New (and not so new) Z′ Gauge Bosons and the LHC/ILC Connection

Tim M.P. Tait

Argonne National Laboratory

LHC/ILC Fermilab
April 13, 2007

Outline

- Introduction / Motivation
- Effective theory for a Z'
- The Z' Zoo
- How LHC sees a Z'
- How ILC sees a Z'
- Outlook

Why a Z′?

- A new gauge boson is an obvious extension of the SM.
- The search for a Z′ is the search for a new force. It is just as natural to wonder if there should be new gauge forces as it is to wonder if there are new heavy forms of matter.
- A new gauge symmetry is telling us the structure of the high energy theory. It is a strong constraint on whatever kind of new physics leads beyond the weak scale, and it has profound implications for how we will describe that (and higher) energy regimes.

Z′ Effective Theory

- To describe a new neutral U(1) gauge boson, we write down an effective theory consistent with the SM gauge symmetries + the new U(1) symmetry.

- There is the possibility of kinetic mixing between the new U(1) and $U(1)_Y$:

$$\mathcal{L}_K = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{\chi}{4}B_{\mu\nu}Z^{\mu\nu}$$

(If there is non-SM matter charged under both hypercharge and the new U(1), it will induce non-zero kinetic mixing χ through loops.)

- We spontaneously break the U(1) symmetry with a new scalar which gets a VEV u:

$$M_{Z'}^2 = \frac{g_{Z'}^2}{8}u^2$$

(If the Higgs is charged under the new U(1) there are also electroweak symmetry-breaking contributions to $M_{Z'}$ and possible Z′-Z mixing through the mass matrix)

- We must choose charges for the SM fields (and any other fields in the theory):

$$\mathcal{L} \supset \sum_f z_f g_{Z'} Z'_\mu \bar{f}\gamma^\mu f$$

fermion-specific charge

The Z′ Zoo

The Regal Z′

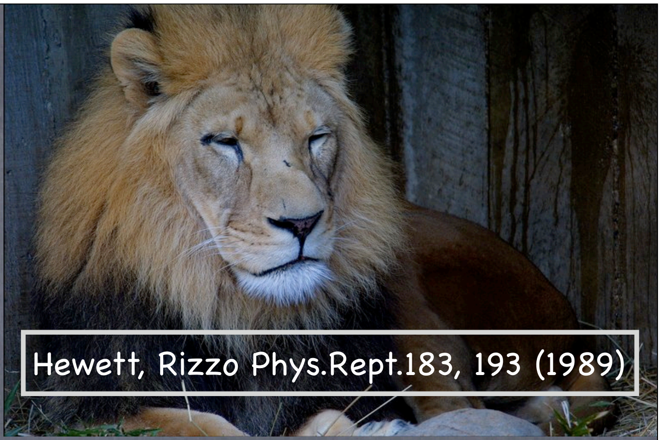
- A well-motivated example of a Z′ comes from embedding the SM into a large GUT symmetry such as SO(10) or E_6.

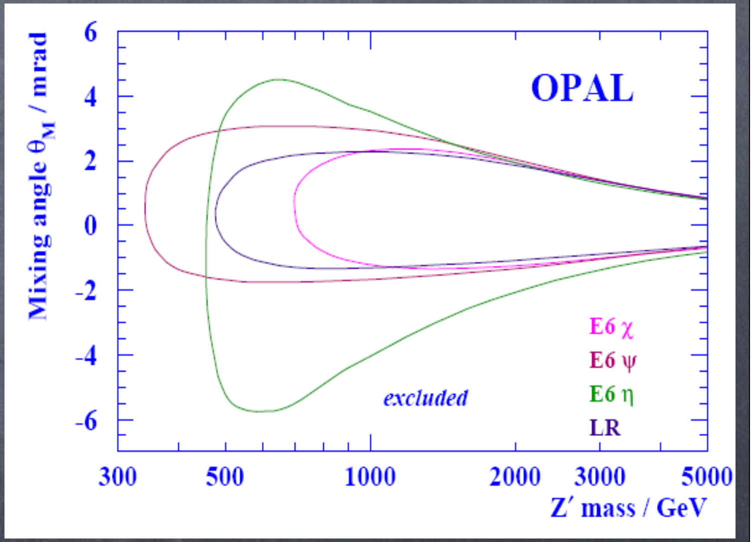
- Their discovery would tell us a lot about the structure of Grand Unification. Their couplings may be somewhat confusing because of mixing between several U(1)'s descending from the GUT.

