Flavour Physics Overview

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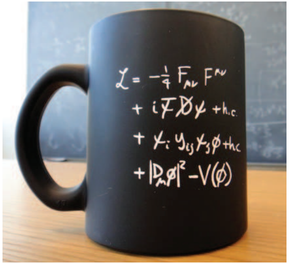
Standard Model

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$



Lagrangian

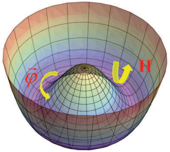
Gauge

Yukawas

EWSB

EWSB

$$SU(2)_L \otimes U(1)_Y \to U(1)_{\mathrm{em}}$$



	Quarks		Leptons	
	$Q = \frac{2}{3}$	$Q = -\frac{1}{3}$	$Q = 0$	$Q = -1$
MATTER	0.002 Up	0.005 Down	< 0.000000001 ν_e Neutrino e	0.0005 Electron
	~ 1.3 Charm	~ 0.1 Strange	< 0.000000001 ν_μ Neutrino μ	0.1 Muon
	173 Top	~ 4.2 Beauty	< 0.000000001 ν_τ Neutrino τ	1.8 Tau
FORCES	0 Photon	0 Gluons	91 80 Z^0 , $W^\pm$	125 Higgs

Standard Model: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

1. **Interactions determined by gauge symmetries. Flavour Universality**

2. **Gauge symmetries require all elementary particles to be massless**

3. **Masses generated through the interaction with the Higgs doublet**

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\bar{u}_j, \bar{d}'_j\right)_L \left[c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)*} \\ -\phi^{(-)} \end{pmatrix} u_{kR} \right] + \left(\bar{\nu}_j, \bar{\ell}'_j\right)_L c_{jk}^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \ell'_{kR} \right\}$$

Mass is the only difference among the three fermion families

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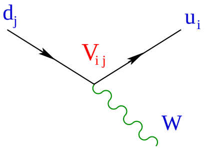
Mass is the only difference among the three fermion families

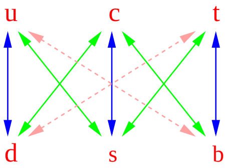
4. Fermion mass eigenstates $\neq$ weak eigenstates

$$\longrightarrow \quad \begin{cases} \textbf{Flavour Mixing:} \quad d'_i = V_{ij}\, d_j \quad , \quad V^\dagger V = V\, V^\dagger = I \\ \textbf{CP violation} \quad (\text{if } N_G \geq 3) \end{cases}$$

Flavour-Changing Charged Currents

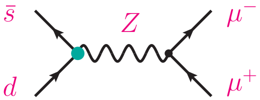
$$\boxed{\mathcal{L}_{\mathrm{CC}} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left\{ \sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, V_{ij}\, d_j + \sum_{ij} \bar{\nu}_i \gamma^\mu (1-\gamma_5)\, U_{ij}^\dagger\, \ell_j \right\} + \mathrm{h.c.}}$$





Flavour-Conserving Neutral Currents (GIM)

NO



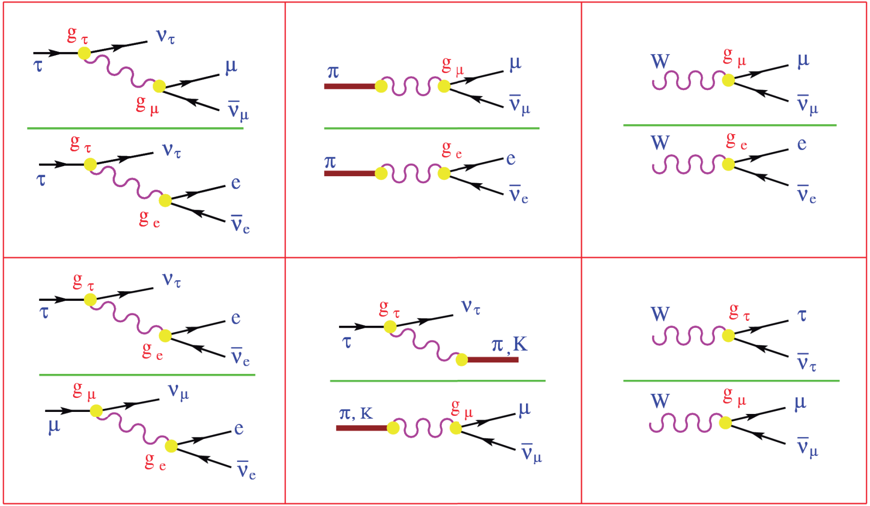
LHCb 2001.10354

$\mathrm{Br}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ (90% CL)

LEPTON UNIVERSALITY

$\frac{g_\mu}{g_e}$

$\frac{g_\tau}{g_\mu}$



CHARGED CURRENT UNIVERSALITY

A. Pich, arXiv:2511.04587

$\left| g_\mu / g_e \right|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0002 ± 0.0011
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0009 ± 0.0018
$B_{W\to\mu}/B_{W\to e}$	1.000 ± 0.002

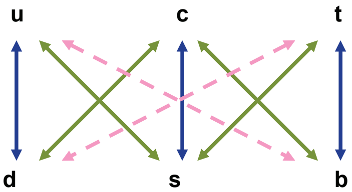
$\left| g_\tau / g_\mu \right|$

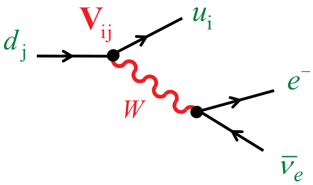
$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0016 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.996 ± 0.004
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.001 ± 0.010

