THEORETICAL ISSUES IN NEUTRINO PHYSICS

C.H. LLewellyn Smith

Department of Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, England

ABSTRACT

A brief review is presented of some issues which might be addressed by future neutrino experiments at the SPS.

1. INTRODUCTION

Accelerator neutrino physics is now twenty years old. A decade ago when the SPS programme was being planned at the Tirrenia conference, I examined the nine questions posed by Lee and Yang in their classic 1960 letter and pointed out that only one had then been satisfactorily answered 1):

Questions raised by Lee and Yang [Phys.Rev. Letters 4, 307 (1960)]	Experimental answers in 1972
1) $\nu_\mu = \nu_e$?	$\nu_\mu \neq \nu_e$
2) Lepton conservation $\nu \to L^+$ and $\to L^-$?	$\sqrt{\frac{\sigma(\nu_\mu \to \mu^+)}{\sigma(\nu_\mu \to \mu^-)}} \leq 0.068$ But several different forms of conservation law still allowed
3) Neutral currents?	$\sqrt{\frac{\sigma(\nu n \to \nu n\pi^0)+\sigma(\nu p \to \nu p\pi^0)}{2\sigma(\nu n \to \mu^- p\pi^0)}} \leq 0.37$
4) "Locality" (vector nature of weak interactions)	No information
5) Universality between ν_μ and ν_e, μ and e?	No information
6) Charge symmetry?	No information
7) CVC; isotriplet current?	No information
8) W ?	$M_W > 1.8$ GeV
9) What happens at high energy ($E_\nu \to$ "unitarity limit")?	No information

Subsequently the situation has changed dramatically, thanks to the classic Gargamelle PS experiments and numerous experiments at the SPS and FNAL. Not only do we have much better answers to Lee and Yang's question (at least the first seven) but the other main questions which were apparent at the Tirrenia meeting have also been answered:

Are there neutral currents with the properties predicted by gauge theories in νN, μN and e^+e^-?

Are there heavy leptons - specifically of the type required by many gauge theories?

Is there a fourth quark?

Do quark parton ideas ($\int F_3\,dx$, $^{18}/5$ etc. work)?

In addition neutrino experiments have taught us a lot about QCD, which had not been invented in 1972.

Given that the obvious things have been done, extremely well, the question is whether there is anything else to do with neutrinos at the SPS. Very generally, despite widespread belief in SU(2) x U(1), there may still be surprises in the weak interactions. There is at present no evidence for deviations from the local Fermi theory, let alone * for the standard $W^{\pm}$ and Z^{o}, with gauge theory couplings between W's, or Higgs bosons. More specifically, even if the standard framework is broadly correct there is much to be learned from more accurate measurements of the parameters. As far as strong interaction physics is concerned, the recent observation by the EMC of pronounced differences between the structure functions of iron and deuterium 2) shows that surprises are still possible at SPS energies. This effect should clearly be studied with neutrinos. In addition there are various specific questions which can be further elucidated by neutrino experiments.

In this talk I shall first discuss our present knowledge of electro-weak interactions. I shall then turn to some more specific questions which could be addressed by future experiments.

2. The Standard Model and Alternatives

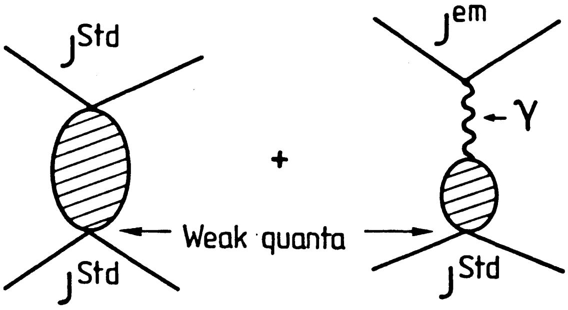
Existing data are all compatible with SU(2) x U(1) except

1) The observation that $\frac{\nu_e}{\nu_\mu} = 0.6 \pm 0.2$ in the 1979 beam dump experiments 3)

2) The observation of same sign dimuons 4).

It is clearly important to confirm these results, find experimental clues to their origin and explore possible theoretical explanations 5). However, given the vast amount of data available and the great difficulty of these measurements, the fact that these are the only problems shows that SU(2) x U(1) is in good shape. On the other hand, it reminds us that SU(2) x U(1) can be threatened by a single decisive experiment.

