

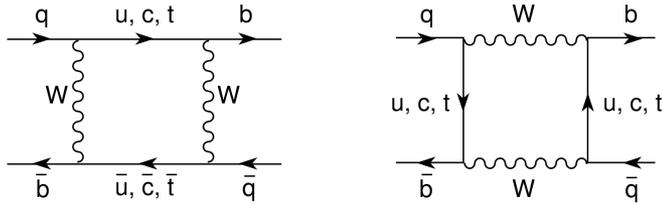
# Flavour Physics & CP

1. Quark Mixing
2.  $P^0$ - $\bar{P}^0$  Mixing & CP Violation
3. Searching for New Physics

2019 CERN Latin-American School of High-Energy Physics (CLASHEP2019)  
Villa General Belgrano, Córdoba, Argentina, 13-26 March 2019



# Bounds on New Flavour Physics



$$\lambda_u + \lambda_c + \lambda_t = 0$$

$$\lambda_i \equiv V_{iq} V_{ib}^*$$

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

Isidori, 1302.0661

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

- Generic flavour structure [ $c_{\text{NP}} \sim \mathcal{O}(1)$ ] ruled out at the TeV scale
- $\Lambda_{\text{NP}} \sim 1$  TeV requires  $c_{\text{NP}}$  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 Hall-Randall, Chivukula-Georgi, D'Ambrosio et al

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

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

**Higgs basis:**  $v \equiv \sqrt{v_1^2 + v_2^2}$  ,  $\tan \beta \equiv v_2/v_1$

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

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

# Yukawa Interactions in 2HDMs

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

SSB ↓

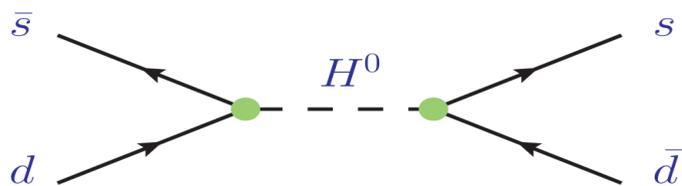
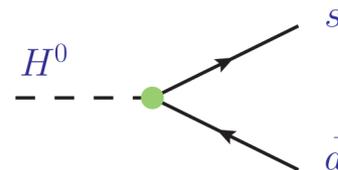
$$\phi_i^{(0)} = \frac{v_i}{\sqrt{2}} e^{i\theta_i}, \quad v = \sqrt{v_1^2 + v_2^2}$$

$$L_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}'_L (M'_d \Phi_1 + Y'_d \Phi_2) d'_R - \bar{Q}'_L (M'_u \tilde{\Phi}_1 + Y'_u \tilde{\Phi}_2) u'_R \right\}$$

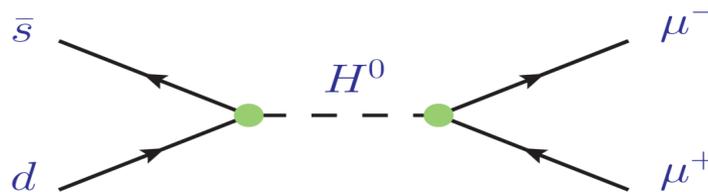
$M'_q$  and  $Y'_q$  unrelated



FCNCs



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



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

## Phenomenological disaster!

# Aligned 2HDM

Pich-Tuzón, 0908.1554

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

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[ \varsigma_d V_{\text{CKM}} M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V_{\text{CKM}} \mathcal{P}_L \right] d + \varsigma_l (\bar{\nu} M_l \mathcal{P}_R l) \right\} - \frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \varphi_i^0 (\bar{f} M_f \mathcal{P}_R f) + \text{h.c.}$$

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

$\varsigma_f \rightarrow$  **New sources of CP violation without tree-level FCNCs**

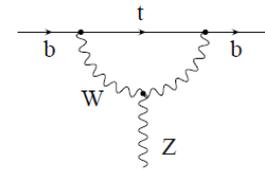
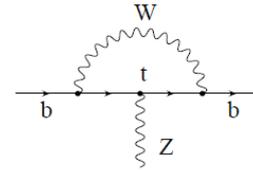
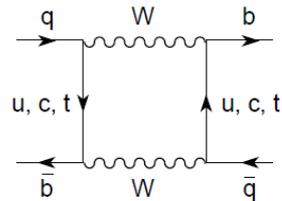
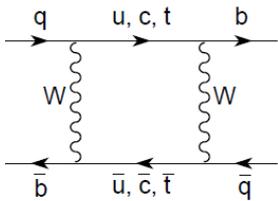
$\mathcal{Z}_2$  models:

Model	$\varsigma_d$	$\varsigma_u$	$\varsigma_l$
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  $\phi_a$  couples to  $f_R$   
(Glashow-Weinberg, Paschos '77)

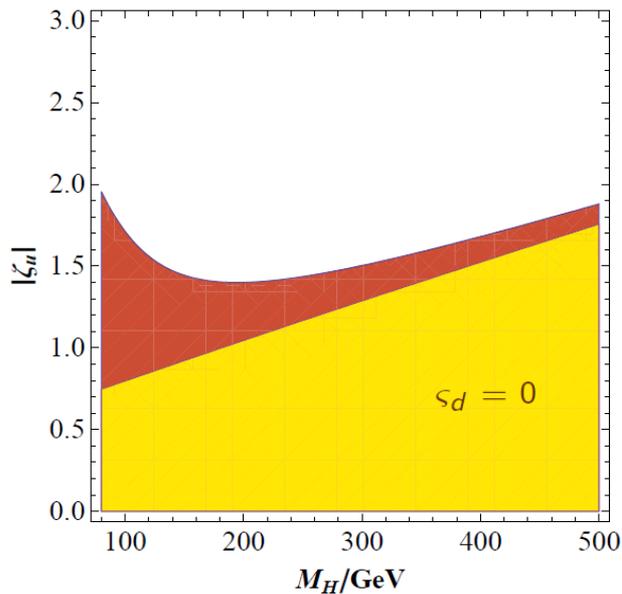
# 1-Loop Constraints on $H^\pm$ Couplings

(95% CL)

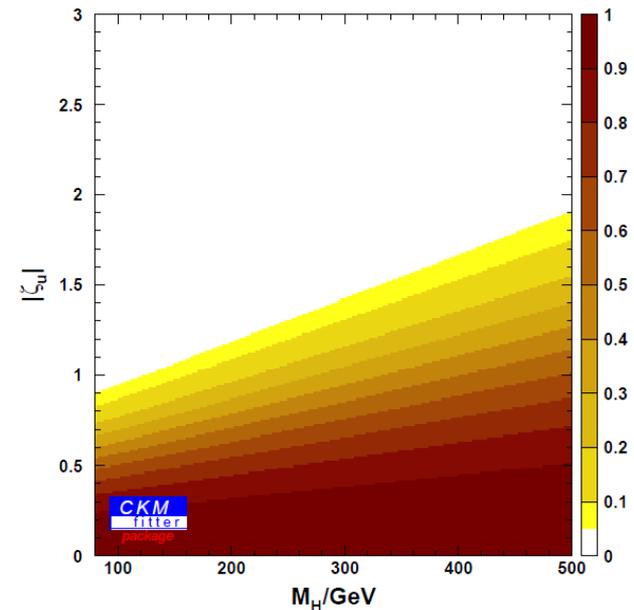


**Virtual  $H^\pm / W^\pm$ . Top-dominated contributions**

$\Delta M_{B_s}$  ( $|s_d| < 50$ )



$Z \rightarrow b\bar{b}$  ( $|s_d| < 50$ )



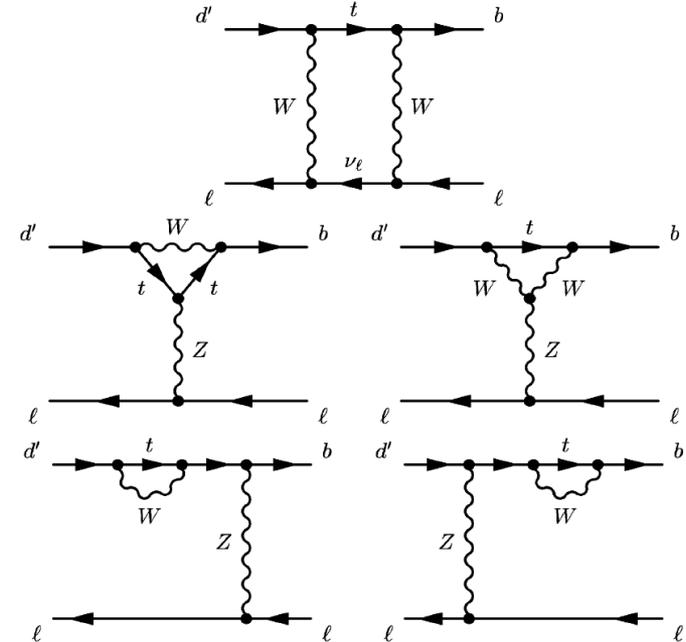
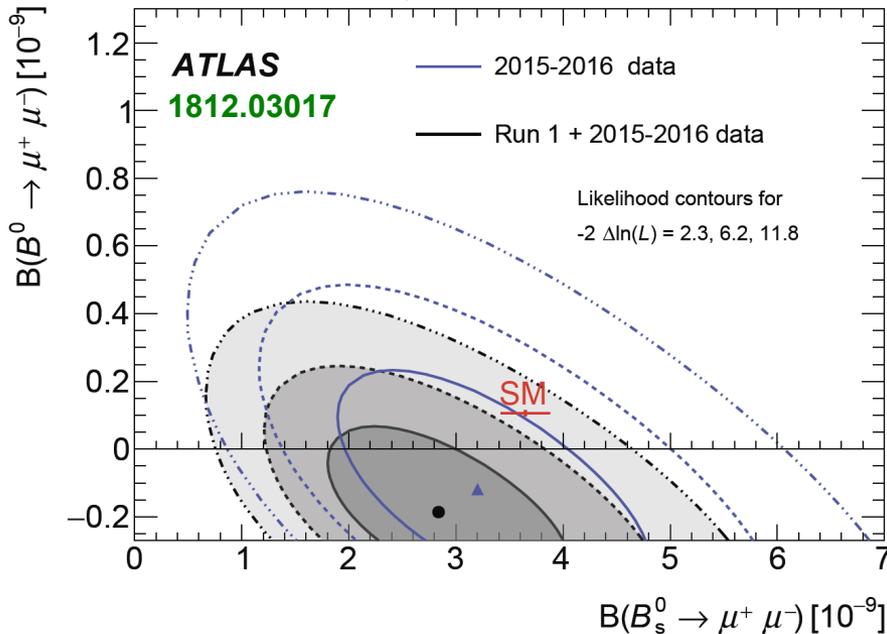
$$|s_u|/M_{H^\pm} < 0.011 \text{ GeV}^{-1}$$

Jung-Pich-Tuzón, 1006.0470

# Rare Decays

Loop & CKM suppression  
 → NP sensitivity

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



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

**Sensitive to (pseudo) scalar contributions**

Li-Lu-Pich, 1404.5865

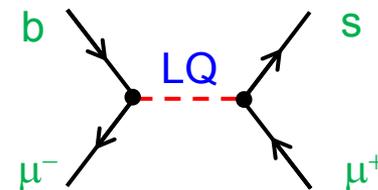
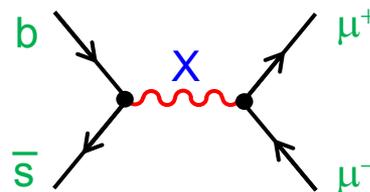
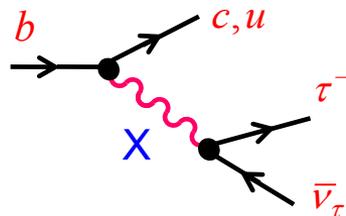
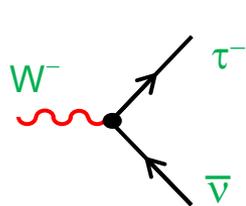
**LHCb, 1703.05747:**

$$\bar{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{exp}} = \left( 3.0 \pm 0.6^{+0.3}_{-0.2} \right) \cdot 10^{-9}$$

$$\bar{B}(B_d^0 \rightarrow \mu^+ \mu^-)_{\text{exp}} < 3.4 \cdot 10^{-10} \quad (95\% \text{ CL})$$

# Many Interesting Flavour Anomalies

$W \rightarrow \tau \nu$ ,  $\tau^\pm \rightarrow \pi^\pm K_S \nu_\tau$ ,  $b \rightarrow c \tau \nu$ ,  $b \rightarrow s \mu^+ \mu^-$ ,  $\varepsilon'_K / \varepsilon_K$ ,  $\varepsilon_K$ ,  $(g-2)_\mu$ ,  $(g-2)_e$ ,  $V_{cb}$ ,  $V_{ub}$ ,  $V_{ud} \dots$



- Evidence for New Physics
- Statistical fluctuation
- Underestimated systematics
- Incorrect SM prediction or measurement



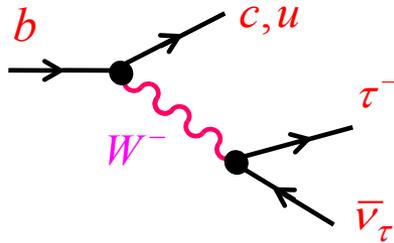
Not easy common explanation (within appealing BSM models)

Separate analyses are (perhaps) more enlightening

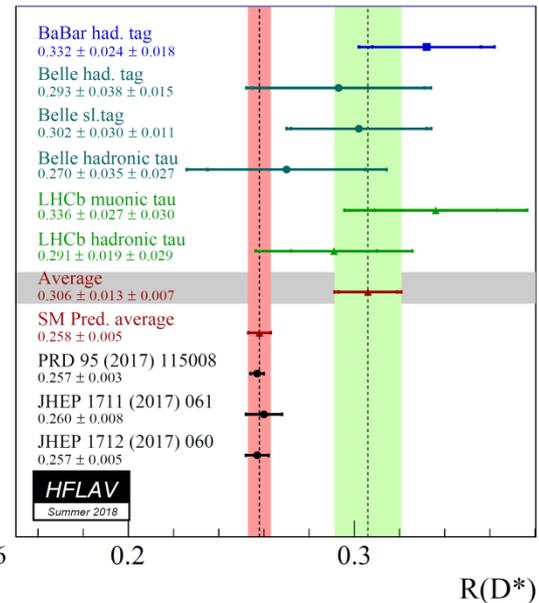
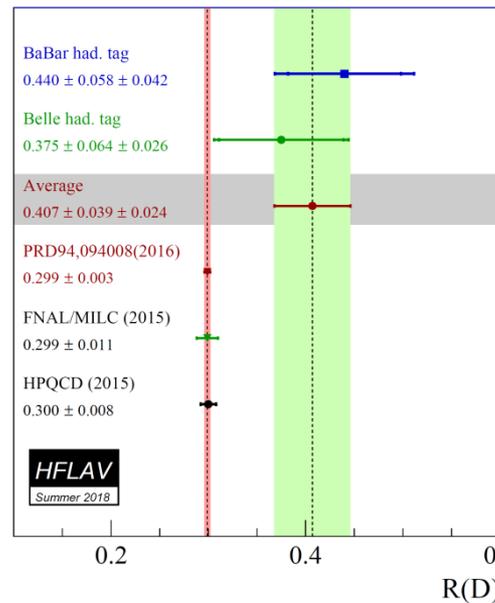
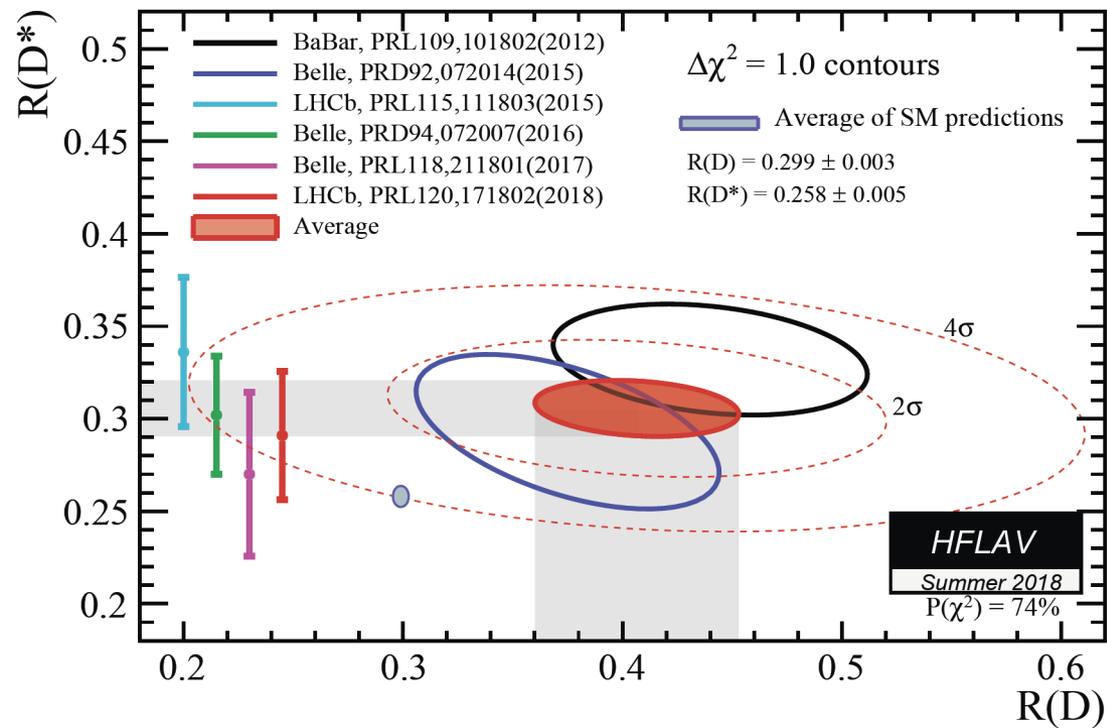
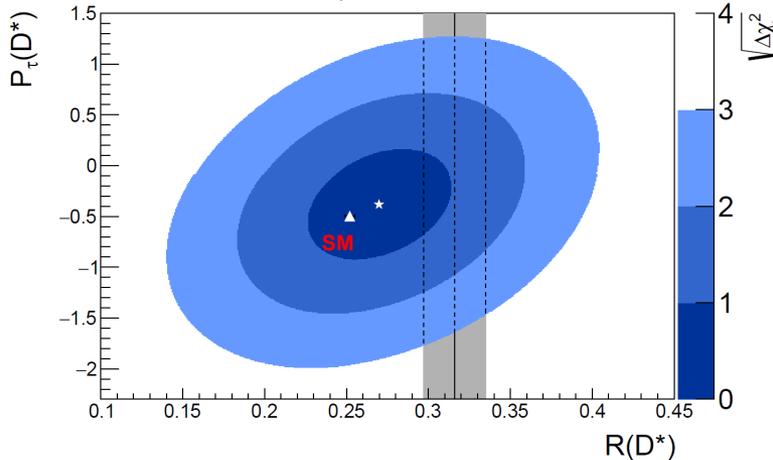
# Flavour Anomaly

