



QCD Factorization
Hadronic B Decays from First Principles

Matthias Neubert (Cornell University)

BaBar Workshop, SLAC, October 3, 2003

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

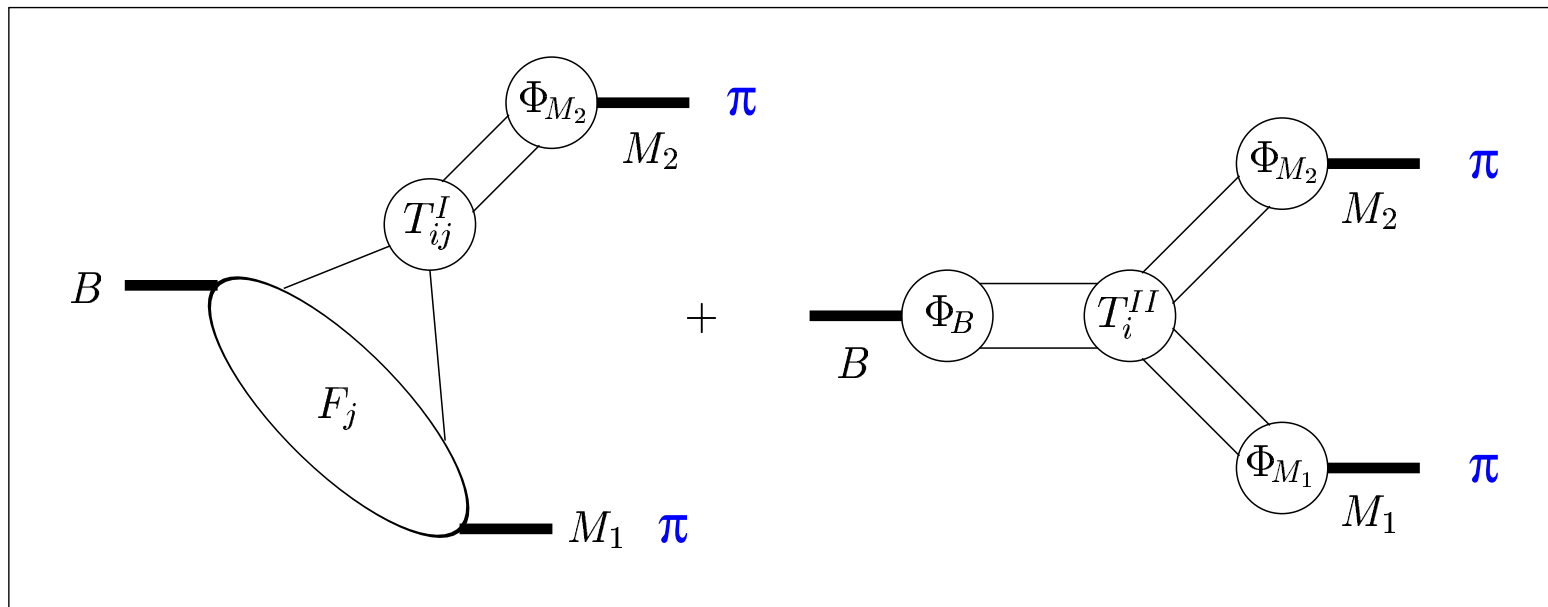
Introduction

- most of B physics beyond $\sin 2\beta$ relies on an analysis of hadronic decays such as $B \rightarrow \pi K, \pi\pi, \phi K_S, \dots$
- 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

Recent Developments

- very close to a proof of QCD factorization for $B \rightarrow K^* \gamma$
(almost as hard as $B \rightarrow \pi \pi$)
[B. Pecjak, Ph.D. thesis, Cornell U.; collab. with T. Becher, R. Hill, MN]

Recent Developments

- very close to a proof of QCD factorization for $B \rightarrow K^* \gamma$
(almost as hard as $B \rightarrow \pi \pi$)
[B. Pecjak, Ph.D. thesis, Cornell U.; collab. with T. Becher, R. Hill, MN]
- recent work on $B \rightarrow M$ form factors using SCET suggests that there is no significant Sudakov suppression of the soft overlap contribution
[T. Becher, R. Hill, B. Lange, MN]
⇒ invalidates main assumption of pQCD approach

