LHC and the scale of Left-Right symmetry

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A Double Feature with Fabrizio Nesti

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Left-right model

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

- Theoretically appealing — Pati, Salam '74, Mohapatra, Pati '75
  - Parity restored at high energies
  - Choice of $U(1)$ charges physical (Y vs. B-L)
- Parity broken spontaneously — Senjanović, Mohapatra '75, Senjanović '79
- RH neutrino-seesaw

plenary talk by Senjanović

Parity, yes. But which?

- The choice of l-r symmetry not unique
- Originally parity
- Charge conjugation
  - equally valid, *P* studied more
- Yukawa term invariance

$$\mathcal{P}: f_L \leftrightarrow f_R \;\&\; \phi \to \phi^\dagger$$

$$\mathcal{C}: f_L \leftrightarrow (f_R)^c \;\&\; \phi \to \phi^T$$

$$Y\, \overline{f}_L \phi f_R + \text{h.c.}$$

$$\mathcal{P}: Y = Y^\dagger \qquad \mathcal{C}: Y = Y^T$$

parallel talk by Nesti

The minimal model

- A bi-doublet and a pair of triplets

$\phi(2, 2, 0)$ $\Delta_L\,(3, 1, 2)\,,\ \Delta_R\,(1, 3, 2)$

- Two-stage symmetry breaking

- 1^{st} $\langle\Delta_L\rangle = 0, \quad \langle\Delta_R\rangle = v_R$ $m_{W_R,\nu_R} \propto v_R$

- 2^{nd} $\langle\phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$ $m^2_{W_L} \propto v^2 = v_1^2 + v_2^2$ $\langle\Delta_L\rangle \propto v^2/v_R$

$v \ll v_R$

- Light neutrinos massive: seesaw (type I and II)

Mohapatra, Senjanović '80

Setting the right scale

- Direct search at D0(dijets) $m_{W_R} > 800$ GeV
- Precision bounds depend on V_R
  - for arbitrary V_R no bound, e.g.
  - in *minimal* models $V_R \simeq V_L$

$$V_R = \begin{pmatrix} e^{i\psi} & 0 & 0 \\ 0 & c\,e^{i\rho} & -s\,e^{i\sigma} \\ 0 & s\,e^{i\tau} & c\,e^{i\nu} \end{pmatrix}$$

$\theta_{12R} = 0, \pi/2$

- Stringent limits from $\Delta F = 2$

Beall, Bander, Soni '82
Mohapatra, Senjanović, Tran '83

  - $K_0 - \overline{K}_0$ mixing $m_{W_R} > 1.6 - 2.5$ TeV
  - recent claims out of LHC reach!

Zhang, An, Ji, Mohapatra '07
Xu, An, Ji '10

  - P only, combined ϵ, ϵ', nEDM $m_{W_R} > 10$ TeV

The right interactions

- Yukawa sector and mass diagonalization

$$\mathcal{L}_Y = \overline{Q}_L \left(Y\phi + \tilde{Y}\tilde{\phi} \right) Q_R + \text{h.c.}$$

$$\begin{aligned} M_u &= U_{uL}\, m_u\, U_{uR}{}^\dagger \\ M_d &= U_{dL}\, m_d\, U_{dR}{}^\dagger \end{aligned}$$

- Gauge interactions in both left and right

$$\mathcal{L}_g = \frac{g}{\sqrt{2}} \left(\overline{u}_L \not{W}_L\, V_L\, d_L + \overline{u}_R \not{W}_R\, V_R\, d_R + \text{h.c.} \right)$$

$$\begin{aligned} V_L &= U_{uL}{}^\dagger U_{dL} \\ V_R &= U_{uR}{}^\dagger U_{dR} \end{aligned}$$

- Tree-level FCNC Higgs

$$\mathcal{L}_H^{fcnc} \simeq \frac{g}{2m_{W_L}} \left[\overline{u}_L \left(V_L m_d V_R{}^\dagger \right) u_R H_0 + \overline{d}_L \left(V_L{}^\dagger m_u V_R \right) d_R H_0^* \right]$$

- “up” governed by “down” masses and vice-versa

Left and right mixings

- A minimal setup with P as L-R symmetry — Kiers et al. '02, Zhang et al. '07
- Usually assumptions are made (e.g. small vev ratio)
- A complete analytical & numerical study — Maiezza et al. '10

