EXPECTED PHYSICS AT PETRA-PEP ENERGIES

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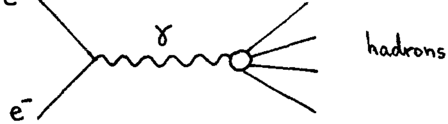
The on-going contructions of the new electron-positron colliding-beam facilities—PETRA and PEP—will allow the continuation of the study of e^+e^- physics up to centre -of- mass energies of 40 GeV. To plan experimental programs at these machines and build relevant detectors, one must take into account the tremendous contribution made by SPEAR and DORIS to our knowledge of particle physics. It is to be hoped that PETRA and PEP will uncover a new physics of their own, but for the time being we may still look at this future physics along the lines that have been traced over the last two years.

1. "Established" features of e^+e^- physics.

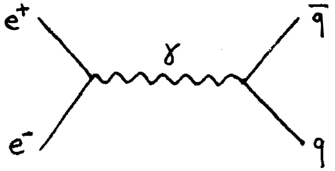
All the e^+e^- data below an energy of 8 GeV is in remarkable agreement with the predictions of the quark-parton model. We can therefore list the main features of the data in quark language :

- the final state of e^+e^- annihilation through one photon has well defined quantum numbers.



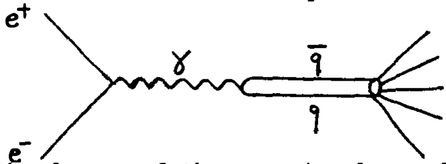
$$\left\{ \begin{array}{l} C = -1 \\ J^P = 1^- \end{array} \right.$$

- the coupling between the photon and the final hadrons proceeds through a pair of quarks



Since quarks are created in pairs, all kinds can be produced (u, d, s, c, ... : quark democracy).

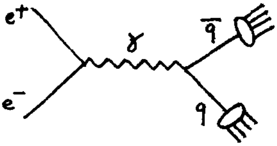
- C = -1 bound states of quarks can be excited directly



ρ, ω, ϕ, ψ, ψ'

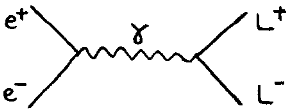
The decays of these copiously produced vector mesons also reveal the existence of scalar resonances via radiative decays.

- the hadronic final state is determined by the quark-to-hadron fragmentation functions. Quarks are revealed by the existence of jets with $\langle p_T \rangle \sim .3$ GeV.



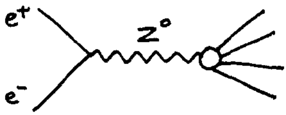
$$R = \frac{\sigma(e^+e^- \to h)}{\sigma(e^+e^- \to \mu^+\mu^-)} \sim \sum_i q_i^2 \qquad \text{(quark charges)}$$

- charged leptons are produced in pairs with a calculable cross section.



e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$

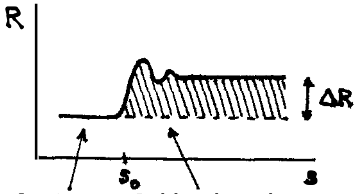
- finally, from the observation of $\bar{\nu}e \to \bar{\nu}e$ (1) we know that e^+e^- is coupled to the neutral weak current probably mediated by the $Z°$ boson.



2. New quark flavours

As we have seen, e^+e^- annihilation is the most direct way to search for new types of hadron constituents. They will be evidenced by the following facts (for a new type of quark, b)

