PASCOS2022 @ MPIK

Explaining recent anomalies in vector-like fermion extensions

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2205.10480, 2204.07022, 2104.04461, 1911.11075, 1906.11297

in collaboration with

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S.Raby [Ohio State U.], A.Trautner [Max Planck Inst.]

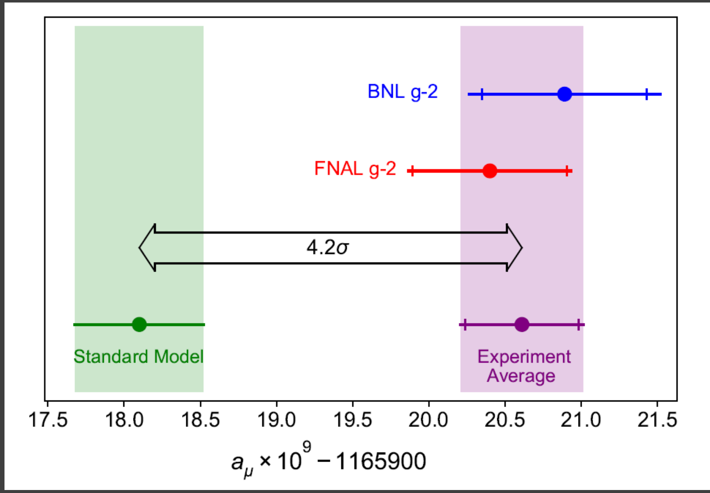
Muon anomalies

- muon g-2

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

$$= (2.51 \pm 0.59) \times 10^{-9}$$

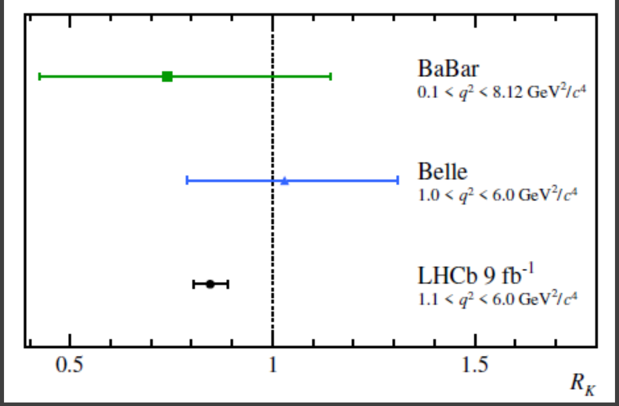
4.2σ discrepancy



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

$$R_K = \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+e^-)} = 0.846^{+0.042}_{-0.039} \pm 0.013$$

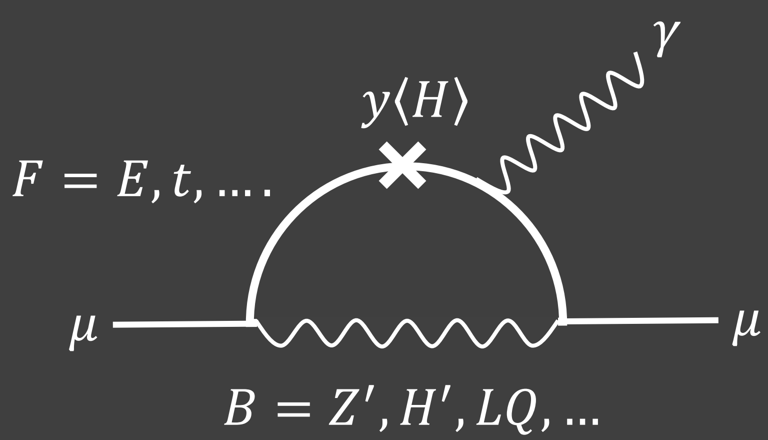
$\sim 3.1\ \sigma$ below unity



✓ anomalies are also found in angular obs. and BRs

Vector-like [VL] lepton and g-2

➢ chiral enhancement



$$\Delta a_\mu \sim \frac{g^2 m_\mu}{8\pi^2 m_B^2} \times y\langle H\rangle$$

$$\sim 2 \times 10^{-9} \times \left(\frac{1\ \mathrm{TeV}}{m_B}\right)^2 \left(\frac{g^2 y}{0.1^3}\right)$$

- without chiral enhancement, $y\langle H\rangle \to m_\mu$
- heavy boson explanation requires chiral enhancement
- VL lepton is a nice candidate for it

Outline

1. Muon anomalies
2. Vector-like U(1)’ model and LHC signal
3. W mass and vector-like leptons
4. Summary

Our Model

JK, S.Raby, A.Trautner, 1906.11297, 1911.11075

➢ 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

VL fermions

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

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

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

Muon anomalies

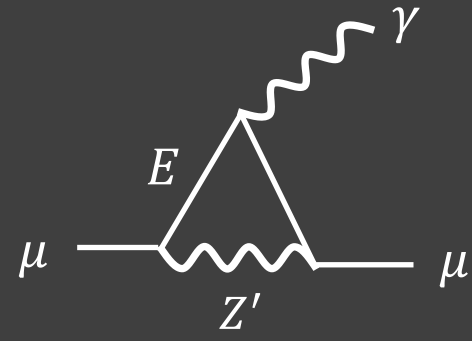
JK, S.Raby, A.Trautner, 1906.11297, 1911.11075

both anomalies are explained by Z' and VL lepton

- muon g-2

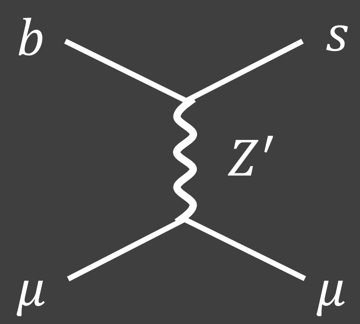
$$\Delta a_\mu \sim 5 \times 10^{-9} \times \left(\frac{500\ \mathrm{GeV}}{m_{Z'}}\right)^2 \left(\frac{g^L_{\mu\mathrm{E}} g^R_{\mu\mathrm{E}}}{0.09}\right)$$

$g^{L/R}_{fF}$: $f - F - Z'$ coupling in L/R current



- $b \to s\mu\mu$ anomaly c.f. $C_9 \sim [-1, -0.5]$ is favored

$$C_9 \sim -0.83 \times \left(\frac{500\ \mathrm{GeV}}{m_{Z'}}\right)^2 \left(\frac{g^L_{sb}}{0.0006}\right)\left(\frac{g^L_{\mu\mu} + g^R_{\mu\mu}}{0.6}\right)$$



$m_{Z'} \sim m_E \sim \mathcal{O}(500\ \mathrm{GeV})$ explain anomalies

Benchmark Points

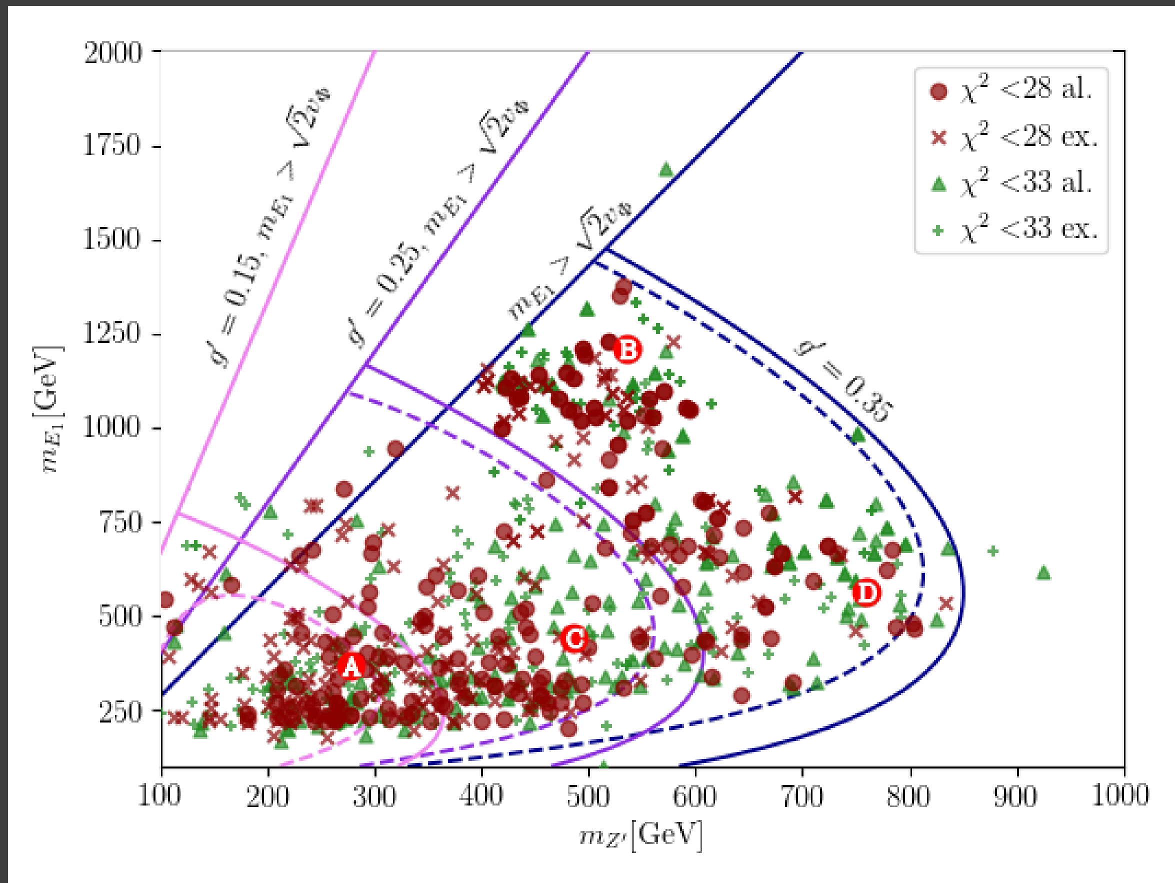
$\chi^2 = 22.6,$ $25.0,$ $23.3,$ 23.8 $N_{dof} = 33$

Observables	Point A	Point B	Point C	Point D	Exp.
$\Delta a_\mu \times 10^9$	2.62	2.52	2.52	2.45	2.68 ± 0.76
$\mathrm{BR}(\mu \to e\gamma) \times 10^{13}$	0.147	1.597	0.061	0.822	< 4.2
$\mathrm{BR}(\tau \to \mu\gamma) \times 10^8$	3.34×10^{-4}	3.62×10^{-4}	3.27×10^{-6}	8.45×10^{-7}	< 4.4
$\mathrm{BR}(\tau \to \mu\mu\mu) \times 10^8$	6.96×10^{-3}	4.77×10^{-4}	6.55×10^{-5}	4.36×10^{-7}	< 2.1
$\mathrm{Re}\, C_9^\mu$	-0.548	-0.806	-0.838	-0.808	-0.7 ± 0.3
$\mathrm{Re}\, C_{10}^\mu$	0.370	0.252	0.347	0.322	0.4 ± 0.2
$\Delta M_d\, [\mathrm{ps}^{-1}]$	0.561	0.610	0.598	0.590	0.506 ± 0.081
$\Delta M_s\, [\mathrm{ps}^{-1}]$	19.6	19.8	19.4	20.0	17.76 ± 2.5
$S_{\psi K_s}$	0.697	0.696	0.692	0.695	0.695 ± 0.019
$S_{\psi\phi}$	0.0366	0.0374	0.0373	0.0379	0.021 ± 0.031
$R^{\mathrm{th}}_{B_s \to \mu\mu}$	0.841	0.890	0.850	0.861	0.75 ± 0.16

best $m_{E_1} > 1.2$ TeV $m_\chi > 750$ GeV $m_{Z'} > 750$ GeV

Most observables are explained within 1 σ

Upper bound on VL lepton mass

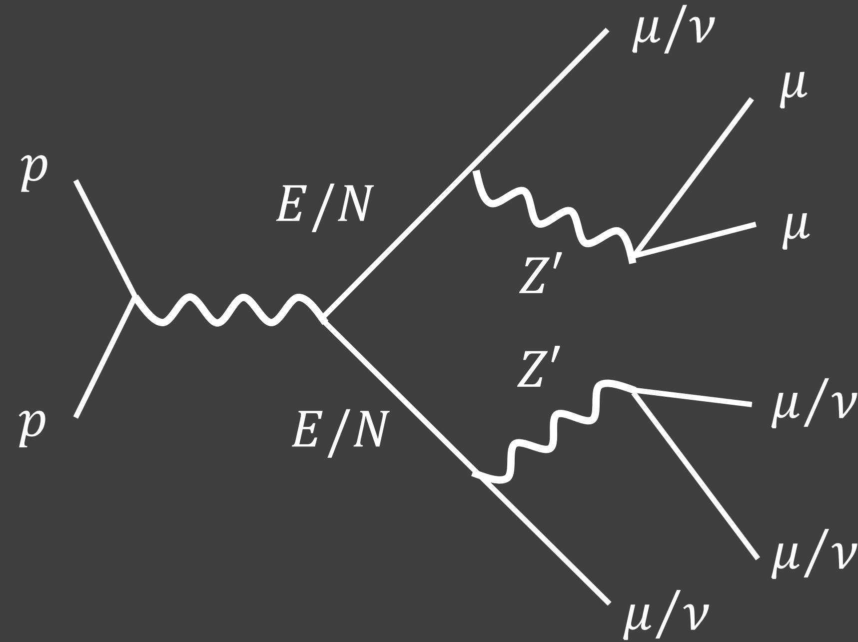


- Δa_μ is explained inside the contours
- VL lepton should be lighter than 1.4 (1.0) TeV for $m_Z' \sim 500$ (750) GeV

