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43. Herbstschule für Hochenergiephysik Maria Laach
Bautzen, 6 – 16 September 2011

- The flavour of flavour physics
- SM flavour sector
- Hadronic B decays: Theoretical Methods
- B–$\bar{B}$ mixing
- Outlook

A Back-of-the-Envelope Estimate

Nutella: $2 \cdot 10^4$ J/g

Butter: $3 \cdot 10^4$ J/g

triglicerides: glycerol $C_3H_8O_3$

fatty acids, e.g. $C_{16}H_{32}O_2$

gasoline, e.g. octane C_8H_{18}

energy ΔE through burning: $C_nH_{2n} \to n \cdot CO_2 + n \cdot H_2O$

$$\frac{\Delta E}{M} = \frac{2n(m_e\alpha^2/9)}{14n \cdot m_p} = \frac{m_e\alpha^2}{63m_p} = 4.6 \cdot 10^{-10} = 4.1 \cdot 10^4 J/g$$

$$\boxed{\Delta E/M \sim m_e\alpha^2/m_p}$$

Flavour

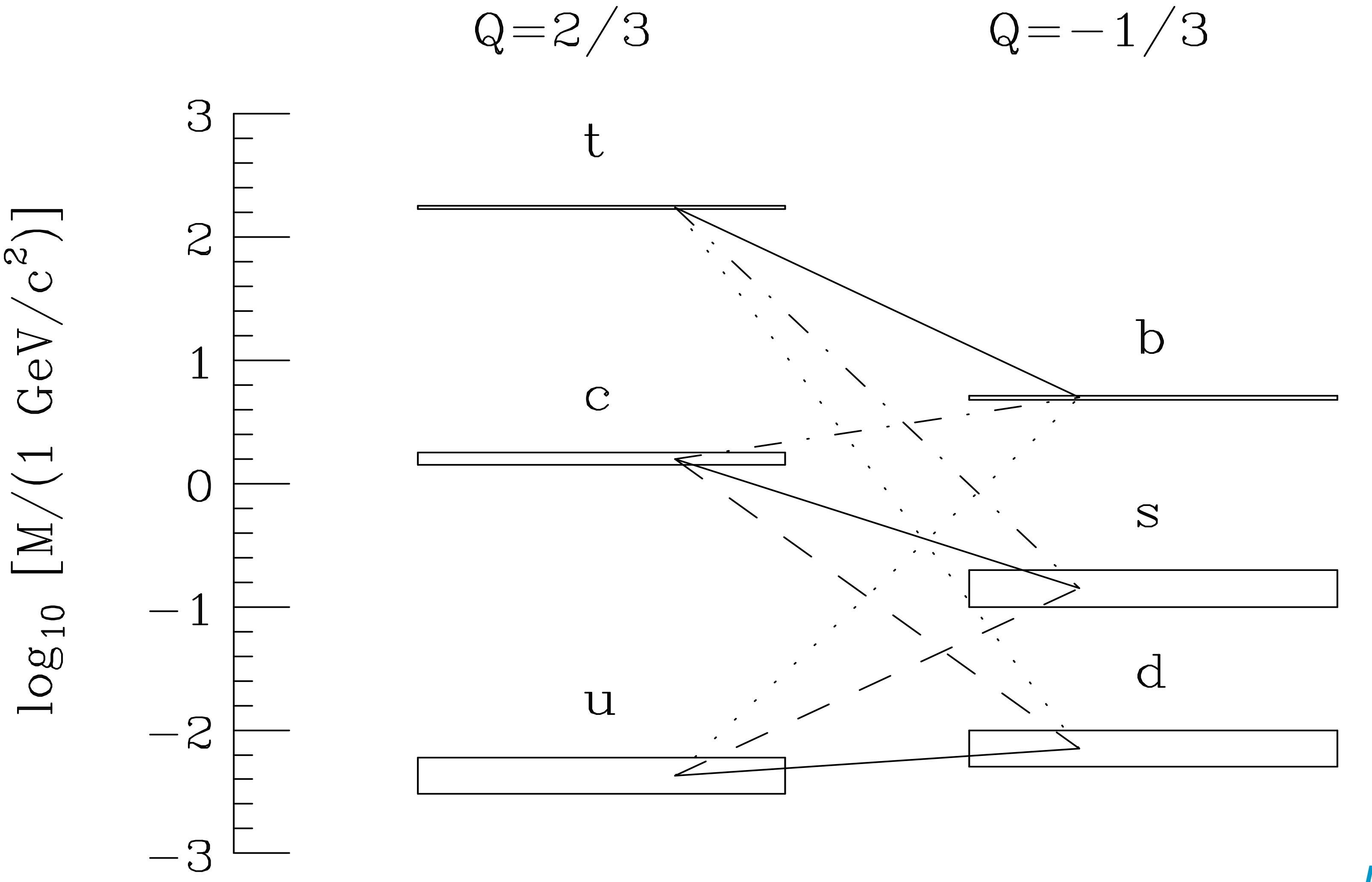
leptons, quarks, part of a bigger structure:

ν_e	ν_μ	ν_τ
e	μ	τ
u	c	t
d	s	b

$\rightarrow$ flavour

- $m_e \rightarrow$ atomic physics
- $m_\mu \rightarrow$ cosmic rays, μ catalyzed fusion (?)
- $m_d > m_u \Rightarrow m_n > m_p$, proton lightest baryon, stable

Quark Spectrum



Rosner

Milestones in Flavour Physics

- discovery of kaons – associated production

$$\begin{array}{ccccccc} & \pi^+ & + \; p & \rightarrow & K^+ & + \; \bar{K}^0 & + \; p \\ S & 0 & 0 & & +1 & -1 & 0 \end{array}$$

- → strangeness → quark model $SU(3)$ (u,d,s) *Gell-Mann*
- parity violation "Θ - τ puzzle" *Lee, Yang*

$$K^+ \rightarrow 2\pi \text{ (P even)} \qquad K^+ \rightarrow 3\pi \text{ (P odd)}$$

