$K\pi$ test-of-sum rule in $K^{(*)}\pi$ and $K^{(*)}\rho$ decays and sensitivity of Belle II

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Belle II Physics Book NP Impact plot meeting
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- $K\pi$ puzzle still an open issue.
- Test-of-sum (isospin) rule proposed to test SM by measuring $\mathcal{B}$ and A_{CP} of all 4 $K\pi$ final states.
- Idea is to extend this isospin rule to the $K^*\pi$, $K\rho$ and $K^*\rho$ systems, make projections for Belle II data, and compare with (N)NLO computations.

⇒ *Show results of 2D fits to A_{CP} vs. isospin sum rule identity parameter for PV and VV systems.*

⇒ *Compare with (N)NLO calculations.*

⇒ *Summarize ΔA_{CP} status using WA measurements.*

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

$\Rightarrow$ *Use Belle results for calculating $I_{K\pi}$, $I_{K\pi}$ vs. $\mathcal{A}_{K^0\pi^0}$ contours, and for projecting to Belle II dataset.*

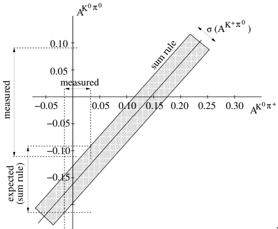
$B \to K\pi$: Test of sum rule

Test-of-sum (isospin) rule for NP nearly free of theoretical uncertainties, where the SM can be tested by measuring all observables:

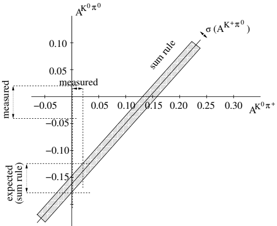
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

$$I_{K\pi} = -0.270 \pm 0.132 \pm 0.060 \ \ (1.9\sigma)$$

Isospin sum rule can be presented as a band in the $\mathcal{A}_{K^0\pi^0}$ vs. $\mathcal{A}_{K^0\pi^+}$ plane.



Current data

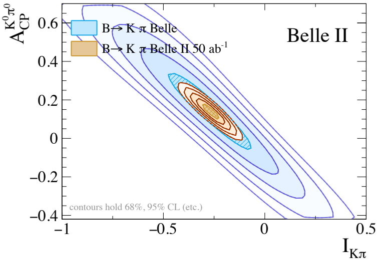


Belle II $\mathcal{L}$ =50ab^{-1}

→ Most demanding measurement is $K^0\pi^0$ final state. With Belle II, the uncertainty on $\mathcal{A}(B \to K^0\pi^0)$ from time-dep. analyses is expected to reach $\sim 4\%$ ⇒ *sufficient for NP studies.*

- 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.

P. Urquijo, BELLE2-NOTE-0021



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:

$K \to K^*$

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

$\pi \to \rho$

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

$K \to K^*$ & $\pi \to \rho$

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

Challenging Dalitz plot analysis involving final states with up to 2 π^0's, and $B \to VV$ decays.

$K^*\pi$: Status

$\mathcal{B}(10^{-6})$			
Mode	BABAR	Belle	LHCb
$K^{*+}\pi^-$	8.2 ± 0.9	$8.4 \pm 1.1^{+1.0}_{-0.9}$	
$K^{*+}\pi^0$	$8.2 \pm 1.5 \pm 1.1$		
$K^{*0}\pi^+$	$10.8 \pm 0.6^{+1.2}_{-1.4}$	$9.7 \pm 0.6^{+0.8}_{-0.9}$	
$K^{*0}\pi^0$	$3.3 \pm 0.5 \pm 0.4$	< 3.5	

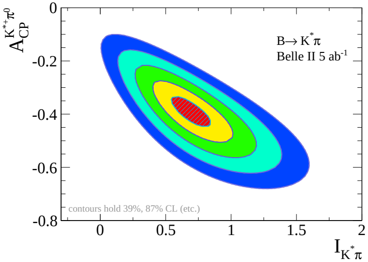
A_{CP}			
Mode	BABAR	Belle	LHCb
$K^{*+}\pi^-$	$-0.24 \pm 0.07 \pm 0.02$	$-0.21 \pm 0.11 \pm 0.07$	
$K^{*+}\pi^0$	$-0.06 \pm 0.24 \pm 0.04$		
$K^{*0}\pi^+$	$0.032 \pm 0.052^{+0.016}_{-0.013}$	$-0.149 \pm 0.064 \pm 0.022$	
$K^{*0}\pi^0$	$-0.15 \pm 0.12 \pm 0.04$		

