Charmless Hadronic B Decays
WG5 Experiment

Martin Beneke, [1], Cheng-Wei Chiang [2], Pablo Goldenzweig [3]

[1]TUM, [2]NTU [3]KIT

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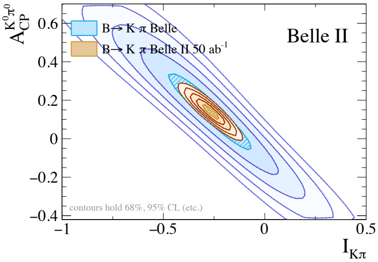
Charmless Hadronic Golden Modes

- CPV in $B \to K\pi$, with emphasis on $K_S^0\pi^0$.
- $B \to K^{(*)}\pi$ & $B \to K^{(*)}\rho$ systems.
  - Include challenging Dalitz plot analyses, and full angular analyses in $B \to VV$ decays (including TP asymmetries). Complete sets of PV and VV channels are not measured by Belle, and Belle II sensitivity studies for individual final states have not been performed.
  - However, comparisons of the Isospin sum rule identity parameter for Belle II projections with (N)NLO calculations have been performed and are included in the report.
- Local CP asymmetries in final states with π or K and other resonances,
  - Interesting channels for Belle II motivated during previous B2TIP workshops include: $B^0 \to K_S^0 K^+ K^-$, $B^0 \to K^+ K^- \pi^0$, $B^+ \to K^+ \pi^0 \pi^0$, $B^+ \to K_S^0 \pi^+ \pi^0$.
  - Experimental activity on $B \to 3h$ has just started, so results will not likely make it into report.
- $B_s \to K^0 \overline{K}^0$
  - First observation with full Belle $121\mathrm{fb}^{-1}$ dataset. Toy study performed for $5\mathrm{ab}^{-1}$ of Belle II data will be included in report.
  - Belle II decay time resolution sensitivity study underway, but may not make it into report.
- $B_s \to \phi\pi^0$
  - Belle analysis with B2BII converted data in BASF2 underway, but no Belle II study yet.[1]

[1] For channels with no theory/experiment input, a brief discussion will be included at the end of the chapter to motivate these analyses for new collaborators.

- 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. *Will need to be addressed with increased data.*

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

Expect analogous sum rules by replacing:

$K \to K^*$

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

$\pi \to \rho$

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

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

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

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

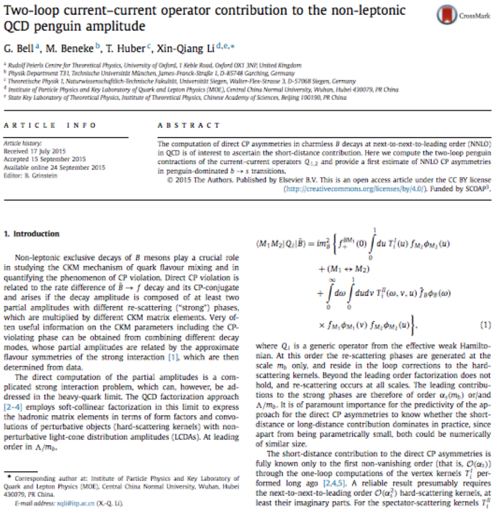
$\Rightarrow$ Compare with (N)NLO calculations[3].

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

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

Theory predictions PLB 750(2015)348-355

Karlsruhe Institute of Technology Belle II



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 3NP, United Kingdom
[b] Physik Department T31, Technische Universität München, James-Franck-Straße 1, D-85748 Garching, Germany
[c] Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Strasse 3, D-57068 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

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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,

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

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}

* 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@itp.ac.cn (X.-Q. Li).

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 ().

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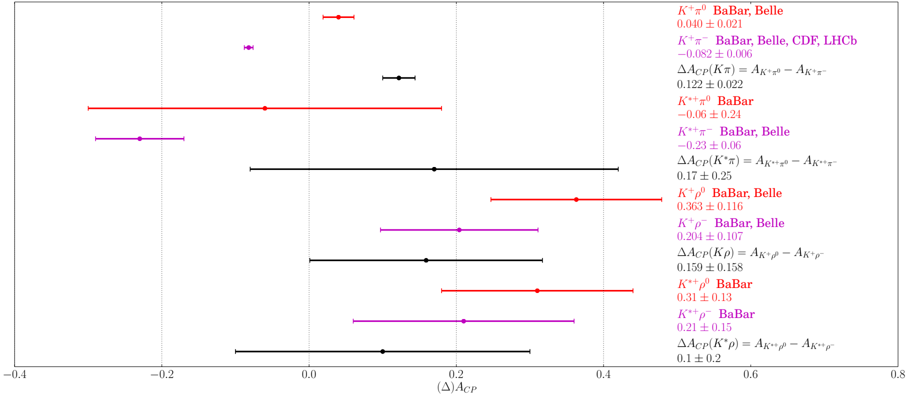
Belle II