$\left| g_\tau / g_e \right|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0018 ± 0.0014
$B_{W\to\tau}/B_{W\to e}$	1.007 ± 0.010

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} Determinations

PDG 2026

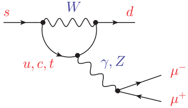
CKM	Value	Source
V_{ud}	0.97367 ± 0.00032	Nuclear β decay
V_{us}	0.22431 ± 0.00085	$K \to (\pi)\,\ell\nu$
V_{ub}	0.00389 ± 0.00016	$b \to u\ell\nu\,,\; B \to \pi\ell\nu$
V_{cd}	0.2247 ± 0.0022	$D \to (\pi)\,\ell\nu\,,\; \nu d \to cX$
V_{cs}	0.969 ± 0.005	$D \to K\ell\nu\,,\; D_s \to \ell\nu$
V_{cb}	0.0407 ± 0.0013	$b \to c\ell\nu\,,\; B \to D^{(*)}\ell\nu$
V_{td}	0.0086 ± 0.0002	$B_d^0 - \bar{B}_d^0$ mixing
V_{ts}	0.0415 ± 0.0009	$B_s^0 - \bar{B}_s^0$ mixing
V_{tb}	1.002 ± 0.024	$p\bar{p}\,,pp \to t\bar{b} + X$

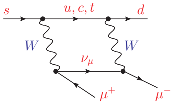
SM loop

$$\sum_j |V_{uj}|^2 = 0.9984\;(7) \quad , \quad \sum_j |V_{cj}|^2 = 0.991\;(10) \quad , \quad \sum_i |V_{ib}|^2 = 1.01\;(5)$$

$$W \to \ell\bar{\nu}_\ell \quad \Rightarrow \quad \sum_i \left(|V_{uj}|^2 + |V_{cj}|^2\right) = 2.002 \pm 0.027$$

Successful Description of Flavour & CP



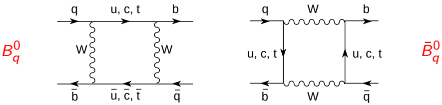


Rare Decays

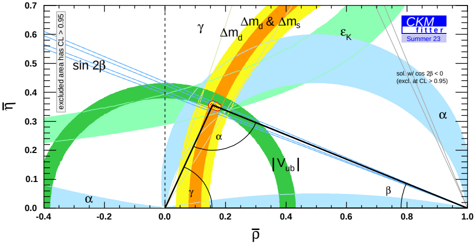
$$\mathrm{Br}(K_L^0 \to \mu^+\mu^-) = 6.8 \times 10^{-9}$$
$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = 3.3 \times 10^{-9}$$
$$\mathrm{Br}(\bar{b} \to \bar{s}\gamma) = 3.1 \times 10^{-4}$$

Meson-Antimeson Mixing

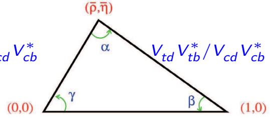
$$\Delta M_{K^0}/M_{K^0} = 7.0 \times 10^{-15}$$
$$\Delta M_{B_d^0}/M_{B_d^0} = 6.3 \times 10^{-14}$$
$$\Delta M_{B_s^0}/M_{B_s^0} = 2.2 \times 10^{-12}$$



CKM Unitarity



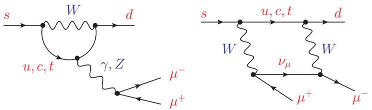
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$V_{ud}V_{ub}^*/V_{cd}V_{cb}^*$

$V_{td}V_{tb}^*/V_{cd}V_{cb}^*$

Successful Description of Flavour & CP



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$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = 3.3 \times 10^{-9}$$

$$\mathrm{Br}(\bar b \to \bar s\gamma) = 3.1 \times 10^{-4}$$

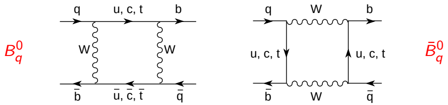
Sensitivity to heavy scales

Meson-Antimeson Mixing

$$\Delta M_{K^0}/M_{K^0} = 7.0 \times 10^{-15} \quad \Rightarrow \quad m_c$$

$$\Delta M_{B_d^0}/M_{B_d^0} = 6.3 \times 10^{-14} \quad \Rightarrow \quad m_t$$

$$\Delta M_{B_s^0}/M_{B_s^0} = 2.2 \times 10^{-12} \quad \Rightarrow \quad m_t$$



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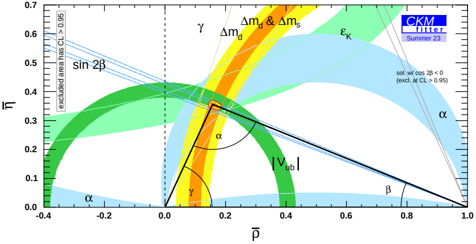

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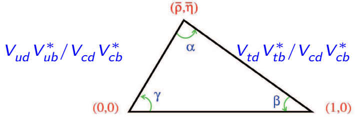


