

PASCOS2021

$\geq 4\mu$ signals from vector-like lepton decaying to
muon-philic Z' boson at LHC

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arXiv:2104.04461

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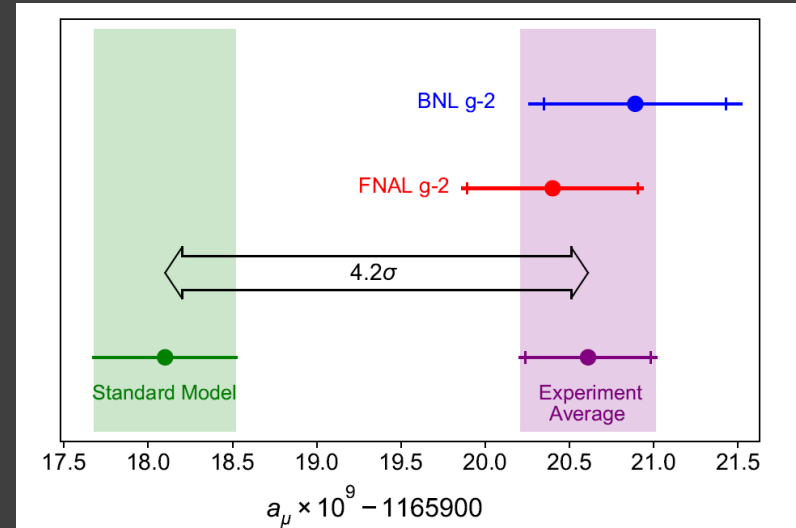
muon anomalies

➤ muon g-2

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

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

4.2 σ discrepancy

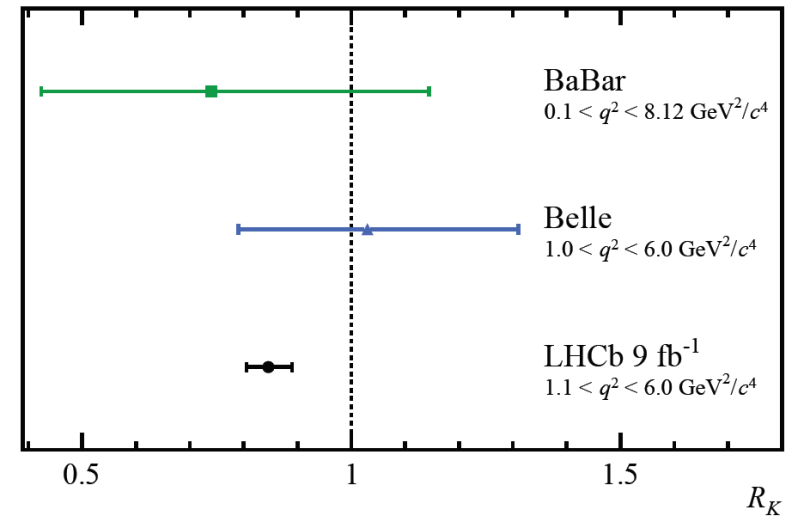


➤ $b \rightarrow s\mu\mu$ anomaly

$$R_K^{\text{exp}} = \frac{\text{Br}(B \rightarrow K\mu\mu)}{\text{Br}(B \rightarrow Kee)} = 0.846_{-0.041}^{+0.044}$$

3.1 σ discrepancy

$\sqrt{\Delta\chi^2} > 5\sigma$ in global fit



LHCb, 2103.11769

Possible explanation

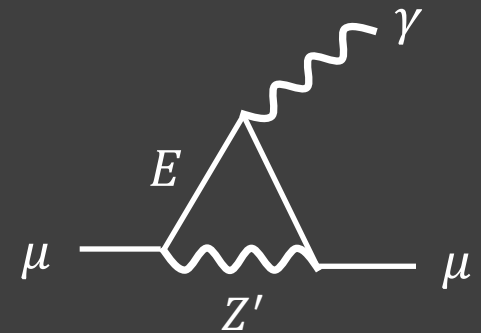
JK, S.Raby, A.Trautner, 1906.11297, 1911.11075

both anomalies are explained in models with Z' and vector-like [VL] lepton

➤ muon g-2

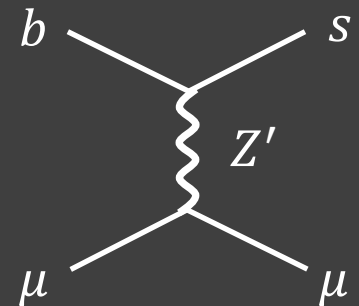
$$\Delta a_\mu \sim 5 \times 10^{-9} \times \left(\frac{500 \text{ GeV}}{m_{Z'}} \right)^2 \left(\frac{g_{\mu E}^L g_{\mu E}^R}{0.09} \right)$$

