Introduction to Deep Inelastic Scattering: Past and Present

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A brief history of Deep Inelastic Scattering (DIS) physics is presented. Going from the glorious years at SLAC 45 years ago, through the high statistics fixed experiments in the eighties and the discoveries at HERA since twenty years, without omitting Polarised Deep Inelastic Scattering, until the most recent open problems in DIS.

1 Introduction

At a moment when many of the people attending the conference have not been involved in the early DIS experiments it could be interesting to review how the field of DIS has started and evolved since 45 years. I shall start to remind the heroic years at SLAC, followed by the era of high precisions fixed target experiments before entering the new kinematic domain and its many surprises at HERA. I shall end by commenting where we are at present five years after the end of data taking at HERA.

2 Glorious years at SLAC

The heroic age of DIS opened in 1968 when a SLAC-MIT experiment [1] studied electron-proton DIS with the new commissioned linear electron accelerator at Stanford. Beam energies of up to 20 GeV were well beyond the 6 GeV peak energy of DESY, the highest electron energies then available. Two important phenomena were observed:

1. The inclusive inelastic cross-section is larger by more than one order of magnitude than expected and only weakly Q^2 dependent.

2. At an invariant hadronic mass (W) of the final state larger than 2 GeV, the structure function F_2 becomes a function of the ratio $\omega = \nu/Q^2$ over a range $0.7 < Q^2 < 2.3\,\mathrm{GeV}^2$.

The results were interpreted with a great intuition by W.K.H. Panovsky in the HEP Conference in Vienna in 1968 [2]: as *"the apparent success of the parametrization of the cross-sections in the variable νQ^2 in at least indicative that point-like interactions are becoming involved."* It was a big surprise that nobody had anticipated except a lone prophet J.D. Bjorken. In 1966 J.D. Bjorken [3] conjectured that in the limit of Q^2 and ν approaching infinity the structure function F_2 becomes function only of the ratio x. It was based on current algebra but *"a more physical description is without question needed"* [4] that J.D. Bjorken himself suggested : *"We suppose* *that the nucleon consists of a certain number of elementary constituents"* [5] that behaves as free particles. However the general feeling was that *"Bjorken's results were highly esoteric"* [6].

There were in 1968 very little interest in DIS scattering. Dick Taylor in his Nobel Prize lecture [7] acknowledged that DIS was not the main focus of the experiment and should be reserved to *"subgroups"*. Nobody expected that the study of the continuum at high W would be so central in the history of high energy physics. At DESY an experiment did notice in November 1967 [8, 9] a surprising slow Q^2 dependence at high W that was tentatively attributed to resonances of high angular momentum.

The constituent model which opened the way for a simple dynamical interpretation of the deep inelastic results was the parton model of R.P. Feynman. But before the SLAC-MIT experiment there were no reasonable candidates for the constituents. Visiting SLAC in summer 1968 R.P. Feynman immediately saw in point-like partons an explanation of SLAC data. But it took many years before the theory was widely accepted. The most accepted theories were : Nuclear Democracy, Resonances Models, Regge Trajectories, VDM ... The Parton Model had to wait for decisive tests. It came first from a measurement of the ratio of longitudinal and transverse photo-absorption cross sections of the victual photon $R(\nu/Q^2) = \sigma_L/\sigma_T$ which combined SLAC and DESY experimental results [10]. R was found to be small and not increasing with Q^2 . It was an elegant indication of spin 1/2 constituents [11]. Further stringent tests of the Quark Parton Model came from neutrino DIS scattering at CERN with the heavy liquid bubble chamber Gargamelle (which discovered later the neutral currents) :

- The Quark Parton Model (QPM) predicts that on an isoscalar target the ratio of the F_2 structure functions in electron and neutrino scattering depends only on the quark charges. When neglecting the strange quark contribution, it gives:

  $$\frac{\frac{1}{2}\int[F_2^{\nu p}(x) + F_2^{\nu n}(x)]\,dx}{\frac{1}{2}\int[F_2^{ep}(x) + F_2^{en}(x)]\,dx} = \frac{2}{e_u^2 + e_d^2},$$

  where e_u and e_d are the electric charges of the u and d quarks. The ratio was found to be 3.4 ± 0.7 [12] as compared to the 18/5 predicted value. It provided the most convincing evidence that nucleons contains fractionally charged quarks as real dynamical entities.

