Flavour Physics

4. Searching for New Physics

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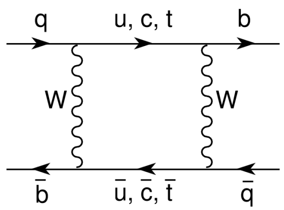
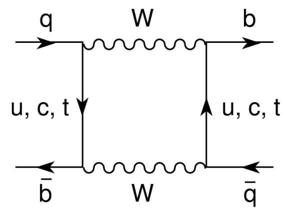
Bounds on New Flavour Physics





$$\lambda_u + \lambda_c + \lambda_t = 0 \qquad \lambda_i \equiv V_{iq}\, V_{ib}^*$$

$$L_{\rm eff} = L_{\rm SM} + \sum_{D>4} \sum_k \frac{c_k^{(D)}}{\Lambda_{\rm NP}^{D-4}}\, O_k^{(D)}$$

Isidori, 1302.0661

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$)		Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar s_R\, d_L)(\bar s_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar b_R\, d_L)(\bar b_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar b_R\, s_L)(\bar b_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

- **Generic flavour structure [$c_{NP} \sim O(1)$] ruled out at the TeV scale**
- **$\Lambda_{NP} \sim 1$ TeV requires c_{NP} to inherit the strong SM suppressions (GIM)**

Minimal Flavour Violation: The up and down Yukawa matrices are the only source of quark-flavour symmetry breaking D'Ambrosio et al , Chivukula-Georgi

Two Higgs Doublet Model: $\phi_a \quad (a = 1, 2)$

$$\langle 0 | \, \phi_a^T(x) | 0 \rangle = \frac{1}{\sqrt{2}} \, (0 \, , \, v_a \, e^{i\theta_a}) \qquad , \qquad \theta_1 = 0 \qquad , \qquad \theta \equiv \theta_2 - \theta_1$$

Higgs basis:

$$v \equiv \sqrt{v_1^2 + v_2^2} \qquad , \qquad \tan\beta \equiv v_2 / v_1$$

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{pmatrix} \phi_1 \\ e^{-i\theta} \, \phi_2 \end{pmatrix}$$

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}} \left(v + S_1 + i \, G^0 \right) \end{bmatrix} \qquad , \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}} \left(S_2 + i \, S_3 \right) \end{bmatrix}$$

Yukawa Interactions in 2HDMs

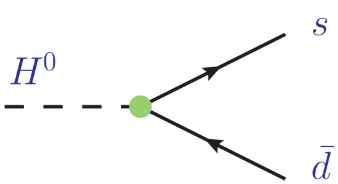
$$\mathcal{L}_Y = -\bar{Q}'_L \left(\Gamma_1 \phi_1 + \Gamma_2 \phi_2\right) d'_R - \bar{Q}'_L \left(\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2\right) u'_R$$

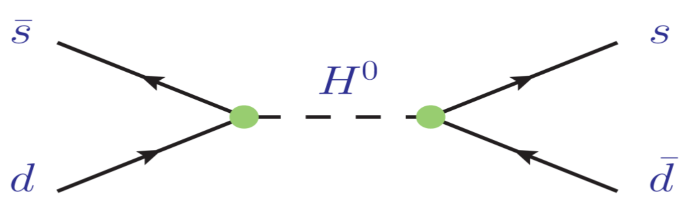
SSB ⬇

$$\phi_i^{(0)} = \frac{v_i}{\sqrt{2}}\, e^{i\theta_i} \quad , \quad v = \sqrt{v_1^2 + v_2^2}$$

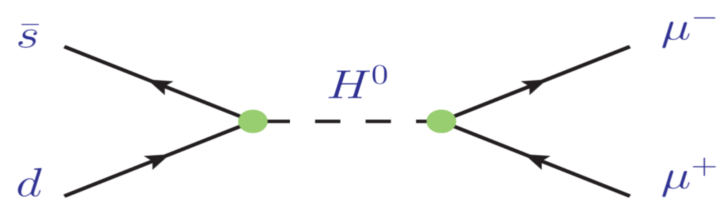
$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}'_L \left(M_d' \Phi_1 + Y_d' \Phi_2 \right) d'_R - \bar{Q}'_L \left(M_u' \tilde{\Phi}_1 + Y_u' \tilde{\Phi}_2 \right) u'_R \right\}$$

M_q' and Y_q' unrelated ➡ **FCNCs**





$K^0 \leftrightarrow \bar{K}^0$



$K^0 \to \mu^-\mu^+$

Phenomenological disaster!

Aligned 2HDM

Pich-Tuzón, 0908.1554

Yukawa alignment in Flavour Space: $Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \quad , \quad Y_u = \varsigma_u^*\, M_u$

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u}\left[\varsigma_d\, V_{\rm CKM} M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V_{\rm CKM} \mathcal{P}_L\right] d + \varsigma_l\, \left(\bar{\nu}\, M_l\, \mathcal{P}_R\, l\right)\right\}$$

$$-\frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0}\, \varphi_i^0\, \left(\bar{f}\, M_f\, \mathcal{P}_R\, f\right) \quad + \quad \text{h.c.}$$

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + \left(\mathcal{R}_{i2} + i\,\mathcal{R}_{i3}\right)\varsigma_{d,l} \qquad , \qquad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + \left(\mathcal{R}_{i2} - i\,\mathcal{R}_{i3}\right)\varsigma_u^*$$

ς_f → **New sources of CP violation without tree-level FCNCs**

$\mathcal{Z}_2$ models:

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

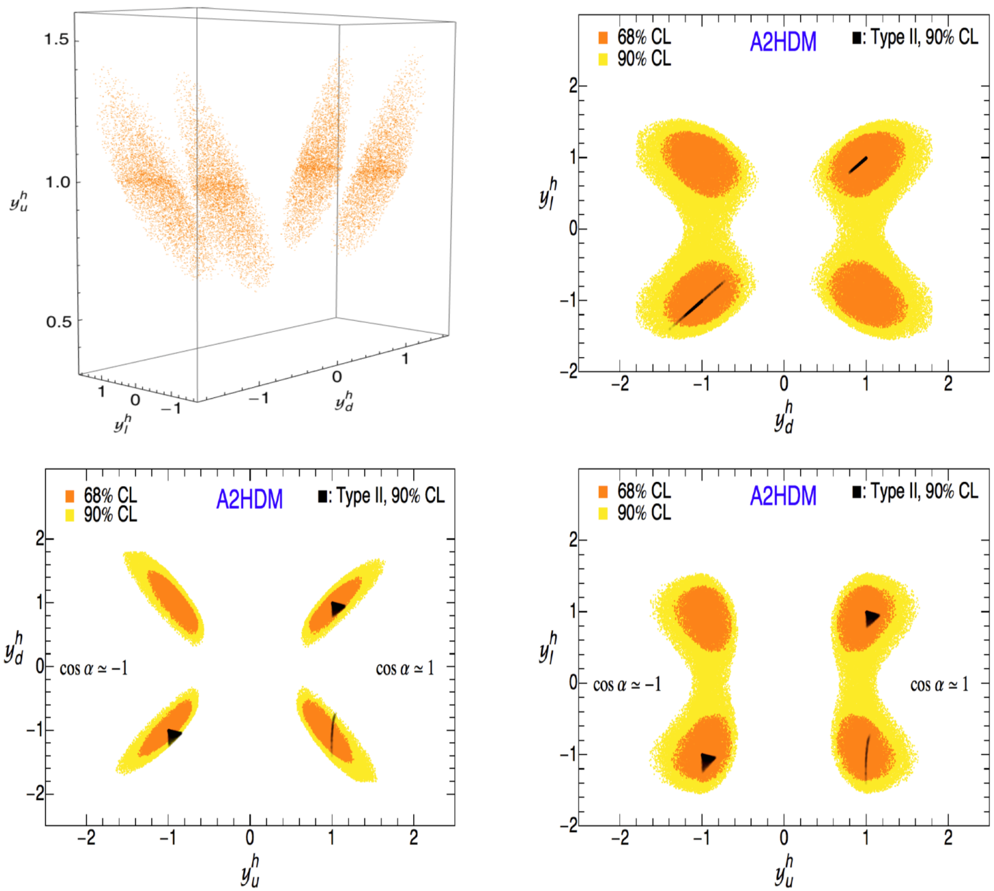
Only one ϕ_a couples to f_R

(Glashow-Weinberg, Paschos '77)

Flavour Alignment (Aligned 2HDM)

Pich-Tuzón

Celis-Ilisie-Pich, 1302.4022, 1310.7941



$|\cos\tilde{\alpha}| > 0.80$ (90% CL)

General setting without FCNCs & new sources of CP violation

$$Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \quad , \quad Y_u = \varsigma_u^*\, M_u$$

- **Rich phenomenology @ LHC**
  Altmannshofer et al, Barger et al, Celis et al, Cervero-Gerard, López-Val et al...

  Many allowed possibilities

  Search for light $H^\pm$, H, A

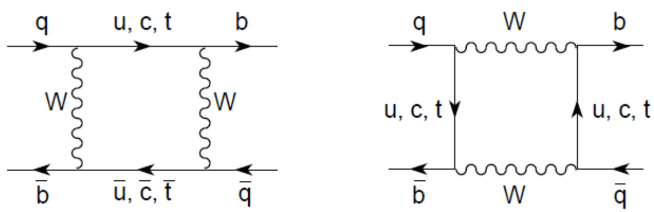
  CP violation

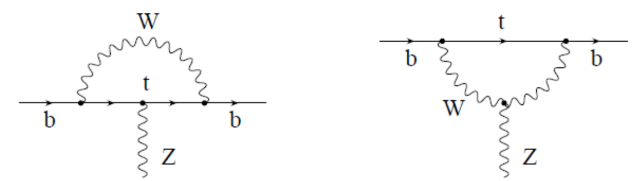
- **Flavour constraints fulfilled**
  Celis et al, Jung et al, Li et al

- **EDMs** Jung-Pich, 1308.6283

- **Usual Z_2 models recovered in particular (CP-conserving) limits**

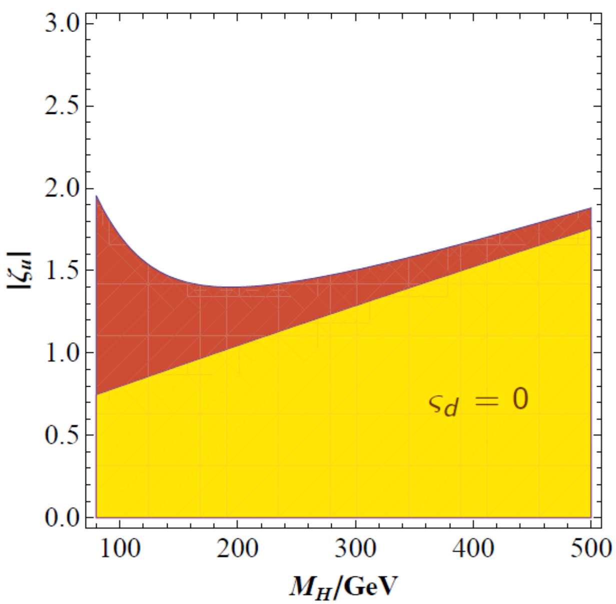
1-Loop Constraints on $H^{\pm}$ Couplings (95% CL)



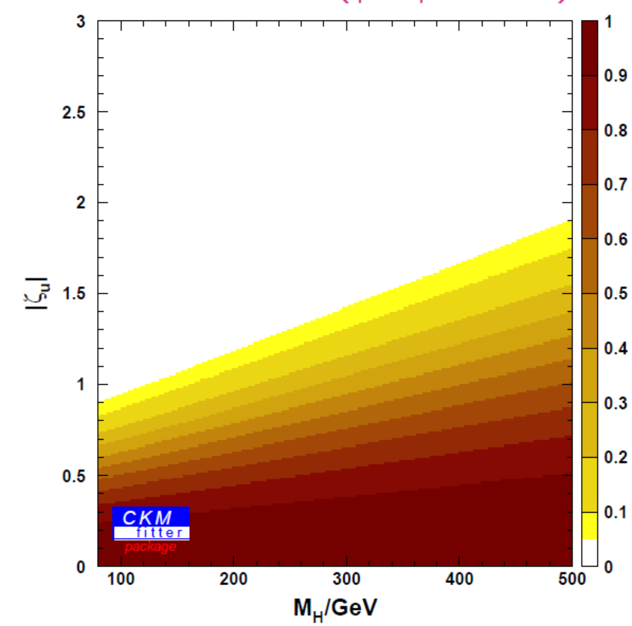


Virtual $H^{\pm}$ / $W^{\pm}$. Top-dominated contributions

ΔM_{B_s} $(|\varsigma_d| < 50)$



$Z \to b\bar{b}$ $(|\varsigma_d| < 50)$



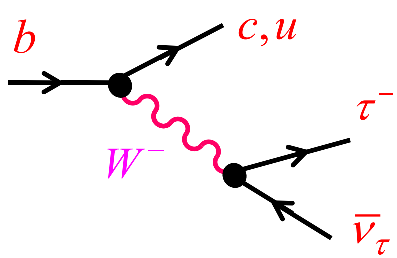
$|\varsigma_u| / M_{H^{\pm}} < 0.011 \text{ GeV}^{-1}$

