Hadronic B decays

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BEAUTY 2006, Oxford, September 26, 2006

- Theory of hadronic decays
  - Summary and comparison of different frameworks
  - New higher-order calculations
  - Power corrections

- Confronting data
  - Global comparison
  - $\pi\pi$, πK after ICHEP06
  - PP vs. PV and the usefulness of S
  - B$\rightarrow$ VV: polarization and a QED surprise

Hadronic B decays - $B \to M_1 M_2$ (2-body, mesons P or V, charmless)

- large variety of transitions :
  flavour
  Dirac structure ($V \mp A$, ...)

Determine CKM parameters

New Physics could be flavour-specific

- SM :

$$\mathcal{L}_{eff} = - \frac{G_F}{\sqrt{2}} \sum_i CKM \cdot O_i$$

weak interactions for $\mu \ll M_W$
+ QCD + QED

Challenge of strong interaction

$\langle M_1 M_2 | O_i | \bar{B} \rangle$

SU(3) [isospin]
$\hat{=}$ graphical amplitudes T, C, P, ...

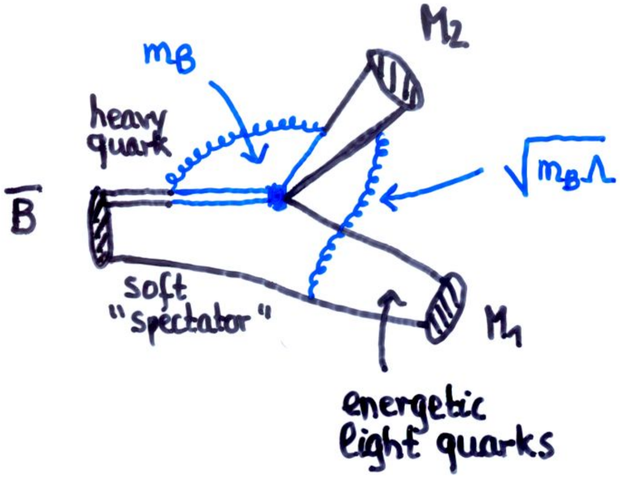
[Zeppenfeld (1981),
...
Chau (1991),
Gronau et al. (1994)
⋮]

Factorization
($1/m_b$ exp.)

[Bauer, Stech, Wirbel (1985),
.....
from QCD: MB, Buchalla, Neubert, Sachrajda (1999)
⋮]

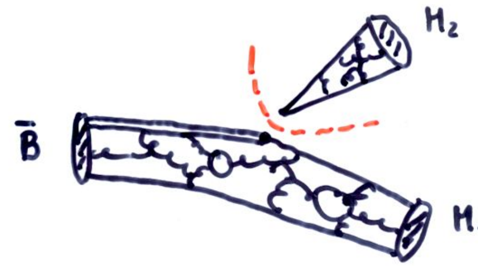
Theory of hadronic decays (factorization)

Scales and factorization



Factorization utilizes the heavy quark and collinear expansion $(\Lambda/m_b, \Lambda/E)$

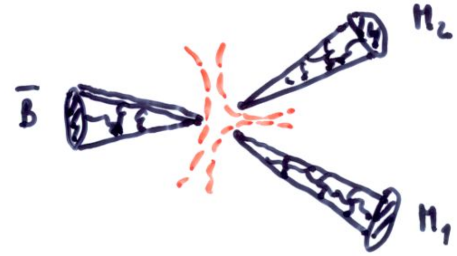
Want to show – at leading order in $1/m_b$ – that the long-distance contributions look like



$\langle M_2 | .. | 0 \rangle$

$\langle M_1 | .. | \bar{B} \rangle$

or even



$\langle M_1 | .. | 0 \rangle$

$\langle M_2 | .. | 0 \rangle$

$\langle 0 | .. | \bar{B} \rangle$

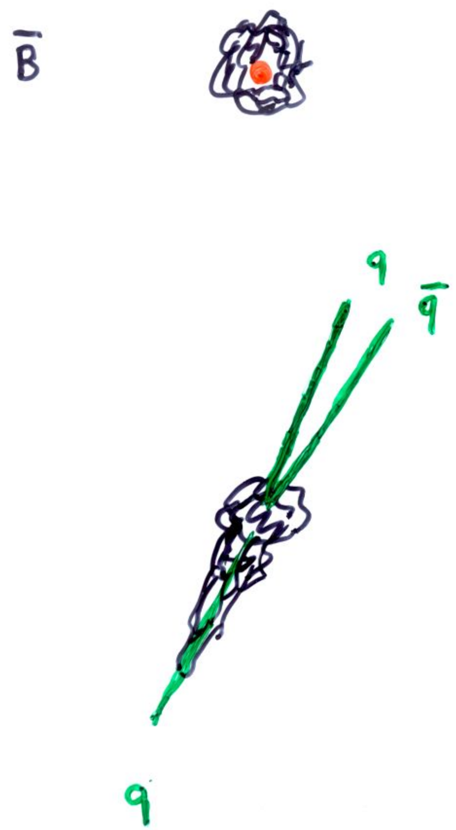
Scales (M_W integrated out)

m_b	hard	for large m_b α_s is small at these scales $\longrightarrow$ perturbation theory applies!
$\sqrt{m_b \Lambda}$	hard-collinear	
Λ	soft or collinear	

↑

long-distance

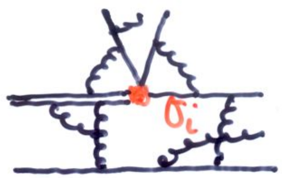
Factorization works (at leading power in $1/m_b$), because .....



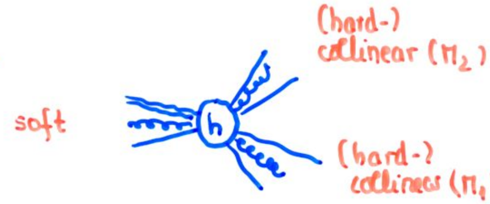
... energetic, low-invariant mass colour-singlet ($\to$ compact) escapes $\bar{B}$ remnant and hadronizes far away <u>independent</u> from the hadronization of q + remnant

Integrating out the scale m_b [QCD → SCET$_\mathrm{I}$]

(BBNS ; Chay, Kim ; MB, Feldmann, Bauer et al.)



Which hard subgraphs



are leading ?

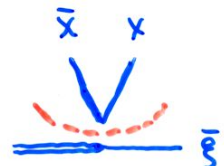
Result:

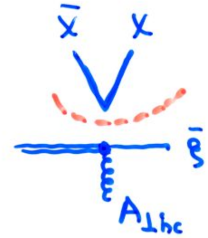
Correction to naive fact.

New effect: spectator scattering

$$(\bar u b)(\bar d u) \longrightarrow \Big[\overset{\bar d}{\bar\chi^{(0)}_{(t n_-)}}\,\overset{u}{\chi^{(0)}}\Big] * \Big(C^{\mathrm{I}} * \big[\overset{\bar u}{\bar\xi}(s n_+)\,\overset{b}{h_v}\big] + C^{\mathrm{II}} * \big[\bar\xi(s_1 n_+) A_\perp(s_2 n_-) h_v\big] \Big)$$

ϕ_{M_2} $\qquad$ $\xi(0)\ \big[F^{BM_1}_{(0)}\big]$ $\qquad$ $\Xi(\tau;0)$





- M_2 factorizes at scales $\mu < m_b$
- Strong phases in perturbative coefficient functions $C^{\mathrm{I,II}}$ ONLY
- Leaves out $1/m_b$ corrections (see below)

Comparison of different approaches / implementations

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \Big(\underbrace{T^I}_{①} \cdot \underbrace{F^{BM_1}_{(0)}}_{②} + \underbrace{H^{II}}_{③} * \underbrace{\Xi^{BM_1}_{(\tau,0)}}_{④} \Big) * \phi_{M_2}$$

	①	②	③	④
PQCD (Keum, Li, Sanda, 2000)	$\alpha_s^0 + \boxed{\alpha_s^1}$ '00 '05 New - see below	calculated ($k_\perp$ - fact.)	α_s^0 '00	calculated (α_s^1) '00
QCDF / SCET				
BBNS (1999)	$\alpha_s^0 + \alpha_s^1$ naive fact. '99	input	$\alpha_s^0 + \boxed{\alpha_s^1}$ '99 '05, '06 New - see below	calculated ($\alpha_s^1 + \alpha_s^2$) '99 '04
BPRS (Bauer et al., 2004)	α_s^0 (naive fact)	fit to data	α_s^0 (from BBNS)	fit to data

(BPRS approach cannot be improved beyond leading order in α_s, because in general $\Xi(\tau)$ is an unknown function; does not require perturbation theory at $\sqrt{m_b \Lambda}$)

The charming penguin saga

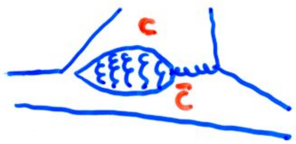
Ciuchini et al. (2001)

Large $1/m_b$ corrections from  or  (annihilation) to P^c

No theoretical arguments given.

