Minimal flavour violation with non-linearly realized EWSB

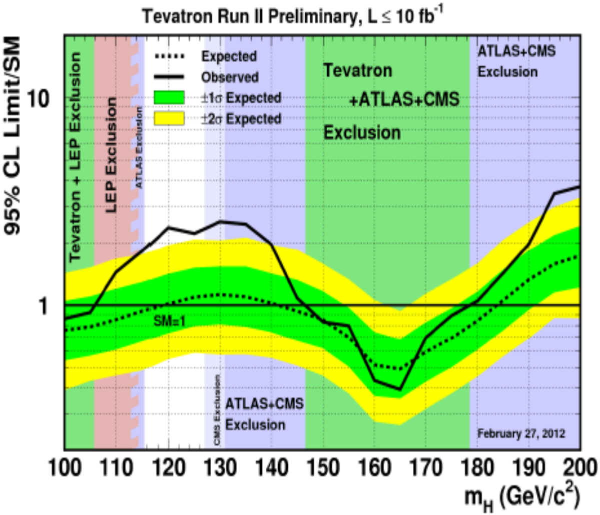
Juan Yepes

Instituto de Física Teórica, IFT-UAM/CSIC
Universidad Autónoma de Madrid

XL International Meeting on Fundamental Physics
Benasque, 2012, May 24th-June 3rd 2012

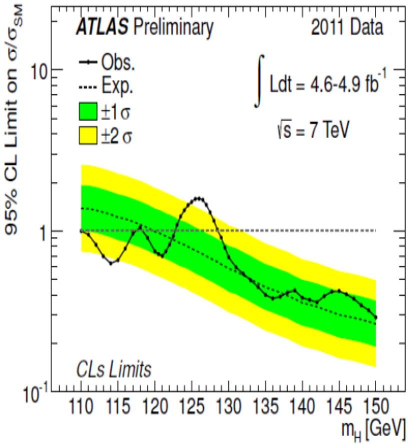
Alonso, Gavela, Merlo, Rigolin & JY, hep-ph/**1201.1511**

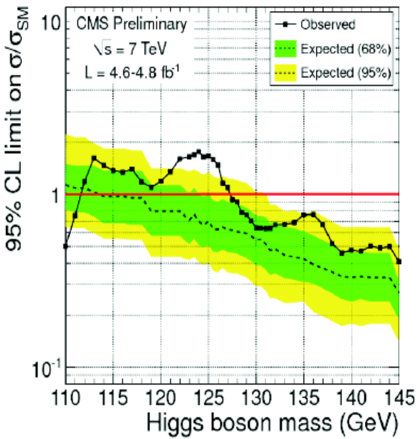
CDF + DØ



$$115 < m_H(GeV) < 135$$

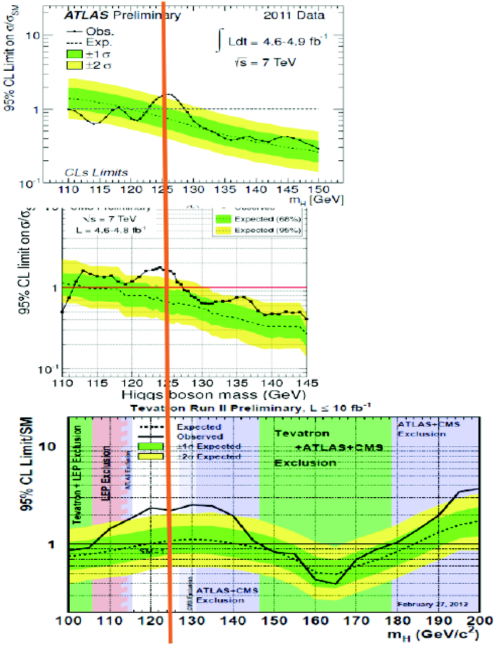
ATLAS & CMS





$122.5 < m_H(\text{GeV}) < 129$

$114.4 < m_H(\text{GeV}) < 127.5$



Blondel resume Moriond 2012

IF NO HIGGS THERE...

IF NO HIGGS THERE...$\rightarrow$ m_H up to TeV $\rightarrow$STRONG INTERACTING REGIME

Kaplan & Georgi '84

IF NO HIGGS THERE...$\rightarrow$ m_H up to TeV $\rightarrow$STRONG INTERACTING REGIME

Kaplan & Georgi '84

IF THERE , AND NOTHING ELSE UP TO TeV...

IF NO HIGGS THERE...→ m_H up to TeV →STRONG INTERACTING REGIME

Kaplan & Georgi '84

IF THERE , AND NOTHING ELSE UP TO TeV...→ STILL STRONG DYNAMICS

Giudice, Grojean, Pomarol & Rattazzi '07

IF NO HIGGS THERE...$\rightarrow$ m_H up to TeV $\rightarrow$STRONG INTERACTING REGIME

Kaplan & Georgi '84

IF THERE , AND NOTHING ELSE UP TO TeV...$\rightarrow$ STILL STRONG DYNAMICS

Giudice, Grojean, Pomarol & Rattazzi '07

Whether it is at the TeV or at 125 GeV

I will assume that the HIGGS DYNAMICS IS STRONG

What about FLAVOR in this context??...

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi ’87.

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi '87.

- SM-flavor symmetry $\mathcal{G}_f$ for $m_{quarks} = 0$

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi '87.

- SM-flavor symmetry $\mathcal{G}_f$ for $m_{quarks} = 0$

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi '87.

- SM-flavor symmetry $\mathcal{G}_f$ for $m_{quarks} = 0$

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

- $Q_L \sim (3, 1, 1), \qquad U_R \sim (1, 3, 1), \qquad D_R \sim (1, 1, 3)$

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi '87.

- SM-flavor symmetry $\mathcal{G}_f$ for $m_{quarks} = 0$

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

- $Q_L \sim (3, 1, 1), \qquad U_R \sim (1, 3, 1), \qquad D_R \sim (1, 1, 3)$

- $\mathscr{L}_Y = \overline{Q}_L Y_D D_R \Phi + \overline{Q}_L Y_U U_R \tilde{\Phi} + \text{h.c.}$

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi '87.

- SM-flavor symmetry $\mathcal{G}_f$ for $m_{quarks} = 0$

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

- $Q_L \sim (3, 1, 1), \qquad U_R \sim (1, 3, 1), \qquad D_R \sim (1, 1, 3)$

- $\mathscr{L}_Y = \overline{Q}_L Y_D D_R \Phi + \overline{Q}_L Y_U U_R \tilde{\Phi} + \text{h.c.}$

$$\overset{\text{recovering } \mathcal{G}_f}{\Longrightarrow} \quad Y_U \sim (3, \overline{3}, 1) \quad \& \quad Y_D \sim (3, 1, \overline{3})$$

MINIMAL FLAVOR VIOLATION (MFV)

Ansatz: Yukawa couplings are the unique sources for flavor effects at low energy in SM and beyond. Chivukula & Georgi '87.

- SM-flavor symmetry $\mathcal{G}_f$ for $m_{quarks} = 0$

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

- $Q_L \sim (3,1,1), \qquad U_R \sim (1,3,1), \qquad D_R \sim (1,1,3)$

- $\mathscr{L}_Y = \overline{Q}_L Y_D D_R \Phi + \overline{Q}_L Y_U U_R \tilde{\Phi} + \text{h.c.}$

$$\overset{\text{recovering } \mathcal{G}_f}{\Longrightarrow} \quad Y_U \sim (3, \overline{3}, 1) \quad \& \quad Y_D \sim (3, 1, \overline{3})$$

$$\mathcal{L} = \mathcal{L}_{SM} + a_i \frac{\mathcal{O}_i^{d=6}}{\Lambda_f^2} + \ldots$$

$$\mathcal{L} = \mathcal{L}_{SM} + a_i \frac{\mathcal{O}_i^{d=6}}{\Lambda_f^2} + \ldots$$

$$\mathrm{O}^{d=6} \sim c_{\alpha\beta}\, \bar{\psi}_\alpha \gamma^\mu \psi_\beta \left(\Phi^\dagger \mathcal{D}_\mu \Phi\right), \;\; c_{\alpha\beta}\, c_{\gamma\delta}\, \bar{\psi}_\alpha \psi_\beta \bar{\psi}_\gamma \psi_\delta$$

$c \sim YY^\dagger$, D'Ambrosio, Giudice, Isidori & Strumia '02

$$\mathcal{L} = \mathcal{L}_{SM} + a_i \frac{\mathcal{O}_i^{d=6}}{\Lambda_f^2} + \dots$$

$$\mathrm{O}^{d=6} \sim c_{\alpha\beta}\, \bar{\psi}_\alpha \gamma^\mu \psi_\beta \left(\Phi^\dagger \mathcal{D}_\mu \Phi\right),\quad c_{\alpha\beta}\, c_{\gamma\delta}\, \bar{\psi}_\alpha \psi_\beta \bar{\psi}_\gamma \psi_\delta$$

$c \sim YY^\dagger$, D'Ambrosio, Giudice, Isidori & Strumia '02

Minimally flavour violating dimension six operator	main observables	Λ_f [TeV] $-$	$+$	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	ϵ_K, Δm_{B_d}	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi$, $\epsilon'/\epsilon, \dots$	~ 1		

$$\mathcal{L} = \mathcal{L}_{SM} + a_i \frac{\mathcal{O}_i^{d=6}}{\Lambda_f^2} + \ldots$$

$$O^{d=6} \sim c_{\alpha\beta}\, \bar{\psi}_\alpha \gamma^\mu \psi_\beta \left(\Phi^\dagger \mathcal{D}_\mu \Phi\right),\quad c_{\alpha\beta}\, c_{\gamma\delta}\, \bar{\psi}_\alpha \psi_\beta \bar{\psi}_\gamma \psi_\delta$$

$c \sim YY^\dagger$, D'Ambrosio, Giudice, Isidori & Strumia '02

Minimally flavour violating dimension six operator	main observables	Λ_f [TeV] $-$	$+$	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)^2$	$\epsilon_K,\quad \Delta m_{B_d}$	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell},\quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	$*$
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell},\quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	$*$
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell},\quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	$*$
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi,\quad \epsilon'/\epsilon, \ldots$	~ 1		

$$\Rightarrow \Lambda_f \sim \text{TeV}$$

Back to STRONG HIGGS DYNAMICS ...

