Predictions for $\sin(2\beta/\phi_1)_{\rm eff}$ in $b \to s$ penguin dominated modes

Jure Zupan

IJS & Univ. of Ljubljana

measuring $\sin 2\beta$

$$S_f = 2\frac{\mathcal{I}m\left[e^{-i2\beta}\bar{A}_f/A_f\right]}{1+|\bar{A}_f|^2/|A_f|^2} \qquad C_f = \frac{1-|\bar{A}_f|^2/|A_f|^2}{1+|\bar{A}_f|^2/|A_f|^2}$$

- choose $\Delta S = 1$ B^0 decays $\Rightarrow$ exploit CKM hierarchy
- split the amplitude according to CKM factors

$$\begin{aligned}\bar{A}_f &= \lambda_c a_f^c + \lambda_u a_f^u + \lambda_t a_f^t \\ &= \lambda_c(a_f^c - a_f^t) + \lambda_u(a_f^u - a_f^t) \\ &= \lambda_c A_f^c + \lambda_u A_f^u\end{aligned}$$

$$\lambda_c + \lambda_u + \lambda_t = 0$$

$$\lambda_c = V_{cb}V_{cs}^*, \lambda_u = V_{ub}V_{us}^* \sim \lambda^2\lambda_c$$

  - a_f^c: $b \to c\bar{c}s$ tree, $c\bar{c}$ rescattering (charming penguin)
  - a_f^u: $b \to u\bar{u}s$ tree, $u\bar{u}$ rescattering ($u-$penguin)
  - a_f^t: QCD penguins, EWP

measuring $\sin 2\beta$

$$S_f = 2\frac{\mathcal{I}m\left[e^{-i2\beta}\bar{A}_f/A_f\right]}{1+|\bar{A}_f|^2/|A_f|^2} \qquad C_f = \frac{1-|\bar{A}_f|^2/|A_f|^2}{1+|\bar{A}_f|^2/|A_f|^2}$$

- because $\lambda_u \sim 0.02\lambda_c$ big hierarchy in A_f

$$\bar{A}_f = \lambda_c A_f^c + \lambda_u A_f^u$$

- as long as $\lambda_c A_f^c \gg \lambda_u A_f^u$

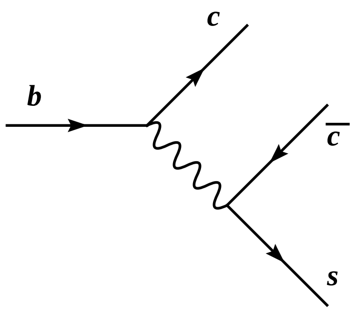
$$\sin 2\beta_{\text{eff}} \equiv -\eta_f^{CP} S_f = \sin 2\beta + 2r_f \cos\delta_f \cos 2\beta \sin\gamma$$

$$C_f = -2r_f \sin\delta_f \sin\gamma$$

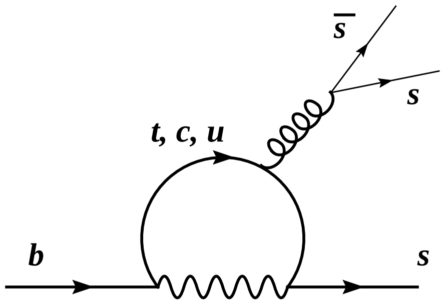
with $\quad r_f e^{i\delta_f} = |\lambda_u/\lambda_c| \cdot \frac{A_f^u}{A_f^c} \simeq 0.02\frac{A_f^u}{A_f^c}$

2 ways to $\sin 2\beta$

- tree dominated:
  $B^0 \to J/\Psi K_S$,...
- expected to be SM dominated $\Rightarrow \sin 2\beta_{\rm eff}^{\rm Tree}$



- penguin dominated:
  $B^0 \to \phi K_S$,...
- possibly large BSM contribs $\Rightarrow \sin 2\beta_{\rm eff}^{\rm Peng}$



