Theoretical tools for B decays: QCD factorization

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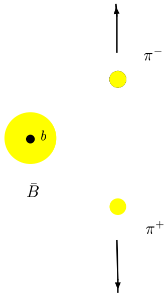
Outline

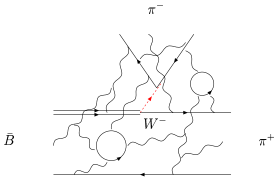
- Lightning review of QCDF
- Higher-order (radiative) corrections (α_s)
- Key hadronic inputs
- Power corrections ($1/m_b$)
- Specific decays and observables

Lightning review of factorization

Exclusive B decays: Simple kinematics, complicated dynamics



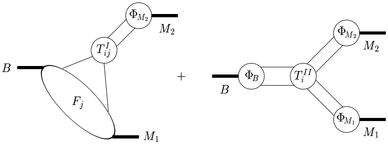
$$\langle \pi^- \pi^+ | \bar{B} \rangle_{\mathcal{L}_{\rm SM}} \quad =$$



Problem with multiple scales: $M_W, m_b, \sqrt{m_b \Lambda_{\rm QCD}}, \Lambda_{\rm QCD}$

Factorization = theory of calculating effects from short-distance scales and parameterising long-distance effects in "universal" quantities.

QCD factorization formula [BBNS]



Form factor term +
Spectator scattering

$$T, C, P^{c,u}, \ldots \quad \sim \quad \langle M_1 M_2 | C_i O_i | \bar{B} \rangle_{\mathcal{L}_{\rm eff}} = \sum_{\rm terms} C(\mu_h) \times \Big\{ F_{B\to M_1} \times \underbrace{T^{\rm I}(\mu_h,\mu_s)}_{1+\alpha_s+\ldots} \star f_{M_2} \Phi_{M_2}(\mu_s)$$

$$+ f_B \Phi_B(\mu_s) \star \Big[\underbrace{T^{\rm II}(\mu_h,\mu_I)}_{1+\ldots} \star \underbrace{J^{\rm II}(\mu_I,\mu_s)}_{\alpha_s+\ldots} \Big] \star f_{M_1} \Phi_{M_1}(\mu_s) \star f_{M_2} \Phi_{M_2}(\mu_s) \Big\}$$

$$+ 1/m_b\text{-suppressed terms}$$

Similar factorization formula for
$B \to (M,\gamma)(\gamma, \ell^+\ell^-, \ell\nu)$
(See talk by Pecjak)

Remarks

- Perturbative vs. non-perturbative

  Magnitudes: 1 or $\alpha_s \ln M_W/\Lambda$ vs Λ/m_b
  Phases: $\alpha_s(m_b)$ vs Λ/m_b.

- Theoretically QCDF = SCET (factorization formula, calculation of corrections) $\neq$ PQCD (disagreement on Sudakov logs) but:
  Different implementations: more/less calculations vs phenomenological fitting used in practice

- Power corrections are definitely important for penguin amplitudes. Some are calculable (scalar penguins) others not (weak annihilation).

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Issues

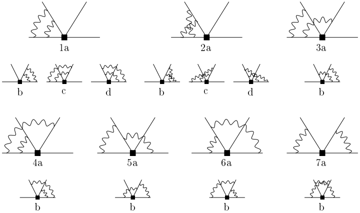
- Knowledge of input ($|V_{ub}|$, hadronic: Form factors, λ_B)
- Importance of higher-order perturbative corrections?
- Theory of power corrections?
- Comparsion with data

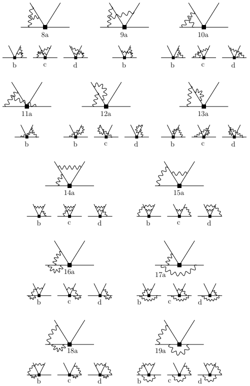
This talk: Briefly discuss new results and key issues on each.

