Scalar resonance effects on the $B_s^0 - \bar{B}_s^0$ mixing angle in $B_s^0 \to J/\psi\phi$

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IX Simpósio Latino Americano de Física de Altas Energias
Memorial da América Latina, São Paulo
December 14, 2012

Beauty Physics

- Current trend in experiments: LHCb has already contributed considerable wealth of data on CP observables.
  Mostly in agreement with previous BaBar, Belle, D0 and CDF results and converging toward Standard Model predictions.
- Notable example: $B_s^0 - \bar{B}_s^0$ mixing phase β_s .
- However, still many hadronic uncertainties. Final word?

Weak decay amplitudes
Effective Hamiltonian

Weak effective Hamiltonian

Sum of local operators Q_i multiplied by short-range Wilson coefficients $C_i(\mu)$ and CKM matrix elements:

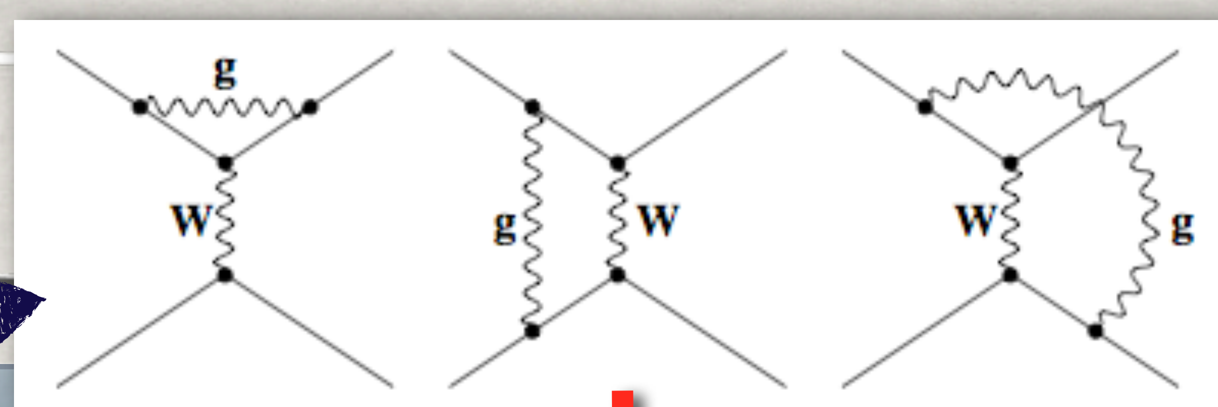
$$\mathcal{H} = \frac{G_F}{\sqrt{2}}\left[V_{ub}V_{us}^*(C_1(\mu)O_1^u + C_2(\mu)O_2^u) - V_{tb}V_{ts}^*\sum_{i=3}^{10} C_i(\mu)O_i\right]$$

O_1 and O_2 are left-handed current-current operators, for example:

$$O_1^u = \bar{s}_\alpha\gamma_\mu(1-\gamma_5)u_\alpha\bar{u}_\beta\gamma_\mu(1-\gamma_5)b_\beta$$

O_3 …. O_{10} are QCD and electroweak penguin operators, for instance:

$$O_4 = \bar{s}_\alpha\gamma_\mu(1-\gamma_5)b_\beta \sum_{q=u,d,s,c} \bar{q}_\beta\gamma_\mu(1-\gamma_5)q_\alpha$$



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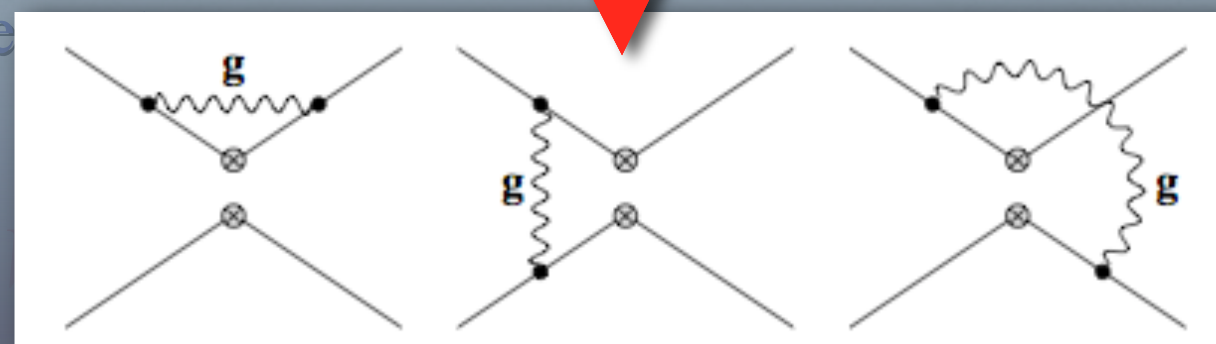

$$\mathcal{H} = \frac{G_F}{\sqrt{2}}\Big[V_{u\ldots} \quad \ldots \quad (\mu) O_i\Big]$$

