Direct CP Violation

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Flavor Physics Lectures
III / XII

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Reading material and references

Lecture material based on several textbooks and online lectures/notes.
Credits for material and figures include:

Literature

- Perkins, Donald H. (2000), *Introduction to High Energy Physics*.
- Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*.
- Stone, Sheldon (2nd edition), B *decays*.

Online Resources

- Belle/BaBar Collaborations, *The Phyiscs of the* B*-Factories*.
  http://arxiv.org/abs/1406.6311
- Bona, Marcella (University of London), CP *Violation Lecture Notes*,
  http://pprc.qmul.ac.uk/ bona/ulpg/cpv/
- Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and* CP *Violation*.
  http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf
- Thomson, Mark (Cambridge University), *Particle Physics Lecture Handouts*,
  http://www.hep.phy.cam.ac.uk/ thomson/partIIIparticles/welcome.html
- Grossman, Yuval (Cornell University), *Just a Taste. Lectures on Flavor Physics*,
  http://www.lepp.cornell.edu/ pt267/files/notes/FlavorNotes.pdf
- Kooijman, P. & Tuning, N., CP *Violation*,
  https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Recap & outline

Last time we:

- Saw explicitely that the eigenstates of the $\mathcal{H}_w$ (mass eigenstates K_S and K_L) are not equal to the strong eigenstates of definite flavor $K^0(d\bar{s})$ and $\overline{K}^0(\bar{d}s)$.
- The K_S and K_L mass eigenstates are not eigenstates of CP, i.e., CP is violated to a small degree $\varepsilon = 2 \times 10^{-3}$.
- CP-violation in mixing leads to $\Gamma(K^0_{t=0} \to \overline{K}^0) \neq \Gamma(\overline{K}^0_{t=0} \to K^0)$, which is quantified by $|\frac{q}{p}| \neq 1$.

Today, we'll:

- Introduce another type of CP violation:
  CP violation in decay (aka "direct" CPV).
- To understand it fully, we'll need to revisit our $\mathcal{C}$ and $\mathcal{P}$ operators in more detail and introduce the weak and strong phases.

CP violation in decay

Good news: *Conceptually, much less complicated than mixing!*

- This "direct" CPV is observed by comparing the decay rate of particles $\Gamma(P \to f)$ and anti-particles $\Gamma(\overline{P} \to \overline{f})$, where:

  P is a pseudoscalar meson

  f and $\overline{f}$ are CP-conjugate final states (i.e., eigenstates of CP).

- Stated simply, if

  $\Gamma(P \to f) \neq \Gamma(\overline{P} \to \overline{f}) \quad \Rightarrow \quad CP$ Violation in decay

  We can express this as an asymmetry:

$$\mathcal{A}_{CP} = \frac{\Gamma(P \to f) - \Gamma(\overline{P} \to \overline{f})}{\Gamma(P \to f) + \Gamma(\overline{P} \to \overline{f})} \neq 0$$

$\Rightarrow$ ***Lets prove this in the next slides***

Condition for direct CP violation

Denote our initial and final states as $|P\rangle$ and $|f\rangle$, respectively.

Define the action of the CP operator on these states by:

$$CP|P\rangle = e^{2i\theta(P)}|\overline{P}\rangle$$

$$CP|f\rangle = e^{2i\theta(f)}|\overline{f}\rangle$$

where $e^{2i\theta(X)}$ is the *intrinsic* CP phase factor associated with X.

If CP is conserved, it commutes with the hamiltonian: $[H, CP] = 0$.

Write the amplitude for the $P \to f$ decay as:

$$A \equiv A(P \to f) = \langle f|H|P\rangle$$

The amplitude for the CP-conjugate process is:

$$\overline{A} \equiv \overline{A}(\overline{P} \to \overline{f}) = \langle \overline{f}|H|\overline{P}\rangle$$

Condition for direct CP violation

Now lets see how the amplitudes are related (assuming CP is conserved):

$$\begin{aligned} A = \langle f|H|P\rangle &= \langle f|(CP)^\dagger(CP)H(CP)^\dagger(CP)|P\rangle \\ &= \langle \overline{f}|(CP)H(CP)^\dagger|\overline{P}\rangle \cdot e^{2i(\theta(P)-\theta(f))} \\ &= \langle \overline{f}|H|\overline{P}\rangle \cdot e^{2i(\theta(P)-\theta(f))} \qquad \text{(using } [H, CP] = 0) \\ &= \overline{A} \cdot e^{2i(\theta(P)-\theta(f))} \end{aligned}$$

$$\Rightarrow \frac{\overline{A}}{A} = e^{-2i(\theta(P)-\theta(f))}$$

Remove the dependence on the intrinsic phases by taking the magnitude of the amplitudes:

$$\left|\frac{\overline{A}}{A}\right| = \left|e^{-2i(\theta(P)-\theta(f))}\right| = 1$$ CP conservation *independent of phase convention*

Arrive at our condition for $DCPV$:

$$\left|\frac{\overline{A}}{A}\right| \neq 1 \quad \Rightarrow$$ CP Violation in decay

CP-violating phase

In the standard model, CP-conjugate amplitudes differ from the original amplitude by at most a phase factor.

$\Rightarrow$ *If only a single amplitude contributes to a given decay process, there cannot be an observable CP asymmetry.*
Do you see why? ($\Rightarrow$ remember $\Gamma = |A|^2$)

Now suppose that there is more than one amplitude A_j for a given decay, and that each amplitude has an associated CP-violating phase ϕ_j.

- Write the overall amplitude for the $P \to f$ decay as:

  $$A \equiv A(P \to f) = \langle f|H|P\rangle = \sum_j A_j = \sum_j a_j e^{i\phi_j}$$

  These phases ϕ_j which change sign under CP are the so-called **weak phases**.
  Can be **phases from the CKM matrix**, *but can also be due to new physics*.

- Similarly for the $\overline{P} \to \overline{f}$ decay:

  $$\overline{A} \equiv \overline{A}(\overline{P} \to \overline{f}) = \langle \overline{f}|H|\overline{P}\rangle = \sum_j \overline{A}_j = \sum_j a_j e^{-i\phi_j}$$

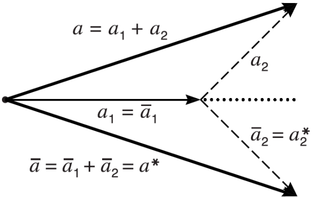
  where the CP-violating phases have changed sign.

