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Top Hypercharge Model

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Enjoyable collaboration with
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Outline

I. Motivations

II. The model

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IV. Summary

Motivations

Theoretical Motivations for BSM Physics

- Fine-tuning problem:
  - Tiny cosmological constant;
  - Gauge hierarchy problem;
  - Radiative corrections to Higgs boson mass;
  - Strong CP problem;
  - Flavor problem;
  - ...
- Aesthetic appeal:
  - Grand unification of couplings;
  - Charge quantization;
  - Reduce number of free parameters;
  - ...
- Such considerations on the theory side call for more fundamental theories.

Experimental Motivations for BSM Physics

- Nonzero neutrino masses;
- Imperfect fitting in electroweak observables;
- Not sufficiently large CP violation or strong first-order phase transition for baryogenesis;
- Existence of dark matter & dark energy;
- ...

- These indirect evidences indicate the inadequacy of the SM to explain observed Universe.

Extra U(1) Symmetry

- Having one (or more) additional $U(1)'$ gauge factors provides one of the simplest extensions of the SM.
- Naively, it does not really solve any of the aesthetic problems. Moreover, its mass is not necessarily at the $\mathcal{O}$(TeV) scale that can be probed at the LHC.
- Also, one needs to worry about the appropriate way to break the extra symmetry.

Extra U(1) Symmetry

- Detailed study of Z-pole observables shows both
  - a small amount of missing invisible width in Z decays [N_ν = 2.9840 ± 0.0082, LEPEWWG (2005), ~ 2σ below SM], and
  - anomalous effective weak charge in atomic parity violation (6% accuracy, ~ 2.3σ above SM).
- One simple solution: a U(1)′ model, *e.g.*, Z_χ from SO(10) $\rightarrow$ SU(5) $\times$ U(1)$_\chi$.

Erler and Langacker (2000)

- Fitting result even favors a family nonuniversal Z', as predicted by some superstring constructions.
- Four electroweak observables with significant deviations from experiments.

PDG 2006

Table 1: **Two σ and more deviations**

Quantity	Value	SM	Pull
$\sigma_{\rm had}$[nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	-2.4
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	-2.7

Remarks

- It is more difficult to reduce the rank of an extended gauge group than it is to break the non-Abelian factor.
- This can be seen by considering Higgs fields in the adjoint representation to break an SU(N) gauge group. In this case, the VEV of the Higgs fields can be made diagonal by an SU(N) transformation and thus commute with all the diagonal generators in SU(N).
- The rank is not reduced, but the original system is broken down to a smaller non-Abelian group in tensor product with U(1)'s.

Extra U(1) Symmetry

- In general, models with at least an extra U(1) symmetry is common in superstring constructions, 4D GUTs, higher-dim orbifold GUTs, as well as models with dynamical symmetry breaking.

  $\Rightarrow$ Existence of at least one additional Z' gauge boson seems ubiquitous.

Cvetic and Langacker (1996);
Kawamura (2000),
Hall and Nomura (2001),
Gogoladze, Mimura, Nandi (2003);
Hill and Simons (2003).

- The extra symmetry can forbid an elementary μ term in SUSY, while allowing effective μ and $B\mu$ terms to be generated at the U(1)$'$ breaking scale (radiatively broken), providing a low-energy solution to the μ problem.

Suematsu and Yamagishi (1995);
Langacker et al (1999).

Extra U(1) Symmetry

- An extra low-energy U(1) symmetry in supersymmetric theories can also naturally solve the proton stability problem by forbidding all the baryon- and/or lepton-violating Yukawa couplings.

Font, Ibanez and Quevedo (1989).

- Accompanying with the extra symmetry are some extra fermions to cancel the anomalies and at least one Higgs singlet for breaking the symmetry.

Model

The Model

- Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_1 \times U(1)_2$ with couplings g_s, g, g_1', and g_2', respectively, above the O(TeV) scale.
- Two-stage symmetry breaking:
  - TeV-scale breaking down to $U(1)_Y$ by a Higgs singlet $\Sigma \sim (1, 1, 1/2, -1/2)$;
  - EW-scale breaking down to $U(1)_{EM}$ by two Higgs doublets $\Phi_1 \sim (1, 2, 1/2, 0)$ and $\Phi_2 \sim (1, 2, 0, 1/2)$.
  - The VEVs of these fields are

$$\langle\Sigma\rangle = \frac{u}{\sqrt{2}} , \ \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ v_1 \end{bmatrix} , \ \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ v_2 \end{bmatrix} , \quad \text{with } \tan\beta \equiv \frac{v_2}{v_1} ,$$

$$Y = Y_1 + Y_2 , \ \frac{1}{g'^2} = \frac{1}{g_1'^2} + \frac{1}{g_2'^2} , \quad \tan\phi \equiv \frac{g_1'}{g_2'} ,$$

rotation angle to Z and Z'

$$g = \frac{e}{\sin\theta} , \ g_1' = \frac{e}{\cos\theta\cos\phi} , \ g_2' = \frac{e}{\cos\theta\sin\phi} .$$

Gauge Boson Spectrum

- After the symmetry breakings, we obtain the usual W boson mass $M_W^2 = g^2(v_1^2 + v_2^2)/4 = g^2v^2/4$.
- Neutral gauge bosons in the gauge basis:

$$M_0^2 = \frac{u^2}{4}\begin{pmatrix} {g_1'}^2(1+\epsilon_1) & -g_1'g_2' & -gg_1'\epsilon_1 \\ -g_1'g_2' & {g_2'}^2(1+\epsilon_2) & -gg_2'\epsilon_2 \\ -gg_1'\epsilon_1 & -gg_2'\epsilon_2 & g^2(\epsilon_1+\epsilon_2) \end{pmatrix},$$

small expansion paras → $\epsilon_1 \equiv v_1^2/u^2$ and $\epsilon_2 \equiv v_2^2/u^2$

