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SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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Flavour Physics at the LHC
Part II

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Flavour Physics at the LHC

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ICTP, Trieste, Italy, 11–16 September 2006

(II)

Lecture II: Moving Towards the LHC

- A Closer Look at Decays of Neutral B Mesons:
  - Time evolution of B_q^0–$\bar{B}_q^0$ mixing.
  - Application: the "golden" decay $B_d^0 \to J/\psi K_{\mathrm{S}}$.
- How Could New Physics (NP) Enter the B-Physics Landscape?
  - Popular NP amplitudes.
  - Implications of the B-factory data for the B_d system.
- Benchmark Processes for the LHC B-Physics Programme:

  $\longrightarrow$ key target: **B_s-meson system**

  - Implications of the measurement of ΔM_s at the Tevatron.
  - $B_s \to J/\psi\phi$: "golden" channel to search for NP in B_s^0–$\bar{B}_s^0$ mixing.
  - $B_s \to D_s^{\pm} K^{\mp}$, $B_s \to K^+K^-$: determinations of γ.
  - $B_{s,d} \to \mu^+\mu^-$, $B_d \to K^{*0}\mu^+\mu^-$: rare decay NP probes.

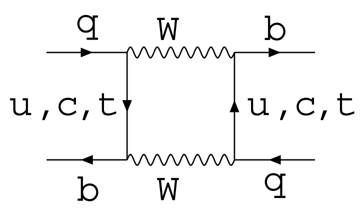
A Closer Look at

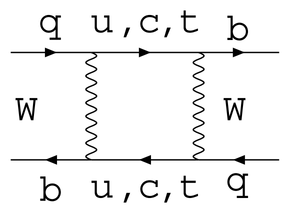
Decays of

Neutral B Mesons

Formalism of B_q^0–$\overline{B_q^0}$ Mixing ($q \in \{d, s\}$)

- Lowest-order SM contributions:





- Time evolution:[1]

$$|\psi_q(t)\rangle = a(t)|B_q^0\rangle + b(t)|\overline{B_q^0}\rangle$$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \Bigg[\underbrace{\begin{pmatrix} M_0^{(q)} & M_{12}^{(q)} \\ M_{12}^{(q)*} & M_0^{(q)} \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma_0^{(q)} & \Gamma_{12}^{(q)} \\ \Gamma_{12}^{(q)*} & \Gamma_0^{(q)} \end{pmatrix}}_{\text{decay matrix}}\Bigg] \cdot \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

- Eigenstates $|B_\pm^{(q)}\rangle$ with their eigenvalues $\lambda_\pm^{(q)}$:

$$|B_\pm^{(q)}\rangle = \frac{1}{\sqrt{1+|\alpha_q|^2}}\left(|B_q^0\rangle \pm \alpha_q|\overline{B_q^0}\rangle\right)$$

$$\lambda_\pm^{(q)} = \left(M_0^{(q)} - \frac{i}{2}\Gamma_0^{(q)}\right) \pm \left(M_{12}^{(q)} - \frac{i}{2}\Gamma_{12}^{(q)}\right)\alpha_q$$

[1] The special form of the Hamiltonian H, with $H_{11} = H_{22}$, is an implication of the CPT theorem.

$$\alpha_q e^{i\Theta^{(q)}_{\Gamma_{12}}} = \pm\sqrt{\frac{4|M^{(q)}_{12}|^2 e^{-i2\delta\Theta^{(q)}_{M/\Gamma}} + |\Gamma^{(q)}_{12}|^2}{4|M^{(q)}_{12}|^2 + |\Gamma^{(q)}_{12}|^2 - 4|M^{(q)}_{12}||\Gamma^{(q)}_{12}|\sin\delta\Theta^{(q)}_{M/\Gamma}}}$$

$$M^{(q)}_{12} \equiv e^{i\Theta^{(q)}_{M_{12}}}|M^{(q)}_{12}|, \quad \Gamma^{(q)}_{12} \equiv e^{i\Theta^{(q)}_{\Gamma_{12}}}|\Gamma^{(q)}_{12}|, \quad \delta\Theta^{(q)}_{M/\Gamma} \equiv \Theta^{(q)}_{M_{12}} - \Theta^{(q)}_{\Gamma_{12}}$$

- Dispersive parts of the boxes: [dominated by top-quark exchange, as $m_t \gg m_{c,u}$]

$$M^{(q)}_{12} = \frac{G_F^2 M_W^2}{12\pi^2}\eta_B M_{B_q}\hat{B}_{B_q} f^2_{B_q}\left(V^*_{tq}V_{tb}\right)^2 S_0(x_t)\underbrace{e^{i(\pi-\phi_{\mathrm{CP}}(B_q))}}$$

$$(\mathcal{CP})|B^0_q\rangle = e^{i\phi_{\mathrm{CP}}(B_q)}|\overline{B^0_q}\rangle$$

  - η_B: perturbative QCD corrections
  - $\hat{B}_{B_q}$: parametrizes $\langle\overline{B^0_q}|(\bar{b}q)_{\mathrm{V-A}}(\bar{b}q)_{\mathrm{V-A}}|B^0_q\rangle$ ($\rightarrow$ "bag parameter")
  - $S_0(x_t \equiv m_t^2/M_W^2)$: top-quark dependence ($\rightarrow$ an "Inami–Lim function")

- Absorptive parts of the boxes:

$$\Gamma^{(q)}_{12}/M^{(q)}_{12} \approx -3\pi/(2S_0(x_t))(m_b/M_W)^2 = \mathcal{O}(m_b^2/m_t^2) \ll 1$$

- Neglecting 2nd order terms in $\Gamma_{12}^{(q)}/M_{12}^{(q)}$:

$$\Rightarrow \boxed{\alpha_q = \pm\left[1+\frac{1}{2}\left|\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}}\right|\sin\delta\Theta_{M/\Gamma}^{(q)}\right]e^{-i\Theta_{M12}^{(q)}}}$$

- Deviation of $|\alpha_q|$ from 1: $\longrightarrow$ **CP violation in B_q^0–$\overline{B_q^0}$ oscillations**

  – "Wrong charge" lepton asymmetries:

$$\mathcal{A}_{\mathrm{SL}}^{(q)} \equiv \frac{\Gamma(B_q^0(t)\to\ell\overline{\nu}_\ell X)-\Gamma(\overline{B_q^0}(t)\to\bar{\ell}\nu_\ell X)}{\Gamma(B_q^0(t)\to\ell\overline{\nu}_\ell X)+\Gamma(\overline{B_q^0}(t)\to\bar{\ell}\nu_\ell X)} = \frac{|\alpha_q|^4-1}{|\alpha_q|^4+1} \approx \left|\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}}\right|\sin\delta\Theta_{M/\Gamma}^{(q)}$$

  – $|\Gamma_{12}^{(q)}/M_{12}^{(q)}| \propto m_b^2/m_t^2$, $\sin\delta\Theta_{M/\Gamma}^{(q)} \propto m_c^2/m_b^2$:

$$\Rightarrow \boxed{\mathcal{A}_{\mathrm{SL}}^{(q)} \text{ is suppressed by } m_c^2/m_t^2 = \mathcal{O}(10^{-4})} \longrightarrow \text{probe for NP!}$$

  – Experimental status:[2] $\mathcal{A}_{\mathrm{SL}}^{(q)} = 0.0030 \pm 0.0078$ ...

- We shall neglect these effects in the following: $\Rightarrow \boxed{\alpha_q = \pm e^{-i\Theta_{M12}^{(q)}}}$

[2] Heavy Flavour Averaging Group (HFAG): http://www.slac.stanford.edu/xorg/hfag/

The B_q^0–$\bar{B}_q^0$ Mixing Parameters

- Masses $M_{\rm H}^{(q)}$ ("heavy") and $M_{\rm L}^{(q)}$ ("light") of the eigenstates:

$$M_q \equiv \frac{M_{\rm H}^{(q)} + M_{\rm L}^{(q)}}{2} = M_0^{(q)}$$

$$\boxed{\Delta M_q \equiv M_{\rm H}^{(q)} - M_{\rm L}^{(q)} = 2|M_{12}^{(q)}| > 0}$$

  – Experimental status:

$$\Delta M_d = (0.507 \pm 0.004)\,\mathrm{ps}^{-1} : \text{ well-settled quantity!}$$

$$\underbrace{\Delta M_s = \begin{cases} 17\,\mathrm{ps}^{-1} < \Delta M_s < 21\,\mathrm{ps}^{-1} \text{ @ 90\% C.L.} & \text{[D0 ('06)]} \\ \left[17.31^{+0.33}_{-0.18}(\mathrm{stat}) \pm 0.07(\mathrm{syst})\right]\mathrm{ps}^{-1} & \text{[CDF ('06)]} \end{cases}}$$

$\rightarrow$ hot topic, see below ...

- Decay widths $\Gamma_{\rm H}^{(q)}$ and $\Gamma_{\rm L}^{(q)}$ of the eigenstates:

$$\Gamma_q \equiv \frac{\Gamma_{\rm H}^{(q)} + \Gamma_{\rm L}^{(q)}}{2} = \Gamma_0^{(q)}$$

$$\boxed{\Delta\Gamma_q \equiv \Gamma_{\rm H}^{(q)} - \Gamma_{\rm L}^{(q)} = 4\,{\rm Re}[M_{12}^{(q)}\Gamma_{12}^{(q)*}]/\Delta M_q}$$

  – Interesting relation:

$$\frac{\Delta\Gamma_q}{\Gamma_q} \approx -\left[\frac{3\pi}{2S_0(x_t)}\frac{m_b^2}{M_W^2}\right]\frac{\Delta M_q}{\Gamma_q} = -\mathcal{O}(10^{-2}) \times \frac{\Delta M_q}{\Gamma_q}$$

$\Rightarrow$ we expect $\Delta\Gamma_d/\Gamma_d \sim 10^{-2}$, whereas $\Delta\Gamma_s/\Gamma_s \sim 10^{-1}$!

  * In fact, elaborate SM calculations: [Review: A. Lenz, hep-ph/0412007]

$$\frac{|\Delta\Gamma_d|}{\Gamma_d} = (3 \pm 1.2) \times 10^{-3}, \qquad \frac{|\Delta\Gamma_s|}{\Gamma_s} = 0.12 \pm 0.05.$$

  – Experimental status: $B_s \to J/\psi\phi$ @ Tevatron $\Rightarrow$

$$\frac{|\Delta\Gamma_s|}{\Gamma_s} = \begin{cases} 0.24^{+0.28+0.03}_{-0.38-0.04} & \text{[D0 ('05)]} \\ 0.65^{+0.25}_{-0.33} \pm 0.01 & \text{[CDF ('05)]} \end{cases}$$

Time-Dependent Decay Rates of Neutral B_q Mesons

- Time evolution due to B_q^0–$\overline{B_q^0}$ mixing:[3] $\Rightarrow$

$$\Gamma(\overset{(-)}{B_q^0}(t) \to f) = \left[\left| g_\mp^{(q)}(t) \right|^2 + \left| \xi_f^{(q)} \right|^2 \left| g_\pm^{(q)}(t) \right|^2 - 2\,\mathrm{Re}\left\{ \xi_f^{(q)} g_\pm^{(q)}(t) g_\mp^{(q)}(t)^* \right\} \right] \Gamma_f$$

  – The time dependence enters through the following functions:

$$g_+^{(q)}(t)\, g_-^{(q)}(t)^* = \frac{1}{4}\left[e^{-\Gamma_{\rm L}^{(q)}t} - e^{-\Gamma_{\rm H}^{(q)}t} - 2\,i\,e^{-\Gamma_q t}\sin(\Delta M_q t) \right]$$

$$\left| g_\mp^{(q)}(t) \right|^2 = \frac{1}{4}\left[e^{-\Gamma_{\rm L}^{(q)}t} + e^{-\Gamma_{\rm H}^{(q)}t} \mp 2\,e^{-\Gamma_q t}\cos(\Delta M_q t) \right]$$

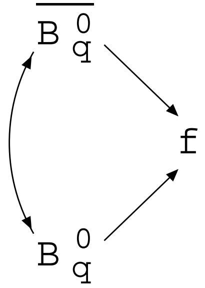
  – The overall normalization Γ_f denotes the "unevolved" $B_q^0 \to f$ rate.

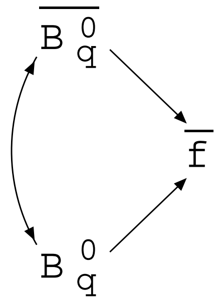
- Substitutions for the $\overset{(-)}{B_q^0}(t) \to \overline{f}$ rates: $\Gamma_f \to \Gamma_{\overline{f}}, \quad \xi_f^{(q)} \to \xi_{\overline{f}}^{(q)}$.

[3] The $\pm$ ambiguity in α_q from the square root is resolved through the *positive* mass difference ΔM_q!

- The quantities $\xi_f^{(q)}$ and $\xi_{\overline{f}}^{(q)}$ describe interference effects:

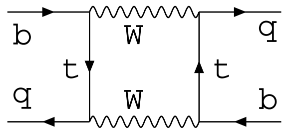
$$\xi_f^{(q)} = e^{-i\Theta_{M_{12}}^{(q)}} \frac{A(\overline{B_q^0} \to f)}{A(B_q^0 \to f)} \qquad \xi_{\overline{f}}^{(q)} = e^{-i\Theta_{M_{12}}^{(q)}} \frac{A(\overline{B_q^0} \to \overline{f})}{A(B_q^0 \to \overline{f})}$$





- $\Theta_{M_{12}}^{(q)}$ is the CP-violating weak B_q^0–$\overline{B_q^0}$ mixing phase:

$$M_{12} = e^{i\Theta_{M_{12}}^{(q)}} |M_{12}|$$



$$\Theta_{M_{12}}^{(q)} - \pi + \phi_{\rm CP}(B_q) = 2\,\text{arg}(V_{tq}^* V_{tb}) \equiv \phi_q = \begin{cases} +2\beta & (B_d \text{ system}) \\ -2\delta\gamma & (B_s \text{ system}) \end{cases}$$

- Note that $\xi_f^{(q)}$ and $\xi_{\overline{f}}^{(q)}$ are convention-independent quantities!

