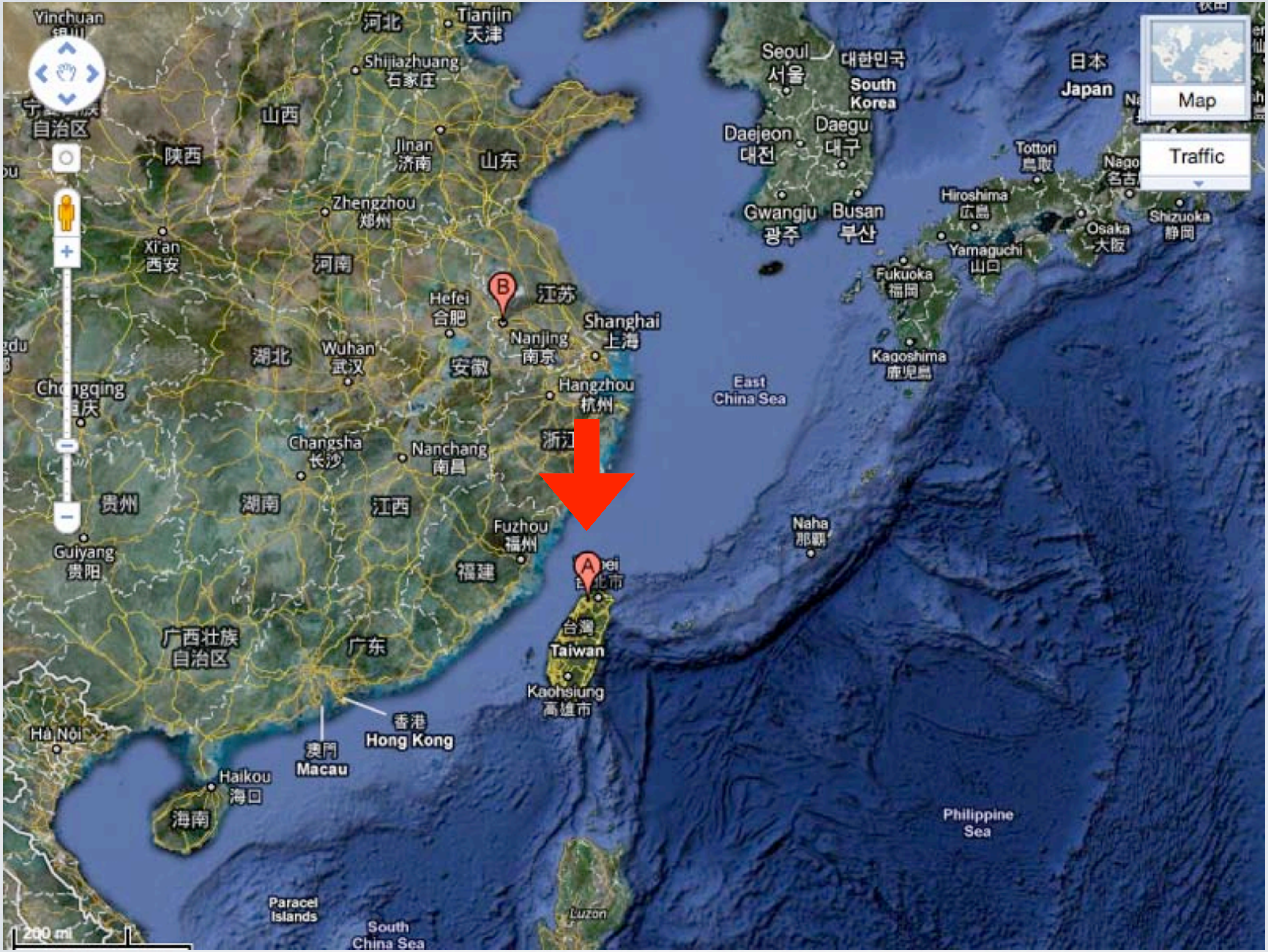
Cross-Strait Conference on
Particle Physics and Cosmology
May 9, 2012

Constraining Leptonic Couplings of a Family-Nonuniversal Z' Boson

Cheng-Wei Chiang (蔣正偉)
National Central University / Academia Sinica / NCTS

In collaboration with Yi-Fan Lin and Jusak Tandean
JHEP 11, 083 (2011) (arXiv:1108.3969 [hep-ph])

National Central University



National Central University

NATIONAL CENTRAL UNIVERSITY

NATIONAL CENTRAL UNIVERSITY

NCU Welcomes You!

Cross-Strait Conference on
Particle Physics and Cosmology
May 9, 2012

Constraining Leptonic Couplings of a Family-Nonuniversal Z' Boson

Cheng-Wei Chiang (蔣正偉)
National Central University / Academia Sinica / NCTS

In collaboration with Yi-Fan Lin and Jusak Tandean
JHEP 11, 083 (2011) (arXiv:1108.3969 [hep-ph])

Outline

- Family-nonuniversal Z’ boson
- Leptonic interactions
- Constraints
  - Flavor-conserving processes
  - Flavor-changing processes
- Predictions
- Summary

