The Littlest Higgs with T Parity (LHT) Enters Madgraph4.0

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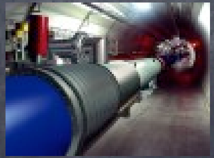
www.lepp.cornell.edu/~maxim/LHTtool



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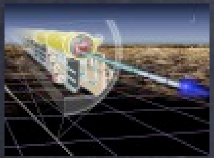
March 23-24,
2007



Evolution of the LHT Idea

- The "Little Higgs" question: Could the Higgs be a pseudo-GSB of a global symmetry broken at a scale f ~ 1TeV?

Georgi, et. al. (1974)

- Higgs mass unstable: With 1-loop corrections, $m_h \rightarrow f$. Solution: Collective Symmetry Breaking.

Arkani-Hamed, Cohen, Georgi (2002)

- An economical implementation: The "Littlest Higgs" model.
  a) EW sector embedded in an SU(5)/SO(5) nlsm.
  b) Heavy vector quark, triplet scalar, and four GB's.

Arkani-Hamed, Cohen, Katz, Nelson (2002)

- Little Hier. Problem: Violates EWPM without fine-tuning. Solution: A Z_2 symmetry dubbed "T Parity" (LH's R Parity).

Cheng and Low (2004)

600GeV < f < 3TeV OK!

Hubisz, Meade, AN, and Perelstein (2005)

Why study LH models?

- Allow strong dynamics to initiate EWSB around 10TeV, generating a composite Higgs while avoiding the usual problems of technicolor.
- Stabilize the Higgs mass with perturbative physics around 1TeV and radiative EWSB.

Why study the LHT?

- Satisfies EW constraints without fine-tuning.
- Provides a WIMP dark matter candidate.
- Predicts the pair production of new heavy particles and a generic missing energy signal that could fake SUSY at the LHC.

LHT Structure

Globally

SU(5) → SO(5) where $\Pi = \begin{pmatrix} * & H & \Phi \\ H^\dagger & * & H^T \\ \Phi & H^* & * \end{pmatrix}$

Gauged subgroup

$[SU(2) \times U(1)]_{1,2} \rightarrow SU(2)_L \times U(1)_Y$

Explicit breaking of the SU(5) global symmetry

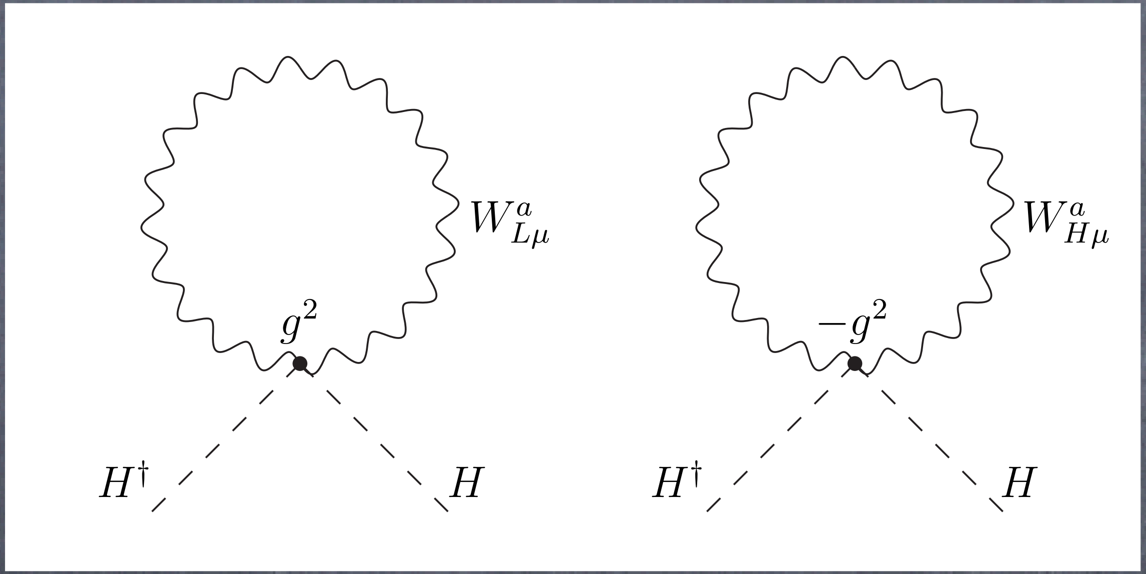
$\rightarrow W_H^a,\ B_H$

T Parity

$[SU(2) \times U(1)]_1 \leftrightarrow [SU(2) \times U(1)]_2$

Bosonic SUSY!

- "Collective Symmetry Breaking"
  → At one-loop order, quadratic divergences in the Higgs mass due to SM particles are cancelled by heavy particles of the same spin-statistics running in the loop.



- At two-loop order, the Higgs mass will receive quadratic corrections, but no fine-tuning required if Λ~10TeV.

