



Probing for $t \rightarrow ch$ at the LHC

George W.S. Hou (侯維恕)
National Taiwan University

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臺灣大學

National Taiwan University





When Higgs meets Top: $t \rightarrow ch^0$ @ LHC



Pro-found if Found

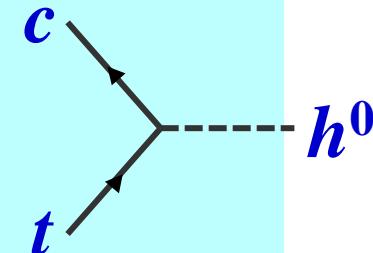
FCNH: verboten in SM
& 2HDM I/II

Glashow-Weinberg 1977

Outline

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

- BaBar Anomaly, 2HDM-III & tch^0 Coupling
- B Physics & $H \rightarrow \tau\tau$ Constraints
- $t \rightarrow ch^0$ Search at LHC



ZZ^*
 gg
 WW^*

bb

C.Kao
talk

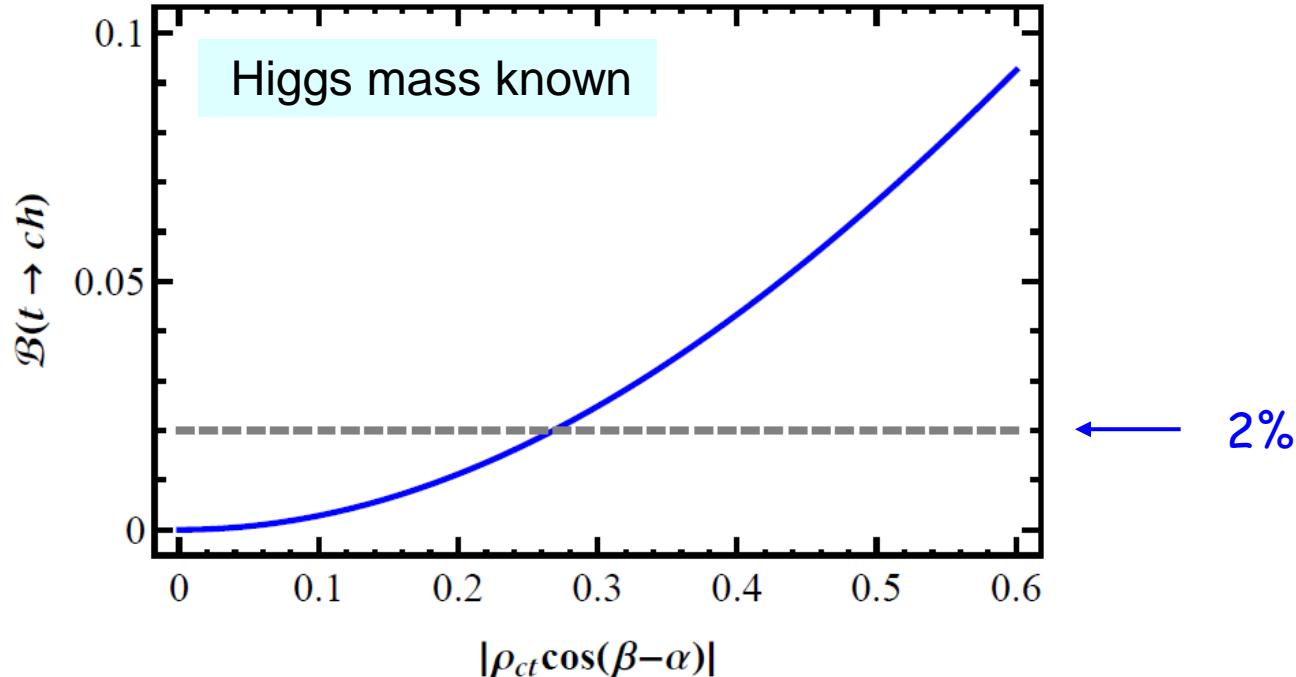
Fajfer, Kamenik, Nisandzic, Zupan, PRL 2012
Crivellin, Greub, Kokulu, PRD 2012; 1303.5877

