When the Higgs Meets the Top

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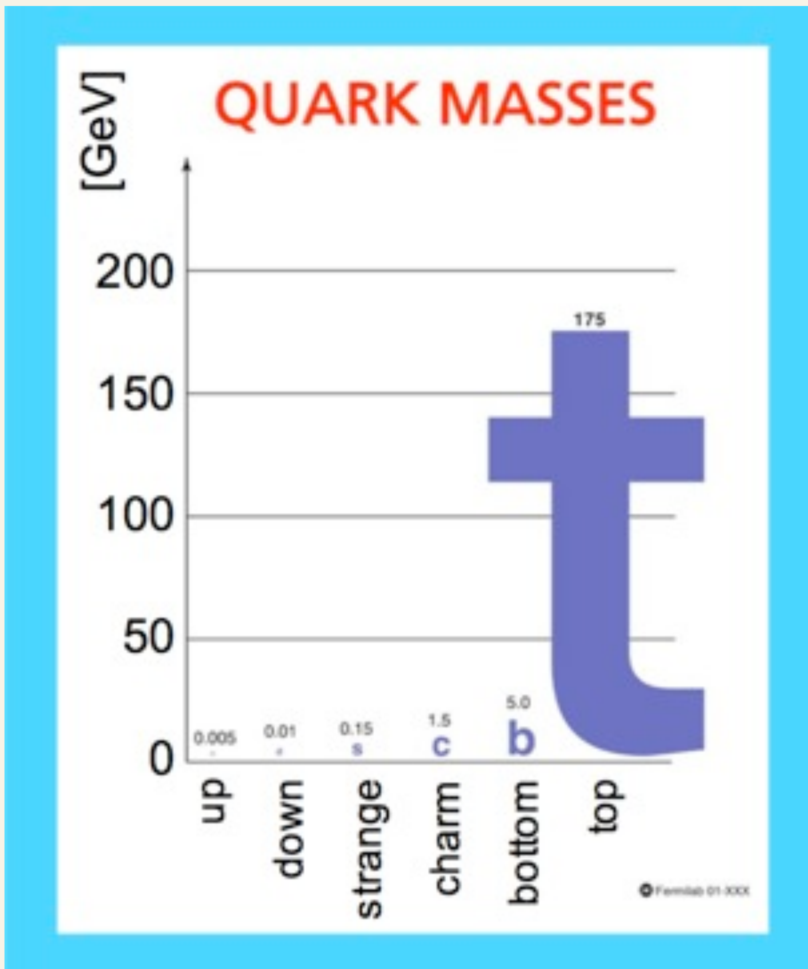
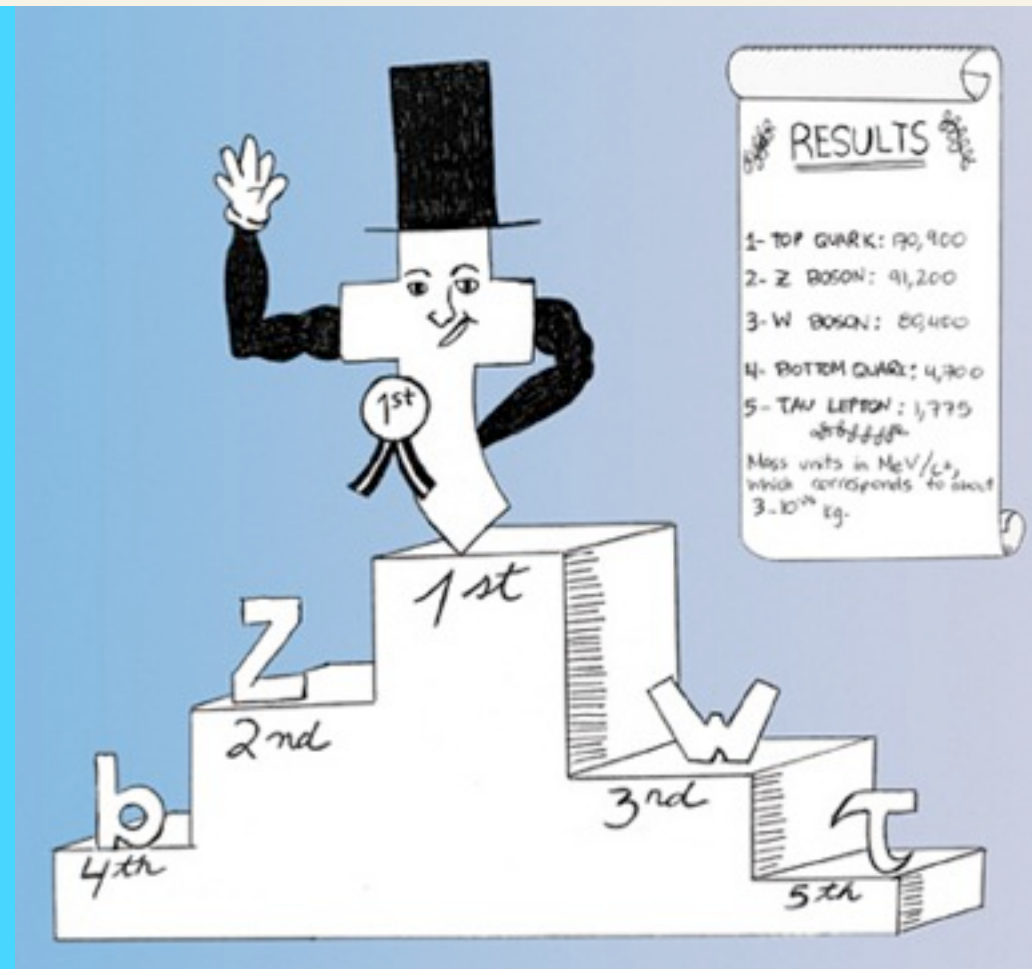
Chen, Hou, Kao, and Kohda, Phys. Lett. B 725, 378 (2013) arXiv:1304.8037;
Kao, Cheng, Hou, and Sayre, Phys. Lett. B 716 (2012) 225.

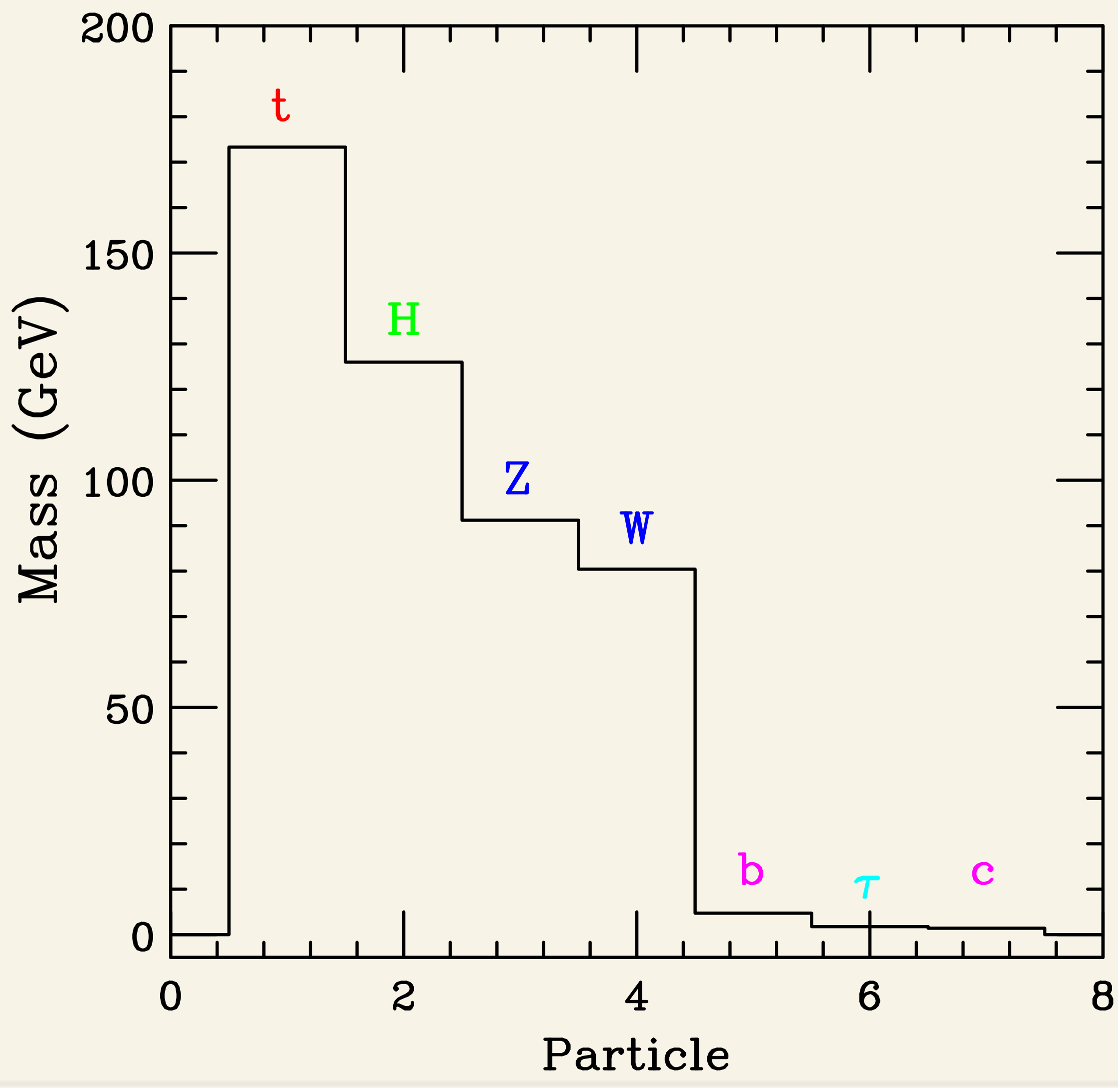
- Introduction and Motivation
- Type III Two Higgs Doublet Models
- The Top Two Higgs Doublet Model
- Flavor Changing Neutral Higgs Boson in Top Decays
- The Discovery Potential at the LHC with bb
- Constraint from the Golden Mode
- Conclusions

Heavyweight Champion before July 4, 2012





The New Runner-up



When the Higgs meets the Top: Search for $t \to ch^0$ at the LHC

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The Higgs boson h^0 and the top quark t are the two most *massive* and *newest* particles ever discovered. If $t \to ch^0$ occurs at the level of a percent or so, the observed ZZ^* and $\gamma\gamma$ signal events may have accompanying cbW activity coming from $t\bar{t}$ feeddown. A general two Higgs doublet model brings in new ct, cc and tt couplings that modify properties of the light Higgs h^0, and $t \to ch^0$ can be searched for via $h^0 \to ZZ^*$, $\gamma\gamma$, WW^* and $b\bar{b}$ (even $\tau^+\tau^-$) modes in $t\bar{t}$ events. Existing data might be able to show some clues for $t \to ch^0$ signature, or should provide important information for $\mathcal{B}(t \to ch^0)$ down to below the percent level.

