Charged Higgs bosons in single top production at the LHC

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Motivation

- The highest priority of the LHC is to confirm or disprove the Higgs mechanism. In the SM the mechanism is implemented with one complex Higgs doublet from which a single neutral Higgs boson emerges after symmetry breaking.
- Recent LHC evidence of neutral Higgs signals compatible with the SM hypothesis, calls for not dismissing the Higgs mechanism as the means for achieving Electro-Weak Symmetry Breaking.
- One of the simplest extensions of the SM is built by adding an extra doublet to the SM field. In this model, instead of one neutral Higgs, we will have several scalars, two of them charged. One can test those models by looking for charged Higgs boson.
- They are predominantly produced in top quark decay as long as $m_{H^\pm} < m_t$. The main source of top quarks is the $pp \to t\bar{t}$.

Motivation

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

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

Outline

- The 2HDMs
- $H^{\pm}$ production channels at hadron colliders in 2HDMs
- top and charged Higgs Branching Ratios
- Constraints on the models
- Single top production
- Single top analysis
- Conclusions

The 2HDMs

The 2HDM potential invariant under $SU(2)_L \otimes U(1)_Y$ with two complex $SU(2)$ Higgs doublets and a softly broken Z_2 symmetry

$$
\begin{aligned}
V_{\rm 2HDM} \quad = \quad & m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) \\
& + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
& + \frac{\lambda_5}{2}\left\{(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right\},
\end{aligned}
$$

The parameters m_3^2, λ_5 and the VEV's will determine the CP nature of the model

$$\Phi_1 \rightarrow \Phi_1 \quad \Phi_2 \rightarrow -\Phi_2$$

m_3^2 and λ_5 real, vacuum configuration (CP-conserving)

$$< \Phi_1 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad < \Phi_2 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

7 free parameters + M_W: m_h, m_H, m_A, $m_{H^\pm}$, $\tan\beta = \frac{v_2}{v_1}$, $\sin(\beta - \alpha)$ and $M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$

The 2HDMs

m_3^2 and λ_5 complex, vacuum configuration (explicit CP-violation)

$$< \Phi_1 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad < \Phi_2 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \quad Im[m_3^2] = v_1 v_2 Im[\lambda_5]$$

8 free parameters + M_W

Extending the Z_2 symmetry to the Yukawa sector

To avoid FCNC at tree level, there are 4 independent ways to couple the Higgs field to the fermions

	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

$H^\pm$ production channels at hadron colliders in 2HDMs

Depend only on $\tan\beta$ and on the charged Higgs mass

$$gg, q\bar{q} \to b\bar{t}H^+ \text{ and } \bar{b}tH^-, \tag{1a}$$
$$bQ \to bQ'H^+ \text{ and } bQ'H^-, \tag{1b}$$
$$cs \to H^\pm(+jet), \tag{1c}$$

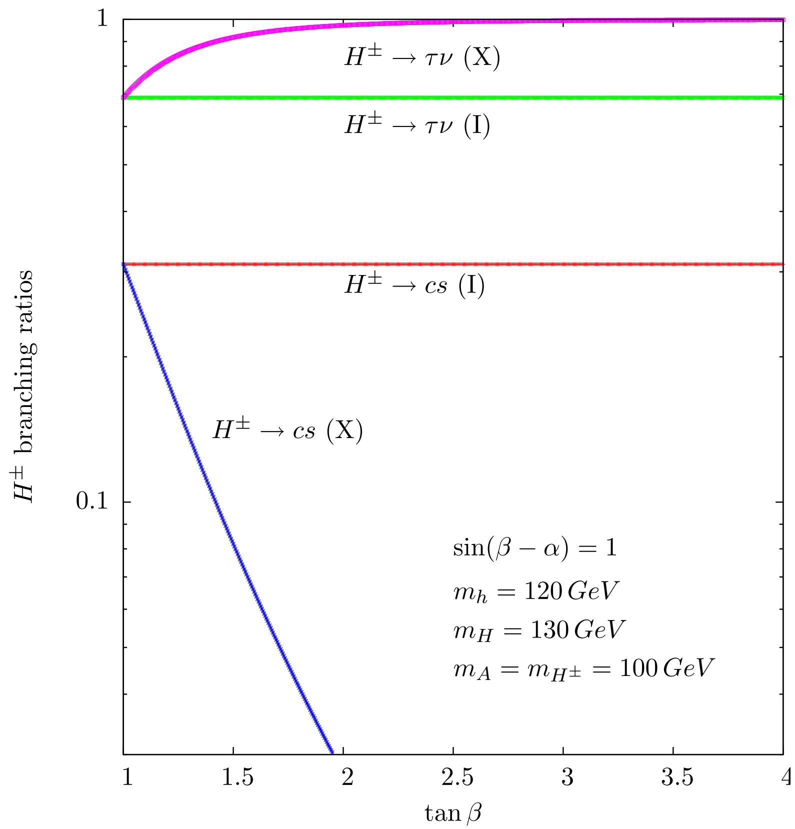
Depend only on $\tan\beta$, $\sin\alpha$ and on the charged Higgs mass

$$gg, b\bar{b} \to W^-H^+ \text{ and } W^+H^-, \tag{2a}$$
$$qQ \to SH^+ \text{ and } SH^-, \tag{2b}$$

