Theoretical Aspects of CP Violation in the B System

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B Physics at the Tevatron, Fermilab, 23–25 September, 1999

- Setting the Stage
- A Brief Overview of the "Standard" Methods
- A Closer Look at New Strategies:
  - γ from $B_{s(d)} \to J/\psi\, K_{\mathrm{S}}$ or $B_{d(s)} \to D^+_{d(s)}\, D^-_{d(s)}$
  - β and γ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$
  - CKM phases and hadronic parameters from studies of angular distributions of certain $B_{d,s}$ decays:
    - $B_d \to J/\psi\, \rho^0$, $B_s \to J/\psi\, \phi$
    - $B_d \to \rho^+\rho^-$, $B_{s,d} \to K^*\, \overline{K^*}$
- Conclusions and Outlook

[For a write-up, see R.F., hep-ph/9908340 & 9908341]

Preliminary Remarks

- CP violation is one of the central and fundamental phenomena in modern particle physics, and is at present one of the least experimentally constrained phenomena.

- In particular the B-meson system provides a very fertile testing ground for the Standard-Model description of CP violation!

- In the search for New Physics, it is crucial to have CP-violating B-decay processes available that can be analysed reliably within the framework of the Standard Model:

$\Rightarrow$ $\boxed{\text{Major Topic of this Talk!}}$

- BaBar (SLAC) and BELLE (KEK) have already seen the first events; CLEO-III (Cornell), HERA-B (DESY), and CDF-II (Fermilab) will start taking data in the near future:

$\Rightarrow$ $\boxed{\text{Beginning of the } B\text{-factory era!}}$

- It may well be that the "definite" answer in the search for new physics will be left for "second-generation" B-physics experiments at hadron machines, such as LHCb, BTeV ...

Standard Model Physics at the LHC

- Workshop held at CERN in 1999:

  http://home.cern.ch/~mlm/lhc99/lhcworkshop.html

- Working groups:
  - QCD
  - EWK
  - Top Physics
  - B physics: Production & Decay

- B-Decay Working Group: CP Violation and Rare Decays
  - Theory Conveners:
    - Patricia Ball
    - R.F.
  - Experimental Conveners:
    - Giuseppe Tartarelli (ATLAS)
    - Pratibha Vikas (CMS)
    - Guy Wilkinson (LHCb)
  - Home page:

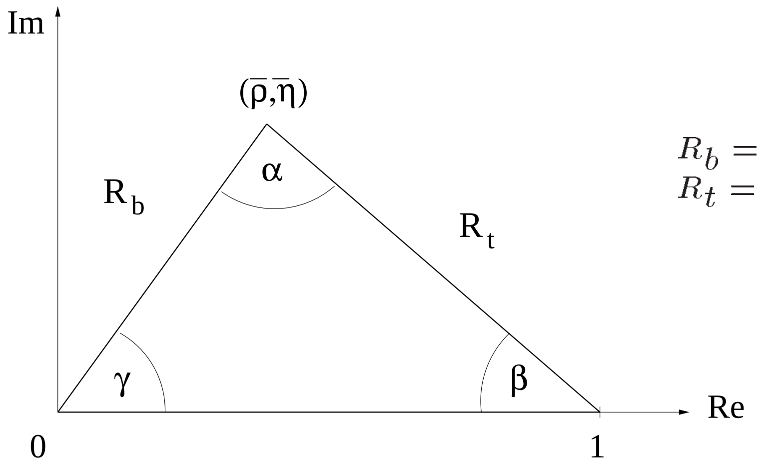
    http://home.cern.ch/~pball/bdecaypage.html

CP Violation Studies at the LHC

- The central goal is to find a coherent picture of the LHC B-physics performance, and to search for new strategies:
  - What can the LHC experiments ATLAS, CMS and LHCb add to the B-factory benchmark modes?
    * $B_d \to J/\psi K_S$ $\quad (B_s \to J/\psi K_S)$
    * $B_d \to \pi^+\pi^-$, $B \to \rho\pi$
    * $B \to \pi K$
  - "Beyond" the B-factories:
    * $B_d \to D^{*-}\pi^+$
    * $B_d \to DK^{*0}$
    * ...
  - Strong emphasis on B_s physics:
    * $B_s \to D_s K$
    * $B_s \to J/\psi\phi$ $\quad (B_d \to J/\psi\rho^0)$
    * $B_s \to K^+K^-$ & $B_d \to \pi^+\pi^-$
    * ...
  - Studies of systematic uncertainties and approaches to control them.
- Work is in progress!
- 2nd plenary meeting will take place at CERN on October 14th and 15th.
- "Preliminary" result: LHC offers an enormous potential for studies of the CKM sector!

Central Target: UT(s) of the CKM Matrix

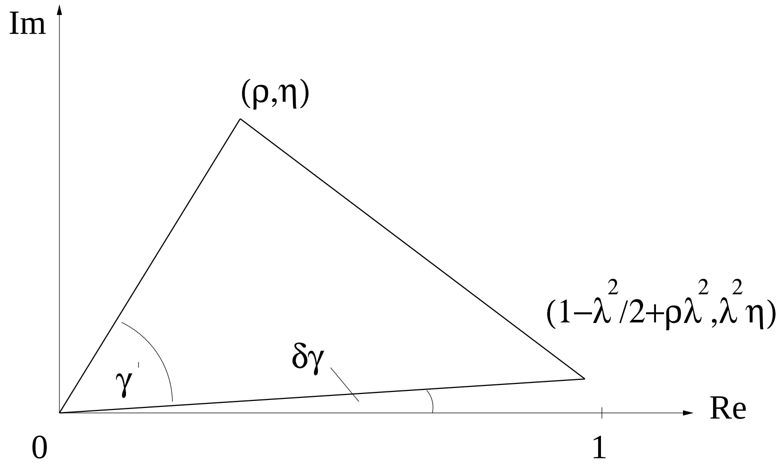
- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$: $\Rightarrow$ UT1



$R_b = 0.41 \pm 0.07$
$R_t = \mathcal{O}(1)$

$$\boxed{\bar\rho \equiv \left(1-\lambda^2/2\right)\rho, \quad \bar\eta \equiv \left(1-\lambda^2/2\right)\eta}$$

- $V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0$: $\Rightarrow$ UT2



- NLO terms: A.J. Buras et al., *Phys. Rev.* **D50** (1994) 3433

Non-leptonic B Decays

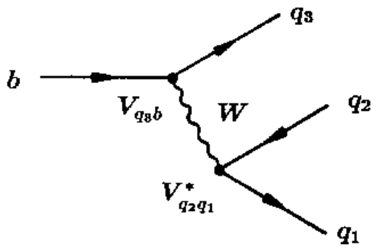
- Non-leptonic B decays are caused by

$$b \to q_1 \, \overline{q}_2 \, q_3 \quad (q_1 \in \{d, s\}; \quad q_2, q_3 \in \{u, d, c, s\})$$

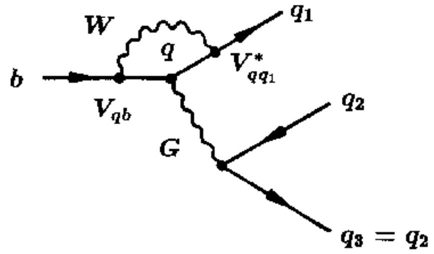
- They can be divided into three classes:
  - $q_2 = q_3 \in \{u, c\}$: tree & penguin diagrams contribute
  - $q_2 = q_3 \in \{d, s\}$: only penguin diagrams contribute
  - $q_2 \neq q_3 \in \{u, c\}$: only tree diagrams contribute

- Lowest order Feynman diagrams:

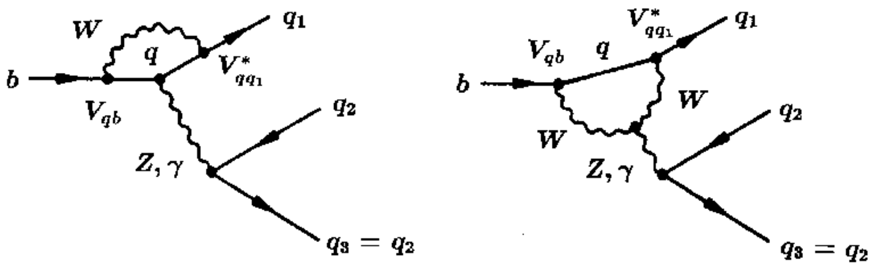
Tree Diagrams:



QCD Penguin Diagrams:



EW Penguin Diagrams:



A Brief Look at the "Standard" Methods to Extract CKM Phases

Selection of review papers:

- Y. Nir, hep-ph/9709301
- R.F., *Int. J. Mod. Phys.* **A12** (1997) 2459
- A.J. Buras and R.F., hep-ph/9704376, in *Heavy Flavours II*, eds. A.J. Buras and M. Lindner (World Scientific, Singapore, 1998)
- Y. Nir and H.R. Quinn, *Annu. Rev. Nucl. Part. Sci.* **42** (1992) 211
- . . .

CP Violation in Neutral B Decays

- A particularly simple and interesting situation arises for B decays into final CP eigenstates, satisfying the relation

$$(\mathcal{CP})|f\rangle = \pm\,|f\rangle.$$

- In this case, the corresponding time-dependent CP asymmetry can be expressed as follows ($\Delta\Gamma_q = 0$):

$$a_{\mathrm{CP}}(t) \equiv \frac{\Gamma(B^0_q(t)\to f) - \Gamma(\overline{B^0_q}(t)\to f)}{\Gamma(B^0_q(t)\to f) + \Gamma(\overline{B^0_q}(t)\to f)} =$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_q\to f)\cos(\Delta M_q t) + \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix-ind}}(B_q\to f)\sin(\Delta M_q t)\,.$$

- Here we have separated the direct CP-violating contributions from the mixing-induced CP-violating contributions, which are characterized by

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_q\to f) \equiv \frac{1-\left|\xi_f^{(q)}\right|^2}{1+\left|\xi_f^{(q)}\right|^2}$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix-ind}}(B_q\to f) \equiv \frac{2\,\mathrm{Im}\,\xi_f^{(q)}}{1+\left|\xi_f^{(q)}\right|^2}\,.$$

- In the B_s system, the width difference $\Delta\Gamma_s$ may be sizeable:

$\Rightarrow$ $a_{\mathrm{CP}}(t)$ has to be modified for $t \gtrsim 2/\Delta\Gamma_s$.

- Essentially all the information needed to evaluate these CP asymmetries is included in the following observable:

$$\xi_f^{(q)} = \mp\, e^{-i\phi_q} \frac{A(\overline{B_q^0} \to f)}{A(B_q^0 \to f)} = \mp\, e^{-i\phi_q} \frac{\sum\limits_{j=u,c} V_{jr}^* V_{jb}\, \mathcal{M}^{jr}}{\sum\limits_{j=u,c} V_{jr} V_{jb}^*\, \mathcal{M}^{jr}},$$

where the $\mathcal{M}^{jr}$ denote hadronic matrix elements of four-quark operators, the label r distinguishes between $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ transitions, and

$$\boxed{\phi_q = \begin{cases} +2\beta & \text{for } q = d \\ -2\delta\gamma & \text{for } q = s \end{cases}}$$

is the weak B_q^0–$\overline{B_q^0}$ mixing phase.

- In general, the observable $\xi_f^{(q)}$ suffers from hadronic uncertainties, which are due to the $\mathcal{M}^{jr}$!