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<u>*Introduction and Motivation*</u>

With the landmark discovery [1, 2] of a 126 GeV boson in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC), efforts have shifted towards Higgs property studies, to confirm that this is indeed the Higgs boson of the Standard Model (SM), or to find deviations indicating that it may not be *the* Higgs boson. In this connection, we stress that the Higgs boson and the top quark are the two most *massive*, as well as *newest*, particles ever discovered. With the Higgs boson as the "mass giver", it is natural to ask whether it reveals any special effects associated with the heaviness of the top quark. A related question is, analogous to the generation repetition seen with fermions, if we have seen one Higgs boson, could there be others.

We wish to explore a possible tch^0 coupling, where h^0 stands for the 126 GeV boson. Absent within SM, this coupling has not been the focus of attention. At the one loop level, the SM branching ratio (for $m_{h^0} = 120$ GeV) $\mathcal{B}(t \to ch^0) \simeq 4.6 \times 10^{-14}$ [3] is extremely suppressed. But with $m_{h^0} < m_t$, $t \to ch^0$ decay [4–7] can readily be searched for in $t\bar{t}$ production. In the post-discovery era, we must search for $t \to ch^0$ at the LHC as part of the Higgs, and top, property programs.

the Cheng-Sher ansatz that $t \to ch^0$ (or $h^0 \to t\bar{c}$) decay was first proposed [4] as the leading effect.

To account for the BaBar anomaly, the FCNH coupling ρ_{ct} of the exotic heavy Higgs doublet need to be of order 1 in strength [9]. For our purpose, keeping notation of the usual 2HDM-II [12], the observed boson h^0 may contain a small admixture $\cos(\beta-\alpha)$ of the exotic neutral Higgs, hence the tch^0 coupling [13]

$$\rho_{ct} \cos(\beta-\alpha)\,\bar{c}th^0 + \text{h.c.}, \qquad (1)$$

which can induce $t \to ch^0$ decay. In Fig. 1 we illustrate the branching ratio $\mathcal{B}(t \to ch^0)$ vs $\rho_{ct}\cos(\beta-\alpha)$. The question is: Considering all available data, what is the allowed $\mathcal{B}(t \to ch^0)$, or equivalently, $\rho_{ct}\cos(\beta-\alpha)$ value? What are the signatures to pursue?

We note that, if we take $\rho_{ct} \sim 1$, which is not quite explored because it is suppressed by $\cos(\beta-\alpha)$ for couplings involving h^0 (but not suppressed for couplings involving the heavy exotic Higgs bosons H^0, A^0 and $H^\pm$), then the analogous parameters ρ_{tt}, ρ_{cc}, ρ_{bb} and $\rho_{\tau\tau}$ will enter the Higgs property study program, as we shall elucidate. An existing study of multi-lepton final states finds a bound [7] of $\mathcal{B}(t \to ch^0) < 2.7\%$. But this should be

Implications of B to D*τν Anomaly

BaBar Collaboration (2012). Fajfer, Kamenik, Nisandzic and Zupan (2012); Crivellin, Greub and Kokulu (2012) & (2013).

The BaBar experiment measured the ratios $\mathcal{R}(D^{(*)}) = \Gamma(\bar{B} \to D^{(*)}\tau\nu)/\Gamma(\bar{B} \to D^{(*)}\ell\nu)$, finding them both larger than SM expectations, with a combined significance of 3.4σ.

- In the type II 2HDM, this implied that $\tan\beta/m_{H^+} = 0.44 \pm 0.02\ \mathrm{GeV}^{-1}$ and $0.75 \pm 0.04\ \mathrm{GeV}^{-1}$ from $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, respectively.
- The two numbers are incompatible with each other, hence "excludes the 2HDM-II charged Higgs boson with a 99.8% confidence level for any value of $\tan\beta/m_{H^+}$".
- Either $\tan\beta/m_{H^+}$ value, however, would over-enhance $B \to \tau\nu$, which is found in agreement with SM expectation, spelling further trouble.

Type III Yukawa Interactions

Mahmoudi and Stal (2009)

We shall use the following notation for the Yukawa couplings of the 2HDM-III Higgs sector

$$\mathcal{L} = -\frac{1}{\sqrt{2}} \sum_{f=}^{u,d,\ell} \bar{f} \left[\left(\kappa^f s_{\beta-\alpha} + \rho^f c_{\beta-\alpha} \right) h^0 + \left(\kappa^f c_{\beta-\alpha} - \rho^f s_{\beta-\alpha} \right) H^0 - i\,\mathrm{sgn}(Q_f) \rho^f \gamma_5 A^0 \right] f - \left[\bar{u} \left(V \rho^d R - \rho^u V L \right) d H^+ + \bar{\nu} \rho^\ell R \ell H^+ + \mathrm{H.c.} \right],$$

where $s_{\beta-\alpha}$ and $c_{\beta-\alpha}$ stand for $\sin(\beta-\alpha)$ and $\cos(\beta-\alpha)$ repectively in the 2HDM-II notation for the sake of comparison.

Implications of BaBar Anomaly for 2HDM-III

- To account for the BaBar anomaly, the FCNH coupling ρ_{ct} of the heavy Higgs doublet needs to be of order 1 in strength.
- The LHC data indicate that $\Gamma(h^0$ to bb) and $\Gamma(h^0$ to $\tau\tau)$ are consistent with SM expectations. Thus ρ_{bb} and $\rho_{\tau\tau}$ must be tiny.
- Then ρ_{tt} and ρ_{cc} could be important in the Higgs property study program.
- Crivellin et al.(2013) suggest $\rho_{cc} < 0.2$ from data of D_s to $\tau\nu$ and D_s to $\mu\nu$.

Data-constrained 2HDM-III

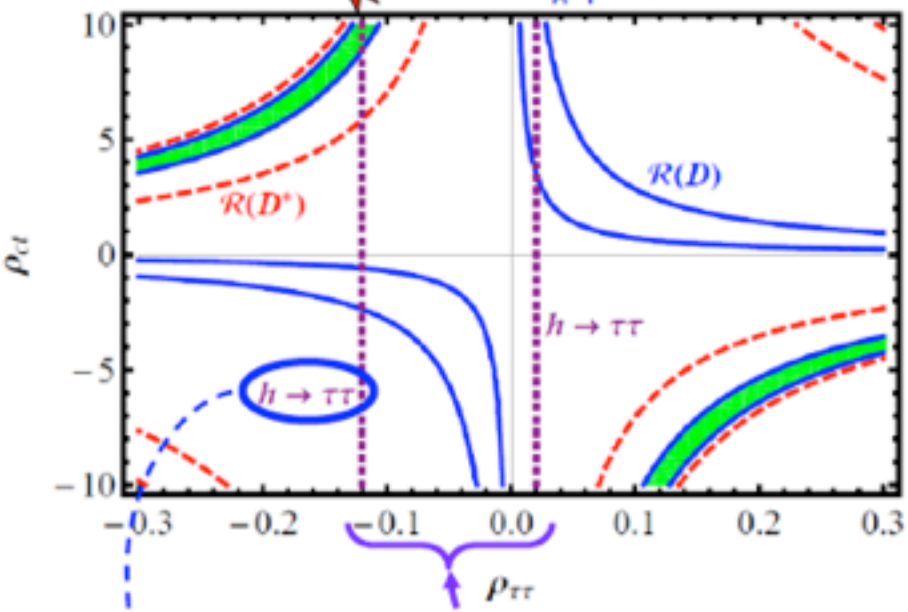
~SM

Higgs → ττ : $\rho_{\tau\tau}$ small

Nonperturb. ρ_{ct} needed

With Regrets, "detach" from BaBar anomaly

m_{H^+} pockets remain



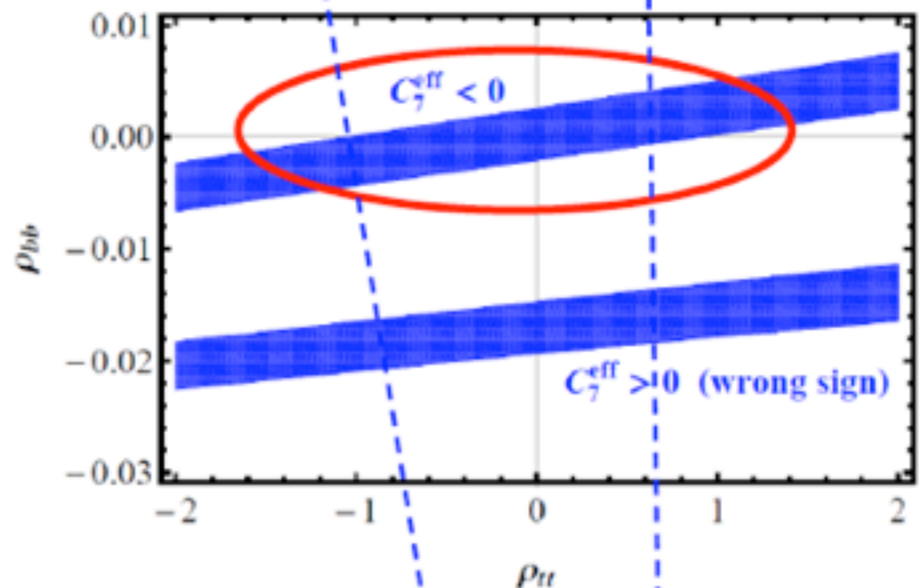
$c_{\beta-\alpha} = 0.2$

$$|s_{\beta-\alpha} + (\rho_{\tau\tau} v/\sqrt{2} m_\tau) c_{\beta-\alpha}| \lesssim \sqrt{2}$$

b → sγ : ρ_{bb} tiny

Because of chiral m_t/m_b and KM enhancement, ρ_{bb} tiny!