$$\Delta m_h^2 \sim \frac{g^4}{(4\pi)^4}\Lambda^2$$

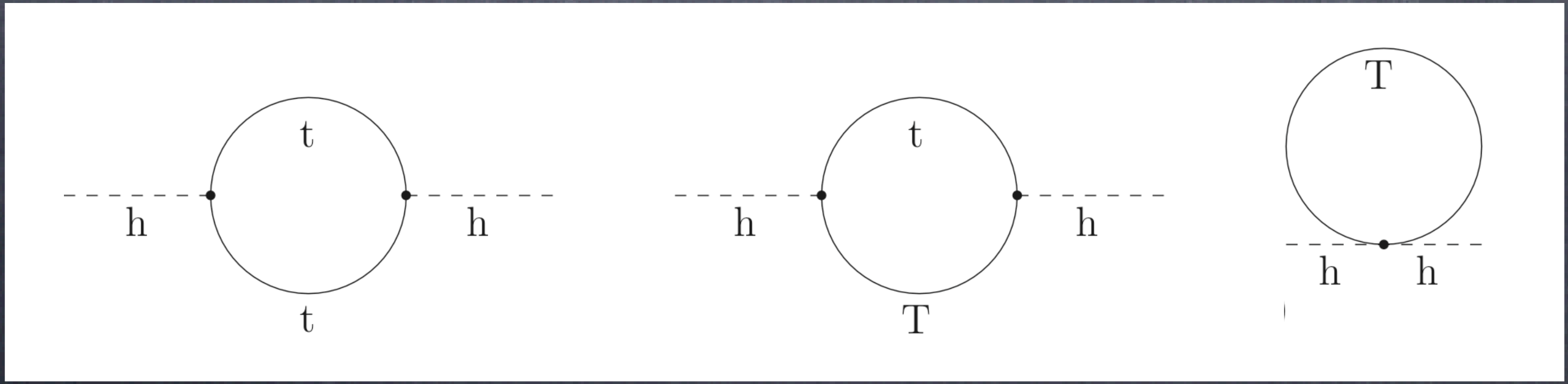
Radiative EWSB

- Implementing the collective symmetry breaking pattern in the top sector introduces a T-even heavy Dirac fermion.*

“T”

- Top sector gives leading contribution in the CW potential.

$$m_h^2 = -\frac{3\lambda_t^2 M_T^2}{8\pi^2}\log\frac{\Lambda^2}{M_T^2}$$



*But the LHT does not require this T. See Cheng, Low, and Wang (2005).

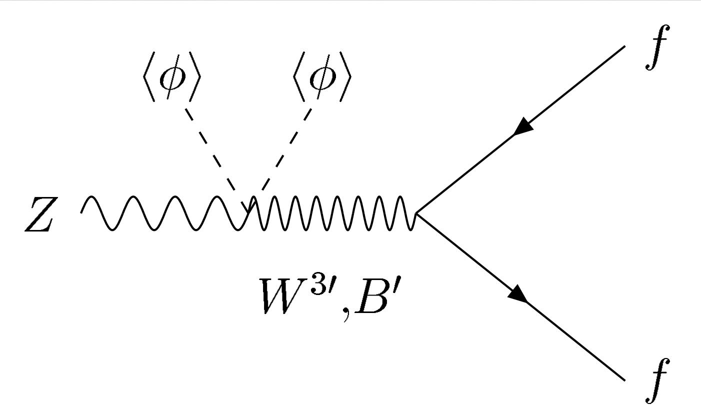
Electroweak Constraints

Hewett, Petriello, Rizzo (2002)
Csaki, Hubisz, Kribs, Meade, Terning (2003)

- Without T Parity,

1) A small but non-vanishing $< \phi >$ due to $h\phi h$ tadpole.

2) The tree-level exchange of heavy gauge bosons.



