Top Partners as a window to Extended Scalar Sectors

Aaron Pierce
University of Michigan
with Jack Kearney (Michigan) and Jesse Thaler (MIT)

1304.xxxx, 1304.yyyy

Higgs discovery

- Obviously a major advance in our understanding of electroweak symmetry breaking.
- A weakly coupled Higgs scalar appears to be responsible for electroweak symmetry breaking
- Serves to sharpen the naturalness question.

One possibility

- The Higgs boson is actually a composite field.
- If there is strong dynamics with a Global symmetry G down to a subgroup H, the Higgs boson can be one of (a number of?) pseudo Nambu-Goldstone boson(s) of the breaking.

Little Higgs Models

Little Higgs Models

HUTP-02/A033
MIT-CTP-3291
hep-ph/0207243

Little Higgses from an Antisymmetric Condensate

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Abstract

We construct an $SU(6)/Sp(6)$ non-linear sigma model in which the Higgses arise as pseudo-Goldstone bosons. There are two Higgs doublets whose masses have no one-loop quadratic sensitivity to the cutoff of the effective theory, which can be at around 10 TeV. The Higgs potential is generated by gauge and Yukawa interactions, and is distinctly different from that of the minimal supersymmetric standard model. At the TeV scale, the new bosonic degrees of freedom are a single neutral complex scalar and a second copy of $SU(2) \times U(1)$ gauge bosons. Additional vector-like pairs of colored fermions are also present.

Little Higgs and Custodial $SU(2)$

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Abstract

In this note we present a little Higgs model that has custodial $SU(2)$ as an approximate symmetry. This theory is a simple modification of the "Minimal Moose" with $SO(5)$ global symmetries protecting the Higgs mass. This allows for a simple limit where TeV physics makes small contributions to precision electroweak observables. The spectrum of particles and their couplings to Standard Model fields are studied in detail. At low energies this model has two Higgs doublets and it favours a light Higgs from precision electroweak bounds, though for different reasons than in the Standard Model. The limit on the breaking scale, f, is roughly 700 GeV, with a top partner of 2 TeV, W' and B' of 2.5 TeV, and heavy Higgs partners of 2 TeV. These particles are easily accessible at hadron colliders.

The Little Higgs from a Simple Group

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February 1, 2008

The Bestest Little Higgs

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Abstract

While little Higgs models provide an interesting way to address the hierarchy problem, concrete models in the literature typically face two major obstacles. First, the mechanism for generating a Higgs quartic coupling often leads to large violations of custodial symmetry. Second, there is a tension between precision electroweak observables in the gauge sector and fine-tuning in the top sector. In this work, we present a new little Higgs model which solves both of these problems. The model is based on an $SO(6) \times SO(6)/SO(6)$ coset space which has custodial symmetry built in. The Higgs quartic coupling takes a particularly simple form and does not suffer from the "dangerous singlet" pathology. We introduce a gauge breaking module which decouples the mass of gauge partners from the mass of top partners, allowing for natural electroweak symmetry breaking. The collider phenomenology is dominated by production and decay of the top partners, which are considerably lighter than in traditional

UW/PT-01/07
HUTP-02/A017
BUHEP-02-23

The Littlest Higgs

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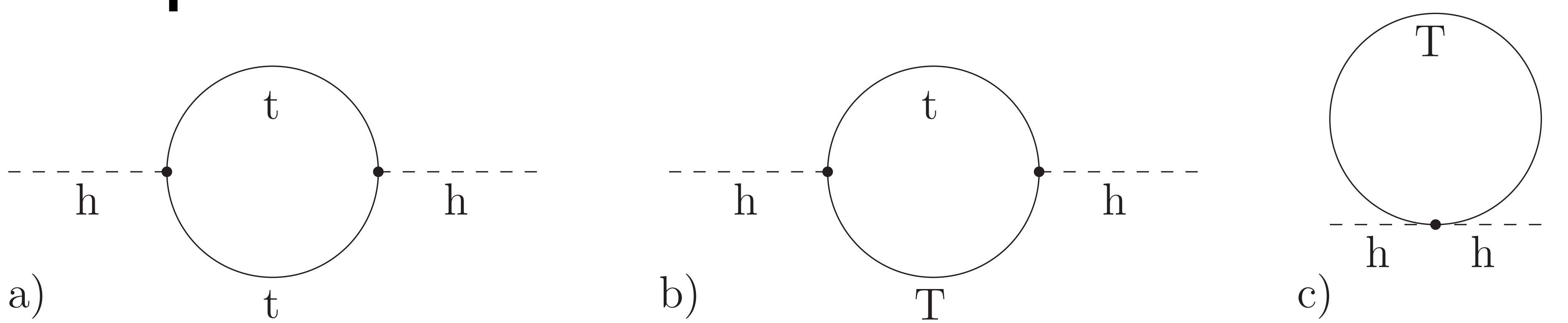
Outline

- Review of Little Higgs
- Model Building lessons:
    - Exotic Tops?
    - Dangerous Singlets
        - Extra Scalars
- Heavy Top Decays to Scalars (T to b H^+)

Little Higgs

- Generate a quartic for the Higgs without introducing quadratic divergence.
- The SM top quadratic divergences are cancelled via diagrams with a top partner loop



- Signal of goldstone nature of Higgs, and collective breaking.

Arkani-Hamed, et al.

hep-ph/0105239, hep-ph/0202089, hep-ph/0206020, hep-ph/0206021

Top Sector: Little Higgs Review

Introduce an SU(3) of Goldstones.

$$V = \exp[2i\pi^a t^a / f] \ ,$$

$$2i\Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi & H \\ -H^\dagger & \phi \end{pmatrix} .$$

Little Higgs and Top Sector

cf. Dobrescu and Hill top color

$$\chi_L = \begin{pmatrix} u \\ b \\ U \end{pmatrix}_L$$

$$\mathcal{L} = -\lambda_1 f \bar{u}_R V_{3i} \, \chi_{L_i} - \lambda_2 f \bar{U}_R U_L$$

$$V_{3i} \to V_{3j} \Lambda^\dagger_{ji}, \qquad \chi_L \to \Lambda \chi_L$$

Perelstein, Peskin, Pierce
http://arxiv.org/pdf/hep-ph/0310039.pdf

Little Higgs and Top Sector

cf. Dobrescu and Hill top color

$$\chi_L = \begin{pmatrix} u \\ b \\ U \end{pmatrix}_L$$

Preserves the SU(3)

$$\mathcal{L} = -\lambda_1 f \bar{u}_R V_{3i}\, \chi_{L_i} - \lambda_2 f \bar{U}_R U_L$$

