Light Composite Higgs The Third Way to Electroweak Symmetry Breaking

2. LHC Phenomenology

M. E. Peskin
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In the first lecture, we surveyed theories that lead to light composite Higgs bosons. We saw that these theories always contain certain types of exotic particles - vectorlike top quarks and extra W and Z bosons. We also saw that these theories have a rather complicated internal structure, with opportunities for the appearance of other types of new particles.

In this lecture, I will survey the new particles and effects that can be found in these models.

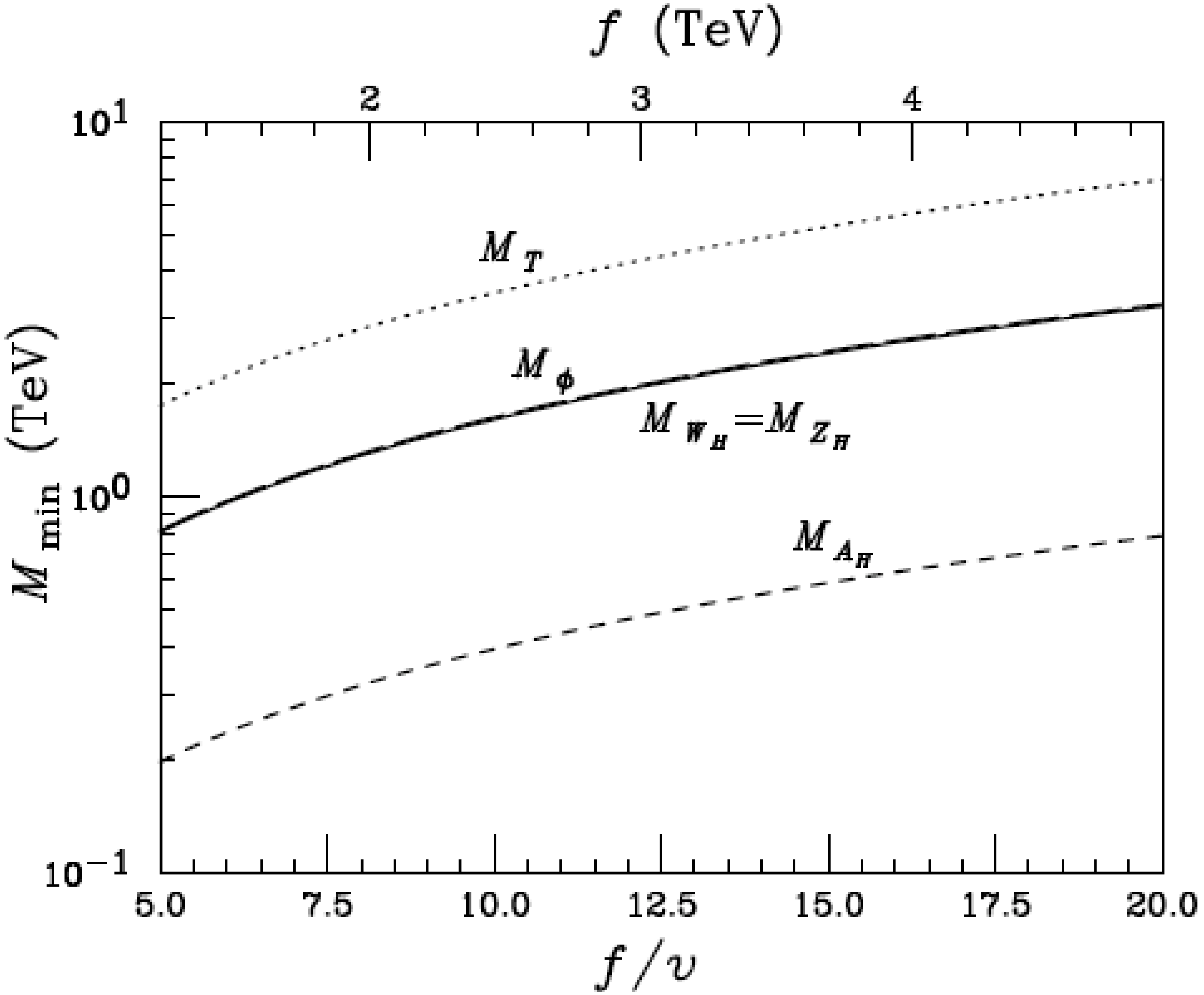
In the previous lecture, I emphasized the role of particles that receive their mass from sources other than the Higgs vacuum expectation value. In this lecture, an important theme will be the differences this makes in thinking about particle searches.

This lecture will be mainly conceptual, and so I will deliberately oversimplify in several ways.

First, I will emphasize the limit in which all effects of electroweak symmetry breaking - including the top quark mass - are zero. In this limit, our massive particles will have definite SU(2)xU(1) quantum numbers and will decay through SU(2)xU(1) conserving interactions.

In more realistic treatments of models, especially with new particles below 1 TeV, new particles will mix with t, b, W, Z, creating additional interactions and decay channels.

Second, I will ignore precision electroweak constraints on masses. New quarks and W, Z bosons below 1 TeV can give substantial corrections to electroweak observables. This leads to strong limits. Here is an illustrative plot from Han, Logan, McElrath, Wang (2003).



I will also ignore flavor constraints. Some flavor observables, e.g. B_d mixing, $b \to s\gamma$, are impacted by mixing of t with heavy quarks.

My philosophy here is that these problems can be remedied through cancellations in complete models. For precision electroweak, there are only three parameters, S, T and the anomalous $Z \to b\bar{b}$ amplitude, receiving contributions of both signs.

We are in a era where the data should rule, so we should extend searches to the maximum number of possibilities.

Begin with vectorlike top quarks.

The simplest possibility, which I presented yesterday in a Little Higgs context, is a vectorlike SU(2) singlet T.

An SU(2)xU(1)=invariant effective Lagrangian for the decay of T is

$$\lambda(\bar{t}, \bar{b})_L H T_R \qquad H = \begin{pmatrix} \pi^+ \\ (h^0 + i\pi^0)/\sqrt{2} \end{pmatrix}$$

(π^+, π^-, π^0) are Goldstone bosons that show up experimentally as the longitudinal polarization states of (W^+, W^-, Z^0)