Only CP-violating weak phases

$$\left|\frac{\overline{A}}{A}\right| = \left|\frac{\sum_j |a_j| e^{-i\phi_j}}{\sum_j |a_j| e^{i\phi_j}}\right| = \left|\frac{\sum_j |a_j| \cos\phi_j - i\sum_j |a_j| \sin\phi_j}{\sum_j |a_j| \cos\phi_j + i\sum_j |a_j| \sin\phi_j}\right| = 1$$

Why?

$\Rightarrow$ *The numerator is just the complex conjugate of the denominator, so the magnitude of the amplitudes are the same.*



Case for 2 interfering amplitudes a_1 and a_2 with only weak phases.

The CP-conjugate amplitude $\bar{a} = \bar{a}_1 + \bar{a}_2$ has the same magnitude as the original amplitude a, *and there is no* CP *asymmetry*

Something is missing...

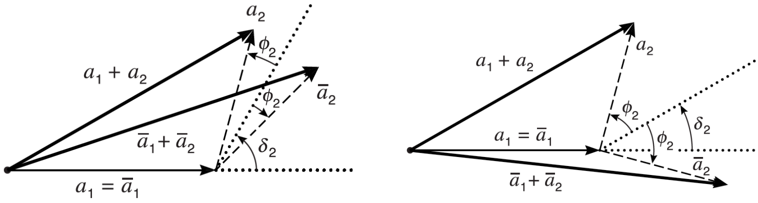
What about the coefficients a_j?

Introduce the strong phase

The coefficients a_j are complex and are of the form $a_j = |a_j|\, e^{i\delta_j}$, where δ_j are non-CP-violating phases that can arise, e.g., from strong interactions in the final state (exchanging gluons - no CPV *that we know of*).

These δ_j do not change sign under CP

$$\left|\frac{\overline{A}}{A}\right| = \left|\frac{\sum_j |a_j| e^{i(\delta_j - \phi_j)}}{\sum_j |a_j| e^{i(\delta_j + \phi_j)}}\right| = \left|\frac{\sum_j |a_j| \cos(\delta_j - \phi_j) - i \sum_j |a_j| \sin(\delta_j - \phi_j)}{\sum_j |a_j| \cos(\delta_j + \phi_j) + i \sum_j |a_j| \sin(\delta_j + \phi_j}\right| \neq 1$$



Case for 2 interfering amplitudes a_1 and a_2 with weak (ϕ) **and strong (δ)** phases.

Direct CPV asymmetry

We can express this result as:

$$|\overline{A}|^2 - |A|^2 = 2\sum_{i,j} |a_i|\,|a_j|\ \sin(\phi_i - \phi_j)\sin(\delta_i - \delta_j)$$

We are usually concerned with only 2 amplitudes, so we can write the asymmetry as:

$$\mathcal{A}_{\mathcal{CP}} = \frac{|\overline{A}|^2 - |A|^2}{|\overline{A}|^2 + |A|^2} = \frac{2|a_1||a_2|\ \sin(\phi_1-\phi_2)\ \sin(\delta_1-\delta_2)}{|a_1|^2+|a_2|^2+|a_1||a_2|\ \cos(\phi_1-\phi_2)\ \cos(\delta_1-\delta_2)}$$

These results have important implications:

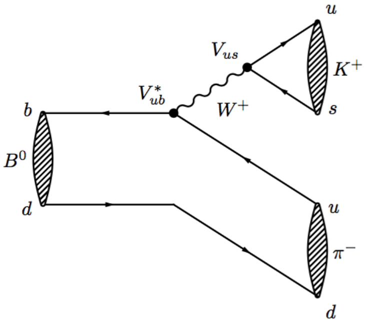
To observe CP-violating effects by comparing $\Gamma(P \to f)$ and $\Gamma(\overline{P} \to \overline{f})$ we need:

1. A minimum of 2 amplitudes contributing to a given decay process.
2. *Both* CP-violating and non-CP-violating phases.

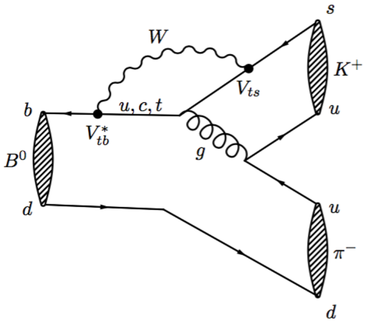
⇒ Lets look at an example in $B^0 \to K^+\pi^-$ decays

$B^0 \to K^+\pi^-$ decays

Amplitude 1 $(\sim V_{ub}^* V_{us})$



Amplitude 2 $(\sim V_{tb}^* V_{ts})$



Recall the Wolfenstein phase convention of the CKM matrix elements

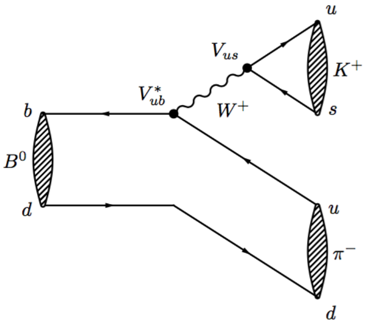
(Lecture 1, Slide 31)

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}| & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^4)$$

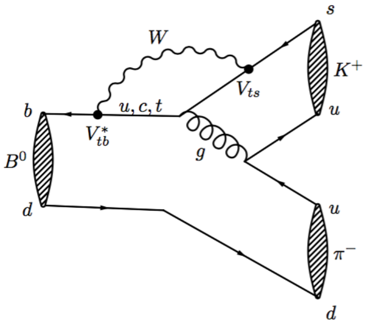
and note which matrix elements contain the CP violating phase

$B^0 \to K^+\pi^-$ decays

Tree amplitude $(\sim V_{ub}^* V_{us})$



Penguin amplitude $(\sim V_{tb}^* V_{ts})$



$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

- Tree amplitude contains the CP-violating phase γ. The relative strong phase shift between the tree and penguin diagrams is δ.

