Flavour Anomalies

Hints of new non-universal interactions?

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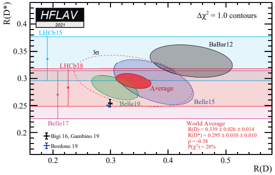
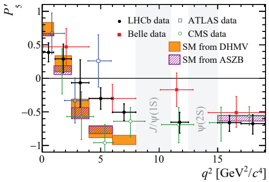
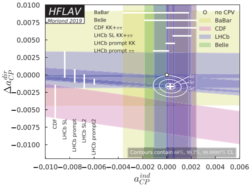
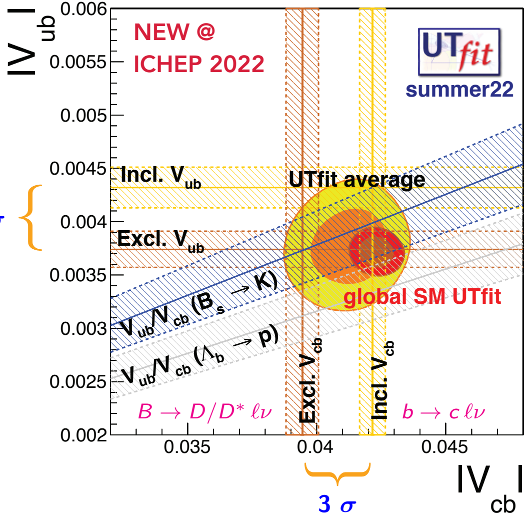






XLIX International Meeting on Fundamental Physics (IMPF22), Benasque (Spain), 5–10 September 2022

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



2–3 σ

$b \to u\,\ell\nu$

$B \to \pi/\rho\,\ell\nu$

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

$b \to c\,\ell\nu$

3 σ

Cabibbo Anomaly $\sim 3\,\sigma$

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

$K \to \pi \ell \nu$ ➡ V_{us}

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

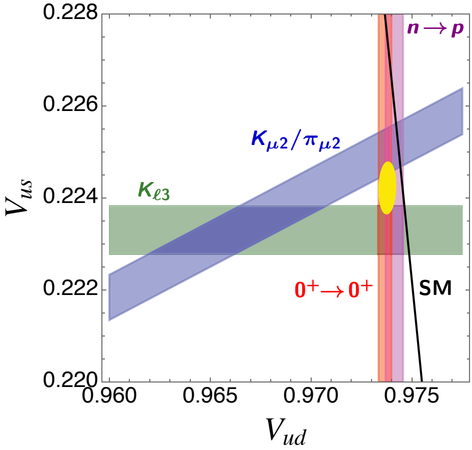
$0^+ \to 0^+$ nuclear β decays ➡ V_{ud}

$n \to p e \nu$ ➡ V_{ud}

Recalculation of radiative corrections

C.-Y. Seng, 2112.10942

Cirigliano et al, 2208.11707



Cabibbo Anomaly $\sim 3\,\sigma$

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

$K \to \pi \ell \nu$ ➡ 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}

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

Recalculation of radiative corrections

C.-Y. Seng, 2112.10942

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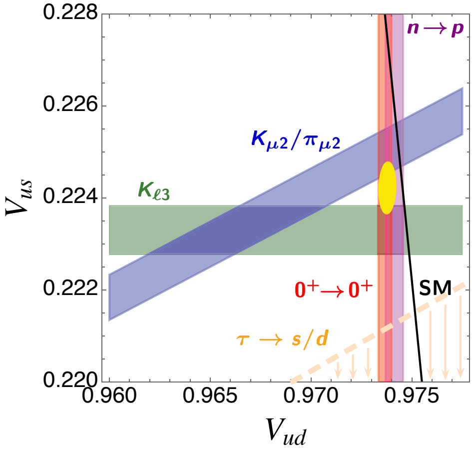
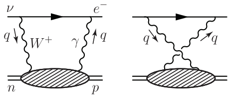


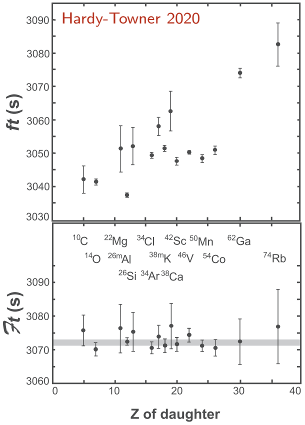
V_{ud}: Superallowed $(0^+ \to 0^+)$ nuclear β transitions

$f_+(0) = 1 + \mathcal{O}[(m_u - m_d)^2]$ ➡ $|V_{ud}|^2 = \frac{\pi^3 \log 2}{ft\, G_F^2 m_e^5\, (1+\delta_{\mathrm{RC}})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\,(1+\delta_{\mathrm{RC}})}$

$\delta_{\mathrm{RC}} = \Delta_R^V + \Delta_{\mathrm{Nucl}}$, $\mathcal{F}t = ft\,(1+\Delta_{\mathrm{Nucl}})$



Nucleus-independent radiative corrections



$$\Delta_R^V = \begin{cases} 0.02361\ (38) & \text{Marciano-Sirlin 2006} \\ 0.02467\ (22) & \text{Seng et al, 1807.10197} \\ 0.02426\ (32) & \text{Czarnecki et al, 1907.06737} \end{cases}$$

➡ $$|V_{ud}| = \begin{cases} 0.97420\ (21) & \text{PDG 2018} \\ 0.97373\ (31) & \text{Hardy-Towner 2020} \end{cases}$$

$$|V_{us}| = \begin{cases} 0.2231\ (6) & K\to\pi\ell\nu \\ 0.2252\ (5) & K/\pi\to\mu\nu \end{cases}$$