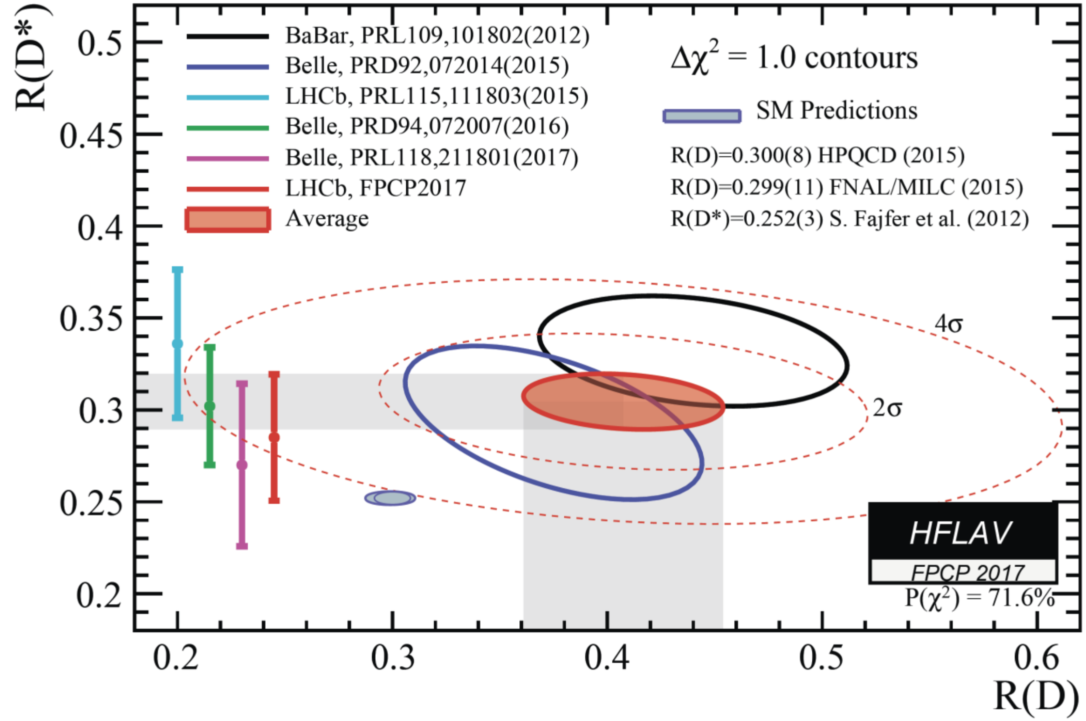
Jung-Pich-Tuzón, 1006.0470

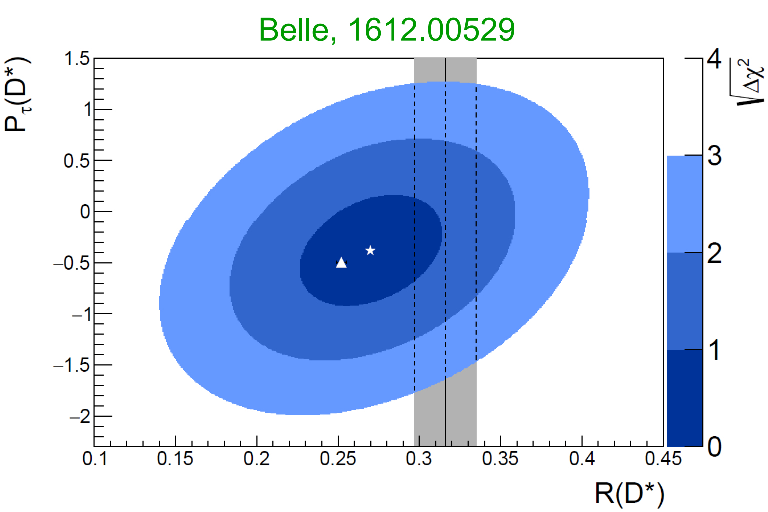
Flavour Anomaly

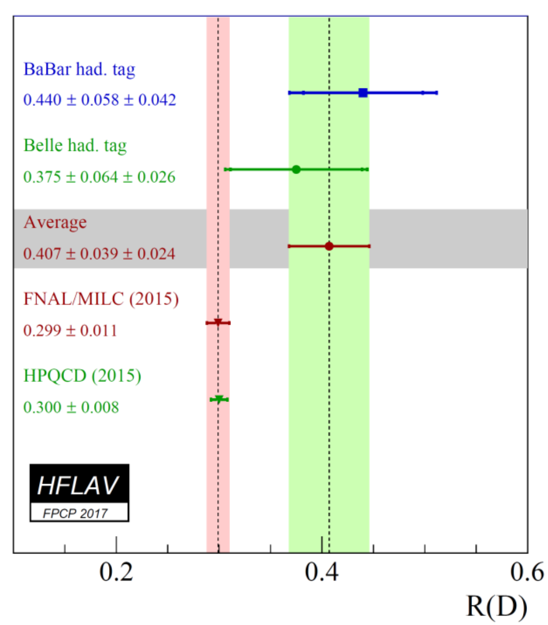
4σ discrepancy

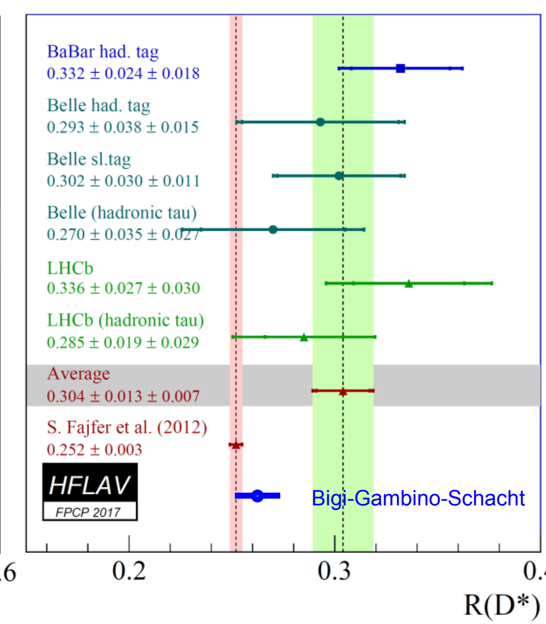
$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$











Model-Independent Analysis of $R(D^{(*)})$

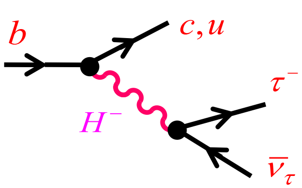
$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{q_u q_d} \left[\bar{q}_u \left(g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R\right) q_d\right] \left[\bar{\ell} \mathcal{P}_L \nu_\ell\right]$$

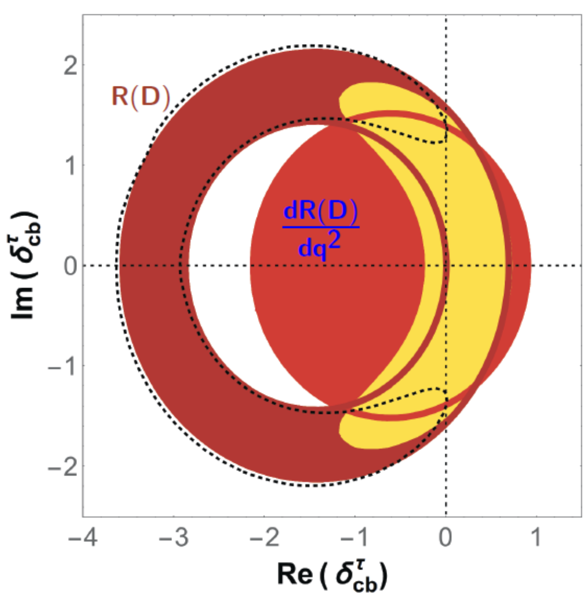
Scalar Form Factors

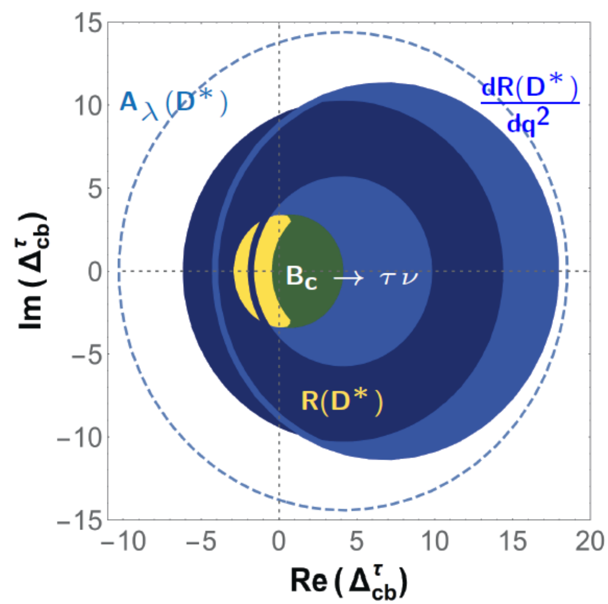
$$\delta R(D) \longleftrightarrow \delta_{cb}^{\ell} \equiv \left(g_L^{cb\ell} + g_R^{cb\ell}\right) \frac{(m_B - m_D)^2}{m_\ell\,(\bar{m}_b - \bar{m}_c)}$$

$$\delta R(D^*) \longleftrightarrow \Delta_{cb}^{\ell} \equiv \left(g_L^{cb\ell} - g_R^{cb\ell}\right) \frac{m_B^2}{m_\ell\,(\bar{m}_b + \bar{m}_c)}$$

95% CL





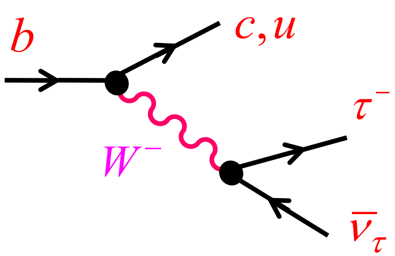


Celis et al.
1612.07757

LHCb, 1711.05623

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)} = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

2 σ above SM prediction



$$\mathcal{R}(J/\psi)_{\text{SM}} \approx 0.25 - 0.28$$

Yu et al, Ivanov et al, Kiselev, Hernández et al

Capdevila et al, 1712.01919

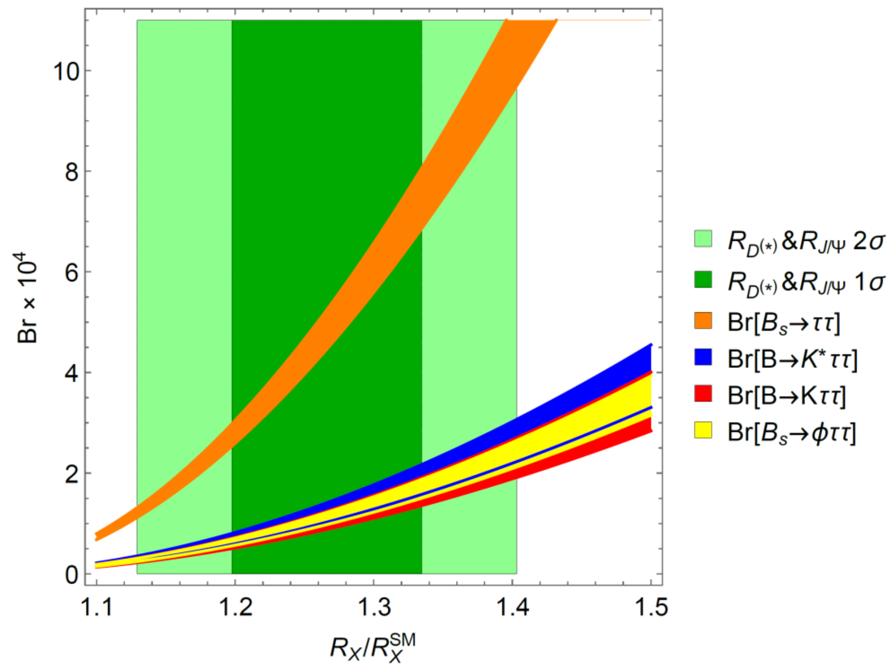
1) New physics only contributes to the SM operator $[\bar{c}\gamma^{\mu}P_L b][\bar{\tau}\gamma_{\mu}P_L\nu_{\tau}]$

$$\Rightarrow \quad R_{J/\psi}/R_{J/\psi}^{\rm SM} = R_D/R_D^{\rm SM} = R_{D^*}/R_{D^*}^{\rm SM}$$

2) At higher scales, it originates from (avoids $b \to s\nu\nu$ constraints)

$$[\bar{Q}_2\gamma^{\mu}Q_3][\bar{L}_3\gamma_{\mu}L_3] + [\bar{Q}_2\gamma^{\mu}\sigma^I Q_3][\bar{L}_3\gamma_{\mu}\sigma^I L_3] \approx 2\,[(\bar{c}_L\gamma_{\mu}b_L)(\bar{\tau}_L\gamma^{\mu}\nu_{\tau L}) + (\bar{s}_L\gamma_{\mu}b_L)(\bar{\tau}_L\gamma^{\mu}\tau_L)]$$

$\Rightarrow$ **Large Br($b \to s\tau^+\tau^-$)**



See also:

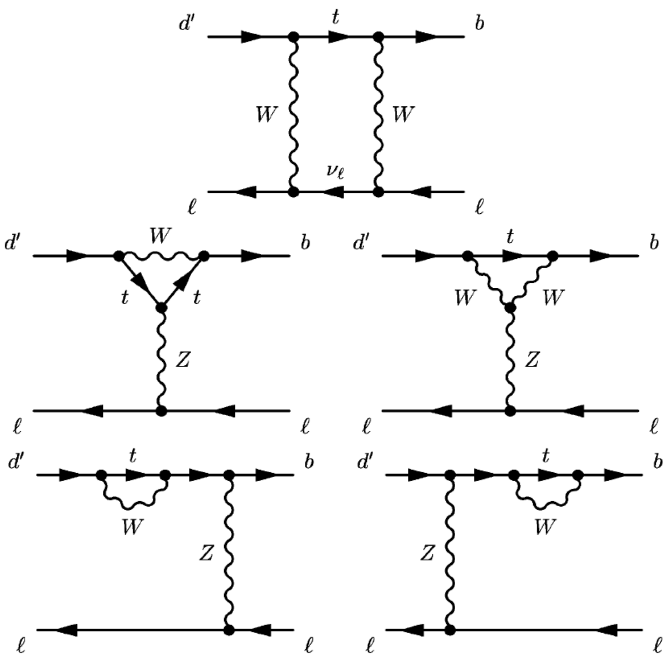
Alonso et al, 1505.05164
Crivellin et al, 1703.09226

