

Direct CP Violation

Prof. Dr. Torben Ferber
Dr. Pablo Goldenzweig

Flavor Physics Lectures
III / XII



Winter Semester 2023/2024
17. November, 2023

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 Physics 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 Physics and CP Violation*.
https://courses.physics.ucsd.edu/2010/Winter/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:

- From first principles, we saw explicitly 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 $\bar{K}^0(\bar{d}s)$.
- We then saw that 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 $\Gamma(K_{t=0}^0 \rightarrow \bar{K}^0) \neq \Gamma(\bar{K}_{t=0}^0 \rightarrow K^0)$, 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 $\Gamma(P \rightarrow f)$ and anti-particles $\Gamma(\bar{P} \rightarrow \bar{f})$, where:

P is a pseudoscalar meson

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

- Stated simply, if

$$\Gamma(P \rightarrow f) \neq \Gamma(\bar{P} \rightarrow \bar{f}) \quad \Rightarrow \quad CP \text{ Violation in decay}$$

We can express this as an asymmetry:

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

\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:

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

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

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 $P \rightarrow f$ decay as:

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

The amplitude for the CP -conjugate process is:

$$\bar{A} \equiv \bar{A}(\bar{P} \rightarrow \bar{f}) = \langle \bar{f}|H|\bar{P}\rangle$$

Condition for direct CP violation

Now let's see how the amplitudes are related (assuming CP is conserved):

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

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

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

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

Arrive at our condition for $DCPV$:

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

CP -violating phase

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

⇒ *If only a single amplitude contributes to a given decay process, there cannot be an observable CP asymmetry.*

Do you see why? (⇒ 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 $P \rightarrow f$ decay as:

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

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 $\bar{P} \rightarrow \bar{f}$ decay:

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

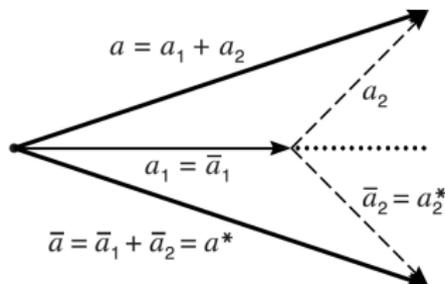
where the CP -violating phases have changed sign.

Only CP-violating weak phases

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

Why?

⇒ *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...

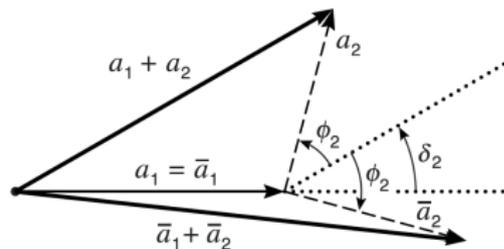
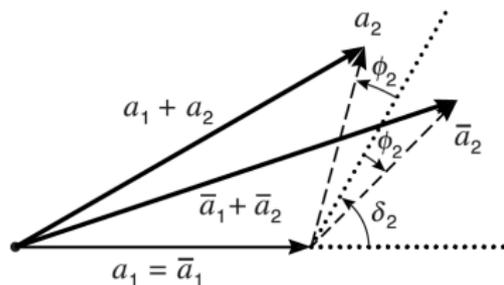
What about the coefficients a_j ?

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

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



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:

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

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

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

These results have important implications:

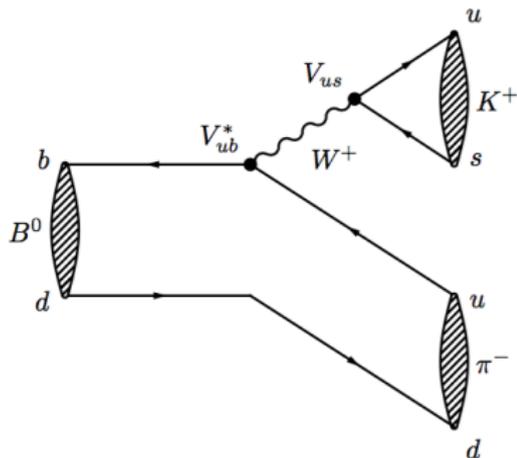
To observe CP -violating effects by comparing $\Gamma(P \rightarrow f)$ and $\Gamma(\bar{P} \rightarrow \bar{f})$ we need:

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

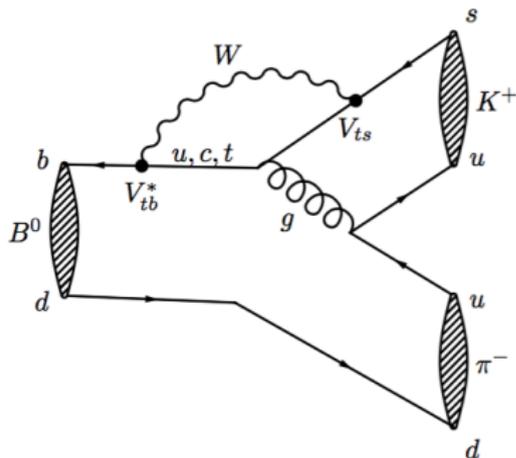
\Rightarrow Lets look at an example in $B^0 \rightarrow K^+ \pi^-$ decays

$B^0 \rightarrow K^+ \pi^-$ 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

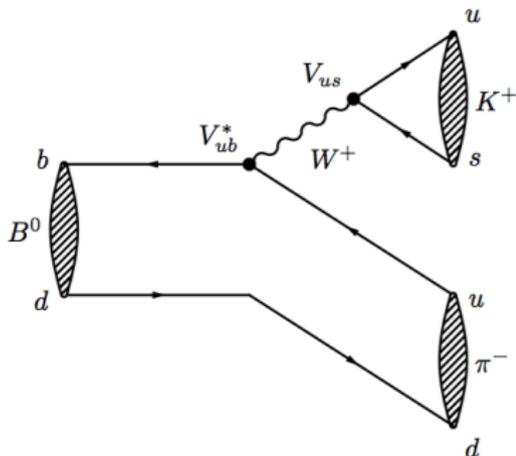
(Lecture 1, Slide 31)

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

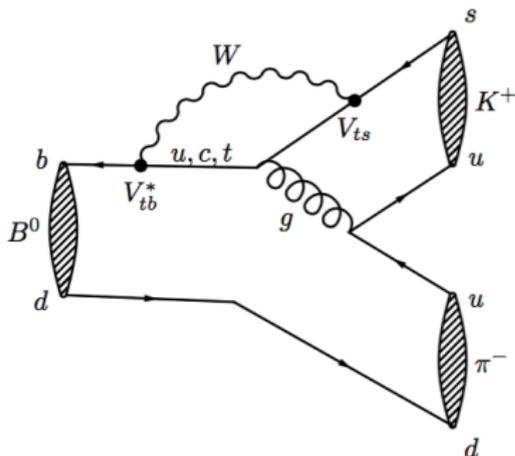
and note which matrix elements contain the CP violating phase

$B^0 \rightarrow K^+ \pi^-$ 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 .

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

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

What can we deduce from these amplitudes?

- If we compute

$$\frac{\Gamma(B^0 \rightarrow K^+ \pi^-) + \Gamma(\bar{B}^0 \rightarrow K^- \pi^+)}{2} \propto |A_P|^2 \left(1 - 2 \frac{A_T}{A_P} \cos \gamma \cos \delta + \left(\frac{A_T}{A_P} \right)^2 \right)$$

- and use the fact that $B^+ \rightarrow K^0 \pi^+$ is almost entirely a penguin process:

$$\Gamma(B^+ \rightarrow K^0 \pi^+) = \Gamma(B^- \rightarrow \bar{K}^0 \pi^-) \propto |A_P|^2$$

- we can compute the ratio:

$$R \equiv \frac{\Gamma(B_d \rightarrow K^\pm \pi^\mp)}{\Gamma(B^\pm \rightarrow K^0 \pi^\pm)} = \left(1 - 2 \frac{A_T}{A_P} \cos \gamma \cos \delta + \left(\frac{A_T}{A_P} \right)^2 \right) \quad (\text{note the } |A_P|^2 \text{ term is gone})$$