"Untagged Rates"

- The expected sizeable width difference $\Delta\Gamma_s$ of the B_s-meson system may provide interesting studies of CP violation through "untagged" rates:

$$\langle\Gamma(B_s(t)\to f)\rangle \equiv \Gamma(B^0_s(t)\to f)+\Gamma(\overline{B^0_s}(t)\to f)$$

- Consider a final state f to which both a B^0_s and a $\overline{B^0_s}$ may decay: $\Rightarrow$

$$\langle\Gamma(B_s(t)\to f)\rangle \propto \left[\cosh(\Delta\Gamma_s t/2)-\mathcal{A}_{\Delta\Gamma}(B_s\to f)\sinh(\Delta\Gamma_s t/2)\right]e^{-\Gamma_s t}$$

$$\mathcal{A}_{\Delta\Gamma}(B_s\to f)\equiv\frac{2\,\mathrm{Re}\,\xi^{(s)}_f}{1+\left|\xi^{(s)}_f\right|^2}$$

- Observations:
  - The rapidly oscillating $\Delta M_s t$ terms cancel!
  - The observable $\mathcal{A}_{\Delta\Gamma}(B_s\to f)$ allows us to obtain information about the phase structure of $\xi^{(s)}_f$: $\Rightarrow$ insights into CP violation!
  - Various "untagged" strategies were proposed (see also below) ...

[Dunietz ('95); R.F. & Dunietz ('96); Dunietz, Dighe & R.F. ('99); ...]

CP-Violating Asymmetries in Neutral B_q Decays

- Particularly simple: $B_q \to f$ with $(\mathcal{CP})|f\rangle = \pm|f\rangle$.

- Time-dependent CP asymmetry:

$$\frac{\Gamma(B^0_q(t) \to f) - \Gamma(\overline{B^0_q}(t) \to \overline{f})}{\Gamma(B^0_q(t) \to f) + \Gamma(\overline{B^0_q}(t) \to \overline{f})} = \left[\frac{\mathcal{A}^{\rm dir}_{\rm CP}\cos(\Delta M_q t) + \mathcal{A}^{\rm mix}_{\rm CP}\sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2) - \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)}\right]$$

$$\mathcal{A}^{\rm dir}_{\rm CP} \equiv \frac{1-|\xi^{(q)}_f|^2}{1+|\xi^{(q)}_f|^2} = \underbrace{\frac{|A(B^0_q \to f)|^2 - |A(\overline{B^0_q} \to \overline{f})|^2}{|A(B^0_q \to f)|^2 + |A(\overline{B^0_q} \to \overline{f})|^2}}_{\text{well-known "direct" CP violation}}$$

$$\mathcal{A}^{\rm mix}_{\rm CP} \equiv \frac{2\,\mathrm{Im}\,\xi^{(q)}_f}{1+|\xi^{(q)}_f|^2} \Rightarrow \boxed{\text{new aspect: "mixing-induced" CP violation!}}$$

- The "untagged" observable $\mathcal{A}_{\Delta\Gamma}$ (see above) is not an independent one:

$$[\mathcal{A}^{\rm dir}_{\rm CP}]^2 + [\mathcal{A}^{\rm mix}_{\rm CP}]^2 + [\mathcal{A}_{\Delta\Gamma}]^2 = 1.$$

- General form of the non-leptonic B-decay amplitudes ($\rightarrow$ Lecture I):[4]

$$\Rightarrow \quad \xi_f^{(q)} = \mp\, e^{-i\phi_q} \left[\frac{e^{+i\varphi_1}|A_1|e^{i\delta_1} + e^{+i\varphi_2}|A_2|e^{i\delta_2}}{e^{-i\varphi_1}|A_1|e^{i\delta_1} + e^{-i\varphi_2}|A_2|e^{i\delta_2}} \right] \quad \Rightarrow$$

calculation of $\xi_f^{(q)}$ is affected by hadronic uncertainties!

- However, if one CKM amplitude plays the dominant rôle:

$$\xi_f^{(q)} = \mp\, e^{-i\phi_q} \left[\frac{e^{+i\phi_f/2}|M_f|e^{i\delta_f}}{e^{-i\phi_f/2}|M_f|e^{i\delta_f}} \right] = \mp\, e^{-i(\phi_q - \phi_f)} \quad \Rightarrow$$

hadronic matrix element $|M_f|e^{i\delta_f}$ cancels!

  – *No* direct CP violation, but *still* mixing-induced CP violation:

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_q \to f) = \pm \sin(\phi_q - \phi_f) \equiv \pm \sin\phi$$

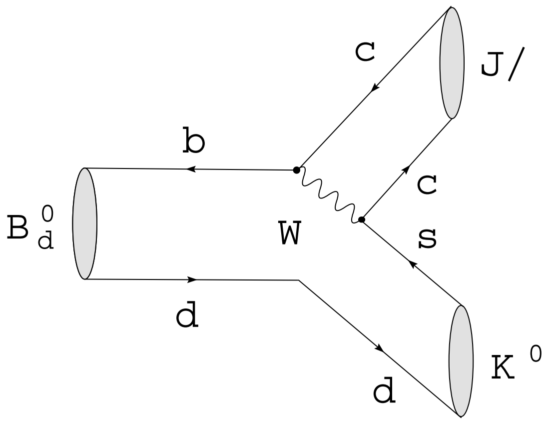
[4]Note that it can explicitly be seen that the convention-dependent phase $\phi_{\rm CP}(B_q)$ cancels!

$$\boxed{B_d^0 \to J/\psi K_{\rm S}}$$

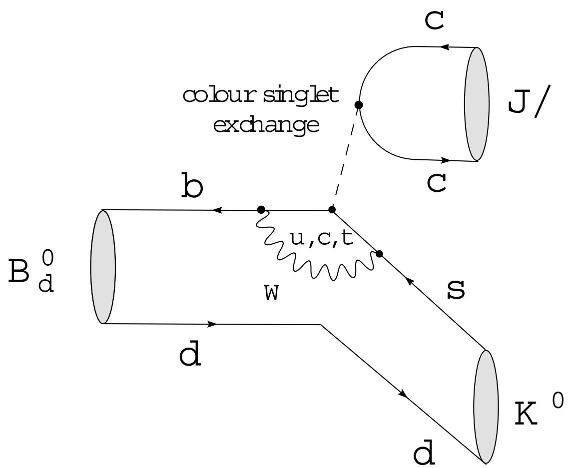
$\longrightarrow$ the "golden" decay for the B factories:

Decay Amplitude & CP Asymmetries

- Decay into a CP eigenstate: $\underbrace{(+1)}_{J/\psi} \times \underbrace{(+1)}_{K_S} \times \underbrace{(-1)^1}_{L=1} = -1.$



$\lambda_c^{(s)} \equiv V_{cs}V_{cb}^*$



$\lambda_j^{(s)} \equiv V_{js}V_{jb}^* \quad (j \in \{u, c, t\})$

- Structure of the decay amplitude: $\left[K_S = \left(\overline{K^0} + K^0\right)/\sqrt{2}\right]$

$$\boxed{A(B_d^0 \to J/\psi K_S) = \lambda_c^{(s)}(A_T^c + A_P^c) + \lambda_u^{(s)} A_P^u + \lambda_t^{(s)} A_P^t}$$

- Unitarity of the CKM matrix: $\lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \;\Rightarrow$

$$\boxed{A(B_d^0 \to J/\psi K_S) \propto \left[1 + \lambda^2 a e^{i\vartheta} e^{i\gamma}\right]} \qquad a e^{i\vartheta} = \left(\frac{R_b}{1-\lambda^2}\right)\left[\frac{A_P^u - A_P^t}{A_T^c + A_P^c - A_P^t}\right]$$

- Calculation of $\xi_{\psi K_S}^{(d)}$: $\quad \xi_{\psi K_S}^{(d)} = +e^{-i\phi_d}\left[\frac{1+\lambda^2 a e^{i\vartheta}e^{-i\gamma}}{1+\lambda^2 a e^{i\vartheta}e^{+i\gamma}}\right]$

- Since the essentially "unknown" hadronic parameter $ae^{i\vartheta}$ enters $\xi_{\psi K_S}^{(d)}$ in a *doubly Cabibbo-suppressed* way, we obtain to a very good approximation:

$$\xi_{\psi K_S}^{(d)} = e^{-i\phi_d} \quad \Rightarrow \quad \boxed{\begin{array}{rcl} \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi\, K_S) & = & 0 \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\, K_S) & = & -\sin\phi_d \stackrel{\rm SM}{=} -\sin 2\beta \end{array}}$$

[Bigi, Carter and Sanda (1980–1981)]

$\longrightarrow$ 1st observation of CP violation *outside* the K system [BaBar & Belle ('01)]

- Current status (ICHEP'06): $\longrightarrow$ *no* signs for direct CP violation, and

$$\sin 2\beta = \left\{ \begin{array}{ll} 0.710 \pm 0.034 \pm 0.019 & \text{(BaBar)} \\ 0.642 \pm 0.031 \pm 0.017 & \text{(Belle)} \end{array} \right\} \Rightarrow \underbrace{\boxed{\sin 2\beta = 0.674 \pm 0.026}}_{\text{world average}}$$

  - Theoretical (hadronic) uncertainties $\lesssim 0.01$.
  - Can be controlled through $B_s \to J/\psi K_S$: $\to$ LHC [R.F. ('99)]

How Could New Physics

Enter the

B-Physics Landscape?

Twofold Impact of NP: Effective Hamiltonians ...

- Possibility I: **Modification of the "Strength" of the SM Operators**

  - New short-distance functions, which depend on the NP parameters, such as masses of charginos, squarks, $\tan\beta \equiv v_2/v_1$ in the MSSM.
  - The NP particles enter in new box and penguin diagrams, and are "integrated out", as the W boson and the top quark:

$$\underbrace{C_k(\mu = M_W) \to C_k^{\rm SM} + C_k^{\rm NP}}_{\text{initial conditions for RG evolution}}$$

  - The $C_k^{\rm NP}$ may also involve new CP-violating phases.

- Possibility II: **New Operators**

  - Operators, which are absent or strongly suppressed in the SM, may actually play an important rôle:

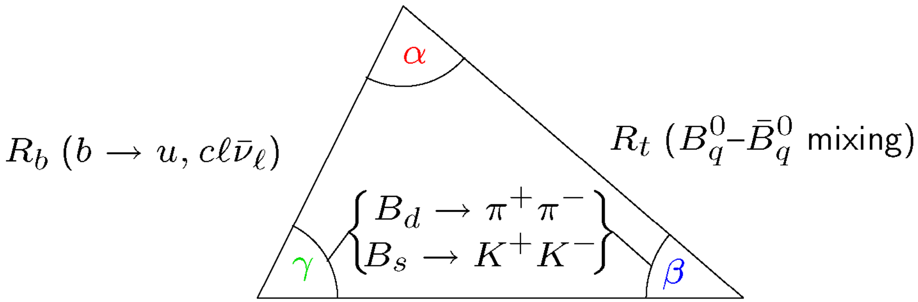
$$\underbrace{\{Q_k\} \to \{Q_k^{\rm SM}, Q_l^{\rm NP}\}}_{\text{operator basis}}$$

  - In general, new sources of flavour and CP violation.

A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$



$B \to \pi K$ (penguins)

$$\left.\begin{matrix} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{matrix}\right\}\text{only trees}$$

$B_d \to \psi K_S$ $(B_s \to \psi\phi : \ \phi_s \approx 0)$

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{matrix} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{matrix}\right\}\text{only trees}$$

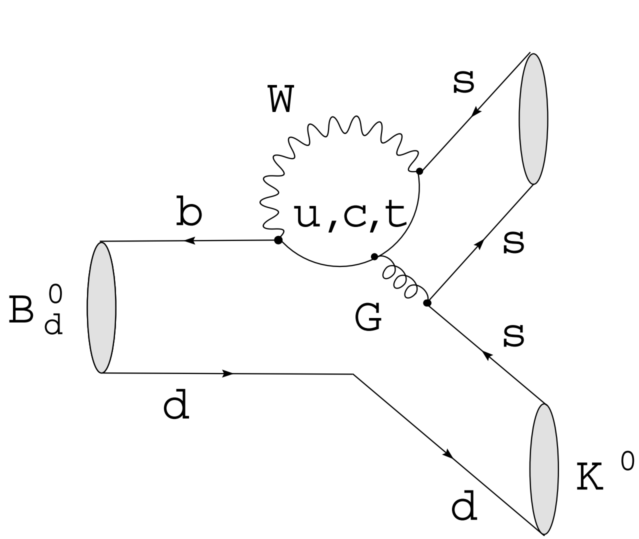
- Moreover "rare" decays: $B \to K^*\gamma$, $B_{d,s} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, ...
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

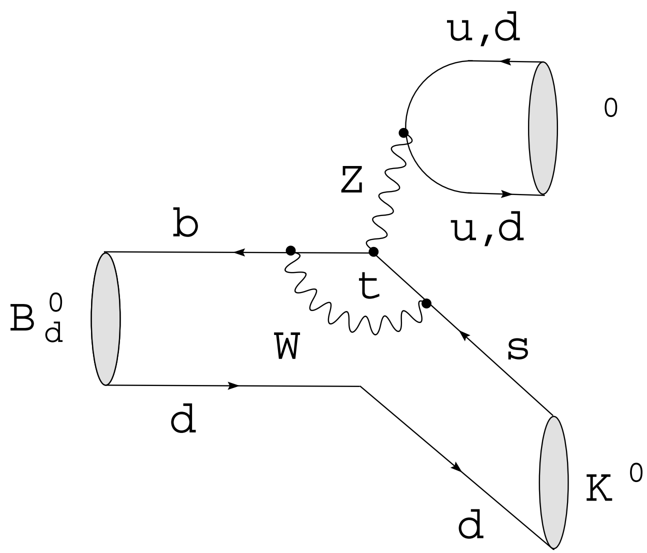
New Physics $\Rightarrow$ Discrepancies

New Physics @ Amplitude Level:

- Typically *small* effects if SM tree processes play the dominant rôle.

