What if SUSY is not right?
Non-susy signals at the LHC

Antonio Delgado
University of Notre Dame

Hierarchy Problem

Standard Model Lagrangian contains only one explicit mass scale:

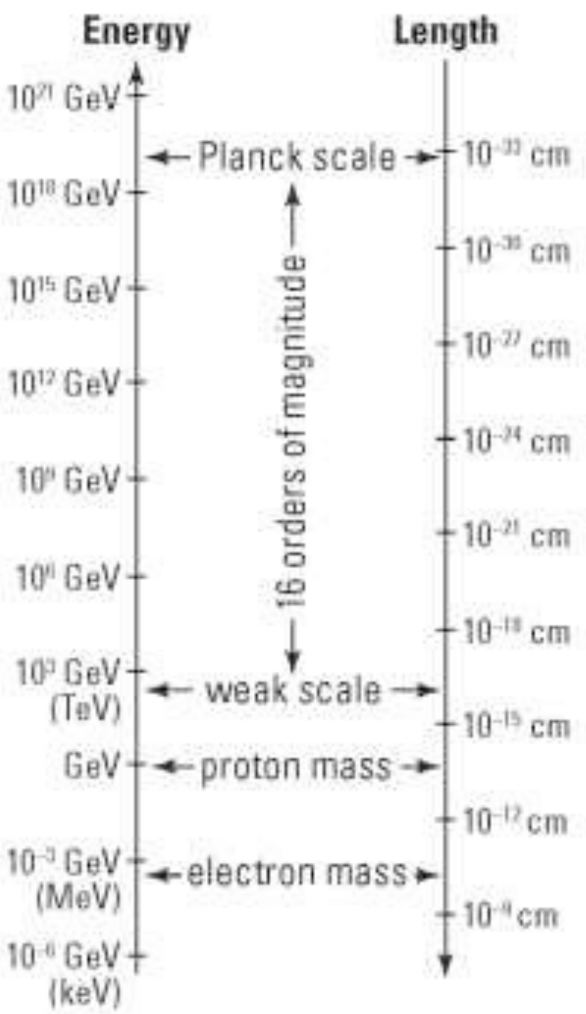
$$-\mathcal{L}_{\text{Higgs}} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

This scale generate Higgs vev, which sets scale for all other particle masses.

But what sets μ?

And why is $\mu << M_{Pl} \sim 10^{18}$ GeV ?

Further: if we set μ, will radiative corrections respect the hierarchy or collapse it?



• There is only one term in the SM that can be quadratically divergent:

the Higgs mass-squared term, $\mu^2 |\phi|^2$.

• Fermion masses and gauge boson masses are protected by the gauge symmetries, because they come from dimensionless couplings at scales above M_W

• Fermions are doubly protected, because their masses also require breaking of the chiral symmetry, which rotates e_L and e_R separately.

• Scalar mass terms cannot be forbidden by any symmetry, since ϕ and ϕ^* will always transform in an opposite manner. They are always in danger of receiving quadratic corrections.

$$\delta\mu^2 \sim \frac{\Lambda^2}{16\pi^2}$$

Because the Higgs mass term sets the scale for all other SM particles, any fine-tuning of the Higgs mass is really a fine-tuning of the entire SM spectrum. The question of how the SM can remain so light in the presence of quadratic divergences is called the **hierarchy problem**.

Thus there should be new physics at or below the TeV scale.

And NOT just any physics -- it must be physics that stabilizes the hierarchy (*i.e.,* that "removes" the quadratic divergences).

Options:

- New physics with no fundamental scalars. No scalars means no quadratically divergent masses. Examples: technicolor; top quark condensate; composite Higgs models; Higgsless models

- New physics that removes hierarchy completely, bringing Planck scale down to weak scale. Example: large extra dimensions.

- New physics that stabilizes the hierarchy temporarily (until 10-100 TeV), by canceling 1-loop divergences. Examples: Veltman condition; little Higgs models.

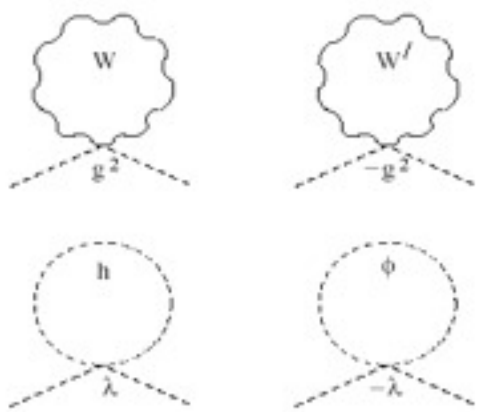
- New physics that cancels all quadratic divergences to all orders. Example: supersymmetry.

→ As a byproduct of many of these models, new avenues for understanding other problems of the Standard Model will open up!

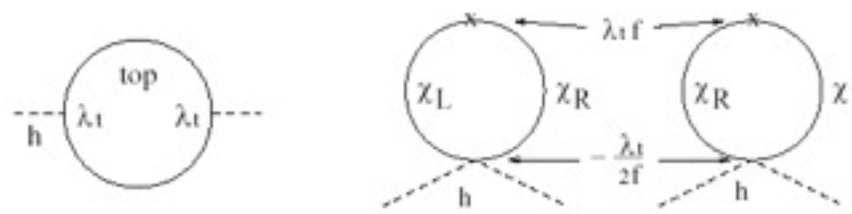
Little Higgs Models

Little Higgs models don’t solve hierarchy problem – they delay it.

- The Higgs becomes a component of a larger multiplet of scalars which transforms non-linearly under a new global symmetry
- New global symmetry undergoes SSB
  $\Rightarrow$ leaves Higgs as Goldstone
- Part of global symmetry is gauged
  $\Rightarrow$ Higgs is pseudo-Goldstone
- Careful gauging removes Higgs 1-loop divergences **(but NOT 2-loop!)**



Similar to SUSY, but partners have same statistics, and cancellation is only 1-loop

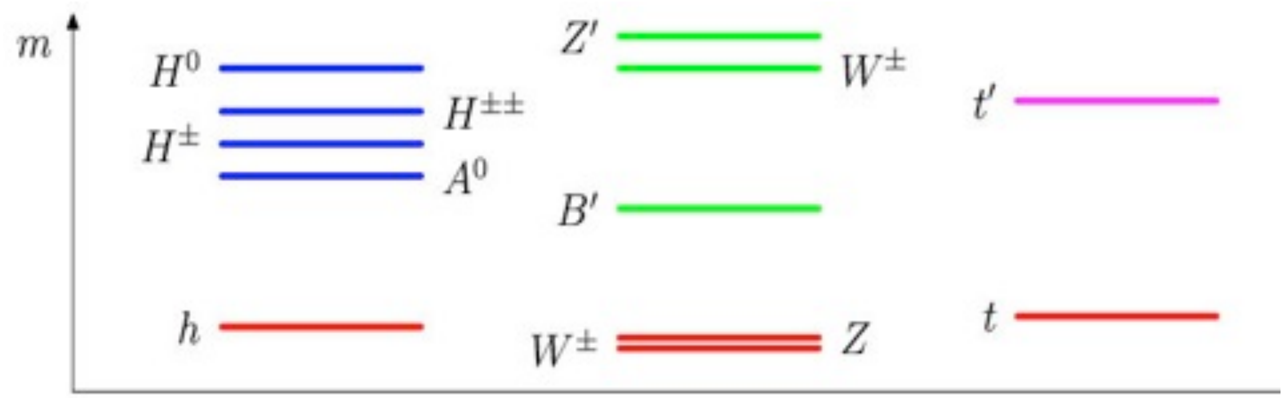


$$\delta\mu^2 \sim \frac{\Lambda^2}{(16\pi^2)^2}$$

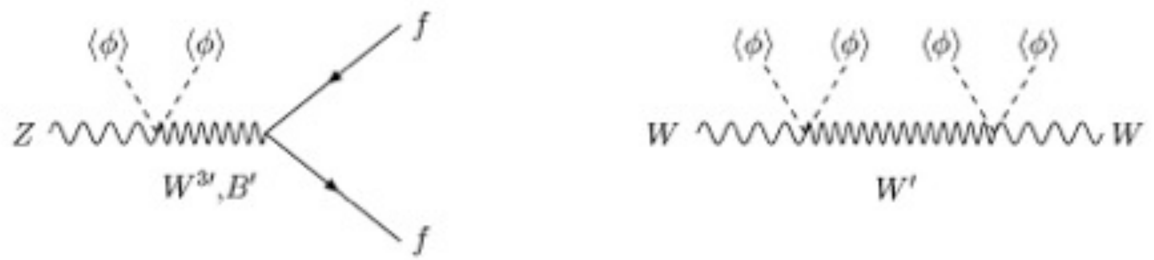
✓ Heavy W_H, Z_H, A_H cancel gauge loops
✓ Scalar triplet cancels Higgs loop
✓ Vector-like charge $+2/3$ quark cancels top loop

Typical spectrum contains:

- vector partners of *B*, *W* bosons
- partner(s) for *t*-quark
- lots of extra Higgs states, incl. multiply charged Higgs.



Models have problem with precision EW constraints. In generic model, *Z'* and *W'* couple to Standard Model fermions with SM-like strength, leading to *Z-Z'* and *W-W'* mixing.

