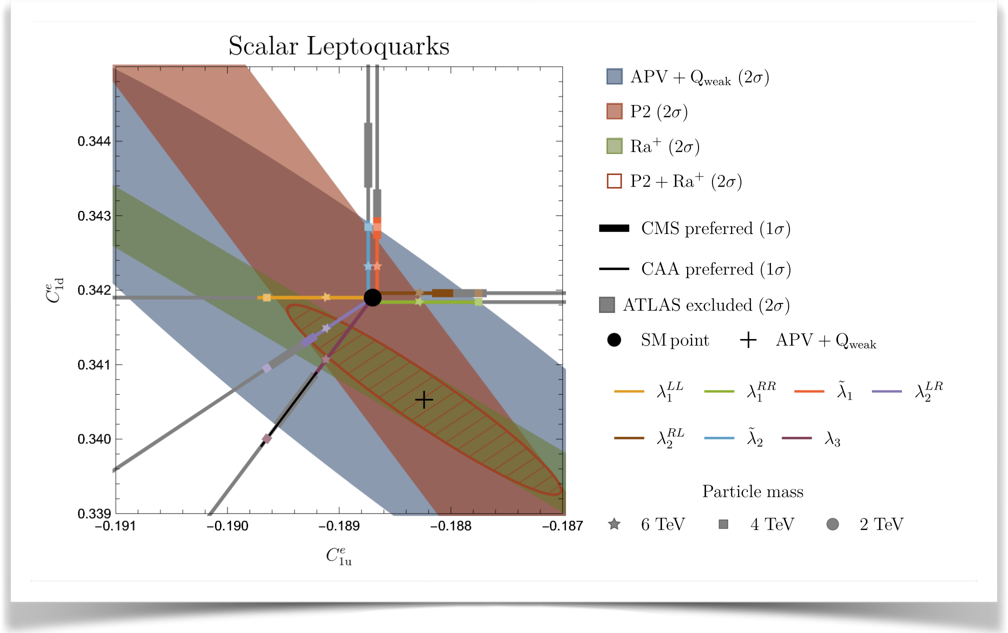
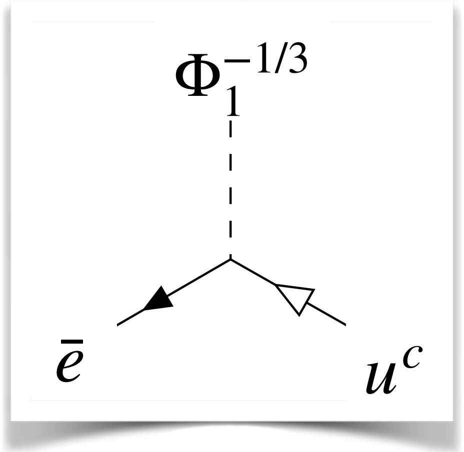
Based on
arXiv:2101.07811
arXiv:2104.06417
arXiv:2105.04844
arXiv:2107.13569

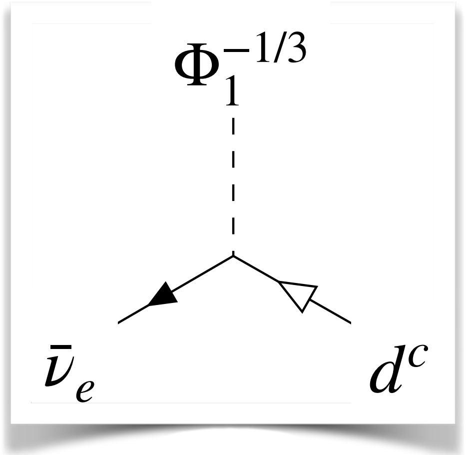
Potential Signatures and Combined Constraints for First Generation Leptoquarks

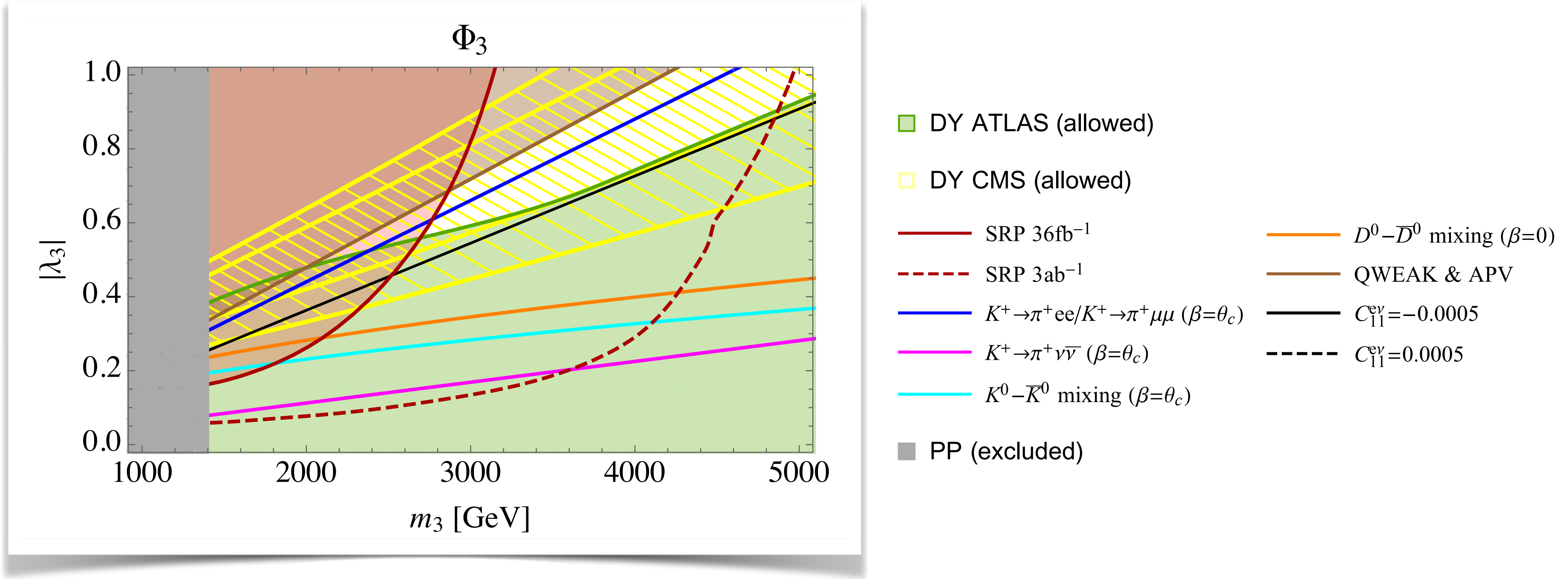
Luc Schnell

SUSY 2021
26 August 2021









1. Introduction

1.1 Flavor Anomalies

1.2 Leptoquarks

1.3 Overview

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1.1 Flavor Anomalies

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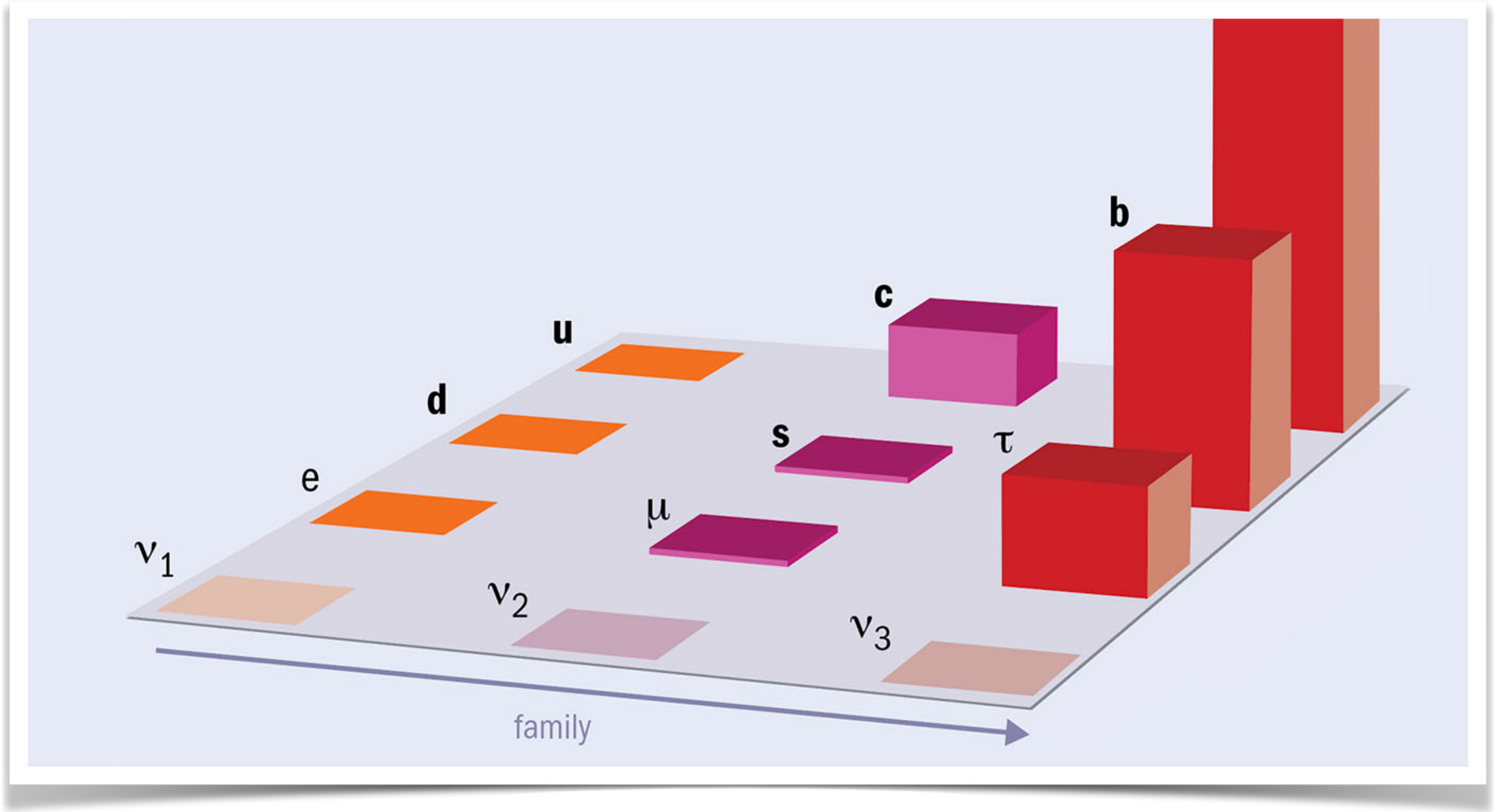

Source: https://cerncourier.com/a/who-ordered-all-of-that/

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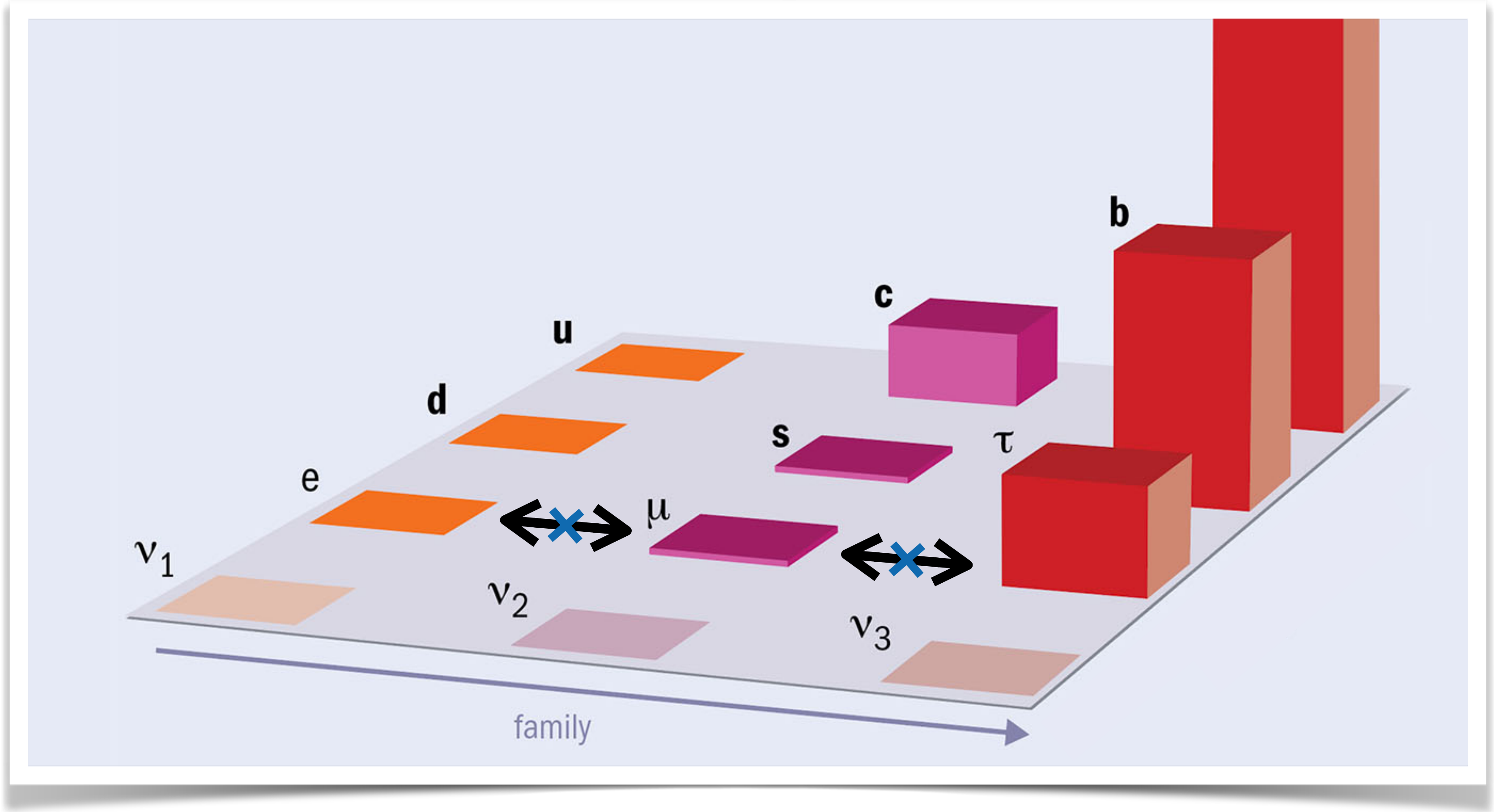

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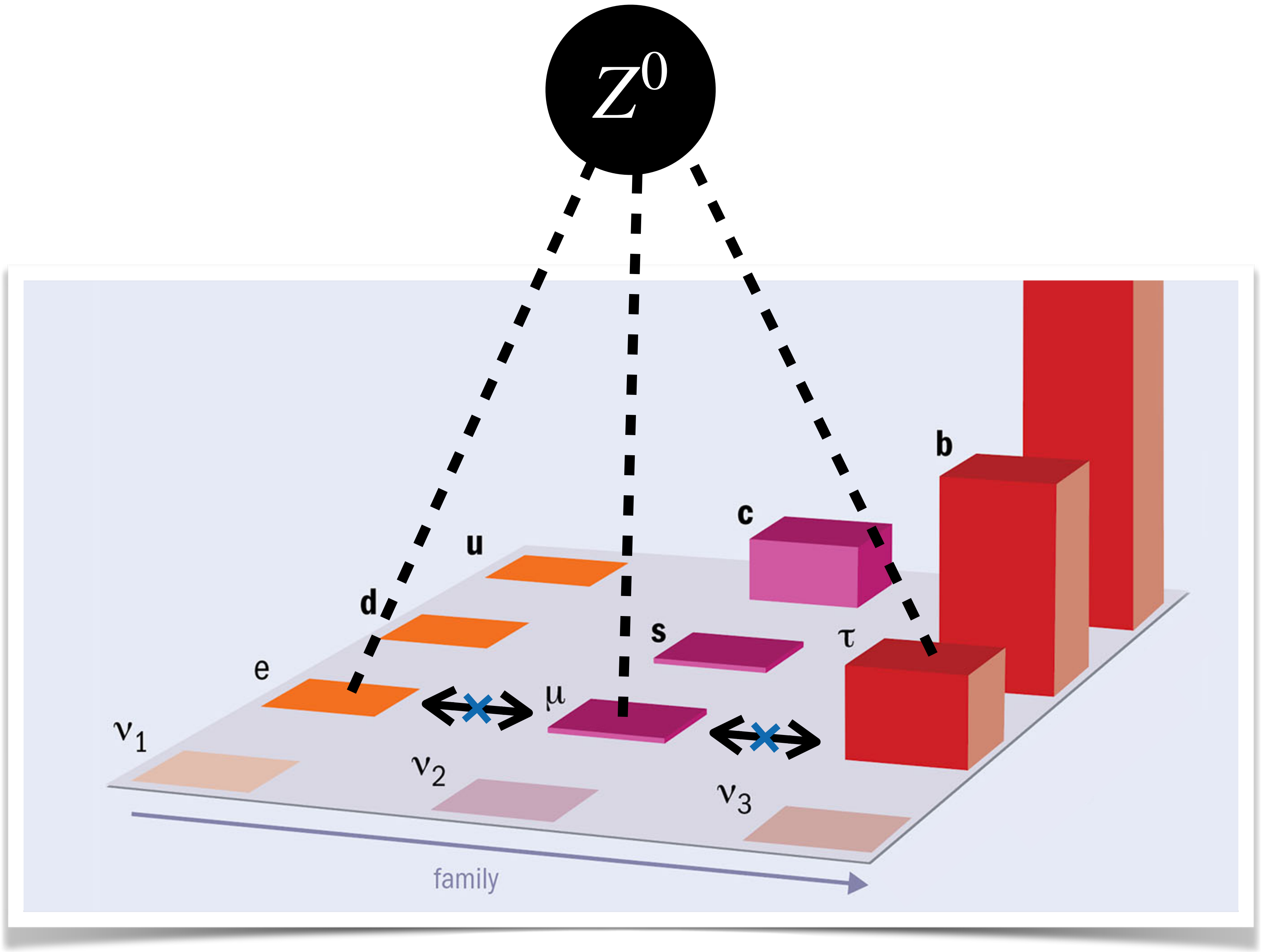

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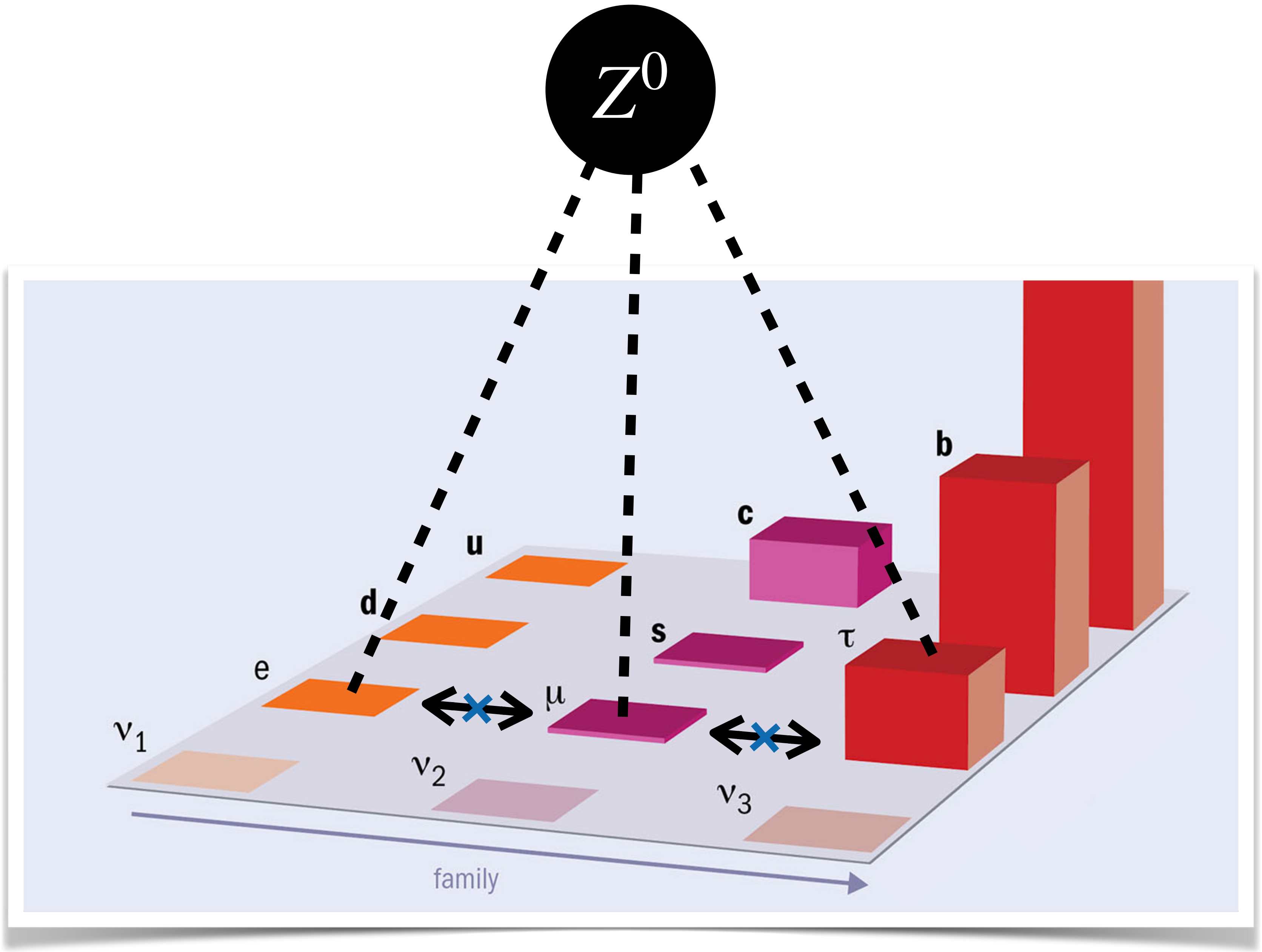

