Z' and ATLAS single eμ event

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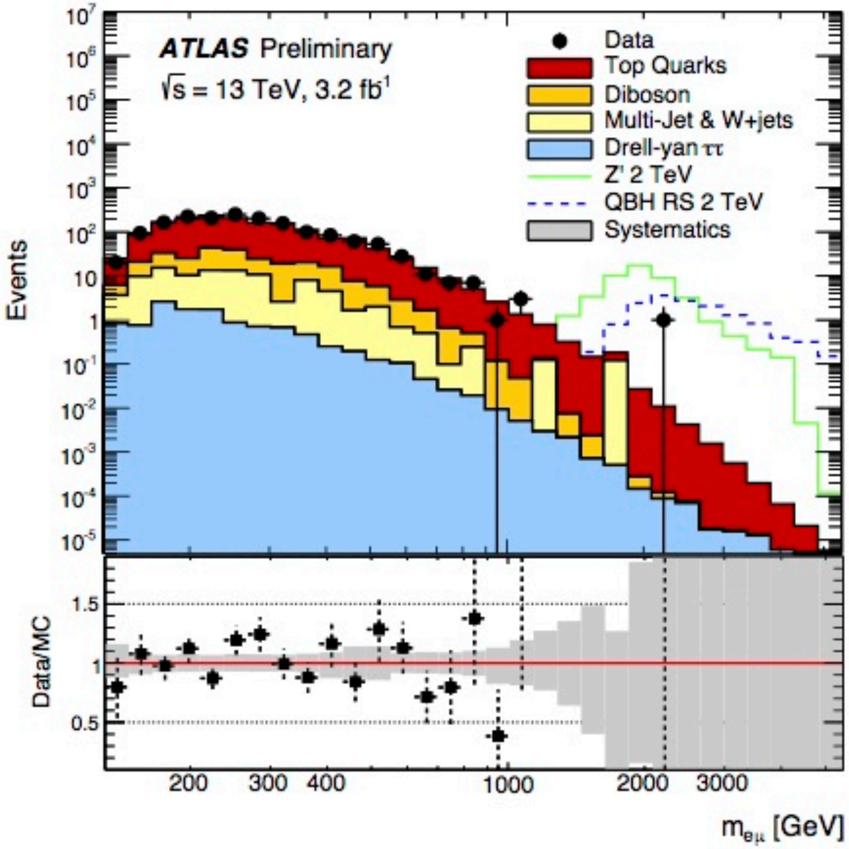

