New Physics in the Beauty System

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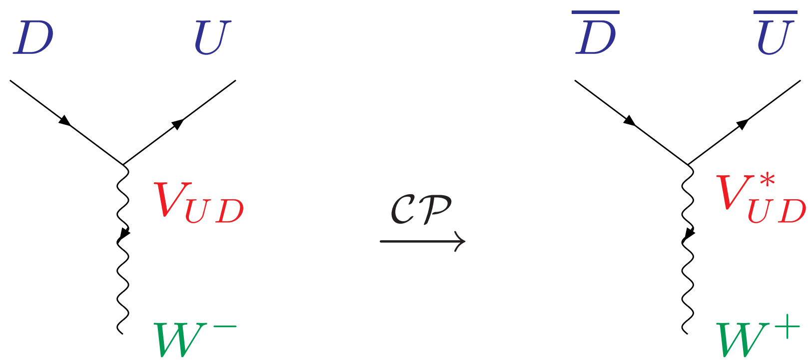
- Setting the Stage
- New Physics at the Amplitude Level: $\longrightarrow$ indications in the data!?
  - Example: $B \to \pi K$.
- New Physics in $B^0_{d,s}$–$\bar{B}^0_{d,s}$ Mixing: $\longrightarrow$ ΔM_s @ Tevatron: $\longrightarrow$ *hot topic* ...
  - How much space is left for New Physics?
  - Perspectives for the LHC.
- Conclusions and Outlook

Setting the Stage

- Standard Model (SM): $\longrightarrow$ Kobayashi–Maskawa mechanism of CP violation:



Recent review: R.F., *J. Phys.* **G32** (2006) R71 [hep-ph/0512253]

The Global Picture in a Nutshell

Impressive precision measurements of the SM @ LEP $\longrightarrow$ still ...

- Is the breaking of the electroweak symmetry and the generation of the particle masses in fact related to the "minimal" Higgs mechanism?

  $\longrightarrow$ direct insights at the LHC $\gtrsim$ autumn 2007

- On the other hand, close connection between the scalar Higgs sector and flavour physics through Yukawa interactions ($\rightarrow$ fermion masses):

  $\longrightarrow$ quark-flavour phenomenology ($\rightarrow$ our focus): flavour "factories"!

- The SM is – with the exception of some "flavour puzzles" (!?) – in good shape! But the SM *cannot* be complete $\longrightarrow$ *indications*:

  – Neutrino oscillations ($\rightarrow$ lepton-flavour phenomenology), dark matter, generation of the baryon asymmetry of the Universe ...

  $\oplus$ fundamental theoretical questions (hierarchy problem etc.)

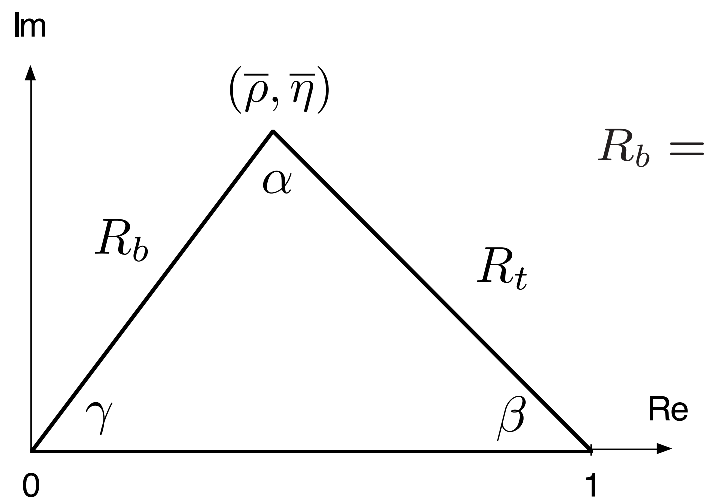
Central Target: Unitarity Triangle (UT)

- Application of the Wolfenstein parametrization: [Wolfenstein (1984)]

$$\hat{V}_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$\longrightarrow$ phenomenological expansion in $\lambda \equiv |V_{us}| = 0.22$ [from $K \to \pi \ell \bar{\nu}_\ell$]

- Unitarity of the CKM matrix: $\hat{V}_{\text{CKM}}^\dagger \cdot \hat{V}_{\text{CKM}} = \hat{1} = \hat{V}_{\text{CKM}} \cdot \hat{V}_{\text{CKM}}^\dagger$ $\Rightarrow$



$$R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

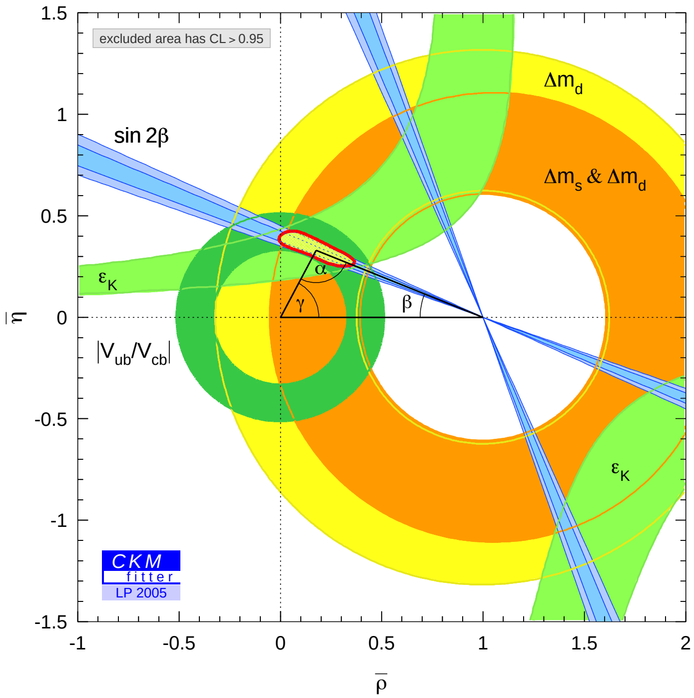
$$R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

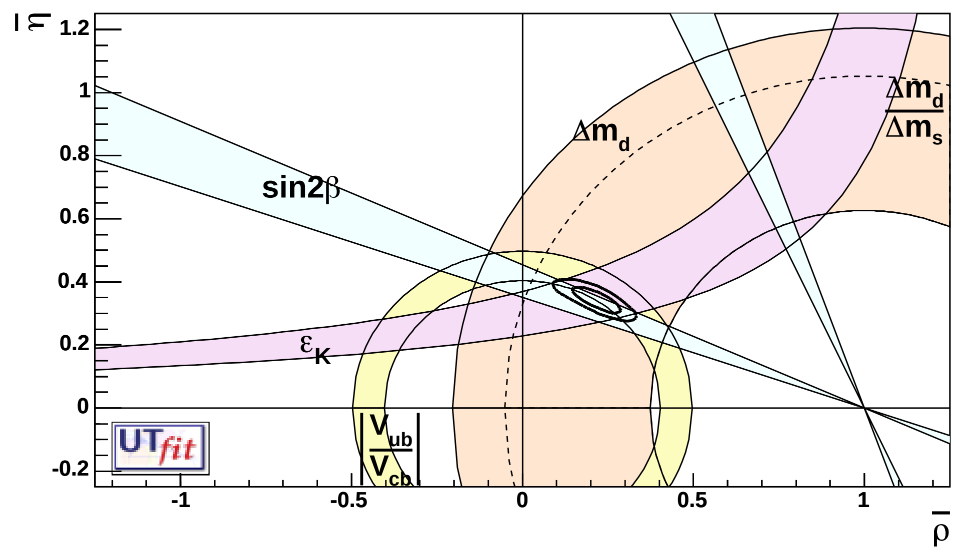
$$\overline{\rho} \equiv (1-\lambda^2/2)\rho, \quad \overline{\eta} \equiv (1-\lambda^2/2)\eta$$

$\longrightarrow$ NLO corrections [Buras *et al.* (1994)]

Status of the Unitarity Triangle

- Two competing groups: $\longrightarrow$ many plots & correlations ...
  - *CKMfitter* Collaboration [http://ckmfitter.in2p3.fr/];
  - *UTfit* Collaboration [http://www.utfit.org]:



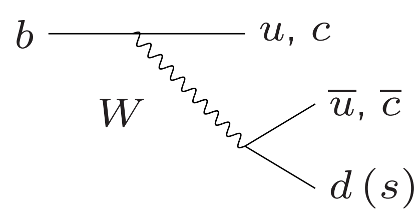


$\Rightarrow$ impressive global agreement with KM, but no longer "perfect" ...

Key Processes for the Exploration of CP Violation

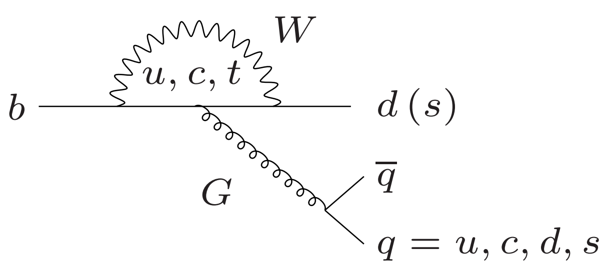
$\longrightarrow$ **non-leptonic B decays:**

- Tree diagrams:

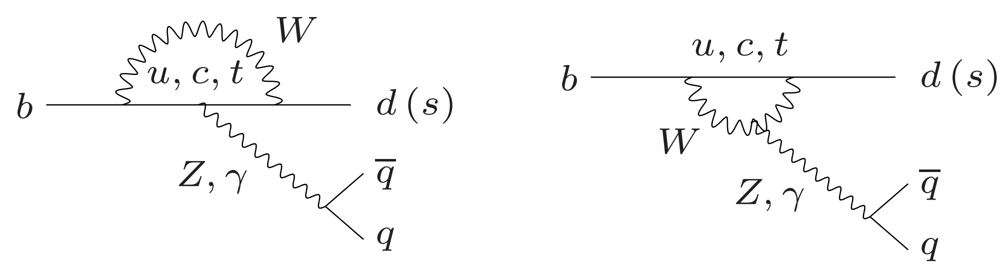


- Penguin diagrams:

◇ QCD penguins:



◇ Electroweak (EW) penguins:



Low-Energy Effective Hamiltonians

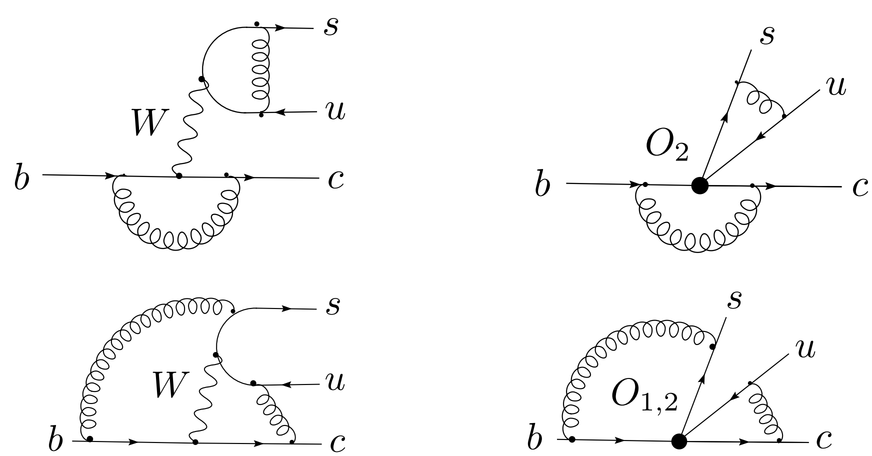
- The operator product expansion allows a systematic separation of the short-distance from the long-distance contributions to $B \to f$:

$$\langle f|\mathcal{H}_{\text{eff}}|B\rangle = \frac{G_{\rm F}}{\sqrt{2}} \sum_j \lambda^j_{\rm CKM} \sum_k C_k(\mu)\, \langle f|Q^j_k(\mu)|B\rangle$$

[$G_{\rm F}$: Fermi's constant, $\lambda^j_{\rm CKM}$: CKM factors, μ: renormalization scale]

- Short-distance physics: [Buras *et al.*; ...]