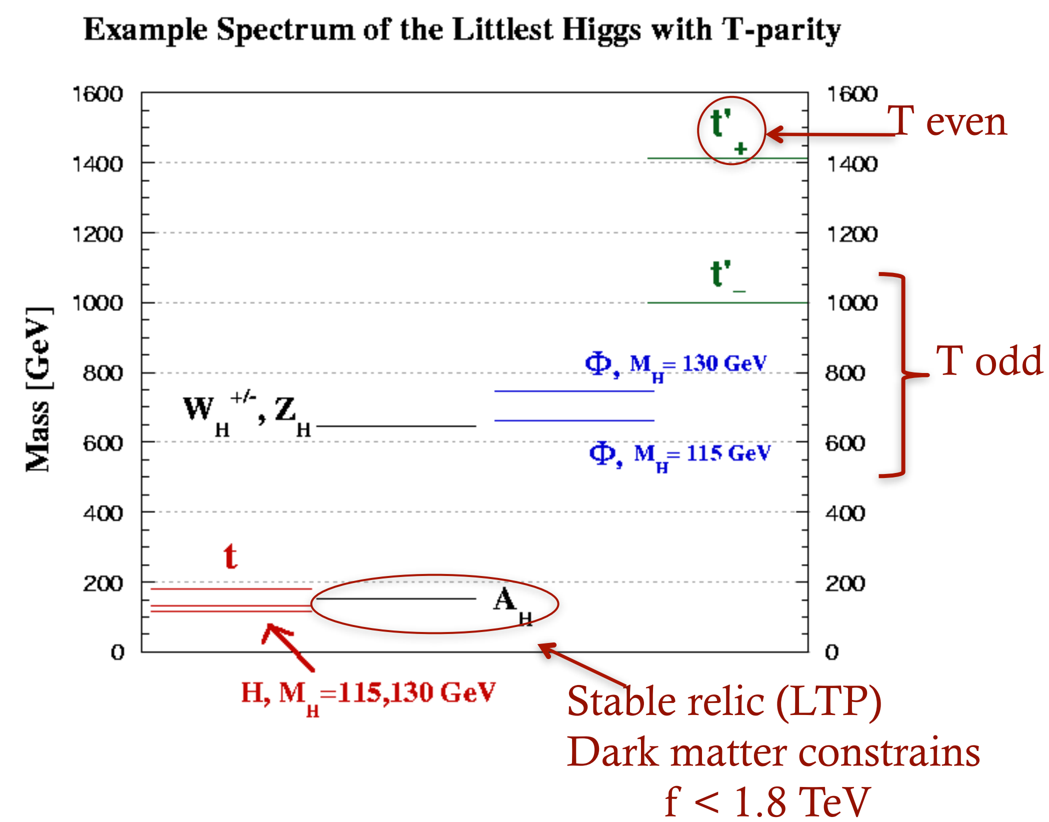


Precision EW constraints then push scale of new physics above 4 TeV at minimum (usually well above) unless *Z'*, *W'* can be decoupled from SM fields.

Solution: Impose T-Parity

$W_H^{\pm}, Z_H$	$m \sim gf$	T odd
A_H	$m \sim \frac{g'}{\sqrt{5}} f$	T odd
Φ	$m \sim \frac{m_H}{v} f$	T odd
t'_+	$m \sim \sqrt{\lambda_1^2 + \lambda_2^2} f$	T even
t'_-	$m \sim \lambda_2 f$	T odd

Also T-odd partners to all SM fermions



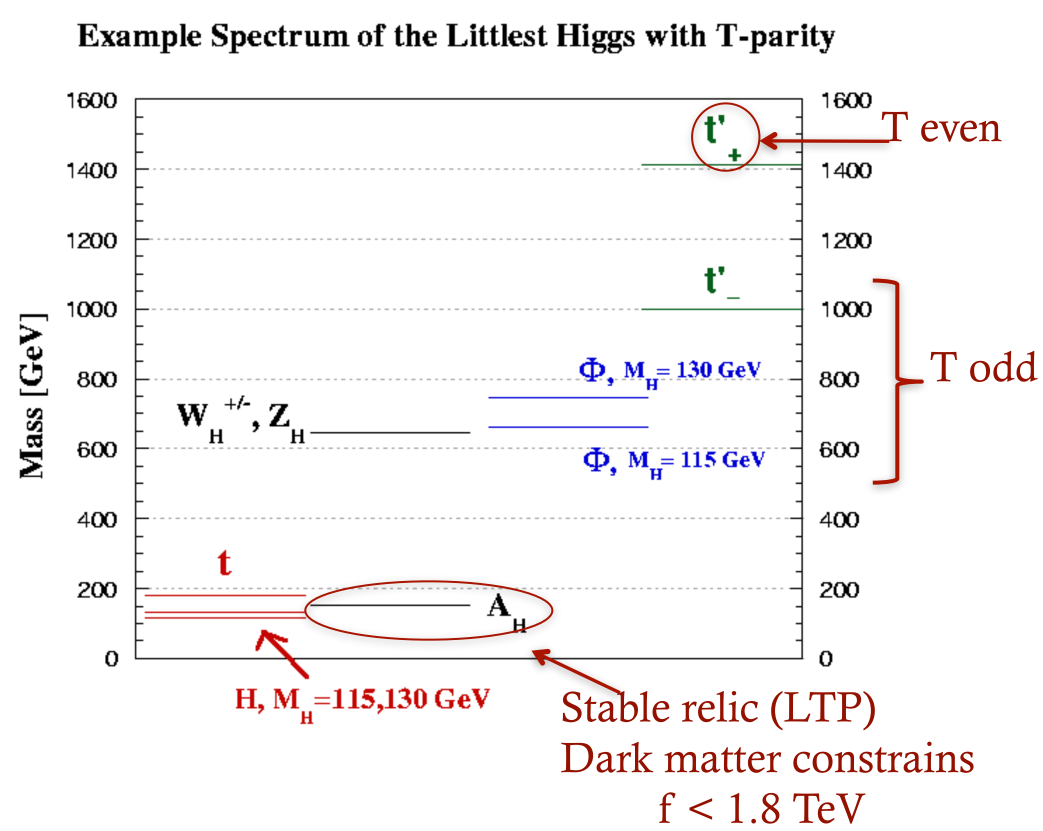
Phenomenology is SUSY-like:

- Missing energy due to A_H (heavy photon) being LTP
- Partners for all SM fermions and (most) gauge bosons, **except with same spins!**

Solution: Impose T-Parity

$W_H^{\pm}, Z_H$	$m \sim gf$	T odd
A_H	$m \sim \frac{g'}{\sqrt{5}} f$	T odd
Φ	$m \sim \frac{m_H}{v} f$	T odd
t'_+	$m \sim \sqrt{\lambda_1^2 + \lambda_2^2} f$	T even
t'_-	$m \sim \lambda_2 f$	T odd

Also T-odd partners to all SM fermions



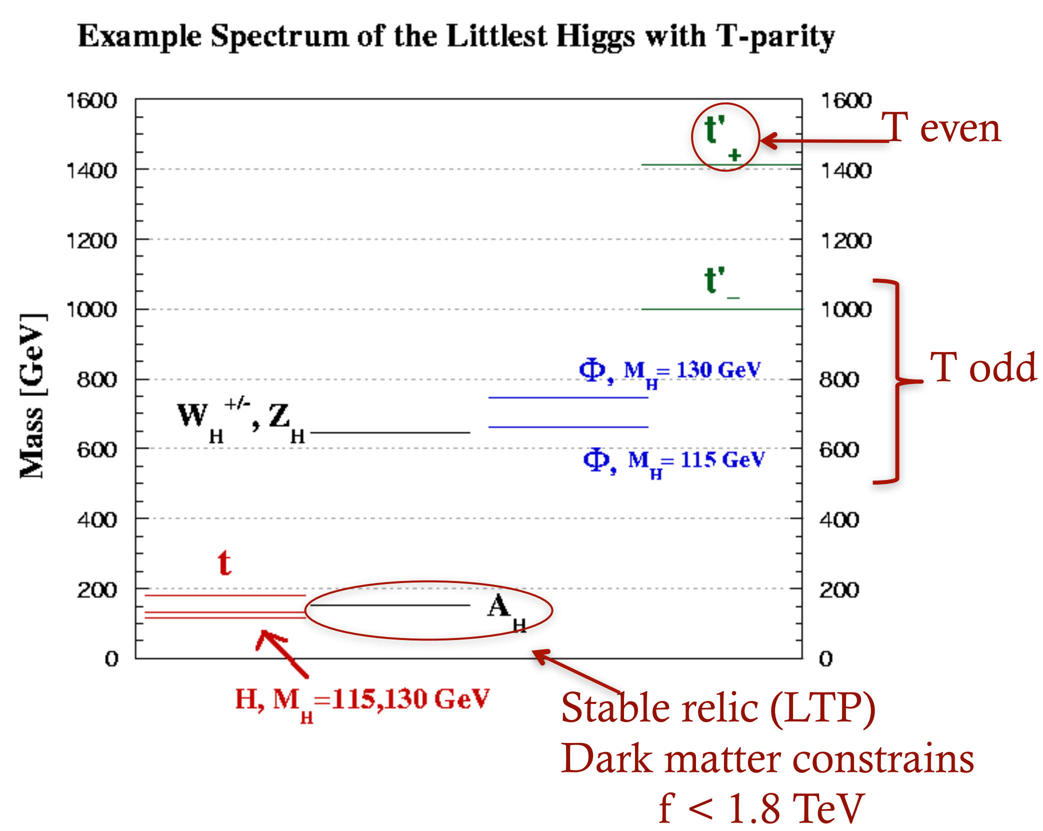
Phenomenology is SUSY-like:

- Missing energy due to A_H (heavy photon) being LTP
- Partners for all SM fermions and (most) gauge bosons, **except with same spins!**

Solution: Impose T-Parity

$W_H^{\pm}$, Z_H	$m \sim gf$	T odd
A_H	$m \sim \frac{g'}{\sqrt{5}} f$	T odd
Φ	$m \sim \frac{m_H}{v} f$	T odd
t'_+	$m \sim \sqrt{\lambda_1^2 + \lambda_2^2} f$	T even
t'_-	$m \sim \lambda_2 f$	T odd