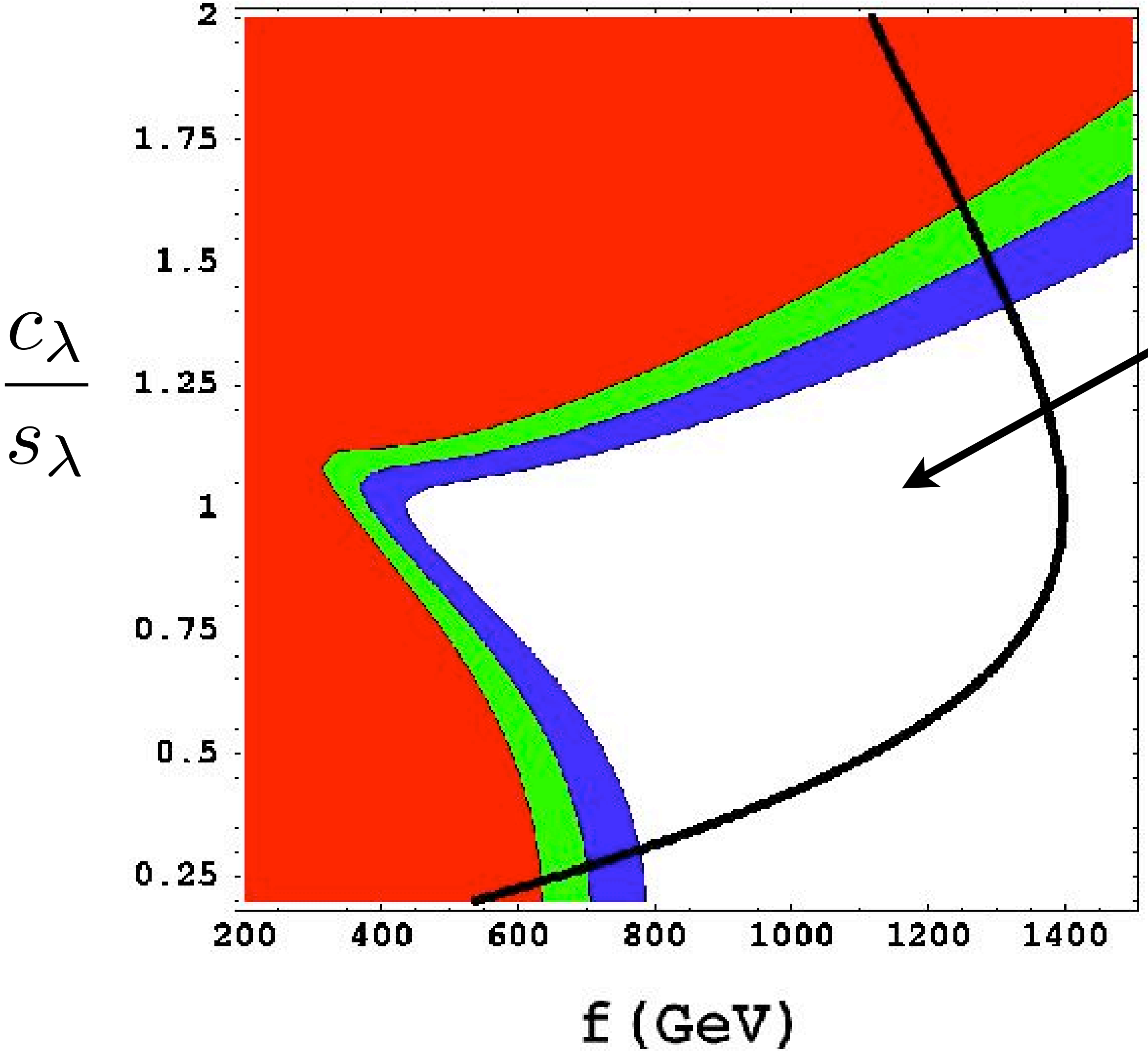
- Adding T Parity,

1) Leading corrections to EWPM occur at one-loop order.

2) Heavy top contributions to the T parameter dominate EWP fits.

LHT Fit to EWPM

Hubisz, Meade, AN, and Perelstein (2005)

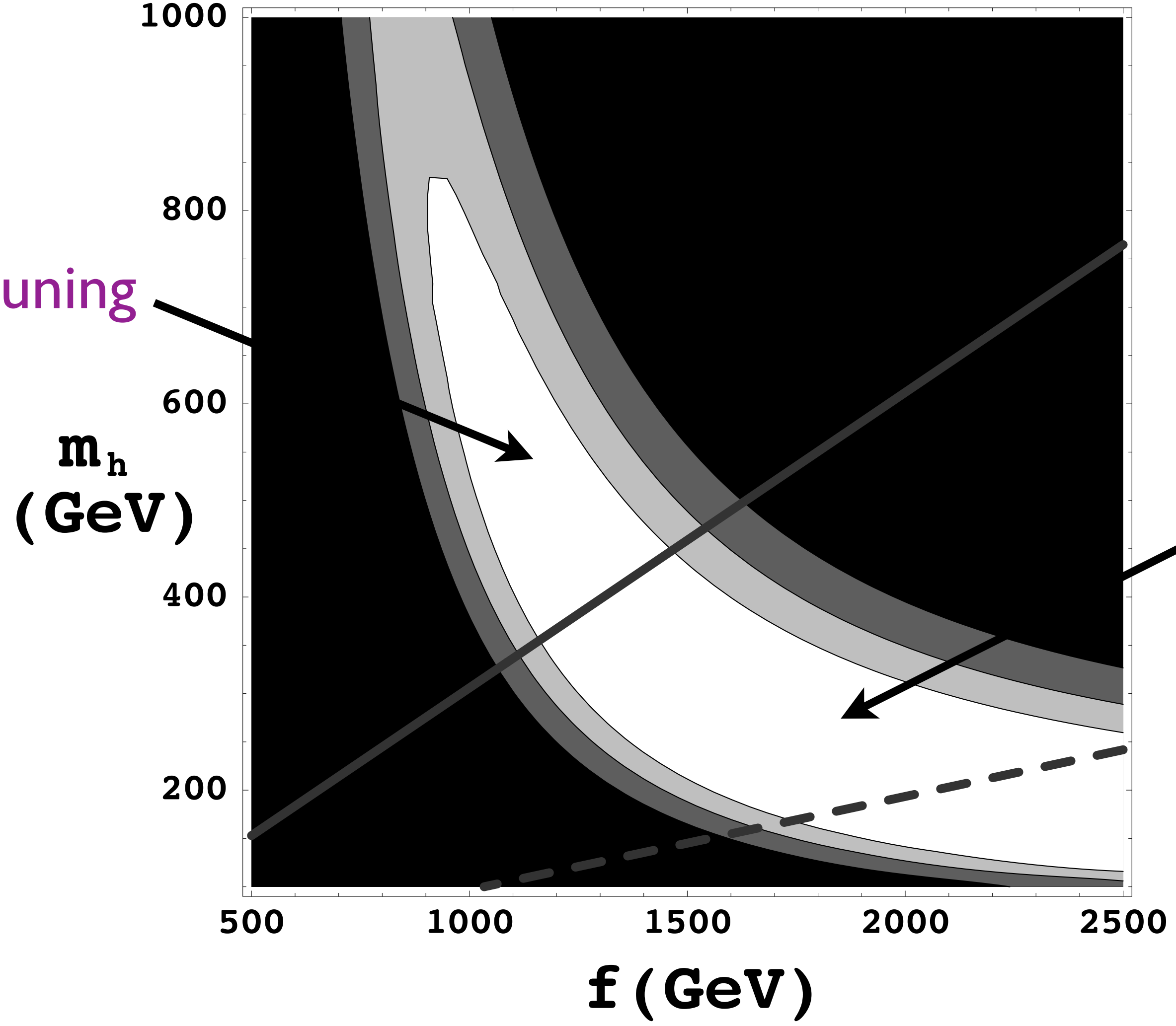


<10% tuning

$$m_{h,ref} = 113\text{GeV}$$

A Heavy Higgs Region

Hubisz, Meade, AN, and Perelstein (2005)