- The gauge basis is related to the mass basis by a rotation matrix R. ⇒

$$\begin{bmatrix} B_\mu^1 \\ B_\mu^2 \\ A_\mu^3 \end{bmatrix} = R \begin{bmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{bmatrix}.$$

- The covariant derivative in the mass basis is then

$$D_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}\left(T^+W_\mu^+ + T^-W_\mu^-\right) - i\left(gT_3R_{32} + g_1'Y_1R_{12} + g_2'Y_2R_{22}\right)Z_\mu$$
$$-i\left(gT_3R_{33} + g_1'Y_1R_{13} + g_2'Y_2R_{23}\right)Z'_\mu - ieQA_\mu .$$

reduces to SM when B^2 decouples

give rise to FCNC currents

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Fermions

- Hinted by their heavier masses, we propose that the third-family fermions are charged differently from those in the first two families under the two U(1)'s:

	first two families	third family
Quarks	$Q_{iL} : (3, 2,\ 1/6,\ 0)\,,$	$Q_{3L} : (3, 2,\ 0,\ 1/6)\,,$
	$u_{iR} : (3, 1,\ 2/3,\ 0)\,,$	$u_{3R} : (3, 1,\ 0,\ 2/3)\,,$
	$d_{iR} : (3, 1,\ -1/3,\ 0)\,,$	$d_{3R} : (3, 1,\ 0,\ -1/3)\,,$
Leptons	$L_{iL} : (1, 2,\ -1/2,\ 0)\,,$	$L_{3L} : (1, 2,\ 0,\ -1/2)\,,$
	$e_{iR} : (1, 1,\ -1,\ 0)\,,$	$e_{3R} : (1, 1,\ 0,\ -1)\,,$
RH neutrinos	$N_k : (1, 1,\ 0,\ 0)\,,$	

- We consider mainly $v_2 \gg v_1$, *i.e.*, large $\tan\beta$.
- The fermion spectrum is anomaly free by construction.

Yukawa Couplings

- Explicitly, the Yukawa terms in the Lagrangian are

$$
\begin{aligned}
-\mathcal{L}_Y = & \; Y_i^u \bar{u}_{iR} \Phi_1 Q_{iL} + Y_3^u \bar{u}_{3R} \Phi_2 Q_{3L} + Y_{ij}^d \bar{d}_{iR} \widetilde{\Phi}_1 Q_{jL} + Y_{33}^d \bar{d}_{3R} \widetilde{\Phi}_2 Q_{3L} \\
& + Y_i^e \bar{e}_{iR} \widetilde{\Phi}_1 L_{iL} + Y_3^e \bar{e}_{3R} \widetilde{\Phi}_2 L_{3L} + Y_{ki}^\nu N_k \Phi_1 L_i + Y_{k3}^\nu N_k \Phi_2 L_3 \\
& + M_{kl}^N N_k N_l + h.c. \; , \\
& \text{where } i, j = 1, 2 \; , \; k, l = 1, 2, 3 \; , \; \widetilde{\Phi} = i\sigma_2 \Phi^* \; .
\end{aligned}
$$

- In the presence of Φ_1 and Φ_2, only mixing between first two families (quarks and leptons) exists.
- Bi-maximal neutrino mixing can be achieved via the mixing in the RH Majorana neutrino mass matrix $M^N{}_{kl}$ through the usual seesaw mechanism.

Models With Similar Ideas

- Top-flavor model: Muller and Nandi (1996)

  $SU(2)_1 \times SU(2)_2 \times U(1)_Y \to SU(2)_L \times U(1)_Y$.

  - symmetry breaking achieved using one Higgs field transforming as a bi-doublet under the two SU(2)'s;
  - needs two Higgs doublets to give masses to third-family and first-two-family fermions, respectively; and
  - contains heavy *W* and *Z* bosons.
- Top hypercharge-like model: He, Tait, and Yuan (2000)

  also $SU(2)_L \times U(1)_1 \times U(1)_2 \to SU(2)_L \times U(1)_Y$.

  - only third-family quarks charged under $U(1)_2$;
  - symmetry breaking achieved using one Higgs field transforming under the two U(1)'s;
  - needs only one Higgs doublet for EWSB, as in the SM;
  - introduces "spectator quarks" for anomaly cancellation and top-seesaw mechanism; and
  - contains only a heavy *Z* boson and no charged Higgs boson.

Electroweak and Flavor Constraints

Z-pole Observables

PDG 2006

- Predicted values of the EW observables are computed in the MS-bar scheme.
- Experimental inputs: $\sin^2\theta \approx 0.2312$, α-hat$(M_Z)^{-1}$=127.904, and v=246.3 GeV.
- Concentrate on larger $\tan\beta$ cases.
- Restrict to $M_{Z'} \geq 1$ TeV to satisfy the requirement of small mixing ($<\sim 10^{-3}$) with the regular Z boson.

EW Observable Fitting

- 24 observables.
- 2 new paras.

