Flavour Physics

Antonio Pich

IFIC, Univ. Valencia - CSIC

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Flavour Structure of the Standard Model

$$\begin{pmatrix} u & \nu_e \\ d & e^- \end{pmatrix} , \quad \begin{pmatrix} c & \nu_\mu \\ s & \mu^- \end{pmatrix} , \quad \begin{pmatrix} t & \nu_\tau \\ b & \tau^- \end{pmatrix}$$

Why 3 ?

- **Pattern of masses**
- **Flavour Mixing,** $\not{CP}$

⟷

Related to SSB

Scalar Sector (Higgs)

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\overline{u}'_j, \overline{d}'_j\right)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] - \left(\overline{\nu}'_j, \overline{l}'_j\right)_L c^{(l)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

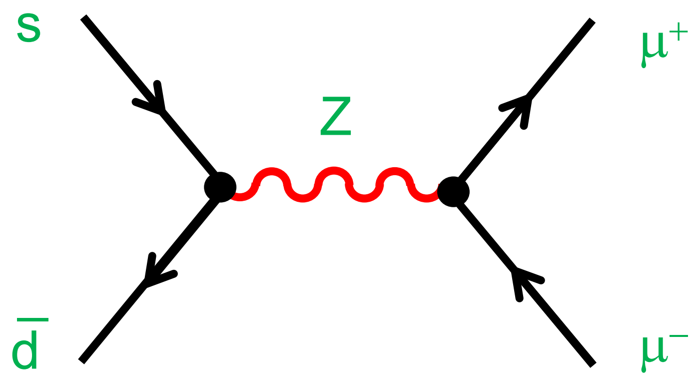
⟹ **SSB**

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\text{v}}\right) \left\{ \overline{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \overline{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \overline{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

$$\left[\mathbf{M}'_d \, , \mathbf{M}'_u \, , \mathbf{M}'_l \right]_{jk} = \left[c^{(d)}_{jk} \, , c^{(u)}_{jk} \, , c^{(l)}_{jk} \right] \frac{\text{v}}{\sqrt{2}}$$

Flavour Conserving Neutral Currents (GIM)

$$\mathcal{L}_{NC}^{Z} = -\frac{e}{2\sin\theta_W\cos\theta_W}\, Z_\mu \sum_f \bar{f}\,\gamma^\mu\,[v_f - a_f\,\gamma_5]\, f$$



NO

$\mathrm{Br}(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$, $\mathrm{Br}(K_S \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ (95% CL)

LHCb, 1706.00758

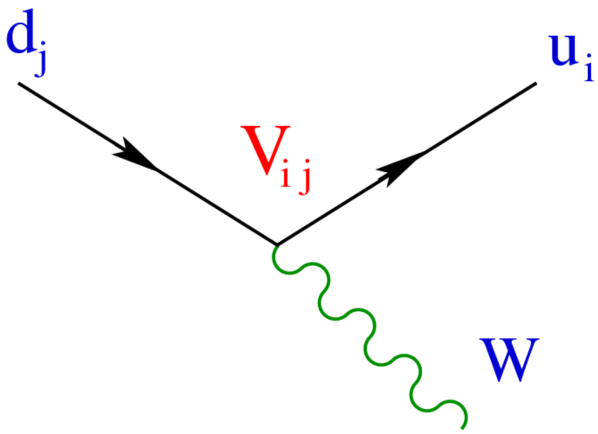
$$K_L \to \pi^{0*} \to (\gamma\gamma)^* \to \mu^+\mu^-$$

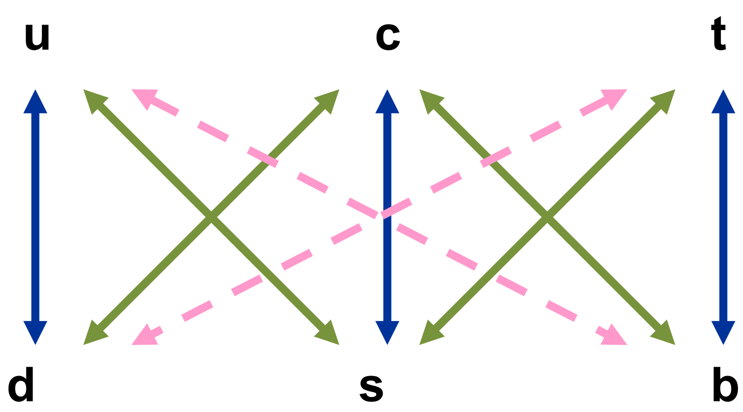
$$K_S \to (\pi^+\pi^-)^* \to (\gamma\gamma)^* \to \mu^+\mu^-$$

Flavour Changing Charged Currents

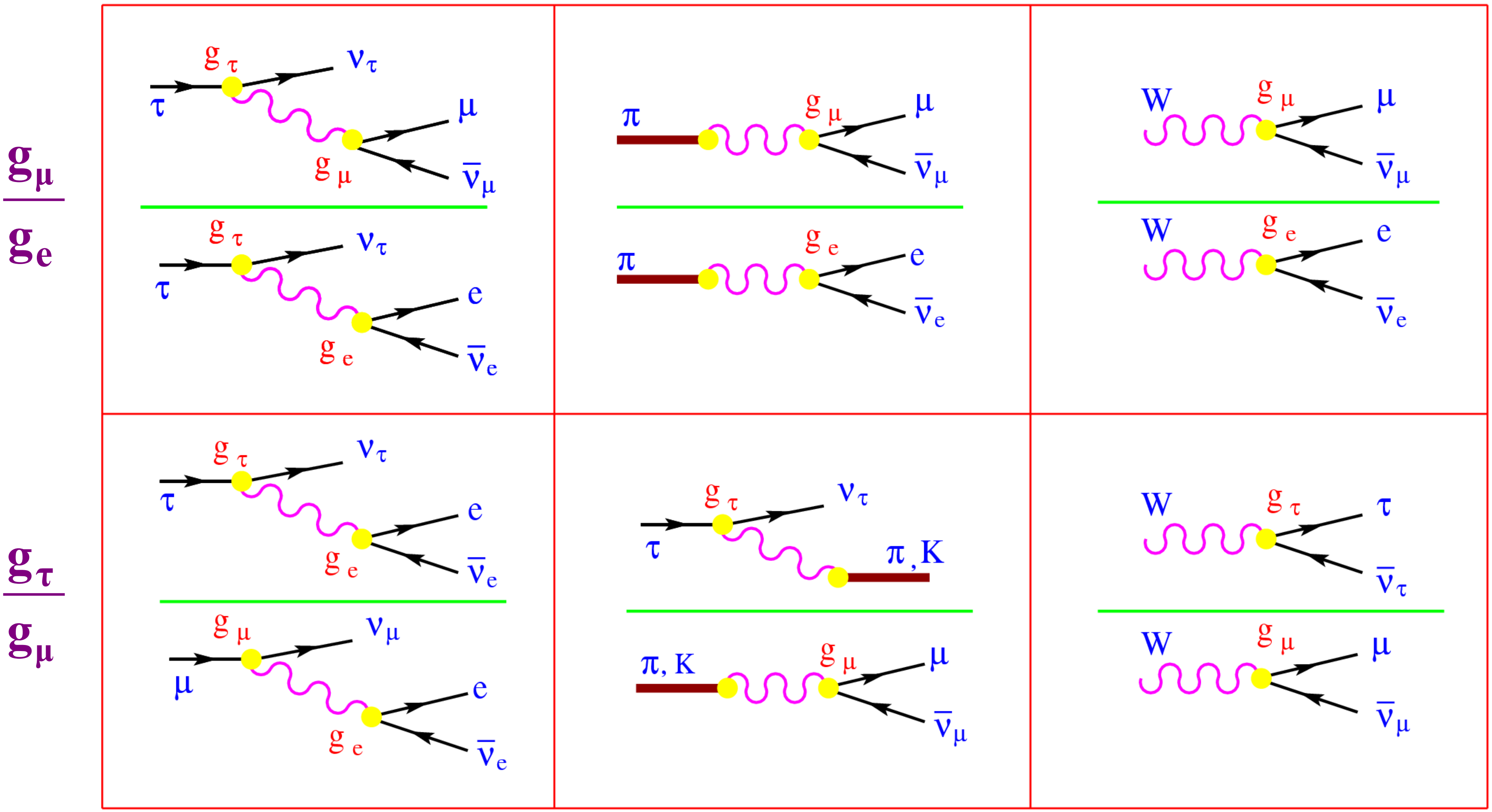
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5)\, l \right] + \text{h.c.}$$

$$\left(\bar{\nu}_{l_j} \equiv \bar{\nu}_i \;\; \mathbf{V}_{ij}^{(l)} \right)$$





LEPTON UNIVERSALITY



CHARGED CURRENT UNIVERSALITY

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	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

$|g_\tau / g_\mu|$

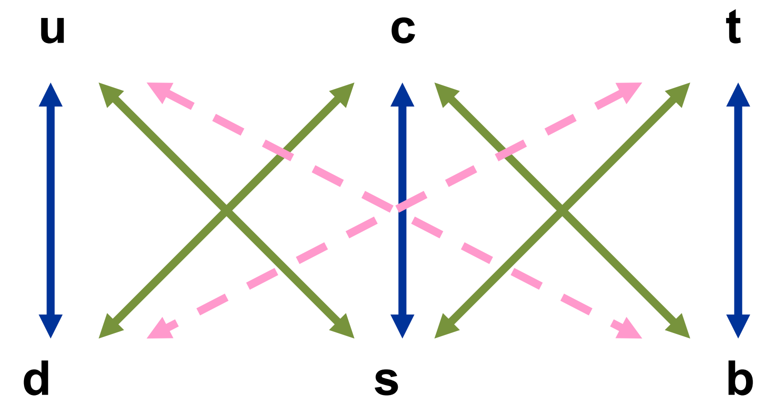
$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

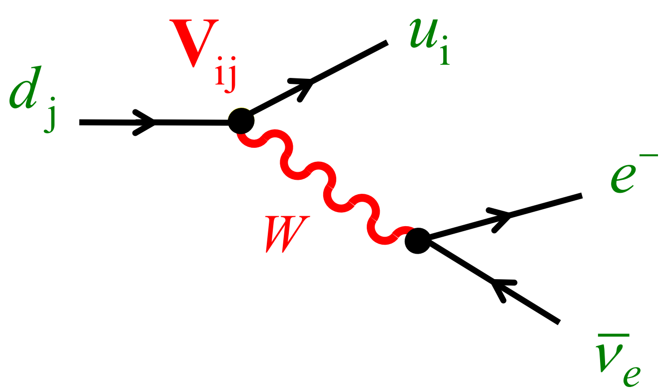
$|g_\tau / g_e|$

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

A. Pich, arXiv:1310.7922

Flavour Changing Charged Currents



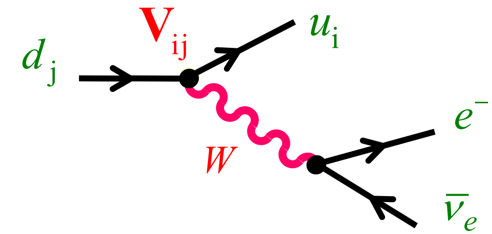


$$\Gamma(d_j \to u_i\, e^-\, \bar{\nu}_e) \propto \left|\mathbf{V}_{ij}\right|^2$$

We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

V_{ij} Determination $(0^- \to 0^-)$



$K \to \pi \ell \nu$, $D \to K \ell \nu \ldots$

$$\langle P'(k') | \bar{u}_i \gamma^\mu d_j | P(k) \rangle = C_{PP'} \left\{ (k+k')^\mu \, f_+(q^2) + (k-k')^\mu \, f_-(q^2) \right\}$$

$$\Gamma(P \to P' l \nu) = \frac{G_F^2 M_P^5}{192 \pi^3} \, |\mathbf{V_{ij}}|^2 \, C_{PP'}^2 \, |f_+(0)|^2 \, \mathbf{I} \, (1 + \delta_{RC})$$

$$\mathbf{I} \approx \int_0^{(M_P - M_{P'})^2} \frac{dq^2}{M_P^8} \, \lambda^{3/2}(q^2, M_P^2, M_{P'}^2) \left| \frac{f_+(q^2)}{f_+(0)} \right|^2$$

$f_-(q^2)$ suppressed

$(k-k')^\mu \; \bar{l} \gamma_\mu (1-\gamma_5) \nu_l \sim m_l$

- Measure the q^2 distribution ➡ $\mathbf{I}$
- Measure Γ ➡ $f_+(0) \, |\mathbf{V_{ij}}|$
- Get a theoretical prediction for $f_+(0)$ ➡ $|\mathbf{V_{ij}}|$

Theory is always needed: Symmetries

$|V_{ud}|$

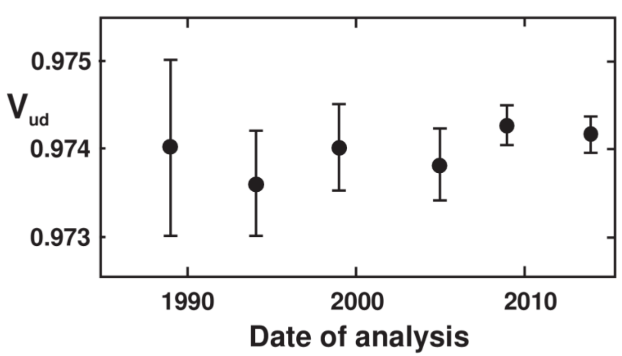
$$f_+(0) = 1 + O[(m_u - m_d)^2]$$

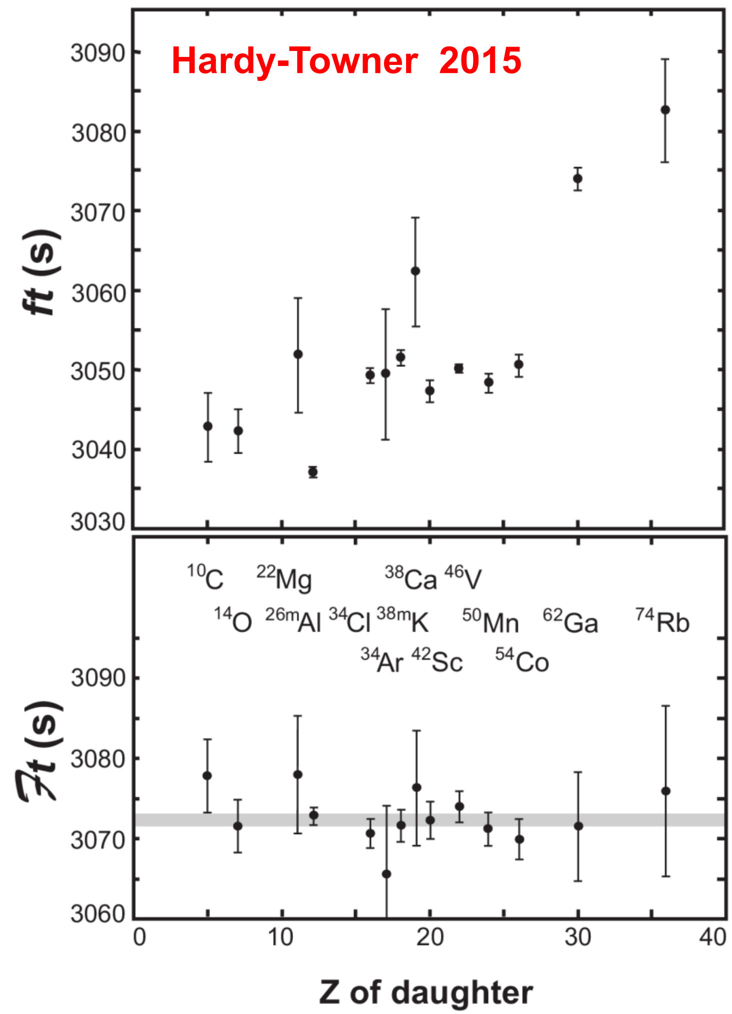
Superallowed Nuclear β Transitions $(0^+ \to 0^+)$

$$|V_{ud}|^2 = \frac{\pi^3 \ln 2}{ft\, G_F^2 m_e^5\, (1+\delta_{RC})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\, (1+\delta_{RC})}$$