Recent Developments

- very close to a proof of QCD factorization for $B \rightarrow K^* \gamma$
(almost as hard as $B \rightarrow \pi \pi$)
[B. Pecjak, Ph.D. thesis, Cornell U.; collab. with T. Becher, R. Hill, MN]
- recent work on $B \rightarrow M$ form factors using SCET suggests that there is no significant Sudakov suppression of the soft overlap contribution
[T. Becher, R. Hill, B. Lange, MN]
⇒ invalidates main assumption of pQCD approach
- no indications for (and strong exp. bounds on) enhanced weak annihilation or charming penguin contributions

Inputs to QCD Factorization

CKM parameters (“CKM”):

- $|V_{ub}|, \gamma$

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, Λ_{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 $B \rightarrow$ two light mesons can be probed using $B^\pm \rightarrow \pi^\pm \pi^0$ (pure tree) and $B^\pm \rightarrow \pi^\pm K^0$, $B^\pm \rightarrow \pi^\pm K^{*0}$, $B^\pm \rightarrow \rho^\pm K^0$ (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 $B^\pm \rightarrow \pi^\pm \pi^0$ branching ratio
(independent of annihilation):

$$\text{Br}(B^\pm \rightarrow \pi^\pm \pi^0) = (6.1^{+1.1}_{-0.7}) \cdot 10^{-6} \times \left[\frac{|V_{ub}|}{0.0037} \frac{F_0^{B \rightarrow \pi}(0)}{0.28} \right]^2$$

$$\text{Exp.: } (5.3 \pm 0.8) \times 10^{-6}$$

Sensitivity to semileptonic form factor and $|V_{ub}|$ can be eliminated in the ratio:

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

Other Tree-Dominated Decays

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

(only S2 and S4 discussed here)

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

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

⇒ default values for neutral modes are too large!

Observations

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

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

⇒ call this **scenario S2** (later also introduce scenario S4)

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

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



Part 2:

Penguin-Dominated Processes

Magnitudes of Penguin Coefficients

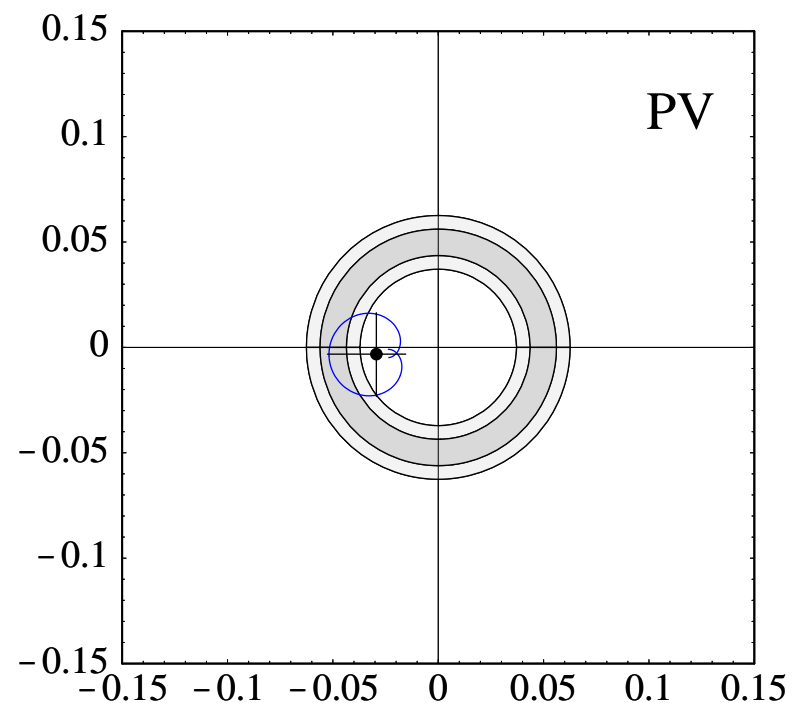
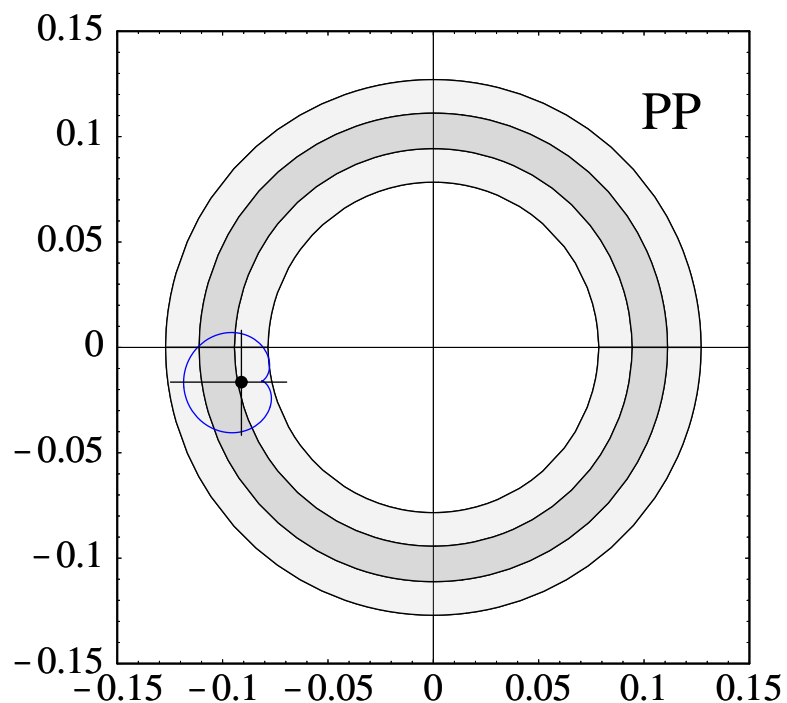
QCD penguin amplitudes (incl. penguin annihilation, charming penguins, etc.) are governed by single parameter $\hat{\alpha}_4^c(M_1 M_2)$, whose magnitude can be determined from the decays:

- $B^\pm \rightarrow \pi^\pm K^0$: $\hat{\alpha}_4^c(\pi K)$ (PP)
- $B^\pm \rightarrow \pi^\pm K^{*0}$: $\hat{\alpha}_4^c(\pi K^*)$ (PV)
- $B^\pm \rightarrow \rho^\pm K^0$: $\hat{\alpha}_4^c(\rho K)$ (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 $B^\pm \rightarrow \pi^\pm \pi^0$ branching ratio to get $|\hat{\alpha}_4^c(M_1 M_2)|$ independent of hadronic form factors:



- ⇒ PP penguin is **right on!**
- ⇒ indeed, strong reduction seen for PV vs. PP!

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

Mode	Theory	S2	Experiment
$B^- \rightarrow \pi^- \bar{K}^0$	$19.3^{+1.9+11.3+1.9+13.2}_{-1.9-7.8-2.1-5.6}$	20.7	20.6 ± 1.3
$B^- \rightarrow \pi^0 K^-$	$11.1^{+1.8+5.8+0.9+6.9}_{-1.7-4.0-1.0-3.0}$	11.9	12.8 ± 1.1
$\bar{B}^0 \rightarrow \pi^+ K^-$	$16.3^{+2.6+9.6+1.4+11.4}_{-2.3-6.5-1.4-4.8}$	18.8	18.2 ± 0.8
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^0$	$7.0^{+0.7+4.7+0.7+5.4}_{-0.7-3.2-0.7-2.3}$	8.3	11.2 ± 1.4
$B^- \rightarrow \pi^- \bar{K}^{*0}$	$3.6^{+0.4+1.5+1.2+7.7}_{-0.3-1.4-1.2-2.3}$	2.2	9.0 ± 1.8
$B^- \rightarrow \pi^0 K^{*-}$	$3.3^{+1.1+1.0+0.6+4.4}_{-1.0-0.9-0.6-1.4}$	2.6	< 31
$\bar{B}^0 \rightarrow \pi^+ K^{*-}$	$3.3^{+1.4+1.3+0.8+6.2}_{-1.2-1.2-0.8-1.6}$	2.4	15.3 ± 3.8
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^{*0}$	$0.7^{+0.1+0.5+0.3+2.6}_{-0.1-0.4-0.3-0.5}$	0.4	< 3.5