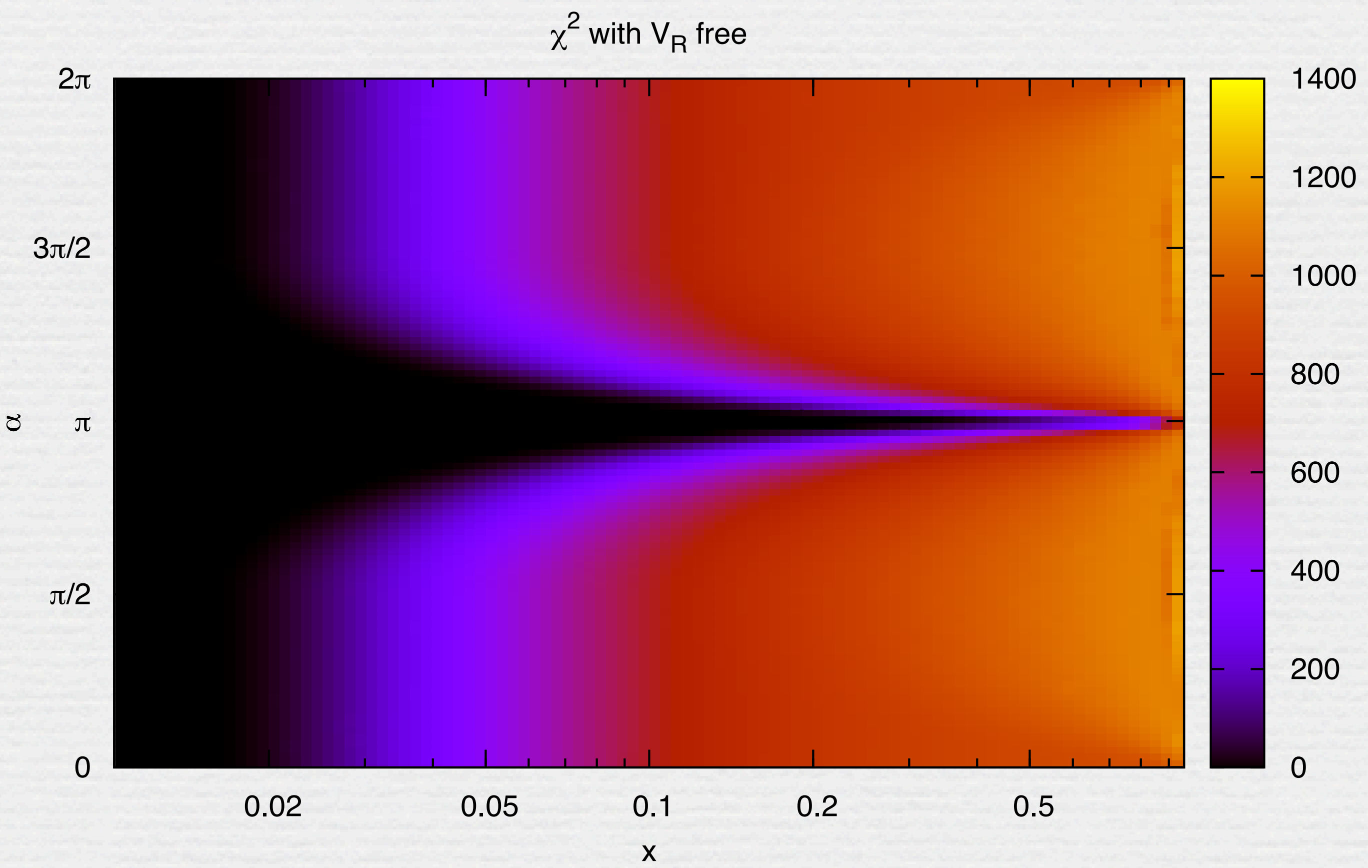
$$M_u = v\left(c\,Y + s\,e^{-i\alpha}\,\tilde{Y}\right)$$
$$M_d = v\left(s\,e^{i\alpha}\,Y + c\,\tilde{Y}\right)$$

