Addressing hadronic uncertainties in extractions of ϕ_s

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LHCb implications workshop

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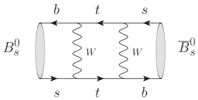
IAS TUM Institute for Advanced Study

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

?

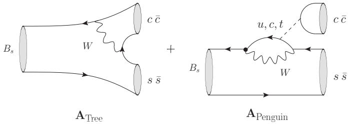
$e^{i\phi_s}$



Mixing-induced CP violation

$\longleftrightarrow$

$e^{i\Delta\phi_f}$



?

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

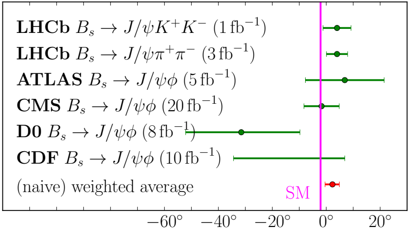
$$\{\phi(1020), \underbrace{f_0(980), \ldots}_{\text{small S-wave}}\} \to K^+K^-$$

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

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 $\Delta\phi_f \approx 0$ and $f_0(980) \approx s\bar{s}$

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

$$B_s \to J/\psi K^+ K^-$$

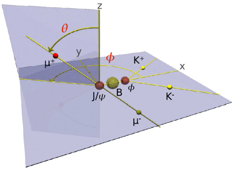
Extracting ϕ_s from $B_s \to J/\psi\phi$

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:

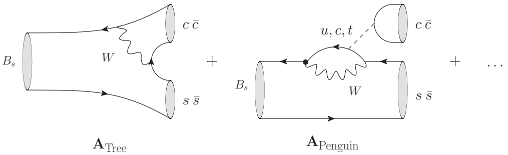
$$\frac{|A_h(t)|^2 - |\overline{A}_h(t)|^2}{|A_h(t)|^2 + |\overline{A}_h(t)|^2} = \frac{\boldsymbol{C_h}\cos(\Delta M_s t) + \boldsymbol{S_h}\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t) + \boldsymbol{\mathcal{A}^h_{\Delta\Gamma}}\sinh(\Delta\Gamma_s t)}$$

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

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

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

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



$\mathrm{h} \in \{\|, \perp, 0, \mathrm{S}\}$

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

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

H. Boos, T. Mannel, J. Reuter; hep-ph/0403085

Non-perturbative hadronic enhancements?

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

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

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

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

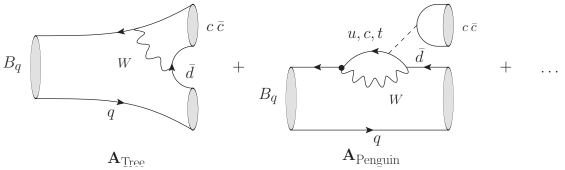
LHCb 1/fb $B_s \to J/\psi K^+ K^-$ analysis included *universal* $\boldsymbol{C} \neq 0$ ($|\lambda| \neq 1$):

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

LHCb: 1304.2600

Controlling penguins via flavour symmetry

$SU(3)_\mathrm{F}$ flavour symmetry: u, d, s degenerate in QCD



$$A(B_q \to (J/\psi\, \bar{d}\, q)_h) = -\lambda\, \mathcal{A}'_h \left[1 - \underbrace{\epsilon\!\!\!/}_{1}\, e^{i\gamma}\, b'_h\, e^{i\theta'_h} \right]$$

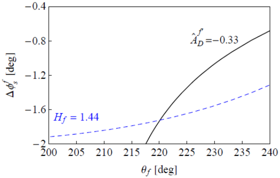
In $SU(3)_\mathrm{F}$ limit:

$$\boxed{\mathcal{A}'_h = \mathcal{A}_h, \quad b'_h = b_h, \quad \theta'_h = \theta_h}$$

$SU(3)_\mathrm{F}$ is $(m_s - m_{u,d})/\Lambda_\mathrm{QCD} \sim f_{B_s}/f_{B_d} - 1 \sim$ **20−30% broken**