## 3.8 $\sigma$ discrepancy

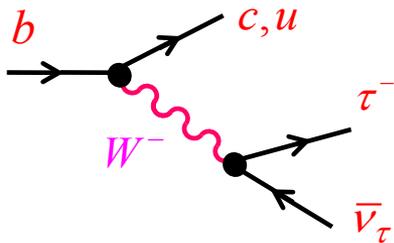
$$R(D^{(*)}) \equiv \frac{\text{Br}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{\text{Br}(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)}$$



Belle, 1612.00529



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



**2  $\sigma$  above SM prediction**

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

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

**D\* longitudinal polarization fraction:**

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$$

Belle, 1903.03102

SM:  $F_L(D^*) = 0.455 \pm 0.003$

Q.-Y. Hu et al, 1810.04939; Alok et al, 1606.03164  
Z.-R. Huang et al, 1808.03565

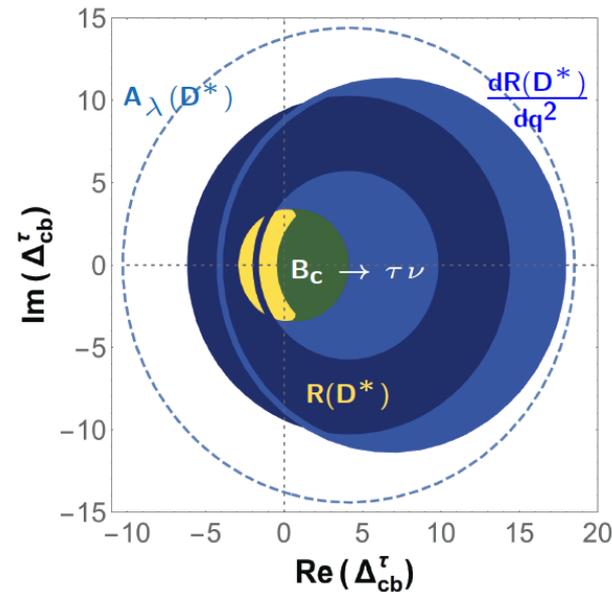
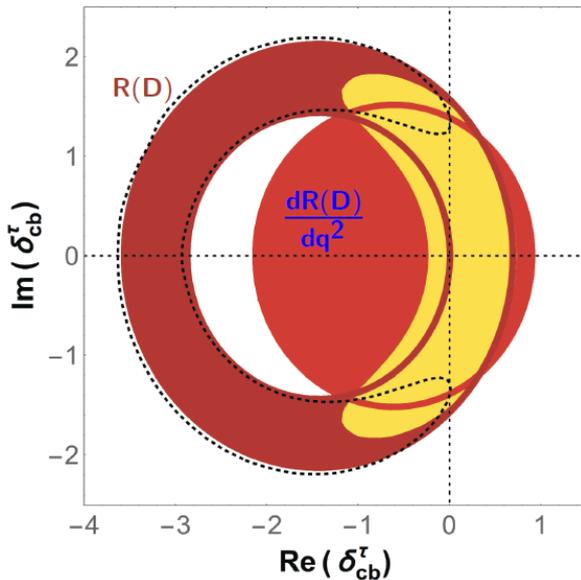
# Scalar contributions to $R(D^{(*)})$

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

Scalar Form Factors

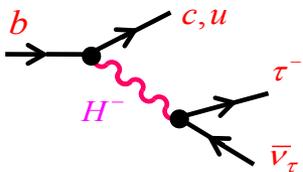
$$\left\{ \begin{array}{l} \delta R(D) \longleftrightarrow \delta_{cb}^\ell \equiv (g_L^{cbl} + g_R^{cbl}) \frac{(m_B - m_D)^2}{m_\ell (\bar{m}_b - \bar{m}_c)} \\ \delta R(D^*) \longleftrightarrow \Delta_{cb}^\ell \equiv (g_L^{cbl} - g_R^{cbl}) \frac{m_B^2}{m_\ell (\bar{m}_b + \bar{m}_c)} \end{array} \right.$$

95% CL



Celis et al.  
1612.07757

$\text{Br}(B_c \rightarrow \tau \nu) < 40\%$



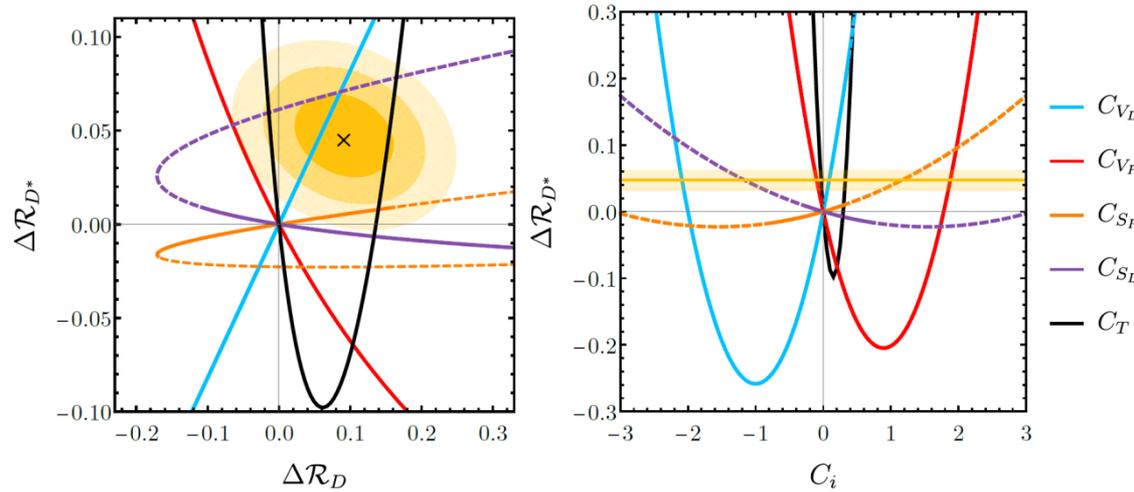
# EFT Analysis

$$H_{\text{eff}}^{b \rightarrow c \tau \nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \left\{ (1 + C_{V_L}) O_{V_L} + C_{V_R} O_{V_R} + C_{S_R} O_{S_R} + C_{S_L} O_{S_L} + C_T O_T \right\} + \text{h.c.}$$

$$O_{V_L} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L), \quad O_{V_R} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L), \quad O_{S_R} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_L), \quad O_{S_L} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_L), \quad O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L)$$

Freytsis et al, Bardhan et al, Cai et al, Hu et al, ...

SMEFT  $\rightarrow$  flavour independent  $O_{V_R} \rightarrow C_{V_R} = 0$

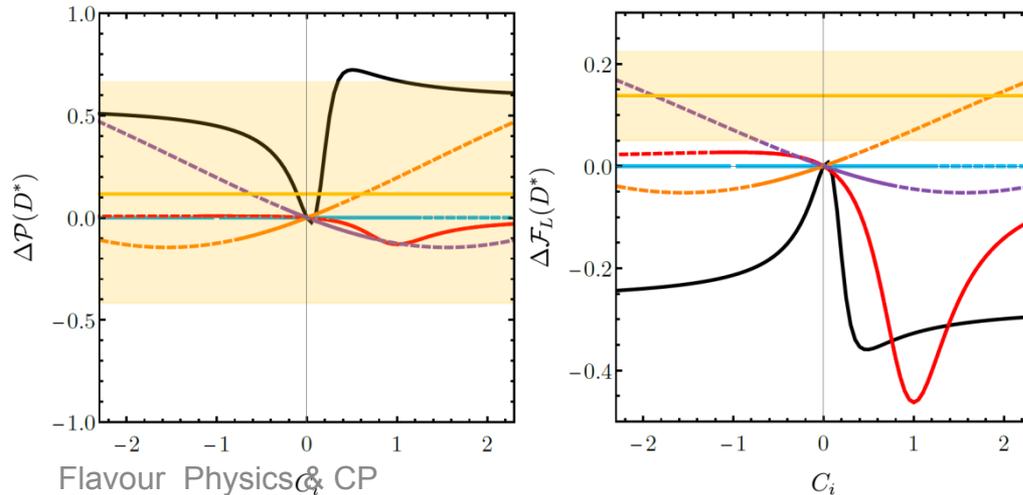


Murgui-Peñuelas-Jung-A.P.

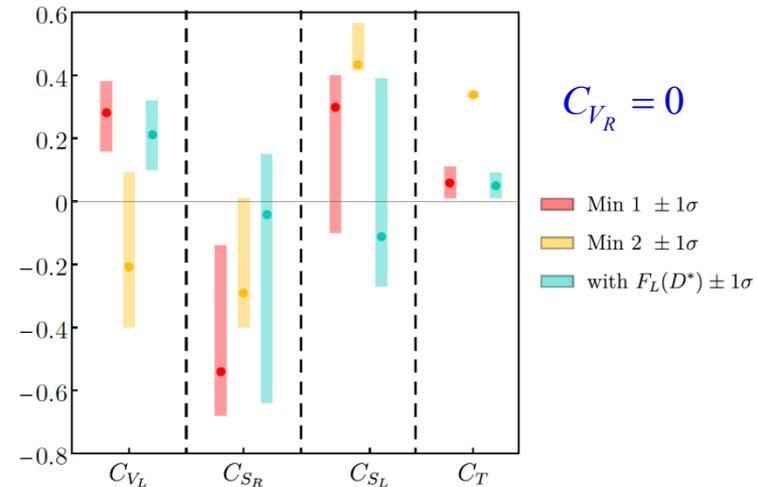
(preliminary)

Excluded by  $\text{Br}(B_c \rightarrow \tau \nu) < 10\%$

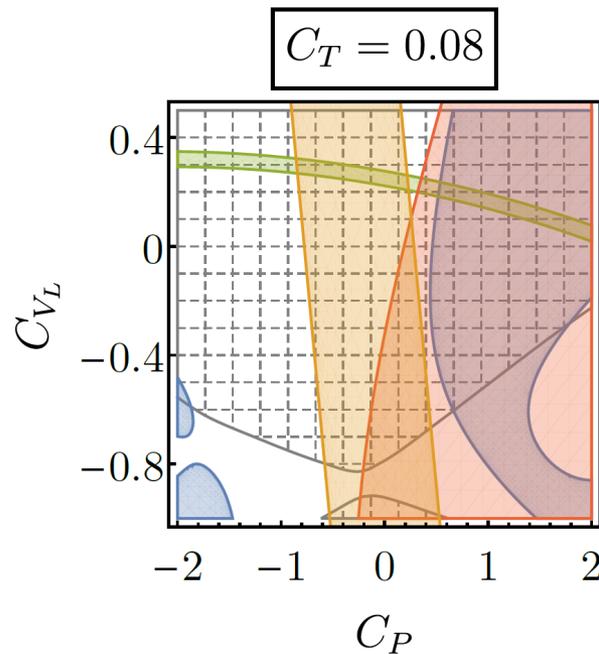
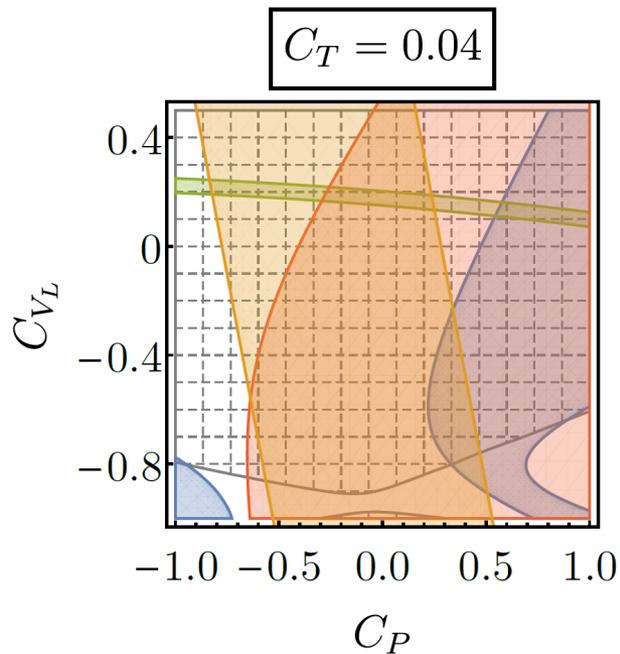
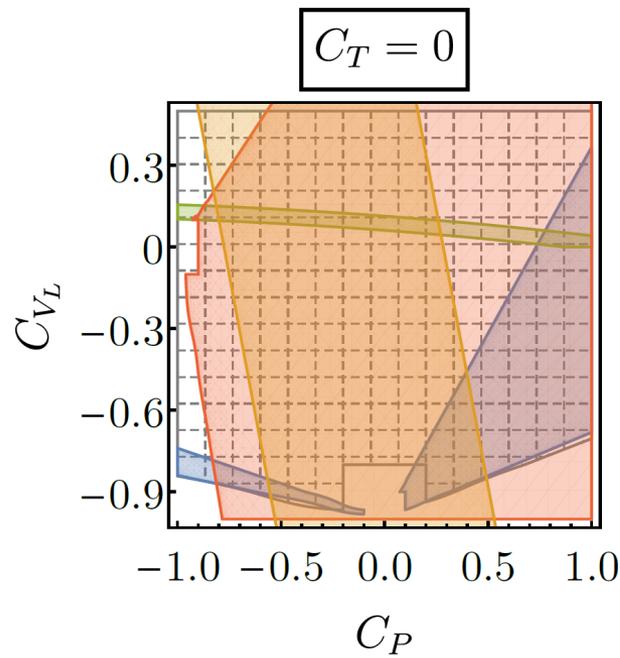
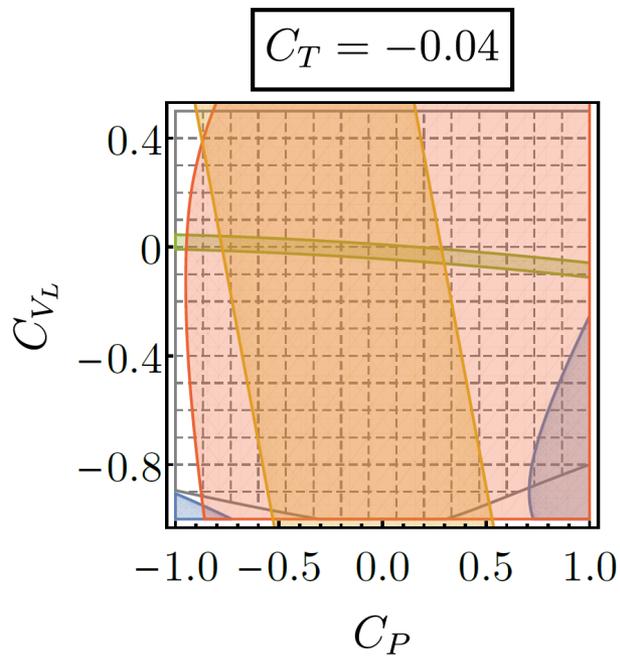
No constraint for  $C_{V_L} = C_{V_R}$ ,  $C_{S_L} = C_{S_R}$



Global Fit ( $q^2$  distribution also)



**It is not easy to accommodate all  $D^*$  data at  $1\sigma$**



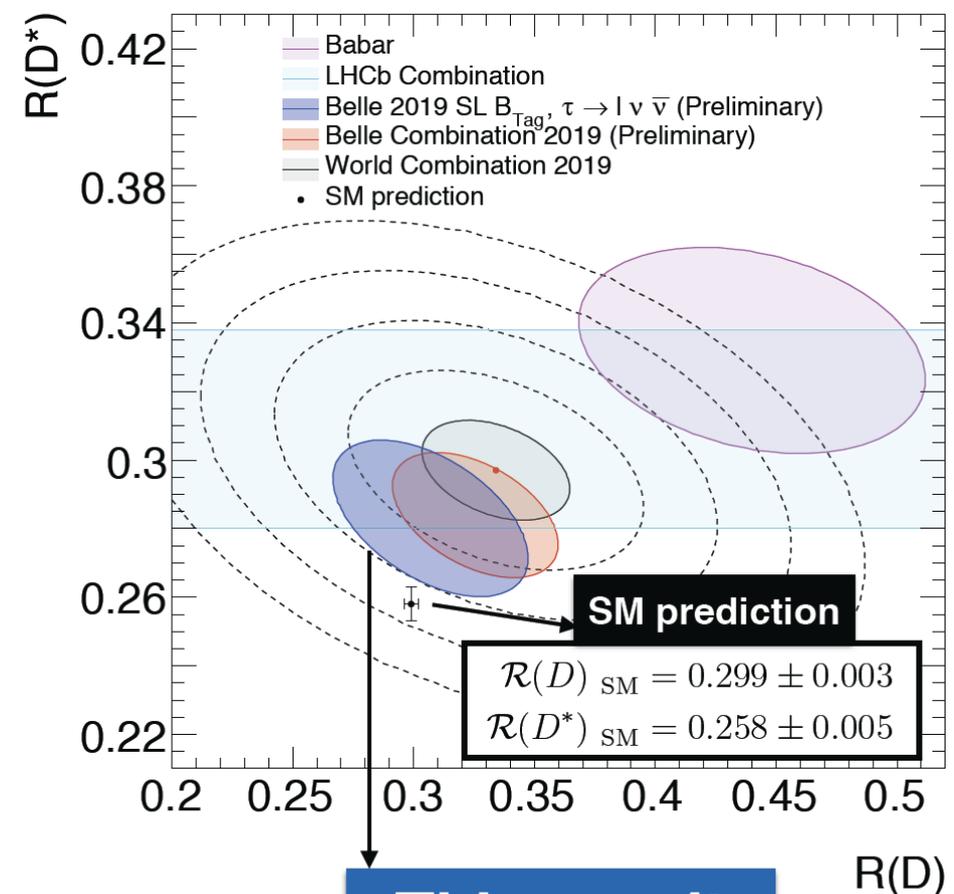
**68% CL**

- $\mathcal{P}(D^*)$
- $\mathcal{F}_L(D^*)$
- $\mathcal{R}(D^*)$
- $\text{Br}(B_c \rightarrow \tau\nu) \geq 10\%$
- $q^2$  distribution

$$C_P \equiv C_{S_L} - C_{S_R}$$

# Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of  $R(D)$  and  $R(D^*)$  to date
- First  **$R(D)$**  measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within  **$1.2\sigma$**
- **$R(D) - R(D^*)$  Belle average** is now within  **$2\sigma$**  of the SM prediction
- **$R(D) - R(D^*)$  exp. world average** tension with SM expectation **decreases from  $3.8\sigma$  to  $3.1\sigma$**