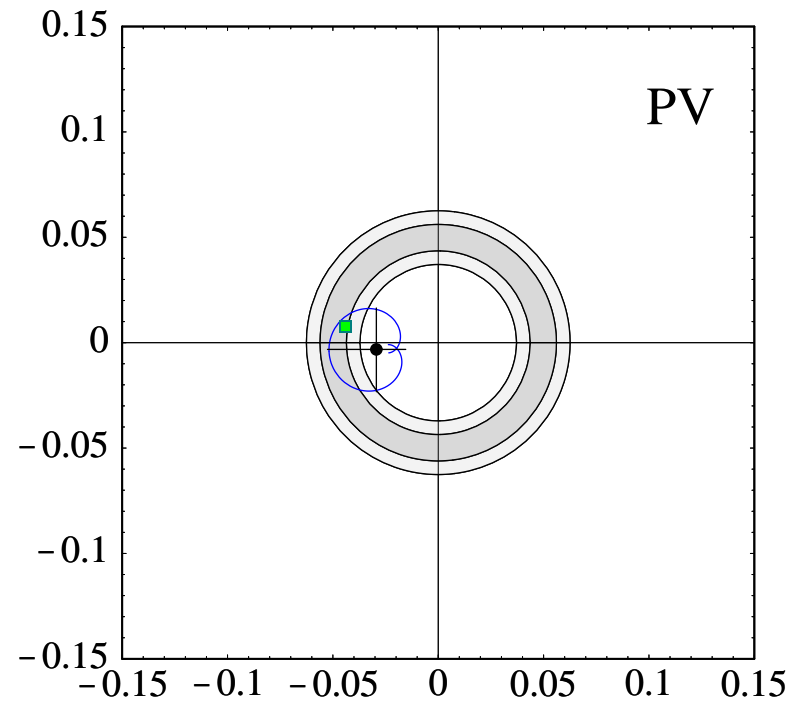
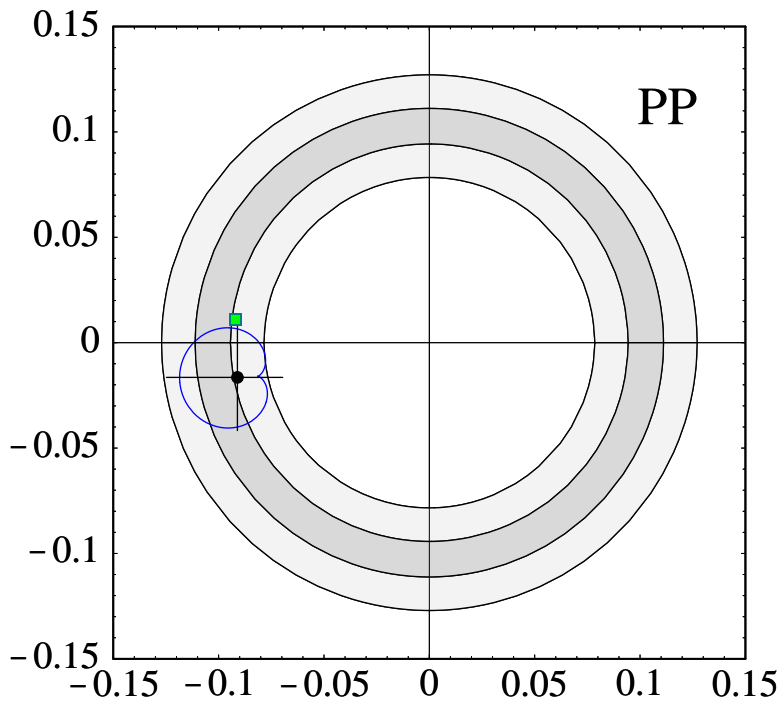
$\Rightarrow B \rightarrow PV$ modes don't look good (but huge uncertainties)

Observations

While the $B \rightarrow \pi K$ modes are well described, the $B \rightarrow \pi K^*$ rates modes are not as small as predicted with default parameters; adjust parameters as follows:

- note huge uncertainties from weak annihilation and strange-quark mass, which are fully correlated between different modes!
- add moderate annihilation terms ($\rho_A = 1$) so as to get a better description (green squares in figure below)
- small effect for PP modes, but sizable for PV modes due to smallness of the penguin amplitude

⇒ call this **scenario S4** (adjusted, but not fitted)



