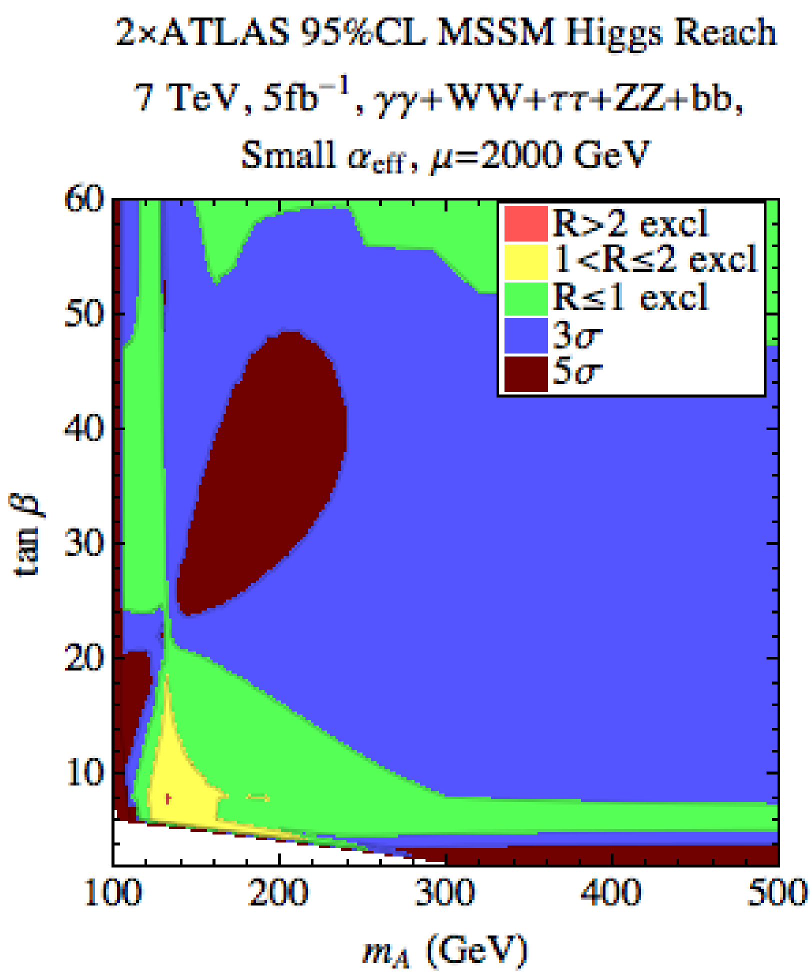
Carena, Mrenna, C.W. '98
Carena, Heinemeyer, Weiglein, C.W. '02

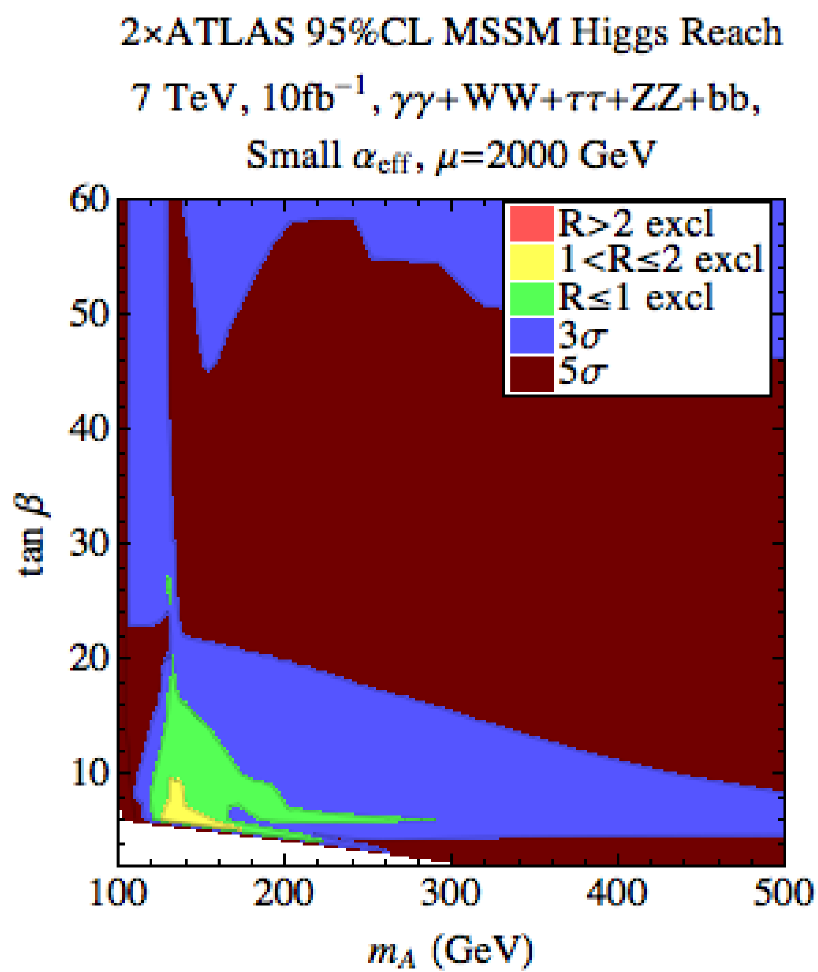
The Higgs width is reduced and the branching ratio of the Higgs decays into photon is consequently increased





The increase in the photon branching ratio leads to large regions of parameter space were discovery of a SM-like Higgs boson is possible at the end of this year





M. Carena, P. Draper, T. Liu, C.W.'11

Higgs Couplings to fermions

- At tree level, only one of the Higgs doublets couples to down-quarks and leptons, and the other couples to up quarks

$$\mathcal{L} = \bar{\Psi}^i_L \left(h_{d,ij} H_1 d_R + h_{u,ij} H_2 u_R\right) + h.c.$$

- Since the up and down quark sectors are diagonalized independently, the interactions remain flavor diagonal.

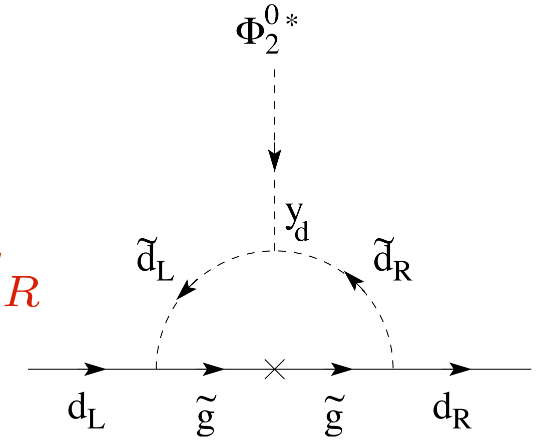
$$\bar{d}_L \frac{\hat{m}_d}{v} \left(\, h + \tan\beta \, (H + iA)\right) d_R + h.c.$$

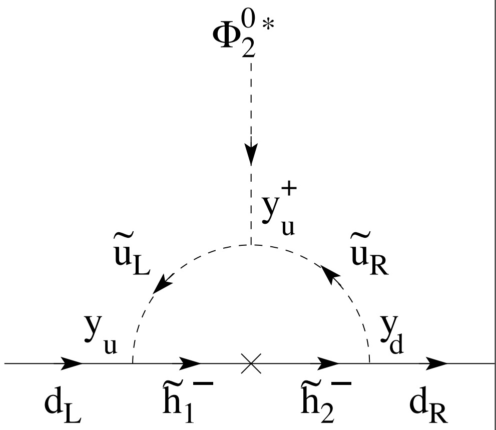
- h is SM-like, while H and A have enhanced couplings to down quarks