$\rho_{ct} = 1$ $\quad m_{H^+} = 700$ GeV



$$\delta C_{7,8} \simeq \frac{1}{3}\left(\rho_{tt} + \frac{V_{cs}^*}{V_{ts}^*}\rho_{ct}\right)\left(\rho_{tt}^* + \frac{V_{cb}}{V_{tb}}\rho_{ct}^*\right)\frac{F^{(1)}_{7,8}(y)}{2m_t^2/v^2} - \left(\rho_{tt} + \frac{V_{cs}^*}{V_{ts}^*}\rho_{ct}\right)\rho_{bb}\frac{F^{(2)}_{7,8}(y)}{2m_t m_b/v^2},$$

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

Chen, Hou, Kao, and Kohda, Phys. Lett. B 725, 378 (2013) arXiv: 1304.8037; Kao, Cheng, Hou, and Sayre, Phys. Lett. B 716 (2012) 225.

- 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

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

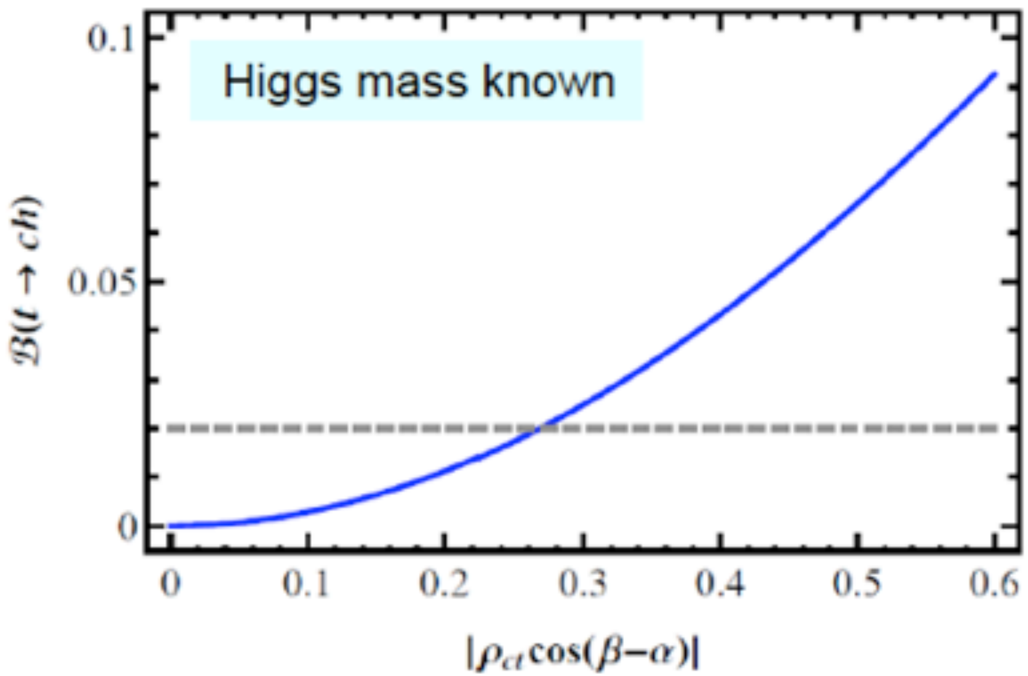
rho$_c$ = m_c/m_t, rho$_H$ = M_H/m_t, + for H^0 and - for A^0.

- The total width is

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

Forbidden Fruit $\mathcal{B}(t \to ch^0)$ vs $\rho_{ct} \cos(\beta - \alpha)$

First discussion: WSH, PLB 1991



2%

How large can ρ_{ct} cos (β–α) be?