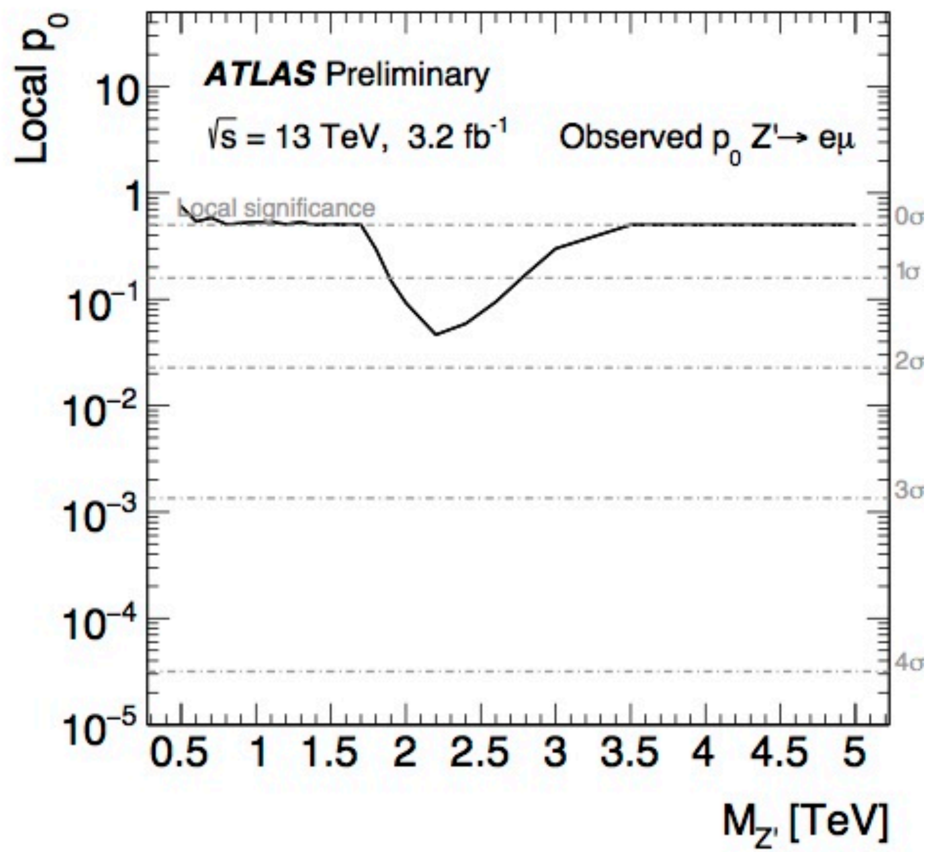

using 3.2 fb^{-1} data at $\sqrt{s} = 13$ TeV

one event at $m_{e\mu} = 2.1$ TeV largest local significance is 1.7σ

$$\sigma(pp \to X) \times B(X \to e^{\pm}\mu^{\mp}) \simeq 1 - 2 \text{ fb}$$

$$\mathcal{L}_{\rm NC} = -g' J^{(2)\mu} Z'_\mu \qquad J^{(2)}_\mu = \sum_{i,j} \bar{\psi}_i \gamma_\mu \left[\epsilon^{\psi}_{Lij} P_L + \epsilon^{\psi}_{Rij} P_R \right] \psi_j$$

$$\epsilon^{u}_{L,R} = Q'^{(u)}_{L,R}\, diag(1,1,1) \qquad \epsilon^{d}_{L,R} = Q'^{(d)}_{L,R}\, diag(1,1,1)$$

$$\epsilon^{l}_{L} = diag(Q'^{(e)}_{L}, Q'^{(\mu)}_{L}, Q'^{(\tau)}_{L})$$

$$\begin{aligned}
\mathcal{L}_{\rm NC} = & -g' Z'_\mu (\bar{u}, \bar{c}, \bar{t})_M \gamma^\mu (V^\dagger_{uL} \epsilon^u_L V_{uL} P_L + V^\dagger_{uR} \epsilon^u_R V_{uR} P_R)\, (u, c, t)^T_M \\
& -g' Z'_\mu (\bar{d}, \bar{s}, \bar{b})_M \gamma^\mu (V^\dagger_{dL} \epsilon^d_L V_{dL} P_L + V^\dagger_{dR} \epsilon^d_R V_{dR} P_R)\, (d, s, b)^T_M \\
& -g' Z'_\mu (\bar{e}, \bar{\mu}, \bar{\tau})_M \gamma^\mu (U^\dagger_{lL} \epsilon^l_L U_{lL} P_L + U^\dagger_{lR} \epsilon^l_R U_{lR} P_R)\, (e, \mu, \tau)^T_M
\end{aligned}$$

$$\Rightarrow \mathcal{L}_{\mathrm{NC}} = -Z'_\mu(\bar{u},\bar{c},\bar{t})_M\gamma^\mu(g^u_L P_L + g^u_R P_R)\,(u,c,t)^T_M$$
$$-Z'_\mu(\bar{d},\bar{s},\bar{b})_M\gamma^\mu(g^d_L P_L + g^d_R P_R)\,(d,s,b)^T_M$$
$$-Z'_\mu(\bar{e},\bar{\mu},\bar{\tau})_M\gamma^\mu(g^l_L P_L + g^l_R P_R)\,(e,\mu,\tau)^T_M$$