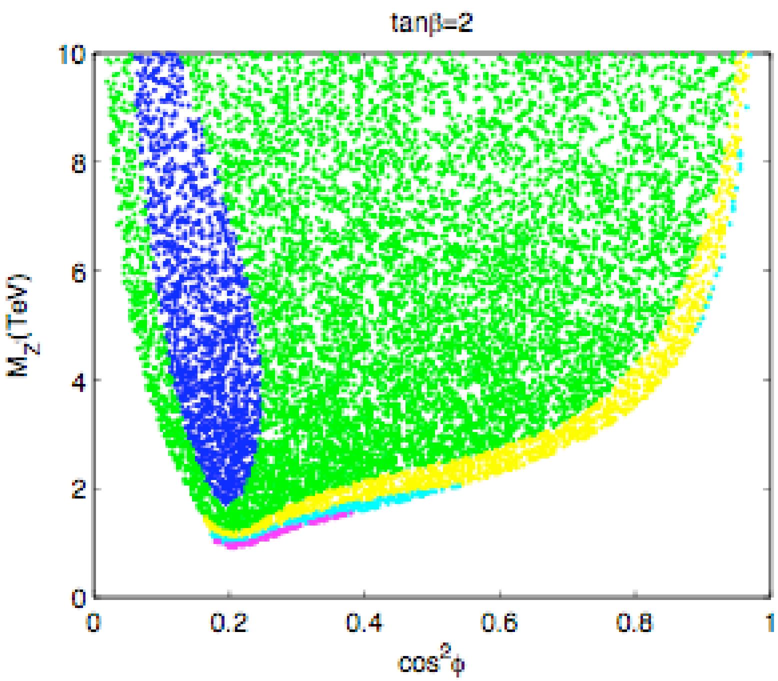
$\tan\beta$	χ^2_{min}
SM	32.01
1	31.89
5	31.87
10	31.90
20	31.92
50	31.92

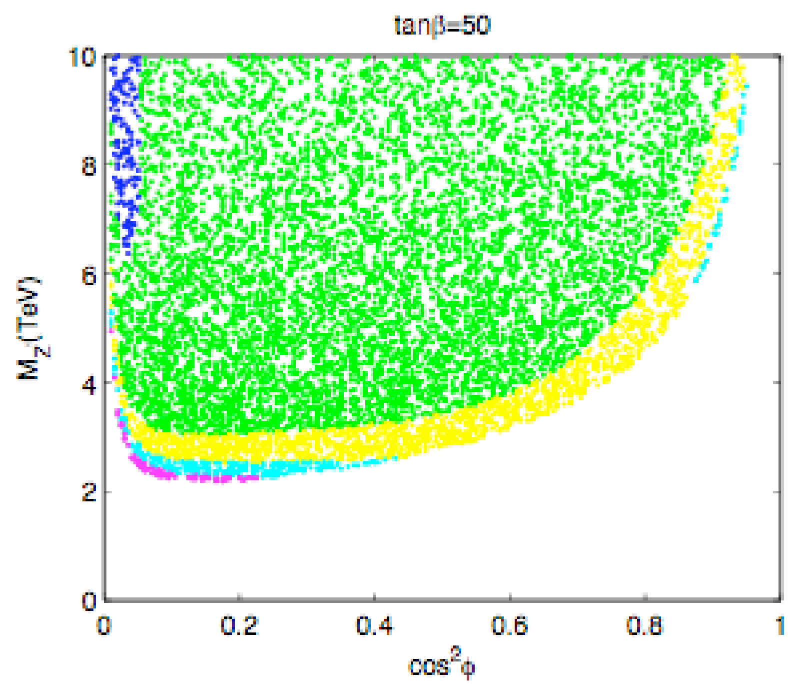
Observables	Experimental data	SM		$\tan\beta = 2$		$\tan\beta = 50$	
		best fit	pull	best fit	pull	best fit	pull
M_W(GeV)	80.450 ± 0.058	80.376	1.3	80.376	1.3	80.376	1.3
Γ_Z(TeV)	2.4952 ± 0.0023	2.4968	-0.7	2.4972	-0.9	2.4971	-0.8
$\sigma_{\rm had}[nb]$	41.541 ± 0.037	41.467	2.0	41.477	1.7	41.470	1.9
R_e	20.804 ± 0.050	20.756	1.0	20.7498	1.1	20.7534	1.0
R_μ	20.785 ± 0.033	20.756	0.9	20.7498	1.1	20.7534	1.0
R_τ	20.764 ± 0.045	20.801	-0.8	20.8110	-1.0	20.8035	-0.9
R_b	0.21629 ± 0.00066	0.21578	0.8	0.21570	0.9	0.21576	0.8
R_c	0.1721 ± 0.0030	0.17230	-0.1	0.17231	-0.1	0.17230	-0.1
A_e	0.15138 ± 0.00216	0.1471	2.0	0.1454	2.8	0.1463	2.4
A_μ	0.142 ± 0.015	0.1471	-0.3	0.1454	-0.2	0.1463	-0.3
A_τ	0.136 ± 0.015	0.1471	-0.7	0.1484	-0.8	0.1472	-0.7
A_b	0.923 ± 0.020	0.9347	-0.6	0.9348	-0.6	0.9347	-0.6
A_c	0.670 ± 0.027	0.6678	0.1	0.6670	0.1	0.6674	0.1
A_s	0.895 ± 0.091	0.9356	-0.4	0.9355	-0.4	0.9355	-0.4
$A^e_{\rm FB}$	0.0145 ± 0.0025	0.01622	-0.7	0.01584	-0.5	0.01604	-0.6
$A^\mu_{\rm FB}$	0.0169 ± 0.0013	0.01622	0.5	0.01584	0.8	0.01604	0.7
$A^\tau_{\rm FB}$	0.0188 ± 0.0017	0.01622	1.5	0.01617	1.5	0.01614	1.6
$A^b_{\rm FB}$	0.0992 ± 0.0016	0.1031	-2.4	0.1019	-1.7	0.1025	-2.1
$A^c_{\rm FB}$	0.0707 ± 0.0035	0.0737	-0.8	0.0728	-0.6	0.0732	-0.7
$A^s_{\rm FB}$	0.0976 ± 0.0114	0.1032	-0.5	0.1020	-0.4	0.1026	-0.4
g_L^2	0.30005 ± 0.00137	0.30378	-2.7	0.30398	-2.9	0.30390	-2.8
g_R^2	0.03076 ± 0.00110	0.03006	0.6	0.03034	0.4	0.03037	0.4
$g_V^{\nu e}$	-0.040 ± 0.015	-0.03936	0.0	-0.03804	-0.1	-0.03780	-0.1
$g_A^{\nu e}$	0.507 ± 0.014	-0.5064	0.0	-0.5071	0.0	-0.5071	0.0