$\hookrightarrow$ must be investigated by comparing calculations at leading power with data

BPRS



non-relativistic $c\bar{c}$ enhancement violates factorization at leading power

I believe this is wrong : $c\bar{c}$ threshold not relevant when integrated over smoothly; in any case there is always a Λ/m_b factor for the long-distance contribution

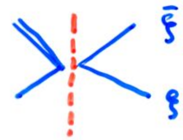
$\Rightarrow$ BPRS treat penguin amplitude P^c as complex fit parameter – one for every SU(2) multiplet.

$\rightarrow$ No CP asymmetry can be predicted from theory alone

Since also C, T are fitted (ϱ, Ξ) and $\arg(C/T)$ is set to zero, this approach has more in common with amplitude fits (like SU(3)) than with QCD / SCET calculations

Integrating out the scale $\sqrt{m_b \Lambda}$ ($SCET_I \to SCET_{II}$ matching)

$$\Xi \sim \langle M_1 | \bar{\xi} \not{A}_\perp h_v | \bar{B} \rangle = J * \phi_{B(\omega)} * \phi_{M_1}$$



J contains hard-collinear spectator interactions

$\Rightarrow$

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = F^{BM_1}_{(0)} \cdot T_i^{I} * \phi_{M_2} + \phi_B * \left[H_i^{II} * J \right] * \phi_{M_1} * \phi_{M_2}$$
$$+ \text{ power corrections}$$

(BBNS, 99)

Remarks

- establishes factorization, but often input parameters are not known with satisfactory accuracy, in particular

$$F^{BM_1}_{(0)}, \quad m_s, \quad \lambda_B^{-1} \equiv \int \frac{d\omega}{\omega} \phi_{B(\omega)}$$

so far philosophy was <u>not</u> to fit these to data

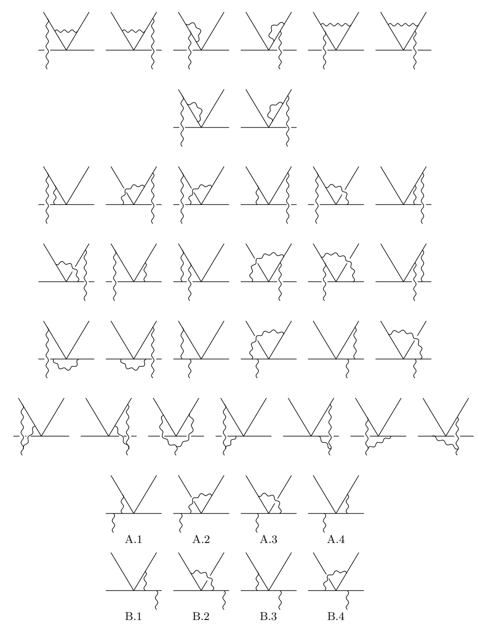
- there are important $1/m_b$ effects (see below)

New higher-order calculations

QCDF: NLO (α_s^2) spectator scattering

$$T_i^{\mathrm{II}} = H_i^{\mathrm{II}} \star J$$

- 1-loop J
  (Becher, Hill, Lee, Neubert 2004; MB, Yang 2005; Kirillin 2005)
  1-loop H^{II} tree amplitudes
  (MB, Jäger 2005; Kivel 2006 [error?])
  1-loop H^{II} penguin amplitudes
  (MB, Jäger 2006) [QCD penguin also: Li, Yang, 2005, but errors]



- Main results:
  - Perturbation theory well-behaved
  - Sizeable enhancement of the colour-suppressed tree amplitude (good!)
  - Negligible correction to QCD penguin amplitude (disappointing!)

Tree amplitudes and $\pi\pi$ branching fractions with NLO spectator scattering

- Requires smallish

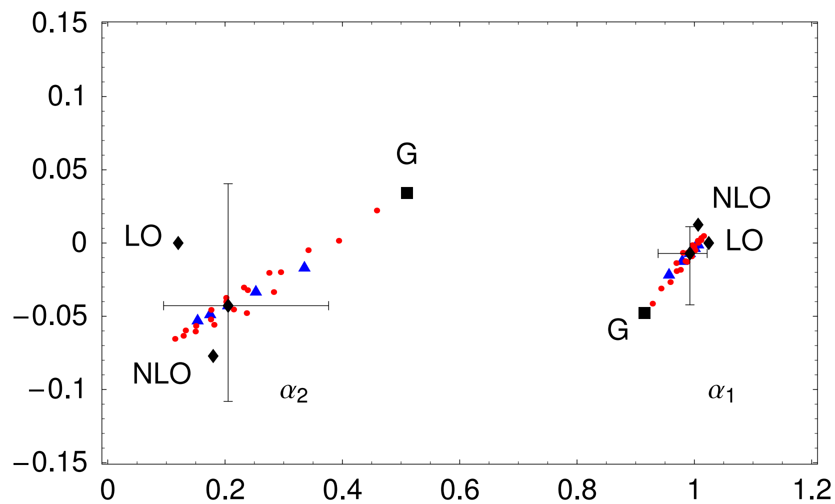
$$|V_{ub}|\, f_+^{B\pi}(0) = 8.1 \cdot 10^{-4}$$

and larger $f_B/(f_+^{B\pi}(0)\lambda_B)$ than expected. λ_B small?

-

$$C/T = \alpha_2/\alpha_1 = 0.55 + 0.07i$$

- $\pi^-\pi^0$, $\pi^+\pi^-$ are ok, $\pi^0\pi^0$ still somewhat low
- $A_{\rm CP}(\pi^+\pi^-) = 0.39 \pm 0.19$ remains a problem (see below)



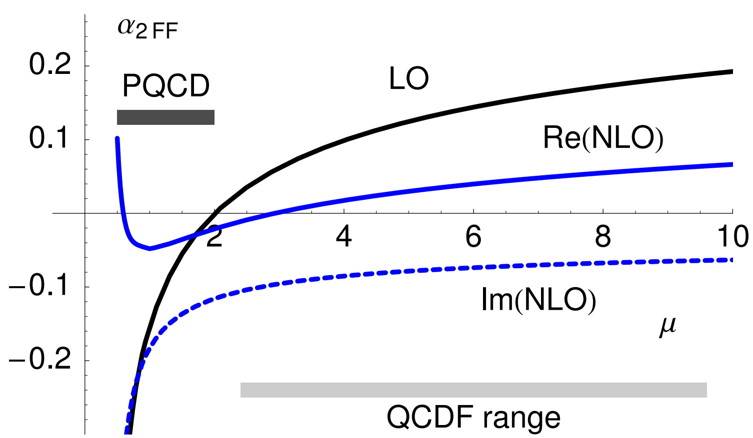
(MB, Jäger, 2005)

10^6 Br$_{\rm Av}$	Theory (NLO$_{\rm sp}$)	Exp.
$\pi^-\pi^0$	$5.5^{+0.3}_{-0.3}$(CKM)$^{+0.5}_{-0.4}$(hadr.)$^{+0.9}_{-0.8}$(pow.)	5.7 ± 0.5
$\pi^+\pi^-$	$5.0^{+0.8}_{-0.9}$(CKM)$^{+0.3}_{-0.5}$(hadr.)$^{+1.0}_{-0.5}$(pow.)	5.2 ± 0.2
$\pi^0\pi^0$	$0.73^{+0.27}_{-0.24}$(CKM)$^{+0.52}_{-0.21}$(hadr.)$^{+0.35}_{-0.25}$(pow.)	1.31 ± 0.21

