Seminar @ Nagoya Univ.

Complete Vector-like 4th Family and U(1)' for Muon Anomalies

arXiv:1906.11297
and working in progress

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with

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Outline

1. Introduction
2. Vector-Like 4^{th} Family with Vector-Like U(1)’
3. Phenomenology
4. LHC Signals
5. Conclusion

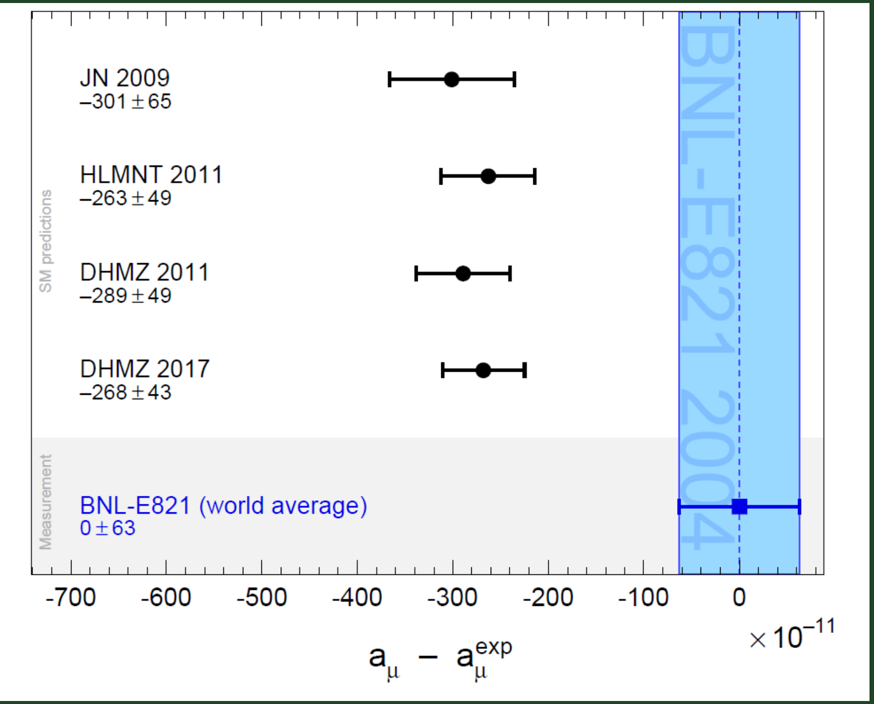
Muon Anomalies

- Muon $g-2$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$$

$$= 2.68\,(63)(43) \times 10^{-9}$$

$$\sim 3.5\,\sigma$$



now new experiment running @ Fermilab

$\longrightarrow$ $> 5\,\sigma$?? + J-PARC

Muon Anomalies

- Muon $g-2$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 2.68\,(63)(43) \times 10^{-9} \quad \sim 3.5\,\sigma$$

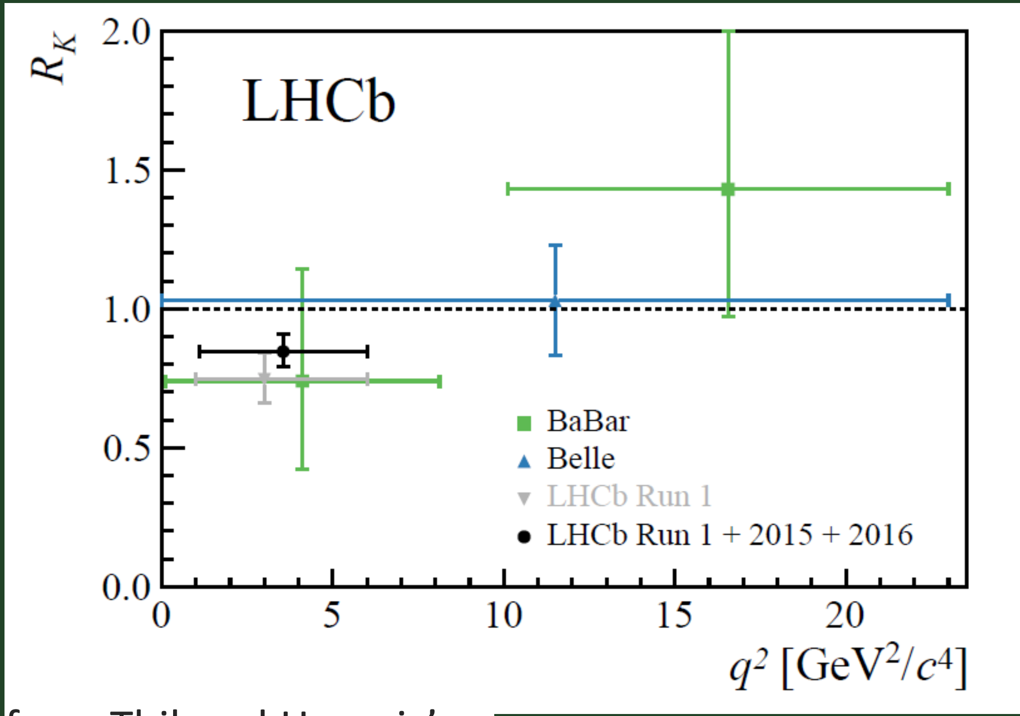
- Muon Anomalies for $b \to s\,\mu^+\mu^-$ Processes

  - Lepton Non-Universality $R_{K^{(*)}}$
  - angular observables in $B \to K^*\mu^+\mu^-$
  - branching ratio of $B_s \to \phi\,\mu^+\mu^-$
  - e.t.c.

$\underline{R_K}$ Anomaly …

$$R_K = \frac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{B(B^+ \to K^+e^+e^-)}{B(B^+ \to J/\psi\,(\to e^+e^-)K^+)}$$

SM holds lepton universality: $R_K = 1$



from Thibaud Humair's slide @ Moriond 2019

- Before Moriond 2019

  $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$

  $\sim 2.6\ \sigma$ below

- After Moriond 2019

  $R_K = 0.846^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}$

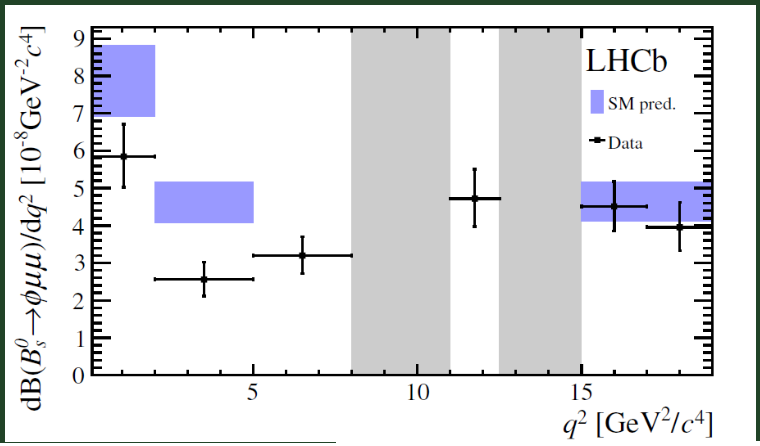
  $\sim 2.5\ \sigma$ below

$b \to s\, \mu^+\mu^-$ Anomalies

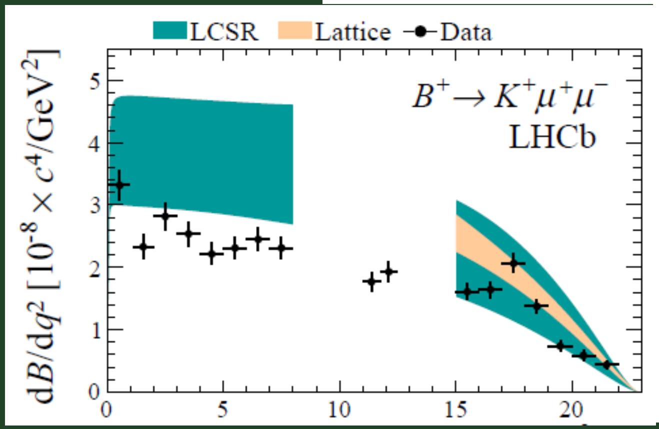
- Lepton Non-Universality

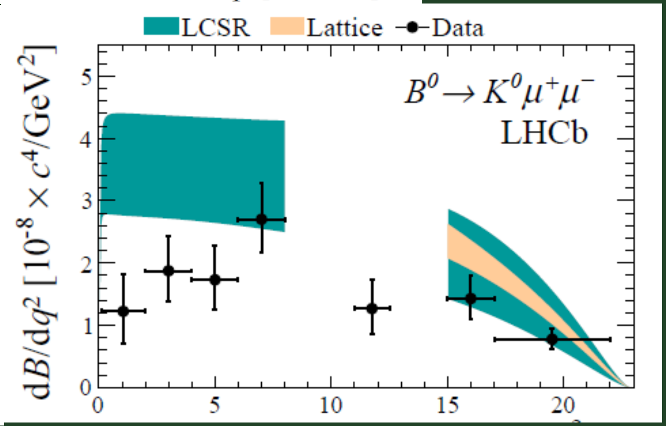
$$R_K = 0.846^{+0.060}_{-0.054}\,{}^{+0.016}_{-0.014}$$ below $R_K^{SM} = 1.0 \sim 2.5\,\sigma$

- Branching ratio $B \to \phi\, \mu^+\mu^-, K\mu^+\mu^-$



below SM pred.
$\sim 3.0\,\sigma$



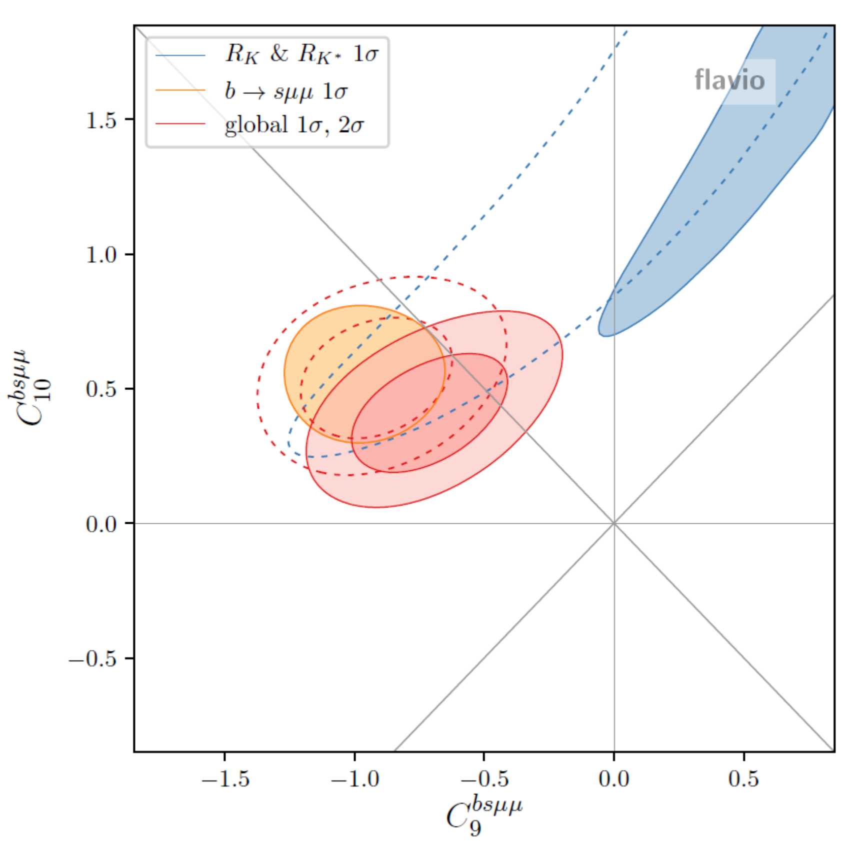


below SM pred.

