Discovery potential of a light H+ at the LHC in the single top mode

cH±arged 2012

October 10

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with R. Guedes and S. Moretti

arXiv:1207.4071 – to appear in JHEP

Motivation

- Should we look for a charged Higgs in single top production?

$$\boxed{\sigma(pp \to t(+\bar{t}) + X \approx \frac{1}{3}\sigma(pp \to t\bar{t} + X)}$$

- Discover particles or exclude models

picture stolen from Y. Yamamoto

Multi-Higgs?

and Outline

- The models (2HDM no CP, with CP, with extensions?)
- Current bounds
- The analysis
- Conclusions

The softly broken Z_2 symmetric 2HDM potential

$$\boxed{\begin{aligned} V(\Phi_1,\Phi_2) &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}] \end{aligned}}$$

$$\boxed{\phi_1 \to \phi_1 \quad \phi_2 \to -\phi_2}$$

- m^2_{12} and λ_5 real, vacuum configuration (CP-conserving)

$$\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}}$$

7 free parameters + M_W: $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta,\ \sin\alpha$ $M^2 = \dfrac{m_{12}^2}{\sin\beta\cos\beta}$

- m^2_{12} and λ_5 complex, vacuum configuration (explicit CP-violating)

$$\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}} \qquad \boxed{\mathrm{Im}[m_{12}^2] = v_1 v_2\,\mathrm{Im}[\lambda_5]}$$

8 free parameters + M_W: $m_{H^\pm},\ \tan\beta,$ others...

I. Ginzburg, M. Krawczyk and P. Osland, hep-ph/0211371.

Common features

➡ $\boxed{\tan\beta = \frac{v_2}{v_1}}$ ratio of vacuum expectation values

Extending the Z_2 symmetry to the fermions – 4 independent Yukawa Lagrangians

	I	II	III	IV
up	Φ_2	Φ_2	Φ_2	Φ_2
down	Φ_2	Φ_1	Φ_1	Φ_2
lepton	Φ_2	Φ_1	Φ_2	Φ_1

III = I' = Y = Flipped

IV = II' = X = Leptonic

➡ same charged Higgs-fermions couplings

$\boxed{\tan\beta}$

- Production process is the same.
- Fermionic decay widths are the same.

Extensions that include 2HDM as a sub-model – example: Model X, in M. Aoki, S. Kanemura and O. Seto PRL102 (2009) 051805

2HDM Lagrangian (CP conserving to CP-violating potential)

- couplings that involve gauge bosons

$$\boxed{\sin(\beta-\alpha)} \rightarrow \boxed{C = c_\beta R_{11} + s_\beta R_{12}}$$

- couplings that involve fermions

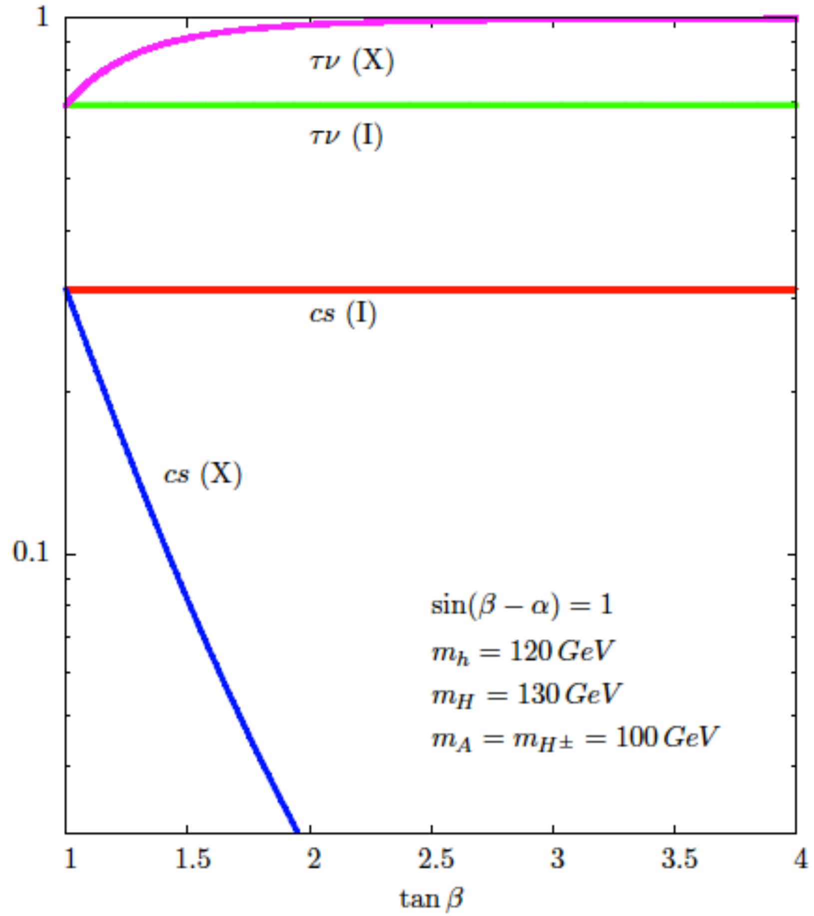
$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