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$





- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

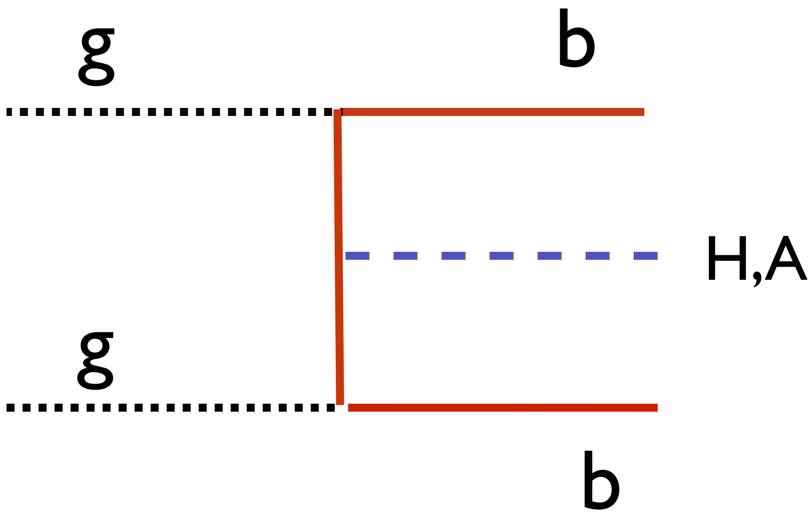
$$\boxed{\tan\beta = \frac{v_2}{v_1}}$$

$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

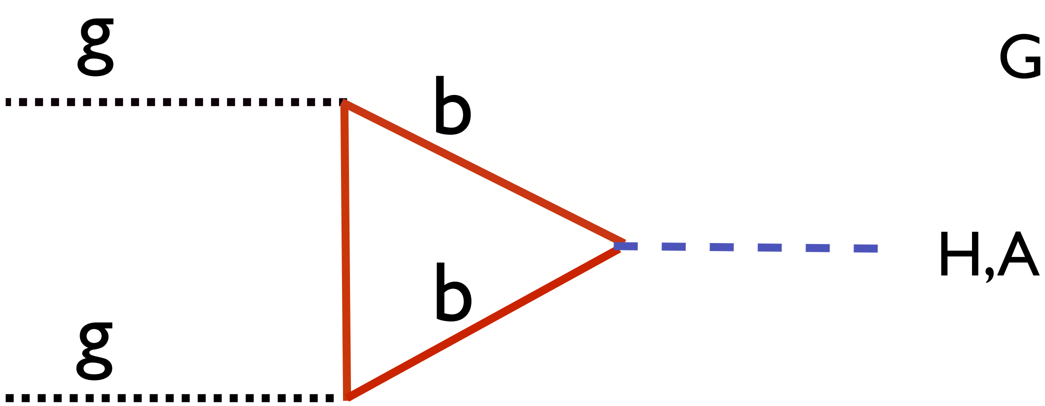
$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



Associated Production



Gluon Fusion

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

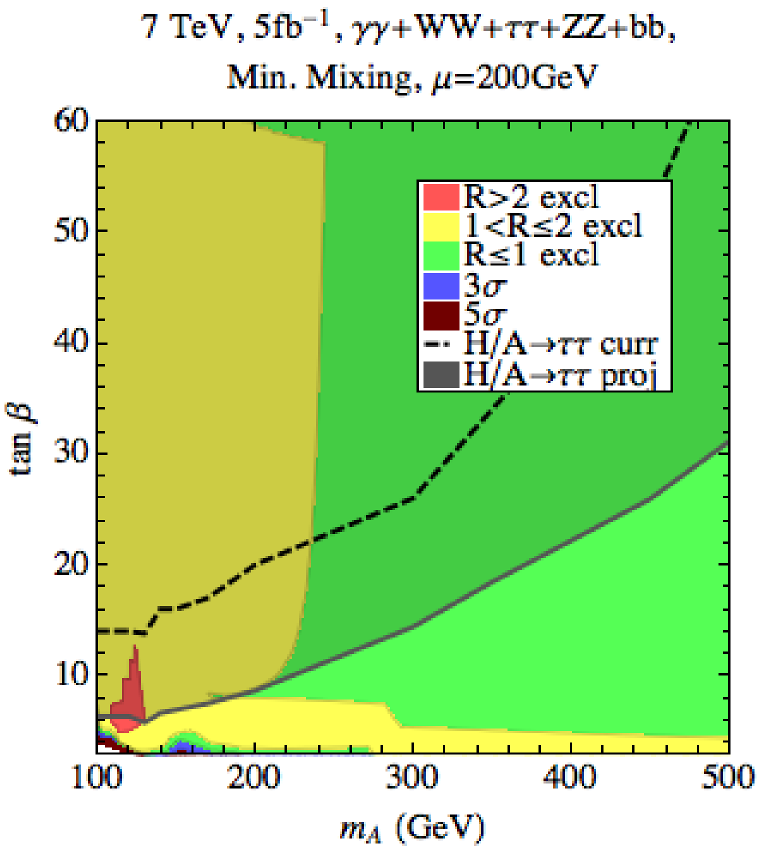
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

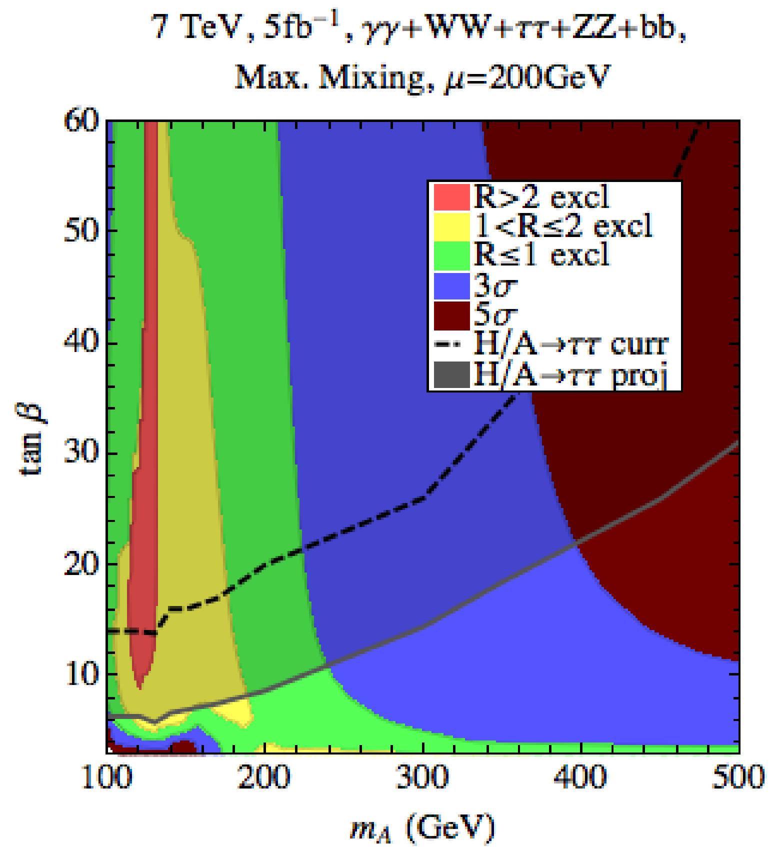
$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by
D. North and M. Spira, arXiv:0808.0087
Further work by Mhulleitner, Rzehak and Spira, 0812.3815

