Flavour - Physics

→ Introduction
→ Starting time
→ lecture notes
→ recording?

- 10:00
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- LHCb γ
- DAMTP γ theory
- EFT • DAMTP: PDF, BSM
- Master: γ
- ATLAS: long life
- LHCb LU $B \to K\ell\ell$
  $B \to K^*\ell\ell$
- ν- Exp
- ν- Exp
- NNLO: weak boson prod.

1. Flavour - Overview — Chapter 1
   - 2.1 - 2.3
   - 2.4.3
   - 3.1
   - 3.2
   - 3.4

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2. H_{eff} — Chapter 4.1
   - 4.2
   - 4.4
   - 5

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3. B - mixing — Chapter 8
   - Chapter 9.1
   - 9.2
   - 9.3.1
   - 9.3.2
   - 9.3.3

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4. BSM searches

Lecture 1

Flavour Physics Overview

Motivation for Flavour physics:

① Precise determination of SM parameter: $m_c, m_b, V_{CKM}, \dots$

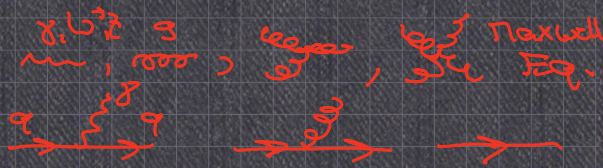
② Study of $\not{CP}$ => Matter in Universe

③ Indirect search for BSM

$$f^{Exp} \pm \delta^{Exp} = f^{SM} \pm \delta^{SM} + f^{BSM}(M_X, g_X)$$

④ To control QCD to fulfill ① - ③

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$



$$+ i \bar{\psi} \not{D} \psi$$

$$+ (D_\mu \phi)^2 - V(\phi)$$ ----> Higgs

new, m?

$$+ \bar{\psi} Y \phi \psi + h.c.$$ ----> Yukawa; m_F

→ $\not{CP}$, CKM-matrix

$$+ \mathcal{L}_{BSM}$$

Particle masses

virtual:

$m_t = 172.9(4)$ GeV

$m_H = 125.10(14)$ GeV

$m_Z = 91.1876(21)$ GeV

$m_W = 80.379(12)$ GeV

→ $m_b = 4.78(6)$ GeV

decay:

$m_\tau = 1.77682(12)$ GeV

$m_c = 1.67(7)$ GeV

$m_\mu = 105.658\ldots$ MeV

$m_s = 93^{+11}_{-3}$ MeV

⋮

0

(13) Heavy Hadrons:

	Mass [GeV]	Lifetime [ps]	$\frac{\tau(X)}{\tau(B_d)}$
$B_d = \bar{b}d$	5.28	1.519 (4)	1
$B^+ = \bar{b}u$	5.28	1.638(4)	1.076(4)
$B_s = \bar{b}s$	5.37	1.516 (6)	0.998(5)
$B_c^+ = \bar{b}c$	6.27	0.510 (9)	0.336 (6)
$\Lambda_b = bud$	5.62	1.471 (9)	0.969(6)
$\Xi_b^0 = bus$	5.79	1.480 (30)	0.974 (20)
$\Xi_b^- = bds$	5.79	1.572 (40)	1.035(26)
$\Omega_b^- = bss$	6.05	$1.64\,(^{+.18}_{-.17})$	$1.08\,(^{+.12}_{-.11})$

Remarks:

- Heavy Quark Expansion (HQE)

$$\Gamma_{total} = \Gamma_0 + \left(\frac{\Lambda}{m_b}\right)^2 \dots$$

Γ_0 → free b-quark decay

$\left(\frac{\Lambda}{m_b}\right)^2$ ≈ $\left(\frac{1}{5}\right)^2 = 4\%$

$$\to \tau(B^+) \simeq \tau(B_d) \simeq \tau(B_s)$$

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Heavy Hadrons:

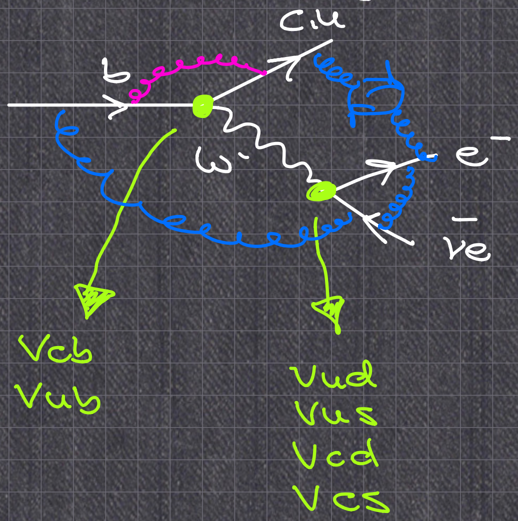
	Mass [GeV]	Lifetime [ps]	$\frac{\tau(X)}{\tau(D^0)}$
$D^0 = c\bar{u}$	1.86	0.4101(15)	1
$D^+ = c\bar{d}$	1.87	1.040(7)	2.536(17)
$D_s^+ = c\bar{s}$	1.97	0.504(4)	1.229(10)
$\Lambda_c = cdu$	2.29	0.200(6)	0.488(15)
$\Xi_c^+ = csu$	2.47	0.442(26)	1.08(6)
$\Xi_c^0 = csd$	2.47	0.112 $\left(^{+13}_{-10}\right)$	0.27(3)
$\Omega_c = css$	2.70	0.268(26)	0.65(6)

HQE:

$$\Gamma_{total} = \Gamma_0 + \left(\frac{\Lambda}{m_c}\right)^2 \ldots$$

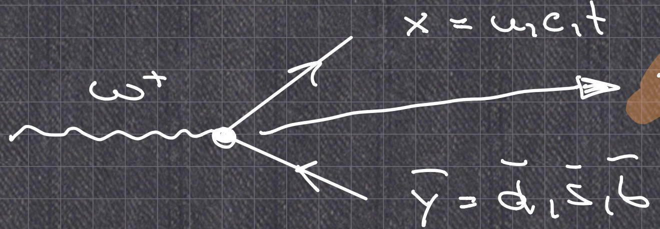
$$\left(\frac{1}{1.5}\right)^2 = 36\% \text{ ?}$$

Decay of heavy quarks:



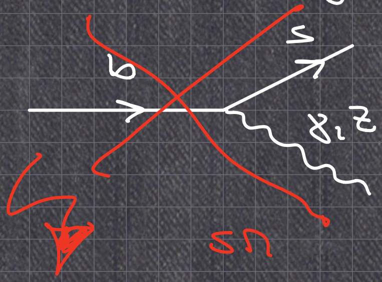
e^-	μ^-	τ^-	d	s	d	s
$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	$\bar{u}$	$\bar{u}$	$\bar{c}$	$\bar{c}$

- Elementary Vertex

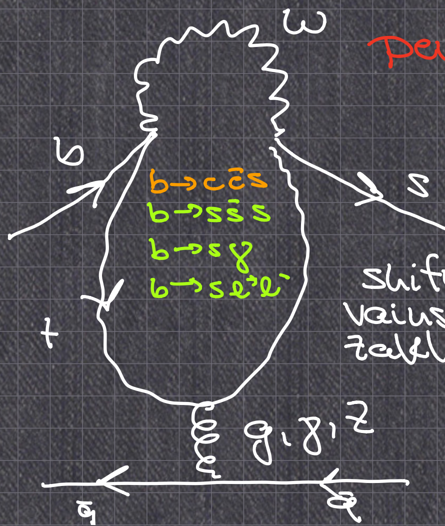


$$i \frac{g_2}{2\sqrt{2}} \gamma_\mu (1-\gamma_5) V_{xy}$$

Flavor changing neutral current



does not exist at tree level in the SM

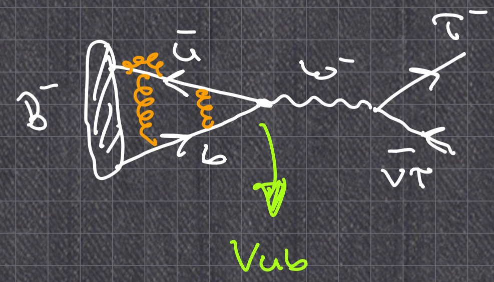


Shifman, Vainshtein, Zakharov

John Ellis

Decay of heavy Hadrons:

a) Leptonic e.g. $B^- \to \tau^- \bar{\nu}_\tau$ (tree), $B_s \to \mu^+\mu^-$ (loop)