PQCD: (partial) NLO (Li, Mishima, Sanda, 2005)

- First NLO corrections (partially) included using vertex and penguin kernels from BBNS (1999).
- Same diagrams, but very different numbers.
  Consider colour-suppressed tree amplitude: large negative correction in BBNS, but huge enhancement in LMS: $C_{\pi\pi} = 0.8e^{2.6i} \longrightarrow 4.3e^{-1.1i}$
- What is going on?

$$a_{2\mathrm{FF}}(\mu) = C_2 + \frac{C_1}{N_c} + \underbrace{\frac{\alpha_s C_F}{4\pi}\frac{C_1}{N_c}\left[12\ln\frac{m_b}{\mu} - \frac{37}{2} - 3i\pi\right]}_{\text{NLO correction (asymptotic LCDA)}}$$



- Wilson coefficients are evaluated at scales down to 500 MeV. This is conceptually incorrect. Running stops around m_b.
- Correction is evaluated at scales, where perturbation theory breaks down. Numerics is unstable against including higher-order corrections. No scale variations are included in theoretical errors.
- I believe this is a general problem of the PQCD approach and therefore – despite its phenomenological successes – do not consider it as a theoretical framework on the same footing as QCDF/SCET.

$1/m_b$-suppressed effects

Most important $1/m_b$ effect : scalar QCD penguins

$$P^c_{\pi\pi} \sim \underbrace{\underset{\text{V-A}}{a_4} + \underset{\substack{\text{operators}\\\text{that Fierz}\\\text{to S-P}}}{r_\chi a_6} + \underset{\substack{\text{penguin}\\\text{annihilation}}}{\beta_3}}_{} \approx \underbrace{\overset{a_4}{[-0.03-0.01i]} + \overset{r_\chi a_6}{[-0.07-0.01i]}}_{\text{calculable}} + \underbrace{\overset{\beta_3}{[-0.01-0.02\, e^{i\cdot\text{any}}]}}_{\text{model parameter } (\rho_A)}$$

$$\underbrace{r_\chi a_6 + \beta_3}_{1/m_b\text{ - suppressed}}$$

- Strict $1/m_b$ expansion is a phenomenological disaster!
- a_6 is fortunately calculable.

  [confirmed - roughly - by data :

PP	$a_4 + r_\chi a_6$
PV	$\approx a_4$
VP	$a_4 - r_\chi a_6$

  ]
- Still need to understand whether a_6 factorizes to all orders. Probably not, but the effect may be small (MB, Neubert)

Weak annihilation

Several annihilation amplitudes : $\underbrace{\beta_1, \beta_2}_{\text{tree}}$, $\underbrace{\beta_3, \beta_4}_{\text{QCD penguin}}$, ...

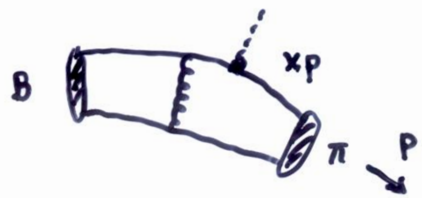
So far no unambiguous <u>empirical</u> evidence that any β_i is relevant at all for charmless decays :

- Some extra contribution to P^c required in QCDF and PQCD , but cannot separate a_6 from β_3 in data
- Constraints from $B \to KK$ only imply that β_i cannot be very large

Theory frameworks	PQCD	BBNS	BPRS	QCD sum rules
	calculable ; large	modelled ; not very large	neglected	calculable ; not very large
	but effect is artificially enhanced by evaluating Wilson coefficients at low scale	makes A_{CP} somewhat model-dependent	except for β_3 fitted with P^c	(Khodjamirian et al. , 2005)

Why does factorization usually not work for power corrections ?

Actually for $B \to \pi$ form factor does not even work at leading power (Brodsky et al.)



$$\supset \int_0^1 dx \, \frac{\phi_\pi(x)}{(1-x)^2} \sim \int_0^1 \frac{dx}{1-x} = \infty$$

Factorization was derived under the assumption that quarks in π are energetic, but the result shows that the dominant contribution arises when the $\bar{q}$ is soft $(x \to 1)$

- $k_\perp$ - factorisation in PQCD makes integrals convergent, but does not imply that soft contribution can be neglected

- Up to now no regularisation and factorization scheme for endpoint singularities is known.

Recently proposal to implement this in SCET (Manohar, Stewart, 2006)
Illustrate for weak annihilation (Arnesen et al., 2006)

$$\supset \quad \alpha_s \int_0^1 dx \, \frac{\phi_{M_2}(x)}{(1-x)^2} \xrightarrow[\substack{\text{expression} \\ \text{with } x=1 \\ \text{region subtracted}}]{\text{replaced by}} \alpha_s \int_0^1 dx \, \frac{\phi_{M_2}(x)}{[1-x]^2_{\not{0}}} \equiv \alpha_s \int_0^1 dx \, \frac{\phi_{M_2}(x) + \bar{x}\, \phi'_{M_2}(1)}{\bar{x}^2}$$

$$- \phi'_{M_2}(1) \cdot \alpha_s \ln \frac{m_B}{\mu_-}$$

convergent

some kind of cut-off "zero-bin"

new cut-off! scale-dependence

compare BBNS

$$\alpha_s \int_0^1 dx \, \frac{\phi_{M_2}(x) + \bar{x}\, \phi'_{M_2}(1)}{\bar{x}^2} + 6\,(1 + \rho_A e^{i\phi_A}) \cdot \alpha_s \ln \frac{m_B}{\Lambda_{QCD}}$$

phenomenological model

Arnesen et al. set $\mu_- = m_b$, but $\alpha_s \ln \frac{m_B}{\mu_-}$ should be interpreted as $\mathcal{O}(1)$.
μ_- dependence is not consistently cancelled in this framework.
$\phi'(1)\,\alpha_s \cdot \log$ should be identified with a yet undefined non-perturbative object.

I do not see how "zero-bin" factorization could possibly be correct. More work needed on this very important (and general) problem of endpoint factorization. Prerequisite for further studies in soft-collinear effective theory. (Feldmann, Hurth, 2004)