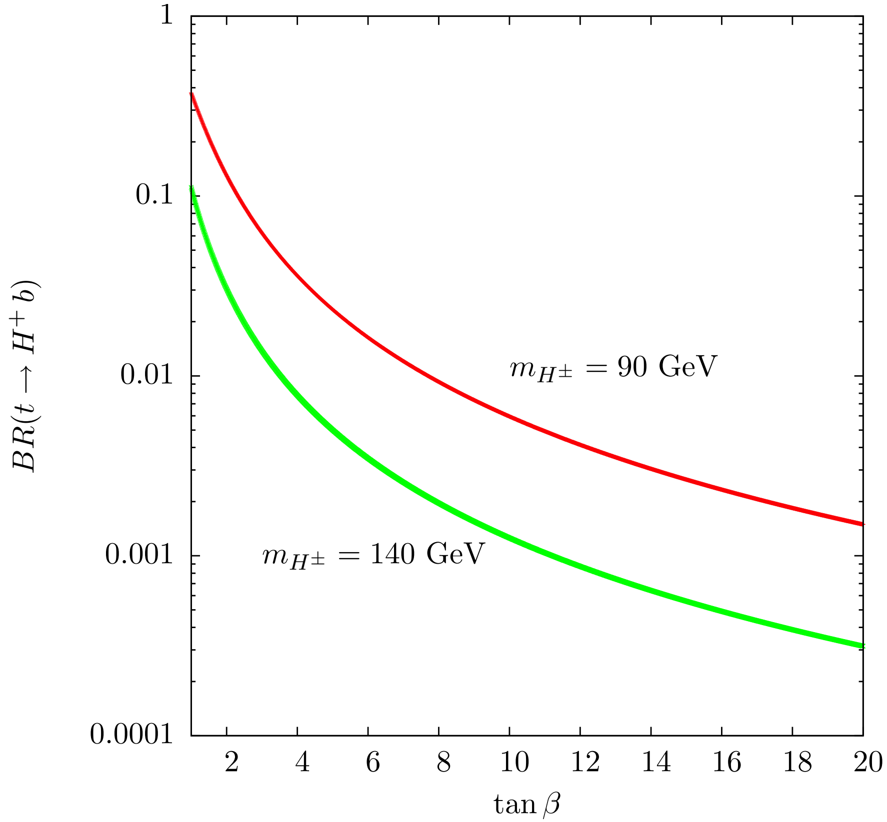
Depend on all parameters via the Higgs self-couplings

$$gg, b\bar{b} \to H^+H^-, \tag{3a}$$
$$q\bar{q} \to H^+H^-, \tag{3b}$$
$$qQ \to q'Q'H^+H^-, \tag{3c}$$

top and charged Higgs Branching Ratios



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



top decays to charged Higgs (+b)

Constraints

Experimental:

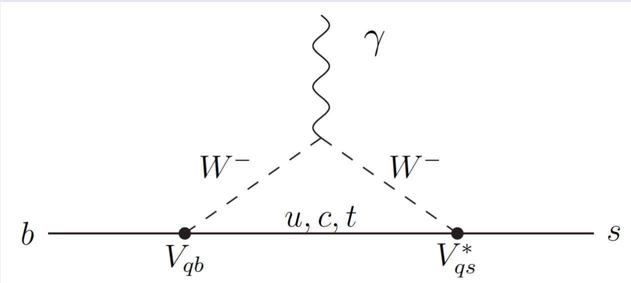
DIRECT BOUNDS LEP

bound for a charged Higgs ($e^+e^- \to H^+H^-$)

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

$BR(H^+ \to \tau\nu) \approx 1 \Rightarrow m_{H^\pm} > 89.6 GeV$ (Model X)

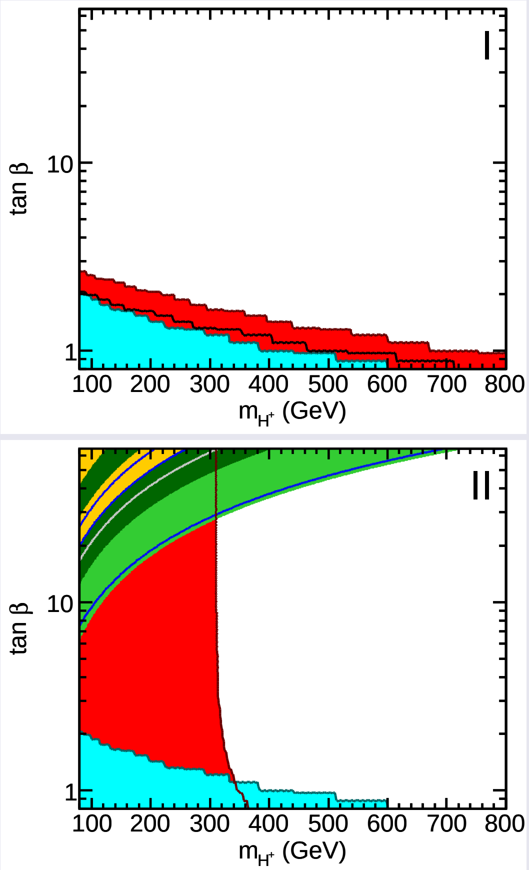
INDIRECT BOUNDS B factories ($B \to X_s\gamma$)