- For point-like constituent the total neutrino and anti-neutrino cross-sections should be proportional to the energy in the centre-of-mass (i.e. the neutrino beam energy). The linearity of the cross-section was indeed well verified by Gargamelle data. [12]

- The Gargamelle group evaluated the Gross-Llewellyn Smith Sum Rule [13] which states that :

  $$\int [F_3^{\nu N}(x)]\,dx = (number\ of\ quarks) - (number\ of\ antiquarks)$$

The measured value of 3.2 ± 0.6 [12] was another significant success of the Quark Parton Model. It is worth to mention that complementary informations from e^+e^- scattering helped the QPM to emerge against strong opposition. However, in 1973, there were still several vital problems :

- The momentum sum rule, directly measured by the Gargamelle group, was strikingly small [12]:

  $$\int [F_2^{\nu p}(x)+F_2^{\nu n}(x)]dx = \int x[u_p(x)+\bar{u}_p(x)+d_p(x)+\bar{d}_p(x)+s_p(x)+\bar{s}_p(x)]dx = 0.49\pm0.07.$$

In QPM, the sum rule represents the fraction of the nucleon's momentum carried by the quarks and the antiquarks. So, where does the other half of the nucleon's momentum comes from ?

- Why the point-like partons appear to be free during the collision?

The paradoxes were splendidly solved by the newly developed QCD in 1973. One of the early convincing tests of the correctness of QCD was the observation of the clear pattern of scaling violations in DIS with increasing Q^2: rise at small x and fall at large x due to the radiation of gluons. The scaling violations were precisely observed in a muon scattering experiment at FNAL in 1975 with a muon beam of 150 GeV [14].

3 High statistics fixed target experiments

The striking early results in DIS led to more than two decades of fixed target experiments using all available leptonic probes at SLAC, FNAL and CERN (see fig. 1). With higher beam energies the new generation of experiments extended the e-N programme of SLAC by an order of magnitude in Q^2 (see fig. 2) :

- `Electron beams`. After the pioneering SLAC-MIT experiment more DIS experiments were carried out at SLAC with unpolarised targets up to the early nineties .
- `Muon beams`. The major collaborations were BFP at FNAL with beams produced by the Tevatron and at CERN BCDMS and EMC (later replaced by NMC) with beams produced by the SPS. The beam fluxes were much lower than at SLAC but compensated by large acceptances and very long targets (up to 40 m long in BCDMS). The scattered muons were measured in an open spectrometer (BFP, EMC and NMC) or an iron toroid (BCDMS).
- `Neutrino beams`. To reach high statistics neutrino experiments at CERN (CDHSW) and at FNAL (CCFRW later replaced by NuTeV) used an heavy target calorimeter and an iron toroid to measure the scattered muon.

3.1 Inclusive measurements

With the high statistics the systematics became by far the largest source of uncertainties for structure functions measurement. Many glaring discrepancies between the muon experiments and between the neutrino experiments have generated heavy discussions for many years. The most spectacular shift was between the muon experiments BCDMS and EMC where a 10 % shift at low x and a 10 % shift at large x of opposite signs could not be compensated by shifts of normalisations [15]

A few years later, a new generation of experiments have helped to clarify the situation.The NMC experiment succeeded the EMC experiment using a large part of the EMC detector and has understood the discrepancy between BCDMS and EMC [16]. Then, more precise inclusive NMC data have superseded the EMC inclusive data. There is at present almost perfect agreement between SLAC, BCDMS and NMC experimental results. However it is still likely that the main correlated systematics of BCDMS is slightly under evaluated [17]. As to the neutrino experiments, quality of the QCD fit of the CDHSW inclusive data at CERN was

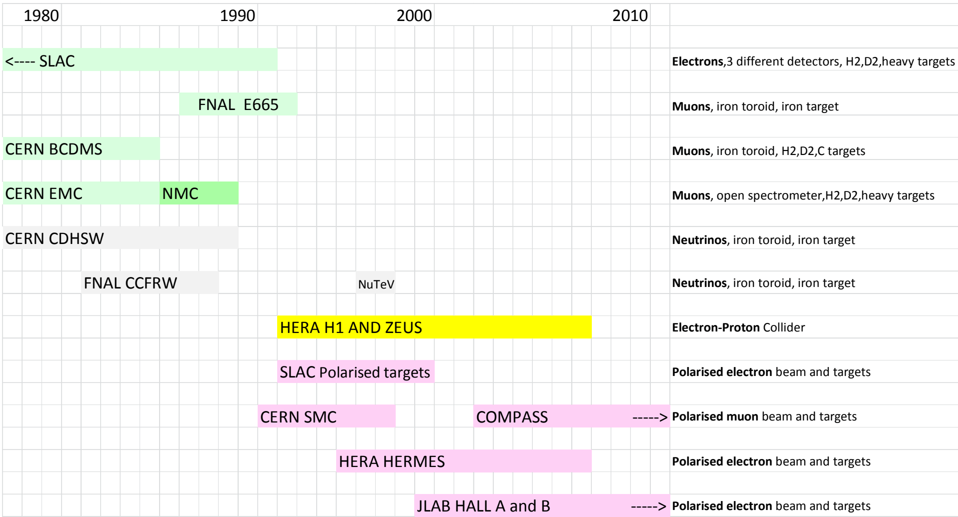

Figure 1: Time-planning of high-statistic fixed target and HERA experiments together with polarised DIS experiments.

