Hard scattering in B decays and γ from $B \to \pi K$ decay

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1) QCD factorization formula for hadronic, two-body B decays – Results for πK and $\pi\pi$ final states.

Theory background: M. Beneke, G. Buchalla, M. Neubert, C.T. Sachrajda, PRL 83 (1999) 1914 and [hep-ph/0006124].

Results based on work in preparation and paper submitted to this conference [hep-ph/0007nnn].
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2) Corrections to heavy quark/large energy symmetries for $B \to$ light form factors.

M. Beneke and T. Feldmann, in preparation

– will be omitted for lack of time.

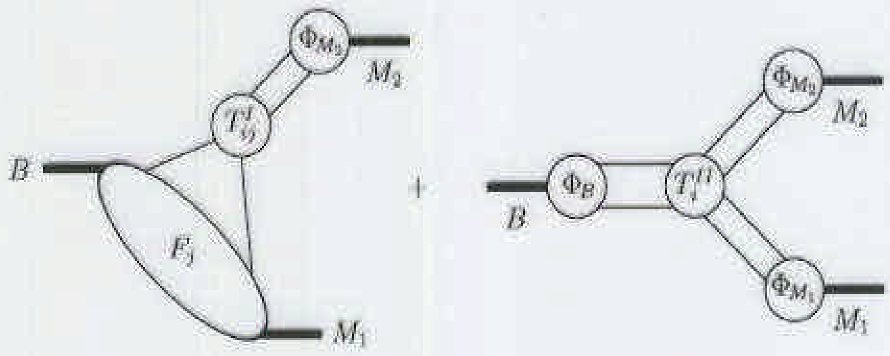
QCD factorization formula

Hard gluon effects ($k > m_b$) can be calculated and lead to the effective hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i^{\text{CKM}} C_i(\mu) Q_i(\mu)$$

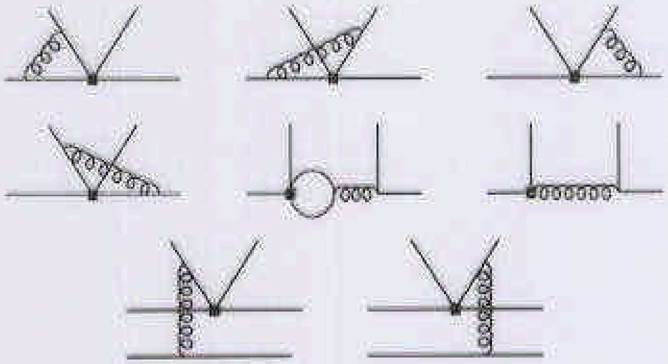
Principal idea: factorize systematically the remaining hard effects ($k \sim m_b$) from long-distance effects ($k \sim \Lambda_{\text{QCD}}$) – heavy quark expansion. Result is:

$$\langle \pi K | Q_i | B \rangle = f_+^{B\to\pi}(0)\, f_K\, T^{\text{I}}_{K,i} * \Phi_K + f_+^{B\to K}(0)\, f_\pi\, T^{\text{I}}_{\pi,i} * \Phi_\pi + \underbrace{f_B f_K f_\pi\, T_i^{\text{II}} * \Phi_B * \Phi_K * \Phi_\pi}_{\text{spectator interaction}}$$



- long-distance: form factor, decay constant, light-cone distribution amplitudes
- short-distance: kernels $T^{I,II} = \alpha_s^0 + \alpha_s^1 + \ldots$, contain all "non-factorizable" corrections and strong phases.

Status: all hard scattering kernel to order α_s (order α_s^0 coincides with the naive factorization approximation).



New results:

I) Factorization proof at 2 loop order for $B \to DL$(ight) and phenomenological analysis of heavy-light final states.

[Not discussed here – see hep-ph/0006124.]

II) "Electroweak penguin effects":

Matrix elements of electro-magnetic penguin operators and electro-magnetic penguin corrections of QCD operators.

[See also Du, Yang, Zhu, hep-ph/0005006; Muta, Sugamoto, Yang, Yang hep-ph/0006022.]

