Non relativistic Quark model

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Our friend, our colleague, gifted by an outstanding intelligence.

Most of the comments amount to say "you asked him any question, he answered very kindly, and gave the *exact answer*"

One can say, he was shy, he had at home no telephone, neither fixed nor mobile ! No internet connection (although he was very skilfull with computers).

He came to the lab only for meetings. He worked at home, And when he came for the next meeting, he brought *"The exact solution"*.

Our Homage

- I am not sure he would have liked what we are doing today, he was so discrete ! **But it is our need to do it.** Some of us admitted to have shed tears.
- He was an amazingly talented scientist, but amazingly unknown. He gave few seminars, went to few conferences.
- He was most of the time silent, but when he spoke.... that was important.
- We are trying in this meeting to illustrate both the outstanding scientist, and his engaging personality, from youth to death.

First papers

- Kinematic properties of helicity amplitudes J.C. Raynal (Orsay, IPN). 1969. Published in Nuovo Cim. A62 (1969) 864-880
- Jean-Claude has no co-author. It is rather unusual at this level, just after the "thèse de 3ème cycle". It has been finally a part of his "thèse d'Etat".

The mystery of strong interactions

Before speaking of our "quarkist quartet" it is useful to remind the ideas floating around about strong interactions.

1958 Freeman Dyson “The correct meson theory will not be found the corrc in the next hundred years ” 1960 Lev Landau : " the Hamiltonian method for 19600

1960 Lev Landau "The Hamiltonian method for strong interactions is dead and must be buried, although of course with deserved honour ”

[quoted from Dokshitzer QCD XL, Collège de France]

Profound studies of general features of the relativistic scattering theory : Pomeranchuk theorem, Froissart bound.

Crossing symetry as the specific feature of a relativistic theory.

Unitarity and its analytic continuation into crossing channels : Mandelstam

Exploration of Analytic properties of scattering amplitudes : Dispersion relations

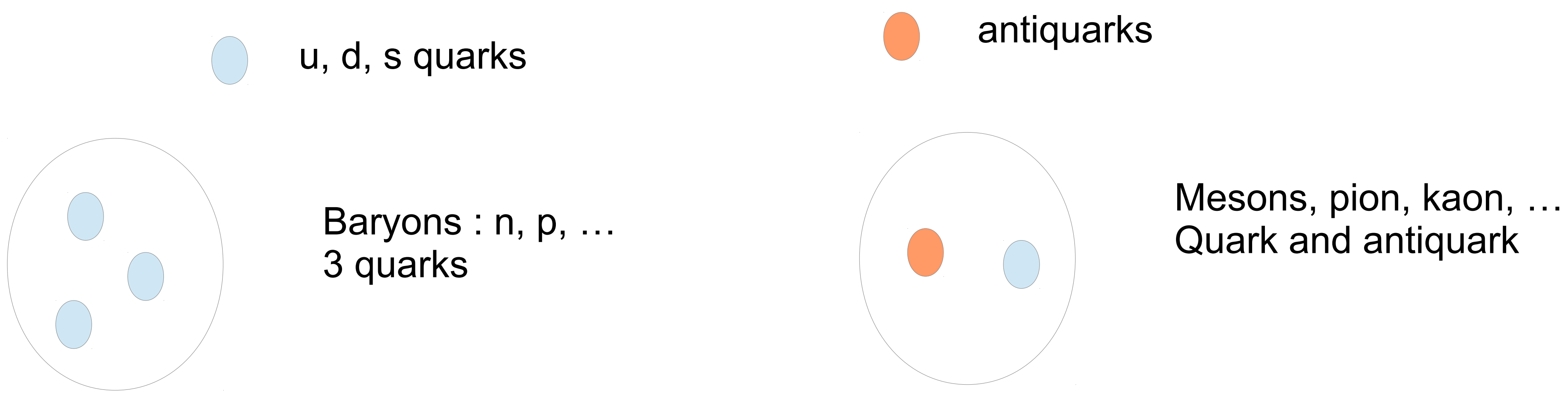
Bootstrap and the birth of string theory : Veneziano amplitude

Regge trajectories,...

