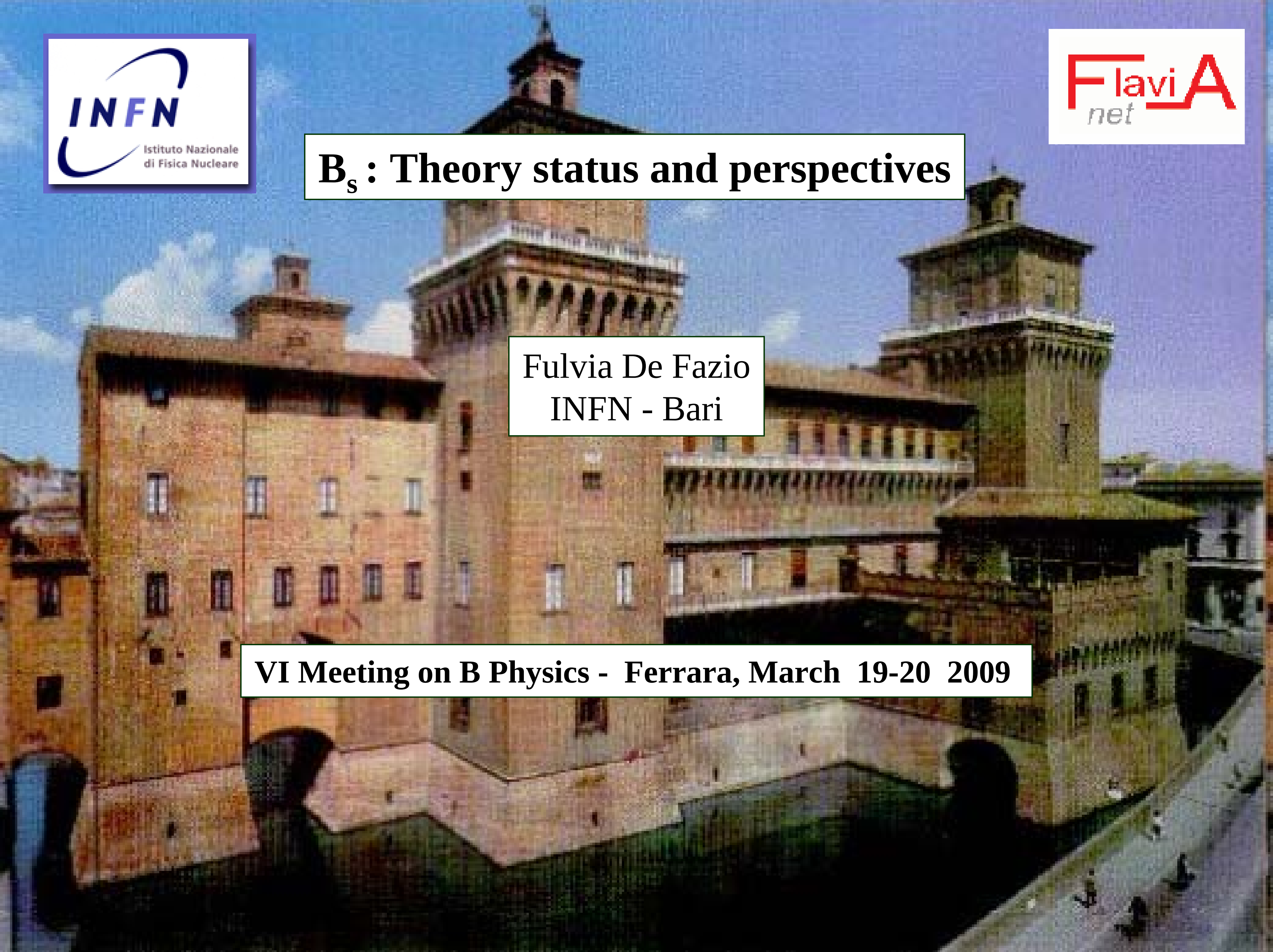

INFN Istituto Nazionale di Fisica Nucleare

FlaviA net

B_s : Theory status and perspectives

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INFN - Bari

VI Meeting on B Physics - Ferrara, March 19-20 2009

Outline

- Notations & known facts about mixing of neutral B mesons

- Determination of Δm, $\Delta\Gamma$, ϕ – theory predictions
  – (some) proposed strategies
  – experimentally adopted strategies

- $B_s \to J/\psi\phi$: discussion of some theoretical uncertainties – role of
  – SU(3) for strong phases

- Other channels: – $f_0(980)$ as a S-wave background to ϕ
  – $B_s \to J/\psi\ f_0(980)$ as an alternative mode
  – other interesting modes

- New Physics: – Δm_s
  – ϕ

- B_s Physics not related to CP violation: some interesting decay modes

- Conclusions

$B_s - \overline{B}_s$ mixing

governed by Schroedinger-like eq.

$$i\frac{d}{dt}\begin{pmatrix}|B_s(t)\rangle \\ |\overline{B}_s(t)\rangle\end{pmatrix} = \left(\hat{M} - i\frac{\hat{\Gamma}}{2}\right)\begin{pmatrix}|B_s(t)\rangle \\ |\overline{B}_s(t)\rangle\end{pmatrix}$$

$$\hat{M},\ \hat{\Gamma} \quad 2\times 2 \quad hermitian \quad matrices \quad \Rightarrow \quad M_{21} = M_{12}^* \quad \Gamma_{21} = \Gamma_{12}^*$$

$$CPT \quad \Rightarrow \quad M_{11} = M_{22} \quad \Gamma_{11} = \Gamma_{22}$$

mass eigenstates

$$|B_{s,L}\rangle = p|B_s\rangle + q|\overline{B}_s\rangle$$
$$|B_{s,H}\rangle = p|B_s\rangle - q|\overline{B}_s\rangle$$

with

$$M_L,\ \Gamma_L$$
$$M_H,\ \Gamma_H$$

Usual notations:

$$\Delta m = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$$

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \qquad \phi_M = \arg(M_{12})$$

$B_s - \overline{B}_s$ mixing

Exact results:

$$(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2$$

$$(\Delta m)(\Delta\Gamma) = 4\,\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

$$\frac{q}{p} = -\frac{\Delta m - i\frac{\Delta\Gamma}{2}}{2\left(M_{12} - i\frac{\Gamma_{12}}{2}\right)}$$

but using: $|\Gamma_{12}| << |M_{12}|$

$$\Delta m = 2|M_{12}|$$

$$\Delta\Gamma = 2|\Gamma_{12}|\cos\phi$$

If CP were conserved…

$$M_{12} = M_{21} = M_{12}^* \quad \Rightarrow \quad \phi_M = 0$$

$$\Gamma_{12} = \Gamma_{21} = \Gamma_{12}^* \quad \Rightarrow \quad \phi = 0$$

$$CP|B_{s,L}\rangle = -|B_{s,L}\rangle$$

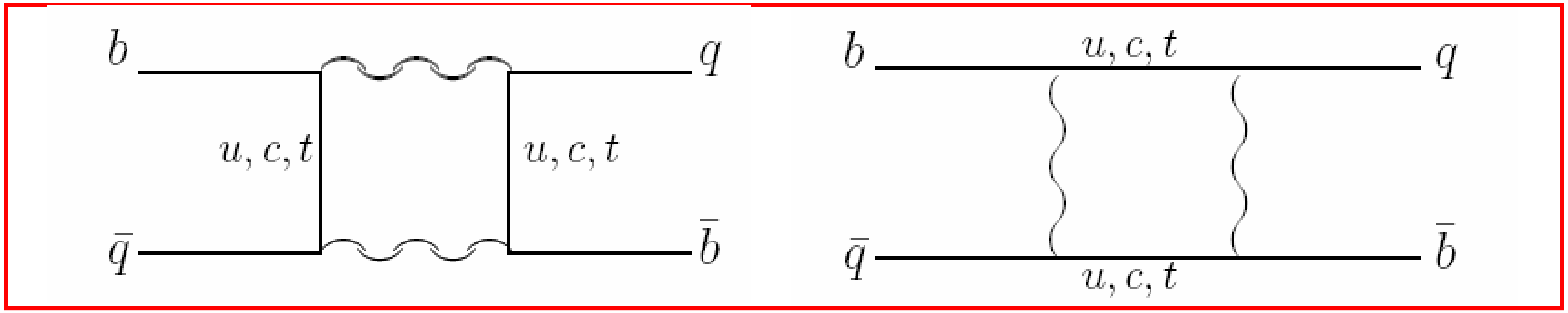
$$CP|B_{s,H}\rangle = |B_{s,H}\rangle$$

(in the phase convention $CP|B_s\rangle = -|\overline{B}_s\rangle$)

$B_s - \overline{B}_s$ mixing

$|M_{12}|$, $|\Gamma_{12}|$, $\phi=\arg(-M_{12}/\Gamma_{12})$ are related to observables

Δm and $\Delta\Gamma$ come from real and Im parts of box diagrams:



- $\Delta m = 2|M_{12}|$ → $|M_{12}|$ takes contribution from **heavy** internal particles: t, NP
- $\Delta\Gamma = 2|\Gamma_{12}|\cos\phi$ → $|\Gamma_{12}|$ sensible to **light** internal particles u,c

Any NP would also affect tree level decays ⇒ assume no NP in Γ_{12}

NP would change instead $|M_{12}|$

$B_q - \overline{B}_q$ mixing

$\phi_M = \arg(M_{12})$

Takes contribution from internal top exchange $\Rightarrow$ $\phi_{M,q} = 2\arg\left(V_{tb}V_{tq}^*\right)$