- CP violation *Christenson et al.*

observed in: $K_L \rightarrow \pi\pi,\, \pi^+\pi^-\gamma,\, \pi^+\pi^-e^+e^-,\, \pi l\nu$

$$B^0 \rightarrow \psi K_S,\; B^0 \rightarrow K^+\pi^-,\; \ldots$$

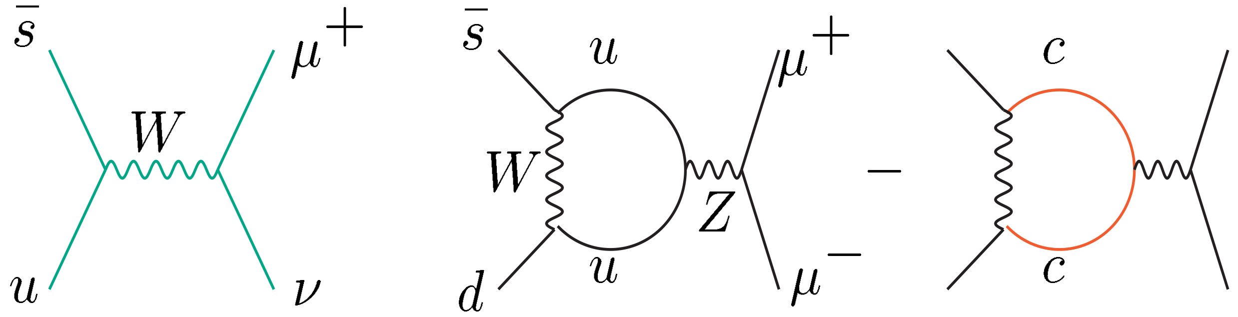
$$\Delta = \frac{\Gamma(K_L\to\pi^- l^+\nu) - \Gamma(K_L\to\pi^+ l^-\bar{\nu})}{+} = (3.32 \pm 0.06)\cdot 10^{-3}$$

LHCb

Milestones in Flavour Physics

- suppression of flavour-changing neutral currents

$$K^+ \to \mu^+\nu \quad 64\% \qquad K_L \to \mu^+\mu^- \quad 7\cdot 10^{-9}$$



$$G_F^2(M_W^2 + m_u^2) - G_F^2(M_W^2 + m_c^2) \sim G_F^2 m_c^2$$

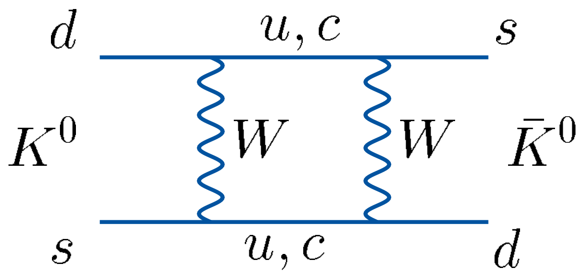
$$\ll G_F^2 M_W^2$$

GIM mechanism

Milestones in Flavour Physics

- K-$\bar{K}$, B_d-$\bar{B}_d$ mixing, GIM, charm and top

$$K_{L,S} = \frac{K^0 \pm \bar{K}^0}{\sqrt{2}}$$



$$\begin{pmatrix} M & M_{12} \\ M_{12} & M \end{pmatrix} \quad \begin{matrix} K^0 \\ \bar{K}^0 \end{matrix}$$

$$\frac{\Delta M_K}{M_K} \approx \frac{G_F^2 f_K^2}{6\pi^2} \left| V_{cs} V_{cd} \right|^2 m_c^2 = 7 \cdot 10^{-15} \qquad \Rightarrow m_c \approx 1.5\,\mathrm{GeV}$$

Gaillard, Lee '74

$$\frac{\Delta M_B}{M_B} \approx \frac{G_F^2 f_B^2}{6\pi^2} \left| V_{tb} V_{td} \right|^2 M_W^2 S\left(\frac{m_t}{M_W}\right) = 6 \cdot 10^{-14} \qquad \Rightarrow m_t \sim M_W$$

ARGUS '87

crucial insights into fundamental physics – indirect probe of high scales

SM Flavour Sector

	q	l	u	d	e	φ	$\tilde{\varphi}$
Y	$1/6$	$-1/2$	$2/3$	$-1/3$	-1	$1/2$	$-1/2$
$SU(2)$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$

$\tilde{\varphi}_i = \varepsilon_{ij}\varphi^*_j$ $X_{\mu\nu} = G_{\mu\nu}\ [SU(3)_C]$, $W_{\mu\nu}\ [SU(2)_L]$, $B_{\mu\nu}\ [U(1)_Y]$; D_μ

all operators of dimension ≤ 4 (up to $X\tilde{X}$) $\Rightarrow$

$$\text{without } \varphi: \qquad \mathcal{L}_{\text{gauge}} = -\frac{1}{2}\text{tr}\, G_{\mu\nu}G^{\mu\nu} - \frac{1}{2}\text{tr}\, W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+\bar{q}i\not{D}q + \bar{l}i\not{D}l + \bar{u}i\not{D}u + \bar{d}i\not{D}d + \bar{e}i\not{D}e$$

$$\mathcal{L}_\varphi = D_\mu\varphi^\dagger D^\mu\varphi - \mu^2\varphi^\dagger\varphi + \lambda(\varphi^\dagger\varphi)^2 - (\bar{q}Y_u u\tilde{\varphi} + \bar{q}Y_d d\varphi + \bar{l}Y_e e\varphi + \text{h.c.})$$

SM Flavour Sector

$$\mathcal{L} = \bar{q}' i \not{D} q' - (\bar{q}' Y_u u' \tilde{\varphi} + \bar{q}' Y_d d' \varphi) + \ldots$$

$$\to \sum_{f'=u'_L,d'_L,u'_R,d'_R} \bar{f}' i \not{\partial} f' - \frac{g_2}{\sqrt{2}} \bar{u}'_L \gamma^\mu d'_L W_\mu - \bar{u}'_L M_u u'_R - \bar{d}'_L M_d d'_R + \ldots$$

$$\to \sum_{f=u_L,d_L,u_R,d_R} \bar{f} i \not{\partial} f - \frac{g_2}{\sqrt{2}} \bar{u}_L V \gamma^\mu d_L W_\mu - \bar{u}_L \mathcal{M}_u u_R - \bar{d}_L \mathcal{M}_d d_R + \ldots$$

with unitary transformations $u'_{L,R} = U_{L,R} u_{L,R}, \qquad d'_{L,R} = D_{L,R} d_{L,R}$

$$U^\dagger_L M_u U_R = \mathcal{M}_u \equiv \text{diag}(m_u, m_c, m_t)$$

$$D^\dagger_L M_d D_R = \mathcal{M}_d \equiv \text{diag}(m_d, m_s, m_b)$$

$$V \equiv U^\dagger_L D_L$$

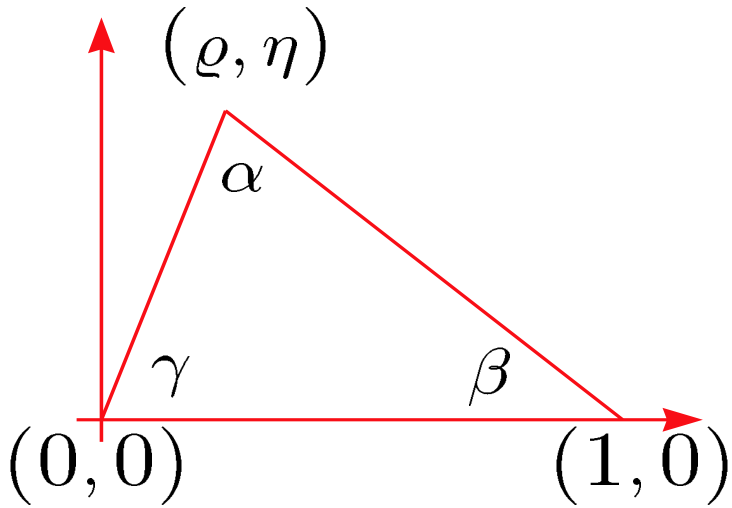
$n \times n$ unitary matrix: n^2 parameters

