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HEAVY CHARGED HIGGS SIGNALS AT THE LHC

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Abstract

We discuss the viability of $gb \rightarrow tH \rightarrow ttb$ charged-Higgs signals at the proposed LHC pp supercollider, in the decay channel $tt \rightarrow (bq\bar{q}')(bl\nu)$. Here one top quark decays hadronically and one semileptonically, with all three b -quarks giving flavor-tagged jets. The principal backgrounds come from ttg, ttq, ttc and ttb continuum production, with possible mis-tagging of g, q and c . We conclude that significant signals can be separated from these backgrounds, for limited but interesting ranges of the parameters $m_{H\pm}$ and $\tan\beta$, with the LHC energy and luminosity.

The search for Higgs bosons is in the forefront of present research effort in particle physics[1]. While there is a single Higgs boson in the Standard Model (SM), the minimal supersymmetric extension (MSSM) has five of them — three neutral (h, H, A) and two charged (H^\pm). Phenomenological interest here has concentrated largely on the neutral sector[2,3,4,5]. As regards H^\pm , it is recognized that top decay would provide viable signals at hadron colliders if $m_{H^\pm} < m_t$ [4,5,6,7,8,9]. On the other hand, the region $m_{H^\pm} > m_t$ is favored by constraints from $b \rightarrow s\gamma$ data[10], if there are no light charginos[11]; this region has been considered problematical, since the principal signal $H \rightarrow tb$ would suffer from large QCD backgrounds at a hadron collider[7,12]. However, the possibility of efficient b -tagging could transform this situation by discriminating against the background, as in the case of neutral Higgs signals in the intermediate mass region[12,13,14]. The present letter is devoted to a quantitative exploration of this possibility; our results apply to two-Higgs-doublet models in general, though we shall refer to particular features of the MSSM from time to time. Some preliminary results from a similar study by Gunion[15] have recently appeared; these are complementary to the present work, since his methods of calculation and analysis differ somewhat from ours. We show below that viable signals may indeed be expected, over a limited but interesting range of H^\pm mass and coupling parameter space, in the proposed Large Hadron Collider (LHC) [16] with pp collisions at CM energy $\sqrt{s} = 14$ TeV.

In two-Higgs-doublet models, where it is usually assumed that up-type and down-type quarks get masses from different vevs, the main H^\pm interactions with quarks are given by

$$L = \frac{gV_{tb}}{2\sqrt{2}M_W} H^+ t [m_t \cot \beta (1 - \gamma_5) + m_b \tan \beta (1 + \gamma_5)] b + \text{h.c.} , \quad (1)$$

neglecting terms suppressed by small quark masses or small KM matrix elements V_{ij} , where $\tan \beta = v_2/v_1$ is the usual ratio of vevs. The principal hadroproduction and decay mechanisms for a heavy charged Higgs boson are therefore

$$gb \rightarrow tH^- \rightarrow t\bar{t}b \rightarrow W^+W^-b\bar{b} , \quad (2)$$

plus the corresponding charge-conjugate channel. (In the MSSM, an alternative decay mode to the same final state, $H^- \rightarrow W^-h \rightarrow W^-b\bar{b}$, is suppressed in the mass range $m_{H^\pm} > m_t$

of present interest[1]). As a tag for top production, we shall assume that one of the W -bosons decays leptonically $W \rightarrow \ell\nu$ (with $\ell = e, \mu$). To enhance the event rate and facilitate event reconstruction, we assume that the other W -boson decays hadronically $W \rightarrow q\bar{q}'$, with invariant mass $m(q\bar{q}') \simeq M_W$. Thus we consider the signal

$$gb \rightarrow tH \rightarrow bbbq'\ell\nu, \quad (3)$$

where all five quarks give separate jets and the lepton is isolated. We also assume that all three b -jets are tagged by a vertex detector; tagging via semileptonic b -decays is less desirable, since the additional missing neutrinos blur the kinematics, but on the other hand it distinguishes b from \bar{b} and removes some ambiguity in the event reconstruction. This final state implies a spectator b -quark in one of the beams; however, we expect that this spectator will be produced at small angle and will not appear in the acceptance region described below. Our approach differs here from Gunion[15] who calculates the subprocess $gg \rightarrow tbH$ where the spectator is explicit.