- comparison of the two: test of KM mechanism

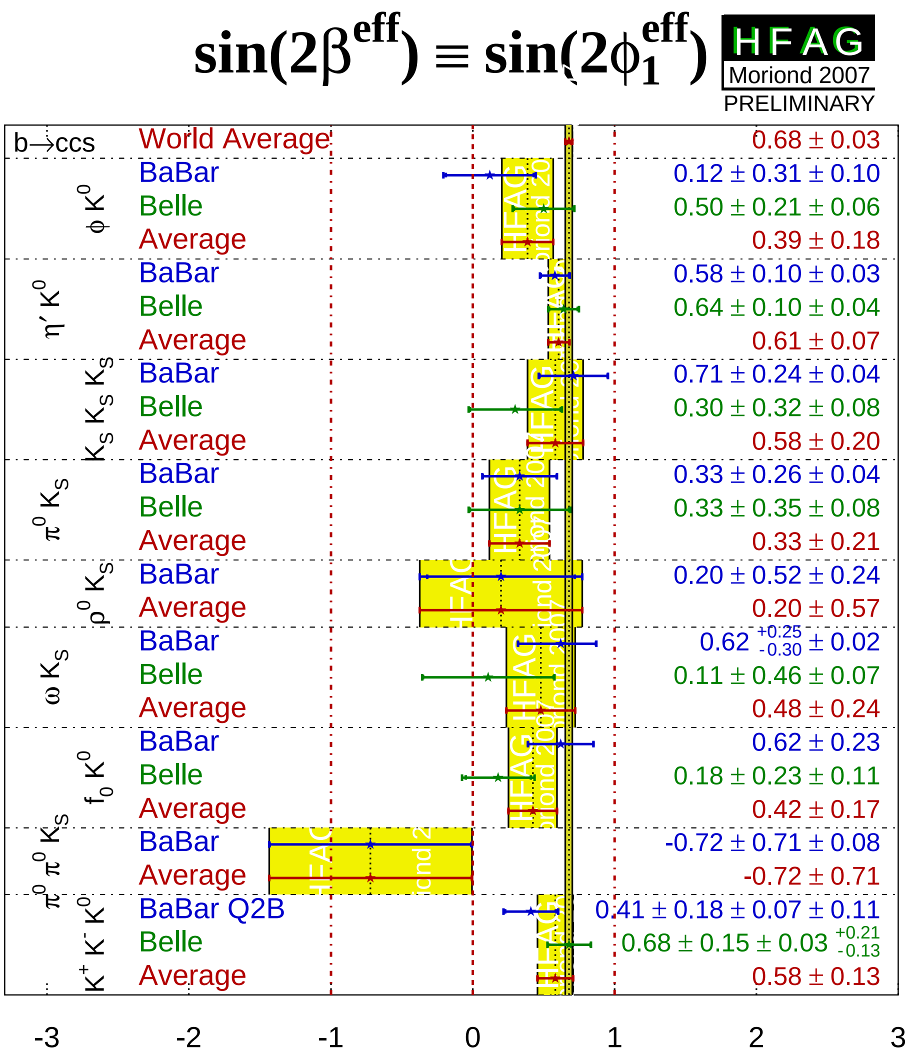
$$\Delta S_f = \sin 2\beta_{\rm eff}^{\rm Peng} - \sin 2\beta_{\rm eff}^{\rm Tree} = O(r_f^{\rm Peng}) - O(r_f^{\rm Tree})$$

  - $r_f^{\rm Tree}$ corrections for $\sin 2\beta$ from $J/\Psi K_S$ below percent level $\Rightarrow$ negligible

Boos, Mannel, Reuter, 2004
Ciuchini, Pierini, Silvestrini, 2005
H.-n. Li, S. Mishima, 2006