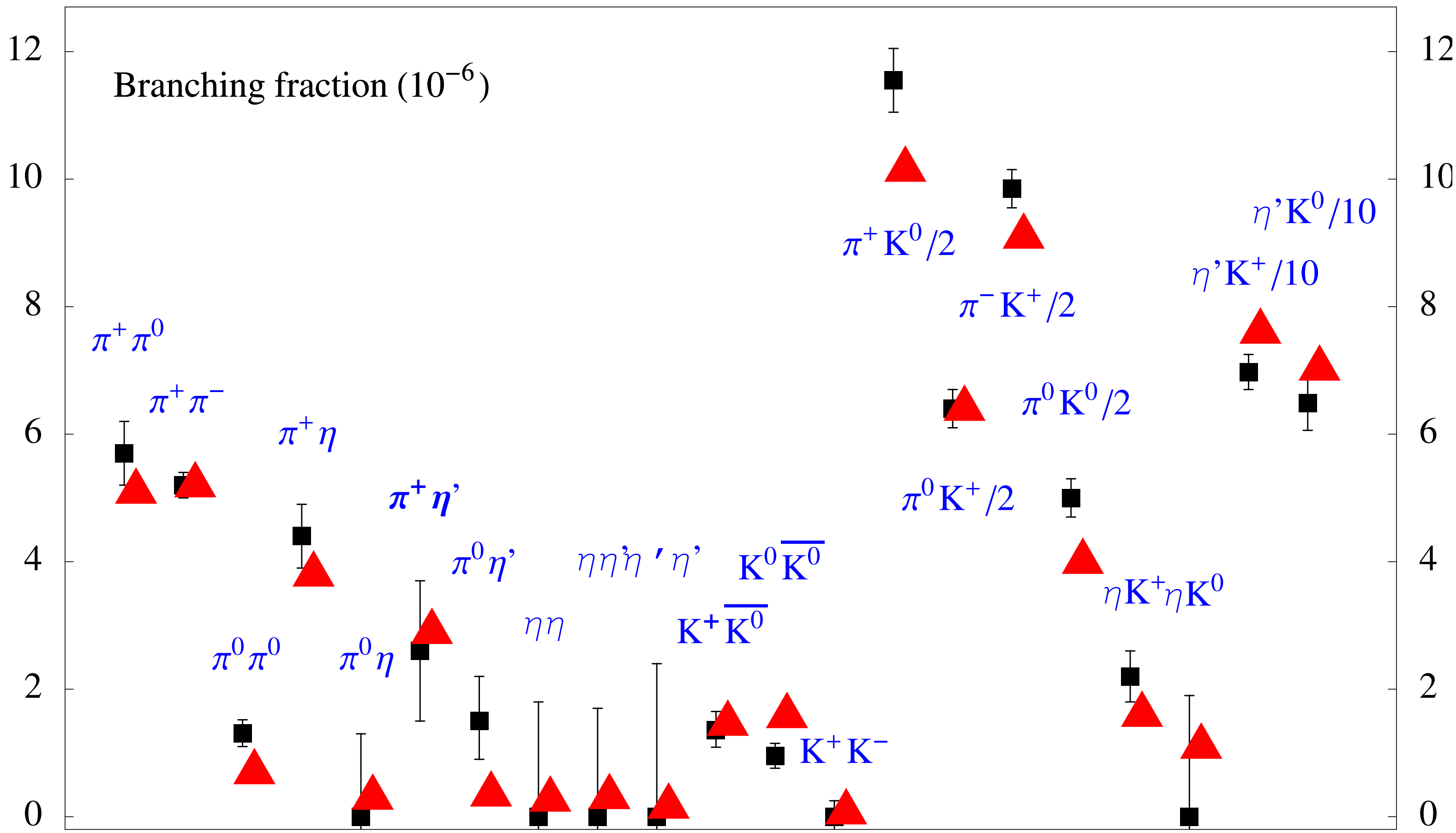
Confronting data: global comparison

Results for many modes available from the BBNS (BBNS, 2001; Du, Yang, Zhu, 2002; MB, Neubert, 2003), PQCD (Li and collaborators, 2000ff) and the BPRS approach. (Bauer, Rothstein, Stewart, 2005; Williamson, Zupan, 2006)
Apologies for not collecting all (too difficult – scattered over many papers [PQCD] or output changes with new data [BPRS]).
Here show QCDF results and focus on global features which I believe are common to all.

- Br, $A_{\rm CP}$ and some S-parameters calculated for all 96 $B_{u,d,s} \longrightarrow PP, PV$ decays at NLO. (MB, Neubert, 2003)

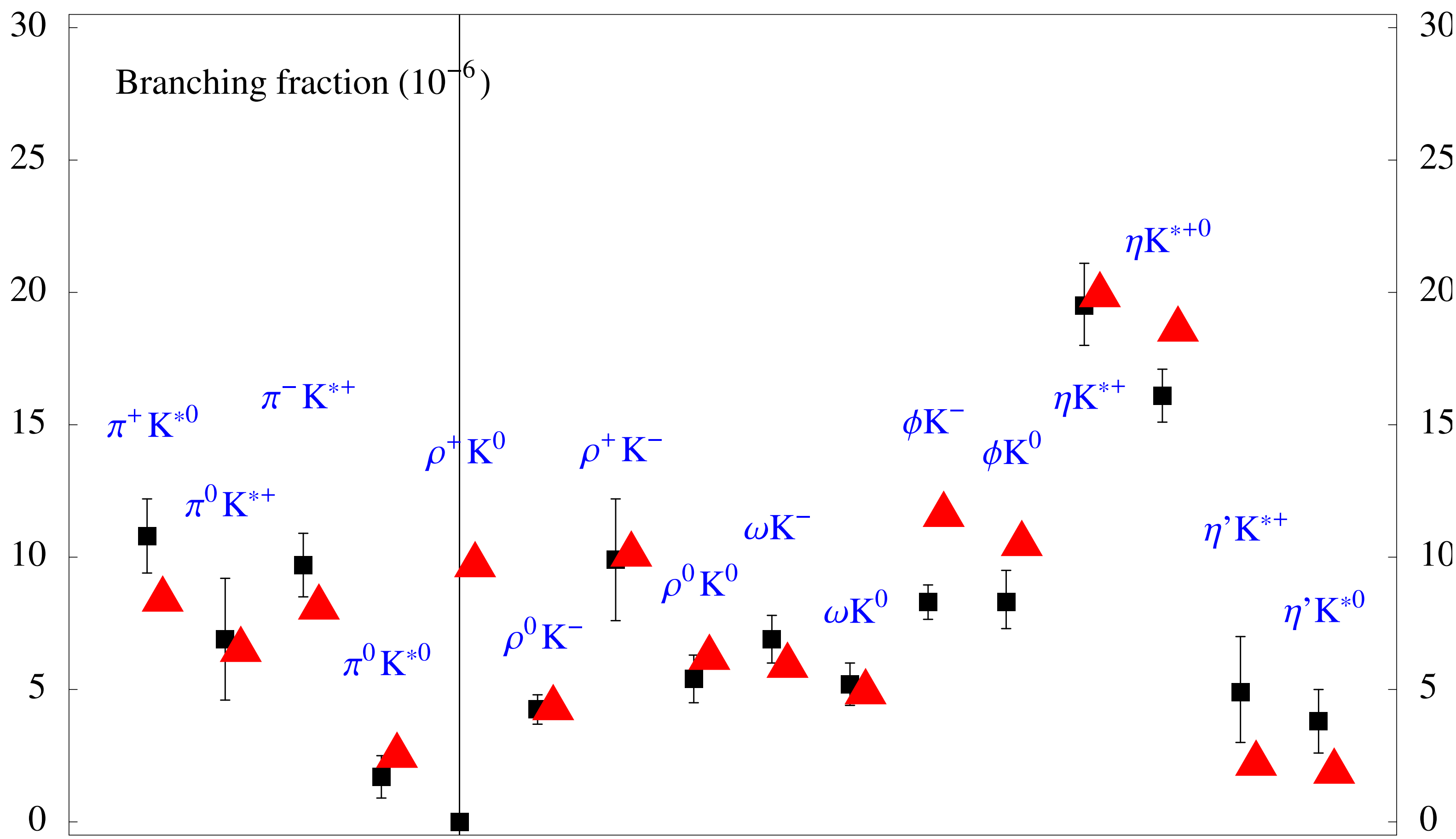
- Noted that smaller $B \longrightarrow \pi$ form factor, small λ_B and some penguin annihilation contribution to P^c provided a globally better description of the data $\longrightarrow$ defines 'scenario' S4.

- Not a fit.
  Still very successful. No update since 2003, but many new data points.



