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Cours/Lecture Series

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1984-1985 ACADEMIC TRAINING PROGRAMME

SPEAKER : R. RÜCKL / University of Munich and
S. REUCROFT / CERN

TITLE : Heavy flavours

DATES : 11, 12, 13, 14, 15 March

TIME : 11.00 hrs - 12.00 hrs

PLACE : Auditorium

ABSTRACT

A 5-lecture experimental/theoretical review of our current knowledge of open charm and beauty properties will be given with emphasis on the latest results and their theoretical interpretation.

The content of each lecture is as follows :

1. Experimental techniques and the status of the determination of masses life-times, branching ratios, etc.
2. Theoretical description of heavy quark decays in the framework of the standard model.
3. Experimental survey of heavy flavour production characteristics.
4. QCD based models of production : strengths and weaknesses.
5. Speculation via experimental aims and theoretical aspirations.

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R. Rückl (University Munich)

Lectures # 2, 4 and 5.

physics aspects

- completion and test of the standard model

  fundamental fields and parameters

  content of matter sector
  strong & electroweak couplings
  mixing angles and masses

  dynamical properties

  spectrum and internal structure of QCD bound states
  hadronization of heavy quarks
  short and long distance interactions
  interplay of fundamental forces

  CP violation, $\Delta I = \frac{1}{2}$ rule, ...

- glimpse at physics beyond the standard model

  fermion mass spectrum and family structure
  search for the Higgs scalar
  heavy SUSY-flavours, excited fermions, ...
  background to rare "exotic" events

- source of useful ν and μ beams at future colliders

  etc.

in these lectures focus on :

Present theoretical understanding of the
PRODUCTION & WEAK DECAY
properties of heavy quark states in the standard model

framework

- $SU(3)_c$ gauge theory of strong interactions
  $SU(2)_L \times U(1) \longrightarrow U(1)_{e.m.}$ gauge theory of weak and e.m. interactions

- quark model for $[Q\bar{q}]$ and $[Qqq]$ bound states
  quarkonium model for $[Q\bar{Q}]$ resonances

- parton model for hard scattering processes

techniques

- perturbation theory
- leading log summation & renormalization group

topics

I. Weak decays

1. Introduction
2. Effective weak Hamiltonian
3. Inclusive decays: hard gluons; spectator model; preasympt. effects
4. Exclusive decays: valence quark approx.; $\frac{1}{N_c}$ & soft gluons
5. Summary

II. Production

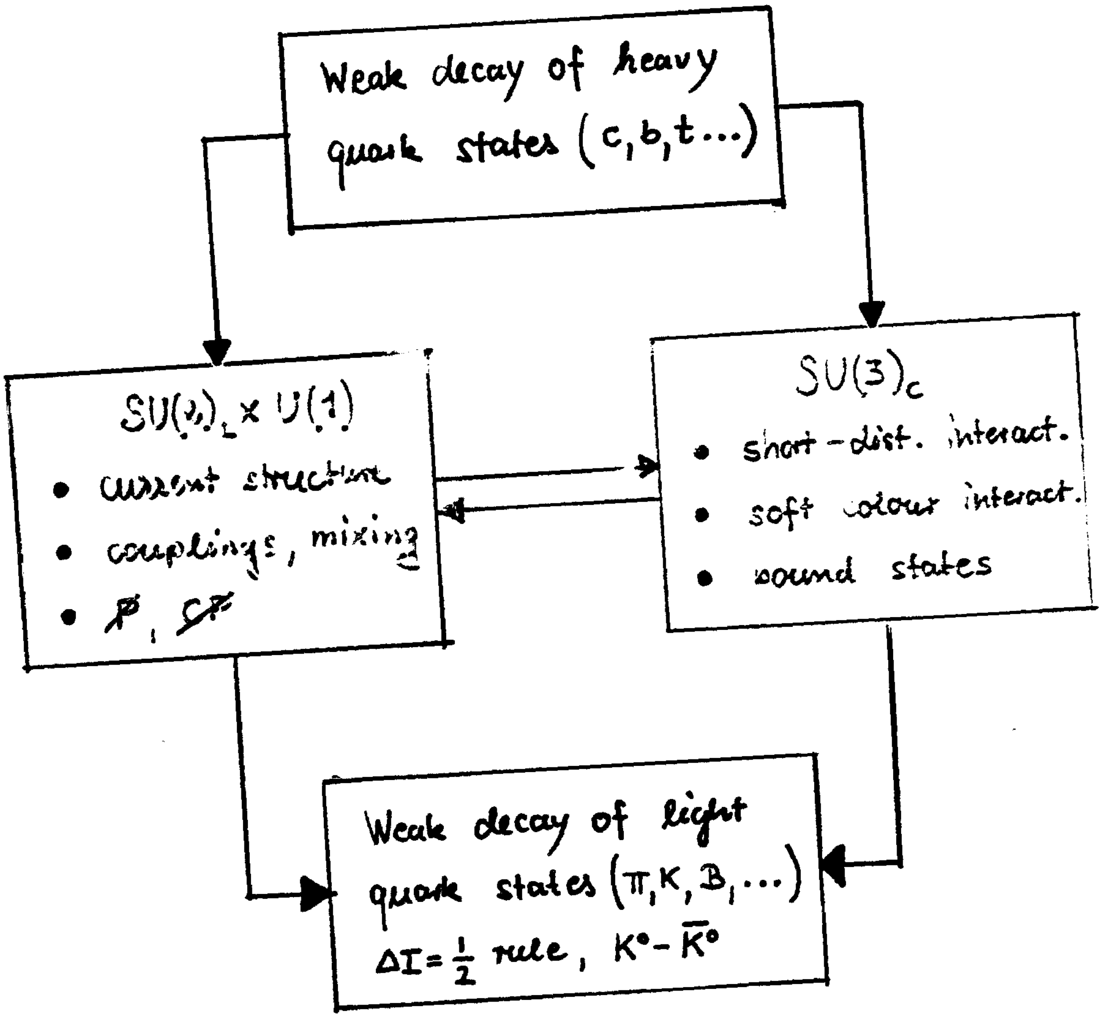
1. Introduction
2. e^+e^--annihilation: fragmentation
3. ν-production: sea & mixing
4. Lepto-, photoproduction: γ-g fusion
5. hadroproduction: creation vs. excitation
6. summary

III. Related issues

1. Hidden flavour production
2. Heavy quarks from high p_T jets
3. Scaling predictions on $\sigma_{tot}(c,b,t)$

I. Weak Decays of Heavy Hadrons

I.1. Introduction



interplay of weak and strong forces $\longrightarrow$ interesting testing ground of the standard model

- asympt. heavy quarks : study of fund. interactions
- not-so-heavy quarks : probe of long dist. aspects *

PRESENT APPROACH

quark-lepton level : $\mathcal{L}_{SU(3)_c \times SU(2)_L \times U(1)}$

$\downarrow$ Op. prod. exp. & Ren. group

H_W^{eff} (l.o. weak + s.d. strong)

hadron-lepton level : $\langle H_W^{eff} \rangle_{hadr} \sim \langle 4\text{-fermi op.} \rangle_{hadr}$

$\downarrow$ Asympt. freedom & models

hadronic weak amplitudes

<u>Main problem</u> : Quark - Hadron connection

lack of complete QCD calculation of

$$\langle H_W^{eff} \rangle \sim \sum C(\mu) \cancel{\langle O(\mu) \rangle}$$

$\uparrow$

INCLUSIVE • free quark approx. (spectator model)
+ pre-asympt. (boundstate) effects

EXCLUSIVE • quark model estimates
+ soft gluon + final state int. + ...