- Potentially *large* effects in the penguin sector through new particles in the loops or new contributions at the tree level: e.g. SUSY, Z' models.





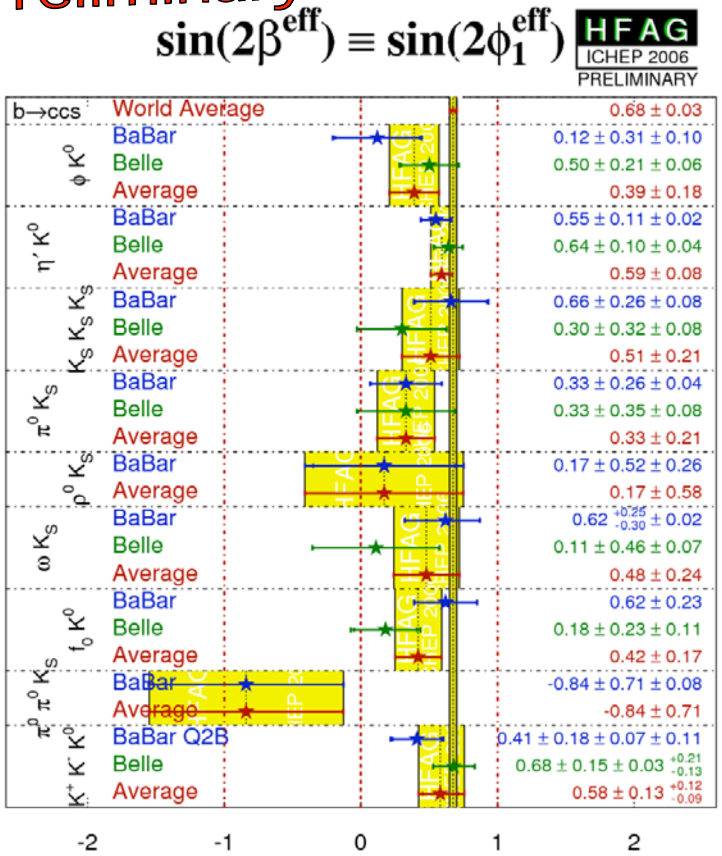
$\longrightarrow$ hot topics ...

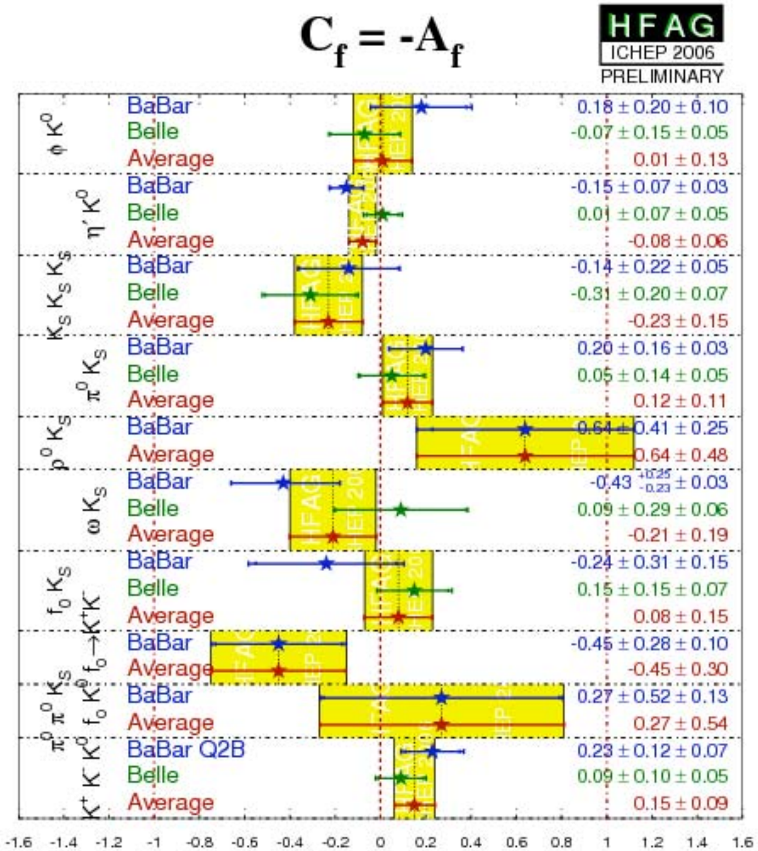
CP Violation in $b \to s$ Penguin Modes

- $B_d \to \phi K_S$ is the key example: amplitude structure of the SM $\Rightarrow$

$$\begin{aligned} \mathcal{A}_{CP}^{dir}(B_d \to \phi K_S) &= 0 + \mathcal{O}(\lambda^2) \equiv C(B_d \to \phi K_S) \\ \mathcal{A}_{CP}^{mix}(B_d \to \phi K_S) &= -\sin\phi_d + \mathcal{O}(\lambda^2) = \mathcal{A}_{CP}^{mix}(B_d \to J/\psi K_S) + \mathcal{O}(\lambda^2) \end{aligned}$$

Preliminary





NP could be present, but still cannot be resolved $\to$ stay tuned ...

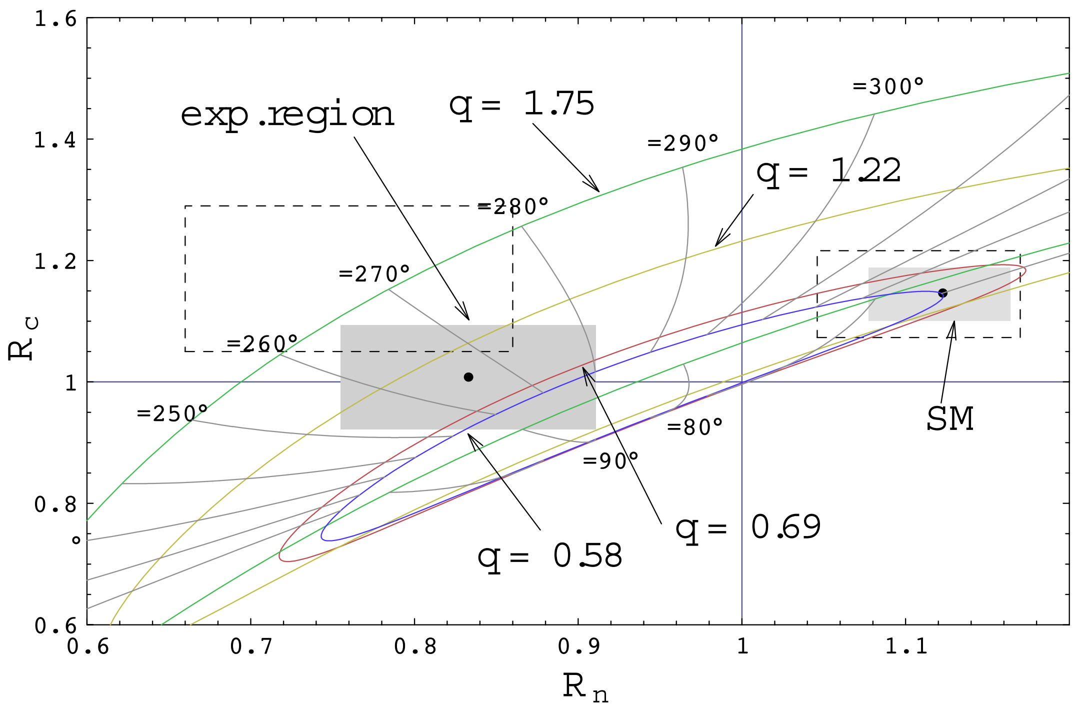
The $B \to \pi K$ Puzzle

- Observables with a sizeable impact of EW penguins: $\longrightarrow$ parameters $\boxed{q,\ \phi}$

$$R_{\rm c} \equiv 2\left[\frac{\mathrm{BR}(B^+\to\pi^0K^+)+\mathrm{BR}(B^-\to\pi^0K^-)}{\mathrm{BR}(B^+\to\pi^+K^0)+\mathrm{BR}(B^-\to\pi^-\bar{K}^0)}\right]$$

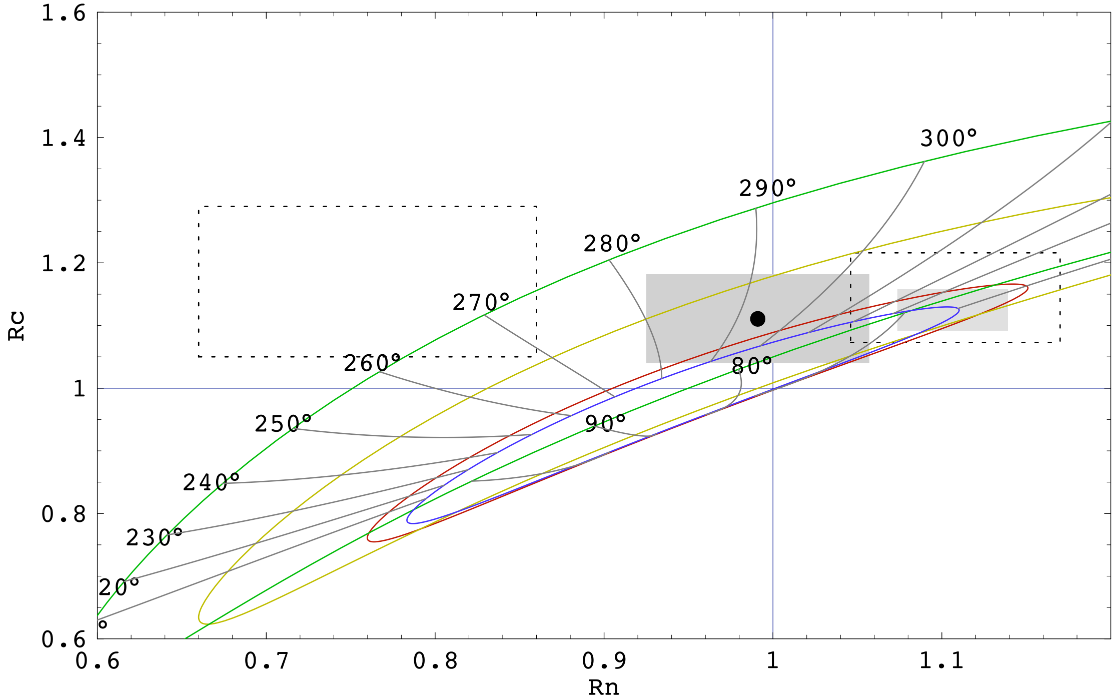
$$R_{\rm n} \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B_d^0\to\pi^-K^+)+\mathrm{BR}(\bar{B}_d^0\to\pi^+K^-)}{\mathrm{BR}(B_d^0\to\pi^0K^0)+\mathrm{BR}(\bar{B}_d^0\to\pi^0\bar{K}^0)}\right]$$

$\longrightarrow$ NP in EWPs!?



[A.J. Buras, R.F., F. Schwab & S. Recksiegel ('03–'05)]

- (Preliminary) Status after ICHEP '06:



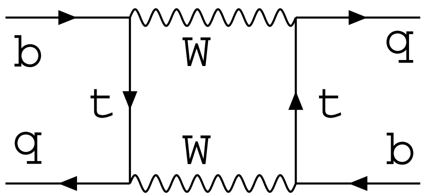
  - The SM prediction is very stable, with further reduced errors!
  - The B-factory data have moved quite a bit towards the SM.
  - Suggested by constraints from rare $B \to X_s \ell^+ \ell^-$ decays ...

- Furthermore puzzling CP asymmetries: $B_d^0 \to \pi^0 K_S$, $B^\pm \to \pi^0 K^\pm$.

NP could be present, but still cannot be resolved

$\longrightarrow$ stay tuned ...