<10% tuning

<1% tuning

$$c_\lambda / s_\lambda = 2$$

BSM Parameter Space

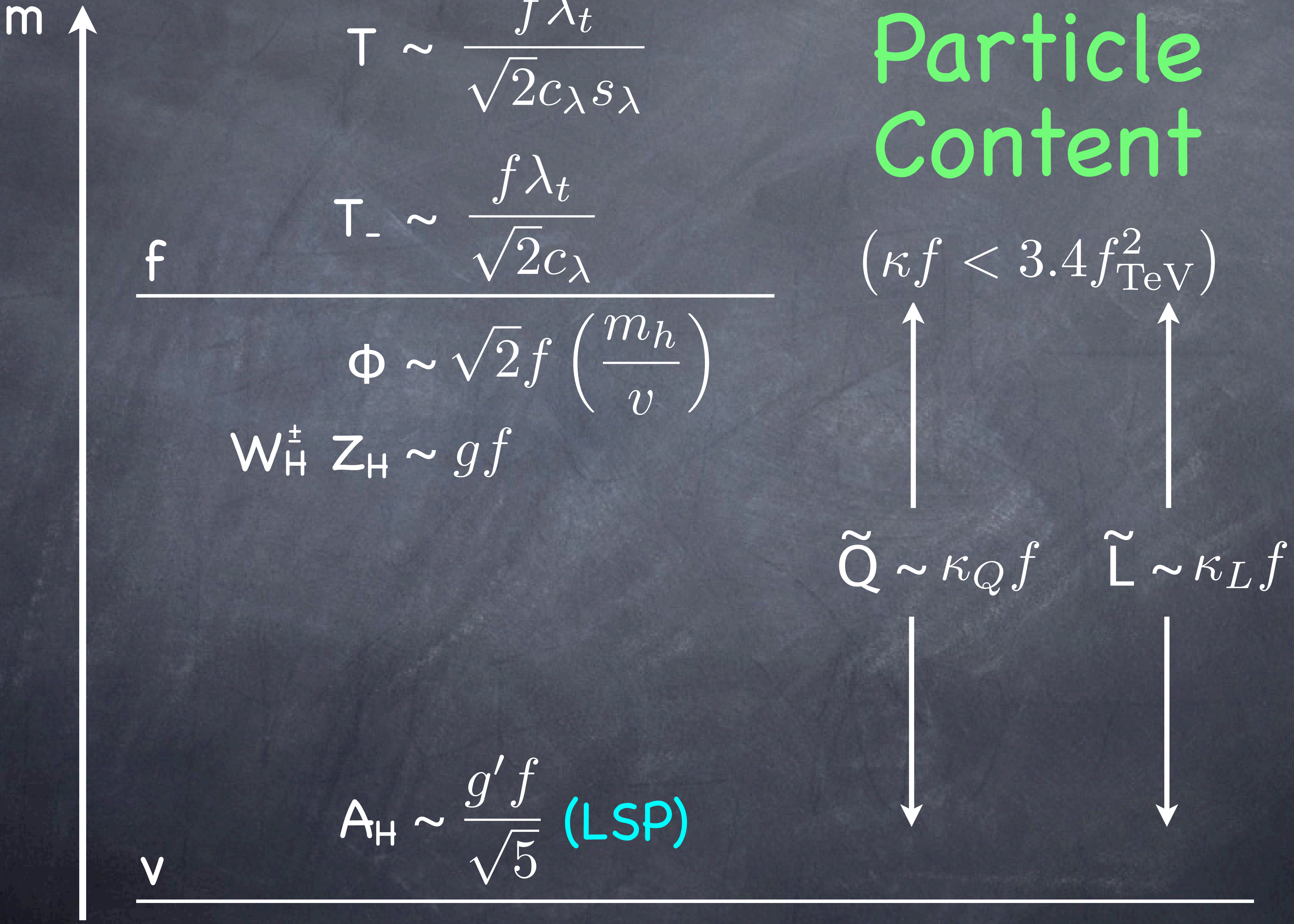
- Flavor diagonal input parameters:

$$f, \quad \theta_\lambda, \quad \kappa_Q, \quad \kappa_L$$

- Derived parameters:

$$\theta_H, \quad \theta_\alpha, \quad \theta_\beta, \text{ and pion mixing angles}$$

BSM Particle Content



m

$T \sim \frac{f\lambda_t}{\sqrt{2}c_\lambda s_\lambda}$

$T_- \sim \frac{f\lambda_t}{\sqrt{2}c_\lambda}$

f

$\Phi \sim \sqrt{2}f\left(\frac{m_h}{v}\right)$

$W_H^\pm \; Z_H \sim gf$

$A_H \sim \frac{g' f}{\sqrt{5}}$ (LSP)