I.2. EFFECTIVE WEAK HAMILTONIAN

$SU(2)_L \times U(1)$

minimal model : no fundam. FCNC interactions (GIM)

Weak decay processes induced by

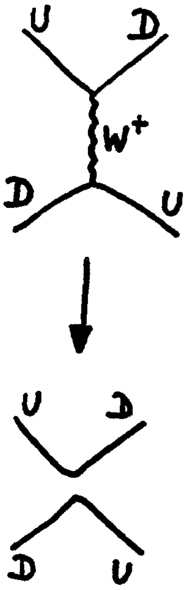
$$\mathcal{L}_{CC} = \frac{g_W}{2\sqrt{2}} \left(W^+_\mu J^\mu_- + W^-_\mu J_+{}^\mu \right)$$

$$J^\mu_- = (J^\mu_+)^\dagger = 2\,\overline{(u\,c\,t)}_L\, \gamma^\mu\, V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L + 2\,\overline{(\nu_e\,\nu_\mu\,\nu_\tau)}_L\, \gamma^\mu \begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix}_L$$

KM - mixing matrix : $|V| \sim \begin{pmatrix} 1 & s & s^3 \\ s & 1 & s^2 \\ s^3 & s^2 & 1 \end{pmatrix}$; $s \cong \sin\vartheta_c = 0.2$

connects mass eigenstates to weak eigenstates !

lowest order hamiltonian



$$H_W = \frac{g_W^2}{8i} \int d^4x\, D_{\mu\nu}(x, m_W^2)\; T\left[J^\mu_+(x)\, J^\nu_-(0) + h.c. \right]$$

$m_W \to \infty$ $\quad (m_Q \ll m_W)$

no strong interactions

$$H_W = \frac{G_F}{\sqrt{2}} \left(J^\mu_+(0)\, J_{-\mu}(0) + h.c. \right)$$

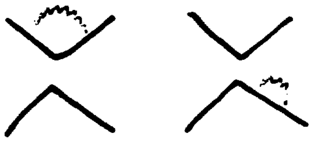
$\underbrace{}$ Lorentz: $(V-A)\cdot(V-A)$

Colour: $1_c \cdot 1_c$

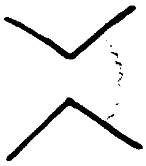
e.g. $\frac{G_F}{\sqrt{2}} V_{cs} V^*_{ud} \left[\bar{c}\,(1-\gamma_5)\gamma^\mu s \right] \left[\bar{d}\,(1-\gamma_5)\gamma_\mu u \right]$

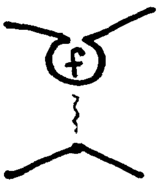
$SU(3)_c$

VIRTUAL GLUON CORRECTIONS $\longrightarrow$

 .... $(V-A)_1 \cdot (V-A)_1$ $m, G_F, \ldots$

colour

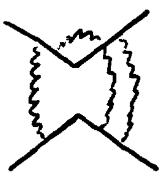
 ... $(V-A)_8 \cdot (V-A)_8$ $\alpha_s \ln \frac{m_W^2}{\mu^2}$ *

 ... PENGUINS $(V-A)_8 \cdot V_8$ GIM $\rightarrow \alpha_s \ln \frac{m_f^2}{\mu^2}$ *

$\longrightarrow$ NEW* EFF. 4-QUARK INTERACTIONS !

s.d. modifications of H_W involve large logarithms

$\longrightarrow$ l.o. considerations not sufficient

 ... $\left(\alpha_s \ln \frac{m_W^2}{\mu^2}\right)^n$ + ... $\alpha_s^{n+1} \ln^n \frac{m_W^2}{\mu^2}$ + ...

lead. log. next-to-lead. log.

summed by RENORMALIZATION GROUP TECHNICS

<u>nonleptonic amplitude</u>

$$T_{if} = \langle f | H_{NL}^{eff} | i \rangle = \frac{g_w^2}{8i} \int d^4x\, D_{\mu\nu}(x, m_w^2) \langle f | \underbrace{T\left[J_+^\mu(x) J_-^\nu(0)\right]} | i \rangle$$

- Wilson expansion: $\sum_{\lambda} \underset{\substack{\uparrow \\ \text{i.g. singular}}}{C_\lambda(x; g_s, m_q \ldots \mu)} \cdot \underset{\substack{\uparrow \\ \text{local, regular} \\ \dim \geq 3}}{O_\lambda^{\mu\nu}(0; \mu)}$

- $m_W \to \infty$: short distances $\left(|x| < \frac{1}{m_W}\right)$ and low dim. operators ($d=6$, 4-quark) dominate

$$T_{if} \cong \frac{G_F}{\sqrt{2}} \sum_k C_k\left(g_s, \frac{m_q}{m_W}, \ldots \frac{m_W}{\mu}\right) \langle f | O_k^{d=6}(\mu) | i \rangle$$

normalization scale (μ) independent (measurable!)

- renorm. group equation:

$$\left(\mu \frac{\partial}{\partial \mu} + \beta \frac{\partial}{\partial g_s} + \delta m \frac{\partial}{\partial m} - \gamma_k\right) C_k\left(g_s, \frac{m}{m_W}, \ldots \frac{m_W}{\mu}\right) = 0$$

(β, δm, γ_k) calculable in perturbative QCD

running; anom. dim.

$$H_{NL}^{eff} = \frac{G_F}{\sqrt{2}} \sum_k C_k\left(\bar{g}_s, \frac{\bar{m}}{m_W} \ldots\right) \exp\left(-\int_{g_s}^{\bar{g}_s} dg \frac{\gamma_k(g)}{\beta(g)}\right) O_k^{d=6}$$

RESULTS

massless theory – leading log. (LL) 1974 Gaillard, Lee; Altarelli, Maiani

$$H^{eff}_{NL} = \frac{G_F}{\sqrt{2}}\left(c_+ O_+ + c_- O_-\right) \qquad (\bar{U}D)_L \equiv \bar{u}(1-\gamma_5)\gamma^\mu D$$

$$O_\pm = \frac{1}{2}\left[(\bar{U}VD)_L(\bar{D}V^\dagger U)_L \pm (\bar{U}VU)_L(\bar{D}V^\dagger D)_L\right]$$

$$c_- = c_+^{-2} = \left(\frac{\alpha_s(\mu^2)}{\alpha_s(m_W^2)}\right)^{\frac{12}{33-2f}} \quad ; \ \mu \sim O(m_Q),\ f = 4,5,6,\ldots$$

\# of flavours

massless – next-to-leading (NLL) 1981 Altarelli et al.

$$c_\pm = c_\pm^{LL}\left(1 + \frac{\alpha_s(\mu^2)}{\pi}\rho_\pm\right) \qquad \text{small effect !}$$

massive – leading 1977 Shifman et al.

- proliferation of operators : $H^{eff}_{NL} = \sum_i \frac{G_F}{\sqrt{2}} c_i O_i$
- mixing under renormalization : $O_i^{ren} = \sum_j Z^{-1}_{ji} O_j$ — matrix
- complication of renorm. group

MASS EFFECTS in $c_\pm$: approx. by scale dep. # flavours
small changes !

→ PENGUINS : $c_P \ll c_\pm$
small heavy-light mixing
$\langle O_P \rangle \not\gg \langle O_\pm \rangle$ for c, b, t, ..

unimportant for heavy flavours !

numerics : $\alpha_s = 0 \longrightarrow c_+ = c_- = 1 \; ; \; c_p = 0$

- $\Lambda_{QCD} = 250$ MeV ; $f = 6$

μ [GeV]		LL		NLL		LL - massive		
		c_+	c_-	c_+	c_-	c_+	c_-	c_p
s	1	0.70	2.03	0.64	2.57	0.70	2.03	~ 0.03
c	2	0.77	1.69	0.73	1.90	0.77	1.68	~ 0.04
b	5	0.85	1.39	0.82	1.49	0.84	1.41	~ 0.03
t	50	0.98	1.04	0.98	1.05	0.98	1.05	—

$c_- > 1 > c_+$: "nonlept." enhancement
"6 (8) - enhancement" in c (s) - decay

$c_\pm \to 1$ for $\mu \to \infty$ (asympt. freedom)

LL effects reinforced by NLL (stable situation)

- $\boxed{\text{EFF. WEAK HAMILTONIAN FOR } c, b, t \text{ - DECAY}}$

$$H_W^{eff} = H_{SL} + H_{NL}^{eff}$$

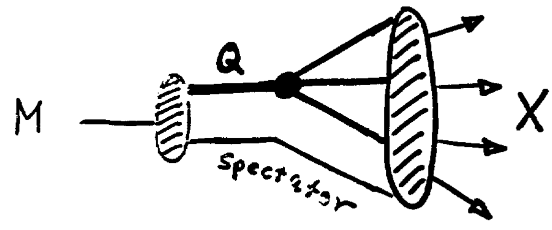
$$\begin{cases} c_+ = 1/\sqrt{c_-} \\ c_-(m_c) \simeq 1.7 - 2.1 \\ c_-(m_b) \simeq 1.4 - 1.5 \\ c_-(m_t) \simeq 1.07 - 1.09 \end{cases} \Lambda_{QCD} \simeq .2 - .5 \text{ GeV}$$

simple & reliable approximation !

