B-Factory Physics

Patricia Ball

CERN & IPPP University of Durham

CTEQ Summer School 2001, St. Andrews, Scotland

1. What is a B-Factory?
2. Essentials of Flavour-Physics
3. Strong Interactions in B-Physics
4. Loop-Processes and the Unitarity-Triangle
5. $|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays
6. CP-Violation in B-Decays
7. Rare Decays and New Physics

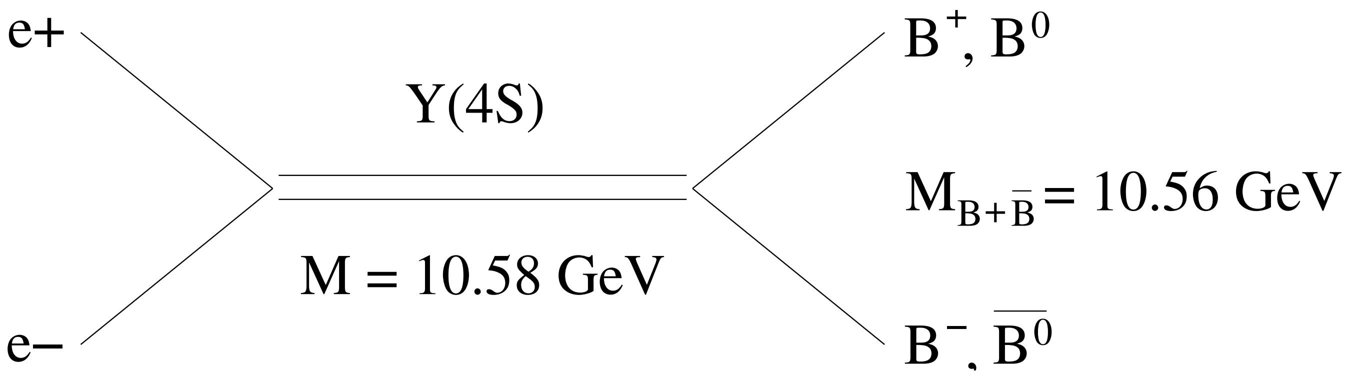
What is a B-Factory?

Any facility, built specifically to do B physics, which produces $> 10^7$ B mesons per year.

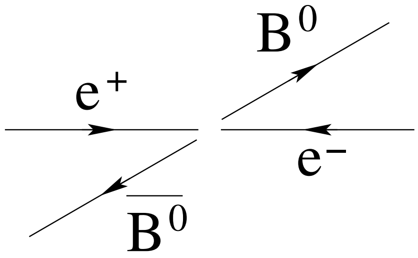
- ⋆ e^+e^- symmetric, e.g. CESR storage ring at Cornell $\longrightarrow$ CLEO
- ⋆ e^+e^- asymmetric, e.g. PEP-II collider at SLAC $\longrightarrow$ BaBar; dito KEK-B machine at KEK $\longrightarrow$ Belle
- fixed-target hadronic, e.g. HERA-B at DESY († deceased)
- hadron collider, e.g. LHC-B at CERN, B-TeV at Fermilab

⋆ running and producing nice & exciting results!

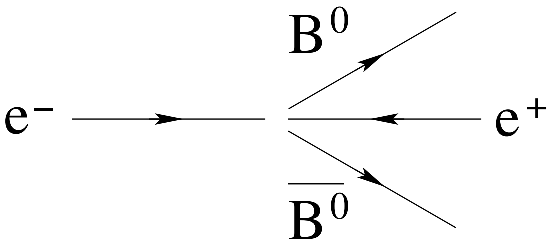
$\longrightarrow$ concentrate on B physics at e^+e^- machines



CLEO: $E_{e^+} = E_{e^-}$



BaBar/Belle: $E_{e^-} > E_{e^+}$



	BaBar	Belle
$p(e^-)$ [GeV]	9	8
$p(e^+)$ [GeV]	3.1	3.5
boost factor $\beta\gamma = \langle p_B \rangle / M_B$	0.56	0.43
mean flight distance $\langle \Delta z \rangle$ [μm]	260	200

$\rightarrow$ displaced B decay vertices

Advantages of $e^+ e^-$ machines:

- possible to trigger on, and record, essentially all $B\,\bar{B}$ events
- high signal-to-background ratio, $\sigma_{b\bar{b}}/\sigma_{\rm hadr} = 0.22$
- in B events, B and $\bar{B}$ are the only particles in the final state
- low interaction rates
- can reconstruct final states containing π^0 and γ

Main disadvantages:

- statistics limited to $O(10^7)$ $B\,\bar{B}$ pairs/year (at design-luminosity, 4months/y running)
- cannot create B_s mesons

Overview of Physics Programme

1. CP-Violation

   - in particular from time-dependent CP-asymmetries ($B_d \to J/\psi$, $B^0 \to \pi^+\pi^-$, ...) – that's why the accelerators are asymmetric in beam-energy!

2. Rare Decays

   - search for physics beyond the SM in e.g. $b \to s\gamma$, $b \to s\ell^+\ell^-$,...: flavour-changing neutral-current (FCNC) transitions, forbidden in the SM at tree-level, induced by radiative corrections

3. Improved determination of $|V_{cb}|$

   - from $B \to D^*(D)e\nu$, using heavy quark effective theory (HQET)
   - from inclusive semileptonic decays

4. Improved determination of $|V_{ub}|$

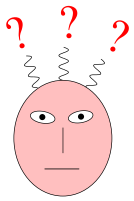
   - from exclusive decays, in particular $B \to \pi e\nu$, $B \to \rho e\nu$
   - from inclusive semileptonic decays, either at large lepton energies or small invariant hadronic masses

Outline

- What is a B-Factory?
- **Essentials of Flavour-Physics**
- Strong Interactions in B-Physics
- Loop-Processes and the Unitarity-Triangle
- $|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays
- CP-Violation in B-Decays
- Rare Decays and New Physics

Essentials of Flavour Physics

$\boxed{\text{Flavour physics originates from the scalar sector of the SM.}}$



Wasn't it the *weak interactions* that violate flavour?

Well, both is correct. Essential point: look at SM *before* or *after* spontaneous symmetry-breaking.

Before: quark-masses from quark-Higgs(-Yukawa)-couplings:

$$\mathcal{L}_{\text{int}}^{Y} = \bar{Q}_{iL} Y_{ij}^{d} d_{Rj} \Phi + \bar{Q}_{Li} Y_{ij}^{u} u_{Rj} \tilde{\Phi} + \text{ h.c.}$$

d_R, u_R: SU(2) singlets;

$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$: SU(2) doublets;

$\Phi, \tilde{\Phi} = i\tau_2 \Phi^*$: Higgs-fields, SU(2) doublets

$\boxed{Y^{u,d} \text{ arbitrary complex matrices.}}$

$\mathcal{L}$ expressed in interaction-basis, weak interactions are flavour-diagonal.

After: $\Phi \to \langle\Phi\rangle_{\rm VEV} = (0, v/\sqrt{2})$

$\to$ $\mathcal{L}_{\rm int}^{Y} \to \mathcal{L}_{\rm mass}^{\rm quark} = \bar{d}_{Li} M_{ij}^{d} d_{Rj} + \bar{u}_{Li} M_{ij}^{u} u_{Rj} + \text{h.c.}$

$\to$ to go to basis of quark mass-eigenstates, need to diagonalize $M^{u,d}$

$\to$ introduce unitary trafos $u_{L(R)} \to U_{L(R)}^{u} u_{L(R)}$, $d_{L(R)} \to U_{L(R)}^{d} d_{L(R)}$, such that

$$\left.\begin{array}{rcl} U_L^{d\dagger} M^d U_R^d & = & \mathrm{diag}(m_d, m_s, m_b, \ldots) \\ U_L^{u\dagger} M^u U_R^u & = & \mathrm{diag}(m_u, m_c, m_t, \ldots) \end{array}\right\} \text{m_i real and positive}$$

$$\begin{array}{rrcl} \Rightarrow & U_L^{d\dagger} M^d M^{d\dagger} U_L^d & = & \mathrm{diag}(m_d^2, m_s^2, m_b^2, \ldots) \\ & U_L^{u\dagger} M^u M^{u\dagger} U_L^u & = & \mathrm{diag}(m_u^2, m_c^2, m_t^2, \ldots) \end{array}$$

NB: $M^q M^{q\dagger}$ is Hermitian.