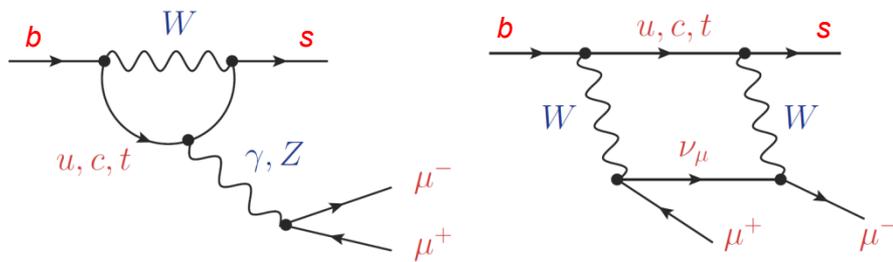


**This result**

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$

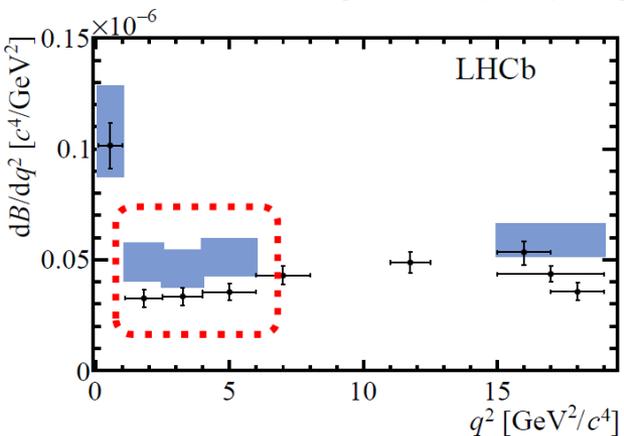
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

# $b \rightarrow s \mu^+ \mu^-$

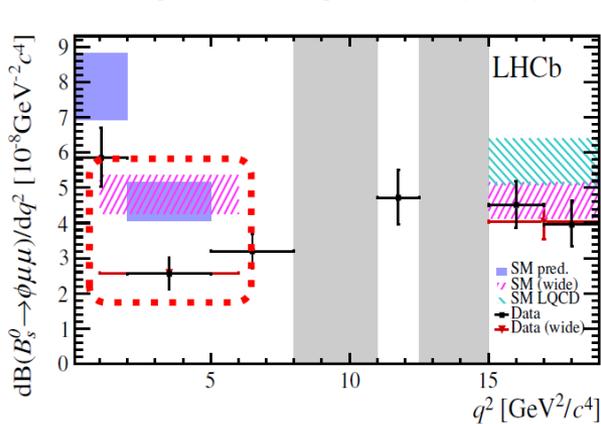


## C. Langenbruch, LHCb Implications 2018

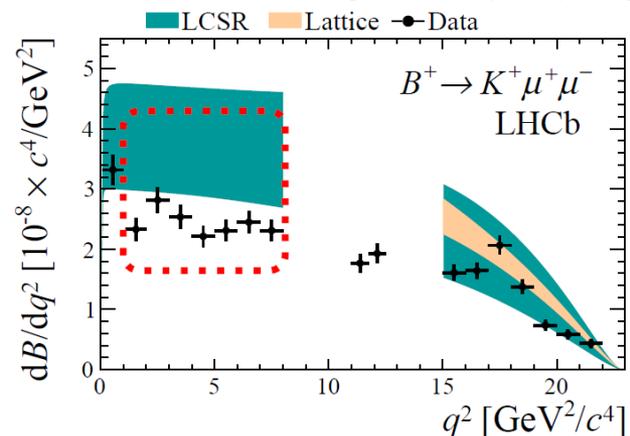
LHCb  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  [JHEP 11 (2016) 047]



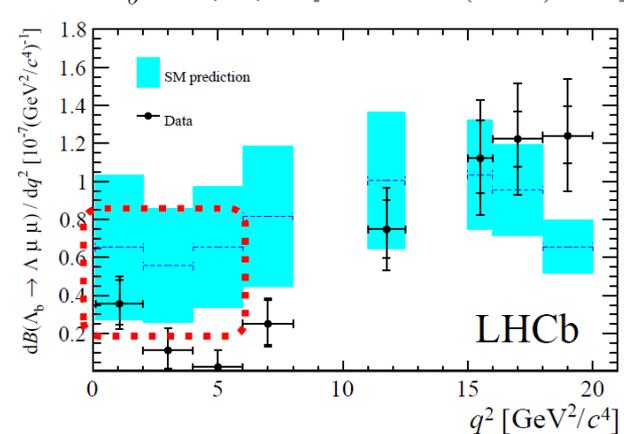
LHCb  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  [JHEP 09 (2015) 179]



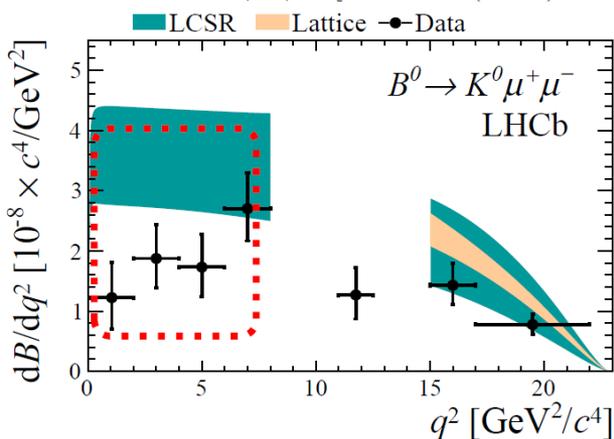
LHCb  $B^+ \rightarrow K^+ \mu^+ \mu^-$  [JHEP 06 (2014) 133]



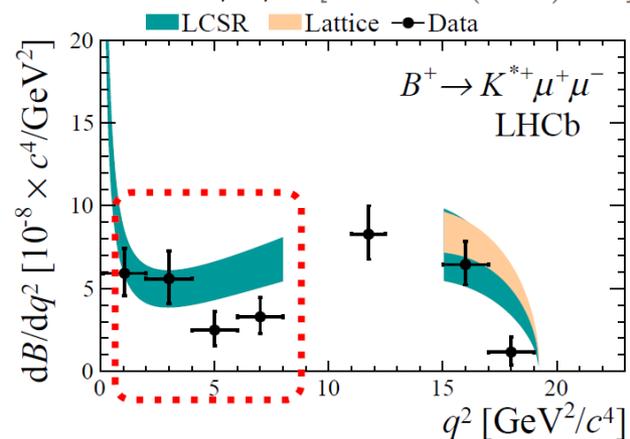
$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$  [JHEP 06 (2015) 115]



LHCb  $B^0 \rightarrow K^0 \mu^+ \mu^-$  [JHEP 06 (2014) 133]



$B^+ \rightarrow K^{*+} \mu^+ \mu^-$  [JHEP 06 (2014) 133]



**Data consistently below SM predictions (1-3  $\sigma$  tensions)**

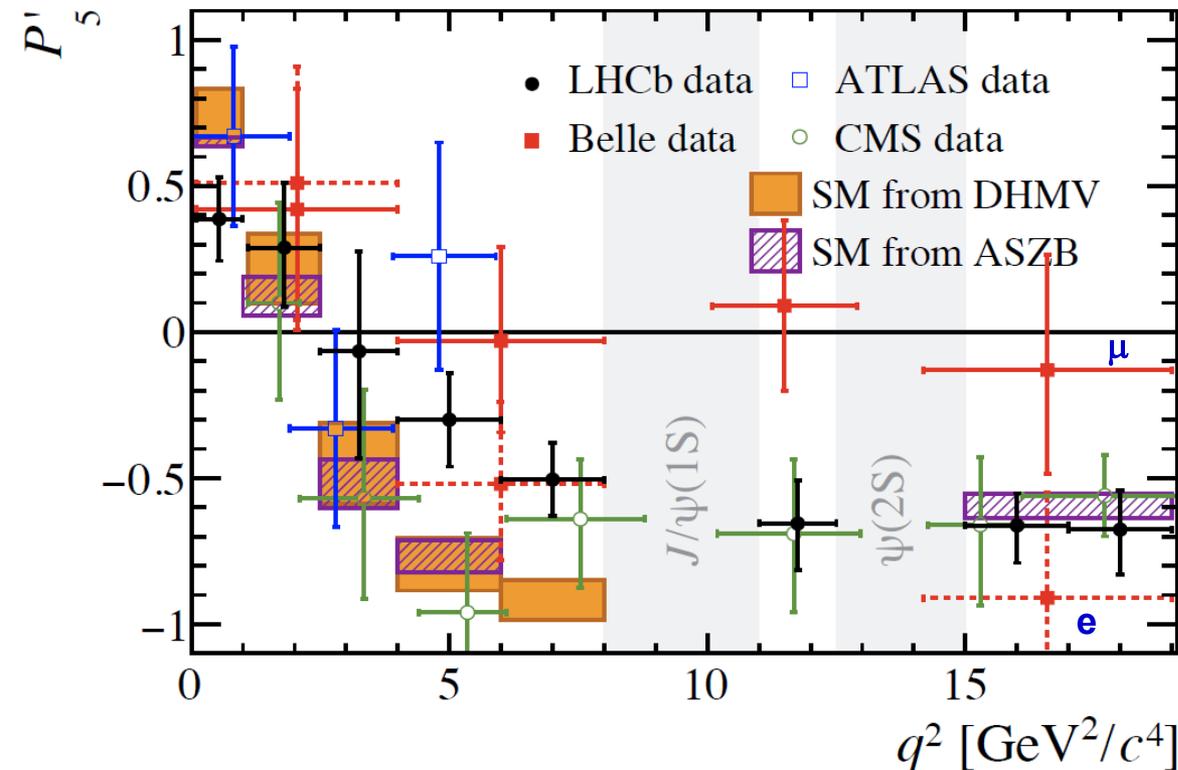
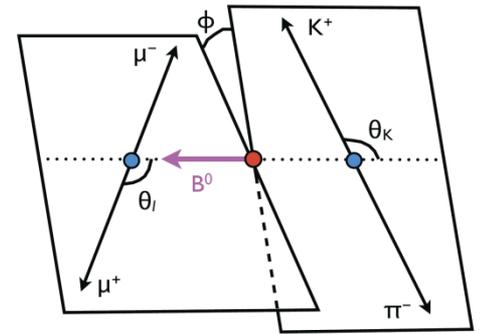
**Large hadronic uncertainties**

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

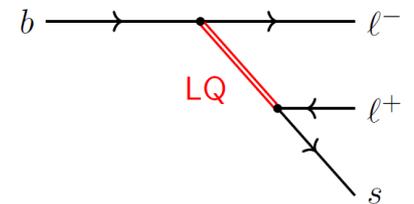
$$\frac{1}{d\Gamma/dq^2 d\cos\theta_\ell d\cos\theta_K d\phi dq^2} \frac{d^4\Gamma}{dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4}(1 - F_L) \sin^2\theta_K \cos 2\theta_\ell \right. \\ \left. - F_L \cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K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

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

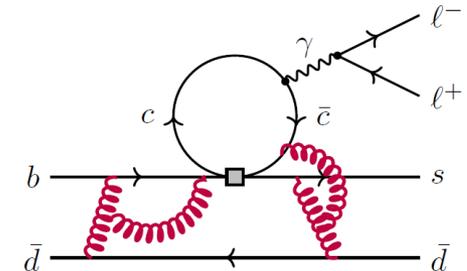
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}$$



## C .Langenbruch, LHCb Implications 2018



NP or SM  $c\bar{c}$ -loop?

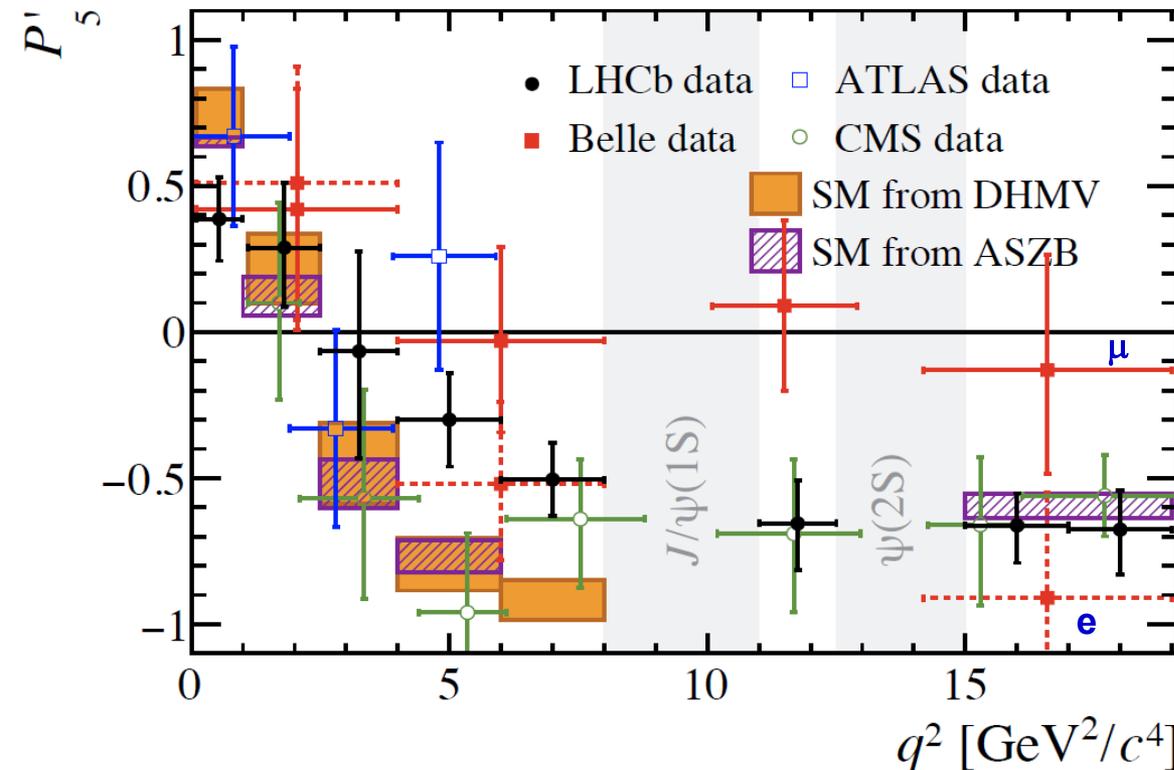
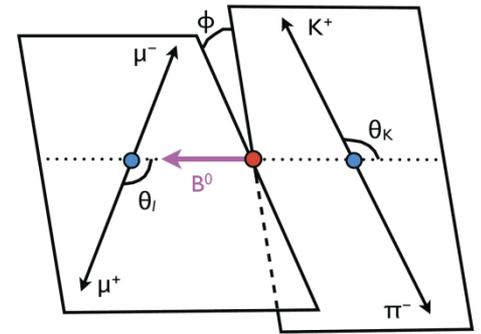


# $B^0 \rightarrow K^{*0} \mu^+ \mu^- \rightarrow K^+ \pi^- \mu^+ \mu^-$

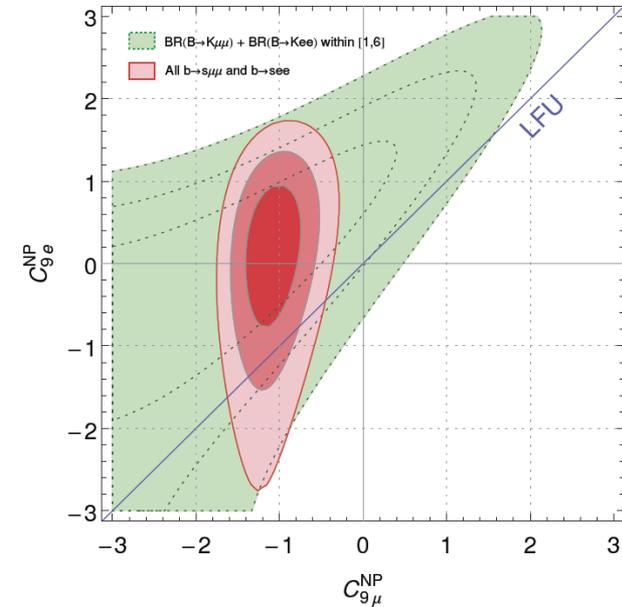
$$\frac{1}{d\Gamma/dq^2 d\cos\theta_\ell d\cos\theta_K d\phi dq^2} \frac{d^4\Gamma}{dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ \left. - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2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

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

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



Descotes-Genon et al, 1510.04239



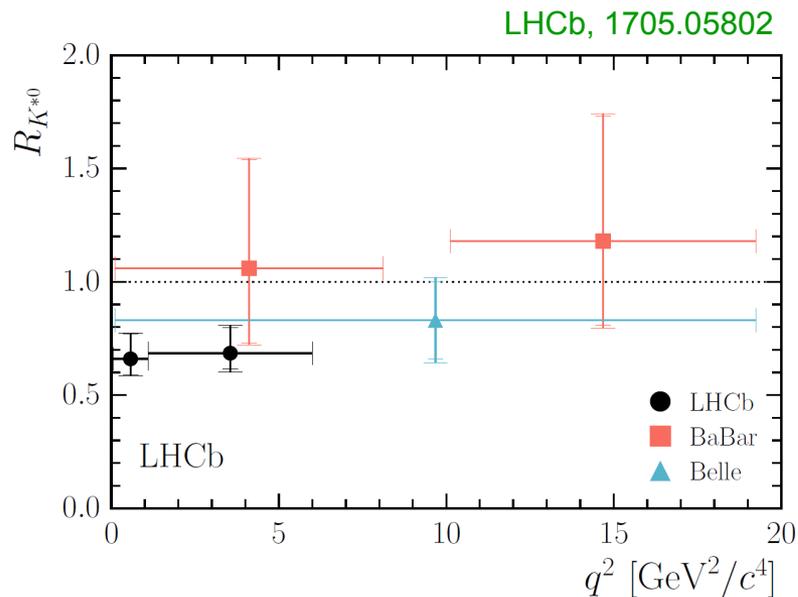
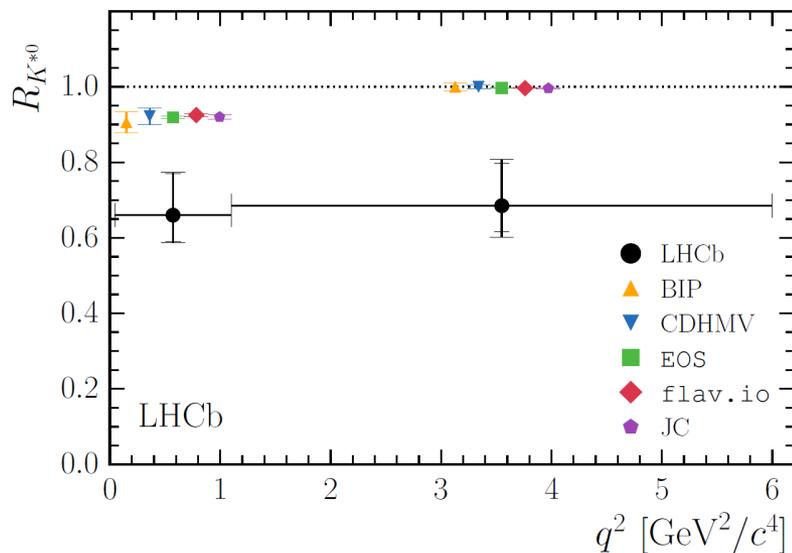
$$O_9 = (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell)$$

