Experimental Highlights

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Highlights at the 13th International Conference on Elastic & Diffractive Scattering (EDS09) of the presentations of new experimental results and developments are presented and discussed.

1 Pedigree and Context

Hadronic physics is the physics of colo(u)r. Colour is the degree of freedom which defines how the hadronic world which we observe and measure is actually the result of the strong interaction. Thus chromodynamics, the theory which we now have for the strong interaction, defines and determines the observable mass of the universe. This mass comes in the form of the atomic nucleus, its constituents - neutrons and protons, their constituents, quarks, and the quantum field dynamics of the non-abelian gauge freedom in chromodynamics. That we can now state all of the above with confidence is *the* monument to the triumphal progress in physics of the last 100 years since Rutherford started it all in Manchester, England, with the first experiment in search of the origin of mass.

Furthermore, the establishment of a theory of matter such as Quantum Chromodynamics (QCD) is a triumph also of human ingenuity founded on the development of the concepts of "structure", "dynamics", and "interaction". One can trace such thinking back through seminal experiments in the last two centuries, back even to ancient civilisation – to Aristotle: "By convention there is colour, by convention sweetness, by convention bitterness, but in reality there are atoms, and space."

So today, and right now at EDS09, we find ourselves concerned with progress in hadronic physics as the physics of the observable mass of the universe, and with a theory, QCD, which is established, but which is also itself complex. This complexity is such that we are a long way from understanding fully the most basic of mechanisms, confinement, by which observable mass is what it is, namely predominantly QCD field energy, gluons, and very much less the constituent mass of the fermion constituents, quarks. It is therefore the case that a cornerstone of contemporary physics continues to be to understand exactly how QCD explains the high energy interactions of hadrons. This is predominantly what we call "diffraction". In so doing, what we can learn conceptually about fundamental mechanisms in QCD, and perhaps beyond, may even lead to a deeper underlying unification.

Less prosaically, and more with the metaphorical "spanner" of the experimentalist in mind, we have at hand the experimental measurements of elastic and inelastic interactions of hadrons at high energy. Most of what we know concerning the elastic scattering of protons has defined what we mean by "diffractive scattering", namely the appealing resemblance of the angular dependence of the cross section to familiar optical diffraction patterns of apertures [1]. The observation of secondary minima and maxima consistent with the femtoscale of the hadronic

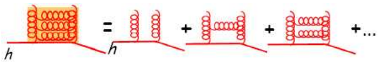
Splitting to off-shell t	Single Regge Pole splitting (momentum fraction $x_{I\!P}$)
	$G_{I\!Ppp} \frac{dx}{x_{I\!P}^{2\alpha(t)-1}} f(t)\, dt$

Table 1: Phenomenological "splitting function" for the high energy, diffractive, interaction of a hadron in terms of the t-channel exchange of a single leading Regge pole; the coupling $G_{I\!Ppp}$, and the dependence $f(t)dt$ on 4-momentum transfer t are not predicted; the trajectory $\alpha(t)$ can be specified by resort to the resonance structure of the crossed channel, thereby specifying the dependence on the fractional momentum $x_{I\!P}$; the Regge pole exchange is illustrated diagrammatically in the expectation that it amounts to an expansion in partonic QCD.

diffractive aperture are governed by the convolution of the form-factors with the dynamics of the mutual interaction of that part of the constituent structure which is resolved in the interaction in each proton.

What (arguably) has been at the root of the importance of diffraction in hadronic physics are the experimental observations that

1. inelastic interactions at high energy are dominated by diffraction-like production: the incident hadrons can be associated with clusters of low mass particles associated in rapidity with one or other of the incident hadrons, and separated from each other and from any other hadrons by a "rapidity gap", and the production angular dependence of the clusters (4-momentum transfer squared t) resembles that of elastic scattering, making hadron diffraction a unique window into the diffractive shadow;

2. all such identified diffractive processes exhibit many common, and quantitatively generic, features in terms of their interaction dynamics, and

3. all diffractive processes alone survive as the only interaction mechanism for elastic and inelastic hadronic interactions at the highest energies.

