Models of Electroweak Symmetry Breaking

M. Perelstein, Cornell

Aspen Winter Conference, Feb 17 2006

- SM: Electroweak gauge symmetry SU(2)xU(1) is fundamental, but spontaneously broken at low energies down to e&m U(1)

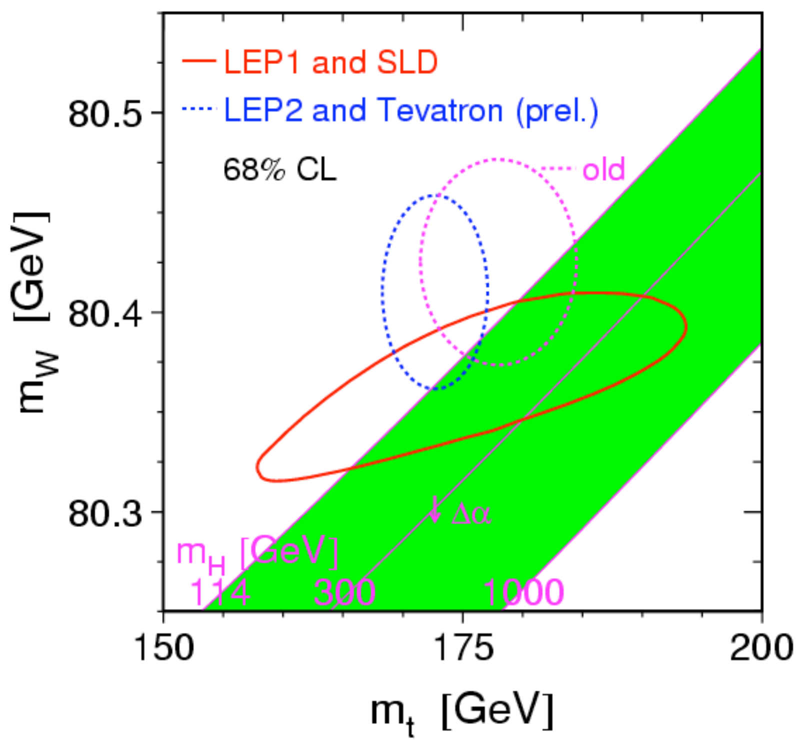
- Uncovering the mechanism of electroweak symmetry breaking (EWSB) is the central question for particle physics in the LHC era

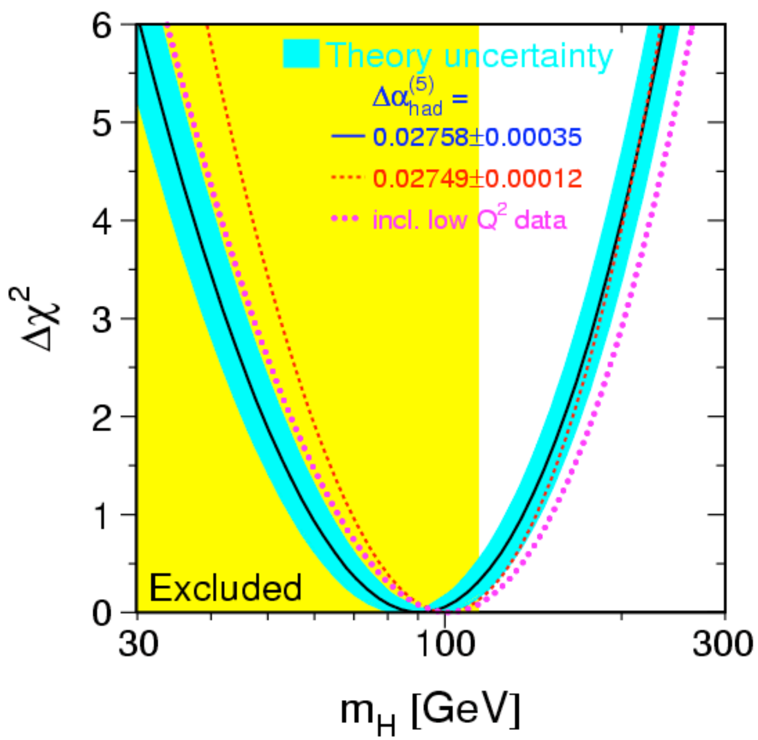
- Standard Model: EWSB is the result of the Higgs mechanism

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

- But the crucial sign of the mass term is chosen by hand - NOT an explanation! ⇨ GO BEYOND THE SM!

- However, precision electroweak measurements (low-energy and Z-pole) and direct measurements of W and top masses are consistent with the SM, light Higgs boson ($m_h = \sqrt{2}\mu \leq 200$ GeV) and no new physics! ➡ BE CAREFUL NOT TO SPOIL THE FIT!





Hypothesis: light, SM-like Higgs + new physics that does not affect precision physics much!

- Can μ^2 be predicted?

- What matters for EWSB is the sign of μ^2 at the electroweak scale $M_{\rm ew}$

- In a generic field theory, valid up to some UV scale Λ where all loops are cut off (e.g. by strings?) expect

$$\mu^2(M_{\rm ew}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2}\Lambda^2 + c_2 \frac{1}{16\pi^2} \log\left(\frac{\Lambda}{M_{\rm ew}}\right) + \text{finite}$$

- The first two terms are dominated by physics at the cutoff $\Rightarrow$ not calculable in the effective field theory

- The log term receives equal contributions from all scales $\Rightarrow$ cutoff contributions not so important

- In general, predicting the sign of μ^2 requires knowing physics at the cutoff scale

- BUT, if $\mu^2(\Lambda)$ and c_1 are suppressed by symmetries, low-energy μ^2 may be dominated by the log-divergent or finite terms ⇨ the sign can be predicted within the effective field theory!

- Another motivation to suppress c_1 : FINE-TUNING

$$c_1 \frac{\Lambda^2}{16\pi^2} \leq m_h^2 \Delta \quad \Rightarrow \quad \Lambda \leq 2 \text{ TeV}$$

- But strongly coupled physics at 2 TeV or below is strongly disfavored by precision electroweak fits:

$\Lambda \geq 10 \text{ TeV}$ is required!

Supersymmetry

- SUSY eliminates all quadratic divergences ⇨ $c_1 = 0$
- Two Higgs doublets H_u and H_d are needed to give Yukawa couplings to both up and down quarks
- SUSY allows a tree-level mass, $W = \mu H_u H_d$
- Need $\mu \ll \Lambda$ ⇨ go beyond MSSM!
- Radiative correction to $m^2(H_u)$ dominated by top loops, has the right sign to trigger EWSB:

$$\delta m^2(H_u)|_{\rm rad} \simeq -\frac{3y_t^2}{8\pi^2}\left(m_Q^2 + m_U^2 + |A_t|^2\right)\ln\left(\frac{M_{\rm mess}}{m_{\tilde{t}}}\right)$$

- But outcome depends on SUSY-breaking tree-level masses m_u^2, m_d^2, b

Fine-Tuning in MSSM EWSB?

- Naturalness: $\delta m_h^2|_{\rm rad} \leq m_h^2 \Delta$

$\delta m_h^2|_{\rm rad} \propto m_{\tilde{t}}^2$ ➡ upper bound on $m_{\tilde{t}}^2$:

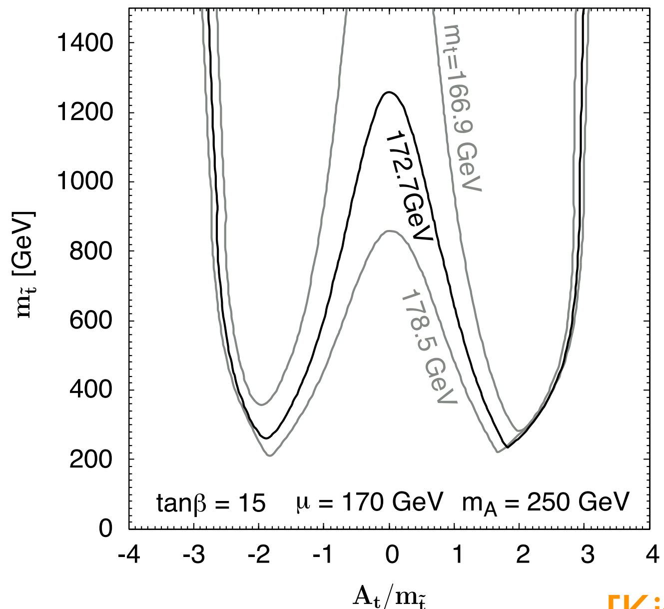
e.g. <20% tuning requires $m_{\tilde{t}}^2 \leq 700$ GeV

- LEP2 lower bound on Higgs mass requires large radiative corrections ➡ large $m_{\tilde{t}}^2$!