The quark model

- The concept of quarks was introduced by Gell-Mann to explain the spectroscopy of baryons and mesons known at that time. (Gell-Mann afterwards declared it was just a mathematical object : "quarks do not exist")
- One considered baryons as buit up of three quarks and mesons of one quark and one antiquark.
- Very soon the idea of taking it seriously and consider wave functions of quarks was developed :

Dalitz, Morpurgo, Moorhouse, Clegg, Greenberg … (they supported us later, accepted to participate to jury's of our theses, ..).



We choose the quark model

- It was in 1970, the "spirit of 68".
- We (the "gang of four") start a regular meeting to study the approaches concerning strong interactions. We choose the quark model, simple and efficient. Le Yaouanc had already worked on quark model for his "thèse de 3ème cycle"
- We did not ask our advisors ! We started computing and publishing.
- The non relativistic quark model : we assume the real existence of quarks, that that they buid-up hadrons via wave functions obeying to Schrödinger equations. One computes everything using these wave functions.
- The concept of quark gave rise to the theory of strong interactions : quantum chromodynamics (QCD) (1973).
- Still, 40 years after nobody can derive the quark model from QCD for light quarks.
- **And yet, quark model describes semi-quantatively a huge amount of experimental data !!!**

Quark model was not welcome in France

- The "bosses" of French particle physics did not like it : it was not rigorous. It was not Lorentz invariant.
- They overlooked the fact that its phenomenology was not bad : "phenemonologist" was almost an insult.
- After 7 years in CNRS we had to be promoted or to be fired. The risk for us of the second solution was high, but finally it did not happen.

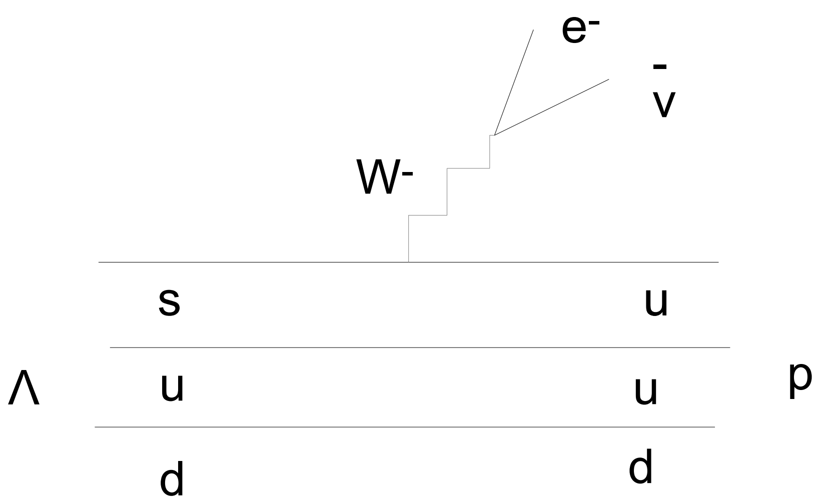
We got the support from foreigners : Dalitz, Morpurgo, Moorhouse, Clegg, and in France from André Martin, Louis Michel, François Lurçat, Tran Truong, Bernard Diu and Jean Illiopoulos.

The model : wave functions

I'll stick to the non relativistic quark model

- QCD was accepted as the theory of strong interactions, mainly thanks to its success in the high energy regime, using asymptotic freedom, **However there was no method to compute properties of hadrons from QCD. Therefore we went on with the quark model**
- The hadrons (baryons and mesons) are described via wave functions in terms of quarks/anti-quarks. For simplicity we were using harmonic oscillator potential which allows analytic computations. Two parameters : the radius of the wave function (taken from the experimental level spacing) and the quark masses which was the "constituent mass", about 300 MeV for u and d quarks, 450 MeV for s

The method : overlaping wave functions



Weak Decay

The calculation is in principle very simple. We use the wave functions of the Λ and the p written *in momentum space*. We apply the momentum conservation when the "s" quarks becomes a "u" quark by emiting a virtual W-. ThIs momentum is computed from the kinematics of the decay $\Lambda \rightarrow p\ e\ \nu$. Then we perform the integration over all the quark momenta, in the Λ rest frame.

If we use Harmonic oscillator potentials, all the calculations can be performed analytically. We have mainly used it. Of course the same method is used with other hadrons, or if a photon is emitted.