- The embedding in the larger gauge group usually forbids large kinetic mixing. SM matter charges are usually of order one (they can be predicted from the embedding in the GUT).

- This means generically these models have Z-Z′ mixing which can induce large corrections to the EW precision data.

- In two Higgs doublet models, the mixing (and thus constraints) can be made small by balancing the mixing effect of one Higgs against the other.





Sabine Riemann, NWU mini-workshop on Z's

The Sophisticated Z′

i.e. "The Littlest Higgs"
Arkani-Hamed, Cohen, Katz, Nelson JHEP 0207, 034 (2002)

- Little Higgs theories make use of (at least one) Z′ to cancel quadratic divergences to the Higgs mass at one loop, by invoking a spontaneously broken global symmetry. The SM Higgs is a pseudo-Goldstone boson resulting from the symmetry-breaking.

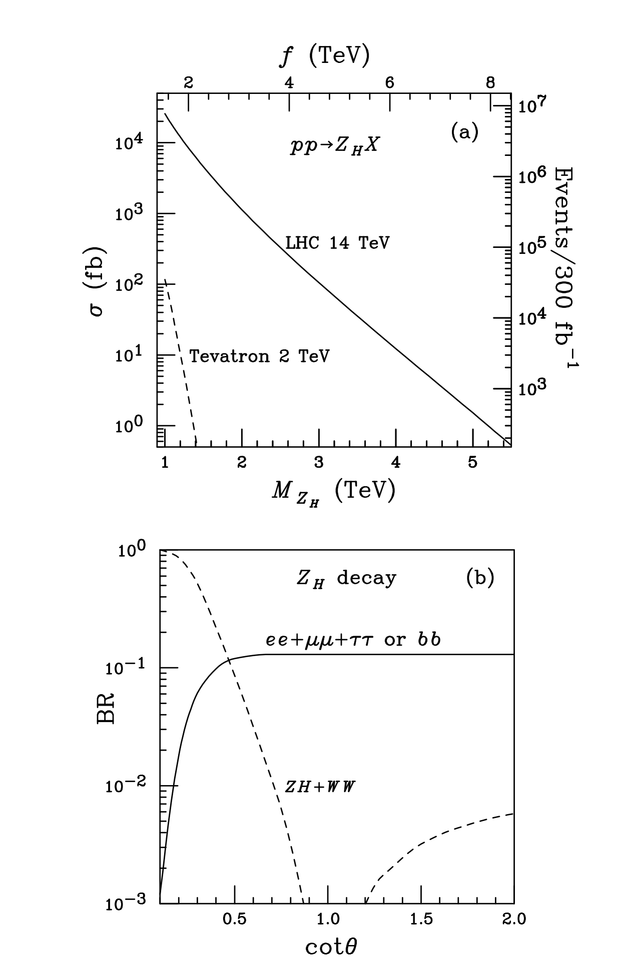
- There is a lot of model-dependence in the Z′ couplings. In models without T-parity, the SM fermions and the Higgs generically couple to the Z′.

- In the Littlest Higgs, the high scale symmetry contains SU(2) x SU(2) x U(1) x U(1). There are two massive neutral bosons, A_H and Z_H.