How do weak interactions look like in the mass-basis?

$$\begin{array}{rcl} \mathcal{L}_W & = & \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{u}_L \gamma^\mu d_L + W_\mu^- \bar{d}_L \gamma^\mu u_L \right) \\ & \to & \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{u}_L \gamma^\mu U_L^{u\dagger} U_L^d d_L + W_\mu^- \bar{d}_L \gamma^\mu U_L^{d\dagger} U_L^u u_L \right) \end{array}$$

$\boxed{V := U_L^{u\dagger} U_L^d \text{ is the CKM quark-mixing matrix.}}$

NB: $Z_\mu \bar{u}_L \gamma^\mu u_L$, $Z_\mu \bar{d}_L \gamma^\mu d_L$ unchanged by this trafo
$\Rightarrow$ no flavour-violation in neutral weak interactions in the SM, i.e. no flavour-changing neutral currents

Intermezzo I: A Short Remainder on CP and its Violation

Discrete symmetries of a quantum field theory (QFT):

C (charge conjugation): particle $\leftrightarrow$ antiparticle

P (parity operation): $\vec{x} \leftrightarrow -\vec{x}$

T (time-reversal): $t \leftrightarrow -t$

CPT theorem:

> Any relativistic QFT with a local Hamiltonian is invariant under CPT.

- QED and QCD preserve C, P and T separately (except for the so-called θ-term in strong interactions: vanishes in massless QCD)
- massless chiral gauge theories (like massless weak interactions) preserve CP
- Nature does not preserve CP:

$$\Gamma(K_S \to \pi\pi) \neq 0, \quad \Gamma(K_L \to \pi\pi) \neq 0$$

If CP was preserved: K_S, K_L were CP-eigenstates, could not decay into CP-eigenstate $\pi\pi$, i.e. one of the two Γ would have to vanish. Experimentally:
$\Gamma(K_L \to \pi\pi)/\Gamma(K_S \to \pi\pi) = 3 \cdot 10^{-3}$.
$\longrightarrow$ sets size of CP-violation

> CP-violation originates in the scalar sector of the SM.

Intermezzo II: $\not{CP}$ and Complex Phases

Manifestations of $\not{CP}$:
e.g. direct $\not{CP}$: $\Gamma(B\to F)\neq\Gamma(\bar{B}\to\bar{F})$

"Common wisdom": $\not{CP}$ is related to complex phases. There are, in principle, two types of them:

(a) CP-odd weak phases ϕ
(cf. expression for $\mathcal{L}_W$ on previous slide)

(b) CP-even strong phases δ

$$\begin{aligned}
\text{Ansatz: }\langle F|\mathcal{L}|B\rangle &= A\exp(i(\phi+\delta))\\
\langle\bar{F}|\mathcal{L}|\bar{B}\rangle &= A\exp(i(-\phi+\delta))\\
\Rightarrow\Gamma(B\to F) &= \Gamma(\bar{B}\to\bar{F}) : \text{no } \not{CP}\\
\text{Instead: }\langle F|\mathcal{L}|B\rangle &= A_1\,e^{i(\phi_1+\delta_1)}+A_2\,e^{i(\phi_2+\delta_2)}\\
\langle\bar{F}|\mathcal{L}|\bar{B}\rangle &= A_1\,e^{i(-\phi_1+\delta_1)}+A_2\,e^{i(-\phi_2+\delta_2)}
\end{aligned}$$

$$\Rightarrow\Gamma(B\to F)-\Gamma(\bar{B}\to\bar{F})\propto$$

$$\propto\ -4A_1A_2\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)$$

$\Rightarrow$: direct $\not{CP}$ only in interference between two amplitudes which differ in both weak and strong phase.
In the SM: only source of CP-odd phases:

$$\boxed{V_{\rm CKM}\neq V_{\rm CKM}^\dagger \text{ in charged weak interactions}}$$

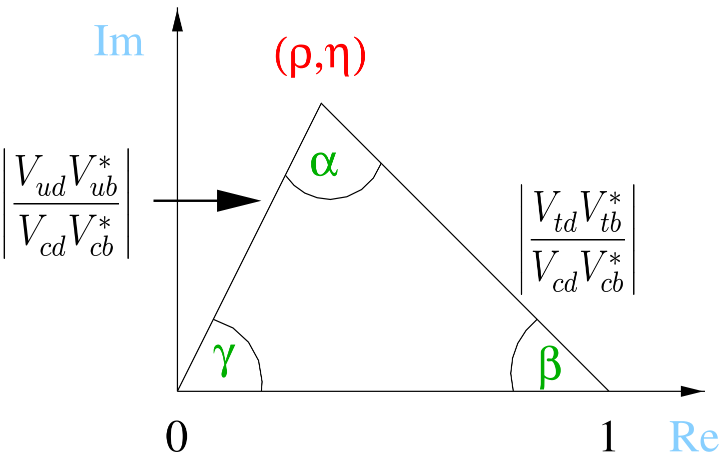
V has how many parameters?

n × n complex matrix:	$2n^2$ real parameters
unitarity:	$-n^2$
rephase quark-fields: ($d \rightarrow e^{i\phi_d} d$ etc.)	–(2n–1) [only phase-differences $\phi_d - \phi_u$ enter V]
	$(n-1)^2$ real parameters
of which	$\frac{1}{2}$n(n–1) Euler-angles
	$\frac{1}{2}$(n–1)(n–2) complex phases

One possible parametrization for 3 generations:
($c_{12} = \cos\theta_{12}$, $s_{13} = \sin\theta_{13}$ etc.)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Picture unitarity relation, e.g. $\sum_{u,c,t} V_{id}V_{ib}^* = 0$ as triangle in complex plane: unitarity triangle (UT)



The Unitarity Triangle (UT) – Wolfenstein-Parametrization

Exploit exp. observed hierarchy of entries in $V_{\rm CKM}$ to derive convenient expansion in small parameter.
$\lambda := V_{us} = 0.22, \ A\lambda^2 := V_{cb}, \ A\lambda^3(\rho - i\eta) := V_{ub}$ $(A \sim O(1))$

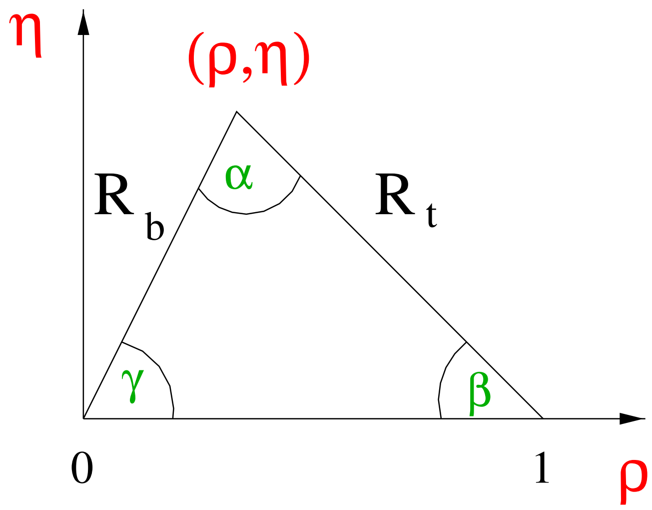
$\Rightarrow V_{\rm CKM} =$

$$= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & AR_b\lambda^3 e^{-i\gamma} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ AR_t\lambda^3 e^{-i\beta} & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\Rightarrow$ Wolfenstein-parametrization (Wolfenstein 1983)

Extend to higher order in λ: Buras 1994.



Exp.:
$$\begin{aligned} R_b &\approx 0.41 \\ R_t &\approx 0.94 \\ \Rightarrow \beta &= 24^o \\ \sin 2\beta &= 0.75 \end{aligned}$$

What to Learn from Measuring the UT

- determine fundamental parameters of the SM
- Is V_{CKM} the only "source" of CP-violation?

$\longrightarrow$ If no: expect angles and sides, measured independently, not to describe one and the same triangle

- can reconstruct Yukawa-matrices $Y^{u,d}$

$\longrightarrow$ guidance for model-builders

Outline

- What is a B-Factory?
- Essentials of Flavour-Physics
- **Strong Interactions in B-Physics**
- Loop-Processes and the Unitarity-Triangle
- $|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays
- CP-Violation in B-Decays
- Rare Decays and New Physics

Strong Interactions in B Decays

Flavour physics governed by interplay of weak and strong interactions.