Complementarity with LHC non-standard Higgs searches

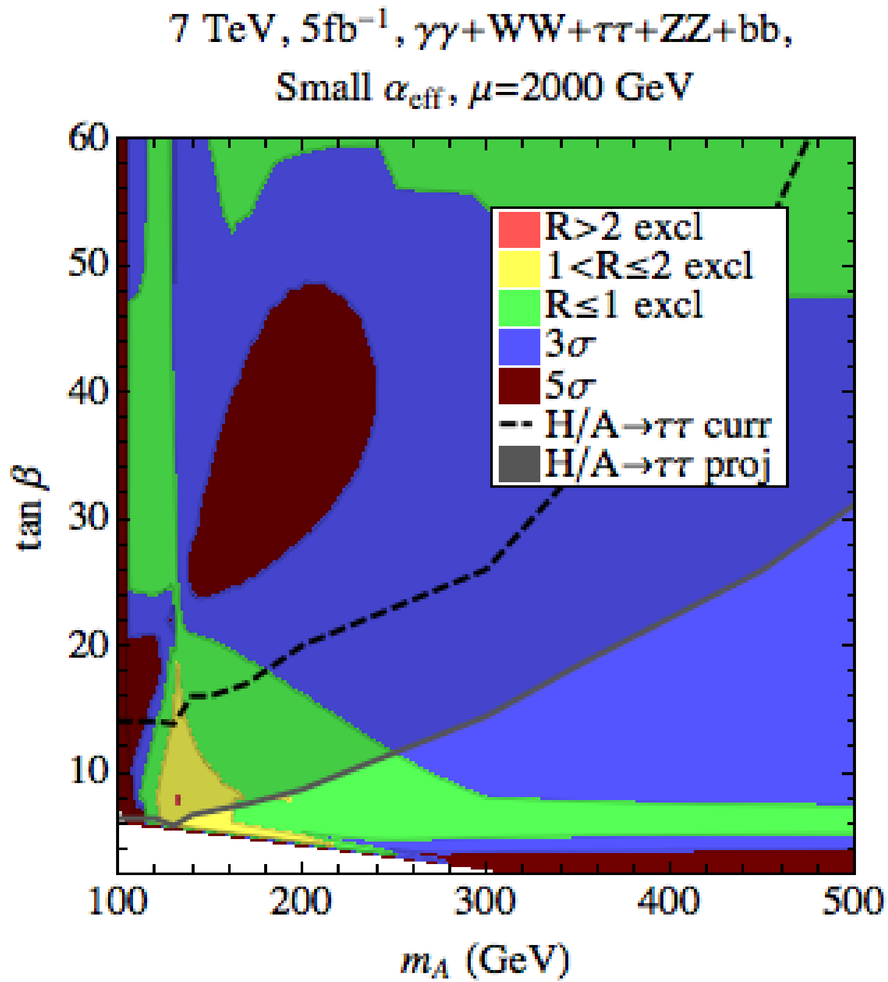




M. Carena, P. Draper, T. Liu, C.W.'11

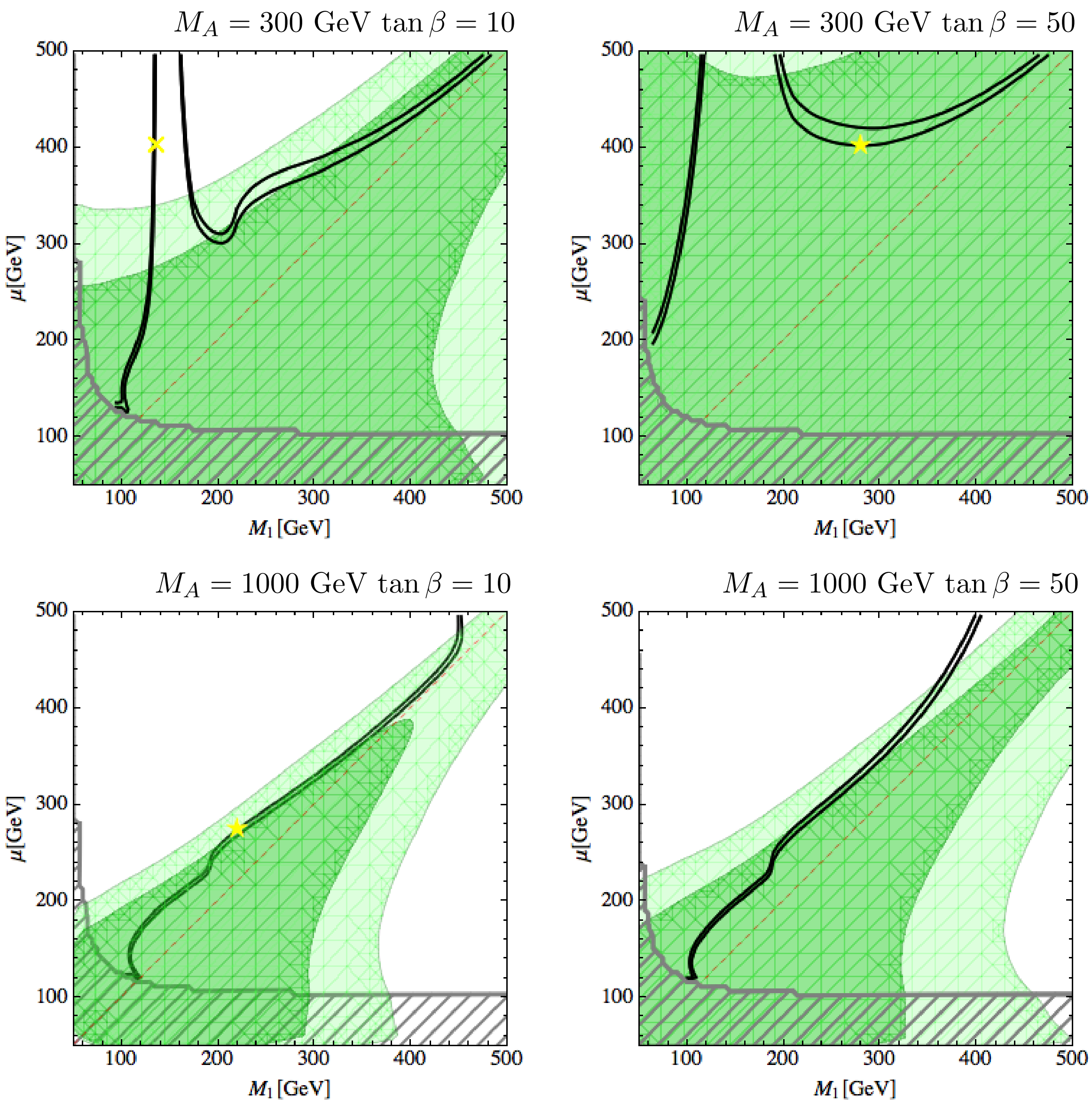
Non-standard Higgs searches allow to probe part of the parameter space for which standard reach is suppressed

Non-Standard Higgs searches heavily constrain the region consistent with photon decay enhancement



Direct Dark Matter Cross Section Constraints (post Xenon)

For lower values of the CP-odd Higgs mass, low values of tan(beta) preferred



Gori, Schwaller, C.W. '11

Search for SM-like Higgs Boson from SUSY Particle Decays

Parameter space consistent with Neutralino Relic Density: Heavy Sleptons

Look for boosted SM-like Higgs bosons, decaying to bottom quarks

Butterworth, Davison, Rubin, Salam'08

Higgs from heavy sparticle decays tend to be boosted

Kribs, Martin, Roy, Spannowsky'10

Countours of proper relic density

$\text{Green}: \tan\beta = 50$

$\text{Black}: \tan\beta = 10$

$m_A = 300\ \text{GeV}$

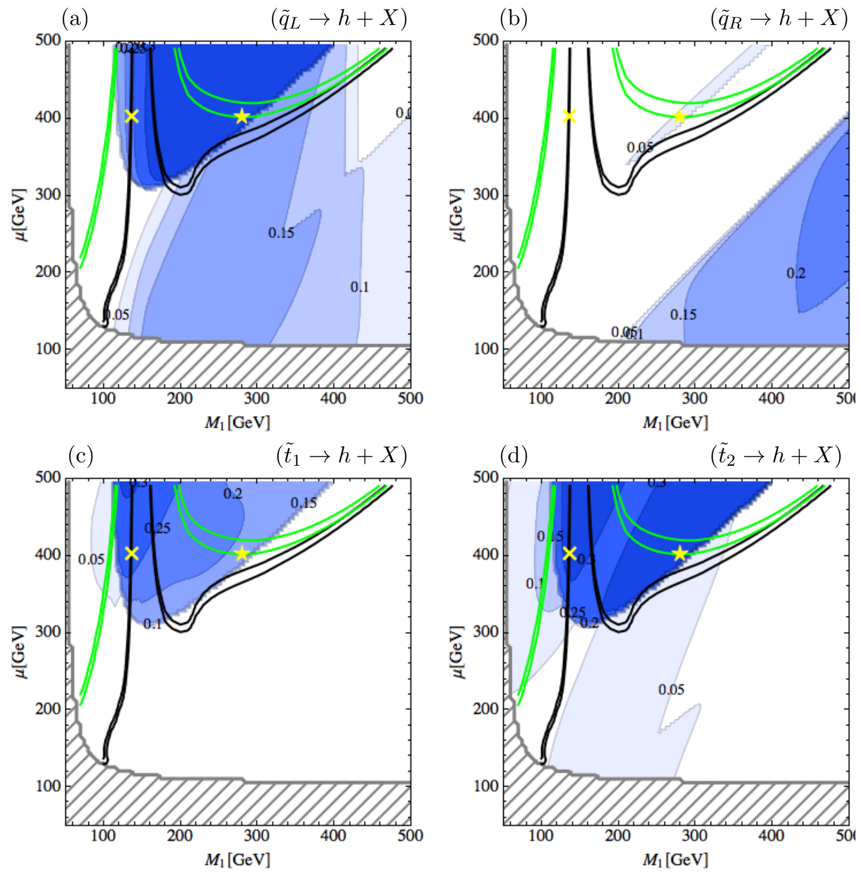
$m_{\tilde{q}} \simeq 1\ \text{TeV}$

$M_{\tilde{g}} \simeq 6 M_1$

$M_2 = 2 M_1$

$\text{Boosted Higgs}: p_T > 200\ \text{GeV}$

	σ[pb]	$\sigma_{\rm cut}$[pb]	σ_h[fb]	$\sigma_{\rm boosted}$[fb]
(I)	1.11	0.52	78	31
(II)	0.73	0.34	116	31
(III)	2.59	0.90	360	135
(IV)	1.60	0.83	231	101



Blue regions :

Appreciable Branching Decay Fraction.