New Physics in B_q^0–$\bar{B}_q^0$ mixing:



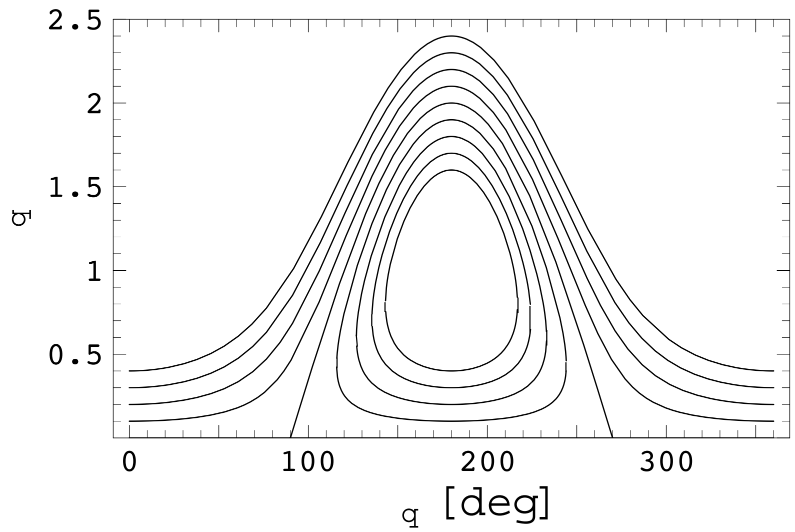
- NP particles in boxes or new tree contributions (e.g. SUSY, Z' models):

$$M_{12}^q = M_{12}^{q,\mathrm{SM}}\left[1+\kappa_q e^{i\sigma_q}\right] \Rightarrow \begin{cases} \Delta M_q = \Delta M_q^{\mathrm{SM}}\left|1+\kappa_q e^{i\sigma_q}\right| \\ \phi_q = \phi_q^{\mathrm{SM}} + \phi_q^{\mathrm{NP}} = \phi_q^{\mathrm{SM}} + \arg(1+\kappa_q e^{i\sigma_q}) \end{cases}$$

[Details: P. Ball & R.F., hep-ph/0604249]

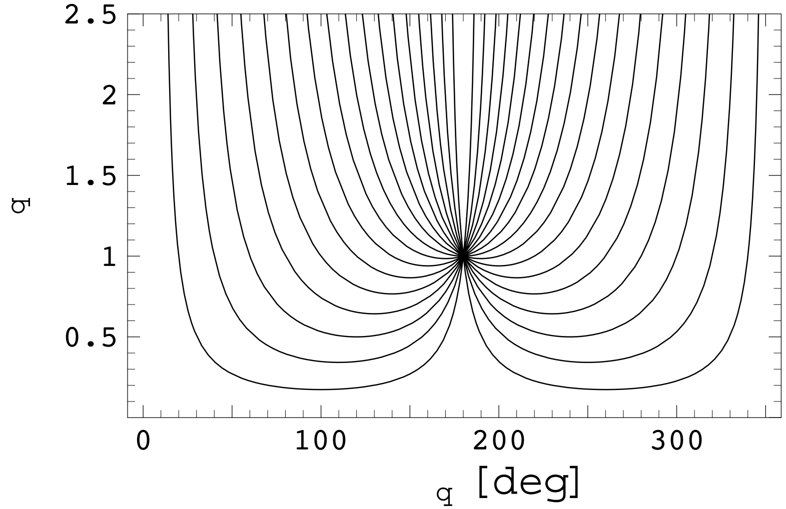
Constraints in the NP Space of B_q^0–$\bar{B}_q^0$ Mixing

- Contours in the σ_q–κ_q plane following from $\rho_q \equiv \Delta M_q/\Delta M_q^{\rm SM}$:



$[0.6 \leq \rho_q \leq 1.4]$

- Contours in the σ_q–κ_q plane following from the NP phase $\phi_q^{\rm NP}$:

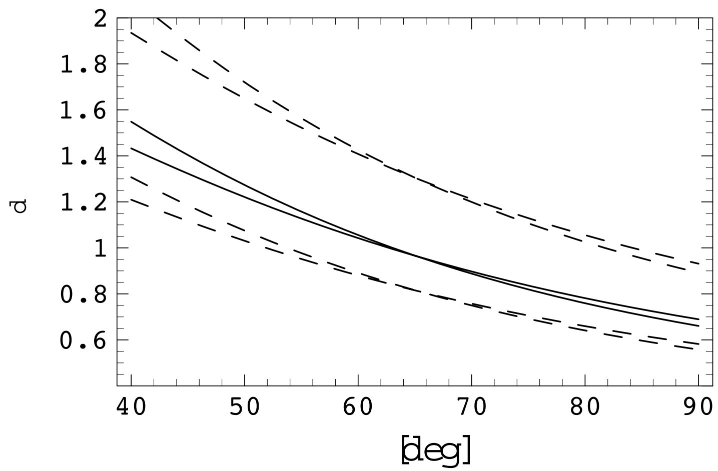


$\left[10^\circ \leq |\phi_q^{\rm NP}| \leq 170^\circ\right]$

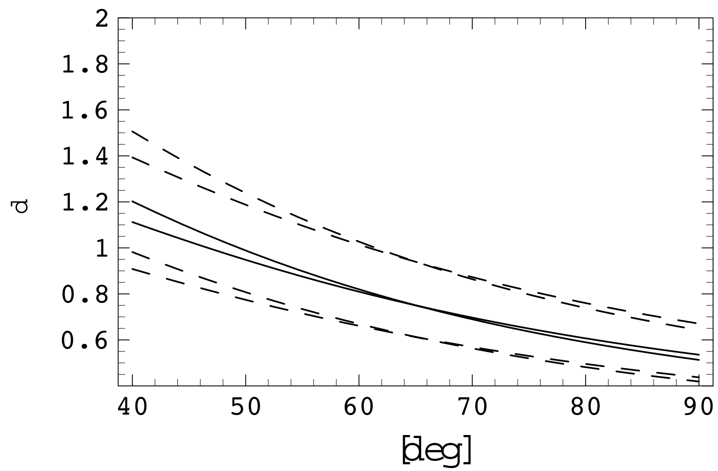
Implications of the B-Factory Data for the B_d System

SM analysis of the mass difference $\Delta M_d = (0.507 \pm 0.004)\,\mathrm{ps}^{-1}$

- CKM parameters: unitarity $\Rightarrow |V_{td}^* V_{tb}| = |V_{cb}|\lambda\sqrt{1 - 2R_b \cos\gamma + R_b^2}$
- Hadronic parameter $f_{B_d}^2 \hat{B}_{B_d}$: lattice $\longrightarrow$ two benchmark parameter sets:
  - JLQCD results (2 flavours of dynamical light Wilson quarks).
  - f_{B_d} from HPQCD (3 dynamical flavours) with $\hat{B}_{B_d}$ from JLQCD.
- Dependence of $\rho_d = \Delta M_d / \Delta M_d^{\mathrm{SM}}$ on γ for $R_b = (0.39, 0.45)$:



JLQCD



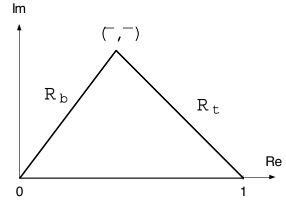
(HP+JL)QCD

Determination of the NP phase $\phi_d^{\rm NP}$

- Determine $\phi_d = 2\beta + \phi_d^{\rm NP}$ from $\mathcal{A}_{\rm CP}^{\rm mix}(B_d^0 \to J/\psi K_{\rm S})$ (and similar modes).[5]

- Calculate the "true" value of β from γ and R_b extracted from *tree* decays:

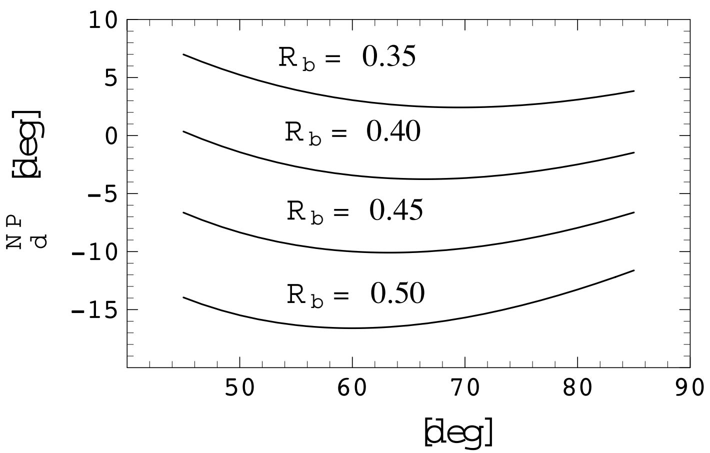
$$\gamma|_{D^{(*)}K^{(*)}} = \left\{ \begin{array}{ll} (62^{+35}_{-25})^\circ & \text{(CKMfitter)} \\ (65 \pm 20)^\circ & \text{(UTfit)} \end{array} \right\} \stackrel{2010}{\longrightarrow} (70 \pm 5)^\circ \text{ @ LHCb}$$

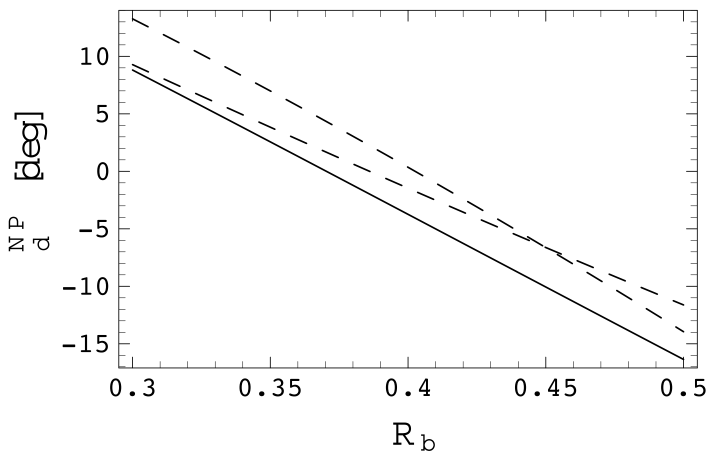


$$R_b^{\rm incl} = 0.45 \pm 0.03, \quad R_b^{\rm excl} = 0.39 \pm 0.06 \quad \text{[see Lecture I]}$$

$$\Rightarrow \; \phi_d^{\rm NP}\Big|_{\rm incl} = -(10.1 \pm 4.6)^\circ, \qquad \phi_d^{\rm NP}\Big|_{\rm excl} = -(2.5 \pm 8.0)^\circ$$

- Illustration of the dependence of $\phi_d^{\rm NP}$ on γ and R_b for $\phi_d = 43.4^\circ$:

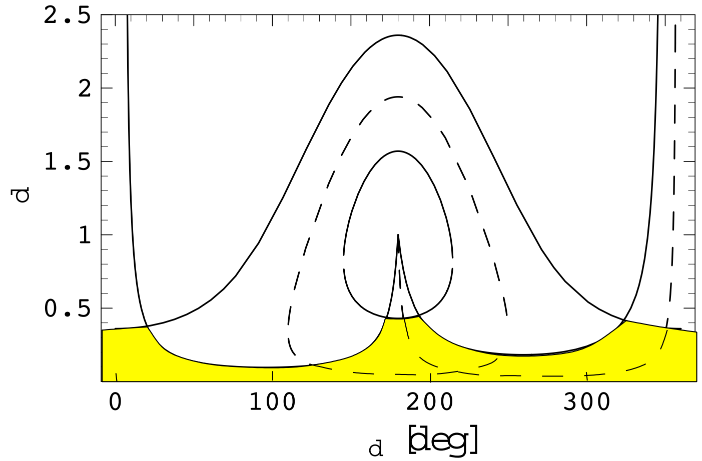




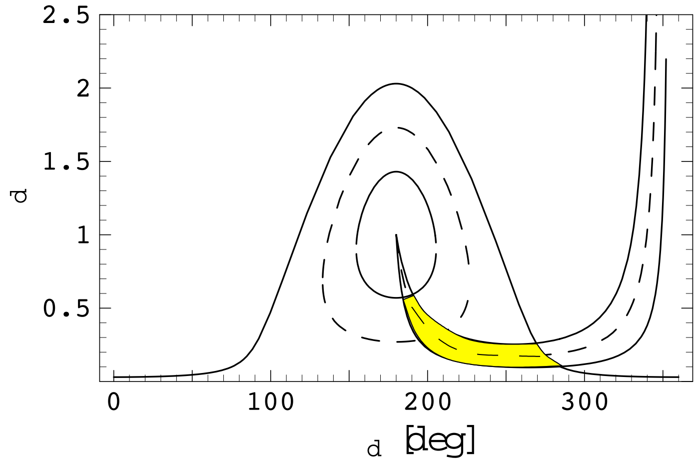
[5] Assumes that NP plays a negligible rôle in the $B \to J/\psi K$ amplitudes [see R.F., hep-ph/0512253].

Combined Constraints on NP through ΔM_d and ϕ_d

- Status in 2006:

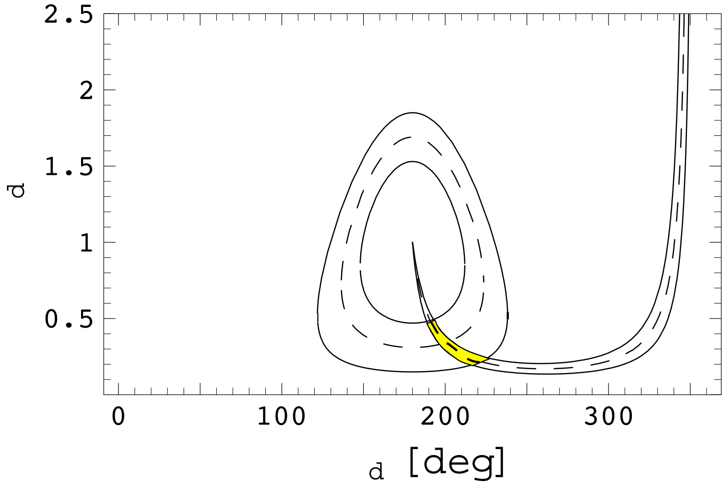


JLQCD and $\phi_d^{\rm NP}\big|_{\rm excl}$



$\underbrace{\text{(HP+JL)QCD}}_{\rightarrow 2010}$ and $\phi_d^{\rm NP}\big|_{\rm incl}$

- Status in our 2010 scenario: $\phi_d^{\rm NP} = -(9.8 \pm 2.0)^\circ \longrightarrow$ NP @ $5\,\sigma$



Benchmark Processes

for the

LHC B-Physics Programme

$\longrightarrow$ key target: B_s-meson system

Hot News of this Spring

- Signals for B_s^0–$\bar{B}_s^0$ mixing at the Tevatron:
  - For many years, only lower bounds on ΔM_s were available from the LEP (CERN) experiments and SLD (SLAC)!
  - Finally, the value of ΔM_s could be pinned down:
    * D0: $\Rightarrow$ two-sided bound $17\,\mathrm{ps}^{-1} < \Delta M_s < 21\,\mathrm{ps}^{-1}$ (90% C.L.)

      $\Rightarrow$ 2.5 σ signal at $\Delta M_s = 19\,\mathrm{ps}^{-1}$
    * CDF: $$\boxed{\Delta M_s = \left[17.33^{+0.42}_{-0.21}(\mathrm{stat}) \pm 0.07(\mathrm{syst})\right]\ \mathrm{ps}^{-1}}$$

- These new results have already triggered considerable theoretical activity:

  M. Carena *et al.*, hep-ph/0603106; M. Ciuchini and L. Silvestrini, hep-ph/0603114; L. Velasco-Sevilla, hep-ph/0603115; M. Endo and S. Mishima, hep-ph/0603251; M. Blanke *et al.*, hep-ph/0604057; Z. Ligeti, M. Papucci and G. Perez, hep-ph/0604112; J. Foster, K.I. Okumura and L. Roszkowski, hep-ph/0604121; K. Cheung *et al.*, hep-ph/0604223; Y. Grossman, Y. Nir and G. Raz, hep-ph/0605028; ...