$\geq 4\mu$ signal

JK, S.Raby 2104.04461

- VL-lepton pair production: $pp \to \bar{L}L \quad L = E/N$

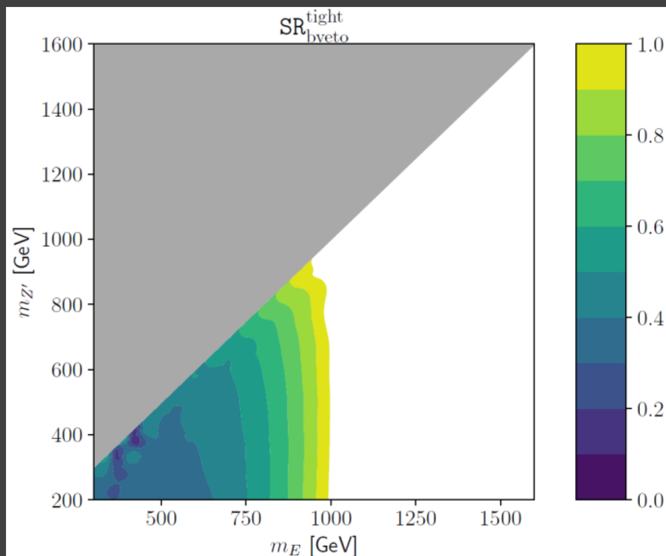


- 6 muons are produced If two $Z' \to \mu\mu$ from $pp \to \bar{E}E \to \mu^- \mu^+ Z' Z'$
- 4 muons are produced if one $Z' \to \mu\mu$ or VL neutrino production
- we recast the ATLAS result searches for 4/5 leptons, 2103.11684

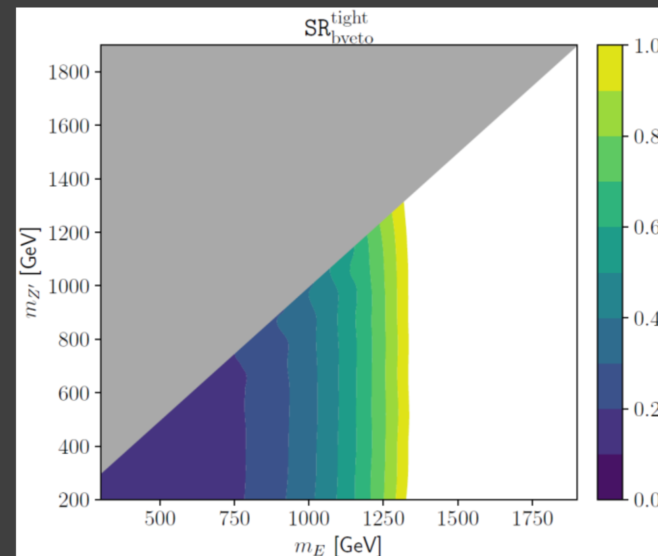
95%C.L. limits on $\mathrm{Br}(E \to Z'\mu)$

ATLAS 2103.11684

- $SU(2)_L$ singlet



- $SU(2)_L$ doublet



Madgraph5+pythia8+Delphes3

- $\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$ gives the strongest bound for $\mathrm{Br}(E \to Z'\mu)$
- limit is 1 (1.3) TeV for $\mathrm{Br}(E \to Z'\mu) = 1$ for singlet (doublet)
- 1.9σ excess in SR5L limit can be explained

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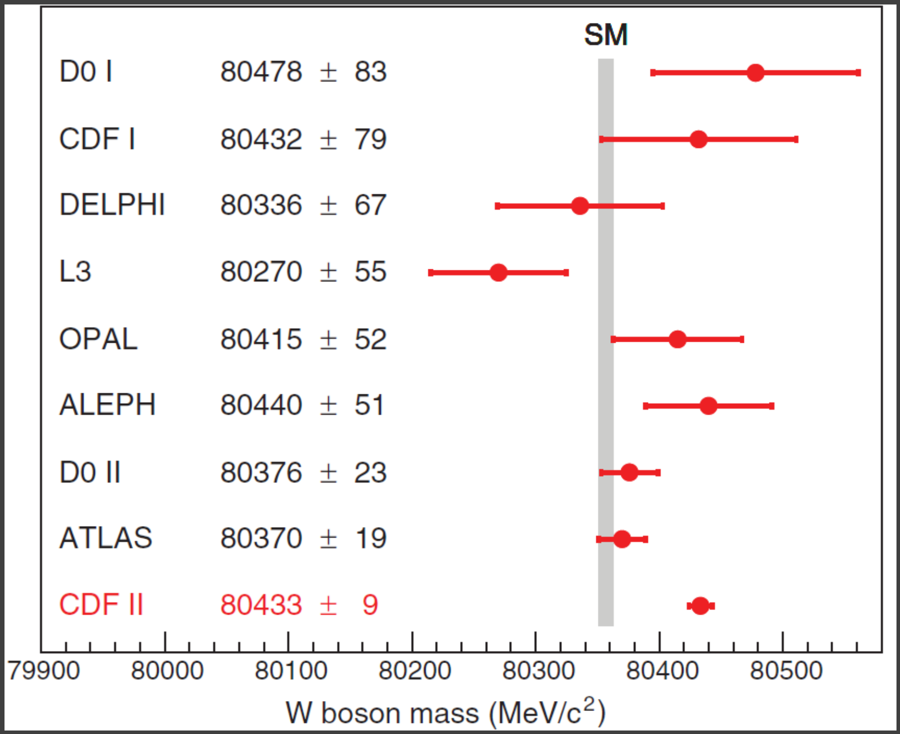
W mass anomaly ?

CDF, Science '22

- CDF measurement

  $m_W = 80.4335\ (94)$ GeV



- PDG average

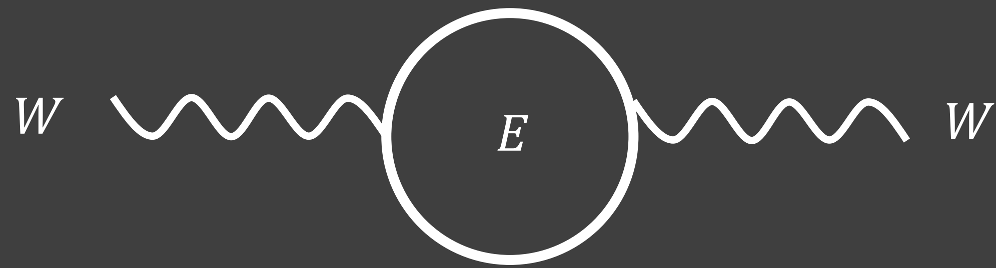
  $m_W = 80.379\ (12)$ GeV

- SM value $_{\text{PDG}}$

  $m_W = 80.361\ (6)$ GeV

new value is 7σ larger than the SM expectation

Vector-like lepton explanation



- W mass shift by VL leptons

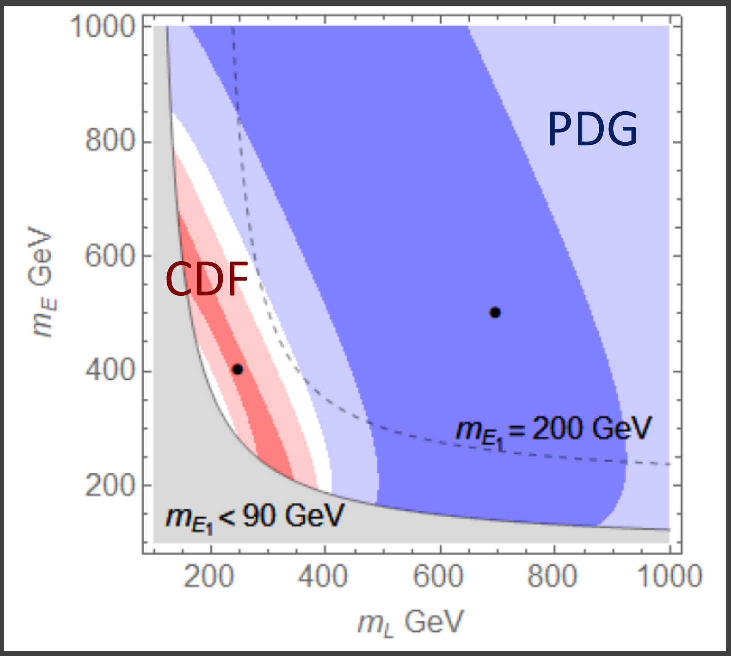
L^- (L^0): charged (neutral) doublet

$$\frac{\delta m_W^2}{m_W^2} \sim 0.0014 \times \left(\frac{250\ \mathrm{GeV}}{m_L}\right)^2 \left(\frac{m_{L^-}^2 - m_{L^0}^2}{(100\ \mathrm{GeV})^2}\right)^2$$

- m_W is explained for $\mathcal{O}(200\ \mathrm{GeV})$ VL lepton with $\mathcal{O}(10\ \mathrm{GeV})$ mass diff.
- large singlet-doublet mixing is required as for muon g-2

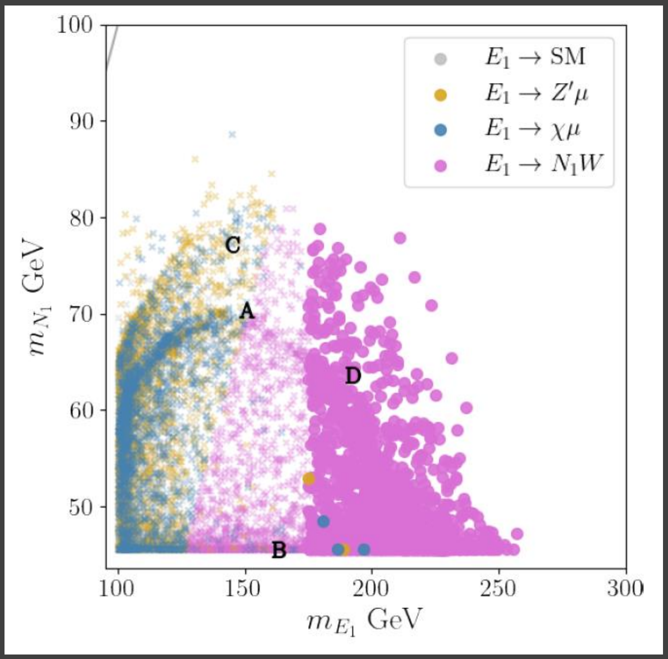
Vector-like lepton explanation

- only charged VLL



2204.07022, JK, S.Okawa, Y.Omura

- with singlet VL neutrino

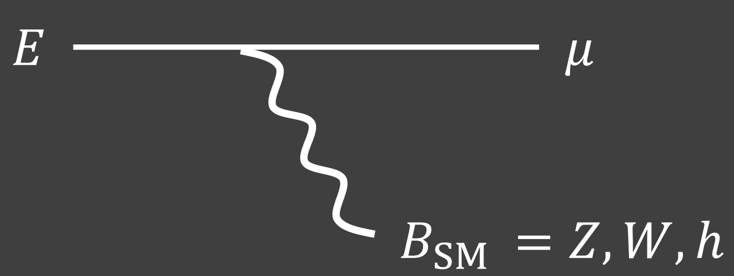


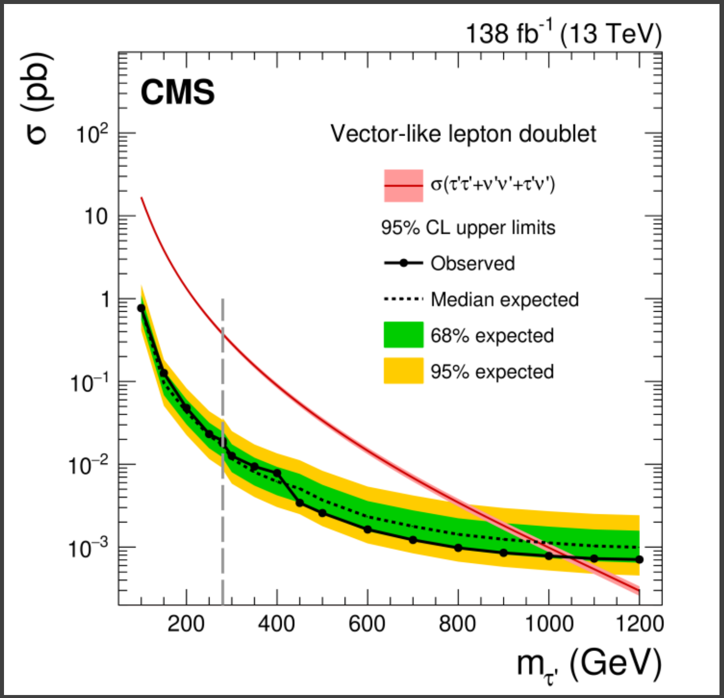
2205.10480, JK, S.Raby

- VLL is lighter than 200 (250) GeV with (without) singlet VL lepton
- muon g-2 can be explained in both cases

LHC limits ?

