Top Decays with Flavor Changing Neutral Higgs Interactions at the LHC

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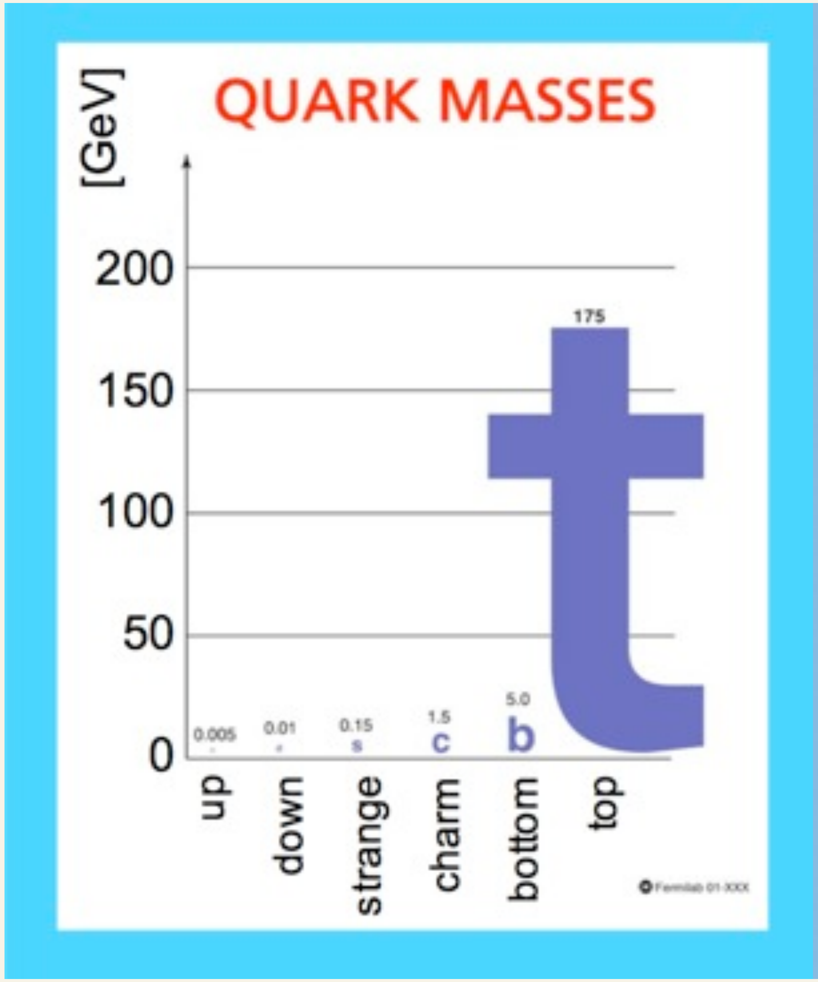
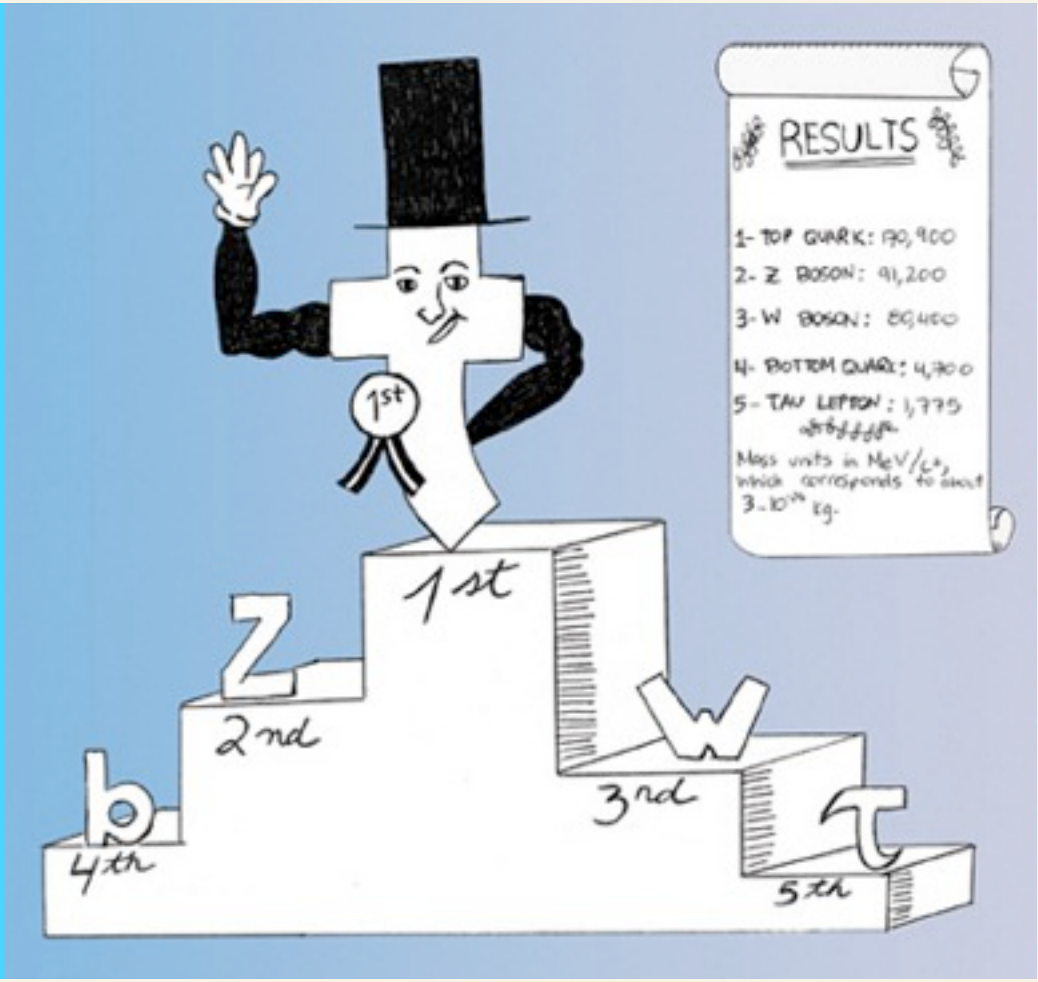
Kao, Cheng, Hou, and Sayre, Phys. Lett. **B716** (2012) 225.

Aguilar-Saavedra and Branco [2000]

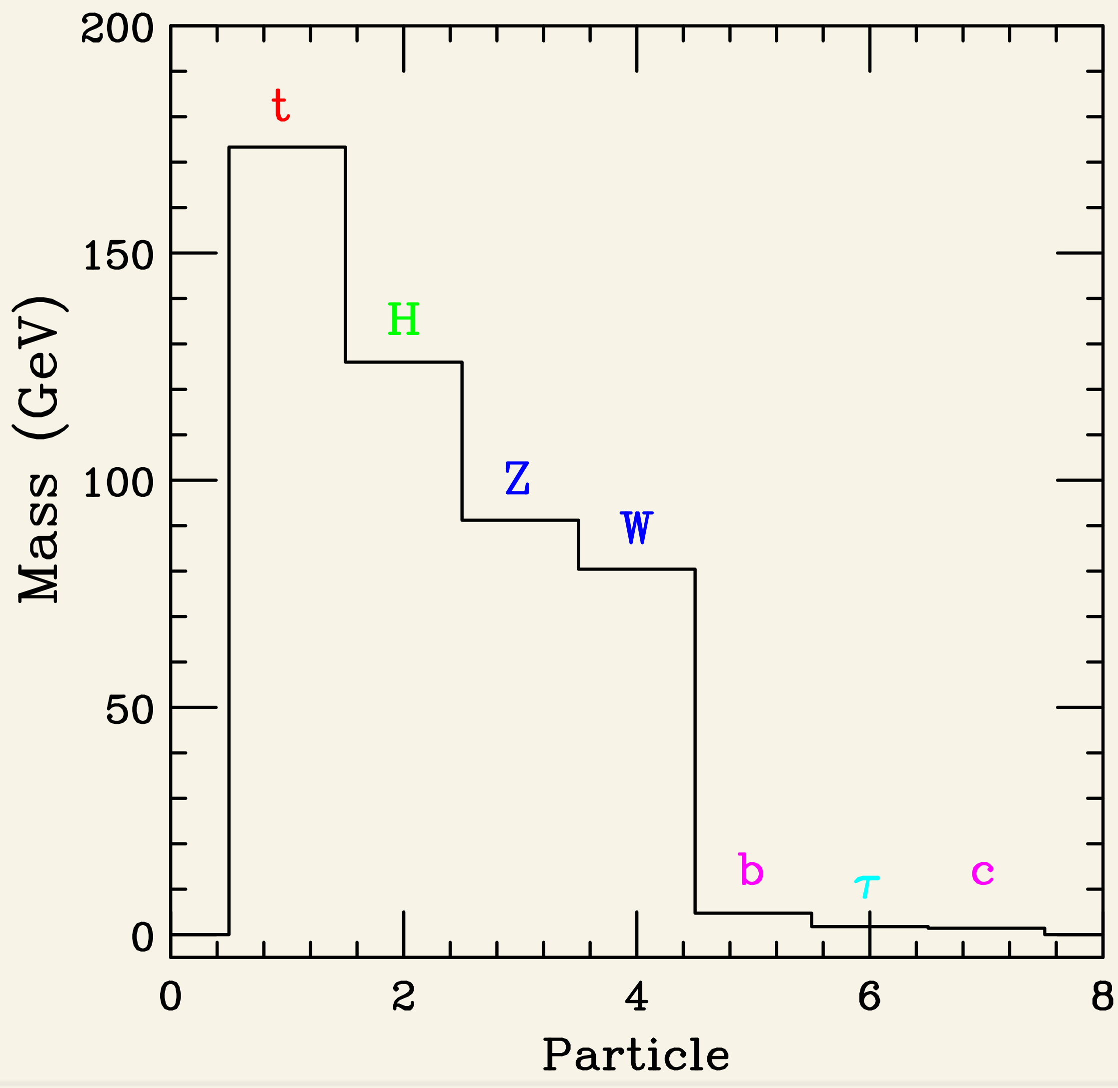
- Introduction
- A Special Two Higgs Doublet Model for the Top
- Flavor Changing Neutral Higgs Boson in Top Decays
- The Physics Background
- Mass Reconstruction
- The Discovery Potential at the LHC
- Conclusions

