Anomalies in Hadronic B-meson decays

(Talk based on 2311.18011 to appear in Phys. Rev. Lett)

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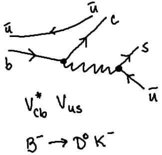
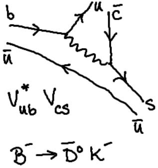
Why hadronic B decays?

- Goal: explore relations among various two body $B \to PP$ decays ($P = \pi, K$)
- Framework: Approximate flavor-SU(3) symmetry $\to u, d, s$ much lighter than b
- Finding: Global fits indicate SU(3) is broken at level much larger than expected
- Hadronic anomaly $\leftrightarrow$ unusually large SU(3) breaking
- Additional work not covered (indicate hadronic puzzles in $B_s^0 \to K^0 \overline{K}^0$):
  - Grossman et. al, 2407.13506
  - Amhis et. al, 2212.03874

Motivation: Study Weak Interactions

- Direct measurement of γ
  – GLW, ADS, GGSZ methods
- Theoretically clean, but statistics limited
- Theoretically clean $\Rightarrow$
  - more observables than parameters
  - obtain γ from fits
  - ***no theory input for hadronic parameters***
- Limited experimental precision
  - Current $\Delta\gamma \sim 7^\circ$ (LHCb-CONF-2022-003)
  - Long term LHCb target $\Delta\gamma \sim 1 - 2^\circ$





Only tree diagrams interfere in the SM

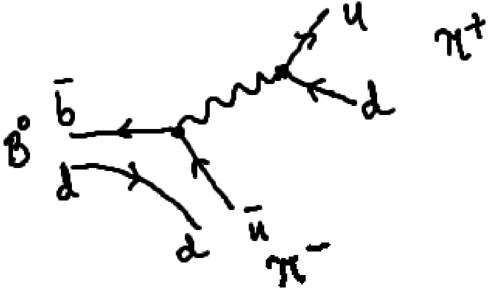
Highly-suppressed loop (box diagrams)

Brod and Zupan (2013)

- Unitarity triangle: $\gamma = \pi - \alpha - \beta$
- Additional methods? Include loops
- Crosschecks of the CKM paradigm

Alternative methods for γ: decays with tree + loop

- Consider the decay $B_d^0 \to \pi^+\pi^-$: $\mathcal{A}(B_d^0 \to \pi^+\pi^-) = -Te^{i\gamma} - P_{tc}$



$+$

$\propto V_{ub}^* V_{ud}$

$\propto V_{tb}^* V_{td}$

Weak-phase information from B decays with tree + loop

- $\mathcal{A}(B \to f) = |a| + |b|\, e^{i\delta}\, e^{i\phi} \quad \to \quad \Gamma \propto |\mathcal{A}|^2$

  $\overline{\mathcal{A}}(\overline{B} \to \overline{f}) = |a| + |b|\, e^{i\delta}\, e^{-i\phi} \quad \to \quad \overline{\Gamma} \propto |\overline{\mathcal{A}}|^2$

  – 4 parameters: 2 magnitudes ($|a|, |b|$), 1 strong phase (δ), 1 weak phase (ϕ)

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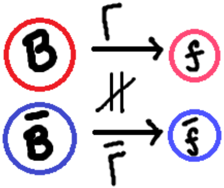

- $f \neq \overline{f}$ Only 2 observables
- Measure Γ and $\overline{\Gamma}$; or

$$\mathcal{B}_{\rm CP} = \frac{\Gamma + \overline{\Gamma}}{2} \text{ and } A_{\rm CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

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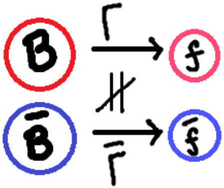

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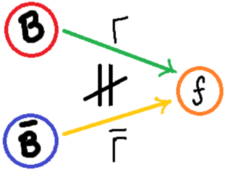

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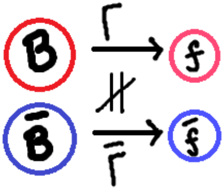

