Pheno2021

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

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in collaboration with

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muon anomalies

- muon g-2

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$
$$= (2.51 \pm 0.59) \times 10^{-9}$$

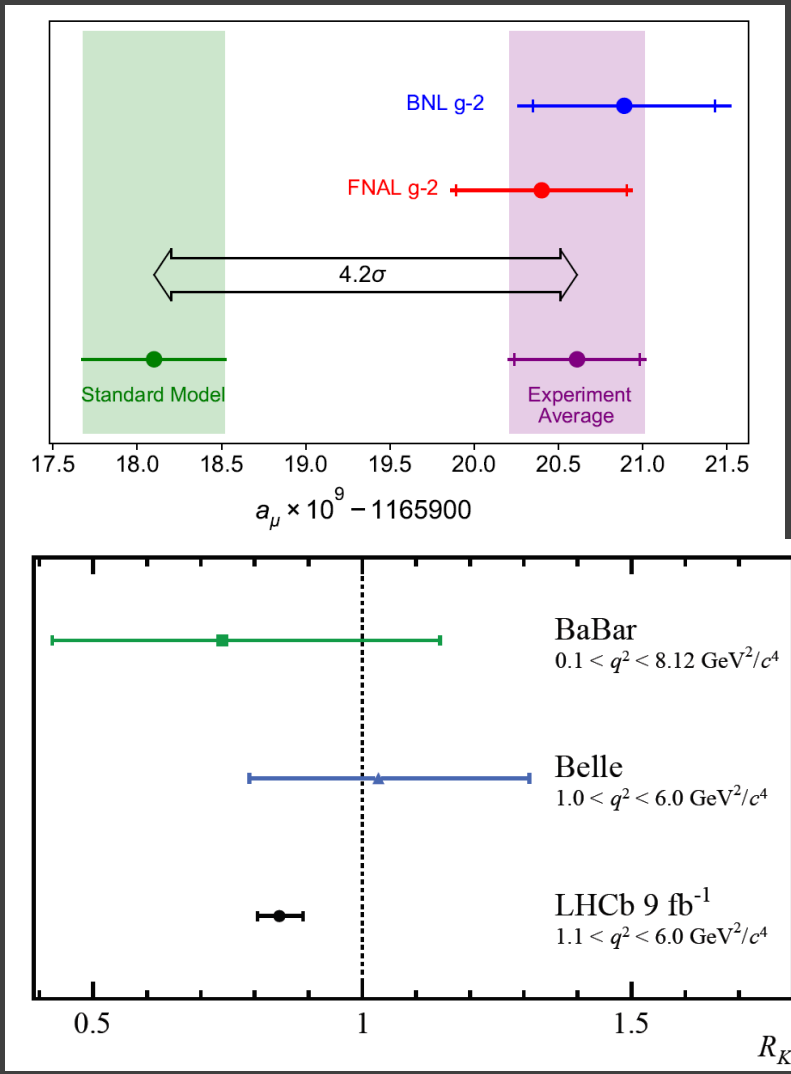
4.2σ discrepancy

- $b \to s\mu\mu$ anomaly

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

3.1σ discrepancy

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



LHCb, 2103.11769

Possible explanation

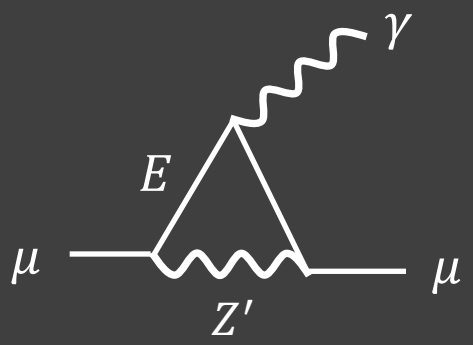
JK, S.Raby, A.Trautner, 1906.11297, 1911.11075

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

- muon g-2

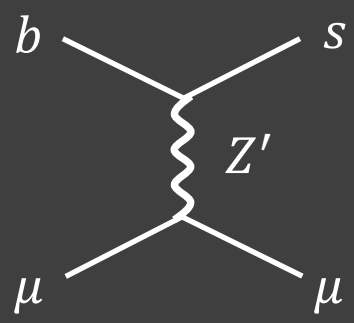
$$\Delta a_\mu \sim 5 \times 10^{-9} \times \left(\frac{500\ \text{GeV}}{m_{Z'}}\right)^2 \left(\frac{g^L_{\mu \text{E}} g^R_{\mu \text{E}}}{0.09}\right)$$