Table 1: The experimental [8] and the predicted values of the Z-pole observables for the SM [8] and our model with $\tan\beta$=2 and 50 as two examples. For best fits, the $\tan\beta = 2$ case has $\cos^2\phi = 0.43$ and $M_{Z'} = 2.4\,$TeV, and the $\tan\beta = 50$ case has $\cos^2\phi = 0.122$ and $M_{Z'} = 10\,$TeV.

Allowed Parameter Space

- Illustrate tanβ = 2 and 50 as two examples.
- No mixing between Z and Z' when tanϕ = tanβ, thus larger χ^2-favored region for low tanβ.
- In general, $M_{Z'} \geq 2$ TeV by EW constraints.





Fermion Mixing

- No mixing between first two and third families yet.
- Introduce, for example, additional Higgs doublet fields Φ_3 ~ (1, 2, -1/6, -1/3) and Φ_4 ~ (1, 2, -1/3, -1/6), the down-type quark mixing is induced from the Yukawa terms:

$$-\mathcal{L}_{Yukawa} = Y^d_{3i} \bar{d}_{3R} \Phi_3 Q_{iL} + Y^d_{i3} \bar{d}_{iR} \Phi_4 Q_{3L} + h.c. \ .$$

- Similar arrangement can be done to the up sector as well.
- The mismatch between the flavor eigenstates and mass eigenstates of the quarks will result in tree-level flavor-changing Z' couplings because the U(1)′ charges of the third-generation quarks are different from those of the first two generations.

FCNC in Down Sector

- Reduce uncertainties from the up sector by assuming no difference between the flavor and mass eigenstates for the up-type quarks, corresponding to the case where only the Φ_3 and Φ_4 Higgs fields are introduced.
- Universal Z' charge for RH fermions for simplicity.

$$\epsilon_L^d = Q_L^d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & x \end{pmatrix} \text{ and } \epsilon_R^d = Q_R^d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

Z' charges in flavor basis

$$\begin{aligned} B_L^d &\equiv V_{dL}^\dagger \epsilon_L^d V_{dL} = V_{\rm CKM}^\dagger \epsilon_L^d V_{\rm CKM} \\ &\approx Q_L^d \begin{pmatrix} 1 & (x-1)V_{ts}V_{td}^* & (x-1)V_{tb}V_{td}^* \\ (x-1)V_{td}V_{ts}^* & 1 & (x-1)V_{tb}V_{ts}^* \\ (x-1)V_{td}V_{tb}^* & (x-1)V_{ts}V_{tb}^* & x \end{pmatrix} \end{aligned}$$

180^o phase

- FCNC coupling hierarchy: $|B_L^{sb}| > |B_L^{db}| > |B_L^{ds}|$.

FCNC in Down Sector

- Dominant off-diagonal Z' coupling is between the LH bottom and strange quarks due to the hierarchical structure in the CKM matrix

  $$B_L^{sb} = \delta_L Q_{dL} V_{tb} V_{ts}^* ,$$

  where $\delta_L Q_{dL} = e/(3 \sin 2\phi \cos\theta)$.

  $\Rightarrow$ No $\tan\beta$ dependence in the FCNC coupling B_L^{sb}.

- Such a coupling can contribute to processes involving $b \leftrightarrow s$ transitions, *e.g.*, $|\Delta B| = |\Delta S| = 2$ operators that affect B_S mixing:

Barger, CWC, Jiang, Langacker (2004)

$$\mathcal{H}_{\rm eff}^{Z'} = \frac{G_F}{\sqrt{2}} \left(\frac{g_2 M_Z}{g_1 M_{Z'}} B_{sb}^L \right)^2 O^{LL}(m_b) \equiv \frac{G_F}{\sqrt{2}} \left(\rho_L^{sb}\right)^2 e^{2i\phi_L} O^{LL}(m_b) ,$$

$$O^{LL} = [\bar{s}\gamma_\mu(1-\gamma_5)b][\bar{s}\gamma^\mu(1-\gamma_5)b]$$

same op as in SM

Remark

- In principle, one can also introduce FCNC in the RH sector. This generally introduces more independent parameters into the game.

