Strong Interaction Effects in Neutrino Physics

Mandy Cooper-Sarkar

Send your minds back to the 1980s

Phil was a graduate student at Oxford 1983-1986
He was in office 666
Which coincidentally was the office I had been in ~10 years earlier

Dusan Radojicic was his supervisor. He speaks very fondly of Phil, despite what Phil says were his ‘eccentricities’ at the time!
Gerald Myatt/ Don Perkins were the other neutrino people
They worked on experiments on BEBC (Big European Bubble Chamber– we haven’t got any more imaginative with names in the subsequent 40 years) in the West Area, which rejoiced in names like WA21,47,59,66

There was even a UK Bubble Chamber Groups annual football tournament –(which came to include many PP groups that had nothing to do with Bubble Chambers)
Phil is proud to have been in goal and thus to have helped Oxford win the loser’s wooden spoon trophy two years in a row!

Phil overlapped with me both in CERN and at Rutherford 1986-1989, we were both looking at neutrino data

Phil's first visit to CERN was in 1983 as a graduate student

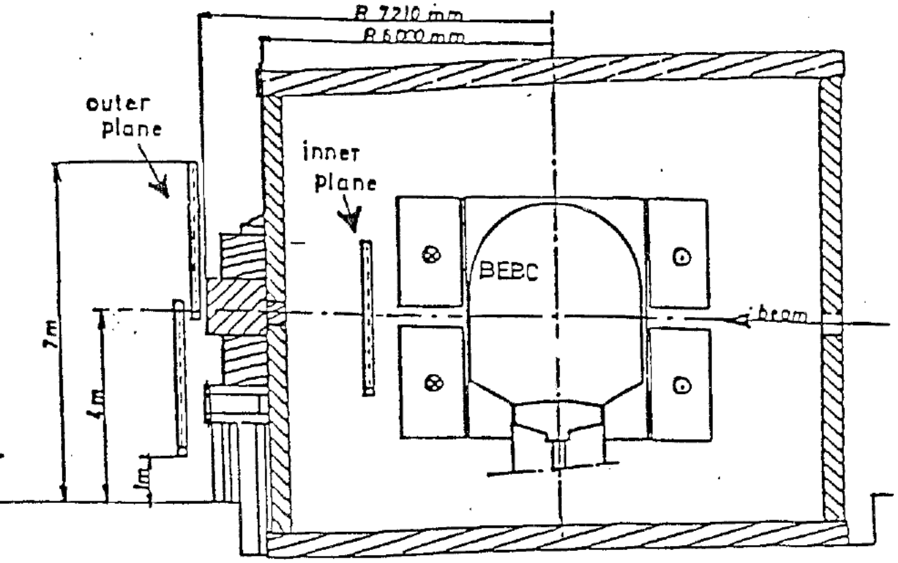
He came for the last run of BEBC on a hydrogen target.

He was travelling with **John Womersley**

Val Gibson and **Paul Dauncey** were both in his year

I was there as a CERN Fellow, as indeed was **Andy Parker**

It is hard now to imagine the conditions under which we worked
CERN had only recently abandoned fast card readers
As terminals (connected to a huge main-frame), rather than cards, came in we worked in terminal rooms
Finally we got them in our offices– Desktops, not laptops
There was no email (but we could type to each other directly through the terminals)
There was no internet
We wrote rather than typed our theses (a typist typed them),
Diagrams were primitive, even drawn by hand..



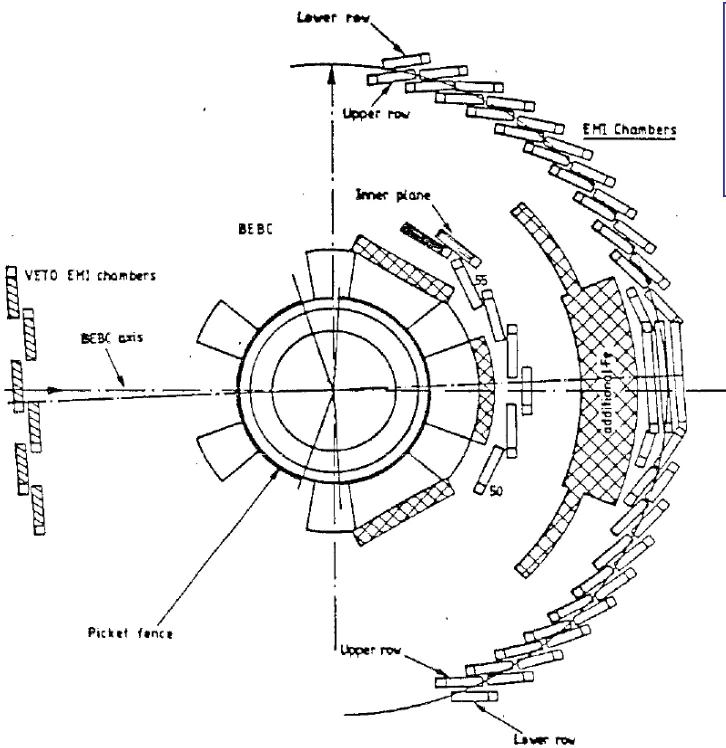


Figure 3.4. The Big European Bubble Chamber.

Extracts from Phil's thesis

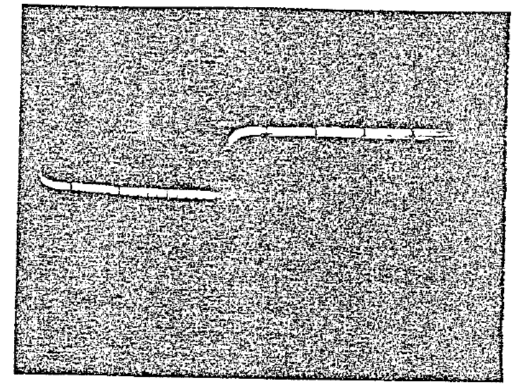


Figure 3.17a. Signal from the Analogue Summer at the Control Room.

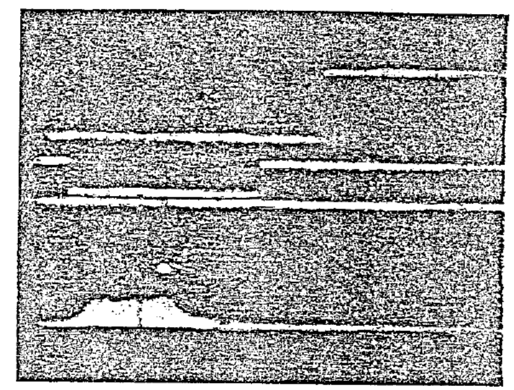
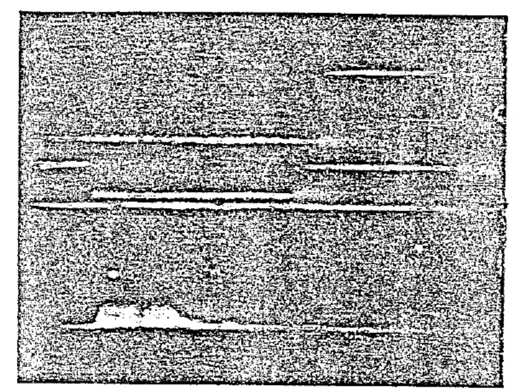


Figure 3.17b. Retention Oscilloscope Display. Default Trigger.