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) = \phi_{\mathrm{M}} - \arg(-\Gamma_{12})$$

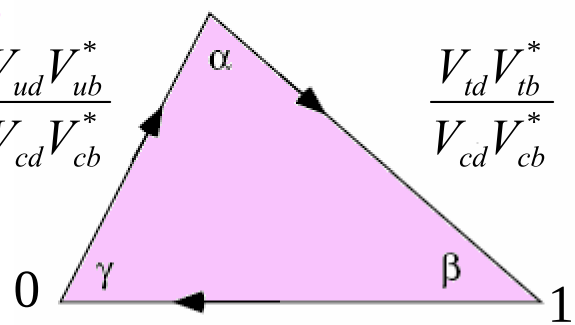
Γ_{12} takes contribution from internal u,c exchange

$$\arg(\Gamma_{12}) \approx 2\arg\left(V_{cb}V_{cq}^*\right),\ 2\arg\left(V_{cb}V_{cq}^*\right)\arg\left(V_{ub}V_{uq}^*\right),\ 2\arg\left(V_{ub}V_{uq}^*\right)$$

Only neglecting these contributions leads to $2\beta_q = 2\arg\left(-\frac{V_{tb}V_{tq}^*}{V_{cb}V_{cq}^*}\right)$

$B_d - \overline{B}_d$

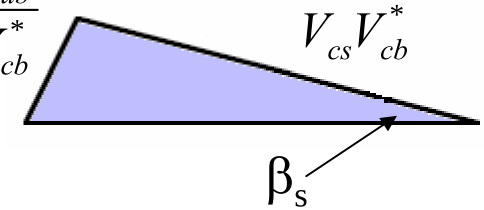
$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$ $\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$



$$\beta_d = \arg\left(-\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*}\right) = 0.38 \pm 0.02 \quad rad$$

$B_s - \overline{B}_s$

$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}$ $\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}$



$$\beta_s = \arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) \approx 0.02 \quad rad$$

$B_s - \overline{B}_s$ mixing

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

→ In the SM it turns out to be tiny

$$\Delta\Gamma = 2|\Gamma_{12}|\cos\phi$$

⇒ Since NP should not affect Γ_{12}
it can only modify $\cos\phi$

⇓

NP can only decrease the value of $\Delta\Gamma$ with respect to SM

Theory predictions: Δm

Calculation of the box diagram with internal top quarks gives rise to an effective hamiltonian composed by a single operator $Q = \bar{s}_L \gamma_\nu b_L \bar{s}_L \gamma^\nu b_L$

with: $$\langle \bar{B}_s | Q | B_s \rangle = \frac{2}{3} f_{B_s}^2 M_{B_s} \frac{B_{B_s}}{b(\mu)}$$

→ renorm. group invariant

→ $b(\mu) = [\alpha_s(\mu)]^{-6/23}$ at LO

The Wilson coefficient of ***Q*** is $$C(m_t, M_W, \mu =) = M_W^2 \, S(x_t) \hat{\eta}_b \, b(\mu)$$

Perturbative quantities: $S_0(x_t) \quad x_t = \frac{m_t^2}{M_W^2}$ Inami , Lim

$\hat{\eta}_B$ Buras et al.

Result:

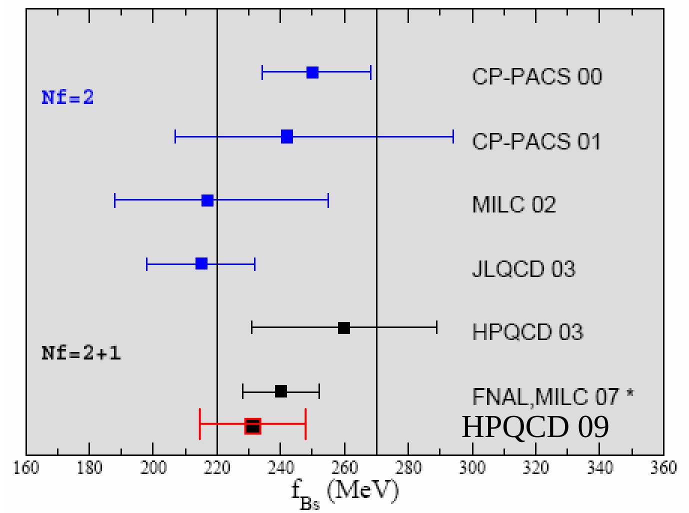
$$\Delta m_s = 2M_{12} = \frac{G_F^2}{6\pi^2} |V_{tb} V_{ts}^*|^2 \; M_W^2 S_0(x_t) \hat{\eta}_B B_{B_s} f_{B_s}^2 M_{B_s}$$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{B_s}}{M_{B_d}} \left| \frac{V_{ts}^2}{V_{td}^2} \right| \xi^2 \qquad \xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$

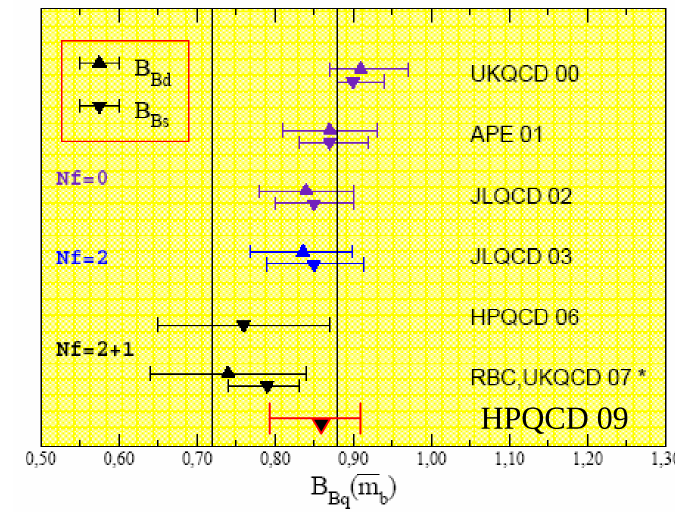
Theory predictions: Δm

Plots from Lubicz and Tarantino, 0807.4605

f_{B_s}



B_{B_s}



Very recent HPQCD results, with n_f=2+1

$$f_{B_s} = 231 \pm 15 \quad \text{MeV}$$

$$B_{B_s} = 0.86 \pm 0.06$$

Sum rules give results in the same ballpark

ξ

$$\xi = 1.258 \pm 0.033$$

HPQCD 09 - 0902.1815

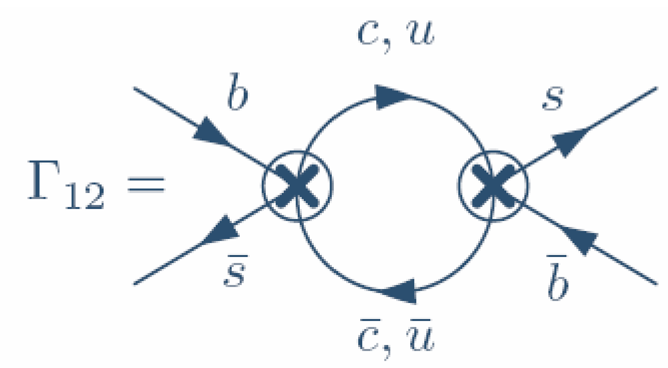
Final result:

$$\Delta m^{SM} = (19.30 \pm 6.68) \quad \text{ps}^{-1}$$

Lenz & Nierste,
JHEP 06 (07) 072

Theory predictions: $\Delta\Gamma$

Exploiting that $m_t, M_W >> m_b$ heavy particles can be integrated out
The effective hamiltonian stems from:



The imaginary part is obtained using the optical theorem

Γ_{12} is written as an expansion in Λ/m_b and α_s

At leading order two operators contribute:

$$Q = \bar{q}_\alpha \gamma_\mu (1-\gamma_5) b_\alpha \bar{q}_\beta \gamma_\mu (1-\gamma_5) b_\beta$$

$$Q_S = \bar{q}_\alpha (1+\gamma_5) b_\alpha \bar{q}_\beta (1+\gamma_5) b_\beta$$

However:

- almost complete cancellation of the coefficient of ***Q*** → **Enters also in Δm**
- too large $1/m_b$ and α_s corrections

A different basis can be used, with a better behaved expansion

Theory predictions: $\Delta\Gamma$

Lenz & Nierste, JHEP 06 (07) 072

Define: $\tilde{Q}_S = \bar{q}_\alpha(1+\gamma_5)b_\beta \bar{q}_\beta(1+\gamma_5)b_\alpha$

$$\langle B_s|\tilde{Q}_S|\bar{B}_s\rangle = \frac{1}{3}M_{B_s}^2 f_{B_s}^2 \tilde{B}'_s$$

Using the fact that
$$R_0 = Q_s + \alpha_1 \tilde{Q}_S + \frac{\alpha_2}{2}Q = O\left(\frac{1}{m_b}\right)$$

one can trade the old basis $\{Q,\ Q_S\}$ for the new basis $\{Q,\ \tilde{Q}_S\}$

Result:

$$\Delta\Gamma_s^{SM} = \left(\frac{f_{B_s}}{240MeV}\right)^2\left[(0.105\pm0.016)B + (0.024\pm0.004)\tilde{B}'_s + O\left(\frac{1}{m_b}\right)\right]\ \text{ps}^{-1}$$

$$\left(\frac{\Delta\Gamma_s}{\Delta m_s}\right)^{SM} = [49.7\pm9.4]\times10^{-4}$$