- However, if the decay $B_q \to f$ is dominated by a single CKM amplitude, the corresponding matrix elements cancel, and $\xi_f^{(q)}$ takes the simple form

$$\boxed{\xi_f^{(q)} = \mp \exp\left[-i\left(\phi_q - \phi_{\mathrm{D}}^{(f)}\right)\right],}$$

where $\phi_{\mathrm{D}}^{(f)}$ is a CP-violating weak decay phase, which is given as follows ($r \in \{d, s\}$):

$$\boxed{\phi_{\mathrm{D}}^{(f)} = \begin{cases} -2\gamma & \text{for dominant } \bar{b} \to \bar{u}\, u\, \bar{r} \text{ CKM amplitudes} \\ 0 & \text{for dominant } \bar{b} \to \bar{c}\, c\, \bar{r} \text{ CKM amplitudes.} \end{cases}}$$

The "Gold-plated" Mode $B_d \to J/\psi\, K_S$

- Feynman diagrams $\Rightarrow$ $\bar{b} \to \bar{c}\, c\, \bar{s}$ dominates $\Rightarrow$

$$\boxed{\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_d \to J/\psi\, K_{\rm S}) = +\sin[-(2\beta - 0)]}$$

- This expression is valid to excellent accuracy, since penguins enter $B_d \to J/\psi\, K_S$ essentially with the same weak phase as the leading tree contribution.

- First attempts to measure $\sin\phi_d = \sin(2\beta)$:

$$\sin(2\beta) = \begin{cases} 3.2^{+1.8}_{-2.0} \pm 0.5 & \text{OPAL Collaboration} \\ 0.79^{+0.41}_{-0.44} & \text{CDF Collaboration} \end{cases}$$

- B-factory era: $\Delta \sin(2\beta)|_{\rm exp} = 0.08$.

- LHC era: $\Delta \sin(2\beta)|_{\rm exp} = \mathcal{O}(0.01)$!!!

- Another important implication of the Standard Model:

$$\boxed{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi\, K_{\rm S}) \approx 0 \approx a_{\rm CP}(B^{\pm} \to J/\psi\, K^{\pm}),}$$

  i.e. very small direct CP violation !

- Theoretical accuracy within the Standard Model?

- Interesting channel in this respect: $B_s \to J/\psi\, K_S$, allowing us to extract γ and to control the – presumably very small – uncertainties in β from $B_d \to J/\psi\, K_S$.
  [R.F., hep-ph/9903455, *Eur. Phys. J.* **C**: DOI 10.1007/s100529900099]

The Decay $B_d \to \pi^+\pi^-$

- If there were no penguin contributions present:

$$\boxed{\mathcal{A}_{\text{CP}}^{\text{mix-ind}}(B_d \to \pi^+\pi^-) = -\sin[-(2\beta + 2\gamma)] = -\sin(2\alpha)}$$

- However, we have to deal with penguin topologies, leading to considerable hadronic uncertainties!

  [Gronau, Silva & Wolfenstein, Aleksan et al., R.F. & Mannel, Ciuchini et al., Marrocchesi & Paver, Ali et al., Charles, . . .]

- There are strategies to control the penguin uncertainties with the help of additional experimental data!

- Gronau–London strategy makes use of the isospin relation

  $A(B_d^0 \to \pi^+\pi^-) + \sqrt{2}\,A(B_d^0 \to \pi^0\pi^0) = \sqrt{2}\,A(B^+ \to \pi^+\pi^0)$:

  [M. Gronau and D. London, *Phys. Rev. Lett.* **65** (1990) 3381]

  – BR$(B_d \to \pi^0\pi^0)\Big|_{\text{TH}} \lesssim \mathcal{O}(10^{-6}) \Rightarrow$ alternatives needed!

- Important alternative: α from $B \to \rho\,\pi$ modes.

  [Lipkin, Nir, Quinn & Snyder, *Phys. Rev.* **D44** (1991) 1454]

- Interesting alternative for 2nd generation B-physics experiments at hadron machines, such as LHCb or BTeV: $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^- \;\Rightarrow\; \beta$ and γ!

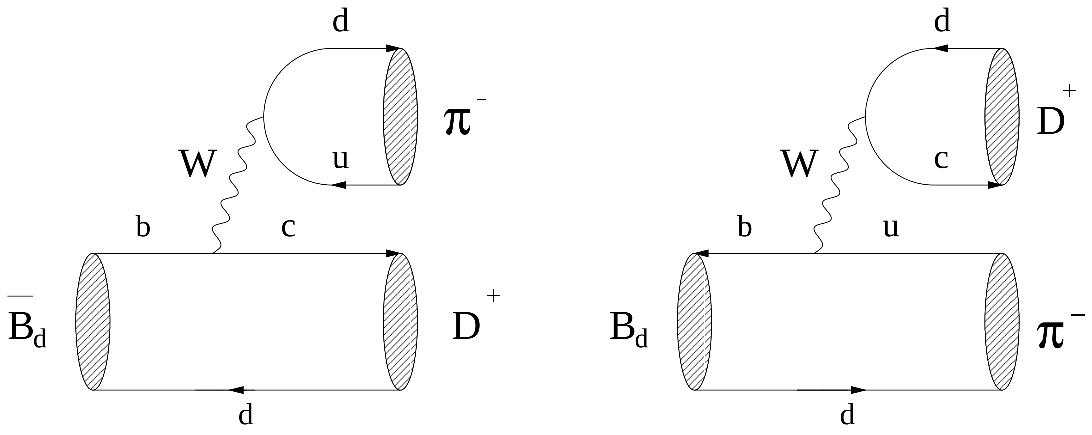
  [R.F., *Phys. Lett.* **B459** (1999) 306]

- Recent CLEO measurements of $B \to \pi K$ modes indicate already that penguins play in fact an important role!

- CLEO '99: BR$(B_d \to \pi^+\pi^-) = \left(4.7^{+1.8}_{-1.5} \pm 0.6\right) \times 10^{-6}$

Analysis of $B_d \to D^{(*)\pm}\pi^\mp$ Decays

- These modes are not decays into CP eigenstates !
- However, both B^0_d and $\overline{B^0_d}$ mesons may decay into $D^{(*)\pm}\pi^\mp$ final states, leading to interference effects between B^0_d–$\overline{B^0_d}$ mixing and decay processes:



$\propto V^*_{ud}V_{cb} = \left(1-\frac{\lambda^2}{2}\right)A\lambda^2$ $\qquad\qquad$ $\propto V^*_{ub}V_{cd} = -A\lambda^4 R_b\, e^{i\gamma}$

– Time-dependent $B^0_d, \overline{B^0_d} \to D^{(*)+}\pi^- \equiv f$ rate:

$$\xi^{(d)}_f = -\,e^{-i\phi_d}\frac{A(\overline{B^0_d}\to f)}{A(B^0_d\to f)} = -\,e^{-i(2\beta+\gamma)}\frac{1}{\lambda^2 R_b}\frac{\overline{M}_f}{M_{\overline{f}}}$$

– Time-dependent $B^0_d, \overline{B^0_d} \to D^{(*)-}\pi^+ \equiv \bar{f}$ rate:

$$\xi^{(d)}_{\bar{f}} = -\,e^{-i\phi_d}\frac{A(\overline{B^0_d}\to \bar{f})}{A(B^0_d\to \bar{f})} = -\,e^{-i(2\beta+\gamma)}\lambda^2 R_b\frac{M_{\overline{f}}}{\overline{M}_f}$$

[R.F., *Int. J. Mod. Phys.* **A12** (1997) 2459; BaBar Physics Book]

– Here, we have

$$\overline{M}_f \equiv \left\langle f \left| \overline{O}_1(\mu)\mathcal{C}_1(\mu) + \overline{O}_2(\mu)\mathcal{C}_2(\mu) \right| \overline{B^0_d} \right\rangle$$

$$M_{\overline{f}} \equiv \left\langle \overline{f} \left| O_1(\mu)\mathcal{C}_1(\mu) + O_2(\mu)\mathcal{C}_2(\mu) \right| \overline{B^0_d} \right\rangle$$

with

$$\begin{aligned} \overline{O}_1 &= (\bar{d}_\alpha u_\beta)_{\text{V–A}} \left(\bar{c}_\beta b_\alpha\right)_{\text{V–A}} \\ \overline{O}_2 &= (\bar{d}_\alpha u_\alpha)_{\text{V–A}} \left(\bar{c}_\beta b_\beta\right)_{\text{V–A}} \\ O_1 &= (\bar{d}_\alpha c_\beta)_{\text{V–A}} \left(\bar{u}_\beta b_\alpha\right)_{\text{V–A}} \\ O_2 &= (\bar{d}_\alpha c_\alpha)_{\text{V–A}} \left(\bar{u}_\beta b_\beta\right)_{\text{V–A}} \end{aligned}$$

– The observables $\xi_f^{(d)}$ and $\xi_{\bar{f}}^{(d)}$ allow a theoretically clean extraction of $2\beta + \gamma$, or equivalently of $\beta - \alpha$:

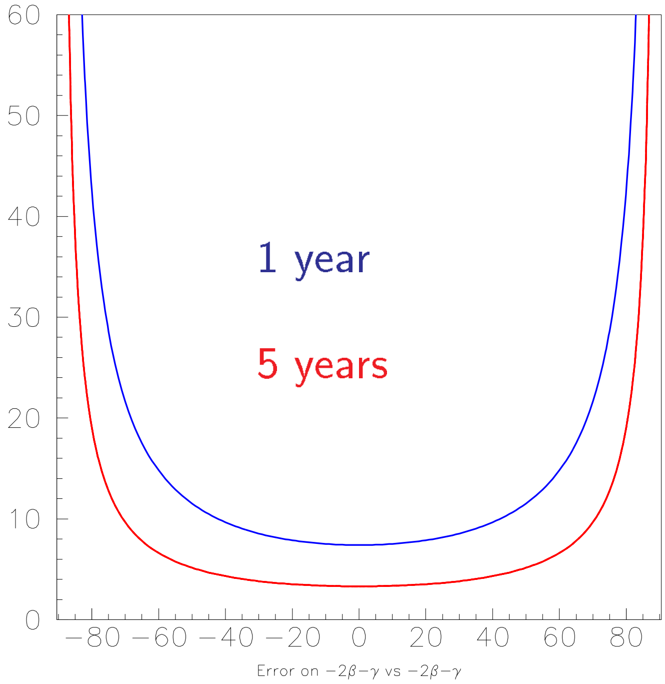
$$\boxed{\xi_f^{(d)} \times \xi_{\bar{f}}^{(d)} = e^{-2i(2\beta+\gamma)} = e^{-2i(\beta-\alpha)}}$$

[Sachs (1985), Dunietz & Sachs (1988), Dunietz (1997)]

- Using $2\beta = \phi_d$ from $B_d \to J/\psi\, K_S$ $\Rightarrow$ extraction of γ!
- Since one decay path is doubly Cabibbo-suppressed by $\lambda^2 R_b \approx 0.02$, the CP-violating effects are tiny.
- However, the BRs $= \mathcal{O}(10^{-3})$ are large, and the $D^{(*)\pm}\pi^\mp$ states can be reconstructed with a good efficiency and modest backgrounds $\Rightarrow$ offer interesting strategy!

  [Promising experimental studies: Gronberg & Nelson (BaBar Book); Rademacker & Wilkinson (LHC Workshop)]

- Experimental feasibility study of the $B_d^0 \to D^{*\pm}\pi^{\mp}$, $D^{*\pm}a_1^{\mp}$ sensitivity to $2\beta+\gamma$ at LHCb:
  [Jonas Rademacker & Guy Wilkinson]
  - Fit of the following variables:
    * $2\beta+\gamma$
    * Strong phase difference
    * $|\overline{M}_f/M_{\overline{f}}|$: assume a value calculated with the help of "factorization" as a constraint in the fit
  - Precision on $2\beta+\gamma$ at LHCb:



$$\Rightarrow \sigma_\gamma^{\mathrm{5yrs}} \sim 4^\circ$$

The "El Dorado" for Hadron Machines:

$\boxed{B_s \text{ System}}$

[For more details, see the talk by Isard Dunietz]

General Remarks and B_s Mixing Parameters

- The e^+–e^- B-factories operating at the $\Upsilon(4S)$ resonance will not be in a position to explore B_s physics.