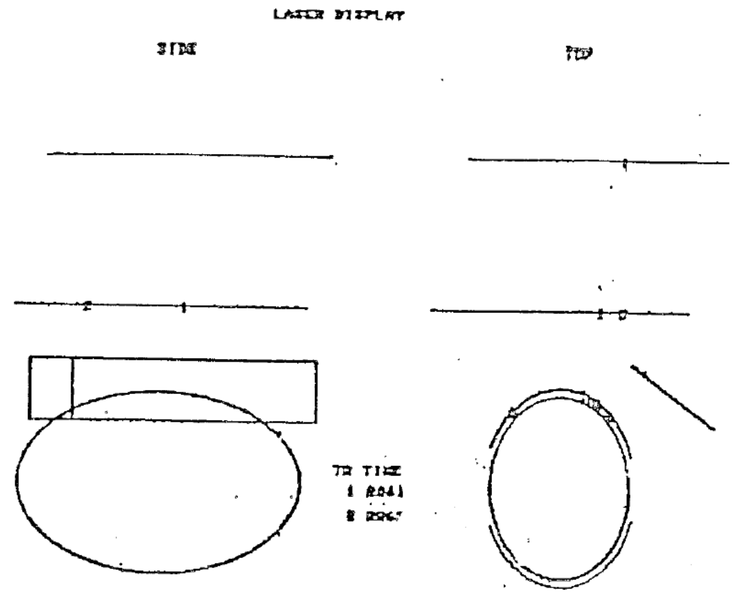
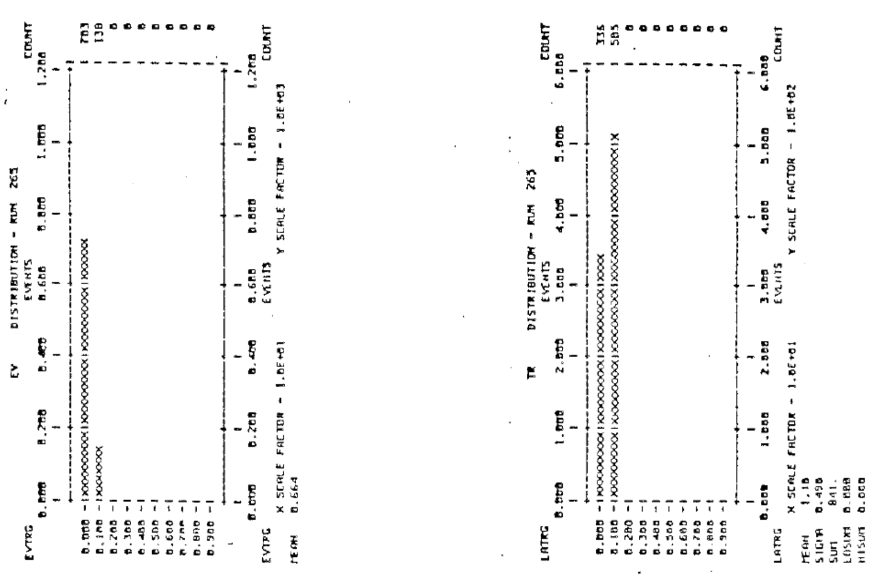


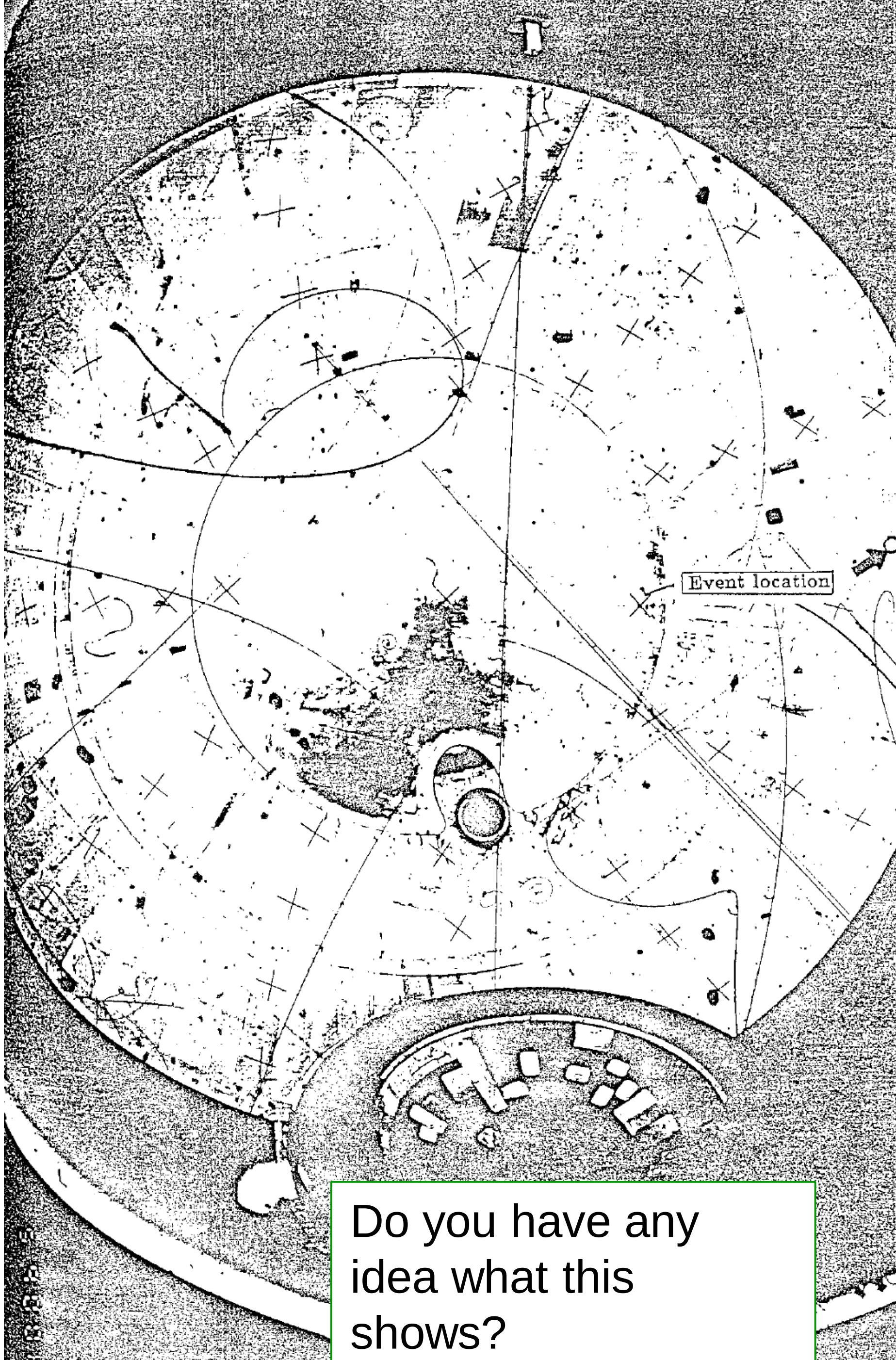
Figure 3.20. On-line Display of Trigger Time-slot.



