Higgs Physics in the SM and Beyond

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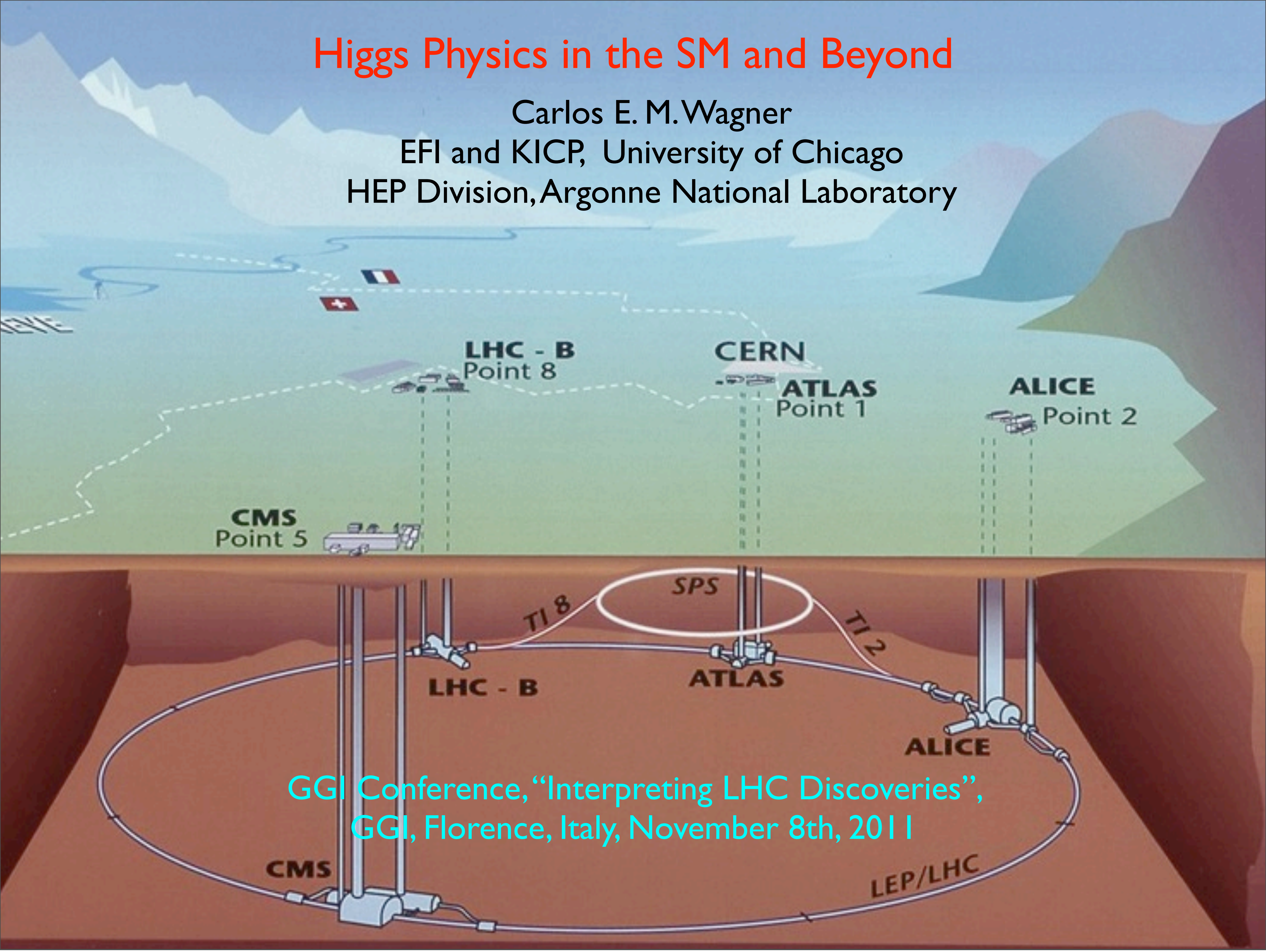
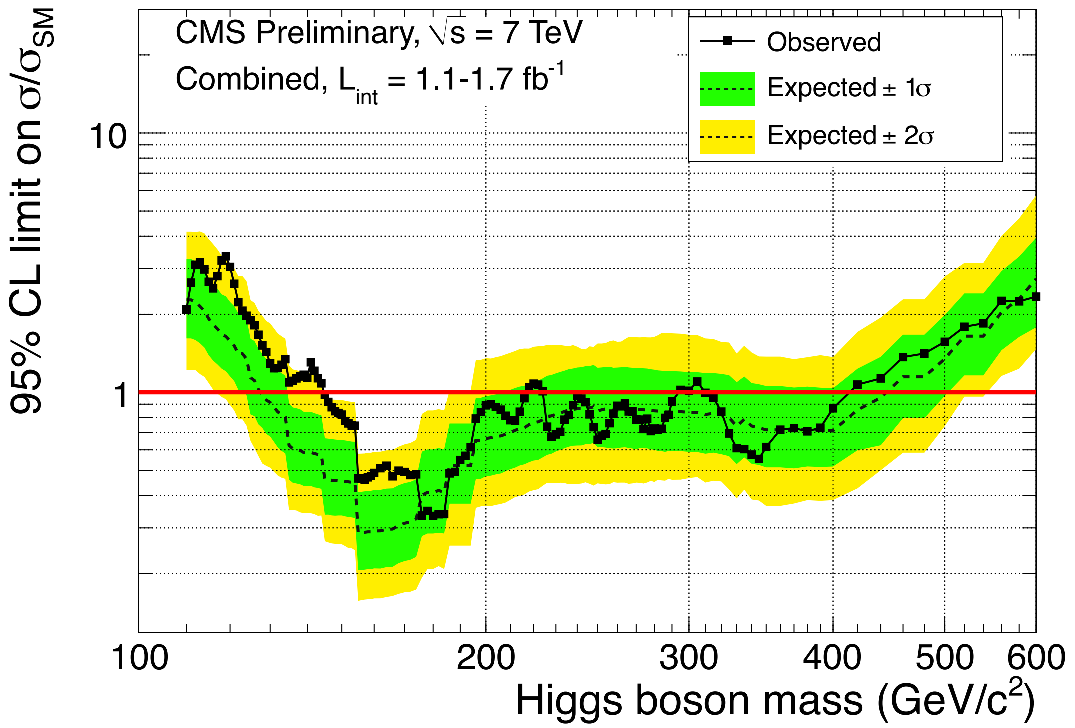


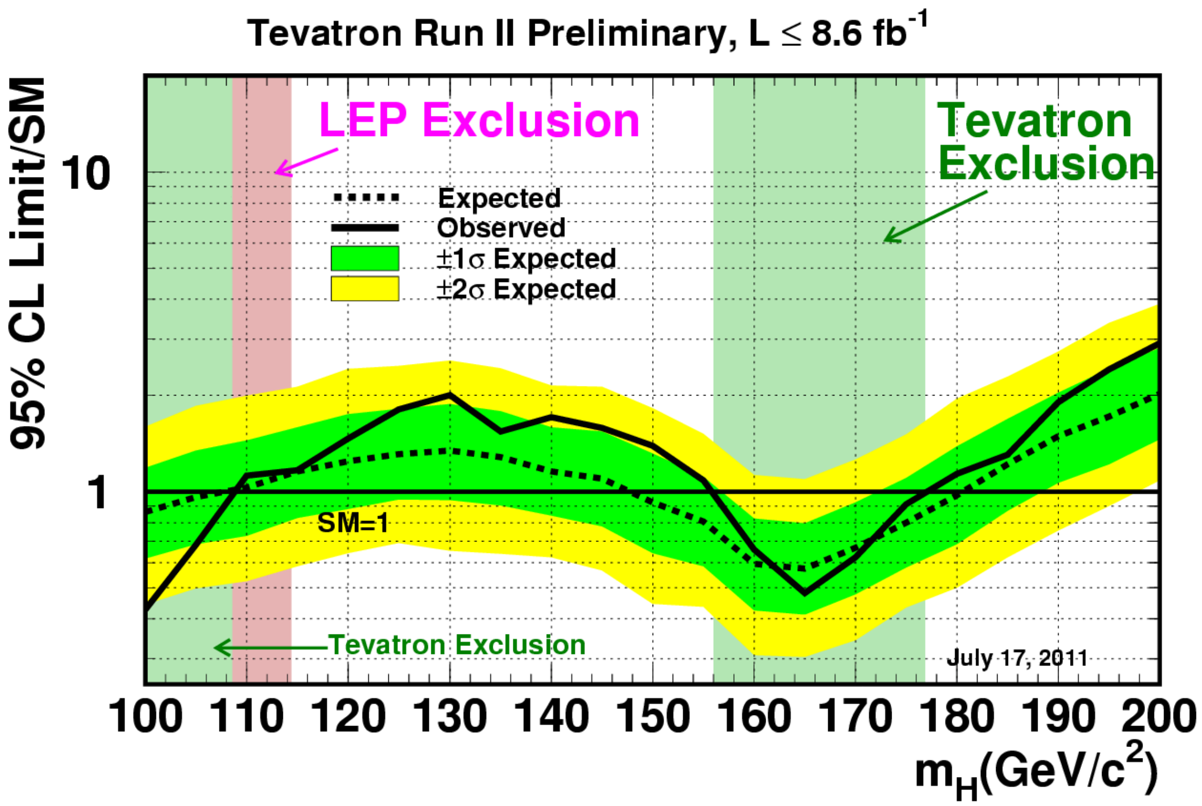
GGI Conference, "Interpreting LHC Discoveries",
GGI, Florence, Italy, November 8th, 2011



We are leaving in exciting times:

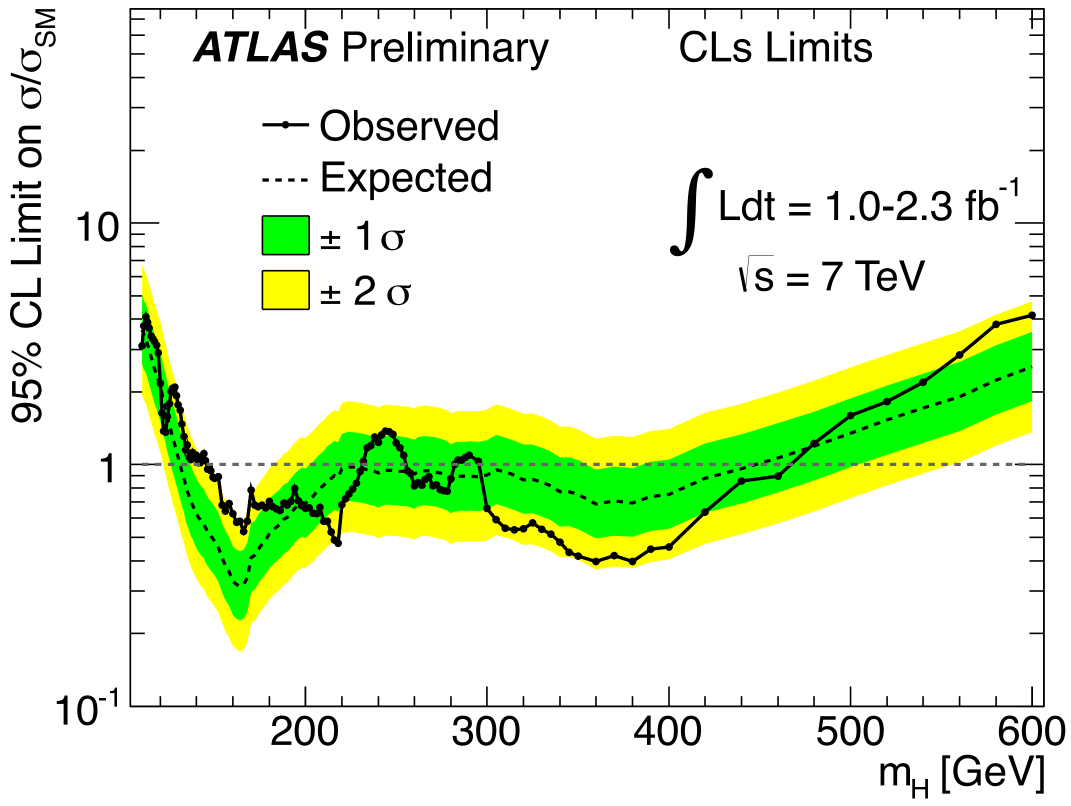
Experiments are starting to test the SM Higgs above the LEP limit, leading to interesting exclusion bounds on its mass.

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

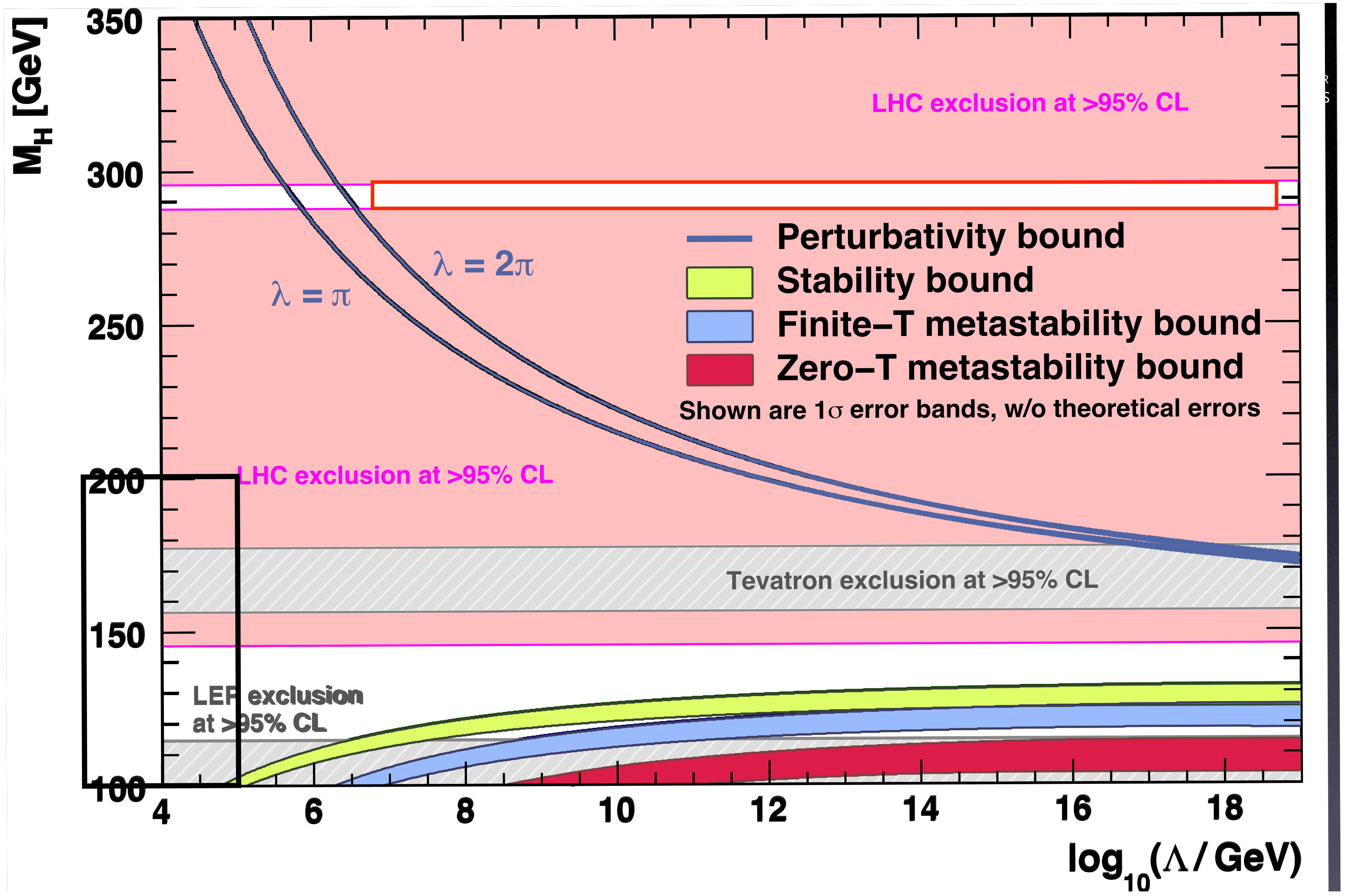


Observed Exclusion : 100-109 and 156-177 GeV/c^2

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

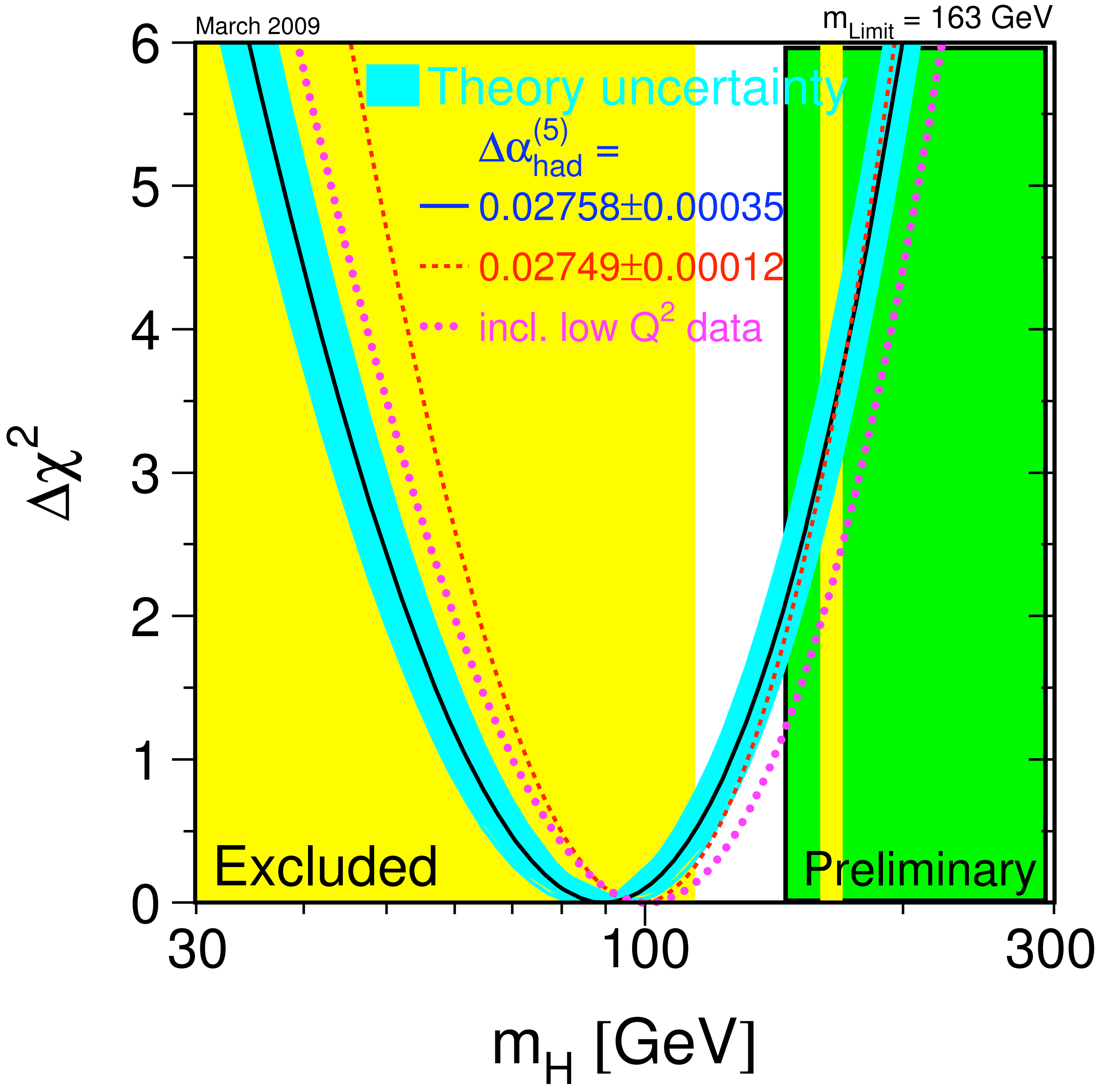


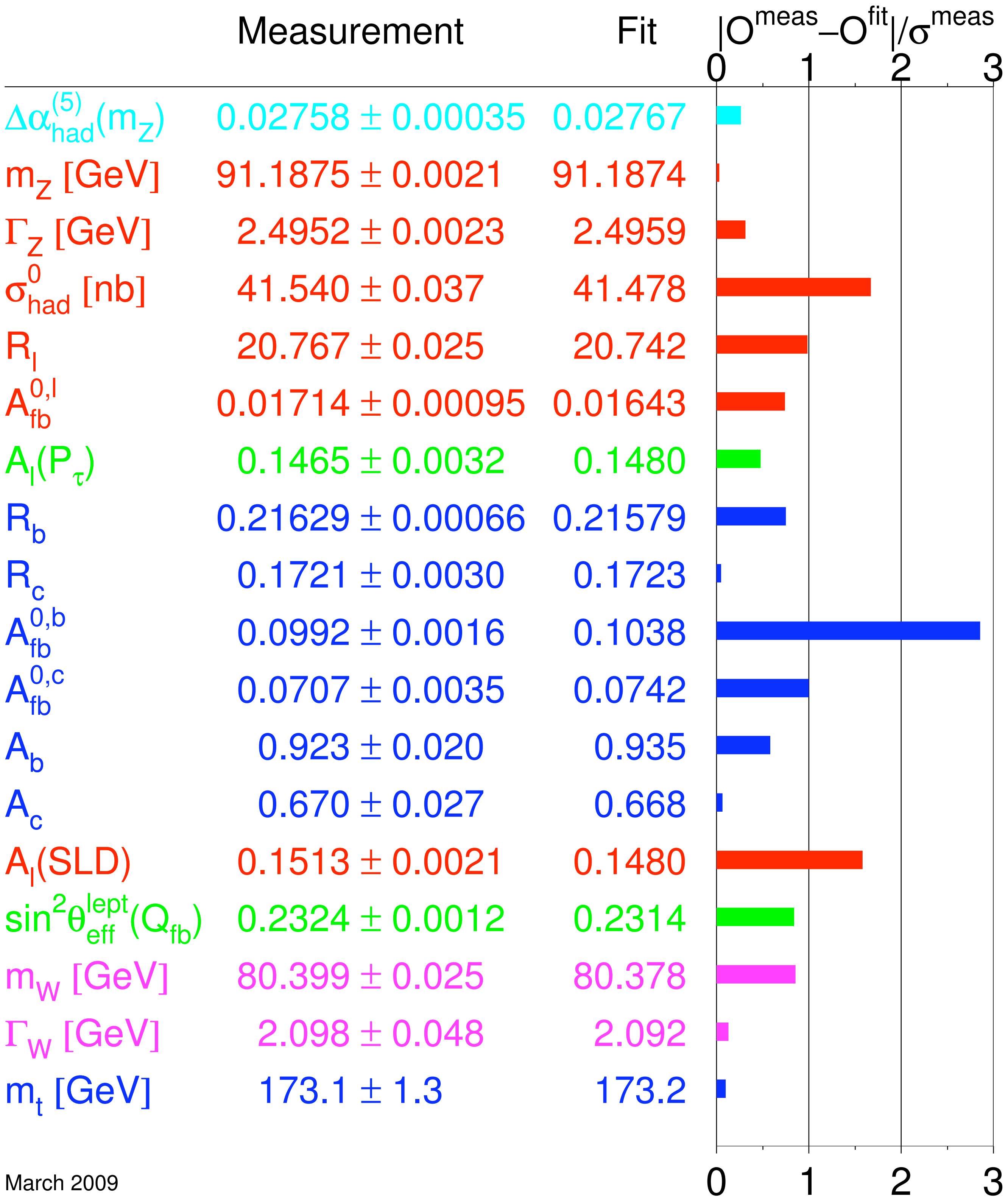
Allowed region consistent with extrapolation of the SM description until very high energies



H. Murayama, SUSY 2011

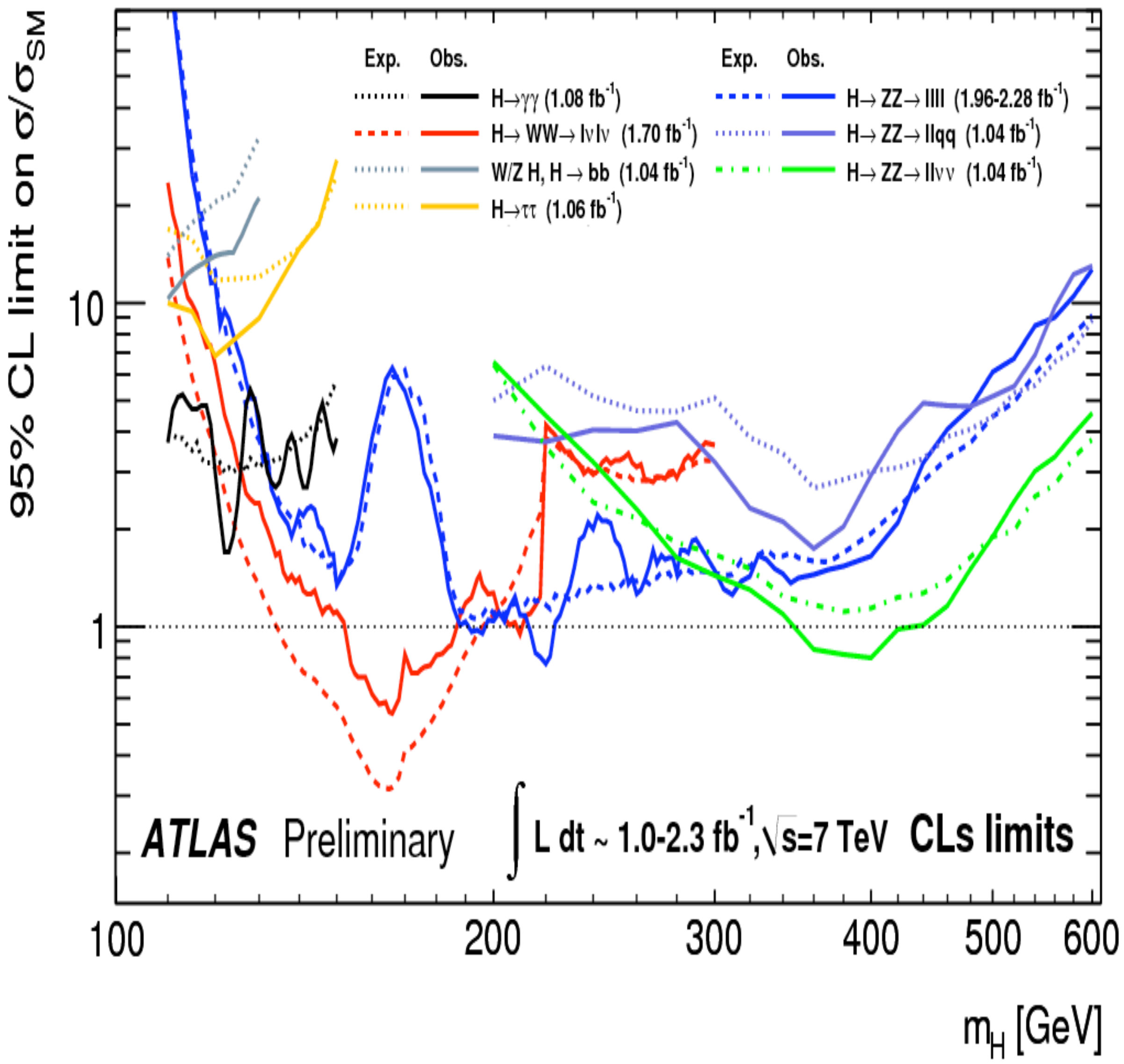
Allowed region also overlaps with the region preferred by SM Precision Electroweak Data

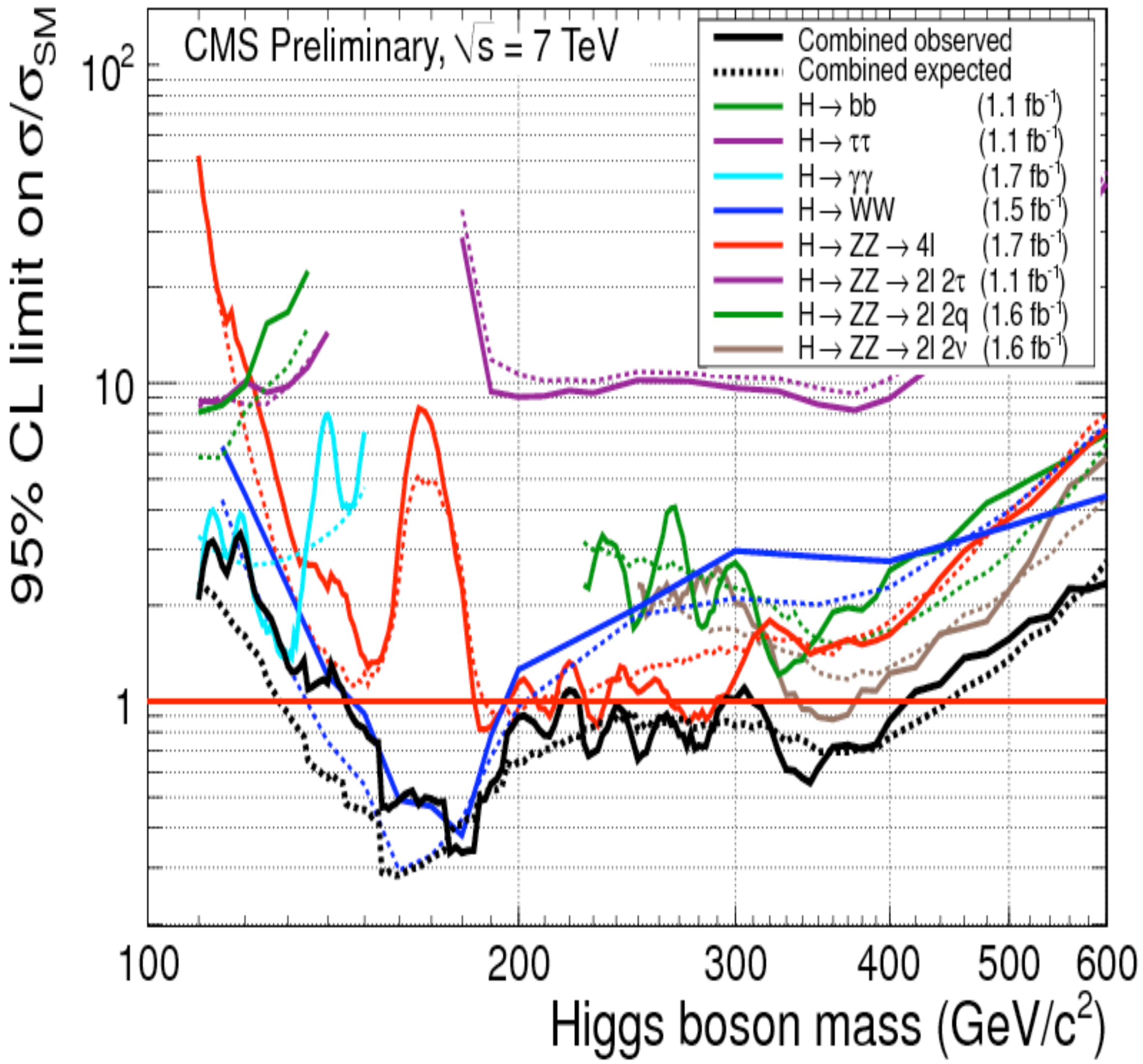




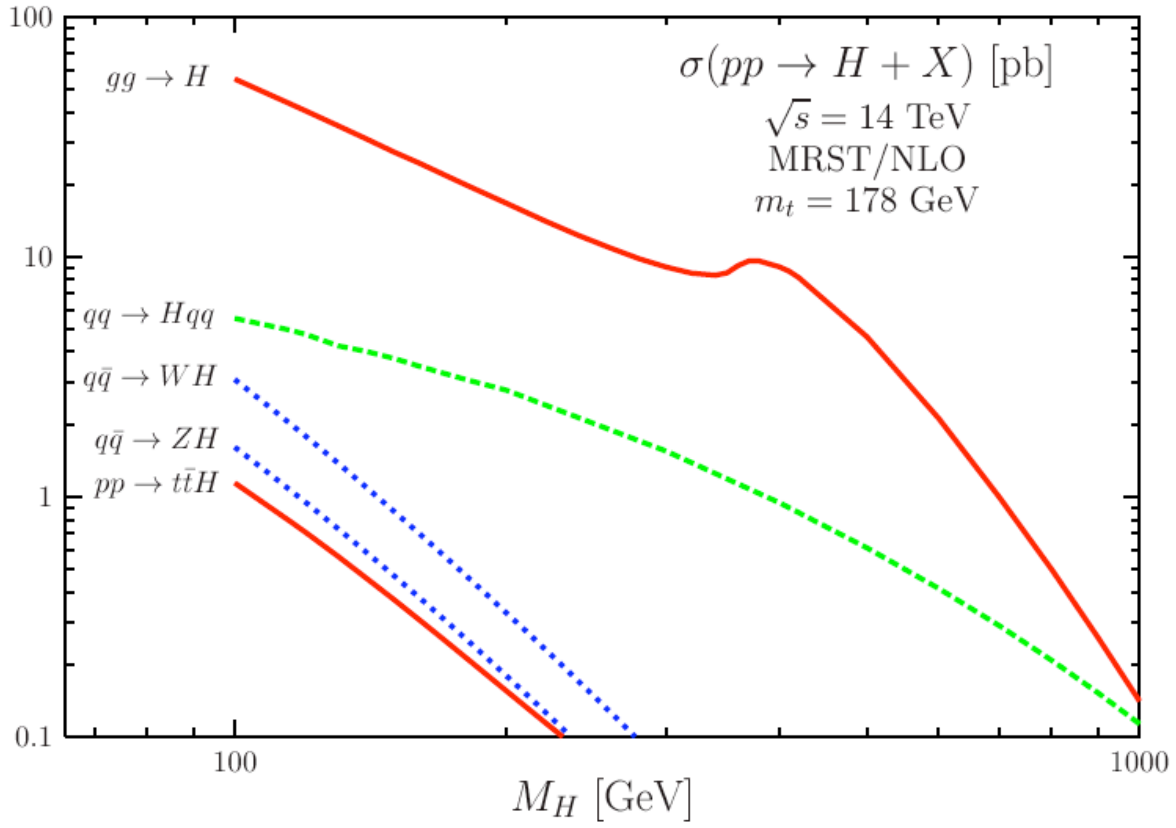
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