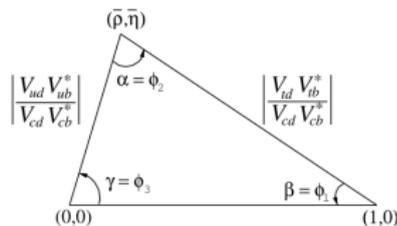
- The minimum value of R (as a function of $\frac{A_T}{A_P}$) is attained when $\frac{A_T}{A_P} = \cos \gamma \cos \delta$, and is given by

$$R \geq 1 - \cos^2 \gamma \cos^2 \delta \geq \sin^2 \gamma$$

- We now have a constraint in the $\rho - \eta$ plane

$$R \geq \frac{\eta^2}{\rho^2 + \eta^2} = \sin^2 \gamma$$

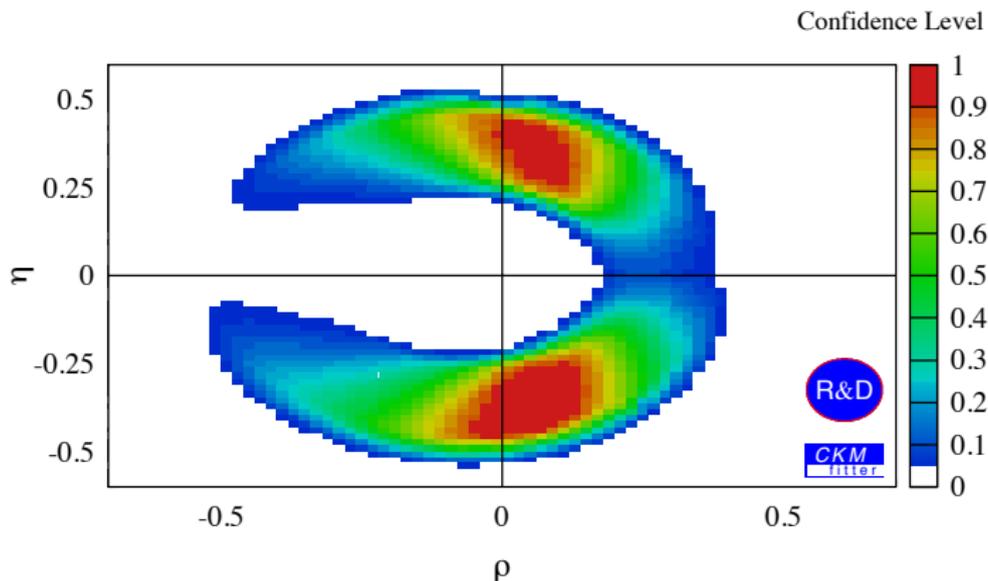
(If you don't see it, make a mini right triangle of origin (0,0), base ρ and height η)



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

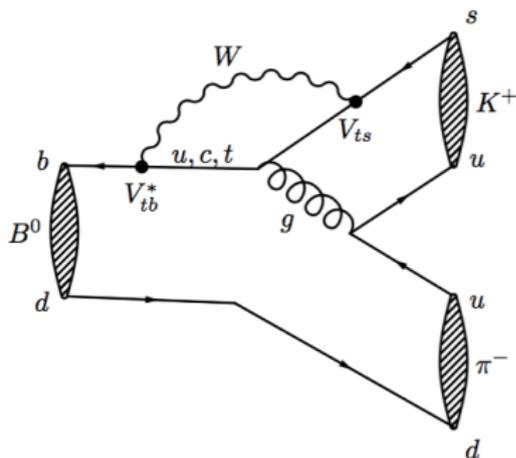
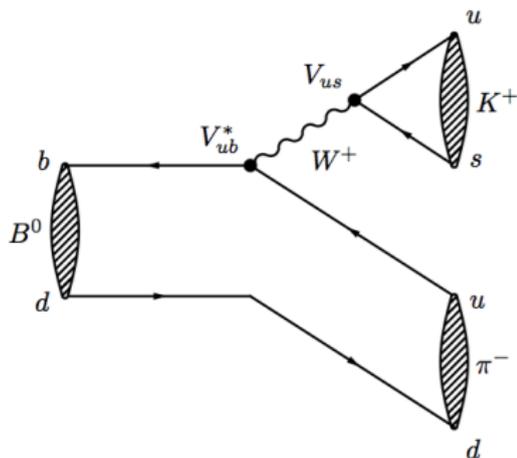
Constraint in the (ρ, η) plane

We can make a constraint on the apex of the Unitary Triangle using the $B \rightarrow K\pi$ and $B \rightarrow \pi\pi$ (*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 $B^+ \rightarrow K^+\pi^0$ decays?