➢ doublet VL lepton





* VLL decaying to tau

- Run1 limit for VL lepton decaying to muon is about 300 GeV

1408.3123, R.Dermisek, J.P.Hall et.al

- Run2 limit may be stronger than 800 GeV

LHC limits ?

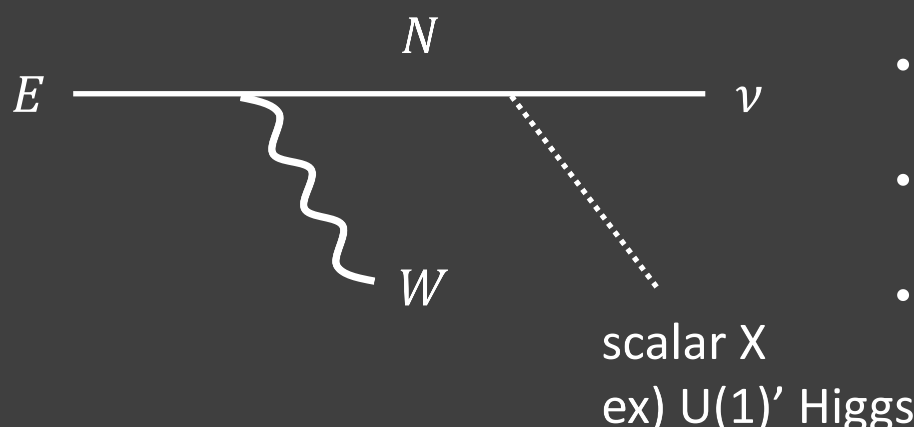
possible ways to relax LHC limits

➢ VL lepton + DM 2204.07022, JK, S.Okawa, Y.Omura

- $m_W, \Delta a_\mu$ and DM are explained
- signal is $2\mu + E_T^{\rm miss}$, same as sleptons
- degenerate region not closed

e.g. ATLAS 1911.12606

➢ VL lepton + VL neutrino + X 2205.10480, JK, S.Raby



- VL neutrino can be singlet-like
- scalar X may decay hadronically
- complicated signals

Summary

- Δa_μ and $b \to s\mu\mu$ anomalies are explained in the VL family + $U(1)'$ model
- $\geq 4\mu$ signals are expected in models with muon-philic VL leptons and Z'
- new CDF value of W mass can be explained by 200 GeV VL leptons
- LHC limits may be evaded if VL lepton decays to DM, VL neutrino + X

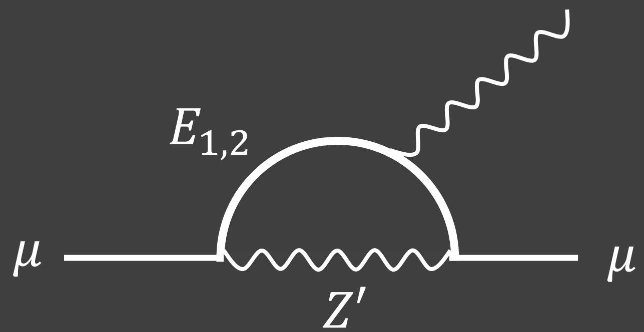
Thank you !

Backup

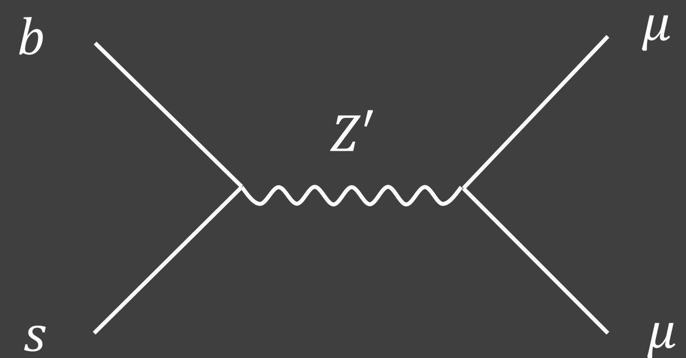
Vector-Like (VL) fermion + $U(1)'$

simultaneous explanation for muon anomalies

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



→ Δa_μ



→ $b \to s\mu\mu$

- Models

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

Mass Matrix and Couplings

- Yukawa interactions and mass matrix

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

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

* similar for quarks/neutrino

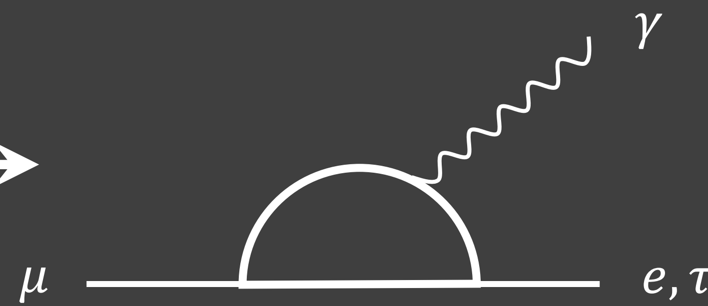
- Z'-coupling in mass basis : $U_R^{e\dagger} M_e U_L^e = \text{diag}\left(m_e, m_\mu, m_\tau, m_{E_1}, m_{E_2}\right)$

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

$\longrightarrow$ Z'-couplings to the SM families

Possible Flavor Violation

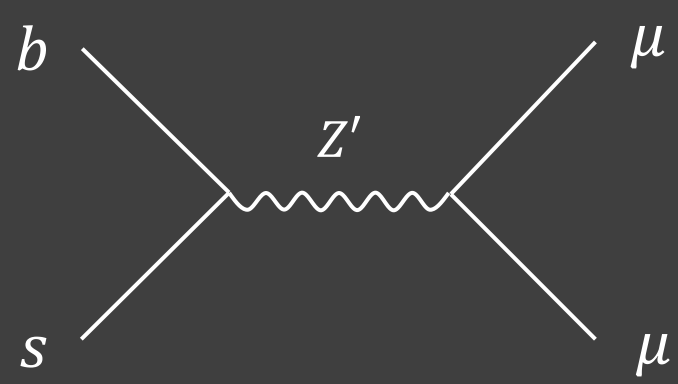
- Lepton flavor violation

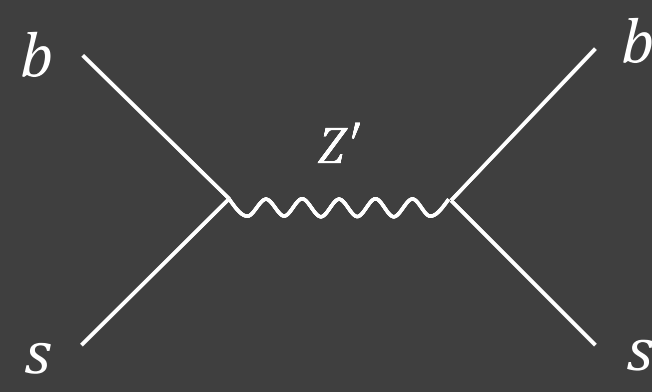


$\Delta a_\mu \sim 2.5 \times 10^{-9}$

$\mu \to e\gamma, \tau \to \mu\gamma, \tau \to 3\mu$ e.t.c.

- Quark flavor violation





$C_9^{NP} \lesssim -0.5$

$B - \overline{B}, K - \overline{K}$ mixing

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

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

M_Q: VL quark [VLQ] mass

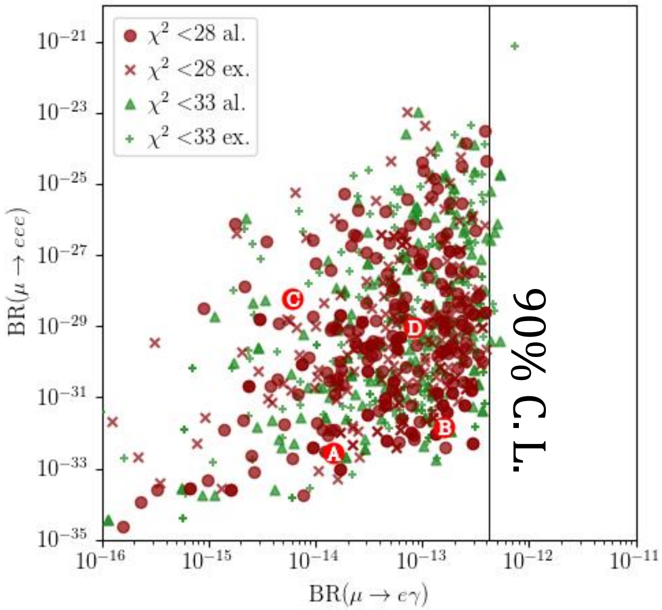
ϵ_{t_R}: mixing bet. top and VLQ

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

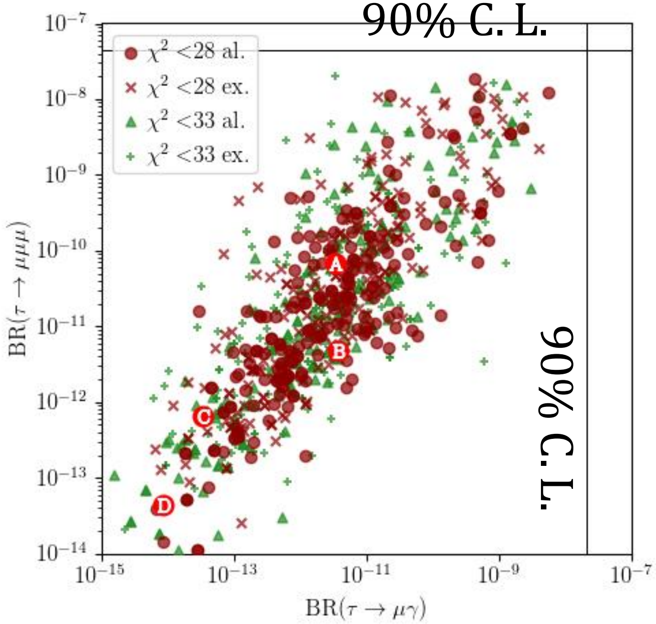
CKM is approximately unitary as far as $\epsilon_{t_R} \lesssim 0.01$