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



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

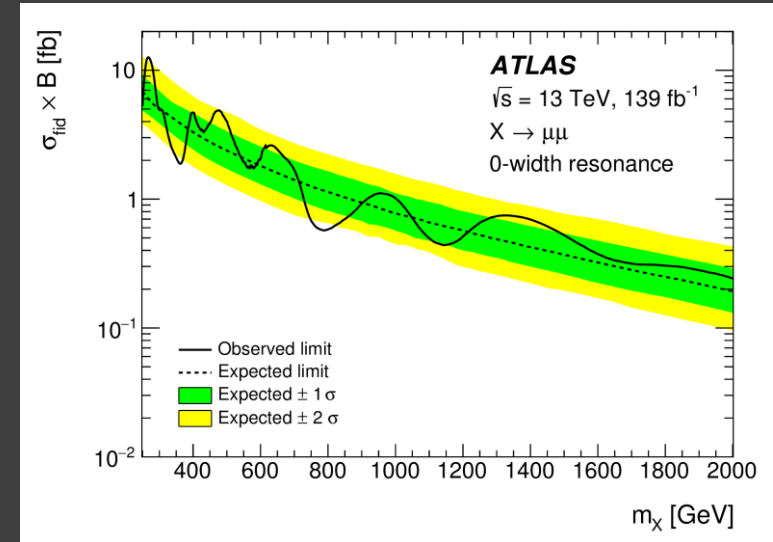
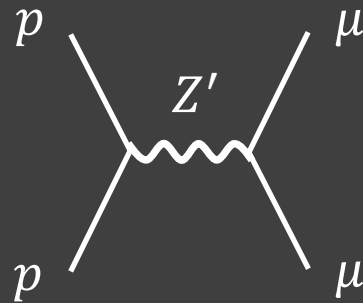
$$C_9 \sim -0.83 \times \left(\frac{500 \text{ GeV}}{m_{Z'}} \right)^2 \left(\frac{g_{sb}^L}{0.0006} \right) \left(\frac{g_{\mu\mu}^L + g_{\mu\mu}^R}{0.6} \right)$$

$$m_{Z'} \sim m_F \sim \mathcal{O}(500 \text{ GeV}) \text{ is predicted}$$


Z' search

➤ dimuon search at LHC

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



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

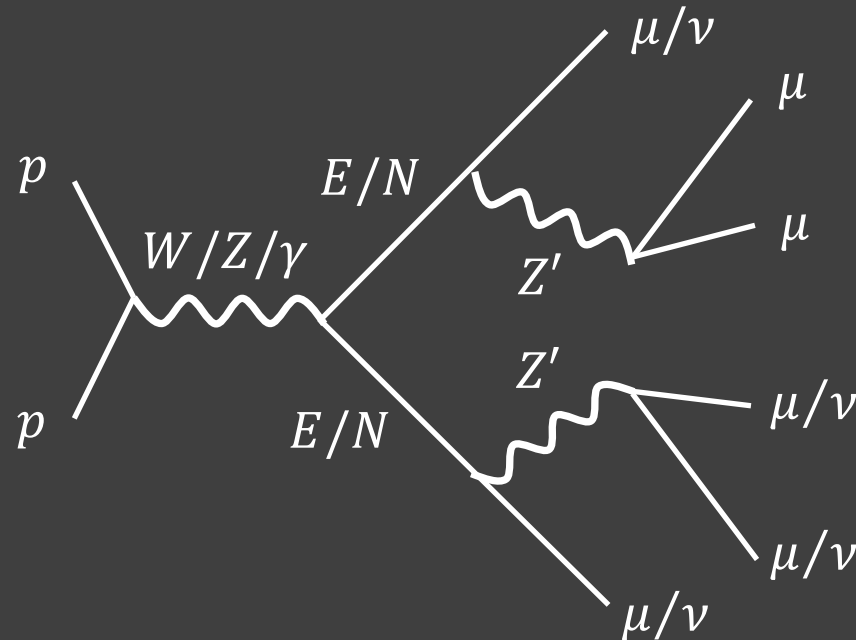
$$C_9 \sim -0.83 \times \left(\frac{500 \text{ GeV}}{m_{Z'}} \right)^2 \left(\frac{g_{sb}^L}{0.0006} \right) \left(\frac{g_{\mu\mu}^L + g_{\mu\mu}^R}{0.6} \right)$$

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

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

$\geq 4\mu$ signal

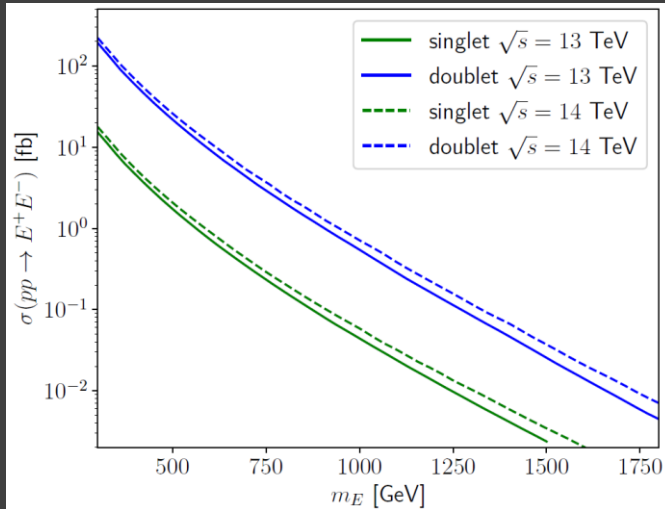
➤ VL-lepton pair production: $pp \rightarrow \bar{L}L$ $L = E/N$



