Department of Physics

‘Physics then and now – the life and work of Don Perkins’ - 14 March 2024

Don Perkins and Charged Currents

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There was a race to test the two neutrino hypothesis. The first beams circulated in CERN's PS in November 1969 and in Brookhaven's AGS in July 1960, putting CERN in pole position. But an experiment that was planned using an internal target, was cancelled when it was realised that the neutrino flux had been overestimated by at least an order of magnitude.

In 2013 Don (who was not involved) wrote that Mel Schwartz later told him that at Brookhaven when they heard the CERN project had been dropped 'they could hardly believe their luck'. The experiment showed that there are two neutrinos, and Schwartz, Steinberger and Lederman later won the Nobel Prize.

CERN's first neutrino results were announced in conferences at Brookhaven and in Sienna:

September 9-11, 1963

INTERNATIONAL CONFERENCE
ON FUNDAMENTAL ASPECTS OF WEAK INTERACTIONS

Speaker

PROCEEDINGS OF
THE SIENNA INTERNATIONAL CONFERENCE
ON ELEMENTARY PARTICLES

30 Settembre - 5 Ottobre 1963 - 30 September - 5 October 1963

1963/64 Results from Neutrino Experiments in the CERN Freon Bubble Chamber

As described in a 2013 article by Don published in EPJH, the Sienna meeting was a chaotic affair

The main focus was on seeking the W (then thought to have a mass of order 1 GeV)

When asked by Luis Alvarez whether CERN had found the W, Gilberto Bernardini (Research Director at CERN) replied that CERN had found di-lepton (electron and muon) events which might – or might not – be due to production and decay of the W boson.

These events were probably early examples of charmed particle production. There were other early hints of things found later:

- The results showed 'a marked increase of the inelastic cross section with energy', now known to be suggestive of point-like behaviour. Don spoke to Bell and Veltman about them. Bell told him that the multi-pion events would be difficult to understand theoretically and suggested he focus on other things
- The results of a short anti-neutrino run were never published (except in a thesis by Enoch Young) because they were confusing – there were fewer charged current events than expected and more events without muons than expected. We now know that this was because the cross-section for antineutrinos is much smaller than for neutrinos (which was not expected) and there are neutral currents

The statistics and size (1.2 m) of the bubble chamber were too small to prove that neutral currents were responsible, but in 1973 Don showed that *if* interpreted as neutral currents the neutrino results gave:

sigma (neutral)/sigma(charged) = 0.17 +/- 0.06 – in agreement with the Gargamelle data

Impact of the SLAC Deep Inelastic Results

- In September 1968 Jerry Friedman presented the first results of the classic SLAC-MIT deep inelastic electron scattering experiments at the International Conference on High Energy Physics in Vienna. The scattering cross sections were much larger than generally expected, and - to first approximation - the dimensionless structure functions exhibited Bjorken scaling. The group knew this suggested scattering from point-like objects, but voted that - against his wishes - Jerry should not say so.

  Panofsky, the Director of SLAC, was not aware of the vote. Speaking as rapporteur he said that *theoretical speculations are focused on the possibility that these data might give evidence on the behavior of point-like, charged structures within the nucleon ...*

- Perhaps the only person who was not surprised was Jim Bjorken (bj) - who had inferred in 1967 from a sum rule of his own and the Adler sum rule that inelastic scattering must be 'comparable to scattering off point-like charges', the total cross section for electron-positron annihilation to hadrons should vary as $1/E^2$, and the total cross section for neutrino scattering should be proportional to E. He had developed the physical picture that underlies the parton model (the name was provided later by Feynman, who developed it independently as a model for proton scattering, and provided the interpretation of the scaling variable x as the fraction of a proton's moment carried by a parton).

  In 1968/9 bj 'derived' scaling. His paper ends *a more physical interpretation of what is going on is, without question, needed*! Having had partons without scaling, he had scaling without partons!

Don wrote later 'Immediately I saw the SLAC data, I realised what an idiot I had been, dashed back to CERN and re-plotted the freon and propane data, and saw that simple linear dependence of the *total* cross-section"

Don's neutrino talk at the Topical Conference on Weak Interactions at CERN in January 1969

In the last 8 of Don's 42 page paper on 'Highly inelastic reactions', he showed that the 1963/64 freon and 1967 propane data exhibit qualitatively much the same behaviour as seen at SLAC, although the number of events was small, and the precision much poorer, the incoming much energy lower and not fixed,

He then showed the Adler sum rule $\int_0^1 (F_2^{\nu n}(x,q^2) - F_2^{\nu p}(x,q^2))\frac{dx}{2} = 1$ (this sum rule is exact) in the form:

$\Rightarrow \lim E\to\infty: \frac{d\sigma^{\nu n}}{dq^2} - \frac{d\sigma^{\nu p}}{dq^2} = \frac{G_F^2}{\pi}$ and recalled that *(as pointed out by Bjorken in 1967)* it is highly suggestive of point-line behaviour