- We shall focus on the following analysis: P. Ball and R.F., hep-ph/0604249.

Space for NP

in the

B_s-Meson System:

$$\boxed{M_{12}^{s} = M_{12}^{s,\mathrm{SM}}\left(1 + \kappa_s e^{i\sigma_s}\right)}$$

$\longrightarrow$ in analogy to the B_d system ...

Constraints on NP through ΔM_s

- CKM unitarity and Wolfenstein expansion: $|V_{ts}^* V_{tb}| = |V_{cb}| \left[1 + \mathcal{O}(\lambda^2)\right]$

  $\Rightarrow$ no information on γ and R_b needed (in contrast to ΔM_d)!

- Numerical results:

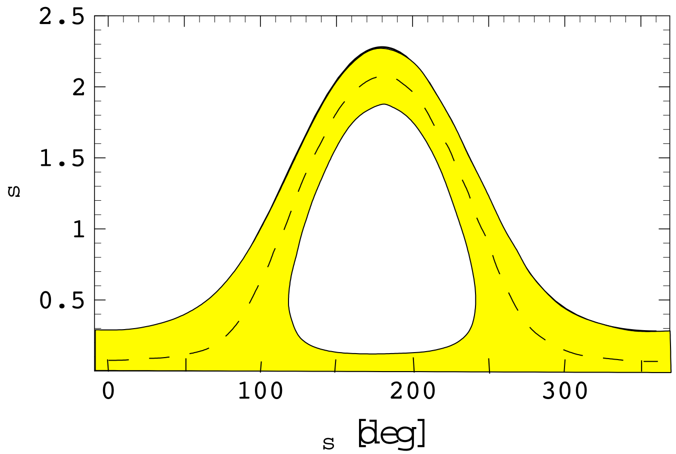
$$\Delta M_s^{\rm SM}\Big|_{\rm JLQCD} = (16.1 \pm 2.8)\ {\rm ps}^{-1}$$

$$\rho_s \equiv \Delta M_s / \Delta M_s^{\rm SM}\Big|_{\rm JLQCD} = 1.08^{+0.03}_{-0.01}(\text{exp}) \pm 0.19(\text{th})$$

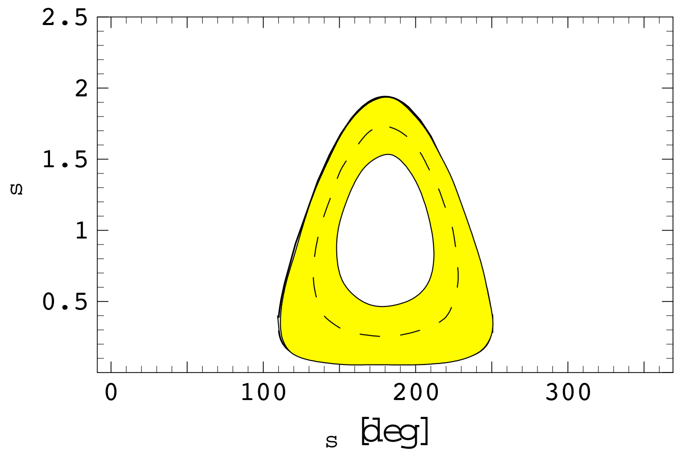
$$\Delta M_s^{\rm SM}\Big|_{\rm (HP+JL)QCD} = (23.4 \pm 3.8)\ {\rm ps}^{-1}$$

$$\rho_s\big|_{\rm (HP+JL)QCD} = 0.74^{+0.02}_{-0.01}(\text{exp}) \pm 0.18(\text{th})$$

- Allowed regions in the σ_s–κ_s plane:



JLQCD



(HP+JL)QCD

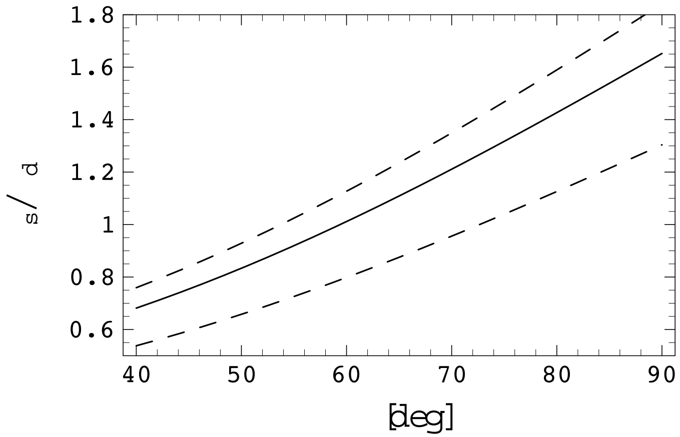
Constraints on NP through ΔM_s and ΔM_d

- The ratio $\Delta M_s/\Delta M_d$ involves just an $SU(3)$-breaking parameter:

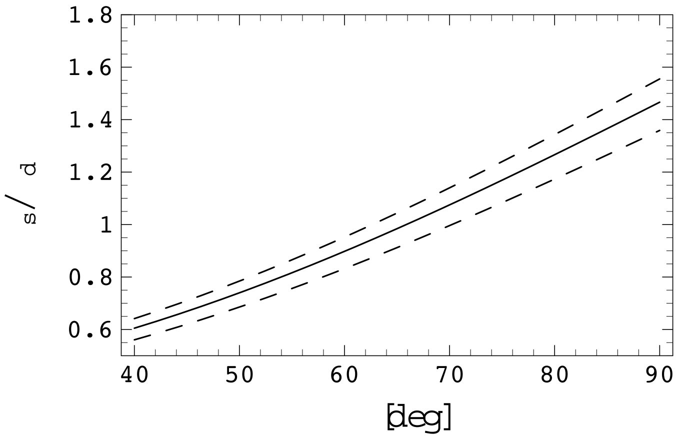
$$\xi \equiv \frac{f_{B_s}\hat{B}_{B_s}^{1/2}}{f_{B_d}\hat{B}_{B_d}^{1/2}} \;\to\; \text{reduced th. uncertainty as compared to } f_{B_q}\hat{B}_{B_q}^{1/2}.$$

- Usually determination of UT side R_t. Different avenue (CKM unitarity):

$$\frac{\rho_s}{\rho_d} = \lambda^2 \underbrace{\left[1 - 2R_b\cos\gamma + R_b^2\right]}_{=R_t^2} \left[1 + (1 - 2R_b\cos\gamma)\lambda^2 + \mathcal{O}(\lambda^4)\right] \frac{1}{\xi^2}\frac{M_{B_d}}{M_{B_s}}\frac{\Delta M_s}{\Delta M_d}$$



JLQCD



(HP+JL)QCD

$$\to \left.\frac{\rho_s}{\rho_d}\right|_{2010} = 1.07 \pm 0.09(\gamma, R_b)^{+0.06}_{-0.08}(\xi) = 1.07 \pm 0.12 \;\Rightarrow\; \boxed{!?}$$

Golden Process to Search

for NP in B_s^0–$\bar{B}_s^0$ Mixing:

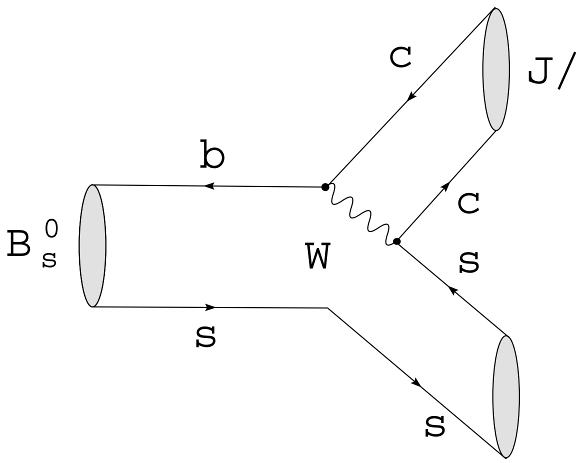
$$\boxed{B_s^0 \to J/\psi\phi}$$

$\rightarrow$ B_s^0 counterpart of $B_d^0 \to J/\psi K_{\rm S}$ ...

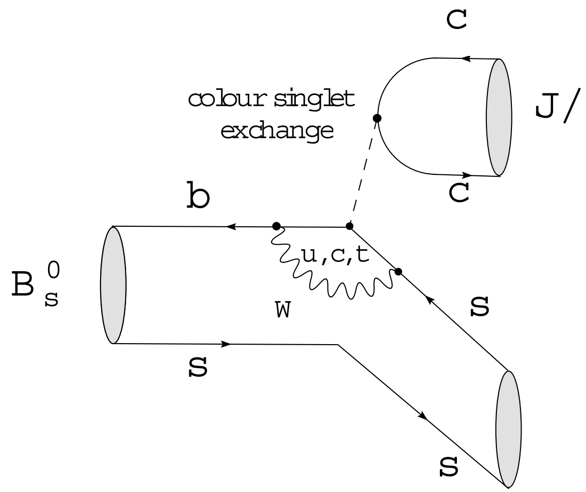
[Dighe, Dunietz & R.F. (1999); Dunietz, R.F. & Nierste (2001)]

Let's have a closer look ...

- Decay topologies:



$\lambda_c^{(s)} \equiv V_{cs} V_{cb}^*$



$\lambda_j^{(s)} \equiv V_{js} V_{jb}^* \quad (j \in \{u, c, t\})$

- Structure of the decay amplitude:

$$A(B_s^0 \to J/\psi\phi) = \lambda_c^{(s)}(A_{\mathrm{T}}^c + A_{\mathrm{P}}^c) + \lambda_u^{(s)} A_{\mathrm{P}}^u + \lambda_t^{(s)} A_{\mathrm{P}}^t$$

- Unitarity of the CKM matrix: $\lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \Rightarrow$

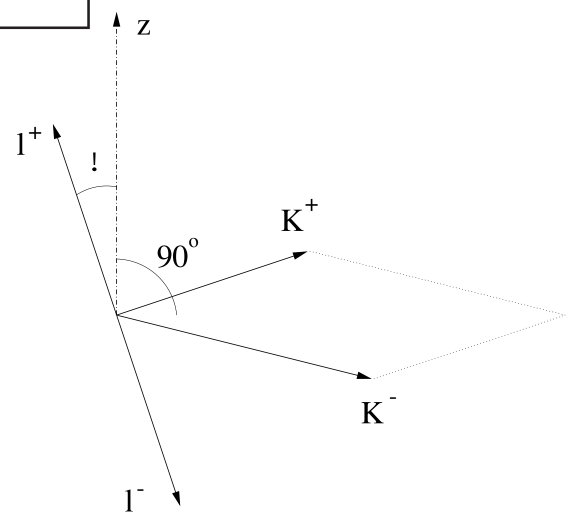
$$A(B_s^0 \to J/\psi\phi) \propto \left[1 + \lambda^2 a e^{i\vartheta} e^{i\gamma}\right] \qquad a e^{i\vartheta} = \left(\frac{R_b}{1-\lambda^2}\right)\left[\frac{A_{\mathrm{P}}^u - A_{\mathrm{P}}^t}{A_{\mathrm{T}}^c + A_{\mathrm{P}}^c - A_{\mathrm{P}}^t}\right]$$

- There is an important difference with respect to $B_d^0 \to J/\psi K_S$:

  final state is an admixture of different CP eigenstates!

- *Angular distribution* of the $J/\psi[\to \ell^+\ell^-]\phi[\to K^+K^-]$ decay products:

  $\Rightarrow$ the different CP eigenstates can be disentangled!



- Time-dependent distribution takes following form:

$$f(\Theta,\Phi,\Psi;t) = \sum_k g^{(k)}(\Theta,\Phi,\Psi)\, b^{(k)}(t)$$

  – Kinematics is described by the $g^{(k)}(\Theta,\Phi,\Psi)$.

  – Time-dependent coefficients $b^{(k)}(t)$: $\to$ real or imaginary parts of

$$A_{\tilde{f}}^*(t)A_f(t) = \langle (J/\psi\phi)_{\tilde{f}}|\mathcal{H}_{\rm eff}|B_s^0(t)\rangle^* \langle (J/\psi\phi)_f|\mathcal{H}_{\rm eff}|B_s^0(t)\rangle$$

  – f and $\tilde{f}$: specify the relative polarization of the J/ψ- and ϕ-mesons in given final-state configurations $(J/\psi\phi)_f$ and $(J/\psi\phi)_{\tilde{f}}$, respectively.

Structure of the Observables

- Consider linear pol. states of the vector mesons, which are longitudinal (0) or transverse to their directions of motion. In the latter case, the pol. states may be parallel $(\|)$ or perpendicular $(\perp)$ to one another.