Darker means larger branching decay fraction.

X : energetic quarks, leptons and missing energy

Gori, Schwaller, Wagner, **Phys.Rev.D83:115022,2011**

Good prospects of observing Higgs in the 14 TeV run and, perhaps, even in the 7 TeV run.

Higgs from SUSY decays at the 7 TeV Run

Simple cuts :

- $\not{E}_T > 200$ GeV,
- at least two jets, with $p_{T1} > 300$ GeV and $p_{T2} > 200$ GeV.

	σ[pb]	$\sigma_{\rm cut}$[pb]	σ_h[fb]	$\sigma_{\rm boosted}$[fb]
(I)	0.092	0.019	2.7	1.1
(II)	0.042	0.015	5.1	1.1
(III)	0.113	0.030	10	3.6
(IV)	0.106	0.029	8.2	3.3

Squark Masses 1 TeV

	σ[pb]	$\sigma_{\rm cut}$[pb]	σ_h[fb]	$\sigma_{\rm boosted}$[fb]
(I)	0.23	0.086	11	3.0
(II)	0.18	0.063	17	2.0
(III)	0.31	0.142	36	11
(IV)	0.36	0.169	45	14

Squark Masses 800 GeV

Gori, Schwaller, Wagner, **Phys.Rev.D83:115022,2011**

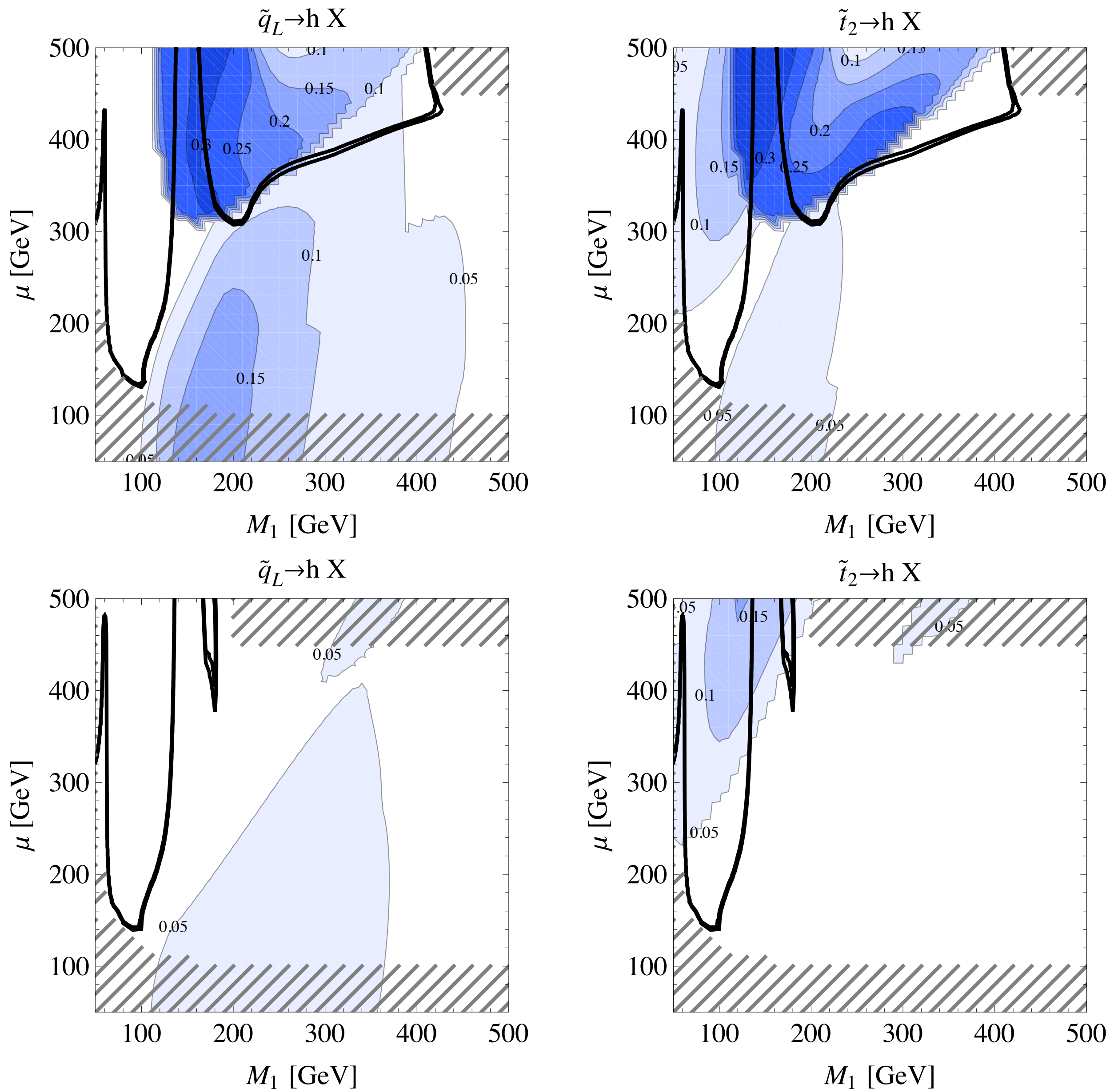
Low statistics, degrading fast for higher SUSY masses

Conclusions

- Search for Higgs bosons in the low mass region is challenging at the LHC
- At an early LHC, and moderate values of the CP-odd Higgs mass, reach in relevant channels is affected by increase in bottom width. Discovery potential increased in large CP-odd Higgs mass region.
- Complementarity between searches at colliders suggests usefulness of eventual combination of Tevatron-LHC results at the end of 2011.
- Non-Standard Higgs searches at the LHC serve to further probe the parameter space.
- Higgs from cascade decays : For heavy squarks and sleptons, in the region consistent with a Dark Matter relic density, and considering the current bounds on squark and gluino masses, statistics will be poor at the 7 TeV machine.
- SUSY decay searches further challenged if slepton masses are not above the neutralino N_2 mass

Backup Slides

Regions of parameter space consistent with Neutralino relic density: Light CP-odd boson and light Sleptons



$M_2 = 2M_1$

$m_{\tilde{q}} \simeq 1$ TeV

$M_{\tilde{g}} \simeq 6M_1$

Upper Row : $m_{\tilde{l}} = 400$ GeV

Lower Row : $m_{\tilde{l}} = 200$ GeV

Clear degradation of Higgs signal for light sleptons

Gori, Schwaller, C.W.'11

Higgs Bosons Decaying to Bottom pairs at the LHC

- In the past the decay of Higgs into bottom quarks have been ignored due to overwhelming backgrounds
- However, the study of jet substructure has revealed new possibilities
- In particular, boosted Higgs bosons decaying to bottom pairs might be easily separated from the QCD background by the use of these techniques
- This is true in the SM model, for a light Higgs produced in association with W bosons, where the proportion of boosted Higgs is small

  Butterworth, Davison, Rubin, Salam'08
  Plehn, Salam, Spannowsky'09 (ttbar+H)
- In the MSSM, there are new possibilities for boosted Higgs