Heavyweight Champion before July 4, 2012





The New Runner-up



A Special Two Higgs Doublet Model for the Top Quark

Das and Kao (1996)

- We propose that the top quark is the only elementary fermion getting a mass from a much larger VEV of a second Higgs doublet.
- The top quark is naturally heavier than other quarks and leptons in the 3 known generations.
- The ratio of the Higgs VEVs, $\tan\beta = |v_2|/|v_1|$, is naturally large, which enhances the Yukawa couplings of the lighter quarks and leptons with the Higgs bosons.
- There are flavor changing neutral Higgs (FCNH) interactions among the up type quarks.

Special Top Two Higgs Doublet Model

We choose the Yukawa interactions to be of the following form

$$\begin{aligned}\mathcal{L}_Y &= -\sum_{m,n=1}^{3} \bar{L}_L^m \phi_1 E_{mn} l_R^n - \sum_{m,n=1}^{3} \bar{Q}_L^m \phi_1 F_{mn} d_R^n \\ &\quad - \sum_{\alpha=1}^{2}\sum_{m=1}^{3} \bar{Q}_L^m \tilde{\phi}_1 G_{m\alpha} u_R^\alpha - \sum_{m=1}^{3} \bar{Q}_L^m \tilde{\phi}_2 G_{m3} u_R^3 \quad + \text{H.c.}, \\ \phi_\alpha &= \begin{pmatrix} \phi_\alpha^+ \\ \frac{v_\alpha+\phi_\alpha^0}{\sqrt{2}} \end{pmatrix}, \quad \tilde{\phi}_\alpha = \begin{pmatrix} \frac{v_\alpha^*+\phi_\alpha^{0\,*}}{\sqrt{2}} \\ -\phi_\alpha^- \end{pmatrix}, \quad \phi_\alpha^- = \phi_\alpha^{+\,*}, \ \alpha = 1,2, \\ L_L^m &= \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L^m, \quad Q_L^m = \begin{pmatrix} u \\ d \end{pmatrix}_L^m, \ m = 1,2,3\,,\end{aligned}$$

where l^m, d^m, and u^m are the gauge eigenstates.

This Lagrangian respects a discrete symmetry,

$$\begin{aligned}\phi_1 &\to -\phi_1, \quad l_R^m \to -l_R^m, \quad d_R^m \to -d_R^m, \quad u_R^\alpha \to -u_R^\alpha, \\ \phi_2 &\to +\phi_2, \quad L_L^m \to +L_L^m, \quad Q_L^m \to +Q_L^m, \quad u_R^3 \to +u_R^3\,,\end{aligned}$$

with $m = 1,2,3$ and $\alpha = 1,2$.

Special Yukawa Interactions

The interactions between u-quarks and neutral Higgs bosons become

$$\mathcal{L}_N^U = -\sum_{u=u,c,t} m_u \bar{u}_L u_R \frac{\phi_1^{0*}}{v_1^*} - \sum_{ab} \bar{u}_L^a \Sigma_{ab} u_R^b \left(\frac{\phi_2^{0*}}{v_2^*} - \frac{\phi_1^{0*}}{v_1^*} \right) + \text{H.c.}\,,$$

$$\Sigma = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} U_R^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R,$$

with U_R and U_L being unitary transformations.

To a good approximation, the unitary matrix U_R has the following form

$$U_R = \begin{pmatrix} \cos\phi & -\sin\phi & -\cos\phi\epsilon_1^* + \sin\phi\epsilon_2^* \\ \sin\phi & \cos\phi & -\sin\phi\epsilon_1^* - \cos\phi\epsilon_2^* \\ \epsilon_1 & \epsilon_2 & 1 \end{pmatrix}.$$

We have introduced two small parameters

$$\epsilon_1 = |\epsilon_1| e^{i\delta_1}, \quad \epsilon_2 = |\epsilon_2| e^{i\delta_2}, \quad |\epsilon_1| \le |\epsilon_2| \sim m_c/m_t\,.$$

Flavor Changing Neutral Higgs Interactions

Then the interactions of quarks with neutral Higgs bosons become

$$
\begin{aligned}
\mathcal{L}_Y^N &= -\sum_{d=d,s,b}\frac{m_d}{v}\bar{d}d(H_1-\tan\beta H_2) - i\sum_{d=d,s,b}\frac{m_d}{v}\bar{d}\gamma_5 d(G^0-\tan\beta A) \\
&\quad -\sum_{u=u,c}\frac{m_u}{v}\bar{u}u[H_1-\tan\beta H_2] + i\sum_{u=u,c}\frac{m_u}{v}\bar{u}\gamma_5 u[G^0-\tan\beta A] \\
&\quad -\frac{m_t}{v}\bar{t}t[H_1+\cot\beta H_2] + i\frac{m_t}{v}\bar{t}\gamma_5 t[G^0+\cot\beta A] + \mathcal{L}_{\rm FCNH}, \\
\mathcal{L}_{\rm FCNH} &= \{-\epsilon_1^*\epsilon_2\bar{u}c[(m_u+m_c)H_2+i(m_c-m_u)A] \\
&\quad -\epsilon_1^*\bar{u}t[(m_u+m_t)H_2+i(m_t-m_u)A] \\
&\quad -\epsilon_2^*\bar{c}t[(m_c+m_t)H_2+i(m_t-m_c)A] \\
&\quad +\epsilon_1^*\epsilon_2\bar{u}\gamma_5 c[(m_c-m_u)H_2+i(m_u+m_c)A] \\
&\quad +\epsilon_1^*\bar{u}\gamma_5 t[(m_t-m_u)H_2+i(m_u+m_t)A] \\
&\quad +\epsilon_2^*\bar{c}\gamma_5 t[(m_t-m_c)H_2+i(m_c+m_t)A]\} \times (\frac{1}{v\sin 2\beta}) + \text{H.c.}
\end{aligned}
$$

The FCNH interactions between u and c quarks leads to $D^0-\bar{D}^0$ mixing.

Flavor Changing Neutral Higgs Interactions in Top Decays

Kao, Cheng, Hou, and Sayre, Phys. Lett. B716 (2012) 225; Chen, Hou, Kao, and Kohda, arXiv:1304.8037/hep-ph; Talk by George Hou.

- Let us consider the following Lagrangian involving flavor changing neutral Higgs interactions with top and charm quarks:

$$\mathcal{L} = -\lambda_{tc}\bar{t}cH^0 - i\lambda_{tc}\bar{t}\gamma_5 cA^0 + \mathrm{H.c.}$$

  where H^0 is a scalar and A^0 is a pseudoscalar.