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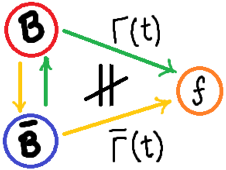
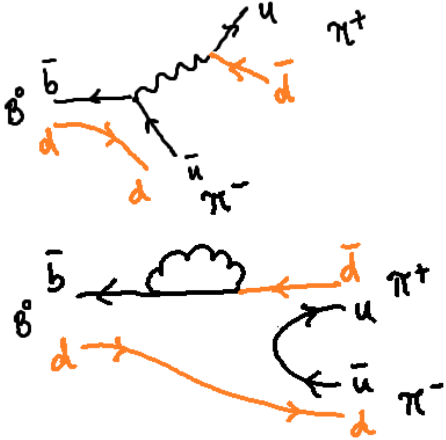
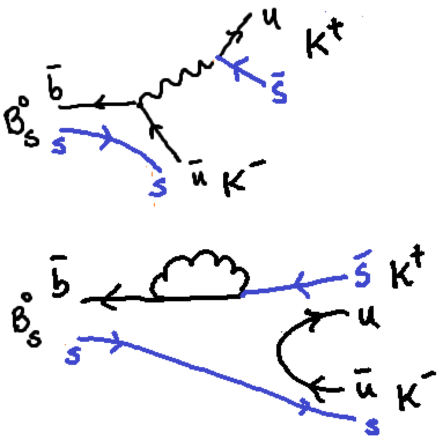


- $f = \overline{f}$: same 2 observables
- Additional observable(s) from B-$\overline{B}$ mixing
- $S_{\rm CP}$ from $\dfrac{\Gamma(t) - \overline{\Gamma}(t)}{\Gamma(t) + \overline{\Gamma}(t)}$

U-spin in hadronic B decays



$B_d^0 \to \pi^+\pi^-$



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

Weak-phase info using U-spin

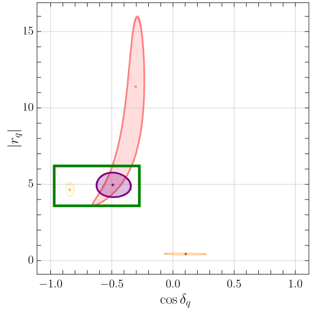
- R. Fleischer, hep-ph/9903456 (Phys. Lett. B 459 (1999) 306)
- 4 observables in $B_s \to K^+K^-$ and $B_d \to \pi^+\pi^-$: $C_{KK}, S_{KK}, C_{\pi\pi}, S_{\pi\pi}$
- $|q/p| \approx 1$ for $B^0_{d,s}$ (can check from semileptonic B decays);
  $\arg(q_s/p_s) \approx 2\beta_s$ $\to$ from $B_s \to J/\Psi\phi$
- Hadronic parameters same for both decays: $(|b/a|, \delta) \leftarrow$ 2 parameters
- Weak decay parameters: $\gamma, \beta_d \leftarrow$ Up to 2 parameters
- $C_{\pi\pi}, C_{KK}, S_{KK}$ sufficient to determine γ + 2 hadronic parameters
- Use $S_{\pi\pi}$ to also get β_d
- Data unavailable at the time

> The strategies proposed in this paper are very interesting for "second-generation" B-physics experiments performed at hadron machines, for example LHCb, where the very

Recent LHCb measurement and theory progress

- LHCb measurement of CP Asymmetries in $B_{s(d)} \to K^+K^-(\pi^+\pi^-)$: 1805.06759, 2012.05319
- Theory investigation of U-spin: Nir, Savoray, and Viernik, 2201.03573
- $C_{KK} = 0.172 \pm 0.031,\ \ S_{KK} = 0.139 \pm 0.032,\ \ C_{\pi\pi} = -0.32 \pm 0.04,\ \ S_{\pi\pi} = -0.64 \pm 0.04$
- Use β_d $(B_d \to J/\Psi K_s)$, β_s $(B_s \to J/\Psi\phi)$, γ $(B \to DK)$
- Find hadronic parameters for both decays $\Rightarrow$ test U-spin
- $\dfrac{|b_s/a_s|}{|b_d/a_d|} = 1.07,\ |a_s/a_d| = 1.26$ $\quad\sim$ 30% U-spin breaking

