Addressing hadronic uncertainties in extractions of ϕ_s

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CKM 2014 workshop

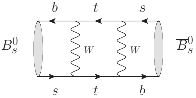
Vienna, 8 - 12 September 2014

IAS TUM Institute for Advanced Study

Probing ϕ_s with $B_s \to J/\psi\, \boldsymbol{s\bar{s}}$ decays

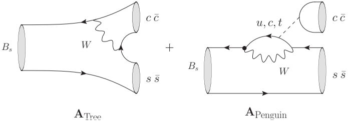
$?$

$e^{i\phi_s}$



Mixing-induced CP violation $\longleftrightarrow$

$e^{i\Delta\phi_f}$



$?$

$B_s \to J/\psi\,(s\bar{s} = \phi)$

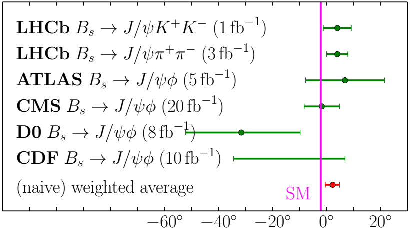
$\{\phi(1020), \underbrace{f_0(980), \ldots\}}_{\text{small S-wave}} \to K^+K^-$

$B_s \to J/\psi\,(s\bar{s} = \boldsymbol{f_0(980)})$

S.Stone, L.Zhang; 0812.2832

$\{f_0(980), \ldots\} \to \pi^+\pi^-$

$\phi_s + \Delta\phi_f$



Are we sensitive to smallish New Physics?

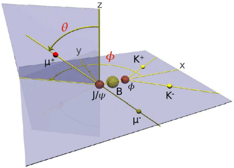
Address assumptions $\boldsymbol{\Delta\phi_f = 0}$ and $\boldsymbol{f_0(980) = s\bar{s}}$

Note: $\Delta\phi_f = 0$ at tree-level is convention dependent. Strictly $\phi_s^{\rm SM} \equiv -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$.

Extracting ϕ_s from $B_s \to J/\psi\phi$

4 transversity amplitudes:
CP even: $\parallel$, **0**
CP odd: $\perp$, **S**

Disentangle with angular analysis!



$$\overset{(-)}{A}_h \equiv A(\overset{(-)}{B}{}^0_s \to (J/\psi K^+K^-)_h)$$
$$h \in \{\parallel, \perp, 0, \mathrm{S}\}$$

20 angular observables:
$$\left|\overset{(-)}{A}_h(t)\right|^2, \ \mathrm{Im}\left(\overset{(-)}{A}_h \overset{(-)}{A}{}^*_{h'}\right), \ \mathrm{Re}\left(\overset{(-)}{A}_h \overset{(-)}{A}{}^*_{h'}\right)$$

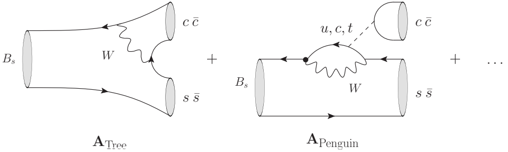
Key time-dependent observables:
$$\frac{|A_h(t)|^2 - |\overline{A_h}(t)|^2}{|A_h(t)|^2 + |\overline{A_h}(t)|^2} = \frac{\boldsymbol{C_h} \cos(\Delta M_s t) + \boldsymbol{S_h} \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t) + \boldsymbol{\mathcal{A}^h_{\Delta\Gamma}} \sinh(\Delta\Gamma_s t)}$$

$$\lambda_h \equiv \frac{q}{p}\frac{\overline{A_h}}{A_h} = -e^{-i\phi_s} \underbrace{\eta_h}_{\text{CP eval}} \sqrt{\frac{1-\boldsymbol{C_h}}{1+\boldsymbol{C_h}}}\, e^{-i\boldsymbol{\Delta\phi_h}}$$