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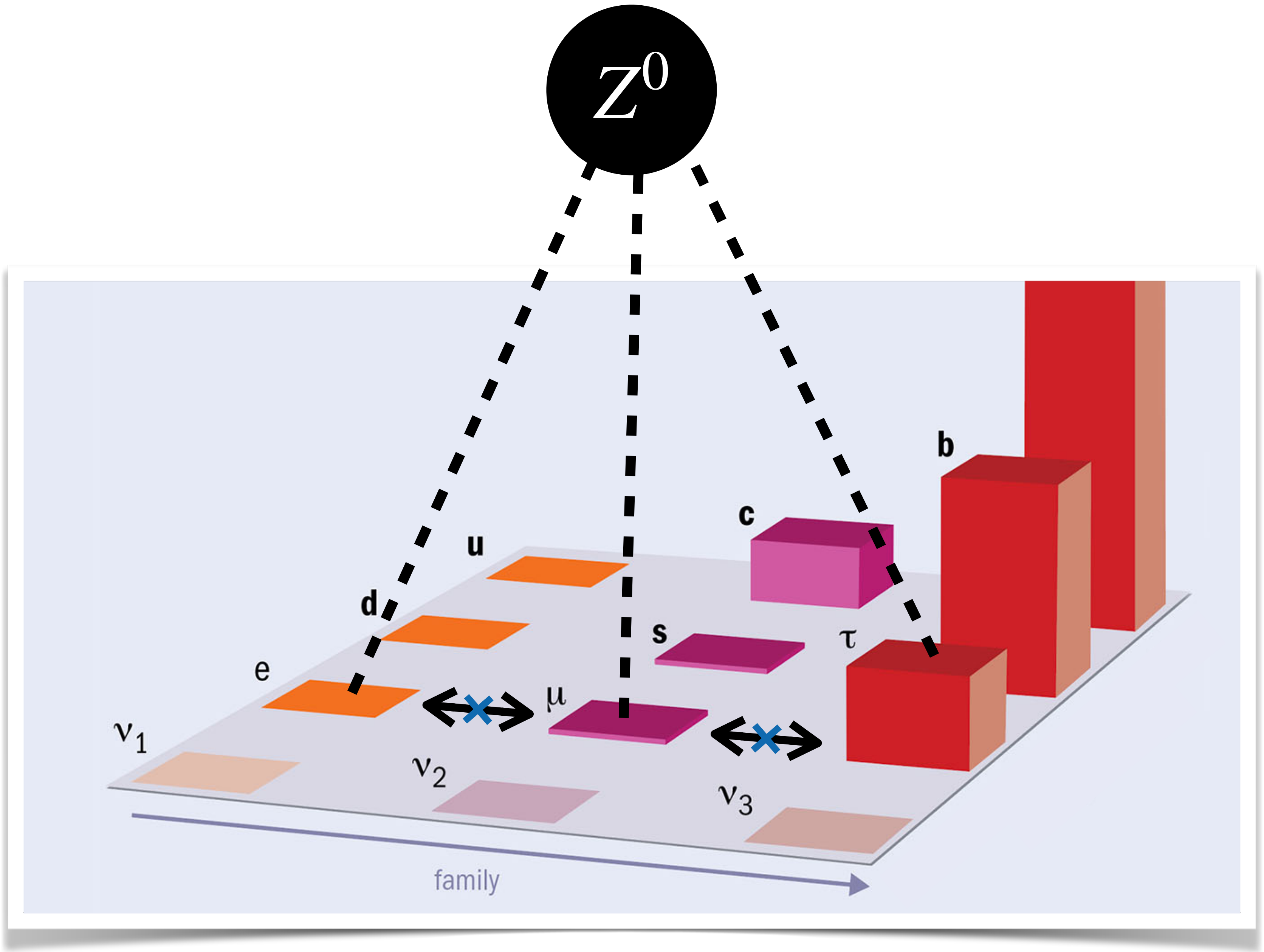

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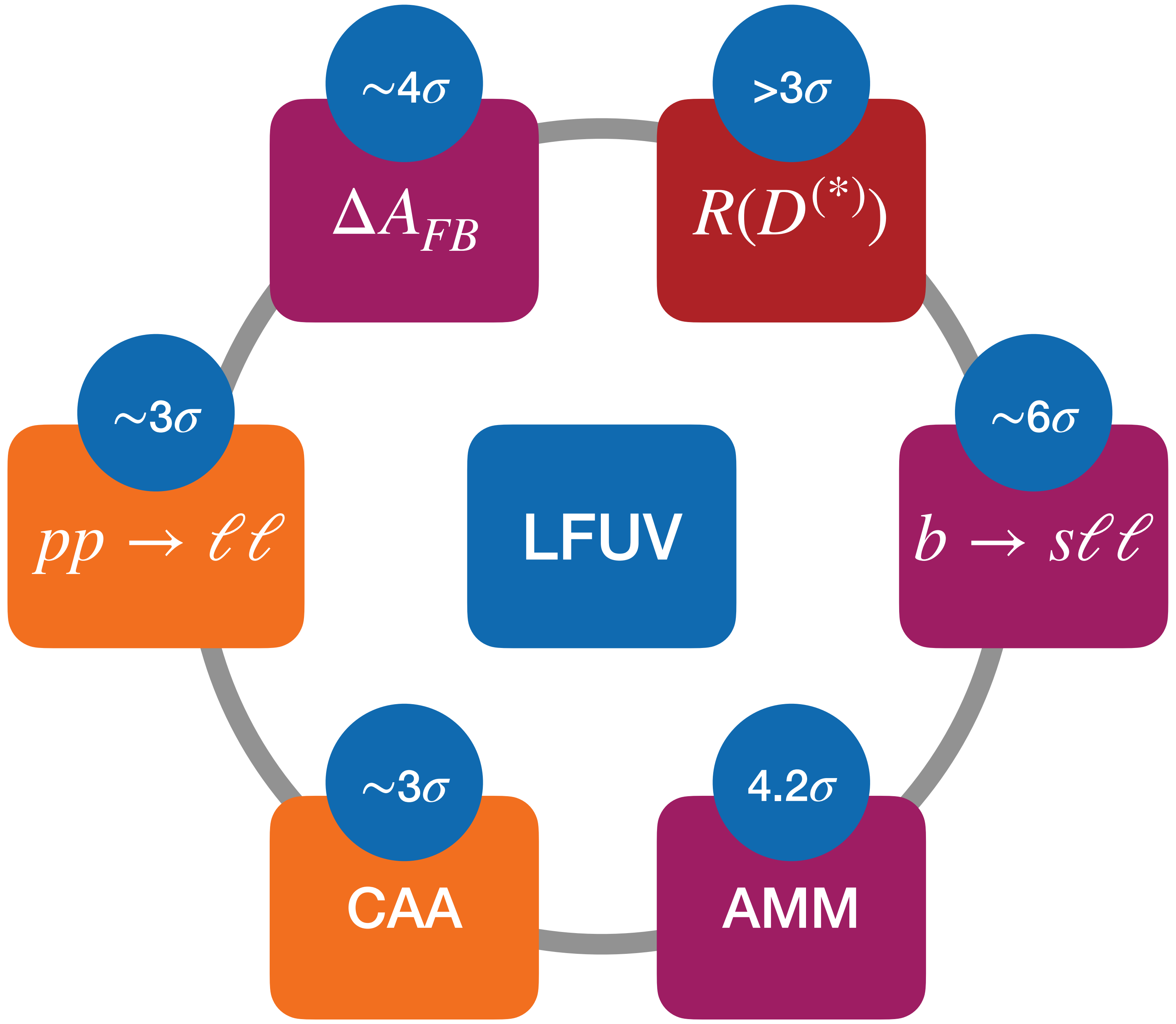

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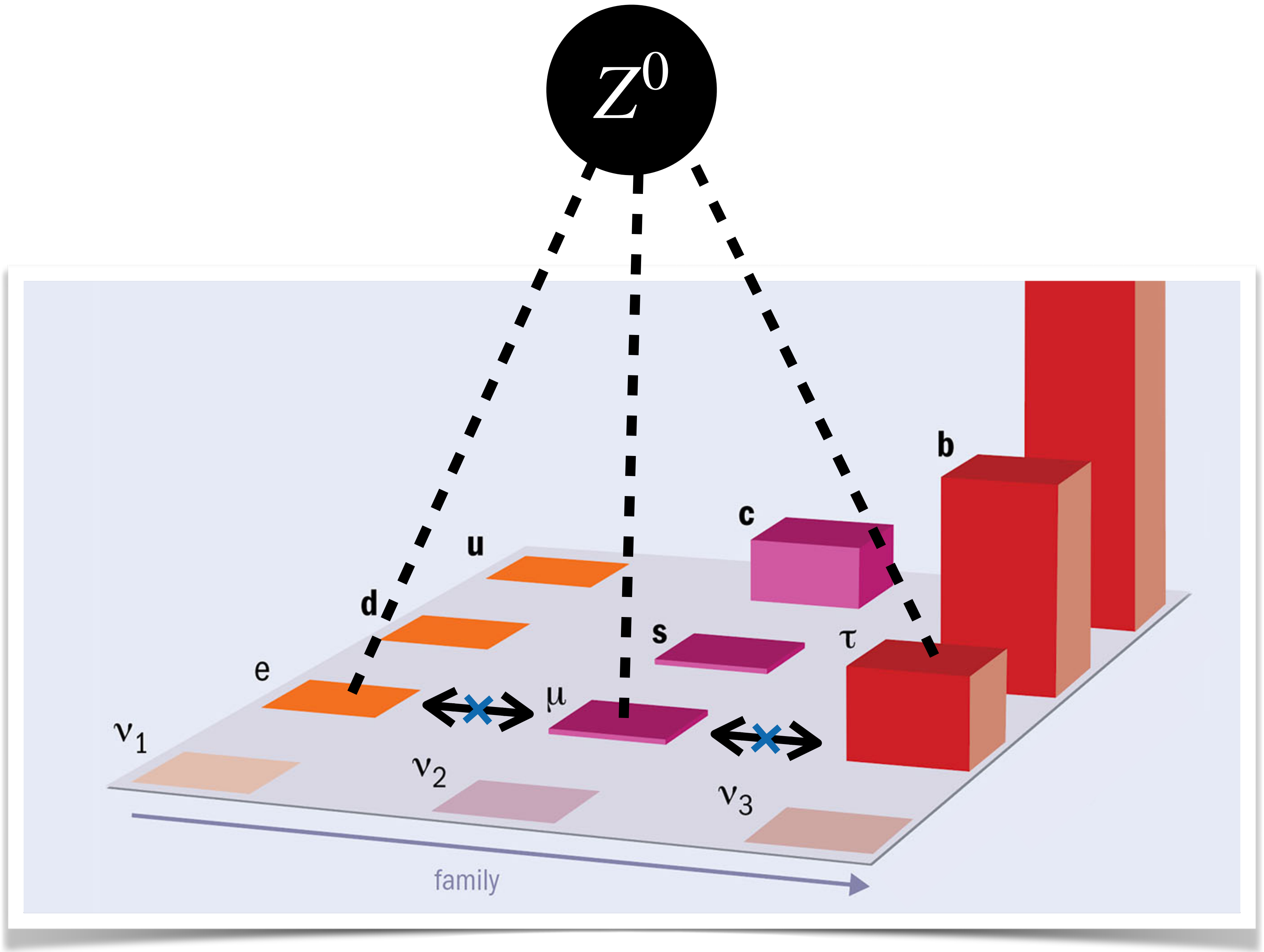

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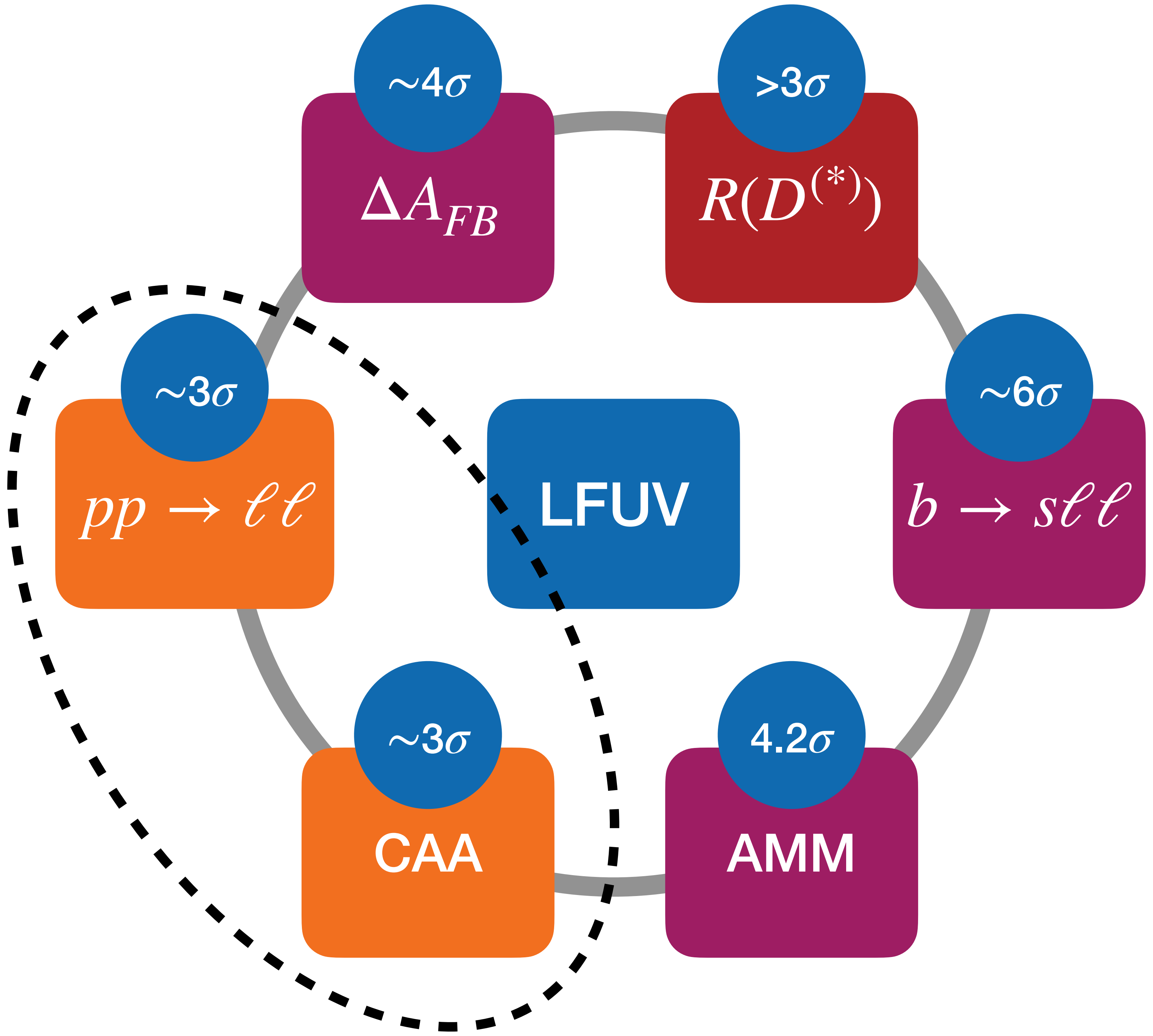

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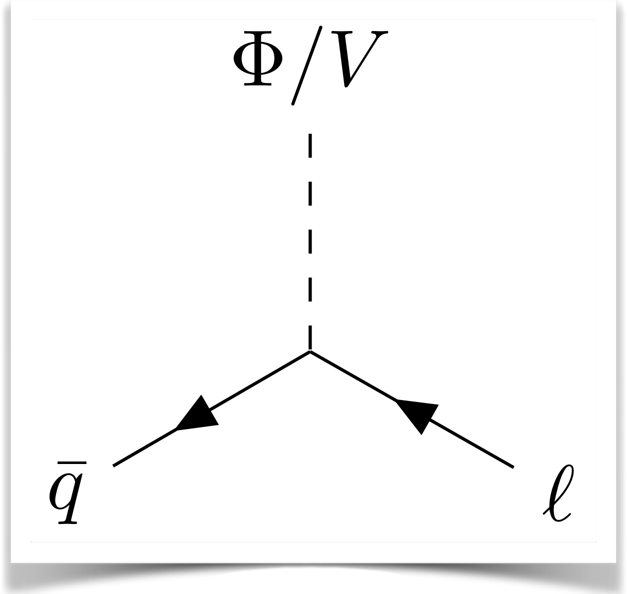
$SU(3)_c$	3	3	3	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	3	1	1	2	2	3
$U(1)_Y$	$-\frac{2}{3}$	$-\frac{8}{3}$	$\frac{7}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$\frac{10}{3}$	$-\frac{5}{3}$	$\frac{1}{3}$	$\frac{4}{3}$



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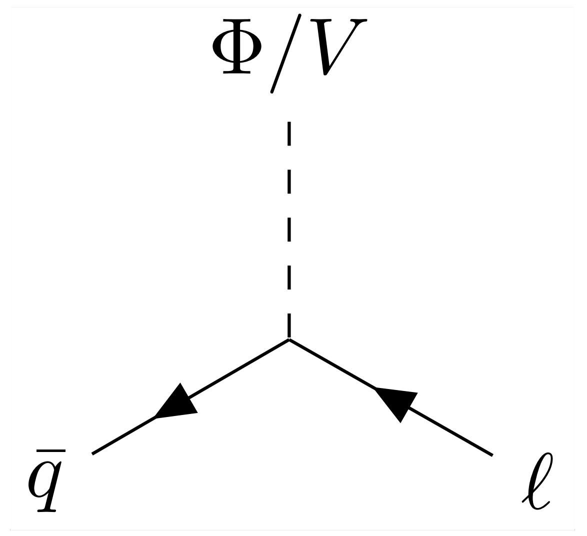

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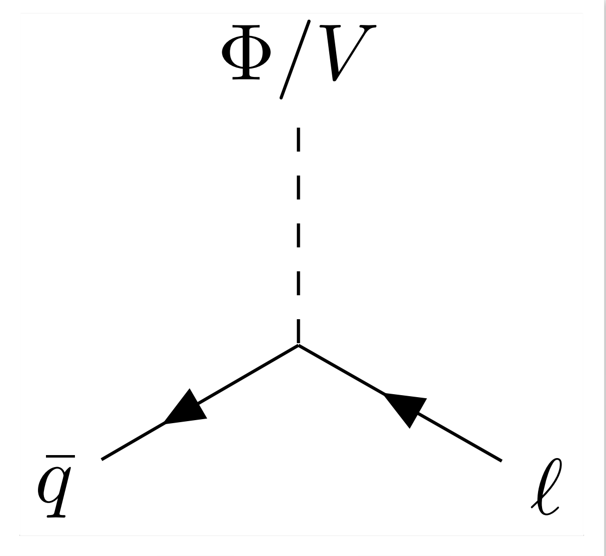

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- If the couplings to the individual SM fermion generations are different, LQs generate **LFUV**. Experimentally, we have the highest sensitivity to LQs interacting with **first generation fermions**.

