

PPP2019@Kyoto



# Complete Vector-like 4<sup>th</sup> Family and U(1)' for Muon Anomalies

arXiv:1906.11297

and working in progress

Junichiro Kawamura (Ohio State University)

with

Stuart Raby (OSU), Andreas Trautner (Max Planck Inst.)

# Outline

1. Introduction
2. Vector-Like 4<sup>th</sup> Family with Vector-Like  $U(1)'$
3. Phenomenology
4. LHC Signals
5. Conclusion

# Muon Anomalies

## ➤ Muon $g - 2$

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

## ➤ Muon Anomalies for $b \rightarrow s \mu^+ \mu^-$ Processes

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

## ➤ ( $R_{D^{(*)}}$ anomaly [ $B \rightarrow D^{(*)} \tau \nu$ ] は考えない)

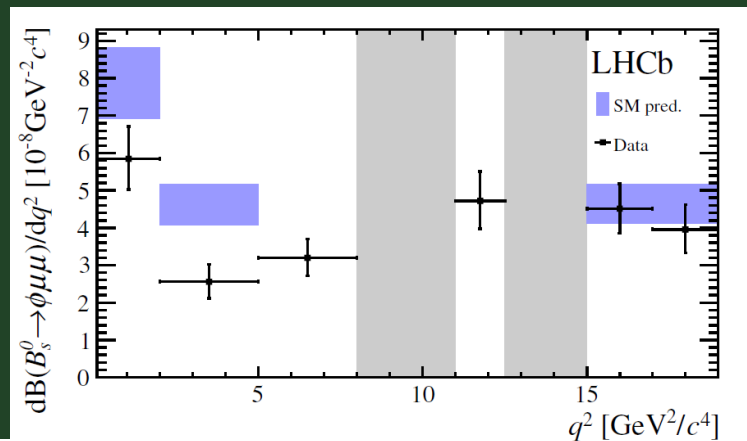
# $b \rightarrow s \mu^+ \mu^-$ Anomalies

## ➤ Lepton Non-Universality

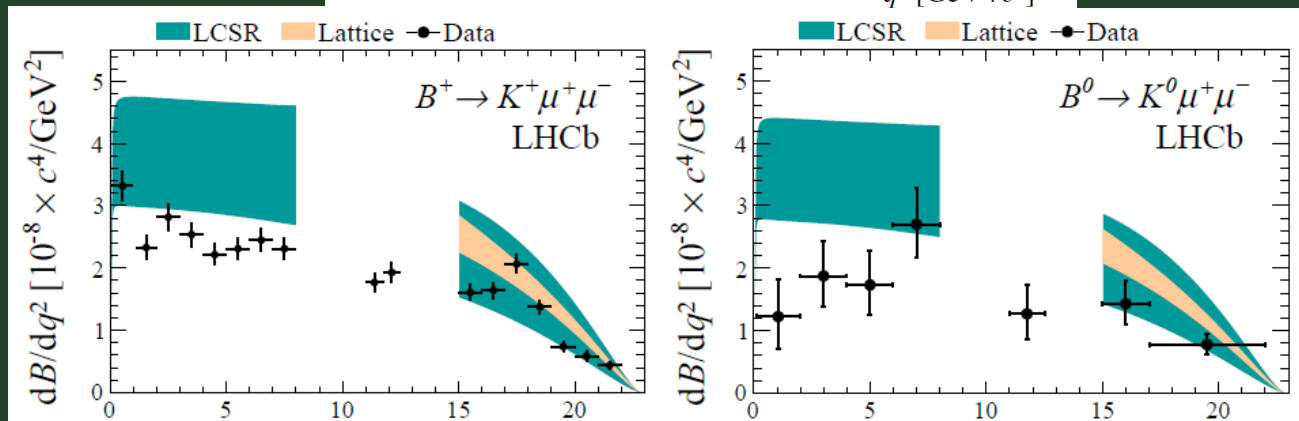
$$R_K = 0.846^{+0.060}_{-0.054} \quad ^{+0.016}_{-0.014}$$

below  $R_K^{SM} = 1.0 \sim 2.5 \sigma$

## ➤ Branching ratio $B \rightarrow \phi \mu^+ \mu^-, K \mu^+ \mu^-$



below SM pred.  
 $\sim 3.0 \sigma$



below SM pred.

# $b \rightarrow s \mu^+ \mu^-$ Anomalies

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

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

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

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

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

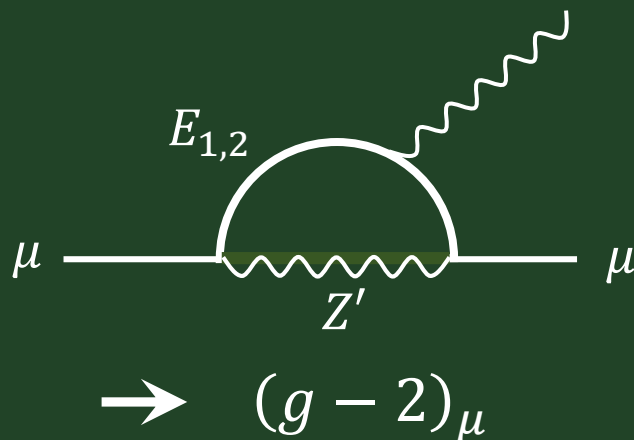
# Outline

1. Introduction
2. Vector-Like 4<sup>th</sup> Family with Vector-Like U(1)'
3. Phenomenology
4. LHC Signatures
5. Conclusion

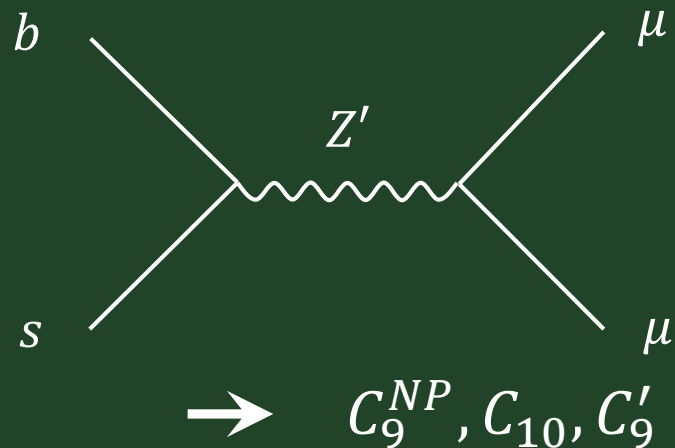
# VL-fermion + $U(1)'$

simultaneous explanation for muon anomalies

## ➤ $U(1)'$ + VL-leptons



## + VL-quarks



## ➤ Models

- $U(1)_{L_\mu - L_\tau}$  + VL-lepton + VL-quark W.Altmannshofer et.al 1604.08221
- $U(1)_{3-4}$  + VL 4<sup>th</sup> 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 4<sup>th</sup> Family + $U(1)'$

	$Q_L$	$\bar{U}_R$	$\bar{D}_R$	$L_L$	$\bar{E}_R$	$\bar{N}_R$	$\bar{Q}_R$	$U_L$	$D_L$	$\bar{L}_R$	$E_L$	$N_L$	$\phi$	$\Phi$
$SU(3)_C$	<b>3</b>	$\bar{3}$	$\bar{3}$	1	1	1	$\bar{3}$	<b>3</b>	<b>3</b>	1	1	1	1	1
$SU(2)_L$	<b>2</b>	1	1	<b>2</b>	1	1	<b>2</b>	1	1	<b>2</b>	1	1	1	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

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

\*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  $L_{L,R} \ni (N'_{L,R}, E'_{L,R})$

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

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

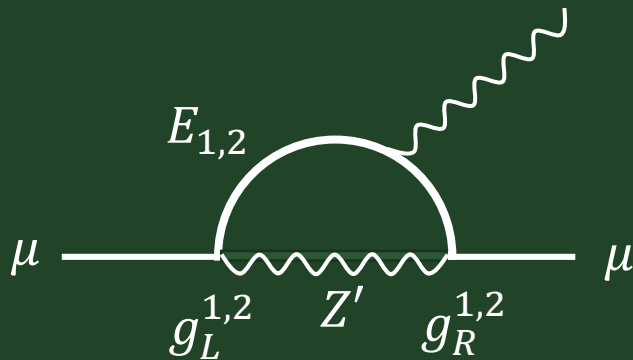
\* similar for quarks/neutrino

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

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

rotation matrices determine  $Z'$ -couplings to the SM families

# Muon $g - 2$



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

➤  $E_E - E'_L$  mixing is induced by Higgs coupling:  $\lambda'_e \bar{L}_R \tilde{H} E_L$

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

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

muon-VLL mixing angle  $\theta_{\mu_{L,R}} \sim \pi/4$  and  $\lambda'_e H/\Phi \gtrsim 0.1$  are necessary

\*  $\exists$  subdominant contributions from  $U(1)'$  breaking scalar  $\chi$

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

➤ To write  $\lambda'_e \bar{L}_R \tilde{H} E_L$

	$Q_L$	$\bar{U}_R$	$\bar{D}_R$	$L_L$	$\bar{E}_R$	$\bar{N}_R$	$\bar{Q}_R$	$U_L$	$D_L$	$\bar{L}_R$	$E_L$	$N_L$	$\phi$	$\Phi$
$SU(3)_C$	3	$\bar{3}$	$\bar{3}$	1	1	1	$\bar{3}$	3	3	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	1	1	2	1	1	1	1
$U(1)_Y$	$\frac{1}{6}$	$-\frac{4}{3}$	$\frac{2}{3}$	-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  $G_{PS} = SU(4) \times SU(2) \times SU(2)$

$$\times (L_L, \bar{D}_R) \in \bar{5}, \quad (Q_L, \bar{U}_R, \bar{E}_R) \in 10 \quad \text{in } SU(5)$$