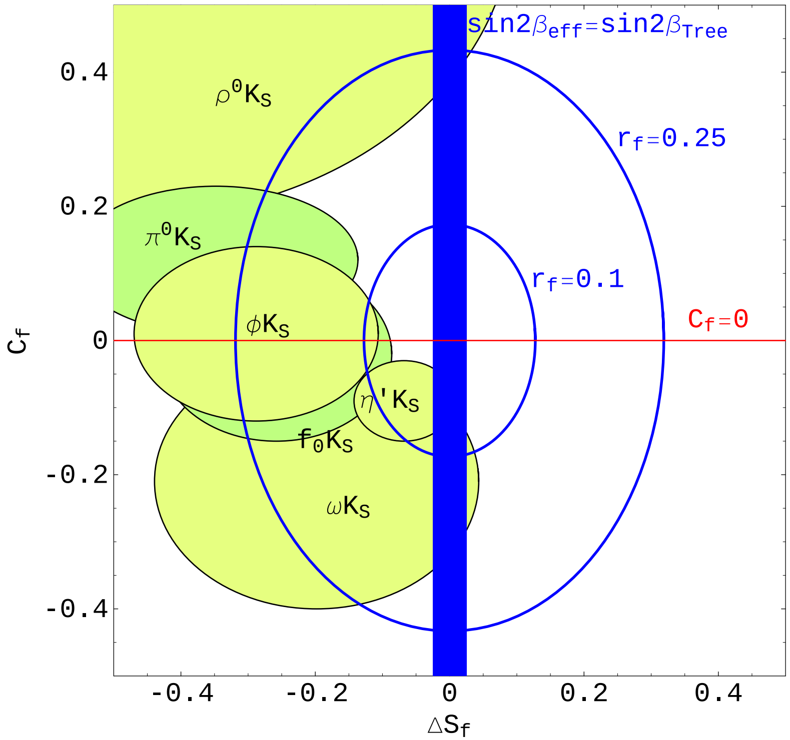
Exp. situation & Questions

see also talk by C.-h. Cheng



- all $\Delta S_f < 0$
- what are the SM expectations?
- what are the errors on theory predictions?
- what errors to expect in the future/can we improve?
- with 50 ab^{-1} of data $S_{\phi K_S, \eta' K_S}$ measured to a precision of a few %

Another look at the data



- 2 measur.: S_f, C_f vs
  2 unknowns: $\sin\gamma\ r_f$, δ_f

$$\Delta S_f = 2\sin\gamma\ r_f \cos\delta_f \cos 2\beta$$

$$C_f = -2\sin\gamma\ r_f \sin\delta_f$$

on plot: $\gamma = 60^\circ$

- to predict ΔS_f need theory input
- answer channel depend.

- $\Delta S_f, C_f$ estimated in several theor. frameworks
  - SU(3) flavor symmetry
  - $1/m_b$ expansion: QCDF, SCET, pQCD

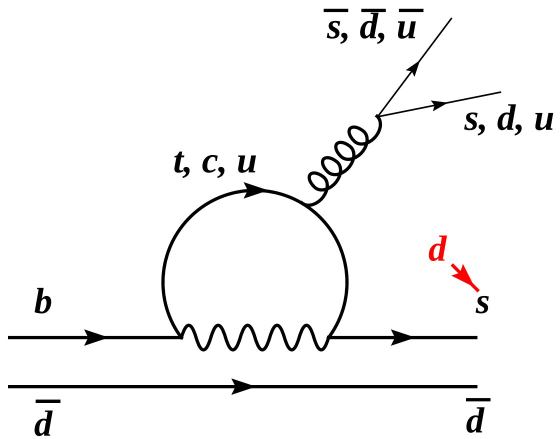
Using SU(3)

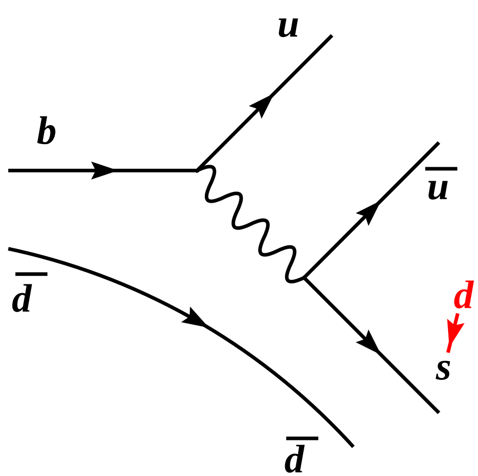
Bounding using $SU(3)_F$

Grossman, Ligeti, Nir, Quinn, 2003
Gronau, Rosner, JZ, 2004, 2006
Raz, 2005

- use $\Delta S = 0$ $SU(3)_F$ related modes ($s \to d$)

$$V_{cb}V_{cs}^{*}A_f^c \to V_{cb}V_{cd}^{*}A_f^{c\prime} \qquad V_{ub}V_{us}^{*}A_f^u \to V_{ub}V_{ud}^{*}A_f^{u\prime}$$





- the hierarchy of tree and penguin contribs. is changed

$$P \to -\lambda P', \; T \to T'/\lambda$$

- from the related modes can bound "tree pollution" r_f

Some further details...