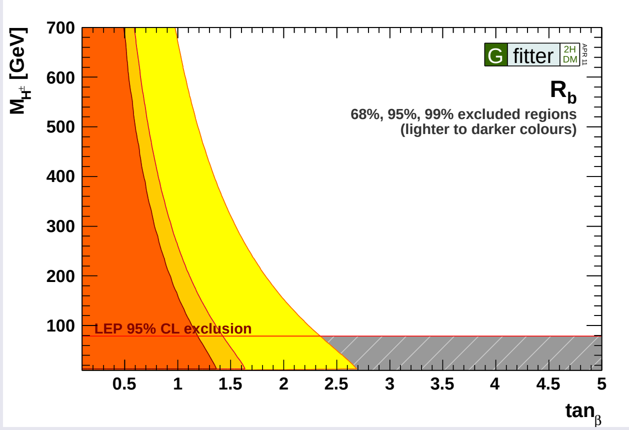
Models II and Y $\Rightarrow m_{H^\pm} > 340 GeV$

Constraints

How small can tan β be? (Best bound for type I and X)



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



The constraints on the model X are similar to the ones for model I.
The constraints on the model Y are similar to the ones the model II.

$\tan\beta > 1$

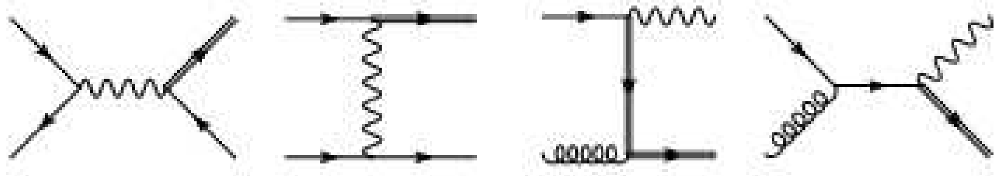
All other bounds: precision electroweak, unitarity, stability..., do not play a role here.

Single top production

- 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 tan β above 1 (B-physics and R_b).
- Yukawa couplings fall with tan β (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 $t\bar{t}$, searches based on single top are then the best way to maximize the exclusion in the (mass, tan β) plane.

Single top production

- $p\,p \to t(\bar{t})\,j \to H^{\pm}\,b\,j$
  $H^{\pm} \to \tau\nu_{\tau}$
- The contributions comes from three channel:
  s-channel, t-channel and Wt-channel.



- Those contribution could improve the region already scrutinized by $t\bar{t}$ production.
- In PRD 84, 055028 (2011) we have performed a parton-level analysis.
- We have shown that the results were promising and deserved a full detector analysis.

Single top analysis

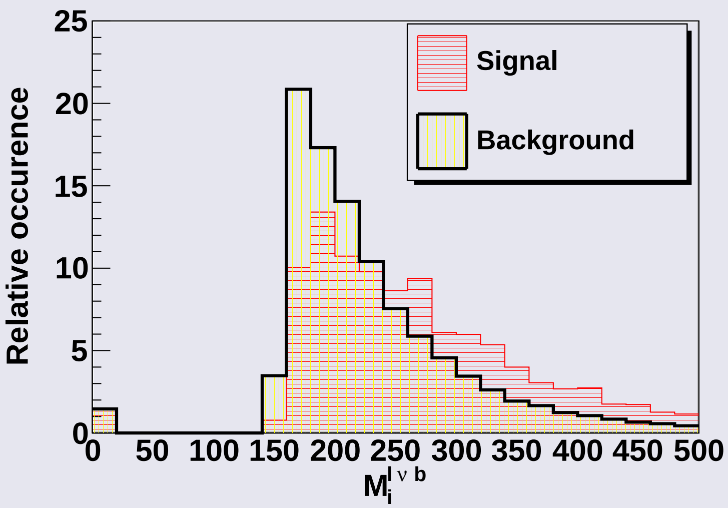
- Signal: The t-channel contribution is important. We have considered only the leptonic τ in the final state.
  $pp \to t(\bar{t})j \to H^{\pm}bj \to \tau\nu_{\tau}bj \to \ell\nu_{l}\nu_{\tau}bj$
  where $\ell = e, \mu$
- Irreducible background: t, s and Wt-channel according SM ($pp \to W^{\pm}bj$)
- Reducible background:
  - $t\bar{t}$
  - W+jets (light jets)
  - Wc+jets
  - Wbb+jets
  - Multijets
- We generated the signal, single top and $t\bar{t}$ processes with POWHEG cross-checked with AcerMC, W+jets with AlpGEN and multijets (jjj) with Calchep. The hadronization was made with Pythia and we used DELPHES for the detector simulation.

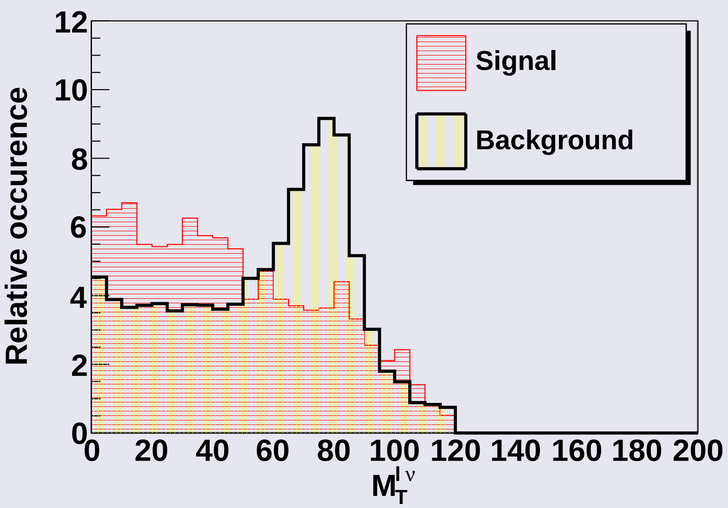
Single top analysis

Beside the trigger, we imposed 11 cuts on the signal and background:

- We demand one electron with transverse moment bigger then 30 GeV or a muon with transverse moment bigger then 20 GeV, at least. In both case, $|\eta| < 2.5$;
- A veto in event with more then one lepton with transverse moment bigger then 10 GeV;
- We demand the lepton transverse moment less then 50 GeV;
- The missing transverse energy should be bigger them 50 GeV;
- We demand just one b-tagged jet;
- We demand b-tagging jet with transverse moment smaller than 75 GeV;
- We demand "top quark mass" to be bigger than 280 GeV;
- The leptonic transverse invariant mass should be $30 < M_T^l < 60$ to charged Higgs mass between 90 and 130 GeV and $30 < M_T^l < 60$ or $M_T^l < 85$ to the rest;
- One jet with $P_T > 30\ GeV$ and $|\eta| \leq 4.9$;
- No jets with $P_T > 15\ GeV$ and $|\eta| \leq 4.9$;
- We demand the jet pseudorapidity to be $|\eta| \leq 2.5$;

“top quark mass” and leptonic transverse invariant mass





Single top analysis

Signal-to-background ratio (S/B) and significance ($S/\sqrt{B}$)

$H^{\pm}$ mass (GeV)	Signal efficiency (%)	Background (B)	S/B (%)	$S/\sqrt{B}$
90	0.016	29.5	130.9	7.11
100	0.016	29.5	137.2	7.45
110	0.018	29.8	153.0	8.35
120	0.019	30.1	158.3	8.69
130	0.017	32.7	129.5	7.41
140	0.048	77.9	150.2	13.26
150	0.049	86.6	138.6	12.90
160	0.044	100.8	108.8	10.92

Knowing the signal efficiency, the background and $\sigma_{(pp\to tj)}$, we can limit

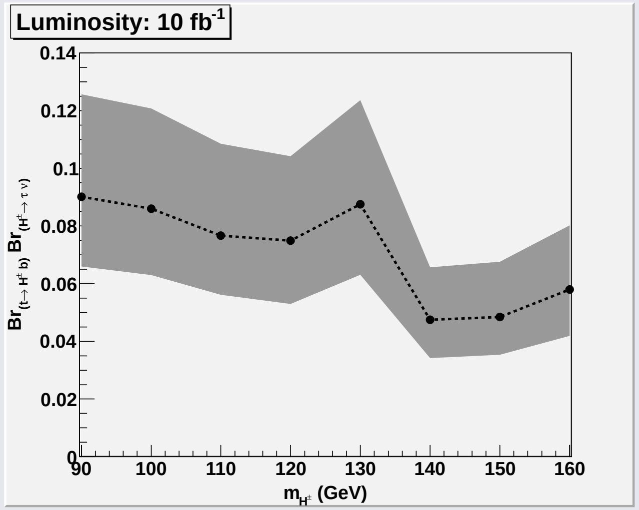
$$\sigma_{(pp\to tj)}\, Br_{(t\to H^+ b)}\, Br_{(H^+\to \ell\nu)},$$