- Extensions of MSSM constructed to diffuse this tension [see e.g. Batra, Delgado, Kaplan, Tait, hep-ph/0309149]

- A simple way to avoid this tension within MSSM: moderately large $\tan\beta$, low $M_{\rm mess}$, large A_t [Kitano, Nomura, hep-ph/0509039, 0602096]

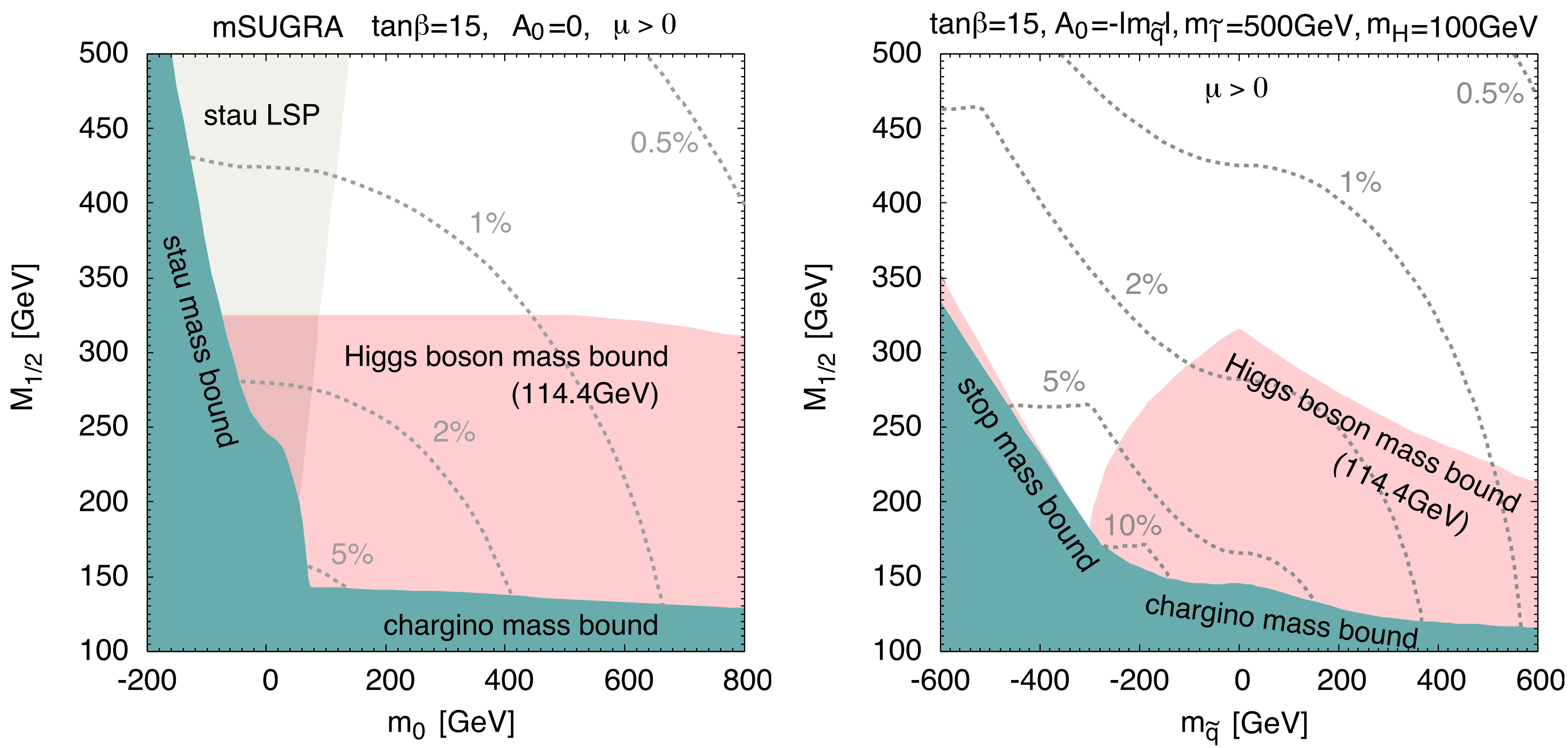
- Can obtain $m_h > 115$ GeV with light stops (< 300 GeV) ⇨ dramatically reduce tuning!



[Kitano, Nomura, hep-ph/0602096]

- Signatures: light stops and light higgsinos (nearly degenerate $\chi_1^0, \chi_2^0, \chi_1^\pm$) ⇨ interesting LHC signals!

Reduction of Fine-Tuning in MSSM with Large At



[Kitano, Nomura, hep-ph/0602096]

Little Higgs Models

- An alternative idea for keeping the Higgs light: Higgs is a Goldstone boson arising from a global symmetry breaking [a la pions in QCD]

- If the global symmetry is exact, $\mu^2 = 0$ exactly!

- Goldstones only interact derivatively ⇒ need to break the global symmetry explicitly by gauge and Yukawa interactions (but no explicit tree-level mass term, $\mu^2(\Lambda) = 0$)

- Generically, the interactions reintroduce a quadratic divergence in Higgs mass at one loop:

$$m_h\big|_{\mathrm{rad}} \sim \frac{\lambda^2}{16\pi^2}\Lambda^2 \quad \text{or} \quad c_1 \sim 1$$

[same as SM!]

- "Collective Symmetry Breaking": no single gauge/ Yukawa coupling breaks the global symmetry completely [Arkani-Hamed, Cohen, Georgi, 2002]
- Example: Littlest Higgs Model [Arkani-Hamed, Cohen, Katz, Nelson, 2002]
- Global symmetry breaking: $SU(5) \to SO(5)$
- Symmetry breaking scale: $f \sim 1$ TeV
- Dynamics up to the cutoff $\Lambda \sim 4\pi f \sim 10$ TeV is described by a non-linear sigma model:

$$\Sigma = \exp(2i\Pi/f)\Sigma_0, \qquad \Pi = \begin{pmatrix} * & H & \Phi \\ H^\dagger & * & H^T \\ \Phi & H^* & * \end{pmatrix}$$

- An $[SU(2)\times U(1)]^2$ subgroup is gauged:

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}.$$

- Each gauged SU(2) preserves an SU(3) global symmetry, which is sufficient to keep the Higgs massless! [same structure for U(1)'s & Yukawas]

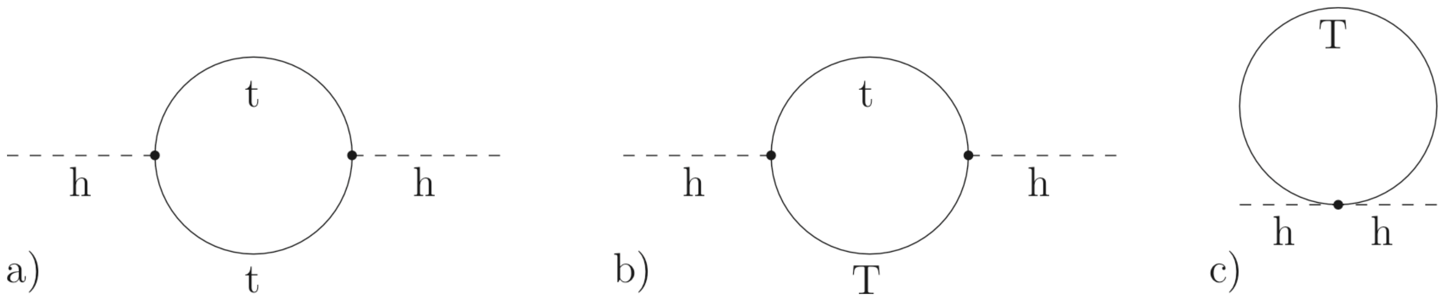
- Every term in $V_{\rm eff}(H)$ has to involve at least two couplings $\Rightarrow$ no one-loop quadratic divergence!