- This is a general feature of Model III of Yukawa Interactions in Two Higgs Doublet Models.

FCNH Yukawa Coupling

Cheng and Sher (1987)

- Let us consider the FCNH coupling of tcH to be the geometric mean of the Yukawa couplings of the quarks:

$$\lambda_{tc} = \frac{\sqrt{m_t m_c}}{v}$$

- In general, we will take it as a free parameter.

Top Decay Width

Hou (1991)

- The FCNH top decay with is

$$\Gamma(t \to c\phi^0) = \frac{|\lambda_{tc}|^2}{16\pi} \times (m_t) \times [(1 \pm \rho_c)^2 - \rho_\phi^2] \times \sqrt{1-(\rho_\phi+\rho_c)^2}\sqrt{1-(\rho_\phi-\rho_c)^2}$$

$rho_c = m_c/m_t$, $rho_H = M_H/m_t$, + for H^0 and - for A^0.

- The total width is

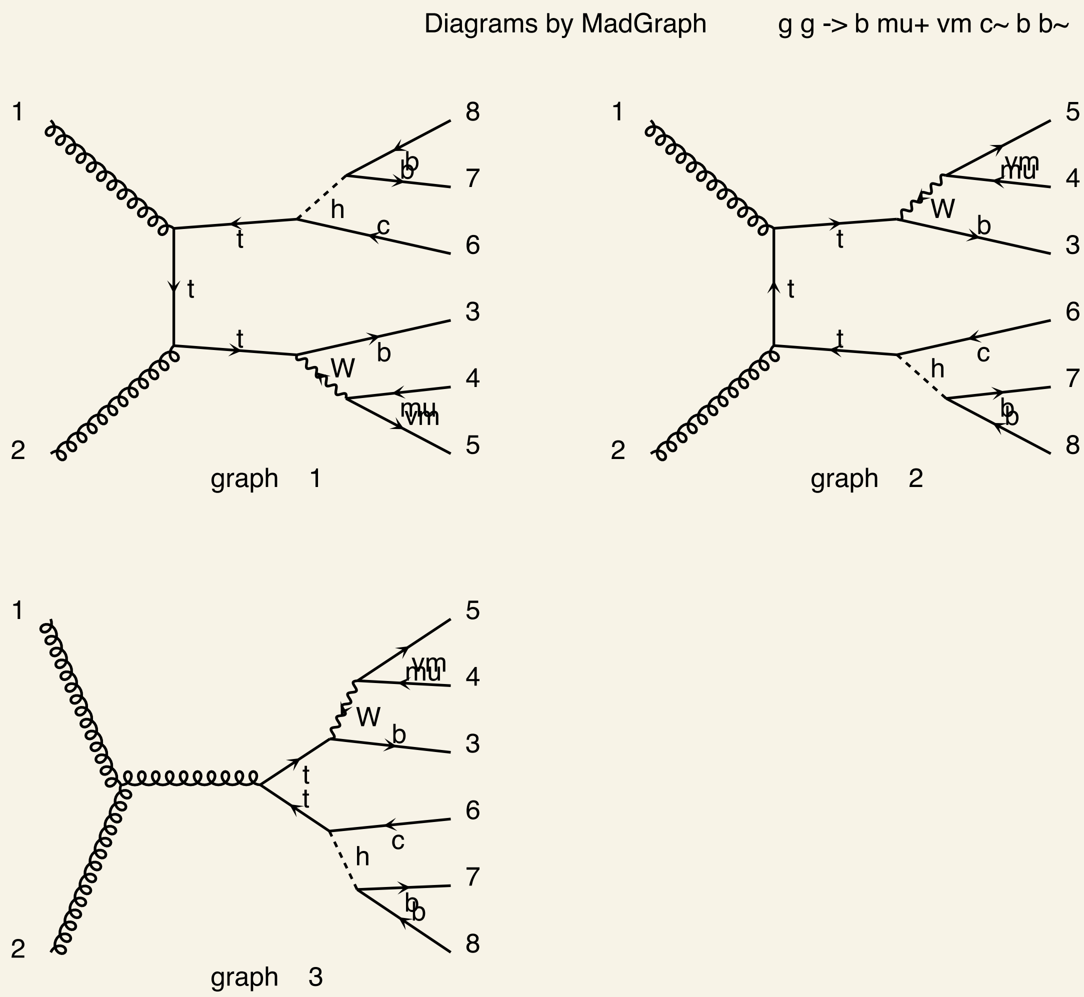
$$\Gamma_t = \Gamma(t \to bW) + \Gamma(t \to c\phi^0)$$

FCNH Branching Fraction

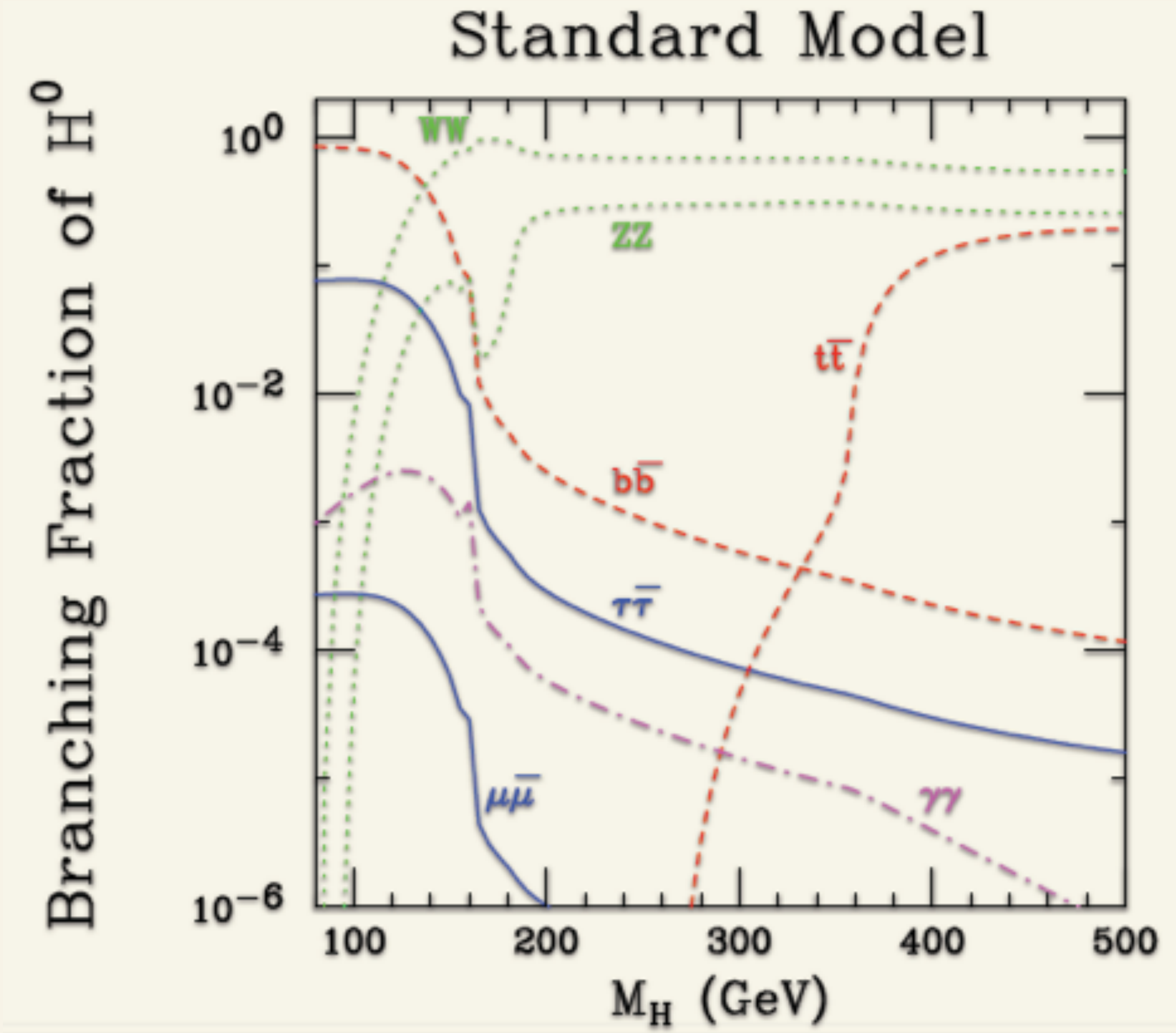
As a case study, we take the FCNH Yukawa couplings to be the geometric mean of the Yukawa couplings of the quarks with m_t = 173.3 GeV and m_c = 1.4 GeV:

$$\begin{aligned} \lambda_{tc} &= \frac{\sqrt{m_t m_c}}{v} \simeq 0.063 \\ \mathcal{B}(t \to c\phi^0) &= 2.6 \times 10^{-3} \quad \text{for } M_\phi = 120 \text{ GeV}\,, \\ \mathcal{B}(t \to c\phi^0) &= 6.2 \times 10^{-4} \quad \text{for } M_\phi = 150 \text{ GeV}\,. \end{aligned}$$