$\longrightarrow$ Wilson-Koeffizienten $C_k(\mu)$ $\longrightarrow$ *perturbative* $\longrightarrow$ known



- Long-distance physics:

$\longrightarrow$ matrix elements $\langle f|Q^j_k(\mu)|B\rangle$ $\longrightarrow$ *non-perturbative* $\longrightarrow$ "unknown"

Impact of New Physics

- 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, $\tan\bar{\beta} \equiv v_2/v_1$ 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 in the SM:

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

  – 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.

Specific New-Physics Analyses

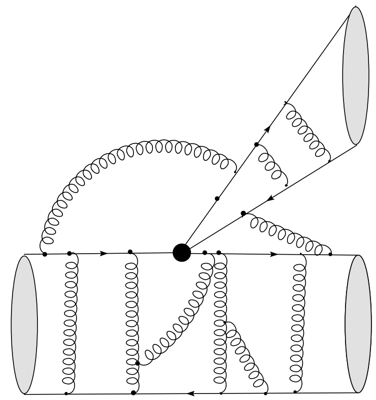
- SUSY models have received a lot of attention:

  Goto *et al.* ('04); Jäger & Nierste ('04); Ciuchini *et al.* ('04); Ball, Khalil & Kou ('04); Ko ('04); Gabrielli, Huitu, Khalil ('05); Foster, Okumura & Roszkowski ('05–'06); ...

- Examples of other fashionable NP scenarios:
  - Left–right-symmetric models [Ball *et al.* ('00); Ball & R.F. ('00); ...]
  - Scenarios with extra dimensions [Buras *et al.* ('03); Agashe *et al.* ('04); ...]
  - Models with an extra Z' boson [Barger *et al.* ('04); ...]
  - "Little Higgs" scenarios [Choudhury *et al.* ('04); Buras *et al.* ('05); ...]
  - Models with a fourth generation [Hou, Nagashima & Soddu ('05)]

- Suffer, in general, from the following problems:
  - Choice of NP model governed by personal "biases".
  - Predictivity inversely proportional to the number of NP parameters.

But Central Problem for NP Searches: $\langle f | Q_k^j(\mu) | B \rangle$



- Interesting recent developments:
  - QCD Factorization (QCDF):
    Beneke, Buchalla, Neubert & Sachrajda (1999–2001); ...
  - Perturbative Hard-Scattering (PQCD) Approach:
    Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...
  - Soft Collinear Effective Theory (SCET):
    Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...
  - QCD light-cone sum-rule methods:
    Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

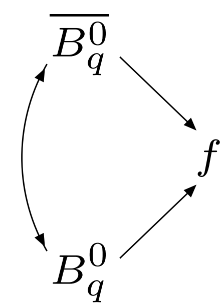
Data $\Rightarrow$ theoretical challenge remains ...

$\Rightarrow$ Circumvent the Calculation of the $\langle f|Q_k^j(\mu)|B\rangle$:

- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\to$ typically strategies to determine the UT angle γ):
  - *Exact* relations: class of pure "tree" decays (e.g. $B \to DK$).
  - *Approximate* relations, which follow from the *flavour symmetries* of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_{\rm F}$:

$$B \to \pi\pi,\ B \to \pi K,\ B_{(s)} \to KK.$$

- Decays of neutral B_d and B_s mesons:



Interference effects through B^0_q–$\overline{B^0_q}$ mixing:

  - Lead to "mixing-induced" CP violation $\mathcal{A}_{\rm CP}^{\rm mix}$!
  - If one CKM amplitude dominates:

$$\Rightarrow \textit{hadronic matrix elements cancel!}$$

$*$ Example: $B^0_d \to J/\psi\, K_{\rm S} \ \Rightarrow\ \sin 2\beta$ [Bigi, Carter & Sanda ('80–'81)]

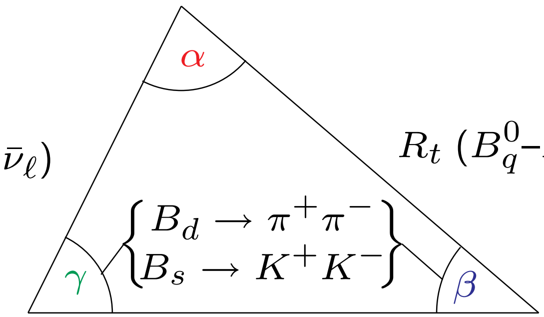
A Brief Roadmap of Quark-Flavour Physics

- <u>CP-B studies through various processes and strategies:</u>

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

R_b $(b \to u, c\ell\bar{\nu}_\ell)$

R_t (B_q^0–$\bar{B}_q^0$ mixing)



$B \to \pi K$ (penguins)

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

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

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

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

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

New Physics	$\Rightarrow$	Discrepancies

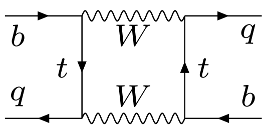
Popular New-Physics Avenues

- Decay Amplitudes:
  - Typically *small* effects if SM tree processes play the dominant rôle.
  - Potentially *large* effects in the penguin sector through new particles in the loop diagrams or new contributions at the tree level.
  - Possible first signals for such NP ($\to$ new CP violation) in the data:

    ◇ $B_d \to \phi K_S$: $(\sin 2\beta)_{\phi K_S} \stackrel{?}{=} (\sin 2\beta)_{\psi K_S}$ [see appendix].

    ♡ $B \to \pi K$: puzzling pattern of certain branching ratios [see below].

- B_q^0–$\bar{B}_q^0$ mixing ($q \in \{d, s\}$):



  - Exchange of NP particles in boxes or new tree contributions:

$$\Delta M_q = \Delta M_q^{\rm SM} + \Delta M_q^{\rm NP} \quad (\to R_t)$$

$$\phi_q = \phi_q^{\rm SM} + \phi_q^{\rm NP} \quad (\to \mathcal{A}_{\rm CP}^{\rm mix})$$

  - B_d system: ΔM_d, ϕ_d well established at the e^+e^- B factories;
  - B_s system: measurement of ΔM_s @ Tevatron $\to$ implications for NP?

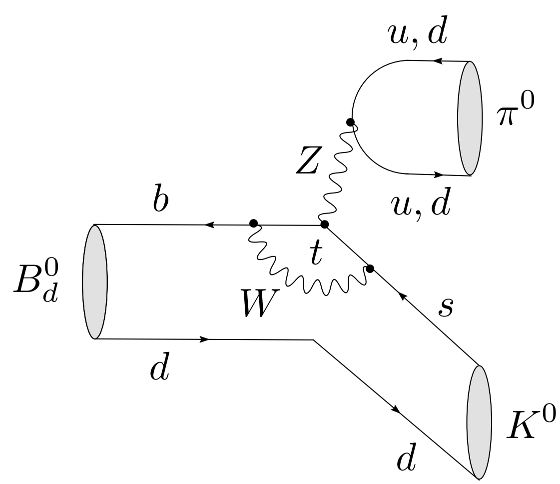
New Physics

at the

Amplitude Level

Challenging the SM

through $B \to \pi K$:



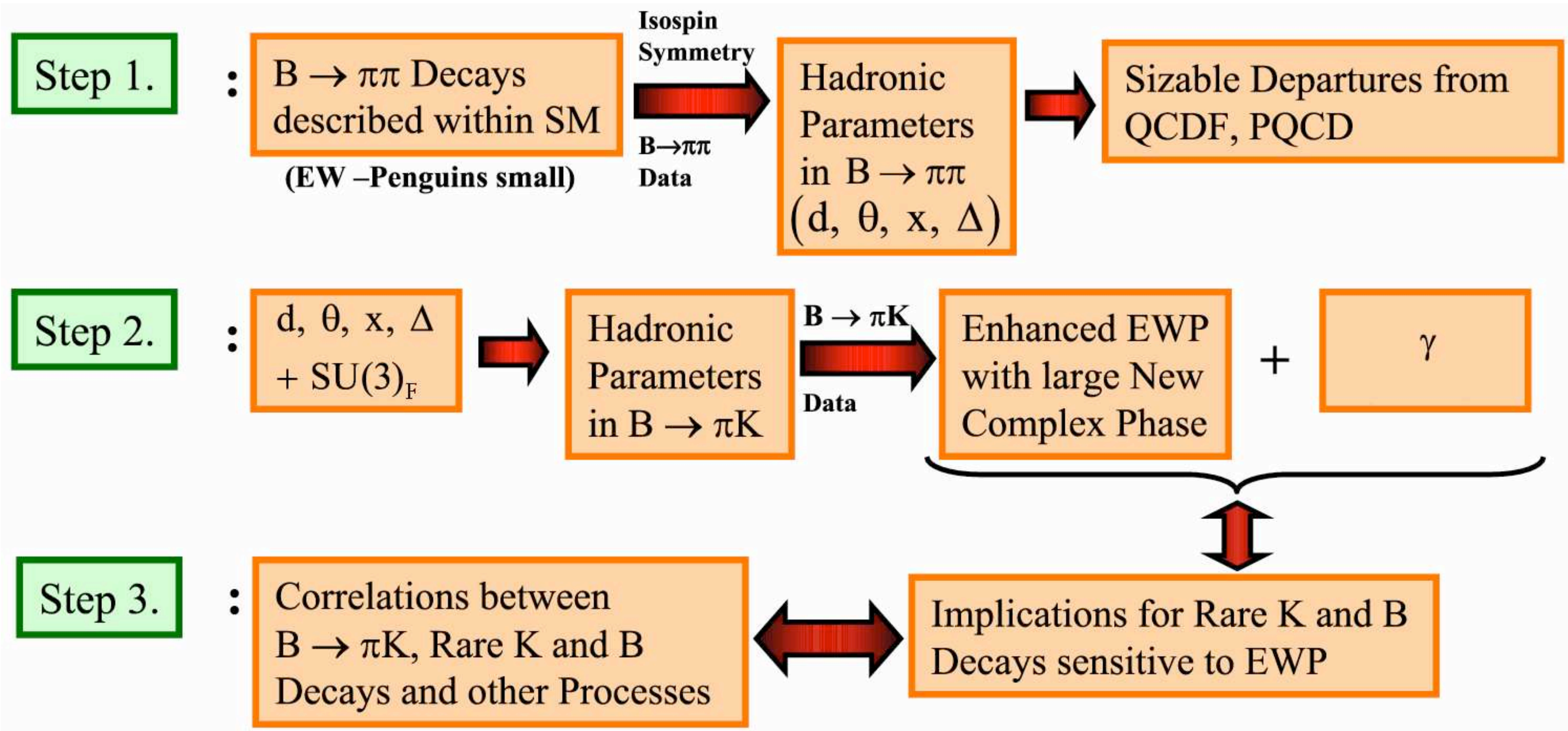
[Long history of $B \to \pi K$ studies: Gronau, Rosner & London ('94); R.F. ('95–'98); R.F. & Mannel ('97); Neubert & Rosner ('98); Buras & R.F. ('98–'00); ...]