Higher-order calculations

Status of $O(\alpha_s^2)$ ("NNLO") calculations

- Spectator-scattering tree amplitudes (MB, Jäger, 2005; Kivel, 2006; Pilipp 2007)
- Spectator-scattering QCD non-singlet and EW penguin amplitudes (MB, Jäger, 2006)
  (Penguin contractions to QCD non-singlet penguin amplitude confirmed by Jain, Stewart, Rothstein 2007; earlier calculation of penguin contractions by Li, Yang, 2005 not confirmed.)
- New since FPCP 2007 – Im(Form-factor term) at 2 loops for tree amplitudes $\alpha_{1,2}$ (Bell, 2007)





Numerical result (tree amplitudes)

$$
\begin{aligned}
a_1(\pi\pi) &= 1.015 + [0.025 + 0.012i]_{\rm NLO} + [? + 0.026i]_{\rm NNLO} \\
&\quad - \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.020]_{\rm LOsp} + [0.034 + 0.029i]_{\rm NLOsp} + [0.012]_{\rm tw3}\right\} \\
&= 0.98 + 0.01i \quad \rightarrow \quad 0.91 - 0.02i \quad (\text{if } 2 \times r_{\rm sp}) \\
a_2(\pi\pi) &= 0.184 - [0.153 + 0.077i]_{\rm NLO} + [? - 0.042i]_{\rm NNLO} \\
&\quad + \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.122]_{\rm LOsp} + [0.050 + 0.053i]_{\rm NLOsp} + [0.071]_{\rm tw3}\right\} \\
&= 0.27 - 0.07i \quad \rightarrow \quad 0.52 - 0.02i \quad (\text{if } 2 \times r_{\rm sp})
\end{aligned}
$$

$$
r_{\rm sp} = \frac{9 f_{M_1} \hat{f}_B}{m_b f_+^{B\pi}(0) \lambda_B}
$$

- Perturbation theory works at scale m_b and $\sqrt{m_b \Lambda}$. Significant radiative NNLO corrections only for the colour-suppressed amplitudes.
- Allows $|C/T|_{\pi\pi} \approx 0.7$, if λ_B is small. The colour-suppressed amplitudes are probably dominated by spectator-scattering. But $\arg\left(C/T_{\pi\pi}\right) \lesssim 15^\circ$.
- $O(\alpha_s^2)$ spectator-scattering correction to penguin amplitude a_4 turned out to be very small.

Penguin amplitudes – Comparison of P/T to data

Final state dependence in good agreement with data.

$$\mathrm{PP} \sim \underbrace{a_4}_{\mathrm{V}\mp\mathrm{A}} + \underbrace{r_\chi a_6}_{\mathrm{S+P}}$$

$$\mathrm{PV} \sim a_4 \approx \frac{\mathrm{PP}}{3}$$

$$\mathrm{VP} \sim a_4 - r_\chi a_6 \sim -\mathrm{PV}$$

$$\mathrm{VV} \sim a_4 \sim \mathrm{PV}$$

Small phases ($\rightarrow$ CP asymmetries)

(Small weak annihilation error for VV unrealistic - similar to VP, PV)

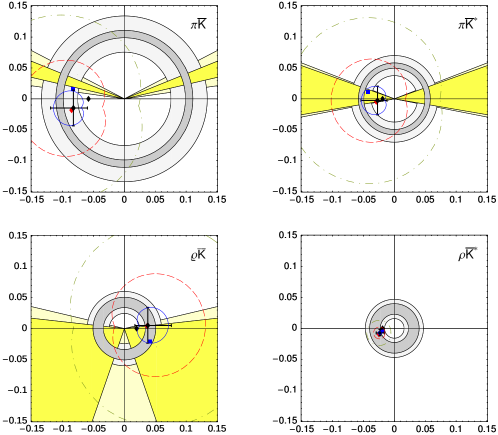


Figure from (MB, Jäger, 2006)

Broad picture

- Radiative corrections help

  Enhancement of $|C/T|$ possible for small λ_B
  Pattern of |P/T| ok
  Phases are generated, but either smallish or uncertain.
- Broad picture ok, but detailed “test” of radiative corrections obscured by other uncertainties.