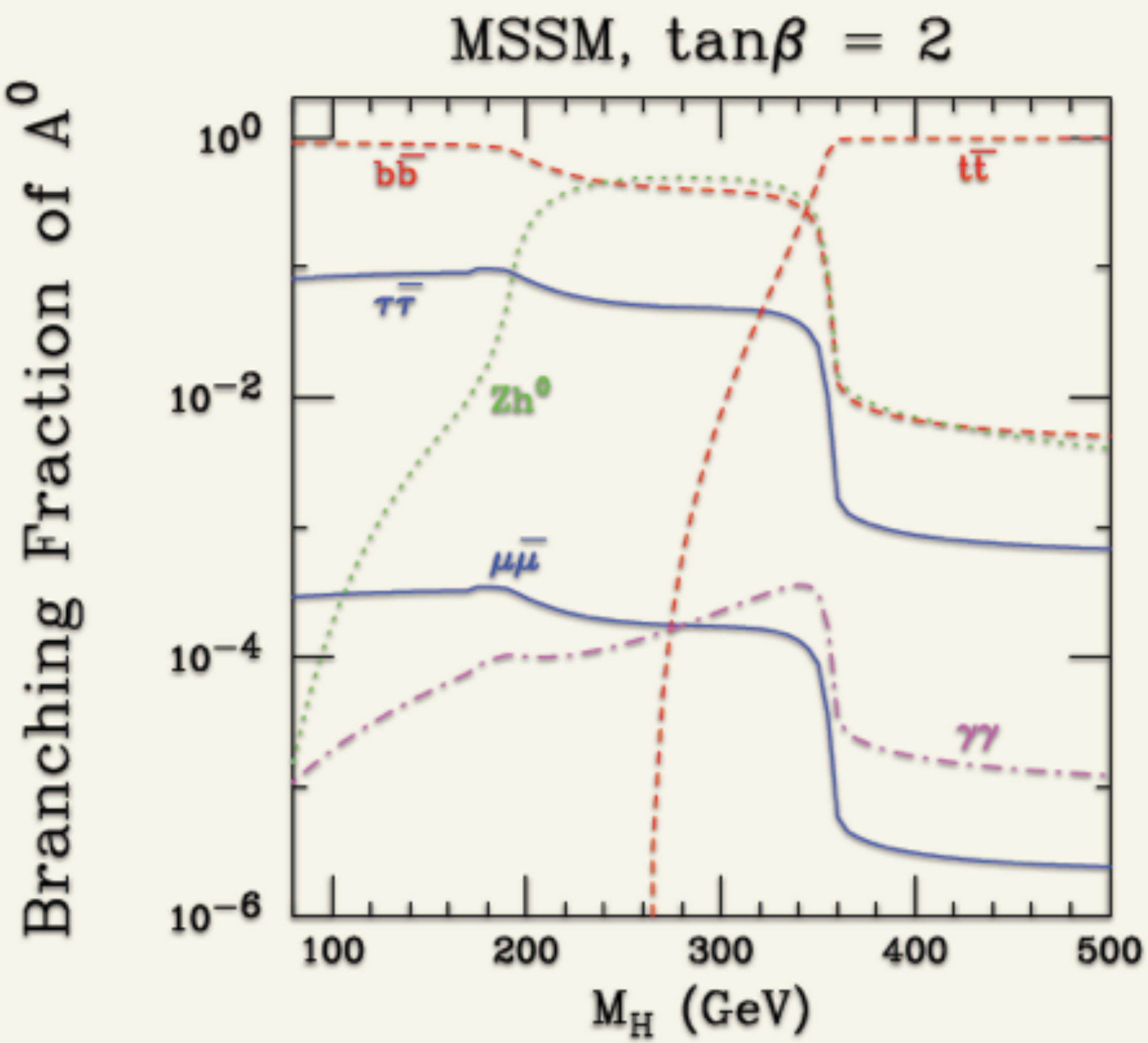
The FCNH Signal



Branching Fractions of the Higgs Boson



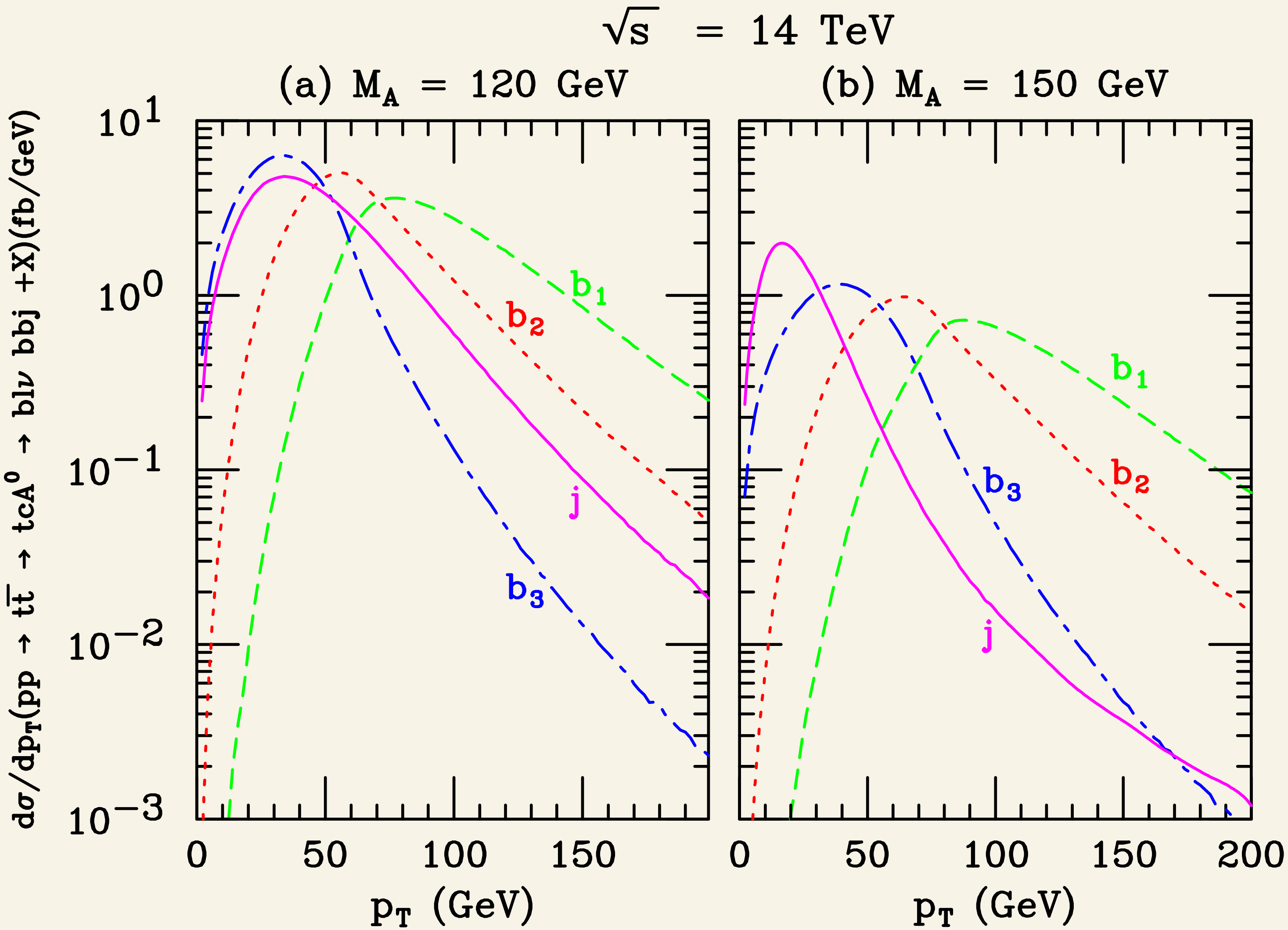
Branching Ratios of a Higgs Pseudoscalar



The FCNH Signal at the LHC

- We employ the programs MadGraph and HELAS to evaluate the exact matrix element for the FCNH signal from gluon fusion and quark-antiquark annihilation in pp collisions.
  Stelzer and Long (1994); Alwall et al. (2007); Murayama, Watanabe and Hagiwara (1991).
- In addition, we apply narrow width approximation to check the exact results.
- The cross sections are evaluated with the parton distribution functions of CTEQ6L1.

