

Testing left-right symmetric extensions of the Standard Model

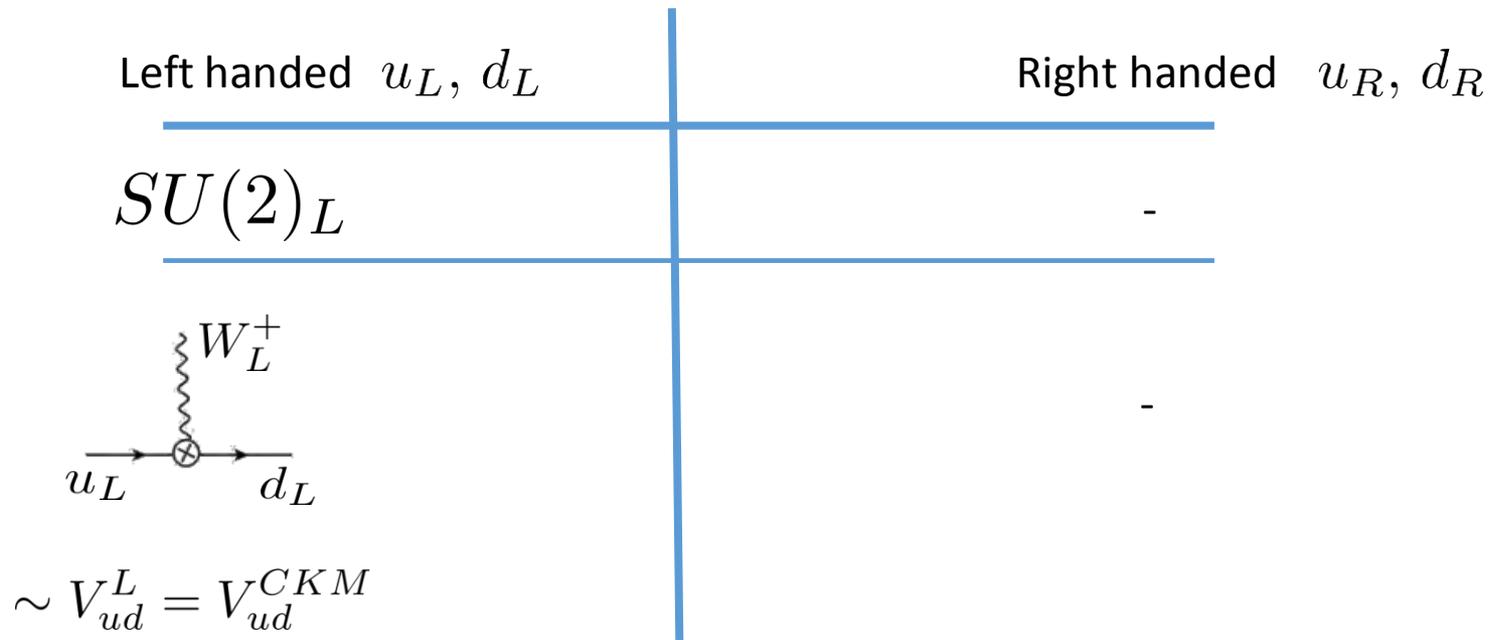
Moriond 2015

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In collaboration with Daniel Boer