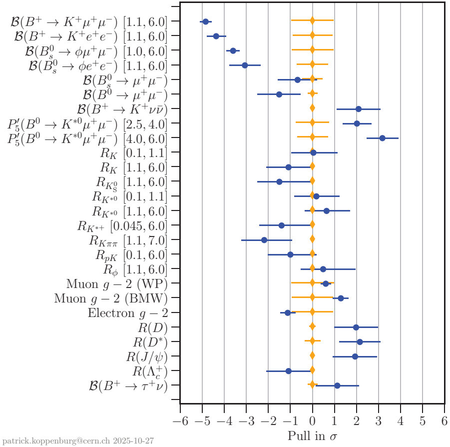
Flavour Anomalies

$b \to c\tau\nu\,,\;\; b \to s\,\mu^+\mu^-\,,\;\; \tau^\pm \to \pi^\pm K_S\nu\,,\;\; B \to K\nu\bar{\nu},\;\; V_{ud_i}\,,\;\; \Delta a_{\rm CP}^{D^0}\;\cdots$

Many already gone

$B \to \tau\nu\,,\;\; W \to \tau\nu\,,\;\; \varepsilon'_K/\varepsilon_K\,,\;\; \varepsilon_K\,,\;\; V_{cb}\,,\, R_K,\;\; (g-2)_{\mu,e}\;\cdots$

Statistical fluctuations, underestimated systematics . . .



Worth a careful investigation

Precision measurements could uncover signals of new underlying dynamics

Accurate control of QCD corrections needed

Cabibbo Anomaly $\sim 3\,\sigma$

CKM Unitarity ➡ $\boxed{1 \;=\; |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \;\approx\; |V_{ud}|^2 + |V_{us}|^2}$

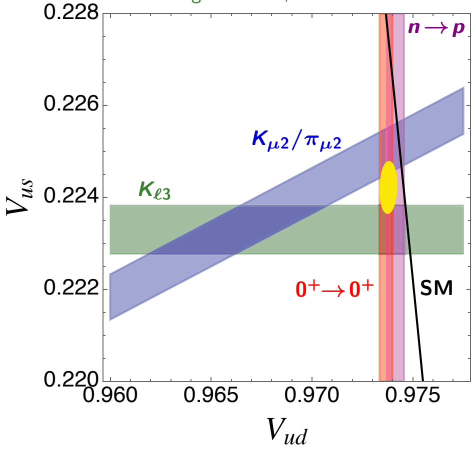
$K \to \pi \ell \nu$ ➡ V_{us}

$K \to \mu\nu / \pi \to \mu\nu$ ➡ V_{us}/V_{ud}

$0^+ \to 0^+$ nuclear β decays ➡ V_{ud}

$n \to p e \nu$ ➡ V_{ud}

Cirigliano et al, 2208.11707



Cabibbo Anomaly $\sim 3\,\sigma$

CKM Unitarity $\longrightarrow$ $\boxed{1 \;=\; |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \;\approx\; |V_{ud}|^2 + |V_{us}|^2}$

$K \to \pi \ell \nu \;\longrightarrow\; V_{us}$

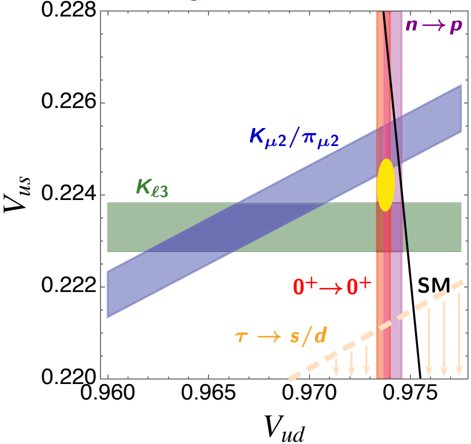
$K \to \mu\nu / \pi \to \mu\nu \;\longrightarrow\; V_{us}/V_{ud}$

$0^+ \to 0^+$ nuclear β decays $\longrightarrow$ V_{ud}

$n \to p e \nu \;\longrightarrow\; V_{ud}$

$\tau \to \nu_\tau s\bar{u} / \tau \to \nu_\tau d\bar{u} \;\longrightarrow\; V_{us}/V_{ud}$

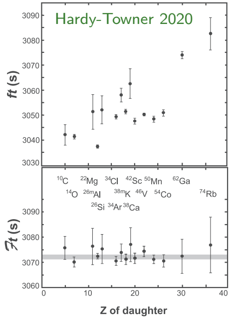
Cirigliano et al, 2208.11707

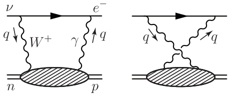


Superallowed $(0^+ \to 0^+)$ nuclear β transitions

$$|V_{ud}|^2 = \frac{\pi^3 \log 2}{ft\, G_F^2 m_e^5 \,(1 + \delta_{\rm RC})} = \frac{(2984.431 \pm 0.003)\ \mathrm{s}}{\mathcal{F}t\,(1 + \Delta_R^V)}$$

$$\mathcal{F}t = ft\,(1 + \Delta_{\rm Nucl})$$





Nucleus-independent radiative corrections

$$\Delta_R^V = 0.02479\,(21)$$

Gorchtein-Seng 2307.01145

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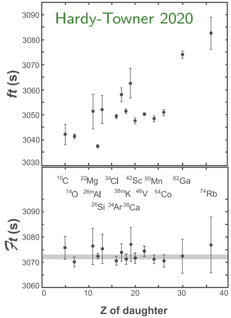