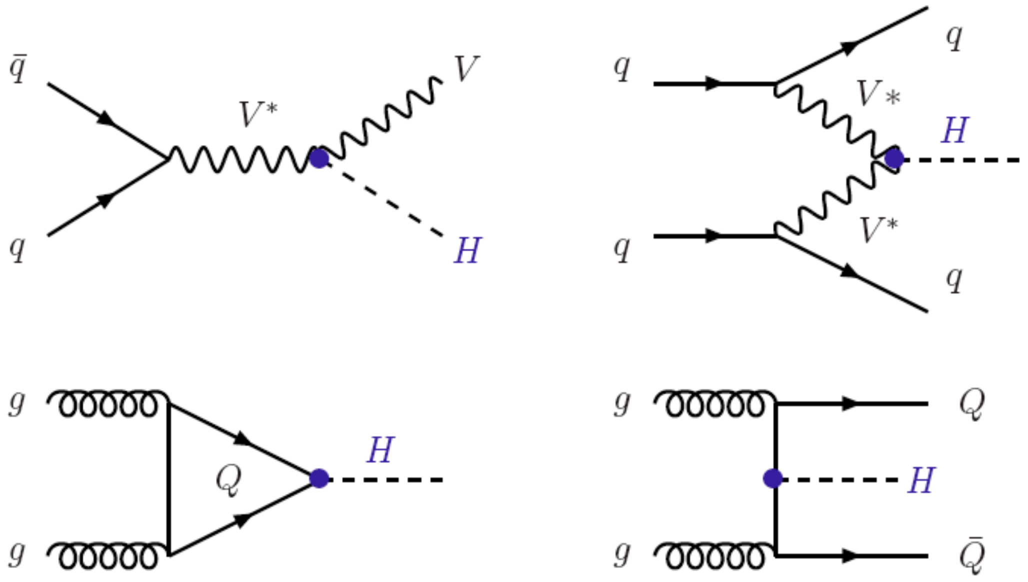
Higgs Limits obtained by combination of multiple channels





Main Higgs Production channels at Hadron Colliders





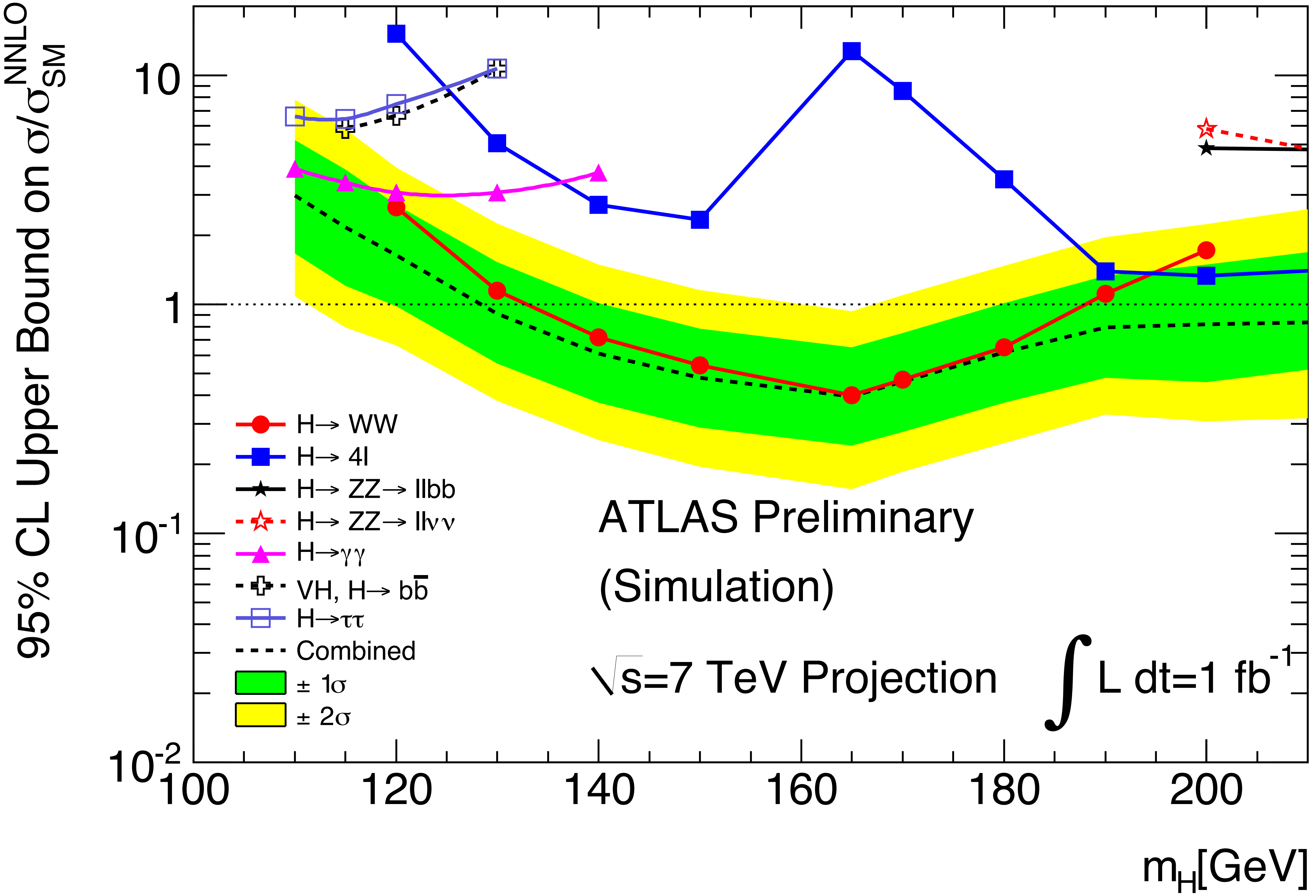
A. Djouadi, hep-ph/0503172

The event rate depends on three quantities

$$B\sigma(p\bar{p} \to h \to X_{\mathrm{SM}}) \equiv \sigma(p\bar{p} \to h)\frac{\Gamma(h \to X_{\mathrm{SM}})}{\Gamma_{\mathrm{total}}}$$

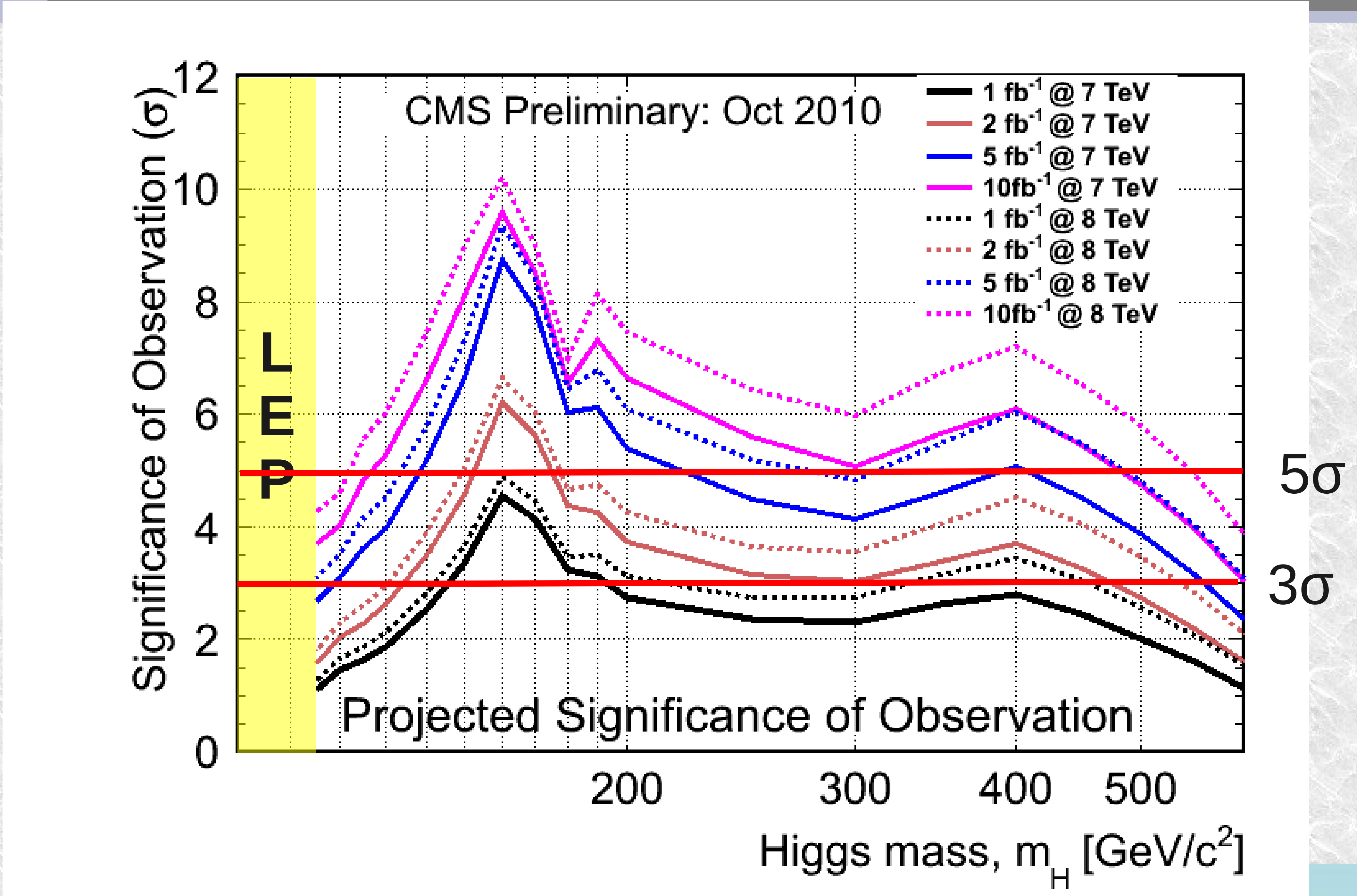
The three of them may be affected by the presence of new physics. If the SM rate is modified, of course, the total width is modified as well. This is particularly true for the WW rate at high Higgs masses and bb at low Higgs masses

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



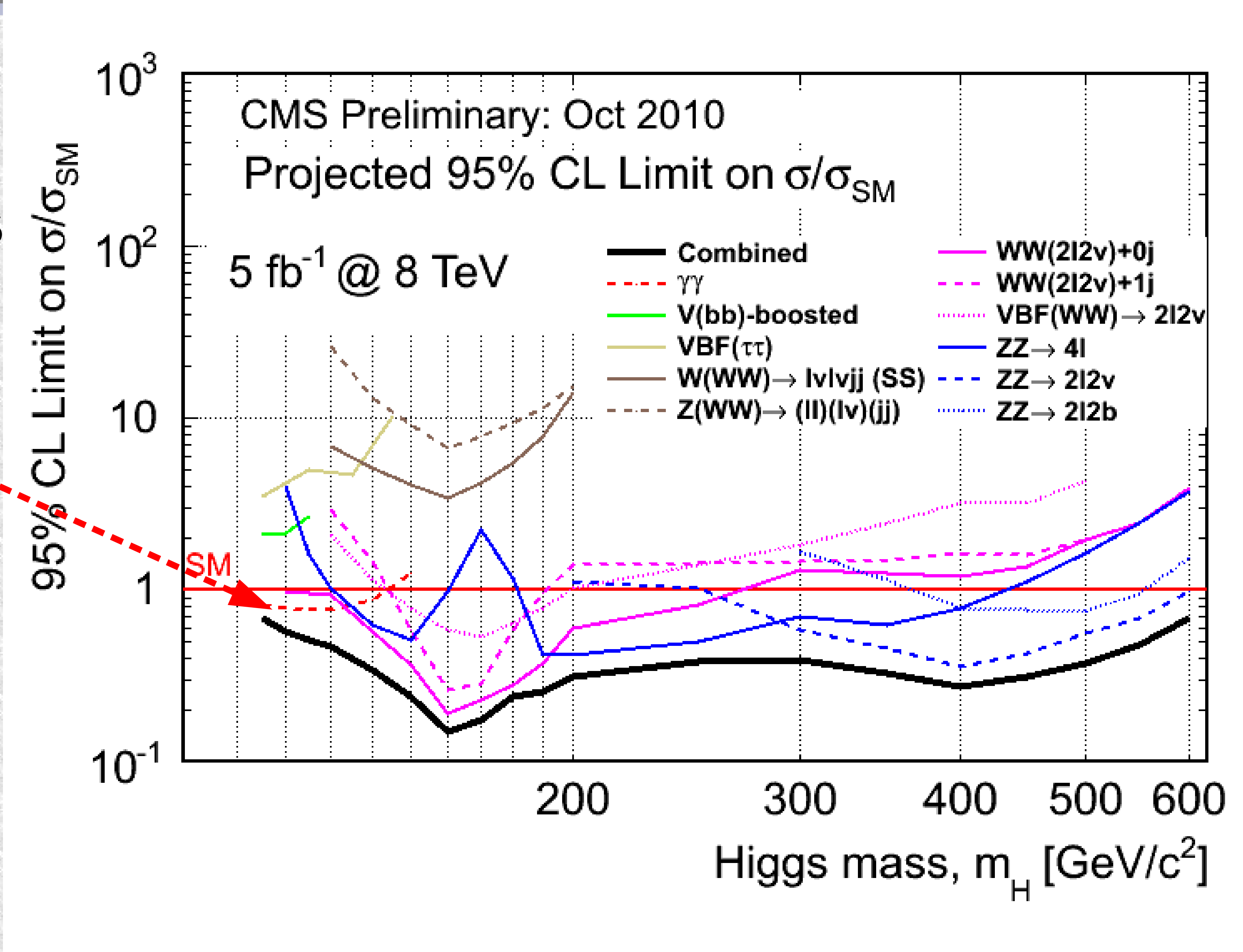
With 5 inverse fb (right now) each experiment expects to be able to probe a SM Higgs in the whole range above 115 GeV and combination of ATLAS and CMS could lead to evidence on this mass range.

Sensitivity to SM Higgs



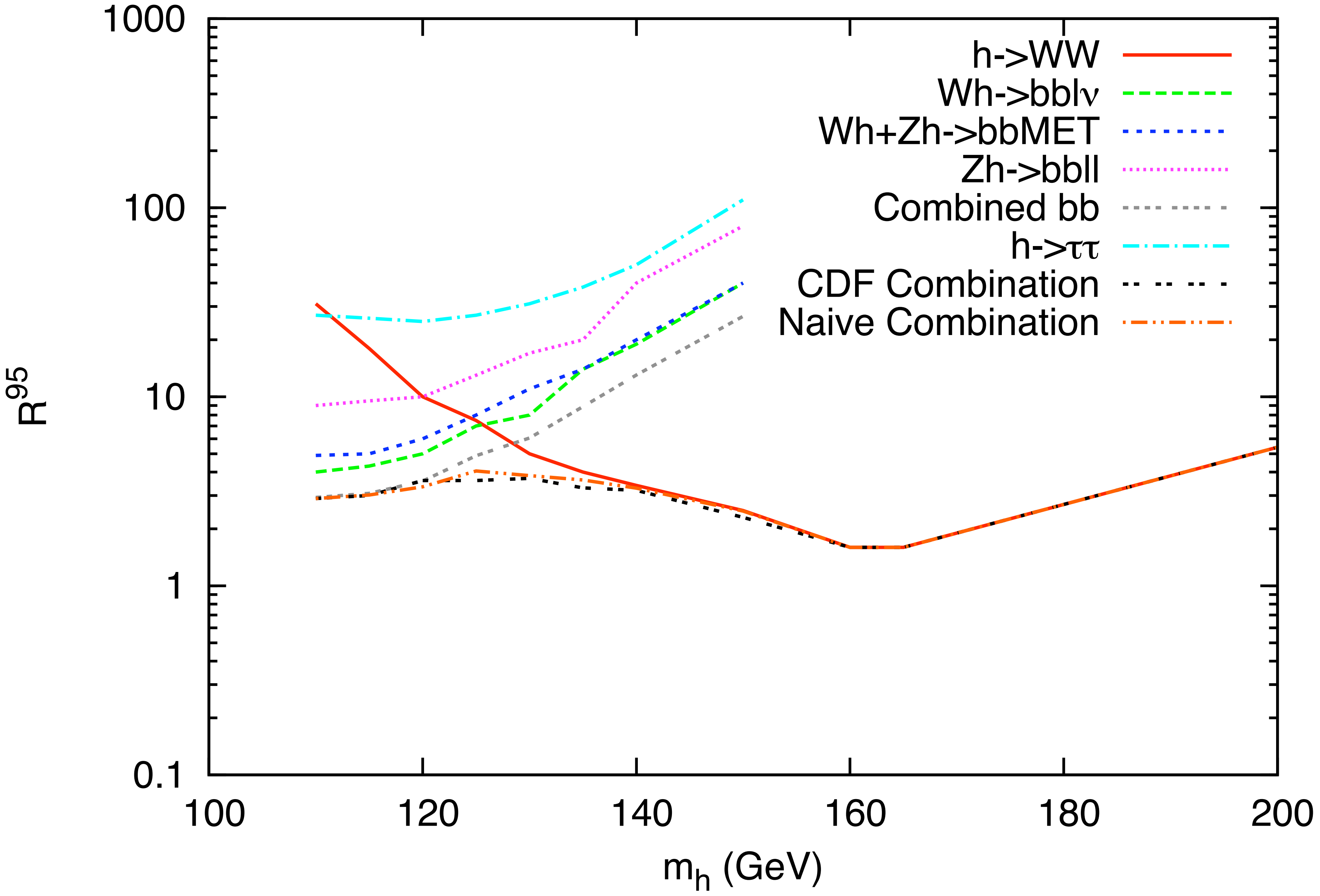
Contributions by channel

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



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

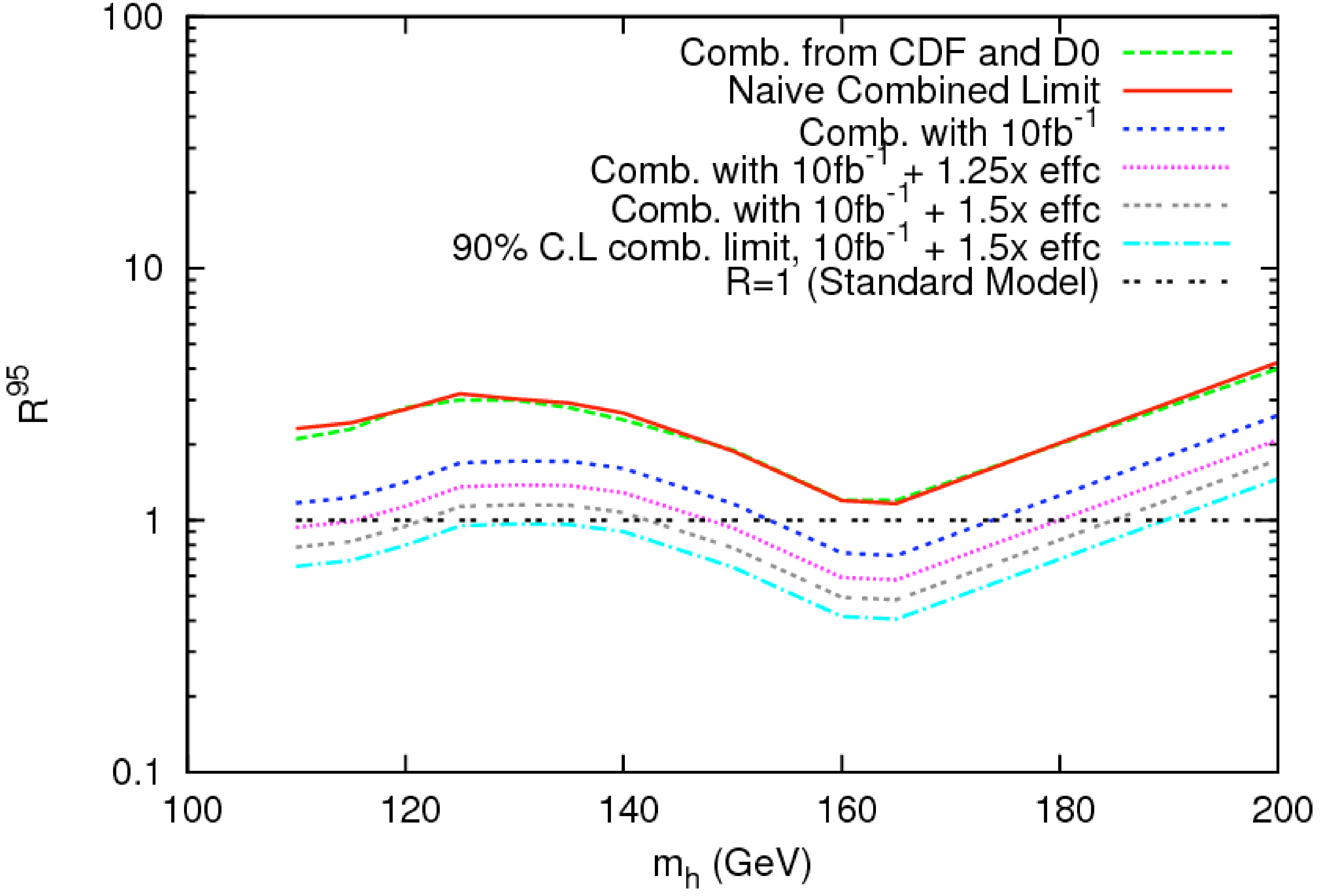
P. Draper, T. Liu and C. Wagner'09



At the Tevatron, the limits also arise from the combination of multiple channels. Main difference : Dominated by decay into bottom quarks in the low mass region.

Prospects for Higgs Searches at the Tevatron

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



Improvements
with respect
to Winter'09
25 percent
already achieved

With the current run, and expected improvements, the Tevatron should probe the Higgs mass region up to 190 GeV

New Physics at the Weak Scale

Modification of the main production rate : Effective Higgs coupling to gluons

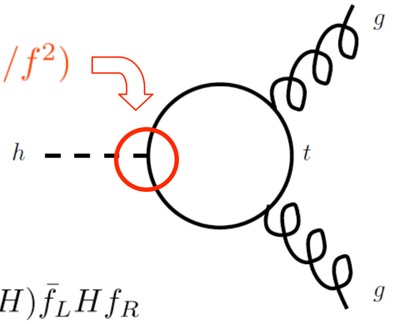
f : Scale of new physics

$$\Gamma(h \to gg) \;=\; \Gamma(h \to gg)_{SM} \left[1 - \xi \, \mathrm{Re} \left(c_H + 2c_y + \frac{4y_t^2 c_g}{g_\rho^2 I_g} \right) \right]$$

$$\xi \equiv \frac{v^2}{f^2}$$

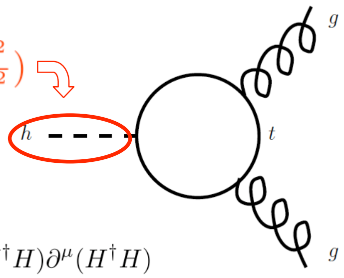
(Giudice et al, 0703164)

$$g_{hff}^{(SM)}(1 - c_y v^2/f^2)$$



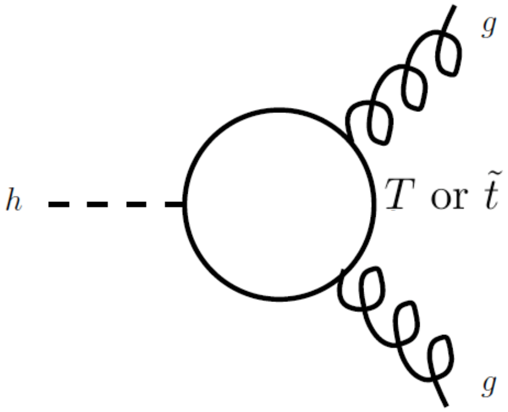
$$c_y \mathcal{O}_y \equiv \frac{c_y\, y_t}{f^2}(H^\dagger H)\bar{f}_L H f_R$$

$$h(1 - \tfrac{c_H}{2}\tfrac{v^2}{f^2})$$



$$c_H \mathcal{O}_H = \frac{c_H}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$$

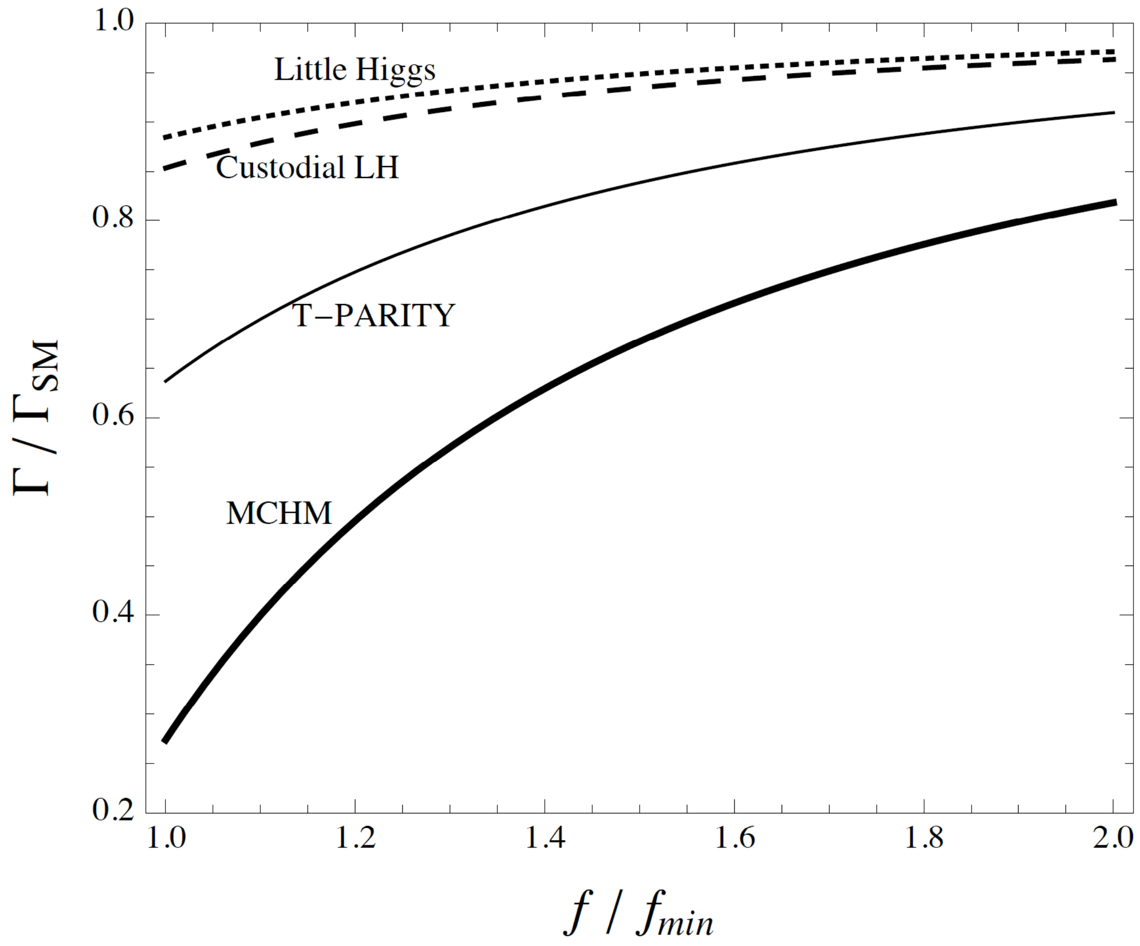
$$c_g \frac{\alpha_s}{2\pi} \frac{y_t v}{m_\rho^2} h G^a_{\mu\nu} G^{a\,\mu\nu}$$



If the Higgs is a Pseudo Nambu-Golstone Boson, the three effects tend to reduce the effective coupling

(Low, Rattazzi, Vichi, 0907.5413)

- For PNGB Higgs, significant reduction is quite possible!



