Experimental overview of hadronic B decays

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Future Challenges in Non-Leptonic B Decays: Theory and Experiment
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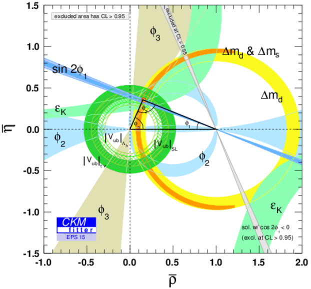
Introduction

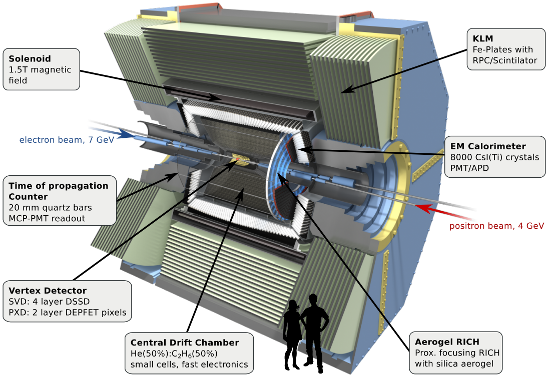
- B decays into two light charmless mesons
  $\rightarrow$ can be used to constrain the unitarity triangle
  $\rightarrow$ partially very sensitive to new physics, *e.g.* loop-dominated decays
- Physics accessed through
  $\rightarrow$ branching fractions
  $\rightarrow$ (time-dependent) *CP* asymmetries
  $\rightarrow$ polarization fractions ($B \rightarrow VV$)
  $\rightarrow$ isospin analysis, *e.g.* $\phi_2(\alpha)$ from $B \rightarrow hh$ with $h = \pi, \rho$



Outline

The Belle II experiment

- Belle II is the successor of the Belle experiment at the assymetric-energy e^+e^- KEKB collider, Japan
- Belle has the world record instantaneous peak luminosity of $2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Total luminosity of 0.7 ab^{-1} collected at the $\Upsilon(4S)$ resonance at Belle



The Belle II experiment

- Belle II includes accelerator and detector upgrades
- 40 times the instant luminosity of Belle
  50 times the integrated luminosity

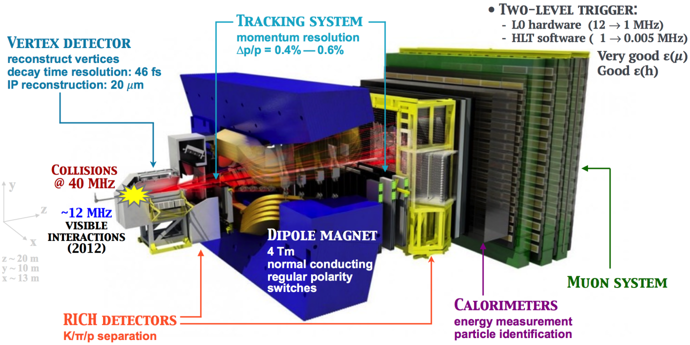
- Accelerator based on the nano-beam technology
- LER-HER energies changed from $3.5 - 8\ \mathrm{GeV}$ to $4 - 7\ \mathrm{GeV}$ to reduce Touschek effect and improve the emittance
- Boost reduced from 0.425 to 0.28 $\Rightarrow$ B meson decay-time resolution worse
- New pixel vertex detector closer to the interaction point to compensate for this effect, improves vertex resolution by $\approx$ a factor of two

- Larger central drift chamber with smaller cells improves $\vec{p}$ resolution
- ARICH and iTOP detectors for particle identification with higher performance and very fast read-out electronics
- New data aquisition system working at a much higher rate

The LHCb upgrade

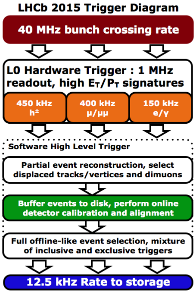
- LHCb is a forward spectrometer with acceptance $2 \leq \eta \leq 5$
- Operates at a fixed instantaneous luminosity of $4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Luminosity to be increased to $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

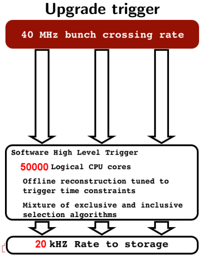
	Period	Energy	Int. lumi
Run I	2011-2012	7–8 TeV	$\sim 3\ \mathrm{fb}^{-1}$
Run II	2015-2018	14 TeV	$\geq 5\mathrm{fb}^{-1}$
Upgrade	ca. 10 y	14 TeV	$\geq 50\ \mathrm{fb}^{-1}$



The LHCb upgrade

- Detector and trigger will be upgraded to be able to fully exploit the available luminosity
- Current Level-0 trigger will not be able to cope with the higher output rate
  $\to$ to be replaced by a software trigger with a faster readout and a better (hadron) reconstruction efficiency
- Current subdetectors cannot handle the high occupancy and some of them also the radiation
  $\to$ new Vertex Locator with improved acceptance, better impact parameter resolution, can withstand the high radiation
  $\to$ improved tracker and PID system (RICH, calorimeters, muon system)
- To be installed by 2018-2019





Outline

1. Belle II and LHCb upgrade
2. $b \to s q \bar{q}$ transitions
   - Precise measurement of $\sin 2\phi_1$ in $b \to c\bar{c}s$ transitions
   - ϕ_1 in $B \to PP$ and $B \to PV$ decays
   - $B \to VV$ decays
3. $b \to d q \bar{q}$ transitions
4. $b \to u \bar{u} d$ transitions
   - $B \to \pi\pi$ isospin analysis
   - $B \to \rho\rho$ isospin analysis
   - Combined result for ϕ_2

Outline

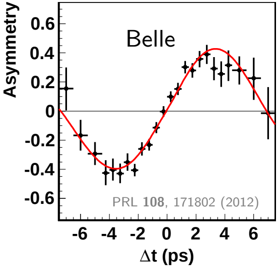
Precise measurement of sin $2\phi_1$ in b $\to$ c$\bar{c}$s transitions

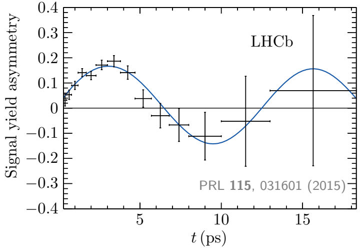
$\phi_1(\beta)$ is the most precisely measured angle of the unitarity triangle