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

Mode	Theory	S2	S4	Experiment
$B^- \rightarrow \pi^- \bar{K}^0$	$19.3^{+1.9+11.3+1.9+13.2}_{-1.9-7.8-2.1-5.6}$	20.7	20.3	20.6 ± 1.3
$B^- \rightarrow \pi^0 K^-$	$11.1^{+1.8+5.8+0.9+6.9}_{-1.7-4.0-1.0-3.0}$	11.9	11.7	12.8 ± 1.1
$\bar{B}^0 \rightarrow \pi^+ K^-$	$16.3^{+2.6+9.6+1.4+11.4}_{-2.3-6.5-1.4-4.8}$	18.8	18.4	18.2 ± 0.8
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^0$	$7.0^{+0.7+4.7+0.7+5.4}_{-0.7-3.2-0.7-2.3}$	8.3	8.0	11.2 ± 1.4
$B^- \rightarrow \pi^- \bar{K}^{*0}$	$3.6^{+0.4+1.5+1.2+7.7}_{-0.3-1.4-1.2-2.3}$	2.2	8.4	9.0 ± 1.8 [was 13 ± 3]
$B^- \rightarrow \pi^0 K^{*-}$	$3.3^{+1.1+1.0+0.6+4.4}_{-1.0-0.9-0.6-1.4}$	2.6	6.5	< 31
$\bar{B}^0 \rightarrow \pi^+ K^{*-}$	$3.3^{+1.4+1.3+0.8+6.2}_{-1.2-1.2-0.8-1.6}$	2.4	8.1	15.3 ± 3.8
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^{*0}$	$0.7^{+0.1+0.5+0.3+2.6}_{-0.1-0.4-0.3-0.5}$	0.4	2.5	< 3.5

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6
- Belle (Jan. 2002): 19.4 ± 6.9

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6
- Belle (Jan. 2002): 19.4 ± 6.9
- BaBar (Mar. 2003): 15.5 ± 3.0

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6
- Belle (Jan. 2002): 19.4 ± 6.9
- BaBar (Mar. 2003): 15.5 ± 3.0
- Beneke, MN (Aug. 2003): ≈ 8.4 (QCD factorization)

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6
- Belle (Jan. 2002): 19.4 ± 6.9
- BaBar (Mar. 2003): 15.5 ± 3.0
- Beneke, MN (Aug. 2003): ≈ 8.4 (QCD factorization)
- Jim Smith to MN (Sept. 12, 2003):
“You have trouble with the $K^* \pi$ decays in particular.
Discuss how long distance effects (charming penguins)
might help...”

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6
- Belle (Jan. 2002): 19.4 ± 6.9
- BaBar (Mar. 2003): 15.5 ± 3.0
- Beneke, MN (Aug. 2003): ≈ 8.4 (QCD factorization)
- Jim Smith to MN (Sept. 12, 2003):
“You have trouble with the $K^* \pi$ decays in particular.
Discuss how long distance effects (charming penguins)
might help...”
- Belle (Aug. 2003): 8.5 ± 1.3

Short History of $B^- \rightarrow \pi^- \bar{K}^{*0}$

Results for the $B^- \rightarrow \pi^- \bar{K}^{*0}$ branching ratio (in units 10^{-6}):

- CLEO (June 2000): 7.6 ± 3.6
- Belle (Jan. 2002): 19.4 ± 6.9
- BaBar (Mar. 2003): 15.5 ± 3.0
- Beneke, MN (Aug. 2003): ≈ 8.4 (QCD factorization)
- Jim Smith to MN (Sept. 12, 2003):
“You have trouble with the $K^* \pi$ decays in particular.
Discuss how long distance effects (charming penguins)
might help...”
- Belle (Aug. 2003): 8.5 ± 1.3
- BaBar (sometime in 2004): ???