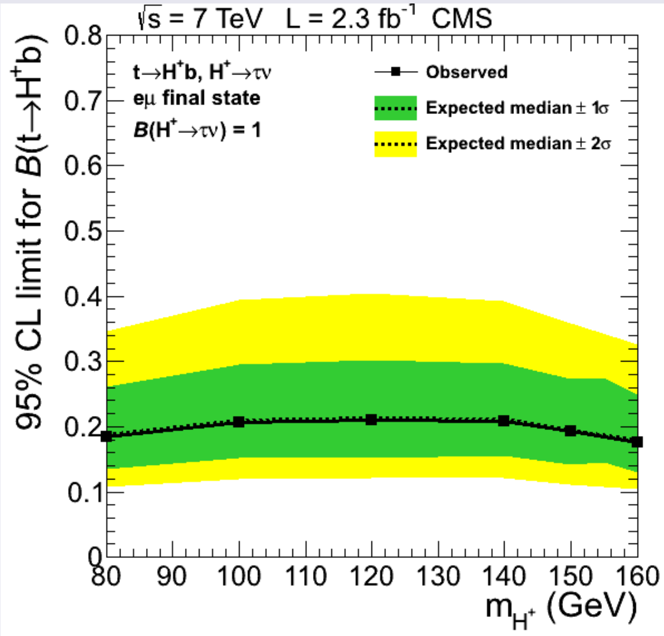
or just

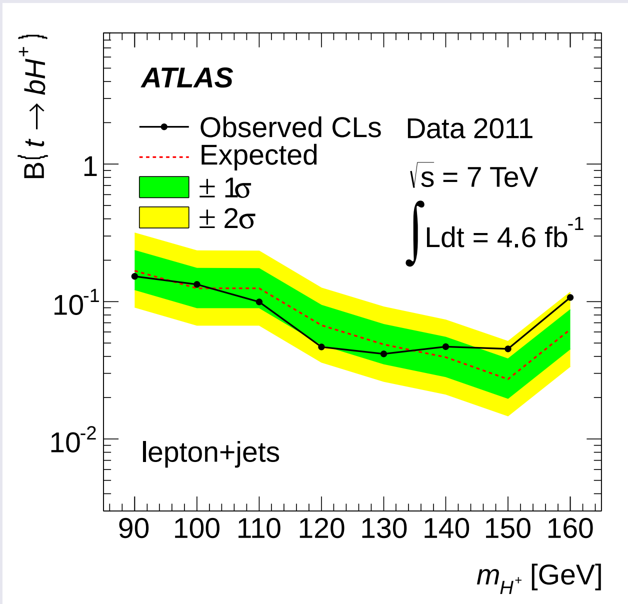
$$Br_{(t\to H^+ b)}\, Br_{(H^+\to \ell\nu)}.$$

Single top analysis

How can the background mimic the signal+background at 95% CL?





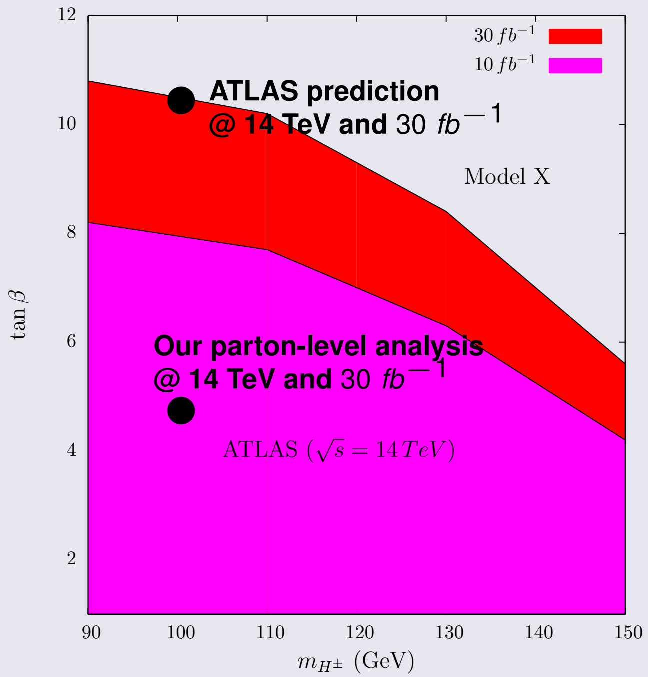


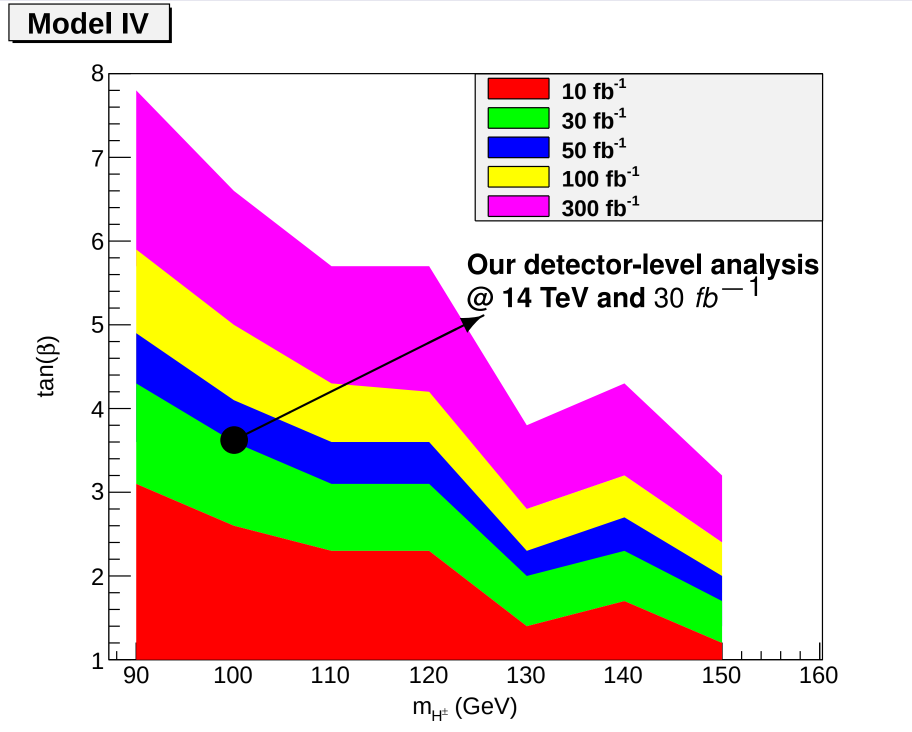
CMS, JHEP 07 (2012) 143

ATLAS, JHEP 06 (2012) 039

Single top analysis

What can we say about tan β exclusion? (Type X)