Breaks symmetry, but no Higgs

$$V_{3i} \to V_{3j} \Lambda^\dagger_{ji}, \qquad \chi_L \to \Lambda \chi_L$$

Perelstein, Peskin, Pierce
http://arxiv.org/pdf/hep-ph/0310039.pdf

Expected decays

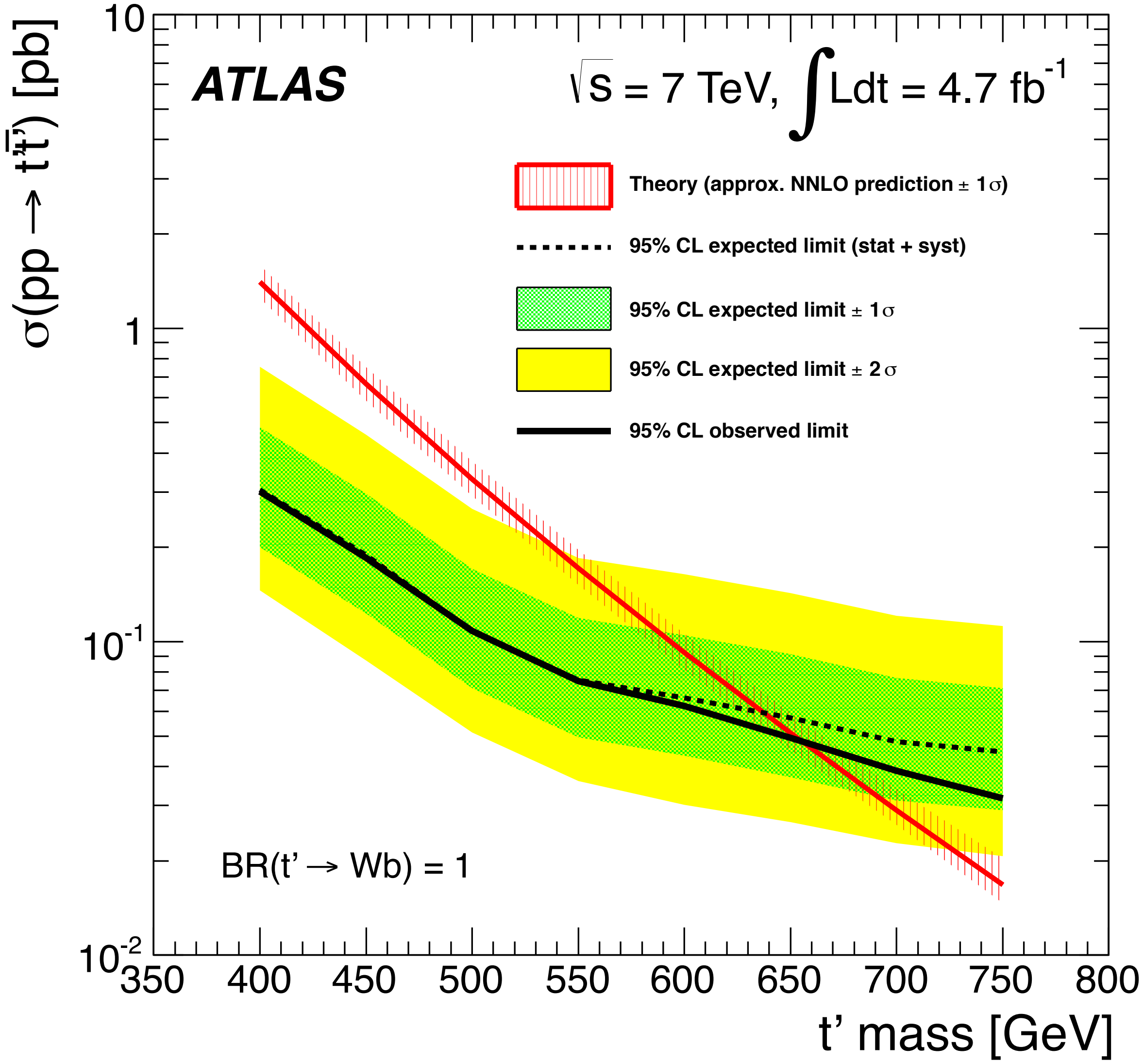
$$T \to th$$

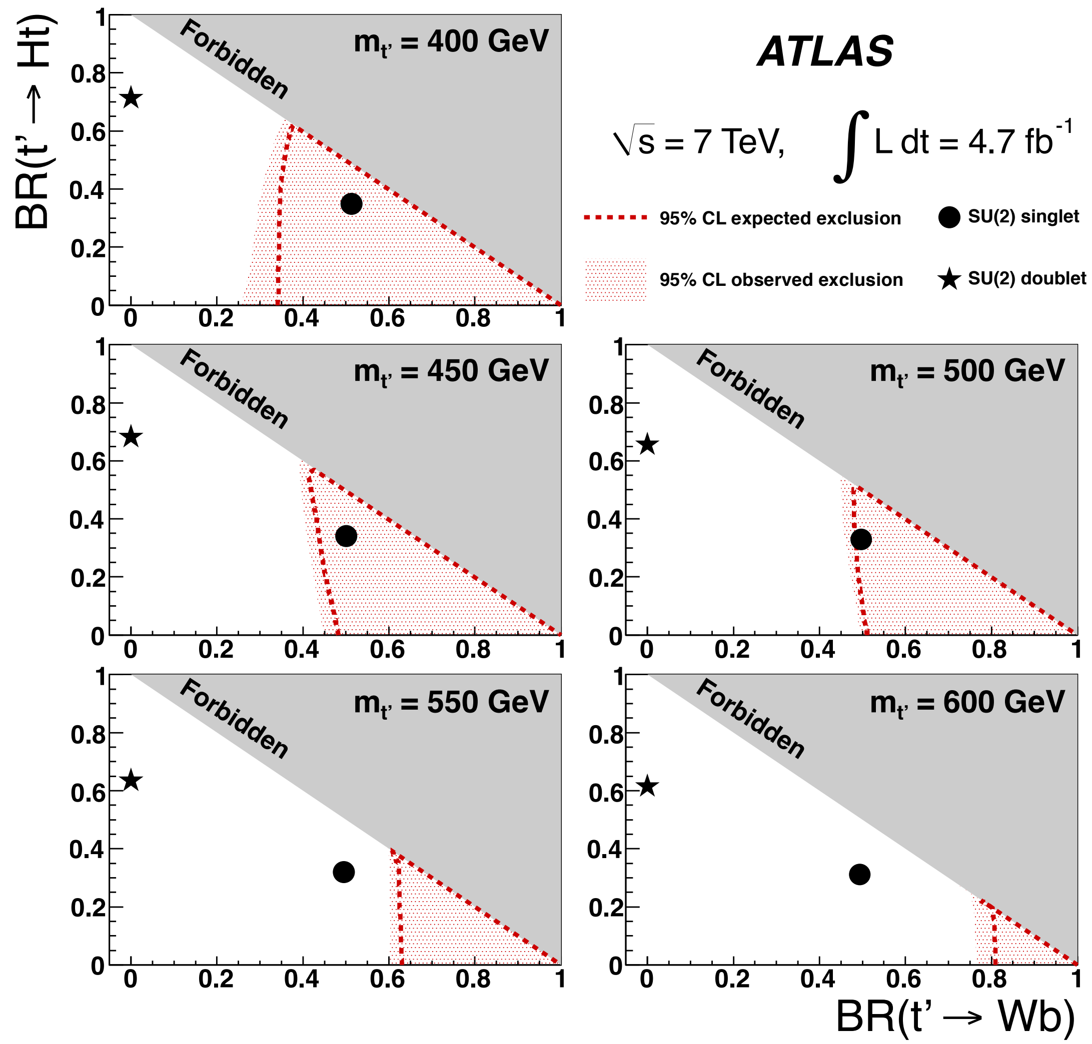
$$T \to bW$$

$$T \to tZ$$

Goldstone Equivalence
suggests 1:2:1

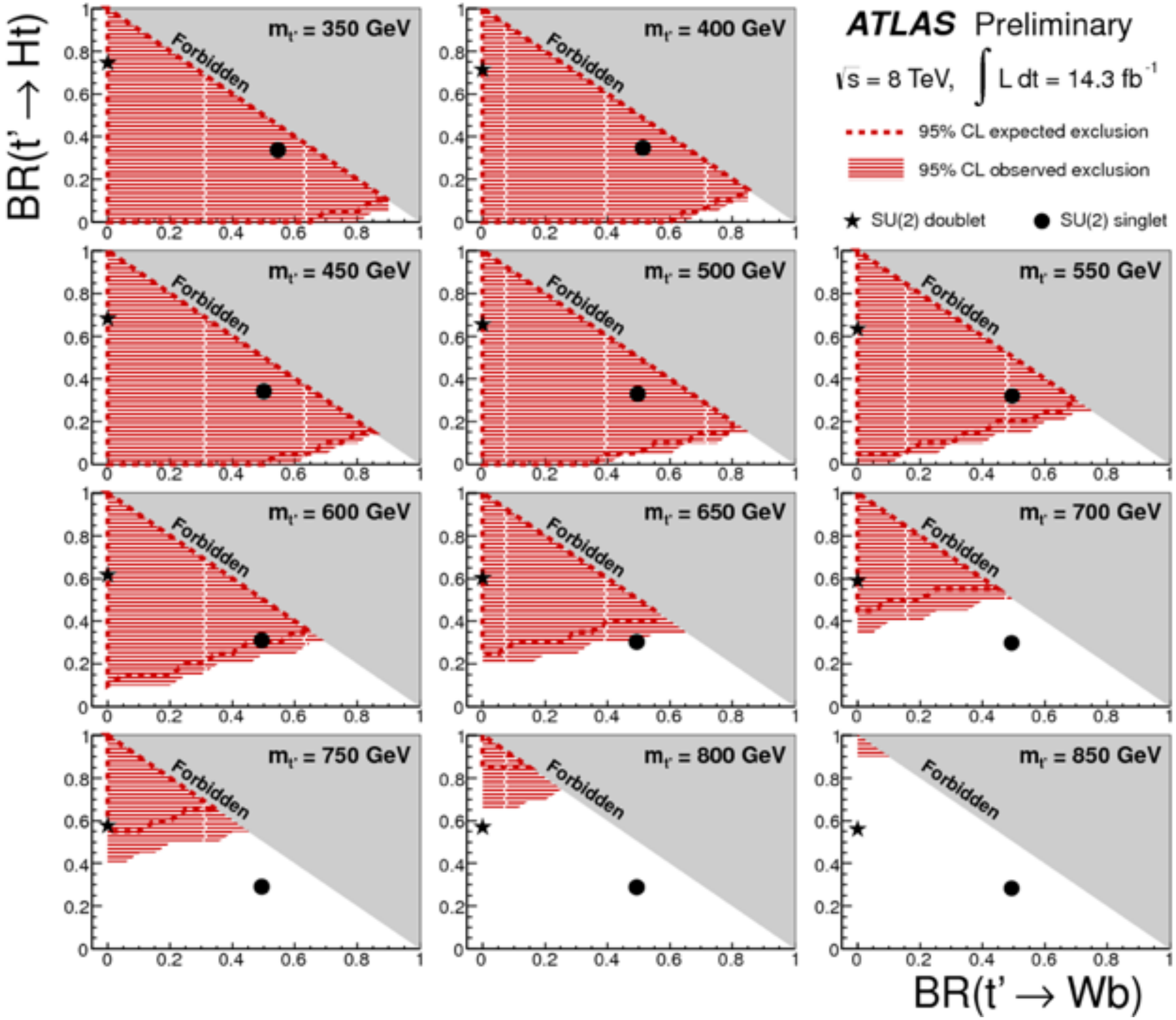
Fairly recent LHC Exclusion (T to bW)





http://arxiv.org/pdf/1210.5468v1.pdf

More Recent (T to th)



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-018/fig_06.png

More on top partners

G Symmetric

$$\mathcal{L}_t = \lambda_1 f \bar{X} \Sigma^\dagger X + \lambda_2 f \bar{\tilde{q}} Q + \lambda_3 f \bar{T} \tilde{t} + \text{h.c.}$$

		$SU(3)_c$	$SU(2)'$	$SU(2)$	$U(1)_Y$
X	p	3	1	2	7/6
	$\tilde{t}$	3	1	1	2/3
	$\tilde{q}$	3	2	1	1/6
$\bar{X}$	$\bar{\tilde{q}}$	$\bar{3}$	1	2	-1/6
	$\bar{\tilde{t}}$	$\bar{3}$	1	1	-2/3
	$\bar{p}$	$\bar{3}$	2	1	-7/6

See Katz, Nelson, Walker, Lee;
Thaler, Schmaltz, Stolarski,

What does this do?

$$\mathcal{L}_t = \lambda_1 f \bar{X} \Sigma^\dagger X + \lambda_2 f \bar{\tilde{q}} Q + \lambda_3 f \bar{T} \tilde{t} + \text{h.c.}$$

$$\mathcal{L}_t \supset \lambda_1 \bar{\tilde{t}} \tilde{q} h + f(\lambda_1 \bar{\tilde{t}} + \lambda_3 \bar{T}) \tilde{t} + f \bar{\tilde{q}} (\lambda_1 \tilde{q} + \lambda_2 Q) + \cdots \ .$$

Two heavy guys: $\sqrt{\lambda_1^2 + \lambda_3^2} f$ $\qquad$ $\sqrt{\lambda_1^2 + \lambda_2^2} f$

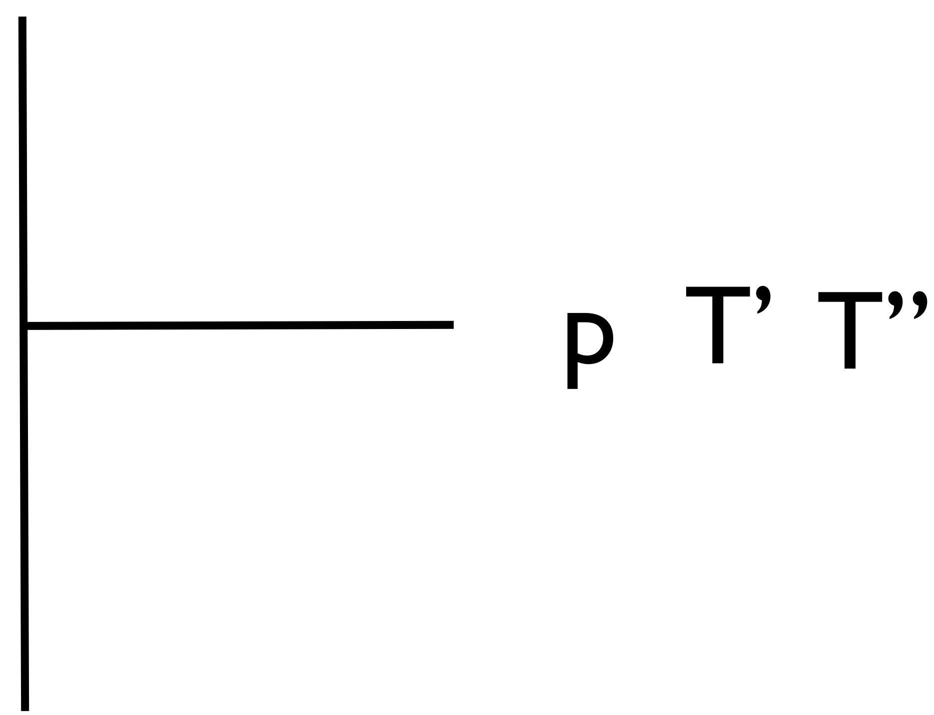
"Light Quark:"

$$q_3 \equiv \frac{(\lambda_2 \tilde{q} - \lambda_1 Q)}{\sqrt{\lambda_1^2 + \lambda_2^2}} \qquad \bar{t} \equiv \frac{(\lambda_3 \bar{\tilde{t}} - \lambda_1 \bar{T})}{\sqrt{\lambda_1^2 + \lambda_3^2}}$$

$$\lambda_t \, h \bar{t} q_3 + \text{h.c.} \qquad \text{where} \qquad \lambda_t = \frac{\lambda_1 \lambda_2 \lambda_3}{\sqrt{\lambda_1^2 + \lambda_2^2} \sqrt{\lambda_1^2 + \lambda_3^2}} \ .$$

What about p?