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

# Towards Grand Unification

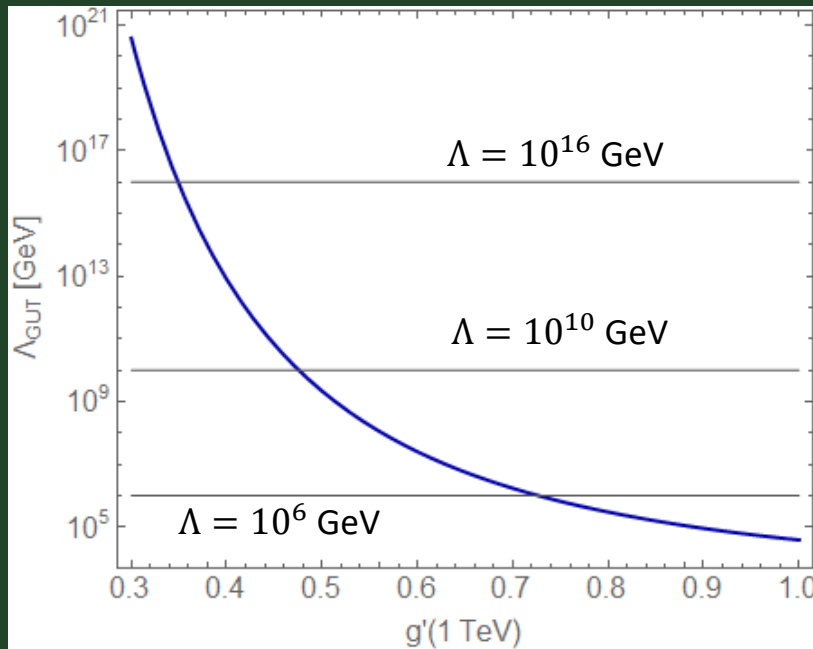
## ➤ UV-completion of model

- 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  $\Lambda \sim 10^{16} \text{ GeV}$
- $g' \lesssim 0.48$  for  $\Lambda \sim 10^{10} \text{ GeV}$

# Neutrino Mass

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

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

$\nu_R$     $N_R$     $N'_R$     $\tilde{\nu}_L$     $\tilde{N}'_L$     $\tilde{N}_L$

Majorana mass

$$M_{10 \times 10} = \begin{pmatrix} M_R & 0 & 0 & \tilde{Y}_\nu^{ij} H & \tilde{\lambda}^N_i H & \lambda_i^N \Phi \\ 0 & 0 & 0 & 0_j & 0 & \lambda_V^N \phi \\ 0 & 0 & 0 & 0 & \tilde{M}_L & \tilde{m}_5 \\ \tilde{Y}_\nu^{ij} H & 0_i & 0 & 0_{3 \times 3} & 0 & 0 \\ \tilde{\lambda}^N_i H & 0 & \tilde{M}_L & 0 & 0 & 0 \\ \lambda_i^{NT} \Phi & \lambda_V^N \phi & \tilde{m}_5 & 0 & 0 & 0 \end{pmatrix}$$

decoupled by  $M_R$

Dirac neutrino  $\sim$  TeV

SM neutrino  $\sim H^2/M_R$

SM and VL neutrinos are secluded by Majorana mass

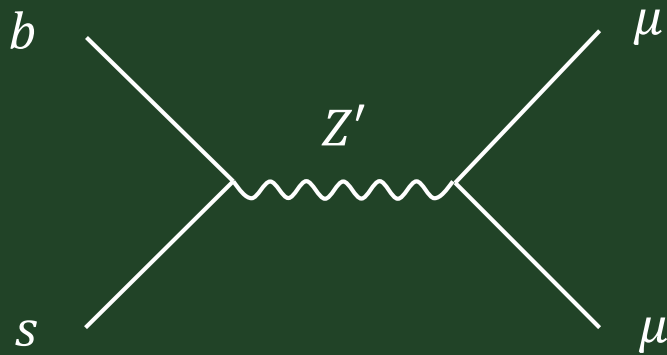
# Outline

1. Introduction
2. Vector-Like 4<sup>th</sup> Family with Vector-Like U(1)' Model
3. Phenomenology
4. LHC Signals
5. Conclusion

# $b \rightarrow s \mu^+ \mu^-$ anomalies

## ➤ $Z'$ boson contribution

$\epsilon_{s_L}, \epsilon_{b_L}$ : mixing bet. VL-quark and  $s_L, b_L$  quark



$$C_9^{NP} \sim -0.7 \times \left( \frac{500 \text{ GeV}}{m_{Z'}} \right)^2 \left( \frac{g_{\mu\mu}^V \cdot g_{bs}^L}{0.0003} \right)$$

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

$$g_{\mu\mu}^V \sim g' (s_{\theta_{\mu L}}^2 + s_{\theta_{\mu R}}^2)$$

$$g_{\mu\mu}^V \sim g' \text{ for } \Delta a_\mu \quad \longrightarrow \quad \epsilon_{s_L} \epsilon_{b_L} \sim 0.003 \times \left( \frac{0.3}{g'} \right)^2$$

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

# CKM Matrix

5 × 5 “CKM” matrix  $\hat{V}_{CKM} = U_u^\dagger \begin{pmatrix} 1_{3 \times 3} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} U_d$

CKM matrix is **NOT** unitary

## ➤ Non-Unitarity

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

$M_Q$ : VL quark (VLQ) mass

$\epsilon_{t_R}$ : mixing bet. top and VLQ

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

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



# $\chi^2$ -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

- $\Delta a_\mu$
- $C_9^{NP}, C_{10}, C'_{9,10}$



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

$x_i$  model prediction

$x_i^0$ : exp. value/SM value

$\sigma_i$ : uncertainty

# Best Fitted Points

Parameters	Point A	Point B	Remark
$\chi^2$	25.1	24.9	$N_{\text{inp}} = 65, N_{\text{obs}} = 98$
$g'$	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]
$\text{Br}(\mu \rightarrow e\gamma) \times 10^{13}$	3.58	2.10	$< 4.2$ (90%C.L.) [1]
$\text{Br}(\tau \rightarrow \mu\gamma) \times 10^8$	$1.96 \times 10^{-5}$	$4.91 \times 10^{-2}$	$< 4.4$ (90%C.L.) [1]
$\text{Br}(\tau \rightarrow \mu\mu\mu) \times 10^8$	$3.03 \times 10^{-5}$	$7.42 \times 10^{-3}$	$< 2.1$ (90%C.L.) [1]
$\text{Re } C_9^\mu$	-0.725	-0.571	-0.7(3) [29]
$\text{Re } C_{10}^\mu$	0.320	0.316	0.4(2) [29]
$\Delta M_d$ [ps $^{-1}$ ]	0.612	0.599	0.507(81) [1]
$\Delta M_s$ [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]

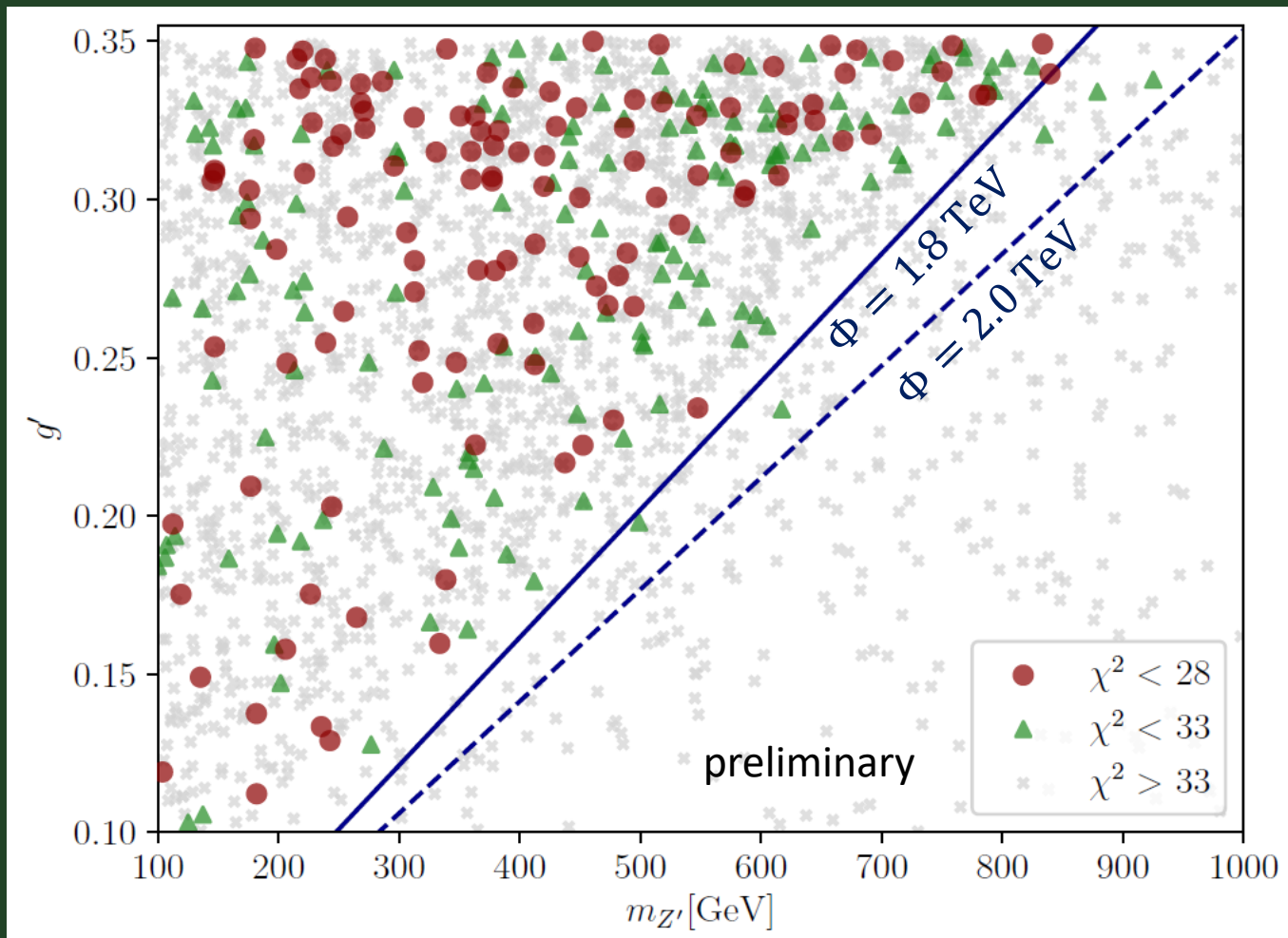
Most observables are explained within  $1 \sigma$