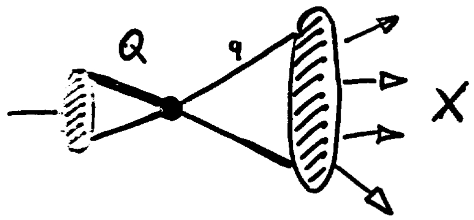
e.g. $H_{NL}^{eff}(c) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \left\{ \frac{c_+ + c_-}{2} (\bar{c}s)_L (\bar{d}u)_L + \frac{c_+ - c_-}{2} (\bar{c}u)_L (\bar{d}s)_L \right\}$

spectator model

1974 Gaillard, Lee, Rosner
1977 Ellis, Gaillard, Nanopoulos



"decay"



"annihilation"

$\boxed{m_Q \to \infty}$

- energy release $\mathcal{O}(m_Q) \to \sum_X$ dual to "free" quark state
  ($e^+e^- \to$ hadr $\equiv e^+e^- \to q\bar{q}$)
- mom. transfer $\mathcal{O}(m_Q) \to$ bound state effects
  soft colour interact.
  negligible

"annihilation" suppressed by M-wave function : $(f_M/M)^2$
helicity conservation: $(m_q/m_Q)^2$

"decay" determined by "free" Q-decay

the same for all hadrons containing Q

μ-decay : $\tau_\mu = \dfrac{192\pi^3}{G_F^2 m_\mu^5}$

$$\boxed{\tau_Q \cong \frac{1}{n_{SL} + n_{NL} \cdot 3} \left(\frac{m_\mu}{m_Q}\right)^5 \tau_\mu \; ; \quad \mathcal{B}_{SL}(Q) \cong \frac{1}{n_{SL} + n_{NL} \cdot 3}} \; !$$

charm ($m_c = 1.5$ GeV) : $\tau_c \cong 7 \cdot 10^{-13}$ s ; $\mathcal{B}_{SL}(c) \cong 20\%$

$\langle \exp \rangle$ $\quad 5 \cdot 10^{-13}$ s $\quad 12\%$

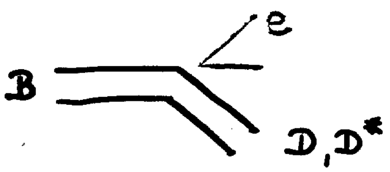
improvements (* somewhat ambiguous)

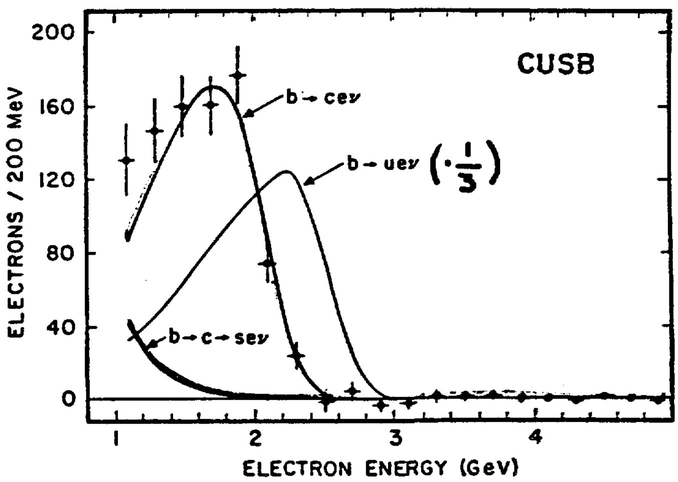
- short distance gluon corrections to H^{eff}_{NL} : $3 \to 2c_+^2 + c_-^2$
- radiative corrections to decay widths : $\left(1 + \dots \frac{\alpha_s}{\pi}\right)$
- * phase space corrections : $I\left(\frac{m_{q_i}}{m_Q}\right)$ masses of decay products
- * Fermi motion : $p_q \lesssim 300$ MeV

uncertainties : effective quark masses (e.g. $m_{u,d} \simeq 0 - 300$ MeV)
normalization of $\alpha_s(\mu)$

B-DECAYS [see RR. CERN print 1983]

(i) semileptonic decay spectrum





Altarelli et al.

✓

→ constrains mass parameters : $m_b - m_c \sim 3.4$ GeV

→ gives $\left|\frac{V_{ub}}{V_{cb}}\right| < 0.116$ Leipzig 1984

theoretically cleanest case !

(ii) Semilept. branching ratio & lifetime

$$m(u,d;\ s;\ c;\ b) = \begin{cases} 0\ ;\ 0.15\ ;\ 1.4\ ;\ 4.8 \quad \text{GeV} \quad (\mathrm{I}) \\ 0.35\ ;\ 0.5\ ;\ 1.8\ ;\ 5.2 \quad \text{GeV} \quad (\mathrm{II}) \end{cases}$$

$$BR_{e,\mu} \simeq \begin{cases} 12\ \% \quad (\mathrm{I}) \\ 15\ \% \quad (\mathrm{II}) \end{cases} \qquad \begin{aligned} BR_e &= (13.0 \pm 1.3)\ \% \\ BR_\mu &= (12.4 \pm 3.5)\ \% \end{aligned}$$

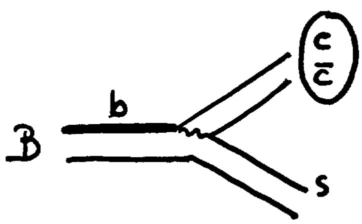
$$\tau_b\, |V_{cb}|^2 \simeq \begin{cases} 2.8 \cdot 10^{-15}\ \text{s} \quad (\mathrm{I}) \\ 3.2 \cdot 10^{-15}\ \text{s} \quad (\mathrm{II}) \end{cases} \qquad \underbrace{\tau_B = (1.4 \pm 0.4) \cdot 10^{-12}\ \text{s}}_{\text{PDG} - 1984}$$

- current-type quark masses preferred : (I)
- QCD corrections needed : $\alpha_s = 0 \longrightarrow BR_{e,\mu} \sim (15-18)\ \%$
- $|V_{cb}| \sim 0.035 - 0.065 \sim \mathcal{O}(\sin^2\theta_c)$

(iii) semi-inclusive decays

$B \to K + X$: $\langle n_s \rangle \simeq 1.4$ $\quad \langle n_K \rangle = 1.45 \pm 0.1$ CLEO

$B \to J/\psi + X$:



J/ψ : colour singlet
factor 1/3 in ampl.
mass set I

$$\underbrace{}_{}$$

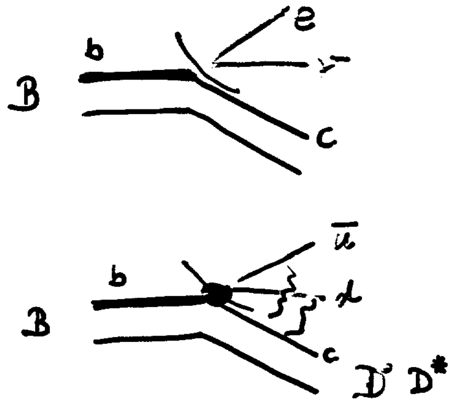
$BR \simeq 1.3\ \%$

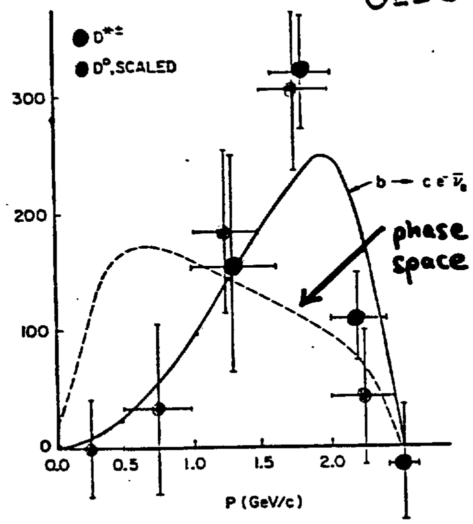
$< 1.6\ \%$ CLEO

Kühn
Nussinov
R.R.