Rare Decays

Loop & CKM suppression → NP sensitivity

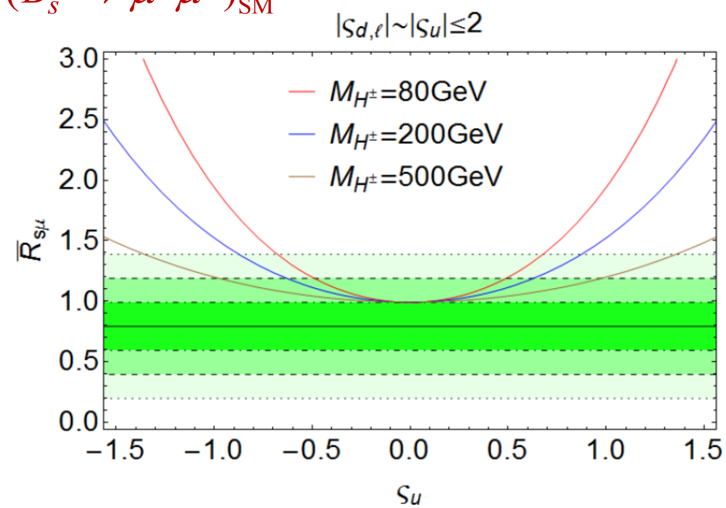
$B_{s,d} \to \mu^+\mu^-$

Sensitive to (pseudo) scalar contributions



$$\overline{R}_{s\mu} \equiv \frac{\overline{B}(B_s^0 \to \mu^+\mu^-)}{\overline{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM}}$$

Li-Lu-Pich, 1404.5865



$W^\pm \leftrightarrow H^\pm$, $Z \leftrightarrow H^0, A^0$

$$\overline{B}(B_q^0 \to \mu^+\mu^-) = \frac{1 + A_{\Delta\Gamma}^{\ell\ell}\, y_q}{1 - y_q^2}\, {\rm Br}(B_q^0 \to \mu^+\mu^-)$$

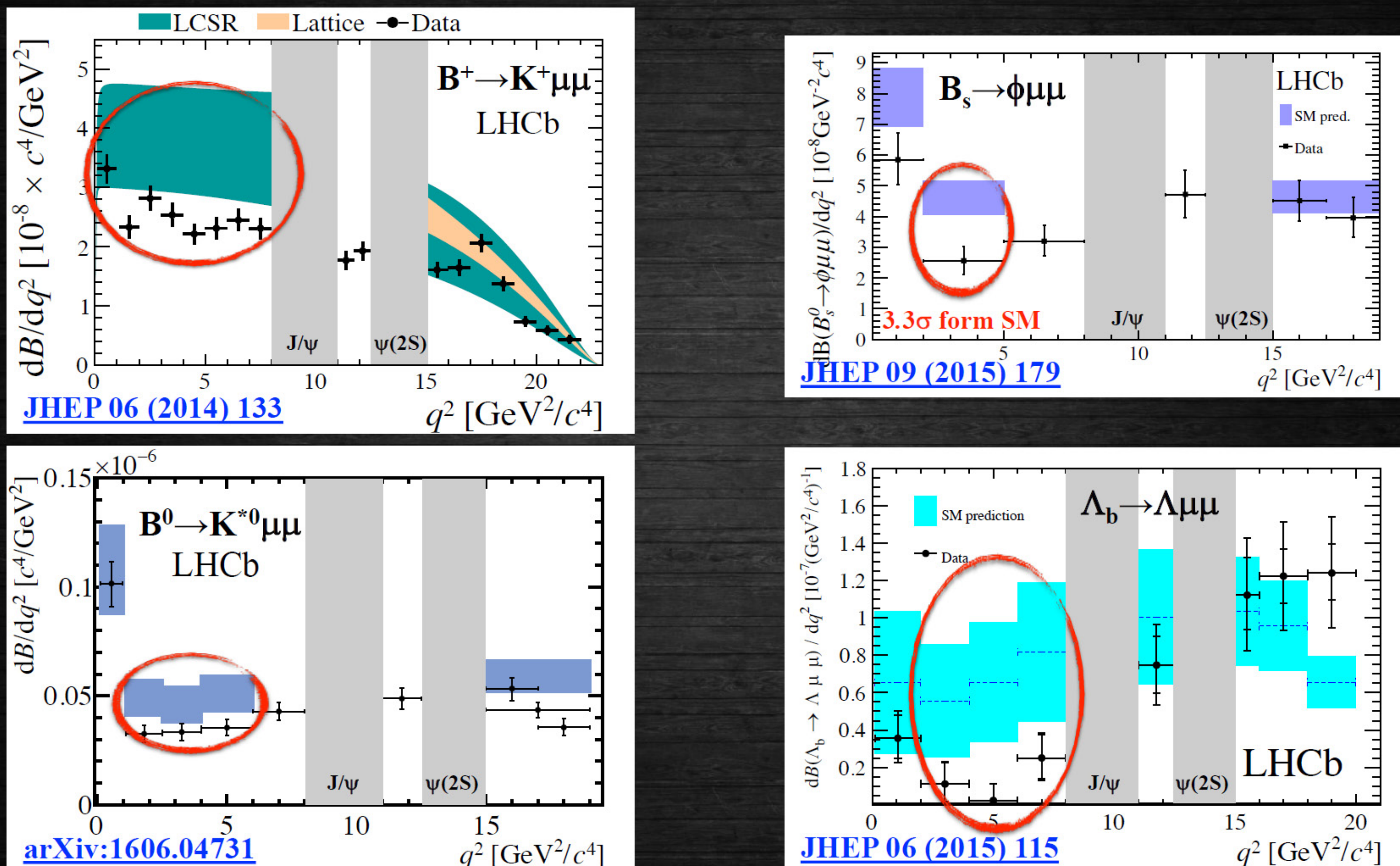
LHCb, 1703.05747: $\overline{B}(B_s^0 \to \mu^+\mu^-)_{\rm exp} = \left(3.0 \pm 0.6 {}^{+0.3}_{-0.2}\right) \cdot 10^{-9}$, $\overline{B}(B_d^0 \to \mu^+\mu^-)_{\rm exp} < 3.4 \cdot 10^{-10}$ (95% CL)

$\left[{\rm SM:}\ (3.65 \pm 0.23) \cdot 10^{-9}\right]$ $\left[{\rm SM:}\ (1.06 \pm 0.09) \cdot 10^{-10}\right]$

LHCb, 1703.02528: $\overline{B}(B_s^0 \to \tau^+\tau^-)_{\rm exp} < 6.8 \cdot 10^{-3}$, $\overline{B}(B_d^0 \to \tau^+\tau^-)_{\rm exp} < 2.1 \cdot 10^{-3}$ (95% CL)

$b \to s\,\mu^+\mu^-$ Differential Branching Ratios

› Results **consistently lower than SM predictions**



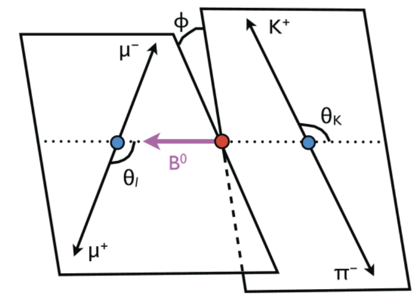
Simone Bifani — CERN Seminar — 6

$B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$

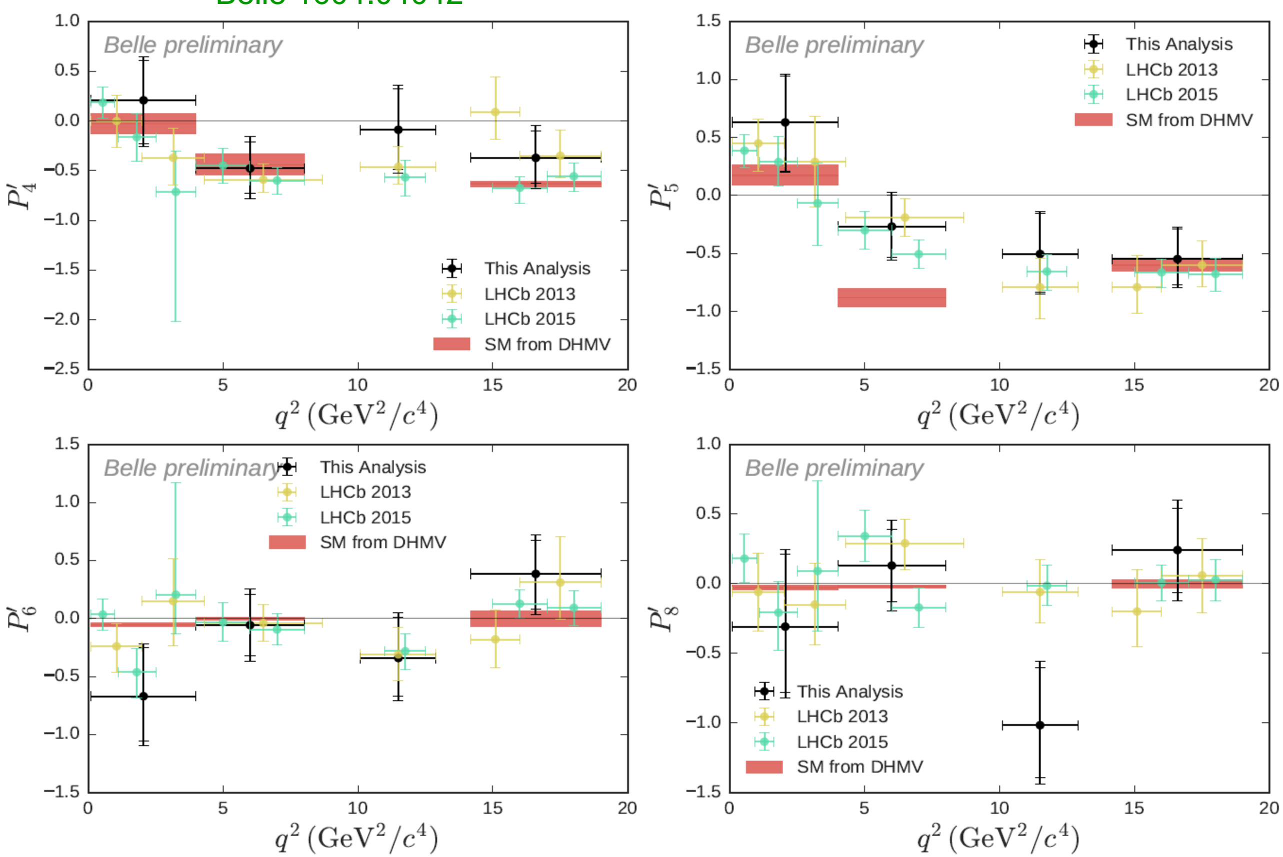
$$\frac{1}{d\Gamma/dq^2}\,\frac{d^4\Gamma}{d\cos\theta_\ell\; d\cos\theta_K\; d\phi\; dq^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$\left. + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\right]$$

$$q^2 = s_{\mu^+\mu^-}$$

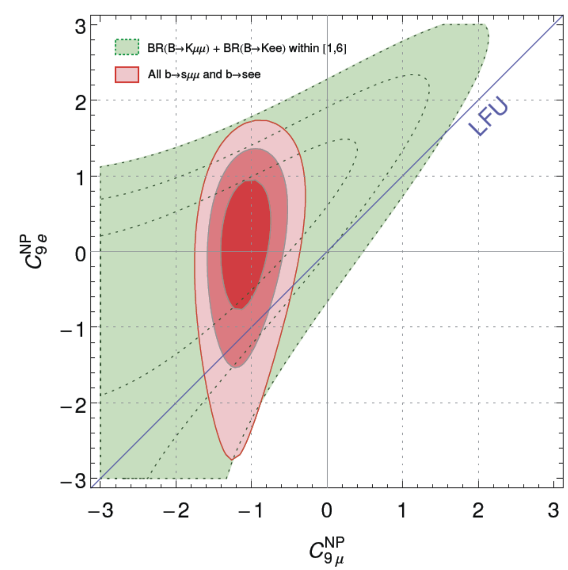
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