- Quad. divergence first appears at two loops: $c_1 \sim \dfrac{g^2}{16\pi^2}$

- For $\Lambda \sim 10\ {\rm TeV}$, there is no fine tuning!

EWSB in Littlest Higgs Model

- Higgs mass is dominated by top and Top loops:



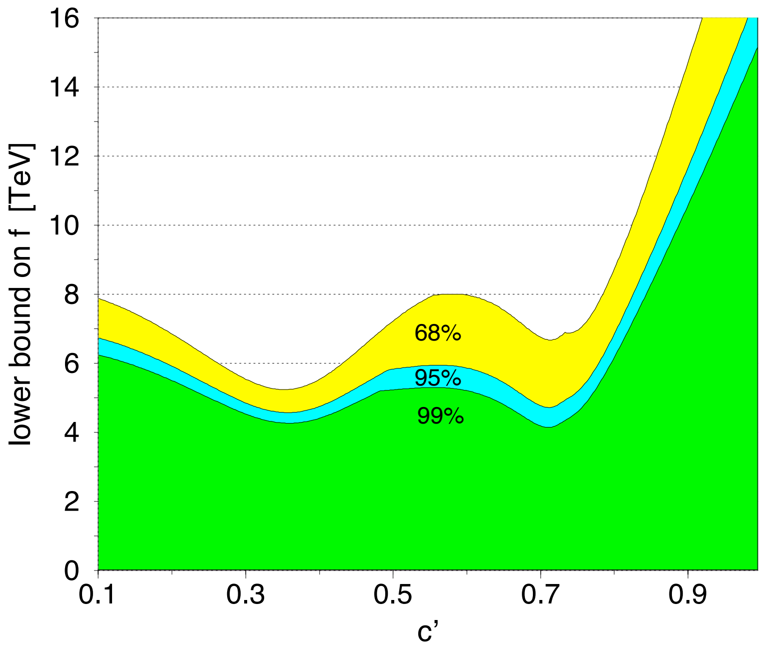
- This contribution is log-divergent and negative:

$$m_{\rm t}^2(H) = -\frac{3\lambda_t^2 M_T^2}{8\pi^2} \log \frac{\Lambda^2}{M_T^2} .$$

- So, EWSB is triggered radiatively - simple mechanism!

Littlest Higgs Phenomenology

- Particle content: heavy top T, weak-triplet scalar Φ, heavy gauge bosons $W'^{\pm}, W'^{3}, B'$
- Very few parameters ➡ predictive!
- Very strong constraints from precision electroweak fits (B' exchanges, triplet vev) - fine-tuning persists!



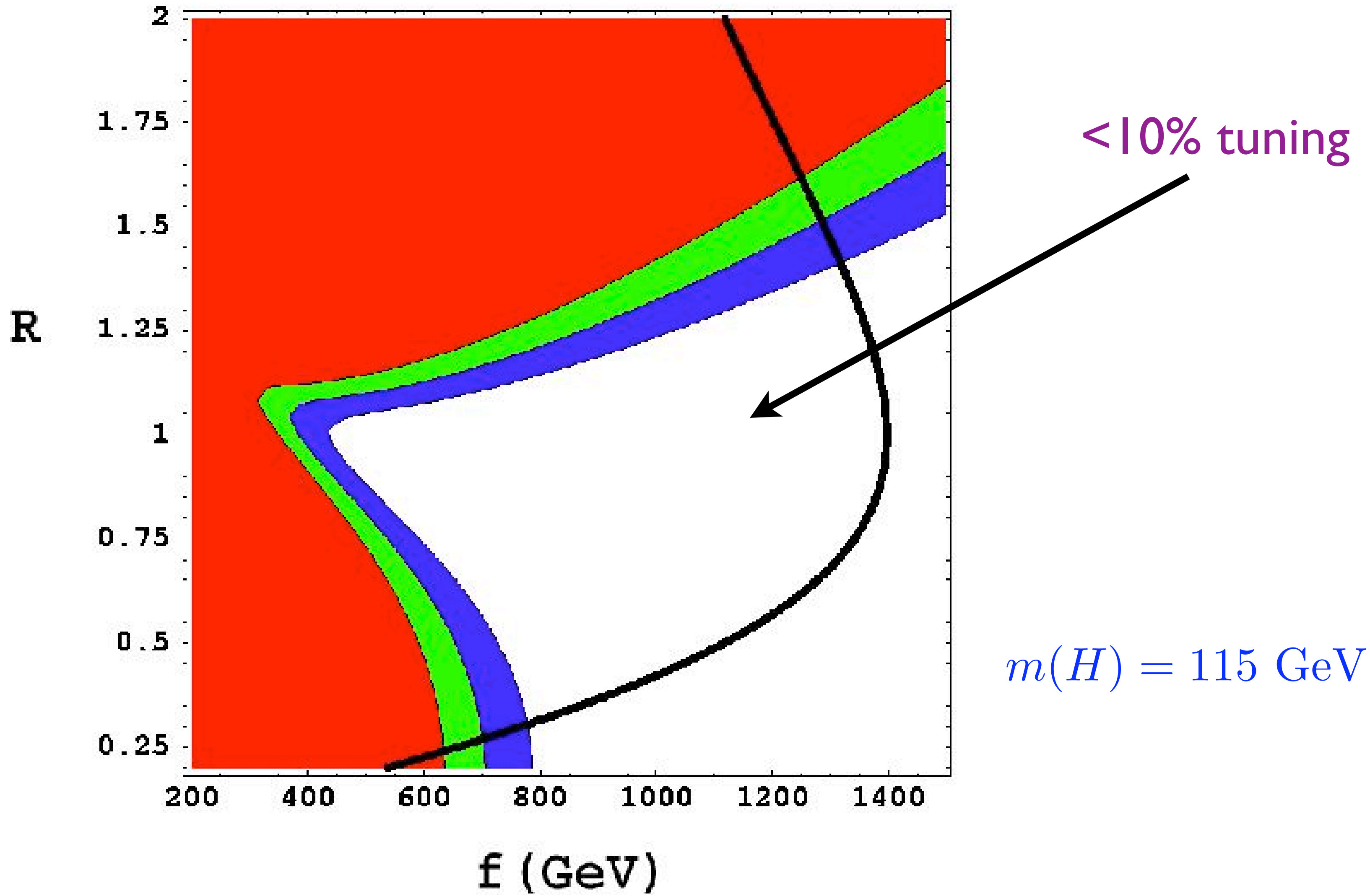
[Csaki et.al., 2002]
[Hewett et.al., 2002]
[Chen & Dawson, 2003]
...

Littlest Higgs with T Parity (LHT)

[H.-C. Cheng and I. Low, 2003-2004]