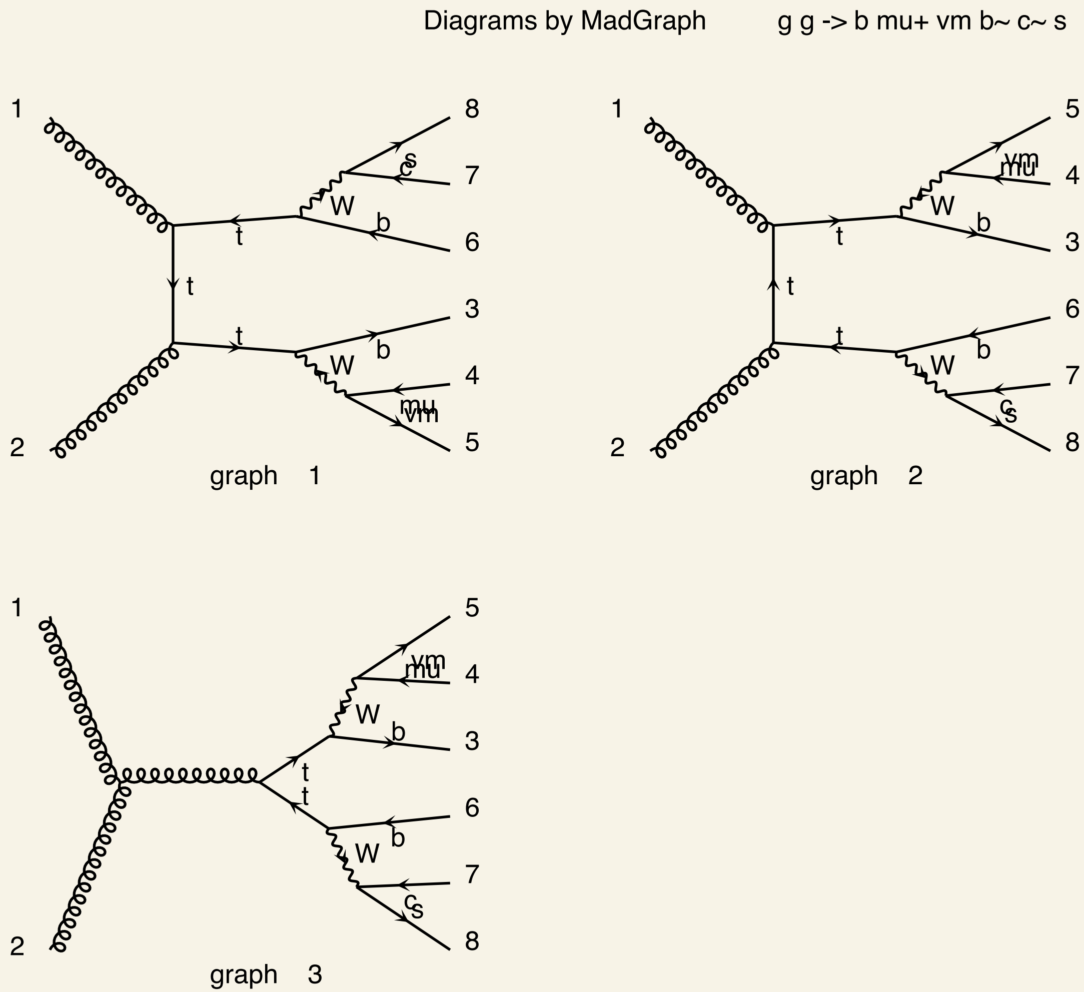
Transverse Momentum Distribution for the Higgs Signal



FCNH Signal Cross Section (fb)

M_A	s(bmncbb)	B(t cH)	Gamma(H)	B(H bb)
120.0	0.440E+02	0.259E-02	0.351E-02	0.728E+00
140.0	0.820E+01	0.117E-02	0.428E-02	0.677E+00
150.0	0.268E+01	0.621E-03	0.473E-02	0.649E+00

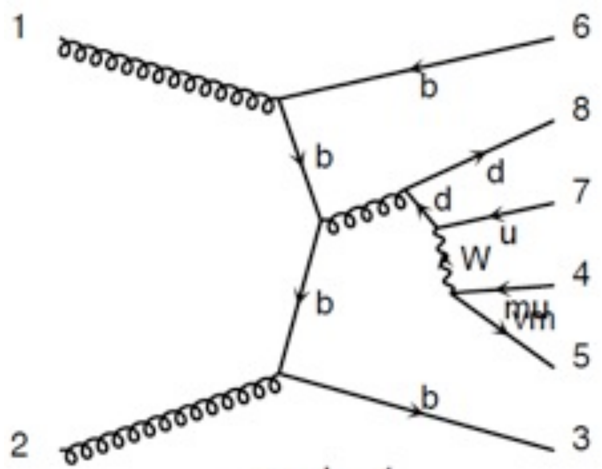
Dominant Physics Background from top quark pairs



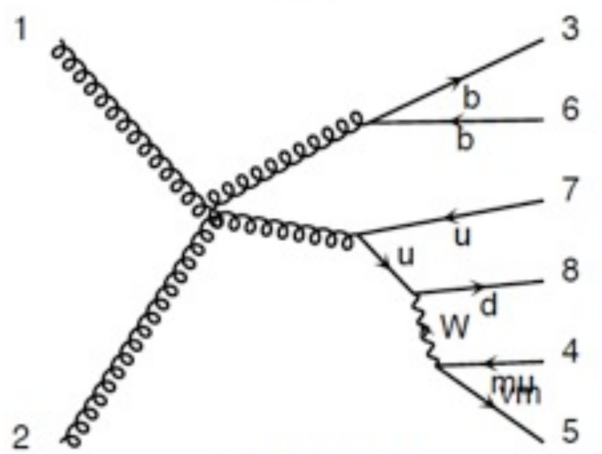
Additional Backgrounds

gg, qq to Wbbjj

- We have included additional backgrounds with Wbbjj:
- gg to Wbbjj
- $q_v q_v$ to Wbbjj
- gq to Wbbjj
- $q_v q_s$ to Wbbjj



