Flavour Physics and

CP Violation

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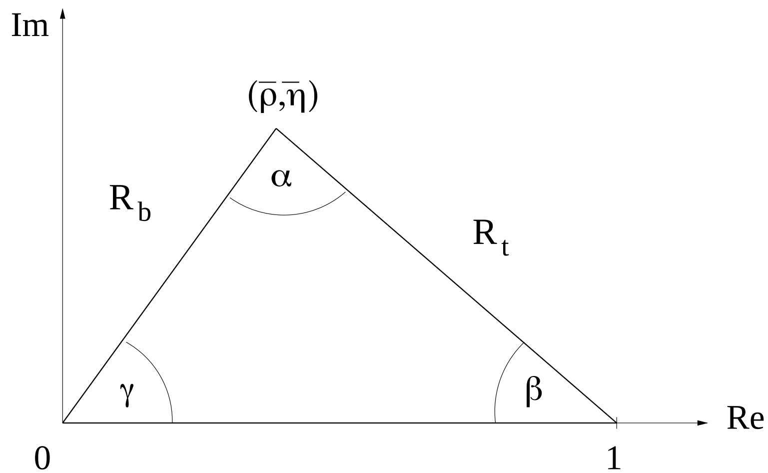
(II)

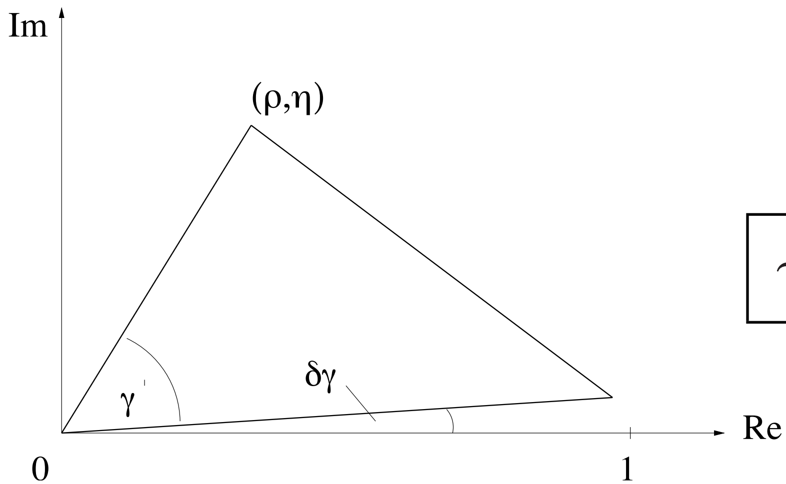
The Central Targets ...

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



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

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



$$\gamma = \gamma' + \delta\gamma, \quad \delta\gamma = \lambda^2\eta = \mathcal{O}(1^\circ)$$

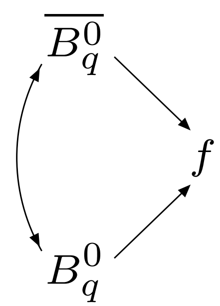
Back to the Key Problem ...

Hadronic matrix elements $\langle \overline{f} | Q_k^j(\mu) | \overline{B} \rangle$

- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\to$ typically strategies to determine 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 $SU(3)_{\mathrm{F}}$:

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

- Decays of neutral B_d and B_s mesons:



Interference effects through B_q^0–$\overline{B_q^0}$ mixing

  - "Mixing-induced" CP violation ...

Lecture II

- Exploring CP Violation through Amplitude Relations:
  - Example: $B^\pm \to K^\pm D$, $B_c^\pm \to D_s^\pm D$
- Exploring CP Violation through Neutral B Decays:
  - Time Evolution of Neutral B Decays
  - B-Factory Benchmark modes: $B_d \to J/\psi K_{\rm S}$, $B_d \to \pi^+\pi^-$
- The "El Dorado" for Hadron Colliders: B_s System
  - Basic Features
  - Benchmark Decays:
    * $B_s \to J/\psi\phi$
    * $B_s \to D_s^\pm K^\mp$ (complements $B_d \to D^\pm\pi^\mp$)
    * $B_s \to K^+K^-$ (complements $B_d \to \pi^+\pi^-$)

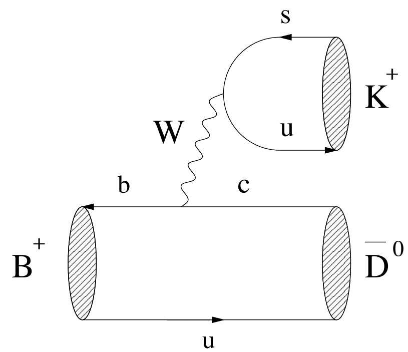
Exploring CP Violation

Through Amplitude Relations:

$$B^{\pm} \longrightarrow K^{\pm} D,\ B_c^{\pm} \longrightarrow D_s^{\pm} D$$

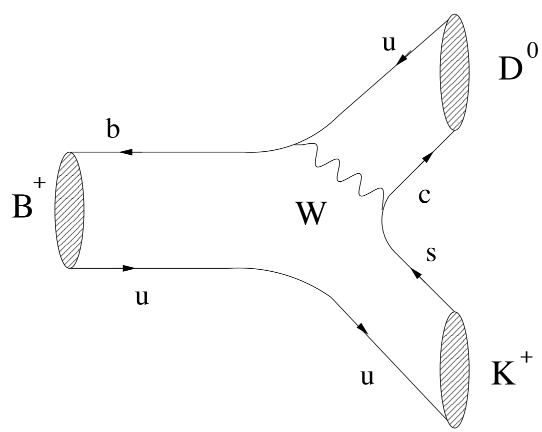
The Classical Triangle Approach [Gronau & Wyler ('91)]