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

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



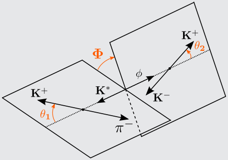
Uncertainty much improved in $K\pi$ but still too large in $K^*\pi$ and $K^{(*)}\rho$ systems to be conclusive.

$B \to VV$

- Decays to spin-1 final states with pairs formed from ω, K^*, ρ, and ϕ can be used to determine the helicity amplitudes of the decay.
- Channels have low $\mathcal{B}$ and high background.

Full angular analysis requires large statistics (e.g., $B^0 \to \phi K^{*0}$). *With the current datasets most analysis are limited to integrating over the angle between the decay planes Φ, and reporting the longitudinal polarization fraction (f_L)*

$$(1 - f_L)\sin^2\theta_1 \sin^2\theta_2 + 4 f_L \cos^2\theta_1 \cos^2\theta_2$$



Highlights to seach for with more data include:

- Angular analysis of $K^*\rho$ channels.
  - $\Rightarrow$ *Observation that there is an enhanced contribution proportional to electromagnetic penguins, which would be revealed in a polarisation analysis.* hep-ph/0512258
- Contribution of electroweak penguins in the hierarchy of the decays to ωK^{*0} and $\omega\phi$.
- **Triple-product asymmetries, which provide a measure of CP violation that does not require flavor tagging or a time-dependent analysis.**

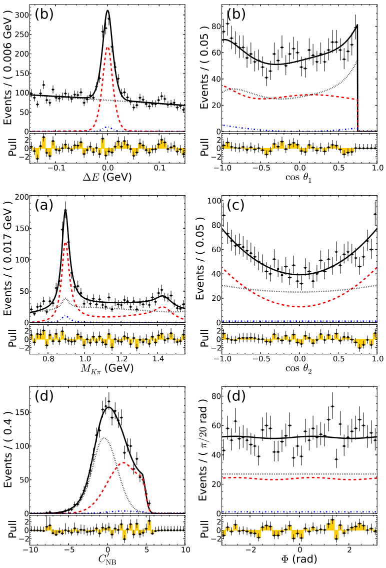
  Phys. Rev. D **84**, 096013 (2011)

Full angular analysis and search for $DCPV$ in $B^0 \to \phi K^{*0}$.

- At Belle/BaBar full angular analysis limited to low-background decays such as $B^0 \to \phi K^{*0}$.
- In the final Belle analysis, a 9D extended unbinned ML fit is used to extract the 26 parameters related to polarization and CPV.
- Figure shows projections onto 6 of the 9 fitted observables.
- All phase ambiguities have been resolved and all parameters related to CP violation are consistent with 0.

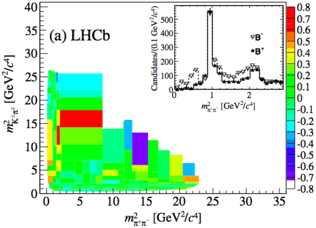
$\Rightarrow$ *Belle II's large dataset is needed to perform full angular analyses on many other $B \to VV$ channels.*

Belle, Phys. Rev. D **88**, 072004 (2013)

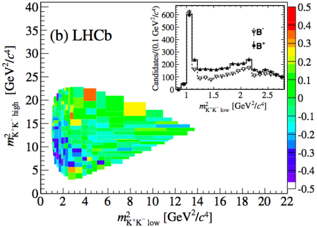


Large CPV effects not associated with resonances $\Rightarrow$ *QCD effects to be understood*

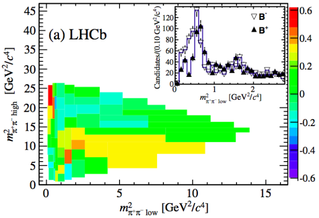
$K\pi\pi$



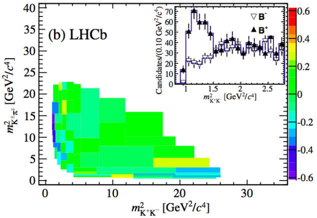
KKK Phys. Rev. Lett. **111**, 101801 (2013)