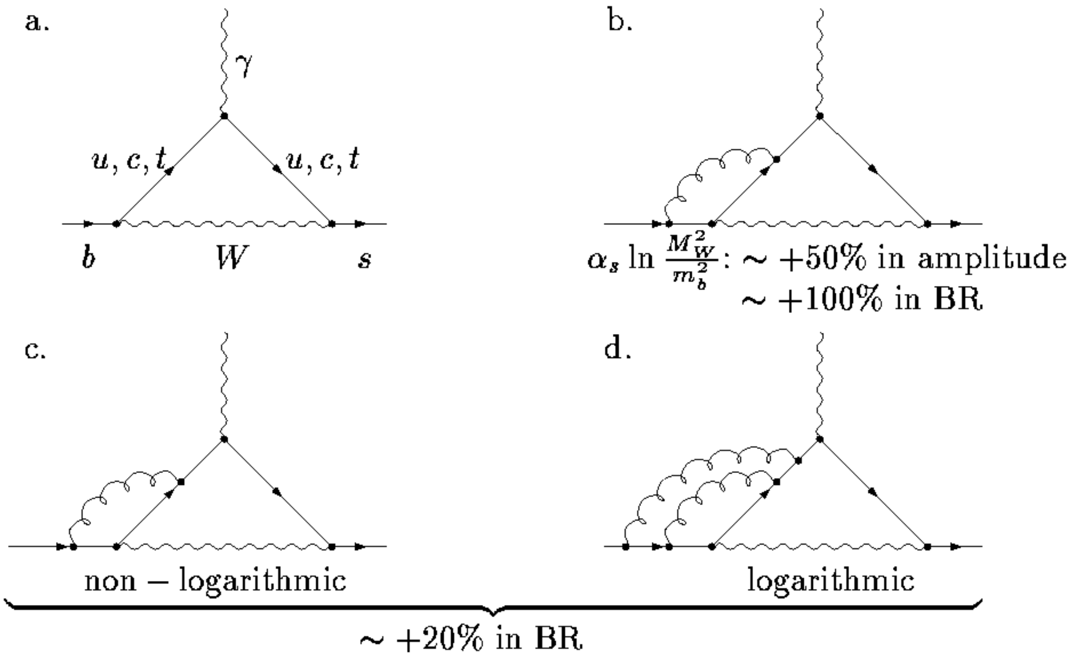
Problem: calculation of hadronic matrix-elements dominated by npQCD (nonperturbative QCD) notoriously difficult (or impossible).

What to do?

- separate long- and short-distance physics by operator-product expansion (OPE)
  $\longrightarrow$ low-energy effective Hamiltonians
- include short-distance pQCD effects by renormalization-group methods
- treat npQCD effects as rigorously as possible:
  - inclusive decays: heavy quark expansion $\rightsquigarrow$ effectively "free-quark" description with small npQCD corrections for rates; spectra more complicated
  - exclusive semileptonic and radiative decays: lattice ($\longrightarrow$ C. Davies' lectures), QCD sum rules
  - factorization + exclusive form factors for nonleptonic decays

The Short-Distance Part

E.g. for the FCNC process $b \to s\gamma$:



↳ this type of diagrams called penguin-diagrams

For reliable prediction, need to resum, to all orders in PT, large logs

$$\boxed{\alpha_s(m_b)\,\ln\frac{m_b}{M}} \qquad M = m_W, m_t$$

$\longrightarrow$ appearance of large logs general feature in processes with largely different mass/energy scales

LL accuracy: resum $\left(\alpha_s(m_b)\,\ln\dfrac{m_b}{M}\right)^n$

NLL accuracy: resum $\alpha_s(m_b)\left(\alpha_s(m_b)\,\ln\dfrac{m_b}{M}\right)^n$

How to do resummation?

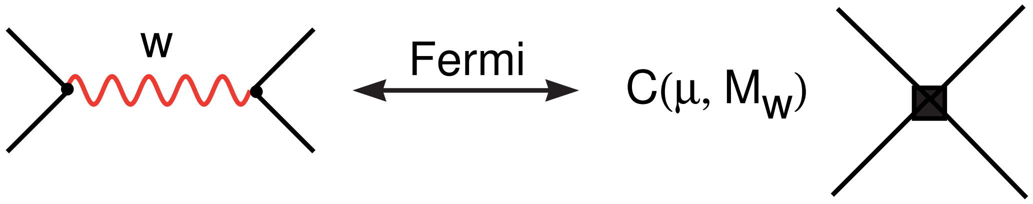
OPE $\quad + \quad$ ren.-group(RG)-techniques

$\downarrow \qquad \downarrow$

"integrate out" (i.e. eliminate as dynamical degress of freedom) heavy particles with masses much larger than characteristic scale of process (here: m_b)

split large logs as $\ln \frac{m_b}{M} = \ln \frac{\mu}{M} + \ln \frac{m_b}{\mu}$, $\mu \sim O(m_b)$; include large logs in Wilson-coefficients which observe RG-equation $\mu \frac{d}{d\mu} C(\mu) = -\frac{\alpha_s}{4\pi} \gamma_0 C(\mu)$

$\rightsquigarrow C(\mu) = \left(\frac{\alpha_s(\mu)}{\alpha_s(Q)}\right)^{\frac{\gamma_0}{2\beta_0}} C(Q)$



Effective Hamiltonian:

$$\boxed{\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{\text{heavy}}) \mathcal{O}_i(\mu)}$$

Operators $\mathcal{O}_i$ carry "opposite" scale-dependence
$\rightarrow \mathcal{H}_{\text{eff}}$ is independent of μ.

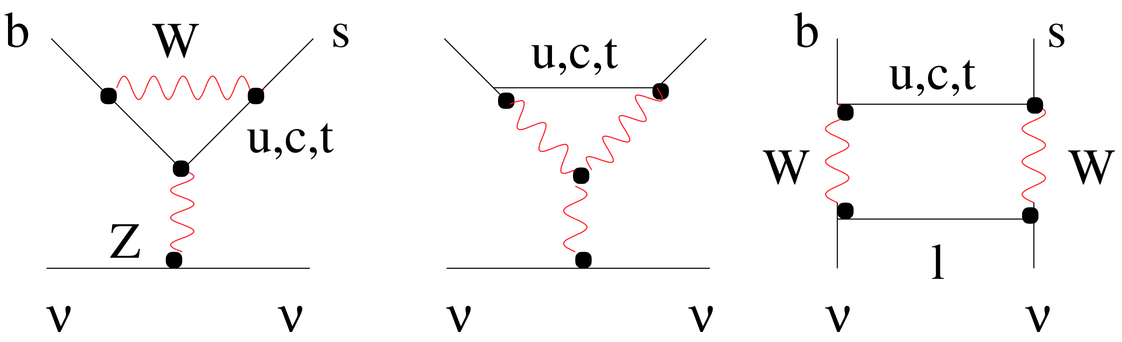
Outline

- What is a B-Factory?
- Essentials of Flavour-Physics
- Strong Interactions in B-Physics
- **Loop-Processes and the Unitarity-Triangle**
- $|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays
- CP-Violation in B-Decays
- Rare Decays and New Physics

Loop-Processes and the UT (I) – GIM-Mechanism

GIM = Glashow/Iliopoulos/Maiani PRD 2 (1970) 1285

Consider effective neutral current interaction $(\bar{s}b)(\bar{\nu}\nu)$ (mediating e.g. $B_s \to \nu\bar{\nu}$):



$$\propto V_{us}V_{ub}^* F(m_u) + V_{cs}V_{cb}^* F(m_c) + V_{ts}V_{tb}^* F(m_t)$$

If all quark masses were equal:

$F(m) \sum_{u,c,t} V_{qs}V_{qb}^* = 0$ by unitarity of the CKM-matrix!

However:

GIM *largely* broken because $m_t > m_W \gg m_c$.

