CP Violation and B Physics at the LHC

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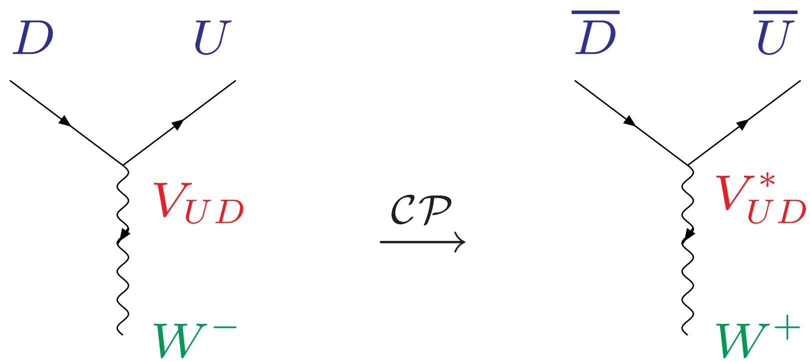
- Setting the Stage
- A Brief Look at the Current B-Factory Data
- Key Targets of the B Physics Programme at the LHC
- Conclusions and Outlook

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]

Why Study Flavour Physics & CP Violation?

- New Physics (NP): $\longrightarrow$ typically new patterns in the flavour sector
  - SUSY scenarios;
  - left–right-symmetric models;
  - models with extra Z' bosons;
  - scenarios with extra dimensions;
  - "little Higgs" scenarios ...
- ν masses: $\longrightarrow$ origin beyond the Standard Model (SM)!
  - CP violation in the neutrino sector?
  - Connection with quark-flavour physics?
- Cosmology: $\longrightarrow$ baryon asymmetry suggests new CP violation!
  - Could be associated with very high energy scales:
    * attractive mechanism: "leptogenesis", involving new CP-violating sources in the decays of heavy Majorana neutrinos.
  - But could also be accessible in the laboratory ...

Challenging the Standard Model through Flavour Studies

Before searching for NP, we have to understand the SM picture!

- Key problem:

  ◇ *impact of strong interactions* $\longrightarrow$ "hadronic" uncertainties

  – Famous example: Re$(\varepsilon'/\varepsilon)_K$, measuring "direct" CPV in K decays.

- Prospects for the "good old" K-meson system [CPV in '64: $\varepsilon_K \sim 10^{-3}$]:

  – Clean tests of the SM are offered by $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$, as their hadronic pieces can be fixed through $K \to \pi\ell\bar{\nu}$ decays!

  – These "rare" decays are *absent* at the tree level of the SM, i.e. originate there exclusively from loops, with BRs$= \mathcal{O}(10^{-10}) \to$ challenging[1]

- The B-meson system is a *particularly promising* probe: $\longrightarrow$ our focus

  – Offers various strategies: simply speaking, there are *many* B decays!

  – Search for clean SM relations that could be spoiled by NP ...

[1] Plans to measure $K^+ \to \pi^+\nu\bar{\nu}$ at the SPS (CERN) and $K_L \to \pi^0\nu\bar{\nu}$ at E391 (KEK/J-PARC).

Where to Study B-Meson Decays?

- B factories: asymmetric e^+e^- colliders @ $\Upsilon(4S) \to B_d^0 \bar{B}_d^0,\ B_u^+ B_u^-$
  - PEP-II with the *Babar* experiment (SLAC);
  - KEK-B with the *Belle* experiment (KEK):

$$\to \begin{cases} \text{could well establish CP violation in the } B \text{ system;} \\ \text{many interesting results with } \sum \mathcal{O}(10^9)\ B\bar{B} \text{ pairs ...} \end{cases}$$

  - Discussion of a super-B factory, with increase of luminosity by $\mathcal{O}(10^2)$.

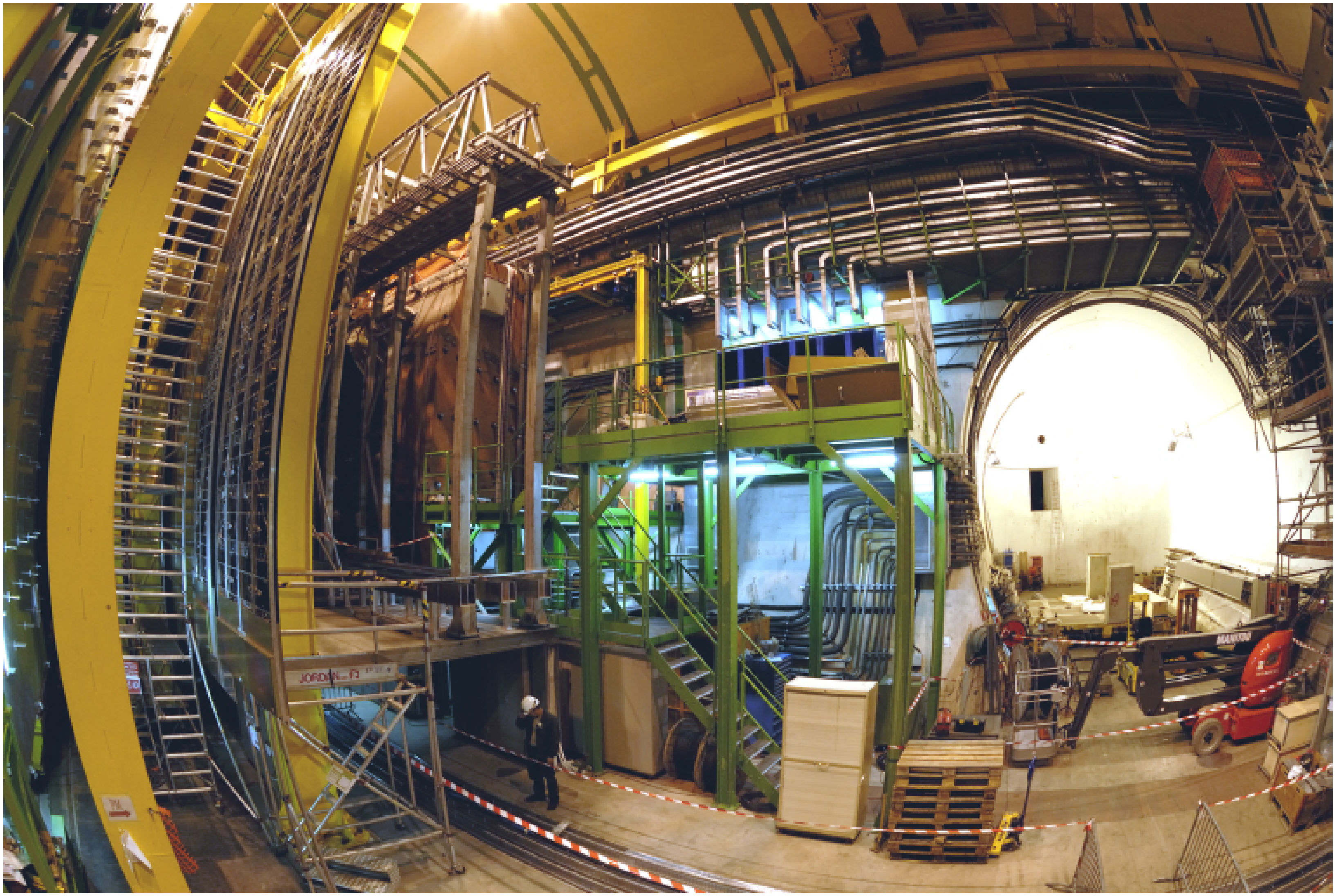
- Hadron colliders: $\to$ produce also B_s mesons,[2] as well as B_c, Λ_b, ...
  - Tevatron: CDF and D0 have reported first $B_{(s)}$-decay results ...
  - ... to be continued at the LHC $\gtrsim 2007$:

ATLAS & CMS (can also address some B physics)

$\oplus$ *dedicated* B-decay experiment: LHCb

[2] Recently, data at $\Upsilon(5S)$ were taken by Belle, allowing also access to B_s decays [hep-ex/0610003].