- Linear polarization amplitudes: $$A_0(t), \quad A_{\|}(t), \quad A_{\perp}(t)$$

  - $A_{\perp}(t)$ describes a CP-odd final-state configuration.
  - $A_0(t)$ and $A_{\|}(t)$ correspond to CP-even final-state configurations.
  - The observables $b^{(k)}(t)$ are then given as follows:

$$|A_f(t)|^2 \quad (f \in \{0, \|, \perp\})$$

$$\text{Re}\{A_0^*(t)A_{\|}(t)\}, \quad \text{Im}\{A_f^*(t)A_{\perp}(t)\} \quad (f \in \{0, \|\}).$$

- Application of the "standard" formalism to the $A_f(t)$ $(f \in \{0, \|, \perp\})$:[6]

$$\xi^{(s)}_{(\psi\phi)_f} \propto e^{-i\phi_s}\Big[1 - \underbrace{2\,i\,\lambda^2 a_f e^{i\theta_f}\sin\gamma + \mathcal{O}(\lambda^4)}_{\text{penguin effects}}\Big] \to e^{-i\phi_s}$$

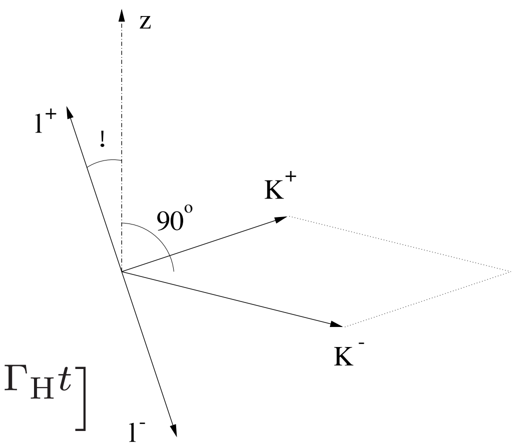
[6] The hadronic penguin effects can be controlled through $B_d \to J/\psi\rho^0$ [R.F. (1999)].

Time-Dependent One-Angle Distribution

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

- The angular dependence allows us to extract the following observables:

$$\boxed{P_+(t) \equiv |A_0(t)|^2 + |A_\parallel(t)|^2, \quad P_-(t) \equiv |A_\perp(t)|^2}$$



- *Untagged* data samples: $\longrightarrow$ untagged rates ...

$$P_\pm(t) + \overline{P}_\pm(t) \propto \left[(1 \pm \cos\phi_s)e^{-\Gamma_{\rm L}t} + (1 \mp \cos\phi_s)e^{-\Gamma_{\rm H}t}\right]$$

- *Tagged* data samples: $\longrightarrow$ CP asymmetries ...

$$\frac{P_\pm(t) - \overline{P}_\pm(t)}{P_\pm(t) + \overline{P}_\pm(t)} = \pm \frac{2\sin(\Delta M_s t)\sin\phi_s}{(1 \pm \cos\phi_s)e^{+\Delta\Gamma_s t/2} + (1 \mp \cos\phi_s)e^{-\Delta\Gamma_s t/2}}$$

Comments

$$\boxed{\phi_s = -2\lambda^2 R_b \sin\gamma + \phi_s^{\rm NP} \approx \phi_s^{\rm NP}} \quad \Rightarrow$$

- CP-violating NP effects would be indicated by the following features:
  - The *untagged* observables depend on *two* exponentials;
  - *sizeable* values of the CP-violating asymmetries.
- These general features hold also for the full three-angle distribution:
  - Much more involved than one-angle case [Dighe, Dunietz & R.F. (1999)].
  - But provides additional information through the following terms:

$$\text{Re}\{A_0^*(t)A_\parallel(t)\}, \quad \text{Im}\{A_f^*(t)A_\perp(t)\} \quad (f \in \{0, \parallel\}).$$

  - No experimental draw-back with respect to the one-angle case!
- Following these lines, $\Delta\Gamma_s$ (see above) and ϕ_s can be extracted:
  - Note: $\Delta\Gamma_s = \Delta\Gamma_s^{\rm SM} \cos\phi_s$ [Grossman (1996)] $\Rightarrow$ *reduction* of $\Delta\Gamma_s$.

News from the Tevatron & Reach at the LHC

- Very recent (preliminary) analysis by D0: [D0Conference note 5144 ('06)]
  - Untagged, time-dependent three-angle $B_s \to J/\psi\phi$ distribution:

$$\Rightarrow \boxed{\phi_s = -0.79 \pm 0.56\,(\text{stat.}) \pm 0.01\,(\text{syst.}) = -(45 \pm 32 \pm 0.6)^\circ}$$

  - Imposing also constraints form semilept. B decays: [D0note 5144-Conf ('06)]

$$\Rightarrow \boxed{\phi_s = -0.56^{+0.44}_{-0.41} = -\left(32^{+25}_{-23}\right)^\circ}$$

$\Rightarrow$ still not stingently constrained, but very accessible @ LHC ...

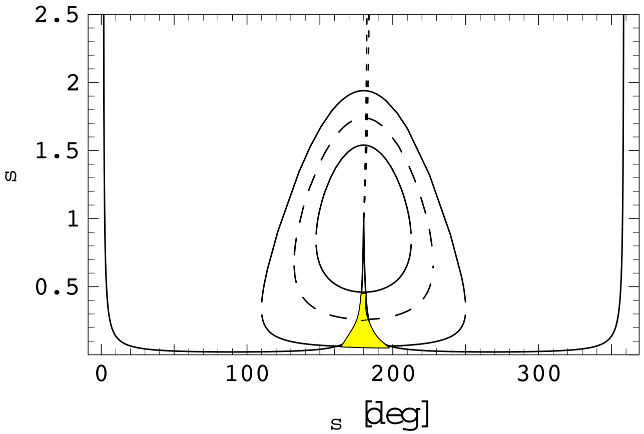
- Experimental reach at the LHC: [O. Schneider, M. Smizanska, T. Speer]
  - LHCb: $\sigma_{\text{stat}}(\sin\phi_s) \approx 0.031$ (1 year, i.e. 2 fb^{-1}) [0.013 (5 years)];
  - ATLAS & CMS: expect uncertainties of $\mathcal{O}(0.1)$ (1 year, i.e. 10 fb^{-1}).

Impact of CP Violation Measurements on σ_s, κ_s

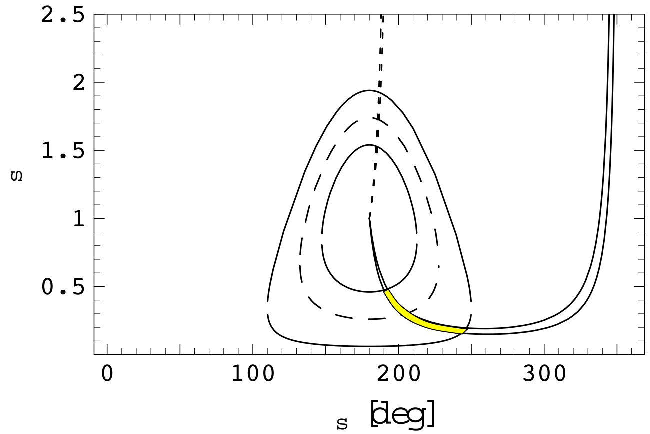
- Illustration through two scenarios ($\sim$ 2010):

(i) $(\sin\phi_s)_{\rm exp} = -0.04 \pm 0.02$, in accordance with the SM;

(ii) $(\sin\phi_s)_{\rm exp} = -0.20 \pm 0.02 \rightarrow$ NP @ $10\,\sigma$: corresponds to B_d "tension" for $\kappa_s = \kappa_d$, $\sigma_s = \sigma_d \rightarrow$ "magnification" of NP in the B_s system!



SM scenario (i)



NP scenario (ii)

- Remarks:
  - Very challenging to establish NP without new CP-violating effects!
  - On the other hand, (ii) corresponds to $0.2 \lesssim \kappa_s \lesssim 0.5$; determination of κ_s with 10% accuracy would require the reduction of the error of $f_{B_s}\hat{B}_{B_s}^{1/2}$ to 10%, i.e. of the current (HP+JL)QCD by a factor of 2...

$\rightarrow$ *let's hope for new CP-violating effects!* [P. Ball & R.F. ('06) $\rightarrow$]

Impact of $\Delta M_s^{\rm exp}$ on NP Scenarios: Examples

Extra Z' boson with flavour non-diagonal couplings:

- Illustration of the ΔM_s constraints under the following conditions:
  - The Z couplings stay flavour diagonal, i.e. Z–Z' mixing is negligible.
  - The Z' has flavour non-diagonal couplings only to left-handed quarks, which means that its effect is described by only one complex parameter.

- The Z' model is characterized by the following parameter:

$$\rho_L e^{i\phi_L} \equiv \frac{g' M_Z}{g M_{Z'}} B^L_{sb} \sim 10^{-3}$$

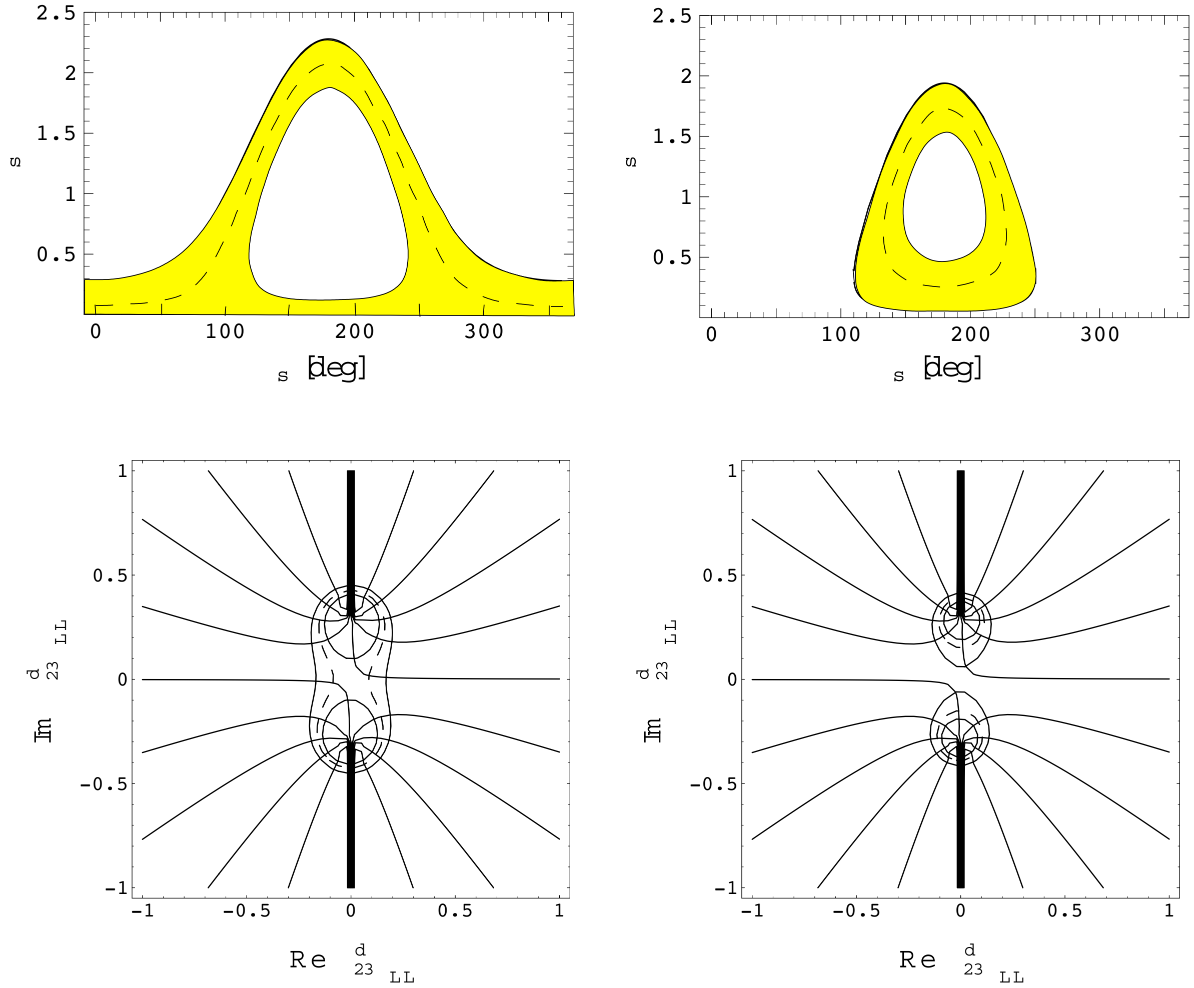
- Translation of the σ_s–κ_s space into the ϕ_L–ρ_L space:

$$\kappa_s < 2.5 \;\Rightarrow\; \rho_L < 2.6 \times 10^{-3} \;\Rightarrow\; 1.5\,\mathrm{TeV} \left(\frac{g'}{g}\right) \left|\frac{B^L_{sb}}{V_{ts}}\right| < M_{Z'}$$

[along Barger, Chiang, Jiang and Langacker, hep-ph/0405108; other recent analysis addressing also ΔM_s: Cheung *et al.*, hep-ph/0604223; Baek *et al.*, hep-ph/0607113]

MSSM in the mass insertion approximation:

- Illustration of the interplay between ΔM_s & mass insertions:



[See also Becirevic *et al.* ('02); Ball, Khalil & Kou ('04); Ciuchini *et al.* ('06); Ciuchini & Silvestrini ('06); Endo & Mishima ('06); Khalil ('06); ...]

