New Ideas in Electroweak Symmetry Breaking and their Experimental Tests

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with Burdman, Pierce hep-ph/0212228 PRL

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Hubisz, Meade, Noble hep-ph/05mmnnn

see also hep-ph/0408072 JHEP

- The Standard Model describes electroweak symmetry breaking but does not explain it:

$$V(H) = -\mu^2 H^+ H + \lambda (H^+ H)^2$$

- Sign of the H^+H term is chosen by hand
- Real explanation of the EWSB requires going beyond the SM
- There is two options:

Add structure to make the theory predictive (i.e. predict the sign of μ^2) (example: SUSY with radiative EWSB)

Get rid of the Higgs altogether, break symmetry by strong dynamics (ex.: technicolor)

- Recently, new models of both classes have been proposed
- I'll talk about 2 examples: LITTLE HIGGS (radiative EWSB) and HIGGSLESS (strongly coupled EWSB)

Part I: HIGGSLESS MODELS
and their LHC phenomenology

- In "SM − Higgs", $W_L W_L$ scattering becomes strongly coupled at

$$\Lambda \sim \frac{4\pi M_W}{g} \sim 1.8 \text{ TeV}$$

- Operators suppressed by $1/\Lambda^n$ will be generated
  ⇒ need to be included in precision electroweak fits

- EW precision experiments require $\Lambda \gtrsim 5\text{-}10$ TeV
  → strongly coupled EWSB ruled out?

- "The Higgsless approach" (Csaki, Grojean, Terning, Murayama, Pilo)

  - introduce new particles around the TeV scale coupled to the SM W/Z bosons

  - diagrams involving new particles suppress $W_L W_L$ (or $W_L Z_L$) scattering @ high energies
    ⇒ raise Λ to the required 5-10 TeV range

• **EXAMPLE:** $W_L^\pm Z_L \to W_L^\pm Z_L$ scattering

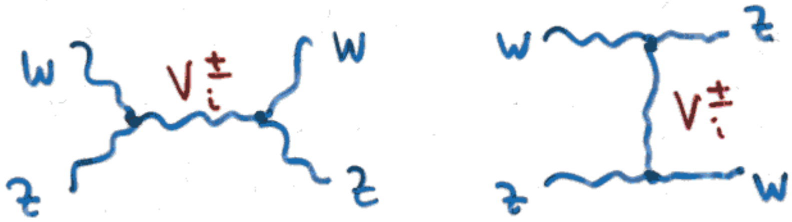
SM − H:

$$\mathcal{M} \propto E^2$$

SM:

$\Rightarrow \quad \mathcal{M} \propto E^0$

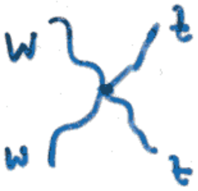
Higgsless:



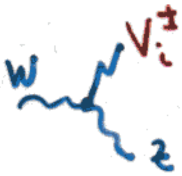
$\Rightarrow \mathcal{M} \propto E^0$

• Cancellation requires **SUM RULES**:

$= g_3$



$= g_4$



$= g_{(i)}$

$$g_4 = g_3^2 + \sum_i g_{(i)}^2$$

$$2(g_4 - g_3^2)(M_W^2 + M_Z^2) + g_3^2 \frac{M_Z^4}{M_W^2} = \sum_i g_{(i)}^2 \left(3M_i^2 - \frac{(M_Z^2 - M_W^2)^2}{M_i^2}\right)$$

- 5D Higgsless models (see G. Cacciapaglia's talk) satisfy the sum rules exactly $(i=1\ldots\infty)$

- 4D "deconstructed" Higgsless models (Foadi, Gopalakrishna, Schmidt, Chivukula, Georgi, MP, ...) satisfy the sum rules to a few % $(i=1\ldots N_s)$

- The sum rules are independent of model-building details (e.g. the fermion sector)

  ⇒ GENERIC prediction of Higgsless mechanism

- This translates into robust predictions for the LHC (Birkedal, Matchev, MP, hep-ph/0412278, PRL - in print)

- Simplifying assumption: sum rules saturated by the 1st resonance
  (checked several models – true to ~5%)

  ⇒ 1-parameter model:

$$g_{(1)} = \frac{g_3 M_Z^2}{\sqrt{3}\, M_W}\,\frac{1}{M_1}$$

- Prediction: a narrow, light resonance in WZ scattering

$$M_1 \lesssim \text{TeV} \qquad \text{(unitarity)}$$

$$\Gamma = \frac{\alpha M_1^3}{144\, s_w^2 M_w^2} \qquad \text{(set couplings to fermions to 0)}$$

[WZ cross section plot]

- WZ collisions at the LHC:

- To suppress the background from the SM $qq' \to WZ$ require 2 observed forward jets