  $\mathcal{O}(m_s/\Lambda_{\rm QCD}) \sim 30\%,\ f_K/f_\pi - 1 \sim 20\%$
- Result: NP + different orders of breaking at play



Is that it for U-Spin?

- What about other U-spin related decays? BB with others, 2211.06994
- Consider U-spin SU(2) subgroup of flavor SU(3)

  $\rightarrow$ quark doublet: (d, s); $\rightarrow$ antiquark doublet: $(\bar{s}, -\bar{d})$;

  $\rightarrow$ meson doublets: (π^-, K^-), (K^+, π^+), (B_d^0, B_s^0)
- Initial state: B doublet; Final state: Doublet$\times$Doublet = Singlet(0) + Triplet(1)
- 6 decays possible: 3 decays each $\Delta S = 0(b \to d), 1(b \to s)$; 4 U-spin RMEs

Decay	Representation	$\mathcal{B}_{\rm CP}$	$C_{\rm CP}$	$S_{\rm CP}$
$B_d^0 \to \pi^+\pi^-$	$M_{1d}^{1/2} + M_{0d}^{1/2}$	$\sim 10^{-6}$	✓	✓
$B_d^0 \to K^+K^-$	$M_{1d}^{1/2} - M_{0d}^{1/2}$	$\sim 10^{-8}$	?	?
$B_s^0 \to \pi^+K^-$	$2\ M_{1d}^{1/2}$	$\sim 10^{-6}$	✓	
$B_s^0 \to K^+K^-$	$M_{1s}^{1/2} + M_{0s}^{1/2}$	$\sim 10^{-5}$	✓	✓
$B_s^0 \to \pi^+\pi^-$	$M_{1s}^{1/2} - M_{0s}^{1/2}$	$\sim 10^{-7}$	?	?
$B_d^0 \to K^+\pi^-$	$2\ M_{1s}^{1/2}$	$\sim 10^{-5}$	✓	

- Each $M_{xq}^{1/2}$ has two parts
- $M_{xq}^{1/2} = V_{ub}^* V_{uq} T_q^x + V_{cb}^* V_{cq} P_q^x$
- 12 measurements
- 4 yet to be measured
- 2 amplitude triangles: $\pi^+\pi^- + K^+K^- = \pi K$

Hints of U-spin breaking

- $\Delta S = 0 \Rightarrow q = d$, $\Delta S = 1 \Rightarrow q = s$

  $\rightarrow$ 7 hadronic parameters $\leftarrow T_q^x, P_q^x$ with $x = 0, 1$

  $\rightarrow$ 6 measurements available ✗

  $\rightarrow$ 2 future measurements $\Rightarrow \gamma$ can be extracted with β_q from independent source

- Apply U-spin! $\Rightarrow$ 8 parameters (γ + 7 hadronic for both $\Delta S = 0, 1$); 12 measurements ✓

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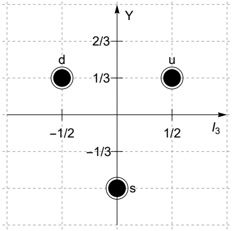
- Apply U-spin! $\Rightarrow$ 8 parameters (γ + 7 hadronic for both $\Delta S = 0, 1$); 12 measurements ✓
- Bad Fit! $\chi^2_{\rm min} = 17.8$ for 4 dof. $\gamma = (67.6 \pm 3.4)^\circ$ close to $\gamma_{\rm direct}$
- U-spin relation(s): $-\dfrac{C^s_{\rm CP}\mathcal{B}^s_{\rm CP}F^d_{\rm PS}}{C^d_{\rm CP}\mathcal{B}^d_{\rm CP}F^s_{\rm PS}} = 1$
- $\mathcal{A}(B^0_d \to \pi^+\pi^-) \approx \mathcal{A}(B^0_s \to \pi^+K^-)$
- $\mathcal{A}(B^0_s \to K^+K^-) \approx \mathcal{A}(B^0_d \to \pi^-K^+)$