CGK

KCHS
CHKK

Kao, Cheng, WSH, Sayre, PLB 2012
Chen, WSH, Kao, Kohda, 1304.8037

First discussion: WSH, PLB 1991



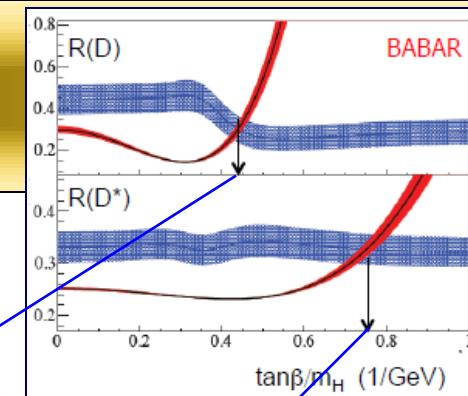
How large can $\rho_{ct} \cos(\beta - \alpha)$ be?

exotic admixture of 126 GeV boson h^0



BaBar “Anomaly”, 2HDM-III & tch^0 Coupling

BaBar “Anomaly”

BaBar,
PRL 2012

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

- In the type II 2HDM, this implied that $\tan\beta/m_{H^+} = 0.44 \pm 0.02 \text{ GeV}^{-1}$ and $0.75 \pm 0.04 \text{ GeV}^{-1}$ 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 $B \rightarrow \tau\nu$, which is found in agreement with SM expectation, spelling further trouble.
- Very (too) Large!

2HDM-III (General) Yukawa Interactions



Crivellin, Greub, Kokulu, PRD 2012

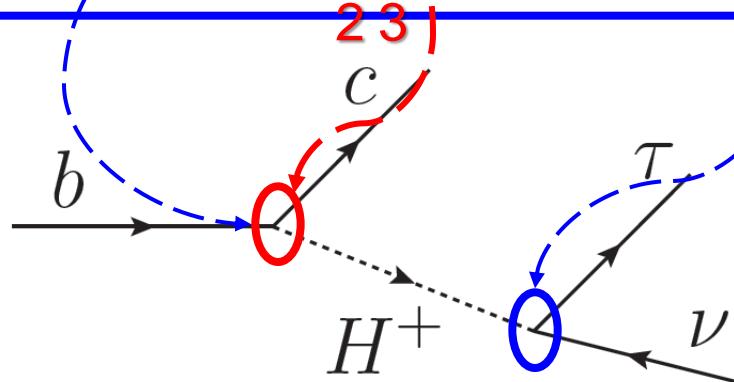
[we use notation of Mahmoudi and Stal, PRD 2010]

$s_{\beta-\alpha}$ ($c_{\beta-\alpha}$) stands for $\sin(\beta - \alpha)$ ($\cos(\beta - \alpha)$)

$$\begin{aligned}
 & - \frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f} [(\kappa^f s_{\beta-\alpha} + \rho^f c_{\beta-\alpha}) h^0 \\
 & \quad + (\kappa^f c_{\beta-\alpha} - \rho^f s_{\beta-\alpha}) H^0 - i \operatorname{sgn}(Q_f) \rho^f \gamma_5 A^0] f \\
 & - [\bar{u} (V \rho^d R - \rho^u V L) d H^+ + \bar{\nu} \rho^\ell R \ell H^+ + \text{h.c.}]
 \end{aligned}$$

“Standard”

Exotic



CGK considered Decoupling Limit:
 $\sin(\beta - \alpha) \rightarrow 1$, h^0 becomes SMH

To consider $t \rightarrow ch^0$:

FCNH

- Need Nondecoupling:
 h^0 mixes in $\cos(\beta - \alpha)$ frac. of H^0
- Not only p_{bb} , but $p_{\tau\tau}$ turn out small
 (next page)
- deviate from CGK [left with m_{H^+} pockets]
- $p_{ct} \sim 1$, implying
 $p_{\tau\tau}$ and p_{cc} need be considered!