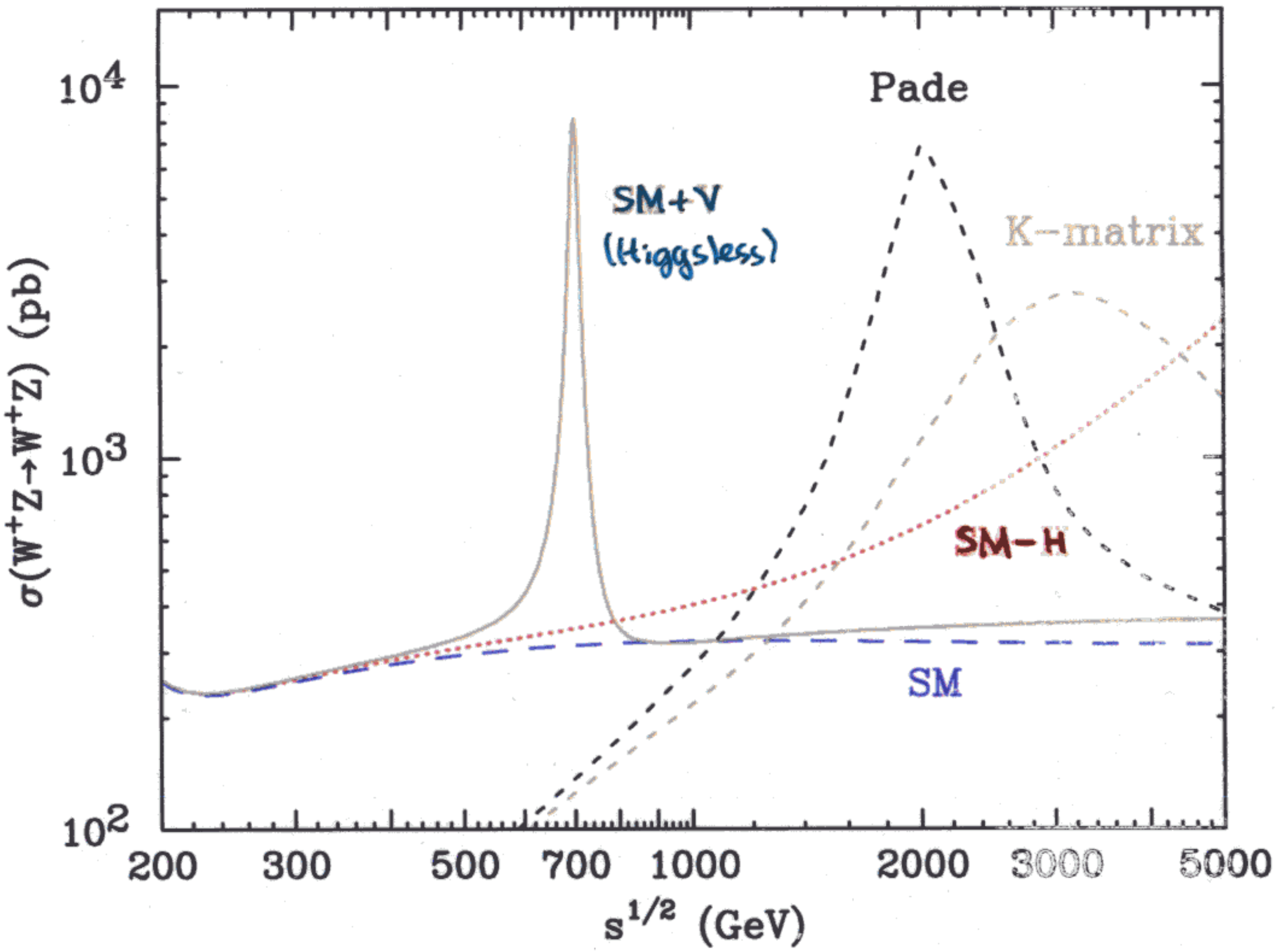
$$(\, 2 \leq |\eta| \leq 4.5, \quad E > 300 \text{ GeV}, \quad p_T > 30 \text{ GeV})$$

[this also eliminates the possible Drell-Yan V_1's!]

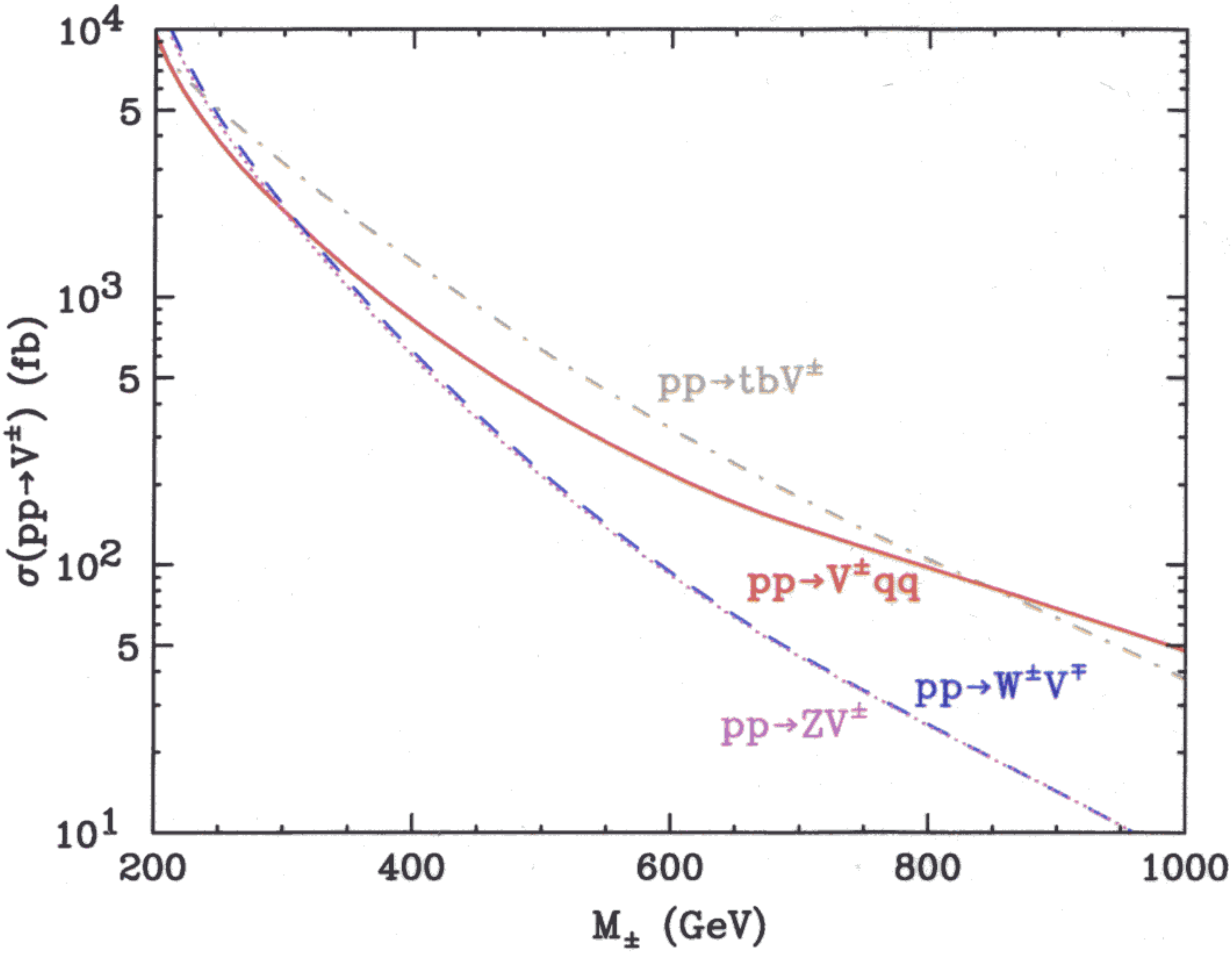
[V_1 production cross section]