Current average: $\phi_1 = (22.6 \pm 0.4)^\circ$ (CKMfitter)

sin $2\phi_1$		
BaBar 0.4 ab^{-1}	0.687 ± 0.028(stat) ± 0.012(syst)	PRD **79** 072009 (2009)
Belle 0.7 ab^{-1}	0.667 ± 0.023(stat) ± 0.012(syst)	PRL **108** 171802 (2012)
LHCb 3 fb^{-1}	0.731 ± 0.035(stat) ± 0.020(syst)	PRL **115** 031601 (2015)
ALEPH	$0.84^{+0.82}_{-1.04}$(stat) ± 0.16(syst)	PL **B492** 259-274(2000)
CDF (full Run I)	$0.79^{+0.41}_{-0.44}$(stat+syst)	PRL **61** 072005 (2000)
OPAL	$3.2^{+1.8}_{-2.0}$(stat) ± 0.5(syst)	EPJ **C5** 379-388 (1998)
Current average	0.710 ± 0.011	CKMfitter

$\sin 2\phi_1$ in $b \to c\bar{c}s$ transitions

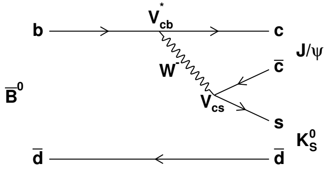


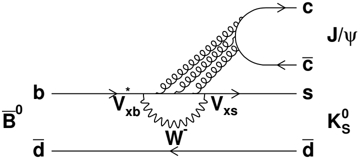


- Most accurately measured in $b \to c\bar{c}s$ transitions, such as $B^0 \to J/\psi K^0_S$
- Access through $\mathcal{S}_{CP} = \sin 2\phi_1$ ($\eta = \pm 1$ for even/odd final state) in the time-dependent *CP* asymmetry of *CP* final states

$$a_{CP}(t) = \frac{N_{B^0 \to J/\psi K^0_S} - N_{\overline{B}^0 \to J/\psi K^0_S}}{N_{B^0 \to J/\psi K^0_S} - N_{\overline{B}^0 \to J/\psi K^0_S}} = \mathcal{A}_{CP} \cos(\Delta m t) + \eta \mathcal{S}_{CP} \sin(\Delta m t)$$

$\sin 2\phi_1$ in $b \to c\bar{c}s$ transitions





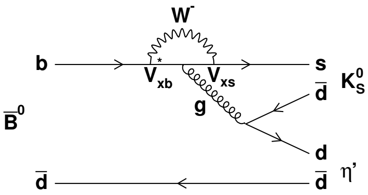
- Relatively large branching fraction – $\mathcal{O}(10^{-4})$
- Theoretically clean – access through tree process, penguin contribution very small, $|\sin 2\phi_1^{eff} - \sin 2\phi_1| \lesssim 0.01$ (arXiv:1212.4789)

  ...at least until now: Future Belle II and LHCb precision expected to be of the same order as the pengin pollution

  $\Rightarrow$ Penguin needs to be controlled, *e.g.* with modes such as $B^0 \to J/\psi\pi^0$ (PRL **95**, 221804 (2005))

Outline

$\sin 2\phi_1$ in $b \to s q\bar{q}$ transitions



- Loop-dominated process, sensitive to contributions from new physics
- Loop sensitive to ϕ_1, just as in $b \to c\bar{c}s$
- Access to an "effective" ϕ_1, $\mathcal{S}_{CP} = \sin 2\phi_1^{eff}$, due to tree contributions
- Deviations of the *CP* parameters and the branching fractions from the SM predictions could be a hint at new physics
- Theoretical uncertainties on branching fractions larger, *CP* parameters provide a more accurate comparison

$\sin 2\phi_1$ in $b \to sq\bar{q}$ transitions

- Search for new physics in the channel-dependent observable $\Delta S = \sin 2\phi_1^{eff} - \sin 2\phi_1$
- Golden modes: $B^0 \to \phi K^0$, $B^0 \to \eta' K^0$ and $B^0 \to K_S^0 K_S^0 K_S^0$
- (Almost) free from tree contributions

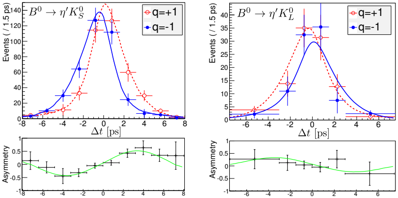
ΔS	QCDf	World average (HFAG)
$B^0 \to \phi K^0$	$0.022^{+0.004}_{-0.002}$ [1]	$+0.06^{+0.11}_{-0.13}$
$B^0 \to \eta' K^0$	0.00 ± 0.01 [2]	-0.05 ± 0.06
$B^0 \to K_S^0 K_S^0 K_S^0$	$0.06^{+0.007}_{-0.018}$ [3]	$+0.04 \pm 0.19$

- Statistical uncertainties still large to challenge the SM

[1] PRD **80**, 114008 (2009)
[2] PRD **80**, 114008 (2009)
[3] PRD **72**, 094003 (2005)

$B^0 \to \eta' K^0$

- $B^0 \to \eta' K^0$ – relatively high branching fraction, $\mathcal{O}(10^{-5})$
- Reconstruction of $B^0 \to \eta' K^0_S$ and $B^0 \to \eta' K^0_L$ (same $|\mathcal{S}_{CP}|$)
  $\eta' \to \rho^0[\pi^+\pi^-]\gamma$, $\eta' \to \eta[\gamma\gamma, \pi^+\pi^-\pi^0]\pi^+\pi^-$
  $K^0_S \to \pi^+\pi^-$, $K^0_S \to \pi^0\pi^0$



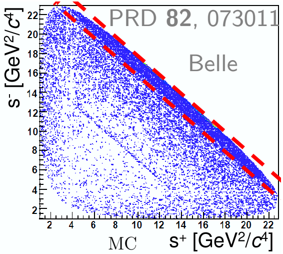
Belle, JHEP **1410**, 165 (2014)

Decay mode	$-\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$\eta' K^0_S$	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
$\eta' K^0_L$	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
$\eta' K^0$	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

	BaBar, 0.4 ab^{-1} PRD **79**, 052003 (2009)	Belle, 0.7 ab^{-1} JHEP **1410** 165 (2014)	Belle II, 50 ab^{-1} estimate	Theory PRD **80**, 114008
$\sigma(\sin 2\phi_1^{eff})$	0.08	0.08	0.01	0.01

$B^0 \to \phi K^0$

- ϕ_1^{eff} obtained directly from a Dalitz plot fit
- Reconstruction of $B^0 \to \phi[K^+K^-]K^0_S[\pi^+\pi^-]$
- The current Belle results a four-fold ambiguity
- Taking into account BES results for $f_X K^0_S$ contributions, the favoured solution is
  $\phi_1^{eff} = (32.2 \pm 9.0(\text{stat}) \pm 2.6(\text{syst}) \pm 1.4(\text{DP}))^\circ$
  $\sin 2\phi_1^{eff} = 0.90^{+0.09}_{-0.19}$