Large m_H-limit

$$\Phi = \begin{pmatrix} \phi^{\dagger} \\ \phi^{0} \end{pmatrix}$$

Large m_H-limit

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \rightarrow \mathbf{U} = e^{i\hat{\pi}/v} \text{ (no mass dimension!)}$$

$$\hat{\pi} = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

Large m_H-limit

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \rightarrow \mathbf{U} = e^{i\hat{\pi}/v} \text{ (no mass dimension!)}$$

$$\hat{\pi} = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

Global

$$SU(2)_L \times SU(2)_R \rightarrow \mathbf{U} \sim (2,2),$$

Local

$$SU(2)_L \times U(1)_Y \rightarrow L(x)\,\mathbf{U}(x)\,R^\dagger(x),$$

$$L(x) = e^{i\vec{\epsilon}_L(x)\cdot\vec{\tau}/2}, \qquad R(x) = e^{i\epsilon_Y(x)\tau_3/2}$$

Large m_H-limit

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \to \mathbf{U} = e^{i\hat{\pi}/v} \text{ (no mass dimension!)}$$

$$\hat{\pi} = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

Global

$$SU(2)_L \times SU(2)_R \to \mathbf{U} \sim (2,2),$$

Local

$$SU(2)_L \times U(1)_Y \to L(x)\,\mathbf{U}(x)\,R^\dagger(x),$$

$$L(x) = e^{i\vec{\epsilon}_L(x)\cdot\vec{\tau}/2}, \qquad R(x) = e^{i\epsilon_Y(x)\tau_3/2}$$

After vev

$$SU(2)_L \times SU(2)_R \to SU(2)_C$$
$$SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

Large m_H-limit

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \to \mathbf{U} = e^{i\hat{\pi}/v} \text{ (no mass dimension!)}$$

$$\hat{\pi} = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

Global

$$SU(2)_L \times SU(2)_R \to \mathbf{U} \sim (2,2),$$

Local

$$SU(2)_L \times U(1)_Y \to L(x)\,\mathbf{U}(x)\,R^\dagger(x),$$

$$L(x) = e^{i\vec{\epsilon}_L(x)\cdot\vec{\tau}/2}, \qquad R(x) = e^{i\epsilon_Y(x)\tau_3/2}$$

After vev

$$SU(2)_L \times SU(2)_R \to SU(2)_C$$
$$SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

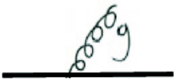
Covariant derivative

$$\mathcal{D}_\mu \mathbf{U} \equiv \partial_\mu \mathbf{U} + \frac{i\,g}{2}\tau_i\,W^i_\mu\,\mathbf{U} - \frac{i\,g'}{2}\mathbf{U}\,\tau_3\,B_\mu\,.$$

What changes if the Higgs has strong interacting dynamics?

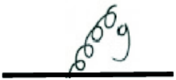
What changes if the Higgs has strong interacting dynamics?

- As in strongly interacting QCD $\alpha_s \sim 1 \Rightarrow$ unsuppressed multiple gluon emission



What changes if the Higgs has strong interacting dynamics?

- As in strongly interacting QCD $\alpha_s \sim 1 \Rightarrow$ unsuppressed multiple gluon emission



Strongly interacting Higgs $\lambda \sim 1 \Rightarrow$ unsuppressed longitudinal $W - Z$ components emission

Low cost of π-fields emission!

What changes if the Higgs has strong interacting dynamics?

Model independent: effective lagrangian approach

What changes if the Higgs has strong interacting dynamics?

Model independent: effective lagrangian approach

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \qquad \rightarrow \qquad \mathbf{U} = e^{i\hat{\pi}/v}$$ (no mass dimension!)

Building blocks: $\mathbf{U}$, $\mathcal{D}_\mu \mathbf{U}$

What changes if the Higgs has strong interacting dynamics?

Model independent: effective lagrangian approach

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \qquad \rightarrow \qquad \mathbf{U} = e^{i\hat{\pi}/v}$$ (no mass dimension!)

Building blocks: $\mathbf{U}$, $\mathcal{D}_\mu \mathbf{U}$

Tower of operators becomes...

$$\Rightarrow$$

STRONG HIGGS DYNAMICS

+

MINIMAL FLAVOR VIOLATION

$$\mathcal{O}_1 \sim \bar{\psi}_\alpha \gamma^\mu \left\{ \mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right\} \psi_\beta , \qquad \mathcal{O}_2 \sim \bar{\psi}_\alpha \gamma^\mu (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \psi_\beta$$

$$\mathcal{O}_3 \sim \bar{\psi}_\alpha \gamma^\mu \mathbf{U}\tau_3\mathbf{U}^\dagger (\mathcal{D}_\mu \mathbf{U})\tau_3\mathbf{U}^\dagger \psi_\beta , \qquad \mathcal{O}_4 \sim \bar{\psi}_\alpha \gamma^\mu \left[\mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right] \psi_\beta$$

STRONG HIGGS DYNAMICS

+

MINIMAL FLAVOR VIOLATION

$$\mathcal{O}_1 \sim \bar{\psi}_\alpha \gamma^\mu \left\{ \mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right\} \psi_\beta , \qquad \mathcal{O}_2 \sim \bar{\psi}_\alpha \gamma^\mu (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \psi_\beta$$

$$\mathcal{O}_3 \sim \bar{\psi}_\alpha \gamma^\mu \mathbf{U}\tau_3\mathbf{U}^\dagger (\mathcal{D}_\mu \mathbf{U})\tau_3\mathbf{U}^\dagger \psi_\beta , \qquad \mathcal{O}_4 \sim \bar{\psi}_\alpha \gamma^\mu \left[\mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right] \psi_\beta$$

MFV with linear EWSB had also 4 ops. $\mathcal{O}^{d=6}$ @ LO

STRONG HIGGS DYNAMICS

+

MINIMAL FLAVOR VIOLATION

$$\mathcal{O}_1 \sim \bar{\psi}_\alpha \gamma^\mu \left\{ \mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right\} \psi_\beta , \qquad \mathcal{O}_2 \sim \bar{\psi}_\alpha \gamma^\mu (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \psi_\beta$$

$$\mathcal{O}_3 \sim \bar{\psi}_\alpha \gamma^\mu \mathbf{U}\tau_3\mathbf{U}^\dagger (\mathcal{D}_\mu \mathbf{U})\tau_3\mathbf{U}^\dagger \psi_\beta , \qquad \mathcal{O}_4 \sim \bar{\psi}_\alpha \gamma^\mu \left[\mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right] \psi_\beta$$

MFV with linear EWSB had also 4 ops. $\mathcal{O}^{d=6}$ @ LO

Only 2 are *siblings* of those ($\mathcal{O}_{1,2}$)

STRONG HIGGS DYNAMICS

+

MINIMAL FLAVOR VIOLATION

$$\mathcal{O}_1 \sim \bar{\psi}_\alpha \gamma^\mu \left\{ \mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right\} \psi_\beta, \qquad \mathcal{O}_2 \sim \bar{\psi}_\alpha \gamma^\mu (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \psi_\beta$$

$$\mathcal{O}_3 \sim \bar{\psi}_\alpha \gamma^\mu \mathbf{U}\tau_3\mathbf{U}^\dagger (\mathcal{D}_\mu \mathbf{U})\tau_3\mathbf{U}^\dagger \psi_\beta, \qquad \mathcal{O}_4 \sim \bar{\psi}_\alpha \gamma^\mu \left[\mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right] \psi_\beta$$

MFV with linear EWSB had also 4 ops. $\mathcal{O}^{d=6}$ @ LO

Only 2 are *siblings* of those ($\mathcal{O}_{1,2}$)

Now $\mathcal{O}_{3,4}$ new!
and...

STRONG HIGGS DYNAMICS

+

MINIMAL FLAVOR VIOLATION

$$\mathcal{O}_1 \sim \bar{\psi}_\alpha \gamma^\mu \left\{ \mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right\} \psi_\beta, \qquad \mathcal{O}_2 \sim \bar{\psi}_\alpha \gamma^\mu (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \psi_\beta$$

$$\mathcal{O}_3 \sim \bar{\psi}_\alpha \gamma^\mu \mathbf{U}\tau_3\mathbf{U}^\dagger (\mathcal{D}_\mu \mathbf{U})\tau_3\mathbf{U}^\dagger \psi_\beta, \qquad \mathcal{O}_4 \sim \bar{\psi}_\alpha \gamma^\mu \left[\mathbf{U}\tau_3\mathbf{U}^\dagger, (\mathcal{D}_\mu \mathbf{U})\mathbf{U}^\dagger \right] \psi_\beta$$

MFV with linear EWSB had also 4 ops. $\mathcal{O}^{d=6}$ @ LO

Only 2 are *siblings* of those ($\mathcal{O}_{1,2}$)

Now $\mathcal{O}_{3,4}$ new!

and...

$\mathcal{O}_4$ is a CP-ODD op.! $\rightarrow$ Natural $\not{CP}$ @ LO!!

STRONG HIGGS DYNAMICS
+
MINIMAL FLAVOR VIOLATION

$$\delta\mathcal{L}_{d_\chi=4} = -\frac{g}{\sqrt{2}}\left[W^{\mu+}\bar{U}_L\gamma_\mu(a_W + i a_{CP})\left(\mathbf{y}_U^2 V + V\mathbf{y}_D^2\right)D_L + h.c.\right] +$$

$$-\frac{g}{2c_W}Z^\mu\left[a_Z^u\bar{U}_L\gamma_\mu\left(\mathbf{y}_U^2 + V\mathbf{y}_D^2V^\dagger\right)U_L + a_Z^d\bar{D}_L\gamma_\mu\left(\mathbf{y}_D^2 + V^\dagger\mathbf{y}_U^2V\right)D_L\right]$$

$$a_Z^u \equiv a_1 + a_2 + a_3\,, \qquad a_Z^d \equiv a_1 - a_2 - a_3\,,$$

$$a_W \equiv a_2 - a_3\,, \qquad a_{CP} \equiv -a_4\,.$$

STRONG HIGGS DYNAMICS

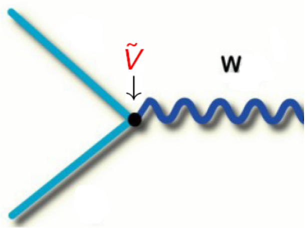
+

MINIMAL FLAVOR VIOLATION

$$\delta\mathcal{L}_{d_\chi=4} = -\frac{g}{\sqrt{2}}\left[W^{\mu+}\bar{U}_L\gamma_\mu(a_W + i a_{CP})\left(\mathbf{y}_U^2 V + V\mathbf{y}_D^2\right)D_L + h.c.\right] +$$

$$-\frac{g}{2c_W}Z^\mu\left[a_Z^u\bar{U}_L\gamma_\mu\left(\mathbf{y}_U^2 + V\mathbf{y}_D^2V^\dagger\right)U_L + a_Z^d\bar{D}_L\gamma_\mu\left(\mathbf{y}_D^2 + V^\dagger\mathbf{y}_U^2V\right)D_L\right]$$

$$a_Z^u \equiv a_1 + a_2 + a_3\,, \qquad a_Z^d \equiv a_1 - a_2 - a_3\,,$$
$$a_W \equiv a_2 - a_3\,, \qquad a_{CP} \equiv -a_4\,.$$



$$\tilde{V}_{ij} = V_{ij}\left[1 + (a_W + i a_{CP})(y_{u_i}^2 + y_{d_j}^2)\right]$$

$\Rightarrow$ Impacts on $\Delta F = 1$ & $\Delta F = 2$ observables...