$\longrightarrow$ "rare" b decays: BR $\sim 10^{-5}$

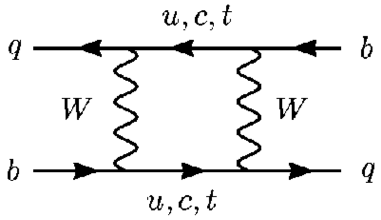
$\longrightarrow$ much larger than for rare K decays: BR $\sim 10^{-8}$ (because of GIM-suppression)

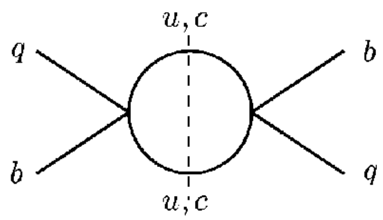
Loop-Processes and the UT (II) – B–$\overline{\text{B}}$ mixing

Flavour eigenstates $B_q = (\bar{b}q)$ and $\bar{B}_q = (b\bar{q})$ $(q = s, d)$ mix by virtue of weak interactions; described by 2-dim. Hamiltonian

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

Diagonal-elements equal by CPT-theorem (acc. to which particle and antiparticle have equal mass and lifetime)

$M_{12} \sim$ 

$\Gamma_{12} \sim$ 

Mass-eigenstates $B_{\text{heavy,light}}$ with different masses and decay widths:

$$\boxed{\Delta M_q = 2|M_{12}^{(q)}|,\ \Delta\Gamma_q = 2\mathrm{Re}(M_{12}^{(q)*}\Gamma_{12}^{(q)})/|M_{12}^{(q)}|}$$

Mixing-phase: $\boxed{\phi_q = \arg M_{12}^{(q)}}$

$$\phi_d = \arg\,(V_{td}^* V_{tb})^2 = 2\beta, \quad \phi_s = \arg\,(V_{ts}^* V_{tb})^2 \approx 0$$

Experimentally:

$$\Delta M_d = (0.479 \pm 0.012)\,\mathrm{ps}^{-1}$$
$$\Delta\Gamma_d/\Gamma_d \sim 0.01$$
$$\Delta M_s > 13.1\,\mathrm{ps}^{-1}(\mathrm{PDG2001})$$
$$\Delta\Gamma_s/\Gamma_s = 0.16^{+0.08}_{-0.09} < 0.31 @ 95\%\,\mathrm{CL}$$

Theoretically: (top-loop is dominant)

$$\Delta M_d = \frac{G_F^2}{6\pi^2}\,\hat\eta_B m_B \hat B_B f_B^2 M_W^2 S_0\left(\frac{m_t^2}{m_W^2}\right)|V_{tb}V_{td}^*|^2$$

Relevant hadronic matrix element:

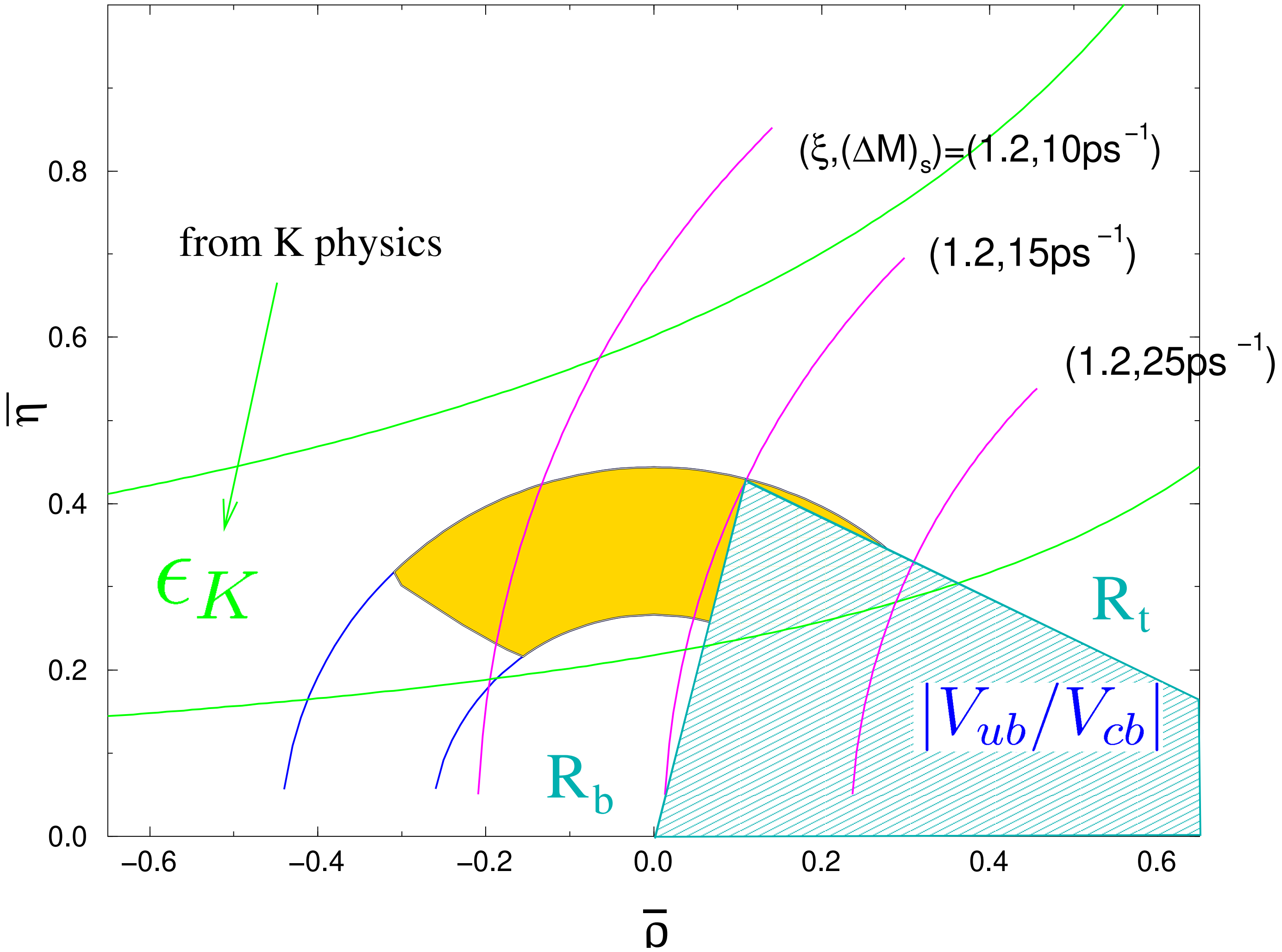
$$\langle \bar B^0|(\bar d b)_{V-A}(\bar d b)_{V-A}|B^0\rangle \propto f_B^2 \hat B_B$$

Most reliable predictions from lattice:
(Kenway, ICHEP 2000)

$$\sqrt{\hat B_B} f_B = (206 \pm 29)\,\mathrm{MeV}$$
$$\xi = \frac{\sqrt{\hat B_{B_s}} f_{B_s}}{\sqrt{\hat B_{B_d}} f_{B_d}} = 1.16 \pm 0.07$$

Aim: determine $|V_{td}|$ (i.e. R_t) from $\Delta M_s/\Delta M_d$ with small theoretical uncertainty.

Effect of B-Mixing on UT



→ measurement of 3 observables (ϵ_K, R_t, R_b) defines closed region in (ρ,η) space

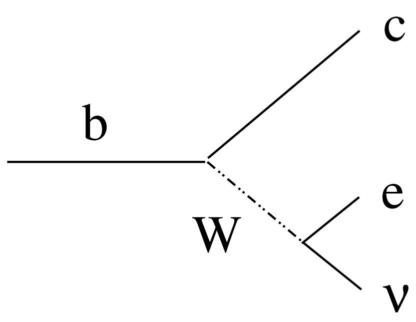
→ $\eta \neq 0$, i.e. presence of CP-violation, follows already from CP-conserving data alone (R_t, R_b)

Outline

- What is a B-Factory?
- Essentials of Flavour-Physics
- Strong Interactions in B-Physics
- Loop-Processes and the Unitarity-Triangle
- **$|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays**
- CP-Violation in B-Decays
- Rare Decays and New Physics

Determination of $|V_{cb}|$

Comparatively "simple": tree-level process:



Realized as e.g. exclusive decays $B \to De\nu$, $B \to D^* e\nu$, BR $\sim$ O(1%).

Hadrons involved $\Rightarrow$ npQCD relevant; can be described by form factors:

$$\begin{aligned} \langle D|\bar{c}\gamma_\mu b|B\rangle &= f_+(q^2)(p_B + p_D)_\mu + f_-(q^2)q_\mu \\ 0 \le q^2 &= (p_B - p_D)^2 \le (m_B - m_D)^2 \end{aligned}$$

Calculation from first principles difficult; however: can exploit additional symmetry of QCD for $m_{b,c} \to \infty$:

heavy quark symmetry $\to$ heavy quark effective theory

Rough idea: very heavy quark becomes “static”, i.e. moves with constant velocity, except for interactions with hard gluons with virtuality $\sim m_b$.