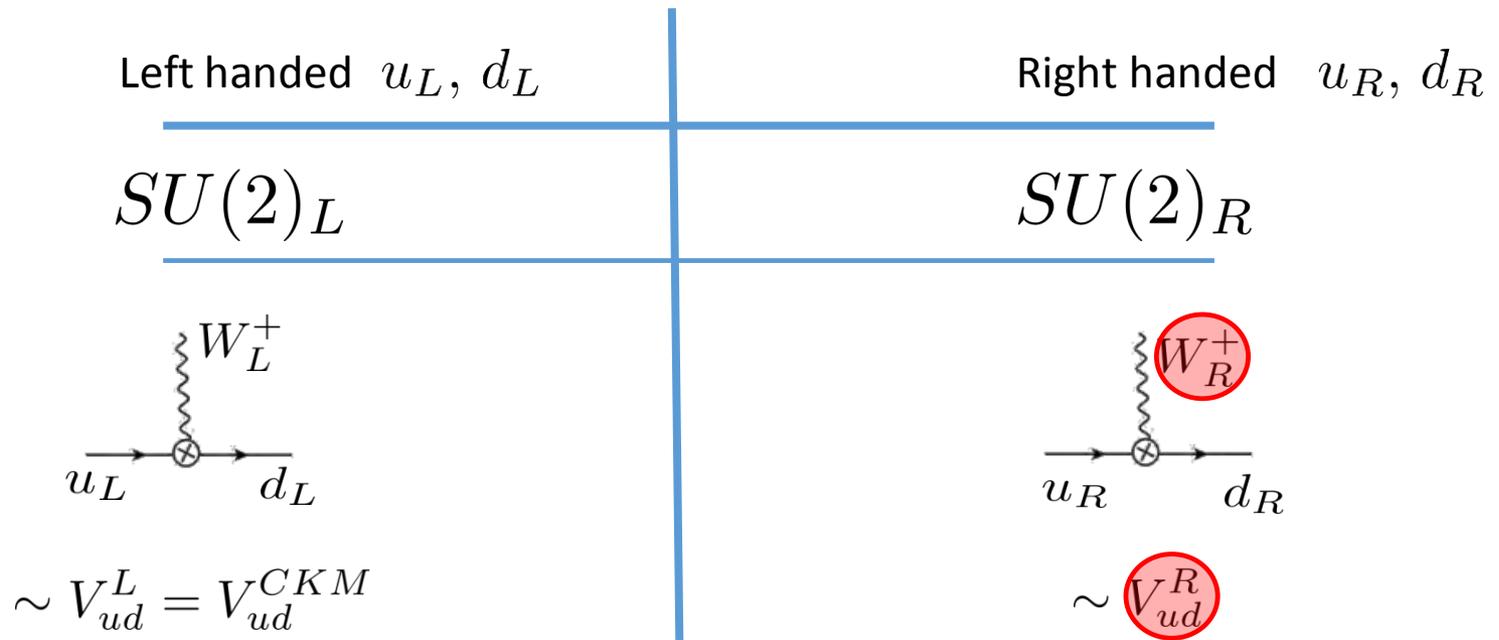
The left-right model

- In the standard model



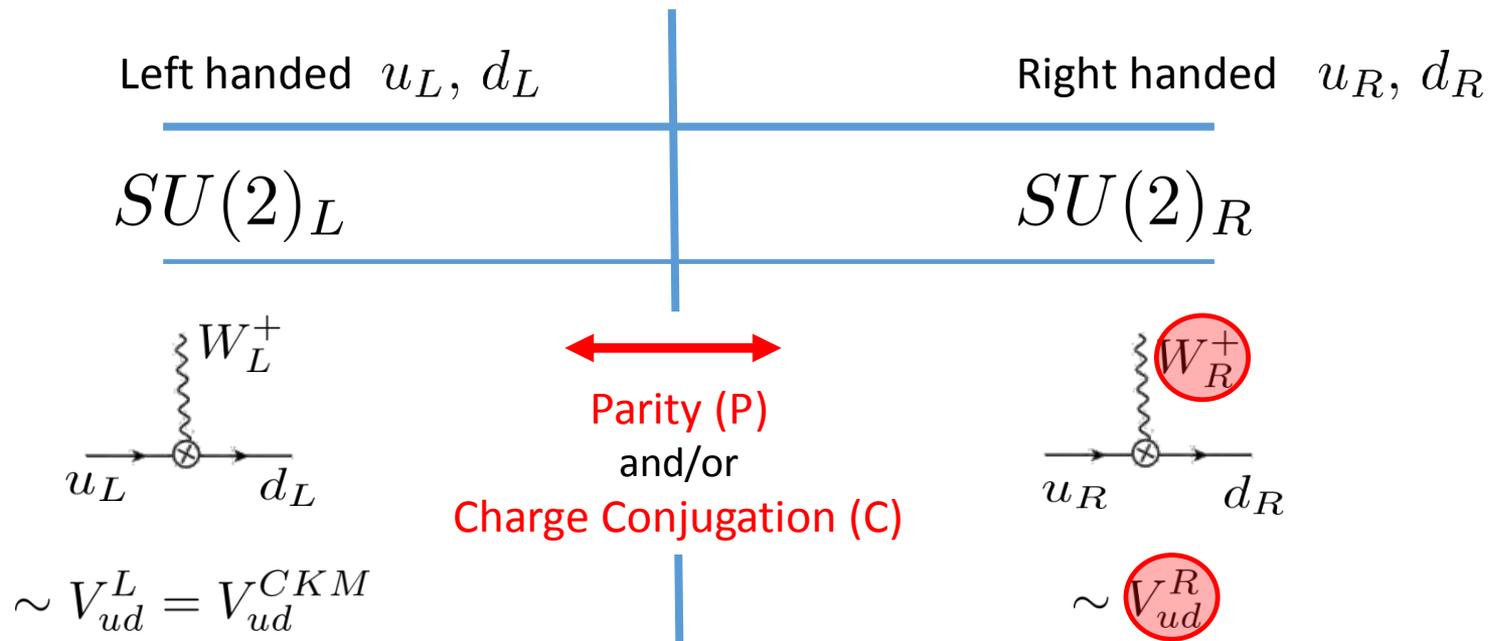
The left-right model

- In the **left-right** model



The left-right model

- In the **left-right** model



Extended Higgs sector

- Additional scalar fields

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix} \quad \phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

- Vacuum expectation values (vevs) to break the $SU(2)_R$ and EW symmetries:

$$\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \quad \langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha} \end{pmatrix}, \quad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

$v_R \gtrsim \text{TeV}$
 Scale of new physics

$\kappa, \kappa' \sim 100 \text{ GeV}$
 Electroweak scale

$v_L \lesssim \text{eV}$
 Neutrino mass scale

Hierarchy of scales

$$v_R \gg \kappa^{(\prime)} \gg v_L$$

The Higgs potential

Deshpande, et. al., PRD , 44 (1990)

$$\begin{aligned}
 V_H^P = & -\mu_1^2 \text{Tr}(\phi^\dagger \phi) - \mu_2^2 [\text{Tr}(\tilde{\phi}^\dagger \phi) + \text{Tr}(\phi^\dagger \tilde{\phi})] - \mu_3^2 [\text{Tr}(\Delta_L \Delta_L^\dagger) + \text{Tr}(\Delta_R \Delta_R^\dagger)] + \lambda_1 [\text{Tr}(\phi^\dagger \phi)]^2 \\
 & + \lambda_2 ([\text{Tr}(\tilde{\phi}^\dagger \phi)]^2 + [\text{Tr}(\phi^\dagger \tilde{\phi})]^2) + \lambda_3 \text{Tr}(\tilde{\phi}^\dagger \phi) \text{Tr}(\phi^\dagger \tilde{\phi}) + \lambda_4 \text{Tr}(\phi^\dagger \phi) [\text{Tr}(\tilde{\phi}^\dagger \phi) + \text{Tr}(\phi^\dagger \tilde{\phi})] \\
