Measuring α in $B^0 \to a_1(1260)^{\pm}\pi^{\mp}$

Status & perspectives for a Super-B

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Outline

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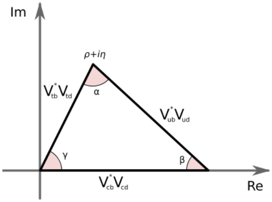
α measurement in non CP-eigenstates

$\alpha = \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$



Experimentally accessible in $b \to u\bar{u}d$ transitions

- Time-dependence $B^0(\to \bar{B}^0) \to a_1^{\pm}\pi^{\mp}$

$$F_{Q_{\rm tag}}^{a_1^{\pm}\pi^{\mp}}(\Delta t) \propto \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \left\{1 + Q_{\rm tag}\left[S_{\pm}\sin(\Delta m_d \Delta t) - C_{\pm}\cos(\Delta m_d \Delta t)\right]\right\}$$

- Penguin pollution and strong phase between tree amplitudes

$$S_{\pm} = \sqrt{1 - C_{\pm}{}^2} \times \sin(2\alpha - 2\Delta\alpha \pm \hat{\delta})$$

8-fold ambiguity:

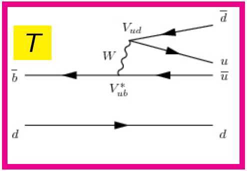
- average out $\hat{\delta}$: $\alpha_{\rm eff} = \frac{1}{4}\left[\arcsin\left(S_+/\sqrt{1-C_+^2}\right) + \arcsin\left(S_-/\sqrt{1-C_-^2}\right)\right]$
- 2 ($\alpha \to \pi/2 - \alpha$) $\times$ 2 (roughly $2\alpha \leftrightarrow \hat{\delta}$) $\times$ 2 (average)
- $\hat{\delta} \approx 0$ from factorization $\Rightarrow$ 2-fold ambiguity

Constraining penguin contribution

Gronau, Zupan, PRD70, 074031; PRD73, 057502

Use simmetries to constrain $\Delta\alpha \equiv \alpha - \alpha_{eff}$.

- SU(2) not a viable option $\Rightarrow$ approx. flavor SU(3)

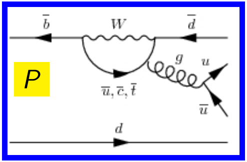


$\Delta S = 0$ decays

- $A(B^0 \to a_1^+ \pi^-) = e^{i\gamma} t_+ + p_+$

$\Delta S = 1$ decays

- $A(B^+ \to a_1^+ K^0) = -(\bar{\lambda})^{-1} \frac{f_K}{f_\pi} p_-$



$P_{\Delta S=1}$ is CKM $(1/\bar{\lambda} = |V_{cs}|/|V_{cd}| \sim 0.23)$ enhanced over $P_{\Delta S=0}$

Derive bounds on $\Delta\alpha$ from ratios of CP-averaged rates of $\Delta S = 1$ and $\Delta S = 0$ B decays in a model dependent approach

- $\cos(2\alpha^{\pm}_{\rm eff} - \alpha) \geq (1 - 2R^0_{\pm})/\sqrt{1 - \mathcal{A}^{\pm\,2}_{CP}}$
- $\cos(2\alpha^{\pm}_{\rm eff} - \alpha) \geq (1 - 2R^+_{\pm})/\sqrt{1 - \mathcal{A}^{\pm\,2}_{CP}}$

Constraining penguin contribution

$K_{1A} \equiv$ SU(3) partner of $a_1(1260)$

SU(3) octet states K_{1A} (C=+1 octet) and K_{1B} (C=-1) octet mix:

- $|K_1(1400)\rangle = \quad |K_{1A}\rangle \cos\theta_{K_1} + |K_{1B}\rangle \sin\theta_{K_1}$
- $|K_1(1270)\rangle = -|K_{1A}\rangle \sin\theta_{K_1} + |K_{1B}\rangle \cos\theta_{K_1}$
- mixing angle $|\theta_{K_1}| \approx 45^\circ$