LFV decays

muon decays



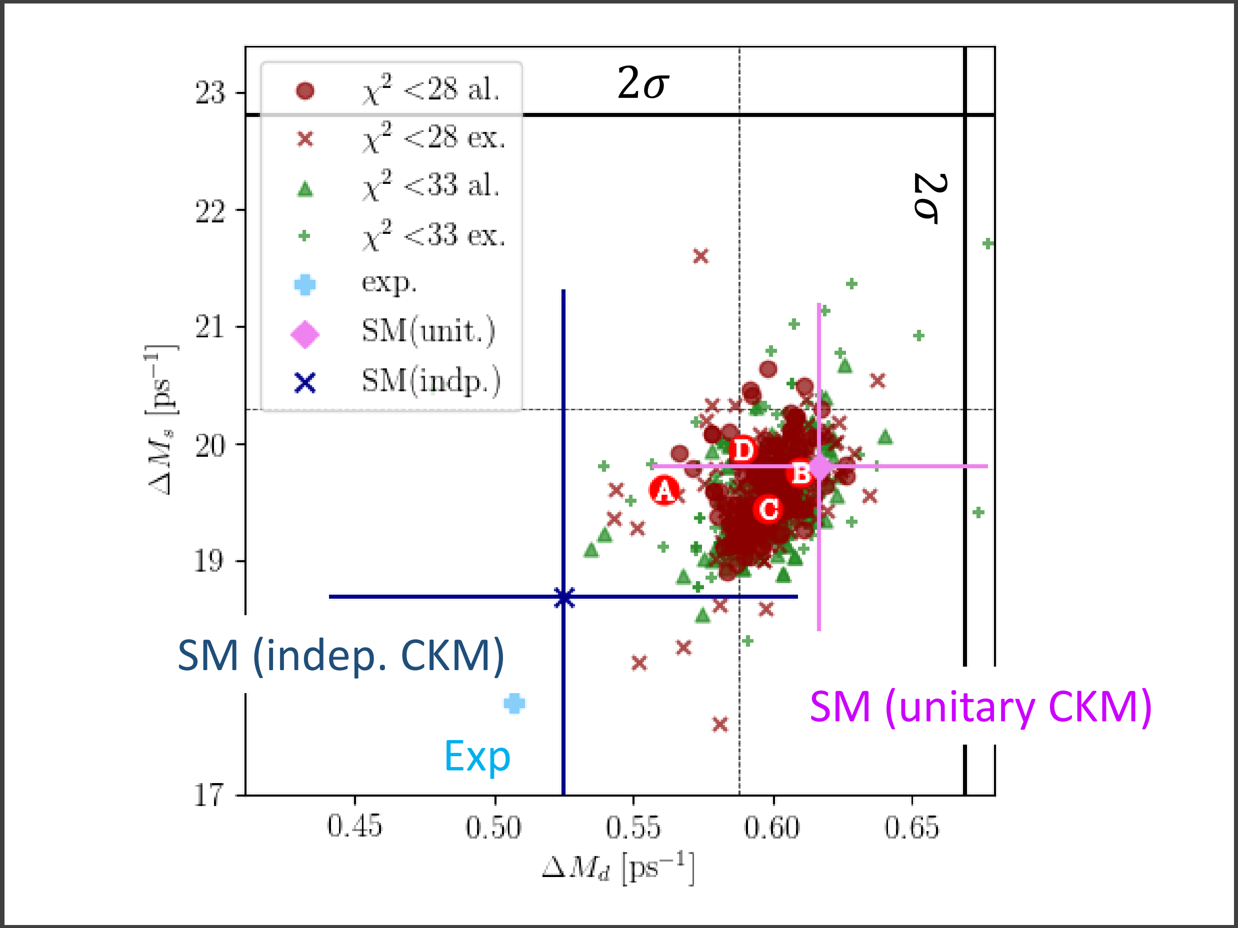
tau decays



$\mathrm{Br}(\mu \to e\gamma) \gg \mathrm{Br}(\mu \to eee)$

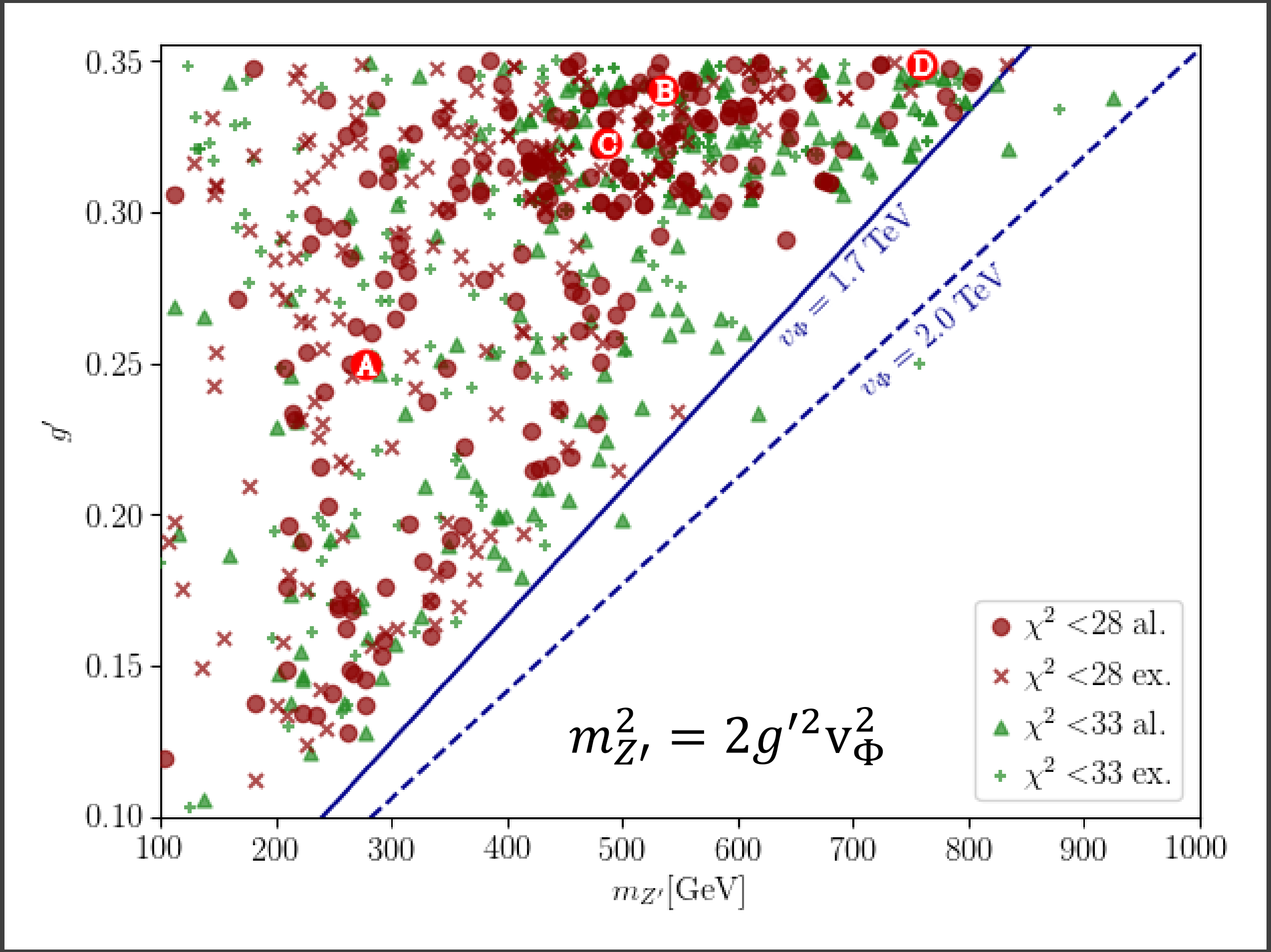
$\mathrm{Br}(\tau \to \mu\gamma) \lesssim \mathrm{Br}(\tau \to \mu\mu\mu)$

B-meson mixing



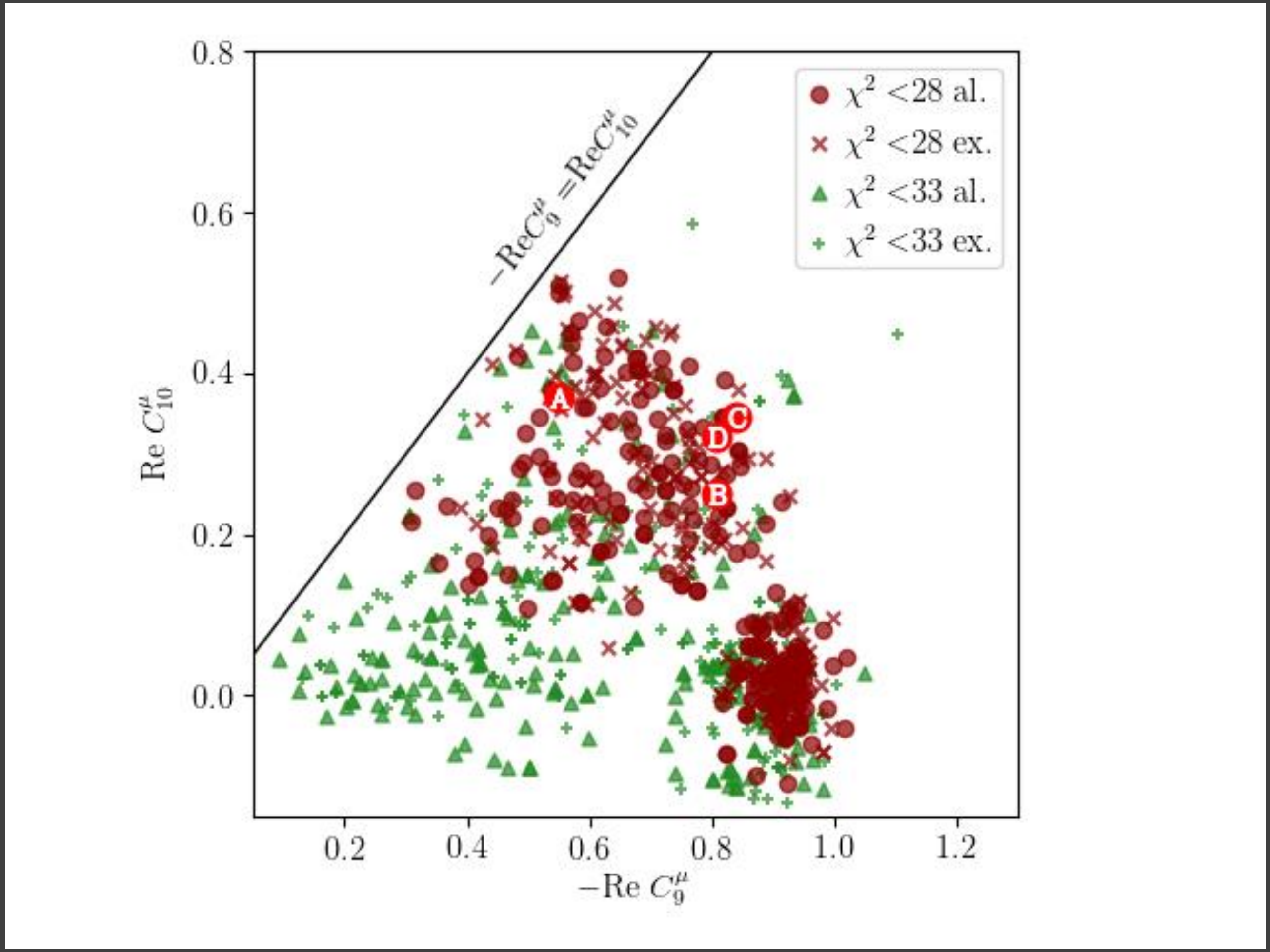
- B meson mixing is consistent with SM
- NP contributions are smaller than CKM uncertainties