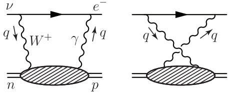

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Gorchtein-Seng 2307.01145

$$\mathcal{F}t = 3070.16\ (1.68)\ \mathrm{s}$$

He et al 2605.13985

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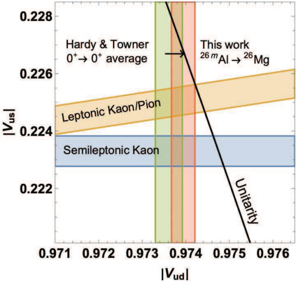

$$\mathcal{F}t|_{\mathrm{HT2020}} = 3072.24\ (1.85)\ \mathrm{s}$$

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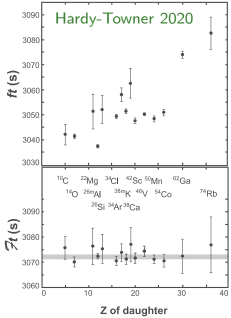
$$\mathcal{F}t = ft\,(1+\Delta_{\rm Nucl})$$



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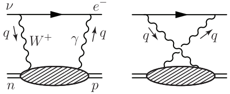

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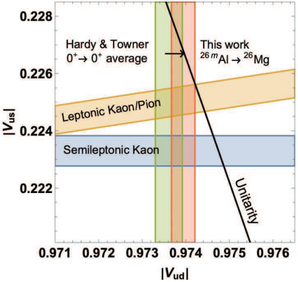


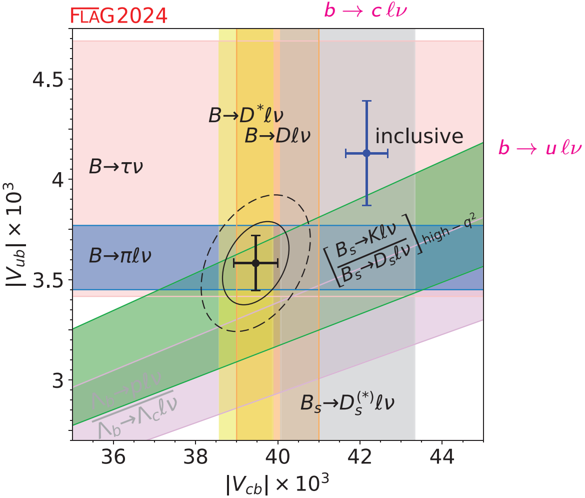
Gorbahn et al 2510.27648

$$\Delta_R^V = 0.02436\,(16) \quad \Longrightarrow \quad |V_{ud}| = 0.97415\,(28)$$

NLO, $\mathcal{O}(\alpha\alpha_s^2)$ corrections

$$\boxed{\Delta_{\rm CKM} \equiv \sum_i |V_{ui}|^2 - 1 = \begin{cases} -0.0012\ (6)\ K_{\ell 3} \\ -0.0004\ (6)\ K_{\ell 2} \end{cases}}$$

V_{cb} & V_{ub} : Inclusive–Exclusive Tension



- $|V_{ub}|$ tension no-longer significant

  Belle-II (2512.08056):

  $$|V_{ub}|_{\rm incl} = (4.01 \pm 0.19\,^{+\,0.07}_{-\,0.08})\cdot 10^{-3}$$

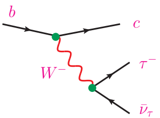
- $|V_{cb}|$ puzzle remains

  Tension reduced with $B\to D^*\ell\bar\nu$ reevaluation

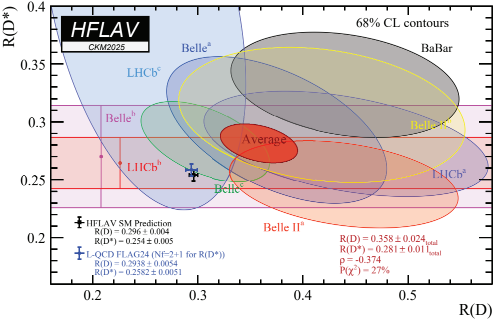
  Jung-Schacht 2604.08391

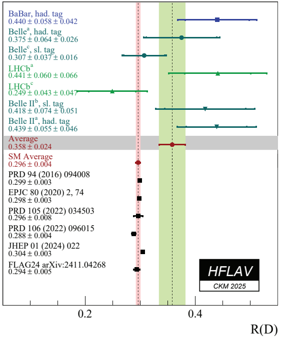
$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

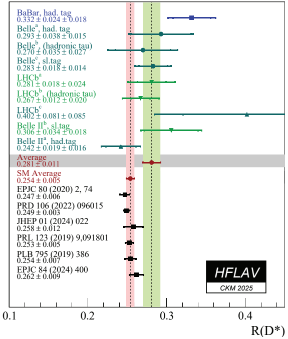
Tree-level process



3.8 σ discrepancy







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

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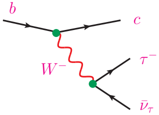
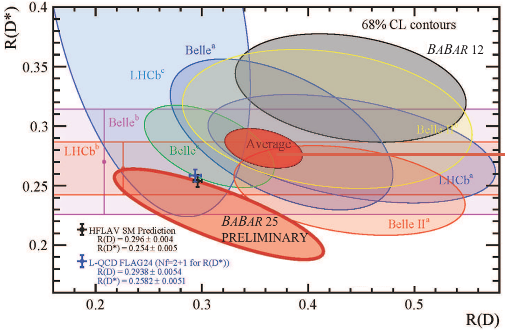


New BaBar Measurement

Experiment	$R(D)$	$R(D^*)$	Correlation
BABAR 12 (hadronic tag)	0.440 ± 0.058 ± 0.042	0.332 ± 0.024 ± 0.018	-0.27
HFLAV (CKM 2025 average)	0.281 ± 0.011	0.358 ± 0.024	-0.374
BABAR 25 (leptonic tag) PRELIMINARY	0.316 ± 0.062 ± 0.019	0.226 ± 0.022 ± 0.012	-0.82