- Our weak interactions are identified as the diagonal sub-group, and we parameterize the couplings as:

$$g_1 = \frac{g_W}{\sin\theta} \qquad g_2 = \frac{g_W}{\cos\theta}$$

(and likewise for the U(1)...)



Han, Logan, McElrath, Wang PRDD67, 095004 (2003)

The Quiet Z′

Kumar, Wells PRD74, 115017 (2006)

- Another interesting phenomenological limit has kinetic mixing, but no underlying charges for the SM fields.

$$\mathcal{L}_K = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{\chi}{4}B_{\mu\nu}Z^{\mu\nu}$$

- The kinetic terms can be diagonalized by the redefinition,

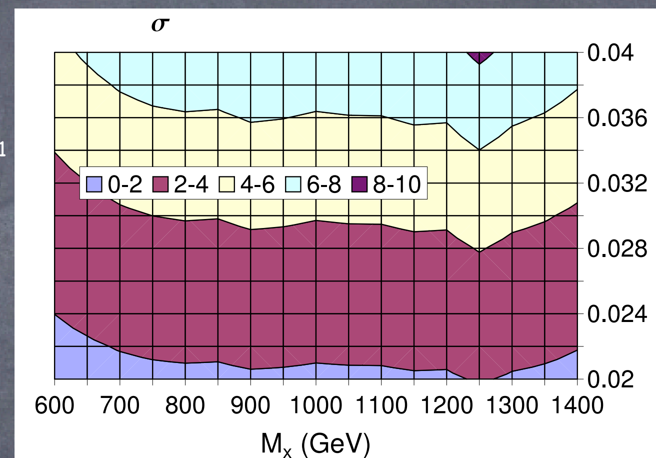
$$\begin{bmatrix} Z_\mu \\ B_\mu \end{bmatrix} = \begin{bmatrix} \sqrt{1-\chi^2} & 0 \\ -\chi & 1 \end{bmatrix} \begin{bmatrix} \hat{Z}_\mu \\ \hat{B}_\mu \end{bmatrix}$$

- This induces couplings to the SM proportional to hyper-charge:

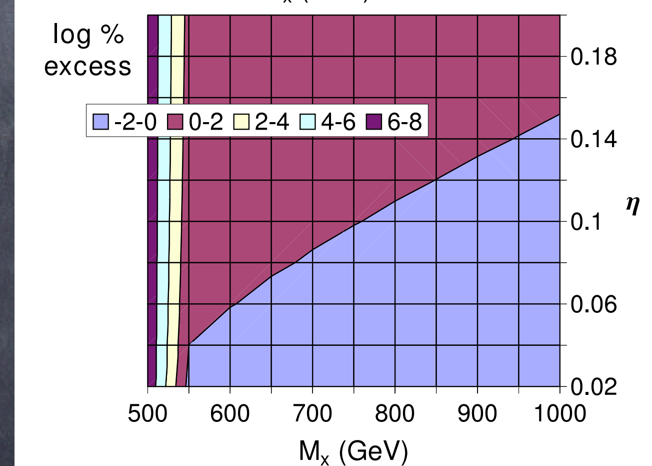
$$g_Y \frac{\chi}{\sqrt{1-\chi^2}} Y_f \equiv g_Y \eta Y_f$$

- (but perhaps with a small coefficient, for example if χ is induced at the loop level from some exotic matter charged under both the new U(1) and the SM).

- The hyper-charge proportionality makes a definite prediction for BRs, etc.