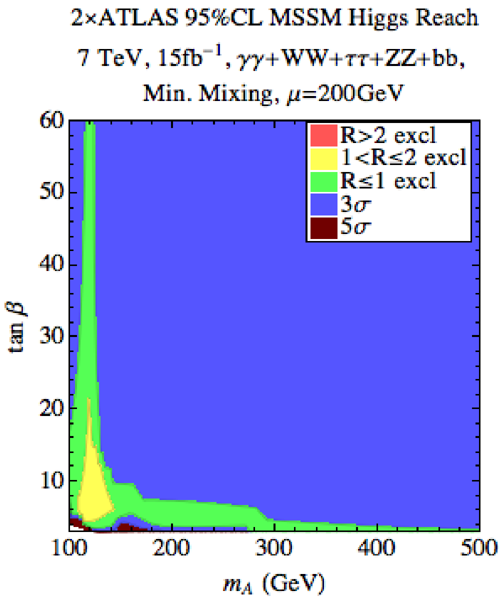
  Kribs, Martin, Roy, Spannowsky'10

MSSM with Higgsino LSP

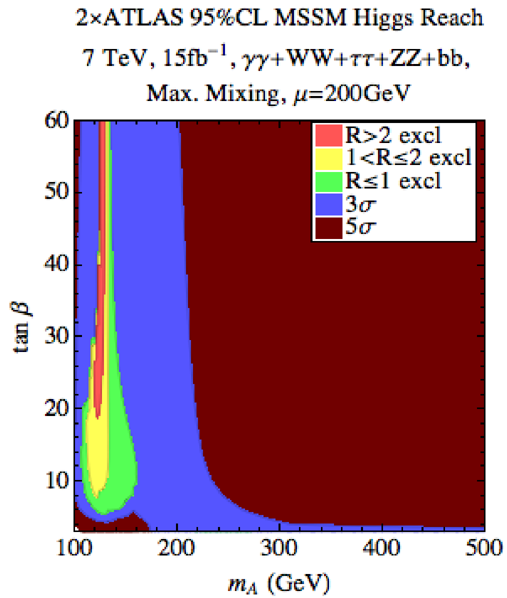
	SHSP 1a / SHSP 1b	SHSP 2a / SHSP 2b	SHSP 3	SHSP 4	SHSP 5	SHSP 6
$\tan\beta$	10	10	10	5	6.5	10
M_1	300 GeV	150 GeV	163 GeV	200 GeV	200 GeV	300 GeV
M_2	600 GeV	300 GeV	400 GeV	400 GeV	400 GeV	600 GeV
M_3	2.1 TeV	1.05 TeV	1.0 TeV	1.4 TeV	1.4 TeV	2.1 TeV
μ	150 GeV	150 GeV	200 GeV	200 GeV	−150 GeV	150 GeV
m_A	1 TeV	1 TeV	1 TeV	150 GeV	150 GeV	200 GeV
a_t	900 GeV	−900 GeV	900 GeV	2.04 TeV[a]	1.4 TeV	900 GeV
$m_{\tilde{q}}$	1 TeV	1 TeV/750 GeV	1 TeV	1 TeV	1 TeV	1 TeV
$m_{\tilde{l}}$	1 TeV/350 GeV	1 TeV/350 GeV	350 GeV	1 TeV	1 TeV	1 TeV
m_h	116 GeV	117 GeV	116 GeV	114 GeV	115 GeV	115 GeV
m_H	1 TeV	1 TeV	1 TeV	161 GeV	157 GeV	202 GeV
m_A	1 TeV	1 TeV	1 TeV	150 GeV	150 GeV	200 GeV
$m_{H^\pm}$	1 TeV	1 TeV	1 TeV	169 GeV	170 GeV	216 GeV
χ_1	138 GeV	110 GeV	140 GeV	157 GeV	136 GeV	138 GeV
χ_2	−158 GeV	−161 GeV	209 GeV	−207 GeV	−163 GeV	−158 GeV
χ_3	206 GeV	174 GeV	−209 GeV	227 GeV	210 GeV	306 GeV
χ_4	625 GeV	338 GeV	429 GeV	433 GeV	426 GeV	623 GeV
χ_1^+	148 GeV	137 GeV	191 GeV	187 GeV	152 GeV	148 GeV
χ_2^+	625 GeV	337 GeV	429 GeV	433 GeV	426 GeV	623 GeV
σ_{tot}	3.9 pb	5.8 pb / 8.07 pb	2.76 pb	2.4 pb	4.1 pb	4.0 pb
% Higgs	4.5%/3.4%	4.2%/6.8%	6.6%	12.8%	8.6%	7.0%
$\sigma_{h/H/A}$	0.18 pb/0.13 pb	0.24 pb/0.55 pb	0.18 pb	0.31 pb	0.35 pb	0.28 pb

Discovery of Higgs boson with 10 inverse fb at a 14 TeV LHC possible

- Kribs et al concentrated on the region of light Higgsinos, where the proportion of boosted Higgs bosons tends to be large.
- The appearence of hard jets, b-tagging and large missing energy already provide interesting ways of suppressing the background
- Highly boosted Higgs provide an additional tool
- Light Higgsinos tend to be inconsistent with the standard neutralino relic density
- It is therefore interesting to study what happens when one departs from these regions.



2×ATLAS 95%CL MSSM Higgs Reach
7 TeV, 15fb^{-1}, $\gamma\gamma$+WW+$\tau\tau$+ZZ+bb,
Min. Mixing, μ=200GeV
R>2 excl
1<R≤2 excl
R≤1 excl
3σ
5σ
tan β
m_A (GeV)



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Max. Mixing, μ=200GeV
R>2 excl
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R≤1 excl
3σ
5σ
tan β
m_A (GeV)

Efficiency Improvements in the low Mass Region

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!):

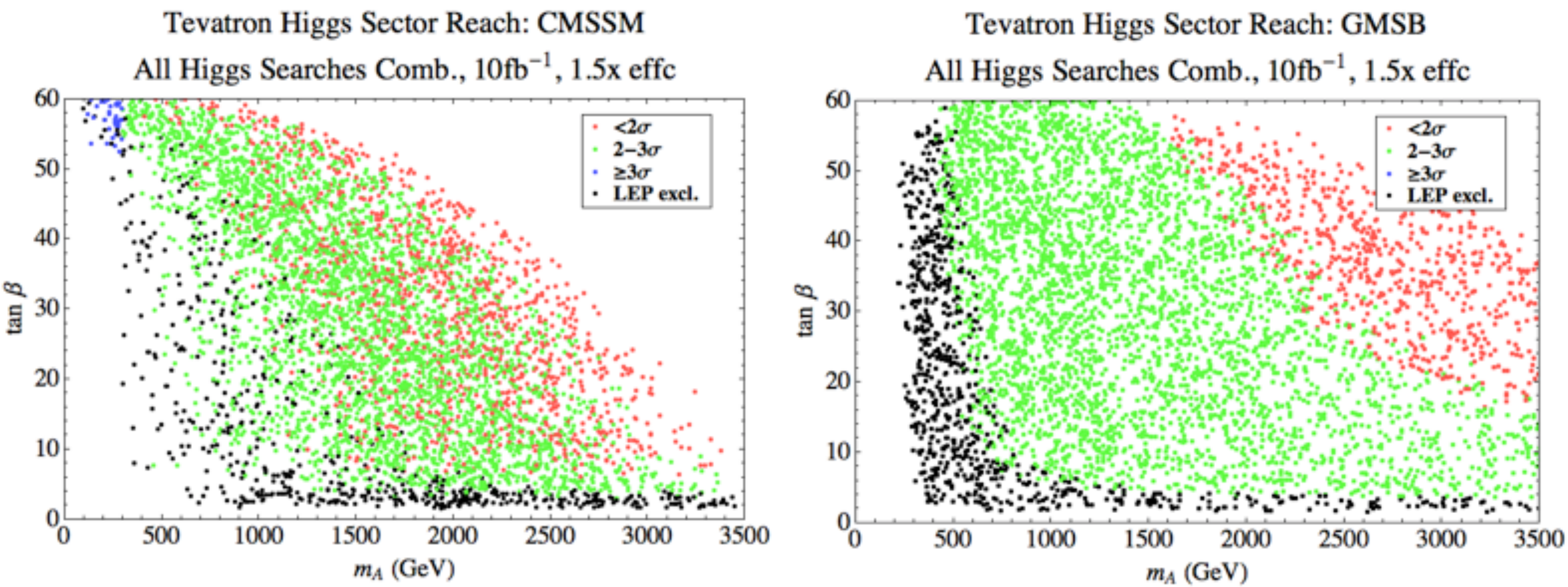
Demonstrated charm quark discrimination ability:	~30% equiv lumi gain
Improved usage of b-Tagging information:	~20% equiv lumi gain
Reduced dijet mass resolution:	~15% equiv lumi gain
for every 1% absolute gain in σ_{Mbb} for up to ~50-60% possible	
Addition of lower yield final states ($H \rightarrow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

