Z', γ'

Bogdan Dobrescu (*Fermilab*)

Nonexotic Z'

T. Appelquist, B. Dobrescu, A. Hopper: hep-ph/0212073

Nonanomalous $U(1)_z$ gauge symmetry *without* new fermions charged under $SU(3)_C \times SU(2)_W \times U(1)_Y$

Allow an arbitrary number of ν_R's

Assume:
- **generation-independent charges,**
- **quark and lepton masses from standard model Yukawa couplings**

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
q_L^i	3	2	$1/3$	z_q
u_R^i	3	1	$4/3$	z_u
d_R^i	3	1	$-2/3$	$2z_q - z_u$
l_L^i	1	2	-1	$-3z_q$
e_R^i	1	1	-2	$-2z_q - z_u$
ν_R^k , $k = 1, ..., n$	1	1	0	z_k
H	1	2	$+1$	$-z_q + z_u$
φ	1	1	0	1

$[SU(3)_C]^2 U(1)_z$, $[SU(2)_W]^2 U(1)_z$, $U(1)_Y [U(1)_z]^2$ and $[U(1)_Y]^2 U(1)_z$ anomalies cancel

Gravitational-$U(1)_z$ and $[U(1)_z]^3$ anomaly cancellation conditions:

$$\frac{1}{3}\sum_{k=1}^{n} z_k = -4z_q + z_u$$

$$\left(\sum_{k=1}^{n} z_k\right)^3 = 9\sum_{k=1}^{n} z_k^3$$

- For $n \leq 2$:

$z_1 = -z_2 \Rightarrow z_u = 4z_q \;\; \Rightarrow$ trivial or Y-sequential $U(1)_z$-charges

- For $n \geq 3$:

$U(1)_{B-L}$ charges: $z_1 = z_2 = z_3 = -4z_q + z_u$

or $z_1 = z_2 = -(4/5)z_3 = -16z_q + 4z_u = -4$

ν *masses: three LH Majorana,*
two dimension-7 and one dimension-12 Dirac operators,
RH Majorana ops. of dimension ranging from 4 to 13

or ...

In general: Z' **mixes with** Z

$\Rightarrow$ **LEP I requires** $M_{Z'} \gtrsim 2\ \mathrm{TeV}$

Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

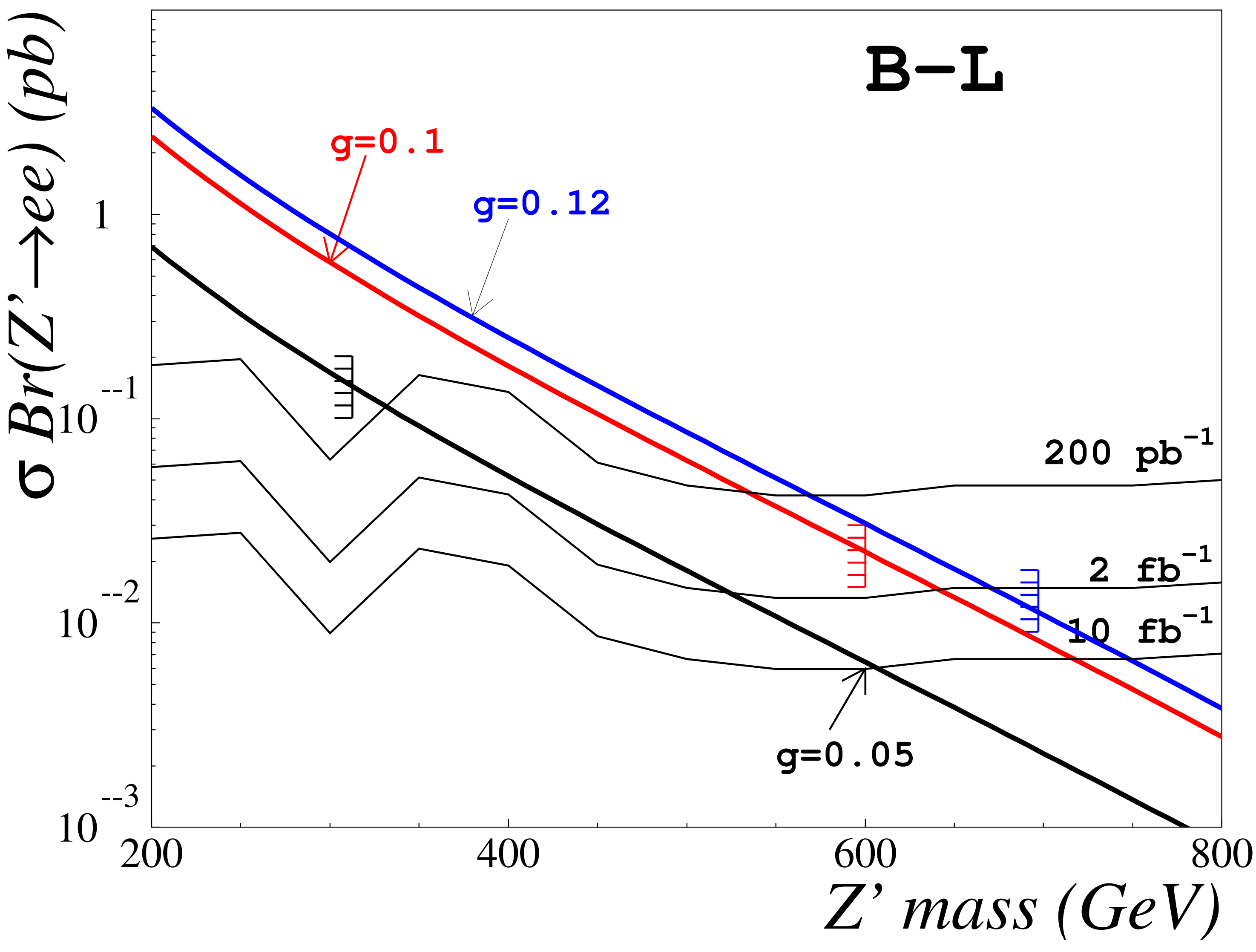
$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} \quad \Longrightarrow \quad z_H = 0$$