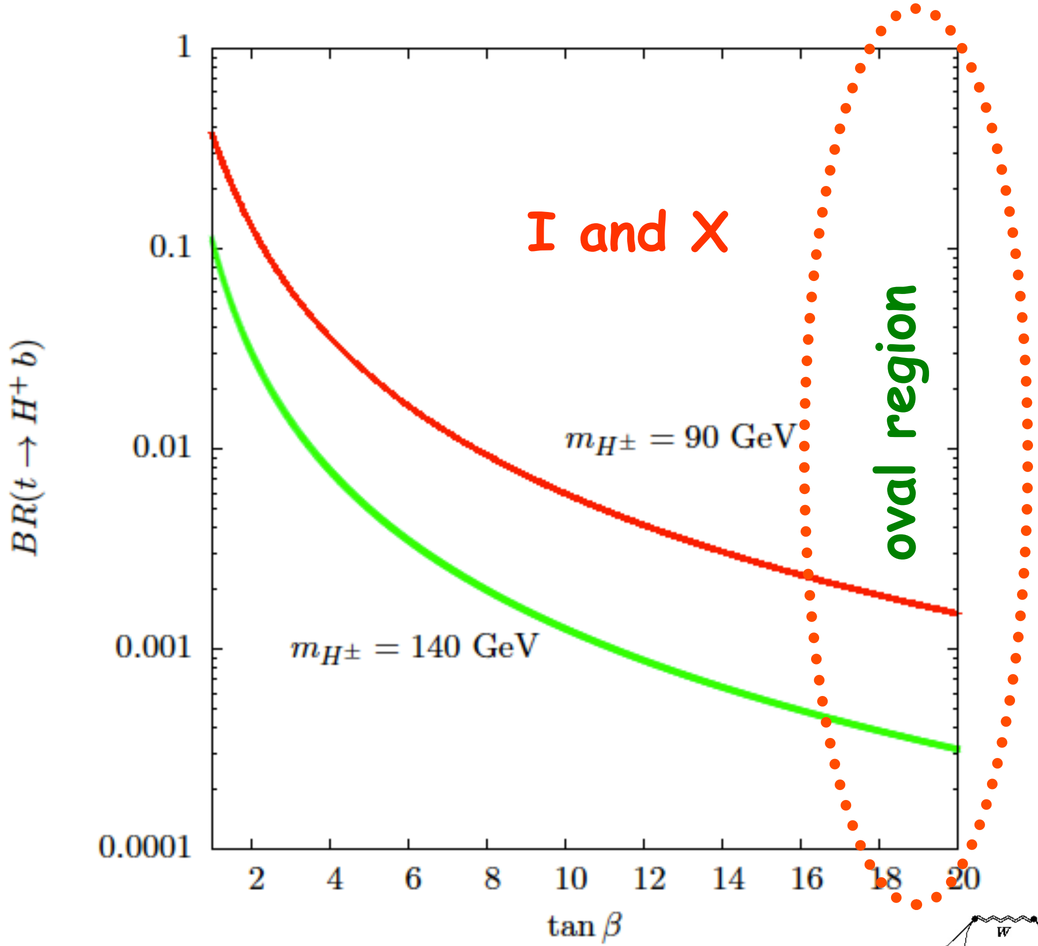
$$\boxed{\sin\alpha \quad \tan\beta}$$

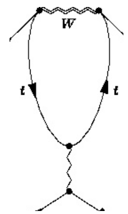
	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$

Model	$g_{\bar{u}dH^+}$	$g_{l\bar{\nu}H^+}$
I	$\frac{ig}{\sqrt{2}M_W} V_{ud}\,[-m_d/\tan\beta P_R + m_u/\tan\beta P_L]$	$\frac{ig}{\sqrt{2}M_W}\,[-m_l/\tan\beta P_R]$
II	$\frac{ig}{\sqrt{2}M_W} V_{ud}\,[m_d \tan\beta P_R + m_u/\tan\beta P_L]$	$\frac{ig}{\sqrt{2}M_W}\,[m_l \tan\beta P_R]$
Y	$\frac{ig}{\sqrt{2}M_W} V_{ud}\,[m_d \tan\beta P_R + m_u/\tan\beta P_L]$	$\frac{ig}{\sqrt{2}M_W}\,[-m_l/\tan\beta P_R]$
X	$\frac{ig}{\sqrt{2}M_W} V_{ud}\,[-m_d/\tan\beta P_R + m_u/\tan\beta P_L]$	$\frac{ig}{\sqrt{2}M_W}\,[m_l \tan\beta P_R]$

top and charged Higgs Branching Ratios in models I and X







top decays to charged Higgs (+b); charged Higgs decays to tau (+ nu). Could be more complicated, $H^+ \to W^+ h$. Or worse, if other light particles are involved.

Constraints - How light is light?

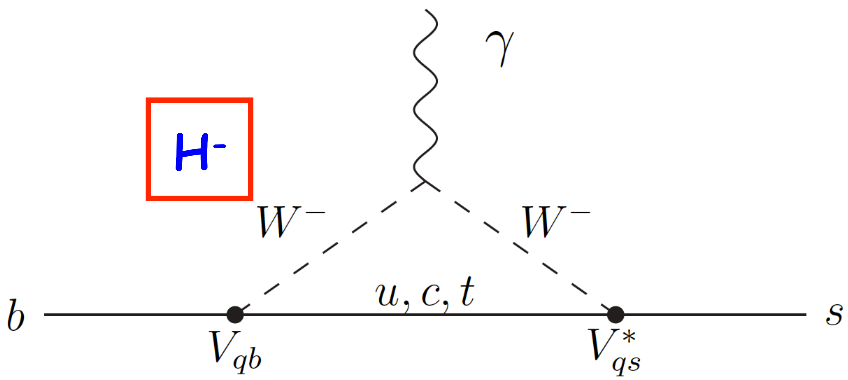
- **DIRECT BOUNDS** LEP bound for a charged Higgs $\boxed{e^+e^- \to H^+H^-}$

$$BR(H^+ \to \tau^+\nu) + BR(H^+ \to c\bar{s}) = 1 \qquad \boxed{m_{H^\pm} > 79.3\,GeV}$$

$$BR(H^+ \to \tau^+\nu) \approx 1 \quad \boxed{m_{H^\pm} > 89.6\,GeV}$$

(Model X)

- **INDIRECT BOUNDS** B factories



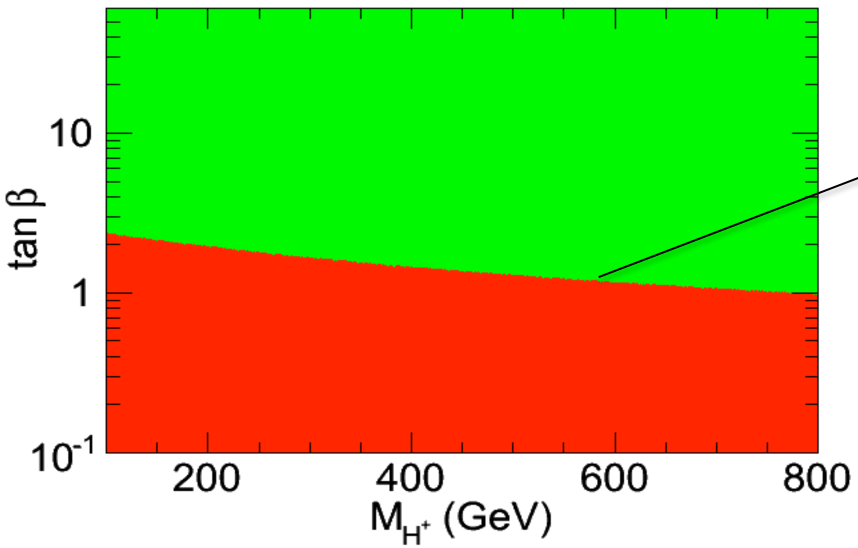
$$B \to X_s\gamma$$

340! Nazila talk this morning.

Models II and Y $\boxed{m_{H^\pm} \gtrsim 300\ GeV}$

Best available bound on the charged Higgs mass

How <u>small</u> can tanβ be?