Low and Vichi, 1010.2753.

f : Scale of new physics

f_{min} : Minimal scale consistent with present EWP tests.

Deformation of the SM Higgs: current constraints

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

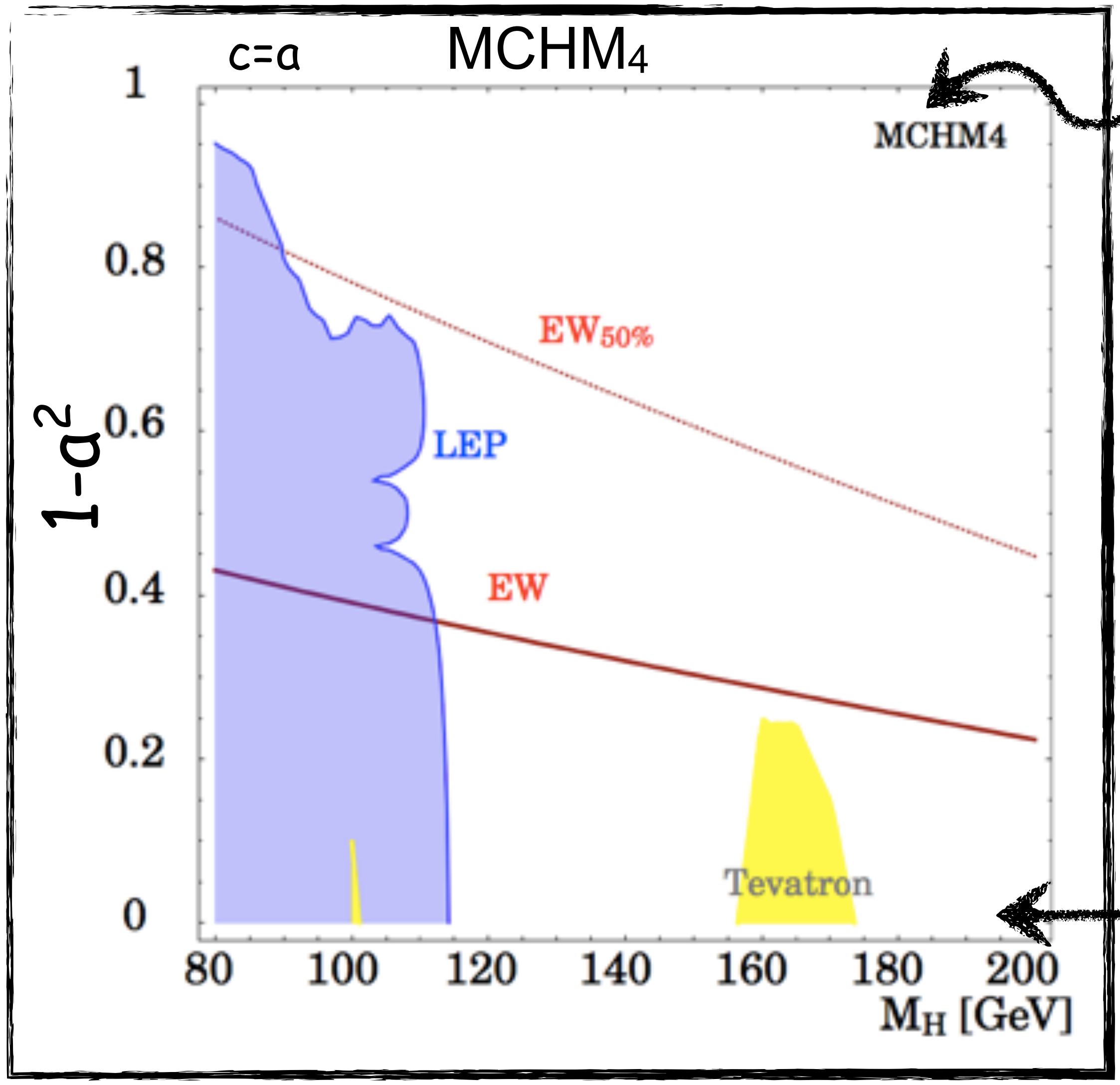
Grojean

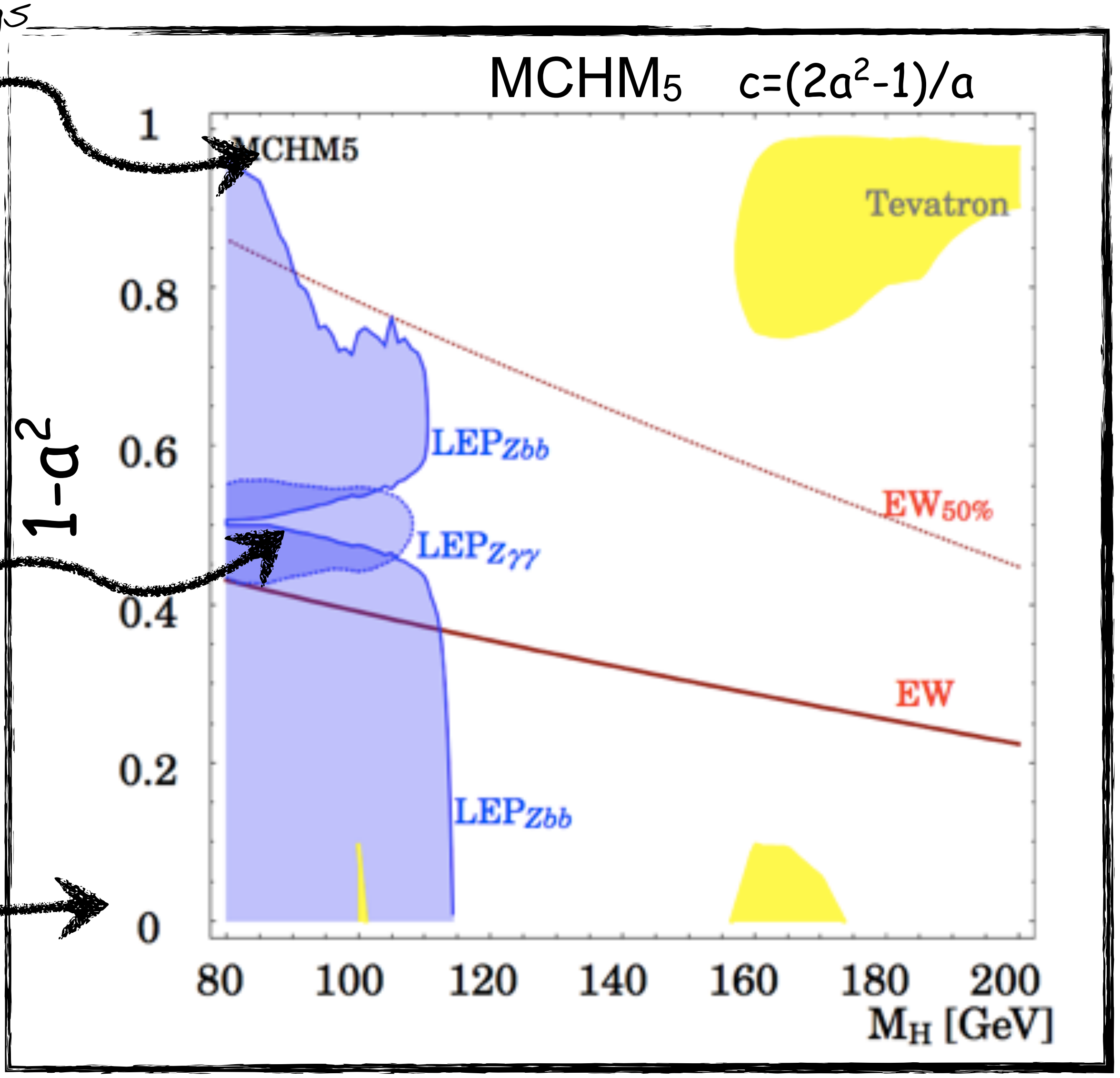
SM ‘a=1’, ‘b=1’ & ‘c=1’

Current EW data constrain only ‘a’ (and marginally ‘c’)

Espinosa, Grojean, Muehlleitner ’10

gaugephobic Higgs





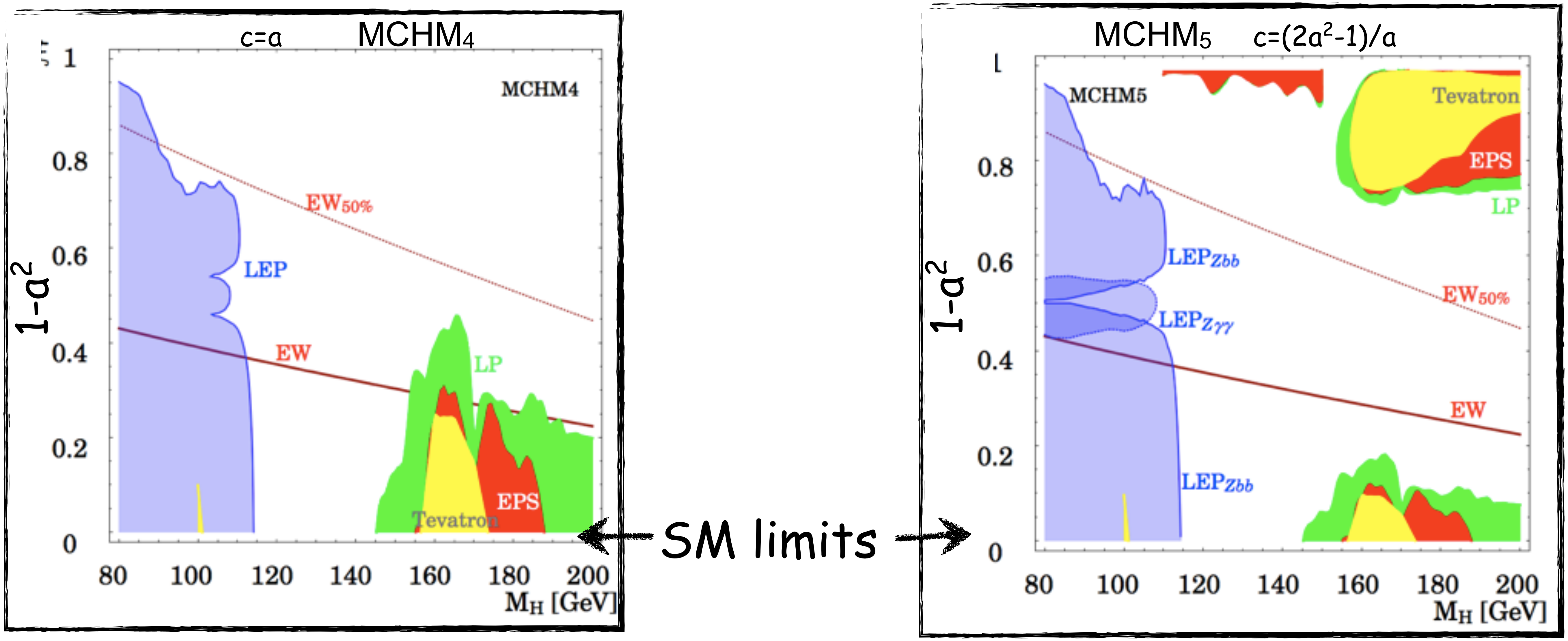
fermiophobic Higgs

SM limits

Deformation of the SM Higgs: LHC constraints

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



$c=a$ MCHM4

MCHM5 $c=(2a^2-1)/a$

SM limits

LHC is now a Higgs exploring machine
(and it has quickly surpassed Tevatron)

Supersymmetry

Mass of the SM-like Higgs h

- Most important corrections come from the stop sector,

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

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,

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

- 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

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

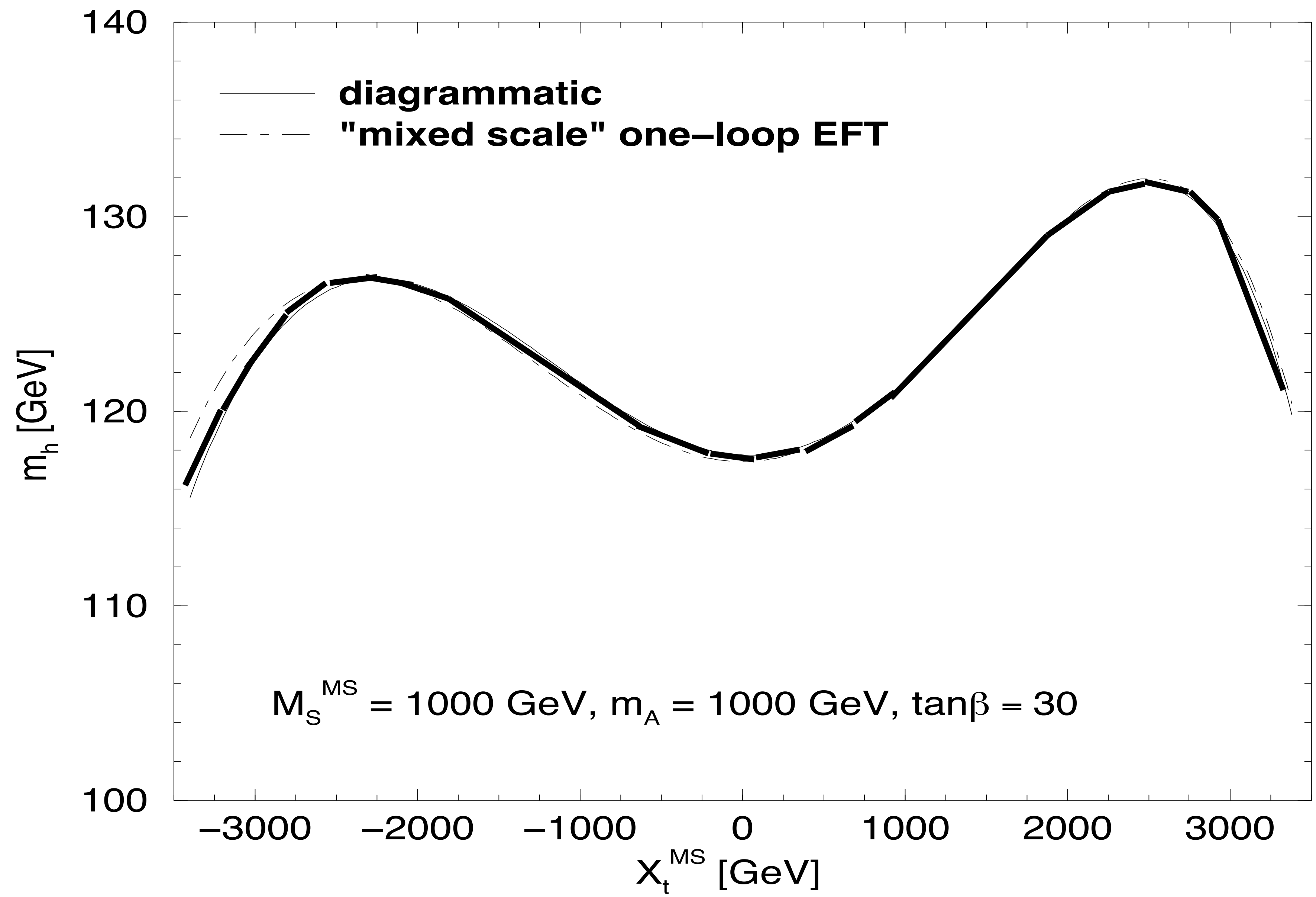
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$

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

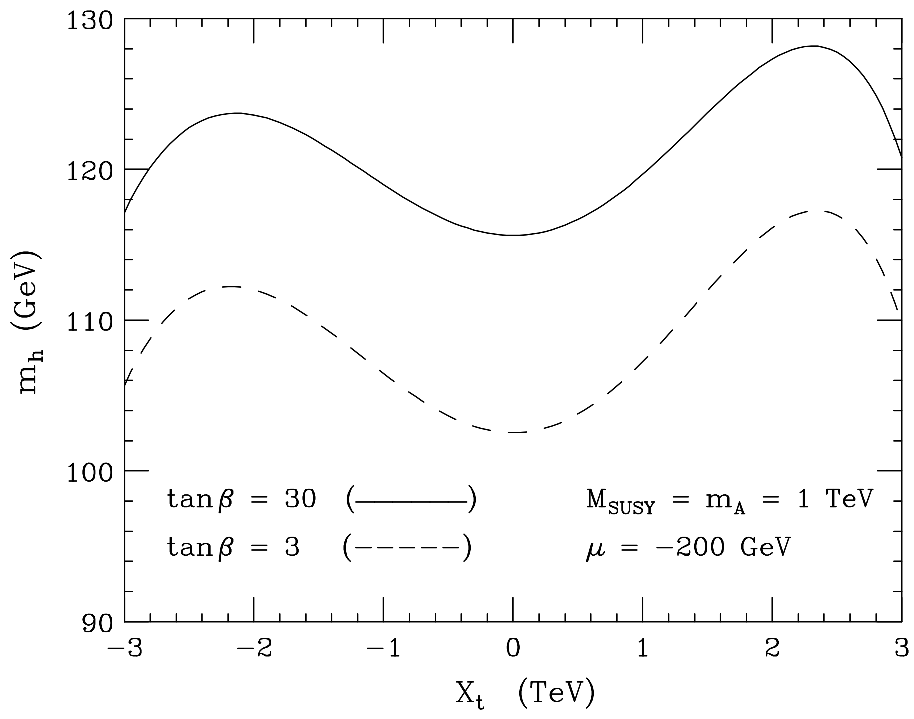
Leading m_t^4 approximation at $O(\alpha\,\alpha_s)$

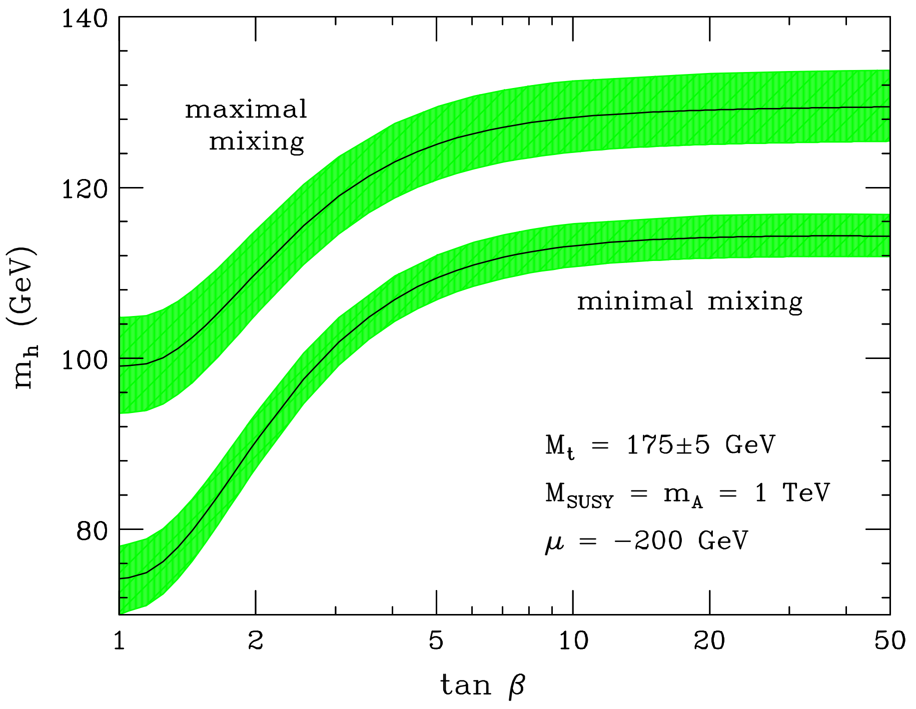


$m_t = 180$ GeV.
For $m_t = 173$ GeV,
the maximum m_h
shifts to 127 GeV.

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

The state-of-the-art computation includes the full one-loop result, all the significant two-loop contributions, some of the leading three-loop terms, and renormalization-group improvements. The final conclusion is that $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].



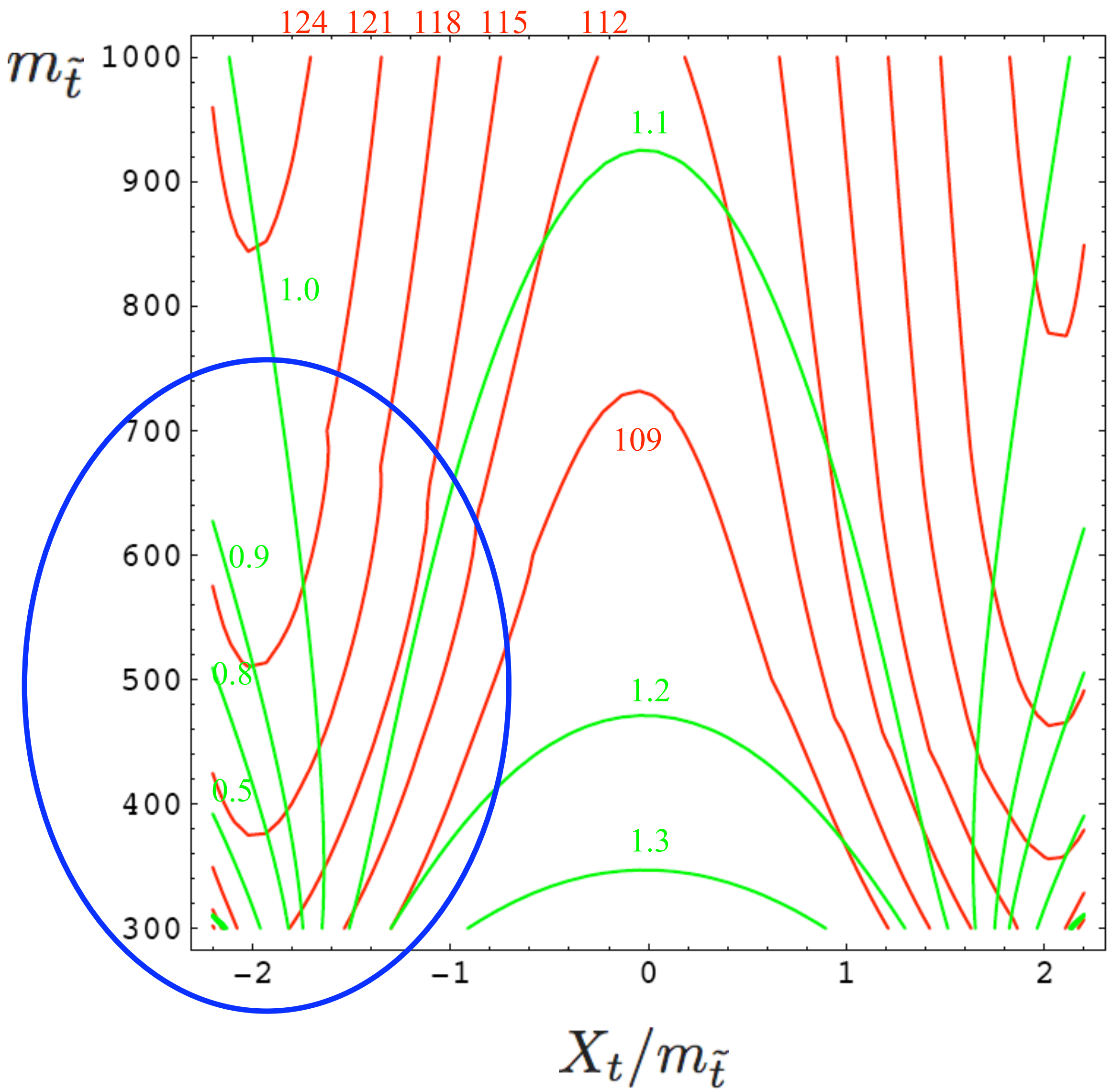


H. Haber, SUSY 2011

Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\rm max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

Minimal models, like the MSSM tend to lead to small Xt and relatively large CP-odd masses. Both stops could be as light as a few hundred GeV if mixing parameter Xt is large.

Gluon Fusion Production Rate in the MSSM

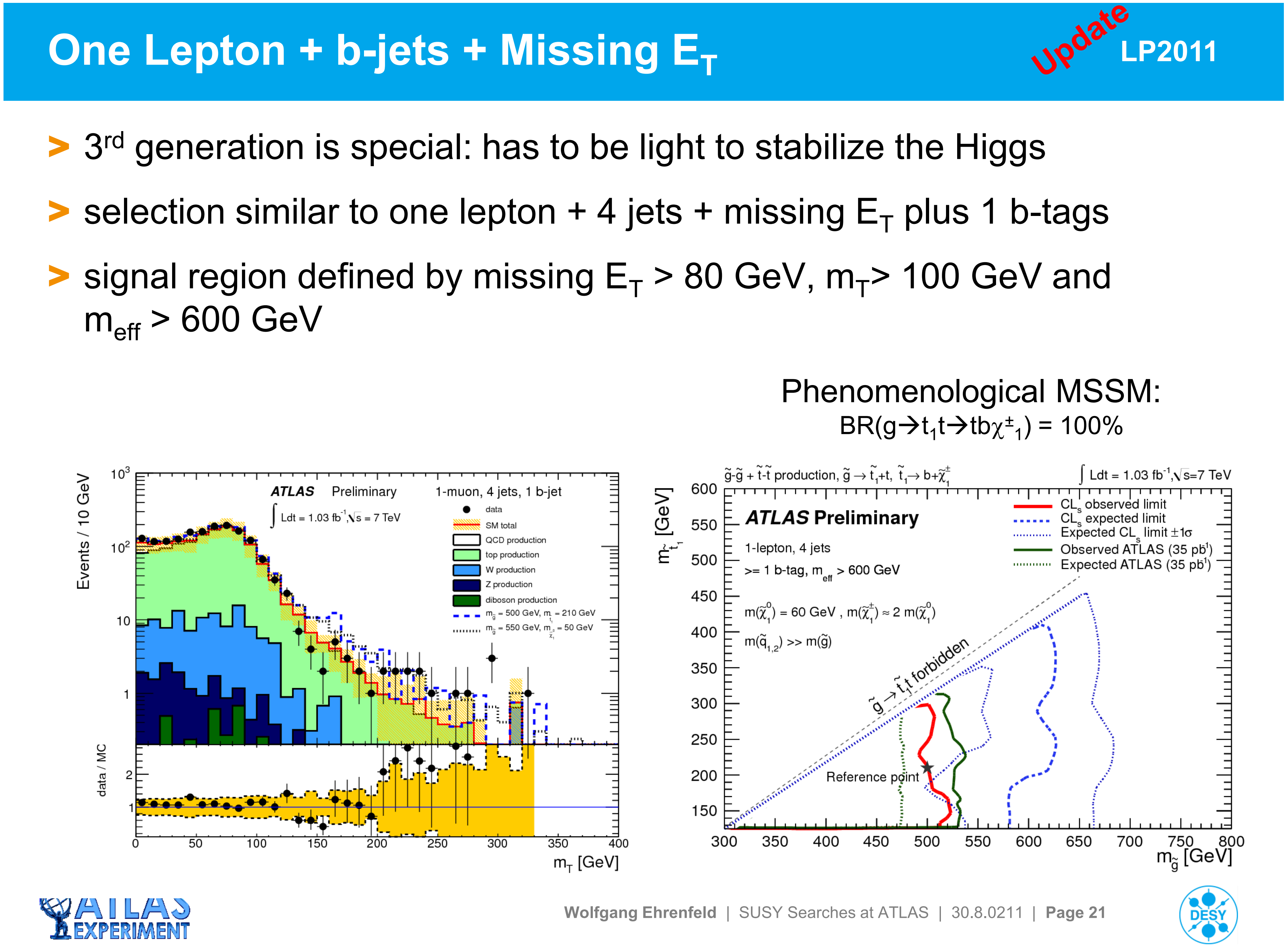


Rate may be modified
for light stops and close to
the large mixing senario.

For stop masses
of order of 1 TeV
the rate modifications
tend to be small

Dermisek and Low, 0701235

LHC Bound on stop masses depends on gluino mass



One Lepton + b-jets + Missing E_T

Update

LP2011

- 3^{rd} generation is special: has to be light to stabilize the Higgs
- selection similar to one lepton + 4 jets + missing E_T plus 1 b-tags
- signal region defined by missing E_T > 80 GeV, m_T> 100 GeV and m_{eff} > 600 GeV

Phenomenological MSSM:

$BR(g \rightarrow t_1 t \rightarrow tb\chi^{\pm}_1) = 100\%$

ATLAS EXPERIMENT

Wolfgang Ehrenfeld | SUSY Searches at ATLAS | 30.8.0211 | **Page 21**

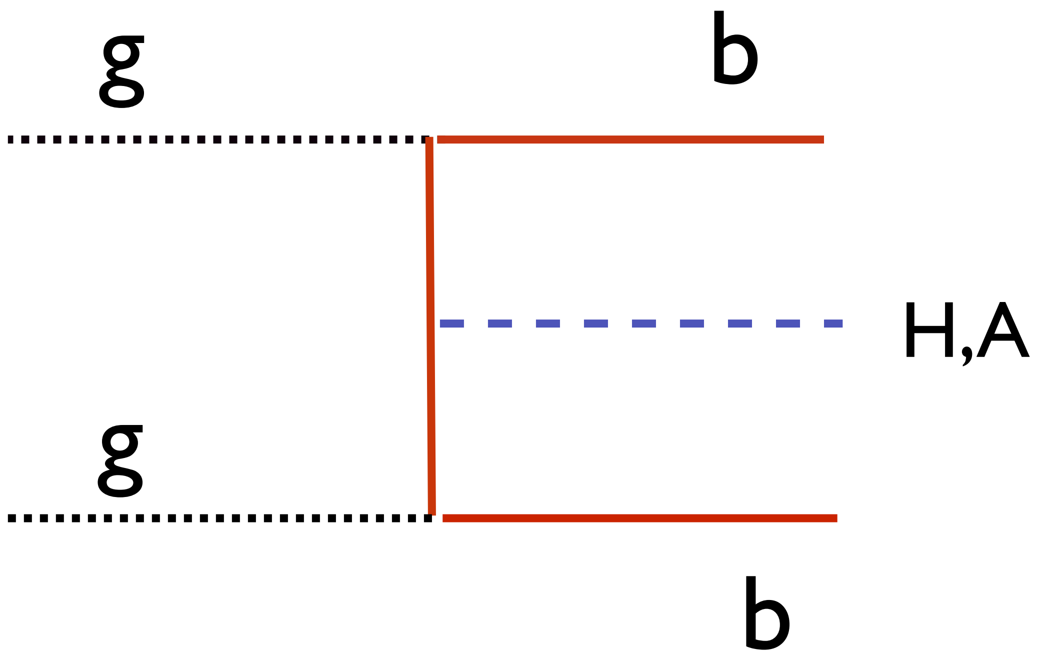
DESY

Relatively light stops are naturally there, they can raise sufficiently the Higgs mass and are not ruled out by current data !