Using
$B = 0.85\pm0.06$
$\tilde{B}'_s = 1.41\pm0.12 \rightarrow$ (lattice)

Precisely predicts $\dfrac{\Delta\Gamma_s}{\Delta m_s}$

$$\left(\frac{\Delta\Gamma_s}{\Delta m_s}\right)^{SM} = [49.7 \pm 9.4] \times 10^{-4}$$

Using the CDF result: $\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \quad \text{ps}^{-1}$

$$\Delta\Gamma_s^{SM} = 0.088 \pm 0.017 \quad \text{ps}^{-1}$$

$$\frac{\Delta\Gamma_s^{SM}}{\Gamma_s} = 0.127 \pm 0.024$$

Experimental violation of these results would signal NP in Δm_s or $\Delta\Gamma_s$

Time evolution

was pure B^0 at t=0

$$\left|B^0(t)\right\rangle = \frac{e^{-imt}}{2}\left\{\left|B^0\right\rangle\left[e^{-\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_H t}{2}} + e^{\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_L t}{2}}\right] + \frac{q}{p}\left|\overline{B}^0\right\rangle\left[e^{\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_L t}{2}} - e^{-\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_H t}{2}}\right]\right\}$$

$$\left|\overline{B}^0(t)\right\rangle = \frac{e^{-imt}}{2}\left\{\frac{p}{q}\left|B^0\right\rangle\left[-e^{-\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_H t}{2}} + e^{\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_L t}{2}}\right] + \left|\overline{B}^0\right\rangle\left[e^{-\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_H t}{2}} + e^{\frac{i\Delta mt}{2}}e^{-\frac{\Gamma_L t}{2}}\right]\right\}$$

was pure $\overline{B}^0$ at t=0

Definitions:

$$A_f = \left\langle f \middle| B^0 \right\rangle \qquad \overline{A}_f = \left\langle f \middle| \overline{B}^0 \right\rangle$$

$$A_{\bar{f}} = \left\langle \bar{f} \middle| B^0 \right\rangle \qquad \overline{A}_{\bar{f}} = \left\langle \bar{f} \middle| \overline{B}^0 \right\rangle$$

$$\left|\bar{f}\right\rangle = CP\left|f\right\rangle$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$A_{CP}^{dir} = \frac{1-\left|\lambda_f\right|^2}{1+\left|\lambda_f\right|^2} \qquad A_{CP}^{mix} = -2\frac{\mathrm{Im}(\lambda_f)}{1+\left|\lambda_f\right|^2} \qquad A_{\Delta\Gamma} = -2\frac{\mathrm{Re}(\lambda_f)}{1+\left|\lambda_f\right|^2}$$

Time dependent decay rates

$$\Gamma(B^0(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, e^{-\Gamma t} \left\{ \frac{1+|\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma\, t}{2} + \frac{1-|\lambda_f|^2}{2} \cos(\Delta m\, t) \right.$$
$$\left. - \mathrm{Re}\, \lambda_f \, \sinh \frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\, \lambda_f \, \sin(\Delta m\, t) \right\}$$

$$\Gamma(\overline{B}^0(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, (1+a) \, e^{-\Gamma t} \left\{ \frac{1+|\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma\, t}{2} - \frac{1-|\lambda_f|^2}{2} \cos(\Delta m\, t) \right.$$
$$\left. - \mathrm{Re}\, \lambda_f \, \sinh \frac{\Delta\Gamma\, t}{2} + \mathrm{Im}\, \lambda_f \, \sin(\Delta m\, t) \right\}$$

$$\Gamma(B^0(t) \to \overline{f}) = \mathcal{N}_f \, \left|\overline{A}_{\overline{f}}\right|^2 \, e^{-\Gamma t} \, (1-a) \left\{ \frac{1+|\lambda_{\overline{f}}|^{-2}}{2} \cosh \frac{\Delta\Gamma\, t}{2} - \frac{1-|\lambda_{\overline{f}}|^{-2}}{2} \cos(\Delta m\, t) \right.$$
$$\left. - \mathrm{Re}\, \frac{1}{\lambda_{\overline{f}}} \, \sinh \frac{\Delta\Gamma\, t}{2} + \mathrm{Im}\, \frac{1}{\lambda_{\overline{f}}} \, \sin(\Delta m\, t) \right\}$$

$$\Gamma(\overline{B}^0(t) \to \overline{f}) = \mathcal{N}_f \, \left|\overline{A}_{\overline{f}}\right|^2 \, e^{-\Gamma t} \left\{ \frac{1+|\lambda_{\overline{f}}|^{-2}}{2} \cosh \frac{\Delta\Gamma\, t}{2} + \frac{1-|\lambda_{\overline{f}}|^{-2}}{2} \cos(\Delta m\, t) \right.$$
$$\left. - \mathrm{Re}\, \frac{1}{\lambda_{\overline{f}}} \, \sinh \frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\, \frac{1}{\lambda_{\overline{f}}} \, \sin(\Delta m\, t) \right\}$$

Determination of Δm, $\Delta\Gamma$, ϕ:
Strategies, experimental methods, theoretical uncertainties

Δm_s: experimental determination

CDF, PRL97 (06) 242003

Measured quantity: mixing amplitude

Dilution factor $D=2P_{tag}-1$

$$A_{mix}(t) = \frac{N_{mixed}(t) - N_{unmixed}(t)}{N_{mixed}(t) + N_{unmixed}(t)} = -D\ \cos(\Delta m t)$$

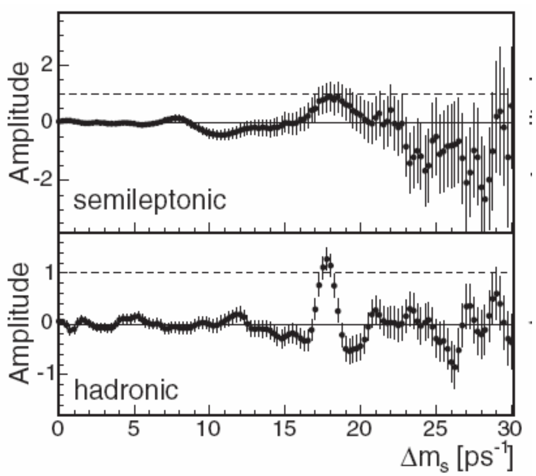
Number of particles decaying after mixing happened

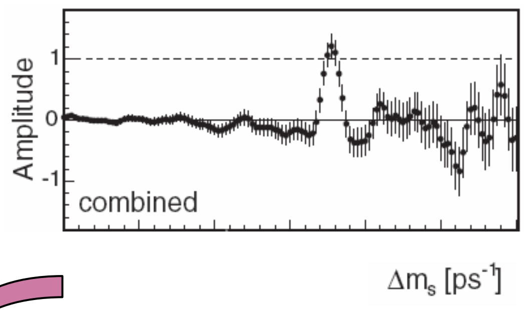
$$N_{mixed}(t) \propto \frac{1}{2}(1-\cos(\Delta m t))$$

Number of particles decaying – no mixing happened

$$N_{unmixed}(t) \propto \frac{1}{2}(1+\cos(\Delta m t))$$

- tagging of flavour at production
- final state flavour determined reconstructing flavour specific final states





$$\Delta m_s = 17.7 \pm 0.10(stat) \pm 0.07(syst) \quad ps^{-1}$$ ← **CDF**

D0 → $$\Delta m_s = 18.53 \pm 0.98(stat+syst) \quad ps^{-1}$$

Asymmetries

- Asymmetries in flavour specific final states (*fs*)
- Asymmetries in final CP eigenstates
- CP asymmetries in flavour specific final states

Flavour specific final state *f*:

$$B^0 \to f \quad \text{but} \quad \overline{B}^0 \not\to f \quad \Rightarrow \quad \overline{A}_f = 0 \quad \Rightarrow \quad \lambda_f = 0$$

$$\overline{B}^0 \to \bar{f} \quad \text{but} \quad B^0 \not\to \bar{f} \quad \Rightarrow \quad A_{\bar{f}} = 0 \quad \Rightarrow \quad \frac{1}{\lambda_{\bar{f}}} = 0$$

CP eigenstate final state f_{CP}:

$$f = f_{CP} = \eta_f \bar{f} \qquad \eta_f = \pm 1$$

Asymmetries in CP eigenstate final state

$$a_f(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = $$

$$= -\frac{A_{CP}^{dir} \cos(\Delta m t) + A_{CP}^{mix} \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

(putting $a = \frac{\Delta\Gamma}{\Delta m} tg\phi = 0$)

If there is only one amplitude contributing to the decay:

$$\left|\frac{\overline{A}_f}{A_f}\right| = 1 \;\Rightarrow\; |\lambda_f| = 1 \;\Rightarrow\; A_{CP}^{dir} = 0 \qquad A_{CP}^{mix} = \eta_f \sin\phi \qquad A_{\Delta\Gamma} = -\eta_f \cos\phi$$

η_f: CP parity of the final state

$$a_f(t) = -\frac{\eta_f \sin\phi \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \eta_f \cos\phi \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