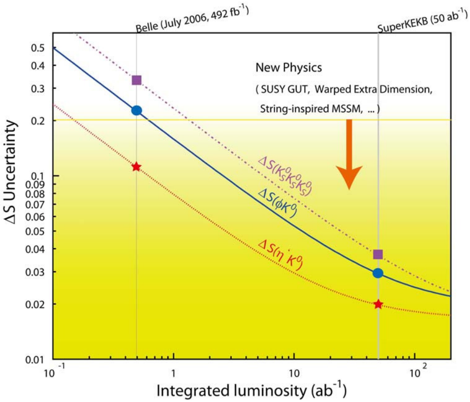


$s_\pm = (p_{K^\pm} + p_{K^0_S})^2$

	BaBar, 0.4 ab^{-1} PRD **79**, 052003	Belle, 0.6 ab^{-1} PRD **82**, 073011	Belle II, 50 ab^{-1} estimate	LHCb, 50 fb^{-1} estimate	Theory PRD **80**, 114008
$\sigma(\phi_1^{eff})$	6.3°	9.5°	0.4°	0.6°	0.06°
$\sigma(\sin 2\phi_1^{eff})$	0.18	0.19	0.02	0.05	0.002 – 0.004

ΔS at Belle II

$$\Delta\mathcal{S} \equiv \mathcal{S}_{CP}(\mathrm{b} \to \mathrm{s}\mathrm{q}\bar{\mathrm{q}}) - \mathcal{S}_{CP}(\mathrm{B} \to J/\psi K^0_S)$$

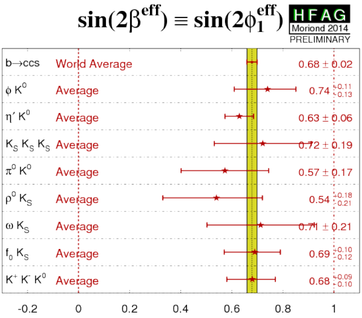


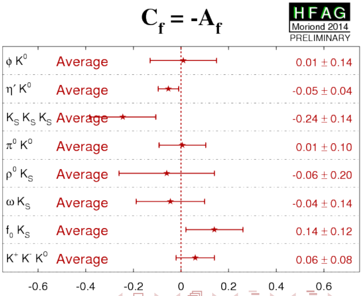
Belle II will be sensitive to a deviation as small as $\Delta\mathcal{S} \sim 0.1$

Refined analysis techniques and reduced systematic uncertainties could further improve the sensitivity

Other $b \to s\bar{q}q$

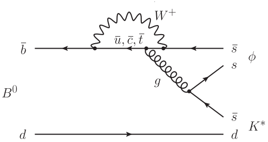
- Also other interesting modes, such as
  $\pi^+\pi^- K^0_S$ ($f_0 K^0_S$, $\rho^0 K^0_S$, multi-body decay) – allow for direct ϕ_1^{eff} measurement
  $\pi^0 K^0$ – a part of the "K-π puzzle"
  ωK^0_S
- $\mathcal{B}$ and $\mathcal{A}_{CP}$ can provide additional information about NP contributions
- $\mathcal{B}$ and $\mathcal{A}_{CP}$ of charged modes such as $B^+ \to \eta^{(\prime)} K^+$, $B^+ \to \omega K^+$ as well

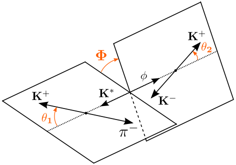




Outline

$B_{ud} \to VV$





- Modes: $B \to \phi[KK]K^*[K\pi]$, $B \to K^*[K\pi]\omega[3\pi]$, $B \to K^*[K\pi]\rho[2\pi]$
- $B \to VV$ decays not *CP* eigenstates
- For spin 1, three possible polarization amplitudes: A_0, A_+ and A_-
- Usually analysis performed using parity-even and -odd amplitudes, $A_{\parallel,\perp} = (A_+ \pm A_-)/\sqrt{2}$
- Major observables are

$$\mathcal{B}(B \to VV)$$

$$f_h = \frac{|A_h|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}, \qquad h = 0, \parallel, \perp$$

$$a_{CP} = \frac{\Gamma(\overline{B} \to VV) - \Gamma(B \to VV)}{\Gamma(\overline{B} \to VV) + \Gamma(B \to VV)}$$

$B^0 \to \phi[K^+K^-]K^*[K^+\pi^-]$ angular analysis

Extraction of f_L in a full amplitude analysis

- sensitive to A
- considers the contributing waves
- considers interference effects

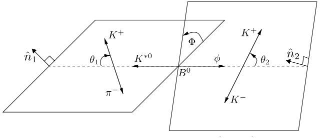
Sometimes not enough data, only fit to (a subset of the) angular and/or mass distributions