($\boldsymbol{C_h}$: direct CPV)

e.g. $\boldsymbol{S_h} = \dfrac{2\mathrm{Im}(\lambda_h)}{1+|\lambda_h|^2} = \eta_h\sqrt{1-\boldsymbol{C_h}}\sin(\phi_s + \Delta\phi_h)$ for each h $\in \{\parallel, \perp, 0, \mathrm{S}\}$

Penguin pollution in $B_s \to J/\psi\phi$



$\text{h} \in \{\parallel, \perp, 0, \text{S}\}$

$$b_h\, e^{i\theta_h} \equiv R_b \left(\frac{A^u_{\text{P,h}} - A^t_{\text{P,h}} + \ldots}{A_{\text{T,h}} + A^c_{\text{P,h}} - A^t_{\text{P,h}} + \ldots} \right)$$

Penguins loop and OZI rule suppressed: $b \sim \mathcal{O}(10^{-2})$

Non-perturbative hadronic enhancements?

$$A(B_s^0 \to (J/\psi s\bar{s})_h) = A_{\text{T,h}} V^*_{cb} V_{cs} + A^u_{\text{P,h}} V^*_{ub} V_{us} + A^c_{\text{P,h}} V^*_{cb} V_{cs} + A^u_{\text{P,h}} V^*_{tb} V_{ts} + \ldots$$

$$\stackrel{\text{SM}}{=} \mathcal{A}_h \left[1 + \underbrace{\epsilon}_{0.05} e^{i\gamma}\, b_h\, e^{i\theta_h} \right], \qquad \left(\epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \right)$$

$$\boldsymbol{C_h} \approx (-10\%) \times b_h \sin\theta_h$$
$$\boldsymbol{\Delta\phi_h} \approx (6^\circ) \times b_h \cos\theta_h$$

S.Faller, R.Fleischer, T.Mannel; 0810.4248

LHCb $B_s \to J/\psi K^+ K^-$ analysis included *universal* $\boldsymbol{C} \neq 0$ ($|\lambda| \neq 1$):

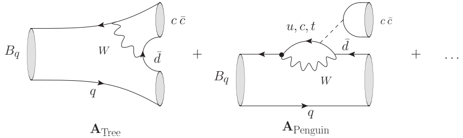
$$\boldsymbol{C} = (6 \pm 4)\%$$

LHCb: 1304.2600

Controlling penguins via flavour symmetry

$SU(3)_F$ flavour symmetry: u, d, s degenerate in QCD

$$(m_s - m_{u,d})/\Lambda_{QCD} \sim f_{B_s}/f_{B_d} - 1 \sim \textbf{20\% broken}$$



$$A(B_q \to (J/\psi\, \bar{d}\, q)_h) \overset{SU(3)_F}{=} -\lambda\, \mathcal{A}_h \left[1 - \underbrace{\epsilon\!\!\!/}_{1}\, e^{i\gamma}\, b_h\, e^{i\theta_h} \right]$$

Candidate (future) control channels: S.Faller, R.Fleischer, T.Mannel; 0810.4248

- $B_s^0 \to J/\psi \bar{K}^{0*}$ - flavour specific: combine $\boldsymbol{C_h}$ with Γ_h

  $\overline{\mathrm{BR}}(B_s \to J/\psi \bar{K}^{0*}) = (4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$, LHCb: 1208.0738

- $B_d^0 \to J/\psi \rho^0$ - also mixing-induced CP observables $\boldsymbol{S_h}$

  $\mathrm{BR}(B_d \to J/\psi \rho^0) = (2.50 \pm 0.10^{+0.18}_{-0.15}) \times 10^{-5}$, LHCb: 1404.5673

Note: K^{0*}, ρ^0 $SU(3)_F$ octets, whereas $\phi = s\bar{s}$ includes a singlet $\{\phi_0, \phi_8\}$

Flavour symmetry: examples and breaking corrections

Example: penguin pollution in $B_d \to J/\psi\, K_S$: extracting $\phi_d + \Delta\phi_{J/\psi K_S}$