$b \to s\,\mu^+\mu^-$ Anomalies

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha}{4\pi} \sum_{j=9,10} \left(C_j\,\mathcal{O}_j + C_j'\mathcal{O}_j'\right) + h.c.$$

$$\mathcal{O}_9^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}_{10}^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu\gamma_5 \mu)$$



J. Aebischer, W.Altmannshofer, et.al
1903.10434

$b \to s\,\mu^+\mu^-$ Anomalies

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{j=9,10} \left(C_j\, \mathcal{O}_j + C_j' \mathcal{O}_j' \right) + h.c.$$

$$\mathcal{O}_9^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}_{10}^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

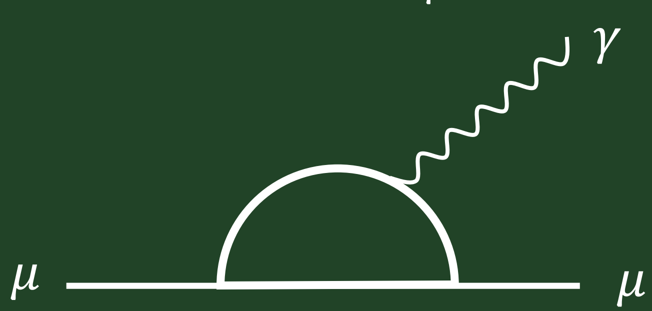
Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10,\ -0.79]$	$[-1.26,\ -0.63]$	5.8σ
$C_9^{\prime bs\mu\mu}$	$+0.09$	$[-0.07,\ +0.24]$	$[-0.23,\ +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59,\ +0.87]$	$[+0.46,\ +1.01]$	5.6σ
$C_{10}^{\prime bs\mu\mu}$	-0.19	$[-0.30,\ -0.07]$	$[-0.41,\ +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05,\ +0.35]$	$[-0.09,\ +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62,\ -0.45]$	$[-0.70,\ -0.36]$	6.5σ

J. Aebischer, W.Altmannshofer, et.al, 1903.10434

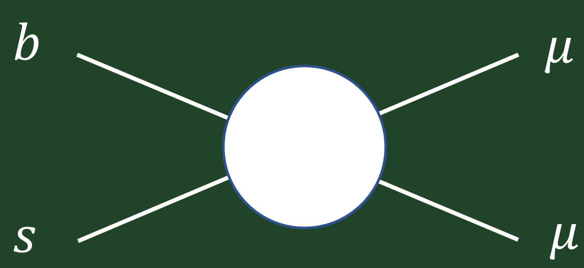
$$\text{pull} = \sqrt{\chi^2_{SM} - \chi^2} > 5.5\sigma$$

Guideline for Model Building

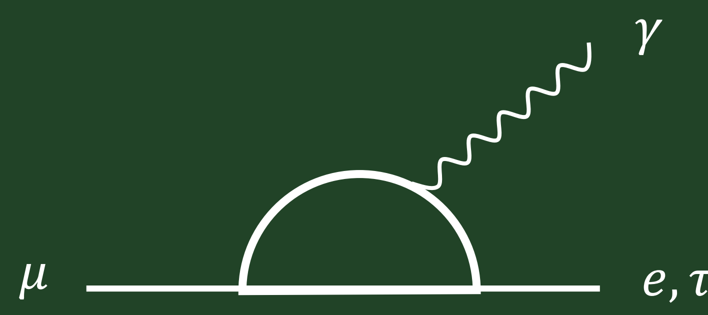
- We need
  - Successful SM observables
  - Muon g-2 : $\Delta a_\mu \sim 2.68 \times 10^{-9}$



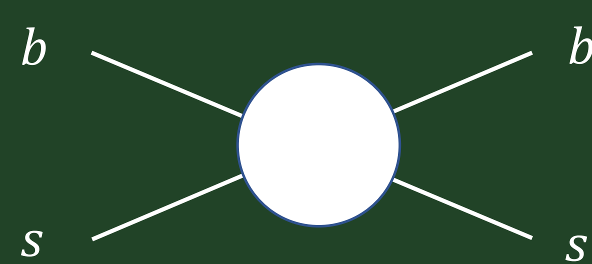
  - $b \to s\, \mu^+\mu^-$: $C_9^{NP} \lesssim -0.5$



- We do not need
  - too light exotic, too large coupling
  - Lepton Flavor Violation (LFV)



  - NP effect to $B - \overline{B},\ K - \overline{K}$ mixing



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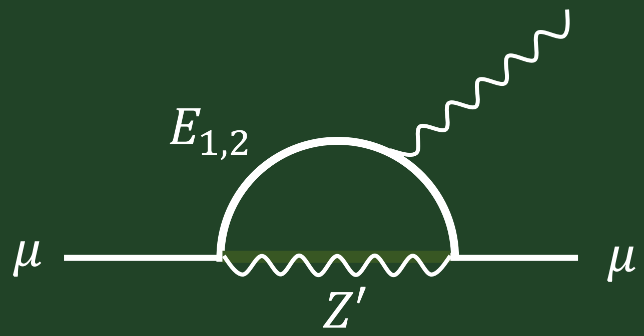
VL-fermion + $U(1)'$

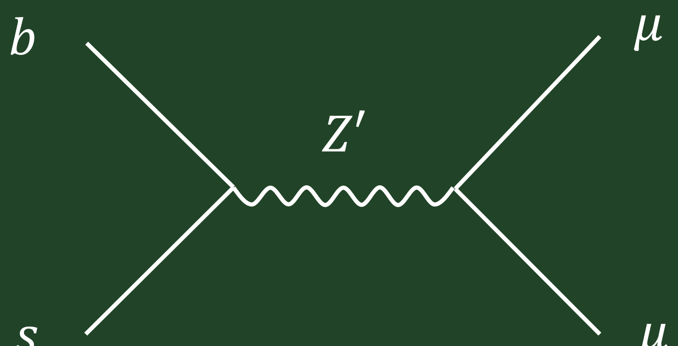
simultaneous explanation for muon anomalies

- $U(1)' +$ VL-leptons



$\rightarrow \quad (g-2)_\mu$

- $+$ VL-qaurks



$\rightarrow \quad C_9^{NP}, C_{10}, C_9'$

- Models

- $U(1)_{L_\mu - L_\tau}$ + VL-lepton + VL-quark — W.Altmannshofer et.al 1604.08221
- $U(1)_{3-4}$ + VL 4$^{\text{th}}$ family — S. Raby, A.Trautner 1712.09360
- e.t.c. — Allanach, Queiroz et.al 1511.07447, Megias, Quiros et.al 1701.05072

Our Model

➢ Complete Vector-Like 4th Family + $U(1)'$

	Q_L	$\overline{U}_R$	$\overline{D}_R$	L_L	$\overline{E}_R$	$\overline{N}_R$	$\overline{Q}_R$	U_L	D_L	$\overline{L}_R$	E_L	N_L	ϕ	Φ
$SU(3)_C$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{3}$	$-\frac{4}{3}$	$\frac{2}{3}$	-1	2	0	$-\frac{1}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	1	-2	0	0	0
$U(1)'$	-1	+1	+1	-1	+1	+1	+1	-1	-1	+1	-1	-1	0	-1

Vector-Like (VL)-fermions

$\langle\phi\rangle\sim\langle\Phi\rangle\sim\mathrm{TeV}$

*similar setup:
A. Falkowski, S. F. King et.al
1803.04430

- Only the VL-family have $U(1)'$ charge
- All Z'- SM particle couplings appear in mass basis
- Unwanted new physics contributions may be evaded

Mass Matrix and Couplings

- Yukawa interactions and mass matrix

$$-\mathcal{L}_{\text{Yukawa}} = \overline{e}_{R_i} Y_e^{ij}\, l_{L_j}\, H + \lambda_e \overline{E}_R L_L H - \lambda'_e \overline{L}_R \widetilde{H} E_L$$
$$+\lambda_V^L \phi\, \overline{L}_R L_L - \lambda_V^E \phi\, \overline{E}_R E_R + \lambda_i^L \Phi \overline{L}_R l_{L_i} - \lambda_i^E \Phi^* \overline{e}_{R_i} E_L$$

$$\longrightarrow \qquad \overline{\hat{E}}_R M_e \hat{E}_L = \begin{pmatrix} \overline{e}_{R_i} & \overline{E}_R & \overline{E'_R} \end{pmatrix} \begin{pmatrix} Y_e^{ij} H & 0 & \lambda_i^L \Phi \\ 0 & \lambda_e H & \lambda_V^E \phi \\ \lambda_j^L \Phi & \lambda_V^L \phi & \lambda'_e H \end{pmatrix} \begin{pmatrix} e_{L_j} \\ E'_L \\ E_L \end{pmatrix}$$

* similar for quarks/neutrino

- Z'-coupling in mass basis : $U_R^{e\dagger} M_e U_L^e = \mathrm{diag}(m_e, m_\mu, m_\tau, m_{E_1}, m_{E_2})$

$$g_{e_L}^{Z'} = g' U_L^{e\dagger} \begin{pmatrix} 0_{3\times3} & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} U_L^e \qquad g_{e_R}^{Z'} = g' U_R^{e\dagger} \begin{pmatrix} 0_{3\times3} & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} U_R^e$$

rotation matrices determine Z'-couplings to the SM families

Diagonalization

$$\overline{\hat{E}}_R M_e \hat{E}_L = \boxed{\begin{pmatrix} \overline{e}_{R_i} & \overline{E}_R \end{pmatrix}} \; \overline{E'_R} \begin{pmatrix} Y_e^{ij} H & 0 & \boxed{\begin{matrix} \lambda_i^L \Phi \\ \lambda_V^E \phi \end{matrix}} \\ 0 & \lambda_e H & \\ \boxed{\begin{matrix} \lambda_j^L \Phi & \lambda_V^L \phi \end{matrix}} & & \lambda'_e H \end{pmatrix} \begin{pmatrix} \boxed{\begin{matrix} e_{L_j} \\ E'_L \end{matrix}} \\ E_L \end{pmatrix}$$

weak singlet

weak doublet

$$U_L = \begin{pmatrix} u_L^{4\times 4} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1_{3\times 3} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad U_R = \begin{pmatrix} u_R^{4\times 4} & 0 \\ 0 & 1 \end{pmatrix}$$

rotating within 4 weak singlets/doublets (+ flip)

$$\longrightarrow \qquad U_R^\dagger \, M_e U_L = \begin{pmatrix} \mathrm{diag}(m_e, m_\mu, m_\tau) & y_{R_i} H & 0 \\ 0 & M_E & \lambda'_e H \\ y_{L_j} H & y_4 H & M_L \end{pmatrix}$$

Approximately diagonalized where $yH \ll M_E, M_L$

SM boson coupling

- SU(2) gauge coupling

$$g W_\mu^a \overline{\hat{F}} \gamma^\mu T^a \left[\begin{pmatrix} 1_{3\times3} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} P_L + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} P_R \right] \begin{pmatrix} e_i \\ E_E \\ E_L \end{pmatrix}$$

E_E: singlet state

E_L: double state

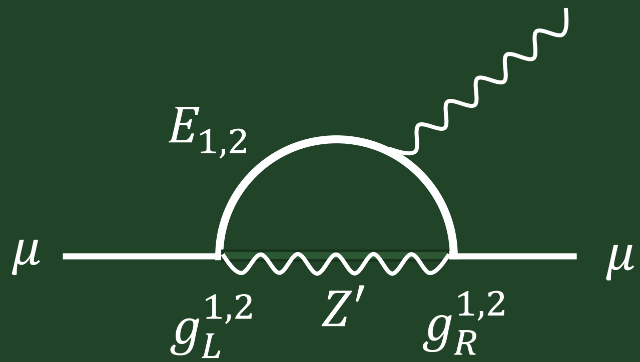
$$\Big\downarrow$$

$$U_L = \begin{pmatrix} u_L^{4\times4} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1_{3\times3} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad U_R = \begin{pmatrix} u_R^{4\times4} & 0 \\ 0 & 1 \end{pmatrix}$$

$$U_L^\dagger \begin{pmatrix} 1_{3\times3} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} U_L = \begin{pmatrix} 1_{3\times3} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad U_R^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R = \begin{pmatrix} 0_{3\times3} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Weak gauge couplings are SM-like at leading order $H \ll \Phi, \phi$
- Higgs boson is SM-like as well

Muon $g-2$



$$c_{LE} = M_L M_E \frac{G_Z(x_L) - G_Z(x_E)}{M_L^2 - M_E^2}$$

$$\Delta a_\mu \sim -\frac{m_\mu}{8\pi^2 m_{Z'}^2} \sum g_L^{Z' E_a} g_R^{Z' E_a} m_{E_a} G_Z(x_a)$$

c.f.)

$$\sim g' Z'_\mu \overline{\hat{E}} \gamma^\mu \left[\begin{pmatrix} s^2_{\theta_{\mu_L}} & \boxed{0} & \boxed{s_{\theta_{\mu_L}} c_{\theta_{\mu_L}}} \\ 0 & 1 & 0 \\ s_{\theta_{\mu_L}} c_{\theta_{\mu_L}} & 0 & c^2_{\mu_L} \end{pmatrix} P_L + \begin{pmatrix} s^2_{\theta_{\mu_R}} & \boxed{s_{\theta_{\mu_R}} c_{\theta_R}} & \boxed{0} \\ s_{\theta_R} c_{\theta_{\mu_R}} & c^2_{\mu_R} & 0 \\ 0 & 0 & 1 \end{pmatrix} P_R \right] \begin{pmatrix} \mu \\ E_E \\ E_L \end{pmatrix}$$