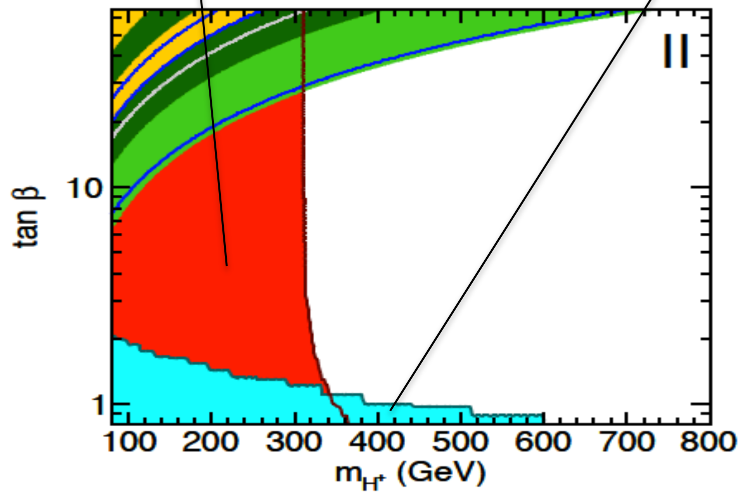
<u>Best bound for type I and X</u>

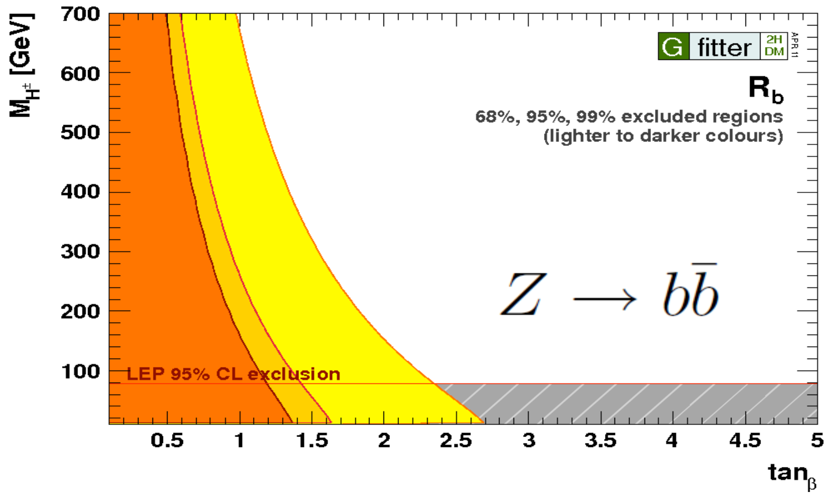
$$\boxed{B \to X_s \gamma}$$

F. Mahmoudi and O. Stal, PRD81 (2010) 035016.

<u>type II</u>

$$\boxed{B_q \bar{B}_q}$$

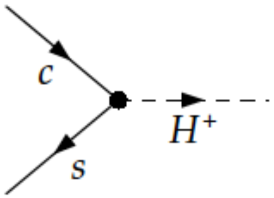


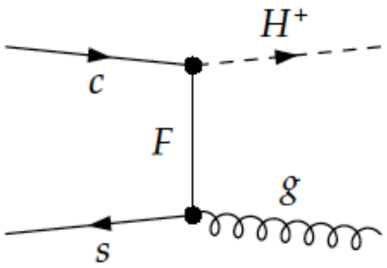


$$\boxed{\tan\beta > 1}$$

All other bounds: precision electroweak, unitarity, stability…, do not play a role here.

Can we probe "oval" region? (Models I and X)





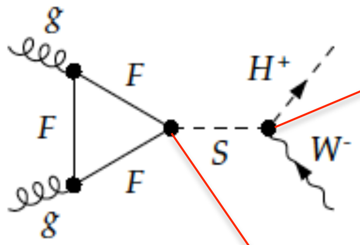
Smaller

CMS study (200 GeV) - For a mass of 100 GeV

tanβ=1 σ=800 fb

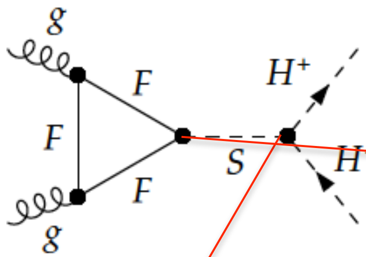
tanβ=4 σ=50 fb

$$\boxed{gg, b\bar{b} \to W^- H^+ \text{ and } W^+ H^-}$$



$$\cos(\beta - \alpha)$$

$$\boxed{\begin{aligned} gg, b\bar{b} &\to H^+ H^-, \\ q\bar{q} &\to H^+ H^-, \\ qQ &\to q' Q' H^+ H^-, \end{aligned}}$$