$\longrightarrow$ heavy degrees of freedom decouple from light degrees of freedom (spectator quark, gluons)

$\longrightarrow$ form factor becomes universal (independent of heavy flavour) Isgur-Wise function: ($p_M = m_M v_M$)

$$\lim_{m_B, m_D \to \infty} \langle D(p_D)|\bar{c}\gamma_\mu b|B(p_B)\rangle \frac{1}{\sqrt{m_B m_D}} = $$
$$= \quad \xi_{IW}(v_B \cdot v_D)(v_B + v_D)_\mu$$

$\longrightarrow$ absolute normalization of $\xi_{IW}(1)$ from flavour-counting:

$$\langle B(v_B)|\bar{b}\gamma_0 b|B(v_B)\rangle \frac{1}{2m_B} \quad = $$
$$\langle B(v_B)|b^\dagger b|B(v_B)\rangle \frac{1}{2m_B} \quad = \quad 1 \equiv \xi_{IW}(1)$$

$\longrightarrow$ heavy quark symmetry broken by power-corrections $\sim \Lambda_{\rm QCD}/m_b$; cannot be calculated from first principles $\longrightarrow$ limits theoretical accuracy

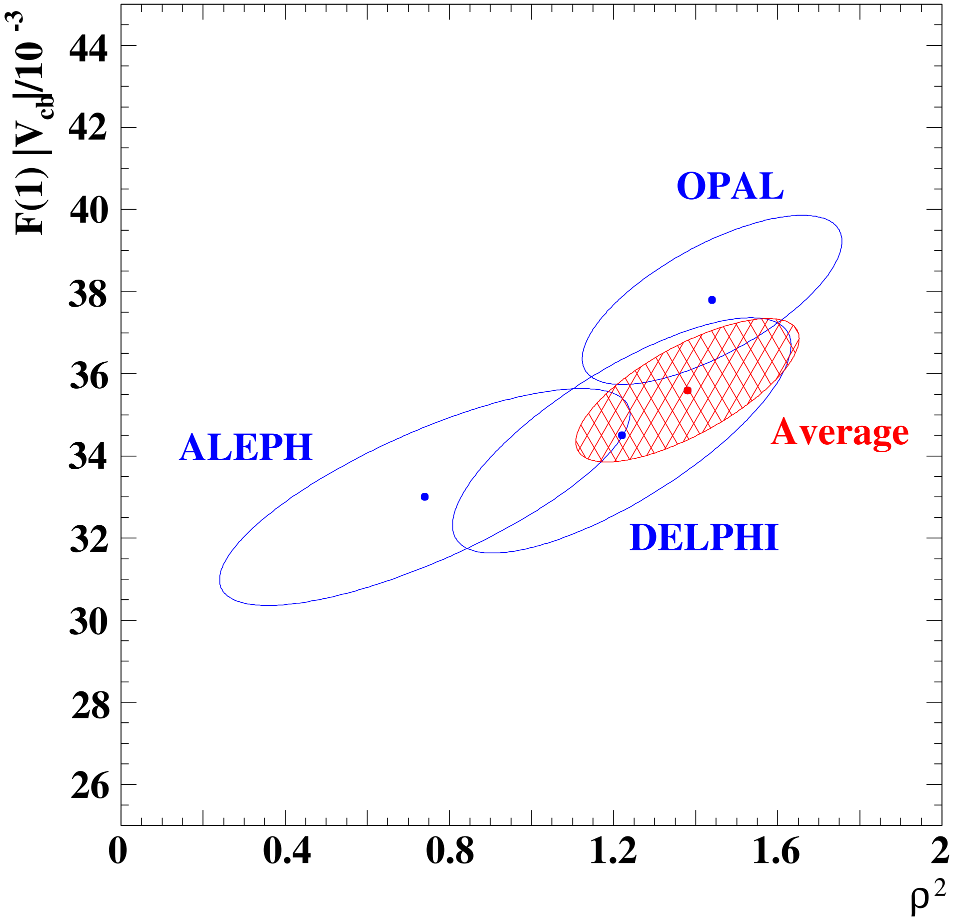
Lattice: mixing with operators $\sim 1/a$, diverging in the continuum limit $a \to 0$

Results from LEP

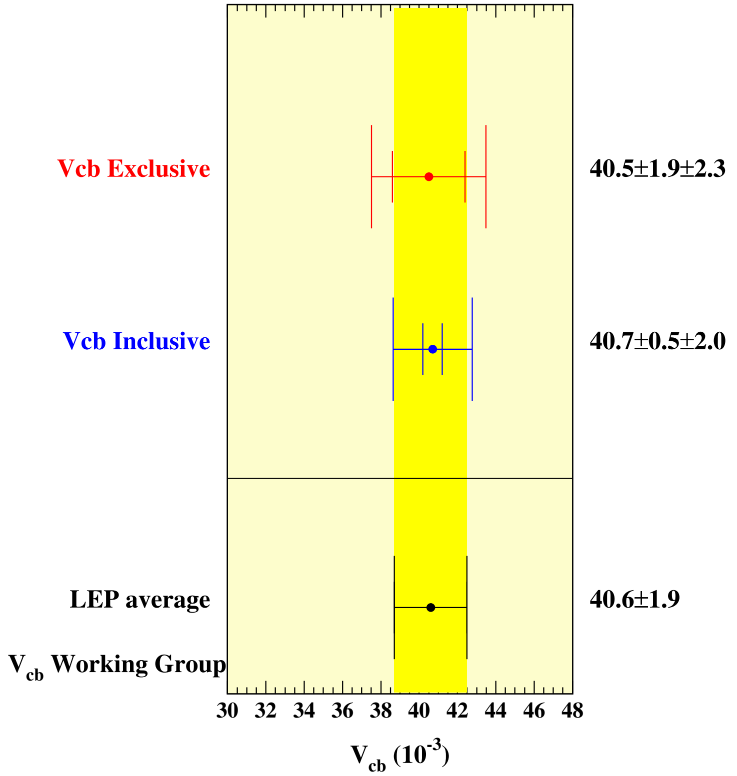
"golden" channel: $B \to D^* e\nu$: only $1/m_{b,c}^2$ and higher corrections (Luke's theorem)

$$\frac{d\Gamma}{dy} = \mathcal{K}(y)\mathcal{F}^2(y)|V_{cb}|^2; \quad \mathcal{F}(y) = \eta_{\mathrm{pert}}(\xi_{IW}(y)+\delta_{1/m_Q^2}); \quad \xi_{IW}(y) = 1-\rho^2(y-1)$$

$\mathcal{K}(y)$: kinematical factor



Measurement from inclusive decay $B \to X_c e\nu$: use heavy quark expansion.



V_{ub} from Exclusive Decays

Best suited: $B \to \pi e \nu$, BR $\sim 2 \cdot 10^{-4}$

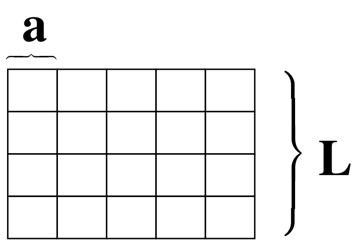
Relevant hadronic matrix element: $(q = p_B - p_\pi)$

$$\langle \pi | \bar{u} \gamma_\mu b | B \rangle = f_+(q^2)(p_B + p_\pi)_\mu + f_-(q^2) q_\mu$$

How to calculate?

Use heavy quark symmetry (relate to $D \to \pi$)?
$\longrightarrow$ only useful near zero recoil
$\Rightarrow$ need either extrapolation in q^2 (model-dependence!) or restricted to small part of phase-space (disfavoured by statistics!)

Use lattice?
$\longrightarrow$ trouble with discretization errors:



lattice-spacing a typically $\sim 1/(2\,\mathrm{GeV})$. Physics involves large scale M $\Rightarrow$ terms $\sim aM$ important $\longrightarrow$ discretization errors