CLEO

$B \to D^0 + X$:

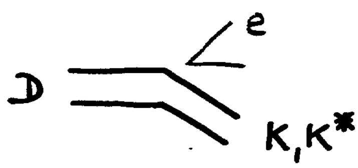


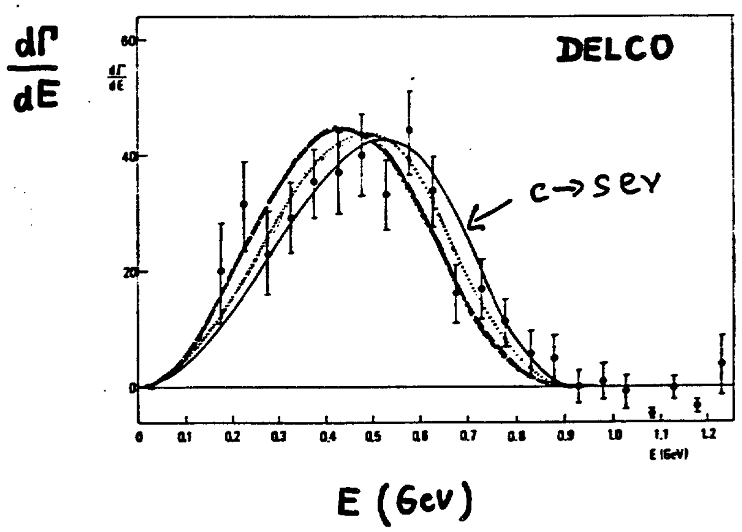


spectator model : SL and NL very similar
→ little communication between the 2 quark currents !

$\boxed{\text{D - DECAYS}}$

(i) semileptonic decay spectrum





Altarelli et al.

$p_F = 0$ MeV
$= 150$ "
$= 300$ "

Fermi motion in D meson

⟶ constraint $m_c - m_s \sim 1.1 - 1.3$ GeV

$|V_{cs}| \sim 1$

(ii) semilept. branching ratio & lifetime

$$m(u,d;s;c) = \begin{cases} 0.15;\ 0.3;\ 1.6 \ \text{GeV} & (\mathrm{I}) \\ 0.3;\ 0.4;\ 1.7 \ \text{GeV} & (\mathrm{II}) \end{cases}$$

$$BR_{e,\mu} \simeq \begin{cases} 13\,\% & (\mathrm{I}) \\ 19\,\% & (\mathrm{II}) \end{cases} \qquad \tau_c \cong \begin{cases} 6.0 \cdot 10^{-13}\ \text{s} & (\mathrm{I}) \\ 7.5 \cdot 10^{-13}\ \text{s} & (\mathrm{II}) \end{cases}$$

Mark III (1985) $\quad BR_e(D^+) = (17.0 \pm 1.9 \pm 0.7)\,\%$

$\quad BR_e(D^0) = (7.5 \pm 1.1 \pm 0.4)\,\%$

PDG (1984) : $\quad \tau(D^+) = \left(9.2 \begin{smallmatrix} +1.7 \\ -1.2 \end{smallmatrix}\right) \cdot 10^{-13}\ \text{s}$

$\quad \tau(D^0) = \left(4.4 \begin{smallmatrix} +0.8 \\ -0.6 \end{smallmatrix}\right) \cdot 10^{-13}\ \text{s}$

- spectator model insufficient: $\dfrac{\tau^+}{\tau^0} \simeq \dfrac{BR_{SL}(D^+)}{BR_{SL}(D^0)} \sim 2-3$ should be ~ 1

! NL decays influenced by non-asymptotic (non-spectator) effects : light constituent cannot be passive

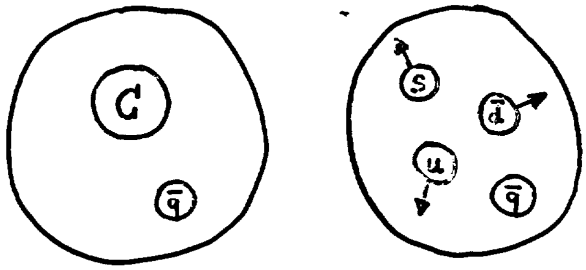
- D^0 seems to deviate most significantly from spectator picture

- QCD corrections obscured by quark mass effects (20% $\longrightarrow$ 15% $\longrightarrow$ 11% $\longrightarrow$ (13-19)%)
  due to LL NLL Masses

pre-asymptotic effects

- $\boxed{\text{quark interference}}$

1981 Peccei, RR
Kobayashi, Yamazaki
1982 Altarelli, Maiani



} interference of the two $\bar{d}$'s in D^+ decay!

$D^0: \bar{q} = \bar{u}$

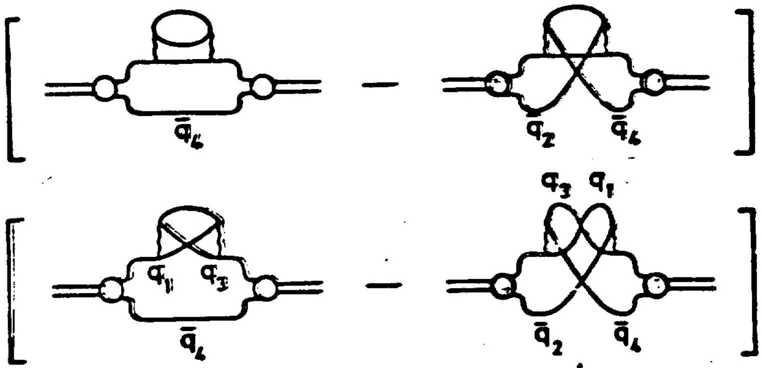
$D^+: \bar{q} = \bar{d}$

$\boxed{\text{PAULI PRINCIPLE}}$

→ RECALCULATION (antisymmetrize!)

$\Gamma = \frac{1}{2}(c_+^2 + c_-^2) \otimes [\ \ldots\ ]$

$+ \frac{1}{2}(c_-^2 - c_+^2) \otimes [\ \ldots\ ]$



spectator — interference

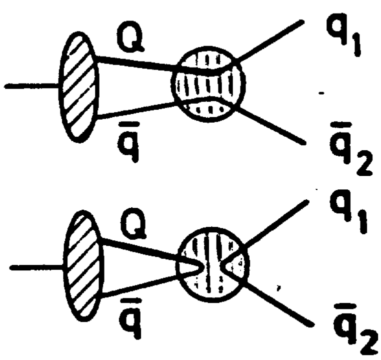
$$\boxed{\Gamma_{NL}(D^+) = (2c_+^2 + c_-^2)\,\frac{G_F^2 m_c^5}{192\pi^3} - (c_-^2 - 2c_+^2)\,\frac{G_F^2 m_c^2}{\pi}\,|\phi(0)|^2} \quad (NR)$$

- since $c_-^2 > 2c_+^2$ DESTRUCTIVE interference → $\tau(D^+)\uparrow$
- model (gaussian, coulomb, bag) wave functions suggest $\Gamma_I' / \Gamma_S' \sim (10 \div 40)\%$

→ $BR_e(D^+) \simeq 13\%$ (mass set I) → 17% (exp) due to Pauli?