- The B_s system is of particular interest for hadron machines !

- Important differences to the B_d system:

  – A large mixing parameter x_s is expected in the SM:

$$x_s \equiv \frac{\Delta M_s}{\overline{\Gamma}_s} = \mathcal{O}(20)$$

    * Probed through $B_s \to D_s^{\pm}\pi^{\mp}$, $D_s^{\pm}a_1^{\mp}$ decays.

  – There may be a sizeable difference $\Delta\Gamma_s \equiv \Gamma_{\rm H}^{(s)} - \Gamma_{\rm L}^{(s)}$ between the decay widths of the B_s mass eigenstates:

    * Most recent theoretical result:

$$\frac{\Delta\Gamma_s}{\overline{\Gamma}_s} = \mathcal{O}(10\%)$$

[M. Beneke et al., *Phys. Lett.* **B459** (1999) 631]

- There is an interesting correlation between $\Delta\Gamma_s$ and ΔM_s:

$$\frac{\Delta\Gamma_s}{\overline{\Gamma}_s} \approx -\frac{3\pi}{2S(x_t)}\frac{m_b^2}{M_W^2}\frac{\Delta M_s}{\overline{\Gamma}_s}$$

- LEP Oscillation WG: $\Delta M_s > 12.4\,\mathrm{ps}^{-1}$ (95% C.L.)

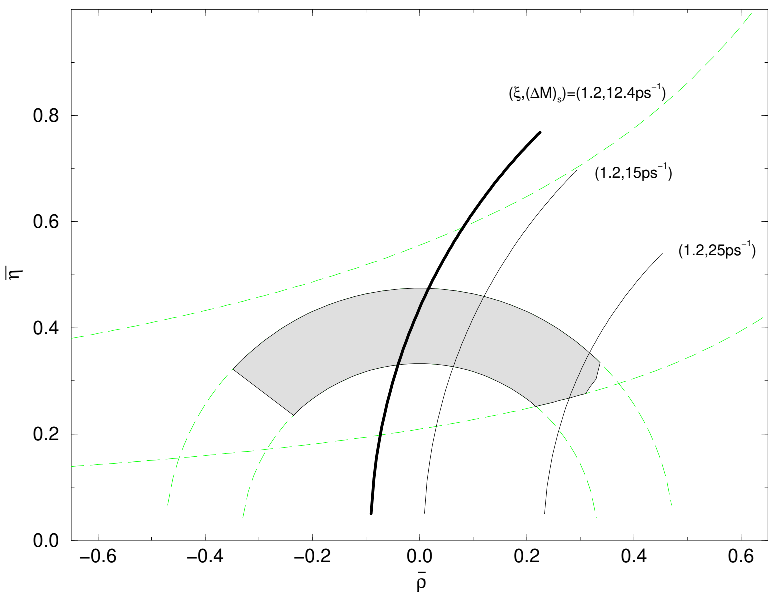
- The mass difference ΔM_s plays an important role to constrain UT1 in the $\overline{\rho}$–$\overline{\eta}$ plane:

  – Comparison with ΔM_d allows us to fix R_t, provided the following $SU(3)$-breaking factor can be fixed reliably:

$$\xi = \frac{F_{B_s}\sqrt{B_{B_s}}}{F_{B_d}\sqrt{B_{B_d}}} \approx 1.15 \qquad \text{[Lattice, QCD Sum Rules]}$$

  – Lower bounds on ΔM_s imply maximal value for R_t:

$$(R_t)_{\max} = 1.0 \times \xi \times \sqrt{\frac{10.2/\text{ps}}{\Delta M_s}} \qquad \text{[Buras ('96)]}$$



- $\underline{\Delta\Gamma_s \neq 0 \quad \Rightarrow \quad \text{CP violation in untagged } B_s \text{ rates:}}$

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

  – Here, the $\Delta M_s t$ oscillations cancel!

  – Promising in terms of efficiency, acceptance & purity.
  [Dunietz ('95); R.F. & Dunietz ('96)]

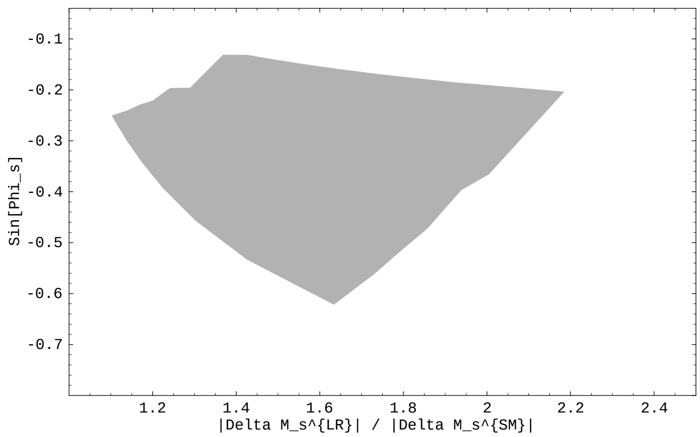
A Brief Look at B_s Benchmark Modes

- $B_s \to D_s^\pm K^\mp$:
  - B_s counterparts to $B_d \to D^{(*)\pm}\pi^\mp$.
  - Probe the CKM combination $\gamma - 2\delta\gamma$ instead of $\gamma + 2\beta$ in a theoretically clean way.
    [R. Aleksan, I. Dunietz & B. Kayser, *Z. Phys.* **C54** (1992) 653]
  - Much larger interference effects than in $B_d \to D^{(*)\pm}\pi^\mp$ since one decay path is just suppressed by $R_b \approx 0.41$, and not doubly Cabibbo-suppressed by $\lambda^2 R_b$.

- $B_s \to J/\psi\, \phi$: very promising for hadron machines!
  - B_s counterparts to $B_d \to J/\psi\, K_S$.
  - Offer interesting strategies to extract the B_s mixing parameters ΔM_s and $\Delta\Gamma_s$ from the corresponding angular distributions.
    [A. Dighe, I. Dunietz & R.F., *Eur. Phys. J.* **C6** (1999) 647]
  - Probe $2\delta\gamma = 2\lambda^2\eta = \mathcal{O}(0.03)$.
  - Hadronic uncertainties within the Standard Model?
  - Can be controlled through $B_d \to J/\psi\, \rho^0$!
    [R.F., *Phys. Rev.* **D60** (1999) 073008]
  - Small CP-violating effects in the Standard Model:

$\Rightarrow$ $\boxed{\text{interesting probe for new-physics contributions to } B_s^0\text{–}\overline{B_s^0} \text{ mixing!}}$ [Nir & Silverman]

– Example: L-R-symmetric model with spontaneous CPV



[Matias ('99)]

– The "integrated" $B_s \to J/\psi(\to l^+l^-)\phi(\to K^+K^-)$ decay rates give the following CP asymmetry:

$$a_{\rm CP}(t) \equiv \frac{\Gamma(t)-\overline{\Gamma}(t)}{\Gamma(t)+\overline{\Gamma}(t)} = D(t)\sin(\Delta m t)\sin\phi_s,$$

where

$$D(t) = \frac{\left(|A_0(0)|^2+|A_{||}(0)|^2-|A_\perp(0)|^2\right)e^{-\overline{\Gamma}t}}{\left(|A_0(0)|^2+|A_{||}(0)|^2\right)e^{-\Gamma_L t}+|A_\perp(0)|^2 e^{-\Gamma_H t}}.$$

– Typical range implied by model calculations:

$$\frac{|A_\perp(0)|^2}{|A_0(0)|^2+|A_{||}(0)|^2} = 0.1 \;\ldots\; 0.5.$$

– An analysis of the full three-angle distribution allows us to separate the different $J/\psi\,\phi$ final-state configurations

$\Rightarrow$ $|A_0(0)|$, $|A_{||}(0)|$, $|A_\perp(0)|$, strong phases ...

[See the talk by Isard Dunietz!]

CP Violation in Charged B Decays

- Since there are no mixing effects present in the charged B-meson system, non-vanishing CP asymmetries

$$\mathcal{A}_{\text{CP}} \equiv \frac{\Gamma(B^+ \to \overline{f}) - \Gamma(B^- \to f)}{\Gamma(B^+ \to \overline{f}) + \Gamma(B^- \to f)}$$

  would give us unambiguous evidence for direct CP violation.

- Such direct CP asymmetries arise from the interference between decay amplitudes with both different CP-violating weak and CP-conserving strong phases.

- In the Standard Model, the weak phases are related to the phases of the elements of the CKM matrix.

- On the other hand, the strong phases are induced by final-state interaction processes.

- In general, the strong phases introduce severe theoretical uncertainties into the calculation of $\mathcal{A}_{\text{CP}}$, thereby destroying the clean relation to the phases of the CKM matrix elements.

- An important tool to overcome these problems is provided by amplitude relations, allowing extractions of γ:
  - exact relations: decays of the type $B \to DK$
    [pioneered by Gronau & Wyler (1991)]
  - relations based on flavour symmetries and certain dynamical assumptions: $B \to \pi\pi, \pi K, KK$ decays.
    [pioneered by Gronau, Hernández, London & Rosner (1994)]

A Brief Look at $B \to DK$ Decays

- Amplitude relations between $B^{\pm} \to DK^{\pm}$ decays:

$$\sqrt{2}A(B^+ \to D^0_+ K^+) = A(B^+ \to D^0 K^+) + A(B^+ \to \overline{D^0} K^+)$$

$$\sqrt{2}A(B^- \to D^0_+ K^-) = A(B^- \to \overline{D^0} K^-) + A(B^- \to D^0 K^-),$$

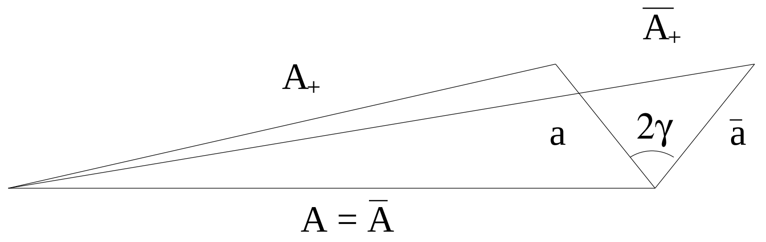
where $|D^0_+\rangle = (|D^0\rangle + |\overline{D^0}\rangle)/\sqrt{2}$.

- "Tree" decays: $\Rightarrow$

$$\begin{aligned} a &\equiv A(B^+ \to D^0 K^+) &=& \; A(B^- \to \overline{D^0} K^-) \times e^{2i\gamma} \\ A &\equiv A(B^+ \to \overline{D^0} K^+) &=& \; A(B^- \to D^0 K^-) \end{aligned}$$

- These relations allow a clean determination of γ:

[M. Gronau & D. Wyler, *Phys. Lett.* **B265** (1991) 172]



- Unfortunately squashed triangles:
  - BR$(B^+ \to \overline{D^0} K^+) = (0.257 \pm 0.065 \pm 0.032) \times 10^{-3}$
  - BR$(B^+ \to D^0 K^+) \lesssim \mathcal{O}(10^{-6})$

- Further experimental problems & improvements:

D. Atwood et al., *Phys. Rev. Lett.* **78** (1997) 3257

- Strategy using neutral, selftagging $B^0_d \to DK^{*0}$ modes:

I. Dunietz, *Phys. Lett.* **B270** (1991) 75

A Brief Look at $B \to \pi K$ Decays

- To obtain direct information on γ in an experimentally feasible way, $B \to \pi K$ decays appear very promising.