V: $\quad n(n-1)/2$ angles

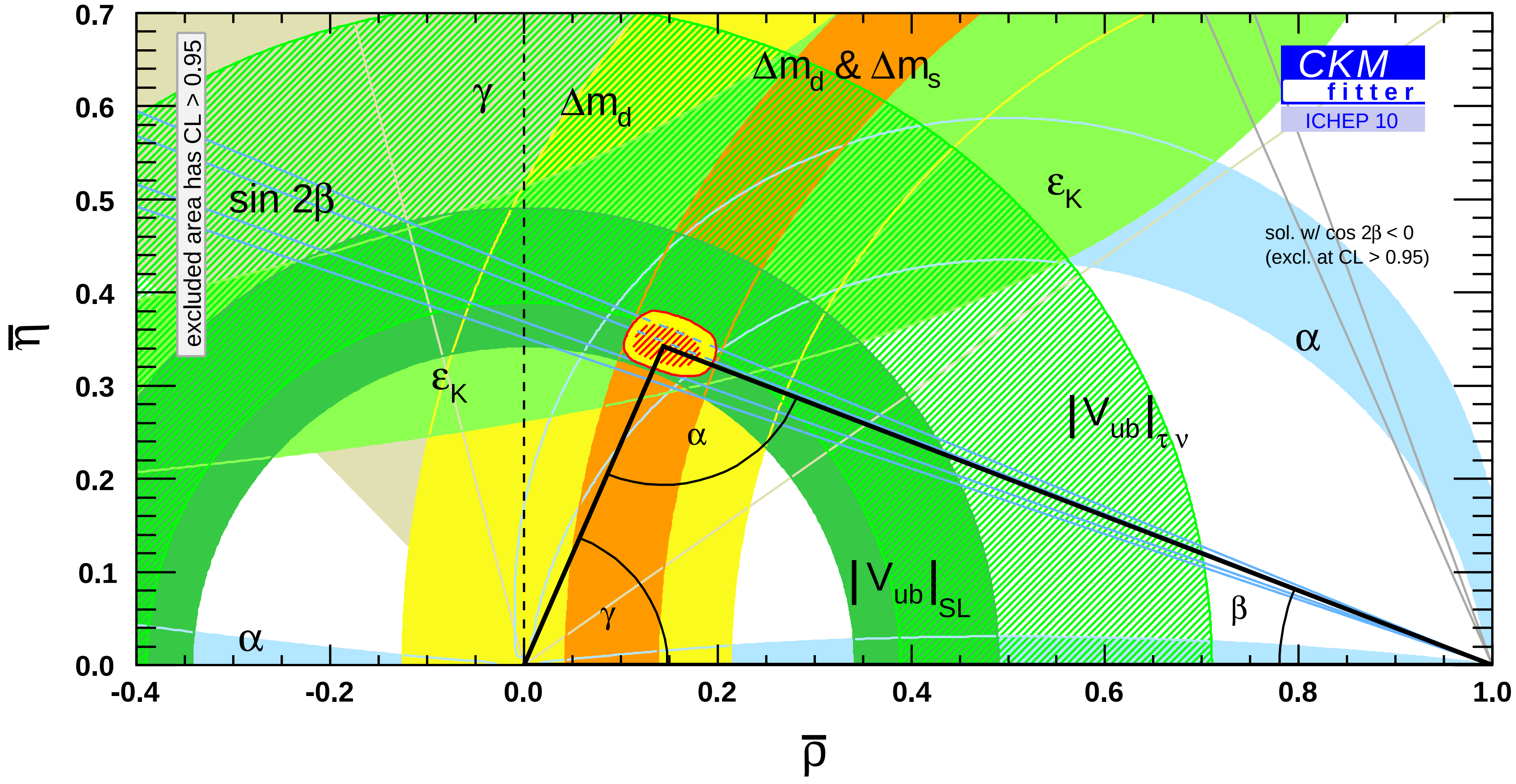
$\quad\quad n^2 - n(n-1)/2 - (2n-1) \equiv (n-1)(n-2)/2$ physical phases

$V = U_L^\dagger D_L$ 3 angles, 1 phase $\leftrightarrow$ CP violation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Status of UT



CKM fitter
ICHEP 10
excluded area has CL > 0.95
γ
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
ε_K
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
α
α
γ
β
$|V_{ub}|_{\tau\nu}$
$|V_{ub}|_{SL}$
$\bar{\eta}$
$\bar{\rho}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

The Flavour Problem

$$\mathcal{L}_{\rm SM,eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SM,nr}$$

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\varphi}, \qquad \mathcal{L}_{\rm SM,nr} = \sum_{d=5,6,\ldots} \sum_k \frac{r_{d,k}}{\Lambda^{d-4}} \mathcal{O}_{d,k}$$

$\mathcal{O}_{6,k}$ e.g.: $\bar q \gamma^\mu q \, \bar q \gamma_\mu q$ [$\rightarrow B$–$\bar B$ mixing], $\bar q \sigma_{\mu\nu} B^{\mu\nu} d\varphi$ [$\rightarrow b \rightarrow s\gamma$], …

$$\Delta\mathcal{L}_{NP} = \frac{c}{\Lambda^2}\, \bar d_L \gamma^\mu b_L \, \bar d_L \gamma_\mu b_L \qquad (B_d\text{–}\bar B_d)$$

$$|M_{12}^{NP}| < |M_{12}^{SM}| \quad \Rightarrow \quad \Lambda > 500\,\mathrm{TeV}\sqrt{c}$$

compare: $(\psi = e,\, p)$

$$\mathcal{L}_{\rm QED,eff} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar\psi i \not{D} \psi - m \bar\psi \psi \quad + \frac{c_5}{\Lambda} \bar\psi \sigma_{\mu\nu} F^{\mu\nu} \psi + \ldots$$

Minimal Flavour Violation (MFV)

D'Ambrosio, Giudice, Isidori, Strumia

large flavour symmetry of $\mathcal{L}_{\mathrm{gauge}}$: $U(1)^5 \otimes \mathcal{G}_q \otimes \mathcal{G}_l$

$\mathcal{G}_q = SU(3)_q \otimes SU(3)_u \otimes SU(3)_d, \qquad \mathcal{G}_l = SU(3)_l \otimes SU(3)_e$

broken by $-\mathcal{L}_Y = \bar{q} Y_u u \tilde{\varphi} + \bar{q} Y_d d \varphi + \bar{l} Y_e e \varphi + \mathrm{h.c.}$