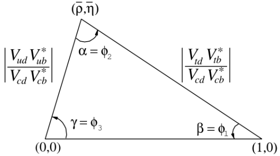
$$\Gamma(B^0 \to K^+\pi^-) \propto \left| A_P - A_T e^{-i\gamma} e^{i\delta} \right|^2$$

$$\Gamma(\overline{B}^0 \to K^-\pi^+) \propto \left| A_P - A_T e^{i\gamma} e^{i\delta} \right|^2$$

What can we deduce from these amplitudes?

- If we compute
  $\frac{\Gamma(B^0\to K^+\pi^-)+\Gamma(\overline{B}^0\to K^-\pi^+)}{2} \propto |A_P|^2 \left(1 - 2\frac{A_T}{A_P}\cos\gamma\,\cos\delta + \left(\frac{A_T}{A_P}\right)^2\right)$
- and use the fact that $B^+ \to K^0\pi^+$ is almost entirely a penguin process:
  $\Gamma(B^+ \to K^0\pi^+) = \Gamma(B^- \to \overline{K}^0\pi^-) \propto |A_P|^2$
- we can compute the ratio:
  $R \equiv \frac{\Gamma(B_d\to K^\pm\pi^\mp)}{\Gamma(B^\pm\to K^0\pi^\pm)} = \left(1 - 2\frac{A_T}{A_P}\cos\gamma\,\cos\delta + \left(\frac{A_T}{A_P}\right)^2\right)$ (note the $|A_P|^2$ term is gone)
- The minimum value of R (as a function of $\frac{A_T}{A_P}$) is attained when $\frac{A_T}{A_P} = \cos\gamma\,\cos\delta$, and is given by
  $R \geq 1 - \cos^2\gamma\,\cos^2\delta \geq \sin^2\gamma$

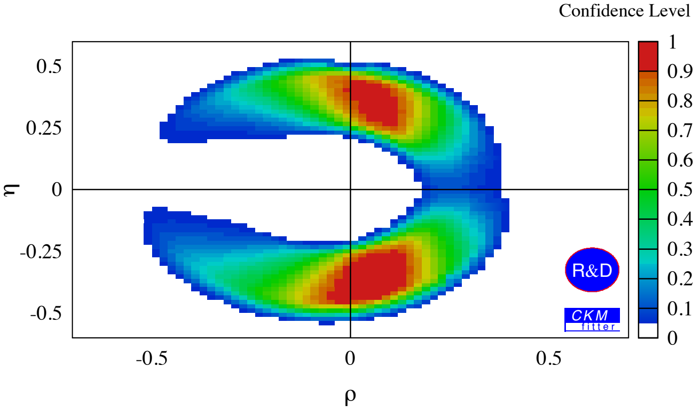
- We now have a constraint in the $\rho - \eta$ plane
  $R \geq \frac{\eta^2}{\rho^2+\eta^2} = \sin^2\gamma$
  (If you don't see it, make a mini right triangle of origin (0,0), base ρ and height η)



$\Rightarrow$ *Constraint from only 2 $K\pi$ measurements!*

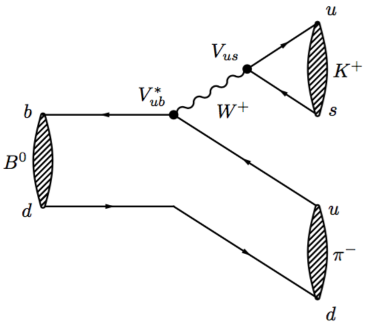
Constraint in the (ρ, η) plane

We can make a constraint on the apex of the Unitary Triangle using the $B \to K\pi$ and $B \to \pi\pi$ *(future lecture)* results.



(Note: these are very old [2002], but the point is to illustrate the idea)
http://ckmfitter.in2p3.fr/www/archives/ckm_charmless2002.html

What about $B^+ \to K^+\pi^0$ decays?

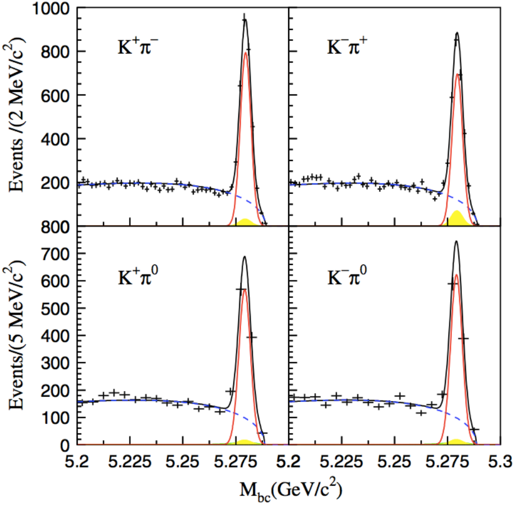


If we replace the spectator d-quark by a u-quark in both $B^0 \to K^+\pi^-$ diagrams, the π^- becomes a π^0, and we have the tree and penguin diagrams for $B^+ \to K^+\pi^0$ decays.

We should expect to see around the same A_{CP} since we're only changing the spectator quark, no?

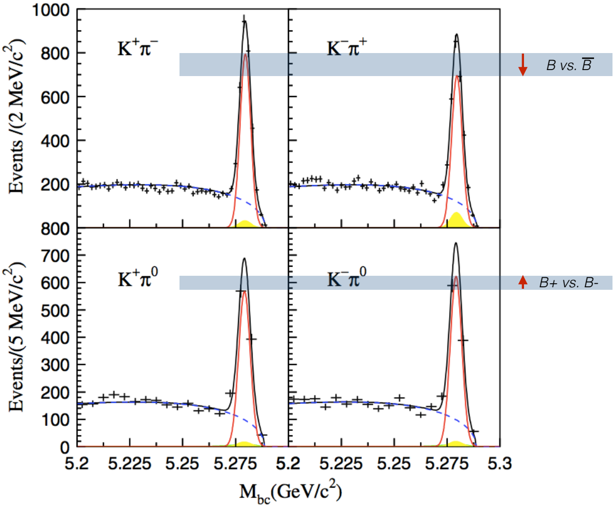
Not quite!

Measurements of $DCPV$ in $B^+ \to K^+\pi^0$ found to be different than $B^0 \to K^+\pi^-$



Not quite!