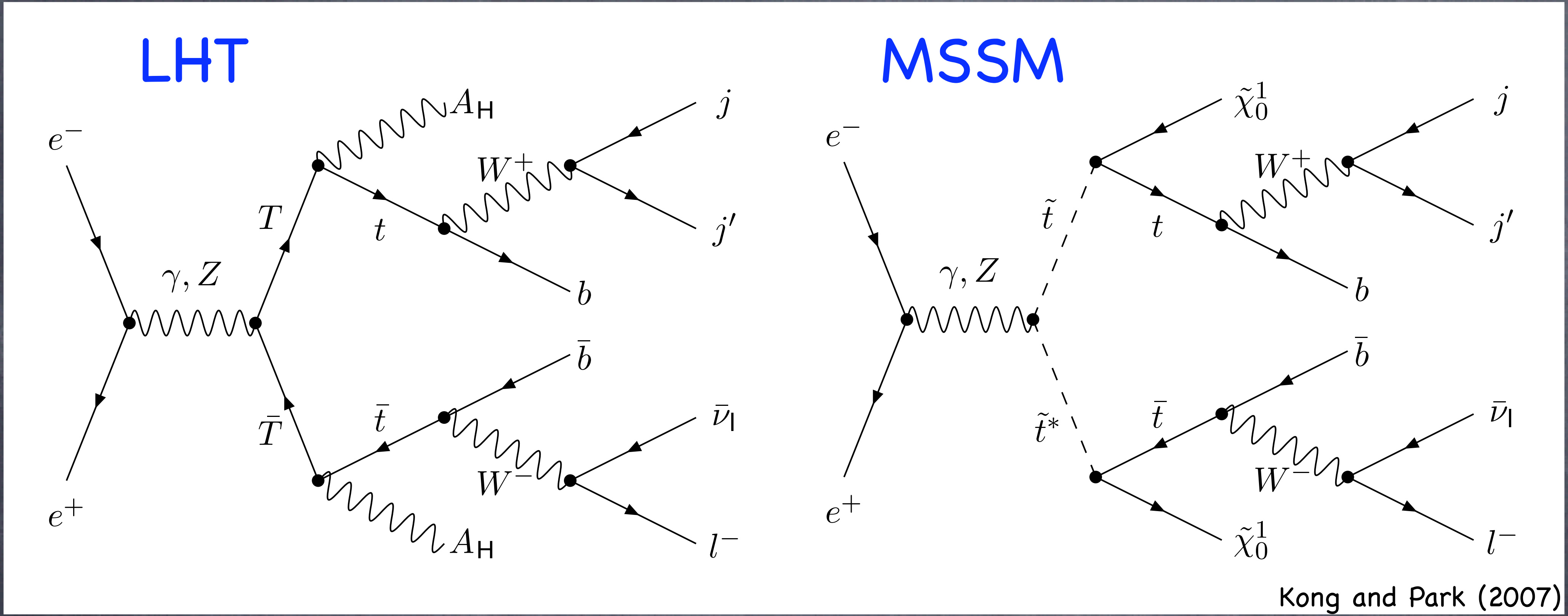
v

$\left(\kappa f < 3.4 f_{\mathrm{TeV}}^2\right)$

$\tilde{Q} \sim \kappa_Q f$

$\tilde{L} \sim \kappa_L f$

Cascade Decays



Kong and Park (2007)

- The LH with T Parity can bear a striking resemblance to SUSY with R Parity!
- But the spin of the LH top partner is different from the spin of the SUSY top partner. The study of spin correlations is essential for determining the underlying theory. Madgraph is a wonderful tool for doing this.

Madgraph4.0 Implementation

- Masses calculated to all orders in v/f.

  e.g. $W_L = \frac{e}{2s_w} f \sqrt{1 - \cos(\sqrt{2}v/f)}$

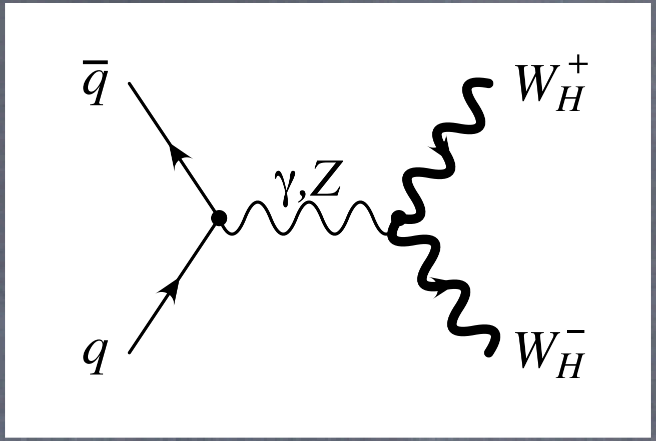
- Couplings calculated to all orders in v/f.

  e.g. $W^+ \; W_H^- \; Z_H \sim \frac{e}{sw} \cos(\theta_H)$

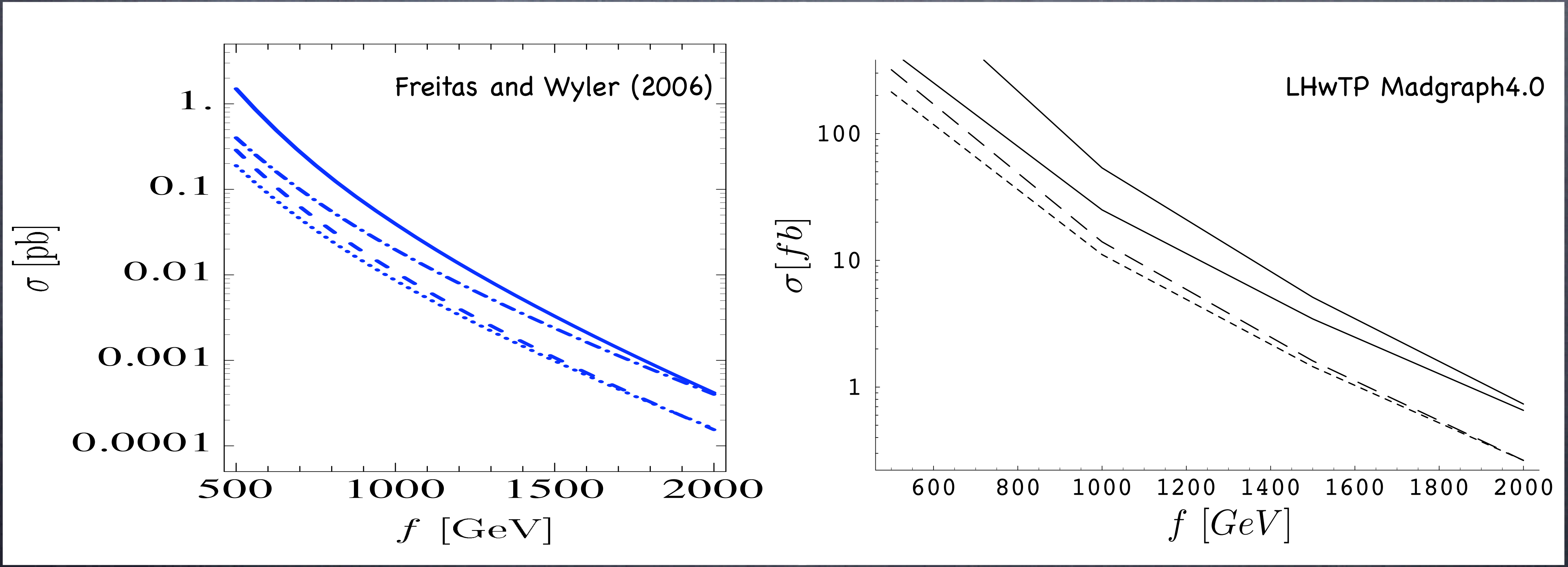
- At the moment, higher derivative operators in the nlsm are not included.
- All dim-4 vertices included, except for phenomenologically less interesting 3- and 4- scalar interactions.
- Interfaced with BRIDGE to calculate decay widths given a choice of input parameters.