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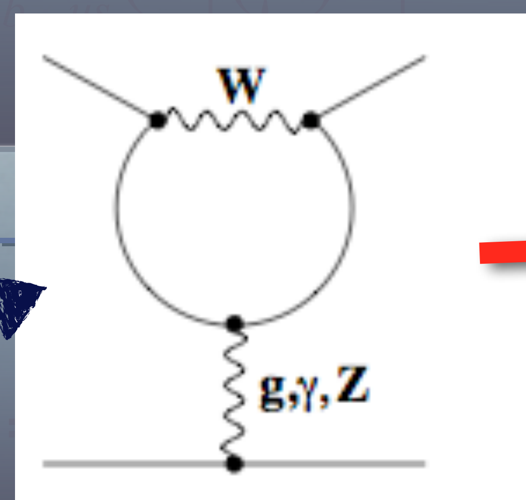

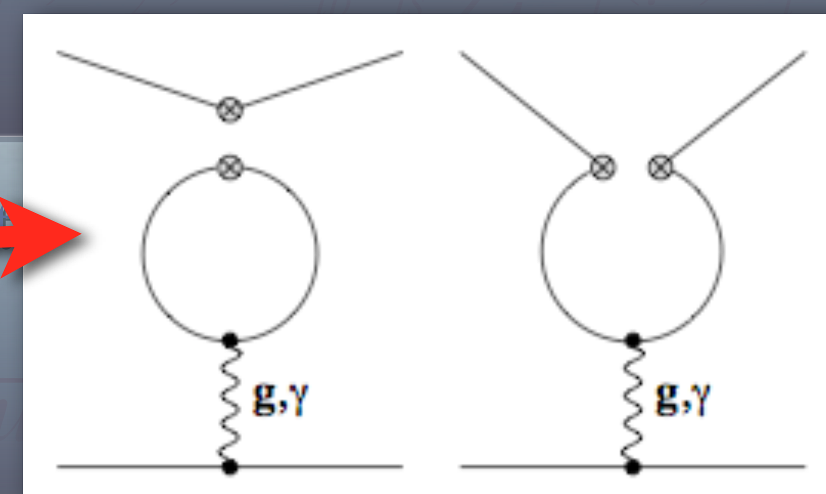

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Decay amplitudes and matrix elements

$$\langle M_1^* M_2 | H_{\mathrm{eff}} | B \rangle = \frac{G_F}{\sqrt{2}} V_{\mathrm{CKM}} \sum_k C_k(\mu) \langle M_1^* M_2 | O_k(\mu) | B \rangle$$

G_F = 1.166 x 10^{-5} GeV^{-2} = Fermi constant, V_{CKM} = CKM matrix element, μ = renormalisation scale

- Wilson coefficients $C(\mu)$ incorporate all short-distance physics below a scale $\mu = m_b$, can be thought of as scale-dependent 'couplings'.

- $\langle M_1 M_2 | O_k(\mu) | B \rangle$ are non-perturbative hadronic matrix elements which describe long-distance physics.

- $O_k(\mu)$ are local operators which drive the decays.

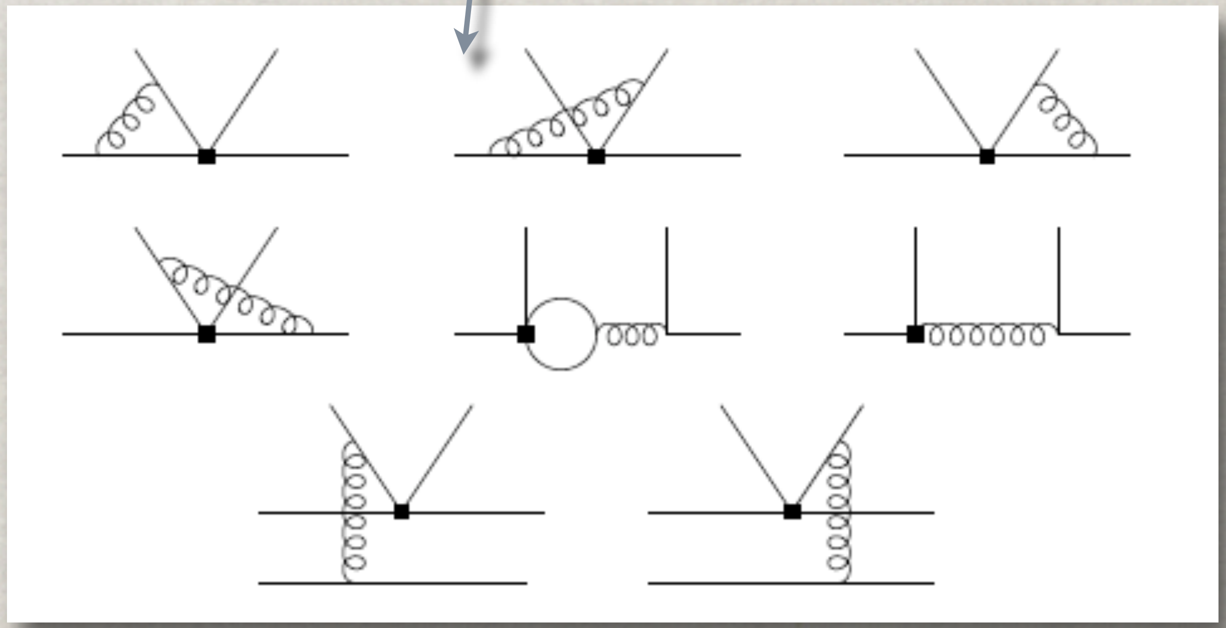
QCD factorization I.