- $B^+ \to K^+\overline{D^0}$: $\to$ *"colour-allowed"* decay



$\propto \lambda |V_{cb}|$

- $B^+ \to K^+ D^0$: $\to$ *"colour-suppressed"* decay

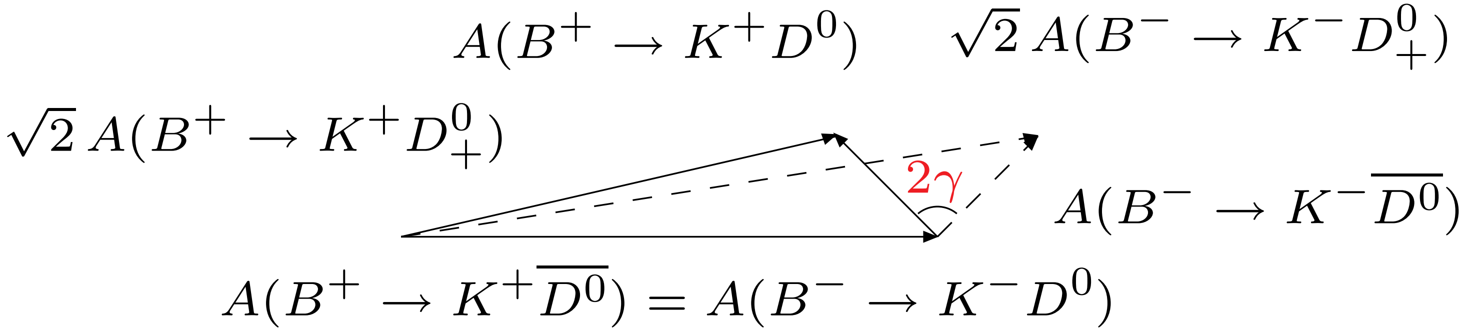


$\propto |V_{ub}| \, e^{i\gamma}$

- $B^+ \to K^+ D^0_+$: $\to$ CP eigenstate D^0_+ $\Rightarrow$ **interference effects!**

$|D^0_+\rangle = \frac{1}{\sqrt{2}}[|\overline{D^0}\rangle + |D^0\rangle]$

- We then arrive at the following amplitude triangles:



$\Rightarrow$ **theoretically *clean* determination of γ!**

- Triangles are unfortunately very squashed:

$$\left| \frac{A(B^+ \to K^+ D^0)}{A(B^+ \to K^+ \overline{D^0})} \right| \approx \frac{1}{\lambda} \frac{|V_{ub}|}{|V_{cb}|} \times \frac{a_2}{a_1} \approx 0.4 \times 0.3 = \mathcal{O}(0.1)$$

$\Rightarrow$ **approach is very difficult in practice!**

- Another – more subtle – problem: $\boxed{\text{BR}(B^+ \to K^+ D^0)}$

  – $D^0 \to K^- \ell^+ \nu_\ell$ would be ideal to measure this tiny branching ratio:

  however, huge background from semileptonic B decays $\Rightarrow$

  – Have to use Cabibbo-allowed hadronic $D^0 \to f_{\rm NE}$ decays:

$$B^+ \to K^+ D^0 \,[\to f_{\rm NE} = \pi^+ K^-, \rho^+ K^-, ...].$$

  – Unfortunately, another decay path into the *same* final state through

$$B^+ \to K^+ \overline{D^0} \,[\to f_{\rm NE}],$$

  where BR$(B^+ \to K^+ \overline{D^0})$ is $\mathcal{O}(10^2)$ *larger* than BR$(B^+ \to K^+ D^0)$, while $\overline{D^0} \to f_{\rm NE}$ is DCS, i.e. $\mathcal{O}(10^{-2})$ *smaller* than $D^0 \to f_{\rm NE}$:

$$\Rightarrow \boxed{\text{interference effects of } \mathcal{O}(1)!}$$

  – If two different final states are measured, γ can be extracted ...

[Atwood, Dunietz & Soni (1997)]

There is another species

of charged B mesons:

B_c System

Preliminaries

- Discovered by CDF through $B_c^+ \to J/\psi\,\ell^+\nu_\ell$: [CDF, *PRL* **81** (1998) 2432]

$$M_{B_c} = (6.40 \pm 0.39 \pm 0.13)\text{GeV}$$
$$\tau_{B_c} = (0.46^{+0.18}_{-0.16} \pm 0.03)\text{ps.}$$

- D0 observed recently $B_c^+ \to J/\psi\,\mu^+ X$: [D0 Note 4539-CONF (Aug 2004)]

$$M_{B_c} = (5.95^{+0.14}_{-0.13} \pm 0.34)\text{GeV}$$
$$\tau_{B_c} = (0.448^{+0.123}_{-0.096} \pm 0.121)\text{ps.}$$

- Now also evidence for $B_c^+ \to J/\psi\pi^+$ at CDF: [CDF Note 7438 (Feb 2005)]

$$\Rightarrow \quad M_{B_c} = (6.2870 \pm 0.0048 \pm 0.0011)\text{GeV.}$$

- Run-II of the Tevatron will provide further insights into B_c physics, and a huge number of B_c mesons will be produced at LHCb:

Can insights into CP violation be obtained from B_c-meson decays?

The Triangle Approach in the B_c-Meson System

- B_c counterparts of $B_u^\pm \to K^\pm D$:

$B_c^\pm \to D_s^\pm D$: $\quad\Rightarrow\quad$ also a determination of γ!

[M. Masetti (1992)]

- For the extraction of γ, the following amplitude relations are used:

$$\sqrt{2}A(B_c^+ \to D_s^+ D_+^0) = A(B_c^+ \to D_s^+ D^0) + A(B_c^+ \to D_s^+ \overline{D^0})$$

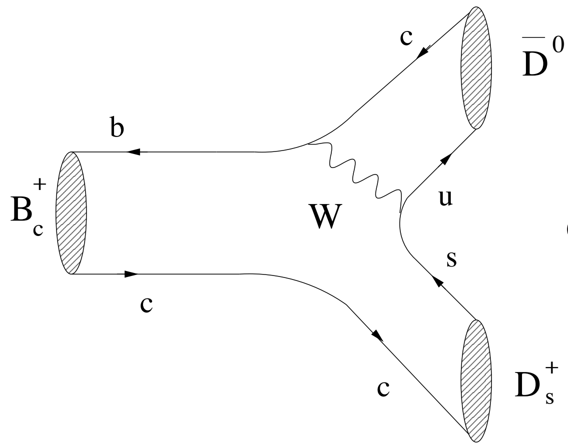
$$\sqrt{2}A(B_c^- \to D_s^- D_+^0) = A(B_c^- \to D_s^- \overline{D^0}) + A(B_c^- \to D_s^- D^0)$$

$$\begin{aligned} A(B_c^+ \to D_s^+ \overline{D^0}) &= A(B_c^- \to D_s^- D^0) \\ A(B_c^+ \to D_s^+ D^0) &= A(B_c^- \to D_s^- \overline{D^0}) \times e^{2i\gamma} \end{aligned}$$

- The situation appears completely analogous to the $B^\pm \to K^\pm D$ case ...