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



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

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

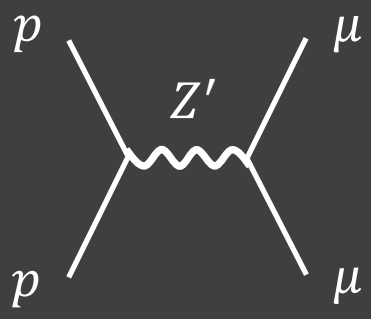


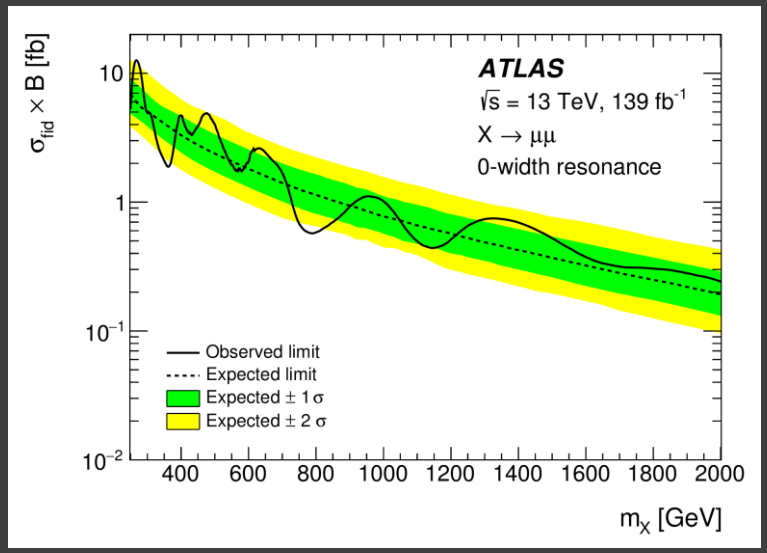
$m_{Z'} \sim m_E \sim \mathcal{O}(500\ \text{GeV})$ is predicted

Z' search

- dimuon search at LHC

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





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

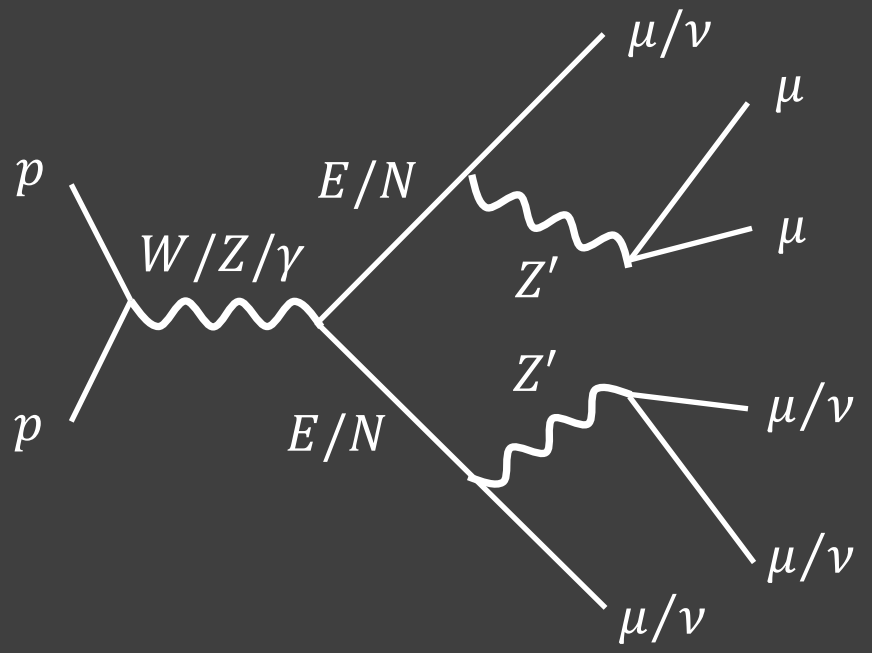
$$C_9 \sim -0.83 \times \left(\frac{500\ \text{GeV}}{m_{Z'}}\right)^2 \left(\frac{g^L_{sb}}{0.0006}\right) \left(\frac{g^L_{\mu\mu} + g^R_{\mu\mu}}{0.6}\right)$$

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

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

$\geq 4\mu$ signal

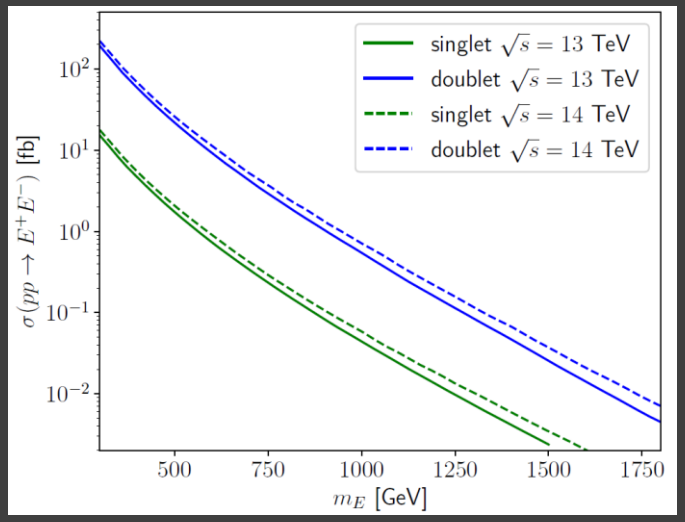
- VL-lepton pair production: $pp \to \bar{L}L \quad L = E/N$