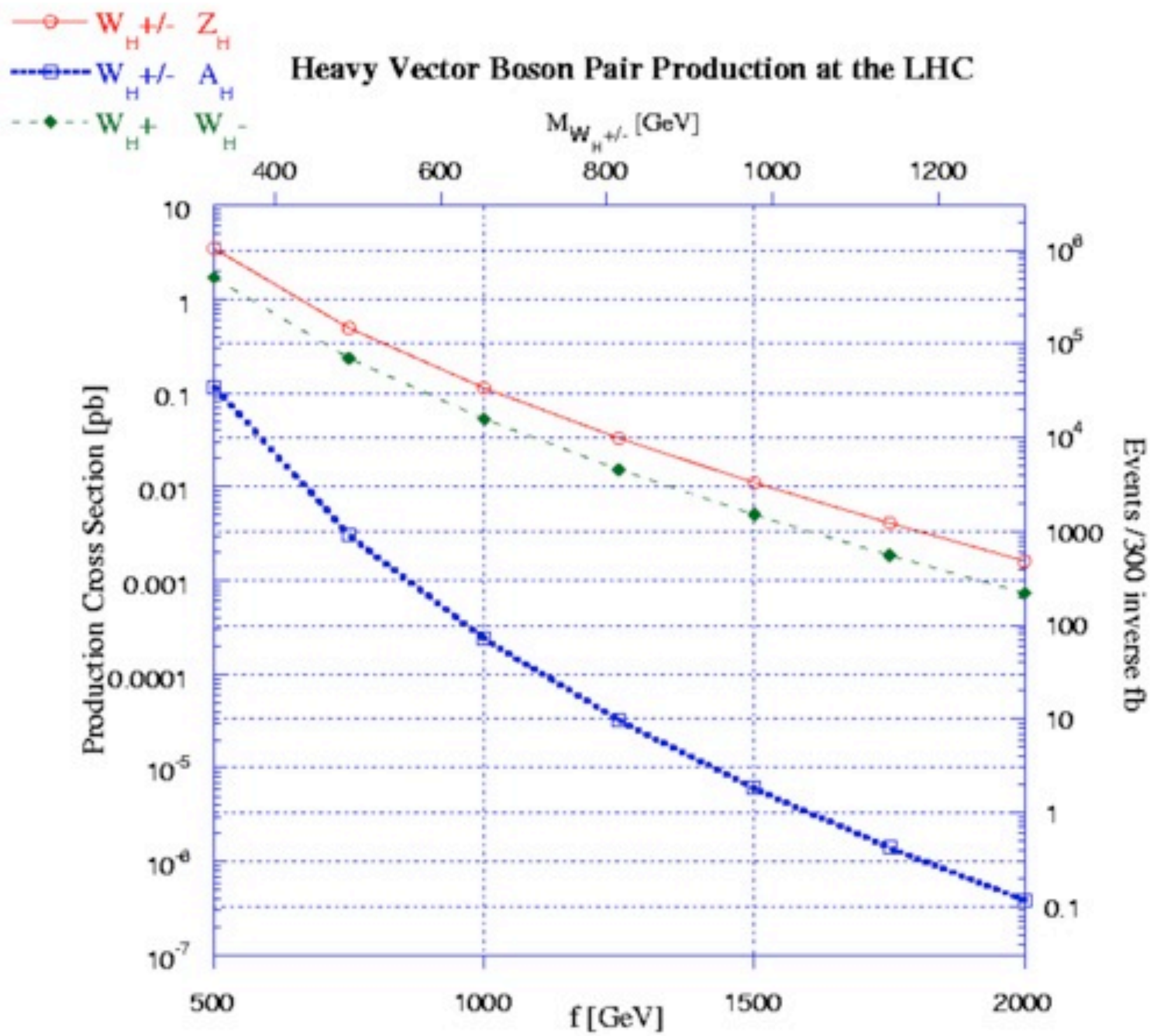
Also T-odd partners to all SM fermions



Phenomenology is SUSY-like:

- Missing energy due to A_H (heavy photon) being LTP
- Partners for all SM fermions and (most) gauge bosons, **except with same spins!**

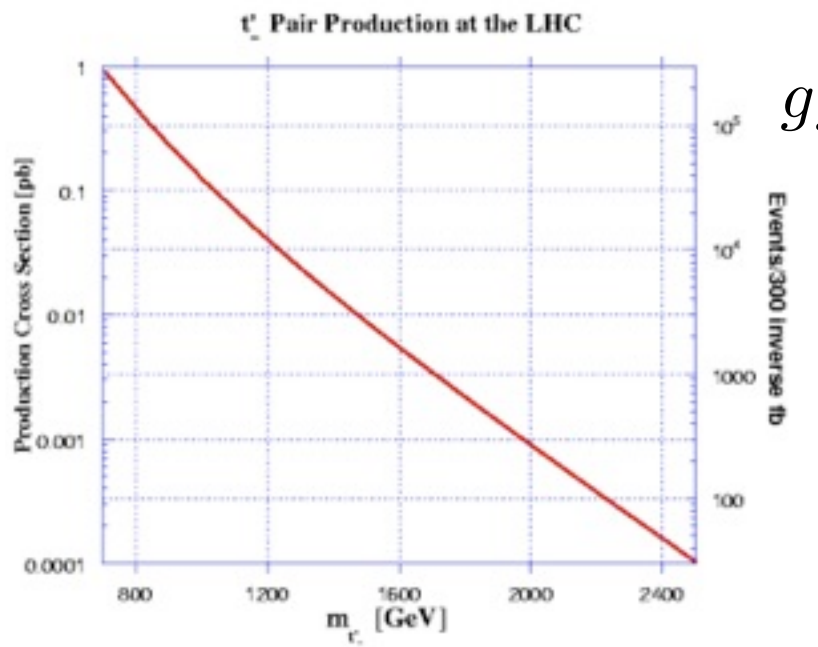
We need techniques to measure spin correlations



$$pp \to W_H^+ Z_H \to (W^+ A_H)(h A_H)$$
$$pp \to W_H^+ W_H^- \to (W^+ A_H)(W^- A_H)$$

Lots of MET in final states!

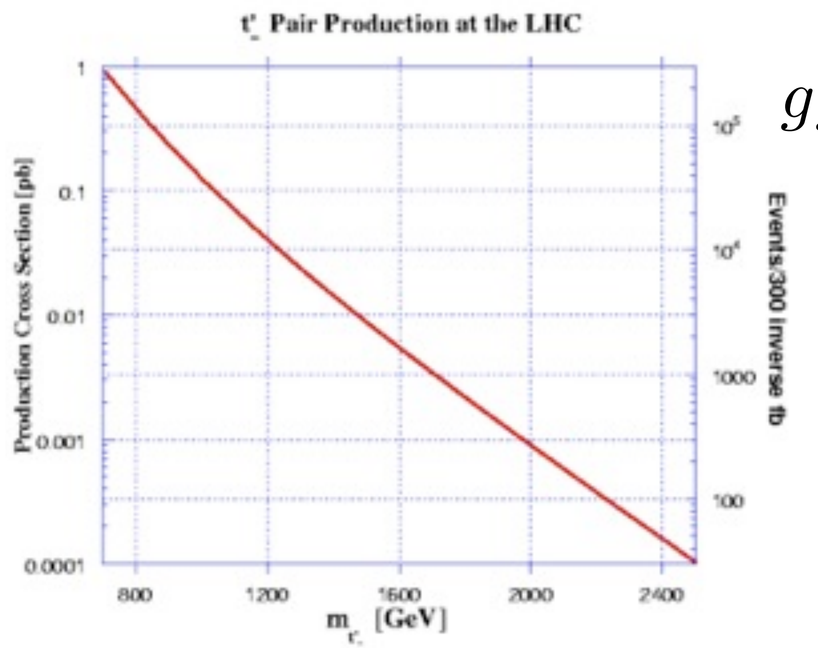
t'_-
(T-odd)



$$gg \to t'_- \bar{t}'_-$$

$$t'_- \to A_H t$$

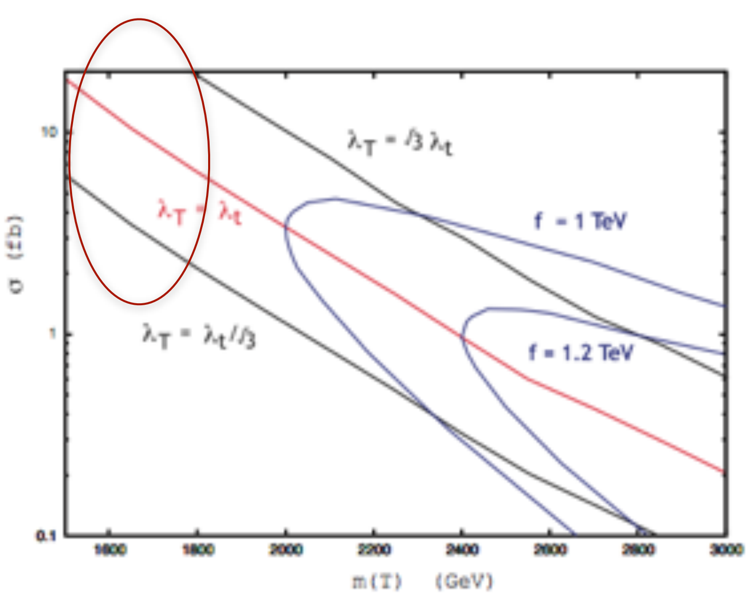
t'_-
(T-odd)