Event Triggers

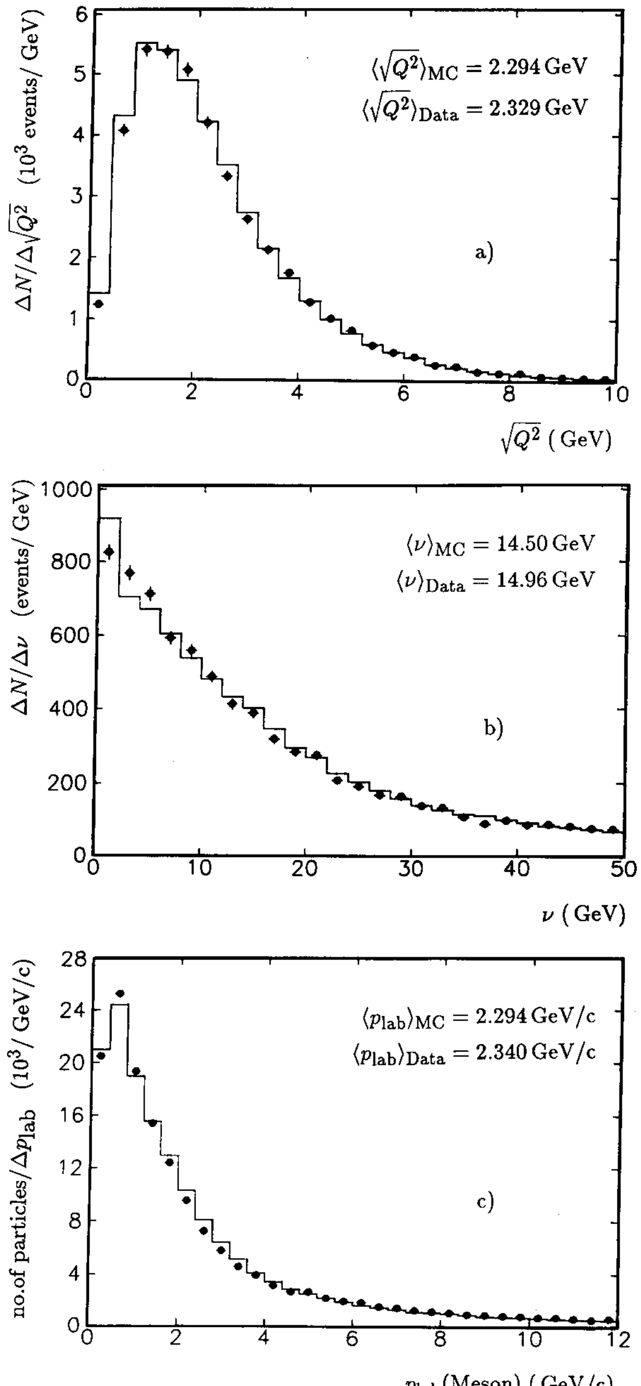
Laser Triggers

Do you remember those little crosses on the green screens?



Do you have any idea what this shows?

Figure 3.22a. Roll 2291 Frame 6.



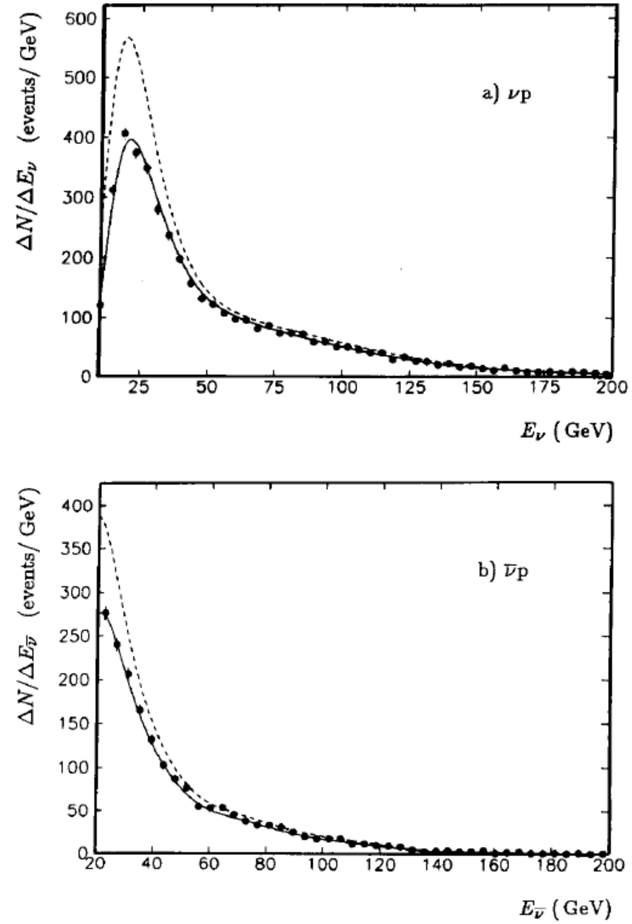


Fig. 3a, b. Spectrum of the (anti)neutrino energy in the observed events. The points represent the raw data, the solid lines the parametrisation of the raw data and the dashed lines the corrected distribution; **a** νp and **b** $\bar{\nu}$p scattering

But then as now we compared data to Monte-Carlo..

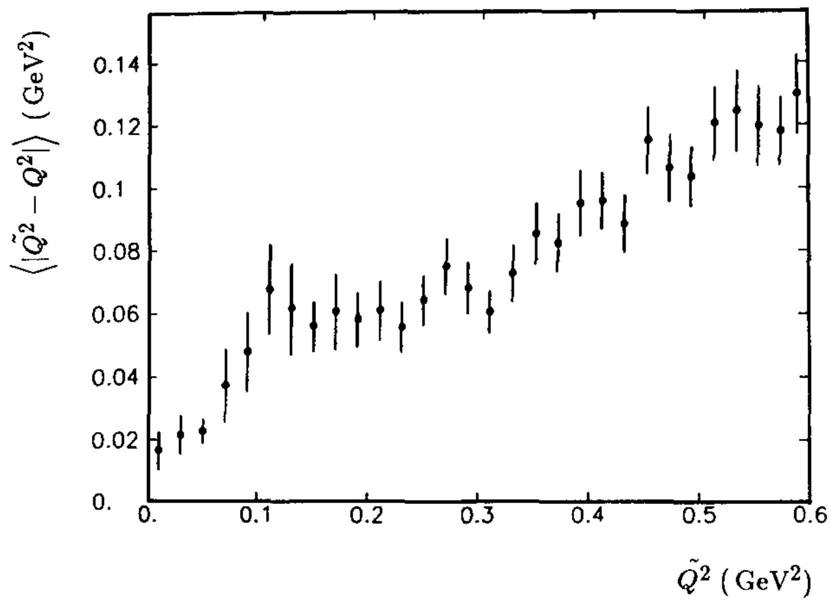


Fig. 4. Smearing of Q^2 (see text). Shown is the result for neutrino scattering which does not significantly differ from the antineutrino result. The error bars indicate the error on the mean

Then as now there were corrections for imperfect measurement

We used to call them **‘smearing factors’**
Probably they should have been called ‘unsmearing factors’

Now this is called unfolding

But what does strong interactions in neutrino physics mean?

It means we were not interested in the neutrinos themselves,
We were interested in them as lepton probes of hadronic structure

YES, **Deep Inelastic Scattering**…..