BaBar 2012: hadronic tag
BaBar 2025: semileptonic tag



This average does not include the *BABAR* 25 preliminary result

The New World Average

(Grillo-Rotondo, Bad Honnef 2026)

$$R_D = 0.336 \pm 0.022 \qquad \rho = -0.51$$
$$R_{D^*} = 0.263 \pm 0.010$$

$2.0/1.6\,\sigma$ from SM

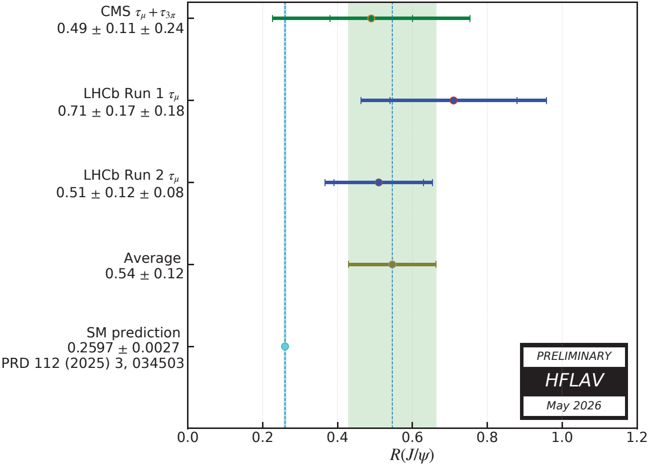
Babar ™ and © L. De Brunhoff

BABAR

David Hitlin December 15, 2025 15 Caltech

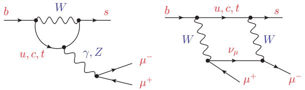
$$\mathcal{R}_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi\, \tau\nu_\tau)}{\mathcal{B}(B_c \to J/\psi\, \mu\nu_\mu)}$$

$2.4\,\sigma$ discrepancy

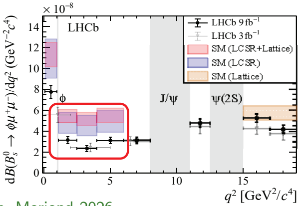


$b \to s\, \mu^+ \mu^-$

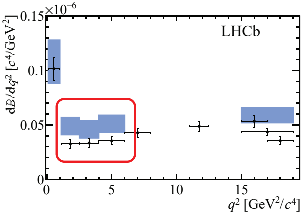
SM loop process



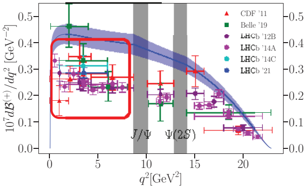
LHCb $B_s^0 \to \phi \mu^+ \mu^-$ [PRL 127 (2021) 151801]



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

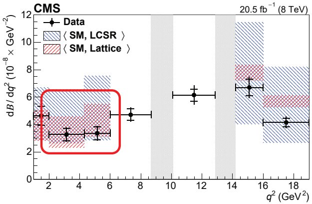


$B^+ \to K^+ \mu^+ \mu^-$ [HPQCD, PRD 107 (2023) 1]

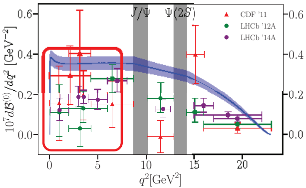


C. Langenbruch, Moriond 2026

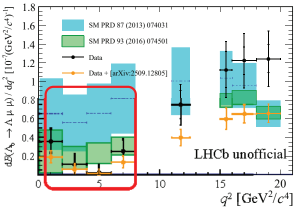
CMS $B^0 \to K^{*0} \mu^+ \mu^-$ [PLB 753 (2016) 424]



$B^0 \to K^0 \mu^+ \mu^-$ [HPQCD, PRD 107 (2023) 1]



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



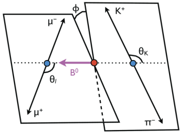
Data consistently below SM predictions **(1-3 σ tensions)** **Large hadronic uncertainties**

$B \to K^* \mu^+\mu^-$
$\to K\pi\,\mu^+\mu^-$

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

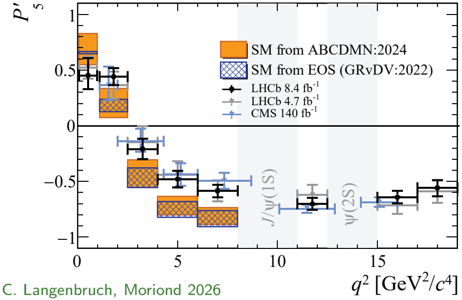
$$q^2 = s_{\mu\mu}$$

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



Observed tensions in optimized observables where form factors cancel at LO

Descotes-Genon et al 2013



C. Langenbruch, Moriond 2026

$B \to K^* \mu^+ \mu^-$
$\to K\pi\, \mu^+ \mu^-$

$$\frac{1}{d\Gamma/dq^2}\,\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
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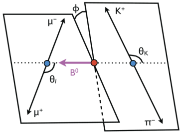
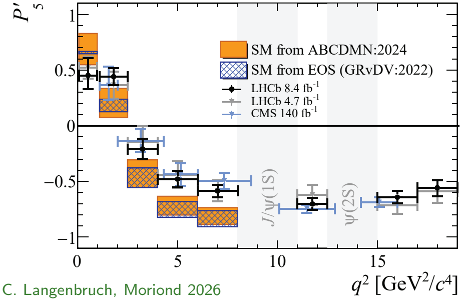