(Marciano – Sirlin)

$$|V_{ud}| = 0.97417 \pm 0.00021$$

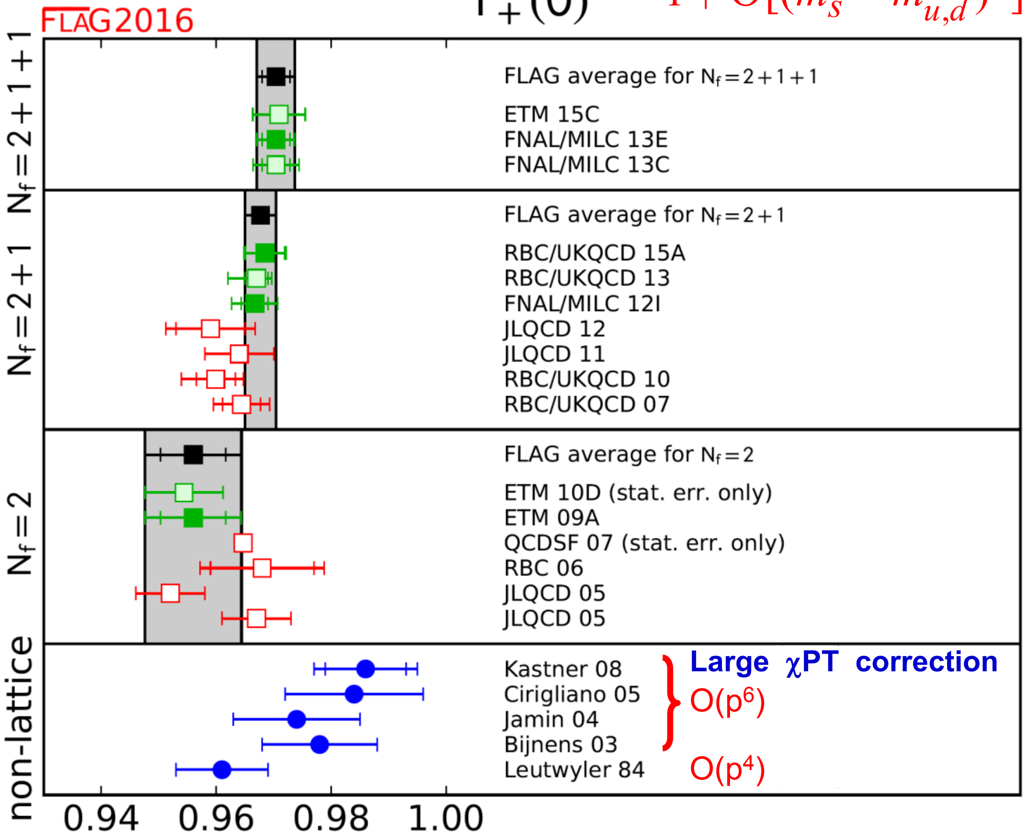


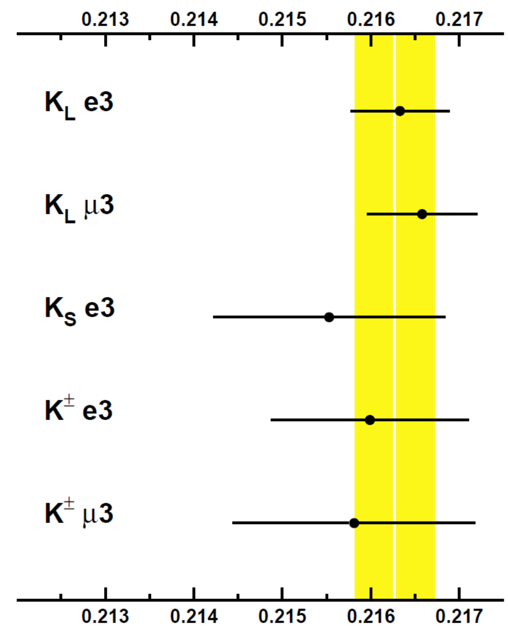


$K \to \pi \ell \nu$ Decays

Flavianet, arXiv:1005.2323 [hep-ph]
Moulson, arXiv:1411.5252 [hep-ph]

$$f_+(0) = 1 + O[(m_s - m_{u,d})^2]$$





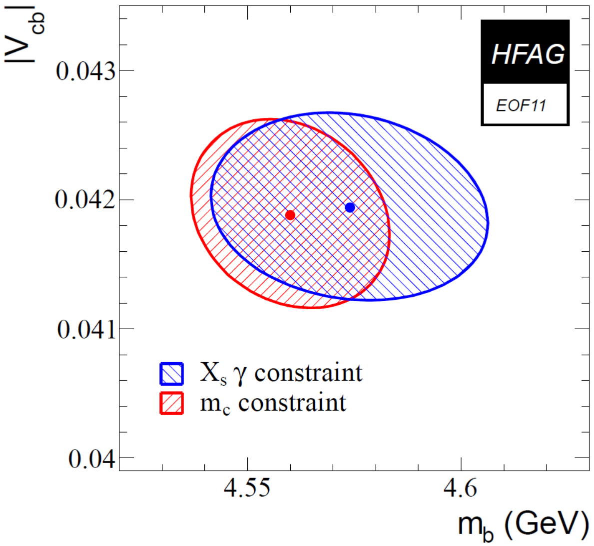
$$|f_+(0)\, V_{us}| = 0.2165 \pm 0.0004$$

2012 :	$f_+(0) = 0.959 \pm 0.005$	→	$|V_{us}| = 0.2255 \pm 0.0014$
2016 :	$f_+(0) = 0.970 \pm 0.003$	→	$|V_{us}| = 0.2232 \pm 0.0008$

Inclusive B Decays (OPE, HQET)

$$\Gamma(\bar{B} \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \left\{ f(\rho) + k(\rho) \frac{\mu_\pi^2}{2m_b^2} + g(\rho) \frac{\mu_G^2}{2m_b^2} \right\}$$

$\rho = m_c/m_b$



Fits to lepton energy, hadronic invariant mass and photon energy moments

HFAG 2016: $|V_{cb}|_{incl} = \begin{cases} (42.19 \pm 0.78) \cdot 10^{-3} & \text{Kinetic mass} \\ (41.98 \pm 0.45) \cdot 10^{-3} & \text{1S mass} \end{cases}$

PDG 2016: $|V_{cb}|_{incl} = (42.2 \pm 0.8) \cdot 10^{-3}$

Gambino- Healey-Turczyk, 1606.06174

Higher Power Corrections

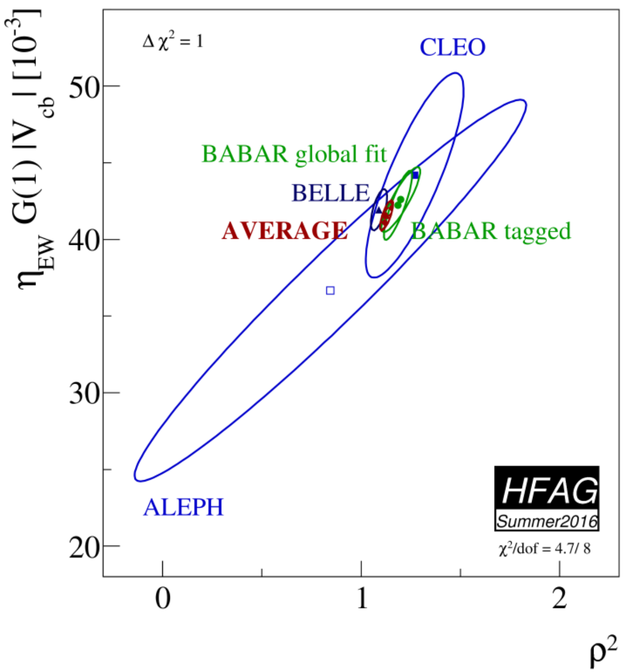
$$|V_{cb}| = (42.00 \pm 0.63) \times 10^{-3}$$

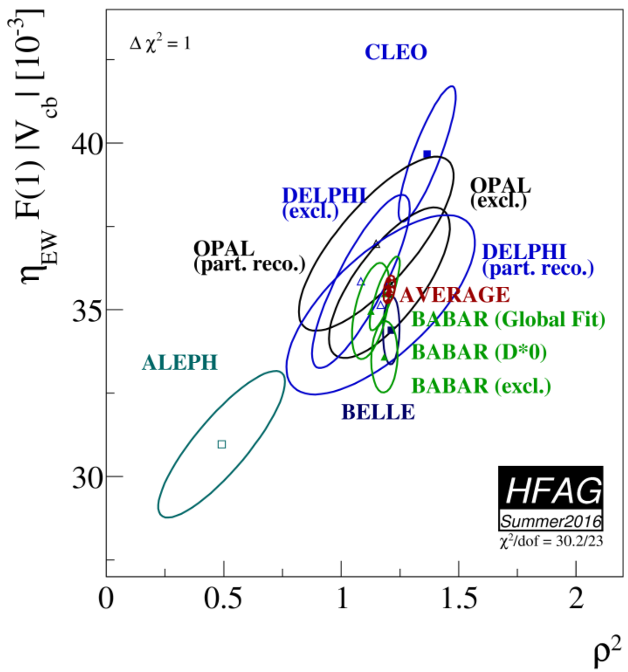
$B \to D \ell \nu$ $B \to D^* \ell \nu$

QCD Symmetries at $1/M_Q \to 0$

HQET

Caprini-Lellouch-Neubert parametrization





$$\eta_{EW}\, G(1)\, |\mathbf{V_{cb}}| = (41.57 \pm 1.00) \cdot 10^{-3}$$

$$\eta_{EW}\, F(1)\, |\mathbf{V_{cb}}| = (35.61 \pm 0.43) \cdot 10^{-3}$$

FNAL / MILC :

$$\eta_{EW}\, G(1) = 1.061 \pm 0.010 \quad \Rightarrow \quad |\mathbf{V_{cb}}| = (39.18 \pm 0.94_{exp} \pm 0.36_{th}) \cdot 10^{-3}$$

$$\eta_{EW}\, F(1) = 0.912 \pm 0.014 \quad \Rightarrow \quad |\mathbf{V_{cb}}| = (39.05 \pm 0.47_{exp} \pm 0.58_{th}) \cdot 10^{-3}$$

$$\Rightarrow \quad \boxed{|\mathbf{V_{cb}}|_{excl} = (39.10 \pm 0.60) \cdot 10^{-3}}$$

3.3 σ discrepancy with inclusive measurement

Parametrization Dependence

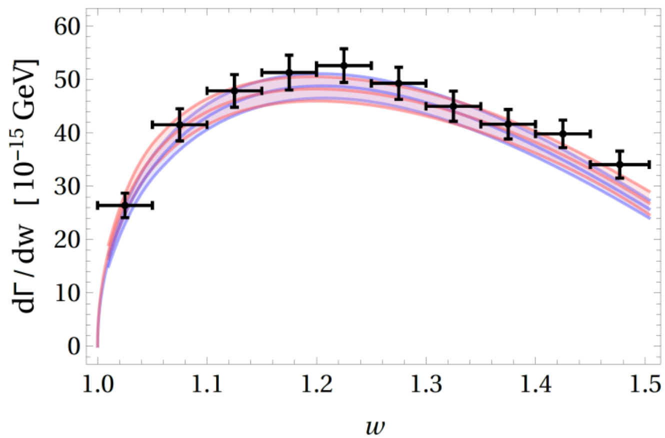
Analyticity, Unitarity
Crossing Symmetry →

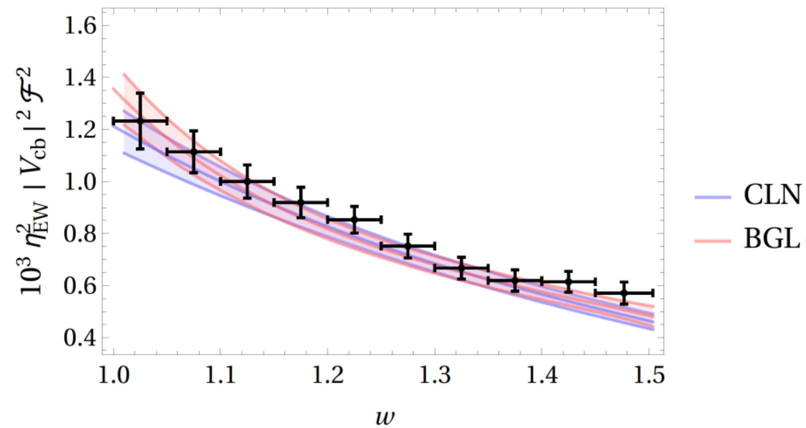
- Boyd-Grinstein-Lebed (BGL)
- Caprini-Lellouch-Neubert (CLN) (HQET relations valid within 2%)

● $B \to D^* \ell \nu$

Belle data (1702.01521) + Lattice + LCSRs

Bigi-Gambino-Schacht, 1703.06124, 1707.09509



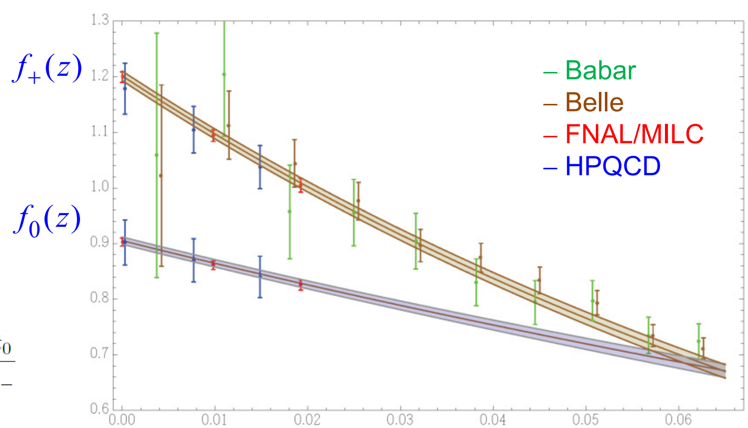


$10^{-3} \cdot \lvert V_{cb} \rvert$
39.2 ± 1.1
40.6 ± 1.3

$w = v_B \cdot v_D$

See also Grinstein-Kobach, 1703.08170; Bernlochner-Ligeti-Papucci-Robinson, 1703.05330, 1708.07134

● $B \to D \ell \nu$



Bigi-Gambino-Schacht, 1606.08030

$$|V_{cb}| = (40.49 \pm 0.97) \cdot 10^{-3}$$

$$t_+ = (m_B + m_D)^2, \qquad t_- = (m_B - m_D)^2,$$

$$z(w, \mathcal{N}) = \frac{\sqrt{1+w} - \sqrt{2\mathcal{N}}}{\sqrt{1+w} + \sqrt{2\mathcal{N}}}, \qquad \mathcal{N} = \frac{t_+ - t_0}{t_+ - t_-}$$

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\|V_{ud}\|$	**0.97417 ± 0.00021** 0.9758 ± 0.0016 0.9749 ± 0.0026	Nuclear β decay $n \to p e^- \bar{\nu}_e$ $\pi^+ \to \pi^0 e^+ \nu_e$
$\|V_{us}\|$	**0.2232 ± 0.0008** 0.2253 ± 0.0007 0.2213 ± 0.0023	$K \to \pi e^- \bar{\nu}_e$ $K/\pi \to \mu\nu$, Lattice, V_{ud} τ decays
$\|V_{cd}\|$	0.230 ± 0.011 **0.216 ± 0.005**	$\nu d \to c X$ $D \to (\pi) l \nu$, Lattice
$\|V_{cs}\|$	**0.997 ± 0.017**	$D \to K l \nu$, $D_s \to l \nu$, Lattice
$\|V_{cb}\|$	0.0405 ± 0.0010 **0.0420 ± 0.0006**	$B \to D^* l \bar{\nu}_l$, $D l \bar{\nu}_l$ $b \to c l \bar{\nu}_l$
$\|V_{ub}\|$	0.00367 ± 0.00015 0.00451 ± 0.00020 **0.00398 ± 0.00040**	$B \to \pi l \bar{\nu}_l$ $b \to u l \bar{\nu}_l$
$\|V_{tb}\| / \sqrt{\sum_q \|V_{tq}\|^2}$ $\|V_{tb}\|$	> 0.92 (95% CL) **1.009 ± 0.031**	$t \to bW / t \to qW$ $p\bar{p} \to tb + X$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \mathbf{0.9988 \pm 0.0005}$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = \mathbf{1.020 \pm 0.063}$$

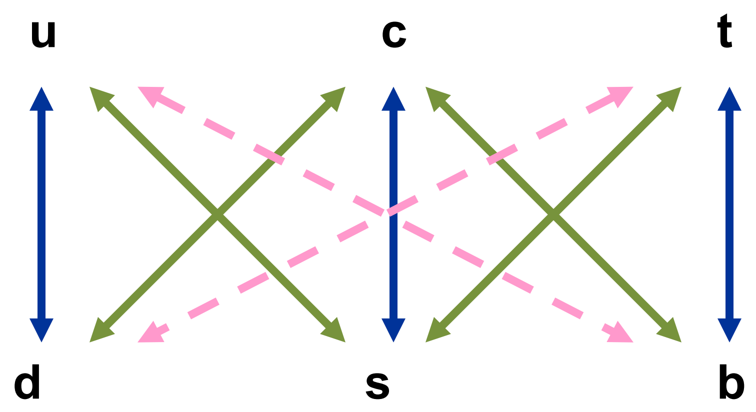
$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = \mathbf{1.042 \pm 0.034}$$