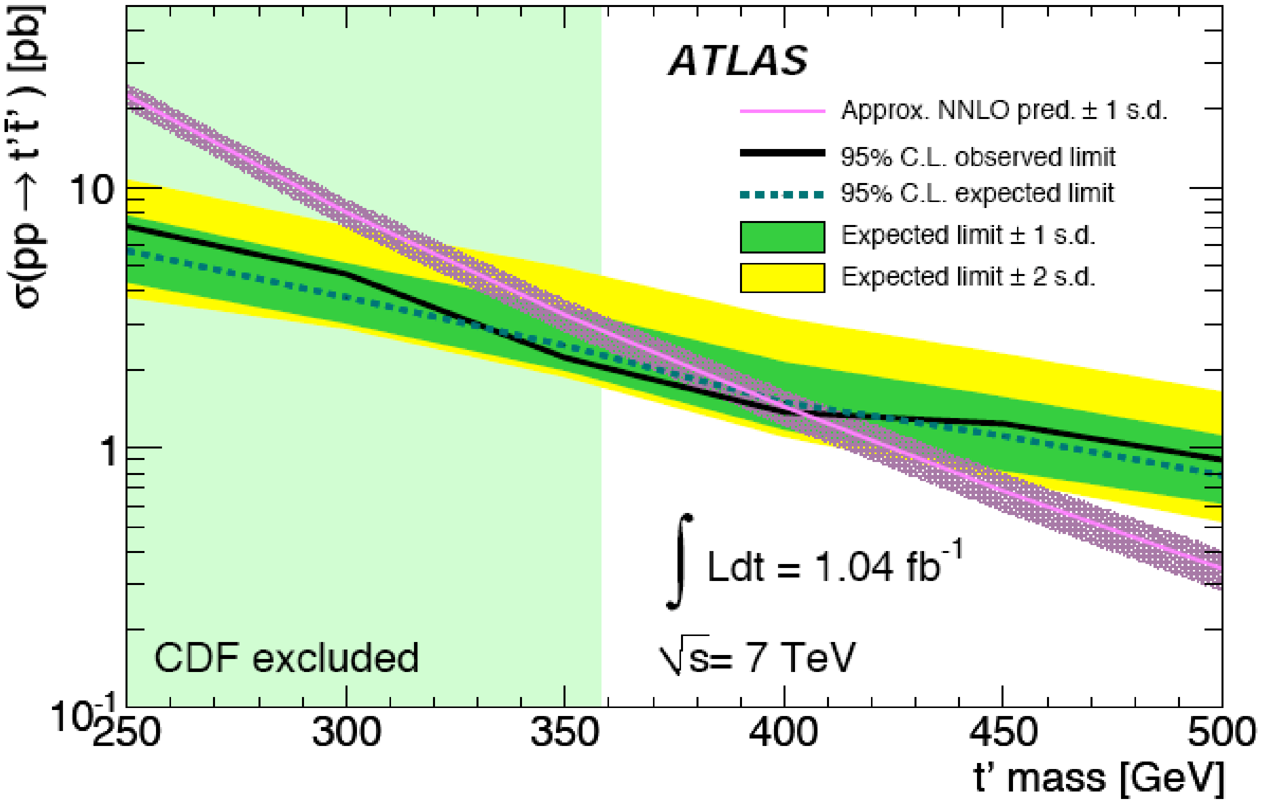
Considering this vertex alone, we obtain the decay pattern

$$\begin{aligned} T \quad &\rightarrow \quad bW^+ \qquad (50\%) \\ &\rightarrow \quad tZ^0 \qquad (25\%) \\ &\rightarrow \quad th^0 \qquad (25\%) \end{aligned}$$

(up to effects of phase space)

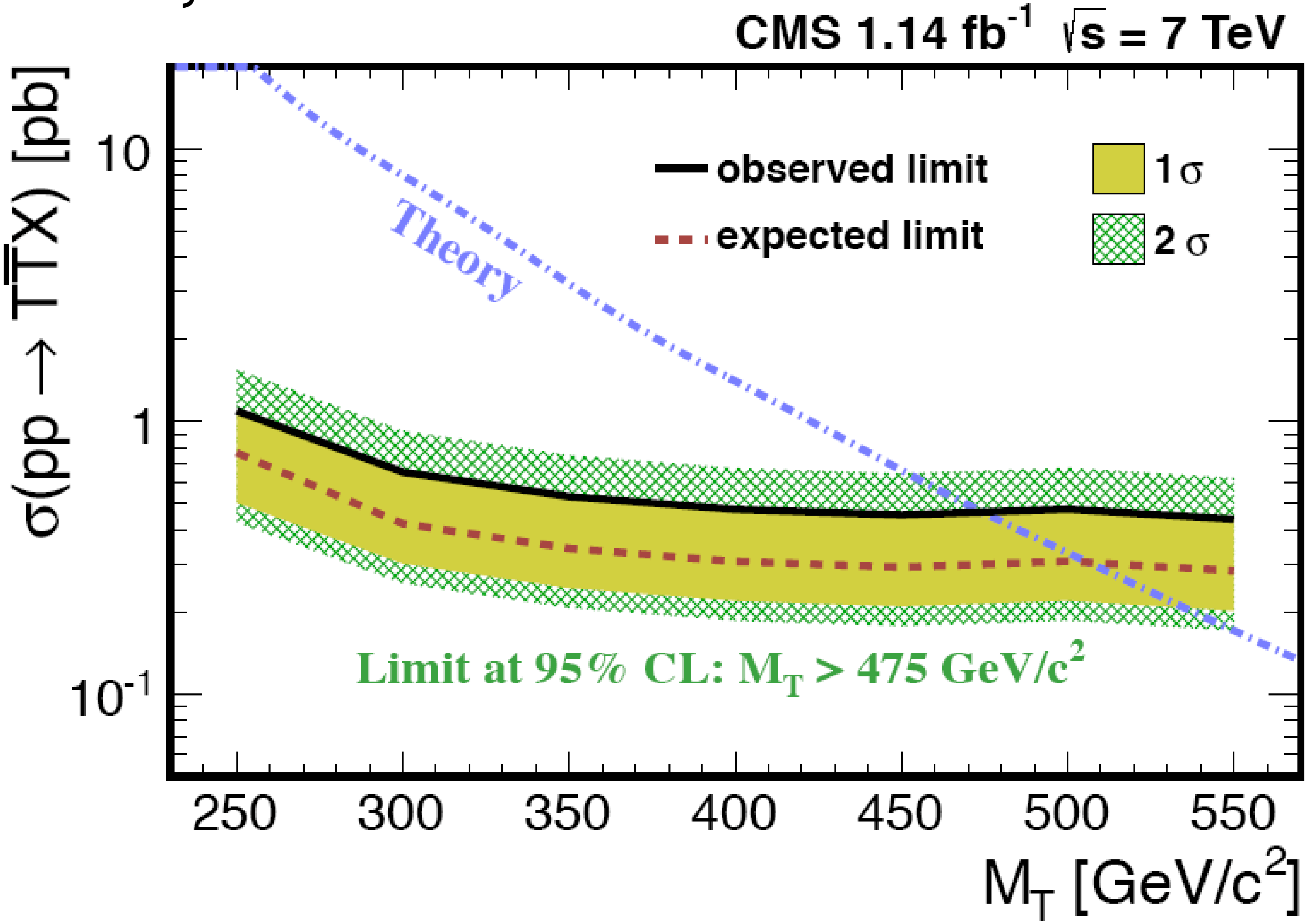
Mass mixing of T with t can change the relative size of the t-Higgs branching ratio, typically lowering it.

The current search for a sequential 4th generation t’ can be reinterpreted in this context. The predicted rate is 1/4 of that assumed there.



t’ can be completely excluded if the mass limit goes above the unitarity limit at ~500 GeV. That restriction on the mass does not apply to T.

CMS has also published a search for $t' \rightarrow t + Z^0$. This also can be reinterpreted in an obvious way to restrict T; the $\sigma \cdot BR \cdot BR$ is smaller by a factor 16.



Probably, stronger constraints could be found in mixed modes.

The most interesting targets are

$$\begin{aligned} T\overline{T} &\rightarrow tZ^0\bar{b}W^- + c.c. \\ &\rightarrow bjj\ell^+\ell^- b + (W) \end{aligned}$$

where $(W) = \ell\nu$ or boosted hadronic W

$$\begin{aligned} T\overline{T} &\rightarrow tZ^0\bar{t}h^0 + c.c. \\ &\rightarrow bjj\ell^+\ell^- b\ell\nu bb \end{aligned}$$

where the lowest-mass (bb) combination is in the light Higgs window.