III) Kernels for asymmetric light-cone distribution amplitudes (as relevant for K)

$\to$ Calculation of non-factorizable $SU(3)$ breaking effects.

IV) Complete calculation of "chirally enhanced $1/m_b$ corrections".

→ very important effect, e.g. in spectator interaction:

$$\int_0^1 \frac{du}{\bar{u}}\frac{dv}{\bar{v}}\Phi_K(u)\left(\Phi_\pi(v)+\frac{2\mu_\pi}{m_b}\frac{\bar{u}}{u}\right)\approx 9\Big(1+\underbrace{\frac{2\mu_\pi}{3m_b}\int_0^1\frac{dv}{\bar{v}}}_{\text{soft dominated}}\Big)$$

where $2\mu_\pi/m_b \equiv -4\langle\bar{q}q\rangle/(f_\pi^2 m_b) \sim \Lambda_{\rm QCD}/m_b$ but ≈ 1 numerically.

Divergent integral → breakdown of factorization at order $1/m_b$, soft rescattering enters at this order.

BUT: the size of this special $1/m_b$ correction is not an indication that the $1/m_b$ expansion breaks down.

Choice of parameters:

- $\int_0^1 dv/\bar{v} = \ln(m_B/0.35\,\text{GeV}) + r$, $r \in [0,3]$ (dark) and [0,6] (light) with arbitrary phase (separately in penguin diagrams and spectator interaction).
- $\lambda_B \in [0.2, 0.5]$ GeV, $m_B/\lambda_B \equiv \int \frac{d\xi}{\xi}\Phi_B(\xi)$
- $\mu \in [m_b/2, 2m_b]$ (renormalization scale)
- $\alpha_s(m_Z) = 0.118$, $|V_{cb}| = 0.039$ and $\left|\frac{V_{ub}}{V_{cb}}\right| = 0.085$ fixed (SM input parameters rather than theory uncertainty).

I: πK and $\pi\pi$ amplitudes

$\pi\pi$:

$$\mathcal{A}(B^0 \to \pi^+\pi^-) = T\,[e^{i\gamma} + (P/T)_{\pi\pi}]$$

πK:

$$\begin{aligned}
\mathcal{A}(B^+ \to \pi^+ K^0) &= P\left(1 - \varepsilon_a\, e^{i\eta} e^{i\gamma}\right), \\
-\sqrt{2}\,\mathcal{A}(B^+ \to \pi^0 K^+) &= P\Big[1 - \varepsilon_a\, e^{i\eta} e^{i\gamma} \\
&\qquad - \varepsilon_{3/2}\, e^{i\phi}(e^{i\gamma} - q\, e^{i\omega})\Big], \\
-\mathcal{A}(B^0 \to \pi^- K^+) &= P\Big[1 - \varepsilon_a\, e^{i\eta} e^{i\gamma} \\
&\qquad - \varepsilon_T\, e^{i\phi_T}(e^{i\gamma} - q_C\, e^{i\omega_C})\Big], \\
\sqrt{2}\,\mathcal{A}(B^0 \to \pi^0 K^0) &= \mathcal{A}(B^+ \to \pi^+ K^0) \\
&\quad + \sqrt{2}\,\mathcal{A}(B^+ \to \pi^0 K^+) - \mathcal{A}(B^0 \to \pi^- K^+)
\end{aligned}$$

	Range, NLO	LO
$-\varepsilon_a\, e^{i\eta}$	$(0.017\text{–}0.021)\, e^{i\,[13,20]^\circ}$	0.019
$\varepsilon_{3/2}\, e^{i\phi}$	$(0.20\text{–}0.38)\, e^{i\,[-30,7]^\circ}$	0.26–0.50
$q\, e^{i\omega}$	$(0.53\text{–}0.63)\, e^{i\,[-7,3]^\circ}$	0.63–0.64
$\varepsilon_T\, e^{i\phi_T}$	$(0.20\text{–}0.29)\, e^{i\,[-19,3]^\circ}$	0.26–0.44
$q_C\, e^{i\omega_C}$	$(0.00\text{–}0.22)\, e^{i\,[-180,180]^\circ}$	0.00–0.11
$(P/T)_{\pi\pi}$	$(0.19\text{–}0.29)\, e^{i\,[-1,23]^\circ}$	0.12–0.21

Remarks:

1) Renormalization scale dependence strongly reduced by LO $\rightarrow$ NLO.