B Constraints

- Use both ΔM_s and BR($B \to X_s\, l\, l$) constraints:

  $\Delta M_s^{exp} = 17.77 \pm 0.10 \pm 0.07$ ps^{-1} ,

  $\Delta M_s^{SM} = 19.52 \pm 5.28$ ps^{-1} ,

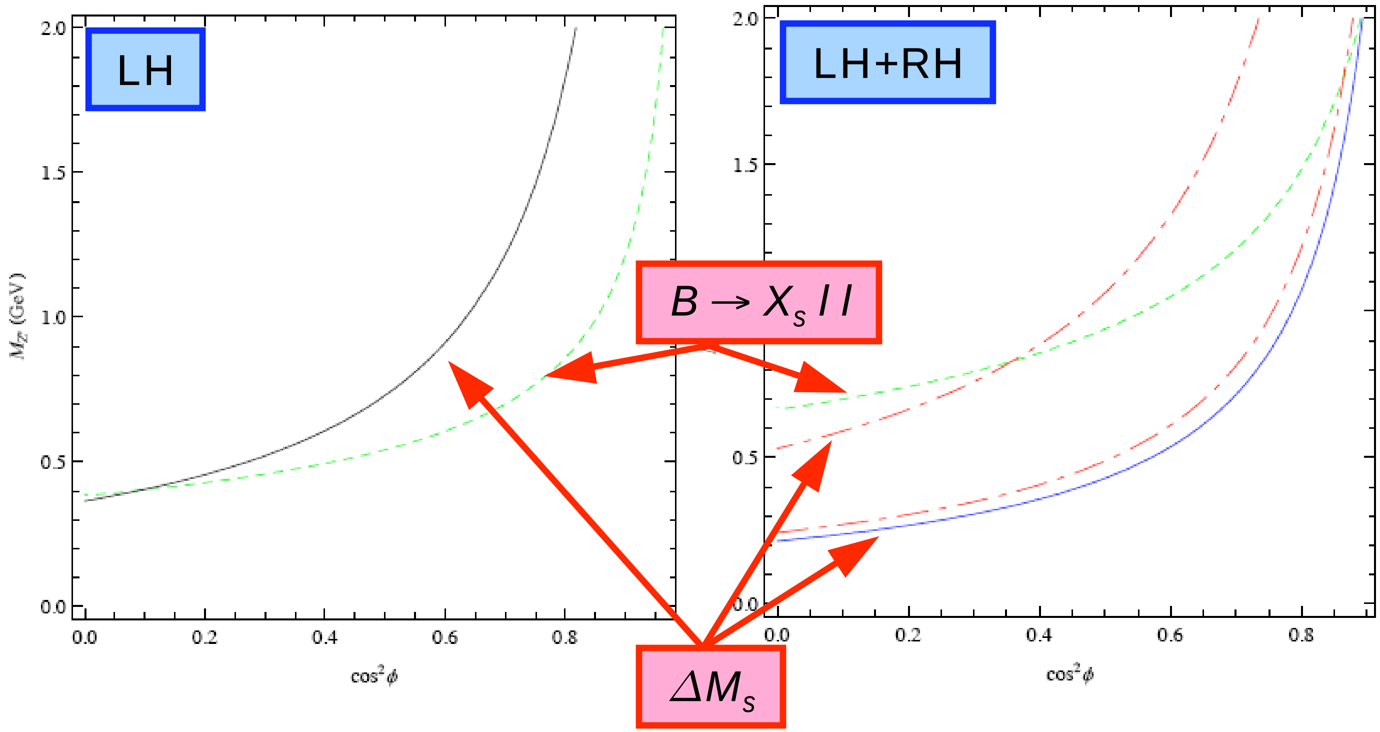
  $\Rightarrow \Delta M_s^{exp} / \Delta M_s^{SM} = 0.89 \pm 0.24$;

  BR($B \to X_s\, l\, l$) = $(4.50 \pm 1.02) \times 10^{-6}$.

CDF (2006)

Cheung, CWC, Deshpande, Jiang (2007)

BABAR (2004) Belle (2005)



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Z' Production at LHC, Dark Matter and Higgs

Direct Searches at CFD Run II (2006)

- Recent data based on integrated luminosity of 819 pb^{-1} of the Drell-Yan process at CDF ($\sqrt{s}$ = 1.96 TeV):

http://www-cdf.fnal.gov/harper/diEleAna.html

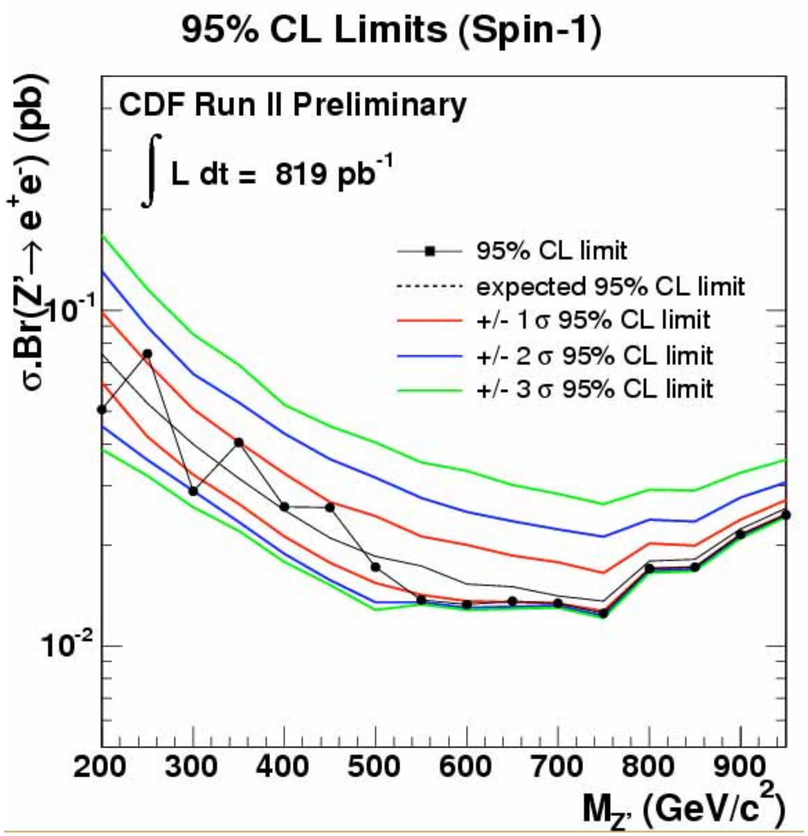


TABLE I: The 95% C.L. limits on $\sigma(Z') \cdot B(Z' \to e^+e^-)$ given by the preliminary CDF result in Ref. [10] as a function of $M_{Z'}$.