- only sensitive to $|A|^2$
- usually a two-body approximation

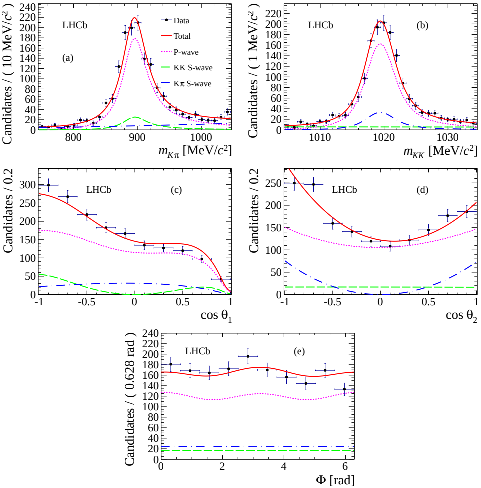
Parameter	Definition	Fitted value
$f_{\rm L}$	$0.5(\lvert A_0\rvert^2/F_{\rm P} + \lvert\overline{A}_0\rvert^2/\overline{F}_{\rm P})$	$0.497 \pm 0.019 \pm 0.015$
$f_\perp$	$0.5(\lvert A_\perp\rvert^2/F_{\rm P} + \lvert\overline{A}_\perp\rvert^2/\overline{F}_{\rm P})$	$0.221 \pm 0.016 \pm 0.013$
$f_{\rm S}(K\pi)$	$0.5(\lvert A_{\rm S}^{K\pi}\rvert^2 + \lvert\overline{A}_{\rm S}^{K\pi}\rvert^2)$	$0.143 \pm 0.013 \pm 0.012$
$f_{\rm S}(KK)$	$0.5(\lvert A_{\rm S}^{KK}\rvert^2 + \lvert\overline{A}_{\rm S}^{KK}\rvert^2)$	$0.122 \pm 0.013 \pm 0.008$
$\delta_\perp$	$0.5(\arg A_\perp + \arg \overline{A}_\perp)$	$2.633 \pm 0.062 \pm 0.037$
$\delta_\parallel$	$0.5(\arg A_\parallel + \arg \overline{A}_\parallel)$	$2.562 \pm 0.069 \pm 0.040$
$\delta_{\rm S}(K\pi)$	$0.5(\arg A_{\rm S}^{K\pi} + \arg \overline{A}_{\rm S}^{K\pi})$	$2.222 \pm 0.063 \pm 0.081$
$\delta_{\rm S}(KK)$	$0.5(\arg A_{\rm S}^{KK} + \arg \overline{A}_{\rm S}^{KK})$	$2.481 \pm 0.072 \pm 0.048$
$\mathcal{A}_0^{CP}$	$(\lvert A_0\rvert^2/F_{\rm P} - \lvert\overline{A}_0\rvert^2/\overline{F}_{\rm P})/(\lvert A_0\rvert^2/F_{\rm P} + \lvert\overline{A}_0\rvert^2/\overline{F}_{\rm P})$	$-0.003 \pm 0.038 \pm 0.005$
$\mathcal{A}_\perp^{CP}$	$(\lvert A_\perp\rvert^2/F_{\rm P} - \lvert\overline{A}_\perp\rvert^2/\overline{F}_{\rm P})/(\lvert A_\perp\rvert^2/F_{\rm P} + \lvert\overline{A}_\perp\rvert^2/\overline{F}_{\rm P})$	$+0.047 \pm 0.074 \pm 0.009$
$\mathcal{A}_S(K\pi)^{CP}$	$(\lvert A_{\rm S}^{K\pi}\rvert^2 - \lvert\overline{A}_{\rm S}^{K\pi}\rvert^2)/(\lvert A_{\rm S}^{K\pi}\rvert^2 + \lvert\overline{A}_{\rm S}^{K\pi}\rvert^2)$	$+0.073 \pm 0.091 \pm 0.035$
$\mathcal{A}_S(KK)^{CP}$	$(\lvert A_{\rm S}^{KK}\rvert^2 - \lvert\overline{A}_{\rm S}^{KK}\rvert^2)/(\lvert A_{\rm S}^{KK}\rvert^2 + \lvert\overline{A}_{\rm S}^{KK}\rvert^2)$	$-0.209 \pm 0.105 \pm 0.012$
$\delta_\perp^{CP}$	$0.5(\arg A_\perp - \arg \overline{A}_\perp)$	$+0.062 \pm 0.062 \pm 0.005$
$\delta_\parallel^{CP}$	$0.5(\arg A_\parallel - \arg \overline{A}_\parallel)$	$+0.045 \pm 0.069 \pm 0.015$
$\delta_S(K\pi)^{CP}$	$0.5(\arg A_{\rm S}^{K\pi} - \arg \overline{A}_{\rm S}^{K\pi})$	$+0.062 \pm 0.062 \pm 0.022$
$\delta_S(KK)^{CP}$	$0.5(\arg A_{\rm S}^{KK} - \arg \overline{A}_{\rm S}^{KK})$	$+0.022 \pm 0.072 \pm 0.004$

LHCb, JHEP **1405**, 069 (2014)

$B^0 \to \phi[K^+K^-]K^*[K^+\pi^-]$ angular analysis



LHCb, JHEP **1405**, 069 (2014) →



$B_{ud} \to VV$: f_L

"Naïve" expectation in $B \to VV$ is $f_0 \equiv f_L \approx 1$
f_L experimental precision at the level of 0.01 at Belle II and LHCb with 50 fb^{-1}

f_L	QCDf[4]	pQCD[5]	BaBar[6]	Belle[7]	LHCb ($1\,\mathrm{fb}^{-1}$)[8]
			value ± stat ± syst	value ± stat ± syst	value ± stat ± syst
ϕK^{*0}	$0.50^{+0.04+0.51}_{-0.07-0.42}$	-	$0.49 \pm 0.03 \pm 0.01$	$0.50 \pm 0.03 \pm 0.02$	$0.50 \pm 0.02 \pm 0.02$
ϕK^{*+}	$0.49^{+0.04+0.51}_{-0.06-0.43}$	-	$0.49 \pm 0.05 \pm 0.03$	$0.52 \pm 0.08 \pm 0.03$	-
$K^{*0}\omega$	$0.58^{+0.07+0.43}_{-0.10-0.14}$	0.82(0.74)	$0.72 \pm 0.14 \pm 0.02$	$0.56 \pm 0.29^{+0.18}_{-0.08}$	-
$K^{*+}\omega$	$0.67^{+0.03+0.32}_{-0.04-0.39}$	0.81(0.73)	$0.41 \pm 0.18 \pm 0.05$	-	-
$K^{*0}\rho^0$	$0.39^{+0.00+0.60}_{-0.00-0.31}$	0.74(0.68)	$0.40 \pm 0.08 \pm 0.11$	-	in progress
$K^{*+}\rho^-$	$0.53^{+0.02+0.45}_{-0.03-0.32}$	0.78(0.71)	$0.38 \pm 0.13 \pm 0.03$	-	-
$K^{*+}\rho^0$	$0.67^{+0.02+0.31}_{-0.03-0.48}$	0.85(0.78)	$0.78 \pm 0.12 \pm 0.03$	-	-
$K^{*0}\rho^+$	$0.48^{+0.03+0.52}_{-0.04-0.40}$	0.82(0.76)	$0.52 \pm 0.10 \pm 0.04$	$0.43 \pm 0.11^{+0.05}_{-0.02}$	-

[4] PRD **80**, 114008 (2009). Errors from varying (i) Gegenbauer moments, decay constants, quark masses, form factors, the λ_B parameter for the B meson wave function, and (ii) $\rho_{A,H}$, $\phi_{A,H}$

[5] PRD **73**, 014011 (2006); PRD **73**, 014024 (2006); PRD **72**, 054015 (2005); PRD **73**, 114014 (2006). Number in parenthesis asymptotic wave function

[6] Top to bottom: PRD **78**, 092008 (2008); PRL **99**, 201802 (2007); PRD **79**, 052005 (2009) (both $K^*\omega$); PRD **85**, 072005 (2012)(both neutral $K^*\rho$); PRD **83**, 051101 (2010); PRL **97**, 201801 (2006)