rather poor [18]. At FNAL, after refurbishing the CCFRW detector the NuTeV experiment succeeded the CCFRW experiment. There was a large discrepancy reaching a 25 % shift at large x between NuTeV and CCFRW inclusive data. Finally NuTeV have understood the origins of the discrepancy [19]. Inclusive NuTev data have then superseded CCFRW data.

3.2 Measurements of flavour content of the sea

Estimates resting on differences or ratios of cross-sections data with the same apparatus are much less affected by systematics. They have brought new insights into the flavour content of the proton at low x. In general, the flavour content of the sea is a complex matter that does not follow the simple democratic production from gluon splitting into $q\,\bar{q}$ pairs :

- `Strange quarks`. Opposite di-muons produced in neutrino-nucleon scattering is a direct probe to measure the strange component of sea quarks in the nucleon. The high statistics neutrino experiments ([20],[21]and [22]) have found that in average the density of strange quarks is twice smaller than the density of the average of $\bar{u}$ and $\bar{d}$ quarks. The result seems to be challenged by new data at LHC [23] determined at $x = 0.023$ and $Q^2 = 1.9\,\mathrm{GeV}^2$.

An interesting situation to follow up in the coming years.

- $\bar{u}$ and $\bar{d}$. When comparing F_2 structure functions of the proton and of the neutron, SLAC, EMC and BCDMS have observed evidence that there is more $\bar{d}$ than $\bar{u}$ in the proton . More precise data came from NMC a few years later [24]:

$$\int [\bar{u}(x) - \bar{d}(x)]\, dx = -0.147 \pm 0.39$$

It is another curious asymmetry of the sea content which has been confirmed by measurements of Drell Yan pairs and production of W bosons in hadron-hadron scattering.

3.3 EMC effect

It was expected that parton distributions in a nucleon embedded in a nucleus would only differ from distributions in a free nucleon at large x due to the well known Fermi motion and at very low Q^2 due to the shadowing effect observed before in photo-productions. In 1982, it came as a surprise when the EMC experiment observed a dependence on the nuclear structure of the structure function $F_2(x, Q^2)$ in iron relative to that for deuterium at high Q^2: a rise at $x \sim 0.05$ and a strong drop at $x \sim 0.5$ [25]. Several dedicated fixed target experiments [26] confirm the effect at large x. Also a small enhancement at x around 0.05 was measured. By extending the measurement down to about $x \sim 10^{-3}$ a strong drop was observed. At present, the effect is not fully understood. So that, it is necessary to use a model to extract Parton Distribution Functions (PDF) of the nucleon from heavy target data.

3.4 Spin crisis

The proton spin sum-rule states that:

$$\frac{1}{2} = \Delta\Sigma + \Delta G + L_q + L_g$$

This means that the proton spin is the sum of the quark ($\Delta\Sigma$), plus the gluon intrinsic spins (ΔG), plus the orbital angular momentum (L_q, L_g contributions). In 1988 the EMC experiment measured the asymmetry of inclusive DIS cross-sections of a polarised muon beam off a longitudinally polarised target and obtained the surprising result that the fraction of the spin carried by the quarks is compatible with zero [27],

$$\Delta\Sigma = 12 \pm 9 \pm 14\%,$$

the so-called spin-crisis. The result has generated a lot of theoretical works and many dedicated experiments (see section 6).

4 Discoveries from HERA

With the opening of a new kinematic space by two orders of magnitude in Q^2(see fig. 2), it was clear from the early proposals of HERA that the physics interest was focused on large Q^2. In the first years of data taking the low Q^2 calorimeter of the H1 detector had a modest granularity and neither ZEUS nor H1 had a very forward proton detector for diffractive events. However at small integrated luminosity (22 nb^{-1}) two unexpected topics emerge and should stay as a part of the hard core of the HERA legacy : low x physics and diffraction.