Control channel: $B_d \to J/\psi\, \pi^0$

S. Faller, R. Fleischer, M. Jung, T. Mannel, PRD 79 014030 (2009)

$$\boxed{\delta(\Delta\phi_{J/\psi K_S}) = \mathcal{O}(1^\circ)}$$

M. Ciuchini, M. Pierini, L. Silvestrini, PRL 95 221804 (2005)/ 1102.0392

Including also $B_s \to J/\psi\, K_S$ results + other $SU(3)_F$ related decays:

$$\Delta\phi_{J/\psi K_S} = (-0.97^{+0.72}_{-0.65})^\circ \qquad \left[b = 0.17^{+0.13}_{-0.06}, \quad \theta = \left(182.4^{+21.2}_{-21.3}\right)^\circ\right]$$

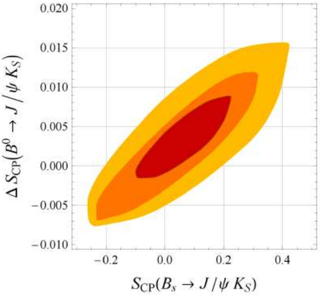
K.De Bruyn, R.Fleischer - in preparation; R.Fleischer BEACH 2014 talk

$SU(3)_F$ breaking corrections

Full fit of $B_{u,d,s} \to J/\psi\, \{K, \pi, (\eta_8)\}$ including linear $SU(3)_F$ breaking terms

M. Jung, Phys.Rev. D86 053008 (2012)

- Breaking terms crucial for goodness of fit
- $\Delta\phi_{J/\psi K_S} \lesssim 1^\circ$
- similarly eventually apply to $B_{u,d,s} \to J/\psi\{\phi, \omega, \rho, K^*\}$



Extracting ϕ_s form $B_s \to J/\psi\pi^+\pi^-$

LHCb analysis of $B_s \to J/\psi X; X \to \pi^+\pi^-$

LHCb 1402.6248, 1405.4140, L. Zhang, S. Stone 1212.6434.

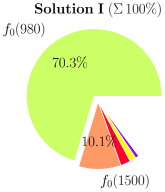
- $\boldsymbol{f_0}$**(980)** 70% or 92% dominant
- Sum of resonances 97.5% CP-odd @95% CL

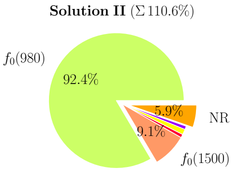
allowing for *universal* direct CPV $\boldsymbol{C_{\pi\pi}} \neq 0$ ($|\lambda| \neq 1$)

$$\boldsymbol{C_{\pi\pi}} = -\underbrace{2\epsilon \sin\gamma}_{10\%}\, b_{\pi\pi} \sin\theta_{\pi\pi} + \mathcal{O}(\epsilon^2) \stackrel{\text{exp}}{=} (11.6 \pm 5.5)\%$$

$$\boldsymbol{\Delta\phi_{\pi\pi}} = \underbrace{2\epsilon \sin\gamma}_{6^\circ}\, b_{\pi\pi} \cos\theta_{\pi\pi} + \mathcal{O}(\epsilon^2) = \quad \textbf{??}$$

Resonance model fits



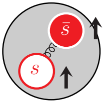


How well are light scalar states (0^{++}) understood?

Is the f_0(980) an $s\bar{s}$ state?

What is the $f_0(980)$? $(J^{PC} = 0^{++})$

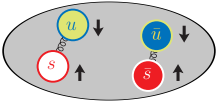
$q\bar{q}$ state



[from here on: $f_0 \equiv f_0(980)$ and $\sigma \equiv f_0(500)$]

$$\begin{pmatrix} f_0 \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos\varphi_M & \sin\varphi_M \\ -\sin\varphi_M & \cos\varphi_M \end{pmatrix} \begin{pmatrix} s\bar{s} \\ \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \end{pmatrix}$$

tetraquark state
$[qq][\bar{q}\bar{q}]$



$$\begin{pmatrix} f_0 \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]) \\ [ud][\bar{u}\bar{d}] \end{pmatrix}$$

Small mixing $\omega \lesssim 5^\circ$ predicted?