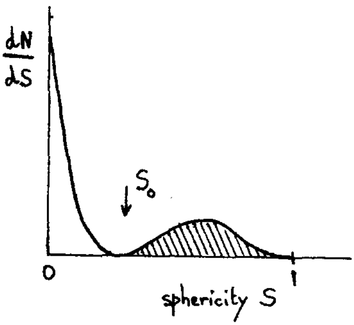
a) threshold effects

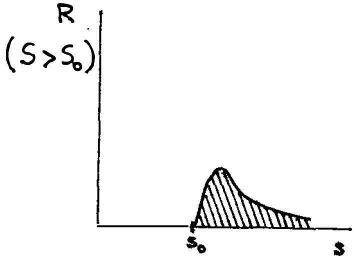


$b\bar{b}$ bound states ? bb, bq, bq resonances

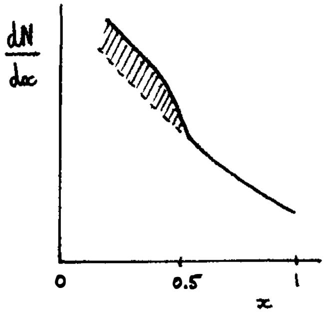
The step in R will depend on the charge of the newly excited quark. With R = 6 and a tri-coloured quark, we have $\frac{\Delta R}{R}$ = .22, .05 for $q = \frac{2}{3}, \frac{1}{3}$ respectively. These values put severe constraints on systematic uncertainties attached to future detectors.

It is to be expected that events initiated by the new heavy quarks will be more isotropically distributed than events initiated by old quarks. This behaviour could be revealed through sphericity distributions.





Such an abrupt change in sphericity will be very helpful to identify a possible threshold. Since just above threshold, pair production of $b\bar{q} + \bar{b}q$ states will occur, we also expect that new events will mostly populate the single hadron inclusive spectrum below x = 0.5.



3. Narrow resonances

If narrow $b\bar{b}$ bound states V occur below $b\bar{b}$ threshold, their measurement will yield the partial width $\Gamma(V \to e^+e^-)$

$$\int dE\ \sigma(e^+e^- \to V) = \frac{6\pi^2}{m_V{}^2}\ \Gamma(V \to e^+e^-)$$

From known vector mesons we expect $\Gamma(V \to e^+e^-)$ to be independent of m_b and to be proportional to q_b^2 :

$$\Gamma(V \to e^+e^-) \sim 1.5 \text{ keV} \quad \text{for } q_b = \frac{1}{3}$$

on the other hand the peak cross section will be reduced due to the energy dispersion of the beams ($\Delta E_B \sim 10^{-3} E_B$). We wish to estimate if such a peak is detectable and for that we need an estimate of the hadronic width $\Gamma(V \to h)$. The value for $(\Gamma\ V \to h)$ is reduced by the Zweig rule and can be estimated by comparing to known decays :

	V	$\frac{\Gamma(V \to h)}{\Gamma(V \to ee)}$	
normal decays	ρ	25 000	
	ω	13 000	
inhibited decays	ϕ	510	($K\bar{K}$ removed)
	ψ	14	

If the Zweig rule works better at higher energies, we expect $\Gamma(V \to h) \lesssim 20$ keV. One should also keep in mind the electromagnetic decay into hadrons

$$\Gamma_{EM}(V \to h) \sim \Gamma(V \to ee) \times R \sim 10 \text{ keV}$$

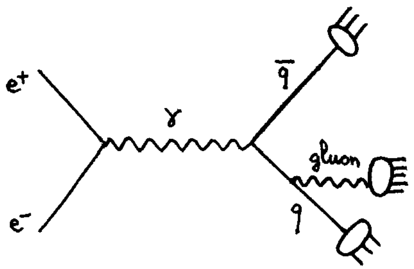
It is interesting to note that even in case of a very small width for the direct hadronic decay, such vector mesons can be detected in the total cross section. For example let us assume

m_V = 20 GeV and consider an energy scan from 10 to 30 GeV with integrated luminosity of $5 10^{37}$ cm^{-2} and energy steps equal to the machine energy resolution : the peak would be detected at a level of 5σ if $\Gamma(V \to h) = 0$, while the significance would increase to 8σ if $\Gamma(V \to h) = 10$ keV.