$$U_{PMNS} = U^\dagger_{lL}U_\nu \quad U_\nu = \mathbf{1} \qquad V_{PMNS} = U^\dagger_{lL}$$

$$g^l_L = g' U_{PMNS}\epsilon^l_L U^\dagger_{PMNS}$$

normal hierarchy(NH)

$$U_{PMNS} = \begin{pmatrix} 0.822 & 0.548 & -0.0518 + 0.144i \\ -0.388 + 0.0791i & 0.643 + 0.0528i & 0.653 \\ 0.399 + 0.0898i & -0.528 + 0.0599i & 0.742 \end{pmatrix}$$

inverse hierarchy(IH).

$$U_{PMNS} = \begin{pmatrix} 0.822 & 0.548 & -0.0525 + 0.146i \\ -0.380 + 0.0818i & 0.634 + 0.0546i & 0.666 \\ 0.407 + 0.0895i & -0.540 + 0.0597i & 0.729 \end{pmatrix}$$

CONSTRAINTS FROM $e^\pm\mu^\mp$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, AND jj PRODUCTION

$$\sigma(pp \to Z') \times B(Z' \to e^+e^-) \lesssim 1.5 \text{ fb}$$

$$\sigma(pp \to Z') \times B(Z' \to \mu^+\mu^-) \lesssim 2 \text{ fb.}$$

$$\sigma(pp \to Z') \times B(Z' \to e^\pm\tau^\mp) \lesssim 5 \text{ fb}$$

$$\sigma(pp \to Z') \times B(Z' \to \mu^\pm\tau^\mp) \lesssim 9 \text{ fb}$$

The dijet limits from ATLAS [11, 13] are about $\sigma(pp \to Z') \times B(Z' \to jj) \times A \lesssim 0.5$ pb for a narrow-width Z', and $\lesssim 1$ pb for $\Gamma_{Z'}/m_{Z'} = 0.15$ at $M_{Z'} \simeq 2.1$ TeV. From the CMS [12], $\sigma(pp \to Z') \times B(Z' \to jj) \times A \lesssim 1$ pb for the narrow-width case. Here A is the acceptance ratio due to selection cuts, and ranges between $40 - 60\%$.

TABLE I. Various experimental constraints coming from the LHC, rare lepton-flavor violating decays, and μ-e conversions, as well as the predictions of the benchmark point (Z' M-1): (NH) $g' = 1$, $\epsilon_L^u = -\epsilon_R^u = diag(0.2, 0.2, 0.2)$, $\epsilon_L^d = -\epsilon_R^d = diag(0.2, 0.2, 0.2)$, $\epsilon_L^l = 1/10 \times diag(-0.404, 0.912, -0.064)$, $\epsilon_R^l = 0$. The total width of the Z' is $\Gamma_{Z'} = 40.7$ GeV, and the Z' production cross section $\sigma(pp \to Z') = 367$ fb at the 13 TeV LHC.

observable	exp.	Z' M-1
$\sigma(pp \to Z') \times B(Z' \to e^\pm \mu^\mp)$ [fb]	$1 \sim 2$ [1]	1.03
$\sigma(pp \to Z') \times B(Z' \to e^+ e^-)$ [fb]	$\lesssim$1.5 [10]	1.4×10^{-7}
$\sigma(pp \to Z') \times B(Z' \to \mu^+ \mu^-)$ [fb]	$\lesssim$2 [10]	0.210
$\sigma(pp \to Z') \times B(Z' \to \tau^+ \tau^-)$ [fb]	-	0.060
$\sigma(pp \to Z') \times B(Z' \to e^\pm \tau^\mp)$ [fb]	$\lesssim$5 [1]	0.782
$\sigma(pp \to Z') \times B(Z' \to \mu^\pm \tau^\mp)$ [fb]	$\lesssim$9 [1]	0.428
$\sigma(pp \to Z') \times B(Z' \to jj)$ [fb]	$\lesssim$500 [11]	362