These in turn have led to the phenomenology of extended, colour singlet, exchange in the t-channel which is related through analyticity to low energy resonance phenomena in the s-channel, the indisputable and indestructible triumph of Regge phenomenology [2]. Despite in many ways its crudity because it is only a leading parametrisation valid at high energy (high s) and small t, "Reggeology" often works extremely well, but sometimes fails magnificently, notably at ultra-high energy where it violates the most rigorous of theoretical requirements, unitarity! In the case of diffractive physics, it triumphs in producing a universally applicable "pomeron" trajectory $\alpha(t)$ with a well determined "intercept" $\alpha(t=0) = 1.085$ and a "slope" $\alpha' \sim 0.25$ ($\alpha(t) = \alpha(t=0) + \alpha' t$) [3], but at the cost of posing a major challenge for its "crossed" s-channel, namely what is the nature of the hadronic system which carries the quantum numbers of the vacuum and which defines this linear trajectory?

High (but not ultra-high) energy diffractive scattering can thus be conveniently characterised in analogy with formal field theory by a phenomenological splitting function as per Table 1, where it is clear that Reggeology is indeed a well founded, but only comparative, phenomenology. A splitting function is the probability of the diagram involving the coupling of the space-like exchange to the particle in question. Reggeology correlates phenomena in terms of a few,

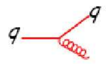
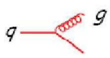
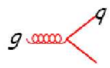
Splitting to off-shell t	QCD LO splitting function (momentum fraction x, n_f flavours	High energy ($x \to 0$)
	$\frac{4}{3}\left[\frac{1+x^2}{1-x} + \frac{3}{2}\delta(1-x)\right] dx\frac{dt}{t}$	$dx\frac{dt}{t}$
	$\frac{4}{3}\frac{1+(1-x)^2}{1-x} dx\frac{dt}{t}$	$\frac{dx}{x}\frac{dt}{t}$
	$\frac{1}{2}\left[x^2 + (1-x)^2\right] dx\frac{dt}{t}$	$dx\frac{dt}{t}$
	$6\left\{\left[\frac{x}{1-x} + \frac{1-x}{x} + x(1-x)\right] + \frac{33-2n_f}{6}\delta(1-x)\right\} dx\frac{dt}{t}$	$\frac{dx}{x}\frac{dt}{t}$

Table 2: QCD Splitting functions at leading order (LO); each process ($q \to q, q \to g, g \to q, g \to g$) is marked with the off-shell parton with space-like mass[2] t and fractional momentum x; the high energy limit corresponds to low fractional momentum x.

rigorously derived, parameters. The recipe in Table 1 gives rise (of course) to the established expectations that the leading diffractive trajectories, the pomeron $\alpha(t=0) = 1.085$ and the f^0-meson $\alpha(t=0) = 0.5$, have respectively characteristic dependences $\frac{dx}{x^{\le 1.17}} \sim \frac{dx}{x}$ and constant in the fractional momentum variable of the Reggeon ($x = x_{I\!P}$). These are more often quoted in terms of the dependence on centre-of-mass energy squared s (valid when s is the only high energy scale) of the contributions of each to the diffractive production cross section, namely a gentle rise $s^{2\alpha(t)-2} \sim s^{0.17}$ and a significant decrease $s^{2\alpha(t)-2} \sim s^{-1}$ respectively, leading directly to the dominance of pomeron exchange in diffraction at high energy, that is at low $x_{I\!P}$.[1]

What somewhat more recently has become an important part of the experimentalist's toolkit is the array of essential facts of QCD, which are best summarised in the "splitting functions" of the chromodynamic quanta, and which are determined from the Lagrangian of gauge field theory, QCD. They turn out to carry a set of very simple, salient, properties (experimentalists always love simplicity!). These are laid out in Table 2 and reveal the simple rules for the high energy (low x)[2] dependences, namely the probability for off-shell "emission" of a gluon $\sim \frac{dx}{x}\frac{dt}{t}$ and of a quark $\sim dx\frac{dt}{t}$. These simple outcomes are equivalent to exchange of field quanta (gluons) in interactions giving rise to no energy dependence of the cross section[3], and to exchange of fermions (quarks) in interactions giving rise to falling energy dependence. Com-

[1]The reason for explicitly laying out the Regge dynamics in the slightly unusual terms of an effective, trajectory dependent, splitting function is because the Regge analytic continuation from the low energy resonance amplitude to the crossed channel amplitude with $t/s \to 0$ is in the variable which corresponds most closely to CM scattering angle $cos\theta^*$ in the resonance amplitude and to $1/x_{I\!P}$ in the high energy amplitude. Its use in this form is also unambiguous when one or more of the initial or final state particles have sizable mass (for example virtual photon) leading to modified CM energy dependence.