See today's talk by Matt Reece!

$pp \to W^+_H W^-_H$



$\bar{q}$
q
γ, Z
W_H^+
W_H^-



Freitas and Wyler (2006)
σ [pb]
1.
0.1
0.01
0.001
0.0001
500
1000
1500
2000
f [GeV]
LHwTP Madgraph4.0
$\sigma\,[fb]$
100
10
1
600
800
1000
1200
1400
1600
1800
2000
$f\ [GeV]$

Future Directions

- Initiate new studies of LHT phenomenology using this new Madgraph4.0 model.

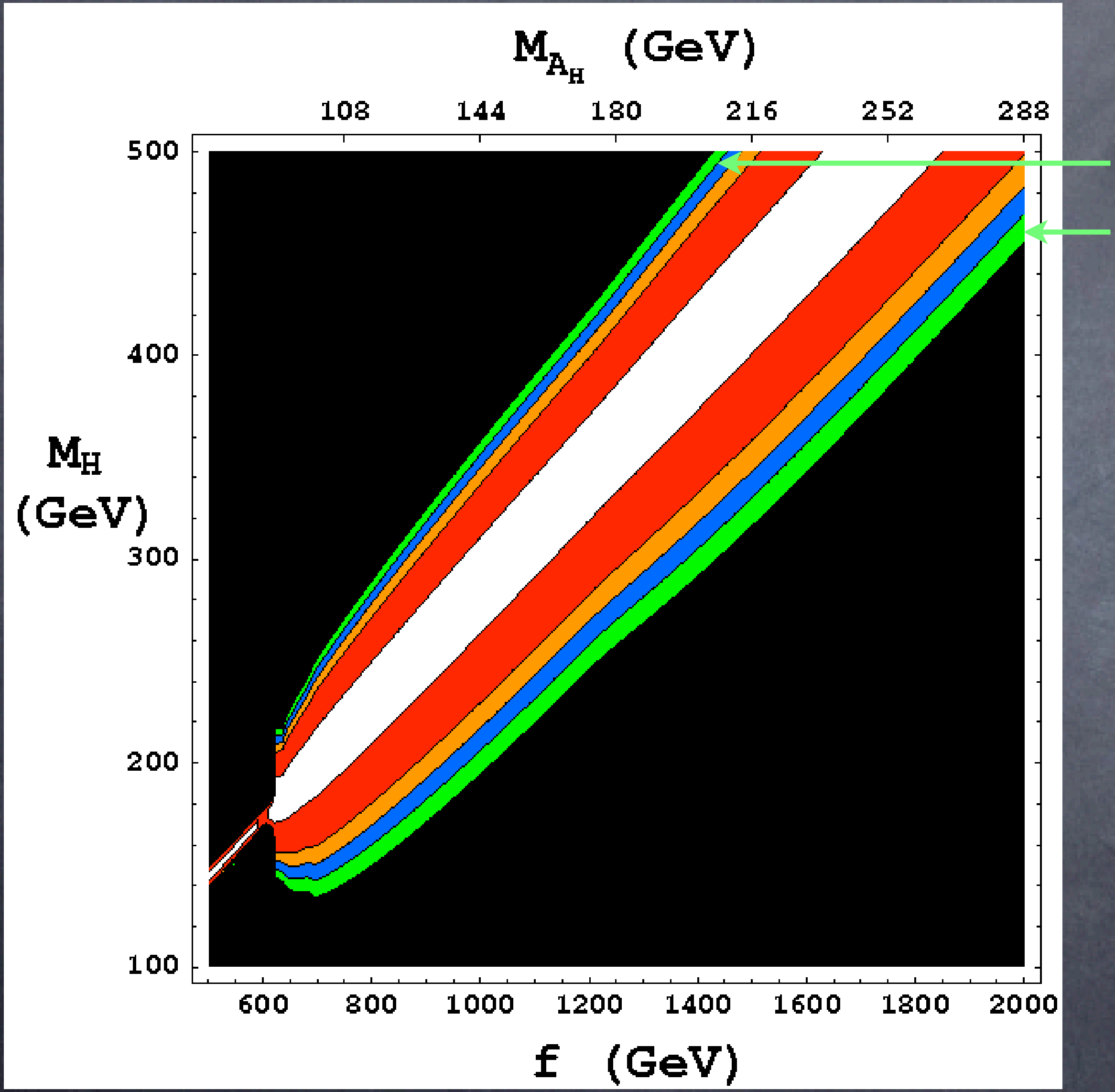
- Implement an alternative LHT model that eliminates the need for a T-even top partner.