Candidate control channels for $B_s \to J/\psi\phi$

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



$$\boxed{B_s^0 \to J/\psi \bar{K}^{0*}}$$

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

$$f_\perp = 0.50 \pm 0.08 \pm 0.02, \quad f_0 = 0.19^{+0.10}_{-0.08} \pm 0.02,$$

LHCb: 1208.0738

- **flavour specific** $\bar{K}^{0*} \to \pi^+ K^-$: combine $\boldsymbol{C_h}$ (direct CPV) with:

$$\boldsymbol{H_h} \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}_h}{\mathcal{A}'_h}\right|^2 \frac{\Gamma[B_s \to \left(J/\psi\bar{K}^{0*}\right)_h, t=0]}{\Gamma[B_s \to (J/\psi\phi)_h, t=0]} = \frac{1 - 2\, b'_h \cos\theta'_h \cos\gamma + {b'_h}^2}{1 + 2\epsilon\, b_h \cos\theta_h \cos\gamma + \epsilon^2 b_h^2}$$

- $|\mathcal{A}_h/\mathcal{A}'_h|^2$ subject to large $SU(3)$ breaking corrections
- "Direct CPV measurement and 3/fb update ongoing!" W.Kanso, CKM 2014

$$\boxed{B_d^0 \to J/\psi\rho^0}$$ 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 $SU(3)_\mathrm{F}$ octets, whereas $\phi = s\bar{s}$ includes a singlet $\{\phi_0, \phi_8\}$

Flavour symmetry in action

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

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

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

$$\delta(\Delta\phi_{J/\psi K_{\rm S}}) = \mathcal{O}(1^\circ)$$

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

Including also $B_s \to J/\psi\, K_{\rm S}$ results + other $SU(3)_{\rm F}$ related decays:

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

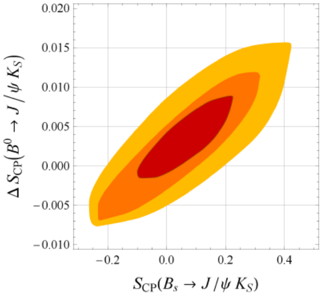
K.De Bruyn, R.Fleischer - in preparation; R.Fleischer BEACH 2014 talk

$SU(3)_{\rm F}$ breaking corrections

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

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

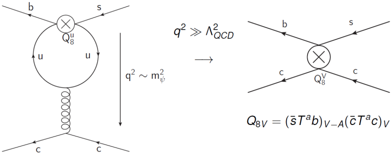
- Breaking terms crucial for goodness of fit
- $\Delta\phi_{J/\psi K_{\rm S}} \lesssim 1^\circ$
- similarly eventually apply to $B_{u,d,s} \to J/\psi\{\phi, \omega, \rho, K^*\}$



Calculating the u-quark penguin

$$\text{effective theory}: \quad \mathcal{H}^{\Delta B=1} = \sum_{q=u,c} V_{qb} V_{qs}^{*} \left(C_0 Q_0^q + C_8 Q_8^q + \sum_{i=3}^{6} C_i Q_i \right)$$

- **Idea**: exploit large $q^2 \sim m_{J/\psi}^2 \gg \Lambda_{\rm QCD}^2$ through u-quark loop
  M. Bander, D. Soni, A. Silverman; Phys. Rev. Lett. 44 (1980)
- **New result**: factorization proof + $1/N_c$ expansion
  preliminary: P. Frings, U. Nierste, M. Wiebusch; CKM 2014



u-penguin $\rightarrow$ effective vertex:

$$Q_{8V} = (\bar{s}\, t^a b)_{V-A} (\bar{c}\, t^a c)_V$$

soft + collinear divergences factorize

Postulate: $\langle f | Q_{8V} | B_q \rangle \leq \frac{1}{N_c} \langle f | Q_0 | B_q \rangle$

$$\langle f | Q_0 | B_q \rangle = 2\, f_\psi\, m_{B_q}\, p_{\rm cm}\, F_1 \left(1 + \mathcal{O}\left(\frac{1}{N_c^2}\right)\right)$$