PDG 2022 ➡

$$1 - \sum_i |V_{ui}|^2 = \begin{cases} 0.00206\ (66) & 3.1\,\sigma \\ 0.00112\ (64) & 1.7\,\sigma \end{cases}$$

V_{ud}: Superallowed $(0^+ \to 0^+)$ nuclear β transitions

$f_+(0) = 1 + \mathcal{O}[(m_u - m_d)^2]$ ➡ $$|V_{ud}|^2 = \frac{\pi^3 \log 2}{ft\, G_F^2 m_e^5\, (1+\delta_{\mathrm{RC}})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\,(1+\delta_{\mathrm{RC}})}$$

$$\delta_{\mathrm{RC}} = \Delta_R^V + \Delta_{\mathrm{Nucl}} \quad , \quad \mathcal{F}t = ft\,(1+\Delta_{\mathrm{Nucl}}) \quad , \quad \Delta_{\mathrm{Nucl}} = \delta_R' + \delta_{\mathrm{NS}} - \delta_C$$

Hardy-Towner 2020:

$$\Delta_R^V = 0.02454\ (19)$$

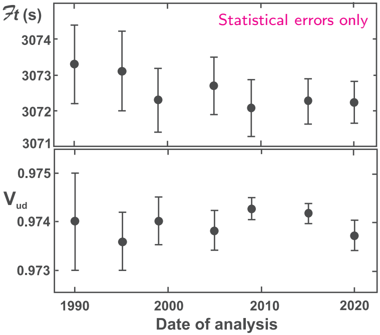
$$\mathcal{F}t = (3072.24 \pm 0.57_{\mathrm{stat}} \pm 0.36_{\delta_R'} \pm 1.73_{\delta_{\mathrm{NS}}})\ \mathrm{s}$$
$$= (3072.24 \pm 1.85)\ \mathrm{s}$$

$\mathcal{F}t$ error 2.6 larger than in 2015 (δ_{NS})

Seng et al, Gorchtein

⬇

$$|V_{ud}| = 0.97373\ (31)$$



➡ $$1 - \sum_i |V_{ui}|^2 = \begin{cases} 0.00206\ (66)_{K\to\pi\ell\nu} & 3.1\,\sigma \\ 0.00112\ (64)_{K/\pi\to\mu\nu} & 1.7\,\sigma \end{cases}$$

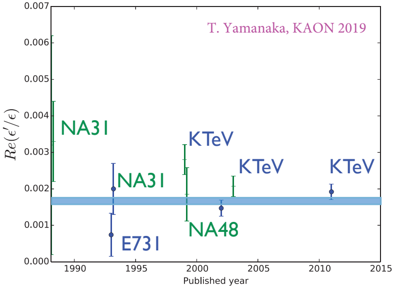
CP Violation in $K \to \pi\pi$

$$\eta_{00} \equiv \frac{\mathcal{M}(K_L^0 \to \pi^0\pi^0)}{\mathcal{M}(K_S^0 \to \pi^0\pi^0)} \equiv \varepsilon - 2\varepsilon' \qquad , \qquad \eta_{+-} \equiv \frac{\mathcal{M}(K_L^0 \to \pi^+\pi^-)}{\mathcal{M}(K_S^0 \to \pi^+\pi^-)} \equiv \varepsilon + \varepsilon'$$

- **Indirect $\not{C}\not{P}$:** $\quad |\varepsilon| = \frac{1}{3}\,|\eta_{00} + 2\,\eta_{+-}| = (2.228 \pm 0.011)\cdot 10^{-3}$
- **Direct $\not{C}\not{P}$:** $\quad \mathrm{Re}(\varepsilon'/\varepsilon) = \frac{1}{3}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|\right) = (16.6 \pm 2.3)\cdot 10^{-4}$

First evidence in 1988 by NA31

Time evolution of ε'/ε measurements



Time evolution of ε'/ε predictions: 10^{-3} units

- 1983	SD (Q_6), LO	~ 2	Gilman-Hagelin
- 1990-2000	SD, large m_t (Q_8), NLO	$\sim \text{few} \cdot 10^{-1}$	Munich, Rome
	+ models of LD contributions	$\sim \mathcal{O}(1)$	Dortmund, Trieste
- 1999-2001	SD + LD (χPT) at NLO	1.7 ± 0.9	Scimemi-Pallante-Pich
- 2000-2003	models of LD contributions	$\sim \mathcal{O}(1)$	Lund, Marseille
- 2003	NLO isospin breaking in χPT	1.9 ± 1.0	Cirigliano-Ecker-Neufeld-Pich
- 2015	Lattice	0.14 ± 0.70	RBC-UKQCD
- 2015-2017	Dual QCD, Lattice input	0.19 ± 0.45	Munich
- 2017	NLO χPT re-analysis	1.5 ± 0.7	Gisbert-Pich
- 2019	χPT re-analysis of NLO IB	1.4 ± 0.5	Cirigliano-Gisbert-Pich-Rodríguez
- 2020 (April)	Lattice re-analysis (no IB)	2.17 ± 0.84	RBC-UKQCD
- 2020 (May)	Lattice input + χPT IB	1.74 ± 0.61	Munich
	Lattice input + naive IB	1.39 ± 0.52	

Empirical Evidence

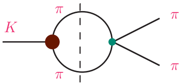
$$A[K^0 \to \pi^+\pi^-] = A_0\, e^{i\delta_0} + \frac{1}{\sqrt{2}} A_2\, e^{i\delta_2} \equiv \mathcal{A}_{1/2} + \frac{1}{\sqrt{2}}\mathcal{A}_{3/2}$$