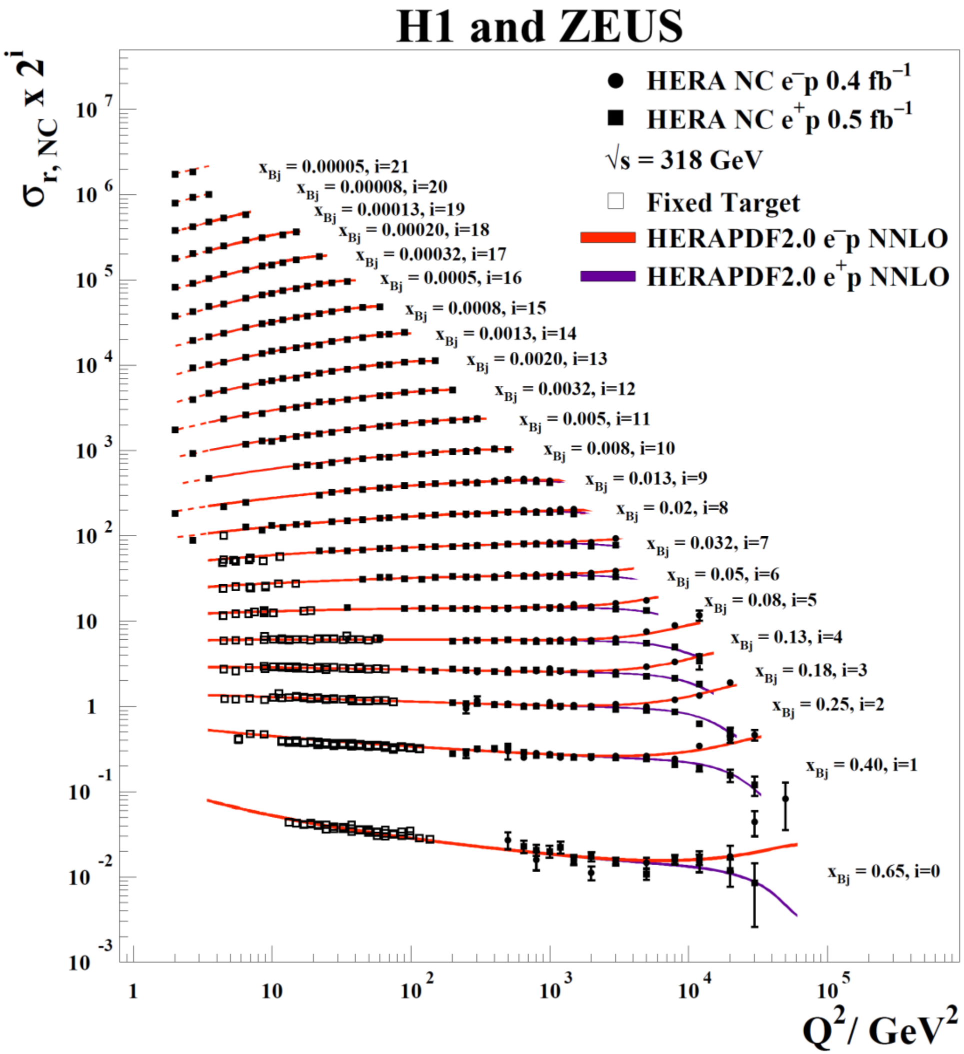
Neutrinos and anti-neutrinos were very versatile probes

They are handed so they resolve quark from anti-quark and so Valence from Sea

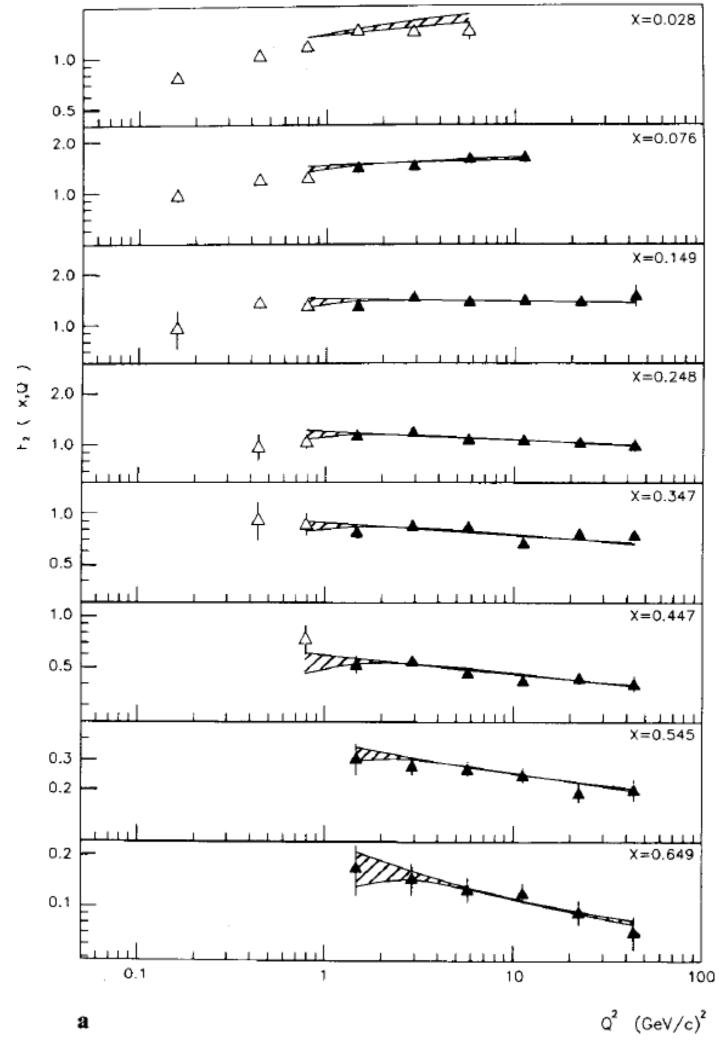
The have charged interactions so they also give u and d-type quark flavour separation

But they have a weak-interaction – at least at the energies we were probing---so statistics were not impressive—
We thought we were doing well having ~5000 events

Before we had THIS….. …..we had this!



2015



Z.Phys.C36(**1987**),1
The WA59 experiment,
(anti-)neutrinos on neon

Well that was what I was interested in… perturbative QCD

But Phil was bolder

He looked at these interactions at low Q^2

Where the scattering wasn't exactly Deep
Where angels fear to tread

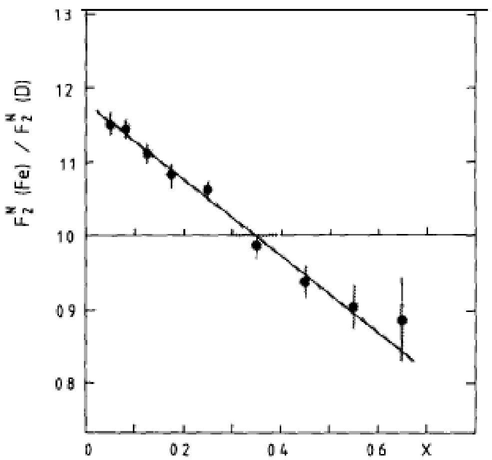
Indeed there is no justification for the parton picture at all
We are way into the non-perturbative regime of QCD

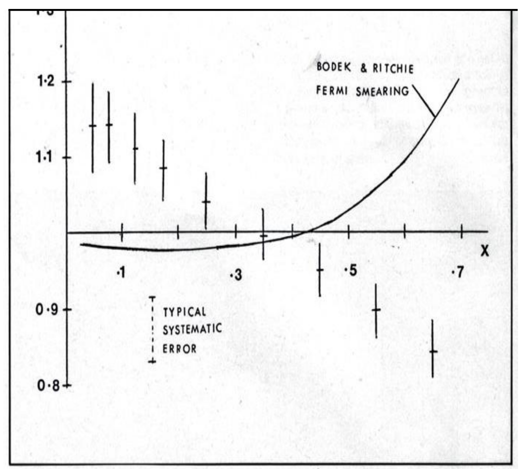
One of his topics was shadowing– the difference between scattering off a nuclear and a nucleon target, with expectations that many nucleons may 'shadow' each other from the probe.

