QCD Factorization for B $\longrightarrow$ PP, PV Decays

Hadronic B Decays from First Principles

Matthias Neubert (Cornell University)

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[based on work with M. Beneke: hep-ph/0308039]

Introduction

- most of B physics beyond $\sin 2\beta$ relies on an analysis of hadronic decays such as $B \to \pi K$, $\pi\pi$, ϕK_S, ...
- crucial for CKM studies and New Physics searches
- recently, have learned how to describe such processes theoretically using heavy-quark expansions:

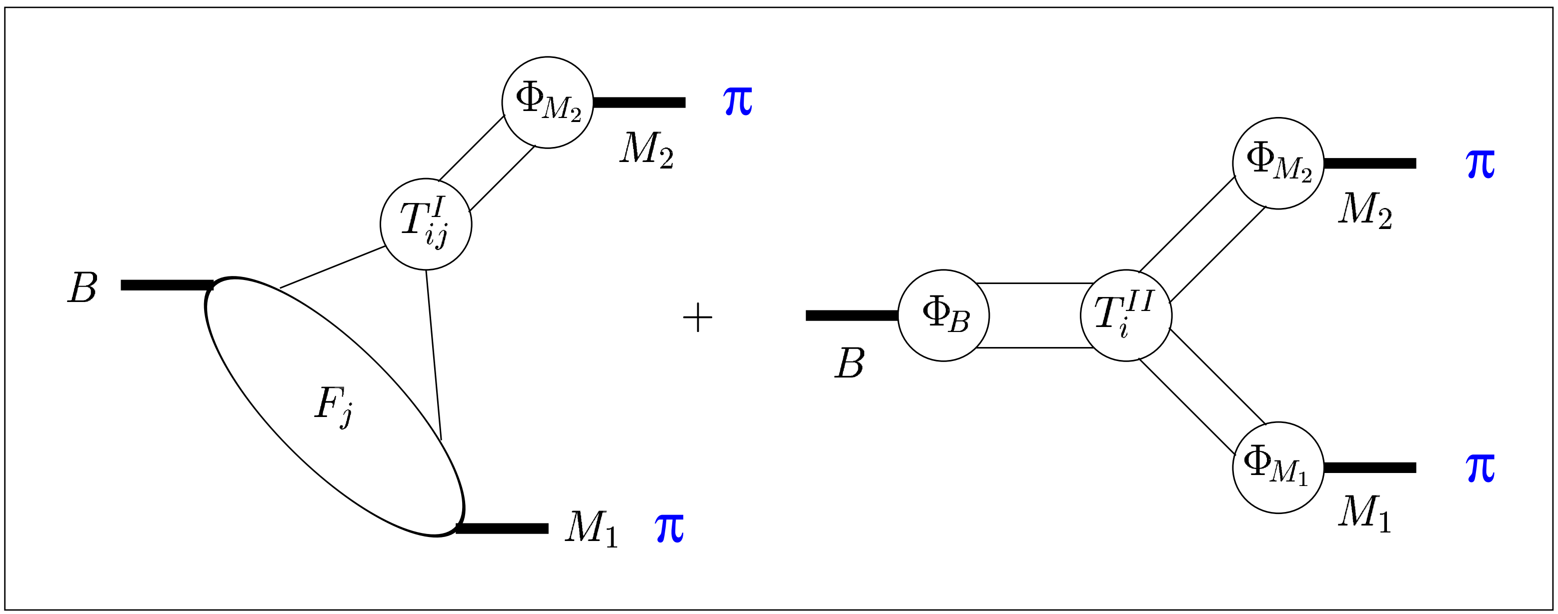
  QCD factorization formalism [Beneke et al. 99]
  & Soft-collinear effective theory [Bauer et al. 00]

- rigorous results in the heavy-quark limit, valid to all orders of perturbation theory

QCD Factorization Approach

Factorization formula for hadronic B-meson decays:

[Beneke, Buchalla, MN, Sachrajda 99]



$\Rightarrow$ model-independent description of hadronic B-decay amplitudes (including their phases) in the heavy-quark limit

Inputs to QCD Factorization

CKM parameters ("CKM"):

- $|V_{ub}|$, γ

SM parameters and hadronic parameters that can be determined from data ("hadronic 1"):

- light quark masses
- decay constants, heavy-to-light form factors

Hadronic parameters that can only be indirectly determined from data ("hadronic 2"):

- Gegenbauer moments (LCDAs)
- transverse vector-meson decay constants

How Heavy is Heavy Enough?