- 6 muons are produced if both $Z' \to \mu\mu$ from $pp \to \bar{E}E \to \mu^-\mu^+Z'Z'$
- 4 muons are produced if one $Z' \to \mu\mu$
- 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

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

$\left|g^L_{\mu\mu}\right| = \left|g^R_{\mu\mu}\right|$ 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
$\mathrm{SR0}^{\mathrm{loose}}_{\mathrm{bveto}}$	≥ 4	≥ 0	$= 0$	veto	$m_{\mathrm{eff}} > 600$ GeV
$\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$	≥ 4	≥ 0	$= 0$	veto	$m_{\mathrm{eff}} > 1250$ GeV
SR5L	≥ 5	≥ 0	≥ 0	-	-

+ trigger condition

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

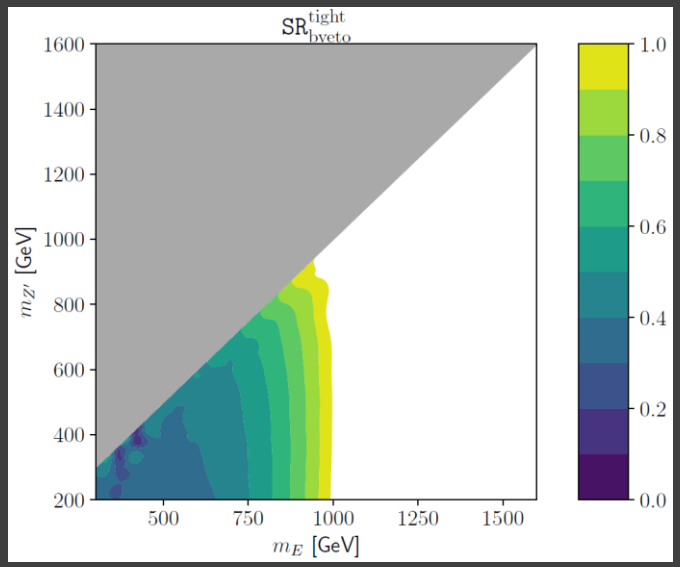
- Experimental result

	$\mathrm{SR0}^{\mathrm{loose}}_{\mathrm{bveto}}$	$\mathrm{SR0}^{\mathrm{tight}}_{\mathrm{bveto}}$	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

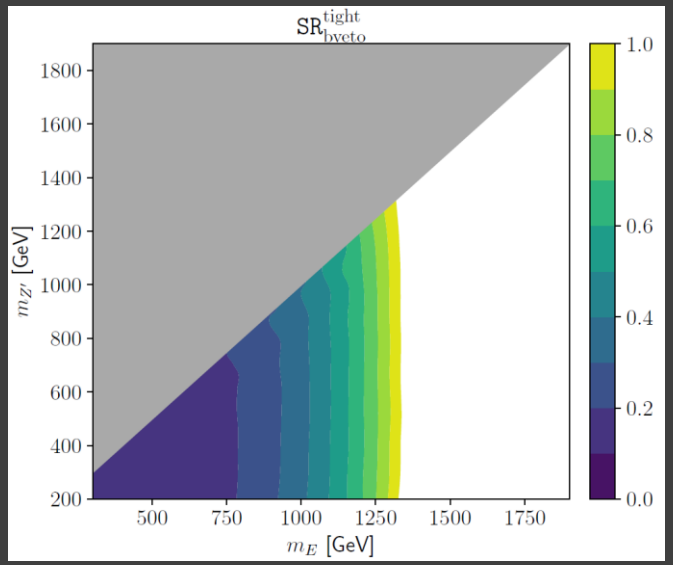
- no evidence of new physics
- 1.9σ excess in SR5L