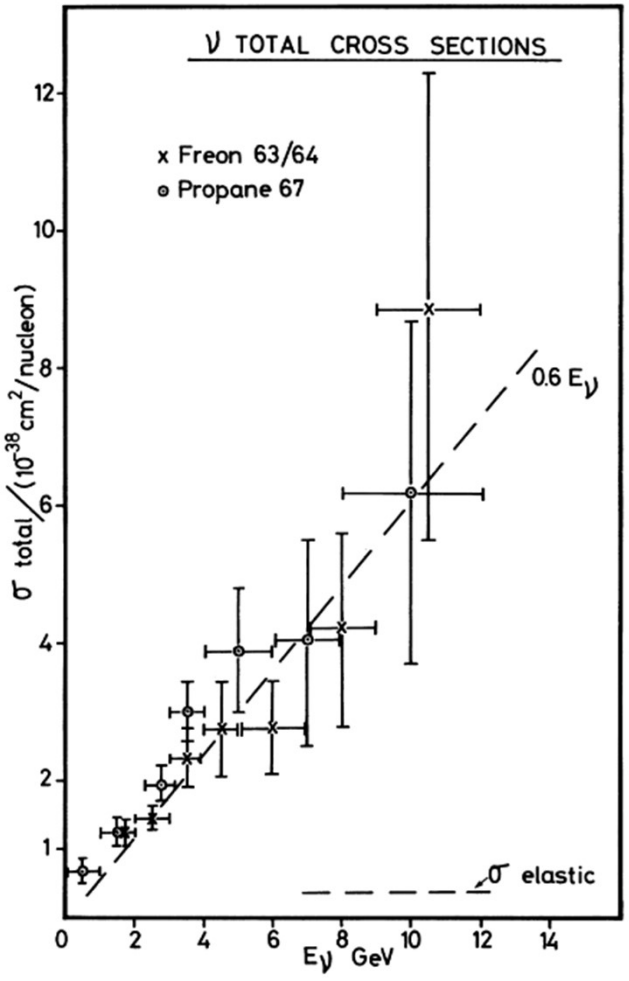
He continued "Another, quite different way to arrive at point-like cross-sections is to postulate point-like constituents in the nucleon. These constituents can be imagined as "bare" quarks if anyone can imagine such objects…. At much higher q^2 the scattering is mostly incoherent …[and]… the total cross-section will be given by the elementary lepton-quark elastic cross-section, i.e. $d\sigma/dq^2$ = constant. The constant factor in the Adler sum rule can be interpreted … [as] … the constant difference in the number of the constituents with isospin up and down *(as pointed out by bj in 1967)* ... The model is almost unbelievably crude and, as Gottfried has remarked, no well-educated person should accept it. Yet it at least has the virtue of making rather definite predication. For example ...

$E \to \infty$, $q^2 \to \infty$ $\sigma^{total}(vn) = 2\sigma^{total}(vp)$ which should be easy to verify in the near future, provided infinity is not too far away"

Don then referred to a third point-of view…. that the high energy, highly inelastic region is dominated by diffractive process

January 1969 Topical Conference on Weak Interactions at CERN 2

Finally Don showed the total cross-sections from the 1963/64 freon and 1967 propane data:



"For a linear energy dependence…

$\sigma_{total} \approx 0.6\ E_\nu\ (GeV) 10^{-38}\ cm^2/nucleon.$

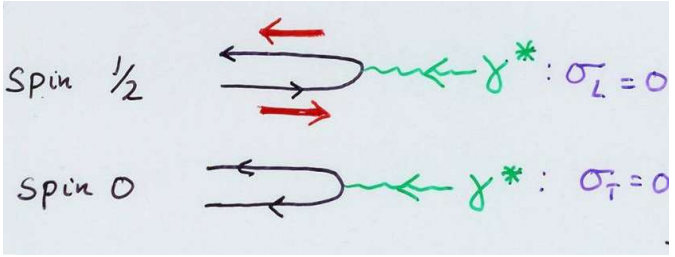
One might remark that the constituent model would also predict a linear dependence with a coefficient ~ 1.4"

Towards the quark-parton model 1

In late 1968 (published January 1969) Curt Callan and David Gross, using formal manipulations of operators, related $\int F_2\, dx/x$ and $\int F_1\, dx/x^2$ to [dJ/dt, J], and found:

$\frac{\sigma_L}{\sigma_T} = 0$ quark model, ∞ algebra of fields

In the parton model:



1st data Sept 1970

$\sigma_L/\sigma_T = 0.2 +/- 0.2$

Spring 1969: David Gross, who was visiting CERN, gave a talk about different approaches to the SLAC data – current algebra at infinite momentum, vector dominance, diffraction models, partons, ...

I was working with John Bell on nuclear shadowing in neutrino reactions. I applied the parton model to neutrino scattering to see if I had understood David's talk. When I asked him if I had got it right, he replied 'great idea, it has not been done, but what's this third structure function?'. Then on the blackboard we used current algebra at infinite momentum to find:

$$\int F_3^{\nu N} \frac{dx}{2x} = 3\left(1 - \frac{\alpha_s}{\pi} + \ldots\right)$$

that evening I realised that this measures the baryon number of the partons

Of course we did not know of the QCD correction (now known to order α_s^3), but we knew that Adler & Tung and Jackiw & Preparata had shown that scaling is violated by powers of $\ln(q^2)$ in perturbation theory, and wrote "No reason to believe field theory relevant – contradicted by experiment"

Towards the quark-parton model 2

1970: Many ideas still on the market – diffractive model, Harari model, generalised vector meson dominance, Veneziano-like model…as well as quarks/partons

I derived results true in all quark-parton models (rederived formally with Abelian scalar and vector gluons):

$$F_3^{\nu p} - F_3^{\nu n} = 12\,(F_1^{ep} - F_1^{en})$$

$$F_2^{ep} + F_2^{en} \geq \frac{5}{18}(F_2^{\nu p} + F_2^{\nu n})$$ equality if no strange quarks: good measurement of quark charges?

but equivalent to $\frac{\sigma_{\gamma^*[I=o]}}{\sigma_{\gamma^*[I=1]}} = \frac{1}{9}$ known to work for real photons: explained by vector dominance - so nothing to do with quarks?