2) Ranges at NLO are obtained by scanning. There are correlations between the parameters, which are not displayed.

Summary:

1) Corrections to naive factorization are important

2) Strong phases are small in general, except for a phase related to electroweak penguins.

$\rightarrow$ direct CP asymmetries up to 10% for $\pi^+\pi^-$, $\pi^0 K^+$, $\pi^- K^+$, $\pi^0 K^0$ depending on γ.

Exceptions:

- $\pi^+ K^0$ very small,
- $\pi^0\pi^0$ anything.

II: "Non-factorizable" $SU(3)$ breaking effects

Bounds [Fleischer-Mannel, Neubert-Rosner] on the angle γ derived from ratios of πK branching fractions rely on an estimate of $SU(3)$ flavour-symmetry violations. E.g.,

$$\frac{\varepsilon_{3/2}}{\sqrt{1-2\varepsilon_a \cos\eta \cos\gamma + \varepsilon_a^2}} = R_{SU(3)} \tan\theta_C \left[\frac{2\text{Br}(B^\pm \to \pi^\pm \pi^0)}{\text{Br}(B^\pm \to \pi^\pm K^0)}\right]^{1/2},$$

where $R_{SU(3)} = 1$ in the $SU(3)$ limit. Write

$$R_{SU(3)} = \frac{f_K}{f_\pi}\,(1 + \delta R_{\rm nf})$$

Result: $|\delta R_{\rm nf}| < 4\%$ even for large variations of the pion and kaon distribution amplitude.

This result is general.

→ $SU(3)$ breaking seems to reside mainly in $f_K/f_\pi \approx 1.22$ (at least at leading power in $1/m_b$).

III: CP averaged branching fraction ratios

Despite significant corrections to naive factorization, the qualitative pattern that emerges for the set of $\pi\pi$ and πK decay modes is similar to that of naive factorization:

the penguin–tree interference is constructive (destructive) in $B \to \pi^+\pi^-$ ($B \to \pi^- K^+$) decays if $\gamma < 90°$.

Taking the currently favoured range $\gamma = (60 \pm 20)°$, we find [CLEO, hep-ex/0001010 in brackets]:

$$\frac{\text{Br}(\pi^+\pi^-)}{\text{Br}(\pi^\mp K^\pm)} = 0.5\text{–}1.9 \quad [0.25 \pm 0.10]$$

0.36±0.26 Be
0.74±0.29 Bb

$$\frac{\text{Br}(\pi^\mp K^\pm)}{2\text{Br}(\pi^0 K^0)} = 0.9\text{–}1.4 \quad [0.59 \pm 0.27]$$

0.44±0.22 Be

$$\frac{2\text{Br}(\pi^0 K^\pm)}{\text{Br}(\pi^\pm K^0)} = 0.9\text{–}1.3 \quad [1.27 \pm 0.47]$$

2.26±1.42 Be

[R_*^{-1} – Neubert-Rosner]

$$\frac{\tau_{B^+}}{\tau_{B^0}} \frac{\text{Br}(\pi^\mp K^\pm)}{\text{Br}(\pi^\pm K^0)} = 0.6\text{–}1.0 \quad [1.00 \pm 0.30]$$

