Rare *B* Decays and all that ...

Thorsten Feldmann and Thomas Mannel

Theoretical Physics I, Siegen University

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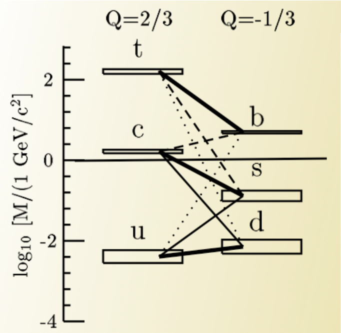
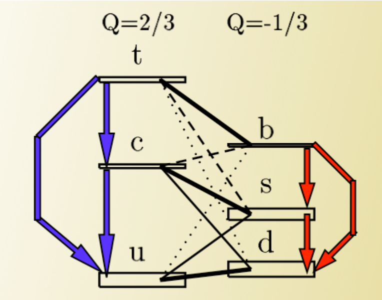
Preliminary Remarks

- Rare Decays: Transitions are suppressed by either
  - Small (combinations of) CKM Matrix elements or
  - Loop factors $1/(16\pi^2)$ or
  - both





Outline of the event:

- Part 1: Rare decays in the Standard Model (TM)
- Part 2: Effective Hamiltonian (TF)

Rare *B* Decays
Introduction and Standard Model

Thomas Mannel

Theoretische Physik I   Universität Siegen

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Outline Part 1

1. Quarks in the SM: $SU(2)_L \times U(1)_Y$
   - Symmetries and Quantum Numbers
   - Quark Mixing and CKM Matrix
2. Peculiarities of Flavour in the Standard Model
   - Peculiarities of SM CP / Flavour
3. Rare Decays: Small CKM Elements
4. Rare Decays: Loop Suppressd FCNC Decays

Gauge Structure of the Standard Model

I assume a few things to be known:

- The Standard Model is a gauge theory based on
  $SU(3)_{QCD} \otimes SU(2)_{Weak} \otimes U(1)_{Hypercharge}$
- Eight gluons, three weak gauge bosons, one photon
- Matter (quarks and leptons):
  Multiplets of the gauge group $\to$ Quantum numbers
- Spontaneous Symmetry Breaking:
  Introduction of scalar fields
- Massless Goldstone Modes:
  Higgs Mechanism:
  $\phi \to$ longitudinal modes of gauge bosons: $\phi \sim \partial_\mu W^\mu$

Matter Fields: Quarks

- Left Handed Quarks:
  $SU(3)_C$ Triplets, $SU(2)_L$ Doublets

$$Q_1 = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \; Q_2 = \begin{pmatrix} c_L \\ s_L \end{pmatrix} \; Q_3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

  $SU(2)_L$ will be gauged

- Right Handed Quarks:
  $SU(3)_C$ Triplets, $SU(2)_R$ Doublets

$$q_1 = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \; q_2 = \begin{pmatrix} c_R \\ s_R \end{pmatrix} \; q_3 = \begin{pmatrix} t_R \\ b_R \end{pmatrix}$$

  $SU(2)_R$ introduced “artificially”

Quantum Numbers

- Hypercharge

$$\boxed{Y = T_{3,R} + \frac{1}{2}(B - L)}$$

- Charge

$$\boxed{q = T_{3,L} + Y = T_{3,L} + T_{3,R} + \frac{1}{2}(B - L)}$$

Higgs Fields: Standard Model

- Single $SU(2)$ Doublett: Two Complex Fields

$$\Phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}$$

- Charge Conjugate Field is also an $SU(2)$ Doublett

$$\widetilde{\Phi} = (i\tau_2)\Phi^* = \begin{pmatrix} \phi_0^* \\ -\phi_- = -\phi_+^* \end{pmatrix}$$