[7] Top to bottom: PRD **88**, 072004 (2013); PRL **94**, 221804 (2005); PRL **101**, 231801 (2008); PRL **101**, 231801 (2008); PRL **95**, 141801 (2005)

[8] JHEP **1405**, 069 (2014); analysis with 3 fb^{-1} ongoing

$B_{ud} \to VV$: $\mathcal{B}$

Branching fraction at the B factories

$$\mathcal{B} = \frac{N_{sig}}{N_{B\bar{B}}\epsilon\eta}$$

ϵ: reconstruction efficiency from MC
η: data-MC eff. correction factor

N_{sig}: signal yield

$N_{B\bar{B}}$: total number of produced $B\bar{B}$

Branching fraction at LHCb

$$\mathcal{B} = \mathcal{B}_{norm} \cdot \frac{\epsilon_{norm}}{\epsilon_{sig}} \cdot \frac{f_{norm}}{f_{u/d/s}} \cdot \frac{N_{sig}}{N_{norm}}$$

Number of B mesons not known
$\Rightarrow$ hence normalisation channel needed
ϵ: data-corrected reconstruction eff.
$f_{u/d/s}$: $B^{\pm}/B^0_d/B^0_s$ production prob.

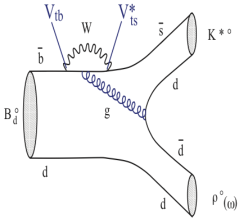
$B_{ud} \to VV$: $\mathcal{B}$

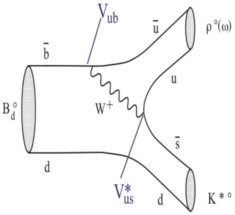
$\mathcal{B}(10^{-6})$	QCDf[4]	pQCD[5]	BaBar[9]	Belle[10]	LHCb ($1\,\mathrm{fb}^{-3}$)
			value ± stat ± syst	value ± stat ± syst	value ± stat ± syst
ϕK^{*0}	$9.5^{+1.3+11.9}_{-1.2-5.9}$	-	$9.7 \pm 0.5 \pm 0.6$	$10.4 \pm 0.5 \pm 0.6$	in progress?
ϕK^{*+}	$10.0^{+1.4+12.3}_{-1.3-6.1}$	-	$11.2 \pm 1.0 \pm 0.9$	$6.7^{+2.1+0.7}_{-1.9-1.0}$	-
$K^{*0}\omega$	$2.5^{+0.4+2.5}_{-0.4-1.5}$	9.6(6.6)	$2.2 \pm 0.6 \pm 0.2$	$1.8 \pm 0.7^{+0.3}_{-0.2}$	-
$K^{*+}\omega$	$3.0^{+0.4+2.5}_{-0.3-1.5}$	7.9(5.5)	< 7.4	-	-
$K^{*0}\rho^0$	$4.6^{+0.6+3.5}_{-0.5-3.5}$	5.9(4.7)	$5.1 \pm 0.6^{+0.6}_{-0.8}$	$2.1^{+0.8+0.9}_{-0.5-0.7}$	-
$K^{*+}\rho^-$	$8.9^{+1.1+4.8}_{-1.0-5.5}$	13(9.8)	$10.3 \pm 2.3 \pm 1.3$	-	-
$K^{*+}\rho^0$	$5.5^{+0.6+1.3}_{-0.5-2.5}$	9(6.4)	$4.6 \pm 1.0 \pm 0.4$	-	-
$K^{*0}\rho^+$	$9.2^{+1.2+3.6}_{-1.1-5.4}$	17(13)	$9.6 \pm 1.7 \pm 1.5$	-	-

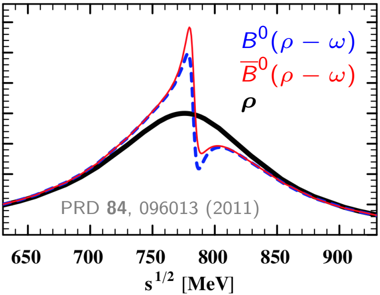
[9] Top to bottom: PRL **98** 051801 (2007); PRL **99**, 201802 (2007); PRD **79**, 052005 (2009) (both $K^*\omega$); PRD **85**, 072005 (2012) (both neutral $K^*\rho$); PRD **83**, 051101 (2010); PRL **97**, 201801 (2006)

[10] Top to bottom: PRL **91**, 201801 (2003); PRL **91**, 201801 (2003); PRL **101**, 231801 (2008); PRD **80**, 051103 (2009)

$B_{ud} \to VV$: a_{CP}







a_{CP} may be significant due to both a (suppressed) tree amplitude contribution and a $\rho - \omega$ interplay

$B_{ud} \to VV$: a_{CP}

$a_{CP}(10^{-2})$	QCDf[4]	BaBar[11] value ± stat ± syst	Belle[12] value ± stat ± syst	LHCb ($1\,\mathrm{fb}^{-1}$)[13] value ± stat ± syst
ϕK^{*0}	$0.8^{+0+0.4}_{-0-0.5}$	$1 \pm 6 \pm 3$	$-0.7 \pm 4.8 \pm 2.1$	$-1.5 \pm 3.2 \pm 10$
ϕK^{*+}	0.05	$0 \pm 9 \pm 4$	$-2 \pm 14 \pm 3$	-
$K^{*0}\omega$	56^{+3+4}_{-4-43}	$45 \pm 25 \pm 2$	-	-
$K^{*+}\omega$	23^{+9+5}_{-5-18}	$29 \pm 35 \pm 2$	-	-
$K^{*0}\rho^0$	-15^{+4+16}_{-8-14}	$-6 \pm 9 \pm 2$	-	in progress
$K^{*+}\rho^-$	32^{+1+2}_{-3-14}	$21 \pm 15 \pm 2$	-	-
$K^{*+}\rho^0$	43^{+6+12}_{-3-28}	$44 \pm 10^{+6}_{-14}$		-
$K^{*0}\rho^+$	-0.3^{+0+2}_{-0-0}	$1 \pm 16 \pm 2$	-	-

[11] Top to bottom: PRD **78**, 092008 (2008); PRL **99**, 201802 (2007); PRD **79**, 052005 (2009) (both $K^*\omega$); PRD **85**, 072005 (2012) (both neutral $K^*\rho$); PRD **83**, 051101 (2010); PRL **97**, 201801 (2006)
[12] Top to bottom: PRD **88**, 072004 (2013); PRL **94**, 221804 (2005)
[13] JHEP **1405**, 069 (2014)

$B_s^0 \to \phi\phi$

- $B_s^0 \to \phi\phi$ is a pure penguin mode; particularly sensitive to new physics
- CP-violating phase ϕ_s accesssible through a time-dependent measurement
- Belle II time resolution does not allow for a time-dependent analysis due to the fast oscillation of B_s^0