[2]We here take x and t to be respectively the fractional momentum and the invariant mass squared of the off-shell product of the quantum splitting.

[3]The simplest manifestation of this universal property of a vector quantum field theory is of course Rutherford scattering in QED.

paring with the Regge phenomenological expectations above, the former suggests that gluon exchange(s) must be important in high energy diffraction. In the last few years, experiment has resolved the basic QCD splitting structure in diffractive dynamics, confirming this likelihood, a major step in confronting the phenomenological "Reggeology" with the rigours of non-abelian, chromodynamic, gauge theory.

It is also a fact that QCD has been used in a monumental theoretical effort to calculate strong interaction dynamics in the form of multiple gluon exchanges between quarks in a calculation of diffractive quark scattering. The result is a triumph in the annals of theoretical QCD, producing from the basic splitting in Table 2 Regge behaviour with a "pomeron" intercept marginally larger than classical Reggeology in soft hadronic physics, $\alpha(t = 0)$ in Table 1 [4], and thereby also establishing new technologies in QCD concerning how to handle multiple, soft, gluons. The result, known as the "hard pomeron" or the BFKL pomeron, or the Lipatov pomeron, has become to many experimentalists something of a holy grail. Now, after a number of false "alarms", experiment has established evidence indicating the existence of a harder pomeron, and one whose intercept evolves with changes in hard (short distance) scale.

Such has been the experimentation with its associated phenomenology which has made possible quantification of diffraction in hadronic physics, and which has thereby simultaneously guided theoretical progress.

On the basis of this "potted" pedigree, since their inception, the major thrust of EDS conferences has been the synergy of simultaneous developments in both experiment and theory. At EDS09 much progress of striking significance continues to be reported. It is based on new and not so new data sets, and on new and not so new formalism and phenomenology, but this time also with the mouth-watering anticipation of the imminent new round of experiments at the CERN LHC. What follows cannot be exhaustive, so it suffers unavoidably from the author's prejudice.

2 Exclusive Diffraction

The aristocrat of sub-nuclear physics is proton-proton (pp) elastic scattering (and its partner antiproton-proton elastic scattering). Unlike its hereditary namesake, this aristocrat continues to thrive and to challenge every theoretical revolution, often leading to new insight as repeatedly it does so.

At EDS09 we have seen a snapshot of how the on-going theoretical developments, driven often by aspects of low-x QCD together with the unassailable rigours of analyticity and the Optical Theorem, continue to reveal new physics insight. "Derivative Dispersion Relations" (DDR) have been brought to bear [5] on the decades of data sets, further tying down the real part of the forward elastic scattering amplitude (the ρ parameter) through its interference with the electromagnetic, Rutherford scattering, amplitude (Fig. 1a). The interplay of contemporary views of proton structure with the outcome of these approaches is now at the stage that a picture of the lateral (transverse) structure of the proton emerges [6]. "Multi-pole" exchange analyses [7] of differential and total cross sections with lower energy data (lower than the LHC!) have been pushed to provide best honest estimates – and they are just that – of what to expect for the total pp cross section at the Terascale. The considerable uncertainties in these expectations highlight the crucial importance of LHC measurements.

The issue facing all elastic scattering cross section measurements has been the lack of a "hard" momentum transfer scale with which to engage partonic (quark and gluon) degrees of