Observed tensions in optimized observables where form factors cancel at LO Descotes-Genon et al 2013

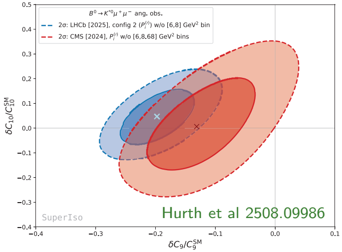


C. Langenbruch, Moriond 2026

New-Physics interpretation

$(\bar s_L\gamma_\mu b_L)\,[\bar\mu\gamma^\mu(\delta C_9 + \delta C_{10}\gamma_5)\mu]$

$\delta C_9 \approx -0.2\; C_9^{\rm SM}$



Hurth et al 2508.09986

$B \to K^* \mu^+ \mu^-$

$\to K\pi\, \mu^+ \mu^-$

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

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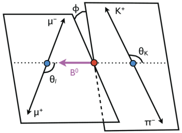
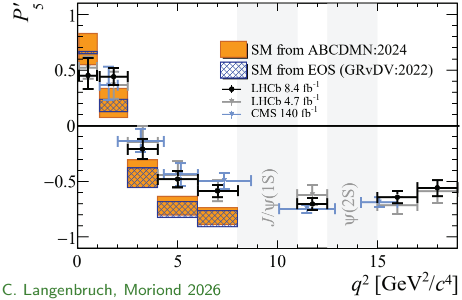
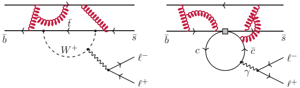


Observed tensions in optimized observables where form factors cancel at LO

Descotes-Genon et al 2013



C. Langenbruch, Moriond 2026



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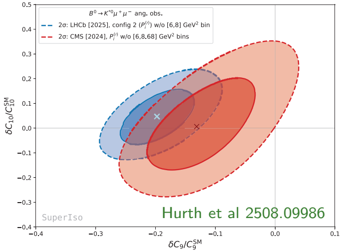
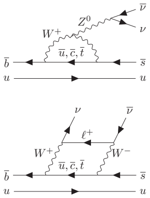


Large hadronic uncertainties

Improvements needed

- Local form factors — Gubernari et al, HPQCD
- Non-local contributions ($c\bar c$ loop) — Frezzoti et al, Gubernari et al



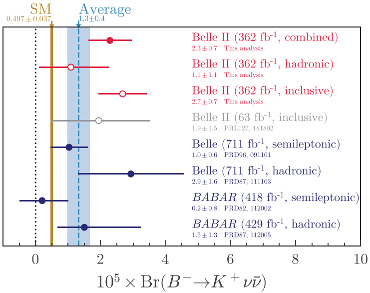
$B^+ \to K^+ \nu\bar{\nu}$

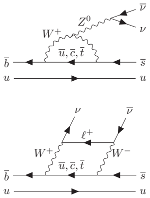
$$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.7) \cdot 10^{-5}$$

Belle-II, 2311.14647

$$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{SM}} = (0.497 \pm 0.037) \cdot 10^{-5}$$

2.7σ discrepancy





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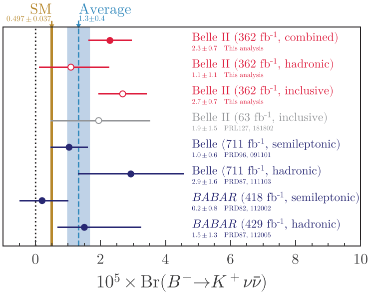
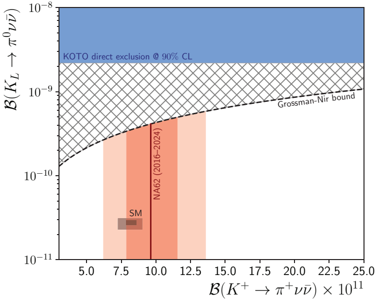




$K \to \pi\nu\bar{\nu}$

S. Martellotti, Beauty 2026

NA62: $\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) = (9.6\,^{+1.9}_{-1.8}) \cdot 10^{-11}$

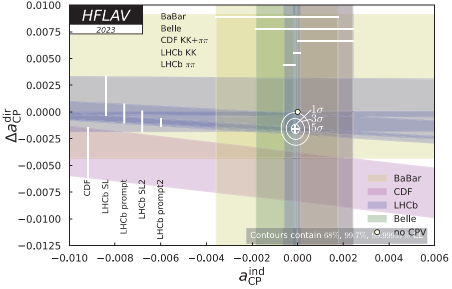
SM: $(7.73 \pm 0.61) \cdot 10^{-11}$

KOTO: $\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu}) < 2.2 \cdot 10^{-9}$ (90% CL)

$\cancel{C}\cancel{P}$ SM: $(2.59 \pm 0.29) \cdot 10^{-11}$

First evidence of $\not{\mathcal{CP}}$ in charm decays (5.3 σ)

LHCb 1903.08726: $\Delta a_{\mathcal{CP}} = (-15.4 \pm 2.9) \cdot 10^{-4}$, $\Delta a_{\mathcal{CP}}^{\mathrm{dir}} = (-15.7 \pm 2.9) \cdot 10^{-4}$



$$\Delta a_{\mathrm{CP}} = a_{\mathrm{CP}}(K^+K^-) - a_{\mathrm{CP}}(\pi^+\pi^-)$$

$$a_{\mathrm{CP}} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

HFLAV combination	$a_{\mathrm{CP}}^{\mathrm{ind}} = (-0.010 \pm 0.012)\%$ $\Delta a_{\mathrm{CP}} = (-0.159 \pm 0.029)\%$