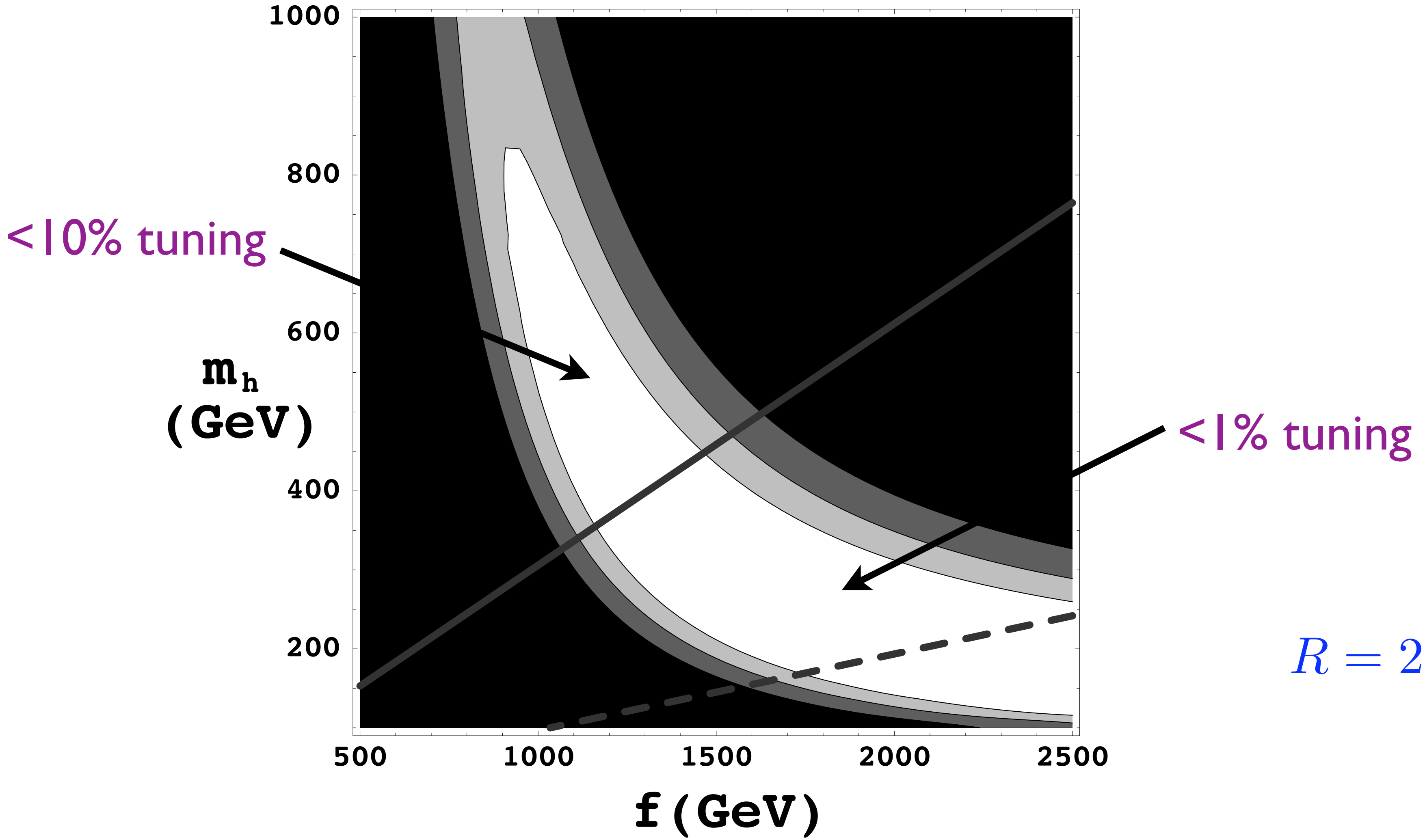
- Recall: in MSSM, all corrections to PEO's are loop-level only as a consequence of R parity!
- Similar parity (T parity) can be introduced in the LH models
- All new particles are T-odd (T is an exception)
- In the gauge sector, $T : SU(2)_1 \times U(1)_1 \leftrightarrow SU(2)_2 \times U(1)_2$
- The triplet is T-odd: $T : \Phi \to -\Phi$ $\Rightarrow$ $\langle \Phi \rangle = 0$
- Need T-odd partners for all weak-doublet fermions

LHT gives acceptable fits to precision electroweak observables without fine-tuning!



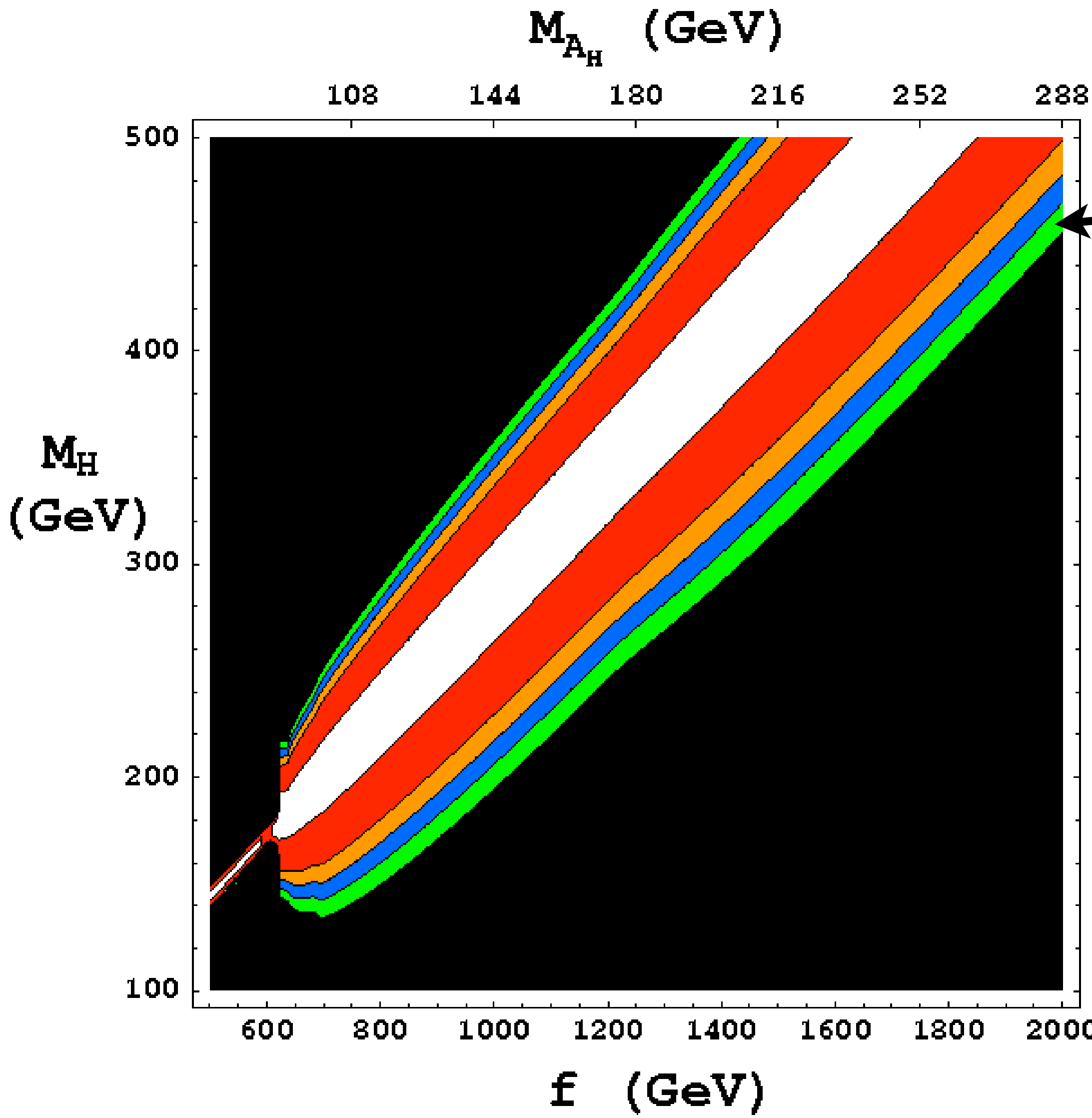
[Hubisz, Meade, Noble, MP, hep-ph/0506042]

In LHT, partial cancelations between Higgs loops and new physics contributions to T allow for a heavy Higgs!