$\Delta F = 1$ observables

FCNC-effective lagrangian

$$\frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}\,,$$

Wilson coefficient C_n:

$$C_n$$

$\Delta F = 1$ observables

FCNC-effective lagrangian

$$\frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}\,,$$

Wilson coefficient C_n:

$$C_n = C_n^{SM}$$

$\Delta F = 1$ observables

FCNC-effective lagrangian

$$\frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}\,,$$

Wilson coefficient C_n:

$$C_n = C_n^{SM} + C_n^{NP}$$

$\Delta F = 1$ observables

FCNC-effective lagrangian

$$\frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}\,,$$

Wilson coefficient C_n:

$$C_n = C_n^{SM} + C_n^{NP}$$

FCNC operators basis

$$\mathcal{Q}_{\bar\nu\nu} = \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar\nu \gamma^\mu (1-\gamma_5)\nu\,,$$
$$\mathcal{Q}_{9V} = \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar\ell \gamma^\mu \ell\,,$$
$$\mathcal{Q}_{10A} = \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar\ell \gamma^\mu \gamma_5 \ell\,,$$

$$\mathcal{Q}_7 = e_q\, \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{q} \gamma^\mu (1+\gamma_5) q\,,$$
$$\mathcal{Q}_9 = e_q\, \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{q} \gamma^\mu (1-\gamma_5) q\,,$$
$$\mathcal{Q}_{7\gamma} = \frac{m_i}{g^2} \bar{d}_i (1-\gamma_5) \sigma_{\mu\nu} d_j\, (e\, F^{\mu\nu})\,,$$
$$\mathcal{Q}_{8G} = \frac{m_i}{g^2} \bar{d}_i (1-\gamma_5) \sigma_{\mu\nu} T^a d_j\, (g_s\, G_a^{\mu\nu})\,.$$

$\Delta F = 1$ observables

FCNC-effective lagrangian

$$\frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}\,,$$

Wilson coefficient C_n:

$$C_n = C_n^{SM} + C_n^{NP}$$

FCNC operators basis

$$\mathcal{Q}_{\bar\nu\nu} = \bar d_i \gamma_\mu (1-\gamma_5) d_j\, \bar\nu \gamma^\mu (1-\gamma_5)\nu\,,$$
$$\mathcal{Q}_{9V} = \bar d_i \gamma_\mu (1-\gamma_5) d_j\, \bar\ell \gamma^\mu \ell\,,$$
$$\mathcal{Q}_{10A} = \bar d_i \gamma_\mu (1-\gamma_5) d_j\, \bar\ell \gamma^\mu \gamma_5 \ell\,,$$
$$\mathcal{Q}_7 = e_q\, \bar d_i \gamma_\mu (1-\gamma_5) d_j\, \bar q \gamma^\mu (1+\gamma_5) q\,,$$
$$\mathcal{Q}_9 = e_q\, \bar d_i \gamma_\mu (1-\gamma_5) d_j\, \bar q \gamma^\mu (1-\gamma_5) q\,,$$
$$\mathcal{Q}_{7\gamma} = \frac{m_i}{g^2} \bar d_i (1-\gamma_5) \sigma_{\mu\nu} d_j\, (e\, F^{\mu\nu})\,,$$
$$\mathcal{Q}_{8G} = \frac{m_i}{g^2} \bar d_i (1-\gamma_5) \sigma_{\mu\nu} T^a d_j\, (g_s\, G_a^{\mu\nu})\,.$$

Wilson coefficient modifications

$$C_n^{NP} \begin{cases} \sim y_t^2\, a_Z^d, & n = \bar\nu\nu, 9V, ..., 9 \\ 0, & n = 7\gamma, 8G \end{cases}$$

$\Delta F = 1$ observables

Operator	Observable	Bound (@ 95% C.L.)
$\mathcal{O}_{9V}$	$B \to X_s l^+ l^-$	$-0.811 < a_Z^d < 0.232$
$\mathcal{O}_{10A}$	$B \to X_s l^+ l^-$,$B \to \mu^+ \mu^-$	$-0.050 < a_Z^d < 0.009$
$\mathcal{O}_{\bar{\nu}\nu}$	$K^+ \to \pi^+ \bar{\nu}\nu$	$-0.044 < a_Z^d < 0.133$

$\Delta F = 2$ observables

$\Delta F = 2$-effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{\Delta F=2} = \frac{G_F^2\, M_W^2}{4\pi^2}\, C(\mu)\, Q, \qquad Q = (\bar{d}_i^{\alpha}\, \gamma_\mu\, P_L\, d_j^{\alpha})(\bar{d}_i^{\beta}\, \gamma^\mu\, P_L\, d_j^{\beta})$$

$\Delta F = 2$ observables

$\Delta F = 2$-effective hamiltonian

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = \frac{G_F^2\, M_W^2}{4\pi^2}\, C(\mu)\, Q, \qquad\qquad Q = (\bar{d}_i^{\alpha}\, \gamma_\mu\, P_L\, d_j^{\alpha})(\bar{d}_i^{\beta}\, \gamma^\mu\, P_L\, d_j^{\beta})$$

Mixing amplitudes:

$$M_{12}^K = \frac{\langle \bar{K}^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | K^0 \rangle^*}{2\, m_K}\,, \qquad\qquad M_{12}^q = \frac{\langle \bar{B}_q^0 | \mathcal{H}_{\rm eff}^{\Delta B=2} | B_q^0 \rangle^*}{2\, m_{B_q}} \quad q = d, s,$$

$\Delta F = 2$ observables

$\Delta F = 2$-effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{\Delta F=2} = \frac{G_F^2\, M_W^2}{4\pi^2}\, C(\mu)\, Q, \qquad Q = (\bar{d}_i^{\alpha}\, \gamma_\mu\, P_L\, d_j^{\alpha})(\bar{d}_i^{\beta}\, \gamma^\mu\, P_L\, d_j^{\beta})$$

Mixing amplitudes:

$$M_{12}^K = \frac{\langle \bar{K}^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | K^0 \rangle^*}{2\, m_K}\,, \qquad M_{12}^q = \frac{\langle \bar{B}_q^0 | \mathcal{H}_{\text{eff}}^{\Delta B=2} | B_q^0 \rangle^*}{2\, m_{B_q}} \quad q = d, s,$$

Either K or B-system,

$$M_{12}$$

$\Delta F = 2$ observables

$\Delta F = 2$-effective hamiltonian

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = \frac{G_F^2\, M_W^2}{4\pi^2}\, C(\mu)\, Q, \qquad Q = (\bar{d}_i^\alpha\, \gamma_\mu\, P_L\, d_j^\alpha)(\bar{d}_i^\beta\, \gamma^\mu\, P_L\, d_j^\beta)$$

Mixing amplitudes:

$$M_{12}^K = \frac{\langle \bar{K}^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | K^0 \rangle^*}{2\, m_K}\,, \qquad M_{12}^q = \frac{\langle \bar{B}_q^0 | \mathcal{H}_{\rm eff}^{\Delta B=2} | B_q^0 \rangle^*}{2\, m_{B_q}} \quad q = d, s,$$

Either K or B-system,

$$M_{12} = (M_{12})_{SM}$$

$\Delta F = 2$ observables

$\Delta F = 2$-effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{\Delta F=2} = \frac{G_F^2\, M_W^2}{4\pi^2}\, C(\mu)\, Q, \qquad Q = (\bar{d}_i^{\alpha}\, \gamma_\mu\, P_L\, d_j^{\alpha})(\bar{d}_i^{\beta}\, \gamma^\mu\, P_L\, d_j^{\beta})$$

Mixing amplitudes:

$$M_{12}^K = \frac{\langle \bar{K}^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | K^0 \rangle^*}{2\, m_K}\,, \qquad M_{12}^q = \frac{\langle \bar{B}_q^0 | \mathcal{H}_{\text{eff}}^{\Delta B=2} | B_q^0 \rangle^*}{2\, m_{B_q}} \quad q = d, s,$$

Either K or B-system,

$$M_{12} = (M_{12})_{SM} + (M_{12})_{NP}$$

$\Delta F = 2$ observables

Neutral kaon oscillation

$$\Delta M_K = 2\left[\mathrm{Re}(M_{12}^K)_{SM} + \mathrm{Re}(M_{12}^K)_{NP}\right],$$

$$\varepsilon_K = \frac{\kappa_\epsilon\, e^{i\,\varphi_\epsilon}}{\sqrt{2}\,(\Delta M_K)_{\mathrm{exp}}}\left[\mathrm{Im}\left(M_{12}^K\right)_{SM} + \mathrm{Im}\left(M_{12}^K\right)_{NP}\right]$$

$\Delta F = 2$ observables

Neutral kaon oscillation

$$\Delta M_K = 2\left[\mathrm{Re}(M_{12}^K)_{SM} + \mathrm{Re}(M_{12}^K)_{NP}\right],$$

$$\varepsilon_K = \frac{\kappa_\epsilon\, e^{i\,\varphi_\epsilon}}{\sqrt{2}\,(\Delta M_K)_{\mathrm{exp}}}\left[\mathrm{Im}\left(M_{12}^K\right)_{SM} + \mathrm{Im}\left(M_{12}^K\right)_{NP}\right]$$

Neglecting all contributions proportional to $y_{u,d,s}$ and y_c^n with $n > 2$:

$$(M_{12}^K)_{NP} \sim \eta_2\,\lambda_t^2\,\mathcal{O}\left(y_t^2\,a_W,\; y_t^4\,a_{CP}^2,\; y_t^4\,(a_Z^d)^2\right)$$
$$+\,\eta_1\,\lambda_c^2\,\mathcal{O}\left(y_c^2\,a_W\right)$$
$$+\,2\,\eta_3\,\lambda_t\,\lambda_c\,\mathcal{O}\left(y_t^2\,a_W,\; y_t^4\,a_{CP}^2\right)$$