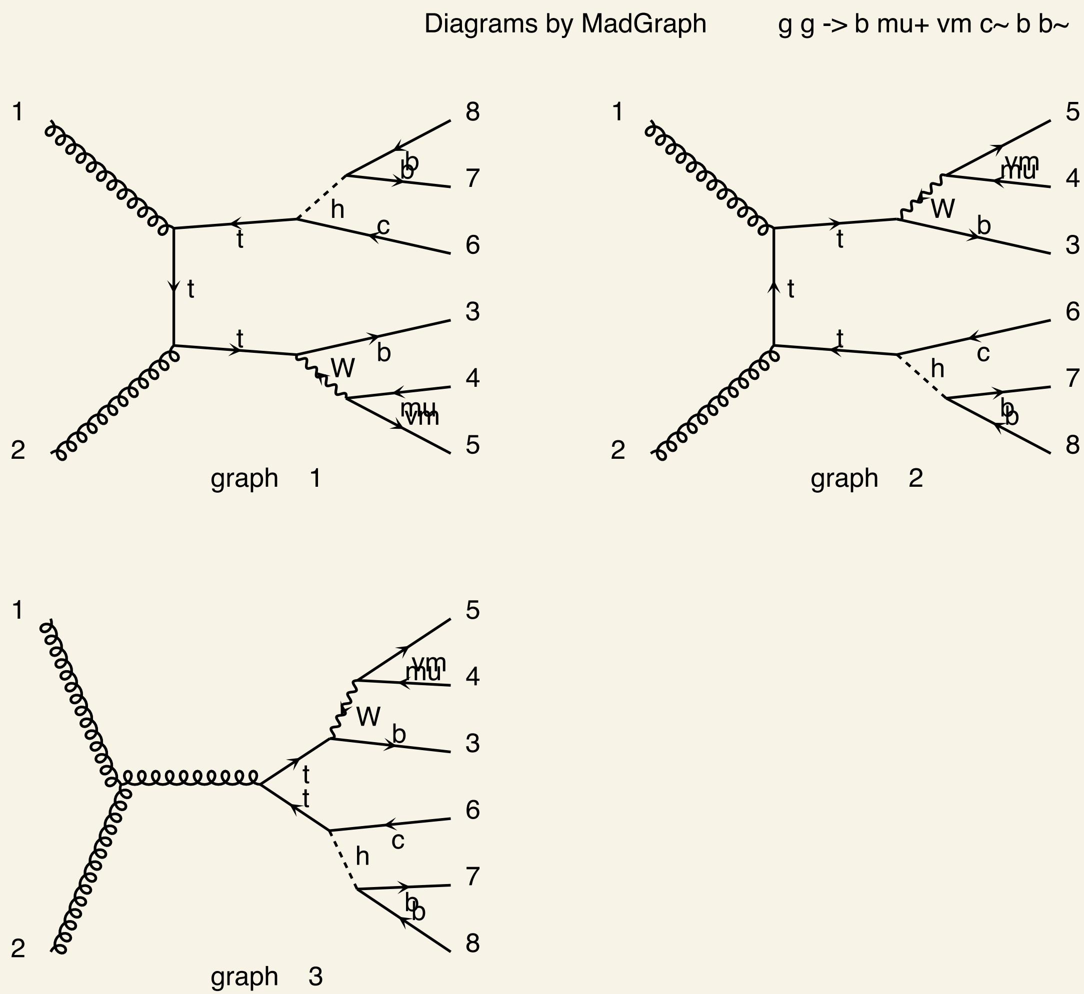
exotic admixture of 126 GeV boson h^0

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

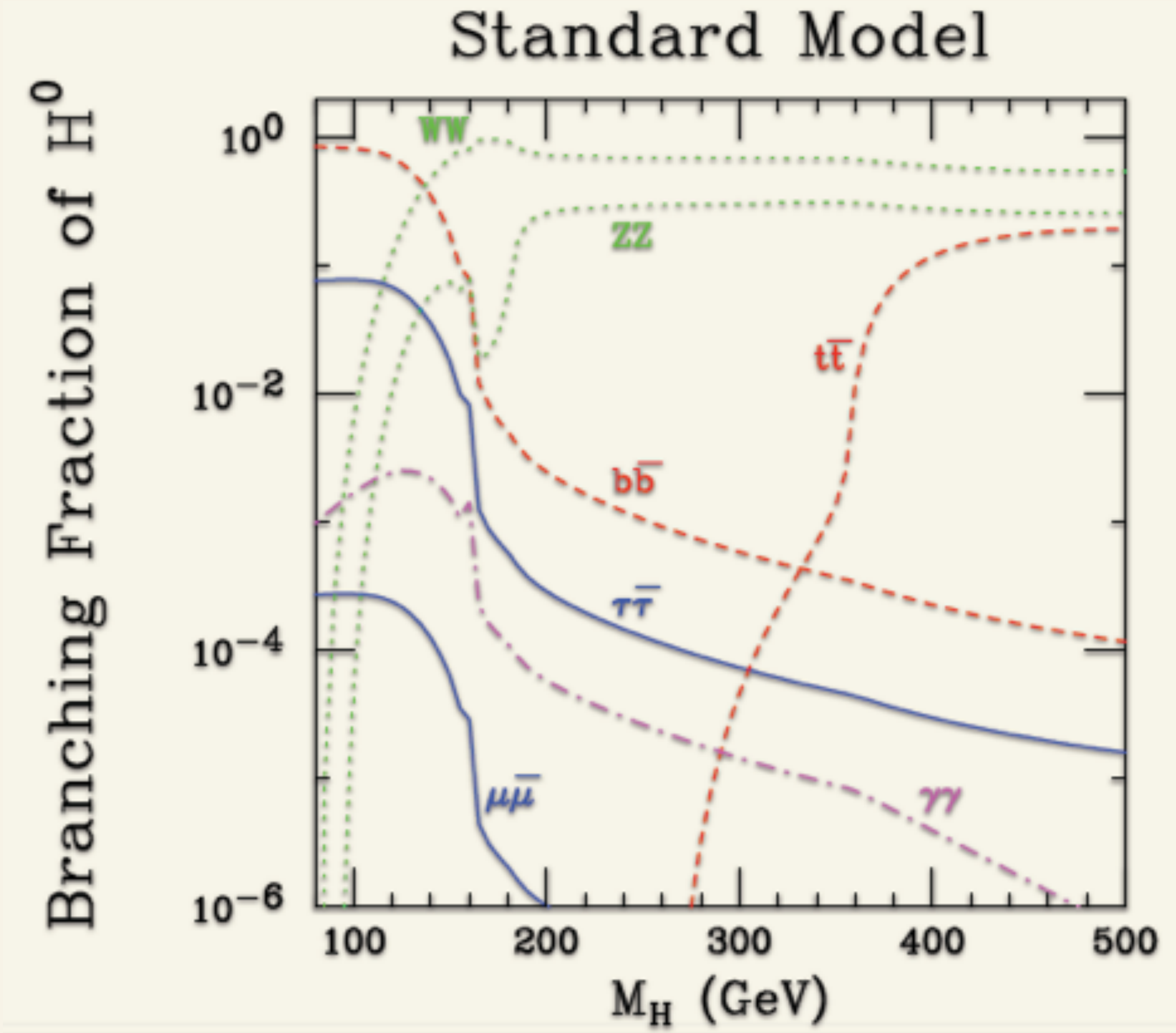


Branching Fractions of the Higgs Boson

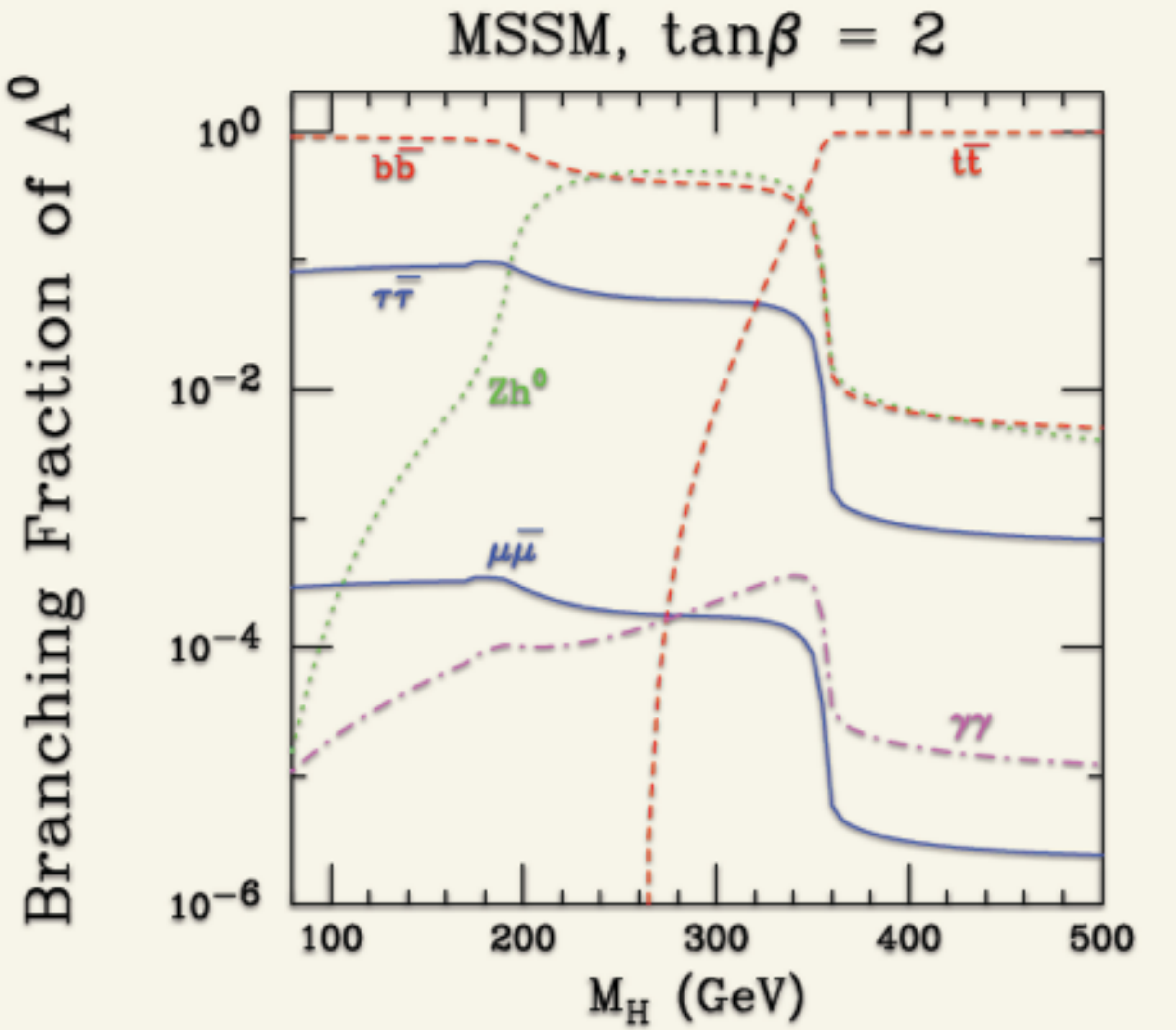
Table 1: Light Higgs h^0 properties in 2HDM-III with $\rho_{ct} \sim 1$. Widths are in MeV units, with $\Gamma_{h^0}^{\rm SM} \simeq 4.55$ MeV.

	$\mathcal{B}^{\rm SM}$	$\Gamma^{\rm SM}$	Γ	Comment
WW^*	21.5%	0.98	hard to change	$\sin(\beta - \alpha) \simeq 1$
ZZ^*	2.7%	0.12	hard to change	$\sin(\beta - \alpha) \simeq 1$
$\gamma\gamma$	0.24%	0.011	hard to change	W-loop dom.
bb	59.4%	2.70	hard to change	$b \to s\gamma$
$\tau\tau$	5.7%	0.26	within fac. 2	direct
cc	2.6%	0.12	up to $\sim \Gamma_{b\bar{b}}$	not measured ($\rho_{cc} \lesssim 0.2$)
gg	7.7%	0.35	up to fac. 2	$\rho_{tt} \sim 1$

Branching Fractions of the Higgs Boson



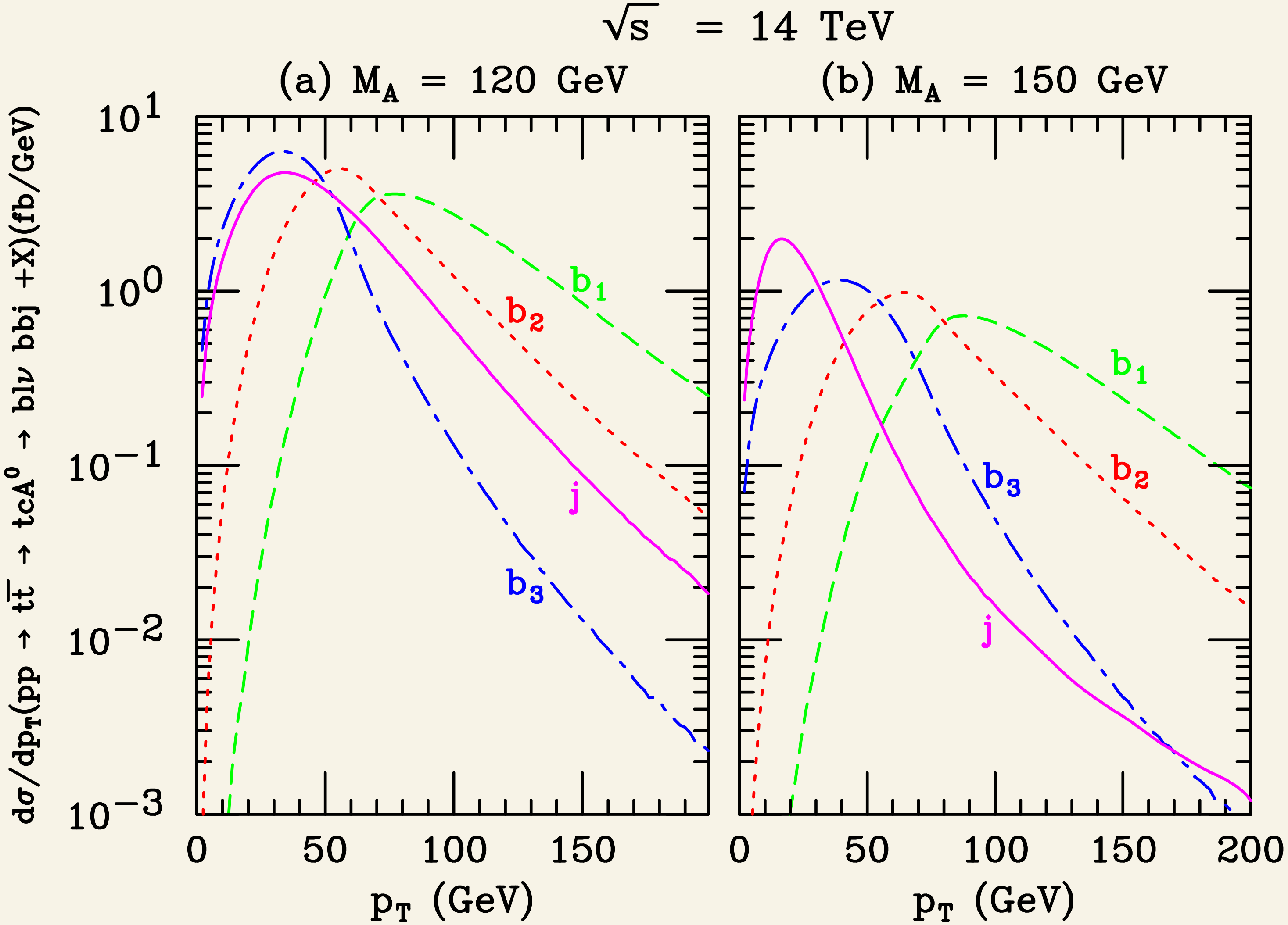
Branching Ratios of a Higgs Pseudoscalar