# Violations of Lepton Flavour

$$R_{K^{*0}} = \frac{\text{Br}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\text{Br}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} \bigg/ \frac{\text{Br}(B^0 \rightarrow K^{*0} e^+ e^-)}{\text{Br}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

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

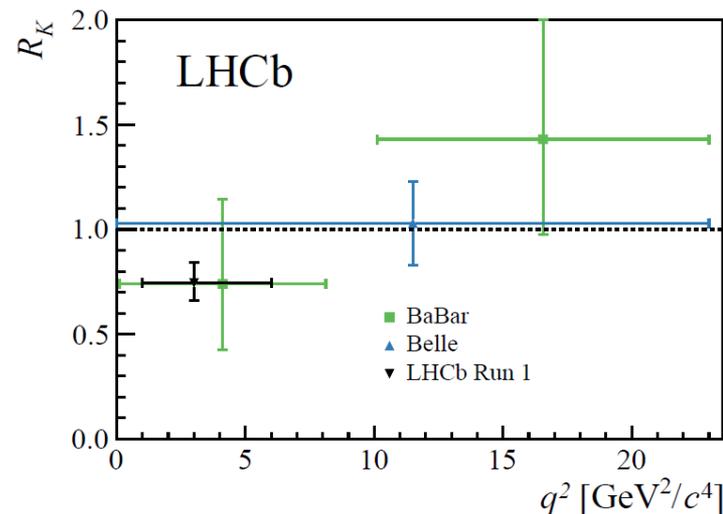
2.1 – 2.5  $\sigma$  deviation from SM



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

$$\frac{\text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{Br}(B^+ \rightarrow K^+ e^+ e^-)} = 0.745 \pm_{-0.074}^{+0.090} \pm 0.036$$

2.6  $\sigma$  below the SM

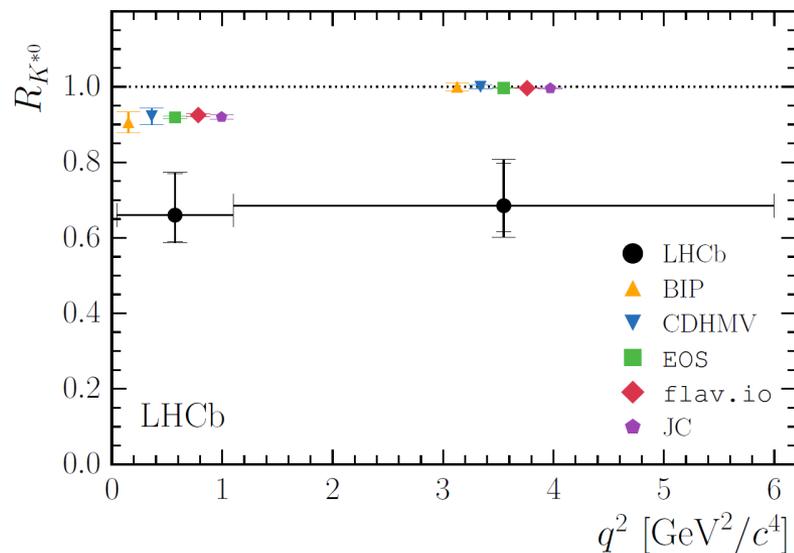


# Violations of Lepton Flavour

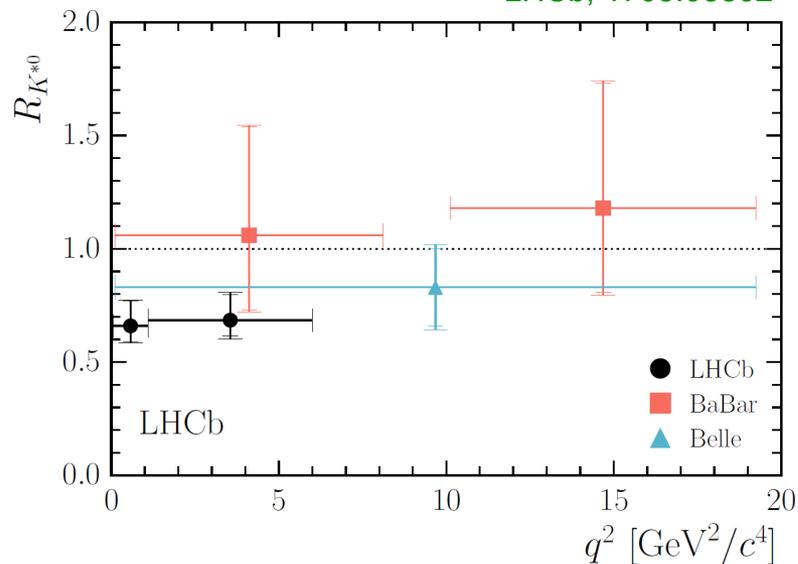
$$R_{K^{*0}} = \frac{\text{Br}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\text{Br}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} \bigg/ \frac{\text{Br}(B^0 \rightarrow K^{*0} e^+ e^-)}{\text{Br}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

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99.7% CL	[0.45, 1.04]	[0.46, 1.10]

2.1 – 2.5  $\sigma$  deviation from SM



LHCb, 1705.05802

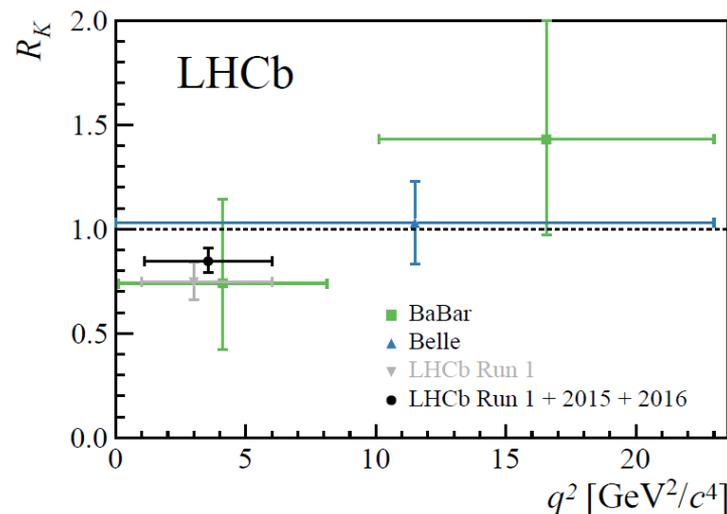


LHC-PAPER-2019-009

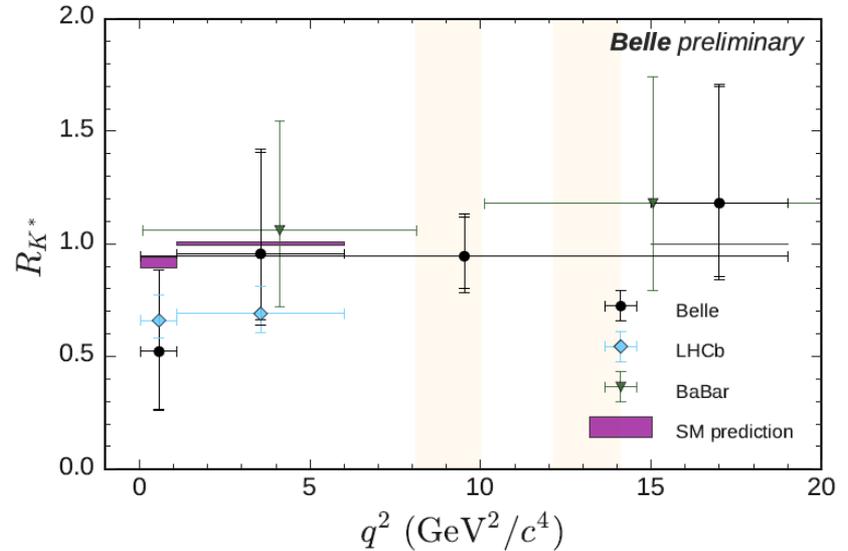
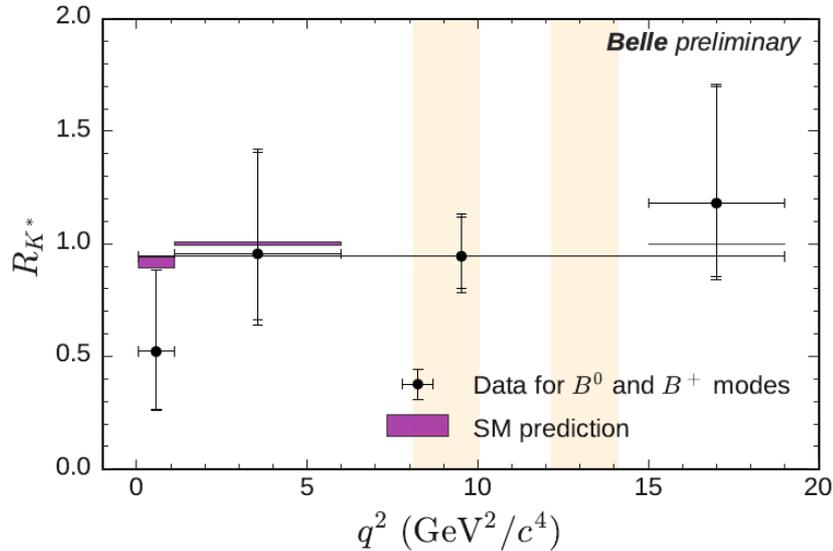
**LHCb:** Moriond 2019, Run 1 + Run 2 ( $q^2 \in [1, 6] \text{ GeV}^2$ )

$$\frac{\text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{Br}(B^+ \rightarrow K^+ e^+ e^-)} = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

2.5  $\sigma$  below the SM



# $R(K^*)$ : (Preliminary) Result



$q^2$ in $\text{GeV}^2/c^4$	All modes	$B^0$ modes	$B^+$ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045, ]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

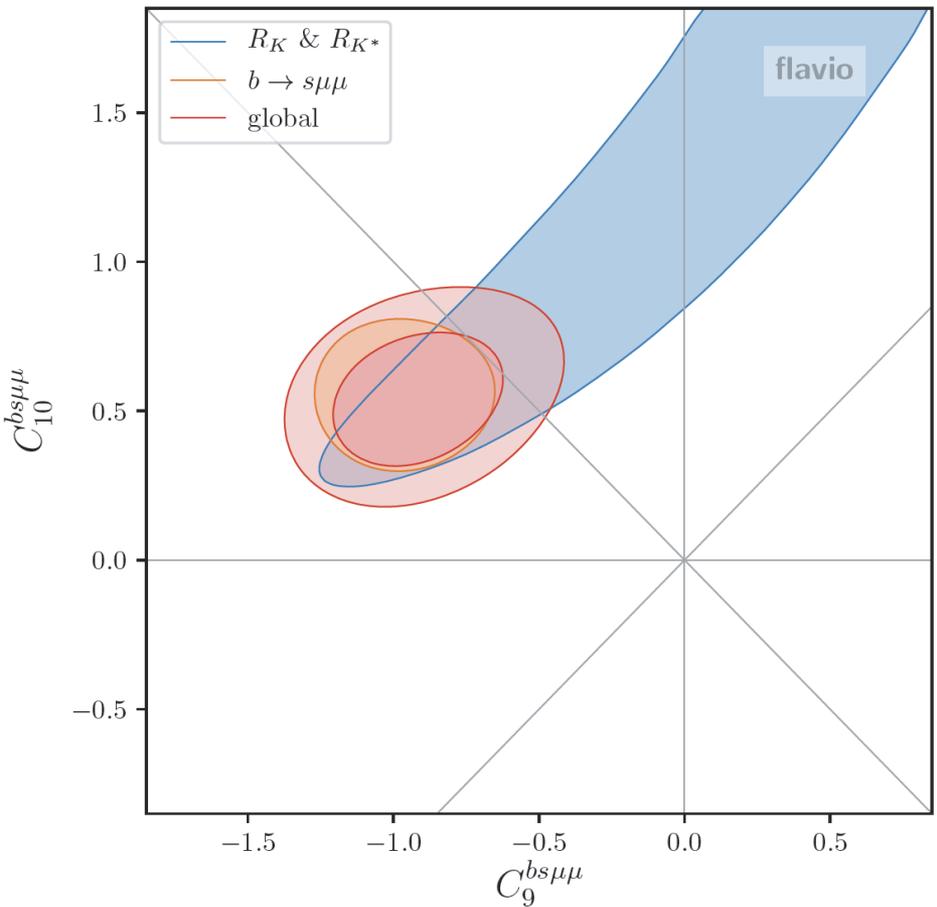
- All measured values are in accordance with the SM and other recent measurements.
- First measurement of  $R(K^{*+})$ .

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

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

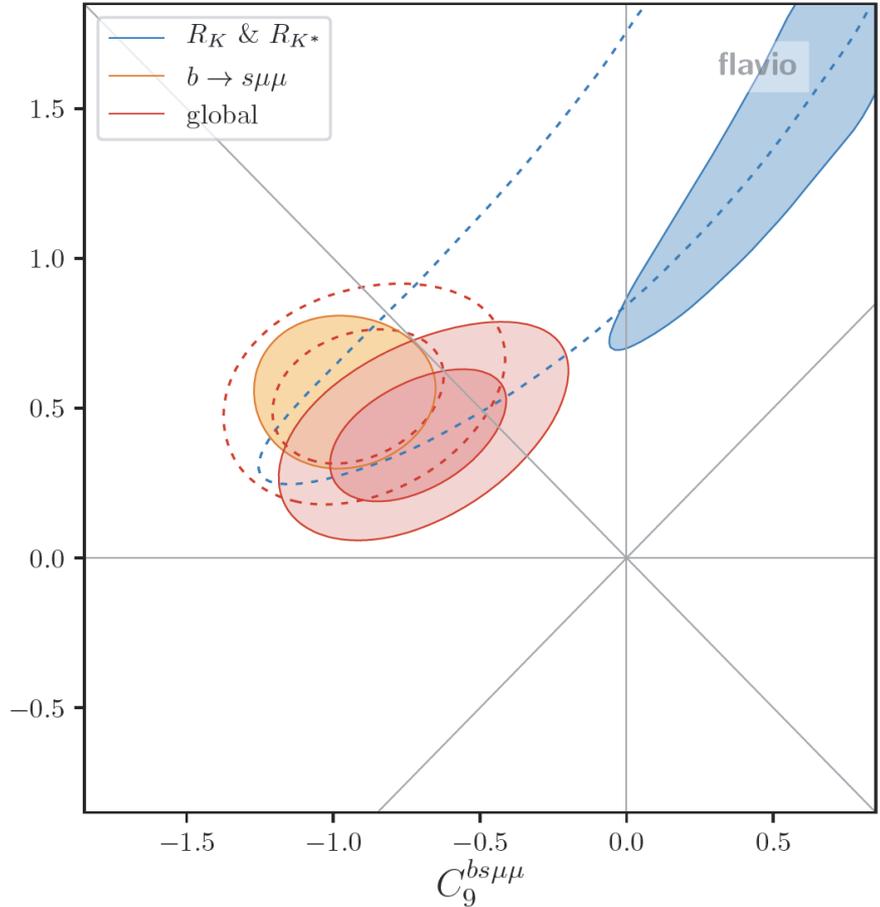
$$O_{10}^\ell = (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

Pre-Moriond Fit



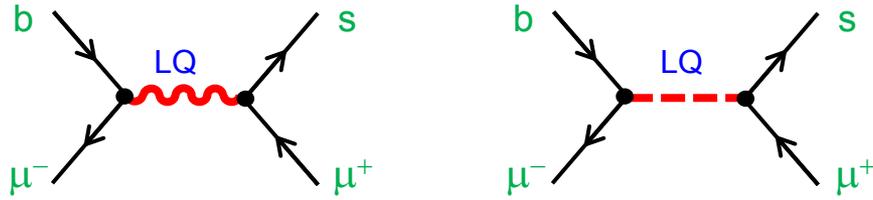
Closer to SM

Post-Moriond Fit



C<sub>10</sub> = - C<sub>9</sub> preferred

# Leptoquark Solutions



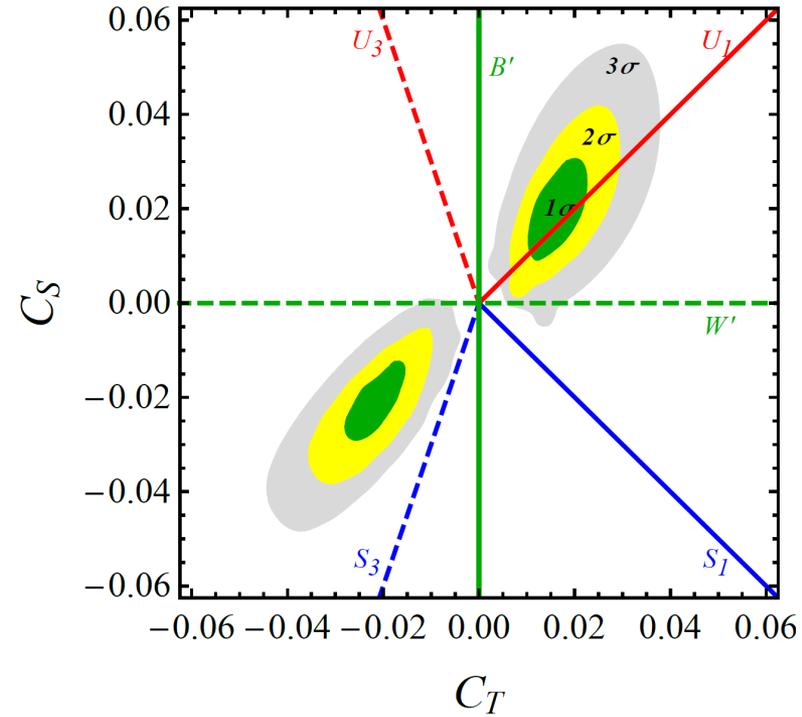
$$\mathcal{L}_{\text{eff}} = -\frac{1}{v^2} \lambda_{ij}^q \lambda_{\alpha\beta}^\ell \left[ C_T (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j) (\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta) + C_S (\bar{Q}_L^i \gamma_\mu Q_L^j) (\bar{L}_L^\alpha \gamma^\mu L_L^\beta) \right]$$

$U(2)_q \otimes U(2)_\ell$  Family Symmetry

Angelescu et al, 1808.08179

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗*
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

Buttazzo et al, 1706.07808

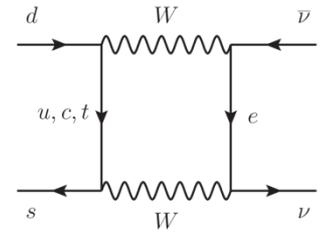
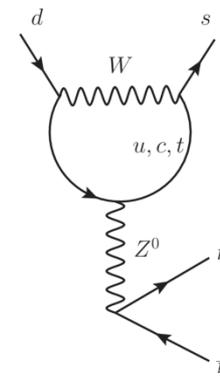


## Possible UV completions:

- 4321 model Di Luzio et al
- (Pati-Salam)<sup>3</sup> Bordone et al
- PS + VLF Calibbi et al
- Warped PS Blanke-Crivellin
- SU(5) GUT ( $R_2$  &  $S_3$ ) Becirevic et al
- $S_1$  &  $S_3$  Crivellin et al, Buttazzo et al, Marzocca
- ...