- Gold plated channel: $2j + 3\ell + \not{E}_T, \quad \sqrt{s_{11}} \approx M_Z$

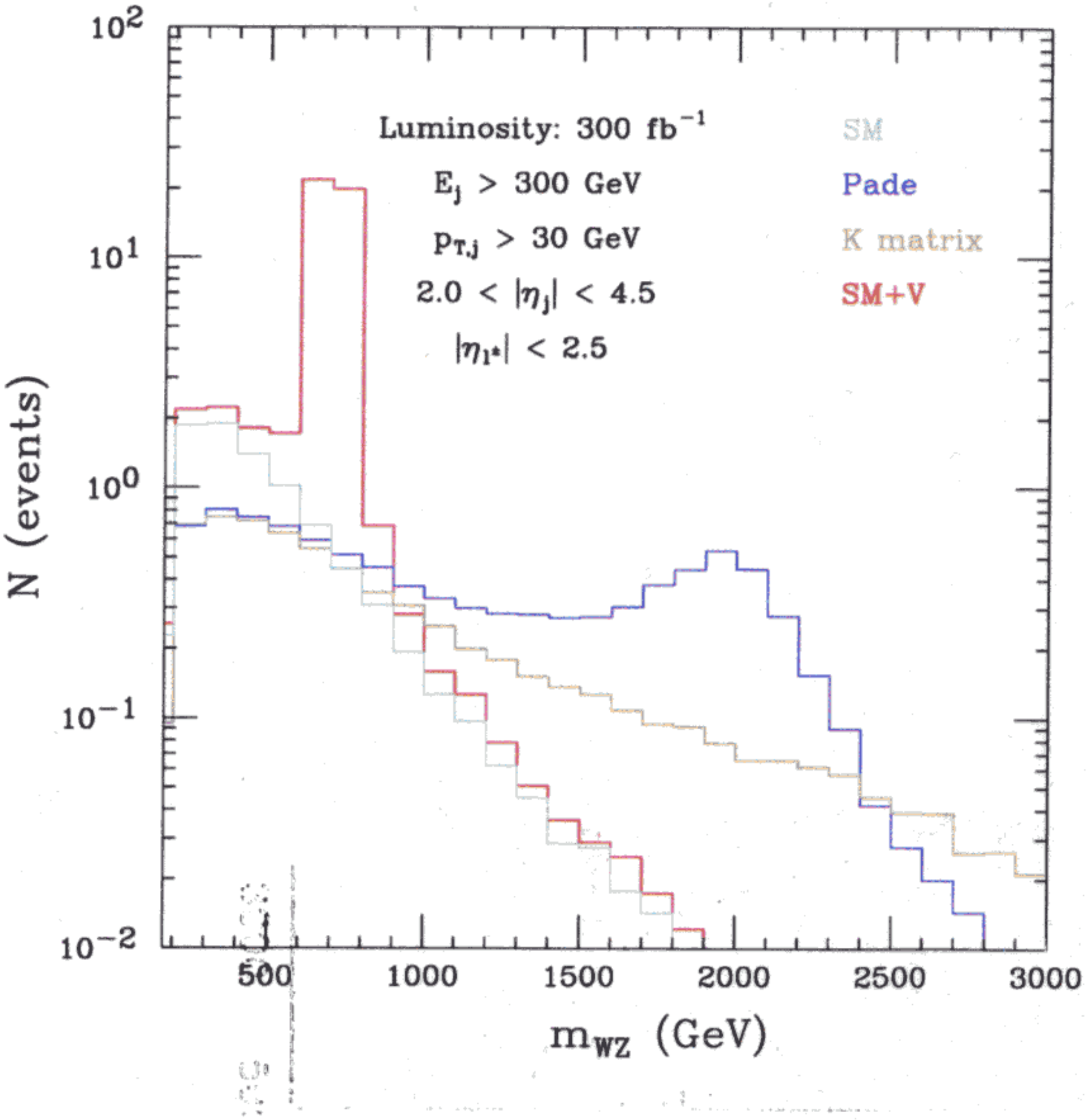
[# of events plot]



Pade
SM+V
(Higgsless)
K−matrix
SM−H
SM
10^4
10^3
10^2
200
300
500
700
1000
2000
3000
5000
$s^{1/2}$ (GeV)
$\sigma(W^+Z \to W^+Z)$ (pb)