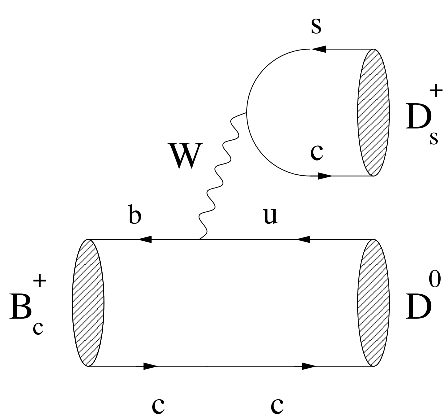
- However, there is an important difference: Feynman diagrams $\longrightarrow$

  - $B_c^+ \to D_s^+ \overline{D^0}$: $\longrightarrow$ *"colour-suppressed"* decay



$$\propto \lambda |V_{cb}|$$

  - $B_c^+ \to D_s^+ D^0$: $\longrightarrow$ *"colour-allowed"* decay

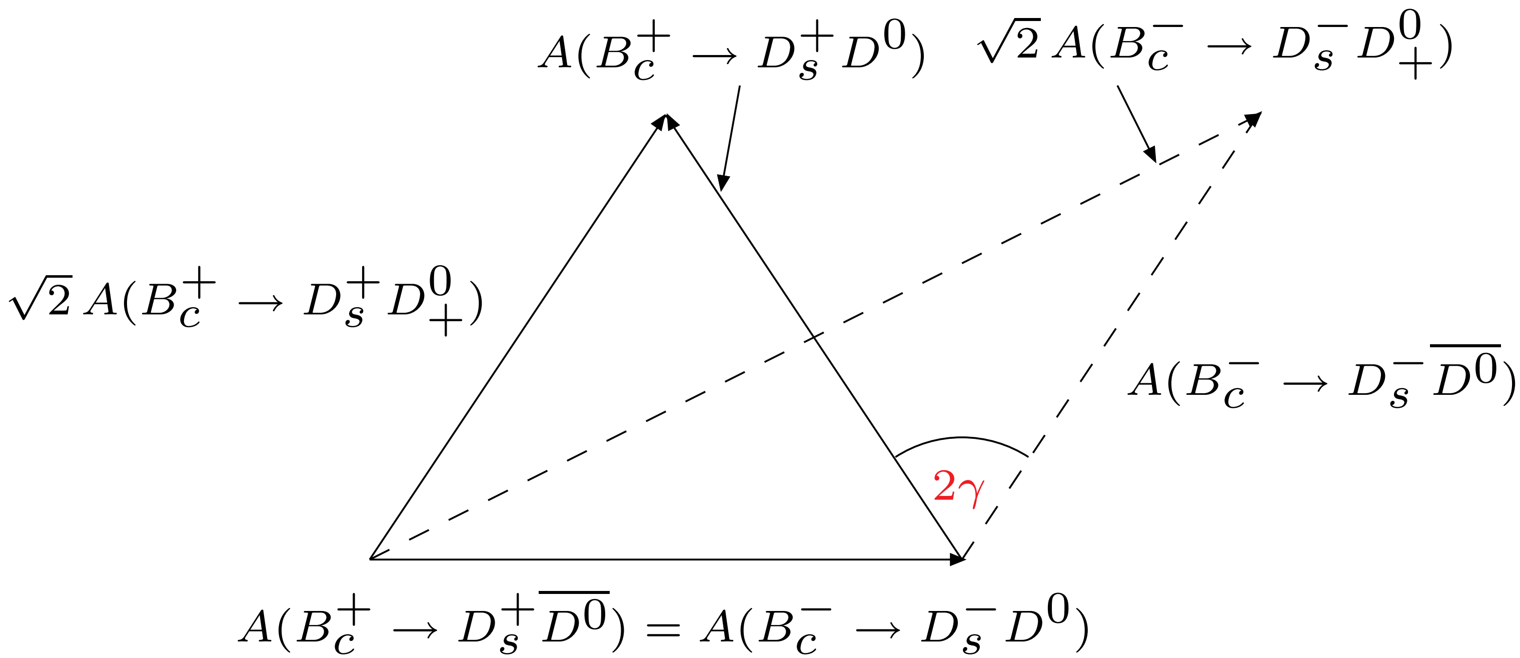


$$\propto |V_{ub}|\, e^{i\gamma}$$

– Consequently, in the $B_c^\pm \to D_s^\pm D$ system, the amplitude associated with the *small* CKM element V_{ub} is *not* colour-suppressed, whereas the larger CKM element V_{cb} enters with a colour-suppression factor:

$$\Rightarrow \quad \left|\frac{A(B_c^+ \to D_s^+ D^0)}{A(B_c^+ \to D_s^+ \overline{D^0})}\right| \approx \frac{1}{\lambda}\frac{|V_{ub}|}{|V_{cb}|} \times \frac{a_1}{a_2} \approx 0.4 \times 3 = \mathcal{O}(1)$$

$\Rightarrow$ *non-squashed* triangles, i.e. *ideal* theoretical realization:



[R.F. & Wyler (2000)]

Status of the Relevant Branching Ratios

- Non-leptonic decays: $\Rightarrow$ large hadronic uncertainties!

  - Factorization (!?), certain form factors have to be used ...

- First estimates of BRs: Liu & Chao (1997); Colangelo & De Fazio (2000); ...

- Most recent analysis, using a *relativistic quark model*:

  - Predicts branching ratios for $B^+ \to \overline{D^0} e^+ \nu_e$, $B^+ \to K^+ \overline{D^0}$ and $B^+ \to D_s^+ \overline{D^0}$ in good accordance with experiment!

  - Application of the model to calculate the B_c branching ratios: $\Rightarrow$

$$B_c^+ \to D_s^+ \overline{D^0} : 1.74 \times 10^{-6}, \quad B_c^+ \to D_s^+ D^0 : 2.48 \times 10^{-6}$$

$$B_c^+ \to D^+ \overline{D^0} : 3.24 \times 10^{-5}, \quad B_c^+ \to D^+ D^0 : 1.11 \times 10^{-7}.$$

[Ivanov, Körner & Pakhomova, *Phys. Lett.* **B555** (2003) 189]

  - Semileptonic B_c decays were recently addressed $\to$ nice testing ground!