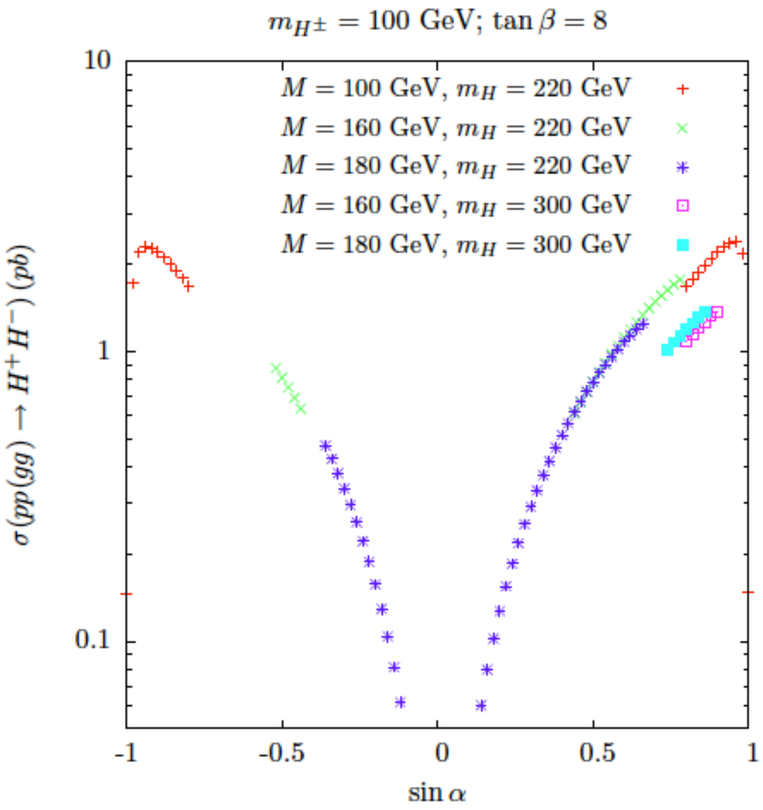


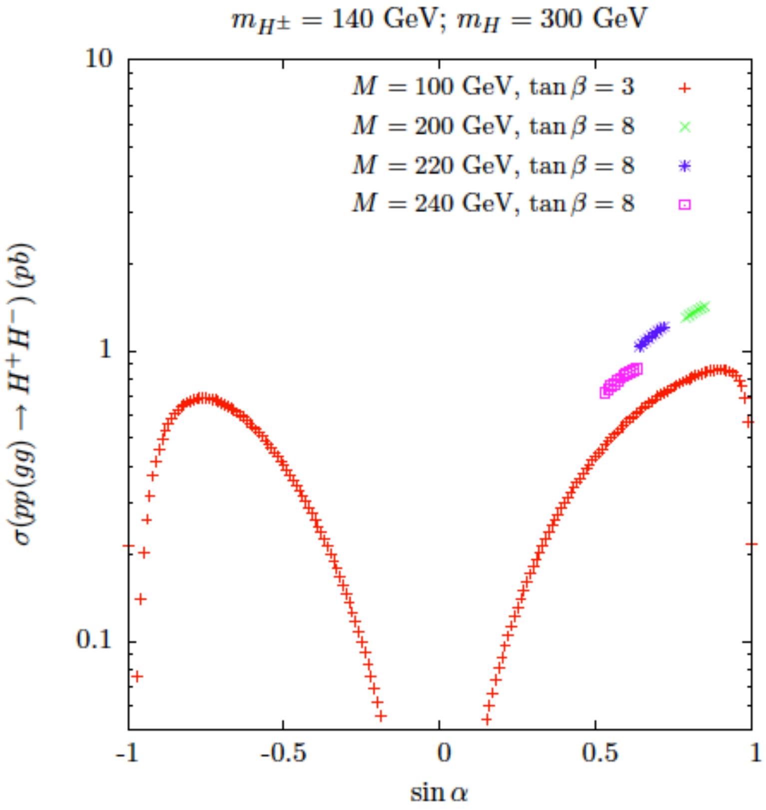
$$\frac{\sin\alpha}{\sin\beta}$$

$$\lambda^{2HDM}_{H^\pm H^\pm H} = -\frac{2}{v\, s_{2\beta}} \left[\left(s_\alpha c_\beta^3 + c_\alpha s_\beta^3\right) m_H^2 - s_{\beta+\alpha} M^2 + s_{2\beta} c_{\beta-\alpha} m_{H^\pm}^2 \right]$$

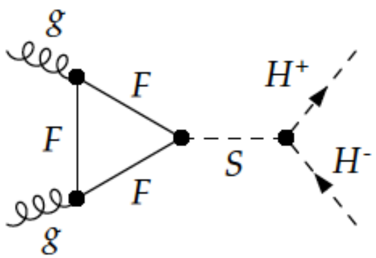
<u>Only Higgs pair production can increase with tanβ.</u>

For resonant production





Lines start and end abruptly due to the theoretical constraints – these do not change with time!



$$\boxed{\sin\alpha\ \cos\alpha\ \tan\beta(m_H^2 - M^2)}$$

So far

A class of models (2HDM and 2HDM-like) can be studied with single top production.

Constraints imply (at least) charged Higgs above 80 GeV (LEP), and tanβ above 1 (B-physics and R_b - charged Higgs mass below top mass).

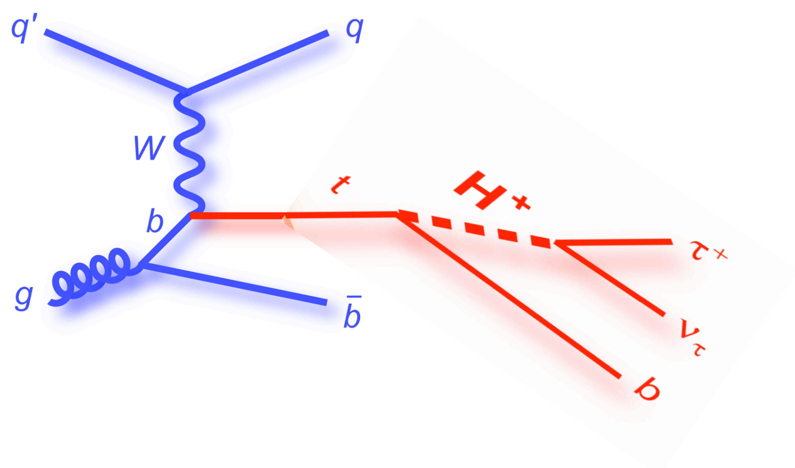
Yukawa couplings fall with $\tan^2\beta$ (type I,X). Other processes (double charged Higgs production) do not have that limitation but a) cross sections are smaller b) strong dependence on the remaining model parameters (resonant production).

After ttbar, searches based on single top are then the best way to maximize the exclusion in the (mass, tanβ) plane.

Could be important in "the MSSM" if $|\Delta b|$ is large! Oscar talk this morning.

Single top@14TeV (7 and 8 TeV bad)

Signal - single top (after cuts signal is t-channel contribution)



Charged Higgs decays to tau nu
and
only leptonic final states are considered.

Background (irreducible) - single top

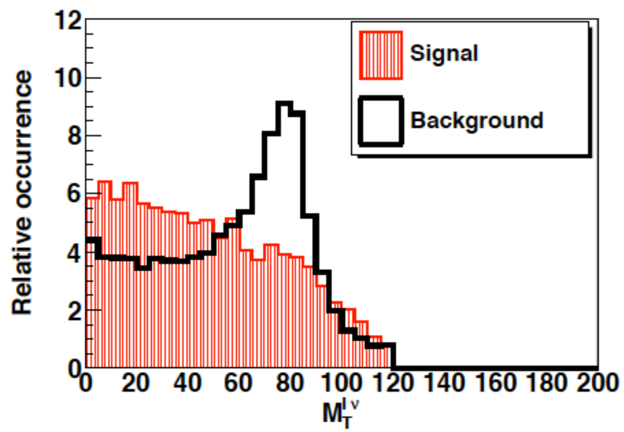
Background (reducible) – ttbar, W+nj, Wc+nj, Wbb+nj (n<4)

"leptonic transverse mass"

$$M_T^{l\nu} = \sqrt{2p_{Tl}\not{p}_T - 2(p_{xl}\not{p}_x + p_{yl}\not{p}_y)};$$

$30\,\mathrm{GeV} < M_T^{l\nu} < 60\,\mathrm{GeV}$ **Masses: 90 to 130 GeV**

$30\,\mathrm{GeV} < M_T^{l\nu} < 60\,\mathrm{GeV}$ or $M_T^{l\nu} > 85\,\mathrm{GeV}$ **above 130 GeV**



Background

POWHEG
(AcerMC)

PYTHIA
(top decays)

AlpGen
(MCFM)

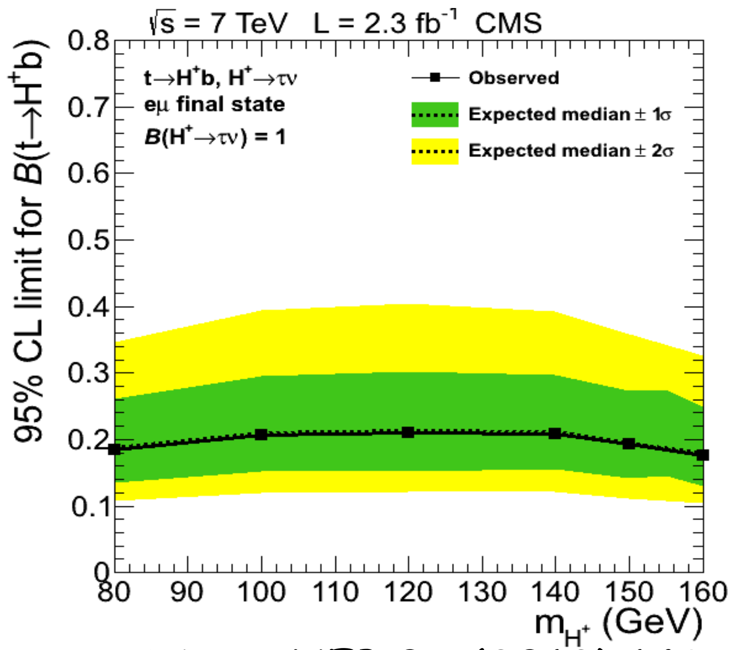
PYTHIA
(hadronisation)
+
DELPHES
(detector effects)