Importance of heavy-quark limit is evident from comparison of nonfactorizable effects seen in kaon, charm and beauty decays; however, $\Lambda_{\rm QCD}/m_b$ corrections may be important if:

- associated with new flavor topologies ("weak annihilation")
- "chirally-enhanced"

Estimate of leading power corrections ("power"):

- parameterize annihilation contributions (largely universal) by quantity ϱ_A (includes "charming penguins"!)
- parameterize power corrections to hard scattering contributions (largely universal) by quantity ϱ_H
- assign 100% uncertainties and arbitrary strong phases to these estimates

Then . . .

Make predictions and listen to data!

- QCD factorization makes many testable predictions
- data can be used to constrain input parameters, and will teach us about the importance of power-suppressed effects

Factorization in Charmless Decays

- factorization in decays $B \to$ two light mesons can be tested using $B^\pm \to \pi^\pm\pi^0$ (pure tree) and $B^\pm \to \pi^\pm K^0$, $B^\pm \to \pi^\pm K^{*0}$, $B^\pm \to \rho^\pm K^0$ (pure penguins), which have negligible amplitude interference
- crucial properties:
  - magnitude of tree amplitude
  - magnitude of T/P ratios
  - strong phase of T/P ratios
- once these tests are conclusive, factorization can be used to constrain the unitarity triangle

Part 1:

Tree-Dominated Processes

Magnitude of the Tree Amplitude

Absolute prediction for $B^\pm \to \pi^\pm \pi^0$ branching ratio:

$$\frac{\Gamma(B^\pm \to \pi^\pm \pi^0)}{d\Gamma(\bar{B}^0 \to \pi^+ l^- \bar{\nu})/dq^2|_{q^2=0}} = 3\pi^2 f_\pi^2 \, |V_{ud}|^2 \, |\underbrace{a_1^{(\pi\pi)} + a_2^{(\pi\pi)}}_{1.17\,^{+0.11}_{-0.07}}|^2$$

- study CP-averaged branching fractions (in units 10^{-6}) for other tree-dominated processes
- theory errors refer to:
  CKM, hadronic 1, hadronic 2, power
- errors are strongly correlated!
  $\Rightarrow$ consider different parameter scenarios S1–S4

  (only S2 and S4 discussed here)

$B \to \pi\pi, \pi\rho$ Branching Ratios

Mode	Theory	Experiment
$B^- \to \pi^-\pi^0$	$6.0\,^{+3.0\,+2.1\,+1.0\,+0.4}_{-2.4\,-1.8\,-0.5\,-0.4}$	5.3 ± 0.8
$\bar{B}^0 \to \pi^+\pi^-$	$8.9\,^{+4.0\,+3.6\,+0.6\,+1.2}_{-3.4\,-3.0\,-1.0\,-0.8}$	4.6 ± 0.4
$B^- \to \pi^-\rho^0$	$11.9\,^{+6.3\,+3.6\,+2.5\,+1.3}_{-5.0\,-3.1\,-1.2\,-1.1}$	9.1 ± 1.1
$B^- \to \pi^0\rho^-$	$14.0\,^{+6.5\,+5.1\,+1.0\,+0.8}_{-5.5\,-4.3\,-0.6\,-0.7}$	11.0 ± 2.7
$\bar{B}^0 \to \pi^+\rho^-$	$21.2\,^{+10.3\,+8.7\,+1.3\,+2.0}_{-\;\;8.4\,-7.2\,-2.3\,-1.6}$	13.9 ± 2.7
$\bar{B}^0 \to \pi^-\rho^+$	$15.4\,^{+8.0\,+5.5\,+0.7\,+1.9}_{-6.4\,-4.7\,-1.3\,-1.3}$	8.9 ± 2.5
$\bar{B}^0 \to \pi^\pm\rho^\mp$	$36.5\,^{+18.2\,+10.3\,+2.0\,+3.9}_{-14.7\,-\;\;8.6\,-3.5\,-2.9}$	24.0 ± 2.5

$\Rightarrow$ default values for neutral modes are too high, but errors ("CKM" and "hadronic 1") are large

Observations

Tree-dominated processes have “simple” dynamics and should be well described by QCD factorization; select parameters as follows (all well motivated):

- form factors: $F_0^{B\to\pi}(0) = 0.25$ (range: 0.28 ± 0.05), $F_0^{B\to K}(0) = 0.31$ (range: 0.34 ± 0.05)
  [favored by recent SCET work and phenomenological analyses]
- strange quark mass: $m_s = 80$ MeV (range: (90 ± 20) MeV)
  [favored by recent, unquenched lattice calculations]
- Gegenbauer moments: $\alpha_2^\pi = 0.3$ (range: 0.1 ± 0.3), $\lambda_B = 200$ MeV (range: (350 ± 150) MeV)
  [large α_2^π favored by QCD sum rules]

$\Rightarrow$ call this scenario S2 (later also introduce scenario S4)