- These modes are not just an "unwanted" background for $B \to \pi\pi$, but have a very interesting physics potential!

- Experimental data are now starting to become available:
  - CLEO '97–'99: CP-averaged BRs $= \mathcal{O}(10^{-5})$
  - CLEO '99: first preliminary results on CP asymmetries
  - Experimental uncertainties are still very large ...

- Interestingly, already CP-averaged branching ratios may lead to highly non-trivial constraints on γ.

  [R.F. and T. Mannel, *Phys. Rev.* **D57** (1998) 2752; M. Neubert and J.L. Rosner, *Phys. Lett.* **B441** (1998) 403]

- Combinations of $B \to \pi K$ decays to determine γ:
  - $B^{\pm} \to \pi^{\pm} K$, $B_d \to \pi^{\mp} K^{\pm}$

    [R.F. ('95); R.F. & Mannel ('97); Gronau & Rosner ('98)]
  - $B^{\pm} \to \pi^{\pm} K$, $B^{\pm} \to \pi^{0} K^{\pm}$

    [Gronau, Rosner, London ('94); Neubert, Rosner; Buras, R.F. ('98)]
  - $B_d \to \pi^{0} K$, $B_d \to \pi^{\mp} K^{\pm}$

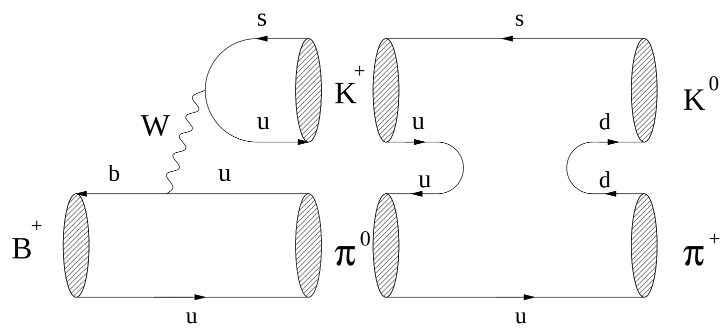
    [Buras & R.F. ('98)]

- From an experimental point of view, K/π separation is essential for these strategies.

- Strategies are not "clean", but nevertheless very interesting!

Theoretical Ingredients of $B \to \pi K$

- The $B \to \pi K$ strategies to probe the CKM angle γ are not theoretically clean, but rely on the following ingredients:
  - Flavour-symmetry arguments, involving either the $SU(2)$ or $SU(3)$ flavour symmetry.
  - Dynamical assumptions, concerning mainly the smallness of certain rescattering effects:
    - Example: $B^+ \to \{\pi^0 K^+\} \to \pi^+ K^0$



[Wolfenstein; Gérard & Weyers; Neubert; Falk, Kagan, Nir & Petrov; Atwood & Soni; Buras, R.F. & Mannel; . . .]

- The theoretical understanding of such final-state interaction processes is very poor at present!

  [Interesting recent work: Beneke, Buchalla, Neubert & Sachrajda ('99)]

- However, there are important indicators for large rescattering effects, which are provided by $B_d \to K^+K^-$ and $B^+ \to K^+\overline{K^0}$ decays.

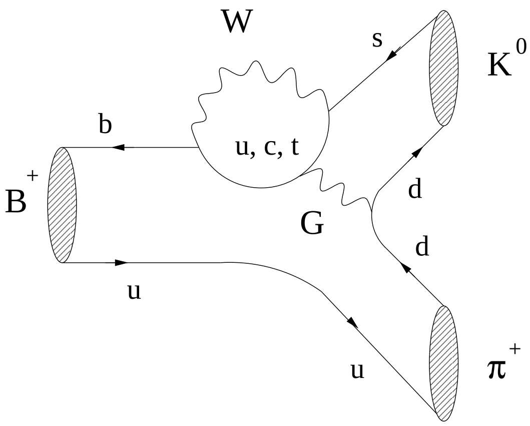
  [R.F.; Gronau & Rosner; Gronau & Pirjol, Agashe & Deshpande; . . .]

- The experimentally observed pattern of all $B \to \pi K$, KK decays will provide valuable information on whether the dynamical assumptions are justified ...

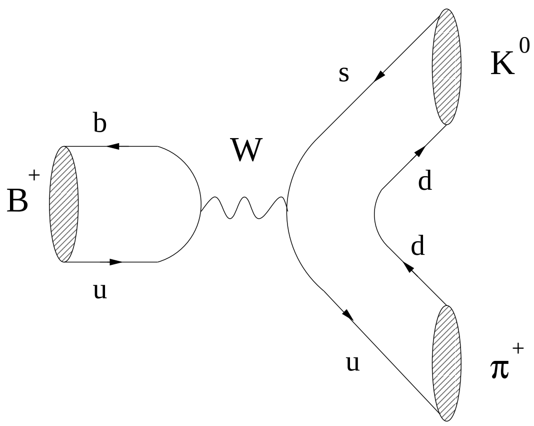
The $B^{\pm} \to \pi^{\pm} K$, $B_d \to \pi^{\mp} K^{\pm}$ Strategy

[R.F., *PLB* **365** (1996) 399; Gronau & Rosner, *PRD* **57** (1998) 2752]

- L.O. Feynman Diagrams contributing to $B^+ \to \pi^+ K^0$:

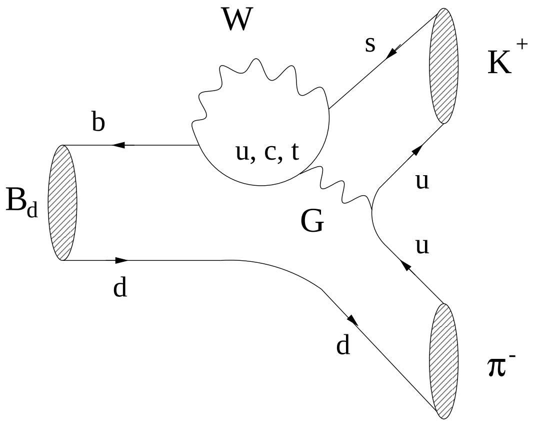


"penguin" P_q $\left(P_{\rm ew}^{(q)\rm C}\right)$

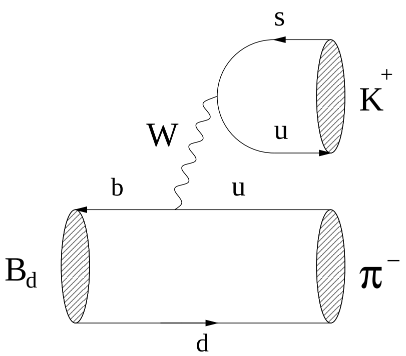


"annihilation" $\mathcal{A}$

- L.O. Feynman Diagrams contributing to $B_d^0 \to \pi^- K^+$:



"penguin" $\tilde{P}_q$ $\left(\tilde{P}_{\rm ew}^{(q)\rm C}\right)$



"tree" $\tilde{\mathcal{T}}$

- $|V_{us}V_{ub}^*/(V_{ts}V_{tb}^*)| \approx 0.02$ $\Rightarrow$ penguins dominate!

- Isospin symmetry of strong interactions $\Rightarrow$

$$\boxed{A(B^+ \to \pi^+ K^0) + A(B_d^0 \to \pi^- K^+) = -\left[T + P_{\rm ew}^{\rm C}\right],}$$

where

$$T = |T| e^{i\delta_T} e^{i\gamma} \quad \text{and} \quad P_{\rm ew}^{\rm C} = |P_{\rm ew}^{\rm C}| e^{i\delta_{\rm EW}^{\rm C}}$$

are usually referred to as "tree" and "colour-suppressed" EW penguin amplitudes, respectively.

- If we use this relation, a measurement of the observables

$$R \equiv \frac{\text{BR}(B_d^0 \to \pi^- K^+) + \text{BR}(\overline{B_d^0} \to \pi^+ K^-)}{\text{BR}(B^+ \to \pi^+ K^0) + \text{BR}(B^- \to \pi^- \overline{K^0})}$$

$$A_0 \equiv \frac{\text{BR}(B_d^0 \to \pi^- K^+) - \text{BR}(\overline{B_d^0} \to \pi^+ K^-)}{\text{BR}(B^+ \to \pi^+ K^0) + \text{BR}(B^- \to \pi^- \overline{K^0})}$$

allows us to fix a contour in the γ–r plane, where

$$r \equiv \frac{|T|}{\sqrt{\langle |P|^2 \rangle}}, \qquad \langle |P|^2 \rangle \equiv \frac{1}{2}\left(|P|^2 + |\overline{P}|^2\right)$$

with

$$P \equiv A(B^+ \to \pi^+ K^0).$$

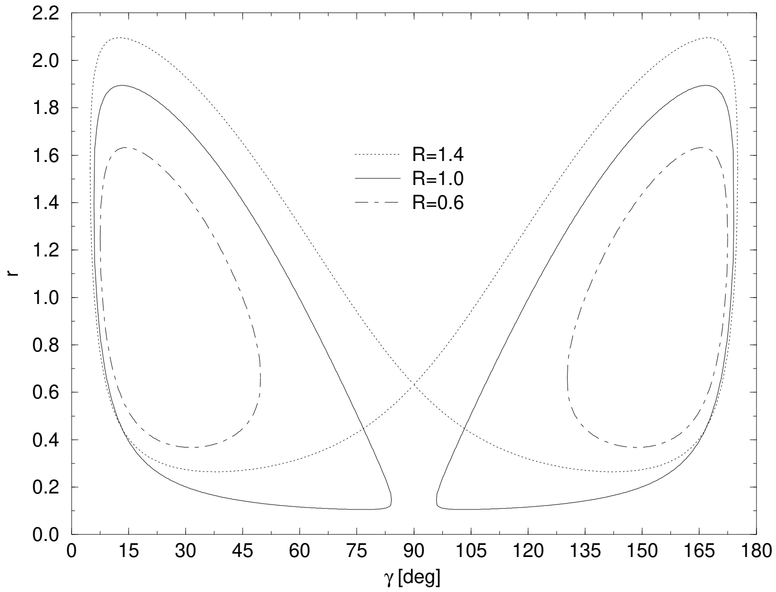
[Explicit expressions: R.F., *Eur. Phys. J.* **C6** (1999) 451]

- CLEO '99: $R = 1.0 \pm 0.3$, $A_0 = -0.17 \pm 0.26$

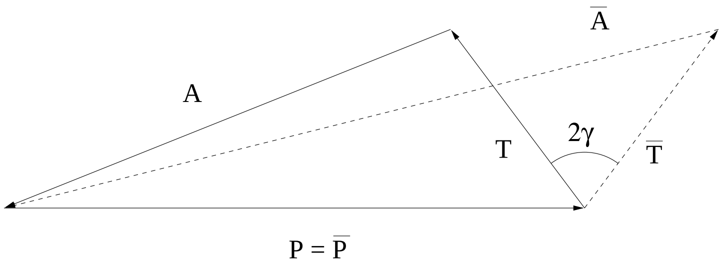
- If we fix the parameter $r \propto |T|$, e.g. with the help of "factorization" and $B \to \pi\, l\, \nu_l$, γ can be extracted !