$a_1(1260)$ decay constant from $\tau^+ \to a_1(1260)^+ \nu_\tau$:

- $f_{a_1} = (203 \pm 18)$ MeV [Bloch, PRD 60, 111502R]

$K_1(1270)$ decay constant from $\tau^+ \to K_1(1270)^+ \nu_\tau$.
$f_{K_{1A}}$ is calculated from $f_{K_1(1270)}$, mixing relations, and masses:

- $f_{K_{1A}} = (207 \pm 20)$ MeV [Cheng, PRD 76, 114020]

$$R_+^0 \equiv \frac{\bar{\lambda}^2 f_{a_1}^2 \mathcal{B}(K_{1A}^+ \pi^-)}{f_{K_{1A}}^2 \mathcal{B}(a_1^+ \pi^-)}$$

Branching fractions used in the ratio are extracted in the Quasi-Two-Body approximation

Outline

$B^0 \to a_1^{\pm}\pi^{\mp}$ branching fraction

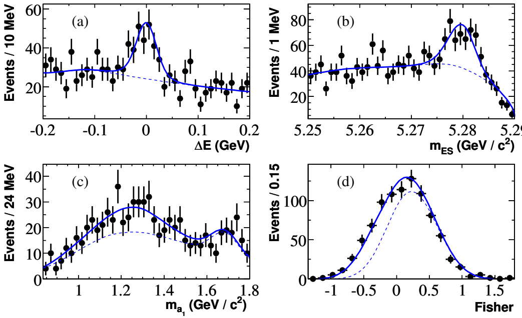
PRL 97, 051802 (2006). $218\,\text{fb}^{-1}$

$a_1(1260)$ parameters poorly known:

- $m^{(PDG)}_{a_1(1260)} = (1230 \pm 40)\,\text{MeV}$
- $\Gamma^{(PDG)}_{a_1(1260)} = 250 \text{ to } 600\,\text{MeV}$

ML fit to ΔE, m_{ES}, $\mathcal{F}$, $m_{\pi\pi\pi}$, $\mathcal{H}$:

- $m^{(fit)}_{a_1(1260)} = (1229 \pm 21)\,\text{MeV}$
- $\Gamma^{(fit)}_{a_1(1260)} = (393 \pm 62)\,\text{MeV}$
- $\mathcal{B} = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$



Most of the systematic uncertainties are of statistical nature:

- PDF parameters (obtained, i.e., from off resonance data sample)
- background channels branching fractions
- $a_2\pi$ cross feed and interference (suppressed by cut on angular variable)

Uncertainty on $a_1 \to \sigma\pi$ BF limits precision to $\sim 0.4 \times 10^{-6}$ (2.5% effect).

$B^0 \longrightarrow a_1^{\pm}\pi^{\mp}$ time-dependent analysis

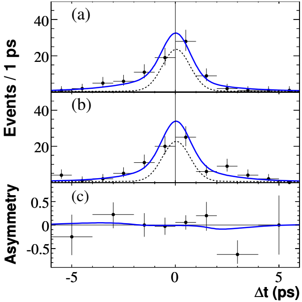
PRL 98, 181803 (2007). 383 fb^{-1}

Fit Δt model to data taking into account flavor-tagging performance and experimental Δt resolution:

- $S = 0.37 \pm 0.21 \pm 0.07$
- $\Delta S = -0.14 \pm 0.21 \pm 0.06$
- $C = -0.10 \pm 0.15 \pm 0.09$
- $\Delta C = 0.26 \pm 0.15 \pm 0.07$
- $\mathcal{A}_{CP} = -0.07 \pm 0.07 \pm 0.02$

Correlations are weak (at O(%) level).