$B \to \pi\pi, \pi\rho, \pi\omega$ Branching Ratios

Mode	Theory	S2	S4	Experiment
$B^- \to \pi^-\pi^0$	$6.0\,^{+3.0\,+2.1\,+1.0\,+0.4}_{-2.4\,-1.8\,-0.5\,-0.4}$	5.5	5.1	5.3 ± 0.8
$\bar{B}^0 \to \pi^+\pi^-$	$8.9\,^{+4.0\,+3.6\,+0.6\,+1.2}_{-3.4\,-3.0\,-1.0\,-0.8}$	4.6	5.2	4.6 ± 0.4
$\bar{B}^0 \to \pi^0\pi^0$	$0.3\,^{+0.2\,+0.2\,+0.3\,+0.2}_{-0.2\,-0.1\,-0.1\,-0.1}$	0.9	0.7	1.9 ± 0.5
$B^- \to \pi^-\rho^0$	$11.9\,^{+6.3\,+3.6\,+2.5\,+1.3}_{-5.0\,-3.1\,-1.2\,-1.1}$	12.6	12.3	9.1 ± 1.1
$B^- \to \pi^0\rho^-$	$14.0\,^{+6.5\,+5.1\,+1.0\,+0.8}_{-5.5\,-4.3\,-0.6\,-0.7}$	10.4	10.3	11.0 ± 2.7
$\bar{B}^0 \to \pi^+\rho^-$	$21.2\,^{+10.3\,+8.7\,+1.3\,+2.0}_{-8.4\,-7.2\,-2.3\,-1.6}$	11.0	11.8	13.9 ± 2.7
$\bar{B}^0 \to \pi^-\rho^+$	$15.4\,^{+8.0\,+5.5\,+0.7\,+1.9}_{-6.4\,-4.7\,-1.3\,-1.3}$	10.8	11.8	8.9 ± 2.5
$\bar{B}^0 \to \pi^\pm\rho^\mp$	$36.5\,^{+18.2\,+10.3\,+2.0\,+3.9}_{-14.7\,-8.6\,-3.5\,-2.9}$	21.8	23.6	24.0 ± 2.5
$\bar{B}^0 \to \pi^0\rho^0$	$0.4\,^{+0.2\,+0.2\,+0.9\,+0.5}_{-0.2\,-0.1\,-0.3\,-0.3}$	1.7	1.1	< 2.5
$B^- \to \pi^-\omega$	$8.8\,^{+4.4\,+2.6\,+1.8\,+0.8}_{-3.5\,-2.2\,-0.9\,-0.9}$	9.1	8.4	5.9 ± 1.0

Part 2:

Penguin-Dominated Processes

Magnitudes of Penguin Coefficients

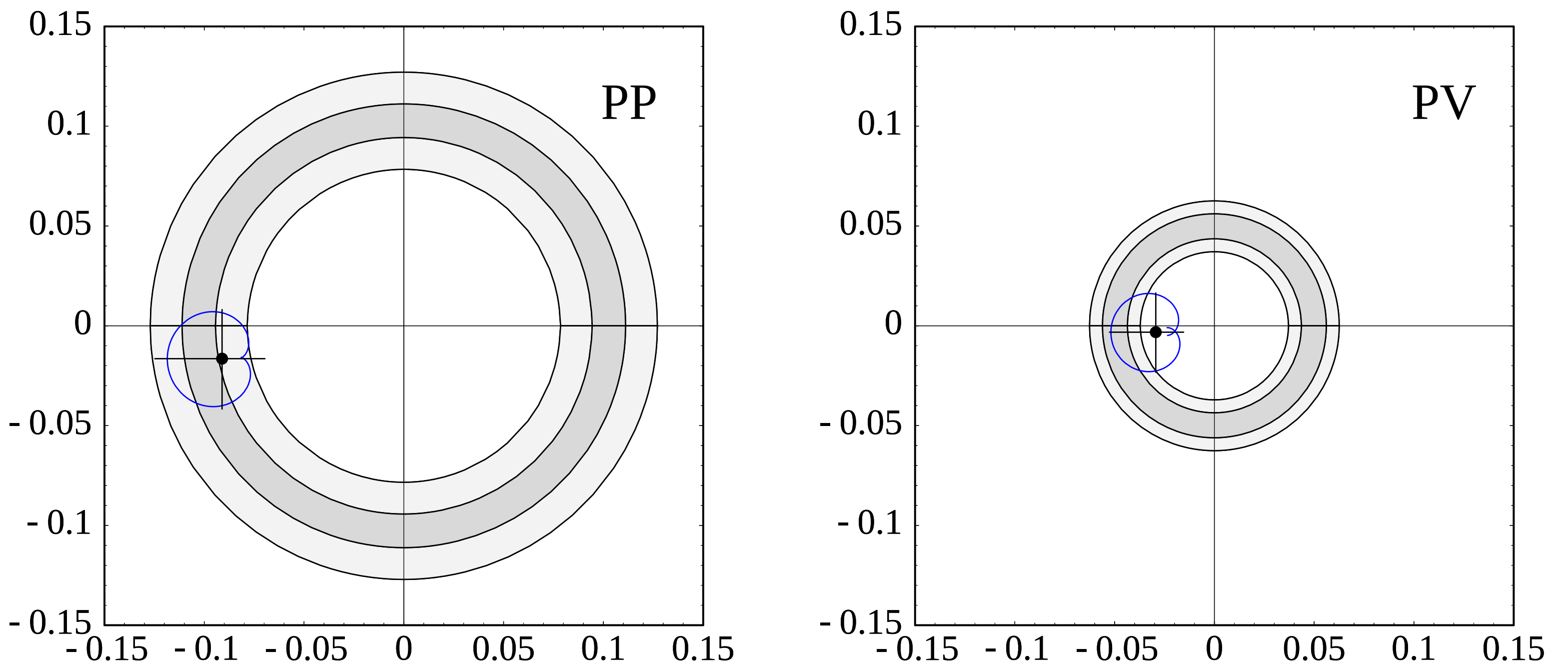
QCD penguin amplitudes (incl. penguin annihilation, charming penguins, etc.) are governed by single parameter $\hat{\alpha}_4^c(M_1 M_2)$, whose magnitude can be determined from the decays:

- $B^\pm \to \pi^\pm K^0$: $\hat{\alpha}_4^c(\pi K)$ (PP)
- $B^\pm \to \pi^\pm K^{*0}$: $\hat{\alpha}_4^c(\pi K^*)$ (PV)
- $B^\pm \to \rho^\pm K^0$: $\hat{\alpha}_4^c(\rho K)$ (VP)

QCD factorization predicts that:

- PV penguin $\approx \frac{1}{2} \times$ PP penguin, since $\langle Q_6 \rangle$ matrix element vanishes at leading order
- VP penguin $\approx \frac{1}{2} \times$ PP penguin, since $\langle Q_4 \rangle$ and $\langle Q_6 \rangle$ matrix elements interfere destructively for VP

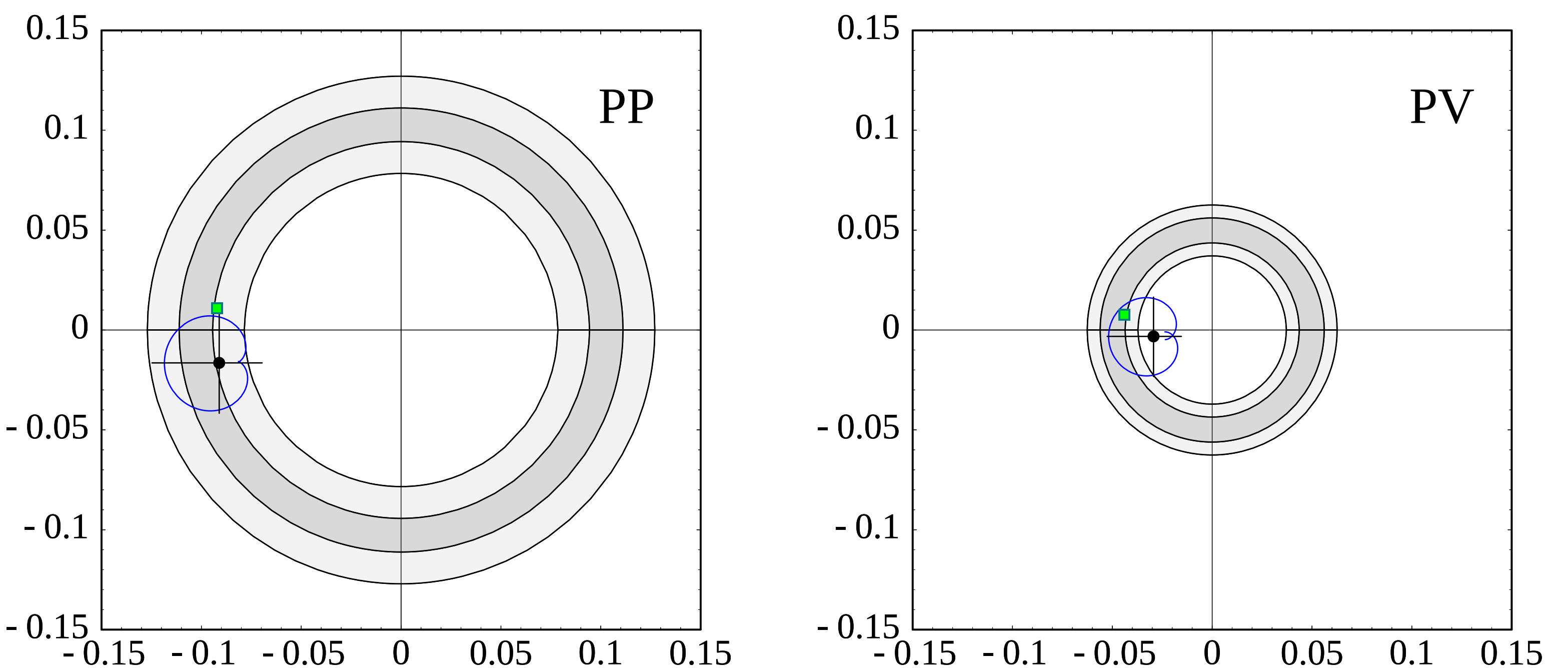
Divide by $B^{\pm} \to \pi^{\pm}\pi^{0}$ branching ratio to get $|\hat{\alpha}_4^c(M_1 M_2)|$ independent of hadronic form factors:



$\Rightarrow$ PP penguin is right on!

$\Rightarrow$ indeed, strong reduction seen for PV vs. PP!

Add moderate annihilation terms ($\varrho_A = 1$) to get a better description of the $B \to \pi K^*$ penguin amplitude (green dots):



$\Rightarrow$ small effect for PP modes, but noticable for PV modes due to smallness of the penguin amplitude

$\Rightarrow$ call this scenario S4 (adjusted, but not fitted)

$B \to \pi K, \pi K^*$ Branching Ratios

Mode	Theory	S4	Experiment
$B^- \to \pi^- \bar{K}^0$	$19.3\,^{+1.9}_{-1.9}\,^{+11.3}_{-\ \ 7.8}\,^{+1.9}_{-2.1}\,^{+13.2}_{-\ \ 5.6}$	20.3	20.6 ± 1.3
$B^- \to \pi^0 K^-$	$11.1\,^{+1.8}_{-1.7}\,^{+5.8}_{-4.0}\,^{+0.9}_{-1.0}\,^{+6.9}_{-3.0}$	11.7	12.8 ± 1.1
$\bar{B}^0 \to \pi^+ K^-$	$16.3\,^{+2.6}_{-2.3}\,^{+9.6}_{-6.5}\,^{+1.4}_{-1.4}\,^{+11.4}_{-\ \ 4.8}$	18.4	18.2 ± 0.8
$\bar{B}^0 \to \pi^0 \bar{K}^0$	$7.0\,^{+0.7}_{-0.7}\,^{+4.7}_{-3.2}\,^{+0.7}_{-0.7}\,^{+5.4}_{-2.3}$	8.0	11.2 ± 1.4
$B^- \to \pi^- \bar{K}^{*0}$	$3.6\,^{+0.4}_{-0.3}\,^{+1.5}_{-1.4}\,^{+1.2}_{-1.2}\,^{+7.7}_{-2.3}$	8.4	9.0 ± 1.8 [was 13 ± 3]
$B^- \to \pi^0 K^{*-}$	$3.3\,^{+1.1}_{-1.0}\,^{+1.0}_{-0.9}\,^{+0.6}_{-0.6}\,^{+4.4}_{-1.4}$	6.5	< 31
$\bar{B}^0 \to \pi^+ K^{*-}$	$3.3\,^{+1.4}_{-1.2}\,^{+1.3}_{-1.2}\,^{+0.8}_{-0.8}\,^{+6.2}_{-1.6}$	8.1	15.3 ± 3.8
$\bar{B}^0 \to \pi^0 \bar{K}^{*0}$	$0.7\,^{+0.1}_{-0.1}\,^{+0.5}_{-0.4}\,^{+0.3}_{-0.3}\,^{+2.6}_{-0.5}$	2.5	< 3.5

$\Rightarrow$ uncertainties from weak annihilation and strange-quark mass are fully correlated between different modes!

