

# Combined Constraints on First Generation Leptoquarks

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## 1 Introduction

**Leptoquarks (LQs)** are hypothetical beyond the Standard Model (BSM) particles that feature tree-level quark-lepton couplings. They appear in (among others)

- Grand Unified Theories (Pati-Salam,  $SU(5)$ , ...)
- R-parity violating MSSM

In recent years they have attracted particular attention, since they can explain the „**flavor anomalies**“, deviations from SM predictions that hint at **Lepton Flavor Universality Violation (LFUV)**:

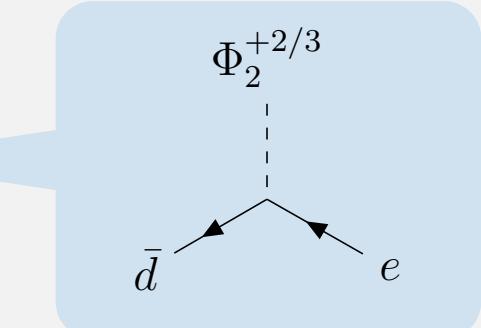
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| <ul style="list-style-type: none"> <li>• <math>R(D^{(*)}) = \frac{\text{Br}(\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)}{\text{Br}(\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell)}</math> with <math>\ell = e, \mu</math></li> <li>• <math>b \rightarrow s\ell^+\ell^-</math> transitions <ul style="list-style-type: none"> <li>- <math>R_K \equiv \frac{\text{Br}(B^+ \rightarrow K^+\mu^+\mu^-)}{\text{Br}(B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^+)} / \frac{\text{Br}(B^+ \rightarrow K^+e^+e^-)}{\text{Br}(B^+ \rightarrow J/\psi(\rightarrow e^+e^-)K^+)}</math></li> <li>- <math>R_{K^*}, B_s^\phi, P_5'</math></li> </ul> </li> <li>• Muon anomalous magnetic moment (AMM): <math>a_\mu = \frac{g_\mu - 2}{2}</math></li> </ul> | $\left. \right\} > 3\sigma^{[2]}$<br>$\left. \right\} \sim 6\sigma^{[3]}$<br>$\left. \right\} 4.2\sigma^{[4]}$ |
|--|--|

## Lepton Flavor Universality Violation (LFUV)

## 2 Setup

We consider the complete set of **LQ interactions with first generation quarks and leptons** (flavor eigenstates).

	<i>L</i>	<i>e</i>
$\bar{Q}$	$\kappa_1^L \gamma_\mu V_1^\mu + \kappa_3 \gamma_\mu (\tau \cdot V_3^\mu)$	$\lambda_2^{LR} \Phi_2$
$\bar{d}$	$\tilde{\lambda}_2 \tilde{\Phi}_2^T i\tau_2$	$\kappa_1^R \gamma_\mu V_1^\mu$
$\bar{u}$	$\lambda_2^{RL} \Phi_2^T i\tau_2$	$\tilde{\kappa}_1 \gamma_\mu \tilde{V}_1^\mu$
$\bar{Q}^c$	$\lambda_3 i\tau_2 (\tau \cdot \Phi_3)^\dagger + \lambda_1^L i\tau_2 \Phi_1^\dagger$	$\kappa_2^{LR} \gamma_\mu V_2^{\mu\dagger}$
$\bar{d}^c$	$\kappa_2^{RL} \gamma_\mu V_2^{\mu\dagger}$	$\tilde{\lambda}_1 \tilde{\Phi}_1^\dagger$
$\bar{u}^c$	$\tilde{\kappa}_2 \gamma_\mu \tilde{V}_2^{\mu\dagger}$	$\lambda_1^R \Phi_1^\dagger$