$\int F_2^{ep} dx = \sum_i Q_i^2 < x_i >$ = 1/3 with 3 quarks, ≥ 2/9 any 3q + sea model, but data = 0.18 *"easily reduced by adding a background of neutral constituents (which could be responsible for binding quarks)"*

- attacked as not in the spirit of the quark model!

1971: Momentum sum rule $\varepsilon(\text{momentum in gluons}) = 1 + \int\left(\frac{3}{4}[F_2^{\nu p} + F_2^{\nu n}] - \frac{9}{2}[F_2^{ep} + F_2^{en}]\right)$

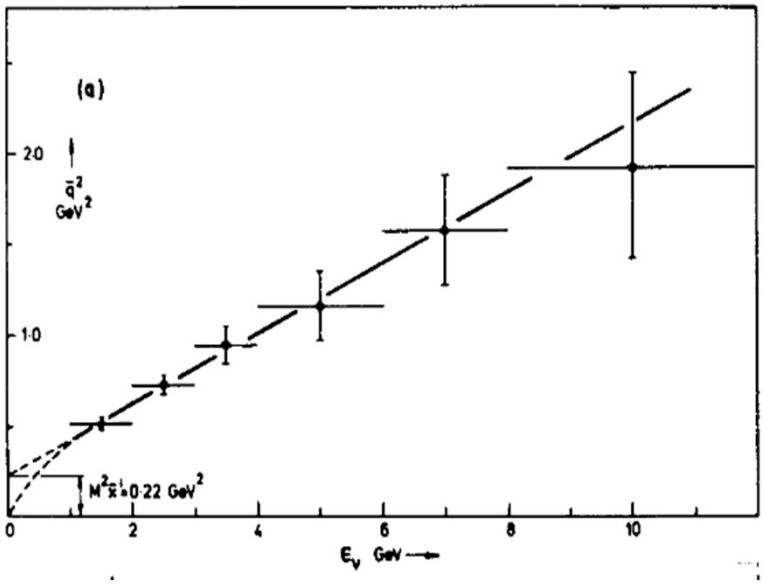
Use of Myatt & Perkins reanalysis of the 1963-67 freon and propane data → ε ≥ 0.52 +/- 0.38

Murray G-M told me we should ignore this and use algebra abstracted from free quark theories

Myatt and Perkins 1971

A short paper on measurement of the structure functions (Budagov et al October 1969), based on the 1963-67 freon and propane data, was followed in March 1971 by a more detailed analysis by Gerald and Don

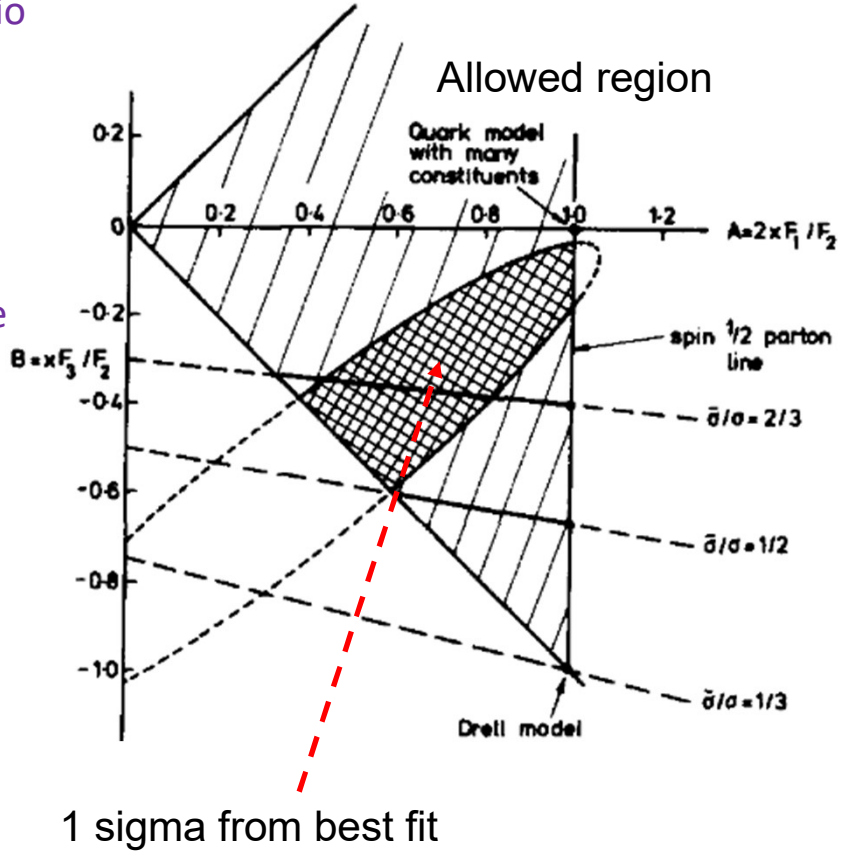
- which showed evidence for scaling:



1972 Physics Report on Neutrino Interactions at Accelerator Energies notes: *E < 2 Gev, so q^2 < 1 and 'assuming exact scaling could be dangerous'*

The neutron to propane ratio of 1.19 in freon (CF_3Br) and 0.69 in propane (C_3H_8) and measurement of the net charge of the secondaries were used were used infer results for n + p (to facilitate comparisons with electro-production), and that

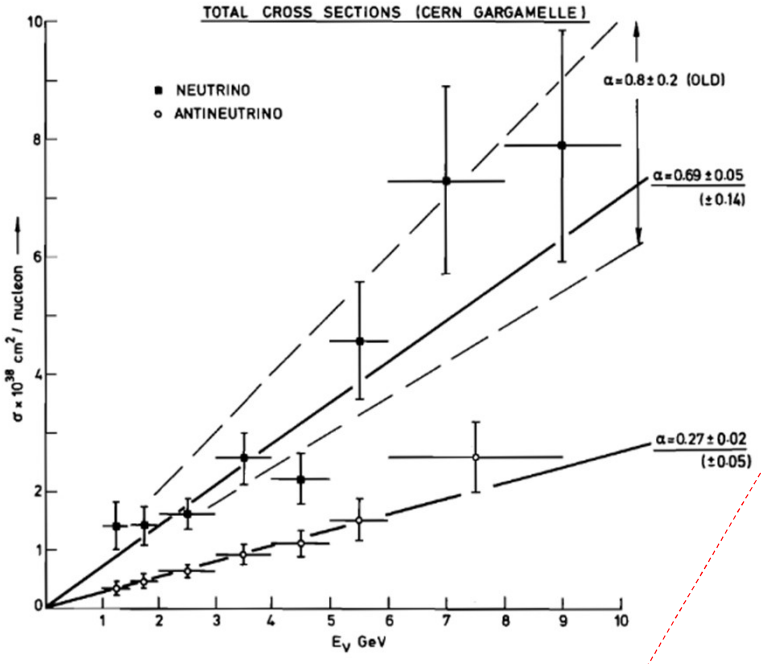
$\sigma^{\nu n}/\sigma^{\nu p}$ = 1.5 +/- 0.3



1 sigma from best fit

At ICHEP 1972 Don was rapporteur on neutrinos

In his introduction he said that preliminary data on cross-sections from about 1000 antineutrino and 1000 neutrino interactions of E > 1 GeV in the CERN Gargamelle chamber (presented in a parallel session: later published – Eichten et al 1973) '**provide an astonishing verification of the Gell-Mann/Zweig quark model of hadrons'**. He showed and discussed inelastic reactions at the end of his talk:



Experiment	Target	$\alpha = \sigma/E$ (units 10^{-38} cm^2/nucleon GeV)	Energy Range	# Events (E > 1 GeV)
CERN 1.2m HLBC	C_3H_8	$\alpha_\nu = 0.80 \pm 0.20$	1-10 GeV	900
Gargamelle	CF_3Br	$\alpha_\nu = 0.69 \pm 0.14$	1-10 GeV	1000
Gargamelle	CF_3Br	$\alpha_{\bar\nu} = 0.27 \pm 0.05$	1- 9 GeV	1000
$R = \sigma^{\bar\nu}/\sigma^{\nu} = 0.38 \pm 0.02$			2- 9 GeV	---

He then compared the observed value of $\int F_2^{\nu N} dx$ with the value implied by electroproduction with some simple assumptions:

Neutrino Data		From electron data, using CVC, |V| = |A| & 10% isoscalar
0.47 ± 0.07	0.49 ± 0.07	0.52 ± 0.08
assuming $\theta_c = 0$	corrected for $\Delta S = 1$,	
n/p = 1	n/p = 1.19 in freon	

and concluded that the agreement 'lends strong support to the view that the coefficients in Table 6 in the energy rage 1< E< 10 represent the values in the scaling region at high energy'

ICHEP 1972 (2)

Don then discussed quark model predictions, assuming spin ½ (which he had shown was favoured by the data):

Model	Nucleon Built From :-	$\frac{\int F_2^{\nu N} dx}{\int F_2^{\gamma N} dx}$	$\sigma^{\bar{\nu}}/\sigma^{\nu}$	$F_2^{\gamma n}(x)/F_2^{\gamma p}(x)$ $x=1 \to 0$
Gell-Mann/Zweig	3 fractional charge quarks	3.6 $(=\frac{18}{5})$	$\frac{1}{3}$	$\frac{1}{4} \to 1$
	3 valence quarks + many $Q\bar{Q}$ pairs	~3.0	~1.0	~1
Han-Nambu	3 integral charge triplets	≤ 3.3	$\frac{1}{3}$	$\frac{1}{2} \to 1$
Integral charge (eg Sakata, GIM)	Integral charge triplet or quartet	≤ 2.0	$\frac{1}{3}$	$0 \to \infty$
Experiment		3.4 ± 0.7	0.38	~0.25 → 1

and turned to momentum sum rules;

$$\left(\int F_2^{\nu N} dx\right)_{\Delta S = 0} = \int (U + D + \bar{U} + \bar{D})\, x dx$$
$$= 0.46 \pm 0.21$$