CMSSM and MGM at the Tevatron

M. Carena, P. Draper, S. Heinemeyer, T. Liu, G. Weiglein, C.W. '10



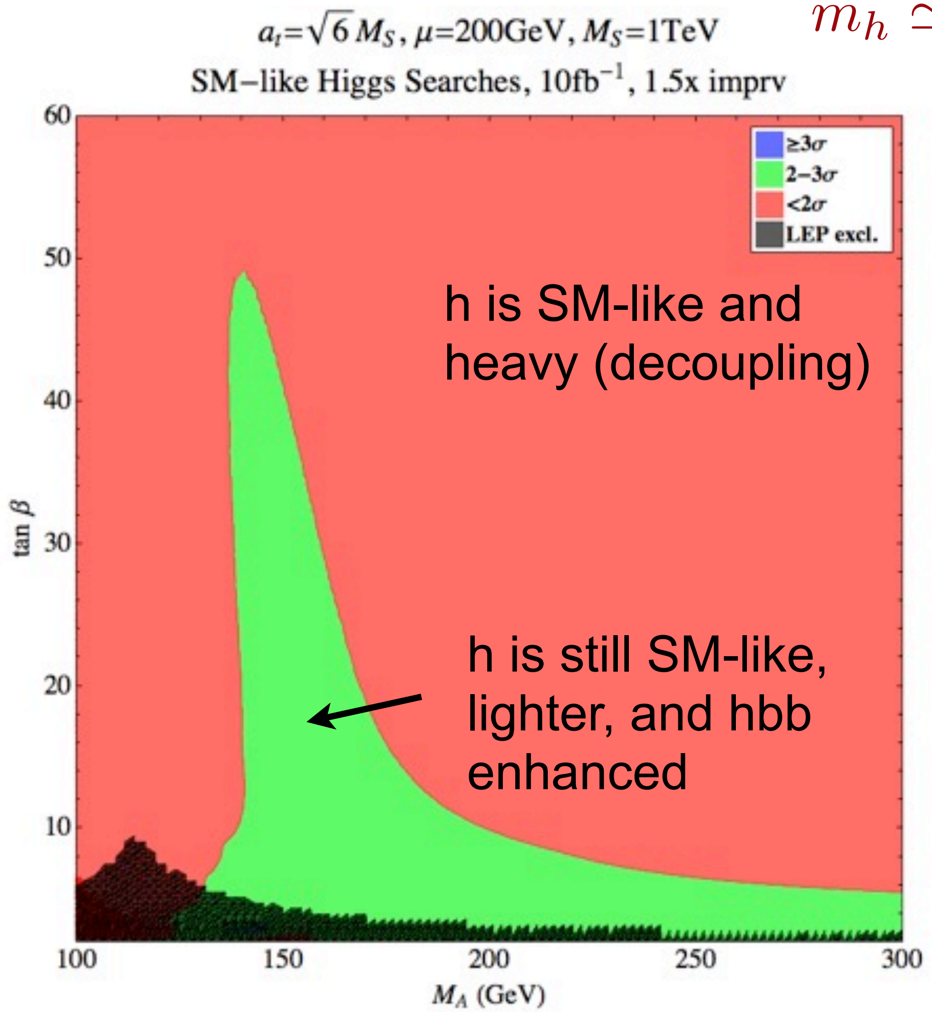
In both cases, the Tevatron could probe most of the models with squarks at the LHC reach and values of the CP-odd mass below 1 TeV.

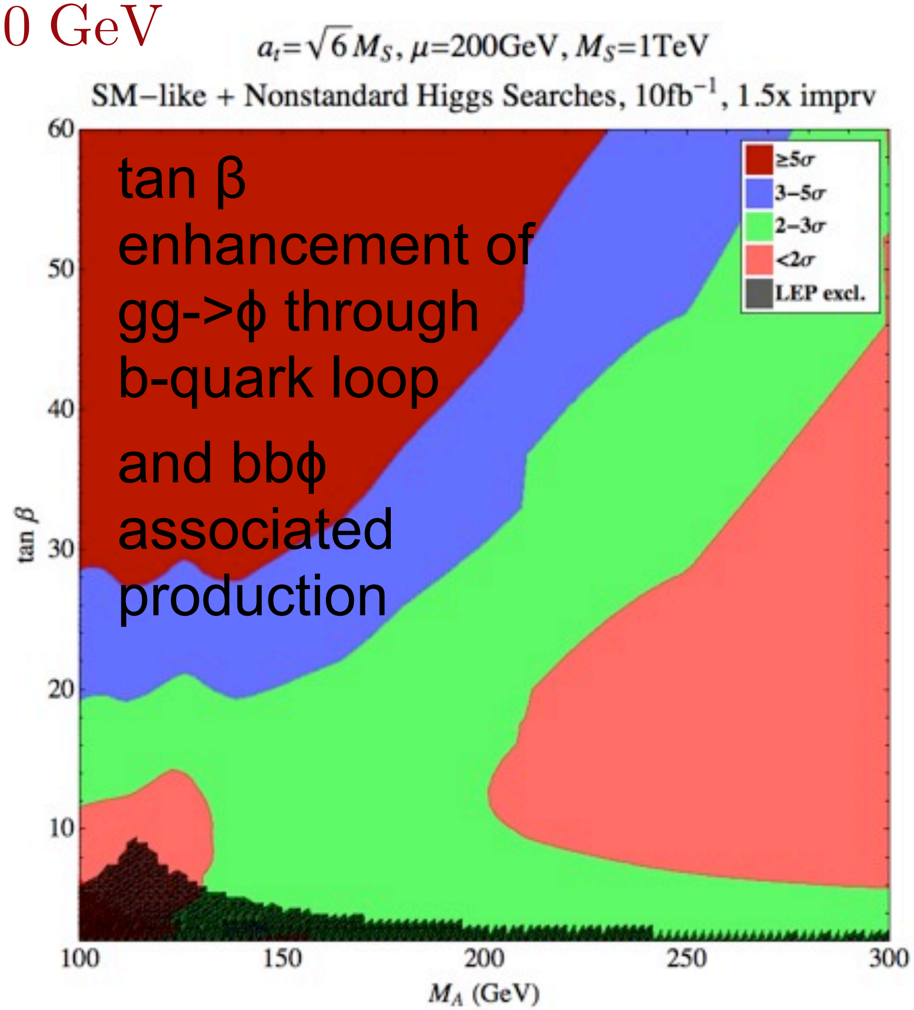
$$\mu^2 \simeq -M_Z^2/2 - m_{H_u}^2$$
$$m_A^2 \simeq -M_Z^2 + (m_{H_d}^2 - m_{H_u}^2)$$

$$m_Q^2 \simeq m_0^2\left(1 - y_t^2/2\right) + 5.5 M_{1/2}^2$$
$$m_U^2 \simeq m_0^2\left(1 - y_t^2\right) + 5 M_{1/2}^2$$