 & + \rho_1 ([\text{Tr}(\Delta_L \Delta_L^\dagger)]^2 + [\text{Tr}(\Delta_R \Delta_R^\dagger)]^2) \\
 & + \rho_2 [\text{Tr}(\Delta_L \Delta_L) \text{Tr}(\Delta_L^\dagger \Delta_L^\dagger) + \text{Tr}(\Delta_R \Delta_R) \text{Tr}(\Delta_R^\dagger \Delta_R^\dagger)] + \rho_3 \text{Tr}(\Delta_L \Delta_L^\dagger) \text{Tr}(\Delta_R \Delta_R^\dagger) \\
 & + \rho_4 [\text{Tr}(\Delta_L \Delta_L) \text{Tr}(\Delta_R^\dagger \Delta_R^\dagger) + \text{Tr}(\Delta_R \Delta_R) \text{Tr}(\Delta_L^\dagger \Delta_L^\dagger)] \\
 & + \alpha_1 \text{Tr}(\phi^\dagger \phi) [\text{Tr}(\Delta_L \Delta_L^\dagger) + \text{Tr}(\Delta_R \Delta_R^\dagger)] \\
 & + \alpha_2 (e^{i\delta_2} [\text{Tr}(\tilde{\phi}^\dagger \phi) \text{Tr}(\Delta_R \Delta_R^\dagger) + \text{Tr}(\phi^\dagger \tilde{\phi}) \text{Tr}(\Delta_L \Delta_L^\dagger)] + \text{h.c.}) \\
 & + \alpha_3 [\text{Tr}(\phi \phi^\dagger \Delta_L \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \phi \Delta_R \Delta_R^\dagger)] + \beta_1 [\text{Tr}(\phi \Delta_R \phi^\dagger \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \Delta_L \phi \Delta_R^\dagger)] \\
 & + \beta_2 [\text{Tr}(\tilde{\phi} \Delta_R \phi^\dagger \Delta_L^\dagger) + \text{Tr}(\tilde{\phi}^\dagger \Delta_L \phi \Delta_R^\dagger)] + \beta_3 [\text{Tr}(\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \Delta_L \tilde{\phi} \Delta_R^\dagger)],
 \end{aligned}$$