- a bound on r_f consists of a sum of modes

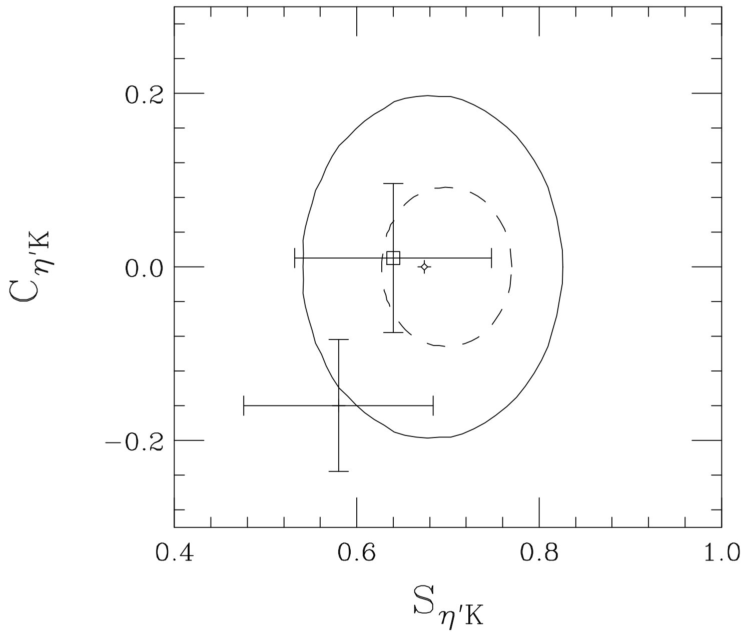
$$r_f \le \frac{\mathcal{R} + \bar\lambda^2}{1-\mathcal{R}}, \quad \mathcal{R} \le \bar\lambda \Sigma_f |a_f| \sqrt{\frac{\bar{\mathcal{B}}_f(\Delta S{=}0)}{\bar{\mathcal{B}}_f(\Delta S{=}1)}}$$

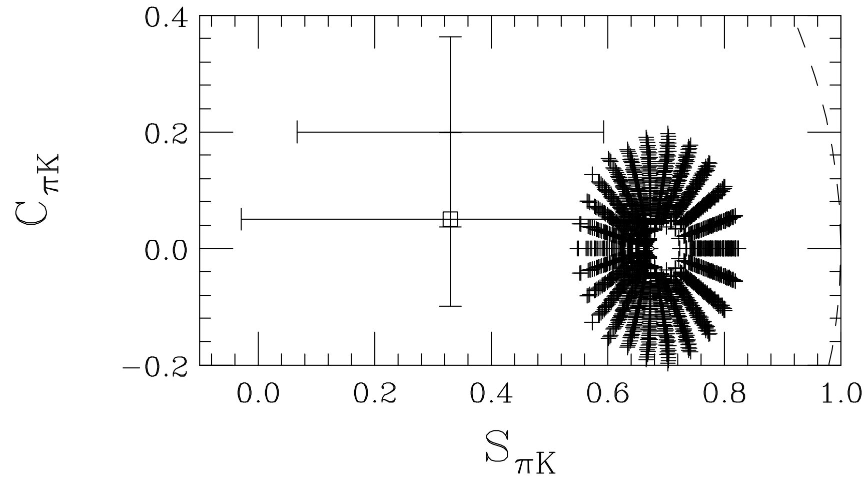
- bound can never be better than $r_f < \bar\lambda^2 \sim 0.05$
- for some $\Delta S = 0$ modes only upper bounds are known
  - for instance for $r_{\eta' K_S}$ only bounds on Br for $\pi^0\eta, \eta^{(\prime)}\eta^{(\prime)}$
  - at present $\mathcal{R}_{\eta' K_S} < 0.116$, while $\mathcal{R} < 0.045$ for QCDF, S4 ($\mathcal{R} < 0.088$ SCET, Sol I.)
- room for improvement
- in general too conservative (if no dynamical assumptions)

Results

- results of 2006 numerical update

Gronau, Rosner, JZ, 2006





- bounds on $\Delta S_{\phi K_S}$ much worse
- possible to treat S_{KKK} in this framework
  - assuming small annihilation