4. Jets

The observed $(1+\cos^2\theta)$ distribution for the jet axis observed at 7.4 GeV is enticing evidence for spin - $\frac{1}{2}$ quarks[2]. At SPEAR jets are only deduced from a sphericity analysis and therefore jet parameters are somewhat difficult to get at. The higher energies of PETRA/PEP will enable us to study jets in a more direct way. Among the more interesting problems to be studied we note :

- first, establish topology of events, namely are there jets ?
- multiplicity, $\langle p_T \rangle$ as a function of s.
- separate the different quarks : this is a very difficult task which includes extensive particle identification and unfolding of x distributions. A first step is to determine the quark-to-hadron fragmentation functions $D_{q \to h}(x)$ for all hadrons.
- are there multi-jets ? They could occur, as for example if quarks radiate gluons[3]. The multiplicity of the gluon jet is expected to be twice the average quark-to-hadron multiplicity[4] and therefore such events would be particularly spectacular to find and a nightmare to reconstruct.



5. Heavy leptons

The leptonic spectroscopy could include some of the following objects :

- sequential leptons with their own leptonic number and associated neutrino

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} L \\ \nu_L \end{pmatrix} \quad \cdots\cdot$$

- "gauge" leptons with electron or muon quantum number = E, M

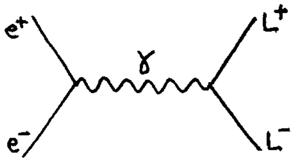
  ortholeptons (5) $\qquad \ell_{E^-} = \ell_{e^-}$

  paraleptons $\qquad \ell_{E^-} = \ell_{e^+}$

- excited leptons decaying radiatively

  $e^* \to e\,\gamma$

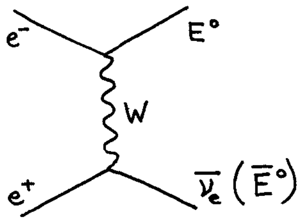
The production mechanism of charged leptons is well-known :

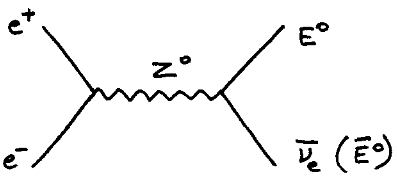


$$\sigma(e^+e^- \to L^+L^-) = \sigma(e^+e^- \to \mu^+\mu^-)\,(1 + \frac{2M_L^2}{s})\sqrt{1 - \frac{4M_L^2}{s}}$$

giving a rather substantial rate a few GeV's above threshold (see Fig. 1).

Neutral leptons can be produced through weak currents :