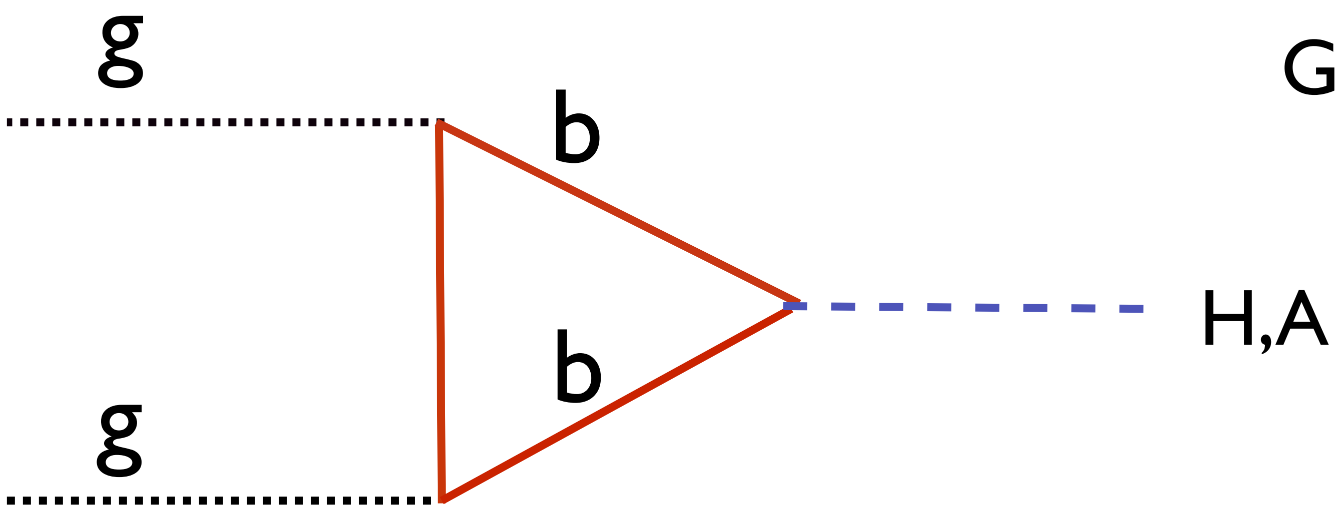
They should be a priority in LHC searches (in all possible stop decay channels)

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.

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

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

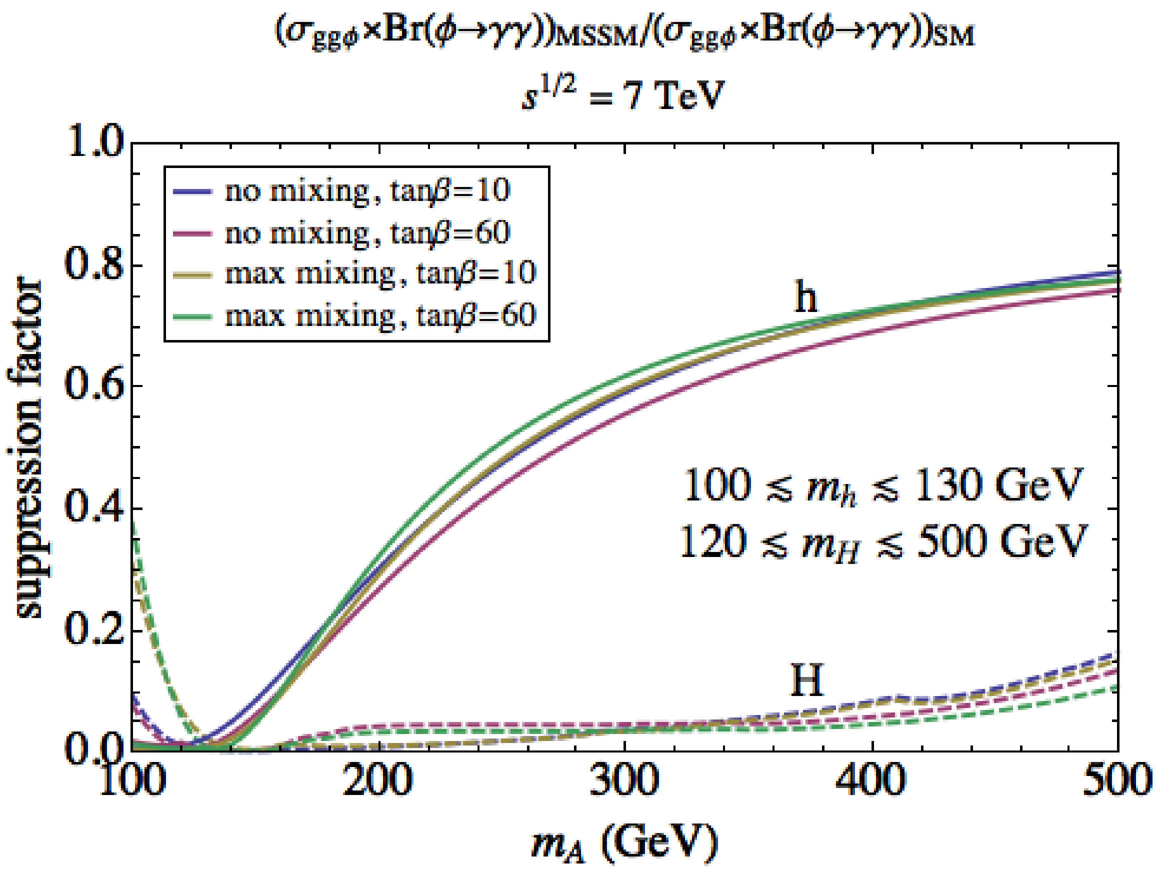
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

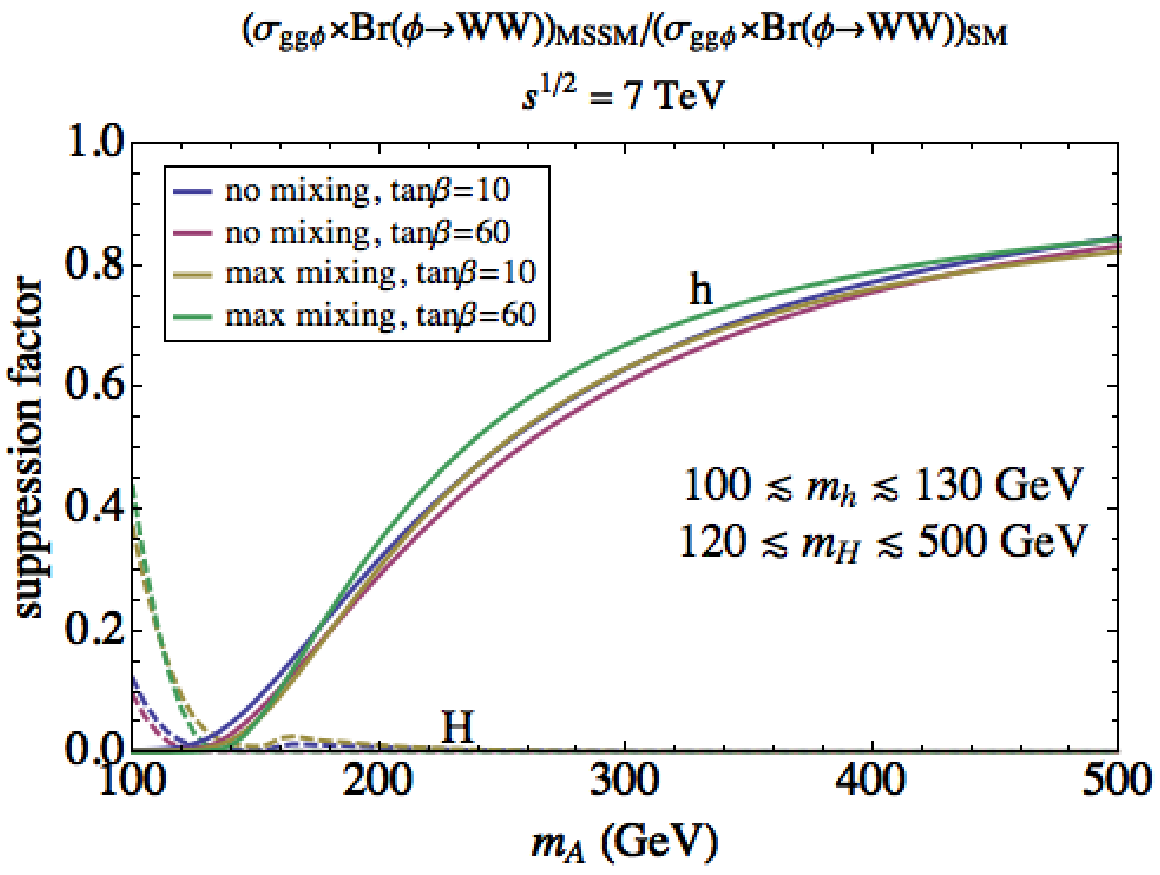
Validity of this approximation confirmed by NLO computation by D. Noth and M. Spira, arXiv:0808.0087
Further work by Muhlleitner, Rzehak and Spira, 0812.3815

MSSM SM-like 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.



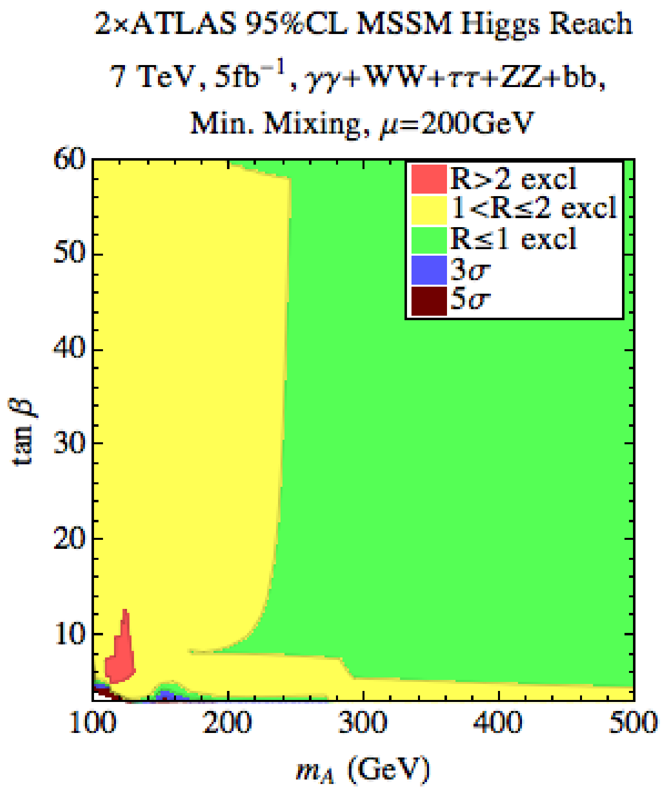


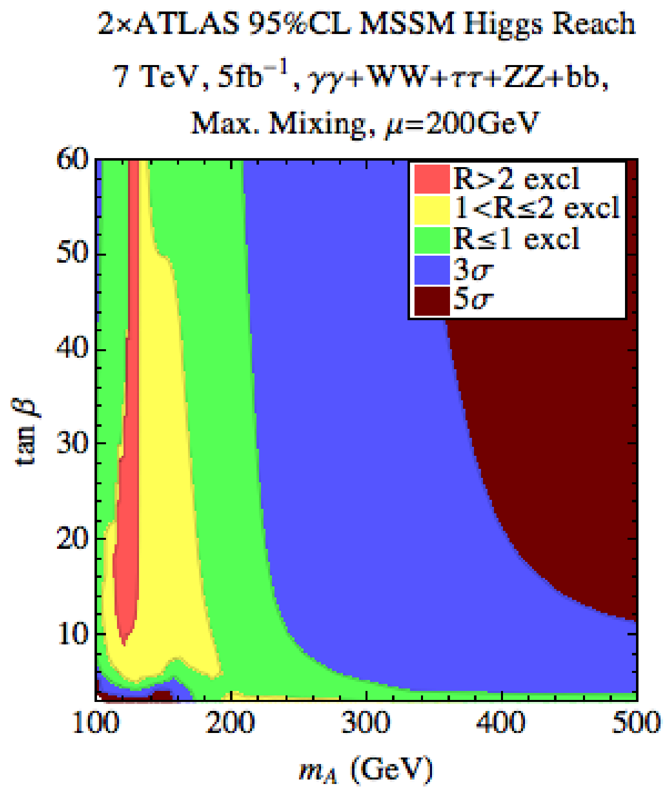
7 TeV LHC MSSM Higgs Reach

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

$m_h \simeq 115\text{GeV}$

$m_h \simeq 130\text{ GeV}$


2×ATLAS 95%CL MSSM Higgs Reach
7 TeV, 5fb^{-1}, $\gamma\gamma$+WW+$\tau\tau$+ZZ+bb,
Min. Mixing, μ=200GeV


2×ATLAS 95%CL MSSM Higgs Reach
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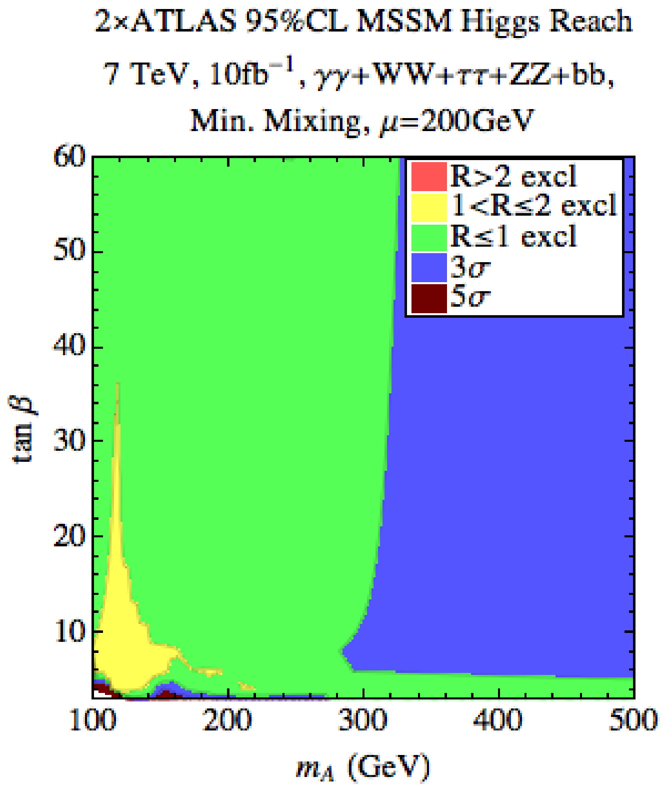
Max. Mixing, μ=200GeV


2×ATLAS 95%CL MSSM Higgs Reach
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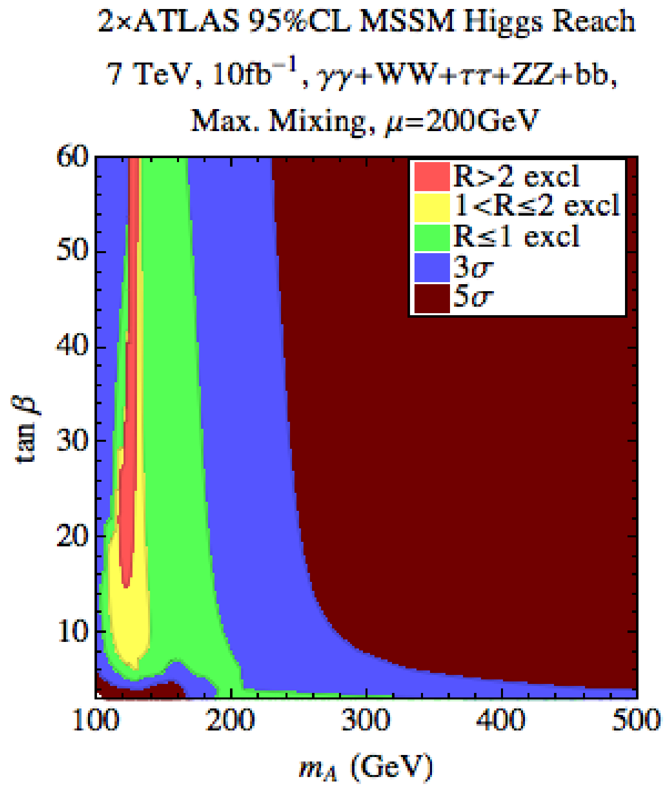
Min. Mixing, μ=200GeV


2×ATLAS 95%CL MSSM Higgs Reach
7 TeV, 10fb^{-1}, $\gamma\gamma$+WW+$\tau\tau$+ZZ+bb,
Max. Mixing, μ=200GeV

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

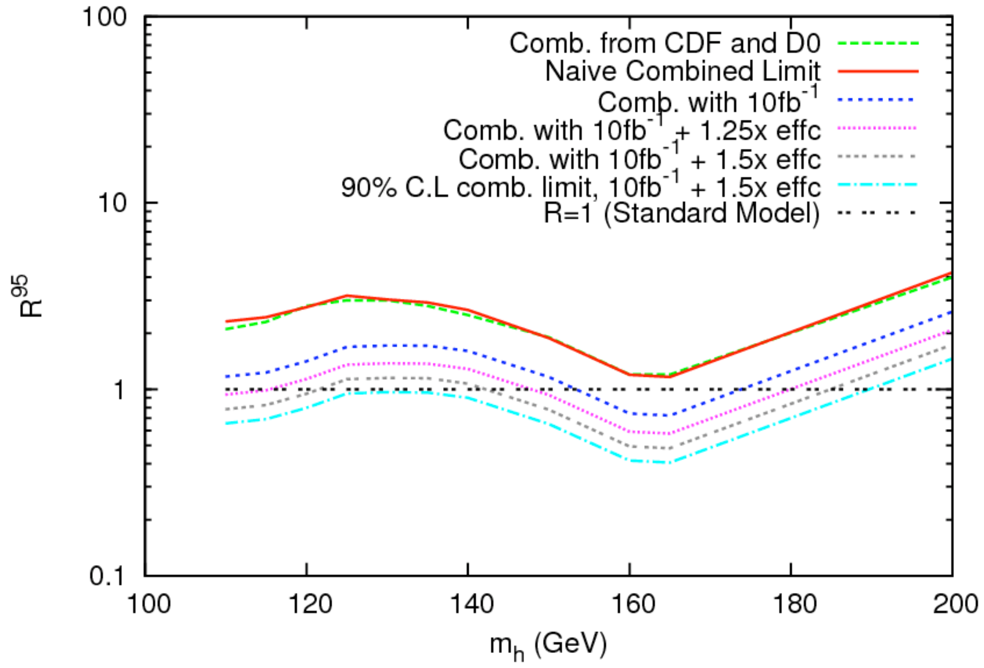
$$Vh, h \to bb$$

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

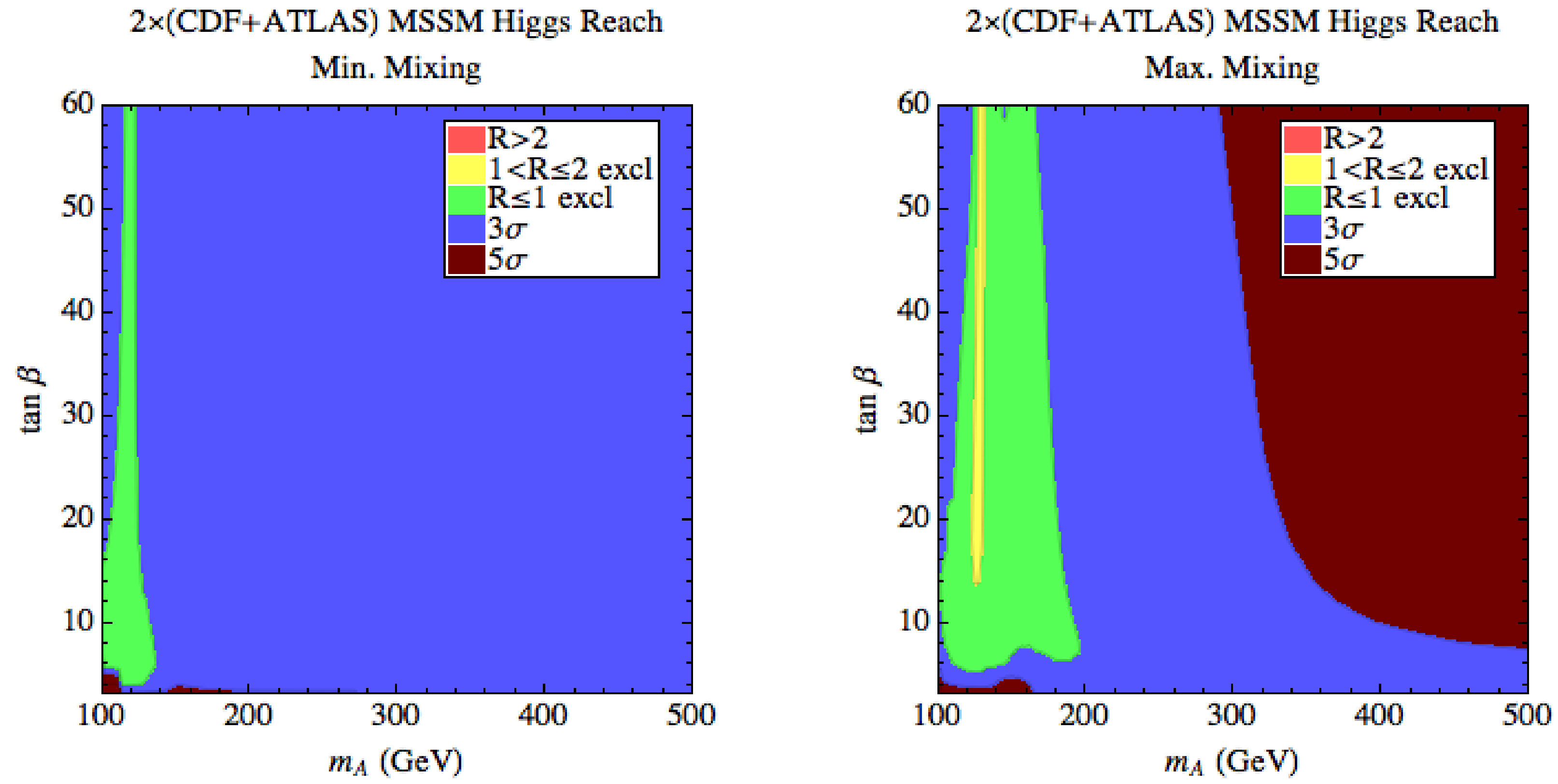
are helpful in partially reducing the reach suppression

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.



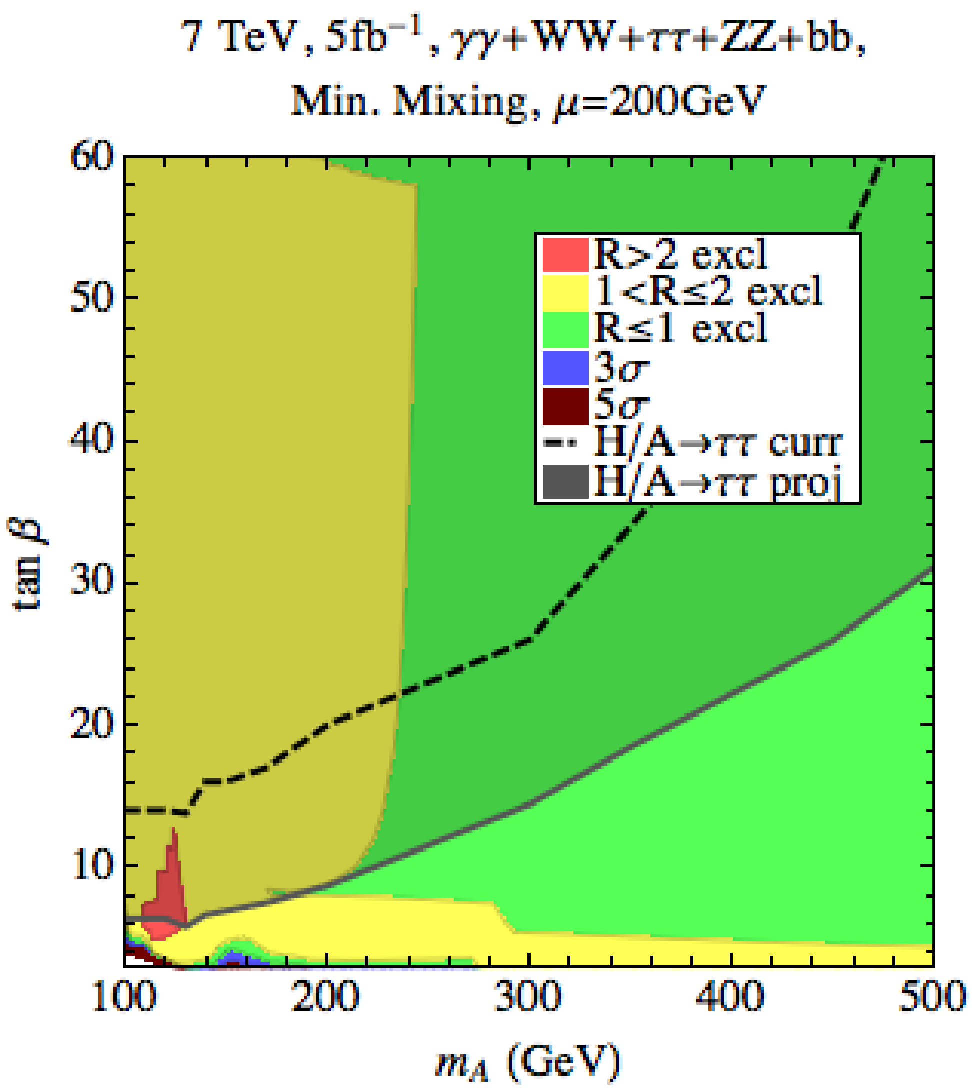
P. Draper, T. Liu and C. Wagner'09

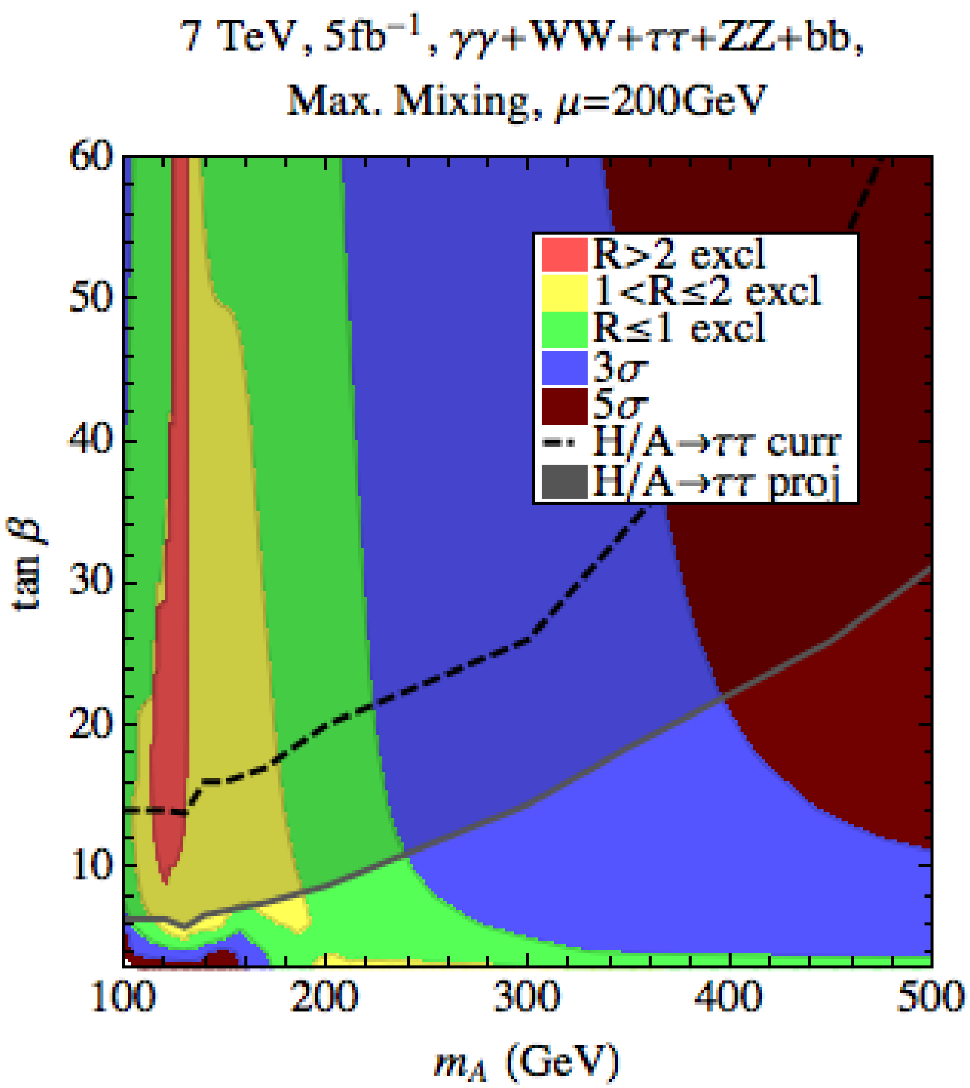


Combination of 5 inverse fb LHC with 10 inverse fb Tevatron data :
Evidence of SM-like Higgs presence in almost all parameter space

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

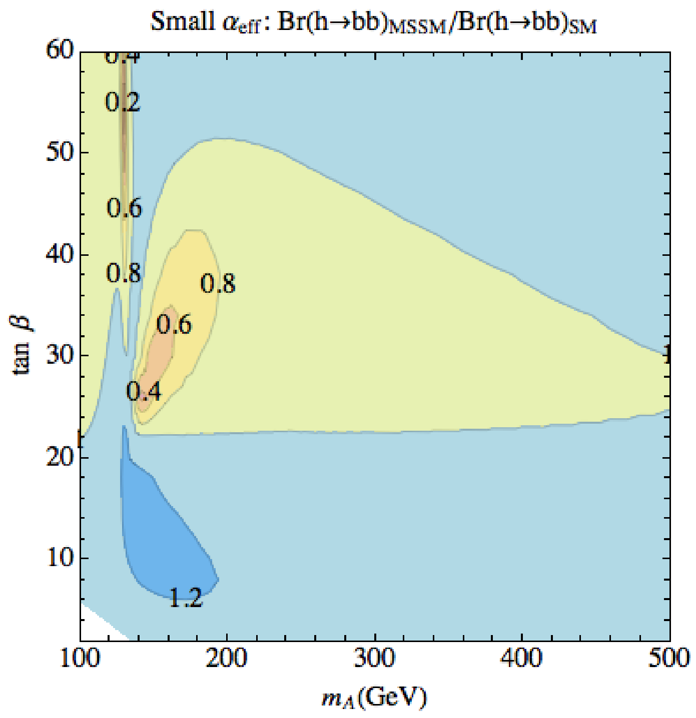
Complementarity with LHC non-standard Higgs searches