Combination with Non-Standard Higgs channels

$m_h \simeq 130$ GeV

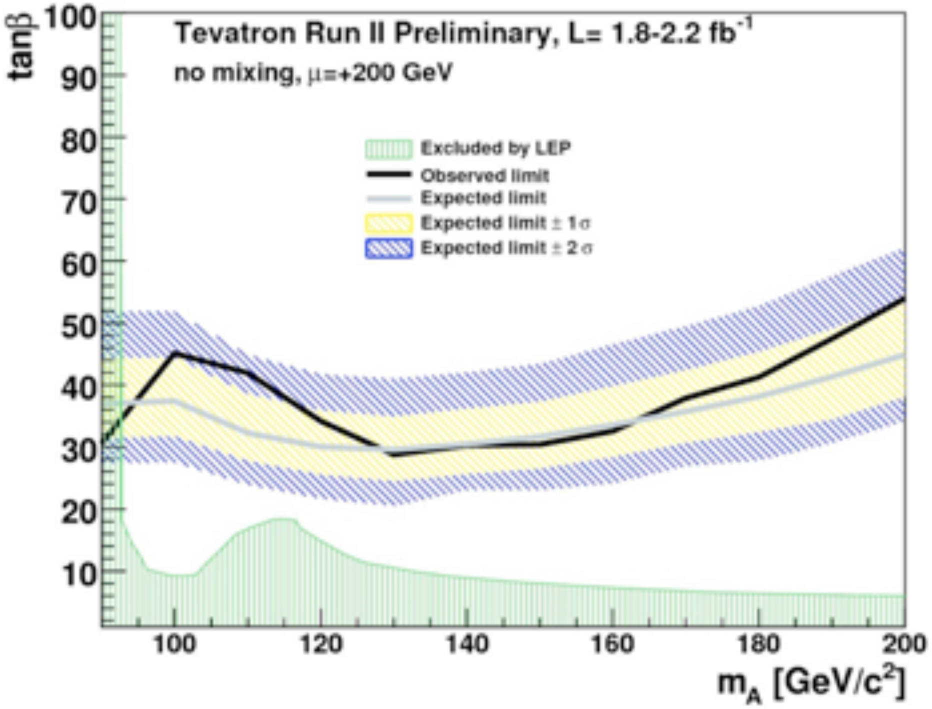


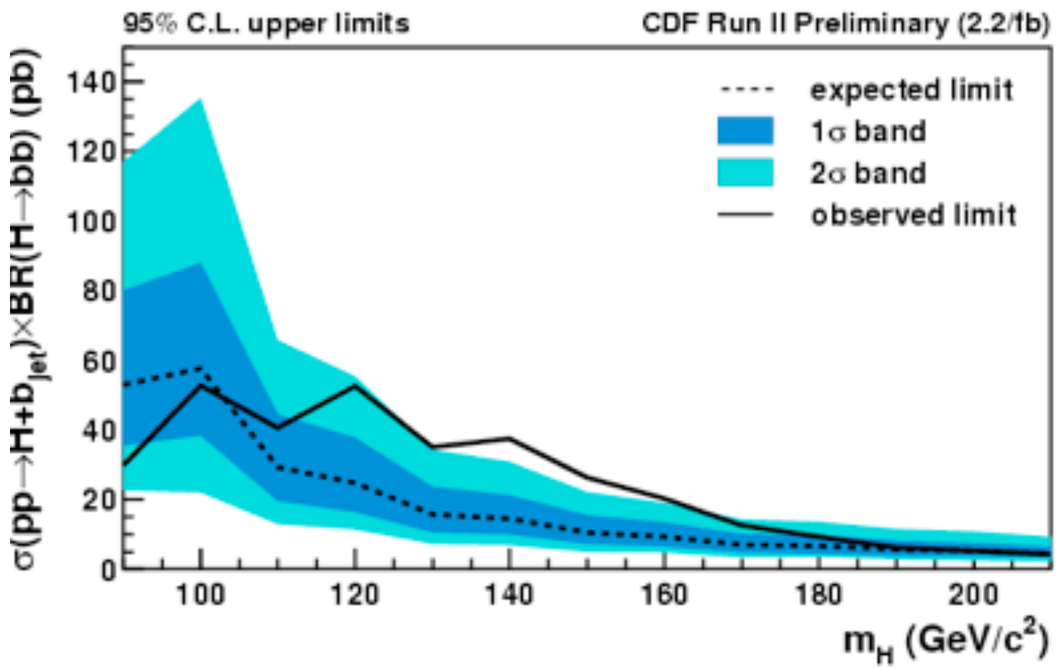


End of 2011

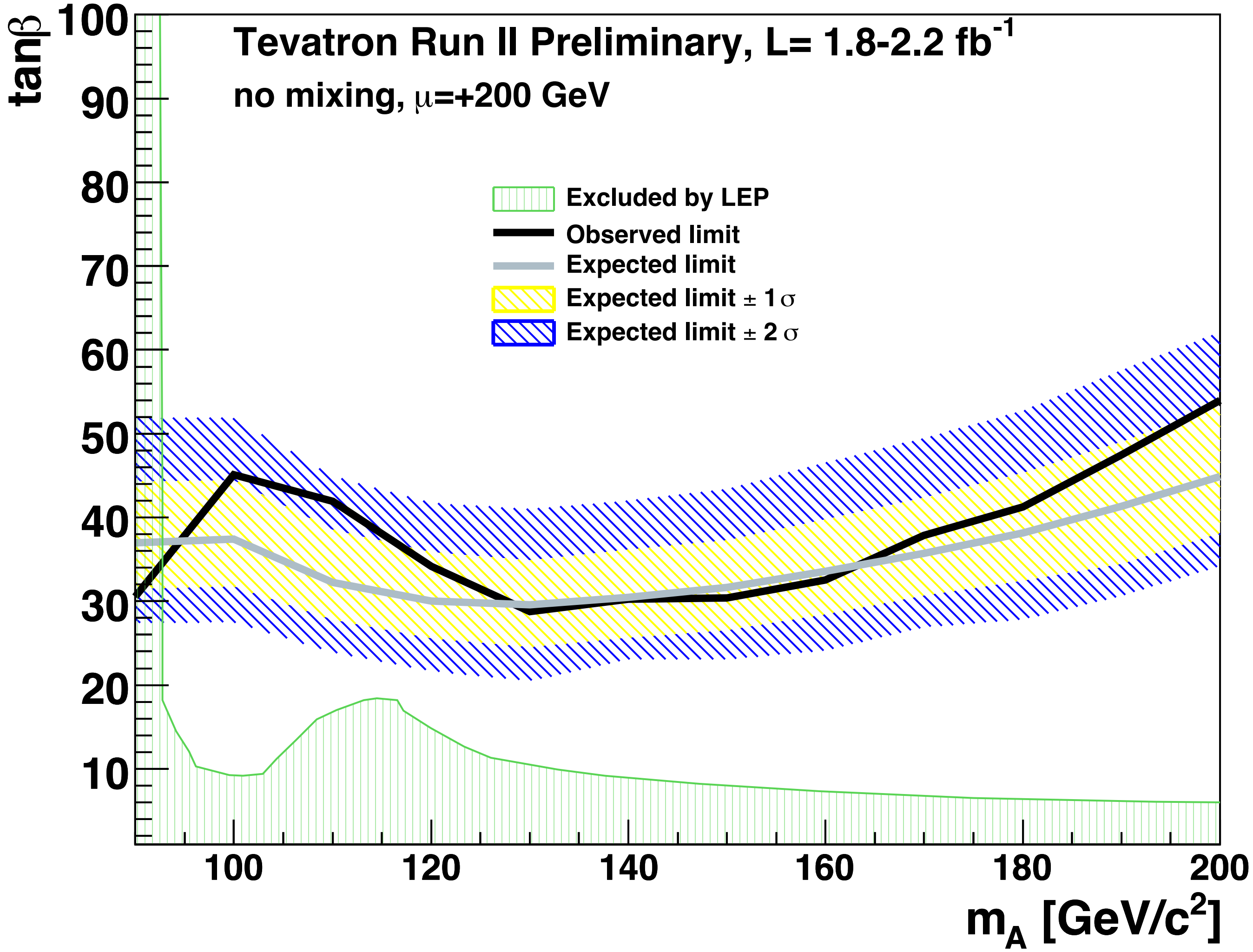
Maximal Mixing Scenario : Red region is barely below 2 sigma. Combination of non-SM channels become significant to probe large regions of parameter space.