$$gg \rightarrow t'_- \bar{t}'_-$$

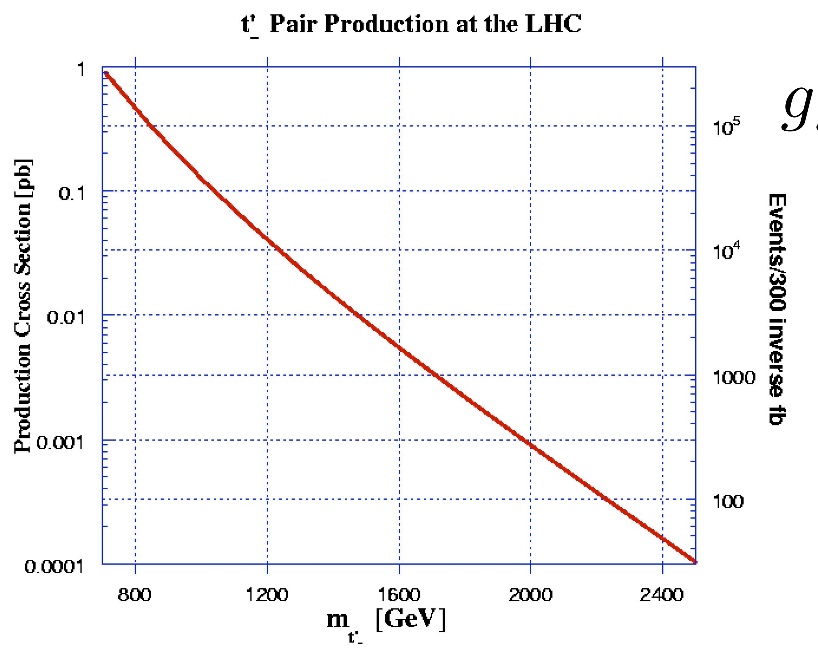
$$t'_- \rightarrow A_H t$$

t'_+
(T-even)



$$q\, b \rightarrow q\, t'_+$$

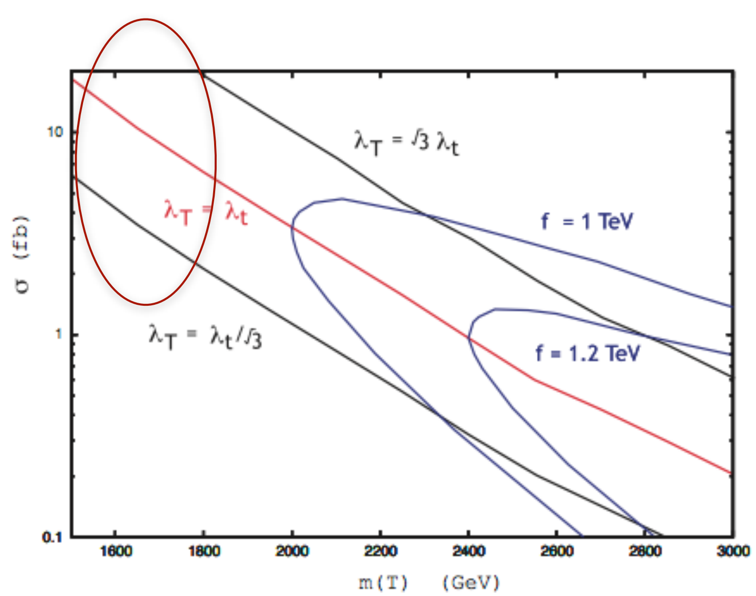
t'_-
(T-odd)



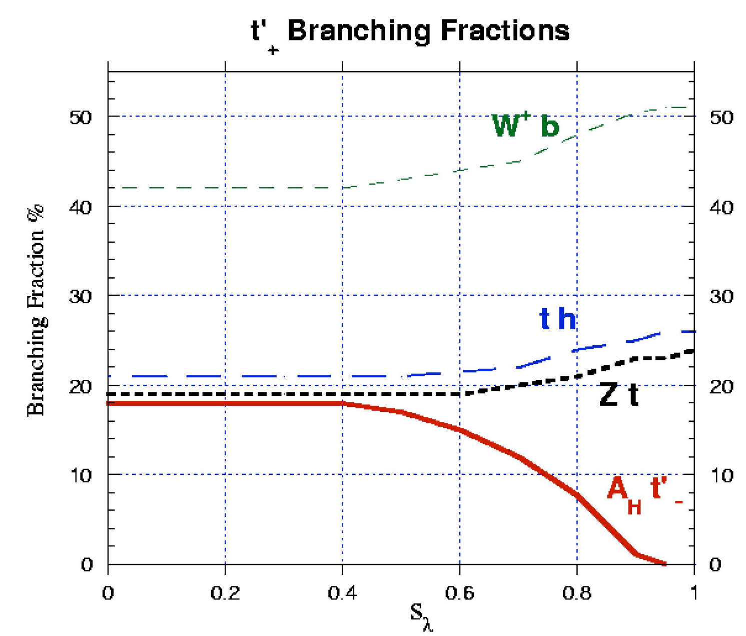
$$gg \longrightarrow t'_- \bar{t}'_-$$

$$t'_- \longrightarrow A_H t$$

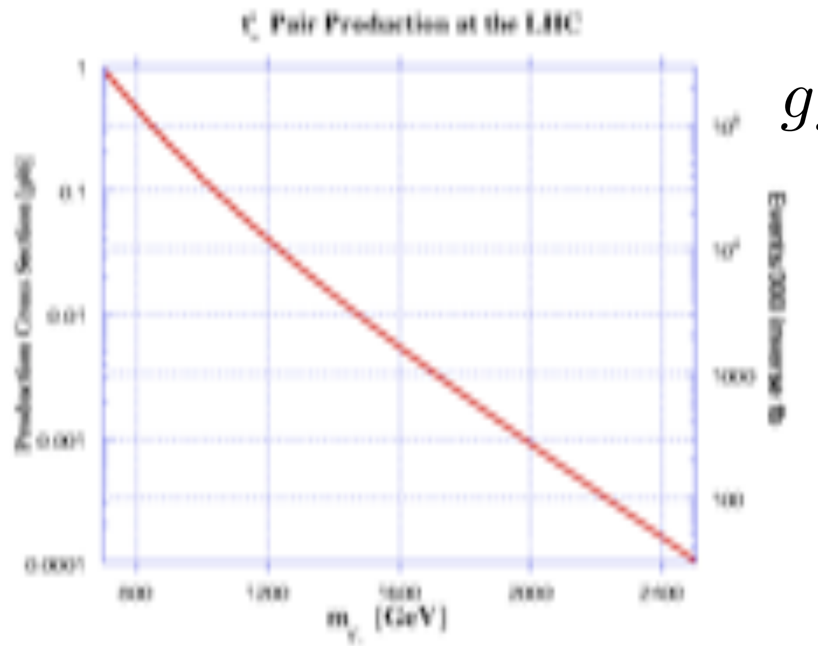
t'_+
(T-even)



$$q\,b \longrightarrow q\,t'_+$$

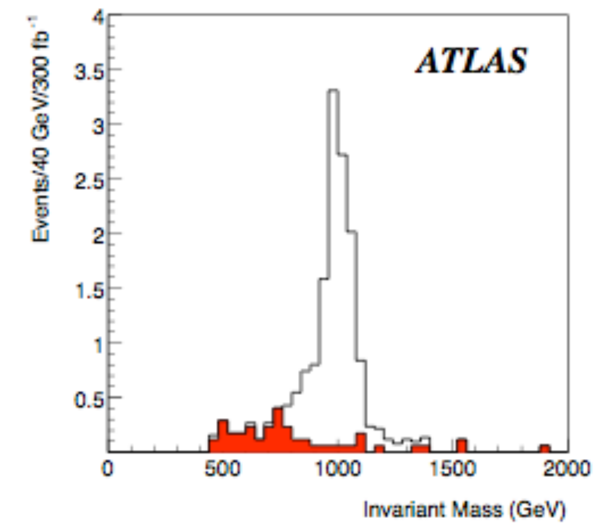


t'_-
(T-odd)

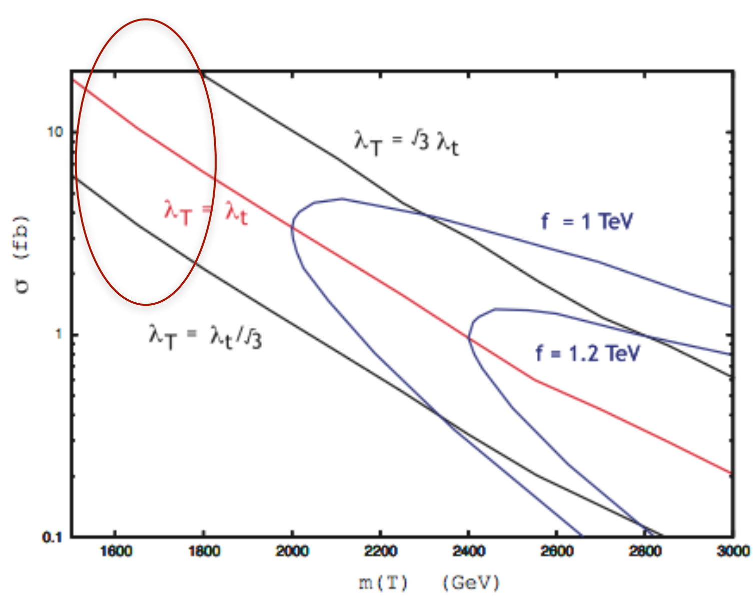


$$gg \longrightarrow t'_- \bar{t}'_-$$

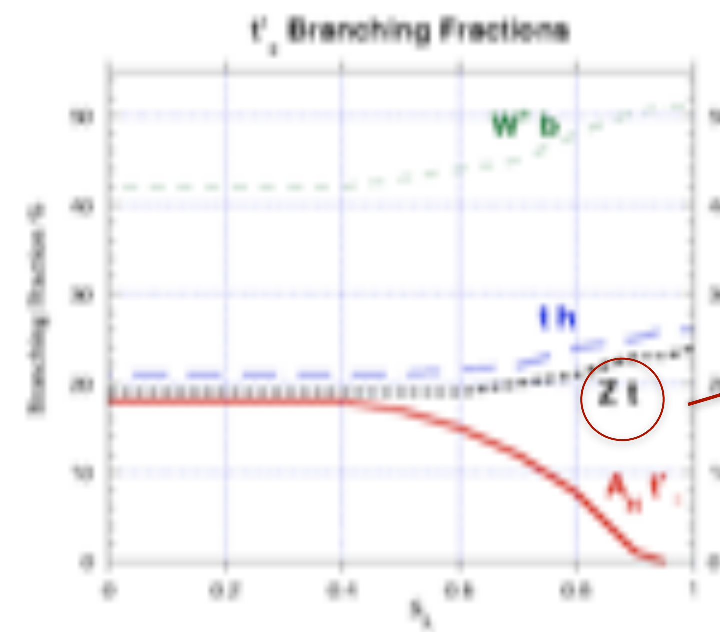
$$\longrightarrow t'_- \longrightarrow A_H t$$



t'_+
(T-even)



$$q\,b \longrightarrow q\,t'_+$$



Little Higgs models don't solve hierarchy problem – they delay it.