Beneke, Buchalla, Neubert & Sachrajda, 1999, 2000 & 2003

$$\langle M_1 M_2 | Q_k(\mu) | B \rangle \sim \langle M_2 | J_1 | 0 \rangle \otimes \langle M_1 | J_2 | B \rangle \left[1 + \sum_n r_n \alpha_s^n + \mathcal{O}(\Lambda_{\mathbf{QCD}}/m_b) \right]$$

Radiative vertex corrections
and hard gluon exchange
with spectator quark

Decay constant
(mostly known experimentally)



Hadronic transition form factor;
estimated with QCD sum rules,
lattice QCD, quark models ...

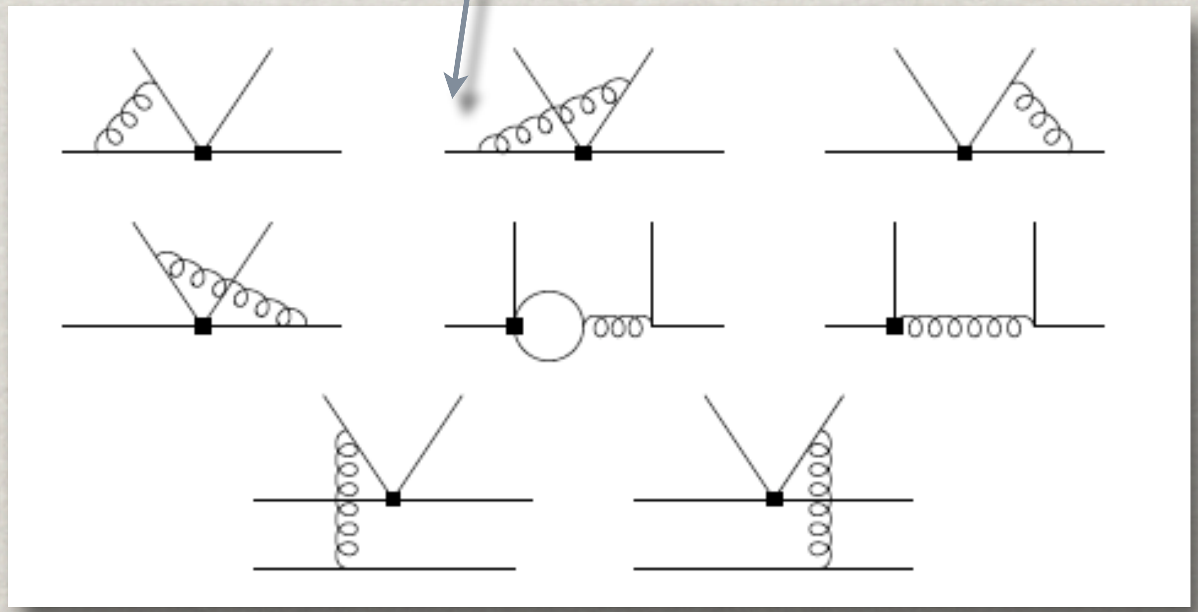
QCD factorization II.

B. E., Furman, Kamiński, Leśniak, Loiseau & Moussallam, 2009

$$\langle (M_1 M_2)_{S,P} M_3 | Q_k(\mu) | B \rangle \sim \langle (M_1 M_2)_{S,P} | J_1 | 0 \rangle \otimes \langle M_3 | J_2 | B \rangle$$
$$\times \left[1 + \sum_n r_n \alpha_s^n + \mathcal{O}(\Lambda_{\mathbf{QCD}}/m_b) \right]$$

Radiative vertex corrections and hard gluon exchange with spectator quark

Scalar or vector form factor; their definition allows for inclusion of pion-pion and kaon-pion form factors.