B Physics & $H \rightarrow \pi\pi$ Constraints

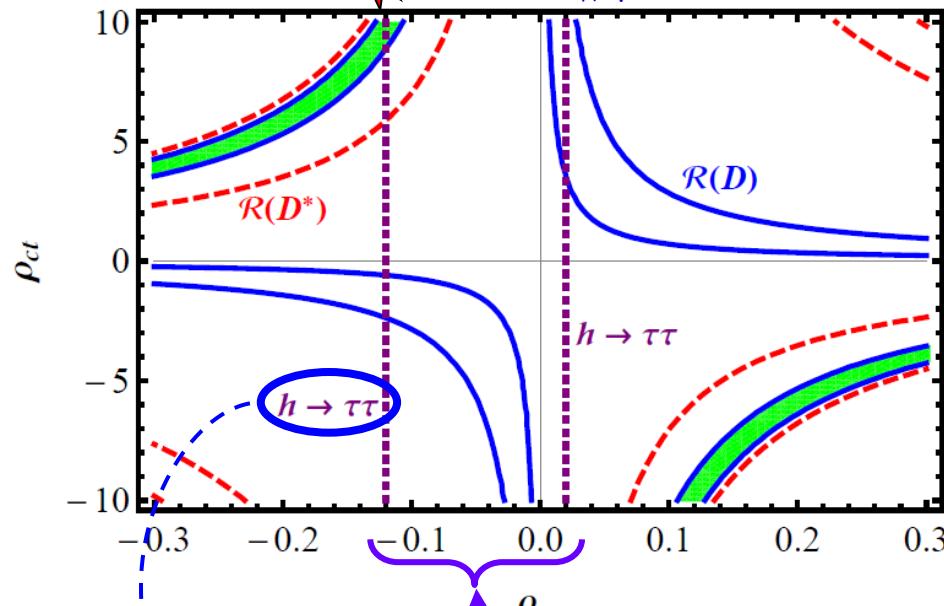
Higgs $\rightarrow \tau\tau$: $\rho_{\tau\tau}$ small

$b \rightarrow s\gamma$: ρ_{bb} tiny

Nonperturb.
 ρ_{ct} needed

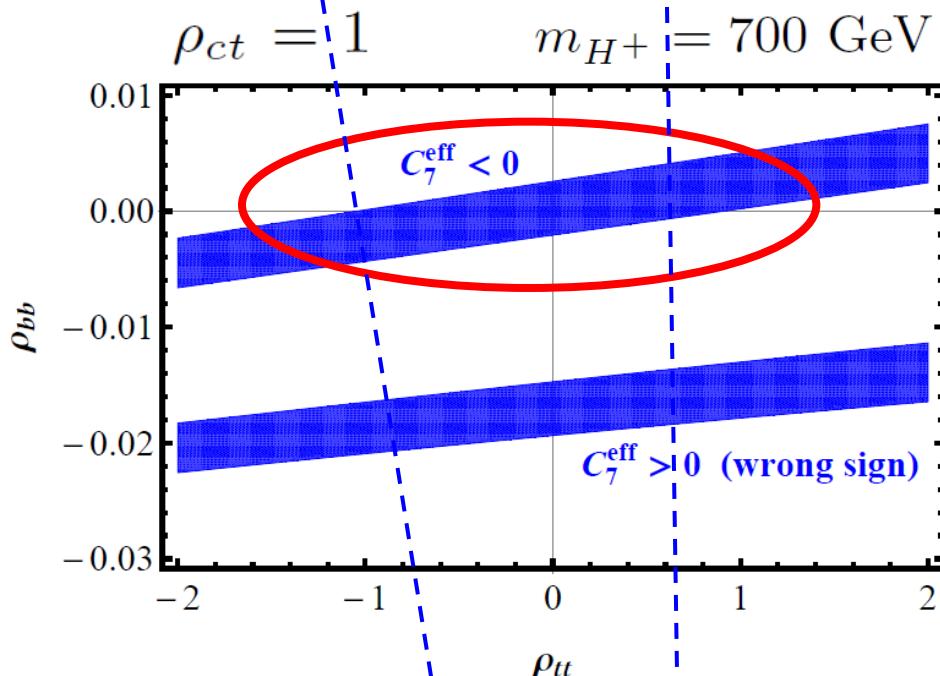
With Regrets,
“detach” from
BaBar anomaly