EW Penguins and the $B \to \pi K$ Puzzle

- $B \to \pi K$ decays with *tiny* EW penguin contributions:
  - Observables can be accommodated in the Standard Model!
  - Example: direct CP asymmetry of $B_d^0 \to \pi^- K^+$.
- $B \to \pi K$ decays with *sizeable* EW penguin contributions:
  - Branching ratios show a surprising pattern!
  - This "puzzle" emerged already in 2000, when CLEO reported the observation of the $B_d^0 \to \pi^0 K^0$ channel with a remarkably prominent rate, and is now also/still present in the BaBar and Belle data (!?) ... [Buras & R.F. ('00)]
  - Has recently received a lot of attention!
    Beneke & Neubert ('03); Yoshikawa ('03); Gronau & Rosner ('03); Barger *et al.* ('04); Wu & Zhou ('05); ...

What's going on? $\to$

A Systematic Strategy in 3 Steps



Comprehensive analysis! Let's here just have a look at ...

[Buras, R.F., Recksiegel & Schwab (2003–2005)]

Decays with a *Sizeable* Impact of EW Penguins

- The key quantities: [Buras & R.F. ('98)]

$$R_{\rm c} \equiv 2\left[\frac{\text{BR}(B^+\to\pi^0K^+)+\text{BR}(B^-\to\pi^0K^-)}{\text{BR}(B^+\to\pi^+K^0)+\text{BR}(B^-\to\pi^-\bar{K}^0)}\right] \stackrel{\rm Exp}{=} 1.01\pm 0.09$$

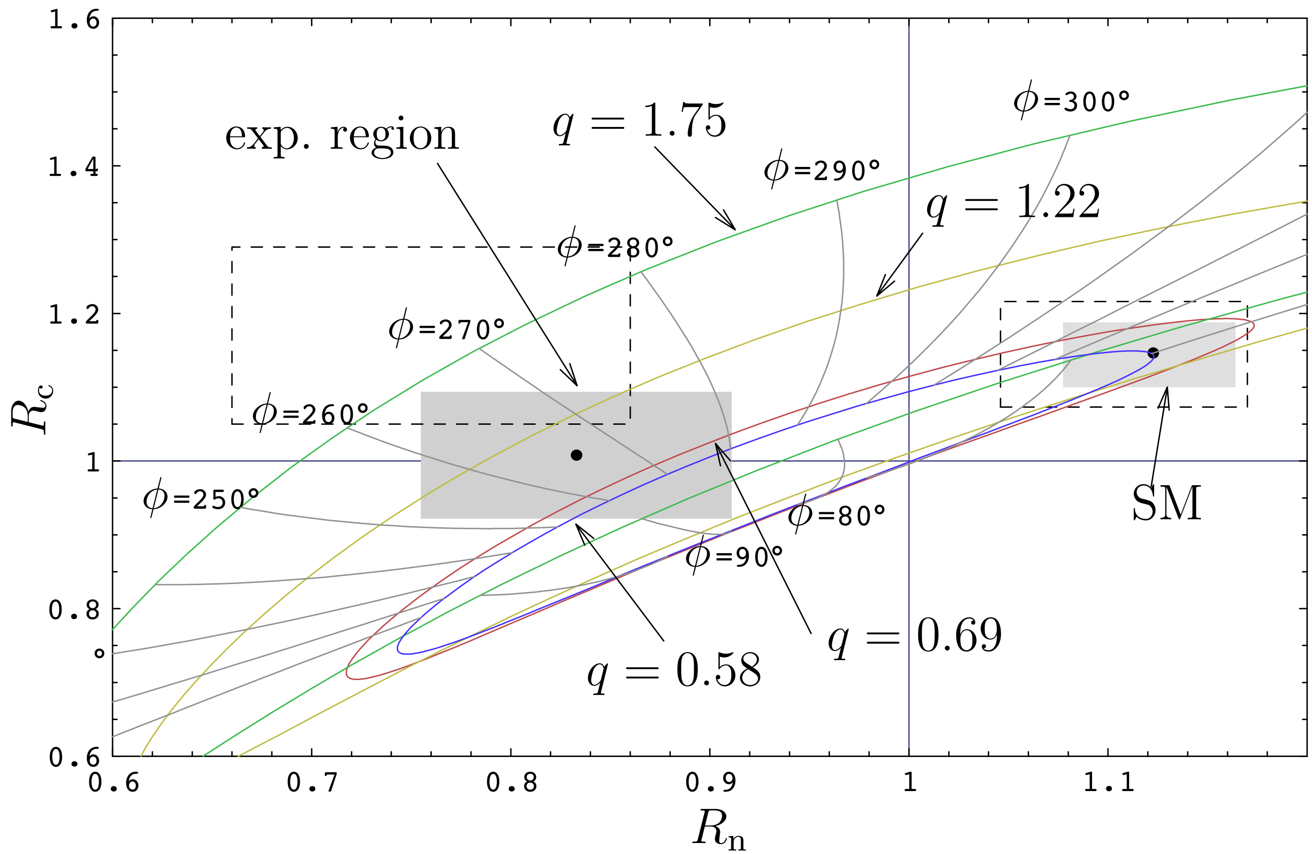
$$R_{\rm n} \equiv \frac{1}{2}\left[\frac{\text{BR}(B^0_d\to\pi^-K^+)+\text{BR}(\bar{B}^0_d\to\pi^+K^-)}{\text{BR}(B^0_d\to\pi^0K^0)+\text{BR}(\bar{B}^0_d\to\pi^0\bar{K}^0)}\right] \stackrel{\rm Exp}{=} 0.83\pm 0.08$$

- Features of the EW penguins:
  - Enter in colour-allowed from through the modes involving π^0's.
  - Description through the following parameters:

$$\underbrace{q \stackrel{\rm SM}{=} 0.58 \quad (\to \text{“strength”})}_{SU(3)\ \text{[Neubert \& Rosner ('98)]}}, \quad \phi \stackrel{\rm SM}{=} 0^\circ \ (\to \text{CP-violating phase})$$

  - Provide an interesting avenue for NP to manifest itself ...
    [R.F. & Mannel ('97); Grossman, Neubert & Kagan ('99); ...]

- Situation in the $R_{\rm n}$–$R_{\rm c}$ plane:



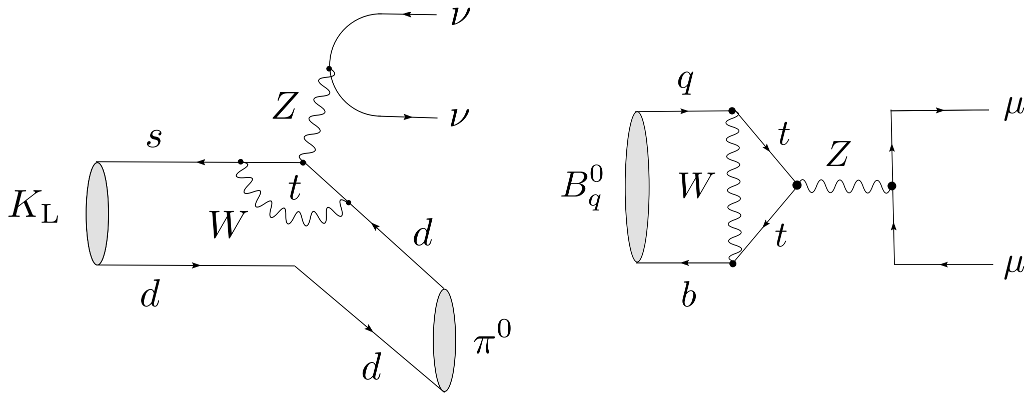
- Allow for NP in the EW penguin sector to resolve this "$B \to \pi K$ puzzle":

$$R_{\rm n,c}|_{\rm exp} \quad \Rightarrow \quad \boxed{q = 0.99\,^{+0.66}_{-0.70}, \qquad \phi = -(94^{+16}_{-17})^\circ}$$

$\Rightarrow$ *Predictions* of CP violation in $B^\pm \to \pi^0 K^\pm$ and $B_d \to \pi^0 K_{\rm S}$ ...

Interplay with Rare K and B Decays

- Attractive possibility for NP to enter EW penguins: Z penguins



  - Modified strength and CP-violating phase!
  - Can be realized, for example, in SUSY ...

- Theoretical considerations allow us to convert the $B \to \pi K$ parameters (q, ϕ) into short-distance functions characterizing rare B and K decays:

"Inami–Lim" functions: $\underbrace{X = |X| e^{i\theta_X}}_{K \to \pi\nu\bar{\nu}}, \quad \underbrace{Y = |Y| e^{i\theta_Y}}_{B_{s,d} \to \mu^+\mu^-}, \quad ...$

- Interesting effects: $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$, ...