Upper bound on Z' mass



$m_{Z'} < 800$ GeV is required for $\chi^2 < 28$

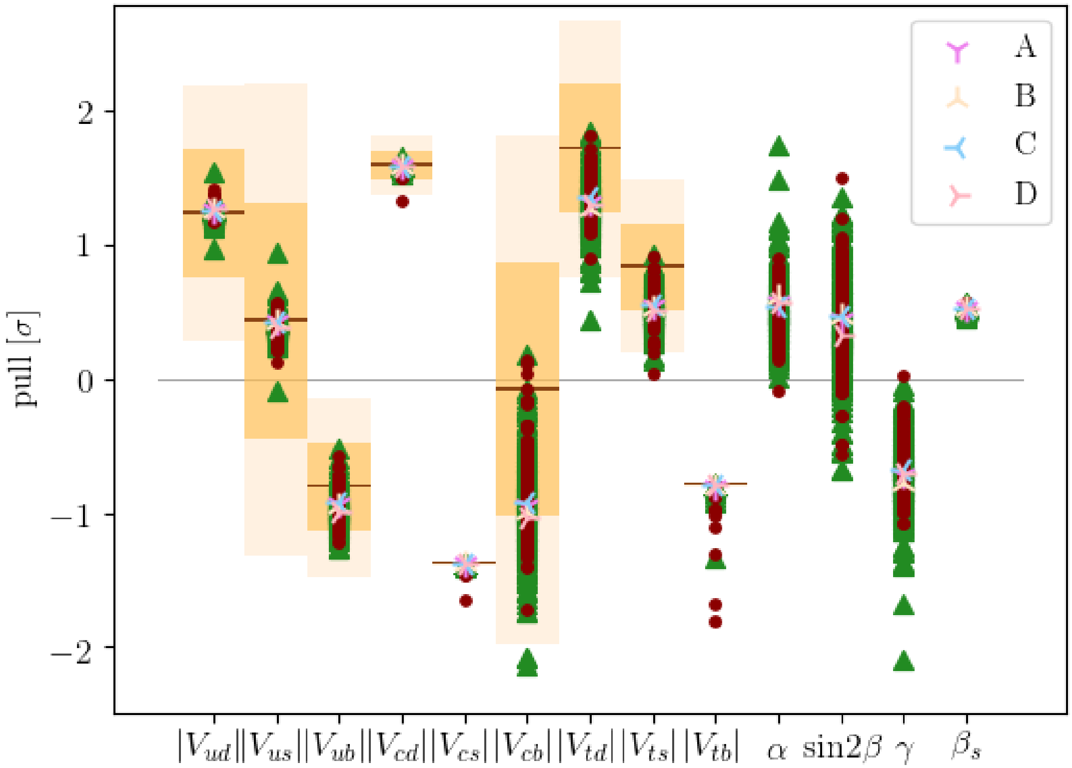
Patterns of C_9, C_{10}



This model predicts $-C_9 > C_{10}$ to explain Δa_μ

CKM elements

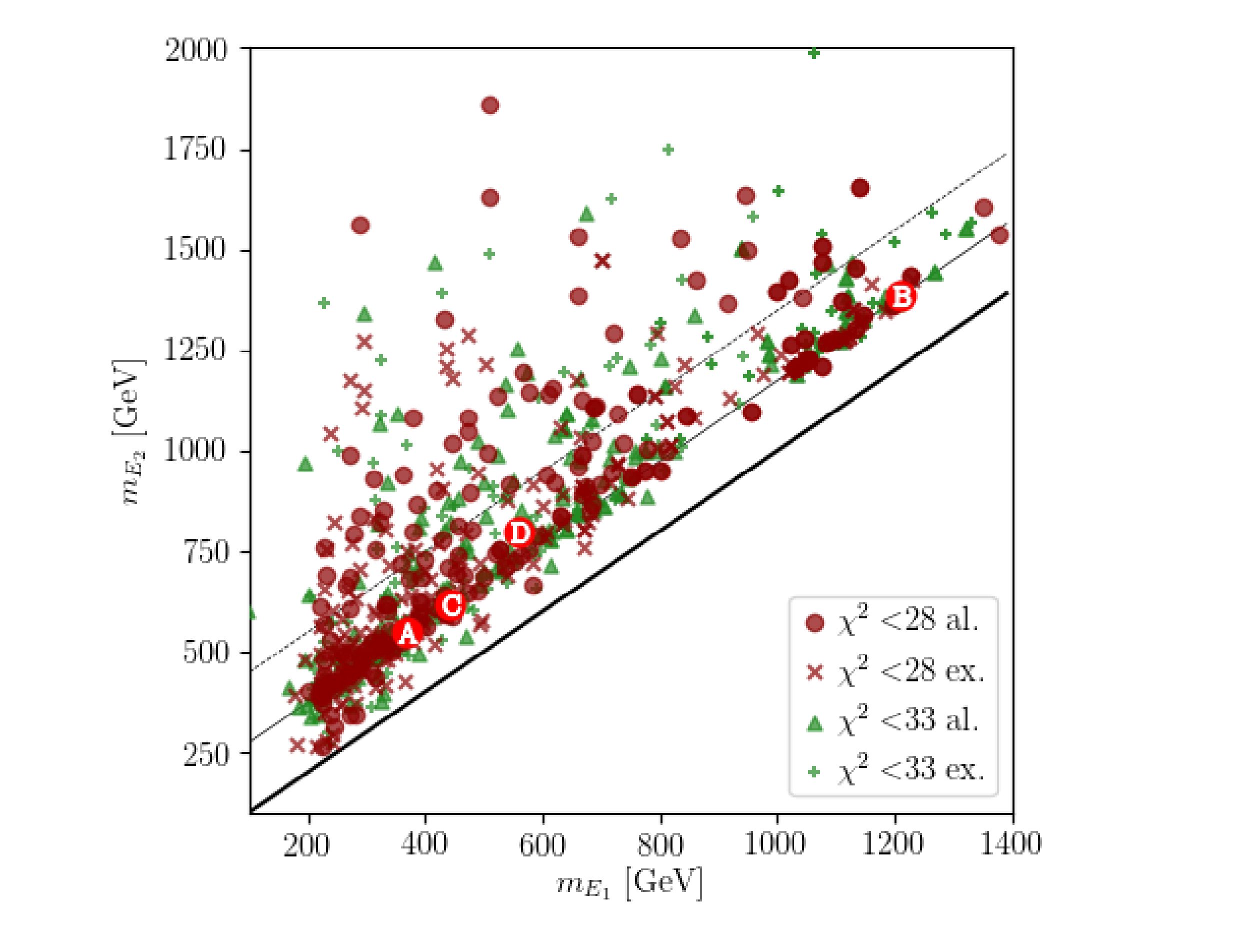
CKM values via SM fit



pulls against individual measurements

CKM values are consistent with SM fit

Heavier VL-lepton

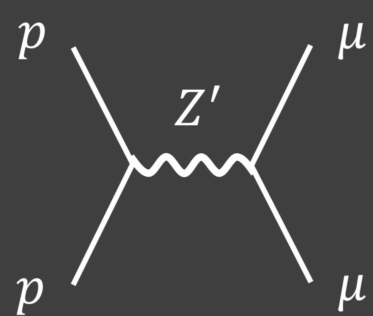


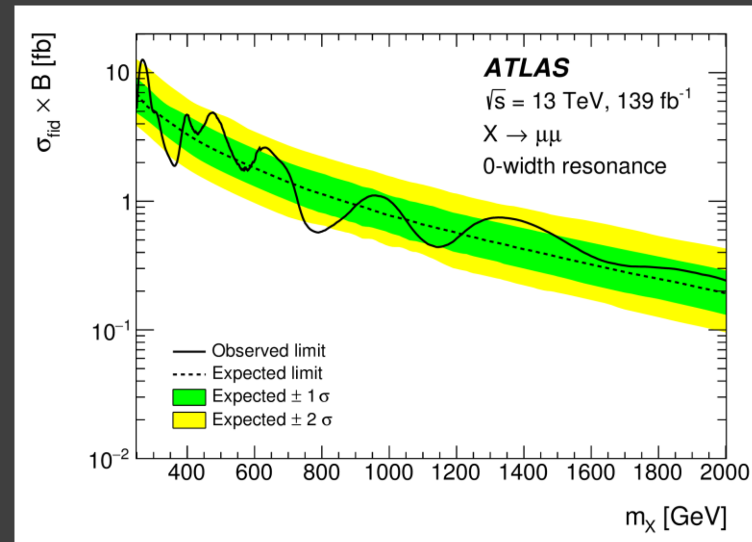
$m_{E_2} \lesssim 1.7$ TeV for $\Delta a_\mu \sim 2.68 \times 10^{-9}$ since LR-effect is crucial

Z' search

- dimuon search at LHC

$$pp \to Z' \to \mu^+\mu^-$$





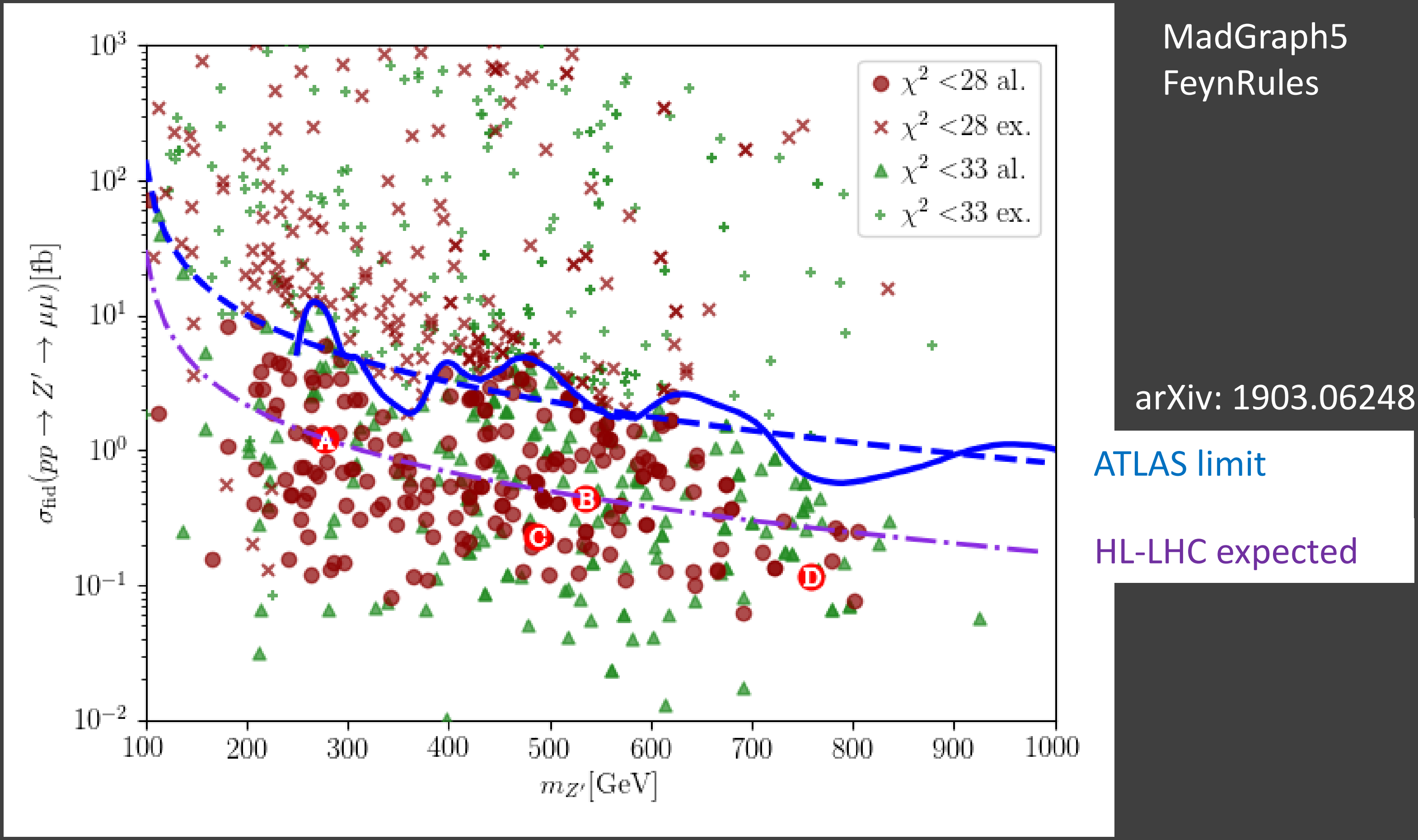
- muon anomalies, $B_s - \overline{B}_s$ mixing

$$C_9 \sim -0.83 \times \left(\frac{500\ \mathrm{GeV}}{m_{Z'}}\right)^2 \left(\frac{g^L_{sb}}{0.0006}\right)\left(\frac{g^L_{\mu\mu} + g^R_{\mu\mu}}{0.6}\right)$$

Z' may strongly couple to leptons, but weakly to quarks

$$\rightarrow \quad \sigma_{\mathrm{fid}}(pp \to Z' \to \mu^+\mu^-) < 1\ \mathrm{fb}$$

Dimuon Z' Search at LHC



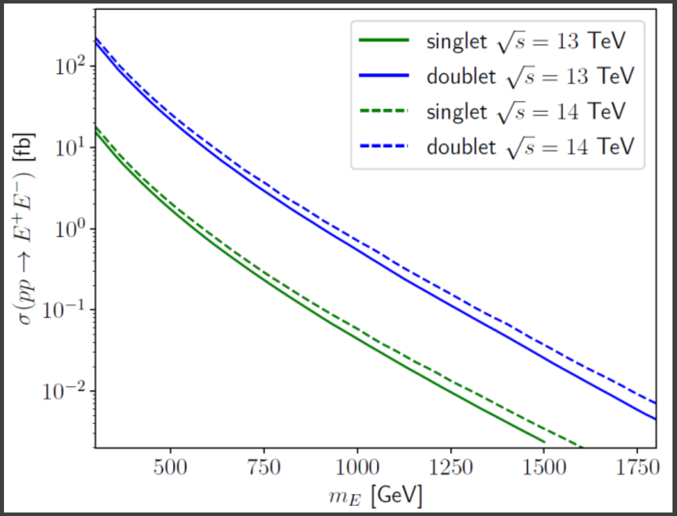
MadGraph5
FeynRules

arXiv: 1903.06248

- Cross sections can be smaller than current limits
- HL-LHC is sensitive to not all, but many points

Assumptions

- VL leptons are assumed to be $SU(2)_L$ singlet or doublet



Madgraph5

production cross section

$m_E = m_N$ for doublet case

- Z' boson decays to muon or neutrino

$$\mathrm{BR}(Z' \to \mu\mu) = \frac{\Gamma(Z' \to \mu\mu)}{\Gamma(Z' \to \nu\nu) + \Gamma(Z' \to \mu\mu)} \simeq \frac{|g^L_{\mu\mu}|^2 + |g^R_{\mu\mu}|^2}{2|g^L_{\mu\mu}|^2 + |g^R_{\mu\mu}|^2} = \frac{2}{3}$$

$|g^L_{\mu\mu}| = |g^R_{\mu\mu}|$ is predicted in C_9-only or C_{10}-only scenario

Recasting ATLAS analysis 2103.11684

- Signal regions

$^* p_T^\mu > 5$ GeV

SR	$N_{e,\mu}$	N_τ	N_b	Z boson	selection
$\mathrm{SR0}_{\mathrm{bveto}}^{\mathrm{loose}}$	≥ 4	≥ 0	$= 0$	veto	$m_{\mathrm{eff}} > 600$ GeV
$\mathrm{SR0}_{\mathrm{bveto}}^{\mathrm{tight}}$	≥ 4	≥ 0	$= 0$	veto	$m_{\mathrm{eff}} > 1250$ GeV
SR5L	≥ 5	≥ 0	≥ 0	-	-