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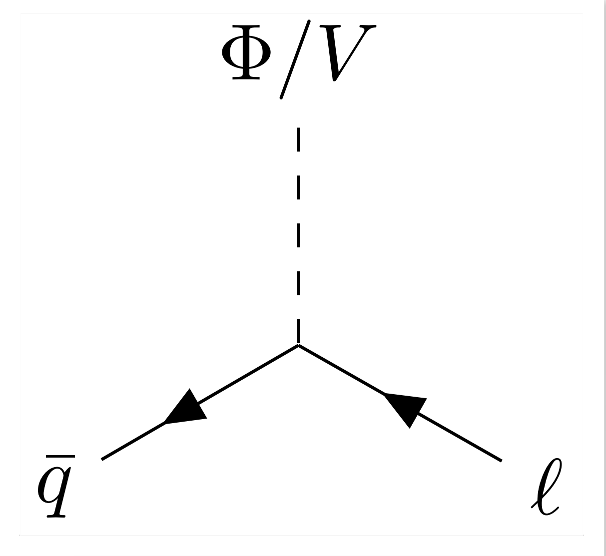

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2. First Generation LQs

2.1 Lagrangian

2.2 Weak Eigenstates → Mass Eigenstates

2. First Generation LQs

2.1 Lagrangian

Interactions with SM fermions:

2. First Generation LQs

2.1 Lagrangian

Interactions with SM fermions:

	L	e
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First generation weak eigenstates

Papers: arXiv:2101.07811, arXiv:2105.04844

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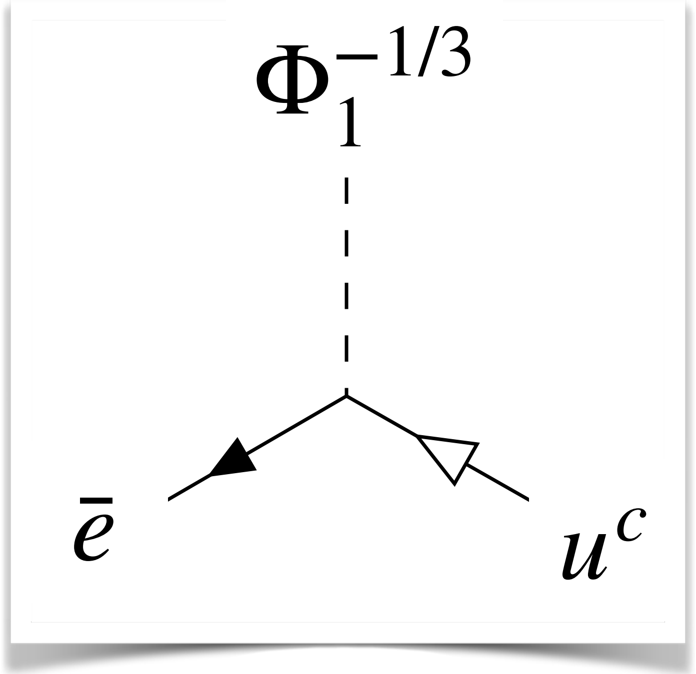
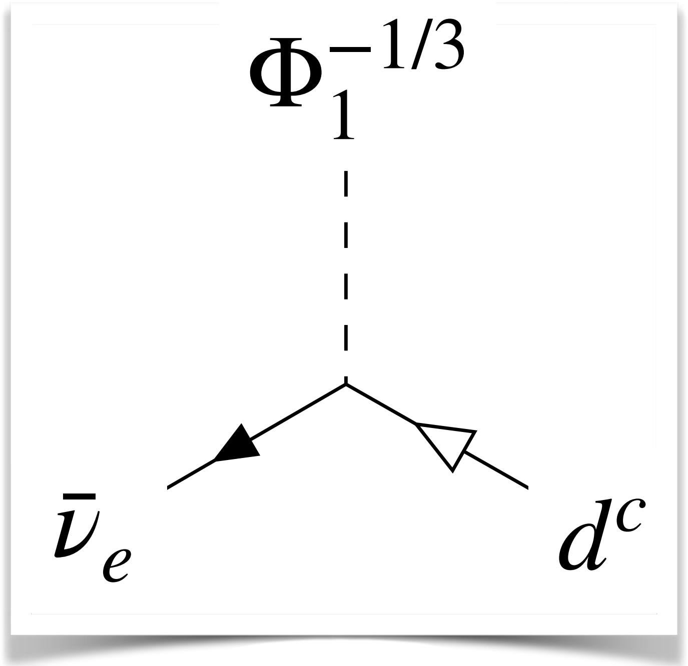
First generation weak eigenstates





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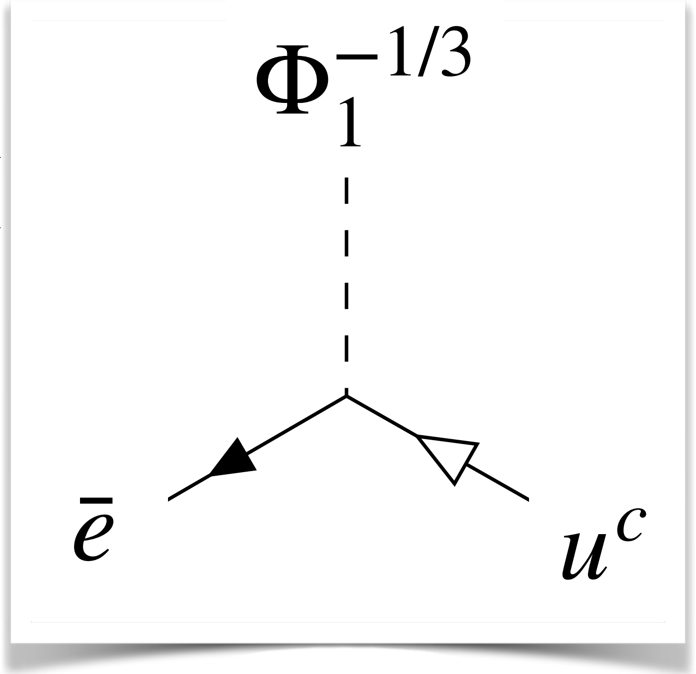

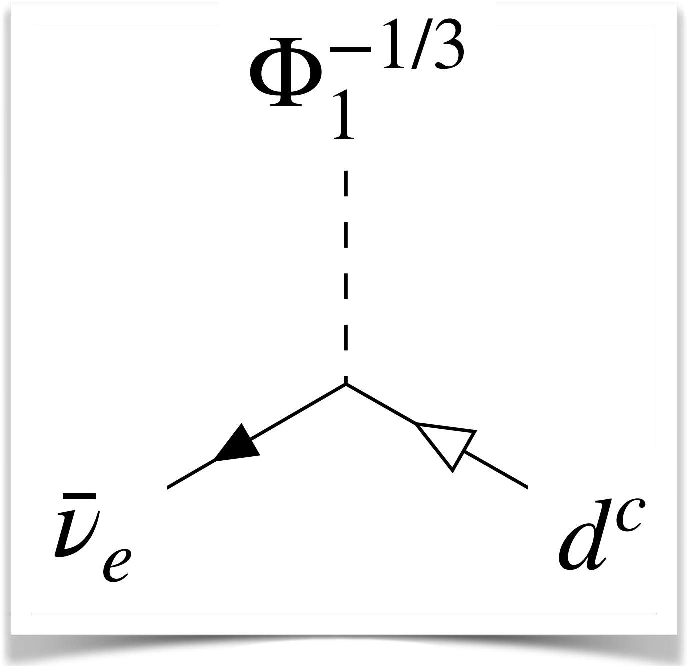

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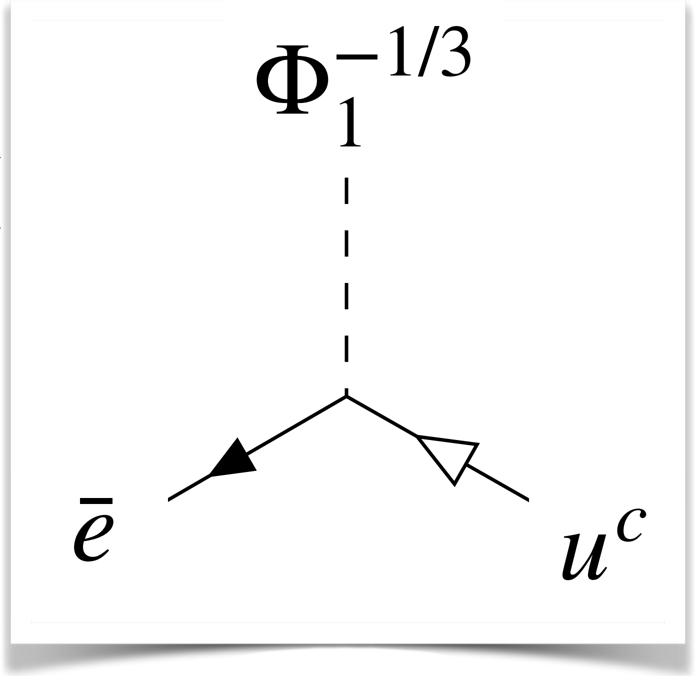

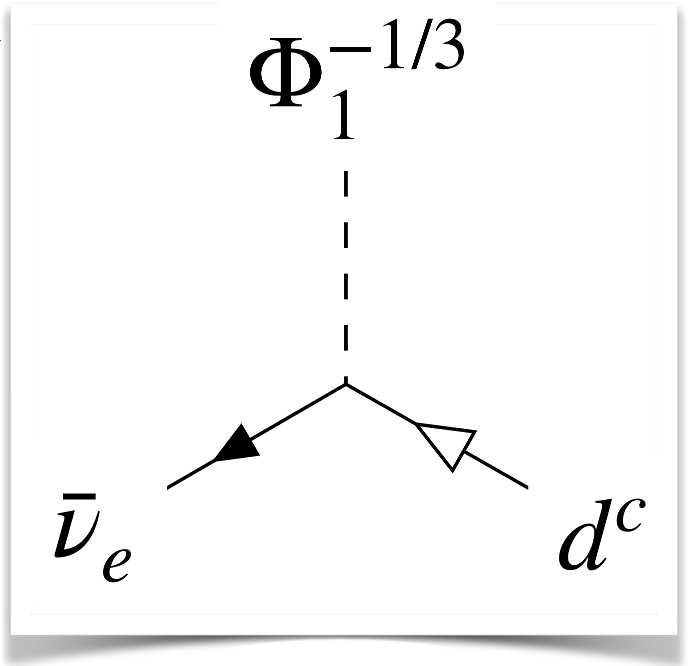

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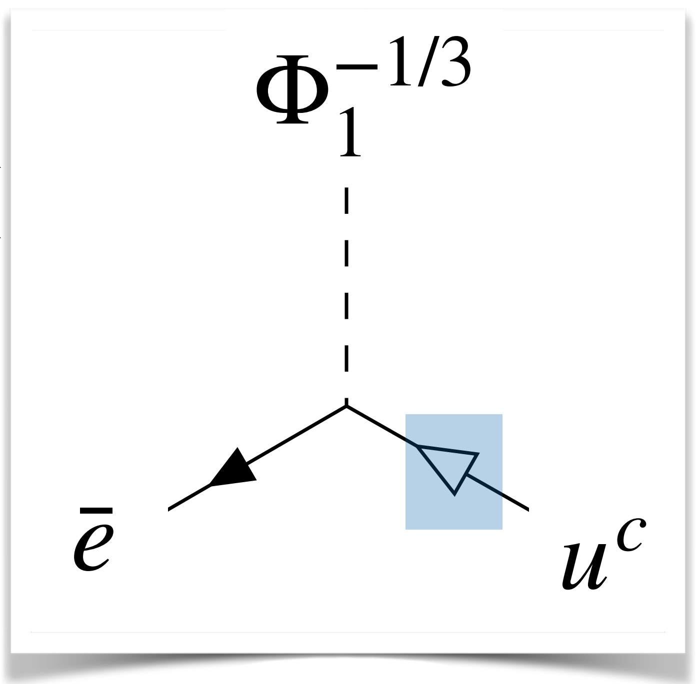

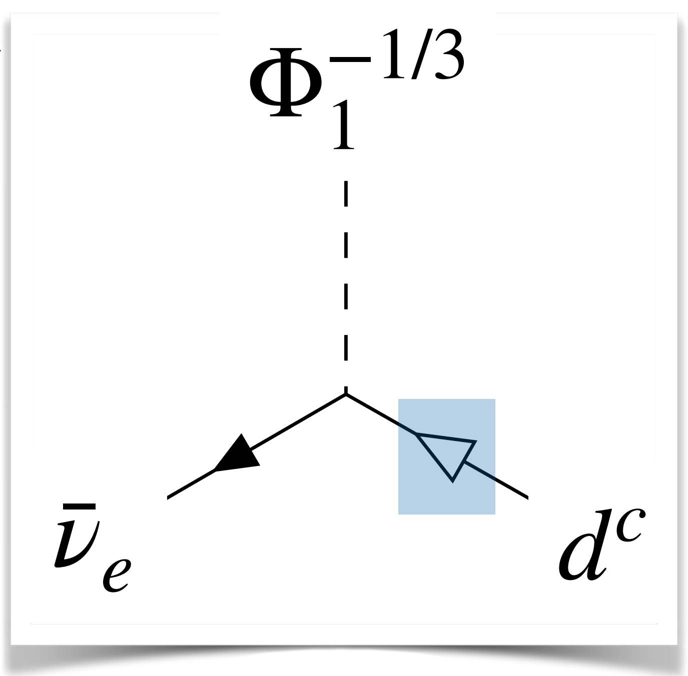

2. First Generation LQs

2.1 Lagrangian

Feynman rules:

2. First Generation LQs

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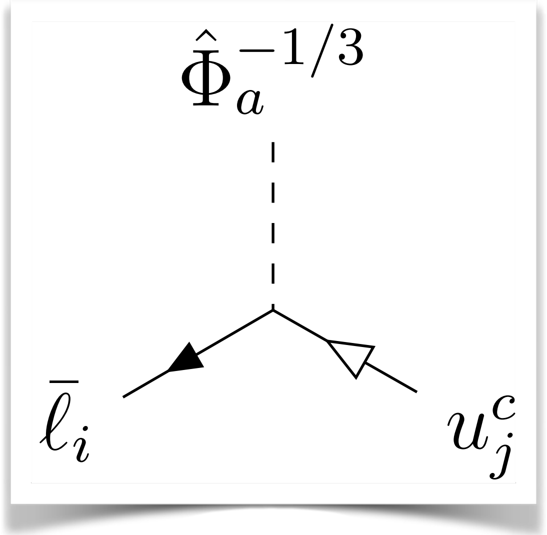

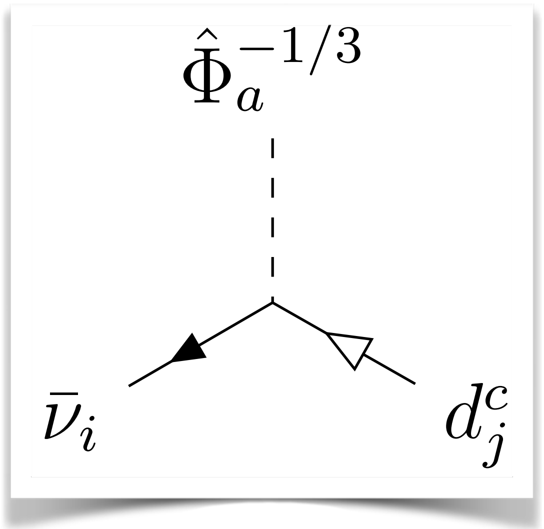

Feynman rules:

- We recently published the **complete Lagrangian and set of Feynman rules** for the scalar LQs, including
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2. First Generation LQs

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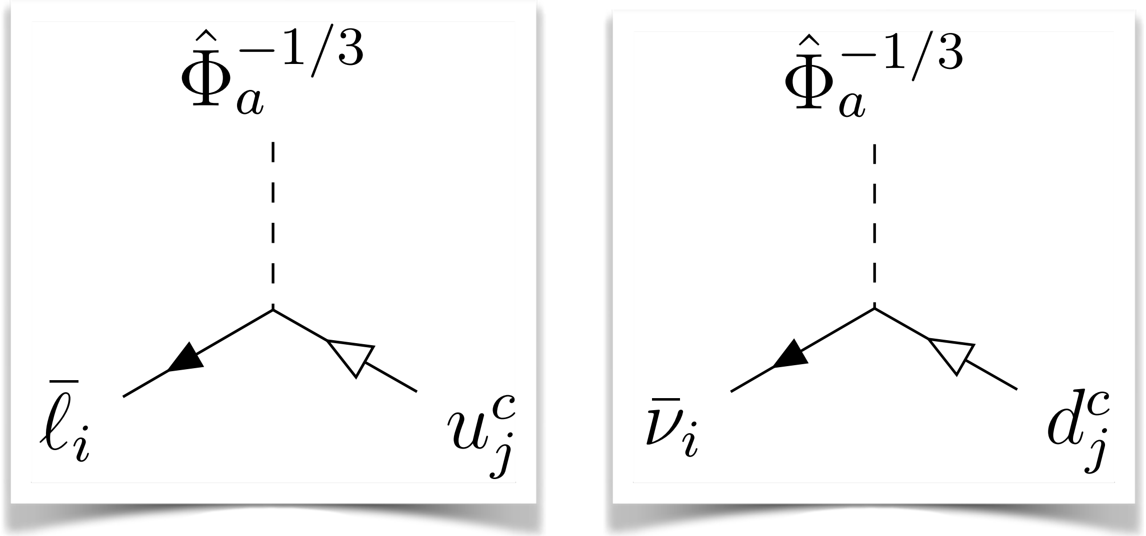

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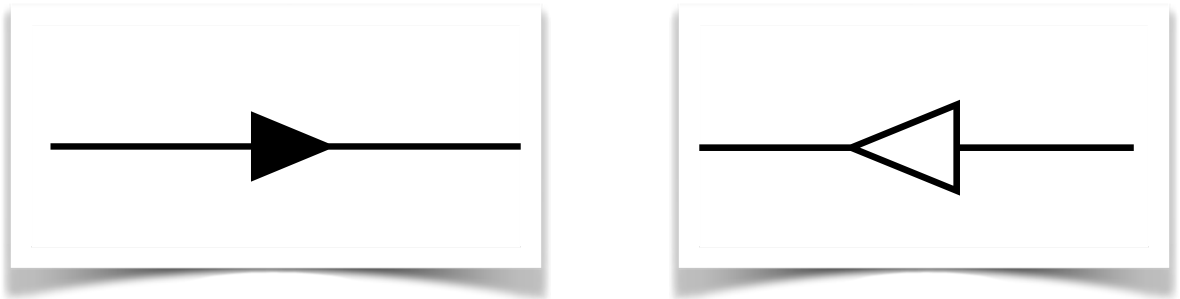
- They feature a **novel representation of interactions involving charge-conjugated fermions.**

A. Denner, H.Eck, O.Hahn, J. Küblbeck (Denner:1992vza)

$$\bar{\psi}_1 \Gamma \psi_2 = \bar{\psi}_2^c \Gamma' \psi_1^c$$



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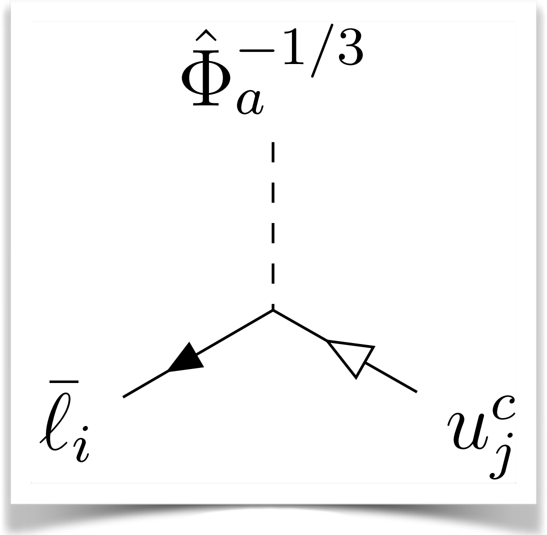
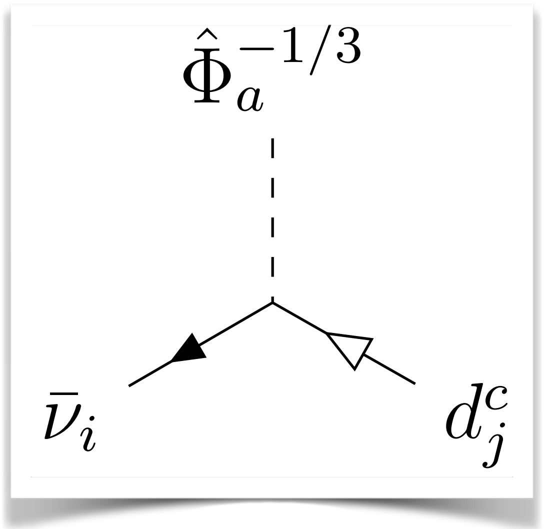




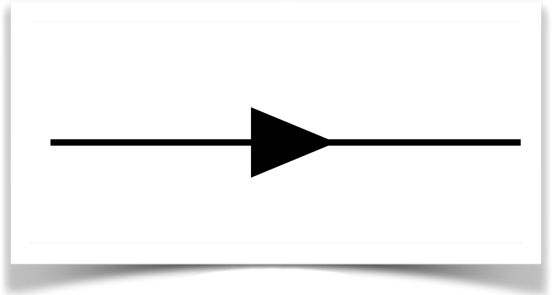
Feynman rules:

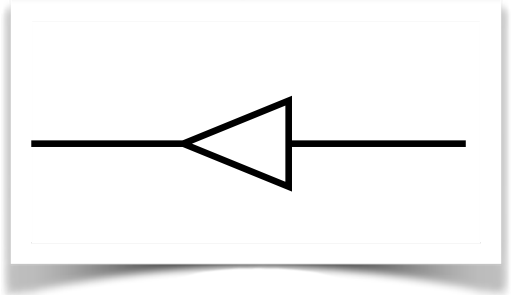
- We recently published the **complete Lagrangian and set of Feynman rules** for the scalar LQs, including
  - Interactions with SM fermions, gauge bosons and the Higgs
  - LQ-LQ-Higgs(-Higgs), LQ-LQ-LQ(-Higgs) and LQ-LQ-LQ-LQ **self-interactions**.