If a Little Higgs at 1 TeV pushes hierarchy problem to 10 TeV, then …

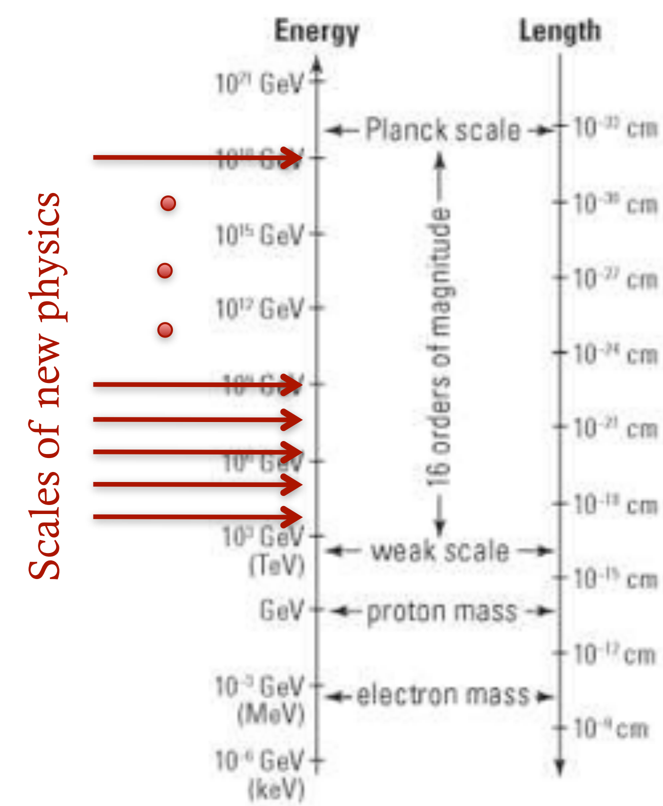
… another Little Higgs at 10 TeV pushes hierarchy problem to 100 TeV, and …

… another pushes it off to 1000 TeV…

… *ad nauseum* (to Planck scale).

OR

We embed Little Higgs into a more complete model at 1-10 TeV, a "UV completion" in which Higgs is composite (or absent).



Beyond the Higgs

The Higgs field plays distinct and important roles in the Standard Model:

1) It breaks the EW symmetry and gives masses to W, Z bosons.

2) It unitarizes $W_L W_L$ scattering.

3) It breaks the chiral symmetry in the fermions, taking distinct states (e_L and e_R are unrelated - important for GUTs) which are massless and chiral and combining them into massive, non-chiral fermions.

4) In generating fermion masses, it must create the 3-generation structure and the CKM matrix, without tree-level flavor-changing neutral currents.

Beyond the Higgs

The Higgs field plays distinct and important roles in the Standard Model:

EASY → 1) It breaks the EW symmetry and gives masses to W, Z bosons.

HARD → 2) It unitarizes $W_L W_L$ scattering.

HARD → 3) It breaks the chiral symmetry in the fermions, taking distinct states (e_L and e_R are unrelated - important for GUTs) which are massless and chiral and combining them into massive, non-chiral fermions.

REALLY HARD → 4) In generating fermion masses, it must create the 3-generation structure and the CKM matrix, without tree-level flavor-changing neutral currents.

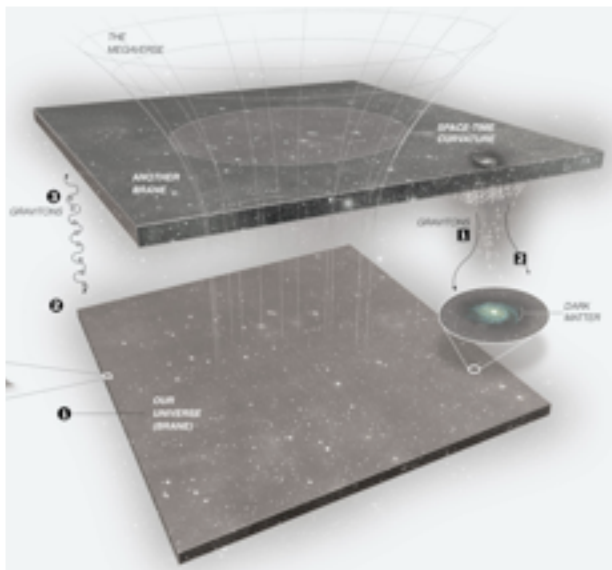
Models that eliminate fundamental Higgs need to solve all three problems:

Technicolor: solved (1) & (2)
Extended Technicolor: solved (1), (2) & (3) *(maybe)*
Walking Extended Technicolor: solved (1) – (4) *(just maybe)*

Serious impediment was incalculability of models due to strong coupling.
Problem solved for certain classes of models by generalizations of AdS/CFT duality.

5-Dimensional/Composite Higgs Models

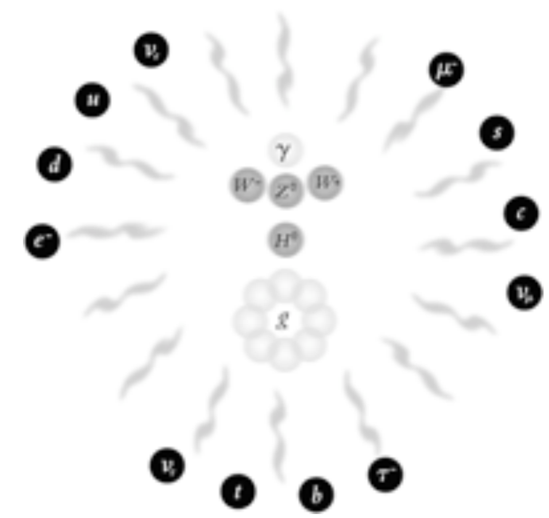
Higgs as composite is very old idea, but required strongly-coupled dynamics, which weren't calculable before AdS/CFT correspondence.



Randall-Sundrum model of two 3-branes in warped 5^{th} dimension

$$=$$

dual



Strongly-coupled gauge theory in 4 dimensions.

Place large gauge group in "bulk" which breaks due to boundary conditions to $[SU(3)_C \times SU(2)_L \times U(1)_Y]_{gauge} \times [SU(2)_R]_{global}$:

$$SO(5) \rightarrow \quad SO(4) = SU(2)_L \times SU(2)_R \quad \rightarrow \quad SU(2)_L$$

Fifth components of 4 zero modes of SO(5)/SO(4) (which are vectors in 5-D and scalars in 4-D) become the 4 d.o.f.'s of the Higgs!

In 5-D, the Higgs is part of a gauge field; in 4-D it is a composite field!

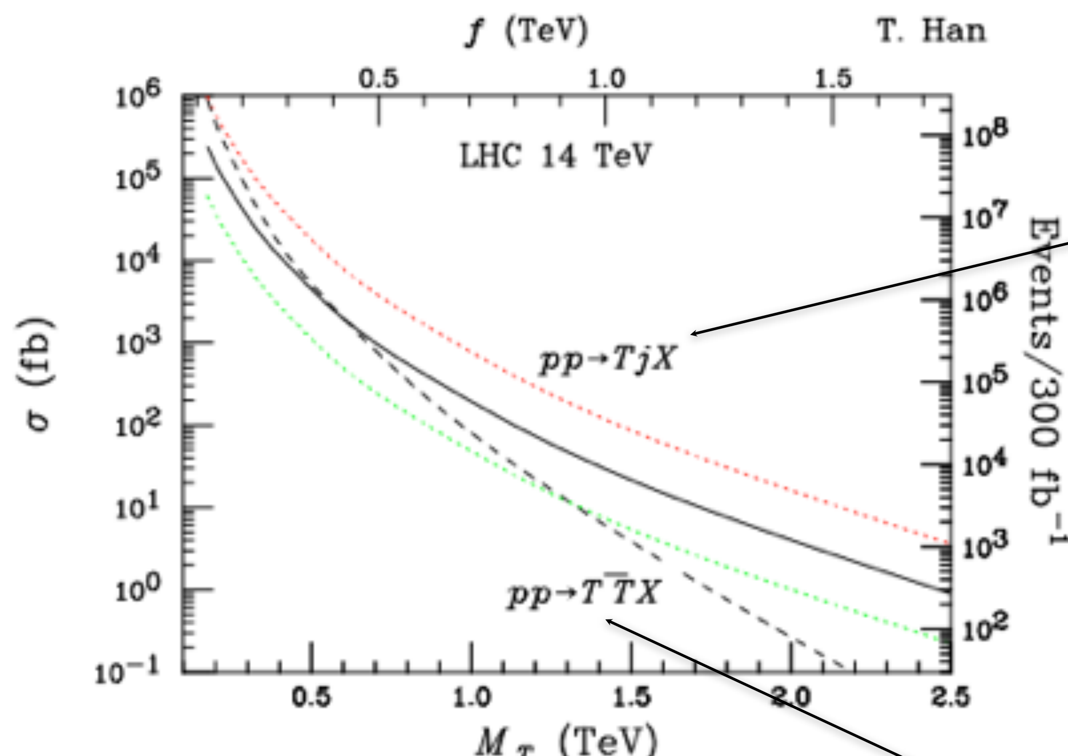
When constructed as a 5-D model, there is an $SU(2)_L \times SU(2)_R$ in the bulk, broken to $SU(2)_L$ on our "brane" – this is required to avoid large contributions to T-parameter in strong coupling dual.