- It is useful to gather these into a 2×2 matrix

$$H = \begin{pmatrix} \phi_0^* & \phi_+ \\ -\phi_- & \phi_0 \end{pmatrix}$$

- Transformation Properties: $L \in SU(2)_L$:

$$\Phi \to L\Phi \qquad \widetilde{\Phi} \to L\widetilde{\Phi}$$

- Transformation Properties: $R \in SU(2)_R$:

$$\begin{pmatrix} \phi_0 \\ \phi_- \end{pmatrix} \to R \begin{pmatrix} \phi_0 \\ \phi_- \end{pmatrix} \qquad \begin{pmatrix} \phi_+ \\ -\phi_0^* \end{pmatrix} \to R \begin{pmatrix} \phi_+ \\ -\phi_0^* \end{pmatrix}$$

- In total:

$$H \to LHR^\dagger \qquad (\text{remember } Q \to LQ \quad q \to Rq)$$

- Hypercharges

$$Y\Phi = -\Phi \qquad Y\widetilde{\Phi} = \widetilde{\Phi} \qquad YH = -HT_{3,R}$$

Gauge Interactions

- $SU(3)_{color}$ is gauged (not relevant for us now)
- $SU(2)_L$ is gauged Three W_a^μ Bosons
- Hypercharge is gauged One B^μ Boson
- Recipe: Replace the ordinary derivative in the kinetic terms by the covariant one

$$\partial^\mu \to D^\mu = \partial^\mu - igT_{L,a}W_a^\mu - iYB^\mu$$
$$+\text{QCD interactions}$$

- Weinberg rotation between W_3^μ and B^μ $\cdots$
- I assume you have heard the rest of the story ...
- This is not relevant for the phenomenon of masses and mixing !

Structure of the Standard Model

- Start out from an $SU(2)_L \times SU(2)_R$ symmetric case:
- Kinetic Term for Quarks and Higgs (i: Generation)

$$\mathcal{L}_{kin} = \sum_i \left[\bar{Q}_i \not{\partial} Q_i + \bar{q}_i \not{\partial} q_i \right] + \frac{1}{2} \mathrm{Tr} \left[(\partial_\mu H)^\dagger (\partial^\mu H) \right]$$

- Potential for the Higgs field

$$V = V(H) = V(\mathrm{Tr} \left[H^\dagger H \right])$$

- Interaction between Quarks and Higgs

$$\mathcal{L}_I = -\sum_{ij} y_{ij} \bar{Q}_i H q_j + \text{ h.c.}$$

- y_{ij} can be made diagonal: Any Matrix y can be diagonalized by a Bi-Unitary Transformation:

$$y = U^\dagger y_{diag} W$$

- Thus

$$\mathcal{L}_I = -\sum_{ijk} \bar{Q}_i (U^\dagger)_{ik} y_k W_{kj} H q_j + \text{ h.c.}$$

- Rotation of Q_i and q_j:

$$Q' = UQ \quad q' = Wq$$

- This has no effect on the kinetic term: $y_{ij} = y_i \delta_{ij}$ is the general case!

$$\mathcal{L}_I = -\sum_i y_i \bar{Q}_i H q_i + \text{ h.c.}$$

Sponaneous Symmetry Breaking

- The Higgs Potential is (Renormalizability):

$$V = \kappa \left(\mathrm{Tr} \left[H^\dagger H \right] \right) + \lambda \left(\mathrm{Tr} \left[H^\dagger H \right] \right)^2$$

- For $\kappa < 0$ we have SSB:
  H acquires a Vacuum Expectation Value (VEV)

$$\mathrm{Tr} \left[\langle H^\dagger \rangle \langle H \rangle \right] = -\frac{\kappa}{2\lambda} > 0$$

- Choice of the VEV

$$< \mathrm{Re}\phi_0 >= v \text{ or } < H >= v \, 1_{2\times 2}$$

- Three massless fields: ϕ_+, ϕ_-, Imϕ_0: Goldstone Bosons
- $\phi_0 \to v + \phi_0'$: One massive field
- Higgs Mechanism: The massless scalars become the longitudinal modes of the massive vector bosons:
  - $\phi_\pm \sim \partial^\mu W_\mu^\pm$
  - $\mathrm{Im}\phi_0 \sim \partial^\mu Z_\mu$
- ϕ_0': Physical Higgs Boson