$$\int F_2^{\gamma N} dx = \frac{1}{9} \int (5[U + D + \bar{U} + \bar{D}] + 2[S + \bar{S}])\, x dx$$

$$1 - \varepsilon = \int (U + D + \bar{U} + \bar{D} + S + \bar{S})\, x dx$$

where ε is the fractional 4-momentum carried by gluons. The data gave

ε = 0.46 +/- 0.21

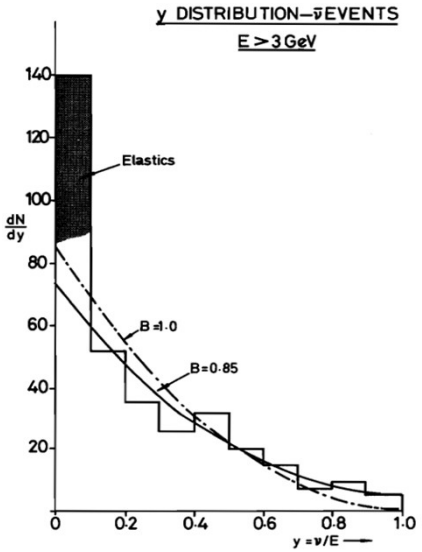
but assuming SU(3) flavour symmetry for the quark/antiquark sea Don gave a value with smaller errors

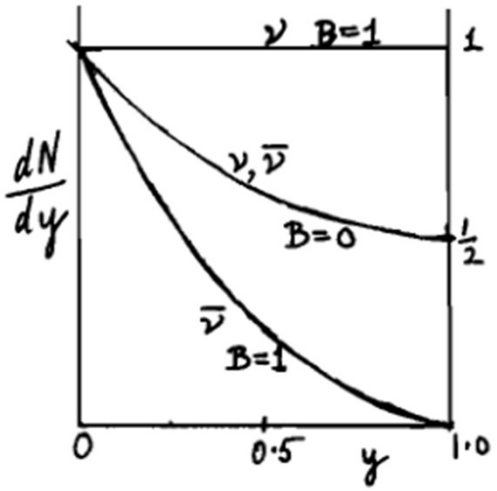
ε = 0.49 +/- 0.08

ICHEP 1972 (3)

Don ended by discussing the antineutrino data in more detail and compared the y distribution with expectations for different values of

$$B = \int xF_3 dx / \int F_2 dx$$





B= 1 - only quarks
= 0 - equal numbers of quarks and antiquarks

Data gave
B = 0.90 +/- 0.04

Finally, since the new data described above comes from the experiments in the Gargamelle bubble chamber, funded by the French Government, it seems not inappropriate to quote a few lines from Voltaire. This clearly warns us not to accept too literally simple pictures, like the quark model, based on heuristic arguments, to describe the internal structure of the nucleon:-

"Les Philosophes qui font des systèmes sur la secrète construction de l'univers, sont comme nos voyageurs qui vont à Constantinople, et qui parlent du Sérail: Ils n'en ont vu que les dehors, et ils prétendent savoir ce que fait le Sultan avec ses Favorites".

The Philosophers who create systems on the secret construction of the universe, are like our travellers who go to Constantinople, and who speak of the Seraglio: they have only seen the exterior, and they claim to know what the Sultan does with his Favourites.

Fifth Hawaii Topical Conference in Particle Physics 8-21 August 1973

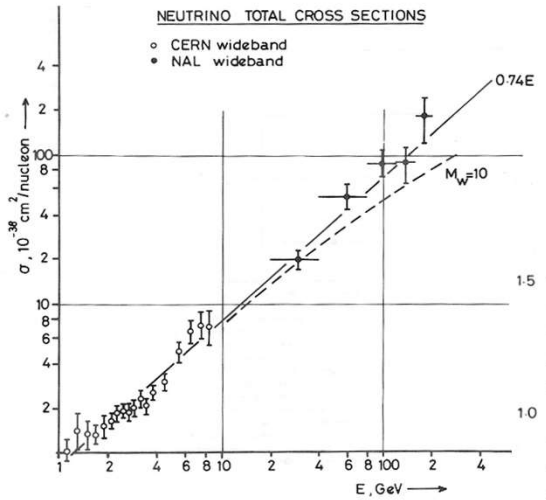
D Morrison, R Feynman, C Llewellyn Smith, D Perkins