Although SU(2) x U(1) generally works so well, it is far from established. It is possible to produce almost exactly the same low energy results in a non gauge theory framework as first pointed out by Bjorken 6). If the standard fermionic currents J^{std} of $SU(2)_L$ couple to new unspecified "weak quanta" (e.g. heavy fermion antifermion pairs) which are electrically charged, then the diagrams:



lead to exactly the standard effective weak Lagrangian (with ρ = 1) at low energies, except for an extra term

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*The situation with respect to the W has of course changed since the SPS Workshop.

$$\frac{4G_F}{\sqrt{2}} \; C \; (J^{em})^2 .$$

In this framework C is automatically of O $(\mathrm{Sin}^4\theta_w)$ and actually vanishes if the low energy behaviour of the weak spectral function is dominated by a single resonance, so there is no conflict with the PETRA limit 7) of $C < 0.02$.

To realize this general formalism in a composite model (e.g. "weak quanta" = heavy fermion antifermion pairs which bind to vector resonances), a binding scale of O(1 TeV) is probably needed 8) to obtain $\mathrm{Sin}^2\theta_w \gg \alpha$. The main difficulty is that one would generally expect a substantial isoscalar ("weak ω") as well as an isovector ("weak ρ") contribution. This shows the importance of improving the limits on isoscalar neutral couplings. Even if the isoscalar is absent for some reason, this sort of model would differ from the standard model at low energies in second order contributions, to which neutrino experiments are becoming sensitive.

Alternative gauge theories are strongly circumscribed by existing data, in particular by the observation that $\rho \simeq 1$ and $C < 0.02$. ($\rho = 1$, $C = 0$ can only be obtained in non-standard models by tuning parameters to particular values 9)). Nevertheless if, for example, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ or $SU(2)_L \times U(1)_R \times U(1)_{B-L}$ models are fitted to low energy neutral current data there is still scope for considerable deviations from the standard predictions for the Z mass, the allowed ranges being 10)

$$1\sigma: \quad 83 \text{ GeV} < M_{Z_1} < 116 \text{ GeV} \qquad M_{Z_2} > 205 \text{ GeV}$$

$$2\sigma: \quad 79 < M_{Z_1} < 135 \qquad M_{Z_2} > 175.$$

The direct limits on the masses of charged vectors $W_R^{\pm}$ coupled to right handed currents, which must exist in models with an $SU(2)_R$ factor, is of O (3 M_{W_L}) both from β decay 11) and from neutrino experiments 12). Recently it has been claimed 13) that the $K_L - K_S$ mass difference gives an indirect limit of 1.6 TeV. However, it turns out 14) that this result is very sensitive to the t quark mass and to the Higgs couplings, which were ignored, and that, for example, with $M_t \sim 20$ GeV, $M_H \sim 100$ GeV, $M_R \sim 300$ GeV is allowed - the limit is much less if M_t is very large.

3. Neutral Current Measurements

Any improvements in the knowledge of weak couplings of quarks and leptons will further constrain non-standard gauge theories and non-gauge models. Specifically

1) Given our total ignorance of the origin of the family structure, we cannot take it for granted that c and s are simply copies of u and d, although the success of the GIM mechanism strongly suggests it for the left handed states. At the very least we would like to measure their weak I_3^R.

2) Writing, in Sakurai's notation,

$$L_{NC}^{\nu} = \frac{G}{\sqrt{2}} \bar{\nu} \gamma_\mu (1-\gamma_5) \nu [\alpha V_\mu^{I=1} + \beta A_\mu^{I=1} + \gamma V_\mu^{I=0} + \delta A_\mu^{I=0}]$$

we would like better knowledge of β and δ, which could distinguish different models: 15),16)

β = 1 standard model
= 1 Bjorken's non-gauge framework with or without a "weak ω"
$\neq$ 1 $SU(2)_L \times SU(2)_R \times U(1)$
= $0.94 \pm .06$ expt
δ = 0 standard model
$\neq$ 0 Bjorken's framework with "weak ω"
= $SU(2)_L \times SU(2)_R \times U(1)$
= $0.10 \pm .09$ expt.

In principle these parameters might be measured directly by studying coherent production of π^0's and η's on I = 0 nuclei. In practice they are obtained by a global fit to all neutral current data. Clearly considerable improvement is desirable, especially for δ.