- The C and CP symmetric potentials are quite similar WD, Boer, NP B **889**, 727 (2014)

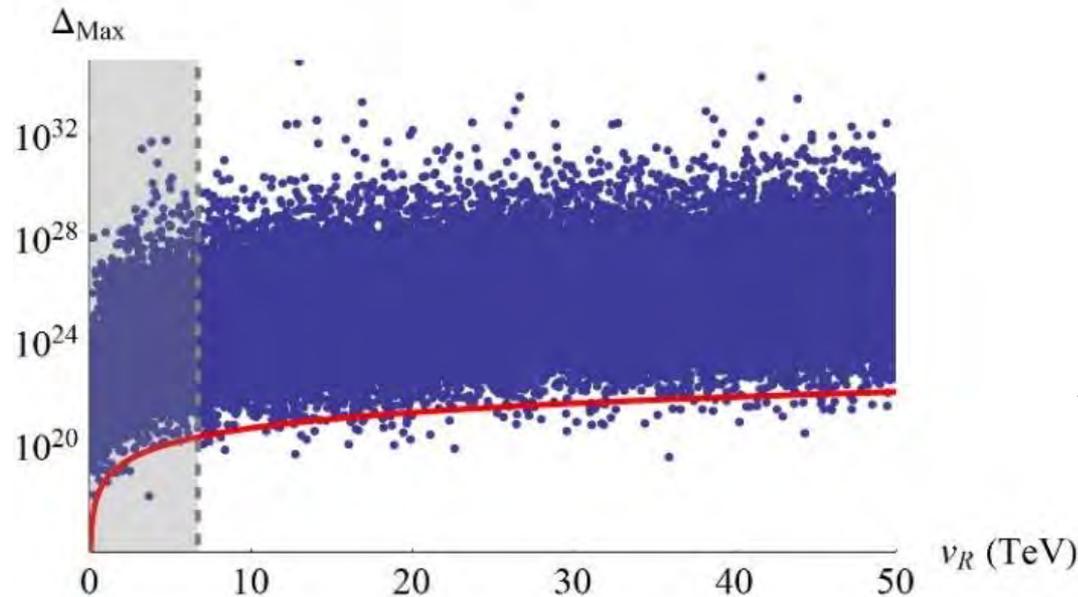
- Gives rise to the vevs of the Higgs fields and interrelates them
- This relates very different scales and gives rise to fine-tuning

Fine-tuning in the Higgs potential

- Large fine-tuning
 - Occurs in many models of new physics, e.g. GUTs

$$\Delta \equiv \frac{d \ln \mathcal{O}}{d \ln p}$$

Barbieri, Giudice, NP B 306, 63 (1988)



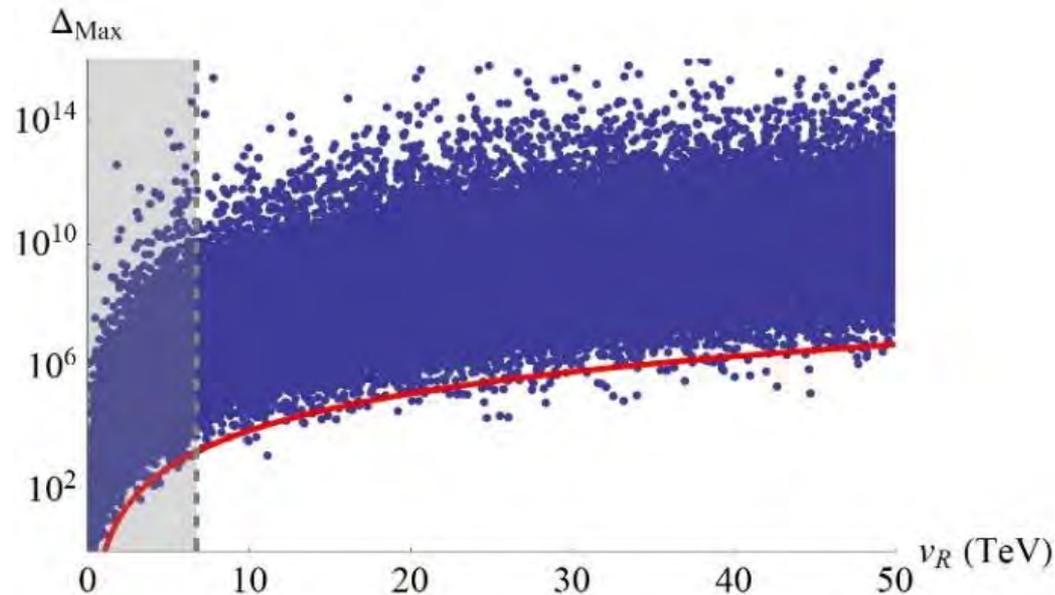
$$\Delta \sim v_R^2 / v_L^2$$

WD, Boer, NP B 889, 727 (2014)