Usual parametrization of transition form factors

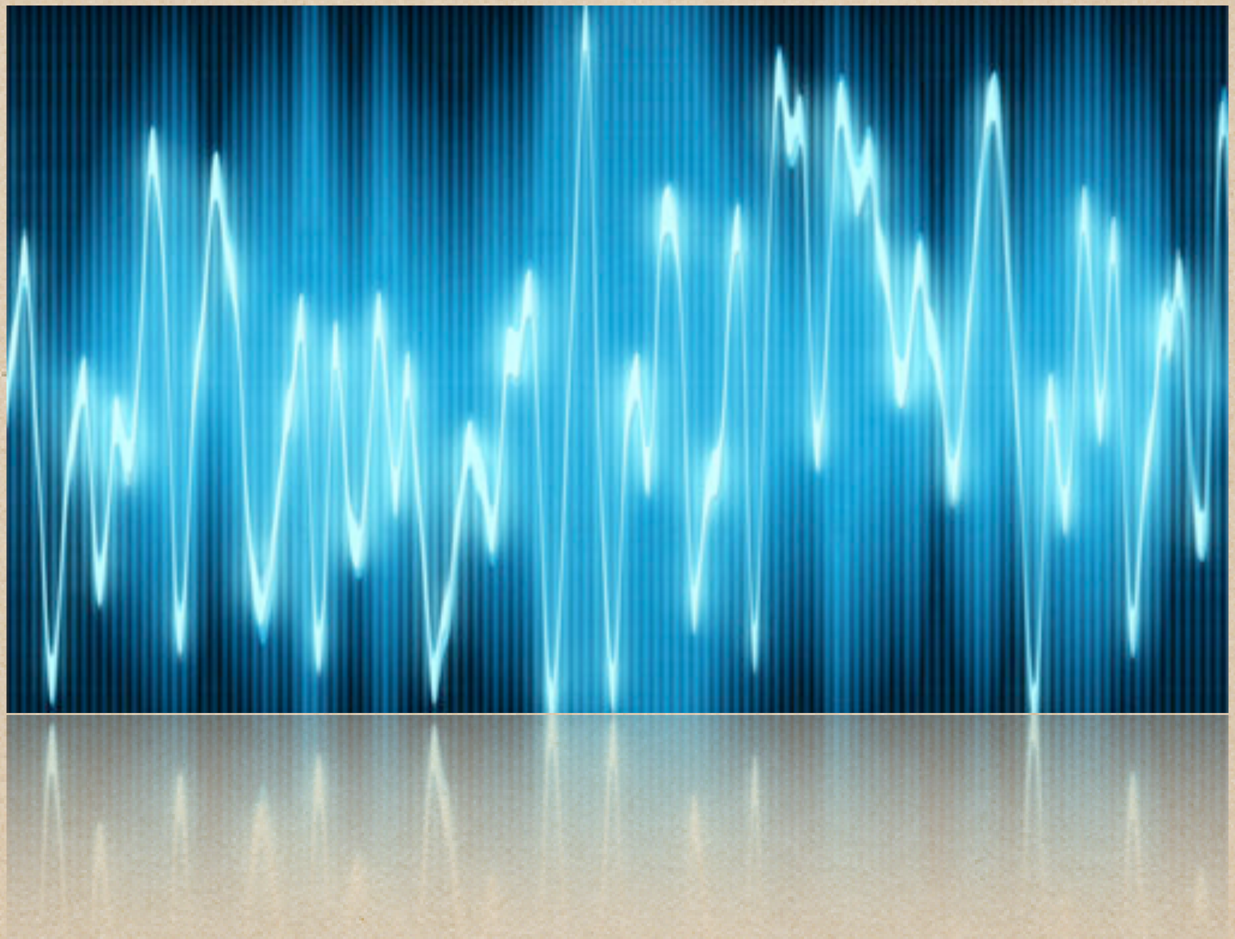
Pseudoscalar- to scalar-meson transitions:

$$\langle M(p_M)|\bar{q}\,\gamma_\mu(1-\gamma_5)b|B(p_B)\rangle = \Big(p_B + p_M - \frac{m_B^2 - m_M^2}{q^2}q\Big)_\mu F_1^{B\to M}(q^2) + \frac{m_B^2 - m_M^2}{q^2}q_\mu\; F_0^{B\to M}(q^2)$$

$$q = p_B - p_M; \quad q = u, d, s$$

Pseudoscalar- to vector-meson transitions:

$$\begin{aligned}\langle M(p_V,\varepsilon_V^*)|\bar{q}\,\gamma_\mu(1-\gamma_5)b|B(p_B)\rangle \;&=\; \varepsilon^*_{V,\mu}(m_B+m_V)A_1^{B\to V}(q^2) - (p_B+p_V)_\mu(\varepsilon_V^*\cdot p_B)\frac{A_2^{B\to V}(q^2)}{m_B+m_V} \\ &- q_\mu(\varepsilon_V^*\cdot p_B)\frac{2m_V}{q^2}\Big[A_3^{B\to V}(q^2) - A_0^{B\to V}(q^2)\Big] + i\epsilon_{\mu\nu\alpha\beta}\,\varepsilon_V^{*\nu}p_B^\alpha p_V^\beta\,\frac{2\,V^{B\to V}(q^2)}{m_B+m_V}\end{aligned}$$



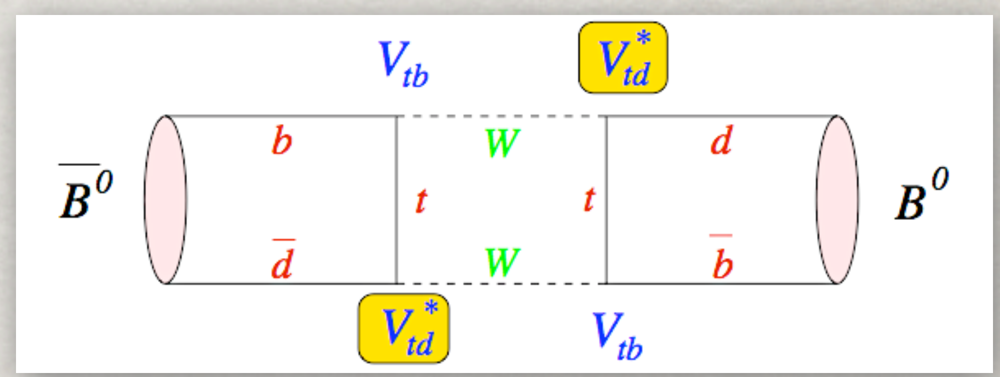
A quantum mechanical tale:

$B^0 - \bar{B}^0$ oscillations

Three types of CP violation

1. Direct *CP* violation: two *CP*-conjugate decays processes have different *absolute* values for their amplitudes: $\left|\frac{\bar{A}}{A}\right| \neq 1$

2. *CP* violation in mixing: mass eigenstates and *CP* eigenstates are not the same, the mixing is driven by box diagrams.



$$B_H = p|B^0\rangle + q|\bar{B}^0\rangle \qquad B_L = p|B^0\rangle - q|\bar{B}^0\rangle \qquad \left|\frac{q}{p}\right| \neq 0$$
$$|p|^2 + |q|^2 = 1 \qquad CP|M^0\rangle = |\bar{M}^0\rangle$$

3. *CP* violation in interference between decays to a *CP* state *f* with *and* without mixing: effect is proportional to imaginary part of the ratio $\lambda_f = \frac{q}{p}\frac{\bar{A}(\bar{B}\to f)}{A(B\to f)}$ and can be non-zero even if $|\lambda_f = 1|$.

Time evolution of B states

Corresponding time-dependent *CP*-violating asymmetry :

$$a_{CP}(t) = \frac{|\mathcal{A}(\bar{B}(t) \to f)|^2 - |\mathcal{A}(B(t) \to f)|^2}{|\mathcal{A}(\bar{B}(t) \to f)|^2 + |\mathcal{A}(B(t) \to f)|^2} =$$

$$= \frac{\left[\left(1 - |\lambda_f|^2\right)\cos(\Delta M t) - 2\,\mathcal{I}m\,\lambda_f \sin(\Delta M t)\right]}{1 + |\lambda_f|^2}$$

Third type of *CP* occurs exactly when $|\lambda_f = 1|$ in which case this expression reduces to:

$$\boxed{a_{CP}(t) = \mathcal{I}m\,\lambda_f \sin(\Delta M t)}$$

The argument of λ_f depends on weak phases:

Phase of $\dfrac{q}{p} = \beta_s$

$$\mathcal{I}m\,\lambda_f = \eta_f \sin(2\phi_{\text{mix}} - 2\phi_{\text{decay}})$$

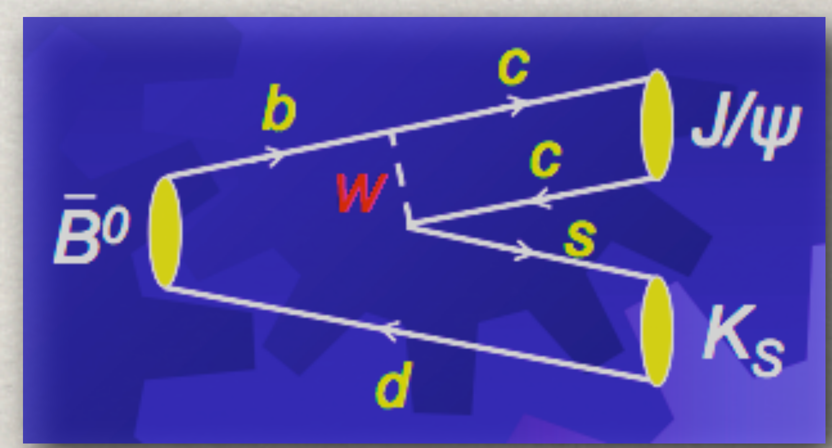
Golden decay mode $B^0 \to J/\psi K_s$

- Amplitude is real to an excellent approximation, *i.e.* $\phi_{\mathrm{decay}} \simeq 0.$

- $\Longrightarrow \quad \mathcal{I}m\,\lambda_f = \sin 2\beta = 0.687 \pm 0.032 \quad \text{(World Average)}$

- Direct determination of $\sin 2\beta$ practically without theoretical uncertainties (~ 1%).

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



$$b \longrightarrow c\bar{c}s$$

Golden decay mode $B_s^0 \to J/\psi\phi$

- Very similar to $B^0 \to J/\psi K_s$, *i.e.* $b \to c\bar{c}s$, $\phi_{\text{decay}} \simeq 0$.

- Expect larger New Physics effects in the suppressed FCNC $b \to s$ transitions as compared with $b \to d$.

- Again direct determination of $\sin 2\beta_s$, where the CKM angle is predicted to be very small in the Standard Model:

$$\beta_s = \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \simeq 0.019 \text{ rad}$$

- Unconfirmed ***initially*** by CDF and D0 who found a (combined) 2.4σ deviation of β_s from Standard Model prediction.

T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 100, 161802 (2008)
V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 101, 241801 (2008)

- Although both Collaborations observed deviation in same direction, the result is not statistically significant.

