

CABIBBO ANOMALY AND CDF-W MASS IN LEFT RIGHT SYMMETRIC MODELS

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In collaboration with

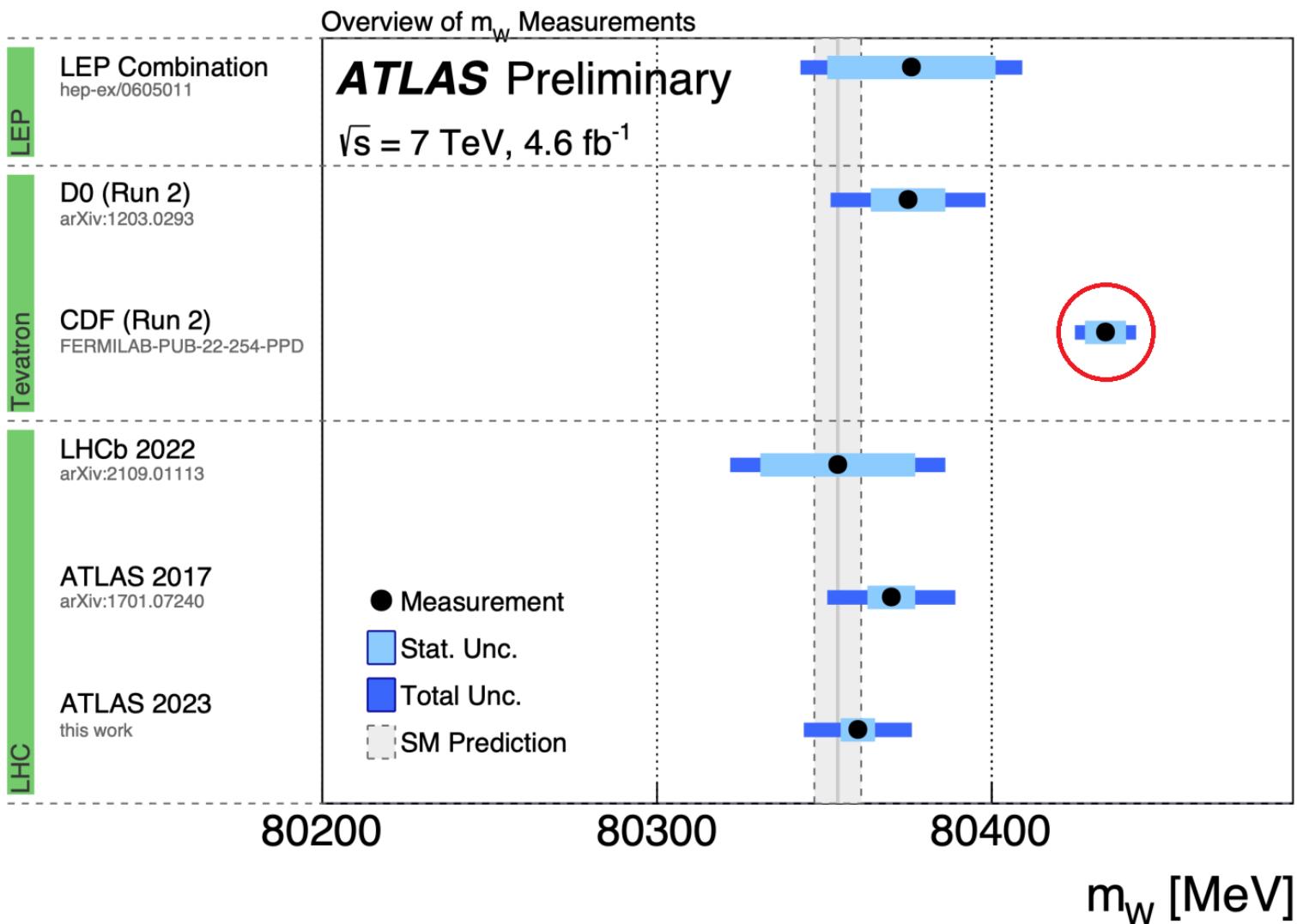
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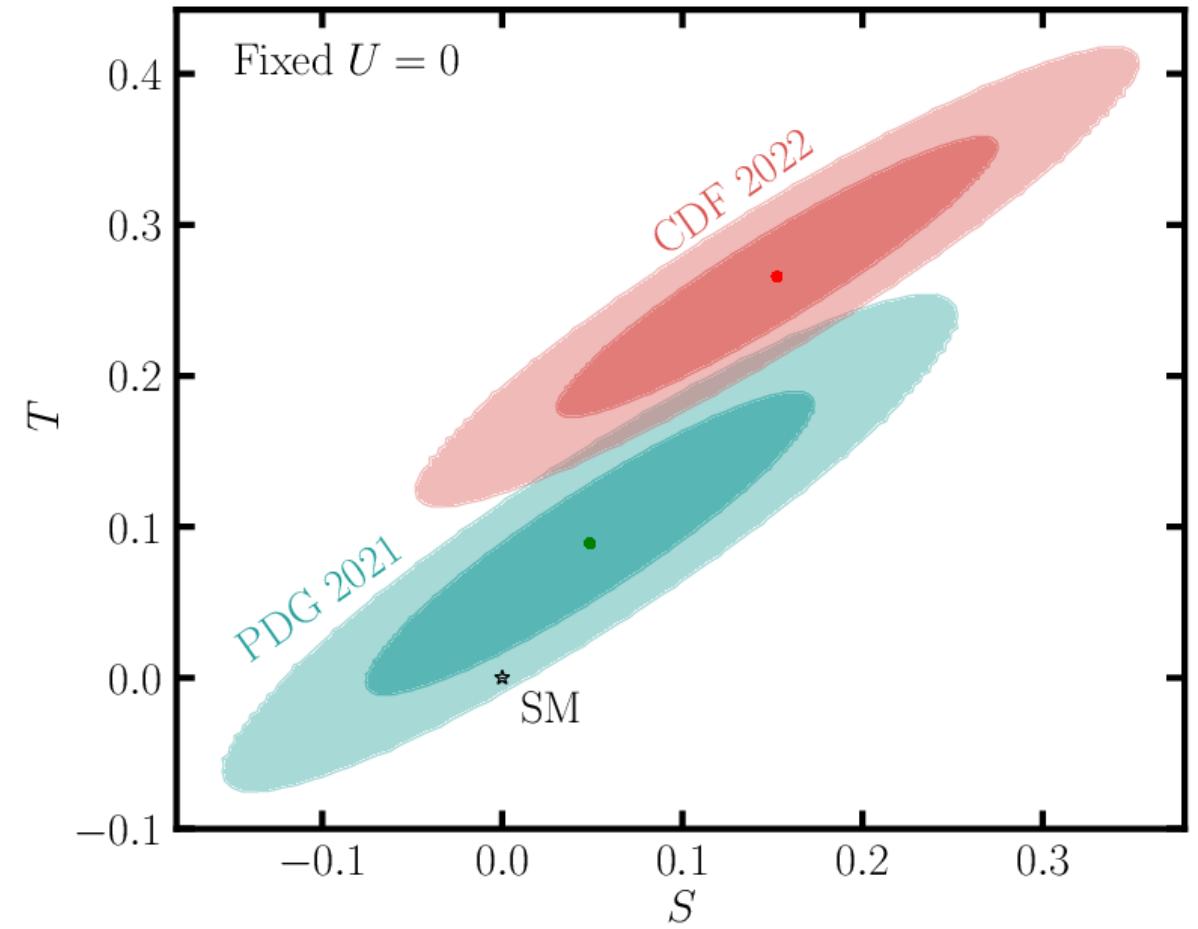
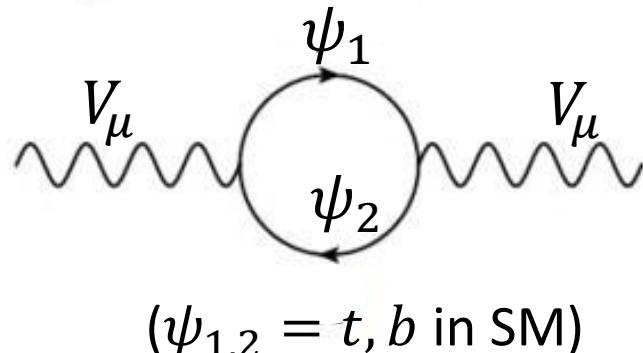
CDF W Mass Shift