[See, e.g., M. Gronau and J. Rosner, *Phys. Rev.* **D57** (1998) 6843]

- Example: $|A_0| = 0.2$ (FSI & EWP effects neglected)



$\longrightarrow$ Mathematical implementation of "isospin triangle":



- The extraction of r may be affected by rescattering effects!

- Interestingly, it is possible to obtain constraints on γ in the case of $R < 1$, which do not depend on r, and where the FSI effects can be included through $B^\pm \to K^\pm K$ decays!
  [R.F. and T. Mannel, *PRD* **57** ('98) 2752; R.F., *EPJ* **C6** ('99) 451]

- The major limitation of the theoretical uncertainty is due to the "colour-suppressed" EWPs ...
  [see also Gronau, Pirjol & Yan, *Phys. Rev.* **D60** (1999) 034021]

The Charged $B^\pm \to \pi^\pm K$, $\pi^0 K^\pm$ Strategy

[Gronau, Rosner & London ('94); Neubert & Rosner ('98)]

- $SU(2)$ isospin symmetry $\Rightarrow$

$$A(B^+ \to \pi^+ K^0) \; + \; \sqrt{2}\, A(B^+ \to \pi^0 K^+) =$$

$$-\left[(T+C) \; + \; P_{\rm ew}\right] \equiv 3\, A_{3/2}\,.$$

- There is no $I = 1/2$ component present in this relation.

- The phase structure of this relation is completely analogous to the $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$ case:

$$T + C = |T+C|\, e^{i\delta_{T+C}}\, e^{i\gamma}, \quad P_{\rm ew} = -\,|P_{\rm ew}| e^{i\delta_{\rm ew}}\,.$$

- Observables of the charged B-meson decays $B^\pm \to \pi^\pm K$ and $B^\pm \to \pi^0 K^\pm$ corresponding to R and A_0:

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

$$A_0^{\rm c} \equiv 2\left[\frac{{\rm BR}(B^+ \to \pi^0 K^+) - {\rm BR}(B^- \to \pi^0 K^-)}{{\rm BR}(B^+ \to \pi^+ K^0) + {\rm BR}(B^- \to \pi^- \overline{K^0})}\right]$$

- General expressions from those for R and A_0 by replacing

$$r \to r_{\rm c} \equiv \frac{|T+C|}{\sqrt{\langle |P|^2\rangle}}\,, \quad \delta \to \delta_{\rm c} \equiv \delta_{T+C} - \delta_{tc}\,, \quad P_{\rm ew}^{\rm C} \to P_{\rm ew}.$$

- CLEO '99: $R_{\rm c} = 1.3 \pm 0.5$, $A_0^{\rm c} = 0.35 \pm 0.34$

- The measurement of $R_{\rm c}$ and $A_0^{\rm c}$ allows us to fix contours in the γ–$r_{\rm c}$ plane, in complete analogy to the $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$ strategy.

- Advantages:
  - $SU(3)$ symmetry suffices to fix $r_{\rm c} \propto |T+C|$:

$$T+C \approx -\sqrt{2}\,\frac{V_{us}}{V_{ud}}\,\frac{f_K}{f_\pi}\left[\frac{A(B^+ \to \pi^+\pi^0)}{1+0.033\times e^{-i\gamma}}\right].$$

  - $SU(3)$ flavour symmetry allows us to control EWPs:

$$\left|\frac{P_{\rm ew}}{T+C}\right| e^{i(\delta_{\rm ew}-\delta_{T+C})} = 0.66\times\left[\frac{0.41}{R_b}\right]$$

    [M. Neubert and J.L. Rosner, *Phys. Lett.* **B441** (1998) 403; see also R.F., *Phys. Lett.* **B365** (1996) 399]

- The contours in the γ–$r_{\rm c}$ plane are affected to a similar extent by rescattering effects as in the $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$ case. They can be taken into account by using additional data provided by $B^\pm \to K^\pm K$.
  [A.J. Buras & R.F., hep-ph/9810260; Gronau & Pirjol, hep-ph/9811335]

- The major limitation of the theoretical accuracy is due to $SU(3)$-breaking effects:
  - The factorizable $SU(3)$-breaking corrections to EWPs turn out to be small in this case.
  - However, non-factorizable $SU(3)$-breaking corrections may play an important role.

- Interesting bounds on γ can be obtained from the CP-averaged BRs! [Neubert & Rosner, *PLB* **441** (1998) 403]

Some Thoughts about New Physics

- Since B_q^0–$\overline{B_q^0}$ mixing ($q \in \{d, s\}$) is a "rare" flavour-changing neutral-current (FCNC) process, it is very likely that it is affected significantly by new physics:
  - May affect mixing parameters ΔM_q and $\Delta\Gamma_q$.
  - May affect the CP-violating weak mixing phases ϕ_q.
- Examples: models with four generations, extended Higgs sectors, Z-mediated FCNCs, non-minimal SUSY models, left-right-symmetric models ...
- Since $B_d \to J/\psi\, K_{\rm S}$ and $B_s \to J/\psi\, \phi$ are governed by current–current, i.e. "tree", processes, new physics is expected to affect their decay amplitudes in a minor way:

  $\Rightarrow$ These modes still measure the B_q^0–$\overline{B_q^0}$ mixing phases !
- Comparison of the thus determined ϕ_q with those implied by the side measuerments of the UT may indicate new physics !
- In the clean strategies to measure γ, using "tree" decays, such as $B \to DK$, $B_d \to D^{(*)\pm}\pi^\mp$ or $B_s \to D_s K$, new physics is also expected to play a very minor role:

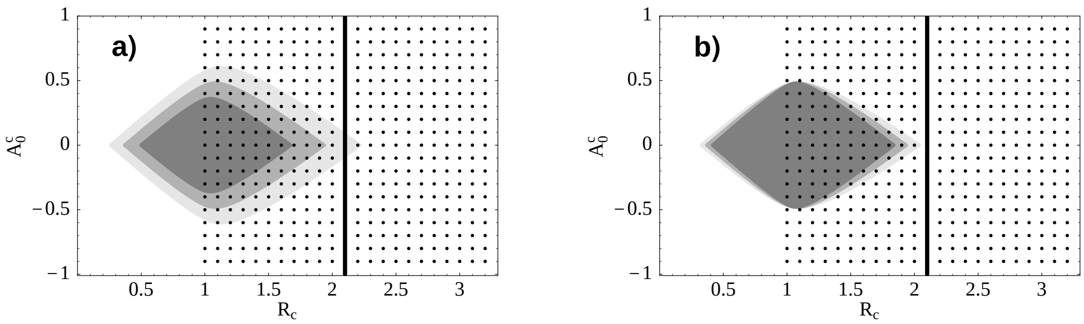
  $\Rightarrow$ "Reference" value for γ, i.e. the weak phase of V_{ub}.
- In contrast, the $B \to \pi K$ strategies to determine γ rely on the interference between "tree" and "penguin" effects:

  $\Rightarrow$ Discrepancies with the "reference" value for γ may well show up in the presence of new physics !

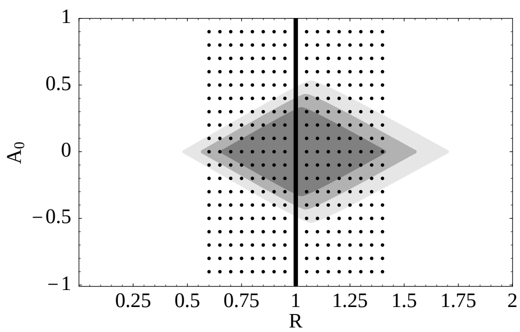
[Recent analysis: Y. Grossman et al., hep-ph/9909297]

- If we are lucky, we may get "immediate" indications for new physics from the $B \to \pi K$ observables:

  - allowed region in the R_c–A_0^c plane, characterizing $B^\pm \to \pi^\pm K$, $B^\pm \to \pi^0 K^\pm$ in the SM [(a) $0.18 \leq r_c \leq 0.30$, $q = 0.63$; (b) $r_c = 0.24$, $0.48 \leq q \leq 0.78$ (FSI effects are neglected)]:



  - allowed region in the R–A_0 plane, characterizing $B^\pm \to \pi^\pm K$, $B_d \to \pi^\mp K^\pm$ within the SM [$0.16 \leq r \leq 0.26$, $q_C\, e^{i\omega_C} = 0.66 \times 0.25$ (FSI effects are neglected)]:



  - A future measurement of observables lying significantly outside of this region would immediately indicate the presence of new physics!

    [R.F. & J. Matias, hep-ph/9906274]

- Also the "new" strategies discussed below, in particular the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ approach, are well suited to search for new physics!

A Closer Look at

$\boxed{\text{New Strategies}}$

Extracting γ from

$B_{s(d)} \to J/\psi\, K_{\mathrm{S}}$

or

$B_{d(s)} \to D^{+}_{d(s)}\, D^{-}_{d(s)}$

R.F., *Eur. Phys. J.* **C**: DOI 10.1007/s100529900099

General Features

- Whereas $e^{i\gamma}$ is strongly Cabibbo-suppressed in the decay $B_d \to J/\psi\, K_S$, this is not the case in $B_s \to J/\psi\, K_S$:

  $\Rightarrow$ sizeable CP-violating effects in $B_s \to J/\psi\, K_S$!

- $B_d \to J/\psi\, K_S$ and $B_s \to J/\psi\, K_S$ are related to each other by interchanging all down and strange quarks!

- The U-spin flavour symmetry allows us to extract γ, as well as interesting hadronic quantities, from the CP asymmetries $\mathcal{A}_{CP}^{dir}(B_s \to J/\psi\, K_S)$, $\mathcal{A}_{CP}^{mix}(B_s \to J/\psi\, K_S)$ and the CP-averaged $B_{d(s)} \to J/\psi\, K_S$ branching ratios.

- The theoretical accuracy is only limited by U-spin-breaking corrections, and there are no problems due to FSI effects.

- Interesting by-product: strategy allows us to take into account the – presumably very small – penguin contributions in the determination of ϕ_d, i.e. of 2β, from $B_d \to J/\psi\, K_S$.

- Important issue in view of the impressive accuracy that can be achieved with second-generation B experiments!

- Moreover, we have an interesting relation:

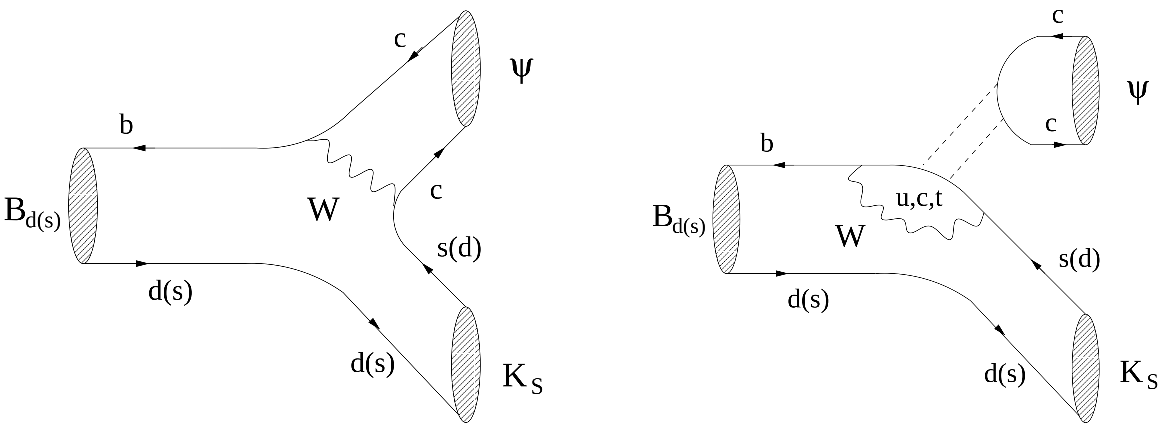
$$\frac{\mathcal{A}_{CP}^{dir}(B_d \to J/\psi\, K_S)}{\mathcal{A}_{CP}^{dir}(B_s \to J/\psi\, K_S)} \approx -\frac{\mathrm{BR}(B_s \to J/\psi\, K_S)}{\mathrm{BR}(B_d \to J/\psi\, K_S)}.$$

- Experimental feasibility depends strongly on the size of the penguin effects in $B_s \to J/\psi\, K_S$!?