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

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

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

$$N_{dof} = N_{obs} - N_{inp} = 33$$



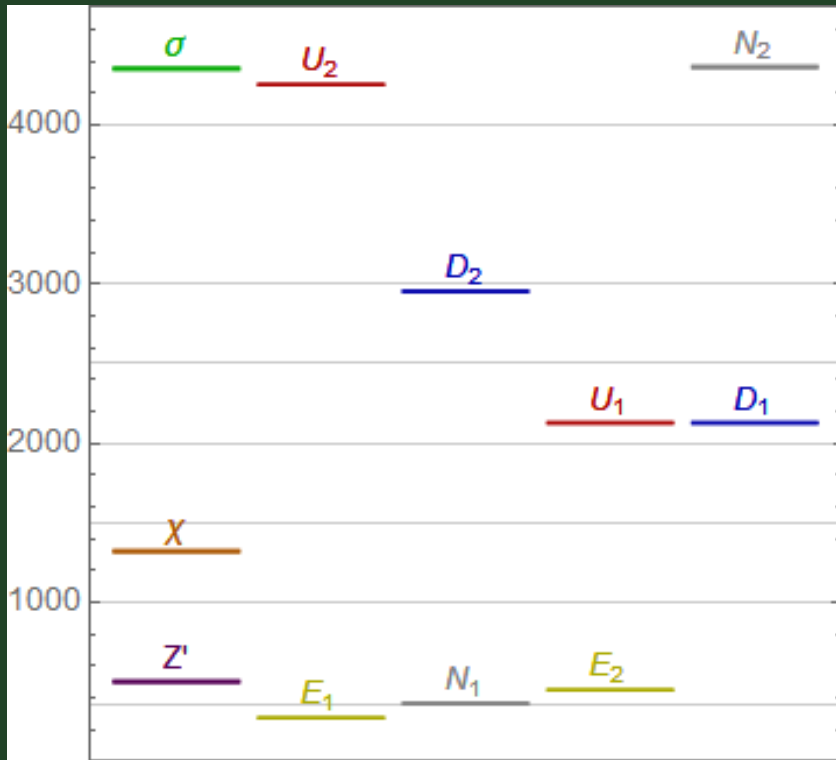
$\Phi < 1.8 \text{ TeV}$  is required for  $\chi^2 < 28$

# Outline

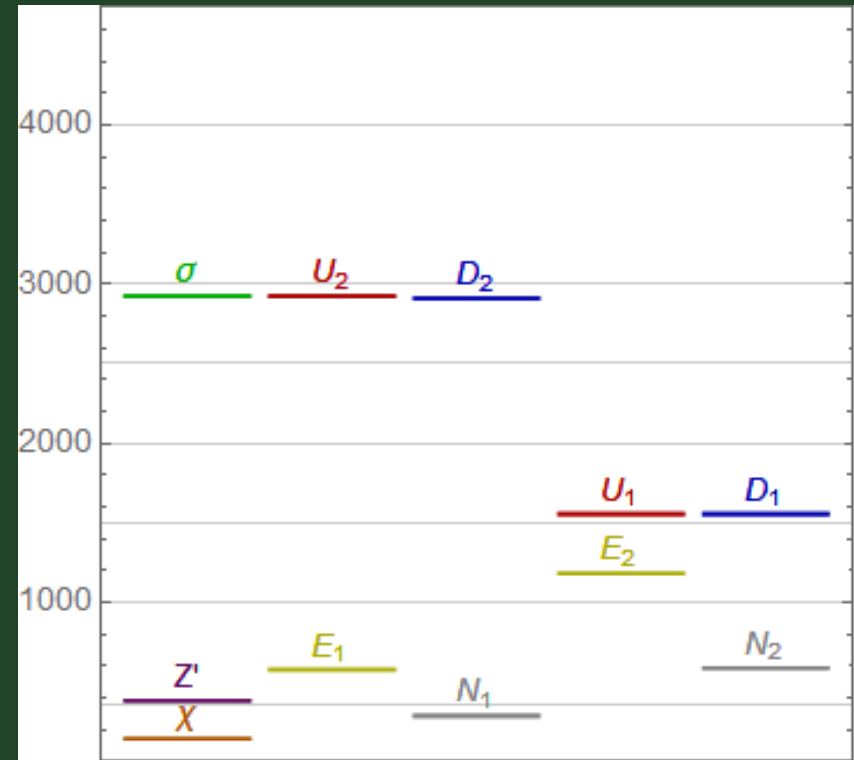
1. Introduction
2. Vector-Like 4<sup>th</sup> Family with Vector-Like U(1)'
3. Phenomenology
4. LHC Signals
5. Conclusion

# Mass Spectrum at Best-Fit Points

➤ Point A :  $m_{E_1} < m_{Z'}, m_\chi$



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



- $\Delta a_\mu$  predicts light  $Z'$  and VL-leptons
- U(1)' breaking scalar  $\chi$  is as light as  $Z'$  since their masses come from  $\Phi$
- VL-family strongly couples to  $Z'$ ,  $\chi$  and VL-family

# Z' signal

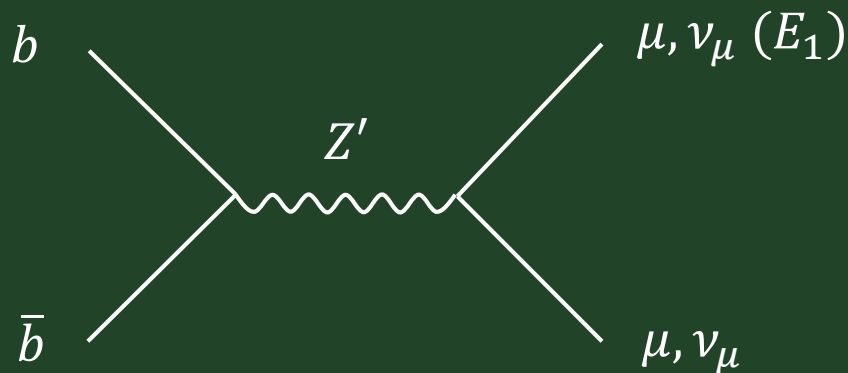
$$\Phi < 1.8 \text{ TeV} \quad \longrightarrow \quad m_{Z'} < 900 \text{ GeV if } g' < 0.35$$

## ➤ 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  $\mathcal{O}(1)$
- $g_{\mu\mu}^L \sim g_{\nu_\mu\nu_\mu}^L : Z' \rightarrow \nu\nu$
- $Z' \rightarrow E_1\mu$  decay possible if  $m_{Z'} > m_{E_1}$



dimuon resonance signal is expected

# Dimuon $Z'$ Search at LHC

MadGraph5  
FeynRules

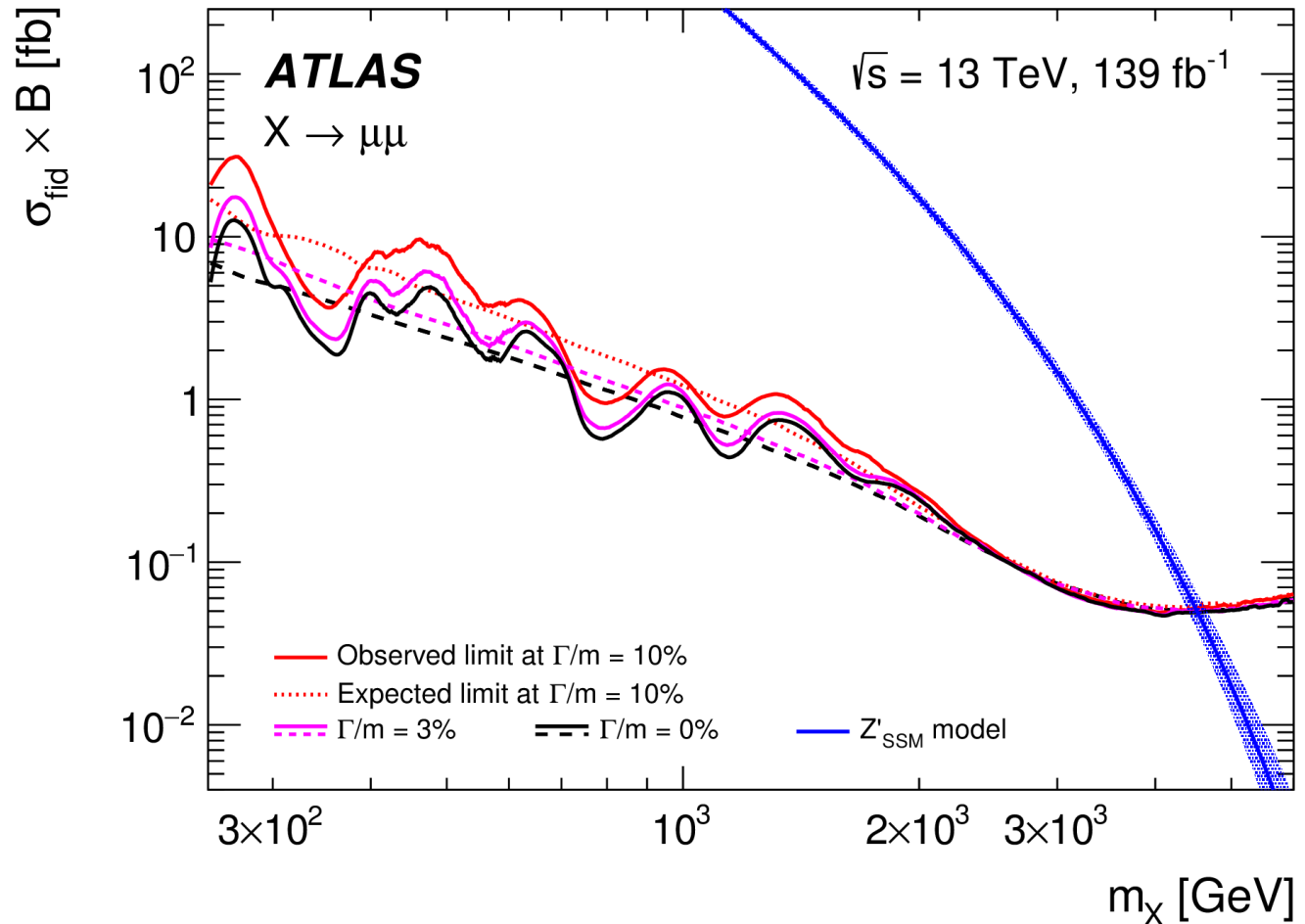
$$\sigma_{fid}(pp \rightarrow Z' \rightarrow \mu^+ \mu^-)$$