Engelhard, Raz, 2005
Engelhard, Nir, Raz, 2005

$$r_{K^+K^-K^0} < 1.02, \qquad r_{K_S K_S K_S} < 0.31$$

$1/m_b$ expansion

see also monday talks by I. Stewart, H.-n. Li

State of the art

- QCDF and SCET: hard kernels known to NLO in $\alpha_S(m_b)$, jet functions to NLO in $\alpha_S(\sqrt{\Lambda m_b})$
- for ΔS_f calculations:
  - QCDF:
    - hard scattering LO in $\alpha_S(m_b)$,$\alpha_S(\sqrt{\Lambda m_b})$
    - soft overlap NLO in $\alpha_S(m_b)$
    - some $1/m_b$ corrections included (modeled)
  - SCET:
    - all hard kernels LO in $\alpha_S(m_b)$
    - jet functions not expanded
    - some $1/m_b$ known, but not included
    - nonpert. param. (also $P_{\rm charm}$) fit from data
  - pQCD:
    - soft overlap contrib. factorized
    - some NLO included
- a lot of work needed to include $1/m_b$ corrections (not clear if possible to fix all)

ϕK_S

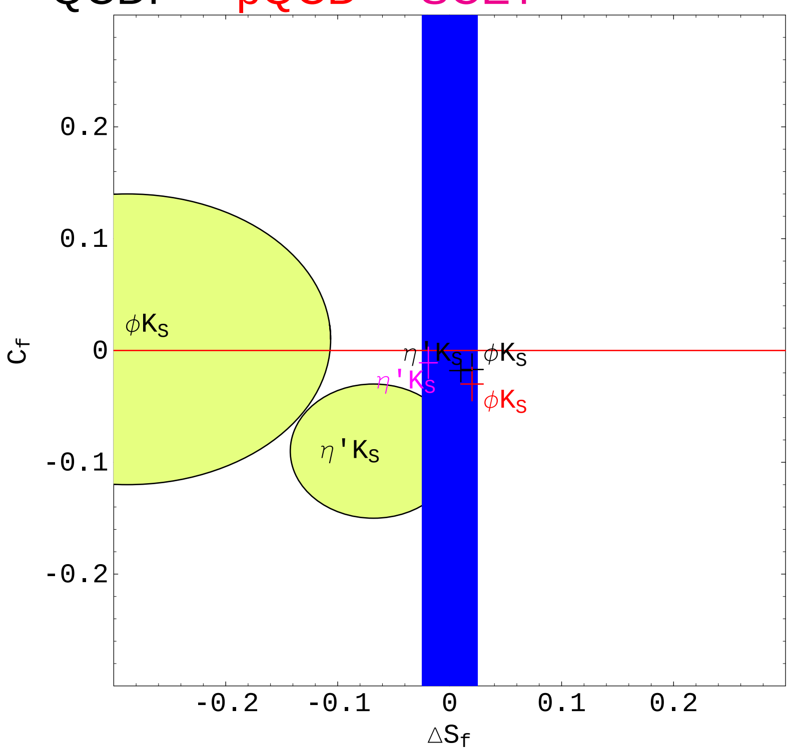
- no $b \to u\bar{u}s$ tree contribution