The principal background sub-processes are QCD production

$$gb \rightarrow t\bar{t}b \quad (4)$$

and fake backgrounds from

$$gg, q\bar{q} \rightarrow t\bar{t}g, \quad gq \rightarrow t\bar{t}q, \quad (5)$$

where the $g(q)$ jet or one of the $W \rightarrow q\bar{q}'$ jets is mistakenly tagged; $tt \rightarrow bbWW \rightarrow bbq'\ell\nu$ decays are understood. There is an electroweak contribution to Eq.(4) from H^\pm exchange in the t -channel, but this is much smaller than the signal (suppressed by additional propagators) and we henceforth neglect it. There is also a possible background from intermediate-mass neutral Higgs boson production and decay:

$$gg \rightarrow t\bar{t}H^0 \rightarrow t\bar{t}b\bar{b}, \quad (6)$$

where one of the final b -quarks does not give a separate jet within acceptance cuts. In the MSSM, this neutral boson could be h or H or A ; with our present heavy H^\pm scenario, we

would then have H and A equally heavy ($m_{H^\pm} \sim m_H \sim m_A$ with their bb contributions suppressed by competing channels $H \rightarrow hh$, WW and $A \rightarrow Zh$) while h couplings are approximately those of the SM. However, the total tth production [5] is then an order of magnitude smaller than $t\bar{t}b$ production via Eq.(4), so we henceforth neglect the channel of Eq.(6).

It is already known[7,12] that these backgrounds are potentially much larger than the signal. However, we shall show that the background of Eq.(4) can be reduced to the same order as the signal (in favorable cases) by a choice of kinematic cuts, while the fake background Eq.(5) is also reduced to a comparable level by the additional b -tagging requirement. We here choose the following acceptance cuts on the 3 tagged plus 2 untagged jets (collectively labelled j), the lepton ℓ and missing transverse momentum \cancel{p}_T :

$$p_T(j), p_T(\ell), \cancel{p}_T > 30 \text{ GeV} , \quad (7)$$

$$|\eta(j)|, |\eta(\ell)| < 2.0 , \quad (8)$$

where p_T and η denote transverse momentum and pseudorapidity. We also require minimum separations $\Delta R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2}$ between the jets and lepton,

$$\Delta R(jj) , \Delta R(j\ell) > 0.4 , \quad (9)$$

to simulate some effects of jet-finding and lepton isolation criteria. We take account of possible invisible neutrino energy in $b \rightarrow c \rightarrow s$ decays by Monte Carlo modelling, and thereafter regard all partons as jets if they pass the above cuts. We simulate calorimeter resolution by a gaussian smearing of p_T , with $(\sigma(p_T)/p_T)^2 = (0.6/\sqrt{p_T})^2 + (0.04)^2$ for jets and $(\sigma(p_T)/p_T)^2 = (0.12/\sqrt{p_T})^2 + (0.01)^2$ for leptons (taking the same resolution for e and μ for simplicity). The \cancel{p}_T is evaluated from the vector sum of lepton and jet momenta, after resolution smearing. We require the invariant mass of the two untagged jets to be consistent with M_W :

$$|m(qq') - M_W| < 15 \text{ GeV} \quad (10)$$

We assume branching fractions $B(t \rightarrow bqq') = 2/3$, $B(t \rightarrow b\ell\nu) = 2/9$, and tagging efficiencies $\epsilon_b = 0.30$, $\epsilon_c = 0.05$, $\epsilon_g = 0.01$ for individual b -jets, c -jets and gluon (or light quark) jets

respectively. We calculate production rates using the MRSD0' parton distributions[17] at scale $Q = m_t$ for both the signal and the backgrounds, assuming $m_t = 150$ GeV throughout. Since the b -quark distribution is inferred via QCD evolution from descriptions of deep inelastic scattering data, there is room for controversy here; however, both the signal and the “true” background of Eq.(4) depend on the same input b -distribution. The net signal and background cross sections, with these cuts and branching/tagging factors, are illustrated in Fig. 1 for pp collisions at $\sqrt{s} = 14$ TeV.