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

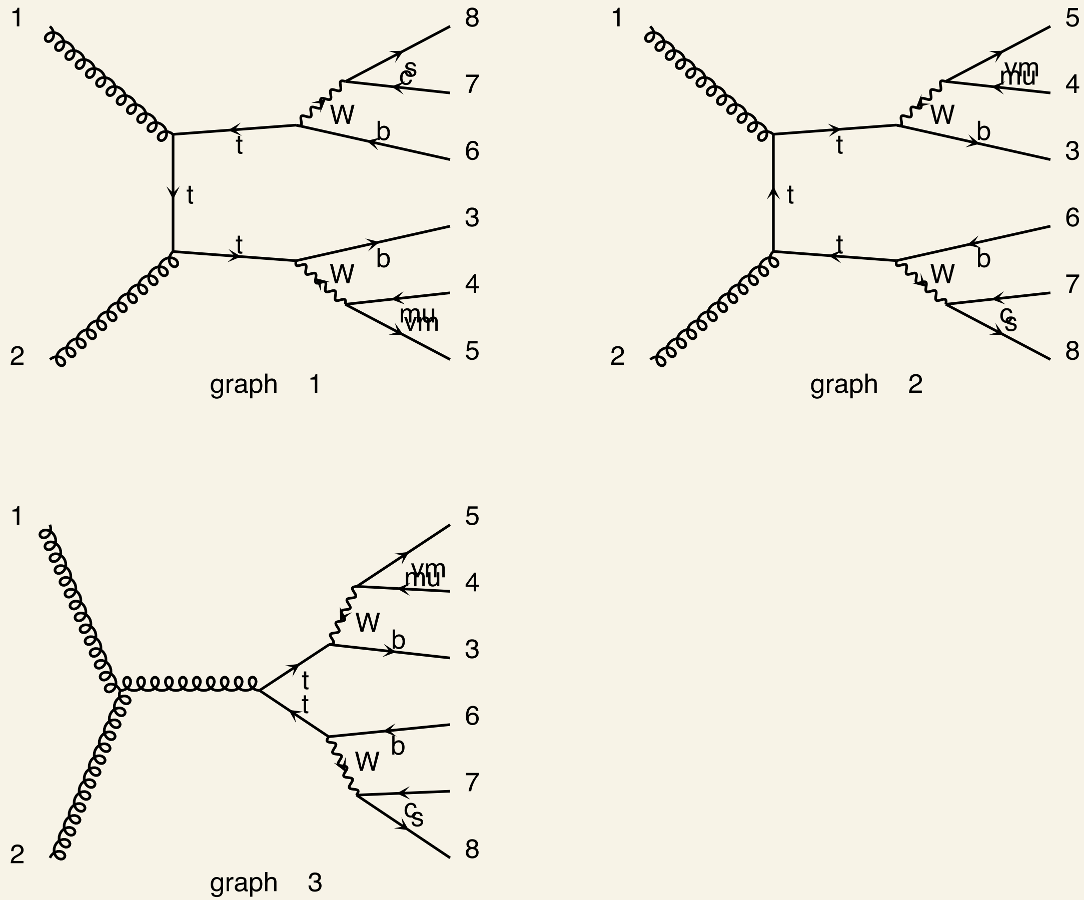


FCNH Signal Cross Section (fb)

- 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

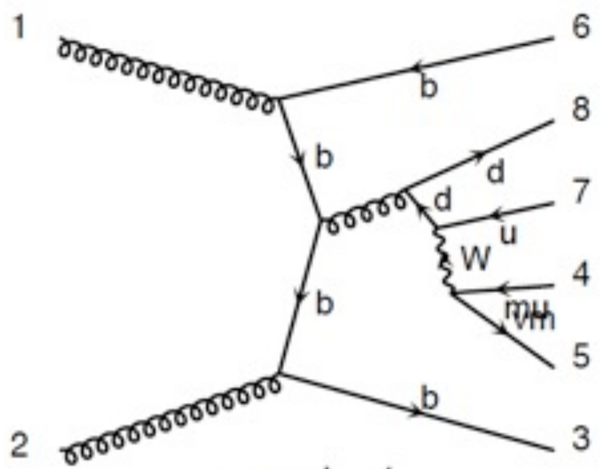
Diagrams by MadGraph   g g -> b mu+ vm b~ c~ s



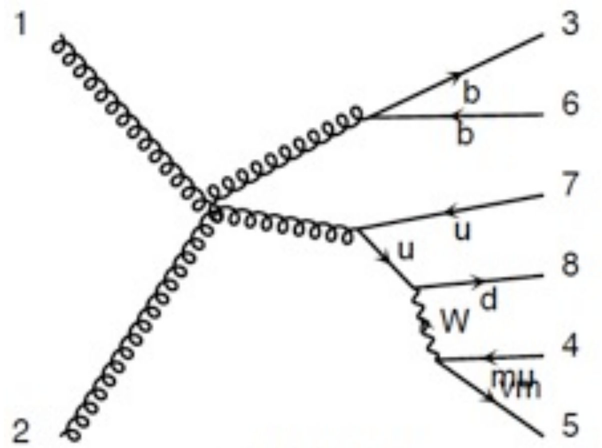
Additional Backgrounds

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

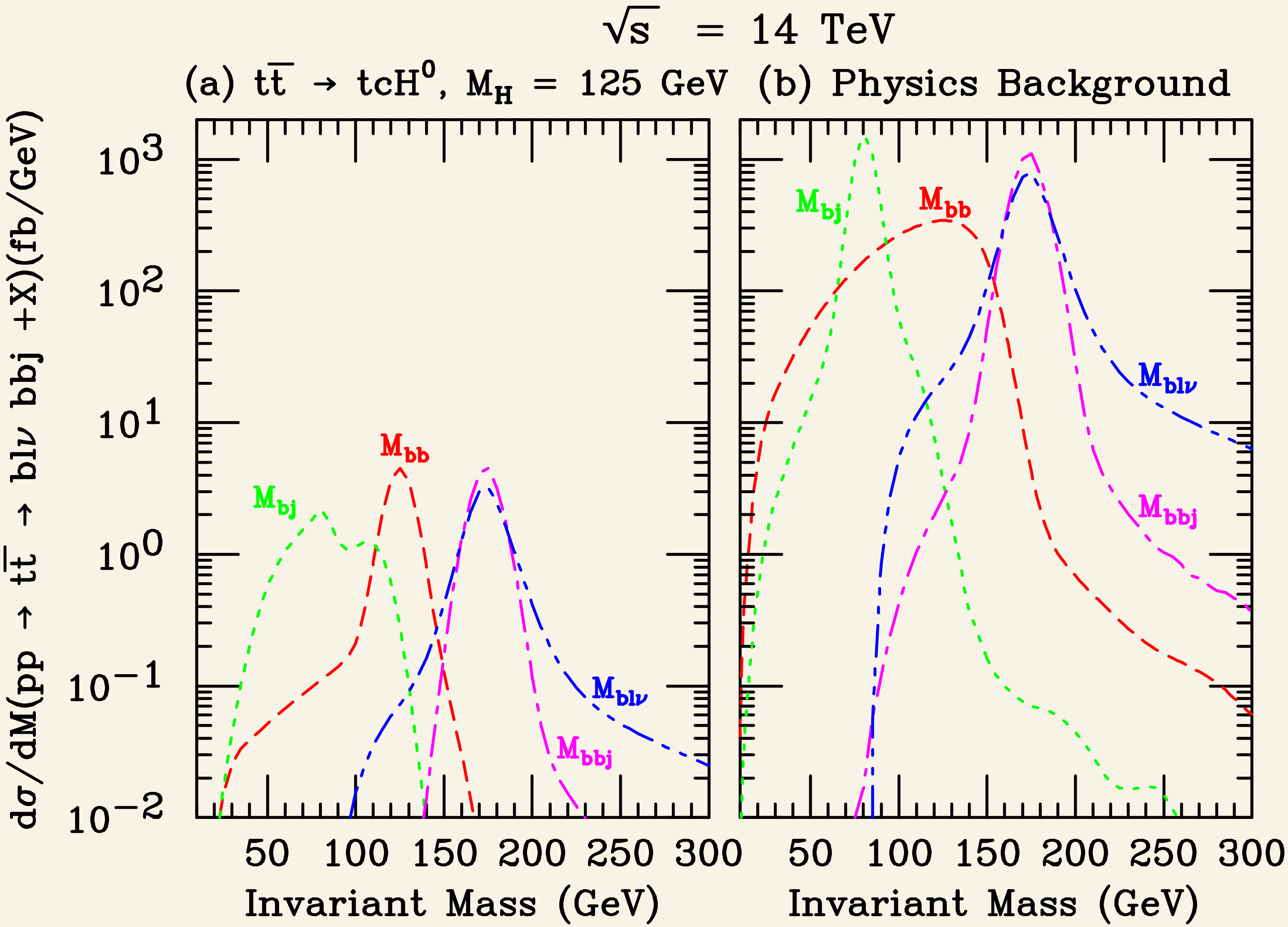


graph 102

Mass Reconstruction

- Since our FCNC signal comes from one top quark decay, we will choose the pair of b jets that minimize $|M_{bbj}-m_t|$ 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 $|M_{bj}-m_{W|}$.
- The remaining b quark (b_3) should reproduce m_t with the charged lepton and neutrino momenta.