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

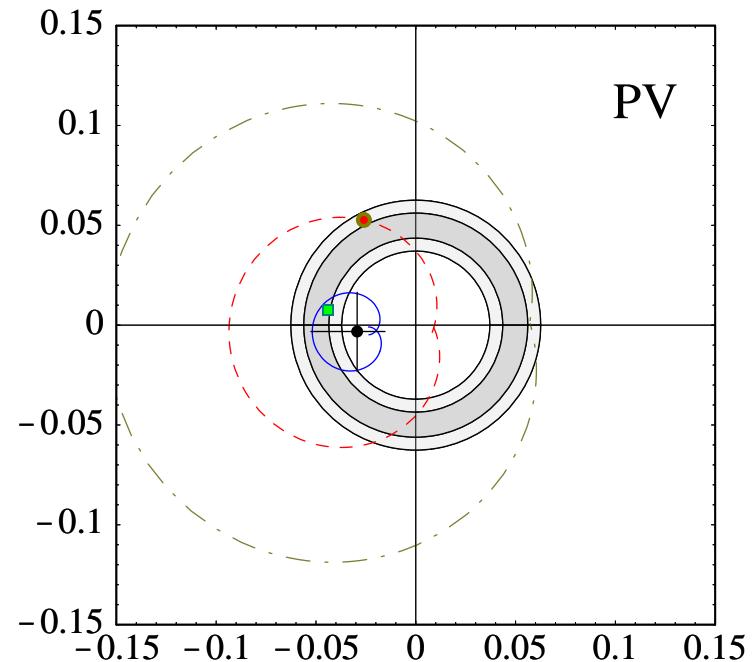
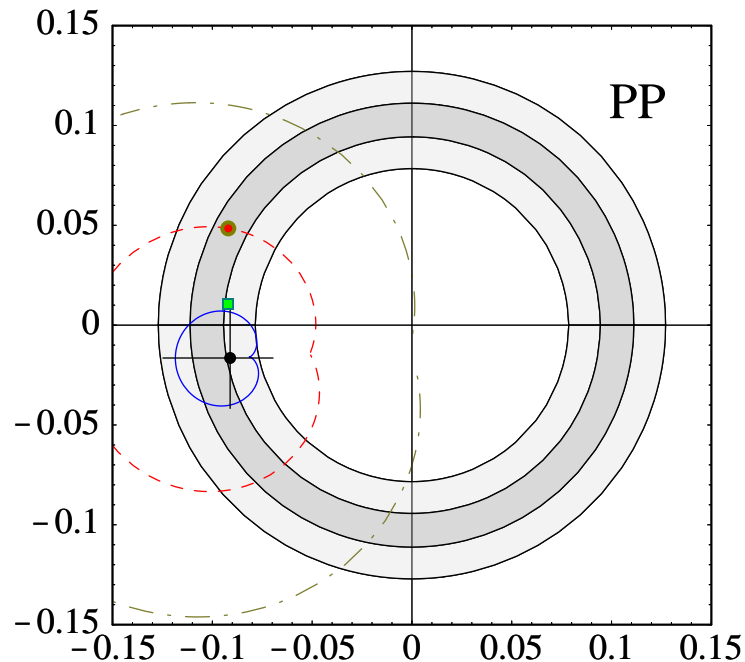
Mode	Theory	S4	Experiment
$B^- \rightarrow \bar{K}^0 \rho^-$	$5.8^{+0.6+7.0+1.5+10.3}_{-0.6-3.3-1.3-3.2}$	9.7	< 48
$B^- \rightarrow K^- \rho^0$	$2.6^{+0.9+3.1+0.8+4.3}_{-0.9-1.4-0.6-1.2}$	4.3	4.1 ± 0.8 [was < 6.2]
$\bar{B}^0 \rightarrow K^- \rho^+$	$7.4^{+1.8+7.1+1.2+10.7}_{-1.9-3.6-1.1-3.5}$	10.1	9.0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

\Rightarrow very good description of all modes but $B \rightarrow K\phi$

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 $\rho_A \geq 2$ are already excluded by the data!