CP Asymmetries in *fs* final state

Assuming no direct CP violation: $A_f = \overline{A}_{\bar{f}}$

$$a_{fs}^{CP} = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to \bar{f})}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to \bar{f})} = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi$$

$$= a = \frac{\Delta\Gamma}{\Delta m} tg\phi$$

Related to an untagged quantity:

$$A_{fs}^{untagged} = \frac{\int_0^\infty dt\,\left[\Gamma(f,t) - \Gamma(\bar{f},t)\right]}{\int_0^\infty dt\,\left[\Gamma(f,t) + \Gamma(\bar{f},t)\right]} =$$

$$= \frac{a_{fs}}{2} \frac{x_s^2 + y_s^2}{1 + x_s^2}$$

$$x_s = \frac{\Delta m}{\Gamma} \qquad y_s = \frac{\Delta\Gamma}{2\Gamma}$$

CP Asymmetries in *fs* final state: D0 analysis

D0 Collab.,PRL98 (07) 151801

Untagged analysis of semileptonic decays

$$B_s^0 \to D_s^- \mu^+ \nu X$$
$$\overline{B}_s^0 \to D_s^+ \mu^- \nu X$$

Results obtained using:

$$A_{fs}^{untagged} = \frac{a_{fs}}{2} \frac{x_s^2 + y_s^2}{1 + x_s^2}$$

$$A_{fs}^{untagged} = \left[1.23 \pm 0.97\,(stat) \pm 0.35\,(syst)\right] \times 10^{-2}$$

$$a_{fs} = \frac{\Delta\Gamma_s}{\Delta m_s} tg\phi = \left[2.45 \pm 1.93\,(stat) \pm 0.35\,(syst)\right] \times 10^{-2}$$

Can be used to determine $\Delta\Gamma_s$ and ϕ

D0 Collab.,PRD76 (07) 057101

Another possibility is to use the relation to the analogous asymmetry in B_d decays and B factories results

Combined result

$$a_{fs} = 0.001 \pm 0.0090$$
$$\Delta\Gamma_s = 0.13 \pm 0.09 \quad ps^{-1}$$
$$\phi = -0.70 \pm^{0.47}_{0.39}$$

→ large uncertainties

$B_s \to J/\psi\phi$

The final state is an admixture of different CP eigenstates

$\longrightarrow$ can be disentangled considering the angular distribution of the decay products:

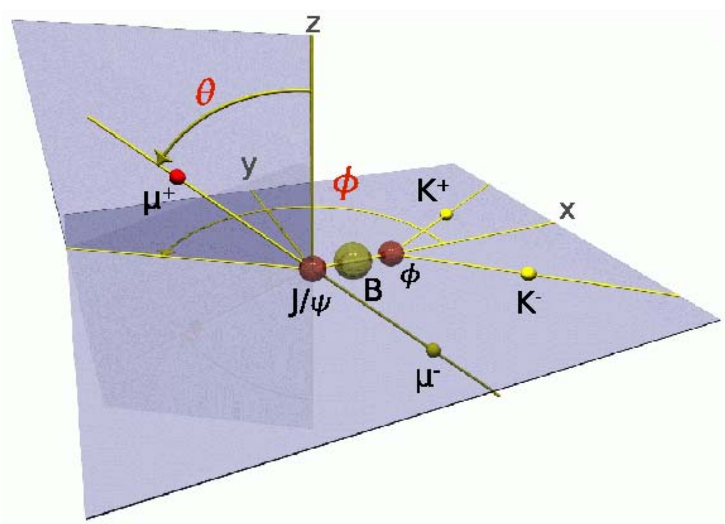
$$J/\psi \to \ell^+\ell^- \qquad \phi \to K^+K^-$$

Three independent polarization amplitudes: $A_0(t),\quad A_\parallel(t),\quad A_\perp(t)$

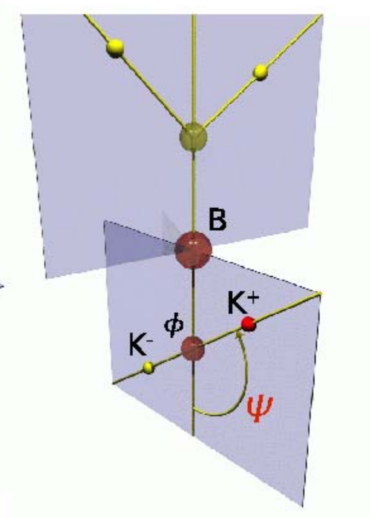
$A_0(t)$, $A_\parallel(t)$: CP even; $A_\perp(t)$: CP odd

with

$$|A|^2 = |A_0|^2 + |A_\parallel|^2 + |A_\perp|^2$$



J/ψ rest frame



φ rest frame

θ, φ, ψ, transversity angles

$B_s \to J/\psi\phi$

Simple example: time-dependent one-angle distribution:

$$\frac{d\Gamma(t)}{d\cos\theta} \propto \Big(\underbrace{|A_0(t)|^2 + |A_\parallel(t)|^2}_{\text{CP even}}\Big)\frac{3}{8}\left(1+\cos^2\theta\right) + \underbrace{|A_\perp(t)|^2}_{\text{CP odd}}\,\frac{3}{4}\sin^2\theta$$

The full three angle distribution contains more information.
However:

- it is more involved
- depends also on the strong phases $\delta_1 = \arg\{A_\parallel(0)^* A_\perp(0)\}$ $\quad\delta_2 = \arg\{A_0(0)^* A_\perp(0)\}$

Method exploited by D0 and CDF

$B_s \to J/\psi\phi$

D0 Collab., PRL 98 (07) 121801

D0 analysis of the angular distribution in **flavour untagged** B_s^0 mesons

Fitting: $$\frac{d^3\Gamma}{d\cos\theta\, d\phi\, d\psi}$$

The result has a **four-fold ambiguity ± ϕ , ±(π-ϕ)** due to the inavriance under simultaneous exchange of the sign of sin ϕ, cos δ_1, cos δ_2

Two sets of solutions:

$$|\phi| = 0.79 \pm 0.56\,(stat) \pm^{0.01}_{0.14}\,(syst)$$
$$\Delta\Gamma_s = 0.17 \pm 0.08\,(stat) \pm 0.02\,(syst)$$

$$|\phi| = 2.35 \pm 0.56\,(stat) \pm^{0.01}_{0.14}\,(syst)$$
$$\Delta\Gamma_s = -0.17 \pm 0.08\,(stat) \pm 0.02\,(syst)$$

set consistent with SM

$B_s \to J/\psi\phi$

CDF Collab., PRL 100 (08) 161802

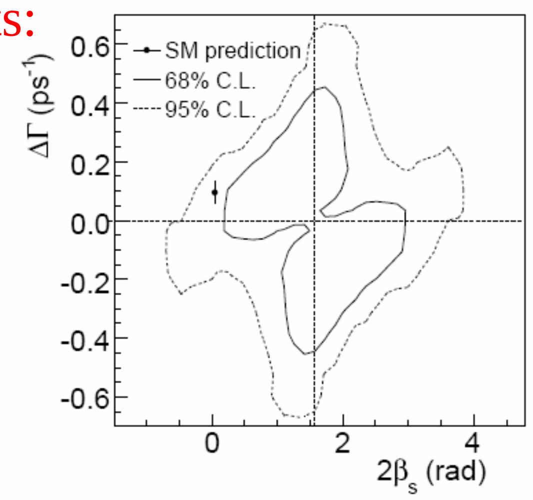
D0 Collab., PRL 101 (08) 241801

CDF and D0 analysis of **flavour tagged** decay

- combines information obtained from both the time dependence both the angular distributions to disentangle the various CP components

- allows to reduce the four-fold ambiguity in a twofold ambiguity

CDF Results:



at 68% C.L.

$$2\beta_s \in [0.32, 2.82]$$

while imposing the SM prediction for Γ_{12}:

$$2\beta_s \in [0.24, 1.36] \cup [1.78, 2.90]$$

Assuming SM predictions for $2\beta_s$ and $\Delta\Gamma$, CDF finds that the probability of a deviation as large as the level of the observed data is 15%

$B_s \to J/\psi\phi$

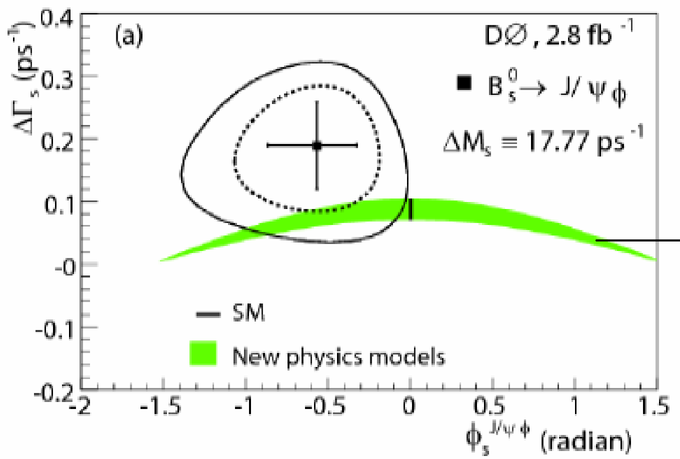
D0 Collab., PRL 101 (08) 241801

Allowed ranges at 90% C.L.

$$-1.22 < \phi < -0.08 \qquad -3.06 < \phi < -1.92$$
$$0.05 < \Delta\Gamma < 0.33 \quad ps^{-1} \qquad -0.33 < \Delta\Gamma < -0.05 \quad ps^{-1}$$

the SM hypothesis for ϕ has a probability of 8.5 %

D0 performs also a fit with constrained δ_i, taken from $B_d \to J/\psi\, K^*$



$$\Delta\Gamma_s = \Delta\Gamma_s^{SM} |\cos\phi_s|$$

$$\Delta\Gamma_s = 0.19 \pm 0.07\,(stat) \pm^{0.02}_{0.01}\,(syst) \quad ps^{-1}$$
$$\phi = -0.57 \pm^{0.24}_{0.30}\,(stat) \pm^{0.08}_{0.02}\,(syst)$$