[Ivanov, Körner & Santorelli, hep-ph/0501051]

Other Interesting Aspects of B_c Mesons

- Lowest lying bound state of two heavy quarks, $\bar{b}$ and c: $\Rightarrow$
  - QCD dynamics of the B_c^+ mesons is similar to quarkonium systems, such as $\bar{b}b$ and $\bar{c}c$, which are approximately non-relativistic.
  - Important difference: B_c contains open flavour

$\Rightarrow$ stable under strong interactions!

- Quarkonium-like B_c mesons provide an important laboratory to explore the interplay of strong and weak interactions:
  - Heavy-Quark Expansions (HQE)
  - Non-Relativistic QCD (NRQCD)
  - Factorization, ...

Can be tested in a setting complementary to weak hadron decays!

$\longrightarrow$ B_c lifetime & inclusive decays, leptonic and semileptonic decays, ...

[For more details, see *B Decays at the LHC*, hep-ph/0003238]

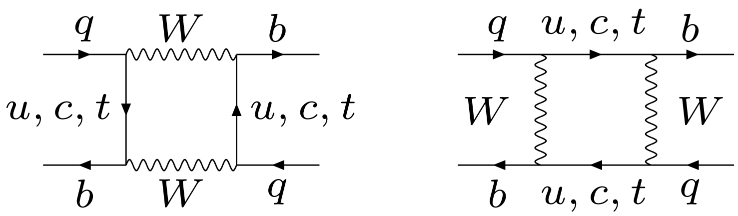
Exploring CP Violation

through

Neutral B Decays

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

- Lowest-order SM contributions:



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

$$i\,\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left[\begin{pmatrix} M_0^{(q)} & M_{12}^{(q)} \\ M_{12}^{(q)*} & M_0^{(q)} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_0^{(q)} & \Gamma_{12}^{(q)} \\ \Gamma_{12}^{(q)*} & \Gamma_0^{(q)} \end{pmatrix}\right]\cdot\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

- Mass eigenstates with masses $M_{\rm H}^{(q)}$, $M_{\rm L}^{(q)}$ and decay widths $\Gamma_{\rm H}^{(q)}$, $\Gamma_{\rm L}^{(q)}$:

$$\Delta M_q \equiv M_{\rm H}^{(q)} - M_{\rm L}^{(q)}, \quad \Delta\Gamma_q \equiv \Gamma_{\rm H}^{(q)} - \Gamma_{\rm L}^{(q)}, \quad \Gamma_q \equiv \frac{1}{2}\left[\Gamma_{\rm H}^{(q)} + \Gamma_{\rm L}^{(q)}\right]$$

Decay Rates of Neutral B_q Mesons

- Time evolution due to B^0_q–$\overline{B^0_q}$ mixing: $\Rightarrow$

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

  - The time dependence enters through the following functions:

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

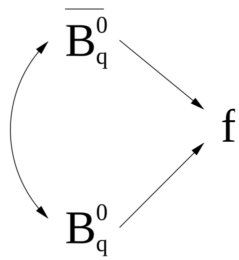
$$\left|g_{\mp}^{(q)}(t)\right|^2=\frac{1}{4}\left[e^{-\Gamma_{\rm L}^{(q)}t}+e^{-\Gamma_{\rm H}^{(q)}t}\mp 2\,e^{-\Gamma_q t}\cos(\Delta M_q t)\right]$$

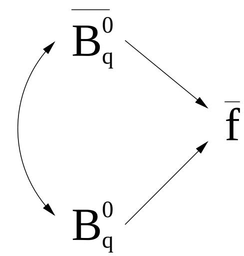
  - The overall normalization Γ_f denotes the "unevolved" $B^0_q\to f$ rate.

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

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

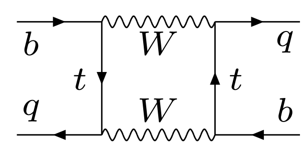
$$\xi_f^{(q)} = e^{-i\Theta_{M_{12}}^{(q)}} \frac{A(\overline{B_q^0} \to f)}{A(B_q^0 \to f)} \qquad \xi_{\overline{f}}^{(q)} = e^{-i\Theta_{M_{12}}^{(q)}} \frac{A(\overline{B_q^0} \to \overline{f})}{A(B_q^0 \to \overline{f})}$$





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

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



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

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

CP Violation in Neutral B_q Decays

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

- Time-dependent CP asymmetry:

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

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

$$\mathcal{A}_{\rm CP}^{\rm mix} \equiv \frac{2\,\mathrm{Im}\,\xi_f^{(q)}}{1+|\xi_f^{(q)}|^2} \quad \Rightarrow$$

new aspect: "mixing-induced" CPV!

- $\Delta\Gamma_q \equiv \Gamma_{\rm H}^{(q)} - \Gamma_{\rm L}^{(q)}$ provides another observable:

$$\mathcal{A}_{\Delta\Gamma} \equiv \frac{2\,\mathrm{Re}\,\xi_f^{(q)}}{1+|\xi_f^{(q)}|^2} \quad \to \quad [\mathcal{A}_{\rm CP}^{\rm dir}]^2 + [\mathcal{A}_{\rm CP}^{\rm mix}]^2 + [\mathcal{A}_{\Delta\Gamma}]^2 = 1.$$

- In general, contributions from two CKM amplitudes:

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

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

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

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

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

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

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

B-Factory

Benchmark

Modes

... in view of BaBar and Belle data!