Mode	Default	Large Annihilation (red dot: $\rho_A = 2$)	Experiment
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^{*0}$	0.7	6.0	< 3.5
$B^- \rightarrow K^- \rho^0$	2.6	9.0	4.1 ± 0.8
$\bar{B}^0 \rightarrow K^- \rho^+$	7.4	19.3	9.0 ± 1.6
$B^- \rightarrow K^- \phi$	4.5	22.4	9.0 ± 0.7
$\bar{B}^0 \rightarrow \bar{K}^0 \phi$	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
$B^- \rightarrow \eta K^-$	1.6	3.1 ± 0.7	$B^- \rightarrow \eta K^{*-}$	19.9	25.9 ± 3.4
$\bar{B}^0 \rightarrow \eta \bar{K}^0$	1.1	< 4.6	$\bar{B}^0 \rightarrow \eta \bar{K}^{*0}$	18.6	17.8 ± 2.1
$B^- \rightarrow \eta' K^-$	76.1	77.6 ± 4.6	$B^- \rightarrow \eta' K^{*-}$	2.2	< 12
$\bar{B}^0 \rightarrow \eta' \bar{K}^0$	70.3	65.2 ± 6.0	$\bar{B}^0 \rightarrow \eta' \bar{K}^{*0}$	1.9	< 6.4
$B^- \rightarrow \pi^- \eta$	3.8	3.9 ± 0.9	$B^- \rightarrow \eta \rho^-$	6.3	8.9 ± 2.7 [was < 6.2]
$\bar{B}^0 \rightarrow \pi^0 \eta$	0.3	< 2.9	$\bar{B}^0 \rightarrow \eta \rho^0$	0.1	< 5.5
$B^- \rightarrow \pi^- \eta'$	2.9	< 7	$B^- \rightarrow \eta' \rho^-$	4.2	13.3 ± 4.7 [was < 33]
$\bar{B}^0 \rightarrow \pi^0 \eta'$	0.4	< 5.7	$\bar{B}^0 \rightarrow \eta' \rho^0$	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
$B^- \rightarrow \pi^- \bar{K}^0$	0.3	-2 ± 9	$B^- \rightarrow K^- \omega$	19.3	0 ± 12
$B^- \rightarrow \pi^0 K^-$	-3.6	1 ± 12	$\bar{B}^0 \rightarrow \bar{K}^0 \omega$	3.7	—
$\bar{B}^0 \rightarrow \pi^+ K^-$	-4.1	-9 ± 4	$B^- \rightarrow K^- \phi$	0.7	3 ± 7
$\bar{B}^0 \rightarrow \pi^0 \bar{K}^0$	0.8	3 ± 37	$\bar{B}^0 \rightarrow \bar{K}^0 \phi$	0.8	19 ± 68
$B^- \rightarrow \pi^- \pi^0$	-0.02	-7 ± 14	$B^- \rightarrow \pi^- \rho^0$	-11.0	-17 ± 11
$\bar{B}^0 \rightarrow \pi^+ \pi^-$	10.3	51 ± 23	$B^- \rightarrow \pi^0 \rho^-$	9.9	23 ± 17
$B^- \rightarrow \pi^- \omega$	-6.0	9 ± 21	$\bar{B}^0 \rightarrow \pi^+ \rho^-$	3.9	-11 ± 17
			$\bar{B}^0 \rightarrow \pi^- \rho^+$	-12.9	-62 ± 27

⇒ no significant discrepancies

Part 5:

Penguin Withdrawal:
Measuring $\sin 2(\beta + \gamma)$ in
 $B \rightarrow \pi^\pm \rho^\mp$ Decays

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

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

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 $B \rightarrow \pi\pi$
- clean measurement of $\sin 2\alpha$ with minimal theoretical uncertainties (well below $\pm 10^\circ$!)
- **best determination of γ to date!**

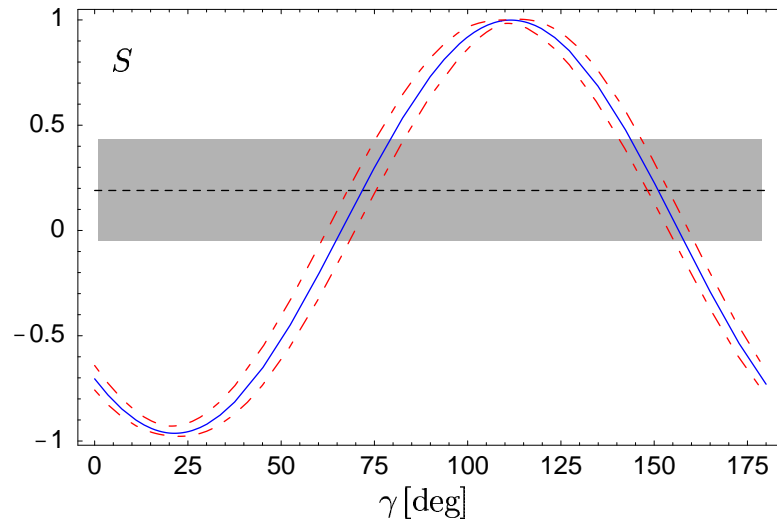
Results (assuming $\beta = 24^\circ$)

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

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

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

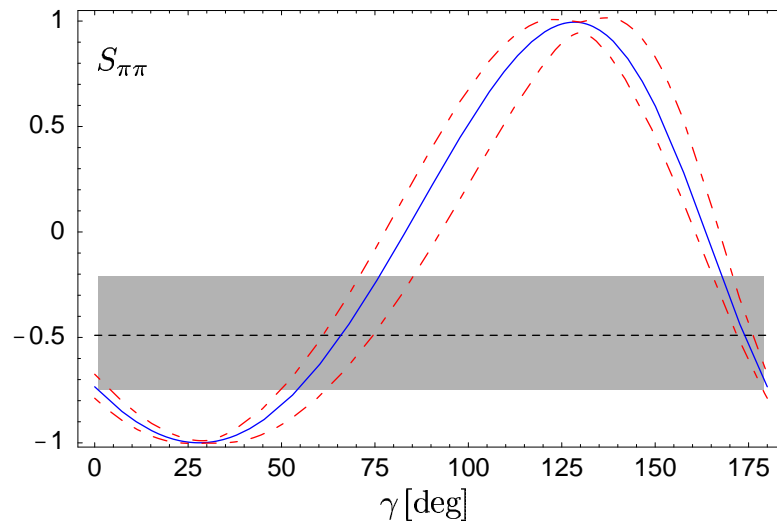
$$[\text{95\% CL: } \gamma = (72 \pm 20)^\circ]$$