$B \to \rho K, \omega K, \phi K$ Branching Ratios

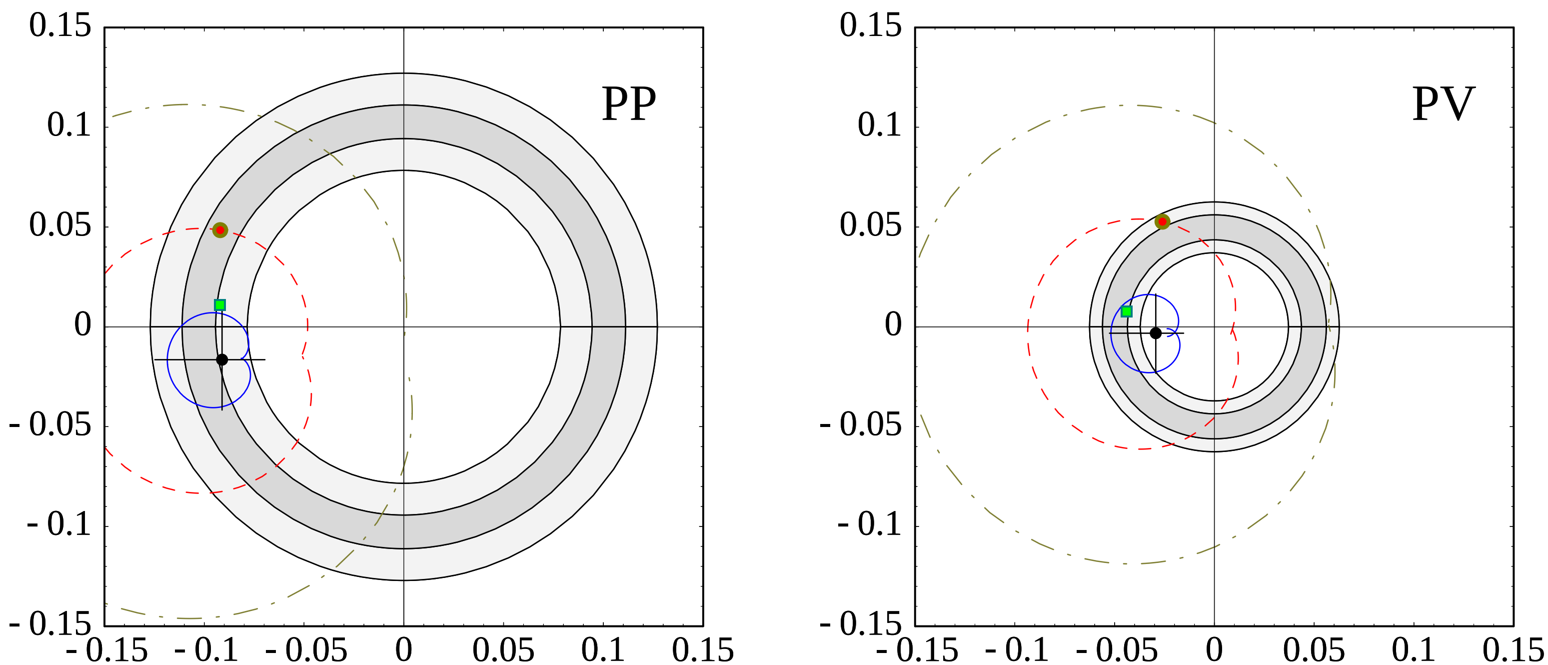
Mode	Theory	S4	Experiment
$B^- \to \bar{K}^0 \rho^-$	$5.8^{+0.6}_{-0.6}{}^{+7.0}_{-3.3}{}^{+1.5}_{-1.3}{}^{+10.3}_{-3.2}$	9.7	< 48
$B^- \to K^- \rho^0$	$2.6^{+0.9}_{-0.9}{}^{+3.1}_{-1.4}{}^{+0.8}_{-0.6}{}^{+4.3}_{-1.2}$	4.3	4.1 ± 0.8 [was < 6.2]
$\bar{B}^0 \to K^- \rho^+$	$7.4^{+1.8}_{-1.9}{}^{+7.1}_{-3.6}{}^{+1.2}_{-1.1}{}^{+10.7}_{-3.5}$	10.1	9.0 ± 1.6
$\bar{B}^0 \to \bar{K}^0 \rho^0$	$4.6^{+0.5}_{-0.5}{}^{+4.0}_{-2.1}{}^{+0.7}_{-0.7}{}^{+6.1}_{-2.1}$	6.2	< 12
$B^- \to K^- \omega$	$3.5^{+1.0}_{-1.0}{}^{+3.3}_{-1.6}{}^{+1.4}_{-0.9}{}^{+4.7}_{-1.6}$	5.9	5.4 ± 0.8
$\bar{B}^0 \to \bar{K}^0 \omega$	$2.3^{+0.3}_{-0.3}{}^{+2.8}_{-1.3}{}^{+1.3}_{-0.8}{}^{+4.3}_{-1.3}$	4.9	5.2 ± 1.1
$B^- \to K^- \phi$	$4.5^{+0.5}_{-0.4}{}^{+1.8}_{-1.7}{}^{+1.9}_{-2.1}{}^{+11.8}_{-3.3}$	11.6	9.0 ± 1.0
$\bar{B}^0 \to \bar{K}^0 \phi$	$4.1^{+0.4}_{-0.4}{}^{+1.7}_{-1.6}{}^{+1.8}_{-1.9}{}^{+10.6}_{-3.0}$	10.5	8.3 ± 1.1

$\Rightarrow$ good description of all modes for a fixed set of parameters

Bounds on Weak Annihilation

Are values $\varrho_A \gg 1$ possible, which could upset the heavy-quark expansion?