- They feature a **novel representation of interactions involving charge-conjugated fermions.**

A. Denner, H.Eck, O.Hahn, J. Küblbeck (Denner:1992vza)

$$\bar{\psi}_1 \Gamma \psi_2 = \bar{\psi}_2^c \Gamma' \psi_1^c$$





- We provide a **FeynRules model file** that allows for exports to FeynArts and MadGraph5_aMC@NLO, constituting a powerful tool for **for the automatization of scalar LQ phenomenology studies**.

2. First Generation LQs

2.2 Weak Eigenstates → Mass Eigenstates

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$$U^{uL} = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{pmatrix}$$
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	$C_{\ell q}^{(1)}$	$C_{\ell q}^{(3)}$	C_{qe}	$C_{\ell u}$	$C_{\ell d}$	C_{eu}	C_{ed}
Φ_1	$\frac{\lvert\lambda_1^L\rvert^2}{4m_1^2}$	$-\frac{\lvert\lambda_1^L\rvert^2}{4m_1^2}$	$*$	$*$	$*$	$\frac{\lvert\lambda_1^R\rvert^2}{2m_1^2}$	$*$
$\tilde{\Phi}_1$	$*$	$*$	$*$	$*$	$*$	$*$	$\frac{\lvert\tilde{\lambda}_1\rvert^2}{2\tilde{m}_1^2}$
Φ_2	$*$	$*$	$-\frac{\lvert\lambda_2^{LR}\rvert^2}{2m_2^2}$	$-\frac{\lvert\lambda_2^{RL}\rvert^2}{2m_2^2}$	$*$	$*$	$*$
$\tilde{\Phi}_2$	$*$	$*$	$*$	$*$	$-\frac{\lvert\tilde{\lambda}_2\rvert^2}{2\tilde{m}_2^2}$	$*$	$*$
Φ_3	$\frac{3\lvert\lambda_3^2\rvert}{4m_3^2}$	$\frac{\lvert\lambda_3^2\rvert}{4m_3^2}$	$*$	$*$	$*$	$*$	$*$
V_1	$-\frac{\lvert\kappa_1^L\rvert^2}{2M_1^2}$	$-\frac{\lvert\kappa_1^L\rvert^2}{2M_1^2}$	$*$	$*$	$*$	$*$	$-\frac{\lvert\kappa_1^R\rvert^2}{M_1^2}$
$\tilde{V}_1$	$*$	$*$	$*$	$*$	$*$	$-\frac{\lvert\tilde{\kappa}_1\rvert^2}{\tilde{M}_1^2}$	$*$

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$\tilde{\Phi}_1$	*	*	*	*	*	*	$\frac{\lvert\tilde{\lambda}_1\rvert^2}{2\tilde{m}_1^2}$
Φ_2	*	*	$-\frac{\lvert\lambda_2^{LR}\rvert^2}{2m_2^2}$	$-\frac{\lvert\lambda_2^{RL}\rvert^2}{2m_2^2}$	*	*	*
$\tilde{\Phi}_2$	*	*	*	*	$-\frac{\lvert\tilde{\lambda}_2\rvert^2}{2\tilde{m}_2^2}$	*	*
Φ_3	$\frac{3\lvert\lambda_3^2\rvert}{4m_3^2}$	$\frac{\lvert\lambda_3^2\rvert}{4m_3^2}$	*	*	*	*	*
V_1	$-\frac{\lvert\kappa_1^L\rvert^2}{2M_1^2}$	$-\frac{\lvert\kappa_1^L\rvert^2}{2M_1^2}$	*	*	*	*	$-\frac{\lvert\kappa_1^R\rvert^2}{M_1^2}$
$\tilde{V}_1$	*	*	*	*	*	$-\frac{\lvert\tilde{\kappa}_1\rvert^2}{\tilde{M}_1^2}$	*

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$\tilde{V}_1$	$*$	$*$	$*$	$*$	$*$	$-\frac{\lvert\tilde{\kappa}_1\rvert^2}{\tilde{M}_1^2}$	$*$

4. Experimental Observables

4.1 Low-Energy Precision Observables

4.2 High-Energy Direct Searches

4. Observables

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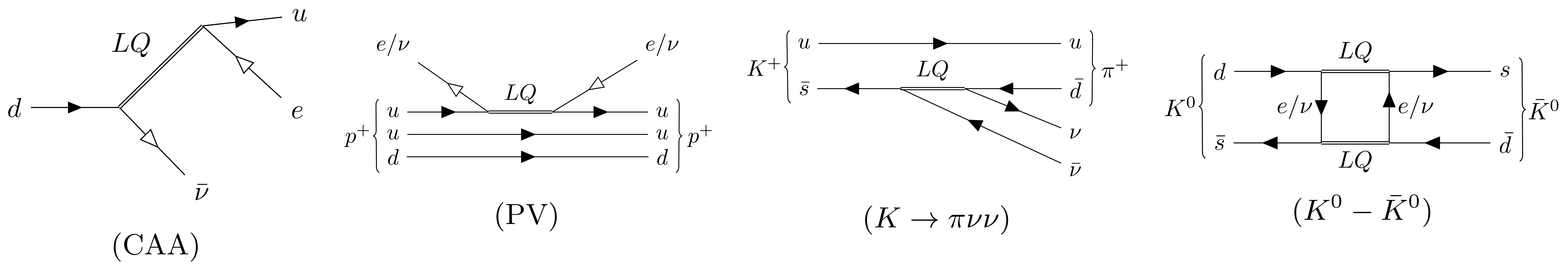

4. Observables

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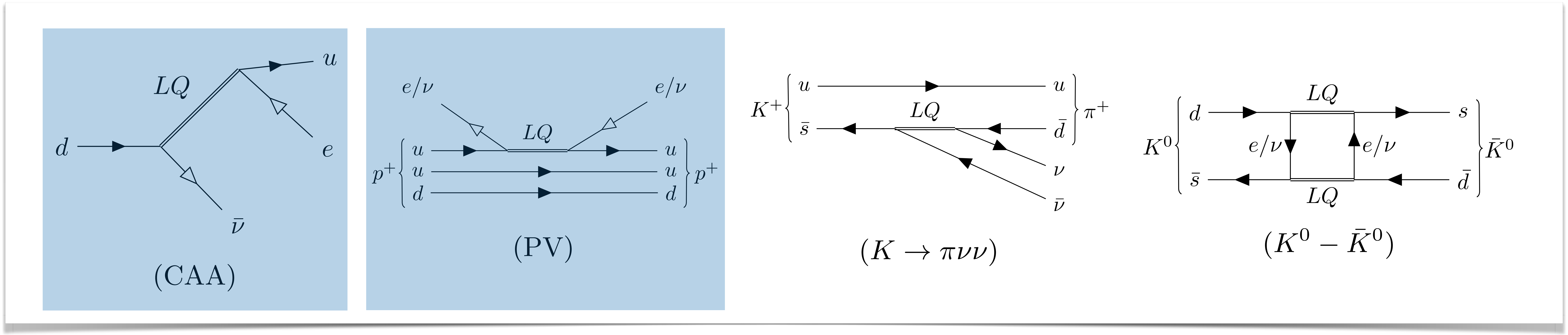

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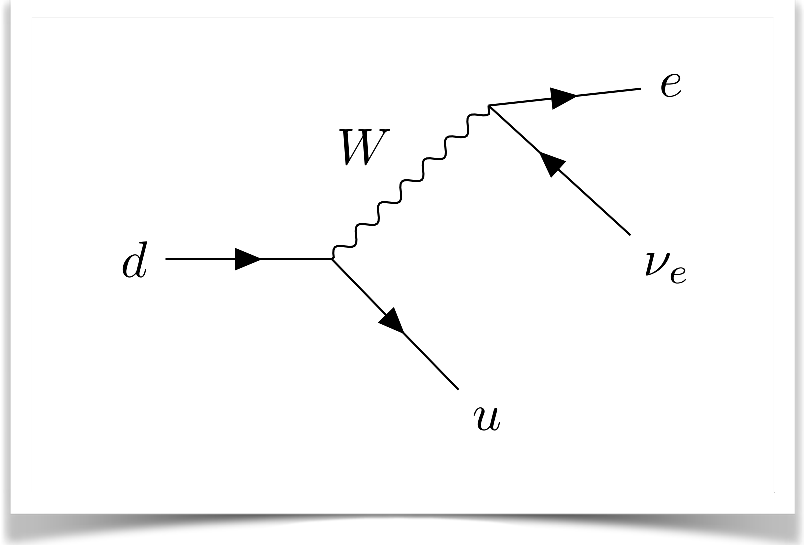

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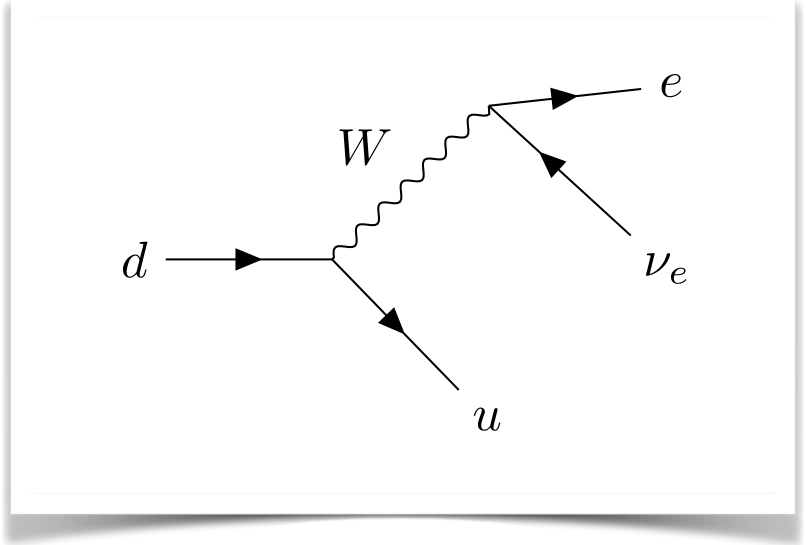

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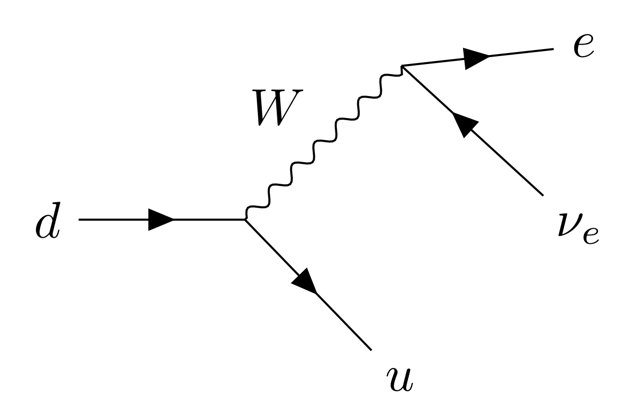

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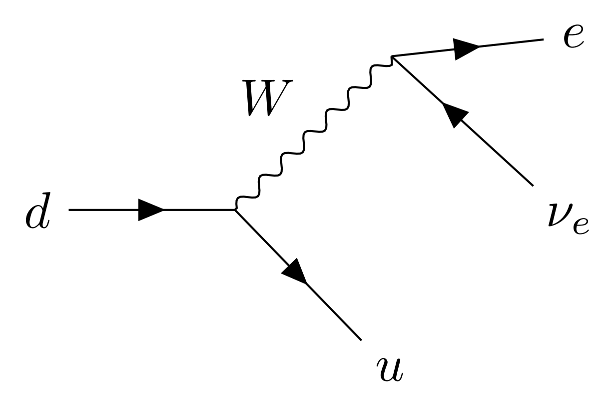

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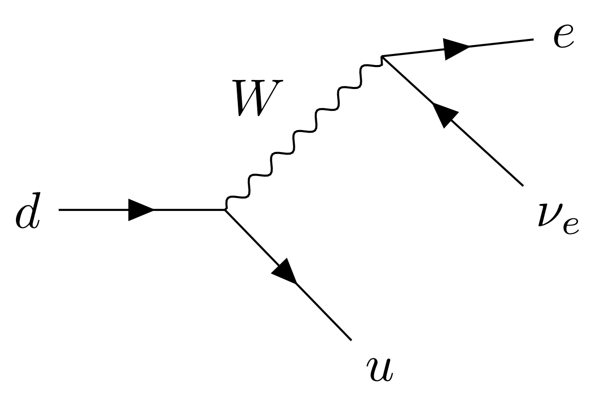

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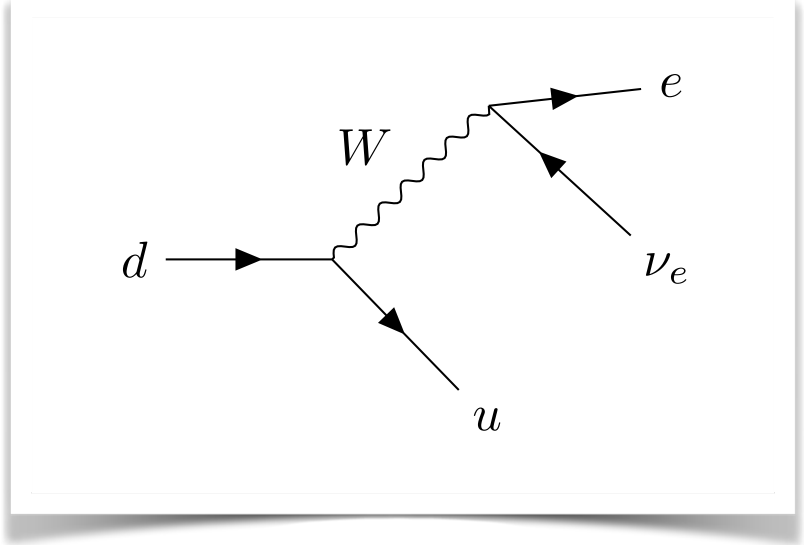

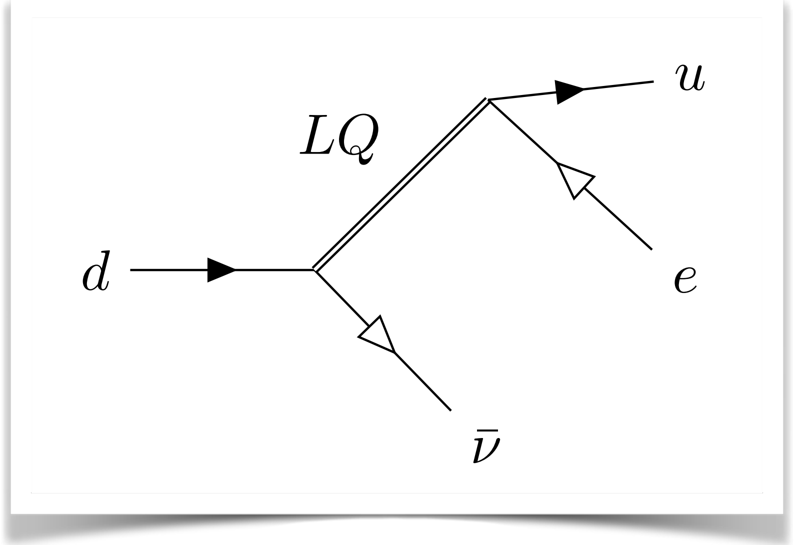

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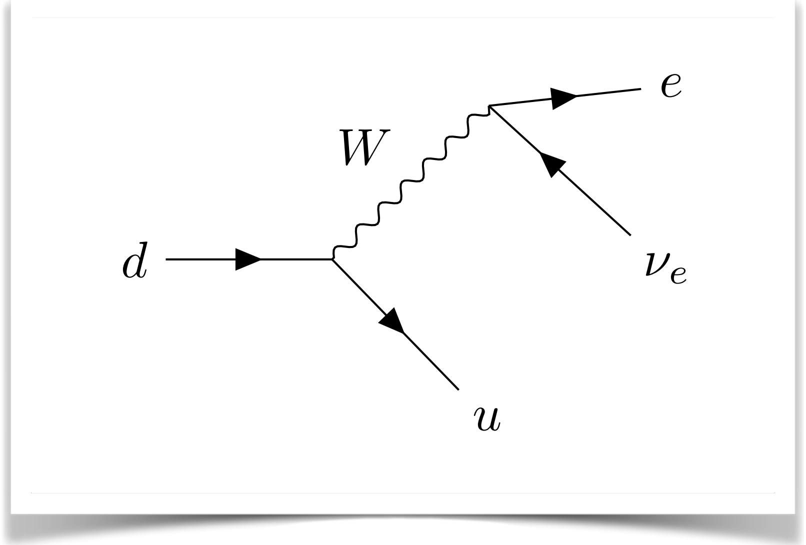

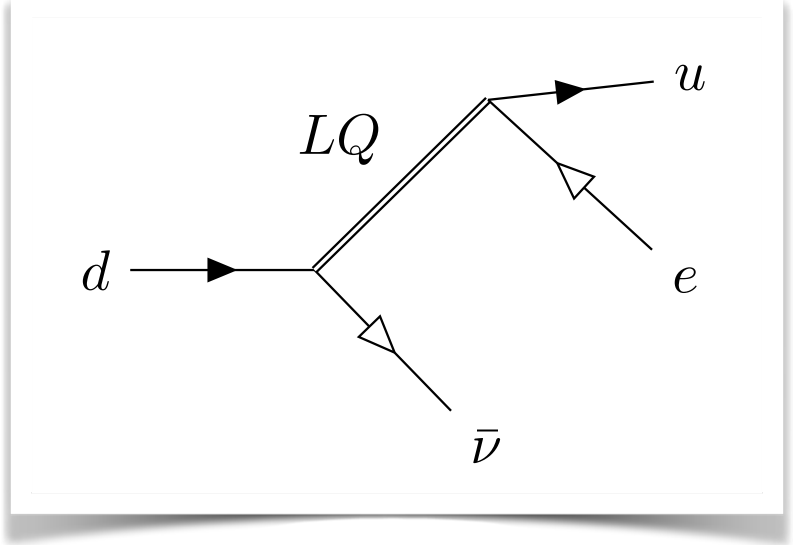

$$C_{11}^{e\nu} = \frac{-1}{\sqrt{2}G_F} \frac{c_{\beta} c_{\beta-\theta}}{V_{ud}} C_{\ell q}^{(3)}\,,$$
$$C_{12}^{e\nu} = \frac{-1}{\sqrt{2}G_F} \frac{s_{\beta} c_{\beta-\theta}}{V_{us}} C_{\ell q}^{(3)}\,,$$