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Outstanding issues (radiative corrections)

- 2-loop form factor-type correction to the dominant penguin amplitude a_4 – at least imaginary part to understand phase of P/T.
- NNLO correction to the (power-suppressed, but calculable) scalar penguin amplitude a_6 [might provide short-distance resolution of some problems with direct CP asymmetries].

Important input parameters

Around 2003 it became clear that a good description of hadronic B decay data requires smaller $|V_{ub}|f^{BM}(0)$ and λ_B than first guesses.

Form factors

- $f_+^{B\pi}(0)$ (from QCD sum rules) has become slightly smaller.
  0.28 (Bagan et al, 1997; Khodjamirian et al, 1997) $\longrightarrow$ 0.26 (Ball et al, 2004; Duplanic et al, 2008)
  good for $\pi\pi$ Br's
- Similar tendency for $T_1^{BK^\star}(0)$ – required for $K^\star\gamma$

$|V_{ub}|$ crisis (about to be resolved?)

- $|V_{ub}|f_+^{B\pi}(0) = (9.1 \pm 0.6 \pm 0.3) \times 10^{-4}$ from semileptonic $B \to \pi l\nu$ spectrum + form factor extrapolation (Ball, 2006)
- $|V_{ub}|f_+^{B\pi}(0) = (8.1 \pm 0.4\,(?)) \times 10^{-4}$ from $B \to \pi^+\pi^-, \pi^+\pi^0, \pi\rho, \ldots$ + factorization
  (MB, Neubert, 2003; Arnesen et al, 2005; MB, Jäger, 2005)

$\Rightarrow$ $|V_{ub}| \simeq 3.5 \times 10^{-4}$, in contrast to determination from moments of inclusive $b \to u\ell\nu$ decay, which was $|V_{ub}| \simeq (4.5 \pm 0.3) \times 10^{-4}$.

But: according to (Neubert, LP07) $|V_{ub}| \simeq (3.7 \pm 0.3) \times 10^{-4}$ after reevaluation of m_b input and omitting $B \to X_s\gamma$ moments!

λ_B crisis? $\quad \lambda_B^{-1} \equiv \int_0^\infty \frac{d\omega}{\omega}\, \Phi_{B+}(\omega)$

λ_B controls the relative importance of hard-spectator scattering and the form factor term. Smaller λ_B implies larger spectator-scattering effects.

- $\lambda_B = (350 \pm 150)$ MeV BBNS assumption
- Theoretical models:
  $\lambda_B = (460 \pm 110)$ MeV (QCD sum rules, Braun et al, 2003),
  (460 ± 160) MeV (QCD sum rules, Khodjamirian et al, 2005)
  (480 ± 120) MeV (shape models with moment constraints: Lee, Neubert, 2005)
- Experimental (BABAR 0704.1478 [hep-ex]):
  $\lambda_B \gtrsim 600$ MeV (90% CL) from upper limit on $B \to \gamma \ell \nu$.

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But tree-dominated charmless decays ($\pi\pi$, $\pi\rho$, $\rho\rho$) all require $\lambda_B \simeq (200 - 250)$ MeV [driven by large |C/T|].

Power corrections

Every amplitude receives corrections $\Lambda/[m_b/2]$, which cannot be calculated in general.
In practice very important for the dominant QCD penguin amplitude P^c:

$$P^c = [a_4^c + r_\chi a_6^c]_{\mathrm{SD}} + [a_4^c + r_\chi a_6^c]_{\mathrm{LD}} + \beta_3^c + \ldots$$

- $[a_4^c + r_\chi a_6^c]_{\mathrm{SD}}$ depends strongly on whether final state is PP, PV, VP or VV in agreement with data. Dominant contribution is a power correction, $r_\chi a_6^c$!
- Short-distance contribution falls short of data by about 0.02-0.03 for PP, PV and VP, ok for VV. Relatively large effect for for PV and VP, less for PP. (MB, Jäger, 2006, see earlier slide on penguin amplitude calculation)
- Don't know which physical effect makes up for the missing contribution:
  - $[a_4^c + r_\chi a_6^c]_{\mathrm{LD}}$, e.g. charm penguin contractions?
  - β_3^c, penguin annihilation (as in BBNS)?
    Up to now, no solid empirical evidence for significant other annihilation amplitudes. (See also Hao et al., 2006)
- Conservative parameterizations should allow long-distance and annihilation amplitudes to be complex $\Rightarrow$ uncertainty in direct CP asymmetry prediction.