Belle 1604.04042



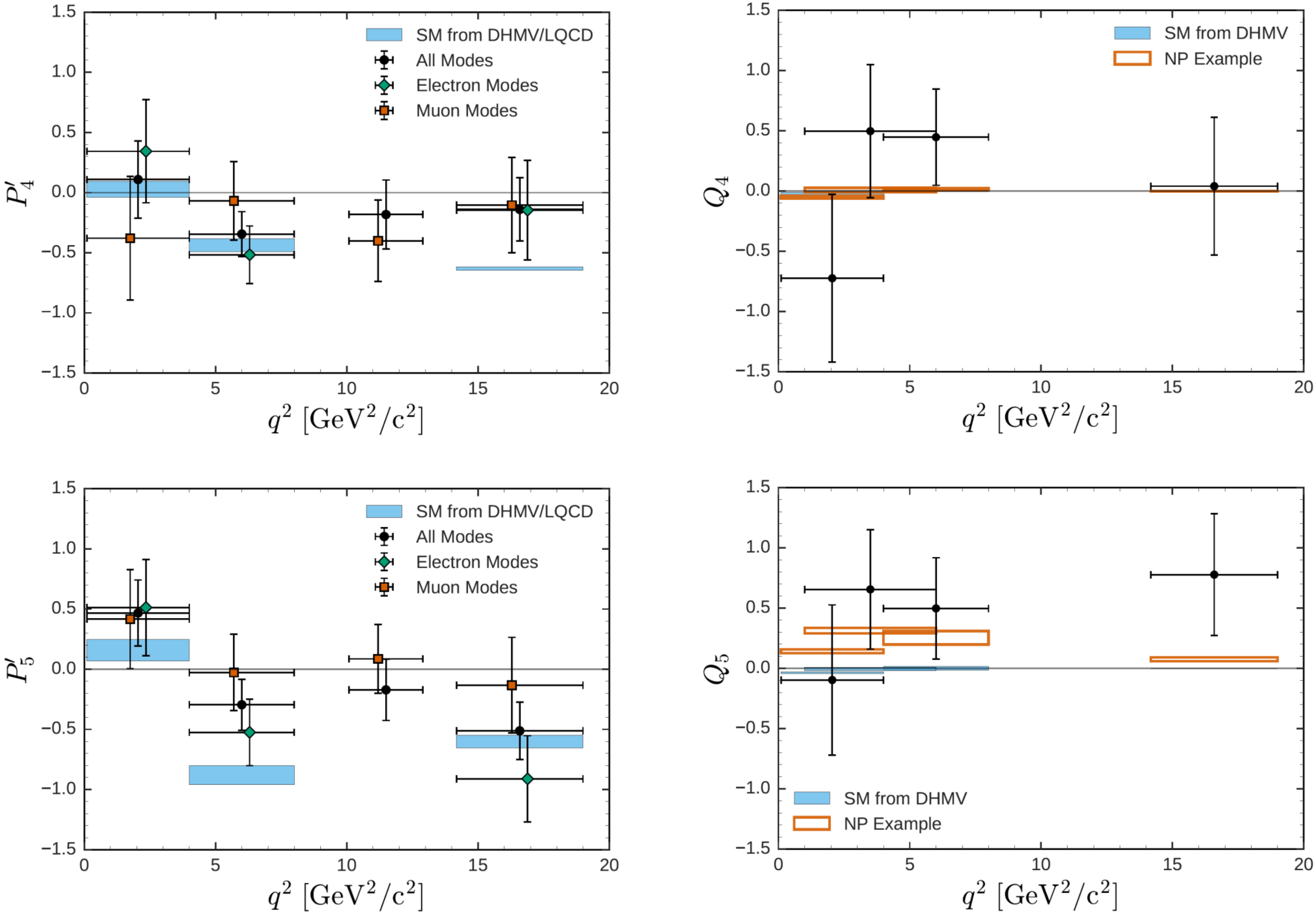
Descotes-Genon et al, 1510.04239



$$O_9 = \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right)$$

Belle, 1612.05014

$Q_i \equiv P_i'^{\mu} - P_i'^{e}$



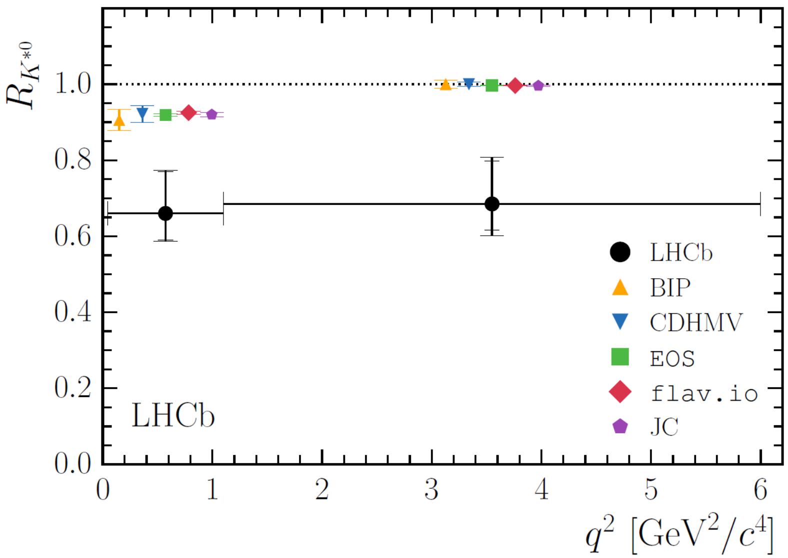
Violations of Lepton Flavour

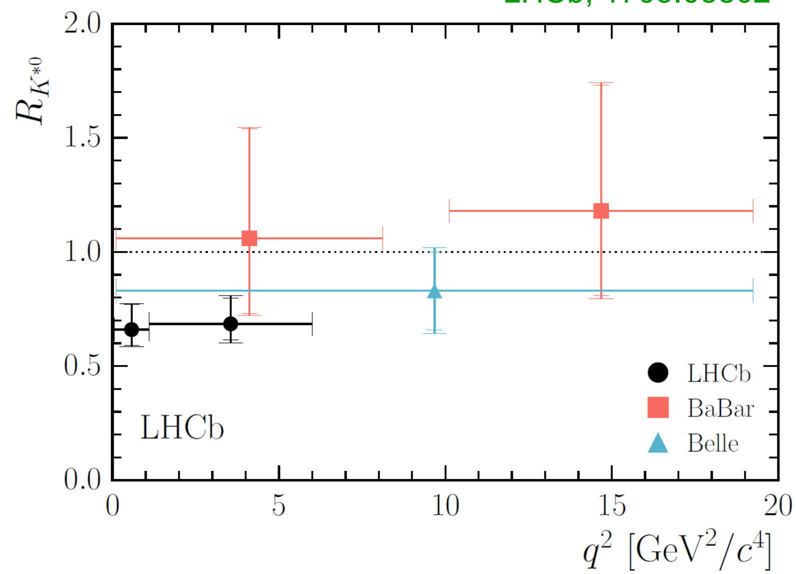
$$R_{K^{*0}} = \frac{\mathrm{Br}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{Br}(B^0 \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathrm{Br}(B^0 \to K^{*0}e^+e^-)}{\mathrm{Br}(B^0 \to K^{*0}J/\psi\,(\to e^+e^-))}$$

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]

2.1 – 2.5 σ deviation from SM

LHCb, 1705.05802

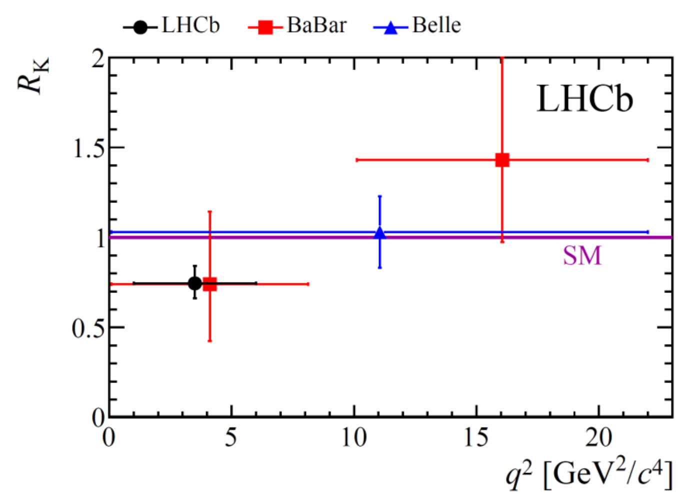




LHCb: 1406.6482 $(q^2 \in [1,6]\ \mathrm{GeV}^2)$

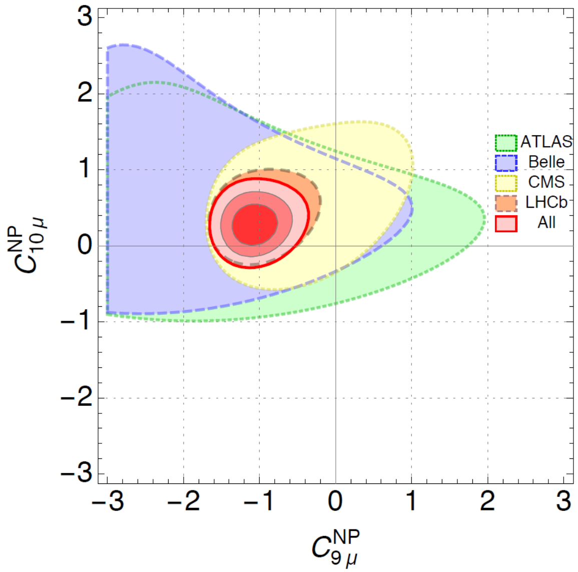
$$\frac{\mathrm{Br}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}(B^+ \to K^+e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

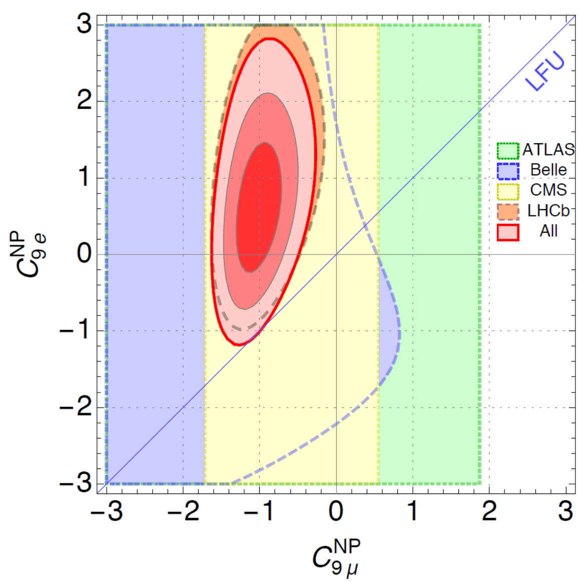
2.6 σ below the SM



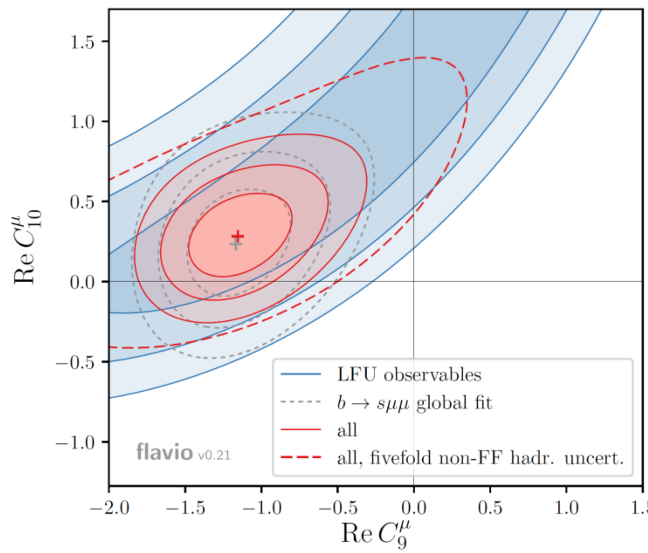
New-Physics Fits with Effective Operators

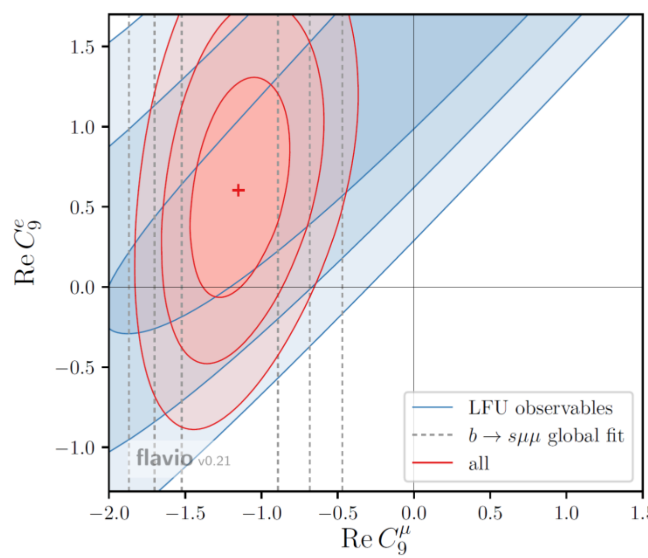
Capdevila et al, 1704.05340



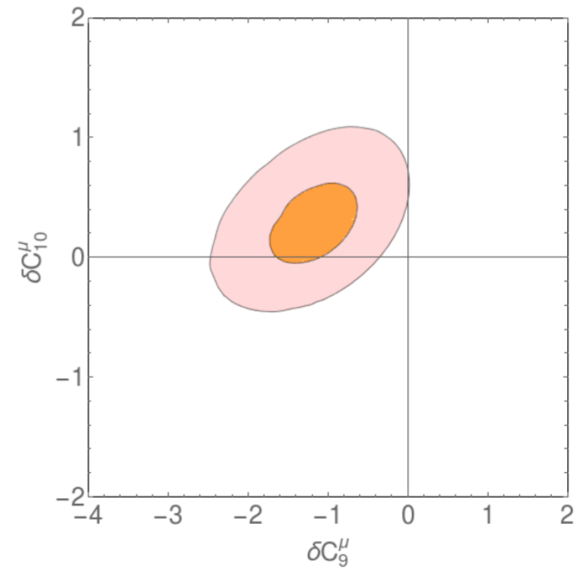


Altmannshofer et al, 1704.05435





Geng et al, 1704.05446



$$C_9^\mu - C_9^e - C_{10}^\mu + C_{10}^e \simeq -1.4$$

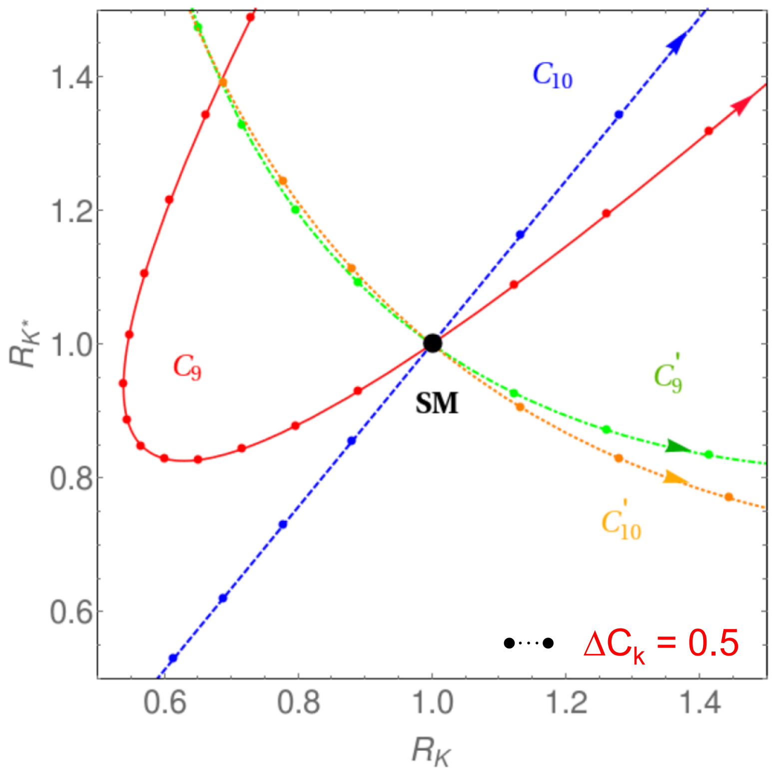
$$H_{\rm eff}^{\rm NP} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{i,\ell} C_i^\ell\, O_i^\ell$$