3) Data which test SU(2) x U(1) to second order are needed to establish that it really is a renormalizable theory and to distinguish it from other models with the same leading order low energy predictions e.g. non-gauge theories of the Bjorken type or "supersymmetric SU(2) x U(1)" in which relatively light SUSY particles in virtual loops alter the radiative corrections 17) and could change the predicted values of $M_{W,Z}$ by a few GeV.

In order to test SU(2) x U(1)it must be shown that all experiments ($\nu, \bar{\nu}, \bar{e}e$, ed, M_W, M_Z) can be described by the same value of $\sin^2\theta_w$, if possible to an accuracy which tests the second order corrections. Very accurate measurements of $\text{Sin}^2\theta_w$ are also needed for comparison with the predictions of grand unified models. As in the case of tests of QED, SU(2) x U(1) should be tested in as many ways as possible since different experiments are sensitive to different higher order contributions and possible breakdowns e.g. from contributions of new particles. For example, suppose that $\text{Sin}^2\theta_w$ is extracted from $\dfrac{\sigma^{nc}_{\nu N}}{\sigma^{cc}_{\nu N}}$ and also from $\dfrac{\sigma(\nu_\mu e \to \nu_\mu e)}{\sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e)}$ assuming $M_t^2 < M_W^2$ in calculating the radiative corrections. If in fact M_t is unexpectedly large, the first result would be larger than the second by $2 \times 10^{-3} \left(\dfrac{M_t}{M_w}\right)^2$ (assuming the theory is otherwise correct).

This gives some idea of the accuracy which is desirable. More specifically, note that the average value of $\dfrac{\sigma^{nc}_{\nu N}}{\sigma^{cc}_{\nu N}}$ gives $\text{Sin}^2\theta = 0.227 \pm .015$ leading to $M_Z = 89^{+2.2}_{-2.0}$ GeV if the lowest order theory is used. Including all electroweak radiative correction (W and Z propagator corrections, vertex corrections, wave function renormalization, two W exchange, real bremsstrahlung etc.) we find 18) $\text{Sin}^2\theta_{\overline{MS}}(M_W) = 0.215 \pm .015$, where this is the value in the $\overline{MS}$ scheme with mass scale $\mu = M_W$, leading to $M_Z = 93.8^{+2.5}_{-2.2}$ GeV, including second order corrections to the mass formula (assuming $M_t \lesssim M_W$, $M_{Higgs} < 1$ TeV and no further quark and lepton doublets). To make a clear cut distinction between the 1st and 2nd order predictions of M_Z, it would be desirable to improve the precision on $\text{Sin}^2\theta$ by a factor of 3 or more. Note that the SLAC ed asymmetry experiment gives $\text{Sin}^2\theta = .223 \pm .015$ which becomes $\text{Sin}^2\theta_{\overline{MS}}(M_W) = 0.215 \pm .015$ when electroweak corrections are included. The fact that the agreement with the neutrino result survives radiative conditions, which might have moved the two values in opposite directions, is non-trivial and shows that incisive tests of the theory are in reach (in passing we note that the SU(5) prediction is $\text{Sin}^2\theta_{\overline{MS}}\,(M_W) = 0.215 \mp .006$ for $\Lambda_{\overline{MS}} = 150^{+250}_{-100}$ MeV).

A further idea of the precision which is desirable can be obtained by considering a simultaneous fit to $\frac{\sigma^{NC}_{\nu N}}{\sigma^{CC}_{\nu N}}$ and $\frac{\sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\bar{\nu} N}}$ in terms of two parameters $\mathrm{Sin}^2\theta$ and ρ^2 using the lowest order theory, where ρ is the usual NC/CC strength parameter. The corrected value is $\mathrm{Sin}^2\theta_{\overline{MS}}(M_W) = \mathrm{Sin}^2\theta_{expt} - 0.004$ in this case, independent of M_t. The predicted value of ρ^2 is $1 - 0.016 + 4 \times 10^{-3}\left(\frac{M_t}{M_W}\right)^2$ (assuming no further quark and lepton doublets and that $M_{Higgs} < 1$ TeV). This suggests that a measurement of ρ^2 to 1% or better would be desirable, although very hard, and might constrain supersymmetric and other non-standard models.