$\pi\pi\pi$



$KK\pi$ Phys. Rev. Lett. **112**, 011801 (2014)



$\Rightarrow$ *Unidentified structure in the $m^2_{K^+K^-}$ projection in $KK\pi$ decays at $< 1.5\ \mathrm{GeV}^2/c^4$. Only present in the B^+ mass projection and gives rise to a large local CP asymmetry.* [*Updated measurement: arXiv: 1408.5373]

Direct CP violation in 3-body $B_{u,d}$ decays

	Theory (%)	Expt (%)	
$\pi^+ \pi^- \pi^-$	$8.7^{+1.7}_{-1.9}$	5.8 ± 1.4	Inclusive CP asymmetries
$K^+ K^- K^-$	$-7.1^{+4.8}_{-4.1}$	-3.6 ± 0.8	
$K^- \pi^+ \pi^-$	$2.7^{+0.7}_{-0.8}$	2.5 ± 0.9	
$K^+ K^- \pi^-$	$-10.0^{+2.1}_{-2.7}$	-12.3 ± 2.2	
$K^- K^+ \pi^0$	$-9.2^{+0.0}_{-0.0}$		predictions
$K^- K^+ K_S$	$-5.5^{+1.5}_{-1.1}$		
$K^- K_S K_S$	$3.5^{+0.3}_{-0.2}$	4 ± 5	
$K_S \pi^+ \pi^0$	$0.64^{+0.07}_{-0.07}$	$7 \pm 5 \pm 3 \pm 4$	BaBar
$(\pi^+ \pi^- \pi^-)_{\text{region I}}$	$22.5^{+2.9}_{-3.3}$	58.4 ± 8.7	not updated yet by LHCb
$(K^+ K^- K^-)_{\text{region I}}$	$-17.7^{+4.9}_{-2.9}$	-22.6 ± 2.2	
$(K^- \pi^+ \pi^-)_{\text{region I}}$	$14.1^{+13.9}_{-11.7}$	67.8 ± 8.5	
$(K^+ K^- \pi^-)_{\text{region I}}$	$-18.2^{+1.8}_{-1.8}$	-64.8 ± 7.2	

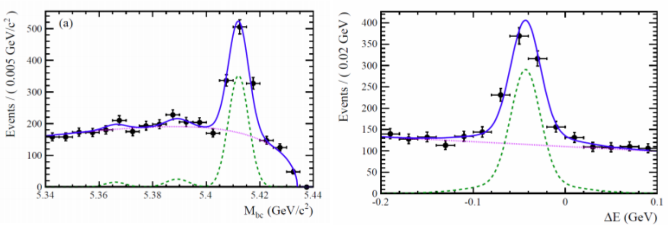
No theory text for report so far. Experimental activity has just started on Belle II MC. Will unlikely make it into report.

See talk by Hai-Yang Cheng at first B2TIP workshop

At e^+e^-, $\Upsilon(5S)$ decays are well-suited for studying large multiplicity B_s decays due to the lower particle momenta, the almost 100% trigger ε, and the excellent π/K separation.

- First observation of $B_s \to K^0\overline{K}^0$ by Belle with 121fb^{-1}: Phys. Rev. Lett. **116**, 161801 (2016)
  Assuming a 5ab^{-1} sample of $\Upsilon(5S)$ data, expect roughly 1200 ± 50 events (assuming similar reconstruction efficiency as Belle). Large yield can be used to perform CP study.

  Toy simulation with Belle II expectations (Pittsburgh B2TIP talk by B. Pal):



- Belle II decay time resolution sensitivity study under way, but may not be ready for report.

Summary

Experimental part of the text is converging and we are awaiting results from ongoing sensitivity studies.

Highlights include:

- New insight into $K\pi$ puzzle with $A_{CP}(\mathcal{B} \to K^0\pi^0)$ reaching 3-4%?
  Surprises on the way from $K^*\pi$ and $K\rho$? Large errors in current experimental results make comparison to (N)NLO calculations difficult. Large Belle II dataset required for enough precision to see differences with theory.
- Full angular analysis and triple-product-asymmetries will become feasible in additional $B \to VV$ channels.
  More surprises on the way from angular analysis in $b \to s$ penguin decays, e.g., $K^*\rho$?
- Observation of large local A_{CP} in additional 3-body decays?
  $B^0 \to K^0_S K^+ K^-$, $B^0 \to K^+ K^- \pi^0$...