Process	Events (1 fb^{-1}) before cuts	Events (1 fb^{-1}) after cuts	Efficiency (%)
Single top (t-channel)	246600	18.5	0.0075
Single top (s-channel)	10650	0	0
Single top (tW)	66000	0.7	0.0010
$t\bar{t}$ (semileptonic)	371133	0	0
$t\bar{t}$ (leptonic)	88940	1.8	0.0020
$t\bar{t}$ (hadronic)	387169	0	0
W+0j	4.3×10^7	0	0
W+1j	8.8×10^6	0.6	7.1×10^{-6}
W+2j	2.8×10^6	3.9	0.00014
W+3j	1.2×10^6	0	0
Wc+0j	7.4×10^5	0	0
Wc+1j	3.2×10^5	3.2	0.0010
Wc+2j	2.0×10^5	1.0	0.0011
Wc+3j	8.9×10^4	0	0
Wbb+0j	6638	0	0
Wbb+1j	6582	0.5	0.007
Wbb+2j	3746	0	0
Wbb+3j	2896	0	0

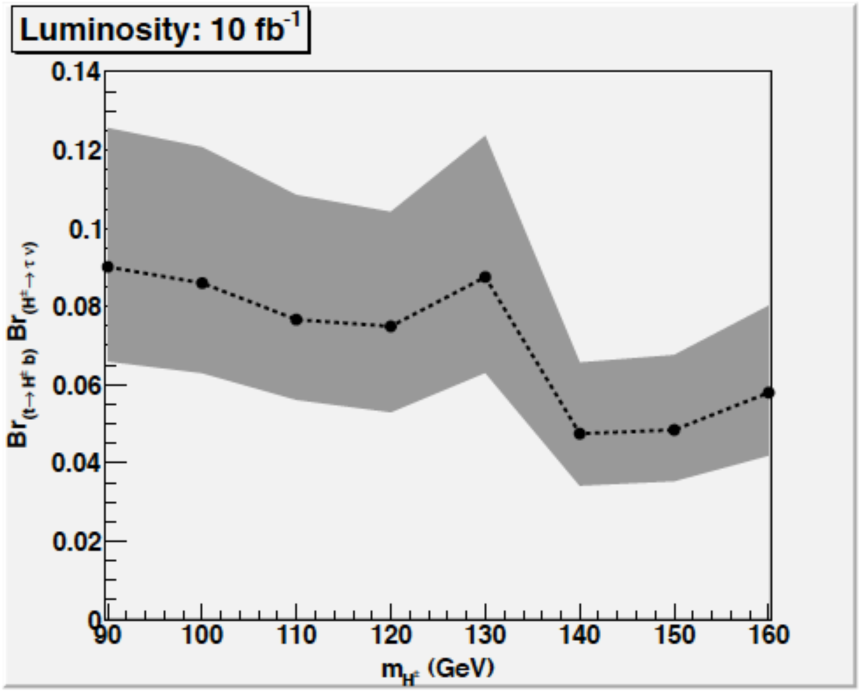
charged Higgs mass 120 GeV

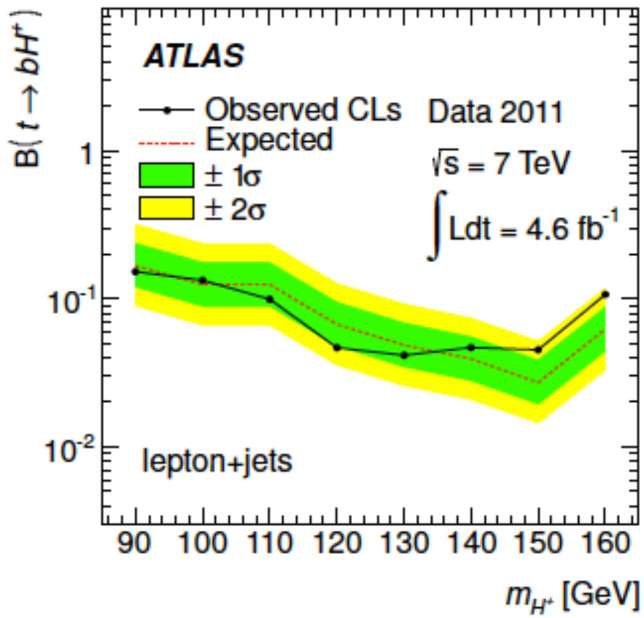
"Model-independent" results

$m_H^{\pm}$ (GeV)	Signal (S)	Background (B)	S/B (%)	$S/\sqrt{B}$
90	38.6	29.5	130.92	7.11
100	40.5	29.5	137.19	7.45
110	45.6	29.8	153.00	8.35
120	47.7	30.1	158.26	8.69
130	42.3	32.68	129.53	7.41
140	117.1	77.9	150.25	13.26
150	120.0	86.6	138.64	12.90
160	109.7	100.8	108.81	10.92