Oblique Corrections

$$m_W^2 = m_{W_{SM}}^2 \left[1 - \frac{\alpha S}{2(c_W^2 - s_W^2)} + \frac{c_W^2 \alpha T}{c_W^2 - s_W^2} + \frac{\alpha U}{4c_W^2} \right]$$

“oblique parameters”



C. Lu, L. Wu, Y. Wu, B. Zhu (April, 2022)

CKM Unitarity Problem

SM predicts unitary V_{CKM} : $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

- V_{ud} from super-allowed nuclear β -decays

- $|V_{ud}|^2 = \frac{K}{2G_F^2 Ft(1+\Delta_R^V)}$

$$|V_{ud}| = 0.973$$

- V_{us} from Kaon decays

- $K_{\ell 3} (K \rightarrow \pi \ell \nu) : |V_{us}| f_+(0)$

- $\frac{K \rightarrow \mu \nu}{\pi \rightarrow \mu \nu} : \left| \frac{V_{us}}{V_{ud}} \right| \times \frac{f_K}{f_\pi}$

$$|V_{us}| = 0.224$$

- V_{ub} from B meson decays

$$|V_{ub}| \simeq 4 \times 10^{-3}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo Anomaly

Since $|V_{ub}| \simeq 10^{-3}$, the unitarity of 1st row reduces to

$$|V_{ud}|^2 + |V_{us}|^2 \stackrel{?}{=} 1 \implies \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \longrightarrow \begin{pmatrix} c\theta_c & s\theta_c \\ -s\theta_c & c\theta_c \end{pmatrix}$$