- A two phase theory

  α and $\tilde{Y}_{i\neq j}$

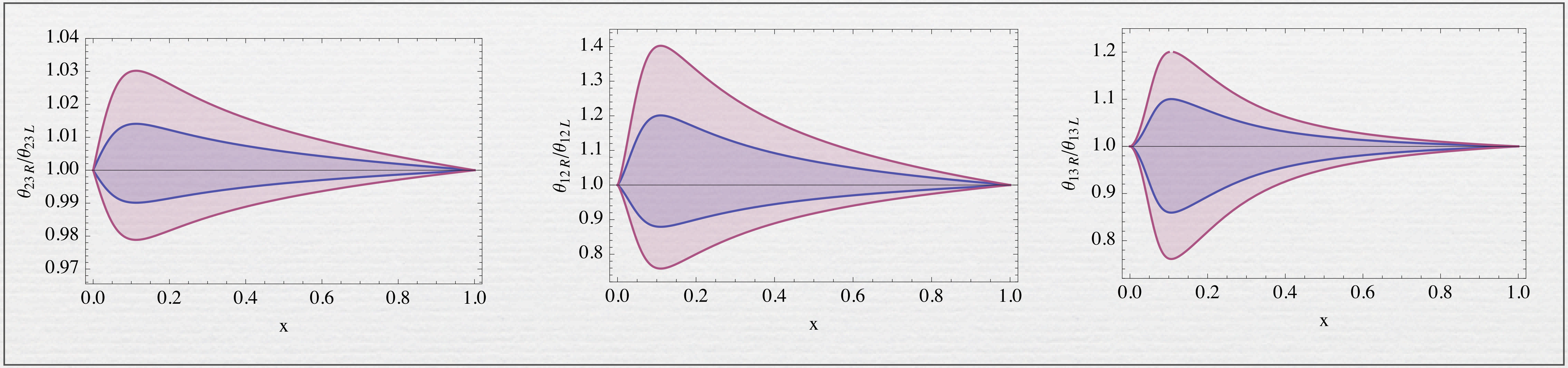
- Matrices hermitian if

  $x \equiv s/c \to 0$ or $\alpha \to 0, \pi$



Left and right mixings

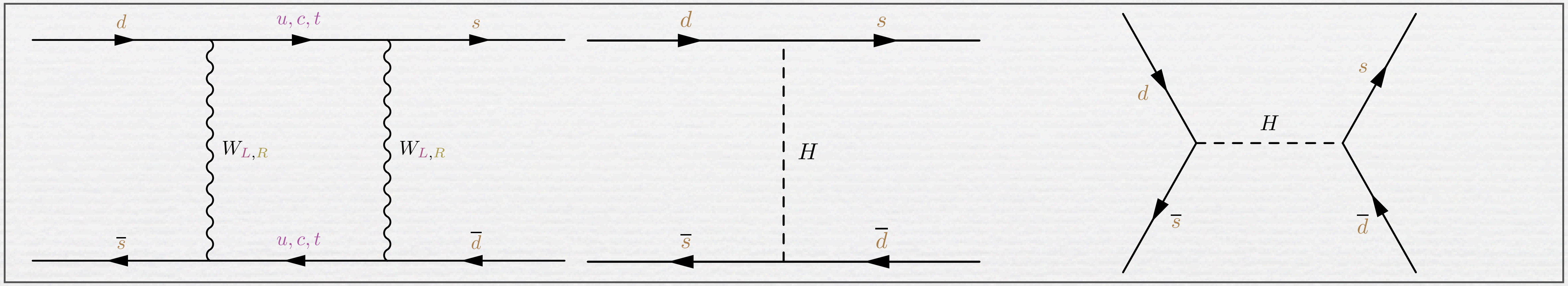
$\mathcal{P} : V_R \simeq S_u V_L S_d \qquad S_{ud} = diag(\pm, \pm, \pm)$ Ecker, Grimus '85



- Angles differ by ~1-20%
- Cabibbo can be reduced, but m_s goes down
- Only two phases; one fixed by CKM, only one remains
- Additional signs S_{ud} in up and down sector available