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

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



$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11} \sim A^4 [\eta^2 + (1.4 - \rho)^2]$$

$$\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (2.4 \pm 0.4) \times 10^{-11} \sim A^4 \eta^2$$

Buras et al

Long-distance contributions are negligible

$$\mathbf{T}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \neq 0 \quad \longrightarrow \quad \cancel{CP}$$

- **BNL-E949: few events!**  $\longrightarrow$   $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$
- **KEK-E391a:**  $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$  (90% C.L.)

Ongoing experiments: NA62, KOTO

# LEPTON FLAVOUR VIOLATION

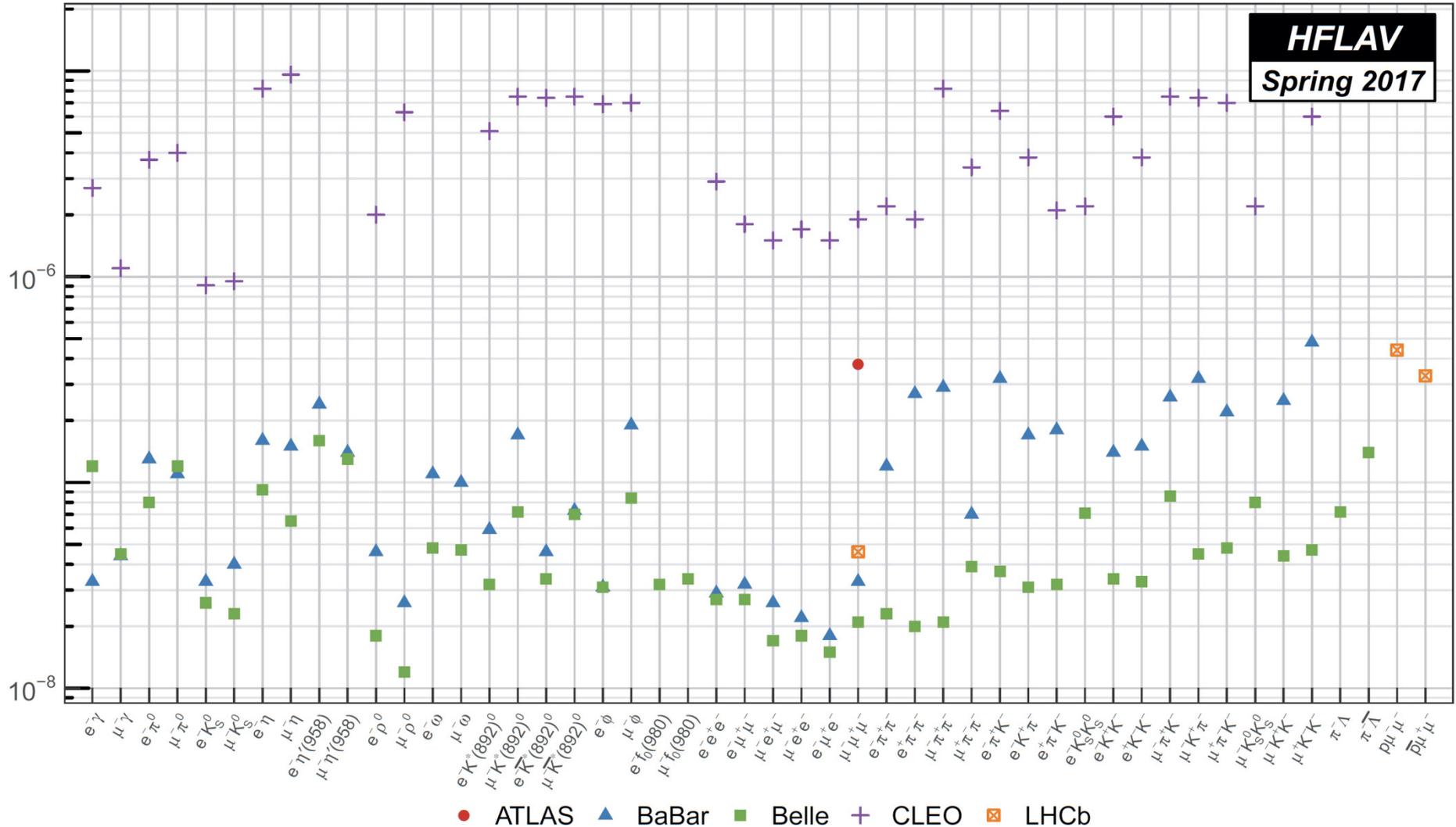
90% CL Upper Limits on  $\text{Br}(l^- \rightarrow X^-)$

[MEG'16, SINDRUM'88, Bolton'88, BABAR, BELLE, LHC]

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

# LEPTON FLAVOUR VIOLATION

90% CL upper limits on  $\tau$  LFV decays



# SUMMARY

- **Flavour Structure and  $CP$**  are major pending questions
- **Related to SSB**  **Scalar Sector (Higgs)**
- Important **cosmological implications (Baryogenesis)**
- Sensitive to **New Physics: Flavour Anomalies!**

**Intriguing signals (most anomalies related to 3<sup>rd</sup> family)**

**Many questions.** Higher statistics & better systematics (QCD) needed

**Eagerly awaiting new experimental results**

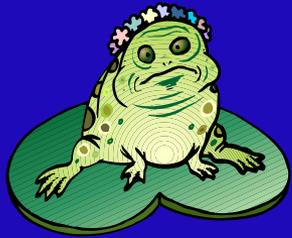
# Quarks



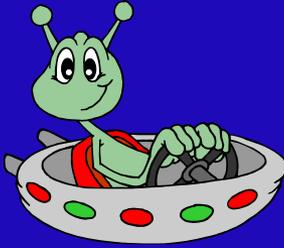
up



down



charm



strange



top



beauty

# Leptons



electron



neutrino e



muon



neutrino μ



tau



neutrino τ

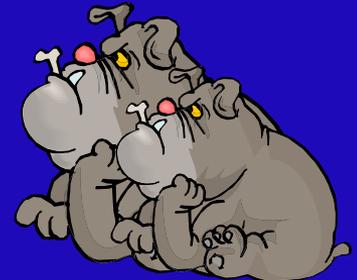
# Bosons



photon



gluon



Z<sup>0</sup> W<sup>±</sup>



Higgs

# Backup



# Flavour Alignment

(Aligned 2HDM)

Pich-Tuzón

Celis-Ilisie-Pich, 1302.4022, 1310.7941

General setting without FCNCs  
& new sources of CP violation

$$Y_{d,l} = \zeta_{d,l} M_{d,l} \quad , \quad Y_u = \zeta_u^* M_u$$

- 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

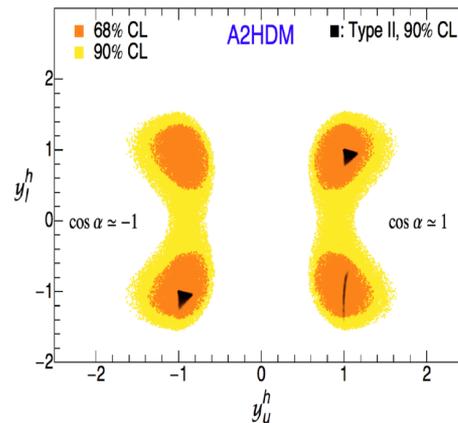
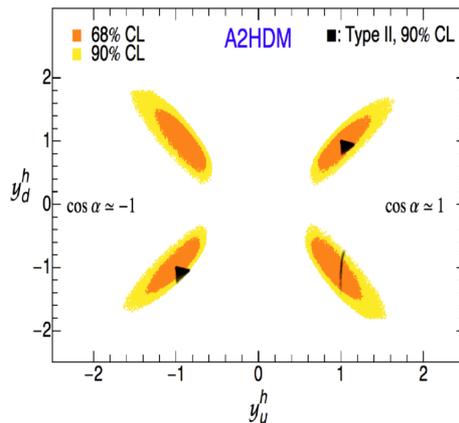
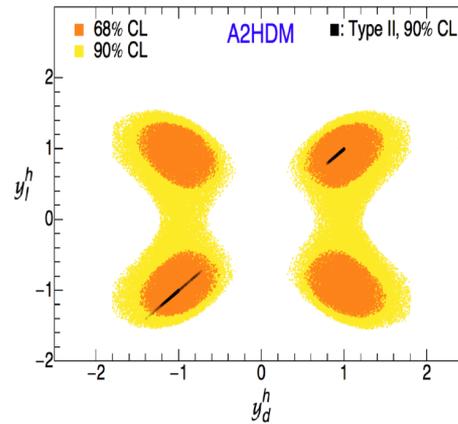
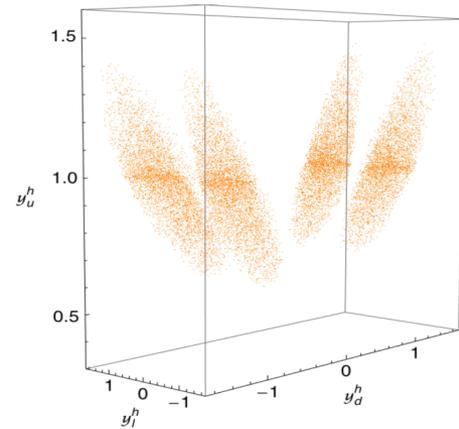
- Flavour constraints fulfilled

Celis et al, Jung et al, Li et al

- EDMs

Jung-Pich, 1308.6283

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



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

# CHARGED CURRENT UNIVERSALITY

A. Pich, arXiv:1310.7922

$$|g_\mu / g_e|$$

$B_{\tau \rightarrow \mu} / B_{\tau \rightarrow e}$	$1.0018 \pm 0.0014$
$B_{\pi \rightarrow \mu} / B_{\pi \rightarrow e}$	$1.0003 \pm 0.0012$
$B_{K \rightarrow \mu} / B_{K \rightarrow e}$	$0.9978 \pm 0.0020$
$B_{K \rightarrow \pi\mu} / B_{K \rightarrow \pi e}$	$1.0010 \pm 0.0025$
$B_{W \rightarrow \mu} / B_{W \rightarrow e}$	$0.996 \pm 0.010$

PIENU 1506.05845

$$|g_\tau / g_\mu|$$

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

$$|g_\tau / g_e|$$

$B_{\tau \rightarrow \mu} \tau_\mu / \tau_\tau$	$1.0030 \pm 0.0015$
$B_{W \rightarrow \tau} / B_{W \rightarrow e}$	$1.031 \pm 0.013$

**2.6  $\sigma$**

**$g_\tau$  anomaly cannot be accommodated within EFT**

**2.4  $\sigma$**

(Assumes  $[U(2) \otimes U(1)]^5$  or  $U(2)^5$  flavour symmetry)

Filipuzzi, Gonzalez-Alonso, Portolés, 1203.2092



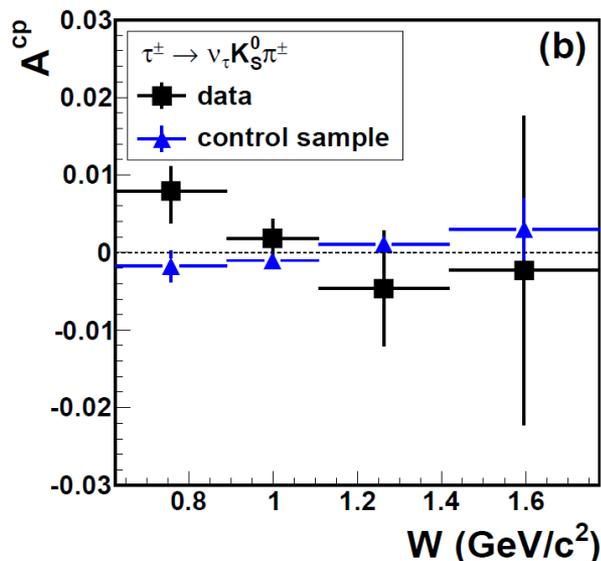
# CP Asymmetry

$$A_\tau \equiv \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S \nu_\tau)} = (-3.6 \pm 2.3 \pm 1.1) \cdot 10^{-3} \quad \text{BaBar'11} \quad (\geq 0 \pi^0)$$

$$A_\tau^{\text{SM}}(\tau^+ \rightarrow \pi^+ K_S \bar{\nu}_\tau) = (3.6 \pm 0.1) \cdot 10^{-3} \quad \text{Bigi-Sanda, Grossman-Nir} \quad \mathbf{2.8 \sigma \text{ discrepancy}}$$



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



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

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

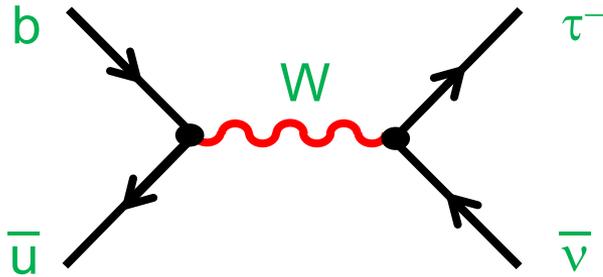
$\beta = K_S$  direction in hadronic rest frame

$\psi = \tau$  direction

**BaBar signal in conflict (with EFT)  
with other sets of flavour data**

Cirigliano-Crivellin-Hoferichter, 1712.06595

# 2006 $B^- \rightarrow \tau^- \nu$ Anomaly



**Belle 2006:** (hadronic tag)

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

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

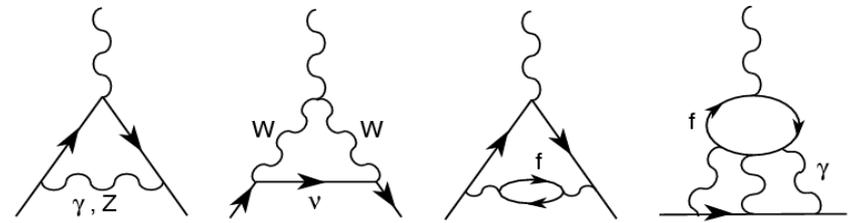
Confirmed by BaBar (2008, 2010, 2013)

**Belle 2013:** (hadronic tag)

$$\text{Br}(B^- \rightarrow \tau^- \nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$$

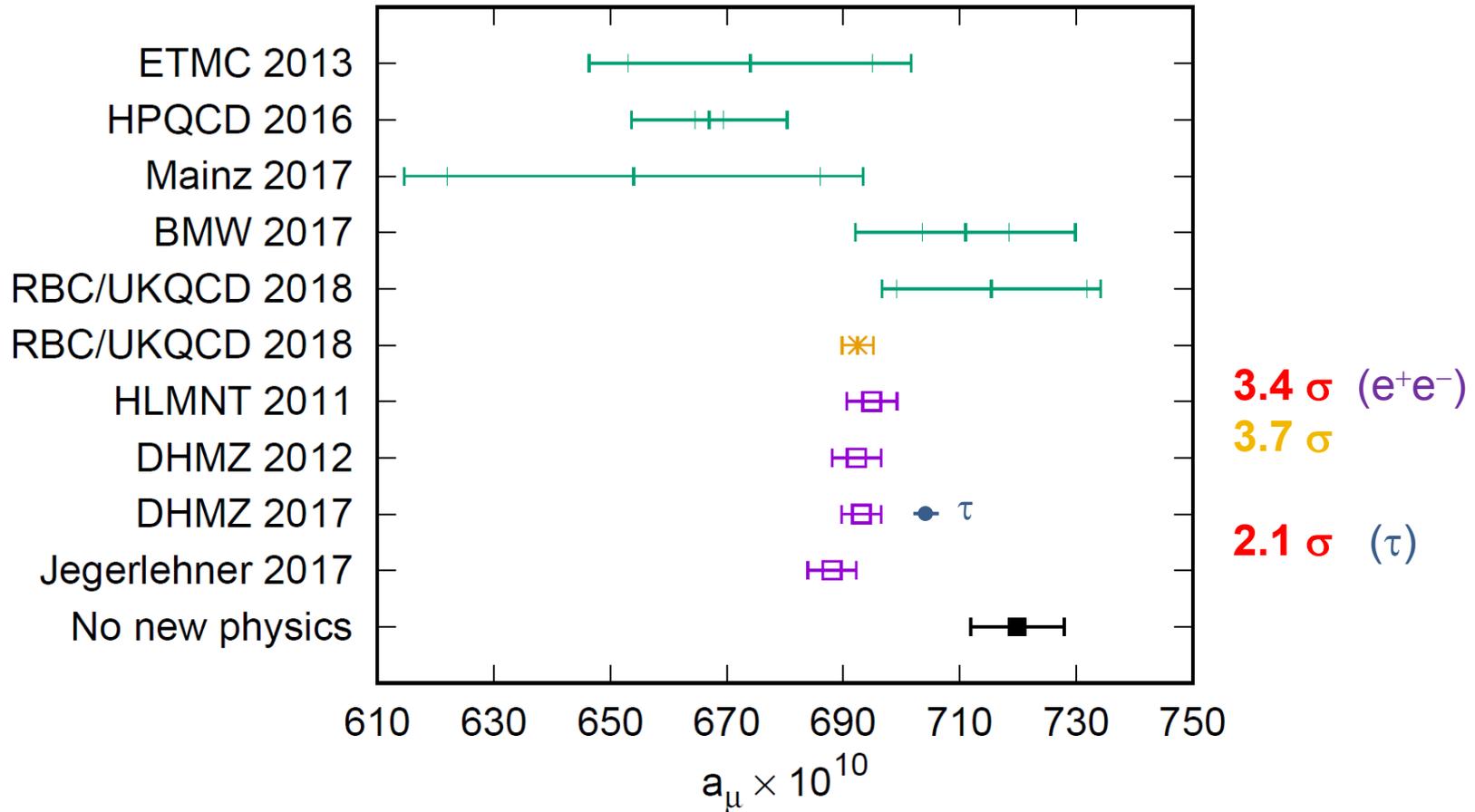
**Current status:** CKM agreement. Tension between Belle and BaBar