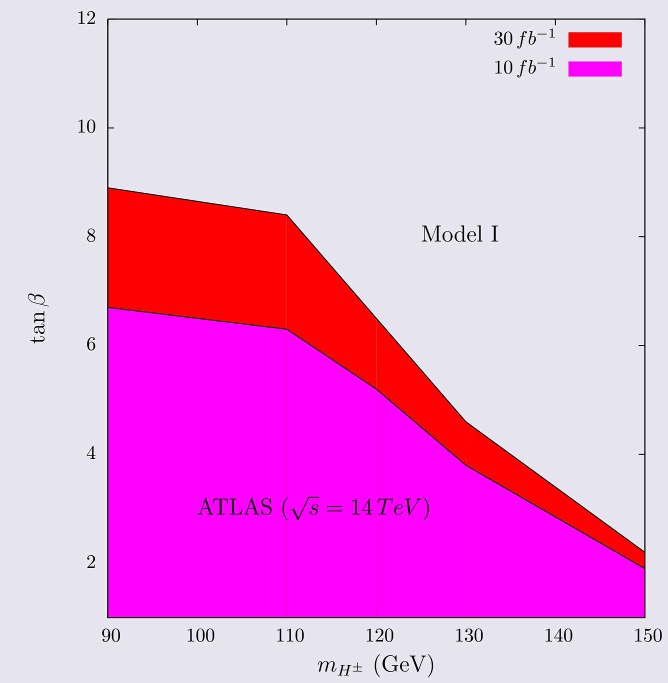


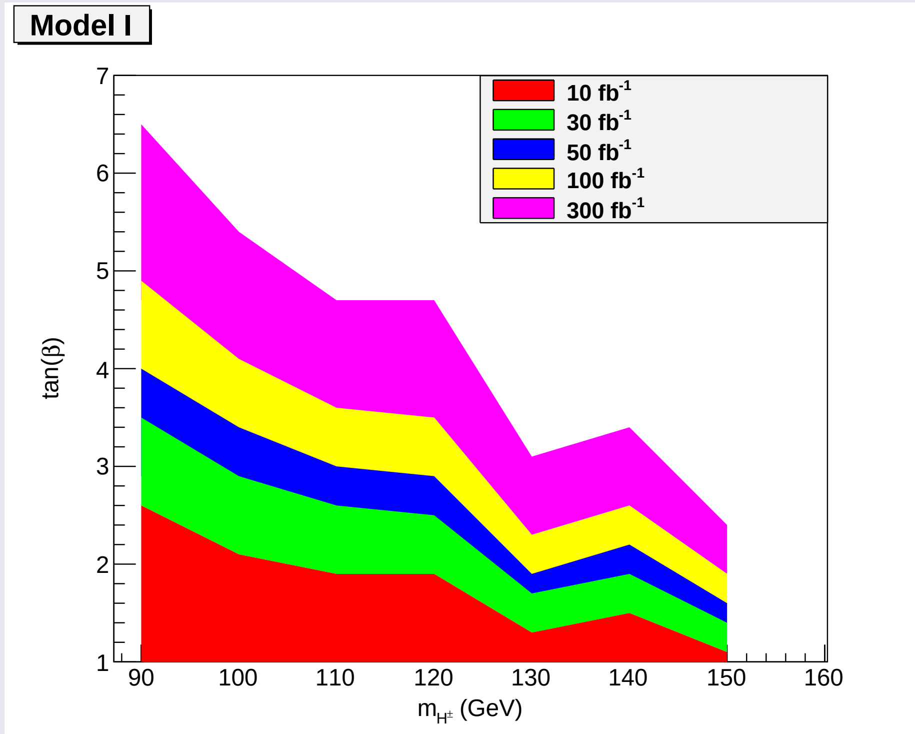


Aoki, Guedes, Kanemura, Moretti, Santos, Yagyu,

PRD84 (2011) 055028.

What can we say about tan β exclusion? (Type I)





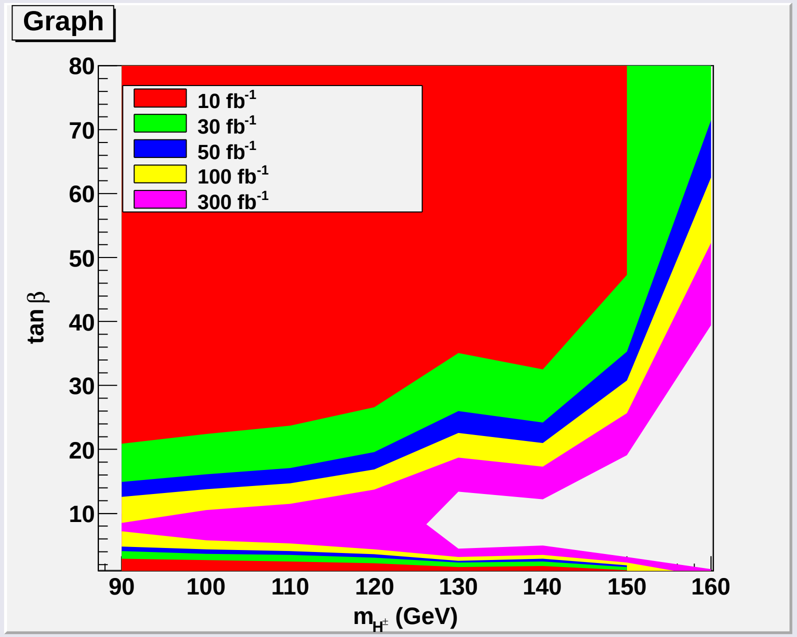
Aoki, Guedes, Kanemura, Moretti, Santos, Yagyu,

PRD84 (2011) 055028.