1.11±0.72 Be

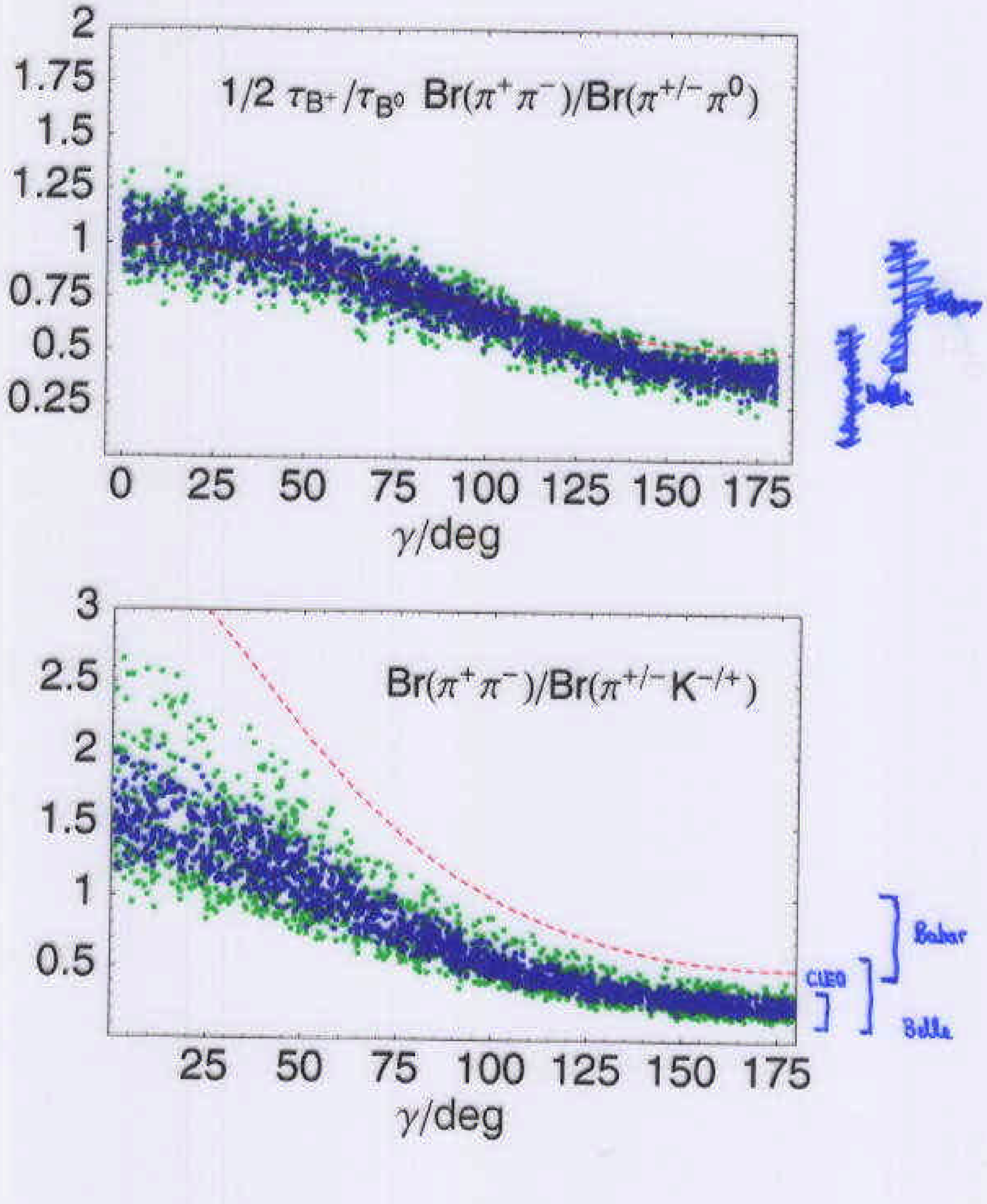
[R – Fleischer-Mannel]