m_{H^+} pockets remain

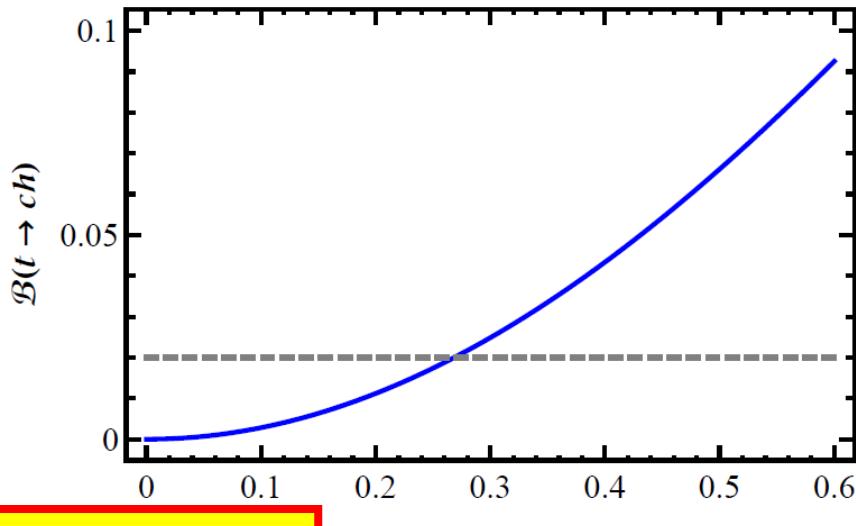


$$|s_{\beta-\alpha} + (\rho_{\tau\tau} v / \sqrt{2} m_\tau) c_{\beta-\alpha}| \lesssim \sqrt{2}$$

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



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



$t \rightarrow ch^0$ Search at LHC

How large can $\mathcal{B}(t \rightarrow ch^0)$ be?

If $\rho_{ct} \sim 1$, what constraint we have on $\cos(\beta-\alpha)$?

N.B. From $\sigma_{tt(\text{bar})}$ measurement with dileptons, one infers $\mathcal{B}(t \rightarrow ch)$ cannot be larger than few %.

Example: Clean Sample of $ZZ^* \rightarrow 4\ell$



$$\sigma_{gg \rightarrow h^0} \cdot \frac{\Gamma_{h^0 \rightarrow ZZ^*}}{\Gamma_{h^0}^{\text{SM}}} \cdot \frac{\Gamma_{h^0}^{\text{SM}}}{\Gamma_{h^0}} \simeq [\sigma \cdot \mathcal{B}]_{ZZ^*}^{\text{SM}}$$

$\sim 22 \text{ pb}$

Consistency of 15-20 evts
 ~ SM w/ little BG,
 for both CMS/ATLAS

With 126 GeV dominantly SMH, i.e. $\sin(\beta-\alpha) \approx 1$ (near Decoupling),
 ZZ^* (and WW^*) Rate hard to change.

The width of 126 GeV Higgs can be enhanced by p_{cc} as not measured.

Gluon Fusion can be enhanced by p_{tt} , even though damped by $\cos(\beta-\alpha)$.

Cf.: $\sigma_{t\bar{t}(\text{bar})} \sim 220 \text{ pb}$, if $t \rightarrow ch$ 2%,
 then $t\bar{t}(\text{bar}) \rightarrow chbW$ is at 9 pb!

Could we have
 seen it already!?

Summary of Constrained 2HDM-III



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

| | \mathcal{B}^{SM} | Γ^{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 | $b \rightarrow s\gamma$ |
| $\tau\tau$ | 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 | $\rho_{tt} \sim 1$ |

- For enhanced $\sigma_{gg \rightarrow h^0}$, then dilution of \mathcal{B}_{ZZ^*} would be necessary, implying enhanced $h^0 \rightarrow c\bar{c}$;
- If $\sigma_{gg \rightarrow h^0}$ is suppressed, or \mathcal{B}_{ZZ^*} is diluted, then more ZZ^* events may come from $t\bar{t}$ feeddown!