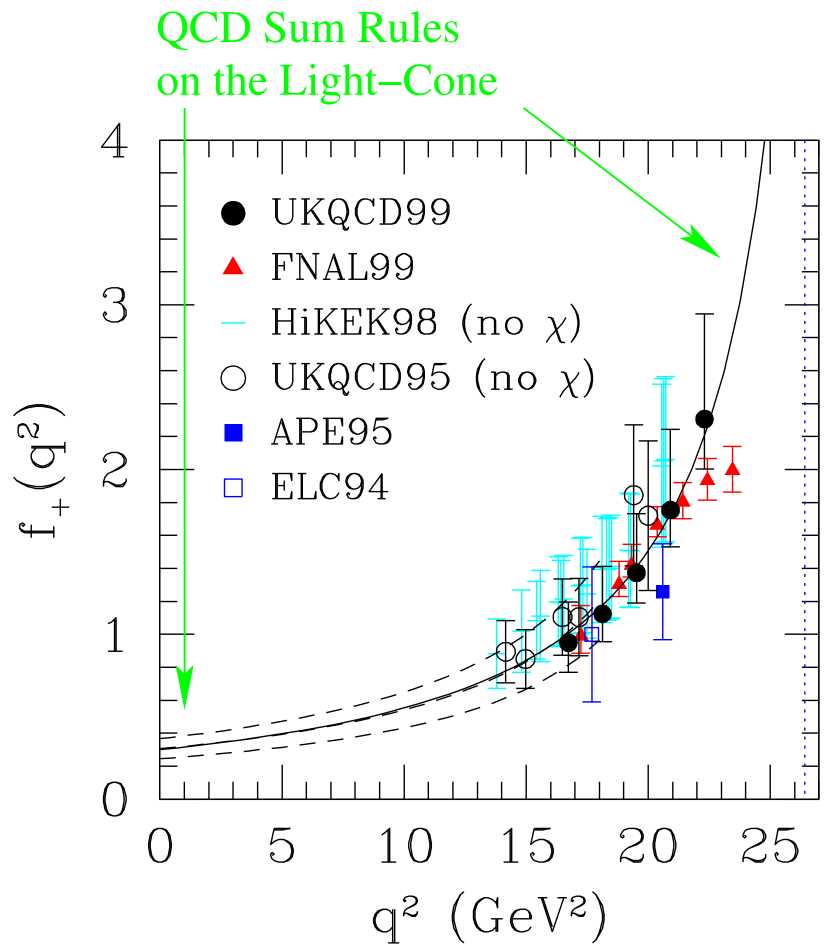
Generic large scale in B-physics: m_b

$\longrightarrow$ cannot be simulated directly as relativistic quark: calculate at smaller masses (and potentially also at $m_b = \infty$) and extra(inter)polate

$\longrightarrow$ or: use nonrelativistic version of lattice-QCD

$\longrightarrow$ $B \to \pi$: also E_π potentially large $\longrightarrow$ restricted to small $E_\pi < 1\,$GeV $\equiv$ large $q^2 > 17$ GeV^2

Results



QCD sum rules on the light-cone: approximate method for calculating heavy-to-light form factors. Nonperturbative input: light-hadron distribution amplitudes

$$\sim \langle \pi | \bar{u}(z)\gamma_\mu\gamma_5 u(-z)|0\rangle|_{z^2=0}.$$

Best suited for describing f_+ at *small* q^2. Guesstimated theoretical uncertainty: $\sim 20\%$.

$|V_{ub}|$ from inclusive decays $\longrightarrow$ later

PDG 2001: $\boxed{|V_{ub}/V_{cb}| = 0.090 \pm 0.025}$

Outline

- What is a B-Factory?
- Essentials of Flavour-Physics
- Strong Interactions in B-Physics
- Loop-Processes and the Unitarity-Triangle
- $|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays
- **CP-Violation in B-Decays**
- Rare Decays and New Physics

Experimental Manifestations

- $\cancel{CP}$ in the decay ($\equiv$ direct $\cancel{CP}$): ($\rightsquigarrow$ different decay rates)

$$\boxed{|\mathcal{A}(B \to F)| \neq |\mathcal{A}(\bar{B} \to \bar{F})|}$$

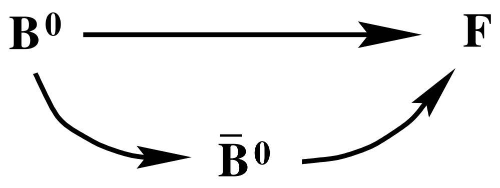
- $\cancel{CP}$ in mixing:

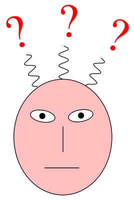
$$\boxed{\text{mass eigenstates} \neq \text{CP eigenstates}}$$

In principle observable in $B^0 \to \ell^- X$ vs. $\bar{B}^0 \to \ell^+ X$; very small effect.

- Most relevant for phenomenology: $\cancel{CP}$ in the interference of decays with and without mixing (mixing-induced $\cancel{CP}$):

$$\boxed{\mathcal{A}(B \to F) \neq \mathcal{A}(\bar{B} \to F) \text{ (i.e. difference in absolute size and/or relative phase)}}$$





Why go for "mixing-induced" CP-asymmetries?

Recall discussion about "CP-Violation and Complex Phases": direct $\not{CP}$ requires interference of two amplitudes with different weak and strong phases each: (i.e. two relative phase-differences)

$$A_f = A_1 e^{i(\phi_1+\delta_1)} + A_2 e^{i(\phi_2+\delta_2)}$$

$\Rightarrow$ $\phi_1 - \phi_2$ can be measured only if npQCD parameters A_1/A_2, $\delta_1 - \delta_2$ known; cannot be calculated to sufficient accuracy from presently available methods

Way out: time-dependence of mixing-induced asymmetries dominated by one single amplitude:

$$\begin{aligned} A(B^0 \to F) \equiv \quad & A_f & = A e^{i(\phi+\delta)} \\ A(\bar{B}^0 \to F) \equiv \quad & \bar{A}_f & = A e^{i(-\phi+\delta)} \end{aligned}$$

$\Rightarrow$ one phase-difference from CP-odd ϕ;

2nd phase-difference from B–$\overline{\text{B}}$ oscillations: relative phase $\Delta M t$; npQCD parameters δ and A cancel in observables!

CP Violation in B_d^0 Decays into CP Eigenstates I

Time-development (oscillation + decay) of particles identified as B^0 $(\bar{B}^0)$ at time $t=0$:

$$|B^0(t)\rangle = g_+(t)|B^0\rangle - e^{-i\phi_d}\, g_-(t)|\bar{B}^0\rangle, \; |\bar{B}^0(t)\rangle = -e^{i\phi_d} g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

with $g_\pm(t) \equiv \frac{1}{2}\left(e^{-i\mu_{\rm heavy}t} \pm e^{-i\mu_{\rm light}t}\right)$, $\mu = m + i\Gamma$, mixing-phase ϕ_d.

Obtain time-dependent CP-asymmetry: $(\mathrm{CP}|F\rangle = \pm|F\rangle)$

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(B_q^0(t)\to F) - \Gamma(\bar{B}_q^0(t)\to F)}{\Gamma(B_q^0(t)\to F) + \Gamma(\bar{B}_q^0(t)\to F)}$$

$$\begin{tikzcd} \mathbf{B^0} \arrow[rr] \arrow[dr, bend right] & & \mathbf{F} \\ & \mathbf{\bar{B}^0} \arrow[ur, bend right] & \end{tikzcd}$$

$$= \left\{\mathcal{A}_{\rm CP}^{\rm dir}(B_q\to F)\cos(\Delta M_q t) + \mathcal{A}_{\rm CP}^{\rm mix}(B_q\to F)\sin(\Delta M_q t)\right\}$$

with $\mathcal{A}_{\rm CP}^{\rm dir} = \dfrac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $\quad \mathcal{A}_{\rm CP}^{\rm mix} = \dfrac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}$, $\quad \lambda_f = -e^{-i\phi_d}\dfrac{\bar{A}_f}{A_f}$

λ_f contains info on weak phases and, in general, also hadronic matrix-elements.

Hadronic matrix-elements drop out in **gold-plated decays!**

CP Violation in B_d^0 Decays into CP Eigenstates II

$\lambda_f = -e^{-i\phi_d} \dfrac{\langle F|H_{\text{eff}}|\bar{B}^0\rangle}{\langle F|H_{\text{eff}}|B^0\rangle}$ contains hadronic matrix-elements.

Express H_{eff} in terms of weak amplitudes: $H_{\text{eff}} = \dfrac{4G_F}{\sqrt{2}} \sum_{k=d,s} \sum_{\alpha=u,c} V_{\alpha b} V_{\alpha k}^* Q^{\alpha k} +$ h. c.