$\Delta F = 2$ observables

Neutral meson oscillation

Mixing amplitude

$$M_{12}^q = (M_{12}^q)_{\mathrm{SM}}\, \mathcal{C}_{B_q}\, e^{2\, i\, \varphi_{B_q}}$$

$B_{d,s}$-mass differences

$$\Delta M_q = 2\, |M_{12}^q| \equiv (\Delta M_q)_{\mathrm{SM}}\, \mathcal{C}_{B_q}$$

NP effects from $\mathcal{C}_{B_{d,s}}$ and $\varphi_{B_{d,s}}$

$$\mathcal{C}_{B_d} = \mathcal{C}_{B_s} = \left| 1 + \mathcal{O}\left(y_t^2\, a_W,\; y_t^4\, (a_Z^d)^2 \right) + i\, \mathcal{O}\left(y_t^2 y_b^2\, a_W a_{CP} \right) \right|$$

$$\varphi_{B_d} = \varphi_{B_s} \sim \mathcal{O}\left(y_t^2 y_b^2\, a_W,\, a_{CP} \right)$$

$\Delta F = 2$ observables

Neutral meson oscillation

Mixing-induced CP asymmetries $S_{\psi K_S}$ & $S_{\psi\phi}$ for $B_d^0 \to \psi\, K_S$ & $B_s^0 \to \psi\, \phi$

$$S_{\psi K_S} = \sin(2\,\beta + 2\,\varphi_{B_d})\,, \qquad S_{\psi\phi} = \sin(2\,\beta_s - 2\,\varphi_{B_s})\,,$$

UT-angles β & β_s

$$\beta \equiv \arg\left(-\frac{V_{cb}^*\, V_{cd}}{V_{tb}^*\, V_{td}}\right)\,, \qquad \beta_s \equiv \arg\left(-\frac{V_{tb}^*\, V_{ts}}{V_{cb}^*\, V_{cs}}\right)\,,$$

$R_{BR/\Delta M}$

$$R_{BR/\Delta M} \sim \frac{\left|1 + (a_W + i\, a_{CP})\; y_b^2\right|^2}{\mathcal{C}_{B_d}}$$

$\Delta F = 2$ observables

B-semileptonic CP-Asymmetry

$$A_{sl}^{b} = (0.594 \pm 0.022)\, a_{sl}^{d} + (0.406 \pm 0.022)\, a_{sl}^{s} \,,$$

NP contributions

$$\Gamma_{12}^{q} = (\Gamma_{12}^{q})_{\rm SM}\, \tilde{\mathcal{C}}_{B_q} \qquad \text{with} \qquad \tilde{\mathcal{C}}_{B_q} = 1 + 2\, a_W\, y_b^2 \,,$$

$$a_{sl}^{q} = \left| \frac{(\Gamma_{12}^{q})_{SM}}{(M_{12}^{q})_{SM}} \right| \frac{\tilde{\mathcal{C}}_{B_q}}{\mathcal{C}_{B_q}} \sin\left(\phi_q + 2\varphi_{B_q}\right) \,,$$

$\Longrightarrow$

ε_K vs. $R_{BR/\Delta M}$

$a's$ from $a_i\mathcal{O}_i$

$$R_{BR/\Delta M} = \frac{BR(B^+ \to \tau^+\nu)}{\Delta M_{B_d}}$$

$$\begin{aligned}
a_{CP} &= \pm 0.1 & \longrightarrow \quad & \delta\varepsilon_K \approx 1.1\%\,, & \delta R_{BR/\Delta M} &\approx -1.4\%\,,\\
a_W &= 0.1(-0.1) & \longrightarrow \quad & \delta\varepsilon_K \approx +26\%(-19\%)\,, & \delta R_{BR/\Delta M} &\approx -25\%(+30\%)\,,\\
a_Z^d &= \pm 0.1 & \longrightarrow \quad & \delta\varepsilon_K \approx 124\%\,, & \delta R_{BR/\Delta M} &\approx -62\%\,.
\end{aligned}$$

ε_K vs. $R_{BR/\Delta M}$

$a's$ from $a_i \mathcal{O}_i$

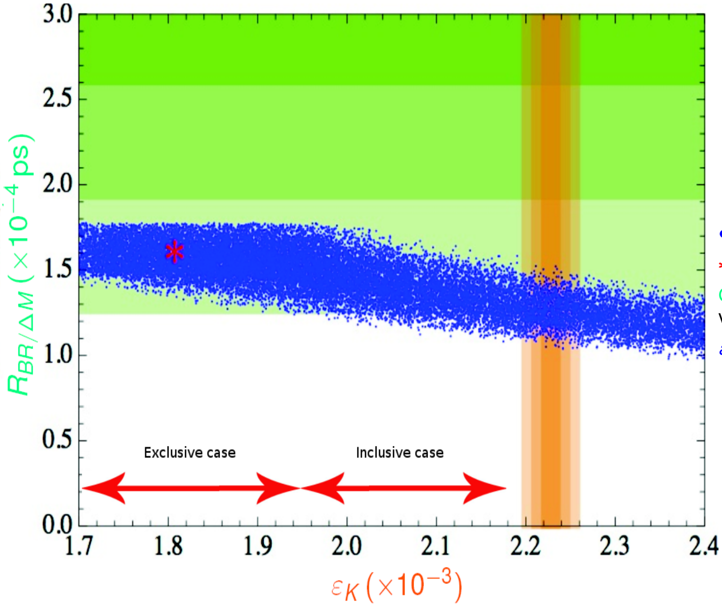
$$R_{BR/\Delta M} = \frac{BR(B^+ \to \tau^+ \nu)}{\Delta M_{B_d}}$$

$$\begin{aligned}
a_{CP} &= \pm 0.1 && \longrightarrow && \delta\varepsilon_K \approx 1.1\%\,, && \delta R_{BR/\Delta M} \approx -1.4\%\,,\\
a_W &= 0.1(-0.1) && \longrightarrow && \delta\varepsilon_K \approx +26\%(-19\%)\,, && \delta R_{BR/\Delta M} \approx -25\%(+30\%)\,,\\
a_Z^d &= \pm 0.1 && \longrightarrow && \delta\varepsilon_K \approx 124\%\,, && \delta R_{BR/\Delta M} \approx -62\%\,.
\end{aligned}$$

$$\varepsilon_K \uparrow (\approx \; \varepsilon_K^{\exp} \;\; \& \;\; S_{\psi K_S} \approx S_{\psi K_S}^{\exp}) \;\; \& \;\; R_{BR/\Delta M} \downarrow$$

$\Rightarrow$ SHD + MFV able to soften $\varepsilon_K - S_{\psi K_S}$ anomaly, but not the SM tension for $BR(B^+ \to \tau^+ \nu)$

ε_K vs. $R_{BR/\Delta M}$ from $\mathcal{O}_4$



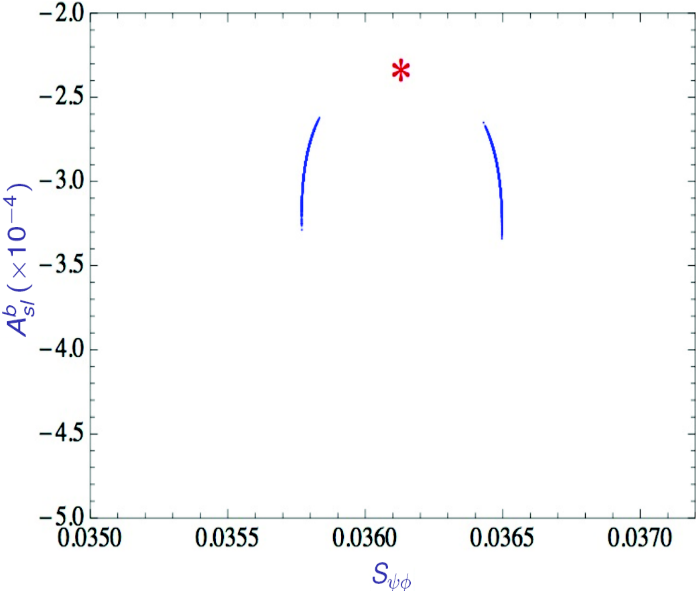
●: correlation $\varepsilon_K - R_{BR/\Delta M}$

∗: SM values

Green & Orange: $1, 2, 3\sigma$ exp values

$a_{CP} \in [-1, 1]$

$S_{\psi\phi}$ vs. A^b_{sl} from $\mathcal{O}_4$



●: correlation $S_{\psi\phi} - A^b_{sl}$

∗: SM values

Large values for a_{CP}

STRONG HIGGS DYNAMICS

+

MINIMAL FLAVOR VIOLATION

$\Downarrow$

- Different MFV phenomenology for the perturbative Higgs and the strong interacting regime, e.g., $\mathcal{O}_4$
- Natural $\not{CP}$ $(\mathcal{O}_4)$ @ LO!!
- $\varepsilon_K - S_{\psi K_S}$ anomaly removed, still SM tension for $BR(B^+ \to \tau^+ \nu)$
- Small $\delta S_{\psi\phi}$ & δA^b_{sl} experimentally allowed

Thanks!