$B_s \to J/\psi\phi$

Combined result (HFAG)

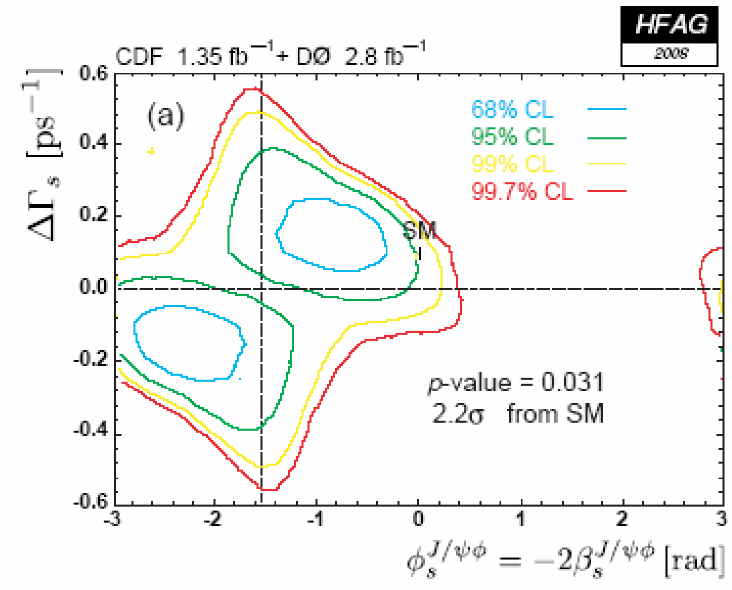
(no assumption on the strong phases)

HFAG, 0808.1297

Numerical results for the two solutions:

$$\begin{aligned}\Delta\Gamma_s &= 0.154^{+0.054}_{-0.070}\ \mathrm{ps}^{-1}\,,\\ &\in [+0.036, +0.264]\ \text{at } 90\%\ \mathrm{CL}\\ \phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} &= -0.77^{+0.29}_{-0.37}\ \mathrm{rad}\,,\\ &\in [-1.47, -0.29]\ \text{at } 90\%\ \mathrm{CL}\,,\end{aligned}$$

$$\begin{aligned}\Delta\Gamma_s &= -0.154^{+0.070}_{-0.054}\ \mathrm{ps}^{-1}\,,\\ &\in [-0.264, -0.036]\ \text{at } 90\%\ \mathrm{CL}\\ \phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} &= -2.36^{+0.37}_{-0.29}\ \mathrm{rad}\,,\\ &\in [-2.85, -1.65]\ \text{at } 90\%\ \mathrm{CL}\,.\end{aligned}$$

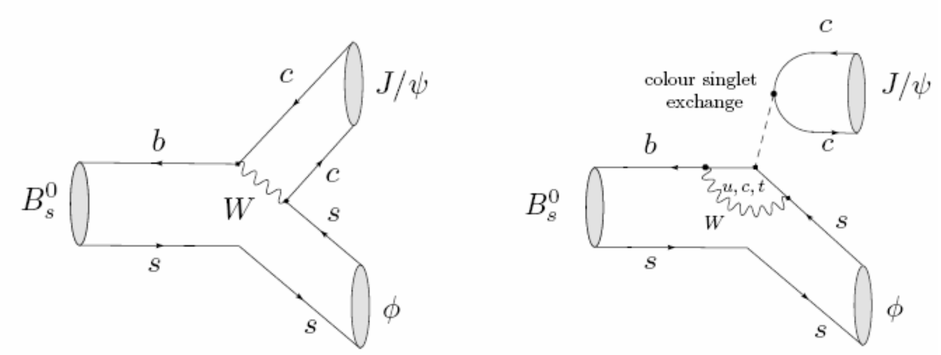


HFAG: consistency of SM predictions is at level of 2.2 σ

$B_s \to J/\psi\phi$: Role of penguins

Faller, Fleischer, Mannel
PRD 79 (09) 014005

Tree and penguin topologies contribute:



T *P*

$$A(B_s^0 \to (J/\psi\phi)_f) = \lambda_c\left(T + P^c\right) + \lambda_u P^u + \lambda_t P^t$$

$$f = 0, \|, \perp$$

$$\lambda_q = V_{qs} V_{qb}^*$$
$$\lambda_t = -\lambda_u - \lambda_c$$

Defining:

$$Q_f = \lambda^2 A(T + P_c - P_t) \qquad R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| \qquad \varepsilon = \frac{\lambda^2}{1-\lambda^2}$$

$$a_f e^{i\theta_f} = R_b\left[\frac{P_u - P_t}{T + P_c - P_t}\right]$$

→ θ_f strong CP-invariant phase

$$A(B_s^0 \to (J/\psi\phi)_f) = \left(1 - \frac{\lambda^2}{2}\right) Q_f\left[1 + \varepsilon\, a_f e^{i\theta_f} e^{i\gamma}\right]$$

$$A(\overline{B}_s^0 \to (J/\psi\phi)_f) = \eta_f\left(1 - \frac{\lambda^2}{2}\right) Q_f\left[1 + \varepsilon\, a_f e^{i\theta_f} e^{-i\gamma}\right]$$

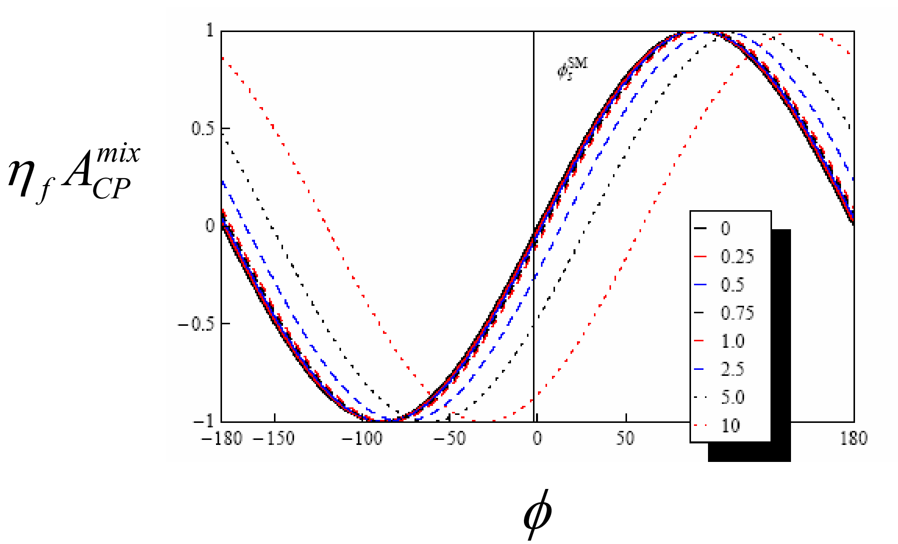
Doubly (ε) Cabibbo –suppressed contributions: Negligible?

$B_s \to J/\psi\phi$: Role of penguins

Reliable estimates of a_f, θ_f are missing.
Factorization would predict $\theta_f = 180°$.
Putting $a_f = 0$ would give: $A_{CP}^{mix} = \eta_f \sin\phi$

↓

Now depends also on a_f, θ_f



→ obtained for $\theta_f = 180°$

Values of $a_f \approx 1$
could lead to $\eta_f A_{CP}^{mix} \approx O(-10\%)$

$B_s \to J/\psi\phi$: Role of penguins

Control channel: $B_s^0 \to J/\psi\, K^{*0}$

Two quantities to be exploited:

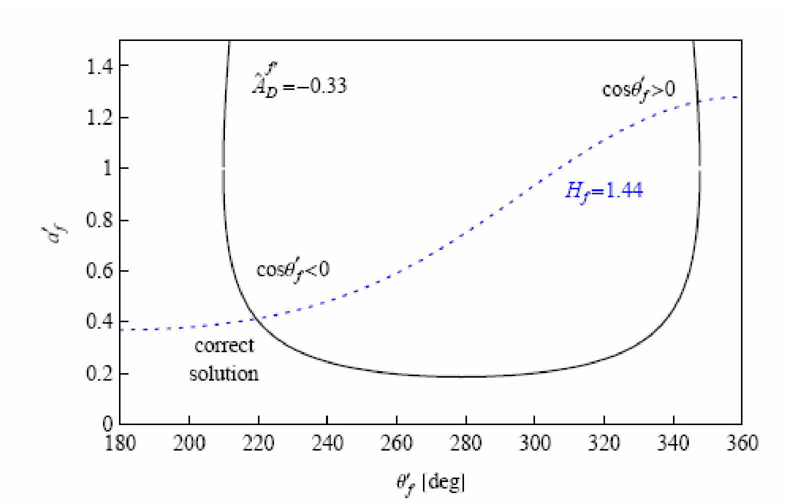
$$H_f = \frac{1}{\varepsilon}\left|\frac{Q_f}{Q'_f}\right|^2 \frac{\Gamma'(f,t=0)}{\Gamma(f,t=0)} = \frac{1-2a'_f\cos\theta'_f\cos\gamma+a'^2_f}{1+2\varepsilon\, a_f\cos\theta_f\cos\gamma+\varepsilon^2 a_f^2}$$

$$A'^{dir}_{CP} = \frac{2a'_f\sin\theta'_f\sin\gamma}{1-2a'_f\cos\theta'_f\cos\gamma+a'^2_f}$$