# $\mu$ Anomalous Magnetic Moment



RBC/UKQCD 1801.07224

LO Hadronic vacuum polarization contribution



**New  $a_\mu$  measurement eagerly expected**

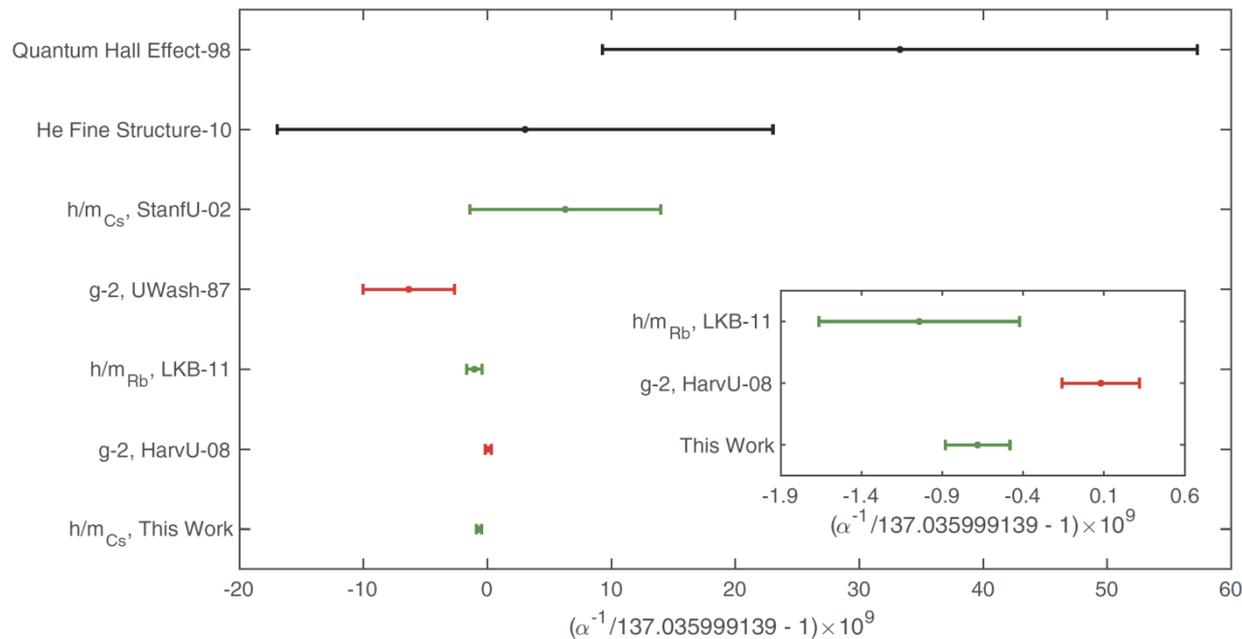
# Electron Anomalous Magnetic Moment

New measurement of  $\alpha$

Parker et al, Science 360 (2018) 191

$$\alpha^{-1}(\text{Cs}) = 137.035\,999\,046 \quad (27)$$

$2.0 \times 10^{-10}$  accuracy



➔  $\Delta a_e \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = [-87 \pm 28_{\text{exp}} \pm 23_{\alpha} \pm 2_{\text{th}}] \times 10^{-14} = [-87 \pm 36] \times 10^{-14}$

**2.4  $\sigma$  (negative) deviation**

Davoudiasl-Marciano, 1806.10252

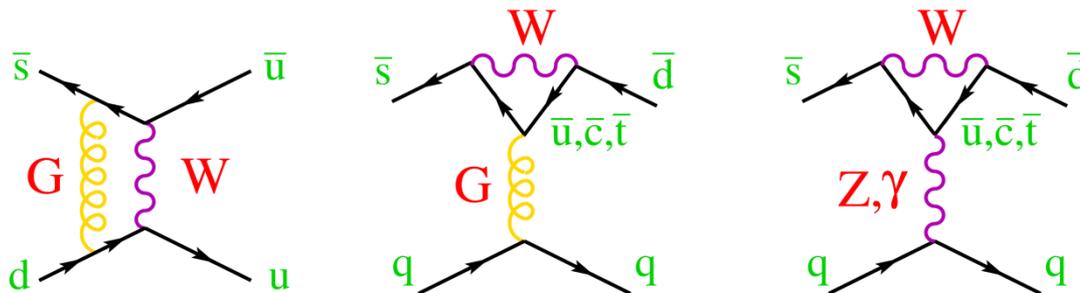
# DIRECT $\mathcal{CP}$ in $K \rightarrow \pi \pi$

$$\eta_{+-} \equiv \frac{T(K_L \rightarrow \pi^+ \pi^-)}{T(K_S \rightarrow \pi^+ \pi^-)} \approx \varepsilon_K + \varepsilon'_K$$

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

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

NA48, NA31  
KTeV, E731



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

- Short-distance OPE  
Ciuchini et al, Buras et al
- Long-distance  $\chi$ PT  
Pallante-Pich-Scimemi  
Cirigliano-Ecker-Neufeld-Pich

$(15 \pm 7) \times 10^{-4}$

2017 update

Gisbert-Pich, 1712.06147

# Empirical Evidence

$$A[K^0 \rightarrow \pi^+\pi^-] \equiv A_0 e^{i\delta_0} + \frac{1}{\sqrt{2}} A_2 e^{i\delta_2} \equiv \mathcal{A}_{1/2} + \frac{1}{\sqrt{2}} \mathcal{A}_{3/2}$$

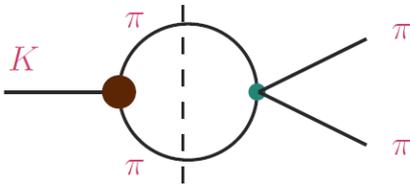
$$A[K^0 \rightarrow \pi^0\pi^0] \equiv A_0 e^{i\delta_0} - \sqrt{2} A_2 e^{i\delta_2} \equiv \mathcal{A}_{1/2} - \sqrt{2} \mathcal{A}_{3/2}$$

$$A[K^+ \rightarrow \pi^+\pi^0] \equiv \frac{3}{2} A_2 e^{i\delta_2} \equiv \frac{3}{2} \mathcal{A}_{3/2}$$

- ①  **$\Delta I = 1/2$  Rule:**  $\omega \equiv \text{Re}(A_2)/\text{Re}(A_0) \approx 1/22$
- ② **Strong Final State Interactions:**  $\delta_0 - \delta_2 \approx 45^\circ$

- **Unitarity:**

## Large $\pi\pi$ Absorptive Cut



$$\mathcal{A}_{\Delta I} \equiv A_I e^{i\delta_I} = \text{Dis}(\mathcal{A}_{\Delta I}) + i \text{Abs}(\mathcal{A}_{\Delta I})$$

$$\text{Abs}\left(\frac{\mathcal{A}_{1/2}}{\mathcal{A}_{3/2}}\right) \approx \text{Dis}\left(\frac{\mathcal{A}_{1/2}}{\mathcal{A}_{3/2}}\right)$$

- **Analyticity:**

Large  $\text{Abs}(\mathcal{A}_{1/2}) \rightarrow$  Large  $\text{Dis}(\mathcal{A}_{1/2})$

# Empirical Evidence

$$\begin{aligned}
 A[K^0 \rightarrow \pi^+\pi^-] &\equiv A_0 e^{i\delta_0} + \frac{1}{\sqrt{2}} A_2 e^{i\delta_2} \equiv \mathcal{A}_{1/2} + \frac{1}{\sqrt{2}} \mathcal{A}_{3/2} \\
 A[K^0 \rightarrow \pi^0\pi^0] &\equiv A_0 e^{i\delta_0} - \sqrt{2} A_2 e^{i\delta_2} \equiv \mathcal{A}_{1/2} - \sqrt{2} \mathcal{A}_{3/2} \\
 A[K^+ \rightarrow \pi^+\pi^0] &\equiv \frac{3}{2} A_2 e^{i\delta_2} \equiv \frac{3}{2} \mathcal{A}_{3/2}
 \end{aligned}$$

- ①  $\Delta I = 1/2$  Rule:  $\omega \equiv \text{Re}(A_2)/\text{Re}(A_0) \approx 1/22$
- ② Strong Final State Interactions:  $\delta_0 - \delta_2 \approx 45^\circ$

## Direct $C/P$

$$\varepsilon'_K = \frac{-i}{\sqrt{2}} e^{i(\delta_2 - \delta_0)} \omega \left\{ \frac{\text{Im}(A_0)}{\text{Re}(A_0)} - \frac{\text{Im}(A_2)}{\text{Re}(A_2)} \right\}$$

- Subtle numerical balance between  $I = 0, 2$  contributions
- Claims of an  $\varepsilon'_K/\varepsilon_K$  anomaly are usually based on incorrect estimates without absorptive contributions:  $\text{Abs}(\mathcal{A}_{\Delta I}) = 0$  (Buras et al)

# Recent $K \rightarrow (\pi\pi)_I$ Lattice Results

Isospin limit:

RBC-UKQCD 1505.07863, 1502.00263

$\sqrt{\frac{3}{2}} \text{Re } A_2 = (1.50 \pm 0.04 \pm 0.14) \cdot 10^{-8} \text{ GeV}$	exp : $1.482(2) \cdot 10^{-8} \text{ GeV}$ 0.1 $\sigma$
$\sqrt{\frac{3}{2}} \text{Im } A_2 = -(6.99 \pm 0.20 \pm 0.84) \cdot 10^{-13} \text{ GeV}$	
$\sqrt{\frac{3}{2}} \text{Re } A_0 = (4.66 \pm 1.00 \pm 1.26) \cdot 10^{-7} \text{ GeV}$	exp : $3.112(1) \cdot 10^{-7} \text{ GeV}$ 1.0 $\sigma$
$\sqrt{\frac{3}{2}} \text{Im } A_0 = -(1.90 \pm 1.23 \pm 1.08) \cdot 10^{-11} \text{ GeV}$	
$\text{Re}(\varepsilon'/\varepsilon) = (1.38 \pm 5.15 \pm 4.59) \cdot 10^{-4}$	exp : $(16.6 \pm 2.3) \cdot 10^{-4}$ 2.1 $\sigma$
$\delta_0 = (23.8 \pm 4.9 \pm 1.2)^\circ$	exp : $(39.2 \pm 1.5)^\circ$ 2.9 $\sigma$
$\delta_2 = -(11.6 \pm 2.5 \pm 1.2)^\circ$	exp : $-(8.5 \pm 1.5)^\circ$ 1.0 $\sigma$

$\Delta I = 1/2$  Rule

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

Large phase shift

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

Ongoing lattice efforts to improve the pion dynamics. New results expected soon

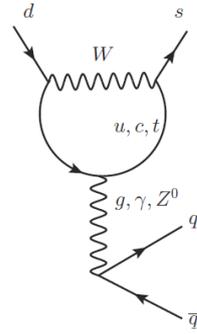
$$\text{Re}(\varepsilon'_K / \varepsilon_K)_{\text{SM}} = -\frac{\omega}{\sqrt{2} |\varepsilon_K|} \left[ \frac{\text{Im } A_0}{\text{Re } A_0} (1 - \Omega_{\text{eff}}) - \frac{\text{Im } A_2^{\text{emp}}}{\text{Re } A_2} \right] \approx 2.2 \cdot 10^{-3} \left\{ B_6^{(1/2)} (1 - \Omega_{\text{eff}})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

$$\Omega_{\text{eff}} = 0.060 \pm 0.077$$

Cirigliano-Ecker-Neufeld-Pich (2003)

# Effective Field Theory: Long & Short distance dynamics

$M_W$  
 $W, Z, \gamma, g$   
 $\tau, \mu, e, \nu_i$   
 $t, b, c, s, d, u$ 
 Standard Model

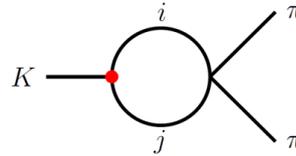


$$\mathcal{L}_{\text{eff}}^{\Delta S=1} = -\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \sum_i C_i(\mu) Q_i(\mu)$$

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

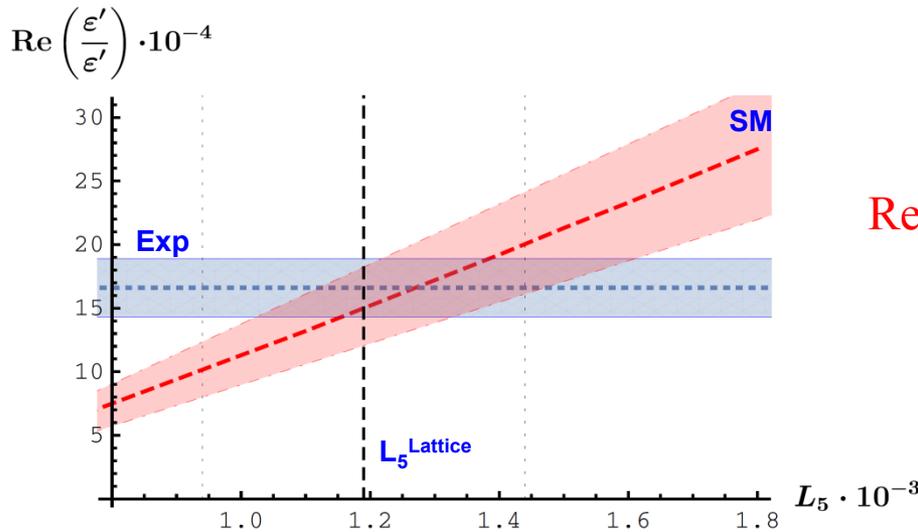
**Large logarithmic corrections**

$M_K$  
 $\gamma; \mu, e, \nu_i$   
 $\pi, K, \eta$ 
  $\chi\text{PT}$



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

**$\chi\text{PT}$ :**  $\log(\mu/m_\pi)$



Gisbert-Pich, arXiv:1712.06147

$$\begin{aligned} \text{Re}(\epsilon'_K / \epsilon_K)_{\text{SM}} &= (15 \pm 2_\mu \pm 2_{m_s} \pm 2_{\Omega_{\text{eff}}} \pm 6_{1/N_c}) \cdot 10^{-4} \\ &= (15 \pm 7) \cdot 10^{-4} \end{aligned}$$

**Large uncertainty, but no anomaly!**

# Possible Caveats / Constraints:

## 1) Saturation of inclusive decay width:

$$\text{Br}(B \rightarrow D^{**} \tau \nu) > 0.5\%$$

Freytsis et al, 1506.08896

▪  $R(D^{**}) \quad \Rightarrow \quad \text{Br}(B \rightarrow D \tau \nu) + \text{Br}(B \rightarrow D^* \tau \nu) = (2.39 \pm 0.13)\%$

▪  $\left. \begin{array}{l} \frac{\text{Br}(B \rightarrow X_c \tau \nu)}{\text{Br}(B \rightarrow X_c \ell \nu)} \Big|_{\text{OPE}} = 0.222 \pm 0.007 \\ \text{Br}(B \rightarrow X_c e \nu) = (10.8 \pm 0.4)\% \end{array} \right\} \Rightarrow \text{Br}(B \rightarrow X_c \tau \nu) = (2.40 \pm 0.12)\%$   
It is not a problem of form factors

▪ LEP:  $\text{Br}(b \rightarrow X \tau \nu) = (2.41 \pm 0.23)\%$

## 2) $b \rightarrow c \tau \nu \quad \leftrightarrow \quad b \bar{c} \rightarrow \tau \nu : \quad \text{Br}(B_c \rightarrow \tau \nu) < 10\%$ (30%, 40%)

Akeroyd-Chen, 1708.04072

Alonso et al, Celis et al

## 3) Differential distributions. Polarizations

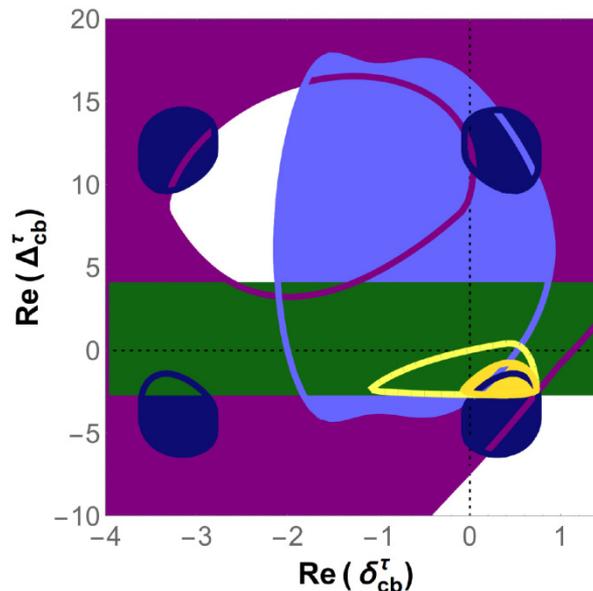
# Scalar contributions to $R(D^{(*)})$

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

Scalar Form Factors

$$\left\{ \begin{array}{l} \delta R(D) \longleftrightarrow \delta_{cb}^\ell \equiv (g_L^{cbl} + g_R^{cbl}) \frac{(m_B - m_D)^2}{m_\ell (\bar{m}_b - \bar{m}_c)} \\ \delta R(D^*) \longleftrightarrow \Delta_{cb}^\ell \equiv (g_L^{cbl} - g_R^{cbl}) \frac{m_B^2}{m_\ell (\bar{m}_b + \bar{m}_c)} \end{array} \right.$$

Real Couplings



95% CL

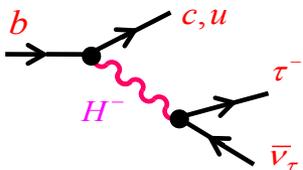
Celis et al, 1612.07757

$R(D^{(*)})$

$d R(D^{(*)}) / dq^2$

$R(X_c)$

$\text{Br}(B_c \rightarrow \tau \nu) < 40\%$



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

➔  $R_{J/\psi}/R_{J/\psi}^{\text{SM}} = R_D/R_D^{\text{SM}} = R_{D^*}/R_{D^*}^{\text{SM}}$