Limits from Kaons

- Bounds from Δm_K , ϵ and ϵ' , calculate M_{12}



$$\mathcal{H}_{full}^{\Delta F=2} = \mathcal{H}_{LL}{}^{\Delta F=2} + \mathcal{H}_{LR}{}^{\Delta F=2} + \mathcal{H}_{RR}{}^{\Delta F=2} + \mathcal{H}_{H}^{\Delta F=2}$$

$$\mathcal{H}_{LL}{}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2} \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu P_L d\bar{d}'\gamma^\mu P_L d \sum_{i,j=c,t} \lambda_i^{LL}\lambda_j^{LL} S_{LL}(x_i, x_j)\,\eta_{LL,ij}$$

$$\mathcal{H}_{LR}{}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2} 8\beta \sum_{d,d'=d,s,b} \bar{d}' P_L d\, \bar{d}' P_R d \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL} S_{LR}(x_i, x_j, \beta)\,\eta_{LR,ij}$$

$$\mathcal{H}_{H}^{\Delta F=2} = -\frac{4G_F}{\sqrt{2}M_H^2} \sum_{d,d'=d,s,b} \bar{d}' P_L d\bar{d}' P_R d \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL} m_i m_j$$

$\lambda_i^{AB} = V_{id'}^{A*} V_{id}^{B}$ ❧ ckm | S_{xx} ❧ Inami-Lin | η ❧ qcd

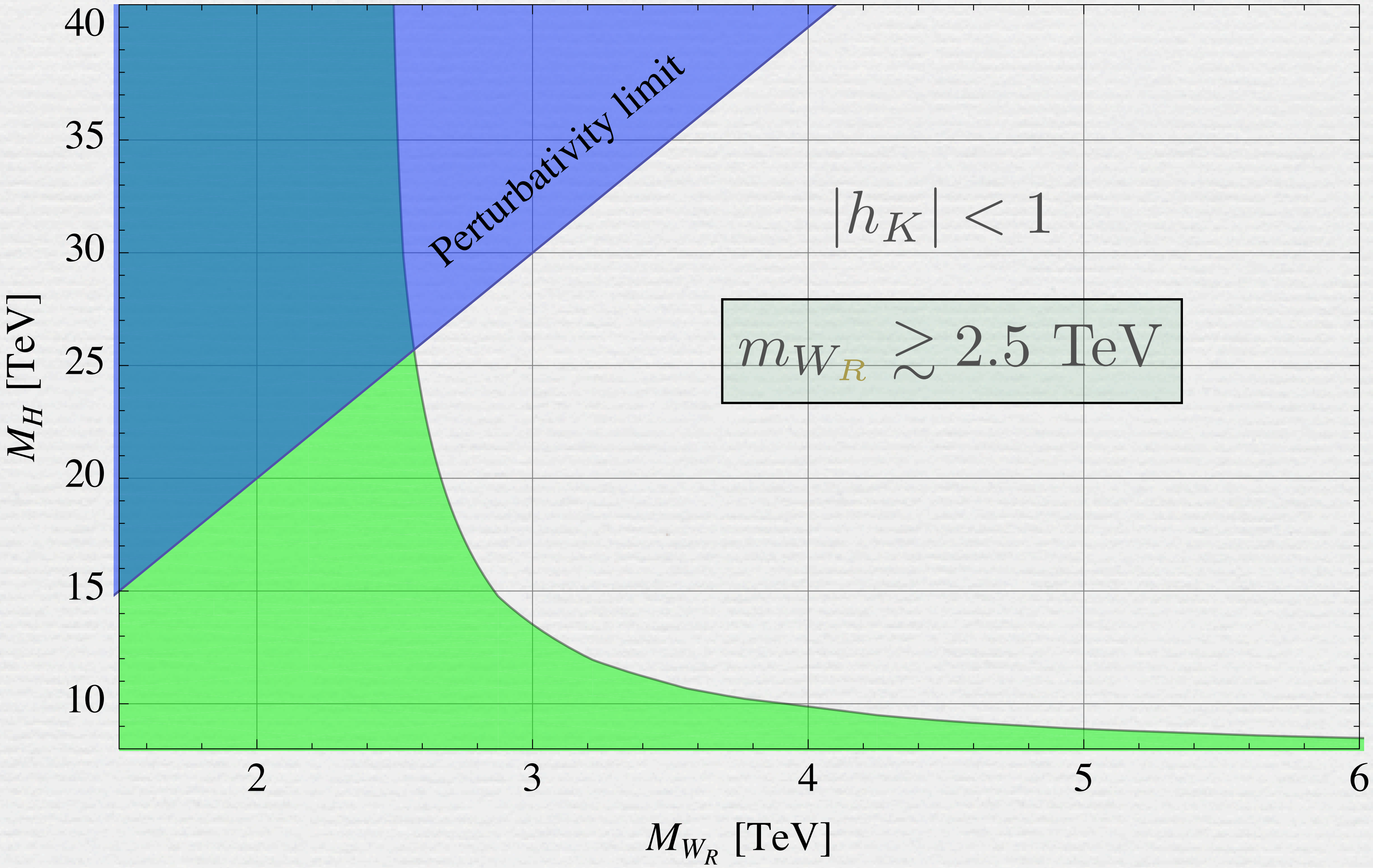
Beall, Bander, Soni '81 Mohapatra, Senjanović, Tran '83, Ecker, Grimus '85...