- It does not participate in the G breaking, so its mass remains at $\lambda_1 f$



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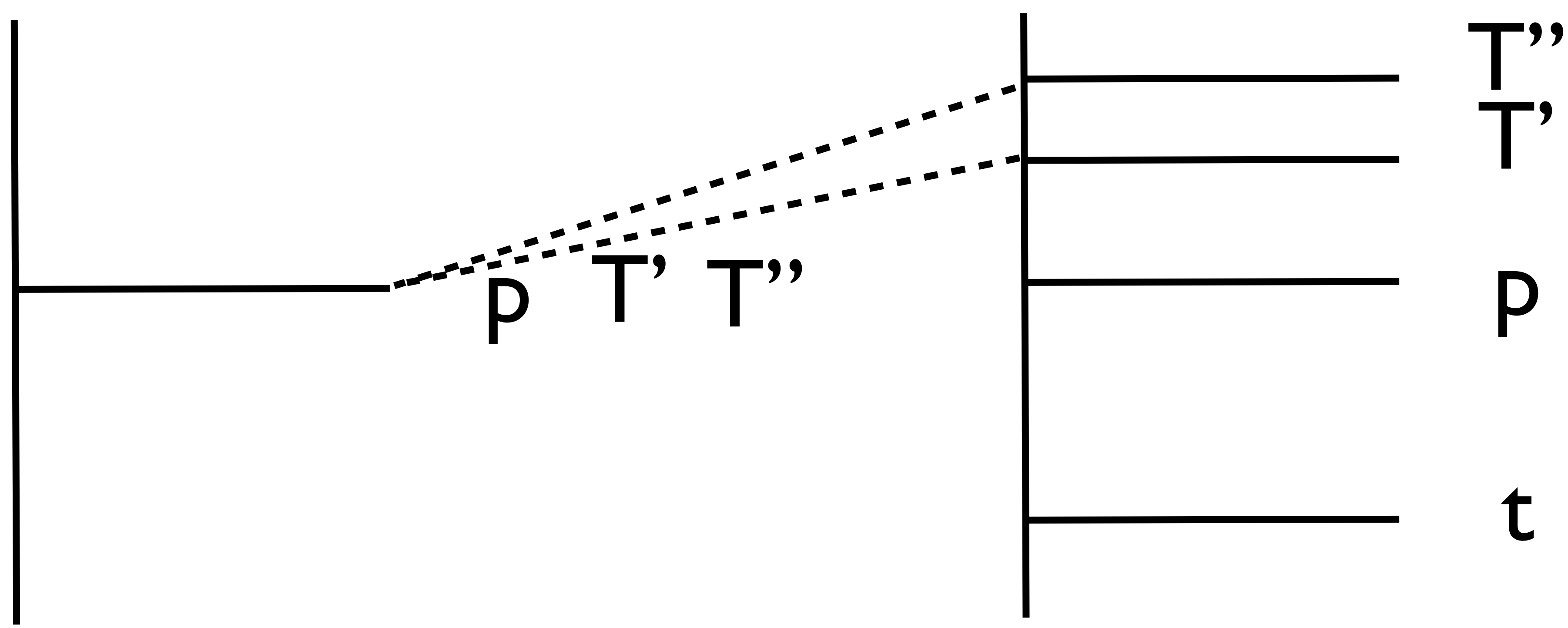


Another Example

$$M_t^2 = \frac{9y_1^2y_2^2y_3^2v^2\sin^2(\beta)}{(y_1^2+y_2^2)(y_1^2+y_3^2)}$$

$$M_T^2 = (y_1^2+y_2^2)f^2 + \frac{9y_1^2y_2^2y_3^2v^2\sin^2(\beta)}{(y_1^2+y_2^2)(y_2^2-y_3^2)}$$

$$M_B^2 = (y_1^2+y_2^2)f^2$$

$$M_{T_5}^2 = (y_1^2+y_3^2)f^2 - \frac{9y_1^2y_2^2y_3^2v^2\sin^2(\beta)}{(y_1^2+y_3^2)(y_2^2-y_3^2)}$$

$$M_{T_6}^2 = M_{T_b^{2/3}}^2 = M_{T_b^{5/3}}^2 = y_1^2f^2$$

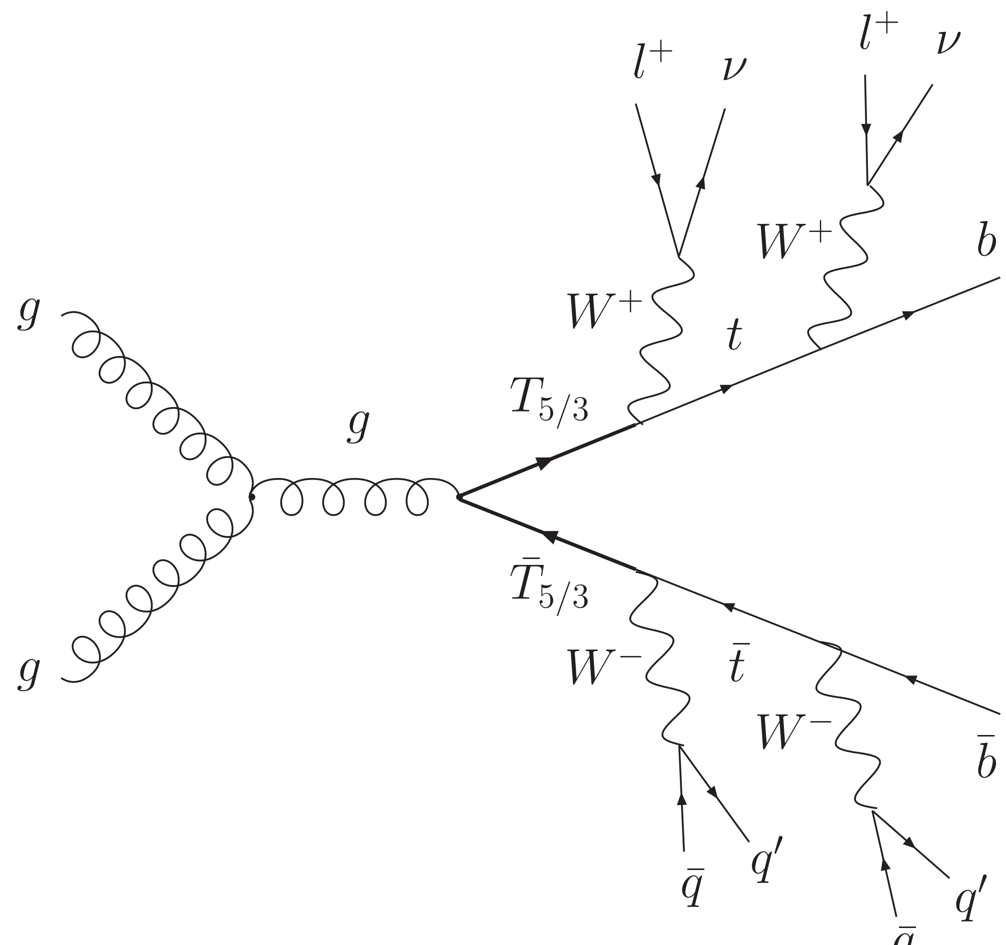
Schmaltz, Stolarski, Thaler [arXiv:1006.1356 [hep-ph]].

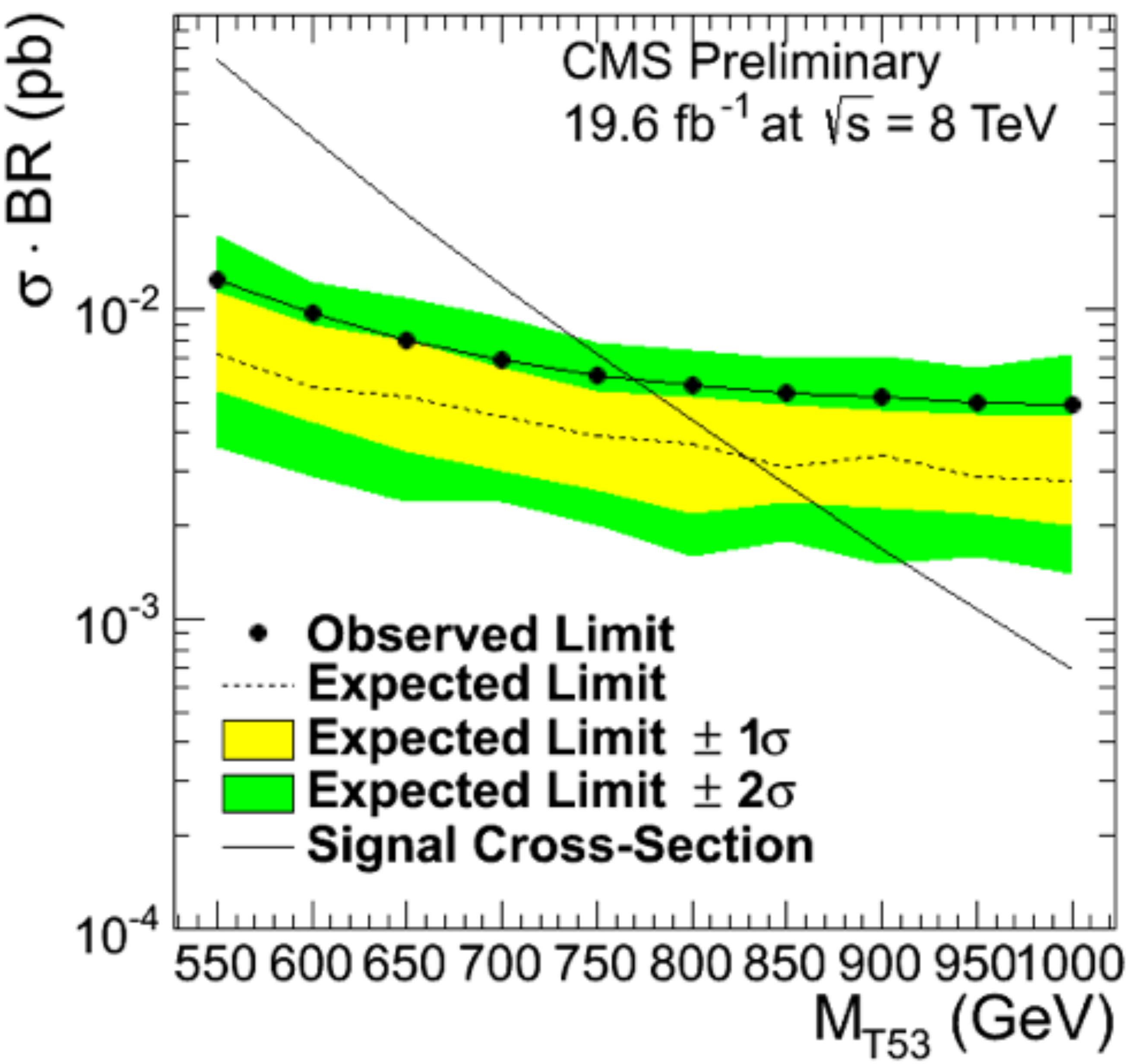
Godfrey, et al. http://arxiv.org/pdf/1201.1951.pdf

Morals (Top Partners)

- The states that do not participate directly in the collective breaking are the lightest.
- These can be "top friends" as described above
- Another example is the "custodial partners" if the fermions have an SU(2) x SU(2) symmetry.
- Lowest states (first to be discovered?) are not the "cancellons"
- More freedom in their phenomenology...