$\Rightarrow$ specific patterns for various NP scenarios of this kind $\rightarrow$

- Constraints from the data for $B \to X_s \ell^+ \ell^-$ processes:

$$\Rightarrow X \leq 1.95, \quad Y \leq 1.43.$$

- On the other hand, the values of (q, ϕ) preferred by the $R_{\rm n,c}|_{\rm exp}$ require:

$$|X|_{\rm min} \approx |Y|_{\rm min} \approx 2.2.$$

- Scenarios for possible future measurements satisfying the bounds:

Quantity	SM	Scen A	Scen B	Scen C	Experiment
$R_{\rm n}$	1.12	0.88	1.03	1	0.83 ± 0.08
$R_{\rm c}$	1.15	0.96	1.13	1	1.01 ± 0.09

Decay	SM	Scen A	Scen B	Scen C	Exp. bound @ 90% C.L.
BR$(K^+ \to \pi^+ \nu \bar{\nu})/10^{-11}$	9.3	2.7	8.3	8.4	$(14.7^{+13.0}_{-8.9})$
BR$(K_{\rm L} \to \pi^0 \nu \bar{\nu})/10^{-11}$	4.4	11.6	27.9	7.2	$< 2.9 \times 10^4$
BR$(K_{\rm L} \to \pi^0 e^+ e^-)/10^{-11}$	3.6	4.6	7.1	4.9	< 28
BR$(B \to X_s \nu \bar{\nu})/10^{-5}$	3.6	2.8	4.8	3.3	< 64
BR$(B_s \to \mu^+ \mu^-)/10^{-9}$	3.9	9.2	9.1	7.0	$< 1.5 \times 10^2$

[Details: A. Buras, R.F., S. Recksiegel & F. Schwab, hep-ph/0512032]

New Physics

in

$B^0_{d,s}$–$\bar{B}^0_{d,s}$ Mixing

- B^0_d–$\bar{B}^0_d$ mixing: well established $\to \Delta M_d = (0.507 \pm 0.004)\,\mathrm{ps}^{-1}$ (!)
- B^0_s–$\bar{B}^0_s$ mixing: long standing experimental challenge ...

Hot News of this Spring

- 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: [→ talk by R. Erbacher]
    - 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.

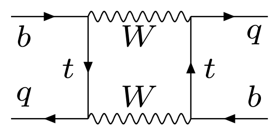
A Closer Look at B_q^0–$\bar{B}_q^0$ Mixing ($q \in \{d, s\}$)

- Low-energy effective Hamiltonian:

$$\langle B_q^0 | \mathcal{H}_{\rm eff}^{\Delta B=2} | \bar{B}_q^0 \rangle = 2 M_{B_q} M_{12}^q$$

$\Rightarrow$ mixing parameters: $\Delta M_q = 2|M_{12}^q|, \quad \phi_q = \arg(M_{12}^q)$

- SM prediction:



$$M_{12}^{q,\rm SM} = \frac{G_{\rm F}^2 M_W^2}{12\pi^2} M_{B_q} (V_{tq}^* V_{tb})^2 S_0(x_t) \hat{\eta}^B \hat{B}_{B_q} f_{B_q}^2$$

$$\Rightarrow \boxed{\phi_d^{\rm SM} = 2\beta, \quad \phi_s^{\rm SM} = -2\lambda^2\eta}$$

- The mass differences $\Delta M_q^{\rm SM} = 2|M_{12}^{q,\rm SM}|$ involve several parameters:
  - CKM factors $V_{tq}^* V_{tb}$: unitarity & tree processes [$\to$ robust under NP].
  - Short-distance: $S_0(x_t)$ [top-quark] & $\hat{\eta}^B$ [pert. QCD] $\to$ *known!*
  - Long-distance: $\hat{B}_{B_q} f_{B_q}^2$ $\to$ *hadronic uncertainties* $\to$ lattice...

CKM Parameters

- Basic assumption for our analysis: **unitarity of the CKM matrix**

$$\Rightarrow \begin{cases} |V_{td}^* V_{tb}| &= |V_{cb}|\lambda\sqrt{1-2R_b\cos\gamma+R_b^2} \\ |V_{ts}^* V_{tb}| &= |V_{cb}|\left[1-\frac{1}{2}(1-2R_b\cos\gamma)\lambda^2+\mathcal{O}(\lambda^4)\right], \end{cases}$$

$$\text{with} \quad R_b \equiv \left[1-\frac{\lambda^2}{2}\right]\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| = \sqrt{\bar\rho^2+\bar\eta^2} \to \text{UT side.}$$

- Semileptonic tree decays:
  - $b\to c\ell\bar\nu_\ell$ processes: $|V_{cb}| = (42.0\pm0.7)\times10^{-3}$
  - $b\to u\ell\bar\nu_\ell$ processes: $\to$ have to be clarified ...

$$\underbrace{|V_{ub}|_{\rm incl} = (4.4\pm0.3)\times10^{-3}, \qquad |V_{ub}|_{\rm excl} = (3.8\pm0.6)\cdot10^{-3}}_{\stackrel{2010}{\longrightarrow}\ (4.4\pm0.2)\times10^{-3}}$$

- Non-leptonic tree decays:[1]

$$\gamma|_{D^{(*)}K^{(*)}} = \left\{\begin{array}{ll} (62^{+35}_{-25})^\circ & \text{(CKMfitter)} \\ (65\pm20)^\circ & \text{(UTfit)} \end{array}\right\} \stackrel{2010}{\longrightarrow} (70\pm5)^\circ \text{ @ LHCb}$$

[1] CPV in $B_d^0\to\pi^+\pi^-$, $B_d^0\to\pi^-K^+$ (involving penguins) $\Rightarrow \gamma = (73.9^{+5.8}_{-6.5})^\circ$ [BFRS '05].

Hadronic Parameters: Lattice QCD

- Front runners: unquenched calculations with 2 or 3 dynamical quarks and Wilson or staggered light quarks, respectively. Despite tremendous progress, still several uncertainties: chiral extrapolations ...

- JLQCD results (2 flavours of dynamical light Wilson quarks):

  [Aoki *et al.* (JLQCD), hep-ph/0307039]

$$\left. f_{B_d}\hat{B}^{1/2}_{B_d}\right|_{\rm JLQCD} = (0.215 \pm 0.019^{+0}_{-0.023})\ {\rm GeV}$$

$$\left. f_{B_s}\hat{B}^{1/2}_{B_s}\right|_{\rm JLQCD} = (0.245 \pm 0.021^{+0.003}_{-0.002})\ {\rm GeV}$$

$$\xi_{\rm JLQCD} \equiv \left.\frac{f_{B_s}\hat{B}^{1/2}_{B_s}}{f_{B_d}\hat{B}^{1/2}_{B_d}}\right|_{\rm JLQCD} = 1.14 \pm 0.06^{+0.13}_{-0}$$

- f_{B_q} from HPQCD (3 dynamical flavours) with $\hat{B}_{B_q}$ from JLQCD:

  [Gray *et al.* (HPQCD), hep-lat/0507015; Okamato, hep-lat/0510113]

$$\left. f_{B_d}\hat{B}^{1/2}_{B_d}\right|_{\rm (HP+JL)QCD} = (0.244 \pm 0.026)\ {\rm GeV}$$

$$\left. f_{B_s}\hat{B}^{1/2}_{B_s}\right|_{\rm (HP+JL)QCD} = (0.295 \pm 0.036)\ {\rm GeV}$$

$$\xi_{\rm (HP+JL)QCD} = 1.210^{+0.047}_{-0.035}$$

$\xleftarrow{2010}$

Space for NP

in the

B_d-Meson System

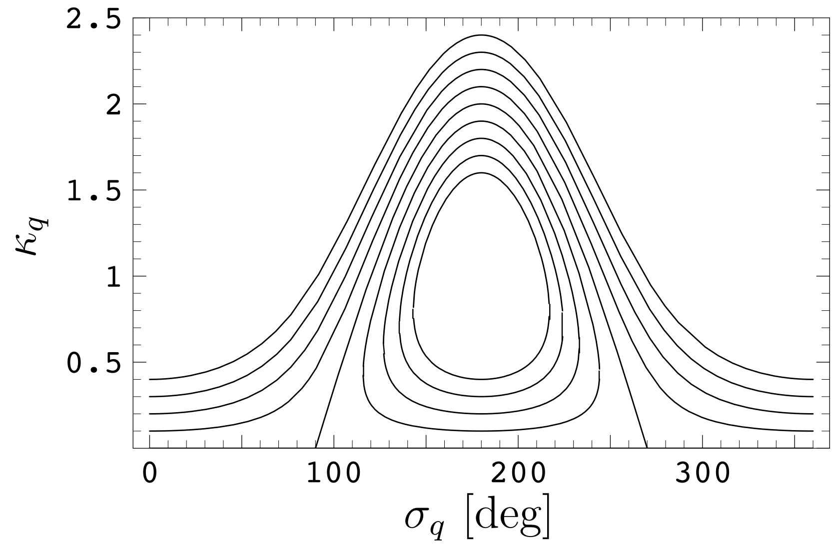
New-Physics Parameters

- Model-independent expression for M_{12}^d in the presence of NP:

$$M_{12}^d = M_{12}^{d,\mathrm{SM}}\left[1+\kappa_d e^{i\sigma_d}\right] \Rightarrow \begin{cases} \Delta M_d = \Delta M_d^{\mathrm{SM}}\left|1+\kappa_d e^{i\sigma_d}\right| \\ \phi_d = \phi_d^{\mathrm{SM}} + \phi_d^{\mathrm{NP}} = \phi_d^{\mathrm{SM}} + \arg(1+\kappa_d e^{i\sigma_d}) \end{cases}$$

- The experimental result for ΔM_d and the theoretical prediction ΔM_d^{SM} provide the following constraint on κ_d and σ_d (holds for $q \in \{d,s\}$):

$$\rho_q \equiv \left|\frac{\Delta M_q}{\Delta M_q^{\mathrm{SM}}}\right| = \sqrt{1+2\kappa_q\cos\sigma_q+\kappa_q^2}$$



$[0.6 \le \rho_q \le 1.4]$

The SM Prediction for ΔM_d

- <u>Numerical values:</u> $[\Delta M_d \overset{\text{HFAG}}{=} (0.507 \pm 0.004)\,\text{ps}^{-1}]$

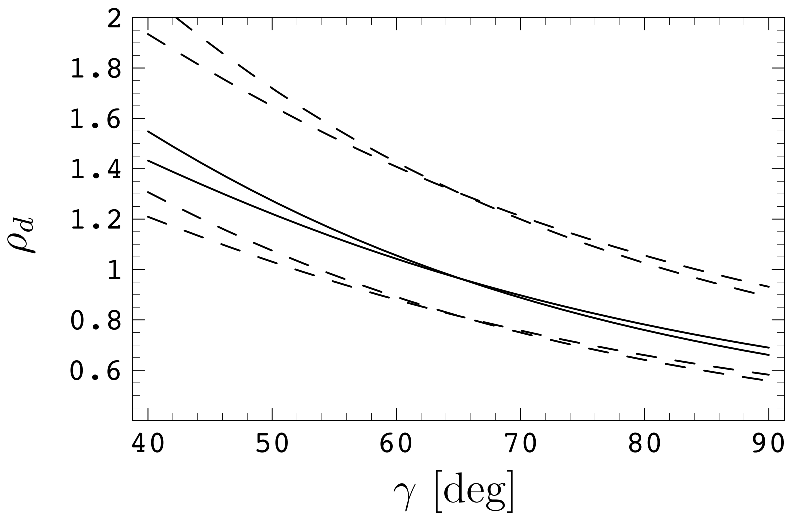
$$\left.\Delta M_d^{\text{SM}}\right|_{\text{JLQCD}} = \left[0.52 \pm 0.17(\gamma, R_b)^{-0.09}_{+0.13}(f_{B_d}\hat{B}_{B_d}^{1/2})\right]\ \text{ps}^{-1}$$

$$\left.\rho_d\right|_{\text{JLQCD}} = 0.97 \pm 0.33(\gamma, R_b)^{-0.17}_{+0.26}(f_{B_d}\hat{B}_{B_d}^{1/2})$$