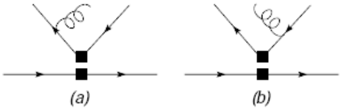
Key issue for progress with (factorization) theory-driven approaches.

New calculations of power corrections

Factorizable $q\bar{q}g$ 3-parton contributions (Yeh, 2008)

Enhancement of $P^c[\pi K]$ by 30%.

Should these diagrams not be part of the QCD matrix element $\langle M|\bar{q}q|0\rangle$ of the $S-P$ current?



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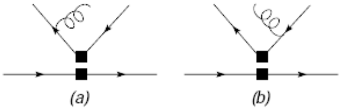
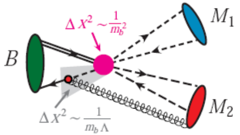


$q\bar{q}g$ 3-parton contributions to annihilation (Arnesen et al., 2007, see also talk by Rothstein)

- Unsuppressed in Λ/m_b relative to 2-parton contributions
- Calculable, no endpoint divergence.
- Numerically small relative to the dominant annihilation contribution β_3^c to P^c, even though β_3^c is a $1/m_b^2$ effect.



No effect on phenomenology.

Theoretical understanding of "endpoint divergences"

Basic problem with collinear/SCET factorization in higher orders in Λ/m_b

$$\int_0^1 \frac{du}{u^2}\,\Phi(u) = \infty, \qquad \int_0^1 \frac{du}{u}\,\Phi_p(u) = \infty, \qquad \text{etc.}$$

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- k_T-factorization (PQCD, Li et al.) does not help, unless it can be shown that there is no contribution from $k_T \sim \Lambda$ even for power corrections – unlikely!
- Rapidity factorization (Zero-bin factorization, Manohar, Stewart, 2006) does not help, until it is clarified where the subtracted contributions are really accounted for – which matrix elements?

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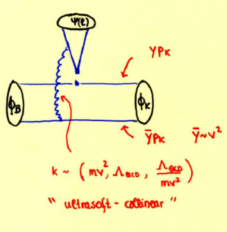
Still no theory.
Some insight from non-relativistic systems (Bell, Feldmann, 2007) especially $B \to \chi_{cJ} K$ (MB, Vernazza, 2008):

- End-point contribution corresponds to NRQCD colour-octet matrix element
- End-point divergence not related to the kaon light-cone distribution amplitude
- End-point contribution is not real. Large phase.

Sketch of spectator-scattering $B \to \chi_{cJ} K$ (MB, Vernazza)



$$A(B\to HK)_{\rm spect} = \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^* \cdot 2C_1 \cdot \frac{\pi\alpha_s C_F}{N_c^2} \langle 0|[n]|H[n]\rangle \cdot \frac{1}{\lambda_B} \cdot M_B$$

$$\int_0^1 dy\, f_K \phi_K(y) \left\{ \left[\frac{C^{8,\rm fin}[n]}{\bar{y}} + \frac{B[n]}{\bar{y}^2} \right] \theta(1-\mu-y) \right.$$

hard / P-wave colour singlet

$$\left. + \; B[n] \frac{1}{\left(b + \sqrt{-(\bar{y}+a)}\right)^4} \theta(y-(1-\mu)) \right\}$$

ultrasoft / S-wave colour octet

$$b = \frac{\delta}{m_b\sqrt{1-z}} \qquad a = \frac{4m_c E_B}{m_b^2(1-z)}$$

Endpoint div. in
hard spectator-scattering
(Song et al., 2002; Meng et al., 2005)