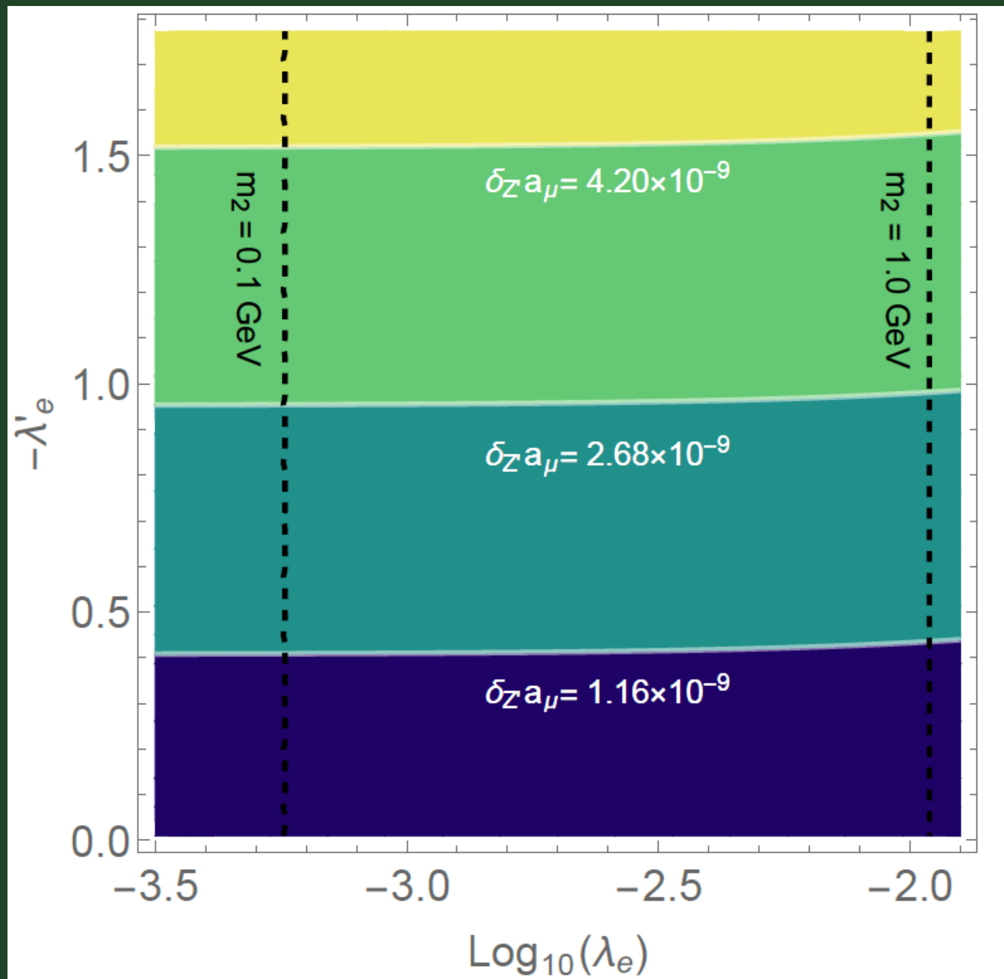
- $E_E - E_L$ mixing is induced by Higgs coupling: $\lambda'_e \overline{L}_R \widetilde{H} E_L$

$$\Delta a_\mu \sim 2.9 \times 10^{-9} \times \sin 2\theta_{\mu_L} \cdot \sin 2\theta_{\mu_R} \times \left(\frac{c_{LE}}{0.1}\right) \left(\frac{\lambda'_e}{1.0}\right) \left(\frac{1\mathrm{TeV}}{\Phi}\right)^2$$

$\theta_{\mu_{L,R}} \sim \pi/4,\ \lambda'_e H/\Phi \gtrsim 0.1$ are needed

* ∃ subdominant contributions from U(1)' breaking scalar χ

Muon mass and $g-2$



c.f.) mass matrix

$$\begin{pmatrix} Y_e^{ij} H & 0 & \lambda_i^L \Phi \\ 0 & \lambda_e H & \lambda_V^E \phi \\ \lambda_j^L \Phi & \lambda_V^L \phi & \lambda'_e H \end{pmatrix}$$

$m_{Z'} = \lambda_V^{L,E}\,\phi = \lambda_2^{E,L}\Phi = 500\ \mathrm{GeV}$, others $= 0$

$\lambda_e H \lesssim m_\mu$ and $\lambda'_e \gtrsim 0.4$ are needed

$(g-2)_\mu$ and $U(1)'$charge

➢ To write $\lambda_e' \overline{L}_R \widetilde{H} E_L$

	Q_L	$\overline{U}_R$	$\overline{D}_R$	L_L	$\overline{E}_R$	$\overline{N}_R$	$\overline{Q}_R$	U_L	D_L	$\overline{L}_R$	E_L	N_L	ϕ	Φ
$SU(3)_C$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{3}$	$-\frac{4}{3}$	$\frac{2}{3}$	-1	2	0	$-\frac{1}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	1	-2	0	0	0
$U(1)'$	-1	+1	+1	-1	+1	+1	+1	-1	-1	+1	-1	-1	0	-1

✓ cannot be like

$U(1)'$	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	0	-1

➢ $SU(5)$ vs Pati-Salam $G_{\mathrm{PS}} = SU(4) \times SU(2) \times SU(2)$

× $(L_L, \overline{D}_R) \in \overline{5}$, $(Q_L, \overline{U}_R, \overline{E}_R) \in 10$ in $SU(5)$

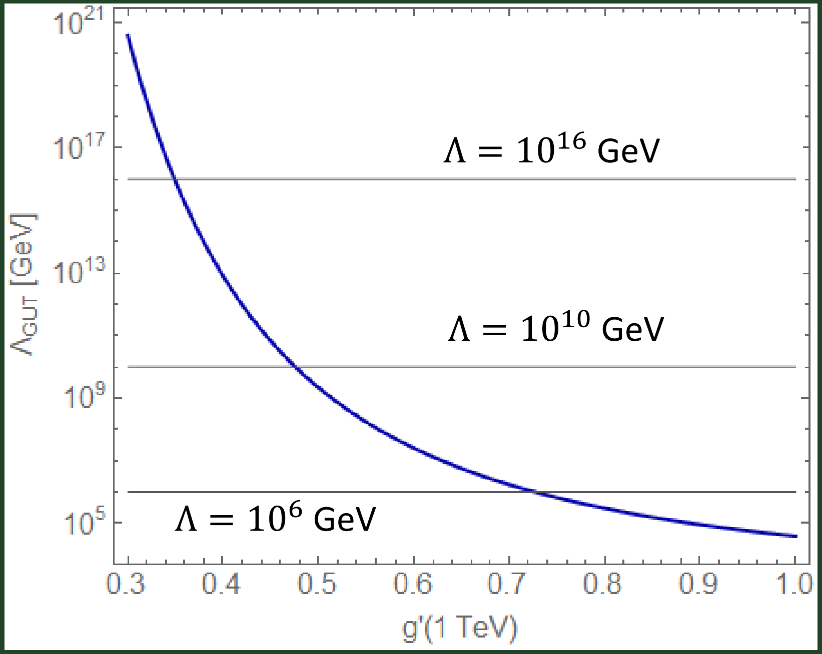
○ $(Q_L \quad L_L) \in (4, 2, 1)$, $\begin{pmatrix} \overline{D}_R & \overline{E}_R \\ \overline{U}_R & \overline{N}_R \end{pmatrix} \in (\overline{4}, 1, 2)$ in Pati-Salam

Towards Grand Unification

➢ UV-completion of model

- extra VL-family, extra U(1)' often appear in GUT/string model
  0409098, 0606187, 0708.2691, 1211.4317
- Complete family may be easily embedded into GUT models

➢ Gauge coupling constant running



$$\frac{d\, g'}{d\, \ln\mu} = \frac{65}{3} \cdot \frac{g'^3}{16\pi^2}$$

- Landau pole easily appear
- $g' \lesssim 0.35$ for $\Lambda \sim 10^{16}$ GeV
- $g' \lesssim 0.48$ for $\Lambda \sim 10^{10}$ GeV

Neutrino Mass

- Majorana mass for $\nu_{R_{1,2,3}}$, $M_R \sim 10^{14}$ GeV

$$M_{Dirac} = \begin{pmatrix} Y_\nu^{ij} H & 0_i & \lambda_i^N \Phi \\ 0_j & \lambda_\nu H & \lambda_V^N \phi \\ \lambda_j^L \Phi & \lambda_V^L \phi & \lambda'_\nu H \end{pmatrix} \xrightarrow{U_L} \widetilde{M}_{Dirac} = \begin{pmatrix} \tilde{Y}_\nu^{ij} H & \tilde{\lambda}^N{}_i H & \lambda_i^N \Phi \\ 0_j & 0 & \lambda_V^N \phi \\ 0 & \widetilde{M}_L & \widetilde{m}_5 \end{pmatrix}$$

$$\begin{array}{cc} & \begin{array}{cccccc} \nu_R & N_R & N'_R & \tilde{\nu}_L & \widetilde{N}'_L & \widetilde{N}_L \end{array} \\ M_{10\times 10} = & \begin{pmatrix} \boxed{M_R} & 0 & 0 & \tilde{Y}_\nu^{ij} H & \tilde{\lambda}^N{}_i H & \lambda_i^N \Phi \\ 0 & 0 & 0 & 0_j & 0 & \lambda_V^N \phi \\ 0 & 0 & 0 & 0 & \widetilde{M}_L & \widetilde{m}_5 \\ \tilde{Y}_\nu^{ij} H & 0_i & 0 & \boxed{0_{3\times 3}} & 0 & 0 \\ \tilde{\lambda}^N{}_i H & 0 & \widetilde{M}_L & 0 & 0 & 0 \\ {\lambda_i^N}^T \Phi & \lambda_V^N \phi & \widetilde{m}_5 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

Majorana mass

decoupled by M_R

Dirac neutrino ~ TeV

SM neutrino ~ H^2/M_R

SM and VL neutrinos are secluded by Majorana mass

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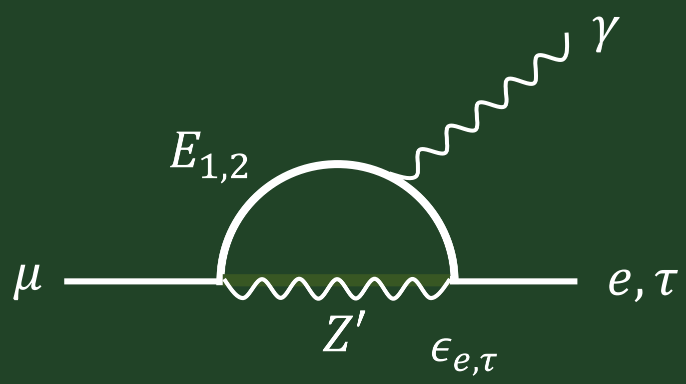
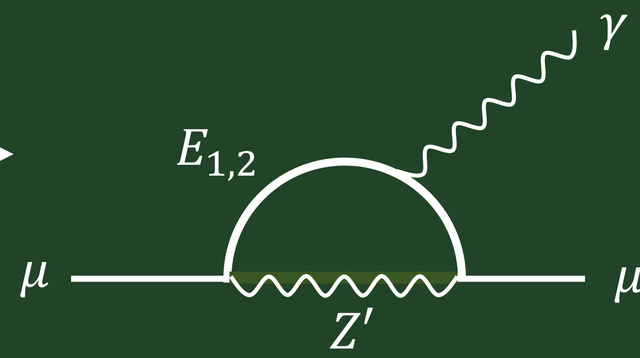
Lepton Flavor Violation (I)

- $\mu \to e\gamma, \tau \to \mu\gamma$

$\epsilon_{e_{L,R}}, \epsilon_{\tau_{L,R}}$: mixing bet. VL-lepton and e, τ



$\leftrightarrow$



similar diagrams with Δa_μ induce $\mu \to e\gamma, \tau \to \mu\gamma$

Exp. limits

$$\mathrm{Br}(\mu \to e\gamma) \sim 2.3 \times 10^{-14} \times \left(\frac{\lambda'_e}{1.0}\right)^2 \left(\frac{\epsilon_e}{10^{-6}}\right)^2 \left(\frac{1.0\ \mathrm{TeV}}{\Phi}\right)^4 < 4.2 \times 10^{-13}\ \text{(90\%C.L.)}$$

$$\mathrm{Br}(\tau \to \mu\gamma) \sim 1.5 \times 10^{-9} \times \left(\frac{\lambda'_e}{1.0}\right)^2 \left(\frac{\epsilon_\tau}{10^{-2}}\right)^2 \left(\frac{1.0\ \mathrm{TeV}}{\Phi}\right)^4 < 4.4 \times 10^{-8}\ \text{(90\%C.L.)}$$

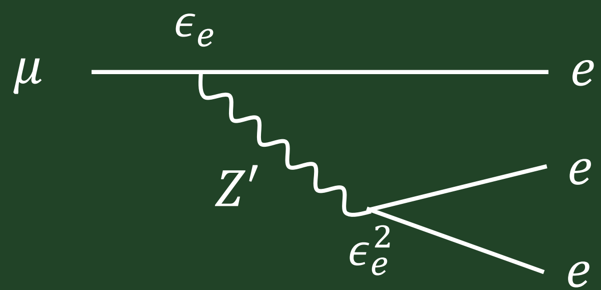
* ∃ subdominant contributions from U(1)' breaking scalar χ

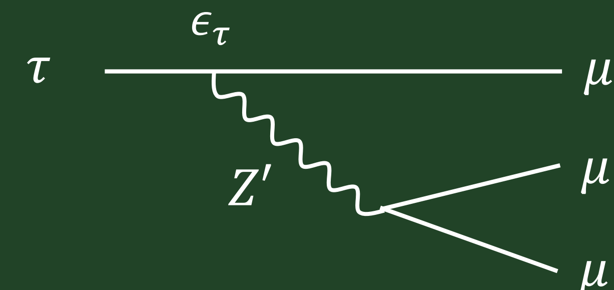
Lepton Flavor Violation (II)

- Z' coupling to SM families $\epsilon_{e_{L,R}}, \epsilon_{\tau_{L,R}}$: mixing bet. VL-lepton and e, τ

$$\sim g' Z'_\mu \begin{pmatrix} \bar{e}_L & \bar{\mu}_L & \bar{\tau}_L \end{pmatrix} \gamma^\mu \begin{pmatrix} \epsilon_{e_L}^2 & \epsilon_{e_L} s_{\theta_{\mu_L}} & \epsilon_{e_L}\epsilon_{\tau_L} \\ \epsilon_{e_L} s_{\theta_{\mu_L}} & s_{\theta_{\mu_L}}^2 & \epsilon_{\tau_L} s_{\theta_{\mu_L}} \\ \epsilon_{e_L}\epsilon_{\tau_L} & \epsilon_{\tau_L} s_{\theta_{\mu_L}} & \epsilon_{\tau_L}^2 \end{pmatrix} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}$$

- $\mu \to eee, \tau \to \mu\mu\mu$ e.t.c.