Charge 5/3





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Corollary

- Fine-tuning is probably a bit worse than you think.
- Typically all Yukawas are sizable to reproduce the top Yukawa.

$$\lambda_t \, h\bar{t}q_3 + \text{h.c.} \qquad \text{where} \qquad \lambda_t = \frac{\lambda_1\lambda_2\lambda_3}{\sqrt{\lambda_1^2+\lambda_2^2}\sqrt{\lambda_1^2+\lambda_3^2}} \; .$$

Lightest state	Cancellon
$\lambda_1 f$	$\sqrt{\lambda_1^2+\lambda_2^2} f$

Model Building
Lesson 2

Extra Scalars?

Collective Quartics

$$V \sim \lambda_1 f^2 \left|\phi + \frac{\text{“}h^2\text{”}}{f} + \cdots\right|^2 + \lambda_2 f^2 \left|\phi - \frac{\text{“}h^2\text{”}}{f} + \cdots\right|^2$$

$$h \to h + \epsilon + \cdots \qquad\qquad \phi \to \phi \mp \frac{h\epsilon + \epsilon h}{f} + \cdots$$

Each term preserves enough symmetry to forbid corrections to Higgs mass

Integrating out ϕ generates the quartic.

Who is ϕ ?

$$\mathbf{2} \otimes \mathbf{2} = \mathbf{3}_S \otimes \mathbf{1}_A, \qquad \mathbf{2} \otimes \overline{\mathbf{2}} = \mathbf{3} \otimes \mathbf{1}$$

Dangerous Singlets

- Thaler and Schmaltz (arXiv:0812.2477)

$$h \to h + \epsilon + \cdots \qquad \eta \to \eta \mp \frac{\epsilon^\dagger h + h^\dagger \epsilon}{f} + \cdots$$

Allows....

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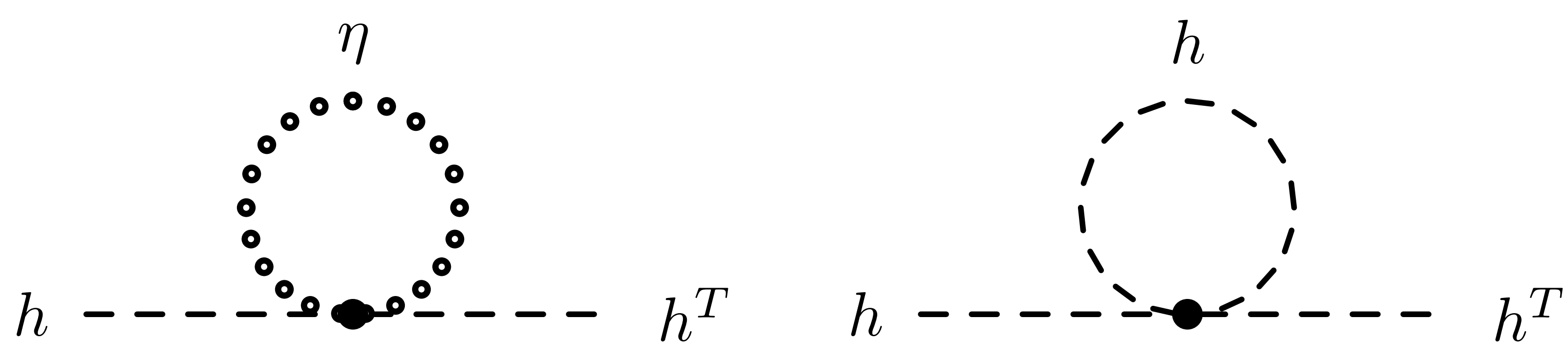
Allows.... ↓

$$\mathcal{L} = M^3 \left(\eta \pm \frac{h^\dagger h}{f} + \cdots \right)$$

This term generates a too large Higgs boson mass!

Diagramatically



Implications

$$\mathbf{2} \otimes \mathbf{2} = \mathbf{3}_S \otimes \mathbf{1}_A, \qquad \mathbf{2} \otimes \overline{\mathbf{2}} = \mathbf{3} \otimes \mathbf{1}$$

$$h^i h^j \to \phi^{ij} \qquad (\mathbf{3}_S),$$

$$h^\dagger \tau^a h \to \phi^a \qquad (\mathbf{3}),$$

$$h^\dagger h \to \eta \qquad (\mathbf{1}),$$

- One solution: a two Higgs doublet model!

$$h_1^i h_2^j \epsilon_{ij} \to \phi \qquad (\mathbf{1}_A),$$

$$h_1^\dagger h_2 \to \phi \qquad (\mathbf{1}).$$

New non-trivial symmetries possible!

Thaler/Schmaltz

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Rho Parameter

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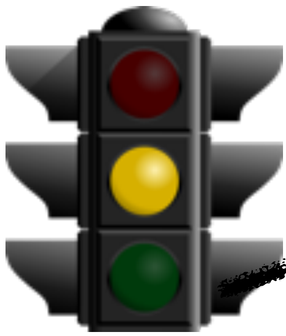

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~~$h_1^i h_2^j \epsilon_{ij} \to \phi \qquad (\mathbf{1}_A),$~~

Vanishes in charge preserving direction

$$h_1^\dagger h_2 \to \phi \qquad (\mathbf{1}).$$

New non-trivial symmetries possible!

Thaler/Schmaltz

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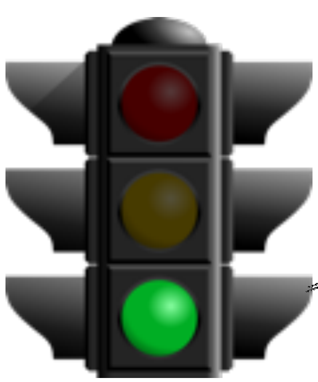

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New non-trivial symmetries possible!

Thaler/Schmaltz

New symmetries

- A complex singlet with a PQ charge SU(6)/Sp(6) (Low, Skiba, Tucker-Smith, Phys.Rev. D66 (2002) 072001, Gregoire, Tucker-Smith, Wacker, Phys.Rev. D69 (2004) 115008)
- A new parity:

$$\phi \to -\phi, \qquad h_1 \to -h_1, \qquad h_2 \to h_2$$

Aside on Little Higgs Model Building

- SO(9)/(SO(5)xSO(4)) (S. Chang hep-ph/0306034) was designed to preserved custodial SU(2). However, it contains a dangerous singlet.
- A relatively straightforward extension of this model a 2 HDM with a SO(10)/SO(5)xSO(5) structure solves this problem (Kearney, AP, Thaler, to appear).

How to build a Little Higgs model

- To avoid quadratically divergent contributions from the EW sector, need **two** weakly gauged subgroups G_1, G_2
- Each G_i commutes with a different subgroup ($X_{1,2}$) acting non-linearly on the Higgs(es). Gauging one does not break all shift symmetries.
- Want X_i to contain G_j. This ensures that a single gauge coupling does not destroy all protective symmetries.

Some LH options

Littlest Higgs	LH from Anti-symmetric Condensate
SU(5)/SO(5) 1 HDM G_i = SU(2) x U(1) X_i = SU(3)	SU(6)/Sp(6) 2 HDM G_i = SU(2) x U(1) X_i = SU(4)
Custodial LH SO(9)/(SO(4)xSO(5)) 1 HDM G_1=SU(2)xU(1) G_2=SO(4) X_i=SO(5) "Dangerous"	**Custodial 2HDM** (Kearney, AP, Thaler) SO(10)/(SO(5)xSO(5)) 2 HDM G_1=SU(2)xU(1) G_2=SO(4) X_i=SO(6)

Two classes of exotic decays are motivated:

$$T \to \text{quarticon} + \text{sm}$$

$$\text{T} \to \text{sm} + 2^{\text{nd}} \text{ Higgs doublet}$$

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$$T \to b + H^{\pm}$$
$$T \to t + (A, H)$$
$$T' \to b + \phi^{\pm}$$
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Where is the second Higgs doublet?

- Clues:
  - Approximately Standard Model Higgs
  - Lack of signals in flavor physics (e.g. b to s gamma).

How to see this second Higgs multiplet?