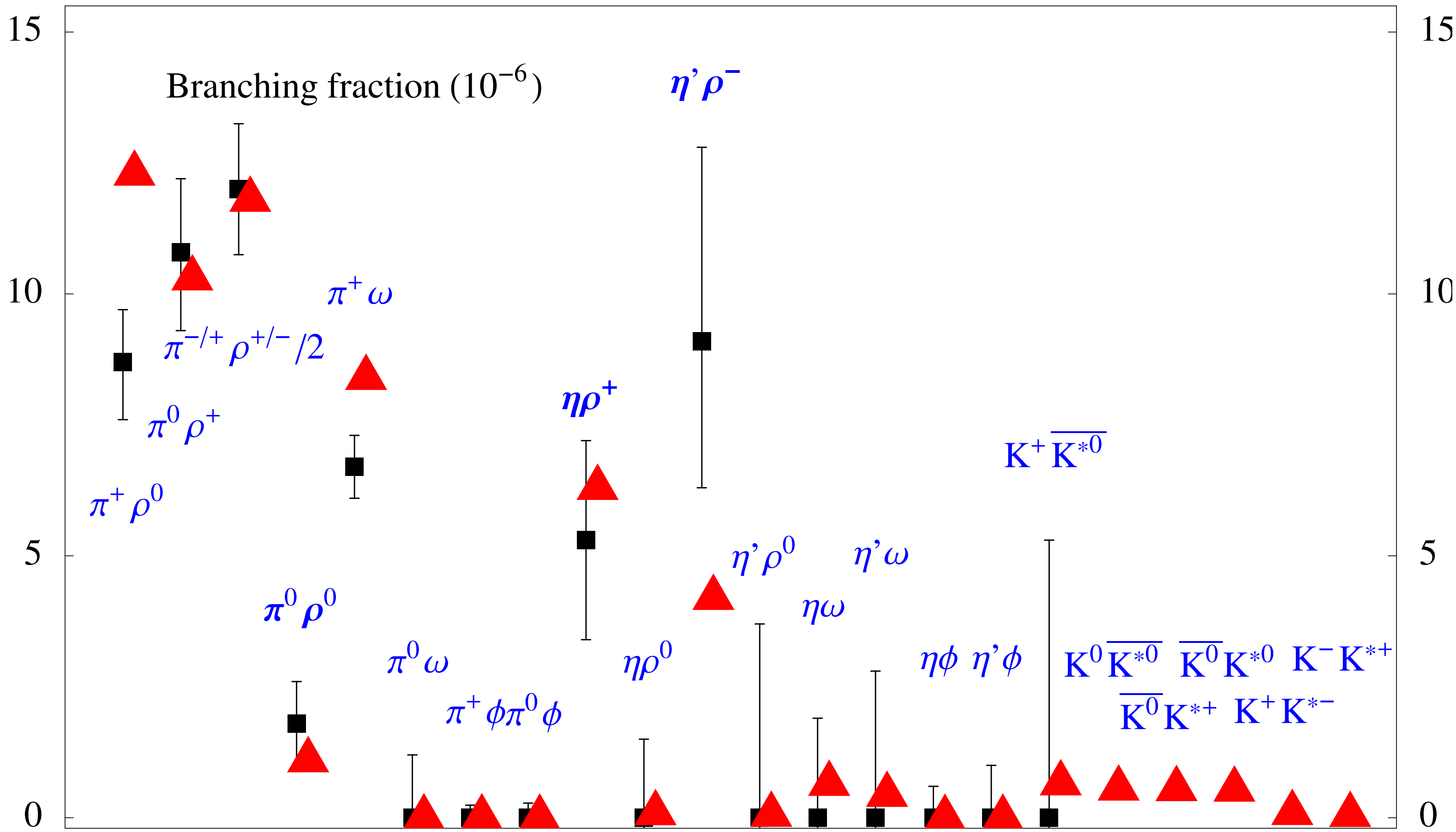
CP-averaged $B \to PP$ branching fractions.

Red triangles: Theory (S4) from MB, M. Neubert, Nucl. Phys. B675 (2003) 333.



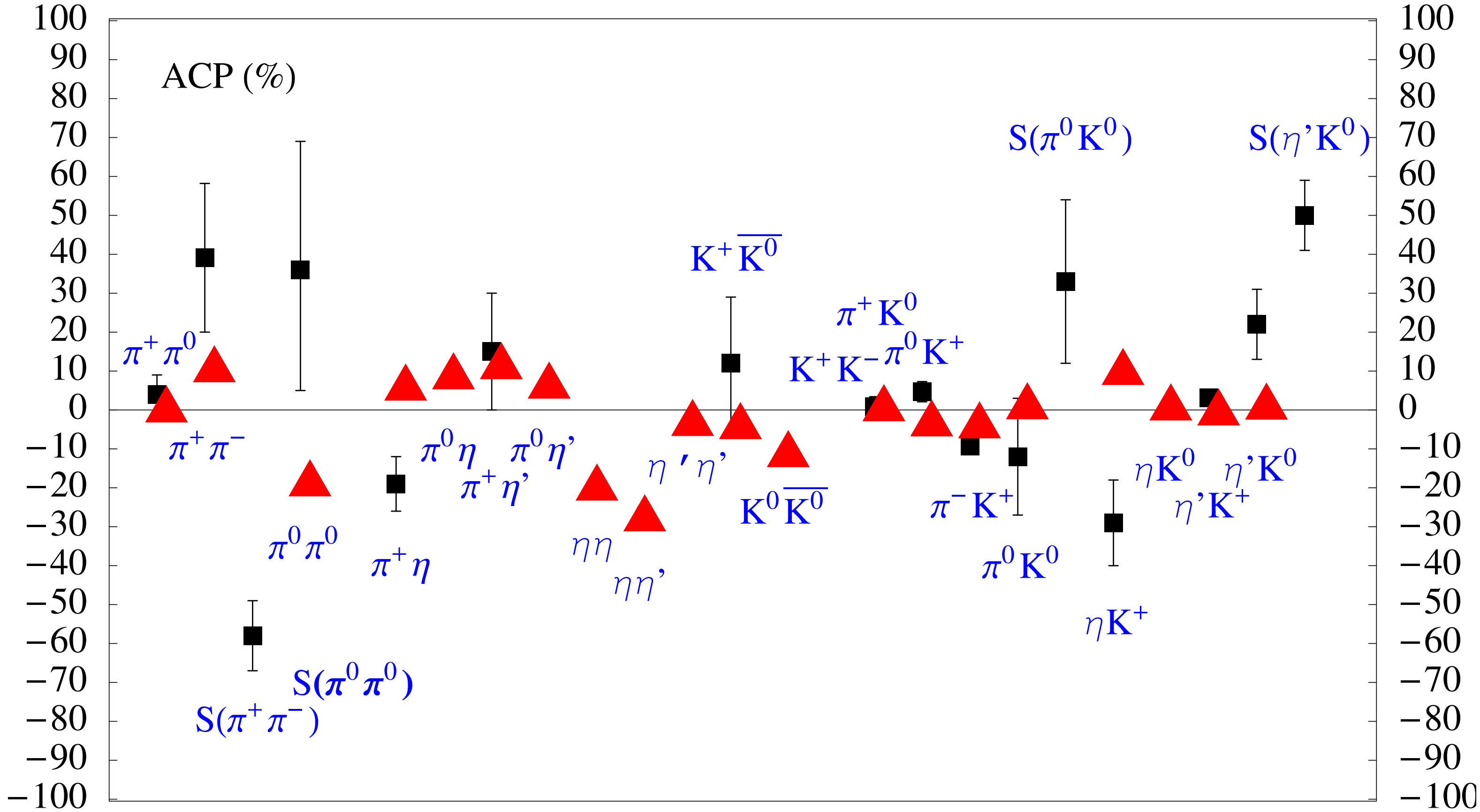
CP-averaged $\Delta S = 1$ $B \to PV$ branching fractions.

Red triangles: Theory (S4) from MB, M. Neubert, Nucl. Phys. B675 (2003) 333.