$\Delta S = 0$	$\Delta S = 1$	Relation	
$B^0_d \to \pi^+\pi^-$	$B^0_s \to K^+K^-$	2.90±0.69	✓
$B^0_s \to \pi^+K^-$	$B^0_d \to \pi^-K^+$	1.21±0.25	✓
$B^0_s \to \pi^+K^-$	$B^0_s \to K^+K^-$	3.43±0.91	✗
$B^0_d \to \pi^+\pi^-$	$B^0_d \to \pi^-K^+$	1.06±0.42	✗

Flavor-SU(3) symmetry: $SU(3)_F$



- 3 light quarks, u, d, s, much lighter than b quark
- $u, d, s = SU(3)_F$ triplet; State $\rightarrow |\mathbf{irrep}, Y, I, I_3\rangle$
- $|u\rangle = \left|\mathbf{3}, \frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right\rangle,\ |d\rangle = \left|\mathbf{3}, \frac{1}{3}, \frac{1}{2}, -\frac{1}{2}\right\rangle,\ |s\rangle = \left|\mathbf{3}, -\frac{2}{3}, 0, 0\right\rangle$

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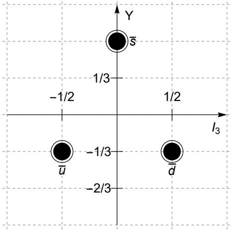

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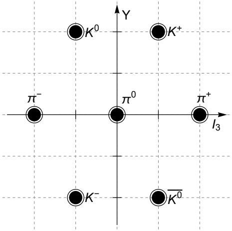
- $\left|\bar{d}\right\rangle = \left|\mathbf{3}^*, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right\rangle$; Y = hypercharge, I = Isospin
- $\mathbf{3} \times \mathbf{3}^* = \mathbf{1} + \mathbf{8}$: *These are the 3 pions, 4 kaons, η, η'*
- $|\pi^+\rangle = \left|u\bar{d}\right\rangle = |\mathbf{8}, 0, 1, 1\rangle$ Similarly other pions and kaons are also octets
- Apply to two-body final states

  $$|PP\rangle_{\rm sym} = (\mathbf{8} \times \mathbf{8})_{\rm sym} = \mathbf{1} + \mathbf{8} + \mathbf{27} = 36$$



Counting parameters in group theory

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$$V_{ub}^* V_{us} \quad \to \quad (\mathbf{3}^* \times \mathbf{3} \times \mathbf{3}^*) = \mathbf{3}^* + \mathbf{6} + \mathbf{15}^*; \quad V_{tb}^* V_{ts} \quad \to \quad \mathbf{3}^*$$

(EWP-tree relations, GPY, hep-ph/9810482)

- Final state: $|PP\rangle_{\rm sym} = |\mathbf{1}\rangle + |\mathbf{8}\rangle + |\mathbf{27}\rangle$

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  C_i contains *SU(2) Clebsch-Gordan Coefficients* and *SU(3) isoscalar factors*

- Independent RMEs: $V_{ub}^{*}V_{us} \quad \to \quad 5, \quad V_{tb}^{*}V_{ts} \quad \to \quad 2$
- Each RME is a complex number: 7 independent RMEs = 13 real parameters

$B \to PP$ data by transition

- $\Delta S = 0$: $\bar{b} \to \bar{d}$ transitions
- 15 measurements available
- 7 RMEs $\to$ 13 hadronic parameters
- $\chi^2_{\rm min}/{\rm dof} = 0.35/2$; $p \sim 0.8$ good fit