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

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

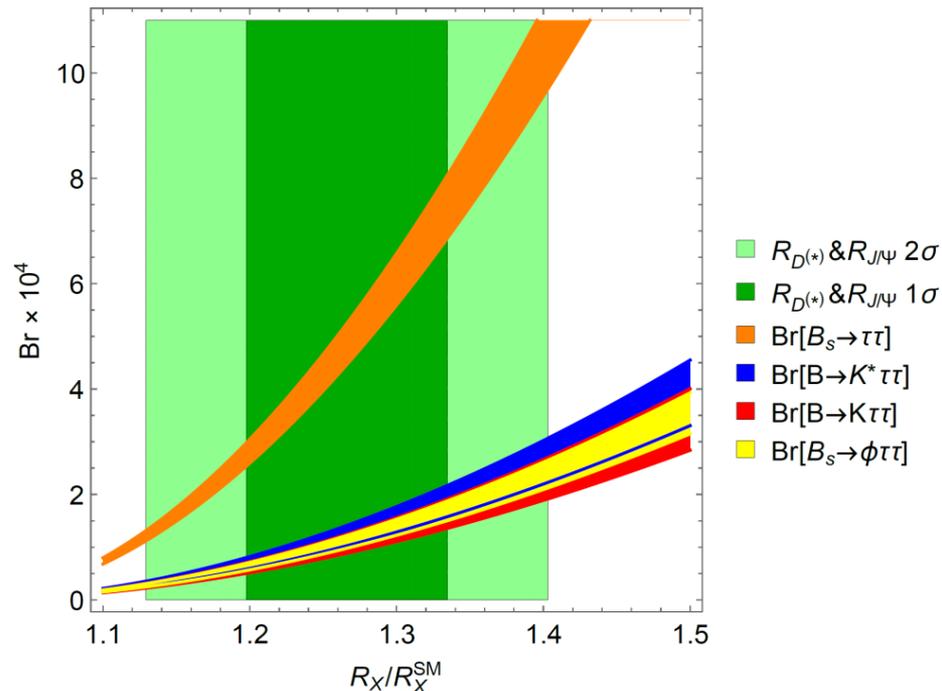
NP mainly coupled to 3<sup>rd</sup> family

➔ Large  $\text{Br}(b \rightarrow s\tau^+\tau^-)$

See also: Alonso et al, 1505.05164;

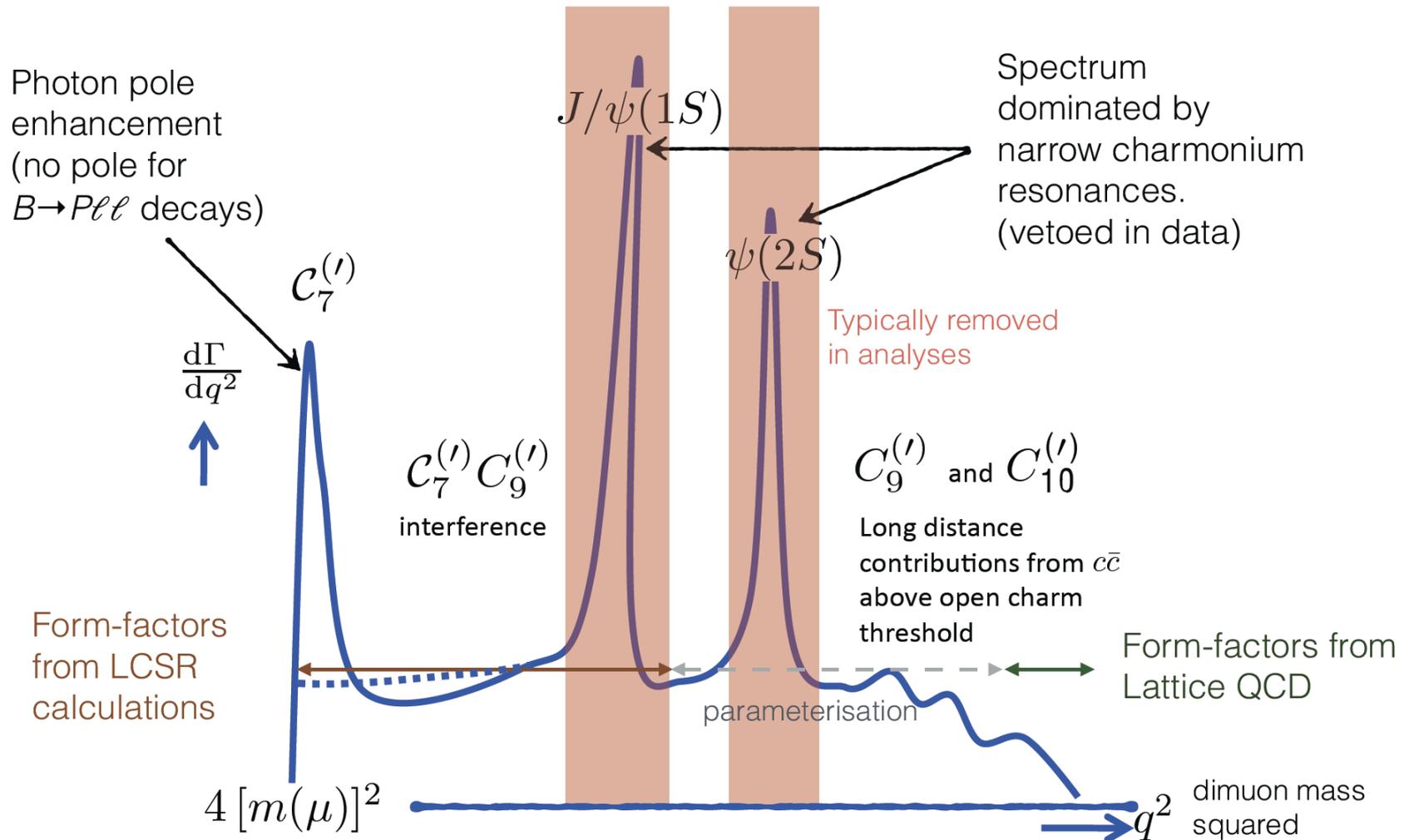
Buttazzo et al, 1706.07808; Crivellin et al, 1703.09226

But  $F_L(D^*) = F_L(D^*)_{\text{SM}} = 0.455 \pm 0.003$

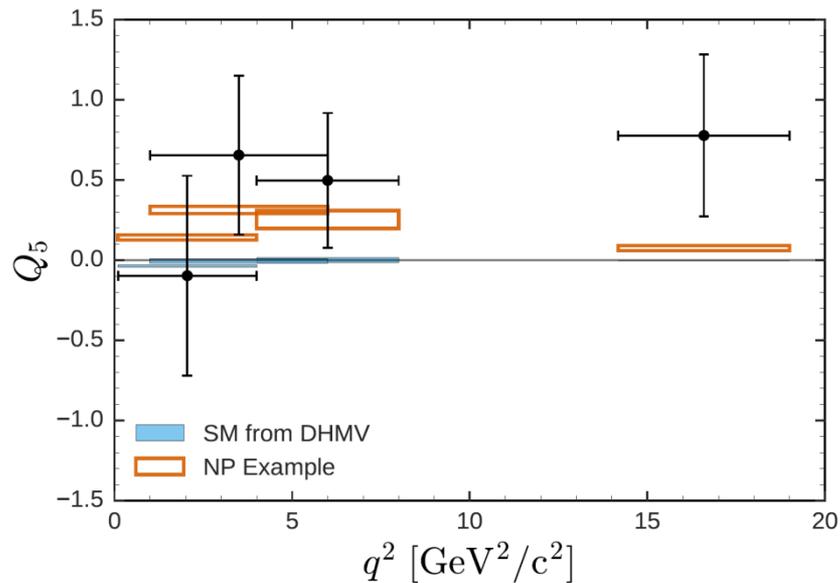
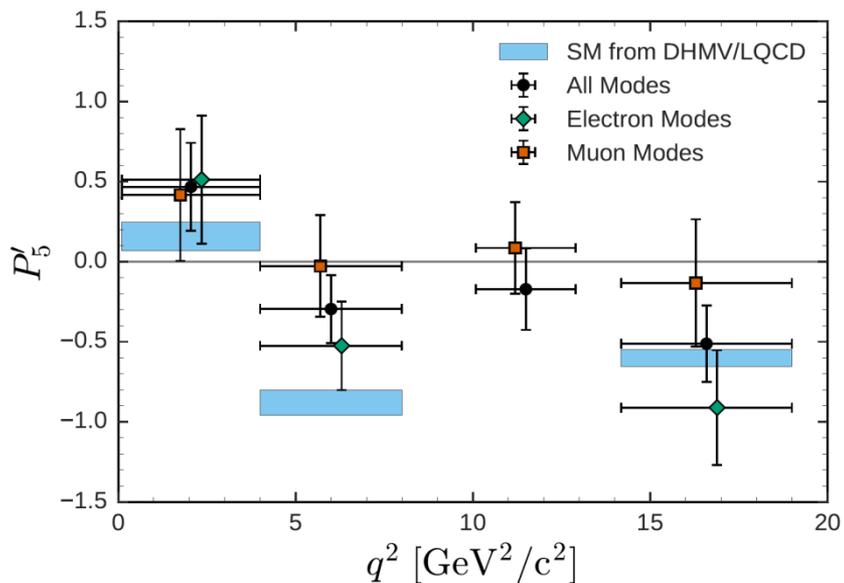
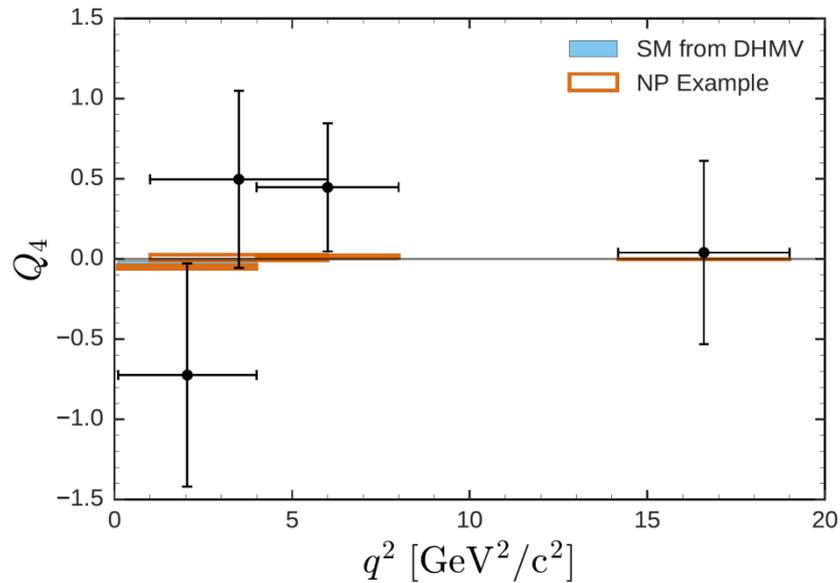
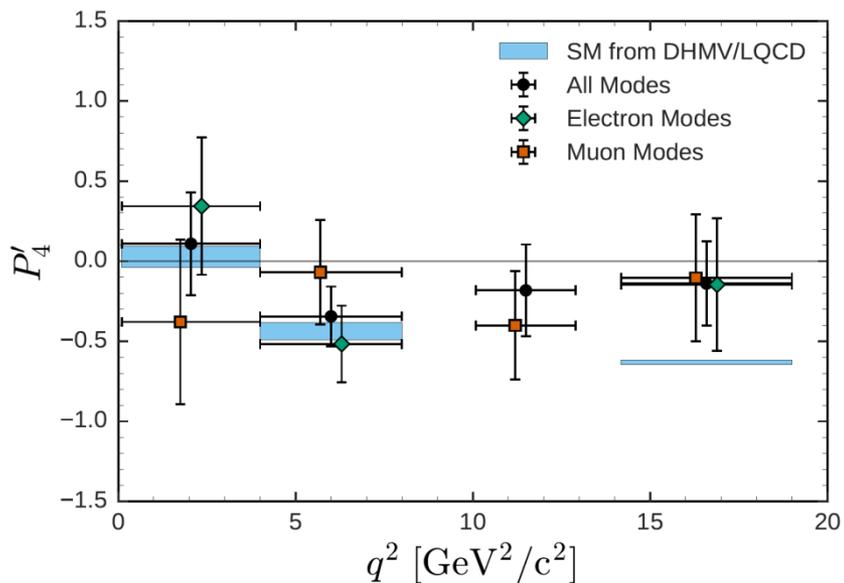


# Expected $B \rightarrow K \ell^+ \ell^-$ Spectrum

C. Marin, LHCb implications 2018

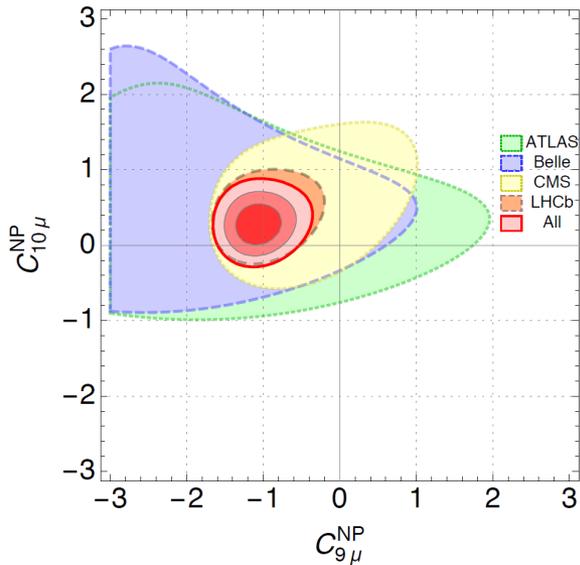


$$Q_i \equiv P_i^{\mu} - P_i^e$$

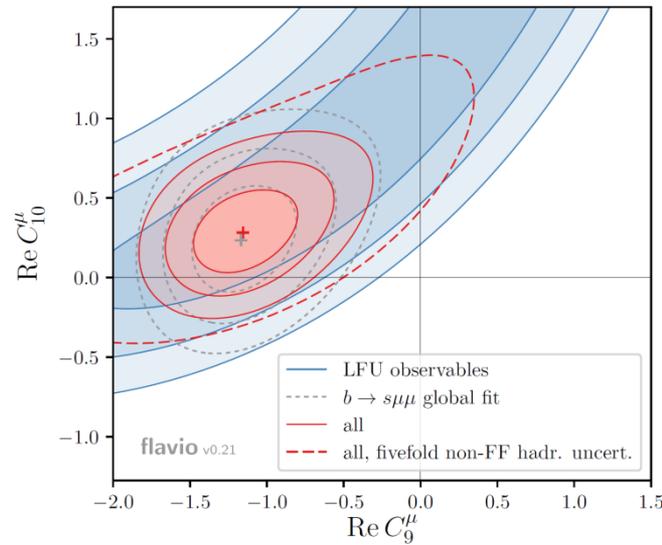


# New-Physics Fits with Effective Operators

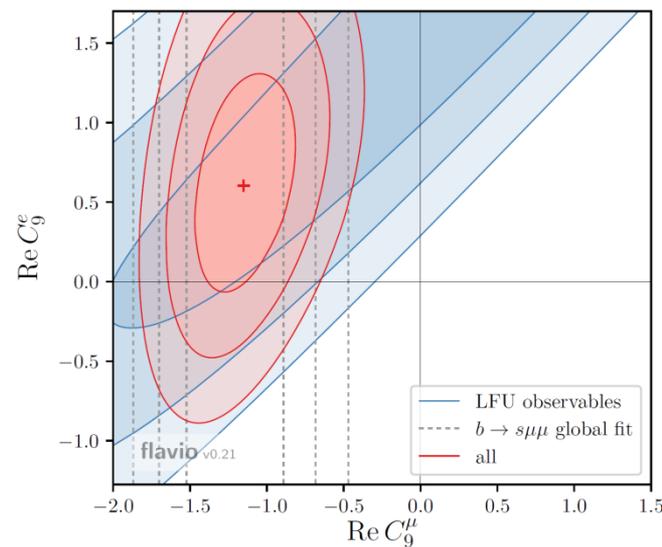
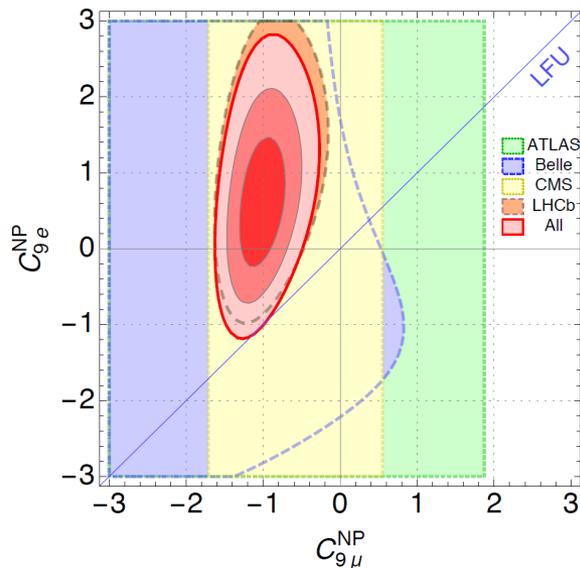
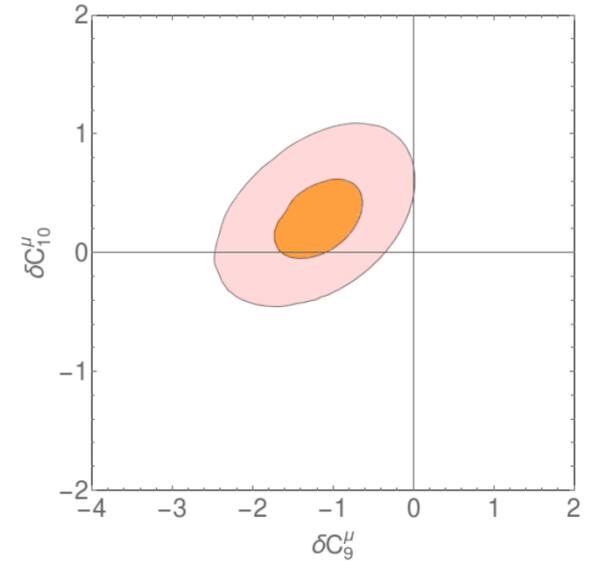
Capdevila et al, 1704.05340