Conservative upper bounds: $\left|\Delta \phi_s^{||(,\dots)}\right| \leq 1.2^\circ, \quad |\Delta \phi_d| \leq 0.9^\circ$

General approach

Assuming no penguin pollution:

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

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.** $D_{00} = 0 \ldots$

$$D_{00} = \arg(A_0^* A_0) \overset{\mathrm{SM}}{\approx} 2\epsilon b_0 \cos\theta_0 \sin\gamma = \Delta\phi_0$$

Upshot: only 1 assumption $>$ 8 assumptions

$B_s \to J/\psi\pi^+\pi^-$

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

LHCb analyses 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

CP violation measurement: (3/fb)

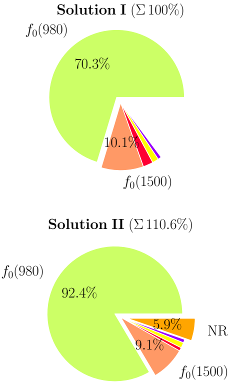
$$\phi_s + \Delta\phi_{\pi\pi} = (4 \pm 4)^\circ$$

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

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

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

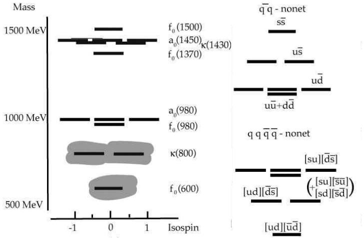
Resonance model fits



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

if not, is that problematic?

The light scalar states below 1 GeV ($J^{PC} = 0^{++}$)



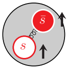
R.Jaffe; hep-ph/0409065

- Nature of light scalars long-standing debate
  (e.g. PDG note on scalars; Klempt, Zaitsev - 0708.4016)
- If $q\bar{q}$ P-waves **expect** inverted nonet mass hierarchy and $\sim \frac{1}{2}$ GeV heavier than $\{\phi, \omega, K^*, \rho\}$ nonet
- popular interpretations include $[qq][\bar{q}\bar{q}]$ **tetraquarks**, **meson-meson molecules**, or some **mixture**

Isosinglets $f_0 = f_0(980)$ and $\sigma = f_0(500)$ can mix:

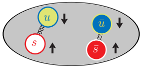
$\boldsymbol{q\bar{q}}$

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



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

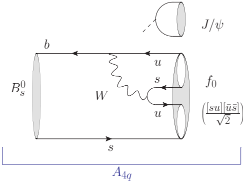
$$\begin{pmatrix} f_0 \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]) \\ [ud][\bar{u}\bar{d}] \end{pmatrix}$$



f_0: $q\bar{q}$ vs tetraquark picture

- different decay dynamics possible for $B_s \to J/\psi f_0$ *R.Fleischer, RK, G.Riciardi; 1109.1112*

$$\Delta\phi_{J/\psi f_0} \in [-3^\circ, 3^\circ]$$



- $B_d \to J/\psi f_0$ potential control channel
- Assuming $\omega \lesssim 5^\circ$: *Maiani, Piccinini, Polosa, Riquer - hep-ph/0407017; 't Hooft, Isidori, Maiani, Polosa, Riquer - 0801.2288*

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

Adding σ to the mix:

$$r^{d,f_0}_{d,\sigma} \equiv \frac{\mathrm{BR}(B_d \to J/\psi\, f_0)}{\mathrm{BR}(B_d \to J/\psi\, \sigma)}\frac{\Phi_d(\sigma)}{\Phi_d(f_0)} \sim \begin{cases} \tan^2\varphi & : \quad q\bar{q} \\ \frac{1}{2} & : \quad \mathrm{tetraquark}\ (\omega = 0^\circ) \end{cases}$$

$$r^{s,\sigma}_{s,f_0} \equiv \frac{\mathrm{BR}(B_s \to J/\psi\, \sigma)}{\mathrm{BR}(B_s \to J/\psi\, f_0)}\frac{\Phi_s(f_0)}{\Phi_s(\sigma)} \sim \begin{cases} \tan^2\varphi & : \quad q\bar{q} \\ 0 & : \quad \mathrm{tetraquark}\ (\omega = 0^\circ) \end{cases}$$