Invariant Mass Distributions



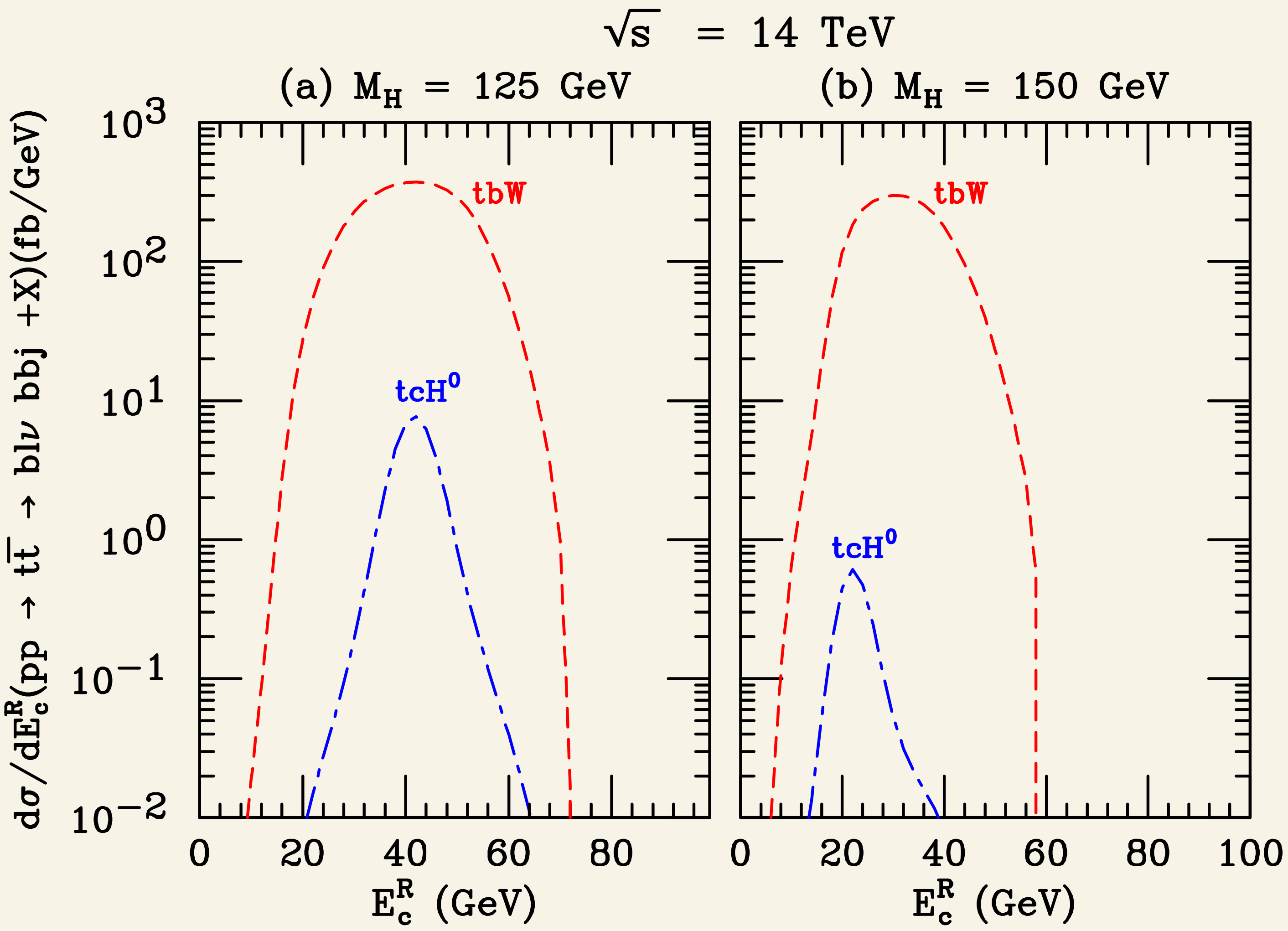
Realistic Acceptance Cuts

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

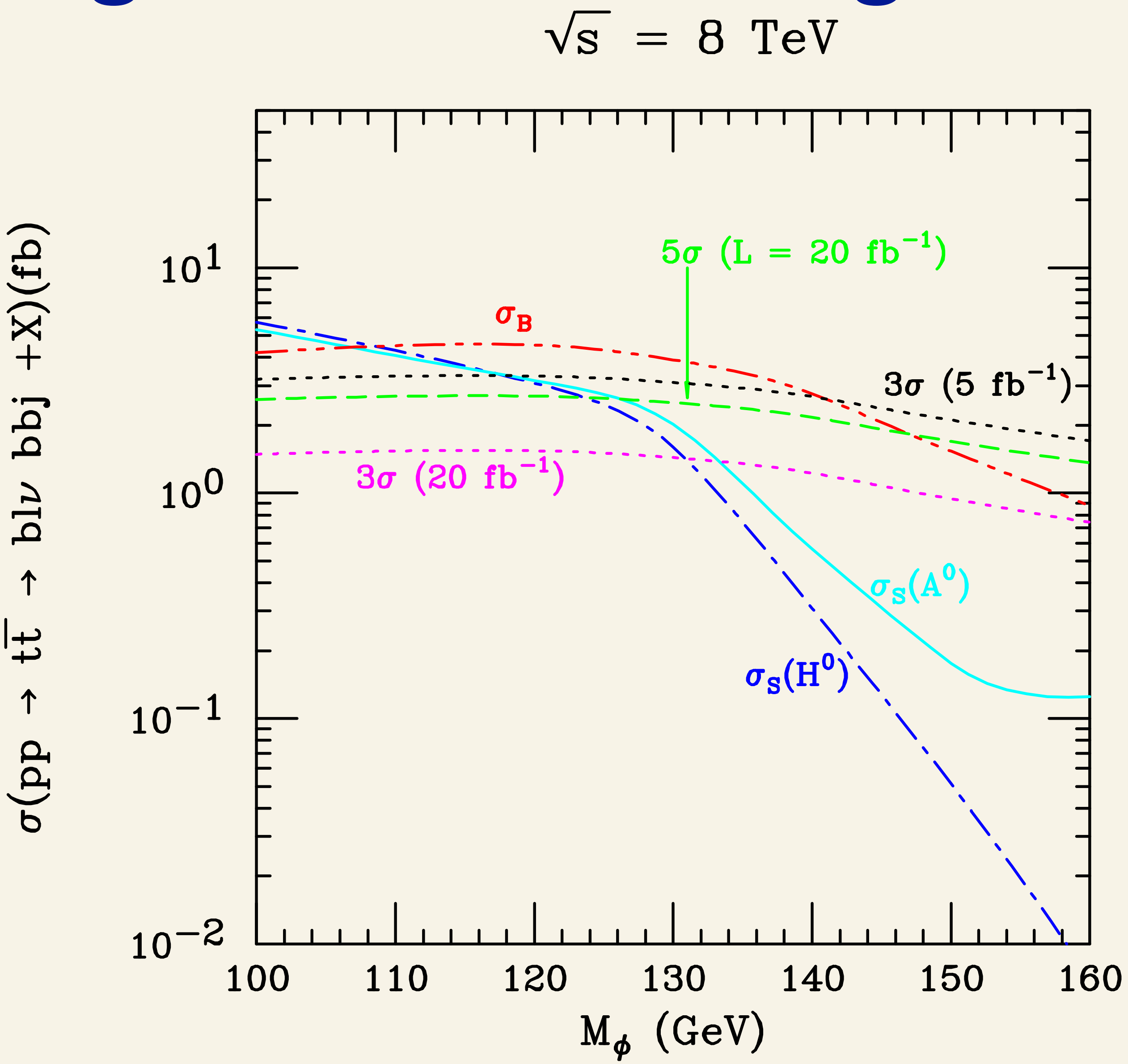
- exactly 4 jets that have $p_T > 15$ GeV and $|\eta| < 2.5$, and three of them must be tagged as b-jets;
- exactly one isolated lepton with $p_T > 20$ GeV and $|\eta| < 2.5$;
- the missing transverse energy must be greater than 20 GeV;
- at least one pair of b-jets such that the invariant mass of $b_1 b_2 j$ 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.

Reconstructed E_{charm}

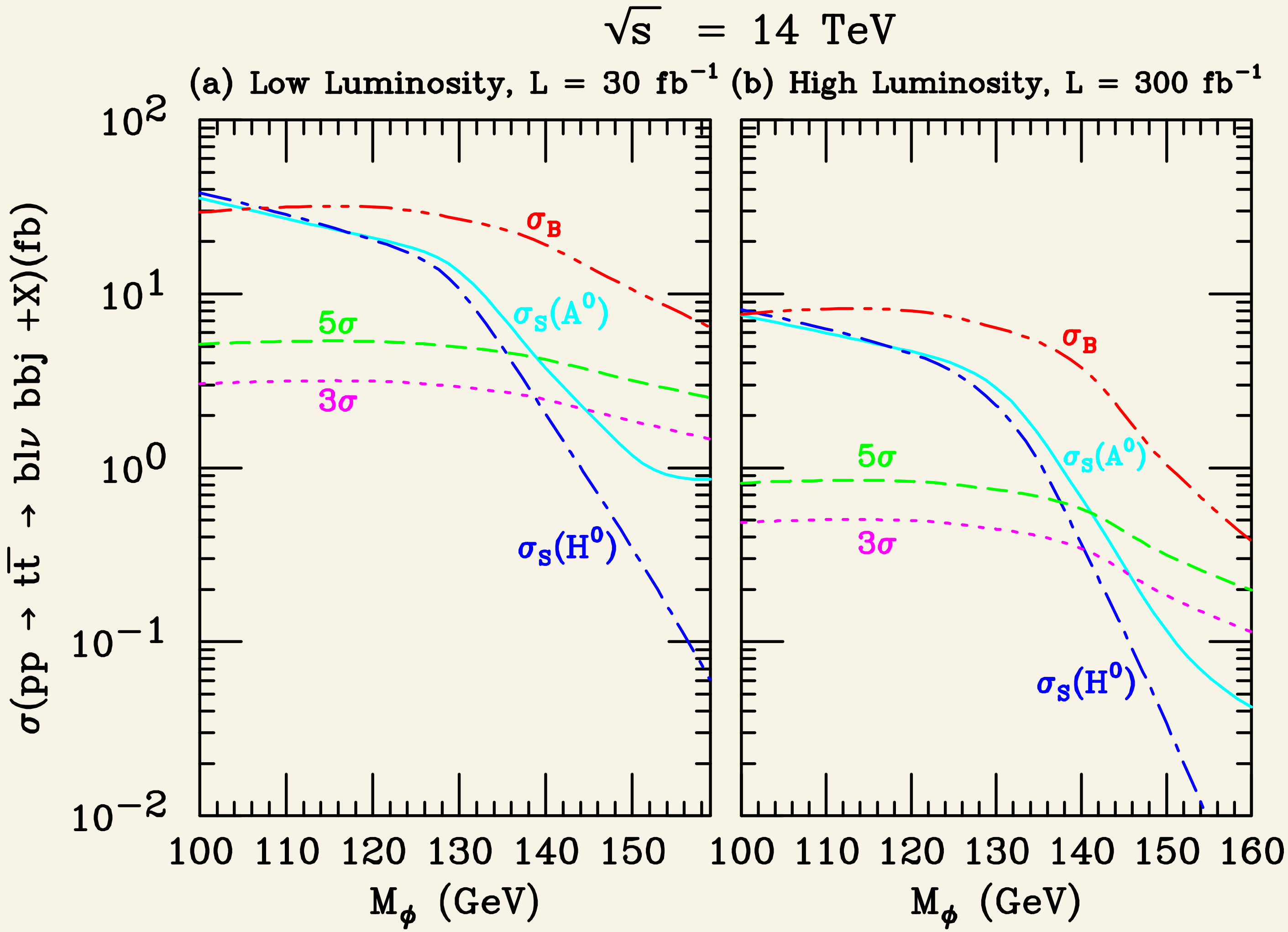
Han, Jiang, and Sher (2001)