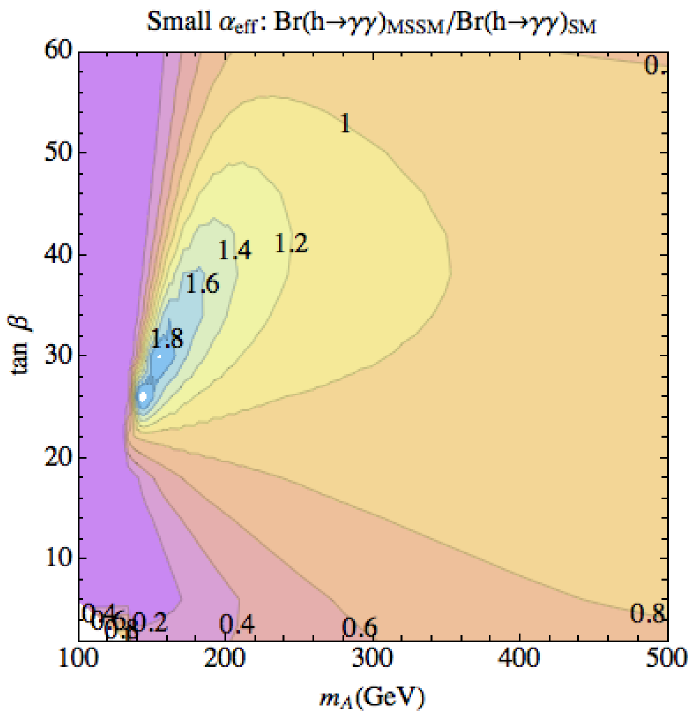




M. Carena, P. Draper, T. Liu, C.W.'11

Non-standard Higgs searches allow to probe part of the parameter space for which standard reach is suppressed. An excess at small CP-odd Higgs masses would mean a weaker reach for SM-like Higgs boson

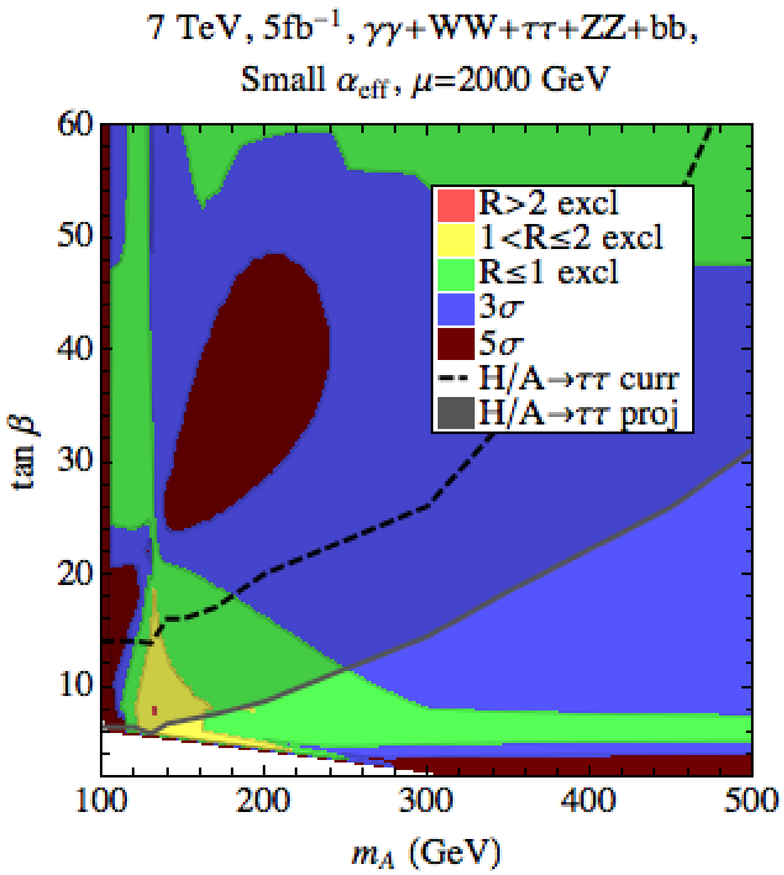




For large values of μ and A_t

one can get suppression of the Higgs decay into bottom quarks and therefore enhancement of photon decay branching ratio

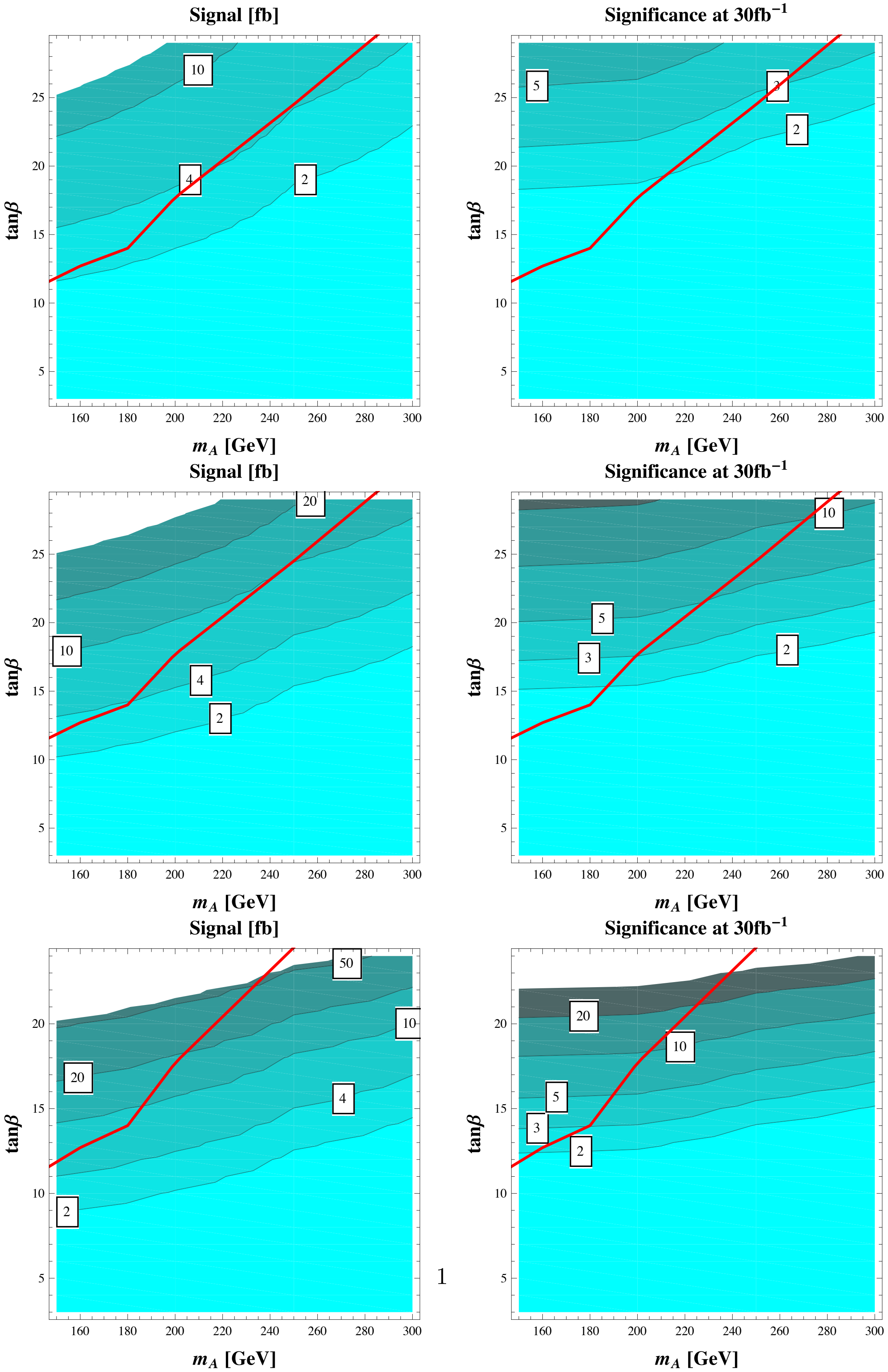
Carena, Mrenna, Wagner'99
Carena, Heinemeyer, Wagner, Weiglein'02



Such scenario, however, demands small values of the the CP-odd Higgs mass and large tanbeta and seems to be in conflict with non-standard Higgs boson searches

Carena, Draper, Liu, Wagner'11

Non-standard Higgs Boson Searches at 7 TeV LHC with b-quark final states



Results obtained setting
p_T cuts of 150 GeV in the
leading b-jet and
about 50 GeV in the
subdominant ones.

An invariant mass window
of about 50 GeV was used.
Angular kinematic variables
tend to be similar in signal
and background, and further
cuts tend to reduce the rate

Gori, Menon, Carena, Wagner, Wang, Juste'11

Higgs Bosons Decaying to Bottom pairs at the LHC

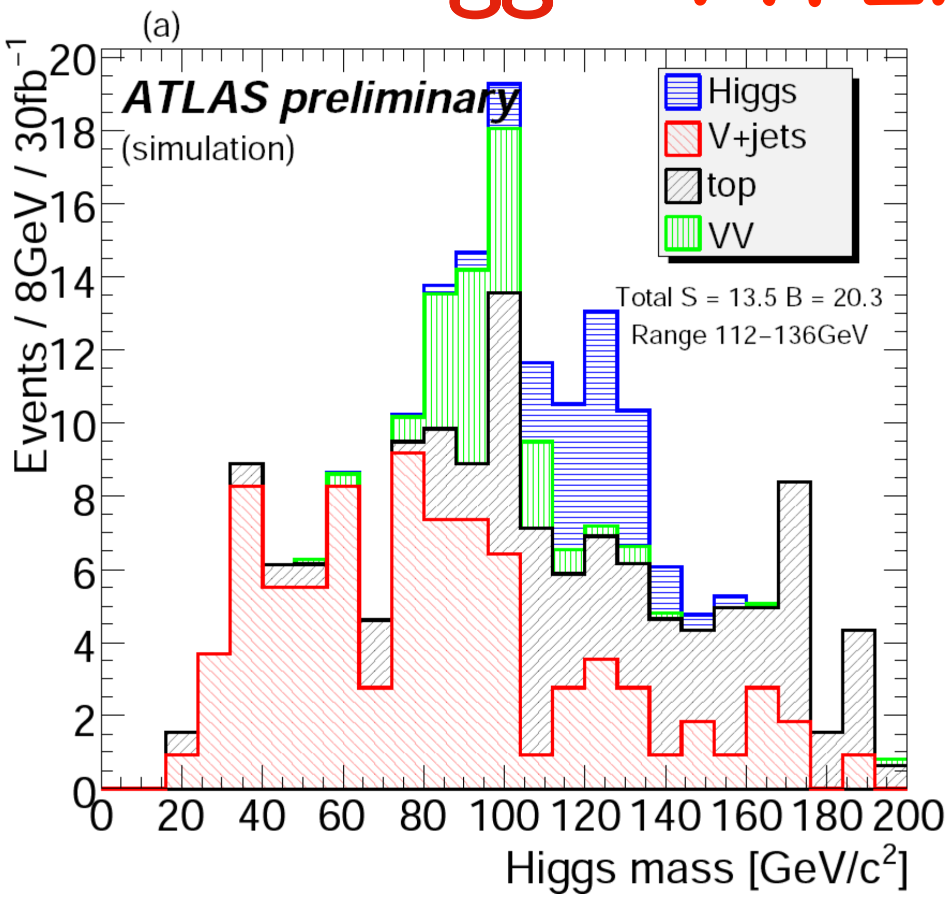
- In the past the decay of Higgs into bottom quarks have been ignored due to overwhelming backgrounds
- However, the study of jet substructure has revealed new possibilities
- In particular, boosted Higgs bosons decaying to bottom pairs might be easily separated from the QCD background by the use of 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 production,

Kribs, Martin, Roy, Sapnnowsky'10

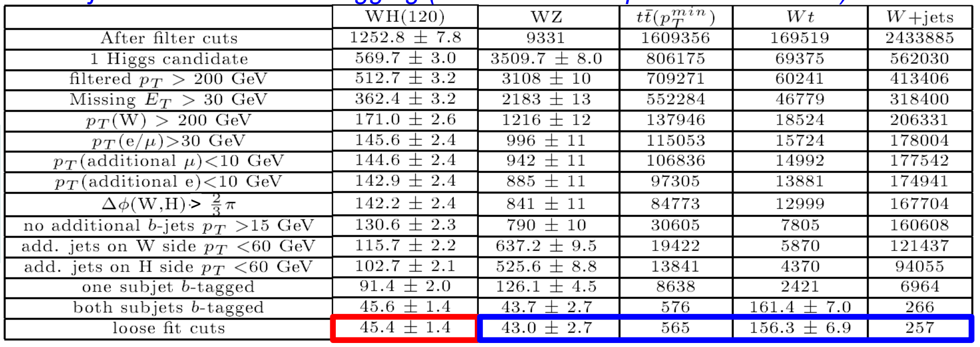
SM Higgs : ATLAS Simulation



The WH (W→lν,H→bb) analysis: cut flow (main signal and backgrounds samples)

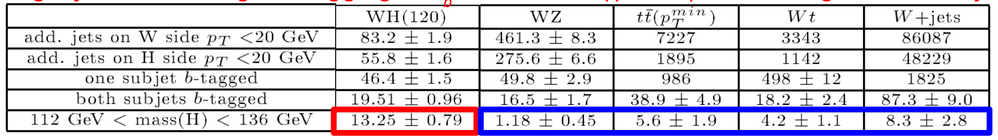
Loose jet veto and loose b-tagging (to be used as input to likelihood fit):

L=30 fb^{-1}



	WH(120)	WZ	$t\bar{t}(p_T^{min})$	Wt	W+jets
After filter cuts	1252.8 ± 7.8	9331	1609356	169519	2433885
1 Higgs candidate	569.7 ± 3.0	3509.7 ± 8.0	806175	69375	562030
filtered p_T > 200 GeV	512.7 ± 3.2	3108 ± 10	709271	60241	413406
Missing E_T > 30 GeV	362.4 ± 3.2	2183 ± 13	552284	46779	318400
p_T(W) > 200 GeV	171.0 ± 2.6	1216 ± 12	137946	18524	206331
p_T(e/μ)>30 GeV	145.6 ± 2.4	996 ± 11	115053	15724	178004
p_T(additional μ)<10 GeV	144.6 ± 2.4	942 ± 11	106836	14992	177542
p_T(additional e)<10 GeV	142.9 ± 2.4	885 ± 11	97305	13881	174941
$\Delta\phi$(W,H)> $\frac{2}{3}\pi$	142.2 ± 2.4	841 ± 11	84773	12999	167704
no additional b-jets p_T >15 GeV	130.6 ± 2.3	790 ± 10	30605	7805	160608
add. jets on W side p_T <60 GeV	115.7 ± 2.2	637.2 ± 9.5	19422	5870	121437
add. jets on H side p_T <60 GeV	102.7 ± 2.1	525.6 ± 8.8	13841	4370	94055
one subjet b-tagged	91.4 ± 2.0	126.1 ± 4.5	8638	2421	6964
both subjets b-tagged	45.6 ± 1.4	43.7 ± 2.7	576	161.4 ± 7.0	266
loose fit cuts	45.4 ± 1.4	43.0 ± 2.7	565	156.3 ± 6.9	257

Tight jet veto and tight b-tagging at ε_b~63 % and c(l)=0.2 (for counting based analysis)



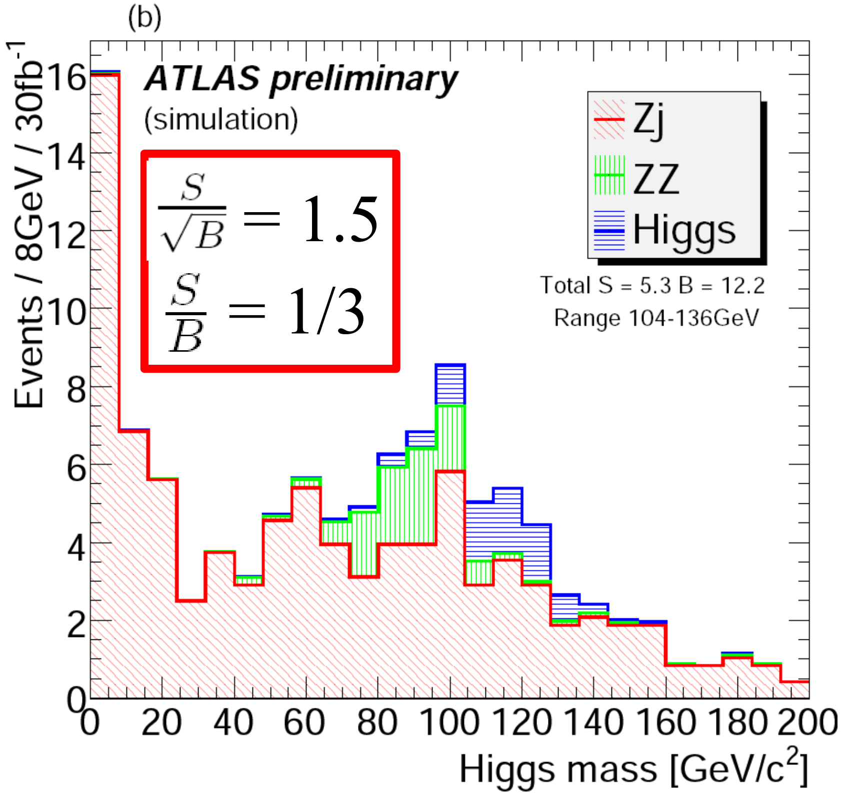
	WH(120)	WZ	$t\bar{t}(p_T^{min})$	Wt	W+jets
add. jets on W side p_T <20 GeV	83.2 ± 1.9	461.3 ± 8.3	7227	3343	86087
add. jets on H side p_T <20 GeV	55.8 ± 1.6	275.6 ± 6.6	1895	1142	48229
one subjet b-tagged	46.4 ± 1.5	49.8 ± 2.9	986	498 ± 12	1825
both subjets b-tagged	19.51 ± 0.96	16.5 ± 1.7	38.9 ± 4.9	18.2 ± 2.4	87.3 ± 9.0
112 GeV < mass(H) < 136 GeV	13.25 ± 0.79	1.18 ± 0.45	5.6 ± 1.9	4.2 ± 1.1	8.3 ± 2.8

Signal events (m_H~120 GeV): ~13.5
Background events: ~20.3

$$\frac{S}{\sqrt{B}} = 3.0 \pm 0.3$$

Giacinto Piacquadio

llbb

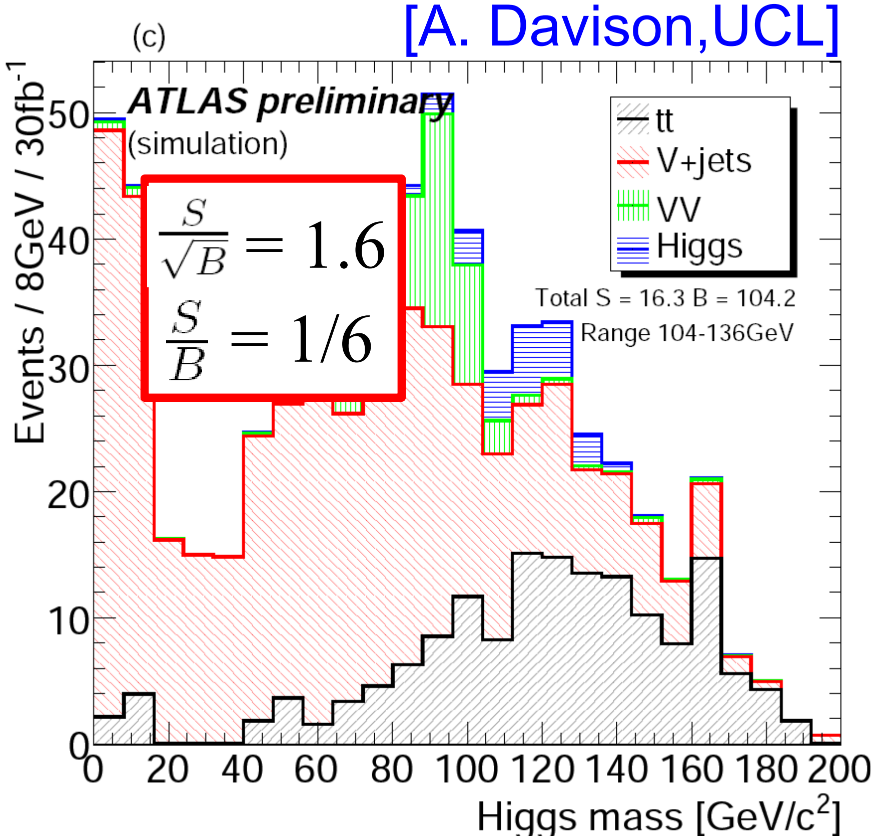


$$\frac{S}{\sqrt{B}} = 1.5$$

$$\frac{S}{B} = 1/3$$

ννbb

[A. Davison,UCL]



$$\frac{S}{\sqrt{B}} = 1.6$$

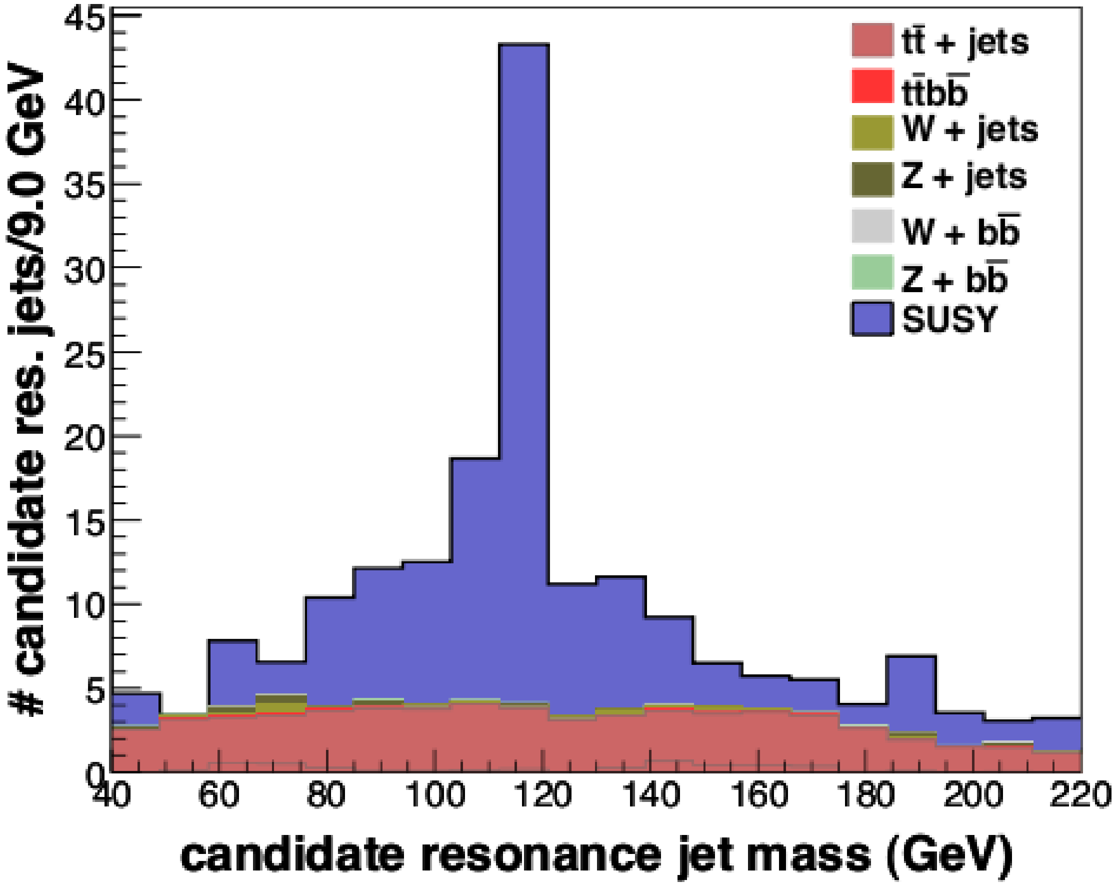
$$\frac{S}{B} = 1/6$$

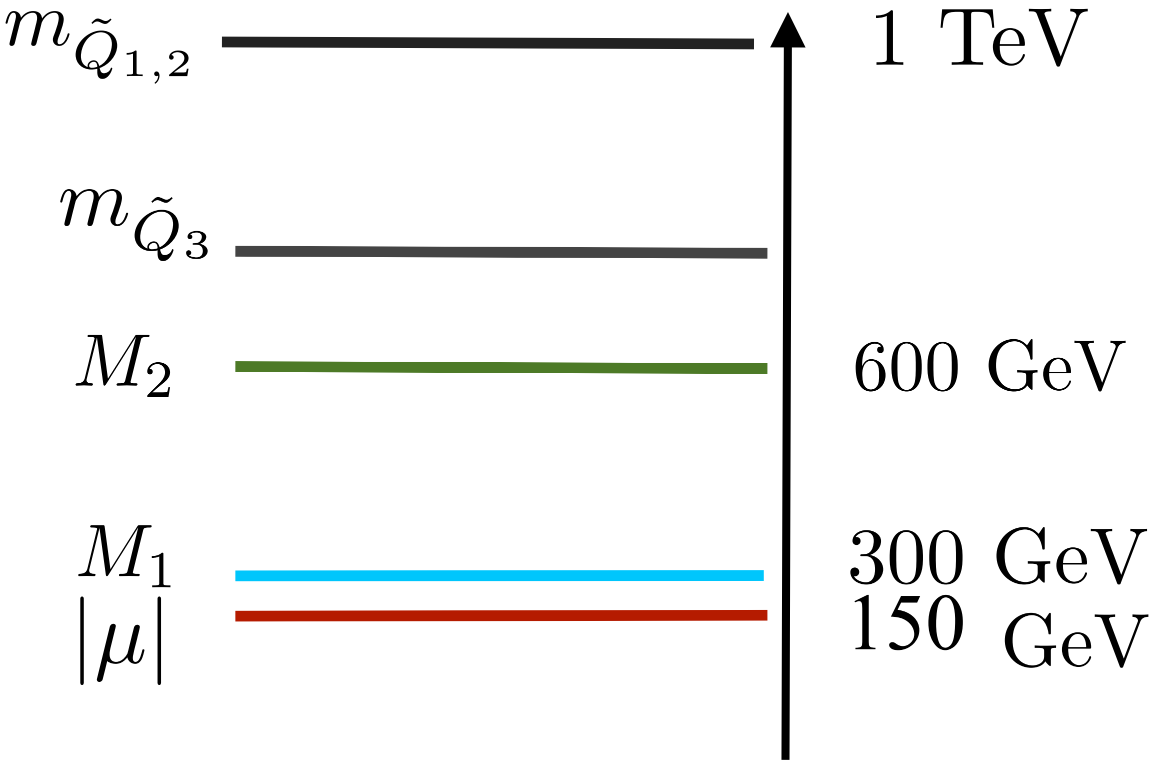
ATL-PHYS-PUB-2009-088 (Aug 2009)

Example 1: MSSM with Higgsino LSP

Kribs, Martin, Roy, Spannowsky'10

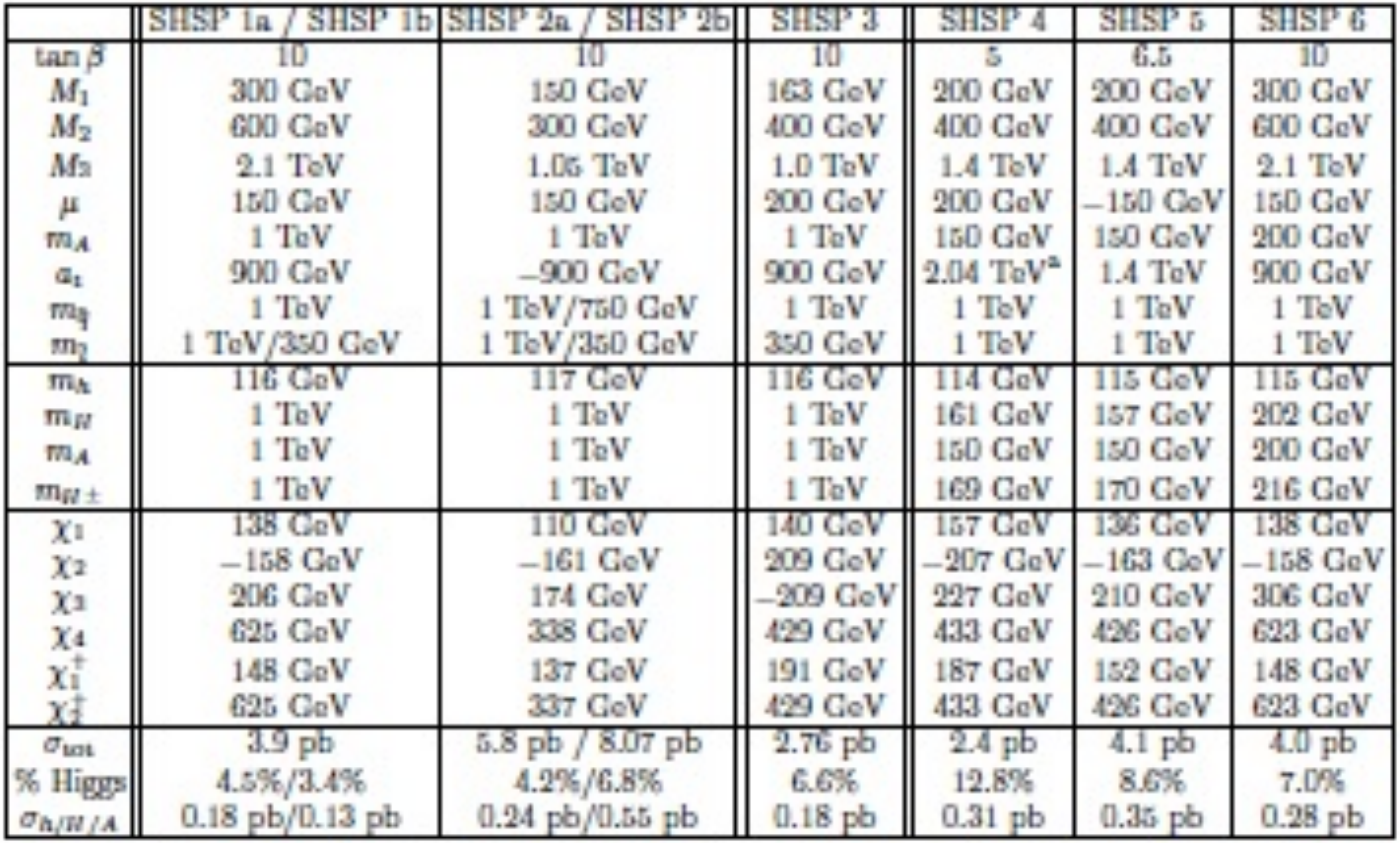
10 fb^{-1} @ 14 TeV





MET > 300 GeV, H_T > 1 TeV, 3+ jets, no lepton, + 1 "tagged" Higgs

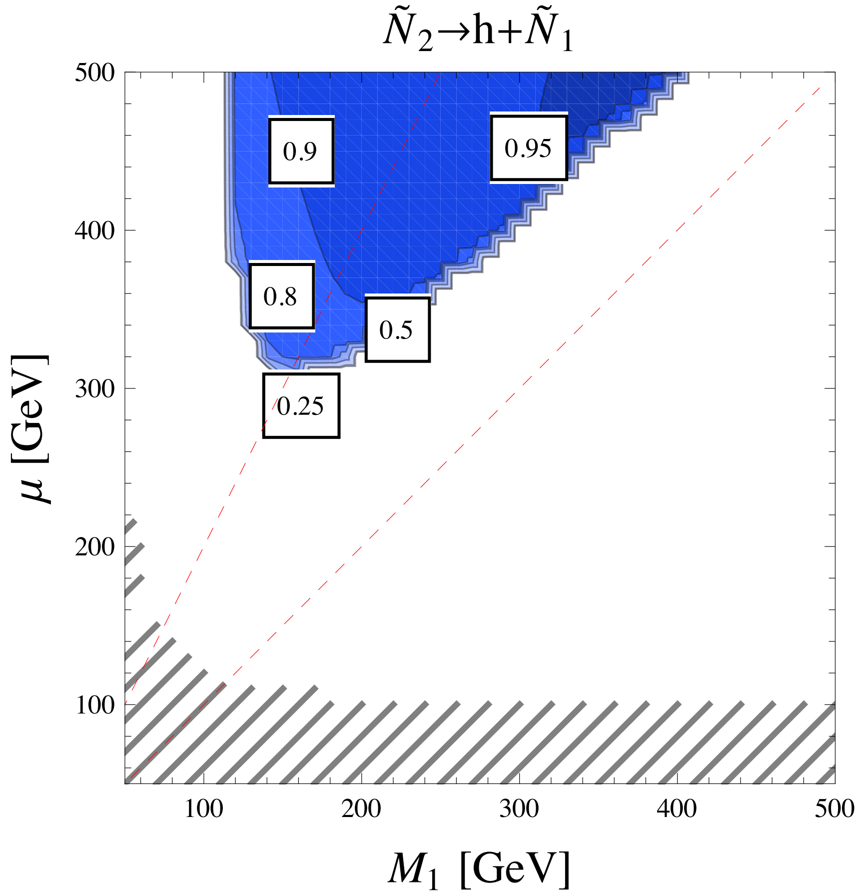
$$BR(\tilde{u}_L, \tilde{d}_L \to h + X) \sim 23\%$$
$$BR(\tilde{u}_R, \tilde{d}_R \to h + X) \sim 16\%$$