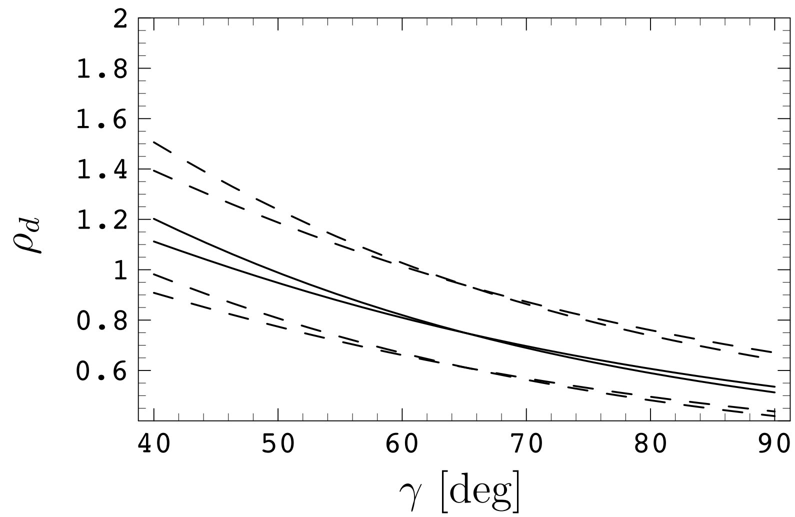
$$\left.\Delta M_d^{\text{SM}}\right|_{\text{(HP+JL)QCD}} = \left[0.69 \pm 0.13(\gamma, R_b) \pm 0.08(f_{B_d}\hat{B}_{B_d}^{1/2})\right]\ \text{ps}^{-1}$$

$$\left.\rho_d\right|_{\text{(HP+JL)QCD}} = 0.75 \pm 0.25(\gamma, R_b) \pm 0.16(f_{B_d}\hat{B}_{B_d}^{1/2})$$

- <u>Illustration of the dependence on γ and $R_b = (0.39, 0.45)$:</u>



JLQCD

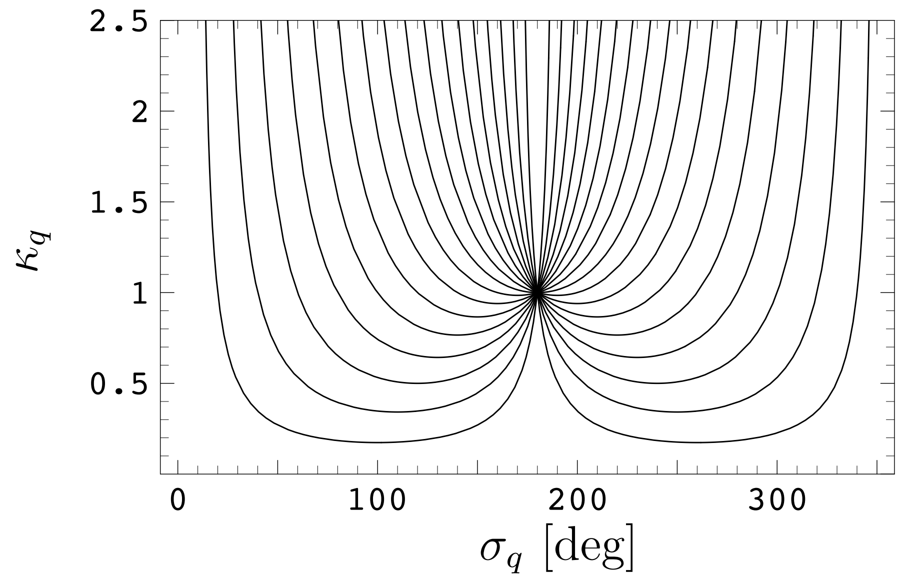


(HP+JL)QCD

Constraints on NP through CP Violation: ϕ_d

- Another constraint on the allowed values of κ_d and σ_d is provided by the experimental value of the B_d mixing phase $\phi_d = \phi_d^{\rm SM} + \phi_d^{\rm NP}$.

- $\phi_d^{\rm NP}$ allows us to determine κ_d as a function of σ_d (holds for $q \in \{d, s\}$):



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

- Interestingly, κ_q is bounded from below for any given value of $\phi_q^{\rm NP} \neq 0$:

  – Example: $|\phi_q^{\rm NP}| = 10^\circ \;\; \Rightarrow \;\; \kappa_q \geq 0.17 \;\; \rightarrow$ clean lower bound!

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

- Basic strategy:[2] [similar effects: UTfit ('05) & BFRS ('05)]
  - Mixing-induced CP violation in $B_d^0 \to J/\psi K_{\rm S}$ (and similar modes):

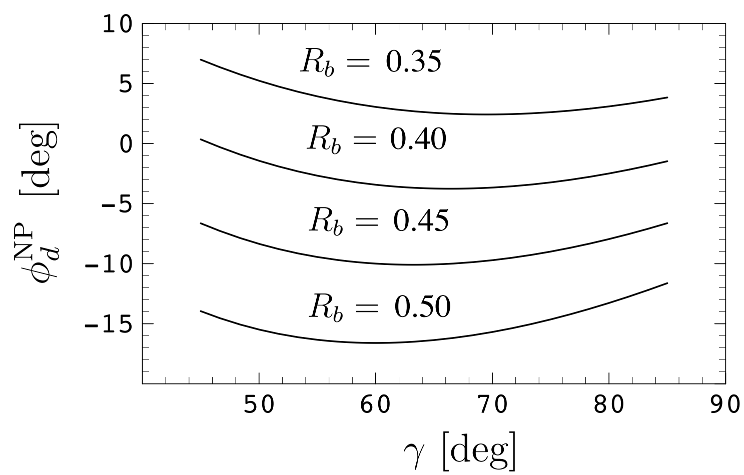
$$(\sin\phi_d)_{c\bar{c}s} = \left\{ \begin{array}{ll} 0.722 \pm 0.040 \pm 0.023 & \text{(BaBar)} \\ 0.652 \pm 0.039 \pm 0.020 & \text{(Belle)} \end{array} \right\} \oplus (\cos\phi_d)_{c\bar{c}s} > 0$$

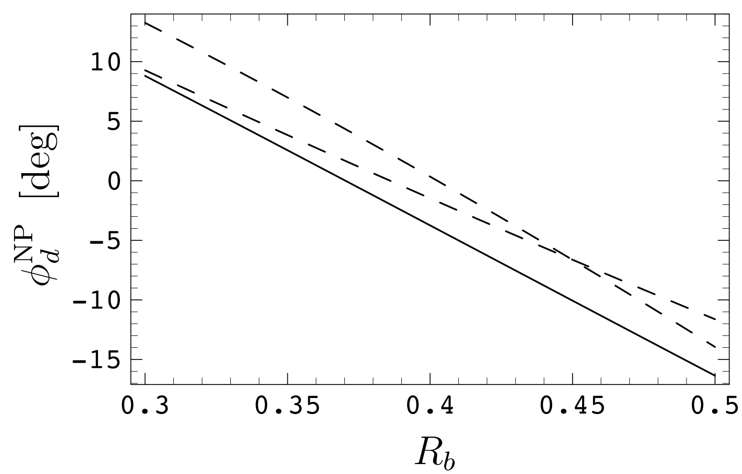
$$\Rightarrow \phi_d = 2\beta + \phi_d^{\rm NP} \stackrel{\rm HFAG}{=} (43.4 \pm 2.5)^\circ$$

  - Comparison with the "true" value of 2β following from γ and R_b:

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

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

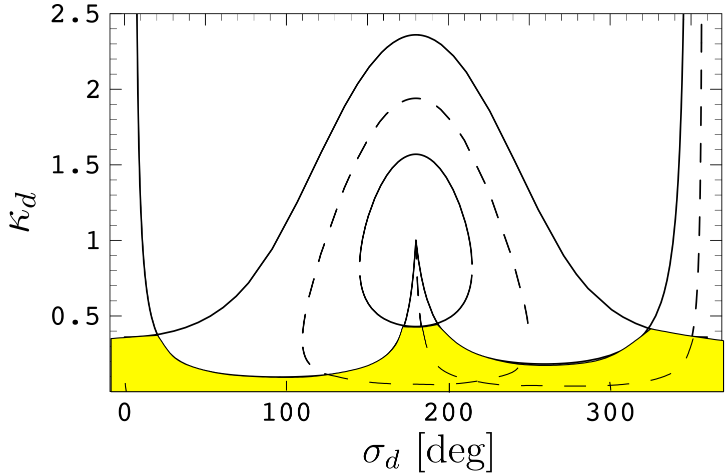




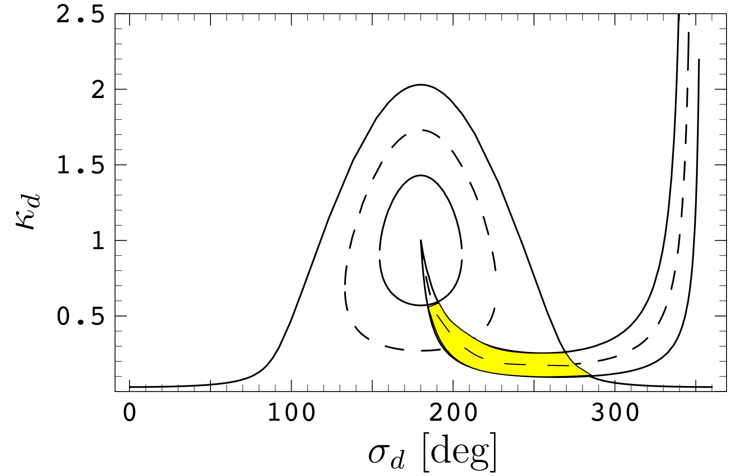
[2] Assumes that NP plays a negligible rôle in the $B \to J/\psi K$ amplitudes [see R.F., hep-ph/0512253].