MFV hypothesis:

Y_f still the only sources of flavour symmetry breaking beyond SM

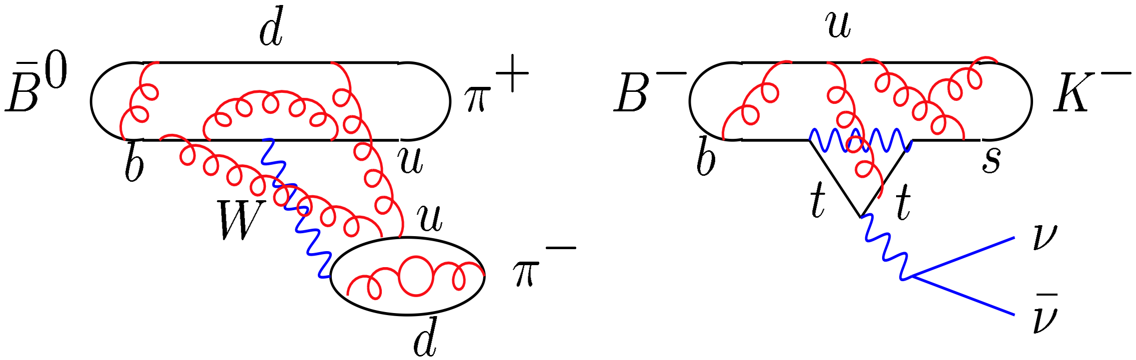
$Y_{u,d}$ *spurions* under $\mathcal{G}_q$: $Y_u \sim (3, \bar{3}, 1)$, $Y_d \sim (3, 1, \bar{3})$

$Y_d = \lambda_d$, $Y_u = V^\dagger \lambda_u$ ($\lambda_{u,d}$ diagonal)

$\Rightarrow \bar{q}\gamma_\mu q \to \bar{q}\gamma_\mu [Y_u Y_u^\dagger]^n q \qquad [Y_u Y_u^\dagger]^n_{i\neq j} \approx \lambda_t^n V_{ti}^* V_{tj}$

$d_{L,j} \to d_{L,i}$ still governed by CKM

Effective Weak Hamiltonians

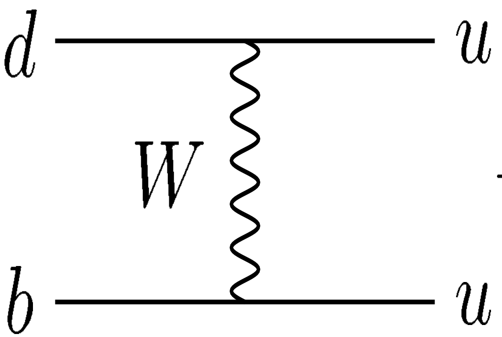


weak decays of B mesons complicated QFT problem

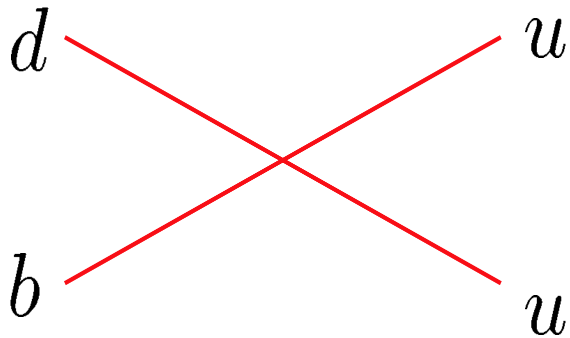
- interplay of strong and electroweak forces
- very different scales $m_t,\ M_W \gg m_b \gg \Lambda_{QCD},\ m_{u,d,s}$
- QCD dynamics at short and long distances

Effective Weak Hamiltonians

Operator Product Expansion (OPE)



$$+\,\mathrm{QCD} \;\simeq\; C\left(\frac{M_W}{\mu}, \alpha_s\right) \cdot$$

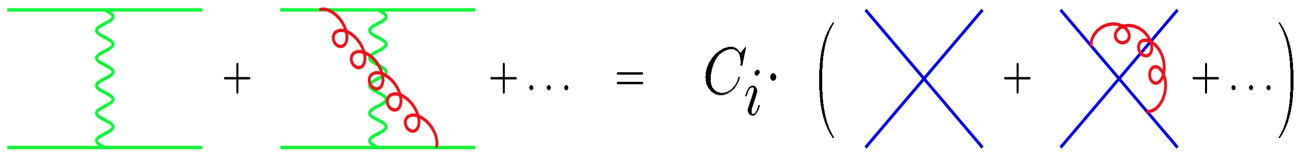


Wilson coefficient · local operator

$\mathcal{H}_{eff} \equiv$ eff. coupling · 4-quark vertex

factorization: high scales $> \mu >$ low scales

OPE: constructing $\mathcal{H}_{eff}$ – calculation of C

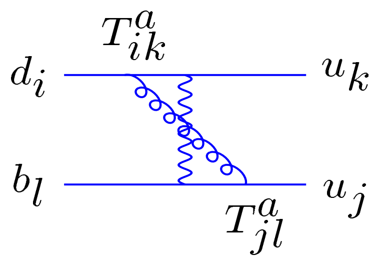


full amplitude A $\qquad\qquad \langle Q_i \rangle$

C_i independent of external states (factorization)

$\rightarrow$ compute A and $\langle Q_i \rangle$ for arbitrary ext. states $\rightarrow$ extract C_i

without QCD: $\quad Q_1 = (\bar{d}_i u_i)_{V-A} (\bar{u}_j b_j)_{V-A}$



with QCD:

$$\rightarrow (\bar{d}_i T^a_{ik} u_k)\,(\bar{u}_j T^a_{jl} b_l) = -\frac{1}{2N} (\bar{d}_i u_i)(\bar{u}_j b_j) + \frac{1}{2} (\bar{d}_i u_j)(\bar{u}_j b_i) \equiv -\frac{1}{2N} Q_1 + \frac{1}{2} Q_2$$

define: $Q_\pm = (Q_1 \pm Q_2)/2 \qquad C_\pm = C_1 \pm C_2$

$$A = \left(1 + \gamma_+ \alpha_s \ln \frac{M_W^2}{-p^2}\right) S_+ + \left(1 + \gamma_- \alpha_s \ln \frac{M_W^2}{-p^2}\right) S_-$$

$$\langle Q_\pm \rangle = \left(1 + \gamma_\pm \alpha_s \left(\frac{1}{\varepsilon} + \ln \frac{\mu^2}{-p^2}\right)\right) S_\pm$$

$$A \stackrel{!}{=} C_+ \langle Q_+ \rangle + C_- \langle Q_- \rangle \Rightarrow C_\pm = 1 + \gamma_\pm \alpha_s \ln \frac{M_W^2}{\mu^2}$$