→ Primed quantities refer to $B_s^0 \to J/\psi\, K^{*0}$

Measuring $H_f,\ A'^{dir}_{CP}$ would fix $a'_f \approx a_f \quad \theta'_f \approx \theta_f$

Example:



The twofold ambiguity may be solved by comparison with $B_d \to J/\psi\,\rho$

However notice that theoretical estimates provide $\left|\frac{Q'_f}{Q_f}\right| \approx 0.2-1.0$

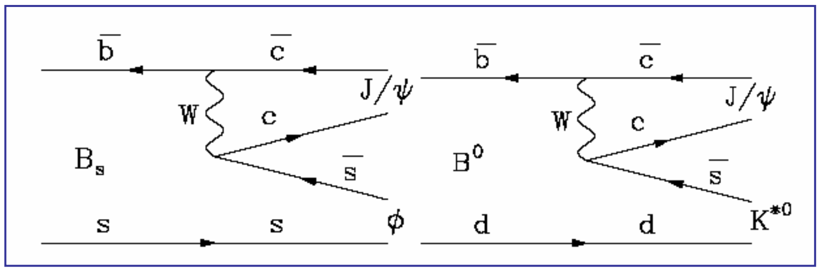
SU(3) accuracy: The case of the strong phases

Gronau, Rosner PLB 669 (08) 321
PLB 666 (08)185

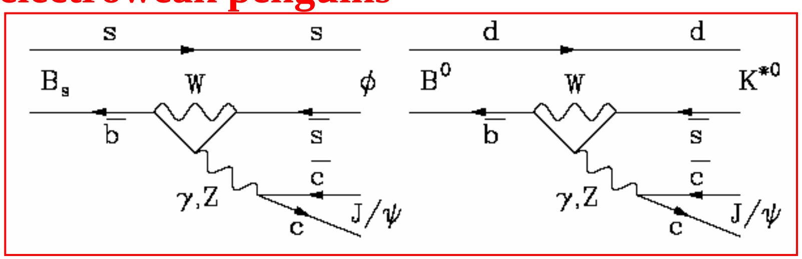
Extracting strong phases from $B_d \to J/\psi\, K^{*0}$ (as already used by D0) would solve the discrete ambiguity in the determination of ϕ

Analogous topologies:

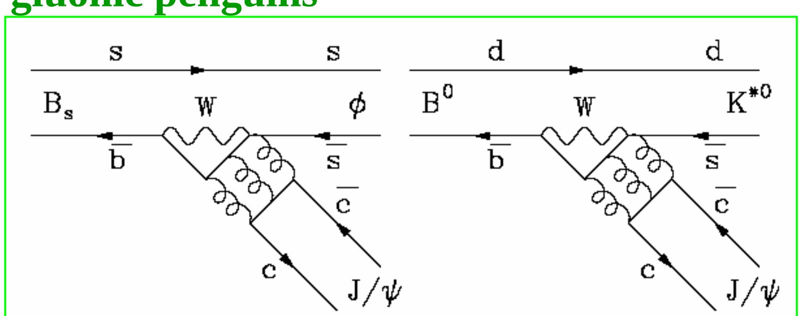
tree



electroweak penguins

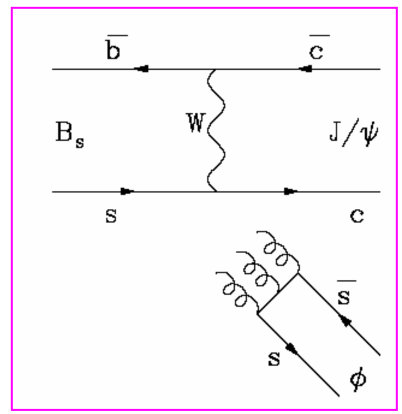


gluonic penguins



Problem: ϕ has also a singlet component

extra diagrams



→ OZI suppressed

\+ others
doubly OZI supp.

This has a counterpart in $B_d \to J/\psi\, \phi$ where it has been estimated to be negligible

The similarity of amplitudes and strong phases in $B_s \to J/\psi\phi$ and $B_d \to J/\psi\, K^{*0}$ seems a well-founded assumption

Other channels induced by $\bar{b} \to \bar{c} c \bar{s}$

M.V. Carlucci, P. Colangelo, FDF
in preparation

- A different charmonium state:

$$B_s \to \psi(2S)\phi\,, \quad B_s \to \chi_{c0}\phi\,, \quad B_s \to \eta_c\phi$$

- ψ + a different light meson:

$$B_s \to \psi\eta \qquad \eta_f = +1$$
$$B_s \to \psi\eta' \qquad \eta_f = +1$$

$$B(B_s \to \psi\,\eta) = 9.3\times 10^{-5}$$
$$B(B_s \to \psi\,\eta') = 1.3\times 10^{-4}$$

Necessity to detect photons in the final state

Improving theoretical prediction
- comparing different form factor sets
- exploting results of SCET- based sum rules
- describing η-η’ mixing in the flavour basis

$$B_s \to \psi f_0(980) \qquad \eta_f = -1$$

Twofold role of f_0: - background to $B_s \to J/\psi\phi$
- interesting final state with $f_0(980) \to \pi^+\pi^-$

Contribution of S-wave to $B_s \to J/\psi\phi$

There might be an S-wave contribution to the K^+K^- system in the region of the ϕ

– it would bias the result
– neglecting this contribution makes the error smaller

In the case of $B_d \to J/\psi K^{*0}$ BaBar finds that the S-wave component $K\pi$ is ~8%

BaBar PRD 76 (07) 031102

It may be argued that due to the narrowness of ϕ (Γ=4.3 MeV)
with respect to K* (Γ=51 MeV) the S-wave component under the ϕ is smaller

True?

Contribution of S-wave to $B_s \to J/\psi\phi$

Stone & Zhang 0812.2832

Hints on the role of S-wave contribution from other channels

$D_s \to K^+K^-\pi^+$

$$\frac{\Gamma(D_s^+ \to f_0(980)\pi^+ \to K^+K^-\pi^+)}{\Gamma(D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+)} = 0.3 \pm 0.1$$

→ Analysis done over all of phase space
What about the low mass region?

Recent analysis performed by CLEO in the low mass region fitting data with a BW for the ϕ plus a linear S-wave component

Conclusion: **The fraction of S-wave depends on the mass interval considered but is *O*(10%) in the region around ϕ**

CLEO, PRL 100 (08) 161804

Contribution of S-wave to $B_s \to J/\psi\phi$

How to get rid of this contribution?

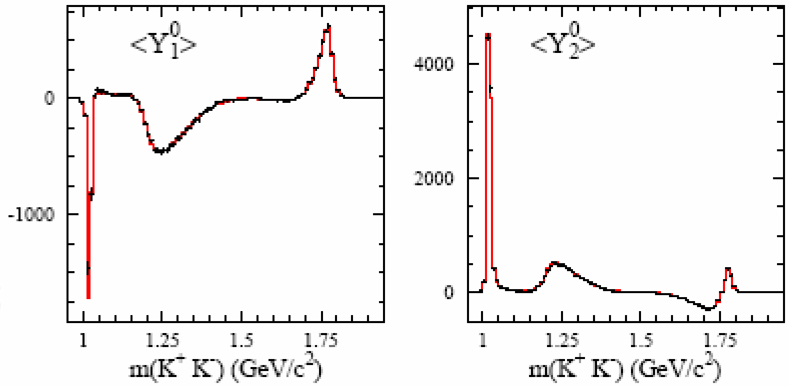
Partial wave analysis

- S, P waves and relative phase can be extracted using:

$$\sqrt{4\pi}Y_0^0 = S^2 + P^2$$
$$\sqrt{4\pi}Y_1^0 = 2SP\cos\phi$$
$$\sqrt{4\pi}Y_2^0 = 0.894P^2$$

- BaBar: $D_s^+ \to \pi^+ K^+ K^-$
- Spherical harmonics moments Y_l^0

K^+K^-



Large interference between S-wave (f_0(980)) and P-wave (ϕ(1020)) in Y_1^0
Y_2^0 takes contribution only from P-wave

A. Palano, talk at LHC-b meeting Bologna, January 09
www.ba.infn.it/~palano/antimo_f0.pdf

$$B_s \to J/\psi \ f_0 \qquad f_0 \to \pi^+\pi^-$$

- No angular analysis required
- No photons to detect

From analysis of BaBar data about the modes $D_s^+ \to \pi^+\pi^-\pi^+$ $\quad D_s^+ \to K^+K^-\pi^+$
It is expected that

$$\frac{B(B_s \to J/\psi f_0, f_0 \to \pi^+\pi^-)}{B(B_s \to J/\psi\phi, \phi \to K^+K^-)} = (19 \pm 2)\%$$

New Physics or not New Physics….

Δm_s

Experimental weighted average (HFAG)

$$\Delta m_s = 17.78 \pm 0.12 \quad \text{ps}^{-1}$$

To be compared to (Lenz & Nierste 07) :

$$\Delta m_s^{SM} = (19.30 \pm 6.68) \quad \text{ps}^{-1}$$

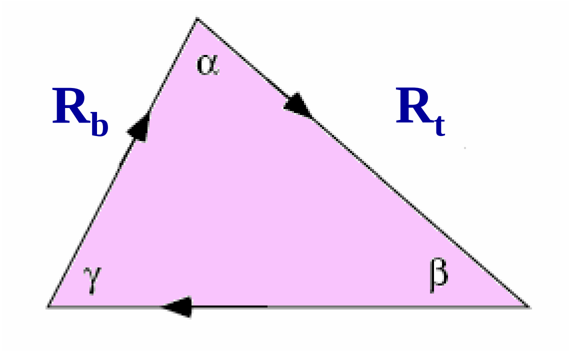
What happens in other NP scenarios?