2 Lectures every morning

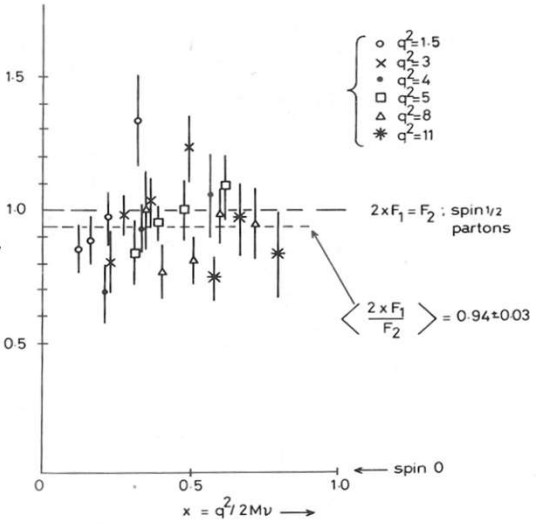
Talks by participants in afternoon

Fifth Hawaii Topical Conference in Particle Physics August 1973

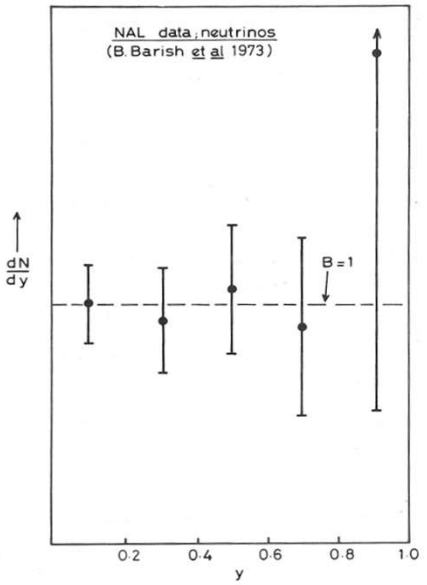
Don began by discussing neutral currents, and ended with an analysis of charged current deep inelastic data from Gargamelle (new results later refined and published – Deden et al 1975), and some early results from the Caltech-Fermilab (Barish et al) and HPW (Cline-Mann-Rubbia et al) experiments at Fermilab:

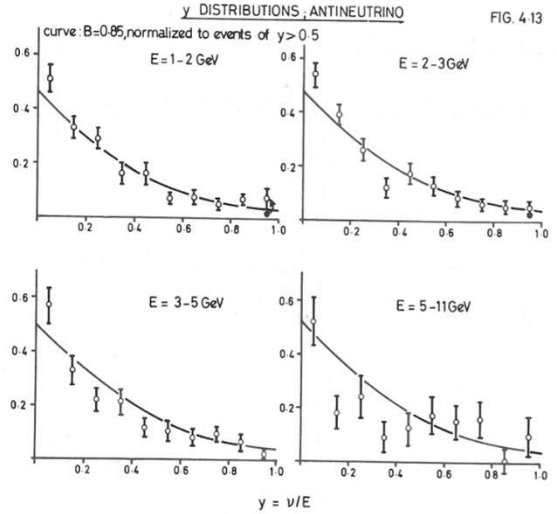


By then the SLAC data were showing spin≈ ½:



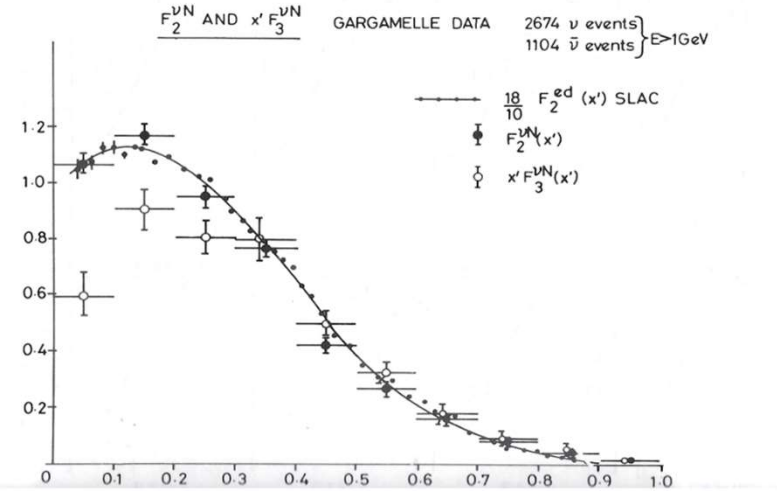
The Gargamelle and Fermilab neutrino data were consistent with a flat y distribution, while the Gargamelle antineutrino data showed≈ $(1-y)^2$:



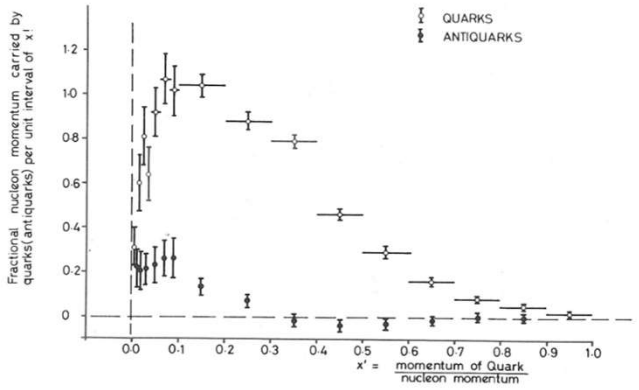


Hawaii Topical Conference (2) data consistent with

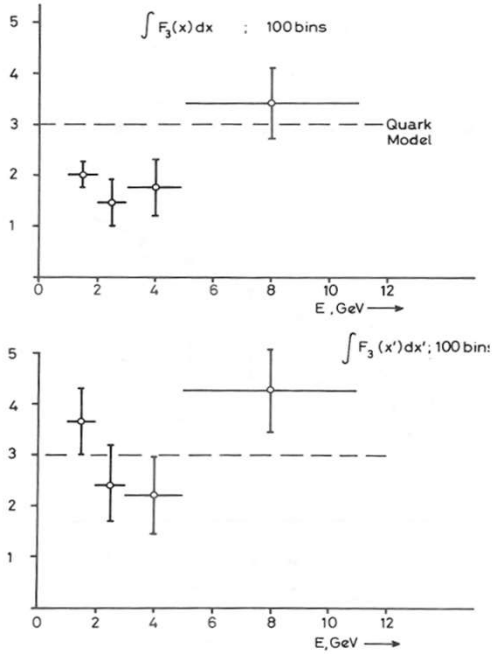
1. Non-integral quark charges :