- A recent picture of the LHCb experiment @ CERN:



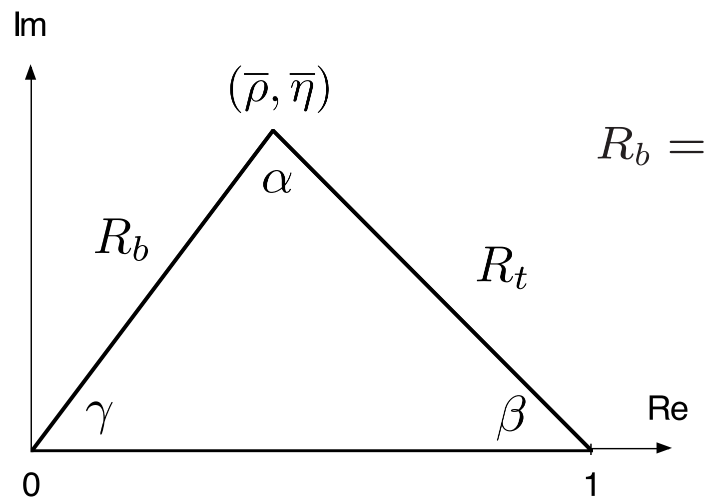
Central Target: Unitarity Triangle (UT)

- 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: $\hat{V}^\dagger_{\text{CKM}} \cdot \hat{V}_{\text{CKM}} = \hat{1} = \hat{V}_{\text{CKM}} \cdot \hat{V}^\dagger_{\text{CKM}}$ $\Rightarrow$



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

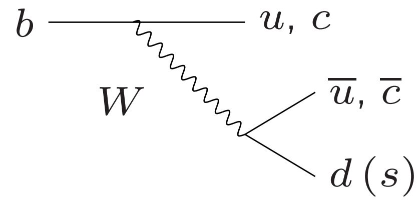
$$R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

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

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

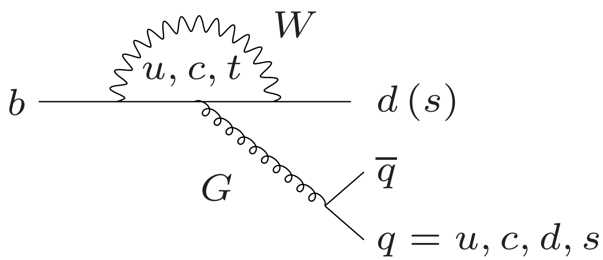
Key Processes for CP Violation: Non-Leptonic B Decays

- Tree diagrams:

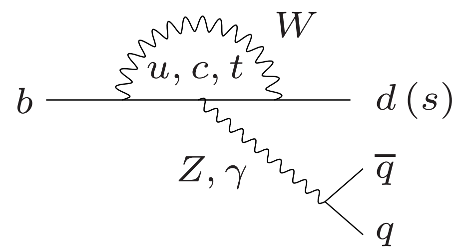


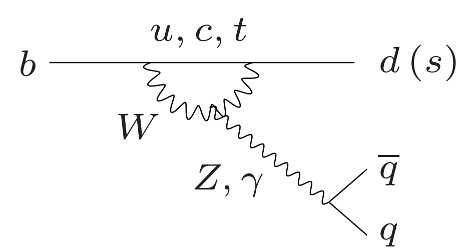
- Penguin diagrams:

  ◇ QCD penguins:



  ◇ Electroweak (EW) penguins:





- The calculation of the decay amplitudes is theoretically very challenging:

$$A(B \to f) \sim \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle f | Q_k(\mu) | B \rangle}_{\text{“unknown”}}$$

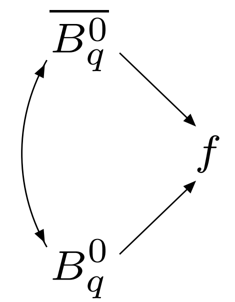
[Details and recent progress $\longrightarrow$ talk by Martin Beneke]

... but calculation of $\langle f|Q_k(\mu)|B\rangle$ can be circumvented:

- 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:

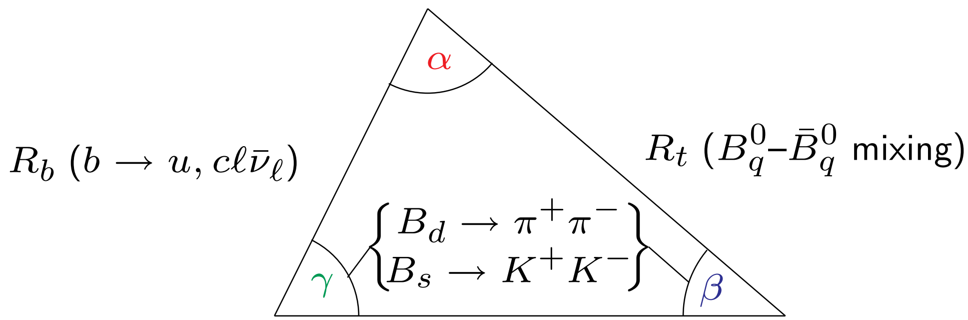
$$\Rightarrow \textit{hadronic matrix elements cancel!}$$

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

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)

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

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

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

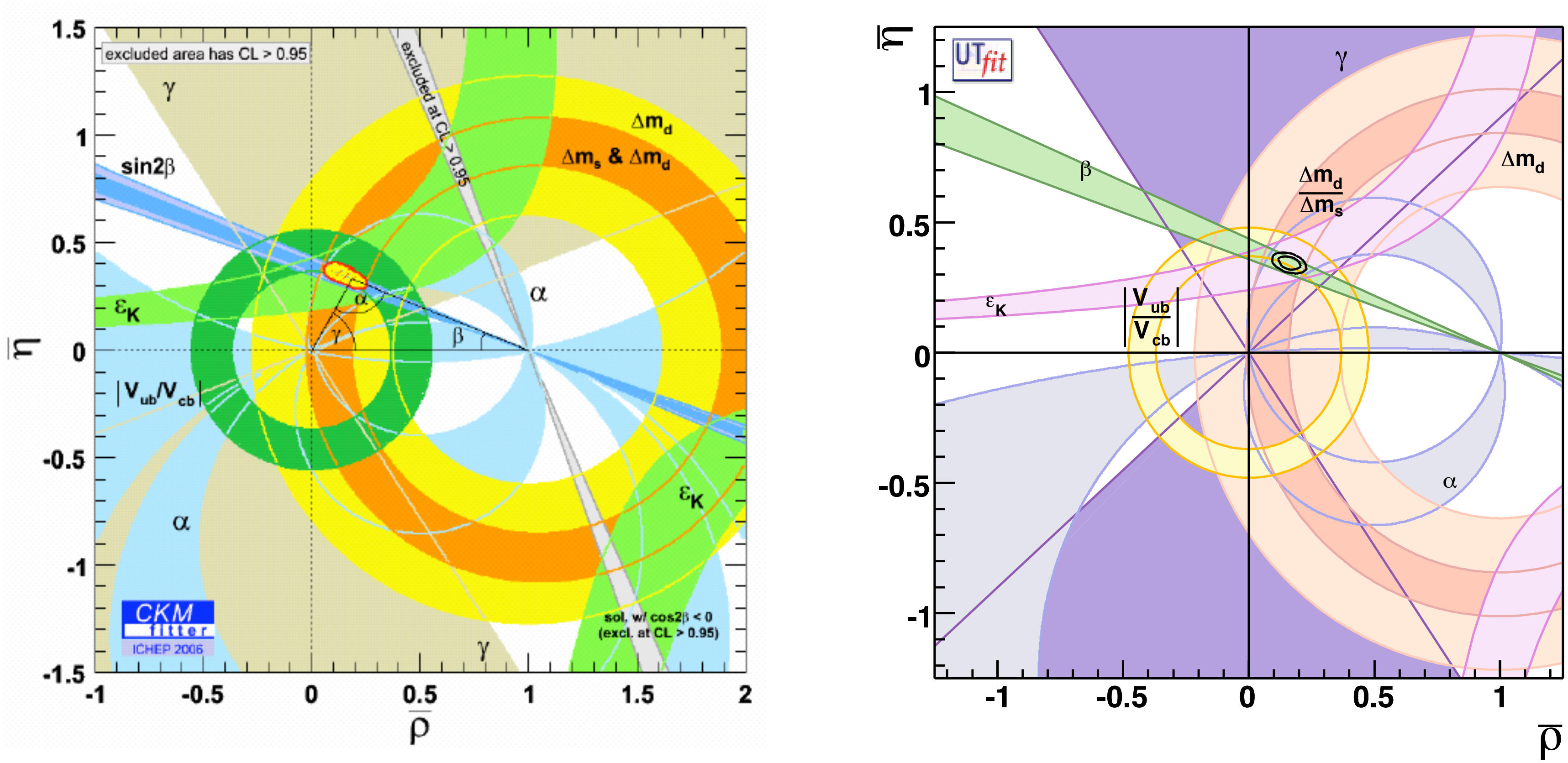
$$\left.\begin{matrix} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{matrix}\right\} \text{only trees}$$

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

New Physics $\Rightarrow$ Discrepancies

Status of the Unitarity Triangle

- Two competing groups: $\rightarrow$ 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" ...