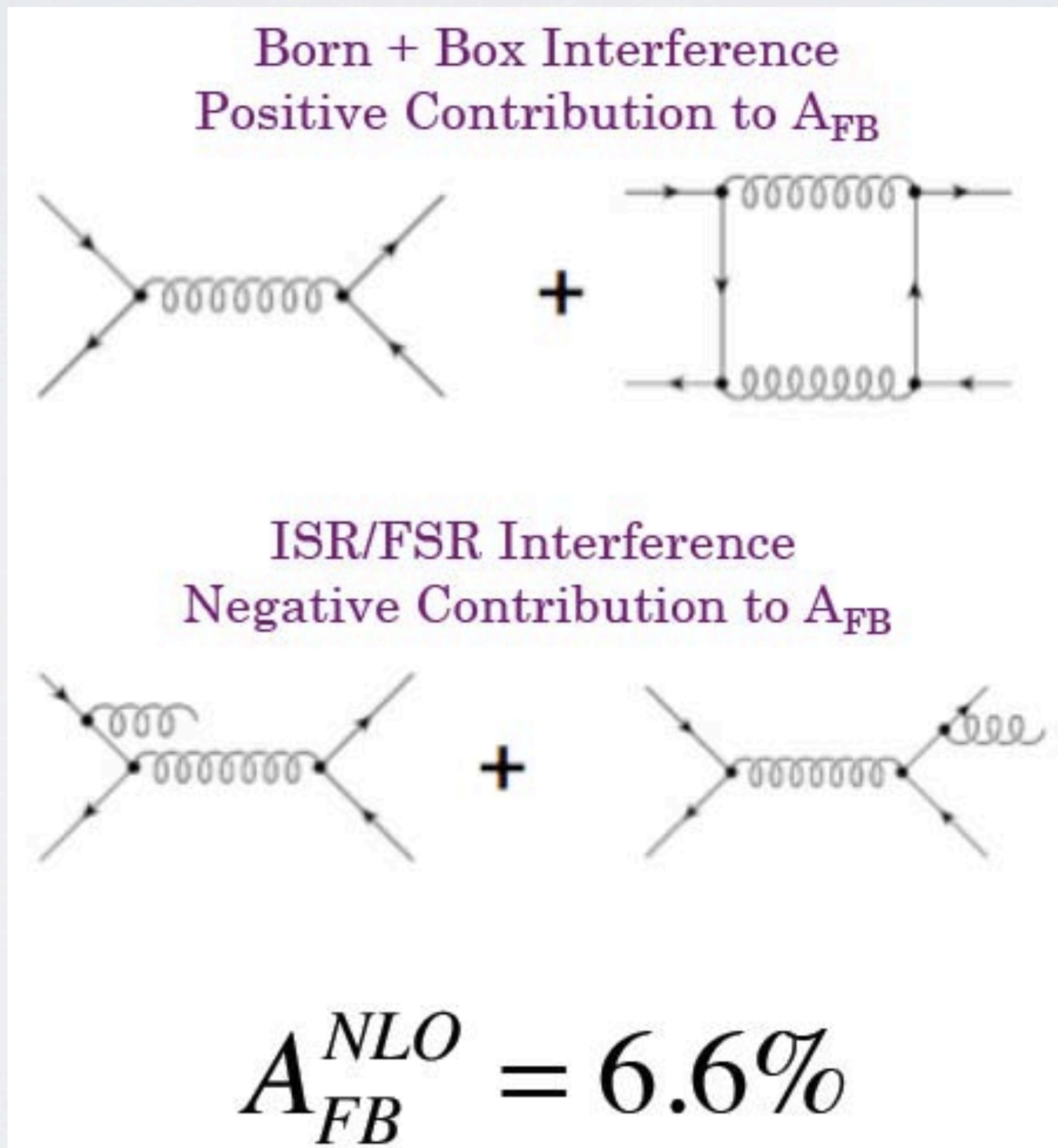
Family-Nonuniversal Z’

Experimental Anomalies

- Fermilab had reported several anomalies in recent years
  - top forward-backward asymmetry
  - like-sign dimuon charge asymmetry in semileptonic b-hadron decays
  - excess production of Wjj events (CDF only)
- One solution is a heavy neutral gauge boson, commonly dubbed as the Z’ boson
  - associated with an extra U(1) symmetry
  - having family-nonuniversal couplings with quarks

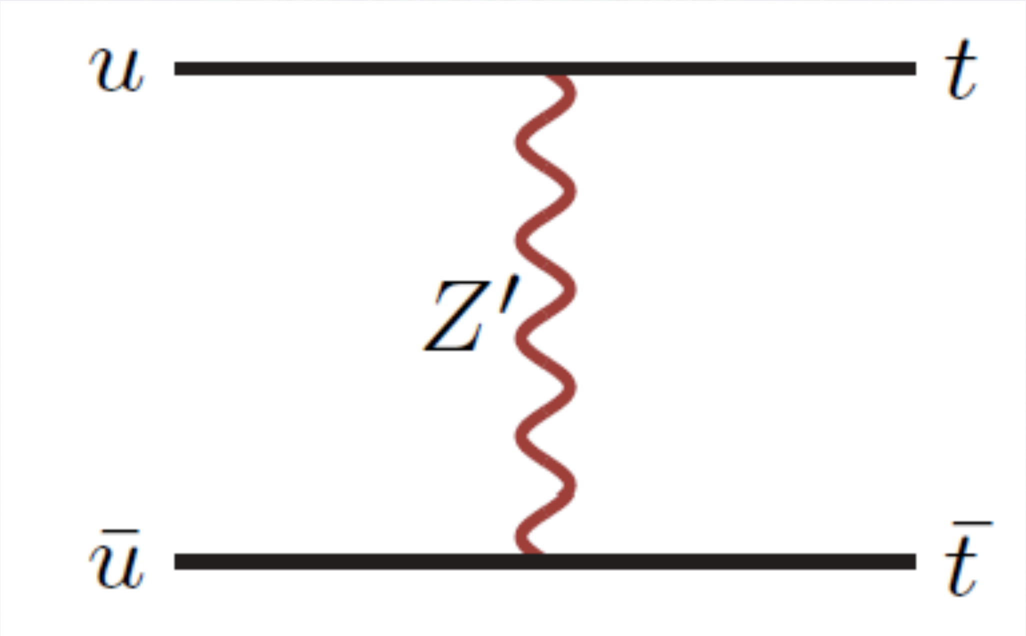
Top FBA in SM

- LO: no asymmetry
- NLO: small positive asymmetry



Top FBA from NP

- Current CDF and D0 measurements using full dataset give a deviation of ~3σ from null asymmetry and ~2σ from SM NLO prediction.
- One possible explanation: t-channel process mediated by a Z' boson with a large O(1) flavor-changing coupling between u and t quarks. Jung, Murayama, Pierce, Wells 2010



FCNC Z'

- Many models (GUT's, SUSY, etc) predict or favor the existence of a heavy neutral vector gauge boson.

- Models with U(1)' may have flavor-changing interactions of the Z' with SM fermions at tree level if
  - there are exotic fermions with separate U(1)' charges
  - the couplings of the Z' with SM fermions are not family universal (new fermions not needed)

- There have been many studies in the literature about low-energy constraints on the Z' boson with tree-level FCNC interactions with quarks.

Some Previous Studies

- Inspire by B physics anomalies since early 2000's, there has been revived interest in using models of Z' boson with FCNC interactions with quarks, particularly in the down sector.

Barger, CWC, Jiang, Langacker and Lee
Cheung, CWC, Deshpande and Yuan
He and Valencia
Chang, Li and Yang

- Fewer studies concentrate on the leptonic sector.

Langacker and Pluemacher
Heeck and Rodejohann

- Do a comprehensive, model-independent study of leptonic couplings.

Kinetic and Mass Terms

- After electroweak symmetry breaking, the most general kinetic Lagrangian for neutral gauge fields with both mass and kinetic mixing

$$\begin{aligned}\mathcal{L}_{\rm km} =& -\tfrac{1}{4} W_3^{\mu\nu} W_{3\mu\nu} - \tfrac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tfrac{1}{4} C^{\mu\nu} C_{\mu\nu} - \tfrac{1}{2}\kappa\, B^{\mu\nu} C_{\mu\nu} \\ &+ \tfrac{1}{2} m_W^2\, W_3^2 + \tfrac{1}{2} m_B^2\, B^2 + \tfrac{1}{2} m_C^2\, C^2 \\ &- m_W m_B\, W_3^\nu B_\nu - m_W\, \mu\, W_3^\nu C_\nu + m_B\, \mu\, B^\nu C_\nu \\ =& -\tfrac{1}{4}\, G_{\mu\nu}^{\rm T}\, K\, G^{\mu\nu} + \tfrac{1}{2}\, G_\nu^{\rm T}\, M_G^2\, G^\nu \ ,\end{aligned}$$

$$\text{where } m_W = \frac{g\, v}{2}\ , m_B = \frac{g_Y v}{2}\ , m_C^2 = M_C^2 + \mu^2\ ,$$