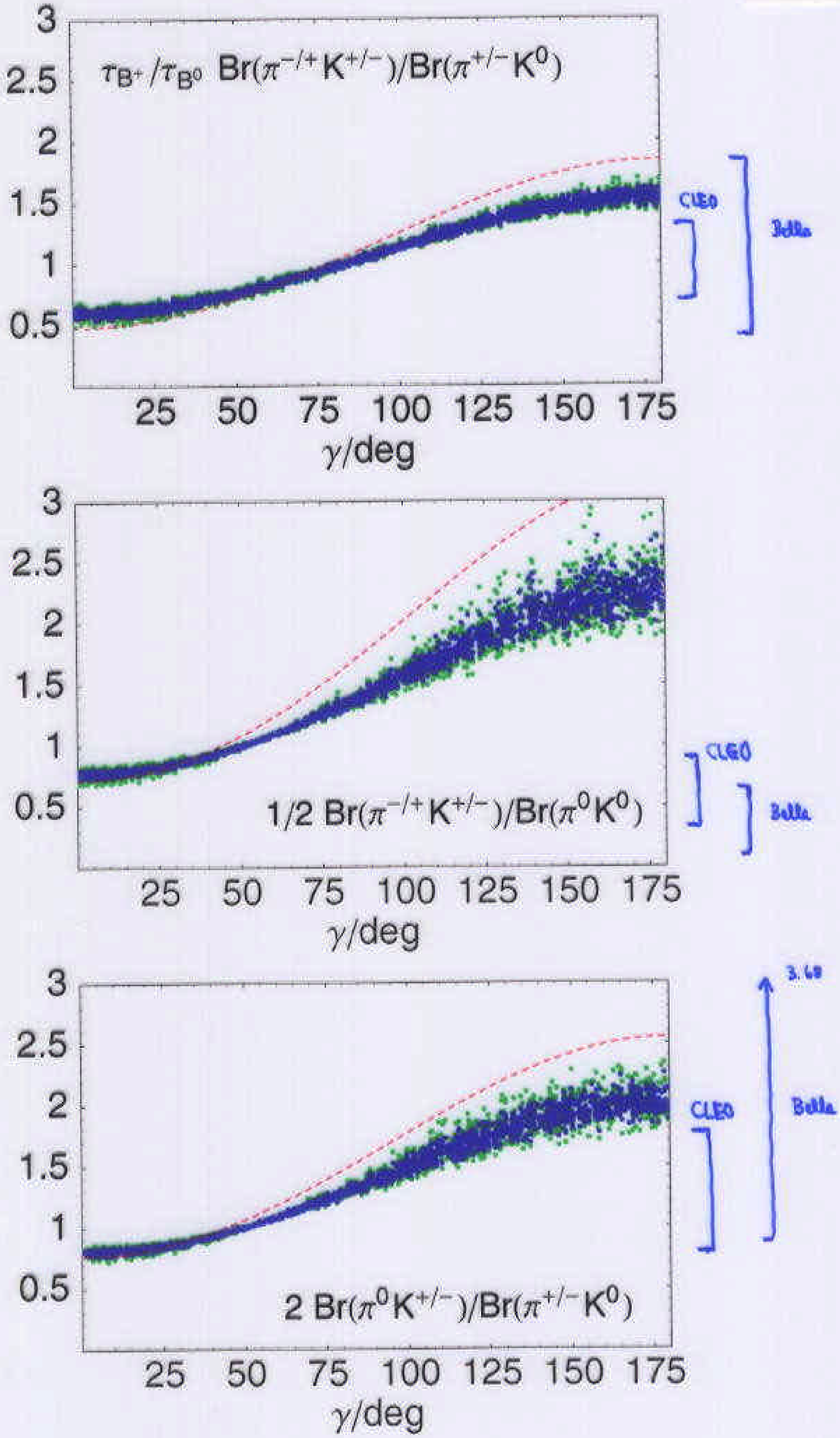
The near equality of the second and the third ratios is a result of isospin symmetry.

We find (almost independently of γ):

$$\text{Br}(B \to \pi^0 K^0) = (4.5 \pm 2.5) \times 10^{-6}\, (V_{cb}/0.039)^2 (f_+^{B\to\pi}(0)/0.3)^2$$

Ratios of CP-averaged $B \to \pi K$ and $\pi\pi$ decay rates. The scattered points cover a realistic (dark) and conservative (light) variation of input parameters. The dashed curve is the LO result, corresponding to conventional factorization.