Cabibbo mixing

With $\Delta_R^V = 0.024\ 62 \pm 0.000\ 14 \Rightarrow V_{ud} = 0.973\ 73 \pm 0.000\ 09$,

deviation from 1st row unitarity:

$$\Delta_{CKM} = (1.12 \pm 0.28) \times 10^{-3} \quad (\sim 3.9\sigma \text{ deficit})$$

(Kirk, 2021)

There is also a less significant deficit in the 1st column unitarity

Left-Right Symmetric Model

(Pati and Salam, 1974; Mohapatra and Pati; Senjanovic and Mohapatra, 1975)

“Left-handed nature of SM is a low energy phenomenon which vanishes at very high scales”

- Parity symmetry is restored; L and R are treated equally
- $\nu_R \Rightarrow$ lightness of neutrino mass

LRSM with Universal Seesaw

(Davidson and Wali, 1987)

- Universal seesaw mechanism to generate fermion masses; requires heavy vector-like (VL) fermions
- Simple Higgs sector : 2 doublet fields
- Fermion mass hierarchy can be explained with $Y \in [10^{-3}, 1]$ rather than $Y \in [10^{-6}, 1]$ as in SM or standard-LRMS

Model Description

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Quarks

$$q_{L_i} (3,2,1, 1/3) = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \quad q_{R_i} (3,1,2, 1/3) = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i$$

$$U_i (3,1,1, 4/3)$$

$$D_i (3,1,1, -2/3)$$

Leptons

$$\psi_{L_i} (1,2,1, -1) = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i \quad \psi_{R_i} (1,1,2, -1) = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}_i$$

$$E_i (1,1,1, -2)$$

$$N_i (1,1,1, 0)$$

Scalar Sector

$$\chi_L (1,2,1,1) \Rightarrow \langle \chi_L^0 \rangle = \kappa_L \simeq 174 \text{ GeV}$$

$$\chi_R (1,1,2,1) \Rightarrow \langle \chi_R^0 \rangle = \kappa_R$$

Gauge Bosons

$$M_{W_L} = \frac{1}{\sqrt{2}} g_L \kappa_L \quad M_{W_R} = \frac{1}{\sqrt{2}} g_R \kappa_R$$

$$M_{Z_L}^2 \simeq \frac{1}{2} (g_L^2 + g_Y^2) \kappa_L^2 \quad M_{Z_R}^2 \simeq \frac{(g_R^4 \kappa_R^2 + g_Y^4 \kappa_L^2)}{2(g_R^2 - g_Y^2)}$$

Seesaw Mechanism

$$\mathcal{L}_Y \supset (\overline{u_L} \quad \overline{c_L} \quad \overline{t_L} \quad \overline{U_L} \quad \overline{C_L} \quad \overline{T_L}) \begin{pmatrix} 0_{3 \times 3} & \begin{matrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{matrix} \\ \begin{matrix} y'_{11} & y'_{12} & y'_{13} \\ y'_{21} & y'_{22} & y'_{23} \\ y'_{31} & y'_{32} & y'_{33} \end{matrix} & \begin{matrix} M_{11} & & \\ & M_{22} & \\ & & M_{33} \end{matrix} \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \\ U_R \\ C_R \\ T_R \end{pmatrix}$$

Under parity symmetry, $\mathcal{Y} = \mathcal{Y}'$

Seesaw Mechanism

$$\mathcal{M} = \begin{pmatrix} 0_{3 \times 3} & \textcolor{red}{y_{U,D,E} \kappa_L} \\ \textcolor{blue}{y'_{U,D,E} \kappa_R} & \textcolor{green}{M_{U,D,E}} \end{pmatrix}_{6 \times 6} \Rightarrow \mathcal{M}_{diag} = U_L^\dagger \mathcal{M} U_R$$

$$U_{X=\{L,R\}} = \begin{pmatrix} \mathbb{1} & -\frac{1}{2}\rho_X^\dagger \rho_X & \rho_X^\dagger \\ & -\rho_X & \mathbb{1} - \frac{1}{2}\rho_X \rho_X^\dagger \end{pmatrix}_{6 \times 6}$$

$$m_0 = \rho_L^\dagger M \rho_R$$

Seesaw mass

$$\left. \begin{array}{l} \rho_L = \kappa_L M^{-1\dagger} y^\dagger \\ \rho_R = \kappa_R M^{-1} y'^\dagger \end{array} \right\}$$