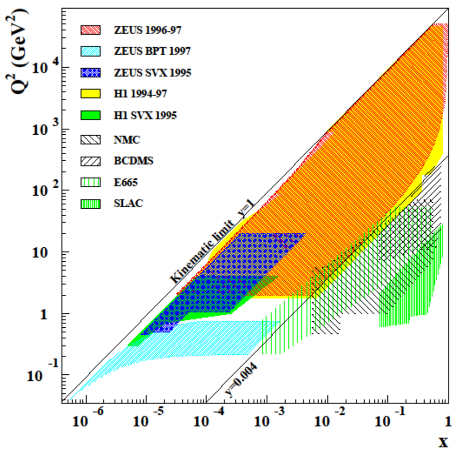

Figure 2: Kinematic regions in x and Q^2 covered by fixed target experiments and the HERA experiments.

4.1 Rise of the DIS cross-section at low x

In 1993 a few months after the end of the first period of data taking, R. Devenish [28], chairperson of the first DIS Workshop, concluded that: *"one of the moments of high drama was the presentation by H1 Collaboration of the first measurement of F_2 at HERA showing that the structure function did increase quite strongly at low x"*. It was also observed from the early data that the rise should be more pronounced as Q^2 increases [29]. Why was it such a surprise? It was commonly accepted that extrapolations at low x indicated a flattish F_2 as $x \to 0$, a Regge-like behaviour: $F_2 \sim x^{-\epsilon}$ where $\epsilon \approx 0.08$. It was however predicted in 1974 by the fathers of QCD [30], but forgotten since, that the gluon should rise at low x for Q^2 high enough and that the rise should increase with Q^2. Quoting from Frank Wilczek [31] in his comments on QCD foundational papers: *"The most dramatic of these tests, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later"* . It was later conjectured in 1983 that the rise should be tamed by saturation effects to prevent reaching the unitarity limit [32]. It is also fair to say that most of the parametrisations of the structure function F_2 had as an option the possibility of a rise at low x. The argument over the interpretation began immediately after the presentation of the data [28]. Was it an indication of the BFKL behaviour? Could it be described by the DGLAP evolution equations? Could the saturation be observed at HERA? Clear answers were given in the following years when more data were accumulated. The Q^2 evolution of the F_2 structure function is perfectly described by DGLAP evolution equations down to $x \sim 10^{-4}$ and $Q^2 \sim 2\,\mathrm{GeV}^2$ and no indication of saturation has been observed (see fig. 3). However new questions about low x physics were raised and are still open (see section 5).

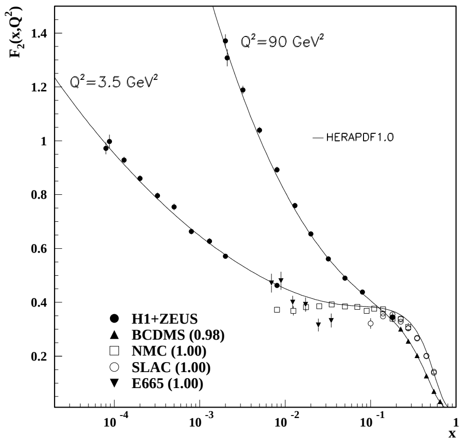

Figure 3: A recent plot of the proton structure function F_2 [33] and the HERAPDF fit [34] based on DGLAP evolution equations.

4.2 Hard diffraction

A new class of DIS events came also as a surprise. About 10 % of Neutral Current DIS events have a large rapidity gap between the proton direction and the first energy deposition in the detector. The DIS Monte Carlo programmes in use in the early years of HERA assumed that there is a colour flow between the struck quark and the proton remnants. Thus, the simulation programmes were not able to describe the data [35]. In the following years, beautiful data, where diffraction scattering can be identified via the rapidity gap or by tagging the forward proton in dedicated very forward detectors, have been accumulated by the H1 and ZEUS collaborations. At present, progresses have been made in understanding these events, but the physics of hard diffraction is not yet fully clarified.

4.3 Electroweak unification

One of the primary goals of physics at HERA was to study the neutral and the charge currents at Q^2 values sufficiently that the electromagnetic and the weak currents are of similar strength. Indeed the plot of neutral and charge currents cross-sections have shown in 1995, quoting from R.Cashmore in DIS-2001 [36]: *"the most graphic and simple demonstration of electroweak unification available"* . It provided a determination of the mass of the vector meson W in full agreement with the world average.