[Ciuchini et al. (hep-ph/0212397) suggested to use $0 < \varrho_A < 8$ to be conservative]



⇒ needs significant fine-tuning! (red: $\varrho_A = 2$, gray: $\varrho_A = 3$)

Even better:

Values $\varrho_A \geq 2$ are already excluded by the data!

Mode	Default	Large Annihilation (red dot: $\varrho_A = 2$)	Experiment
$\bar{B}^0 \to \pi^0 \bar{K}^{*0}$	0.7	6.0	< 3.5
$B^- \to K^- \rho^0$	2.6	9.0	4.1 ± 0.8
$\bar{B}^0 \to K^- \rho^+$	7.4	19.3	9.0 ± 1.6
$B^- \to K^- \phi$	4.5	22.4	9.0 ± 0.7
$\bar{B}^0 \to \bar{K}^0 \phi$	4.1	20.2	8.3 ± 1.1

Part 3:

Processes With Flavor Singlets

Final States Containing η or η'

Mode	S4	Experiment	Mode	S4	Experiment
$B^- \to \eta K^-$	1.6	3.1 ± 0.7	$B^- \to \eta K^{*-}$	19.9	25.9 ± 3.4
$\bar{B}^0 \to \eta \bar{K}^0$	1.1	< 4.6	$\bar{B}^0 \to \eta \bar{K}^{*0}$	18.6	17.8 ± 2.1
$B^- \to \eta' K^-$	76.1	77.6 ± 4.6	$B^- \to \eta' K^{*-}$	2.2	< 12
$\bar{B}^0 \to \eta' \bar{K}^0$	70.3	65.2 ± 6.0	$\bar{B}^0 \to \eta' \bar{K}^{*0}$	1.9	< 6.4
$B^- \to \pi^- \eta$	3.8	3.9 ± 0.9	$B^- \to \eta \rho^-$	6.3	8.9 ± 2.7 [was < 6.2]
$\bar{B}^0 \to \pi^0 \eta$	0.3	< 2.9	$\bar{B}^0 \to \eta \rho^0$	0.1	< 5.5
$B^- \to \pi^- \eta'$	2.9	< 7	$B^- \to \eta' \rho^-$	4.2	13.3 ± 4.7 [was < 33]
$\bar{B}^0 \to \pi^0 \eta'$	0.4	< 5.7	$\bar{B}^0 \to \eta' \rho^0$	0.1	< 12

$\Rightarrow$ no need for mysterious, enhanced decays mechanisms!
(anomaly, intrinsic charm, etc.)

Part 4:

CP Asymmetries

(Test of small strong phases)

Direct CP Asymmetries (in %)

Mode	S4	Experiment	Mode	S4	Experiment
$B^- \to \pi^- \bar{K}^0$	0	-2 ± 9	$B^- \to K^- \omega$	19	0 ± 12
$B^- \to \pi^0 K^-$	–4	1 ± 12	$\bar{B}^0 \to \bar{K}^0 \omega$	4	—
$\bar{B}^0 \to \pi^+ K^-$	–4	-9 ± 4	$B^- \to K^- \phi$	1	3 ± 7
$\bar{B}^0 \to \pi^0 \bar{K}^0$	1	3 ± 37	$\bar{B}^0 \to \bar{K}^0 \phi$	1	19 ± 68
$B^- \to \pi^- \pi^0$	0	-7 ± 14	$B^- \to \pi^- \rho^0$	–11	-17 ± 11
$\bar{B}^0 \to \pi^+ \pi^-$	10	51 ± 23	$B^- \to \pi^0 \rho^-$	10	23 ± 17
$B^- \to \pi^- \omega$	–6	9 ± 21	$\bar{B}^0 \to \pi^+ \rho^-$	4	-11 ± 17
			$\bar{B}^0 \to \pi^- \rho^+$	–13	-62 ± 27

$\Rightarrow$ no significant discrepancies

$\Rightarrow$ our biggest success: They are all small!