+ trigger condition

$$m_{\mathrm{eff}} = E_T^{\mathrm{miss}} + \sum_{\ell=e,\mu} p_T^\ell + \sum_{j(p_T>40\mathrm{GeV})} p_T^j$$

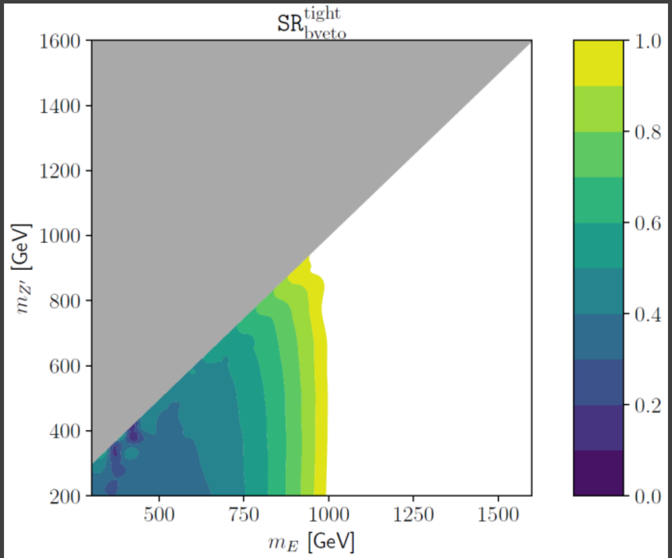
- Experimental result

	$\mathrm{SR0}_{\mathrm{bveto}}^{\mathrm{loose}}$	$\mathrm{SR0}_{\mathrm{bveto}}^{\mathrm{tight}}$	SR5L
data	11	1	21
SM	$11.5^{+2.9}_{-2.2}$	$3.5^{+2.0}_{-2.2}$	12.4 ± 2.3
S^{95}	9.79	3.87	17.88

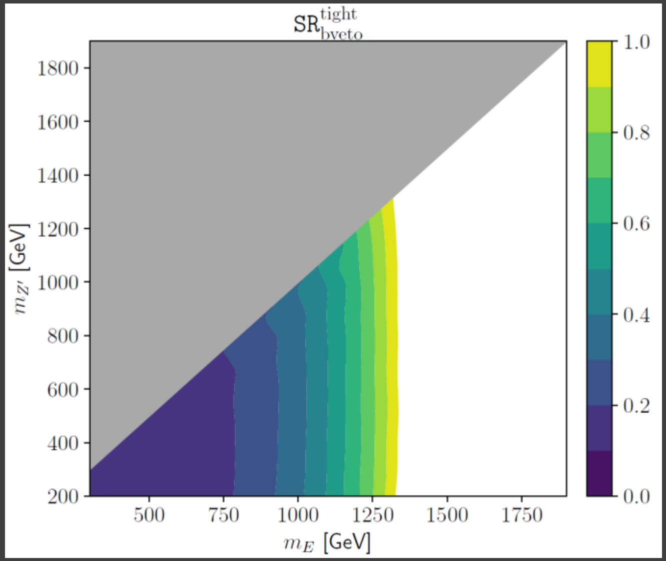
- no evidence of new physics
- 1.9σ excess in SR5L

95%C.L. limits on $\mathrm{Br}(E \to Z'\mu)$

➢ $SU(2)_L$ singlet



➢ $SU(2)_L$ doublet



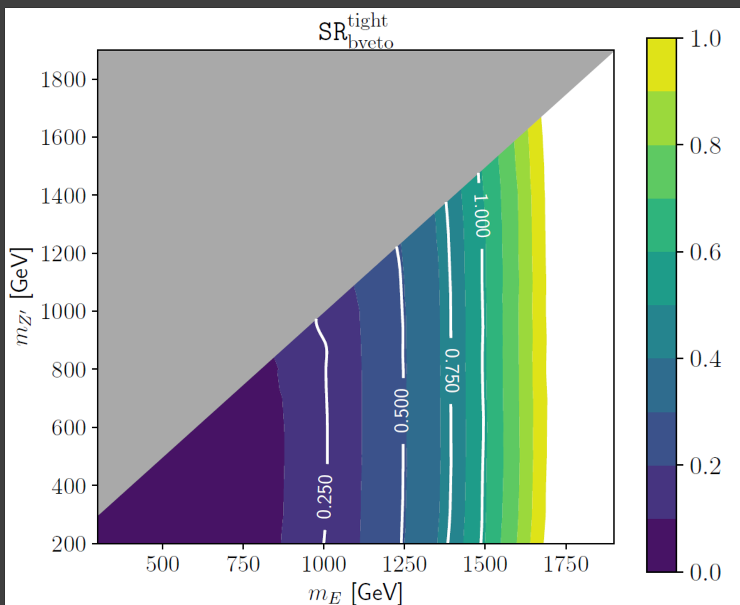
Madgraph5+pythia8+Delphes3

- $\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$ gives the strongest bound for $\mathrm{Br}(E \to Z'\mu)$
- limit is 1 (1.3) TeV for $\mathrm{Br}(E \to Z'\mu) = 1$ for singlet (doublet)
- SR5L limit is weaker because of the excess

Future limits at HL-LHC: $L = 3\text{ab}^{-1}$

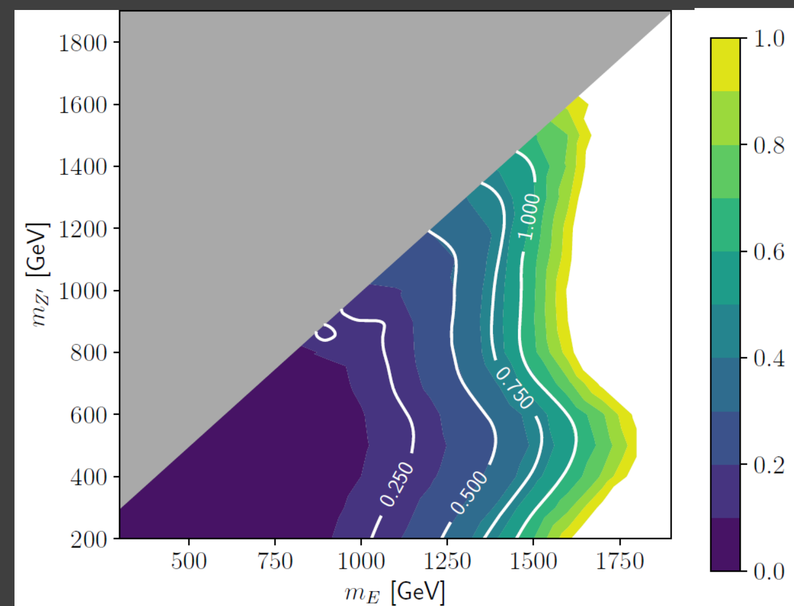
- $\text{SR0}^{\text{tight}}_{\text{bveto}}$

*doublet VL lepton



bkg = $3000/139\ b^{13\text{TeV}} = 76.6$

- $\text{SR0}^{\text{tight}}_{\text{bveto}}$
  $+|m_{\text{OS}} - 500| < 100\ (250)$ GeV



bkg = 10

Madgraph5+pythia8+Delphes3

- background colors are exclusion upper bounds
- white lines are discovery potential for a given $\text{Br}(E \to Z'\mu)$ attached on the line
- if $\text{Br}(E \to Z'\mu) = 1$, exclusion (discovery) limit is 1.7 (1.5) TeV by $\text{SR0}^{\text{tight}}_{\text{bveto}}$

Current limits on doublet-like VL lepton

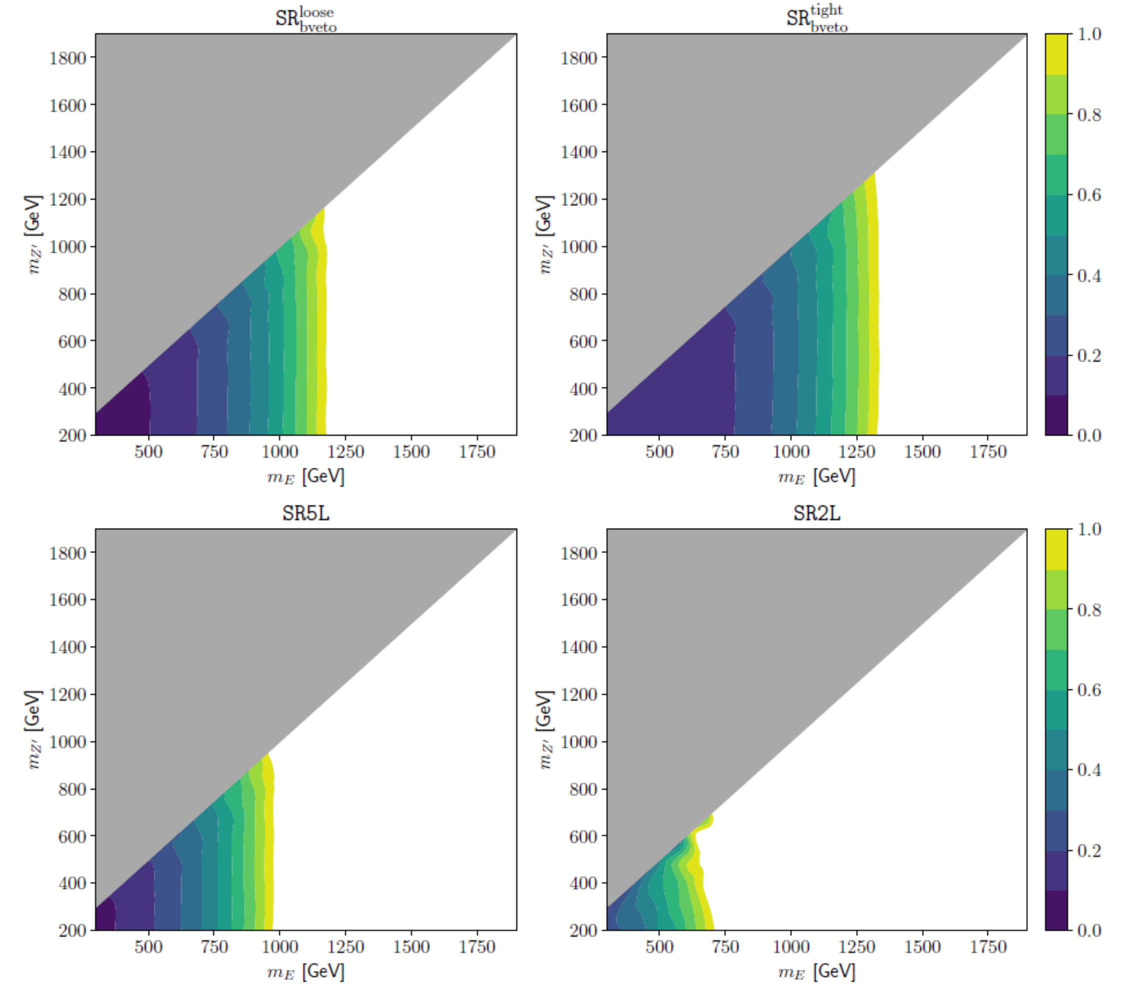
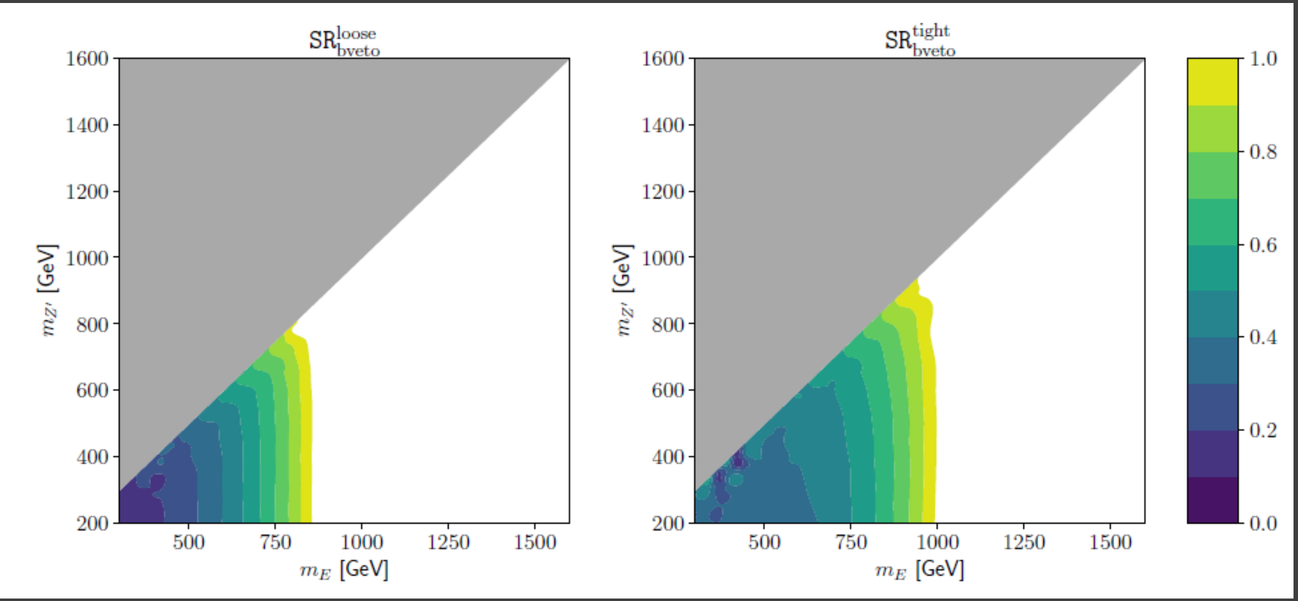


Figure 3: Limits on BR $(E \to Z'\mu)$ for the doublet-like VL lepton.