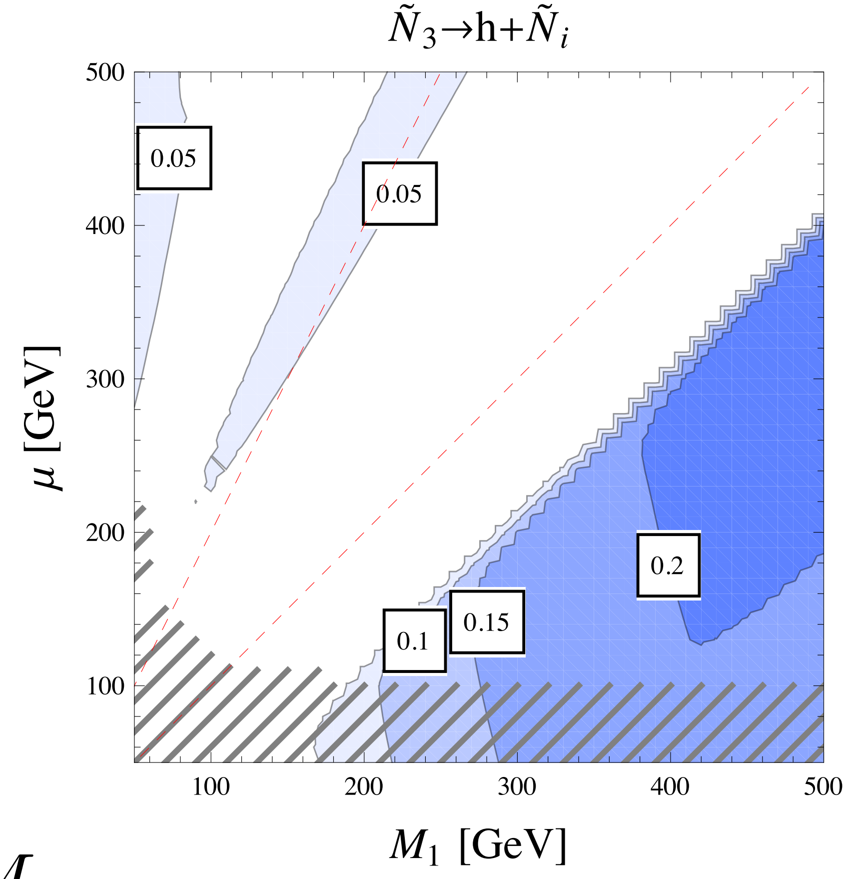
	SHSP 1a / SHSP 1b	SHSP 2a / SHSP 2b	SHSP 3	SHSP 4	SHSP 5	SHSP 6
$\tan\beta$	10	10	10	5	6.5	10
M_1	300 GeV	150 GeV	163 GeV	200 GeV	200 GeV	300 GeV
M_2	600 GeV	300 GeV	400 GeV	400 GeV	400 GeV	600 GeV
M_3	2.1 TeV	1.05 TeV	1.0 TeV	1.4 TeV	1.4 TeV	2.1 TeV
μ	150 GeV	150 GeV	200 GeV	200 GeV	-150 GeV	150 GeV
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
$\chi_1^\pm$	148 GeV	137 GeV	191 GeV	187 GeV	152 GeV	148 GeV
$\chi_2^\pm$	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

- 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.

Chargino and Neutralino Decays into Higgs

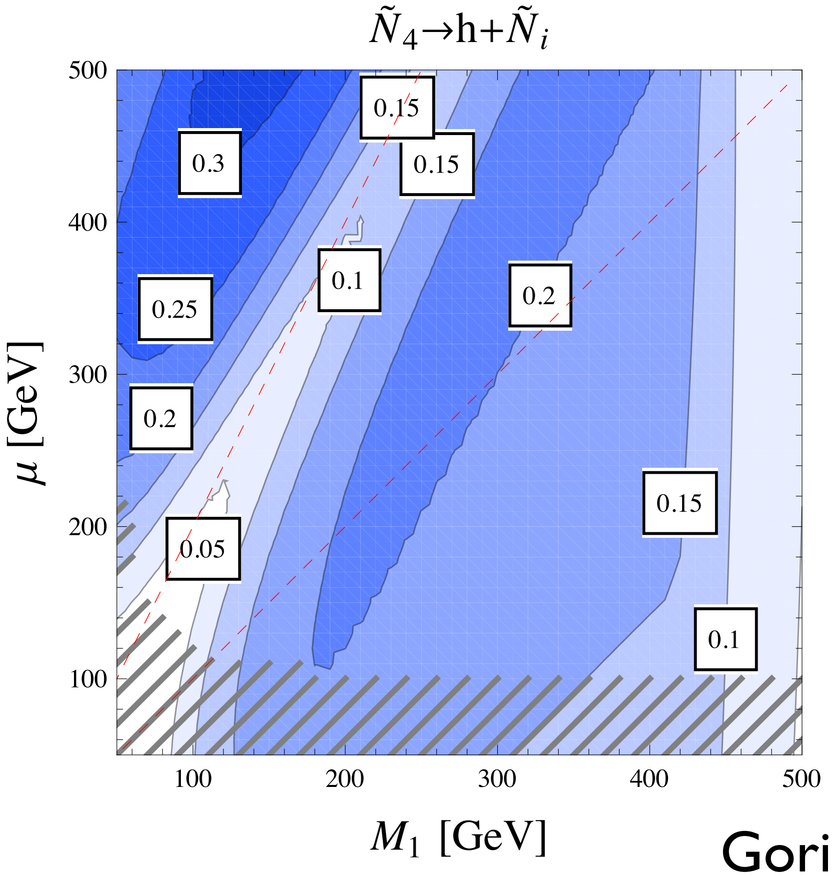


$\tilde{N}_2 \to h + \tilde{N}_1$

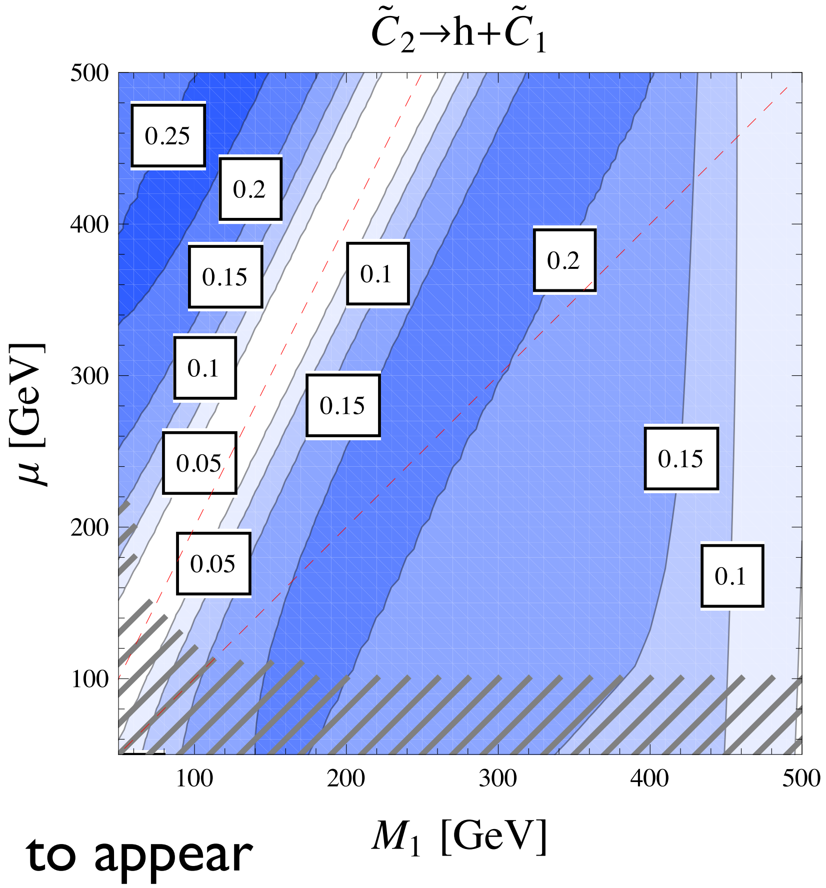


$\tilde{N}_3 \to h + \tilde{N}_i$

$$M_2 = 2M_1$$



$\tilde{N}_4 \to h + \tilde{N}_i$



$\tilde{C}_2 \to h + \tilde{C}_1$

Gori, Schwaller, C.W., to appear

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

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

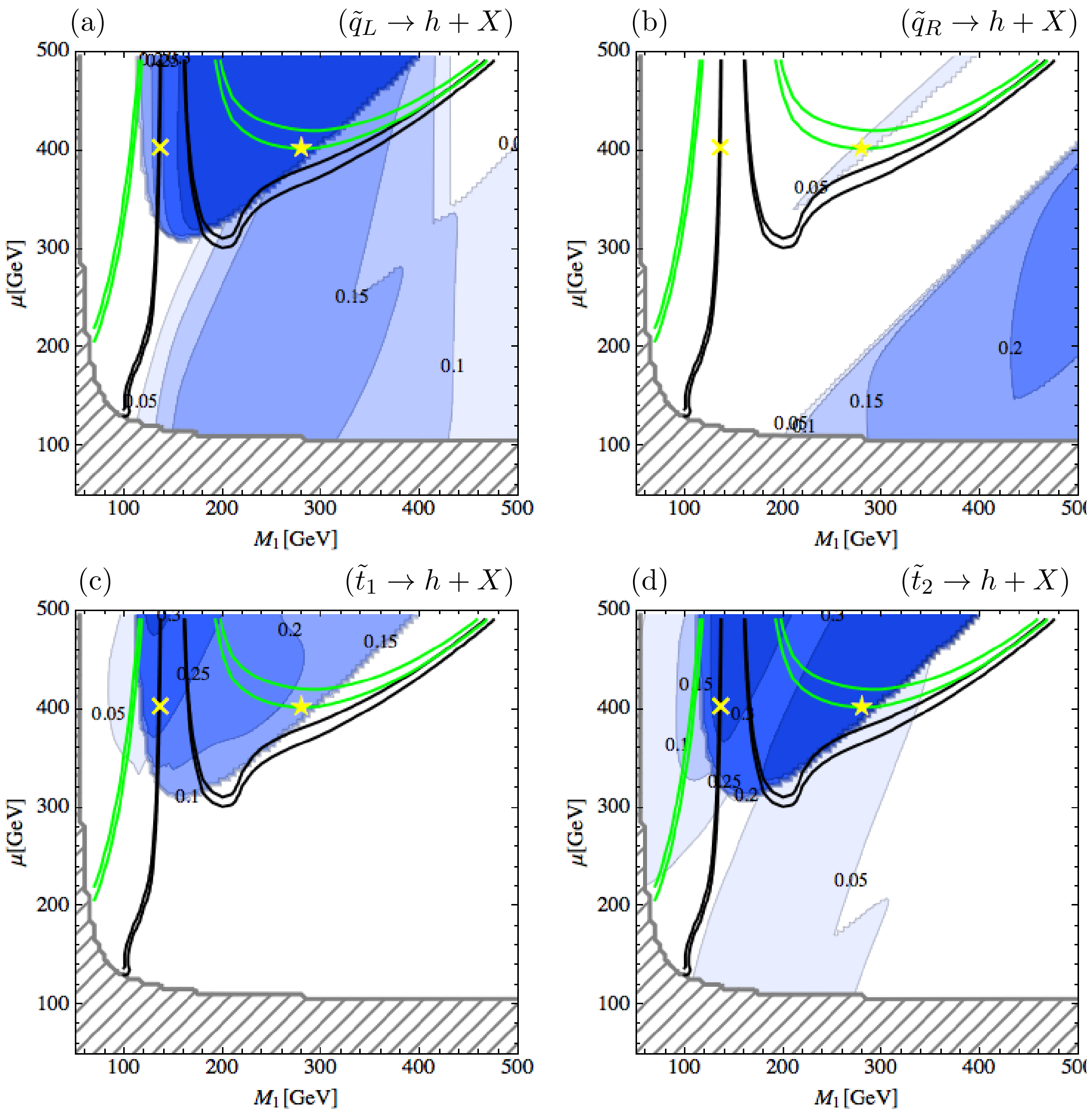
$\text{Black}: \tan\beta = 10$

$m_A = 300 \text{ GeV}$

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

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

$M_2 = 2 M_1$



Blue regions :

Appreciable Branching Decay Fraction.

Darker means larger branching decay fraction.

X : energetic quarks, leptons and missing energy

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

	σ[pb]	σ_{cut}[pb]	σ_h[fb]	σ_{boosted}[fb]
(I)	1.11	0.52	78	31
(II)	0.73	0.34	116	31
(III)	2.59	0.90	360	135

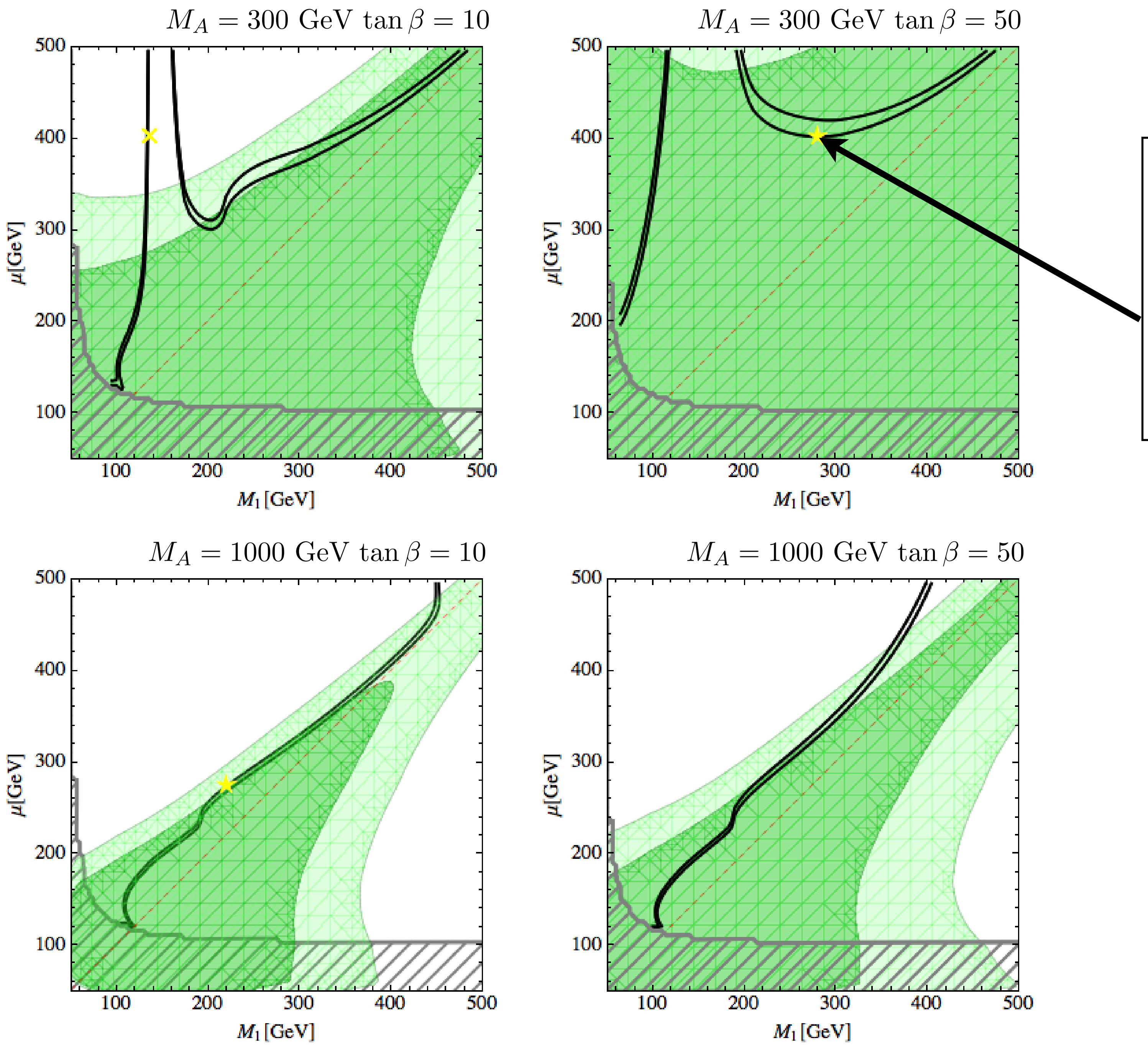
Gori, Schwaller, Wagner, **Phys.Rev.D83:115022,2011**

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

Direct Dark Matter Cross Section Constraints (post Xenon)

(I) $M_A = 1000$ GeV $M_1 = 220$ GeV $\mu = 280$ GeV $\tan\beta = 10\,,$
(II) $M_A = 300$ GeV $M_1 = 280$ GeV $\mu = 400$ GeV $\tan\beta = 50\,,$
(III) $M_A = 300$ GeV $M_1 = 135$ GeV $\mu = 400$ GeV $\tan\beta = 10\,.$

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



Slightly smaller tan(beta) = 40 leads to same signatures with similar parameters

Gori, Schwaller, C.W. '11

The EFT Approach

Study extensions with ``heavy” BMSSM degrees of freedom that couple to the Higgs sector.

(``heavy” stands for heavier than MSSM Higgses, typically $1 - 2\ \mathrm{TeV}$)

- Allows relatively model-independent survey: integrate-out and describe by

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2 + \frac{\omega_2}{3M^3}(H_u H_d)^3 + \cdots$$

Brignole, Casas, Espinosa, Navarro, ‘03
Dine, Seiberg, Thomas, ’07
Antoniadis et. al. ’07 ...

Kähler potential starts at order $1/M^2$. Also F-term ~~SUSY~~.

- Matter sector more constrained, restrict here to Higgs sector (e.g. singlets, triplets, “$Z's$”, W')

The EFT Approach

(Carena, Kong, EP & Zurita, 2009)

- Impose some ``sanity" checks:

  - Higher orders in 1/M expansion should be expected to be small

  Technical comment: both $1/M$ and $1/M^2$ can be phenomenologically relevant, without signalling breakdown of EFT expansion!

The EFT Approach

(Carena, Kong, EP & Zurita, 2009)

- Impose some ``sanity" checks:

  - Higher orders in 1/M expansion should be expected to be small

  Technical comment: both $1/M$ and $1/M^2$ can be phenomenologically relevant, without signalling breakdown of EFT expansion!

$$V \supset \frac{1}{2}\lambda_1(H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2(H_u^\dagger H_u)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u H_d)(H_u^\dagger H_d^\dagger)$$
$$+ \left\{\frac{1}{2}\lambda_5(H_u H_d)^2 + \left[\lambda_6(H_d^\dagger H_d) + \lambda_7(H_u^\dagger H_u)\right](H_u H_d) + \text{h.c.}\right\}$$

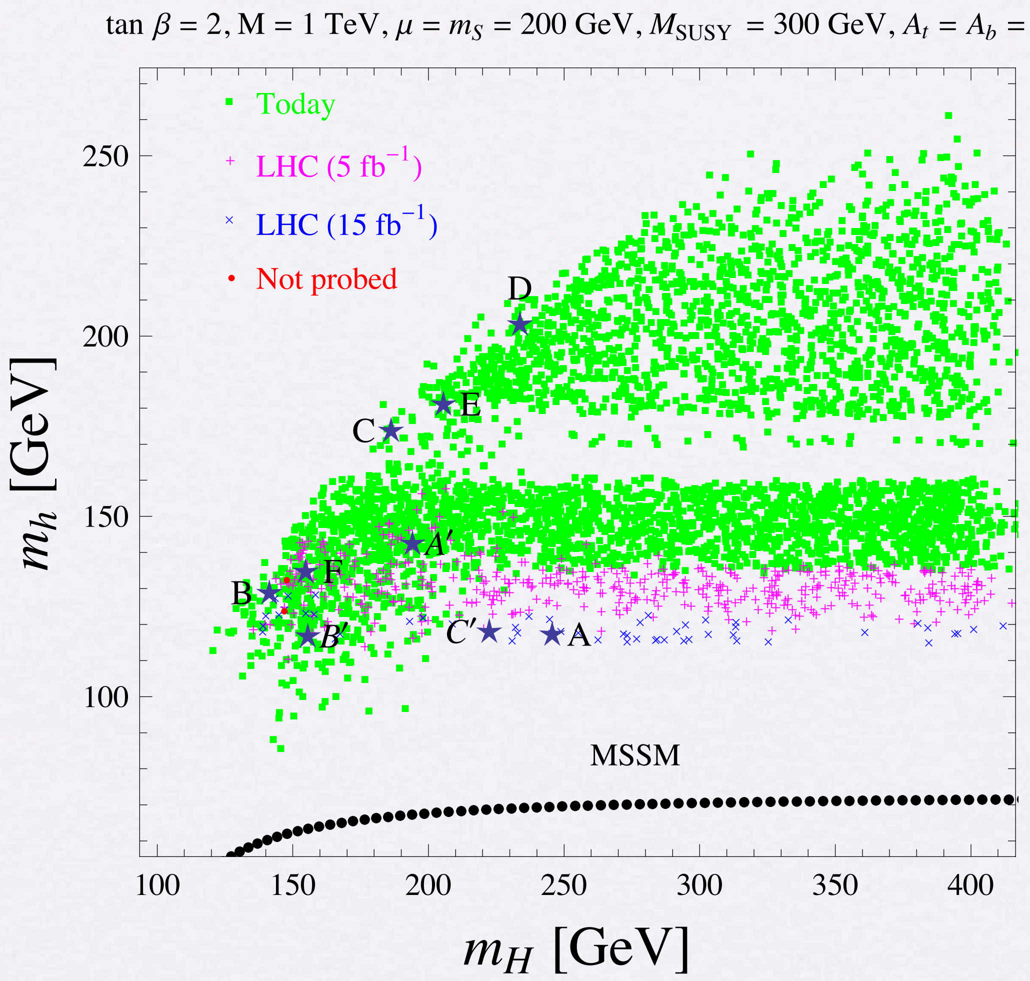
Special structure of MSSM potential + SUSY higher-dimension operators:

$\lambda_1, \lambda_2, \lambda_3, \lambda_4 \sim g^2 + \mathcal{O}(1/M^2)$ ⟵ can be relevant!

$\lambda_5, \lambda_6, \lambda_7 \sim \mathcal{O}(1/M) + \mathcal{O}(1/M^2)$

Benchmark Models

Most recent LHC searches in $WW, ZZ, \gamma\gamma, \tau\tau, t \to H^+ b$



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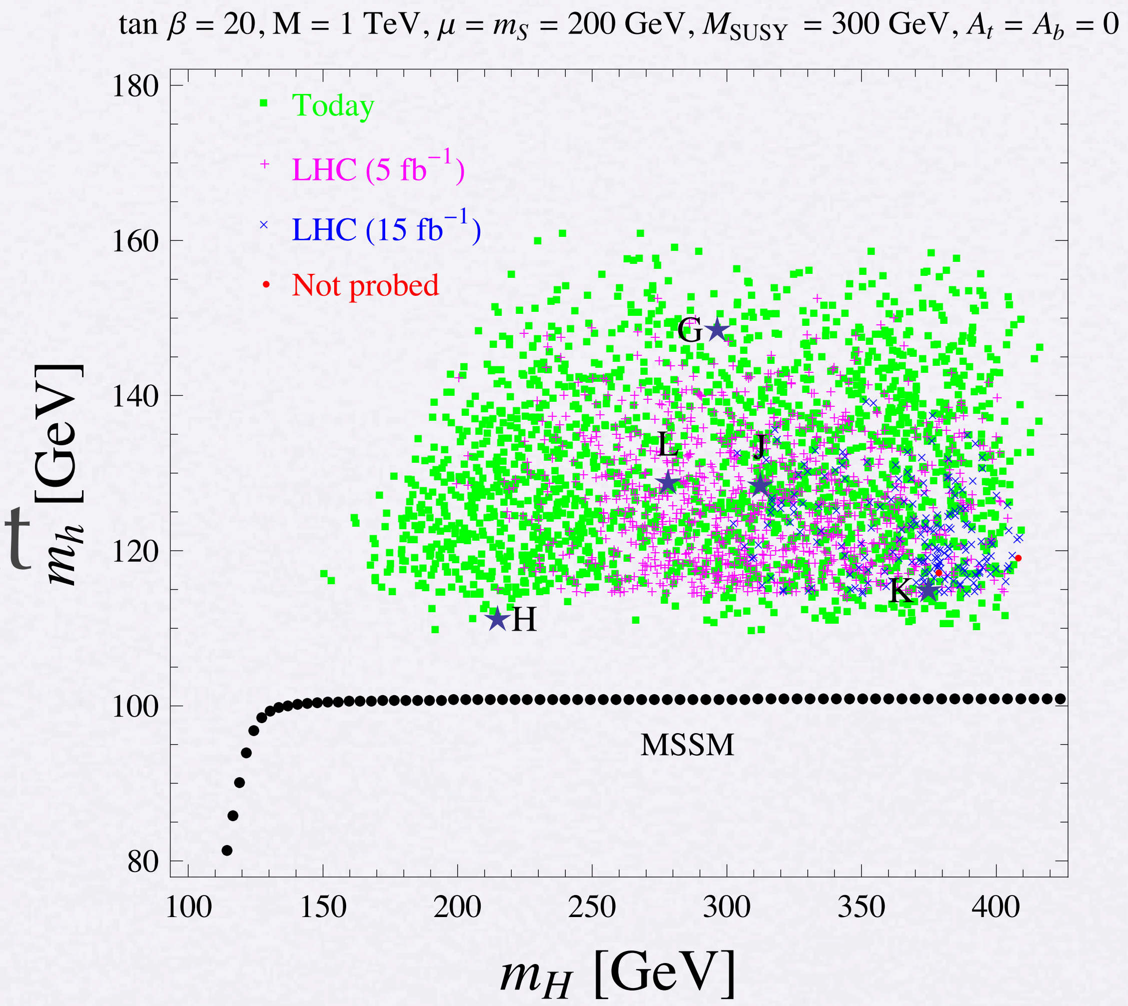


Carena, Ponton, Zurita ’11

Green points and some old benchmarks have been excluded by LHC
Stops are light, with masses lower than 500 GeV.