Fiducial region

$$p_T(l) > 30 \text{ [GeV]}$$

$$|\eta(l)| < 2.5$$

$$m_{ll} > m_{Z'} - 2\Gamma_{Z'}$$



production cross section is very small

# Dimuon $Z'$ Search at LHC

MadGraph5  
FeynRules

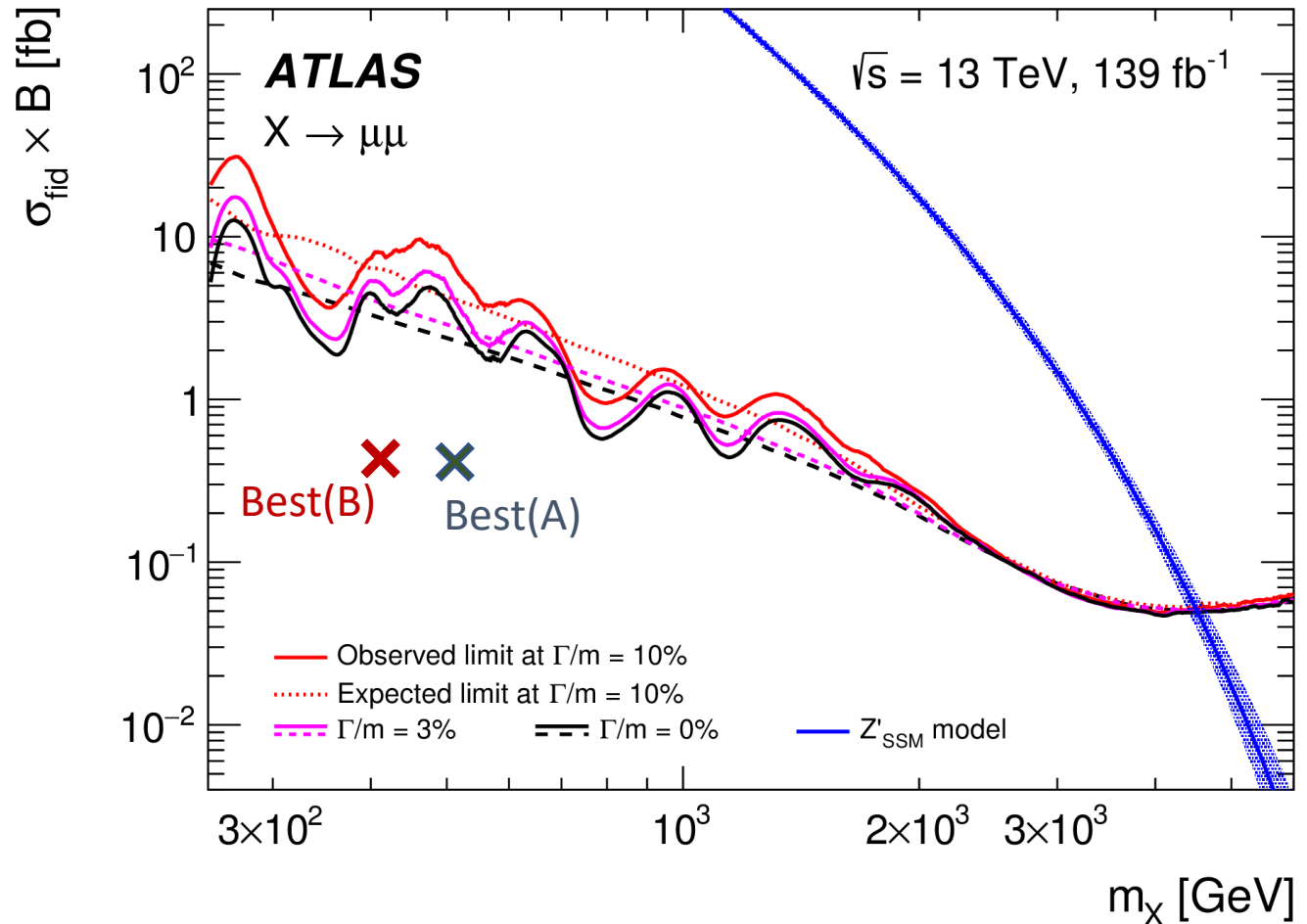
$$\sigma_{fid}(pp \rightarrow Z' \rightarrow \mu^+ \mu^-) = 0.477 \text{ (A)}, 0.482 \text{ (B) [fb]}$$