graph 1

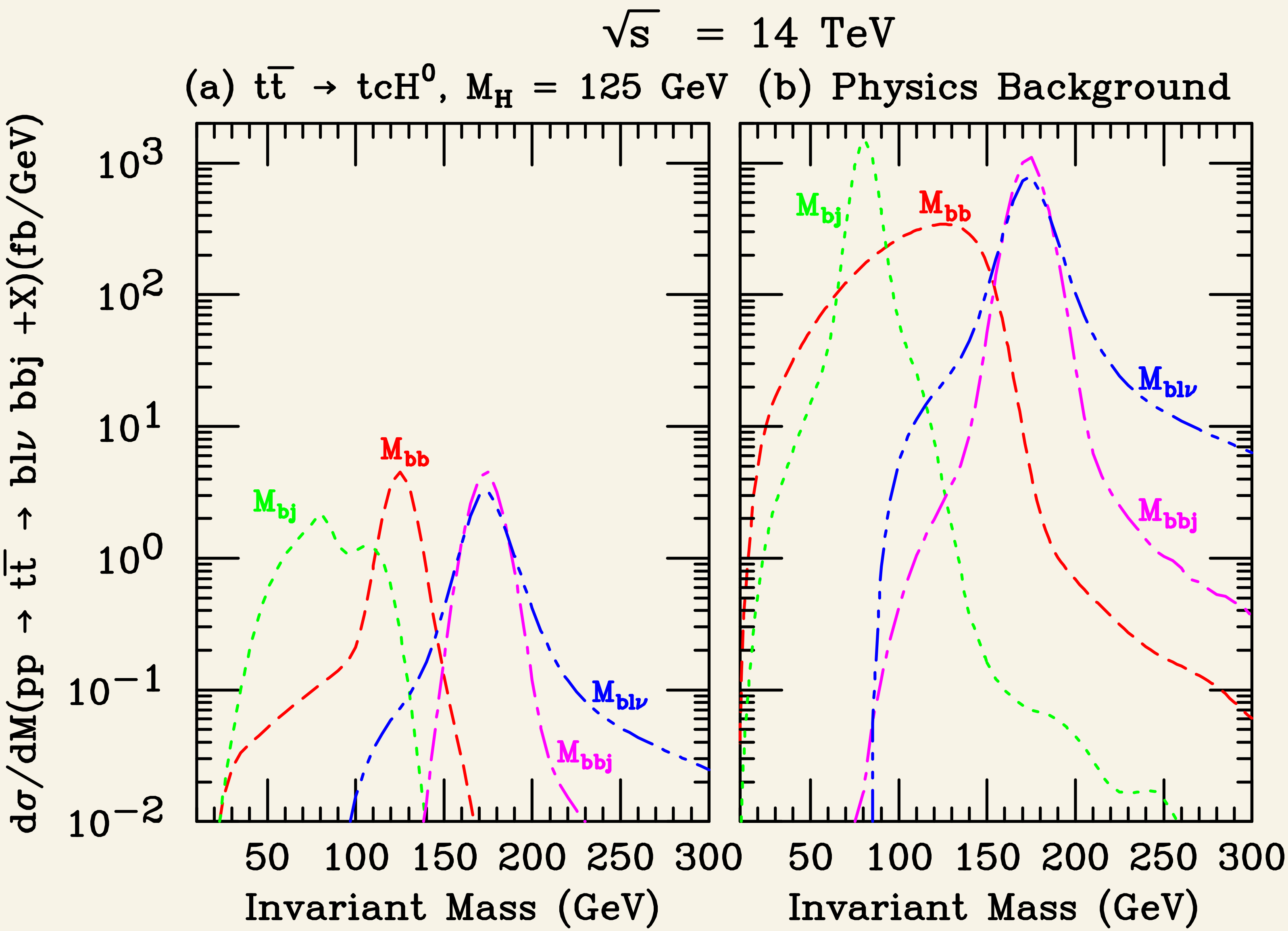


graph 102

Mass Reconstruction

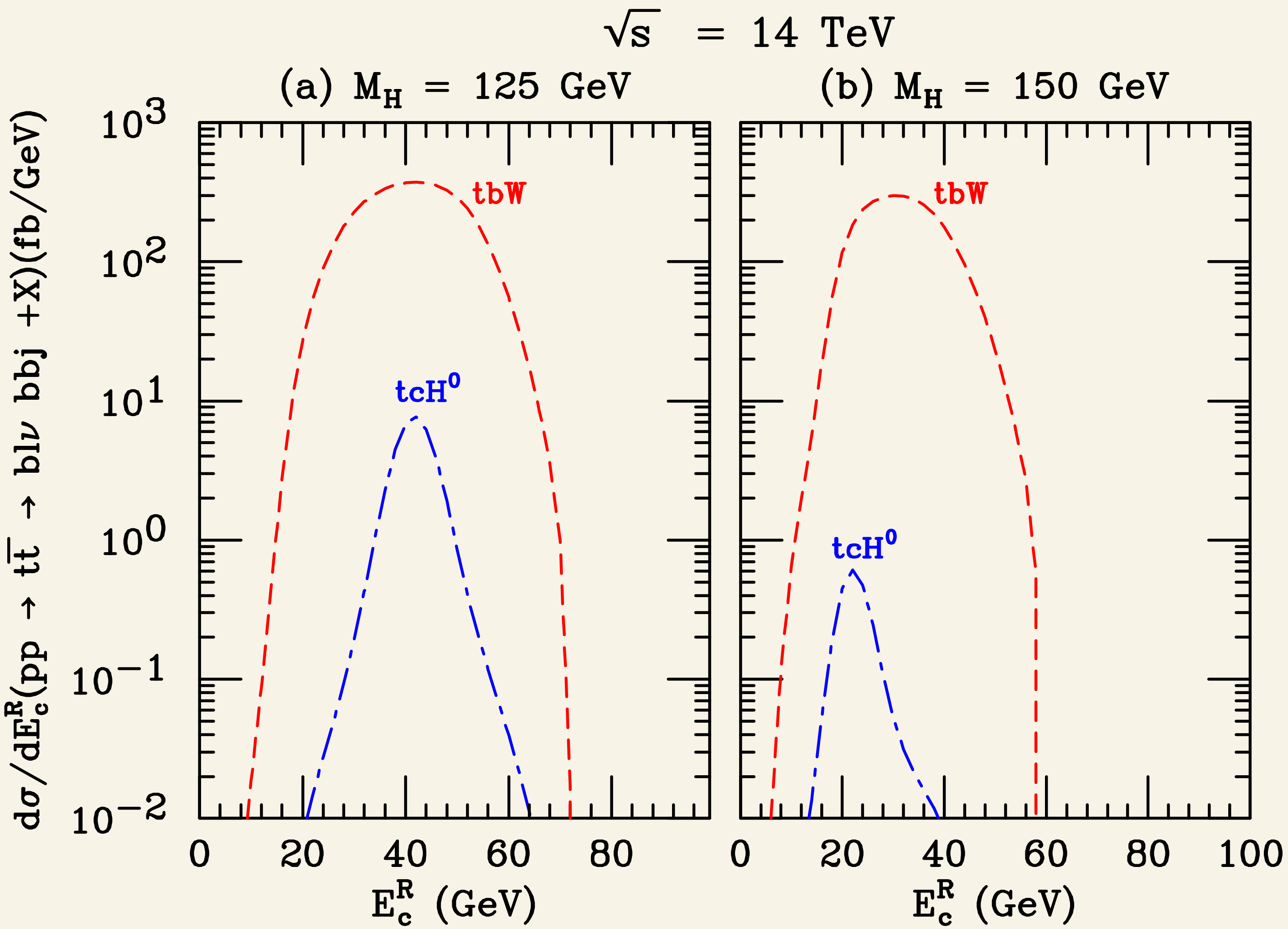
- Since our FCNC signal comes from one top quark decay, we will choose the pair of b jets that minimize $|M_{bbj}\text{-}m_t|$ as b_1b_2 and label the other b jet as b_3.
- For a correctly reconstructed event, b_1 and b_2 are the products of a Higgs decay as well, such that their invariant mass has a peak near M_H.
- For a background event, we identify b_2 as the member of this pair that minimizes $|M_{bj}\text{-}m_{W|}$.
- The remaining b quark (b_3) should reproduce m_t with the charged lepton and neutrino momenta.