This suggests some general remarks that apply to a wide variety of searches:

Many processes in the light composite Higgs story have W, Z in the final state. In this context, general tags for boosted hadronic W, Z can be important. The strategy is

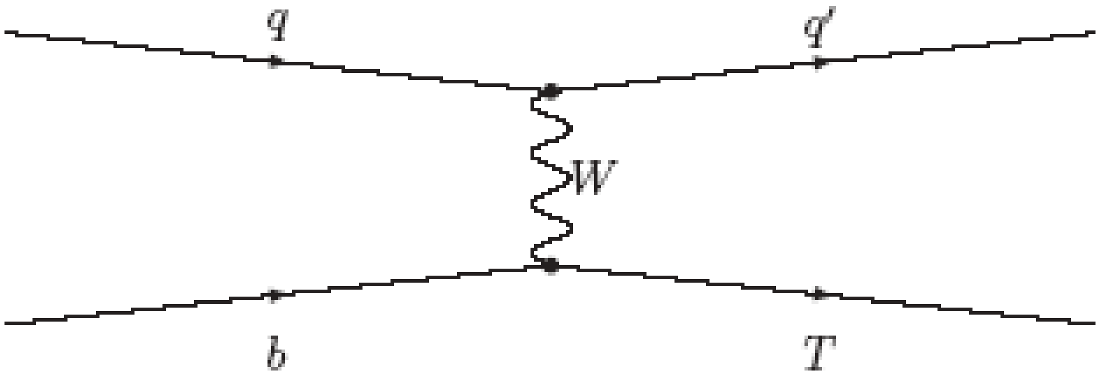
aggressive pruning of subjets with $z < 0.2$,
then, 2 subjets summing to m(jj) ~ m_W

Any LHC search that involves 2 b-tagged jets should look for a peak in m(bb), either generally in the light Higgs window or specifically at the mass where the Higgs is suggested (and, eventually, discovered).

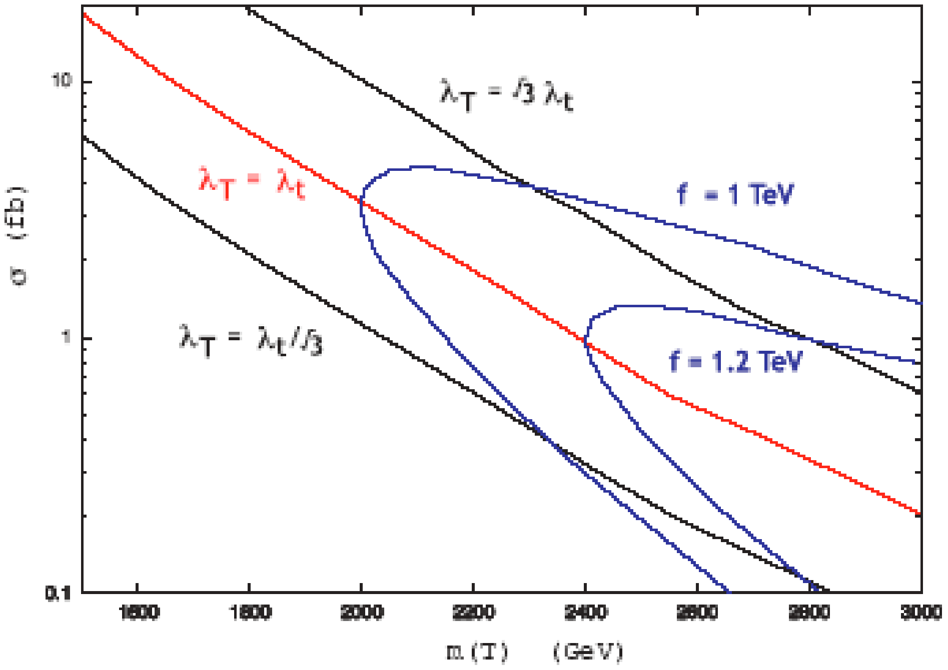
Confirmation of the Higgs with a (bb) resonance in an exotic channel would be truly remarkable discovery.

In the limit of $\sqrt{s} \gg 2m_T$, pair production is the dominant process. However, at the kinematic limits, single production can dominate and give the most effective search.

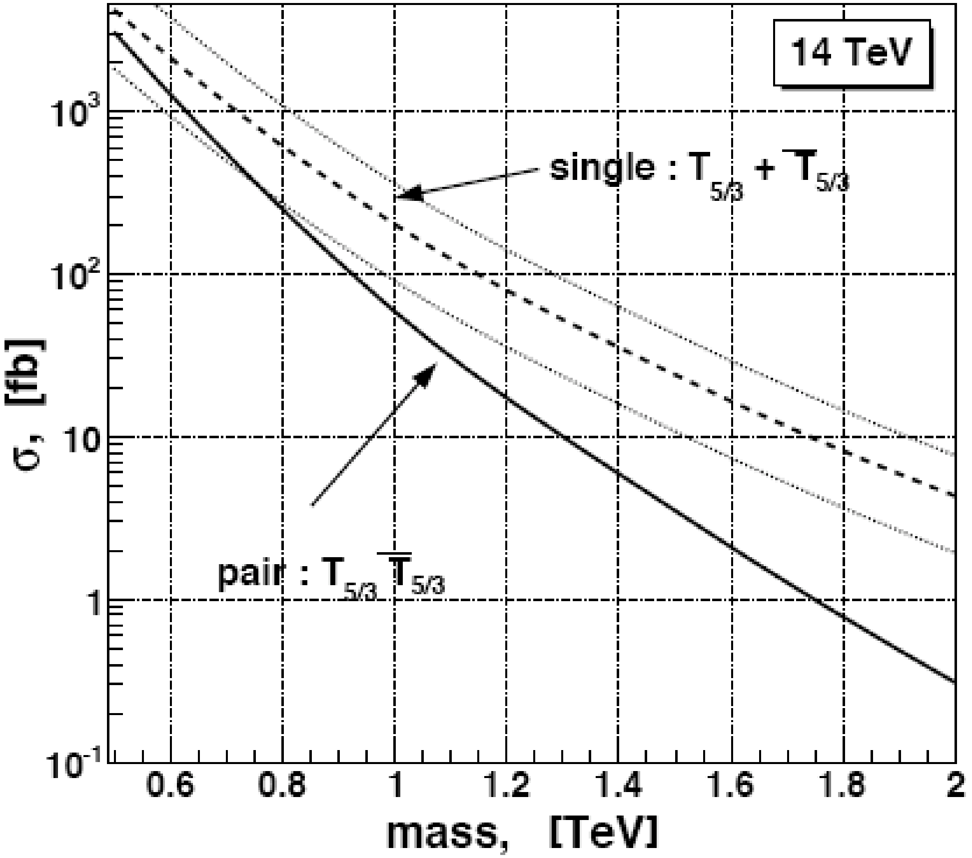
The most interesting reaction is



The final state is a centrally produced T plus a forward jet. A strategy is to identify a high-pT W, add a single jet or b-jet that gives approximate pT balance, and look for a resonance.