Paper: arXiv:2101.07811

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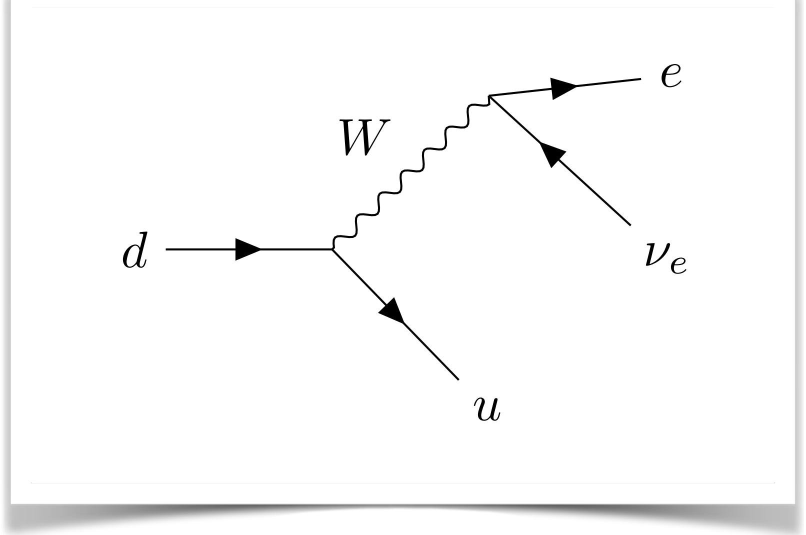

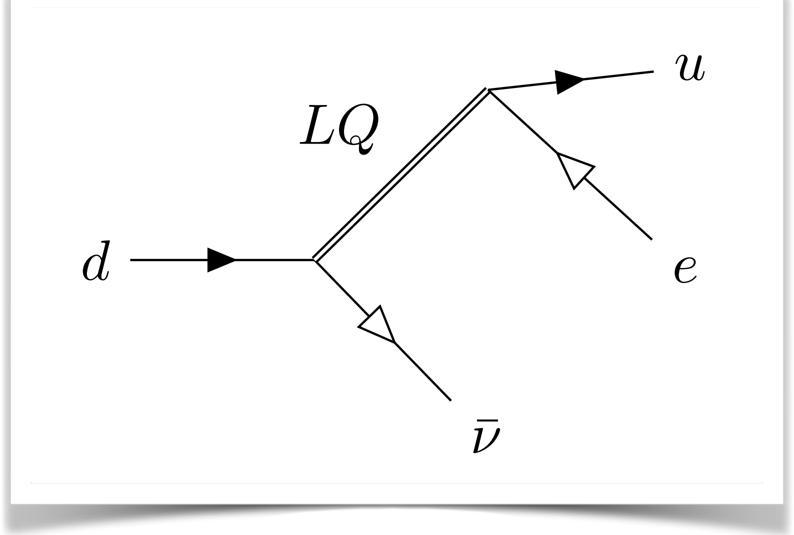

$$C_{11}^{e\nu} = \frac{-1}{\sqrt{2}G_F} \frac{c_\beta c_{\beta-\theta}}{V_{ud}} C_{\ell q}^{(3)}\,,$$
$$C_{12}^{e\nu} = \frac{-1}{\sqrt{2}G_F} \frac{s_\beta c_{\beta-\theta}}{V_{us}} C_{\ell q}^{(3)}\,,$$

$$V_{ud}^{\beta} = V_{ud}^{L}\left(1 + C_{11}^{e\nu_e}\right)$$

4. Observables

4.1 Low-Energy Precision Observables

Parity violation experiments:

4. Observables

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Paper: arXiv:2107.13569

4. Observables

4.2 High-Energy Direct Searches

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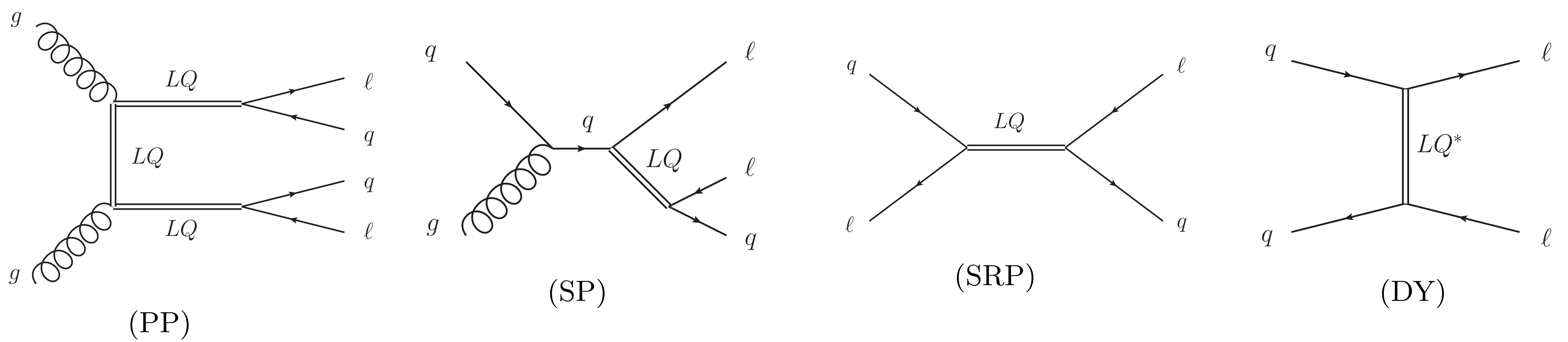

Papers: arXiv:2101.07811, arXiv:2104.06417

4. Observables

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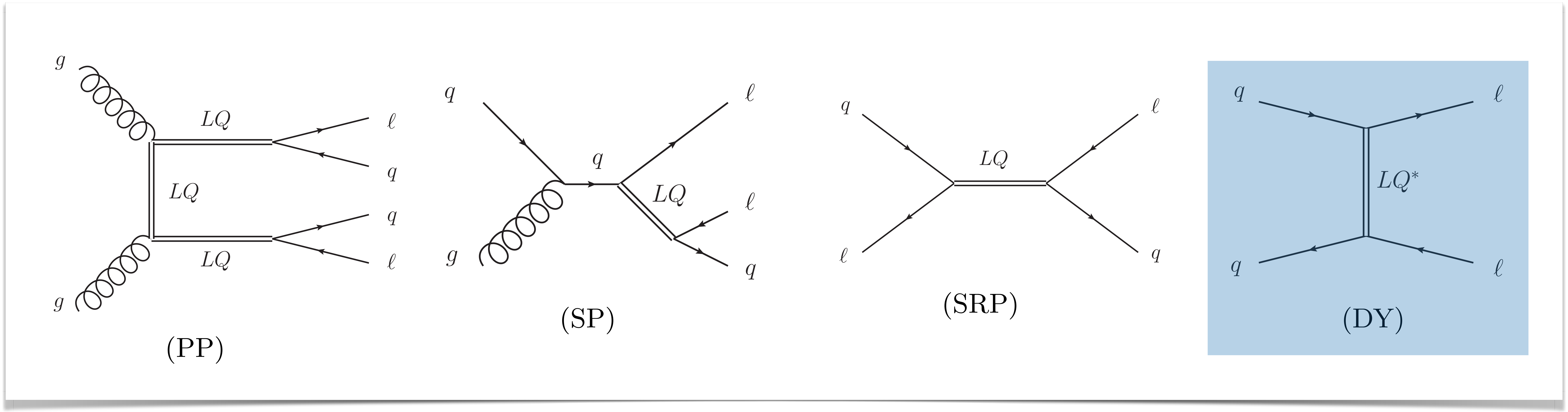

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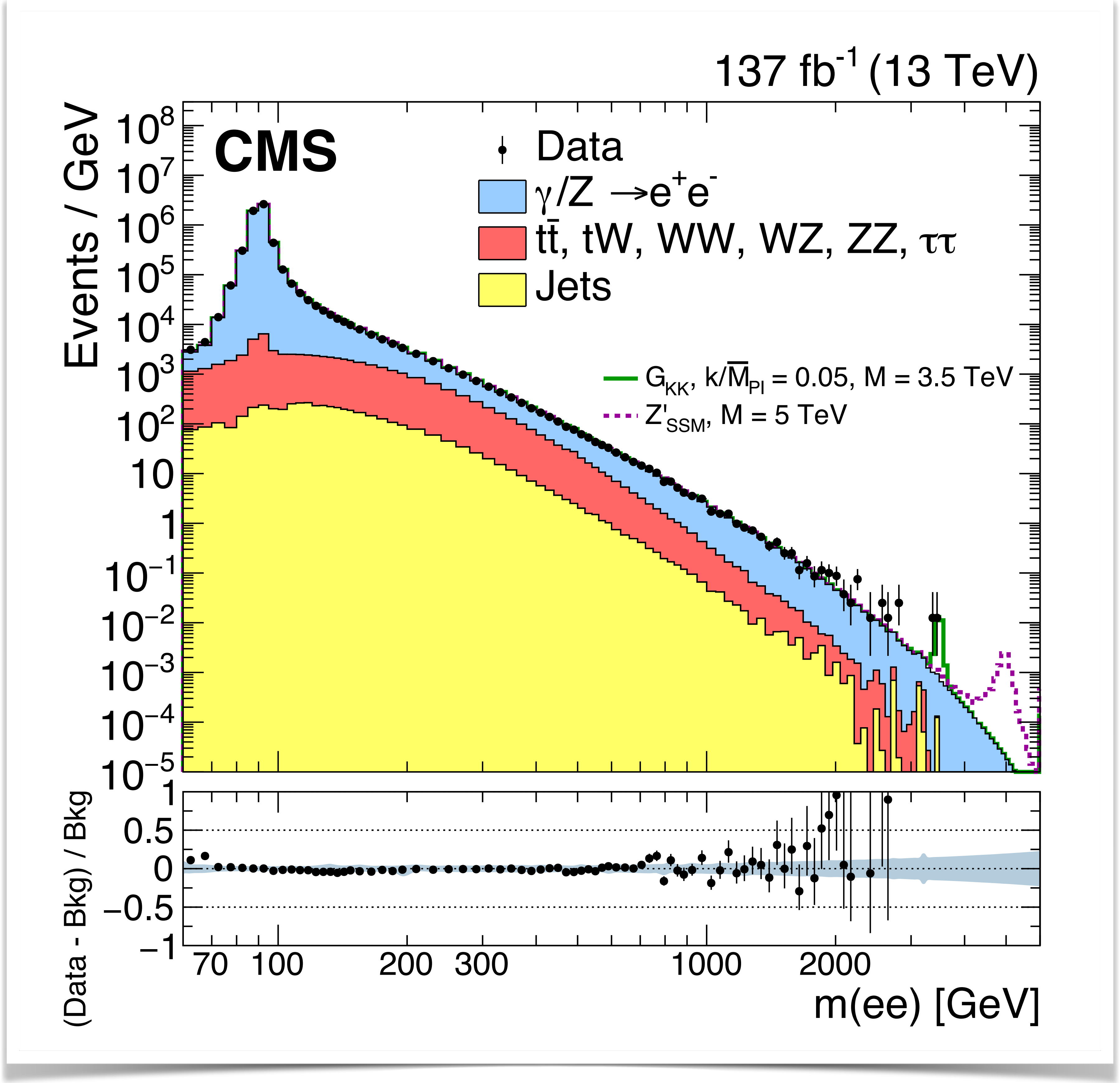

Source: arXiv:2103.02708

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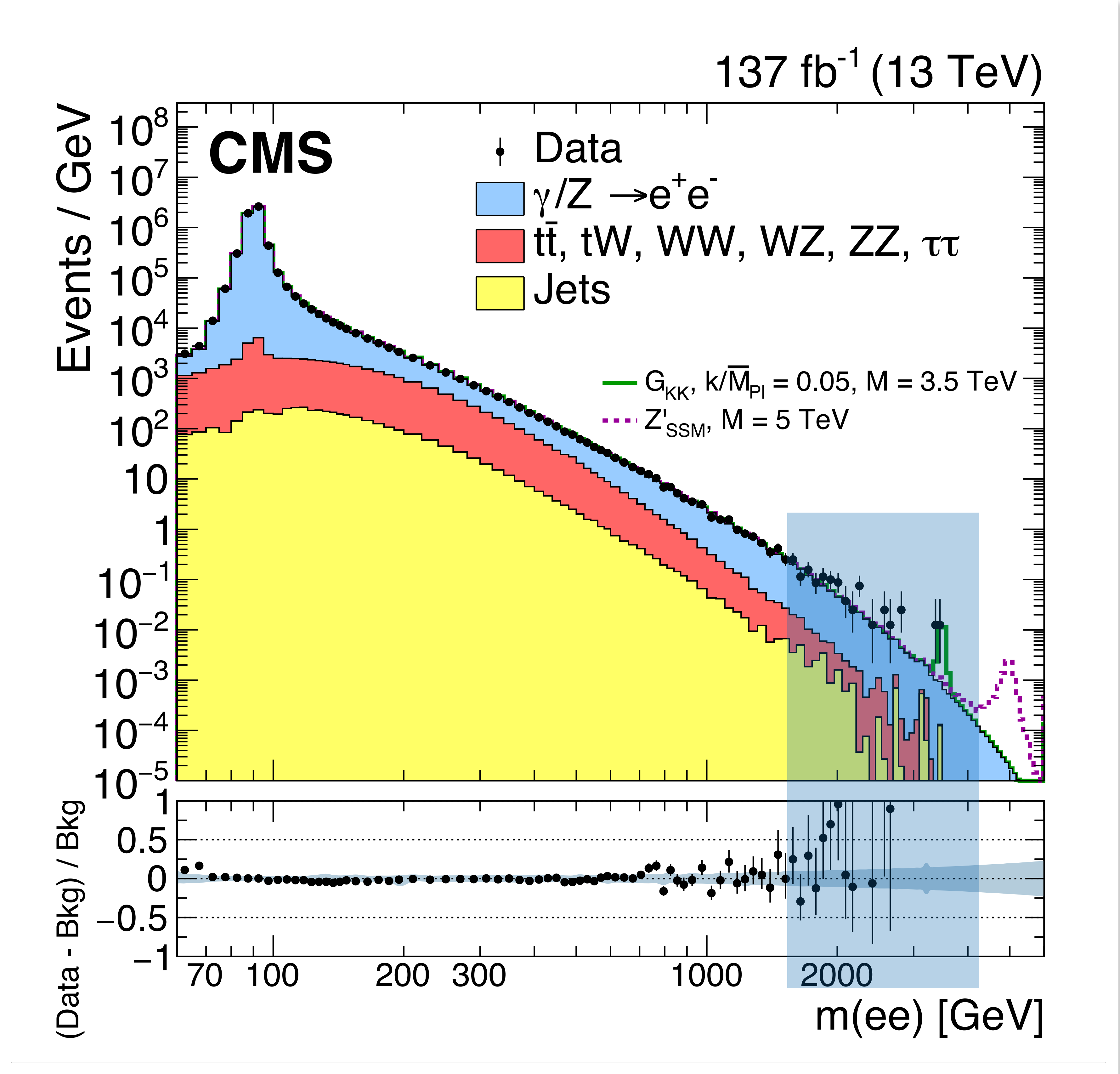

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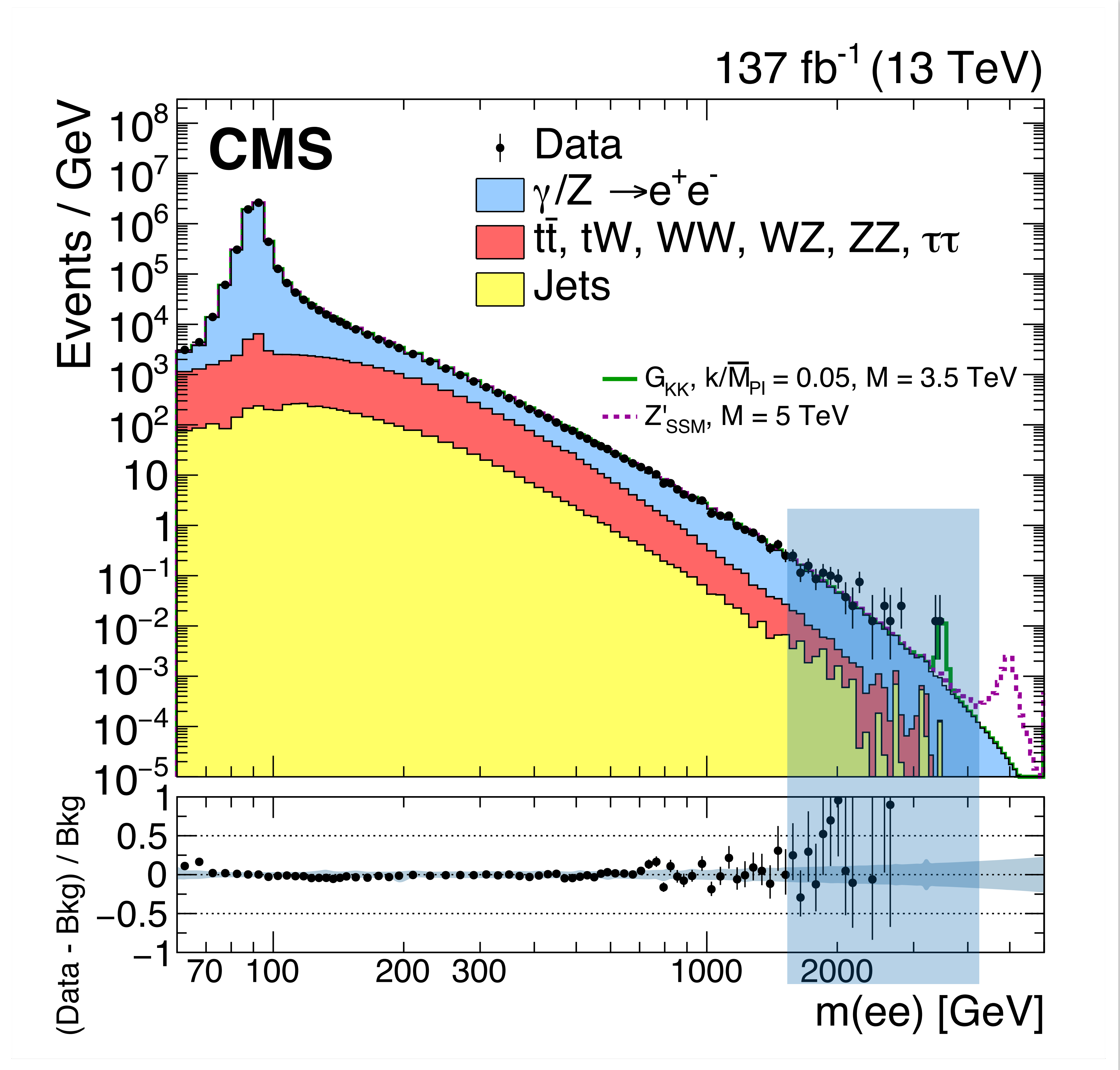