[Hubisz, Meade, Noble, MP, hep-ph/0506042]

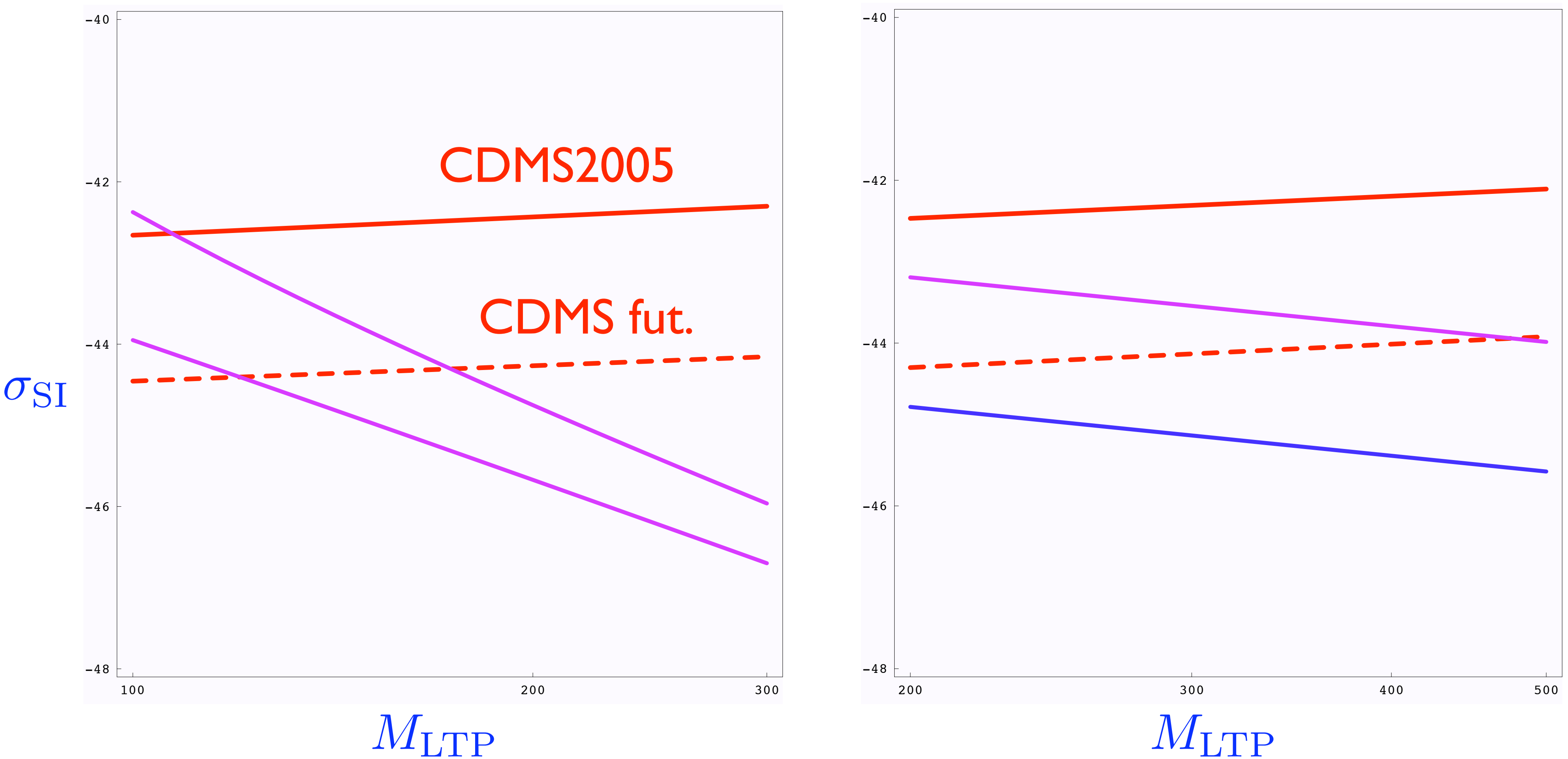
The lightest T-odd particle (LTP) is typically the "heavy photon", ideal WIMP dark matter candidate!



$\Omega_{\rm LTP} h^2 = 0.111$
(100% of WMAP value)

[Hubisz, Meade, hep-ph/0411264]

LTP dark matter could be soon discovered in direct detection experiments



[preliminary!]

[Birkedal, Noble, MP, Spray, in preparation]

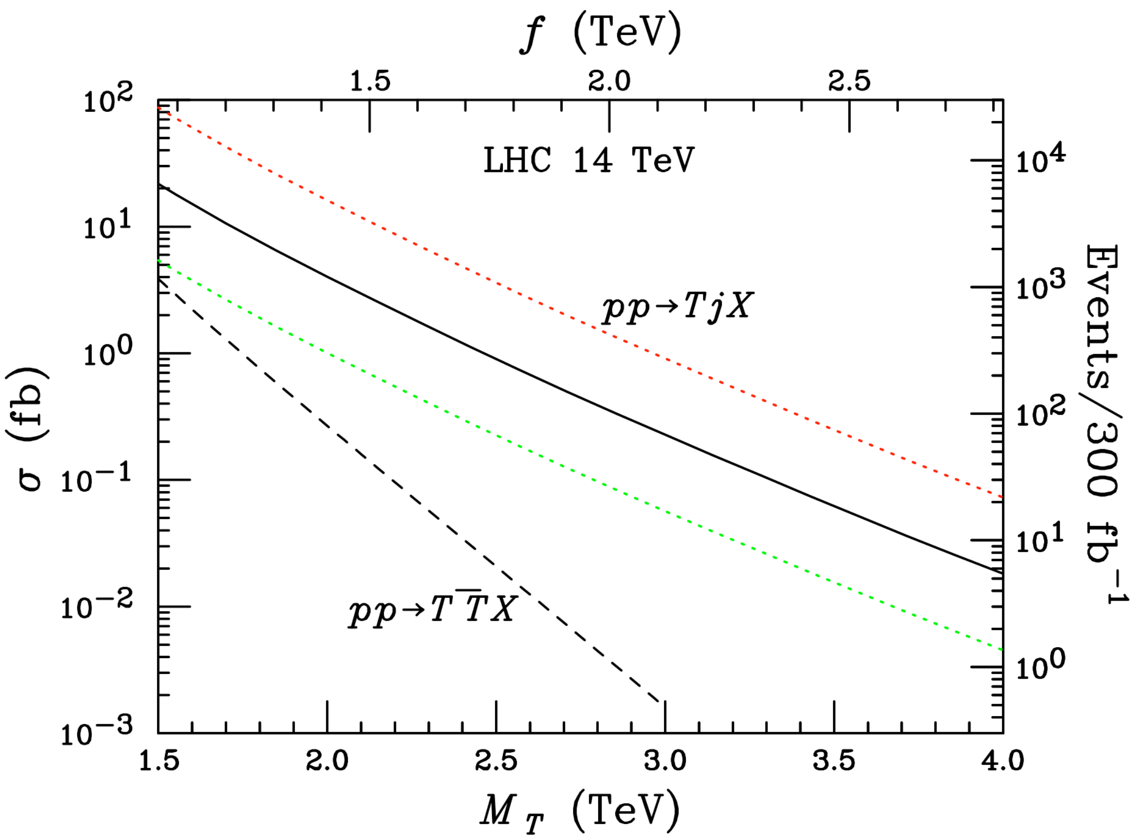
LHT Collider Phenomenology

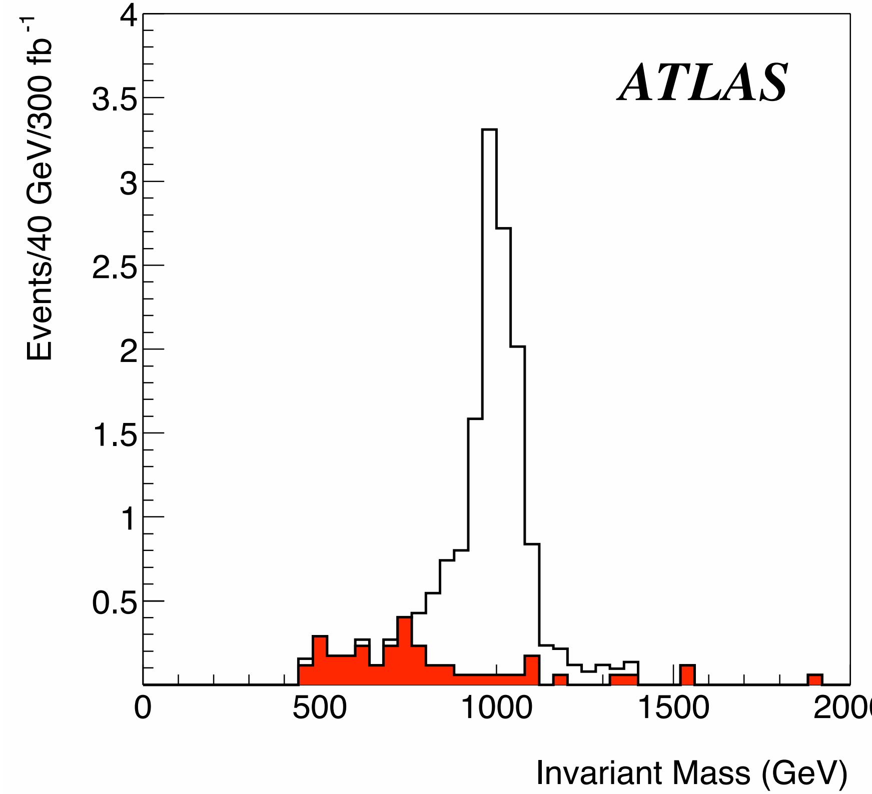
- Phenomenology of the T-odd sector is very similar to MSSM with R parity: pair-production, cascade decays down to the LTPs → jets/leptons + missing Et
- T-odd partners have same spin as SM (like UED)
- Details differ from MSSM and UED - e.g. there's no gluon partner, an extra T-odd top, etc.
- Some mass ratios firmly predicted:

$$\frac{M(W'^{\pm})}{M_{\mathrm{LTP}}} = \frac{\sqrt{5}g}{g'} \approx 4$$

- Detailed studies are needed!

T-even heavy top phenomenology similar to the "old" Littlest Higgs* (but may be lighter ⇒ easier!)





[Han, Logan, Wang, 2002]

$T \to Zt \to \ell^+\ell^-\ell^\pm b\nu$

* branching ratios of T decays may be modified...

Gauge-Higgs Unification

- A 5D gauge field decomposes into a 4D gauge field and a 4D scalar:

$$A_M(x,y) \rightarrow A_\mu(x),\ \ A_5(x) \equiv \Phi(x)$$

- Identify the scalar with the SM Higgs!
- 4D scalar mass is protected by 5D gauge invariance
- Higgs potential is finite: $\mu^2(\Lambda) = c_1 = c_2 = 0$ predictive!
- Top loops dominate the potential and trigger EWSB!
- Difficult to construct a realistic model: for example Yukawa~gauge coupling... but progress is being made!

EWSB without a Higgs?

- Quark condensates break EW symmetry at the QCD confinement scale
- New confining interaction at the TeV scale could account for the observed EWSB ("technicolor")
- In SM-H, elastic scattering of massive gauge bosons (for example $W_L^+ W_L^- \to W_L^+ W_L^-$) 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 and need to be included in precision electroweak fits
- EW precision experiments require $\Lambda > 5 - 10 \text{ TeV}$ - strongly coupled EWSB ruled out?

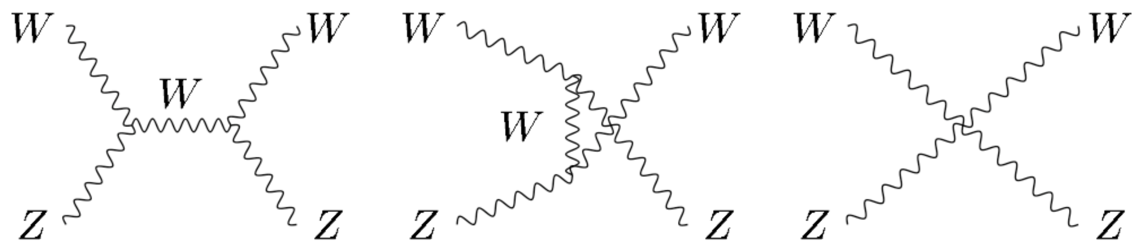
The “Higgsless” Approach

[Csaki, Grojean, Terning, Murayama, Pilo, ‘03-04]

- Introduce new particles around the TeV scale, coupled to the SM W/Z bosons
- Diagrams involving new particles cancel the growing pieces of the W/Z scattering amplitudes at high energies
- Cancellations are due to symmetries of the theory (5D locality, gauge invariance)
- Raise the cutoff Λ to the required 5-10 TeV range

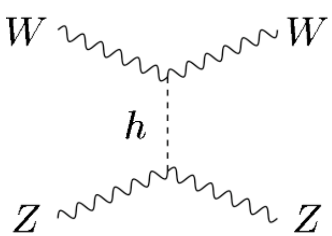
Example: Unitarity in $W_L^\pm Z_L \to W_L^\pm Z_L$ Scattering

SM sans Higgs:



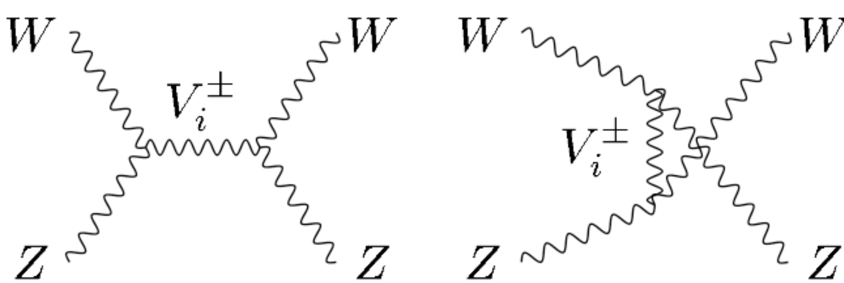
$$\mathcal{M} \propto E^2$$

SM:



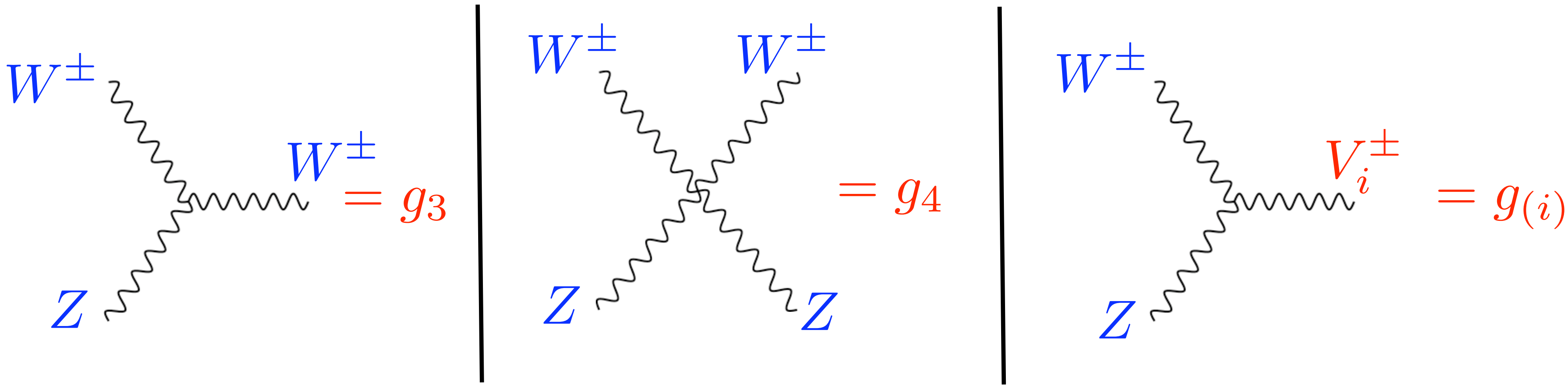
$$\mathcal{M} \propto E^0\,!$$

Higgsless:



$$\mathcal{M} \propto E^0\,!$$

Cancellation requires SUM RULES:



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

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

- 5D Higgsless models satisfy the sum rules exactly $(i = 1 \ldots \infty)$
- 4D "deconstructed" Higgsless models satisfy the sum rules to a few % $(i = 1 \ldots N_s)$
  [Foadi, Gopalakrishna, Schmidt, Chivukula, Georgi, MP,...]
- The sum rules are independent of the model-building details (e.g. the fermion sector) $\Longrightarrow$ GENERIC prediction of Higgsless mechanism

- This translates into robust predictions for the LHC

[Birkedal, Matchev, MP, hep-ph/0412278]

- Simplifying assumption: sum rules saturated by the 1st resonance (checked several models - true to a few %) ⇨ 1-parameter model:

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

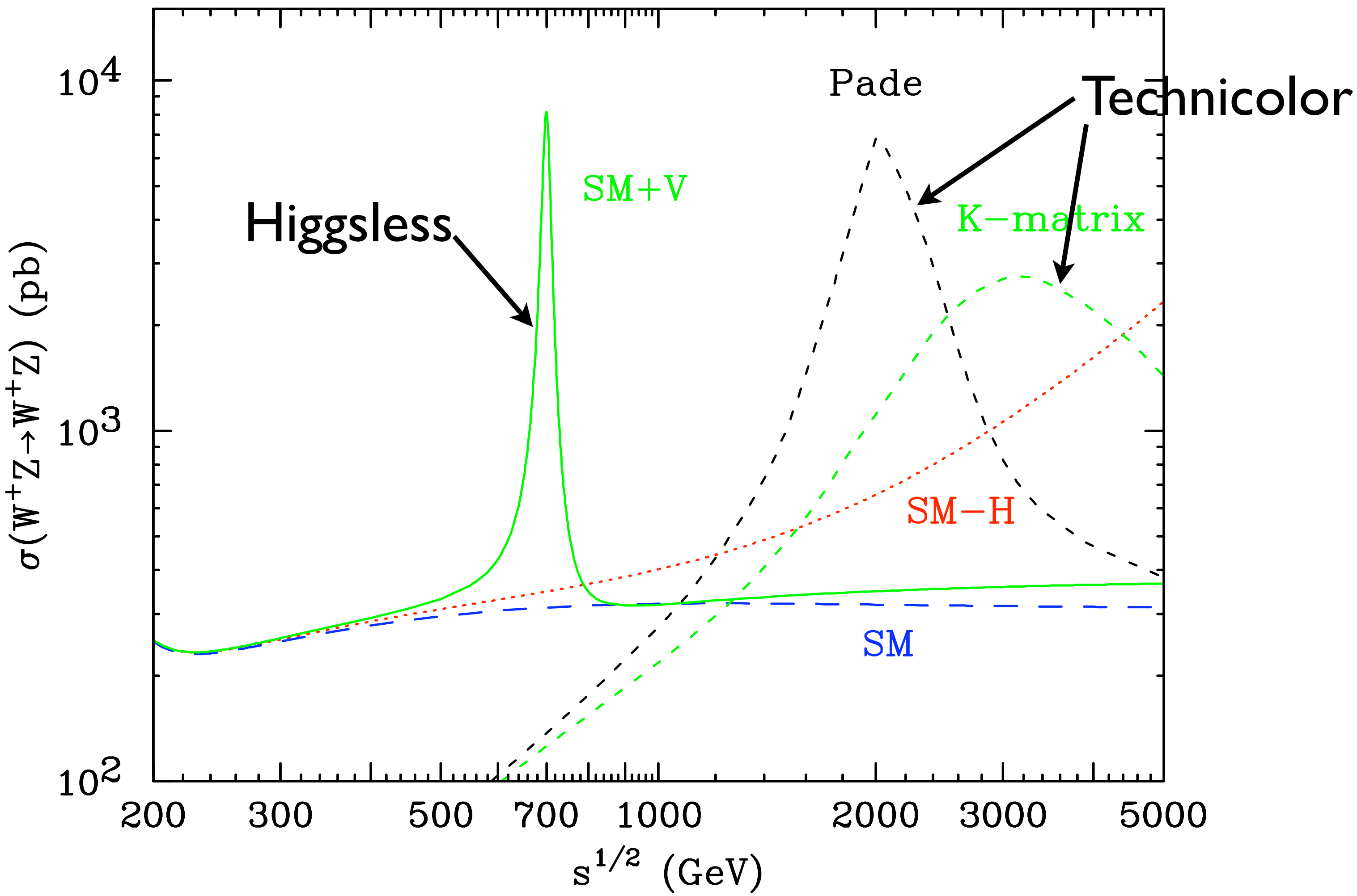
- Prediction: a narrow, light resonance in WZ scattering (absent in the SM and 2HDM!)

$M_1 \leq 1 \text{ TeV}$ (unitarity)

$$\Gamma = \frac{\alpha M_1^3}{144 s_W^2 M_W^2}$$

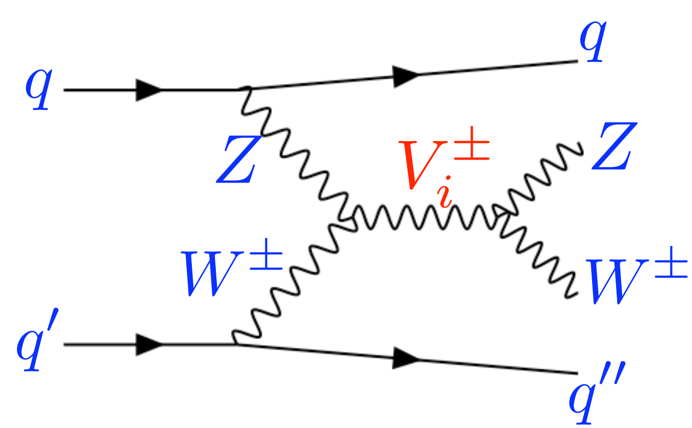
(set couplings to fermions to 0)

WZ Elastic Scattering Cross Section in 5 Models



[Birkedal, Matchev, MP, hep-ph/0412278]

- WZ collisions at the LHC:

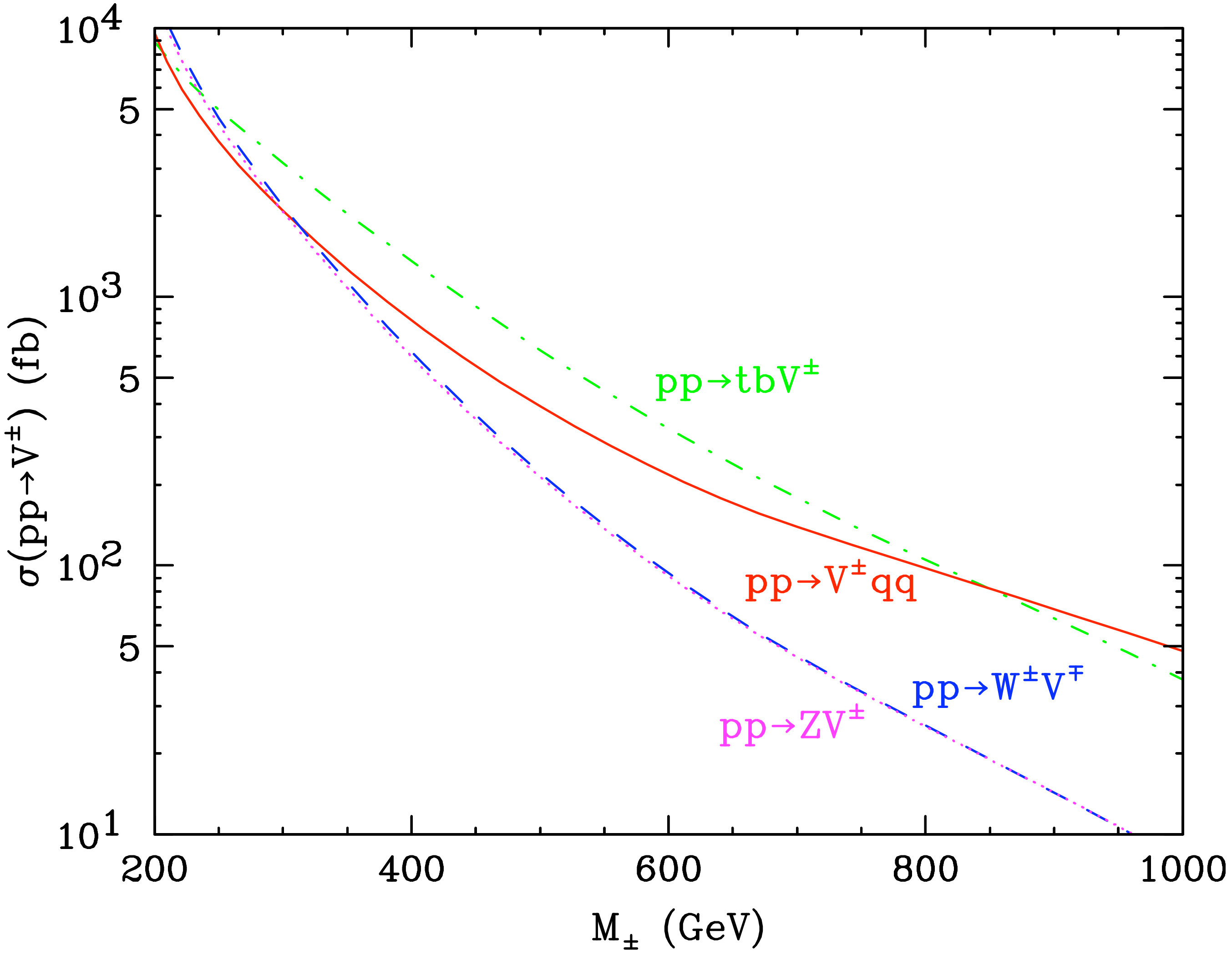


- To suppress backgrounds from the SM s-channel process $q + q' \to WZ$ require 2 observed forward jets