However the result depends on the frame we use. Empirically we choose to take the rest frame of the heaviest hadron, in the previous example it is the Λ rest frame.
For example in the extreme case of $\omega \rightarrow \pi^0\ \gamma$ the decay width in the π rest frame is about **30 times** larger than in the ω rest frame, and the latter prediction of 626 keV is much closer to experimental : 860 keV. (indeed : $M_{\pi 0}$ = 135 MeV, M_ω = 782 MeV)

Strong decay one hadron to two hadrons

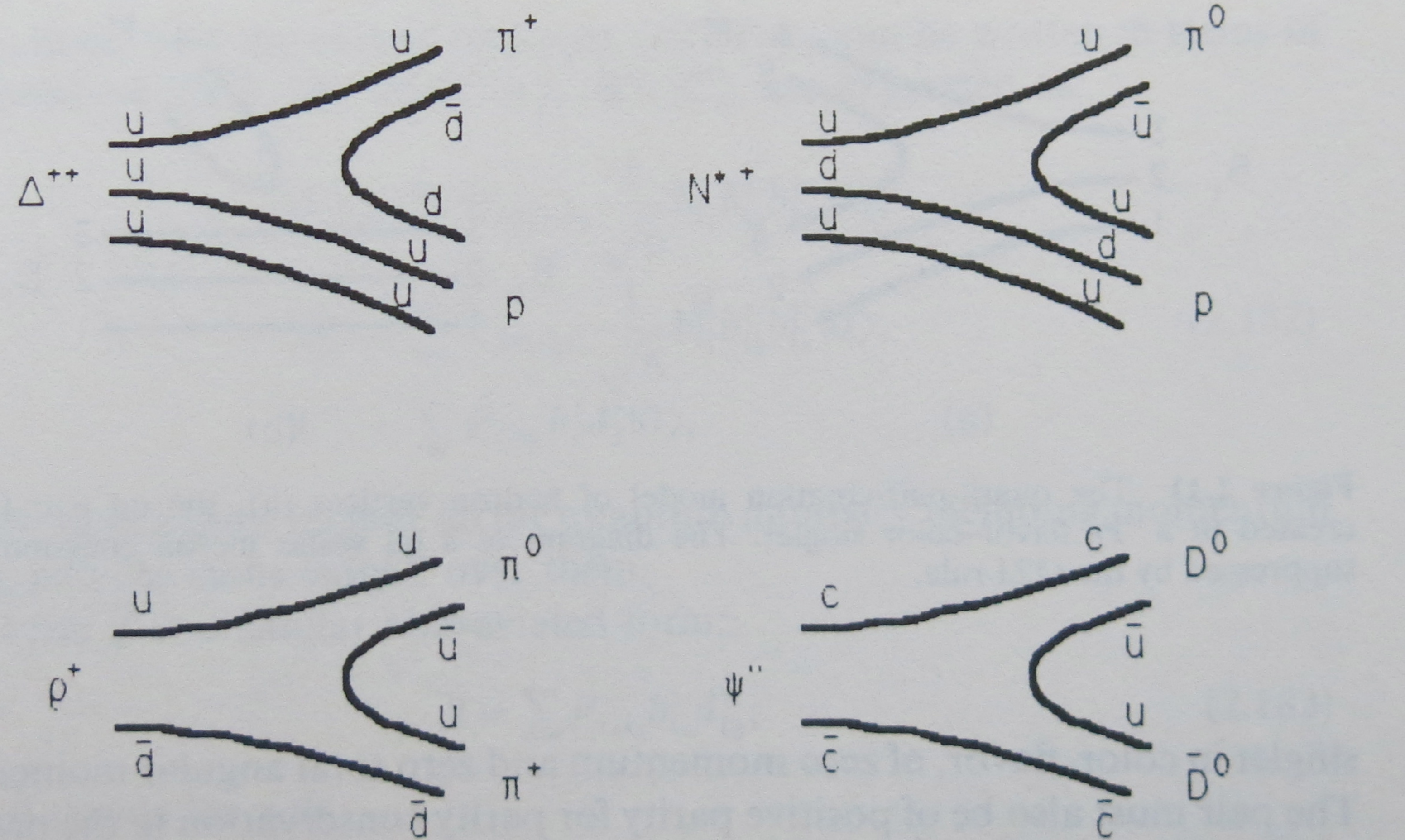


Figure 2.10 Examples of OZI-allowed decays, $\Delta^{++}\to p\pi^+$, $N^{*+}\to p\pi^0$, $\rho^+\to\pi^0\pi^+$, $\psi''\to D^0\bar{D}^0$.