If $\mathrm{Sin}^2\theta$ is measured in $\nu_\mu e$ scattering, the problems are purely experimental [19]. In ν_μ hadron scattering, however, we must also worry about theoretical uncertainties in extracting $\mathrm{Sin}^2\theta$ from the data. In particular it has been claimed [20] that higher twist corrections to the parton model could produce essentially irreducible errors in $\mathrm{Sin}^2\theta$ as large as 10%, making further experiments pointless. Luckily this conclusion is wrong for isoscalar targets. The largest terms in σ_{NC} and σ_{CC} can be related by isospin invariance alone. The QCD parton model is only needed for two relatively small terms for which we multiply the parton results by $1 + \varepsilon(x,Q^2)$ and $1 + \hat{\varepsilon}(x,Q^2)$, where ε behaves as $O(\langle p_T^2\rangle/Q^2)$ and $\hat{\varepsilon}$ as $O(m_q^2/Q^2)$ at large Q^2, where m_q is the constituent quark mass. The hypothetical cross-sections ($\hat{\sigma}$) for the case of only $u,d,\bar{u},\bar{d}$ quarks with $\theta_{KM} = 0$, and an $I = 0$ target are then related by [21]

$$\frac{d^2\hat{\sigma}^{\nu(\bar{\nu})}_{NC}}{dxdy} = \left(\frac{1}{2} - z + \frac{5z^2}{9}\right)\frac{d^2\hat{\sigma}^{\nu(\bar{\nu})}_{CC}}{dxdy} + \frac{5z^2}{9}\,\frac{d^2\hat{\sigma}^{\bar{\nu}(\nu)}_{CC}}{dxdy}$$

$$+ \left(\frac{\varepsilon z^2}{18} + \frac{z^2-z}{4}\,\hat{\varepsilon}\right)\left(\frac{d^2\hat{\sigma}^{\nu}_{CC}}{dxdy} + \frac{d^2\hat{\sigma}^{\bar{\nu}}_{CC}}{dxdy}\right)$$

where $z = \mathrm{Sin}^2\theta$.

With, very conservatively, $\langle\varepsilon\rangle \simeq 0.1$ $\langle\hat{\varepsilon}\rangle \simeq 0.05$, the error in $\mathrm{Sin}^2\theta$ due to higher twists is ± 0.005. This can be removed essentially completely by a Q^2 cut (using only hadronic information to determine Q^2 so that the cut is the same for NC and CC).

Including the contributions of other quarks and taking $\theta_{KM} \neq 0$, there are further uncertainties which are dominated by ignorance of the element U_{cs} of the Kobayashi-Maskawa matrix and of the strange quark distribution. The full range $0.80 \lesssim |U_{cs}| \lesssim 0.98$ which is allowed phenomenological gives [21] an error $\delta\,\mathrm{Sin}^2\theta_W = \pm\,0.008$. However, if the common assumption that U_{cs} is close to one is accepted the error is much less [21]. For example, assuming $|U_{cs}| > 0.95$ the error from ignorance of the strange quark contribution is only ± 0.002. In this case the largest error is ± 0.004 from ignorance of the $d \to c$ contribution, and hence of $|U_{dc}|$, due to the fact that the mixture of charmed particles produced by neutrinos is poorly known and there are large errors in the leptonic branching ratios, which are needed to extract $\nu d \to \mu^- c$ from dimuon production. Ideally it would be useful to study charm production directly in a holographic bubble chamber. This might also clear up the same sign dimuon mystery.

In conclusion, it seems that unless $|U_{cs}| - 1$ is unexpectedly large and remains unknown, theoretical uncertainties will not frustrate more accurate measurements of $\mathrm{Sin}^2\theta$ in semi-leptonic neutrino interactions. In any case, the theoretical uncertainty can be reduced to ± 0.003 (from uncertainties in $|U_{dc}|$) by using the Paschos Wolfenstein relation

$$\Delta \equiv \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar{\nu} N}} = \frac{1}{2} - \mathrm{Sin}^2\theta_W$$

from which the contribution of the sea drops out. However, Δ is subject to systematic errors which are hard to control to the level of accuracy required.

4. Properties of Neutrinos

The importance of measuring neutrino masses/mixing angles/oscillations needs no further emphasis [22]. The recent discussion [23,22,24] of the possibility of observing the decay of neutrinos with masses below 70 MeV, where there is an open window [25], reminds us of our ignorance of this subject.