$$\frac{A_f^u}{A_f^c} = \frac{a_f^u - a_f^t}{a_f^c - a_f^t} \sim O(1)$$

  a_f^i either $\alpha_S(m_b)$ or $1/m_b$ suppressed

- extremely clean, r_f at percent level: $r_f \simeq 0.02 \frac{A_f^u}{A_f^c}$

– QCDF – pQCD – SCET



- both QCDF and pQCD

$$\Delta S_{\phi K_S} = 0.02 \pm 0.01$$

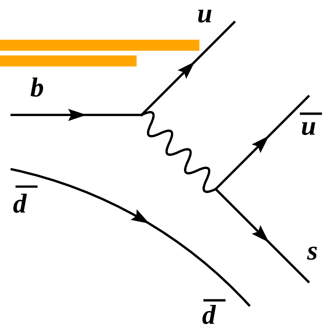
  Beneke, 2005
  Li, Mishima, 2006

- FSI rescattering does not change this

  Cheng, Chua, Soni, 2005

- no prediction in SCET yet

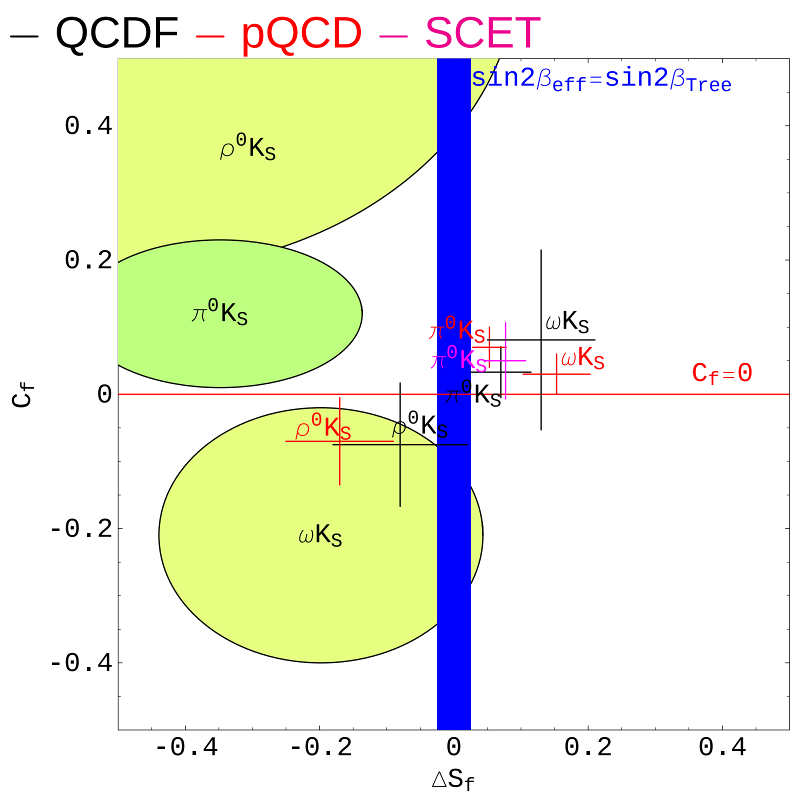
$\eta' K_S$



- there is $b \to u\bar{u}s$ tree level contribution
- r_f still small, since A_f^c is also enhanced $\Rightarrow$ $\Rightarrow$ to explain large $Br(B \to \eta' K_S)$
  - enhancement can be understood through interference of $A(B \to \eta_{q,s} K_S)$ — Lipkin, 1991
  - gluonic contributions and/or SU(3) breaking needed — Beneke, Neubert, 2002, 2003; Williamson, JZ, 2006; Gerard, Kou, 2006
- QCDF: $\Delta S_{\eta' K_S} = 0.01 \pm 0.01$ — Beneke, 2005

  SCET: $\Delta S_{\eta' K_S} = -0.019 \pm 0.008(-0.010 \pm 0.010)$ — Williamson, JZ, 2006
- destructive interference in $B \to \eta K_S$, A_f^c is suppressed, $\Delta S_{\eta K_S}$ can be large, even $O(1)$

Other 2-body modes



Beneke, Neubert, 2003, Beneke 2005
Li, Mishima, Sanda, 2005, Li, Mishima, 2006
Williamson, JZ, 2006

- receive $b \to u\bar{u}s$ tree contribs
- $\Delta S_f \sim O(0.1)$
- $\Delta S_{\rho K_S}$ the only one that predicted to be negative
- FSI could change appreciably $S_{\omega K_S, \rho K_S}$, but still $\Delta S_f \sim O(0.1)$

Cheng, Chua, Soni, 2005

Mode	QCDF	pQCD	SCET
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$0.053^{+0.02}_{-0.03}$	0.077 ± 0.030
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$-0.187^{+0.10}_{-0.06}$	–
ωK_S	0.13 ± 0.08	$0.153^{+0.03}_{-0.07}$	–

Three-body

- $B \to \pi^0 \pi^0 K_S$, $B \to K_S K_S K_S$ CP-even

  Gershon, Hazumi, 2004

- $B \to K^+ K^- K_S$ both components
  - non ϕK_S $B \to K^+ K^- K_S$ mostly CP even
- no $b \to u\bar{u}s$ tree in $B \to K_S K_S K_S$ $\Rightarrow$ naively one expects $\Delta S_{K_S K_S K_S}$ very small, while others $\sim O(0.1)$
- calc. based on HMχPT+model of form factors & non-res. amplitude behaviour give all $\Delta S_f \sim 0.05$