"Vacuum" quantum numbers : 3P0

- The final state has one quark and one antiquark more than th initial state. We know that strong interaction preserve momentum, angular momentum, Parity, Charge conjugation, isospin. There for we create :

  a quark anti-quark pair with vanishing total momentum, P = + C = + , then J=0 implies L=1 S=1, this is called 3P0 state. We fit one parameter for the strength of this pair creation and assume it does not depend on the momentum of the quark. Once these rules are settled we apply the sames techniques as before. We did not expect the model would work so well : never accurately, but semi-quantitavely on a very large amount of decays.
- We realised afterwards that a lady, L. Micu, had proposed this model in 1969

widths have been taken from Table III of Cashmore (Ref. 1), and signs have been taken from experiment II. Partial widths in parentheses have been taken elsewhere, often from the pole residue estimation (Table IV of first paper of Ref. 1). Signs in parentheses with subscripts R refer to new results in (R).

Reaction	S_q	$M(l,s)/\sqrt{3}$	Additional coefficients	$A(N^*\to PD)$ or $A(N^*\to N\pi)$	$a(N^*\to PD)$ or $a(N^*\to N\pi)$	Experimental sign $\times\Gamma^{1/2}$	r
$S_{11}(1535)\to N\pi$	$\frac{1}{2}$	$+0.13-0.26k^2$		$+0.07$	$+0.24$	$+0.19$	$+0.8$
	$\frac{3}{2}$	$+0.063-0.13k^2$		$+0.035$	$+0.12$		$+1.6$
$SD_{11}\to\Delta\pi$	$\frac{1}{2}$	$-0.37k^2$	$+$	-0.016	$+0.030$	$(-)_R$	$(+)_R$
$SS_{11}\to N\rho_1$	$\frac{1}{2}$	$-0.036+0.075k^2$	$-$	$+0.036$	$+0.0$	(0.10)	$(0.46/k^{1/2})$
	$\frac{3}{2}$	$+0.036-0.075k^2$	$-$	-0.036	$+0.0$	(0.10)	$(+)_R$
$SD_{11}\to N\rho_3$	$\frac{1}{2}$	$-0.053k^2$	$-$	$+0.0$	$+0.0$		
$SP_{11}\to N\sigma$	$\frac{1}{2}$	$-0.085k$	$-$	$+0.0$	$+0.0$	$(-)_R(0.18)$	$(0.35/k^{3/2})(-)_R$
$S_{11}(1700)\to N\pi$	$\frac{3}{2}$	$+0.063-0.13k^2$		$+0.02$	$+0.08$	$+0.27$	$+3.4$
	$\frac{1}{2}$	$+0.13-0.26k^2$		$+0.02$	$+0.16$		$+1.7$
$SD_{11}\to\Delta\pi$	$\frac{3}{2}$	$-0.18k^2$	$+$	-0.03	-0.10		$+$
	$\frac{1}{2}$	$-0.37k^2$	$+$	-0.06	-0.20	$-$	$+$
$SS_{11}\to N\rho_1$	$\frac{3}{2}$	$+0.036-0.075k^2$	$-$	-0.036	-0.0	$+0.10$	$-0.48/k^{1/2}$
	$\frac{1}{2}$	$-0.036+0.075k^2$		$+0.036$	$+0.0$		$+0.48/k^{1/2}$
$SD_{11}\to N\rho_3$	$\frac{3}{2}$	$+0.053k^2$	$-$	-0.0	-0.0		
$SP_{11}\to N\sigma$	$\frac{3}{2}$	$-0.042k$	$-$	$+0.0$	$+0.0$	-0.34	$-1.4/k^{3/2}$
		$-0.085k$		$+0.0$	$+0.0$	-0.34	$-0.7/k^{3/2}$