Kinetic and Mass Terms

$$\mathcal{L}_{\mathrm{km}} = -\,\tfrac{1}{4}\,G^{\mathrm{T}}_{\mu\nu}\,K\,G^{\mu\nu} \;+\; \tfrac{1}{2}\,G^{\mathrm{T}}_{\nu}\,M^2_G\,G^{\nu}\;\;,$$

$$\text{where } G \;=\; \begin{pmatrix} B \\ W_3 \\ C \end{pmatrix}\;,\;\; K \;=\; \begin{pmatrix} 1 & 0 & \kappa \\ 0 & 1 & 0 \\ \kappa & 0 & 1 \end{pmatrix},$$

$$M^2_G \;=\; \begin{pmatrix} m^2_B & -m_B\,m_W & m_B\,\mu \\ -m_B\,m_W & m^2_W & -m_W\,\mu \\ m_B\,\mu & -m_W\,\mu & m^2_C \end{pmatrix}$$

Canonical Kinetic Terms

- Using a non-unitary transformation and a Weinberg angle rotation,

$$\begin{pmatrix} B \\ W_3 \\ C \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\kappa/\sqrt{1-\kappa^2} \\ 0 & 1 & 0 \\ 0 & 0 & 1/\sqrt{1-\kappa^2} \end{pmatrix} \begin{pmatrix} \cos\theta_{\rm W} & -\sin\theta_{\rm W} & 0 \\ \sin\theta_{\rm W} & \cos\theta_{\rm W} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \hat{A} \\ \hat{Z} \\ \hat{Z}' \end{pmatrix},$$

$$\text{where } \sin\theta_{\rm W} = \frac{m_B}{M_Z}\ ,\ M_Z^2 = \frac{m_W^2}{\cos^2\theta_{\rm W}}$$

one puts the kinetic terms into the canonical form

$$\mathcal{L}_{\rm km} = -\tfrac{1}{4}(\hat{A}^{\mu\nu}\ \hat{Z}^{\mu\nu}\ \hat{Z}'^{\mu\nu}) \begin{pmatrix} \hat{A}_{\mu\nu} \\ \hat{Z}_{\mu\nu} \\ \hat{Z}'_{\mu\nu} \end{pmatrix} + \tfrac{1}{2}(\hat{A}^{\nu}\ \hat{Z}^{\nu}\ \hat{Z}'^{\nu}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & M_Z^2 & \Delta \\ 0 & \Delta & M_{Z'}^2 \end{pmatrix} \begin{pmatrix} \hat{A}_{\nu} \\ \hat{Z}_{\nu} \\ \hat{Z}'_{\nu} \end{pmatrix}$$

Z-Z' Mixing

- The Z-Z' mixing comes from the parameters

$$\Delta = \frac{\kappa\, m_B - \mu}{\sqrt{1-\kappa^2}} M_Z \ , \quad M^2_{Z'} = \frac{m_C^2 - 2\kappa\,\mu\, m_B + \kappa^2\, m_B^2}{1-\kappa^2}$$

two sources

- In the end,

$$\begin{pmatrix} \hat{A} \\ \hat{Z} \\ \hat{Z}' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\xi & -\sin\xi \\ 0 & \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix},$$

$$\tan(2\xi) = \frac{2\Delta}{M_Z^2 - M_{Z'}^2}$$

Mass Eigenvalues

- Mass eigenvalues for Z and Z' bosons are

$$m^2_{Z,Z'} \;=\; \tfrac{1}{2}\left(M_Z^2 + M_{Z'}^2\right) \mp \tfrac{1}{2}\sqrt{\left(M_Z^2 - M_{Z'}^2\right)^2 + 4\Delta^2}$$

$$\left(m_{Z'}^2 - M_Z^2\right)\tan^2\xi \;=\; M_Z^2 - m_Z^2$$

Interactions with Charged Leptons

LEPTONIC INTERACTIONS

- In the gauge basis:

$$\mathcal{L}_{\rm int} = -\, g_Z J_Z^\lambda\, \hat{Z}_\lambda \,-\, g_{Z'} J_{Z'}^\lambda\, \hat{Z}'_\lambda$$

family-universal

$$g_Z\, J_Z^\lambda = \bar{\hat{\ell}} \gamma^\lambda \big(g_L P_L + g_R P_R\big) \hat{\ell}$$

$$g_{Z'}\, J_{Z'}^\lambda = \bar{\hat{\ell}} \gamma^\lambda \big(g'_L P_L + g'_R P_R\big) \hat{\ell}$$

$$g'_L = \mathrm{diag}\big(L'_e, L'_\mu, L'_\tau\big) \;, \quad g'_R = \mathrm{diag}\big(R'_e, R'_\mu, R'_\tau\big)$$

family-nonuniversal in general

Leptonic Interactions

- In terms of mass eigenstates

$$\mathcal{L}_{\rm int} = -\,\bar{\ell}_i\gamma^\lambda\Big(\beta_L^{\ell_i\ell_j}\,P_L + \beta_R^{\ell_i\ell_j}\,P_R\Big)\ell_j\,Z_\lambda$$
$$-\,\bar{\ell}_i\gamma^\lambda\Big(b_L^{\ell_i\ell_j}\,P_L + b_R^{\ell_i\ell_j}\,P_R\Big)\ell_j\,Z'_\lambda$$

tree-level FCNC possible for both Z and Z'

$$\text{where } \beta_{L,R}^{\ell_i\ell_j} = \big(\beta_{L,R}^{\ell_j\ell_i}\big)^* = \delta_{ij}\,c_\xi\,g_{L,R} + s_\xi\,\big(B_{L,R}\big)_{ij}$$
$$b_{L,R}^{\ell_i\ell_j} = \big(b_{L,R}^{\ell_j\ell_i}\big)^* = -\delta_{ij}\,s_\xi\,g_{L,R} + c_\xi\,\big(B_{L,R}\big)_{ij}$$
$$B_L = V_L^\dagger\,g'_L V_L\;,\quad B_R = V_R^\dagger\,g'_R V_R$$
$$\mathrm{diag}\big(m_e, m_\mu, m_\tau\big) = V_L^\dagger\hat{M}_\ell V_R$$

REMARKS

- Presence of nonzero off-diagonal elements of $B_{L,R}$, due to (1) nonuniversality of the diagonal elements of $g'_{L,R}$ and (2) the charged-lepton mixing,
  gives rise to flavor-changing couplings of the Z' to the leptons at tree level.
  ➠ b terms

- Z-Z' mixing introduces not only family nonuniversality, but also flavor violation into the tree-level interactions of the Z boson.
  ➠ β terms

Correlation

- Moreover, there is a relation between the b couplings and the β couplings

$$\beta^{\ell_i \ell_j}_{L,R} \; = \; \delta_{ij} \, \frac{g_{L,R}}{c_\xi} \; + \; t_\xi \, b^{\ell_i \ell_j}_{L,R}$$