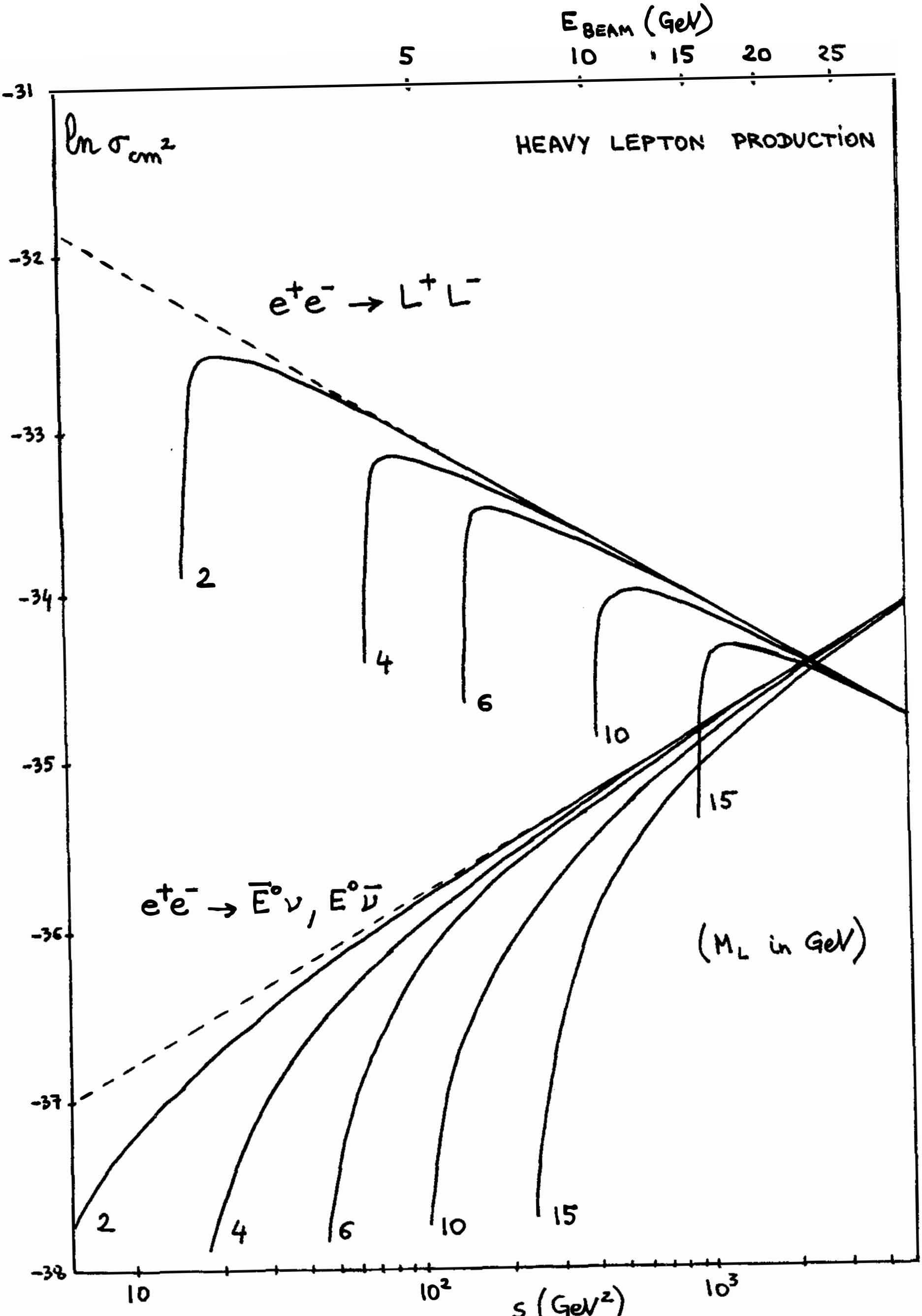




The rate for these processes depends on the relevant couplings ; an estimate by Bjorken and Llewellyn-Smith(6) yields :

$$\sigma(e^+e^- \to E^\circ\bar{\nu}) \sim 10^{-7}\,\sigma(e^+e^- \to \mu^+\mu^-)\,(1 - \frac{M_E^2}{s})^2\, s^2 \qquad s << M_Z^2,\ M_W^2$$

and shows that at the highest energy of PETRA/PEP rates for neutral leptons might be comparable -if they exist- to these of charged leptons (Fig. 1).



E BEAM (GeV)
5
10
15
20
25
-31
-32
-33
-34
-35
-36
-37
-38
ln σ cm²
HEAVY LEPTON PRODUCTION
e⁺e⁻ → L⁺L⁻
2
4
6
10
15
e⁺e⁻ → Ē°ν, E°ν̄
(M_L in GeV)
2
4
6
10
15
10
10²
10³
s (GeV²)

FIG. 1

The expected decay modes are :

$$\text{para}\left\{\begin{array}{lll} E^+ & \to \nu_e & (e^+ \nu_e) \\ & \nu_e & (\mu^+ \nu_\mu) \\ & \nu_e & (\text{hadrons}) \\ M^+ & \to \nu_\mu & \ldots\ldots\ldots \end{array}\right. \qquad \text{ortho}\left\{\begin{array}{ll} E^+ \to \bar{\nu}_e & \ldots\ldots \\ M^+ \to \bar{\nu}_\mu & \ldots\ldots \end{array}\right.$$

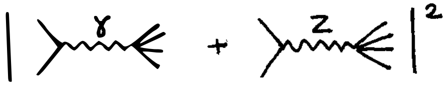
$$\text{para}\left\{\begin{array}{lll} E^\circ & \to e^+ & (e^- \bar{\nu}_e) \\ & e^+ & (\mu^- \bar{\nu}_\mu) \\ & e^+ & (\text{hadrons}) \\ M^\circ & \to \mu^+ & \ldots\ldots\ldots \end{array}\right. \qquad \text{ortho}\left\{\begin{array}{ll} E^\circ \to e^- & \ldots\ldots \\ M^\circ \to \mu^- & \ldots\ldots \end{array}\right.$$

The di-lepton final states are particularly important, since their relative abundance (e^+e^- : $\mu^+\mu^-$: $e^\pm$ $\mu^\mp$) is a good clue to the nature of the heavy lepton. It is also worth pointing out that decays like $E^\circ \to e^+$ (hadrons) with no missing neutrino can be kinematically reconstructed, thus yielding direct evidence on a mass plot.