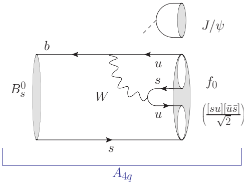
L.Maiani, F.Piccinini, A.Polosa, V.Riquer - hep-ph/0407017;

G.'t Hooft, G.Isidori, L.Maiani, A.Polosa, V.Riquer - 0801.2288

(a mixture, or a KK molecule . . .)

Extra decay topologies possible

R.Fleischer, RK, G.Ricciardi; 1109.1112



Constraints from $B_d \to J/\psi \pi^+ \pi^-$

BR prediction in tetraquark picture: *R.Fleischer, RK, G.Ricciardi; 1109.1112*

$$\mathrm{BR}(B_d \to J/\psi f_0\,[\to \pi^+\pi^-])\big|_{\mathrm{tetraquark}} \sim (1\text{–}3) \times 10^{-6}$$

LHCb bound: $< \mathbf{1.1 \times 10^{-6}}$ (90% CL) *LHCb: 1301.5347*

Predicted relation to σ decay: *S.Stone, L.Zhang; PRL 111, 6 (2013) - 1305.6554*

$$\frac{\mathrm{BR}(B_d \to J/\psi f_0)}{\mathrm{BR}(B_d \to J/\psi \sigma)} \underbrace{\frac{\Phi_d(\sigma)}{\Phi_d(f_0)}}_{\text{phase space}} \sim \begin{cases} \tan^2 \varphi_M & : \quad q\bar{q} \\ \frac{1}{2} & : \quad \text{tetraquark} \end{cases}$$

LHCb bound: $0.011^{+0.012}_{-0.007}{}^{+0.060}_{-0.047}$ or $< \mathbf{0.098}$ (90% CL) *LHCb: 1404.5673*

Conclude: (?)

- tetraquark picture ruled out by $8\,\sigma$
- f_0 mostly $s\bar{s}$ due to $\varphi_M < 17^\circ$ (90% CL)

Another look at the tetraquark picture (I)

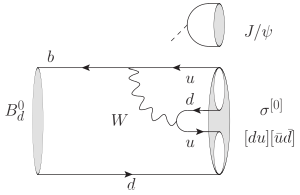
R.Fleischer, RK, G.Riciardi in preparation

Sub-leading topologies?

In $B_d \to J/\psi(d\bar{d})$ sub-leading topologies not CKM suppressed!

Unique topology for $B_d \to J/\psi[ud][\bar{u}\bar{d}]$

Enhancing $B_d \to J/\psi\sigma$?



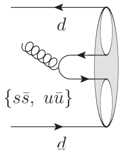
Non-trivial mixing?

- Bound $\omega \lesssim 5^\circ$ from 2004 using $m_\kappa = 797$ MeV ($\kappa = [su][\bar{u}\bar{d}]; \ldots$)

L.Maiani, F.Piccinini, A.Polosa, V.Riquer - hep-ph/0407017;

G.'t Hooft, G.Isidori, L.Maiani, A.Polosa, V.Riquer - 0801.2288

- With updated mass $m_\kappa = 682$ MeV (PDG) we find $\boxed{\omega \approx 20^\circ}$



$$f_0 = \cos\omega \left(\frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}} \right) - \sin\omega\,[ud][\bar{u}\bar{d}]$$

From $d\bar{d}$ seed f_0 production vanishes at:

$$\omega = \tan^{-1}(1/\sqrt{2}) \simeq 35^\circ \quad (SU(3)_{\mathrm{F}} \text{ limit})$$

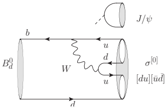
Another look at the tetraquark picture (II)