- $\frac{1}{\varepsilon}$ divergence $\leftrightarrow$ $M_W \to \infty$ limit; $\ln M_W$ dep. $\leftrightarrow$ renorm. in eff. theory
- $C_\pm$ indep. of ext. states – factorization: $\ln \frac{M_W^2}{-p^2} = \ln \frac{M_W^2}{\mu^2} + \ln \frac{\mu^2}{-p^2}$
- $\mathcal{H}_{eff} = C_+(\mu) Q_+ + C_-(\mu) Q_-$, with $\langle f | Q_\pm | B \rangle (\mu)$ at $\mu \approx m_b \ll M_W$
- μ cancels between $C(\mu)$ and $\langle Q \rangle (\mu)$
- W-boson "integrated out"; extraction of C: "matching" calculation
- $\mathcal{H}_{eff}$ systematic low energy approx. of SM

Renormalization Group (RG)

$$C_\pm = 1 + \frac{\alpha_s}{4\pi}\frac{\gamma_\pm^{(0)}}{2} \cdot \ln\frac{\mu^2}{M_W^2} \qquad \gamma_+^{(0)} = 4, \qquad \gamma_-^{(0)} = -8$$

$$C_- - 1 = (-7\%) \cdot (-6) \approx 42\% \qquad \alpha_s \ln\frac{\mu}{M_W} = \mathcal{O}(1) \text{ for } \mu \approx m_b$$

resummation of PT

LO	$\alpha\ell$	$\alpha^2\ell^2$	$\alpha^3\ell^3$	$\rightarrow$	$\mathcal{O}(1)$
NLO	α	$\alpha^2\ell$	$\alpha^3\ell^2$	$\rightarrow$	$\mathcal{O}(\alpha)$
		α^2	$\alpha^3\ell$		

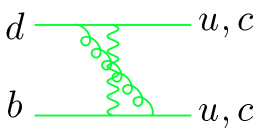
RGE: $$\frac{d}{d\ln\mu}C_\pm(\mu) = \frac{\alpha_s}{4\pi}\gamma_\pm^{(0)} \cdot C_\pm(\mu)$$

$\gamma_\pm^{(0)}$: anomalous dimension

using $d\alpha_s/d\ln\mu = -2\beta_0\alpha_s^2/(4\pi)$; $\beta_0 = (33-2f)/3$; $C_\pm(M_W) = 1$

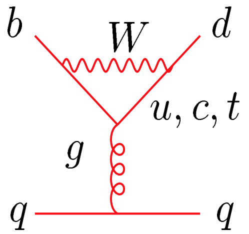
$$C_\pm(\mu) = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{\gamma_\pm^{(0)}}{2\beta_0}} = \left[1 + \beta_0\frac{\alpha_s(\mu)}{4\pi}\ln\frac{M_W^2}{\mu^2}\right]^{-\frac{\gamma_\pm^{(0)}}{2\beta_0}}$$

$\Delta B = 1$ Effective Hamiltonian



$$Q_1^p = (\bar{d}p)_{V-A}(\bar{p}b)_{V-A} \qquad p = u, c$$

$$Q_2^p = (\bar{d}_i p_j)_{V-A}(\bar{p}_j b_i)_{V-A}$$

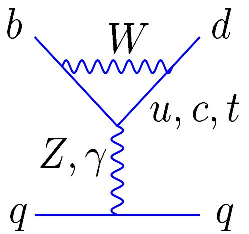


$$Q_3 = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V-A}$$

$$Q_4 = (\bar{d}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

$$Q_5 = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V+A}$$

$$Q_6 = (\bar{d}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}, \qquad Q_{7\gamma} = \frac{e m_b}{4\pi^2} \bar{d}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$



$$Q_7 = (\bar{d}b)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}q)_{V+A}$$

$$Q_8 = (\bar{d}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V+A}$$

$$Q_9 = (\bar{d}b)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}q)_{V-A}$$

$$Q_{10} = (\bar{d}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V-A}, \quad Q_{8g} = \frac{g m_b}{4\pi^2} \bar{d}_L \sigma_{\mu\nu} G^{\mu\nu} b_R$$

$\Delta B = 1$ Effective Hamiltonian

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} \left(C_1 Q_1^u + C_2 Q_2^u + \sum_{penguins} C_k Q_k \right)$$

$$+ \frac{G_F}{\sqrt{2}} V_{cd}^* V_{cb} \left(C_1 Q_1^c + C_2 Q_2^c + \sum_{penguins} C_k Q_k \right)$$

at $\mu_W = \mathcal{O}(M_W, m_t) \quad \rightarrow C_i(\mu_W),\ i = 1, \ldots, 10$

$q = u, d, s, c, b \qquad \downarrow \qquad f = 5$ **RG evolution**

$\mu_b \sim m_b$

$$\mathrm{LO}: \left(\alpha_s \ln \frac{M_W}{\mu}\right)^n, \ \alpha \ln \frac{M_W}{\mu} \left(\alpha_s \ln \frac{M_W}{\mu}\right)^n$$

$$\mathrm{NLO}: \alpha_s \left(\alpha_s \ln \frac{M_W}{\mu}\right)^n, \ \alpha \left(\alpha_s \ln \frac{M_W}{\mu}\right)^n$$

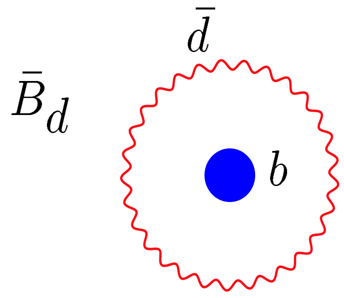
Hamiltonian (e.g. for $B \to \pi\pi$, $\rho\rho$)

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} \left(\overbrace{C_1 Q_1^u + C_2 Q_2^u}^{(\bar{u}b)(\bar{d}u)\downarrow} + \overbrace{\sum_{penguins} C_p Q_p}^{(\bar{d}b)(\bar{q}q)\downarrow} \right)$$