Upper limits on $\mathrm{Br}(E \to Z'\mu)$

Current limits on singlet-like VL lepton

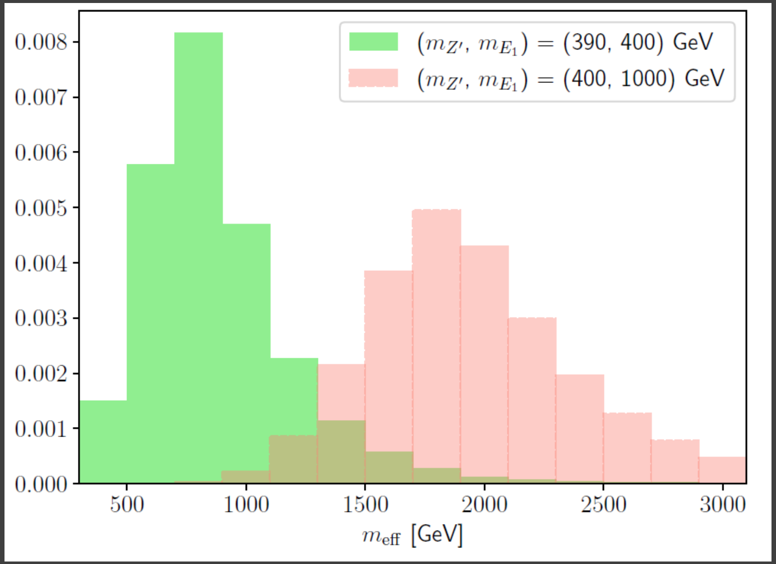


Upper limits on $\mathrm{Br}(E \to Z'\mu)$

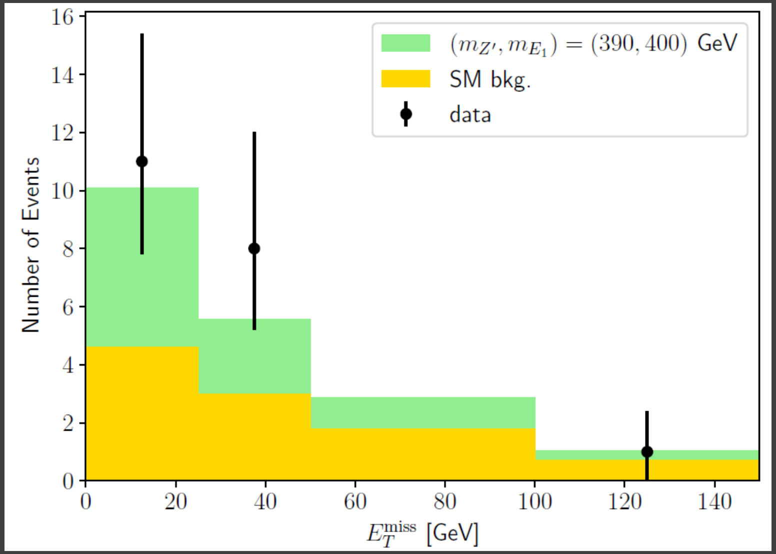
Explanation of excess in $\geq 5\ell$ signal

explain the excess in SR5L and null excess in $\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$, $\mathrm{SR0}^{\mathrm{loose}}_{\mathrm{bveto}}$

- m_{eff} distribution



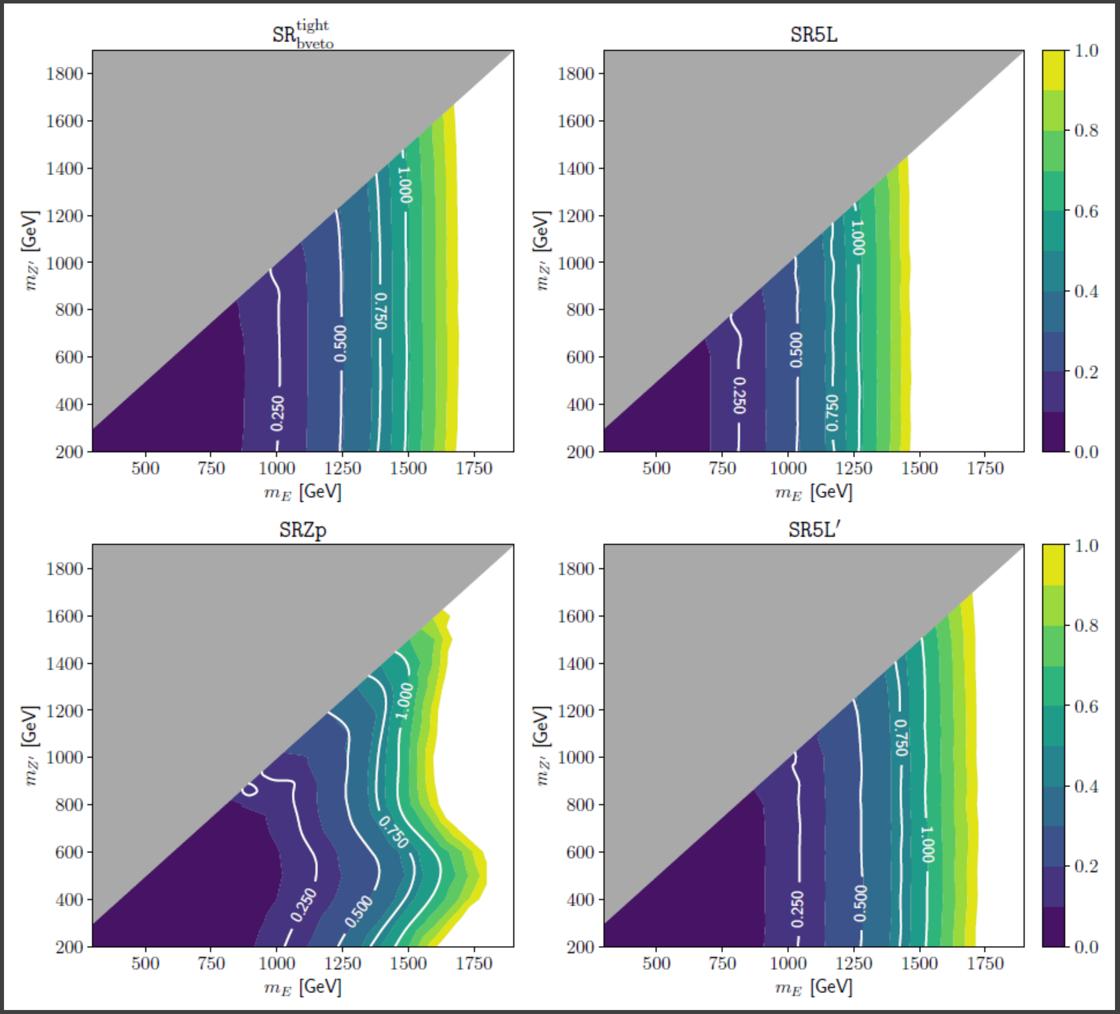
- E_T^{miss} distribution $\mathrm{Br}(Z' \to E\mu) = 0.25$



Madgraph5+pythia8+Delphes3

- limits from $\mathrm{SR0}^{\mathrm{tight(loose)}}_{\mathrm{bveto}}$ are weaker for light spectra
- excess explained by singlet VL lepton if $(m_{Z'}, m_E) = (390, 400)$ GeV
- Our model only has muons, but the experiment also counts electrons

Future limits for doublet-like VL leptons

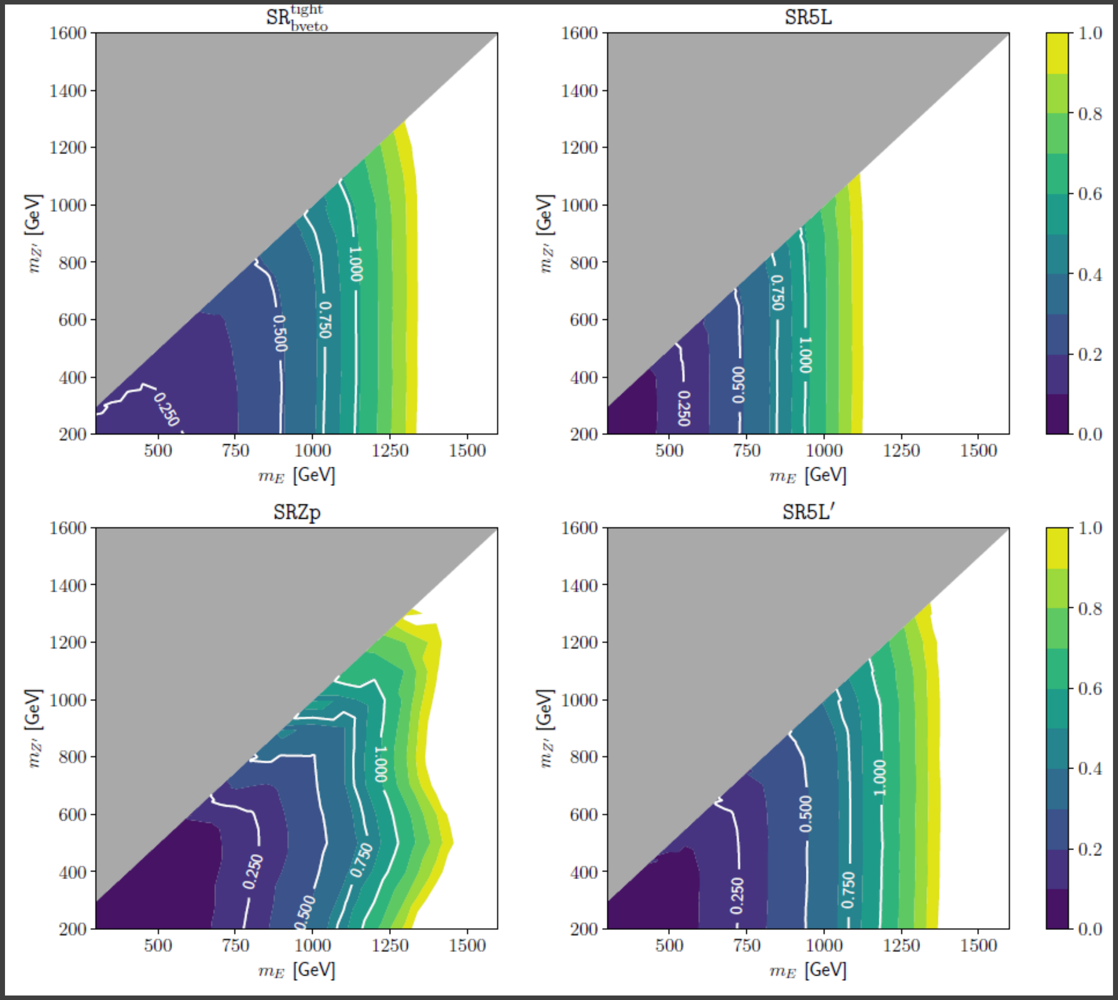


Future limits on $\mathrm{Br}(E \to Z'\mu)$

SRZp : $\mathrm{SR0}_{\mathrm{bveto}}^{\mathrm{tight}} + |m_{\mathrm{OS}} - 500| < 100\ (250)$ GeV