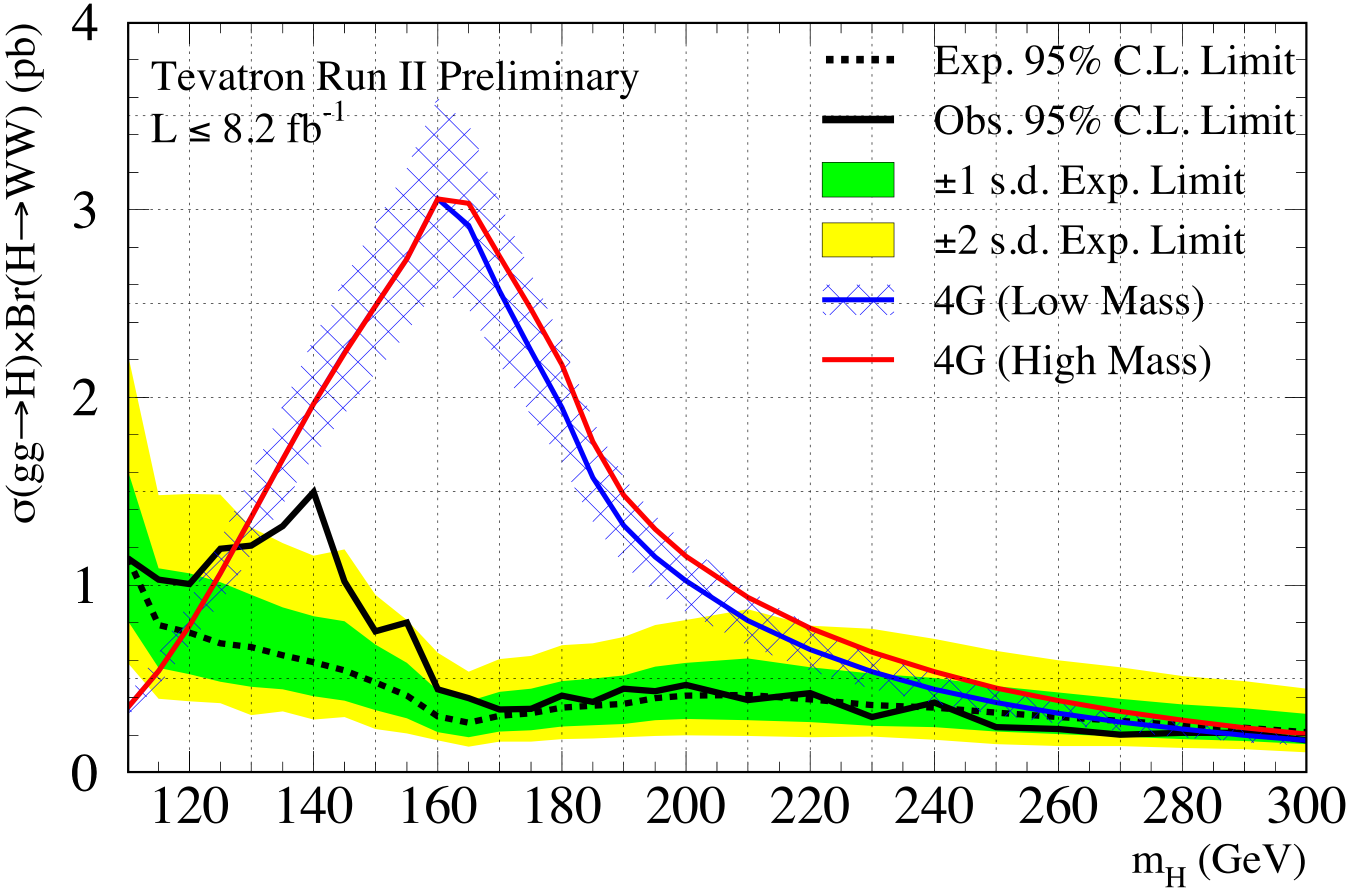
Searches for non-standard Higgs bosons at the Tevatron





Combination of CDF and D0
Non-Standard Higgs Searches

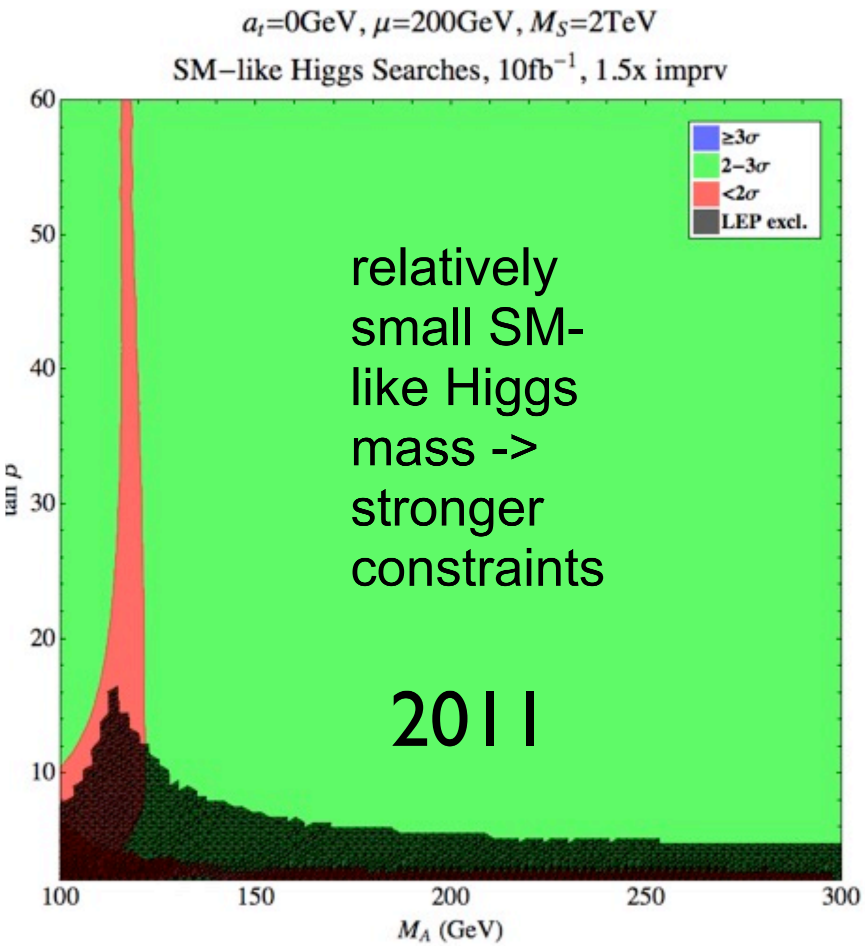



Tevatron Run II Preliminary
L ≤ 8.2 fb-1
Exp. 95% C.L. Limit
Obs. 95% C.L. Limit
±1 s.d. Exp. Limit
±2 s.d. Exp. Limit
4G (Low Mass)
4G (High Mass)
σ(gg→H)×Br(H→WW) (pb)
mH (GeV)
0
1
2
3
4
120
140
160
180
200
220
240
260
280
300

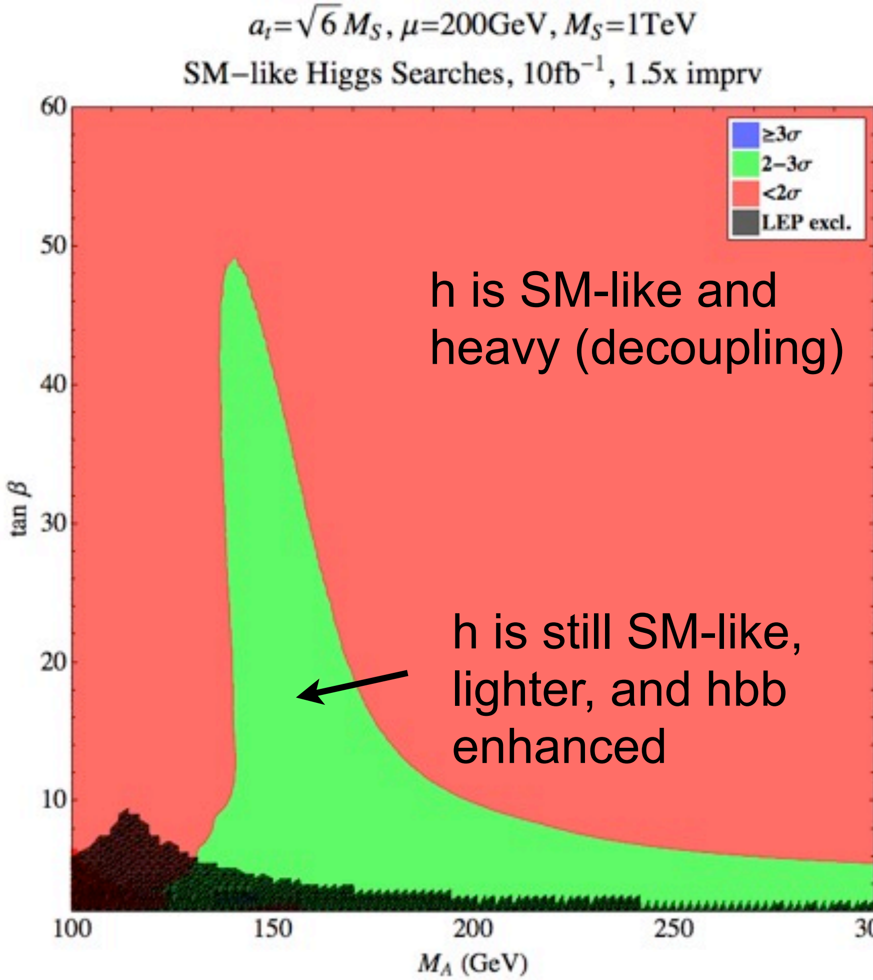
P. Draper, T. Liu and C.W. '10

SM-like Higgs search channels at the Tevatron.

$m_h \simeq 115\text{GeV}$



$m_h \simeq 130$ GeV



At the end of the Tevatron run, more than 2 sigma sensitivity is achieved in most parameter space in minimal mixing, while weaker reach in maximal mixing scenario.