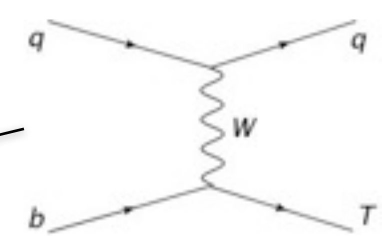
The top partners fill out (2,2) irrep:

$$\begin{pmatrix} T & T_{5/3} \\ B & T_{2/3} \end{pmatrix}$$

$Q = 5/3$

$Q = -1/3$ $\qquad$ $Q = 2/3$





Usual gluon production – kinematically suppressed

$$T_{(2/3)} \to Zt$$

(Same analysis as Little Higgs)

In 5-D, the Higgs is part of a gauge field; in 4-D it is a composite field!

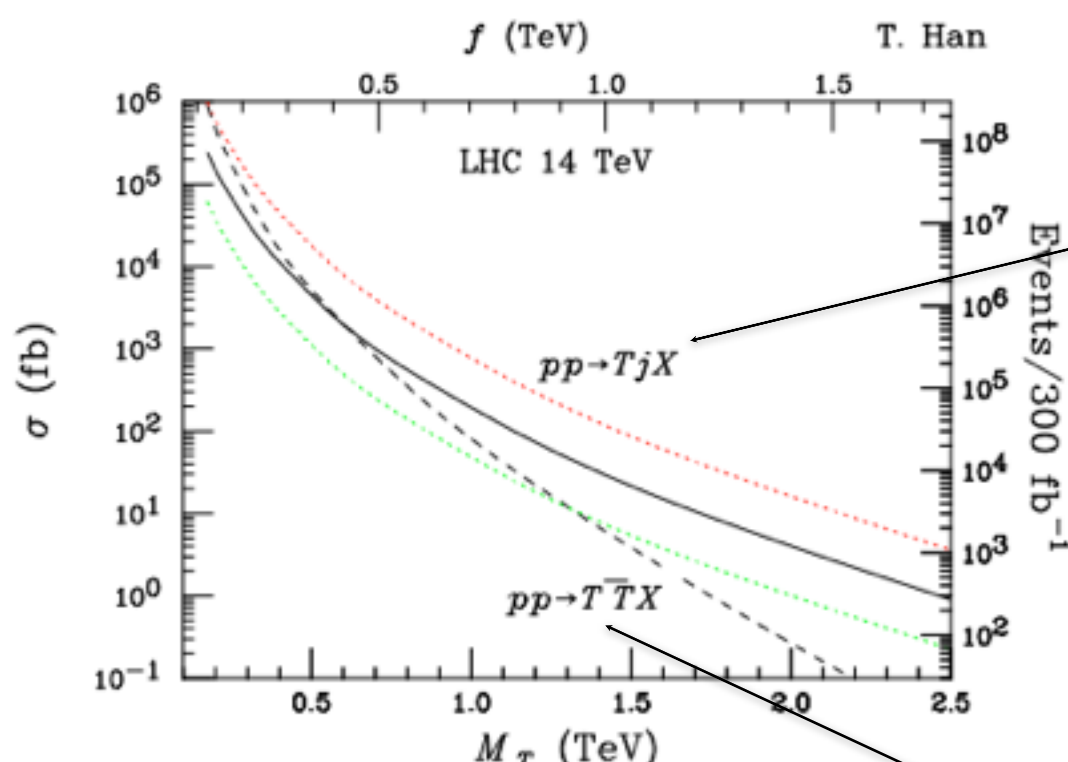
When constructed as a 5-D model, there is an $SU(2)_L \times SU(2)_R$ in the bulk, broken to $SU(2)_L$ on our "brane" – this is required to avoid large contributions to T-parameter in strong coupling dual.

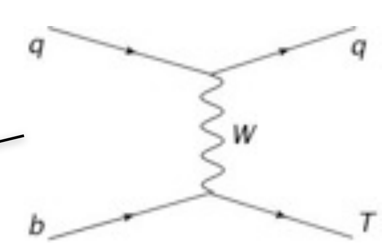
The top partners fill out (2,2) irrep:

$$\begin{pmatrix} T & T_{5/3} \\ B & T_{2/3} \end{pmatrix}$$

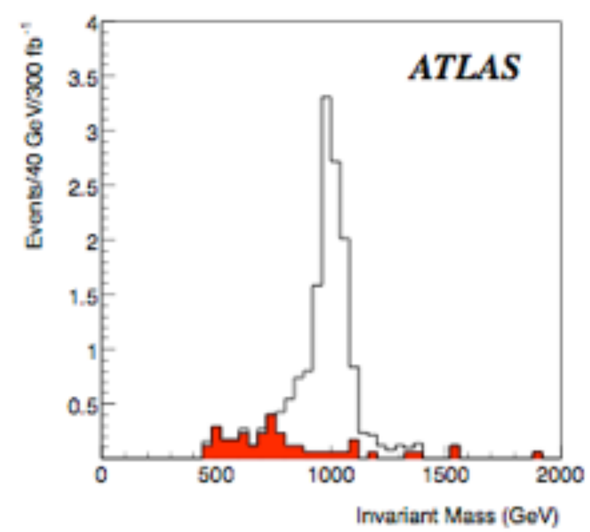
$Q = 5/3$

$Q = -1/3$ $\quad$ $Q = 2/3$





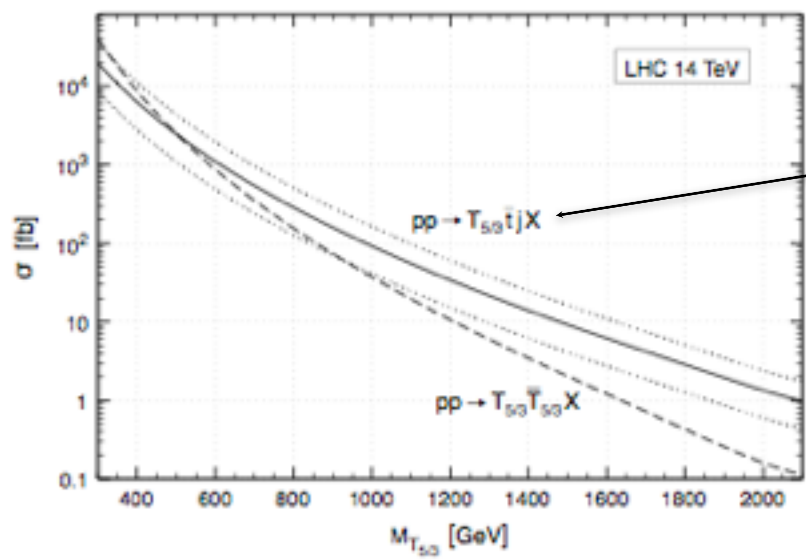
Usual gluon production –
kinematically suppressed

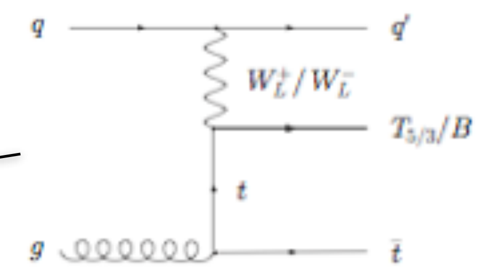


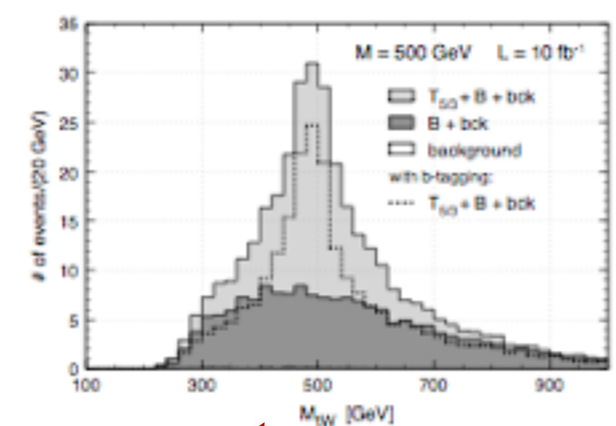
$T_{(2/3)} \to Zt$

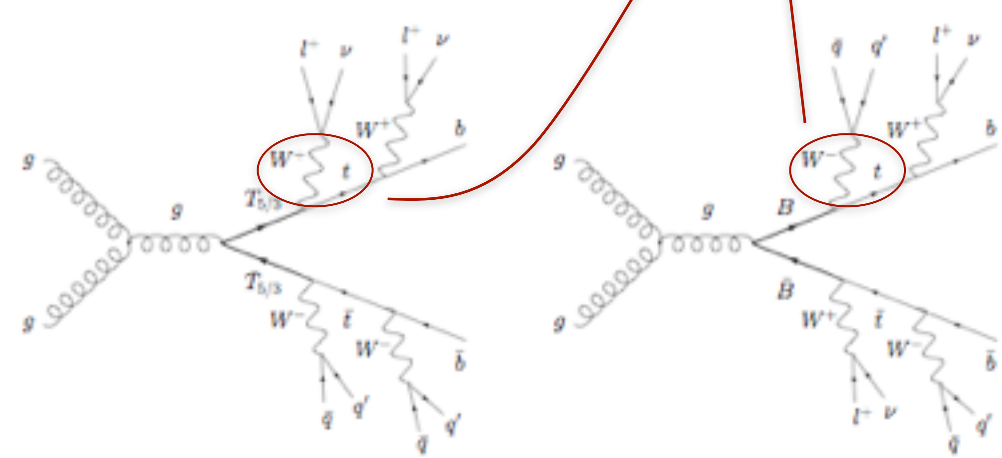
(Same analysis as Little Higgs)

The $T_{5/3}$ state is more unusual:









Most background-free discovery through dileptons + MET, with b-tagging.

If M=500 GeV, discovery with 5 – 10 fb^{-1}.

Contino, Servant

In the same way there are other exotic states that can appear in this extra dimensional dimensional description of strongly couple Higgses.