- The Quarks become massive:

$$\mathcal{L}_I = -\sum_i y_i v \bar{Q}_i q_i + \text{ h.c. } + \cdots$$

- We have $\bar{Q}_1 q_1 = \bar{u}_L u_R + \bar{d}_L d_R$ etc.
- Thus

$$\mathcal{L}_{mass} = -m_u(\bar{u}u + \bar{d}d) - m_c(\bar{c}c + \bar{s}s) - m_t(\bar{t}t + \bar{b}b)$$

- This is not (yet) what we want ...
- We still have too much symmetry!

Custodial $SU(2)$

- Symmetry of the Higgs Sector in the Standard Model:

$$SU(2)_L \otimes SU(2)_R \xrightarrow{SSB} SU(2)_{L+R} = SU(2)_C$$

- Note that we cannot have explicit breaking of $SU(2)_R$ in the Higgs sector:

$$\mathrm{Tr}\left[H\tau_i H^\dagger\right] = 0$$

- $SU(2)_C$: Custodial Symmetry!
  $\longrightarrow$ Extra Symmetry in the Higgs sector !
- This is more than needed: Only $U(1)_Y$ is needed
- $U(1)_Y$ will be related to the τ_3 direction of $SU(2)_R$

- Consequences of $SU(2)_C$:
  - Relation between charged and neutral currents: ρ parameter
  - Masses of $W^\pm$ and of Z^0 are equal
  - Up- and Down-type quark masses are equal in each family
  - No mixing occurs among the families
- $SU(2)_C$ is broken by:
  - Yukawa Couplings
  - Gauging only the Hypercharge

$$Y = T_3^{(R)} + \frac{1}{2}(B - L)$$

Breaking $SU(2)_C$: Yukawa Couplings

- Explicit breaking of $SU(2)_C$ by Yukawa Couplings:

$$\mathcal{L}'_I = -\sum_{ij} y'_{ij} \bar{Q}_i H (2T_{3,R}) q_j + \text{ h.c.}$$

- Effect of this term:
  - Introduces a splitting between up- and down quark masses
  - Introduces mixing between different families
  - Affects the ρ parameter
- Total Yukawa Coupling term:

$$\mathcal{L}_I + \mathcal{L}'_I = -\sum_{ij} \bar{Q}_i H (y_i \delta_{ij} + 2T_{3,R} y'_{ij}) q_j + \text{ h.c.}$$

Quark Mass Matrices

- Use the projections

$$P_\pm = \frac{1}{2} \pm T_{3,R} \quad \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

- Up quark Yukawa couplings:

$$\mathcal{L}^u_{mass} = -\sum_{ij} \bar{Q}_i H (y_i \delta_{ij} + y'_{ij}) P_+ q_j + \text{ h.c.}$$

- Down quark Yukawa couplings:

$$\mathcal{L}^d_{mass} = -\sum_{ij} \bar{Q}_i H (y_i \delta_{ij} - y'_{ij}) P_- q_j + \text{ h.c.}$$

- $\to$ mass terms, once $\mathrm{Re}\phi_0 \to v$

- More compact notation

$$\mathcal{U}_{L/R} = \begin{bmatrix} u_{L/R} \\ c_{L/R} \\ t_{L/R} \end{bmatrix} \quad \mathcal{D}_{L/R} = \begin{bmatrix} d_{L/R} \\ s_{L/R} \\ b_{L/R} \end{bmatrix}$$