- $\mathcal{A}_{K^{*+}\pi^-}$ measured by both Belle and BaBar with high precision.
- Most challenging mode $K^{*+}\pi^0$. [1]
  $\mathcal{A}_{cp}(K^{*+}(K^+\pi^0)\pi^0)) = -0.06 \pm 0.24 \pm 0.04$

[1] Unpublished BaBar measurement not included [arXiv:1501.00705]: $\mathcal{A}_{cp}(K^{*+}(K_S\pi^+)\pi^0)) = -0.52 \pm 0.14 \pm 0.04 \pm 0.04$

- ***Calculate $I_{K^*\pi}$ and projections for Belle II using BaBar's complete set of measurements.***
- Given that $\mathcal{A}_{K^{*+}\pi^0}$ is not systematically limited, treat all errors as reducible for sensitivity study.
- $I_{K^*\pi}$ values result of GammaCombo fit.

$\Rightarrow$ *Large positive identity parameter $I_{K^*\pi}$.*



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

Scenario	$\mathcal{A}_{K^{*+}\pi^0}$ Value	Stat.	$I_{K^*\pi}$
BaBar	-0.06	0.24	0.69 ± 0.32
Belle II 5 ab^{-1}			0.69 ± 0.15
Belle II 50 ab^{-1}			0.69 ± 0.06

$\mathcal{B}(10^{-6})$		
Mode	BABAR	Belle
$K^+\rho^-$	$6.6 \pm 0.5 \pm 0.8$	$15.1^{+3.4+2.4}_{-3.3-2.6}$
$K^+\rho^0$	$3.56 \pm 0.45^{+0.57}_{-0.46}$	$3.89 \pm 0.47^{+0.43}_{-0.41}$
$K^0\rho^+$	$8.0^{+1.4}_{-1.3} \pm 0.6$	
$K^0\rho^0$	$4.4 \pm 0.7 \pm 0.3$	$6.1 \pm 1.0^{+1.1}_{-1.2}$

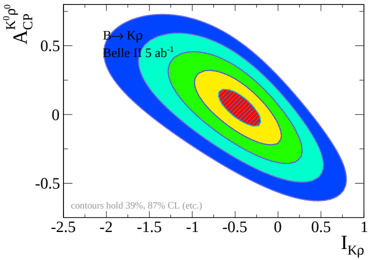
A_{CP}		
Mode	BABAR	Belle
$K^+\rho^-$	$0.20 \pm 0.09 \pm 0.08$	$0.22^{+0.22+0.06}_{-0.23-0.02}$
$K^+\rho^0$	$0.44 \pm 0.10^{+0.06}_{-0.14}$	$0.30 \pm 0.11^{+0.11}_{-0.05}$
$K^0\rho^+$	$-0.12 \pm 0.17 \pm 0.02$	
$K^0\rho^0$	$0.05 \pm 0.26 \pm 0.10 \pm 0.03$	$0.03^{+0.23}_{-0.24} \pm 0.11 \pm 0.10$

- Most limiting mode $\mathcal{A}_{K^0\rho^0}$.

$K\rho$: Test of sum rule

- ***Calculate $I_{K\rho}$ and projections for Belle II using BaBar's complete set of measurements.***
- Again, stat. limited so treat all syst. errors as reducible.
- $I_{K\rho}$ values result of GammaCombo fit.

$\Rightarrow$ *Large negative identity parameter $I_{K\rho}$.* Same (different) sign as $I_{K\pi}$ ($I_{K^*\pi}$).



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

Scenario	$\mathcal{A}_{K^0\rho^0}$ Value	$\mathcal{A}_{K^0\rho^0}$ Stat.	$I_{K\rho}$
BaBar	0.05	0.26	-0.44 ± 0.49
Belle II 5 ab^{-1}			-0.44 ± 0.25
Belle II 50 ab^{-1}			-0.44 ± 0.11

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,

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

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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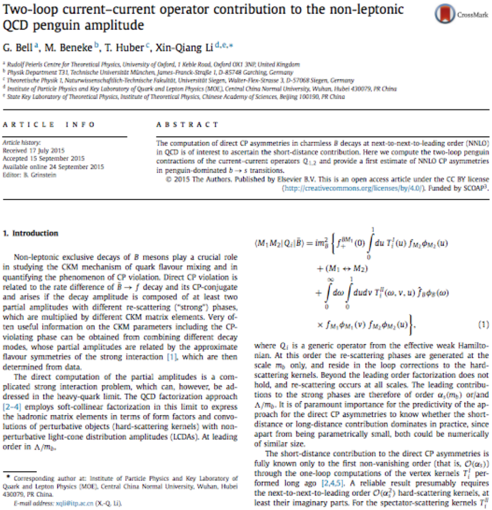