$M_{Z'}$ (GeV)	$\sigma \cdot B^{95}$ (pb)	$M_{Z'}$ (GeV)	$\sigma \cdot B^{95}$ (pb)
200	0.0505	600	0.0132
250	0.0743	650	0.0136
300	0.0289	700	0.0134
350	0.0404	750	0.0126
400	0.0261	800	0.0171
450	0.0259	850	0.0172
500	0.0172	900	0.0215
550	0.0138	950	0.0246

The initial LHC reach will be 2 TeV (with power to discriminate among models) and can go up to 5 TeV.

Discovery Reach of Z' at LHC

- The LHC can readily discover an extra neutral gauge boson with a mass of about 1 TeV cleanly from the Drell-Yan process.

Dittmar, Nicollerat, Djouadi (2004) ; Rizzo (2006)

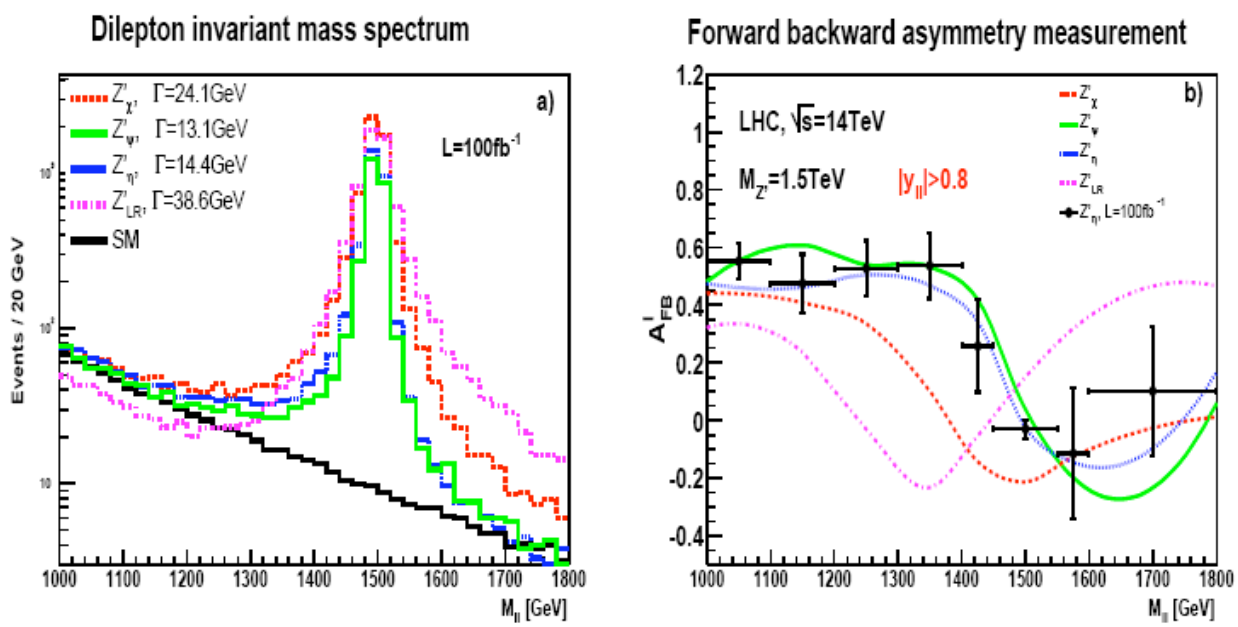


Figure 4: *The dilepton invariant mass spectrum (a) and A^{ℓ}_{FB} (b) as a function of $M_{\ell\ell}$ for four Z' models. For the forward-backward charge asymmetry, the rapidity of the dilepton system is required to be larger than 0.8. A simulation of the statistical errors, including random fluctuations of the Z'_η model and with errors corresponding to a luminosity of 100 fb^{-1} has been included in (b).*

Discovery Reach of Z' at ILC

Cvetic and Godfrey (1995)

- At the ILC (500 GeV and 50 fb^{-1}), observations of:
  - leptonic cross sections,
  - leptonic FB asym.,
  - hadronic FB asym.,
  - ratio of hadronic to QED x-sec.,

  should be able to probe a Z' up to ~ 1-3 TeV through virtual exchanges.