Fiducial region

$$p_T(l) > 30 \text{ [GeV]}$$

$$|\eta(l)| < 2.5$$

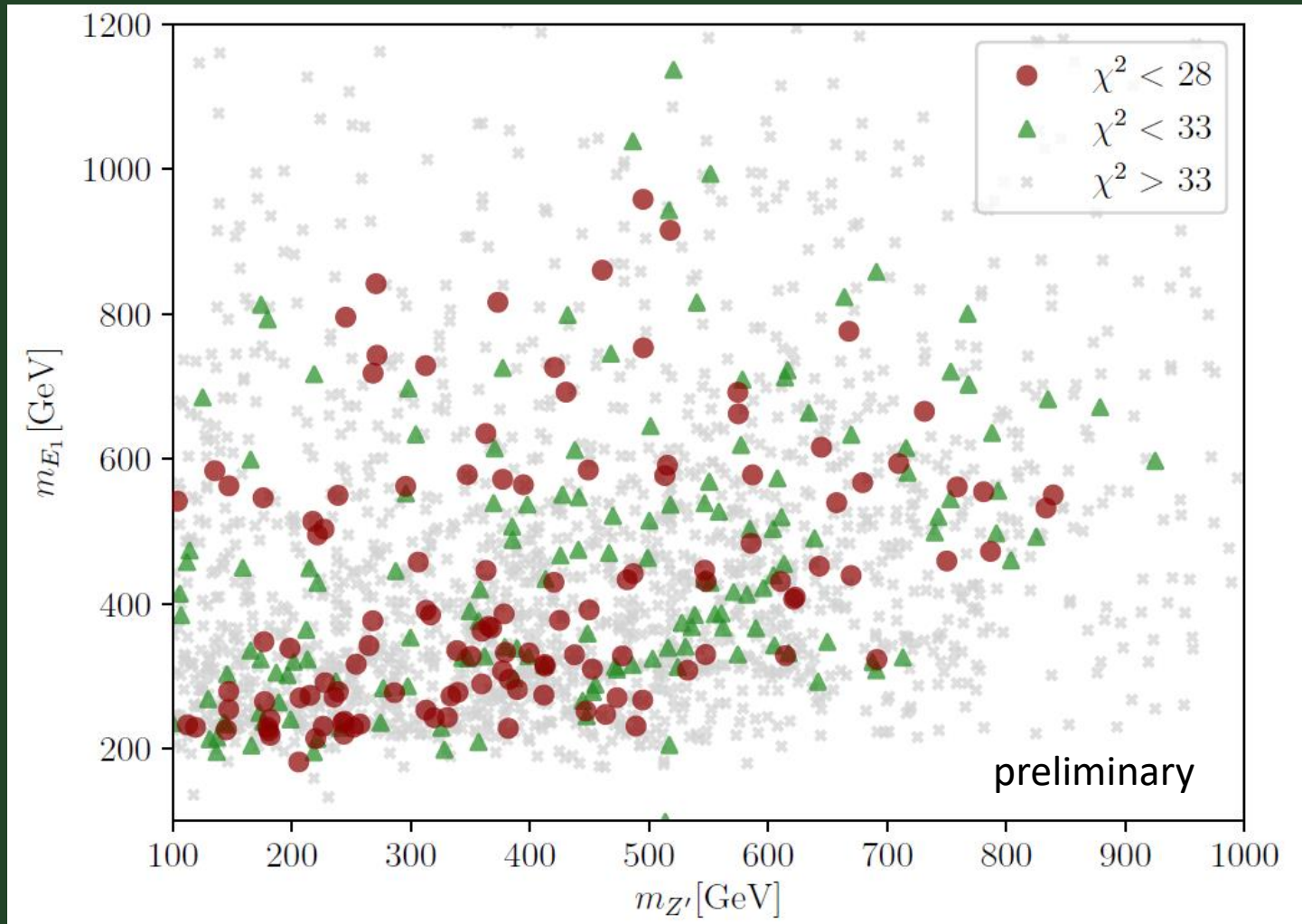
$$m_{ll} > m_{Z'} - 2\Gamma_{Z'}$$



production cross section is very small



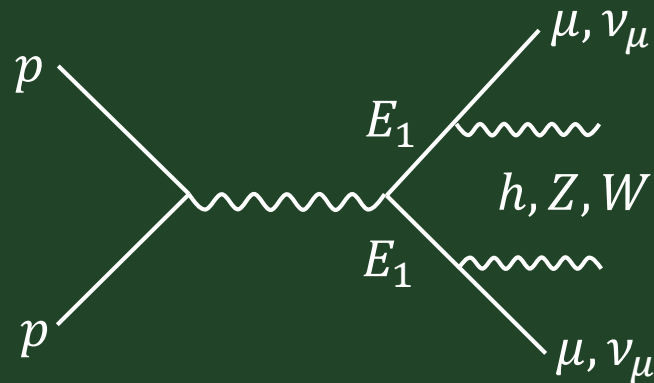
# Lightest VL-lepton mass



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

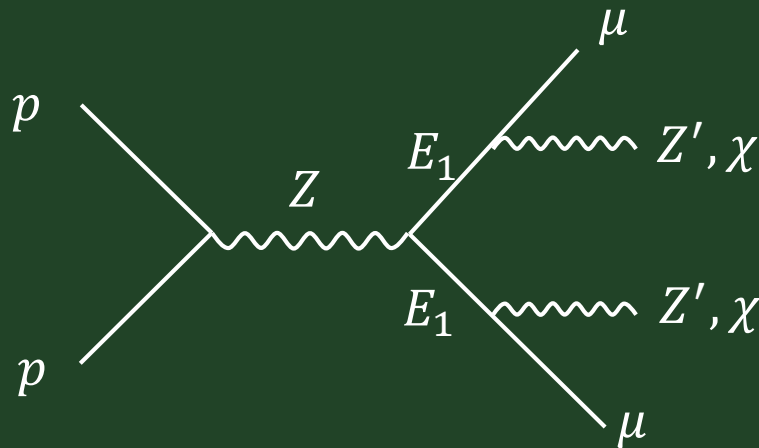
# LHC signal of $E_1$

➤ If  $m_{E_1} < m_{Z'}, m_\chi$



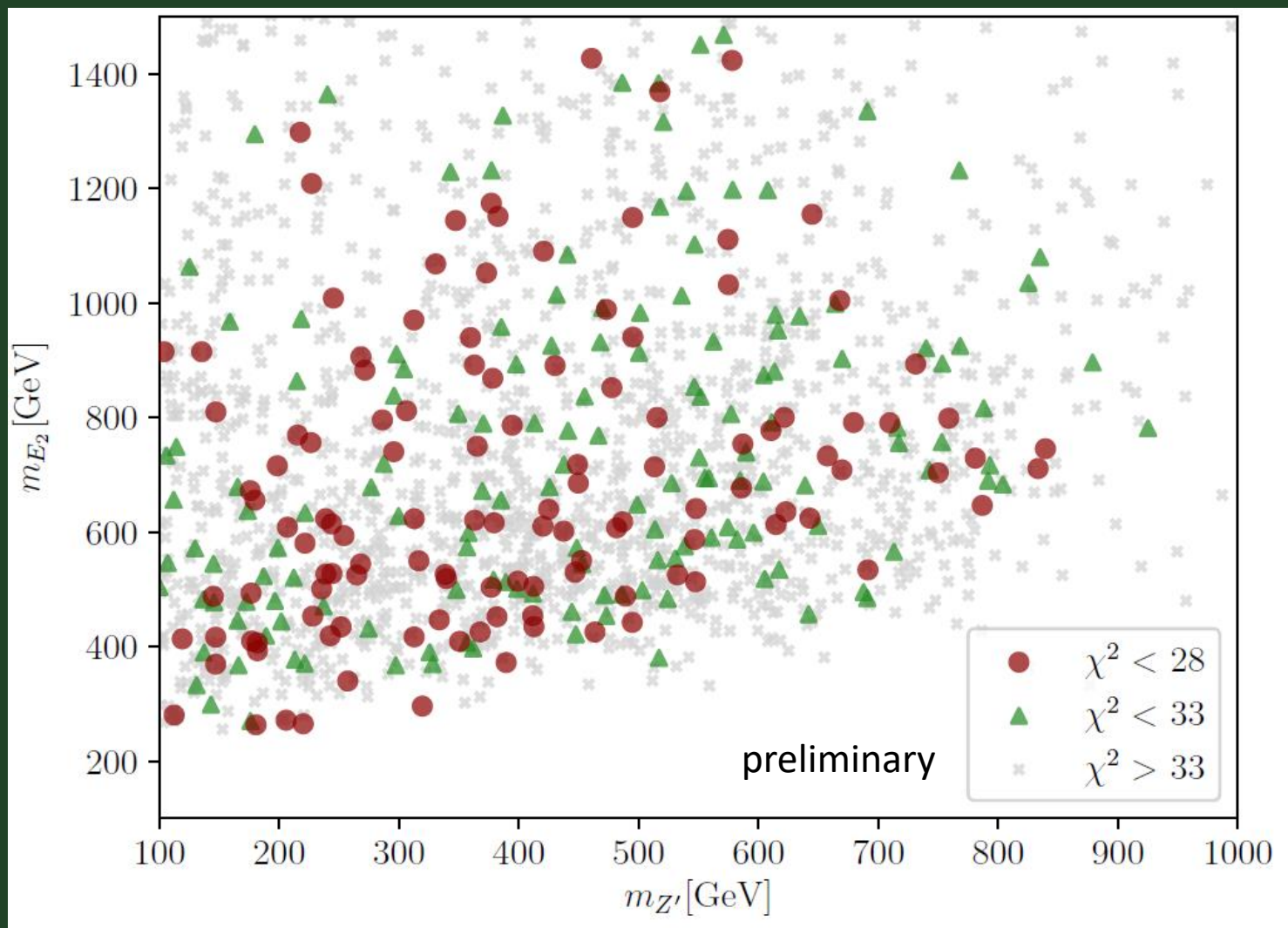
- usual VL-lepton signal
- $\exists$  signals from VL-neutrino if doublet
- There is no experimental Run-2 study