Large uncertainty in SM prediction:

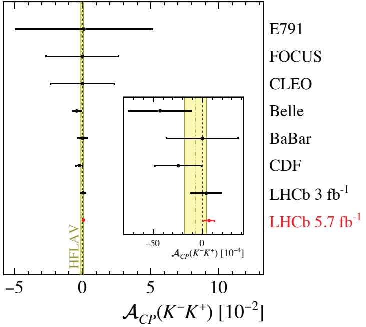
- QCD Light-Cone Sum Rules: $|\Delta a_{\mathcal{CP}}^{\mathrm{dir}}| \leq 2.4 \cdot 10^{-4}$ Lenz et al 2312.13245, Khodjamirian-Petrov 1706.07780
- Naive perturbative QCD (+ LCSR): $|\Delta a_{\mathcal{CP}}^{\mathrm{dir}}| \lesssim 3.6 \cdot 10^{-4}$ Chala et al 1903.10490
- Re-scattering: $\Delta a_{\mathcal{CP}}^{\mathrm{dir}}$ ➡ $\Delta U = 0$ rule in charm Grossman-Schacht 1903.10952
- Nearby resonance Schacht-Soni 2110.07619

Time-integrated CP asymmetry

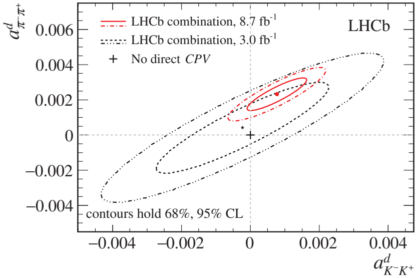
$$\mathcal{A}_{\rm CP}(f) \approx a_f^d + \frac{\langle t\rangle_f}{\tau_{D^0}}\,\Delta Y$$

$$a_f^d \equiv \frac{|\mathcal{M}(D^0\to f)|^2 - |\mathcal{M}(\bar{D}^0\to \bar{f})|^2}{|\mathcal{M}(D^0\to f)|^2 + |\mathcal{M}(\bar{D}^0\to \bar{f})|^2}$$

$$\mathcal{A}_{\rm CP}(K^-K^+) = (6.8 \pm 5.4 \pm 1.6)\cdot 10^{-4}$$



LHCb 2209.03179



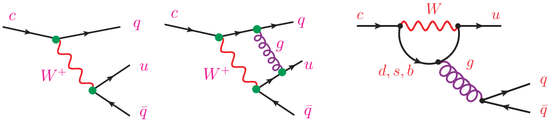
Evidence of direct $\not{CP}$ in $D^0\to\pi^-\pi^+$ (3.8σ)

$$a^d_{\pi^-\pi^+} = (23.2\pm 6.1)\cdot 10^{-4}$$

$$a^d_{K^-K^+} = (7.7\pm 5.7)\cdot 10^{-4}$$

$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$

Short-distance contributions



$(q = d, s)$

$$\boxed{\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} \left[\sum_{i=1}^{2} C_i(\mu) \left(\lambda_d Q_i^d + \lambda_s Q_i^s \right) - \lambda_b \sum_{i=3}^{6} C_i(\mu) Q_i \right] + \mathrm{h.c.}}$$

$$\lambda_q = V_{cq}^* V_{uq} \qquad (q = d, s, b)$$

$$\lambda_d + \lambda_s + \lambda_b = 0$$

$$\begin{aligned}
Q_1^d &= (\bar{d}c)_{V-A}(\bar{u}d)_{V-A} \quad , & Q_2^d &= (\bar{d}_j c_i)_{V-A}(\bar{u}_i d_j)_{V-A} \doteq (\bar{u}c)_{V-A}(\bar{d}d)_{V-A} \\
Q_1^s &= (\bar{s}c)_{V-A}(\bar{u}s)_{V-A} \quad , & Q_2^s &= (\bar{s}_j c_i)_{V-A}(\bar{u}_i s_j)_{V-A} \doteq (\bar{u}c)_{V-A}(\bar{s}s)_{V-A} \\
Q_3 &= (\bar{u}c)_{V-A} \textstyle\sum_q (\bar{q}q)_{V-A} \quad , & Q_4 &= (\bar{u}_j c_i)_{V-A} \textstyle\sum_q (\bar{q}_i q_j)_{V-A} \doteq \textstyle\sum_q (\bar{q}c)_{V-A}(\bar{u}q)_{V-A} \\
Q_5 &= (\bar{u}c)_{V-A} \textstyle\sum_q (\bar{q}q)_{V+A} \quad , & Q_6 &= (\bar{u}_j c_i)_{V-A} \textstyle\sum_q (\bar{q}_i q_j)_{V+A} \doteq -2 \textstyle\sum_q (\bar{q}c)_{S-P}(\bar{u}q)_{S+P}
\end{aligned}$$

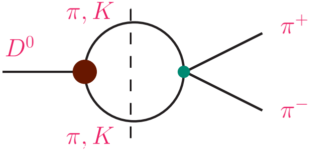
$|\lambda_b| \approx A^2 \lambda^5 \sqrt{\rho^2 + \eta^2} \ll |\lambda_s| \approx |\lambda_d| \approx \lambda \sim 0.22$ ➔ **Penguins irrelevant in rates**