- 6 muons are produced if both $Z' \rightarrow \mu\mu$ from $pp \rightarrow \bar{E}E \rightarrow \mu^- \mu^+ Z' Z'$
- 4 muons are produced if one $Z' \rightarrow \mu\mu$
- 4 muons are also produced from VL neutrino production

Assumptions

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



production cross section

$m_E = m_N$ for doublet case

Madgraph5

- Z' boson decays to muon or neutrino

$$\text{BR}(Z' \rightarrow \mu\mu) = \frac{\Gamma(Z' \rightarrow \mu\mu)}{\Gamma(Z' \rightarrow \nu\nu) + \Gamma(Z' \rightarrow \mu\mu)} \simeq \frac{|g_{\mu\mu}^L|^2 + |g_{\mu\mu}^R|^2}{2|g_{\mu\mu}^L|^2 + |g_{\mu\mu}^R|^2} = \frac{2}{3}$$

$|g_{\mu\mu}^L| = |g_{\mu\mu}^R|$ is predicted in C_9 -only or C_{10} -only scenario

Recasting ATLAS analysis 2103.11684

➤ Signal regions

$$*p_T^\mu > 5 \text{ GeV}$$

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

+ trigger condition

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

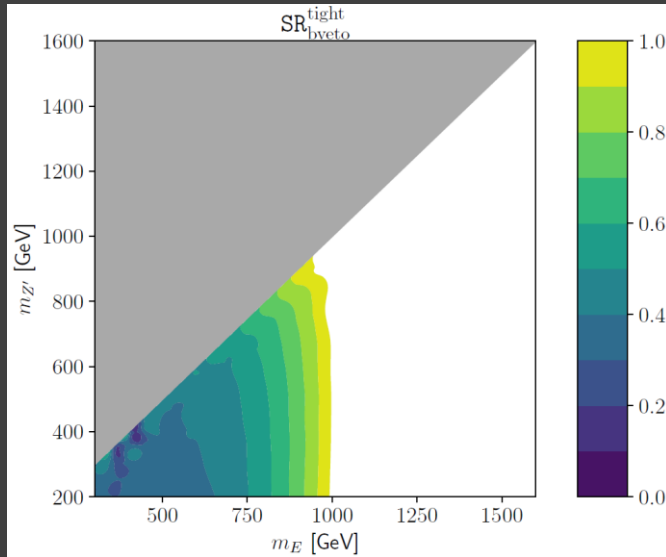
➤ Experimental result

	SR0 ^{loose} _{bveto}	SR0 ^{tight} _{bveto}	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

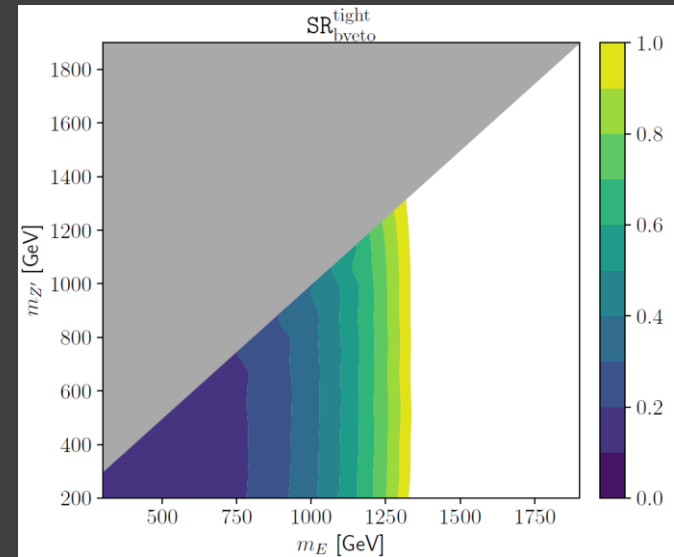
- no evidence of new physics
- 1.9σ excess in SR5L