$B(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$ [20]	4.4×10^{-13}
$B(\mu^- \to e^- e^- e^+)$	$< 1.0 \times 10^{-12}$ [15]	1.1×10^{-16}
$B(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [15]	1.2×10^{-13}
$B(\tau^- \to \mu^- \mu^- \mu^+)$	$< 2.1 \times 10^{-8}$ [15]	1.2×10^{-11}
$B(\tau^- \to \mu^- e^- e^+)$	$< 1.8 \times 10^{-8}$ [15]	2.7×10^{-11}
$B(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$ [15]	4.8×10^{-14}
$B(\tau^- \to e^- e^- e^+)$	$< 2.7 \times 10^{-8}$ [15]	1.5×10^{-17}
$B(\tau^- \to e^- \mu^- \mu^+)$	$< 2.7 \times 10^{-8}$ [15]	5.0×10^{-11}
$B(\mu\mathrm{Ti} \to e\mathrm{Ti})$	$< 6.1 \times 10^{-13}$ [24]	0
$B(\mu\mathrm{Au} \to e\mathrm{Au})$	$< 7.0 \times 10^{-13}$ [15]	0
$B(\mu\mathrm{Al} \to e\mathrm{Al})$	-	0

$$B(l_j \to l_i\gamma) = \frac{\alpha_e \tau_j m_j}{9(4\pi)^4}\left(\frac{m_j}{m_{Z'}}\right)^4 \left(\left|\sum_k (g^l_L)_{jk}(g^l_L)_{ki} - \frac{3m_k}{m_j}(g^l_L)_{kj}(g^l_R)_{ki}\right|^2 + (L \leftrightarrow R)\right)$$

$\mu \to e\gamma$. If both left- and right-handed couplings are nonzero, the diagram with the mass insertion in the τ running in the loop will be enhanced by the factor m_τ/m_μ. Therefore, in order to dodge the experimental limit of $B(\mu \to e\gamma)$, we assume $g^l_R = 0$.

$$B(l_j \to l_i l_k \bar{l}_l) = \frac{\tau_j m_j}{1536\pi^3} \left(\frac{m_j}{m_{Z'}}\right)^4$$

$$\times \left(\left|(g_L^l)_{ij}(g_L^l)_{kl} + (g_L^l)_{kj}(g_L^l)_{il}\right|^2 + \left|(g_L^l)_{ij}(g_R^l)_{kl}\right|^2 + \left|(g_L^l)_{kj}(g_R^l)_{il}\right|^2 + (L \leftrightarrow R) \right)$$

limit of $\mu^- \to e^- e^- e^+$ is less than 1.0×10^{-12}

$$(g_L^l)_{11} \approx 0$$

How to tune zero in

$Z'ee$ coupling, i.e $(g^l_L)_{11}$. The Z' couplings are $g^l_L = g' U_{PMNS} \epsilon^l_L U^\dagger_{PMNS}$, where $\epsilon^l_L = diag(Q'^{(e)}_L, Q'^{(\mu)}_L, Q'^{(\tau)}_L)$. The coupling $(g^l_L)_{ij}$ depends linearly on $Q'^{(e)}_L, Q'^{(\mu)}_L, Q'^{(\tau)}_L$ with coefficients $(\vec{A}_{ij})_l$,

$$(\vec{A}_{ij})_l = (U_{PMNS})_{il}(U^*_{PMNS})_{jl}$$

$$(g^l_L)_{ij} = g'(\vec{A}_{ij})_l \, Q'^{(l)}_L \text{ , or } g'\vec{A}_{ij} \cdot \vec{Q}'_L$$

$\vec{A}_{12} \simeq (-0.319, 0.353, -0.034)$ $\qquad$ $\vec{A}_{11} \simeq (0.676, 0.301, 0.023)$

$$\vec{A}_{12} - \vec{A}_{11} \frac{\vec{A}_{11} \cdot \vec{A}_{12}}{|\vec{A}_{11}|^2} = \vec{A}_{12} + 0.201 \vec{A}_{11} \propto (-0.404, 0.912, -0.064)$$