1980 Fritzsch, Minkowski
Barnreuther et al.
Bander et al.

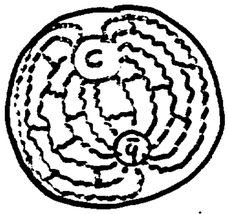
- $\boxed{\text{flavour annihilation}}$



$$\frac{\Gamma_{ann}}{\Gamma_{decay}} \sim \left(\frac{f_P}{M}\right)^2 \left(\frac{m_q}{M}\right)^2 \ll 1$$

overlap at origin — helicity conservation (V-A)

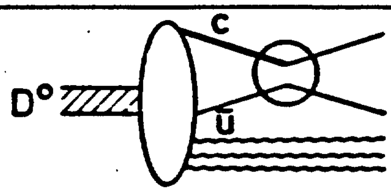
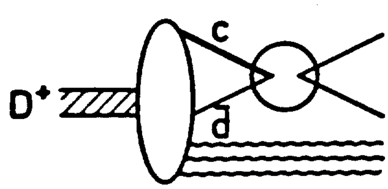
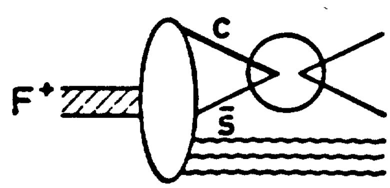
However, since ~~Thus, if~~



$$|D\rangle = \quad = c_1 |\underbrace{c\bar{q}}_{\text{spin } 0}\rangle + c_2 |\underbrace{c\bar{q}}_{\text{spin } 1} g\rangle^{*} + \ldots\ldots$$

* non-negligible !?

no helicity suppression!

Qualitative pattern	main modes	C.s.	
	s $\bar{d}$	d s $\bar{d}$ $\bar{s}$	
		u $\bar{d}$	l^+ ν_l
	u $\bar{d}$	u $\bar{s}$	l^+ ν_l

difficult to quantify if important

- $\tau(D^0) < \tau(D^+)$
- enhance $\Gamma_{C.S.}(D^+)$
- $\tau(F^+) < \tau(D^+)$

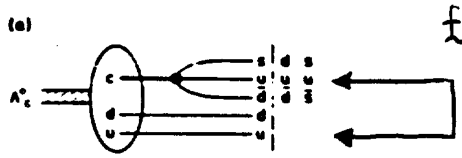
$BR_e(D^0) \simeq 13\% \longrightarrow 8\%$
mass set I — exp

due to annihilation?

1980 Barger et al.
1982 RR

Charmed baryon decays

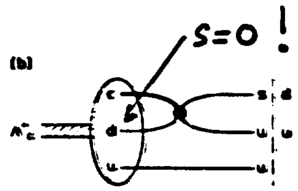
(a)



flavour decay

"Pauli" - interference !

(b)



flavour annihilation

even on valence quark level
no helicity suppression !

NR-model → • $\boxed{\Gamma_{Spect} : \Gamma_{Int} : \Gamma_{Ann} \sim 1 : 0.7 : 3}$

• $\tau(\Lambda_c^+) \sim 3 \cdot 10^{-13}$ sec , $BR_{SL}(\Lambda_c^+) \sim 5\%$

• $\tau(D^0) \lesssim \tau(\Lambda_c^+) < \tau(F^+) \lesssim \tau(D^+)$

exp : $2.2 \cdot 10^{-13}$ sec $4.8 \cdot 10^{-13}$ sec

B decays

both – Pauli interference & flavour annihilation –
involve hadronic bound state wave functions

→ effects scale with $\frac{|\phi(0)|^2}{M^3}$ → decrease by $\left(\frac{M_D}{M_B}\right)^{2 \sim 3}$

$\boxed{\text{expected} < 10\% \;!!}$

Signatures : $\tau(B^\mp) > \tau(B^0)$; $BR_{SL}(B^\mp) > BR_{SL}(D^0)$

$BR(B^- \to J/\psi\, X) > BR(B^0 \to J/\psi\, X)$

would signal pre-asympt. effects !

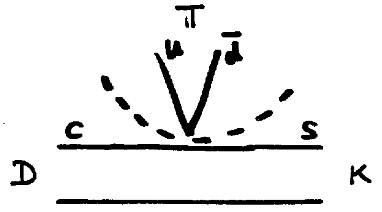
Factorization & vacuum saturation

1974 Gaillard et al.
1977 Ellis et al.
1978 Fakirov, Stech
Cabibbo, Maiani

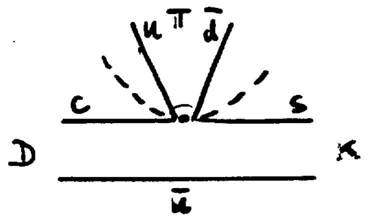
- valence quark description
- only s.d. gluon effects

example: $\langle K^-\pi^+ | H_{NL}^{eff} | D^0 \rangle = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \cdot$

see I.2.



$\frac{c_+ + c_-}{2}$

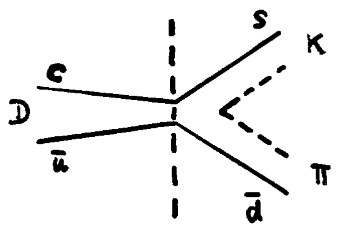


$\frac{1}{3}\ \frac{c_+ - c_-}{2}$

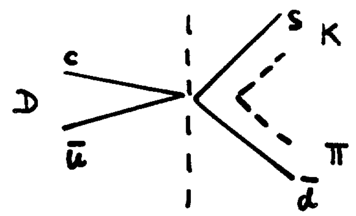
$\Big\} \ \langle \pi^+ | (\bar{u}d)_L | 0 \rangle \langle K^- | (\bar{s}c)_L | D^0 \rangle$

$f_\pi p_\pi^\mu \cdot \left((p_D + p_K)_\mu f_+ + (p_D - p_K)_\mu f_- \right)$

colour singlet projection factor



$\frac{1}{3}\ \frac{c_+ + c_-}{2}$



$\frac{c_+ - c_-}{2}$

$\Big\} \ \langle K^-\pi^+ | (\bar{s}d)_L | 0 \rangle \langle 0 | (\bar{u}c)_L | D^0 \rangle$

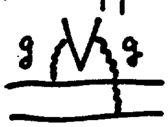
$\langle K\pi | V_\mu | 0 \rangle \cdot q^\mu f_D = 0$

in the SU(3) limit: CVC

- "annihilation" negligible (CVC + form factor)

$\longrightarrow$

- "colour suppression" maximal

if  negligible

Result

$$A(D^0 \to K^-\pi^+) = \frac{G_F}{\sqrt{2}} \cdot V_{cs} V_{ud}^* \cdot \Big[\overbrace{\frac{c_+ + c_-}{2}}^{c_1} + \underset{\xi}{\frac{1}{3}} \overbrace{\frac{c_+ - c_-}{2}}^{c_2} \Big] \cdot$$

$$\cdot f_\pi \left(m_D^2 - m_K^2\right) f_S^{DK}(m_\pi^2)$$

$$f_S = f_+(q^2) + \frac{q^2}{m_D^2 - m_K^2} f_-(q^2)$$

$$= \underbrace{(c_1 + \xi c_2)}_{a_1} \cdot \hat{A}$$

$$\Gamma(D^0 \to K^-\pi^+) = \frac{1}{2m_D} \cdot a_1^2 |\hat{A}|^2 \cdot \frac{1}{8\pi} \sqrt{\left(1 - \left(\frac{m_K}{m_D} + \frac{m_\pi}{m_D}\right)^2\right)\left(1 - \left(\frac{m_K}{m_D} - \frac{m_\pi}{m_D}\right)^2\right)}$$

$$= a_1^2 \, \hat{\Gamma}$$

calculable number!

similar results are obtained for all <u>two-body modes</u>:

- coefficient a_i incorporates short-distance corrections and colour suppression factor ($\alpha_s = 0 \to a_1 = 1$)
- bare partial width $\hat{\Gamma}$ incorporates phase space and form factors (i.e. SU(3), SU(6) breaking effects!)