SM part

Z' part

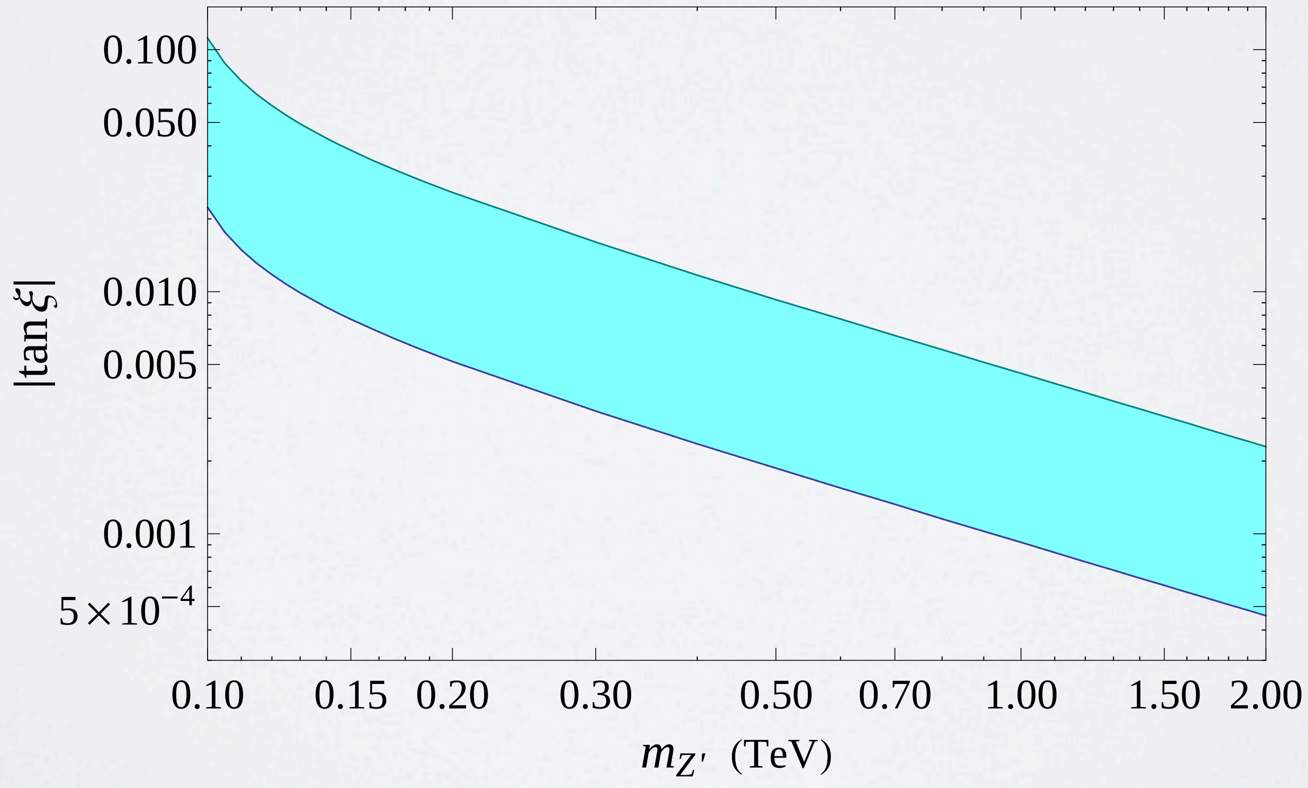
- Couplings of Z and Z' to charged lepton pairs are directly related once the mixing angle ξ is specified.

MIXING FROM EW DATA

- Using the electroweak data $\rho=1.0008^{+0.0017}_{-0.0007}$, one can fix ξ once the Z' mass is known

$$\rho_0 = \frac{m_W^2}{c_{\rm w}^2\, m_Z^2} \simeq 1 + \frac{m_{Z'}^2 - m_Z^2}{m_Z^2}\,\xi^2$$

- Values of $|\tan\xi|$ for 100 GeV ≤ $m_{Z'}$ ≤ 2 TeV:



Constraints from Flavor-Conserving Processes

Leptonic Z Decays

- The amplitude for the Z → l^+l^- decay is

$$\mathcal{M}_{Z\to l^+l^-} = \bar{l}\gamma_\lambda\big(\beta_L^{ll}P_L + \beta_R^{ll}P_R\big)l\,\varepsilon_Z^\lambda$$

- FBA at Z pole and decay rate are

$$A_{\rm FB}^{(0,l)} = \frac{3}{4}\,A_e A_l\ , \quad A_l = \frac{\big(\beta_L^{ll}\big)^2 - \big(\beta_R^{ll}\big)^2}{\big(\beta_L^{ll}\big)^2 + \big(\beta_R^{ll}\big)^2}$$

$$\Gamma_{Z\to l^+l^-} = \frac{\sqrt{m_Z^2 - 4m_l^2}}{16\pi\, m_Z^2}\ \overline{\big|\mathcal{M}_{Z\to l^+l^-}\big|^2}$$

$$\overline{\big|\mathcal{M}_{Z\to l^+l^-}\big|^2} = \frac{2}{3}\Big[\big(\beta_L^{ll}\big)^2 + \big(\beta_R^{ll}\big)^2\Big]\big(m_Z^2 - m_l^2\big) + 4\,m_l^2\,\beta_L^{ll}\beta_R^{ll}$$

In Comparison with Data

- PDG data:

$$A_e^{\mathrm{exp}} = 0.1515 \pm 0.0019\ ,\ \ \Gamma^{\mathrm{exp}}_{Z\to e^+e^-} = 83.91 \pm 0.12\ \mathrm{MeV}$$
$$A_\mu^{\mathrm{exp}} = 0.142 \pm 0.015\ ,\ \ \Gamma^{\mathrm{exp}}_{Z\to \mu^+\mu^-} = 83.99 \pm 0.18\ \mathrm{MeV}$$
$$A_\tau^{\mathrm{exp}} = 0.143 \pm 0.004\ ,\ \ \Gamma^{\mathrm{exp}}_{Z\to \tau^+\tau^-} = 84.08 \pm 0.22\ \mathrm{MeV}$$

- After fixing $g_{L,R}$ to their SM values, one obtains

$$A_e^{\mathrm{SM}} = A_\mu^{\mathrm{SM}} \ = \ A_\tau^{\mathrm{SM}} = 0.1475 \pm 0.0010$$
$$\Gamma^{\mathrm{SM}}_{Z\to e^+e^-} = \Gamma^{\mathrm{SM}}_{Z\to \mu^+\mu^-} = 84.00 \pm 0.06\ \mathrm{MeV}$$
$$\Gamma^{\mathrm{SM}}_{Z\to \tau^+\tau^-} = 83.82 \pm 0.06\ \mathrm{MeV}$$