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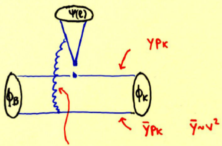

$$k \sim \left(mv^2, \Lambda_{QCD}, \frac{\Lambda_{QCD}^2}{mv^2}\right)$$

" ultrasoft - collinear "

$$A(B \to HK)_{\text{spect}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \cdot 2C_1 \cdot \frac{\pi \alpha_s C_F}{N_c^2} \langle 0 | [n] | H[n] \rangle \cdot \frac{1}{\lambda_B} \cdot M_B$$

$$\int_0^1 dy\, f_K \phi_K(y) \left\{ \left[\frac{e^{B \,\text{fin}}[n]}{\bar{y}} + \frac{B[n]}{\bar{y}^2} \right] \theta(1-\mu-y) \right.$$

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$$\left. + \; B[n] \frac{1}{\left(b + \sqrt{-(\bar{y}+a)}\right)^4} \theta(y - (1-\mu)) \right\}$$

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$$b = \frac{\gamma}{m_b \sqrt{1-z}} \qquad a = \frac{4 m_c E_B}{m_b^2 (1-z)}$$

Endpoint div. in hard spectator-scattering

(Song et al., 2002; Meng et al., 2005)

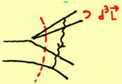
NEW

$$\int_0^1 dy\, \phi_K(y) \{ \; \} = e^{B \,\text{fin}}[n] \int_0^1 dy \frac{\phi_K(y)}{\bar{y}} + B[n] \int_0^1 dy \frac{\phi_K(y) + \bar{y} \phi_K'(1)}{\bar{y}^2} + B[n] \phi_K'(1) \ln \mu$$

$$- B[n] \phi_K'(1) \left\{ \ln \mu + \ln \frac{m_b^2 (1-z)}{\gamma^2} - i\pi - 2 \ln(1+A) + 1 + \frac{2}{3} \frac{4+A}{(1+A)^2} \right\}$$

" large log" $\ln \frac{m_b^2}{m_c^2 v^2}$: endpoint log

$$A = \sqrt{- \frac{4(E_B + i\epsilon)}{\gamma^2 / m_c}} = \mathcal{O}(1)$$



X = intermediate state above open $c\bar{c}$ threshold $D D_s, \ldots$

Large rescattering phase from endpoint contribution, none from hard scattering.

Specific decays and observables

- $B \longrightarrow PP$
  very well studied, benchmarks for theory, CKM physics and New Physics searches
- $B \longrightarrow PV, VP$
  α, penguin physics, better access to electroweak penguins [largely unexplored]
- $B \longrightarrow VV$
  Longitudinal amplitudes similar to PV, VP: α
  Polarization physics plagued by large theoretical uncertainties (Kagan, 2004; MB, Rohrer, Yang, 2006)
  Useful strategies fit (transverse) penguin amplitudes to $\Phi K^\star$ and make predictions for $\rho K^\star$ etc.
  (combine with "SU(3)" approach)

- $B \longrightarrow VA, AV$ – NEW (Cheng, Yang; 2007)
  hadronic parameters less well known
- $B \longrightarrow SP$ (Cheng, Chua, Yang; 2006)
- $B \longrightarrow SV$ – NEW (Cheng, Chua, Yang; 2007)
  hadronic parameters less well known
  quark composition of scalar mesons?
- $B \longrightarrow$ three body (see talk by Cheng)

Mode	Theory	Expt	Mode	Theory	Expt
$B^- \to f_0(980)K^{*-}$	$7.4^{+0.4+0.2+7.2}_{-0.4-0.2-2.9}$	10.4 ± 2.6	$\overline{B}^0 \to f_0(980)\overline{K}^{*0}$	$6.4^{+0.4+0.3+7.0}_{-0.4-0.3-2.6}$	$5.2 \pm 2.2 < 8.6$
$B^- \to f_0(980)\rho^-$	$1.3^{+0.1+0.4+0.1}_{-0.1-0.3-0.1}$	< 3.8	$\overline{B}^0 \to f_0(980)\rho^0$	$0.01^{+0.00+0.00+0.02}_{-0.00-0.00-0.01}$	< 1.06
			$\overline{B}^0 \to f_0(980)\omega$	$0.06^{+0.02+0.00+0.02}_{-0.01-0.00-0.02}$	< 3.0
$B^- \to K_0^{*-}(1430)\phi$	$16.7^{+6.1+1.6+52.1}_{-4.6-1.6-10.1}$		$\overline{B}^0 \to \overline{K}_0^{*0}(1430)\phi$	$16.4^{+6.1+1.6+51.6}_{-4.6-1.5-10.1}$	4.6 ± 0.9
$B^- \to \overline{K}_0^{*0}(1430)\rho^-$	$66.2^{+25.0+2.8+70.8}_{-19.5-2.4-26.3}$		$\overline{B}^0 \to K_0^{*-}(1430)\rho^+$	$51.0^{+16.1+1.4+68.6}_{-13.1-1.2-23.8}$	