➤ If  $m_{E_1} > m_{Z'}, m_\chi$



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

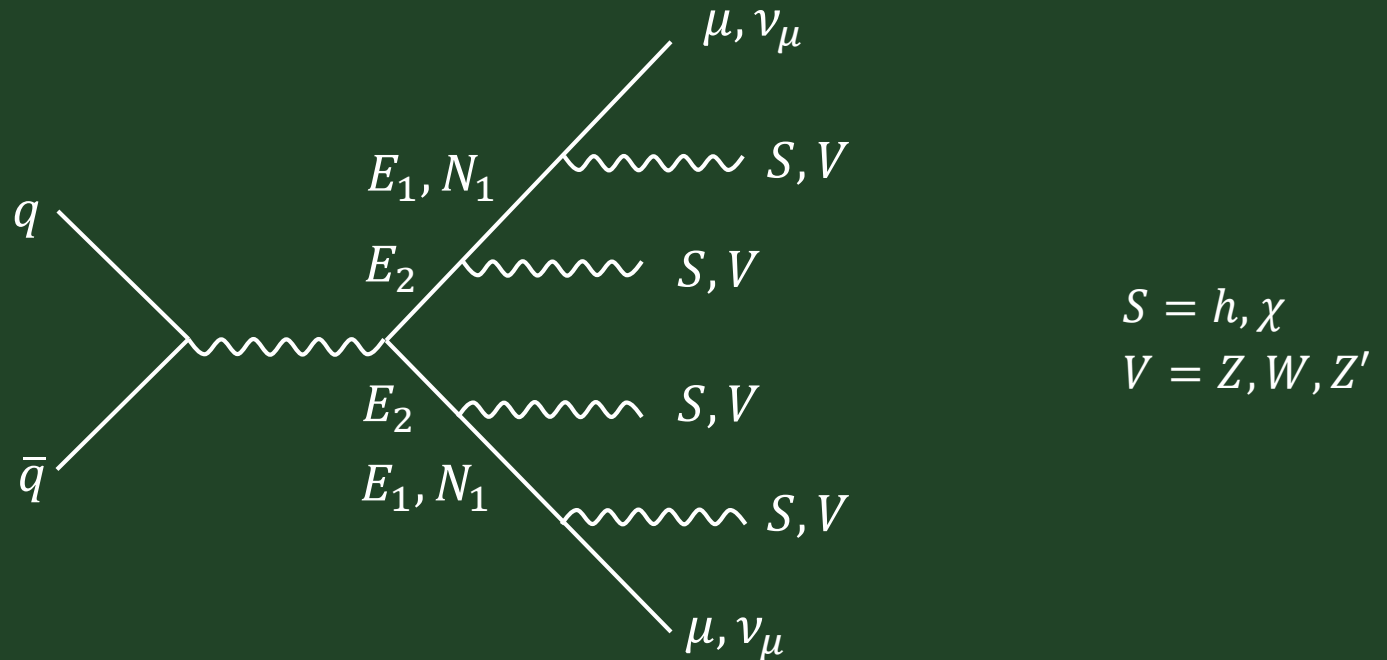
# Heavier VL-lepton



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

# LHC signal of VL lepton

➤ Typical signals

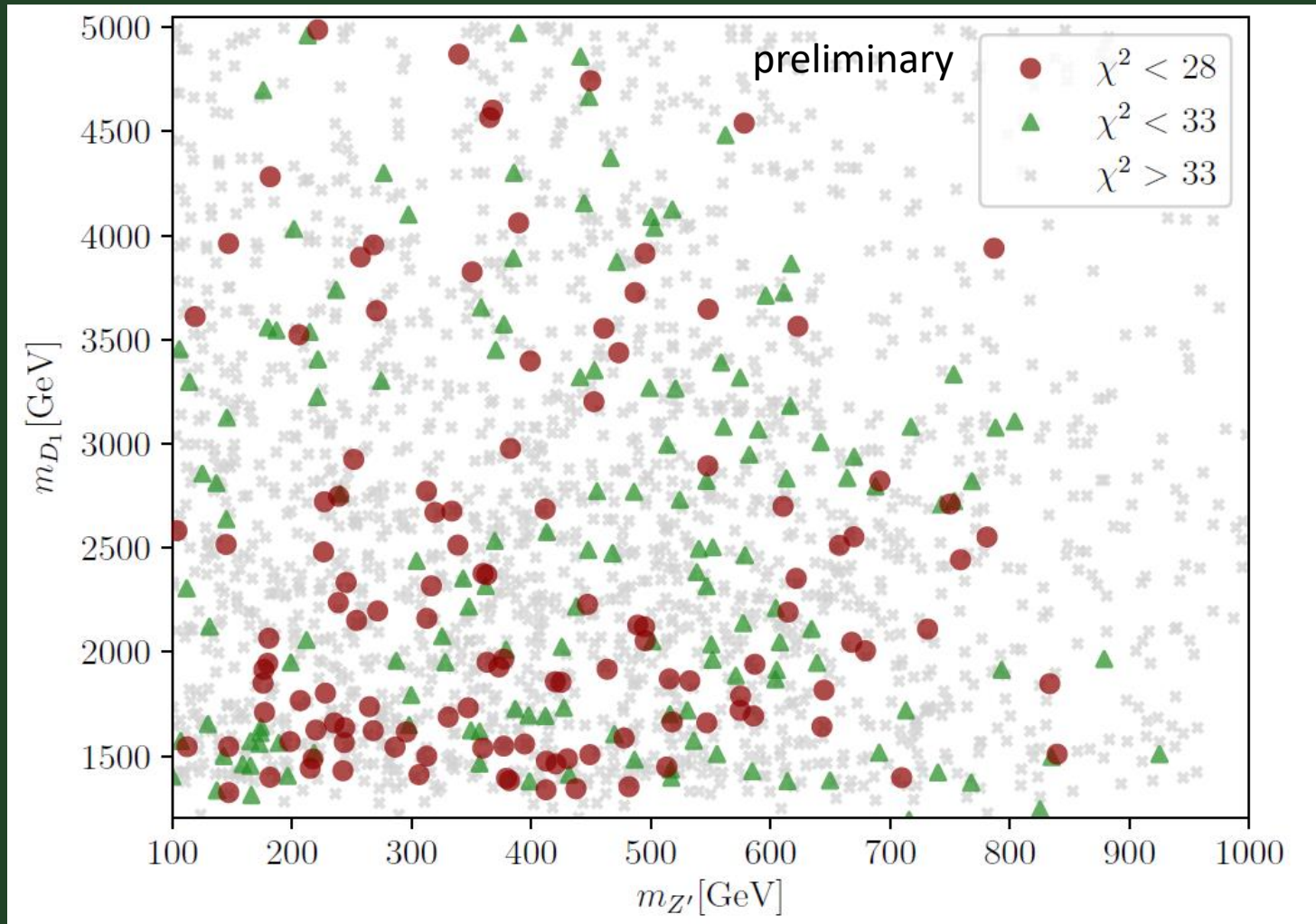


➤ Distinctive signal

$$E_2 E_2 \rightarrow E_1 Z + E_1 Z \rightarrow \mu Z' Z + \mu Z' Z$$

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

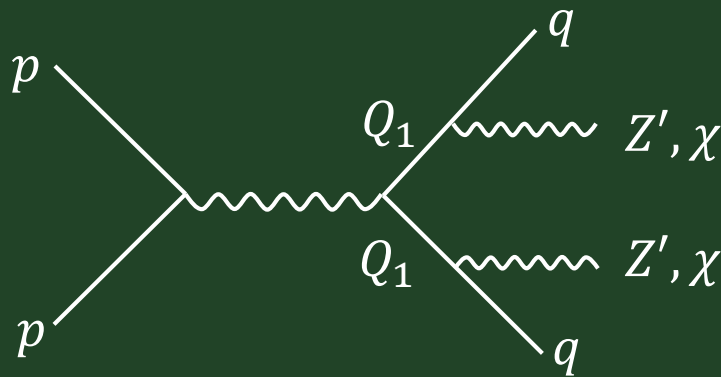
# VL quark



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  $Z' \rightarrow \nu\nu$
- dimuon resonances are expected

## ➤ Distinctive Signals

- $Q_1 Q_1 \rightarrow q Z' + q Z' : 2 \text{ jet} + 2 (\mu\mu)_{Z'}$  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

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

Thank you for attention

Backup



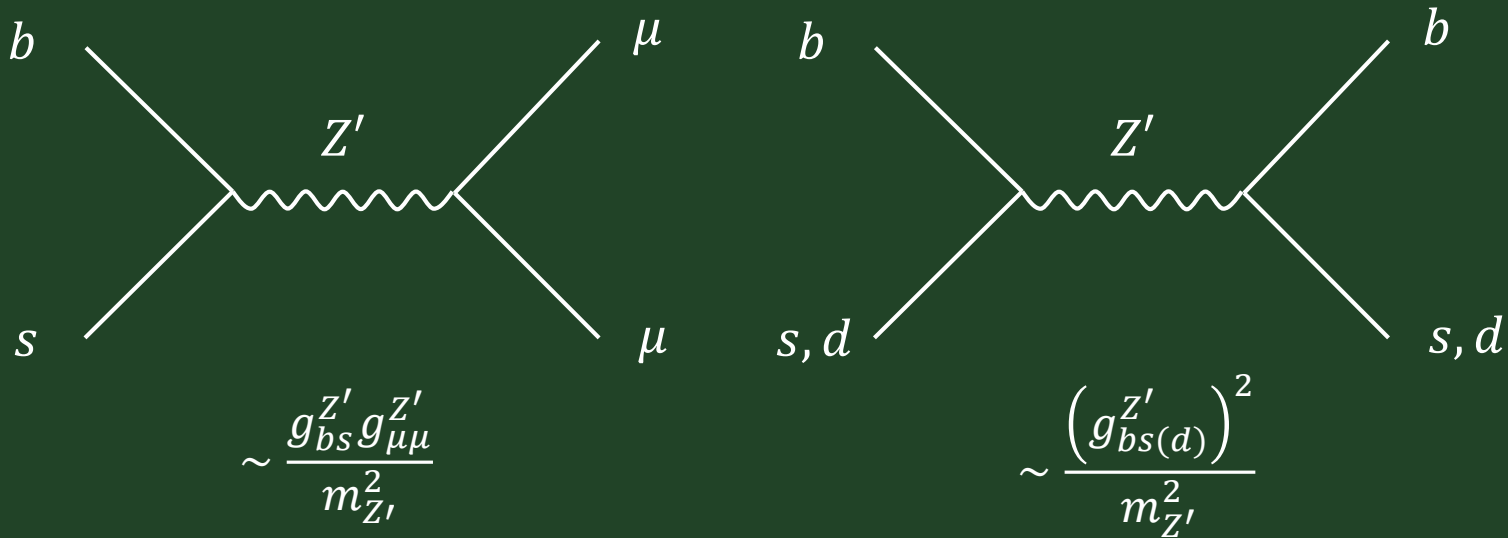
# Mass and Decays at best(A)

	Mass [GeV]	Width [GeV]	Decay 1	Br	Decay 2	Br
$Z'$	494.7	0.7723	$\mu\mu$	0.4058	$\nu\nu$	0.3529
$\chi$	1314.	2.290	$N_1 N_1$	0.2934	$E_1 \mu$	0.1477
$\sigma$	4345.	3.667	$U_1 t$	0.2516	$D_1 b$	0.2476
$E_1$	267.2	$2. \times 10^{-6}$	$h\mu$	0.6774	$Z\mu$	0.1693
$N_1$	359.2	0.5505	$W E_1$	1.000	$W\mu$	0.0000
$E_2$	442.4	1.783	$Z E_1$	0.8646	$W N_1$	0.1084
$N_2$	4357.	0.0019	$W\mu$	0.3745	$Z\nu$	0.1872
$D_1$	2120.	1.535	$Z' b$	0.4514	$W t$	0.3629
$U_1$	2120.	1.538	$Z' t$	0.4552	$h t$	0.1840
$D_2$	2947.	1.029	$W U_1$	0.4983	$Z D_1$	0.2493
$U_2$	4252.	1.042	$W D_1$	0.4901	$Z U_1$	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
$\chi$	135.4	$9. \times 10^{-9}$	$\mu\mu$	0.8094	$bs$	0.0945
$\sigma$	2915.	5.575	$E_2 E_2$	0.2688	$E_1 E_1$	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	$W N_2$	0.4698	$Z E_1$	0.2340
$D_1$	1548.	0.3587	$Z's$	0.2889	$\chi s$	0.2874
$U_1$	1548.	0.3594	$Z'c$	0.2833	$\chi c$	0.2818
$D_2$	2902.	0.1854	$Z'b$	0.4448	$\chi b$	0.4432
$U_2$	2915.	0.0441	$W D_1$	0.3897	$h U_1$	0.1969

# Meson Mixing

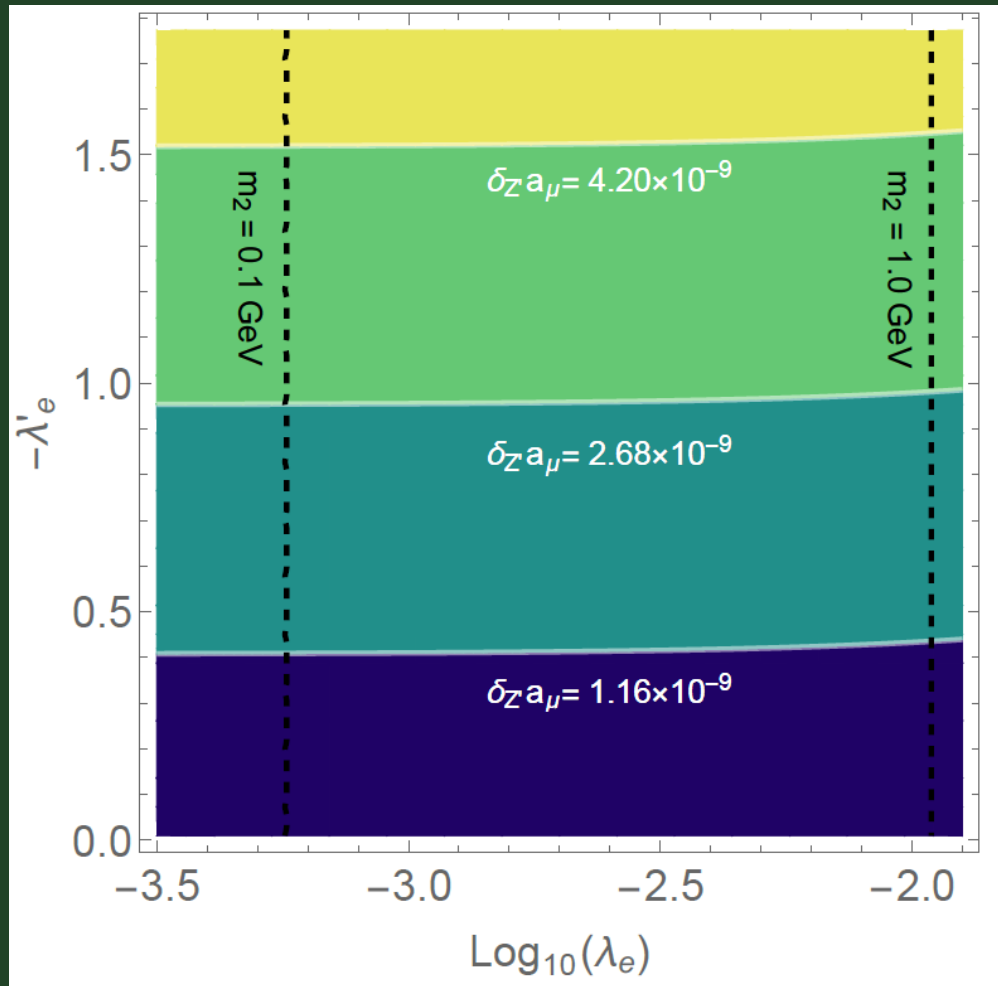


➤ CKM matrix and SM-boson couplings

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

$|V_{td}| \sim 0.009 \ll |V_{ts}| \sim 0.04 \longrightarrow$  NP effects to  $\Delta M_d$  are as important as  $\Delta M_s$