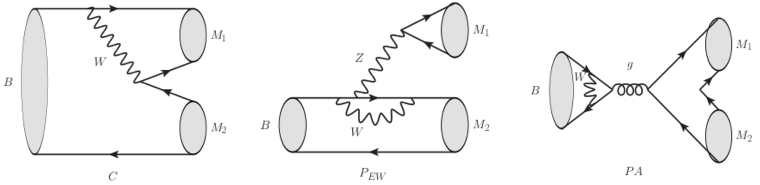
Measurements of $DCPV$ in $B^+ \to K^+\pi^0$ found to be different than $B^0 \to K^+\pi^-$



$$\mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \ \ (4\sigma)$$

Additional SM Diagrams or New Physics?

- The difference could be due to:
  - Neglected diagrams contributing to B decays (theoretical uncertainty is still large).
    $K^+\pi^- : T + P + P_{EW}^C$
    $K^+\pi^0 : T + P + C + P_{EW} + P_{EW}^C + PA$



  - Some unknown NP effect that violates Isospin.

⇒ **In combination with other $K\pi$ measurements** *and with the larger Belle II dataset, strong interaction effects can be controlled and the validitiy of the SM can be tested in a model-independent way.*

$B \to K\pi$: Current experimental status

Complete set of measurements from Belle and BaBar.

$\mathcal{B}(10^{-6})$			
Mode	BABAR	Belle	LHCb
$K^+\pi^-$	$19.1 \pm 0.6 \pm 0.6$	$20.0 \pm 0.34 \pm 0.60$	
$K^+\pi^0$	$13.6 \pm 0.6 \pm 0.7$	$12.62 \pm 0.31 \pm 0.56$	
$K^0\pi^+$	$23.9 \pm 1.1 \pm 1.0$	$23.97 \pm 0.53 \pm 0.71$	
$K^0\pi^0$	$10.1 \pm 0.6 \pm 0.4$	$9.68 \pm 0.46 \pm 0.50$	

A_{CP}			
Mode	BABAR	Belle	LHCb
$K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
$K^+\pi^0$	$0.030 \pm 0.039 \pm 0.010$	$0.043 \pm 0.024 \pm 0.002$	
$K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$	$-0.011 \pm 0.021 \pm 0.006$	$-0.022 \pm 0.025 \pm 0.010$
$K^0\pi^0$	$-0.13 \pm 0.13 \pm 0.03$	$0.14 \pm 0.13 \pm 0.06$	

$B \to K\pi$: Test-of-sum Rule

Asymmetry (test-of-sum) rule for NP nearly free of theoretical uncertainties, where the SM can be tested by measuring all observables: [PLB 627, 82(2005), PRD 58, 036005(1998)]

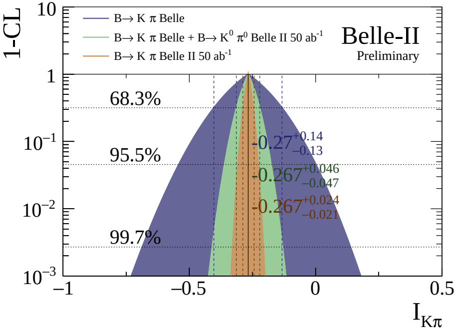
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

$\left(I_{K\pi} = -0.0088^{+0.0016+0.0131}_{-0.0017-0.0091}\right)$ [@NNLO] PLB 750(2015)348-355

$\boldsymbol{I_{K\pi} = -0.270 \pm 0.132 \pm 0.060}$ **[Belle]**

- Most demanding measurement is $K^0\pi^0$ final state: $\mathcal{A}_{K^0\pi^0} = 0.14 \pm 0.13 \pm 0.06$.
  Belle, PRD 81, 011101(R) (2010)
- With Belle II, the uncertainty on $\mathcal{A}_{K^0\pi^0}$ from time-dep. analysis is expected to reach $\sim 4\%$.

  $\Rightarrow$ *Sufficient for NP studies*



Modified P_{EW} Sector

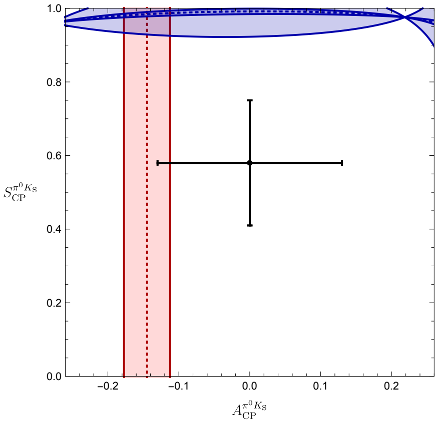
- Data point is the WA for $\mathcal{A}_{K^0\pi^0}$ and $\mathcal{S}_{K^0\pi^0}$.
- The $\mathcal{A}_{K^0\pi^0}$ value obtained from the sum rule with WA inputs for all other $\mathcal{A}_{K\pi}$ and $\mathcal{B}(K\pi)$ values.
- Isospin relation involving tighter constraints from CKM angle γ:

$$\sqrt{2}\mathcal{A}_{K^0\pi^0} + \mathcal{A}_{K^+\pi^0} = -\left(\hat{T}+\hat{C}\right)\left(e^{i\gamma} - qe^{i\phi}e^{i\omega}\right).$$

EW penguin effects described by

$$qe^{i\phi}e^{i\omega} \equiv -\left(\hat{P}_{EW} + \hat{P}^{C}_{EW}\right) / \left(\hat{T}+\hat{C}\right).$$

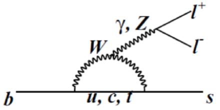
R. Fleischer *et al.*, arXiv:1712.02323, Moriond QCD



- Discrepancy can be resolved if:
  CP asymmetries move by $\approx 1\sigma$; $\mathcal{B}(K^0\pi^0)$ moves by $\approx 2.5\sigma$.
- **Or NP from EW Z penguins that couple to quarks:**
  Includes models with extra Z' bosons, which can be used to resolve anomalies in $B \to K^{(*)}\ell\ell$ measurements.