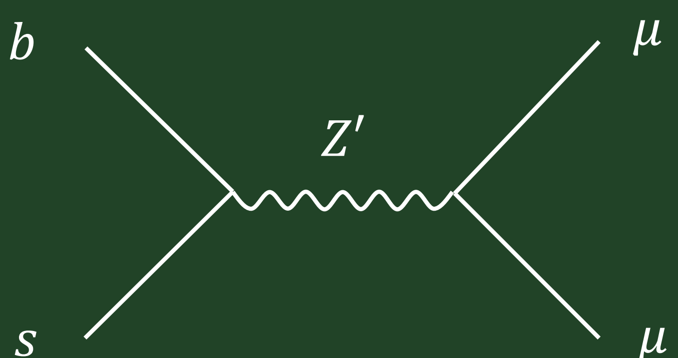


$$\mathrm{Br}(\mu \to eee) \sim 4.6 \times 10^{-40} \times \left(\frac{\epsilon_e}{10^{-6}}\right)^6 \left(\frac{1.0\ \mathrm{TeV}}{\Phi}\right)^4 \qquad < 1.0 \times 10^{-12} \text{ (90\%C.L.)}$$

$$\mathrm{Br}(\tau \to \mu\mu\mu) \sim 8.2 \times 10^{-9} \times \left(\frac{\epsilon_\tau}{10^{-2}}\right)^2 \left(\frac{1.0\ \mathrm{TeV}}{\Phi}\right)^4 \qquad < 2.1 \times 10^{-8} \text{ (90\%C.L.)}$$

$b \to s\mu^+\mu^-$ anomalies

- Z' boson contribution



$$C_9^{NP} \sim -0.7 \times \left(\frac{500\ \mathrm{GeV}}{m_{Z'}}\right)^2 \left(\frac{g^V_{\mu\mu} \cdot g^L_{bs}}{0.0003}\right)$$

$$g^L_{bs} \sim g' \epsilon_{s_L} \epsilon_{b_L}$$

$$g^V_{\mu\mu} \sim g'(s^2_{\theta_{\mu_L}} + s^2_{\theta_{\mu_R}})$$

$g^V_{\mu\mu} \sim g'$ for Δa_μ $\longrightarrow$ $\epsilon_{s_L}\epsilon_{b_L} \sim 0.003 \times \left(\frac{0.3}{g'}\right)^2$

- small mixing angles are enough in quark sector
- small, but mixing between VL and SM family is required

CKM Matrix

5 × 5 "CKM" matrix $\hat{V}_{CKM} = U_u^\dagger \begin{pmatrix} 1_{3\times3} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{0} \end{pmatrix} U_d$

CKM matrix is NOT unitary

- Non-Unitarity

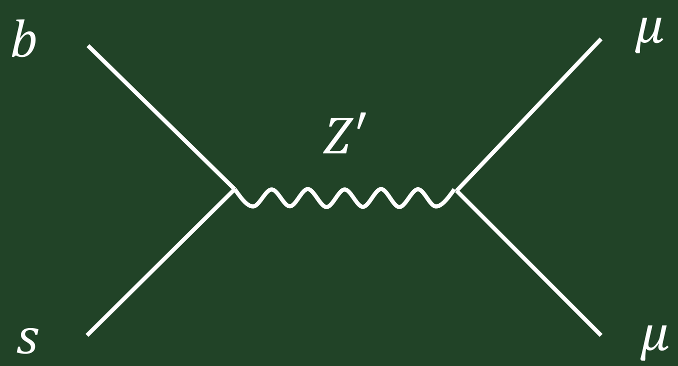
$$\sum_{k=1,2,3} [V_{CKM}]_{ik}[V_{CKM}]_{kj} = \delta_{ij} + \mathcal{O}\left(\epsilon_{t_\mathrm{R}}^2 \frac{m_t^2}{M_Q^2}\right)$$

M_Q: VL quark (VLQ) mass
ϵ_{t_R}: mixing bet. top and VLQ

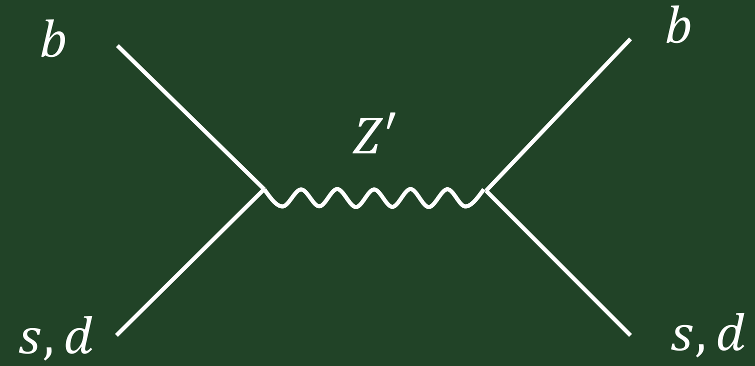
$$\epsilon_{t_R}^2 \frac{m_t^2}{M_Q^2} \sim 7.2 \times 10^{-7} \times \left(\frac{\epsilon_{t_R}}{0.01}\right)^2 \left(\frac{2\ \mathrm{TeV}}{M_Q}\right)^2$$

CKM is still very unitary as far as $\epsilon_{t_R} \lesssim 0.01$

Meson Mixing



$$\sim \frac{g_{bs}^{Z'} g_{\mu\mu}^{Z'}}{m_{Z'}^2}$$



$$\sim \frac{\left(g_{bs(d)}^{Z'}\right)^2}{m_{Z'}^2}$$

- CKM matrix and SM-boson couplings

$$\Delta M_{q=s,d} \sim \left| \underbrace{\frac{G_F^2}{6\pi^2} m_W^2 \left(V_{tb}^* V_{tq}\right)^2 S_0 \eta_B m_{B_q}^2 \hat{B}_{B_q}}_{\text{SM}} + \underbrace{\frac{1}{m_{B_q}} \frac{\left(g_{bs(d)}^{Z'}\right)^2}{m_{Z'}^2} \langle \overline{B_q} | Q^{VLL} | B_q \rangle}_{\text{NP}} + \cdots \right|$$

$|V_{td}| \sim 0.009 \ll |V_{ts}| \sim 0.04$ $\longrightarrow$ NP effects to ΔM_d are as important as ΔM_s

χ^2-Fitting

- 65 parameters

  2 mass parameters $m_{Z'}, v_\phi$, 59 couplings, 4 phases in Yukawa

- 98 observables

  - SM fermion mass, V_{CKM}
  - SM lepton/boson/top decays
  - LFV decays
  - Meson mixing, rare B/K decays

  - Δa_μ
  - $C_9^{NP}, C_{10}, C'_{9,10}$

Minimizing $$\chi^2 = \sum_{i=1}^{98} \frac{\left(x_i - x_i^0\right)^2}{\sigma_i^2}$$

x_i model prediction

x_i^0: exp. value/SM value

σ_i: uncertainty

Best Fitted Points

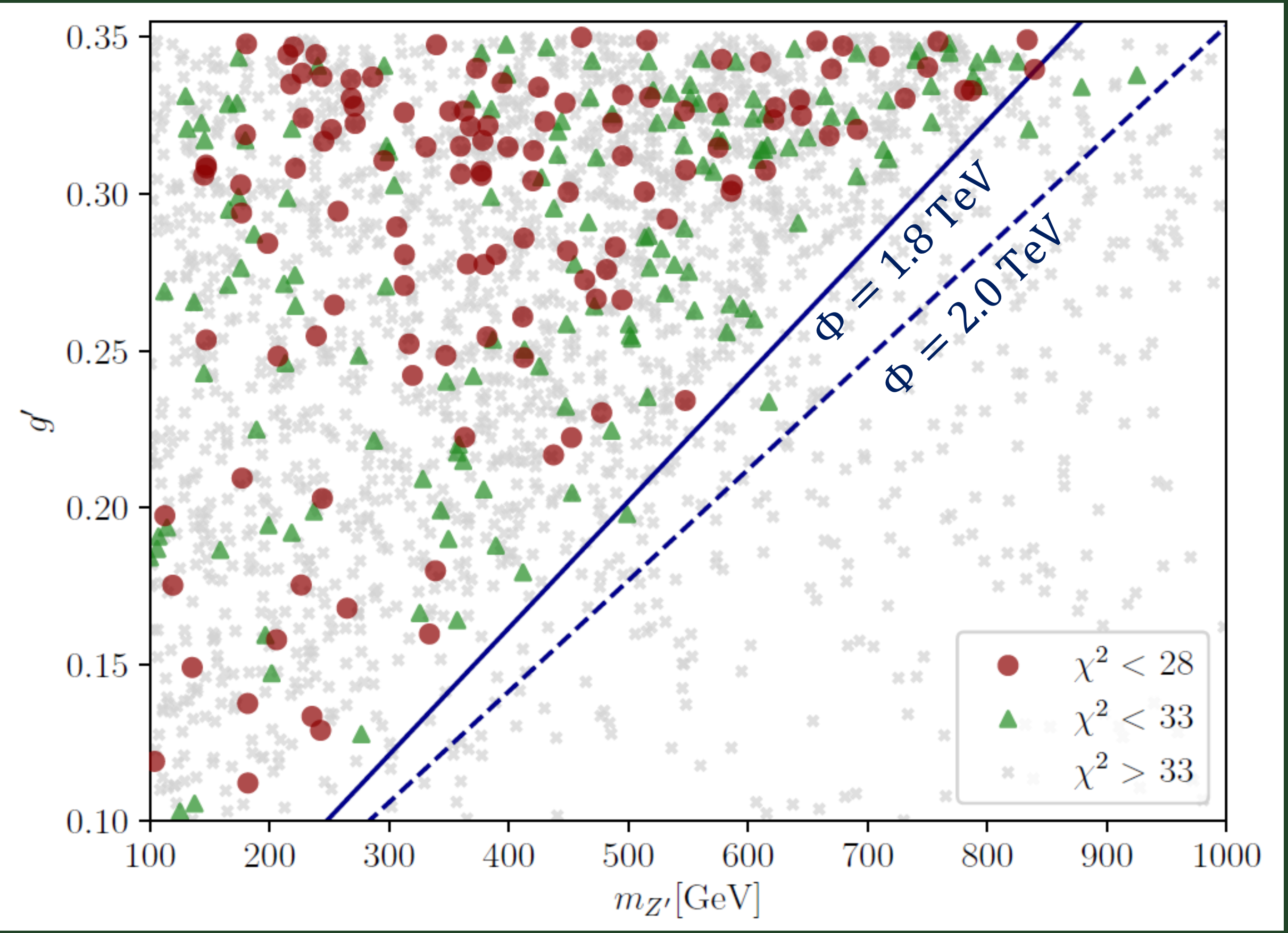
Parameters	Point A	Point B	Remark
χ^2	25.1	24.9	$N_{\rm inp} = 65,\ N_{\rm obs} = 98$
g'	0.266	0.306	$\lesssim 0.35$ for $\Lambda_{g'} = 10^{16}$ GeV
$(v_\Phi,\ v_\phi)$ [TeV]	$(1.31,\ 4.36)$	$(0.872,\ 2.92)$	
Observables	Point A	Point B	Data
$\Delta a_\mu \times 10^9$	2.56	2.43	2.68(76) [1]
$\mathrm{Br}(\mu \to e\gamma) \times 10^{13}$	3.58	2.10	< 4.2 (90%C.L.) [1]
$\mathrm{Br}(\tau \to \mu\gamma) \times 10^8$	1.96×10^{-5}	4.91×10^{-2}	< 4.4 (90%C.L.) [1]
$\mathrm{Br}(\tau \to \mu\mu\mu) \times 10^8$	3.03×10^{-5}	7.42×10^{-3}	< 2.1 (90%C.L.) [1]
$\mathrm{Re}\, C_9^\mu$	-0.725	-0.571	$-0.7(3)$ [29]
$\mathrm{Re}\, C_{10}^\mu$	0.320	0.316	0.4(2) [29]
ΔM_d [ps^{-1}]	0.612	0.599	0.507(81) [1]
ΔM_s [ps^{-1}]	19.4	19.8	17.8(2.5) [1]
$S_{\psi K_s}$	0.688	0.686	0.695(19) [84]
$S_{\psi\phi}$	0.0374	0.0363	0.021(31) [84]