Signal versus Background

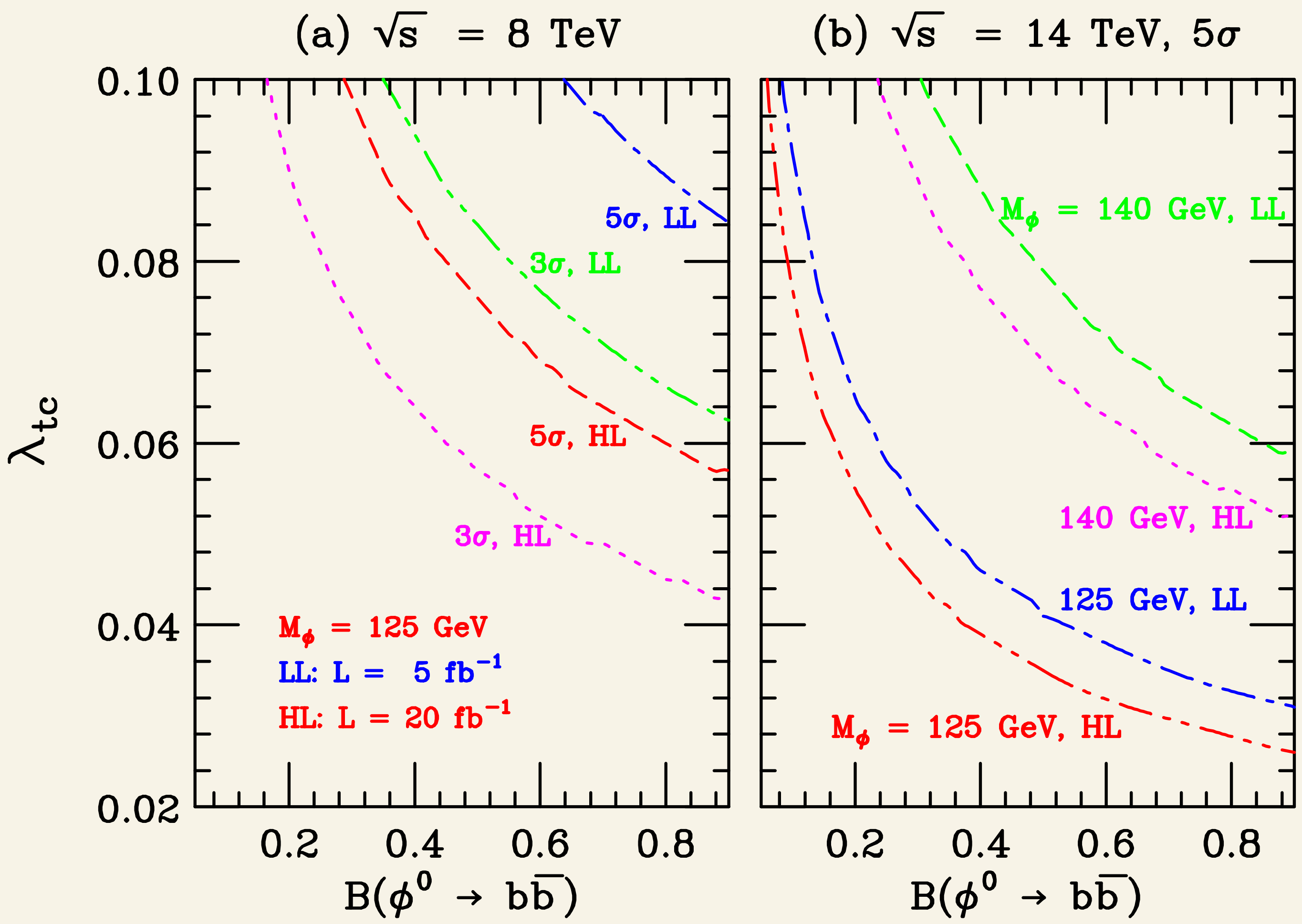


Signal versus Background

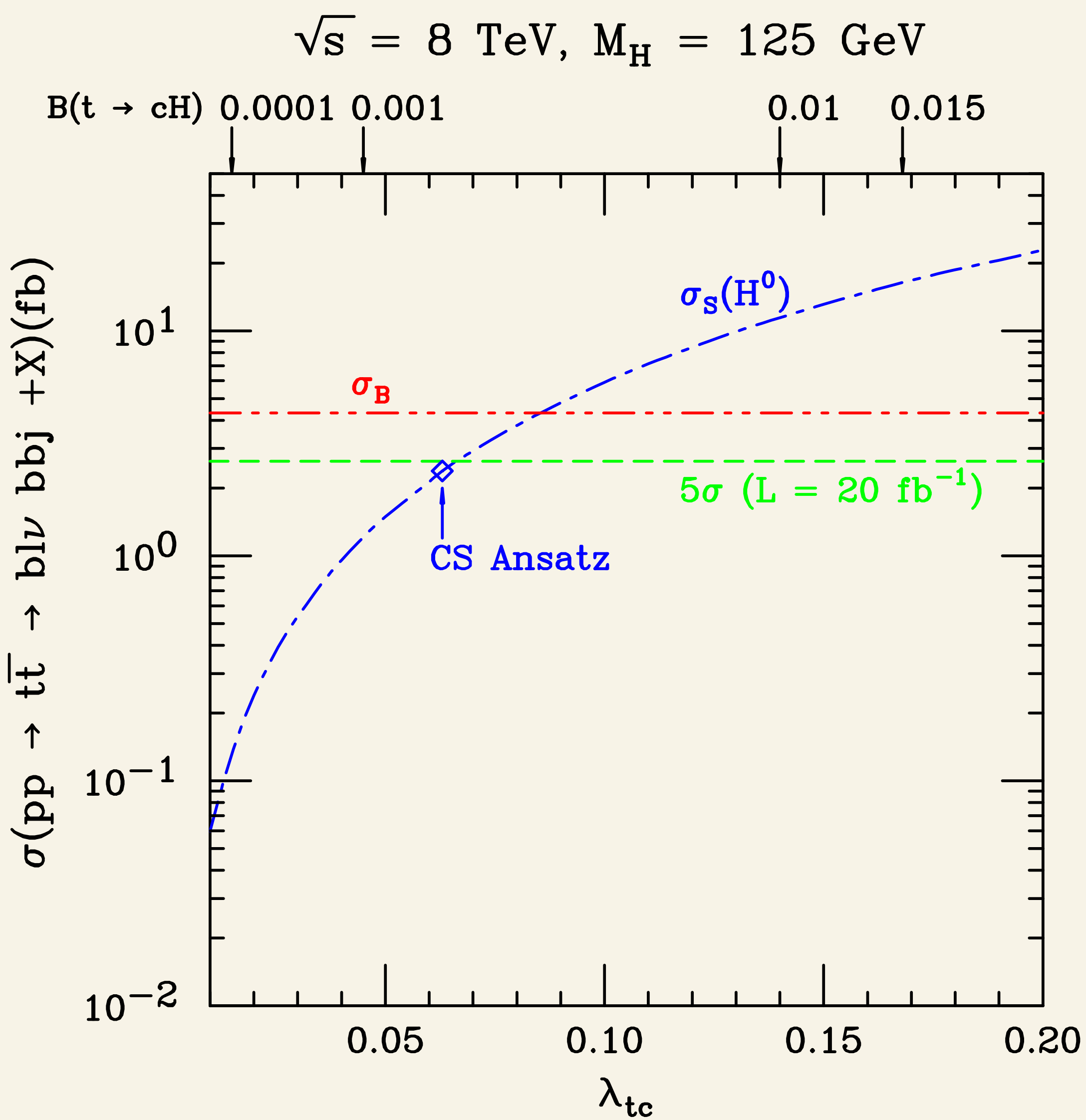


Discovery Contours

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



Discovery Potential with 8 TeV



Comparison of Production Rates with H_T(jets)

Kao, Cheng, Hou, and Sayre [2011]

(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)

Comparison of Production Rates with H_T(jets+leptons)

Kao, Cheng, Hou, and Sayre (2011)