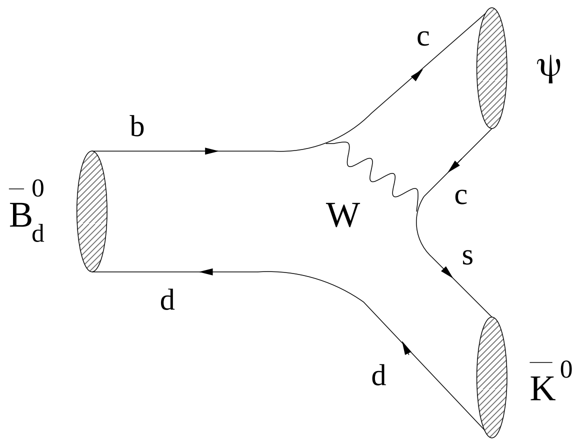
Exploring CP Violation

Through

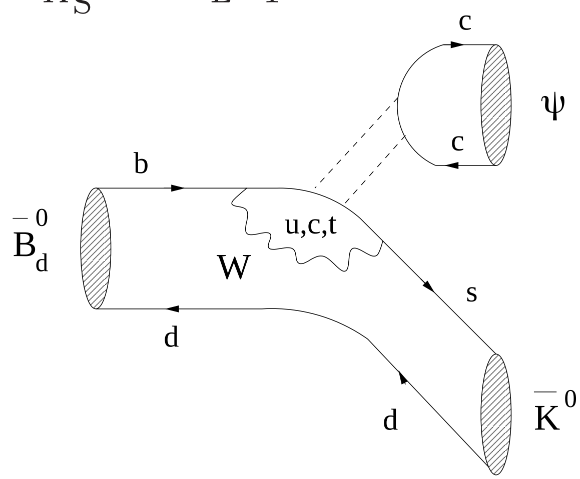
$$\boxed{B_d \to J/\psi K_{\mathrm{S}}}$$

The "Golden" B-Decay Mode ...

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



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



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

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

$$A(\overline{B^0_d} \to J/\psi K_\mathrm{S}) = \lambda_c^{(s)}(A_\mathrm{T}^c + A_\mathrm{P}^c) + \lambda_u^{(s)} A_\mathrm{P}^u + \lambda_t^{(s)} A_\mathrm{P}^t$$

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

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

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

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

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

[Bigi, Carter and Sanda (1980–1981)]

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

- Current status: → *no* signs for direct CP violation, and

$$\sin 2\beta = \left\{ \begin{array}{ll} 0.722 \pm 0.040 \pm 0.023 & \text{(BaBar)} \\ 0.728 \pm 0.056 \pm 0.023 & \text{(Belle)} \end{array} \right\} \Rightarrow \underbrace{\boxed{\sin 2\beta = 0.725 \pm 0.037}}_{\text{world average}}$$

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

- *Excellent* agreement with the "CKM fits" of the SM! [NP: see Lecture III]

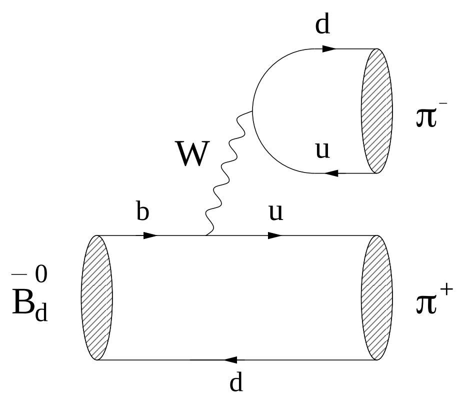
Exploring CP Violation

Through

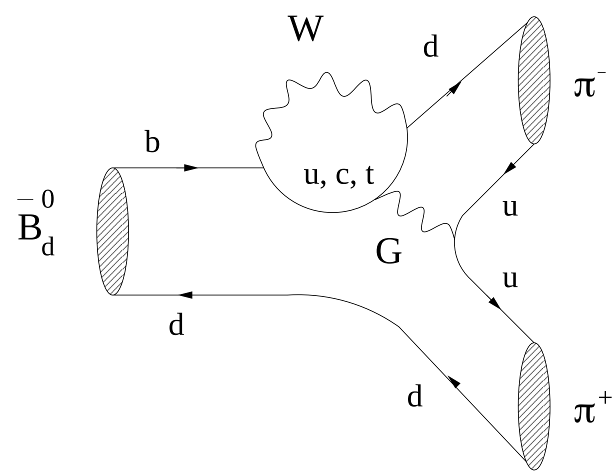
$$\boxed{B_d \to \pi^+\pi^-}$$

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

- Decay into a CP eigenstate: eigenvalue $+1$.



$\lambda_u^{(d)} \equiv V_{ud}V_{ub}^*$



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

- Structure of the decay amplitude:

$$\boxed{A(B_d^0 \to \pi^+\pi^-) = \lambda_u^{(d)}(A_{\rm T}^u + A_{\rm P}^u) + \lambda_c^{(d)} A_{\rm P}^c + \lambda_t^{(d)} A_{\rm P}^t}$$

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

$$\boxed{A(B_d^0 \to \pi^+\pi^-) \propto \left[e^{i\gamma} - de^{i\theta}\right]} \quad de^{i\theta} = \frac{1}{R_b}\left[\frac{A_{\rm P}^c - A_{\rm P}^t}{A_{\rm T}^u + A_{\rm P}^u - A_{\rm P}^t}\right]$$

- Consequently, we obtain: $$\xi^{(d)}_{\pi^+\pi^-} = -e^{-i\phi_d}\left[\frac{e^{-i\gamma}-de^{i\theta}}{e^{+i\gamma}-de^{i\theta}}\right]$$

  - In contrast to $B_d \to J/\psi K_S$, $de^{i\theta}$ is *not* doubly Cabibbo-suppressed:

$\Rightarrow$ "penguin problem" in $B_d \to \pi^+\pi^-$!

  - If (!) we had negligible penguin contributions ($d = 0$):

$$\xi^{(d)}_{\pi^+\pi^-} \longrightarrow -e^{-i(\phi_d+2\gamma)} \stackrel{\rm SM}{=} -e^{-i(2\beta+2\gamma)}$$

$$\Rightarrow \begin{cases} \mathcal{A}^{\rm mix}_{\rm CP}(B_d \to \pi^+\pi^-) = +\sin(\underbrace{2\beta + 2\gamma}_{2\pi-2\alpha}) = -\sin 2\alpha \\ \mathcal{A}^{\rm dir}_{\rm CP}(B_d \to \pi^+\pi^-) = 0 \end{cases}$$

- Comments on the parametrization of the CP-violating observables:

  - ϕ_d and γ enter directly and not α.
  - Since ϕ_d can be fixed through $B_d \to J/\psi K_S$, we may use the CP-violating observables of $B_d \to \pi^+\pi^-$ to probe the UT angle γ.
  - This is advantageous in order to deal with penguins and NP.