Pierce, Perelstein, MEP



Mrazek, Wulzer

(for $\mathcal{T}$, to be discussed)

Another possibility here is a vectorlike SU(2) doublet (T, B).

T and B must be close in mass: $\Delta m \sim \alpha_w M_T$
Again, the mass is not limited by unitarity bounds.

A decay effective Lagrangian is

$$\lambda_1 \bar{t}_R \epsilon_{ab} H_a \begin{pmatrix} T \\ B \end{pmatrix}_b + \lambda_2 \bar{b}_R H^\dagger \begin{pmatrix} T \\ B \end{pmatrix} + c.c.$$

I guess that λ_1 dominates; couplings of b_R are more constrained.
Then the decay pattern is

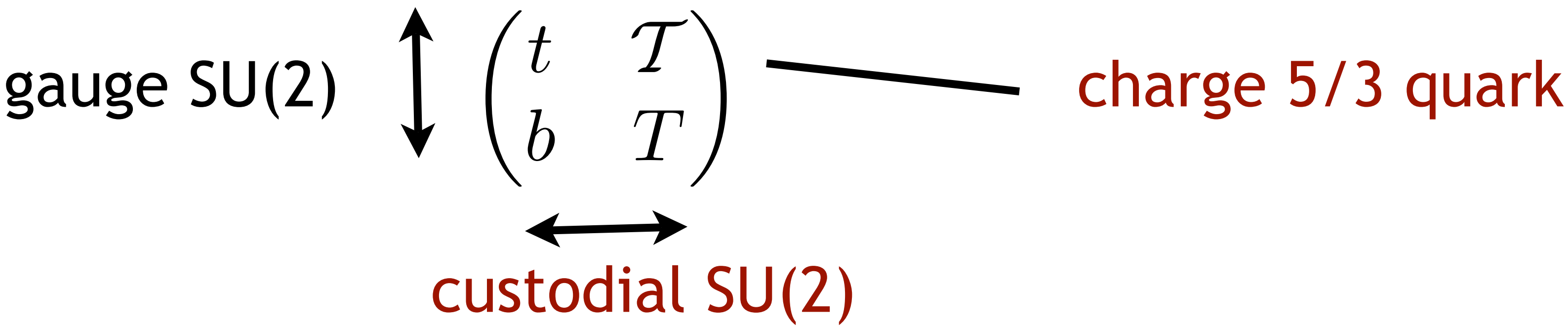
$$\begin{aligned} T &\rightarrow tZ^0 \qquad (50\%) \\ &\rightarrow th^0 \qquad (50\%) \\ B &\rightarrow tW^- \qquad (100\%) \end{aligned}$$

In the limit of SU(2)xU(1) symmetry, transverse W and Z do not mediate decays. However, mass mixing can add a decay like that of a sequential 4th generation quark ($T \rightarrow bW^+$), at a rate suppressed by $(m_t/M_T)^2$

Vectorlike quarks in other SU(2)xU(1) representations are also possible. Here is an interesting one.

Agashe, Contino, Da Rold, and Pomarol worried about the effect of radiative corrections from T on $\Gamma(Z \to b\bar{b})$. They identified a custodial symmetry that can forbid large corrections. This is an SU(2) that is unbroken at the stage where the T obtains mass.

The multiplet of vectorlike quarks is



$$\begin{pmatrix} t & \mathcal{T} \\ b & T \end{pmatrix}$$

gauge SU(2)

charge 5/3 quark

custodial SU(2)

$(\mathcal{T}, T)$ form an SU(2) isospin doublet, degenerate up to $\Delta m \sim \alpha_w M_T$

The effective Lagrangian for decay is

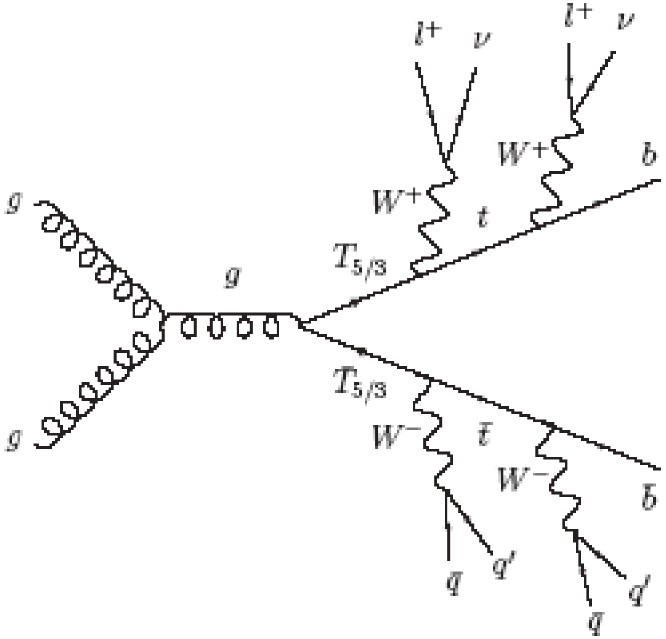
$$\lambda\, \bar{t}_R H^\dagger \begin{pmatrix} \mathcal{T} \\ T \end{pmatrix} + c.c.$$

which predicts the decay pattern

$$\begin{array}{ccll} \mathcal{T} & \to & tW^+ & \\ T & \to & tZ^0 & (50\%) \\ & \to & th^0 & (50\%) \end{array}$$

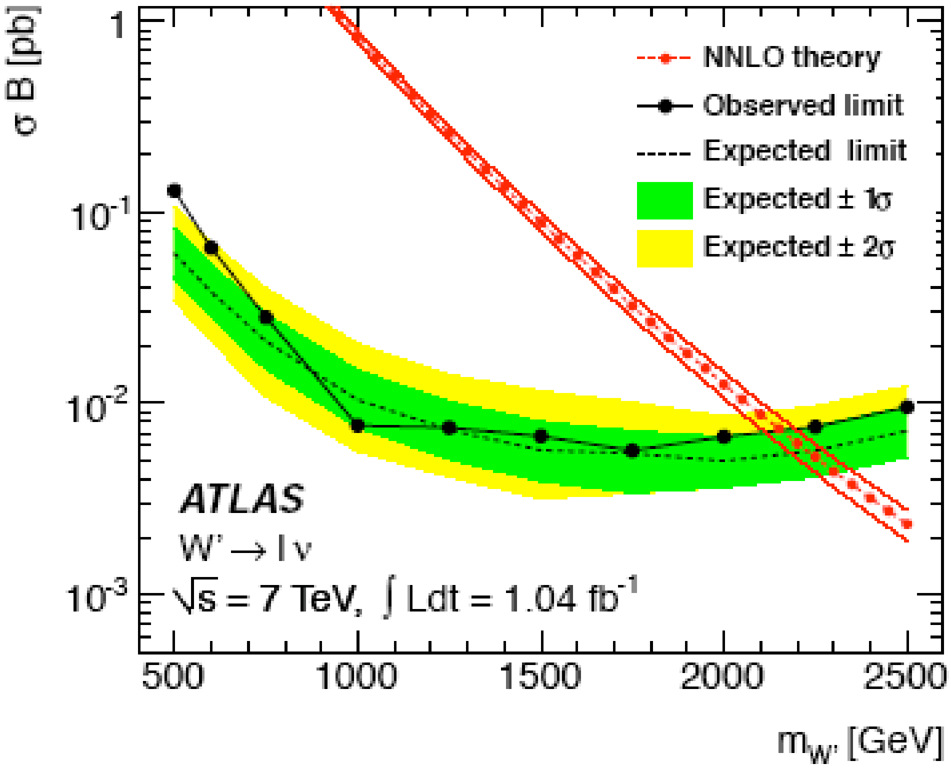
Decay of the $\mathcal{T}$ leads to remarkable like-sign dilepton events.