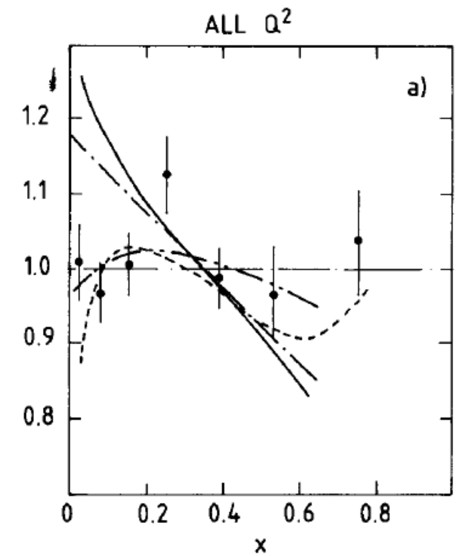
But when Phil hit the field this was not looking very clear in either neutrino or charged lepton probes

We had just had the surprise of the 'EMC' effect which suggested anti-shadowing if anything!

The 'EMC' effect
Phys.Lett.B(1984)133 WA59 and WA25 antineutrinos on Ne/D_2







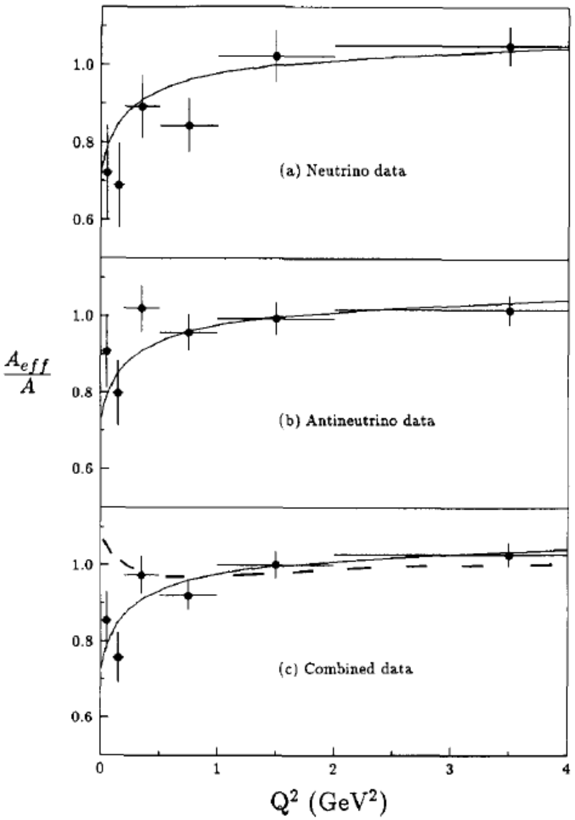
The original EMC effects in muons– the paper showed ONLY statistical uncertainties! JJ Aubert 1983

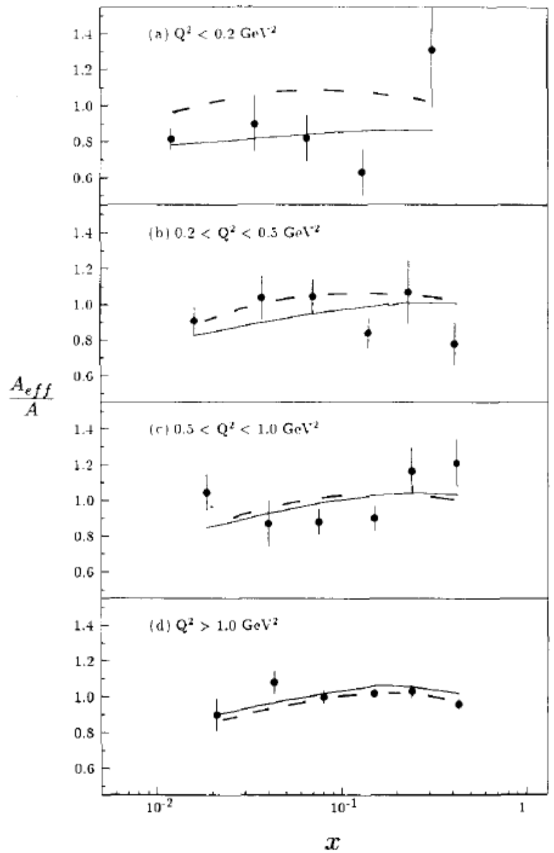
The original EMC effect once you consider systematic uncertainties. Clearly systematic uncertainties dominate and are immensely important

The EMC effect in antineutrinos –total errors dominated by statistical– but perhaps not so uncompetitive after all!

Phil's work added to the (anti-)neutrino data analysis, showing shadowing at low Q^2 and low x

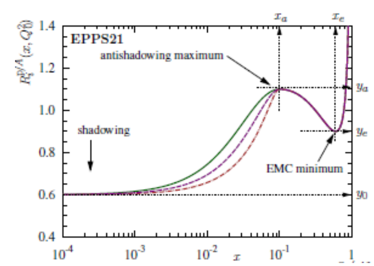
Phys Lett B 232(1989)417 WA59 and WA25 (anti)neutrinos on Ne/D_2





We have compared the kinematical distributions of both neutrino and antineutrino events obtained on neon and deuterium targets in similar experimental conditions. The comparison reveals a depletion of the charged current cross section per nucleon in neon at very low Q^2. The depletion cannot be interpreted as due to instrumental effects or to Pauli exclusion effects or to coherent interactions. Interpreted as due to geometric shadowing of the weak propagator, however, it agrees well with predictions derived from PCAC. In particular, the data confirm the PCAC prediction that the propagation of the weak current through nuclear matter at low Q^2 (below about 0.2 GeV^2) is dominated by the pion.

First appearance of the log x scale, the modern way to present it →



If you read the conclusions you will also notice that 'the geometric shadowing of the weak propagator agrees well with the predictions derived from PCAC.