Summary of Constrained 2HDM-III



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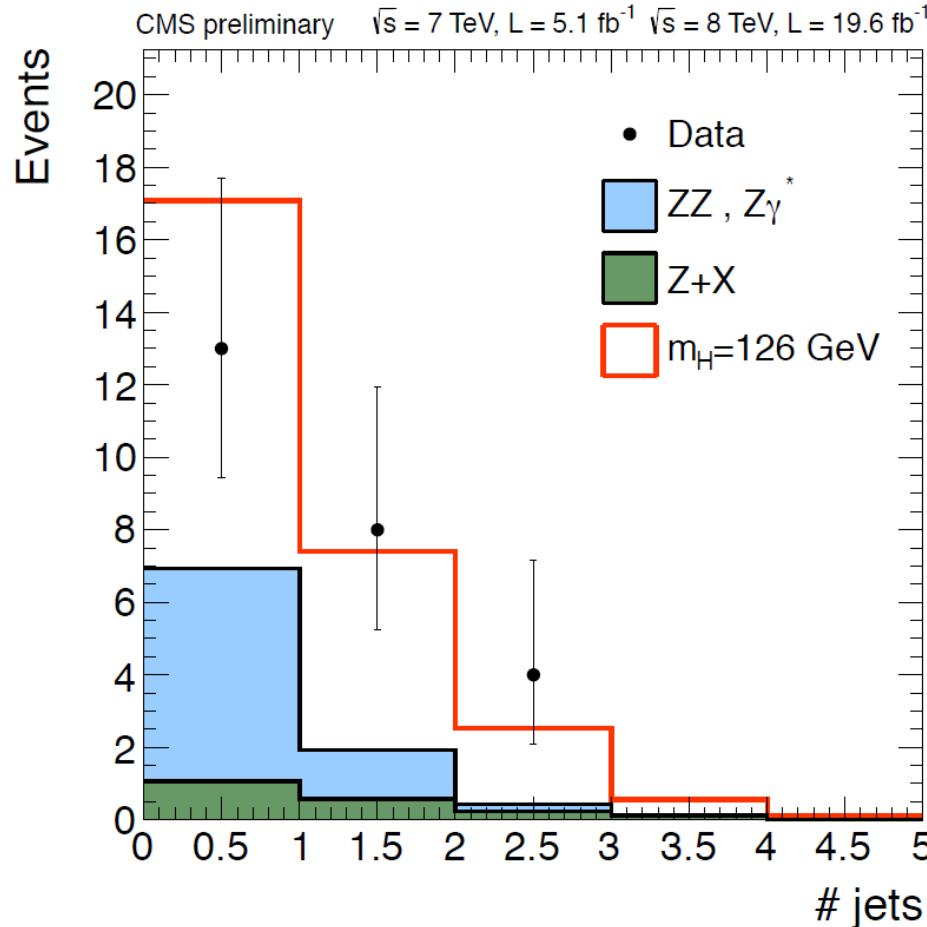
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P_{cc} , P_{tt}
 P_{ct}

**New Sector
to be probed
at the LHC**

- For enhanced $\sigma_{gg \rightarrow h^0}$, then dilution of \mathcal{B}_{ZZ^*} would be necessary, implying enhanced $h^0 \rightarrow c\bar{c}$;
- If $\sigma_{gg \rightarrow h^0}$ is suppressed, or \mathcal{B}_{ZZ^*} is diluted, then more ZZ^* events may come from $t\bar{t}$ feeddown!