Combined Constraints on NP through ΔM_d and ϕ_d

- Status in 2006:

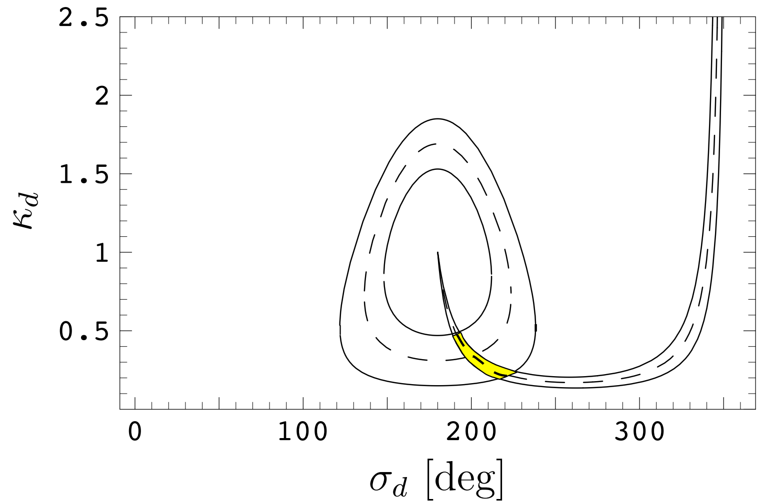


JLQCD and $\phi_d^{\mathrm{NP}}\big|_{\mathrm{excl}}$



(HP+JL)QCD and $\phi_d^{\mathrm{NP}}\big|_{\mathrm{incl}}$

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



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

- Numerical results:

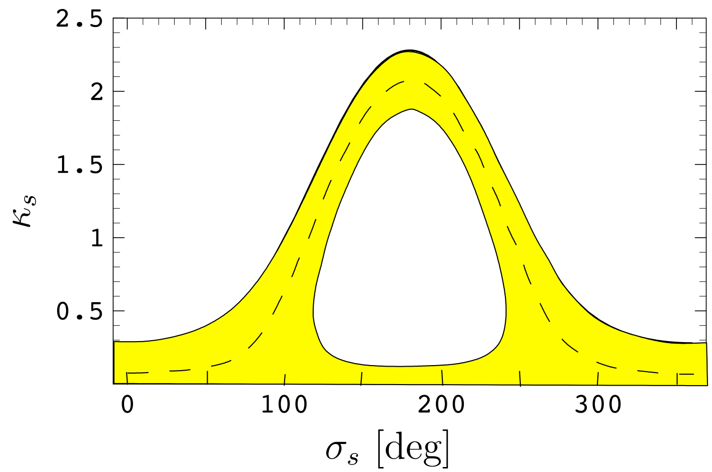
$$\Delta M_s^{\rm SM}\Big|_{\rm JLQCD} = (16.1 \pm 2.8)\,{\rm ps}^{-1}$$

$$\rho_s|_{\rm JLQCD} = 1.08^{+0.03}_{-0.01}(\text{exp}) \pm 0.19(\text{th})$$

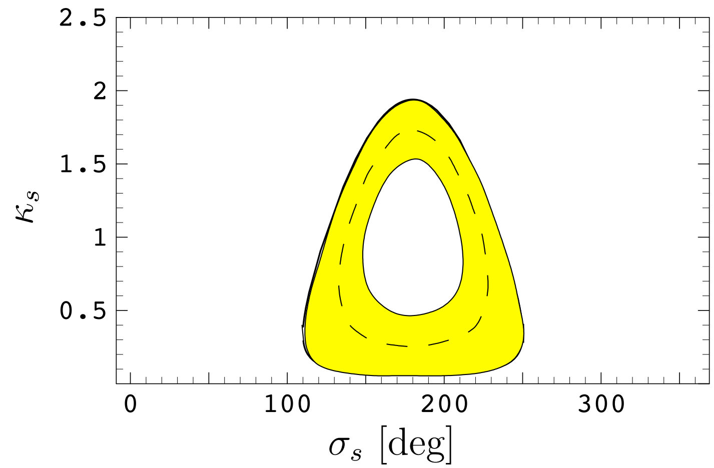
$$\Delta M_s^{\rm SM}\Big|_{\rm (HP+JL)QCD} = (23.4 \pm 3.8)\,{\rm ps}^{-1}$$

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

- Allowed regions in the σ_s–κ_s plane:



JLQCD



(HP+JL)QCD

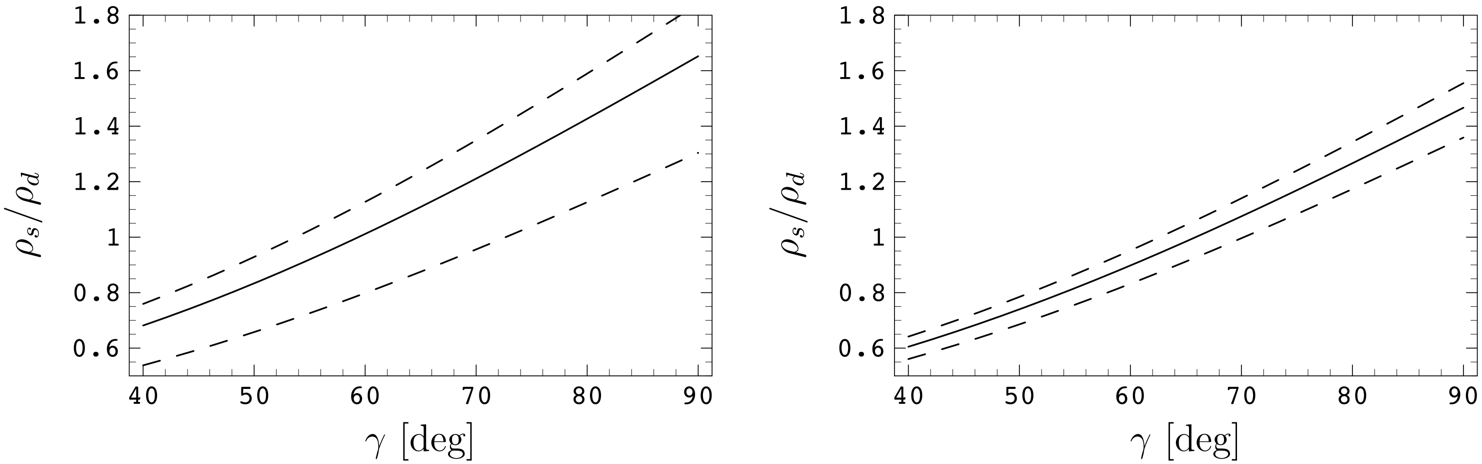
Constraints on NP through ΔM_s and ΔM_d

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

  $\longrightarrow$ reduced theoretical uncertainty as compared to $f_{B_q}\hat{B}_{B_q}^{1/2}$.

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

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



JLQCD (HP+JL)QCD

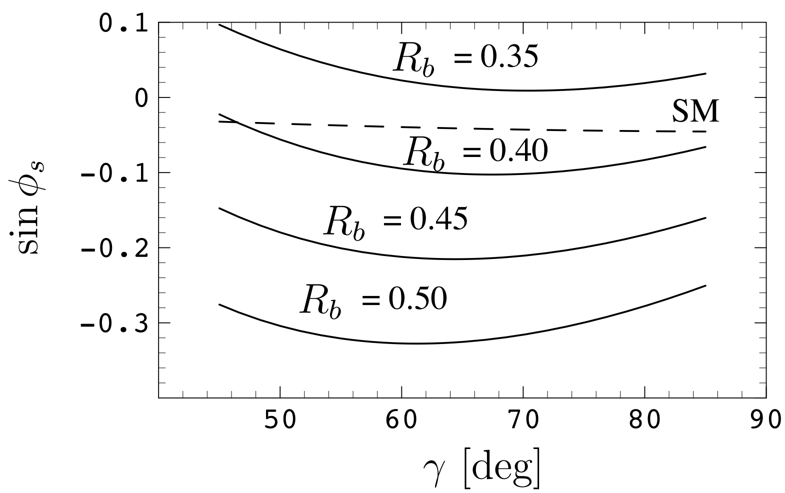
$$\longrightarrow \left.\frac{\rho_s}{\rho_d}\right|_{2010} = 1.07 \pm 0.09(\gamma, R_b)^{+0.06}_{-0.08}(\xi) = 1.07 \pm 0.12 \Rightarrow \boxed{!?}$$

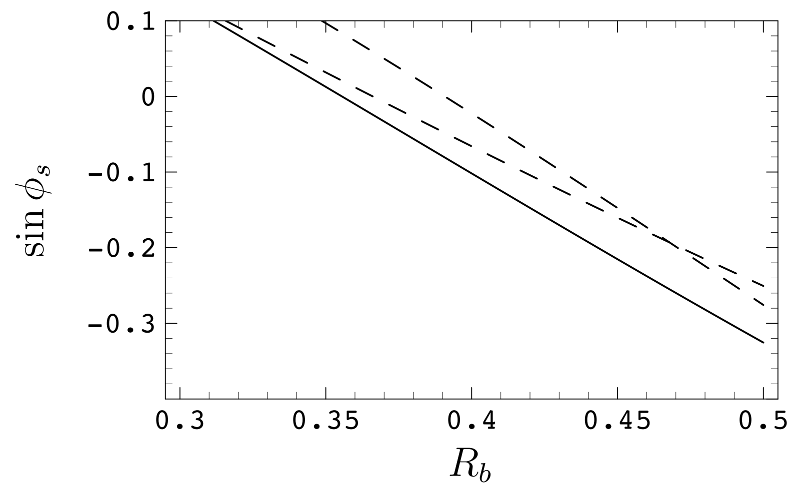
CP Violation in the B_s System

- Golden decay $B_s \to J/\psi\phi$: $\Rightarrow$ $\boxed{\sin\phi_s = \sin(-2\lambda^2 R_b \sin\gamma + \phi_s^{\rm NP})}$
  - No experimental insights yet ...
  - But very accessible at the LHC:
    - LHCb: $\sigma_{\rm stat}(\sin\phi_s) \approx 0.031$ (1 year) [0.013 (5 years)];
    - ATLAS & CMS: expect uncertainties at the 0.1 level (1 year).