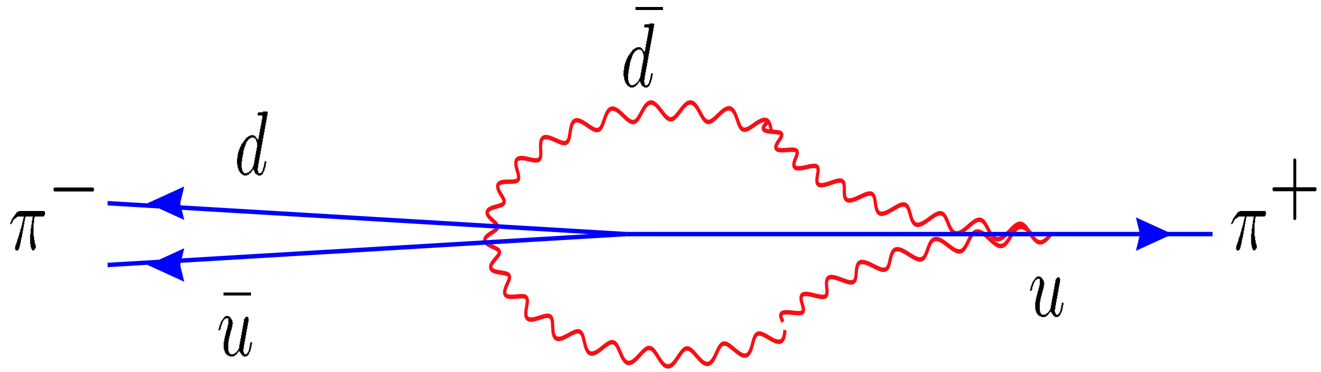
$$+ \frac{G_F}{\sqrt{2}} V_{cd}^* V_{cb} \left(C_1 Q_1^c + C_2 Q_2^c + \sum_{penguins} C_p Q_p \right)$$

similar for $B \to K^* \rho$, $B \to J/\Psi K_S$ $(d \leftrightarrow s)$

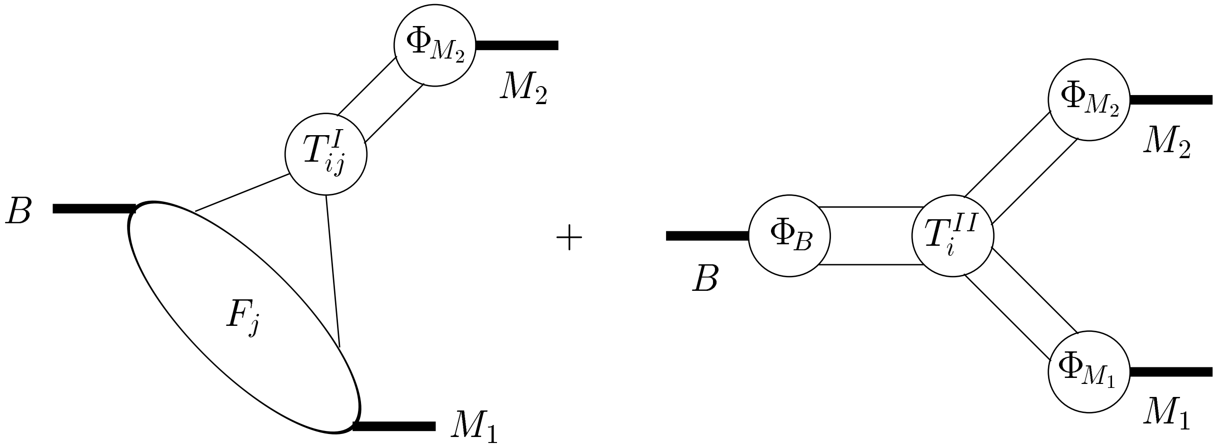
tree dominated	$\bar{B}_d \to \pi^+ \pi^-$, $\rho^+ \rho^-$	$b(\bar{d}) \to d\bar{u}u(\bar{d})$
pure penguin	$B^- \to \bar{K}^0 \pi^-$	$b(\bar{u}) \to s\bar{d}d(\bar{u})$
pure annihilation	$\bar{B}_d \to K^+ K^-$	$b(\bar{d}) \to u\bar{s}s\bar{u}$



$m_B \gg \Lambda_{\rm QCD}$



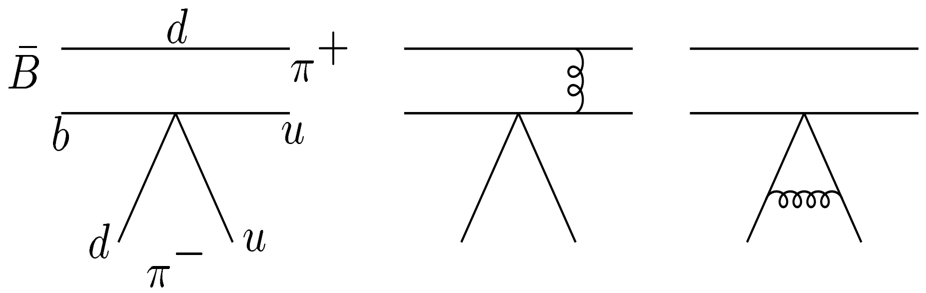
$B \to M_1 M_2$ simplifies in the heavy-quark limit

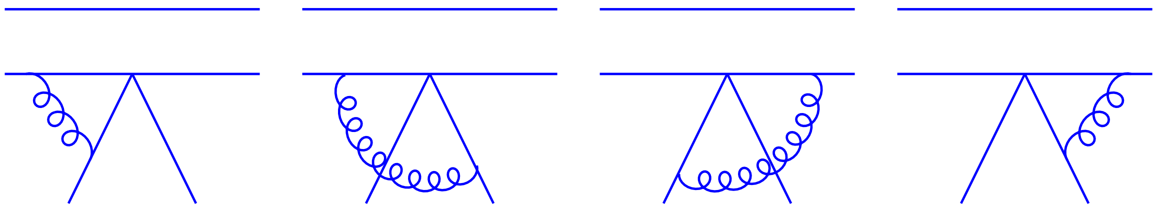


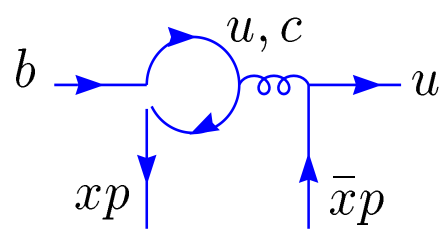
- successful phenomenology
  (penguin/tree; $V_L V_L$ vs. PP penguins; annihilation modes small; moderate direct CPV)
- form factors: reduced dependence in amplitude ratios
- computation of SU(3) breaking
- limitation: power corrections (weak annihilation)

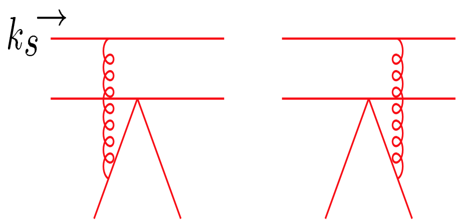
Theory of $B \to M_1 M_2$ — QCD Factorization