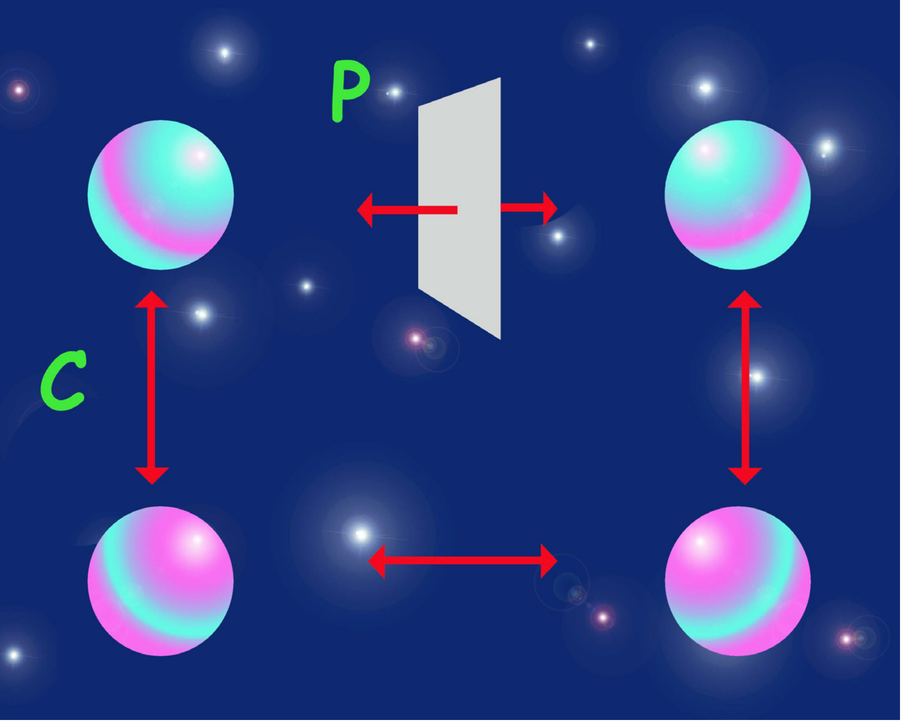
$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = \mathbf{2.002 \pm 0.027} \quad \text{(LEP)}$$

Hierarchical Structure

$$\mathbf{V} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \approx \sin\theta_C \approx 0.223 \quad ; \quad A \approx 0.84 \quad ; \quad \sqrt{\rho^2+\eta^2} \approx 0.4$$





- $\mathcal{C}, \mathcal{P}$: Violated maximally in weak inter.
- $\mathcal{CP}$: Symmetry of nearly all phenom.
- Slight (~0.2%) $\not{\mathcal{CP}}$ in K^0 decays (1964)
- Sizeable $\not{\mathcal{CP}}$ in B^0 decays (2001)
- Huge Matter - Antimatter Asymmetry

  ➡ Baryogenesis

$\mathcal{CPT}$ **Theorem:**	$\not{\mathcal{CP}} \Longleftrightarrow \not{\mathcal{T}}$

Thus, $\not{\mathcal{CP}}$ requires:

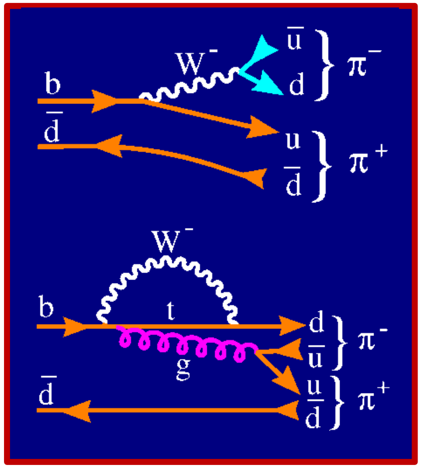
- Complex Phases
- Interferences

Standard Model $\not{\mathcal{CP}}$: 3 fermion families needed

DIRECT $\not{\mathcal{CP}}$

$$\left|\mathbf{T}\left(\mathrm{P}\to \mathrm{f}\right)\right| \neq \left|\mathbf{T}\left(\overline{\mathrm{P}}\to \overline{\mathrm{f}}\right)\right|$$

$\overline{B}_d^0$



$$\mathbf{T}\left(\mathrm{P}\to \mathrm{f}\right) = \mathrm{T}_1\, e^{i\phi_1}\, e^{i\delta_1} + \mathrm{T}_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$\mathcal{CP}$

$$\mathbf{T}\left(\overline{\mathrm{P}}\to \overline{\mathrm{f}}\right) = \mathrm{T}_1\, e^{-i\phi_1}\, e^{i\delta_1} + \mathrm{T}_2\, e^{-i\phi_2}\, e^{i\delta_2}$$

$$A^{\mathrm{CP}}_{\mathrm{P}\to\mathrm{f}} \equiv \frac{\Gamma\left(\mathrm{P}\to \mathrm{f}\right) - \Gamma\left(\overline{\mathrm{P}}\to \overline{\mathrm{f}}\right)}{\Gamma\left(\mathrm{P}\to \mathrm{f}\right) + \Gamma\left(\overline{\mathrm{P}}\to \overline{\mathrm{f}}\right)} = \frac{-2\,\mathrm{T}_1\,\mathrm{T}_2\,\sin(\phi_2-\phi_1)\,\sin(\delta_2-\delta_1)}{\mathrm{T}_1^{\,2} + \mathrm{T}_2^{\,2} + 2\,\mathrm{T}_1\,\mathrm{T}_2\,\cos(\phi_2-\phi_1)\,\cos(\delta_2-\delta_1)}$$

One needs:

- **2 Interfering Amplitudes**
- **2 Different Weak Phases** $\left[\sin(\phi_2-\phi_1)\neq 0\right]$
- **2 Different FSI Phases** $\left[\sin(\delta_2-\delta_1)\neq 0\right]$

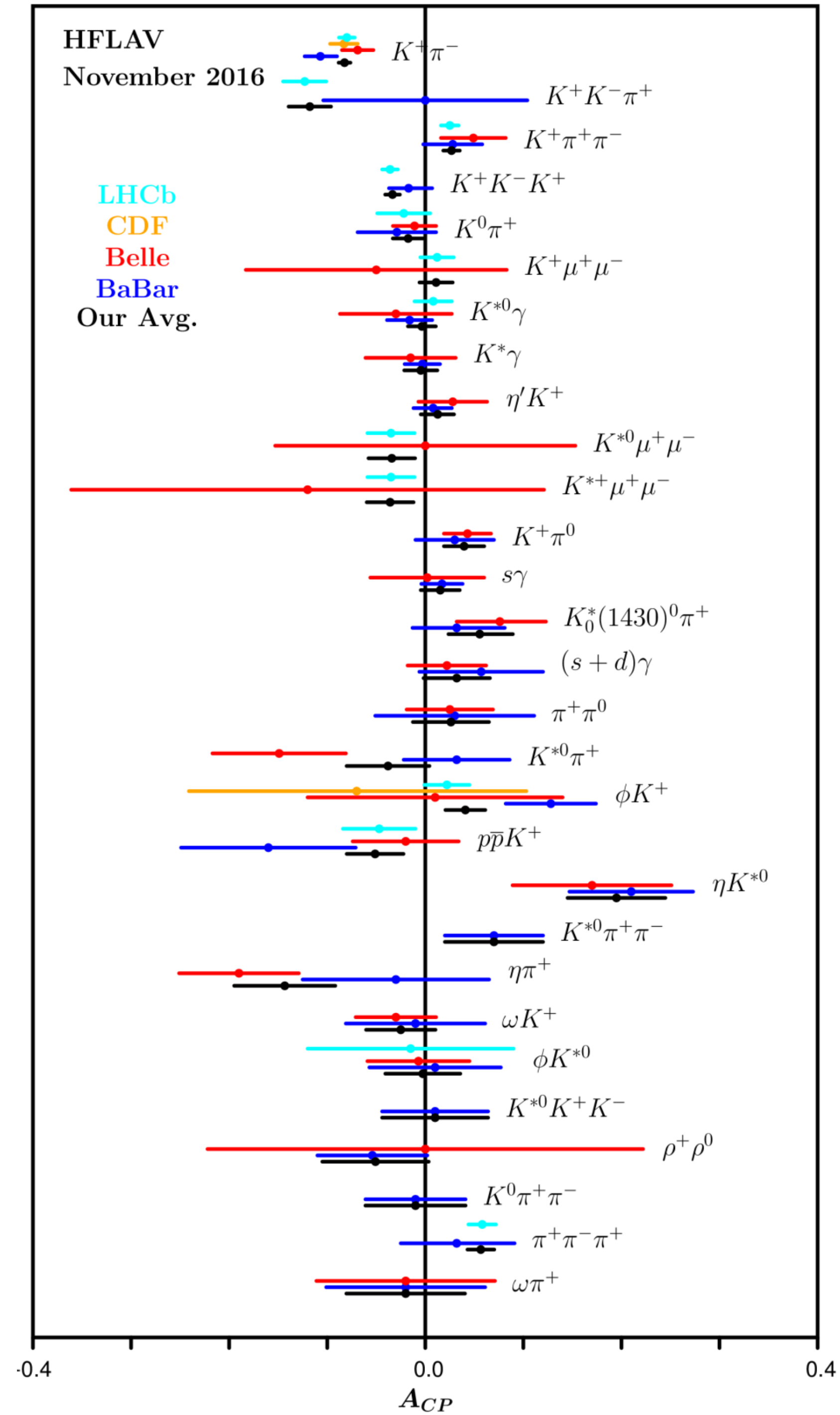
DIRECT $\not{CP}$

$$A_{CP}(B \to f) \equiv \frac{\mathrm{Br}(\bar{B} \to \bar{f}) - \mathrm{Br}(B \to f)}{\mathrm{Br}(\bar{B} \to \bar{f}) + \mathrm{Br}(B \to f)}$$

$$A_{CP}(B_d^0 \to \pi^- K^+) = -0.082 \pm 0.006 \qquad \textbf{(13.7 σ)}$$

$$A(B_s^0 \to \pi^- K^+) = -0.26 \pm 0.04 \qquad \textbf{(6.5 σ)}$$

$$A_{CP}(B^+ \to K^+ K^- \pi^+) = -0.118 \pm 0.022 \qquad \textbf{(5.4 σ)}$$

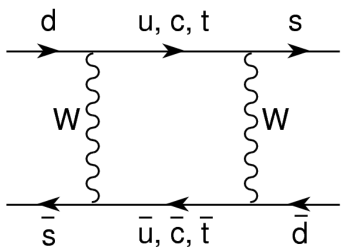


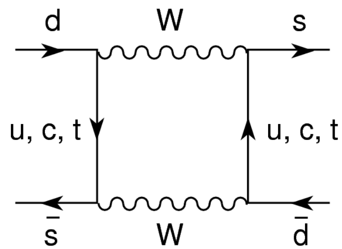
Large & Interesting Signals

Big challenge: Get reliable SM predictions

Severe hadronic uncertainties

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING





$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$\langle \bar{K}^0 | \mathbf{H} | K^0 \rangle \sim \sum_{ij} \lambda_i \lambda_j \; S(r_i, r_j)\; \eta_{ij} \;\; \langle O_{\Delta S=2} \rangle$$

$$\langle O_{\Delta S=2} \rangle = \alpha_s(\mu)^{-2/9} \langle \bar{K}^0 | (\bar{s}_L \gamma^\alpha d_L)(\bar{s}_L \gamma_\alpha d_L) | K^0 \rangle \equiv \left(\frac{4}{3} M_K^2 f_K^2\right) \hat{B}_K$$

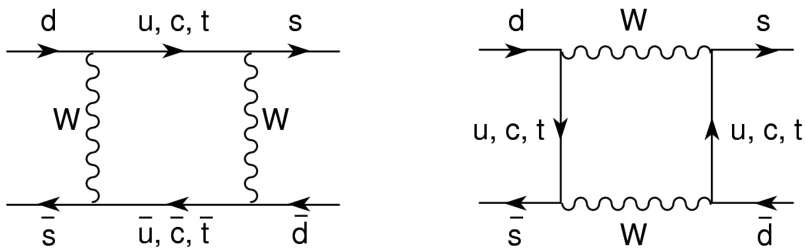
$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \qquad (i = u, c, t)$$

- **GIM Mechanism:** $\lambda_u + \lambda_c + \lambda_t = 0$

$$\left(M_{K_L} - M_{K_S}\right) / M_{K^0} = (7.00 \pm 0.01) \times 10^{-15}$$

- $\mathcal{CP}$ **:** $\mathrm{Im}\,\lambda_t = -\,\mathrm{Im}\,\lambda_c \simeq \eta \lambda^5 A^2$
- **Hard GIM Breaking:** $S(r_i, r_i) \sim r_i$ ➡ **t quark**

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING



$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$K^0 \to \pi^- l^+ \nu_l \quad (\bar{s} \to \bar{u}) \qquad ; \qquad \bar{K}^0 \to \pi^+ l^- \bar{\nu}_l \quad (s \to u)$$

$$\frac{\Gamma(K^0_L \to \pi^- l^+ \nu_l) - \Gamma(K^0_L \to \pi^+ l^- \bar{\nu}_l)}{\Gamma(K^0_L \to \pi^- l^+ \nu_l) + \Gamma(K^0_L \to \pi^+ l^- \bar{\nu}_l)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2\,\mathrm{Re}(\bar{\varepsilon}_K)}{1+|\bar{\varepsilon}_K|^2} = (0.332 \pm 0.006)\%$$

➡ $\mathrm{Re}(\bar{\varepsilon}_K) = (1.66 \pm 0.03) \cdot 10^{-3}$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K \qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K$$

$$\varepsilon_K = (2.228 \pm 0.011) \cdot 10^{-3}\, e^{i\phi_\varepsilon}$$

$$\phi_\varepsilon = (43.52 \pm 0.05)^\circ$$

➡ $\eta\left[(1-\rho)A^2 + 0.22\right] A^2\, \hat{B}_K = 0.143$

Buras et al

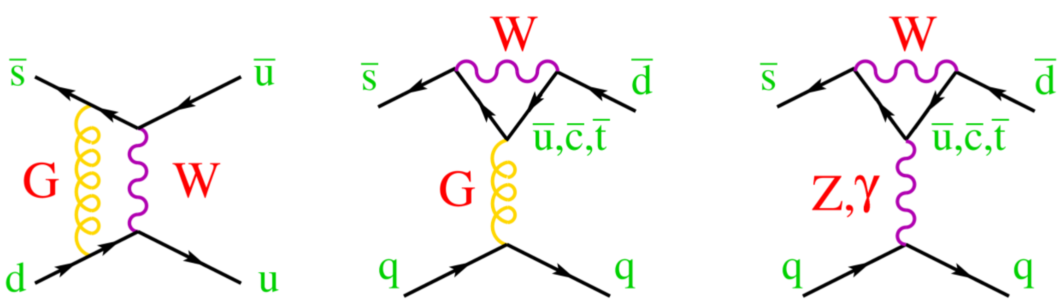
DIRECT $\not{CP}$ in $K \to \pi\pi$

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

$$\mathrm{Re}\left(\varepsilon'_K / \varepsilon_K\right) \approx \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\} = (16.6 \pm 2.3)\cdot 10^{-4}$$

NA48, NA31 (1988-2003)

KTeV, E731 (1993-2010)



- Short-distance OPE

  Ciuchini et al, Buras et al

- Long-distance χPT

  Pallante-Pich-Scimemi (2001)

  Cirigliano-Ecker-Neufeld-Pich (2003)

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

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

Isospin limit: RBC-UKQCD 1505.07863, 1502.00263

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

$\Delta I = 1/2$ Rule

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

Large phase shift

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

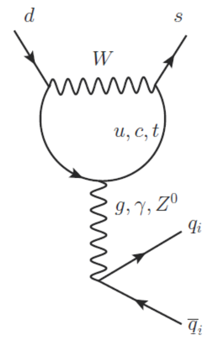
Anomaly? ➡ New-physics ? (Buras et al, Kitahara et al, Endo et al, Cirigliano et al…)

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

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

Effective Field Theory: Long & Short distance dynamics

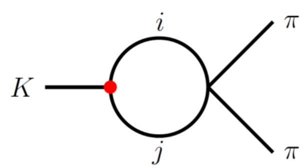
M_W	W, Z, γ, g τ, μ, e, ν_i t, b, c, s, d, u		Standard Model
	↓ OPE		
$\lesssim m_c$	$\gamma, g\ ;\ \mu, e, \nu_i$ s, d, u		$\mathcal{L}_{\rm QCD}^{(n_f=3)}\,,\ \mathcal{L}_{\rm eff}^{\Delta S=1,2}$
	↓ $N_C \to \infty$		
M_K	$\gamma\ ;\ \mu, e, \nu_i$ π, K, η		χPT