(a) B^0 tag
(b) $\bar{B}^0$ tag
(c) asymmetry



$$\alpha_{\text{eff}} = (79 \pm 7)^{\circ}$$
$$\{11, 41, 49, 79, 101, 131, 139, 169\}^{\circ}$$

Main syst. errors: PDF parameters, $B\bar{B}$ CP violation, interference with $a_2\pi$

$B^0 \rightarrow a_1^- K^+$ and $B^+ \rightarrow a_1^+ K^0$

PRL 100, 051803 (2008). 383 fb^{-1}

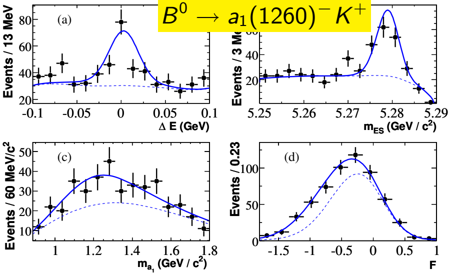
$a_1(1260)$ resonance parameters fixed to values determined in $a_1\pi$ analysis.

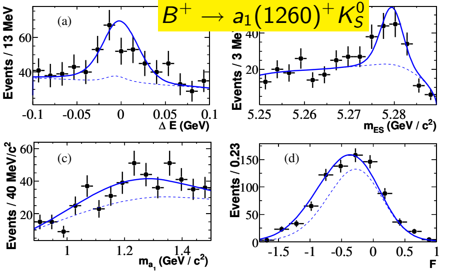
ML fit to ΔE, m_{ES}, $\mathcal{F}$, $m_{\pi\pi\pi}$, $\mathcal{H}$:

- $\mathcal{B}(a_1^- K^+) = (16.4 \pm 3.0 \pm 2.4) \times 10^{-6}$
  $S = 5.1\sigma$
- $\mathcal{B}(a_1^+ K^0) = (34.8 \pm 5.0 \pm 4.4) \times 10^{-6}$
  $S = 6.2\sigma$
- Th.: $\mathcal{B}(B^+ \rightarrow a_1^+ K^0) \sim \mathcal{B}(B^0 \rightarrow a_1^- K^+)$
  - not consistent with experiment [Cheng, PRD 76, 114020]

Main systematics:

- PDF parameters
- Fit bias





$B^0 \to K_1^+ \pi^-$ and $B^+ \to K_1^0 \pi^+$

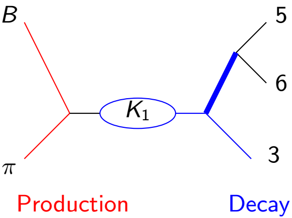
arXiv:0909.2171, submitted to PRD. 413 fb^{-1}

Wide overlapping $J^P = 1^+$ mesons

- decay to $K\pi\pi$ final states (different BFs)
- $K_1(1270)$ also decays (11%) to ωK
- interference between signal components

K_1 resonance parameters fixed to values determined from analysis of ACCMOR data: NPB 187, 1 (1981).

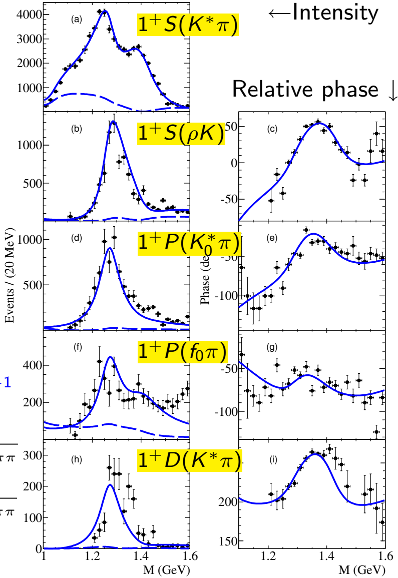
- K-matrix with 2 resonances, and 6 channels [Aitchison]



$$F_i = e^{i\delta_i} \sum_j R_j (1 - i\mathbf{K}\boldsymbol{\rho})^{-1}_{ij}$$

$$R_j = \frac{f_{pa} f_{aj}}{M_a - M_{K\pi\pi}} + \frac{f_{pb} f_{bj}}{M_b - M_{K\pi\pi}}$$

$$K_{ij} = \frac{f_{ai} f_{aj}}{M_a - M_{K\pi\pi}} + \frac{f_{bi} f_{bj}}{M_b - M_{K\pi\pi}}$$