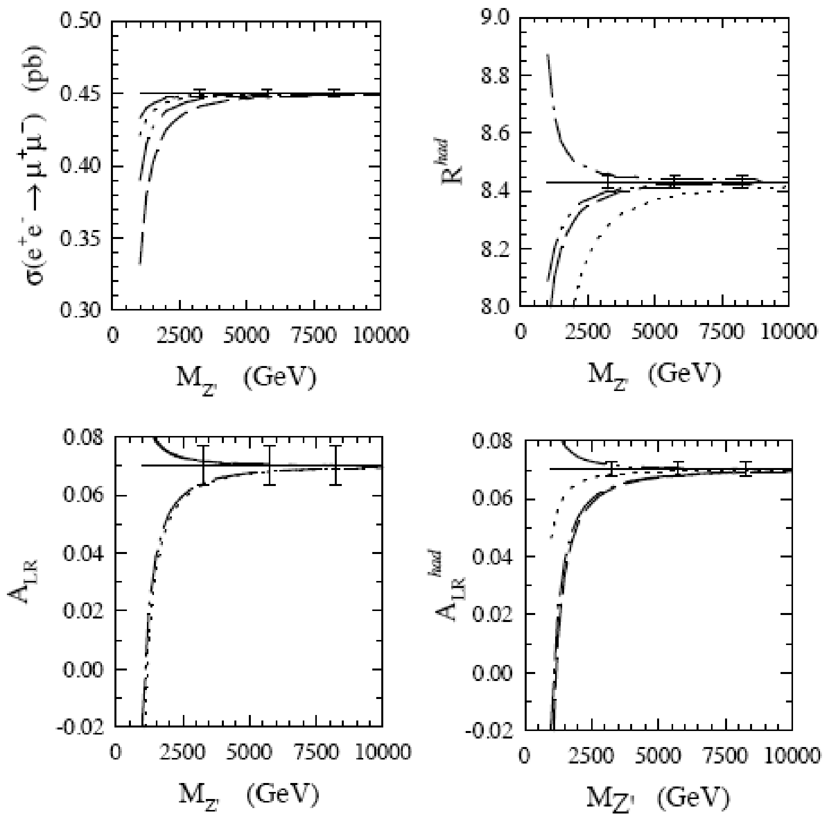


Figure 2: $\sigma(e^+e^- \to \mu^+\mu^-)$, R_{had}, A_{LR}, and A_{LR}^{had} for $\sqrt{s} = 500$ GeV as a function of $M_{Z'}$. The error bars are statistical errors based on 50 fb^{-1} integrated luminosity. In all cases the solid line is the standard model prediction, the dot-dash line is for model-χ, the dot-dot-dash model is for model-LR, the dashed line is for model-ALR and the dotted line is for model-SSM.

Further Determinations

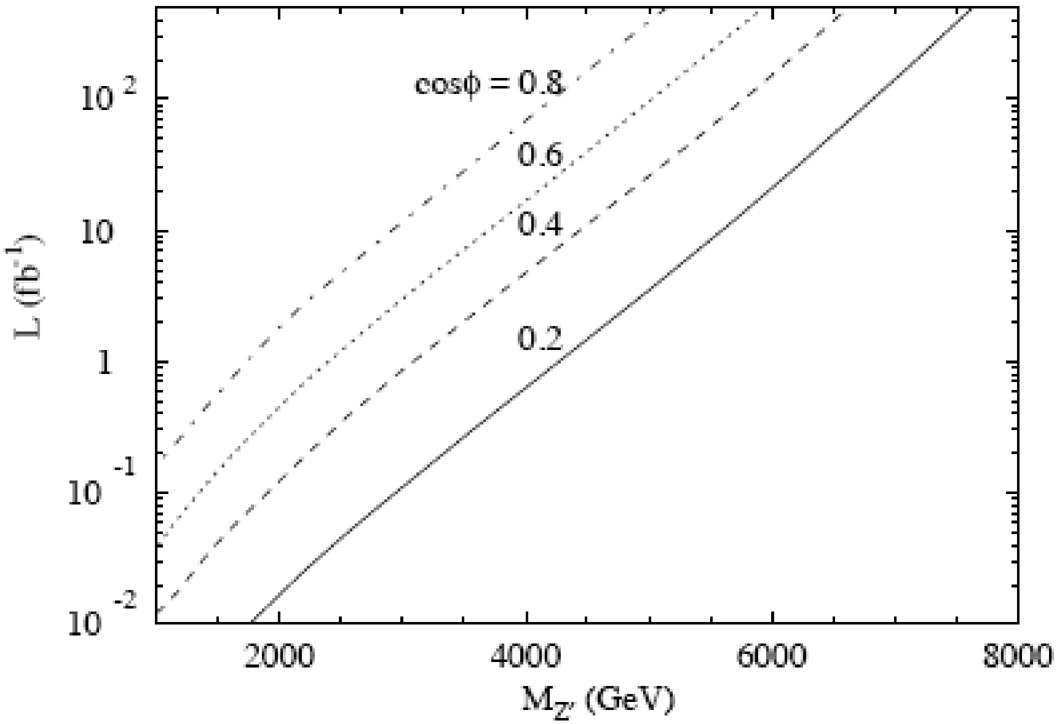
- If one Z' gauge boson is really found at the LHC, the next job would be to determine its couplings to chiral fermions in order to pin down its origin (*e.g.*, which model it belongs to).
- A combination of forward-backward asymmetries as a function of rapidity, rapidity distributions, rare decays ($Z' \to W\,l\,\nu$), and associated production of $Z'Z$, $Z'W$, $Z'\gamma$ should provide significant diagnostic ability up to 1 - 2 TeV.

Drell-Yan Process

- As in other Z' models, the Z' in our model can be searched for through the Drell-Yan processes.
- For the mass range we consider, the decay width of the Z' is typically a few tens of GeV.
- Apply simple cuts of requiring:
  - p_T of the outgoing leptons be larger than 20 GeV,
  - absolute value of rapidities of the leptons be less than 2.5, and
  - invariant mass of the lepton pair be between $M_{Z'}-\Gamma_{Z'}/2$ and $M_{Z'}+\Gamma_{Z'}/2$.
- After these cuts, SM background becomes negligible compared to the signal.