- Nevertheless, data triggered **many** papers on New Physics contributions.

- As was pointed out, one factor of uncertainty was not taken into account by either Collaboration: the final-state vector meson decay $\phi \to K^+K^-$ may very well be contaminated by an S-wave under the ϕ threshold, in particular from thescalar resonance $f_0(980) \to (K^+K^-)_S$.

- This has already known from the decay $B_d \to J/\psi K^{*0}(892)$ where a $(K\pi)$ S-wave component in the $K^*(892)$ mass region is observed (~ 8% pollution).

A first qualitative attempt to predict the ratio, **S. Stone & L. Zhang (2009)**

$$\mathcal{R}_{f_0/\phi} = \frac{\Gamma(B_s^0 \to J/\psi f_0(980), f_0(980) \to \pi^+\pi^-)}{\Gamma(B_s^0 \to J/\psi\phi, \phi \to K^+K^-)} ,$$

was made by Stone and Zhang and gives a result of the order of $20\% - 30\%$. Their estimate relies on experimental data on $D_s^+ \to f_0(980)\pi^+$ and $D_s^+ \to \phi\pi^+$ decays and seems to indicate that the S-wave contribution of $f_0(980) \to K^+K^-$ cannot be ignored when analyzing the angle β_s in $B_s^0 \to J/\psi\phi$.

E687 Collaboration estimation:

$$\frac{\Gamma(D_s^+ \to f_0\pi^+ \to K^+K^-\pi^-)}{\Gamma(D_s^+ \to \phi\pi^+ \to K^+K^-\pi^-)} = 0.28 \pm 0.12,$$

CLEO estimate of the semileptonic, integrated branching fraction ratio

$$\frac{\mathcal{B}(D_s^+ \to f_0 e^+\nu, f_0 \to \pi^+\pi^-)}{\mathcal{B}(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)} = (13 \pm 4)\%$$

The ratio in terms of the differential decay ratio (CLEO):

$$\mathcal{R}_{f_0/\phi} \quad = \quad \frac{\frac{d\Gamma}{dq^2}(D_s^+ \to f_0 e^+\nu, f_0 \to \pi^+\pi^-)\big|_{q^2=0}}{\frac{d\Gamma}{dq^2}(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)\big|_{q^2=0}} = 0.42 \pm 0.11.$$

Combining these three experimental estimates yields a window of $0.2 \lesssim \mathcal{R}_{f_0/\phi} \lesssim 0.5$ for the ratio based on D_s decays.

Evaluation of $B_s^0 \to f_0(980)$ with nonperturbative approaches

- An important ingredient is the $B_s \to f_0(980)$ transitions form factor.

  What is the composition of this scalar meson? Decays predominantly into two pions and two kaons (just at threshold). It certainly has a $|\bar{u}u\rangle$ and $|\bar{s}s\rangle$ component, probably also pion and kaon cloud.

- So far only few calculations available:

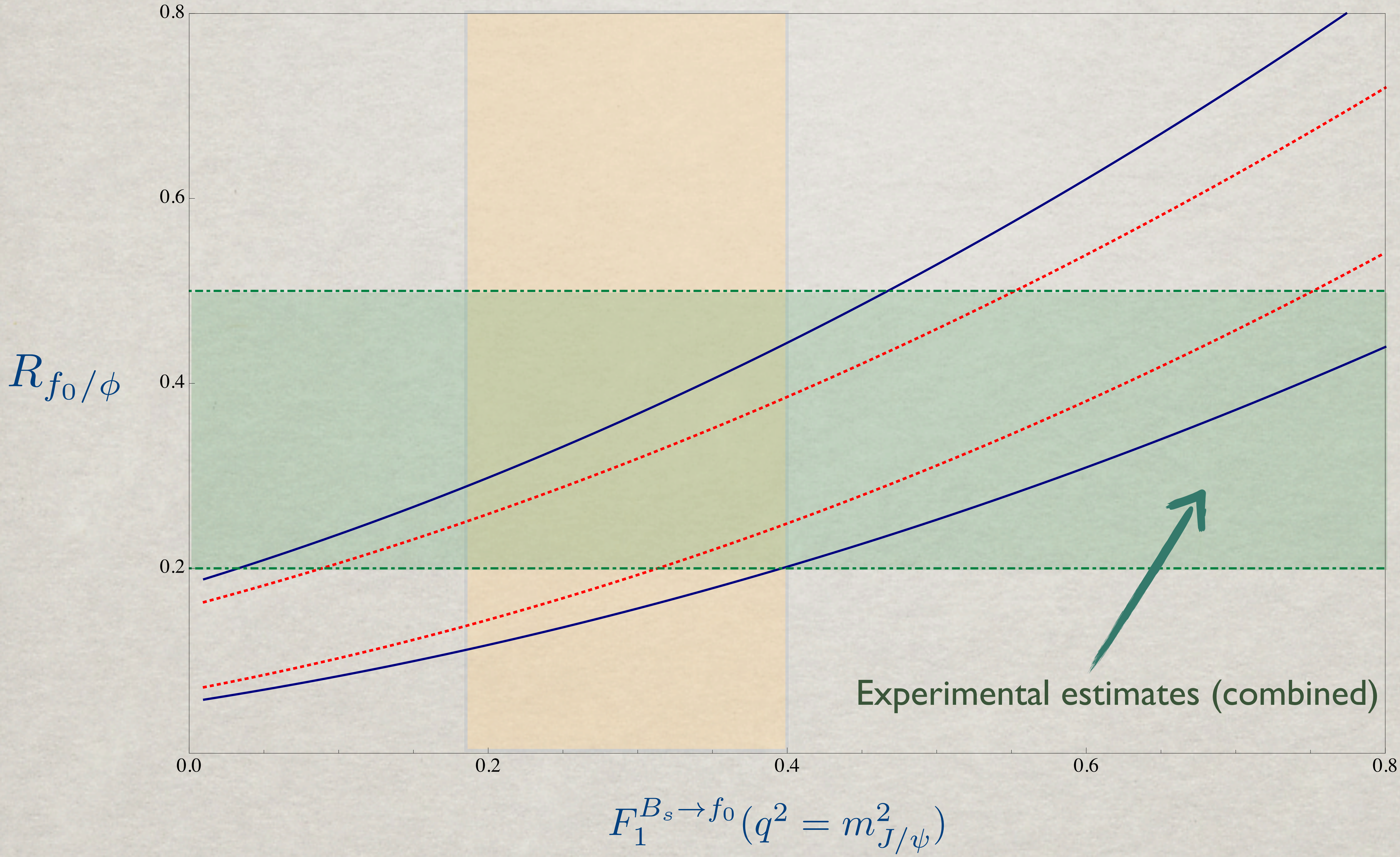
  pQCD: $F_{0,1}(0) \simeq 0.35$ (Li, Liu & Wang, 2009)