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

➤ $SU(2)_L$ singlet



➤ $SU(2)_L$ doublet



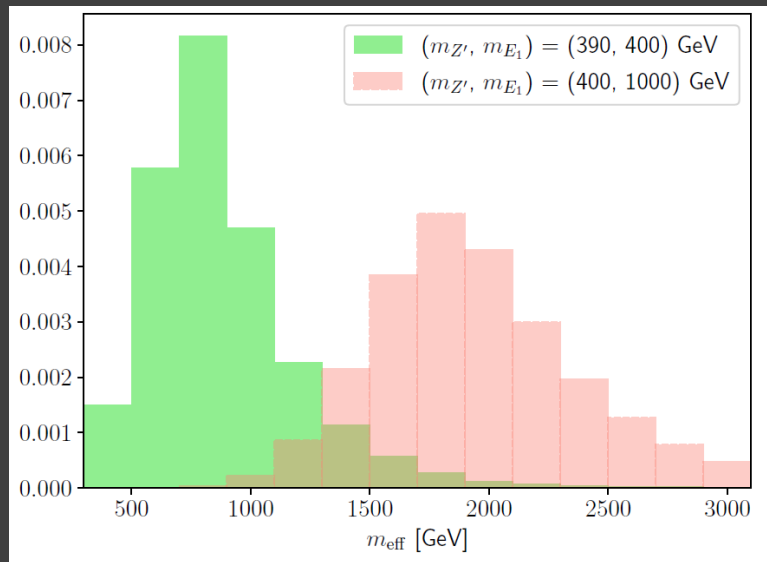
Madgraph5+pythia8+Delphes3

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

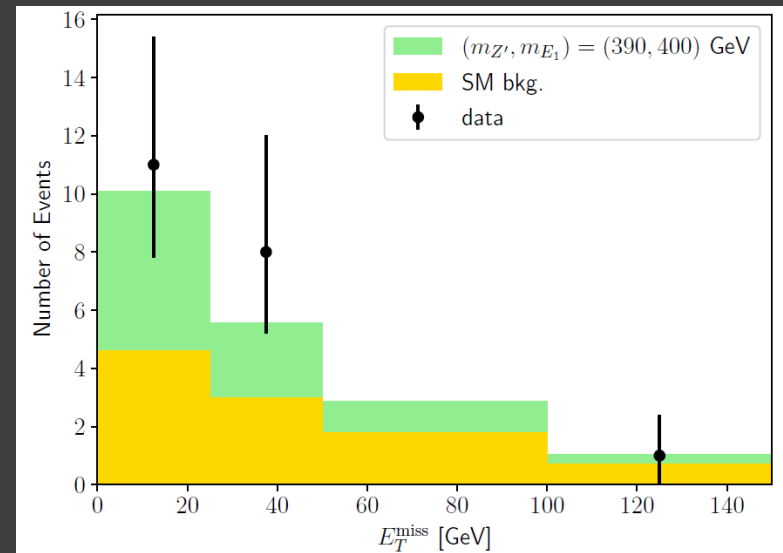
Explanation of excess in $\geq 5\ell$ signal