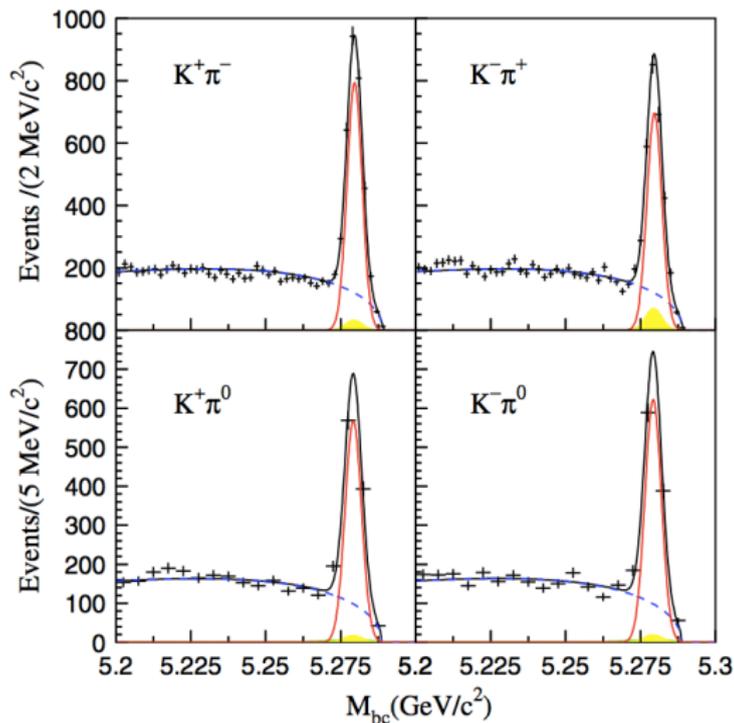


If we replace the spectator d -quark by a u -quark in both $B^0 \rightarrow K^+\pi^-$ diagrams, the π^- becomes a π^0 , and we have the tree and penguin diagrams for $B^+ \rightarrow K^+\pi^0$ decays.

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

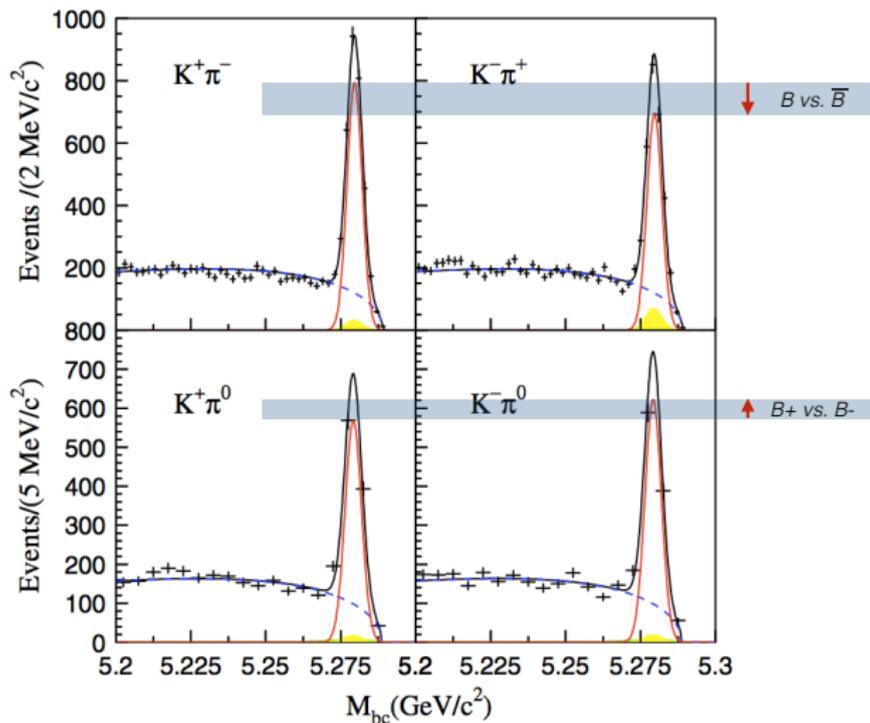
Not quite!