- Within the SM, decays proceed via one loop diagram: JHEP0712:040,2007

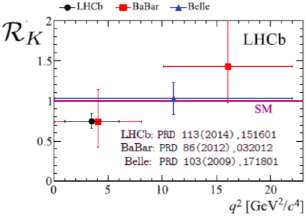
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1.00030^{+0.00010}_{-0.00007}$$



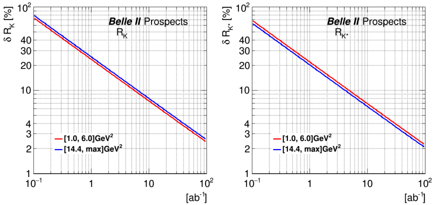
- LHCb reported a 2.6σ deviation for the dilepton invariant mass squared region $1 < q^2 < 6\ \mathrm{GeV}^4/c^2$:

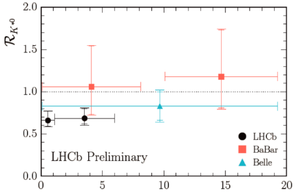
$$\mathcal{R}_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Phys. Rev. Lett. **113** 151601 (2016)



- Electrons and muons have the same ε at Belle II:
  $\Rightarrow$ *Both low and high q^2 regions possible.*





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

More data:

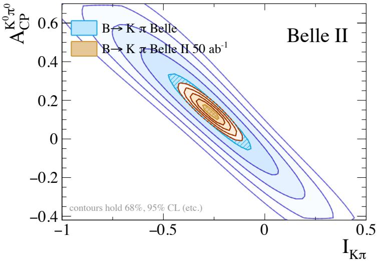
Extrapolate Belle measurements to 5 and 50 ab^{-1}

- Systematic uncertainties scale primarily with integrated luminosity, with the exception of A_{CP} measurements of channels with K_S^0:
  $\Rightarrow$ *asymmetry of K^0/ $\overline{K}^0$ interactions in material* ($\sigma_{ired} \approx 0.2\%$)
  Phys. Rev. D **84**, 111501 (2011)
- Ideally separate the reducible and irreducible systematic errors (unchanged throughout data accumulation) when extrapolating.
  - Few modes are systematically limited, so treat all syst. errors as reducible (with few exceptions, e.g., $K_S^0\pi^0$, next slide).
  - Apply scaling to all stat. and syst. errors to Belle results via:

$$\sigma_{Belle\ II} = \sqrt{(\sigma^2_{stat} + \sigma^2_{syst})\frac{\mathcal{L}_{Belle}}{\mathcal{L}_{BelleII}} + \sigma^2_{ired}}$$

$B \to K\pi$: Projections for Belle II

- Perform a 2D scan of $\mathcal{A}_{K^0\pi^0}$ vs. $I_{K\pi}$ for different Belle II scenarios.
  - The only possible correlated errors for the A_{CP} measurements are caused by the detector bias, which is estimated with different methods for each channel. $\Rightarrow$ *Assume that the bias errors are not correlated.*
  - Additionaly the systematic uncertainties are conservatively provided and they are still smaller than the statistical errors.



Projections for the $B \to K\pi$ isospin sum rule parameter, $I_{K\pi}$, at the Belle measured central value.

Scenario	$\mathcal{A}_{K^0\pi^0}$ Value	Stat.	(Red., Irred.)	$I_{K\pi}$
Belle	0.14	0.13	$(0.06, 0.02)$	-0.27 ± 0.14
Belle + $B \to K^0\pi^0$ at Belle II 5 ab^{-1}		0.05	$(0.02, 0.02)$	-0.27 ± 0.07
Belle II 50 ab^{-1}		0.01	$(0.01, 0.02)$	-0.27 ± 0.03

$K^*\pi$ and $K^{(*)}\rho$ systems

Expect analogous sum rules by replacing:

$\boldsymbol{K \to K^*}$

$$I_{K^*\pi} = \mathcal{A}_{K^{*+}\pi^-} + \mathcal{A}_{K^{*0}\pi^+} \frac{\mathcal{B}(K^{*0}\pi^+)}{\mathcal{B}(K^{*+}\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^{*+}\pi^0} \frac{\mathcal{B}(K^{*+}\pi^0)}{\mathcal{B}(K^{*+}\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^{*0}\pi^0} \frac{\mathcal{B}(K^{*0}\pi^0)}{\mathcal{B}(K^{*+}\pi^-)}$$

$\boldsymbol{\pi \to \rho}$

$$I_{K\rho} = \mathcal{A}_{K^+\rho^-} + \mathcal{A}_{K^0\rho^+} \frac{\mathcal{B}(K^0\rho^+)}{\mathcal{B}(K^+\rho^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\rho^0} \frac{\mathcal{B}(K^+\rho^0)}{\mathcal{B}(K^+\rho^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\rho^0} \frac{\mathcal{B}(K^0\rho^0)}{\mathcal{B}(K^+\rho^-)}$$

$\boldsymbol{K \to K^*}$ & $\boldsymbol{\pi \to \rho}$

$$I_{K^*\rho} = \mathcal{A}_{K^{*+}\rho^-} + \mathcal{A}_{K^{*0}\rho^+} \frac{\mathcal{B}(K^{*0}\rho^+)}{\mathcal{B}(K^{*+}\rho^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^{*+}\rho^0} \frac{\mathcal{B}(K^{*+}\rho^0)}{\mathcal{B}(K^{*+}\rho^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^{*0}\rho^0} \frac{\mathcal{B}(K^{*0}\rho^0)}{\mathcal{B}(K^{*+}\rho^-)}$$

For each set of decays[1], perform a 2D scan of A_{CP} (for most limiting final state) vs. the isospin sum rule parameter.

$\Rightarrow$ Compare with (N)NLO calculations[2].

[1] For the PV & VV systems, BaBar $\mathcal{B}$ and A_{CP} used for projections (Belle results n/a) - see BKUP slides.

[2] No NNLO calc. for VV system, as longitudinal A_{CP} fraction n/a for all final states.

Theory predictions PLB 750(2015)348-355

Two-loop current–current operator contribution to the non-leptonic QCD penguin amplitude

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ABSTRACT

The computation of direct CP asymmetries in charmless B decays at next-to-next-to-leading order (NNLO) in QCD is of interest to ascertain the short-distance contribution. Here we compute the two-loop penguin contractions of the current–current operators $Q_{1,2}$ and provide a first estimate of NNLO CP asymmetries in penguin-dominated $b \to s$ transitions.