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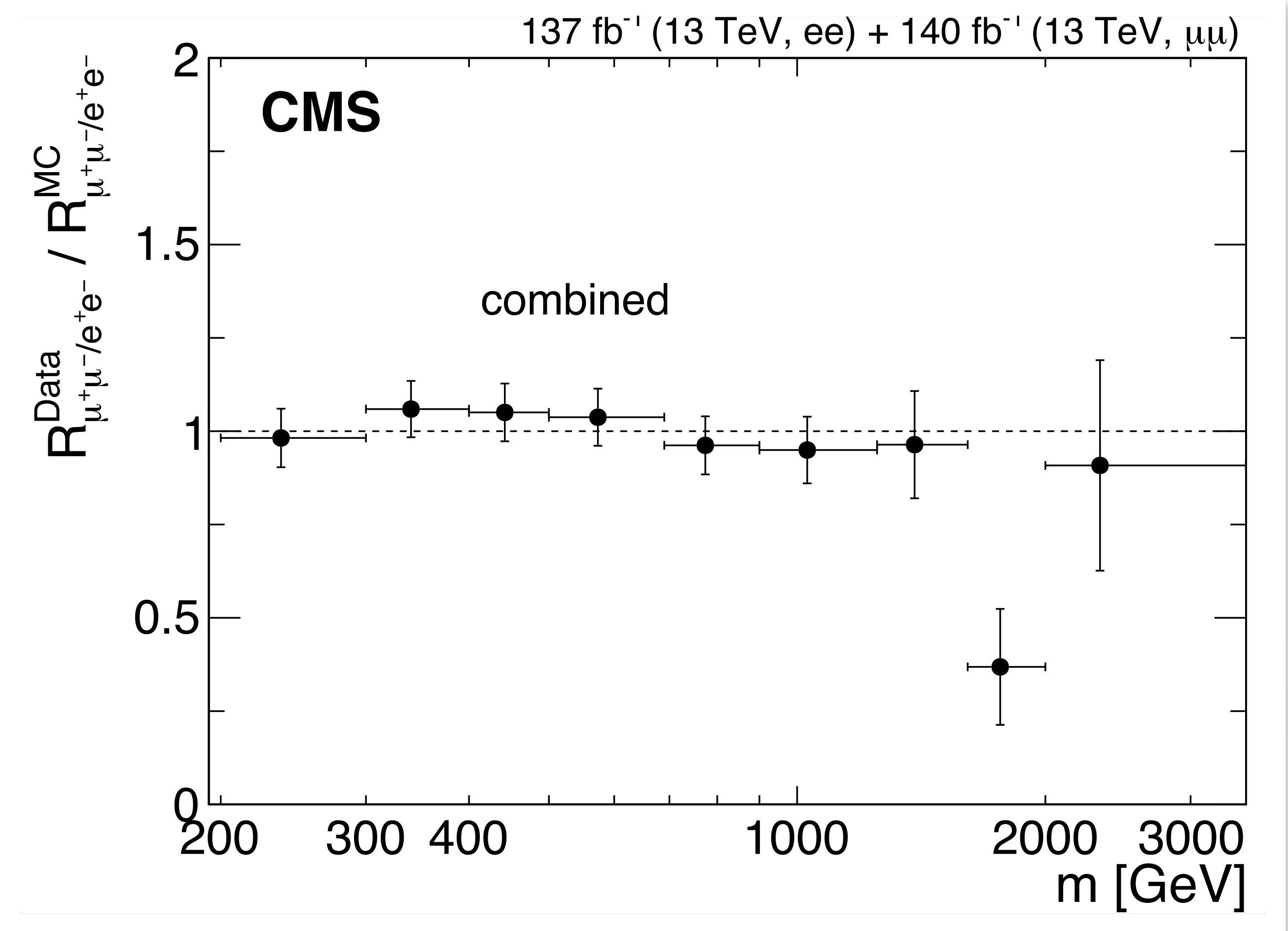

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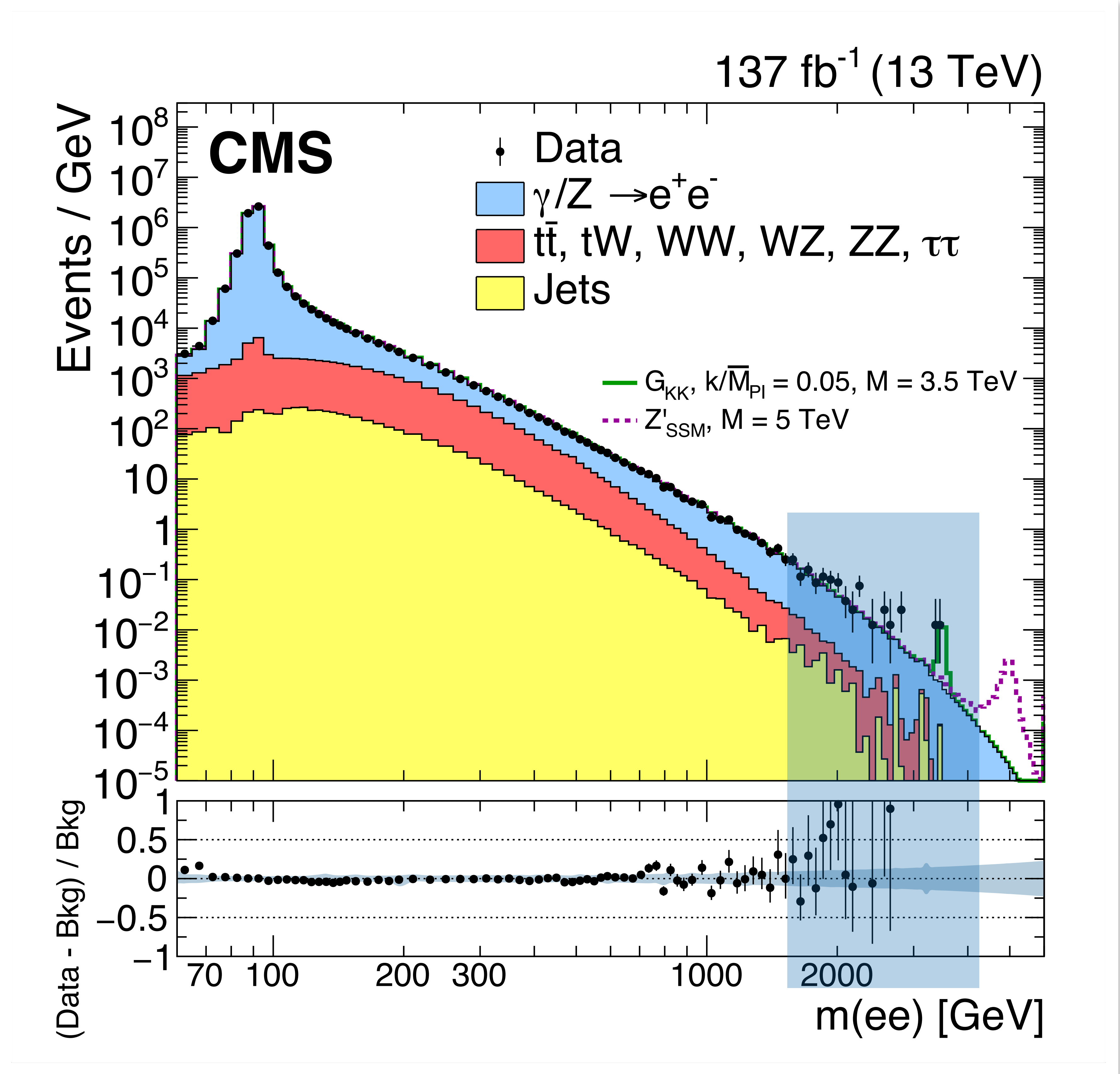

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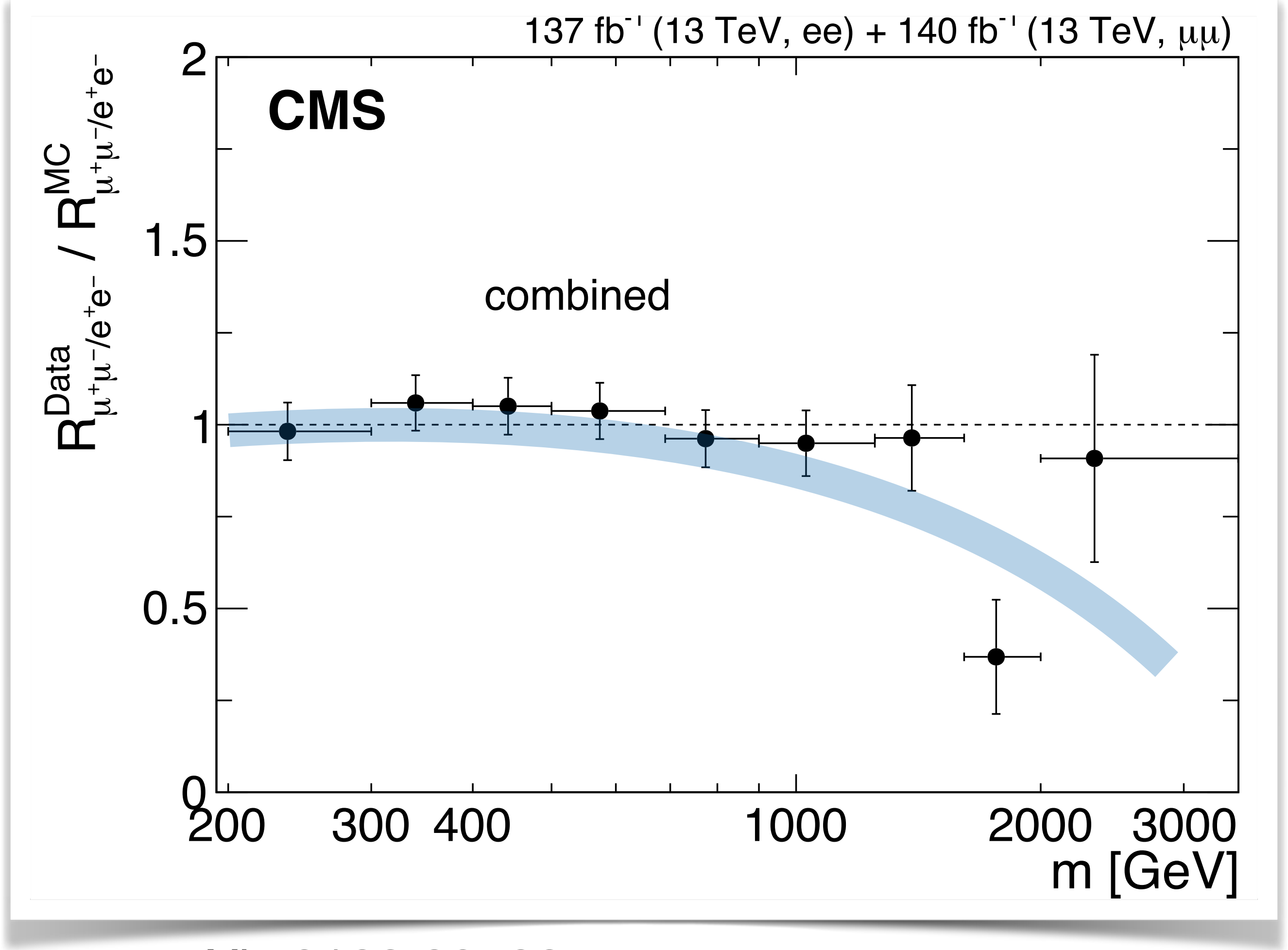

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5.1 CMS Non-Resonant Di-Lepton Analysis

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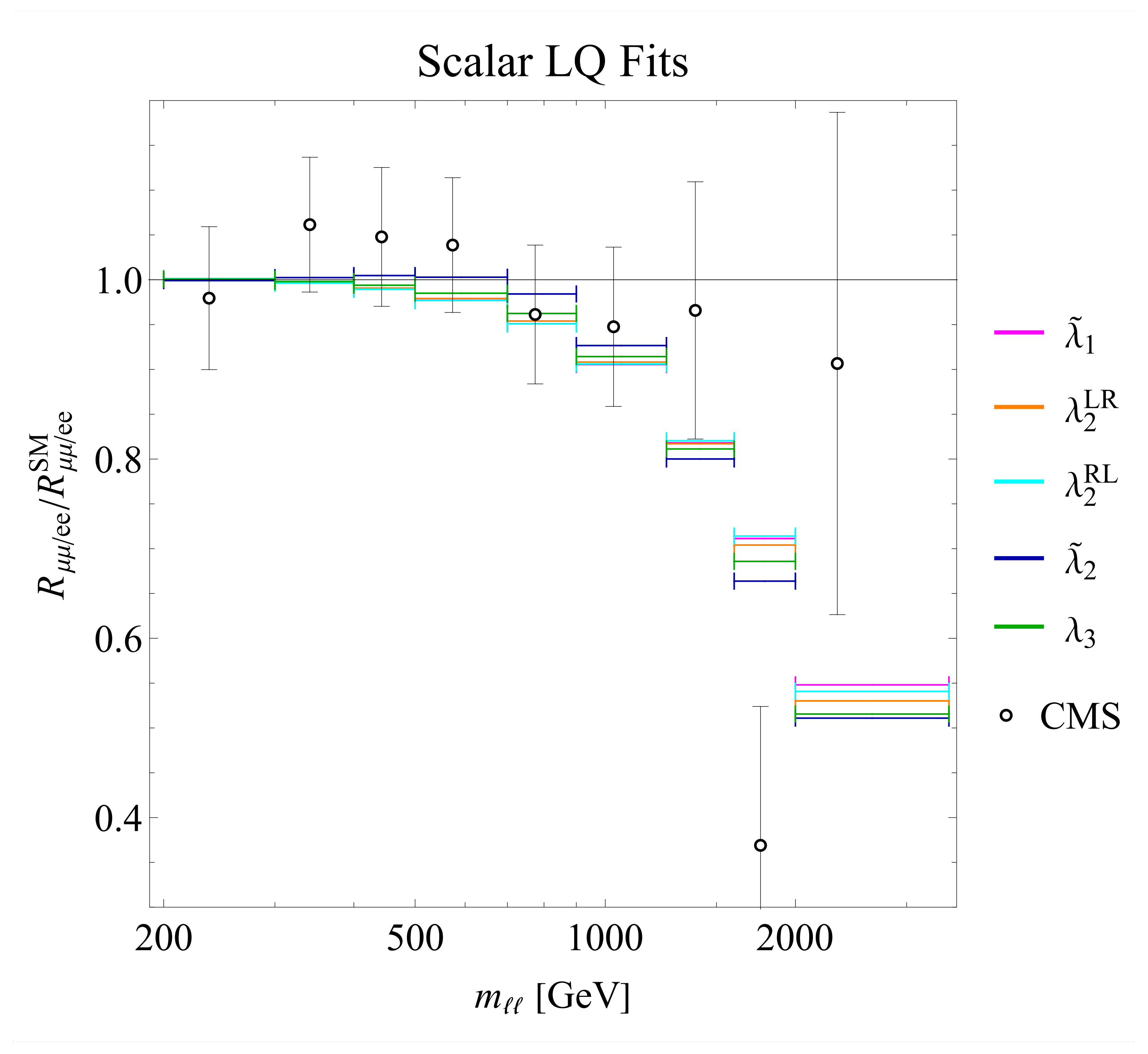

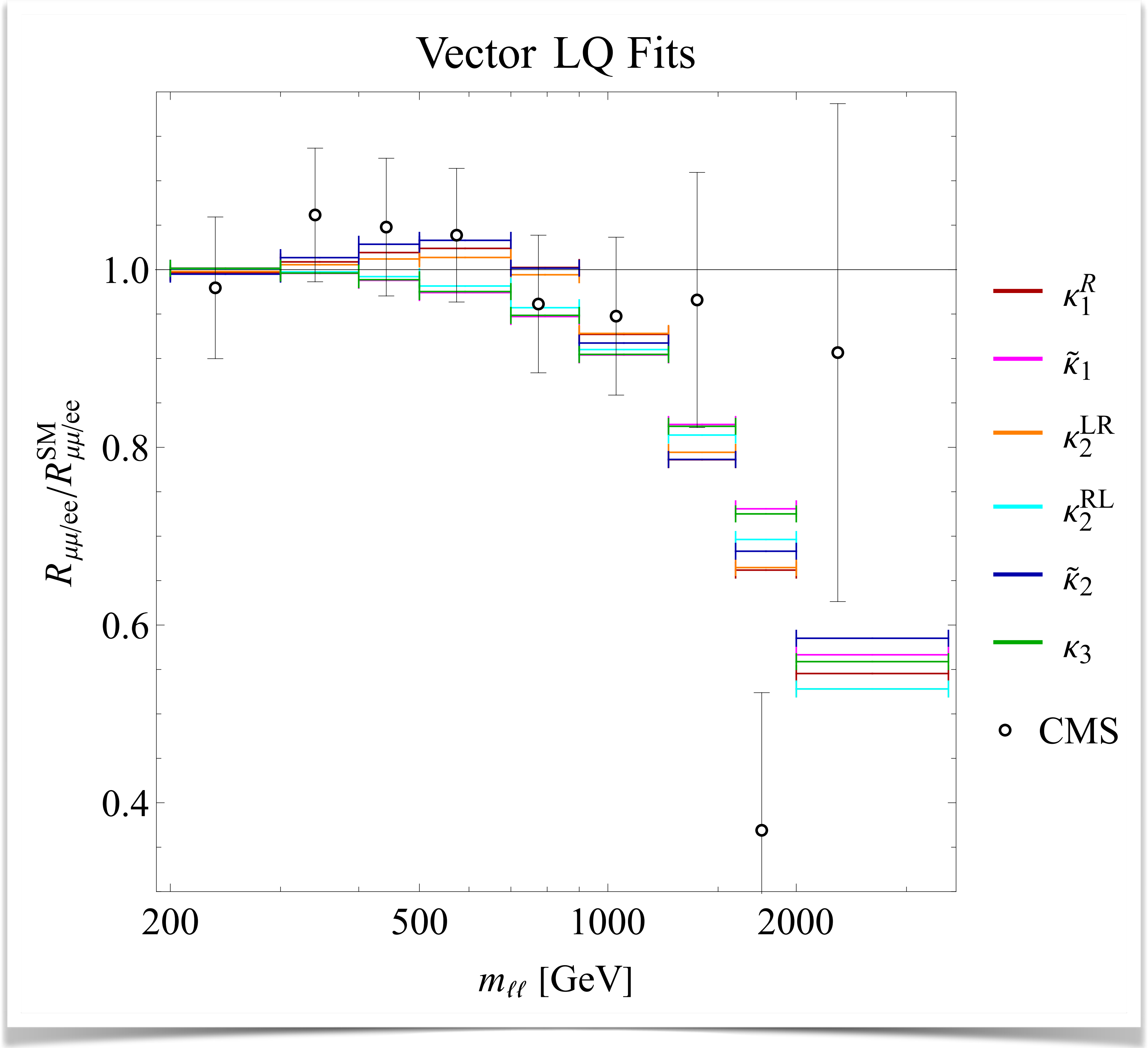

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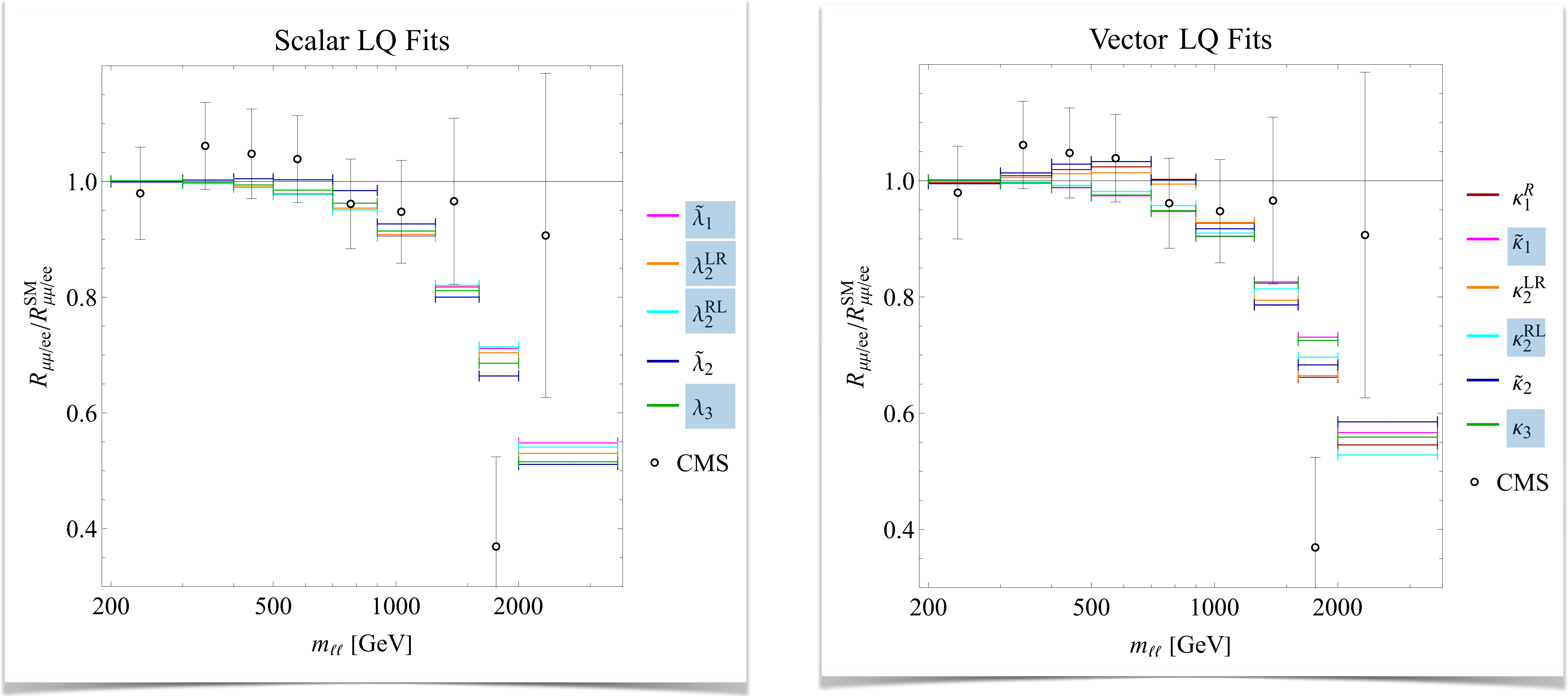

- LQ representations **interfering constructively** with the SM are preferred.