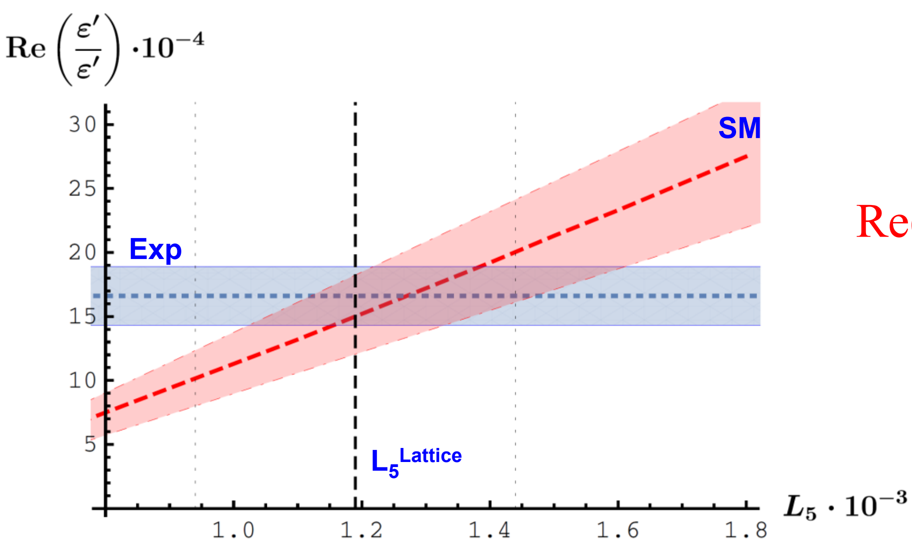
$$\mathcal{L}_{\rm eff}^{\Delta S=1} = -\frac{G_F}{\sqrt{2}}\, V_{ud}\, V_{us}^* \sum_i C_i(\mu)\ Q_i(\mu)$$

Large logarithmic corrections

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



χPT: $\log(\mu/m_\pi)$

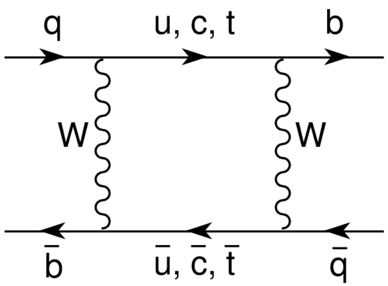


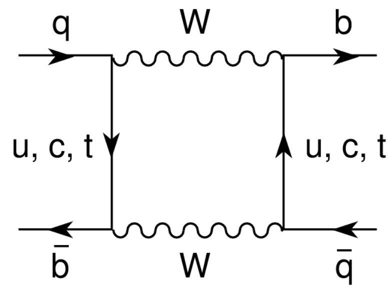
Gisbert-Pich, arXiv:1712.xxxx

$$\mathrm{Re}(\varepsilon'_K/\varepsilon_K)_{\rm SM} = \left(15 \pm 2_{\mu} \pm 2_{m_s} \pm 2_{\Omega_{\rm eff}} \pm 6_{1/N_c}\right)\cdot 10^{-4}$$
$$= (15 \pm 7)\cdot 10^{-4}$$

Large uncertainty, but no anomaly!

$B^0 - \bar{B}^0$ MIXING





$$V_{ud}\, V_{ub}^* \sim V_{cd}\, V_{cb}^* \sim V_{td}\, V_{tb}^* \sim A\lambda^3$$

$$\langle \bar{B}^0 | \mathrm{H} | B^0 \rangle \sim |V_{td}|^2\, S(r_t, r_t) \left(\frac{4}{3} M_B^2\, f_B^2\right) \hat{B}_B$$

$$\Delta M_{B_d^0} = (0.5064 \pm 0.0019)\ \mathrm{ps}^{-1} \quad \Rightarrow \quad |V_{td}|$$

- $\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.770 \pm 0.004$
- $\Delta M_{B_s^0} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$
- $\Delta\Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1$
- $\mathrm{Re}\left(\bar{\varepsilon}_{B_d^0}\right) = -0.0005 \pm 0.0004$

$$\Delta M_{B_s^0} / \Gamma_{B_s^0} = 26.72 \pm 0.09$$

$$|V_{ts}|^2 \gg |V_{td}|^2$$

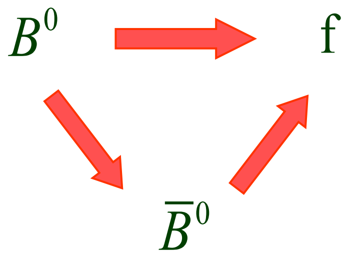
$$\Delta\Gamma_{B_s^0} / \Gamma_{B_s^0} = -0.130 \pm 0.009$$

$$\mathrm{Re}\left(\bar{\varepsilon}_{B_s^0}\right) = -0.0002 \pm 0.0007$$

$\not{C}\!\not{P}$ very small

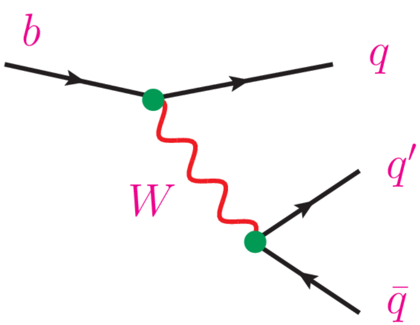
$$|q/p| - 1 \sim m_c^2 / m_t^2$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



CP self-conjugate: $\bar{\mathrm{f}} = \eta_{\mathrm{f}}\, \mathrm{f}$

$$\frac{q}{p} \approx \frac{\mathbf{V}_{tb}^* \mathbf{V}_{tq}}{\mathbf{V}_{tb} \mathbf{V}_{tq}^*} = e^{-2i\phi_M} \quad ; \qquad \phi_M \approx \begin{cases} \beta & (B_d^0) \\ -\beta_s \approx -\lambda^2 \eta & (B_s^0) \end{cases}$$



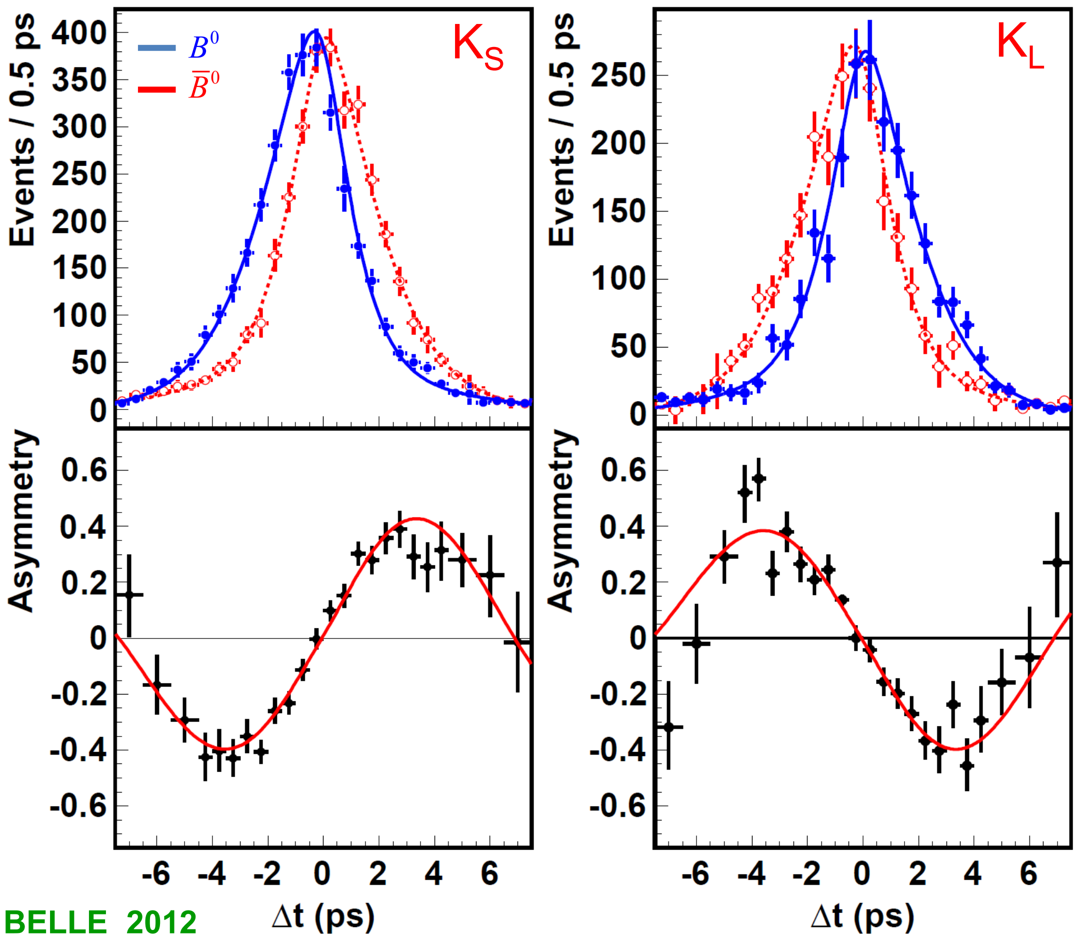
Assumption: **Only 1 decay amplitude**

$$\frac{\mathrm{A}_{b\to q\bar{q}q'}}{\mathrm{A}_{\bar{b}\to\bar{q}q\bar{q}'}} = \frac{\mathbf{V}_{qb} \mathbf{V}_{qq'}^*}{\mathbf{V}_{qb}^* \mathbf{V}_{qq'}} = e^{-2i\phi_D} \quad \Rightarrow \quad \rho_{\bar{f}} = \bar{\rho}_f^* = \eta_f\, e^{2i\phi_D} \qquad C_f = 0$$

$$\Rightarrow \quad \frac{\Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right) - \Gamma\left(B^0 \to \mathrm{f}\right)}{\Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right) + \Gamma\left(B^0 \to \mathrm{f}\right)} = -\eta_{\mathrm{f}}\ \sin(2\phi)\ \sin(\Delta M\, t) \quad ; \qquad \phi = \phi_M + \phi_D$$

Direct information on the CKM matrix

$$\frac{\Gamma(\bar{B}^0 \to J/\psi\, K_S) - \Gamma(B^0 \to J/\psi\, K_S)}{\Gamma(\bar{B}^0 \to J/\psi\, K_S) + \Gamma(B^0 \to J/\psi\, K_S)} = -\eta_f \;\sin(2\beta)\;\sin(\Delta M\, t)$$

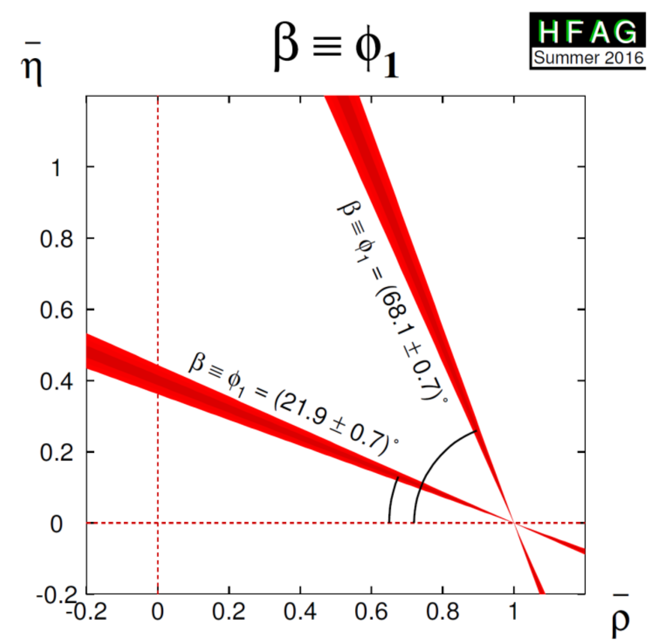


BELLE 2012

HFAG:

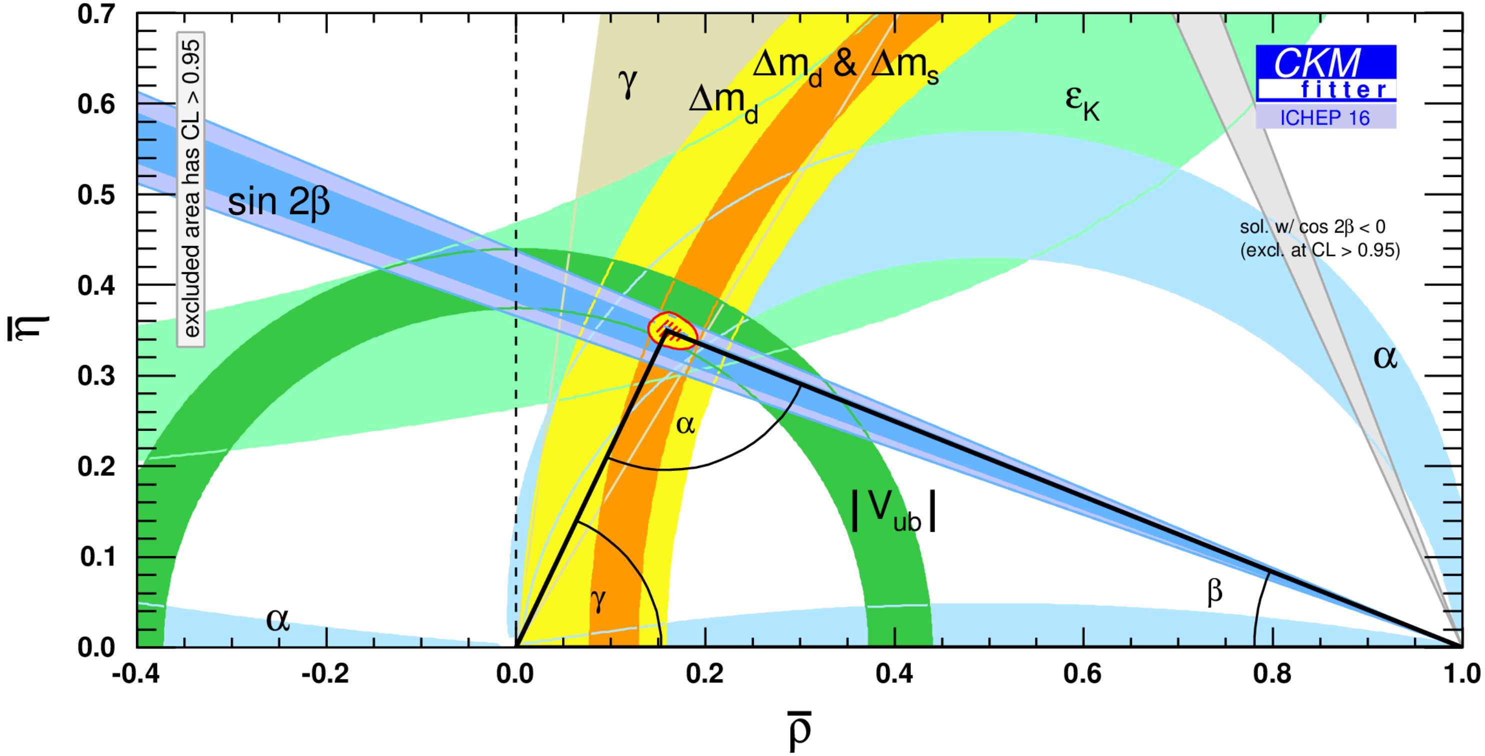
sin(2β) = 0. 69 ± 0.02

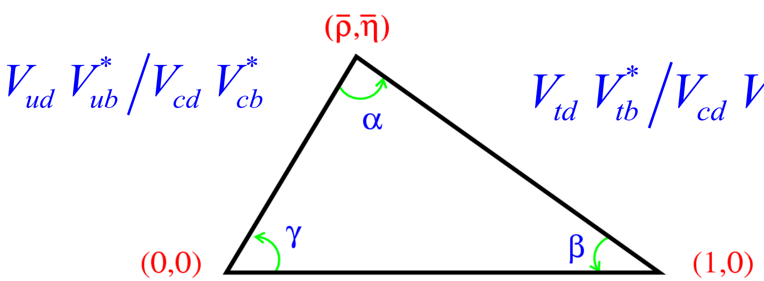
$B^0 \to J/\psi\, K_{S,L}\,,\, \psi(2S)\, K_S\,,\, \chi_c\, K_S\,,\, \eta_c\, K_S$