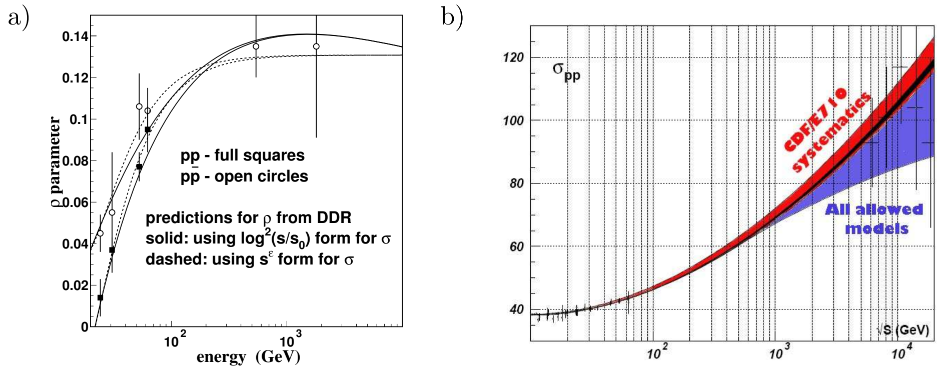


Figure 1: (a) the ρ-parameter, the ratio of the real to imaginary forward elastic pp scattering amplitude as a function of energy showing the different predictions based on DDR (see text); (b) predictions for the total pp cross section in the LHC energy region based on a multi-pole analysis of elastic diffractive data, revealing large uncertainties in expectation.

freedom. The relationship between the "soft" Reggeon phenomenology, which has so far worked better than anything else, and the theoretical calculus of non-abelian QCD applied to strong hadronic interactions, requires measurements to elucidate when and how partonic degrees of freedom emerge from soft, extended (colour singlet), hadronic physics.

It is here that the HERA electron-proton collider has opened completely new horizons in the last 17 years. Exclusive diffraction at HERA is measured in low-x (high energy) electroproduction, where the dominant mechanism is space-like virtual photon (γ^*) exchange, but with the magnitude of the 4-momentum transfer squared Q^2 much less – but still sub-femtoscopic – than the virtual photon-proton interaction energy squared W^2. These processes are diffractive when the exclusive final state involves a photon or a vector meson (VM) $ep \rightarrow e\,\mathrm{VM}\,p$ (Fig. 2a). With (diffractive) data for the electroproduction of $\rho(770)$, $\varphi(1010)$, $\omega(770)$, J/Ψ and Υ over a wide range of Q^2, it is therefore possible to probe the short distance mechanisms which, as the resolution changes, reveal the QCD view of the colour singlet exchange, the pomeron, of Regge theory.

There is a magnificently simple kinematic approach to the issue of the size of an exclusive diffractive interaction. One has to consider the interplay of spatial dimension of probe Q^2, 4-momentum transfer squared t, quark mass m_q, and final state meson mass squared M^2 in the diagram that must accompany any diffractive process involving a gauge boson (Fig. 2b). As we have appreciated for decades, indeed from the days of vector dominance to the days of HERA, any electroweak gauge boson couples to matter through a quark. Thus any interaction of a gauge boson with matter is sensitive to the "virtuality" of the inner, space-like, quark in Fig. 3a, that is to its spatial extent. The issue of how "hard" is the dynamics of a process is driven entirely by the "size" of this inner quark, in other words how large is its virtuality v (taken to be its space-like 4-momentum squared). The application of simple kinematics leads to

$$v = m_q^2 - \frac{Q^2 + M^2 - t}{2}\left(1 \mp \sqrt{1 - \frac{4m_q^2}{M^2}}\right), \tag{1}$$

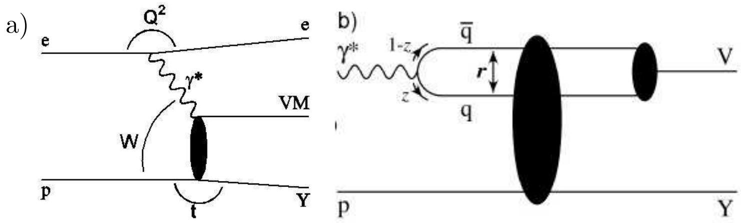


Figure 2: (a) "Elastic" (diffractive) scattering of a vector meson (VM) at HERA at high virtual photon-proton interaction energy W, specified by the magnitude of 4-momentum transfer squared Q^2 being much less than W^2 but still sufficient to resolve quark degrees of freedom; Y is a proton or low mass excitation of a proton (N^*); (b) the only way in which a gauge boson can couple to hadronic matter, namely through a quark; the dimension of the gauge boson, here a virtual photon, is specified by Q^2.

revealing how different possible measures, Q^2, M^2, t, and m_q may contribute to this virtuality.