Significance at LHC, 100 fb^{-1}



Deviation in $\mu^+\mu^-$ at ILC, 500 fb^{-1}

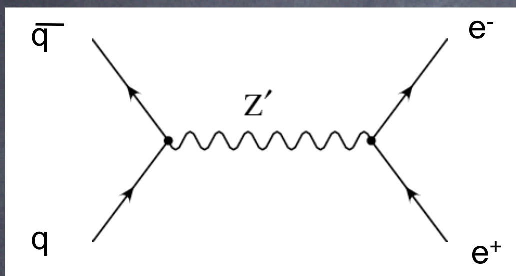
The Eclectic Z′

- A final possibility that occurs is a Z′ which couples differently to different families.
- A well motivated example comes from Top-color, which uses the gauge dynamics of a U(1) that prefers to couple to the third family to select the right vacuum for electroweak symmetry-breaking.
- Such Z′s have interesting decay modes into (i.e.) third family fermions, appearing as resonances into tops, bottoms, and/or taus.
- They run the risk of inducing FCNCs when we rotate quarks from the gauge to the mass basis.

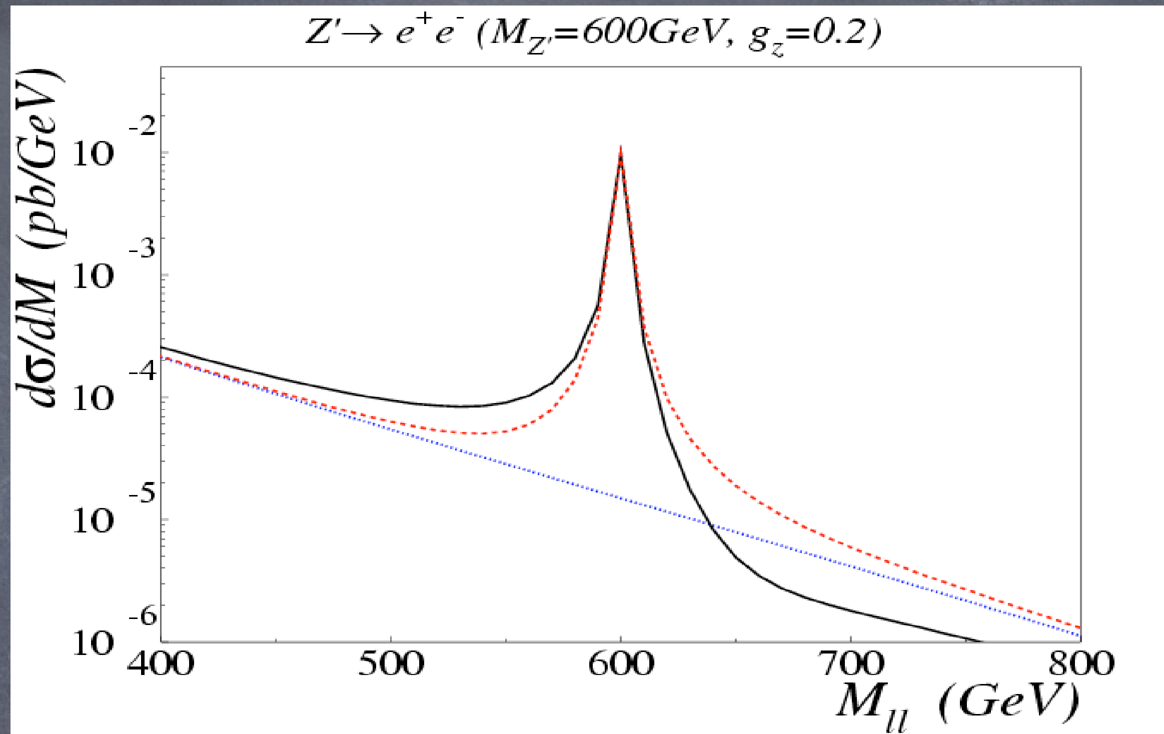
$$(\bar{d} \;\; \bar{s} \;\; \bar{b}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_Z \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \rightarrow (\bar{d}' \;\; \bar{s}' \;\; \bar{b}') \begin{pmatrix} & & \\ & U^\dagger & \\ & & \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_Z \end{pmatrix} \begin{pmatrix} & & \\ & U & \\ & & \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

- RS models have low energy effective theory descriptions which gauge bosons that also tend to prefer to couple more strongly to the third generation.