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

- $SU(2)_L$ singlet



- $SU(2)_L$ doublet



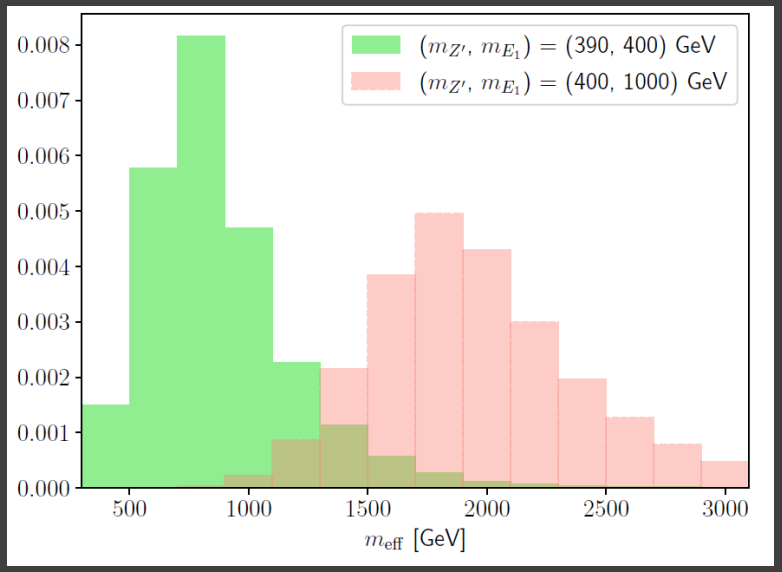
Madgraph5+pythia8+Delphes3

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

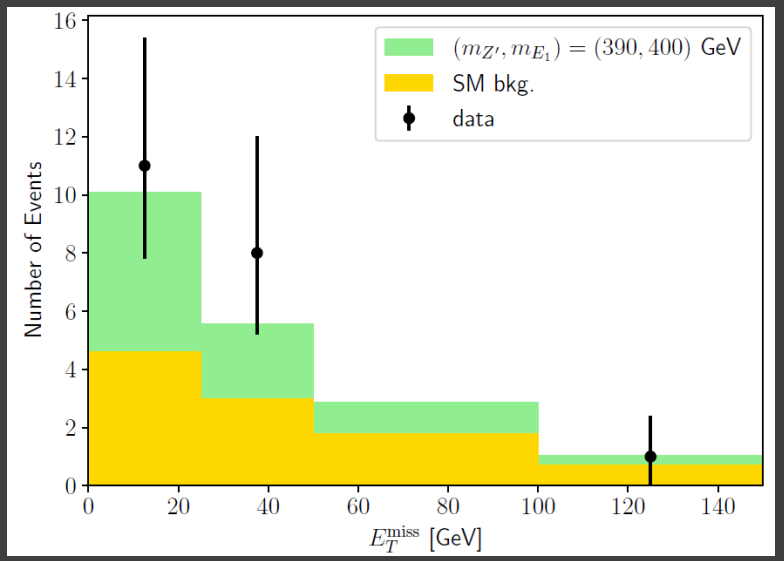
Explanation of excess in $\geq 5\ell$ signal

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 targets electrons

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 $\mathrm{Br}(E \to Z'\mu) \sim 1$
- 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

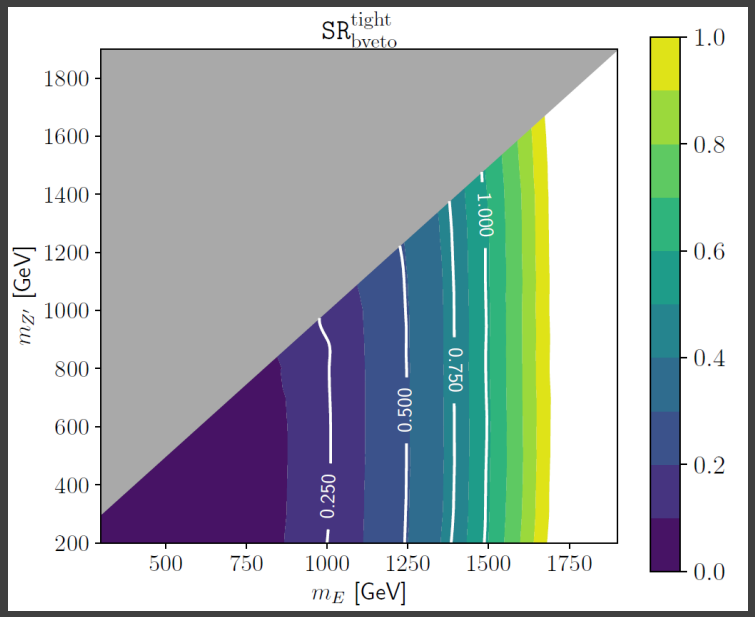
Thank you !