Most observables are explained within 1 σ

exception: $\Delta a_e, \mathrm{Br}(\mu \to e\gamma), \Delta M_d$ and CKM elements

Global analysis on $m_{Z'} - g'$

$m_{Z'}^2 = 2g'^2\Phi^2$



$\Phi < 1.8$ TeV is required for $\chi^2 < 28$

CKM matrix

- Independent measurement

$$|V_{CKM}| = \begin{pmatrix} 0.9742 & 0.2243 & 0.00394 \\ 0.218 & 0.997 & 0.04228 \\ 0.0081 & 0.0394 & 1.019 \end{pmatrix}$$

- Fit with unitarity

$$|V_{CKM}| = \begin{pmatrix} 0.97446 & 0.22452 & 0.00365 \\ 0.22438 & 0.97359 & 0.04214 \\ 0.00896 & 0.04133 & 0.999105 \end{pmatrix}$$

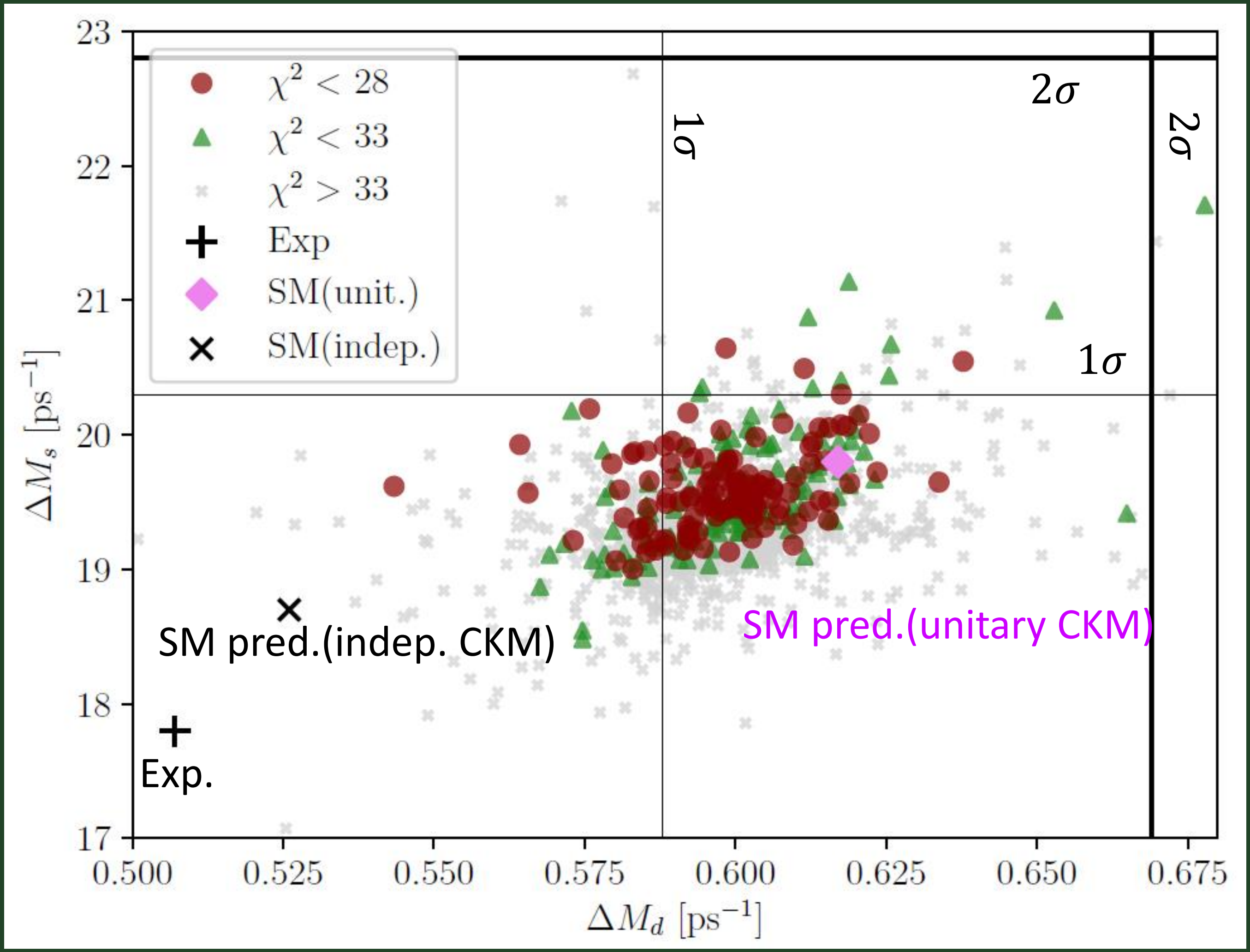
PDG

- Extended CKM matrix at Point A

$$|\hat{V}_{CKM}| = \begin{pmatrix} 0.9745 & 0.2245 & 0.003594 & 0 & 0 \\ 0.224324 & 0.9736 & 0.04131 & 0 & 0 \\ 0.008827 & 0.04052 & 0.9991 & 0.001086 & 0.000008 \\ 0.000010 & 0.000044 & 0.001084 & 0.9999 & 0.01364 \\ 0.000003 & 0.000012 & 0.000287 & 0.003122 & 0.000043 \end{pmatrix}$$

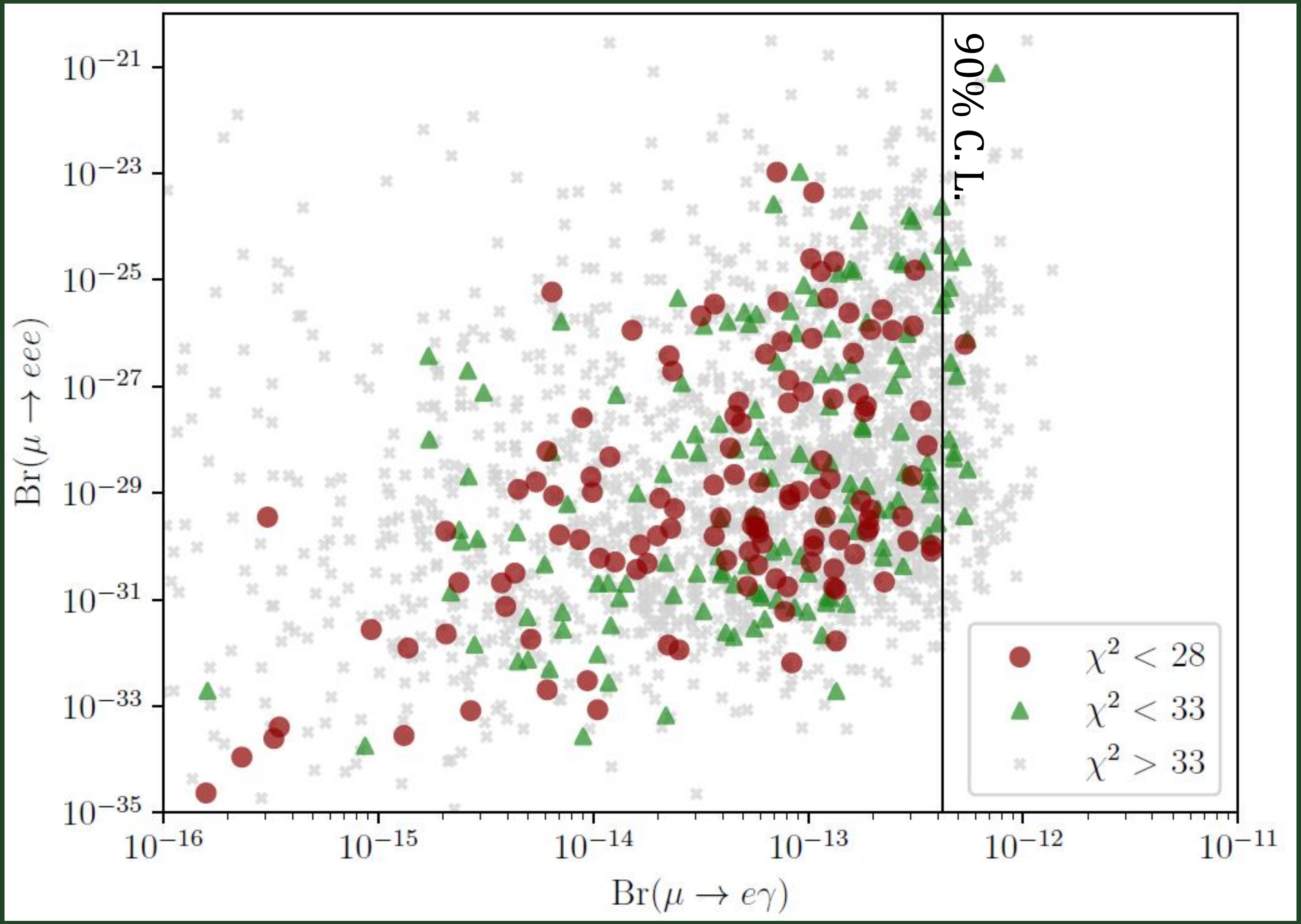
- Fit to the independent measurement values, but more like unitarity-fit
- CP-phases are also well fitted
- SM CKM matrix is nearly unitary: $\left[V_{CKM}^{\dagger} V_{CKM}\right]_{ij} = \delta_{ij} + \mathcal{O}(10^{-7})$

B-meson mixing



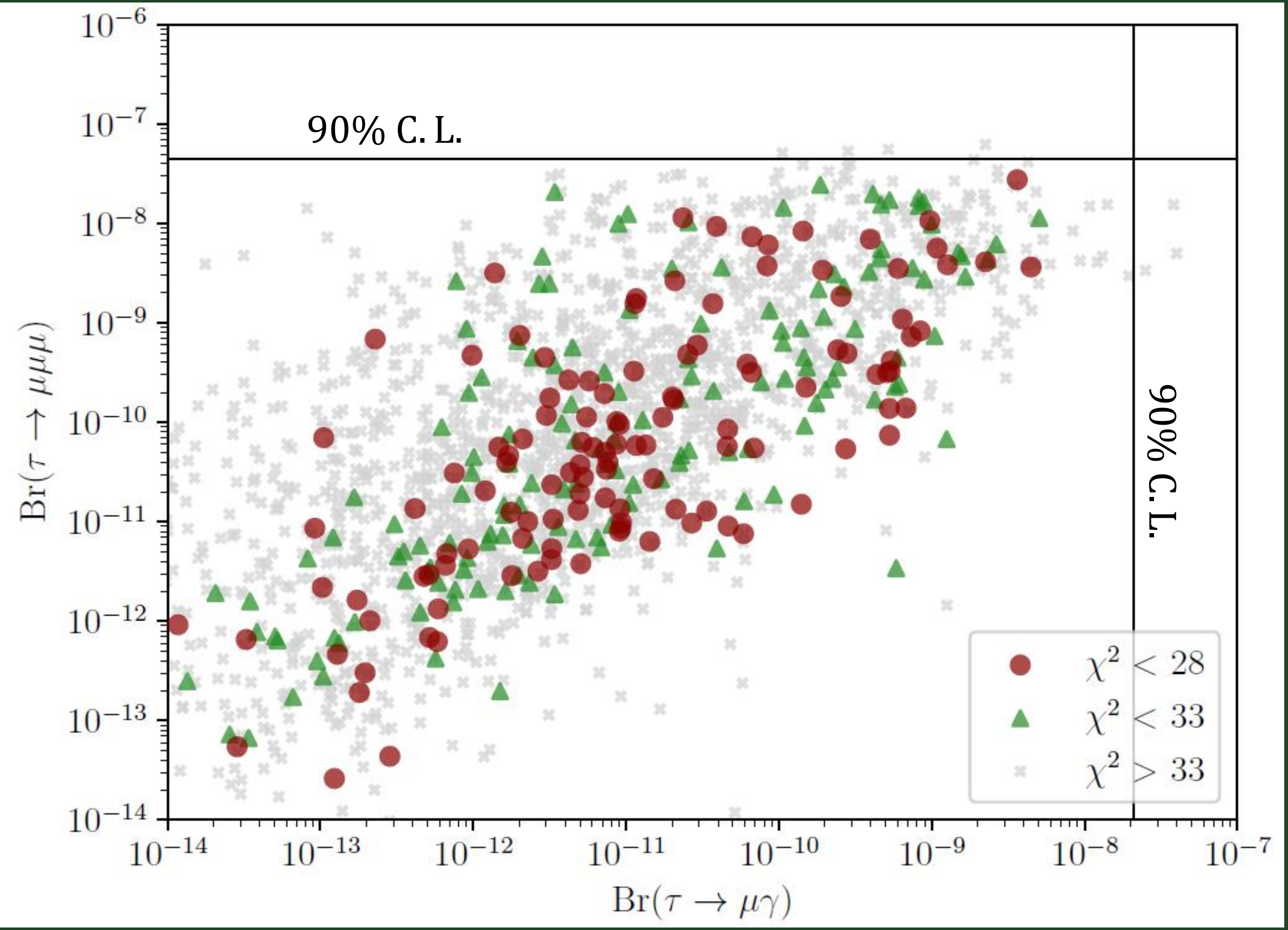
CKM values are more relevant than NP effects