Invariant Mass Distributions

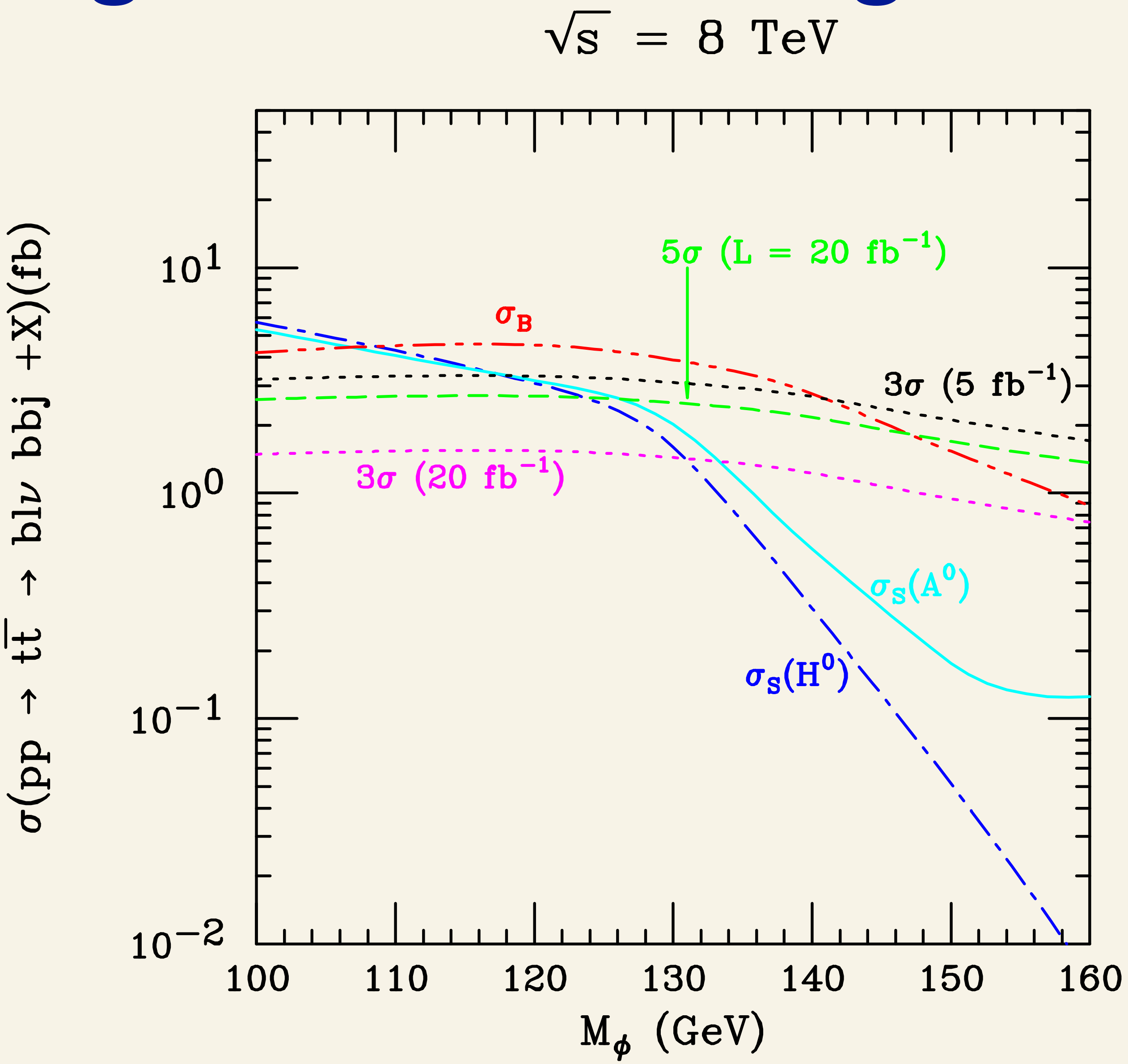


Reconstructed E_{charm}

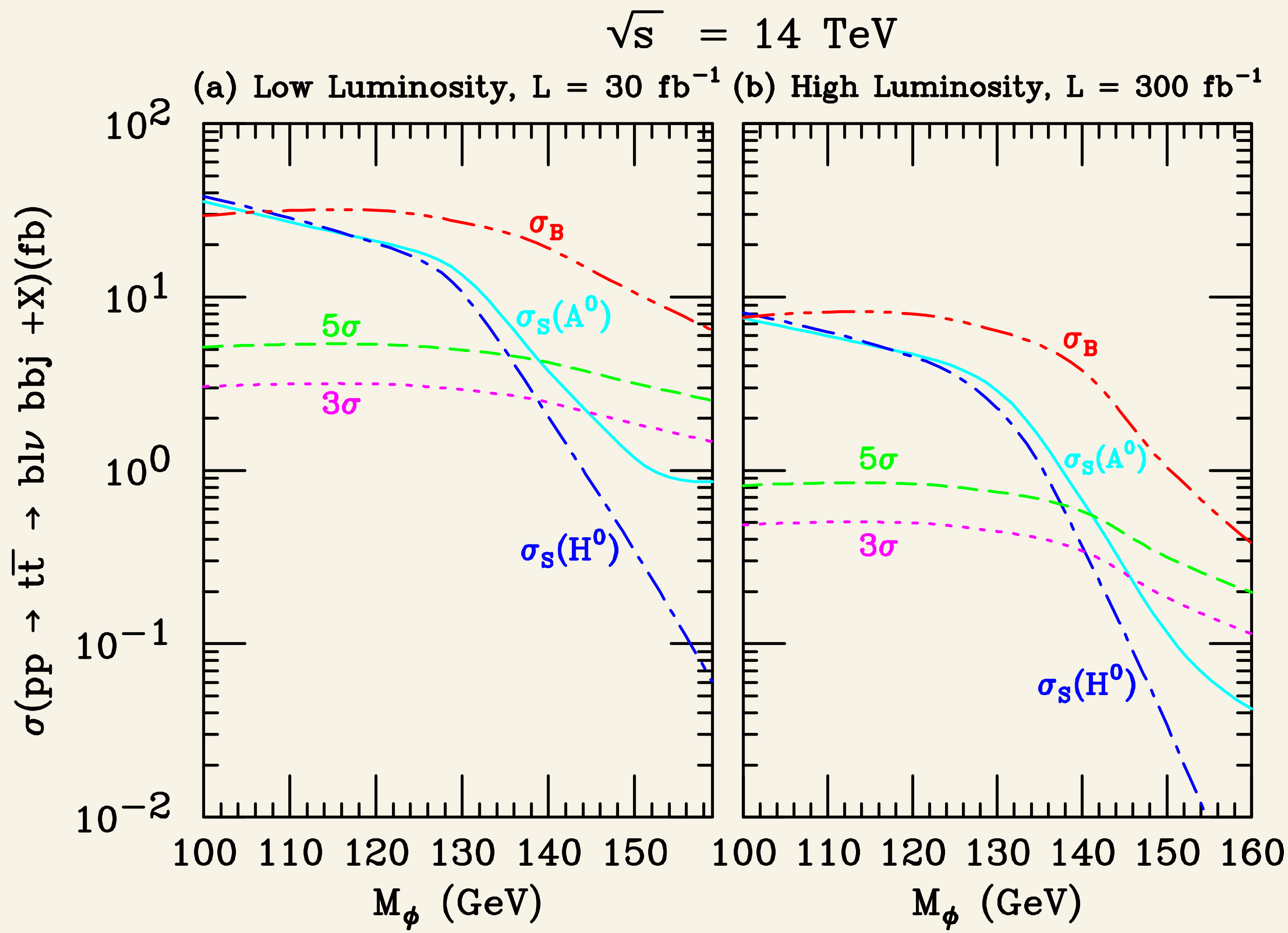
Han, Jiang, and Sher (2001)