4.4 Gluon density

HERA is a unique facility to extract the gluon density and the running coupling constant α_s from inclusive cross-sections, jet production and heavy quarks productions. In the very first analyses in 1993, assuming that α_s takes the word average value, it has been possible to extract the gluon density from the scaling violations and in 1995 to make a direct measurement of the gluon density from the rate of multi-jet events [37]. The full agreement at Leading Order between indirect extraction and direct measurement of the gluon density was not a surprise. It has however constituted an important test of perturbative QCD.

5 High precision and extension of the physics domain at HERA

After the early discoveries, the statistics has gradually increased until the year 2000. There have been a major upgrade of luminosity in 2001-2002. Data-taking has ended in 2007. The analysis of the data has been a permanent fight against systematics towards high precision together with searches beyond the standard model which unfortunately were not successful. Tremendous progress on the physics of DIS has been obtained over the years in theory and experiment. In DIS new domains of investigation were developed beyond the simple measurement of inclusive cross-sections. The most up-to-date status of these studies are the object of the Workshop. Let make here just a few general comments.

- `The longitudinal Structure Function` $F_L(x, Q^2)$. Since the early SLAC measurements in 1969, it has taken 40 years to get precise data on $F_L(x, Q^2)$ [38]. The result is in perfect agreement with the prediction of perturbative QCD down to $x \sim 10^{-4}$ and $Q^2 \sim 2\ \mathrm{GeV}^2$. Quoting from G.Altarelli in DIS-2009 :*"I had not expected that it would take such a long time to have a meaningful test of this simple prediction"* [39].

- `Physics at low` x. There are some hints of possible departure from standard evolution in associated production of jets in the forward direction at small x. BFKL evolution, Dipole models, Colour Glass Condensate, Geometric Scaling are appealing physics pictures of the physics but there is still no satisfactory theoretical understanding of the domain of high densities of quarks at small x.

- `Diffraction.` In addition to the measurement of Diffractive Structure Functions, measurement of Deep Virtual Compton Scattering (DVCS), production of Vector Mesons and comparison between diffractive processes at HERA and at hadron-hadron colliders have brought more insight into the study of diffraction without fully clarifying the concept of diffraction in QCD.

- `Rate of jets production.` The production of jets in DIS has become a very matured domain. It is at present one of the best tools to disentangle the value of α_s from the gluon density at NLO. The precision is so good that theoretical calculations at NNLO, as existing in inclusive processes, are highly demanded.

- `Heavy quarks productions.` In the recent years, impressive progress has been achieved by the H1 and ZEUS collaboration on the measurement of the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ in DIS processes. Clear pattern of scaling violations have been observed. They are well described by perturbative QCD. The heavy quark structure functions contribute at present to the precision of the extraction of parton densities in the proton.

- `PDFs fits.` A new step in the history of DIS has been the combination of H1 and ZEUS data before any QCD fits. The precision was naturally improved by reducing the statistical errors but also by decreasing the systematic uncertainties because different experimental techniques were used in the detectors. The gain is the production of HERAPDF fits only using the HERA DIS data with an excellent precision which rival the global fits. The precision of the parton densities is even improved when jet cross-sections and heavy quark structure functions are combined to the inclusive measurement in the QCD fit. It is anticipated that determination of PDFs with the best precision would be of growing importance for our ability to extract new physics at LHC. Conversely, measurements of Standard Physics processes at LHC should improve knowledge of parton densities in a large part of the x range.

6 Spin Physics

Since 20 years after the early measurement of EMC, in parallel to the e-p collider physics at HERA, the domain of Spin Physics in DIS has been considerably studied. Dedicated fixed target experiments at SLAC, CERN, DESY and Jlab have accumulated inclusive and semi-inclusive data on Polarised DIS. Complementary informations has been brought by experiments at RHIC. Direct measurements and NLO QCD fits have provided important information on the constituents of the nucleon. The total contribution of valence quarks, strange quarks, sea quarks and gluons do not match the 1/2 spin value of the nucleon. At present, we still do not know where the proton spin comes from.

7 Concluding remarks

No doubt that in the history of high energy physics DIS processes have been crucial for establishing the dynamical reality of quarks and the impressive correctness of perturbative QCD. As will be shown all along the workshop the very exciting comparison between the first LHC results and the predictions mainly based on PDFs extracted from DIS processes will underline the central role of DIS.

However a few important issues remain open in the field od DIS including:

- Precise determination of the strong running constant. It is not yet clear whether determinations of α_s from DIS and from other processes do agree.
- The genuine uncertainty of PDFs is still a topic of many debates and studies [40].
- Understanding of low x physics and diffractive processes has made progress in the last years but is not yet satisfying.
- The origin of the proton spin is a mystery.

More insights into these questions are expected at the Workshop but probably not the final answer.

8 Acknowledgements

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