$\Delta m_s > \left(\Delta m_s\right)^{SM}$ is favoured in
- Two Higgs Doublet Model type II
- MSSM with low Tan β
- Littlest Higgs model without T-parity
- Universal Extra dimensions

$\Delta m_s < \left(\Delta m_s\right)^{SM}$ is favoured in
- MSSM with MFV and large Tan β

Δm_s

Relations between Δm_s and other observables hold either in SM or in MFV.
Violation of such relations would imply new low energy operators
and/or new sources of flavour/CP violation



$$R_b = \sqrt{1 + R_t^2 - 2R_t \cos\beta}$$

$$\cot\gamma = \frac{1 - R_t \cos\beta}{R_t \sin\beta}$$

R_b and γ can be determined from tree level decays
R_t and β from loop-induced processes and are therefore sensitive to NP

testing the previous relations may reveal NP effects

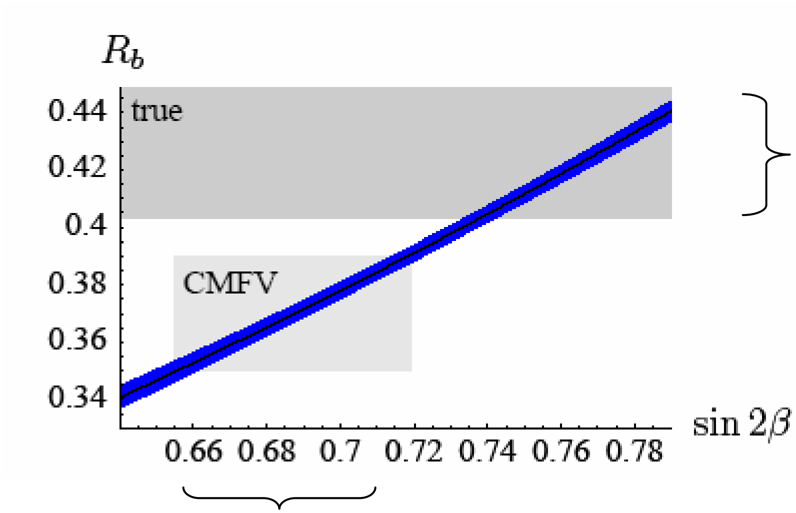
Recall that

$$R_t \Leftrightarrow \Delta m_s$$

$$\sin 2\beta \Leftrightarrow A_{CP}^{mix}(B_d \to J/\psi\, K_s)$$

Δm_s

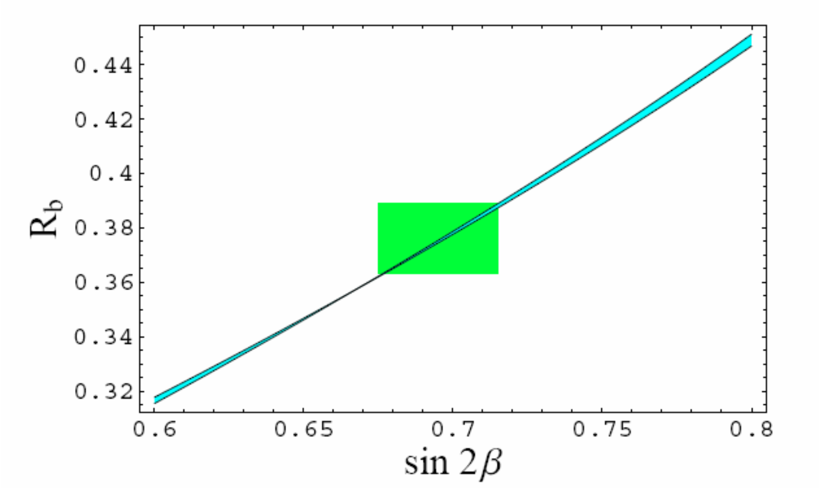
Blanke et al. JHEP 10 (06) 003



Value of R_b from tree level processes

Measured value of sin 2β

Updated values of ξ and of Δm_s seem to give a better agreement

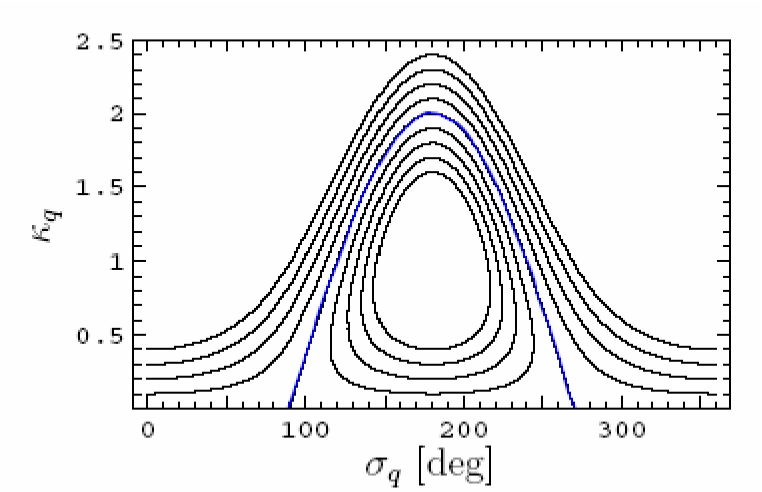


Δm_s

Ball & Fleischer
EPJC 48 (06) 413
Ball, hep-ph/0703214

Effect of possible new physics on Δm_s → $\Delta m_s = \Delta m_s^{SM}\left[1 + k_s e^{i\sigma_d}\right]$

Quantify the deviation from the SM → $\rho_s = \left|\frac{\Delta m_s^{\exp}}{\Delta m_s^{SM}}\right| = \sqrt{1 + 2k_s \cos\sigma_s + k_s^2}$



The blue line is ρ_s=1

Even the perfect coincidence of $\Delta m_s^{\exp}$ with Δm_s^{SM}
would not exclude NP in B_s mixing:
There are anyway allowed regions in the (σ_s, k_s) plane

ϕ

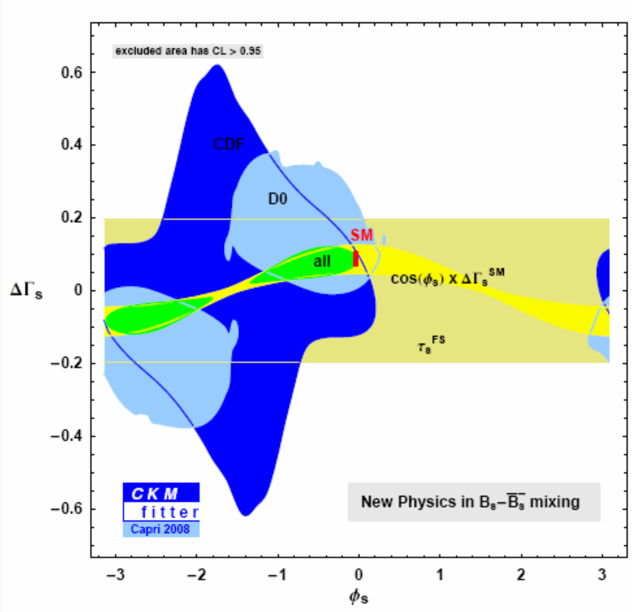
UT*fit*

FIRST EVIDENCE OF NEW PHYSICS IN $b \leftrightarrow s$ TRANSITIONS
(UT*fit* Collaboration)

With the procedure we followed to combine the available data, we obtain an evidence for NP at more than 3σ.

UT*fit* Collab., 0803.0659

CKMfitter



J. Charles, Talk @ 2nd Workshop on Theory, Phenomenology & Experiments in HF Physics - Capri 08

using all $(\phi_s, \Delta\Gamma_s)$ inputs, $\phi_s = -2\beta_s$ is excluded at 2.4σ, while the 2D hypothesis $\phi_s = -2\beta_s$, $\Delta\Gamma_s = \Delta\Gamma_s^{SM}$ is excluded at only 1.9σ

in contrast to UTfit, we do not find an "evidence" ($\gtrsim 3\sigma$) for New Physics in ϕ_s, even with the non conservative treatment of Tevatron data errors

New Physics: a model independent parameterisation

New Physics may affect ΔM_s and ϕ_s →

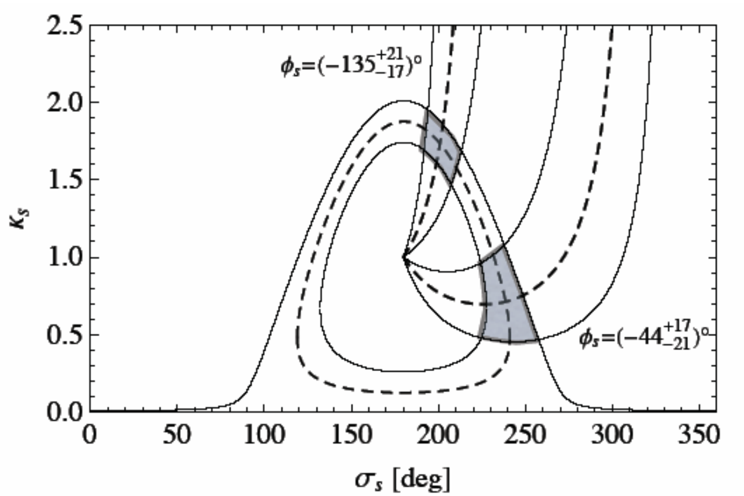
$$\Delta m_s = \Delta m_s^{SM}\left[1 + k_s e^{i\sigma_d}\right]$$

$$\phi_s = \phi_s^{SM} + \phi_s^{NP} = \phi_s^{SM} + \arg\left(1 + k_s e^{i\sigma_d}\right)$$

$$\rho_s = \left|\frac{\Delta m_s^{\exp}}{\Delta m_s^{SM}}\right| = \sqrt{1 + 2k_s \cos\sigma_s + k_s^2} \quad \Rightarrow \quad k_s = -\cos\sigma_s \pm \sqrt{\rho_s^2 - \sin^2\sigma_s}$$

$$k_s = \frac{\tan\phi_s^{NP}}{\sin\sigma_s - \cos\sigma_s \tan\phi_s^{NP}}$$

Constraints in the (σ_s, k_s) plane



Rare $b \to s$ induced B_s decays

Can provide information on NP scenarios, in particular can constrain the size of possible extra dimensions