- Mass Term for Up-type quarks

$$\mathcal{L}^u_{mass} = -v\, \bar{\mathcal{U}}_L Y^u \mathcal{U}_R + \text{ h.c.}$$

with $Y^u = (y + y')$

- Mass Term for down-type quarks

$$\mathcal{L}^d_{mass} = -v\, \bar{\mathcal{D}}_L Y^d \mathcal{D}_R + \text{ h.c.}$$

with $Y^d = (y - y')$

- Mass matrices:

$$\mathcal{M}^u = v\,Y^u \qquad \mathcal{M}^d = v\,Y^d$$

- In general non-diagonal: Diagonalization by a bi-unitary transformation:

$$\mathcal{M} = U^\dagger \mathcal{M}_{diag} W$$

- New basis for the quark fields

$$\mathcal{L}^u_{mass} = -\bar{\mathcal{U}}_L U^{u,\dagger} \mathcal{M}^u_{diag} W^u \mathcal{U}_R + \text{ h.c.}$$

and

$$\mathcal{L}^d_{mass} = -\bar{\mathcal{D}}_L U^{d,\dagger} \mathcal{M}^d_{diag} W^d \mathcal{D}_R + \text{ h.c.}$$

Quark Mixing: The CKM Matrix

- Effect of the basis transformation:
  - Mass matrices become diagonal
  - Interaction with $\mathrm{Re}\,\phi_0$ (= Physical Higgs Boson) becomes diagonal !
  - Interaction with $\mathrm{Im}\,\phi_0$ (= Z_0) becomes diagonal !

$$\begin{aligned}\mathcal{L}_{\mathrm{Re}\,\phi_0} &= -\mathrm{Re}\,\phi_0[\mathcal{U}_L Y^u \mathcal{U}_R + \mathcal{D}_L Y^d \mathcal{D}_R] \\ \mathcal{L}_{\mathrm{Im}\,\phi_0} &= -\mathrm{Im}\,\phi_0[\mathcal{U}_L Y^u \mathcal{U}_R - \mathcal{D}_L Y^d \mathcal{D}_R]\end{aligned}$$

- NO FLAVOUR CHANGING NEUTRAL CURRENTS (at tree level in the Standard Model)
- $\rightarrow$ GIM Mechanism

- Effect on the charged current ONLY:
  Interaction with ϕ_-:

$$\begin{aligned}
&\sum_{ij} \bar{Q}_i (y_i \delta_{ij} + y'_{ij}) \phi_- \tau_- P_+ q_j + \text{ h.c.} \\
&= \mathcal{D}_L Y^u \mathcal{U}_R \phi_- + \text{ h.c.} \\
&= \bar{\mathcal{D}}_L U^{d,\dagger} (U^d U^{u,\dagger}) Y^u_{diag} W^u \mathcal{U}_R \phi_- + \text{ h.c.}
\end{aligned}$$

- In the charged currents flavour mixing occurs!
- Parametrized through the
  Cabbibo-Kobayashi-Maskawa Matrix:

$$V_{CKM} = U^d U^{u,\dagger}$$

Properties of the CKM Matrix

- V_{CKM} is unitary (by our construction)
- Number of parameters for n families
  - Unitary $n \times n$ matrix: n^2 real parameters
  - Freedom to rephase the $2n$ quark fields: $2n - 1$ relative phases
- $n^2 - 2n + 1 = (n-1)^2$ real parameters
  - * $(n-1)(n-2)/2$ are phases
  - * $n(n-1)/2$ are angles
- Phases are sources of CP violation
- $n = 2$: One angle, no phase $\to$ no CP violation
- $n = 3$: Three angles, one phase
- $n = 4$: Six angles, three phases

CKM Basics

- Three Euler angles θ_{ij}

$$U_{12} = \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad U_{13} = \begin{bmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{bmatrix}, \quad U_{23} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}$$

- Single phase δ: $U_\delta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta_{13}} \end{bmatrix}.$
- PDG CKM Parametrization:

$$V_{\mathrm{CKM}} = U_{23} U_\delta^\dagger U_{13} U_\delta U_{12}$$

- Large Phases in $V_{ub} = |V_{ub}| e^{-i\gamma} = s_{13} e^{-i\delta_{13}}$ and $V_{td} = |V_{td}| e^{i\beta}$