  LQCDSR: $F_{0,1}(0) \simeq 0.185$ (Colangelo, de Fazio & Wang, 2010)

  CLFD: $F_{0,1}(0) \simeq 0.35$ (B.E., Leitner, Dedonder & Loiseau, 2009)

- Lack of numerical results for more sophisticated Bethe-Salpeter amplitudes and of higher moments of LCDA $\Rightarrow$ precision calculation delayed.

$$\mathcal{R}_{f_0/\phi} = \frac{\Gamma(B_s^0 \to J/\psi f_0(980), f_0(980) \to K^+K^-)}{\Gamma(B_s^0 \to J/\psi \phi, \phi \to K^+K^-)}$$



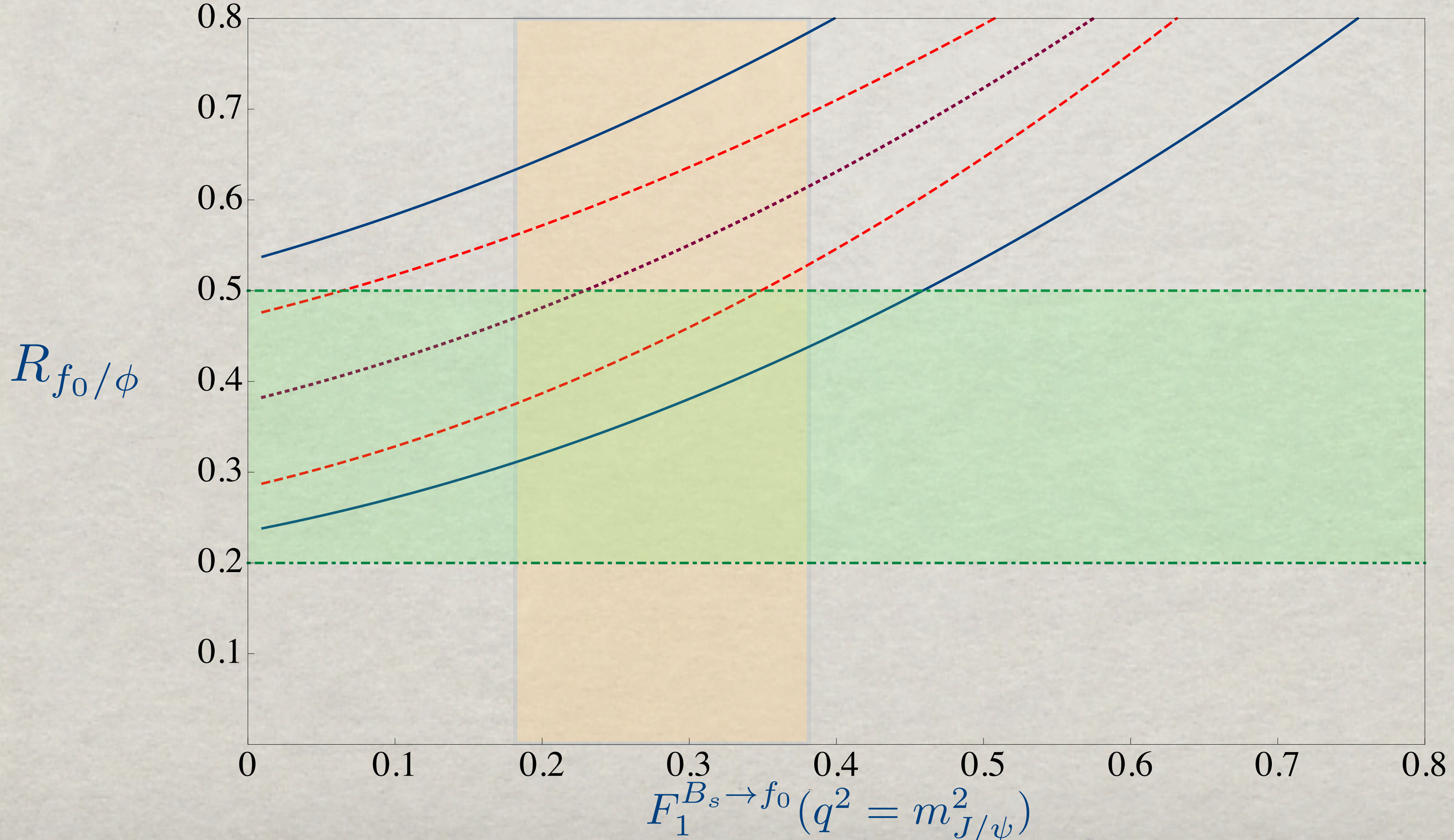
Error bands:

Uncertainties on the decay constants f_{B_s} and $\bar{f}_{f_0}$ and on decay rates $f_0(980) \to K^+K^-$ and $\phi \to K^+K^-$.

New Physics ?

- Allowing for additional penguin amplitudes $\zeta^{(h)}$ with same FCNC : $b \to c\bar{s}s$
- Can have origin in beyond Standard Model physics.
- Fit additional amplitudes to branching ratios, polarizations, asymmetries of $B_s \to \phi J/\psi$

$$\mathcal{A} = |\mathcal{A}^{\rm SM}|\, e^{2i\beta_s^{\rm SM}} + |\mathcal{A}^{\rm NP}|\, e^{i(2\beta_s^{\rm SM} - \phi_s^{\rm NP})} = |\mathcal{A}^{\rm SM}|\, e^{2i\beta_s^{\rm SM}} \left(1 + \mathcal{R}\, e^{-i\phi_s^{\rm NP}}\right)$$



Current experimental status

$$\mathcal{R}_{f_0/\phi} = 0.275 \pm 0.041 \pm 0.061 \quad \text{(D}\emptyset\text{ Collaboration)}$$

$$\mathcal{R}_{f_0/\phi} = 0.257 \pm 0.020 \pm 0.014 \quad \text{(CDF Collaboration)}$$

$$\mathcal{R}_{f_0/\phi} = 0.252^{+0.046+0.027}_{-0.032-0.033} \quad \text{(LHCb Collaboration)}$$

Ratios imply that $\zeta^{(h)} = 0$

and $F_1^{B_s^0 \to f_0}(m_{J/\psi}^2) < 0.4$ **!!**

Current experimental status

What about $2\beta_s$??

$B_s^0 \to J/\psi\phi$

$$\beta_s + \Delta_{\phi J/\psi} = \begin{cases} (0.0 \pm 6.6)^\circ & \text{LHC}b\ \text{(Moriond 2012)} \\ (-35.1^{+21.7}_{-20.6})^\circ & \text{D}\emptyset\ (2012) \\ [-34.9^\circ, 6.9^\circ] & \text{CDF}\ (2012) \end{cases}$$

***S*-wave contributions included in analysis**

$B_s^0 \to J/\psi f_0(980)$

$$\beta_s + \Delta_{J/\psi f_0} = (-25 \pm 25)^\circ \quad \text{LHC}b\ (2012)$$

Hadronic phase not well known

Future improvements: Bethe Salpeter & Distribution Amplitudes

- ✓ Light Cone Distribution amplitudes are poorly known for heavy mesons.
- ✓ Same applies to scalar mesons (flavor-mixing angle, pion/kaon loop contributions).
- ✓ Nonperturbative calculation of distribution amplitudes within Dyson-Schwinger & Bethe-Salpeter framework:

1st step: **Beyond rainbow-ladder aproach** in nonperturbative quark-gluon ansatz; State-of-the-Art lattice data on nonperturbative gluon propagator.

2nd step: Compute Bethe-Salpeter amplitude (BSA) beyond ladder approach. Obtain PDF moments from BSA — available moments (3–4) from lattice-QCD not better than 20%.

$$\varphi_\pi(x) = Z_2\, \mathrm{tr}_{\mathrm{CD}} \int \frac{d^4k}{(2\pi)^4}\, \delta(n\cdot k - x\, n\cdot P)\, \gamma_5\, \gamma\cdot n\, S(k)\Gamma_\pi(k;P)S(k-P)$$

$$(n\cdot P)^{m+1} \int_0^1 dx\, x^m\, \varphi_\pi(x) = Z_2\, \mathrm{tr}_{\mathrm{CD}} \int \frac{d^4k}{(2\pi)^4}\, (n\cdot k)^m\, \gamma_5\, \gamma\cdot n\, \chi_\pi(k;P)$$

Pion's Bethe-Salpeter wave function