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



Not quite!

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



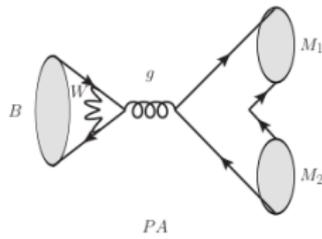
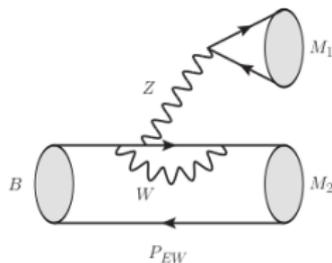
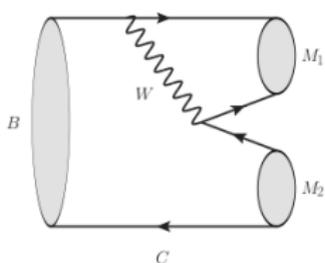
$$\mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \quad (4\sigma)$$

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 validity of the SM can be tested in a model-independent way.**

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

$B \rightarrow K\pi$: 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)]

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

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

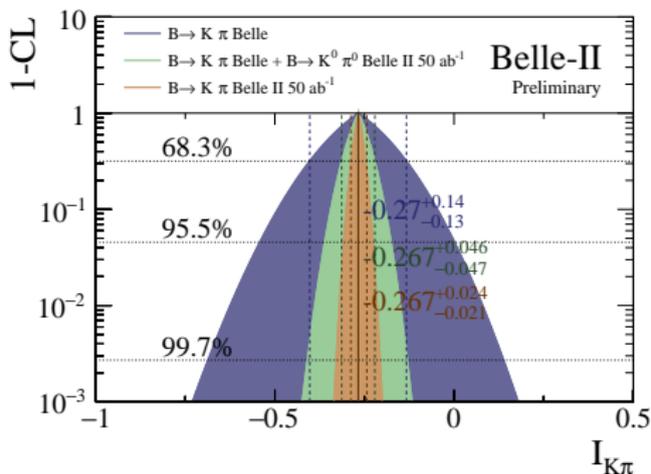
$$I_{K\pi} = -0.270 \pm 0.132 \pm 0.060 \text{ [Belle]}$$

- 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 :

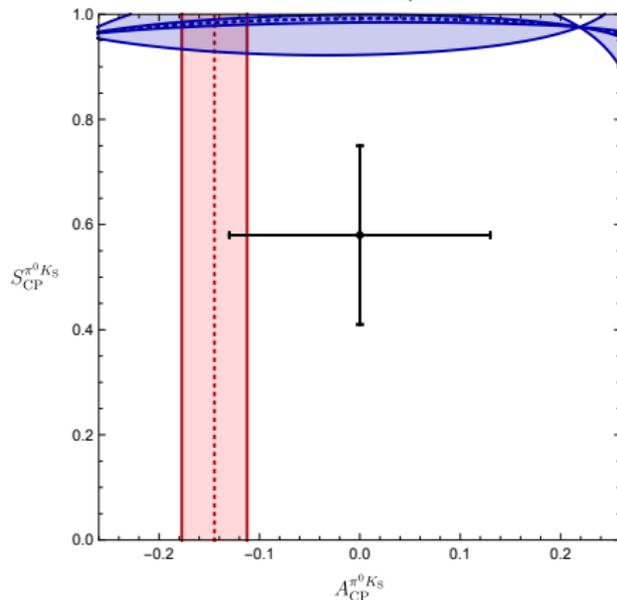
$$\sqrt{2}\mathcal{A}_{K^0\pi^0} + \mathcal{A}_{K^+\pi^0} = -\left(\hat{T} + \hat{C}\right) \left(e^{i\gamma} - qe^{i\phi}e^{i\omega}\right).$$