LFV muon decays



$\mathrm{Br}(\mu \to e\gamma) \gg \mathrm{Br}(\mu \to eee)$ due to the scaling $\epsilon_e^2 \gg \epsilon_e^6$

LFV tau decays



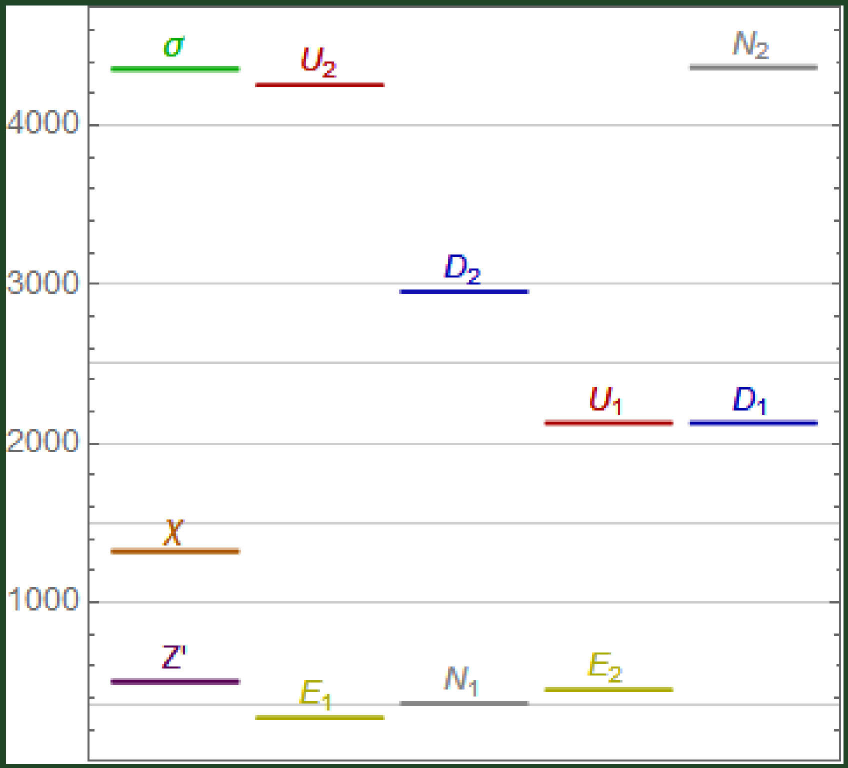
$\mathrm{Br}(\tau \to \mu\gamma) \lesssim \mathrm{Br}(\tau \to \mu\mu\mu)$ due to the scaling $\epsilon_\tau^2 \sim \epsilon_\tau^2$

Outline

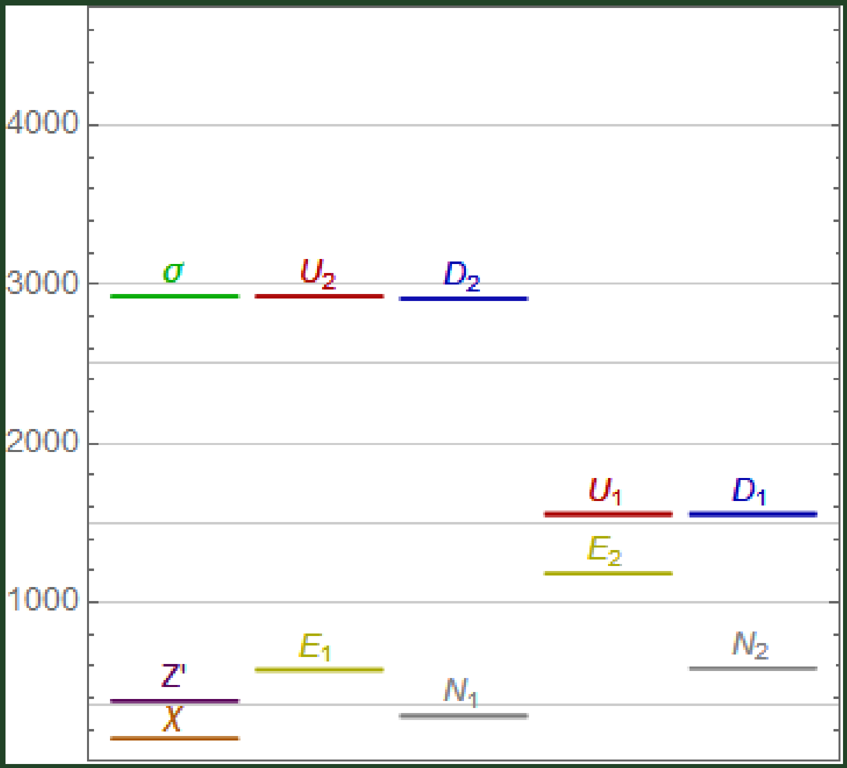
1. Introduction
2. Vector-Like 4^{th} Family with Vector-Like U(1)’
3. Phenomenology
4. LHC Signals
5. Conclusion

Mass Spectrum at Best-Fit Points

- Point A : $m_{E_1} < m_Z', m_\chi$



- Point B : $m_{E_1} > m_{Z'}, m_\chi$



- Δa_μ predicts light Z' and VL-leptons
- U(1)' breaking scalar χ is as light as Z' since their masses come from Φ
- VL-family strongly couples to Z', χ and VL-family

Z' signal

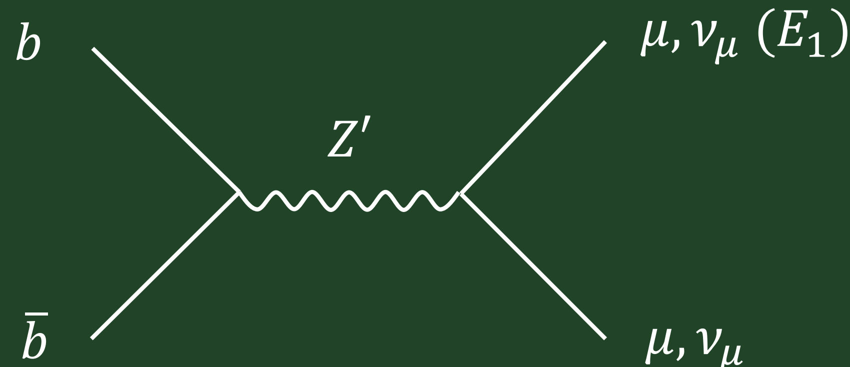
$$\Phi < 1.8\ \mathrm{TeV} \longrightarrow m_{Z'} < 900\ \mathrm{GeV} \text{ if } g' < 0.35$$

➢ quark coupling

- $g_{bs}^{L} \sim g'\epsilon_{s_L}\epsilon_{b_L} \sim 0.003 \times \left(\frac{0.3}{g'}\right)$
- $g_{bb}^{L} \sim \epsilon_{b_L}^{2} \gg g_{ss}^{L} \sim \epsilon_{s_L}^{2}$ is favored

➢ lepton coupling

- $g_{\mu\mu}^{L} \sim s_{\theta_{\mu_L}}^{2}, g_{\mu\mu}^{R} \sim s_{\theta_{\mu_R}}^{2}$ are $\mathcal{O}(1)$
- $g_{\mu\mu}^{L} \sim g_{\nu_\mu\nu_\mu}^{L} : Z' \to \nu\nu$
- $Z' \to E_1\mu$ decay possible if $m_{Z'} > m_{E_1}$



dimuon resonance signal is expected

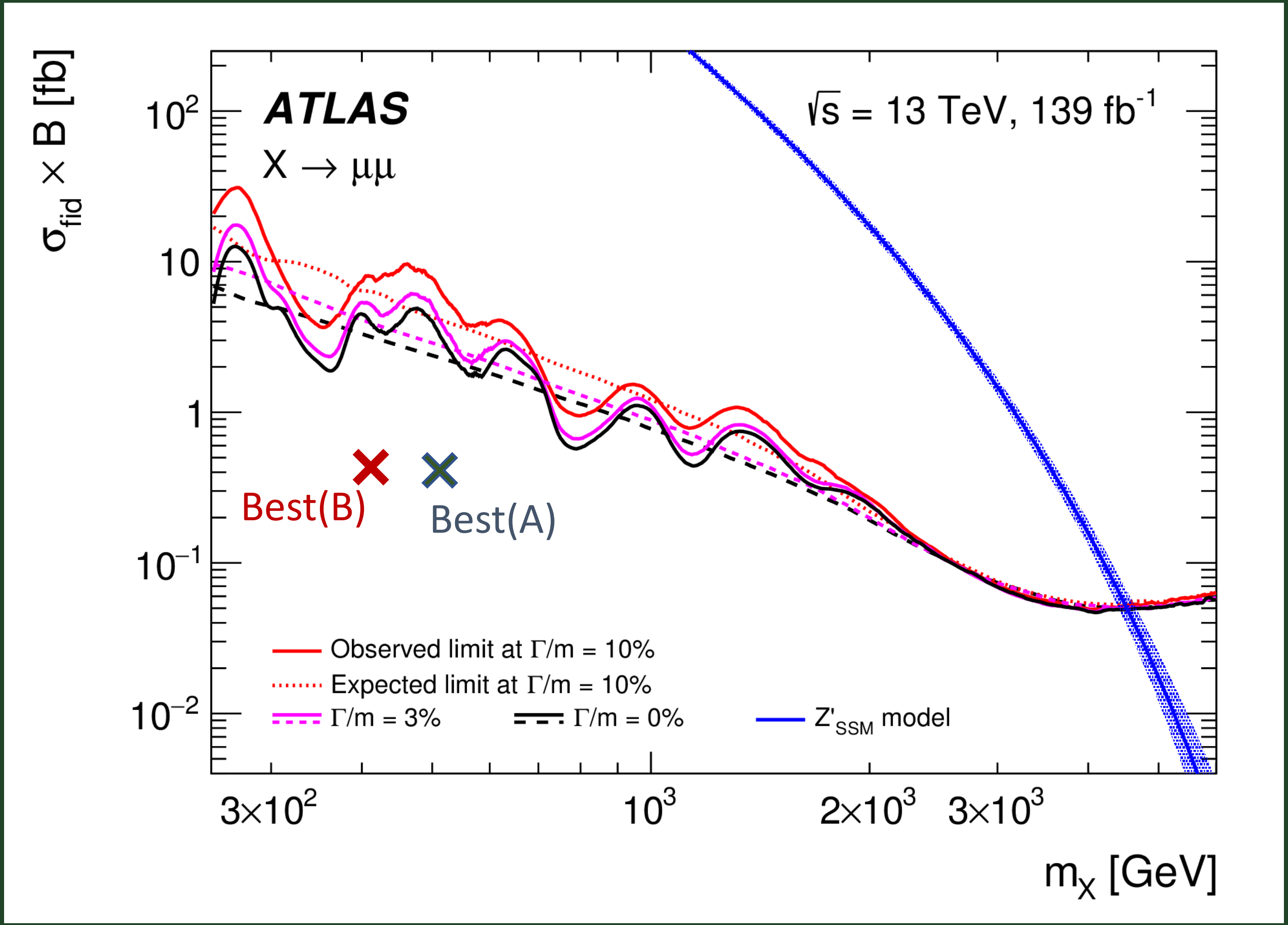
Dimuon Z' Search at LHC

$$\sigma_{fid}(pp \to Z' \to \mu^+\mu^-) = 0.477\ (\mathrm{A}), 0.482(\mathrm{B})\ [\mathrm{fb}]$$