Drell-Yan Process

- Total luminosities required for a 5 σ discovery for different cosϕ and $M_{Z'}$ in the model.
- With 100 fb^{-1}, the discovery reaches for cosϕ = 0.8, 0.6, 0.4 and 0.2 are about 4.1, 5.0, 5.8 and 6.9 TeV.
- Production cross section is strongly dependent of cosϕ.



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Dark Matter Candidate

- Stability of dark matter is usually achieved using a discrete global symmetry (*e.g.*, a Z_2 symmetry such as the R parity in SUSY $\Rightarrow$ LSP).
- However, the global symmetry can be broken by non-renormalizable higher-dim operators due to quantum gravity effects if it is not gauged.
- A possible solution: a gauged Z_2 symmetry derived from a continuous local symmetry that is broken at the TeV scale
  $\Rightarrow$ stable particle with mass ~ O(TeV).

Krauss and Wilczek (1989)

Dark Matter Candidate

- Introduce a singlet scalar field ϕ ~ (1, 1, -1/4, 1/4).
- Relevant Lagrangian for ϕ and its couplings to Σ (both carrying U(1)′ charges) is

$$-\mathcal{L} = m_\phi^2|\phi|^2 + \frac{\lambda_\phi}{2}|\phi|^4 + \lambda'_\phi|\phi|^2|\Sigma|^2 + \left(\tilde{m}_\phi\phi^2\Sigma + h.c.\right) \ .$$

- After the $U(1)_1 \times U(1)_2 \rightarrow U(1)_Y$ breaking, ϕ becomes a stable particle due to the gauged Z_2 symmetry under which ϕ goes to $-\phi$ and the other fields are invariant.
- Interaction with the flavor sector depends on its mixing with Φ_1 and Φ_2.

Higgs Potential

- Most general CP-conserving, renormalizable Higgs potential (without ϕ yet):

$$
\begin{aligned}
V_H &= -m_{11}^2\Phi_1^\dagger\Phi_1 - m_{22}^2\Phi_2^\dagger\Phi_2 - \left[A_m\Phi_1^\dagger\Sigma\Phi_2 + h.c.\right] \\
&+ \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
&+ \lambda_5\left(\Sigma^\dagger\Sigma\right)\left(\Phi_1^\dagger\Phi_1\right) + \lambda_6\left(\Sigma^\dagger\Sigma\right)\left(\Phi_2^\dagger\Phi_2\right) - m_\Sigma^2\Sigma^\dagger\Sigma + \frac{1}{2}\lambda_\Sigma\left(\Sigma^\dagger\Sigma\right)^2 ,
\end{aligned}
$$

  A_m is dim-1 and chosen to be real, λ_i are dimensionless.
- Two global SU(2) symmetries if we neglect the terms $-[A_m\Phi_1^\dagger\Sigma\Phi_2$ + h.c.] and $\lambda_4(\Phi_1^\dagger\,\Phi_2)(\Phi_2^\dagger\,\Phi_1)$.
- In this case, it is always possible to make an $SU(2)_1\times SU(2)_2$ rotation so that the left-over $U(1)_{EM}$ gauge symmetry is unbroken.

Alignment Issue

- After introducing the two terms into the Higgs potential, the $SU(2)_1 \times SU(2)_2$ global symmetries is broken down to the SU(2) global symmetry identified as the $SU(2)_L$.
- For simplicity and without loss of generality, assume that no CP violation and positive v_1, v_2 and A_m .
- One can make an $SU(2)_L$ rotation so that Φ_2 does not break the $U(1)_{EM}$ gauge symmetry.
- If A_m is around the EW scale and $\lambda_4 \sim O(1)$, the magnitude of the $-[A_m \Phi_1^\dagger \Sigma \Phi_2 + \text{h.c.}]$ terms is much larger than that of $\lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$ because u is much larger than v_1 and v_2.
- Therefore, the Higgs potential naturally leads to an alignment that $U(1)_{EM}$ is not broken.

Higgs Spectrum

- There are 10 degrees of freedom in the three Higgs fields. After $SU(2)_L \times U(1)_1 \times U(1)_2 \rightarrow U(1)_{EM}$, there will be left with 6 physical Higgs fields:
  three CP-even ones (H_1, H_2 and H_3),
  one CP-odd one (A), and
  one charged pair ($H^\pm$).
- The squared mass of the CP-odd Higgs is proportional to $A_m u$ and $\tan\beta$ enhanced.

$$m_A^2 = \frac{A_m\left(v_1^2 v_2^2 + u^2 v_1^2 + u^2 v_2^2\right)}{\sqrt{2} u v_1 v_2} \to \frac{\tan\beta}{\sqrt{2}} A_m u \ .$$

- The charged Higgses have the squared mass

$$m_{H^\pm}^2 = \frac{A_m u (v_1^2 + v_2^2)}{\sqrt{2} v_1 v_2} - \frac{1}{2}\lambda_4 v^2 \to m_A^2 - \frac{1}{2}\lambda_4 v^2 \ .$$

Summary

- We construct a model based upon the gauge group of $SU(3)_C \times SU(2)_L \times U(1)_1 \times U(1)_2$, where an extra heavy Z' possibly exists at the TeV scale.
- Fermions in the third family are charged differently from the first two families under $U(1)_1 \times U(1)_2$, thereby inducing tree-level FCNC currents.
- Some constraints are imposed on its parameters from electroweak precision observables and B physics data, with the former being stronger and more solid.
- We compute its production rate at the LHC.
- We discuss a possible dark matter candidate by gauging a discrete Z_2 symmetry.
- Future project: Higgs sector phenomenology.