Field	$\Phi_1$	$\tilde{\Phi}_1$	$\Phi_2$	$\tilde{\Phi}_2$	$\Phi_3$	$V_1$	$\tilde{V}_1$	$V_2$	$\tilde{V}_2$	$V_3$
$SU(3)_c$	3	3	3	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	3	1	1	2	2	3
$U(1)_Y$	− $\frac{2}{3}$	− $\frac{8}{3}$	$\frac{7}{3}$	$\frac{1}{3}$	− $\frac{2}{3}$	$\frac{4}{3}$	$\frac{10}{3}$	− $\frac{5}{3}$	$\frac{1}{3}$	$\frac{4}{3}$

**Table 1:** The ten possible LQ representations ( $\Phi$  with spin  $S = 0$ ,  $V$  with  $S = 1$ ) under the SM gauge group.

After spontaneous symmetry breaking and the subsequent **mass diagonalization** for left-handed quarks (flavor eigenstates  $\rightarrow$  mass eigenstates), the first generation LQs also couple to **second generation quarks**.

$$\begin{aligned}
 d_{L,f} &\rightarrow U_{fi}^{d_L} d_{L,i}, & U^{dL} = \begin{pmatrix} \cos(\beta) & \sin(\beta) \\ -\sin(\beta) & \cos(\beta) \end{pmatrix} \\
 d_{R,f} &\rightarrow U_{fi}^{d_R} d_{R,i}, \\
 u_{L,f} &\rightarrow U_{fi}^{u_L} u_{L,i}, & U^{uL} = \begin{pmatrix} \cos(\beta - \theta_c) & \sin(\beta - \theta_c) \\ -\sin(\beta - \theta_c) & \cos(\beta - \theta_c) \end{pmatrix} \\
 u_{R,f} &\rightarrow U_{fi}^{u_R} u_{R,i},
 \end{aligned}$$

## 3 Observables

### Low Energy Precision Observables

- **Cabibbo Angle Anomaly (CAA):** can be explained with first generation LQs

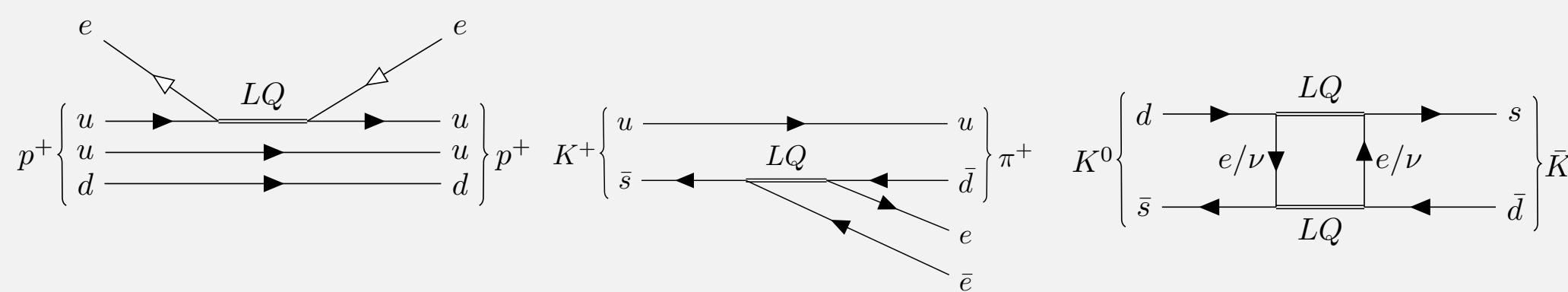
$$\mathcal{H}_{\text{eff}}^{\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{jk} \hat{C}_{jk}^{e\nu} [\bar{u}_j \gamma^\mu P_L d_k] [\bar{e} \gamma_\mu P_L \nu_e],$$

$$V_{us}^\beta = 0.2281(7) \quad V_{ud}^\beta = V_{ud}^L (1 + C_{11}^{e\nu_e}) \quad V_{us}^{K_{\mu 3}} = 0.22345(67)$$

$$V_{us}^\beta|_{\text{NNC}} = 0.2280(14) \quad V_{us}^{K_{\mu 2}} = 0.22534(42)$$

- **Tree-level neutral current:** constraints from parity violation experiments (QWEAK and APV),  $K \rightarrow \pi e^+ e^-$ / $K \rightarrow \pi \mu^+ \mu^-$  and  $K \rightarrow \pi \nu \bar{\nu}$ .