How the LHC sees a Z′



Carena, Daleo, Dobrescu, Tait
PRD70, 093009 (2004)



- The LHC directly produces a Z′, seeing (for example) a resonance in leptons.
- Leptons are a nice clean signal, with reasonably small backgrounds at large invariant mass.
- Other channels may also be available if we're lucky!

Cross Section at the LHC

- Assuming flavor-universal couplings and a narrow width, we write the cross section into leptons at a hadron collider as:

$$\sigma\left(pp \to Z' X \to \ell^+ \ell^- X\right) \quad = \quad \frac{\pi}{48s}\left[c_u w_u + c_d w_d\right]$$

- The w's contain the QCD information, including PDFs (this factorization works to NLO QCD and receives small corrections at NNLO).

Carena, Daleo, Dobrescu, Tait
PRD70, 093009 (2004)

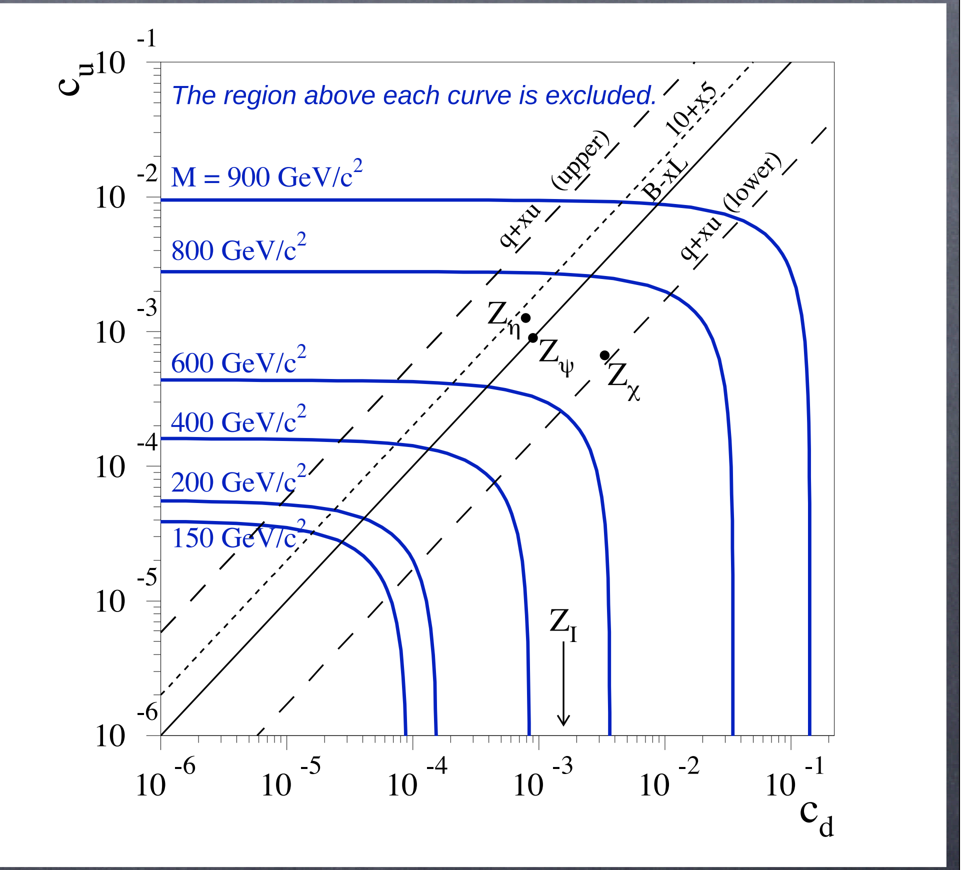
- The c's contain all of the Z' model-specific stuff:

$$\begin{aligned} c_u &\equiv \left(z_q^2 + z_u^2\right) BR\left(Z' \to \ell^+ \ell^-\right) \\ c_d &\equiv \left(z_q^2 + z_d^2\right) BR\left(Z' \to \ell^+ \ell^-\right) \end{aligned}$$