S.Stone, L.Zhang; PRL 111, 6 (2013) - 1305.6554

Confrontation with experiment

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

$$\mathrm{BR}(B_d \to J/\psi f_0\,[\to \pi^+\pi^-]) < \mathbf{1.1 \times 10^{-6}}\ (90\%\ \mathrm{CL})$$ *LHCb: 1301.5347*

$$r^{d,f_0}_{d,\sigma} \equiv \frac{\mathrm{BR}(B_d \to J/\psi f_0)}{\mathrm{BR}(B_d \to J/\psi \sigma)} \frac{\Phi_d(\sigma)}{\Phi_d(f_0)} \overset{\dagger}{\sim} \begin{cases} \tan^2\varphi & : \quad q\bar{q} \\ \frac{1}{2} & : \quad \mathrm{tetraquark}\ (\omega = 0^\circ) \end{cases}$$

$$r^{d,f_0}_{d,\sigma} = 0.011^{+0.012\,+0.060}_{-0.007\,-0.047} < \mathbf{0.098}\ (90\%\ \mathrm{CL})$$ *LHCb: 1404.5673*

$$r^{s,\sigma}_{s,f_0} \equiv \frac{\mathrm{BR}(B_s \to J/\psi\, \sigma)}{\mathrm{BR}(B_s \to J/\psi\, f_0)} \frac{\Phi_s(f_0)}{\Phi_s(\sigma)} \overset{\dagger}{\sim} \begin{cases} \tan^2\varphi & : \quad q\bar{q} \\ 0 & : \quad \mathrm{tetraquark}\ (\omega = 0^\circ) \end{cases}$$

$$r^{s,\sigma}_{s,f_0} < \mathbf{0.018}\ (90\%\ \mathrm{CL})$$ *LHCb: 1402.6248*

Conclusions?

- $r^{d,f_0}_{d,\sigma}$ result rules out tetraquark picture ("$8\,\sigma$")
- f_0 mostly $s\bar{s}$ due to small mixing φ

† Caveats

- sizable asymmetries possible in production of f_0/σ (e.g $|F^{B_q\sigma}/F^{B_q f_0}| \neq 1$)
- sub-leading topologies? (no CKM suppression in $B_d \to J/\psi\{f_0, \sigma\}$)
- tetraquark mixing? $(\omega \neq 0^\circ)$

The tetraquark picture: caveats (I)

Non-trivial mixing?

Bound $\omega \lesssim 5^\circ$ used $m_\kappa = 797$ MeV ($\kappa = [su][\bar{u}\bar{d}]; \ldots$) *Maiani, Piccinini, Polosa, Riquer - hep-ph/0407017; 't Hooft, Isidori, Maiani, Polosa, Riquer - 0801.2288*

With $m_\kappa = 682$ MeV (PDG 2013) we find $\boxed{\omega \approx 20^\circ}$

$$r_{d,\sigma}^{d,f_0}\Big|_{4q} \sim \frac{1}{2}\left|\frac{1-\sqrt{2}\tan\omega}{1+\frac{1}{\sqrt{2}}\tan\omega}\right|^2, \qquad r_{s,f_0}^{s,\sigma}\Big|_{4q} \sim \left|\tan\left[\omega + \tan^{-1}(\sqrt{2}X_c)\right]\right|^2$$

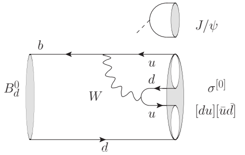
expect $|X_c| = |(A_{\mathrm{E},\sigma} + A_{\mathrm{PA},\sigma})/A_{\mathrm{T},f_0}| \lesssim 5\%$ $\left(B_d \to J/\psi\phi,\ \frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)$

$\Longrightarrow$ can shift ω by $\pm 5^\circ$

Sub-leading topologies?