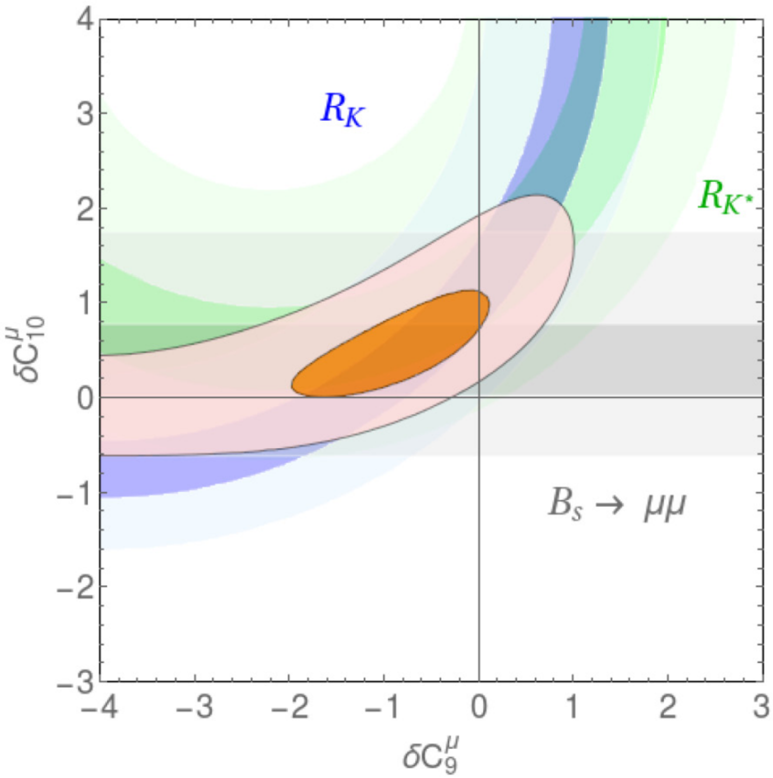
$$O_9^\ell = \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right)$$

$$O_{10}^\ell = \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\gamma_5 \ell\right)$$

Geng et al, 1704.05446

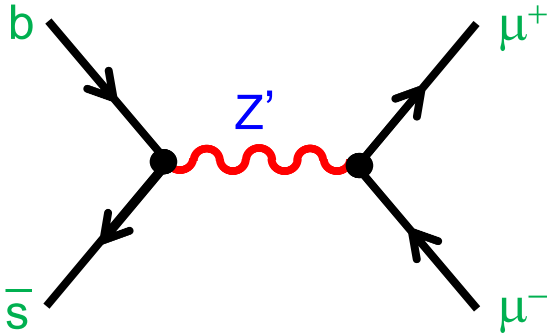
SM: $C_9(m_b) \approx -C_{10}(m_b) = 4.27$





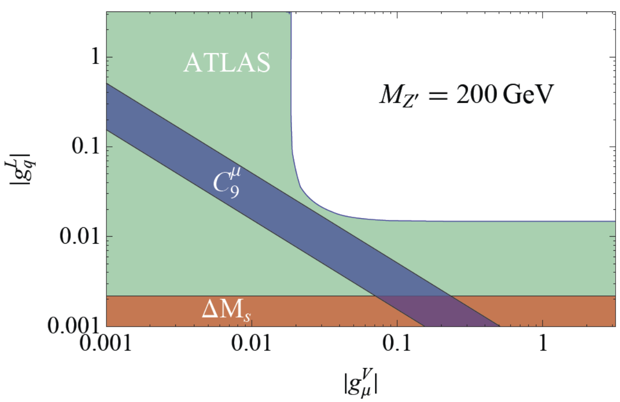
$$O_9^{\ell} = \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right) \qquad O_9^{\ell'} = \left(\bar{s}\,\gamma_\mu P_R b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right)$$

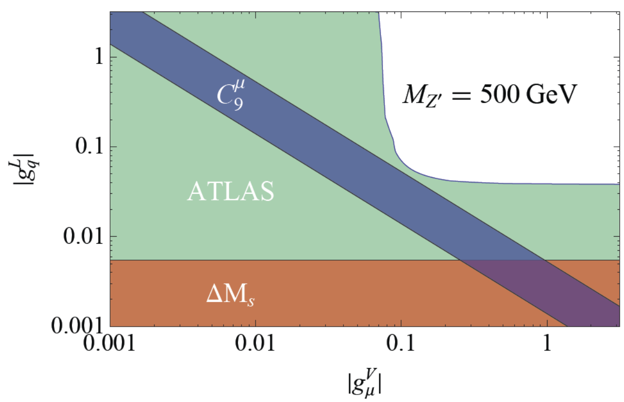
$$O_{10}^{\ell} = \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\gamma_5\ell\right) \qquad O_{10}^{\ell'} = \left(\bar{s}\,\gamma_\mu P_R b\right)\left(\bar{\ell}\,\gamma^\mu\,\gamma_5\ell\right)$$



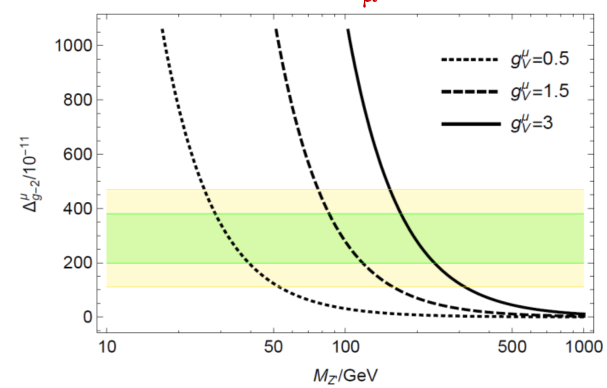
$$\mathcal{L} \supset \frac{g_2}{2c_W} Z'_\alpha \left\{ \left[\bar{s}\gamma^\alpha (g_L^Q P_L + g_R^Q P_R) b + h.c. \right] + \bar{\ell}\gamma^\alpha (g_V^\ell + \gamma_5 g_A^\ell)\ell \right\}$$

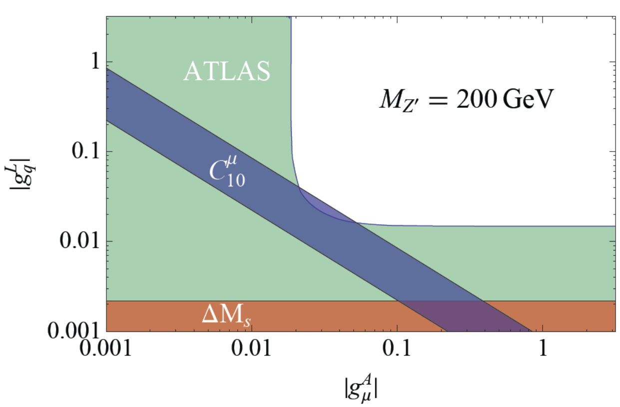
$$\frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \cdot \left\{ C_9^\ell,\, C_{10}^\ell \right\} = \frac{M_Z^2}{2 m_{Z'}^2} \cdot \left\{ g_L^Q g_V^\ell,\, g_L^Q g_A^\ell \right\}$$

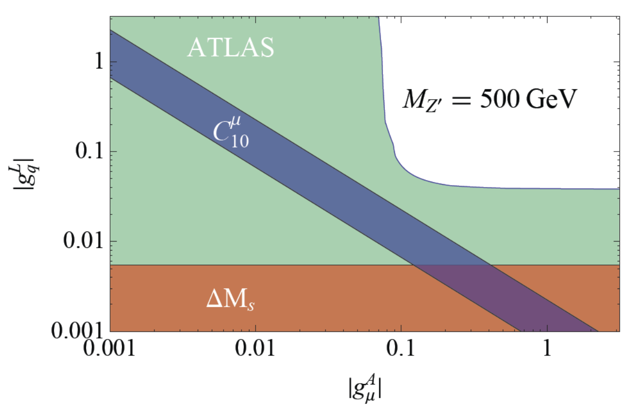




(g-2)$_\mu$

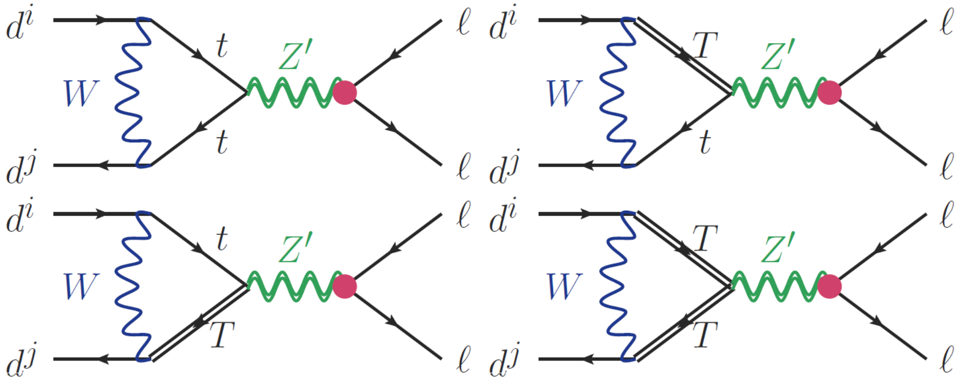






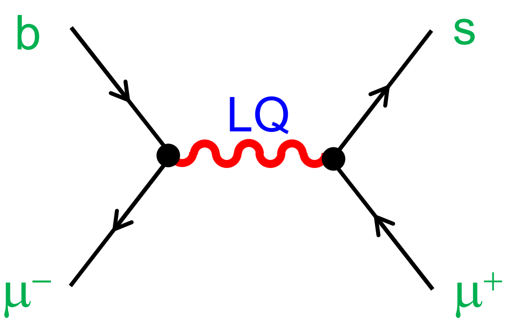
Di Chiara et al, 1704.06200

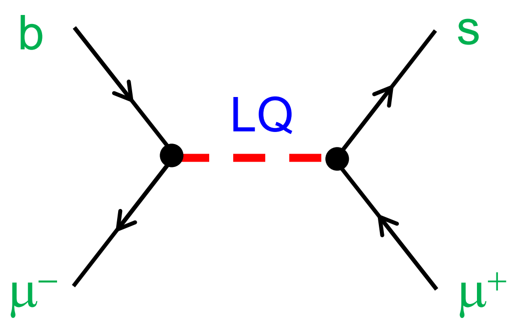
More possibilites…



Flavour conserving Z’

Kamenik et al, 1704.06005



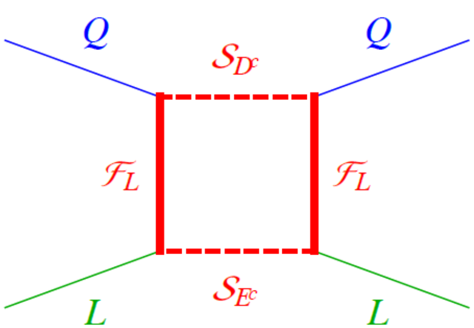


Leptoquarks

Hiller- Nisandzic, 1704.05444

D’Amico et al, 1704.05438

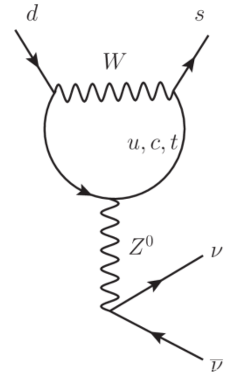
Becirevic-Sumensari, 1704.05835

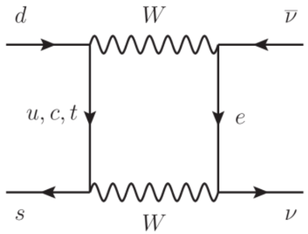


New Fermions and Scalars

D’Amico et al, 1704.05438

$K \to \pi \nu \bar{\nu}$





$$\mathbf{T} \sim F\left(V_{is}^* V_{id}, m_i^2/M_W^2\right) \left(\overline{\nu}_L \gamma_\mu \nu_L\right) \left\langle \pi \middle| \overline{s}_L \gamma_\mu d_L \middle| K \right\rangle$$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu \overline{\nu}\right) = (7.8 \pm 0.8) \times 10^{-11} \sim A^4 \left[\eta^2 + (1.4 - \rho)^2\right]$$

$$\mathrm{Br}\left(K_L \to \pi^0 \nu \overline{\nu}\right) = (2.4 \pm 0.4) \times 10^{-11} \sim A^4 \ \eta^2$$