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

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

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



Conclusions

- gaining theoretical control over exclusive hadronic decays of B mesons constitutes the most pressing challenge to heavy-flavor theory

Conclusions

- gaining theoretical control over exclusive hadronic decays of B mesons constitutes the most pressing challenge to heavy-flavor theory
- QCD factorization theorems make a large class of such decays accessible to a theoretical treatment based on the heavy-quark expansion

Conclusions

- gaining theoretical control over exclusive hadronic decays of B mesons constitutes the most pressing challenge to heavy-flavor theory
- QCD factorization theorems make a large class of such decays accessible to a theoretical treatment based on the heavy-quark expansion
- SCET provides the tools to understand factorization using the language of effective field theory

Conclusions

- gaining theoretical control over exclusive hadronic decays of B mesons constitutes the most pressing challenge to heavy-flavor theory
- QCD factorization theorems make a large class of such decays accessible to a theoretical treatment based on the heavy-quark expansion
- SCET provides the tools to understand factorization using the language of effective field theory
- QCD factorization provides a successful, global description of the available data on charmless B decays and makes many more predictions (also B_s decays)

Conclusions

It would be ignorant to say that we don't have a theory of hadronic B decays!

Points for Discussion

1. If experimental data remain high, QCD factorization has trouble accounting for the $K^*\pi$ decay rates in particular. Discuss how long distance effects (charming penguins) might help this situation and contrast with your other favorite explanations for the difference. If charming penguins enhance some modes, are they problematic somewhere else?

Points for Discussion

1. If experimental data remain high, QCD factorization has trouble accounting for the $K^*\pi$ decay rates in particular. Discuss how long distance effects (charming penguins) might help this situation and contrast with your other favorite explanations for the difference. If charming penguins enhance some modes, are they problematic somewhere else?

- Data have come down ...
- Apart from SU(3) breaking and EW penguins (small in SM), the modes $B^- \rightarrow \pi^- \bar{K}^{*0}$ and $B^- \rightarrow K^- \phi$ are given in terms of the same penguin amplitude, but data pull in opposite directions

Points for Discussion

- **Note:** The charming penguin approach is not an alternative to QCD factorization, but rather treats the penguin amplitude as a fit parameter. Charming penguins are part of QCD factorization as are other, indistinguishable contributions to the penguin amplitude such as weak (penguin) annihilation.

Points for Discussion

2. What is the bottom line on the effect of annihilation diagrams?
How do we test the contributions of such diagrams with data?

Points for Discussion

2. What is the bottom line on the effect of annihilation diagrams?
How do we test the contributions of such diagrams with data?

- Annihilation is a small effect in PP modes, but larger in PV and VP modes due to reduction of the penguin contributions
- Annihilation contributions can be fixed and bound using data, as I have discussed

Points for Discussion

3. Give an unbiased contrast of the present status of the QCD fact and pQCD approaches. :-)

Points for Discussion

3. Give an unbiased contrast of the present status of the QCD fact and pQCD approaches. :-)

- pQCD assumes that heavy-to-light form factors are **perturbative** and so count as $O(\alpha_s)$, whereas QCD factorization assumes that these form factors are dominated by soft dynamics
- pQCD includes some (gauge-dependent!) power-suppressed terms (k_\perp) in leading-order predictions, whereas QCD factorization uses a strict $1/m_b$ expansion
 \Rightarrow large, but unphysical strong phases!
[criticized in BBNS2, but never fixed]
- One is a good theory, one is not :-)

Points for Discussion

4. Do we get any insight from comparisons of new QCD calculations with the phenomenological approach in the previous talk?

Points for Discussion

4. Do we get any insight from comparisons of new QCD calculations with the phenomenological approach in the previous talk?

- The previous talk uses a parameterization, not a theory
- The previous talk assumes $SU(3)$ symmetry and neglects many contributions to the decay amplitudes, we don't