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

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

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

- **Unitarity:** $\delta_0 = (39.2 \pm 1.5)^\circ$ ➔ $A_0 \approx 1.3 \times \mathrm{Dis}(\mathcal{A}_0)$



$$A_I = \mathrm{Dis}(\mathcal{A}_I)\,\sqrt{1+\tan^2\delta_I} \qquad \tan\delta_I = \frac{\mathrm{Abs}(\mathcal{A}_I)}{\mathrm{Dis}(\mathcal{A}_I)}$$

- **Analyticity:** $\Delta\, \mathrm{Dis}(\mathcal{A}_I)[s] = \frac{1}{\pi}\int dt\, \frac{\mathrm{Abs}(\mathcal{A}_I)[t]}{t-s-i\epsilon} + \text{subtractions}$

Large δ_0 ➔ Large $\mathrm{Abs}(\mathcal{A}_0)$ ➔ Large correction to $\mathrm{Dis}(\mathcal{A}_0)$

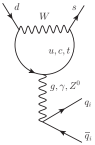
Claims of an ε'/ε anomaly originate in incorrect treatments of the $\pi\pi$ cut

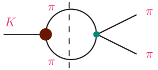
SM Prediction of ε'/ε

Cirigliano, Gisbert, Pich, Rodríguez-Sánchez, 1911.01359

Effective Field Theory

M_W	W, Z, γ, g; τ, μ, e, ν_i; t, b, c, s, d, u	Standard Model
	↓ OPE	
$\lesssim m_c$	γ, g ; μ, e, ν_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	γ ; μ, e, ν_i; π, K, η	χPT





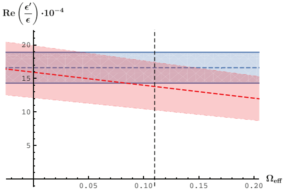
$$\mathcal{L}_{\rm eff}^{\Delta S=1} \sim \sum_i C_i(\mu) Q_i(\mu)$$

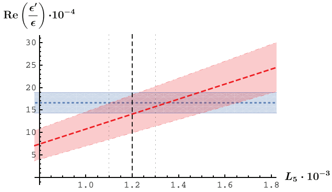
Large logarithms:

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

χPT: $\log(\mu/m_\pi)$

→ $$\mathrm{Re}\,(\varepsilon'/\varepsilon)_{\rm SM} = (14 \pm 5)\cdot 10^{-4}$$

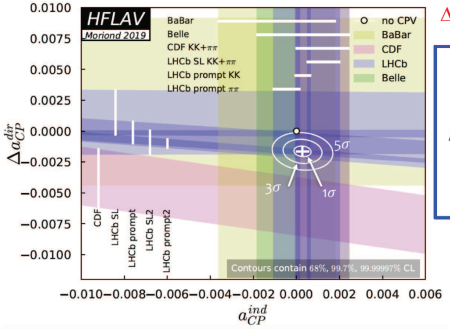




$$\mathrm{Re}\,(\varepsilon'/\varepsilon)_{\rm SM} = \left(13.8\,{}^{+0.5}_{-0.4}{}_{m_s}\;{}^{+1.7}_{-1.3}{}_{\mu}\;{}^{+3.1}_{-3.2}{}_{\nu_\chi} \pm 1.3_{\gamma_5} \pm 2.1_{L_{5,8}} \pm 1.3_{L_7} \pm 0.2_{K_i} \pm 0.3_{X_i}\right)\cdot 10^{-4}$$

First evidence of $\not{CP}$ in charm decays $(5.3\,\sigma)$

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



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

HFLAV combination

$a_{CP}^{\rm ind} = (0.028 \pm 0.026)\%$

$\Delta a_{CP}^{\rm dir} = (-0.164 \pm 0.028)\%$

Consistency with NO CPV hypothesis: 5×10^{-8}

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

Large uncertainty in SM prediction:

- Naive perturbative QCD (+ LCSR) ➔ $|\Delta a_{\mathcal{CP}}^{\rm dir}| \leq 3\cdot 10^{-4}$ — Chala et al, 1903.10490
- Re-scattering: $\Delta a_{\mathcal{CP}}^{\rm dir}$ ➔ $\Delta U = 0$ rule in charm — Grossman-Schacht, 1903.10952
- Dispersive work in progress — Solomonidi, Vale-Silva, A.P.

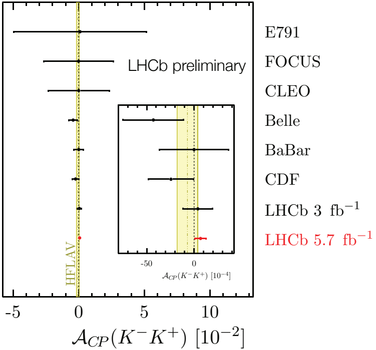
S. Maccolini, ICHEP 2022

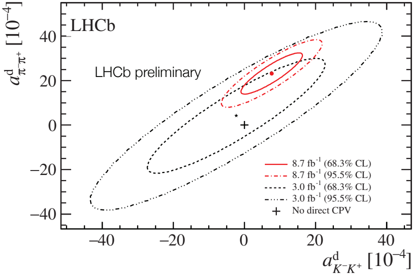
Time-integrated CP asymmetry

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

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

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





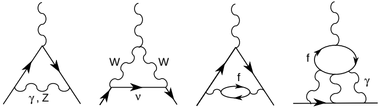
Evidence of direct $\not{CP}$ in $D^0\to\pi^-\pi^+$ (3.8σ)

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

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

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

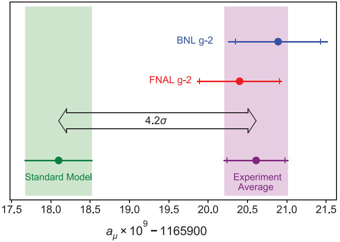
μ Anomalous Magnetic Moment



$$\mu_\ell = \frac{e}{2m_\ell}\,\frac{g_\ell}{2} \qquad , \qquad a_\ell \equiv \frac{1}{2}\,(g_\ell - 2)$$