One possible example is a lepton triplet with Y=1:

$$X = \begin{pmatrix} X^{++} \\ X^{+} \\ X^{0} \end{pmatrix} \longrightarrow \text{Can mix with SM leptons through Higgs interactions}$$

Bounds on FCNCs coming from anomalous decays of the muon put bounds on the mixing between X and SM

$$\mu \to e\gamma$$

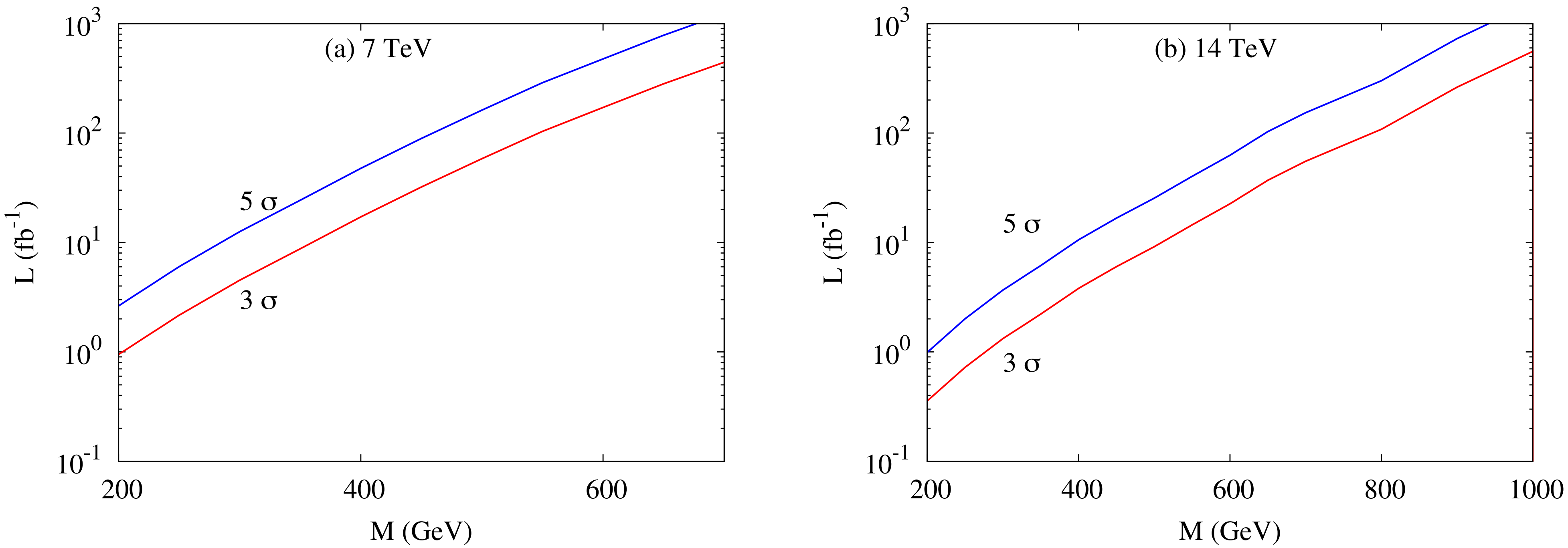
$$\mu \to eee \qquad \longrightarrow \qquad \lambda \sim 10^{-3}$$

$$\mu \to e \text{ conversion}$$

Such a small mixing imply:

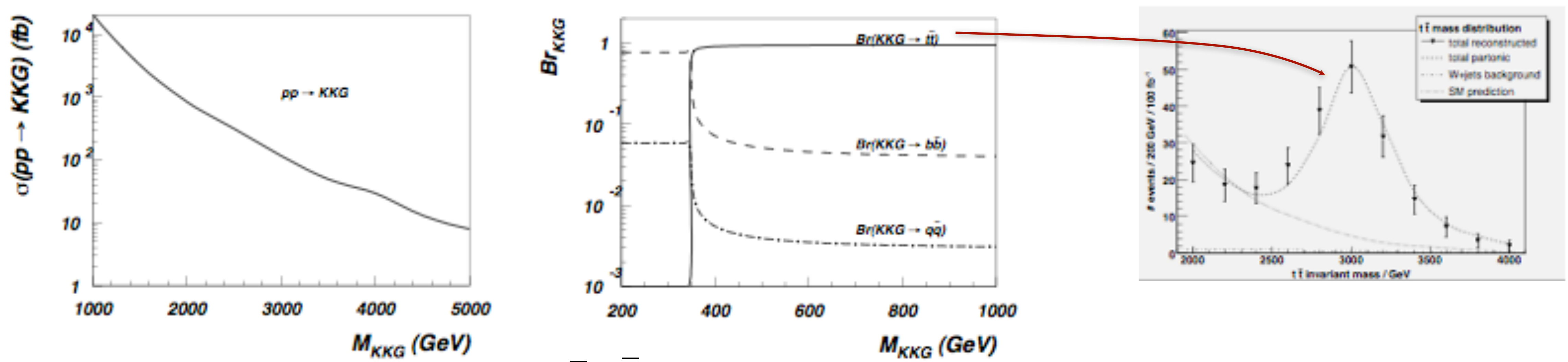
-Small splitting among the different particles in X which means that cascade decays produce very soft particles.
-Associated production with another lepton is very much suppressed.

$$pp \to X^{--} X^{++} \to \ell^- W^- \ \ell^+ W^+ \to \ell^- \ell^- \nu \ell^+ jj$$



AD, García-Cely, Han

Kaluza-Klein modes of *W, Z* are similar to traditional *W', Z'* but there are now also KK gluons and fermions!



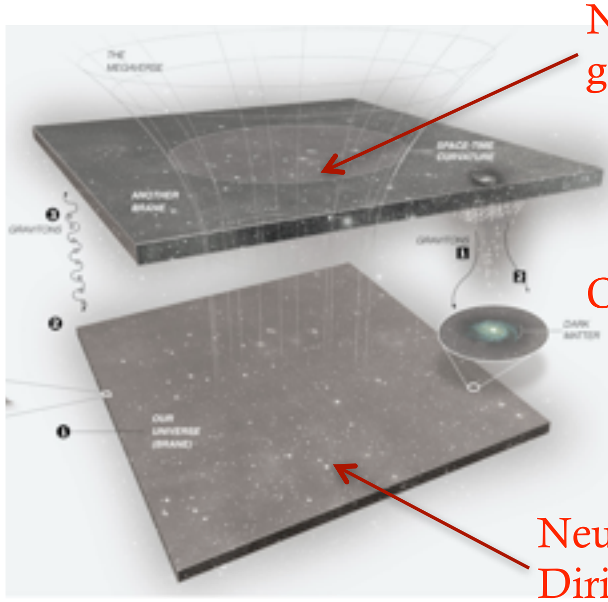
$$pp \longrightarrow \hat{g} \longrightarrow \bar{t}t, \bar{b}b, \bar{q}q$$

LHC will probe to KK masses of several TeV!

Aside #1: this model doesn't need T-parity because of custodial symmetry, so no dark matter candidate – but of course, T-parity can be added anyway!

Aside #2: In 4-D, strong dynamics generate Higgs, and then Higgs breaks EW symmetry. The W, Z are 0-modes in 5-D.