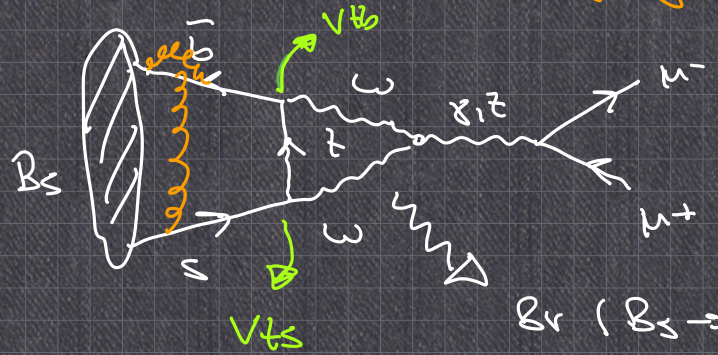


non-perturbative physics

$$\langle 0 | \bar{u}\gamma^\mu \gamma_5 b | B_q(p) \rangle = i \underbrace{f_{B_q}}_{\text{decay constant}} p^\mu$$

⇝ Lattice QCD

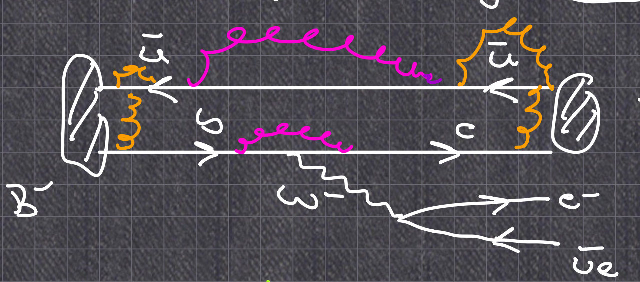
numbers: Google "FLAG lattice"



→ f_{B_s}

$Br(B_s \to \mu\mu) \simeq 3 \cdot 10^{-9}$

b) semileptonic e.g. $B^- \to D^0 e^- \bar{\nu}_e$ (tree), $B^0 \to K^{*0} \mu^+\mu^-$ (loop)

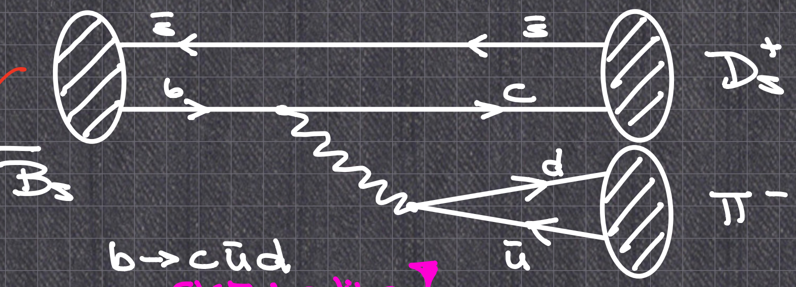


non-perturbative physics

$\langle D^0 | \bar{c}\gamma^\mu(\gamma_5) b | B \rangle \sim$ Form factor $f(q^2)$

→ lattice QCD, sum rules

c) non-leptonic



$b \to c\bar{u}d$

CKM leading!