An experiment which has been considered for the SPS is a search for the tau neutrino[26]. It is known that $\tau \to x\bar{\nu}e$, $x\bar{\nu}\mu$, $x\bar{u}d$ in a way which is well described by V-A theory. Here x could be $\bar{\nu}_e$, $\bar{\nu}_\mu, \nu_\mu, \nu_e$ or, if none of these, $x = \nu_\tau$ by definition. For $x = \bar{\nu}_e$ or $\bar{\nu}_\mu$, $\frac{\tau \to e}{\tau \to \mu}$ is predicted to be 2 or 1/2 respectively [27] and both are completedly excluded. $x=\nu_\mu$ is also completely excluded by the failure to see $\nu_\mu \to \tau$. $x = \nu_e$ is excluded, but only at the 90% confidence level, by the fact that it would have led to an apparent anomalous NC/CC ratio from $\nu_e \to \tau \to$ hadrons in the beam dump experiment [3]. Invoking a little theory, $x = \nu_e$ would lead to the expectation that $\frac{\tau \to \gamma}{\tau \to \mathrm{all}} \approx \alpha/\pi$ in contrast to the experimental upper limit of 6.4×10^{-4}. Furthermore in a gauge theory, there is no leptonic GIM mechanism if ν_τ does not exist and one or more of decays such as $\tau \to eee$, $\tau \to \mu\mu\mu$, $\tau \to ee\mu$ would occur [28] at a rate far above the limits of a few times 10^{-4}.

Theoretically, it seems essentially impossible to avoid the conclusion that ν_τ exists and its discovery, although very nice, would be no surprise. The question seems to be whether it would be possible to establish the non-existence of ν_τ - which would necessitate some radical new idea e.g. that ν_τ decays with a short lifetime.

5. Hadronic Final States

It is hard to be specific about the interest of studying multiparticle final states because of our almost total theoretical ignorance about quark jet and target fragmentation, beyond the QCD predictions for the evolution of fragmentation functions and the ability to invent classical Monte-Carlo models which incorporate some QCD inspired ideas and can be tailored to the data. Precisely because of this ignorance, however, it is important to obtain more experimental information. Here it would seem that neutrino experiments are in principle in a favourable position because we know the flavour of the produced quark in the majority of cases (this is also true to some extent in muon experiments since $Q_u^2 = 4Q_d^2$). Furthermore there is a unique opportunity to study $\nu d \to \mu^- c \to$ hadrons and $\nu s \to \mu^- c \to$ hadrons. Well measured events of this sort from a holographic bubble chamber would be very useful in teaching us about the dynamics.

There is also a great deal which can be learned by studying the exclusive production of charmed baryons in wide band neutrino experiments. Two events have been observed [29] which have been interpreted as $\nu p \to \mu^- \Sigma_c^{++}$, $\Sigma_c^{++} \to \Lambda_c \pi^+$ (Σ_c^{++} is the J = 1/2 uuc state). The interpretation is based on the fact that the $(\Lambda_c \pi^+) - \Lambda_c$ mass difference agrees with the theoretical prediction [30] for $\Sigma_c^{++} - \Lambda_c$. It would be nice to have more events to substantiate this interpretation and measure the cross-section which contains very interesting information. It would be even nicer to observe $\nu p \to \mu^- \Sigma_c^{*++}$ (Σ_c^{*++} is the J = 3/2 uuc state which has not yet been discovered), for which the cross-section is predicted 31) to be larger than for Σ_c^{++}. This would provide a valuable new strong hyperfine mass splitting and the cross-section would also be most interesting.

6. Nuclear Effects

The recent observation by the EMC of substantial differences between the structure functions of iron and deuterium 2) has two important implications for the SPS programme. First, assuming that the effect is confirmed, it becomes important to improve our knowledge of the structure functions of hydrogen and deuterium (assuming that nuclear effects turn out to be relatively small in deuterium!); precision measurements of quark and gluon distributions in neutrons and protons are needed a) because we may hope eventually to calculate them accurately from first principles, e.g. from lattice QCD, whereas presumably accurate calculations for iron will be impossible, and b) as input for other calculations e.g. of cross-sections at the $\bar{p}p$ collider. Second, further SPS experiments may be needed to understand the origin of the EMC effect.