$\not{CP}$ Signal

$$V_{ud}\,V_{ub}^{*} + V_{cd}\,V_{cb}^{*} + V_{td}\,V_{tb}^{*} = 0$$





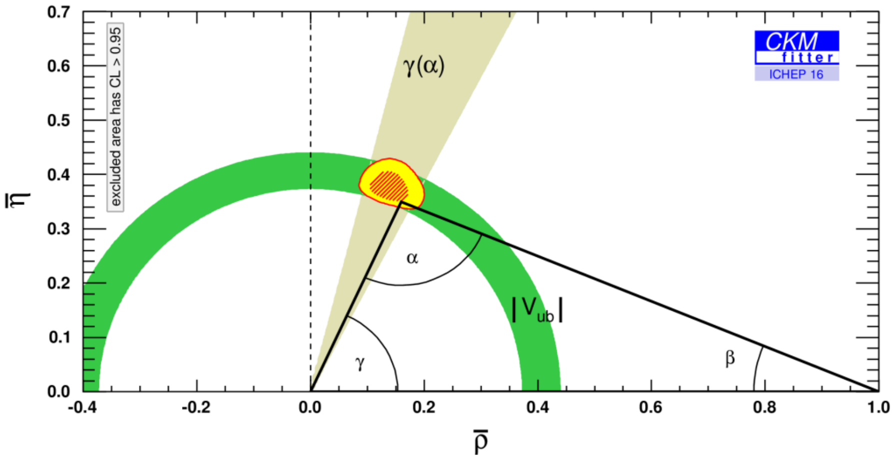
UT*fit*

$$\bar\eta \equiv \eta\left(1-\frac{1}{2}\lambda^2\right) = 0.343\pm 0.011$$

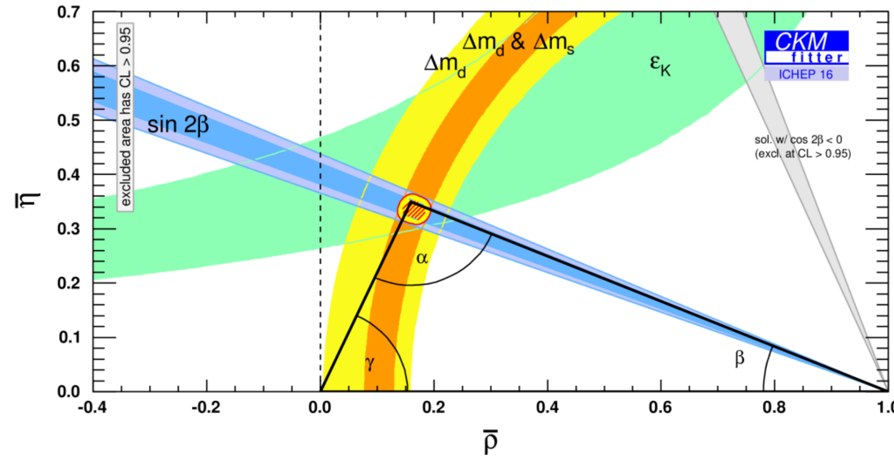
$$\bar\rho \equiv \rho\left(1-\frac{1}{2}\lambda^2\right) = 0.153\pm 0.013$$

$\alpha = 91.0\pm 2.5^\circ$; $\beta = 23.2\pm 1.2^\circ$; $\gamma = 65.3\pm 2.0^\circ$

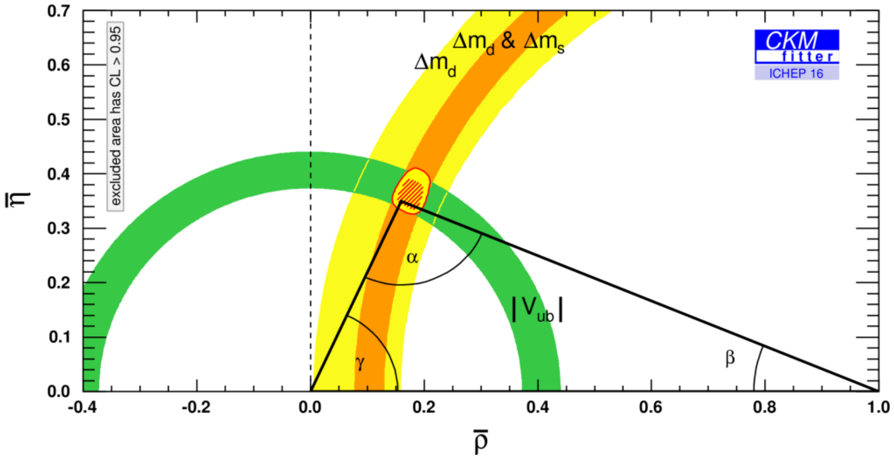
Tree-level determinations



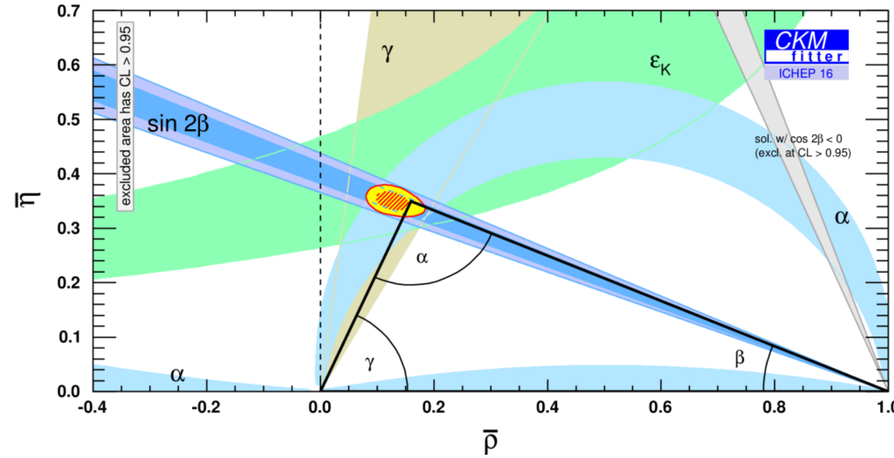
Loop processes



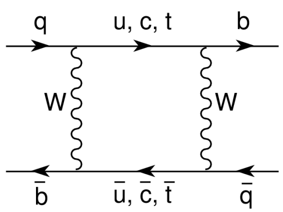
CP Conserving

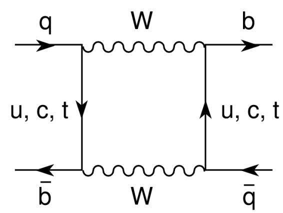


CP Violating



Bounds on New Flavour Physics





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

Isidori, 1302.0661

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Bounds on Λ in TeV ($c_{\rm NP}=1$) Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Im	Observables
$(\bar s_L \gamma^\mu d_L)^2$	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 [$c_{\rm NP} \sim O(1)$] ruled out at the TeV scale**
- **$\Lambda_{\rm NP} \sim 1$ TeV requires $c_{\rm NP}$ 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, Buras et al

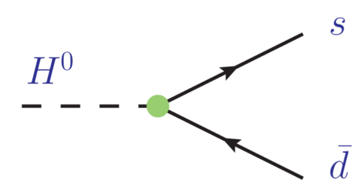
Yukawa Interactions in 2HDMs

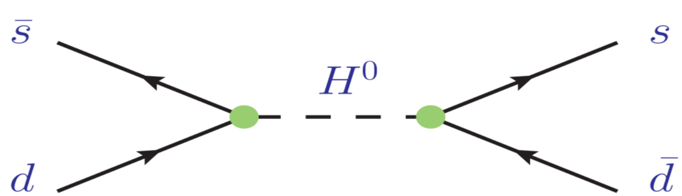
$$\mathcal{L}_Y = -\bar{Q}'_L \left(\Gamma_1 \phi_1 + \Gamma_2 \phi_2\right) d'_R - \bar{Q}'_L \left(\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2\right) u'_R$$

SSB ⬇ $\qquad \phi_i^{(0)} = \frac{\mathrm{v}_i}{\sqrt{2}} \quad , \quad \mathrm{v} = \sqrt{\mathrm{v}_1^2 + \mathrm{v}_2^2}$

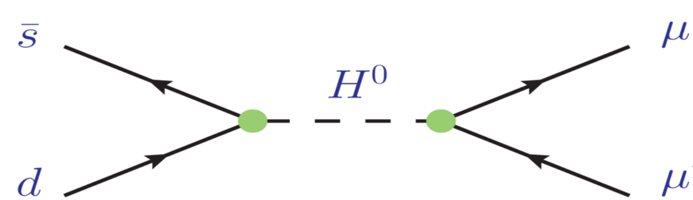
$$\mathcal{L}_Y = -\frac{\sqrt{2}}{\mathrm{v}} \left\{ \bar{Q}'_L \left(M_d' \Phi_1 + Y_d' \Phi_2\right) d'_R - \bar{Q}'_L \left(M_u' \tilde{\Phi}_1 + Y_u' \tilde{\Phi}_2\right) u'_R \right\}$$

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

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

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

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

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

$\mathcal{Z}_2$ models:

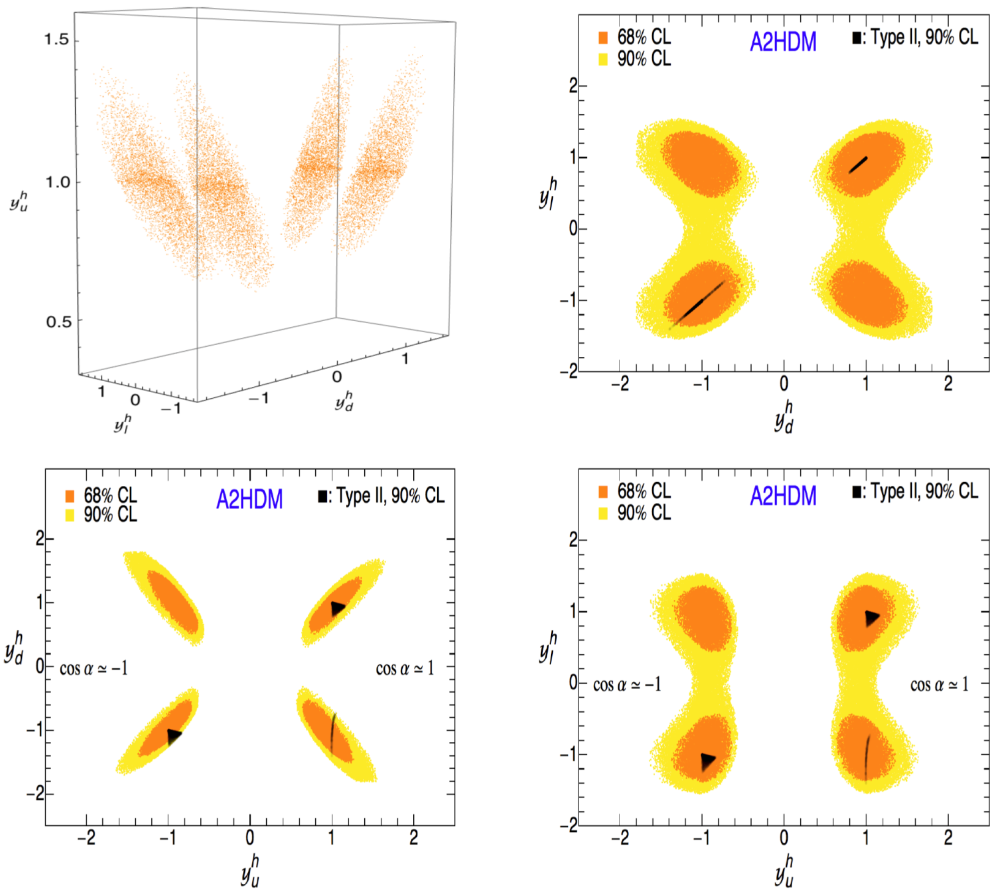
Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Only one ϕ_a couples to f_R
(Glashow-Weinberg, Paschos '77)

Flavour Alignment (Aligned 2HDM)

AP-Tuzón

Celis-Ilisie-AP, 1302.4022, 1310.7941



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

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

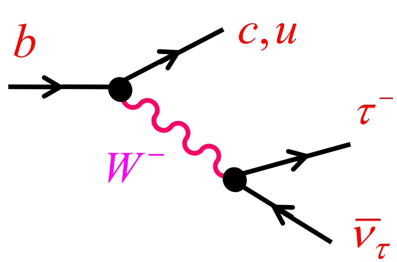
- **EDMs** Jung-AP, 1308.6283

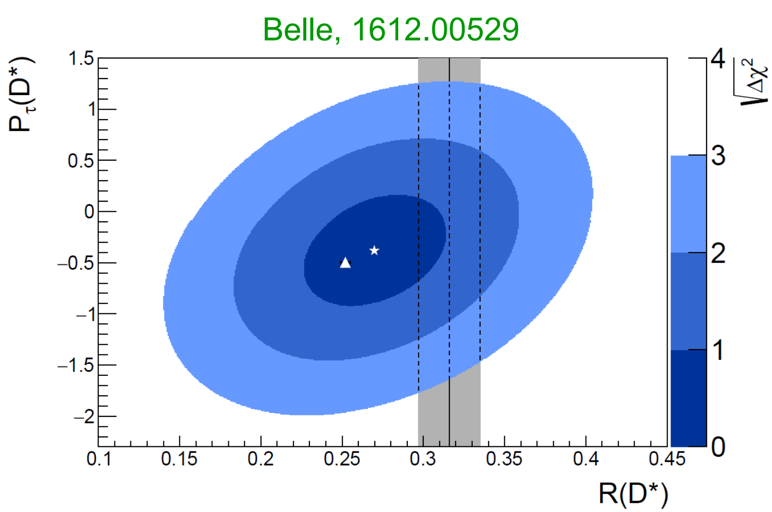
- **Usual Z_2 models recovered in particular (CP-conserving) limits**

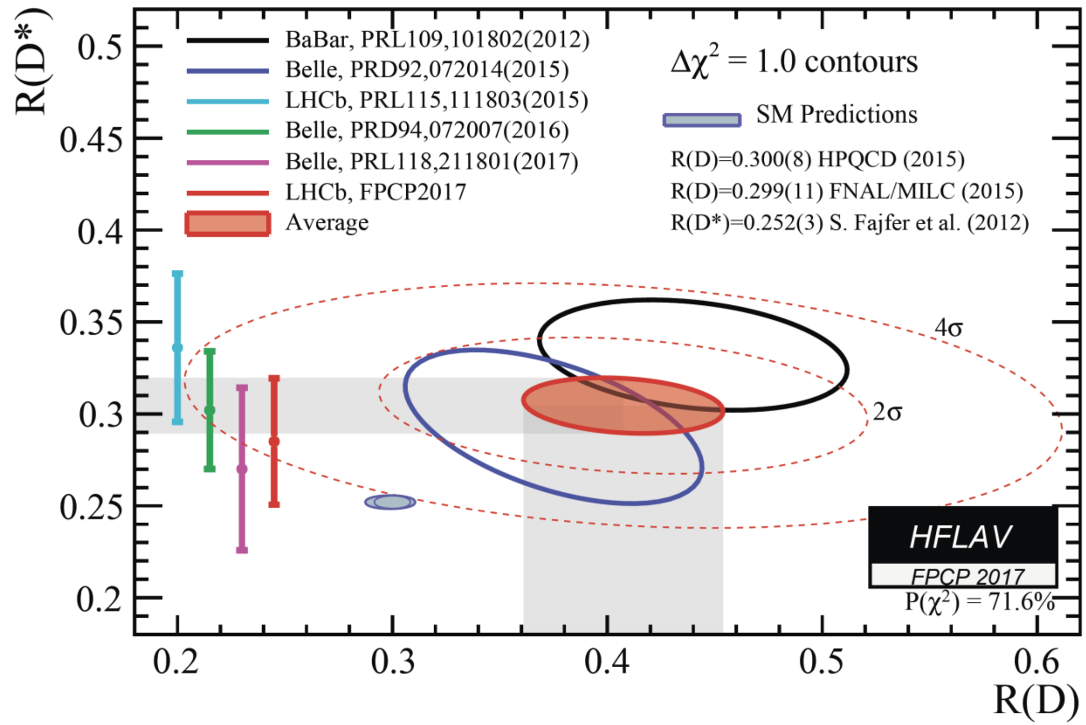
Flavour Anomaly

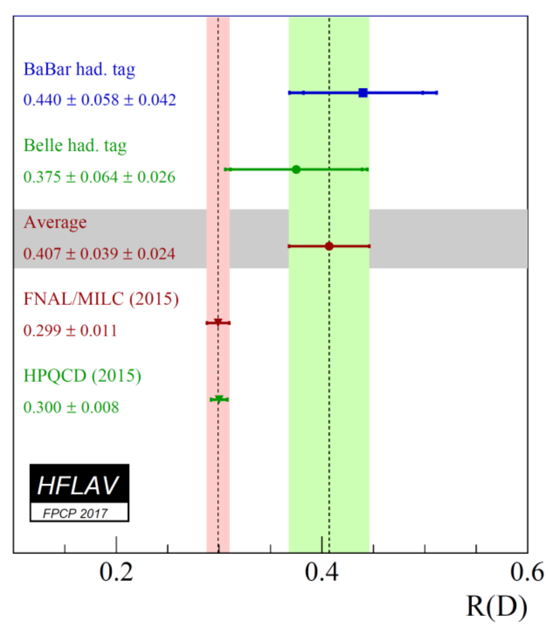
4σ discrepancy

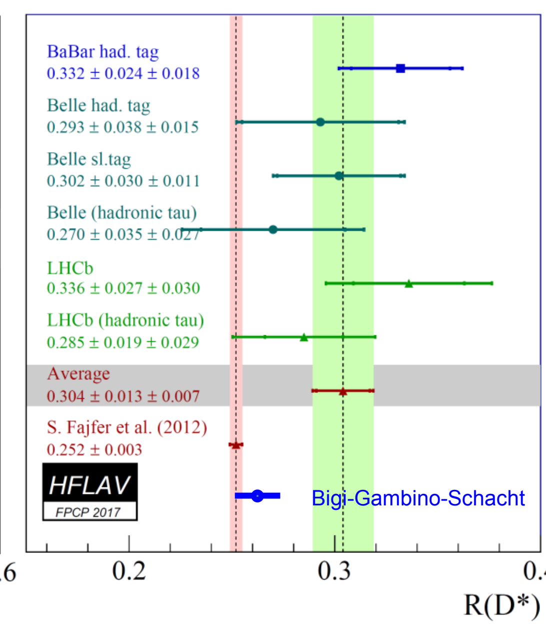
$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$