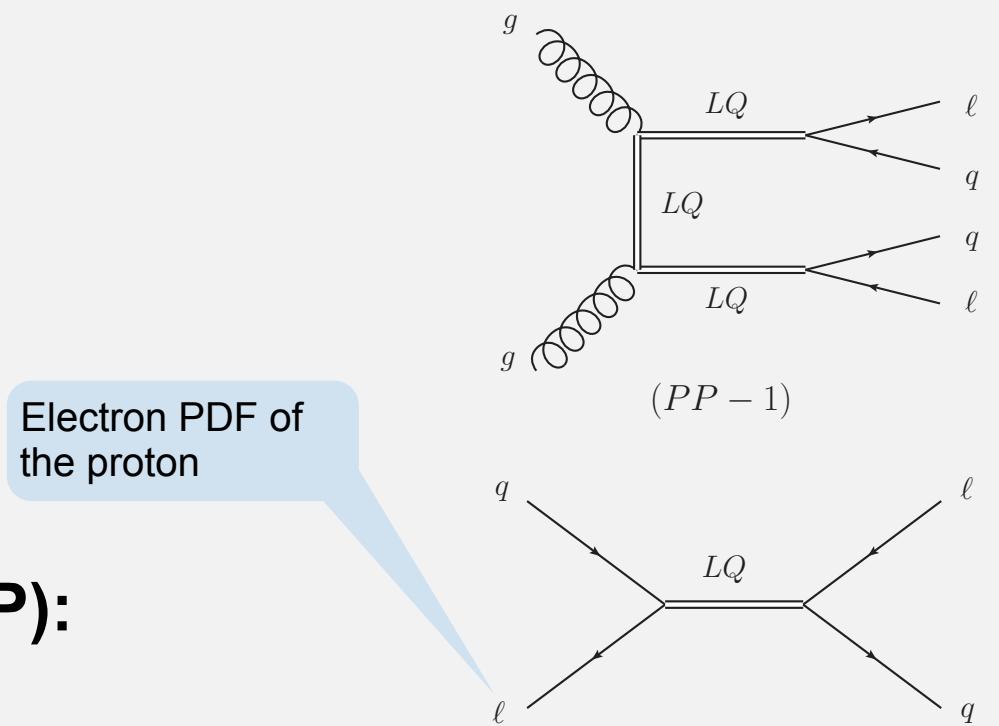
- **$D^0 - \bar{D}^0$  and  $K^0 - \bar{K}^0$  mixing:** constraints on one-loop LQ contributions.



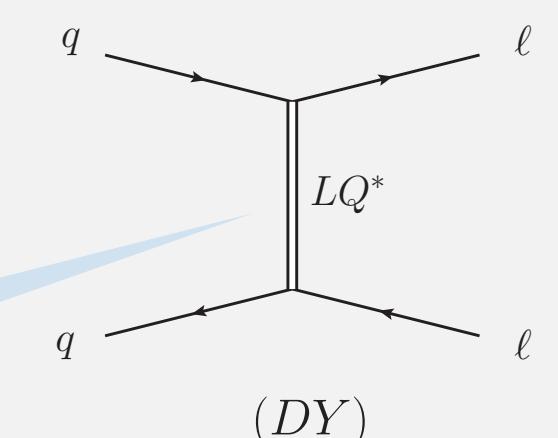
**Figure 1:** Feynman diagrams depicting the LQ contributions to the low energy processes  $ep \rightarrow ep$  (QWEAK),  $K \rightarrow \pi e^+ e^-$  and  $K^0 - \bar{K}^0$  mixing.