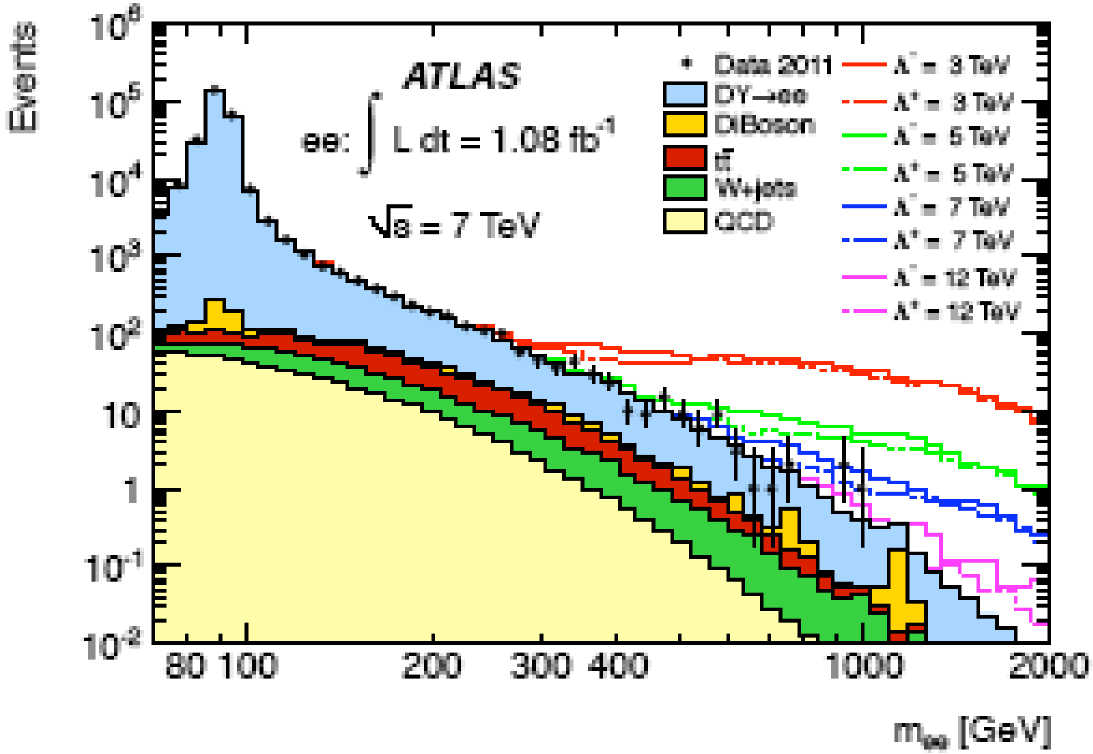
Contino and Servant (2010)
have discussed the reconstruction
of the $\mathcal{T}$ in these events.

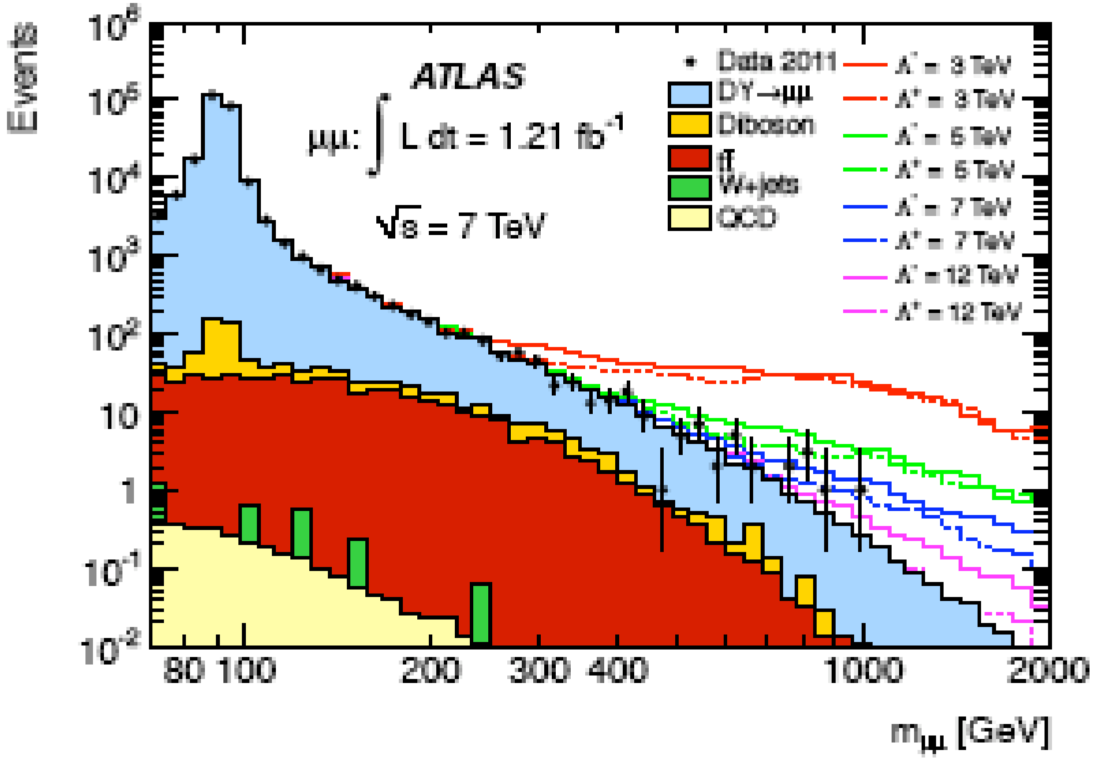


Next, consider higher-mass W, Z bosons.

There are of course sensitive searches for sequential W, Z. These can be reinterpreted as searches for KK W and Z bosons and related massive bosons.