Backup

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

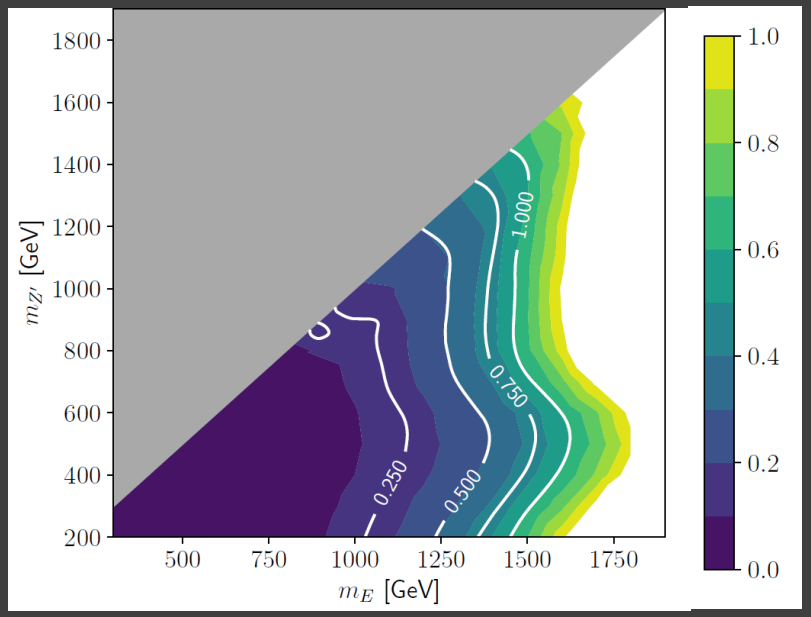
- $\text{SR0}_{\text{bveto}}^{\text{tight}}$

*doublet VL lepton



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