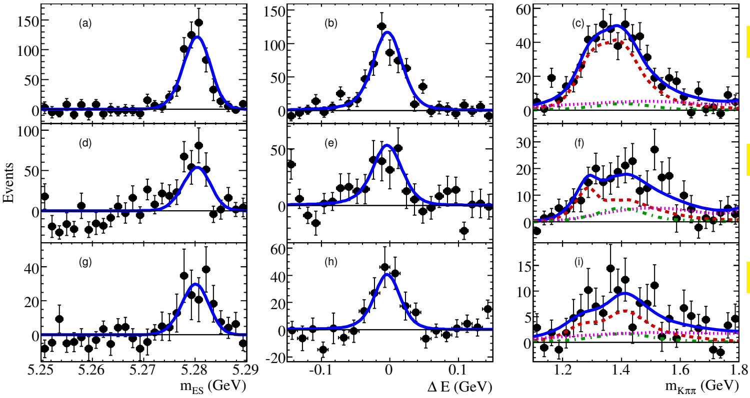
$B^0 \to K_1^+\pi^-$ and $B^+ \to K_1^0\pi^+$

arXiv:0909.2171, submitted to PRD. 413 fb^{-1}

ML fit to ΔE, m_{ES}, $\mathcal{F}$, $m_{K\pi\pi}$, $\mathcal{H}$:

- $\mathcal{B}(K_1^+\pi^-) = (3.1^{+0.8}_{-0.7}) \times 10^{-5}$ $(S = 7.5\sigma)$
- $\mathcal{B}(K_1^0\pi^+) = (2.9^{+2.9}_{-1.7}) \times 10^{-5}$ $(S = 3.2\sigma)$

(combined contribution of $K_1(1270)$ and $K_1(1400)$)



B^0 (K^* sel.)

B^0 (ρ sel.)

B^+ (K^* sel.)

$B^0 \to K_1^+\pi^-$ and $B^+ \to K_1^0\pi^+$

arXiv:0909.2171, submitted to PRD. 413 fb^{-1}

Use $m_{K\pi\pi}$ distribution to distinguish between $K_1(1270)$ and $K_1(1400)$

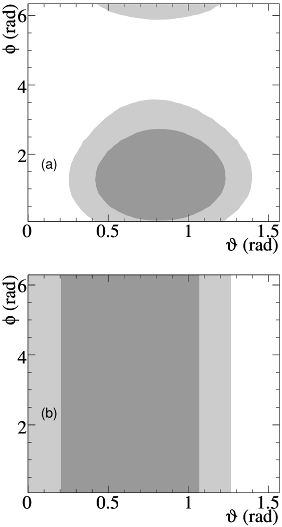
- scan over production parameters $f_{pa} \equiv \cos\vartheta$; $f_{pb} \equiv \sin\vartheta e^{i\varphi}$
- non-parametric templates describe different $m_{K\pi\pi}$ distribution and efficiencies

Main systematics:

- Signal – non-res bkg interference
- K_1 K-matrix parameters: mass poles, decay parameters

Use $\mathcal{B}(K_1(1270)\pi)$, $\mathcal{B}(K_1(1400)\pi)$, production parameters, and mixing angle to extract $\mathcal{B}(K_{1A}\pi)$.

(ϑ, φ) scan



Bounds on $\Delta\alpha$

arXiv:0909.2171, submitted to PRD. 413 fb^{-1}

Evaluate bounds on $\Delta\alpha$ by MC based method

- Generate input according to the experimental distributions
- For each set of generated values, evaluate the bounds
- Get limits by counting the fraction of bounds within a given value

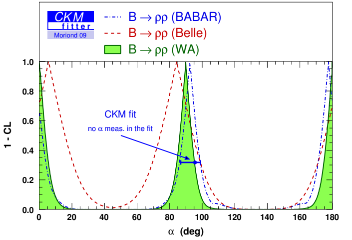
$\Delta\alpha = 11^\circ$ @ 68% CL

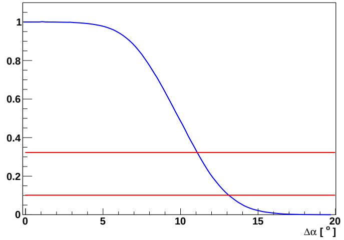
$\Delta\alpha = 13^\circ$ @ 90% CL

$\alpha = (79 \pm 7 \pm 11)^\circ$

Selected solution compatible with global CKM fits

$-1.8^\circ < \Delta\alpha < 6.7^\circ$, $\alpha_{\rho\rho} = (92.4^{+6.0}_{-6.5})^\circ$