EW penguin effects described by

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

- 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 $B \rightarrow K^{(*)}\ell\ell$ measurements.*

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



More data:

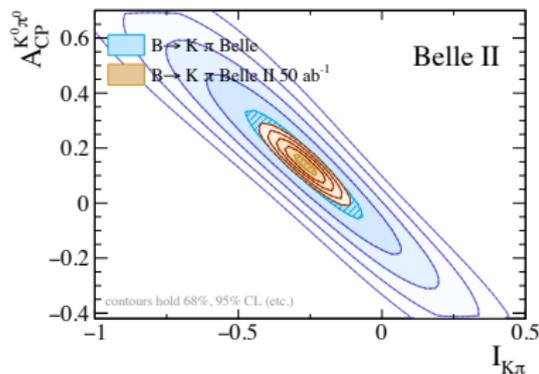
Extrapolate Belle measurements to 5 and 50 ab^{-1}

- 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/\bar{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:

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

$B \rightarrow K\pi$: 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.
 - Additionally the systematic uncertainties are conservatively provided and they are still smaller than the statistical errors.



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

Scenario	Value	$\mathcal{A}_{K^0\pi^0}$		$I_{K\pi}$
		Stat.	(Red., Irred.)	
Belle	0.14	0.13	(0.06, 0.02)	-0.27 ± 0.14
Belle + $B \rightarrow K^0\pi^0$ 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:

$K \rightarrow K^*$

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

$\pi \rightarrow \rho$

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

$K \rightarrow K^* \text{ \& } \pi \rightarrow \rho$

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

For each set of decays¹, perform a 2D scan of A_{CP} (for most limiting final state) vs. the isospin sum rule parameter.

⇒ Compare with (N)NLO calculations².

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

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

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



G. Bell^a, M. Beneke^b, T. Huber^c, Xin-Qiang Li^{d,e,*}

^a Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 2JG, United Kingdom

^b Physik Department T11, Technische Universität München, James-Frank-Straße 1, D-85748 Garching, Germany

^c Theoretische Physik I, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, D-57080 Siegen, Germany

^d Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, Hubei 430079, PR China

^e State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, PR China

ARTICLE INFO

Article history:

Received 17 July 2015

Accepted 15 September 2015

Available online 24 September 2015

Editor: B. Grösser

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 $b \rightarrow s$ transitions.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCDFP.

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 $B \rightarrow f$ 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 ,

$$\begin{aligned} \langle M_1 M_2 | Q_i | \bar{B} \rangle = & i m_b^3 \left\{ f_s^{M_1} \int_0^1 du T_i^f(u) f_{M_2} \phi_{M_2}(u) \right. \\ & + (M_1 \leftrightarrow M_2) \\ & + \int_0^1 d\omega \int_0^1 d\omega' \int_0^1 dv T_i^f(\omega, v, u) \int_0^1 \phi_B(\omega) \\ & \left. \times f_{M_1} \phi_{M_1}(v) f_{M_2} \phi_{M_2}(u) \right\}, \quad (1) \end{aligned}$$

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^f 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^f

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 (\circ) , respectively.

* Corresponding author at: Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, Hubei 430079, PR China.

E-mail address: xqli@tp.ccn.u.cn (X.-Q. Li).