ATLAS
ee: ∫ L dt = 1.08 fb⁻¹
√s = 7 TeV
Data 2011
DY→ee
DiBoson
tt̄
W+jets
QCD
Λ⁻ = 3 TeV
Λ⁺ = 3 TeV
Λ⁻ = 5 TeV
Λ⁺ = 5 TeV
Λ⁻ = 7 TeV
Λ⁺ = 7 TeV
Λ⁻ = 12 TeV
Λ⁺ = 12 TeV
Events
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
80
100
200
300
400
1000
2000
m_ee [GeV]


ATLAS
μμ: ∫ L dt = 1.21 fb⁻¹
√s = 7 TeV
Data 2011
DY→μμ
Diboson
tt̄
W+jets
QCD
Λ⁻ = 3 TeV
Λ⁺ = 3 TeV
Λ⁻ = 5 TeV
Λ⁺ = 5 TeV
Λ⁻ = 7 TeV
Λ⁺ = 7 TeV
Λ⁻ = 12 TeV
Λ⁺ = 12 TeV
Events
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
80
100
200
300
400
1000
2000
m_μμ [GeV]

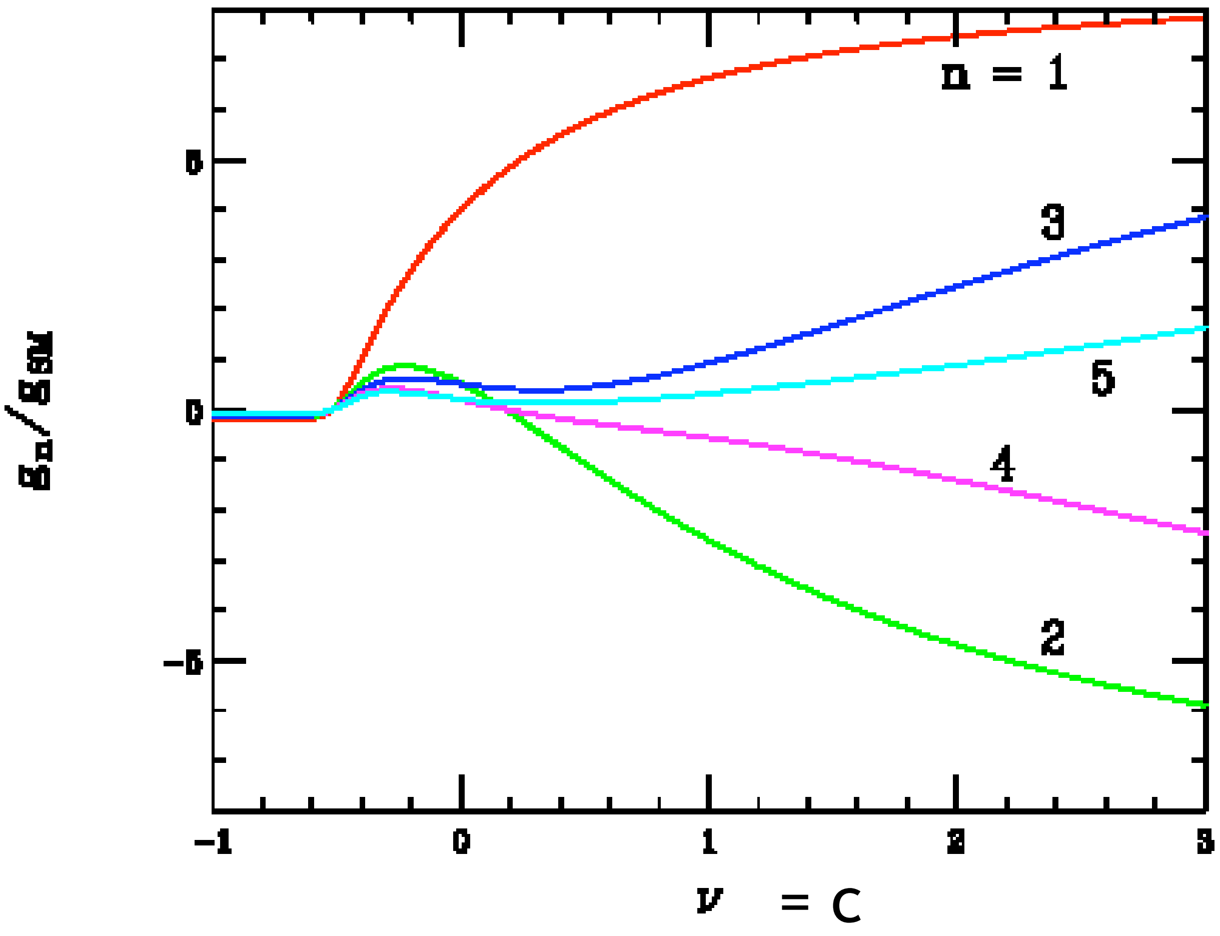
We are interested in the production of excited or KK W and Z bosons from initial $q\overline{q}$ pairs through vector and axial currents. The main question is the strength of the coupling.

For KK W and Z, this is a geometrical question, having to do with the form of the wavefunctions and their overlap.

Here is the answer in a particular Randall-Sundrum model:

Davoudiasl, Hewett, Rizzo

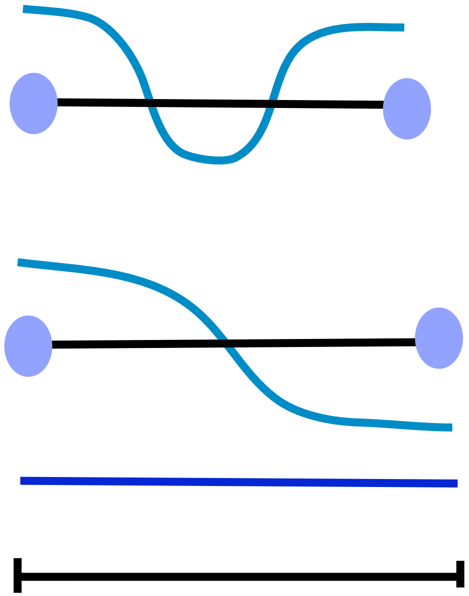
Large enhancements are possible, but, for searches, we are particularly concerned about suppressions.



The situation is particularly clear in the case of a flat extra dimension. Light quarks and leptons have wavefunctions that are flat in the extra dimension. But KK states with n > 0 have nontrivial wavefunctions. In the simplest case, these wavefunctions are orthogonal to the constant mode. A parity symmetry $x^5 \rightarrow -x^5$ can enforce absolute orthogonality.

However, even with a parity symmetry, the suppression of the coupling to a level-2 resonance not absolute. Radiative corrections generate some boundary terms, e.g.,

$$\int_{\partial M} d^3x \ (F_{\mu\nu})^2$$



These permit the 0+0 -> 2 transitions with suppressed stregth,

$$\mathcal{O}(\epsilon g) \quad \epsilon \sim 0.1 - 0.3$$

The coupling parameter ϵ comes squared in the prodution rate, and it is squared again if are searching a dilepton or light quark final state, e.g. $u\bar{d} \to W' \to \ell\nu$.