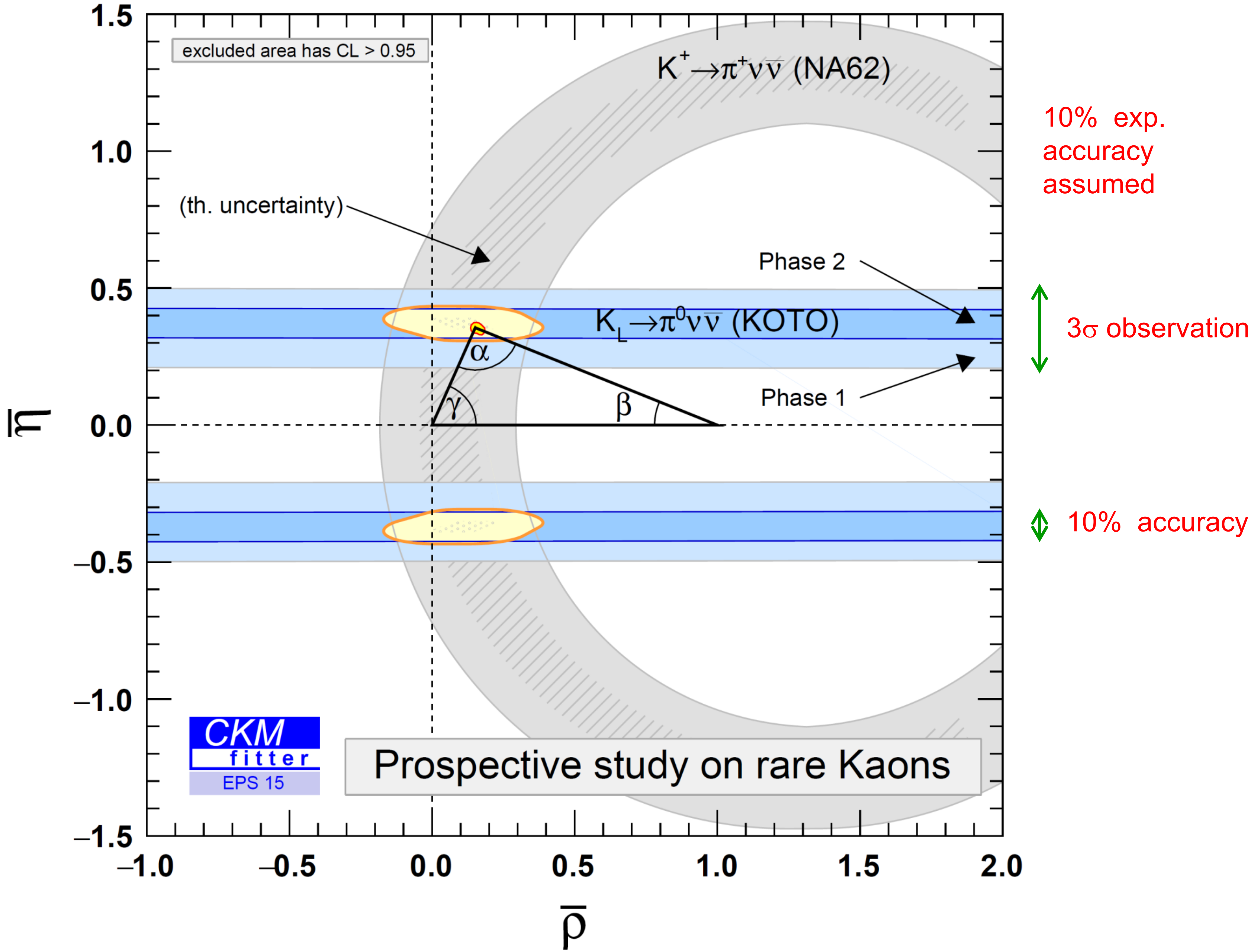
Buras et al

Long-distance contributions are negligible

$\mathbf{T}\left(K_L \to \pi^0 \nu \overline{\nu}\right) \neq 0$ ➡ $\not{CP}$

- **BNL-E949:** **few events!** ➡ $\mathrm{Br}\left(K^+ \to \pi^+ \nu \overline{\nu}\right) = \left(1.73\,^{+1.15}_{-1.05}\right) \cdot 10^{-10}$
- **KEK-E391a:** $\mathrm{Br}\left(K_L \to \pi^0 \nu \overline{\nu}\right) < 2.6 \times 10^{-8}$ (90% C.L.)

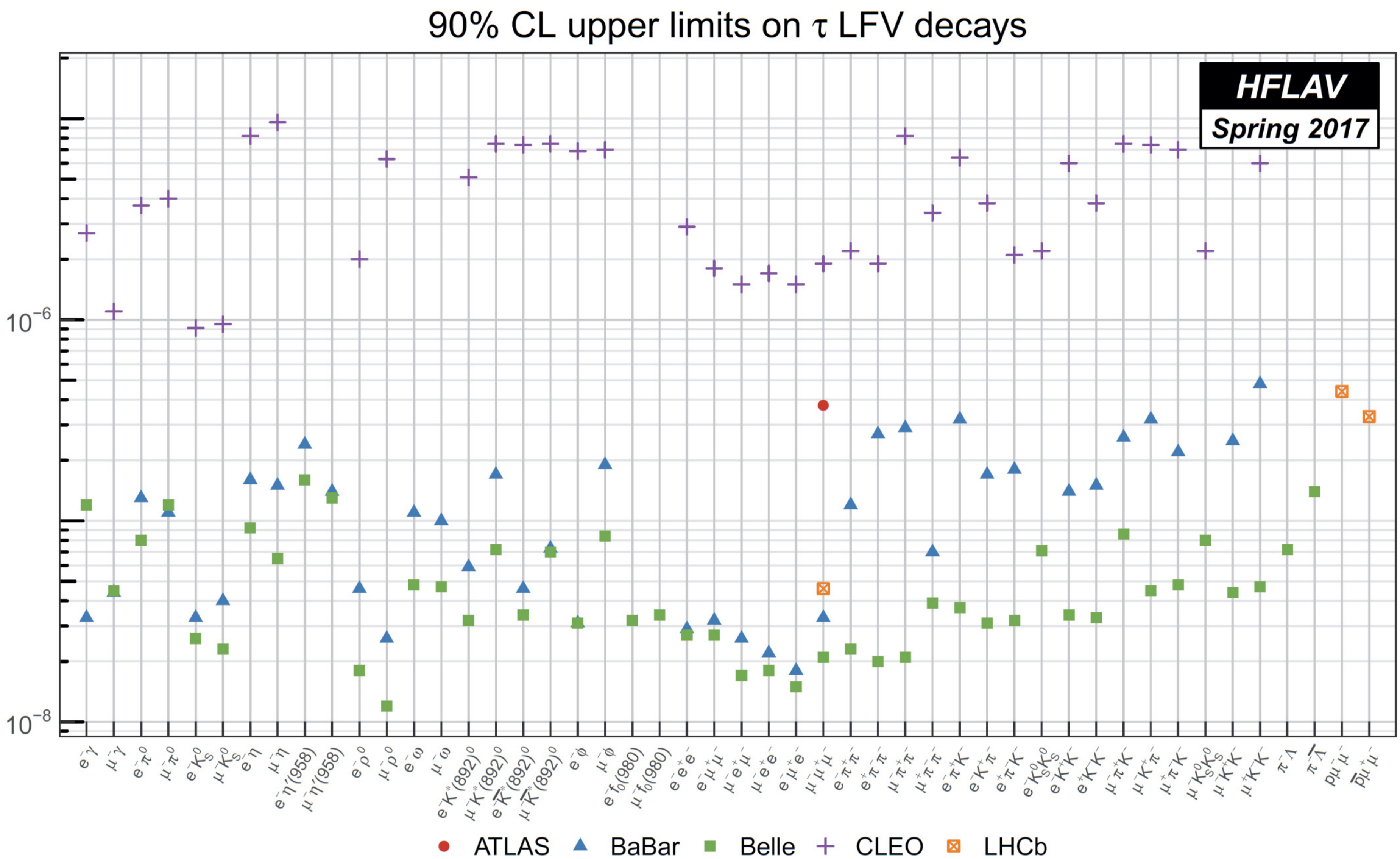
Ongoing experiments: NA62, KOTO


excluded area has CL > 0.95
$K^+ \to \pi^+ \nu \bar{\nu}$ (NA62)
(th. uncertainty)
Phase 2
$K_L \to \pi^0 \nu \bar{\nu}$ (KOTO)
Phase 1
α
γ
β
CKM fitter
EPS 15
Prospective study on rare Kaons
$\bar{\eta}$
$\bar{\rho}$
10% exp. accuracy assumed
3σ observation
10% accuracy

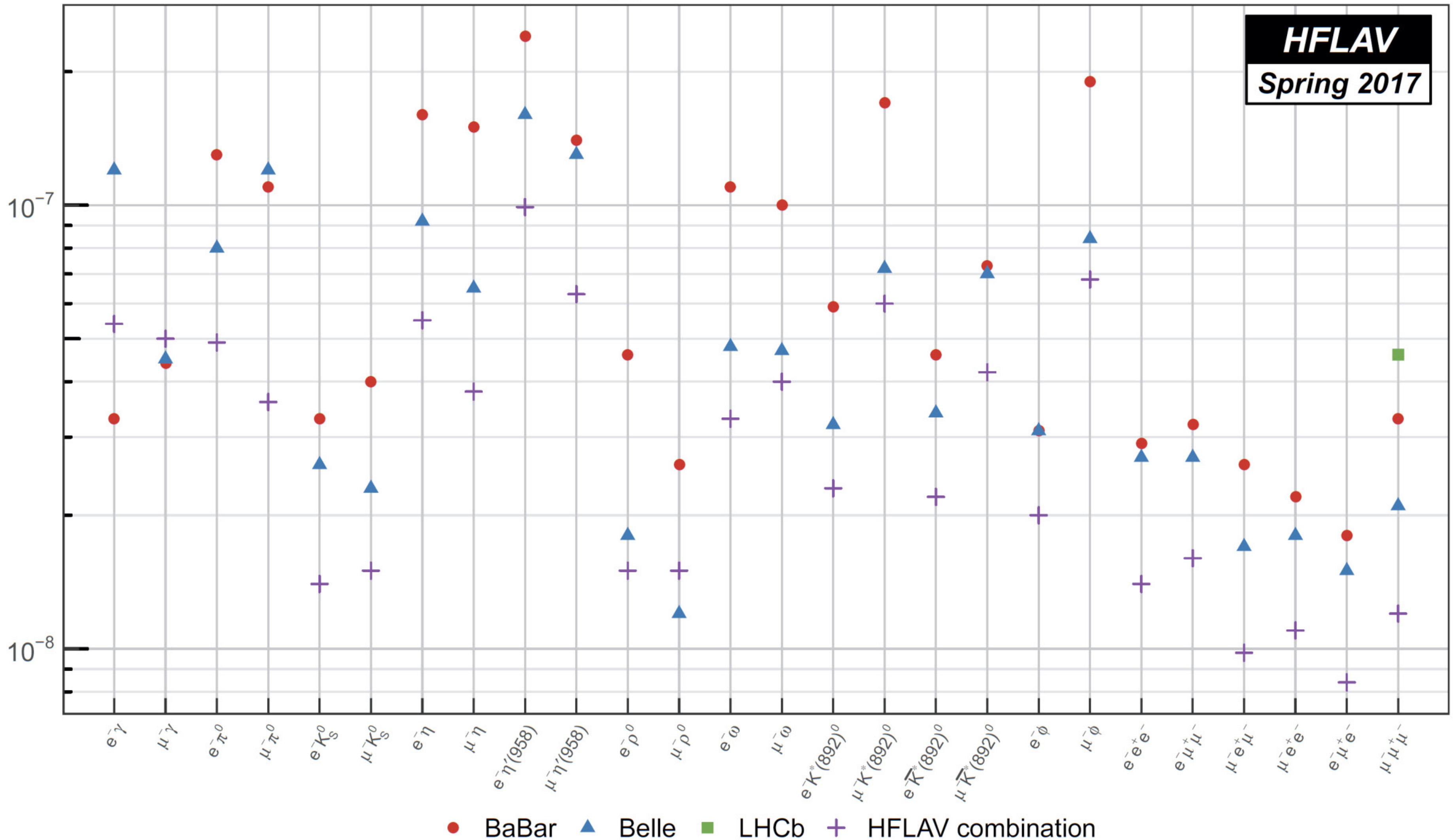
LEPTON FLAVOUR VIOLATION

90 % CL Upper Limits on Br($l^- \to X^-$) [MEG'16,SINDRUM'88, Bolton'88, BABAR , BELLE, LHC]

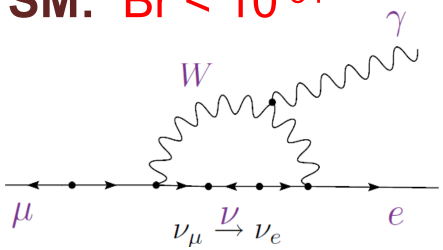
Decay	U.L.	Decay	U.L.	Decay	U.L.
$\mu^- \to e^-\gamma$	$4.2 \cdot 10^{-13}$	$\mu^- \to e^-e^+e^-$	$1.0 \cdot 10^{-12}$	$\mu^- \to e^-\gamma\gamma$	$7.2 \cdot 10^{-11}$
$\tau^- \to e^-\gamma$	$3.3 \cdot 10^{-8}$	$\tau^- \to e^-e^+e^-$	$2.7 \cdot 10^{-8}$	$\tau^- \to e^-e^+\mu^-$	$1.8 \cdot 10^{-8}$
$\tau^- \to \mu^-\gamma$	$4.4 \cdot 10^{-8}$	$\tau^- \to e^-\mu^+\mu^-$	$2.7 \cdot 10^{-8}$	$\tau^- \to \mu^-e^+\mu^-$	$1.7 \cdot 10^{-8}$
$\tau^- \to e^-e^-\mu^+$	$1.5 \cdot 10^{-8}$	$\tau^- \to \mu^-\mu^+\mu^-$	$2.1 \cdot 10^{-8}$	$\tau^- \to e^-\pi^0$	$8.0 \cdot 10^{-8}$
$\tau^- \to \mu^-\pi^0$	$1.1 \cdot 10^{-7}$	$\tau^- \to e^-\eta'$	$1.6 \cdot 10^{-7}$	$\tau^- \to \mu^-\eta'$	$1.3 \cdot 10^{-7}$
$\tau^- \to e^-\eta$	$9.2 \cdot 10^{-8}$	$\tau^- \to \mu^-\eta$	$6.5 \cdot 10^{-8}$	$\tau^- \to e^-K^{*0}$	$3.2 \cdot 10^{-8}$
$\tau^- \to e^-K_S$	$2.6 \cdot 10^{-8}$	$\tau^- \to \mu^-K_S$	$2.3 \cdot 10^{-8}$	$\tau^- \to \mu^-\rho^0$	$1.2 \cdot 10^{-8}$
$\tau^- \to e^-K^+K^-$	$3.4 \cdot 10^{-8}$	$\tau^- \to e^-K^+\pi^-$	$3.1 \cdot 10^{-8}$	$\tau^- \to e^-\pi^+K^-$	$3.7 \cdot 10^{-8}$
$\tau^- \to \mu^-K^+K^-$	$4.4 \cdot 10^{-8}$	$\tau^- \to \mu^-K^+\pi^-$	$4.5 \cdot 10^{-8}$	$\tau^- \to \mu^-\pi^+K^-$	$8.6 \cdot 10^{-8}$
$\tau^- \to e^-\pi^+\pi^-$	$2.3 \cdot 10^{-8}$	$\tau^- \to \mu^-\pi^+\pi^-$	$2.1 \cdot 10^{-8}$	$\tau^- \to \mu^-\omega$	$4.7 \cdot 10^{-8}$
$\tau^- \to \mu^-K^{*0}$	$5.9 \cdot 10^{-8}$	$\tau^- \to e^-\phi$	$3.1 \cdot 10^{-8}$	$\tau^- \to \Lambda\pi^-$	$7.2 \cdot 10^{-8}$
$\tau^- \to e^+K^-K^-$	$3.3 \cdot 10^{-8}$	$\tau^- \to e^+K^-\pi^-$	$3.2 \cdot 10^{-8}$	$\tau^- \to e^+\pi^-\pi^-$	$2.0 \cdot 10^{-8}$
$\tau^- \to \mu^+K^-K^-$	$4.7 \cdot 10^{-8}$	$\tau^- \to \mu^+K^-\pi^-$	$4.8 \cdot 10^{-8}$	$\tau^- \to \mu^+\pi^-\pi^-$	$3.9 \cdot 10^{-8}$