No Z_{B-L}-Z mixing at tree level!

Best bounds on $z_l g_z$ come from limits on direct production at the Tevatron and at LEP II

M. Carena, A. Daleo, B. Dobrescu, T. Tait: hep-ph/0408098

Z' searches at the Tevatron:



More general charges are allowed in the presence of new fermions:

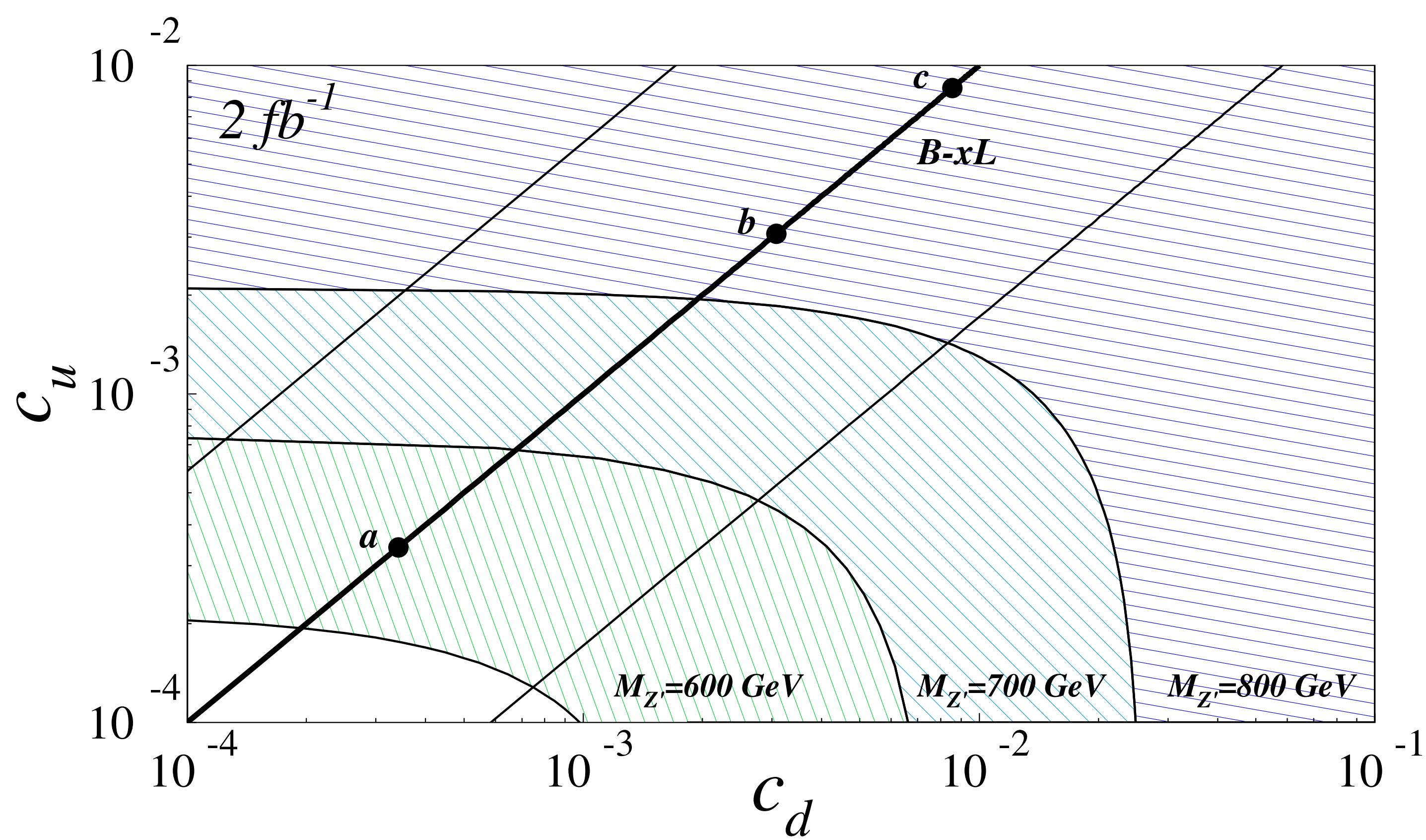
	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
q_L	3	2	$1/3$	$1/3$	$1/3$	$1/3$	0
u_R	3	1	$4/3$	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	3	1	$-2/3$	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν'_R				$\cdot$	$\cdot$	$-1-x/3$	$\cdot$
ψ^l_L	1	2	-1	-1	$\cdot$	$-(1+x)/3$	$-2x/5$
ψ^l_R				$-x$	$\cdot$	$2/3$	$(-1+x/5)/3$
ψ^e_L	1	1	-2	-1	$\cdot$	$\cdot$	$\cdot$
ψ^e_R				$-x$	$\cdot$	$\cdot$	$\cdot$
ψ^d_L	3	1	$-2/3$	$\cdot$	$\cdot$	$-2/3$	$(1-4x/5)/3$
ψ^d_R				$\cdot$	$\cdot$	$(1+x)/3$	$x/15$