A Brief Look

at the Current

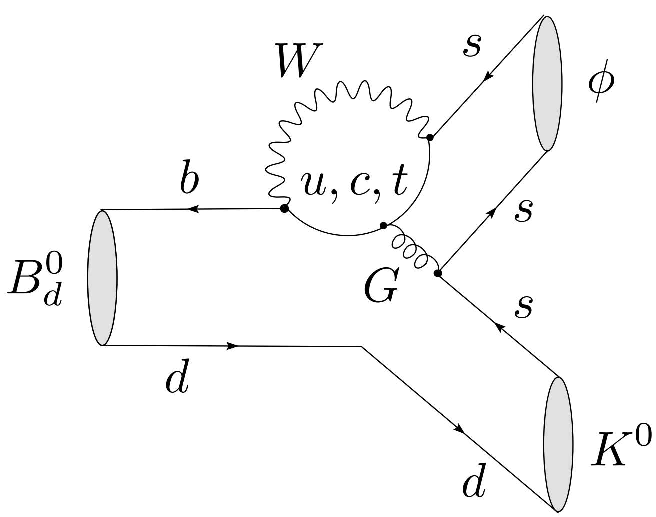
B-Factory Data:

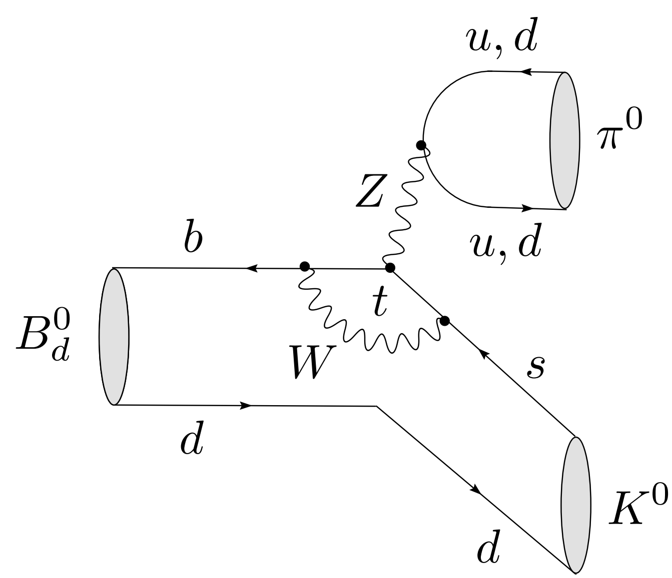
Two popular avenues for New Physics to manifest itself ...

1. 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.





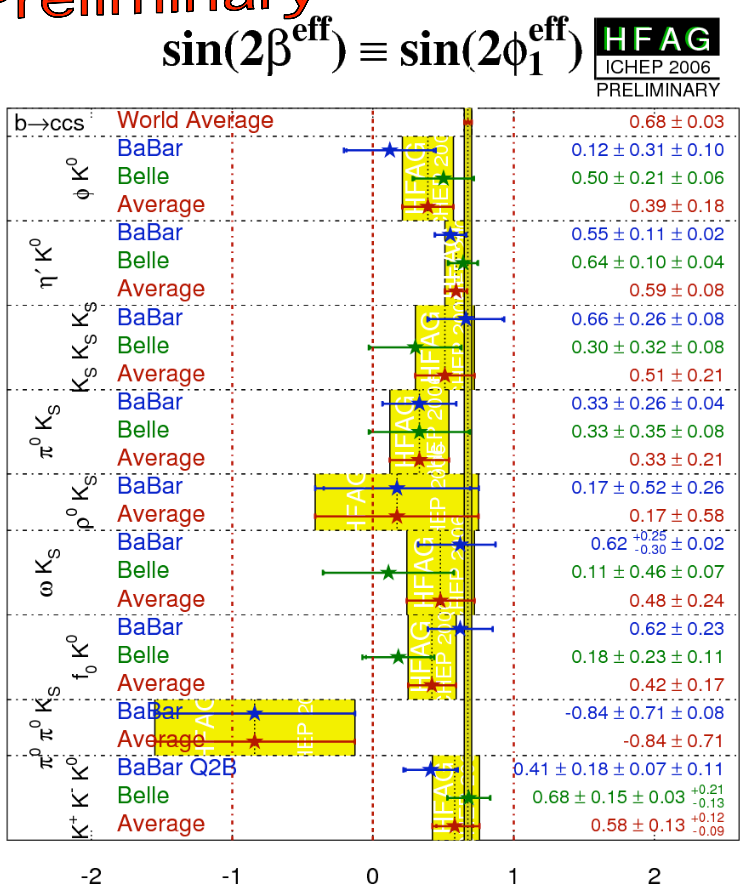
$\longrightarrow$ hot topics ...

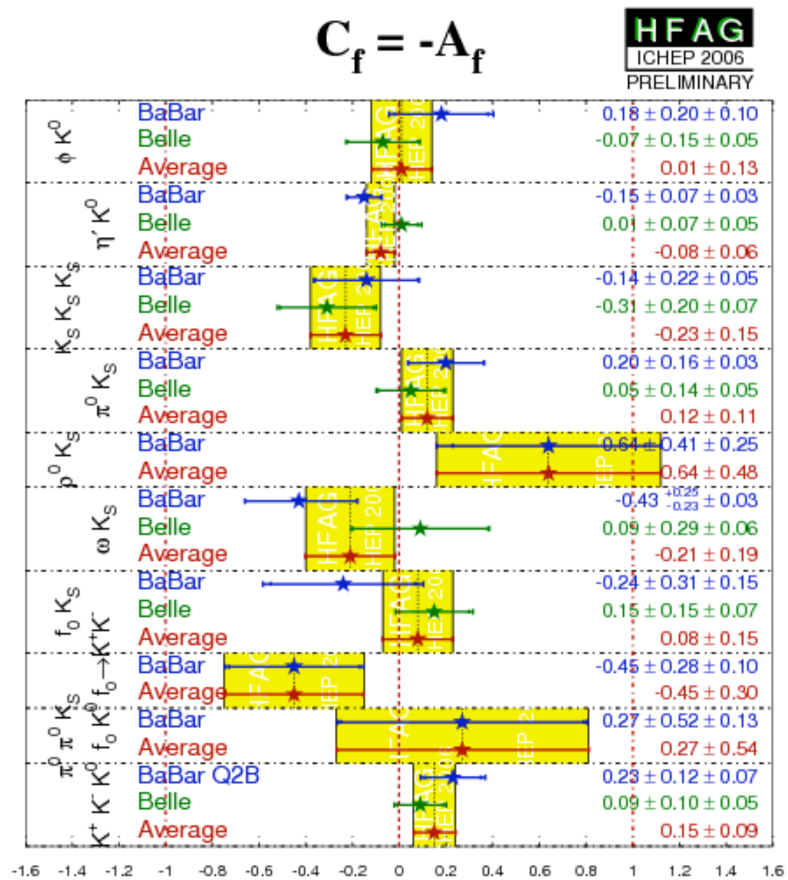
CP Violation in $b \longrightarrow s$ Penguin Modes

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

$$
(\sin 2\beta)_{\phi K_S} = (\sin 2\beta)_{\psi K_S} + \mathcal{O}(\lambda^2), \quad \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \phi K_S) = 0 + \mathcal{O}(\lambda^2)
$$