Combined bound

- LR box enhanced over LL, dominant is c-c
  - a factor of 8 from the loop diagram
  - a factor of -9 from $S_{LR} \simeq -9\, m_c{}^2/m_{W_L}^2$ → enhancement of 1000
  - a factor of 20 from the matrix element

$$h_K = \frac{\mathrm{Re}\left\langle K^0 | \mathcal{H}^{\Delta S=2}_{LR+H} | \overline{K}^0 \right\rangle}{\mathrm{Re}\left\langle K^0 | \mathcal{H}^{\Delta S=2}_{SM} | \overline{K}^0 \right\rangle}$$

- s_{12R} does not help
- Higgs with $S_t = -1$
- LD contribution?



ε and ε'

$$\varepsilon_K = -e^{i\pi/4}\mathrm{Im}\left\langle K^0|\mathcal{H}^{\Delta S=2}|\overline{K^0}\right\rangle/\sqrt{2}\Delta m_K$$

- Contributions from the c-c (real in SM) and c-t term

$$\mathcal{P}: \quad h_\epsilon \simeq \mathrm{Im}\left[e^{i(\theta_d-\theta_s)}\left(A_{cc}+A_{ct}e^{i\arg(V_{Ltd})}\cos(\theta_c-\theta_t)\right)\right]$$

- From $|h_\varepsilon| < 0.3$ UTfit '08 a bound could emerge
- Although P a two phase theory $\theta_d - \theta_s \neq 0$ enough to cancel both W and Higgs Zhang et al. '07

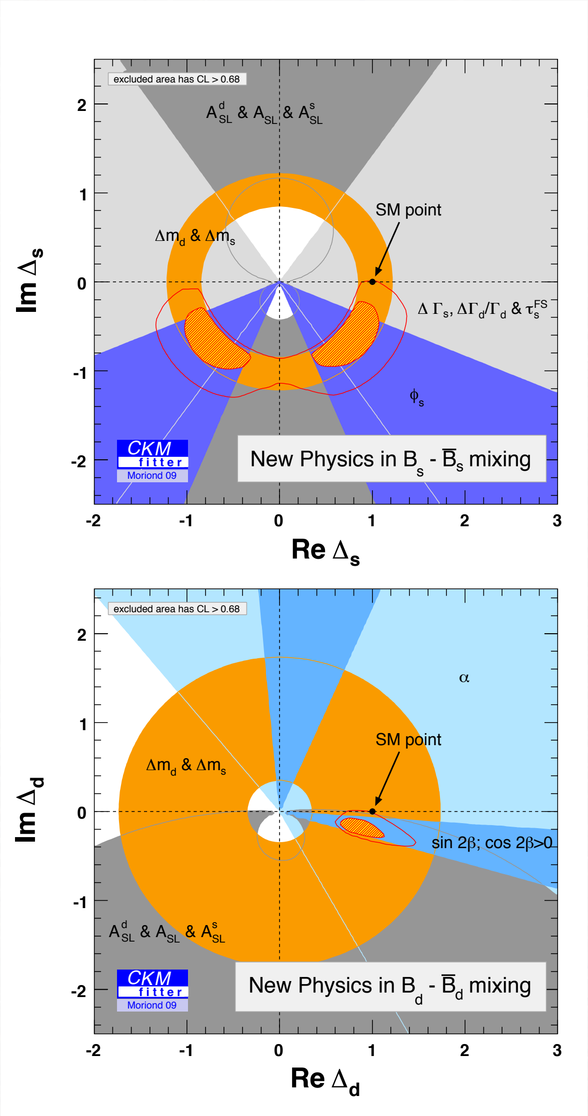
- Direct CP violation more involved

$$S_q = +1 \quad m_{W_R} > 4.2 \text{ TeV}$$
$$S_u = -1 \quad m_{W_R} > 3.1 \text{ TeV}$$