1. Introduction

Non-leptonic exclusive decays of B mesons play a crucial role in studying the CKM mechanism of quark flavour mixing and in quantifying the phenomenon of CP violation. Direct CP violation is related to the rate difference of $\bar{B} \to f$ decay and its CP-conjugate and arises if the decay amplitude is composed of at least two partial amplitudes with different re-scattering ("strong") phases, which are multiplied by different CKM matrix elements. Very often useful information on the CKM parameters including the CP-violating phase can be obtained from combining different decay modes, whose partial amplitudes are related by the approximate flavour symmetries of the strong interaction [1], which are then determined from data.

The direct computation of the partial amplitudes is a complicated strong interaction problem, which can, however, be addressed in the heavy-quark limit. The QCD factorization approach [2–4] employs soft-collinear factorization in this limit to express the hadronic matrix elements in terms of form factors and convolutions of perturbative objects (hard-scattering kernels) with non-perturbative light-cone distribution amplitudes (LCDAs). At leading order in Λ/m_b,

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle = i m_B^2 \Big\{ f_+^{BM_1}(0) \int_0^1 du\, T_i^I(u)\, f_{M_2}\phi_{M_2}(u) + (M_1 \leftrightarrow M_2) + \int_0^\infty d\omega \int_0^1 du dv\, T_i^{II}(\omega, v, u)\, \hat{f}_B \phi_B(\omega) \times f_{M_1}\phi_{M_1}(v)\, f_{M_2}\phi_{M_2}(u) \Big\}, \quad (1)$$

where Q_i is a generic operator from the effective weak Hamiltonian. At this order the re-scattering phases are generated at the scale m_b only, and reside in the loop corrections to the hard-scattering kernels. Beyond the leading order factorization does not hold, and re-scattering occurs at all scales. The leading contributions to the strong phases are therefore of order $\alpha_s(m_b)$ or/and Λ/m_b. It is of paramount importance for the predictivity of the approach for the direct CP asymmetries to know whether the short-distance or long-distance contribution dominates in practice, since apart from being parametrically small, both could be numerically of similar size.

The short-distance contribution to the direct CP asymmetries is fully known only to the first non-vanishing order (that is, $\mathcal{O}(\alpha_s)$) through the one-loop computations of the vertex kernels T_i^I performed long ago [2,4,5]. A reliable result presumably requires the next-to-next-to-leading order $\mathcal{O}(\alpha_s^2)$ hard-scattering kernels, at least their imaginary parts. For the spectator-scattering kernels T_i^{II}

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For table on next slide:

- A_{CP}, ΔA_{CP}, and I_{xy} in %.
- The results listed in the Exp. (WA) column are taken from HFLAV 2014 results (arXiv:1412.7515).
- However, the Belle II fit projections were computed with results from ***a single experiment***: $K\pi$ Belle; $K^*\pi$ & $K\rho$ BaBar.
- The results of the GammaCombo fits are added in the last column. Also shown are the A_{CP} input used in the 2D fit (A_{CP} vs I_{xy}).
- The results of projecting to 5 and 50 ab^{-1} of Belle II data are shown in ()(), respectively.

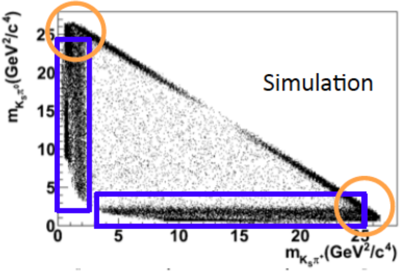
Comparison w/theory (Modified Table I)