RESULTS

- Constraints on chiral flavor-conserving Z' couplings with charged leptons for $m_{Z'}$ = 150 GeV:

$$-0.071 \leq b_L^{ee} \leq 0.006\,, \quad -0.11 \leq b_R^{ee} \leq -0.009\,,$$
$$-0.13 \leq b_L^{\mu\mu} \leq 0.25\,, \quad -0.15 \leq b_R^{\mu\mu} \leq 0.27\,,$$
$$-0.070 \leq b_L^{\tau\tau} \leq 0.083\,, \quad -0.002 \leq b_R^{\tau\tau} \leq 0.16\,.$$

- Flipping sign of ξ also flips the signs of $b^{ll}_{L,R}$ numbers.
- In general:

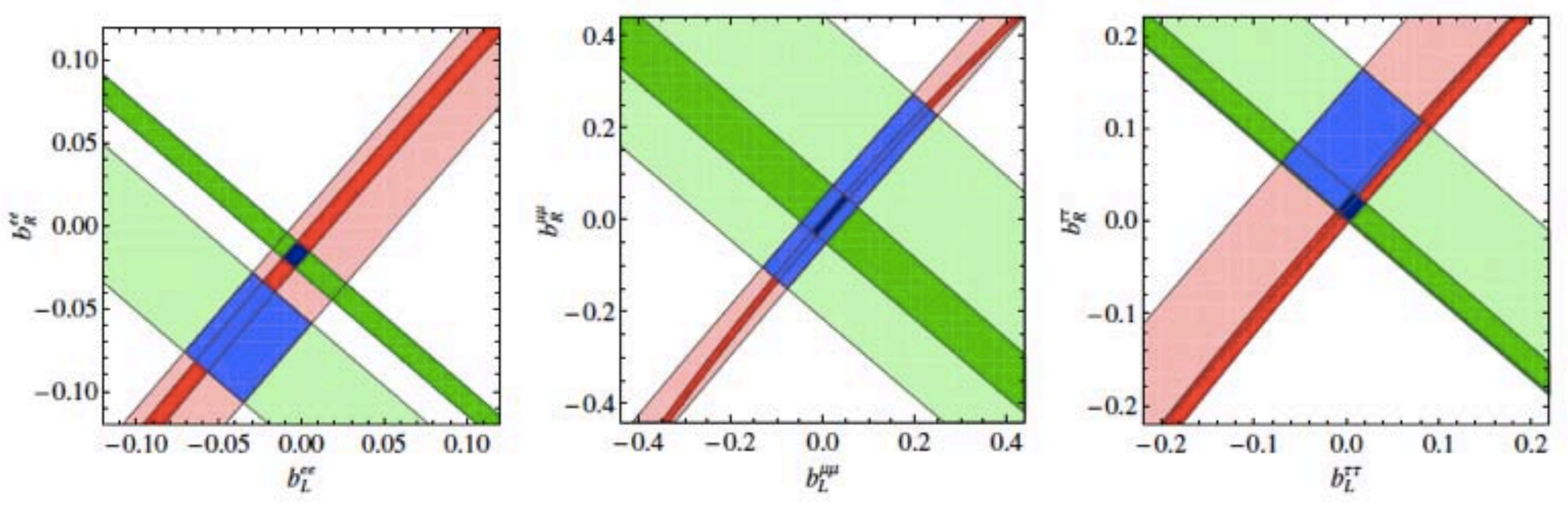


Figure 2. Values of $b^{ll}_{L,R}$ for $m_{Z'}$ = 150 GeV and mixing angle ξ = 0.008 (lighter colors), 0.038 (darker colors), as described in the text, subject to constraints from A_l and $\Gamma_{Z\to l^+l^-}$ data.

THE $e^+e^- \to l^+l^-$ SCATTERING

- With the inclusion Z'-mediated process, the scattering amplitude of $e^+e^- \to l^+l^-$ ($l \neq e$) is

$$\mathcal{M}_{e^+e^-\to\bar{l}l} = -\frac{e_p^2\,\bar{l}\gamma^\nu l\,\bar{e}\gamma_\nu e}{s} + \frac{\bar{l}\gamma^\nu\left(\beta_L^{ll}P_L + \beta_R^{ll}P_R\right)l\,\bar{e}\gamma_\nu\left(\beta_L^{ee}P_L + \beta_R^{ee}P_R\right)e}{m_Z^2 - s} + \frac{\bar{l}\gamma^\nu\left(b_L^{ll}P_L + b_R^{ll}P_R\right)l\,\bar{e}\gamma_\nu\left(b_L^{ee}P_L + b_R^{ee}P_R\right)e}{m_{Z'}^2 - s}$$

- Assumptions:
  - s not close to Z or Z' mass.
  - neglecting contributions of flavor-changing couplings through t-channel.

- Use LEP-II data of $\sqrt{s}$ = 136 – 207 GeV.

More Stringent Bounds

- Constraints on chiral flavor-conserving Z' couplings with charged leptons for $m_{Z'}$ = 150 GeV:

$$-0.071 \leq b_L^{ee} \leq 0.006\ , \quad -0.10 \leq b_R^{ee} \leq -0.009\ ,$$
$$-0.033 \leq b_L^{\mu\mu} \leq 0.080\ , \quad -0.029 \leq b_R^{\mu\mu} \leq 0.095\ ,$$
$$-0.070 \leq b_L^{\tau\tau} \leq 0.024\ , \quad 0 \leq b_R^{\tau\tau} \leq 0.083\ .$$

- For a wider mass range (0.5 – 2 TeV) and in units of 10^{-4} GeV^{-1}:

$$-5.1 \lesssim \frac{b_L^{ee}}{m_{Z'}} \lesssim -1.2\ , \qquad -5.4 \lesssim \frac{b_R^{ee}}{m_{Z'}} \lesssim -1.1\ ,$$
$$-4.3 \lesssim \frac{b_L^{\mu\mu}}{m_{Z'}} \lesssim 3.4\ , \qquad -4.3 \lesssim \frac{b_R^{\mu\mu}}{m_{Z'}} \lesssim 2.1\ ,$$
$$-6.1 \lesssim \frac{b_L^{\tau\tau}}{m_{Z'}} \lesssim -2.0\ , \qquad 1.9 \lesssim \frac{b_R^{\tau\tau}}{m_{Z'}} \lesssim 5.9\ .$$

a reflection of $|\tan\xi| \propto 1/m_{Z'}$

Constraints from Flavor-Changing Tree Processes

Flavor-Changing Processes

- Tree-level flavor-changing processes
  - $Z \to e\mu$, $Z \to e\tau$, $Z \to \mu\tau$
  - $\mu \to 3e$, $\tau \to 3e$, $\tau \to 3\mu$
  - $\tau \to \mu\, e\, \underline{e}$, $\tau \to e\, \mu\, \underline{\mu}$ (single/double flavor-changing)
  - $\tau \to e\, e\, \underline{\mu}$, $\tau \to \mu\, \mu\, \underline{e}$ (double flavor-changing)
  - Muonium-antimuonium conversion $\mu^+e^- \to e^+\mu^-$
  - Flavor-violating $e^+e^- \to \underline{l}\, l'$
- Loop-mediated processes
  - $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$
  - Charged leptons' anomalous magnetic moments
  - Charged leptons' electric dipole moments