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

➤ m_{eff} distribution



➤ E_T^{miss} distribution $\text{Br}(Z' \rightarrow E\mu) = 0.25$



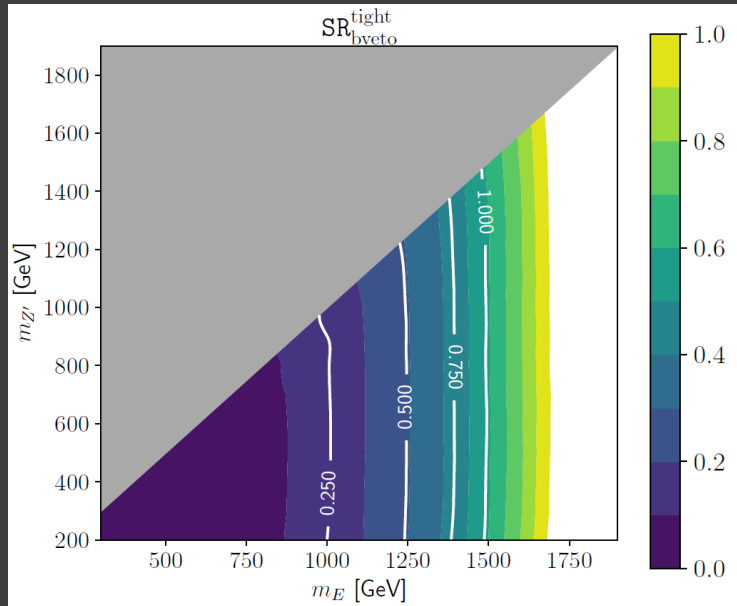
Madgraph5+pythia8+Delphes3

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

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

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

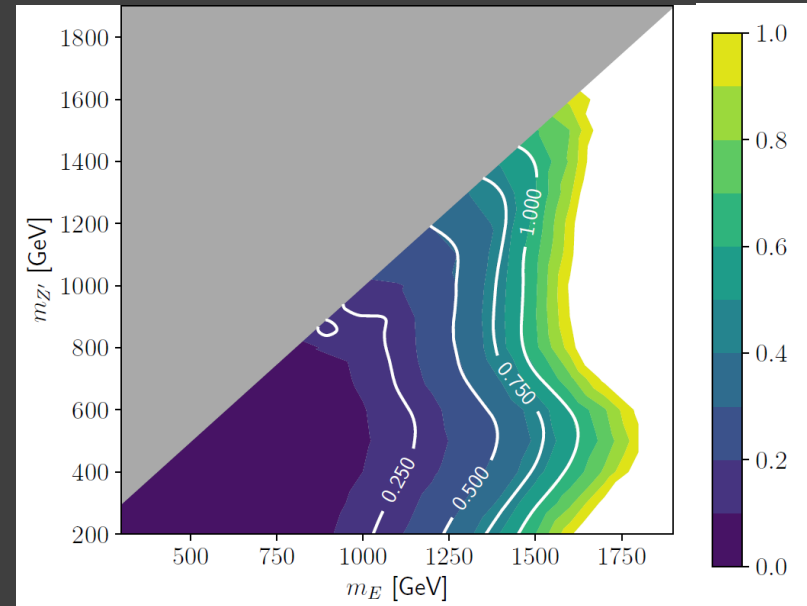
*doublet VL lepton



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

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

$$+ |m_{\text{OS}} - 500| < 100 \text{ (250) GeV}$$