Beneke, G.B., Neubert, Sachrajda









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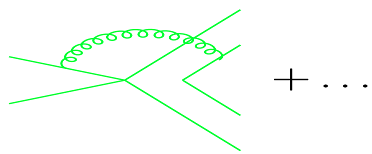
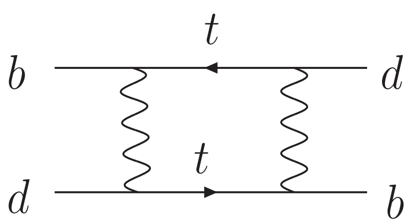
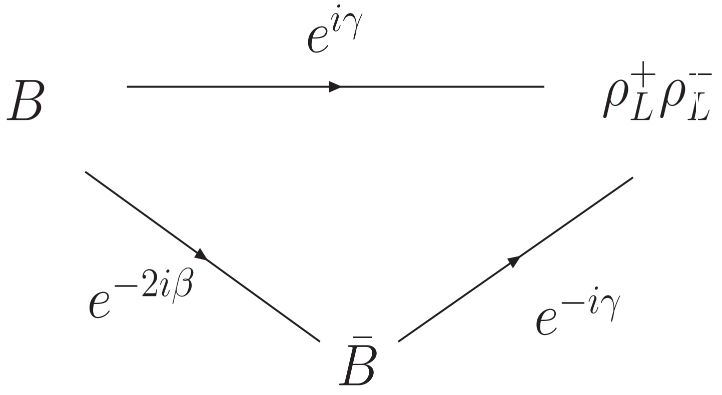


$$\langle \pi\pi | Q | B \rangle = F(B \to \pi) \cdot \int_0^1 dx\, T^I(x)\, \Phi_\pi(x) + \int_0^1 d\xi\, dx\, dy\, T^{II}(\xi, x, y)\, \Phi_B(\xi)\, \Phi_\pi(x)\, \Phi_\pi(y)$$

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}(t)\to\rho_L^+\rho_L^-)-\Gamma(B(t)\to\rho_L^+\rho_L^-)}{+} = S_\rho \sin(\Delta M_d t) - C_\rho \cos(\Delta M_d t)$$

without penguins $\to S = \sin 2\alpha$, $C = 0$





$$\exp(-2i(\beta+\gamma+\alpha-\alpha)) = \exp(2i\alpha)$$

$$A(\bar{B}\to\rho^+\rho^-) \sim \sqrt{\bar{\rho}^2+\bar{\eta}^2}e^{-i\gamma} + re^{i\varphi}$$

$$\sim \lambda_u\, a_u + \lambda_c\, a_c$$

$\tau \equiv \cot\beta = 2.54 \pm 0.13$

$B \to \rho_L^+\rho_L^-$: $S = -0.05 \pm 0.17$ $r \approx r\cos\varphi = 0.04 \pm 0.02$

$$\bar\eta \doteq \frac{1 + \tau S - \sqrt{1 - S^2}}{(1+\tau^2)S}(1 + r\cos\varphi) \qquad \bar\rho = 1 - \tau\,\bar\eta$$

$$\gamma \doteq \frac{\pi}{2} - \beta + \frac{S}{2} + \tau\, r\cos\varphi$$

$$\Rightarrow \qquad \gamma = 72.4^\circ \pm 1.3^\circ(\beta) \pm 5.1^\circ(S) \pm 3.2(r\cos\varphi)$$

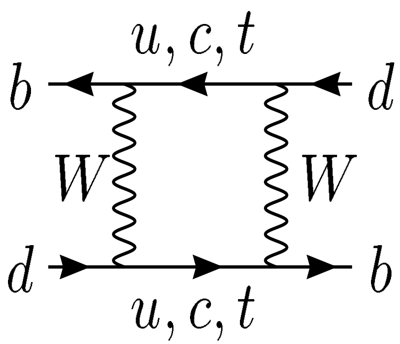
B–$\bar{B}$ Mixing

$$\boldsymbol{B}^T = (B, \bar{B}) \equiv (|1\rangle, |2\rangle), \qquad B = \bar{b}d, \qquad i\partial_t \boldsymbol{B}(t) = H\boldsymbol{B}(t)$$

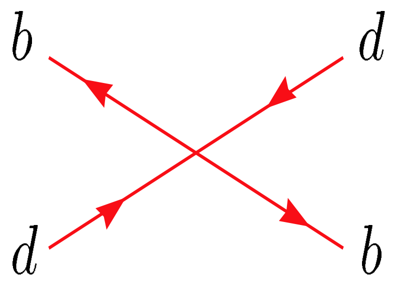
$$H = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{11} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11} \end{pmatrix}$$

$$\Delta M \equiv M_H - M_L = 2|M_{12}| = \frac{1}{M} \left|\langle B|\mathcal{H}_{eff}|\bar{B}\rangle\right|$$

M_{12}^d:



$+\,\mathrm{QCD} \;\simeq\; C(\mu_t)\cdot$



Γ_{12}: absorptive part of box (real intermediate u, c)

$\frac{M_{12}^{s[d]}}{M} \sim 10^{-12}[3 \cdot 10^{-14}]$	$\frac{\Gamma_{12}}{M_{12}} \sim \frac{m_b^2}{m_t^2}$	$\frac{\Gamma_{12}}{\Gamma} \sim 16\pi^2 \frac{f_B^2}{M_B^2} \lvert V_{cs[d]}\rvert^2 \sim 10^{-1}[3 \cdot 10^{-3}]$

B–$\bar{B}$ Mixing

$$B(t) = g_+(t) B - \tfrac{q}{p} g_-(t) \bar{B}, \qquad \bar{B}(t) = g_+(t) \bar{B} - \tfrac{p}{q} g_-(t) B$$

$$CP|B\rangle = -|\bar{B}\rangle, \qquad CP(\bar{d}b)_{V-A}[CP]^{-1} = -(\bar{b}d)_{V-A}$$

$$B_{H,L} = pB \pm q\bar{B}, \qquad \frac{q}{p} \equiv \frac{M_{12}^* - i\Gamma_{12}^*/2}{(\Delta M + i\Delta\Gamma/2)/2} \doteq \frac{M_{12}^*}{|M_{12}|}\left(1 - \frac{1}{2}a\right)$$

$$\Delta M \equiv M_H - M_L = 2|M_{12}|$$

$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H = -\Delta M \; \mathrm{Re}\frac{\Gamma_{12}}{M_{12}}, \qquad a = \mathrm{Im}\frac{\Gamma_{12}}{M_{12}}$$

$$g_+(t) = e^{-iMt - \frac{1}{2}\Gamma t}\left[\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right]$$

$$g_-(t) = e^{-iMt - \frac{1}{2}\Gamma t}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right]$$

$$\mathcal{A}(t) = \frac{\Gamma(\bar{B}(t) \to \bar{f}) - \Gamma(B(t) \to f)}{+}$$

$$\mathcal{A}_{fs}(t) = \frac{\Gamma(\bar{B}(t) \to l^+ X) - \Gamma(B(t) \to l^- X)}{+} = \frac{\left|\frac{p}{q}\right|^2 - \left|\frac{q}{p}\right|^2}{+} = a$$