Suppose one weak amplitude (e.g. $b \to c\bar{c}s$) dominates:

$\lambda_f(b \to c\bar{c}s) = -e^{-i\phi_d} \dfrac{V_{cb}V_{cs}^* \langle F|Q^{cs}|\bar{B}^0\rangle}{V_{cb}^* V_{cs} \langle F|Q^{cs\dagger}|B^0\rangle} = -\eta_F e^{-2i\beta}$ with CP $|F\rangle = \eta_F\, |F\rangle$, $\eta_F = \pm 1$

- λ_f pure phase $\longrightarrow$ no direct ~~CP~~
- $A_{CP} = (\text{Im}\,\lambda_f) \sin \Delta M t$ $\longrightarrow$ direct extraction of weak phase with very small theoretical uncertainty (given by subdominant weak amplitudes)
- subdominant contributions to $b \to c\bar{c}s$ CKM-suppressed as $\lambda^2 \sim O(4\%)$ $\longrightarrow$ realized as e.g. $B_d \to J/\psi K_S$, $B_s \to D_s^+ D_s^-$ (gold-plated decays)

The general case: **Penguin-Pollution**

(2nd weak ampl. often gen. by penguins, e.g. in $B_d \to \pi^+\pi^-$)

$$\begin{aligned} A_f &= A_1 e^{i(\phi_{A_1}+\delta_1)} + A_2 e^{i(\phi_{A_2}+\delta_2)} \\ \lambda_f &= -\eta_f e^{-2i\phi_1} \frac{1+re^{i(\Delta-\phi_2+\phi_1)}}{1+re^{i(\Delta+\phi_2-\phi_1)}} \end{aligned}$$

with $\phi_{1,2} = \phi_{A_{1,2}} - \frac{1}{2}\phi_d^{\rm mix}$, $\Delta = \delta_2 - \delta_1$, $r = A_2/A_1$.
For r small:

$$\begin{aligned} \mathcal{A}^{\rm dir} &\approx 2r\sin(\phi_1-\phi_2)\sin\Delta \\ \mathcal{A}^{\rm mix} &\approx \eta_f\left[\sin 2\phi_1 - 2r\cos 2\phi_1 \sin(\phi_1-\phi_2)\cos\Delta\right] \end{aligned}$$

$\longrightarrow$ no clean measurement of ϕ_1, ϕ_2

r, Δ not yet accessible to calculation from first principles; try to exploit symmetries and limits:

- U-spin symmetry: assume invariance of QCD under $d \leftrightarrow s$ $\leadsto$ $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ determined by the same QCD parameters $\leadsto$ 4 unknowns r, Δ, ϕ_1, ϕ_2, 4 observed $\mathcal{A}^{\rm dir,mix}$ $\leadsto$ extraction of ϕ_1, ϕ_2
- heavy quark limit: can show that QCD-factorization works in the limit $m_b \to \infty$; reduce A_f to perturbatively calculable hard-scattering amplitude and nonperturbative quantities (form factors, hadron wave-functions)

Problem: No systematic way for improvement: symmetry-breaking corrections to U-spin not accessible, QCD-factorization shown to break down at $O(1/m_b)$.

Other Strategies for Theoretically Clean Extractions of Weak Phases

- mostly trigonometric relations between amplitudes of processes related by isospin or SU(3) symmetry, e.g. $B^0 \longrightarrow \pi^+\pi^-$, $B^0 \longrightarrow \pi^0\pi^0$, $B^+ \longrightarrow \pi^+\pi^0$ and CP-conjugates

Intermezzo I: B-Tagging at B-Factories

How to identify flavour of B?

Charged B's: look for semileptonic decay e.g. $B^+ \to \ell^+ X \Rightarrow$ identifies 2nd B as B^- at production time.

Neutral B's: a bit different due to mixing: look again for sl. decay e.g. $B^0 \to \ell^+ + X \Rightarrow$ identifies 2nd B as having opposite flavour at decay-time of 1st B (to be specific: measured in the restsystem of $Y(4S)$).

However: at second glance, things are not that obvious. . .

At $Y(4S)$, B^0–$\bar{B}^0$ pair produced in a correlated wave-function, quantum-numbers being fixed by those of $Y(4S)$. In particular: $Y(4S)$ is C-odd, so that (in the restsystem of $Y(4S)$):

$$
\begin{aligned}
&|B^0(\vec{k})\bar{B}^0(-\vec{k})\rangle_{C=-1} = \\
&= \quad \frac{1}{\sqrt{2}}\left[|B^0(\vec{k})\rangle \otimes |\bar{B}^0(-\vec{k})\rangle - |\bar{B}^0(\vec{k})\rangle \otimes |B^0(-\vec{k})\rangle\right]
\end{aligned}
$$

$\Rightarrow$ B's cannot have the same flavour at the same time.

If B's were produced in a C-even state, this wouldn't be the case and one could not identify flavour of one by flavour-specific decay of the other!

Intermezzo II:
How could New Physics manifest itself?

Recall: UT already fixed by R_t and R_b (3rd side $\equiv 1$).

Central values of present data:
$R_t = 0.94$, $R_b = 0.41 \Rightarrow \beta = 24^o$, $\sin 2\beta = 0.74$.

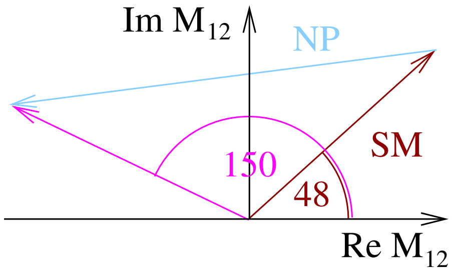
NP in R_b? — Unlikely: determined from tree-level decays.

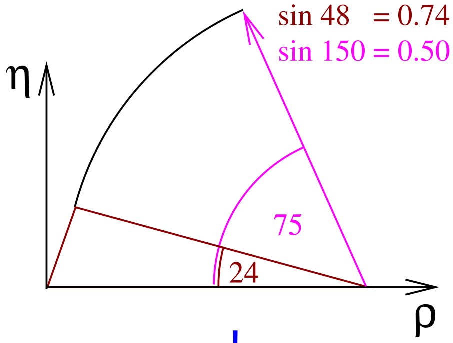
NP in R_t? — Actually – why not? R_t determined from B-mixing, i.e. loop-process, i.e. NP not loop-suppressed w.r.t. SM.

However: so far, all data agree with constraint from ϵ_K, i.e. NP does not change R_t too much (or does change both in a way to make things look consistent).

Let's play malicious: suppose NP does not change R_t, i.e. $|M_{12}|$, but does change ϕ_d, i.e. arg M_{12}:

$$\begin{aligned} M_{12} &= M_{12}^{SM} + M_{12}^{NP} \\ |M_{12}| &= |M_{12}^{SM}| \end{aligned}$$





Central value of $\sin 2\beta$ from BaBar/Belle: 0.5!

$\Rightarrow$ UT does not close any more!

Outline

- What is a B-Factory?
- Essentials of Flavour-Physics
- Strong Interactions in B-Physics
- Loop-Processes and the Unitarity-Triangle
- $|V_{cb}|$ and $|V_{ub}|$ from Semileptonic Decays
- CP-Violation in B-Decays
- **Rare Decays and New Physics**

Rare Decays and New Physics

Rare decays $\Leftrightarrow$ flavour-changing neutral current (FCNC) decays, i.e. $b \to s, d$

Recall: no FCNC in the SM at tree-level; loop-induced by charged gauge-bosons

$\Rightarrow$ potential new-physics (NP) contributions not loop-suppressed w.r.t. SM

$\Rightarrow$ strong sensitivity of rare decays to NP, up to mass-scales ~ 1 TeV (decoupling for $M_{\rm NP} \to \infty$)

Interesting decay modes:

inclusive	exclusive
$B \to X_s\gamma$	$B \to K^*\gamma$
$B \to X_s\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$
$B \to X_s\nu\bar\nu$	$B \to K^*\nu\bar\nu$
	$B \to \ell^+\ell^-$

$X_s \to X_d$, $K^* \to \rho$: CKM-suppressed

Only seen channels to date:

$$\begin{aligned} B(B \to X_s\gamma) &= (3.1 \pm 1.1) \cdot 10^{-4} \\ B(B \to K^*\gamma) &= (3.8 \pm 0.9) \cdot 10^{-5} \end{aligned}$$

Concentrate on $B \to X_s\gamma$.

Calculation of Decay Rate

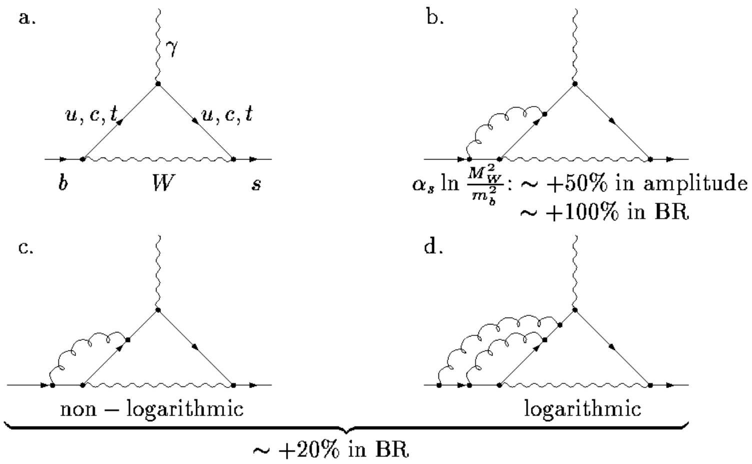
Heavy Quark Expansion (HQE):

$$B(B \to X_s\gamma) = B(b \to s\gamma) \; + \underbrace{O(\frac{1}{m_b^2})}_{\downarrow} \; + \underbrace{O(\frac{1}{m_c^2})}_{\downarrow}$$

binding of b in B, “Fermi-motion”

long-distance emission of γ via $b \to \underbrace{(c\bar{c})}_{\gamma} s$

- $B(b \to s\gamma)$ known to NLO in QCD; perturbative QCD effects extremely important



- power-suppressed terms $O(1/m_{b,c}^2)$ small $\sim$ 5%
- agreement between experiment and SM-prediction within errors $\leadsto$ bounds on NP
- relevant operator in the SM: magnetic transition $O_7 = \bar{s}_L \sigma_{\mu\nu} m_b b_R F^{\mu\nu}$
- LO QCD corrections also available in a number of extensions of the SM: left-right-symmetric model, 2-Higgs-doublet model, several SUSY-scenarios

$b \longrightarrow s\gamma$ and Supersymmetry

If SUSY was exact: $B(B \to X_s\gamma) = 0$!