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

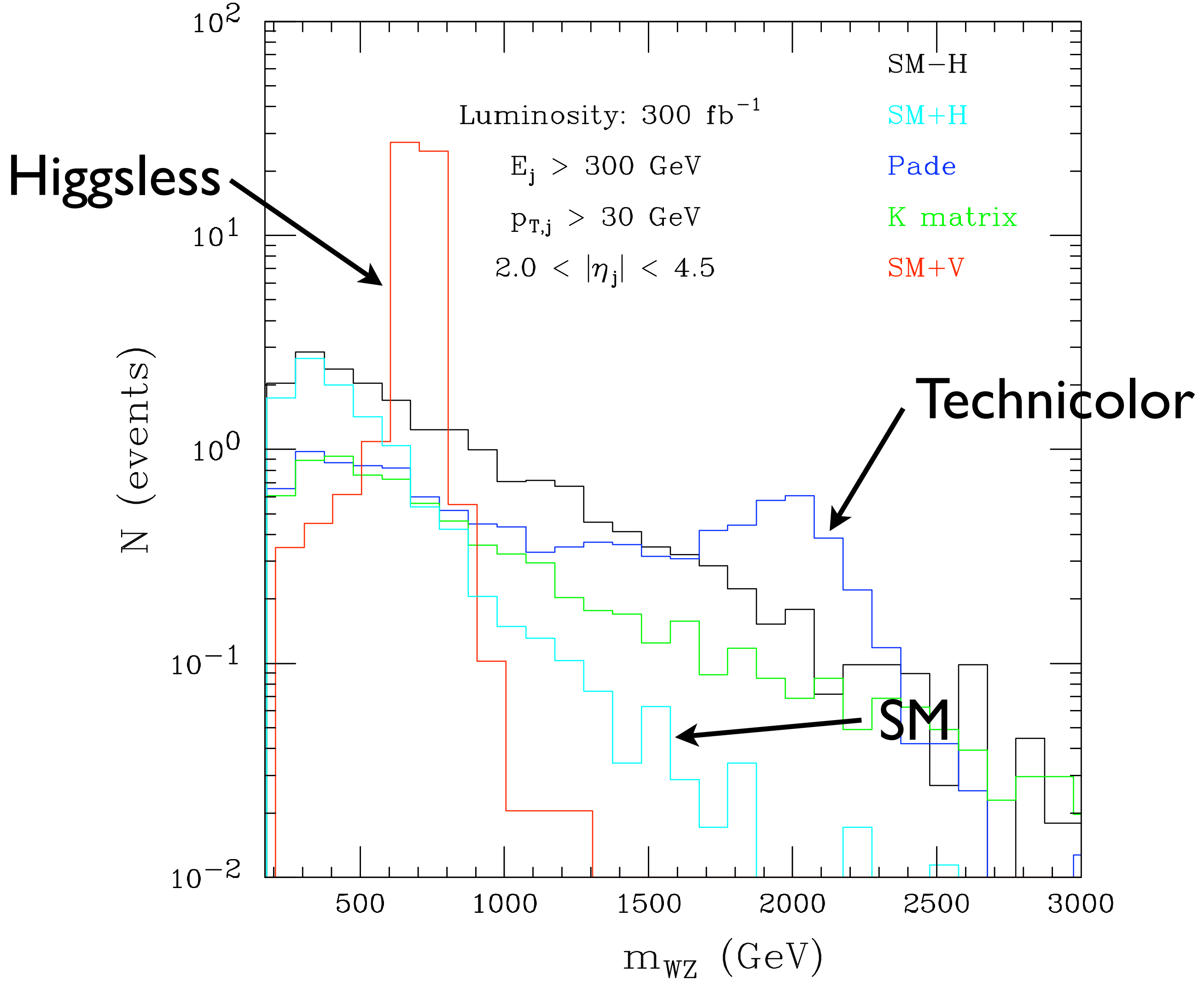
[The same cuts also eliminate the "signal background" from the possible Drell-Yan V_1's!]

$V^{\pm}$ production cross section at the LHC



[Birkedal, Matchev, MP, hep-ph/0412278]

Gold-Plated Channel: 2j+3l+Et_miss, $\sqrt{s_{\ell\ell}} \approx M_Z$



Number of events at the LHC, 300 fb-1

[Birkedal, Matchev, MP, hep-ph/0412278]

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

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

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

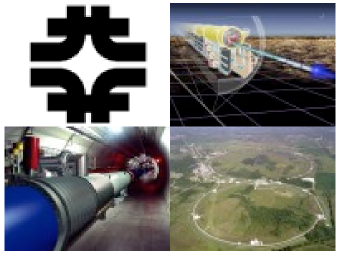
- The HL resonance will be discovered, with moderate luminosity

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

- Uncertainty dominated by Et_miss - 10%?

Conclusions

- SM can describe EWSB but not explain it - need to go beyond the SM to find a real mechanism
- Data: a Light Higgs boson probably plays a role in EWSB
- SUSY still our favorite theory with light Higgs, naturalness may serve as a guidance in the (huge!) parameter space
- A recent alternative: Higgs as a Goldstone boson (Little Higgs), simple radiative EWSB mechanism!
- LH with T parity gives good fits to data with no tuning, good dark matter candidate, can fake SUSY - interesting pheno!
- EWSB by strong dynamics is also possible (but conspiracies must occur to fake light Higgs in loops), e.g. Higgsless
- HL gives spectacular signal in vector boson scattering at the LHC



Monte Carlo Tools for Beyond the Standard Model Physics

FERMILAB, MARCH 20-21, 2006

Home
Programme
Registration
Participants
Questionnaire
Local Information

This mini-workshop aims to gather together theorists and experimentalists interested in developing and using Monte Carlo tools for Beyond the Standard Model Physics in an attempt to be prepared for the analysis of data focusing on the Large Hadron Collider. Since a large number of excellent tools already exist for the study of low energy supersymmetry and the MSSM in particular, this workshop will instead focus on tools for alternative TeV-scale physics models. The main goals of the workshop are:

- To survey what is available. To this end, the organisers have designed a questionnaire to provide feedback on user experiences with Monte Carlo tools for BSM.
  Please fill out the questionnaire (even if you will not be able to attend) **before the workshop**, it only takes a few minutes!
- To identify promising models (or processes) for which the tools have not yet been constructed and start filling up these gaps.
- To propose ways to streamline the process of going from models to events, i.e. to make the process more user-friendly so that more people can get involved and perform serious collider studies outside of the MSSM.

We envision a small but intensive workshop with a small number of talks and ample time for discussions between model builders, Monte Carlo experts, and experimentalists interested in exotics searches at the Tevatron and the LHC.

Please follow the link on the left to register. **There is no registration fee**
Please contact the organizing committee if you are interested in giving a talk at the workshop.

Organizing committee: Mu Chun Chen, Bogdan Dobrescu, Chris Hill, Jay Hubisz, Joe Lykken, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Jose Santiago, Peter Skands.
To contact the organizing committee send an e-mail to:
mc4bsm.AT.phys.ufl.edu
This workshop is sponsored by FERMILAB

theory.fnal.gov/mc4bsm