- One approach: associated production with a top quark
  - $g\ b \rightarrow t\ H^{\pm}$ (Moretti, Roy)
- In this heavy charged Higgs regime, decays are likely dominated by (tb)
  - Large backgrounds from tt + nj, ttbb
  - charm mistag important (Kearney, AP, Thaler)
  - Looks Challenging

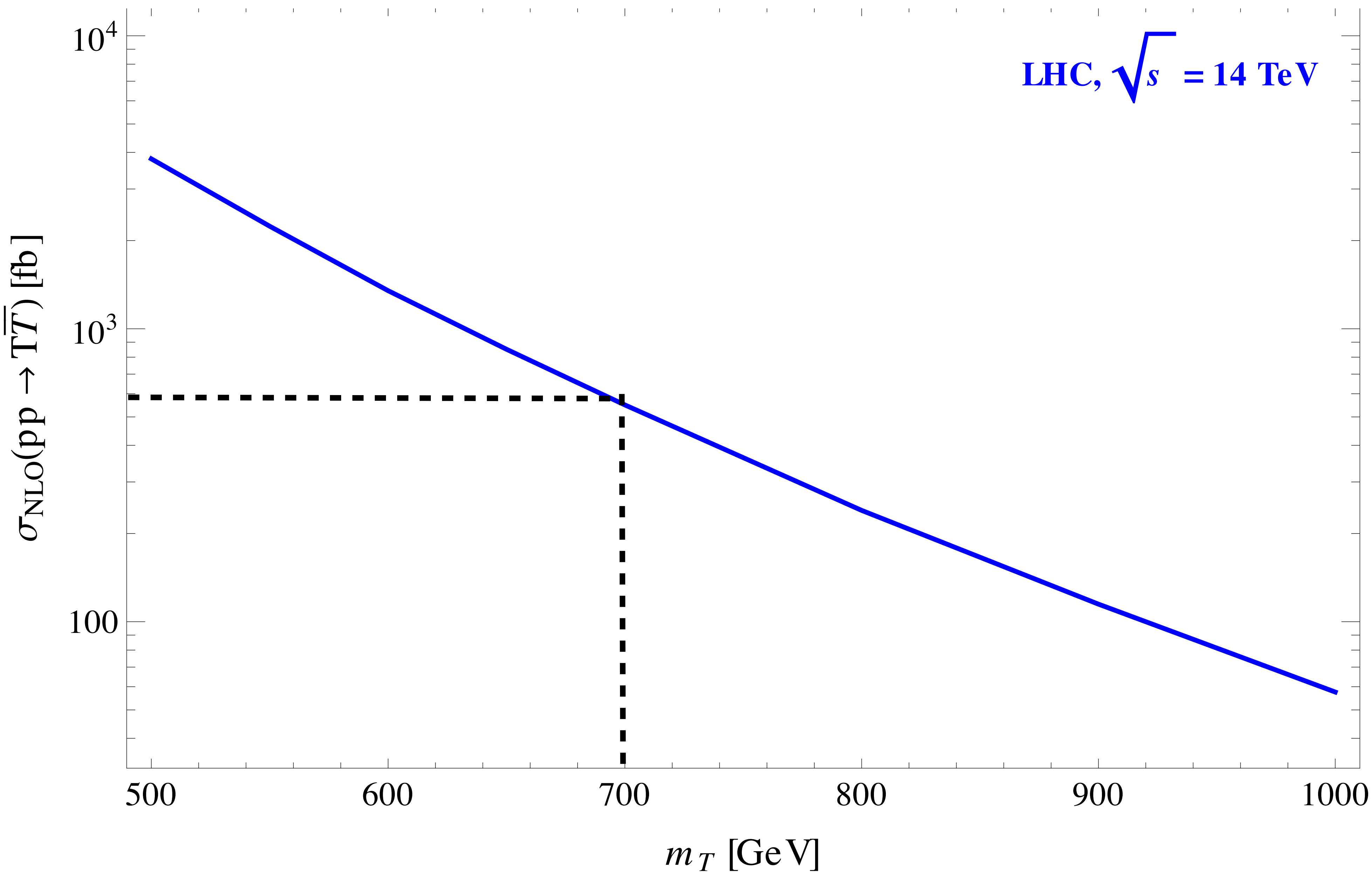
Can we see charged Higgses in Heavy Top Decays?

$T \to b\, H^{\pm}$

cf. Kribs, Martin, Roy, Spannowsky (0912.4731)

Production Cross Section

Generated with HATHOR 1007.1327



Here ~.7 pb. For heavy masses, single T potentially important

Finding the events

- Dig out from SM backgrounds
  - tt + nj
  - tt +bb
- Dig out from Little higgs “backgrounds.”
- MadGraph, MLM matching, with Pythia to DELPHES.

Idea

- Assume discovered, hopefully soon in T to b W, e.g.
- Can we test for the presence of these exotic decays?

$$T \to (bW) = \frac{1-\epsilon}{2}$$

$$T \to (th) = \frac{1-\epsilon}{4}$$

$$T \to (tZ) = \frac{1-\epsilon}{4}$$

$$T \to (bH^{\pm}) = \epsilon$$

Our Topology

$$pp \to (T \to bW^{\mp} \to bjj)(T \to bH^{\pm} \to btb \to bbb\ell^{\pm}\nu).$$

Keep in mind: m_T = 700 GeV, m_{H+} = 500 GeV

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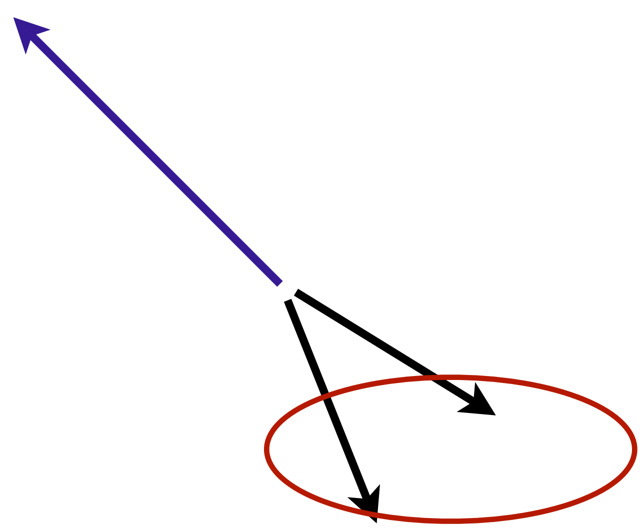

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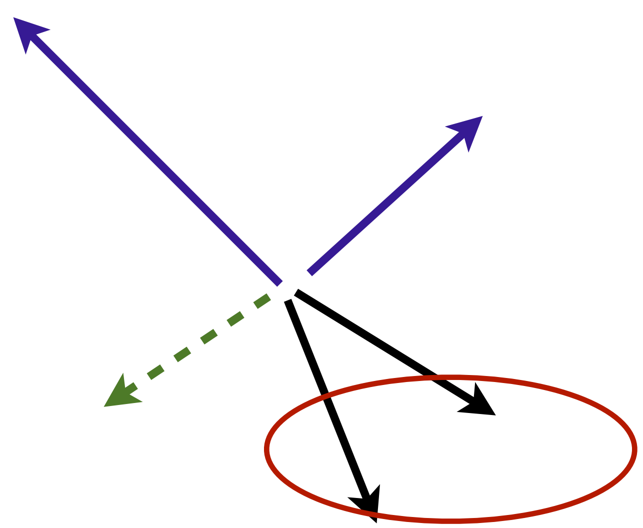

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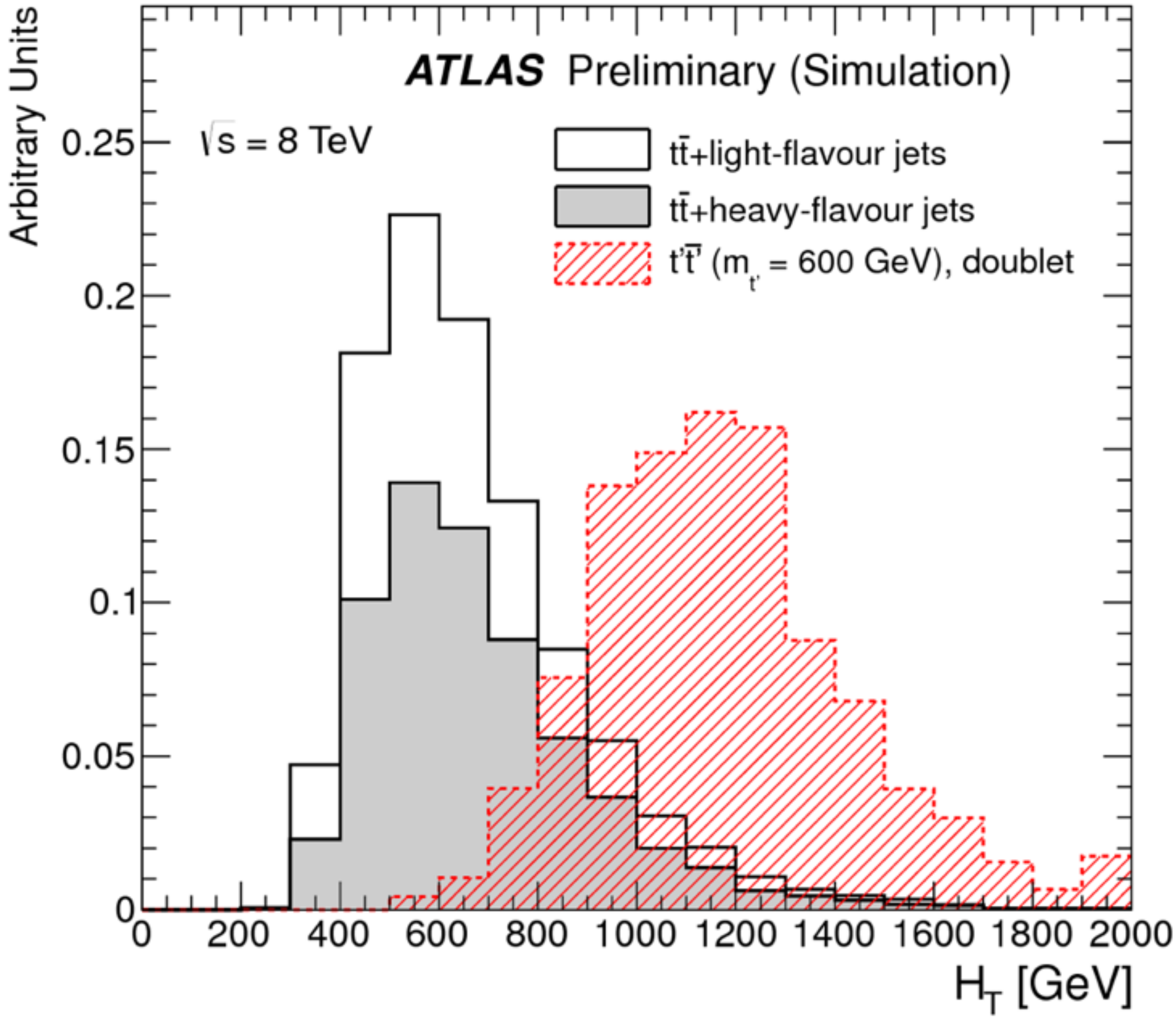
Basic idea

- Four hard b jets (a combinatoric challenge!)
  - reduce gluon splitting b's
- One very hard b jet (160 GeV)
- A large overall effective mass (1.2 TeV)

Very helpful in getting away from Standard Model Backgrounds



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-018/

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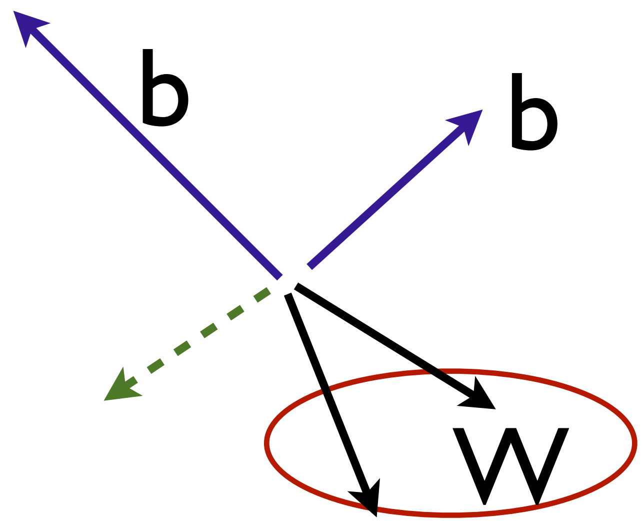