CKM Unitarity Relations

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Off diagonal zeros of $V_{CKM}^\dagger V_{CKM} = 1 = V_{CKM} V_{CKM}^\dagger$
- $V_{CKM}^\dagger V_{CKM} = 1 : \left\{ \begin{array}{l} V_{ub} V_{ud}^* + V_{cb} V_{cd}^* + V_{tb} V_{td}^* = 0 \\ V_{ub} V_{us}^* + V_{cb} V_{cs}^* + V_{tb} V_{ts}^* = 0 \\ V_{us} V_{ud}^* + V_{cs} V_{cd}^* + V_{ts} V_{td}^* = 0 \end{array} \right.$
- $V_{CKM} V_{CKM}^\dagger = 1 : \left\{ \begin{array}{l} V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0 \\ V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0 \\ V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0 \end{array} \right.$

Wolfenstein Parametrization of CKM

- Diagonal CKM matrix elements are almost unity
- CKM matrix elements decrease as we move off the diagonal
- Wolfenstein Parametrization:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1 - \rho - i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

- Expansion in $\lambda \approx 0.22$ up to λ^3
- A, ρ, η of order unity

Unitarity Triangle(s)

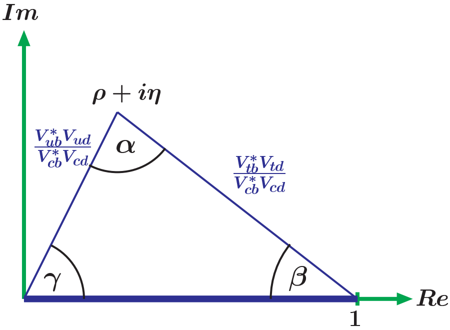
- The unitarity relations:
  Sum of three complex numbers = 0
- Triangles in the complex plane
- Only two out of the six unitarity relations involve terms of the same order in λ:

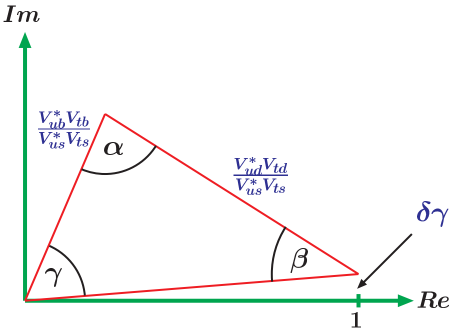
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$
$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$$

- Both correspond to

$$A\lambda^3(\rho + i\eta - 1 + 1 - \rho - i\eta) = 0$$

- This is THE unitarity triangle ...





- Definition of the CKM angles α, β and γ
- To leading order Wolfenstein:

$$V_{ub} = |V_{ub}| e^{-i\gamma} \quad V_{tb} = |V_{tb}| e^{-i\beta}$$

  all other CKM matrix elements are real.
- $\delta\gamma$ is order λ^5

- Aerea of the Triangle(s): Measure of CP Violation
- Invariant measure of CP violation:

$$\mathrm{Im}\Delta = \mathrm{Im}\, V_{ud} V_{td}^* V_{tb} V_{ub}^* = c_{12} s_{12} c_{13}^2 s_{13} s_{23} c_{23} \sin\delta_{13}$$

- Maximal possible value $\delta_{\max} = \frac{1}{6\sqrt{3}} \sim 0.1$
- CP Violation is a small effect:
  Measured value $\delta_{\exp} \sim 0.0001$
- CP Violation vanishes in case of degeneracies: (Jarlskog)

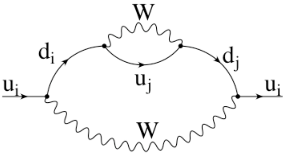
$$\begin{aligned} J &= \mathrm{Det}([M_u\, ,\, M_d]) \\ &= 2i\mathrm{Im}\Delta (m_u - m_c)(m_u - m_t)(m_c - m_t) \\ &\qquad \times (m_d - m_s)(m_d - m_b)(m_s - m_b) \end{aligned}$$