Any $t\bar{t}(\text{bar}) \rightarrow chbW?$

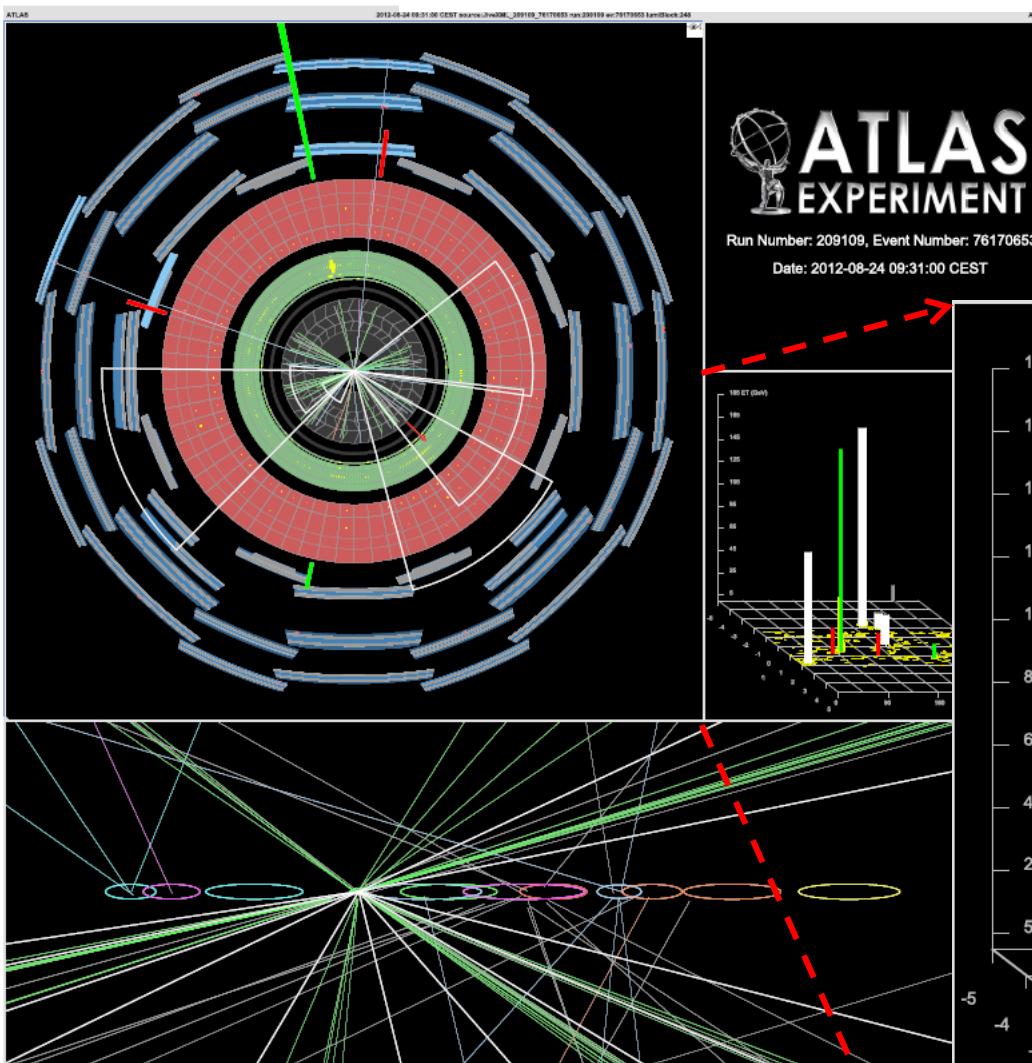


Simple CLs estimate
gives (95% C.L.)