Zhang et al. '07

Maiezza, Nesti, M.N., Senjanović '10

Bd and Bs



- No chiral enhancement (factor of 1.5)
- Dominant terms t-t, both LR and RR
- A loose bound emerges from Δm_{B_q}

$$|h_d| \simeq \frac{\Delta m_{B_d}^{LR}}{\Delta m_{B_d}^{exp}} \simeq \left(\frac{0.46\,\text{TeV}}{M_{W_R}}\right)^2 \left[1 - 0.60 \ln \frac{0.45\,\text{TeV}}{M_{W_R}}\right]$$

$$|h_s| \simeq \frac{\Delta m_{B_s}^{LR}}{\Delta m_{B_s}^{exp}} \simeq \left(\frac{0.47\,\text{TeV}}{M_{W_R}}\right)^2 \left[1 - 0.50 \ln \frac{0.47\,\text{TeV}}{M_{W_R}}\right]$$

- Demanding $|h_q| < 0.8$

[TeV]	m_{W_R}	m_H
B_d	1.9	13
B_s	1.8	12

- CP discrepancy remains!
- No more phases left and $\theta_b - \theta_{d,s}$ too small
- C can do it recall Nesti

Summary of bounds

	m_{W_R} [TeV]	m_H [TeV]
Δm_K	2.3	7.7
Δm_{B_d}	1.9	13
Δm_{B_s}	1.8	12
CP in B_q	x	x
ε_K	-	-
ε'	3.1(4.2)	-
nEDM	(4-10)*	(25)*

Maiezza, Nesti, MN, Senjanović '10

*assuming $\overline{\theta} = 0$

Conclusions & Outlook

- Left-right symmetry at LHC?
- A complete analysis of both *P* and *C*
  - *P* marginally detectable at ~3 TeV
  - *C* within reach @ 2-3 TeV (hints from B_s)
- Long distance?
- Lepton Flavor Violation
- A possible handle on leptonic CP-phases

Backup Slides

Lepton Flavor Violation

- Rich LFV phenomenology   recall Senjanović   Inami-Lim'82
  Swartz '89
  Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04
  MN, Nesti, Senjanović, Tello, to appear
  - tree level $\mu \to 3e$
  - correlations between $\mu \to 3e, \mu \to e\gamma$ and $\mu \to e$
- $\mu - e$ conversion will improve by 4-6 orders
- CP-odd & T-odd triple spin correlations studied
  - seesaw w.o. interactions
  - l-r well possible up to 10-30 TeV

CP phases in μ N $-$ e N

- Boxes & penguins with W and Δ — Bajc, MN, Senjanović '10
- Form a correlation $(\vec{s}_\mu \times \vec{s}_e) \cdot \vec{p}_e$ — Davidson '08, Ayazi, Farzan '09
- An example

$$\mathcal{L}_{eff} = G_F \sum_{q=u,d} \left(A_L \bar{e}_L \gamma^\mu \mu_L + A_R \bar{e}_R \gamma^\mu \mu_R\right) \left(V_L^q \bar{q}_L \gamma^\mu q_L + V_R^q \bar{q}_R \gamma^\mu q_R\right) + \text{h.c.}$$

- Correlation proportional to $\delta_{CP} = \dfrac{Im(A_L{}^* A_R)}{|A_L|^2 + |A_R|^2}$

$$A_L(W_L) \approx 0, \quad A_R(W_R) \approx \frac{\alpha}{\pi}\left(\frac{M_L}{M_R}\right)^2 \left(\frac{M_N}{M_{W_R}}\right)^2$$

$$A_L(\Delta_L) \sim A_R(\Delta_R) \approx \frac{\alpha}{\pi}\left(\frac{M_L}{M_R}\right)^2 Y_\Delta^2$$

$$\delta_{CP} = \frac{\text{Im}(A_L(\Delta_L) A_R{}^*(\Delta_R + W_R))}{|A_L|^2 + |A_R|^2} \neq 0$$