- Similar strategy provided by $B_{d(s)} \to D_{d(s)}^+\, D_{d(s)}^-$ decays.

The $B_{d(s)} \to J/\psi\, K_{\rm S}$ Decay Amplitudes

- Feynman diagrams:



- The $B^0_d \to J/\psi\, K_{\rm S}$ decay amplitude:

$$A(B^0_d \to J/\psi\, K_{\rm S}) = \lambda_c^{(s)}\left(A_{\rm cc}^{c'} + A_{\rm pen}^{c'}\right) + \lambda_u^{(s)} A_{\rm pen}^{u'} + \lambda_t^{(s)} A_{\rm pen}^{t'}$$

$$= \left(1-\frac{\lambda^2}{2}\right)\mathcal{A}'\left[1+\left(\frac{\lambda^2}{1-\lambda^2}\right)a'e^{i\theta'}e^{i\gamma}\right],$$

where

$$\mathcal{A}' \equiv \lambda^2 A\left(A_{\rm cc}^{c'} + A_{\rm pen}^{ct'}\right) \quad \text{with} \quad A_{\rm pen}^{ct'} \equiv A_{\rm pen}^{c'} - A_{\rm pen}^{t'},$$

$$a'e^{i\theta'} \equiv R_b\left(1-\frac{\lambda^2}{2}\right)\left(\frac{A_{\rm pen}^{ut'}}{A_{\rm cc}^{c'} + A_{\rm pen}^{ct'}}\right).$$

- The $B^0_s \to J/\psi\, K_{\rm S}$ decay amplitude:

$$A(B^0_s \to J/\psi\, K_{\rm S}) = -\lambda\,\mathcal{A}\left[1 - a\,e^{i\theta}e^{i\gamma}\right],$$

where $\mathcal{A}$ and $a\,e^{i\theta}$ take the same form as $\mathcal{A}'$ and $a'e^{i\theta'}$.

Observables

- "Untagged" rate:

$$|A(t)|^2 + |\overline{A}(t)|^2 = |\mathcal{N}|^2 \left[R_{\rm L}\, e^{-\Gamma_{\rm L} t} + R_{\rm H}\, e^{-\Gamma_{\rm H} t}\right].$$

- Time-dependent CP asymmetry:

$$a_{\rm CP}(t) \equiv \frac{|A(t)|^2 - |\overline{A}(t)|^2}{|A(t)|^2 + |\overline{A}(t)|^2}$$

$$= 2\, e^{-\Gamma t}\left[\frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M t)}{e^{-\Gamma_{\rm H} t} + e^{-\Gamma_{\rm L} t} + \mathcal{A}_{\Delta\Gamma}\left(e^{-\Gamma_{\rm H} t} - e^{-\Gamma_{\rm L} t}\right)}\right].$$

- The $B_s \to J/\psi\, K_{\rm S}$ observables $\mathcal{A}_{\rm CP}^{\rm dir}$, $\mathcal{A}_{\rm CP}^{\rm mix}$ and $\mathcal{A}_{\Delta\Gamma}$ depend on the three "unknowns" a, θ and γ, as well as on the B^0_s–$\overline{B^0_s}$ mixing phase ϕ_s.

- However, not independent quantities:

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

- Consequently, the CP-violating observables of the decay $B_s \to J/\psi\, K_{\rm S}$ do not provide sufficient information to extract γ and the corresponding hadronic parameters!

Extracting γ from $B_{s(d)} \to J/\psi\, K_{\rm S}$ Decays

- In order to extract γ, another observable is needed, in addition to $\mathcal{A}_{\rm CP}^{\rm dir}$, $\mathcal{A}_{\rm CP}^{\rm mix}$ and $\mathcal{A}_{\Delta\Gamma}$:

$$R \equiv \frac{1}{2}\left(R_{\rm H} + R_{\rm L}\right) = 1 - 2\, b \cos\rho \cos\gamma + b^2.$$

- In contrast to $\mathcal{A}_{\rm CP}^{\rm dir}$, $\mathcal{A}_{\rm CP}^{\rm mix}$ and $\mathcal{A}_{\Delta\Gamma}$, the overall normalization $|\mathcal{N}|^2$ is required to determine R, since

$$\begin{aligned}\langle\Gamma(t)\rangle &\equiv \Gamma(B(t)\to f) + \Gamma(\overline{B}(t)\to f)\\ &= \mathsf{PhSp} \times |\mathcal{N}|^2 \times \left[R_{\rm H} e^{-\Gamma_{\rm H} t} + R_{\rm L} e^{-\Gamma_{\rm L} t}\right].\end{aligned}$$

- In the case of $B_s \to J/\psi\, K_{\rm S}$, this normalization can be fixed through the CP-averaged $B_d \to J/\psi\, K_{\rm S}$ rate!

- To this end, it is useful to introduce the following observable:

$$\begin{aligned}H &\equiv \frac{1}{\epsilon}\left(\frac{|\mathcal{A}'|}{|\mathcal{A}|}\right)^2 \left[\frac{M_{B_d}\Phi(M_{J/\psi}/M_{B_d}, M_K/M_{B_d})}{M_{B_s}\Phi(M_{J/\psi}/M_{B_s}, M_K/M_{B_s})}\right]^3 \frac{\langle\Gamma(0)\rangle}{\langle\Gamma'(0)\rangle}\\ &= \frac{1 - 2\, a\, \cos\theta\cos\gamma + a^2}{1 + 2\,\epsilon\, a'\cos\theta'\cos\gamma + \epsilon^2\, a'^2},\end{aligned}$$

where

$$\Phi(x,y) = \sqrt{\left[1-(x+y)^2\right]\left[1-(x-y)^2\right]}, \quad \epsilon = \frac{\lambda^2}{1-\lambda^2}.$$

- U-spin flavour symmetry of strong interactions implies:

$$|\mathcal{A}'| = |\mathcal{A}| \quad \text{and} \quad a' = a\,, \quad \theta' = \theta.$$

$\Rightarrow$ $\boxed{\text{can determine } a,\ \theta \text{ and } \gamma \text{ as a function of } \phi_s \text{ by combining } H \text{ with } \mathcal{A}_{\rm CP}^{\rm dir} \text{ and } \mathcal{A}_{\rm CP}^{\rm mix} \text{ or } \mathcal{A}_{\Delta\Gamma}.}$

- $\phi_s = -2\delta\gamma$ is expected to be negligibly small in the SM. It can be probed with the help of $B_s \to J/\psi\, \phi$.
[A. Dighe, I. Dunietz and R.F., *Eur. Phys. J.* **C6** (1999) 647]

- The theoretical accuracy is only limited by U-spin-breaking corrections, and there are no problems due to FSI effects.

- Interesting by-product: strategy allows us to take into account the – presumably very small – penguin contributions in the determination of ϕ_d, i.e. of 2β, from $B_d \to J/\psi\, K_{\rm S}$.

- Important issue in view of the impressive accuracy that can be achieved with second-generation B experiments!

- Moreover, we can predict the direct CP-violating asymmetry arising in $B_d \to J/\psi\, K_{\rm S}$:

$$\frac{\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi\, K_{\rm S})}{\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi\, K_{\rm S})} = -\,\epsilon\, H\,, \quad \epsilon = \frac{\lambda^2}{1-\lambda^2} \approx 0.05\,.$$

- Experimental feasibility depends strongly on the value of the "penguin parameter" a, which is very difficult to estimate!

- Similar strategy provided by $B_{d(s)} \to D^+_{d(s)}\, D^-_{d(s)}$ decays.

Extracting β and γ from

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

and

$B_s \to K^+K^-$

R.F., *Phys. Lett.* **B459** (1999) 306

Preliminaries

- In the literature, the decay $B_d \to \pi^+\pi^-$ usually appears as a tool to determine $\alpha = 180° - \beta - \gamma$.

- Although there are several strategies on the market to take care of the corresponding penguin uncertainties, they are usually very challenging from an experimental point of view.

- In the following, a new way of making use of the CP-violating observables of the decay $B_d \to \pi^+\pi^-$ is discussed:

> Combining them with those of $B_s \to K^+K^-$ – the U-spin counterpart of $B_d \to \pi^+\pi^-$ – a simultaneous determination of $\phi_d = 2\beta$ and γ becomes possible!

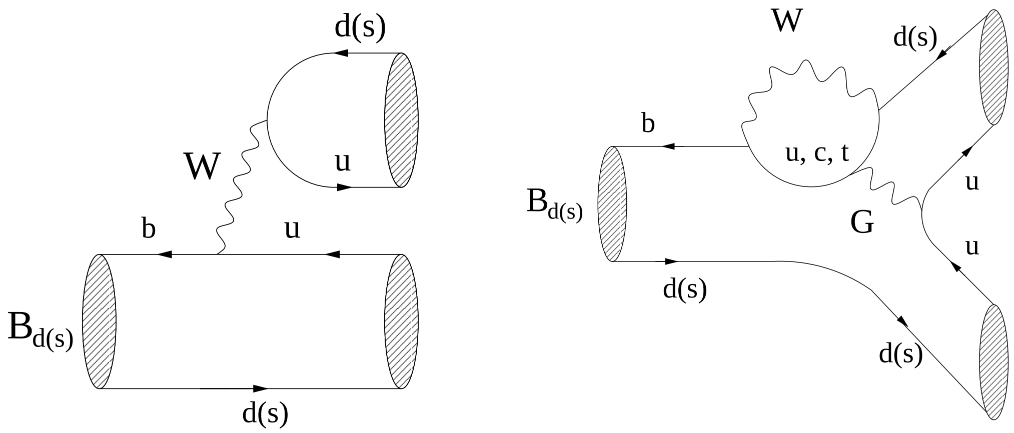
- This new strategy is not affected by any penguin topologies – it rather makes use of them – and does not rely on certain "plausible" dynamical or model-dependent assumptions!

- Moreover, final-state interaction effects, which led to considerable attention in the recent literature in the context of the determination of γ from $B \to \pi K$ decays, do not lead to any problems, and the theoretical accuracy is only limited by U-spin-breaking effects.

- Conceptually quite similar to the extraction of γ from $B_{s(d)} \to J/\psi\, K_S$ or $B_{d(s)} \to D^+_{d(s)}\, D^-_{d(s)}$; however, more "favourable" concerning U-spin-breaking effects and the experimentally feasibility. Ideally suited for LHCb!

Decay Amplitudes

- Feynman diagrams:



- The $B_d^0 \to \pi^+\pi^-$ decay amplitude:

$$A(B_d^0 \to \pi^+\pi^-) = \lambda_u^{(d)} \left(A_{\rm cc}^u + A_{\rm pen}^u\right) + \lambda_c^{(d)} A_{\rm pen}^c + \lambda_t^{(d)} A_{\rm pen}^t$$

$$= e^{i\gamma}\left(1-\frac{\lambda^2}{2}\right)\mathcal{C}\left[1 - d\, e^{i\theta} e^{-i\gamma}\right],$$

where

$$\mathcal{C} \equiv \lambda^3 A\, R_b \left(A_{\rm cc}^u + A_{\rm pen}^{ut}\right) \quad \text{with} \quad A_{\rm pen}^{ut} \equiv A_{\rm pen}^u - A_{\rm pen}^t,$$

$$d\, e^{i\theta} \equiv \frac{1}{(1-\lambda^2/2)R_b}\left(\frac{A_{\rm pen}^{ct}}{A_{\rm cc}^u + A_{\rm pen}^{ut}}\right).$$

- The $B_s^0 \to K^+K^-$ decay amplitude:

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

where $\mathcal{C}'$ and $d' e^{i\theta'}$ take the same form as $\mathcal{C}$ and $d\, e^{i\theta}$.