Figure 1, which does not include tag-factors, shows that the charged-Higgs signal has an appreciable size for some ranges of the parameters m_{H^\pm} and $\tan\beta$. The $\tan\beta$ dependence is given by a factor $(m_t/\tan\beta)^2 + (m_b \tan\beta)^2$, with a minimum at $\tan\beta = \sqrt{m_t/m_b}$. The neighbourhood of this minimum is unpromising for H^\pm detection, but many $SUSY-GUT$ models suggest that $\tan\beta$ lies near 1 or alternatively is very large[18]. Tagging reduces the major ttg and ttq backgrounds by a factor 1/30 relative to the signal, making them roughly comparable for favourable $\tan\beta$. To improve the signal/background ratio further and to estimate the mass m_{H^\pm} , we propose the following strategy for event reconstructions.

- (a) Reconstruct the missing neutrino momentum, by equating $\mathbf{p}_T(\nu) = \mathbf{p}_T$ and fixing the longitudinal component $p_L(\nu)$ by the invariant mass constraint $m(\ell\nu) = M_W$. The latter gives two solutions in general; if they are complex we discard the imaginary parts and the solutions coalesce. We note that the sign \pm of this W (and hence by inference the other W too) is determined by the sign of the lepton charge.
- (b) There are now 6 ways in which two of the b -jets can be paired with the two W 's to form top candidates (unless some of the b -jets are also lepton-tagged and thus have known signs). Together with the two-fold ambiguity from (a), this gives 12 candidate reconstructions, in each of which there are two top mass values m_{t1} , m_{t2} . We select the assignment with best fit to the top mass (that will be known), determined by minimizing $|m_{t1} + m_{t2} - 2m_t|$ subject to the requirements $|m_{t1} - m_{t2}| < 50$ GeV and $|m_{t1} + m_{t2} - 2m_t| < 60$ GeV. If these requirements cannot be met, we reject the event as unreconstructable.

- (c) In the selected best-fit assignment above, there are 2 ways in which the remaining b -jet can be paired with one of the top candidates, so we have 2 candidate values for the reconstructed charged-Higgs mass $\tilde{m}_{H\pm} = m(b, t1), m(b, t2)$. Unless the charge of the b -jet can be identified, there is no way to choose between them (unless the b -jet is also lepton-tagged), so we retain both values; thus even the signal events contain an irreducible combinatorial background. However, the correct pairings will give a peak in the $\tilde{m}_{H\pm}$ distribution while the incorrect pairings and background events will be more broadly distributed.

This strategy is more ambitious than that of Ref.[15], where a b -jet is combined only with a reconstructed $t \rightarrow bj\bar{j}$ hadronic system.

Figure 2 compares the signal and background contributions to the $\tilde{m}_{H\pm}$ distributions, for $m_{H\pm} = 200, 300, 400, 500$ GeV with either $\tan\beta = 1$ or $\tan\beta = 50$; there are two possible values and hence two counts per event in this graph. For the most favourable of the cases illustrated, namely $m_{H\pm} = 200$ GeV with $\tan\beta = 50$, the signal integrated over the range $180 < \tilde{m}_{H\pm} < 220$ GeV is 5 counts over a total background of 4 counts for each fb^{-1} of luminosity. With 100fb^{-1} of luminosity (one years running at design luminosity $10^{34} \text{cm}^{-2} \text{s}^{-1}$) this signal would be very significant. As $m_{H\pm}$ increases, both the signal and background fall at comparable rates; for $m_{H\pm} = 500$ GeV, the signal in a 60 GeV bin is 1.0 over a background of 1.6 counts/ fb^{-1} that would still be very significant with 100fb^{-1} luminosity. If we take $\tan\beta = 1(2)$ instead, the background remains essentially the same while all the signals drop by a factor 2.8(11); hence the regions $\tan\beta \leq 1$ and $\tan\beta \geq 30$ are very promising while the region $2 \leq \tan\beta \leq 15$ is problematical. Thus far we have assumed $m_t = 150$ GeV; for $m_t = 180$ GeV instead, the $\tan\beta = 1$ signals shown here increase by about 50% (except near threshold $m_{H\pm} \sim m_t$) while the net background falls by about 20%. Lastly we remark that the assumed cuts above are rather stringent, reducing the Higgs signal by factors of order 10–30 depending on $m_{H\pm}$, and the tagging efficiencies may prove to be better than we have assumed here[14]; in these respects our event rates may be viewed as conservative.