5. Results

5.2 Parity Violation Experiments

$C^e_{1u} - C^e_{1d}$ Plane:

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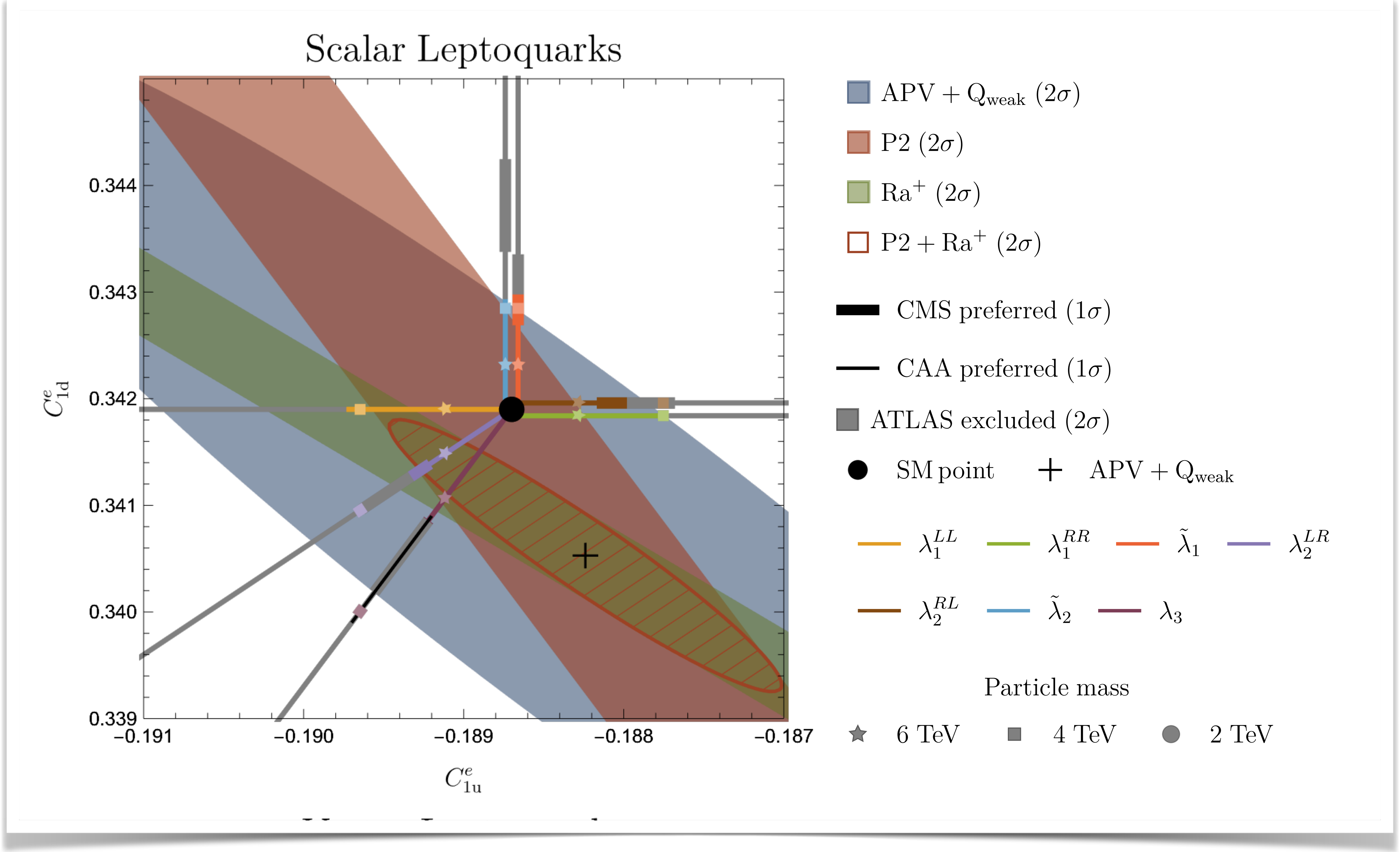

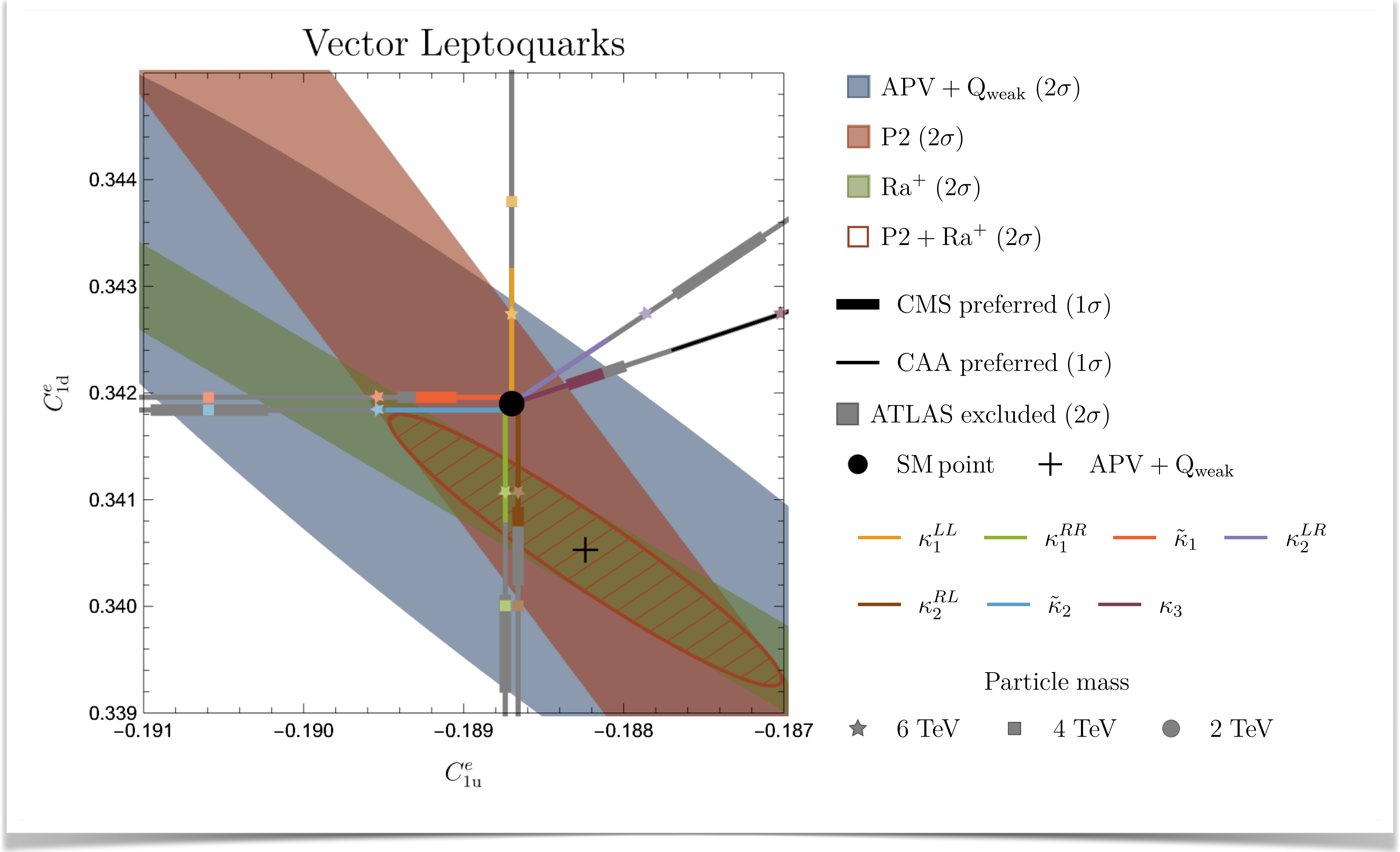

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5. Results

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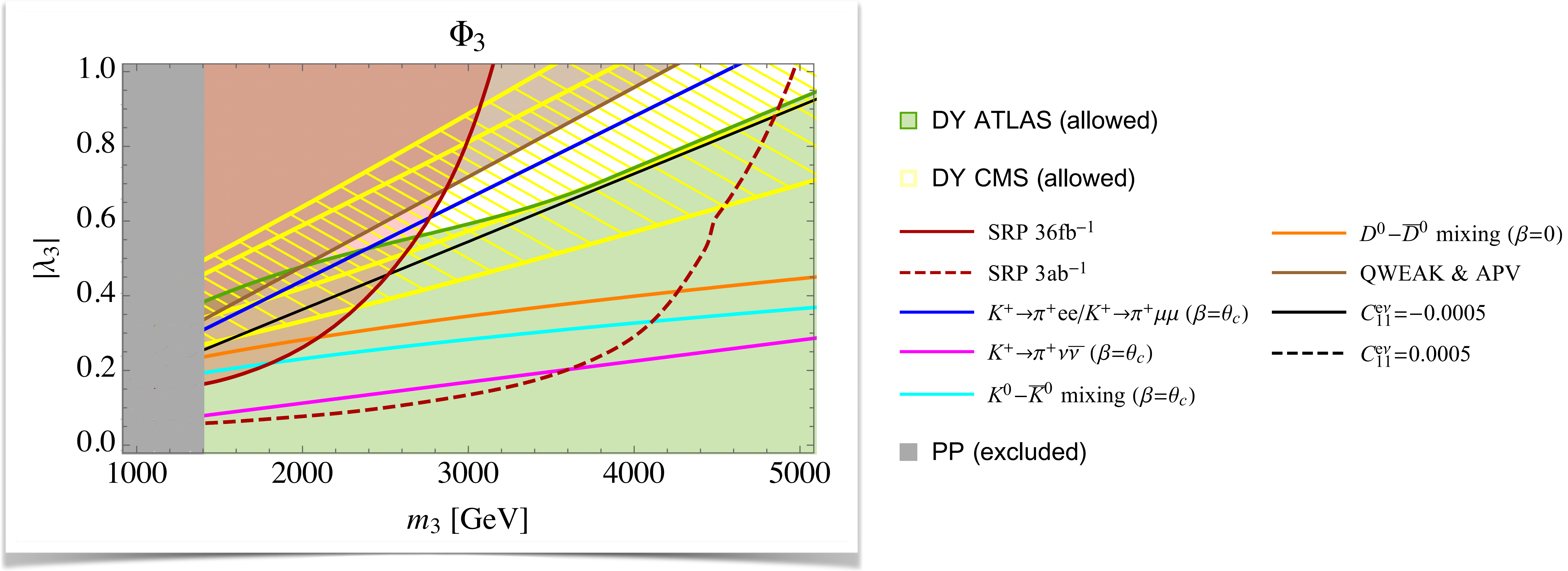

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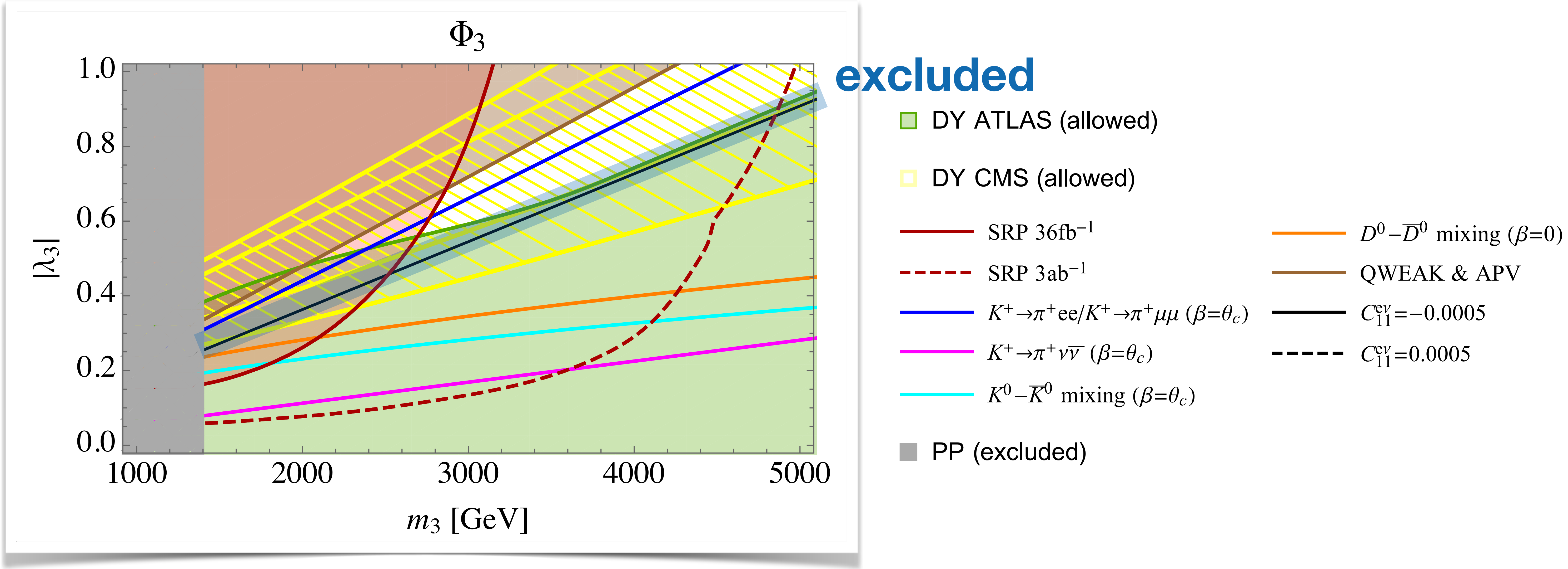

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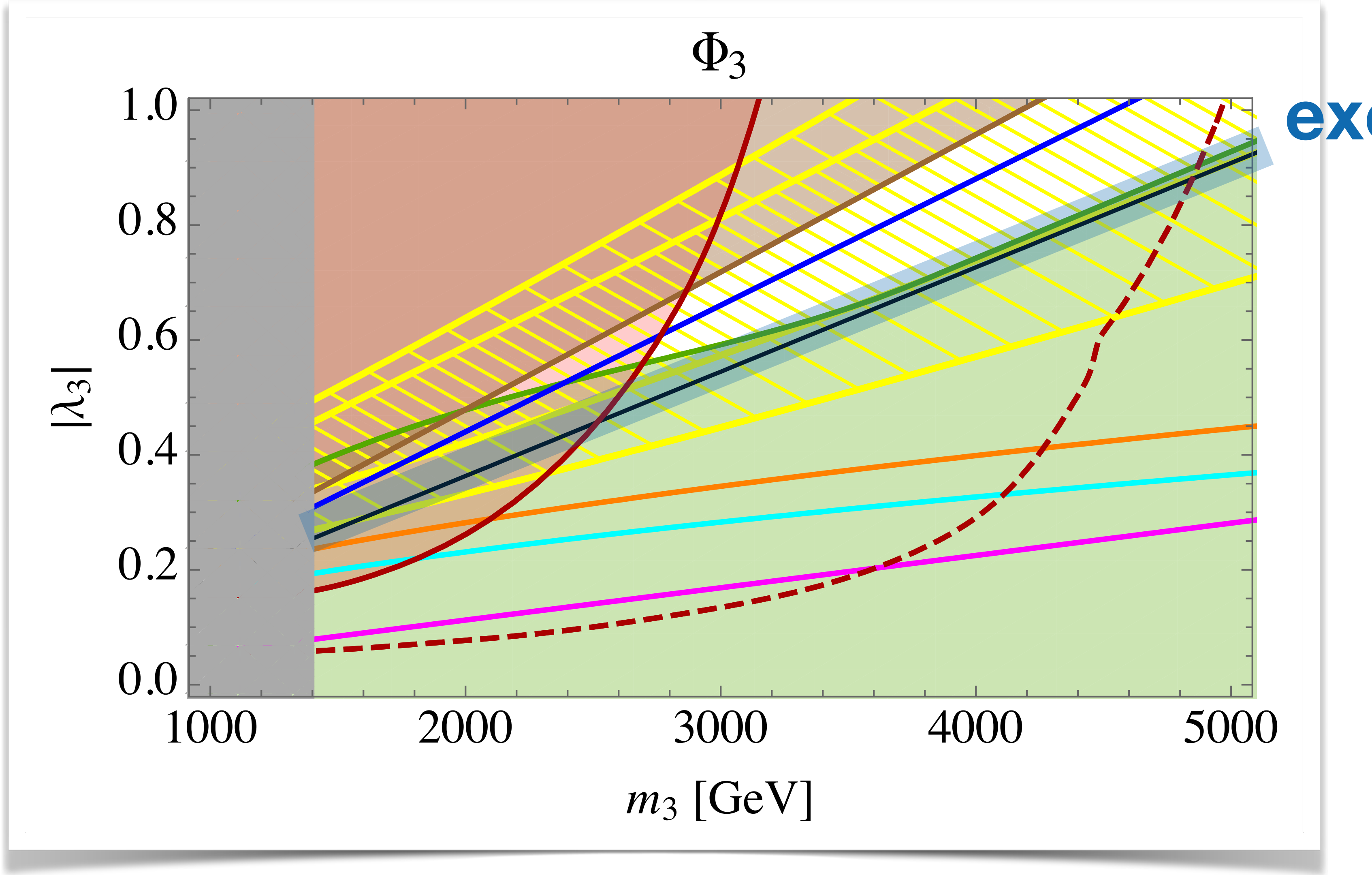
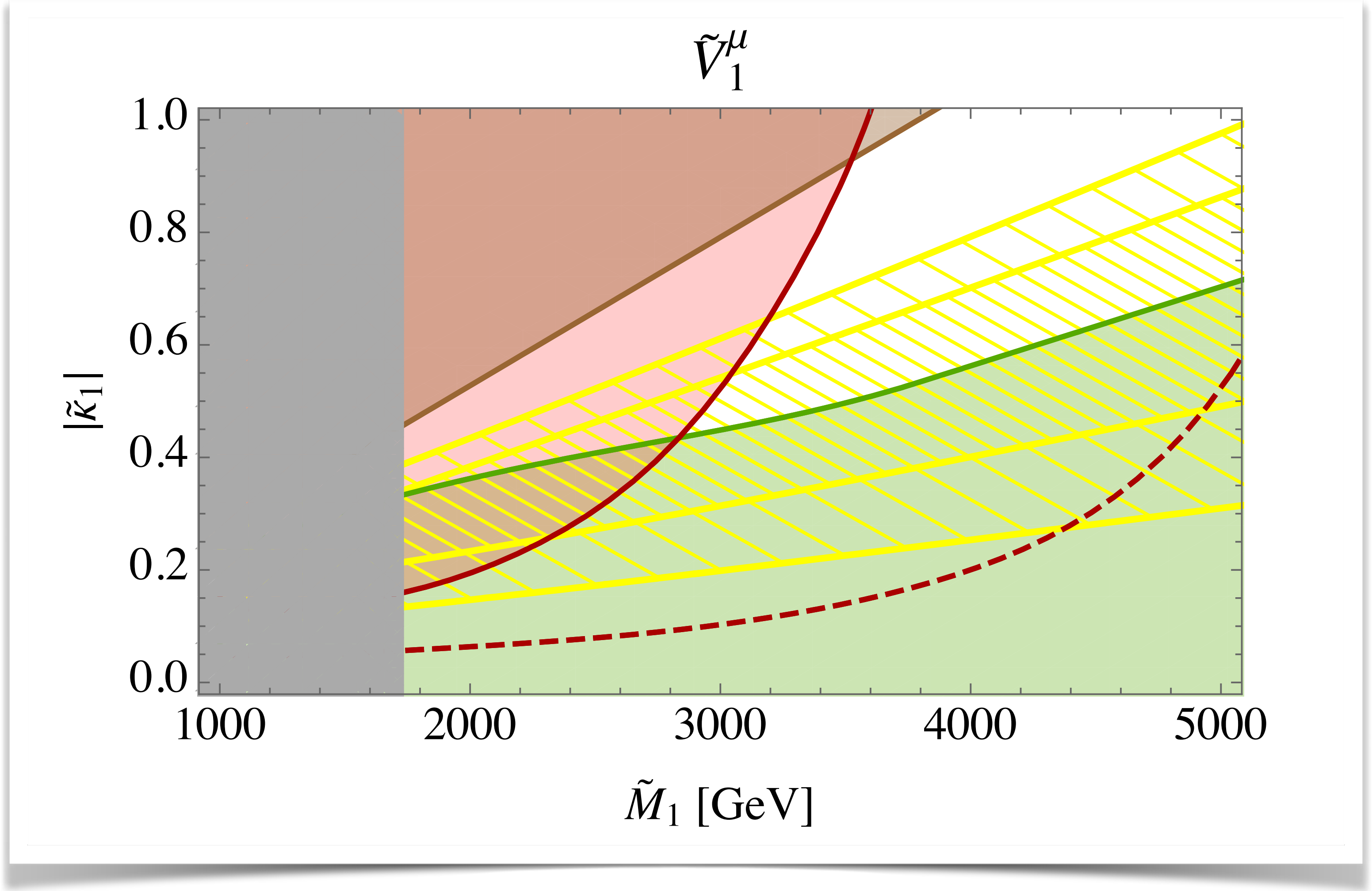


excluded

- DY ATLAS (allowed)
- DY CMS (allowed)
- SRP 36fb^{-1}
- SRP 3ab^{-1}
- $K^+ \to \pi^+ ee / K^+ \to \pi^+ \mu\mu$ $(\beta = \theta_c)$
- $K^+ \to \pi^+ \nu\bar{\nu}$ $(\beta = \theta_c)$
- $K^0 - \bar{K}^0$ mixing $(\beta = \theta_c)$
- $D^0 - \bar{D}^0$ mixing $(\beta = 0)$
- QWEAK & APV
- $C_{11}^{e\nu} = -0.0005$
- $C_{11}^{e\nu} = 0.0005$
- PP (excluded)