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

Could enhance $\mathrm{BR}(B_d \to J/\psi\sigma)$ in $r_{d,\sigma}^{d,f_0}$



R.Fleischer, RK, G.Riiardi in progress

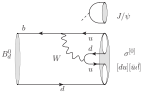
The tetraquark picture: caveats (II)

Include also : $r_{d,\sigma}^{s,f} \equiv \frac{\mathrm{BR}(B_s \to J/\psi\, f_0)}{\mathrm{BR}(B_d \to J/\psi\, \sigma)} \frac{\Phi_d(\sigma)}{\Phi_s(f_0)}$

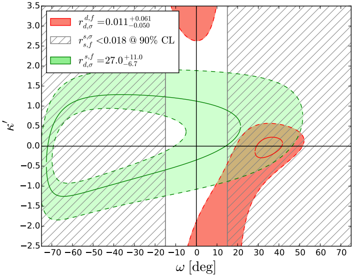
Apply 30% symmetry breaking errors to ratios

Relative size special topology:

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



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

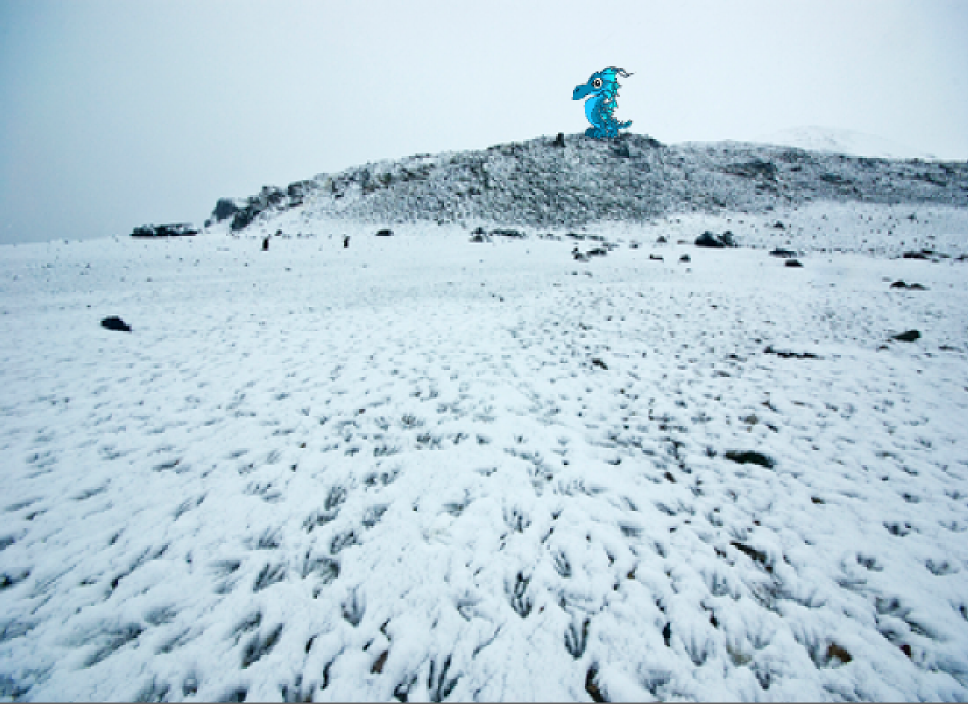


R.Fleischer, RK, G.Riciardi in progress

Conclusions?

- Tetraquark picture can survive B decay constraints
  ...though Occam's razor favours $q\bar{q}$ like production
- Important is possible CPV dynamics such as $\mathcal{A}_{4q}^{(\prime)}$, or K-K/π-π equivalent etc.

$$\text{e.g.} \quad |\kappa| \sim 0.5 \quad \Longrightarrow \Delta\phi_{f_0} \approx \underbrace{\epsilon \sin\gamma}_{3^\circ} \cdot \mathrm{Re}(\kappa) \sim \pm\mathbf{1.5^\circ}$$



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
- **Take care** interpreting ϕ_s averages including $f_0(980)$
  $\to$ tetraquark picture can survive current B decay constraints
  $\to$ non-$q\bar{q}$ dynamics could give sizable uncertainty