10^4
5
10^3
5
10^2
5
10^1
200
400
600
800
1000
$\sigma(pp \to V^\pm)$ (fb)
$M_\pm$ (GeV)
$pp \to tbV^\pm$
$pp \to V^\pm qq$
$pp \to W^\pm V^\mp$
$pp \to ZV^\pm$



Luminosity: 300 fb^{-1}
E_j > 300 GeV
$p_{T,j}$ > 30 GeV
2.0 < $|\eta_j|$ < 4.5
$|\eta_{l^*}|$ < 2.5
SM
Pade
K matrix
SM+V
N (events)
m_{WZ} (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
500
1000
1500
2000
2500
3000

- Discovery reach at the LHC (10 signal events):

$$M_1 \lesssim 550 \text{ GeV}, \qquad 10\, fb^{-1}$$

$$M_1 \lesssim 1 \text{ TeV}, \qquad 60\, fb^{-1}$$

- Mass measurement: $M^2 = s(WZ)$

Uncertainty dominated by $\not{E}_T$ $\sim 10\%$?

- Could we test the sum rule ($\Leftrightarrow$ "prove Higgsless") ?

  - Requires a measurement of g_1

  - Width measurement – limited by $\not{E}_T$ resolution, probably impossible – resonance too narrow!

  - Rate measurement:

$$\text{Rate} = \sigma_{tot} \cdot Br(V_1 \to WZ)$$

p.d.f. uncertainties

all decay channels need to be reconstructed!

$\Rightarrow$ probably have to wait for ILC for a good coupling measurement

Part II: LITTLE HIGGS MODELS

- Idea: keep the Higgs in the theory, but construct a model that would predict the sign of μ^2

- In SM, μ^2 receives large radiative corrections:

$$\mu^2(M_W) = \mu^2(\Lambda) + \frac{g^2}{16\pi^2}\left(c_1 \Lambda^2 + c_2 M^2 \log\Lambda + \dots\right)$$

(Here Λ = strong coupling scale)

- $\mu^2(\Lambda)$ and c_1 are dominated by UV physics
  $\Rightarrow$ uncalculable (except perhaps by non-perturbative or "stringy" techniques)

- To construct a predictive, perturbative theory:
  - suppress the uncalculable contributions by symmetries
  - make sure that the calculable contributions have the correct sign $(c_2 < 0)$

[e.g. SUSY: $c_1 = 0$, $c_2 < 0$ – top, μ-problem...]

The Littlest Higgs

[Arkani-Hamed, Cohen, Katz, Nelson 2002]

- Consider a model with $SU(5)$ global symmetry spontaneously broken to $SO(5)$ by

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

- Low-energy dynamics is described by 14 pion fields

$$\Sigma(x) = e^{2i\Pi/f}\, \Sigma_0$$

$$\Pi = \sum_{a=1}^{14} \pi^a(x)\, X^a$$

- Gauge an $[SU(2) \times U(1)]^2$ subgroup of $SU(5)$:

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_1 = \mathrm{diag}\left(-\tfrac{3}{10}, -\tfrac{3}{10}, \tfrac{1}{5}, \tfrac{1}{5}, \tfrac{1}{5}\right); \quad Y_2 = \mathrm{diag}\left(-\tfrac{1}{5}, -\tfrac{1}{5}, -\tfrac{1}{5}, \tfrac{3}{10}, \tfrac{3}{10}\right)$$

The Littlest Higgs - cont'd

- The gauge - Goldstone boson sector is described by

$$\mathcal{L}_{kin} = \frac{f^2}{8} \mathrm{Tr}\, (D_\mu \Sigma)(D^\mu \Sigma)^\dagger$$

with the covariant derivative

$$D_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) \\ - i \sum_{j=1}^{2} g'_j B_j^a (Y_j \Sigma + \Sigma Y_j)$$

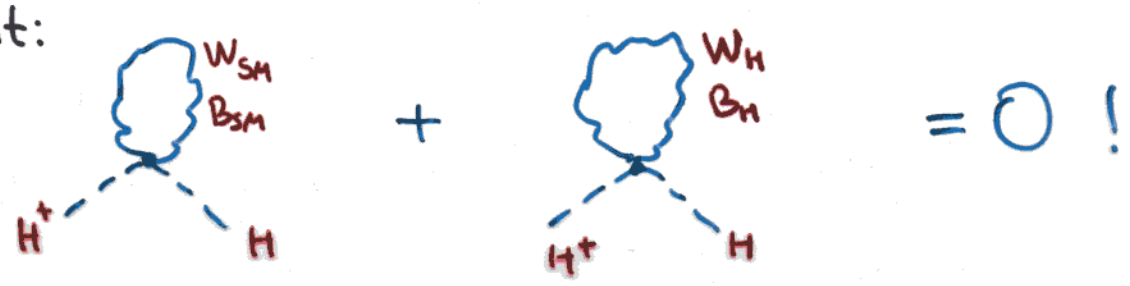
- The vev $\langle \Sigma \rangle = \Sigma_0$ breaks

$$[SU(2) \times U(1)]^2 \to SU(2) \times U(1) \quad \text{- SM EW group!}$$

- Spectrum: SM + 4 heavy gauge bosons
  + 10 physical Goldstones: H, ϕ

- At tree level, $m(H) = 0$ ✓

- At one-loop level, $m(H)$ is NOT quadratically divergent:



Collective Symmetry Breaking

- There is a symmetry reason for this cancellation!