SM-like Higgs decays into lighter Higgs bosons

POINT F

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
64	135	155	125
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
$\leq 10^{-2}$	0.99	0.59	1.14
channel	BMSSM	channel	BMSSM
$h \to b\bar{b}$	0.15	$h \to AA$	0.84
$H \to WW$	0.12	$H \to AA$	0.84
$H \to b\bar{b}$	0.02	$A \to b\bar{b}\ /\ \tau\bar{\tau}$	0.91 / 0.09
$H^+ \to \bar{\tau}\nu_\tau$	0.56	$H^\pm \to W^\pm + A$	0.40

$pp \to H \to WW$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.18	1.8	4.9	30

Carena, Ponton, Zurita ’11

It happens in many other models. Standard decays suppressed

Carena, Ellis, Mrenna, Pilaftsis, Wagner’02 (CPX)
Dermisek and Gunion ’05 (nMSSM)

Associated production with gauge bosons present a clear LHC search opportunity
Carena, Han, Huang, C.W.’07

- Carachteristic CP violating scenarios

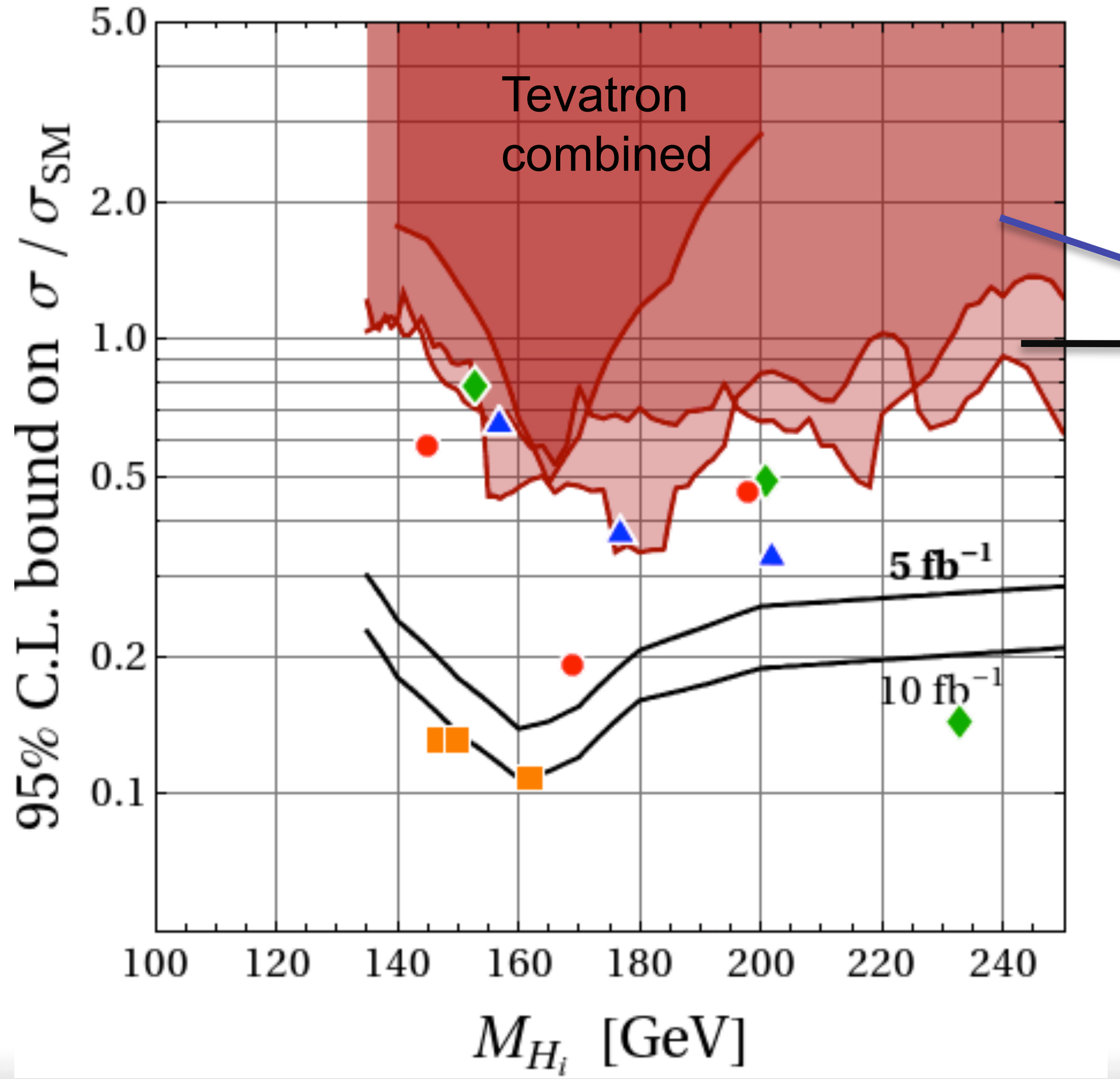
Altmanshoffer, Carena, Gori, de la Puente'11

- 3 Heavy Higgs bosons (mHi > 140 GeV)

→ due to scalar- pseudoscalar mixing

a) all 3 Hi couple to WW (main search channel)

b) all 3 Hi decay mainly into bb; still with ~ 10 fb^{-1} can be seen in WW decays



Atlas up to 2.3 fb-1

CMS up to 1.7 fb-1

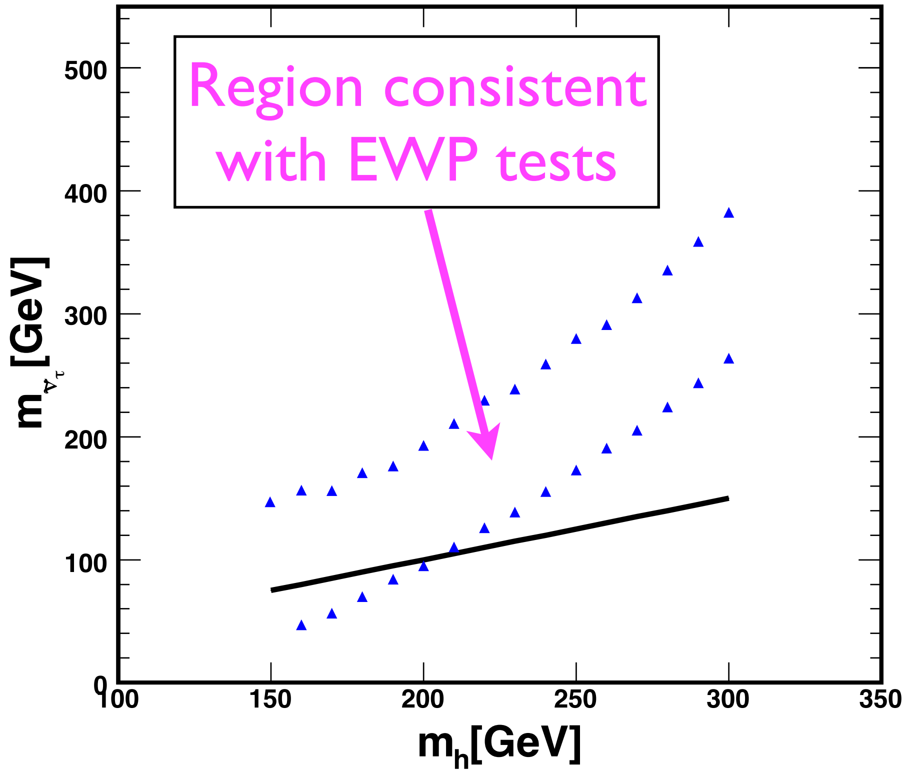
Another Example of SUSY Model with heavy Higgs

Model with enhanced SU(2) D-terms

Batra, Delgado, Kaplan, Tait'03

Enhanced D-term also split slepton sector. SUSY contribution to rho parameter compensate the one of the heavy Higgs.

Large coupling of Higgs to sneutrinos induced large decay rate.
Sneutrinos decay subsequently into neutrinos and the DM particle



Medina, Shah, C.W.'09

$$g_{h\tilde{\nu}_\tau\tilde{\nu}_\tau} \simeq -i\,\frac{(g^2\Delta + g_Y^2)\,v}{2\sqrt{2}}.$$

$$\Gamma(h \to VV) \simeq \frac{G_F(|Q_V|+1)\,m_h^3}{\sqrt{2}\;16\;\pi}\left(1-\frac{4m_V^2}{m_h^2}+\frac{12m_V^4}{m_h^4}\right)\left(1-\frac{4m_V^2}{m_h^2}\right)^{1/2}$$

$$\Gamma(h \to \tilde{\nu}_\tau\tilde{\nu}_\tau) \simeq \frac{(g^2\Delta + g_Y^2)^2\,v^2}{128\;\pi\;m_h}\left(1-\frac{4m_{\tilde{\nu}_\tau}^2}{m_h^2}\right)^{1/2}$$

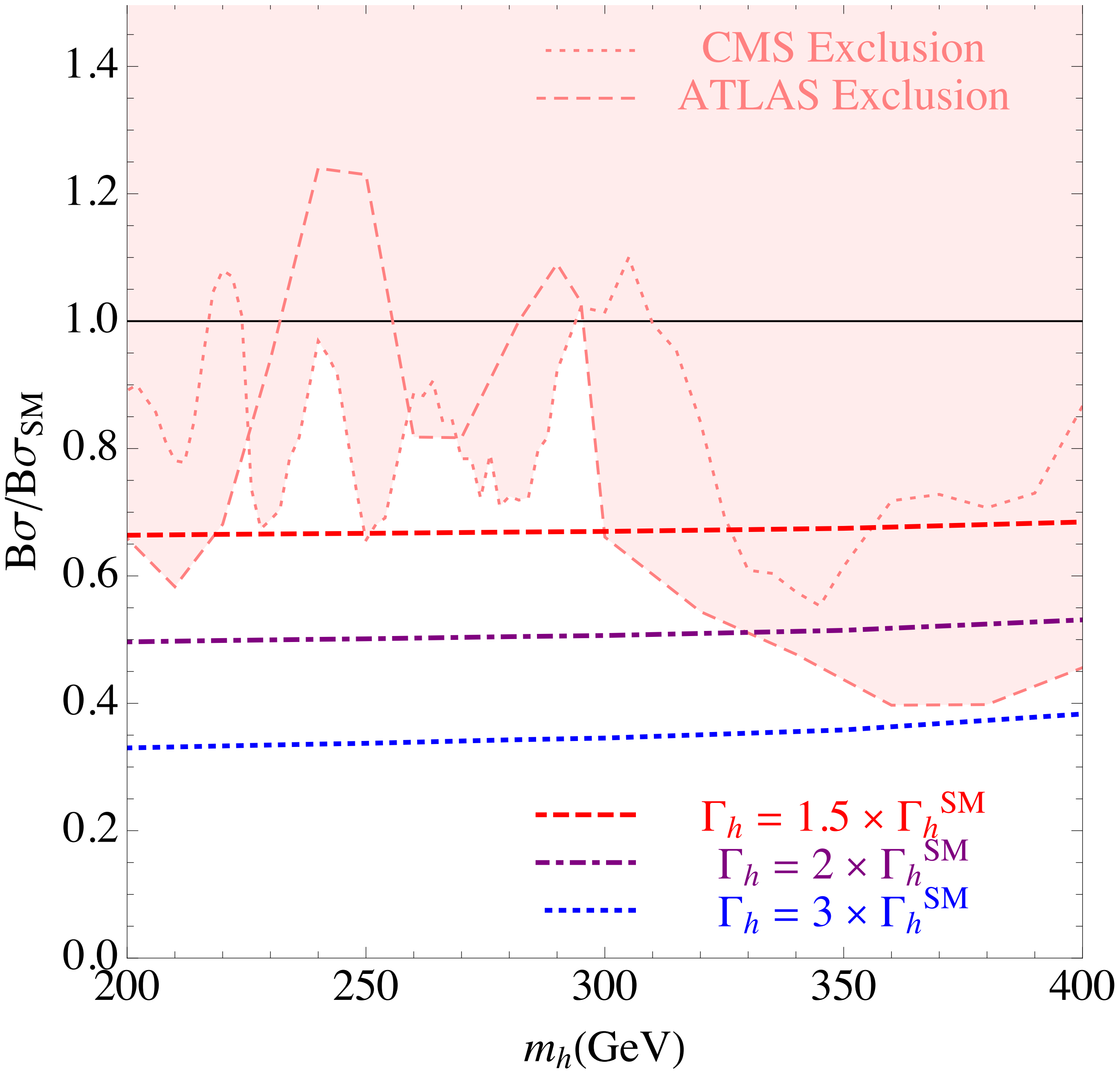
For Higgs masses between 150 GeV and 200 GeV, large invisible width, of order of or larger than the VV width may be obtained

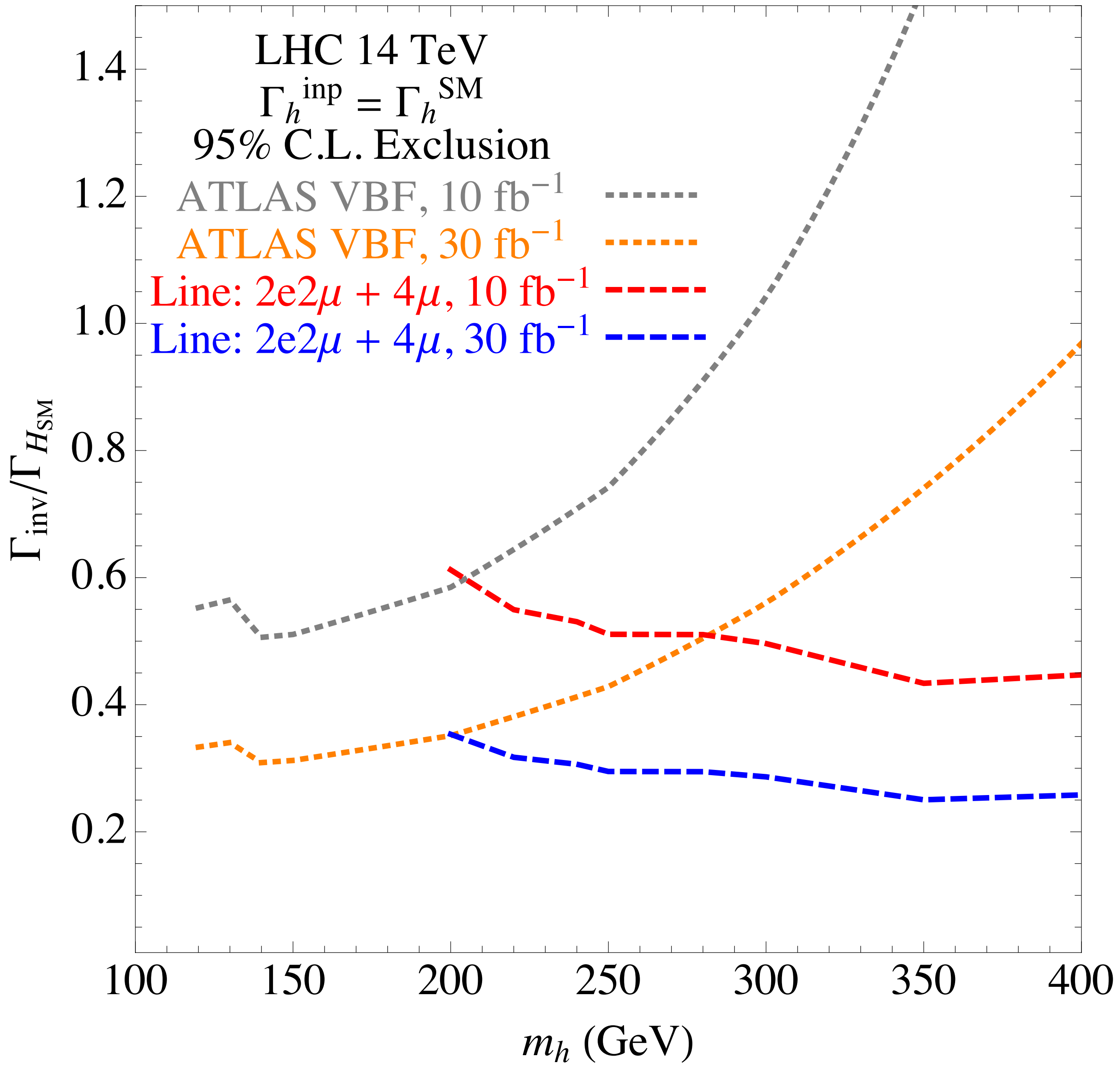
Dark Matter and the Higgs Decay Width

- If Dark Matter particles are lighter than half of the Higgs mass, Higgs can decay into them
- This would induce a modification of the total width, which will affect all visible branching ratios
- In such a scenario, it would be important to measure the invisible width
- In the low mass region, the LHC can measure this width by looking in the weak boson fusion production (Zeppenfeld, Eboli, '00)
- In the high mass region, one could get information by measuring the total width from the lineshape of H-> 4 lepton channel

Searches on Weak Boson Fusion are Complementary to Line Shape determination

Shaughnessy, Low, Schwaller, C.W., arXiv:1110.4405



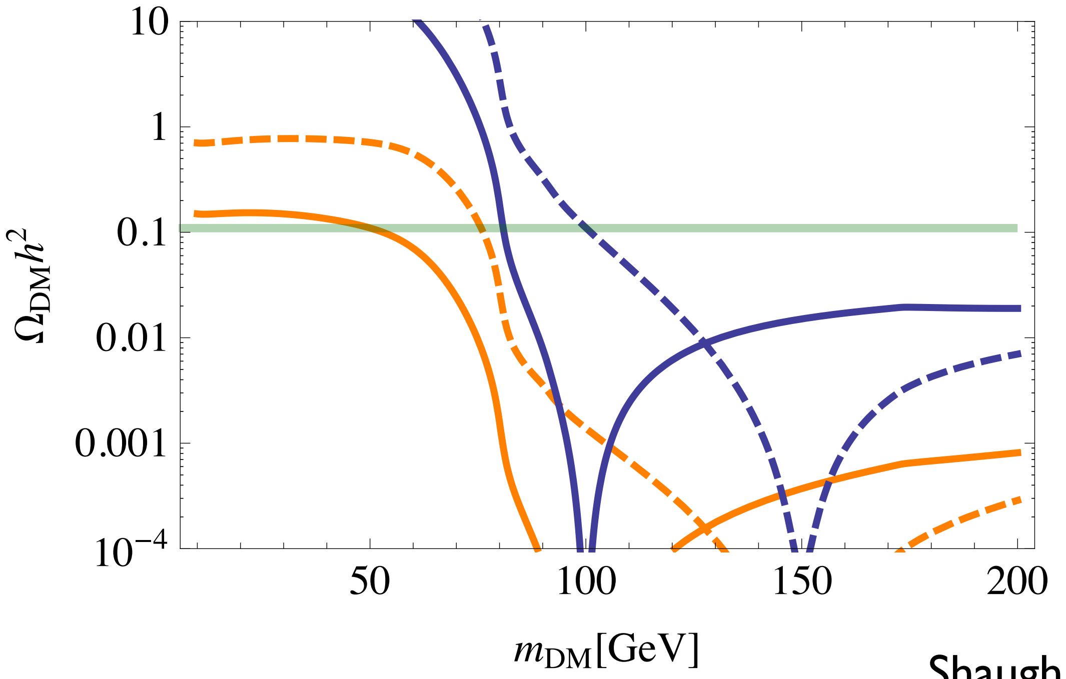


Dark Matter Higgs Portal

$$\mathcal{L} = \delta_c\, m_s^2 |S|^2 + \delta_c\, \lambda_s H^\dagger H |S|^2\,,$$

$$\mathcal{L} = \delta_c\, m_f \bar{\psi}\psi + \delta_c\, \frac{\lambda_f}{\Lambda} H^\dagger H \bar{\psi}\psi\,,$$

$\delta_c = 1/2$ for a real scalar and a Majorana fermion and 1 otherwise.

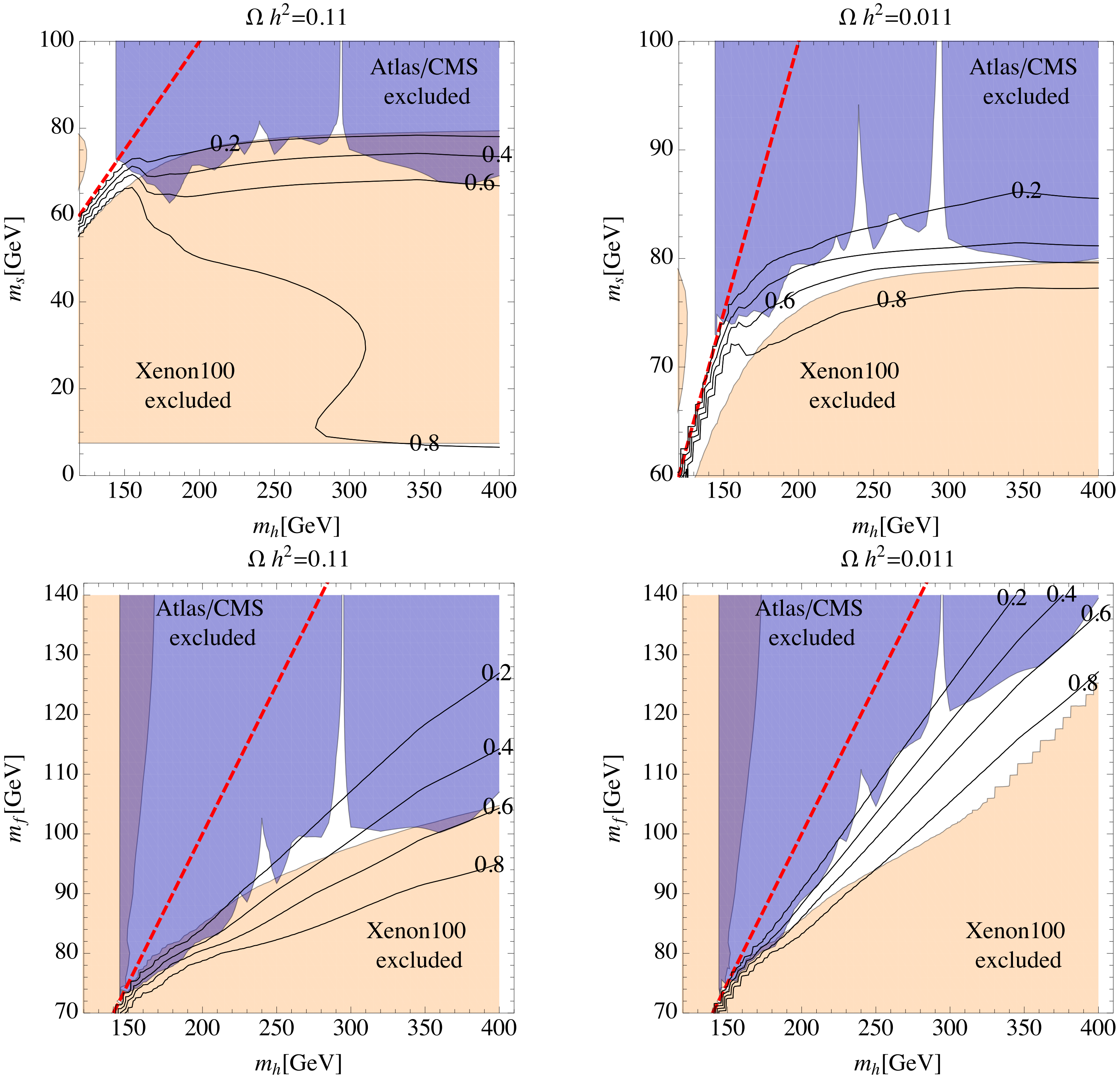


Relatively light scalars and heavy fermions are accomodated naturally in this framework

Shaughnessy, Low, Schwaller, C.W., arXiv:1110.4405

FIG. 6: *Relic density for scalar (orange/light grey) and fermion (blue/dark grey) dark matter as a function of the dark matter mass. The curves are shown for Higgs masses of 200 GeV (solid) and 300 GeV (dashed), for a fixed couplings of* $\lambda_s = 1$ *and* $\tilde{\lambda}_f = 1$ *respectively for scalars and fermions. The light green band is the WMAP-7 measured [31] dark matter relic density.*

Allowed parameter region for scalars and fermion Dark Matter cases



Scalars (fermions) lighter (heavier) than the weak bosons considered.

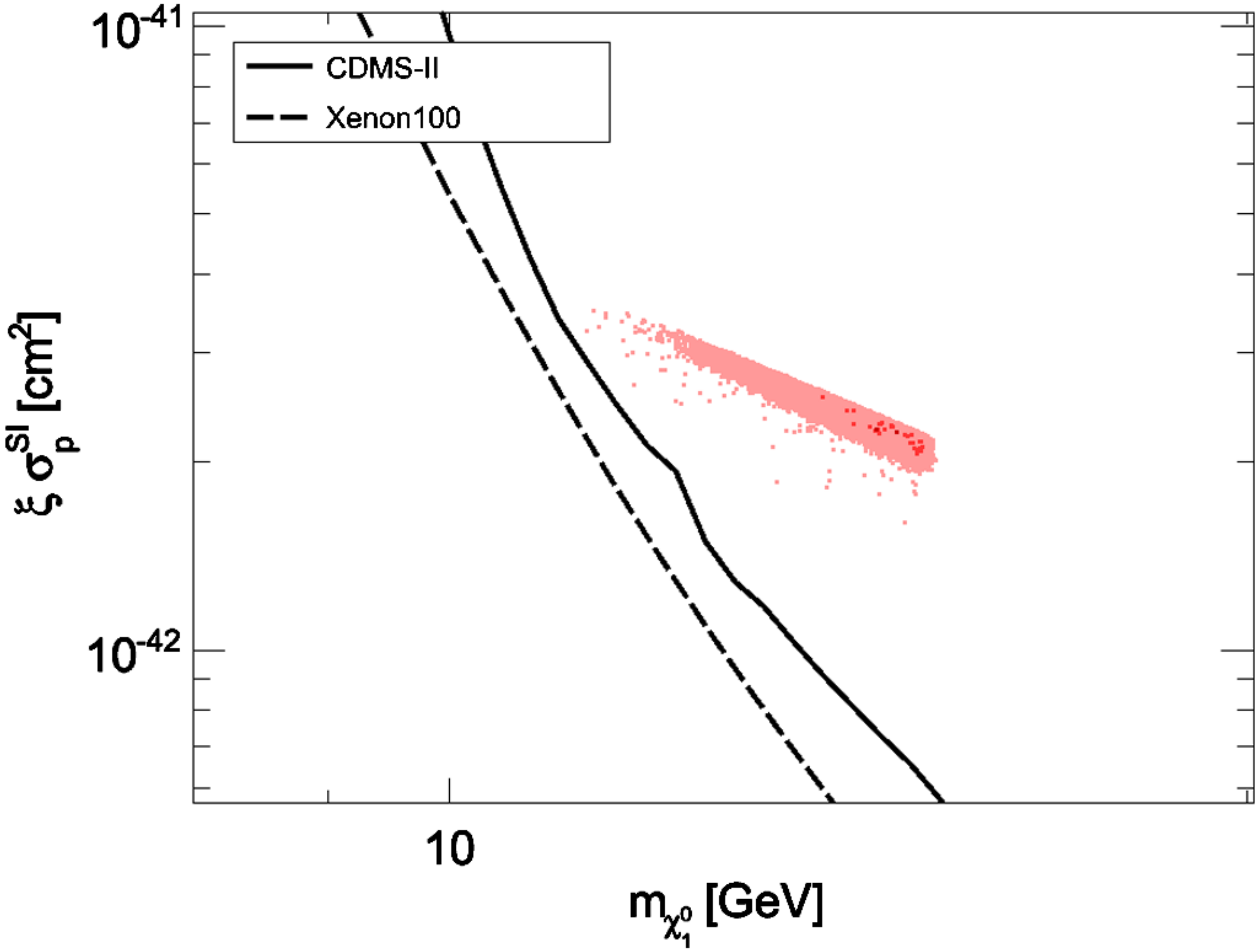
Couplings fixed to obtained desired relic density.

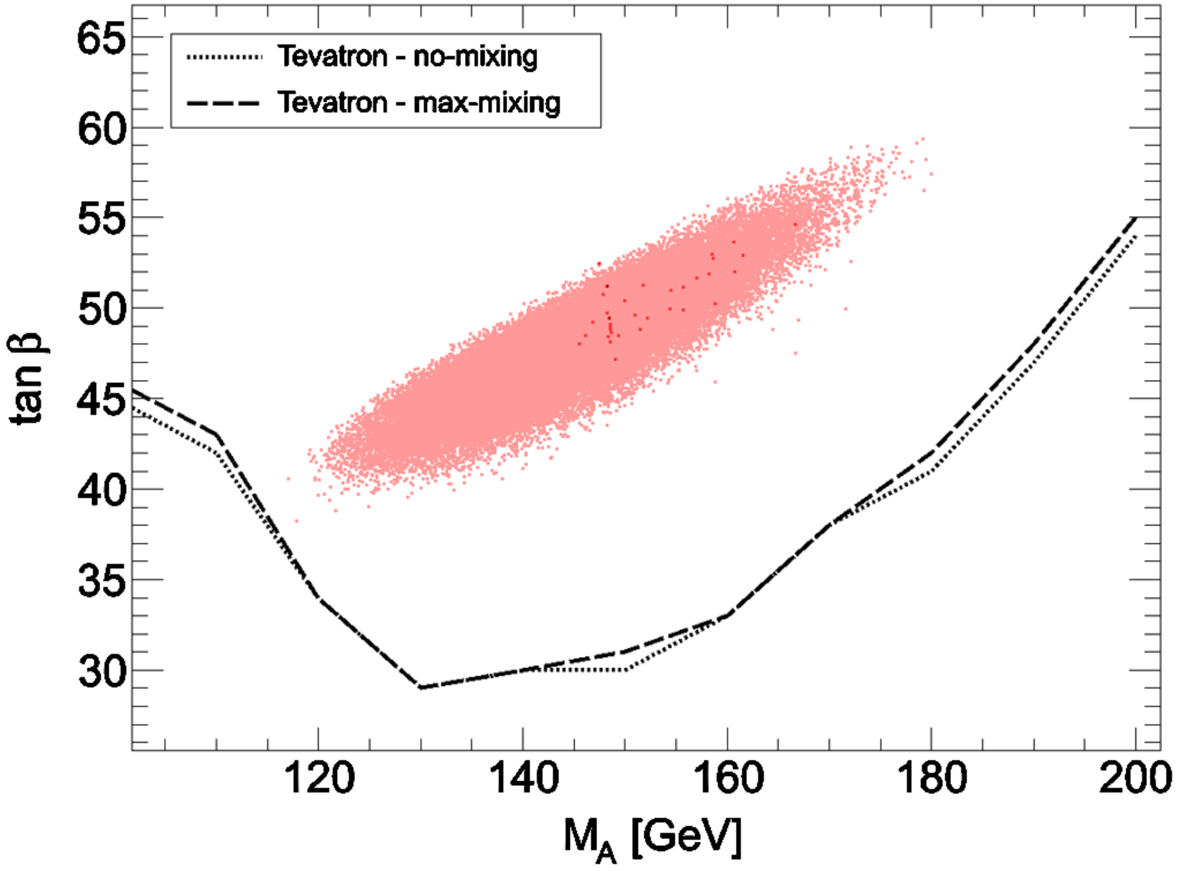
Solid lines denote production rate compared to the SM one.

Shaughnessy, Low, Schwaller, C.W., arXiv:1110.4405

Light Dark Matter : Heavily constrained in the MSSM

D.Albornoz Vasquez,G. Belanger, C. Bœhm, A. Pukhov, and J. Silk
PHYSICAL REVIEW D **82,** 115027 (2010)





$M_1 \in [1, 100]$ GeV, $M_2 \in [100, 2000]$ GeV,
$\mu \in [0.5, 1000]$ GeV, $\tan\beta \in [1, 75]$,
$m_{\tilde{l}} \in [100, 2000]$ GeV, $m_{\tilde{q}} \in [300, 2000]$ GeV,
$A_t \in [-3000, 3000]$ GeV, $m_A \in [100, 1000]$ GeV.