$$\text{bkg} = 10$$

Madgraph5+pythia8+Delphes3

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

Summary

- $\geq 4\mu$ signals are expected in models with muon-philic VL leptons and Z'
- current (future) limit is more than 1 (1.2) TeV if $\text{Br}(E \rightarrow Z'\mu) \sim 1$
- excess in $\geq 5e/\mu$ signal region can be explained if $m_E \sim m_{Z'} \sim 400$ GeV
- flavor information e/μ is crucial to test muon anomaly explanations

Thank you !

Backup

Current limits on doublet-like VL lepton

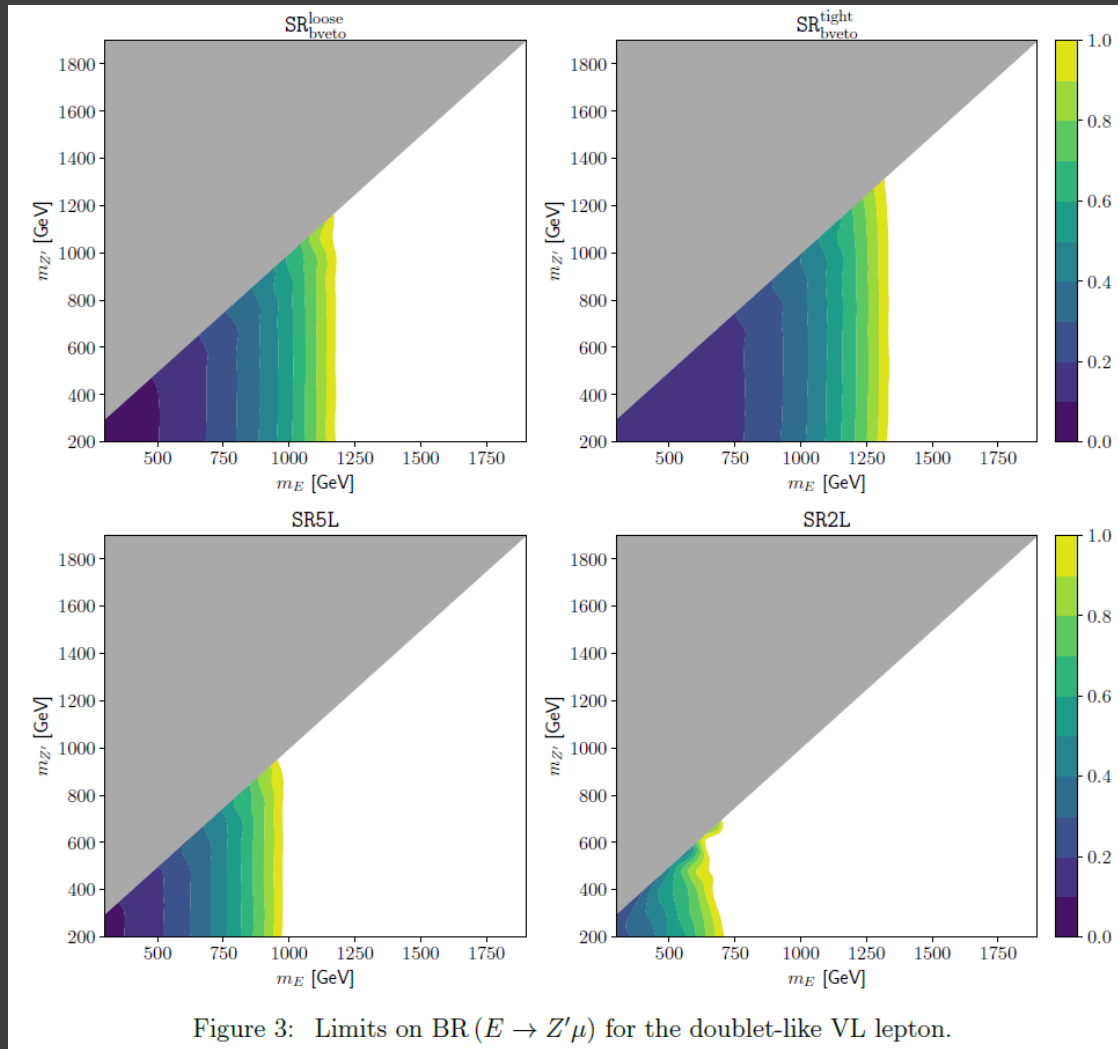
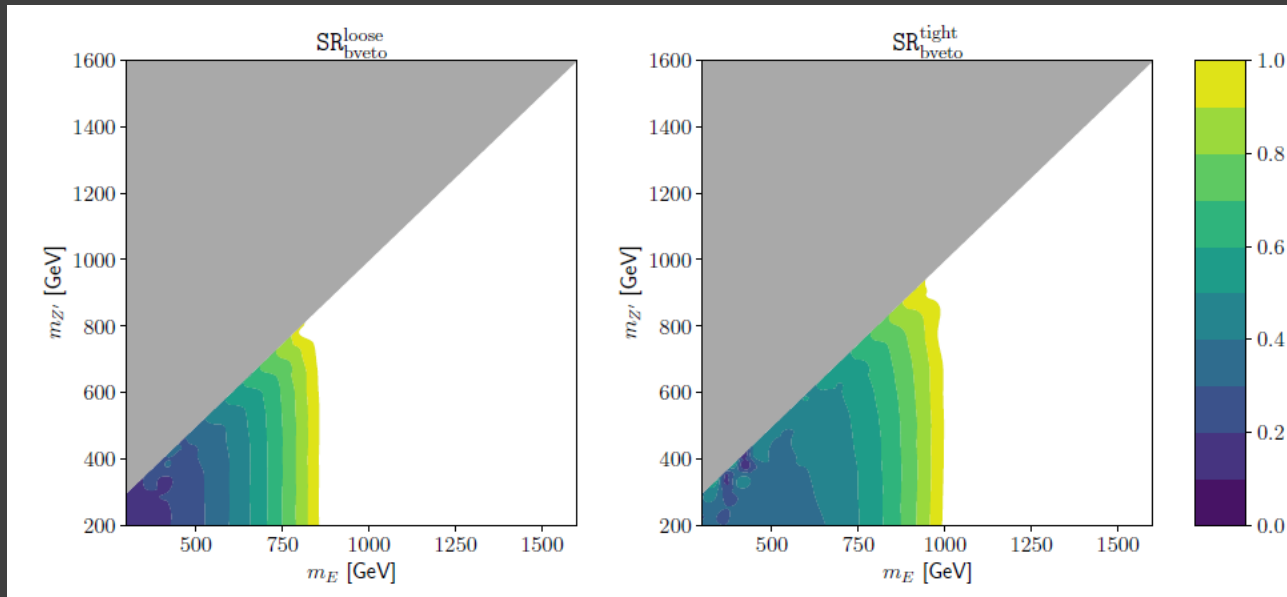