# Muon mass and $g - 2$



c.f.) mass matrix

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

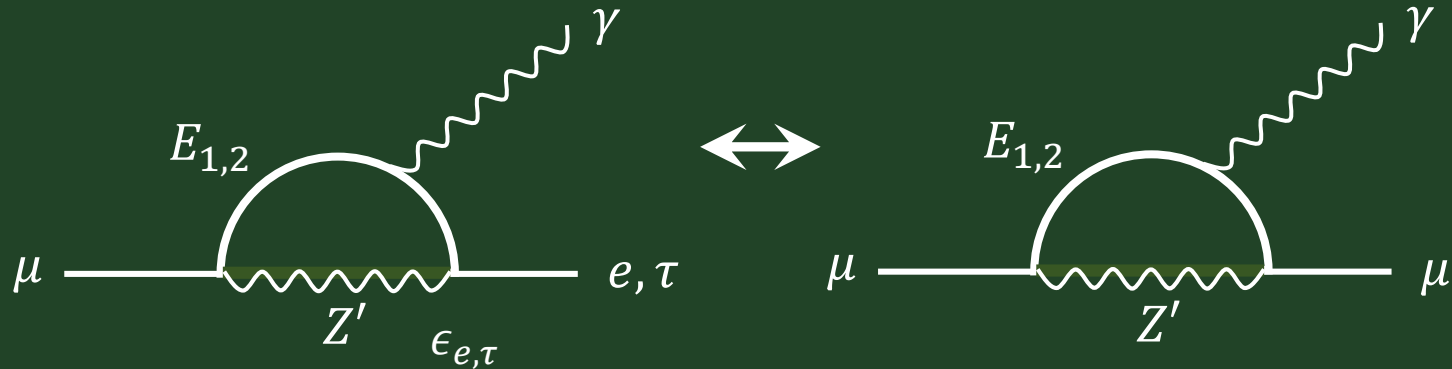
$$m_{Z'} = \lambda_V^{L,E} \phi = \lambda_2^{E,L} \Phi = 500 \text{ GeV}, \text{ others} = 0$$

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

# Lepton Flavor Violation (I)

➤  $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma$

$\epsilon_{eL,R}, \epsilon_{\tau L,R}$  : mixing bet. VL-lepton and  $e, \tau$



similar diagrams to  $\Delta a_\mu$  induce  $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma$

Exp. limits

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

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

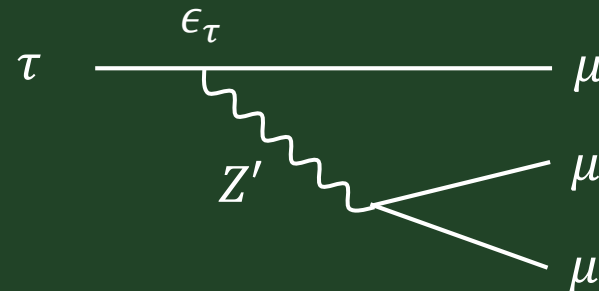
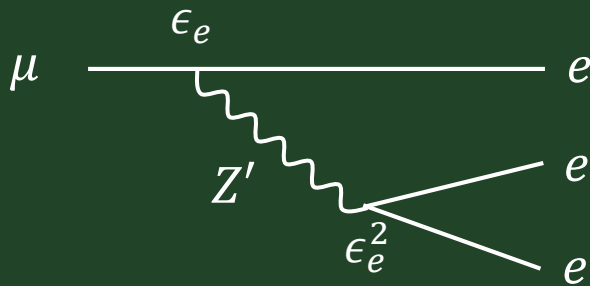
\*  $\exists$  subdominant contributions from  $U(1)'$  breaking scalar  $\chi$

# Lepton Flavor Violation (II)

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

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

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



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

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

# 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

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

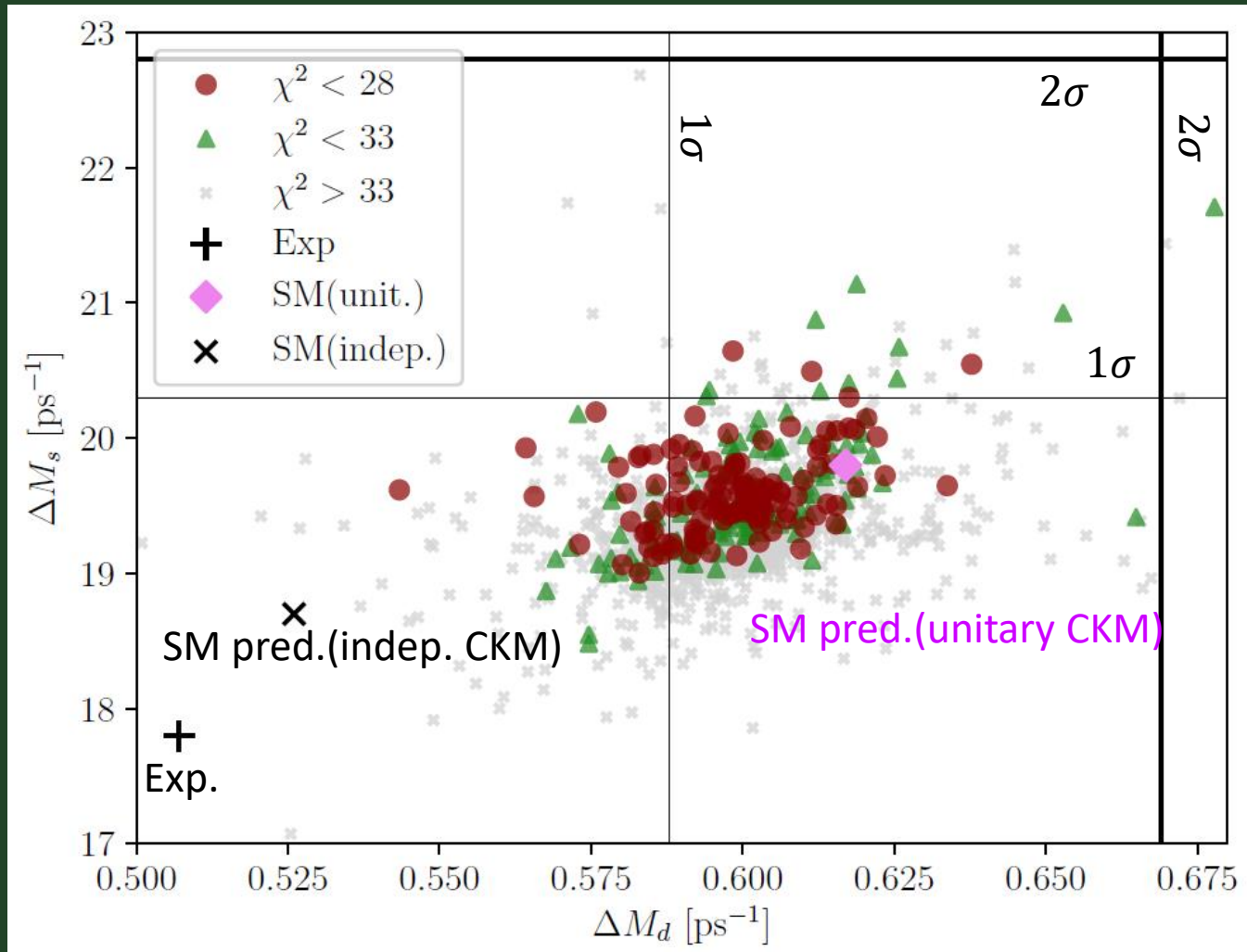
PDG

➤ 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:  $[V_{CKM}^\dagger V_{CKM}]_{ij} = \delta_{ij} + \mathcal{O}(10^{-7})$