Signal versus Background

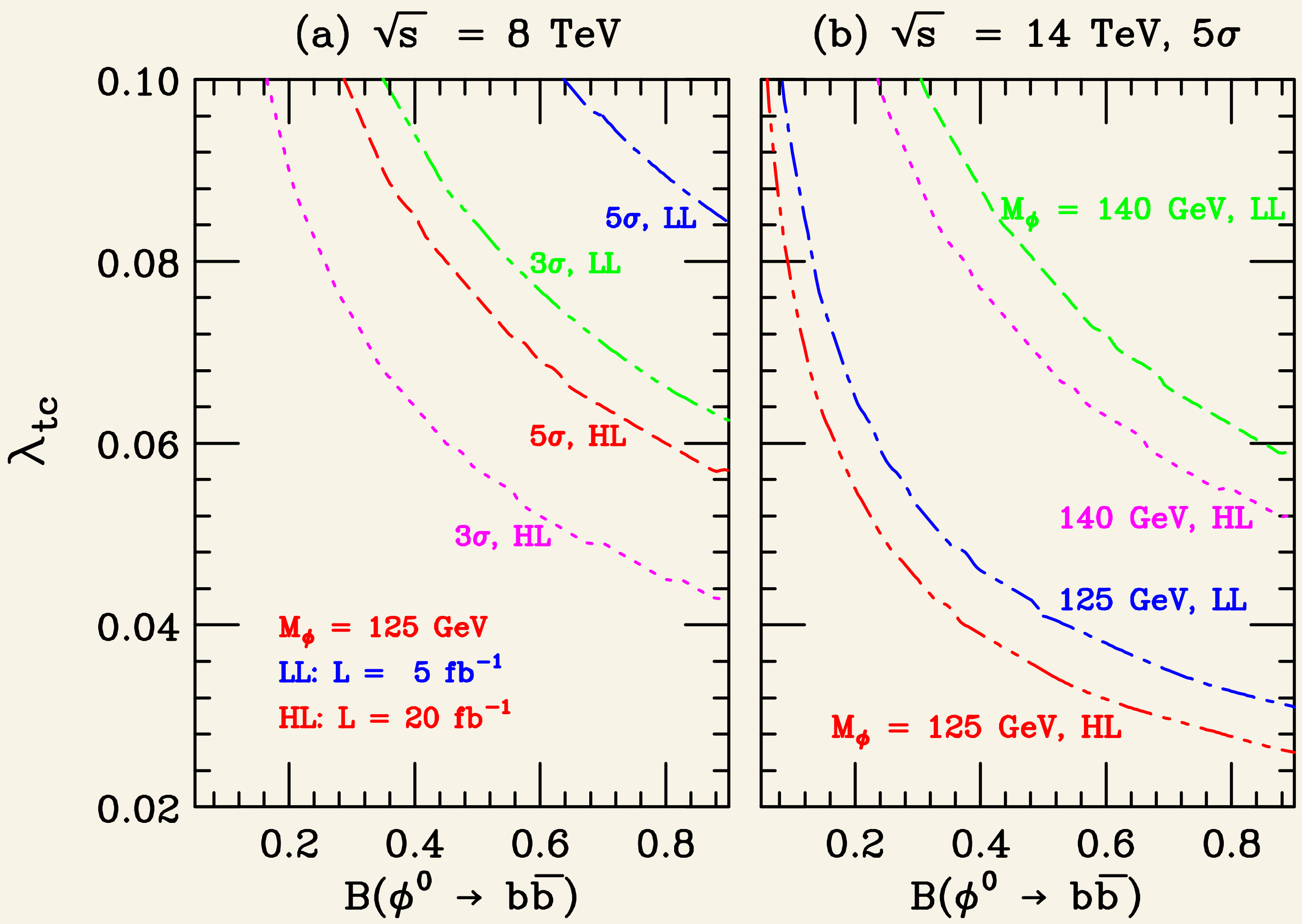


Signal versus Background

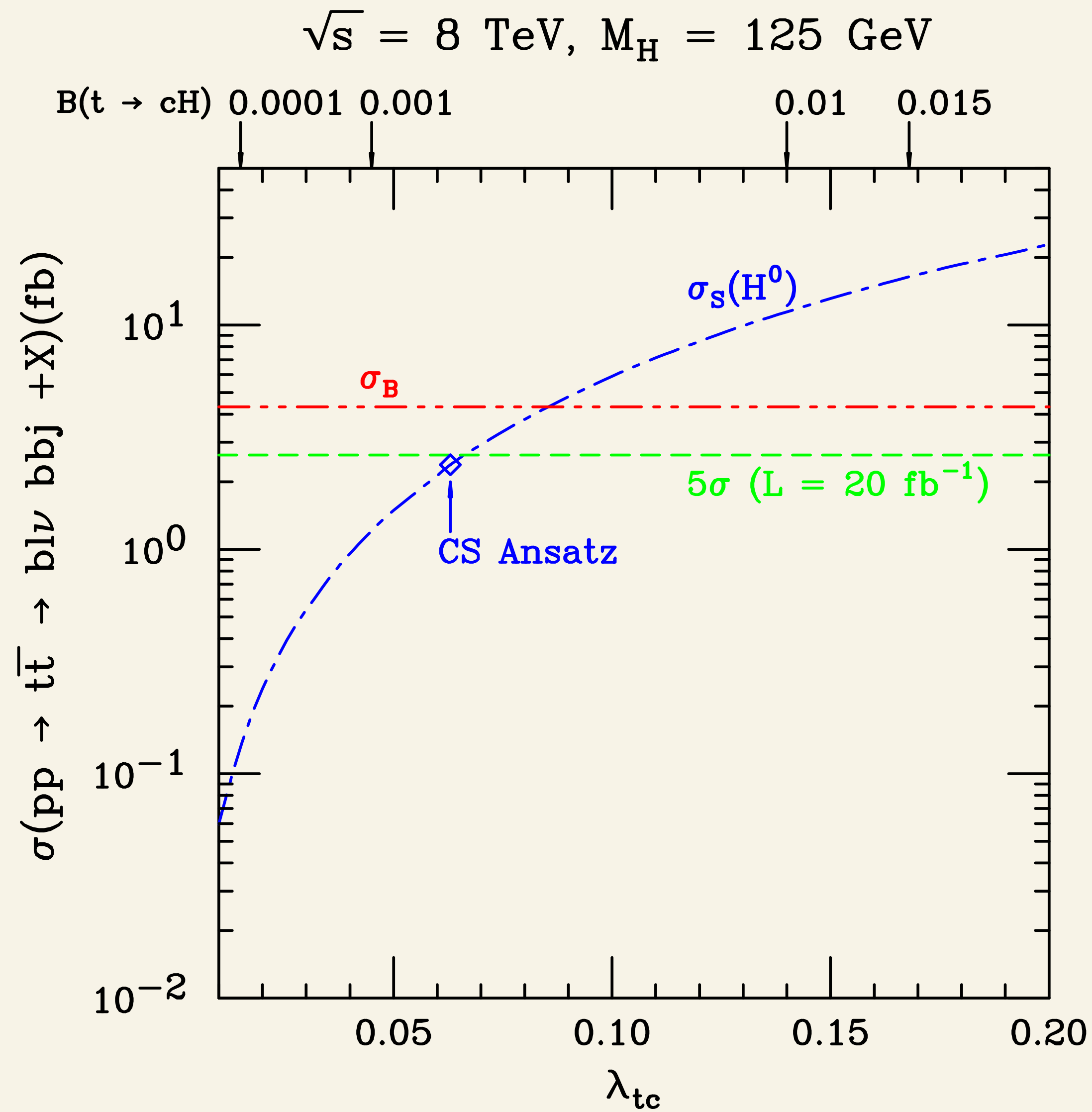


Discovery Contours

L = 20 fb^{-1} at 8 TeV; 30 fb^{-1} at 14 TeV



Discovery Potential with 8 TeV



Conclusions

- It is of great interest to search for the link between the top quark (t) and the Higgs boson (h^0).
- A discovery of the t to ch^0 process with present data would suggest the existence of an extended Higgs sector beyond the usual 2HDM-II and MSSM.
- Actual experimental studies, incorporating h^0 to bb, ZZ*, WW*, and $\tau^+\tau^-$ modes, will provide important information for the FCNH couplings.
- We might find out if nature chooses the same mechanism for electroweak symmetry breaking and tree-level FCNC.

Bonus Slides

Realistic Acceptance Cuts

For (a) the early LHC and (b) full CM energy with low luminosity, we require that in every event there should be

- exactly 4 jets that have $p_T > 15$ GeV and $|\eta| < 2.5$, and three of them must be tagged as b-jets;
- exactly one isolated lepton with $p_T > 20$ GeV and $|\eta| < 2.5$;
- the missing transverse energy must be greater than 20 GeV;
- at least one pair of b-jets such that the invariant mass of $b_1 b_2 j$ should be near m_t: $|M_{b_1 b_2 j} - m_t| \leq 25$ GeV;
- the pair of b-jets, $b_1 b_2$, that reconstructs the hadronically decaying top should also satisfy $|M_{b_1 b_2} - M_\phi| \leq 0.15 M_\phi$;
- a third b jet such that the invariant mass of $b_3 \ell \nu$ should be near m_t: $|M_{b_3 \ell \nu} - m_t| \leq 25$ GeV;
- the reconstructed W must satisfy $|M_{\ell\nu} - m_W| \leq 15$ GeV.

Comparison of Production Rates with H_T(jets+leptons)

Kao, Cheng, Hou, and Sayre (2012)

(Aguilar-Saavedra and Branco [2000])

	Low Luminosity (10 fb^{-1})		High Luminosity (100 fb^{-1})	
	Before Cuts	Standard Cuts	Before Cuts	Standard Cuts
Signal	200 (267)	46.7 (98.2)	1630 (2150)	394 (797)
$t\bar{t}$	5491 (7186)	20.2 (33.2)	44540 (58230)	174 (270)
$Wbbjj$	58 (77)	0.232 (0.3)	476 (644)	2.00 (2.2)

Comparison of Production Rates with H_T(jets)

Kao, Cheng, Hou, and Sayre [2012]

(Aguilar-Saavedra and Branco [2000])

	Low Luminosity (10 fb^{-1})		High Luminosity (100 fb^{-1})	
	Before Cuts	Standard Cuts	Before Cuts	Standard Cuts
Signal	200 (267)	30.4 (98.2)	1630 (2150)	251 (797)
$t\bar{t}$	5491 (7186)	10.1 (33.2)	44540 (58230)	83.9 (270)
$Wbbjj$	58 (77)	0.085 (0.3)	476 (644)	0.680 (2.2)