- Illustration of the impact of NP through the following assumption:

$$\sigma_d = \sigma_s, \quad \kappa_d = \kappa_s \quad \Rightarrow \quad \phi_d^{\rm NP} = \phi_s^{\rm NP}$$

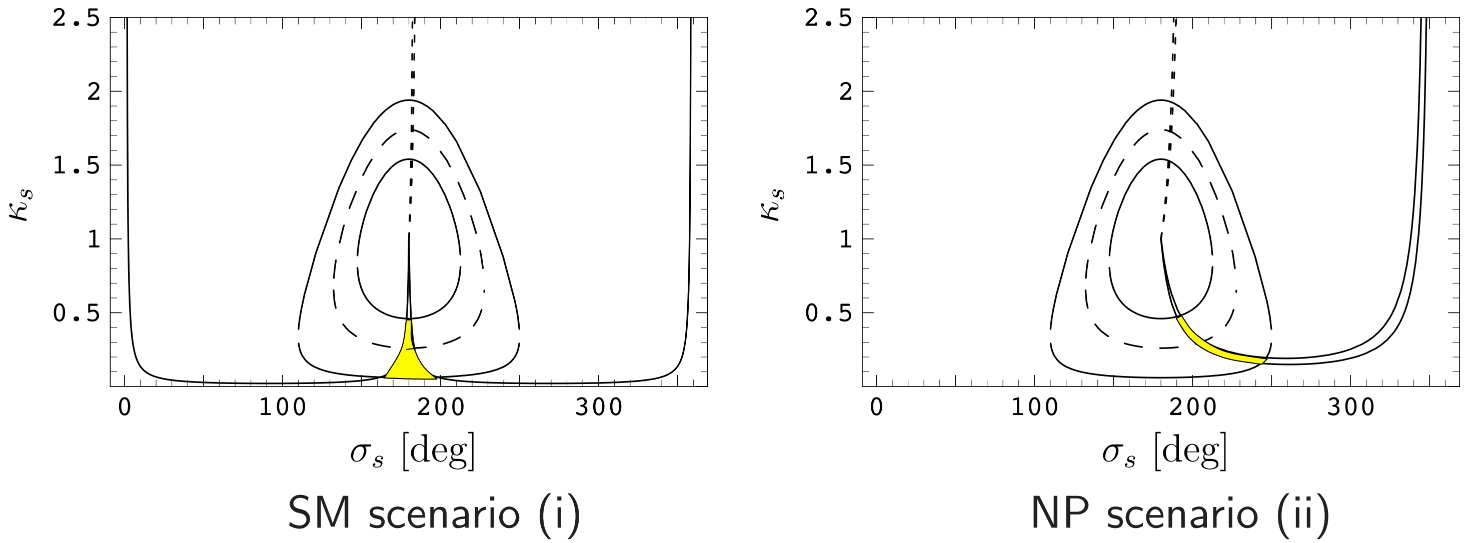




$\Rightarrow$ "magnification" of the B_d effects in the B_s system!

- Impact of CP violation measurements on σ_s, κ_s in our 2010 scenario:

  (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 @ $10\,\sigma$ (see above).



- Comments and remarks:

  – Dotted lines: $\cos\phi_s < 0$; can be excluded [Dunietz, R.F. & Nierste ('01)].
  – 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!*

Impact of the CDF Measurement

on two

Popular NP Scenarios:

- an extra Z' boson with flavour non-diagonal couplings;
- generic effects in the minimal supersymmetric extension of the SM (MSSM) in the “mass insertion approximation”.

$\longrightarrow$ illustrations, not comprehensive analyses ...

Z' Gauge Boson with Non-Universal Couplings

- Examples: GUTs, superstrings and theories with large extra dimensions.

  [Langacker & Plümacher (2000); Cvetic *et al.* (2001 and 2002)]

- 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.

- We then obtain the following contribution to M_{12}^s:

$$M_{12}^{s,Z'} = \frac{G_{\rm F}}{\sqrt{2}} \rho_L^2 e^{2i\phi_L} \frac{4}{3} \hat{\eta}^B \hat{B}_{B_s} f_{B_s}^2 M_{B_s}, \quad \rho_L e^{i\phi_L} \equiv \frac{g' M_Z}{g M_{Z'}} B_{sb}^L \sim 10^{-3}$$

  - g and g': $U(1)_Y$ and $U(1)'$ couplings. Generically, we expect $g/g' = \mathcal{O}(1)$ if both $U(1)$ groups have the same origin (e.g. GUT frameworks).
  - $M_{Z,Z'}$: gauge-boson masses; $M_Z/M_{Z'} = \mathcal{O}(0.1)$ for a TeV-scale Z'.
  - B_{sb}^L is the FCNC coupling of the Z' to b_L and s_L; if it is set by the quarks' Yukawa couplings, we expect $|B_{sb}^L| \approx |V_{ts}^* V_{tb}|$.

  [Barger, Chiang, Jiang and Langacker, hep-ph/0405108]

- The impact of the ΔM_s measurement on the Z' parameters follows from the previous discussion through the following simple replacements:

$$\rho_L \leftrightarrow (\kappa_s/f)^{1/2}, \qquad \phi_L \leftrightarrow \sigma_s/2$$

$$f = \frac{16\pi^2}{\sqrt{2}} \frac{1}{G_F M_W^2 S_0(x_t)|V_{ts}|^2} = (3.57 \pm 0.01) \times 10^5$$

  - $\kappa_s < 2.5 \quad \Rightarrow \quad \rho_L < 2.6 \times 10^{-3}$.
  - Assuming $\phi_s^{\rm NP} = -10^\circ$, we would have much stronger constraints:

$$0.2 < \kappa_s < 0.5 \quad \Rightarrow \quad 0.5 \times 10^{-3} < \rho_L < 1.2 \times 10^{-3};$$

$\longrightarrow$ further improvement would have to rely on lattice...

- The bounds on ρ_L can be converted into bounds on the mass of the Z':
  - ΔM_s bound: $\rho_L < 2.6 \times 10^{-3} \quad \Rightarrow \quad 1.5\,\mathrm{TeV}\left(\frac{g'}{g}\right)\left|\frac{B_{sb}^L}{V_{ts}}\right| < M_{Z'}$
  - CPV scenario: $\Rightarrow \quad 3\,\mathrm{TeV}\left(\frac{g'}{g}\right)\left|\frac{B_{sb}^L}{V_{ts}}\right| < M_{Z'} < 7.5\,\mathrm{TeV}\left(\frac{g'}{g}\right)\left|\frac{B_{sb}^L}{V_{ts}}\right|$

$\Rightarrow$ interplay between flavour & collider physics!

[Another recent analysis: Cheung, Chiang, Deshpande & Jiang, hep-ph/0604223]

MSSM in the Mass Insertion Approximation

- In SUSY, many more possible ways in which both lepton and quark flavours can change, and about 100 soft SUSY-breaking terms, which could give rise to huge – and unobserved – flavour violation!

- Possible solution: assumption that the squark (and slepton) masses are approximately "aligned" with the quark (and lepton) masses:

  $\longrightarrow$ the off-diagonal terms in the sfermion mass matrices,

$$(\delta^f_{ij})_{AB} \equiv (\Delta m^2_{ij})_{AB}/m^2_{\tilde{f}}\,,$$

  can be treated as perturbations: "mass insertion approximation" (MIA).

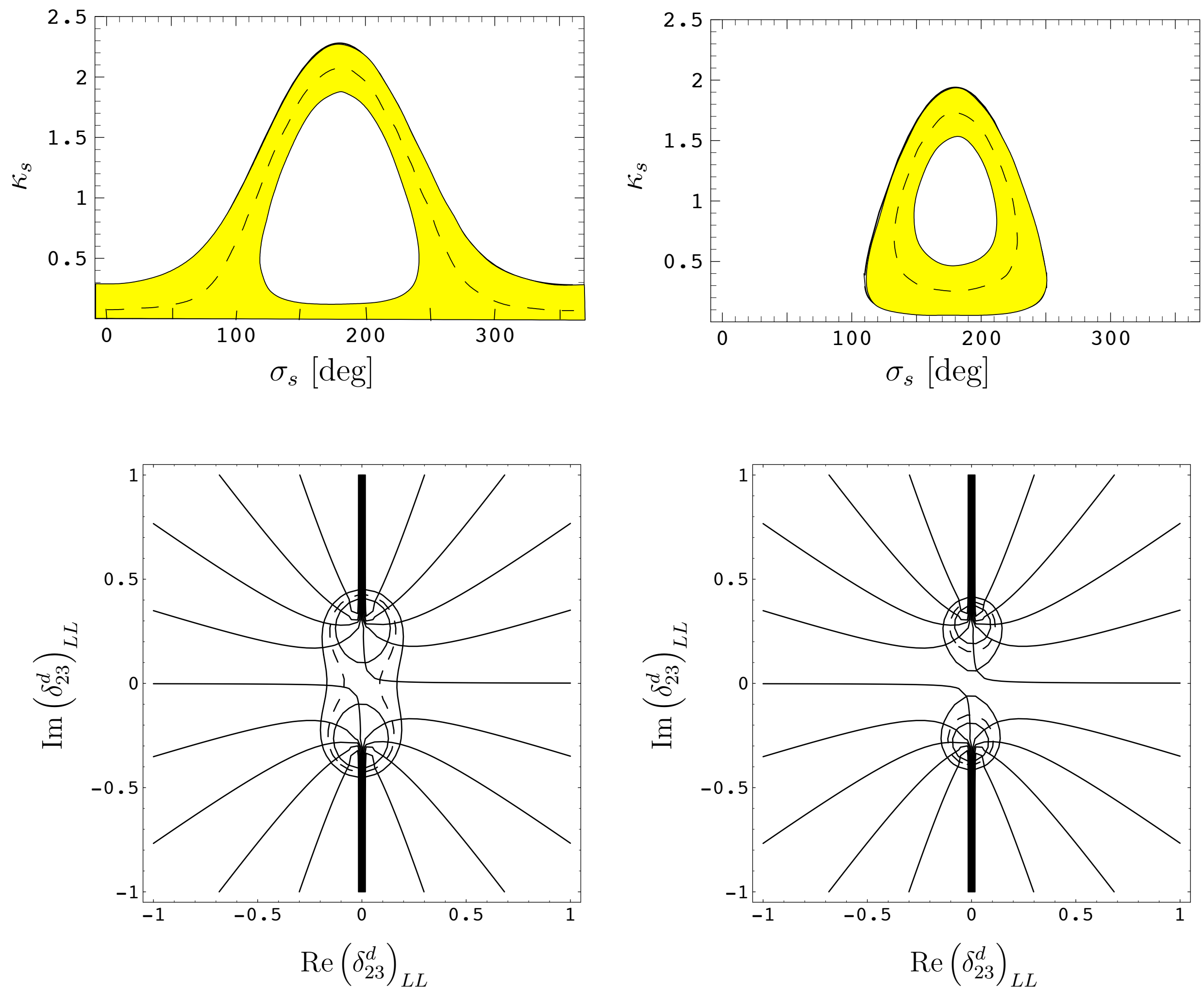
  [Hall, Kostelecky & Raby (1986); Gabbiani *et al.* (1996)]

- Here just an illustration of the interplay between ΔM_s & mass insertions:

  – we set all but one mass insertion to 0;
  – we restrict ourselves to bounds on $(\delta^d_{23})_{LL}$ and the impact of a future measurement of ϕ_s on these bounds.