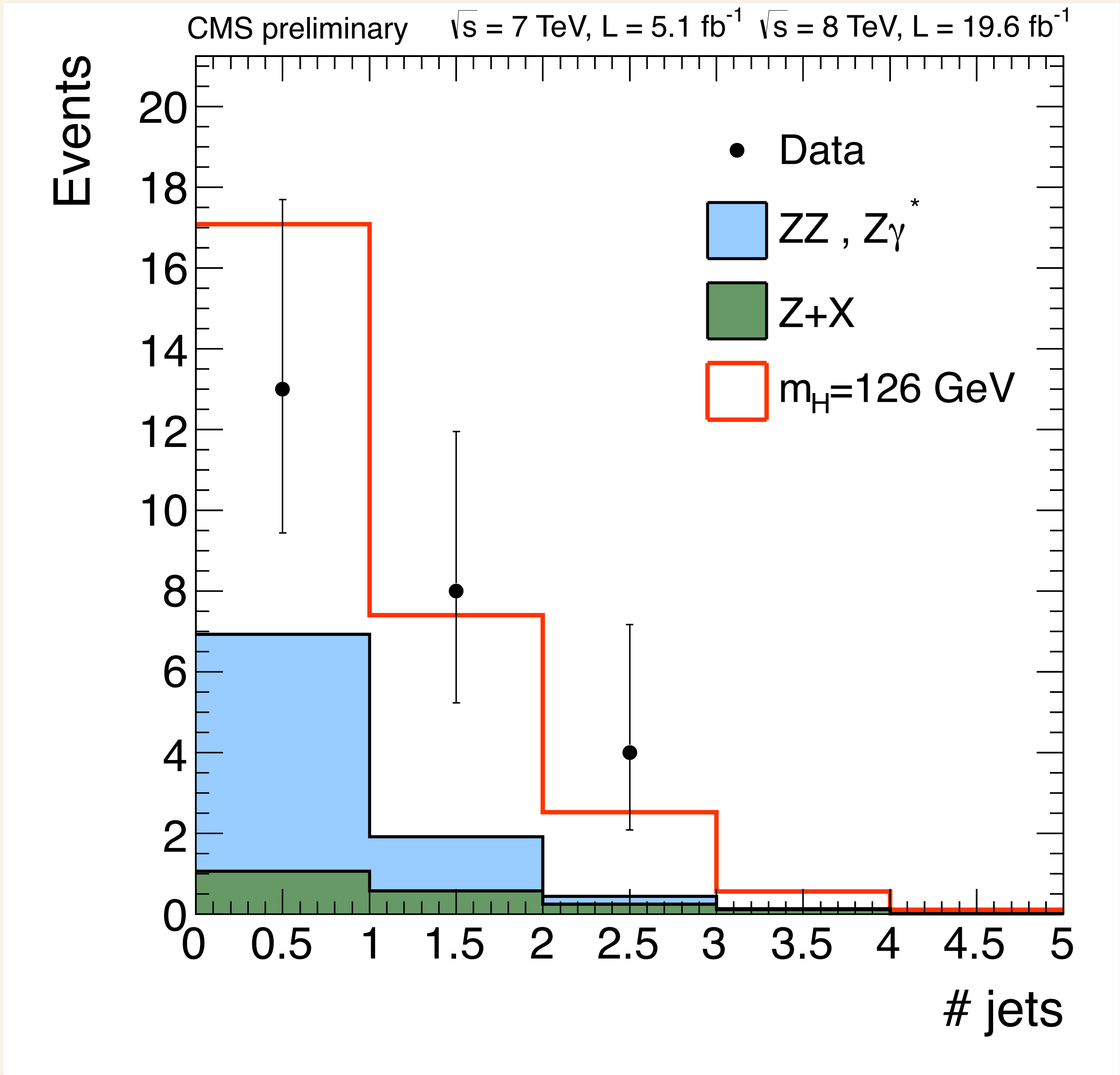
(Aguilar-Saavedra and Branco [2000])

	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)

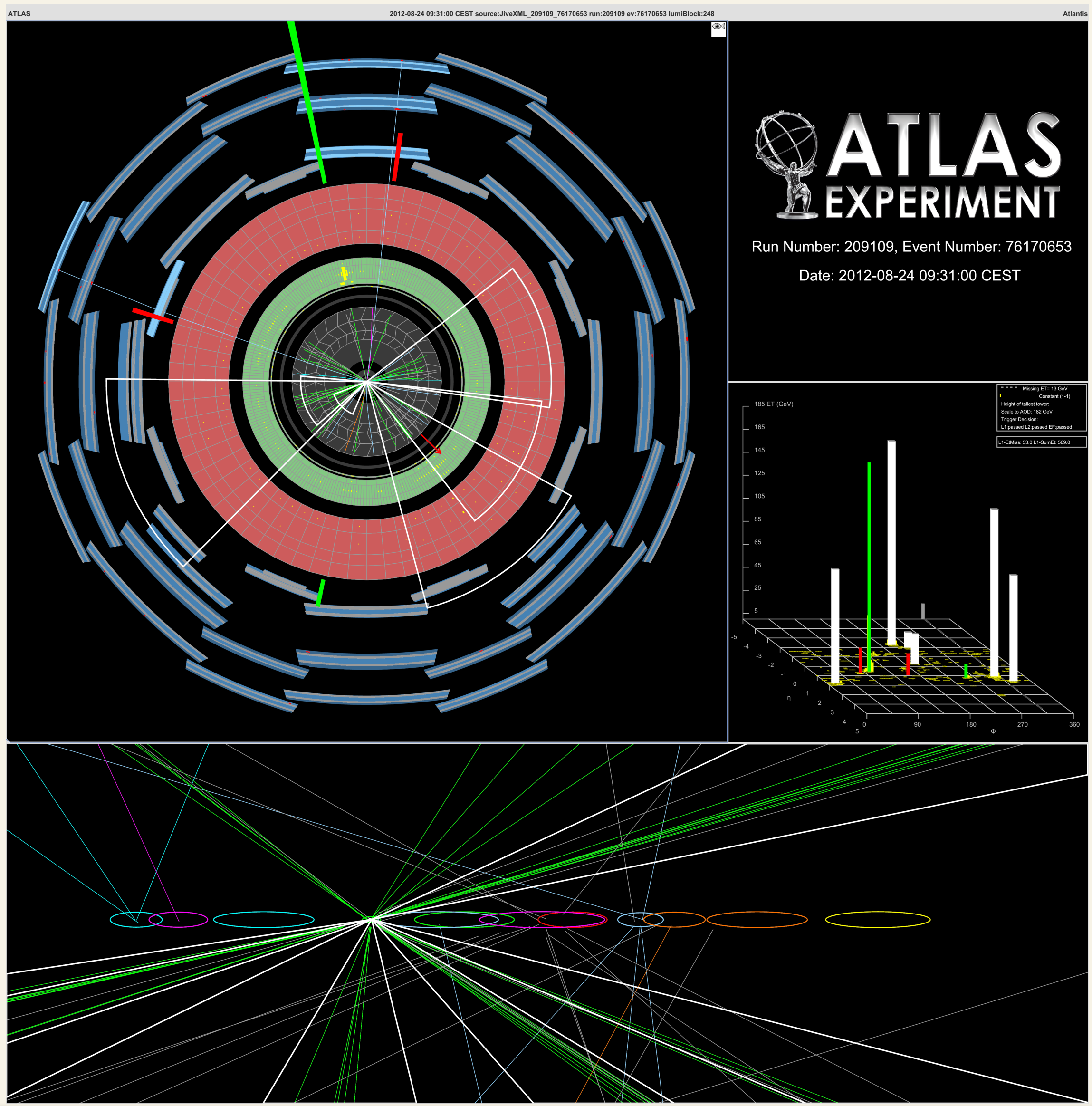
Constraint from the Golden Mode for Higgs Discovery

- The CMS preliminary result with full 7 and 8 TeV data shows 13, 8, and 4 events with 0, 1, and 2 jets, respectively, after selecting events with 121.5 GeV $< M_{4l} <$ 130.5 GeV.
- The resulting 95% confidence level limit on the relative signal strength between t to ch^0 and inclusive Higgs production is around 31%,
- That can be converted to a limit of 6.5 pb on the effective cross section of t to ch^0 at 8 TeV, or a branching ratio limit around 1.5%.

The Golden Mode for Higgs Discovery



The Golden Mode for Higgs Discovery

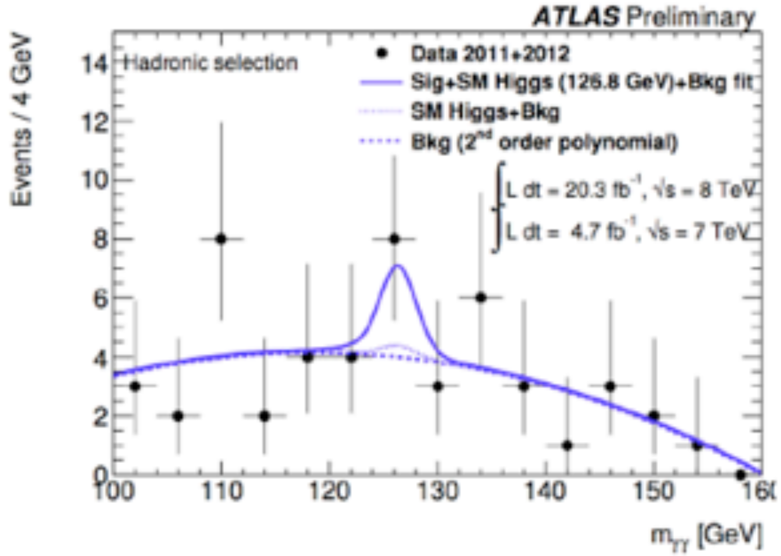


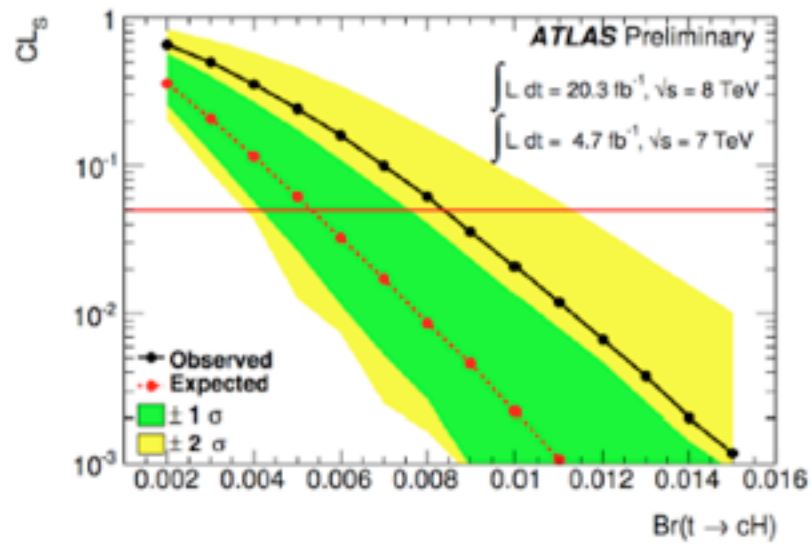
ATLAS Results presented by Ashutosh Kotwal

Neutral Higgs Bosons with Non-SM Properties

"Search for flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC"
[ATLAS-CONF-2013-081]

- Look for Higgs in diphoton mass spectrum
  - Model background shape with *SHERPA*





BR($t \rightarrow cH$) < 0.83% (observed) at 95% CL (< 0.53 % expected for SM)

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*, $\tau^+\tau^-$ and $\gamma\gamma$ 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.