3 classes of amplitudes : $c_1 = \frac{c_+ + c_-}{2}$, $c_2 = \frac{c_+ - c_-}{2}$, $\xi = \frac{1}{3}$

coefficient	type	
$a_1 = c_1 + \xi c_2$	$D^0 \to K^- \pi^+$	$\Gamma = a_i^2 \cdot \hat{\Gamma}$
$a_2 = \xi c_1 + c_2$	$D^0 \to \bar{K}^0 \pi^0$	
$a_3 = a_1 + \underbrace{x}_{O(1)} a_2$	$D^+ \to \bar{K}^0 \pi^+$	

MODE	1984 MARK III	$\hat{\Gamma}$ $\Gamma / \lvert a_i \rvert^2$	a_i $\lvert a_i \rvert$	$\Gamma = a_i^2 \hat{\Gamma}$ + FSI (Bauer, Stech)	
$D^0 \to K^- \pi^+$	13.7 ± 2.5	17.0	0.9	13.7	$a_1 = 1.2$
$K^- \rho^+$	27.4 ± 4.3	33.8	0.8	27.0	
$K^{-*} \pi^+$	11.7 ± 3.1	9.6	1.1	7.9	
$\pi^- \pi^+$ •	0.53 ± 0.14	1.0	0.7	0.6	
$K^- K^+$ •	1.69 ± 0.25	1.3	1.2	1.4	
$D^+ \to \bar{K}^0 K^+$ •	1.07 ± 0.30	1.3	0.9	1.4	
$D^0 \to \bar{K}^0 \pi^0$	4.7 ± 1.0	16.1	0.55	4.7	$a_2 = -0.7$
$\to \bar{K}^0 \rho^0$	3.3 ± 1.0	7.5	0.65	3.8	
$\to \bar{K}^{0*} \pi^0$	$2.3^{+2.7}_{-2.3}$ +	20.2	0.35	5.6	
$D_s^+ \to \pi^+ \phi$ •	0.84 ± 0.25	2.1	0.65	0.8	
$D^+ \to \bar{K}^0 \pi^+$	3.6 ± 0.5	17.0	0.45	3.3	$a_3 = a_1 + a_2$
$\to \bar{K}^0 \rho^+$	7.8 ± 3.5	34.0	0.50	6.6	
$\to \bar{K}^{0*} \pi^+$	1.3 ± 1.2	9.5	0.40	1.9	

→ classification physical (distinct $a_1 - a_2 - a_3$)

→ relative pattern in each class correct

- $SU(3)/SU(6)$ breaking $(f_\pi, f_K, f_\rho, \dots f_+^{D\pi}, f_+^{DK}, \dots)$
- flavour mixing $\left(\left| \frac{V_{us}}{V_{ud}} \right| \simeq \left| \frac{V_{cd}}{V_{cs}} \right| \simeq 0.055 \right)$

result $$a_1 = \frac{c_+ + c_-}{2} + \xi \frac{c_+ - c_-}{2} \sim 1 \text{ to } 1.2$$

$$a_2 = \xi \frac{c_+ + c_-}{2} + \frac{c_+ - c_-}{2} \sim -0.5 \text{ to } -0.7$$

- short distance QCD interpretation (Bauer, Stech)

$\xi = \frac{1}{3} \longrightarrow$ ✓ $a_1 \sim 1.1$ to 1.2; ↯ $a_2 \sim -0.06$ to -0.24 $\Big\}$ $c_-(m_c^2) \simeq 1.7 - 2.1$

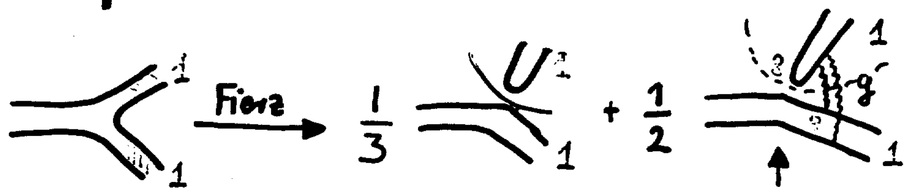
✓ $a_1 \sim 1.3$, $a_2 \sim -0.5$ $\Big\}$ $c_-(\mu^2) \simeq 2.8$

$$\langle H_W^{eff} \rangle \sim c(\mu) \langle O(\mu) \rangle_{vac.\,sat.} \; : \; \boxed{\mu < m_c}$$

i.e. relevant scale smaller than usually assumed

- soft gluon interpretation

$\xi = 0$:



colour mixed amplitude — zero in usual approx.

the two contributions may in fact cancel if g's !! are important

→ soft gluons may alter colour projection factors !

(Deshpande et al)

$a_1 \sim 1.2$ to 1.4; $a_2 \sim -0.5$ to -0.7 $\Big\}$ $c_-(m_c^2) \simeq 1.7$ to 2.1

"no colour suppression" ruled out : $\xi \simeq 1 \rightarrow a_1 \simeq a_2 \simeq 0.7$

• $1/N_c$ expansion (Buras, Gerard, RR)

drop consistently all non-leading terms in $1/N_c$!

① → short-distance enhancement factor

$$\frac{2c_+^2+c_-^2}{3} \longrightarrow \frac{c_+^2+c_-^2}{2} \left(> \frac{2c_+^2+c_-^2}{3} \right)$$

② → Pauli interference effect

$$2c_+^2 - c_-^2 \longrightarrow c_+^2 - c_-^2 \left(< 2c_+^2 - c_-^2 \right)$$

→ $BR_e(D^+)$ as before

→ $BR_e(D^0)$ smaller

③ → $\xi = 0$: a_1 and a_2 as above

⇒ towards a picture without "annihilation"

(also Shifman, Voloshin
Tadic, Trampetic)

standard model can well account for weak decays of heavy quark states

WEAK INTERACTION (GWS - GIM - KM)

- all fermions in sequential I_W - doublets
- no flavour chang. neutral currents
- interesting pattern of flavour mixing $\begin{pmatrix} 1 & s & s^3 \\ s & 1 & s^2 \\ s^2 & s^2 & 1 \end{pmatrix}$

STRONG INTERACTION (QCD)

- Short distance modification of H_W^{eff} consistent with observed nonlept. enhancement and 2-body decay pattern
- "free" quark decay (as expected from AF) consistent with inclusive B-decays
- clear indication of pre-asymptotic and soft hadronic effects in D-decays:

$$\frac{\tau(D^+)}{\tau(D^0)} \sim 2-3 \quad \text{and} \quad \xi \sim 0$$

Despite of qualitative understanding of (internal structure of bound states, soft gluons, $\frac{1}{N_c}$) lack of clear-cut quant. calculation

MORE SPECIFICALLY

2-body decays

annihilation mechanism (probably) unimportant !

- theor. expectation : suppressed by vector current conservation in the SU(3) limit and by form factors
- exp. indication : no decay seen which can only proceed via annihilation

observed 2-body decay pattern consistent with

- c-quark decay mechanism
- $\xi \simeq 0$ and/or $\frac{c_-}{c_+} > 3$ (*)

inclusive decays

annihilation mechanism getting less important !

- orig. theor. expectation : few % for $f_D \sim 200$ MeV
  $m_s \sim 500$ MeV
  $m_c \sim 1.8$ GeV
- exp. indication: $F \to n\pi$ not seen
  $BR_e(D^0)$ increased from 5 to 8 %

- larger NL-enhancement than so far believed
  $\mu \sim m_c : \frac{c_-}{c_+} \sim 3 \longrightarrow \mu \sim \frac{1}{2} m_c : \frac{c_-}{c_+} \sim 5$!! (see *)

- theor. arguments ($1/N_c$ - exp.) to use

$$\frac{c_+^2 + c_-^2}{2} \quad \text{instead of} \quad \frac{2c_+^2 + c_-^2}{3}$$

$\longrightarrow$ enforces NL-enhancement even more

$\hookrightarrow$ possible scenario: [illegible]

D^0: free c-decay $\quad BR_e(D^0) \sim \dfrac{1}{2 + 3\,\dfrac{c_+^2 + c_-^2}{2}} \sim 6\%$

quark mass effects

$\downarrow$

3%

D^+: free c-decay + interference with constituent $\bar{d}$

$$BR_e(D^+) \sim \frac{1}{2 + 3\left[\dfrac{c_+^2 + c_-^2}{2} + \underset{\boxed{\text{take } 70\%}}{\alpha}\, \dfrac{c_+^2 - c_-^2}{2}\right]} \sim 14\%$$

mass effects

$\downarrow$

17%

Test: $\boxed{\text{F decays}}$ if there is no annihilation

F^+ should behave like D^0!