Preliminary





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

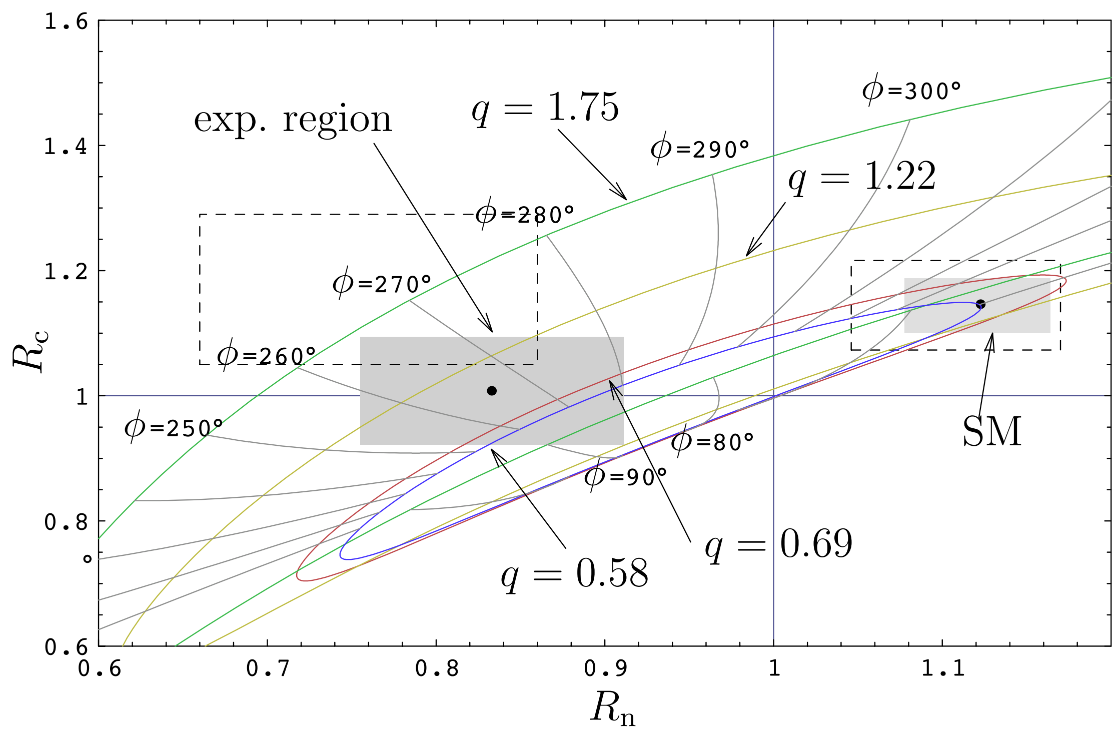
The $B \to \pi K$ Puzzle

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

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

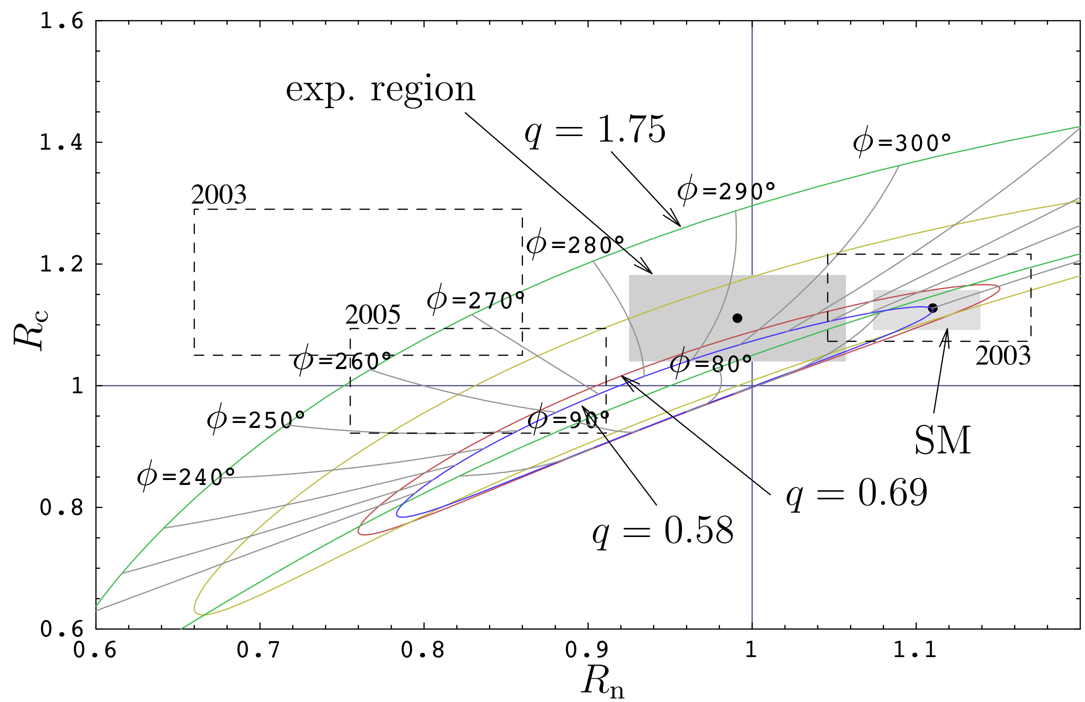
$$R_{\rm n} \equiv \frac{1}{2}\left[\frac{\text{BR}(B_d^0\to\pi^-K^+)+\text{BR}(\bar{B}_d^0\to\pi^+K^-)}{\text{BR}(B_d^0\to\pi^0K^0)+\text{BR}(\bar{B}_d^0\to\pi^0\bar{K}^0)}\right]$$

$\longrightarrow$ 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 ...

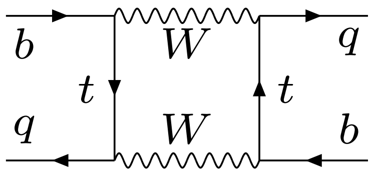
- Furthermore puzzling CP asymmetries: $B_d^0 \to \pi^0 K_S$, $B^{\pm} \to \pi^0 K^{\pm}$.

$\oplus$ correlations with rare B and K decays

NP could be present, but still cannot be resolved

$\to$ stay tuned ...

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



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

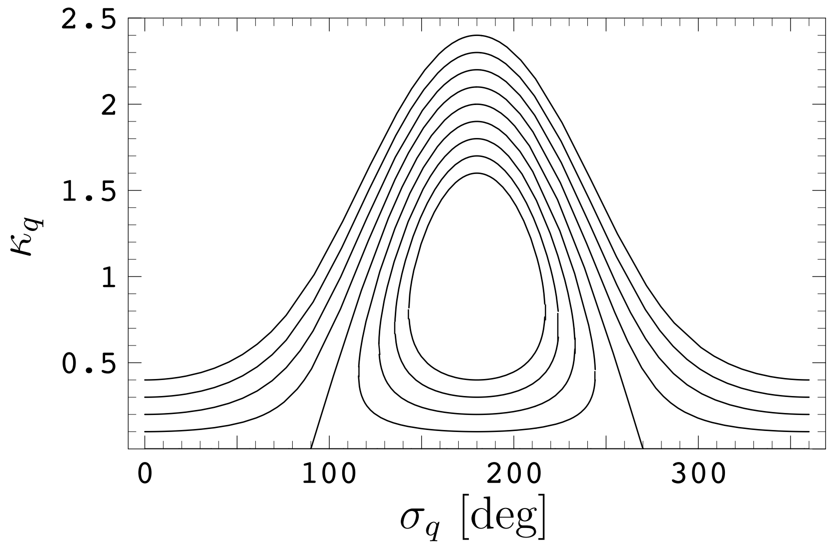
$$\boxed{M_{12}^q = M_{12}^{q,\mathrm{SM}}\left(1+\kappa_q e^{i\sigma_q}\right)} \Rightarrow$$

  - Mass difference: $\Delta M_q = \Delta M_q^{\mathrm{SM}}\left|1+\kappa_q e^{i\sigma_q}\right|$
  - Mixing phase: $\phi_q = \phi_q^{\mathrm{SM}} + \phi_q^{\mathrm{NP}} = \phi_q^{\mathrm{SM}} + \arg(1+\kappa_q e^{i\sigma_q})$

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

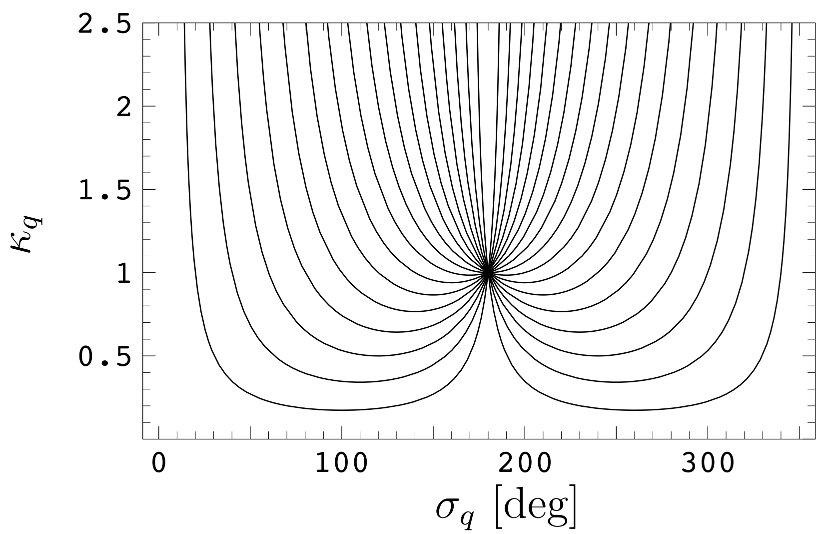
Constraints in the NP Space of B_q^0–$\bar{B}_q^0$ Mixing

- 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 $\phi_q^{\rm NP}$:

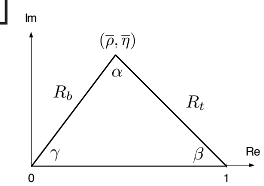


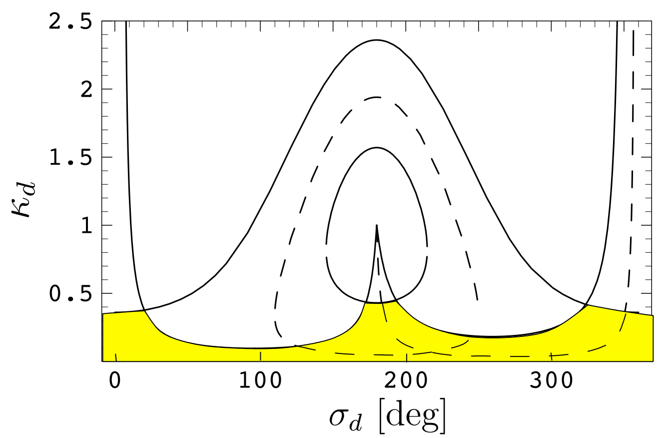
$\left[10^\circ \leq |\phi_q^{\rm NP}| \leq 170^\circ\right]$

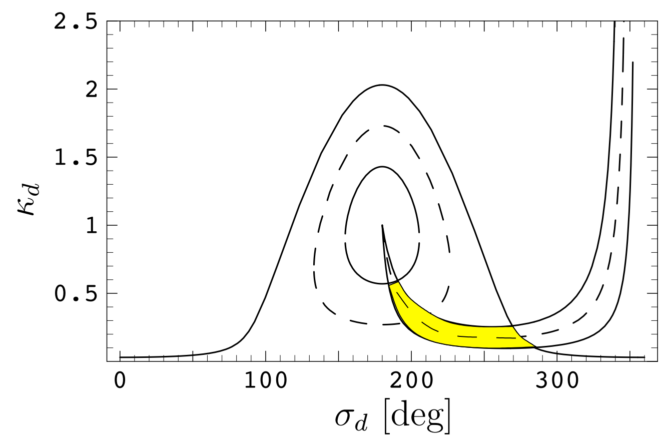
Implications of the B-Factory Data for the B_d System

- Determination of $\rho_d = \Delta M_d / \Delta M_d^{\rm SM}$: $\rightarrow$ $\Delta M_d^{\rm SM}$ required, involving ...
  - CKM parameter $|V_{td}^* V_{tb}|$: $\rightarrow$ governed by γ, if unitarity is used.
  - Hadronic parameter $f_{B_d}^2 \hat{B}_{B_d}$: lattice $\rightarrow$ two benchmark 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.