And PCAC was Phil's other main topic in these years

So what is it? Partially Conserved Axial Vector Current

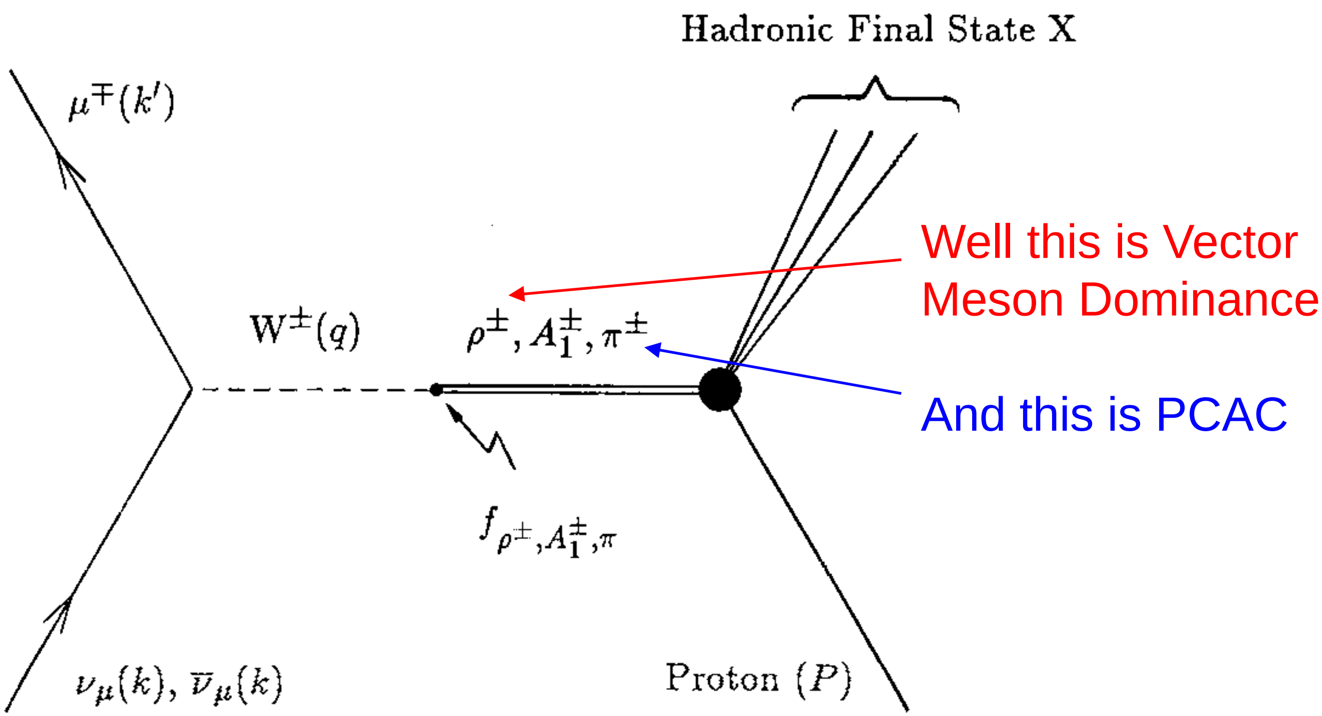


Fig. 1. Feynman-diagram for the scattering of neutrinos off protons according to the Extended Vector Meson Dominance Model (EVDM)

This may even be of use to you if you have ever tried to explain how a pion of spin 0^- can decay via a spin 1 W-boson, to a clever student

In those days we already thought of weak interactions in terms of V – A
And the Vector Current is conserved whereas the Axial-Vector Current is not.
That's why the behaviour of charge lepton scattering and neutrino scattering don't have to be the same as $Q^2 \to 0$

So what does PCAC mean?

Adler (1964) said that the cross section for neutrino nucleon scattering in the forward direction (ie as $Q^2 \to 0$) can be expressed in terms of the pion nucleon scattering cross section.

$$\left.\frac{\mathrm{d}^2\sigma(\nu_\mu \mathrm{p} \to \mu^- \mathrm{X})}{\mathrm{d}Q^2\,\mathrm{d}\nu}\right|_{\substack{Q^2 \lesssim M_\pi^2 \\ \Delta S = \Delta C = 0}} = \left(\frac{G_F f_\pi}{2\pi}\right)^2 \frac{2E_\mu}{\nu E_\nu}\,\sigma(\pi^+ \mathrm{p} \to \mathrm{X}; Q^2) \cdot \left[1 - \frac{\nu}{E_\mu}\frac{m_\mu^2}{Q^2 + M_\pi^2} + \frac{\nu^2}{4E_\nu E_\mu}\frac{m_\mu^2(Q^2 + m_\mu^2)}{(Q^2 + M_\pi^2)^2}\right].$$

This is valid for $Q^2 \sim m_\pi^2$
To test this experimentally we are going to need to predict for somewhat higher Q^2 and for this we use Vector Meson Dominance, but since we have both V and A we will have to have both ρ and A1 exchange

So the complete prediction is

$$
\left.\frac{d^2\sigma(\nu_\mu\, p \to \mu^- X)}{dQ^2\, d\nu}\right|_{\Delta S=\Delta C=0}
$$

$$
= \left(\frac{G_F}{2\pi}\right)^2 f_\pi^2 \frac{|\mathbf{q}|}{E_\nu^2} \frac{\varepsilon}{1-\varepsilon}\, \sigma(\pi^+ p \to X; Q^2) \cdot \left[\left(\frac{M_{A_1}^2}{Q^2+M_{A_1}^2}\right)^2 \right.
$$

$$
\left. - \frac{\nu}{E_\mu} \frac{M_{A_1}^2}{Q^2+M_{A_1}^2} \frac{m_\mu^2}{Q^2+M_\pi^2} + \frac{\nu^2}{4E_\nu E_\mu} \frac{m_\mu^2(Q^2+m_\mu^2)}{(Q^2+M_\pi^2)^2}\right]
$$

$$
+ \left(\frac{G_F}{2\pi}\right)^2 \frac{Q^2|\mathbf{q}|}{E_\nu^2} \frac{1}{1-\varepsilon} \cdot \left(\frac{f_{\rho^\pm}}{Q^2+M_\rho^2}\right)^2
$$

$$
\cdot \left[\sigma_T(\rho^+ p \to X; Q^2) + \varepsilon\, \sigma_L(\rho^+ p \to X; Q^2)\right]
$$

$$
+ \left(\frac{G_F}{2\pi}\right)^2 \frac{Q^2|\mathbf{q}|}{E_\nu^2} \frac{1}{1-\varepsilon} \cdot \left(\frac{f_{A_1^\pm}}{Q^2+M_{A_1}^2}\right)^2
$$

$$
\cdot \left[\sigma_T(A_1^+ p \to X; Q^2) + \varepsilon\, \sigma_L^{(1)}(A_1^+ p \to X; Q^2)\right]
$$

$$
+ C \cdot \left(\frac{G_F}{\pi}\right)^2 Q^2 \frac{E_\nu + E_\mu}{2E_\nu^2} \frac{f_{\rho^\pm} f_{A_1^\pm}}{(Q^2+M_\rho^2)(Q^2+M_{A_1}^2)}
$$

$$
\cdot \sqrt{\sigma_T(\rho^+ p \to X; Q^2) \cdot \sigma_T(A_1^+ p \to X; Q^2)}.
$$

And there are ways to estimate these π-p, ρ-p and A_1-p cross sections e.g.

$$
\sigma_T(\rho^0 p \to X; Q^2) = \frac{(Q^2+M_\rho^2)^2}{4\pi\alpha f_{\rho^0}^2}\, s^{IV}\, \sigma_T(\gamma p \to X; Q^2),
$$

which I will NOT go into further

Dusan tells me that on one of Phil’s visits to CERN he dared to enter the office of John Bell- to discuss PCAC

They landed up discussing the Philosophy of Physics, which was one of Phil’s interests

But all the time he did not realise he was talking to the author of Bell’s theorem !

Can we understand PCAC in modern terms?