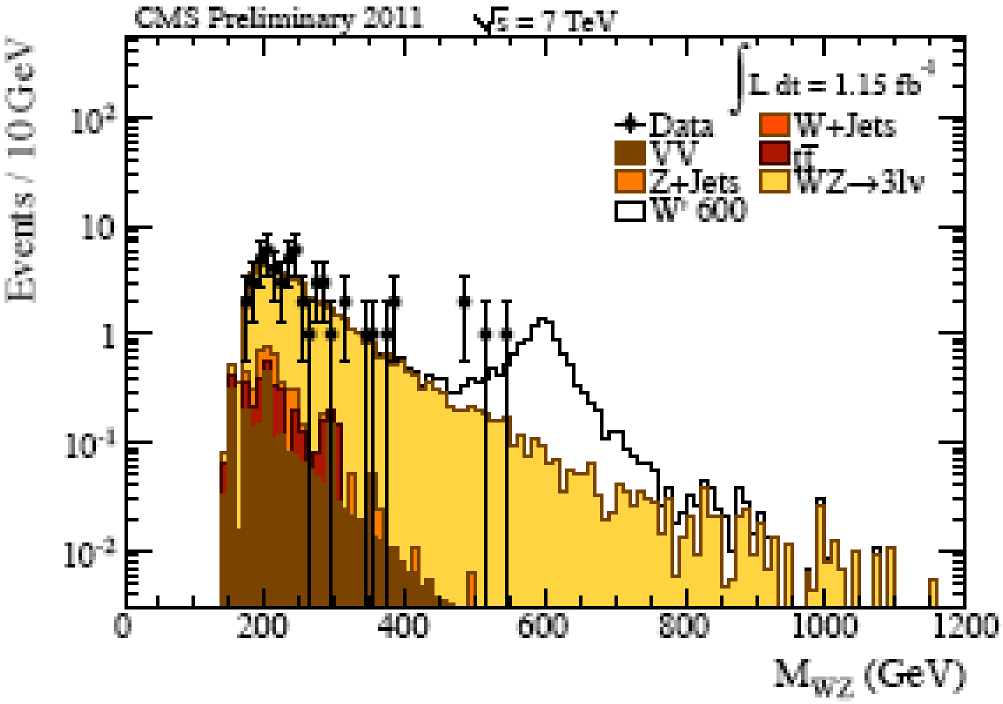
Thus, it is relevant and even important to search for resonances in Drell-Yan with sensitivity $10^{-2} - 10^{-3}$ of the cross section for a sequential W or Z.

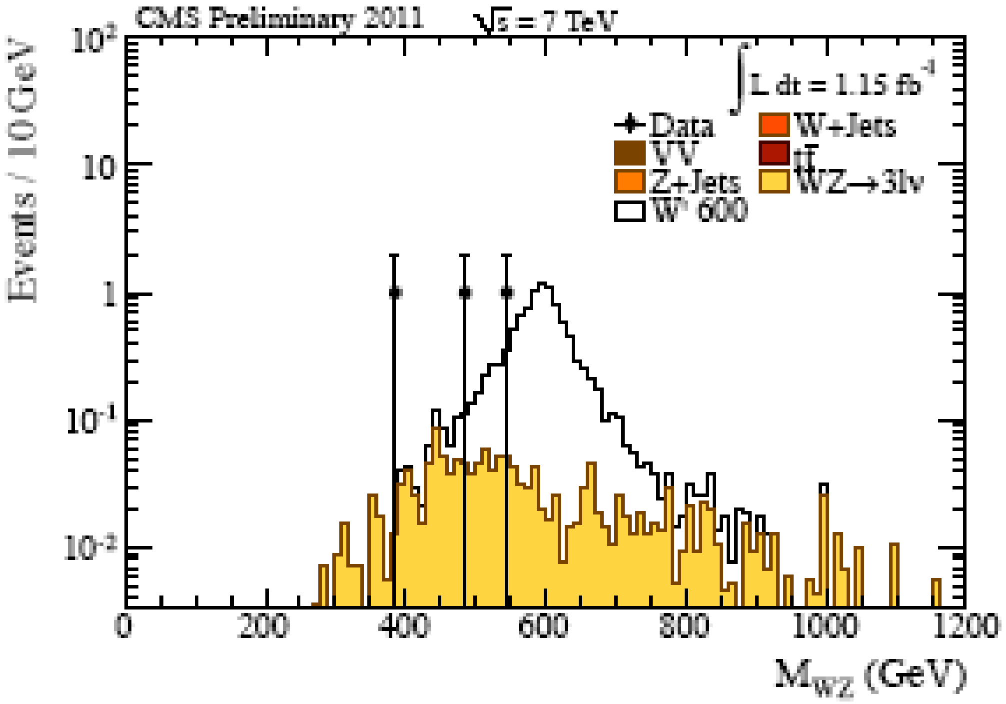
If m_μ / m_e is explained, as in RS theory, by wavefunction overlaps of the leptons and Higgs bosons, we expect different couplings of the heavy W or Z to $\mu \; vs. \; e$. Thus, it is not correct in general to assume μ/e universality.

If W', Z' do not decay to light quarks and leptons, what do they decay to ? The philosophy of Agashe, Contino, Grojean, Sundrum, and others working in this area is that these bosons should decay to states that are "more composite", in particular, W, Z, top.

RS models give a concrete picture of this. The wavefunctions of W, Z, top are nontrivial, peaking near the weak brane.

This motivates resonance searches in 2 vector bosons. The most sensitive public one is from CMS:



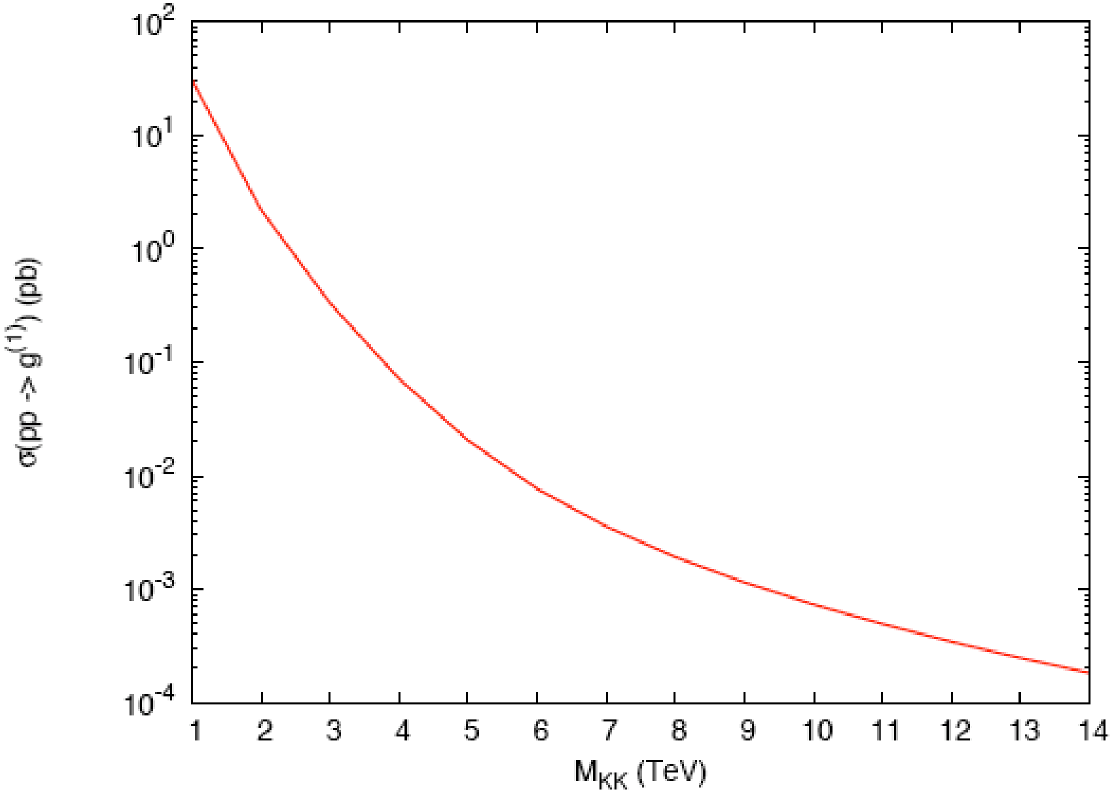


w. minimum

$$H_{T\ell} = \sum_{\ell} E_{T\ell}$$

A particularly interesting final state is $t\bar{t}$. We might expect KK W and Z states to decay to $t\bar{t}$. But, also, color octet KK states such as the KK excitations of the gluon can be found in .