f	NLO	NNLO	NNLO + LD	Exp (WA)	Exp (GC fit and B2 proj.)
$\pi^-\bar{K}^0$	$0.71\,^{+0.13}_{-0.14}\,^{+0.21}_{-0.19}$	$0.77\,^{+0.14}_{-0.15}\,^{+0.23}_{-0.22}$	$0.10\,^{+0.02}_{-0.02}\,^{+1.24}_{-0.27}$	-1.7 ± 1.6	**Belle input**
$\pi^0 K^-$	$9.42\,^{+1.77}_{-1.76}\,^{+1.87}_{-1.88}$	$10.18\,^{+1.91}_{-1.90}\,^{+2.03}_{-2.62}$	$-1.17\,^{+0.22}_{-0.22}\,^{+20.00}_{-\;\,6.62}$	4.0 ± 2.1	
$\pi^+ K^-$	$7.25\,^{+1.36}_{-1.36}\,^{+2.13}_{-2.58}$	$8.08\,^{+1.52}_{-1.51}\,^{+2.52}_{-2.65}$	$-3.23\,^{+0.61}_{-0.61}\,^{+19.17}_{-\;\,3.36}$	-8.2 ± 0.6	
$\pi^0\bar{K}^0$	$-4.27\,^{+0.83}_{-0.77}\,^{+1.48}_{-2.23}$	$-4.33\,^{+0.84}_{-0.78}\,^{+3.29}_{-2.32}$	$-1.41\,^{+0.27}_{-0.25}\,^{+5.54}_{-6.10}$	1 ± 10	-14 ± 13
ΔA_{CP}	$2.17\,^{+0.40}_{-0.40}\,^{+1.39}_{-0.74}$	$2.10\,^{+0.39}_{-0.39}\,^{+1.40}_{-2.86}$	$2.07\,^{+0.39}_{-0.39}\,^{+2.76}_{-4.55}$	12.2 ± 2.2	
$I_{K\pi}$	$-1.15\,^{+0.21}_{-0.22}\,^{+0.55}_{-0.84}$	$-0.88\,^{+0.16}_{-0.17}\,^{+1.31}_{-0.91}$	$-0.48\,^{+0.09}_{-0.09}\,^{+1.09}_{-1.15}$	-14 ± 11	$-27 \pm 14(7)(3)$
$\pi^-\bar{K}^{*0}$	$1.36\,^{+0.25}_{-0.26}\,^{+0.60}_{-0.47}$	$1.49\,^{+0.27}_{-0.29}\,^{+0.69}_{-0.56}$	$0.27\,^{+0.05}_{-0.05}\,^{+3.18}_{-0.67}$	-3.8 ± 4.2	**BaBar input**
$\pi^0 K^{*-}$	$13.85\,^{+2.40}_{-2.70}\,^{+5.84}_{-5.86}$	$18.16\,^{+3.11}_{-3.52}\,^{+\;\,7.79}_{-10.57}$	$-15.81\,^{+3.01}_{-2.83}\,^{+69.35}_{-15.39}$	-6 ± 24	-6 ± 24
$\pi^+ K^{*-}$	$11.18\,^{+2.00}_{-2.15}\,^{+\;\,9.75}_{-10.62}$	$19.70\,^{+3.37}_{-3.80}\,^{+10.54}_{-11.42}$	$-23.07\,^{+4.35}_{-4.05}\,^{+86.20}_{-20.64}$	-23 ± 6	
$\pi^0\bar{K}^{*0}$	$-17.23\,^{+3.33}_{-3.00}\,^{+\;\,7.59}_{-12.57}$	$-15.11\,^{+2.93}_{-2.65}\,^{+12.34}_{-10.64}$	$2.16\,^{+0.39}_{-0.42}\,^{+17.53}_{-36.80}$	-15 ± 13	
ΔA_{CP}	$2.68\,^{+0.72}_{-0.67}\,^{+5.44}_{-4.30}$	$-1.54\,^{+0.45}_{-0.58}\,^{+4.60}_{-9.19}$	$7.26\,^{+1.21}_{-1.34}\,^{+12.78}_{-20.65}$	17 ± 25	
$I_{K^*\pi}$	$-7.18\,^{+1.38}_{-1.28}\,^{+3.38}_{-5.35}$	$-3.45\,^{+0.67}_{-0.59}\,^{+9.48}_{-4.95}$	$-1.02\,^{+0.19}_{-0.18}\,^{+4.32}_{-7.86}$	-5 ± 45	$69 \pm 32(15)(6)$
$\rho^-\bar{K}^0$	$0.38\,^{+0.07}_{-0.07}\,^{+0.16}_{-0.27}$	$0.22\,^{+0.04}_{-0.04}\,^{+0.19}_{-0.17}$	$0.30\,^{+0.06}_{-0.06}\,^{+2.28}_{-2.39}$	-12 ± 17	**BaBar input**
$\rho^0 K^-$	$-19.31\,^{+3.42}_{-3.61}\,^{+13.95}_{-\;\,8.96}$	$-4.17\,^{+0.75}_{-0.80}\,^{+19.26}_{-19.52}$	$43.73\,^{+7.07}_{-7.62}\,^{+\;\,44.00}_{-137.77}$	37 ± 11	
$\rho^+ K^-$	$-5.13\,^{+0.95}_{-0.97}\,^{+6.38}_{-4.02}$	$1.50\,^{+0.29}_{-0.27}\,^{+\;\,8.69}_{-10.36}$	$25.93\,^{+4.43}_{-4.90}\,^{+25.40}_{-75.63}$	20 ± 11	
$\rho^0\bar{K}^0$	$8.63\,^{+1.59}_{-1.65}\,^{+2.31}_{-1.69}$	$8.99\,^{+1.66}_{-1.71}\,^{+3.60}_{-7.44}$	$-\,0.42\,^{+0.08}_{-0.08}\,^{+19.49}_{-\;\,8.78}$	6 ± 20	5 ± 26
ΔA_{CP}	$-14.17\,^{+2.80}_{-2.96}\,^{+7.98}_{-5.39}$	$-5.67\,^{+0.96}_{-1.01}\,^{+10.86}_{-\;\,9.79}$	$17.80\,^{+3.15}_{-3.01}\,^{+19.51}_{-62.44}$	17 ± 16	
$I_{K\rho}$	$-8.75\,^{+1.62}_{-1.66}\,^{+4.78}_{-6.48}$	$-10.84\,^{+1.98}_{-2.09}\,^{+11.67}_{-\;\,9.09}$	$-\,2.43\,^{+0.46}_{-0.42}\,^{+\;\,4.60}_{-19.43}$	-37 ± 37	$-44 \pm 49(25)(11)$

Improvements to theoretical predictions

- Complete the NNLO calculation of the leading-power penguin amplitude a_p^4.
- Compute the scalar penguin amplitude a_p^6 to the same precision.
- Attempt to improve the modelling of the weak-annihilation amplitudes.

Decay channel	$\mathcal{B}\,(10^{-6})$
$K^0\pi^+\pi^0$	$45.9 \pm 2.6 \pm 3.0 \pm 8.6$
$K^{*0}(892)\pi^+$	$14.6 \pm 2.4 \pm 1.3 \pm 0.5$
$K^{*+}(892)\pi^0$	$9.2 \pm 1.3 \pm 0.6 \pm 0.5$
$K_0^{*0}(1430)\pi^+$	$50.0 \pm 4.8 \pm 6.0 \pm 4.0$
$K_0^{*+}(1430)\pi^0$	$17.2 \pm 2.4 \pm 1.5 \pm 1.8$
$\rho^+(770)K^0$	$9.4 \pm 1.6 \pm 1.0 \pm 2.6$



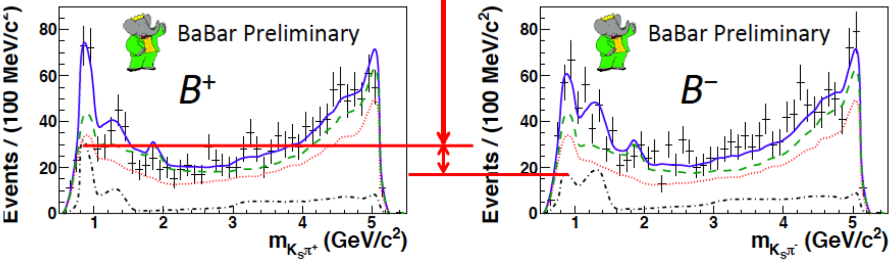
Resonances / Reference amplitude	Relative phases (°) $K^{*0}(892)\pi^+$	$K^{*+}(892)\pi^0$	$(K\pi)_0^{*0}\pi^+$	$(K\pi)_0^{*+}\pi^0$	$\rho^+(770)K_S^0$
$B^+ \to K^{*0}(892)\pi^+$	0	-96 ± 44	174 ± 11	-91 ± 43	-122 ± 38
$B^+ \to K^{*+}(892)\pi^0$	–	0	-90 ± 42	6 ± 10	-27 ± 26
$B^+ \to (K\pi)_0^{*0}\pi^+$	–	–	0	95 ± 42	64 ± 37
$B^+ \to (K\pi)_0^{*+}\pi^0$	–	–	–	0	-32 ± 25
$B^+ \to \rho^+(770)K_S^0$	–	–	–	–	0