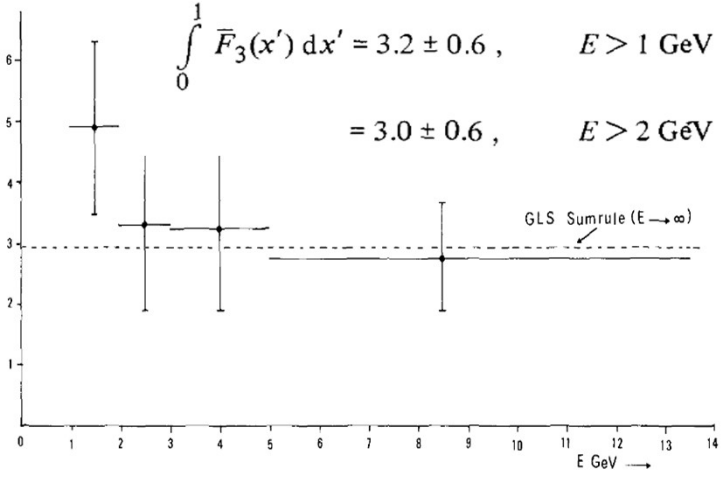
2. some antiquarks at small x: 2



3. constituents with 1/3 baryon number:



Deden et al 1975:



In the following years, increasingly accurate data accumulated from wide and narrow band neutrino experiments at

CERN: Gargamelle (12 m^3 - freon) @ PS beam(1970-76), then@ SPS (1976-79), BEBC (35 m^3 hydrogen, deuterium, neon) 1974- 84, CDHS – a counter experiment
and
Fermilab: HPWF, Caltech-Fermilab (counter experiments), 12' bubble chamber

Apart from some hiccups (HPWF 'alternating currents'; 'high y anomaly' – 1974, still claimed 1976; dimuons)

the data **confirmed the underlying picture, and saw scaling violations and QCD corrections to sum rules**

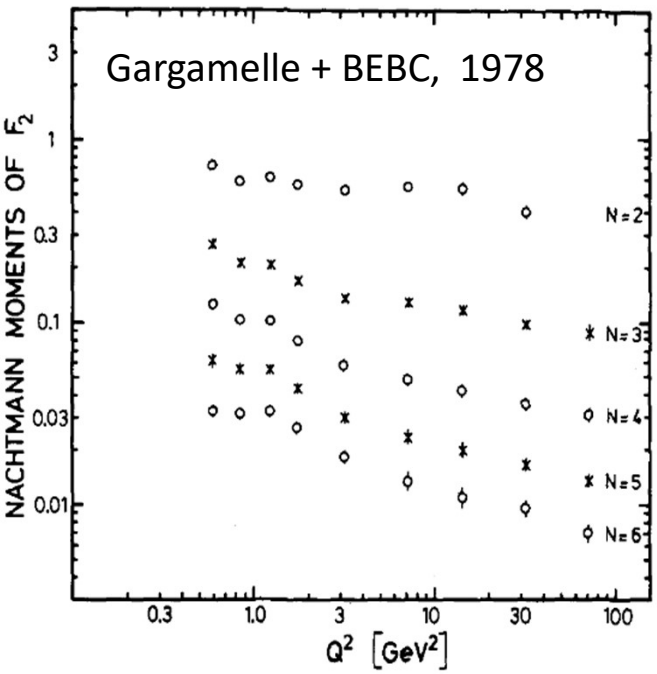
Don moved to BEBC, where he proposed the beam dump experiment that looked for prompt neutrinos

In 1977 he was (characteristically) the first to analyse scaling violations in neutrino scattering:

With Schreiner and Scott, he looked at neutrino data from the Argonne 12' chamber, the Fermilab 15' chamber, HPWF and Fermilab. Their main conclusion was that

"the x distributions in electron, muon and neutrino scattering can be described in terms of a simple and universal parametrization of deviations from exact scaling – whatever their origin"

This was followed by papers that compared the moments of structure functions to QCD predictions

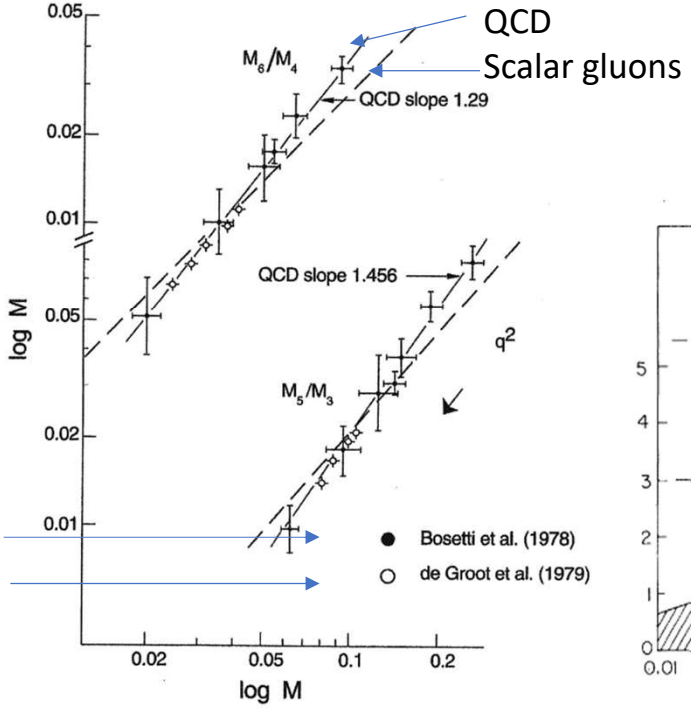


Moments of structure functions compared to QCD predictions:

CDHS data and scalar gluon line added later:

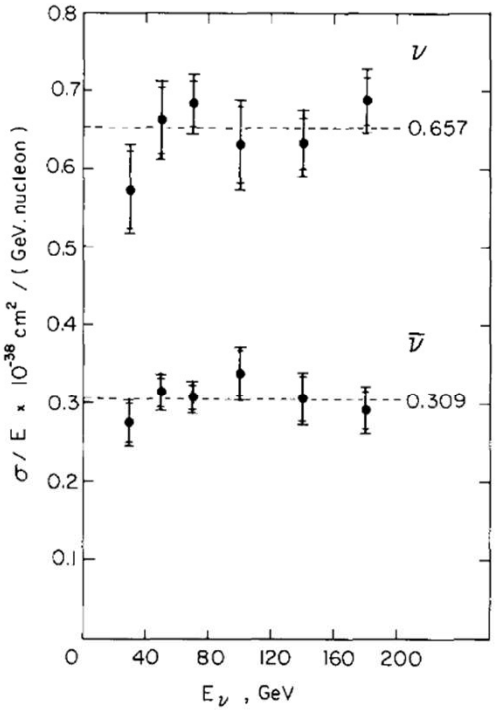
Don was a co-author of three 1982 papers (Bosetti et al, Bolognese et al) that gave final Gargamelle and BEBC results:

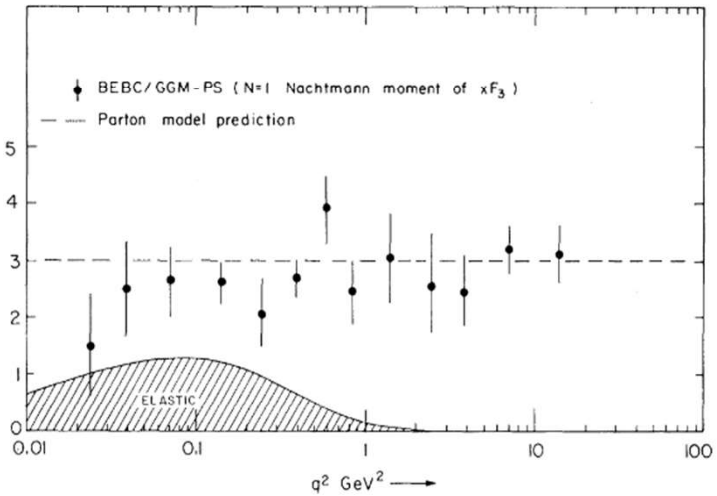
$$\sigma_S/\sigma_T = 0.08 \pm 0.12\ (0.04)$$



Gargamelle/BEBC

CDHS





While playing a leading role in particle physics, Don was also a good citizen, having served as

- Member of the Emulsion Panel, which first met in November 1945, with Rotblat as Chair, representatives of Ilford Ltd, and Livesey (Cambridge), May (King's College, London), Perkins, (Imperial College)and Powell, (Bristol)
- Head of Department 1986-91, Chair of the Committee of Heads of Science Departments 1987-1990
- Member of the Nuclear Physics Board1972 -75, Chair 1985-89
- Chair Particle Physics Selection Panel 1975-78.
- Member CERN Scientific Policy Committee 1980-8 and an excellent Chair 1984-86 (as I observed after I joined in 1986), to which he continued to make acute comments in the annual meetings to which former members were invited
- Member Scientific Council, DESY 1981-84
- Member HERA Management Committee 1985 – 90
- Member Science and Engineering Research Council
- UK Delegate, CERN Council 1986 – 90
- Member NSERC Grants Committee, Ottawa1991 – 95
- Member NRC Advisory Cttee on TRIUMF, Vancouver 1995 – 98

the author of a superb text book, on which generations of particle physicists (world-wide) were brought up

and a good friend, an inspiration, and a great physicist


Don when elected to the Royal Society in 1966

Copyright Godfrey Argent Studio

For Don's own retrospective accounts see

FROM PIONS TO PROTON DECAY: Tales of the Unexpected

Annu. Rev. Nucl. Part. Sci. 2005. 55:1–26
doi: 10.1146/annurev.nucl.55.102703.130016

An early neutrino experiment: how we missed quark substructure in 1963

Eur. Phys. J. H 38, 713–726 (2013) DOI: 10.1140/epjh/e2013-40024-3

Early steps towards quarks and their interactions using neutrino beams in CERN bubble chamber experiments

Eur. Phys. J. H 41, 157–164 (2016)
DOI: 10.1140/epjh/e2016-70016-2

For the history of the parton model see

From concrete quarks to QCD: a personal perspective
C Llewellyn Smith
Eur. Phys. J. H (2023) 48:13
https://doi.org/10.1140/epjh/s13129-023-00061-4