Comparison of $B \to \pi\pi$ and $B \to \rho\rho$

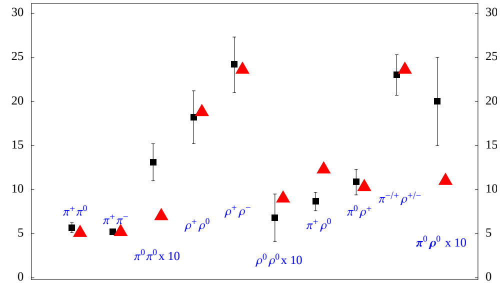
	$B \to \rho\rho$	$B \to \pi\pi$
$\lvert T\rvert/(10^{-8}\,\mathrm{GeV}^{-1})$	$4.74^{+1.29}_{-0.69}$	$2.15^{+0.58}_{-0.55}$
r_C	$0.28^{+0.24}_{-0.24}$	$0.57^{+0.34}_{-0.40}$
δ_C	$(-8^{+35}_{-42})^\circ$	$(-4^{+22}_{-23})^\circ$
r_P	$0.10^{+0.05}_{-0.06}$	$0.42^{+0.17}_{-0.15}$
δ_P	$(25^{+18}_{-38})^\circ$	$(0^{+26}_{-12})^\circ$

(update of MB, Rohrer, Yang; 2006)

$$\begin{aligned}
\sqrt{2}\,A^L_{B^-\to\rho^-\rho^0} &= (T^L + C^L)\,e^{-i\gamma} \\
A^L_{\bar{B}^0\to\rho^+\rho^-} &= T^L e^{-i\gamma} + P^L \\
-A^L_{\bar{B}^0\to\rho^0\rho^0} &= C^L e^{-i\gamma} - P^L
\end{aligned}$$

- Difference in $|T|$ reflects different smaller $f_\pi F_+^{B\pi}(0)$ vs $f_\rho F_+^{B\rho}(0)$.
- Non-universality of C/T follows from
$$\frac{C}{T} = \frac{\alpha_2 - \alpha_4^u + \ldots}{\alpha_1 + \alpha_4^u + \ldots}$$
  and the non-universality of $\alpha_4^u \sim P$ netween PP and VV.

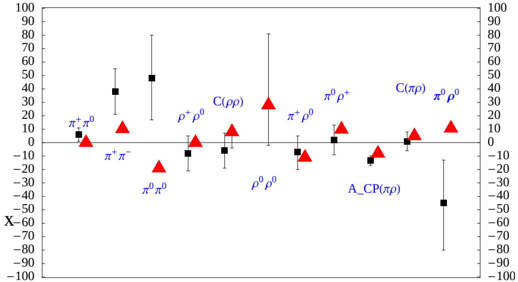
  Explains why $\mathrm{Br}(B^0 \to \rho^+\rho^-) \approx (4-5) \times \mathrm{Br}(B^0 \to \pi^+\pi^-)$ while $\mathrm{Br}(B^0 \to \rho^0\rho^0) \approx \mathrm{Br}(B^0 \to \pi^0\pi^0)$ is possible.
- $B^0 \to \rho^+\rho^-$ ideal for theory-driven determination of α, since the interfering pengion amplitude is small.
- Major discrepancy is with the BELLE value of $C(\pi^+\pi^-)$.