$P_{13}(1860)\to N\pi$	$\frac{1}{2}$	$+0.019k-0.23k^3$		$+0.055$	$+0.27$	$+0.25$	$+0.93$
$PP_{13}\to\Delta\pi$	$\frac{1}{2}$	$+0.069k-0.085k^3$	$+$	$+0.024$	$+0.10$		
$PF_{13}\to\Delta\pi$	$\frac{1}{2}$	$+0.25k^3$	$+$	$+0.037$	$+0.15$		
$PP_{13}\to N\rho_1$	$\frac{1}{2}$	$-0.16k+0.19k^3$	$+$	-0.050	-0.18	-0.44	$+2.4$
$PP_{13}\to N\rho_3$	$\frac{1}{2}$	$-0.079k+0.098k^3$	$+$	-0.024	-0.08		
$PF_{13}\to N\rho_3$	$\frac{1}{2}$	$-0.29k^3$	$+$	-0.015	-0.06		
$PD_{13}\to N\sigma$	$\frac{1}{2}$	$-0.074k^2+0.065k^4$	$+$	-0.010	-0.04		
$D_{13}(1520)\to N\pi$	$\frac{1}{2}$	$-0.26k^2$		$+0.055$	$+0.19$	$+0.26$	$+1.3$
$DS_{13}\to\Delta\pi$		$-0.13+0.26k^2$	$+$	$+0.11$	$+0.23$	$+0.12$	$+0.52$
$DD_{13}\to\Delta\pi$		$-0.026k^2$	$+$	$+0.017$	$+0.04$	$+0.095$	$+2.4$
$DD_{13}\to N\rho_1$		$+0.075k^2$	$-$	$+0.0$	$+0.0$		
$DS_{13}\to N\rho_3$		$-0.18+0.37k^2$	$-$	-0.18	-0.0	-0.14	$+0.13/k^{1/2}$
$DD_{13}\to N\rho_3$		$-0.37k^2$		-0.0	-0.0		
$DP_{13}\to N\sigma$		$+0.042k$	$-$	$+0.0$		(0.055)	$(0.22/k^{3/2})$
$D_{13}(1700)\to N\pi$	$\frac{3}{2}$	$+0.041$		$+0.0145$	$+0.060$	$+0.115$	$+1.9$
$DS_{13}\to\Delta\pi$		$+0.20-0.40k^2$	$+$	$+0.135$	$+0.42$	$+0.13$	$+0.31$
$DD_{13}\to\Delta\pi$		$-0.33k^2$	$+$	-0.053	-0.16	$(-)_R(0.055)$	$(+)_R(0.34)$
$DD_{13}\to N\rho_1$		$+0.024k^2$	$-$	-0.0	-0.0		
$DS_{13}\to N\rho_3$		$-0.058+0.12k^2$	$-$	$+0.058$	$+0.0$	$(+)_R(0.55)$	$(+)_R(0.17/k^{1/2})$
$DD_{13}\to N\rho_3$		$-0.095k^2$	$-$	$+0.0$			
$DP_{13}\to N\sigma$		$-0.067k$	$-$	$+0.0$	$+0.0$	-0.32	$-0.8/k^{3/2}$
$D_{15}(1670)\to N\pi$	$\frac{3}{2}$	$+0.10k^2$		$+0.03$	$+0.13$	$+0.24$	$+1.8$
$DD_{15}\to\Delta\pi$		$-0.37k^2$	$+$	-0.048	-0.15	-0.27	$+1.8$
$DD_{15}\to N\rho_1$		$+0.058k^2$	$-$	-0.0	-0.0		
$DD_{15}\to N\rho_3$		$+0.11k^2$	$-$	-0.0	-0.0		
$F_{15}(1688)\to N\pi$	$\frac{1}{2}$	$-0.24k^3$		$+0.045$	$+0.19$	$+0.28$	$+1.85$
$FP_{15}\to\Delta\pi$		$+0.17k+0.21k^3$	$+$	-0.052	-0.16	$+0.145$	-0.9
$FF_{15}\to\Delta\pi$		$+0.17k^3$	$+$	-0.009	-0.035	$(-)_R$	$(+)_R$
$FF_{15}\to N\rho_1$		$+0.19k^3$	$+$	-0.0	-0.0		
$FP_{15}\to N\rho_3$		$-0.19k+0.24k^3$	$+$	$+0.0$	$+0.0$	$+0.13$	$+0.11/k^{3/2}$
$FF_{15}\to N\rho_3$		$-0.20k^3$	$+$	$+0.0$	$+0.0$		
$FD_{15}\to N\sigma$		$+0.0023k^2$	$+$	-0.0	-0.0	$+0.12$	$-\infty$

The column to the right
Is the ratio expriment/theory
The result should be of
order +1 (the sign
is meaningful)
And there are more
such results !