- Determination of the NP phase: $\rightarrow$ $\phi_d^{\rm NP} = (2\beta)_{\psi K_S} - (2\beta)_{\rm true}^{\rm tree}$
  - $\phi_d^{\rm NP}$ is governed by $R_b \propto |V_{ub}/V_{cb}|$;
  - Unfortunately, discrepancy between $|V_{ub}|_{\rm excl}$ and $|V_{ub}|_{\rm incl}$ ...







JLQCD and $\phi_d^{\rm NP}|_{\rm excl} = -(2.5 \pm 8.0)^\circ$ (HP+JL)QCD and $\phi_d^{\rm NP}|_{\rm incl} = -(10.1 \pm 4.6)^\circ$

Key Targets of the

B Physics Programme

at the LHC

$\longrightarrow$ high statistics and *complementarity* to B factories:

fully exploit the B_s-meson system!

General Features of the B_s System

- Rapid B_s^0–$\bar{B}_s^0$ oscillations: $\Delta M_s \stackrel{\rm SM}{=} \mathcal{O}(20\,{\rm ps}^{-1}) \gg \Delta M_d \stackrel{\rm exp}{=} 0.5\,{\rm ps}^{-1}$

  $\Rightarrow$ challenging to resolve them experimentally!

- The width difference $\Delta\Gamma_s$ is expected to be of $\mathcal{O}(10\%)$: [→ talk by A. Lenz]
  - Experimental status: $B_s \to J/\psi\phi$ @ Tevatron $\Rightarrow$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \left\{ \begin{array}{ll} 0.24^{+0.28+0.03}_{-0.38-0.04} & \text{[D0 ('05)} \\ 0.65^{+0.25}_{-0.33} \pm 0.01 & \text{[CDF ('05)]} \end{array} \right\} \stackrel{\text{LHCb}}{\longrightarrow} \boxed{\text{precision} \sim 0.01}$$

  - May provide interesting CPV studies through "untagged" rates:

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

    * The rapidly oscillating $\Delta M_s t$ terms cancel!
    * Various "untagged" strategies were proposed.

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

- The CP-violating phase of B_s^0–$\bar{B}_s^0$ mixing is *tiny* in the SM:

$$\boxed{\phi_s \stackrel{\rm SM}{=} -2\lambda^2\eta \approx -2^\circ} \quad \Rightarrow \quad \text{interesting for NP searches (see below)!}$$

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: [→ talk by S. Menzemer]
    - D0: ⇒ two-sided bound $17\,\mathrm{ps}^{-1} < \Delta M_s < 21\,\mathrm{ps}^{-1}$ (90% C.L.)

      ⇒ 2.5 σ signal at $\Delta M_s = 19\,\mathrm{ps}^{-1}$
    - CDF: $\boxed{\Delta M_s = [17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst})]\ \mathrm{ps}^{-1}}$ $\gtrsim 5\sigma$

- 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; G. Isidori and P. Paradisi, hep-ph/0605012; S. Khalil, hep-ph/0605021; Y. Grossman, Y. Nir and G. Raz, hep-ph/0605028; S. Baek, J.H. Jeon and C.S. Kim, hep-ph/0607113; ...

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 ...

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

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:

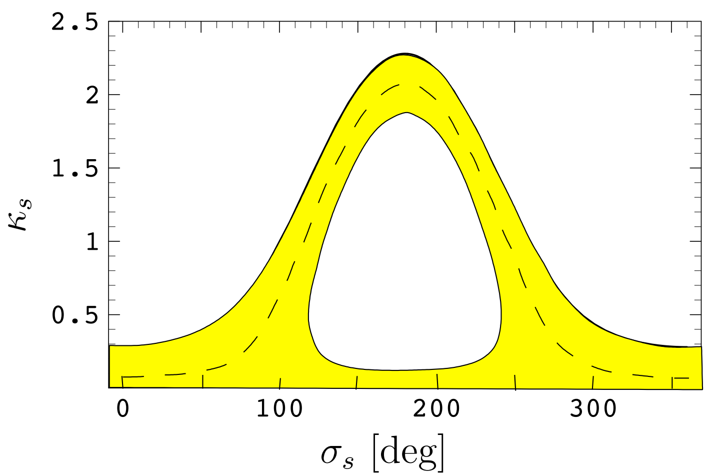
$$\Delta M_s^{\rm SM}\Big|_{\rm JLQCD} = (16.1 \pm 2.8)\,{\rm ps}^{-1}$$

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

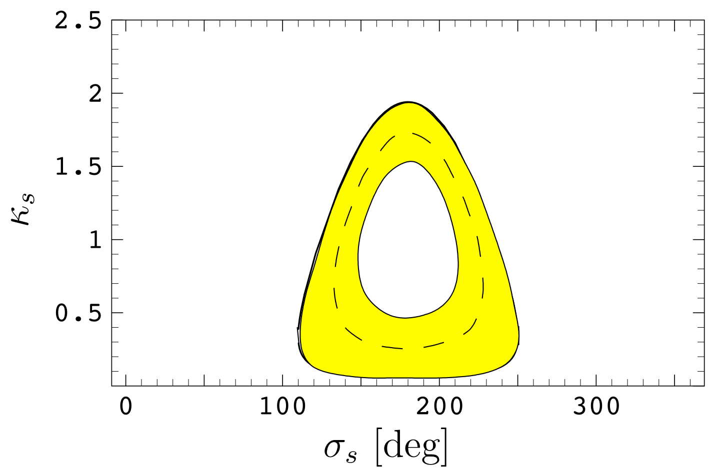
$$\Delta M_s^{\rm SM}\Big|_{\rm (HP+JL)QCD} = (23.4 \pm 3.8)\,{\rm ps}^{-1}$$

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

- Allowed regions in the σ_s–κ_s plane:



JLQCD



(HP+JL)QCD

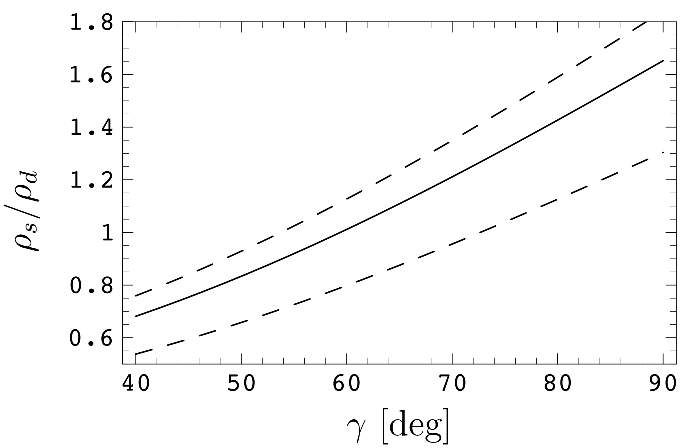
Constraints on NP through ΔM_s and ΔM_d

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

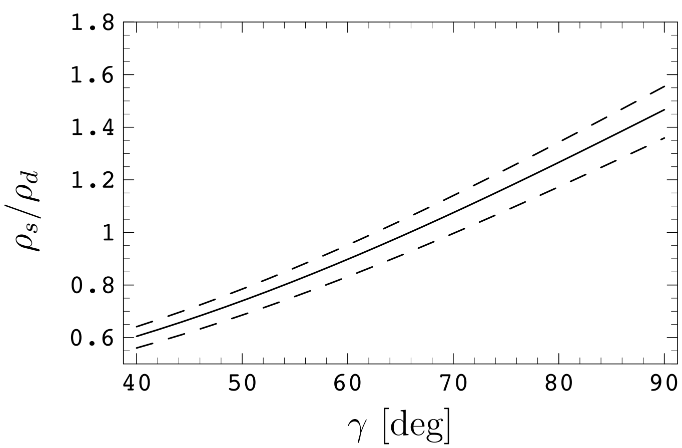
$$\xi \equiv \frac{f_{B_s}\hat{B}_{B_s}^{1/2}}{f_{B_d}\hat{B}_{B_d}^{1/2}} \rightarrow \text{reduced th. uncertainty as compared to } f_{B_q}\hat{B}_{B_q}^{1/2}.$$

- Usually determination of UT side R_t. Different avenue (CKM unitarity):[3]

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



JLQCD



(HP+JL)QCD

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

[3] Scenario for 2010: $\gamma = (65 \pm 20)^\circ \xrightarrow{\text{LHCb}} (70 \pm 5)^\circ$ with (HP+JL)QCD lattice values.