Outline

Analysis technique with 75 ab^{-1}

With current analysis technique:

- input to ML fit: $20k \rightarrow 3M$ events
- # signal events: $400 \rightarrow 60000$

$150\times$ luminosity

- Most systematics statistical in origin
  - PDF parameterization
  - background channels
- Model systematics can be reduced by increasing the complexity of the model and floating additional parameters
  - Masses and widths
  - Interference effects
- Cross-check with different final states

	$\mathcal{B}$ (10^{-6})
PDF	2.1
B background	1.3
$a_2(1320)^{\pm}\pi^{\mp}$	1.3
$a_1 \rightarrow \sigma\pi$	0.8

	S	C	ΔS	ΔC	$\mathcal{A}_{CP}$
PDF pars.	4.8	5.3	3.3	5.3	1.5
Fit bias	0.8	0.2	0.8	1.0	0.3
SCF, $B\bar{B}$ CPV	4.1	4.3	4.2	4.0	0.5
$a_2(1320)^{\pm}\pi^{\mp}$	2.8	4.5	3.2	0.6	0.2
DCS decays	0.8	2.2	0.0	2.2	0.1

	$\mathcal{B}$ (10^{-6})	θ	ϕ
Scan	0.9	0.04	0.16
$K-$matrix par.	2.2	0.01	0.36
Interference	6.0	0.25	0.52
Particle ID	0.9	−−	−−

Analysis technique with 75 ab^{-1}

Extrapolation to Super-B based on comparison with $B^0 \to \rho^+\rho^-$ decays

- Similar S/B
  - $S_{a_1\pi} = 608,\ B_{a_1\pi} = 29300$
  - $S_{\rho\rho} = 730,\ B_{\rho\rho} = 37424$
- Similar SCF and $B\bar{B}$ levels

At Super-B, $B \to a_1\pi$ is a systematic limited measurement

- $\sigma(\alpha) \approx 0.75^\circ$ (see A. Bevan @ Warwick)
- bound on $\Delta\alpha \searrow 9^\circ$
- further improvement on $\Delta\alpha$ determination from a full SU(3) analysis?

Analysis technique with 75 ab^{-1}

Current analysis not really portable to higher luminosity.

- increased data samples require more CPU
    - increase S/B using tag-side B information ...
        - see A. Perez @ Warwick workshop
    - ... and cleaner decays
        - i.e. $K_1(1270) \to \omega\pi$
          (but large uncertainties on branching fraction)
- computational cost grows with more parameters and precision
    - increase granularity (n steps) and number of dimensions (d) in LH scan for $B \to K_1\pi$ decays: $\sim n^d$

A proposal for a strategy

Possible strategy:

- split data in $m_{\pi\pi\pi}$ ($m_{K\pi\pi}$) bins
  - kinematics allows to identify the primary π from B decay
- select a region in the $\pi\pi\pi$ ($K\pi\pi$) Dalitz plot with similar kinematics and resolution
- extract signal (i.e. correctly reconstructed B) contribution to each bin with a ML fit to m_{ES}, ΔE, $\mathcal{F}$ and correct for efficiency
- perform a (TD) partial wave analysis of the three-body system and look at resulting $m_{\pi\pi\pi}$ ($m_{K\pi\pi}$) spectrum

Feasibility should be investigated

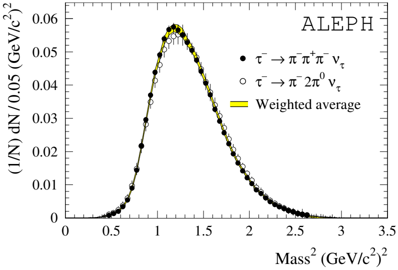
A closer look at decay constants

f_{a_1}

The determination of parameters of a broad resonance, i.e. $a_1(1260)$, is in general model dependent