  Cheng, Low, and Wang (2005)

- Make use of your feedback! We would appreciate your help in test-driving this newly minted model!
  www.lepp.cornell.edu/~maxim/LHTtool

Pair-Annihilation

Hubisz and Meade (2004)



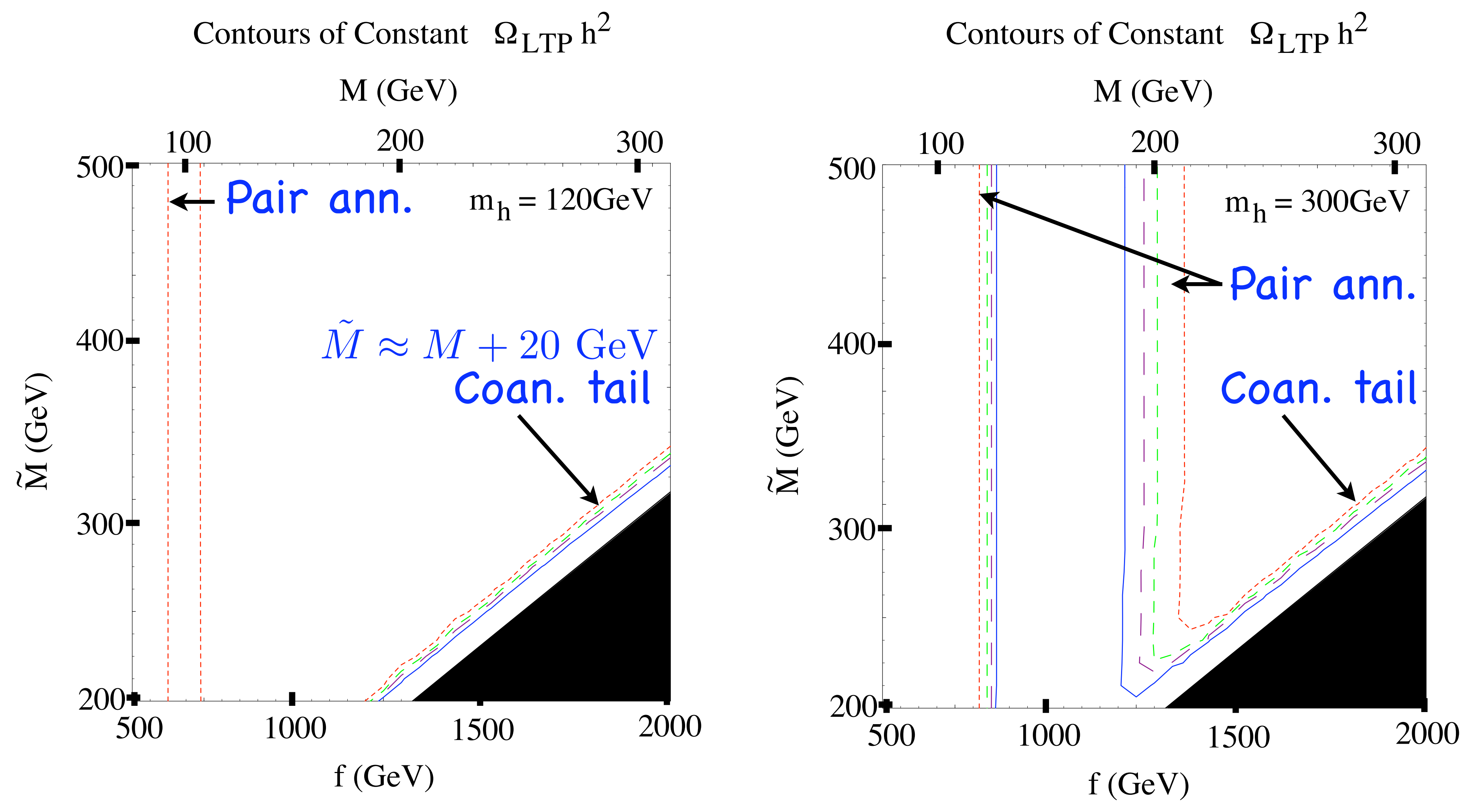
"High" $m_h \approx 2.38M + 24\mathrm{GeV}$

"Low" $m_h \approx 1.89M - 83\mathrm{GeV}$

Regions where B_H accounts for 100% of the WMAP DM value.

$$\Omega_{dm}h^2 = 0.111 \pm 0.018$$

Coannihilation

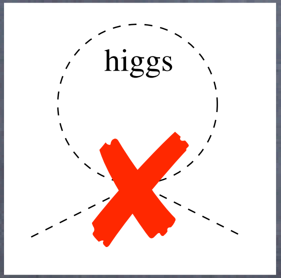


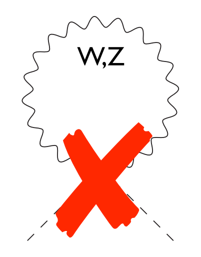
Collective Symmetry Breaking

Idea from Arkani-Hamed, Cohen, Georgi (2001)

$$D_\mu \Sigma = \partial_\mu \Sigma - i \sum_j \left[g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + g_j' B_j (Y_j \Sigma + \Sigma Y_j) \right]$$

g_1 turned off → only gauge $Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$





SU(3)$_1$

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

SU(3)$_2$

g_2 turned off → only gauge $Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

The Top Sector

To the third-family quark doublet add a new Weyl fermion.

$$\chi = (d_3, u_3, \tilde{t})$$

Explicitly breaks SU(5)!