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Further cuts

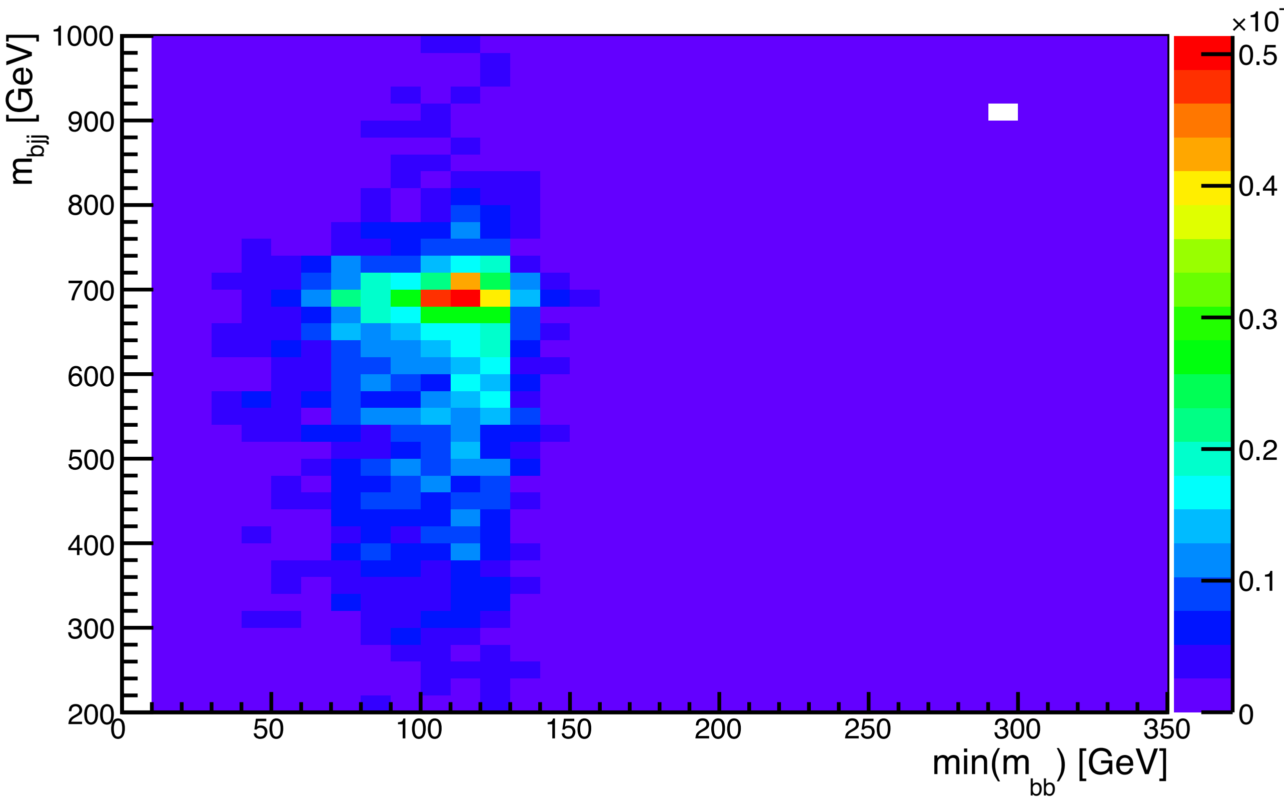
- m_{jj} ~ M_W (within 20 GeV, also close in delta R)
- M_{bW} ~ 700 GeV.

Getting Away from New "Backgrounds"

- Other heavy top decays (to Z, W, h) are "backgrounds" to our signal.
- In all cases, marked by a relatively low invariant mass object (compared to charged Higgs)
- Consider $(m_{bb})^{min}$= the **minimum** invariant mass of b pairs in the event