90% CL upper limits on τ LFV decays
HFLAV
Spring 2017
10^{-6}
10^{-8}
$e^-\gamma$
$\mu^-\gamma$
$e^-\pi^0$
$\mu^-\pi^0$
$e^-K_S^0$
$\mu^-K_S^0$
$e^-\eta$
$\mu^-\eta$
$e^-\eta'(958)$
$\mu^-\eta'(958)$
$e^-\rho^0$
$\mu^-\rho^0$
$e^-\omega$
$\mu^-\omega$
$e^-K^*(892)^0$
$\mu^-K^*(892)^0$
$e^-\bar{K}^*(892)^0$
$\mu^-\bar{K}^*(892)^0$
$e^-\phi$
$\mu^-\phi$
$e^-f_0(980)$
$\mu^-f_0(980)$
$e^-e^+e^-$
$e^-\mu^+\mu^-$
$\mu^-e^+\mu^-$
$\mu^-e^+e^-$
$e^-\mu^+e^-$
$\mu^-\mu^+\mu^-$
$e^-\pi^+\pi^-$
$e^+\pi^-\pi^-$
$\mu^-\pi^+\pi^-$
$\mu^+\pi^-\pi^-$
$e^-\pi^+K^-$
$e^-K^+\pi^-$
$e^+\pi^-K^-$
$e^-K_S^0K_S^0$
$e^-K^+K^-$
$e^+K^-K^-$
$\mu^-\pi^+K^-$
$\mu^-K^+\pi^-$
$\mu^+\pi^-K^-$
$\mu^-K_S^0K_S^0$
$\mu^-K^+K^-$
$\mu^+K^-K^-$
$\pi^-\Lambda$
$\pi^-\bar{\Lambda}$
$p\mu^-\mu^-$
$\bar{p}\mu^+\mu^-$
ATLAS
BaBar
Belle
CLEO
LHCb

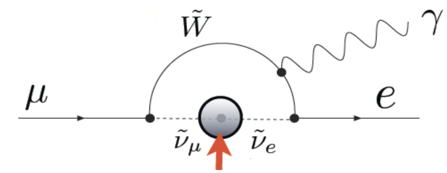
90% CL upper limits on τ LFV decays



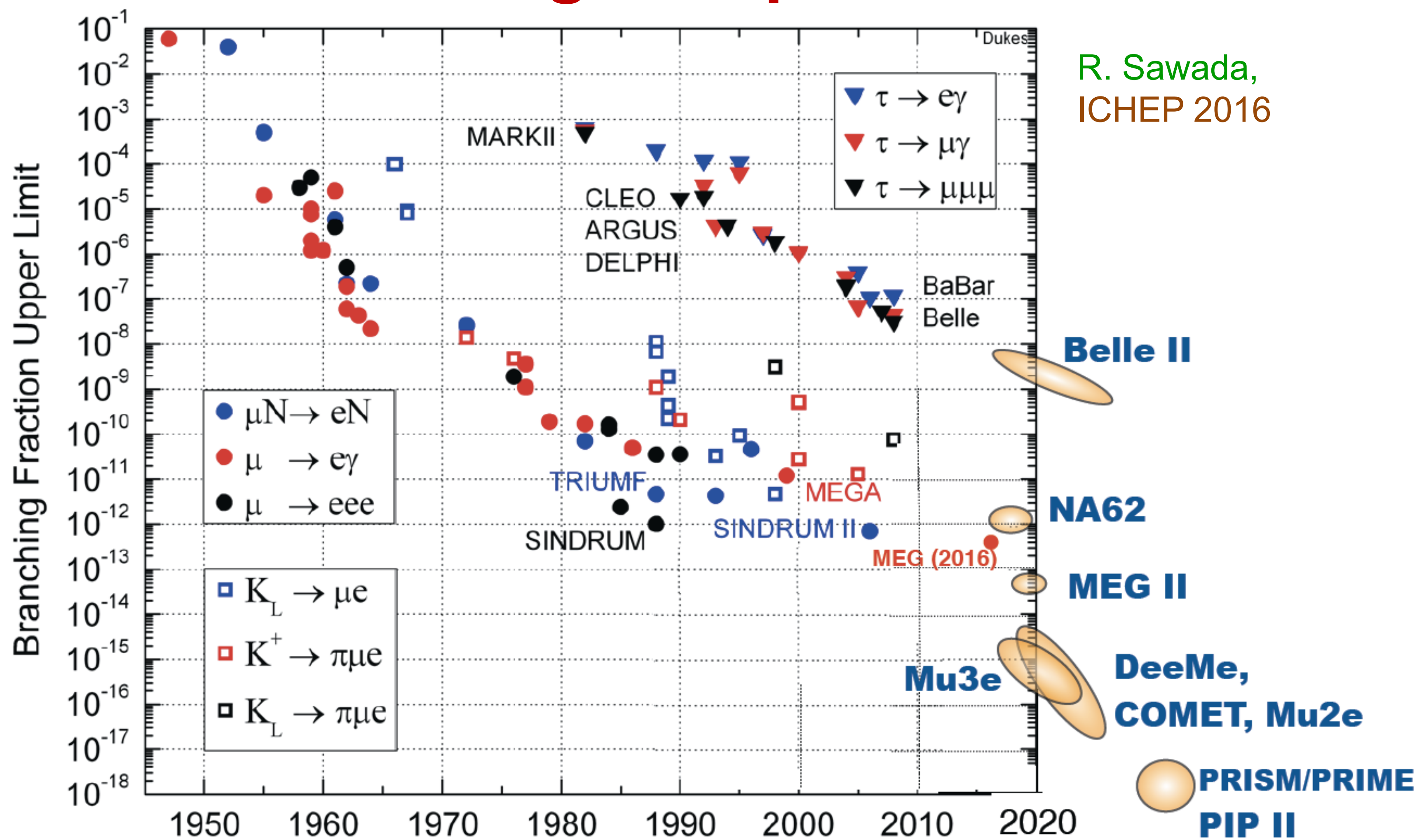
SM: Br < 10^{-54}



New Physics ?



Exciting Prospects



R. Sawada,
ICHEP 2016

SUMMARY

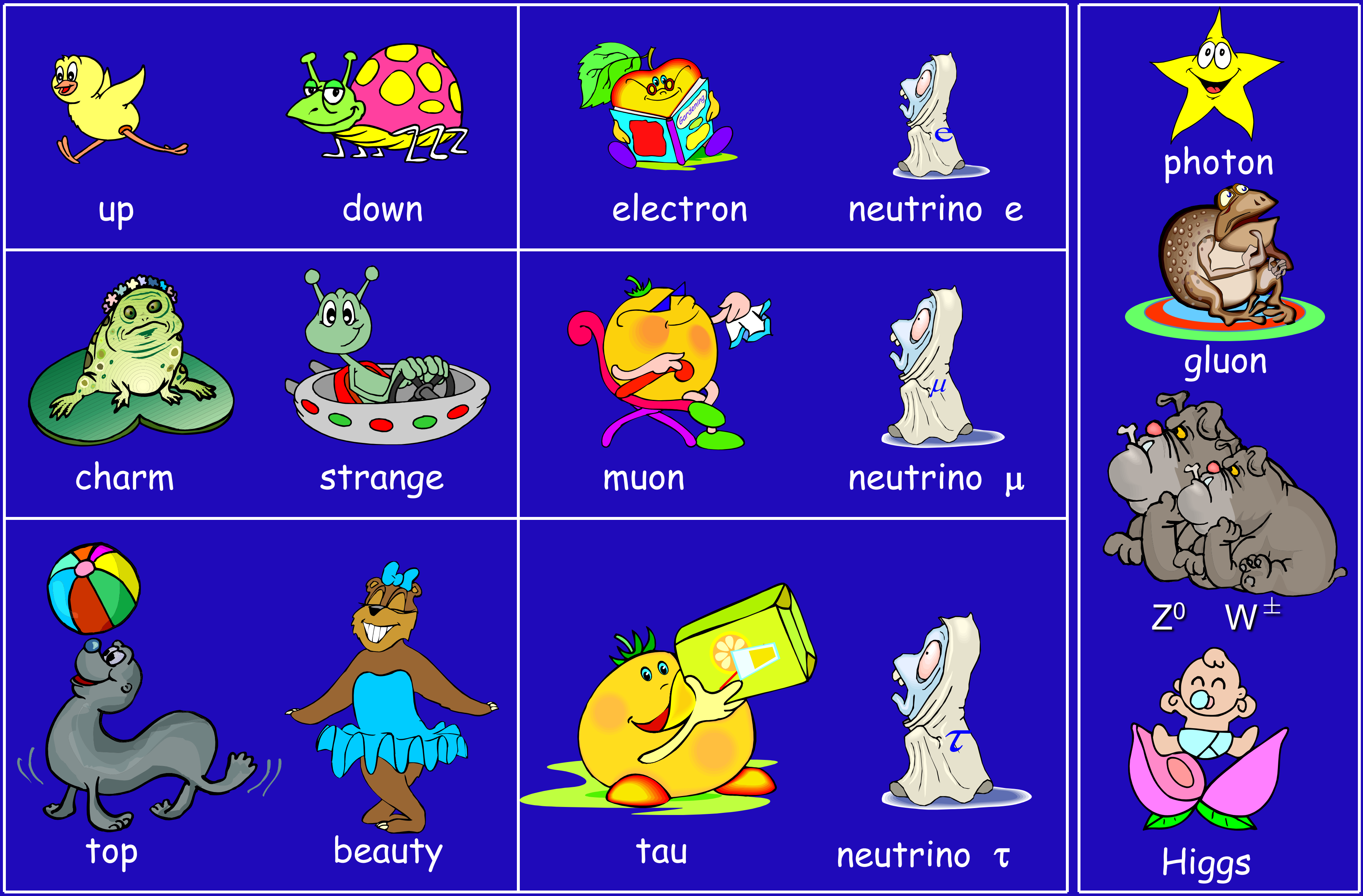
- **Flavour Structure and** $\not{CP}$ are major pending questions
- **Related to SSB** → **Scalar Sector** (Higgs)
- Important **cosmological implications** (Baryogenesis)
- $\not{CP}$ is highly constrained in the SM: **1 phase only**
- Sensitive to **New Physics:** **Flavour Anomalies!**

Better control of **QCD** effects needed

Challenging future ahead: Belle-II, LHC, NA62, J-Parc, BES-III…

Wait and see…

Quarks Leptons Bosons



Backup

CHARGED CURRENT UNIVERSALITY

A. Pich, arXiv:1310.7922

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0020
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.996 ± 0.010

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

2.6 σ

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0030 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.031 ± 0.013

2.4 σ

g_τ anomaly cannot be accommodated with EFT

Filipuzzi, Gonzalez-Alonso, Portoles, 1203.2092

CP Asymmetry in τ Decay

$$A_\tau \equiv \frac{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)} = (-3.6 \pm 2.3 \pm 1.1)\cdot 10^{-3}$$

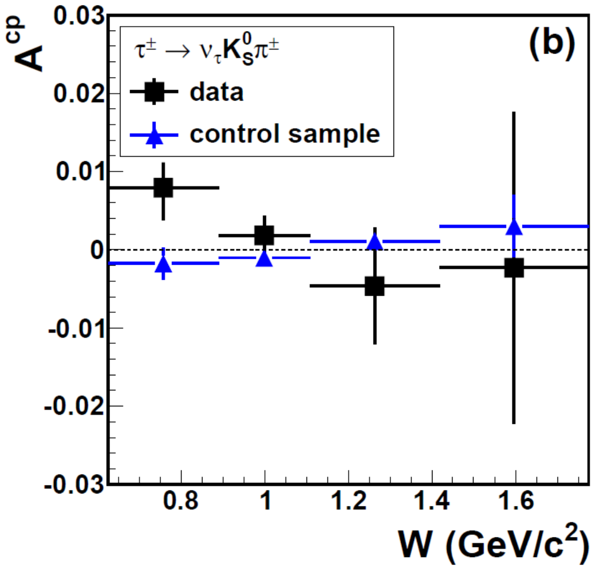
BaBar'11
$(\geq 0\, \pi^0)$

$$A_\tau^{\rm SM}\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) = (3.6 \pm 0.1)\cdot 10^{-3}$$

Bigi-Sanda, Grossman-Nir

2.8 σ discrepancy

Belle does not see any asymmetry at the 10^{-2} level



$$A_i^{\rm CP} \simeq \langle \cos\beta \cos\psi \rangle_i^{\tau^-} - \langle \cos\beta \cos\psi \rangle_i^{\tau^+}$$

bins (i) of $W = \sqrt{Q^2}$

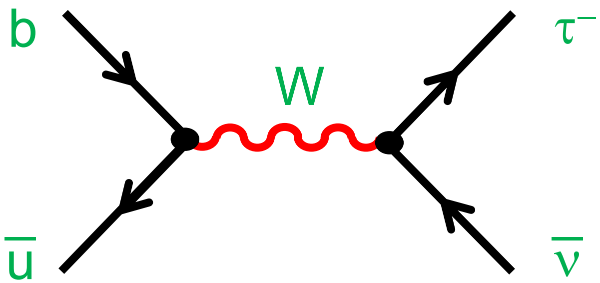
$\beta = K_S$ direction in hadronic rest frame

$\psi = \tau$ direction

BaBar signal incompatible with other sets of flavour data

Cirigliano-Crivellin-Hoferichter, 1712.06595

2006 $B^- \to \tau^- \nu$ Anomaly



Belle 2006: (hadronic tag)

$$\mathrm{Br}(B^- \to \tau^- \nu) = (1.7\,{}^{+0.56}_{-0.49}\,{}^{+0.46}_{-0.51}) \times 10^{-4}$$

➡ **Large $|V_{ub}|$** ➡ **Tension in CKM fit**

Confirmed by BaBar (2008, 2010, 2013)