R.Fleischer, RK, G.Riciardi in preparation

$$H^{d,f}_{d,\sigma} \equiv \frac{\mathbf{BR}(B_d \to J/\psi\, f_0)}{\mathbf{BR}(B_d \to J/\psi\, \sigma)} \frac{\Phi_d(\sigma)}{\Phi_d(f_0)} \left|\frac{\mathcal{A}'_\sigma}{\mathcal{A}_{f_0}}\right|^2_{\omega=0}, \quad H^{s,f}_{d,\sigma} \equiv \frac{\mathbf{BR}(B_s \to J/\psi\, f_0)}{\mathbf{BR}(B_d \to J/\psi\, \sigma)} \frac{\Phi_d(\sigma)}{\Phi_s(f_0)} \epsilon \left|\frac{\mathcal{A}'_\sigma}{\mathcal{A}_{f_0}}\right|^2_{\omega=0}$$

$$\overset{\text{exp}}{=} 0.023^{+0.131}_{-0.102} < 0.24\ (95\%\ \text{CL}) \qquad \overset{\text{exp}}{=} 0.61^{+0.32}_{-0.23}$$

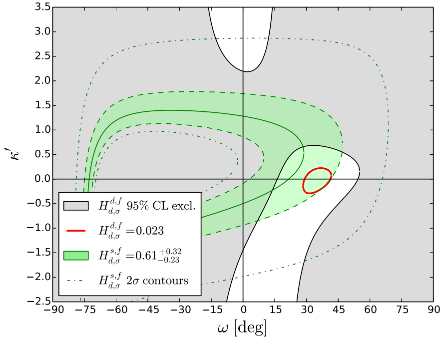
$\boldsymbol{H \to 1}$ for no mixing and no sub-leading topologies



Relative size special topology:

$$\kappa' \equiv R_b \frac{\tilde{A}'_{4q}}{\tilde{A}^{(c)}_{\mathrm{T}} + \tilde{A}^{(c)}_{\mathrm{P}}}$$

For illustration: $\kappa' \in \mathcal{R}$, $b^{(\prime)} = 0$



- moderate mixing $\omega \sim 20^\circ$ **resolves all experimental tensions**
- sizable $\tilde{A}'_{4q}$ topology could be present ($|\kappa'| \sim 0.5$)

Consequences of f_0 tetraquark picture

$$H_{d,\sigma}^{s,f} \equiv \frac{\mathbf{BR}(\boldsymbol{B_s \to J/\psi f_0})}{\mathbf{BR}(\boldsymbol{B_d \to J/\psi \sigma})} \frac{\Phi_d(\sigma)}{\Phi_s(f_0)} \epsilon \left| \frac{\mathcal{A}'_\sigma}{\mathcal{A}_{f_0}} \right|^2 \overset{\text{exp}}{=} 0.61^{+0.32}_{-0.23}$$

$$\to \left\{ \begin{array}{ccc} 1 & : & q\bar{q} \quad \forall \text{ mixing} \\ \left| \frac{1}{1+\frac{1}{\sqrt{2}}\tan\omega} \right|^2 & : & \text{tetraquark} \end{array} \right\} \text{neglecting sub-leading topologies}$$

$$\therefore \quad \boxed{H_{d,\sigma}^{s,f} \text{ ratio to watch}}$$

For sizable $|\kappa'| \sim 0.5$ and $\tilde{A}_{4q} \sim \tilde{A}'_{4q}$,
extraction of ϕ_s from $B_s \to J/\psi f_0$ has:

$$\Delta\phi_{f_0} \approx \underbrace{\epsilon \sin\gamma}_{3^\circ} \cdot \text{Re}(\kappa) \sim \pm \mathbf{1.5^\circ}$$

Nature of f_0 relevant for $B_d \to J/\psi \pi^+\pi^-$ analysis!