- $\Gamma = 250 - 600\,\mathrm{MeV}$
- badly defined mass and width
- difficult to define a single weak decay constant
- test f_{a_1} in $B^+ \to \bar{D}^0 a_1^+$ decays? [Cheng, PRD 69, 074025]

ALEPH, EPJC 4, 409



Method	f_{a_1} (MeV)	Ref.
QCD sum rule	238 ± 10	NPB 776, 187
$f_{K_1(1270)}$ + SU(3)	$215 - 223$ *	PLB 623, 65
$\tau^- \to \pi^-\pi^+\pi^-\nu$	203 ± 18	PRD 60, 111502R

* depends on K_1 mixing angle

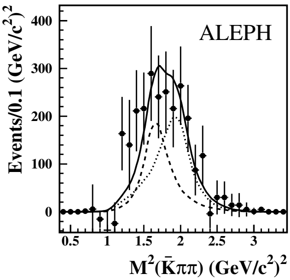
A closer look at decay constants
$f_{K_{1A}}$

$\tau \rightarrow K\pi\pi\nu$ decays:

- dominant $K_1(1270)$ component $\Rightarrow |f_{K_1(1270)}| = 175 \pm 19\,\text{MeV}$
- $K_1(1400)$ component not well measured
- $f_{K_1(1400)}$ from covariant quark model using $|f_{a_1}| = 203\,\text{MeV}$ as input [Cheng, PRD 69, 074025]

$$\Gamma(\tau \rightarrow K_1\nu_\tau) = \frac{G_F^2}{16\pi}|V_{us}|^2 f_{K_1}{}^2 \frac{(m_\tau^2 + 2m_{K_1}^2)(m_\tau^2 - m_{K_1}^2)^2}{m_\tau^3}$$

ALEPH, EPJC 11, 599



$K_{1A} \equiv K_1(1270)$ and $K_1(1400)$ mixture

- a consequence of SU(3) breaking
- $f_{K_{1A}}$ calculated from $f_{K_1(1270)}$ and $f_{K_1(1400)}$

$$f_{K_{1A}} = \frac{m_{K_1(1270)} f_{K_1}(1270) \sin\theta_{K_1} + m_{K_1(1400)} f_{K_1(1400)} \cos\theta_{K_1}}{m_{K_{1A}}}$$

Digression: mixing angle

Mixing angle can be obtained from

- $\tau \to K_1 \nu$ decays

$$\frac{\mathcal{B}(\tau \to K_1(1270)\nu)}{\mathcal{B}(\tau \to K_1(1400)\nu)} = \left| \frac{\sin\theta_{K_1} - \delta\cos\theta_{K_1}}{\cos\theta_{K_1} + \delta\sin\theta_{K_1}} \right|^2 \times \Phi$$

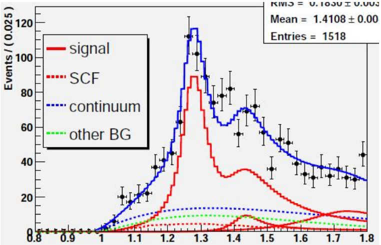
- K_1 decays to ρK and $K^*\pi$
- 4 solutions: $\theta_{K_1} = \pm 33^\circ, \pm 57^\circ$ [Suzuki, PRD47, 1252]
- used in most theory papers

Analysis of ACCMOR data yields $\theta_{K_1} \sim -72^\circ$

- not fully consistent with Suzuki's, but large uncertainties involved
- consistent with CLEO: $\theta_{K_1} = \pm 49^\circ, \pm 69^\circ$ [CLEO, PRD 62, 072006]
- used throughout BaBar analysis of $B \to K_1 \pi$ decays

How Super-B could help solving ambiguities:

- $B \to K_1 \gamma$ decays (Sanchez @ Warwick)



- $J/\psi \to K_1^0 \bar{K}^0$ decays [Cheng, PRD 67, 094007]