MadGraph5
FeynRules

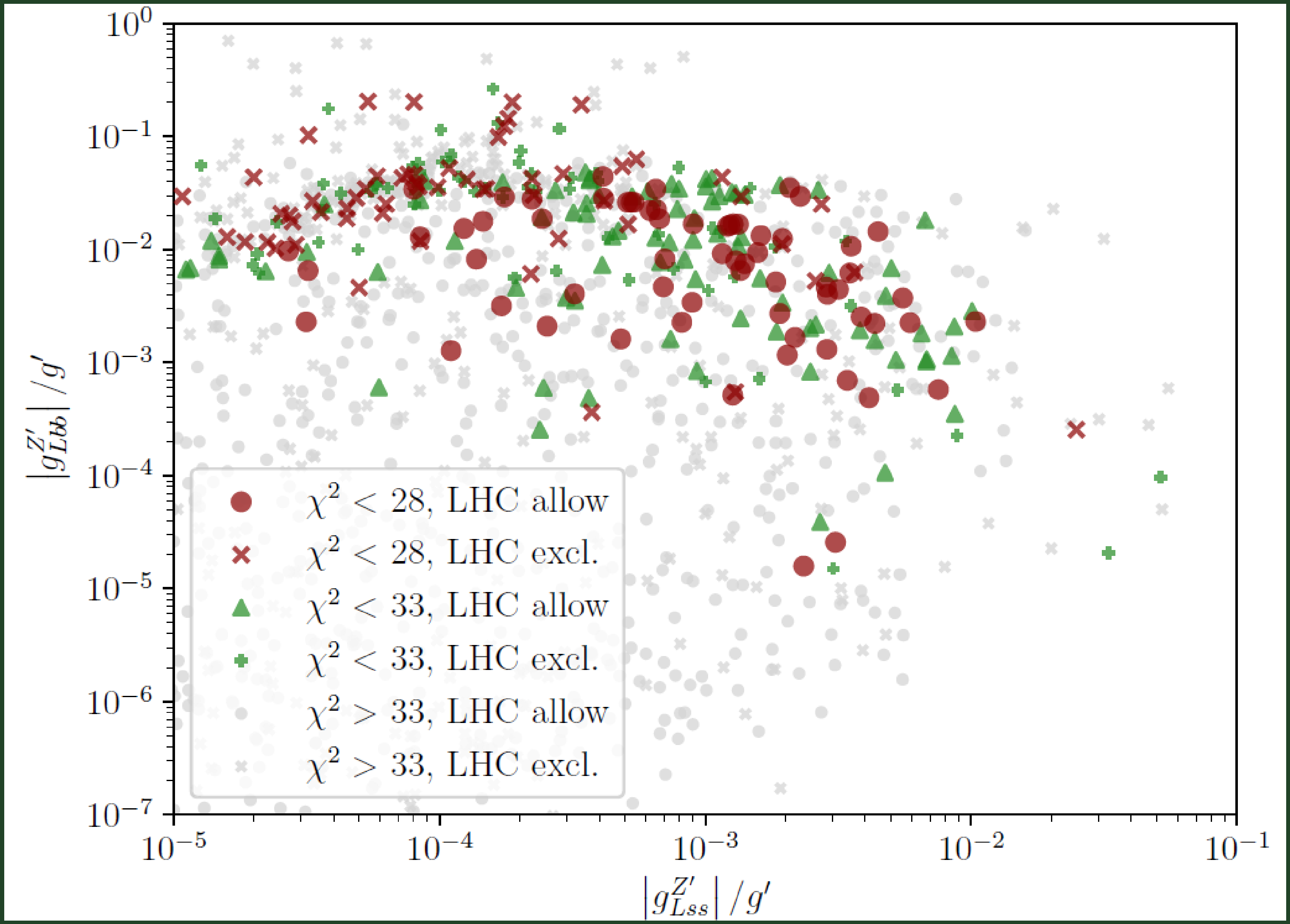
Fiducial region

$p_T(l) > 30\ [\mathrm{GeV}]$
$|\eta(l)| < 2.5$
$m_{ll} > m_{Z'} - 2\Gamma_{Z'}$



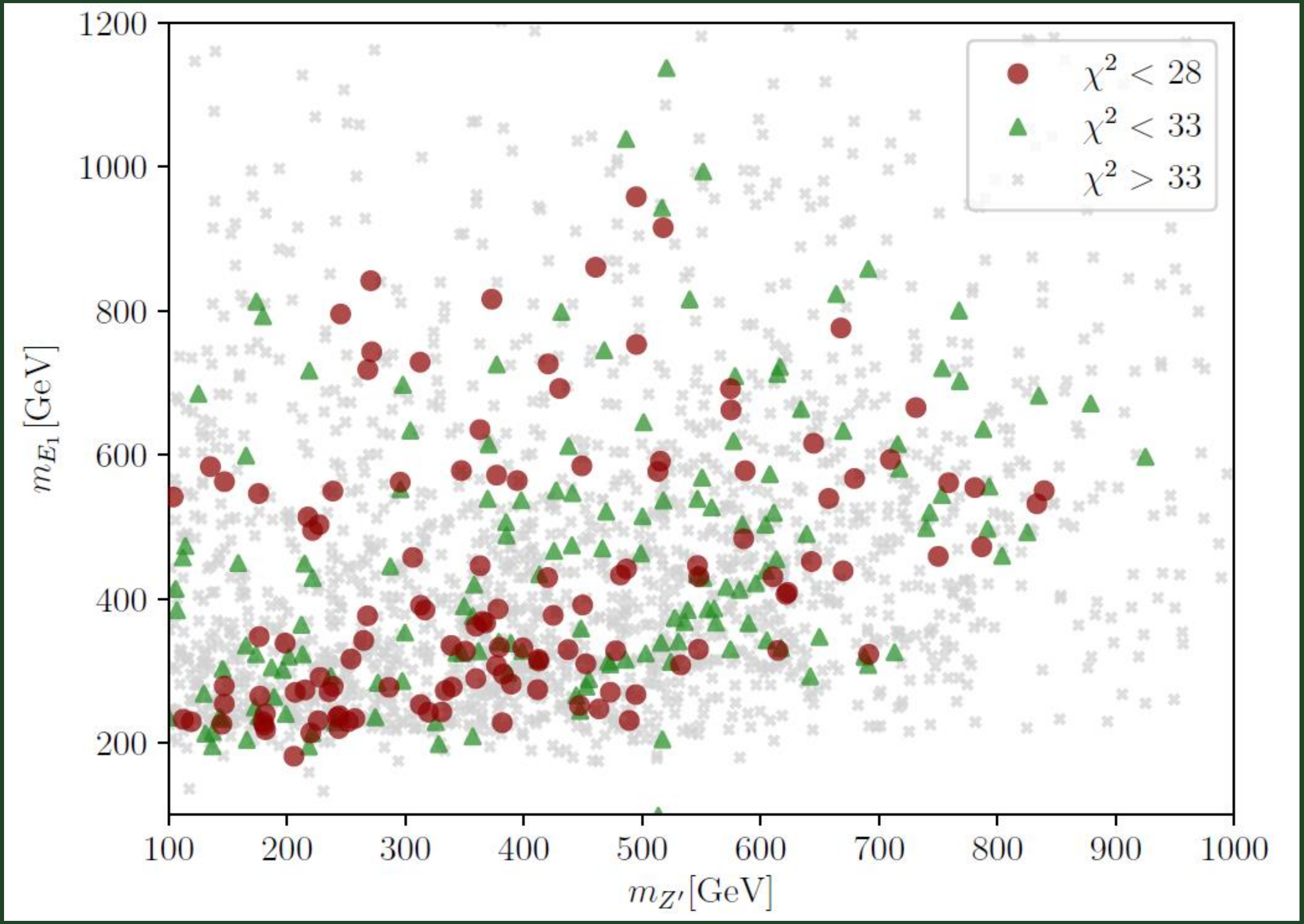
production cross section is very small

Dimuon Z' Search at LHC



$g^L_{ss} \gtrsim 10^{-4}$ ($\epsilon_{s_L} \gtrsim 10^{-2}$) is favored to suppress $g^L_{bb} \lesssim 10^{-2}$

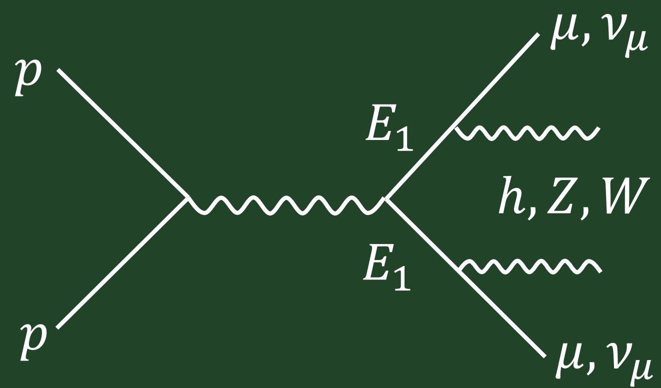
Lightest VL-lepton mass



most points have $m_{E_1} < 800$ GeV

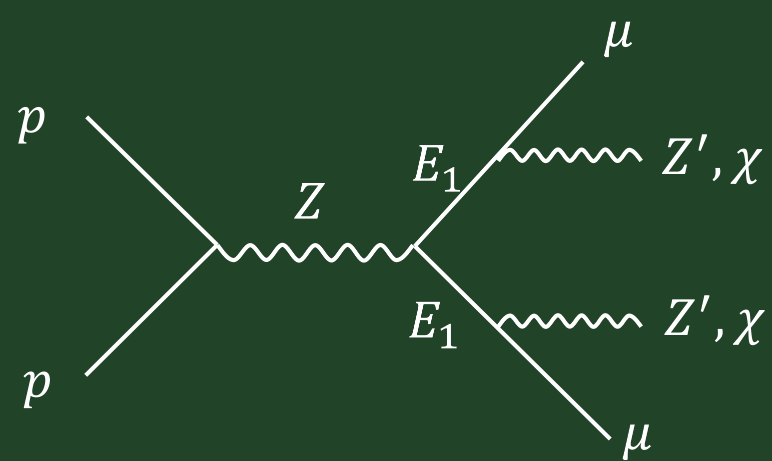
LHC signal of E_1

➢ If $m_{E_1} < m_{Z'}$



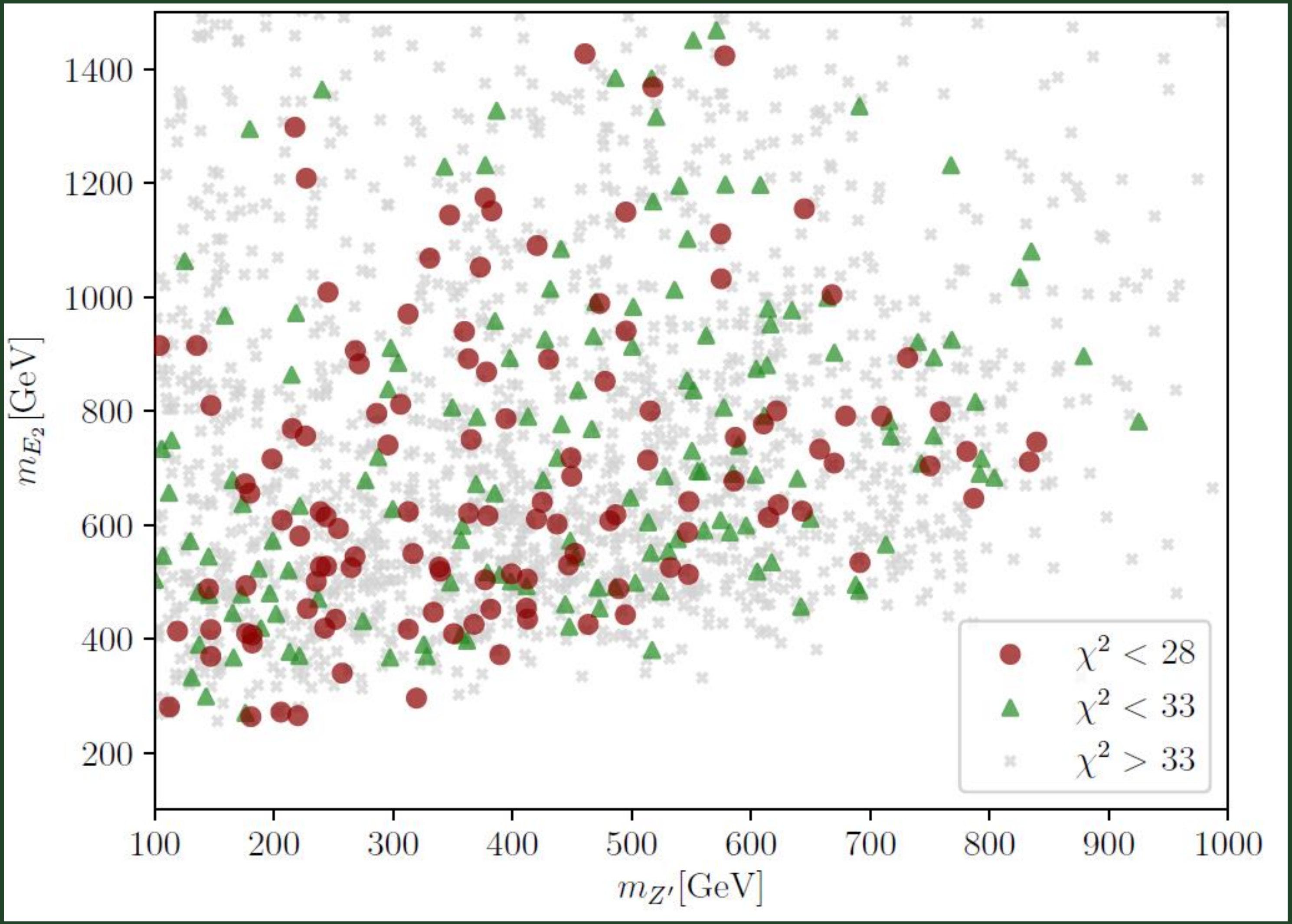
- usual VL-lepton signal
- ∃ signals from VL-neutrino if doublet
- There is no experimental Run-2 study

➢ If $m_{E_1} > m_{Z'}, m_\chi$



- Signal: $2\mu + 2\ (Z', \chi)$
- $Z' \to \mu\mu$ or $\nu_\mu \nu_\mu$
- $\chi \to tt$ (if $m_\chi > 2m_t$), $\mu\mu$ (else)
- clean signal: $\mu\mu + 2\ (\mu\mu)_{Z',\chi}$