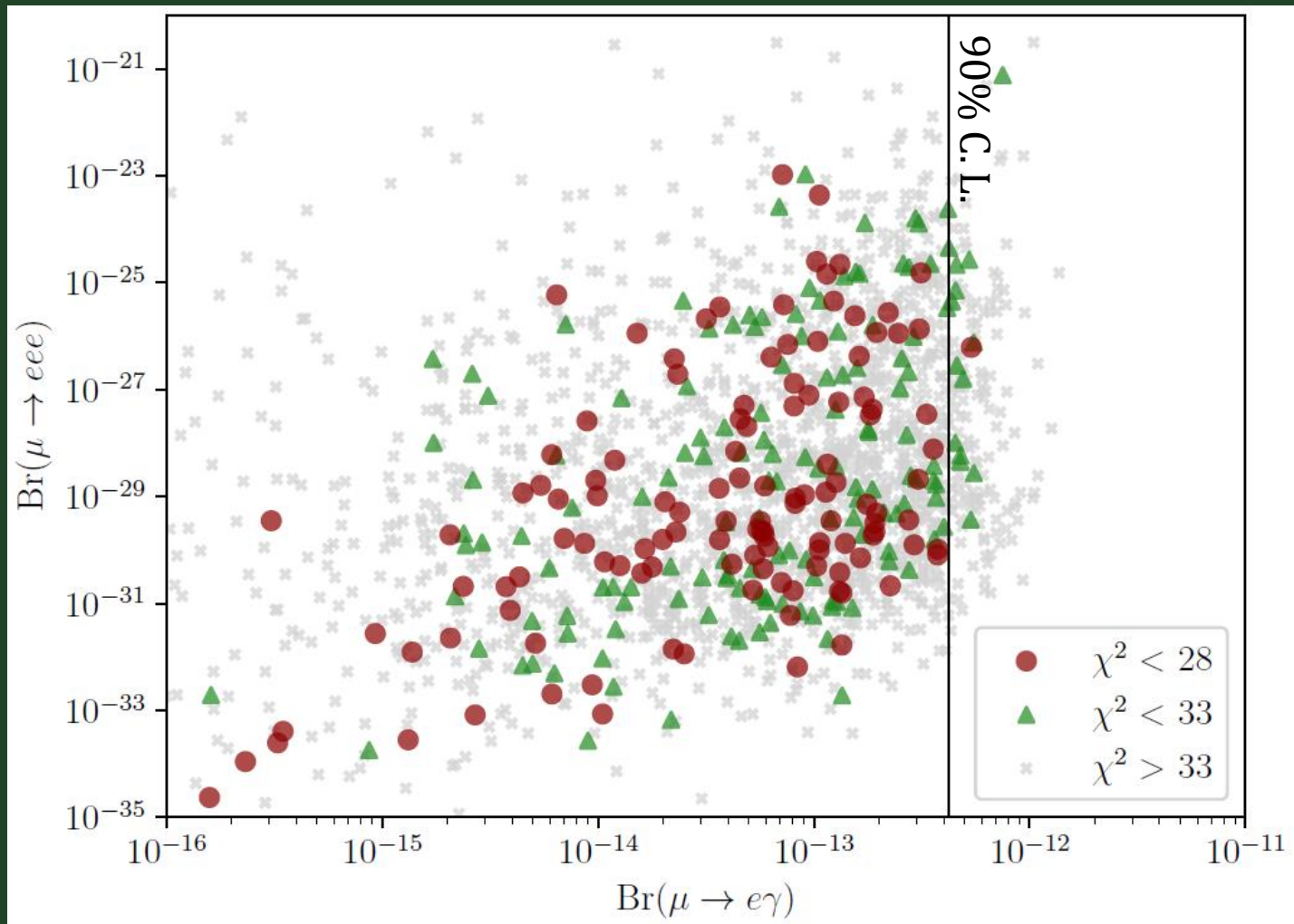
# B-meson mixing



CKM values are more relevant than NP effects

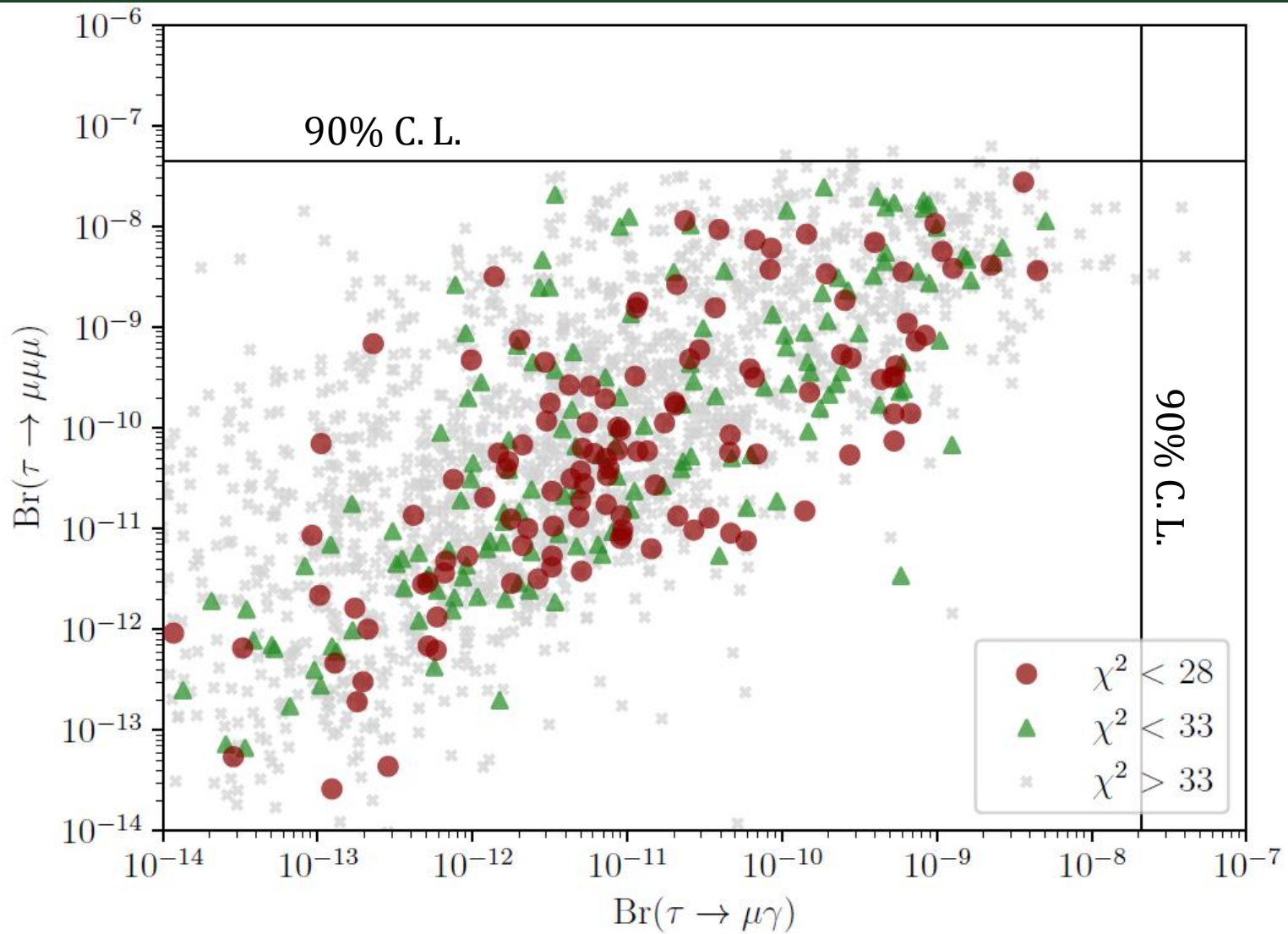


# LFV muon decays



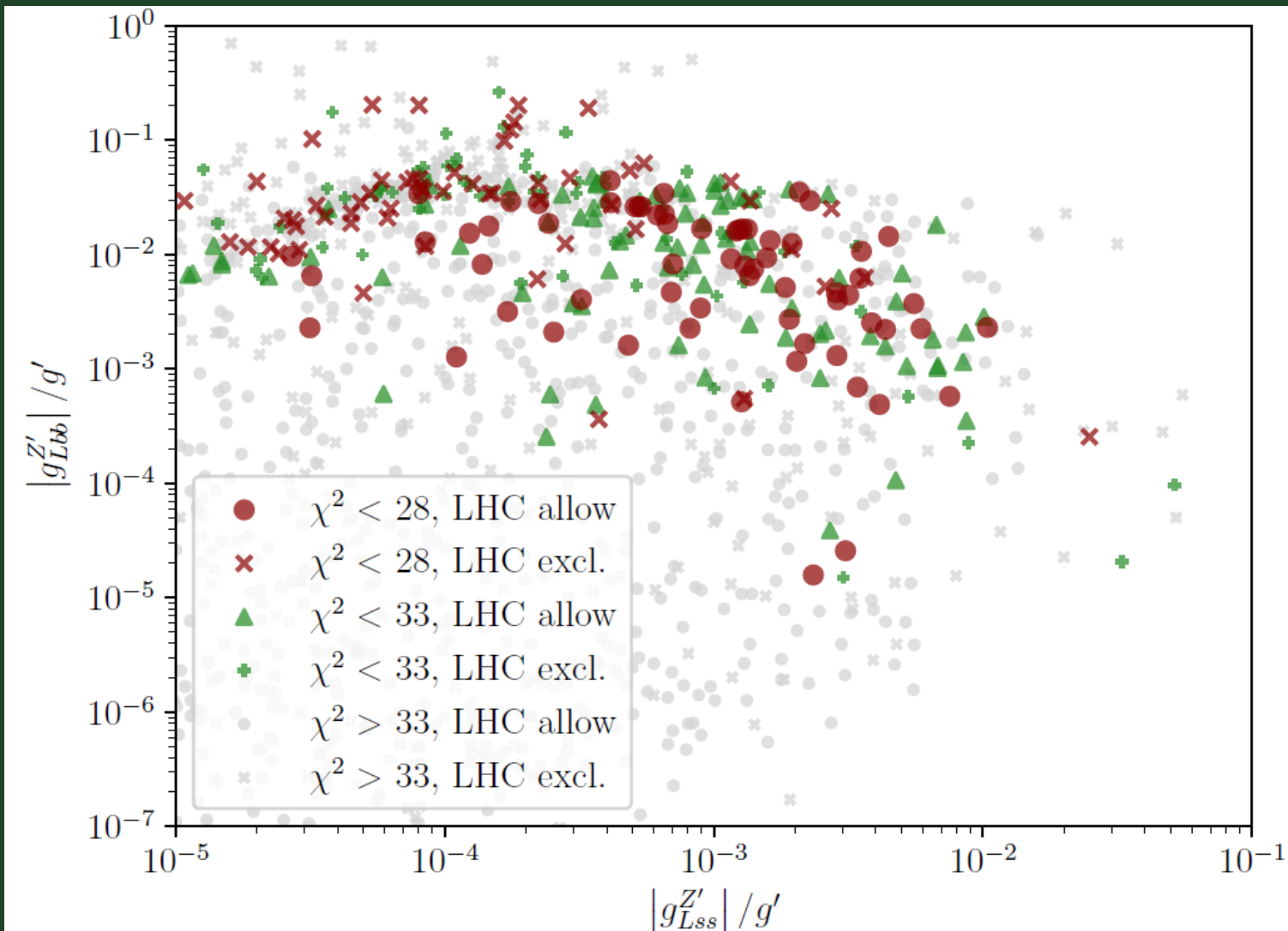
$\text{Br}(\mu \rightarrow e\gamma) \gg \text{Br}(\mu \rightarrow eee)$  due to the scaling  $\epsilon_e^2 \gg \epsilon_e^6$

# LFV tau decays



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

# Dimuon $Z'$ Search at LHC



$g_{SS}^L \gtrsim 10^{-4}$  ( $\epsilon_{SL} \gtrsim 10^{-2}$ ) is favored to suppress  $g_{bb}^L \lesssim 10^{-2}$

# Z' boson couplings

➤ VL lepton dominantly mix with muon

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

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

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

# B – Z' mixing



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

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

$$\sim 0.005 \text{ (I)}, 0.009 \text{ (II)}$$