We conclude that the outlook is promising. With our assumed tagging efficiencies and cuts, significant $H \rightarrow tb$ charged-Higgs signals would be detectable for a limited but interesting range of the parameters $m_{H\pm}$ and $\tan\beta$.

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Figure captions

Fig. 1: Comparison of charged-Higgs signal and principal backgrounds in the $pp \rightarrow ttbX$ channel at $\sqrt{s} = 14$ TeV, including branching fractions and acceptance cuts but excluding b -tag factors, with $m_t = 150$ GeV: (a) cross sections versus $\tan\beta$ for $m_{H^\pm} = 300$ GeV; (b) cross sections versus m_{H^\pm} for $\tan\beta = 1$.

Fig. 2: Comparison of charged-Higgs signals and summed backgrounds in the distribution versus reconstructed charged-Higgs mass \tilde{m}_{H^\pm} , with two counts per event. The cases $m_{H^\pm} = 200, 300, 400, 500$ GeV are shown for (a) $\tan\beta = 1$ and (b) $\tan\beta = 50$.

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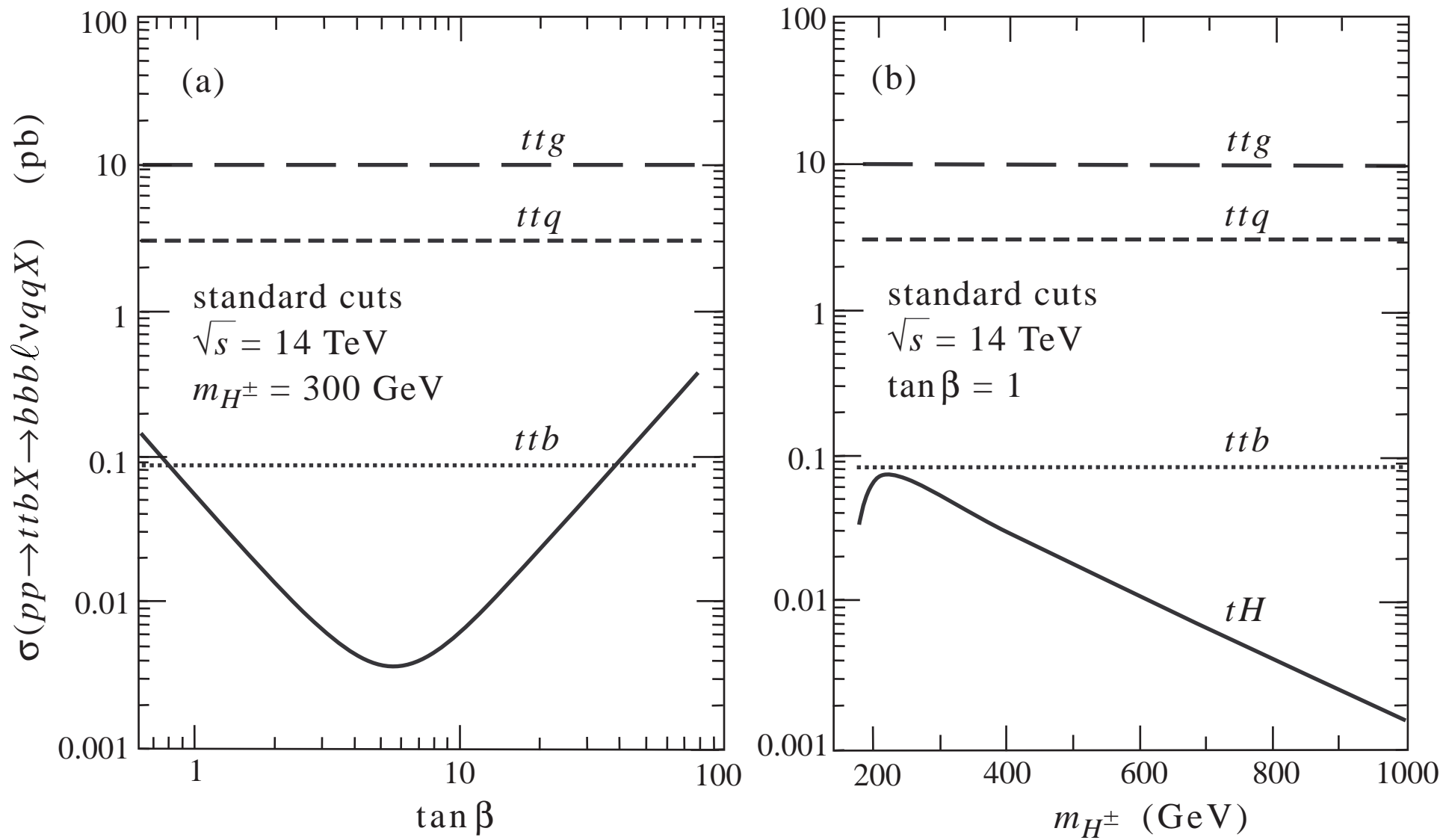