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

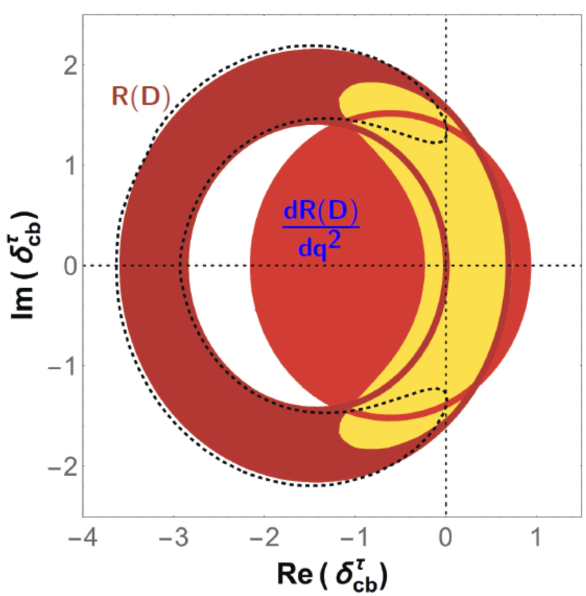
$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{q_u q_d} \left[\bar{q}_u \left(g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R\right) q_d\right] \left[\bar{\ell} \mathcal{P}_L \nu_\ell\right]$$

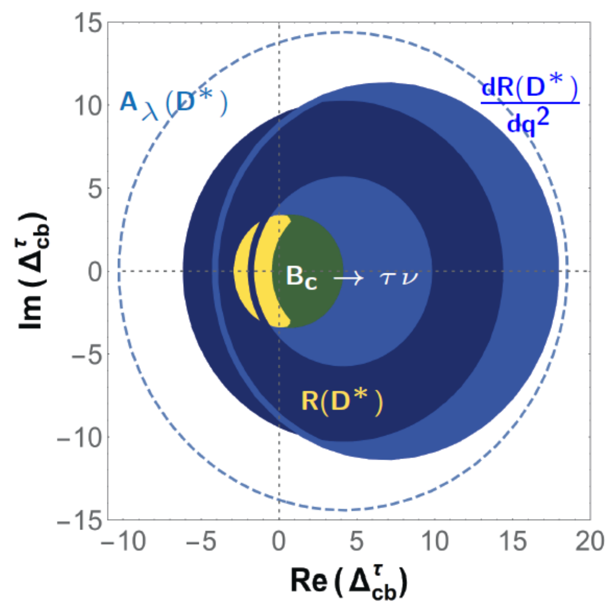
Scalar Form Factors

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

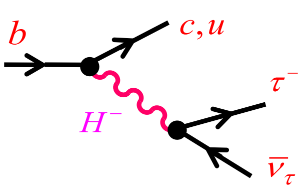
$$\delta R(D^*) \longleftrightarrow \Delta_{cb}^{\ell} \equiv \left(g_L^{cb\ell} - g_R^{cb\ell}\right) \frac{m_B^2}{m_\ell\,(\bar{m}_b + \bar{m}_c)}$$

95% CL





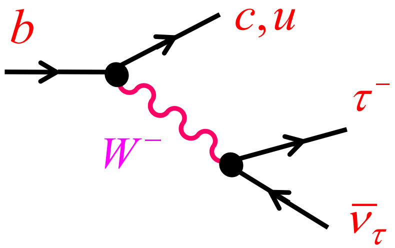
Celis et al. 1612.07757



LHCb, 1711.05623

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

2 σ above SM prediction



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

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

Capdevila et al, 1712.01919

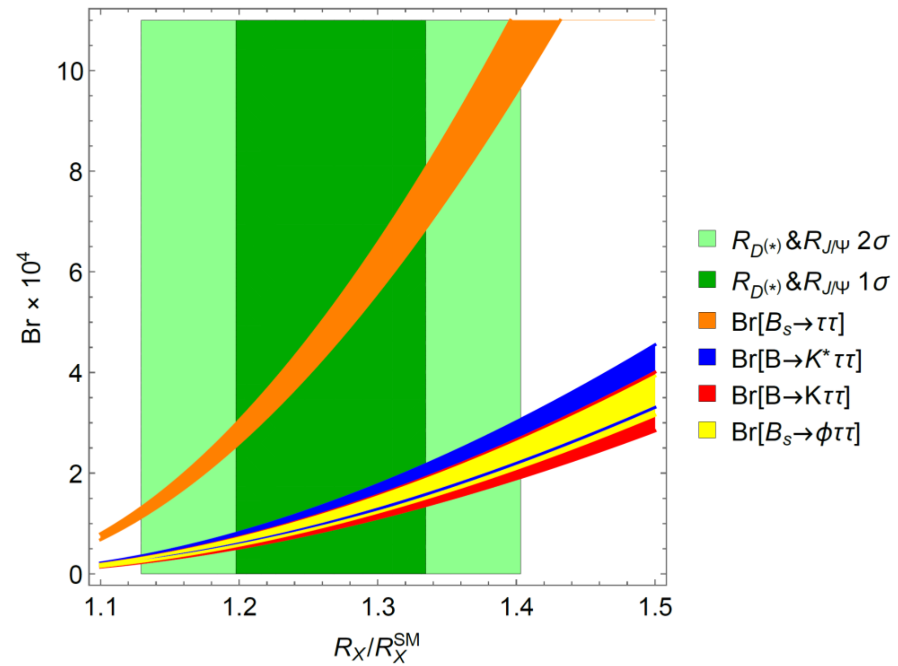
1) New physics only contributes to the SM operator $[\bar{c}\gamma^{\mu}P_L b][\bar{\tau}\gamma_{\mu}P_L\nu_{\tau}]$

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

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:

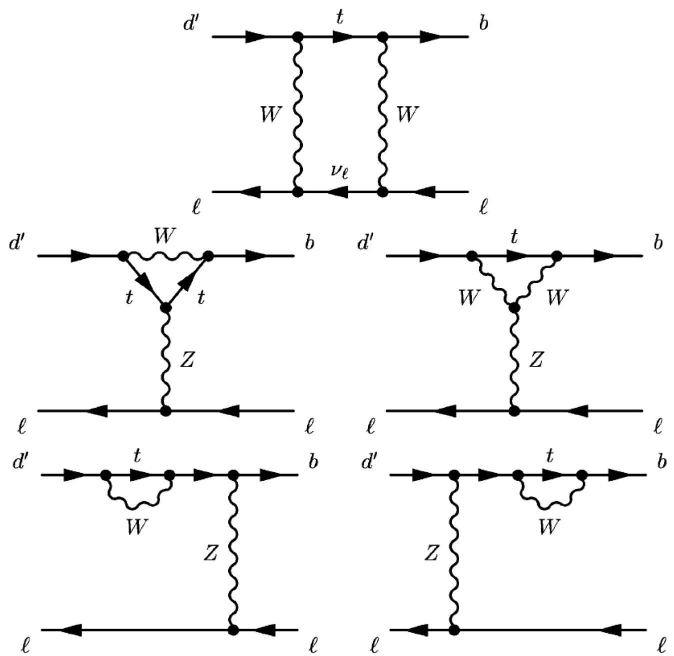
Alonso et al, 1505.05164
Crivellin et al, 1703.09226

Rare Decays

Loop & CKM suppression → NP sensitivity

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

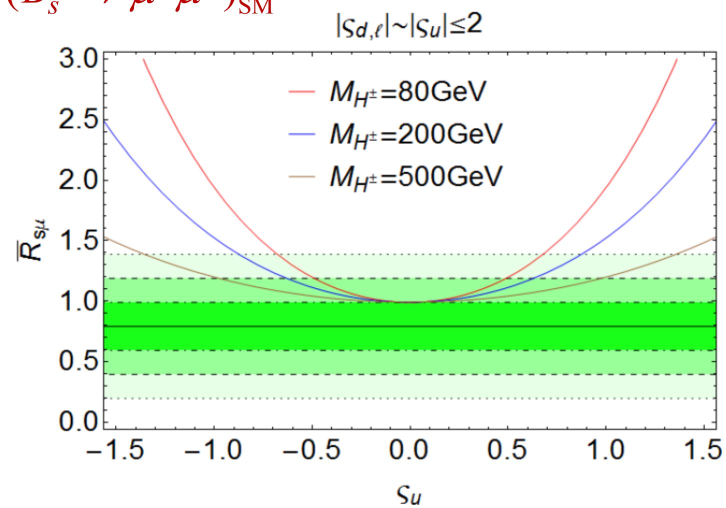
Sensitive to (pseudo) scalar contributions



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

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

Li-Lu-Pich, 1404.5865



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

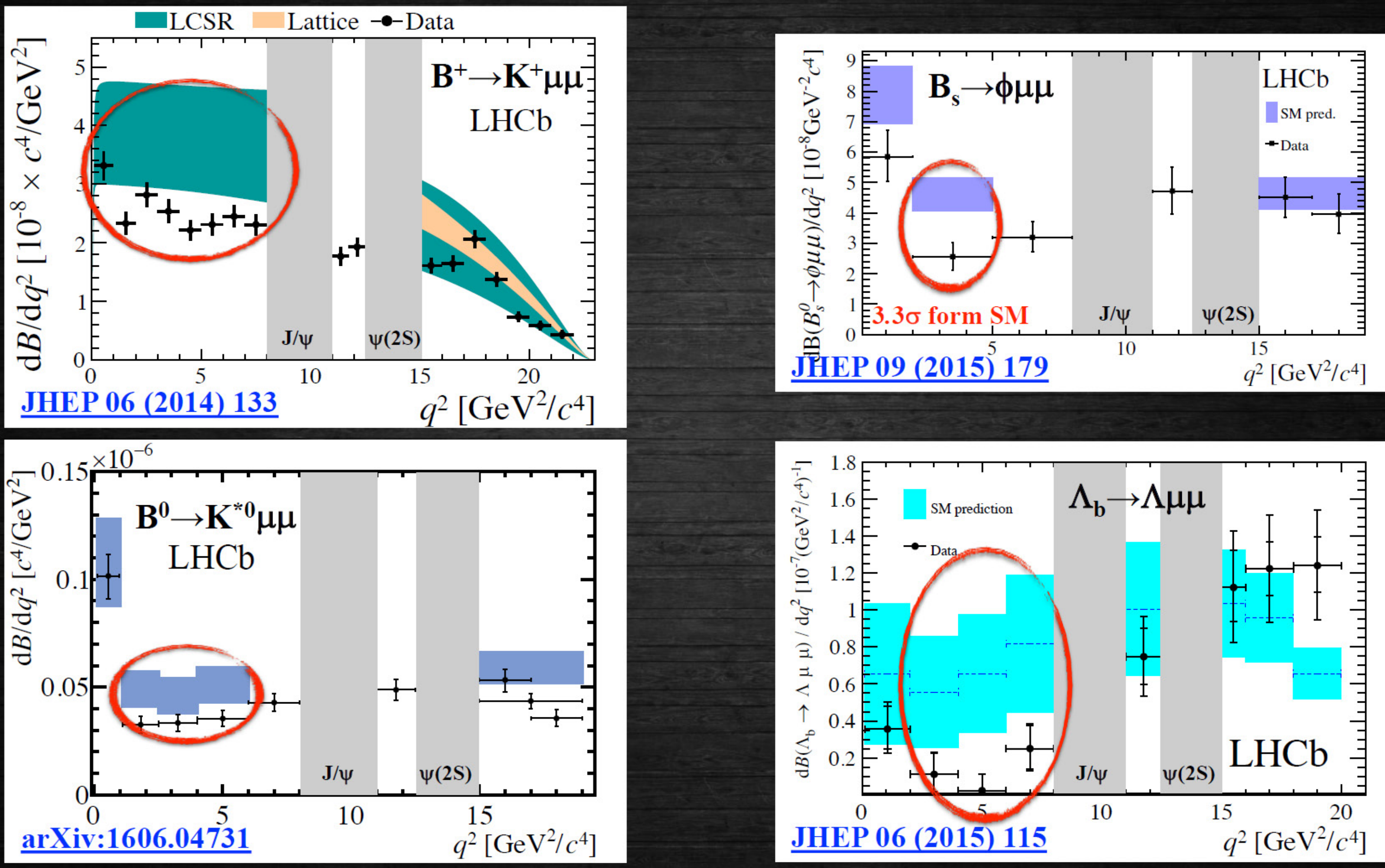
LHCb, 1703.05747: $\overline{B}(B_s^0 \to \mu^+\mu^-)_{\rm exp} = \left(3.0 \pm 0.6 {}^{+0.3}_{-0.2}\right) \cdot 10^{-9}$, $\overline{B}(B_d^0 \to \mu^+\mu^-)_{\rm exp} < 3.4 \cdot 10^{-10}$ (95% CL)

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

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**



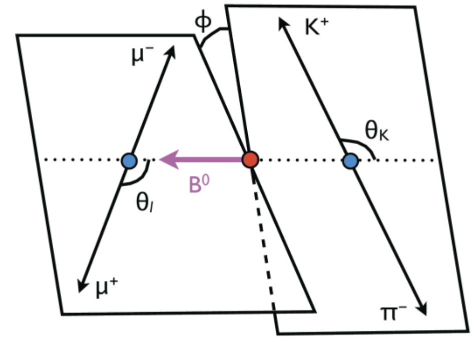
Simone Bifani CERN Seminar 6

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

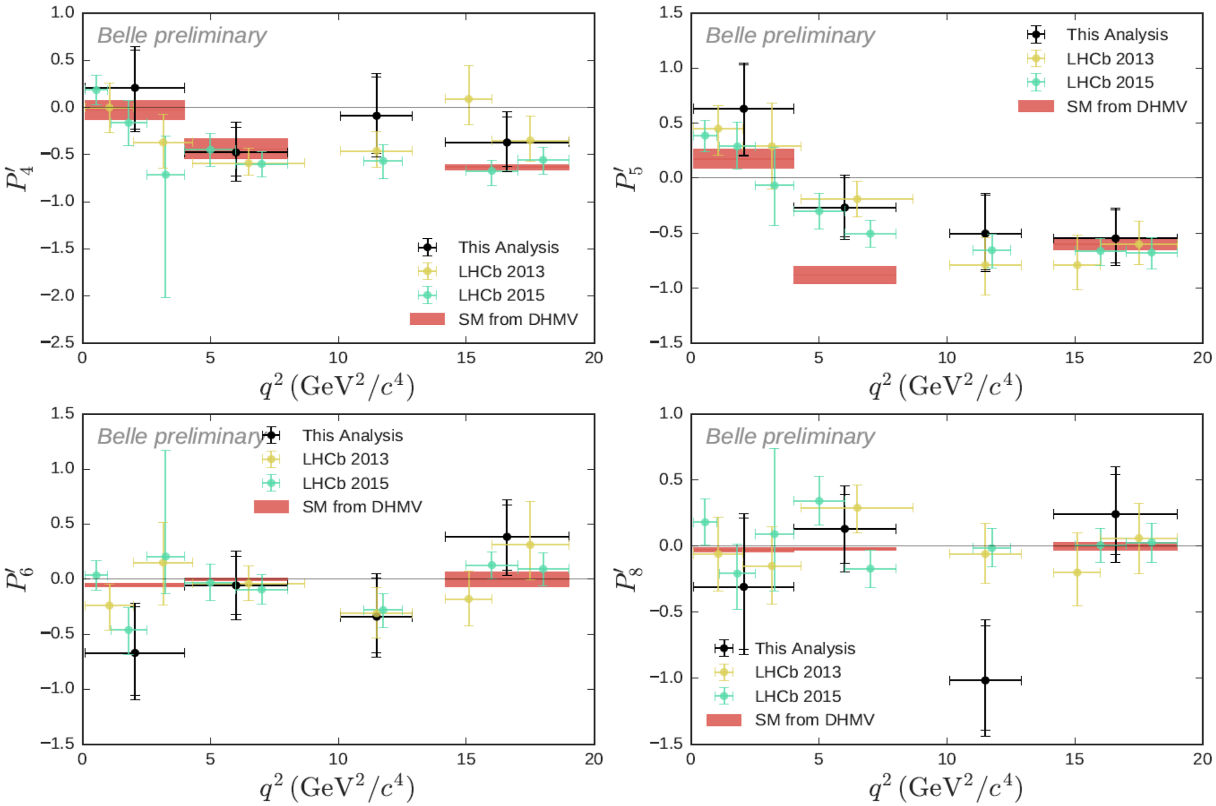
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \frac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