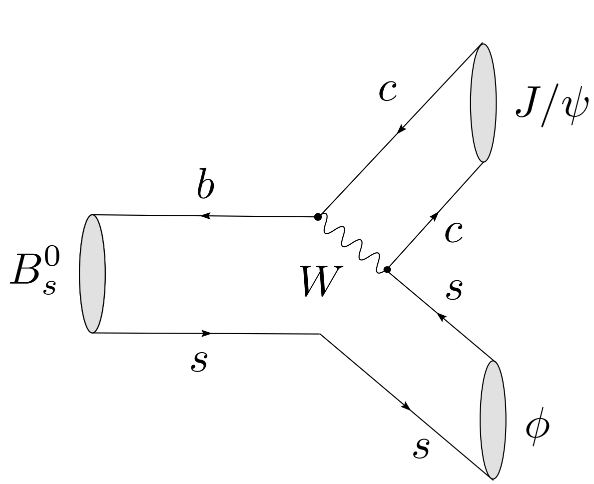
Golden Process to Search for NP in B_s^0–$\bar{B}_s^0$ Mixing:

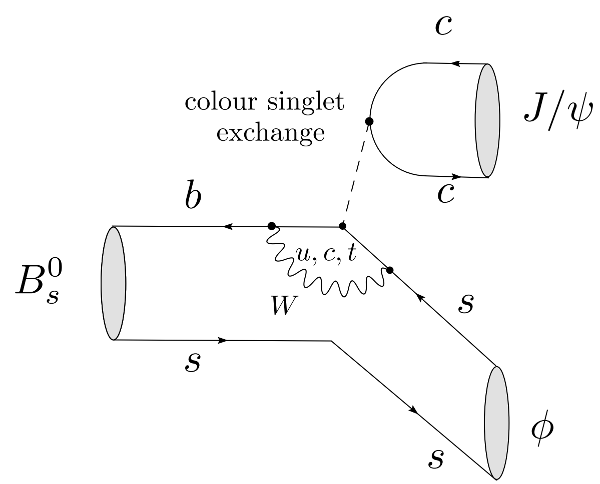
$$\boxed{B_s^0 \to J/\psi\phi}$$

$\longrightarrow$ 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 ...





- 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!

- Linear polarization amplitudes: $A_0(t), \quad A_\parallel(t), \quad A_\perp(t)$

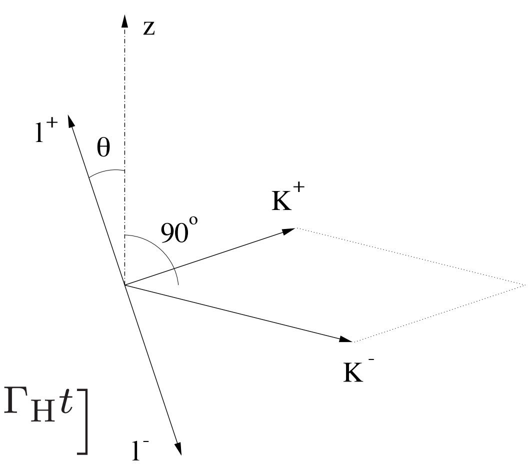
  - $A_0(t)$ and $A_\parallel(t)$ correspond to CP-even final-state configurations;
  - $A_\perp(t)$ describes a CP-odd final-state configuration.

Simple: 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 stringently constrained, but very accessible @ LHC ...

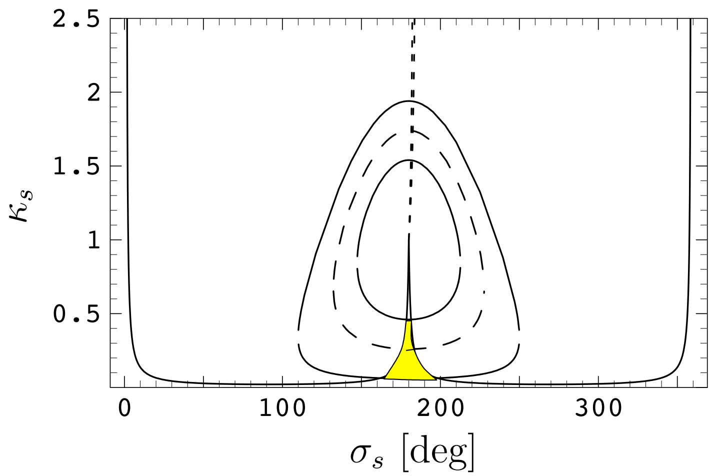
- Experimental reach at the LHC: [O. Schneider, M. Smizanska, T. Speer]
  - LHCb: $\sigma_{\rm stat}(\sin\phi_s) \approx 0.031$ (1 year, i.e. 2 fb^{-1}) [0.013 (5 years)];
  - ATLAS & CMS: expect uncertainties of $\mathcal{O}(0.1)$ (1 year, i.e. 10 fb^{-1}).

Impact of CP Violation Measurements on σ_s, κ_s

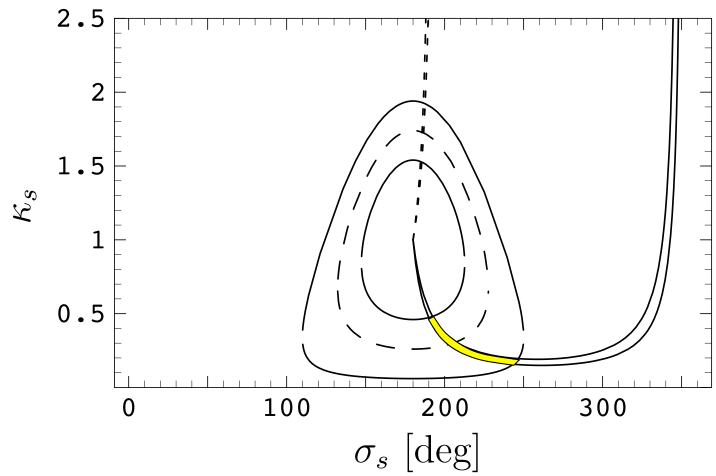
- Illustration through two scenarios ($\sim$ 2010):

  (i) $(\sin\phi_s)_{\rm exp} = -0.04 \pm 0.02$: corresponds to the SM;

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



SM scenario (i)



NP scenario (ii)

- Remarks:

  – It is very challenging to establish NP without new CP-violating effects.

  – But the data still leave a lot of space for such effects in specific NP scenarios (SUSY, Z', ...), which could be detected at the LHC!

[Details: P. Ball & R.F., hep-ph/0604249 $\oplus$ references therein]

Further Benchmark Decays

for the

LHCb Experiment

$\longrightarrow$ very rich physics programme ...

Two Major Lines of Research

1. Precision measurements of γ:

   - Tree strategies, with expected sensitivities after 1 year of taking data:
     - $B_s^0 \to D_s^{\mp} K^{\pm}$: $\sigma_\gamma \sim 14^\circ$
     - $B_d^0 \to D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the
     - $B^{\pm} \to D^0 K^{\pm}$: $\sigma_\gamma \sim 5^\circ$

     current B-factory data: $$\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (62^{+35}_{-25})^\circ & \text{(CKMfitter)} \\ (65 \pm 20)^\circ & \text{(UTfit)} \end{cases}$$

   - Decays with penguin contributions:
     - $B_s^0 \to K^+ K^-$ and $B_d^0 \to \pi^+ \pi^-$: $\sigma_\gamma \sim 5^\circ$
     - $B_s^0 \to D_s^+ D_s^-$ and $B_d^0 \to D_d^+ D_d^-$

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

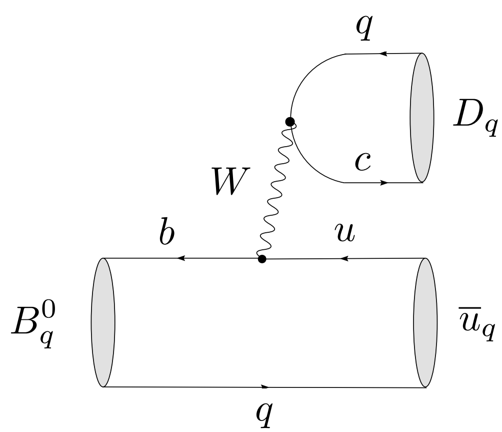
   - $B_s^0 \to \mu^+ \mu^-$, $B_d^0 \to \mu^+ \mu^-$
   - $B_d^0 \to K^{*0} \mu^+ \mu^-$, $B_s^0 \to \phi \mu^+ \mu^-$; ...

$\to$ let's have a closer look at some decays ...

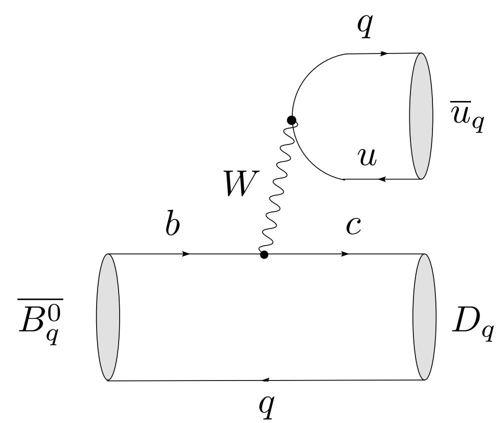
[For a recent experimental overview, see A. Schopper, hep-ex/0605113]

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

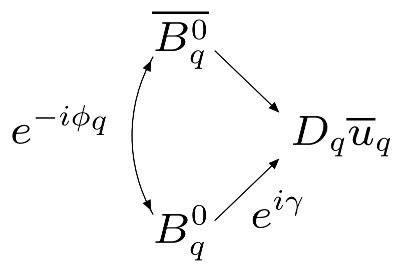
- General case:



$\propto e^{i\gamma}$



no weak phase



$\boxed{\phi_q + \gamma}$

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

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

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

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

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

$$\Rightarrow \boxed{\text{theoretically } clean \text{ determination of } \phi_q + \gamma} \quad \xrightarrow{\phi_q \text{ known}} \quad \boxed{\gamma}$$

[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 $\rightarrow$ *impossilbe* ...