CP-violating Observables

- $\underline{B_d \to \pi^+\pi^-:}$ ($\Delta\Gamma_d$ neglected)

$$\boxed{a_{\rm CP}(t) = \mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M_d t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M_d t)}$$

$$\mathcal{A}_{\rm CP}^{\rm dir} = -\left[\frac{2\,d\sin\theta\sin\gamma}{1-2\,d\cos\theta\cos\gamma+d^2}\right]$$

$$\mathcal{A}_{\rm CP}^{\rm mix} = +\left[\frac{\sin(\phi_d+2\gamma)-2\,d\,\cos\theta\,\sin(\phi_d+\gamma)+d^2\sin\phi_d}{1-2\,d\cos\theta\cos\gamma+d^2}\right]$$

- $\underline{B_s \to K^+K^-:}$ ($\Delta\Gamma_s$ taken into account)

$$\boxed{a_{\rm CP}(t) = 2\,e^{-\Gamma t}\left[\frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M t)+\mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M t)}{e^{-\Gamma_{\rm H}t}+e^{-\Gamma_{\rm L}t}+\mathcal{A}_{\Delta\Gamma}\left(e^{-\Gamma_{\rm H}t}-e^{-\Gamma_{\rm L}t}\right)}\right]}$$

$$\mathcal{A}_{\rm CP}^{\rm dir} = +\left[\frac{2\,\tilde{d}'\sin\theta'\sin\gamma}{1+2\,\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}\right]$$

$$\mathcal{A}_{\rm CP}^{\rm mix} = +\left[\frac{\sin(\phi_s+2\gamma)+2\,\tilde{d}'\,\cos\theta'\,\sin(\phi_s+\gamma)+\tilde{d}'^2\sin\phi_s}{1+2\,\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}\right]$$

$$\mathcal{A}_{\Delta\Gamma} = -\left[\frac{\cos(\phi_s+2\gamma)+2\,\tilde{d}'\cos\theta'\cos(\phi_s+\gamma)+\tilde{d}'^2\cos\phi_s}{1+2\,\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}\right],$$

where

$$\tilde{d}' \equiv \left(\frac{1-\lambda^2}{\lambda^2}\right)d' \approx 20\times d'.$$

- The $\phi_{d,s}$ denote the $B^0_{d,s}$–$\overline{B^0_{d,s}}$ mixing phases.

Extracting β and γ

- $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other by interchanging all strange and down quarks:

$$U\text{-spin symmetry} \quad \Rightarrow \quad d' = d, \quad \theta' = \theta. \qquad (*)$$

- Consequently, if we assume that ϕ_s is negligibly small, or that it is fixed through $B_s \to J/\psi\,\phi$, the four CP-violating observables provided by $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ depend – in the strict U-spin limit – on the four "unknowns"

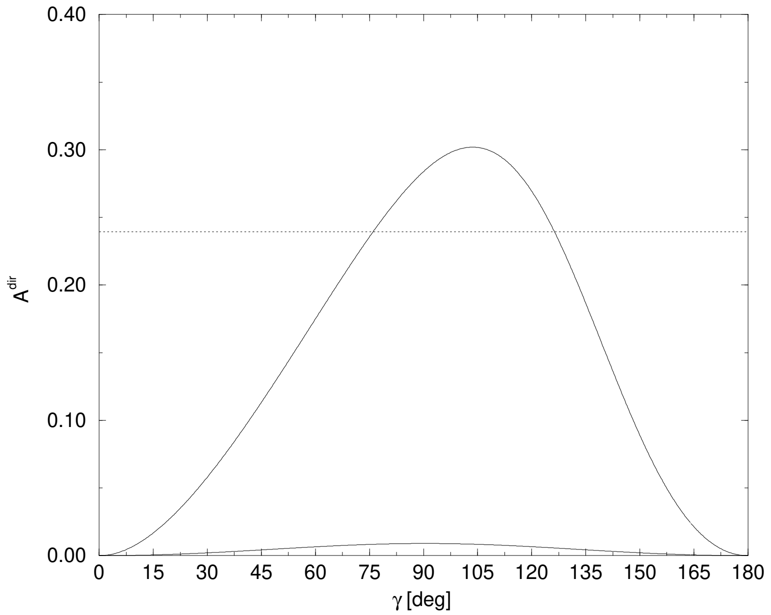
$$d, \quad \theta, \quad \phi_d = 2\beta \quad \text{and} \quad \gamma :$$

  - $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$

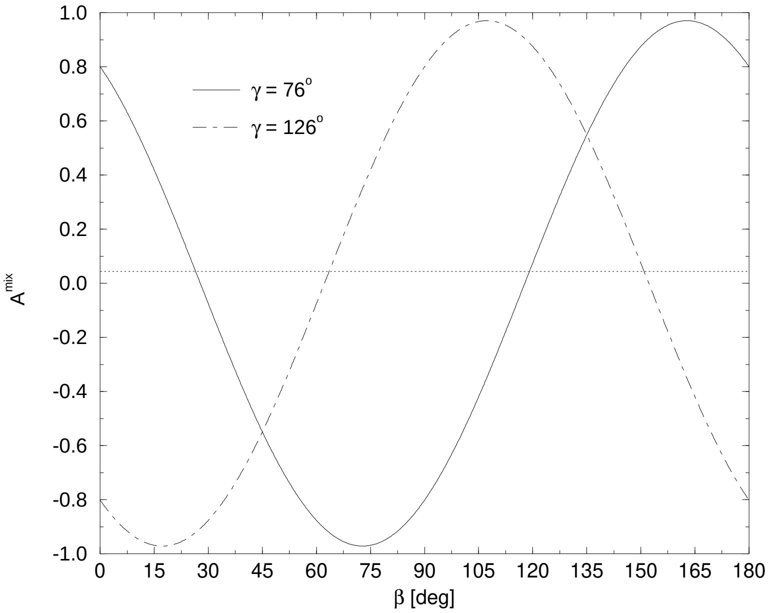
    $\Rightarrow$ $\tilde{d}'$ and θ' as functions of γ.
  - The U-spin relation $(*)$ allows us then to determine $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ as a function of γ $\Rightarrow$ γ.
  - Using in addition $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$ $\Rightarrow$ β.

- An illustrative example:
  - Input parameters:
    * negligible B_s^0–$\overline{B_s^0}$ mixing phase, i.e. $\phi_s = 0$
    * $2\beta = 53^\circ$, $\gamma = 76^\circ$, $d = d' = 0.3$, $\theta = \theta' = 210^\circ$
  - Output for the observables:
    * $B_d \to \pi^+\pi^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = +24\%$, $\mathcal{A}_{\rm CP}^{\rm mix} = +4.4\%$
    * $B_s \to K^+K^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = -17\%$, $\mathcal{A}_{\rm CP}^{\rm mix} = -28\%$.

- The dependence of $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^+\pi^-)$ on γ fixed through the CP-violating $B_s \to K^+K^-$ observables:



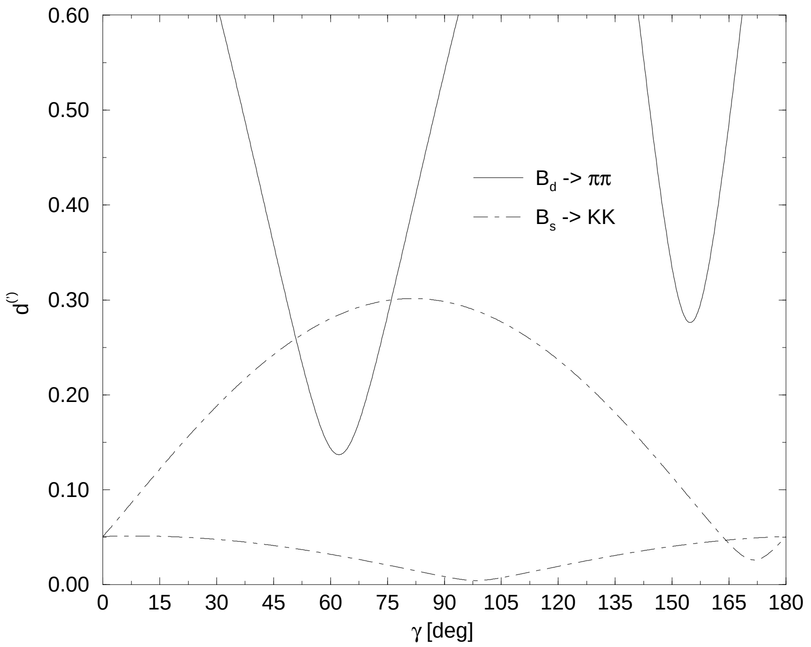
- The dependence of $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^+\pi^-)$ on β fixed through the CP-violating $B_s \to K^+K^-$ observables:



A Different Way of Combining the Observables

- Using $\phi_d = 2\beta$ as an input, there is a different strategy to combine $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$ with $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$!

- These quantities allow us to fix contours in the γ–d and γ–d' planes as functions of the B_d^0–$\overline{B_d^0}$ and B_s^0–$\overline{B_s^0}$ mixing phases in a theoretically clean way:



- U-spin relation $d' = d$ suffices to extract γ and d, θ, θ' !

> The theoretical accuracy of γ and d, θ, θ' is only limited by U-spin-breaking effects !

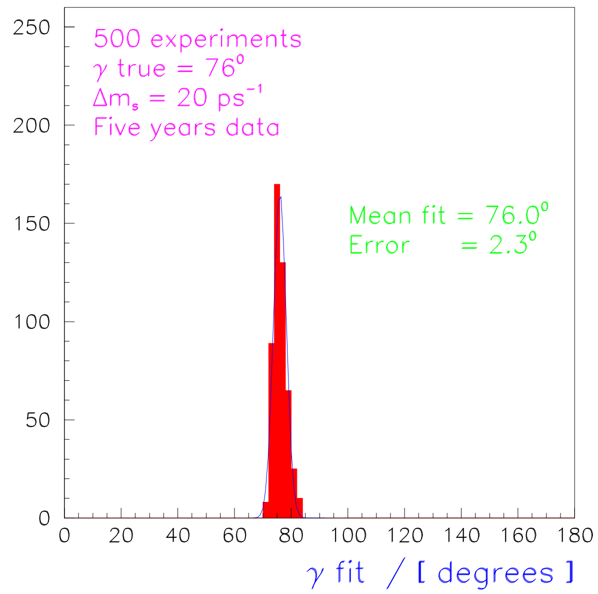
- First exp. feasibility study for LHCb by Guy Wilkinson:
  - at LHCb, 6.9k and 3.6k rec. & tagged $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ events are expected per year

$$\Rightarrow \boxed{B_d \to \pi^+\pi^-,\ B_s \to K^+K^- \text{ well suited!}}$$

  - Same example as discussed before:

$$A_{\rm dir}^{\pi\pi} = 24\%,\ A_{\rm mix}^{\pi\pi} = 4.4\%$$
$$A_{\rm dir}^{KK} = -17\%,\ A_{\rm mix}^{KK} = -28\%$$
$$2\beta = 53^\circ,\ \gamma = 76^\circ,\ \phi_s = 0$$
$$\Delta M_s = 20\ {\rm ps}^{-1} = 20,\ \Delta\Gamma/\Gamma = 20\%$$

    * Assuming U-spin flavour symmetry and external knowledge of ϕ_s and 2β, then fit $\gamma \Rightarrow$



- Need to explore fuller range of parameters ...