Comparison w/theory (Modified Table I)

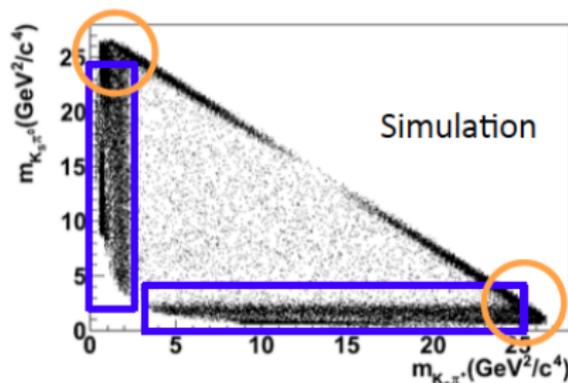
f	NLO	NNLO	NNLO + LD	Exp (WA)	Exp (GC fit and B2 proj.)
$\pi^- \bar{K}^0$	0.71 ^{+0.13 +0.21} _{-0.14 -0.19}	0.77 ^{+0.14 +0.23} _{-0.15 -0.22}	0.10 ^{+0.02 +1.24} _{-0.02 -0.27}	-1.7 ± 1.6	Belle input
$\pi^0 K^-$	9.42 ^{+1.77 +1.87} _{-1.76 -1.88}	10.18 ^{+1.91 +2.03} _{-1.90 -2.62}	-1.17 ^{+0.22 +20.00}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

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

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



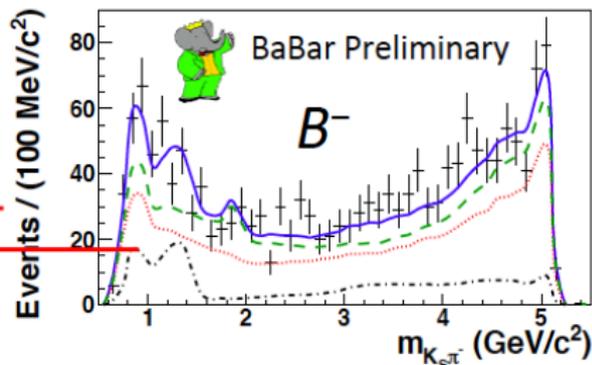
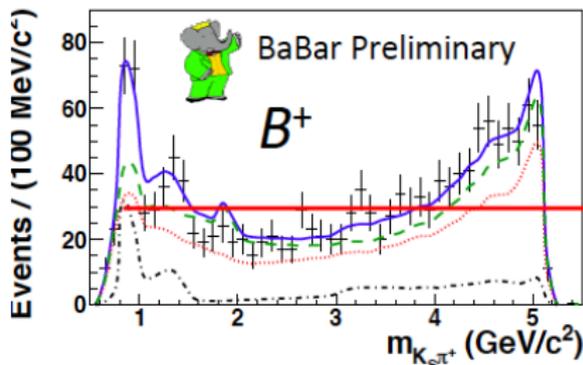
Reference amplitude	Resonances	Relative phases ($^\circ$)				
		$K^{*0}(892)\pi^+$	$K^{*+}(892)\pi^0$	$(K\pi)_0^{*0}\pi^+$	$(K\pi)_0^{*+}\pi^0$	$\rho^+(770)K_S^0$
$B^+ \rightarrow K^{*0}(892)\pi^+$		0	-96 ± 44	174 ± 11	-91 ± 43	-122 ± 38
$B^+ \rightarrow K^{*+}(892)\pi^0$		-	0	-90 ± 42	6 ± 10	-27 ± 26
$B^+ \rightarrow (K\pi)_0^{*0}\pi^+$		-	-	0	95 ± 42	64 ± 37
$B^+ \rightarrow (K\pi)_0^{*+}\pi^0$		-	-	-	0	-32 ± 25
$B^+ \rightarrow \rho^+(770)K_S^0$		-	-	-	-	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 $B^+ \rightarrow K^{*+}\pi^0$
- 3.4σ significance estimated including statistical, systematic and model uncertainties
- A_{CP} for $B^+ \rightarrow K^{*0}\pi^+$ 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