θ_{K_1} relevant for

- $\mathcal{B}(B \to K_{1A}\pi)$ from $\mathcal{B}(K_1\pi)$
- $f_{K_{1A}}$ from f_{a_1} and $f_{K_1(1270)}$
- estimates of several observables from phenomenology

A closer look at decay constants
$f_{K_{1A}}$

$f_{K_1(1400)}$ and $f_{K_{1A}}$ depend on mixing angle

- $f_{K_{1A}}(\theta_{K_1} = -57^\circ)$ available, $f_{K_{1A}}(\theta_{K_1} = -72^\circ)$ needed
- A naïve argument is used to test $f_{K_{1A}}$ variation with mixing angle

$$\frac{m_{K_1(1400)} f_{K_1(1400)}}{m_{K_1(1270)} f_{K_1(1270)}} = \frac{\cos\theta_{K_1} + \delta \sin\theta_{K_1}}{\sin\theta_{K_1} - \delta\cos\theta_{K_1}}$$

$$\cancel{SU(3)} \Rightarrow |\delta| = \frac{m_s - m_u}{\sqrt{2}(m_s + m_u)} \approx 0.18$$

$$f_{K_{1A}} = \frac{m_{K_1(1270)} f_{K_1(1270)} \sin\theta_{K_1} + m_{K_1(1400)} f_{K_1(1400)} \cos\theta_{K_1}}{m_{K_{1A}}}$$

$$m_{K_{1A}}{}^2 = m^2_{K_1(1270)} \sin^2\theta_{K_1} + m^2_{K_1(1400)} \cos^2\theta_{K_1}$$

$$\theta_{K_1} = -57^\circ \Rightarrow |f_{K_{1A}}| = 207\text{ MeV}$$
$$\theta_{K_1} \to -72^\circ \Rightarrow |f_{K_{1A}}| \searrow 20 \div 30\text{ MeV}$$

Worst case scenario yields a $1^\circ \div 2^\circ$ effect on $\Delta\alpha$ bound, when combined with the other uncertainties

SU(3) symmetry

SU(3) with $B^0 \to \rho^+\rho^-$ decays (and $K^*\rho$) [BaBar, PRD 76, 052007]:

- SU(3) breaking correction from neglected annihilation diagrams
- $O(2^\circ)$ precision: limited by theory uncertainties (A. Bevan @ Warwick) [Beneke, PLB 638, 68]

SU(3) with $B^0 \to a_1(1260)^\pm\pi^\mp$

- analysis of ACCMOR data in K_1 system
  - ~~SU(3)~~ $\Rightarrow$ mixing
  - SU(3) relations between decay constants
- extraction of decay constants
- ~~SU(3)~~ $\Rightarrow$ ratios of decay constants in $R^+_\pm$, $R^0_\pm$
  - annihilation diagrams: study $B^0 \to K_1^\pm K^\mp$ decays! $\mathcal{B} = O(10^{-7})$ [Cheng, PRD76, 114020]
  - may also shed light on high $\mathcal{B}(B \to K_1\pi)$

Outline

Summary

- So far, α from $a_1\pi$ has been a BaBar-only business
  - Very recent α estimate, as a result of a long-term effort
  - More educated estimates of Super-B reach after cross-check by Belle
- $(P/T)_{\rho\rho} < (P/T)_{a_1\pi} < (P/T)_{\rho\pi} < (P/T)_{\pi\pi}$
  - ☺: $(P/T)_{a_1\pi}$ smaller than $(P/T)_{\rho\pi}$ and $(P/T)_{\pi\pi}$
  - ☹: rely on SU(3)
- SU(3) based bounds on $\Delta\alpha \Rightarrow$ resume full SU(3) fit to get $\Delta\alpha$?
- Getting the most out of $B \rightarrow a_1\pi$ decays at a Super-B factory is not an experimental matter only
  - will benefit from some guidance from theory
  - analysis of τ, $c\bar{c}$, D and B decays (interesting on their own) would pin down theoretical and model uncertainties
- ☺: "redundant", independent measurement of α
  - How will $\alpha_{a_1\pi}$ be used? Should any discrepancy be interpreted as hint of NP? or SM "background"? or model uncertainties?