Two-loop current–current operator contribution to the non-leptonic QCD penguin amplitude

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For table on next slide:

- The A_{CP} and isospin identity parameters listed in the Exp. (WA) column are taken from HFAG 2014 results (arXiv:1412.7515).
- However, the B2 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_x).
- The results of projecting to 5 and 50 ab^{-1} are shown in ().

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	$-44 \pm 49(25)(11)$

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

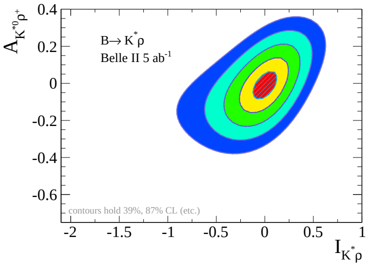
- NNLO computation not possible for transverse amplitudes: power-suppressed and there is no QCD factorization theorem for them.
- For longitudinal component, comparison of NNLO computation to experiment not possible since A_{CP} not available for individual helicity amplitudes in $K^{*+}\rho^-$.
- NLO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

$\mathcal{B}(10^{-6})$		
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
$K^{*+}\rho^-$	$0.21 \pm 0.15 \pm 0.02$
$K^{*+}\rho^0$	$0.31 \pm 0.13 \pm 0.03$
$K^{*0}\rho^+$	$-0.01 \pm 0.16 \pm 0.02$
$K^{*0}\rho^0$	$-0.06 \pm 0.09 \pm 0.02$

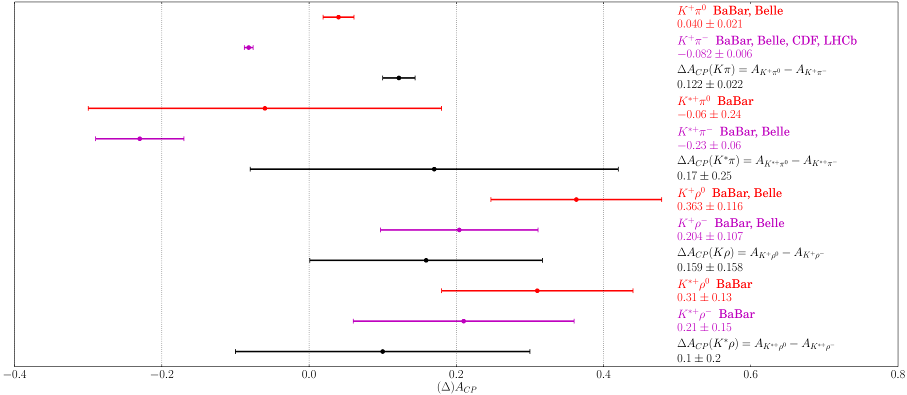
- Most limiting mode $\mathcal{A}_{K^{*0}\rho^+}$.

- ***Calculate $I_{K^*\rho}$ and projections for Belle II using BaBar's complete set of measurements.***
- Comparison to NLO coming soon.



Projections for the $B \to K^*\rho$ isospin sum rule parameter, $I_{K^*\rho}$, at the BaBar measured central value.

Scenario	$\mathcal{A}_{K^{*0}\rho^+}$ Value	$\mathcal{A}_{K^{*0}\rho^+}$ Stat.	$I_{K^*\rho}$
BaBar	-0.01	0.16	0.004 ± 0.264
Belle II 5 ab^{-1}			0.004 ± 0.123
Belle II 50 ab^{-1}			0.004 ± 0.044



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

Summary

- Test-of-sum rule extended to $K^*\pi$ and $K^{(*)}\rho$ systems.
- GammaCombo fits to identity parameter vs. most demanding final state.
- Projections of results to 5 and 50 ab^{-1} of Belle II data.
- Large errors in (N)NLO computations and current experimental results make comparison difficult. Large Belle II dataset required for enough precision to see differences with theory.
- ΔA_{CP} relations tabulated for all sets of decays. Uncertainty still too large for $K^*\pi$ and $K^{(*)}\rho$ to be conclusive.