Slide credit: T. Latham, BaBar, BEACH 2014, Birmingham

Experimental challenges: e.g., $K^{*+}(K_S\pi^+)\pi^0$ [Unpublished]

- First evidence of direct CP violation in $B^+ \to K^{*+}\pi^0$
- 3.4σ significance estimated including statistical, systematic and model uncertainties
- A_{CP} for $B^+ \to K^{*0}\pi^+$ consistent with zero (as expected)

Decay channel	A_{CP}
$K^0\pi^+\pi^0$	$0.07 \pm 0.05 \pm 0.03 \pm 0.04$
$K^{*0}(892)\pi^+$	$-0.12 \pm 0.21 \pm 0.08 \pm 0.11$
$K^{*+}(892)\pi^0$	$-0.52 \pm 0.14 \pm 0.04 \pm 0.04$
$K_0^{*0}(1430)\pi^+$	$0.14 \pm 0.10 \pm 0.04 \pm 0.14$
$K_0^{*+}(1430)\pi^0$	$0.26 \pm 0.12 \pm 0.08 \pm 0.12$
$\rho^+(770)K^0$	$0.21 \pm 0.19 \pm 0.07 \pm 0.30$



Slide credit: T. Latham, BaBar, BEACH 2014, Birmingham

$K^*\rho$: Status

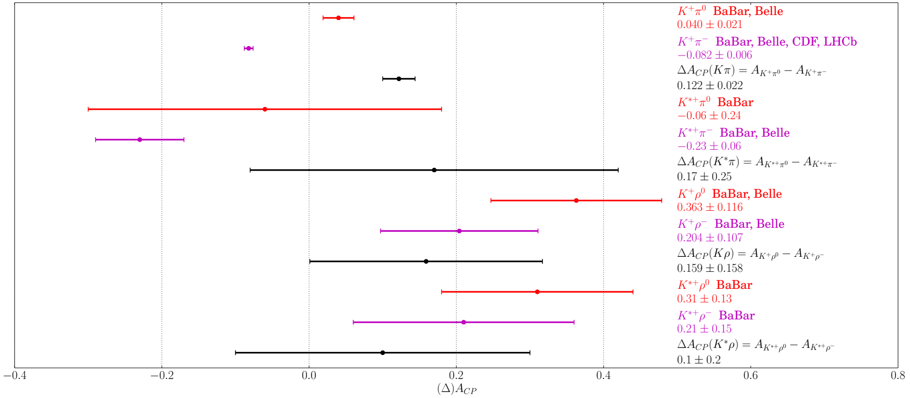
For $B \to VV$ decays, must separate out the longitudinal and transverse components:

- NNLO computation not possible for transverse amplitudes: power-suppressed and there is no QCD factorization theorem for them.
- For longitudinal component, comparison of NNLO computation to experiment not possible since A_{CP} not available for individual helicity amplitudes in $K^{*+}\rho^-$.
- NLO computation available for comparison.
- Many modes still uncovered by Belle & LHCb.

$\mathcal{B}(10^{-6})$		
Mode	BABAR	Belle
$K^{*+}\rho^-$	$10.3 \pm 2.3 \pm 1.3$	
$K^{*+}\rho^0$	$4.6 \pm 1.0 \pm 0.4$	
$K^{*0}\rho^+$	$9.6 \pm 1.7 \pm 1.5$	
$K^{*0}\rho^0$	$5.1 \pm 0.6^{+0.6}_{-0.8}$	$2.1^{+0.8+0.9}_{-0.7-0.5}$

A_{CP}	
Mode	BABAR
$K^{*+}\rho^-$	$0.21 \pm 0.15 \pm 0.02$
$K^{*+}\rho^0$	$0.31 \pm 0.13 \pm 0.03$
$K^{*0}\rho^+$	$-0.01 \pm 0.16 \pm 0.02$
$K^{*0}\rho^0$	$-0.06 \pm 0.09 \pm 0.02$

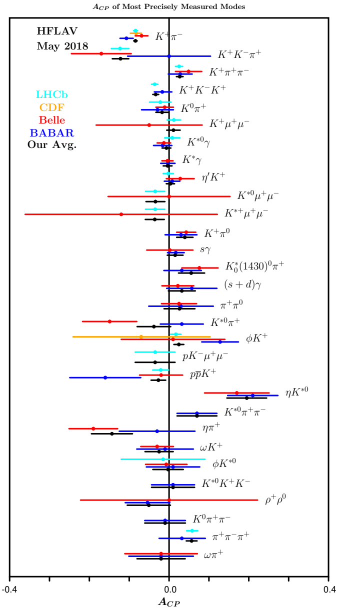
Summary of WA $(\Delta)A_{CP}$ results for $K^{(*)}\pi$ and $K^{(*)}\rho$



Uncertainty much improved in $K\pi$ but still too large in $K^*\pi$ and $K^{(*)}\rho$ systems to be conclusive.

Many Belle $\mathcal{B}$ and A_{CP} measurements missing for the PV and VV channels. Challenging Dalitz plot and VV analyses.

Summary of most precisely measured modes *Lots to study!*



Aside - Why "Penguin"?

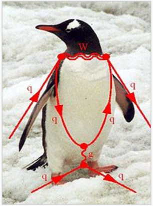
In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They refer to one-loop processes in which a quark temporarily changes flavor (via a W or Z loop), and the flavor-changed quark engages in some tree interaction, typically a strong one. For tree interactions where some quark flavors (e.g. very heavy ones) have much higher interaction amplitudes than others, such as CP-violating or Higgs interactions, these penguin processes may have amplitudes comparable to or even greater than those of the direct tree processes. A similar diagram can be drawn for leptonic decays.[1]

They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[2] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name [edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[3]

> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.



Example of a penguin diagram

Extra reading

- Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and CP Violation*.
http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf
Pages 171-183.
- Measurements of branching fractions and direct CP asymmetries for $B \to K\pi$, $B \to \pi\pi$ and $B \to KK$ decays (Belle Collaboration, 2014)