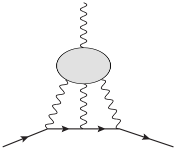
White Paper (2020) — G. Colangelo, Moriond EW 2021

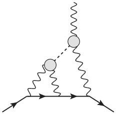
Contribution	Value $\times 10^{11}$
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	−98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice , $udsc$)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, uds)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Experiment (E821)	116 592 089(63)
Difference: $\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM}$	279(76)



$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59)\cdot 10^{-11} \qquad (4.2\sigma)$$

Light-by-Light Contributions





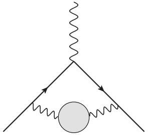
Colangelo, Moriond EW 2021

Contribution	PdRV(09) *Glasgow consensus*	N/JN(09)	J(17)	WP(20)
π^0, η, η'-poles	114(13)	99(16)	95.45(12.40)	93.8(4.0)
π, K-loops/boxes	−19(19)	−19(13)	−20(5)	−16.4(2)
S-wave $\pi\pi$ rescattering	−7(7)	−7(2)	−5.98(1.20)	−8(1)
subtotal	88(24)	73(21)	69.5(13.4)	69.4(4.1)
scalars	–	–	–	} − 1(3)
tensors	–	–	1.1(1)	}
axial vectors	15(10)	22(5)	7.55(2.71)	6(6)
u, d, s-loops / short-distance	–	21(3)	20(4)	15(10)
c-loop	2.3	–	2.3(2)	3(1)
total	105(26)	116(39)	100.4(28.2)	92(19)

A lot of work since Glasgow consensus (Prades, de Rafael, Vainshtein, 2009):

Masjuan, Sánchez-Puertas (17); Colangelo, Hagelstein, Hoferichter, Laub, Procura, Stoffer (17-20); Hoferichter, Hoid, Kubis, Leupold, Schneider (18); Bijnens, Hermansson-Truedsson, Laub, Rodríguez-Sánchez (20, 21); . . .

Errors reduced, size unchanged ➡ **Cannot account for the anomaly**



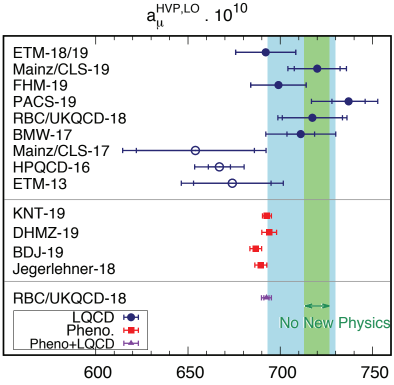
LO Hadronic Vacuum Polarization

Aoyama et al, 2006.04822

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

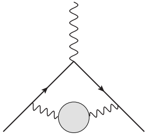
$\uparrow$

Dominated (75%) by 2π contribution



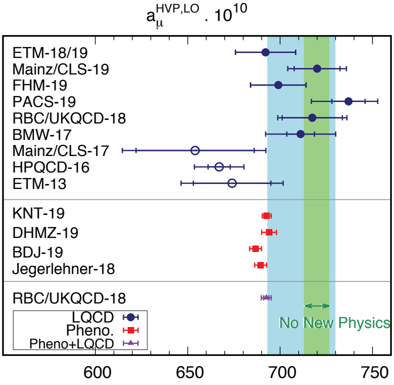
$$R(s) = 12\pi\, \mathrm{Im}\Pi_{\mathrm{em}}(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

2020 $\Rightarrow$ $\Delta a_\mu \equiv a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (279 \pm 76)\cdot 10^{-11}$ (3.7σ)



LO Hadronic Vacuum Polarization

Aoyama et al, 2006.04822



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

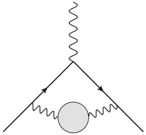
$\uparrow$

Dominated (75%) by 2π contribution

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

Data need to be undressed $\longrightarrow$ MC

2020 ➡ $\Delta a_\mu \equiv a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (279 \pm 76) \cdot 10^{-11}$ (3.7σ)



LO Hadronic Vacuum Polarization

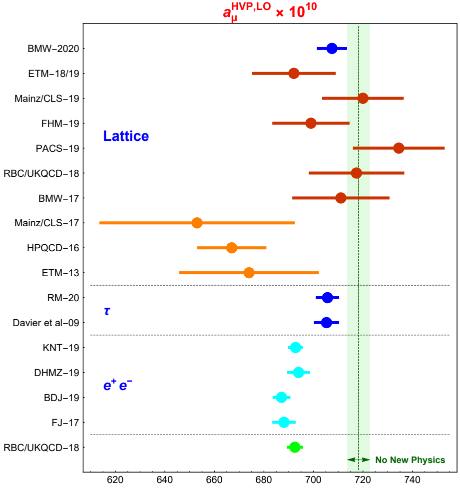
$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{s_{\mathrm{th}}}^{\infty} \frac{ds}{s^2}\, \hat{K}(s)\, R(s)$$

$\uparrow$

Dominated (75%) by 2π contribution

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

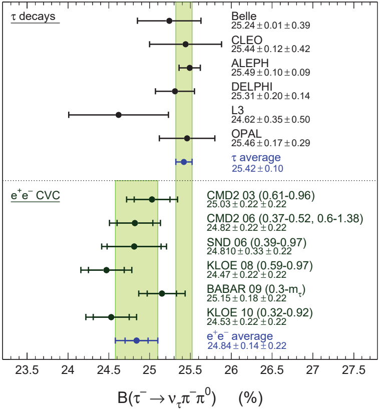
$$\frac{d\Gamma(\tau^- \to \nu_\tau V^-)}{ds} \propto \sigma^{I=1}(e^+e^- \to V^0)$$