Appelquist-Cheng-Dobrescu (ACD) Model
with a single Universal Extra Dimension (UED)

- Compactification on a orbifold: the 5th dim ***y*** varies on a circle of radius **R** with periodic boundary conditions; fields are required to have a definite parity under $y \to -y$

- MFV model

- The existence of an extra dim reflects in the appearance of a tower of KK modes for each particle of the model

Modification of the Wilson coefficients in effective hamiltonians

$$C\left(x_t, \frac{1}{R}\right) = C_{(0)}(x_t) + \sum_{n=1}^{\infty} C_n(x_t, x_n) \qquad x_n = \frac{m_n^2}{M_W^2}$$

$$m_n = \frac{n}{R}$$

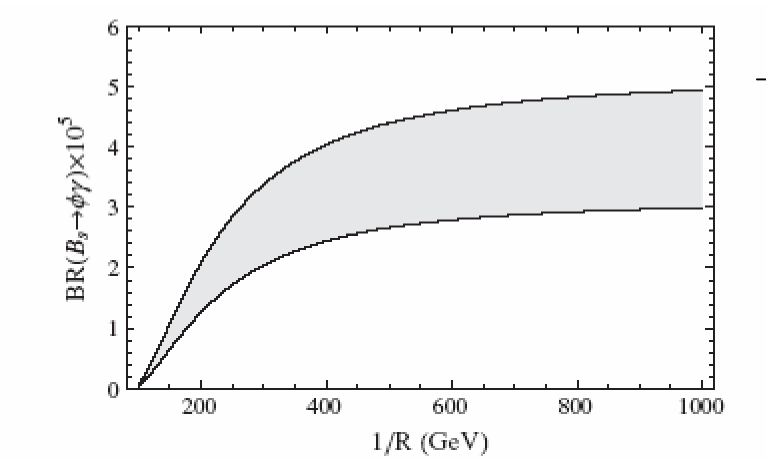
SM result ($C_{(0)}(x_t)$)

A bound on 1/R might be established studying various observables in these modes

$B_s \to \phi\gamma$

Branching ratio vs 1/R

Colangelo, Ferrandes, Pham, FDF
PRD 77 (08) 019



SM result

$$\mathcal{B}(B_s \to \phi\gamma) = (4.2 \pm 0.3) \times 10^{-5}$$

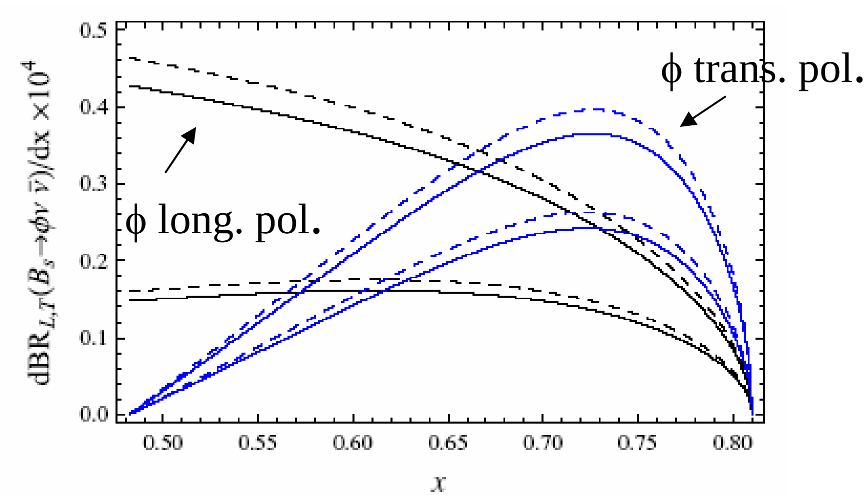
To be compared to Belle's result

$$\mathcal{B}(B_s \to \phi\gamma)_{exp} = (5.7^{+1.8}_{-1.5}(\text{stat})^{+1.2}_{-1.1}(\text{syst})) \times 10^{-5}$$

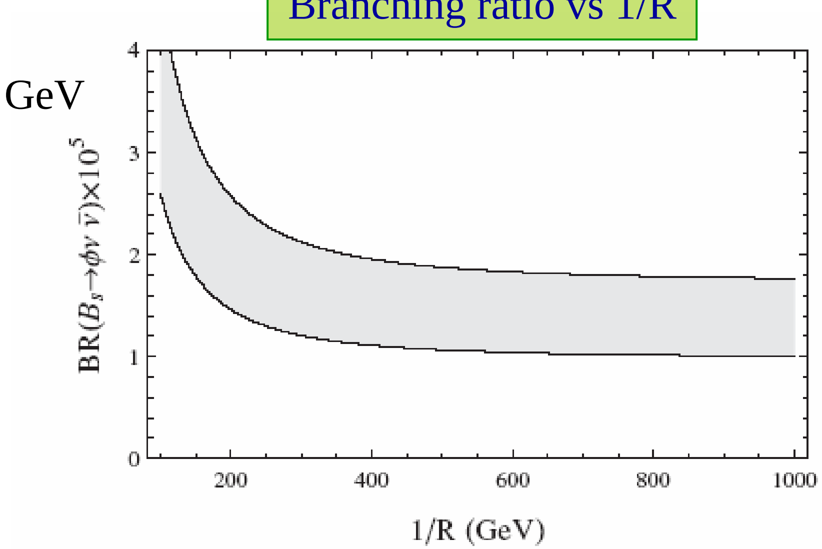
$B_s \to \phi\nu\bar{\nu}$

missing energy distribution

SM
1/R=500 GeV



Branching ratio vs 1/R



SM

$$\mathcal{B}(B_s \to \phi\nu\bar{\nu}) = (1.4 \pm 0.4) \times 10^{-5}$$

Conclusions

B_s Physics will give us fundamental insights in the research for New Physics

Future directions:

- reduction of theoretical and experimental uncertainties
- explore new channels
- analyse rare B_s decays as a probe of new Physics
  (combine with analogous information from rare B decays)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IFAE 2009 - VIII Edizione
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Fisica oltre il Modello Standard
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Backup slides

Untagged decays

$$\Gamma(f,t) = \Gamma(B^0(t) \to f) + \Gamma(\overline{B}^0(t) \to f) =$$
$$= N_f \left|A_f\right|^2 \left(1 + \left|\lambda_f\right|^2\right) e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

Integrating over time:

$$Br(f)_{untagged} = \frac{1}{2}\int_0^\infty dt \;\; \Gamma(f,t) =$$
$$= \frac{N_f}{2}\left|A_f\right|^2 \left(1 + \left|\lambda_f\right|^2\right) \frac{1}{\Gamma}\left[1 + \frac{\Delta\Gamma}{2\Gamma} A_{\Delta\Gamma} + O\left(\frac{(\Delta\Gamma)^2}{\Gamma^2}\right)\right]$$

$$\Rightarrow \quad \Gamma(f,t) = 2Br(f)_{untagged}\, \Gamma e^{-\Gamma t}\left[1 + \frac{\Delta\Gamma}{2} A_{\Delta\Gamma}\left(t - \frac{1}{\Gamma}\right)\right] + O\left((\Delta\Gamma t)^2\right)$$

A fit to this quantity allows to determine the product $\Delta\Gamma \cdot A_{\Delta\Gamma}$

Asymmetries in *fs* final state

$$A_0(t)=\frac{\Gamma(B^0(t)\to f)-\Gamma(B^0(t)\to \bar f)}{\Gamma(B^0(t)\to f)+\Gamma(B^0(t)\to \bar f)}$$

When *f*=*fs*

$$\Gamma\left(B^0(t)\to f\right)=N_f\left|A_f\right|^2\frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right)+\cos\left(\Delta m t\right)\right]$$

$$\Gamma\left(B^0(t)\to \bar f\right)=N_f\left|\bar A_{\bar f}\right|^2\frac{e^{-\Gamma t}}{2}(1-a)\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right)-\cos\left(\Delta m t\right)\right]$$

Assuming no direct CP violation: $A_f=\bar A_{\bar f}$

$$A_{fs}(t)=\frac{\cos\left(\Delta m t\right)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right)}+\frac{a}{2}\left[1-\frac{\cos^2\left(\Delta m t\right)}{\cosh^2\left(\frac{\Delta\Gamma t}{2}\right)}\right]$$

a being small: $a=\frac{\Delta\Gamma}{\Delta m}tg\phi$

May give access to $\Delta\Gamma$