Decay	$\mathcal{B}_{\rm CP}$	$C_{\rm CP}$	$S_{\rm CP}$
$B^+ \to K^+\overline{K}^0$	✓	✓	
$B^+ \to \pi^+\pi^0$	✓	✓	
$B^0 \to K^0\overline{K}^0$	✓	✓	✓
$B^0 \to \pi^+\pi^-$	✓	✓	✓
$B^0 \to \pi^0\pi^0$	✓	✓	?
$B^0 \to K^+K^-$	✓	?	?
$B_s^0 \to \pi^+K^-$	✓	✓	
$B_s^0 \to \pi^0\overline{K}^0$	?	?	?

- $\Delta S = 1$: $\bar{b} \to \bar{s}$ transitions
- 15 measurements available
- 7 RMEs $\to$ 13 hadronic parameters
- $\chi^2_{\rm min}/{\rm dof} = 1.8/2$; $p \sim 0.4$ good fit

Decay	$\mathcal{B}_{\rm CP}$	$C_{\rm CP}$	$S_{\rm CP}$
$B^+ \to \pi^+K^0$	✓	✓	
$B^+ \to \pi^0K^+$	✓	✓	
$B^0 \to \pi^-K^+$	✓	✓	
$B^0 \to \pi^0K^0$	✓	✓	✓
$B_s^0 \to K^+K^-$	✓	✓	✓
$B_s^0 \to K^0\overline{K}^0$	✓	?	?
$B_s^0 \to \pi^+\pi^-$	✓	?	?
$B_s^0 \to \pi^0\pi^0$	✓	?	?

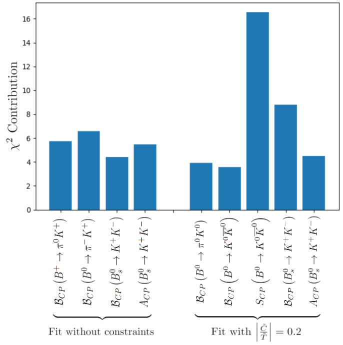
Combined $B \to PP$ data: the anomaly

- BB with others in arxiv:2311.18011: fit the entire set of $B \to PP$ data
- 30 observables, 26 parameters: fit gives $|T_s/T_d| = 12 \pm 4$
- SU(3) hypothesis: 30 observables, 13 parameters: fit gives $\chi^2_{\rm min}/{\rm dof} \sim 44/17$ (3.6σ)
- Fit with QCDf-inspired constraint $|C/T| = 0.2$
  - $\to$ $\Delta S = 1$ fit: $\chi^2_{\rm min}/{\rm dof} \sim 7/3$, $p \sim 0.1$
  - $\to$ $\Delta S = 0$ fit: $\chi^2_{\rm min}/{\rm dof} \sim 19/3$, $p \sim 3 \times 10^{-4}$ or 3.6σ away from SM SU(3)$_F$
  - $\to$ Combined fit: $\chi^2_{\rm min}/{\rm dof} \sim 56/18$, $p \sim 10^{-5}$ or 4.4σ away from SM SU(3)$_F$
- Both fits find deviations in $B_s^0 \to K^+K^-$ observables
- Deviations also in $B^+ \to \pi^0 K^+, B^0 \to \pi^- K^+, \pi^0 K^0, K^0\overline{K}^0$

Results highlights

- Ratios of $\Delta S = 1$ and $\Delta S = 0$ diagrams $|D'/D|$

$\lvert\tilde{T}'/\tilde{T}\rvert$	$\lvert\tilde{C}'/\tilde{C}\rvert$	$\lvert\tilde{P}'_{uc}/\tilde{P}_{uc}\rvert$	$\lvert\tilde{A}'/\tilde{A}\rvert$	$\lvert P\tilde{A}'_{uc}/P\tilde{A}_{uc}\rvert$	$\lvert\tilde{P}'_{tc}/\tilde{P}_{tc}\rvert$	$\lvert P\tilde{A}'_{tc}/P\tilde{A}_{tc}\rvert$
12±4	6.6±2.2	16±22	14±13	10±13	0.97±0.52	1.3±2.7