Flavor-Changing Z Decays

- Z-Z' mixing induces tree-level flavor-changing Z decays

$$\mathcal{M}_{Z\to l\bar{l}'} = \bar{l}\gamma_\lambda\left(\beta_L^{ll'} P_L + \beta_R^{ll'} P_R\right) l' \, \varepsilon_Z^\lambda$$

$$\Gamma_{Z\to l\bar{l}'} = \frac{|\mathbf{p}_l|\, t_\xi^2}{8\pi m_Z^2}\left\{\left(\left|b_L^{ll'}\right|^2 + \left|b_R^{ll'}\right|^2\right)\left[\frac{2m_Z^2 - m_l^2 - m_{l'}^2}{3} - \frac{(m_l^2 - m_{l'}^2)^2}{3m_Z^2}\right] + 4 m_l m_{l'}\, \mathrm{Re}\left(b_L^{ll'*} b_R^{ll'}\right)\right\}$$

- PDG upper limits:

$$\mathcal{B}(Z\to e^\pm\mu^\mp) < 1.7\times 10^{-6}$$

$$\mathcal{B}(Z\to e^\pm\tau^\mp) < 9.8\times 10^{-6}$$

$$\mathcal{B}(Z\to \mu^\pm\tau^\mp) < 1.2\times 10^{-5}$$

- Assuming that only one of $\beta^{ll'}_{L,R}$ is nonzero at a time, we then obtain constraints on $b^{ll'}_{L,R}$ after specifying ξ associated with a given Z' mass.

Results

- For $m_{Z'}$ = 150 GeV,

$$\left|b^{e\mu}_{L,R}\right| \leq 0.17 \ , \ \left|b^{e\tau}_{L,R}\right| \leq 0.41 \ , \ \left|b^{\mu\tau}_{L,R}\right| \leq 0.44$$

- For the higher masses ($m_{Z'}$ = 0.5 – 2 TeV) and in units of 10^{-3} GeV^{-1}:

$$\frac{\left|b^{e\mu}_{L,R}\right|}{m_{Z'}} \lesssim 1.4 \ , \ \frac{\left|b^{e\tau}_{L,R}\right|}{m_{Z'}} \lesssim 3.5 \ , \ \frac{\left|b^{\mu\tau}_{L,R}\right|}{m_{Z'}} \lesssim 3.8$$

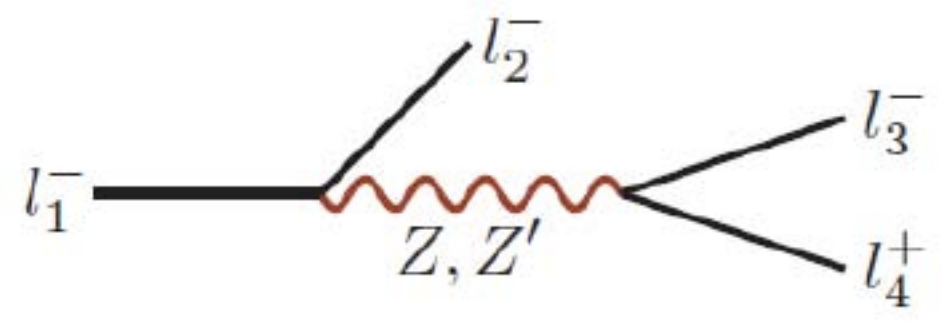
➠ O(1) coupling for $m_{Z'}$ = 1 TeV.

also equivalent to constraint on effective 4-fermion interactions

$\mu \to 3e$ and $\tau \to 3e$

- PDG upper bounds:

$$\mathcal{B}(\mu^- \to e^- e^+ e^-)_{\rm exp} < 1.0 \times 10^{-12}$$
$$\mathcal{B}(\tau^- \to e^- e^+ e^-)_{\rm exp} < 2.7 \times 10^{-8}$$



- Assume that only one of $\beta^{e\mu}_{L,R}$ is non-vanishing at a time.
- For $m_{Z'}$ = 150 GeV:

$$\left|b_L^{e\mu}\right| \leq 4.6 \times 10^{-5} \ , \ \left|b_R^{e\mu}\right| \leq 5.7 \times 10^{-5}$$
$$\left|b_L^{e\tau}\right| \leq 0.018 \ , \ \left|b_R^{e\tau}\right| \leq 0.022$$

- For $m_{Z'}$ = 0.5 – 2 TeV, we have

$$\frac{\left|b_L^{e\mu}\right|}{m_{Z'}} \lesssim 1.4 \times 10^{-7}\ {\rm GeV}^{-1} \ , \ \frac{\left|b_R^{e\mu}\right|}{m_{Z'}} \lesssim 1.8 \times 10^{-7}\ {\rm GeV}^{-1}$$
$$\frac{\left|b_L^{e\tau}\right|}{m_{Z'}} \lesssim 5.3 \times 10^{-5}\ {\rm GeV}^{-1} \ , \ \frac{\left|b_R^{e\tau}\right|}{m_{Z'}} \lesssim 6.9 \times 10^{-5}\ {\rm GeV}^{-1}$$

- $\tau \to 3\mu$ cannot provide useful constraints on $|b_{L,R}^{\mu\tau}|$.

$\tau \to \mu\, e\, \underline{e}$, $\tau \to e\, \mu\, \underline{\mu}$

- PDG data

$$\mathcal{B}(\tau^- \to \mu^- e^+ e^-)_{\text{exp}} < 1.8 \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)_{\text{exp}} < 2.7 \times 10^{-8}$$

- For $m_{Z'}$ = 150 GeV:

$$\left|b^{\mu\tau}_{L,R}\right| \leq 0.019$$

and weak bound on $|b_{L,R}^{e\tau}|$.

- For $m_{Z'}$ = 0.5 – 2 TeV, we have

$$\frac{\left|b^{\mu\tau}_{L,R}\right|}{m_{Z'}} \lesssim 6 \times 10^{-5}\ \text{GeV}^{-1}$$

- As we will see, $\mu \to 3e$, $\tau \to 3e$, and $\tau \to \mu\, e\, \underline{e}$ provide most stringent restrictions on flavor-changing couplings.

τ → e e <u>μ</u>, τ → μ μ <u>e</u>

- PDG data

$$\mathcal{B}(\tau^- \to \mu^+ e^- e^-)_{\rm exp} < 1.5 \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to e^+ \mu^- \mu^-)_{\rm exp} < 1.7 \times 10^{-8}$$

- Constraints

$$\frac{\left|b^{\mu e}_{L,R} b^{\mu\tau}_{L,R}\right|}{m^2_{Z'}} \le 7.2 \times 10^{-9}\ \mathrm{GeV}^{-2}$$
$$\frac{\left|b^{\mu e}_{L,R} b^{\mu\tau}_{R,L}\right|}{m^2_{Z'}} \le 1.0 \times 10^{-8}\ \mathrm{GeV}^{-2}$$

are roughly 3 orders of magnitude less strict than the corresponding constraints inferred from single flavor-changing processes.