YES in terms of broken chiral symmetry…

$$j\gamma_\mu \partial^\mu \psi_R - m\psi_L = 0$$

$$j\gamma_\mu \partial^\mu \psi_L - m\psi_R = 0 .$$

If ONLY quark masses were zero we would have chiral symmetry but the QCD the vacuum state has non vanishing quark-antiquark condensate $\langle 0 \mid q\bar{q} \mid 0 \rangle$, so cannot be chiral symmetric .

If we have spontaneous chiral symmetry breaking we will get a triplet of massless q-qbar states, pseudoscalar Goldstone bosons, suggestively called π^i, and a massive isosinglet called σ. Their interactions with a nucleon doublet can be described by a chiral symmetric Lagrangian with a potential of Mexican hat form and

$$\langle 0 \mid \pi^i \mid 0 \rangle = 0 \text{ and } \langle 0 \mid \sigma \mid 0 \rangle = \vartheta.$$

The Lagrangian is invariant under axial SU(2) transformation and this would imply a conserved axial vector current BUT if those pseudoscalar bosons are NOT QUITE massless THEN

$$\langle 0 \mid \partial^\mu J^i_{A\mu} \mid \pi^n(p) \rangle = \vartheta m^2_\pi \delta^{ni} .$$

the axial current is not conserved even under spontaneous chiral symmetry breaking

And the divergence of the hadronic current is proportional to the pion field operator

$$\partial^\mu J^i_{A\mu} = \vartheta m^2_\pi \pi^i .$$

So to confront this with (anti-)neutrino proton data
Z.Phys.C37(1987)25

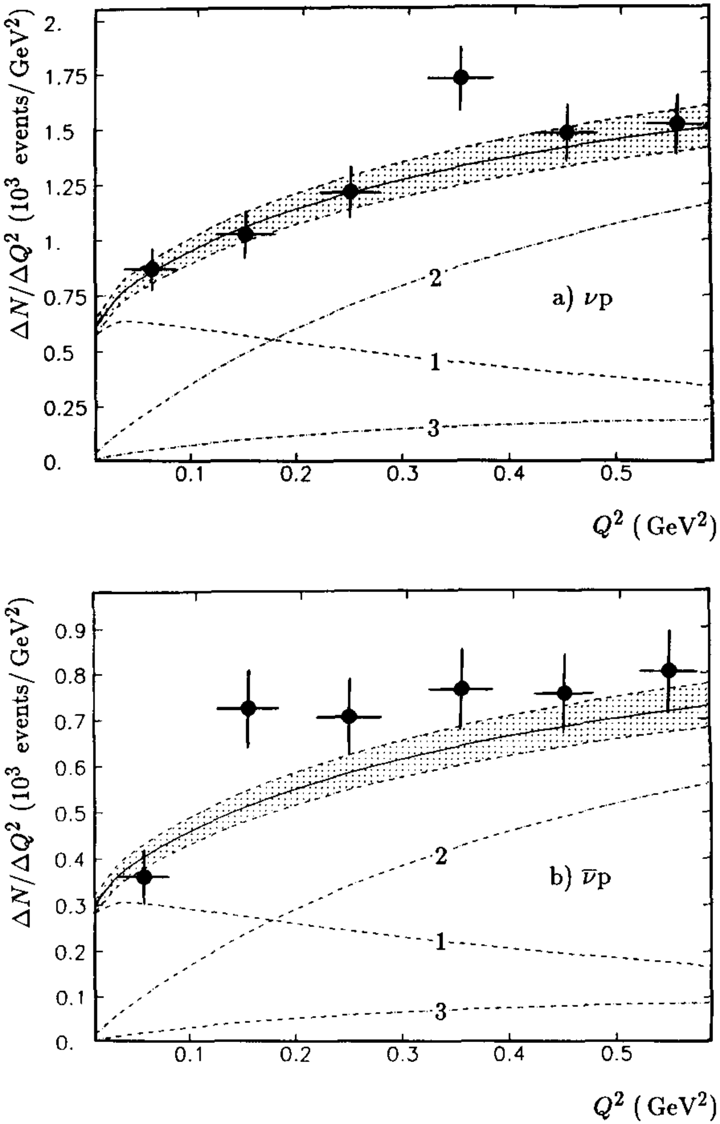


Fig. 6a, b. Q^2 distribution. The data points show the experimental results (Table 3a, b). The solid line is the theoretical prediction (without (3)), the shaded area corresponds to a one standard deviation error. The dashed lines show contributions (1) of the PCAC-term, (2) of the EVDM-term proportional to $\sigma_T + \varepsilon\sigma_L$ and (3) the maximum modulus of the $V \times A$ interference term. **a** νp and **b** $\bar{\nu}$p scattering

In 1964 Adler proposed at test of the PCAC hypothesis in high energy neutrino interactions at $Q^2=0$ [3]. Using an Extended Vector Meson Dominance Model (EVDM) [13] and various additional assumptions concerning the cross sections of virtual π, ρ and A_1-mesons, Adler's prediction is extrapolated to higher, experimentally accessible values of Q^2.

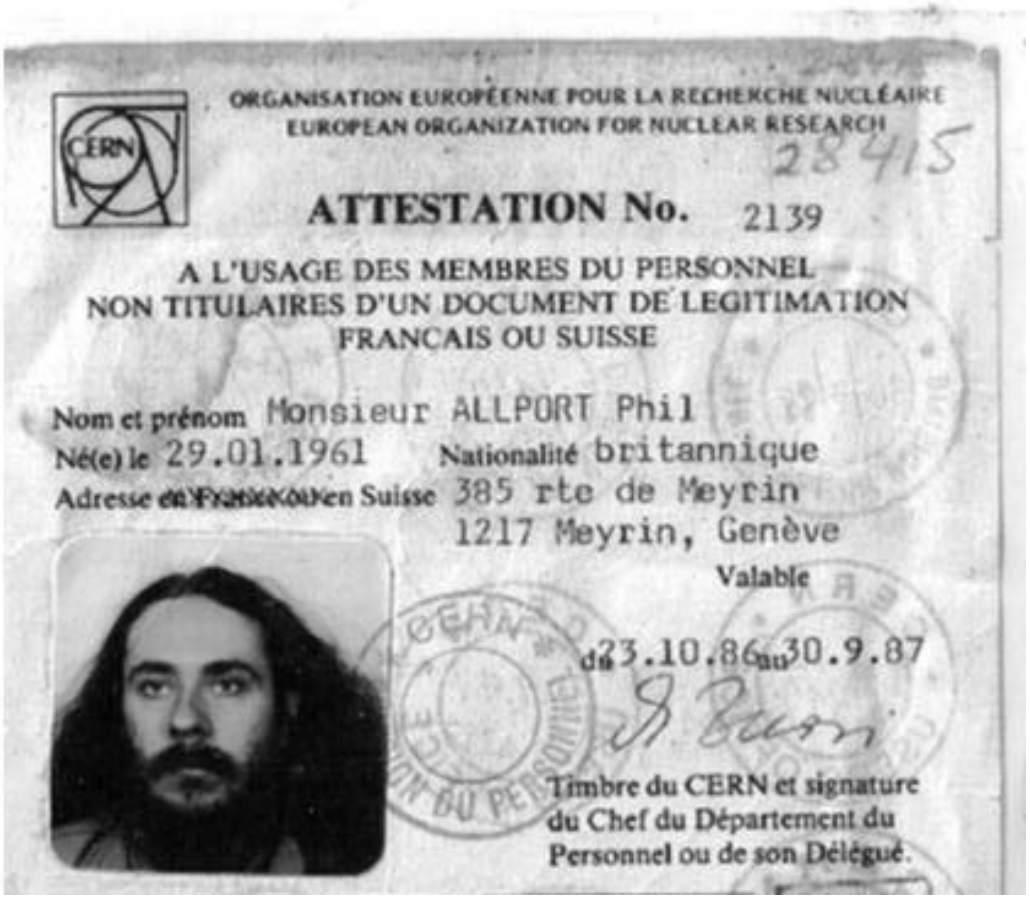
The data of this experiment is used to test the theoretical prediction in the regime of high energy transfer $\nu > 2$ GeV. Good agreement is found, both in absolute magnitude and in the shapes of the distributions. This applies in particular for $Q^2 \lesssim 0.2$ GeV^2, where the main contribution to the theoretically predicted cross section is due to the PCAC hypothesis. Hence this analysis, which constitutes a significant test of Adler's theorem, confirms the PCAC hypothesis for $\nu > 2$ GeV.