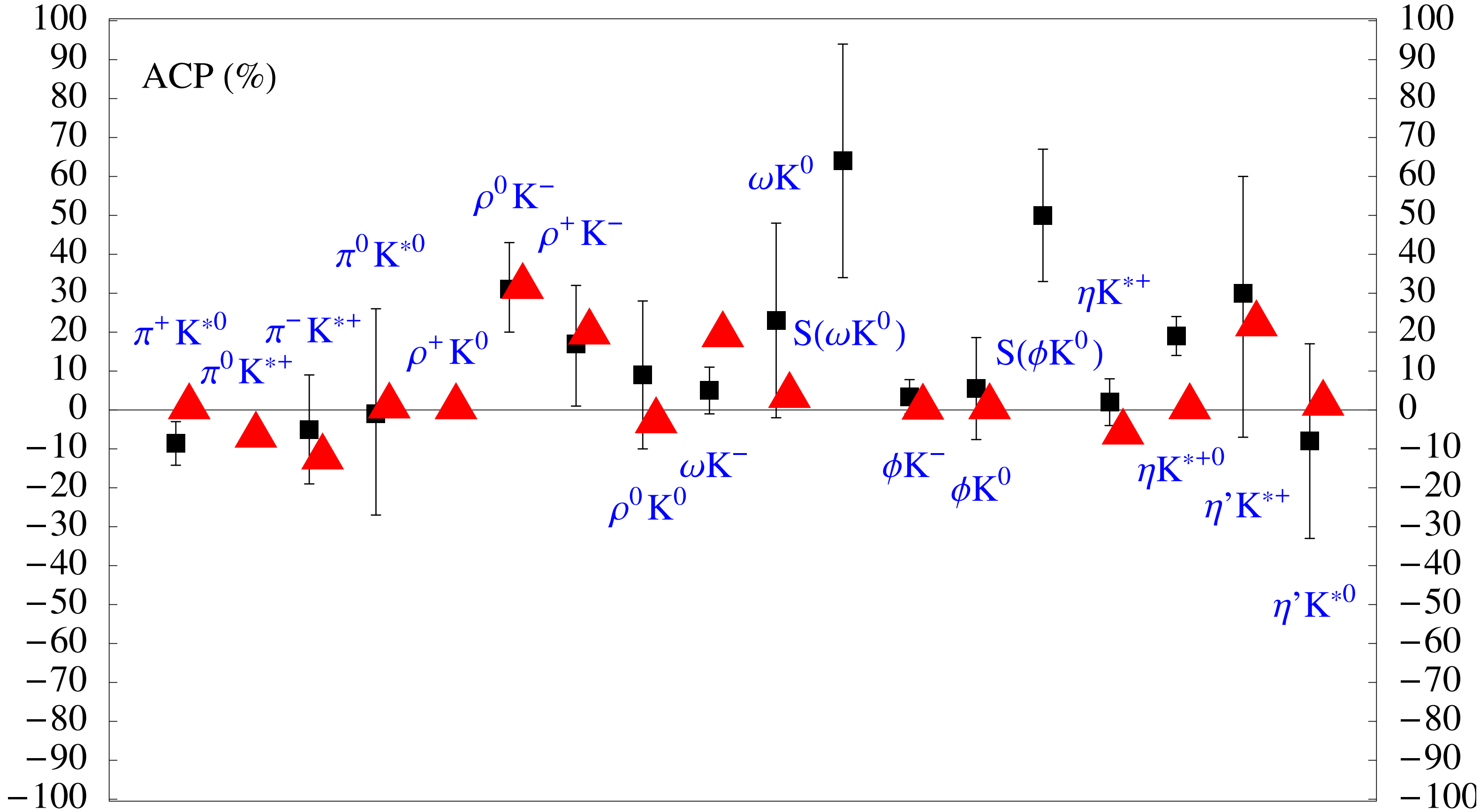
CP-averaged $\Delta S = 0$ $B \to PV$ branching fractions.

Red triangles: Theory (S4) from MB, M. Neubert, Nucl. Phys. B675 (2003) 333.



$B \to PP$ CP asymmetries.

Red triangles: Theory (S4) from MB, M. Neubert, Nucl. Phys. B675 (2003) 333.



$\Delta S = 1$ $B \to PV$ CP asymmetries.

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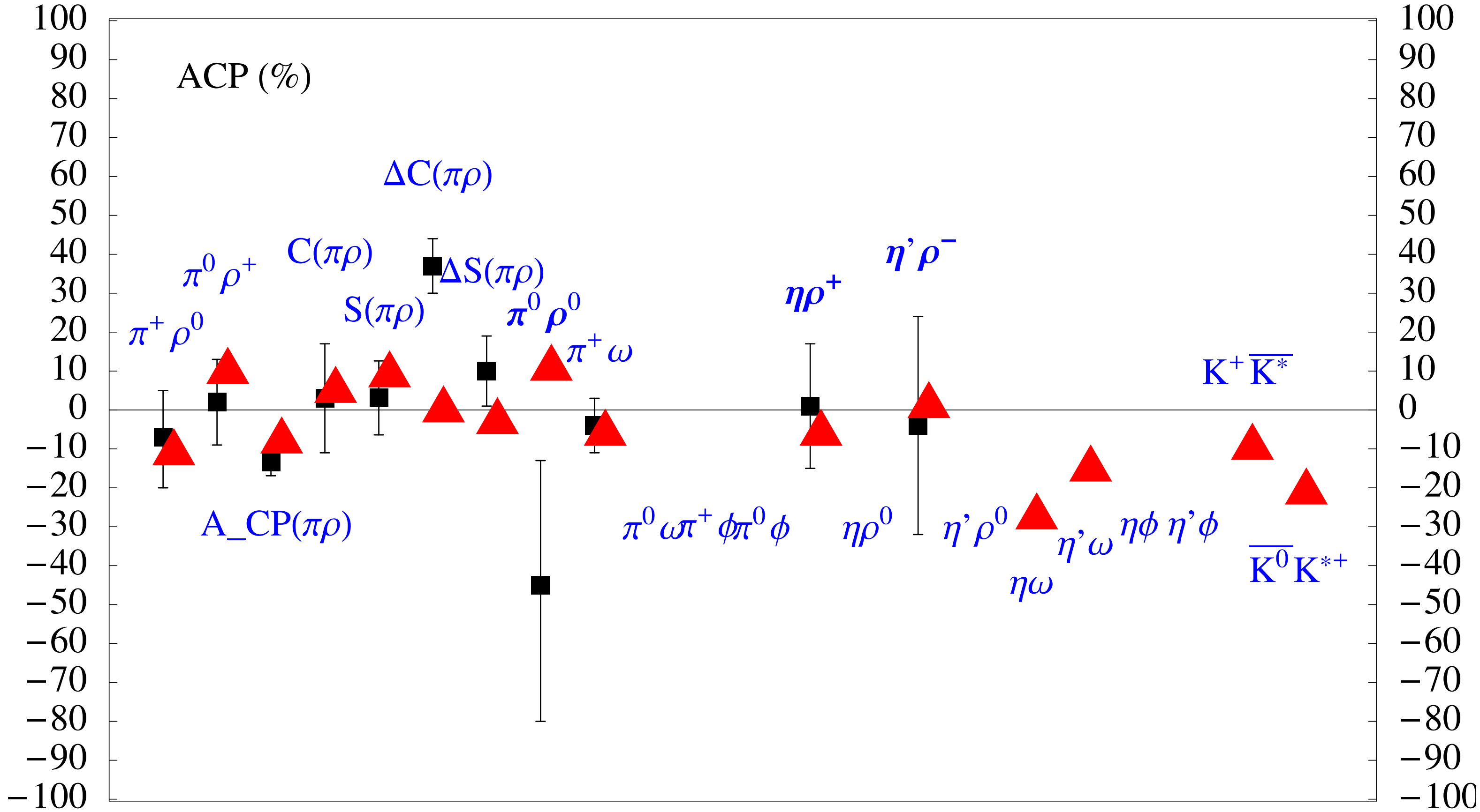


$\Delta S = 0$ $B \to PV$ CP asymmetries and $\Delta C_{\pi\rho}$, $\Delta S_{\pi\rho}$.

Red triangles: Theory (S4) from MB, M. Neubert, Nucl. Phys. B675 (2003) 333.

Summary of the global comparison

- Hierarchy of branching fractions ranging from $1 \cdot 10^{-6}$ to $70 \cdot 10^{-6}$ $(\eta' K)$ is well predicted/reproduced.

- Direct CP asymmetries are generally found small in agreement with expectations. Some predictions are quantitatively very good ($\pi\rho$, ρK, πK^* vs πK, $\eta' K^*$), but there are also serious discrepancies ($\pi^+\pi^-$, $\pi^+ K^-$, $\pi^+\eta$, ηK).
  Expect all kinds of corrections to be more important for direct CP asymmetries, because leading terms starts with α_s.

- Devil is in details difficult to see in the global comparison: the $\pi^0\pi^0$ rate, the $\pi^+ K^-$ and $\pi^+\pi^-$ CP asymmetry, ...

  Also required annihilation with strong phase to improve the comparison – some model-dependence!

Confronting data: selected topics

The $B \to \pi K$ puzzle (Yoshikawa; Gronau, Rosner; MB, Neubert; Schwab et al. 2003) – after ICHEP06

Construct ratios with little dependence on γ, but sensitive to electroweak penguins.