- Experimental status of the CP-violating observables:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = \begin{cases} -0.09 \pm 0.15 \pm 0.04 & \text{(BaBar '04)} \\ -0.56 \pm 0.12 \pm 0.06 & \text{(Belle '05)} \end{cases}$$

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = \begin{cases} +0.30 \pm 0.17 \pm 0.03 & \text{(BaBar '04)} \\ +0.67 \pm 0.16 \pm 0.06 & \text{(Belle '05)} \end{cases}$$

- The large direct CP violation in $B_d \to \pi^+\pi^-$, which is indicated by the Belle data, requires large penguins and large CP-conserving phases):[1]

$\Rightarrow$ **penguins *cannot* be neglected** $\Rightarrow$ use data to control them...

- Several strategies were proposed, including the following ones:
  - Isospin analysis of the $B \to \pi\pi$ system: [Gronau & London (1990)]
    - Essentially *clean*, but difficult to implement in practice.
  - Complement $B_d \to \pi^+\pi^-$ with $B_s \to K^+K^-$: [R.F. (1999)]
    - U-spin strategy, ideally suited for LHCb $\to$ **B_s decays**

[1] This feature is consistent with the direct CP violation observed in $B_d \to \pi^\mp K^\pm$; see Lecture III.

The "El Dorado" for

Hadron Colliders:

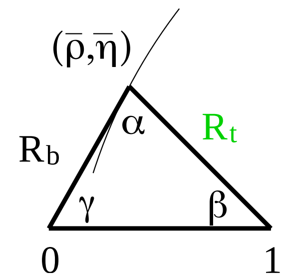
B_s System

- At the e^+e^- B factories operating @ $\Upsilon(4S)$, *no* B_s mesons are accessible!

- However, plenty of B_s mesons are produced at hadron colliders ...

Basic Features of the B_s System

- Mass difference ΔM_s.
  - $\Delta M_s/\Delta M_d \;\Rightarrow\; R_t$ from $\xi \equiv \sqrt{\hat{B}_{B_s}} f_{B_s}/(\sqrt{\hat{B}_{B_d}} f_{B_d})$
  - $\Delta M_s|_{\rm exp} > 14.4\,\text{ps}^{-1}$ (95% C.L.) $\;\Rightarrow\; \gamma \lesssim 90^\circ$
  - Important aspect of lattice studies: uncertainties of ξ...



[Kronfeld & Ryan (2000); Battaglia *et al.* (2000); Hashimoto (2004)]

- Decay width difference $\Delta\Gamma_s$:
  - $\Delta\Gamma_s/\Gamma_s = \mathcal{O}(10\%)$, while $\Delta\Gamma_d/\Gamma_d$ is negligible!
  - Interesting studies with "untagged" B_s-decay rates:

$$\langle\Gamma(B_q(t)\to f)\rangle \equiv \Gamma(B^0_q(t)\to f) + \Gamma(\overline{B^0_q}(t)\to f).$$

[Dunietz (1995); R.F. & Dunietz (1996–97)]

  - *First* Tevatron-II results using $B_s \to J/\psi\phi$: [Dighe, Dunietz & R.F. ('99)]

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \begin{cases} 0.65^{+0.25}_{-0.33} \pm 0.01 & \text{(CDF)} \\ 0.21^{+0.33}_{-0.45} & \text{(D0)} \end{cases}$$

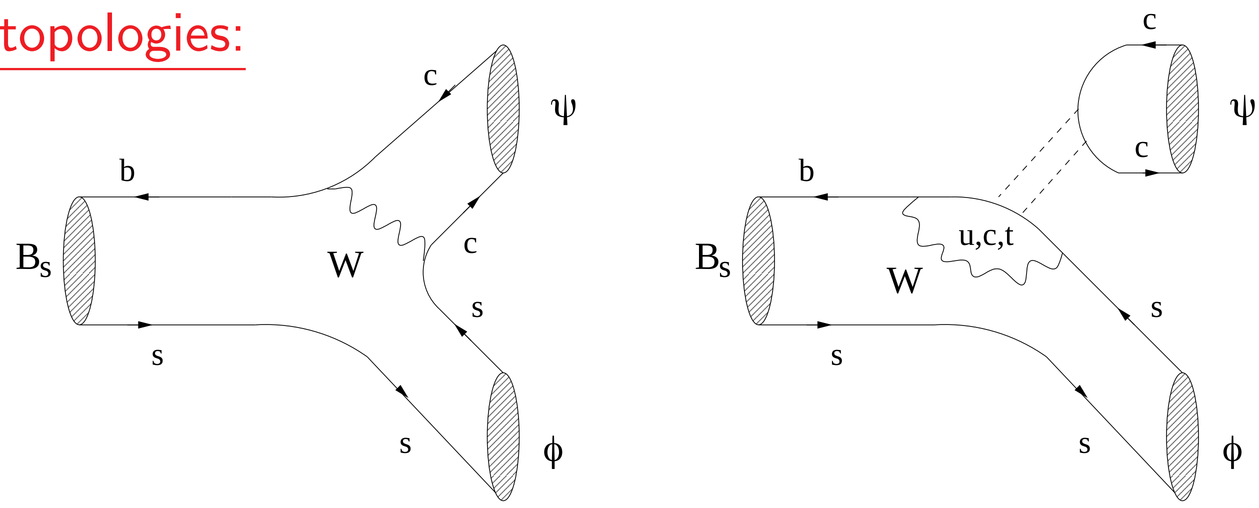
Benchmark

Decays of

B_s Mesons

CP Violation in $B_s \to J/\psi\phi$

- Decay topologies:



$\Rightarrow$ B_s counterpart of the "golden" decay $B_d \to J/\psi K_{\rm S}$

- The amplitude structure is therefore analogous to $B_d \to J/\psi K_{\rm S}$:

$$A(B_s \to J/\psi\, \phi) \propto \left[1 + \lambda^2 a' e^{i\vartheta'} e^{i\gamma}\right], \quad a' e^{i\vartheta'} = \left.\frac{\text{"Penguin"}}{\text{"Tree"}}\right|_{B_s \to \psi\phi} = \mathcal{O}(0.2) = \mathcal{O}(\overline{\lambda})$$

- However, there is an important difference:

Final state is an admixture of different CP eigenstates $\Rightarrow$

- Using the angular distribution of the $J/\psi[\to \ell^+\ell^-]\phi[\to K^+K^-]$ decay products, the different CP eigenstates can be disentangled: $\to$
  - Direct CP-violating effects: $0 + \mathcal{O}(\overline{\lambda}^3)$
  - Mixing-induced CP-violating effects: $\Rightarrow$ determination of

$$\boxed{\sin\phi_s + \mathcal{O}(\overline{\lambda}^3) = \sin\phi_s + \mathcal{O}(10^{-3})}$$

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

- Standard Model: $\phi_s = -2\delta\gamma = -2\lambda^2\eta = \mathcal{O}(10^{-2}) \quad \Rightarrow$
  - Extraction of $\delta\gamma$ affected by hadronic uncertainties of $\mathcal{O}(10\%)$.
  - Can be controlled through $B_d \to J/\psi\rho^0$ [R.F. (1999)]

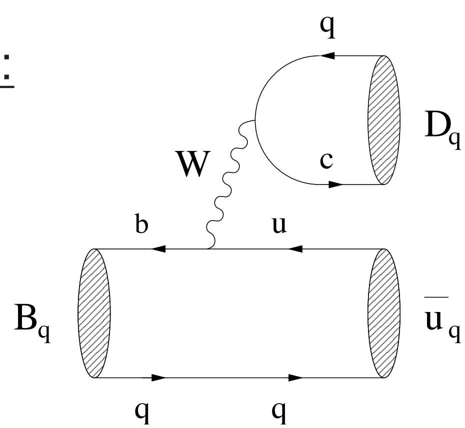
- Big Hope: Experiments will find a *sizeable* value of $\sin\phi_s$

... would give us an *immediate* signal for CP-violating NP!

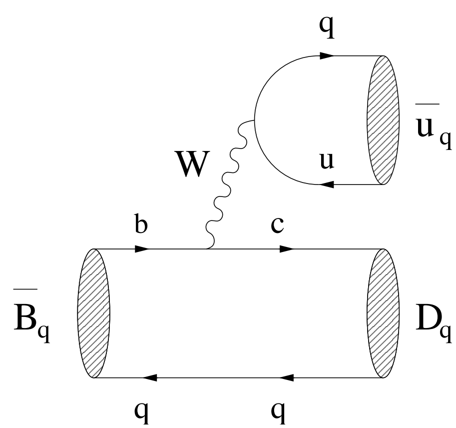
[Nir & Silverman (1990); ...; Dunietz, R.F. & Nierste (2001)]

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

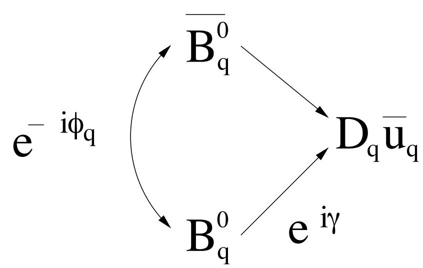
- General case:



$\propto e^{i\gamma}$



no weak phase



$$\boxed{\phi_q + \gamma}$$

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

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

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

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

- The observables provided by the $\cos(\Delta M_q t)$ and $\sin(\Delta M_q t)$ terms of the time-dependent rates allow a *clean* determination of $\phi_q + \gamma$.

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

- Since ϕ_q can be determined separately, γ can be extracted ...

- <u>However, there are also problems:</u>

  – We encounter an *eightfold* discrete ambiguity for $\phi_q + \gamma$!?

  – In the case of $q = d$, an additional input is required to extract x_d since interference effects of $\mathcal{O}(x_d^2)$ would otherwise have to be resolved ...

- <u>Combined analysis of $B_s^0 \to D_s^{(*)+} K^-$ and $B_d^0 \to D^{(*)+} \pi^-$:</u>

  $\boxed{s \leftrightarrow d}$ $\Rightarrow$ <u>U-spin symmetry provides an interesting play ground:</u>

  – An *unambiguous* value of γ can be extracted from the observables!

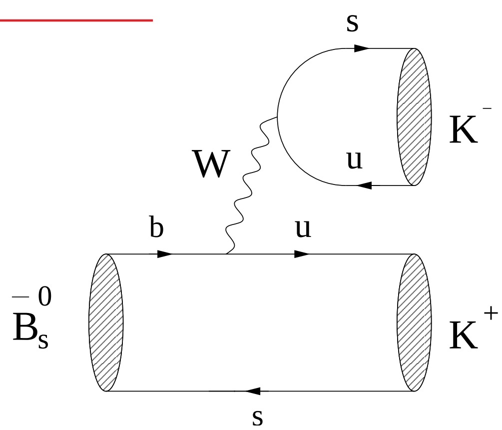
  – To this end, x_d has *not* to be fixed, and x_s may *only* enter through a $1 + x_s^2$ correction, which is determined through *untagged* B_s rates!

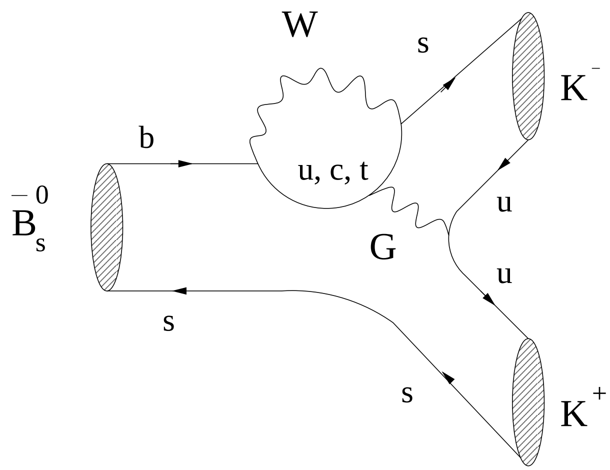
  – Very promising first studies by LHCb [G. Wilkinson @ CKM 2005] ...