Further Benchmark

Decays of B_s Mesons

for the LHCb Experiment

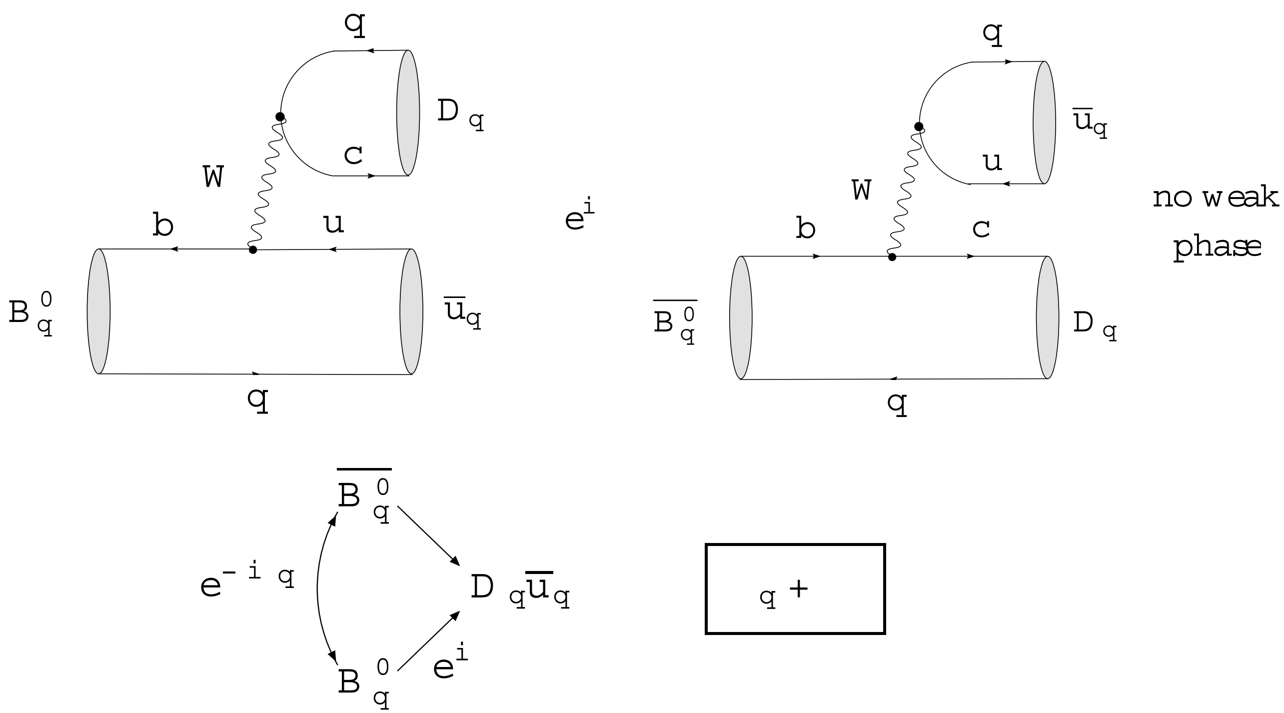
1. Precision measurements of γ: tree vs. penguin $\Rightarrow$ discrepancies?

2. Analyses of rare decays which are absent at the SM tree level.

[For a recent experimental overview, see A. Schopper, hep-ex/0605113]

CP Violation in $B_s \to D_s^{\pm} K^{\mp}$ and $B_d \to D^{\pm}\pi^{\mp}$

- <u>General case:</u>



- <u>$q = s$:</u> $D_s \in \{D_s^+, D_s^{*+}, ...\}$, $u_s \in \{K^+, K^{*+}, ...\}$:

  $\to$ hadronic parameter $X_s e^{i\delta_s} \propto R_b \Rightarrow$ <u>*large*</u> interference effects!

- <u>$q = d$:</u> $D_d \in \{D^+, D^{*+}, ...\}$, $u_d \in \{\pi^+, \rho^+, ...\}$:

  $\to$ hadronic parameter $X_d e^{i\delta_d} \propto -\lambda^2 R_b \Rightarrow$ <u>*tiny*</u> interference effects!

- $\cos(\Delta M_q t)$ and $\sin(\Delta M_q t)$ terms of the time-dependent decay rates:

$$\Rightarrow \boxed{\text{theoretically } \textit{clean} \text{ determination of } \phi_q + \gamma} \stackrel{\phi_q \text{ known}}{\longrightarrow} \boxed{\gamma}$$

[Dunietz & Sachs (1988); Aleksan, Dunietz & Kayser (1992); Dunietz (1998); ...]

- However, there are also problems:
  - We encounter an *eightfold* discrete ambiguity for $\phi_q + \gamma$!?
  - In the $q = d$ case, an additional input is required to extract X_d since $\mathcal{O}(X_d^2)$ interference effects would have to be resolved $\to$ *impossilbe* ...

- Combined analysis of $B_s^0 \to D_s^{(*)+} K^-$ and $B_d^0 \to D^{(*)+} \pi^-$: [R.F. (2003)]

$\boxed{s \leftrightarrow d}$ $\Rightarrow$ U-spin symmetry provides an interesting playground:[7]

  - An *unambiguous* value of γ can be extracted from the observables!
  - To this end, X_d has *not* to be fixed, and X_s may *only* enter through a $1 + X_s^2$ correction, which is determined through *untagged* B_s rates!
  - Promising first studies by LHCb: $\boxed{\longrightarrow}$

[7] The U-spin is an $SU(2)$ subgroup of the $SU(3)_{\rm F}$ flavour-symmetry group, connecting d and s quarks in analogy to the conventional isospin symmetry, which relates d and u quarks to each other.

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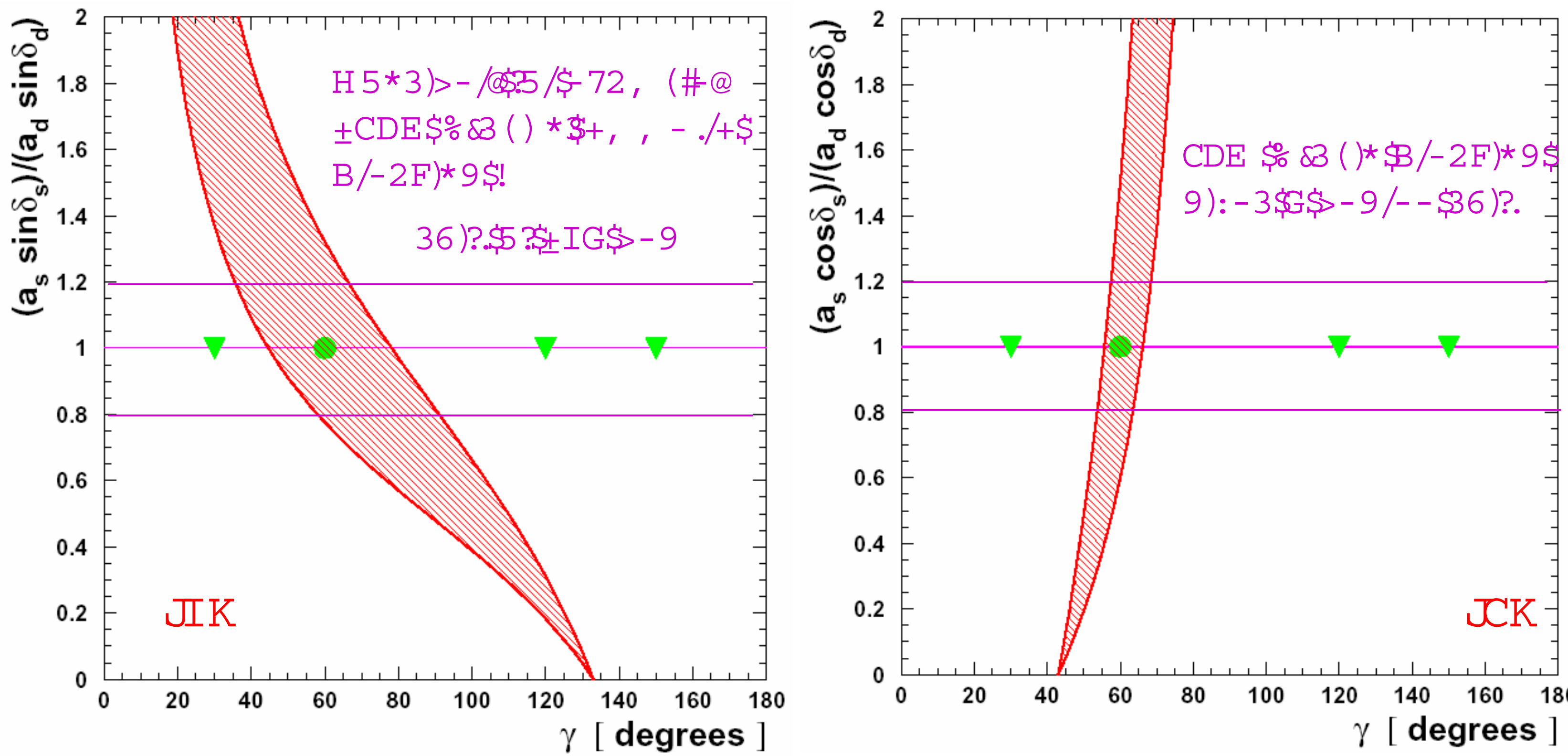

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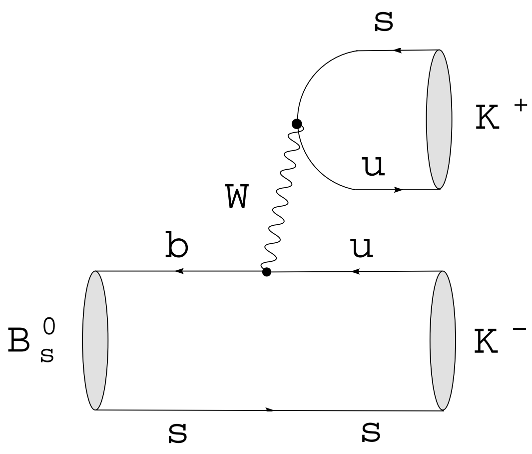
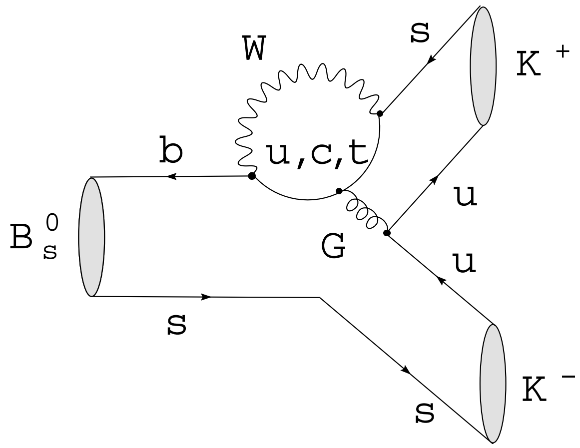
[G. Wilkinson @ CKM 2005]

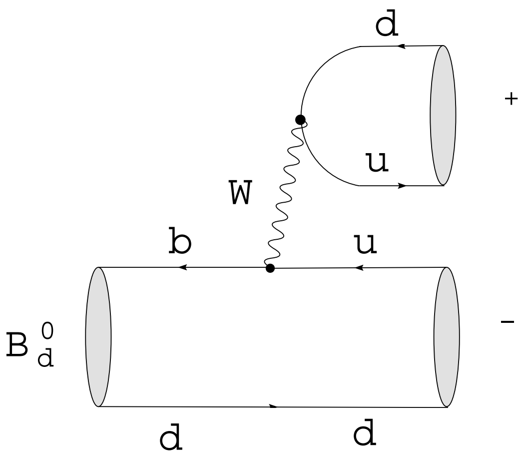
The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

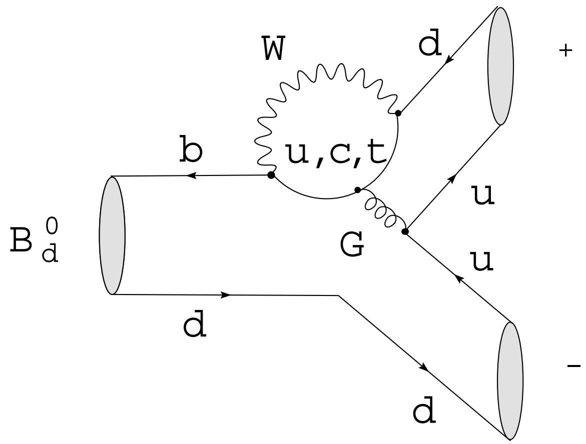
- $B_s^0 \to K^+K^-$:





- $B_d^0 \to \pi^+\pi^-$:





$$\Rightarrow \quad \boxed{s \leftrightarrow d}$$

- Structure of the decay amplitudes in the Standard Model:

$$A(B_d^0 \to \pi^+\pi^-) \quad \propto \quad \left[e^{i\gamma} - d e^{i\theta} \right]$$

$$A(B_s^0 \to K^+K^-) \quad \propto \quad \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2} \right) d' e^{i\theta'} \right]$$

$$\boxed{d\, e^{i\theta} = \left. \frac{\text{“penguin”}}{\text{“tree”}} \right|_{B_d \to \pi^+\pi^-}, \quad d'\, e^{i\theta'} = \left. \frac{\text{“penguin”}}{\text{“tree”}} \right|_{B_s \to K^+K^-}}$$

[d, d': real hadronic parameters; θ, θ': strong phases]

- General form of the CP asymmetries:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = G_1(d, \theta, \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = G_2(d, \theta, \gamma, \phi_d)$$

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) = G_1'(d', \theta', \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = G_2'(d', \theta', \gamma, \phi_s)$$

- $\phi_d = 2\beta$ (from $B_d \to J/\psi K_{\rm S}$) and $\phi_s \approx 0$ are known parameters:

  - $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ & $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$: $\Rightarrow$ $\boxed{d = d(\gamma)}$ (clean!)

  - $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$ & $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$: $\Rightarrow$ $\boxed{d' = d'(\gamma)}$ (clean!)