Peculiarities of SM Flavour Mixing

- Hierarchical structure of the CKM matrix
- Quark Mass spectrum ist widely spread
  $m_u \sim 10$ MeV to $m_t \sim 170$ GeV
- PMNS Matrix for lepton flavour mixing is not hierarchical
- Only the charged lepton masses are hierarchical
  $m_e \sim 0.5$ MeV to $m_\tau \sim 1772$ MeV
- Up-type leptons $\sim$ Neutrinos have very small masses
- (Enormous) Suppression of Flavour Changing Neutral Currents:
  $b \to s$, $c \to u$, $\tau \to \mu$, $\mu \to e$, $\nu_2 \to \nu_1$

Peculiarities of SM CP Violation

- Strong CP remains mysterious
- Flavour diagonal CP Violation is well hidden:
  e.g electric dipole moment of the neutron:
  At least three loops (Shabalin)



$$\begin{aligned} d_e &\sim e\,\frac{\alpha_s}{\pi}\,\frac{G_F^2}{(16\pi^2)^2}\,\frac{m_t^2}{M_W^2}\,\mathrm{Im}\Delta\,\mu^3 \\ &\sim 10^{-32}\,e\,cm \quad \text{with } \mu \sim 0.3\,\mathrm{GeV} \\ d_{\mathrm{exp}} &\leq 3.0 \times 10^{-26}\,e\,cm \end{aligned}$$

- Pattern of mixing and mixing induced CP violation determined by GIM: Tiny effects in the up quark sector
    - $\Delta C = 2$ is very small
    - Mixing with third generation is small: charm physics basically “two family”
    - $\to$ CP violation in charm is small in the SM
- Fully consistent with particle physics observations
- ... but inconsistent with matter-antimatter asymmetry

??? Many Open Questions ???

- Our Understanding of Flavour is unsatisfactory:
  - 22 (out of 27) free Parameters of the SM originate from the Yukawa Sector (including Lepton Mixing)
  - Why is the CKM Matrix hierarchical?
  - Why is CKM so different from the PMNS?
  - Why are the quark masses (except the top mass) so small compared with the electroweak VEV?
  - Why do we have three families?
- Why is CP Violation in Flavour-diagonal Processes not observed? (e.g. z.B. electric dipolmoments of electron and neutron)
- Where is the CP violation needed to explain the matter-antimatter asymmetry of the Universe?

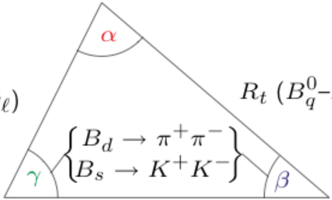
Rare Decays: Small CKM Elements

- Focus on Non-leptonic Decays
- Small CKM Elements: Non-Charmed Decays

Roadmap of Bottom Decays (R. Fleischer)

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

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



R_t $(B_q^0\text{–}\bar{B}_q^0$ mixing)

$B \to \pi K$ (penguins)

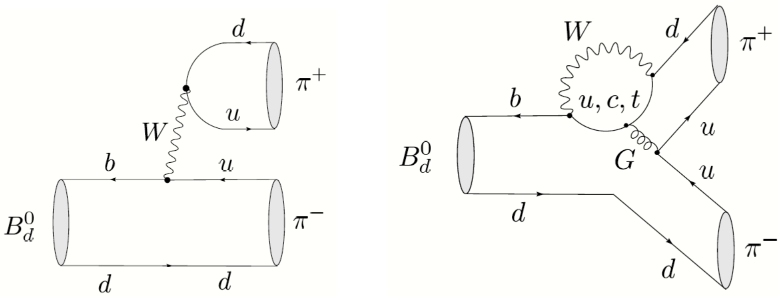
$B_d \to \psi K_S$ $(B_s \to \psi\phi : \phi_s \approx 0)$

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

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

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

$B \longrightarrow \pi\pi$



- Interplay between “Tree” and ”Penguin”
- Tree $\sim V_{ub}^* V_{ud} \sim \lambda^3$
- Penguin $\sim V_{tb}^* V_{td} \sim \lambda^3$
- Expect sizable direct CP violation