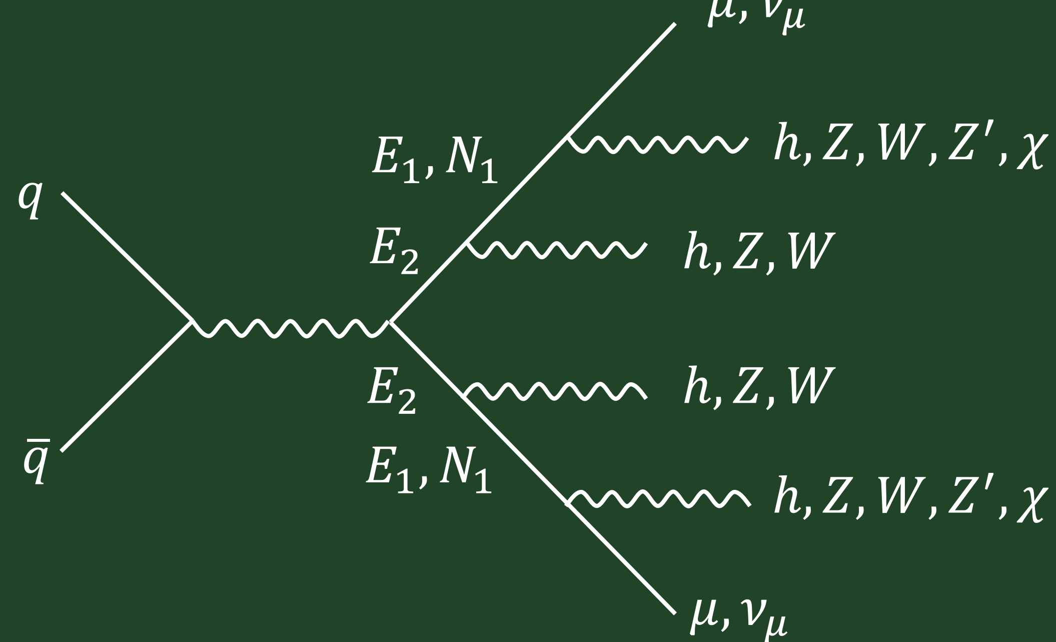
Heavier VL-lepton



$m_{E_2} \lesssim 1.2$ TeV for $\Delta a_\mu \sim 2.68 \times 10^{-9}$ since LR-effect is crucial

LHC signal of VL lepton

- Typical signals

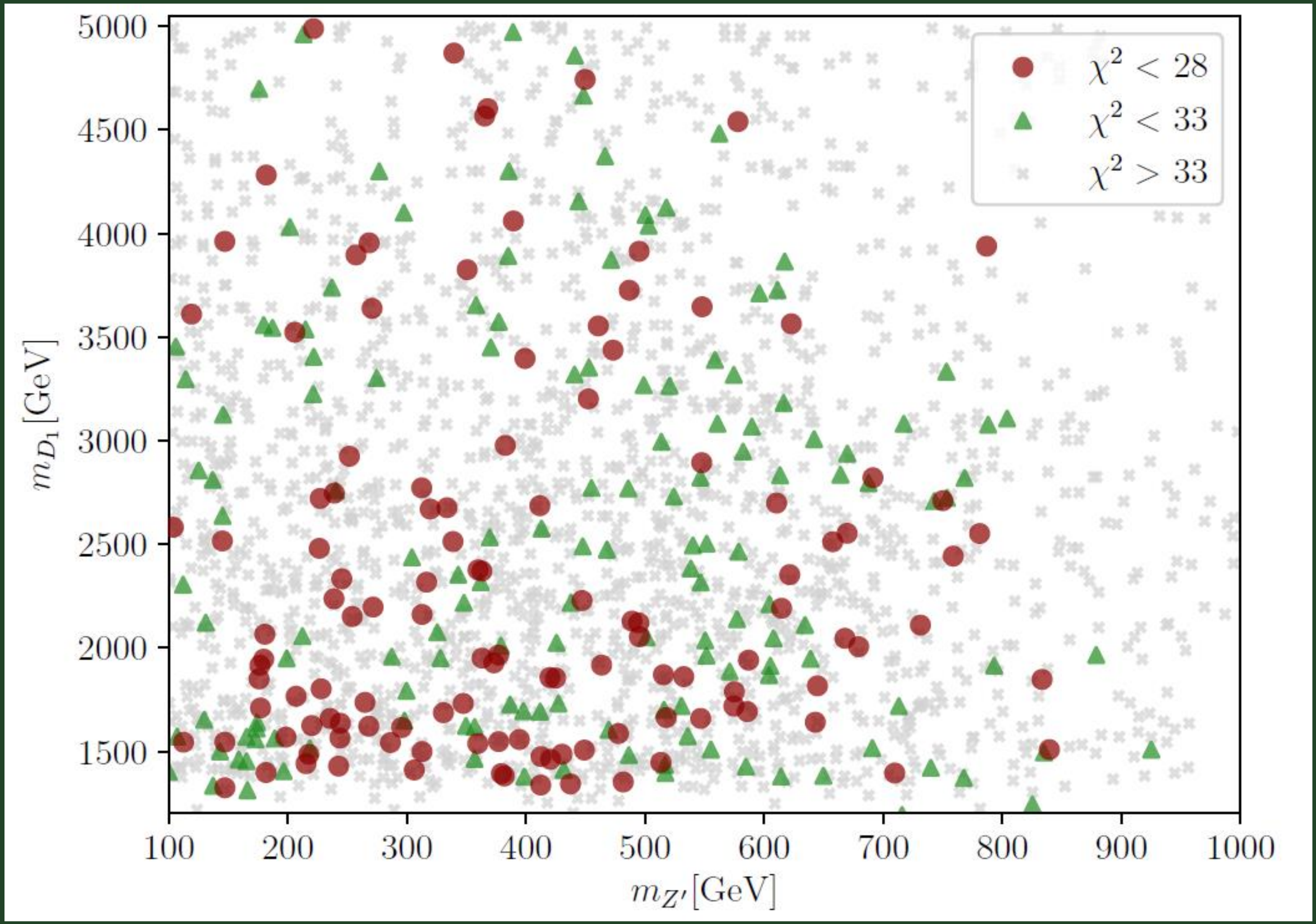


- Distinctive signal

$$E_2 E_2 \to E_1 Z + E_1 Z \to \mu\, Z' Z + \mu\, Z'\, Z$$

$2\mu + 2\,(\ell\ell)_Z + 2(\mu\mu)_{Z'}$: 10 lepton signal is possible

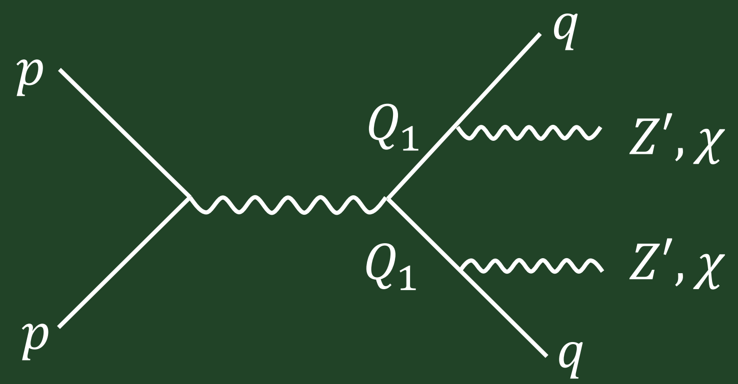
VL quark



There is no stringent upper bound on VL quark

LHC signal of VL quark

- Typical signals



- larger production than VL-leptons
- SUSY-like signal if $Z', \chi \to \nu\nu$
- dimuon resonances are expected

- Distinctive Signals

- $Q_1 Q_1 \to q\, Z' + q\, Z'$: 2 jet + 2 $(\mu\mu)_{Z'}$ signal
- doublet VL quarks tend to be lighter than singlet ones for $C_9^{NP} \propto g_{d_L}^{Z'}$
- heavier states may produce more bosons if they are light

Summary

- SM extension via complete Vector-Like 4th family and $U(1)'$
- All Z' couplings to SM particles are controlled by mixing
- Pati-Salam like $U(1)'$ charge is needed to explain $(g-2)_\mu$
- The muon anomalies can be explained with small couplings
- Consistent with current limits from LHC
- Dramatic multi-lepton (w/resonance) signals are expected

Thank you for attention

Backup

Mass and Decays at best(A)

	Mass [GeV]	Width [GeV]	Decay 1	Br	Decay 2	Br
Z'	494.7	0.7723	$\mu\mu$	0.4058	$\nu\nu$	0.3529
χ	1314.	2.290	N_1N_1	0.2934	$E_1\mu$	0.1477
σ	4345.	3.667	U_1t	0.2516	D_1b	0.2476
E_1	267.2	$2. \times 10^{-6}$	$h\mu$	0.6774	$Z\mu$	0.1693
N_1	359.2	0.5505	WE_1	1.000	$W\mu$	0.0000
E_2	442.4	1.783	ZE_1	0.8646	WN_1	0.1084
N_2	4357.	0.0019	$W\mu$	0.3745	$Z\nu$	0.1872
D_1	2120.	1.535	$Z'b$	0.4514	Wt	0.3629
U_1	2120.	1.538	$Z't$	0.4552	ht	0.1840
D_2	2947.	1.029	WU_1	0.4983	ZD_1	0.2493
U_2	4252.	1.042	WD_1	0.4901	ZU_1	0.2450

Mass and Decays at best(B)

	Mass [GeV]	Width [GeV]	Decay 1	Br	Decay 2	Br
Z'	377.1	0.1112	$\mu\mu$	0.5193	$\nu\nu$	0.4793
χ	135.4	$9.\times10^{-9}$	$\mu\mu$	0.8094	bs	0.0945
σ	2915.	5.575	E_2E_2	0.2688	E_1E_1	0.1486
N_1	280.2	0.0003	$W\mu$	0.5232	$Z\nu$	0.2578
E_1	571.9	0.4464	$\chi\mu$	0.5495	$Z'\mu$	0.3684
N_2	580.7	0.4718	$\chi\nu$	0.5427	$Z'\nu$	0.3741
E_2	1174.	23.07	WN_2	0.4698	ZE_1	0.2340
D_1	1548.	0.3587	$Z's$	0.2889	χs	0.2874
U_1	1548.	0.3594	$Z'c$	0.2833	χc	0.2818
D_2	2902.	0.1854	$Z'b$	0.4448	χb	0.4432
U_2	2915.	0.0441	WD_1	0.3897	hU_1	0.1969

Z' boson couplings

- VL lepton dominantly mix with muon

$$\sim -g' Z'_\mu \bar{E} \gamma^\mu \begin{pmatrix} \epsilon_{e_L}^2 & \epsilon_{e_L} s_{\theta_{\mu_L}} & \epsilon_{e_L}\epsilon_{\tau_L} & 0 & \epsilon_{e_L} \\ \epsilon_{e_L} s_{\theta_{\mu_L}} & s_{\theta_{\mu_L}}^2 & \epsilon_{\tau_L} s_{\theta_{\mu_L}} & 0 & s_{\theta_{\mu_L}} c_{\theta_{\mu_L}} \\ \epsilon_{e_L}\epsilon_{\tau_L} & \epsilon_{\tau_L} s_{\theta_{\mu_L}} & \epsilon_{\tau_L}^2 & 0 & \epsilon_{\tau_L} \\ 0 & 0 & 0 & 1 & 0 \\ \epsilon_{e_L} & s_{\theta_{\mu_L}} c_{\theta_{\mu_L}} & \epsilon_{\tau_L} & 0 & c_{\theta_L}^2 \end{pmatrix} P_L \begin{pmatrix} e \\ \mu \\ \tau \\ E_E \\ E_L \end{pmatrix}$$

$$\sim -g' Z'_\mu \bar{E} \gamma^\mu \begin{pmatrix} \epsilon_{e_R}^2 & \epsilon_{e_R} s_{\theta_{\mu_R}} & \epsilon_{e_R}\epsilon_{\tau_R} & \epsilon_{e_R} & 0 \\ \epsilon_{\mu_R} s_{\theta_{\mu_R}} & s_{\theta_{\mu_R}}^2 & \epsilon_{\tau_R} s_{\theta_{\mu_R}} & s_{\theta_{\mu_R}} c_{\theta_{\mu_R}} & 0 \\ \epsilon_{e_R}\epsilon_{\tau_R} & \epsilon_{\tau_R} s_{\theta_{\mu_R}} & \epsilon_{\tau_R}^2 & \epsilon_{\tau_R} & 0 \\ \epsilon_{e_R} & s_{\theta_{\mu_R}} c_{\theta_{\mu_R}} & \epsilon_{\tau_R} & c_{\theta_R}^2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} P_R \begin{pmatrix} e \\ \mu \\ \tau \\ E_E \\ E_L \end{pmatrix}$$

Large mixing angle $\theta_{\mu_{L,R}}$ and tiny mixing $\epsilon_{e_{L,R}} \ll \epsilon_{\tau_{L,R}} \ll 1$

$\underline{B - Z'}$ mixing

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

$$\epsilon \sim \frac{g_Y g'}{6\pi^2} \mathrm{Log}\left(\frac{M_E^2}{M_L^2} \cdot \frac{M_Q^2 M_D^2}{M_U^4}\right)$$

~ 0.005 (I), 0.009 (II)