Fig. 1

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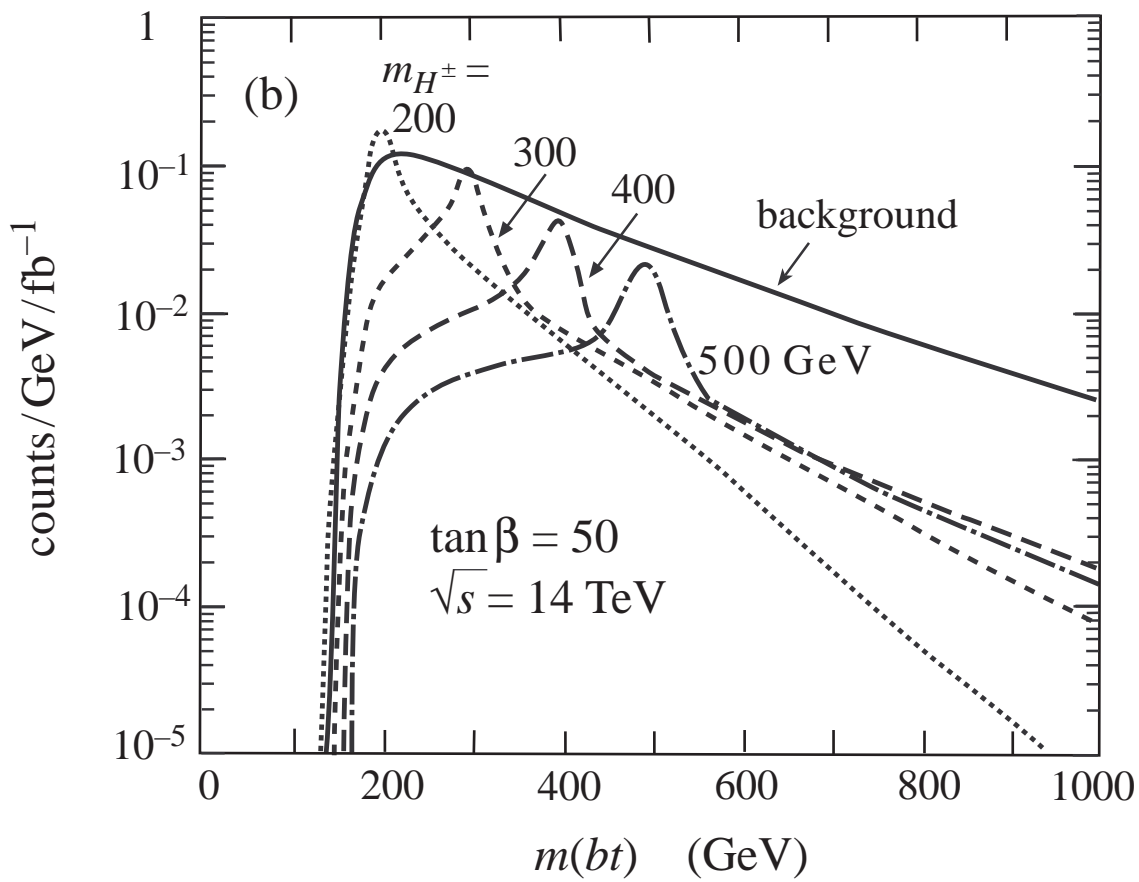
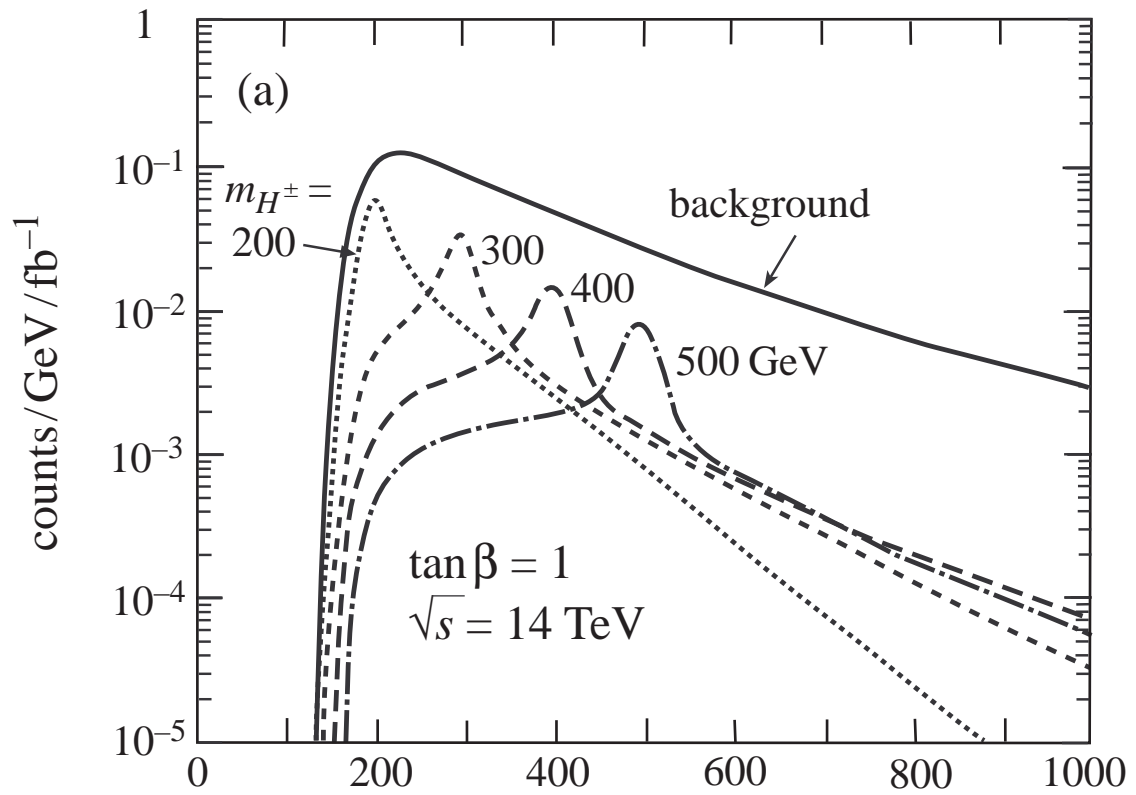


Fig. 2