Belle 2013: (hadronic tag) $\mathrm{Br}(B^- \to \tau^- \nu) = (0.72\,{}^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$

Current status: CKM agreement. Tension between Belle and BaBar

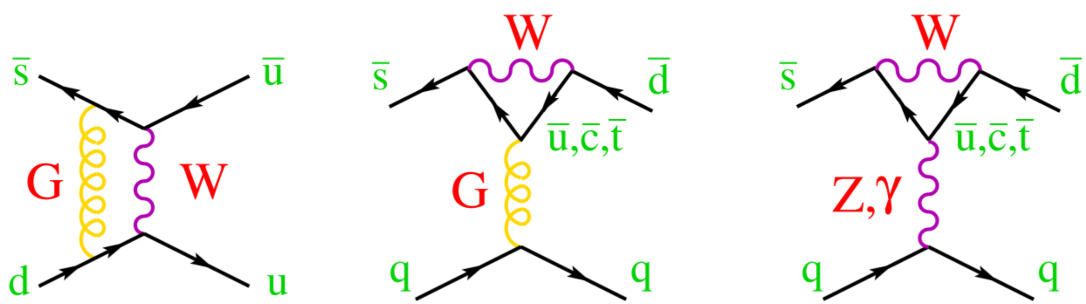
DIRECT $\not{CP}$ in $K \to \pi\pi$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K + \varepsilon'_K \qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K - 2\,\varepsilon'_K$$

$$\mathrm{Re}\left(\varepsilon'_K/\varepsilon_K\right) \approx \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\} = (16.8 \pm 1.4)\cdot 10^{-4}$$

NA48, NA31

KTeV, E731



$$\mathrm{Re}\left(\varepsilon'_K/\varepsilon_K\right)_{\mathrm{Th}} = \left(19\,^{+11}_{-9}\right)\cdot 10^{-4}$$

- Short-distance OPE

  Ciuchini et al, Buras et al
- Long-distance χPT

  Pallante-Pich-Scimemi

  Cirigliano-Ecker-Neufeld-Pich

$(15 \pm 7) \times 10^{-4}$ **2017 update** Gisbert-Pich, 1712.06147

Recent $K\to(\pi\pi)_I$ Lattice Results

Isospin limit: RBC-UKQCD 1505.07863, 1502.00263

$$\sqrt{\frac{3}{2}}\,\mathrm{Re}\,A_2 = (1.50 \pm 0.04 \pm 0.14)\cdot 10^{-8}\ \mathrm{GeV} \qquad \mathrm{exp}: 1.482\,(2)\cdot 10^{-8}\ \mathrm{GeV} \quad 0.1\,\sigma$$

$$\sqrt{\frac{3}{2}}\,\mathrm{Im}\,A_2 = -(6.99 \pm 0.20 \pm 0.84)\cdot 10^{-13}\ \mathrm{GeV}$$

$$\sqrt{\frac{3}{2}}\,\mathrm{Re}\,A_0 = (4.66 \pm 1.00 \pm 1.26)\cdot 10^{-7}\ \mathrm{GeV} \qquad \mathrm{exp}: 3.112\,(1)\cdot 10^{-7}\ \mathrm{GeV} \quad 1.0\,\sigma$$

$$\sqrt{\frac{3}{2}}\,\mathrm{Im}\,A_0 = -(1.90 \pm 1.23 \pm 1.08)\cdot 10^{-11}\ \mathrm{GeV}$$

$$\mathrm{Re}\,(\varepsilon'/\varepsilon) = (1.38 \pm 5.15 \pm 4.59)\cdot 10^{-4} \qquad \mathrm{exp}: (16.6 \pm 2.3)\cdot 10^{-4} \quad 2.1\,\sigma$$

$$\delta_0 = (23.8 \pm 4.9 \pm 1.2)^\circ \qquad \mathrm{exp}: (39.2 \pm 1.5)^\circ \quad 2.9\,\sigma$$

$$\delta_2 = -(11.6 \pm 2.5 \pm 1.2)^\circ \qquad \mathrm{exp}: -(8.5 \pm 1.5)^\circ \quad 1.0\,\sigma$$

$\Delta I = 1/2$ Rule

$$\omega \equiv \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \approx \frac{1}{22}$$

Large phase shift

$$\delta_0 - \delta_2 = (47.5 \pm 0.9)^\circ$$

Anomaly? ➡ New-physics ? (Buras et al, Kitahara et al, Endo et al, Cirigliano et al…)

$$\mathrm{Re}(\varepsilon'_K/\varepsilon_K)_{\mathrm{SM}} = -\frac{\omega}{\sqrt{2}\,|\varepsilon_K|}\left[\frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}(1-\Omega_{\mathrm{eff}}) - \frac{\mathrm{Im}\,A_2^{\mathrm{emp}}}{\mathrm{Re}\,A_2}\right] \approx 2.2\cdot 10^{-3}\left\{B_6^{(1/2)}(1-\Omega_{\mathrm{eff}}) - 0.48\,B_8^{(3/2)}\right\}$$

$\Omega_{\mathrm{eff}} = 0.060 \pm 0.077$ Cirigliano-Ecker-Neufeld-Pich (2003)

Effective Field Theory: Long & Short distance dynamics

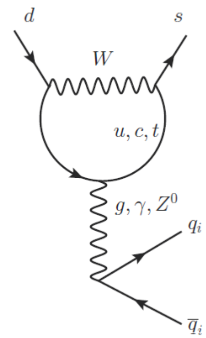
M_W — W, Z, γ, g; τ, μ, e, ν_i; t, b, c, s, d, u — Standard Model

↓ OPE

$\lesssim m_c$ — $\gamma, g\, ;\, \mu, e, \nu_i$; s, d, u — $\mathcal{L}_{\rm QCD}^{(n_f=3)}$, $\mathcal{L}_{\rm eff}^{\Delta S=1,2}$

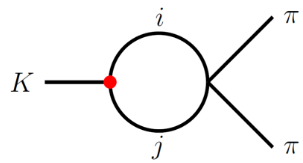
↓ $N_C \to \infty$

M_K — $\gamma\, ;\, \mu, e, \nu_i$; π, K, η — χPT



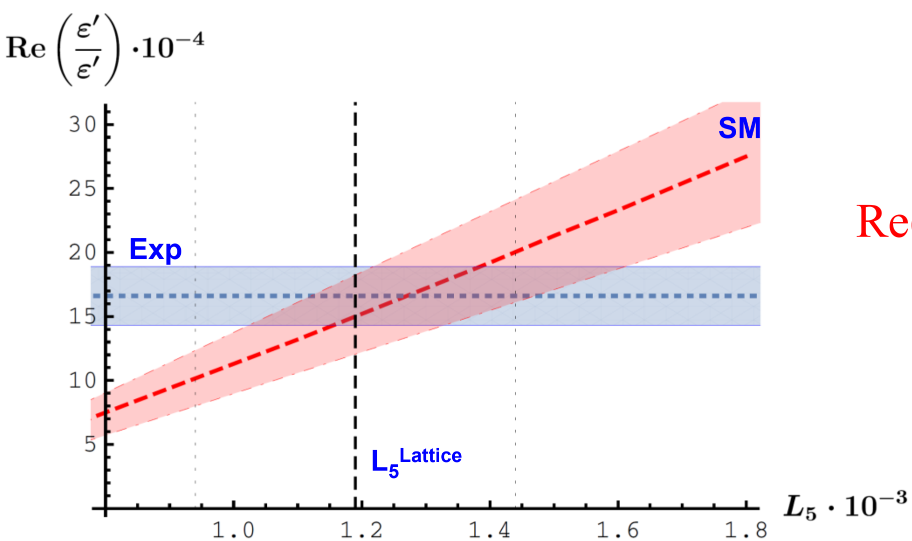
$$\mathcal{L}_{\rm eff}^{\Delta S=1} = -\frac{G_F}{\sqrt{2}}\, V_{ud}\, V_{us}^*\, \sum_i C_i(\mu)\;\; Q_i(\mu)$$

Large logarithmic corrections



OPE: $\alpha_s^k(\mu)\, \log^n(M_W/\mu)$

χPT: $\log(\mu/m_\pi)$



Gisbert-Pich, arXiv:1712.06147

$$\mathrm{Re}(\varepsilon_K'/\varepsilon_K)_{\rm SM} = \left(15 \pm 2_\mu \pm 2_{m_s} \pm 2_{\Omega_{\rm eff}} \pm 6_{1/N_c}\right)\cdot 10^{-4}$$

$$= \left(15 \pm 7\right)\cdot 10^{-4}$$

Large uncertainty, but no anomaly!

T Violation @ Babar

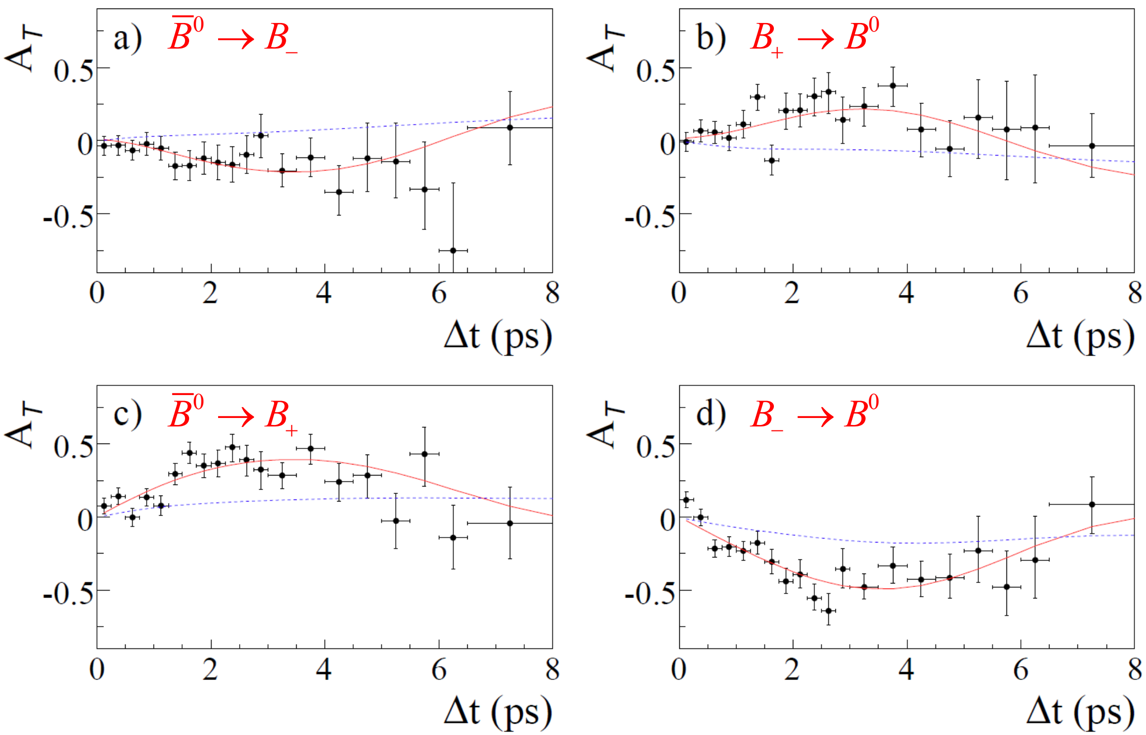
Quantum Entanglement

1207.5832

Flavour $\left(B^0 \to l^+ X\,,\ \bar{B}^0 \to l^- X\right)$ and CP $\left(B_+ \to J/\psi K_L\,,\ B_- \to J/\psi K_S\right)$ tags

(Bañuls-Bernabeu-Martínez-Villanueva)

$e^+ e^- \to \Upsilon(4S) \to (B_1(t_1) \to f_1\,,\ B_2(t_2) \to f_2) \equiv (f_1\,,\ f_2)$; $t_2 > t_1$



$$S_{B_- \to \bar{B}^0} - S_{\bar{B}^0 \to B_-} = -1.37 \pm 0.14 \pm 0.06$$

$$S_{B^0 \to B_+} - S_{B_+ \to B^0} = 1.17 \pm 0.18 \pm 0.11$$

$\not{T}$ established at 14 σ

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + i\, G^0\right) \end{bmatrix} \qquad , \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + i\, S_3\right) \end{bmatrix}$$

Goldstones: $G^\pm\, ,\; G^0$

Mass eigenstates: $\varphi_i^0(x) = \{h(x), H(x), A(x)\} \;=\; \mathcal{R}_{ij}\; S_j(x)$

CP-conserving scalar potential: $A(x) = S_3(x)$ **CP-odd**

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos\tilde\alpha & \sin\tilde\alpha \\ -\sin\tilde\alpha & \cos\tilde\alpha \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}$$

CP-even

Gauge couplings: $g_{\varphi_i^0 VV} \;=\; \mathcal{R}_{i1}\; g_{hVV}^{\mathrm{SM}}$

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 \;=\; \left(g_{hVV}^{\mathrm{SM}}\right)^2$$

Yukawa Interactions in 2HDMs

$$\mathcal{L}_Y = -\bar{Q}_L' (\Gamma_1 \phi_1 + \Gamma_2 \phi_2) d_R' - \bar{Q}_L' (\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2) u_R' - \bar{L}_L' (\Pi_1 \phi_1 + \Pi_2 \phi_2) \ell_R' + \text{h.c.}$$

↓ SSB

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}_L' (M_d' \Phi_1 + Y_d' \Phi_2) d_R' + \bar{Q}_L' (M_u' \tilde{\Phi}_1 + Y_u' \tilde{\Phi}_2) u_R' + \bar{L}_L' (M_\ell' \Phi_1 + Y_\ell' \Phi_2) \ell_R' + \text{h.c.} \right\}$$

M_f' and Y_f' unrelated → **FCNCs**

$$\sqrt{2}\, M_d' = v_1 \Gamma_1 + v_2 \Gamma_2 e^{i\theta} \quad , \quad \sqrt{2}\, M_u' = v_1 \Delta_1 + v_2 \Delta_2 e^{-i\theta}$$

$$\sqrt{2}\, Y_d' = v_1 \Gamma_2 e^{i\theta} - v_2 \Gamma_1 \quad , \quad \sqrt{2}\, Y_u' = v_1 \Delta_2 e^{-i\theta} - v_2 \Delta_1$$