"Background" Distributions

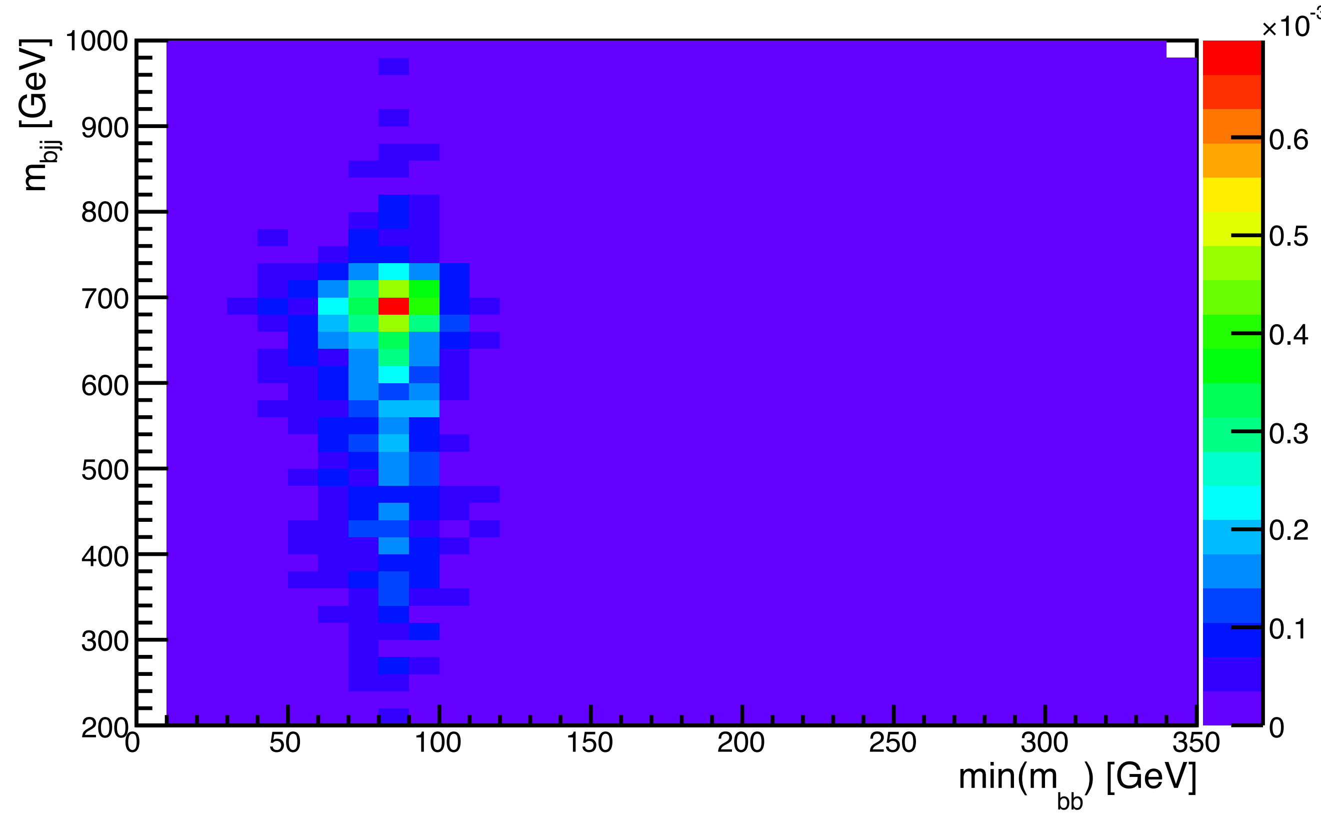
T to th



$$T \to bW \to bjj$$

$$T \to bh \to tbb \to 3b + l\nu$$

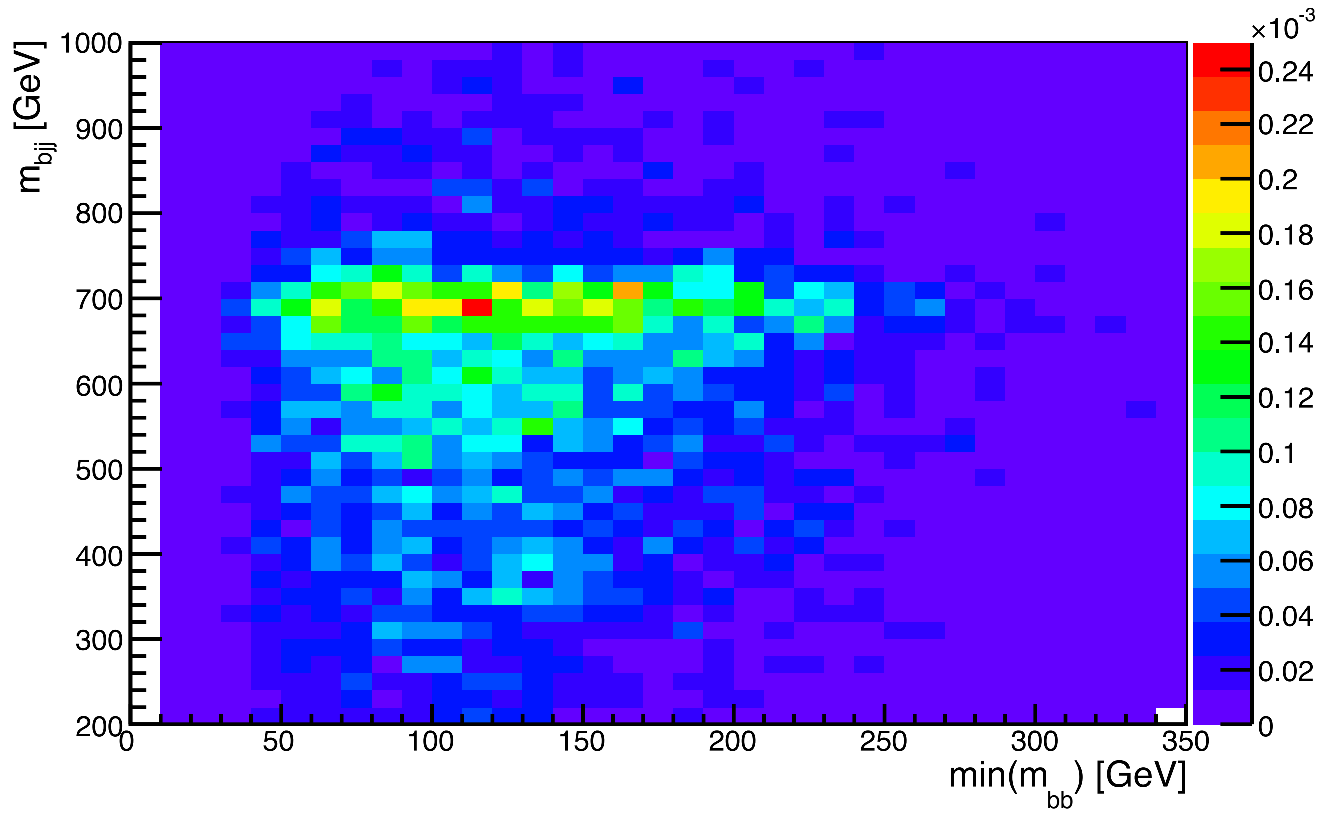
T to tZ



$$T \to bW \to bjj$$

$$T \to bZ \to tbb \to 3b + l\nu$$

Signal

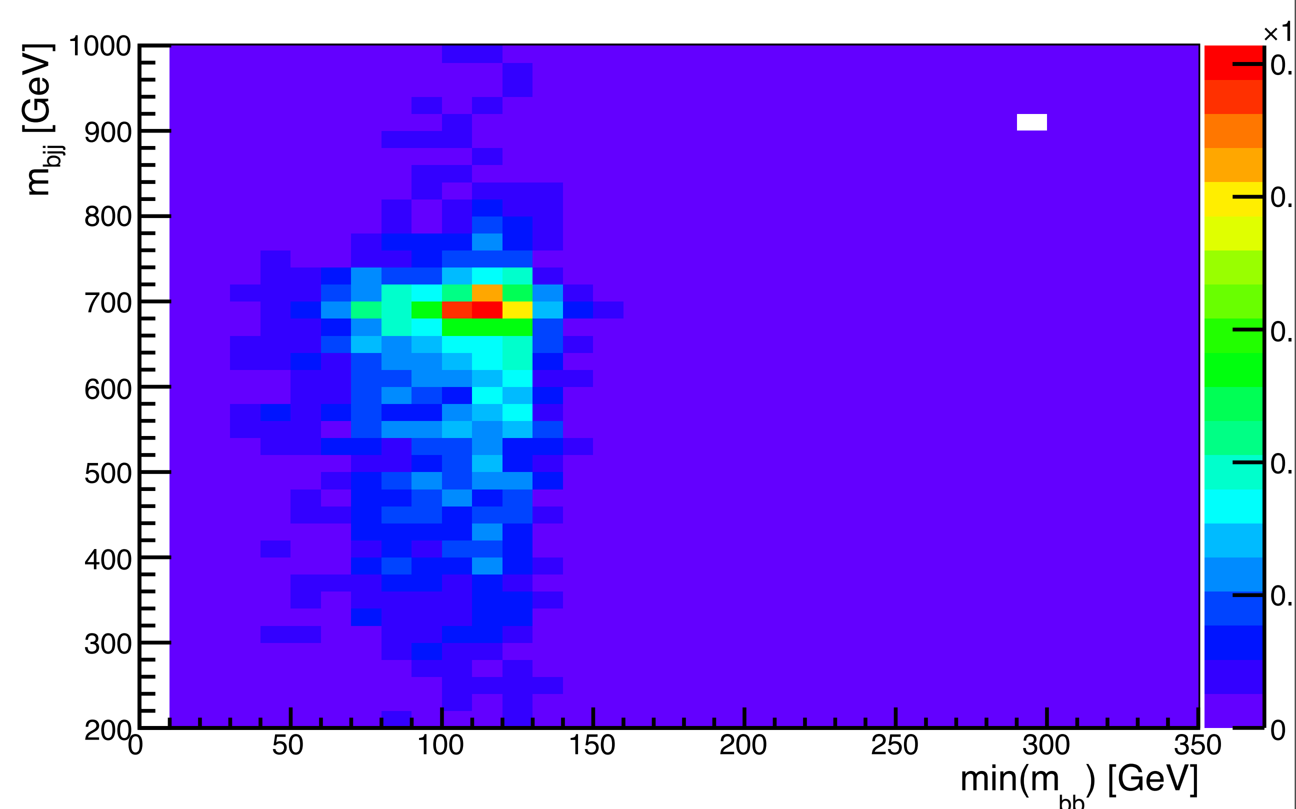


$$T \to bW \to bjj$$

$$T \to bH^{\pm} \to tbb \to 3b + l\nu$$

"Background'

T to th



$$T \to bW \to bjj$$

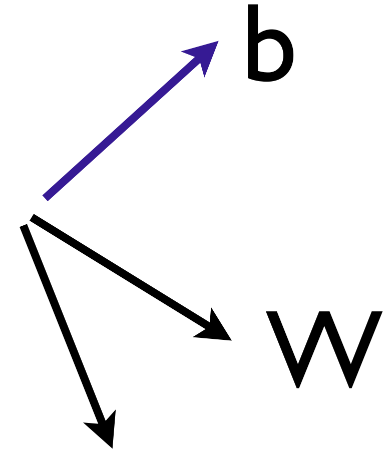
$$T \to th \to tbb \to 3b + l\nu$$

On $(m_{bb})^{min}$ and SM backgrounds

ttbb:

Gluonic splitting can give low invariant mass b pairs

ttjj:



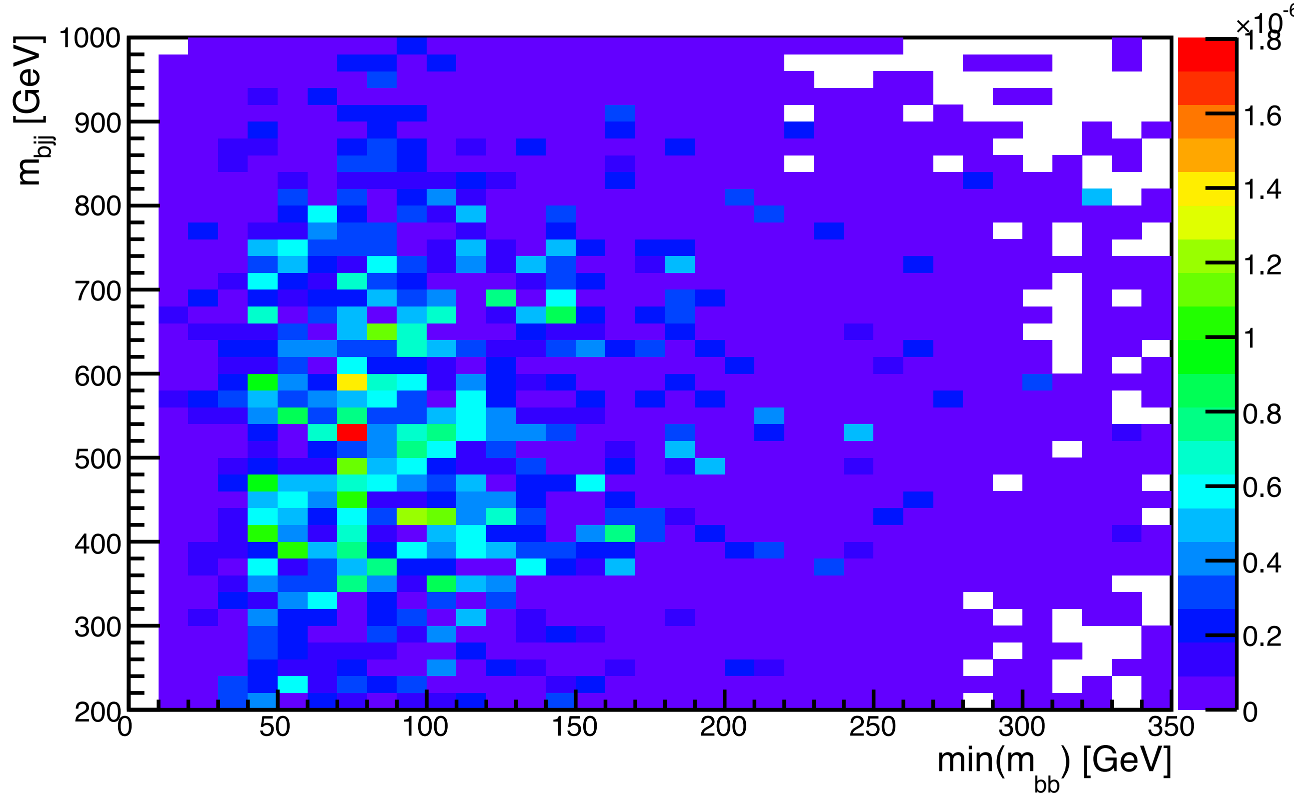
Totally obvious: If both faking jets come from a W, then this will help.

Pretty obvious: If one faking jets come from a W, then this will help.

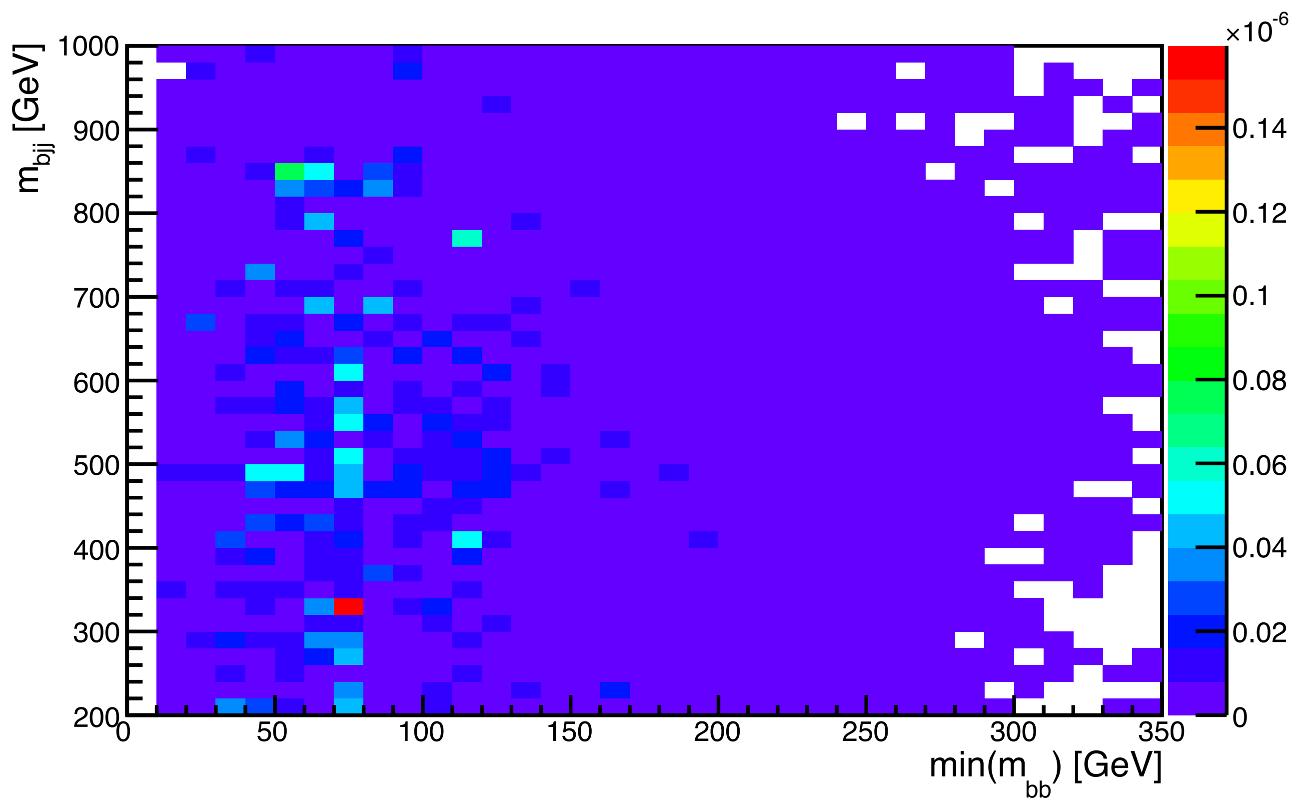
$$m_{bq}^2 = (p_b + p_q)^2 = (p_t - p_{q'})^2 = m_t^2 - 2p_t \cdot p_{q'} = m_t^2 - 2m_t E_{q'}$$