(also interesting $B^\pm$ vs. $\overset{(-)}{B^0}$ decays)

(see Buras, Gerard, RR)

II. HEAVY QUARK PRODUCTION

II.1. Introduction

- original hope: production of heavy quarks requires localization of a large amount of energy in a small space-time region
  i.e. short-distance process
  $\longrightarrow$ testing ground of perturb. QCD

- usual procedure: factorization of process in

long and short distance dynamics

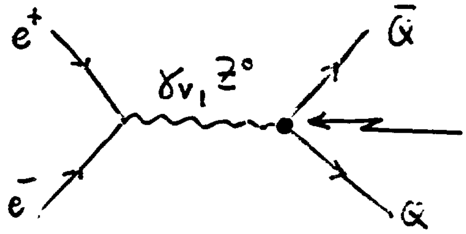
QCD improved parton model — perturb. QCD subprocesses

$f(x, Q^2)$, $D(z, Q^2)$ — $\alpha_s(Q^2)$

works for e^+e^-, deep inel. scatt., Drell-Yan, large-p_T jets, large-p_T photons, ...

- apply to open flavour production

production mechanism



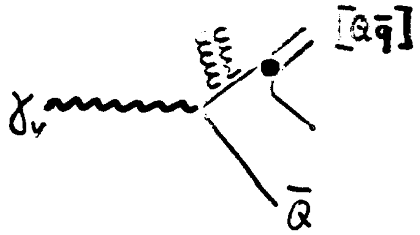
$e_Q \bar{Q}\gamma^\mu Q$; $\bar{Q}(v_Q - a_Q\gamma^5)\gamma^\mu Q$

Well understood heavy flavour factory (see Figure) –

study • *quarkonia*

spectroscopy and decays

• *heavy quark fragmentation*



gluon bremsstrahlung and hadronization

see I. → • *Weak decays* of $[Q\bar{q}]$, $[Qqq]$ states

• *Q-q interactions*

TASSO ('84) from $p_{T\,in}$ distributions:

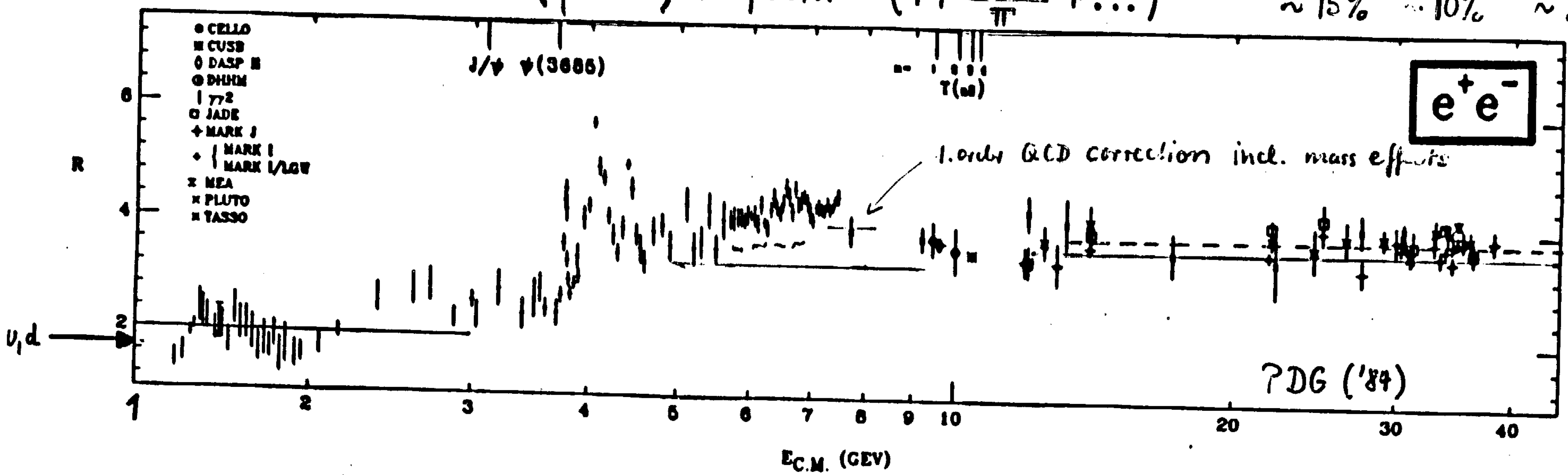
$$\frac{\alpha_s^c}{\alpha_s} = 1.00 \pm 0.2 \pm 0.2$$

→ flavour blindness of QCD

QED pointlike γq-coupling : $R = \dfrac{\sigma(e^+e^- \to hadr)}{\sigma(e^+e^- \to \mu^+\mu^-)} = R_{u,d} + R_s + R_c + R_b$

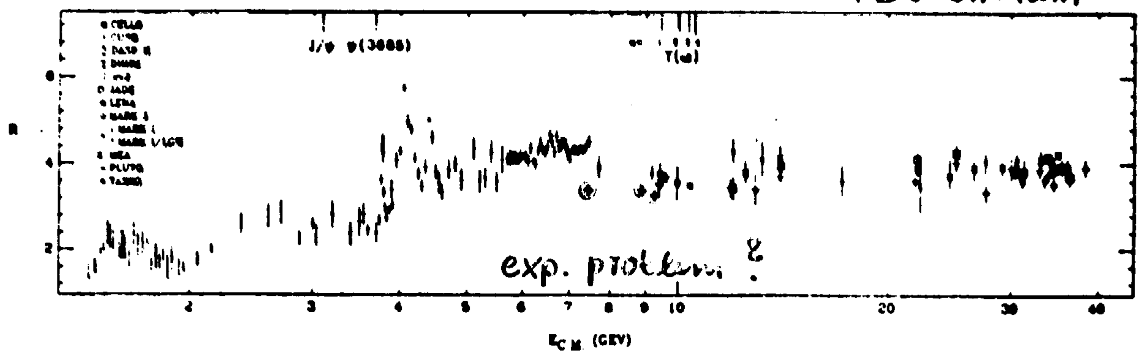
$= \dfrac{5}{3} + \dfrac{1}{3} + \dfrac{4}{3} + \dfrac{1}{3}$

QCD correction ($\beta \sim 1$) : factor $\left(1 + \dfrac{\alpha_s(s)}{\pi} + \dots\right)$ $\sim 15\%$ $\sim 10\%$ $\sim 5\%$

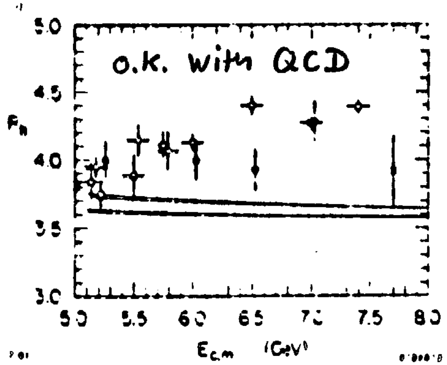


On page S64 (page 142 in the Data Booklet), in the figure for R, data points from the LENA experiment were inadvertently omitted. The corrected figure is given below. The reference for the LENA data is B. Niczyporuk et al., Zeit. fur Physik C15, 299 (1982).