Tools

$$\mathcal{D}_\mu \mathbf{U} \equiv \partial_\mu \mathbf{U} + \frac{i\,g}{2}\tau_i\, W_\mu^i\, \mathbf{U} - \frac{i\,g'}{2}\mathbf{U}\,\tau_3\, B_\mu$$

$$\mathbf{T} = \mathbf{U}\tau_3\mathbf{U}^\dagger\,, \qquad \mathbf{T} \to L\,\mathbf{T}L^\dagger\,,$$

$$\mathbf{V}_\mu = (\mathcal{D}_\mu\mathbf{U})\mathbf{U}^\dagger\,, \qquad \mathbf{V}_\mu \to L\,\mathbf{V}_\mu L^\dagger\,.$$

Lagrangian for interaction between the gauge fields and the scalar sector:

$$\mathcal{L} = -\frac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{v^2}{4}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu] + \delta\mathcal{L}\,,$$

$$\delta\mathcal{L}_{d_\chi=2} = a_{WZ}\,\frac{v^2}{4}\,\mathrm{Tr}[\mathbf{T}\,\mathbf{V}_\mu]\,\mathrm{Tr}[\mathbf{T}\,\mathbf{V}^\mu]\,,$$

Non-linear Yukawa interactions:

$$\mathscr{L}_Y = \frac{v}{\sqrt{2}}\,\overline{Q}_L\,\mathcal{Y}\,\mathbf{U}\,Q_R + \text{h.c.}\,, \qquad Q_R = (u_R, d_R)$$

Tools

$$\mathcal{Y} \equiv \begin{pmatrix} Y_U & 0 \\ 0 & Y_D \end{pmatrix} = \begin{pmatrix} V^\dagger \mathbf{y}_U & 0 \\ 0 & \mathbf{y}_D \end{pmatrix}$$

Spurion field $\sim (8,1,1)$ for new FCNC effects

$$\lambda_F \equiv Y_U Y_U^\dagger + Y_D Y_D^\dagger = V^\dagger \mathbf{y}_U^2 V + \mathbf{y}_D^2$$

$d_\chi = 4$ ops.

$$\mathcal{O}_1 = \frac{i}{2} \bar{Q}_L \lambda_F \gamma^\mu \{\mathbf{T}, \mathbf{V}_\mu\} Q_L\,, \qquad \mathcal{O}_2 = i \bar{Q}_L \lambda_F \gamma^\mu \mathbf{V}_\mu Q_L\,,$$

$$\mathcal{O}_3 = i \bar{Q}_L \lambda_F \gamma^\mu \mathbf{T} \mathbf{V}_\mu \mathbf{T} Q_L\,, \qquad \mathcal{O}_4 = \frac{1}{2} \bar{Q}_L \lambda_F \gamma^\mu [\mathbf{T}, \mathbf{V}_\mu] Q_L\,.$$

Effective Low-Energy Lagrangian

$$\begin{aligned} \delta\mathcal{L}_{d_\chi=4} = & -\frac{g}{\sqrt{2}} \left[W^{\mu +} \bar{U}_L \gamma_\mu (a_W + i a_{CP}) \left(\mathbf{y}_U^2 V + V \mathbf{y}_D^2 \right) D_L + h.c. \right] + \\ & -\frac{g}{2 c_W} Z^\mu \left[a_Z^u \bar{U}_L \gamma_\mu \left(\mathbf{y}_U^2 + V \mathbf{y}_D^2 V^\dagger \right) U_L + a_Z^d \bar{D}_L \gamma_\mu \left(\mathbf{y}_D^2 + V^\dagger \mathbf{y}_U^2 V \right) D_L \right] \end{aligned}$$

$$\begin{aligned} a_Z^u &\equiv a_1 + a_2 + a_3\,, & a_Z^d &\equiv a_1 - a_2 - a_3\,, \\ a_W &\equiv a_2 - a_3\,, & a_{CP} &\equiv -a_4\,. \end{aligned} \qquad (0.1)$$

Non Unitarity and CP Violation

$$\tilde{V}_{ij} = V_{ij}\left[1 + (a_W + i a_{CP})(y_{u_i}^2 + y_{d_j}^2)\right]$$

$$\sum_k \tilde{V}_{ik}^* \tilde{V}_{jk} \simeq \delta_{ij} + \left[2\, a_W\, y_t^2 + (a_W^2 + a_{CP}^2)\, y_t^4\right] \delta_{it}\delta_{jt}$$

$\sum_k \tilde{V}_{ki}^* \tilde{V}_{kj} \simeq \delta_{ij} + \left[2\, a_W\, y_t^2 + (a_W^2 + a_{CP}^2)\, y_t^4\right] V_{ti}^* V_{tj}$

$$\arg\left(-\frac{\tilde{V}_{ik}^* \tilde{V}_{il}}{\tilde{V}_{jk}^* \tilde{V}_{jl}}\right) = \arg\left(-\frac{V_{ik}^* V_{il}}{V_{jk}^* V_{jl}}\right) + a_{CP}\left[2\, a_W\, \left(y_{u_j}^2 - y_{u_i}^2\right)\left(y_{d_l}^2 - y_{d_k}^2\right) + \right.$$
$$\left. - \left(3\, a_W^2 - a_{CP}^2\right)\left(y_{u_j}^2 - y_{u_i}^2\right)\left(y_{d_l}^2 - y_{d_k}^2\right)\left(y_{u_i}^2 + y_{u_j}^2 + y_{d_k}^2 + y_{d_l}^2\right)\right] + O(a^4)\,,$$

$$\arg\left(-\frac{\tilde{V}_{tb}^* \tilde{V}_{td}}{\tilde{V}_{ub}^* \tilde{V}_{ud}}\right) \simeq \alpha + 2\, y_b^2\, y_t^2\, a_W\, a_{CP}\,,$$

$$\arg\left(-\frac{\tilde{V}_{cb}^* \tilde{V}_{cd}}{\tilde{V}_{tb}^* \tilde{V}_{td}}\right) \simeq \beta - 2\, y_b^2\, y_t^2\, a_W\, a_{CP}\,,$$

$$\arg\left(-\frac{\tilde{V}_{ub}^* \tilde{V}_{ud}}{\tilde{V}_{cb}^* \tilde{V}_{cd}}\right) \simeq \gamma - 2\, y_c^2\, y_b^2\, a_W\, a_{CP} \simeq \gamma\,.$$

$\Delta F = 1$ observables

FCNC-effective lagrangian

$$\frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}\,,$$

Wilson coefficient C_n:

$$C_n = C_n^{SM} + C_n^{NP}$$

FCNC operators basis

$$\begin{aligned}
\mathcal{Q}_{\bar{\nu}\nu} &= \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{\nu}\gamma^\mu (1-\gamma_5)\nu\,, & \mathcal{Q}_7 &= e_q\, \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{q}\gamma^\mu (1+\gamma_5) q\,,\\
\mathcal{Q}_{9V} &= \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{\ell}\gamma^\mu \ell\,, & \mathcal{Q}_9 &= e_q\, \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{q}\gamma^\mu (1-\gamma_5) q\,,\\
\mathcal{Q}_{10A} &= \bar{d}_i \gamma_\mu (1-\gamma_5) d_j\, \bar{\ell}\gamma^\mu \gamma_5 \ell\,, & \mathcal{Q}_{7\gamma} &= \frac{m_i}{g^2} \bar{d}_i (1-\gamma_5) \sigma_{\mu\nu} d_j\, (e\, F^{\mu\nu})\,,\\
& & \mathcal{Q}_{8G} &= \frac{m_i}{g^2} \bar{d}_i (1-\gamma_5) \sigma_{\mu\nu} T^a d_j\, (g_s\, G_a^{\mu\nu})\,.
\end{aligned}$$

Leading NP contributions non-linear MFV operators:

$$\begin{aligned}
C_{\nu\bar{\nu}}^{NP} &= -\kappa\, y_t^2\, a_Z^d\,, & C_7^{NP} &= +2\kappa\, s_W^2\, y_t^2\, a_Z^d\,,\\
C_{9V}^{NP} &= \kappa\, (1-4s_W^2)\, y_t^2\, a_Z^d\,, & C_9^{NP} &= -2\kappa\, c_W^2\, y_t^2\, a_Z^d\,,\\
C_{10A}^{NP} &= -\kappa\, y_t^2\, a_Z^d\,, & C_{7\gamma}^{NP} &= C_{8G}^{NP} = 0\,.
\end{aligned}$$

$B^+ \to \tau^+ \nu$

$B^+ \to \tau^+ \nu$-tree-level charged current process.

$$BR(B^+ \to \tau^+ \nu) = \frac{G_F^2\, m_{B^+}\, m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 F_{B^+}^2\, |V_{ub}|^2 \left|1 + (a_W + i\, a_{CP})\; y_b^2\right|^2 \tau_{B^+}\,,$$

F_{B^+} is B decay constant.

$\Delta F = 2$ observables

$\Delta F = 2$-effective hamiltonian

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = \frac{G_F^2\, M_W^2}{4\pi^2}\, C(\mu)\, Q$$

Q neutral meson mixing operator:

$$Q = (\bar{d}_i^\alpha\, \gamma_\mu\, P_L\, d_j^\alpha)(\bar{d}_i^\beta\, \gamma^\mu\, P_L\, d_j^\beta)$$

Mixing amplitudes M_{12}^i ($i = K, d, s$):

$$M_{12}^K = \frac{\langle \bar{K}^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | K^0 \rangle^*}{2\, m_K}\,, \qquad M_{12}^q = \frac{\langle \bar{B}_q^0 | \mathcal{H}_{\rm eff}^{\Delta B=2} | B_q^0 \rangle^*}{2\, m_{B_q}}\,,$$

with $q = d,\, s$. For the K system, $M_{12}^K = (M_{12}^K)_{SM} + (M_{12}^K)_{NP}$. Neglecting all contributions proportional to $y_{u,d,s}$ and y_c^n with $n > 2$:

$$(M_{12}^K)_{SM} = R_K \Big[\eta_2\, \lambda_t^2\, S_0(x_t) + \eta_1\, \lambda_c^2\, S_0(x_c) + 2\, \eta_3\, \lambda_t\, \lambda_c\, S_0(x_c,\, x_t)\Big]^*\,,$$

$$(M_{12}^K)_{NP} = R_K \Bigg[\eta_2\, \lambda_t^2 \left(y_t^2\, (2\, a_W + y_t^2\, a_{CP}^2)\, G(x_t) + \frac{(4\,\pi\, y_t^2\, a_Z^d)^2}{g^2}\right) + 2\eta_1\, \lambda_c^2\, a_W\, y_c^2\, G(x_c) + 2\, \eta_3\, \lambda_t\, \lambda_c \left(y_t^2\, (2\, a_W + a_{CP}^2\, y_t^2)\, H(x_t, x_c) + 2\, a_W\, y_c^2\, H(x_c, x_t)\right)\Bigg]^*$$

$$R_K \equiv \frac{G_F^2\, M_W^2}{12\,\pi^2}\, F_K^2\, m_K\, \hat{B}_K$$

$\Delta F = 2$ observables

Neutral kaon oscillation

$$\Delta M_K = 2\left[\mathrm{Re}(M_{12}^K)_{SM} + \mathrm{Re}(M_{12}^K)_{NP}\right],$$

$$\varepsilon_K = \frac{\kappa_\epsilon\, e^{i\,\varphi_\epsilon}}{\sqrt{2}\,(\Delta M_K)_{\mathrm{exp}}}\left[\mathrm{Im}\left(M_{12}^K\right)_{SM} + \mathrm{Im}\left(M_{12}^K\right)_{NP}\right]$$

Neutral meson oscillation

$$M_{12}^q = (M_{12}^q)_{\mathrm{SM}}\, \mathcal{C}_{B_q}\, e^{2\,i\,\varphi_{B_q}},$$