Also (e.g.):
Feldman, Liu, Nath, Piem (2010)
Kuflik, AP, Zurek (2010);

Bottino, Donato, Fornengo, Scopel'10
Belli et al'11

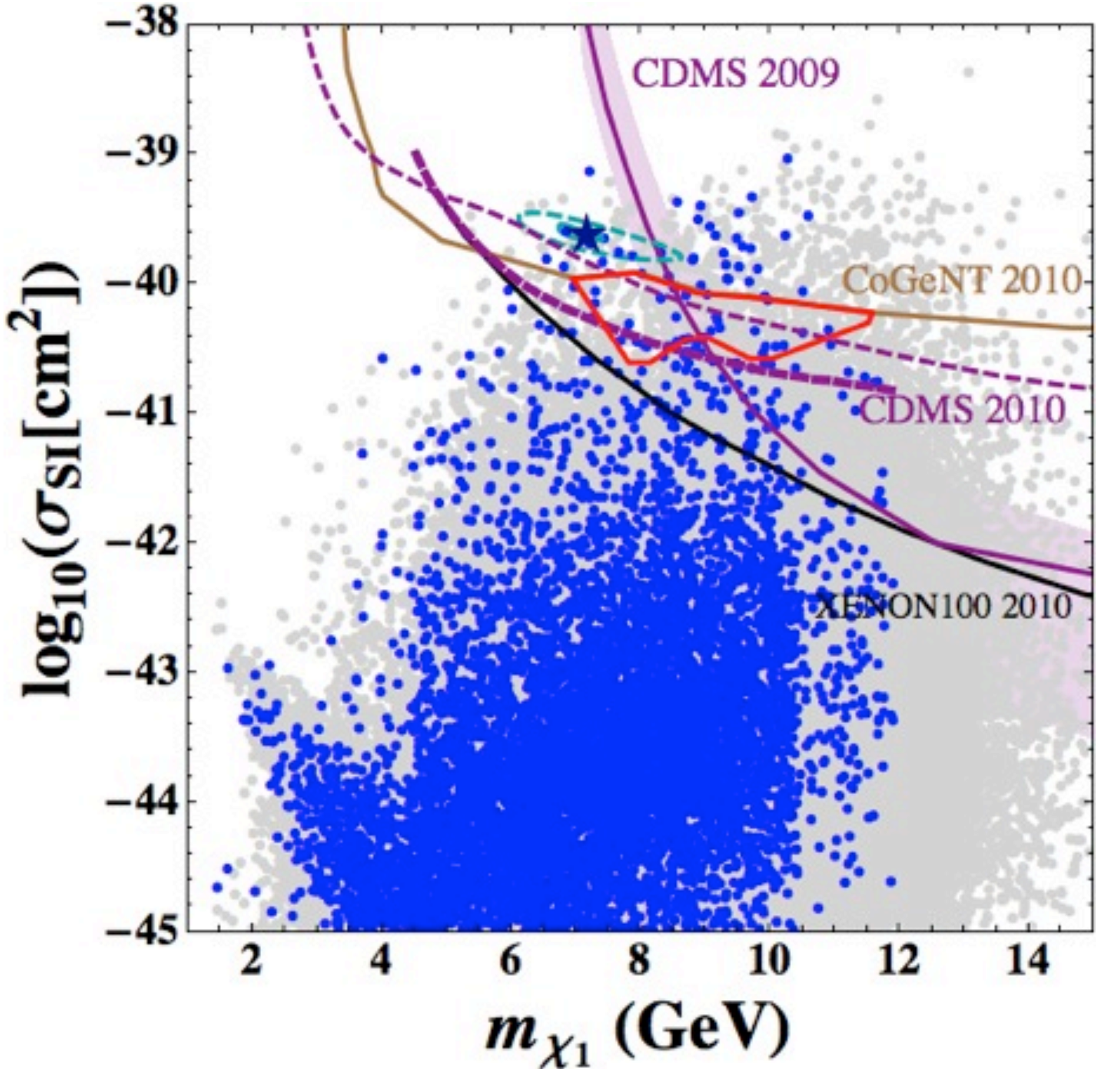
Dark Light Higgs (NMSSM near the PQ symmetry limit)

Numerical Results

★

λ	$\kappa(10^{-3})$	$A_\lambda(10^3)$	A_κ	μ	$\tan\beta$	m_{h_1}
0.1205	2.720	2.661	-24.03	168.0	13.77	0.811
m_{a_1}	m_{χ_1}	m_{h_2}	Brhh	Braa	Ωh^2	$\sigma_{SI}(10^{-40})$
16.7	7.20	116	0.158%	0.310%	0.112	2.34

$0.09 \leqslant \Omega h^2 \leqslant 0.13$



$$0.05 \leqslant \lambda \leqslant 0.15, \quad 0.001 \leqslant \kappa \leqslant 0.005,$$
$$|\varepsilon'| \leqslant 0.25, \quad -30\text{GeV} \leqslant A_\kappa \leqslant -15\text{GeV},$$
$$5 \leqslant \tan\beta \leqslant 50, \; 100\text{GeV} \leqslant \mu \leqslant 250\text{GeV}$$

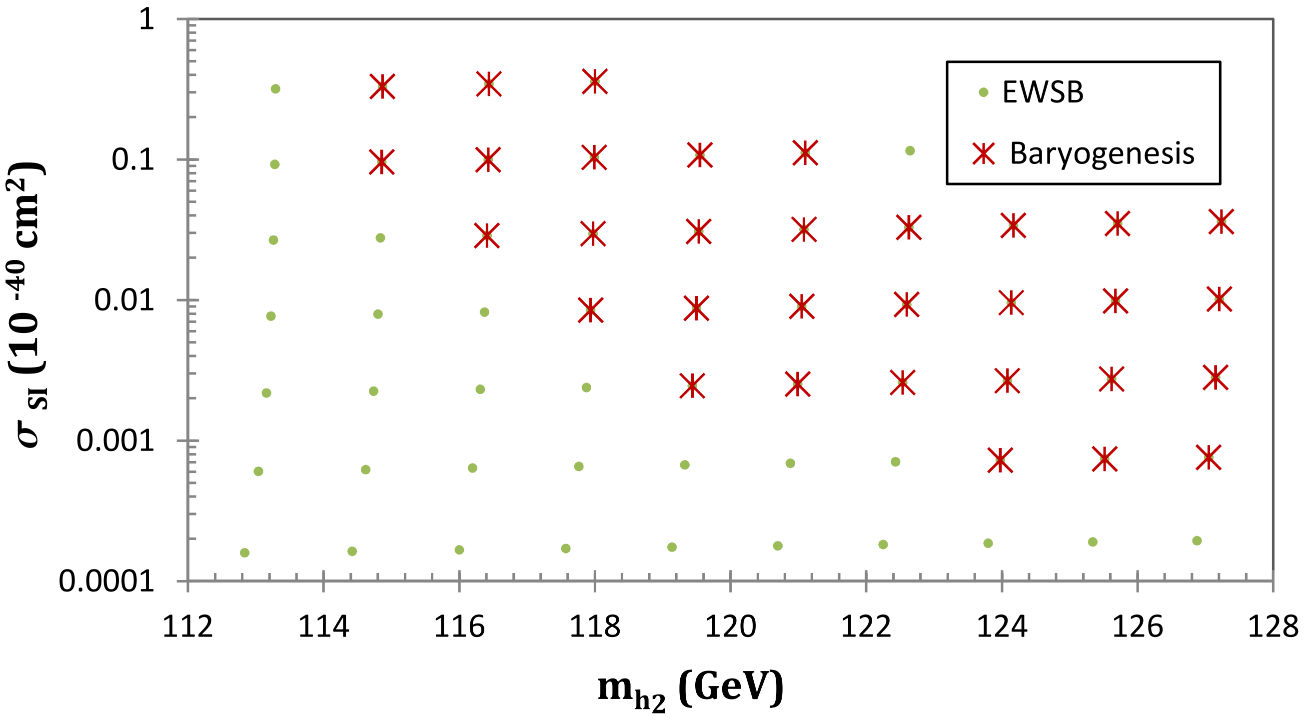
- The blue points fall in a 3 sigma range of the observed relic density.
- All points have passed the current exp. bounds of flavor physics, meson decays, and collider exp.

T. Liu

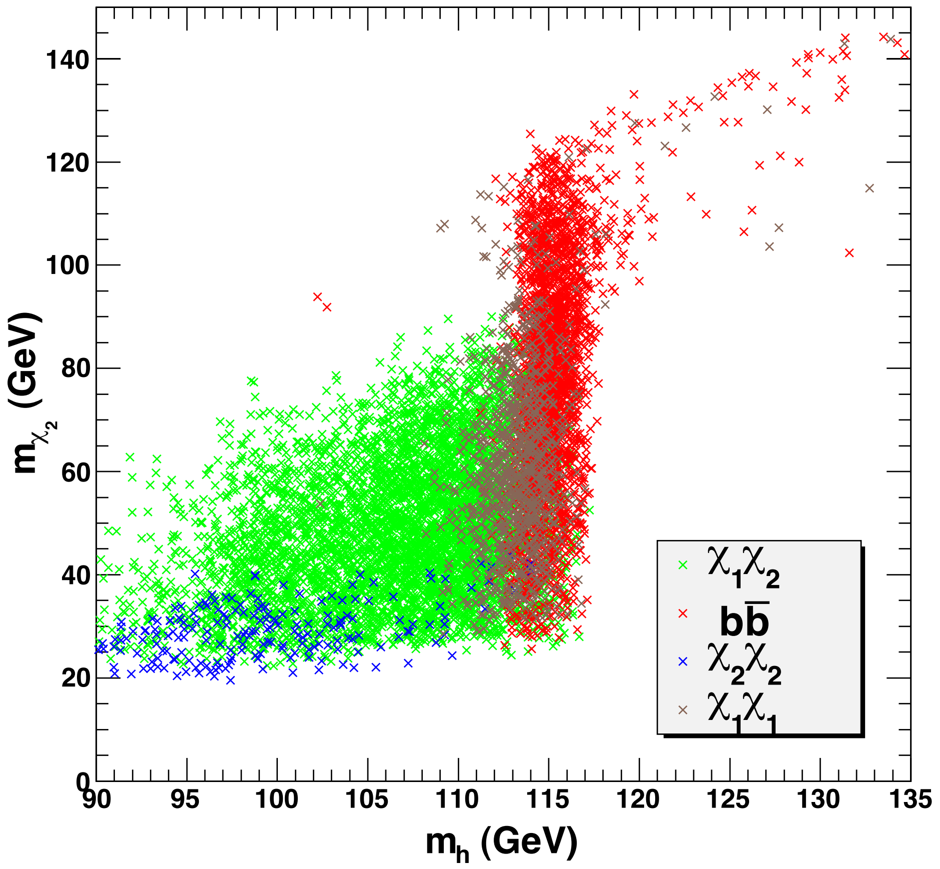
P. Draper, T.L., C. Wagner, L.T. Wang and H. Zhang, Phys. Rev. Lett. 106 (2011)

Mixed Decays into Higgs and Dark Matter

Weiner,Chang' 09



Carena, Shah, C.W.'11



Liu, Huang, Zhang'11

A strongly first order phase transition may be obtained (red dots). Consistency with COGENT demands SM-like Higgs mass mh2 closer to or smaller than the LEP limit value.

LEP limit may be avoided due to the existence of additional decay modes

$$h_2 \to \chi_2\chi_1 \to h_1\chi_1\chi_1 \; (f\bar{f} + \text{Miss.Energy})$$

$$h_2 \to \chi_2\chi_2 \to h_1h_1\chi_1\chi_1 \; (2\times f\bar{f} + \text{Miss.Energy})$$

The bottom quark decay branching ratio can be naturally smaller than 20 %. New decays into mesons and leptons plus missing energy.

Many other decay possibilities exist. See, for instance, Chang, Dermisek, Gunion, Weiner, arXiv:0801.4554

Conclusions

- Allowed SM-Higgs mass window at the LHC is consistent with precision measurements and with the extrapolation of SM description to very high energies. The analysis of the current data will allow to test the SM in the whole allowed Higgs masss range.

- New physics can modify the production and decay channels in a significant way. No Higgs signal could point to many interesting possibilities beyond the absence of a Higgs.

- Models with pseudo-Goldstone bosons tend to induce a smaller gluon fusion production rate.

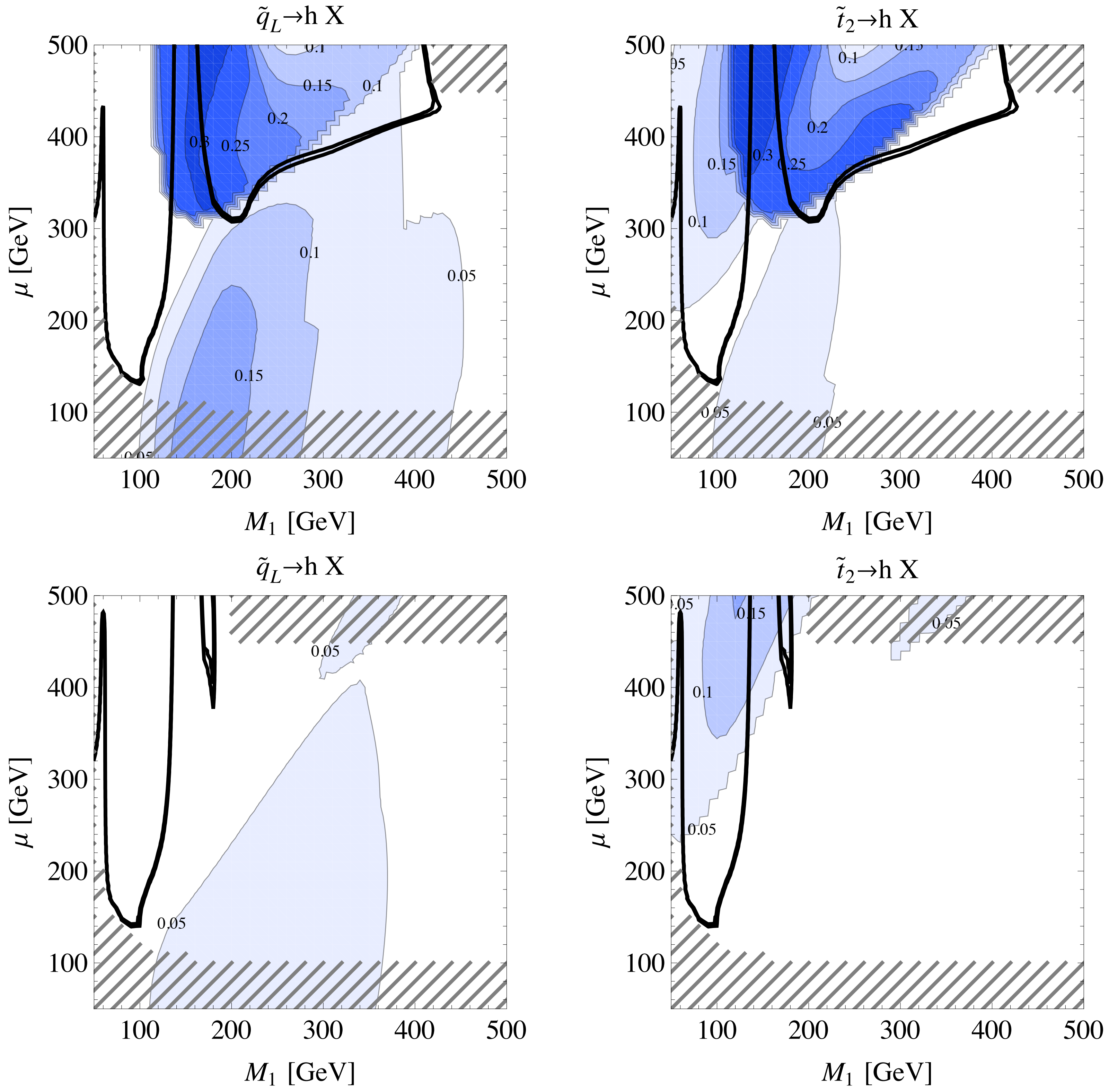
- In the minimal supersymmetric model, rates may be modified by mixing or by presence of light stops. For moderate CP-odd Higgs masses, the width of the SM-like Higgs tends to be enhanced, inducing a suppression of all relevant LHC branching ratios.

- Beyond the minimal model, there can be new decays as well as heavier Higgs bosons, implying very rich Higgs physics

- Decays associated with Dark Matter particles are an interesting possibility that will be probed at the LHC

Beyond the MSSM

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



$$M_2 = 2M_1$$
$$m_{\tilde{q}} \simeq 1\ \text{TeV}$$
$$M_{\tilde{g}} \simeq 6M_1$$

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., to appear

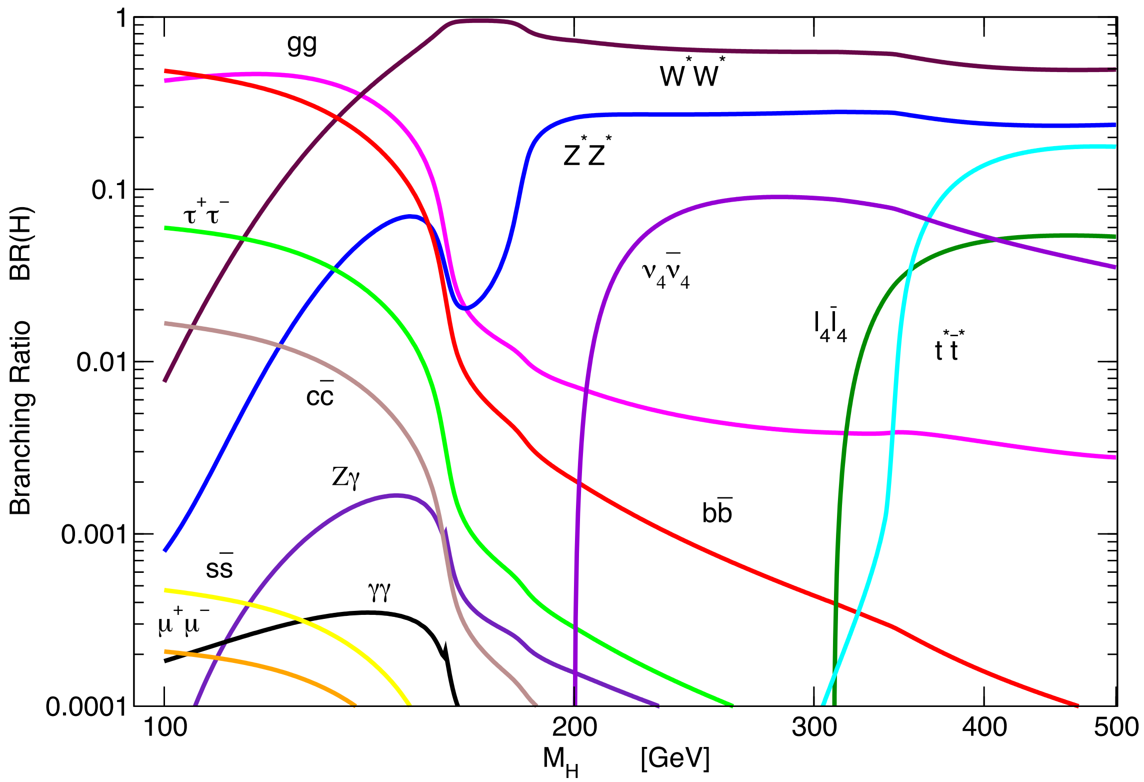
$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_f A_f(\tau_f)\right|^2$$

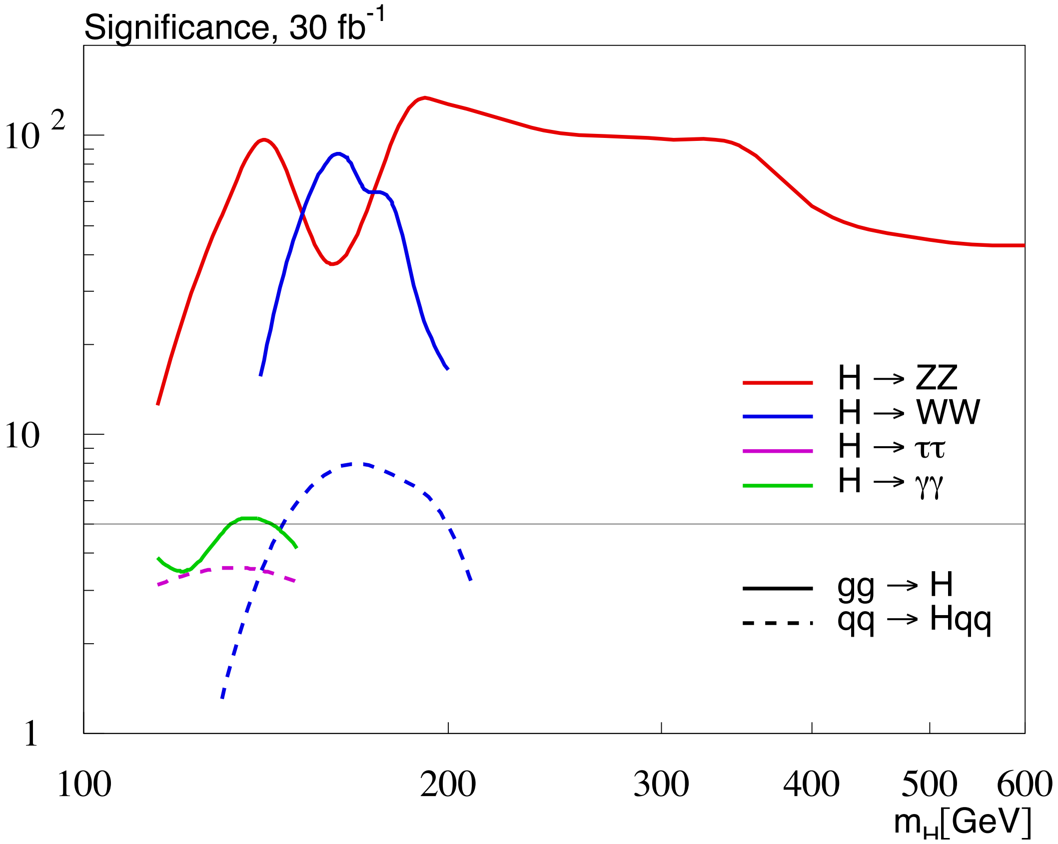
$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W)\right|^2$$

$$A_f(\tau) = 2\left[\tau + (\tau - 1) f(\tau)\right]\,\tau^{-2}$$

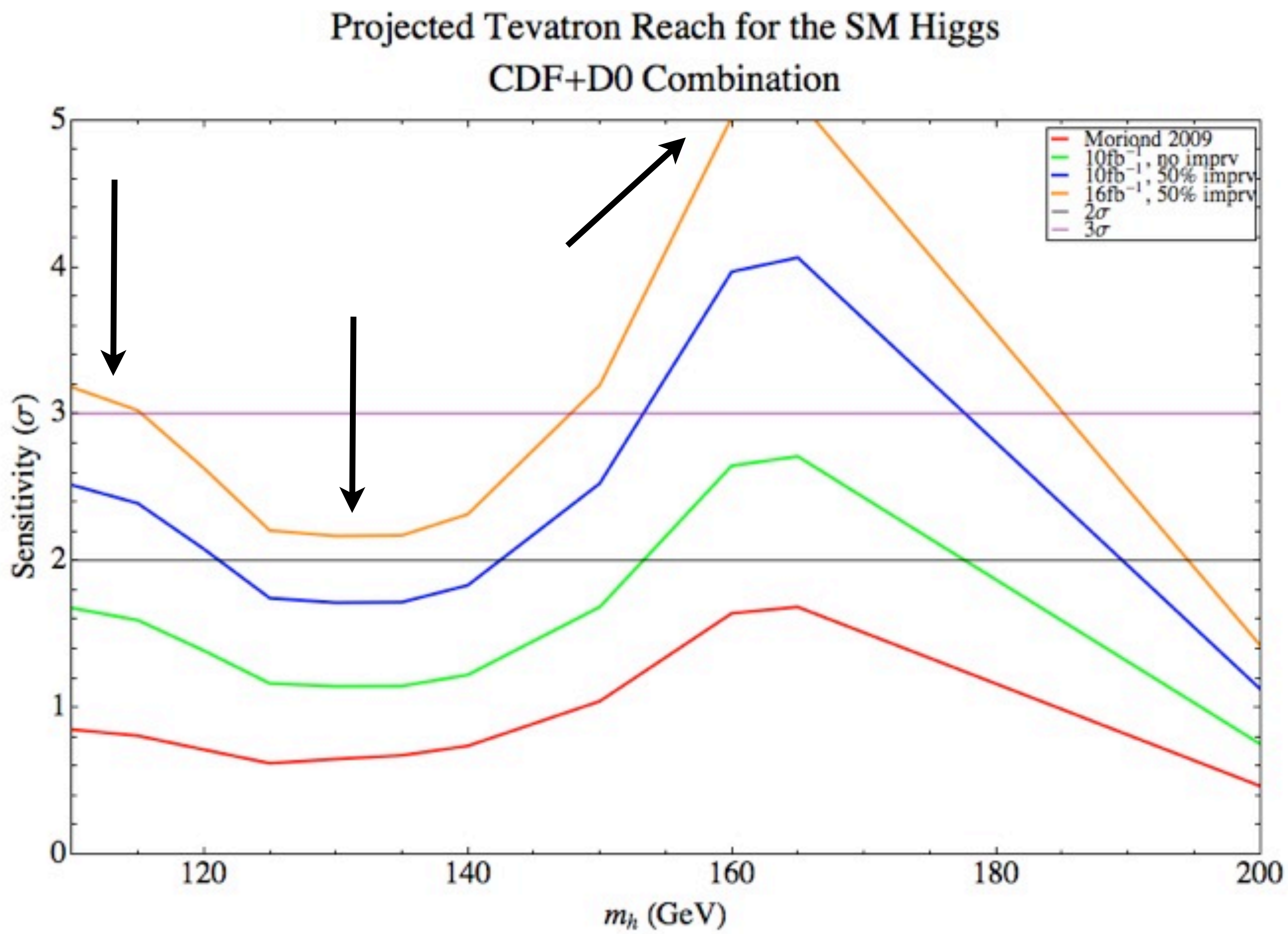
$$A_W(\tau) = -\left[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)\right]\,\tau^{-2}$$

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$


Branching Ratio BR(H)
1
0.1
0.01
0.001
0.0001
100
200
300
400
500
M_H [GeV]
gg
W*W*
Z*Z*
τ+τ−
ν4ν̄4
l4l̄4
t*t̄*
cc̄
bb̄
Zγ
ss̄
γγ
μ+μ−


Significance, 30 fb-1
10 2
10
1
100
200
300
400
500
600
m_H[GeV]
H → ZZ
H → WW
H → ττ
H → γγ
gg → H
qq → Hqq

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.

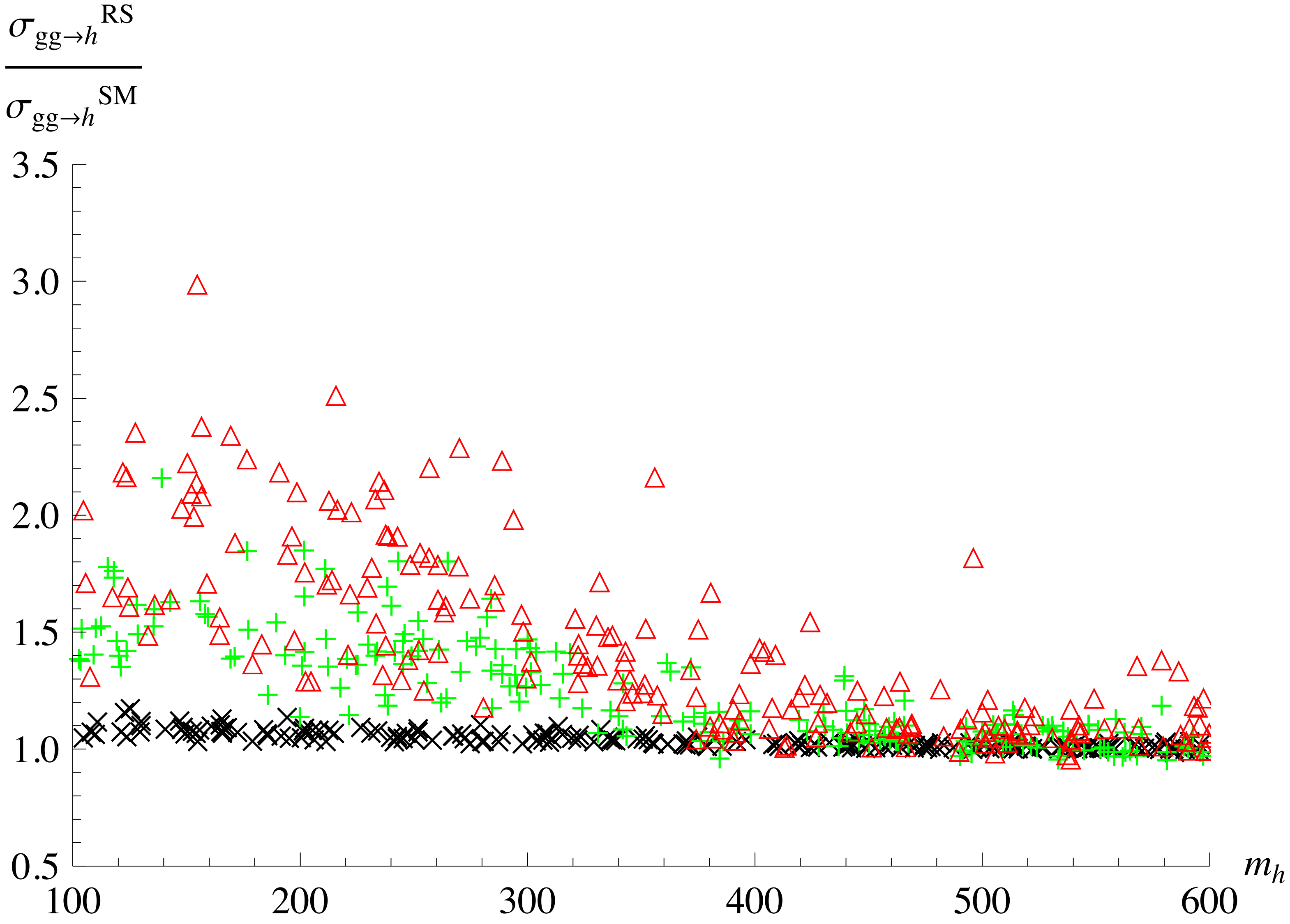
Warped Extra Dimensions with Higgs in the Bulk

$$\frac{y_{RS}^{\text{light}}}{m^{\text{light}}} A_{1/2}(\tau_{\text{light}}) + \sum_{\text{heavy}} \frac{Y_i}{M_i} = \text{Tr}(\hat{Y}\hat{M}^{-1}) + \frac{y_{RS}^{\text{light}}}{m^{\text{light}}} \left(A_{1/2}(\tau_{\text{light}}) - 1\right)$$

$$\text{Tr}(\hat{Y}\hat{M}^{-1}) = \text{Tr}\left(\frac{\partial \hat{M}}{\partial \tilde{v}} \hat{M}^{-1}\right) = \frac{\partial \ln \text{Det}(\hat{M})}{\partial \tilde{v}}$$

$$Y^u \sqrt{R}(\bar{Q}_L^u U_R + \bar{Q}_L^d D'_R)H + Y^d \sqrt{R}(\bar{Q}_L^u U'_R + \bar{Q}_L^d D_R)H + (L \leftrightarrow R) + \text{h.c.}$$

$$\frac{\sigma_{gg\to h}^{RS}}{\sigma_{gg\to h}^{SM}} = \left(\frac{v_{SM}}{\tilde{v}}\right)^2 \left|\frac{\text{Tr}(Y_u Y_u^\dagger + Y_d Y_d^\dagger)\tilde{v}^2 R'^2 + \frac{\Delta_2^t}{m_t} + \frac{\Delta_2^b}{m_b} + x_t A_{1/2}(\tau_t) + x_b A_{1/2}(\tau_b)}{A_{1/2}(\tau_t) + A_{1/2}(\tau_b)}\right|^2$$



$\frac{\sigma_{gg\to h}^{RS}}{\sigma_{gg\to h}^{SM}}$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
100
200
300
400
500
600
m_h

SO(5) Gauge Higgs Unification Models

$$f = \frac{\sqrt{2}}{g_5(\int_0^L a^{-2})^{1/2}}.$$

$$\sum_{\text{top}} \frac{y_{nn}}{m_n} = \frac{\cos(\tilde{v}/f)}{f\,\sin(\tilde{v}/f)}$$

$$R_g^{1/2} \approx \cos(\tilde{v}/f) + \mathcal{O}(m_b^2/M_{\rm KK}^2)$$ (spinorial representation)

$$R_g^{1/2} \approx \frac{\cos(2\tilde{v}/f)}{\cos(\tilde{v}/f)}$$ (fundamental representation)

	4	**5**
$f = 500$ GeV	$R_g = 75\%$	$R_g = 35\%$
$f = 1000$ GeV	$R_g = 95\%$	$R_g = 82\%$