6. Weak current effects

It will be one of the most fascinating problems for the next generation of e^+e^- colliding devices to uncover effects from the neutral weak current. In general the amplitude for $e^+e^- \to$ any final state will have two interfering pieces from the electromagnetic and weak currents :

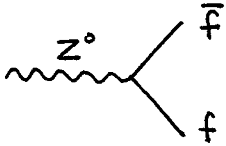
$$\sigma = \sigma_\gamma + \sigma_{\gamma z} + \sigma_z =$$



For the total hadronic rate (or $\mu^+\mu^-$ production) σ_γ will decrease like $1/s$ while σ_z is expected to increase like s and $\sigma_{\gamma z}$ will remain constant, provided $s \ll M_z^2$. It is this fact which makes higher energies so desirable : however at PETRA/PEP σ_z will probably be still too small leaving only the interference $\sigma_{\gamma z}$ to be measured. It will be the purpose of still higher energy storage rings to uncover σ_z.

Since the hadronic state is produced through spin - $\frac{1}{2}$ quarks, we only need to consider couplings to fermions. Measurements of the interference will therefore lead to fundamental couplings of the Z° current to quarks and leptons.

We write the couplings as :



$f = e, \mu, q$

$$\mathcal{L}_{Zf\bar{f}} = e\, M_Z \sqrt{g}\, \bar{f}\, \gamma_\mu\, (v_f - a_f \gamma_5) f$$

For $f \equiv \mu^-$, we can compute the effect on the total rate, the forward-backward asymmetry and the muon polarisation (assuming μ-e universality)

$$r_\mu = \frac{\sigma(ee \to \mu\mu)}{\sigma_{point}} = 1 - \frac{2sgv^2}{1 - \frac{s}{m_Z^2}} + \left[\frac{(v^2 + a^2)gs}{1 - \frac{s}{m_Z^2}}\right]^2$$