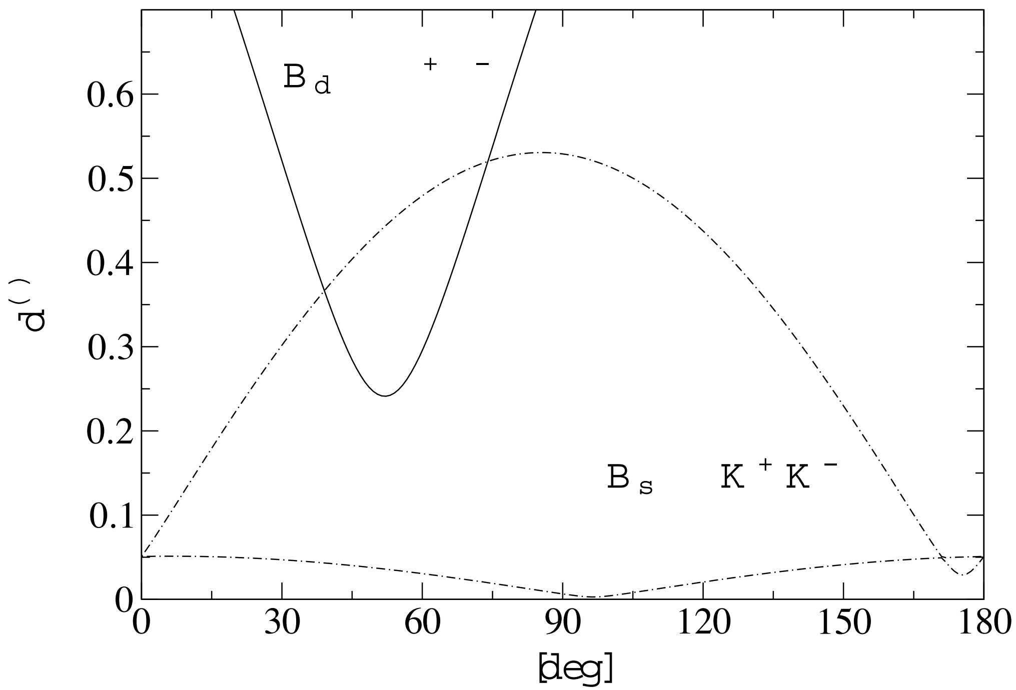
- Example:

  - Input parameter:

    - $\phi_d = 43.4^\circ$, $\phi_s = -2^\circ$, $\gamma = 74^\circ$, $d = d' = 0.52$, $\theta = \theta' = 146^\circ$

  - CP asymmetries:

    - $B_d \to \pi^+\pi^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = -0.37$, $\mathcal{A}_{\rm CP}^{\rm mix} = +0.50$
    - $B_s \to K^+K^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = +0.12$, $\mathcal{A}_{\rm CP}^{\rm mix} = -0.19$



- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

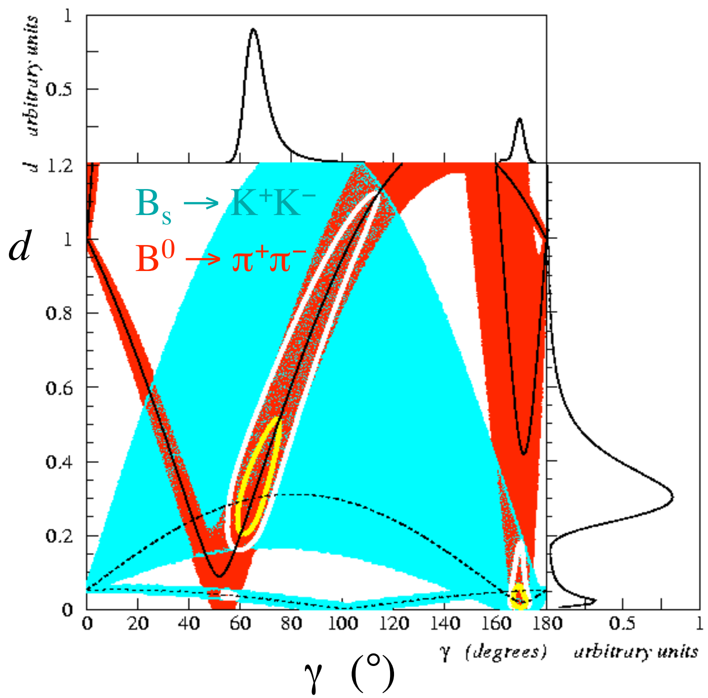
$$\boxed{U\text{-spin symmetry} \quad \Rightarrow \quad d = d', \quad \theta = \theta'}$$

– $d = d'$: $\Rightarrow$ $\boxed{\text{determination of } \gamma,\ d,\ \theta,\ \theta'}$

[R.F. (1999)]

– $\theta = \theta'$: $\Rightarrow$ test of the U-spin symmetry!

- Detailed experimental feasibility studies show that the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ strategy is very promising for LHCb:



$\longrightarrow$ experimental accuracy for γ of a few degrees!

[CERN-LHCb/2003-123 & 124]

- Recent news from the Tevatron: [CDF Collaboration, hep-ex/0607021]

Observation of $B_s \to K^+K^-$ @ CDF

  – 36 ± 32 events were seen, which correspond to the branching ratio

$$\mathrm{BR}(B_s \to K^+K^-) = (33 \pm 5.7 \pm 6.7) \times 10^{-6}.$$

- Theoretical prediction: [Buras, R.F. Schwab & Recksiegel ('04)]

  – Requires the knowledge of an $SU(3)$-breaking from-factor ratio (which cancels in $de^{i\theta} = d'e^{i\theta'}$) [QCD sum rules: Khodjamirian et al. ('03)].

  – $B \to \pi\pi$ data: $\Rightarrow$ $\mathrm{BR}(B_s \to K^+K^-) = (38^{+32}_{-23}) \times 10^{-6}$.

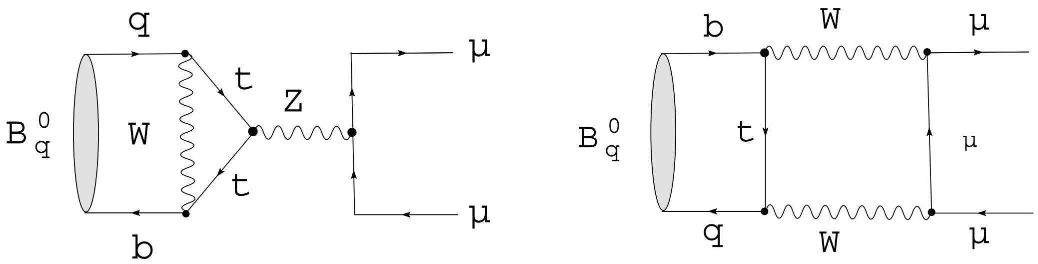
  – Dynamical assumptions (small annihilation) and $B_d \to \pi^{\mp}K^{\pm}$ data:

$$\Rightarrow \mathrm{BR}(B_s \to K^+K^-) = (35 \pm 7) \times 10^{-6}$$

$\Rightarrow$ excellent agreement!

The Rare Decays $B_q \to \mu^+\mu^-$ $(q \in \{d, s\})$

- Originate from Z penguins and box diagrams in the Standard Model:



- Corresponding low-energy effective Hamiltonian: [Buchalla & Buras (1993)]

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}}\left[\frac{\alpha}{2\pi \sin^2 \Theta_{\rm W}}\right] V_{tb}^* V_{tq} \eta_Y Y_0(x_t)(\bar{b}q)_{\rm V-A}(\bar{\mu}\mu)_{\rm V-A}$$

  – α: QED coupling; $\Theta_{\rm W}$: Weinberg angle.
  – η_Y: short-distance QCD corrections (calculated ...)
  – $Y_0(x_t \equiv m_t^2/M_W^2)$: Inami–Lim function, with top-quark dependence.

- Hadronic matrix element: $\longrightarrow$ very simple situation:

  – Only the matrix element $\langle 0|(\bar{b}q)_{\rm V-A}|B_q^0\rangle$ is required: f_{B_q}

$\Rightarrow$ belong to the cleanest rare B decays!

[Details: Buras & R.F., hep-ph/9704376]

- Most recent SM predictions: [Blanke, Buras, Guadagnoli, Tarantino ('06)]

  $\rightarrow$ use the data for the ΔM_q to reduce the hadronic uncertainties:

$$\begin{aligned}\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) &= (3.35 \pm 0.32) \times 10^{-9} \\ \mathrm{BR}(B_d \rightarrow \mu^+\mu^-) &= (1.03 \pm 0.09) \times 10^{-10}\end{aligned}$$

- Most recent experimental upper bounds from the Tevatron:

  – CDF collaboration @ 95% C.L.: [CDF Public Note 8176 (2006)]

$$\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) < 1.0 \times 10^{-7}, \quad \mathrm{BR}(B_d \rightarrow \mu^+\mu^-) < 3.0 \times 10^{-8}$$

  – D0 collaboration @ 90% C.L. (95% C.L.): [D0note 5009-CONF (2006)]

$$\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) < 1.9\,(2.3) \times 10^{-7}$$

  $\Rightarrow$ still a long way to go (?) $\rightarrow$ LHC (background under study)

- However, NP may significantly enhance $\mathrm{BR}(B_s \rightarrow \mu^+\mu^-)$:

  – In SUSY secenarios: BR $\sim (\tan\beta)^6$ $\rightarrow$ dramatic enhancement (!);
  [see, e.g., Foster *et al.* and Isidori & Paride ('06) for recent analyses]

  – NP with modified EW penguin sector: sizeable enhancement.

The Rare Decay $B_d^0 \to K^{*0}\mu^+\mu^-$

- Key observable for NP searches: Forward–Backward Asymmetry

$$A_{\rm FB}(s) = \frac{1}{{\rm d}\Gamma/{\rm d}s}\left[\int_0^1 {\rm d}(\cos\theta)\frac{{\rm d}^2\Gamma}{{\rm d}s\,{\rm d}(\cos\theta)} - \int_{-1}^0 {\rm d}(\cos\theta)\frac{{\rm d}^2\Gamma}{{\rm d}s\,{\rm d}(\cos\theta)}\right]$$

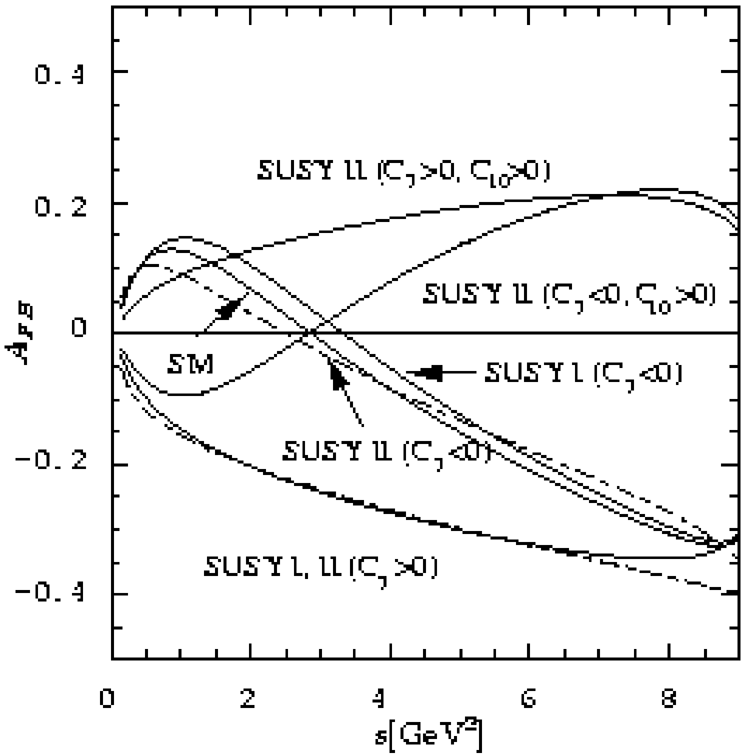
  - θ is the angle between the B_d^0 momentum and that of the μ^+ in the dilepton centre-of-mass system,
  - and $s = (p_{\mu^+} + p_{\mu^-})^2$.

- Particularly interesting:

$$\boxed{A_{\rm FB}(s_0)|_{\rm SM} = 0}$$ [Burdman ('98); Ali *et al.* ('00); ...]

  - The value of s_0 is very robust with respect to hadronic uncertainties!
  - SUSY extensions of the SM:

    $\to$ may yield $A_{\rm FB}(\hat{s})$ of opposite sign or without a zero point $\to$



[A. Ali *et al.*, *Phys. Rev.* **D61** (2000) 074024]

- Sensitivity at the LHC:
  - LHCb: ~ 4400 decays/year, yielding $\Delta s_0 = 0.06$ after one year.
  - ATLAS will collect about 1000 $B^0 \to K^{*0}\mu^+\mu^-$ decays per year.
- Other $b \to s\mu^+\mu^-$ decays under study:

$$\Lambda_b \to \Lambda\mu^+\mu^-,\ B_s^0 \to \phi\mu^+\mu^- \ \ldots$$

Conclusions and Outlook (I)

- Status of new physics in the beauty system in September 2006:
  - The data agree globally with the Kobayashi–Maskawa picture!
  - But we have also hints for discrepancies: $\longrightarrow$ first signals of NP?

    $\longrightarrow$ would require *new* sources of CP violation $\longrightarrow$ study further ...
  - Recent excitement: measurement of ΔM_s @ Tevatron:

    $\longrightarrow$ still a lot of space for NP! Smoking gun: new CP violation ...
- New perspectives for B-decay studies @ LHC $\gtrsim$ autumn 2007:[8]
  - Fully exploit the B_s physics potential (taking over from CDF & D0).
  - Various determinations of γ $\longrightarrow$ key ingredient for NP searches!
  - Many other promising topics to study: rare decays $B_{s,d} \to \mu^+\mu^-$, ...
- Further precision B-decay measurments in the next decade:

  $\longrightarrow$ e^+e^- super-B factory [KEK, new Frascati proposal] (?)

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[8] Future of the K system: rare $K \to \pi\nu\bar{\nu}$ decays, with plans for experiments @ CERN & KEK/J-PARC.

Conclusions and Outlook (II)

Flavour physics & CP violation in direct context with LHC

- Main goals of the ATLAS and CMS experiments:
  - Exploration of the mechanism of EW symmetry breaking: Higgs!?
  - Production and observation of *new* particles ...
  - Then back to questions of dark matter, baryon asymmetry ...

$\oplus$ complementary and further studies at ILC/CLIC

- Synergy with the flavour sector:

$B \quad \oplus \quad K$, D, top physics & lepton/neutrino sector

  - If discovery of new particles, which kind of new physics?
  - Insights into the corresponding new flavour structures and possible new sources of CP violation through studies of flavour processes.
  - Sensitivity on very high energy scales of new physics through precision measurements, also if NP particles cannot be produced at the LHC ...

4th meeting takes place at CERN from 9–11 October 2006.