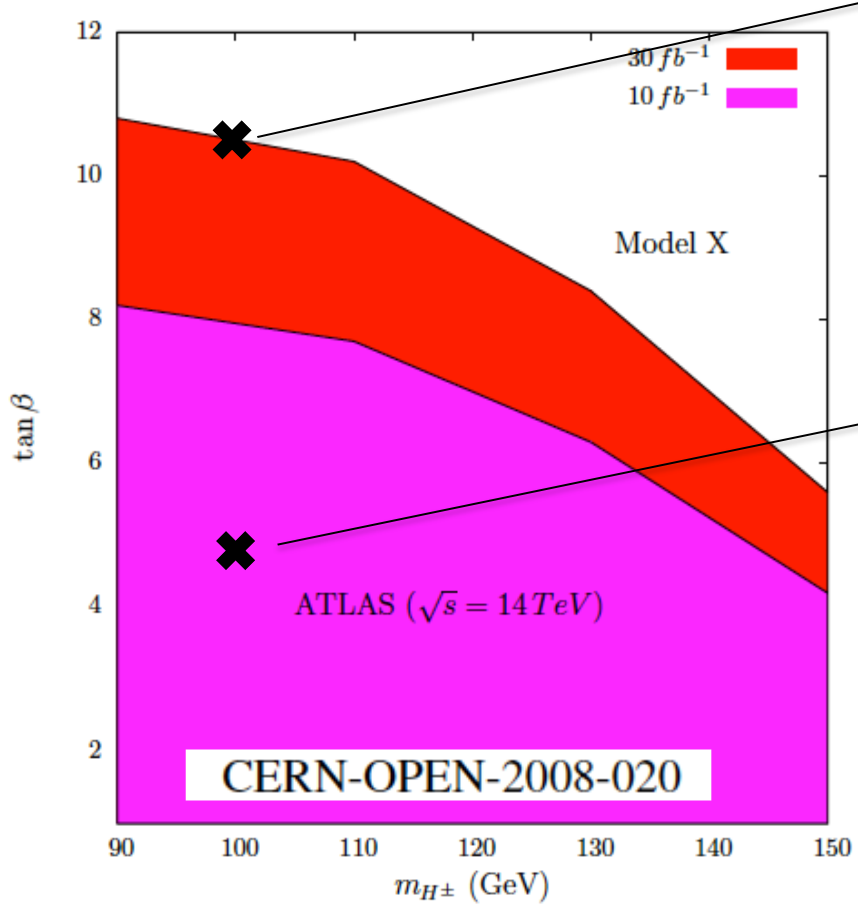
CMS, JHEP 07 (2012) 143





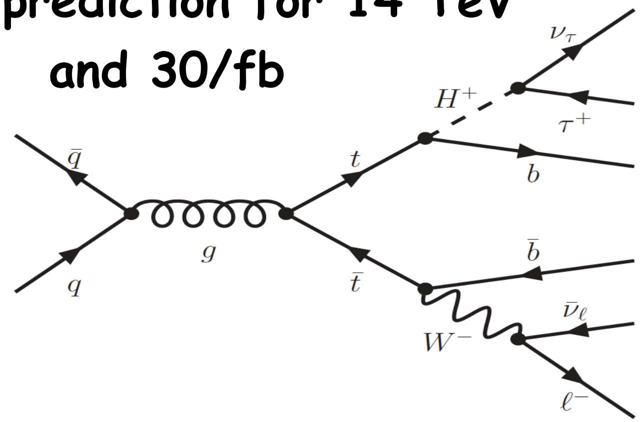
ATLAS, JHEP 06 (2012) 039

Type X 2HDM-like models

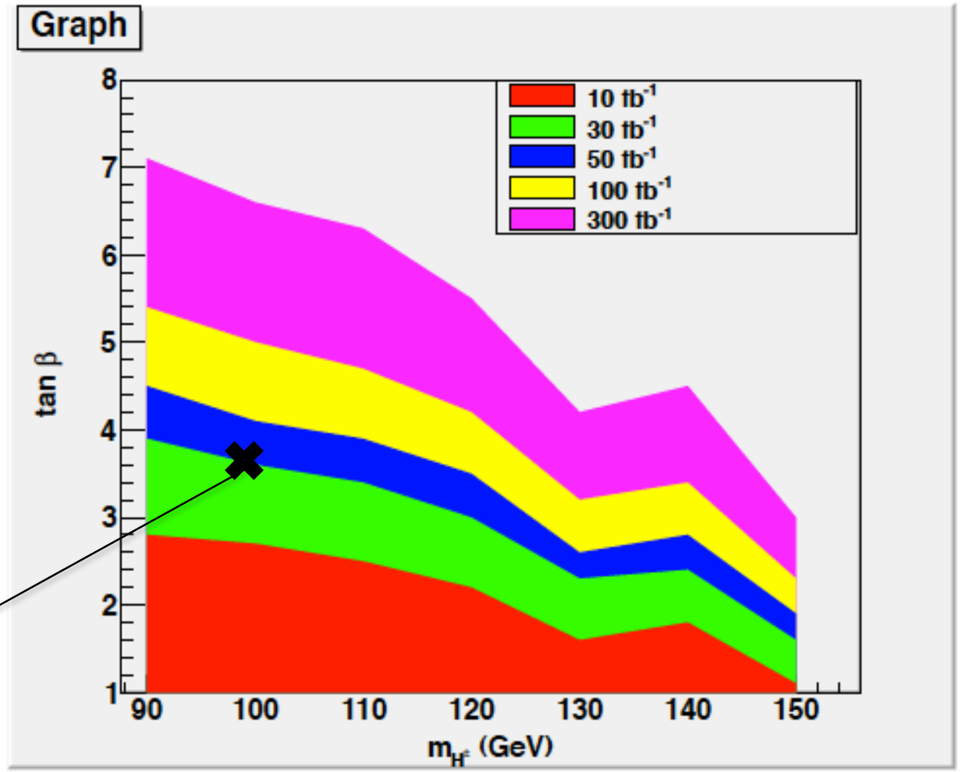


Aoki, Guedes, Kanemura, Moretti, Santos, Yagyu, PRD84 (2011) 055028.