  - recall the gauged SU(2) generators:

$$Q_1^a = \begin{pmatrix} \sigma^a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma_a^* \end{pmatrix}$$

  - imagine that $g_1 = 0$, $g_2' \neq 0$

  - the "upper-left-corner" global SU(3) is not broken by gauging:

$$\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

  - the vev Σ_0 breaks $SU(3) \to SU(2)$

    the SM Higgs is the Goldstone in $SU(3)/SU(2)$

$$\Rightarrow \quad \delta M_H^2 \propto g_1^2$$

  - same argument with $1 \leftrightarrow 2$ $\Rightarrow \delta M_H^2 \propto g_2^2$

$$\Rightarrow \quad \delta M_H^2 \propto g_1^2 g_2^2$$

- There is a quadratic divergence at two-loop level!

  BUT $c_1 \approx g^2/16\pi^2 \ll 1$.

The Littlest Higgs: the Top Sector

- Need to generate top Yukawa coupling without inducing one-loop quadratic divergences

- Again, make use of the collective symmetry breaking idea

- Add a pair of colored, SU(2) singlet, $Y = \pm 2/3$ fermions: $\tilde{t}$ and $\tilde{t}^c$

- Define $\chi = (t, b, \tilde{t})$

- Yukawa couplings arise from

$$\mathcal{L}_t = \frac{\lambda_1}{2} f \, \epsilon_{ijk} \epsilon_{xy} \chi_i \Sigma_{jx} \Sigma_{ky} u_3^c + \lambda_2 f \tilde{t} \tilde{t}^c$$

- 1st term preserves "upper-left-corner" SU(3)

  $\Rightarrow$ $m(H) = 0$ when $\lambda_2 = 0$

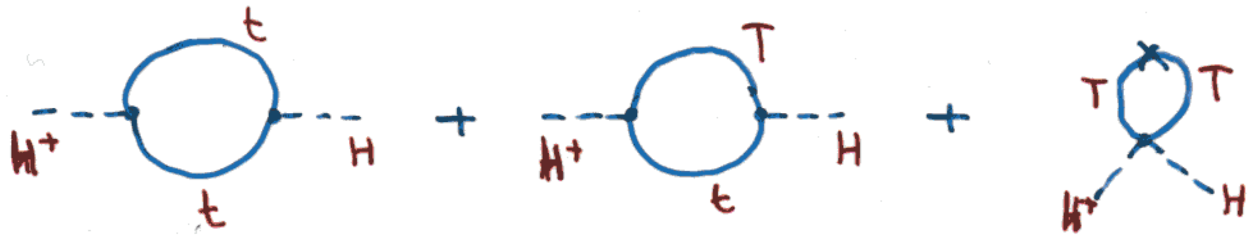
- 2nd term preserves the "lower-right-corner" SU(3)

  $\Rightarrow$ $m(H) = 0$ when $\lambda_1 = 0$

$\Rightarrow$ $\delta m^2(H) \propto \lambda_1^2 \lambda_2^2$

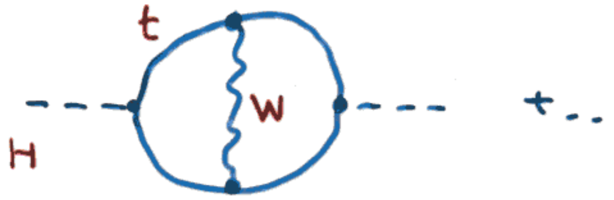
$\Rightarrow$ only two-loop quadratic divergence

Electroweak Symmetry Breaking in the LH



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

- An uncalculable 2-loop contribution:



$$= c\,\frac{g^2}{16\pi^2}\,\frac{\lambda^2}{16\pi^2}\,\Lambda^2$$

- $\Lambda \approx 4\pi f \sim 4\pi M_T$

  $\Rightarrow$ the calculable piece dominates by

$$\frac{\lambda^2}{g^2}\log\frac{\Lambda^2}{M_T^2} \sim 10 \qquad [c \sim 1]$$

- Other (subdominant) contributions: gauge boson + Higgs loops [log-div. @ 1 loop, quad-div. @ 2 loops]

LH Top Sector: Details

- Mass eigenstates:

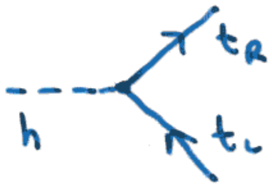
  – the SM top t

$$m_t = \frac{\lambda_t v}{\sqrt{2}} , \qquad \lambda_t = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

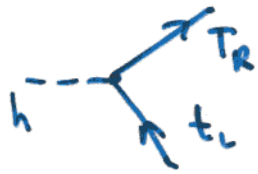
  – the "heavy top" T

$$m_T = \sqrt{2(\lambda_1^2 + \lambda_2^2)}\, f \geq \lambda_t f$$

- Feynman rules in the top-Higgs sector:



$$\frac{i\lambda_t}{\sqrt{2}}$$



$$\frac{i\lambda_T}{\sqrt{2}}$$

$$\frac{i\lambda_T}{2f}$$

$$\lambda_T = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

- SUM RULE

$$\frac{m_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}$$

ensures the cancellation of 1-loop quad. div. !

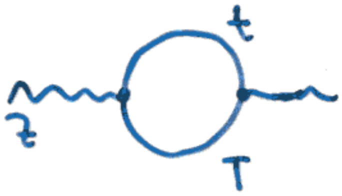
How Heavy is the Heavy Top?

- Upper bound: naturalness

$$M_T \lesssim 2\,\text{TeV} \cdot \left(\frac{M_H}{200\,\text{GeV}}\right)^2 \qquad [10\%]$$

- Lower bound: precision electroweak constraints

1. Top sector contribution [1-loop]



$$+ \ldots \Rightarrow T = \frac{3}{16\pi}\frac{1}{S_W^2 C_W^2}\frac{M_t^4}{M_Z^2 M_T^2}\left(\log\frac{M_T^2}{m_t^2} + \frac{1}{2}\right)$$

$$\Rightarrow \quad M_T \gtrsim 1\ \text{TeV} \qquad [95\%\ \text{c.l.}]$$

2. Gauge sector contribution [tree]

$+ \ldots$

3. Scalar contribution (incl. triplet vev)

[Csàki et al. ; Hon et al ; Chen+Dawson ; ...]