Insights into U-spin-breaking Effects

- The approach discussed a couple of minutes ago allows us to extract γ, as well as $d = d'$ and θ, θ'.

- These quantities allow us to determine, in addition, the "normalization" factors $|\mathcal{C}|$ and $|\mathcal{C}'|$ from the CP-averaged $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ branching ratios !

- A first consistency check is provided by $\theta' = \theta$.

- Moreover, the "factorization" approximation implies

$$\left|\frac{\mathcal{C}'}{\mathcal{C}}\right|_{\rm fact} = \frac{f_K}{f_\pi}\frac{F_{B_sK}(M_K^2;0^+)}{F_{B_d\pi}(M_\pi^2;0^+)}\left(\frac{M_{B_s}^2-M_K^2}{M_{B_d}^2-M_\pi^2}\right),$$

providing another interesting check !

- Interestingly, $d'e^{i\theta'} = d\,e^{i\theta}$ is not affected by U-spin-breaking corrections within a "modernized" version of the BSS mechanism! What about non-factorizable effects?

- Another implication of $d'e^{i\theta'} = d\,e^{i\theta}$:

$$-\frac{\mathcal{A}_{\rm CP}^{\rm dir}(B_s\to K^+K^-)}{\mathcal{A}_{\rm CP}^{\rm dir}(B_d\to \pi^+\pi^-)} = \frac{\text{BR}(B_d\to\pi^+\pi^-)}{\text{BR}(B_s\to K^+K^-)}$$

$$\times\left|\frac{\mathcal{C}'}{\mathcal{C}}\right|^2\left[\frac{M_{B_d}}{M_{B_s}}\frac{\Phi(M_K/M_{B_s},M_K/M_{B_s})}{\Phi(M_\pi/M_{B_d},M_\pi/M_{B_d})}\frac{\tau_{B_s}}{\tau_{B_d}}\right].$$

Comments

- An alternative way to fix certain contours through the CP-violating observables $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$ was recently proposed by Charles:
  - Different parametrization of $B_d \to \pi^+\pi^-$ was chosen;
  - α was set in correlation with a hadronic parameter $|P/T|$, which represents – sloppily speaking – the ratio of the "penguin" to the "tree" contributions.

    [J. Charles, *Phys. Rev.* **D59** (1999) 054007]

- Unfortunately, it is very difficult to fix $|P/T|$ in a theoretically reliable way, in particular as it is also affected by final-state-interaction effects.

- In the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ strategies, there are no problems of this kind, and the theoretical accuracy is only limited by U-spin-breaking corrections!

- Should be very interesting for "second-generation" B-physics experiments at hadron machines (LHCb, BTeV).

- Interesting variant for the asymmetric $e^+ e^-$ B-factories:

$$\boxed{B_s \to K^+K^- \quad \Rightarrow \quad B_d \to \pi^\mp K^\pm}$$

  - uses $SU(3)$ and "plausible" dynamical assumption!

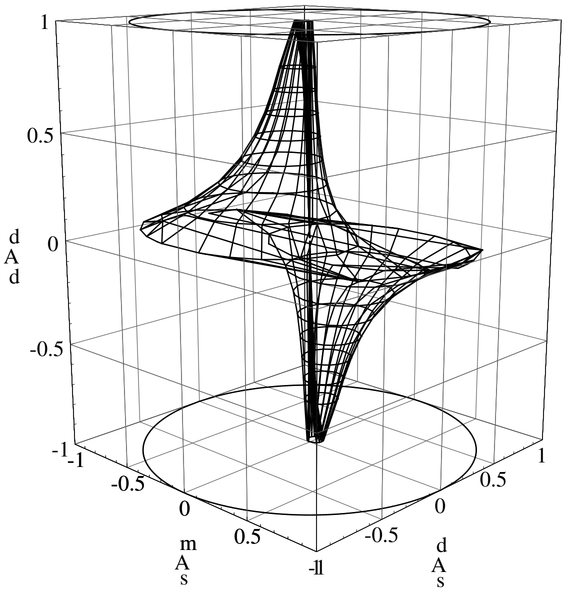
Searching for New Physics

- Since "penguin" processes play an important role in the decays $B_s \to K^+K^-$ and $B_d \to \pi^+\pi^-$, they may well be affected by new physics:

  $\Rightarrow$ discrepancies of the extracted values of γ with clean strategies (e.g. $B_s \to D_s^\mp K^\pm$) or fits of the UT!

- If we are lucky, we may get "immediate" indications for new physics from the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ strategy:

  – Allowed region in the space of $A_s^{\rm d} \equiv \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$, $A_s^{\rm m} \equiv \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$ and $A_d^{\rm d} \equiv \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$, which characterize the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ system within the Standard Model ($\phi_s = 0$):



  – A future measurement of observables lying significantly outside of this region would immediately indicate the presence of new physics!

  [R.F. & J. Matias, hep-ph/9906274]

CKM Phases

and

Hadronic Parameters

from

Angular Distributions

of $B_{d,s}$ Decays

[R.F., *Phys. Rev.* **D60** (1999) 073008]

General Remarks

- A particularly interesting laboratory is provided by quasi-two-body modes $B_q \to X_1\, X_2$ of neutral B_q-mesons, where both X_1 and X_2 carry spin and continue to decay through CP-conserving interactions.

  [I. Dunietz et al., *Phys. Rev.* **D43** (1991) 2193; R.F. and I. Dunietz, *Phys. Rev.* **D55** (1997) 259; *Phys. Lett.* **B387** (1996) 361]

- In this case, the time-dependent angular distribution of the decay products of X_1 and X_2 provides valuable information both on hadronic physics and on CKM phases:

$$f(\Theta, \Phi, \Psi; t) = \sum \mathcal{O}^{(k)}(t)\, g^{(k)}(\Theta, \Phi, \Psi),$$

  where Θ, Φ and Ψ denote the angles describing the kinematics of the decay products of X_1 and X_2.

- There are two kinds of observables $\mathcal{O}^{(k)}(t)$:

  i) $|A_f(t)|^2$

  ii) $\Re[A^*_{\tilde{f}}(t) A_f(t)]$, $\Im[A^*_{\tilde{f}}(t) A_f(t)]$.

  [Example: A. Dighe, I. Dunietz and R.F., *Eur. Phys. J.* **C6** (1999) 647]

- In comparison with $B_q \to P_1\, P_2$ strategies, the angular distributions of the $B_q \to X_1\, X_2$ modes provide many more cross checks and allow in certain cases the resolution of discrete ambibuities in the extraction of CKM phases!

- General formalism to extract CKM phases and hadronic parameters from the time-dependent angular distributions of certain $B_q \to X_1\, X_2$ decays, taking also into account penguin contributions:

R.F., *Phys. Rev.* **D60** (1999) 073008

- If we fix the mixing phase ϕ_q separately, it is possible to determine a CP-violating weak phase ω, which is usually given by the angles of the UT, and interesting hadronic quantities as a function of a *single* hadronic parameter.

- If we determine this parameter, for instance, by comparing $B_q \to X_1\, X_2$ with an $SU(3)$-related mode, all remaining parameters, including ω, can be extracted.

- If we are willing to make more extensive use of flavour-symmetry arguments, it is in principle possible to determine the B_q^0–$\overline{B_q^0}$ mixing phase ϕ_q as well.

- As the technical details of this approach are rather involved, let us just have a brief look at ...

Some Applications

- The decays $B_d \to J/\psi\,\rho^0$ and $B_s \to J/\psi\,\phi$:
  - Structure of decay amplitudes is very similar to the ones of $B_s \to J/\psi\,K_S$ and $B_d \to J/\psi\,K_S$.
  - Can be related to each other through $SU(3)$ and dynamical arguments, involving "exchange" and "penguin annihilation" topologies, thereby allowing the
    * extraction of the B^0_d–$\overline{B^0_d}$ mixing phase $\phi_d = 2\beta$:
    $$\hat{A}^f_{\rm M} \approx \eta_f \sin\phi_d, \quad \hat{I}^f_{\rm M} \approx \cos\Delta_{f,\perp}\cos\phi_d$$
    $$\Rightarrow \phi_d \text{ can be fixed } \underline{\text{unambiguously}}\,!$$
    * extraction of γ, if penguins in $B_d \to J/\psi\,\rho^0$ sizeable.
  - Interesting by-product: penguin effects in the extraction of ϕ_s from $B_s \to J/\psi\,\phi$ can be included.
  - Moreover, valuable insights into $SU(3)$-breaking effects.
- The decays $B_d \to \rho^+\rho^-$ and $B_s \to K^{*+}K^{*-}$:
  - Structure of decay amplitudes completely analogous to the ones of $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$.
  - Can be related to each other through U-spin aruments, thereby allowing the extraction of γ and $\phi_{d,s}$.
  - Moreover, valuable insights into hadronic physics!
- The decays $B_d \to K^{*0}\,\overline{K^{*0}}$ and $B_s \to K^{*0}\,\overline{K^{*0}}$:
  - Pure "penguin" modes.
  - U-spin counterparts, allowing extraction of γ and $\phi_{d,s}$!

Conclusions and Outlook

- The B-physics potential of the Fermilab Tevatron in Run II and beyond appears to be very rich! Many exciting topics:
  - $B_d \to J/\psi\, K_S$:
    - $\Delta \sin(2\beta) = ?$
    - Keep in mind that Standard Model predicts very small direct CP violation for $B \to J/\psi\, K$.
    - Theoretical accuracy in the SM? $(B_s \to J/\psi\, K_S)$
  - $B_d \to \pi\pi$:
    - Penguins $\Rightarrow$ serious problems in the extraction of α!
    - Probably a hard job!
    - New strategies desirable . . . $(B_s \to K^+K^-)$
  - $B_d \to D^{(*)\pm}\pi^{\mp}$:
    - Theoretically clean strategy to extract $\gamma + 2\beta$.
  - $B \to DK$:
    - Theoretically clean strategy to extract γ.
  - $B \to \pi K$:
    - Have a very interesting physics potential!
    - Probe γ and EWPs.
    - Field of active research . . .

- The B_s system is the "promised land" for hadron machines:
  - Will not be accessible at $\Upsilon(4S)$; hadron machines provide a lot of statistics: very desirable for B_s studies!
  - Reach for B_s mixing parameters ΔM_s and $\Delta\Gamma_s$?
  - $B_s \to D_s K$:
    - Theoretically clean strategy to extract $\gamma - 2\delta\gamma$.
  - $B_s \to J/\psi\,\phi$:
    - Extraction of mixing parameters & $2\,\delta\gamma = \mathcal{O}(0.03)$.
    - Interesting probe for new-physics!
    - Theoretical accuracy in the SM? ($B_d \to J/\psi\,\rho^0$)
- New strategies to extract CKM phases:
  - γ from $B_{s(d)} \to J/\psi\, K_{\rm S}$ or $B_{d(s)} \to D^+_{d(s)}\, D^-_{d(s)}$
  - β and γ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$:
    - First experimental feasibility studies for LHCb appear very promising! What about BTeV?
  - Angular distributions of certain $B_{d,s}$ decays.
- Additional interesting topics:
  - Resolution of discrete ambiguities.
  - CP violation in inclusive modes to probe γ.
  - Search for new physics with D decays.
  - ...