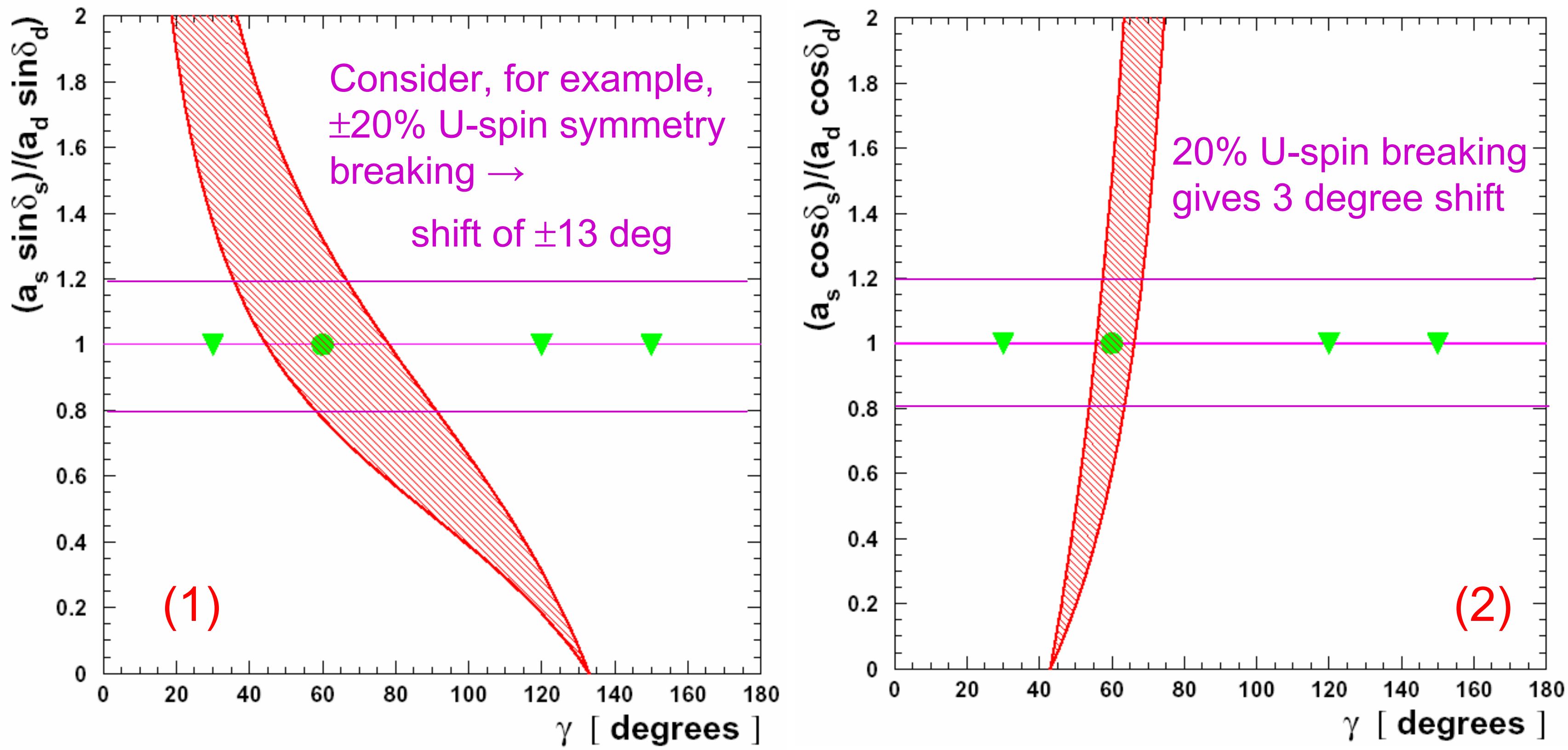
- Combined analysis of $B_s^0 \to D_s^{(*)+} K^-$ and $B_d^0 \to D^{(*)+} \pi^-$: [R.F. (2003)]

$\boxed{s \leftrightarrow d}$ $\Rightarrow$ U-spin symmetry provides an interesting playground:[4]

  - 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: $\boxed{\rightarrow}$

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

Full U-Spin Symmetry: 5 years

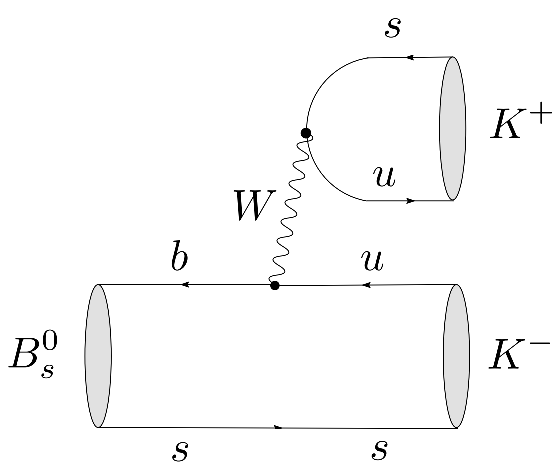


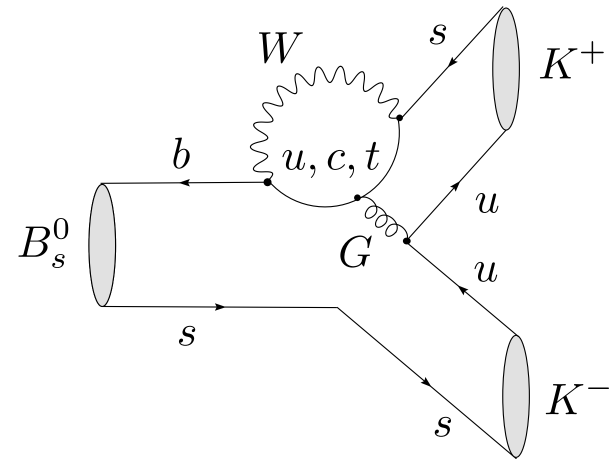
Both expressions now giving very interesting precision on γ .
Right hand plot has precision of 5 degrees, and small systematic.
Ambiguous solutions now excluded.

[G. Wilkinson @ CKM 2005]

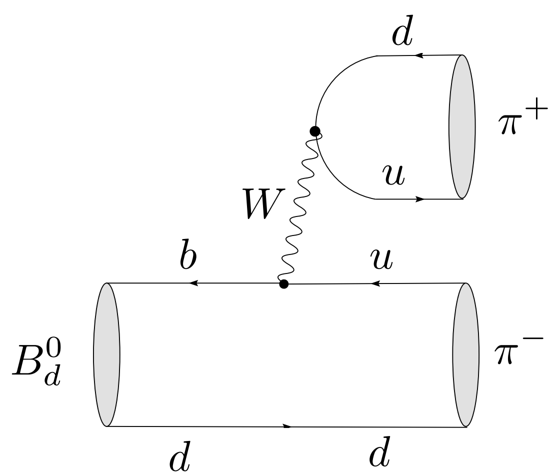
The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

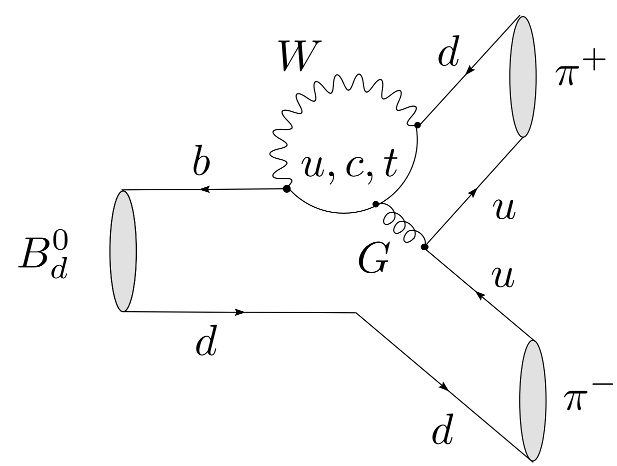
- $B_s^0 \to K^+K^-$:





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





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

- Structure of the decay amplitudes in the Standard Model:

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

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

$$d\, e^{i\theta} = \frac{\text{"penguin"}}{\text{"tree"}}\bigg|_{B_d \to \pi^+\pi^-}, \quad d'\, e^{i\theta'} = \frac{\text{"penguin"}}{\text{"tree"}}\bigg|_{B_s \to K^+K^-}$$

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

- General form of the CP asymmetries (time-dependent rate asymmetries):