Altmannshofer et al, 1704.05435



Geng et al, 1704.05446



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

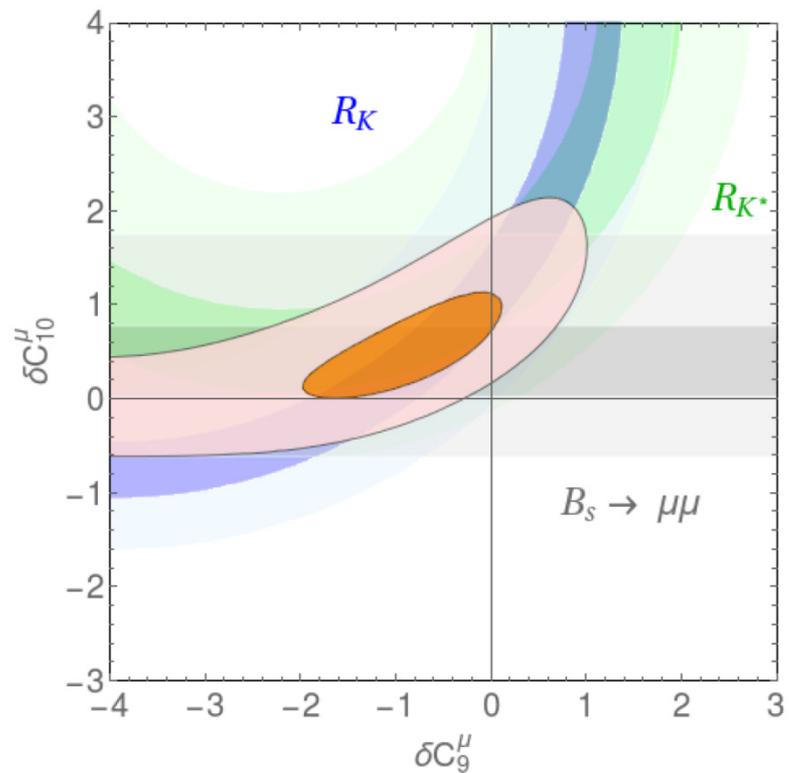
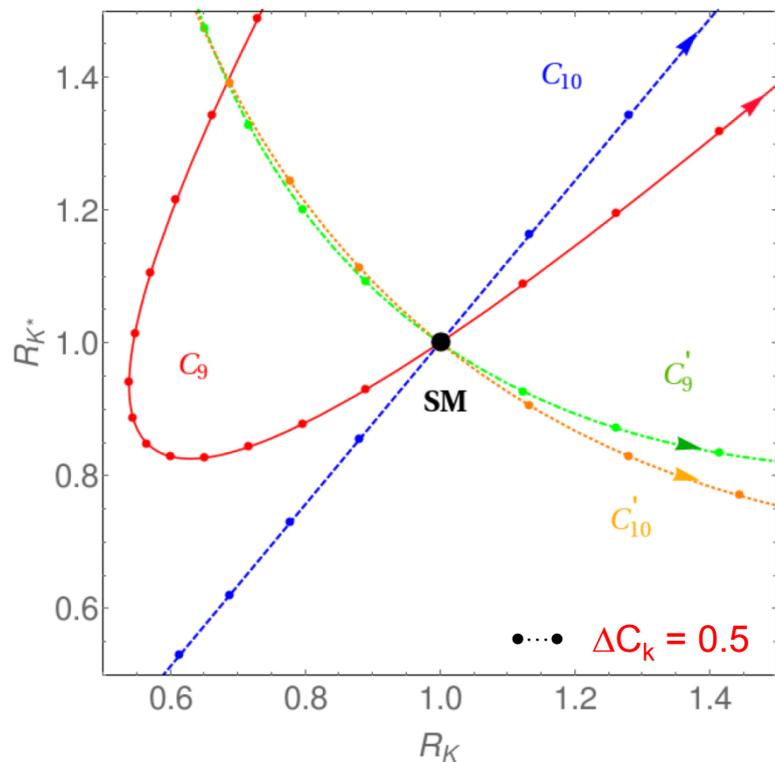
$$H_{\text{eff}}^{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{i,\ell} C_i^{\ell} O_i^{\ell}$$

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

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

Also: Hurth et al, 1705.06274; D'Amico et al, 1704.05438; Hiller-Nisandzic, 1704.05444; Ciuchini et al, 1704.05447; ...

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



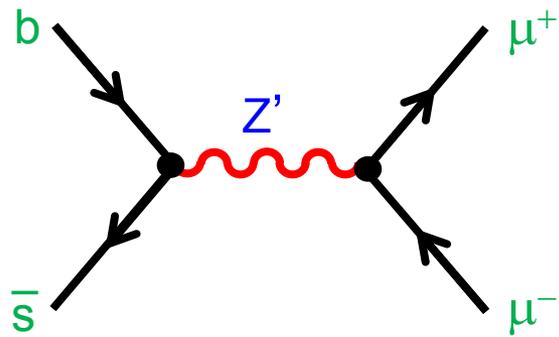
$$O_9^L = (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell)$$

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

$$O_9^R = (\bar{s} \gamma_\mu P_R b) (\bar{\ell} \gamma^\mu \ell)$$

$$O_{10}^R = (\bar{s} \gamma_\mu P_R b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

The  $B_s \rightarrow \mu\mu$  constraint on  $C_{10}$  gets weakened if (pseudo)scalar operators are included (Arbey et al, 1806.02791)

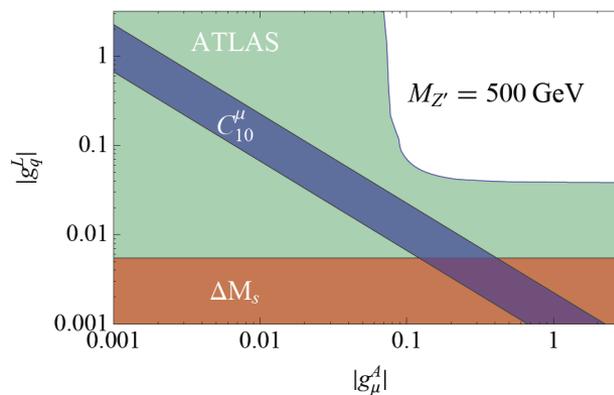
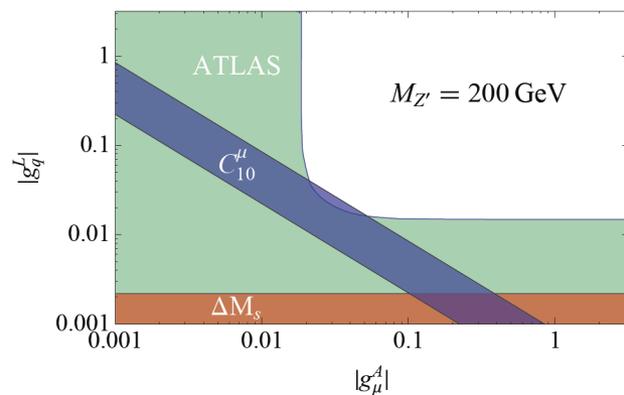
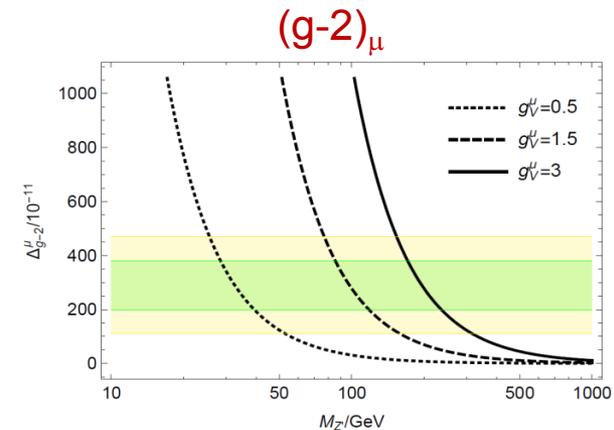
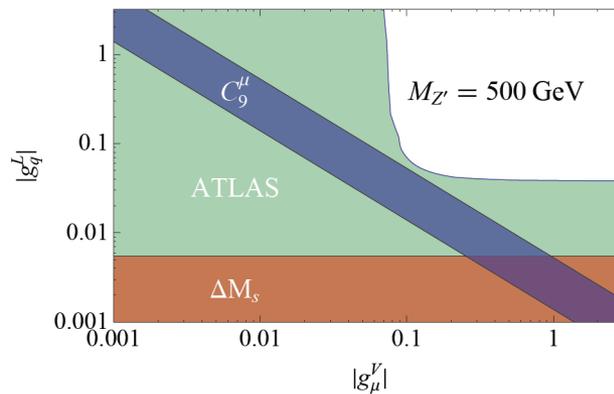
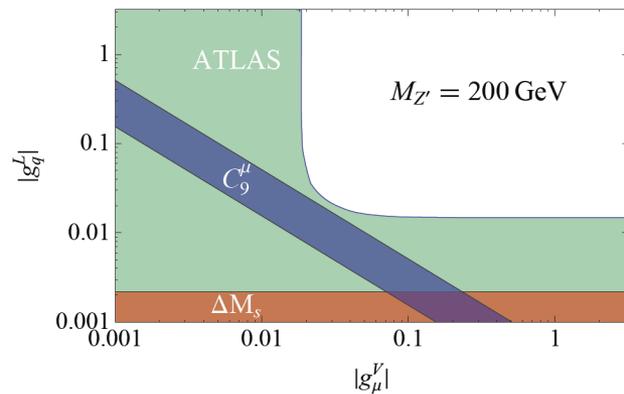


$$\mathcal{L} \supset \frac{g_2}{2c_W} Z'_\alpha \left\{ \left[ \bar{s} \gamma^\alpha (g_L^Q P_L + g_R^Q P_R) b + h.c. \right] + \bar{\ell} \gamma^\alpha (g_V^\ell + \gamma_5 g_A^\ell) \ell \right\}$$



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

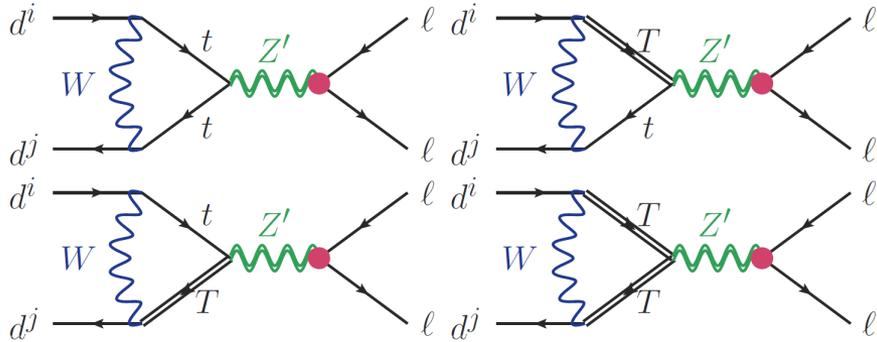
Di Chiara et al, 1704.06200



## Many possibilities:

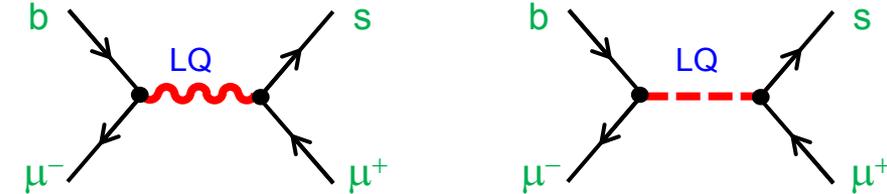
- $L_\mu - L_\tau$  Altmannshofer et al, ...
- $Z' + \text{VLQ}$  Kamenik et al
- Fermiophobic Falkowski et al
- Horizon. Sym. Guadagnoli et al
- ... Faisel-Tandean, ...

# More possibilities...



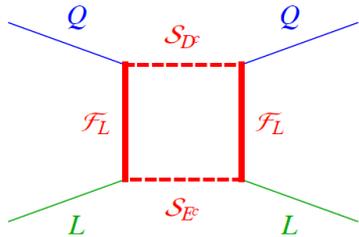
Flavour conserving  $Z'$

Kamenik et al, 1704.06005



Leptoquarks

Hiller-Schmaltz, 1408.1627; Bauer et al, 1511.01900;  
Hiller- Nisandzic, 1704.05444; D'Amico et al,  
1704.05438; Becirevic-Sumensari, 1704.05835; ...



New Fermions and Scalars

D'Amico et al, 1704.05438; ...

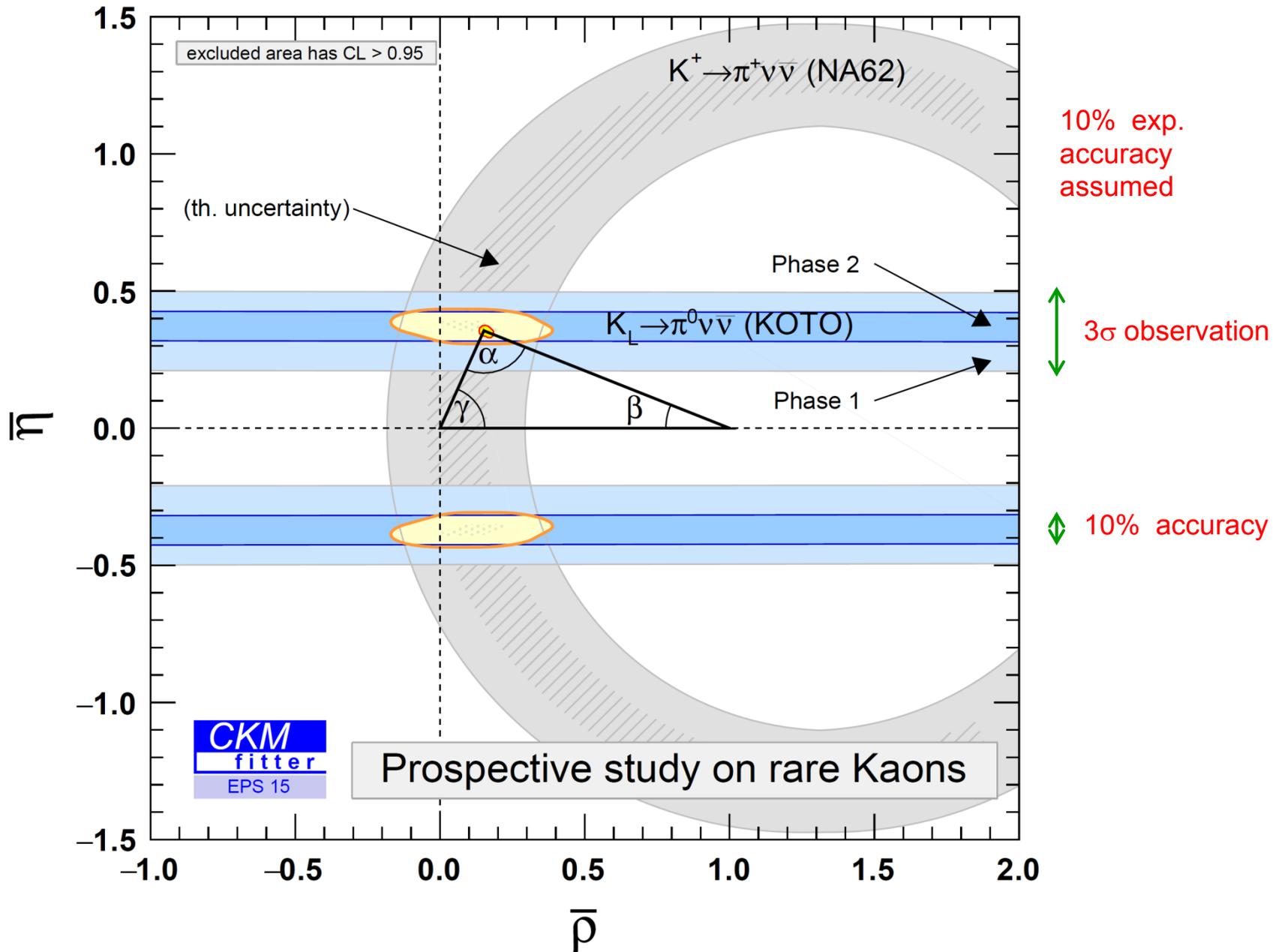
**LFUV**  $\rightarrow$  **LFV**

$$\mathcal{H}_{NP} = G \bar{b}'_L \gamma^\lambda b'_L \bar{\tau}'_L \gamma_\lambda \tau'_L$$

$$b'_L = \sum_{i=1}^3 U_{L3i}^d d_{Li}, \quad \tau'_L = \sum_{i=1}^3 U_{L3i}^\ell \ell_{Li}$$

Glashow-Guadagnoli-Lane, 1411.0565

$$\mathcal{B}(B^+ \rightarrow K^+ \mu^\pm e^\mp) \cong 2\rho_{NP}^2 \left| \frac{U_{L31}^\ell}{U_{L32}^\ell} \right|^2 \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) = (2.16_{-1.50}^{+2.54}) \left| \frac{U_{L31}^\ell}{U_{L32}^\ell} \right|^2 \times 10^{-8}$$



# T Violation @ Babar

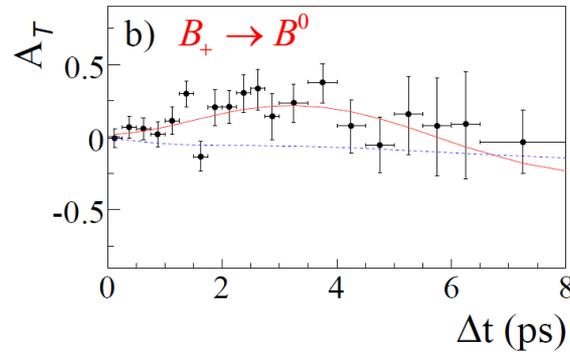
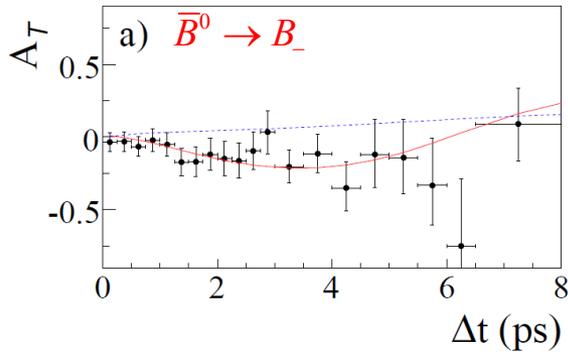
Quantum Entanglement

1207.5832

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

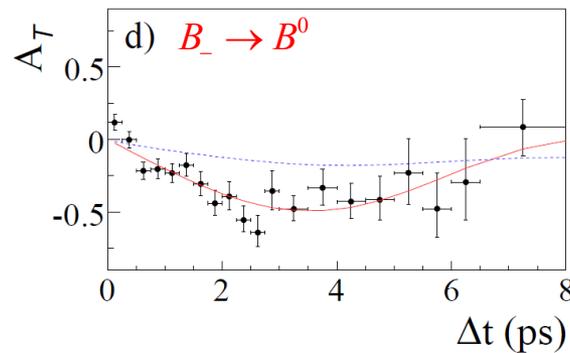
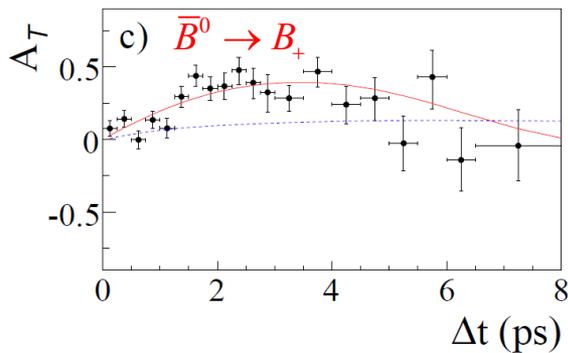
(Bañuls-Bernabeu-Martínez-Villanueva)

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



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

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



**T** established at  $14\sigma$