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

Current limits on doublet-like VL lepton

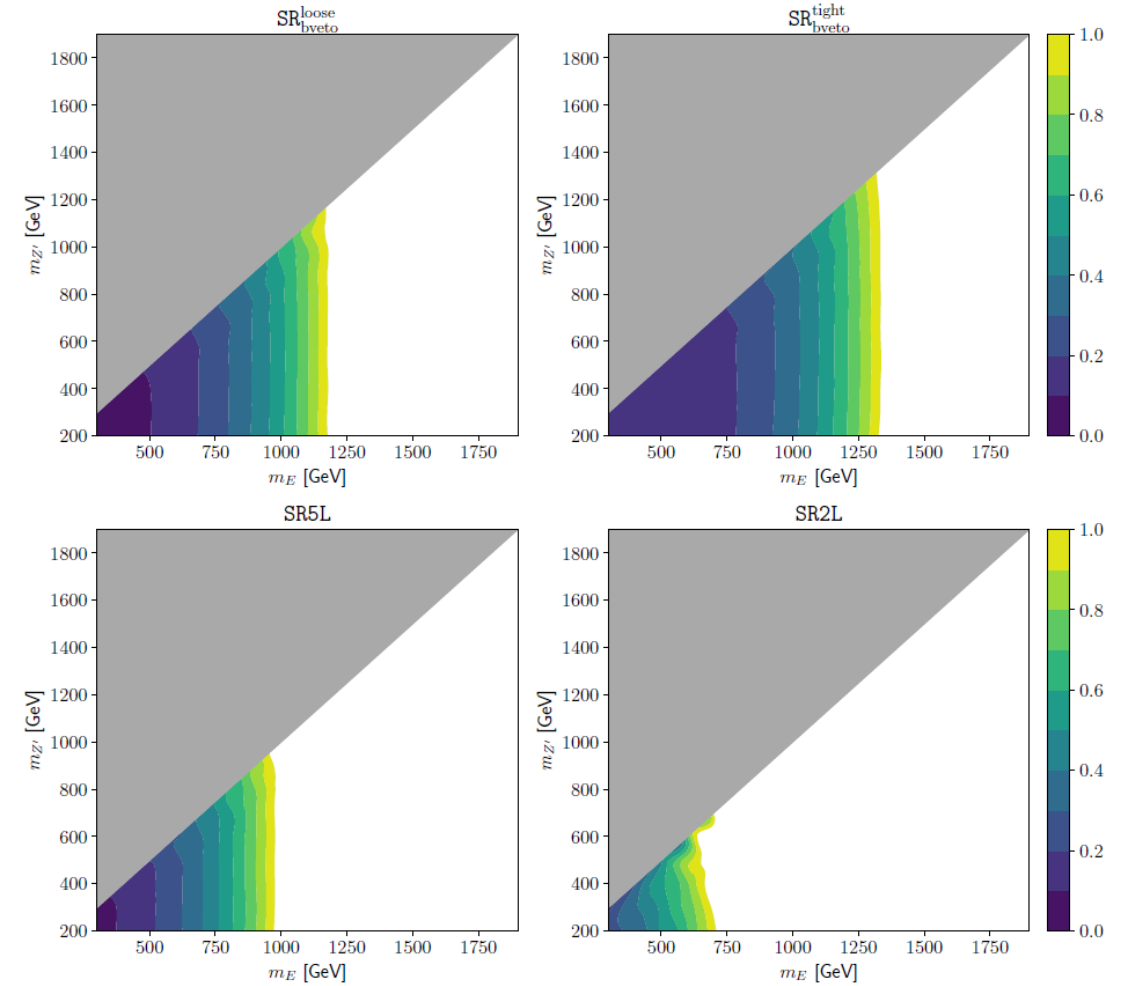
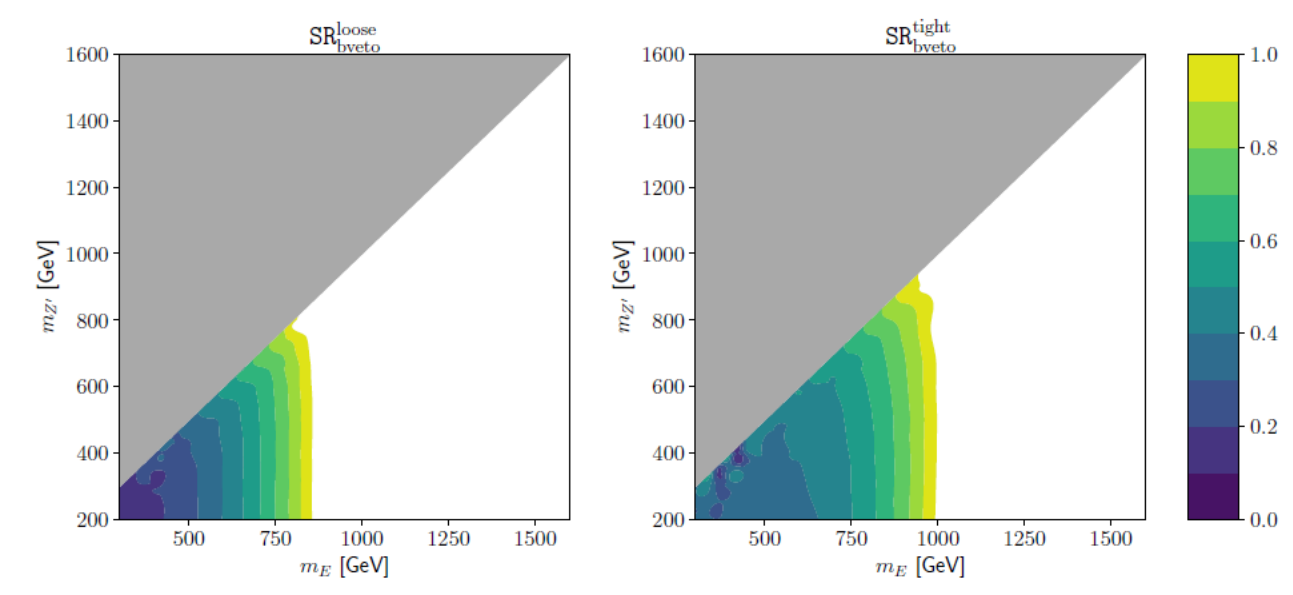