### Direct LHC Searches

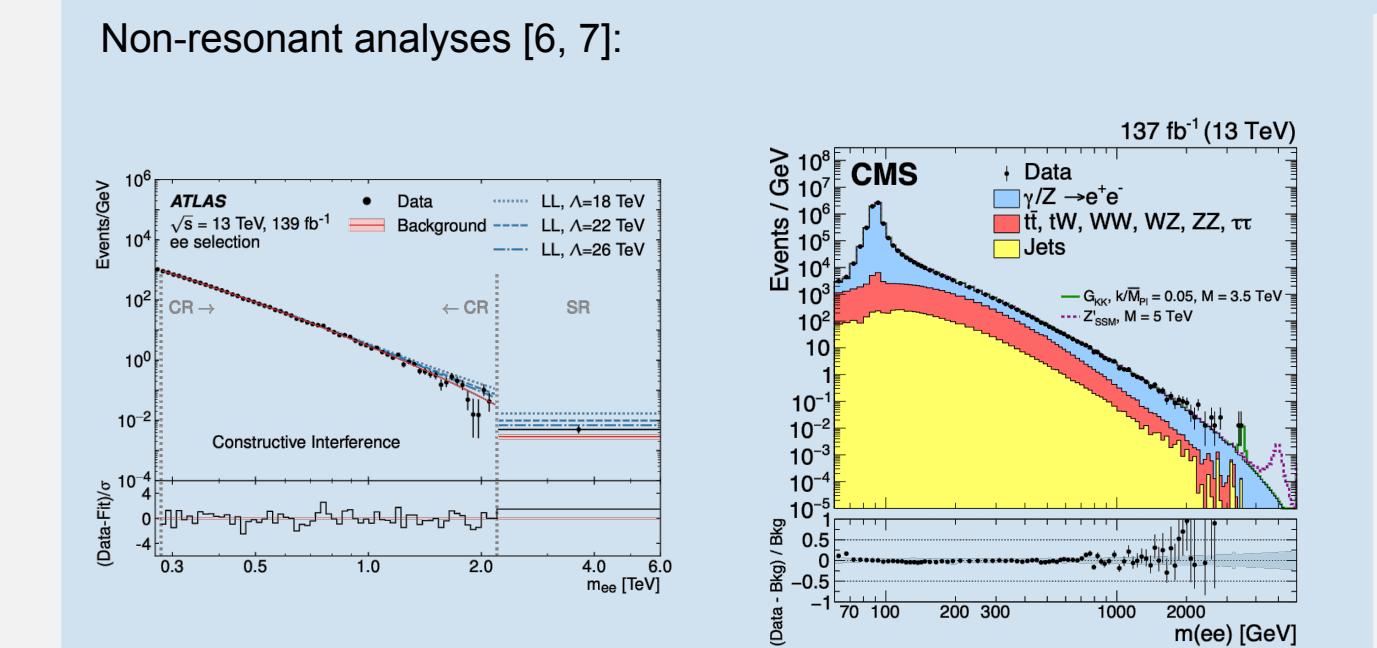
- **Pair production (PP):**



- **Single Resonant Production (SRP):**



- **Drell-Yan-like Signatures (DY):**



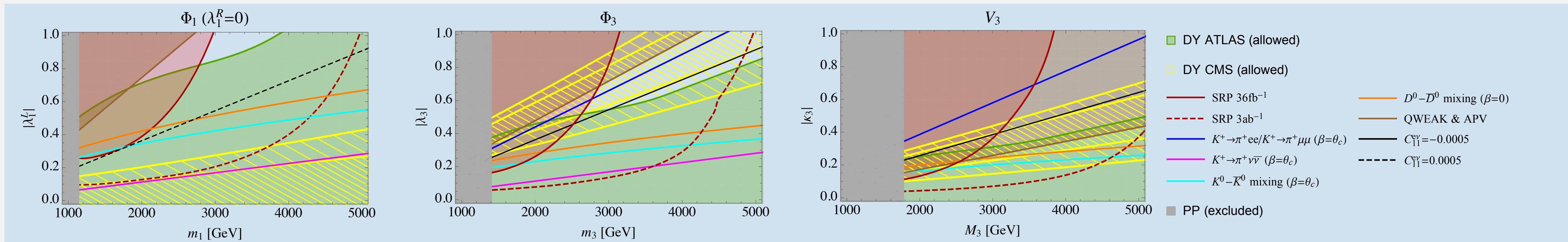
**Figure 2:** Feynman diagrams showing the high-energy search channels for first generation LQs at the LHC.