NP effects from $\mathcal{C}_{B_{d,s}}$ and $\varphi_{B_{d,s}}$

$$M_{12}^q = R_{B_q}\left[\lambda_t^2\, S_0(x_t)\right]^*, \qquad \text{with} \qquad R_{B_q} \equiv \frac{G_F^2\, M_W^2}{12\,\pi^2} F_{B_q}^2\, m_{B_q}\, \hat{B}_{B_q}\, \eta_B\,,$$

$B_{d,s}$-mass differences

$$\Delta M_q = 2\,|M_{12}^q| \equiv (\Delta M_q)_{\mathrm{SM}}\, \mathcal{C}_{B_q}\,,$$

$$\mathcal{C}_{B_d} = \mathcal{C}_{B_s} = \left|1 + 2\,a_W\left(y_t^2\,\frac{G(x_t)}{S_0(x_t)} + y_b^2\right) + \frac{(4\,\pi\,y_t^2\,a_Z^d)^2}{g^2\,S_0(x_t)} + 2\,i\,a_W\,a_{CP}\,y_t^2\,y_b^2\,\frac{G(x_t)}{S_0(x_t)}\right|.$$

$\Delta F = 2$ observables

Neutral meson oscillation

Mixing-induced CP asymmetries $S_{\psi K_S}$ & $S_{\psi\phi}$ for $B_d^0 \to \psi\, K_S$ & $B_s^0 \to \psi\,\phi$

$$S_{\psi K_S} = \sin(2\,\beta + 2\,\varphi_{B_d})\,, \qquad S_{\psi\phi} = \sin(2\,\beta_s - 2\,\varphi_{B_s})\,,$$

UT-angles β & β_s

$$\beta \equiv \arg\left(-\frac{V_{cb}^*\,V_{cd}}{V_{tb}^*\,V_{td}}\right)\,, \qquad \beta_s \equiv \arg\left(-\frac{V_{tb}^*\,V_{ts}}{V_{cb}^*\,V_{cs}}\right)\,,$$

New phases

$$\varphi_{B_d} = \varphi_{B_s} = 2\,a_W\,a_{CP}\,y_t^2\,y_b^2\,\frac{G(x_t)}{S_0(x_t)}\,.$$

$R_{BR/\Delta M}$

$$R_{BR/\Delta M} = \frac{3\,\pi\,\tau_{B^+}}{4\,\eta_B\,\hat{B}_{B_d}\,S_0(x_t)}\,\frac{m_\tau^2}{M_W^2}\,\frac{|V_{ub}|^2}{|V_{tb}^*\,V_{td}|^2}\left(1-\frac{m_\tau^2}{m_{B_d}^2}\right)^2\frac{\left|1+(a_W+i\,a_{CP})\,y_b^2\right|^2}{\mathcal{C}_{B_d}}$$

$\Delta F = 2$ observables

B-semileptonic CP-Asymmetry

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \,,$$

N_b^{++} & N_b^{--} number of events containing two μ^+ or μ^-. In $p\bar{p}$ colliders, such events can only arise through $B^0_d - \bar{B}^0_d$ or $B^0_s - \bar{B}^0_s$ mixings.

$$A^b_{sl} = (0.594 \pm 0.022)\, a^d_{sl} + (0.406 \pm 0.022)\, a^s_{sl} \,,$$

$$a^d_{sl} \equiv \left| \frac{\left(\Gamma^d_{12}\right)_{SM}}{\left(M^d_{12}\right)_{SM}} \right| \sin\phi_d = (5.4 \pm 1.0) \times 10^{-3} \, \sin\phi_d \,,$$

$$a^s_{sl} \equiv \left| \frac{\left(\Gamma^s_{12}\right)_{SM}}{\left(M^s_{12}\right)_{SM}} \right| \sin\phi_s = (5.0 \pm 1.1) \times 10^{-3} \, \sin\phi_s \,,$$

$$\phi_d \equiv \arg\left(-\left(M^d_{12}\right)_{SM} / \left(\Gamma^d_{12}\right)_{SM} \right) = -4.3^\circ \pm 1.4^\circ \,,$$

$$\phi_s \equiv \arg\left(-\left(M^s_{12}\right)_{SM} / \left(\Gamma^s_{12}\right)_{SM} \right) = 0.22^\circ \pm 0.06^\circ \,.$$

NP contributions

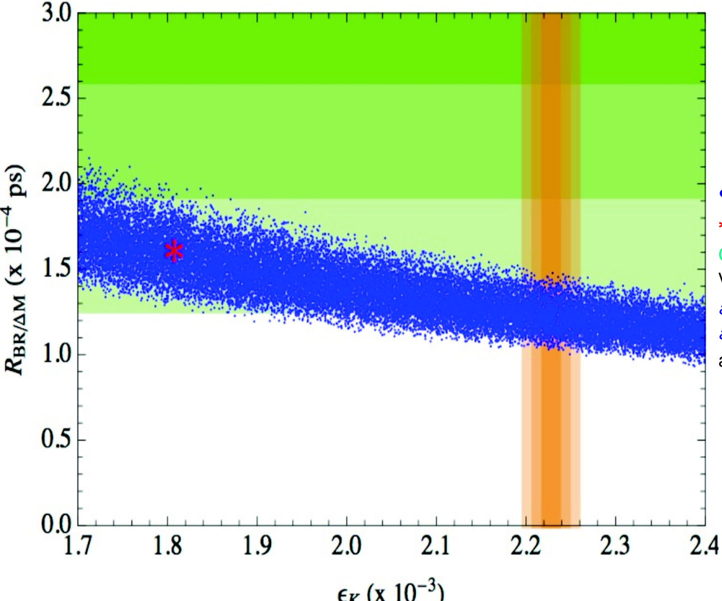
$$\Gamma^q_{12} = (\Gamma^q_{12})_{\rm SM}\, \tilde{\mathcal{C}}_{B_q} \qquad \text{with} \qquad \tilde{\mathcal{C}}_{B_q} = 1 + 2\, a_W\, y_b^2 \,,$$

$$a^q_{sl} = \left| \frac{\left(\Gamma^q_{12}\right)_{SM}}{\left(M^q_{12}\right)_{SM}} \right| \frac{\tilde{\mathcal{C}}_{B_q}}{\mathcal{C}_{B_q}} \sin\left(\phi_q + 2\varphi_{B_q}\right) \,,$$

Impact on the observables of specific parameter values

Parameter	$\delta\varepsilon_K$	$\delta R_{BR/\Delta M}$	δA^b_{sl}
$a_{CP} = 0.1(-0.1)$	$\approx 1.1\%$	$\approx -1.4\%$	$\approx 1.1\%(-1.6\%)$
$a_W = 0.1(-0.1)$	$\approx +26\%(-19\%)$	$\approx -25\%(+30\%)$	$\approx +33\%(-23\%)$
$a^d_Z = \pm 0.1$	$\approx 124\%$	$\approx -62\%$	$\approx 160\%$

ε_K vs. $R_{BR/\Delta M}$ from $\mathcal{O}_{1,2,3}$



●: correlation $\varepsilon_K - R_{BR/\Delta M}$

∗: SM values

Green & Orange: $1, 2, 3\sigma$ exp values

$a_W \in [-1, 1]$,
$a_Z^d \in [-0.1, 0.1]$
and $a_{CP} = 0$

Phenomenological Analysis

Input parameters and the SM analysis

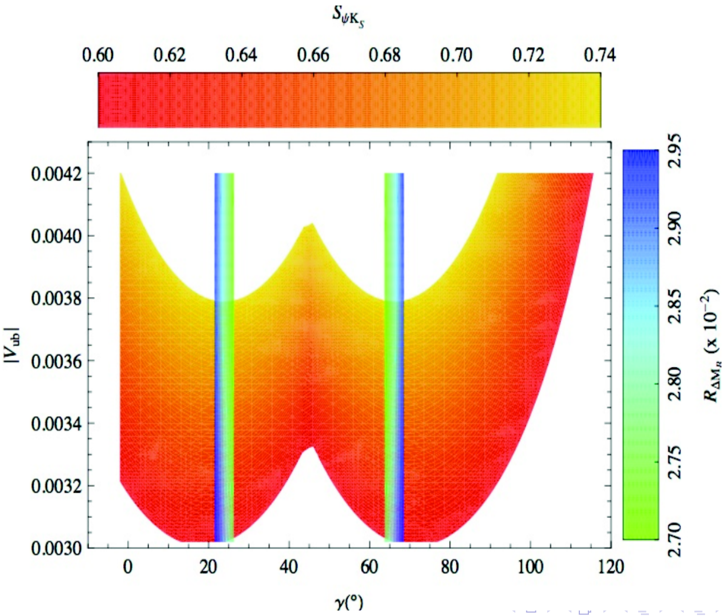
- Wolfenstein parametrization to describe the CKM matrix, where the parameters are fixed considering the value of V_{us}, V_{cb}, γ and $|V_{ub}|$, which are related to tree-level processes and therefore hardly affected by NP contributions.
- V_{us} and V_{cb} appear to be relatively well measured, compared to V_{ub} which has an error still of the order of 10%.
- Actual tension between the exclusive and the inclusive experimental determinations of $|V_{ub}|$, which translates into the well known $\varepsilon_K - S_{\psi K_S}$ and $BR(B^+ \to \tau^+ \nu)$ anomalies.
- γ of the B_d unitarity triangle, despite of being a tree-level SM processes, still suffers from a large uncertainty. Two scenarios:
- *Exclusive determination of* $|V_{ub}|$, $S_{\Psi K_S}$ is predicted to be very close to the experimental determination of $\sin(2\beta)_{b\to c\bar{c}s}$, while $\varepsilon_K \approx 1.8 \times 10^{-3}$ is clearly below the measured value. Furthermore, for such a value of $|V_{ub}|$ the $BR(B^+ \to \tau^+ \nu)$ is predicted to be smaller than the central experimental value by more than 2σ. If NP is advocated in order to solve (or at least to soften) these anomalies it should enhance the value of ε_K and $BR(B^+ \to \tau^+ \nu)$, while having negligible impact on $S_{\psi K_S}$.
- *Inclusive determination of* $|V_{ub}|$, the SM prediction for ε_K is closer to its experimental determination and $BR(B^+ \to \tau^+ \nu)$ agrees with exp. within the 1σ level. However, $S_{\psi K_S}$ is above the measured value. If NP is advocated in order to solve (or at least to soften) this anomaly , it should deplete $S_{\psi K_S}$, while leaving basically unchanged ε_K and $BR(B^+ \to \tau^+ \nu)$.