ϵ'

$$H_{\Delta S=1} = \sqrt{2} G_F \lambda_u^{LL} \left[\left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_L}^2)} \right)^{-\frac{2}{b}} O_+^{LL}(\mu) + \left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_L}^2)} \right)^{\frac{4}{b}} O_-^{LL}(\mu) \right]$$
$$+ \sqrt{2} G_F \frac{M_{W_L}^2}{M_{W_R}^2} \lambda_u^{RR} \left[\left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_R}^2)} \right)^{-\frac{2}{b}} O_+^{RR}(\mu) + \left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_R}^2)} \right)^{\frac{4}{b}} O_-^{RR}(\mu) \right]$$
$$+ 2\sqrt{2} G_F \sin\zeta \, \lambda_u^{LR} e^{i\alpha} \left[\left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_L}^2)} \right)^{\frac{8}{b}} O_-^{LR}(\mu) + \left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_L}^2)} \right)^{-\frac{1}{b}} O_+^{LR}(\mu) \right]$$
$$+ 2\sqrt{2} G_F \sin\zeta \, \lambda_u^{RL} e^{-i\alpha} \left[\left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_L}^2)} \right)^{\frac{8}{b}} O_-^{RL}(\mu) + \left(\frac{\alpha_S(\mu^2)}{\alpha_S(M_{W_L}^2)} \right)^{-\frac{1}{b}} O_+^{RL}(\mu) \right]$$

L-R mixing: $\tan\zeta \, e^{i\alpha} = e^{i\alpha} \left(M_{W_L}^2 / M_{W_R}^2 \right) 2x / \left(1 + x^2 \right)$

- Bound of
- However with

$S_q = +1 \quad m_{W_R} > 4.2 \text{ TeV}$

$S_u = -1 \quad m_{W_R} > 3.1 \text{ TeV}$

Matrix Elements

$$\left\langle M^0 \left| \bar{d}' \gamma_\mu P_L d \, \bar{d}' \gamma_\mu P_L d \right| \overline{M}^0 \right\rangle = \left\langle M^0 \left| \bar{d}' \gamma_\mu P_R d \, \bar{d}' \gamma_\mu P_R d \right| \overline{M}^0 \right\rangle = \frac{2}{3} f_M^2 m_M \mathcal{B}_M^{LL}$$

$$\left\langle M^0 \left| \bar{d} P_L d' \, \bar{d} P_R d' \right| \overline{M}^0 \right\rangle = \frac{1}{2} f_M^2 m_M \mathcal{B}_M^{LR} \left[\left(\frac{m_M}{m_{d'} + m_d} \right)^2 + \frac{1}{6} \right]$$

$$\mathcal{B}_K^{LR} = 0.81 \qquad f_K = 0.113 \text{ GeV} \qquad \mathcal{B}_K^{LL} = 0.721(05)(40)$$

$$\mathcal{B}_{B_d}^{LR} = 1.15 \qquad f_{B_d} = 0.134 \text{ GeV} \qquad \mathcal{B}_{B_d}^{LL} = 1.17(5)(7)$$

$$\mathcal{B}_{B_s}^{LR} = 1.16 \qquad f_{B_s} = 0.161 \text{ GeV} \qquad \mathcal{B}_{B_s}^{LL} = 1.23(3)(5)$$

$$\left\langle K^0 \left| \bar{d} \gamma_\mu P_L s \, \bar{d} \gamma_\mu P_L s \right| \overline{K}^0 \right\rangle \simeq 0.00304 \, \text{GeV}^3 \qquad \left\langle K^0 \left| \bar{d} P_L s \, \bar{d} P_R s \right| \overline{K}^0 \right\rangle \simeq 0.059 \, \text{GeV}^3$$

$$\left\langle B_d \left| \bar{d} \gamma_\mu P_L b \, \bar{d} \gamma_\mu P_L b \right| \overline{B}_d \right\rangle \simeq 0.074 \, \text{GeV}^3 \qquad \left\langle B_d \left| \bar{d} P_L b \, \bar{d} P_R b \right| \overline{B}_d \right\rangle \simeq 0.096 \, \text{GeV}^3$$

$$\left\langle B_s \left| \bar{s} \gamma_\mu P_L b \, \bar{s} \gamma_\mu P_L b \right| \overline{B}_s \right\rangle \simeq 0.114 \, \text{GeV}^3 \qquad \left\langle B_s \left| \bar{s} P_L b \, \bar{s} P_R b \right| \overline{B}_s \right\rangle \simeq 0.139 \, \text{GeV}^3.$$