- Precise PEC bound very model-dependent:

e.g. in $SU(2) \times SU(2) \times U(1)$ $\quad f \gtrsim 1$ TeV

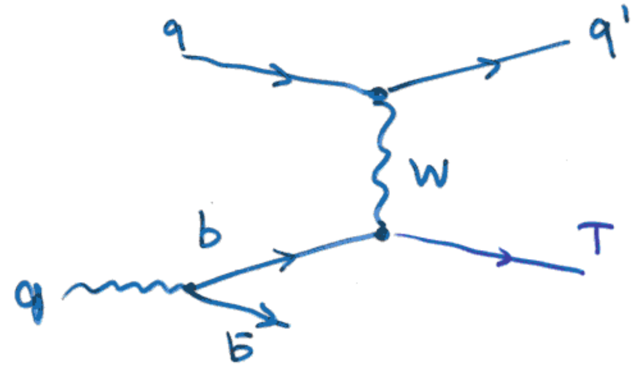
$m_T \gtrsim 2f$

Finding the Heavy Top

- Production mechanisms @ the LHC:

  - pair production $q\bar{q} \to T\bar{T}$, $gg \to T\bar{T}$

  - single T production



[cross section plot]

  - single production dominant for $M_T \gtrsim 1$ TeV

- Decay channels:

$$Br(T \to th) = Br(T \to t Z_0) = 25\%$$
$$Br(T \to bW) = 50\%$$ [G. B. Eq. Th.]

$$\Gamma(T) = \frac{\lambda_T^2}{16\pi} M_T$$

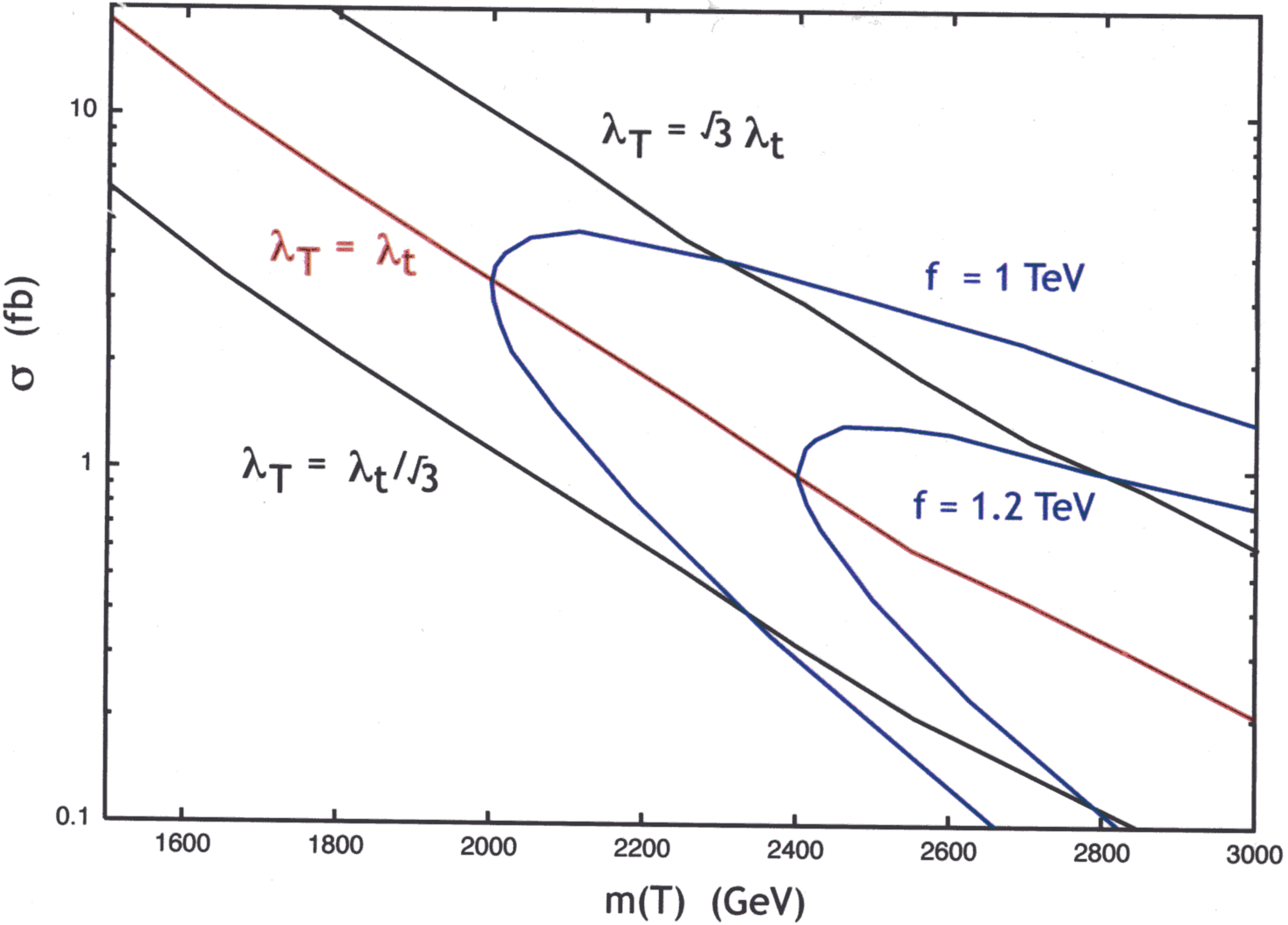
- Example: $T \to bW$ [ATLAS, hep-ph/0405156]

$\ell + \not{E}_T + 2$ b-jets (1 tagged)

Backgrounds: $t\bar{t}$, $W + b\bar{b}$

$\boxed{\text{OK for 1 TeV } T}$

Single Heavy Top Production Cross Section



Testing the Cancellation?