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

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

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

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 [old]
R_{00}	0.79 ± 0.08	0.93 ± 0.07 [1.04]
R_L	1.01 ± 0.02	1.06 ± 0.05 [1.12]
$\delta A_{\rm CP}$	0.03 ± 0.03	0.14 ± 0.03 [0.15]

- $\delta A_{\rm CP}$ seems to require large enhancement of the colour-suppressed tree amplitude (r_C).
  The required enhancement is out of reach in factorization.
- Ratios now closer to expectations. Enhancement of EW $b \to s$ penguin amplitude no longer compelling.
- Smaller Br($\pi^0 K^0$) would make the R-ratios fit better.

The $\pi\pi$ final states ...

... pose problems to the factorization approaches.

- Direct CP asymmetry $A_{\rm CP}(\pi^+\pi^-) = 0.39 \pm 0.19$

  Magntiude of P/T appears to be in good agreement with data.
  Phase too small to be near the experimental value.
  But recall Babar measures $0.16 \pm 0.11 \pm 0.03$ vs. Belle $0.55 \pm 0.08 \pm 0.05$.

- Br$(\pi^0\pi^0) = (1.31 \pm 0.21) \cdot 10^{-6}$

  Indicates large C/T.
  LO (naive factorization): $0.1 \cdot 10^{-6}$
  NLOsp with small λ_B: $\approx 0.7 \cdot 10^{-6}$
  but $1.3 \cdot 10^{-6}$ only by pushing parameters to the extreme.

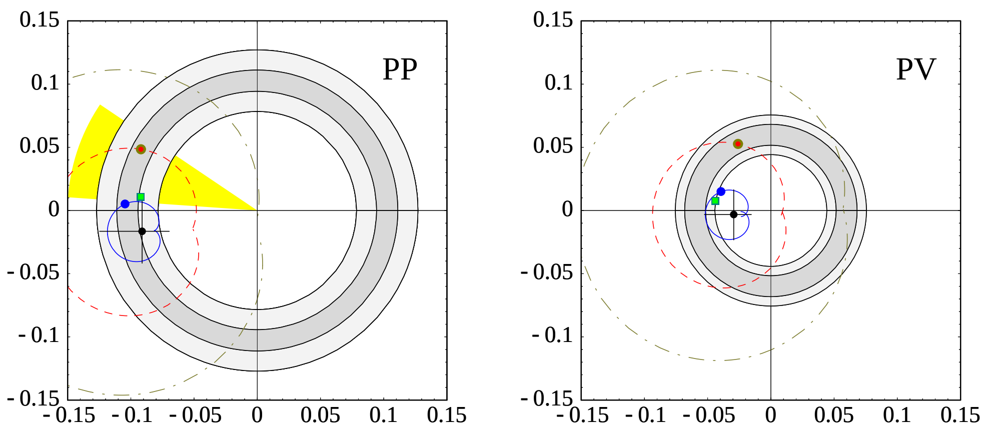
$$C \sim \alpha_2(\pi\pi) = 0.184 - [0.153 + 0.077i\,]_V + \left[\frac{r_{\rm sp}}{0.485}\right] \Big\{[0.122]_{\rm LO} + [0.050 + 0.053i\,]_{\rm NLO} + [0.071]_{\rm tw3}\Big\}$$

$$= 0.27 - 0.02i \quad \rightarrow \quad 0.52 + 0.03i \quad (\text{if } 2 \times r_{\rm sp}) \qquad \Big[r_{\rm sp} = 9 f_\pi \hat{f}_B / (m_b f_+^{B\pi}(0) \lambda_B)\Big]$$

Spectator-scattering is essential.

What do we learn (about factorization) from PV?

No helicity information ($\rightarrow$ VV)
Main difference is hierarchy of QCD penguin amplitudes



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

$$\text{PV} \sim a_4 \approx \frac{\text{PP}}{3} \qquad \text{VP} \sim a_4 - r_\chi a_6 \sim -\text{PV}$$

- Good agreement of the calculated QCD penguin amplitudes. (Figure shows πK vs. πK^*.)
  Interference of $V \mp A$ and $S + P$ as predicted by factorization.
  Similar inteference explains hierarchies of $B \to \eta^{(\prime)} K^{(*)}$ rates. (MB, Neubert 2002)
  $\Rightarrow$ I consider this as the strongest evidence that factorization is at work for the penguin amplitudes.

- Smaller P in $B \to PV$ is good for α determination from time-dependent CP asymmetry S.

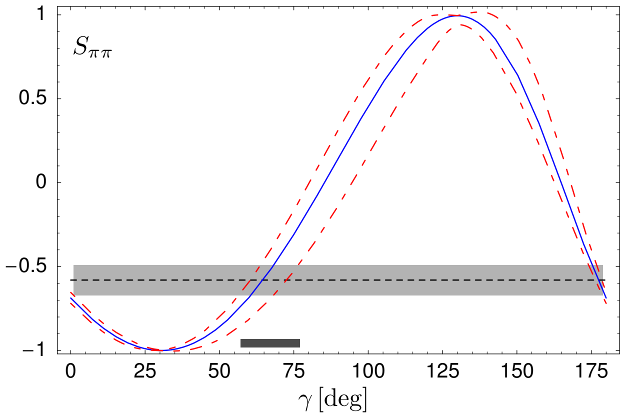
$\gamma\,[\alpha]$ from time-dependent CP asymmetries S in $b \to d$ transitions

$$S_{\pi\rho} = \frac{2R}{1+R^2}\sin 2\alpha - \frac{2R}{1+R^2}\left\{ a\cos\delta_a \left(\frac{2\sin 2\alpha}{1+R^2}\cos\gamma + \sin(2\beta+\gamma)\right)\right.$$
$$\left. - \, b\cos\delta_b \left(\frac{2R^2\sin 2\alpha}{1+R^2}\cos\gamma + \sin(2\beta+\gamma)\right)\right\} + \ldots \qquad (\alpha \equiv \pi - \beta - \gamma)$$

$$A_{\rho\pi}T_{\rho\pi}/(A_{\pi\rho}T_{\pi\rho}) = R\,e^{i\delta_T} \quad R = 0.91\,^{+0.26}_{-0.21},\;\; \delta_T \approx 0$$
$$P_{\pi\rho}/T_{\pi\rho} = a\,e^{i\delta_a},\;\; P_{\rho\pi}/T_{\rho\pi} = -b\,e^{i\delta_b}, \quad a \approx b \approx 0.1,\;\; \cos\delta_{a,b} \approx 1$$

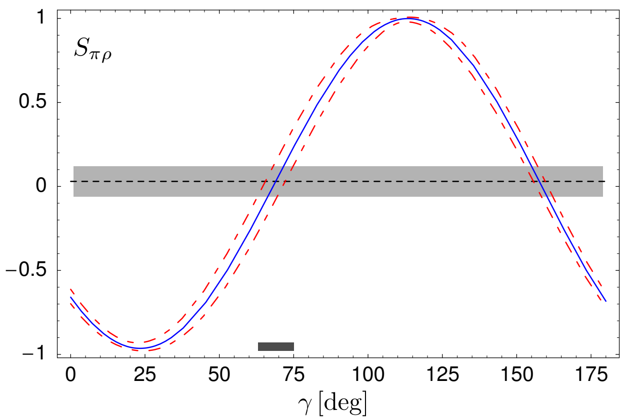
For $S_{\pi\pi}$ $[S_{\rho\rho}]$ put $R = 1$, $\delta_T = 0$, $a = -b \approx 0.3\,[0.1]$, $\delta_a = \delta_b$.