A user-friendly parametrization:

$$\sigma\left(p\bar{p} \to Z'X \to l^+l^-X\right) = \frac{\pi}{48\,s}\left[c_u\, w_u\left(\frac{M_{Z'}^2}{s}, M_{Z'}\right) + c_d\, w_d\left(\frac{M_{Z'}^2}{s}, M_{Z'}\right)\right]$$

All the information about charges is contained in:

$$c_{u,d} = g_z^2\,(z_q^2 + z_{u,d}^2)\,\mathrm{Br}(Z' \to l^+l^-)$$



Could there exist

massless gauge bosons

other than the photon?

$U(1)_{B-L}$ is the only global symmetry of the standard model that can be gauged and unbroken.

Z_{B-L} coupling to ordinary matter: $N_n\, g_z$

(N_n = number of neutrons)

To avoid deviations from Newton's law:

$$g_z \ll \frac{m_n}{M_{\rm Pl}} \sim 10^{-19}$$

Tests of the equivalence principle: $g_z < 10^{-24}$

weaker limit if $B-L$ force is screened by ν's *(Okun, et al)*

But **even when** $z_q = z_u = z_d = z_l = z_e = 0$

there can still be interactions of the standard model fields with the new massless gauge boson:

higher-dimensional operators!

γ' couplings to leptons:

$$\frac{1}{M^2} P_{\mu\nu} \; (\bar{l}_L \sigma^{\mu\nu} C_e H e_R + \mathrm{h.c.})$$

C_e: 3×3 matrix in flavor space,

dimensionless parameters

γ' couplings to quarks: similar dimension-6 operators

In the mass eigenstate basis $C_e \to C'_e = U^e_L C_e U^{e\dagger}_R$

U^e_L and U^e_R are the unitary matrices that diagonalize the masses of the electrically-charged leptons.