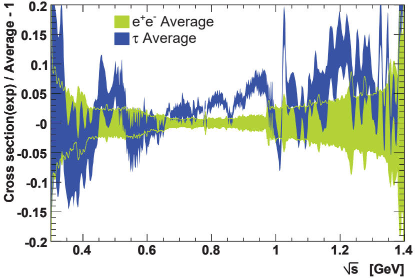
The BMW-2020 and τ results were not included in the WP 2020 value

e^+e^- versus τ data

Davier et al, 0906.5443



Davier et al, 0908.4300

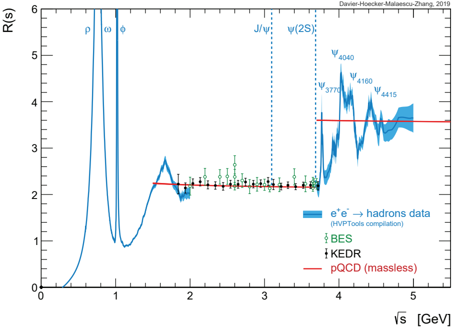


Isospin-breaking corrections: Cirigliano et al, hep-ph/0104267, hep-ph/0207310
Flores-Baez et al, hep-ph/0608084

Updated in Miranda-Roig, 2007.11019

Major tensions in hadronic e^+e^- data

Davier et al, 1908.00921



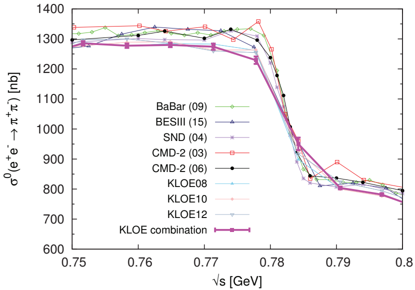
Experimental Discrepancies

- BaBar/KLOE disagreement at $\rho(\pi\pi)$
- Differences in $\phi(K^+K^-)$ largely exceed the quoted uncertainties
- Inclusive results larger than exclusive ones around 2 GeV

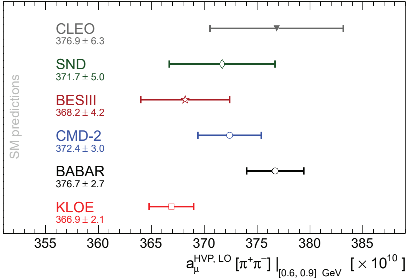
- Compilation of different data sets with quite different systematics
- Energy scanning versus Initial State Radiation method (BaBar, KLOE)
- Modelling of Final State Radiation needed (usually with scalar QED)
- The most relevant discrepancy for $a_\mu^{\mathrm{HVP,LO}}$ is Babar vs KLOE at $\rho(\pi\pi)$

KLOE data vs other experiments

KLOE-2, 1711.03085



Aoyama et al, 2006.04822

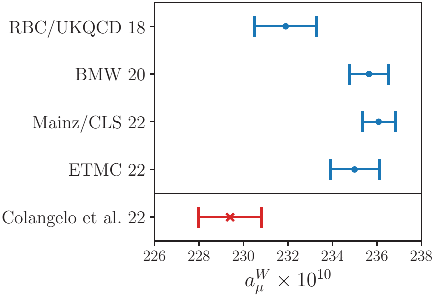


Discrepancies in the differential distribution are much larger than what gets reflected in the integral over the mass spectrum

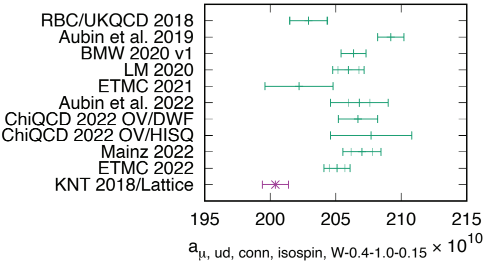
Compensating effects → **Underestimated systematics**

Recent Lattice simulations agree with BMW & τ

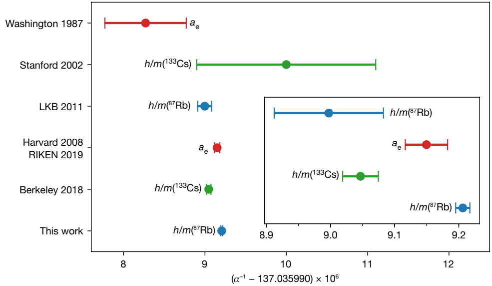
Comparison performed with specific windows in Euclidean time to increase reliability



M. Bruno, Lattice 2022



Electron Anomalous Magnetic Moment



Morel et al, Nature 588 (2020) 61

New measurement of α

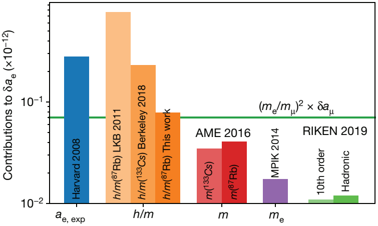
$$\alpha^{-1}(\mathrm{Rb}) = 137.035\,999\,206\ (11)$$

8.1×10^{-11} accuracy

$5.8\,\sigma$ discrepancy with Cs experiment

$$\Delta a_e \equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}}$$

$$= \begin{cases} (-8.8 \pm 3.6) \cdot 10^{-13} & (\mathrm{Cs},\ -2.4\sigma) \\ (+4.8 \pm 3.0) \cdot 10^{-13} & (\mathrm{Rb},\ +1.6\sigma) \end{cases}$$