$$\mathcal{B}(t \rightarrow ch) < 1.5\%$$

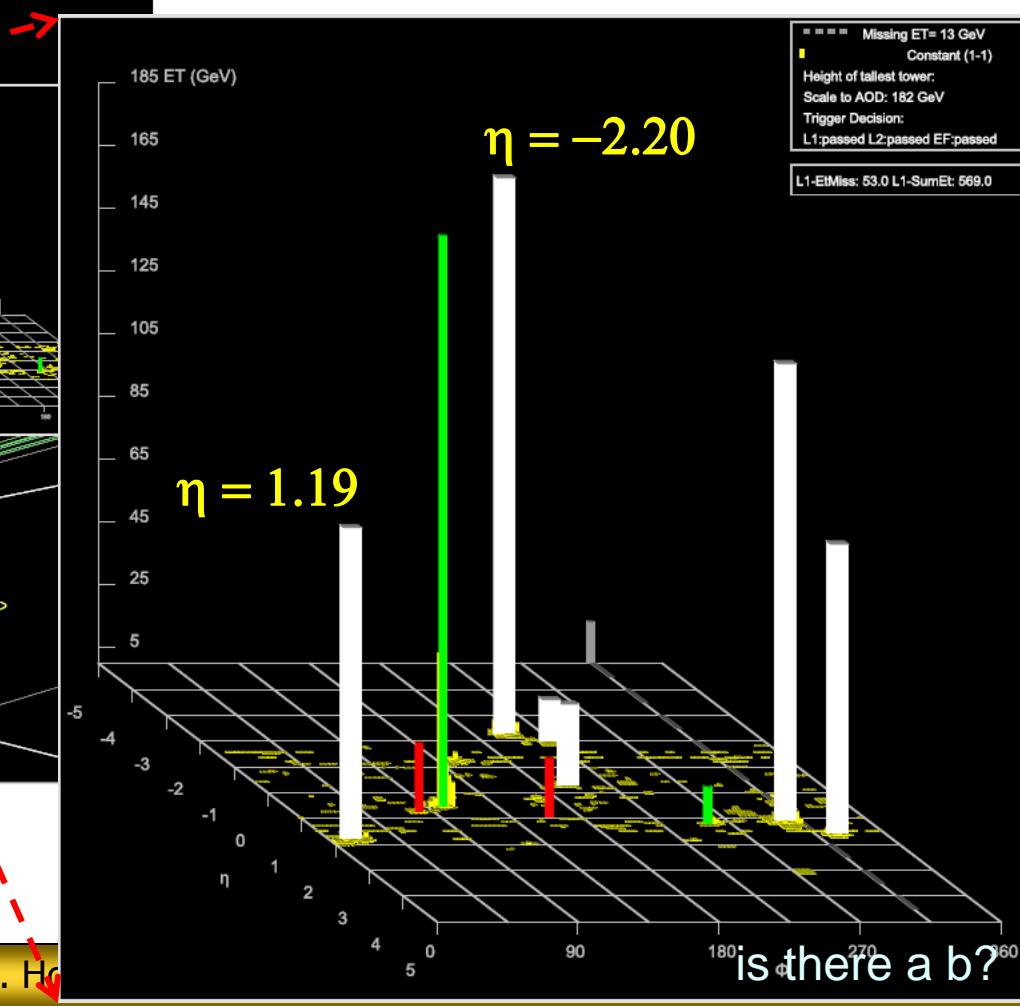
Best done directly
by the Experiments.

One ATLAS eeμμ + 4j Event!



“Passed VBF Selection”

Is there bias even in ZZ*?