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

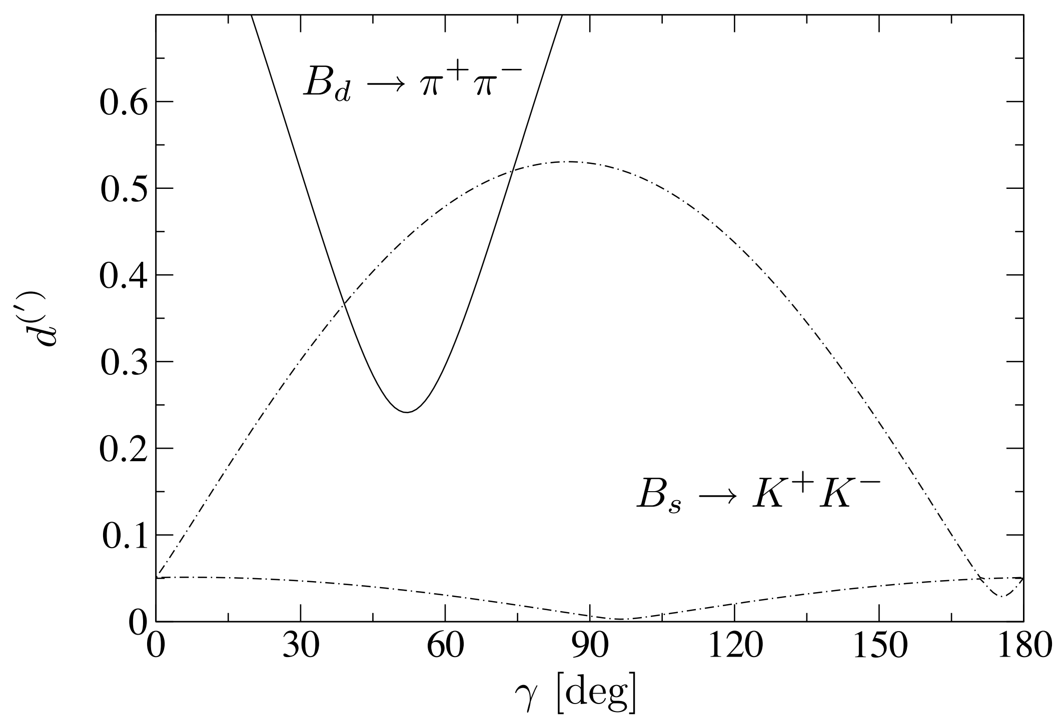
$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) = G_1'(d', \theta', \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = G_2'(d', \theta', \gamma, \phi_s)$$

- $\phi_d = 2\beta$ (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:
    * $\phi_d = 43.4°$, $\phi_s = -2°$, $\gamma = 74°$, $d = d' = 0.52$, $\theta = \theta' = 146°$
  - CP asymmetries:
    * $B_d \to \pi^+\pi^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = -0.37$, $\mathcal{A}_{\rm CP}^{\rm mix} = +0.50$
    * $B_s \to K^+K^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = +0.12$, $\mathcal{A}_{\rm CP}^{\rm mix} = -0.19$

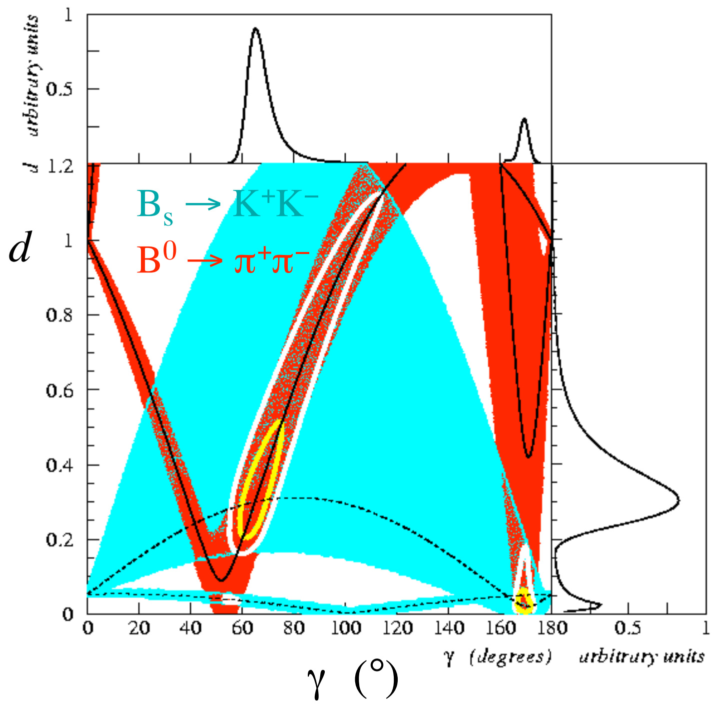


- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

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

  - $d = d'$: $\Rightarrow$ determination of γ, d, θ, θ' [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:



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

[CERN-LHCb/2003-123 & 124; talk by A. Sarti at Flavour LHC Workshop, October '06, CERN]

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

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

– 236 ± 32 events were seen, which correspond to the branching ratio

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

$$\text{update @ BEAUTY '06:} \to (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}.$$

- 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)].

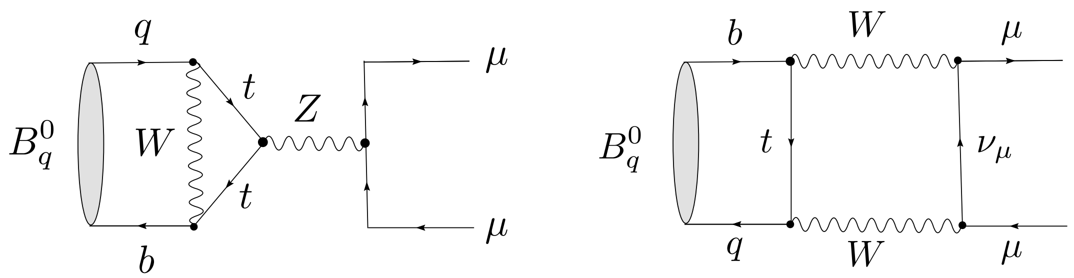
– Dynamical assumptions (small annihilation) and $B_d \to \pi^\mp K^\pm$ data:

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

$\Rightarrow$ good 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: $\to$ 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!**

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

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

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

- Most recent experimental upper bounds from the Tevatron:

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

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

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

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

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

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

  – 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**

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

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

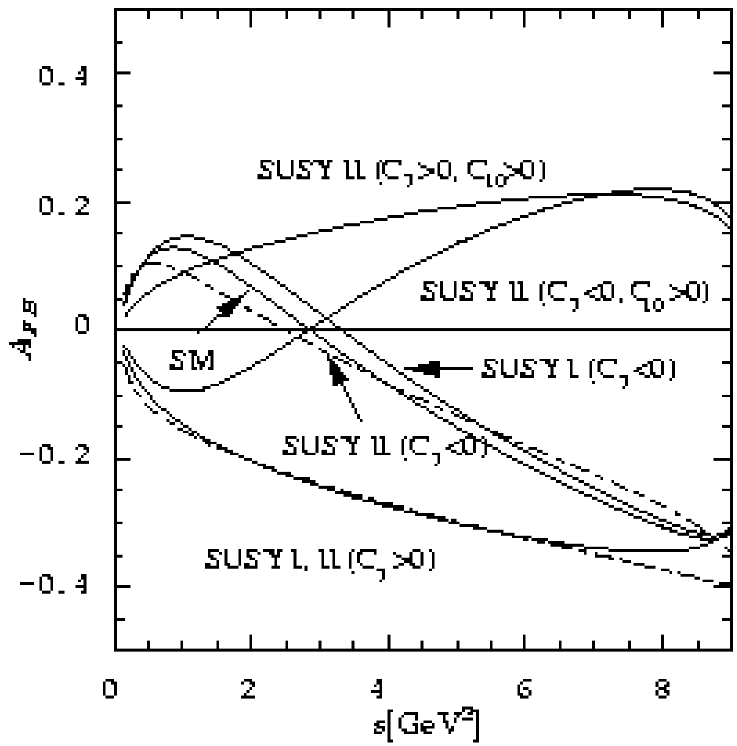
- Particularly interesting:

$$\boxed{A_{\rm FB}(\hat{s}_0)|_{\rm SM} = 0}$$

[Burdman ('98); Ali *et al.* ('00); ...]

  - The value of $\hat{s}_0$ 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 $\Delta\hat{s}_0 = 0.06$ 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: $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ ...
- Current B-factory data: inclusive $b \to s\ell^+\ell^-$ BRs and the integrated asymmetries $\int A_{\rm FB}$ in accordance with SM, but still large uncertainties.

Conclusions and Outlook (I)

- Tremendous progress in B physics during the recent years:

  Fruitful interplay between theory and experiment

  – e^+e^- B factories: have already produced $\sum \mathcal{O}(10^9)$ $B\bar{B}$ pairs;

  – Tevatron: has recently succeeded in observing B_s^0–$\bar{B}_s^0$ mixing.

- Status in October 2006:

  – The data agree globally with the Kobayashi–Maskawa picture!

  – But we have also hints for discrepancies: $\to$ first signals of NP??

- New perspectives for B-decay studies @ LHC $\gtrsim$ autumn 2007:

  – Large statistics and full exploitation of the B_s physics potential, thereby complementing the physics programme of the e^+e^- B factories.

  – Precision determinations of γ: $\to$ key ingredients for NP searches!

  – Powerful studies of rare decays: $B_{s,d} \to \mu^+\mu^-$, ...

$\to$ much more stringent CKM consistency tests!

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:[5]

$B \quad \oplus \quad K$, 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 ...

[5] Topic of CERN Workshop: `http://flavlhc.web.cern.ch/flavlhc/`