PDG erratum



E. Bloom ('81 Moriond):

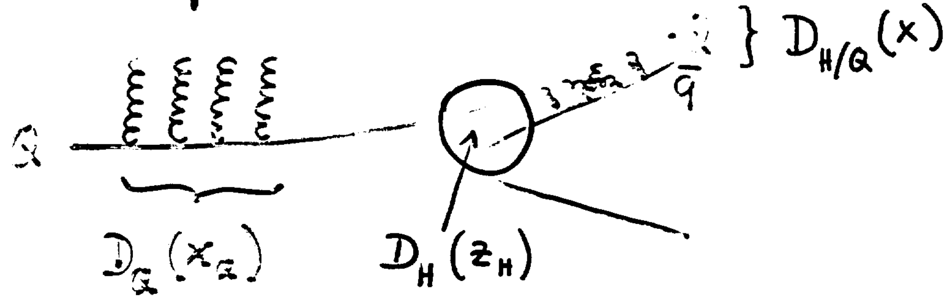


Heavy Quark Fragmentation

'76 Azimov et al.
'77 Suzuki
'78 Bjorken
Georgi, Politzer
'83 Peterson et al.

2-step picture

Azimov et al. Leningrad '83



$$D_{H/Q}(x) = \int dx_Q \int dz_H \; \delta(x - x_Q z_H)\, D_Q(x_Q)\, D_H(z_H)$$

$$\langle x \rangle \simeq \langle x_Q \rangle \langle z_H \rangle$$

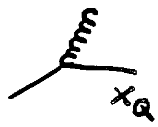
① QCD Q-jet evolution

$$x_Q = \frac{E_Q}{W}$$

$$D_Q(x_Q) \simeq A\,(1-x_Q)^b \cdot \frac{1}{\alpha} \frac{1+x_Q^2}{1-x_Q}$$

calculable in lead. log QCD
if $1 - x_Q \gg \frac{1}{m_Q R} \sim \frac{O(500\,\mathrm{MeV})}{m_Q}$

basic splitting:

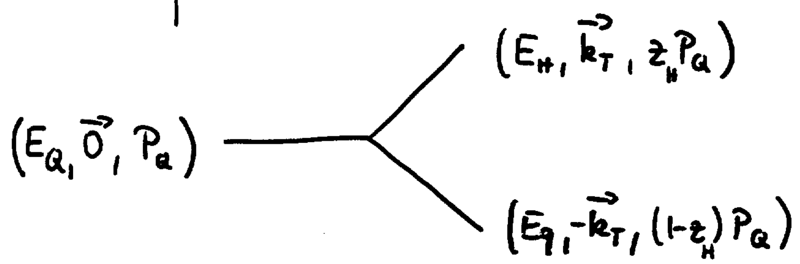


$$\rightarrow \quad \langle x_Q \rangle \simeq \left[\frac{\alpha_s(m_Q^2)}{\alpha_s(W^2)}\right]^{-\frac{32/3}{33-2f}} \simeq \begin{cases} 0.75 & Q = c \\ 0.85 & Q = b \end{cases}$$

at $W \simeq 20$ GeV

② hadronization (non-perturb.!)

quantum mechanical model:



everybody on-shell
energy conservation violated

$$\rightarrow \text{probability} \sim \frac{1}{(E_Q - E_H - E_q)^2}$$

$$\sim \frac{1}{\left[1 - \frac{m_{TH}^2}{m_Q^2}\frac{1}{z_H} - \frac{m_{Tq}^2}{m_Q^2}\frac{1}{1-z_H}\right]^2}$$

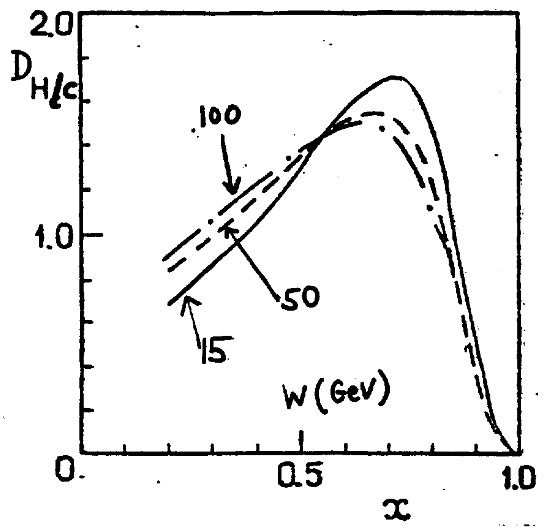
$$\rightarrow D_H(z_H) \simeq \frac{N}{z_H\left(1 - \frac{1}{z_H} - \frac{\varepsilon}{1-z_H}\right)^2}$$

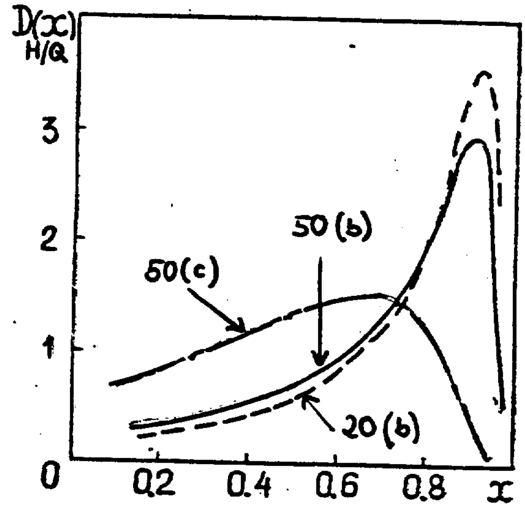
$$\varepsilon \simeq \frac{m_{Tq}^2}{m_{TH}^2} \simeq \left(\frac{500\ \text{MeV}}{m_Q}\right)^2 \simeq \begin{cases} 0.1 & Q = c \\ 0.01 & Q = b \end{cases}$$

$$\langle z_H \rangle \simeq \begin{cases} 0.6 & Q = c \\ 0.8 & Q = b \end{cases}$$

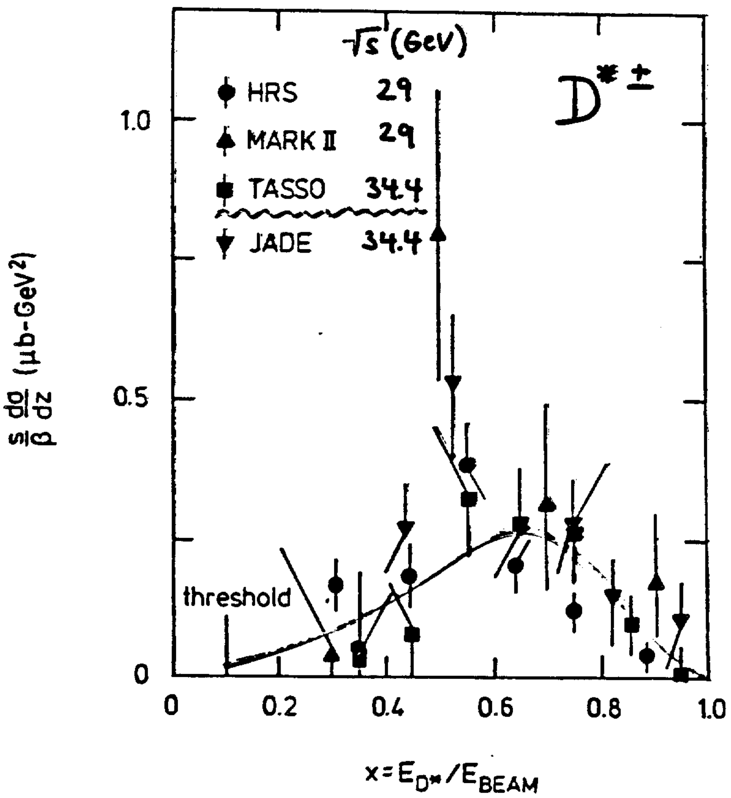
examples

- **theory** (Azimov et al.)





- **experiment** (Izen Lund '84)



TASSO fit to

$$D_{D^*}(x) = \frac{N}{x\left(1 - \frac{1}{x} - \frac{\varepsilon_{eff}}{1-x}\right)^2}$$

$$\downarrow$$

$$\varepsilon_{eff} = 0.25^{+0.11}_{-0.08}$$

$$\langle x \rangle = 0.59 \pm 0.04$$

see also ARGUS
CLEO
EMC
CDHS
⋮