ATLAS prediction for 14 TeV and 30/fb

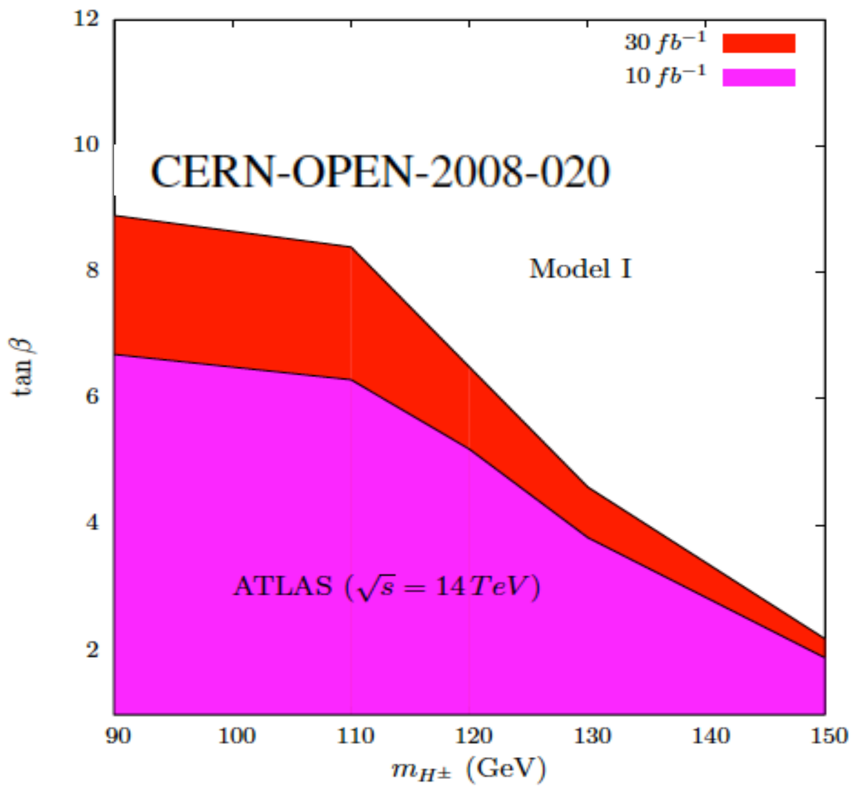


Our parton-level analysis for 30/fb

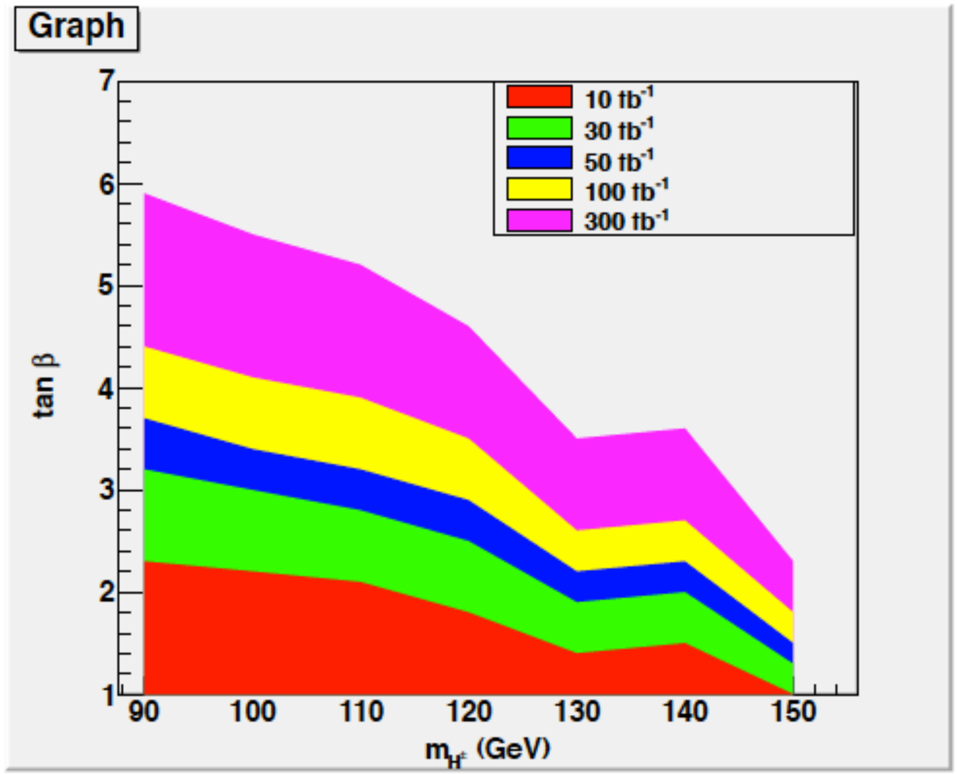


Final analysis for 30/fb

Type I 2HDM-like models



Similar trend for type I models. Branching ratios are slightly smaller than the type X ones.

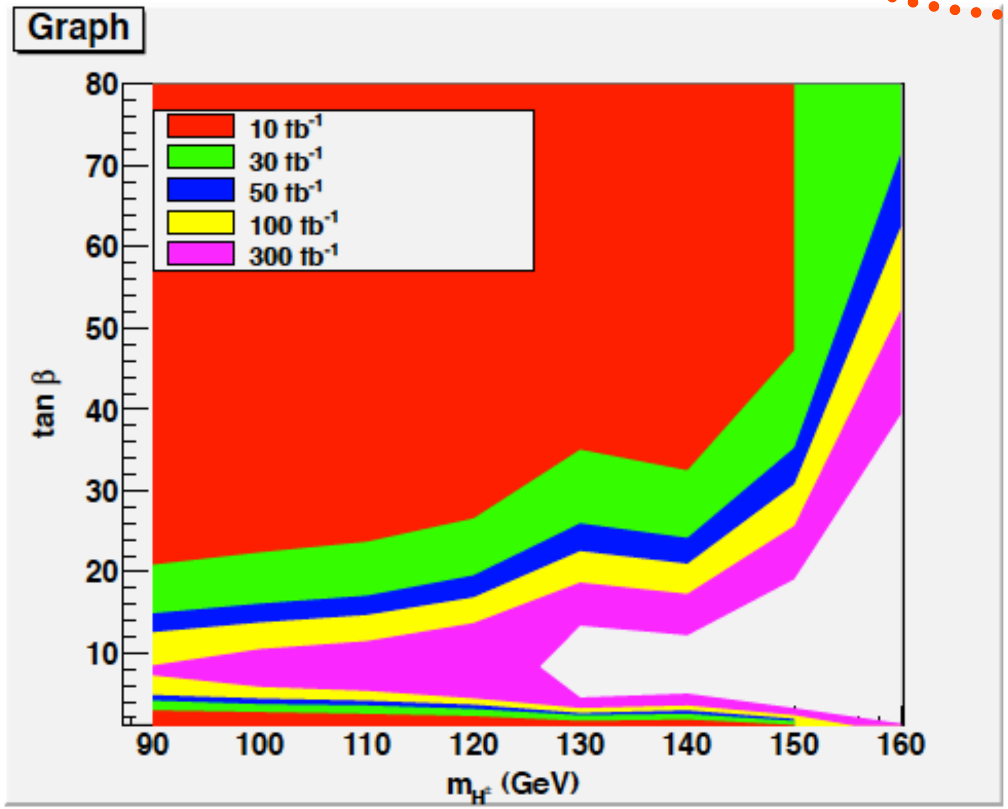


<u>Theoretical bounds</u> to the rescue (in the exact Z_2 model, m_{12}=0). Taking the lightest neutral Higgs 125 GeV

$$\boxed{0.18 \lesssim \tan\beta \lesssim 5.59}$$

B. Gorczyca, M. Krawczyk, arXiv: 1112.5086

Type II 2HDM-like models



Find a way to evade the B-physics constraints.

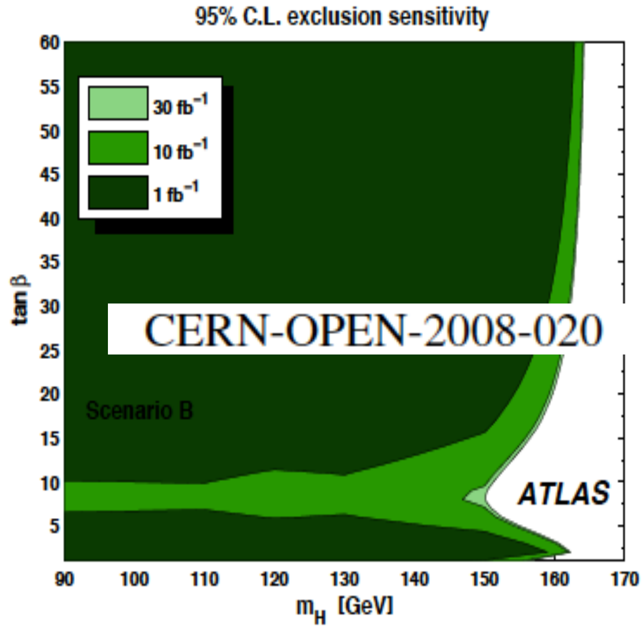
Next step would be to consider all channels for the tau decays.