CKM phase (penguins) needed for $\not{C}\not{P}$: (small effect)

$$\mathrm{Im}(\lambda_d) \approx -\mathrm{Im}(\lambda_b) = A^2 \lambda^5 \eta + \mathcal{O}(\lambda^7) \approx 1.4 \cdot 10^{-4} \quad , \quad \mathrm{Im}(\lambda_s) = \mathcal{O}(\lambda^7)$$

SM estimate of $C\!\!\!/ P\!\!\!/$ $D \to \pi\pi, KK$ asymmetries

A.P., E. Solomonidi, L. Vale-Silva, 2305.11951



- **SM decay amplitudes at large N_C:** NLO Wilson coefficients, lattice decay constants and form factors
- **FSI implemented through a dispersive approach:** Coupled channels, all available scattering data

$A_{CP} \times 10^4$	Th	Exp	$A_{CP} \times 10^4$	Th	Exp
$D^0 \to \pi^-\pi^+$	2	23.2 ± 6.1	$D^0 \to K^-K^+$	-2	7.7 ± 5.7
$D^0 \to \pi^0\pi^0$	3	0 ± 60	$D^0 \to K_S K_S$	-7	-190 ± 110
$D^+ \to \pi^0\pi^+$	0	40 ± 130	$D^+ \to K_S K^+$	0	-1 ± 7

SM prediction for $D^0 \to \pi^-\pi^+$ asymmetry well below experimental measurement

Missing (nonperturbative) effects, experimental problem or New Physics?

On-going work: input uncertainties, additional re-scattering channels. . .

Summary

- Flavour structure and $\not{\mathcal{CP}}$ are major pending questions (underlying dynamics?)
- Related to SSB $\longrightarrow$ Scalar sector (Higgs)
- Important cosmological implications (Baryogenesis)
- Sensitive to New Physics (flavour anomalies?)
- $\not{\mathcal{CP}}$ is highly constrained in the SM: 1 phase only
- Many interesting ($\not{\mathcal{CP}}$) signals within experimental reach
- Improved control of QCD effects urgently needed

Eagerly awaiting new experimental results (higher statistics & better systematics)

Don Quixote and the Windmills

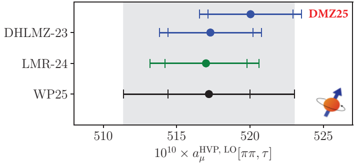
Backup

μ Anomalous Magnetic Moment

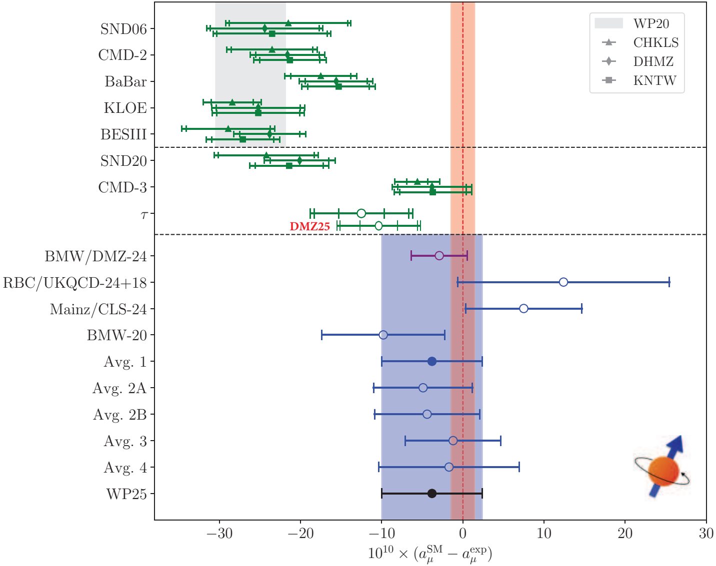
2025 Status

WP25, 2505.21476

Davier et al, 2504.13789



DMZ25 not included in WP25

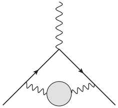


$$a_\mu^{\text{SM}} - a_\mu^{\text{exp}} = -(38 \pm 63) \cdot 10^{-11}$$

FNAL Muon $g-2$, 2606.17323

LO Hadronic Vacuum Polarization

2020 Status

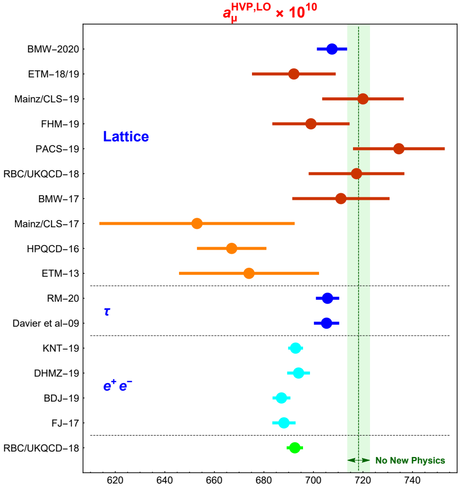


$$a_\mu^{\rm HVP,LO} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{s_{\rm th}}^\infty \frac{ds}{s^2}\, \hat{K}(s)\, R(s)$$

Dominated (75%) by 2π contribution

$$R(s) = \frac{\sigma^0[e^+e^- \to {\rm hadrons}\,(\gamma)]}{4\pi\alpha^2/(3s)}$$

$$\frac{d\Gamma(\tau^- \to \nu_\tau V^-)}{ds} \propto \sigma^{I=1}(e^+e^- \to V^0)$$



The BMW-2020 and τ results were not included in the WP 2020 value