Background Distributions

We discovered the W in fakes.



ttbb



ttjj

$$T \to (bW) = \frac{1-\epsilon}{2}$$

$$T \to (th) = \frac{1-\epsilon}{4}$$

$$T \to (tZ) = \frac{1-\epsilon}{4}$$

$$T \to (bH^{\pm}) = \epsilon$$

m_T	$m_{H^\pm}$	Efficiency	$\epsilon\ (S/\sqrt{B} = 3)$	$\epsilon\ (S/\sqrt{B} = 5)$
	400	4.06E-3	0.09	0.16
700	500	4.16E-3	0.09	0.16
	600	2.18E-3	0.19	0.40

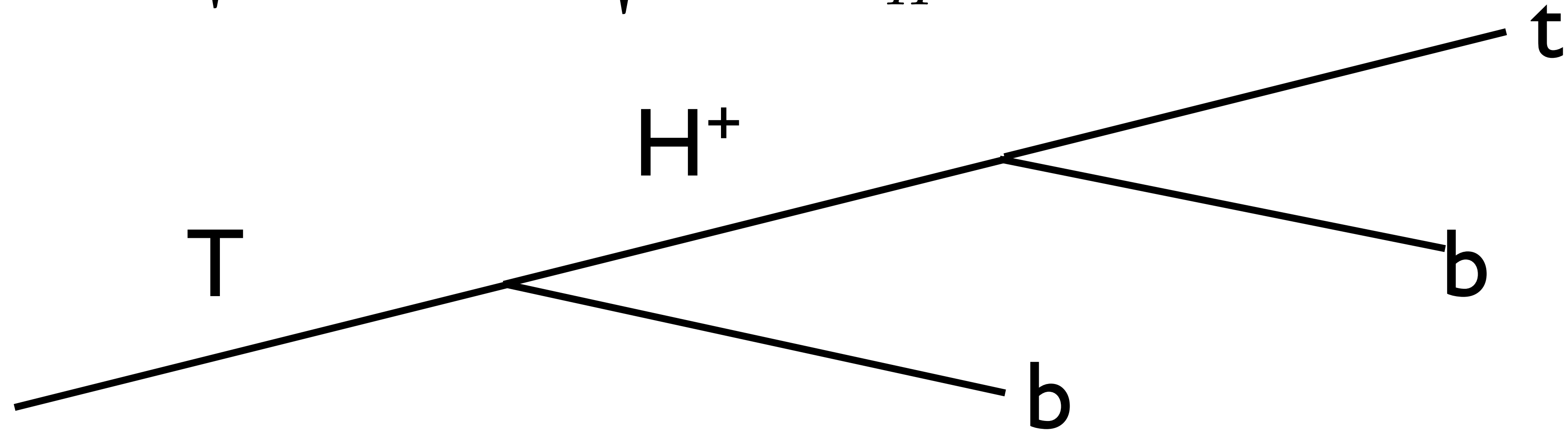
Preliminary

Table 3: Efficiencies for passing the given selection criteria, and corresponding values of ϵ yielding $S/\sqrt{B} = 3$ and 5 with the branching ratios described above for several representative values of $m_{H^\pm}$.

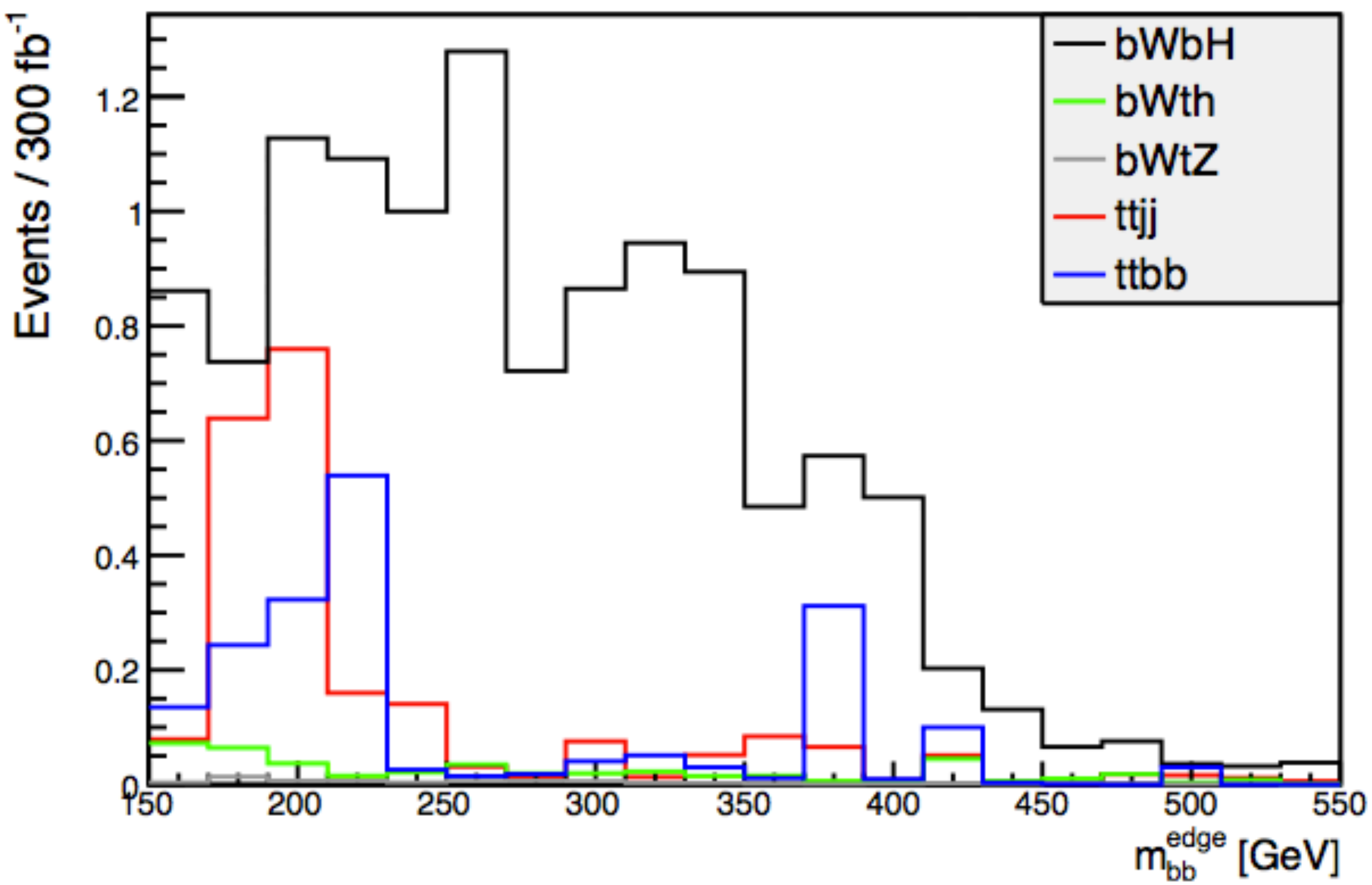
On the Charged Higgs

- Can go after reconstruction of the charged Higgs boson resonance in (tb)
- Can look for an edge in the m_{bb} distribution at

$$m_{bb} \leq m_T \sqrt{1 - \frac{m_{H^\pm}^2}{m_T^2}} \sqrt{1 - \frac{m_t^2}{m_{H^\pm}^2}}.$$



Edge Plot



14 TeV

$\epsilon = .1$

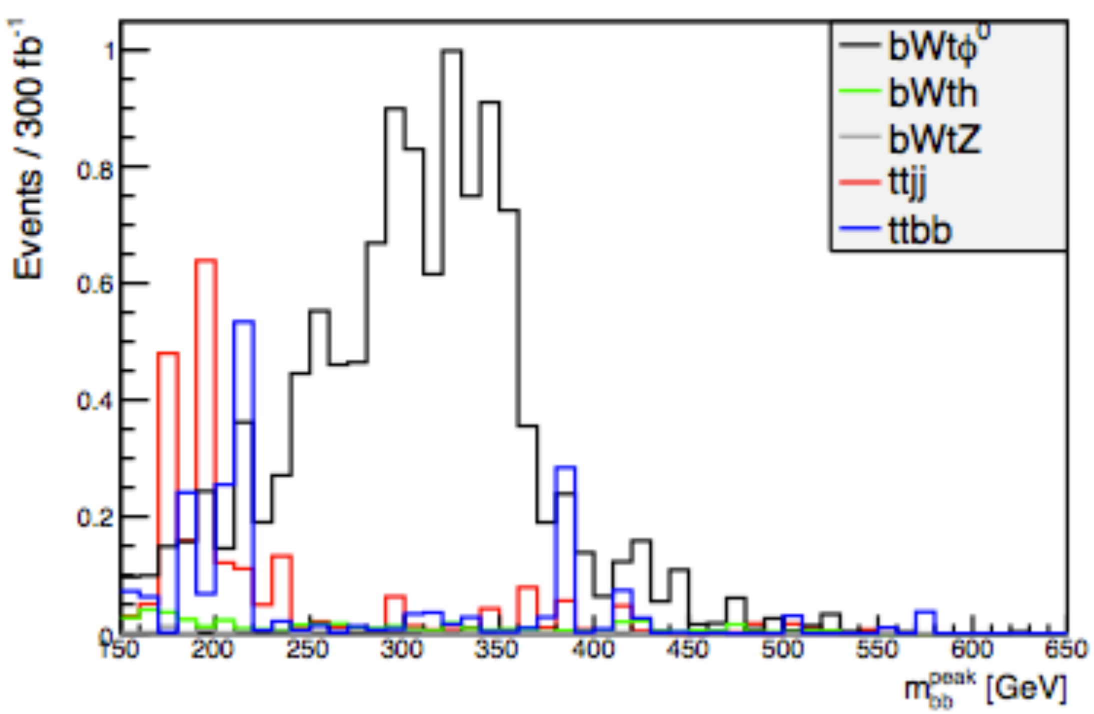
Preliminary

Kearney, AP, Thaler

Use the b's that don't give the best $m_T \approx m_{b\ell\nu}$

Other Quarticons?

- Clearly $T \to b\phi^{\pm}$
- Will catch $T \to t\phi^0 \to tbb$ with this analysis, too.



Conclusions

- Little Higgs theories (or more generally, Higgs as a pNGB) remain a possibility worth hunting for if naturalness is the right guide.
- The minimal searches (T to bW, tZ, th) are useful, but need not be the whole story
- There can be many top partners with interesting phenomenology. Discovery and determination of branching ratios can be an important window on to the physics of the symmetry breaking.