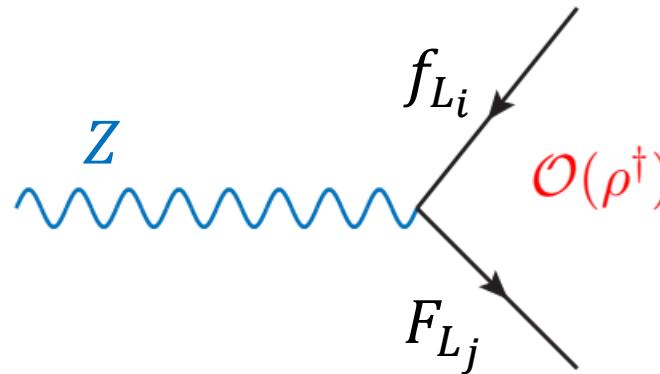
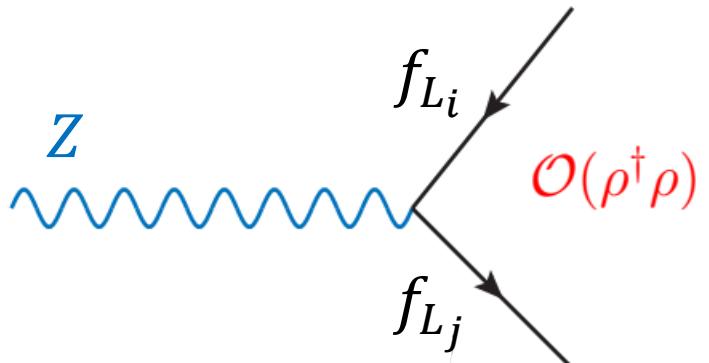
Under parity symmetry,

$$\rho_R = \frac{\kappa_R}{\kappa_L} \rho_L$$

$$m_0 = \kappa_L \kappa_R \frac{y^2}{M}$$

Flavor changing neutral current interactions appear at tree level

(Z-RR interactions remain diagonal)



f : SM fermion
 F : VL-fermion

Provides oblique corrections

Non unitarity is introduced in the “CKM” mixing

$$\mathcal{L}_{W_L} \supset -\frac{g_L}{\sqrt{2}} \bar{u}_L \gamma^\mu W_{L\mu}^+ \left(V_{L_u} V_{L_d}^\dagger - \underbrace{\frac{1}{2} (V_{L_u} \rho_{L_D}^\dagger \rho_{L_D} V_{L_d}^\dagger + V_{L_u} \rho_{L_U}^\dagger \rho_{L_U} V_{L_d}^\dagger)}_{\text{non-unitarity}} \right) d_L$$

Explains Cabibbo anomaly

Resolving Cabibbo Anomaly

Assuming a simple mass mixing (each generation of VLF gives mass to their respective SM counterpart):

$$(\bar{f}_L \quad F_L) \begin{pmatrix} 0 & y\kappa_L \\ y\kappa_R & M \end{pmatrix}_{2 \times 2} \begin{pmatrix} f_R \\ F_R \end{pmatrix}$$

$$\begin{pmatrix} f_L \\ F_L \end{pmatrix} \longrightarrow \begin{pmatrix} c_L & s_L \\ -s_L & c_L \end{pmatrix} \begin{pmatrix} f_L \\ F_L \end{pmatrix}$$

$$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \longrightarrow \left[\begin{array}{ll} \begin{pmatrix} V_{ud} \cancel{c}_{Lu} & V_{us} \cancel{c}_{Lu} \\ V_{cd} & V_{cs} \end{pmatrix} & u \text{ and VL-U mixing} \\ \begin{pmatrix} V_{ud} \cancel{c}_{Ld} & V_{us} \\ V_{cd} c_{Ld} & V_{cs} \end{pmatrix} & d \text{ and VL-D mixing} \\ \begin{pmatrix} V_{ud} & V_{us} \cancel{c}_{Ls} \\ V_{cd} & V_{cs} c_{Ls} \end{pmatrix} & s \text{ and VL-S mixing} \end{array} \right] \longrightarrow L_{(u,d)} \simeq 0.034$$