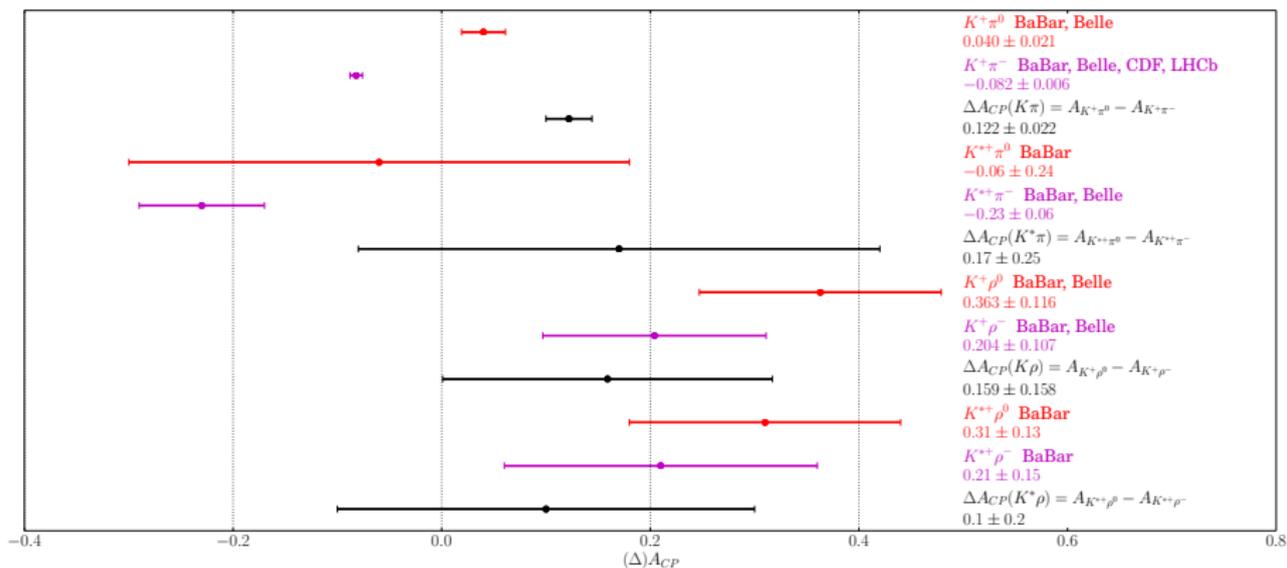
For $B \rightarrow VV$ decays, must separate out the longitudinal and transverse components:

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

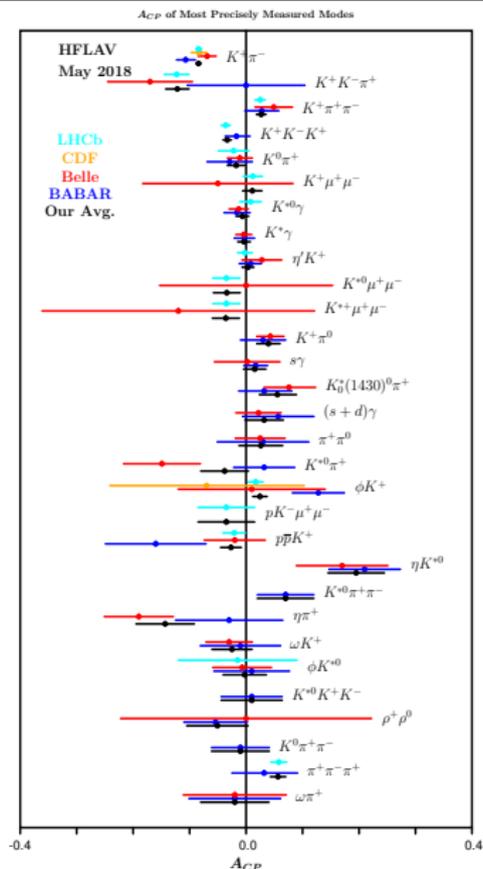
Summary of WA (Δ) A_{CP} results for $K^{(*)}\pi$ and $K^{(*)}\rho$



Uncertainty much improved in $K\pi$ but still too large in K^π 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 [\[edit \]](#)

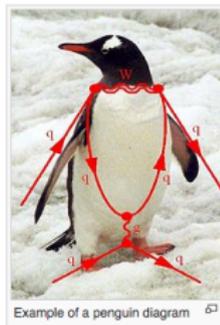
John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:^[3]

“ 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.

”



- Richman, Jeremy D. (UCSB), *Heavy Quark Physics 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 $B \rightarrow K\pi$, $B \rightarrow \pi\pi$ and $B \rightarrow KK$ decays (Belle Collaboration, 2014)