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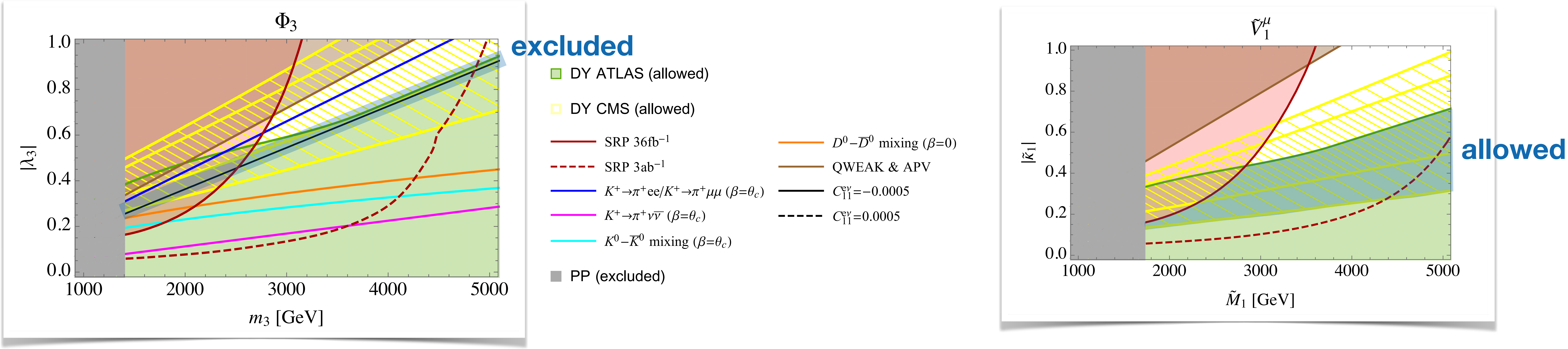

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- The **non-resonant di-lepton analyses** performed by CMS and ATLAS are highly relevant for first generation LQs. The excess in di-electrons found by the former can be explained with the LQ representations $\tilde{S}_1, S_2, \tilde{V}_1, V_2$ $(\kappa_2^{RL} \neq 0)$ and V_3 that interfere constructively with the SM contribution.

Thank you for your attention.

Backup Slides

4. Observables
4.2 High-Energy Searches

Non-resonant di-lepton analysis by ATLAS:

Paper: arXiv:2101.07811

4. Observables

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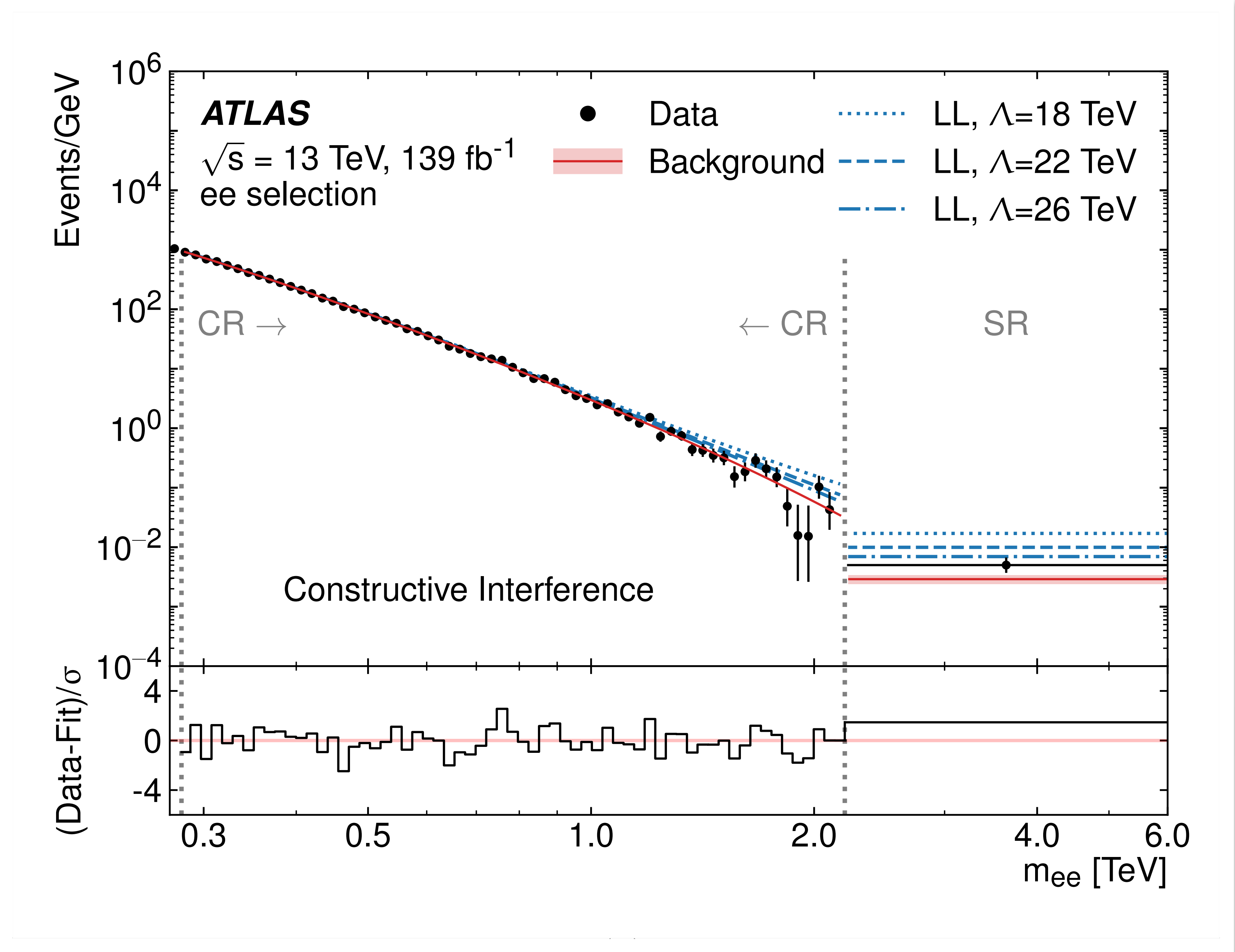

Source: arXiv:2006.12946

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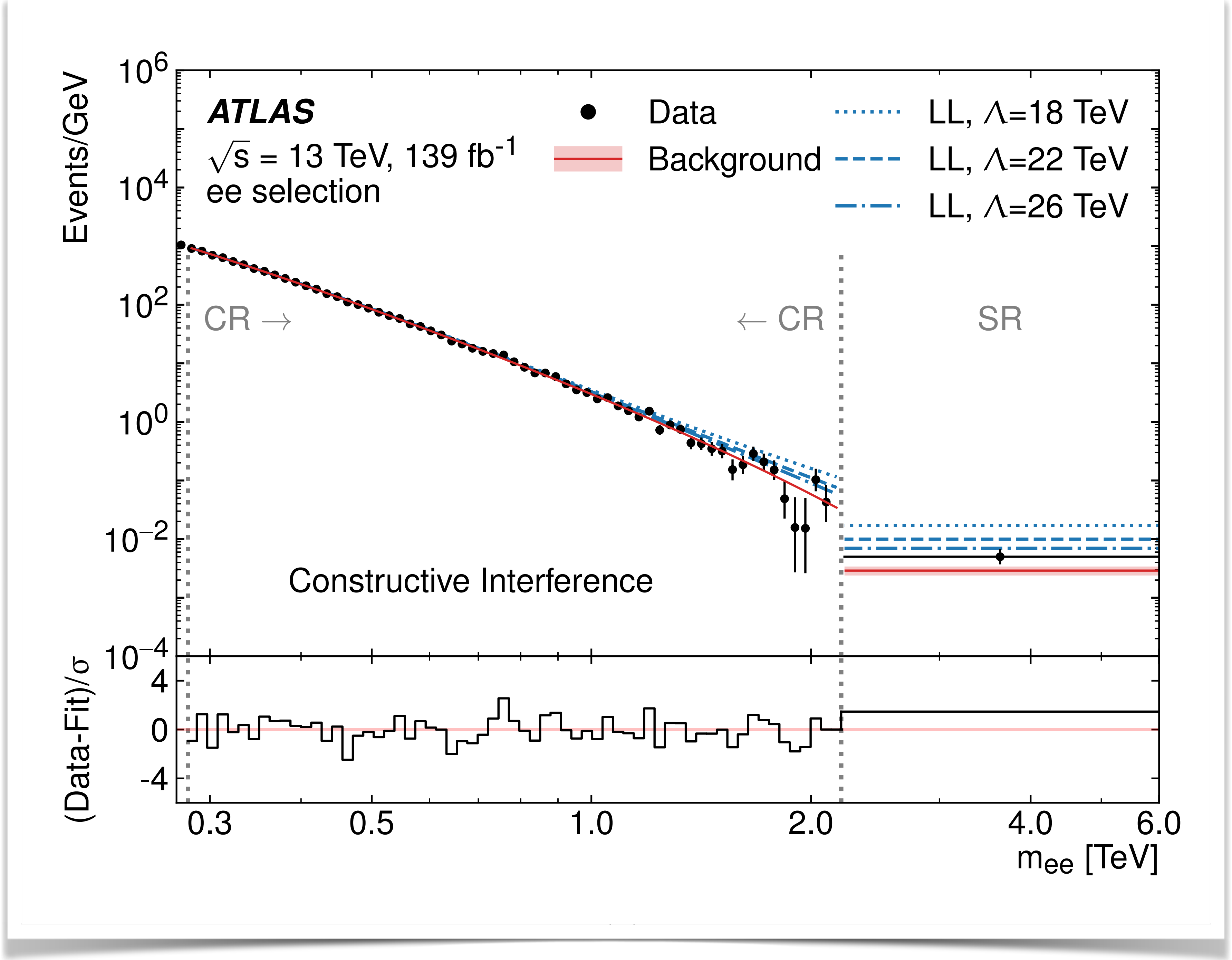
- Their measurements can be recasted, yielding **stringent constraints on first generation LQs**.



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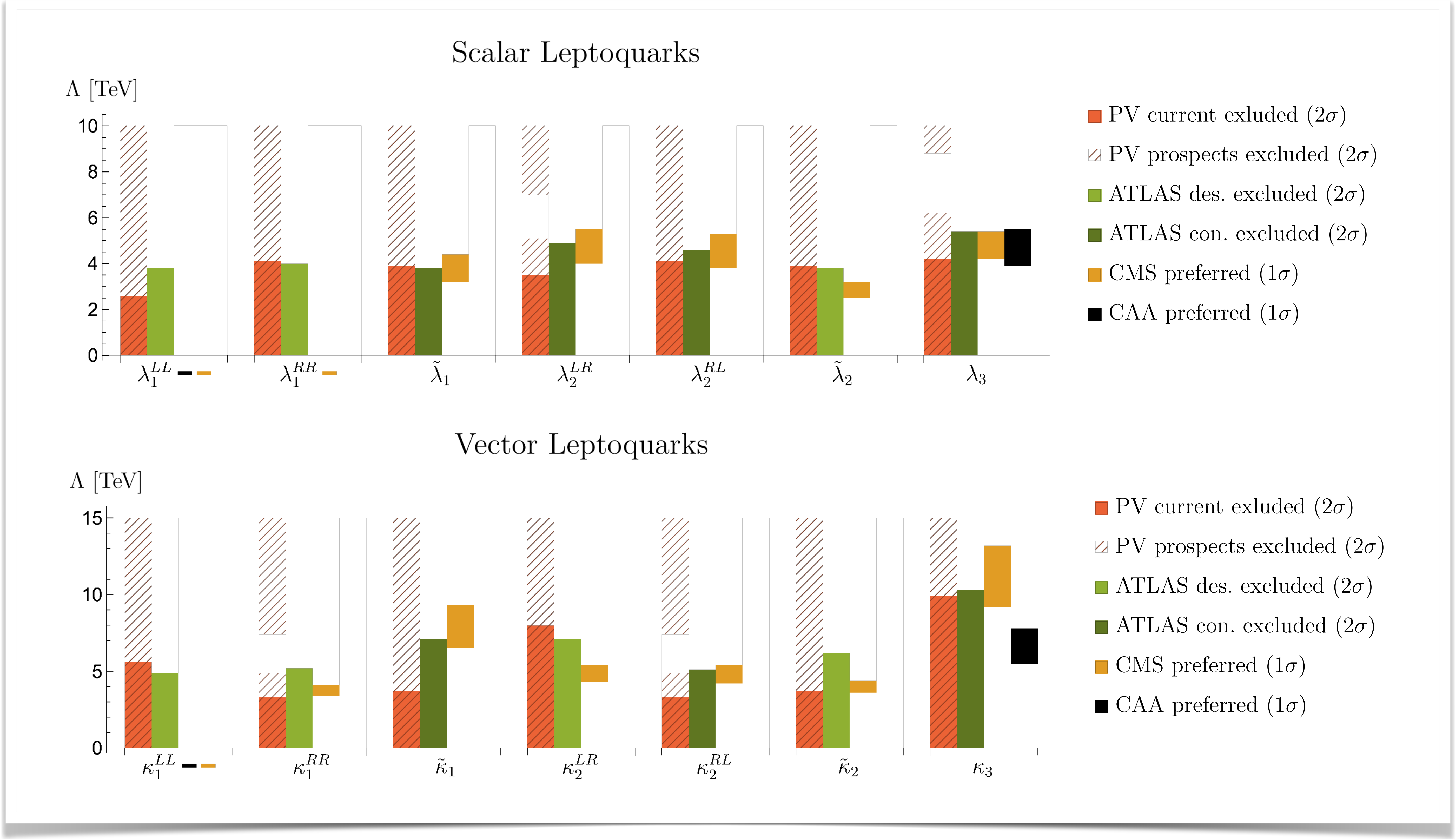

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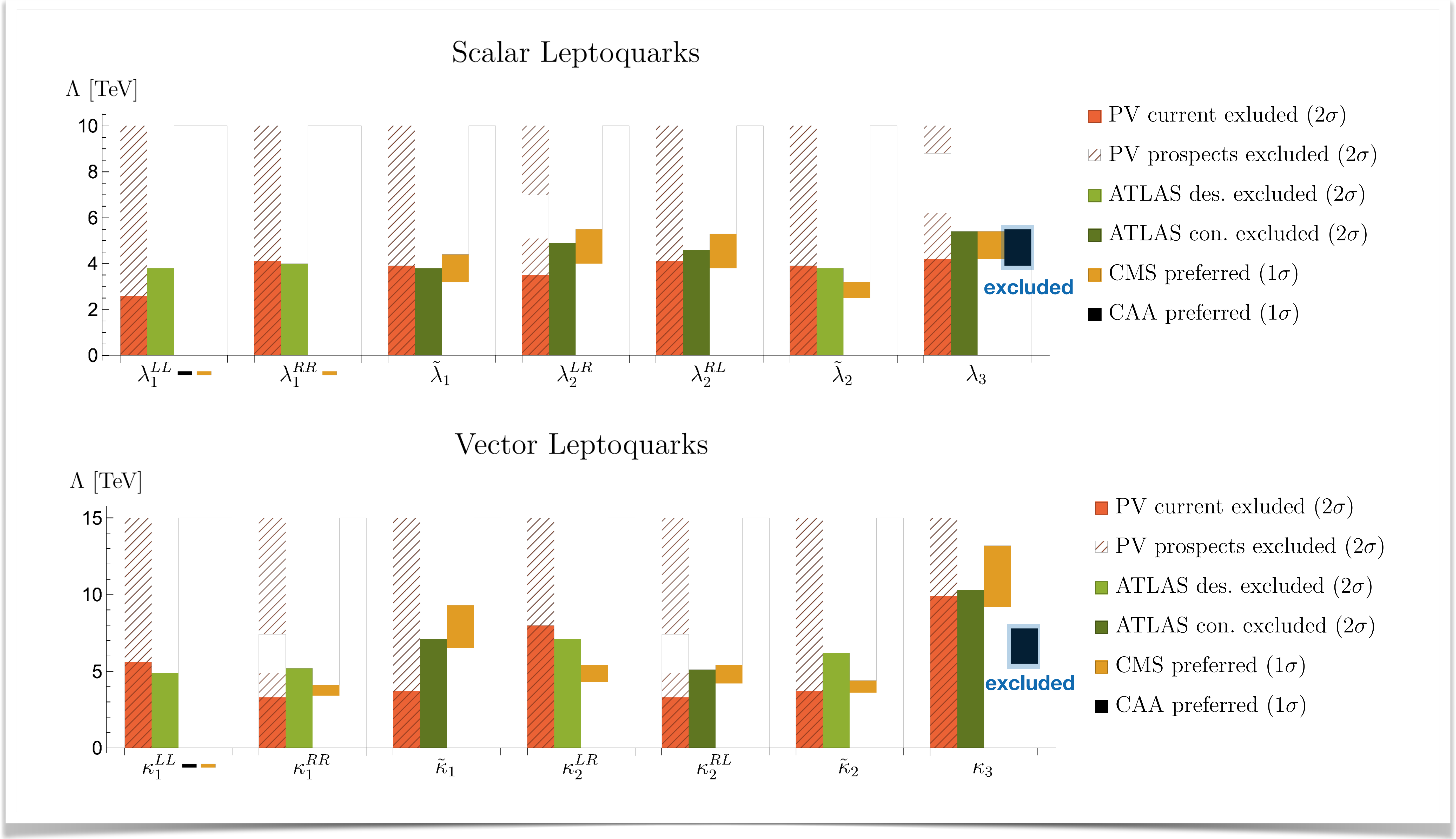

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