- Missing observables can shed light:
- $\mathcal{B}$: $B_s^0 \to \pi^0 \overline{K}^0$
- C: $B^0 \to K^+ K^-$, $B_s^0 \to \pi^0 \overline{K}^0, K^0 \overline{K}^0, 2\pi$
- S: $B^0 \to \pi^0 \pi^0, K^+ K^-$, $B_s^0 \to \pi^0 \overline{K}^0, K^0 \overline{K}^0, 2\pi$

- Work in progress:
  - → include ηs
  - → parametric SU(3) breaking

Summary

- We see signs of anomalies in hadronic B decays
- Large U-spin breaking needed to explain U-spin related $B^0_{(s)} \to DD$ (D = Doublet)
- Puzzle appears also in SU(3)$_F$ related $B \to PP$ (P = pseudoscalar)
- Puzzles involve $B^0_s \to K^+K^-$
- Puzzles need unusually large T_s/T_d
- Emerging cracks in the fabric of flavor symmetries
- Lack of QCD understanding or hint for new physics in $b \to s$?
- Lots of data to come in the next decade
- The future is bright!

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Back-up Slides

Data on $\Delta S = 0$ decays

Decay	$\mathcal{B}_{CP}$ $(\times 10^{-6})$	$C_{\rm CP}$	$S_{\rm CP}$
$B^+ \to K^+ \overline{K}^0$	1.31±0.14	0.04±0.14†	
$B^+ \to \pi^+ \pi^0$	5.59±0.31	0.008±0.035	
$B^0 \to K^0 \overline{K}^0$	1.21±0.16†	0.06±0.26	-1.08±0.49
$B^0 \to \pi^+ \pi^-$	5.15±0.19	0.311± 0.030	-0.666± 0.029
$B^0 \to \pi^0 \pi^0$	1.55± 0.16	0.30±0.20	
$B^0 \to K^+ K^-$	0.080±0.015		
$B_s^0 \to \pi^+ K^-$	$5.90^{+0.87}_{-0.76}$	0.225±0.012	
$B_s^0 \to \pi^0 \overline{K}^0$			

† data from the PDG

other data from HFLAV

Data on $\Delta S = 1$ decays

Decay	$\mathcal{B}_{CP}$ $(\times 10^{-6})$	$C_{\rm CP}$	$S_{\rm CP}$
$B^+ \to \pi^+ K^0$	23.52±0.72	-0.016 ± 0.015	
$B^+ \to \pi^0 K^+$	13.20±0.46	0.029±0.012	
$B^0 \to \pi^- K^+$	19.46±0.46	-0.0836 ± 0.0032	
$B^0 \to \pi^0 K^0$	10.06±0.43	-0.01 ± 0.10	0.57±0.17
$B_s^0 \to K^+ K^-$	$26.6^{+3.2}_{-2.7}$	-0.17 ± 0.03	0.14±0.03
$B_s^0 \to K^0 \overline{K}^0$	17.4±3.1		
$B_s^0 \to \pi^+ \pi^-$	$0.72^{+0.11}_{-0.10}$		
$B_s^0 \to \pi^0 \pi^0$	2.8±2.8*		