Z's at the LHC

200 pb^{-1}

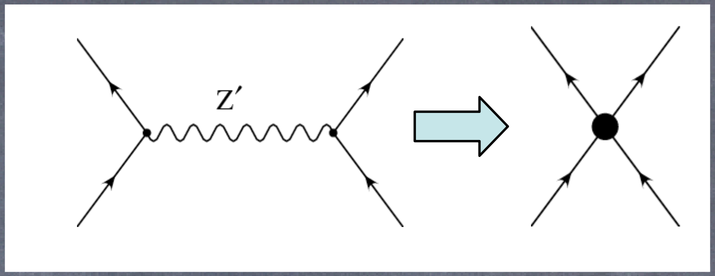
- Seeing a Z' at a hadron collider will eventually tell us the mass, the width (if very large), and cu and cd.
- Some kinematic observables and/or higher order processes can help break the degeneracy in c_u and c_d, but this needs more study.



CDF, PRL95, 252001 (2005)

How the ILC sees a Z′

- Presumably (at least to begin with) the ILC operates below the Z′ mass. In that regime, it does not produce the resonance directly, but instead sees it as an effective 4-point interaction.



- ILC doesn't really directly access the mass, or width, (or gauge coupling):

$$\frac{g_{Z'}^2}{s - M_{Z'}^2} \left[\bar{e}\gamma_\mu (z_l P_L + z_e P_R) e\right] \left[\bar{f}\gamma^\mu (z_{f_L} P_L + z_{f_R} P_R) f\right]$$

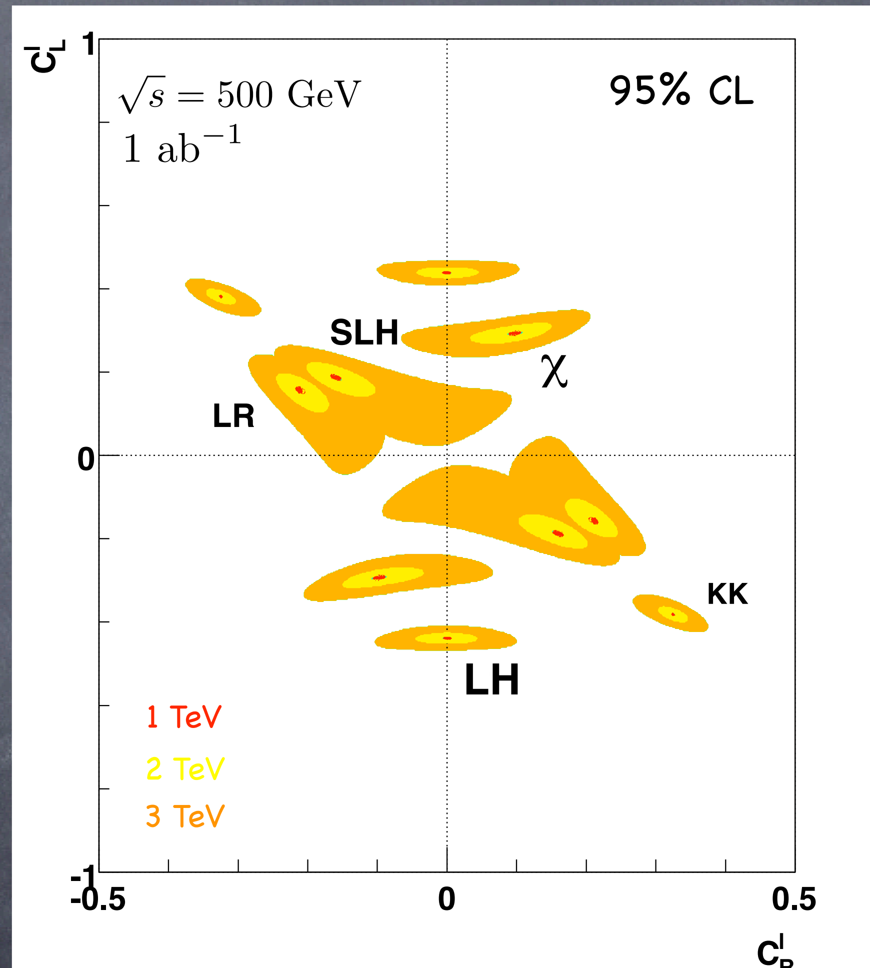
$$\rightarrow -\frac{1}{u^2}\left(1 + \frac{s}{M_{Z'}^2} + \ldots\right) \left[\bar{e}\gamma_\mu (z_l P_L + z_e P_R) e\right] \left[\bar{f}\gamma^\mu (z_{f_L} P_L + z_{f_R} P_R) f\right]$$