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

- <u>$1\,\sigma$ constraints on $(\delta^d_{23})_{LL}$ from ΔM_s:</u> $[M_{\rm S} = m_{\tilde q} = m_{\tilde g} = 500\,{\rm GeV}]$



$\Rightarrow$ still all values of ϕ_s allowed!

- *If* SUSY is found at the LHC, and the gluino and average squark masses are measured, MIA analyses of flavour processes will help us to constrain the soft SUSY breaking terms $\rightarrow$ insights into SUSY breaking.

Conclusions and Outlook (I)

- Status of new physics in the beauty system in May 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:[3]
  - Various determinations of γ $\longrightarrow$ key ingredient for NP searches!
  - Fully exploit the B_s physics potential (taking over from CDF & D0).
  - 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] (?)

[3] 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)

CP violation and flavour physics in the context of the 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

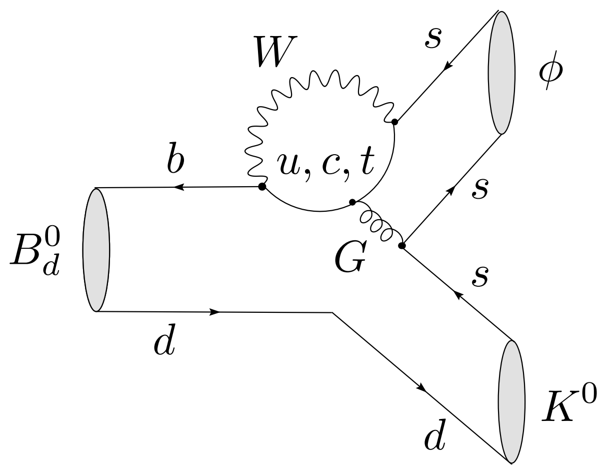
  - If discovery of new particles, which kind of new physics?
  - Insights into the corresponding new flavour structures and possible new sources of CP violation through studies of flavour processes.
  - Sensitivity on very high energy scales of new physics through precision measurements, also if NP particles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

3rd meeting takes place at CERN from Mon – Wed *this* week....

Appendix

Challenging the SM

through $B_d \to \phi K_S$:



$\Rightarrow$ $b \to s$ penguin process

CP Asymmetries & Impact of New Physics

$$\frac{\Gamma(B^0_d(t)\to f)-\Gamma(\overline{B^0_d}(t)\to \overline{f})}{\Gamma(B^0_d(t)\to f)+\Gamma(\overline{B^0_d}(t)\to \overline{f})}=\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M_d t)+\mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M_d t)$$

- SM relations:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d\to\phi K_{\rm S})=0+\mathcal{O}(\lambda^2)\;\;[\lambda\equiv|V_{us}|=0.22]$$
$$\underbrace{\mathcal{A}_{\rm CP}^{\rm mix}(B_d\to\phi K_{\rm S})}_{\equiv-(\sin 2\beta)_{\phi K_{\rm S}}}=\underbrace{\mathcal{A}_{\rm CP}^{\rm mix}(B_d\to\psi K_{\rm S})}_{\equiv-(\sin 2\beta)_{\psi K_{\rm S}}}+\mathcal{O}(\lambda^2) \quad (1)$$

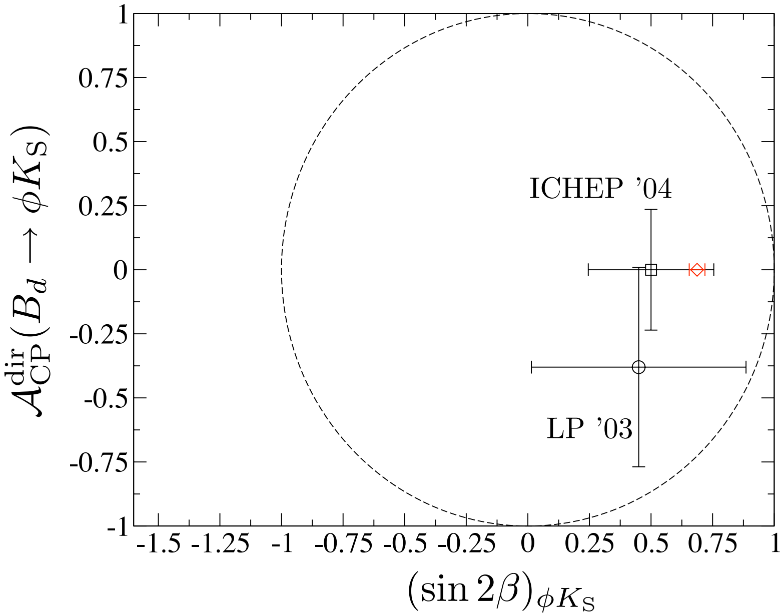
[R.F. ('97); Grossman & Worah ('97)]

- $B_d\to\phi K_{\rm S}$ is a sensitive probe for the search for new physics:
  - Decay is dominated by QCD penguins.
  - Electroweak penguins have a significant impact as well [R.F. ('94)]
  - Model-independent studies of new physics [R.F. & Mannel ('01)]

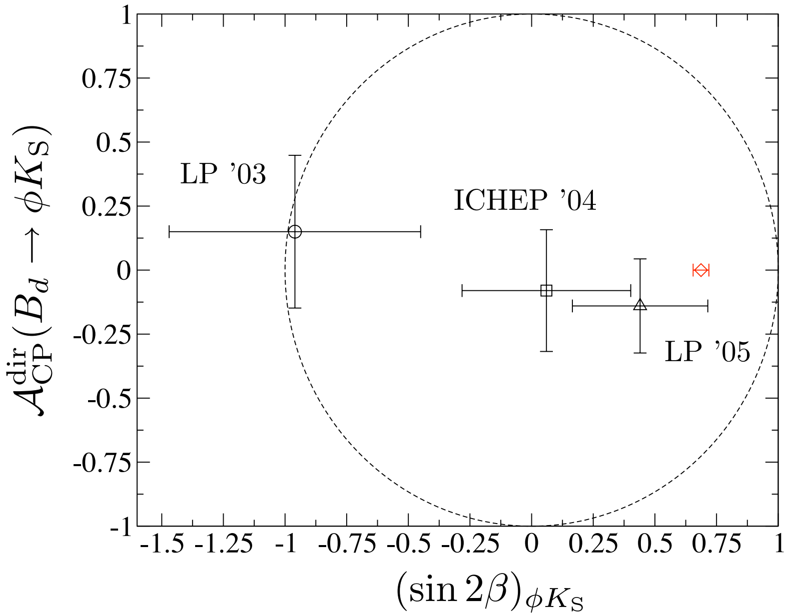
$\longrightarrow$ (1) may well be violated through new physics!

Time Evolution of the $B \to \phi K$ Data

- BaBar:



- Belle:



- Compilation of the "Heavy Flavour Averaging Group" (HFAG):

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \phi K_{\rm S}) = -0.09 \pm 0.14, \qquad (\sin 2\beta)_{\phi K_{\rm S}} = 0.47 \pm 0.19$$

$$\Rightarrow \mathcal{S}_{\phi K} \equiv (\sin 2\beta)_{\phi K_{\rm S}} - (\sin 2\beta)_{\psi K_{\rm S}} = -0.22 \pm 0.19$$

$\Rightarrow$ stay tuned & monitor similar modes!

NP may originate in the EW penguin sector:

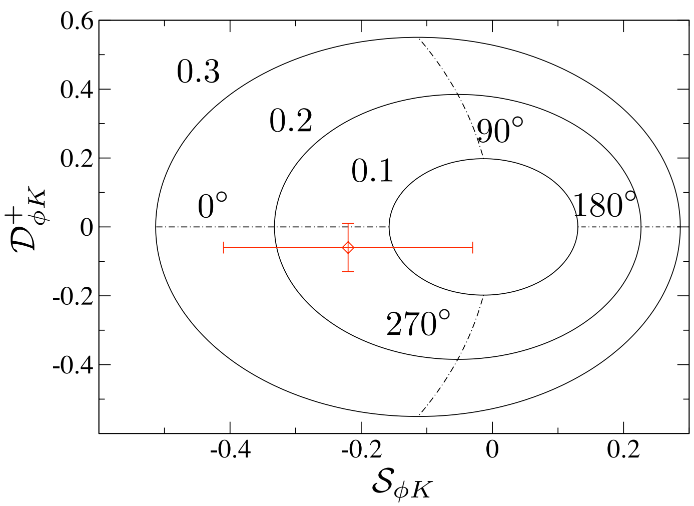
- Assume that NP enters the $I = 0$ isospin sector ($I = 1$ is dynamically suppressed), involving a CP-violating NP phase ϕ_0:

$$A(B_d^0 \to \phi K^0) = \tilde{A}_0 \left[1 + \tilde{v}_0 e^{i(\tilde{\Delta}_0 + \phi_0)}\right] = A(B^+ \to \phi K^+)$$

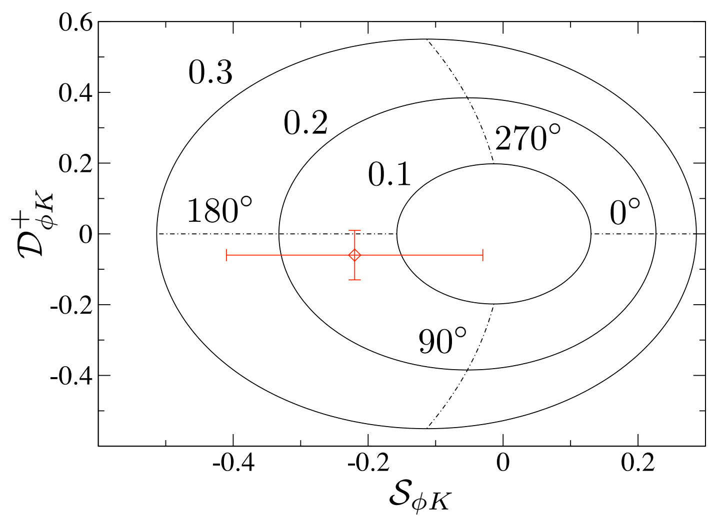
$$\tilde{v}_0 e^{i\tilde{\Delta}_0}|_{\rm fact}^{\rm SM} \approx 0.2 \times e^{i180^\circ}$$

- Observables: $\mathcal{S}_{\phi K} \quad \oplus \quad \mathcal{D}_{\phi K}^{+} \equiv [\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \phi K_{\rm S}) + \mathcal{A}_{\rm CP}^{\rm dir}(B^\pm \to \phi K^\pm)]/2$

  - $\phi_0 = -90^\circ$:



  - $\phi_0 = +90^\circ$: $\longrightarrow$ favoured !?



[Detailed discussion: R.F., hep-ph/0512253]