Figure 3: Limits on $\text{BR}(E \rightarrow Z'\mu)$ for the doublet-like VL lepton.

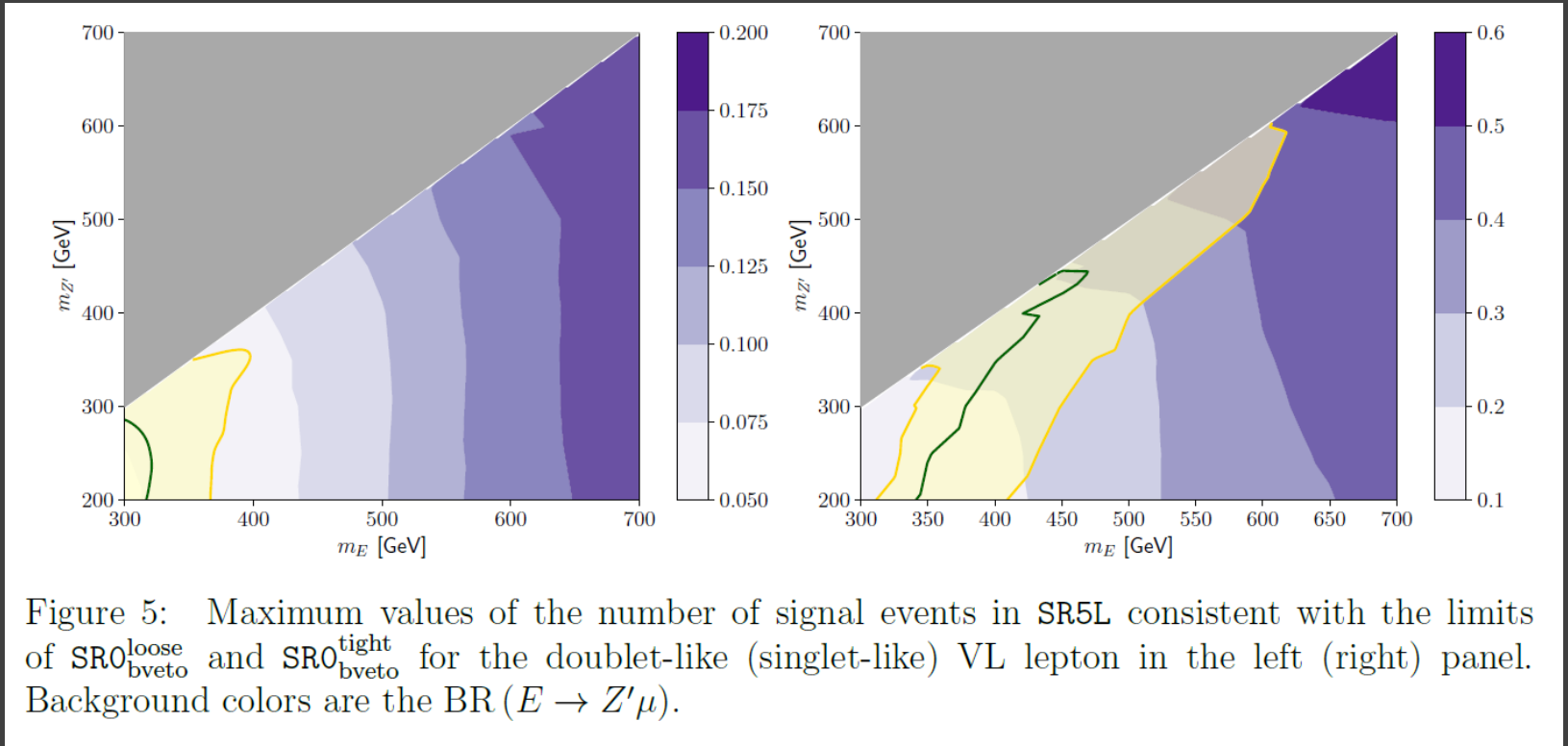
Upper limits on $\text{Br}(E \rightarrow Z'\mu)$

Current limits on singlet-like VL lepton



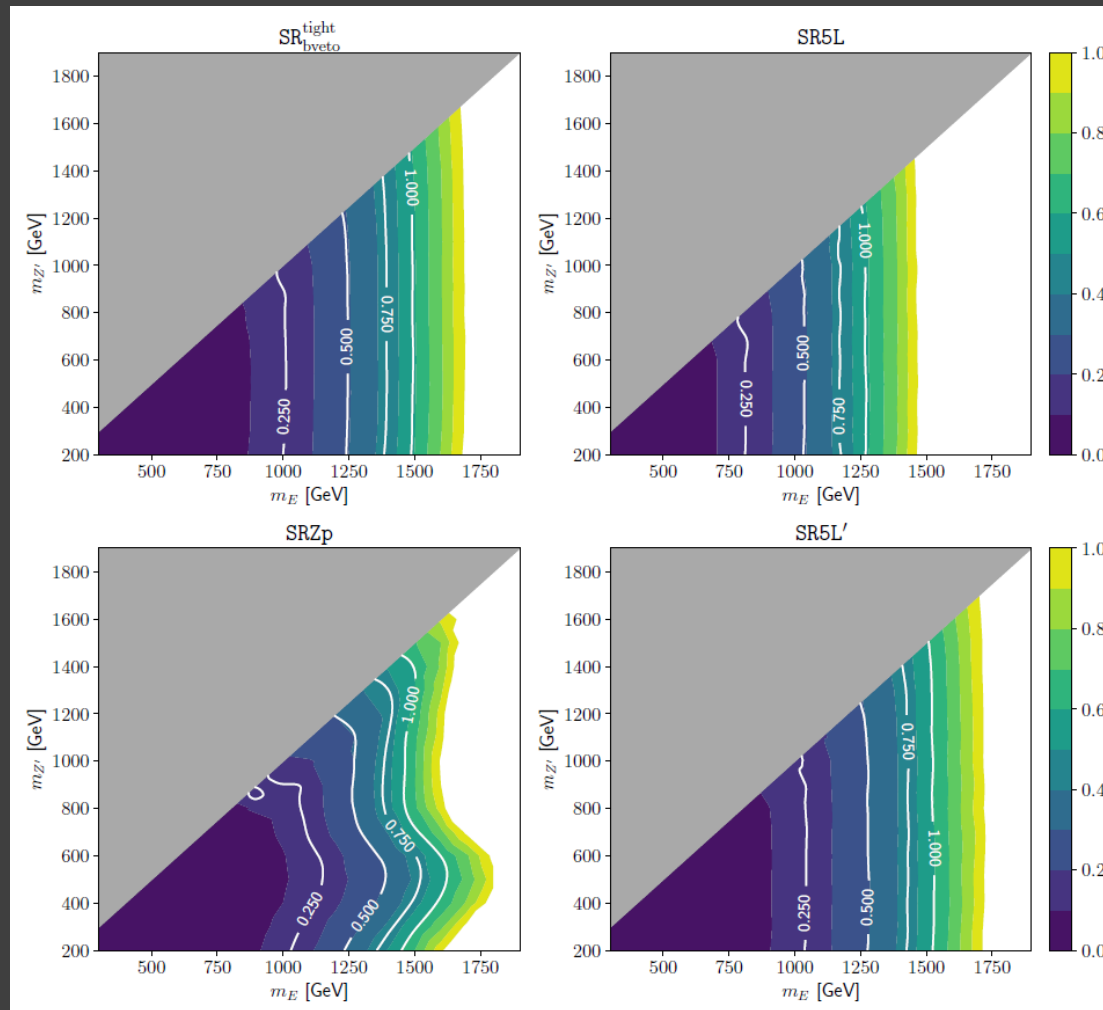
Upper limits on $\text{Br}(E \rightarrow Z' \mu)$