## 4 Phenomenological Analysis

### Low Energy Precision Observables

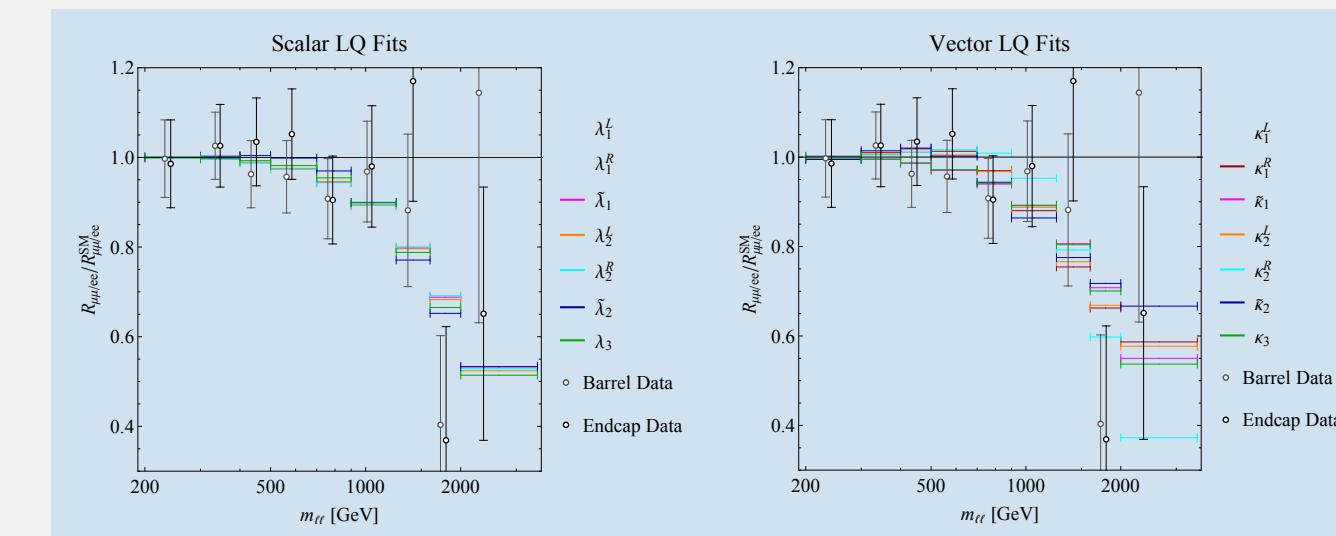
- The **CAA** could be explained by contributions from  $\Phi_3, V_3$ . However, DY searches as well as the meson mixing constraints exclude sizeable contributions  $C_{11}^{e\nu}$  (black lines in Figure 4).
- The **neutral current and meson mixing limits** (blue, cyan and orange lines in Figure 4) depend on the angle  $\beta$  relating left-handed down-type quark flavor and mass eigenstates.