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

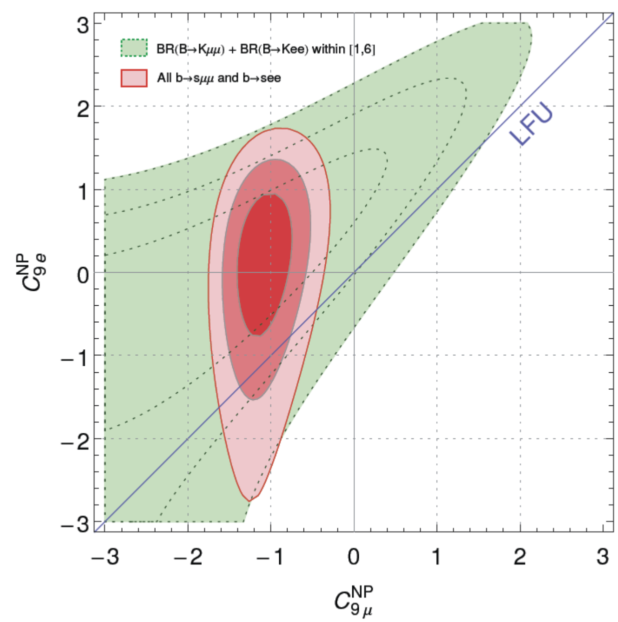
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



Belle 1604.04042



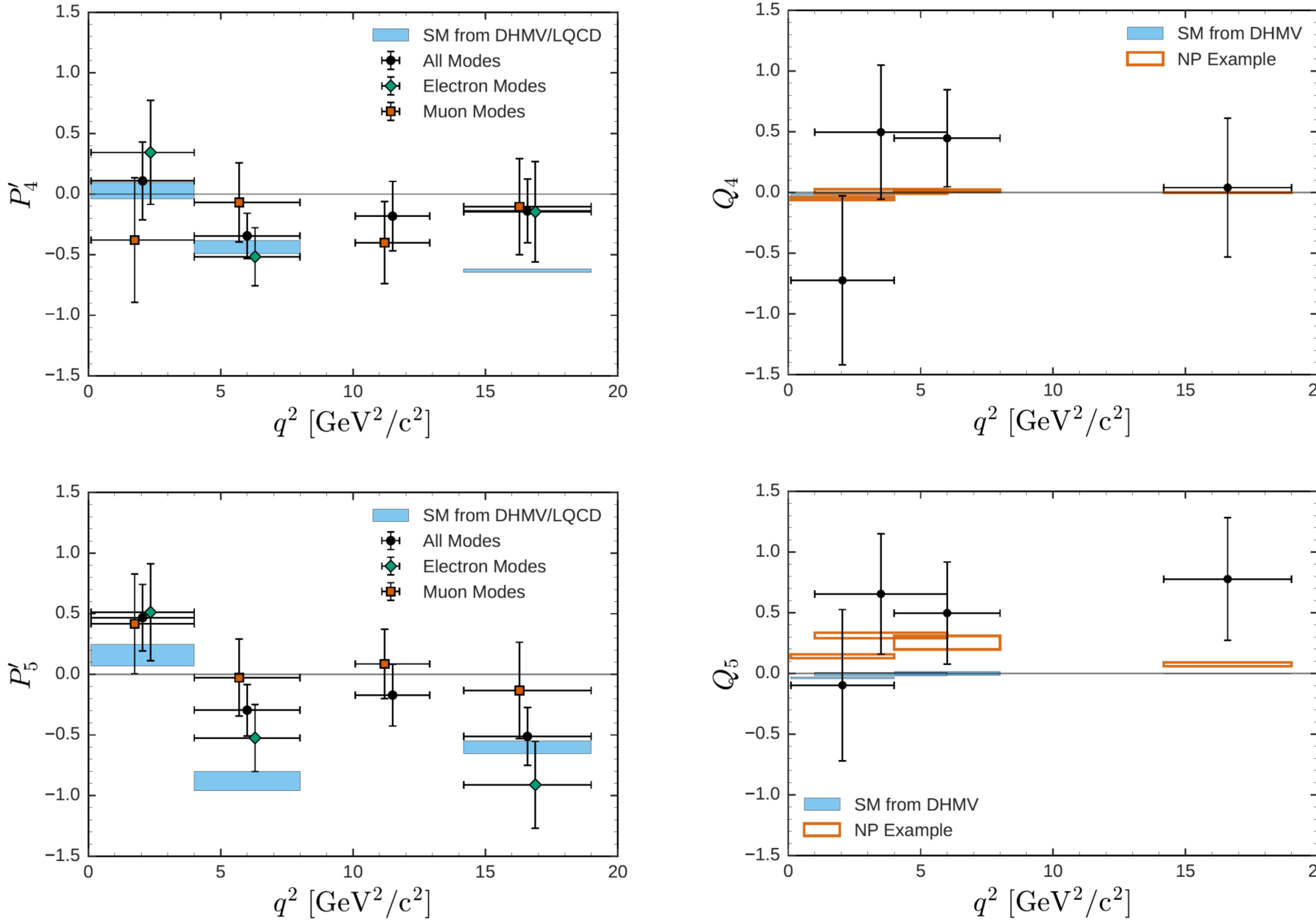
Descotes-Genon et al, 1510.04239



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

Belle, 1612.05014

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

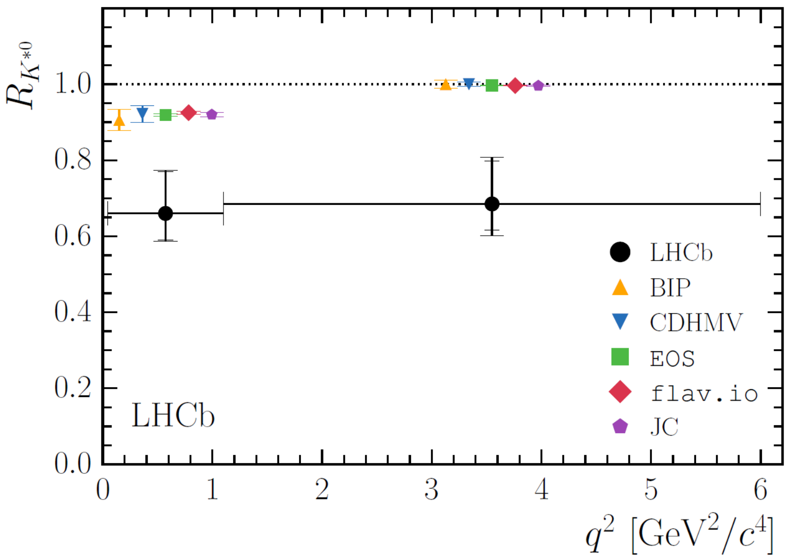


Violations of Lepton Flavour

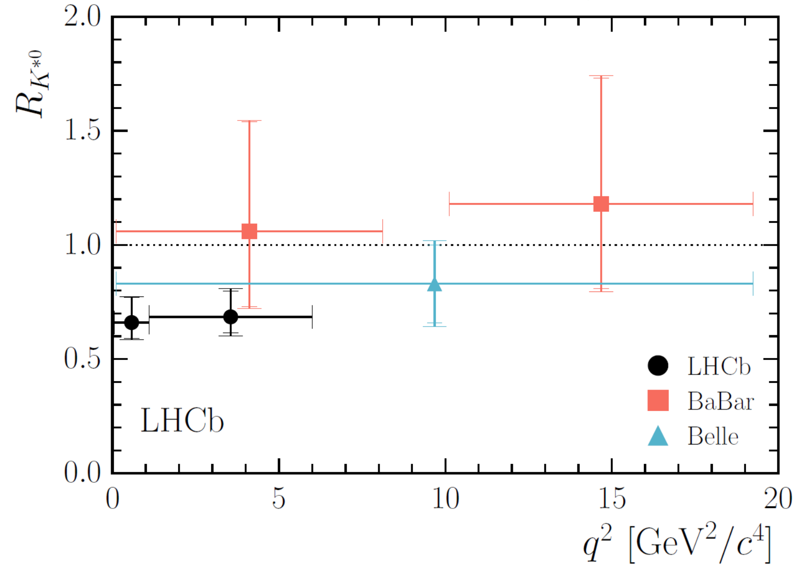
$$R_{K^{*0}} = \frac{\mathrm{Br}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{Br}(B^0 \to K^{*0} J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathrm{Br}(B^0 \to K^{*0} e^+ e^-)}{\mathrm{Br}(B^0 \to K^{*0} J/\psi\,(\to e^+ e^-))}$$

	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



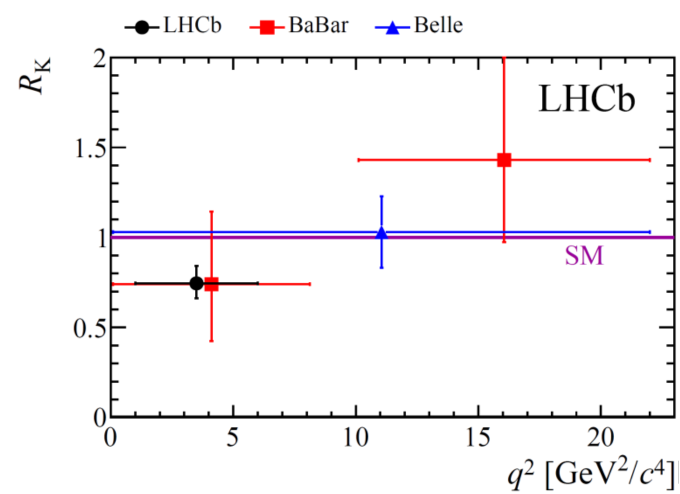
LHCb, 1705.05802



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

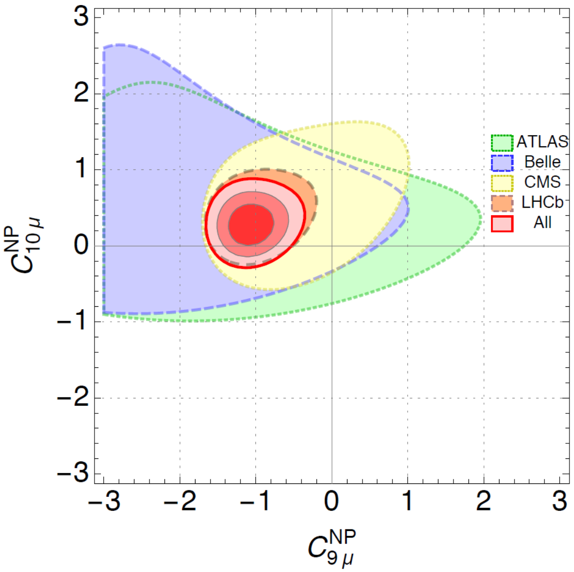
$$\frac{\mathrm{Br}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}(B^+ \to K^+ e^+ e^-)} = 0.745\,^{+\,0.090}_{-\,0.074} \pm 0.036$$

2.6 σ below the SM

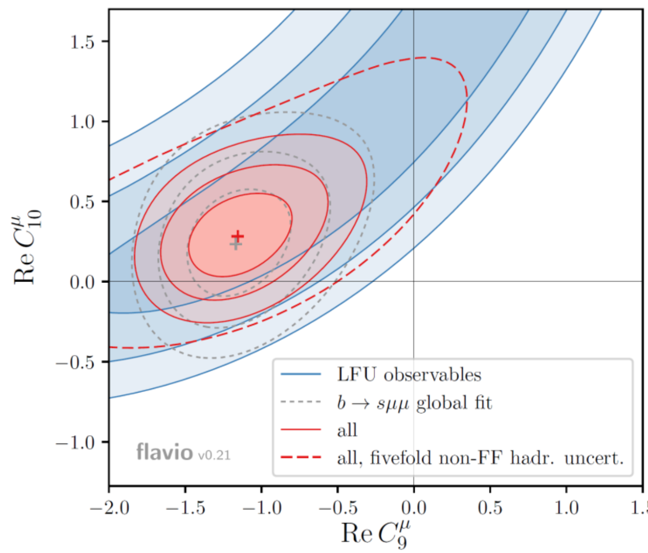


New-Physics Fits with Effective Operators

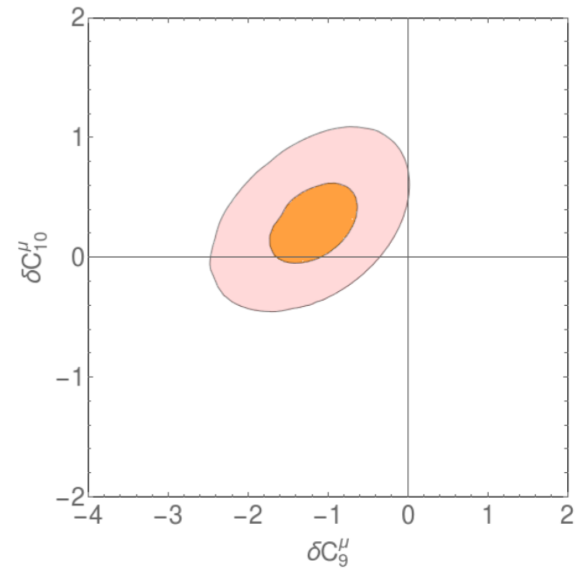
Capdevila et al, 1704.05340

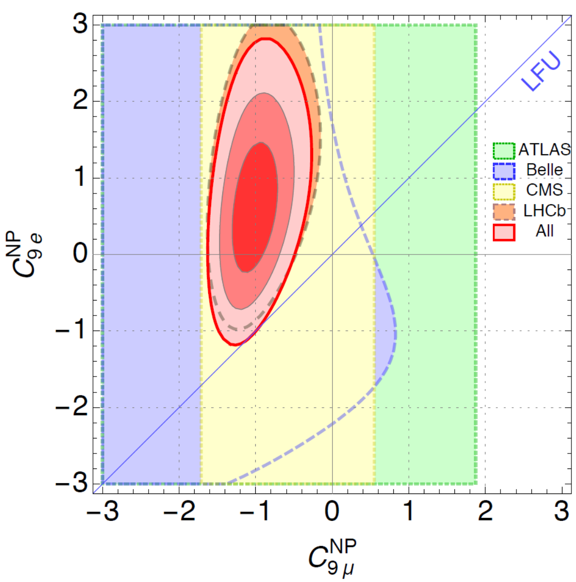


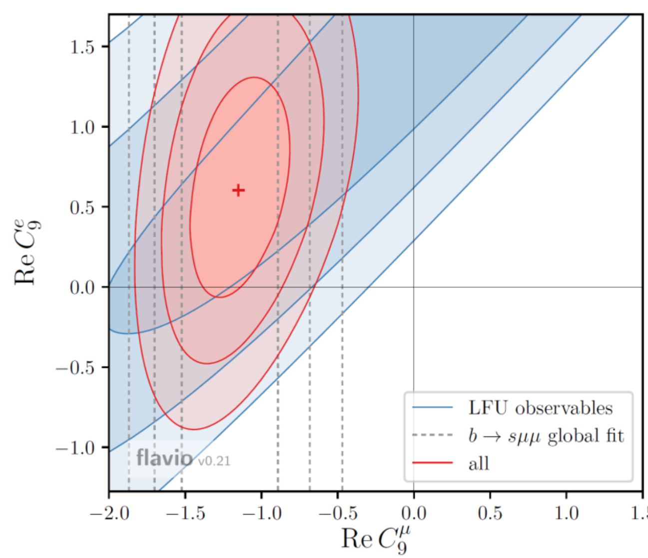
Altmannshofer et al, 1704.05435



Geng et al, 1704.05446







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

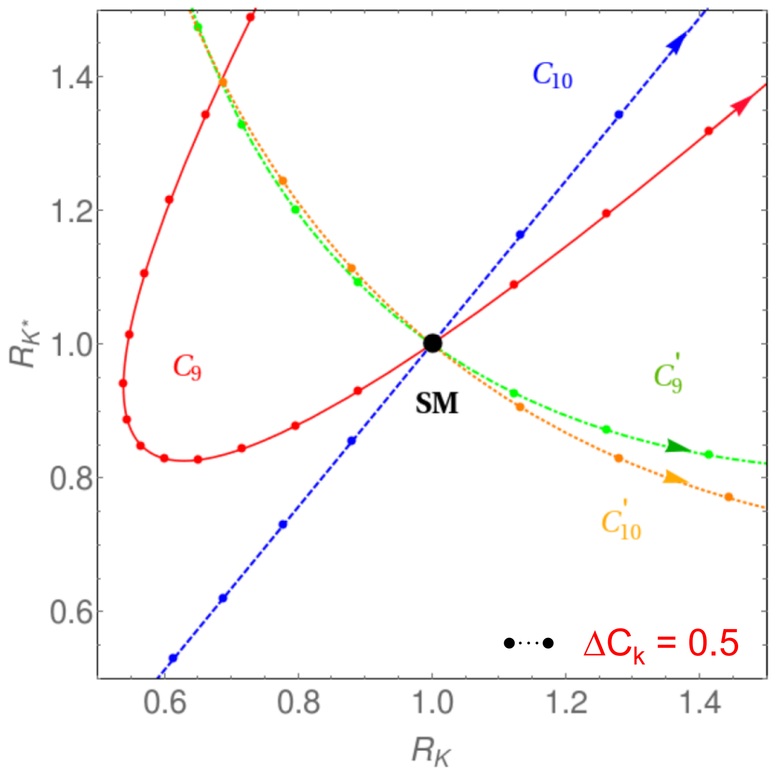
$$H_{\mathrm{eff}}^{\mathrm{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{i,\ell} C_i^\ell\, O_i^\ell$$