Muonium Conversion

- The experimental information on $\mu^+ e^- \to \mu^- e^+$ is available in terms of the effective parameter G_C defined by

$$\mathcal{L}_{\text{eff}} = \sqrt{8}\, G_C \, \bar{\mu}\gamma^\nu P_{L,R} e \, \bar{\mu}\gamma_\nu P_{L,R} e \; + \; \text{h.c.}$$

and has been measured to be $|G_C| < 0.0030 G_F$, where G_F is the Fermi coupling constant.

- Attributing this to the Z′ implies that

$$\frac{\left|b^{\mu e}_{L,R}\right|}{m_{Z'}} = 2\sqrt{\sqrt{2}\,|G_C|} \leq 4.4 \times 10^{-4}\ \text{GeV}^{-1}$$

far less restrictive than previous pages.

$$e^+e^- \to \bar{l}l'$$

- Limits on cross sections $\sigma(ll') \equiv \sigma(e\underline{e} \to \underline{l}l') + \sigma(ee \to l\underline{l}')$ were acquired by the OPAL Collaboration at LEP-II energies, 200GeV ≤ √s ≤ 209GeV: OPAL 2001
  $\sigma(e\mu)_{exp} < 22$ fb, $\sigma(e\tau)_{exp} < 78$ fb, and $\sigma(\mu\tau)_{exp} < 64$ fb
- More recent bounds on cross sections at much lower energies, around 11 and 1GeV, were reported by the BaBar and SND Collaborations, respectively. BaBar 2007 SND2010
- We obtain

$$\left|b_L^{\mu e}\right| < 0.76\ ,\ \left|b_R^{\mu e}\right| < 0.52$$

$$\left|b_L^{\tau e}\right| < 1.4\ ,\ \left|b_R^{\tau e}\right| < 1.0$$

$$\left|b_{L,R}^{e\mu} b_{L,R}^{\tau e}\right| \leq 0.017\ ,\ \left|b_{L,R}^{e\mu} b_{R,L}^{\tau e}\right| \leq 0.012$$

Constraints from Flavor-Changing Loop Processes

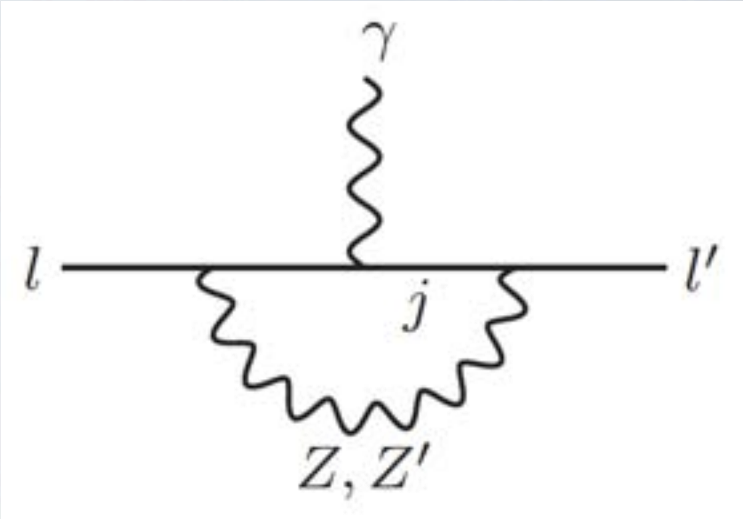
$l \to l'\gamma$

- Latest data from MEG Collab.:

$$\mathcal{B}(\mu \to e\gamma)_{\rm exp} < 2.4 \times 10^{-12}$$

- Due to mass enhancement, we obtain

$$\frac{\left|b^{\mu\tau}_{L,R} b^{\tau e}_{R,L}\right|}{m^2_{Z'}} \leq 2.6 \times 10^{-11}$$



- The other two modes

$$\mathcal{B}(\tau \to e\gamma)_{\rm exp} < 3.3 \times 10^{-8}$$

$$\mathcal{B}(\tau \to \mu\gamma)_{\rm exp} < 4.4 \times 10^{-8}$$

are not strong enough.

Anomalous Magnetic Moment

- Anomalous magnetic moments from e and μ from Z' are

$$a_e^{Z'} = \frac{m_e m_\tau \,\mathrm{Re}\left(b_L^{e\tau} b_R^{\tau e}\right)}{4\pi^2\, m_{Z'}^2} \;, \quad a_\mu^{Z'} = \frac{m_\mu m_\tau \,\mathrm{Re}\left(b_L^{\mu\tau} b_R^{\tau\mu}\right)}{4\pi^2\, m_{Z'}^2}$$

- Current between data and SM:

Jegerlehner and Nyffeler 2009

$$a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = (-206 \pm 770) \times 10^{-14}$$
$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (29 \pm 9) \times 10^{-10}$$

- We obtain

$$-4.2 \times 10^{-7} \leq \frac{\mathrm{Re}\left(b_L^{e\tau} b_R^{\tau e}\right)}{m_{Z'}^2 \,\mathrm{GeV}^{-2}} \leq 2.4 \times 10^{-7}$$
$$0 \leq \frac{\mathrm{Re}\left(b_L^{\mu\tau} b_R^{\tau\mu}\right)}{m_{Z'}^2 \,\mathrm{GeV}^{-2}} \leq 8.0 \times 10^{-7}$$

less stringent than previous processes.

ELECTRIC DIPOLE MOMENT

- Electric dipole moments from e and μ from Z' are

$$d_e^{Z'} = \frac{e_p\, m_\tau\, \mathrm{Im}\big(b_L^{e\tau} b_R^{\tau e}\big)}{8\pi^2\, m_{Z'}^2}\ ,\quad d_\mu^{Z'} = \frac{e_p\, m_\tau\, \mathrm{Im}\big(b_L^{\mu\tau} b_R^{\tau\mu}\big)}{8\pi^2\, m_{Z'}^2}$$

- SM predictions are orders of magnitude smaller than current data

$$\big|d_e\big|_{\exp} \leq 1.6 \times 10^{-27}\, e\,\mathrm{cm}\ ,\quad \big|d_\mu\big|_{\exp} \leq 1.8 \times 10^{-19}\, e\,\mathrm{cm}$$

- These constraints translate to

$$\frac{\big|\mathrm{Im}\big(b_L^{e\tau} b_R^{\tau e}\big)\big|}{m_{Z'}^2} \leq 3.6 \times 10^{-12}\ \mathrm{GeV}^{-2}$$

$$\frac{\big|\mathrm{Im}\big(b_L^{\mu\tau} b_R^{\tau\mu}\big)\big|}{m_{Z'}^2} \leq 4.1 \times 10^{-4}\ \mathrm{GeV}^{-2}$$

possibly strong constraint, but relative phase uncertain

Predictions Based On Above Constraints

Observables to Test

- In the following, we take the upper limits of our strongest constraints to make predictions for observables.