  Cheng, Chua, Soni, 2005, 2007

- more work needed

Conclusions

- experimental ΔS_f are consistently lower than theoretical predictions
- conservative* average of $(\Delta S_f)_{\rm Corr} = (\Delta S_f)_{\rm Exp} - (\Delta S_f)_{\rm Th}$

$$\overline{(\Delta S_f)}_{\rm Corr} = \sin 2\beta^{\rm Peng} - \sin 2\beta^{\rm Tree}$$
$$= -0.133 \pm 0.063 \qquad (> 2.1\sigma \text{ effect})$$

* no 3-body, $(\Delta S_f)_{\rm Th}$ the lowest value in Beneke 2005 QCDF scan, only exp. error in average (almost exactly the same result if $(\Delta S_f)_{\rm Th}$ the smallest th. pred., exp.+ th. err. added quadratically)

Backup slides

$B \to K\eta$ vs $B \to K\eta'$

- Lipkin '91: constructive and destructive interf.

$$A_{\bar{B}\to\bar{K}\eta'} = \cos\phi A_{\bar{B}\to\bar{K}\eta_s} + \sin\phi A_{\bar{B}\to\bar{K}\eta_q}$$
$$A_{\bar{B}\to\bar{K}\eta} = -\sin\phi A_{\bar{B}\to\bar{K}\eta_s} + \cos\phi A_{\bar{B}\to\bar{K}\eta_q}$$

  with $\phi = (39.3 \pm 1.0)^\circ$, so that $\cos\phi \simeq \sin\phi$

- If $A_{\bar{B}\to\bar{K}\eta_q} \simeq A_{\bar{B}\to\bar{K}\eta_s}$
  - $\Rightarrow$ a constructive interference in $A_{\bar{B}\to\bar{K}\eta'}$
  - $\Rightarrow$ a destructive interference in $A_{\bar{B}\to\bar{K}\eta}$

$B \to K\eta$ vs $B \to K\eta'$

- Lipkin '91: constructive and destructive interf.

$$A_{\bar{B}\to\bar{K}\eta'} = \cos\phi A_{\bar{B}\to\bar{K}\eta_s} + \sin\phi A_{\bar{B}\to\bar{K}\eta_q}$$
$$A_{\bar{B}\to\bar{K}\eta} = -\sin\phi A_{\bar{B}\to\bar{K}\eta_s} + \cos\phi A_{\bar{B}\to\bar{K}\eta_q}$$

  with $\phi = (39.3 \pm 1.0)^\circ$, so that $\cos\phi \simeq \sin\phi$

- If $A_{\bar{B}\to\bar{K}\eta_q} \simeq A_{\bar{B}\to\bar{K}\eta_s}$
  - $\Rightarrow$ a constructive interference in $A_{\bar{B}\to\bar{K}\eta'}$
  - $\Rightarrow$ a destructive interference in $A_{\bar{B}\to\bar{K}\eta}$
- exactly what happens in QCDFact, SCET
  - penguin dominated mode

$$A_{\bar{B}\to\bar{K}\eta_q} \simeq \frac{1}{\sqrt{2}}(P^{K\eta_q} + 2P_g^{K\eta_q}) + \dots$$
$$A_{\bar{B}\to\bar{K}\eta_s} \simeq P^{K\eta_s} + 2P_g^{K\eta_s} + \dots$$

$B \to K\eta^{(\prime)}$ hierarchy

- SU(3) break. $1 + \Delta r_{(g)} = P_{(g)}^{K\eta_s} / P_{(g)}, \quad P_{(g)} \equiv P_{(g)}^{K\eta_q}$

$$A_{B^- \to \eta K^-} \propto (\sqrt{2} - r_g \tan\phi) P_g + \left(\frac{1}{\sqrt{2}} - r \tan\phi\right) P + \cdots$$

$$= (0.59 + 0.8\Delta r_g) P_g - (0.11 + 0.8\Delta r) P + \cdots$$

$$A_{B^- \to \eta' K^-} \propto (r_g + \sqrt{2}\tan\phi) P_g + \left(r + \frac{\tan\phi}{\sqrt{2}}\right) P + \cdots$$

$$= (2.16 + \Delta r_g) P_g + (1.59 + \Delta r) P + \cdots$$

- $Br(B \to \eta K) \ll Br(B \to \eta' K)$ for most $\arg(P_g/P)$, no cancelation between P and P_g needed
- the suppression is larger for P than for P_g
- $P_g, \Delta r_{(g)} = 0 \Rightarrow Br(\eta K) \sim O(10^{-7})$ and not $\sim O(10^{-6})$