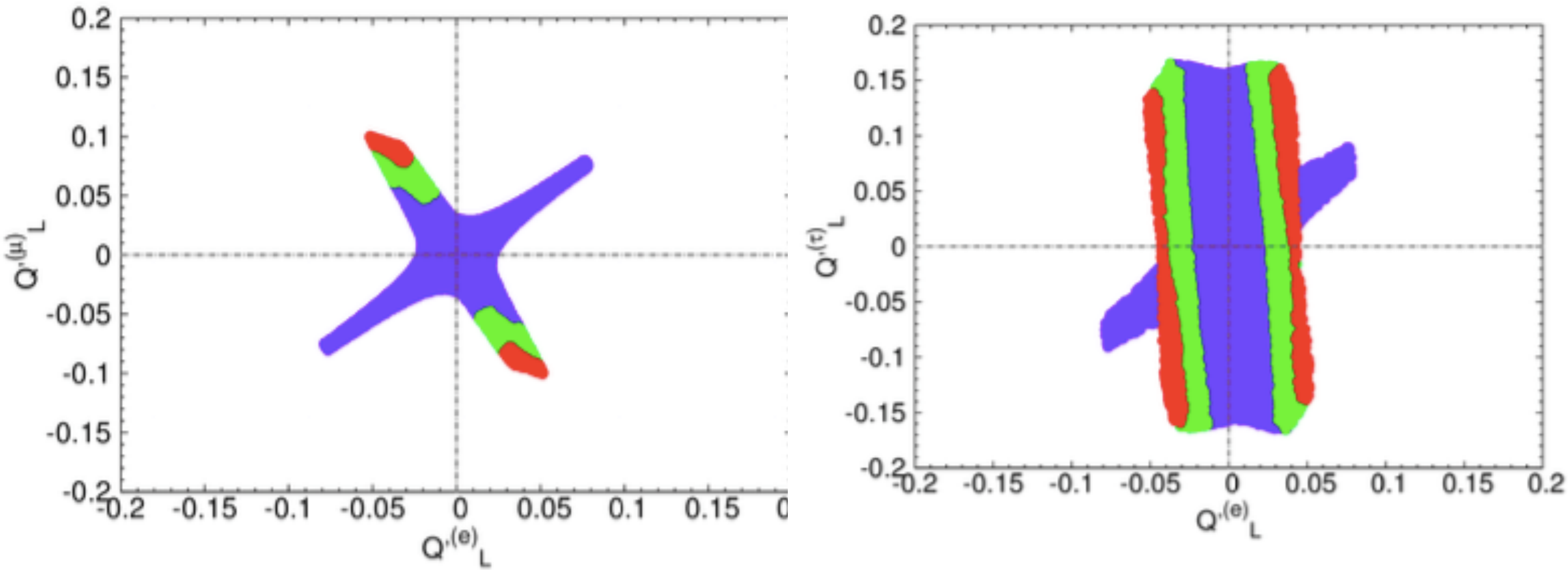

FIG. 1. Scanning over $Q_L^{\prime(e)}$, $Q_L^{\prime(\mu)}$, and $Q_L^{\prime(\tau)}$, while fixing $g' = 1$, $\epsilon_L^{u,d} = -\epsilon_R^{u,d} = diag(0.2, 0.2, 0.2)$, and $\epsilon_R^l = 0$. The colored points satisfy all the experimental limits listed in Table I, except for $\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \simeq 1 \sim 2$ fb. Blue points: $\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 0.5$ fb, are the majority. Green points: $0.5 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 1.0$ fb. Red points: $1.0 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 2.0$ fb are the minority.