- We only list those that can be quickly tested by upcoming experiments.

SUMMARY OF STRONGEST LIMITS

- Define

$$\hat{b}^{\ell_i \ell_j}_{L,R} = \frac{b^{\ell_i \ell_j}_{L,R}}{m_{Z'}}$$

- For $m_{Z'}$ = 150 GeV and in units of GeV^{-1}:

$$-4.7 \times 10^{-4} \leq \hat{b}^{ee}_L \leq 0.4 \times 10^{-4} \,, \quad -6.6 \times 10^{-4} \leq \hat{b}^{ee}_R \leq -0.6 \times 10^{-4} \,,$$
$$-2.2 \times 10^{-4} \leq \hat{b}^{\mu\mu}_L \leq 5.4 \times 10^{-4} \,, \quad -2.0 \times 10^{-4} \leq \hat{b}^{\mu\mu}_R \leq 6.3 \times 10^{-4} \,,$$
$$-4.6 \times 10^{-4} \leq \hat{b}^{\tau\tau}_L \leq 1.6 \times 10^{-4} \,, \quad 0 \leq \hat{b}^{\tau\tau}_R \leq 5.6 \times 10^{-4} \,.$$

$$|\hat{b}^{e\mu}_L| \leq 3.1 \times 10^{-7} \,, \qquad |\hat{b}^{e\mu}_R| \leq 3.8 \times 10^{-7} \,,$$
$$|\hat{b}^{e\tau}_L| \leq 1.2 \times 10^{-4} \,, \qquad |\hat{b}^{e\tau}_R| \leq 1.5 \times 10^{-4} \,,$$
$$|\hat{b}^{\mu\tau}{}_{L,R}| \leq 1.2 \times 10^{-4} \,,$$

SUMMARY OF STRONGEST LIMITS

- For $m_{Z'}$ = 0.5 – 2 TeV and in units of GeV^{-1}:

$$-5.1\times10^{-4}\lesssim\hat{b}_L^{ee}\lesssim-1.2\times10^{-4}\ ,\quad -5.4\times10^{-4}\lesssim\hat{b}_R^{ee}\lesssim-1.1\times10^{-4}\ ,$$

$$-4.3\times10^{-4}\lesssim\hat{b}_L^{\mu\mu}\lesssim3.4\times10^{-4}\ ,\quad -4.3\times10^{-4}\lesssim\hat{b}_R^{\mu\mu}\lesssim2.1\times10^{-4}\ ,$$

$$-6.1\times10^{-4}\lesssim\hat{b}_L^{\tau\tau}\lesssim-2.0\times10^{-4}\ ,\quad 1.9\times10^{-4}\lesssim\hat{b}_R^{\tau\tau}\lesssim5.9\times10^{-4}$$

$$|\hat{b}_L^{e\mu}|\ \lesssim\ 1.4\times10^{-7}\ ,\qquad |\hat{b}_R^{e\mu}|\ \lesssim\ 1.8\times10^{-7}\ ,$$

$$|\hat{b}_L^{e\tau}|\ \lesssim\ 5.3\times10^{-5}\ ,\qquad |\hat{b}_R^{e\tau}|\ \lesssim\ 6.9\times10^{-5}\ ,$$

$$|\hat{b}^{\mu\tau}_{L,R}|\ \lesssim\ 6\times10^{-5}\ ,$$

- Constraints on flavor-conserving couplings have come from Z-pole and LEP-II data.
- Constraints on flavor-changing couplings have come from μ → 3e, τ → 3e, and τ → μ e $\underline{e}$ data.

PREDICTIONS FOR Z' DECAYS

- Flavor-conserving ones:

$$\Gamma_{Z'\to e^+e^-} \lesssim 7\times 10^{-9}\ m_{Z'}^3\ \mathrm{GeV}^{-2}\ ,$$

$$\Gamma_{Z'\to \mu^+\mu^-} \lesssim 4\times 10^{-9}\ m_{Z'}^3\ \mathrm{GeV}^{-2}\ ,$$

$$\Gamma_{Z'\to \tau^+\tau^-} \lesssim 9\times 10^{-9}\ m_{Z'}^3\ \mathrm{GeV}^{-2}$$

leading to a few GeV if $m_{Z'}$ = 1 TeV.

- Flavor-changing ones:

$$\Gamma_{Z'\to e^\pm\mu^\mp} \lesssim 4\times 10^{-15}\ m_{Z'}^3\ \mathrm{GeV}^{-2}\ ,$$

$$\Gamma_{Z'\to e^\pm\tau^\mp} \lesssim 6\times 10^{-10}\ m_{Z'}^3\ \mathrm{GeV}^{-2}\ ,$$

$$\Gamma_{Z'\to \mu^\pm\tau^\mp} \lesssim 4\times 10^{-10}\ m_{Z'}^3\ \mathrm{GeV}^{-2}$$

leading to a very stringent constraint for the first mode, a few tenth GeV for last two if $m_{Z'}$ = 1 TeV.

PREDICTIONS FOR Z DECAYS

- For $m_{Z'}$ = 150 GeV:

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \leq 4.5 \times 10^{-12}$$

$$\mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \leq 6.8 \times 10^{-7}$$

$$\mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \leq 5.1 \times 10^{-7}$$

- The latter two predictions are, respectively, only less than 25 times away from the existing PDG limits

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp})_{\rm exp} < 1.7 \times 10^{-6}$$

$$\mathcal{B}(Z \to e^{\pm}\tau^{\mp})_{\rm exp} < 9.8 \times 10^{-6}$$

$$\mathcal{B}(Z \to \mu^{\pm}\tau^{\mp})_{\rm exp} < 1.2 \times 10^{-5}$$

Loop Processes

- Radiative lepton flavor-changing decays

$$\mathcal{B}(\tau \to e\gamma) \leq 2.3 \times 10^{-8} \ , \ \ \mathcal{B}(\tau \to \mu\gamma) \leq 2.1 \times 10^{-8}$$

not far from the current upper limits

$$\mathcal{B}(\tau \to e\gamma)_{\rm exp} < 3.3 \times 10^{-8} \ , \ \ \mathcal{B}(\tau \to \mu\gamma)_{\rm exp} < 4.4 \times 10^{-8}$$

- The other processes do not receive much enhancement from the Z' boson.

SUMMARY

- We have analyzed family-nonuniversal couplings of charged leptons to a Z’ boson with general kinetic and mass mixing with the Z boson.
- Employing current experimental data and taking a model-independent approach, we have performed a comprehensive study of constraints on both flavor-conserving and flavor-violating leptonic Z’ couplings.
- Using the upper limits of the most constrained couplings, we have estimated the maximum rates of a number of flavor-conserving and flavor-violating decays to be tested in upcoming experiments.

Thank You!