- S parameters have large sensitivity to γ if γ is near 70°.
- Theoretical uncertainties enter only in the sub-leading correction term, which is especially small for $\pi\rho$ and $\rho\rho$. Strong phases enter only as $\cos$.



$$S_{\pi\pi} = -0.58 \pm 0.09$$

$$\Rightarrow \qquad \gamma = (65\,^{+12}_{-8})^\circ$$



$$S_{\pi\rho} = 0.03 \pm 0.09$$

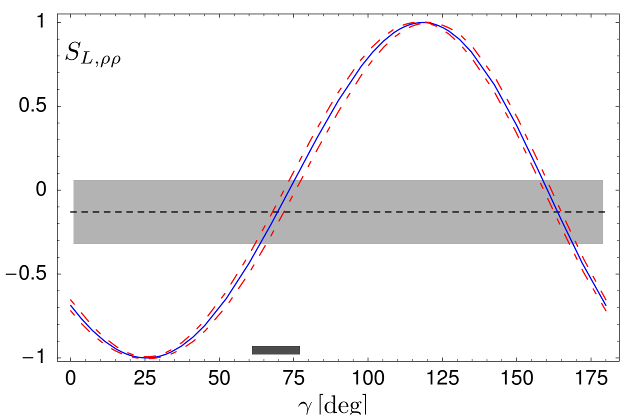
$$\Rightarrow \qquad \gamma = (69\,^{+6}_{-6})^\circ$$

Mutually consistent

$$\gamma = (68 \pm 4)^\circ$$

and consistent with the standard mixing-based fit (from UTfit):

$$\gamma = (61 \pm 5)^\circ$$



$$S_{\rho\rho} = -0.13 \pm 0.19$$

$$\Rightarrow \qquad \gamma = (69\,^{+8}_{-8})^\circ$$

Polarization in $B \to VV$

Interesting because helicity information probes tensor structure of flavour-changing interactions.
For V-A interactions expect

$$A_0 \gg A_- \, [1/m_b] \gg A_+ \, [1/m_b^2]$$

$\Rightarrow$ Transverse polarization is a power correction and $f_L = |A_0|^2 / \sum_{0,\pm} |A_i|^2 \approx 1$

- Observations:
  Confirmed for tree-dominated decays. Not for penguin-dominated decays, for which

  $$A_0 \sim A_- \qquad \text{(no suppression!)}$$

  But $A_+ \ll A_-$ seems to be ok.

- Theoretical calculation: The transverse VV penguin amplitude may receive a large contribution from weak annihilation, which precludes a reliable prediction of f_L. (Kagan, 2004)
  No contradiction (but also no prediction).
  To my knowledge this is the only plausible standard model "explanation".

f_L	data	theory
$\rho^+\rho^-$	0.967 ± 0.024	$0.93^{+0.03}_{-0.04}$
$\rho^-\rho^0$	$0.92^{+0.04}_{-0.05}$	$0.95^{+0.03}_{-0.03}$
ΦK^{*-}	0.50 ± 0.07	$0.81^{+0.23}_{-0.44}$
ΦK^{*0}	0.48 ± 0.04	$0.81^{+0.23}_{-0.45}$

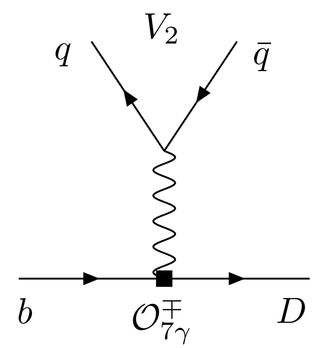
["theory" from (MB, Rohrer, Yang; unpublished)]

Parametric hierarchy not true for electromagnetic interactions. (MB, Rohrer, Yang, 2005)
Instead

$$\mathcal{A}_0 : \mathcal{A}_- : \mathcal{A}_+ = 1 : \frac{m_b}{\Lambda} : 1$$

Enhancement of transverse polarization by $(m_b/\Lambda)^2$.

- γ nearly on-shell, $q^2 = m_{V_2}^2 \sim \Lambda^2$
  - ⋆ V_2 longitudinal $\Rightarrow$ photon propagator is cancelled $\Rightarrow$ effective local four-quark interaction
  - ⋆ for V_2 transverse no cancellation $\Rightarrow$ local $b \to D\gamma$ transition followed by long-distance $\gamma \to V_2$ transition $\Rightarrow$ enhanced by large photon propagator



- Largest contribution to the transverse electroweak penguin amplitudes!

$$P_-^{\text{EW}}(V_1V_2) = C_7 + C_9 + \frac{1}{N_c}(C_8 + C_{10}) - \frac{2\alpha_{\text{em}}}{3\pi} C_{7\gamma}^{\text{eff}} \frac{m_B \bar{m}_b}{m_{V_2}^2} + \ldots$$

- Magntiude of this amplitude is related to $B \to K^*\gamma$.

Check this for the $B \to \rho K^*$ system

$$\begin{aligned}
\mathcal{A}_h(\rho^- \bar{K}^{*0}) &= P_h \\
\sqrt{2}\,\mathcal{A}_h(\rho^0 K^{*-}) &= [P_h + P_h^{EW}] + e^{-i\gamma}\,[T_h + C_h] \\
\mathcal{A}_h(\rho^+ K^{*-}) &= P_h + e^{-i\gamma}\,T_h \qquad (T_h,\ C_h \text{ CKM suppressed}) \\
-\sqrt{2}\,\mathcal{A}_h(\rho^0 \bar{K}^{*0}) &= [P_h - P_h^{EW}] + e^{-i\gamma}\,[-C_h],
\end{aligned}$$

Compare leading QCD penguin to EW penguin amplitude (in some units)

$$P_-(\rho K^*) \approx -1 \qquad P_-^{\mathrm{EW}}(\rho K^*) \approx -0.3 + 0.7 \text{ [new]}$$

A very large effect.

Consider CP-averaged negative helicity decay rate ratio ($p_h^{EW} = P_h^{EW}/P_h$)

$$R \equiv \frac{\bar{\Gamma}_-(\rho^0 \bar{K}^{*-})}{\bar{\Gamma}_-(\rho^0 \bar{K}^{*0})} = \left|\frac{1 + p_-^{EW}}{1 - p_-^{EW}}\right|^2 + \Delta = \begin{cases} 0.4 \pm 0.1 & \\ 1.5 \pm 0.2 & \text{without dipole operator} \end{cases}$$

(Fit P_- to data, use QCDF for the other amplitudes)

Available data:

	$\mathrm{Br}_{\mathrm{Av}}/10^{-6}$	A_{CP}	f_L
$\rho^- \bar{K}^{*0}$	9.2 ± 1.6	-0.01 ± 0.16	0.48 ± 0.08
$\rho^0 K^{*-}$	$10.6^{+3.8}_{-3.5}$	$0.20^{+0.32}_{-0.29}$	$0.96^{+0.06}_{-0.15}$

$$\mathcal{F} \equiv \frac{f_-(\rho^0 \bar{K}^{*-})}{f_-(\rho^- \bar{K}^{*0})} \overset{\text{exp.}}{=} 0.1^{+0.3}_{-0.1} \qquad \mathcal{F} \overset{\text{th.}}{=} \begin{cases} 0.4 \pm 0.1 & \\ 0.7 \pm 0.1 & \text{without dipole operator} \end{cases}$$

Detecting physics beyond the Standard Model

- ⋆ New Physics could enhance chirlaity-flipped electromagnetic dipole operator
- ⋆ $Q^+_{7\gamma}$ contribution to $\bar{\mathcal{A}}_+$ is suppressed only by $C^+_{7\gamma}/C^-_{7\gamma}$, while other contributions have additional Λ/m_b suppression $\Rightarrow$ Sensitivity to $C^+_{7\gamma} \approx 0.1$ may be possible.
- ⋆ An alternative to studies of photon polarization in $B \longrightarrow K^\star\gamma$. Here the ρ meson (decay) acts as the polarization analyzer.

Summary

- Too much to summarize for one talk.
  Apologies to the many people whose work I have not presented. Especially work on strategies that are more data-driven (SU(3) fits, BPRS-WZ fits).
  I have naturally focussed on what I understand and on what I think is correct.
- Instead of a summary three messages:

1 We have learned a lot about hadronic dynamics but I think we also know γ very well from charmless hadronic final states. There should be some way to include this information in the CKM fit beyond the few standard methods!

2 The subject has been an extremely fertile ground for developing new theoretical concepts.

3 There is much more to learn: experimentalists should keep on collecting as many measurements as possible.