In principle, the cross sections are not forbidding for very high mass KK gluons. The problem is to reduce QCD background by identifying top in the decays. It is in this context that the new boosted top taggers were first analyzed.



Lillie, Randall, Wang (2007)

I explained in the previous lecture that, in RS models, the specifically must have a wavefunction shifted closer to the weak brane.   Thus, composite bosons (Z and g) decaying to top quarks decay mainly to $t_R\bar{t}_L$.

Boosted polarized top quarks can be recognized by their momentum splitting between b and W. In particular, t_R and $\bar{t}_L$ decay to a higher-energy W and a lower-energy b

$$\frac{d\Gamma}{dz_W} \sim 2m_W^2 + z_W(m_t^2 - 2m_W^2)$$

The examples that I have given are still quite straightforward in the sense that quarks and leptons are considered separately and ordered by generation. More imaginative possibilities have been considered in the literature. Here is one, due to Agashe and Servant:

Represent each generation by 3 16-dimensional multiplets of SO(10), using an orbifold projection to give a single set of light fermions. The particle content for each generation is

$$\left(\begin{matrix} \mathbf{u_L} \ , \mathbf{d_L} \\ u'^c_R \\ d'^c_R \\ \nu'_L \ , e'_L \\ e'^c_R \\ \nu'^c_R \end{matrix}\right)_{B=1/3} , \quad \left(\begin{matrix} u'_L \ , d'_L \\ \mathbf{u^c_R} \\ \mathbf{d^c_R} \\ \nu'_L \ , e'_L \\ e'^c_R \\ \nu'^c_R \end{matrix}\right)_{-1/3} , \quad \left(\begin{matrix} u'_L \ , d'_L \\ u'^c_R \\ d'^c_R \\ \boldsymbol{\nu}_{\mathbf{L}} \ , \mathbf{e_L} \\ \mathbf{e^c_R} \\ \boldsymbol{\nu}^{\mathbf{c}}_{\mathbf{R}} \end{matrix}\right)_{0}$$

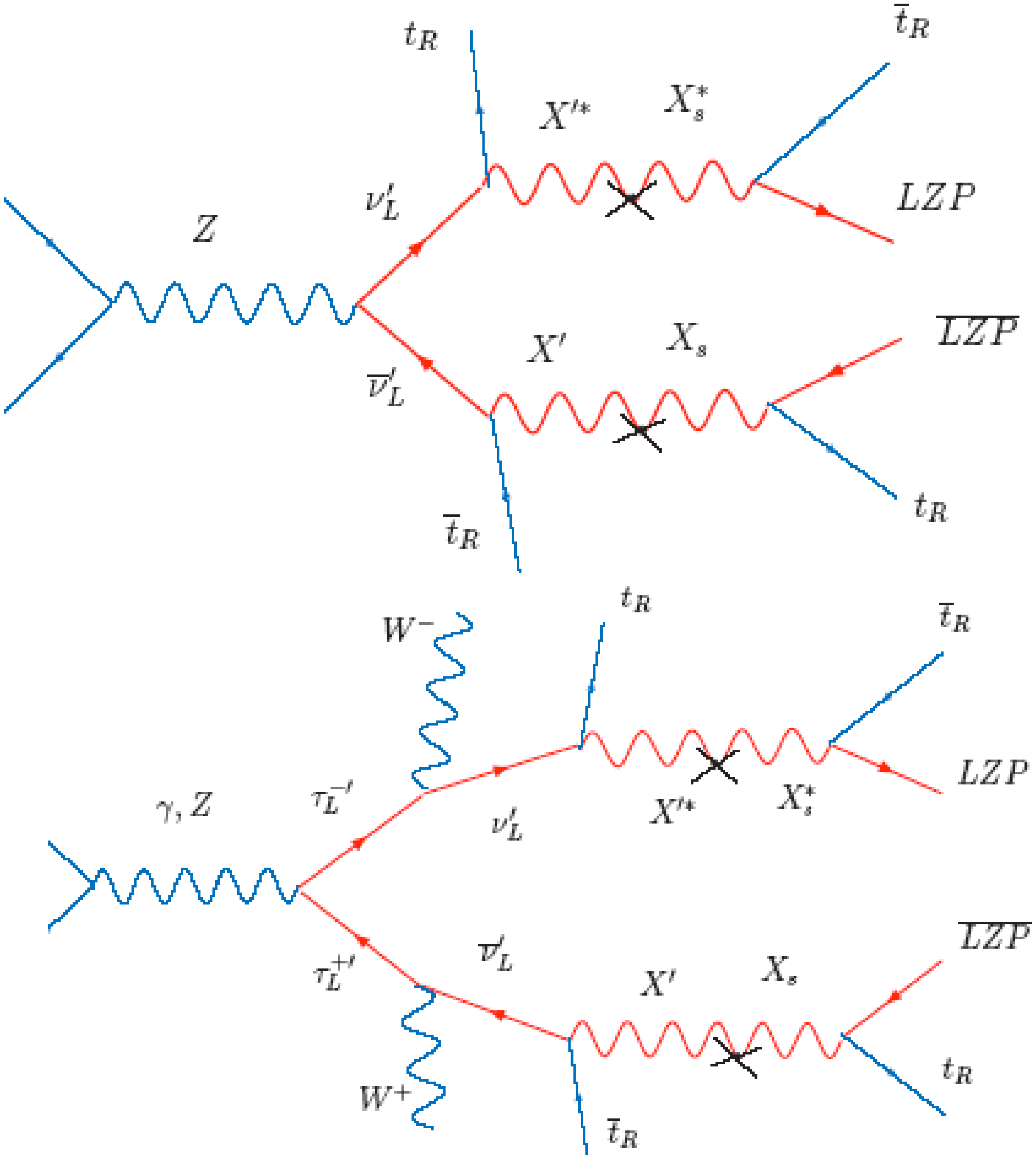
where boldfaced entries have zero models and baryon number is assigned as shown.

Note that many particles with the wrong baryon number appear. These particles are not necessarily at the GUT scale; they have KK states at the TeV scale. So we need an additional Z_3 discrete symmetry to protect against proton decay.

The lightest particles carrying this Z_3 quantum number will be stable. In this model, the n=1 KK fermions are lighter than the n=1 KK gauge bosons. The lightest states with Z_3 charge are (3rd generation) neutrinos. These provide WIMP dark matter with masses in the hundred of GeV.

Within this structure, color 3 and color singlet states are connected by KK gauge bosons with TeV masses.

This leads to a variety of unusual processes, for example:



with transitions mediated by emission of W, Z, t

Agashe, Falkowski, Low, Servant

This will get much crazier if I do not stop here.

The morals are:

It is necessary to think differently about particles that do not receive mass from the Higgs vacuum expectation value. More standard searches apply, but their results must be reinterpreted.

Effective Lagrangians with manifest SU(2)xU(1) symmetry are very useful in analyzing the properties of these particles.

Predicted decays and transitions typically emit W, Z, top. Boosted particle methods will be very useful in these contexts.

We dont know what is out there. If you use your imagination, you have as good a chance as anyone to perform the unexpectedly correct search.

Good luck!