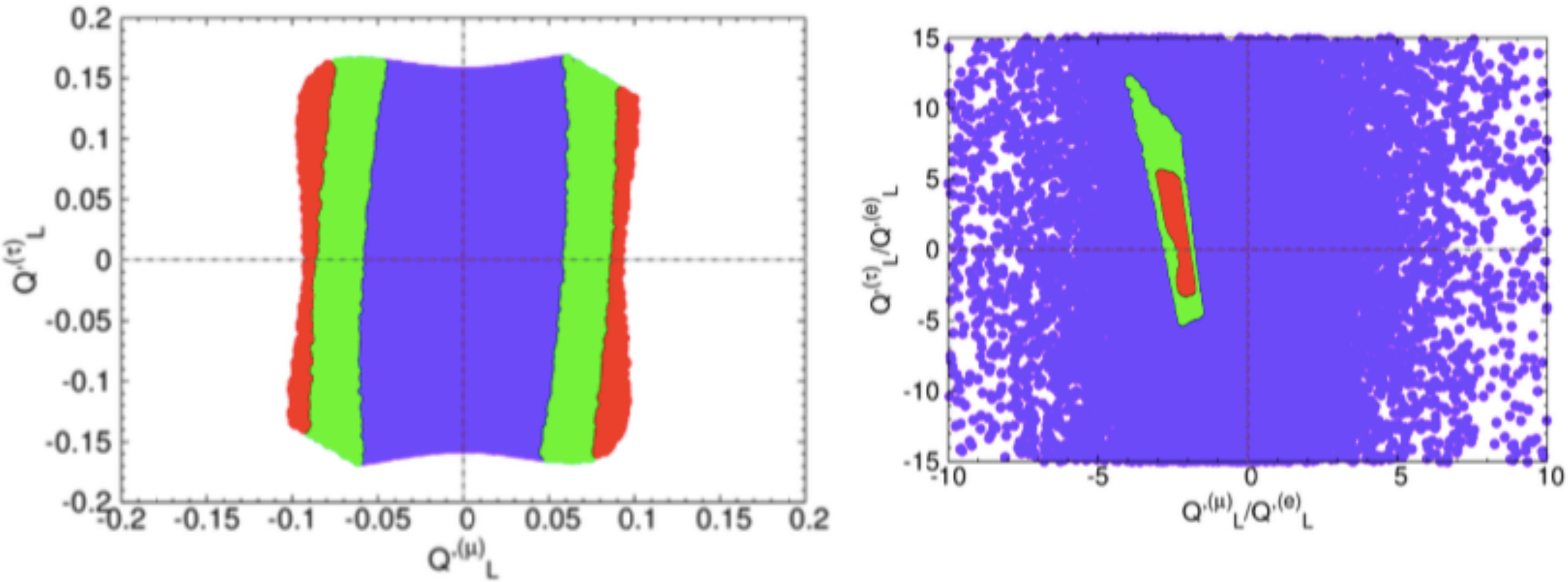

FIG. 1. Scanning over $Q_L^{\prime(e)}$, $Q_L^{\prime(\mu)}$, and $Q_L^{\prime(\tau)}$, while fixing $g' = 1$, $\epsilon_L^{u,d} = -\epsilon_R^{u,d} = diag(0.2, 0.2, 0.2)$, and $\epsilon_R^l = 0$. The colored points satisfy all the experimental limits listed in Table I, except for $\sigma(pp \to Z') \times B(Z' \to e^\pm \mu^\mp) \simeq 1 \sim 2$ fb. Blue points: $\sigma(pp \to Z') \times B(Z' \to e^\pm \mu^\mp) \leq 0.5$ fb, are the majority. Green points: $0.5 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm \mu^\mp) \leq 1.0$ fb. Red points: $1.0 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm \mu^\mp) \leq 2.0$ fb are the minority.

Conclusion

Three U'(1) charges for charged leptons

Universal and axial-vector-like couplings to quarks

to enhance the $Z'\mu e$ but suppress $Z'ee$ couplings

assign the $U'(1)$ charges, $\epsilon_L^l = 1/10 \times diag(-0.404, 0.912, -0.064)$,