Figure 3: Limits on BR $(E \to Z'\mu)$ for the doublet-like VL lepton.

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

Current limits on singlet-like VL lepton



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

Maximum number of signals in SR5L

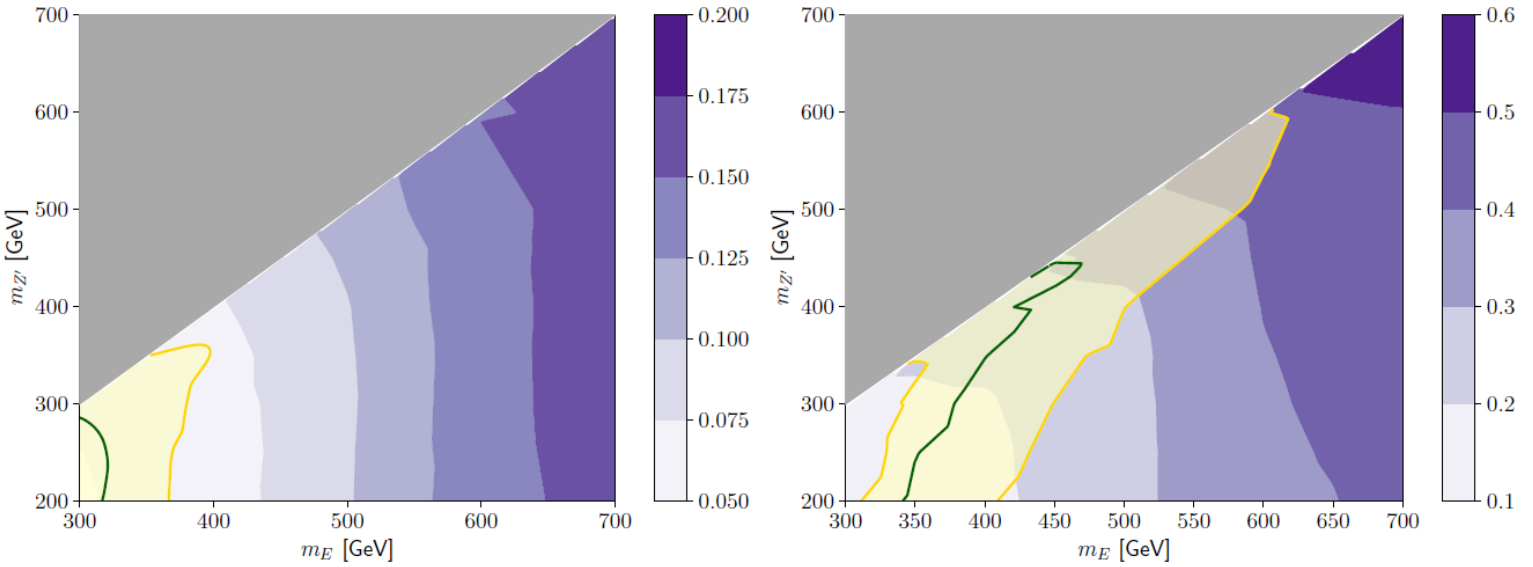
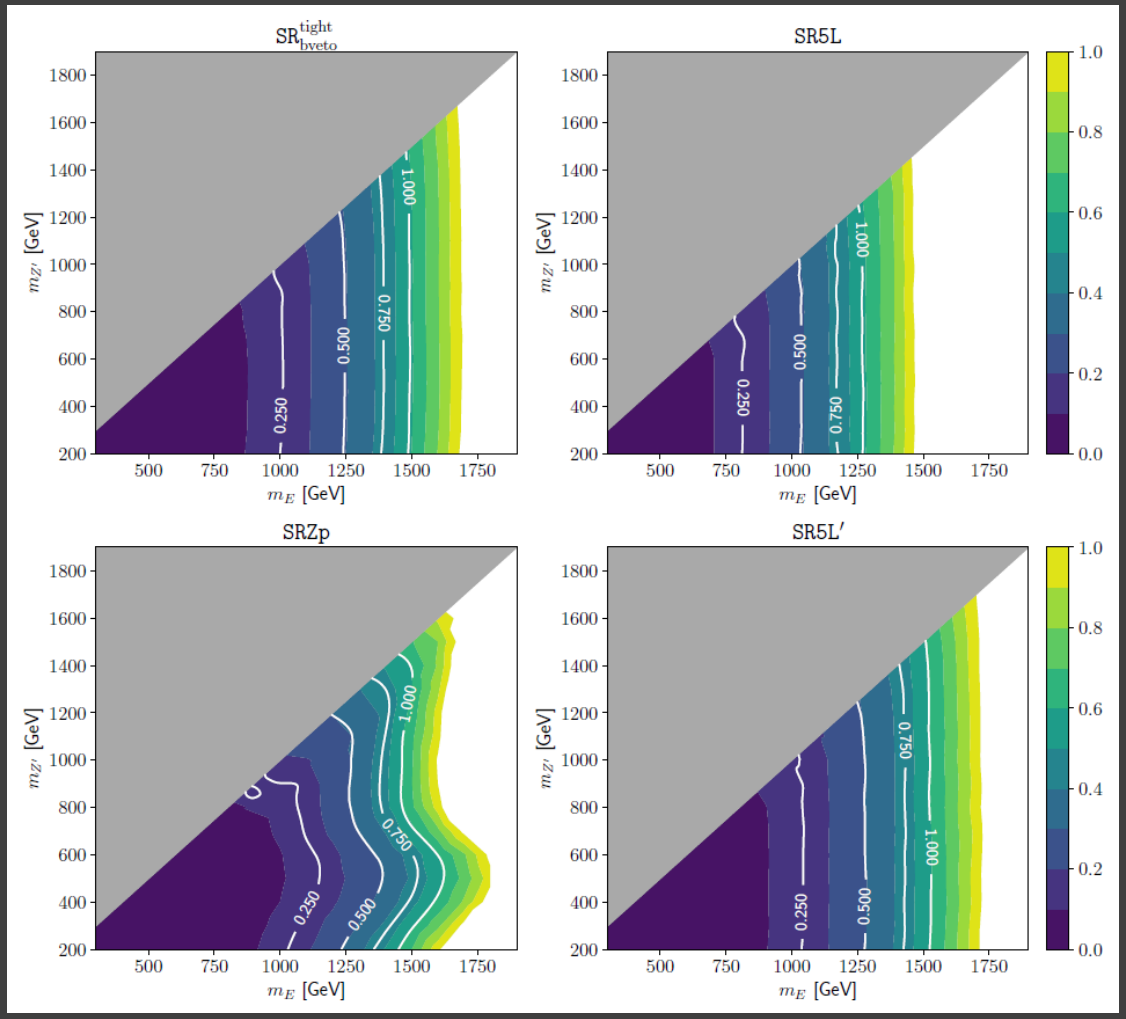