$\bar{B} \not\to l^+ X, \qquad B \not\to l^- X$

$$\begin{aligned} \mathcal{A}_{fcp}(t) &= \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{+} \\ &= -\frac{2\mathrm{Im}\xi}{1+|\xi|^2} \sin \Delta M t + \frac{|\xi|^2 - 1}{|\xi|^2 + 1} \cos \Delta M t \end{aligned}$$

$\xi \equiv \frac{M_{12}^*}{|M_{12}|} \frac{A(\bar{B} \to f_{CP})}{A(B \to f_{CP})}, \qquad \Delta\Gamma = a = 0$

- precision CKM: CPV in $B \to M_1 M_2$, α, β, γ

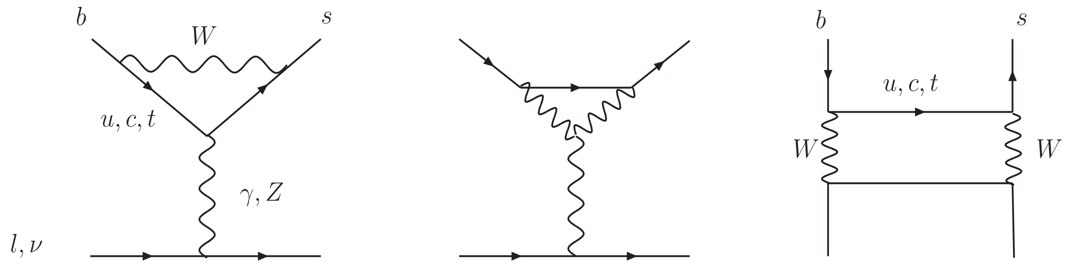
- rare decays: $B_s \to \mu^+\mu^-$, $B \to K^{(*)} l^+ l^-$, $K^{(*)}\nu\bar{\nu}$
  $B \to K^*\gamma$, $\rho\gamma$, $\rho l\nu$, $\tau\nu$, $D\tau\nu$

- B_s mixing, CPV in $B_s \to \psi\varphi$

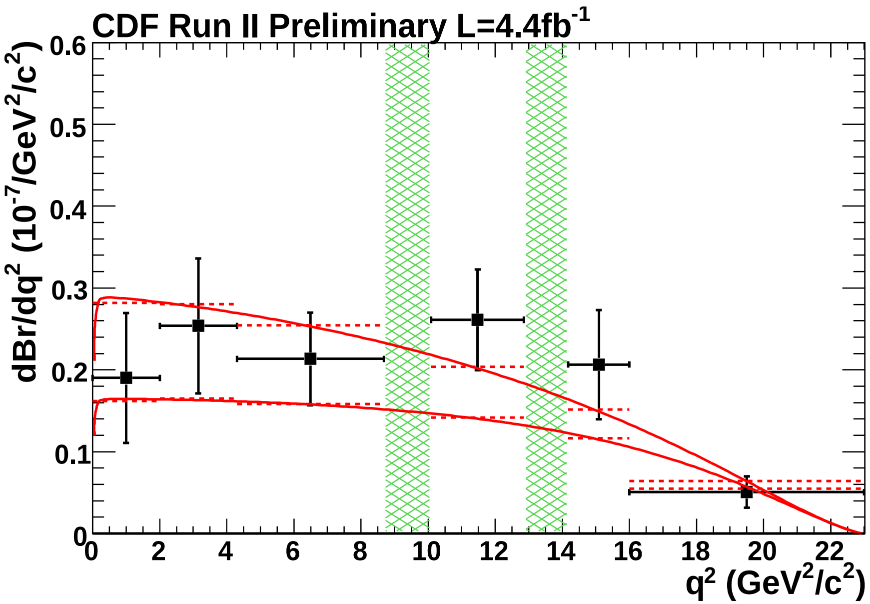
- kaon physics: $K^+ \to \pi^+\nu\bar{\nu}$ (NA62), $K_L \to \pi^0\nu\bar{\nu}$

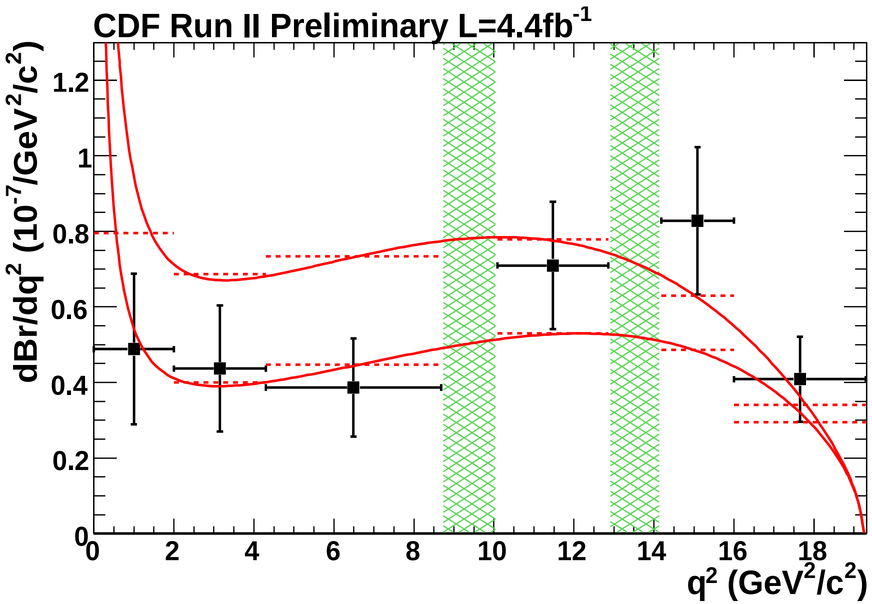
- charm physics

- lepton flavour violation: $\mu \to e\gamma$, $\tau \to \mu\gamma$



$B^- \to K^- \mu^+ \mu^-$ $\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$





$$BR/10^{-6} = \quad 0.38 \pm 0.05 \pm 0.03 \qquad 1.06 \pm 0.14 \pm 0.09$$ CDF

Outlook

Flavour $\rightarrow$ major challenge for particle physics

- CKM confirmed – exp. information on rare processes, CPV still limited
- fermion masses, mixing angles, generations ?
- new physics flavour problem

SM $\rightarrow$ testable predictions

- flavour physics complements direct collider searches for NP
- theoretical issue: QFD $\leftrightarrow$ QCD

Numerous flavour experiments $\rightarrow$ era of precision studies

- LHCb, Atlas, CMS; Belle II, SuperB; NA62 general:

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M. Artuso *et al.*, B, D and K decays, Eur. Phys. J. C **57** (2008) 309 [arXiv:0801.1833 [hep-ph]]

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G. Isidori, B physics in the LHC era, [arXiv:1001.3431 [hep-ph]]

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A. Pich, Effective field theory, arXiv:hep-ph/9806303