$$A_\mu = \frac{F - B}{F + B} \simeq - \frac{3\ sga^2}{2(1 - \frac{s}{m_Z^2})}$$

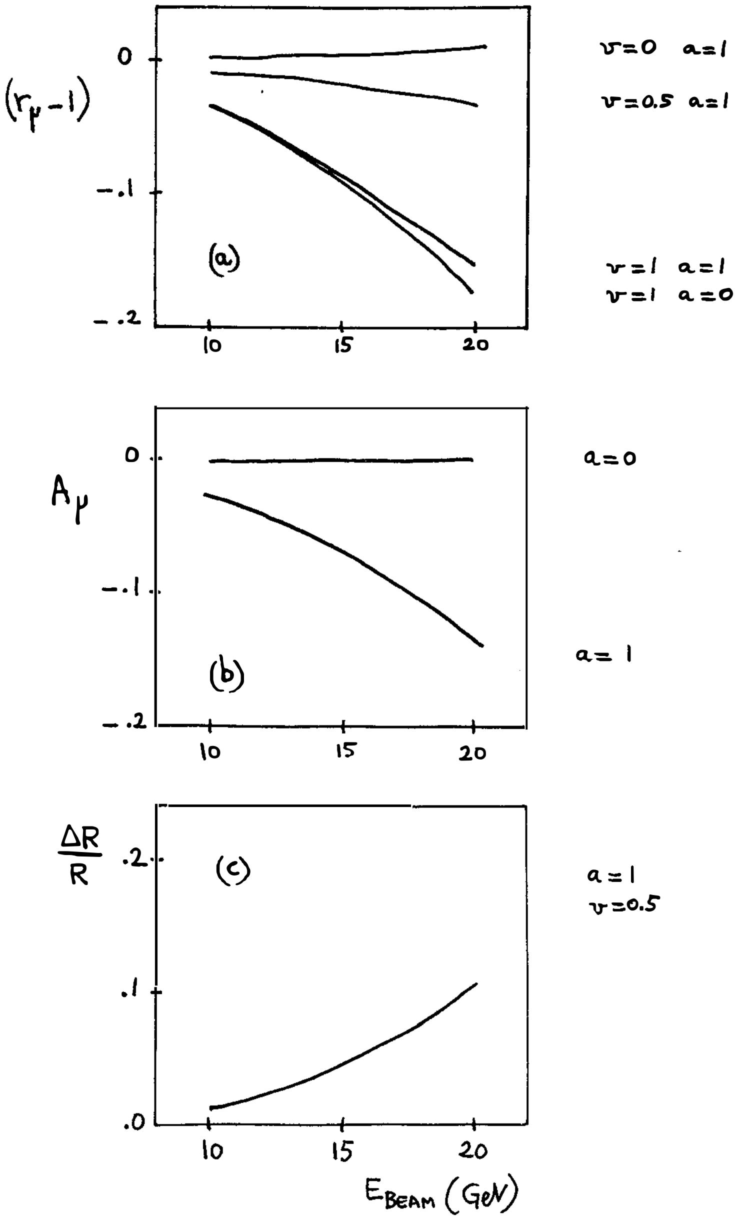
$$H_\mu \simeq \frac{2sgav}{1 - \frac{s}{m_Z^2}}$$

The actual values will permit to measure v and a in magnitude and sign. Some examples are shown in Fig. 2 (a)(b) for r_μ and A_μ, the quantities most accessible to experiment. It is interesting to note that even at PETRA/PEP energies, the effect of both the Z° propagator and the squared weak term are relatively important for the value of r_μ. Also, a careful measurement of A_μ at different energies will give some information on the Z° mass.

The same formalism can apply to the total hadronic rate by proper summation over all flavours and colours of quarks :

$$r = \frac{\sigma(ee \to \text{hadrons})}{\sigma_{point}}$$

$$= \sum_i q_i^2 + \frac{2sgv}{1 - \frac{s}{m_Z^2}} \sum_i q_i v_i + \left(\frac{gs}{1 - \frac{s}{m_Z^2}}\right)^2 (v^2 + a^2) \sum_i (v_i^2 + a_i^2)$$



0
-.1
-.2
$(r_\mu - 1)$
(a)
10
15
20
v=0 a=1
v=0.5 a=1
v=1 a=1
v=1 a=0
0
-.1
-.2
A_μ
(b)
10
15
20
a=0
a= 1
$\frac{\Delta R}{R}$
.2
.1
.0
(c)
10
15
20
E_{BEAM} (GeV)
a=1
v=0.5

FIG. 2

The effect of the weak current will be determined by the coupling v_i and a_i of the quarks. We have made a numerical estimate assuming the model of Weinberg-Salam with $\sin^2\theta_W = \frac{3}{8}$: the result is given in Fig. 2 (c) for the ratio R. With this choice of couplings, the ratio R increases by roughly 10 % between beam energies of 10 and 20 GeV, the effect being due to the decrease of r_μ, the increase of the interference term and the squared weak term in r. It is important to remark that—within the Weinberg-Salam model—some 4 % of the hadronic rate[7] would be mediated by the weak current at $\sqrt{s}$ = 40 GeV. Observable effects should occur, including parity violation (as seen through Λ° decays, for instance).

Acknowledgements

I thank M.K. Gaillard and my colleagues preparing experiments at PETRA for interesting discussions.

References

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(5) I follow the notation of C. LLEWELLYN-SMITH, Invited paper presented at the Royal Society meeting on New Particles and New Quantum Numbers (March 1976).

(6) J.D. BJORKEN and C. LLEWELLYN-SMITH Phys. Rev. 7D, 887 (1973)

(7) This point was already stressed in C. JARLSKOG and F.J. YNDURAIN Phys. Let. 63B, 215 (1976)