Figure 5: Maximum values of the number of signal events in SR5L consistent with the limits of $\mathtt{SR0}^{\text{loose}}_{\text{bveto}}$ and $\mathtt{SR0}^{\text{tight}}_{\text{bveto}}$ for the doublet-like (singlet-like) VL lepton in the left (right) panel. Background colors are the BR $(E \to Z'\mu)$.

The excess in explained in yellow region

Future limits for doublet-like VL leptons

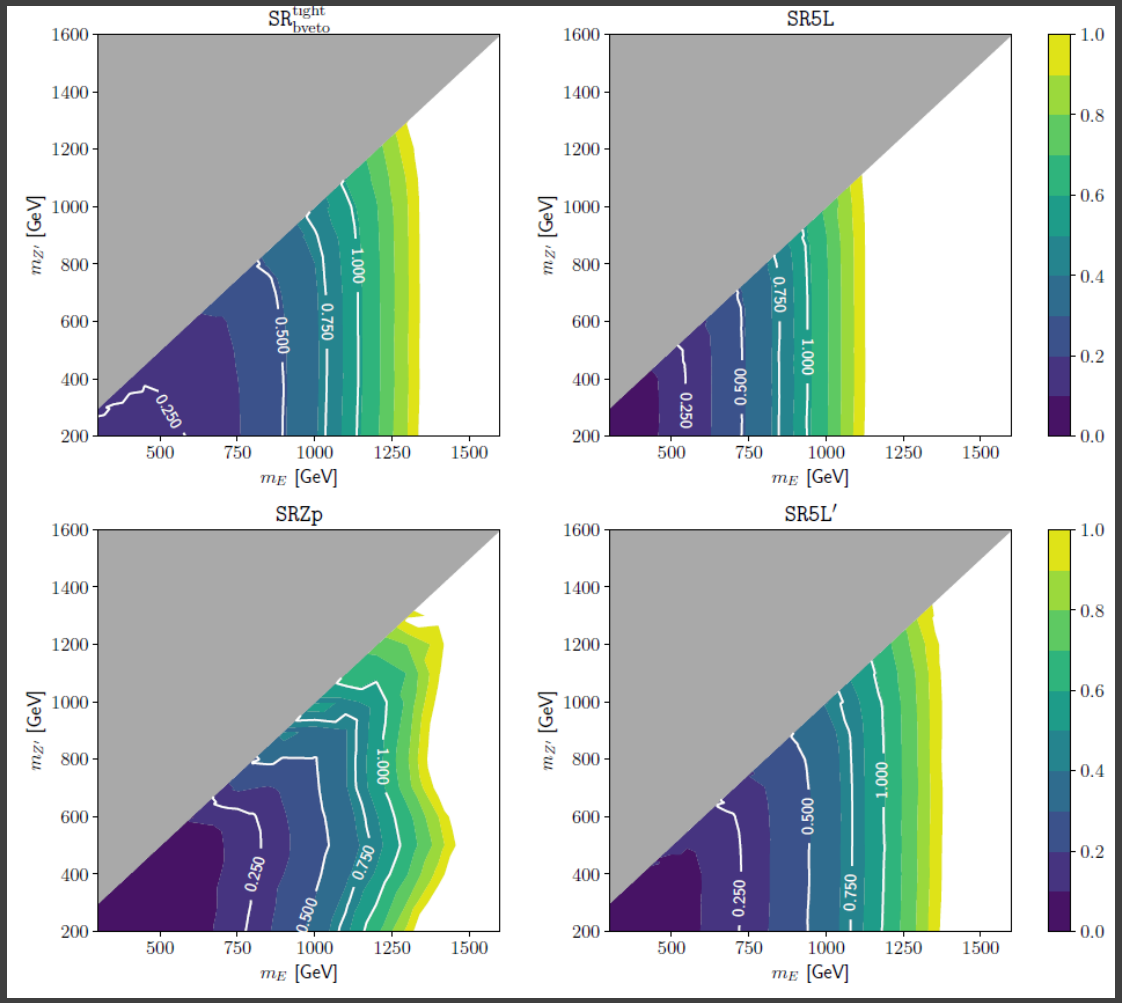


Future limits on $\mathrm{Br}(E \to Z'\mu)$

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

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