Part 5:

Hadronic Effects on Time-Dependent CP Asymmmetries

Important predictions for New Physics searches:

$$
\begin{aligned}
S_{\phi K_S} - S_{J/\psi K_S} &= 0.01 - 0.05 \\
S_{\eta' K_S} - S_{J/\psi K_S} &= 0.00 - 0.03 \\
S_{\pi^0 K_S} - S_{J/\psi K_S} &= 0.06 - 0.13
\end{aligned}
$$

- model-independent predictions in heavy-quark limit (plus leading $\Lambda_{\rm QCD}/m_b$ corrections)
- consistent with, but more powerful than, bounds obtained assuming SU(3) symmetry (< 0.34, < 0.49, < 0.19)

  [Grossman, Ligeti, Nir, Quinn 03; Gronau, Grossman, Rosner 03]

Part 6:

Measuring $\sin 2(\beta+\gamma)$ in $B \longrightarrow \pi^{\pm}\rho^{\mp}$ Decays

CP Violation in $B \to \pi^\pm \rho^\mp$

Described in terms of 5 parameters: $C, \Delta C, S, \Delta S, A_{\rm CP}$

Parameter S has a clean interpretation:

$$S = \frac{2R}{1+R^2}\,\sin 2\alpha + \mathcal{O}(P/T)\,,$$

where $R = 0.9 \pm 0.2$ is a ratio of form factors, and the P/T correction is fortuitously small

- penguin “pollution” much less than in $B \to \pi\pi$
- clean measurement of $\sin 2\alpha$ with minimal theoretical uncertainties (well below $\pm 10°$)
- best determination of γ to date!

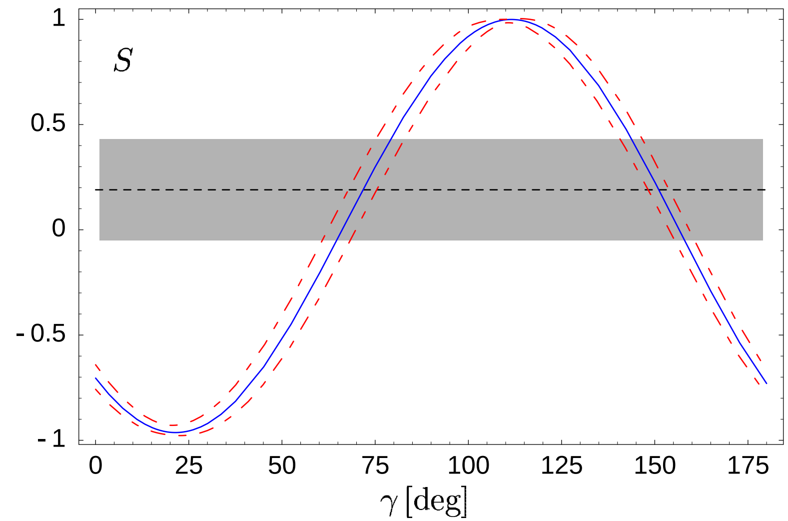
Results (assuming $\beta = 24^\circ$)

$B \to \pi^\pm \rho^\mp$ decay:

$\gamma = (72 \pm 11)^\circ$

or $\gamma = (151 \pm 10)^\circ$

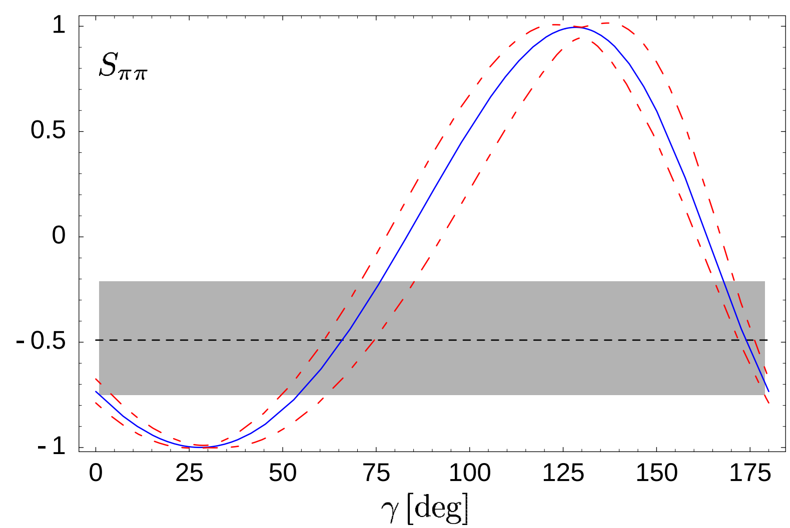
[95% CL: $\gamma = (72 \pm 20)^\circ$]



$B \to \pi^+ \pi^-$ decay:

$\gamma = (66\,^{+19}_{-16})^\circ$

or $\gamma = (174\,^{+9}_{-8})^\circ$



Conclusions

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- This theory provides a successful, global description of all available data on charmless B decays and makes many more predictions (also for B_s decays)
- Significant progress toward a theory (not just a model) of hadronic B decays has been made!