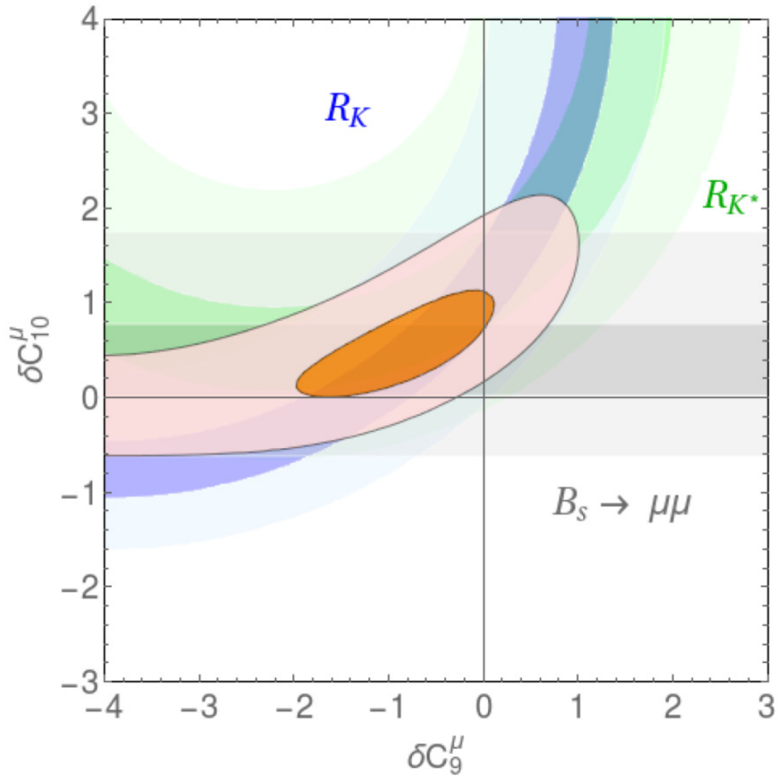
$$O_9^\ell = \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu\,\ell\right)$$

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

Geng et al, 1704.05446

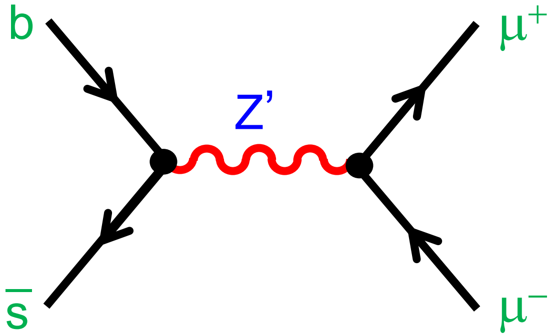
SM: $C_9(m_b) \approx -C_{10}(m_b) = 4.27$





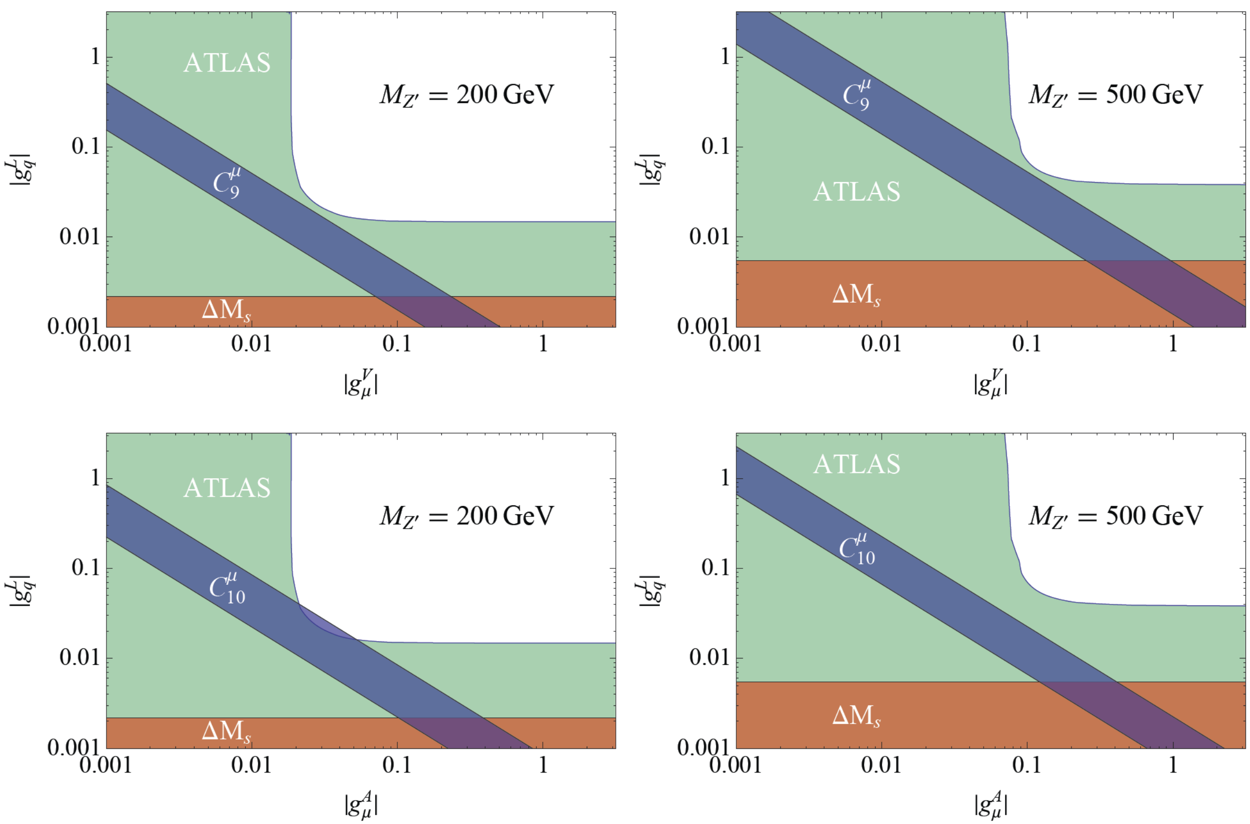
$$O_9^{\ell} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\gamma^\mu \ell\right) \qquad O_9^{\ell'} = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\ell}\gamma^\mu \ell\right)$$

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

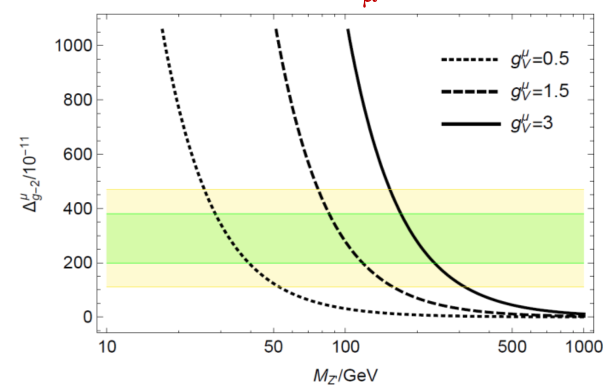


$$\mathcal{L} \supset \frac{g_2}{2c_W} Z'_\alpha \left\{ \left[\bar{s}\gamma^\alpha (g_L^Q P_L + g_R^Q P_R) b + h.c. \right] + \bar{\ell}\gamma^\alpha (g_V^\ell + \gamma_5 g_A^\ell)\ell \right\}$$

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

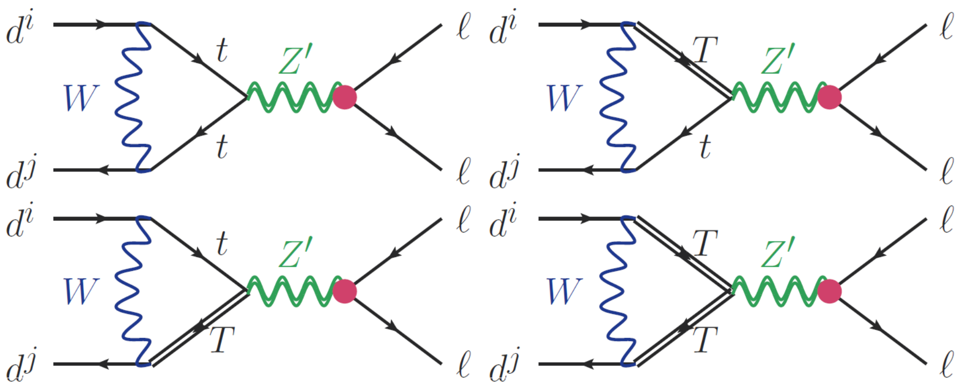


$(g-2)_\mu$



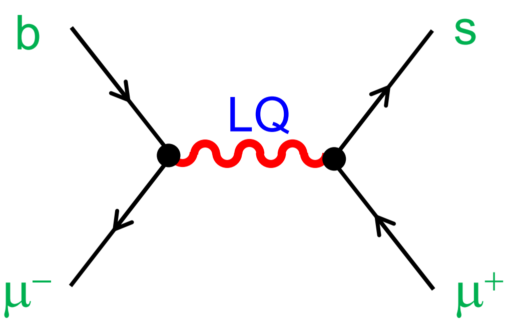
Di Chiara et al, 1704.06200

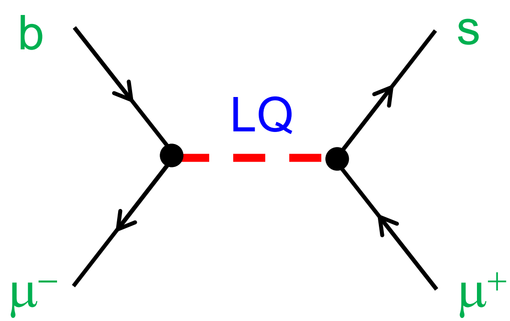
More possibilites…



Flavour conserving Z'

Kamenik et al, 1704.06005



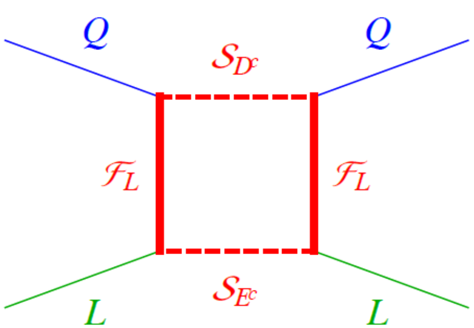


Leptoquarks

Hiller- Nisandzic, 1704.05444

D'Amico et al, 1704.05438

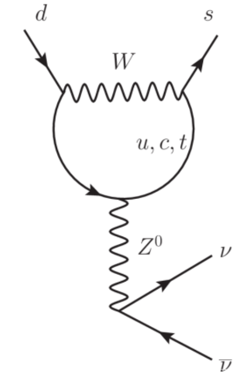
Becirevic-Sumensari, 1704.05835

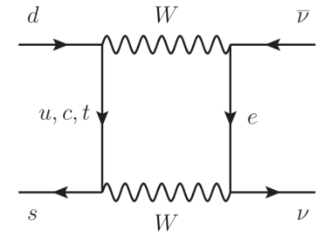


New Fermions and Scalars

D'Amico et al, 1704.05438

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





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

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

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

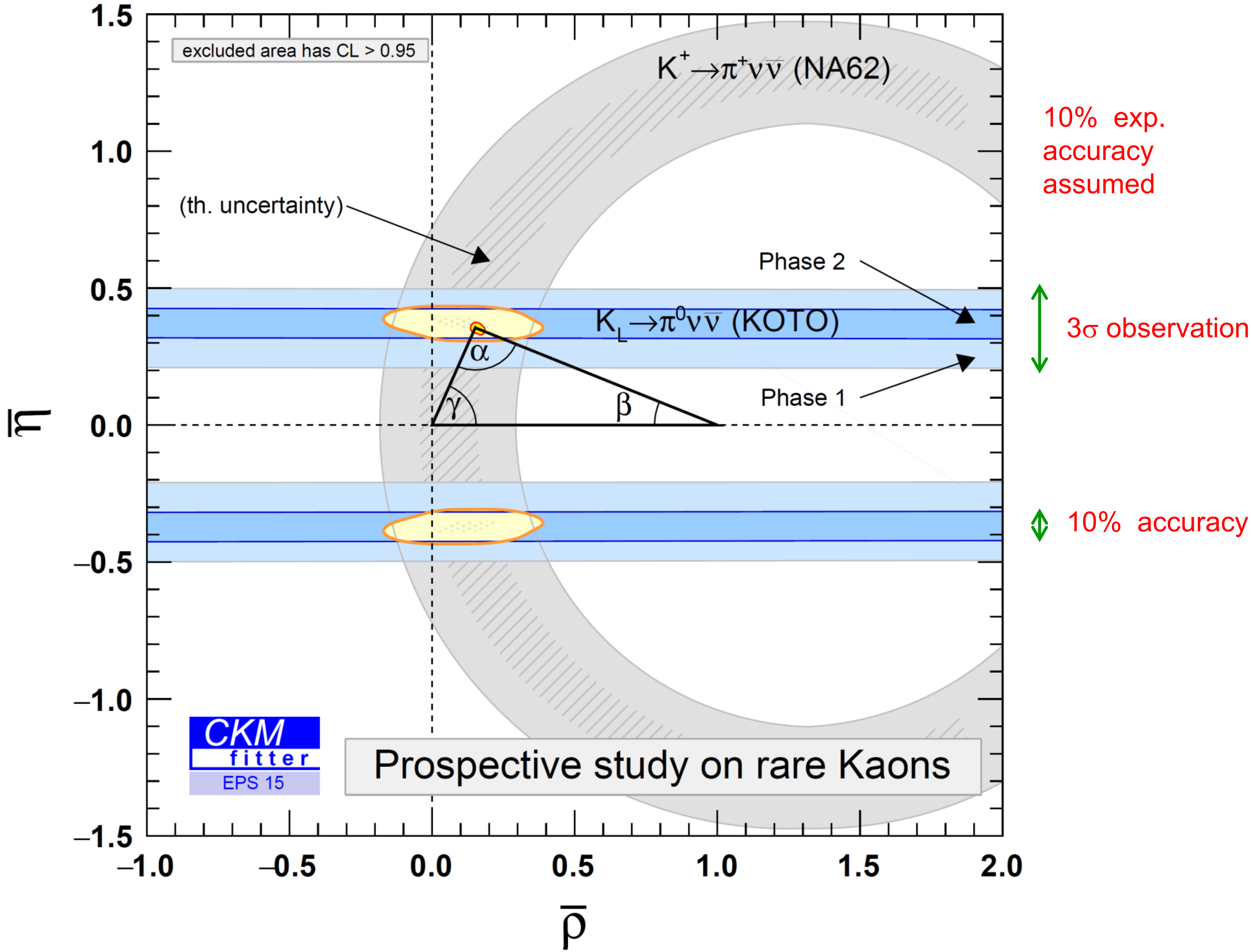
Buras et al

Long-distance contributions are negligible

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

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

New Experiments Needed: **NA62, K0TO** **(ORKA, Project-X)**


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
β
γ
10% exp. accuracy assumed
3σ observation
10% accuracy
CKM fitter
EPS 15
Prospective study on rare Kaons
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
–0.5
–1.0
–1.5
–1.0
–0.5
0.0
0.5
1.0
1.5
2.0

SUMMARY

- **Flavour Structure and** $\not{CP}$ are major pending questions
- **Related to SSB** → **Scalar Sector** (Higgs)
- Important **cosmological implications** (Baryogenesis)
- Sensitive to **New Physics:** **Flavour Anomalies!**
- $\not{CP}$ is highly constrained in the SM: **1 phase only**
- Many interesting $\not{CP}$ signals within experimental reach
- Better control of **QCD** effects urgently needed
- **Challenging future ahead:**

  BES-III, LHCb, NA62, J-Parc, Super-Belle, τcF, …