[R.F., *Nucl. Phys.* **B671** (2003) 459]

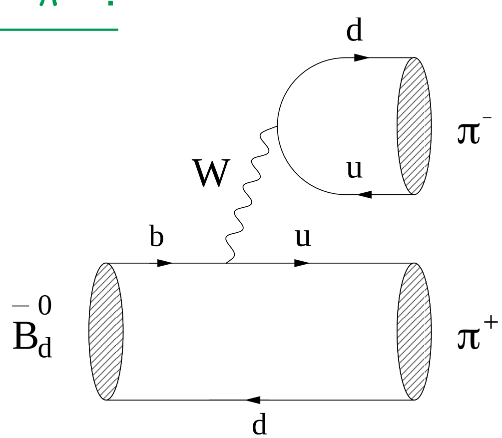
The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

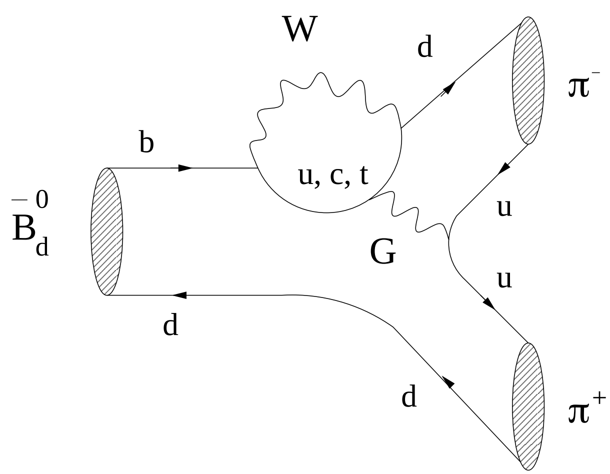
- $\overline{B^0_s} \to K^+K^-$:





- $\overline{B^0_d} \to \pi^+\pi^-$:





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

- Structure of the decay amplitudes in the SM [see above]:

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

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

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

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

- General form of the CP asymmetries:

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

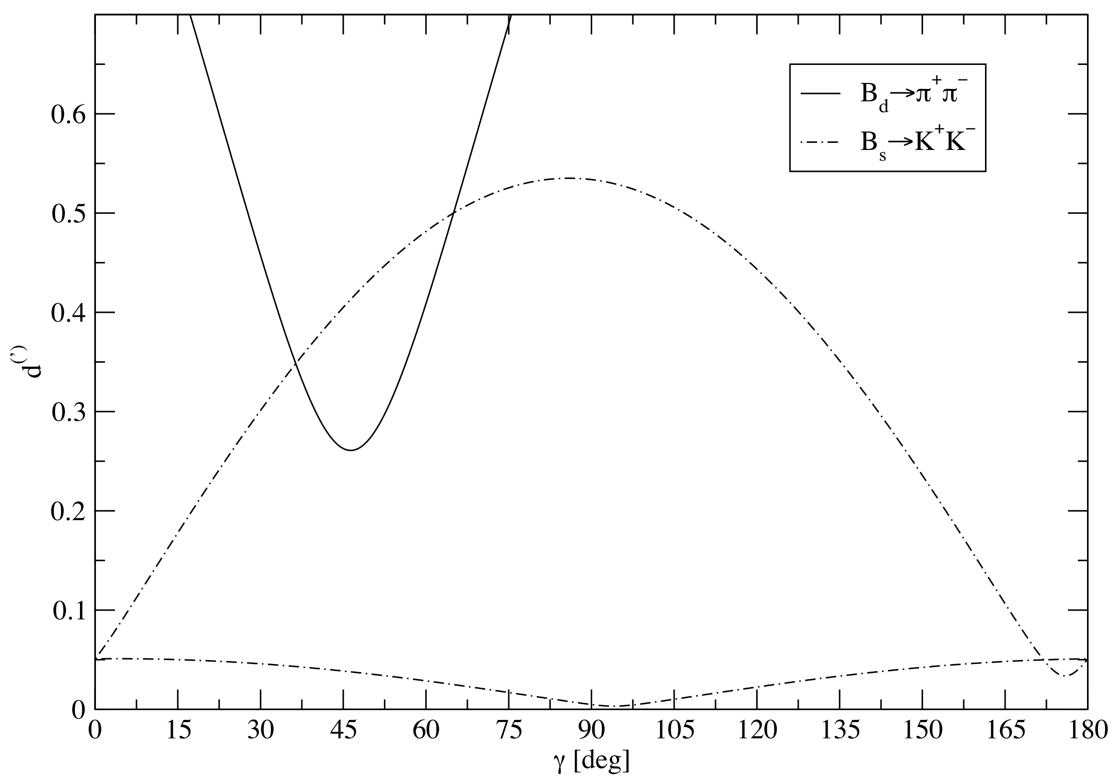
$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) = G_1'(d', \theta', \gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = G_2'(d', \theta', \gamma, \phi_s)$$

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

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

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

- Example:
  - Input parameter:
    * $\phi_d = 47°$, $\gamma = 65°$, $d = d' = 0.5$, $\theta = \theta' = 140°$
    * B_s^0–$\overline{B_s^0}$ mixing phase is neglected, i.e. $\phi_s = 0$
  - CP asymmetries:
    * $B_d \to \pi^+\pi^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = -0.37$, $\mathcal{A}_{\rm CP}^{\rm mix} = +0.61$
    * $B_s \to K^+K^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = +0.13$, $\mathcal{A}_{\rm CP}^{\rm mix} = -0.14$



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

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

  - $d = d'$: $\Rightarrow$ determination of γ, d, θ, θ'
  - $\theta = \theta'$: $\Rightarrow$ test of the U-spin symmetry!

[R.F. (1999)]

- 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 $\mathcal{O}(1^\circ)$

... first steps at Tevatron-II may be possible!

[Recent analyses: G. Balbi *et al.*, CERN-LHCb/2003-123 & 124]

The Major Lessons of Lecture II

- Amplitude relations allow us to eliminate the hadronic uncertainties:
  - γ can be cleanly extracted from $B^\pm \to K^\pm D$, $B_c^\pm \to D_s^\pm D$ decays, where the latter modes offer theoretical advantages.
  - Practical implementation is challenging; several variants proposed ...
- In the decays of neutral B_q mesons, interference effects between B_q^0–$\overline{B_q^0}$ mixing and decay processes can be used:

$\Rightarrow$ mixing-induced CP violation

  - If the decay is dominated by a single weak amplitude, the hadronic matrix element cancels $\to$ clean determination of $\sin(\phi_q - \phi_f)$.
  - Otherwise, amplitude relations provide again a useful tool ...
- The B_s-meson system is the "El Dorado" for hadron colliders:
  - Mixing parameters ΔM_s and Γ_s are of key interest.
  - Several promising decays to explore CP violation...

Impact of NP? $\to$ Lecture III