• Interactions of the mass-eigenstate leptons with P^μ (chirality-flip operators $\sim v_h \approx 174$ GeV) :

$$\frac{v_h}{M^2} P_{\mu\nu} \overline{e'} \sigma^{\mu\nu} \left(\mathrm{Re}C'_e + i\,\mathrm{Im}C'_e \gamma_5\right) e'$$

$\rightarrow$ magnetic-like and electric-like dipole moments

$\mathrm{Re}(C'_e)^{ij}$, $\mathrm{Im}(C'_e)^{ij}$ **could have any value** $\lesssim 4\pi$ **, but:**

chirality-flip operators $\rightarrow$ **probably** $\left|(C_e)_{ij}\right| \lesssim \left|\lambda_e^{ij}\right|$

$$\Longrightarrow \quad \left|(C'_e)_{ij}\right| \lesssim \frac{m_\tau}{v_h} \approx 10^{-2}$$

$\left|(C'_e)_{11}\right|$ **may naturally be below** $m_e/v_h \approx 3 \times 10^{-6}$

Kinetic mixing of $U(1)_Y \times U(1)_z$ gauge bosons:

$c_0 B^{\mu\nu} P_{\mu\nu}$ **dimension-four operator!**

Holdom 1985:

Kinetic terms can be diagonalized and canonically normalized by a $SL(2,R)$ transformation.

Global $SO(2)$ symmetry: linear combination of $U(1)$ fields that couples to hypercharge is the real B^μ.

Orthogonal combination ("paraphoton" $= \gamma'$) does not have any renormalizable couplings to standard model fields.

Conclusion:
kinetic mixing has no effect on the standard model fields other than a renormalization of the hypercharge gauge coupling.

Bosonic interactions of the paraphoton:

$$\frac{1}{M^2} H^\dagger H \left(c_1 B_{\mu\nu} + \tilde{c}_1 \widetilde{B}_{\mu\nu} + c_2 P_{\mu\nu} + \tilde{c}_2 \widetilde{P}_{\mu\nu} \right) P^{\mu\nu}$$

- **renormalize the $U(1)$ gauge couplings**
- **include vertices with two $U(1)$ gauge bosons and Higgs bosons.**

These are all operators of $d \leq 6$ involving both γ' and Standard Model fields

The strength of the γ' interaction with the electrons depends on

$$c_e \equiv \frac{v_h}{m_e} \left| \left(C'_e \right)_{11} \right| \lesssim O(1)$$

Similar parameters defined for interactions such as $\mu^+\mu^-\gamma'$, $\mu^\pm e^\mp \gamma'$, ...

Various measurements set limits on these parameters.

Primordial Nucleosynthesis

Constraints on new particles with mass below several MeV.

Maximum number of new relativistic degrees of freedom:

$\Delta g_*^{\max} = \frac{7}{8} \Delta N^{\max}$; **at the** 2σ **level:** $\Delta N_\nu^{\max} \approx 0.6$

γ' **must go out of equilibrium at** $T_P > T_{\rm BBN} \approx 1$ **MeV**

Number of degrees of freedom contributed by γ' during BBN:

$$\Delta g_*(T_{\rm BBN}) = 2\left[\frac{g_*(T_{\rm BBN})}{g_*(T_P)}\right]^{4/3} \quad \longrightarrow \quad g_*(T_P) > \frac{20.0}{(\Delta N_\nu^{\rm max})^{3/4}} \gtrsim 30$$

Freeze-out temperature:

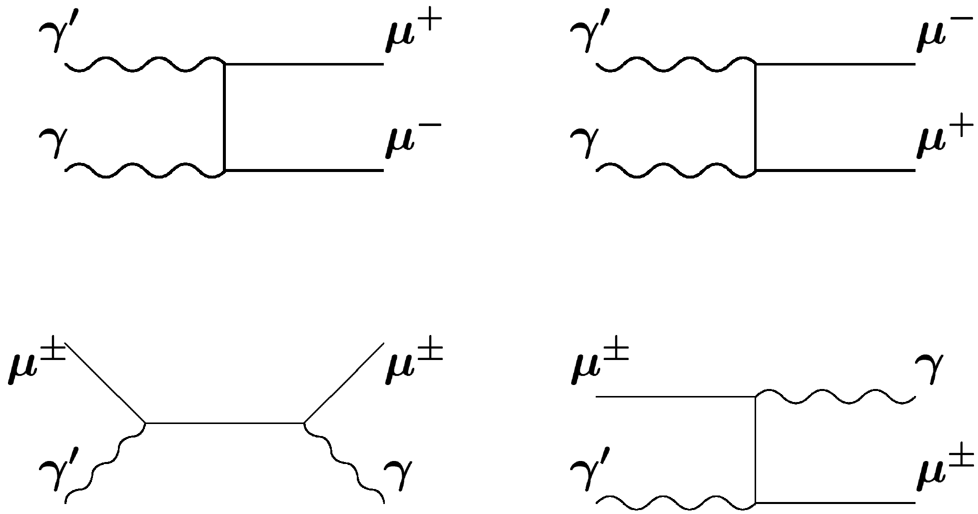
$$T_P > T_{\rm QCD} \approx 150 - 180 \text{ MeV}$$

$$g_*(T_P) = 247/4$$

(for $T_P \lesssim T_{\rm QCD}$: $g_* = 69/4$ is too small)

At $T \approx 200$ MeV: $\gamma', \gamma, e, \mu, u, d, g, \nu_e, \nu_\mu, \nu_\tau$ are in equilibrium.