- Theoretical bounds to the rescue (in the exact Z_2 model, $m_3 = 0$). Taking the lightest neutral Higgs 125 GeV: $0.18 \lesssim \tan\beta \lesssim 5.59$
  B. Gorczyca, M. Krawczyk, arXiv: 1112.5086
- Similar trend for type I models. Branching ratios are slightly smaller than the type X ones.

Single top analysis

What can we say about tan β exclusion? (Type II 2HDM-like models)



Find a way to evade the B-physics constraints

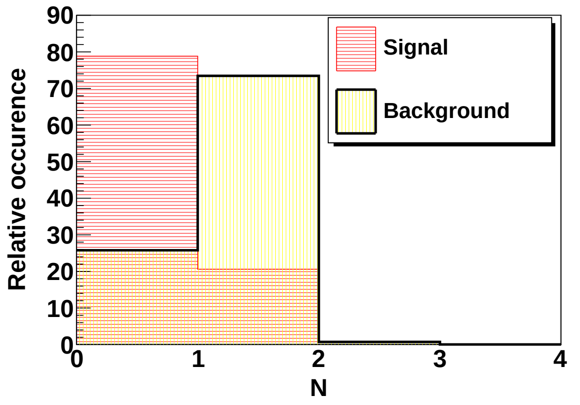
Conclusion

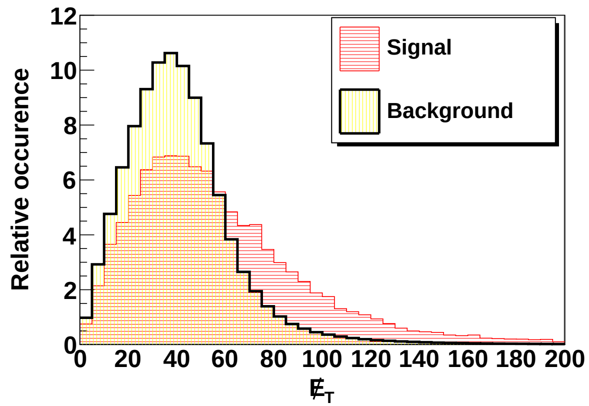
- Single top channel looks good.
- The factor of ~ 3 in production is turned into a factor between 2 and 3 after the analysis.
- ATLAS and CMS can improve the factor.
- Light charged Higgs in Type-II-like models will be excluded (charged Higgs discovered) by the end of the 14 TeV run.
- In Type-I (X) models, $\tan\beta$ will be probed in the range 1 to 15, depending on the charged Higgs mass, by the end of the 13/14 TeV run.