Comparison of tree-dominated PP, PV, VV decays with pions and ρ-mesons only.

(Triangles: theory [MB, Neubert, 2003; MB, Rohrer, Yang, 2006])

Branching fractions



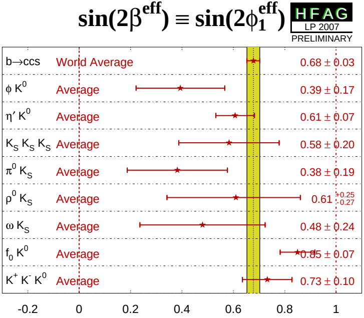
Direct CP asymmetries

$\sin(2\beta)$ from $b \to s$ transitions (MB, 2005; Cheng, Chua, Soni 2005)

(see talk by Chua)

No new theoretical result from QCD factorization:
$\Delta S_f \equiv S_{f(b\to s)} - \sin(2\beta)_{J/\psi K_S}$ is small and positive except for ρK_S and ηK_S.
(Numbers are an update from MB, 2005)

Mode	ΔS_f (Theory)	ΔS_f [Range*]
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$[+0.03, 0.13]$
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.01]$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$	$[+0.00, 0.03]$
ηK_S	$0.10^{+0.11}_{-0.07}$	$[-0.76, 0.27]$
ϕK_S	$0.02^{+0.01}_{-0.01}$	$[+0.01, 0.05]$
ωK_S	$0.13^{+0.08}_{-0.08}$	$[+0.02, 0.21]$



* from a random scan of $2 \cdot 10^5$ input parameter sets and requiring that experimental branching fractions are reproduced within $\pm 3\sigma$

$B \to \pi K$ ratios and asymmetries

Construct ratios with little dependence on γ, but sensitive to electroweak penguins.
Difference in CP asymmetries in final states with charged kaons.

$$R_{00} = \frac{2\Gamma(\bar{B}^0 \to \pi^0 \bar{K}^0)}{\Gamma(B^- \to \pi^- \bar{K}^0)} = |1 - r_{\rm EW}|^2 + 2\cos\gamma\,\mathrm{Re}\,r_C + \ldots$$

$$R_L = \frac{2\Gamma(\bar{B}^0 \to \pi^0 \bar{K}^0) + 2\Gamma(B^- \to \pi^0 K^-)}{\Gamma(B^- \to \pi^- \bar{K}^0) + \Gamma(\bar{B}^0 \to \pi^+ K^-)} = 1 + |r_{\rm EW}|^2 - \cos\gamma\,\mathrm{Re}(r_T\, r_{\rm EW}^*) + \ldots$$

$$\delta A_{\rm CP} = A_{\rm CP}(\pi^0 K^\pm) - A_{\rm CP}(\pi^\mp K^\pm) = -2\sin\gamma\Big(\mathrm{Im}(r_C) - \mathrm{Im}(r_T\, r_{\rm EW})\Big) + \ldots$$

theory: $r_{\rm EW} \approx 0.12 - 0.01i, \quad r_C \approx 0.03[\times 2?] - 0.02i, \quad r_T \approx 0.18 - 0.02i$

	theory	data
R_{00}	0.79 ± 0.08	0.92 ± 0.07
R_L	1.01 ± 0.02	1.07 ± 0.05
$\delta A_{\rm CP}$	0.03 ± 0.03	0.14 ± 0.03

Same for ρK etc.?

No qualitative change since 2006:

- Enhancement of $|C/T|$ (or smaller $\mathrm{Br}(\pi^0 K^0)$) helps for ratios.
- No significant evidence for anomaly in electroweak penguins from ratios.
- $\delta A_{\rm CP}$ difficult to explain. Would need very large and imaginary colour-suppressed tree or electroweak penguin. Not possible in SM + factorization.

Conclusion

- New final states are being explored.
- Calculations of radiative corrections are proceeding to NNLO: important to complete the calculation of the QCD penguin amplitude.
- Theoretical understanding of power corrections crucial for further progress – perhaps too hard.
- No qualitative changes in data and theory since FPCP 2007.