τ_{B^+}/τ_{B^0} Br($\pi^{-/+}K^{+/-}$)/Br($\pi^{+/-}K^0$)
CLEO
Belle
γ/deg
1/2 Br($\pi^{-/+}K^{+/-}$)/Br(π^0K^0)
CLEO
Belle
γ/deg
2 Br($\pi^0K^{+/-}$)/Br($\pi^{+/-}K^0$)
3.60
CLEO
Belle
γ/deg

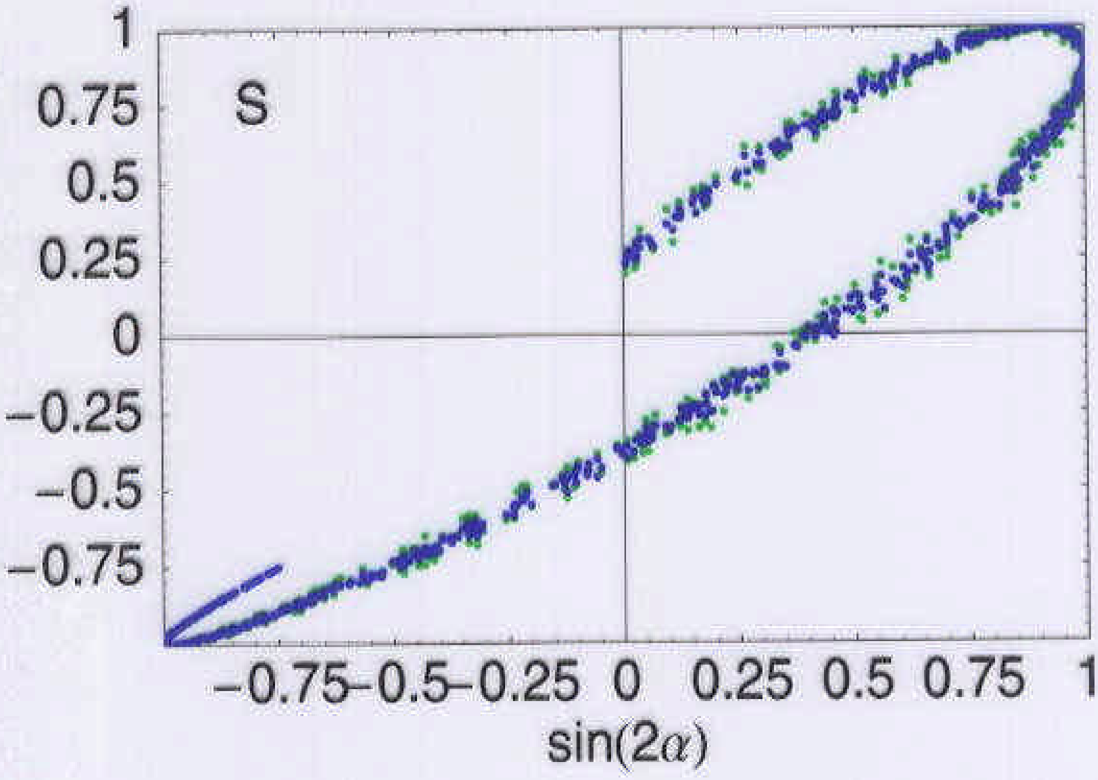
IV: $\sin(2\alpha)$ from $B_d \to \pi^+\pi^-$ decays

Time-dependent, mixing-induced CP asymmetry without isospin analysis?

$$\mathcal{A}(t) = -S \cdot \sin(\Delta M t) + C \cdot \cos(\Delta M t)$$

$$S = \sin(2\alpha) + \mathcal{O}(P/T)$$
$$C = \mathcal{O}(P/T)$$

Fix $\sin(2\beta) = 0.75$ and $\alpha, \beta, \gamma > 0$.



→ useful constraints on $\sin(2\alpha)$ can be obtained since $(P/T)_{\pi\pi}$ is well-predicted.

Conclusion

Examined consequences of QCD factorization for πK final states, including chirally enhanced $1/m_b$ corrections.

* significant corrections with respect to naive factorization
* qualitative pattern of (CP-averaged) branching fractions similar.
* moderately small strong phases (direct CP asymmetries)
* robust predictions for many observables
* disagreement with CLEO data of 01/2000 for $\pi^0 K^0$ final state (data too large) and relative branching fractions of $\pi\pi$ and πK modes (data too small).

Future detailed publication will explore correlations to constrain the parameter introduced to account for chirally-enhanced terms.