### Exclusion Plots



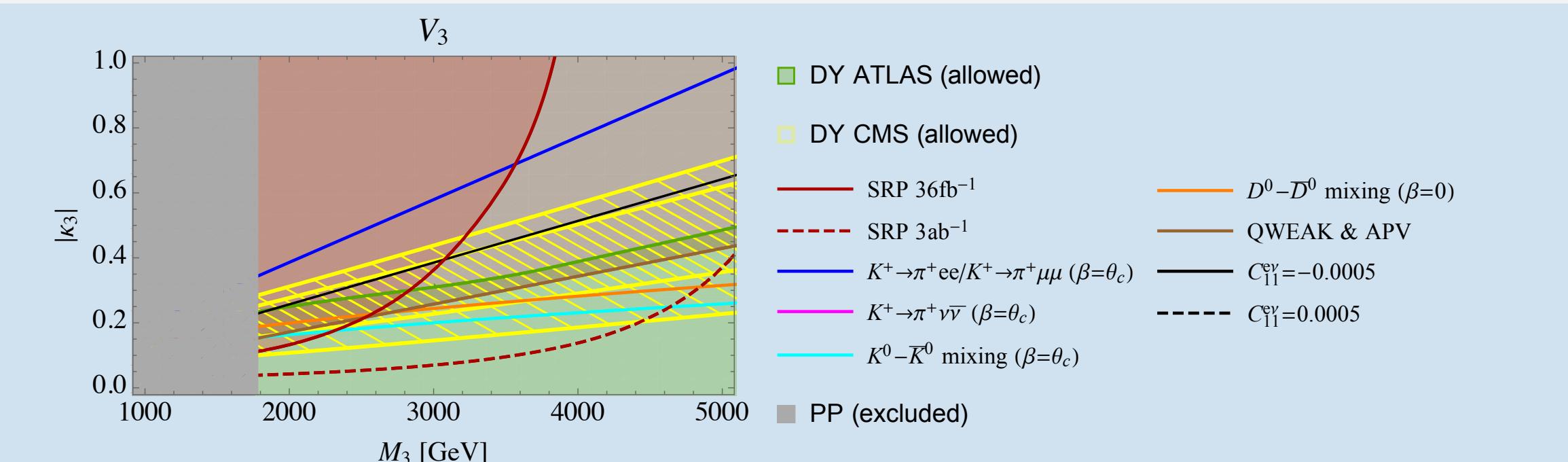
### Direct LHC Searches

- PP** (gray regions in Figure 4) sets coupling independent limits on the LQ masses.
- The excess in electron pairs found in **CMS' non-resonant DY analysis** (yellow regions in Figure 4) prefers the LQ representations  $\tilde{\Phi}_1, \Phi_2, \Phi_3, \tilde{V}_1, V_2$  ( $\kappa_2^{RL} \neq 0$ ) and  $V_3$  interfering constructively with the SM.



**Figure 3:** Ratio  $R_{\mu\mu/ee}/R_{\mu\mu/ee}^{\text{SM}}$  for  $R_{\mu\mu/ee} = (d\sigma(q\bar{q} \rightarrow \mu\bar{\mu})/dm_{\mu\mu})/(d\sigma(q\bar{q} \rightarrow e\bar{e})/dm_{ee})$  given as a function of the invariant di-lepton mass  $m_{\ell\ell}$ . The CMS measurements (black and gray points) prefer the LQ fits (colored lines) over the SM solution (black line at 1.0) [1].

- ATLAS' non-resonant DY bounds** (green regions in Figure 4) are more constraining than the resonant DY searches.



## 5 Conclusions

- We performed a combined analysis of constraints on first generation LQs, including both low energy precision observables and direct searches.
- The **CAA** could be explained by  $\Phi_3$ ,  $V_3$ , but the size of this effect is too constrained by DY and the meson mixing.
- The **non-resonant DY** analysis of ATLAS gives stringent constraints on first generation LQs. The representations  $\tilde{\Phi}_1$ ,  $\Phi_2$ ,  $\tilde{V}_1$ ,  $V_2$  ( $\kappa_2^{RL} \neq 0$ ) and  $V_3$  can account for the di-electron excess found in the CMS non-resonant DY analysis without violating other bounds.

## References

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