SR5L' : SR5L+Z-veto $+m_{\mathit{eff}} > 1000$ GeV

Future limits for singlet-like VL leptons

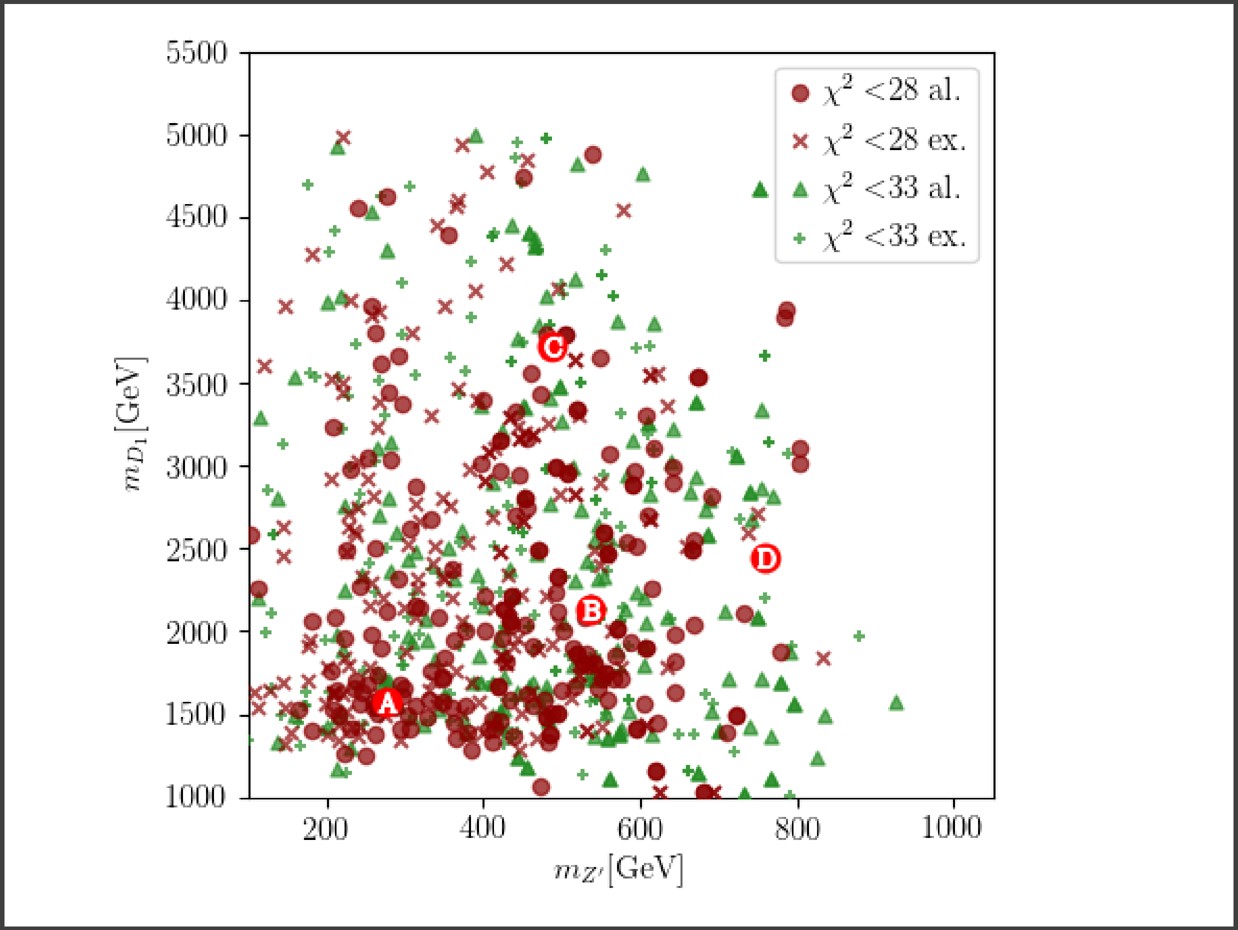


Future limits on $\mathrm{Br}(E \to Z'\mu)$

SRZp : $\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}} + |m_{\mathrm{OS}} - 500| < 100\ (250)$ GeV

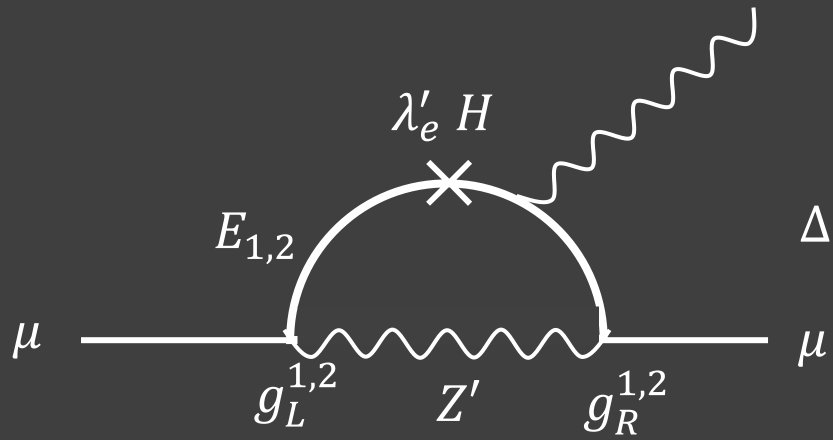
SR5L' : SR5L+Z-veto $+m_{\mathrm{eff}} > 1000$ GeV

Masses of VL quarks



There is no stringent upper bound on VL quark

Muon $g-2$



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

VL lepton mass

➢ Δa_μ is proportional to Higgs coupling: $\lambda'_e \overline{L}_R \widetilde{H} E_L$

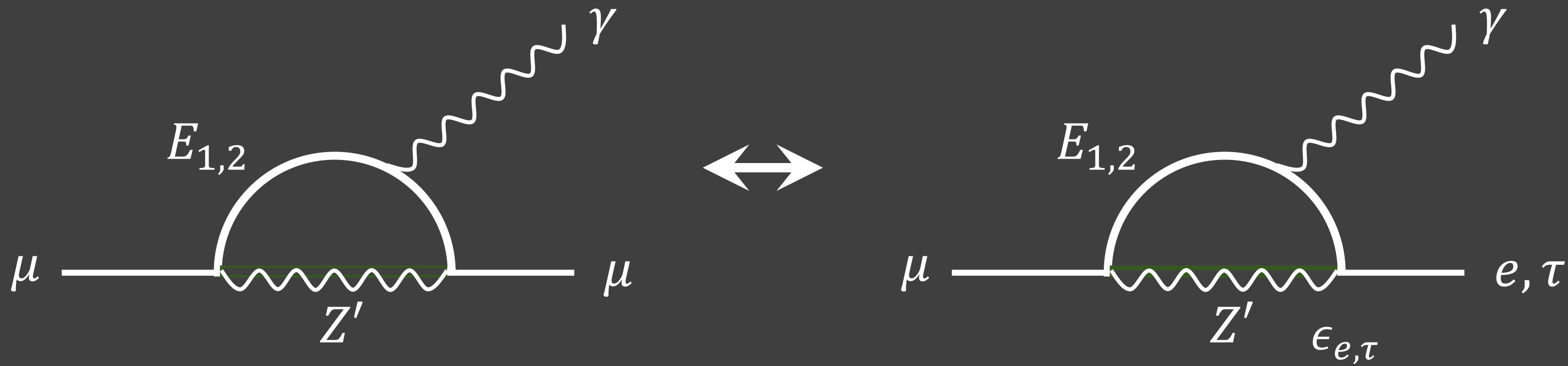
$$\Delta a_\mu \lesssim 2.9 \times 10^{-9} \times \left(\frac{c_{LE}}{0.1}\right)\left(\frac{\lambda'_e H}{174\ \mathrm{GeV}}\right)\left(\frac{1\mathrm{TeV}}{\Phi}\right)^2 \qquad c_{LE} = M_L M_E \frac{G_Z(x_L) - G_Z(x_E)}{M_L^2 - M_E^2}$$

$\lambda'_e H / \Phi \gtrsim 0.1$ are needed

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



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

Exp. limits

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

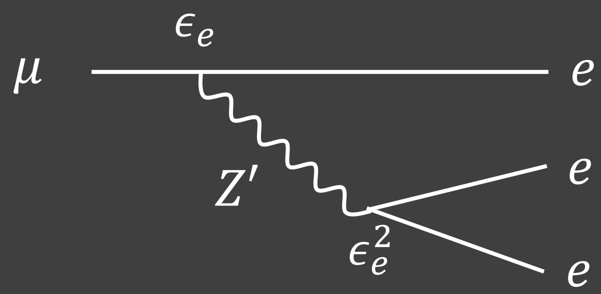
$$\mathrm{Br}(\tau \to \mu\gamma) \sim 1.5 \times 10^{-9} \times \left(\frac{\lambda'_e}{1.0}\right)^2 \left(\frac{\epsilon_\tau}{10^{-2}}\right)^2 \left(\frac{1.0\ \mathrm{TeV}}{\Phi}\right)^4 < 4.4 \times 10^{-8} \text{ (90\%C.L.)}$$

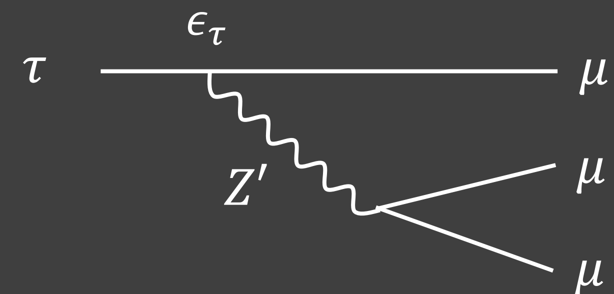
Lepton Flavor Violation (II)

- 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.





$$\mathrm{Br}(\mu \to eee) \sim 2.3 \times 10^{-40} \times \left(\frac{\epsilon_e}{10^{-6}}\right)^6 \left(\frac{1.0\ \mathrm{TeV}}{\Phi}\right)^4 \quad < 1.0 \times 10^{-12} \text{ (90\%C.L.)}$$

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

Neutrino Mass

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

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

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

Majorana mass

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

decoupled by M_R

Dirac neutrino ~ TeV

SM neutrino $\sim H^2/M_R$

SM and VL neutrinos are secluded by Majorana mass

Benchmark point A

$$m_{Z'} = 277.608, \quad v_\phi = 4079.3, \quad g' = 0.250042, \quad \lambda_\chi = 0.689454, \quad \lambda_\sigma = 0.210518$$

inputs

$$M_e = \begin{pmatrix} 0.000486575 & 0.000000322078 & -0.0000009971 & 0 & 0.000201232 \\ 0.0000000453521 & 0.159775 & 0.00162206 & 0 & -153.074 \\ -0.0000614248 & -0.00512644 & -1.74616 & 0 & -0.0409467 \\ 0 & 0 & 0 & 0.0000361209 & 448.074 \\ -0.00000237863 & -312.626 & 0.0547758 & 289.432 & -174.104 \end{pmatrix},$$

$$M_n = \begin{pmatrix} 0. & 0. & 0. & 0 & 0 \\ -15.7947 & 28.3788 \cdot e^{-0.0735218i} & 15.4093 \cdot e^{0.107535i} & 0 & 0 \\ 10.4292 \cdot e^{1.19397i} & 67.3777 \cdot e^{0.0000000228655i} & -53.4556 & 0 & 0 \\ 0 & 0 & 0 & 1.54426 & -454.964 \\ -0.00000237863 & -312.626 & 0.0547758 & 289.357 & -21.7762 \end{pmatrix}$$

$$M_u = \begin{pmatrix} 0.000893504 & 0.00562655 & 0.688382 \cdot e^{1.52313i} & 0 & -0.0228009 \\ -0.000172924 & 0.631189 & -0.119538 & 0 & -40.8575 \\ 0.535431 \cdot e^{1.72288i} & 4.4472 & -171.657 & 0 & -8.7671 \\ 0 & 0 & 0 & -0.000301965 & -3596.52 \\ 0.0051151 & 214.302 & -96.8583 & 3445.76 & 5.50646 \end{pmatrix},$$

$$M_d = \begin{pmatrix} 0.0121338 & 0.0527148 & 0.0199472 \cdot e^{-3.08081i} & 0 & -0.0254167 \\ -0.00528222 & -0.0409769 & -2.58755 & 0 & -41.2307 \\ 0.00189847 \cdot e^{-1.62491i} & -0.0198056 & -1.21195 & 0 & 6.1041 \\ 0 & 0 & 0 & -0.122713 & -1571.54 \\ 0.0051151 & 214.302 & -96.8583 & 3445.76 & -1.99223 \end{pmatrix}$$

mass and widths

	Mass [GeV]	Width [GeV]	Decay 1	BR	Decay 2	BR
Z'	277.6	0.1361	$\mu\mu$	0.5091	$\nu\,\nu$	0.4907
χ	651.9	0.669538	$E_1\mu$	0.4391	$N_1\nu$	0.4227
σ	1871.7	0.9049	N_2N_2	0.2988	E_2E_2	0.1473
E_1	367.9	0.0354639	$Z'\mu$	1.	$h\mu$	0.
N_1	422.2	0.0817534	$Z'\nu$	0.9995	$W\mu$	0.0003
N_2	459.	0.113389	WE_1	0.8792	$Z'\nu$	0.1179
E_2	548.3	4.07452	WN_1	0.4799	ZE_1	0.4415
D_1	1572.1	0.0371	$Z'b$	0.4117	χb	0.2831
U_1	3453.7	3.0221	$Z'c$	0.4117	χc	0.3829
D_2	3453.8	3.0228	$Z's$	0.4063	χs	0.3779
U_2	3596.8	0.1085	$Z'c$	0.4504	χc	0.4213