- But it can probe high mass scales and measure the charges very cleanly...

Z′s at the ILC

Godfrey, Kalyniak, Tomkins
ILC-2005 talk [hep-ph/0511335]

- Using a variety of observables and beam polarization, the ILC can discriminate between Z′ models by studying (i.e.) the coupling to left- versus right-handed leptons.
- (C′s in this plot are just coupling factors with the gauge coupling extracted).
- Note degeneracies when both couplings flip sign together.

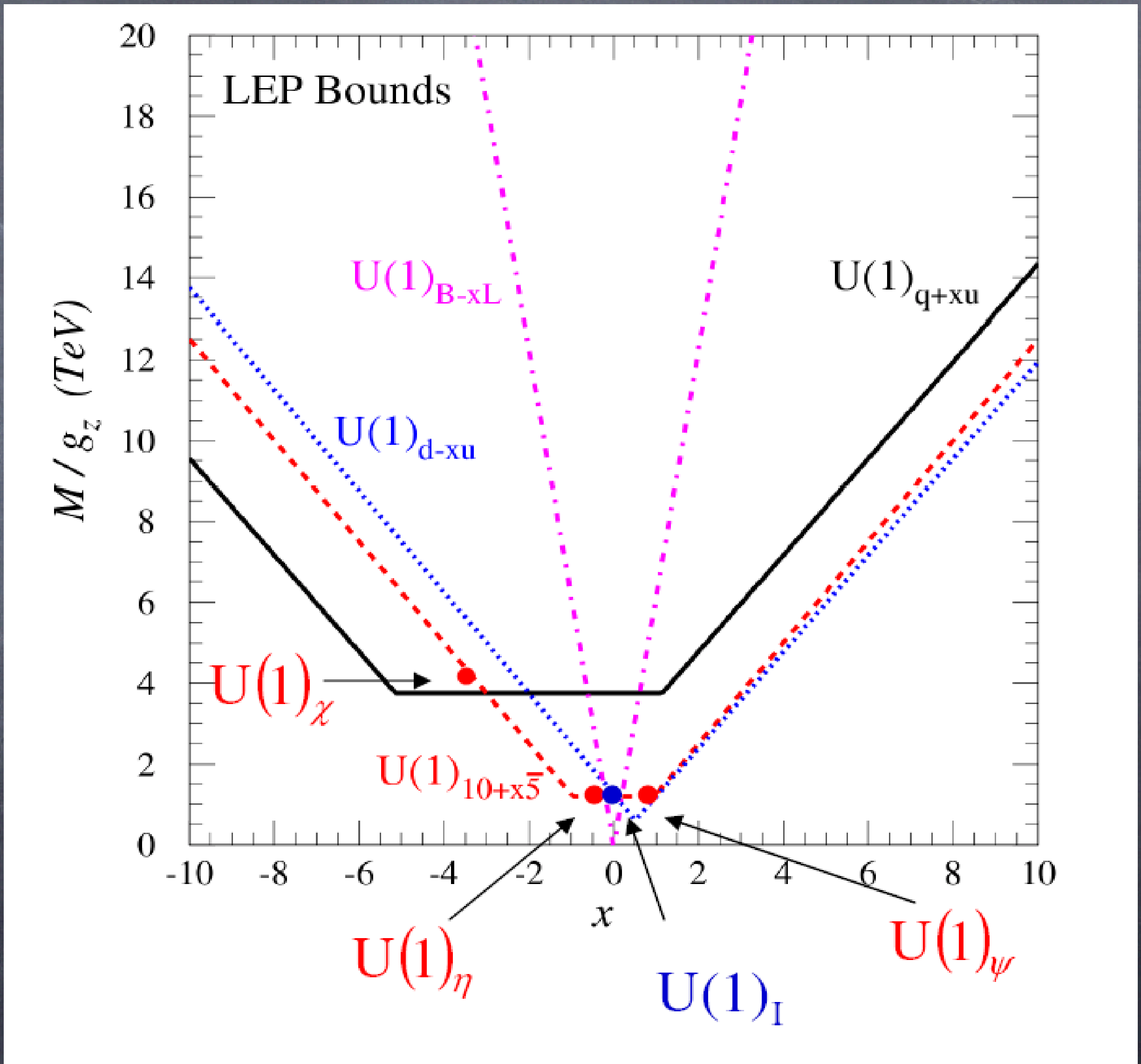


Outlook

- Z's are really cool!
- There are many different types, with different motivations, implications, and signatures. We need to be ready for a plethora of possibilities!
- At the LHC, we can access the mass and gauge coupling, and some combinations of charges.
- At the ILC (far below threshold) we get the fermion charges
- The two are perfectly complementary!

Supplemental Slides

LEP II Bounds



Carena, Daleo, Dobrescu, Tait
PRD70, 093009 (2004)

Anomaly Cancellation