Summary

- Flavour structure and $\mathcal{C}\!\!\!/\mathcal{P}$ 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 3rd family)**

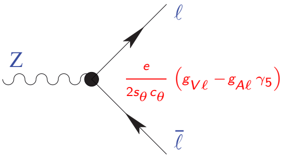
Many questions. Higher statistics & better systematics (QCD) needed

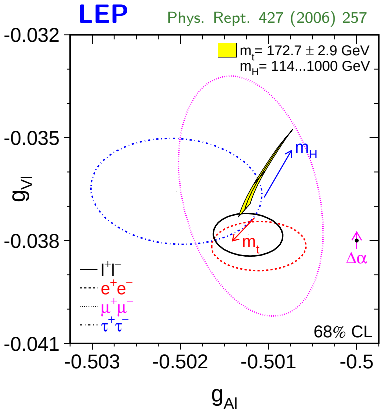
Eagerly awaiting new experimental results


Look, your worship, it's just the spectrum of the Standard Model
Massive & dark SUSY states show up through a hidden portal from a warped dimension

Backup

Lepton Flavour Universality in Z Decays





V_{ij} Determinations

PDG 2022

CKM	Value	Source
V_{ud}	0.97373 ± 0.00031	Nuclear β decay
V_{us}	0.2243 ± 0.0008	$K \to (\pi)\,\ell\nu$
V_{ub}	0.00382 ± 0.00020	$b \to u\ell\nu\,,\; B \to \pi\ell\nu$
V_{cd}	0.221 ± 0.004	$D \to (\pi)\,\ell\nu\,,\; \nu d \to cX$
V_{cs}	0.975 ± 0.006	$D \to K\ell\nu\,,\; D_s \to \ell\nu$
V_{cb}	0.0408 ± 0.0014	$b \to c\ell\nu\,,\; B \to D^{(*)}\ell\nu$
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}	1.014 ± 0.029	$p\bar{p}\,,\, pp \to t\bar{b} + X$

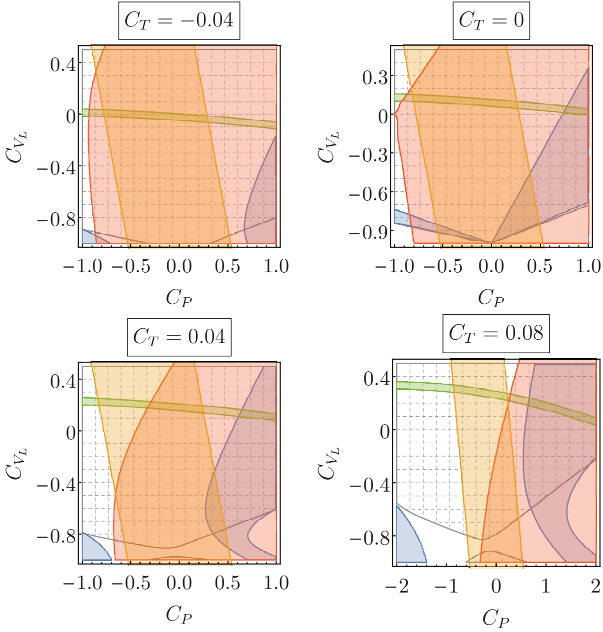
} SM loop (V_{td}, V_{ts})

$$\sum_j |V_{uj}|^2 = 0.9985\ (7) \quad , \quad \sum_j |V_{cj}|^2 = 1.001\ (12) \quad , \quad \sum_i |V_{ib}|^2 = 1.03\ (6)$$

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

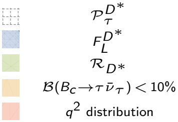
$\mathbf{D^*}$ Observables

Murgui-Peñuelas-Jung-Pich, 1904.09311



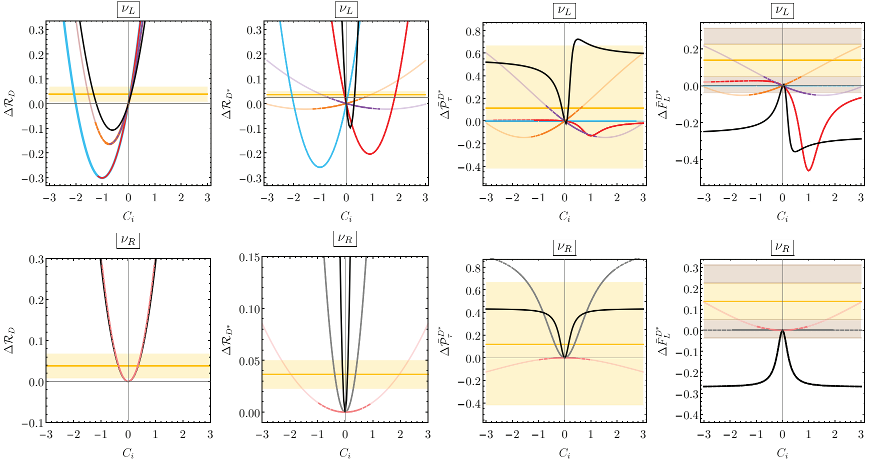
It is not possible to accommodate all D^* data at 1σ

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



Sensitivity to individual Wilson coefficients

Mandal-Murgui-Peñuelas-Pich, 2004.06726



ν_L	C_{LL}^V	C_{RL}^V	C_{RL}^S	C_{LL}^S	C_{LL}^T
ν_R	$C_{LR}^V = C_{RR}^V$		$C_{RR}^S = C_{LR}^S$		C_{RR}^T

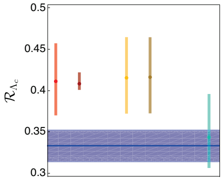
$F_L^{D^*}$ always below the exp. 1σ region