- Recall that the LH cancellation hinges on the sum rule:

$$\frac{m_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}$$

- In principle, all 4 quantities are measurable
  - f can be found from gauge boson studies

$$pp \to Z_H + X, \qquad Z_H \to \ell^+\ell^-$$

$$\Rightarrow M(Z_H), \quad \Gamma(Z_H) \qquad \Rightarrow f, \ \psi$$

  - how well can we reconstruct M_T?
  - how to measure λ_T?

$$\sigma_{prod} \propto \lambda_T^2$$

p.d.f. uncertainties?

- In the original littlest Higgs, there is some tension (not fatal but troublesome) between naturalness (low f) and precision electroweak (high f)

- I know of 2 simple solutions to this:

  (1) Make W_H, Z_H heavy (~6 TeV)

  $\Rightarrow$ suppress their tree-level contribution to PE obs.

  keep T light (~1 TeV) $\Rightarrow$ preserve naturalness

  [Schmaltz, Kaplan; Nelson, Katz, Walker]

  (2) Introduce T-parity (a lá R-parity of MSSM)

  $\Rightarrow$ NO tree-level contributions to PE obs.

[Cheng, Low]

  – Allows to keep both W_H, Z_H and T light (a few 100 GeV – 1 TeV) $\Rightarrow$ naturalness OK ✓

[plot]

  – Has a dark matter candidate – B_H

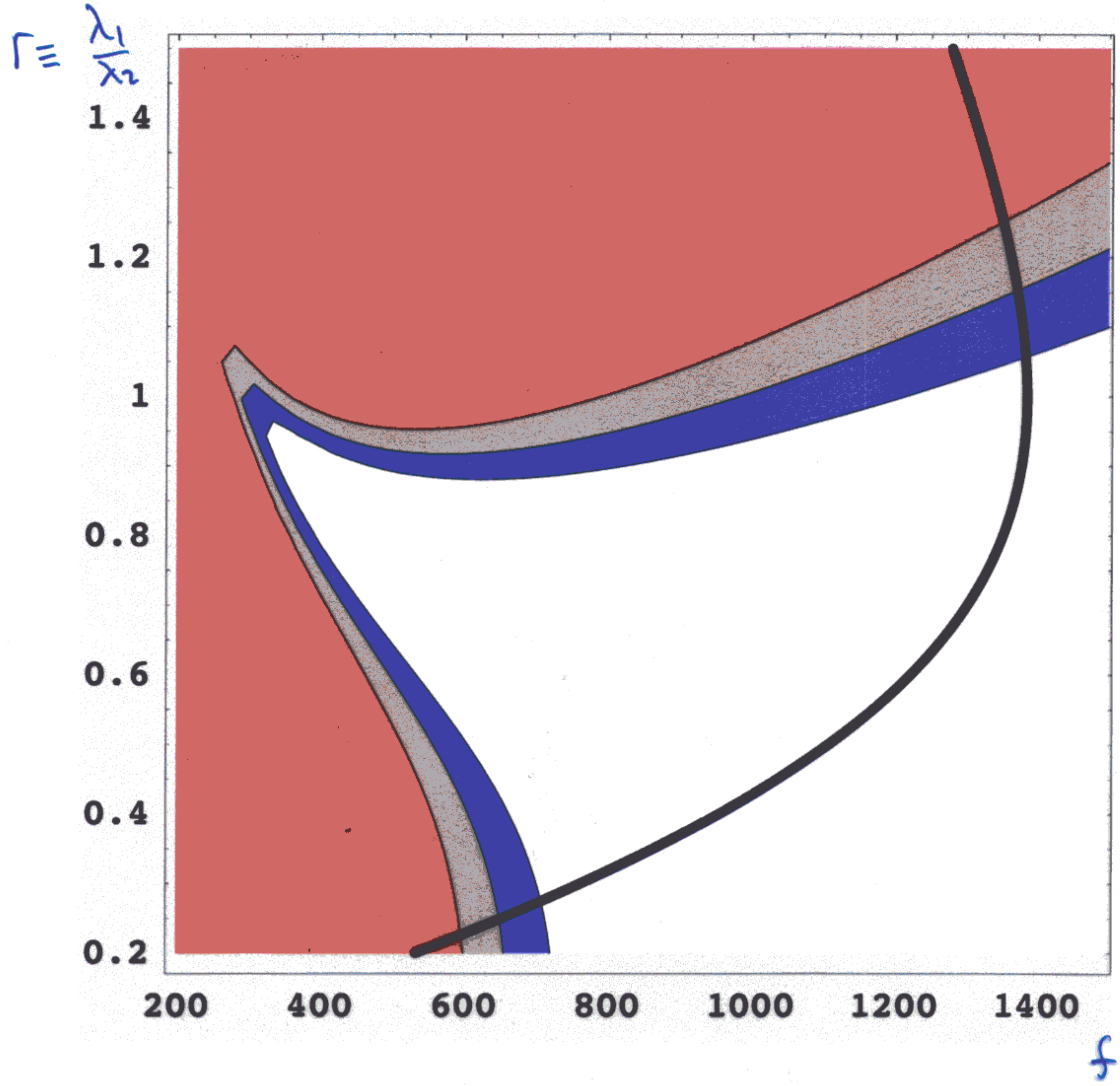
  – T-odd particles need to be pair-produced