Only - sign

$\Psi'' \rightarrow D^{(*)} \bar{D}^{(*)}$ and wave functions nodes

$\Psi''(4.028)$ is the second radial excitation of the charmonium ($c\bar{c}$). Experimental data where known for the three channels

$D\bar{D}$, $D^*\bar{D}+D\bar{D}^*$, $D^*\bar{D}^*$, and people were comparing the ratios of branching fractions to a simple counting of spin degrees of freedom. **It did not work.**

If we use the 3P0 quark pair creation model, we must consider also the wave function of the $\Psi''(4.028)$: it has nodes.

This was published in 1977

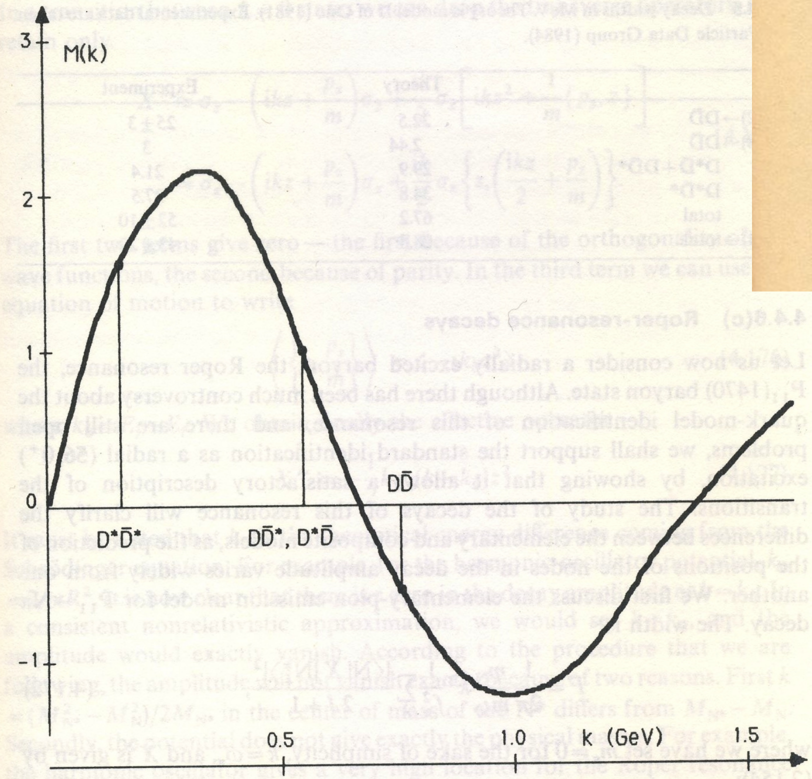


Figure 4.1 A plot of the spatial part $M(k)$ of the QPC amplitude for the decay of the ψ(4.028), from Ono (1983). The node structure originates in the analogous structure of the 3S radial wave function of the decaying state.

$$\frac{\sigma^{\exp}(D\bar{D})}{\sigma^{th}_{SC}(D\bar{D})} : \frac{\sigma^{\exp}(D\bar{D}^{*}+\bar{D}D^{*})}{\sigma^{th}_{SC}(D\bar{D}^{*}+\bar{D}D^{*})} : \frac{\sigma^{\exp}(D^{*}\bar{D}^{*})}{\sigma^{th}_{SC}(D^{*}\bar{D}^{*})}$$

$$= 1 : 5 : 100 \,, \qquad (2)$$

Table 1

Variation of the results (normalized to 100 for $D^*\bar{D}^*$) with R^2 (GeV^{-2})

	$\frac{\sigma(D\bar{D})}{F_1}$	$\frac{\sigma(D\bar{D}^*+\bar{D}D^*)}{4F_2}$	$\frac{\sigma(D^*\bar{D}^*)}{7F_3}$
Exp.	1	5	100
Spin counting	100	100	100
$R^2 = 2.8$	4.2	27.0	100
$R^2 = 4.0$	0.06	13.6	100
$R^2 = 5.2$	1.04	5.2	100

Who did what ?

- This work was collective and it is difficult to remember who did what. We were discussing and the physical ideas came from the discussion
- However, some of the formulae to deal with these decays where mathematically rather tricky using all kinds of special functions, complex 6J and 9J coefficients and I am sure of something : I was unable to derive this.
- I guess it was Jean_Claude, which does not mean that Jean-Claude did not take part in the generation of the physical ideas. He did not speak much, but he spoke well