$G_F = 1.16637(1) \times 10^{-5}$ GeV^{-2}	[30]	$m_{B_d} = 5279.5(3)$ MeV	[30]
$M_W = 80.399(23)$ GeV	[30]	$m_{B_s} = 5366.3(6)$ MeV	[30]
$s_W^2 \equiv \sin^2\theta_W = 0.23116(13)$	[30]	$F_{B_d} = 205(12)$ MeV	[32]
$\alpha(M_Z) = 1/127.9$	[30]	$F_{B_s} = 250(12)$ MeV	[32]
$\alpha_s(M_Z) = 0.1184(7)$	[30]	$\hat{B}_{B_d} = 1.26(11)$	[32]
$m_u(2\text{ GeV}) = 1.7 \div 3.1$ MeV	[30]	$\hat{B}_{B_s} = 1.33(6)$	[32]
$m_d(2\text{ GeV}) = 4.1 \div 5.7$ MeV	[30]	$F_{B_d}\sqrt{\hat{B}_{B_d}} = 233(14)$ MeV	[32]
$m_s(2\text{ GeV}) = 100^{+30}_{-20}$ MeV	[30]	$F_{B_s}\sqrt{\hat{B}_{B_s}} = 288(15)$ MeV	[32]
$m_c(m_c) = (1.279 \pm 0.013)$ GeV	[36]	$\xi = 1.237(32)$	[32]
$m_b(m_b) = 4.19^{+0.18}_{-0.06}$ GeV	[30]	$\eta_B = 0.55(1)$	[37, 38]
$M_t = 172.9 \pm 0.6 \pm 0.9$ GeV	[30]	$\Delta M_d = 0.507(4)\,\text{ps}^{-1}$	[30]
$m_K = 497.614(24)$ MeV	[30]	$\Delta M_s = 17.77(12)\,\text{ps}^{-1}$	[30]
$F_K = 156.0(11)$ MeV	[32]	$\sin(2\beta)_{b\to c\bar{c}s} = 0.673(23)$	[30]
$\hat{B}_K = 0.737(20)$	[32]	$\phi_s^{\psi\phi} = 0.55^{+0.38}_{-0.36}$	[39, 40]
$\kappa_\epsilon = 0.923(6)$	[41]	$\phi_s^{\psi\phi} = 0.03 \pm 0.16 \pm 0.07$	[42]
$\varphi_\epsilon = (43.51 \pm 0.05)^\circ$	[43]	$R_{\Delta M_B} = (2.85 \pm 0.03) \times 10^{-2}$	[30]
$\eta_1 = 1.87(76)$	[44]	$A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093) \times 10^{-2}$	[34]
$\eta_2 = 0.5765(65)$	[37]	$\|V_{us}\| = 0.2252(9)$	[30]
$\eta_3 = 0.496(47)$	[45]	$\|V_{cb}\| = (40.6 \pm 1.3) \times 10^{-3}$	[30]
$\Delta M_K = 0.5292(9) \times 10^{-2}\,\text{ps}^{-1}$	[30]	$\|V_{ub}^{\text{incl.}}\| = (4.27 \pm 0.38) \times 10^{-3}$	[30]
$\|\epsilon_K\| = 2.228(11) \times 10^{-3}$	[30]	$\|V_{ub}^{\text{excl.}}\| = (3.38 \pm 0.36) \times 10^{-3}$	[30]
$\tau_{B^\pm} = (1641 \pm 8) \times 10^{-3}$ ps	[30]	$\|V_{ub}^{\text{comb.}}\| = (3.89 \pm 0.44) \times 10^{-3}$	[30]
$BR(B^+ \to \tau^+\nu) = (1.65 \pm 0.34) \times 10^{-4}$	[30]	$\gamma = (73^{+22}_{-25})^\circ$	[30]

Table 2: *Values of the experimental quantities used as input parameters. Notice that $m_i(m_i)$ are the masses m_i at the scale m_i in the $\overline{MS}$ scheme while M_t is the top-quark pole mass.*

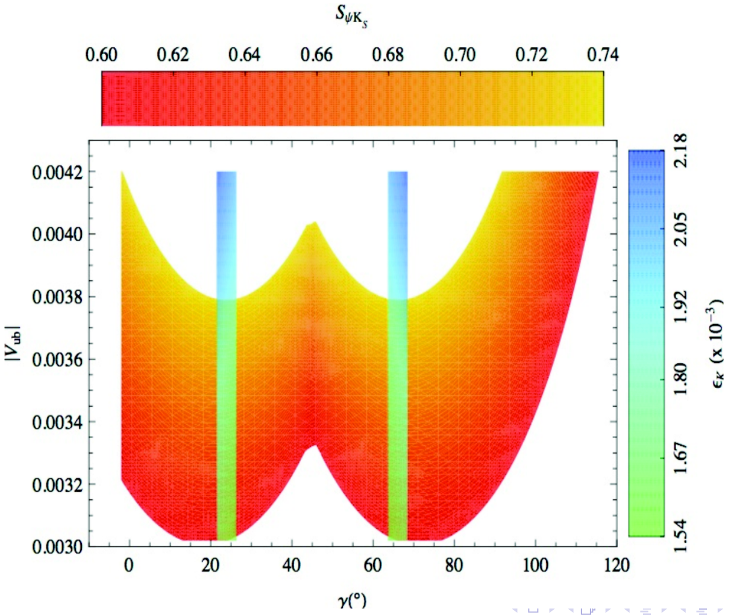
Phenomenological Analysis

$|V_{ub}| - \gamma$ parameter space



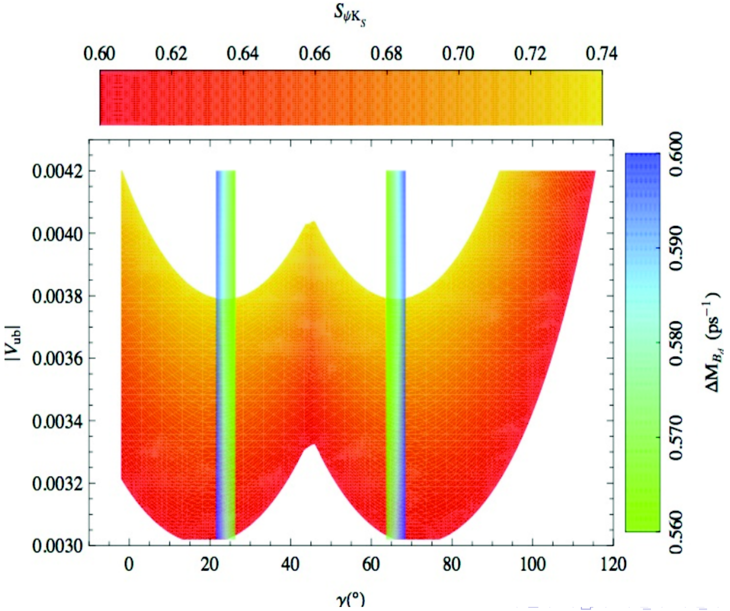
Phenomenological Analysis

ε_K



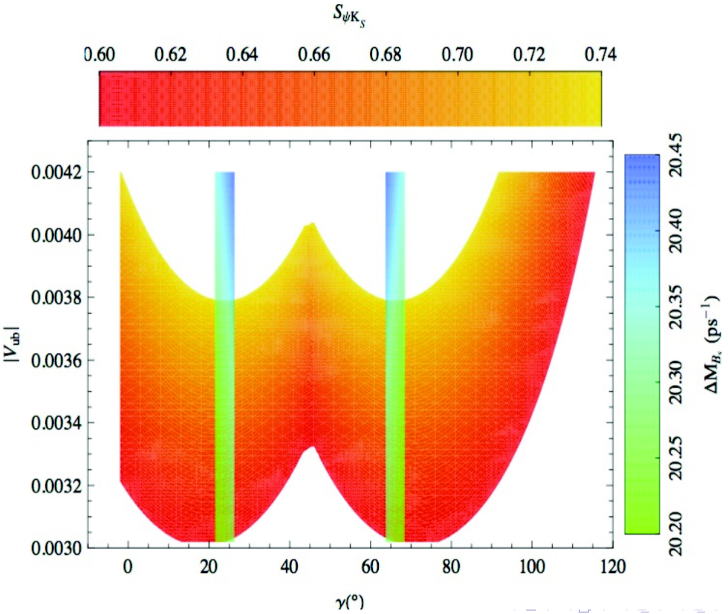
Phenomenological Analysis

ΔM_{B_d}



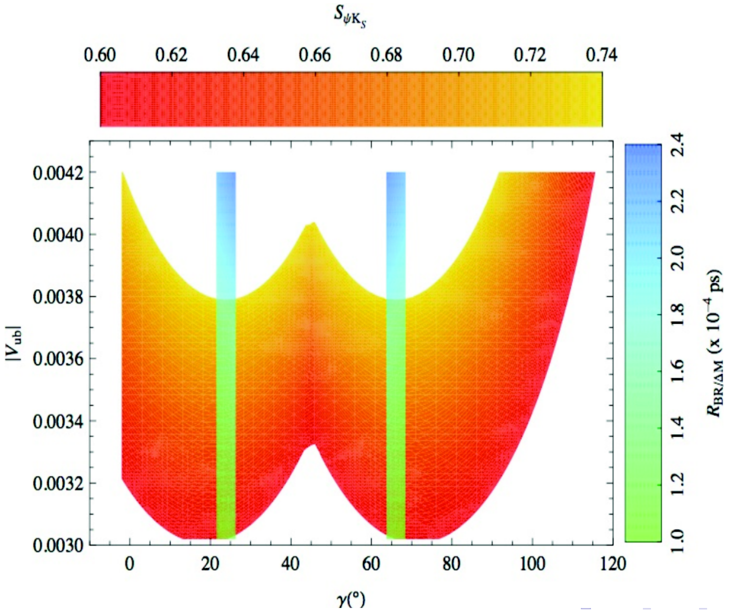
Phenomenological Analysis

ΔM_{B_s}



Phenomenological Analysis

$R_{BR/\Delta M}$



Phenomenological Analysis

In order to illustrate the features of the MFV scenario with a strong interacting Higgs sector, the numerical analysis of the following sections will be presented choosing as reference point, $(|V_{ub}|, \gamma) = (3.5 \times 10^{-3}, 66^\circ)$, corresponding to $S_{\psi K_S} \simeq 0.692$ and $R_{\Delta M_B} \simeq 2.83 \times 10^{-2}$. For this point