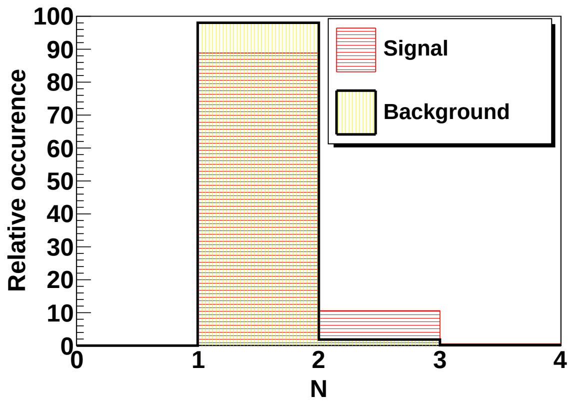
Backup

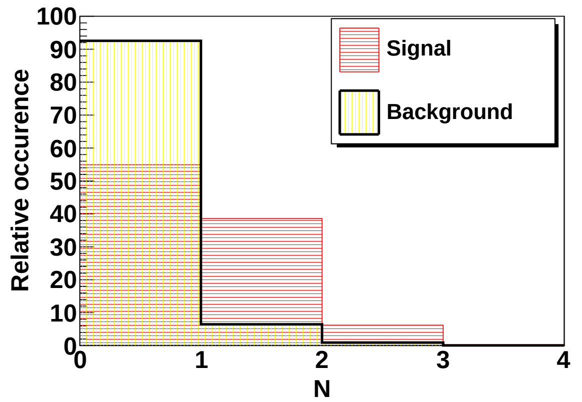
- Backup

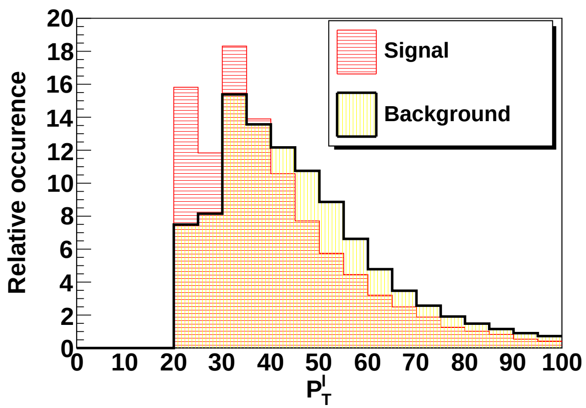
Plots

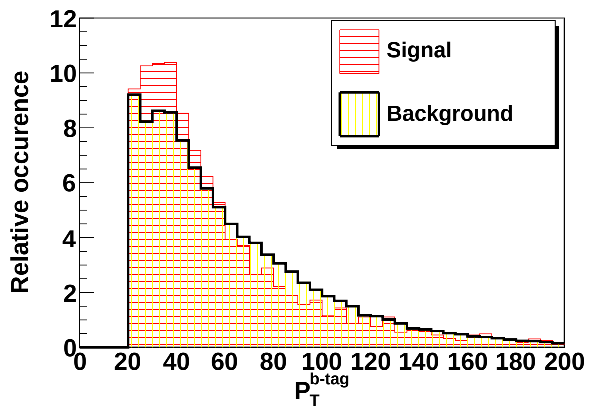

Signal
Background
Relative occurence
N


Signal
Background
Relative occurence
$\not{E}_T$

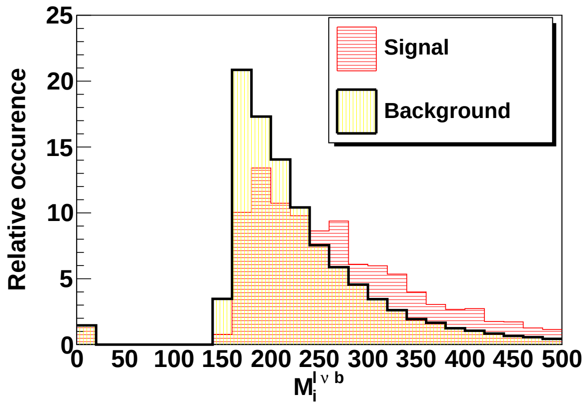

Signal
Background
Relative occurence
N

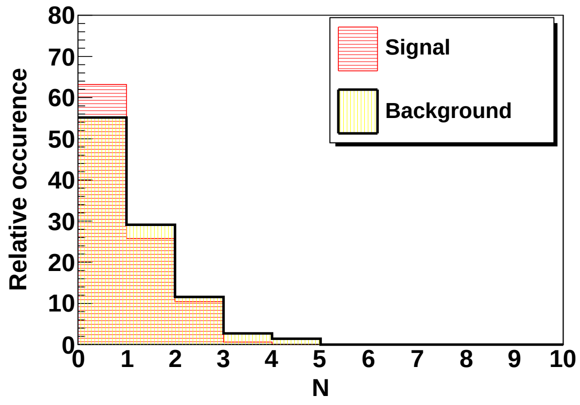

Signal
Background
Relative occurence
N

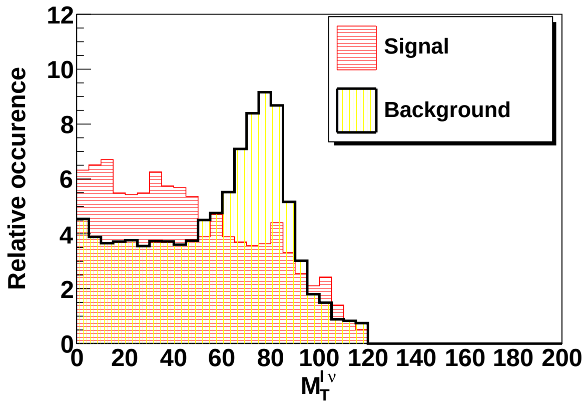

Signal
Background
Relative occurence
P_T^l

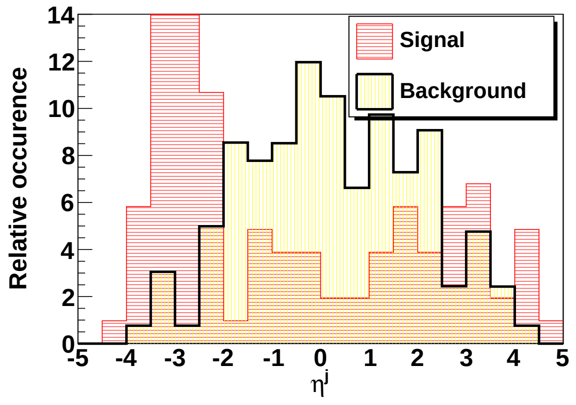

Signal
Background
Relative occurence
$P_T^{b\text{-}tag}$

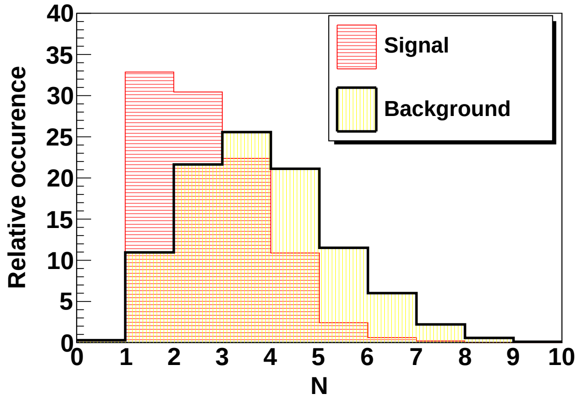
Plots


Signal
Background
Relative occurence
0 5 10 15 20 25
0 50 100 150 200 250 300 350 400 450 500
M_i^{l ν b}


Signal
Background
Relative occurence
0 10 20 30 40 50 60 70 80
0 1 2 3 4 5 6 7 8 9 10
N


Signal
Background
Relative occurence
0 2 4 6 8 10 12
0 20 40 60 80 100 120 140 160 180 200
M_T^{l ν}


Signal
Background
Relative occurence
0 2 4 6 8 10 12 14
-5 -4 -3 -2 -1 0 1 2 3 4 5
η^j


Signal
Background
Relative occurence
0 5 10 15 20 25 30 35 40
0 1 2 3 4 5 6 7 8 9 10
N