PDG $3.00(23) \cdot 10^{-3}$ → 4.6σ 2007.10338 + references

QCDf $4.42(21) \cdot 10^{-3}$

Additional assumption for non-perturbative physics

QCD factorisation

CKM matrix

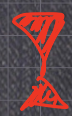
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{ub}, V_{cb} → B-decays

V_{td}, V_{ts}, V_{tb} → loop

Remarks:

- V_{CKM} is unitary per construction
- 4 parameter
  - 3 real angles
  - 1 phase ≡ C̸P



⇒ Wolfenstein parametrization

(Taylor expansion of V_{CKM} in "standard-parametrisation ≡ product of 3 rotation matrices); $V_{us} \doteq \lambda = 0.224837\ldots$ small

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

"CKMfitter" (see also "UTfit")

$$\lambda = 0.224837 \begin{smallmatrix} +0.000251 \\ -0.000061 \end{smallmatrix}$$

$$A = 0.8235 \begin{smallmatrix} +0.0056 \\ -0.0145 \end{smallmatrix}$$

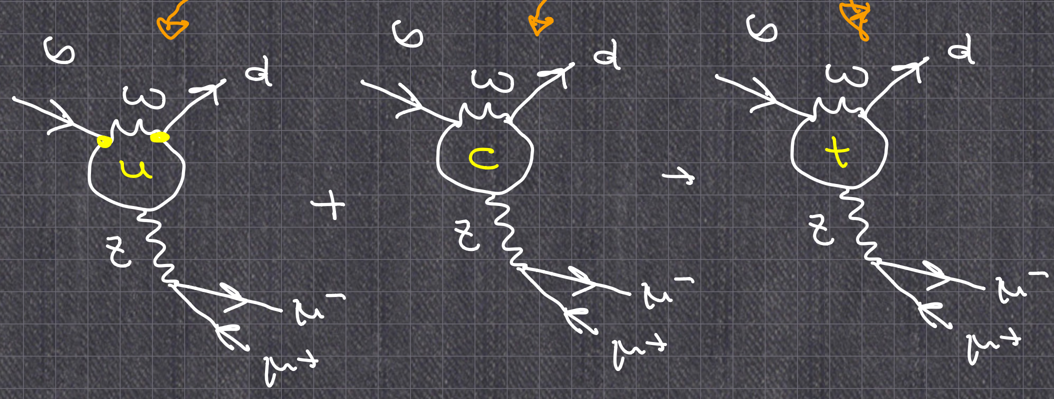
$$\bar\rho = 0.1568 \begin{smallmatrix} +0.0102 \\ -0.0061 \end{smallmatrix}$$

$$\bar\eta = 0.3499 \begin{smallmatrix} +0.0079 \\ -0.0065 \end{smallmatrix} \equiv \not{CP}$$

The Unitarity Triangle

$$V_{CKM}^{t} V_{CKM} = \mathbb{1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

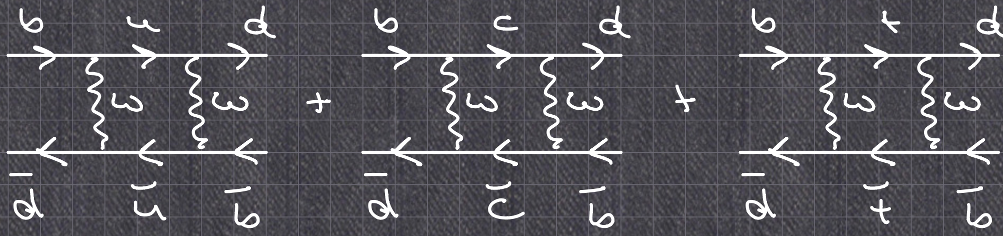


Assume: $m_u = m_c = m_t$

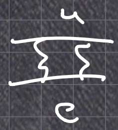
$\Rightarrow A(b \to d\, \mu^+ \mu^-) = 0$!

GIM mechanism

B-mixing:



$\sim (V_{ud} V_{ub}^*)^2$ $\sim (V_{cd} V_{cb}^*)^2$ $\sim (V_{td} V_{tb}^*)^2$

$+$ 

$+ \ldots$ $\Rightarrow$ mixing is proportional to

$$\left(V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^*\right)^2$$