* data from Belle

other data from HFLAV

Fit results

Fit $\Delta S = 0$	$\lvert\widetilde{T}\rvert$	$\lvert\widetilde{C}\rvert$	$\lvert\widetilde{P}_{uc}\rvert$	$\lvert\widetilde{A}\rvert$
	4.0 ± 0.5	6.6 ± 0.7	3 ± 4	6 ± 5
	$\lvert\widetilde{PA}_{uc}\rvert$	$\lvert P_{tc}\rvert$	$\lvert PA_{tc}\rvert$	
	0.7 ± 0.8	0.8 ± 0.4	0.2 ± 0.4	
Fit $\Delta S = 1$	$\lvert\widetilde{T}'\rvert$	$\lvert\widetilde{C}'\rvert$	$\lvert\widetilde{P}'_{uc}\rvert$	$\lvert\widetilde{A}'\rvert$
	48 ± 14	41 ± 14	48 ± 15	81 ± 28
	$\lvert\widetilde{PA}'_{uc}\rvert$	$\lvert P'_{tc}\rvert$	$\lvert PA'_{tc}\rvert$	
	7 ± 4	0.78 ± 0.16	0.24 ± 0.04	
Fit $SU(3)_F$	$\lvert\widetilde{T}\rvert$	$\lvert\widetilde{C}\rvert$	$\lvert\widetilde{P}_{uc}\rvert$	$\lvert\widetilde{A}\rvert$
	4.7 ± 0.5	5.8 ± 0.6	2.1 ± 0.5	4.2 ± 0.7
	$\lvert\widetilde{PA}_{uc}\rvert$	$\lvert P_{tc}\rvert$	$\lvert PA_{tc}\rvert$	
	0.70 ± 0.09	1.15 ± 0.04	0.214 ± 0.018	

Electro-weak penguin operators

- EWP operators $\propto V_{tb}^* V_{ts}$
- Operators of the type $\mathbf{3}^* \times \mathbf{8} = \mathbf{3}^* + \mathbf{6} + \mathbf{15}^*$
- Reminder: tree operators also have $\mathbf{3}^* + \mathbf{6} + \mathbf{15}^*$
- Resulting RMEs in $\langle B| H |PP\rangle$ of the type:

  $\langle \mathbf{3}^*| \mathbf{6} |\mathbf{8}\rangle$, $\langle \mathbf{3}^*| \mathbf{15}^* |\mathbf{8}\rangle$, and $\langle \mathbf{3}^*| \mathbf{15}^* |\mathbf{27}\rangle$

  Identical in trees and EWPs
- This is the source of EWP-Tree relations
- Breaking EWP-Tree relations is effectively SU(3) breaking

Weak-phase information from B decays with tree + loop

- $\mathcal{A}(B \to f) = |a| + |b| e^{i\phi} e^{i\delta} \quad \to \quad \Gamma \propto |\mathcal{A}|^2$

  $\overline{\mathcal{A}}(\overline{B} \to \bar{f}) = |a| + |b| e^{-i\phi} e^{i\delta} \quad \to \quad \overline{\Gamma} \propto |\overline{\mathcal{A}}|^2$

  – 4 parameters: 2 magnitudes ($|a|, |b|$), 1 rel. strong phase (δ), 1 rel. weak phase (ϕ)
- 2 Observables: $\mathcal{B}_{\rm CP} = \dfrac{\Gamma + \overline{\Gamma}}{2\Gamma_B}$, $\quad C_{\rm CP} = \dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$ (direct CP asymmetry)
- For $B^0 \to f$ with $f = \bar{f}$ additional observable $S_{\rm CP}$ (indirect CP asymmetry)

  B-mixing: $|B\rangle_{\rm mass} = p\,|B\rangle + q\,|\bar{B}\rangle$ with $\lambda = \dfrac{q}{p}\dfrac{\bar{\mathcal{A}}}{\mathcal{A}} \Rightarrow S_f = \dfrac{2{\rm Im}[\lambda]}{1 + |\lambda|^2}$
- Information about q/p comes from $B - \bar{B}$ mixing (independent source)
- For B_s, additional observable $A^{\Delta\Gamma} = \dfrac{-2{\rm Re}[\lambda]}{1 + |\lambda|^2}$ (since $\Delta\Gamma_s$ is sizable)
- $C_{\rm CP} = \dfrac{1 - |\lambda|^2}{1 + |\lambda|^2} \quad \Rightarrow$ Identity: $(C_{\rm CP})^2 + (S_{\rm CP})^2 + (A^{\Delta\Gamma})^2 = 1$ (LHCb)