$\Rightarrow b \to s\gamma$ sensitive to SUSY-breaking parameters

Broken SUSY with new manifestations of flavour-violation:

- standard CKM-mechanism as in SM

- flavour-violation from off-diagonal terms in squark mass-matrix (in super CKM-basis with squark-fields rotated exactly as their quark superpartners)

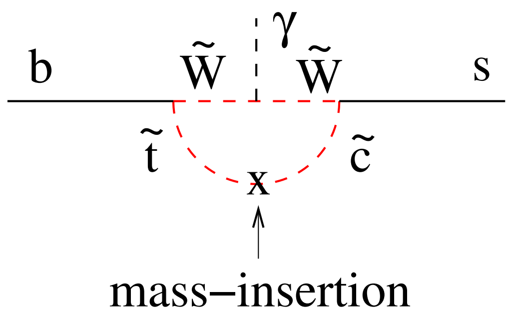


diagram not CKM-suppressed!

- more important in most of SUSY parameter-space: large contributions from flavour-off-diagonal quark-squark-gluino couplings

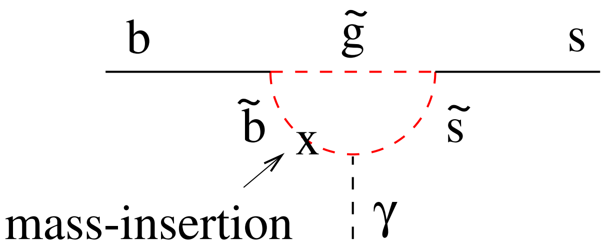
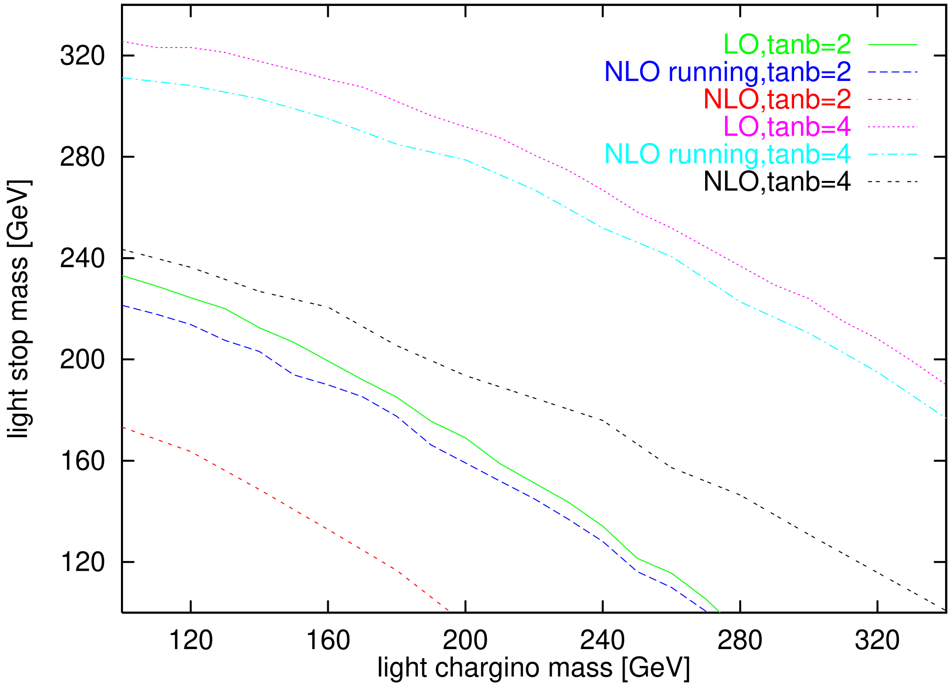


diagram $\propto g_s^2$!

SM-predictions in agreement with experiment, despite potentially huge SUSY-effects. Why are they small?
$\rightsquigarrow$ SUSY flavour-problem

Strong bounds on SUSY-parameters!

SUSY-Bounds and QCD



- only a few NLO calculations available for SUSY-scenarios

← results in a specific SUSY-scenario (Cuichini et al. 1998): bounds rather sensitive to NLO QCD contribution

Where are the brave knights to calculate more of that???

(need divergent parts of 3-loop diagrams etc.)

Calculation of Spectra

Experiment: large background from $b \to c\bar{u}d\gamma$, $u\bar{u}d\gamma$ for $E_\gamma < 2\,$GeV.

$\to$ measure only partially integrated rate $B(B \to X_s\gamma)(E_\gamma^{\rm min}) = \int_{E_\gamma^{\rm min}}^{E_\gamma^{\rm max}} dE_\gamma \, \frac{dB}{dE_\gamma}$

Heavy quark expansion:

$$\begin{aligned} \frac{1}{B}\frac{dB}{dx_\gamma} &= \delta(1-x_\gamma) - \frac{\alpha_s}{\pi} C_F \mathcal{D}_1(x_\gamma) - \frac{7}{4}\frac{\alpha_s}{\pi} C_F \mathcal{D}_0(x_\gamma) + \ldots \\ \mathcal{D}_k(x) &= \left(\frac{\ln^k(1-x)}{1-x}\right)_+, \quad 0 \le x_\gamma = \frac{2E_\gamma}{m_B} \le 1 \end{aligned}$$

For $x_\gamma \to 1$, need to resum large IR-logs $\sim \alpha_s^n \mathcal{D}_k(x_\gamma)$ $(0 \le k \le 2n-1)$ into universal function $f(x_\gamma)$

Situation completely analogous to $b \to ue\nu$: need to separate from background $b \to ce\nu$

- go for either small invariant hadron mass or large electron energies
- define $z = 1 - \frac{m_X^2}{4E_X^2}$ (which implies that the hard scale in the process is not m_B, but $2E_X$; X: hadron "jet" in $B \to X_u e\nu$)

$$\Rightarrow \frac{1}{\Gamma}\frac{d\Gamma^{\mathrm{SL}}}{dz} = \delta(1-z)$$
$$-\frac{\alpha_s}{\pi}C_F\mathcal{D}_1(z) - \frac{7}{4}\frac{\alpha_s}{\pi}C_F\mathcal{D}_0(z) + \ldots$$

Same structure and coefficients as for $b \to s\gamma$!

Resummation of large logs into the same universal function f occurring in $b \to s\gamma$; f related to the shape-function of heavy quark effective theory: $(k_+ = -m_X^2/(4E_X^2))$

$$\phi(k_+) \equiv \langle B(v)|h_v^\dagger \delta(k_+ - iD_+)h_v|B(v)\rangle$$

(nonperturbative part of ϕ describes Fermi-motion of b quark in B-meson)

Resummed hadron-energy spectrum in $B \to X_u e\nu$ ($w = 2E_X/m_B$):

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dw} = 2w^2 \{1 - \Theta(w-1)\exp[h(w-1)]\}$$

$$f(z) = \frac{d}{dy}\exp[h(y)]_{y=1-z}$$

(explicit expression for h in U. Aglietti, hep–ph/0104020)

Perturbative expansion agrees with fixed order calculations up to terms $\sim \alpha_s \times$ constant.

Can use universality of f to formulate relations between distributions in $b \to s\gamma$ and $b \to ue\nu$ where dependence on f drops out

$\to$ theoretically clean determination of $C_7|V_{ts}^* V_{tb}|/|V_{ub}|^2$ (to NLO in threshold-log resummation and up to higher-twist corrections)

Relevance of nonperturbative terms in f?

Topic in rapid development! Expect more complete predictions for spectra soon!