Isospin Relations in $B \longrightarrow \pi\pi$

- Isospin relation: $\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$
- In combination with

$$\frac{1}{\sqrt{2}} A^{+-} = T e^{i\gamma} + P e^{-i\beta} \qquad T : \text{tree amplitude}$$

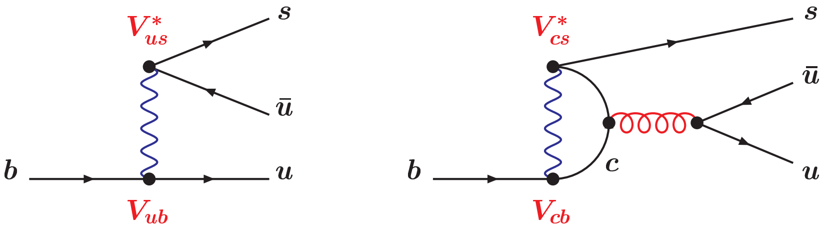
$$A^{00} = C e^{i\gamma} - P e^{-i\beta} \qquad P : \text{penguin amplitude}$$

$$A^{+0} = (C + T) e^{i\gamma} \qquad C : \text{Color suppressed amplitude}$$

gives a good handle on α (Gronau, London, Wyler)

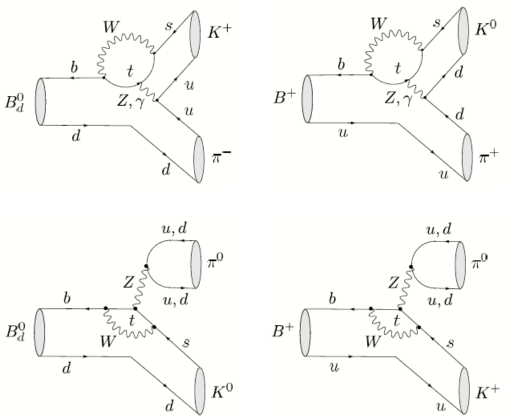
- P is (expected to be) sizable
- Separate measurement of $B_d \to \pi^0\pi^0$ and $\overline{B}_d \to \pi^0\pi^0$

$B \longrightarrow \pi K$

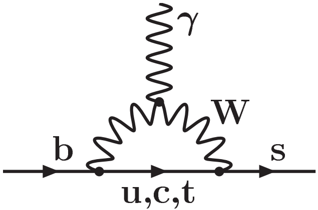


- ...

- Electroweak penguins can be significant!



Rare Decays: FCNC's



- Example: $b \to s\gamma$

$$\mathcal{A}(b \to s\gamma) = V_{ub} V_{us}^* f(m_u) + V_{cb} V_{cs}^* f(m_c) + V_{tb} V_{ts}^* f(m_t)$$

- In case of degenarate masses up-type masses:

$$\mathcal{A}(b \to s\gamma) = f(m) \left[V_{ub} V_{us}^* + V_{cb} V_{cs}^* + V_{tb} V_{ts}^* \right] = 0$$

- Loop induced Processes: Sensitivity to "new physics"
- Exclusive as well as inclusive decays of the form $b \to s\gamma$ and $b \to s\ell\ell$
- $b \to s\ell\ell$ contains a lot of information through various observables
  - Lepton invariant mass
  - Lepton energy spectra
  - Forward Backward Asymmetries
  - ...

$B \to X_s\gamma$

- Complete NNLO Calculation has been performed
- Theory Predictions: (from Flächer @ EPS07)

> Misiak et al. hep-ph/0609232
  - **BF($B \to X_s\gamma$) = (3.15 ± 0.23) 10^{-4} for E_γ > 1.6 GeV**
  - dedicated error analysis resulting in 7% error

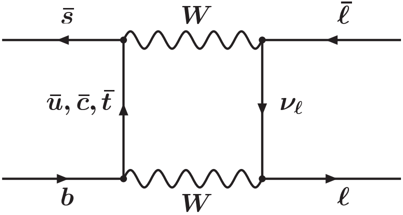
> Becher et al. hep-ph/0610067
  - **BF($B \to X_s\gamma$) = (2.98 ± 0.26) 10^{-4} for E_γ > 1.6 GeV**
  - larger perturbative uncertainty resulting in 9% error