W Mass Shift from T Parameter

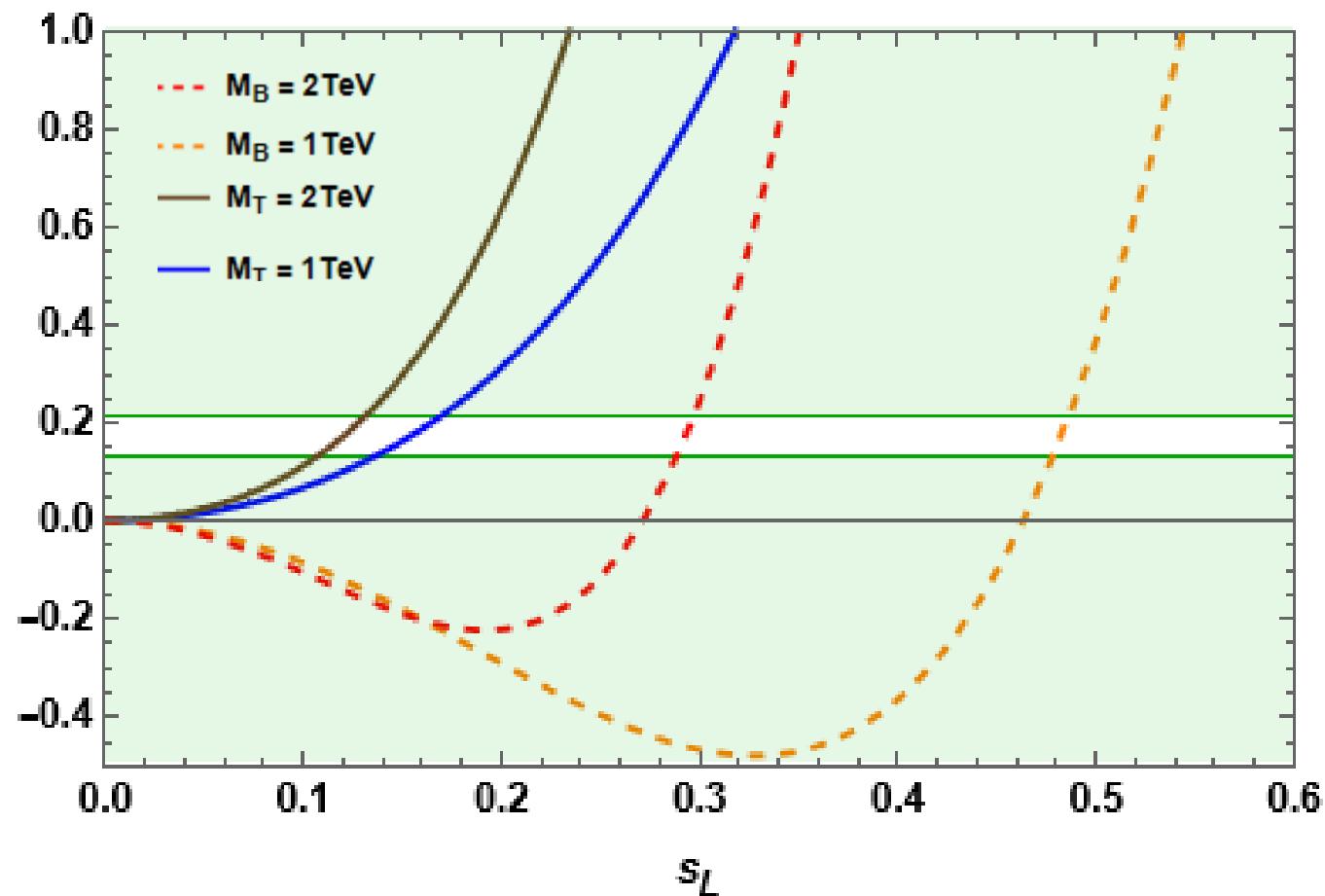
(corrections to S parameter is ~ 0)

Under small angle approximation,

(Chen, Dawson and Furlan, 2017)

$$\Delta T^B = -\frac{N_c m_t^2}{8\pi s_w^2 M_W^2} s_{L_b}^2 \log(r_B) + \mathcal{O}\left(s_{L_b}^4, \frac{1}{r_B}\right)$$

$$\Delta T^T = \frac{N_c m_t^2}{8\pi s_w^2 M_W^2} s_{L_t}^2 (\log(r_T) - 1) + \mathcal{O}\left(s_{L_t}^2, \frac{1}{r_T}\right)$$



VL-top provides positive shift to explain W mass excess

Constraints

SM fermion mass constraint under parity symmetry:

$$m_f = \frac{s_L^2}{\kappa_L} \kappa_R M_F \quad \xrightarrow{\hspace{1cm}} \quad \kappa_R M_F \in [16, 1.5 \times 10^6] \text{ GeV}^2$$

contradicts the experimental limits:

$$\kappa_R \gtrsim 10 \text{ TeV and } M_F > 1 \text{ TeV}$$

Constraint from Z decay width: $\Delta\Gamma_Z \leq 2.3 \text{ MeV}$

$$Z f_L \bar{f}_L: (T_{3L} - Q s_w^2) \rightarrow T_{3L} \mathbf{c}_L^2 - Q s_w^2$$

For mixing angles resolving Cabibbo anomaly:

$$d: \Delta\Gamma_Z \simeq 1 \text{ MeV} \quad u: \Delta\Gamma_Z \simeq 0.8 \text{ MeV} \quad s: \Delta\Gamma_Z \simeq \cancel{19.7} \text{ MeV}$$

Combined Solution

- Evade Z decay constraints
 - ✓ Up – quark or down- quark mixing for Cabibbo anomaly → also explain **non-unitarity in 1st column**
- Top quark mixing ⇒ W mass shift from T parameter
- Evade SM mass restriction: go to a basis where SM fermions are “massless” (perturbative)