First test of PCAC at higher energies.
Well done Phil…. for the painstaking work
And the good company in those far-off years
both in CERN and at Rutherford

BUT…before I close…

For those of you too young to remember him, you have to appreciate what Phil looked like then!

And he used to wear a dirty ‘flasher’ mac, once seen never forgotten.
Even Dusan remembers the coat and says Phil wore it summer and winter and that it was part of Phil’s charming personality


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
28415

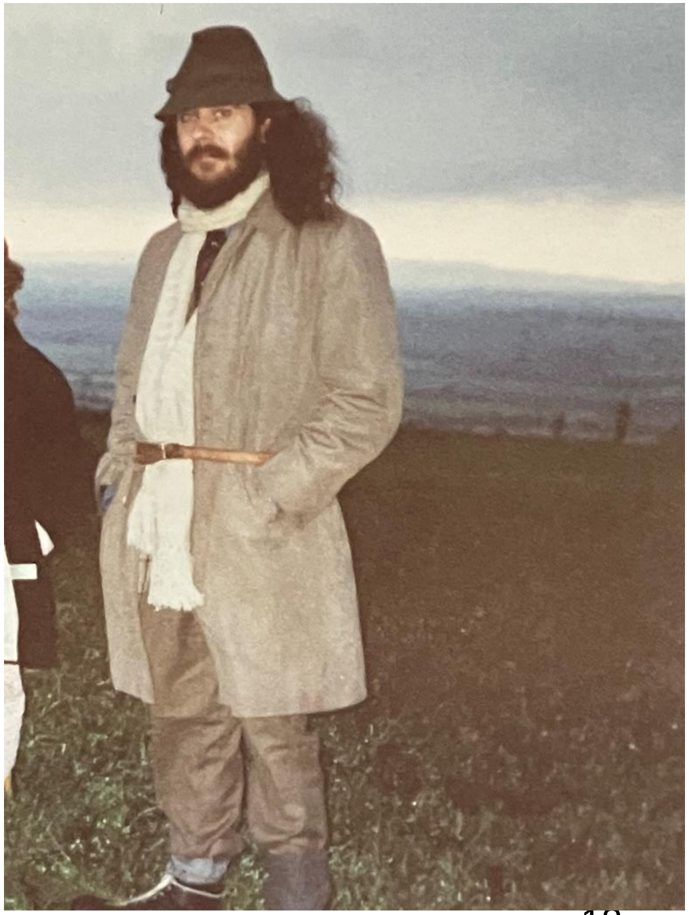
ATTESTATION No. 2139

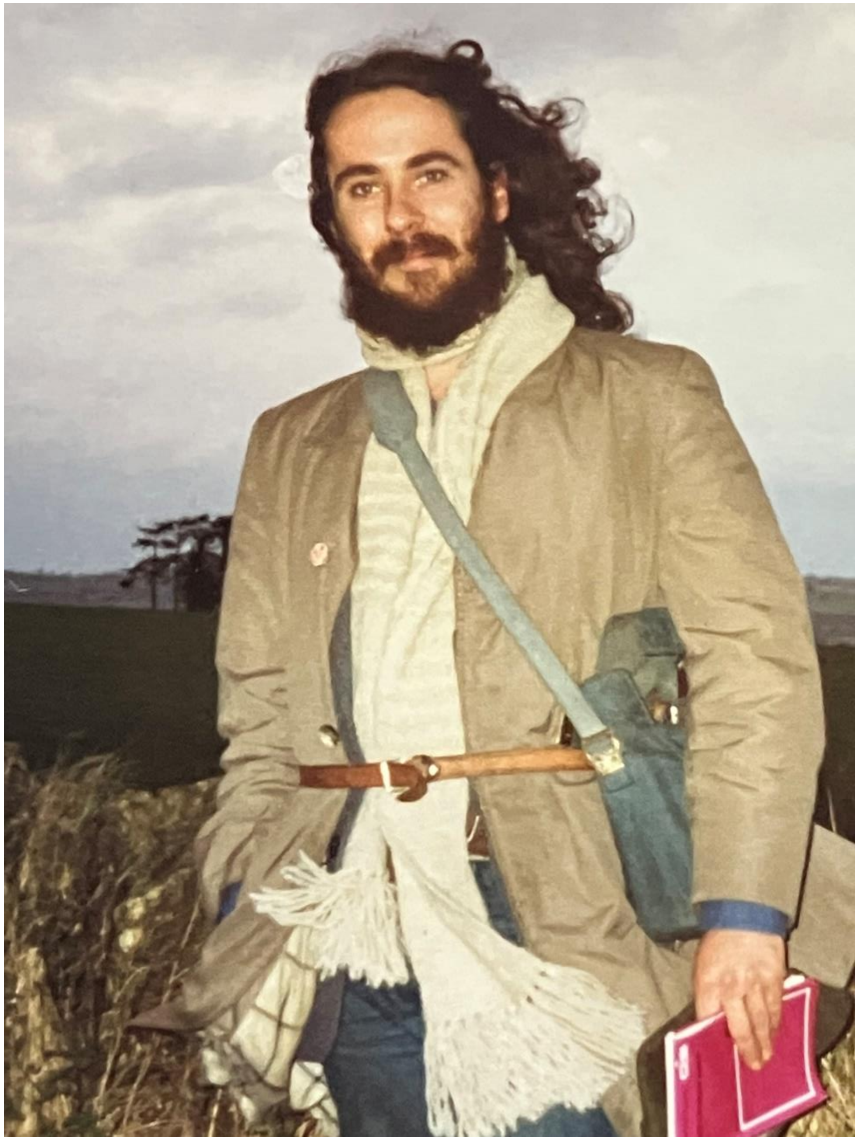
A L’USAGE DES MEMBRES DU PERSONNEL
NON TITULAIRES D’UN DOCUMENT DE LEGITIMATION
FRANCAIS OU SUISSE

Nom et prénom Monsieur ALLPORT Phil
Né(e) le 29.01.1961 Nationalité britannique
Adresse ~~en France ou~~ en Suisse 385 rte de Meyrin
1217 Meyrin, Genève

Valable
du 23.10.86 au 30.9.87

Timbre du CERN et signature
du Chef du Département du
Personnel ou de son Délégué.





But these are my favourites
However did he become a pillar of the community?
I will leave that to other speakers!