  $\Rightarrow$ looks much like SUSY @ the LHC

  [Hubisz, Meade, hep-ph/0411264]

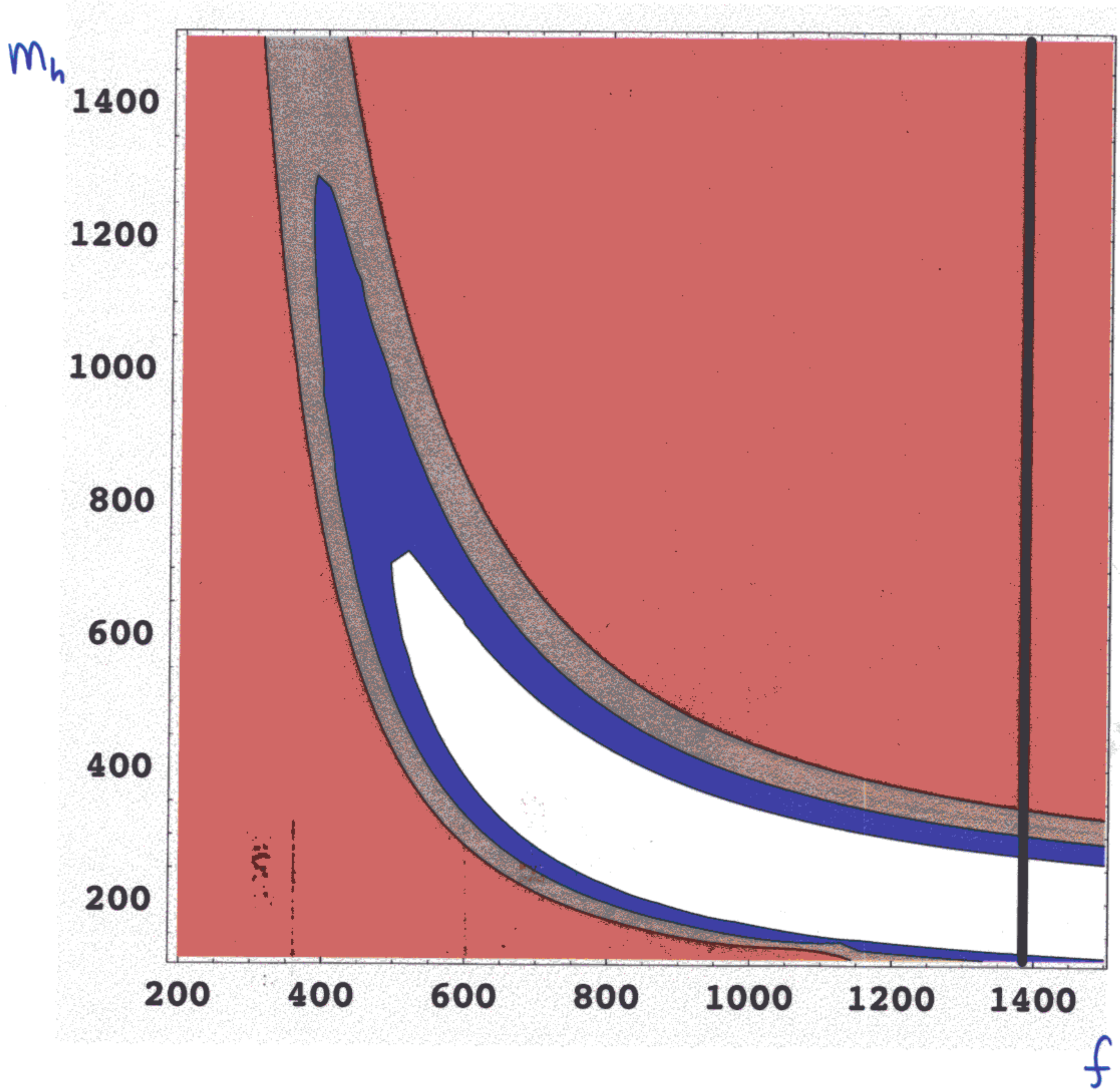
  – Allows to raise M_H to about 500-600 GeV

  [plot]



Precision electroweak constraints on LH with T-parity

[Hubisz, Meade, Noble, MP, to appear]



$M_T = \sqrt{2}\, f$

[Hubisz, Meade, Noble, MP, to appear]

Heavy Gauge Bosons

- Littlest Higgs predicts 4 new gauge bosons at $\sim$ TeV scale: $W_H^\pm$, W_H^3, B_H

- Universal coupling to fermions:

$$g \cot\psi \, W^a_{H\,\mu} \left(\bar{L} \gamma^\mu \tau^a L + \bar{Q} \gamma^\mu \tau^a Q \right)$$

where $\cot\psi = g_2/g_1$ – the only parameter!

[couplings of B_H are model-dependent]

- Copious production @ the LHC via Drell-Yan: discovery reach $\sim 5-6$ TeV

- Robust prediction of the $W_H^3 Zh$ coupling (Consequence of divergence cancellation! unique for the littlest Higgs!)

$$\Gamma(W_H^3 \to Zh) = \frac{g^2 \cot^2 2\psi}{192\pi} M$$

- Measuring $\sigma \cdot Br(W_H^3 \to e^+e^-)$ and $\sigma \cdot Br(W_H^3 \to Zh)$ provides a TEST of this prediction!

[Burdman, MP, Pierce, 2002]

CONCLUSIONS

- New ideas in EWSB have emerged recently, both on the strong-dynamics and radiative SB sides
- Discussed 2 examples: higgsless and little higgs
- Both models have striking LHC signatures, independent of model-building details
- Both models obey certain sum rules which could in principle be tested experimentally by the LHC and/or ILC – worth thinking about!
- ATLAS & CMS should be prepared to search for these models!