Insert result

Insert number

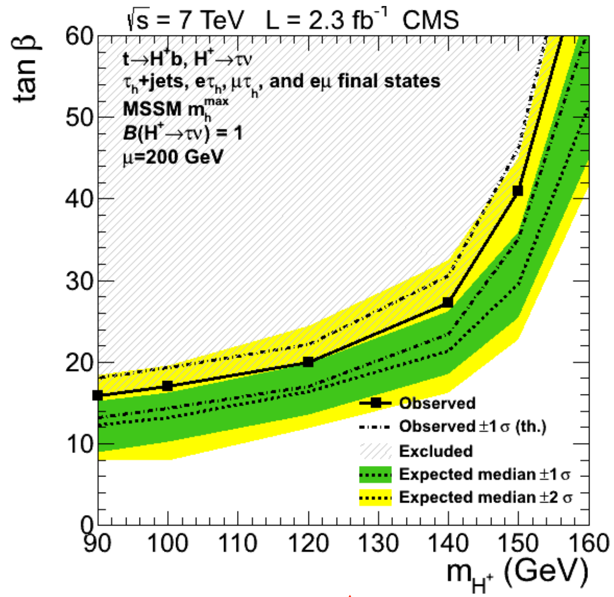
"……….. is better than we expected …… years ago!" – the unknown experimental physicist at the LHC.

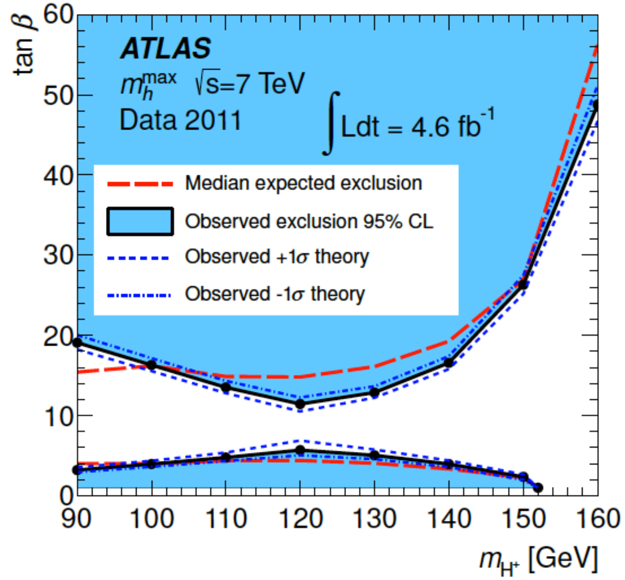
Then (14 TeV prediction) and now (7 TeV result)



BEFORE

CMS, JHEP 07 (2012) 143





"AFTER"

ATLAS, JHEP 06 (2012) 039

Conclusions

Single top channel looks good.

The factor of ~3 in production is turned into a factor between 2 and 3 after the analysis.

ATLAS and CMS can improve the factor.

Light charged Higgs in Type-II-like models will be excluded (charged Higgs discovered) by the end of the 14 TeV run.

In Type-I (X) models, $\tan\beta$ will be probed in the range 1 to 15 (my guess), depending on the charged Higgs mass, by the end of the 13/14 TeV run.

the end

a) 1 electron P_T > 30 GeV and |η|< 2.5 or 1 muon P_T > 20 GeV and |η|< 2.5

b) Veto events with two or more leptons with P_T > 10 GeV

c) Exclude events with leptons with P_T > 55 GeV

d) Veto events with missing E_T below 50 GeV

e) Exactly one b-tagged jet with 20 GeV < P_T < 75 GeV

f) top quark invariant mass above 280 GeV

$$a = \left(\frac{p_{zl}}{p_l}\right)^2 - 1,$$

$$b = 2\left(\frac{p_{xl}\not{p}_x + p_{yl}\not{p}_y}{p_l} + \frac{m_{H^+}^2}{2p_l}\right)\frac{p_{zl}}{p_l},$$

$$c = \left(\frac{p_{xl}\not{p}_x + p_{yl}\not{p}_y}{p_l} + \frac{m_{H^+}^2}{2p_l}\right)^2 - \not{p}_T^2.$$

$$\not{p}_z = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

g) "leptonic transverse mass"

$$M_T^{l\nu} = \sqrt{2p_{Tl}\not{p}_T - 2(p_{xl}\not{p}_x + p_{yl}\not{p}_y)}.$$

$30\,\mathrm{GeV} < M_T^{l\nu} < 60\,\mathrm{GeV}$ **charged Higgs masses 90 to 130 GeV**

$30\,\mathrm{GeV} < M_T^{l\nu} < 60\,\mathrm{GeV}$ or $M_T^{l\nu} > 85\,\mathrm{GeV}$ **above 130 GeV**

h) One and only one non-b jet, P_T above 30 GeV

i) Accept events where jets have |η| > 2.5

Parametrisation (8)

W. Khater and P. Osland, Nucl. Phys. B 661, 209 (2003).

- 2 charged, $H^{\pm}$, and 3 neutral, h_1, h_2 and h_3 **3 masses**

- $$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \qquad R\,\mathcal{M}^2\,R^T = \mathrm{diag}\left(m_1^2, m_2^2, m_3^2\right)$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$ **3 angles**

- $\mathrm{Re}\left[m_{12}^2\right]$ **soft breaking term**

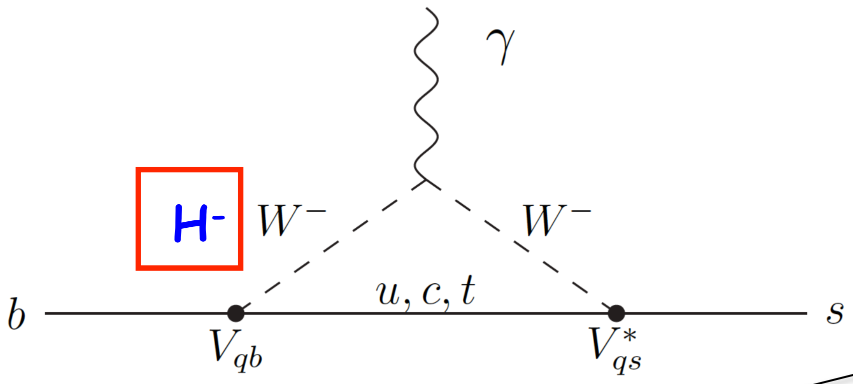
- $\tan\beta$ **ratio of vacuum expectation values**

- $$m_3^2 = \frac{m_1^2\,R_{13}(R_{12}\tan\beta - R_{11}) + m_2^2\,R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

Experimental

- <u>INDIRECT BOUNDS</u> B factories

$$B \to X_s \gamma$$



Models II and Y $X_i Y_i = 1$

Models I and X $X_i Y_i = 1/\tan^2\beta$

$$\mathcal{L}_Y^{\pm} = (2\sqrt{2}G_F)^{1/2} \sum_{i=2}^{n} (X_i \overline{U}_L V M_D D_R + Y_i \overline{U}_R M_U V D_L + Z_i \overline{N}_L M_E E_R) H_i^+ + \text{h.c.}$$

$$\text{BR}(b \to s\gamma) = C|\eta_2 + G_W(x_t) + (|Y|^2/3)G_W(y_t) + (XY^*)G_H(y_t)|^2,$$

Models II and Y $\boxed{m_{H^\pm} \gtrsim 300\ GeV}$ Best available bound on the charged Higgs mass

Models I and X $\boxed{\tan\beta > 1}$ $m_{H^\pm} = 100\, GeV$

Combined "model independent" results