Cabibbo anomaly

$$(d \quad D \quad S) : \begin{pmatrix} 0 & 0 & y_d \kappa_L \\ 0 & 0 & M_{1d} \\ y_d \kappa_R & M_{1d} & M_{2d} \end{pmatrix}$$



$$\Delta_{CKM} = s_{Ld}^2$$

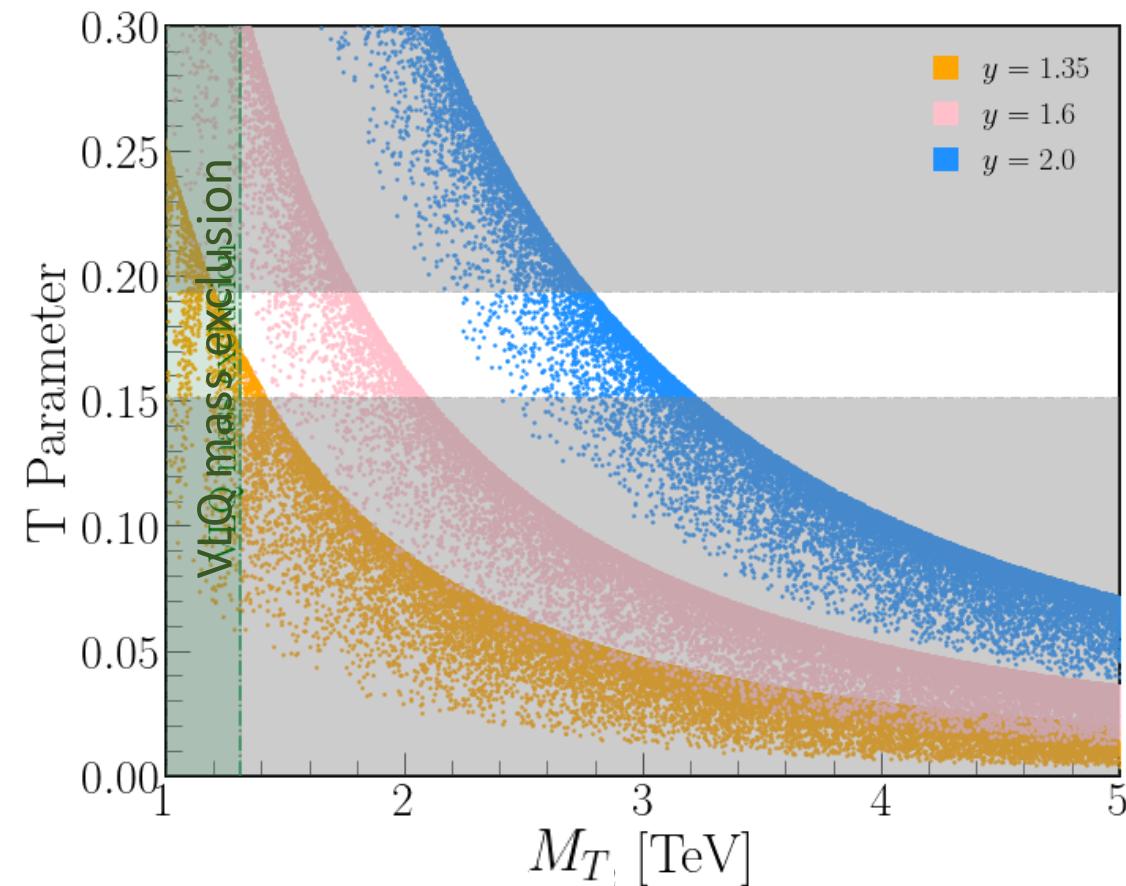
T parameter

$$(t \quad C \quad T) : \begin{pmatrix} 0 & 0 & y_t \kappa_L \\ 0 & 0 & M_{1t} \\ y_t \kappa_R & M_{1t} & M_{2t} \end{pmatrix}$$