Higgsless Models

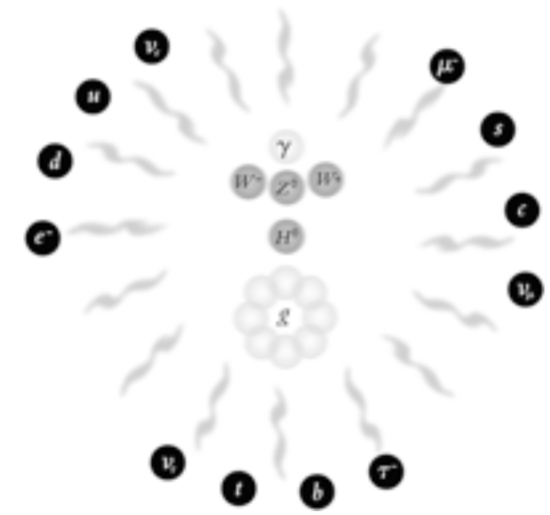


Neumann for all groups

Orbifolding

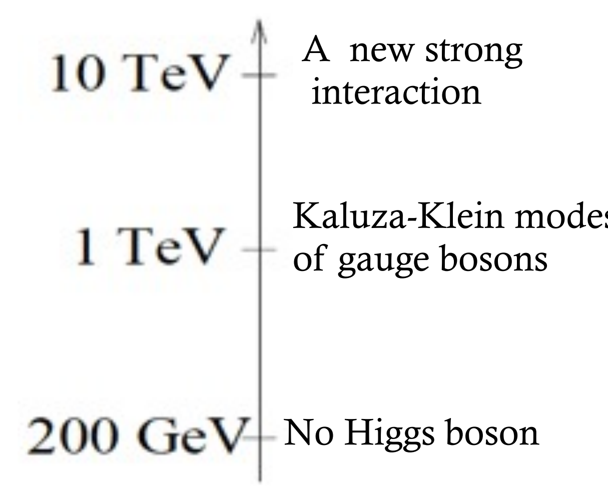
Neumann for EM, Dirichlet for weak

= dual

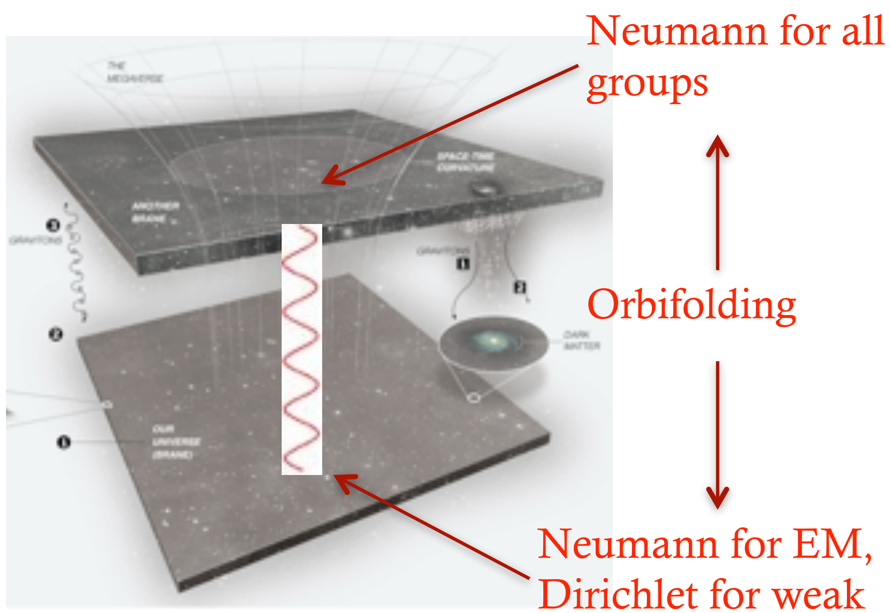


Randall-Sundrum model of two 3-branes in warped 5th dimension

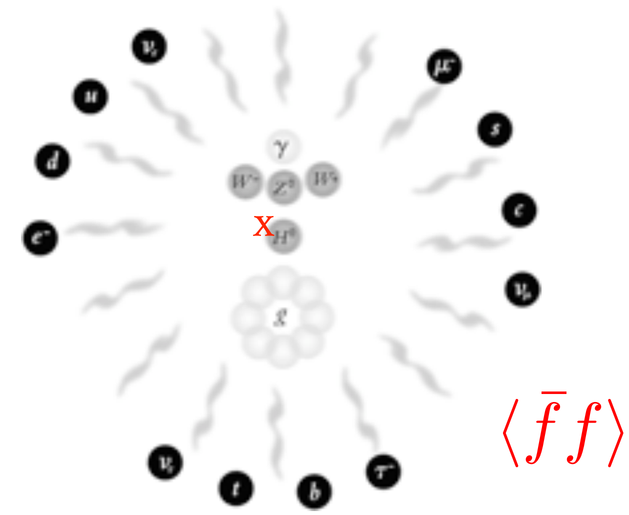
Strongly-coupled gauge theory in 4 dimensions.



Higgsless Models



= dual

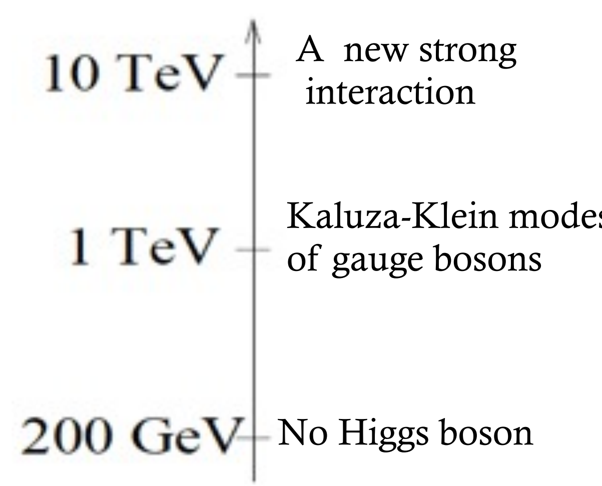


Randall-Sundrum model of two 3-branes in warped 5th dimension

Strongly-coupled gauge theory in 4 dimensions.

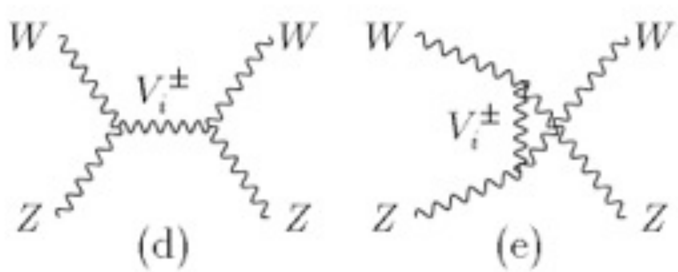
Higgsless models are a version in which condensates break EW symmetry in 4-D model, but boundary conditions break EW symmetry in dual, 5-D picture.

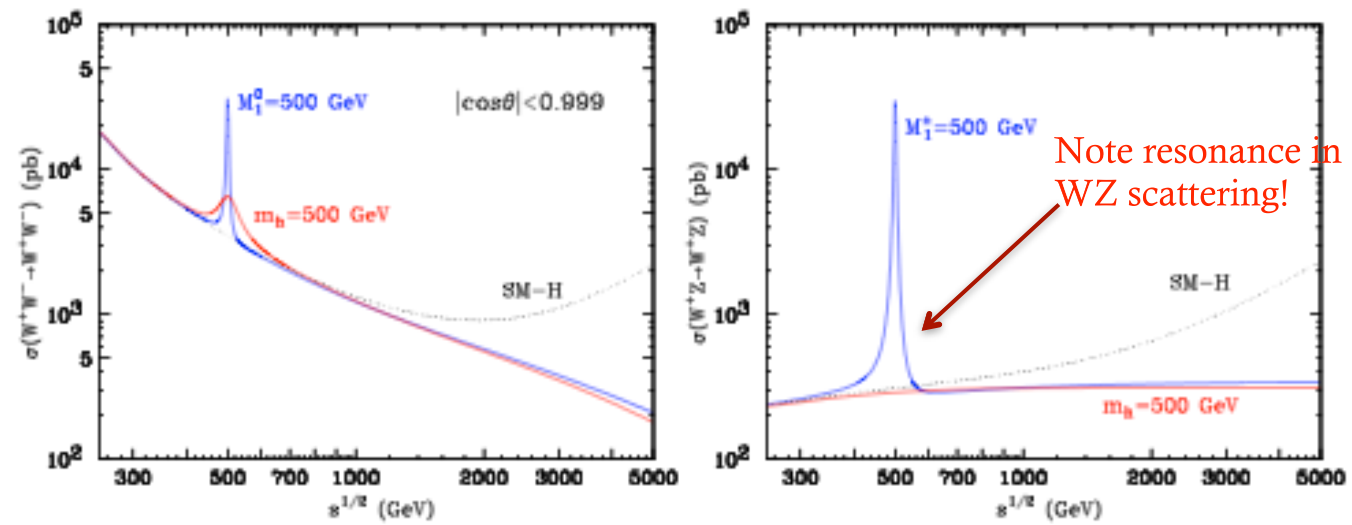
- Fermions get masses by mixing with composite state → mixing prop to mass. Therefore light fermions do not couple strongly to …
- Kaluza-Klein excitations of gauge bosons (Regge states in dual theory)



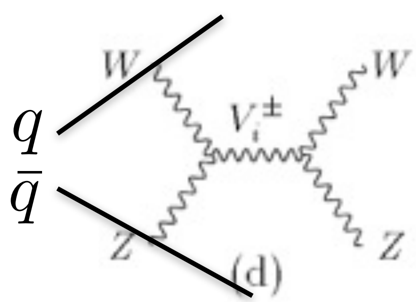
Unitarity preserved by cancellations among tower of KK states (excited W and Z states). These states can be produced at LHC and studied!

BUT, KK states have tiny couplings to fermions (except top), so must be produced in WZ scattering:

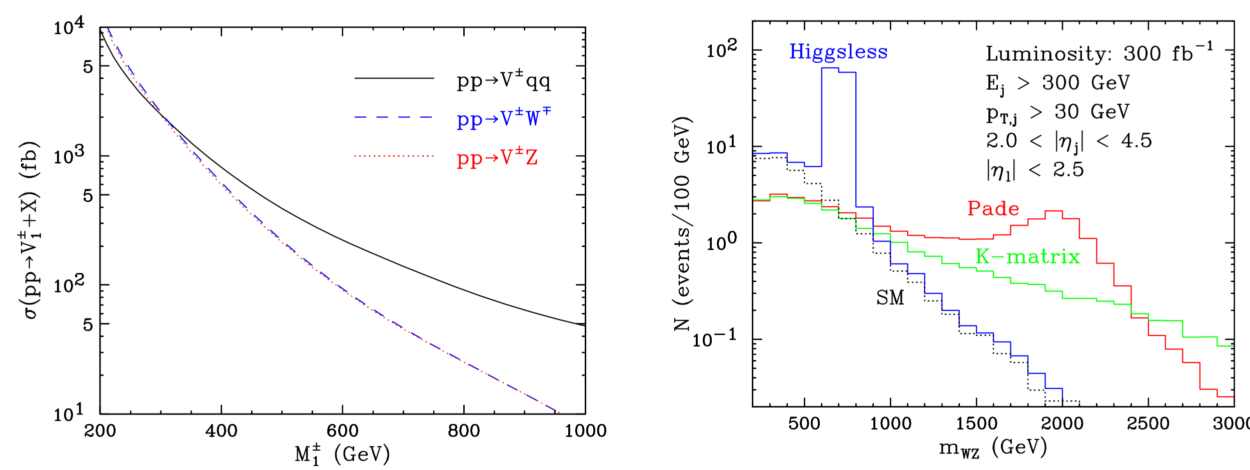




LHC:



$$2j + 3\ell + \not{E}_T$$



Birkedal, Matchev, Perelstein

Conclusions

Conclusions

The LHC is about to start proving the scale where the realm of EWSB has to be uncovered.

Conclusions

The LHC is about to start proving the scale where the realm of EWSB has to be uncovered.

Several possibilities exists for explaining the nature of the mechanism:

-Just the SM: one Higgs and no reason for it to be light

-SUSY: the paradigm of weak explanation of the weak scale

-Alternative explanations: Little Higgs, composite Higgs, no Higgs

Conclusions

The LHC is about to start proving the scale where the realm of EWSB has to be uncovered.

Several possibilities exists for explaining the nature of the mechanism:

-Just the SM: one Higgs and no reason for it to be light

-SUSY: the paradigm of weak explanation of the weak scale

-Alternative explanations: Little Higgs, composite Higgs, no Higgs

In this review talk I have summarized several of the non-susy models and their signals a the LHC. Some of them are somewhat similar to susy (MET), like the LH (or UED), others rely more on resonances. It is important to have multiple observations in order to correctly identify the physics BSM.