- P-symmetric case (similar for C and CP)

Fine-tuning in the Higgs potential

- Fine-tuning can be significantly decreased in some cases e.g. $v_L = 0$
 - But requires justification

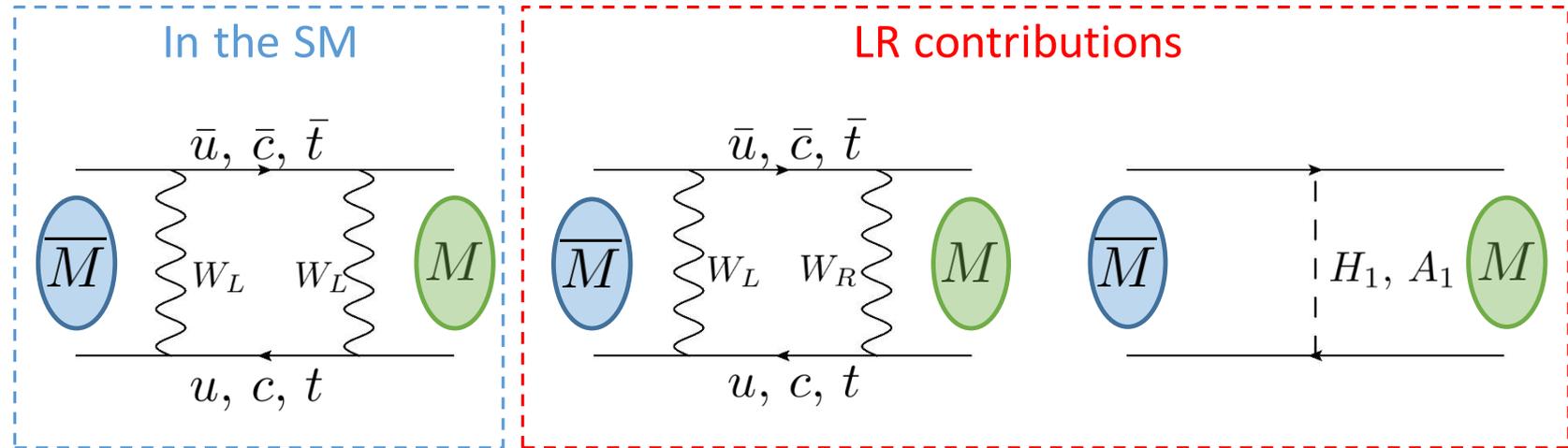


$$\Delta \sim v_R^4 / \kappa^4$$

WD, Boer, NP B **889**, 727 (2014)

- P-symmetric case (similar for C and CP)

Constraints: $B-\bar{B}$ and $K-\bar{K}$ mixing



- The left-right contributions depend on V_R^{CKM}
- The P and/or C cases lead to different predictions for V_R^{CKM}
- The “C+P” case can be excluded in this way

Ball, Frere, Matias, NP B **572**, 3 (2000)
 Ball, Fleischer, PL B **475**, 111 (2000)

Meson mixing: P or C case

- Combining K- and B-mixing observables gives the bounds

$$P : M_{W_R} \gtrsim 3 \text{ TeV}$$

Bertolini, Maiezza, Nesti, PR D **89** 095028 (2014)

$$C : M_{W_R} \gtrsim 3 \text{ TeV}$$

- Better than direct limits
- In the future masses up to $M_{W_R} \sim 8 \text{ TeV}$ will be probed by Belle, LHCb
 - Achievable by the mid 2020s
- Meson mixing data could in principle distinguish between the P and C cases

Summary

- Left-right models have certain attractive features
 - Symmetry between left and right
 - Natural embedding into GUTs
- The Higgs potential requires a large amount of fine-tuning
 - However, this can be significantly reduced in some cases ($v_L = 0$)
- Two possible LR symmetries: P and C
- “C+P” case can be excluded
- B & K mixing observables could distinguish between P and C cases
 - Probed up to roughly 3 TeV so far
 - In the future a this will be probed up to $M_{W_R} \sim 8 \text{ TeV}$