$$\Delta T \simeq \frac{N_c}{16\pi M_W^2 s_W^2} M_T^2 s_{Lt}^4$$

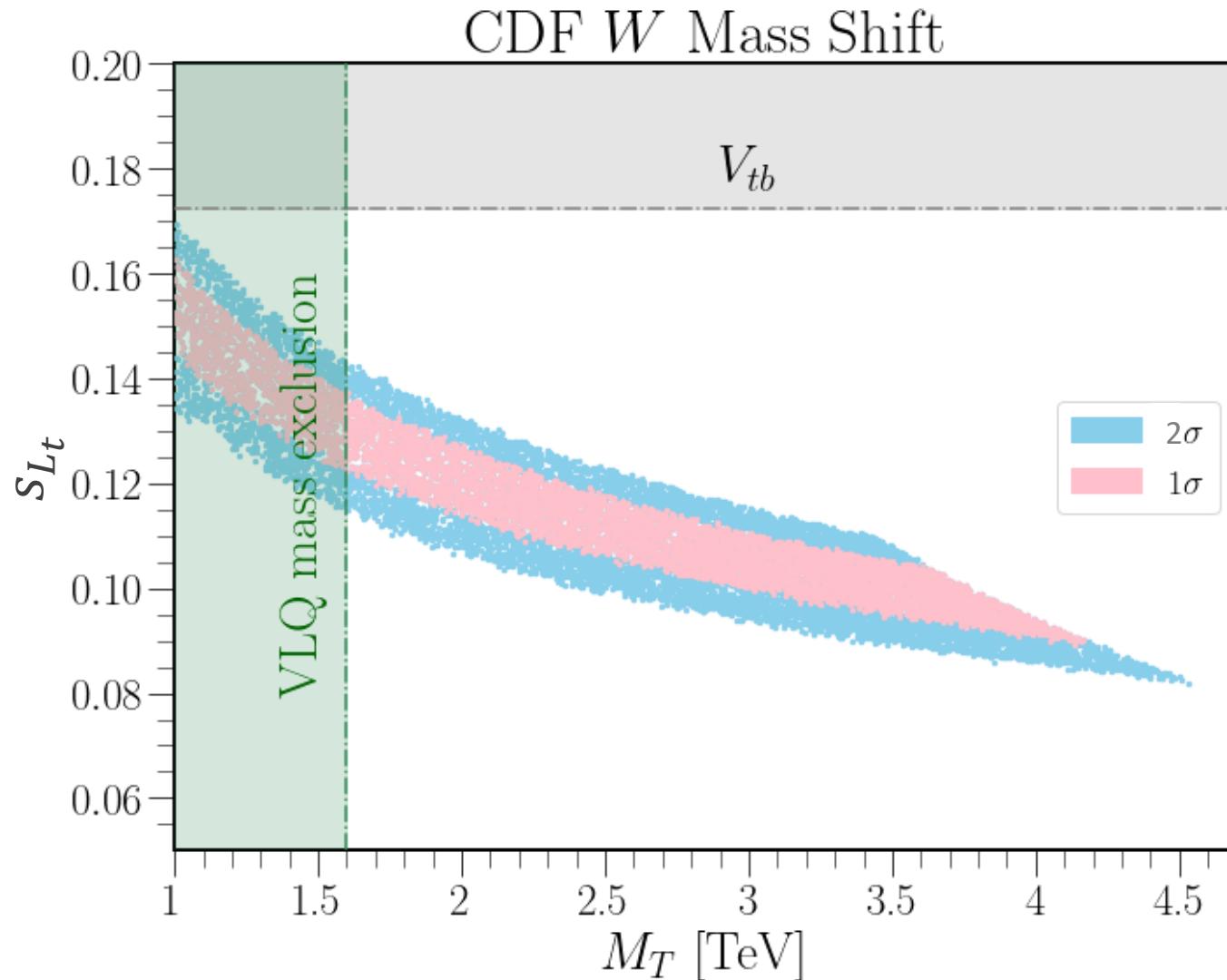
Combined Solution: Stability of Higgs Potential



$$V \supset \frac{\lambda_{1L}}{2}(\chi_L^\dagger \chi_L)^2 + \frac{\lambda_{1R}}{2}(\chi_R^\dagger \chi_R)^2 + \lambda_2 (\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R)$$

- Lower bound on VLQ mass $\Rightarrow y \geq 1.35$ to explain CDF W mass shift
- Large y can turn λ_{1L} negative in VLQ mass range $\in [1, 40]$ TeV ...
 - ... unless λ_{1R} becomes active at lower scale \sim lowest of VLQ mass; changes RGE
- Achieved by lowering the mass of second Higgs (M_H) to the lightest VLQ mass \Rightarrow Predicts heavy Higgs mass

Results and Predictions



- down mixes w/ 2 VL-down quarks and top w/ 2 VL-up quarks
- $M_T \lesssim 4.5$ TeV explains W mass shift
- $M_D \lesssim 16$ TeV resolves Cabibbo anomaly
- $M_H \lesssim 4.5$ TeV ensures Higgs potential stability

Concluding Remarks

- UV-complete left-right symmetric model with a universal seesaw and simple Higgs sector; heavily constrained
- Resolve Cabibbo angle anomaly and explain W mass shift simultaneously under parity symmetry
 - Unique and non-trivial solution where light quark mixes with two VLQs
 - Both up- and down-type VLQs are necessary
 - Upper limit on VLQ $\sim \mathcal{O}(\text{TeV})$; testable in the near future
 - Ensuring Higgs potential stability predicts a TeV scale heavy Higgs
 - Heavy Higgs mass \lesssim lightest VLQ mass

Thank You

Backup Slides

$$V_{CKM} = \begin{pmatrix} V_{ud} c_{L_1^d} & V_{us} c_{L_1^d} & V_{ub} c_{L_1^d} & -s_{L_1^d} s_{L_2^d} & c_{L_2^d} s_{L_1^d} & 0 \\ V_{cd} & V_{cs} & V_{cb} & 0 & 0 & 0 \\ V_{td} c_{L_1^u} & V_{td} c_{L_1^u} & V_{td} c_{L_1^u} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -V_{td} c_{L_2^u} s_{L_1^u} & -V_{ts} c_{L_2^u} s_{L_1^u} & -V_{tb} c_{L_2^u} s_{L_1^u} & 0 & 0 & 0 \\ V_{td} s_{L_2^u} s_{L_1^u} & V_{ts} s_{L_2^u} s_{L_1^u} & V_{tb} s_{L_2^u} s_{L_1^u} & 0 & 0 & 0 \end{pmatrix}$$

$$\begin{pmatrix} A & & & & & \\ & A & & & & \\ & & A c_{L_1^u}^2 + B s_{L_1^u}^2 & & & \\ & & & X & X & \\ & & & 0 & & \\ & & & & X & X \\ & & & & X & X \\ & & & & X & X \end{pmatrix}$$

$$\begin{pmatrix} A c_{L_1^d}^2 + B s_{L_1^d}^2 & & X & X & & \\ & A & & & & \\ & & A & & & \\ & & & X & X & \\ & & & X & X & \\ & & & & X & X \\ & & & & & 0 \end{pmatrix}$$