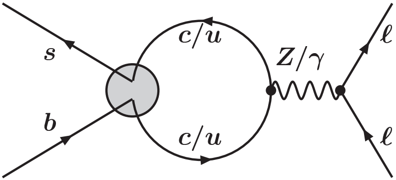
> Andersen et al. hep-ph/0609250
  - **BF($B \to X_s\gamma$) = (3.47 ± 0.48) 10^{-4} for E_γ > 1.6 GeV**
  - 11% uncertainty from variation of renormalisation scale

- HFAG Average: $(3.55 \pm 0.26) \times 10^{-4}$

$B \to X_s \ell^+ \ell^-$

- In addition to the diagrams for $B \to X_s \gamma$





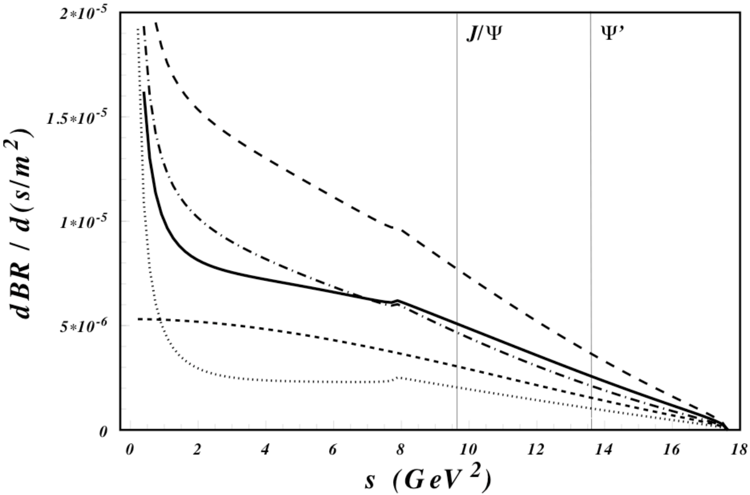
Observables in $B \to X_s \ell^+ \ell^-$

- Doubly differential rate: $d^2\Gamma/(dM_{\ell\ell}^2 d(\cos\theta))$
- Total rate R(or rate within cuts)
- Forward backward Asymmetry A_{FB}

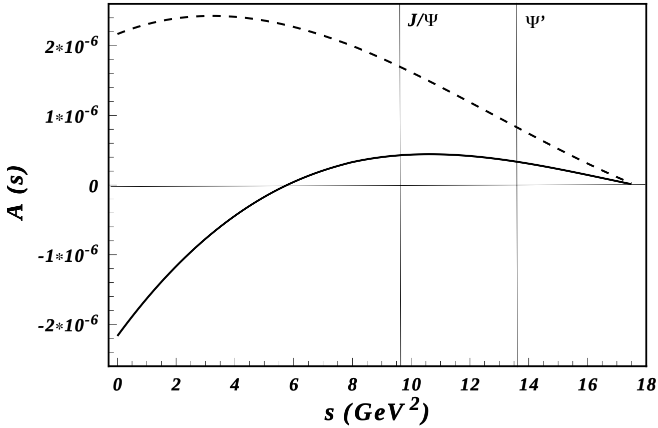
$$A_{FB}(M_{\ell\ell}^2) = \left[\frac{\int_{-1}^{0} d(\cos\theta) - \int_{0}^{-1} d(\cos\theta)}{\int_{-1}^{0} d(\cos\theta) + \int_{0}^{-1} d(\cos\theta)}\right] \frac{d^2\Gamma}{dM_{\ell\ell}^2\, d(\cos\theta)}$$

- Observables depend on the Wilson Coefficients
  $\to$ Try to extract $C_1 \ldots C_{10}$

The lepton invariant mass spectrum of $B \to X_s \ell\ell$



The forward-backward of $B \to X_s \ell\ell$



Extraction of Wilson Coefficients (Example)