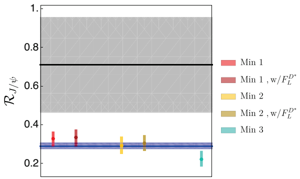
Solid (dashed) lines indicate ranges satisfying $\mathrm{Br}(B_c \to \tau\nu) < 10\%$ (30%). Fainted lines do not fulfil this constraint

Predictions from global fit:

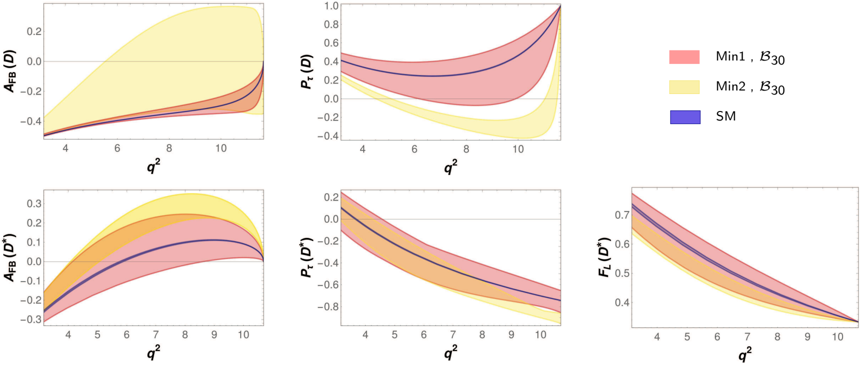
Murgui-Peñuelas-Jung-Pich, 1904.09311

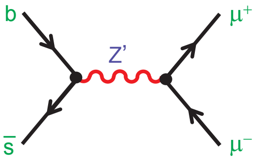
$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell)}$$





$$\frac{\mathcal{B}(B_c \to J\psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \to J\psi \ell \bar{\nu}_\ell)}$$



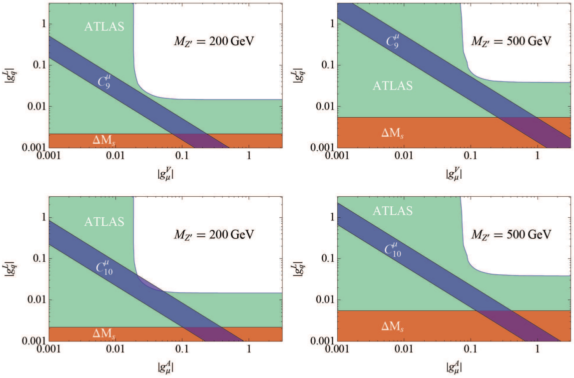


$$\mathcal{L} \supset \frac{g_2}{2c_W} Z'_\alpha \left\{ \left[\bar{s}\gamma^\alpha (g_L^Q P_L + g_R^Q P_R) b + h.c. \right] + \bar\ell \gamma^\alpha (g_V^\ell + \gamma_5 g_A^\ell)\ell \right\}$$

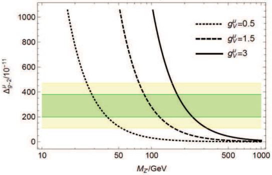
$$\Downarrow$$

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

Di Chiara et al, 1704.06200



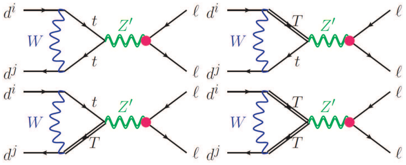
(g-2)$_\mu$



Many possibilities:

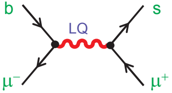
- L_μ-L_τ Altmannshofer et al, …
- Z' + VLQ Kamenik et al
- Fermiophobic Falkowski et al
- Horizon. Sym. Guadagnoli et al
- … Faisel-Tandeam, …

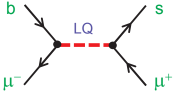
More possibilities…



Flavour conserving Z'

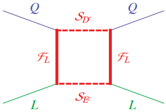
Kamenik et al, 1704.06005





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 ➡ LFV

Glashow-Guadagnoli-Lane, 1411.0565

$$\mathcal{H}_{NP} = G\, \bar{b}'_L \gamma^\lambda b'_L\, \bar{\tau}'_L \gamma_\lambda \tau'_L \qquad b'_L = \sum_{i=1}^{3} U^d_{L3i}\, d_{Li}\,, \qquad \tau'_L = \sum_{i=1}^{3} U^\ell_{L3i}\, \ell_{Li}$$

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

Anatomy of ε'/ε calculation

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = -\frac{\omega_+}{\sqrt{2}|\varepsilon|}\left\{\frac{\mathrm{Im}\,A_0^{(0)}}{\mathrm{Re}\,A_0^{(0)}}\,(1-\Omega_{\mathrm{eff}}) - \frac{\mathrm{Im}\,A_2^{\mathrm{emp}}}{\mathrm{Re}\,A_2^{(0)}}\right\}$$

$$\mathcal{A}_n^{(X)} = a_n^{(X)}\left[1 + \Delta_L\,\mathcal{A}_n^{(X)} + \Delta_C\,\mathcal{A}_n^{(X)}\right]$$

Cirigliano-Gisbert-Pich-Rodríguez 2019

1. **O(p^4) χPT Loops: Large correction** (NLO in $1/N_C$) FSI

$$\Delta_L\,\mathcal{A}_{1/2}^{(8)} = 0.27 + 0.47\,i \quad ; \quad \Delta_L\,\mathcal{A}_{3/2}^{(g)} = -0.50 - 0.21\,i$$