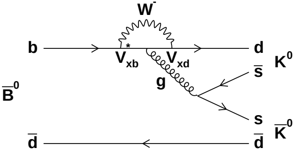
  $\sigma(t)_{\mathrm{LHCb}} \approx 40\ \mathrm{fs} \ll T_{B_s^0} \approx 360\ \mathrm{fs} \approx \sigma(t)_{\mathrm{BelleII}}$

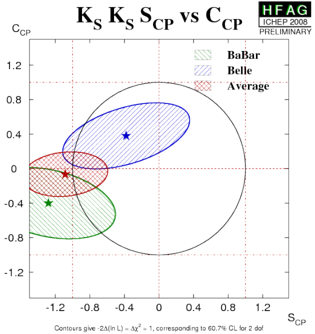
- Theoretical prediction in $b \to s\bar{s}s$ decays $|\phi_s^{s\bar{s}s}| \leq 0.02\ \mathrm{rad}$ (QCDf)

	CDF PRL **107**, 261802 (2011) value ± stat ± syst	LHCb 1 fb^{-1} PL **B713**, 369 (2012) value ± stat ± syst	LHCb 3 fb^{-1} PRD **90** 052011 (2014) value ± stat ± syst	LHCb 50 fb^{-1}
$f_L(B_s^0 \to \phi\phi)$	$0.365 \pm 0.044 \pm 0.027$	$0.291 \pm 0.024 \pm 0.010$	-	-
$\phi_s(B_s^0 \to \phi\phi)$	-	-	$-0.17 \pm 0.15 \pm 0.03$	± 0.03

Outline

$B_{ud} \to KK$





- $B \to KK$ a $b \to dq\bar{q}$-dominated penguin transition
- Assuming t quark dominance in the loop, decay amplitude phase cancels the mixing phase

  $\Rightarrow \mathcal{A}_{CP} = \mathcal{S}_{CP} = 0$
- However, u or c contribution or new physics effects could lead to deviations from zero

- Experimental uncertainties still very large
- BaBar result outside of physical region, does not allow for straightforward interpretation

$B_s^0 \to K^0\overline{K}^0$

- $B_s^0 \to K^0\overline{K}^0$ interesting due to its large branching fraction
- Predicted in the region $(16 - 27) \times 10^{-6}$
- Belle result based on $121.4\ \mathrm{fb}^{-1}$ (arXiv:1512.02145)
  $\mathcal{B}(B_s^0 \to K^0\overline{K}^0) = (19.6^{+5.8}_{-5.1}(\mathrm{stat}) \pm 1.0(\mathrm{syst}) \pm 2.0(N_{B_s^0\overline{B}_s^0})) \times 10^{-6}$

$B^0 \to K^{*0}\overline{K}^{*0}$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$

- $B^0 \to K^{*0}\overline{K}^{*0}$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$ related through *U*-spin symmetry
- Polarization fraction of $B_s^0 \to K^{*0}\overline{K}^{*0}$ surprisingly low
- Good prospects for a precise measurement of $B_s^0 \to K^{*0}\overline{K}^{*0}$ at LHCb
  ongoing analysis with 3 fb^{-1} for both channels
  expected precision at 50 fb^{-1} for ϕ_s^{eff} is 0.02

$B^0 \to K^{*0}\overline{K}^{*0}$	BaBar 0.35 ab^{-1} PRL **100** 081801 (2008) value ± stat ± syst	QCDf Nucl.Phys. **B774** 64 (2007)	QCDf ($+\phi K^*$ exp) Nucl.Phys. **B774** 64 (2007)
f_L	$0.80^{+0.10}_{-0.12} \pm 0.06$	$0.69^{+0.01+0.34}_{-0.01-0.27}$	$0.69^{+0.01+0.16}_{-0.01-0.20}$
$\mathcal{B}(10^{-6})$	$1.28^{+0.35}_{-0.30} \pm 0.11$	$0.6^{+0.1+0.5}_{-0.1-0.3}$	$0.6^{+0.1+0.3}_{-0.1-0.2}$

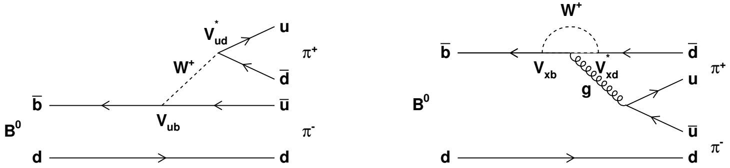
$B_s^0 \to K^{*0}\overline{K}^{*0}$	LHCb 1 fb^{-1} arXiv:1503.05362v2 value ± stat ± syst	QCDf Nucl.Phys. **B774** 64 (2007)	QCDf ($+\phi K^*$ exp) Nucl.Phys. **B774** 64 (2007)
f_L	$0.201 \pm 0.057 \pm 0.040$	$0.63^{+0.42}_{-0.29}$	$0.72^{+0.16}_{-0.21}$
$\mathcal{B}(10^{-6})$	$10.6 \pm 1.8 \pm 1.0 \pm 0.6(f_s/f_d)$	$9.1^{+0.5+11.3}_{-0.4-6.8}$	$7.9^{+0.4+4.3}_{-0.4-3.9}$

Outline

1. Belle II and LHCb upgrade
2. $b \to sq\bar{q}$ transitions
   - Precise measurement of $\sin 2\phi_1$ in $b \to c\bar{c}s$ transitions
   - ϕ_1 in $B \to PP$ and $B \to PV$ decays
   - $B \to VV$ decays
3. $b \to dq\bar{q}$ transitions
4. $b \to u\bar{u}d$ transitions
   - $B \to \pi\pi$ isospin analysis
   - $B \to \rho\rho$ isospin analysis
   - Combined result for ϕ_2

Outline

Measurement of ϕ_2 in a B → $\pi\pi$ isospin analysis



- Tree process sensitive to ϕ_2, $\mathcal{S}_{CP} = \sin 2\phi_2$
- Due to penguin pollution, measurement of an effective ϕ_2
- $\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}^2_{CP}} \sin(2\phi_2 - 2\Delta\phi_2)$
- Can recover ϕ_2 with an $SU(2)$ isospin analysis (PRL **65**, 3381 (1990))

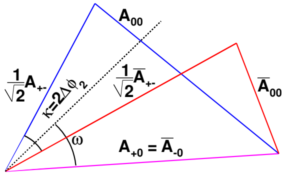
  Using isospin, the set of $B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$, decays obey the amplitude relations

$$A_{+0} = \frac{1}{\sqrt{2}} A_{+-} + A_{00}, \qquad \bar{A}_{-0} = \frac{1}{\sqrt{2}} \bar{A}_{+-} + \bar{A}_{00}$$