Conclusions

- Excellent exp. ϕ_s progress from $B_s \to J/\psi\,\{K^+K^-, \pi^+\pi^-\}$
  $\to$ (alas) no clear signal of NP
- Sensitivity to small NP requires **control of hadronic uncertainties** in decays e.g. penguin diagrams

- Treat uncertainties in $B_s \to (J/\psi\, s\bar{s})_{\parallel,\perp,0,S}$ **separately**
  $\to$ can control with flavour symmetry related modes
  $\to$ eventually full $SU(3)$ fit including breaking corrections
- Suitability of $f_0(980)$ for precision ϕ_s extractions **debatable**
  $\to$ tetraquark picture still compatable with data
  $\to$ unique tetraquark dynamics give sizable uncertainty
- **Average** $\phi_s + \Delta\phi_f$ results **carefully**

Backup

General approach

$$\left(\overset{(-)}{A}_h \equiv A(\overset{(-)}{B}{}^0_s \to (J/\psi K^+ K^-)_h) = |\overset{(-)}{A}_h| e^{i \overset{(-)}{\delta}_h} \right) \quad \text{for} \quad h \in \{\|, \perp, 0, \mathrm{S}\}$$

Assuming no penguin pollution:

$$\overline{A}_h = A_h \quad \Longrightarrow \quad |A_\||, |A_\perp|, |A_0|, |A_\mathrm{S}|, \delta_\| - \delta_0, \delta_\perp - \delta_0, \delta_\mathrm{S} - \delta_0, \phi_s \quad \text{(8 params)}$$

Flavour symmetry approach assumes SM:

$$A_h \overset{SM}{=} \mathcal{A}_h \left(1 + \epsilon\, b_h e^{i\theta_h} e^{i\gamma}\right), \quad \overline{A}_h \overset{SM}{=} \mathcal{A}_h \left(1 + \epsilon\, b_h e^{i\theta_h} e^{-i\gamma}\right)$$

General approach: no assumptions *B. Bhattacharya, A. Datta, D. London, 1209.1413*

$$|A_h|, |\overline{A}_h|, \quad \left.\begin{array}{l} \overset{(-)}{\delta}_{hh'} \equiv \arg(\overset{(-)}{A}_h) - \arg(\overset{(-)}{A}_{h'}) \\ D_{hh'} \equiv \arg(\overline{A}_h) - \arg(A_{h'}) \end{array}\right\} \text{7 indep.}, \phi_s \quad \text{(16 params)}$$

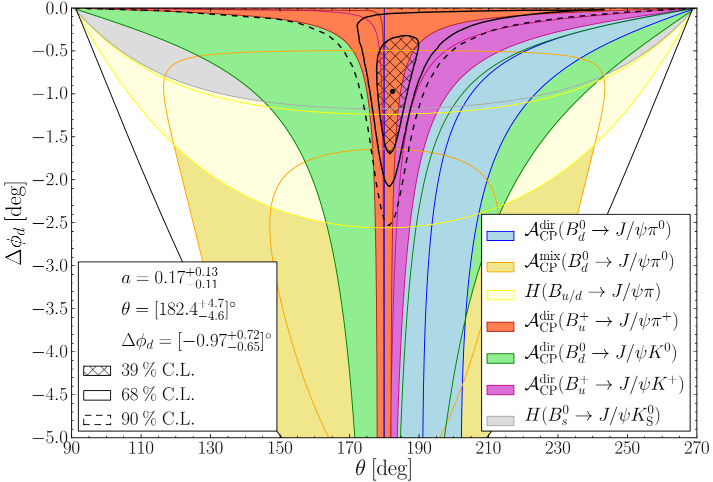
- Still can't isolate ϕ_s - need **one** theoretical assumption **e.g.** $D_{00} = 0 \ldots$

$$D_{00} = \arg(A_0^* A_0) \overset{\mathrm{SM}}{\approx} 2\epsilon b_0 \cos\theta \sin\gamma = \Delta\phi_0$$