Dominant γ' annihilation channels:



Interaction rate of γ': $\Gamma = n_{\gamma'} \langle \sigma |v| \rangle$

Number density of γ': $n_{\gamma'} = \frac{2\zeta(3)}{\pi^2} T^3 \approx 0.24\, T^3$

Thermally averaged cross section: $\langle \sigma |v| \rangle \sim \frac{\alpha c_\mu^2 m_\mu^2}{M^4}$

Expansion rate of the universe: $$H \approx \frac{T^2}{M_{\rm Pl}} \left(\frac{2\pi^3}{45} g_*(T) \right)^{1/2}$$

At the freeze-out temperature: $\Gamma_s \approx H$

$$\Longrightarrow \quad \frac{M}{\sqrt{c_\mu}} \approx 3.9 \text{ TeV} \times [g_*(T_P)]^{-1/8} \left(\frac{T_P}{1 \text{ GeV}} \right)^{1/4}$$

Measurements of light element abundances set a limit on the effective mass scale:

$$M \gtrsim 1.5 \text{ TeV} \times \sqrt{c_\mu}$$

Star cooling

Effective coupling of γ' to electrons: $$g_{\gamma' e} = \frac{c_e}{M^2} m_e^2$$

Red giant stars: γ' emission via Bremsstrahlung & Compton-like processes

$$g_{\gamma' e}^2 / 4\pi < 2.5 \times 10^{-27} \quad \Rightarrow \quad \frac{M}{\sqrt{c_e}} \gtrsim 3.2 \text{ TeV}$$

For supernovae: ν emission rate $\gg$ γ' emission rate
$\Rightarrow$ no useful bound on electron-γ' coupling
(strong bound on quark-γ' couplings)

Flavor-changing neutral currents

Chirality-flip transition:

$$\Gamma\left(\mu \to e\gamma'\right) = c_{e\mu}^2 \frac{m_\mu^5}{8\pi M^4}$$

Standard model:

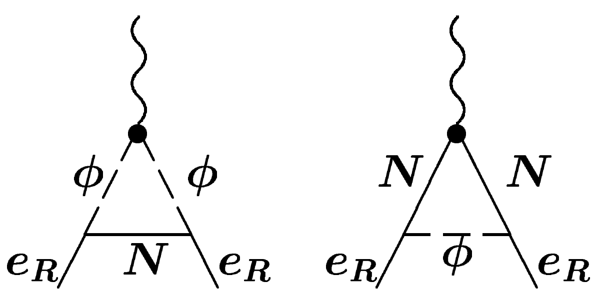
$$\Gamma\left(\mu \to e\nu\bar{\nu}\right) = \frac{m_\mu^5 G_F^2}{192\pi^3} \approx 3.2 \times 10^{-10}\mathrm{eV}$$

$$\mathrm{Br}\left(\mu \to e\gamma'\right) < 3 \times 10^{-5} \qquad \Rightarrow \qquad \frac{M}{\sqrt{c_{e\mu}}} \gtrsim 15\ \mathrm{TeV}$$

	l_L	e_R	N_L	N_R	H	ϕ
$SU(2)_W$	2	1	1	1	2	1
$U(1)_Y$	-1	-2	0	0	$+1$	-2
$U(1)_D$	0	0	$+1$	$+1$	0	-1

Yukawa interaction: $\lambda_\phi^j \, \overline{e}_R^j N_L \, \phi + \mathrm{h.c.}$

Contribution to the $iP_{\mu\nu}\overline{e}_R\gamma^\mu\partial^\nu e_R$ operator ($\sim P_{\mu\nu}\bar{l}_L\sigma^{\mu\nu}e_R H$):



$$\Rightarrow \quad (C_e)_{ij} = \frac{g_p}{192\pi^2}\sum_k \left(\lambda_\phi^i \lambda_\phi^{*k} \lambda_e^{kj} + \lambda_e^{ik} \lambda_\phi^k \lambda_\phi^{*j}\right)$$

Conclusions

New massless gauge boson may couple to quarks and leptons via dimension-6 operators suppressed by the TeV scale!

The lightest particle charged under the new $U(1)$ is a dark matter candidate.

Look for γ' (coupling to t-quark) and $U(1)'$-charged particles at the Tevatron, LHC, ILC, ...