Measurement of ϕ_2 in a $B \to \pi\pi$ isospin analysis

$$A_{+0} = \frac{1}{\sqrt{2}} A_{+-} + A_{00}, \qquad \bar{A}_{-0} = \frac{1}{\sqrt{2}} \bar{A}_{+-} + \bar{A}_{00}$$

Express as triangles with $A_{+0} = \bar{A}_{-0}$ in the limit of neglecting isospin breaking



Triangles can flip around $A_{+0} = \bar{A}_{-0}$

$\Rightarrow$ 4-fold ambiguity in $2\Delta\phi_2$

$\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}^2} \sin(2\phi_2 - 2\Delta\phi_2)$

$\Rightarrow$ 2-fold ambiguity of ϕ_2 in measured $\mathcal{S}_{CP}$

Therefore, 8-fold ambiguity in ϕ_2

Triangles and ϕ_2 constrained from 6 physical observables

$\mathcal{B}(\pi^+\pi^-)$, $\mathcal{B}(\pi^0\pi^0)$, $\mathcal{B}(\pi^+\pi^0)$

$\mathcal{A}_{CP}(\pi^+\pi^-)$, $\mathcal{S}_{CP}(\pi^+\pi^-)$, $\mathcal{A}_{CP}(\pi^0\pi^0)$

Measurement of ϕ_2 in a $B \to \pi\pi$ isospin analysis

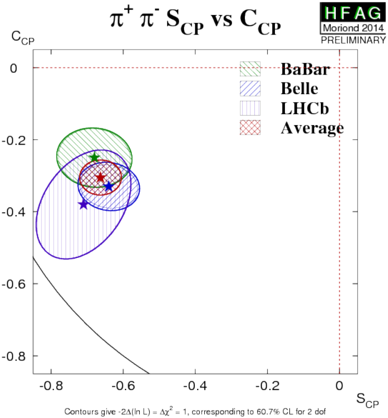
$\mathcal{B}(10^{-6})$	$B^0 \to \pi^+\pi^-$	$B^0 \to \pi^0\pi^0$	$B^+ \to \pi^+\pi^0$
	value ± stat ± syst	value ± stat ± syst	value ± stat ± syst
BaBar[14]	$5.5 \pm 0.4 \pm 0.3$	$1.83 \pm 0.21 \pm 0.13$	5.5 ± 0.46
Belle 0.25 ab^{-1}[15]	-	$2.32^{+0.4+0.2}_{-0.5-0.3}$	-
Belle 0.7 ab^{-1}[16]	$5.04 \pm 0.21 \pm 0.18$	$0.90 \pm 0.12 \pm 0.10$	5.86 ± 0.29
CDF[17]	$5.02 \pm 0.33 \pm 0.35$	-	-
CLEO[18]	$4.5^{+1.4+0.5}_{-1.2-0.4}$	< 4.4	$4.6^{+1.8-0.6}_{-1.6-0.7}$
LHCb[19]	$5.08 \pm 0.17 \pm 0.37$	-	-
QCDf[4]	$7.0^{+0.4+0.7}_{-0.7-0.7}$	$1.1^{+1.0+0.7}_{-0.4-0.3}$	$5.9^{+2.2+1.4}_{-1.1-1.1}$
pQCD[5]	$6.5^{+6.7}_{-3.8}$	$0.29^{+0.5}_{-0.2}$	$4.0^{+3.4}_{-1.9}$

[14] Left to right: PRD **75**, 012008 (2007); PRD **87**, 052009 (2013); PRD**76**, 091102 (2007)
[15] PRL **94**, 181803 (2005)
[16] Left to right: PRD **87**, 031103 (2013); preliminary; PRD **87**, 031103 (2013)
[17] PRL **106**, 181802 (2011)
[18] Left to right: PRD **68**, 052002 (2003); PRD **68**, 052002 (2003); PRD **68**, 052002 (2003)
[19] JHEP **1210**, 037 (2012)

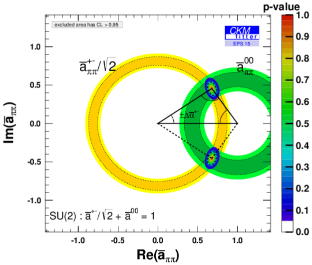
Measurement of ϕ_2 in a $B \to \pi\pi$ isospin analysis

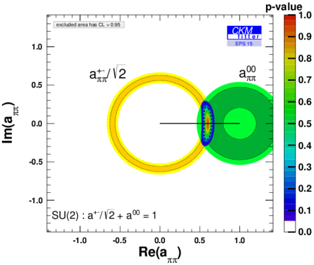
$\mathcal{A}_{CP}(10^{-2})$	$B^0 \to \pi^0\pi^0$ value $\pm$ stat $\pm$ syst
BaBar[a]	$+43 \pm 26 \pm 5$
Belle 0.25 ab^{-1} [b]	$+44^{+53}_{-52} \pm 17$
Belle 0.7 ab^{-1} [c]	$-38 \pm 36 \pm 3$

[a] PRD **87**, 052009 (2013)
[b] PRL **94**,181803 (2005)
[c] preliminary



Measurement of ϕ_2 in a B → ππ isospin analysis





- One triangle happens to be flat ⇒ four solutions
- To resolve the ambiguity

  Measurement of $\mathcal{S}_{CP}(\pi^0\pi^0)$, intended at Belle II with converted photons

  Measurement of B → ρρ, B → ρπ
- BaBar $71^\circ < \phi_2 < 109^\circ$, 68% CL
  Belle $23.8^\circ < \phi_2 < 66.8^\circ$, 68% CL

Outline

Measurement of ϕ_2 in a $B \to \rho\rho$ isospin analysis

- In an analogous way to the $\pi\pi$ system, isospin analysis in $B \to \rho\rho$
- Analysis can be performed in each polarization component, longitudinal preferred due to higher fraction

f_L	$B^0 \to \rho^+\rho^-$ value ± stat ± syst	$B^0 \to \rho^0\rho^0$ value ± stat ± syst	$B^+ \to \rho^+\rho^0$ value ± stat ± syst
BaBar[20]	$0.992 \pm 0.024^{+0.026}_{-0.013}$	$0.75^{+0.11}_{-0.14} \pm 0.06$	$0.95 \pm 0.015 \pm 0.006$
Belle[21]	$0.988 \pm 0.012 \pm 0.023$	$0.21^{+0.18}_{-0.22} \pm 0.15$	$0.95 \pm 0.11 \pm 0.2$
LHCb($3\ \mathrm{fb}^{-1}$)[22]	-	$0.745^{+0.048}_{-0.058} \pm 0.034$	in progress
QCDf[4]	$0.92^{+0.01+0.01}_{-0.02-0.02}$	$0.92^{+0.03+0.06}_{-0.04-0.37}$	$0.96^{+0.01+0.02}_{-0.01-0.02}$
pQCD[5]	-	0.78	-