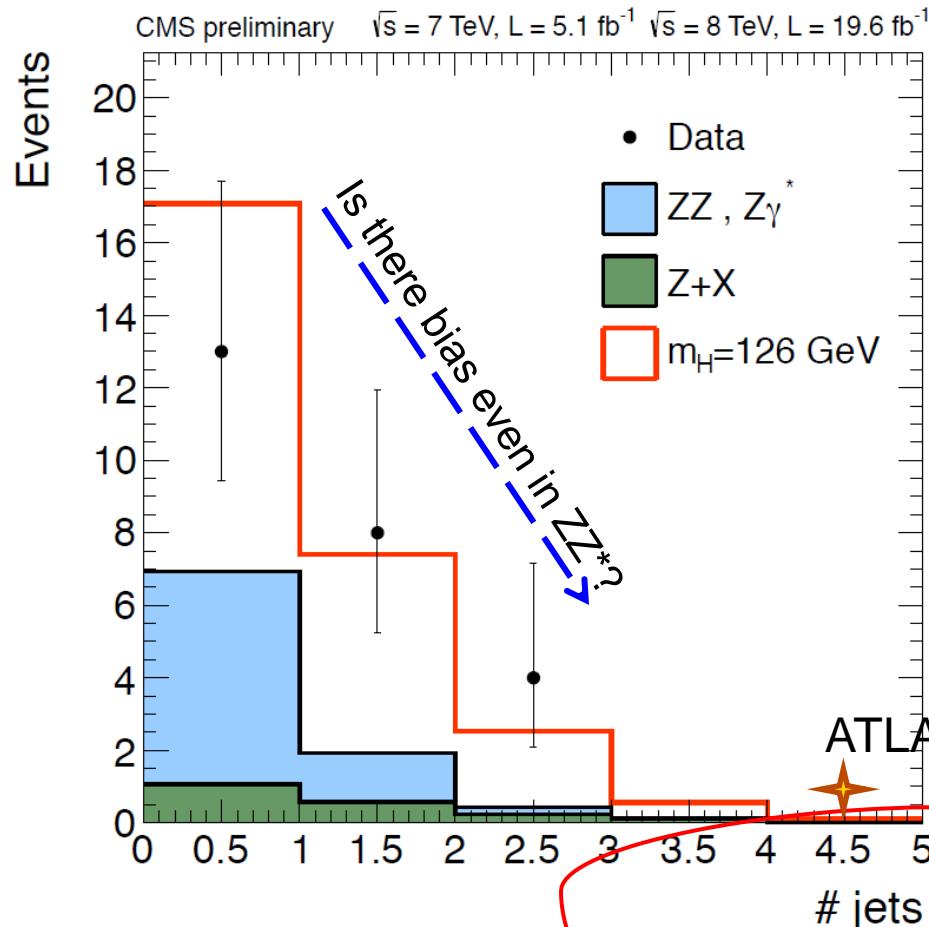
ATLAS-CONF-2013-013, (extra) Fig. 38

[thanks to Bill Murray]

No Evidence of Excess Jets in ZZ^* ...



Any $t\bar{t}(\text{bar}) \rightarrow chbW?$



Illustration

Simple CLs estimate
gives (95% C.L.)

$$\mathcal{B}(t \rightarrow ch) < 1.5\% \quad 2.2\%$$

Best done directly
by the Experiments

ATLAS $4\ell + 4j$ evt

Craig et al., PRD 2012: < 2.7% (can improve)

also the $h^0 \rightarrow WW^*, b\bar{b}, \tau^+\tau^-$ and $\gamma\gamma$ modes

KCHS'12: Can probe down to 1%

- $\gamma\gamma + 4j, \gamma\gamma + jj + l\nu$: [$\gamma\gamma$ in Higgs window]
Because of background concerns, evts perhaps rejected by $\Delta\eta$ (VBF)
→ Even the study of such BG may be interesting; b/t tags if found.
- $WW^* + \text{jets}, WW^* + \text{jets} + W$: [no Higgs Mass]

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Searching for $t \rightarrow ch$ with multileptons

Nathaniel Craig,^{1,2} Jared A. Evans,¹ Richard Gray,¹ Michael Park,¹ Sunil Somalwar,¹
Scott Thomas,¹ and Matthew Walker¹

¹*Department of Physics, Rutgers University, Piscataway, New Jersey 08854, USA*

²*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*

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Can
be
Improved

The results of a multilepton search conducted by the CMS collaboration with 5 fb^{-1} of data collected from 7 TeV pp collisions are used to place the first bound on the rare flavor-changing decay of the top quark to a Higgs boson and charm quark. Combining results from a number of exclusive three- and four-lepton search channels yields an estimated upper limit of $\text{Br}(t \rightarrow ch) < 2.7\%$ for a Higgs boson mass of 125 GeV. The sensitivity of future dedicated searches for $t \rightarrow ch$ could be improved by adding exclusive same sign dilepton channels, as well as by subdividing channels based on b -quark tagging and partial



Conclusion



- Great interest to search for link btwn top and Higgs
- Intense efforts of Higgs search in past two years
→ Can push $\mathcal{B}(t \rightarrow ch)$ down to % level!
- Illustrated with ZZ^* + jets, but best done by Expts
 - [tantalizing single $4\ell + 4j$ evt seen by ATLAS]
 - $\gamma\gamma + \text{jets}$ [or $\gamma\gamma + \ell + \text{MET} + \text{jets}$] has not yet been studied
 - Should update “ WW^* ” multi- ℓ (5 fb^{-1} CMS data) study
 - “Theory” study of $bb(\bar{b})$ suggest 1% limit reachable,

Combined Expt'l Study \Rightarrow Reach below 1% [cf. $t \rightarrow cZ$]

Discovery of $t \rightarrow ch^0$ process with 2011-2012 data would imply the existence of not only an extended Higgs sector, but one beyond the usual 2HDM-II of minimal SUSY.