Backup Slides

$$\hat{\alpha}(M_Z)T \equiv \frac{\Pi_{WW}^{\text{new}}(0)}{M_W^2} - \frac{\Pi_{ZZ}^{\text{new}}(0)}{M_Z^2}$$

$$\frac{\hat{\alpha}(M_Z)}{4\hat{s}_Z^2\hat{c}_Z^2}S \equiv \frac{\Pi_{ZZ}^{\text{new}}(M_Z^2) - \Pi_{ZZ}^{\text{new}}(0)}{M_Z^2} - \frac{\hat{c}_Z^2 - \hat{s}_Z^2}{\hat{c}_Z\hat{s}_Z} \frac{\Pi_{Z\gamma}^{\text{new}}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}^{\text{new}}(M_Z^2)}{M_Z^2}$$

$$\frac{\hat{\alpha}(M_Z)}{4\hat{s}_Z^2}(S + U) \equiv \frac{\Pi_{WW}^{\text{new}}(M_W^2) - \Pi_{WW}^{\text{new}}(0)}{M_W^2} - \frac{\hat{c}_Z}{\hat{s}_Z} \frac{\Pi_{Z\gamma}^{\text{new}}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}^{\text{new}}(M_Z^2)}{M_Z^2}$$

$$\Pi_{ab}(q^2) = \frac{1}{2\pi^2} \sum_{ij} \int_0^1 dx \ f_{ab}(q^2, x) \ \ln \left[\frac{m_{ij}^2(x) - q^2 x(1-x)}{\mu^2} \right]$$

$$f_{ab}(q^2, x) = \frac{g_L^a g_L^{b*} + g_R^a g_R^{b*}}{2} \left[x(1-x) q^2 - \frac{m_{ij}^2(x)}{2} \right] + \frac{g_L^a g_R^{b*} + g_R^a g_L^{b*}}{2} \left(\frac{m_i m_j}{2} \right)$$

Backup Slides

RGE of quartic couplings in LRSM

$$\begin{aligned} 16\pi^2 \frac{d\lambda_{1_L}}{dt} &= 12\lambda_{1_L}^2 + 4\lambda_2^2 + \frac{9}{4}(g_L^4 + g_L^2 g_B^2 + \frac{3}{4}g_B^4) - \lambda_{1_L}(9g_L^2 + \frac{9}{2}g_B^2) \\ &\quad + 4\lambda_{1_L}\{3\text{Tr}(\mathcal{Y}_L^u \mathcal{Y}_L^{u\dagger}) + 3\text{Tr}(\mathcal{Y}_L^d \mathcal{Y}_L^{d\dagger}) + \text{Tr}(\mathcal{Y}_L^e \mathcal{Y}_L^{e\dagger})\} \\ &\quad - 4\left\{3\left(\text{Tr}(\mathcal{Y}_L^u \mathcal{Y}_L^{u\dagger})\right)^2 + 3\left(\text{Tr}(\mathcal{Y}_L^d \mathcal{Y}_L^{d\dagger})\right)^2 + \left(\text{Tr}(\mathcal{Y}_L^e \mathcal{Y}_L^{e\dagger})\right)^2\right\} \end{aligned}$$

$$\delta_\lambda = \frac{3}{16\pi^2} \left(y_u^4 \ln \left[\frac{M_{U_3}}{M_{U_2}} \right] + y_d^4 \ln \left[\frac{M_{U_3}}{M_{D_2}} \right] \right)$$

$$\begin{aligned} 16\pi^2 \frac{d\lambda_{1_R}}{dt} &= 12\lambda_{1_R}^2 + 4\lambda_2^2 + \frac{9}{4}(g_R^4 + g_R^2 g_B^2 + \frac{3}{4}g_B^4) - \lambda_{1_R}(9g_R^2 + \frac{9}{2}g_B^2) \\ &\quad + 4\lambda_{1_R}\{3\text{Tr}(\mathcal{Y}_R^u \mathcal{Y}_R^{u\dagger}) + 3\text{Tr}(\mathcal{Y}_R^d \mathcal{Y}_R^{d\dagger}) + \text{Tr}(\mathcal{Y}_R^e \mathcal{Y}_R^{e\dagger})\} \\ &\quad - 4\left\{3\left(\text{Tr}(\mathcal{Y}_R^u \mathcal{Y}_R^{u\dagger})\right)^2 + 3\left(\text{Tr}(\mathcal{Y}_R^d \mathcal{Y}_R^{d\dagger})\right)^2 + \left(\text{Tr}(\mathcal{Y}_R^e \mathcal{Y}_R^{e\dagger})\right)^2\right\} \end{aligned}$$