- Longitudinal polarization fraction closer to the naïve expectation of 1
- Tension in the $\rho^0\rho^0$ mode between BaBar and Belle

[20] Left to right: PRD **76**, 052007 (2007); PRD **78**, 071104 (2008); PRL **102**, 141802 (2009)
[21] Left to right: arXiv:1510.01245; PRD **89**, 072008 (2014); PRL **91**, 221801 (2003)
[22] PLB **747**, 468-478 (2015)

$B \to \rho\rho$ isospin analysis

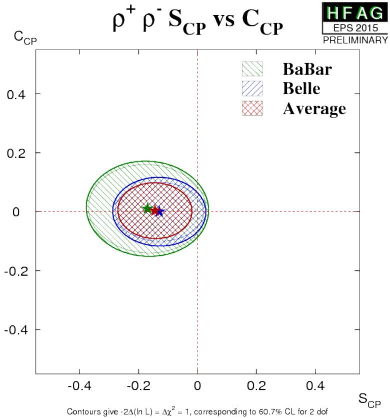
$\mathcal{B}(10^{-6})$	$B^0 \to \rho^+\rho^-$	$B^0 \to \rho^0\rho^0$	$B^+ \to \rho^+\rho^0$
	value ± stat ± syst	value ± stat ± syst ± BF	value ± stat ± syst
BaBar[23]	$25.5 \pm 2.1^{+3.6}_{-3.9}$	$0.92 \pm 0.32 \pm 0.14$	$23.7 \pm 1.4 \pm 1.4$
Belle[24]	$28.3 \pm 1.5 \pm 1.5$	$1.02 \pm 0.30 \pm 0.15$	$31.7 \pm 7.1^{+3.8}_{-6.7}$
LHCb($3\ \text{fb}^{-1}$)[25]	-	$0.94 \pm 0.17 \pm 0.09 \pm 0.06$	in progress
QCDf[4]	$25.5^{+1.5+2.4}_{-2.6-1.5}$	$0.9^{+1.5+1.1}_{-0.4-0.2}$	$20.0^{+4.0+2.0}_{-1.9-0.9}$
pQCD[5]	$25.3^{+25.3}_{-13.8}$	$0.92^{+1.10}_{-0.56}$	$16.0^{+15.0}_{-8.1}$

[23] Left to right: PRD **76**, 052007 (2007); PRD **78**, 071104 (2008); PRL **102**, 141802 (2009)
[24] Left to right: arXiv:1510.01245; PRD **89**, 072008 (2014); PRL **91**, 221801 (2003)
[25] PLB **747**, 468-478 (2015)

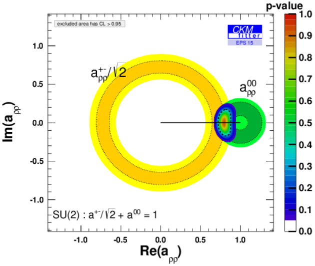
Measurement of ϕ_2 in a $B \to \rho\rho$ isospin analysis

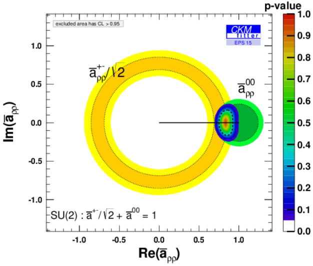
$\mathcal{A}_{CP}(10^{-2})$	$B^0 \to \rho^0\rho^0$
BaBar[a]	$20 \pm 80 \pm 30$
QCDf	30^{+17+14}_{-16-26}
pQCD	80

[a] PRD **78**, 071104 (2008)



Measurement of ϕ_2 in a B → $\rho\rho$ isospin analysis





- Both triangles flat $\Rightarrow \Delta\phi_2 = 0 \Rightarrow$ two solutions
- $\phi_2 > 90^\circ$ favoured from $SU(3)$ symmetry considerations

  BaBar $\phi_2 = (92.4^{+6.0}_{-6.5})^\circ$

  Belle $\phi_2 = (93.7 \pm 10.6)^\circ$ (preliminary)

Outline

ϕ_2 from $B \to \rho\pi$

- A (challenging) time-dependent Dalitz analysis of $B \to \rho\pi$ can further constrain ϕ_2
- Study performed by BaBar and by Belle
- BaBar scan of ϕ_2 unstable
- For the moment, no real constraint from $B \to \rho\pi$

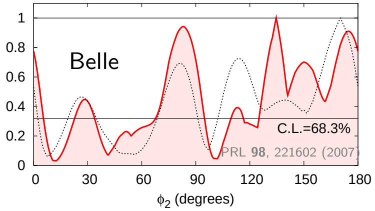
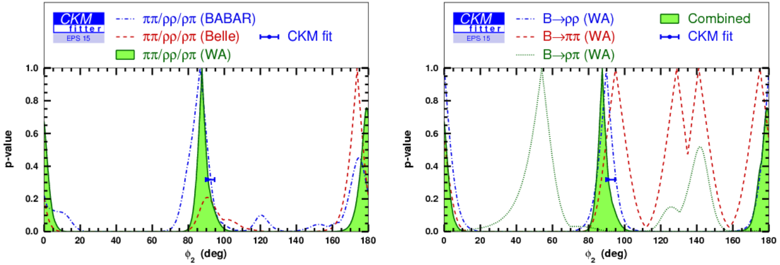


Figure: Dotted and solid curves correspond to the result from the TDPA only and that from the TDPA and an isospin (pentagon) combined analysis, respectively.

Combined result for ϕ_2



$$\phi_2[fit] = (90.6^{+3.9}_{-1.1})^\circ$$

Belle II expected to push the precision of ϕ_2 down to 1° (combining all modes)

Summary and outlook

- Loop-dominated $b \to s q\bar{q}$ and $b \to d q\bar{q}$ transitions potentially sensitive to new physics effects
- *CP* violation observed or evidence found in certain $b \to s q\bar{q}$ modes
- Current experimental precision not enough to challenge the SM, but good prospects for a precise measurement at Belle II and LHCb
- Theoretical uncertainties, especially on the branching fractions, also large

- Good prospects for a precise measurement of the angle ϕ_2 at Belle II and LHCb

  Combined uncertainty expected to be below 1°

Thank you for your attention!