Maximum number of signals in SR5L



The excess is explained in yellow region

Future limits for doublet-like VL leptons

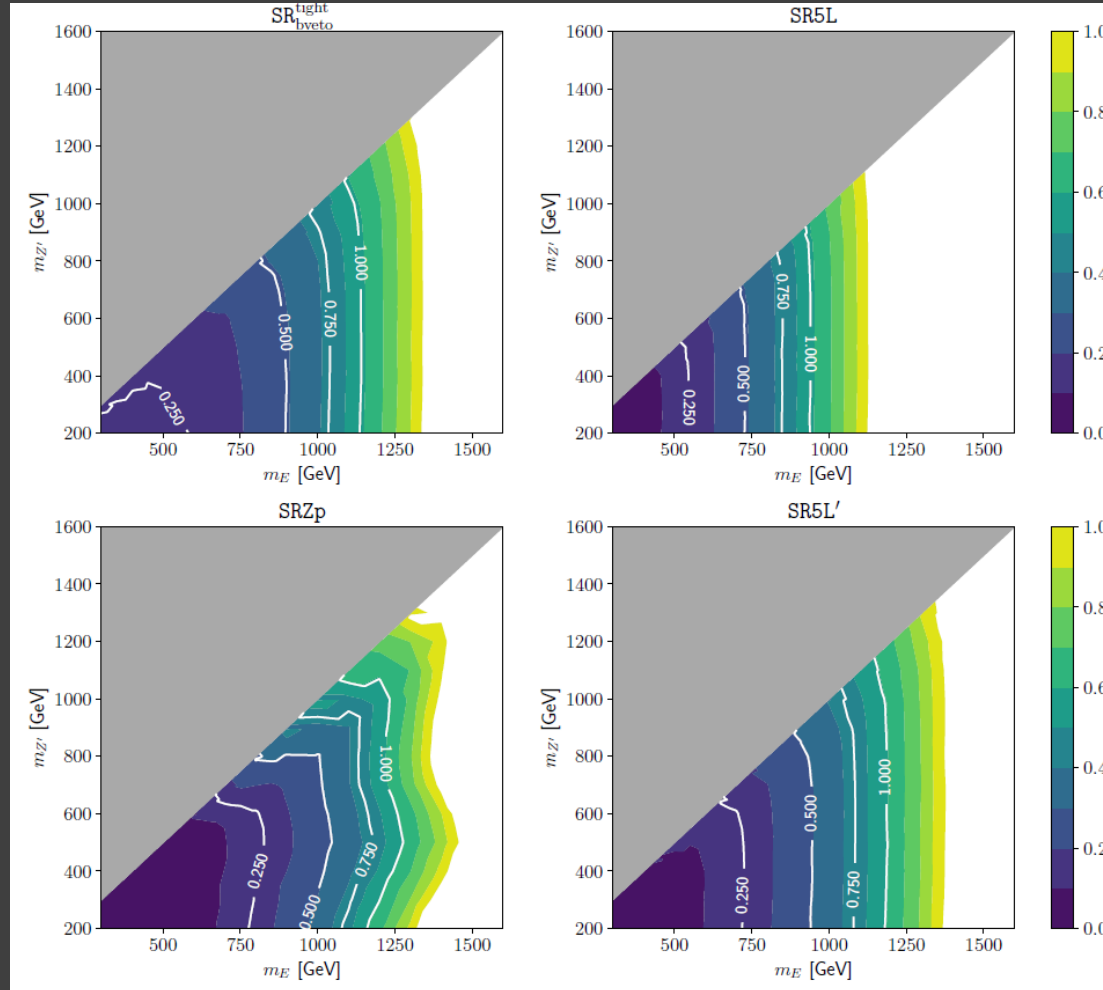


Future limits on $\text{Br}(E \rightarrow Z' \mu)$

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

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

Future limits for singlet-like VL leptons



Future limits on $\text{Br}(E \rightarrow Z' \mu)$

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

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