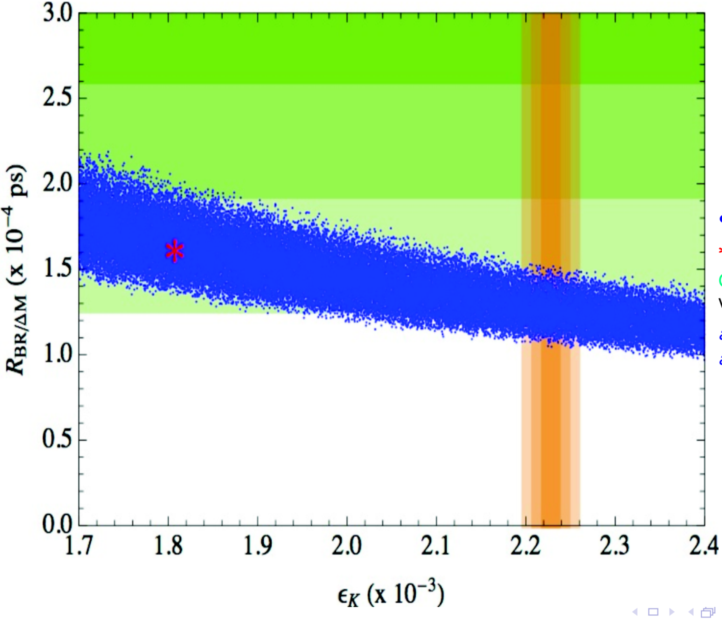
$$\varepsilon_K = 1.8 \times 10^{-3}\,, \qquad R_{BR/\Delta M} = 1.6 \times 10^{-4}\ \mathrm{ps}\,.$$

$$S_{\psi\phi} = 0.036\,.$$

$$A^b_{sl} = -2.3 \times 10^{-4} \qquad \left(a^d_{sl} = -4.0 \times 10^{-4}\,, \qquad a^s_{sl} = 1.9 \times 10^{-5}\right)\,,$$

$$\begin{aligned} a_{CP} &= 0.1(-0.1) &\longrightarrow&\qquad \delta A^b_{sl} \approx 1.1\%(1.6\%)\\ a_W &= 0.1(-0.1) &\longrightarrow&\qquad \delta A^b_{sl} \approx 33\%(-23\%)\\ a^d_Z &= \pm 0.1 &\longrightarrow&\qquad \delta A^b_{sl} \approx 160\%\,. \end{aligned}$$

ε_K vs. $R_{BR/\Delta M}$ from all $\mathcal{O}_i$



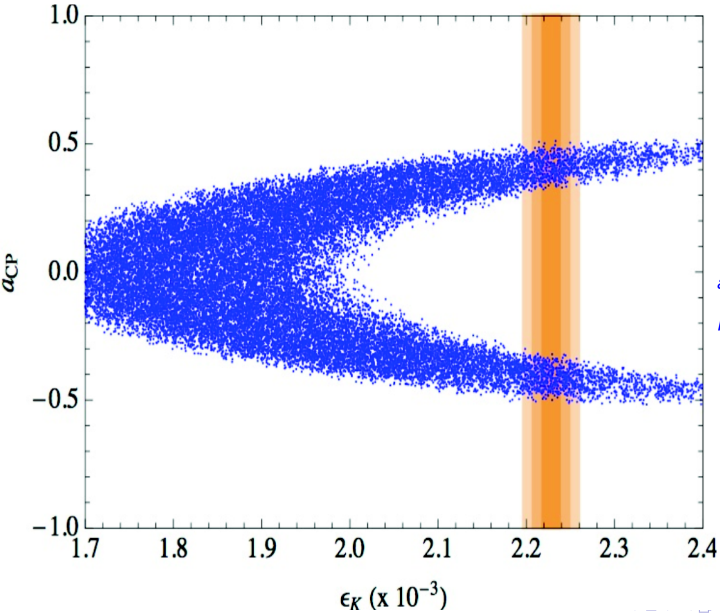
●: correlation $\varepsilon_K - R_{BR/\Delta M}$

$*$: SM values

Green & Orange: $1, 2, 3\sigma$ exp values

$a_W, a_{CP} \in [-1, 1]$,
$a_Z^d \in [-0.1, 0.1]$

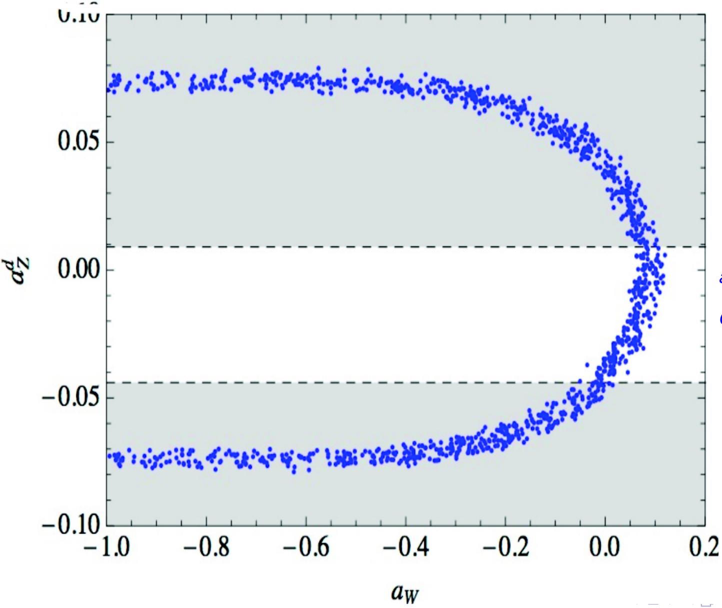
From $\mathcal{O}_4$



a_{CP} from $\mathcal{O}_4$

R inside its 3σ exp. value

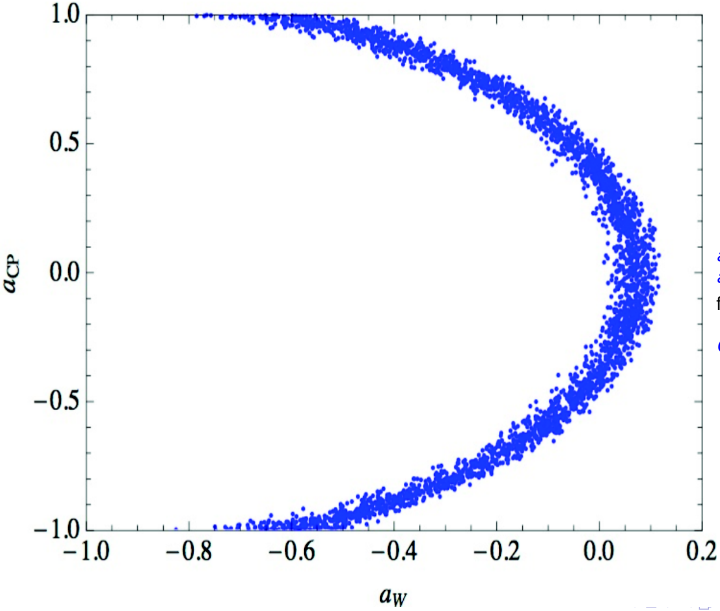
From $\mathcal{O}_{1,2,3}$



a_W-a_Z^d from $\mathcal{O}_{1,2,3}$

Obs inside its 3σ exp. value

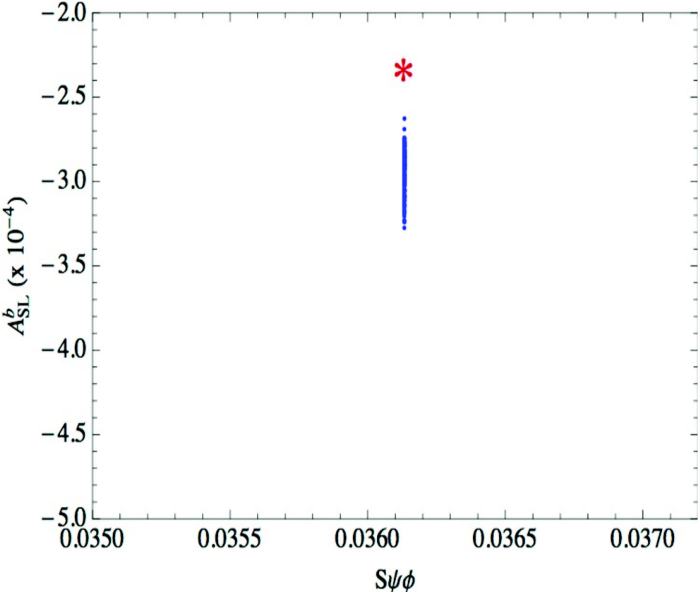
From all $\mathcal{O}_i$



$a_W - a_{CP}$ and $a_Z^d \in [-0.044, 0.009]$ from $\mathcal{O}_i$

Obs inside its 3σ exp. value

$S_{\psi\phi}$ vs. A^b_{sl} from $\mathcal{O}_{1,2,3}$

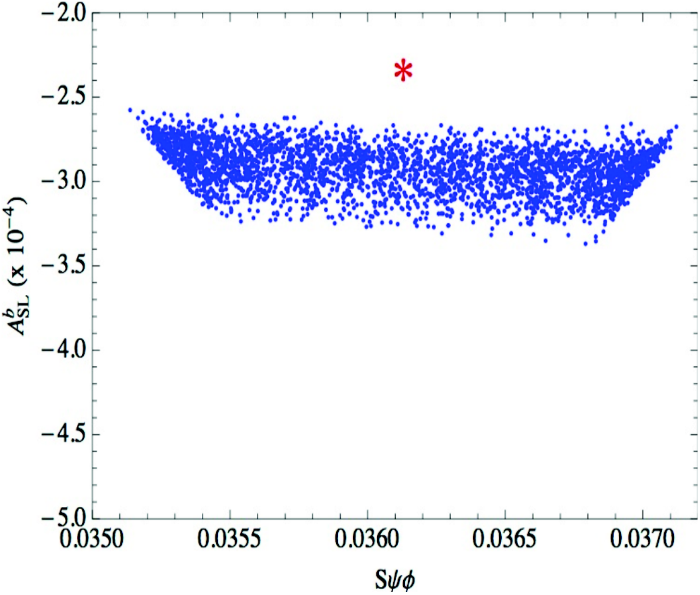


●: correlation $S_{\psi\phi} - A^b_{sl}$

∗: SM values

$a_W \in [-1, 1]$, $a_{CP} = 0$,
$a^d_Z \in [-0.044, 0.009]$

$S_{\psi\phi}$ vs. A^b_{sl} from all $\mathcal{O}_i$



●: correlation $S_{\psi\phi} - A^b_{sl}$

*: SM values

$a_W, a_{CP} \in [-1, 1]$,
$a^d_Z \in [-0.044, 0.009]$