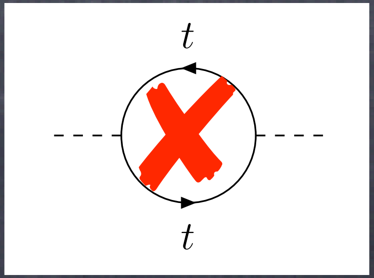
Write down a Lagrangian that follows the collective symmetry breaking pattern.

$$\mathcal{L}_t = \lambda_1 f \epsilon_{ijk}\epsilon_{xy}\chi_i\Sigma_{jx}\Sigma_{ky}u_3^c + \lambda_2 f\tilde{t}\tilde{t}^c + h.c$$

↓ Breaks SU(3)$_2$

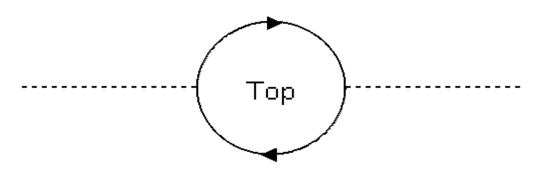
↓ Breaks SU(3)$_1$

In the mass eigenbasis, we find the SM top Yukawa coupling and a new "heavy top" T with an f-scale Dirac mass.



Top Sector Modification:

$\mathcal{L}_{Teven}$ must follow the collective symmetry breaking pattern to cancel,



Extend the two fermion doublets in this sector to SU(3) representations.

$$\mathcal{Q}_1 = \begin{pmatrix} q_1 \\ U_{L1} \\ 0 \end{pmatrix}, \mathcal{Q}_2 = \begin{pmatrix} 0 \\ U_{L2} \\ q_2 \end{pmatrix}$$ where, under T Parity, $U_{L1} \leftrightarrow -U_{L2}$

Then the top sector Lagrangian supporting collective symmetry breaking is,

$$\mathcal{L}_t = \frac{1}{2\sqrt{2}}\lambda_1 f \epsilon_{ijk}\epsilon_{xy}\left[(\bar{\mathcal{Q}}_1)_i\Sigma_{jx}\Sigma_{ky} \underset{\downarrow}{-} (\bar{\mathcal{Q}}_2\Sigma_0)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right]u_R + \lambda_2 f(\bar{U}_{L1}U_{R1} \underset{\downarrow}{+} \bar{U}_{L2}U_{R2}) + \text{h.c.}$$

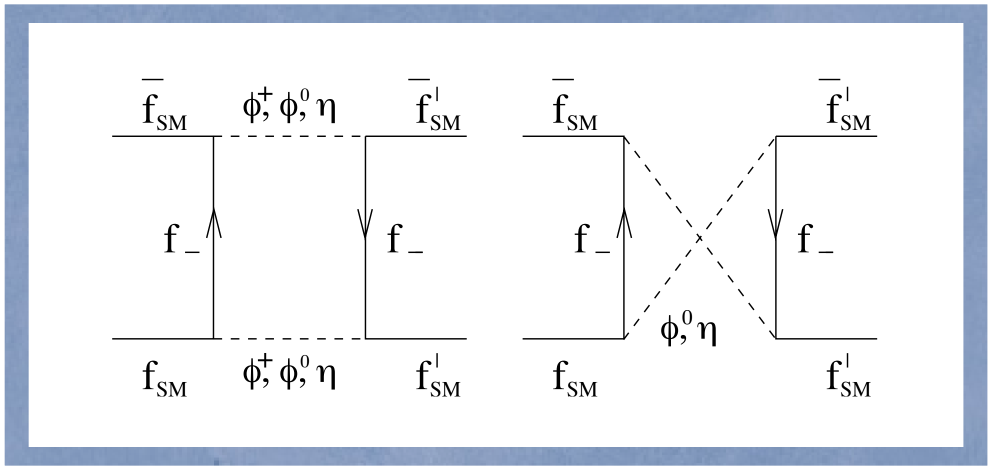
Breaks one T-even SU(3) Breaks other T-even SU(3)

In the mass eigenbasis, we find,

$$\begin{aligned} t_L &= u_{L+} - s_\lambda^2 \frac{v}{f} U_{L+} & T_{L+} &= U_{L+} + s_\lambda^2 \frac{v}{f} u_{L+} \\ t_R &= c_\lambda u_R - s_\lambda U_{R+} & T_{R+} &= c_\lambda U_{R+} + s_\lambda u_R \end{aligned}$$

T-odd Fermion Corrections

The leading contributions to four-fermion operators, in the limit where κ >> g, come from,



$$\mathcal{O}_{4-\mathrm{f}} = -\frac{\kappa^2}{128\pi^2 f^2}\bar{f}_L\gamma^\mu f_L \bar{f}'_L\gamma_\mu f'_L$$

Strongest constraint comes from eedd coefficient.

$$\delta_{eedd} < \frac{2\pi}{(26.4TeV)^2} \quad\Rightarrow\quad M^{T-odd}_{\mathrm{TeV}} = \sqrt{2}\kappa f < 4.8 f^2_{\mathrm{TeV}}$$

Assuming a universal, flavor-diagonal κ, the 12 T-odd fermion doublets contribute,

$$T_{\mathrm{T-odd}} = -12\times\frac{\kappa^2}{192\pi^2\alpha}\left(\frac{v}{f}\right)^2$$