$$SU(3)_C^2 - U(1)_Z \to A_{33Z} = 3\left(2z_q - z_u - z_d\right) \qquad SU(2)_W^2 - U(1)_Z \to A_{22Z} = \left(9z_q + \sum_{j=1}^{3} z_{L_j}\right)$$

$$U(1)_Y^2 - U(1)_Z \to A_{YYZ} = \left(2z_q - 16z_u - 4z_d + 2\sum_{j=1}^{3}\left(z_{L_j} - 2z_{e_j}\right)\right)$$

$$U(1)_Z^2 - U(1)_Y \to A_{ZZY} = \left(6\left(2z_q^{\ 2} - 2z_u^{\ 2} + z_d^{\ 2}\right) - 2\sum_{j=1}^{3}\left(z_{L_j}^{\ 2} - 2z_{e_j}^{\ 2}\right)\right)$$

$$U(1)_Z^3 \to A_{ZZZ} = 9\left(2z_q^3 - z_u^3 - z_d^3\right) + \sum_{j=1}^{3}\left(2z_{L_j}^{\ 3} - z_{e_j}^{\ 3} - z_{\upsilon_j}^3\right)$$

Carena, Daleo, Dobrescu, Tait
PRD70, 093009 (2004)

New fermions can help cancel anomalies, requiring them to be charged under some of the SM gauge interactions.

Model Lines

Carena, Daleo, Dobrescu, Tait
PRD70, 093009 (2004)

	B-xL	Q+xu	10+x5	d-xu
$q_L=(u_L,d_L)$	+1/3	+1/3	+1/3	0
u_R	+1/3	$+x/3$	-1/3	$-x/3$
d_R	+1/3	$(2-x)/3$	$-x/3$	+1/3
$l_L=(e_L,\nu_L)$	$-x$	-1	$+x/3$	$(x-1)/3$
e_R	$-x$	$-(2+x)/3$	-1/3	$+x/3$

x is a continuous parameter that defines the model.

b-couplings at the ILC