- **Upshot: only 1 assumption $>$ 8 assumptions**

Penguin pollution in ϕ_d extraction

K.De Bruyn, R.Fleischer - in preparation; R.Fleischer BEACH 2014 talk



Tetraquark picture

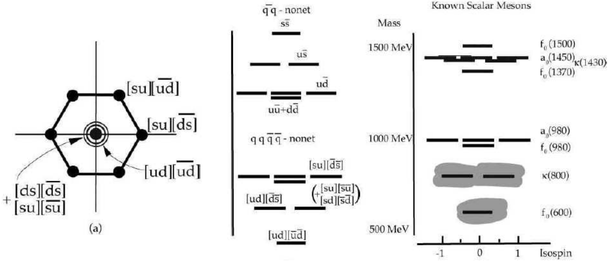
tetraquark: diquark–antidiquark (colour) bound state

$$\text{diquark} \equiv [q_1\, q_2],\ \text{colour}\ \bar{\mathbf{3}},\ \text{flavour}\ \bar{\mathbf{3}},\ S = 0$$

- light scalar nonet:

$$\sigma = [ud][\bar{u}\bar{d}] \qquad \kappa = [su][\bar{u}\bar{d}];\, [sd][\bar{u}\bar{d}]\ \ (+\mathrm{c.d})$$

$$f_0 = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}} \qquad a_0 = [su][\bar{s}\bar{d}];\, \frac{[su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]}{\sqrt{2}};\, [sd][\bar{s}\bar{u}]$$



R.Jaffe; hep-ph/0409065

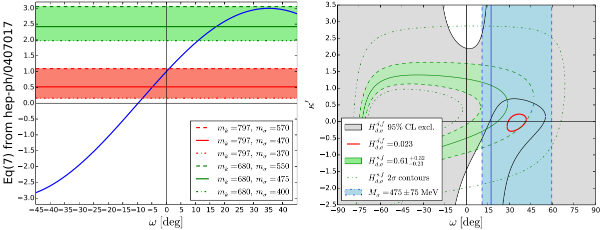
Tetraquark mixing angle estimate

Assuming $M_{f_0}^2 = M_{a_0}^2$, estimate of mixing angle is:

L.Maiani, F.Piccinini, A.Polosa, V.Riquer; hep-ph/0407017

$$\cos 2\omega + 2\sqrt{2}\sin 2\omega = 1 + 4\frac{M_{a_0}^2 + M_\sigma^2 - 2M_\kappa^2}{M_{a_0(980)}^2 - M_\sigma^2}$$

Update $M_\kappa = 797 \pm 19 \pm 43\ \mathrm{MeV} \rightarrow M_\kappa = 682 \pm 29\ \mathrm{MeV}$ (PDG)



Using instead data from strong/EM decays of light scalars:

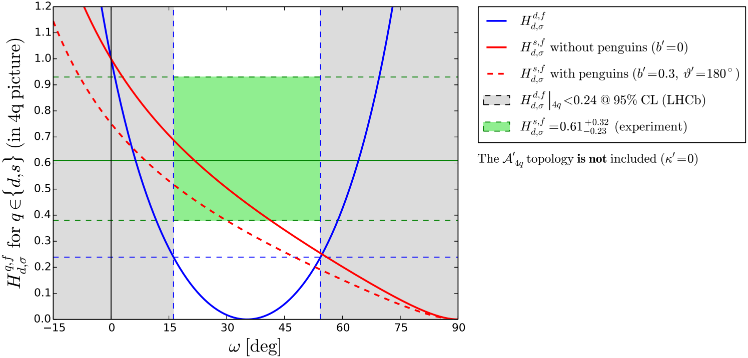
F.Giacosa - hep-ph/0605191

$$\omega = -12^\circ\ (\tfrac{\chi^2}{3} = 0.65),\ \omega = 21.6^\circ\ (\tfrac{\chi^2}{2} = 5.17),\ \omega = 35.8^\circ\ (\tfrac{\chi^2}{4} = 2.04)$$

or: *F.Giacosa, G.Pagliara - 0905.3706*

$$\omega = (1.2 \pm 8)^\circ\ (\chi^2 = 1.17)$$

Impact of penguins on tetraquark picture



The $\mathcal{A}'_{4q}$ topology **is not** included ($\kappa'=0$)

R.Fleischer, RK, G.Riciardi in preparation