Assuming that it is not due to a subasymptotic effect ("higher twist"), which would be totally unexpected theoretically and seems somewhat disfavoured experimentally, the EMC data show that, relative to deuterium, in iron 32) a) the valence quarks are "softer" b) there is (roughly 50%) more sea c) the gluons are slightly softer. Regardless of any theory, we clearly need confirmation of these effects on a variety of targets and to observe them with neutrinos. More specifically we can ask questions such as

1) Is the effect due to iron or deuterium? This can be answered with neutrinos by

studying $$\frac{F_2^{\nu p} + F_2^{\bar{\nu} p} (= F_2^{\nu n})}{F_2^{\nu D}} .$$

More generally $$\frac{Z\ F_2^{\nu p} + N F_2^{\bar{\nu} p}}{F_2^{\nu A(N,Z)}}$$ is obviously of interest.

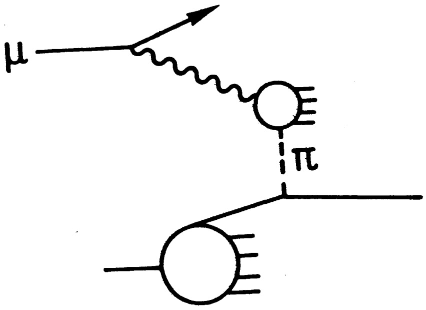
2) Does a careful comparison of $pp \to \mu\bar{\mu}x$ with $pA \to \mu\bar{\mu}x$ reveal a large sea in the latter case (this may be complicated by a slower approach to scaling for a nuclear target due to initial state absorption effects at low Q^2)?

3) If the size of the sea in iron and deuterium are different, is this true for all flavours?

In retrospect the EMC effect is not all that surprising. After all, nuclei are rather dense. At the central nuclear density of 0.17 nucleons fm^{-3} the average spacing between the centre of neighbouring nucleons is 1.8 fms-not much more than twice radius of the proton, which is 0.8 fms. Even in deuterium with $\langle r \rangle = 4.2$ fms, a Hulthén wave function gives a 5% probability that $r < .5$ fms and the view that there is actually a 0(5%) probability that the six quarks sit in one bag has some advocates 33).

It is becoming increasingly evident 34) that it is impossible to describe nuclei accurately in terms of N, Δ, π etc. without reference to the colour degree of freedom and it would seem that a proper discussion of the EMC effect must start from QCD. Nevertheless, if we start with the idea that the nuclear environment mainly changes the outside of the nucleon we can imagine that it might be possible to describe the effect very approximately in terms of a modification of the pion field. If we suppose that iron contains extra pions relative to deuterium it is clear that they will increase the structure function at small x ($x_{max} = M_\pi/M_N$ for a stationary pion) and decrease it at large x by removing momentum from the nucleons in the infinite momentum frame.

Phenomenologically the data can be explained in this way if, relative to deuterium, iron contains about 8 extra pions which carry about 5% of the momentum. Theoretically we require one pion exchange diagrams



to be about twice as big in nuclei as in deuterium. When corrections to the impulse approximation are included, a considerable enhancement is expected due to a modification of the pion propagator in nuclear matter or, equivalently, initial state correlations and a resonant coherent final state response due to the attractive πN force. Such enhancements have long been predicted 35) by nuclear physicists but no way of observing them clearly has been found; they are of considerable interest, being directly connected with the physics of the phase transition known as "pion condensation" expected to take place for $\rho > 0.35$ nucleons fm^{-3} which is important for neutron stars. It seems that with acceptable nuclear parameters the EMC effect can probably be explained by this enhancement but, alas, the parameters are extremely uncertain 36).

The pion model is speculative but it provides a first example of the sort of guidance which theory should provide for experiment. It predicts the character of the excess events at small x in which the $\gamma^*\pi$ invariant mass is relatively small. It predicts that the percentage of $s\bar{s}$ in the sea is less in iron than in deuterium, as the extra pions are mainly non-strange 37). In principle it can guide us to the most interesting nuclei to study but relevant calculations with finite nuclei are not available. In particular it is not yet clear whether the effect would be fully developed in He^4 - large density but all surface.

It must be stressed that the EMC effect has no influence on QCD scaling violation tests in nuclei, which do not depend on the assumption that nuclei are made of protons and neutrons.

7) Conclusions

In addition to the specific topics which I have discussed there are many which I have omitted either because they have been covered by other speakers (e.g. scaling violations) or because of lack of time (e.g. study of the evolution of jets in nuclei).

Much has been learned from the very thorough neutrino experiments at the SPS. Nevertheless these experiments may still reveal surprises. Even if orthodoxy prevails, there is still much which could be learned from high precision experiments both about the electroweak and the strong interactions.

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37) This was pointed out by K. Winter.