2. **O(p^4) LECs fixed at $N_C \to \infty$: Small correction**

$$\Delta_C\,[\mathcal{A}_{1/2}^{(8)}]^- = 0.10 \pm 0.05 \quad ; \quad \Delta_C\,[\mathcal{A}_{3/2}^{(g)}]^- = -0.19 \pm 0.19$$

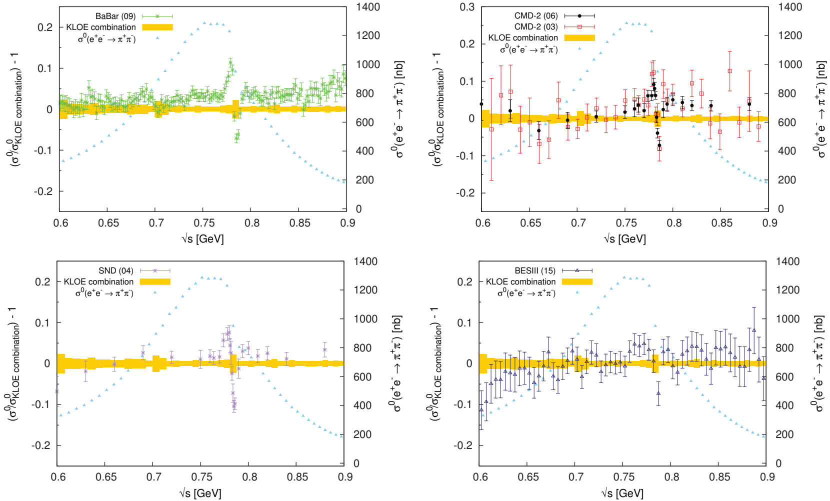
3. **Isospin Breaking** $O\left[(m_u - m_d)\,p^2, e^2 p^2\right]$**: Sizeable correction**

$$\Omega_{\mathrm{eff}} = 0.11 \pm 0.09$$

4. **Re(g$_8$), Re(g$_{27}$), $\chi_0 - \chi_2$ fitted to data**

KLOE data vs other experiments

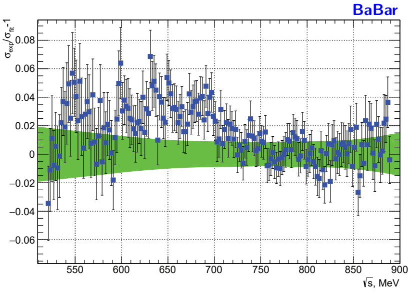
KLOE-2, 1711.03085

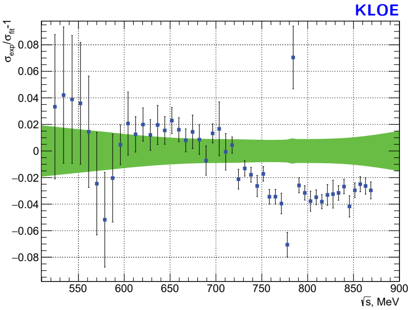


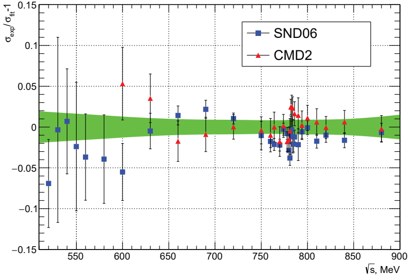
Internal tensions also among the three KLOE datasets: 2008, 2010, 2012

Comparison with SND 2020

2004.00263





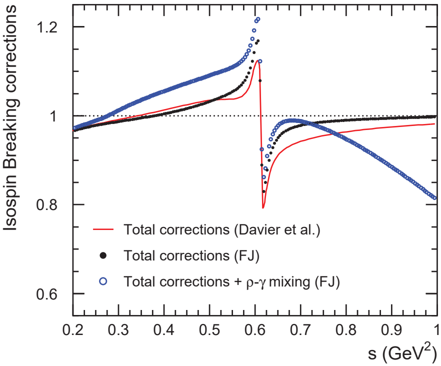


Measurement	$a_\mu(\pi\pi) \times 10^{10}$
This work	$409.79 \pm 1.44 \pm 3.87$
SND06	$406.47 \pm 1.74 \pm 5.28$
BaBar	$413.58 \pm 2.04 \pm 2.29$
KLOE	$403.39 \pm 0.72 \pm 2.50$

$525\ \text{MeV} \leq \sqrt{s} \leq 883\ \text{MeV}$

Isospin-breaking corrections applied to τ data

Z. Zhang, 1511.05405



In order to achieve compatibility with e^+e^- data, FJ introduces huge IB corrections (blue line), which are not supported by the explicit calculations available

My Personal Summary

- Unsatisfactory situation
- Large (underestimated) systematic errors
- Better data samples needed

  Belle-II, Beijing, Novosibirsk

- Lattice will certainly help
- Forthcoming MUonE experiment at CERN: $\sigma(\mu e \to \mu e)$

  Measure $\Pi_{\mathrm{em}}(Q^2)$ with space-like data

The μ anomaly does not necessarily imply New Physics

CP Asymmetry

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

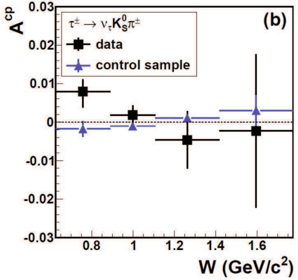
BaBar'11 $\left(\geq 0\, \pi^0\right)$

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

Bigi-Sanda, Grossman-Nir

2.8 σ discrepancy

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



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

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

$\beta = K_S$ direction in hadronic rest frame

$\psi = \tau$ direction

BaBar signal incompatible (with EFT) with other sets of flavour data

Cirigliano-Crivellin-Hoferichter, 1712.06595

Rendón-Roig-Toledo, 1902.08143