The results (only some of which are compiled in Figure 3a) are spectacular in how they reveal the evolution of the energy dependence of elastic scattering from "soft" (low v) to the "hard" (high v) domains [8]. They demonstrate unequivocally that the Regge phenomenology in the form of the trajectory $\alpha(t)$, which using Table 1 for a single leading trajectory "intercept" now drives a dependence of the cross section of the form $(Q^2+W^2)^{2\alpha(t)-2}$, changes as a function of the size of the interaction because of, one or more of, Q^2 and the masses of the vector meson and of its quarks. There are also measurements with sensitivity to t which indicate similar dependence on the size of the interaction.

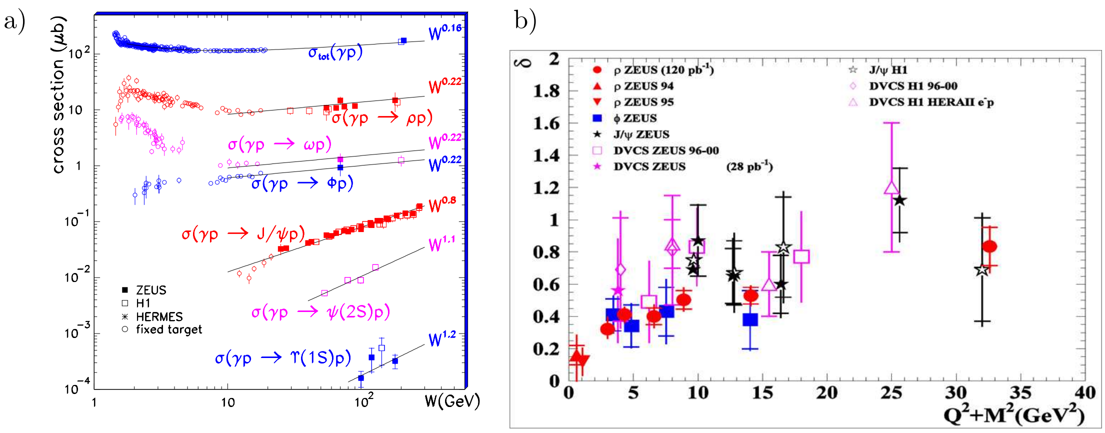


Figure 3: (a) measurements of the total cross section for "elastic" virtual photon-proton electroproduction production; (b) dependence of the W^2 dependence of different total cross sections for "elastic" virtual photon-proton electroproduction; for a single leading trajectory of "intercept" of $\alpha(t=0)$, the W^2 dependence amounts to W^δ where $\delta = 2\alpha(t=0) - 2$.

The initial significance of these and many other similar observations should not be missed. The HERA measurements produce first-time evidence, that is they discover, that the long standing, original, success of the Regge approach with universal, generic, trajectories specified by t-channel, colour singlet, quantum numbers and related wherever possible to cross channel resonances, fails, and the failure is because "size matters". The smaller is the size of the interaction, the steeper is the energy dependence, that is the higher is the trajectory intercept $\alpha(t=0)$. We have therefore the evidence that the pomeron evolves through different manifestations as interaction size changes from large (soft) to small (hard). And given our dynamical picture of hard interactions in terms of field quanta in QCD, we see that these measurements are exactly what is needed to address the inter-relation of the soft pomeron with what may be the "hard" pomeron of Lipatov and colleagues [4] in QCD.

The measurements, which include exclusive electroproduction spanning different ranges of Q^2, M^2, t and m_q, have yet to be exhaustively analysed in terms of sensitivity to the inner quark virtuality. Figure 3b summarises how the $\frac{1}{x_{I\!P}}$ – or W^2+Q^2 at fixed M^2 – dependences, plotted as δ in a Regge motivated parametrisation $(W^2+Q^2)^\delta$ evolve.[1] Here there is some evidence of a universal dependence, even though the kinematic analysis based on inner quark virtuality (1), if right, implies that things may be more complicated.

All of the above discussion rests on the validity of the assumption of the coupling of electroweak gauge bosons with a quark, and how the dynamics varies with the size of this coupling within the target hadron, the proton. We are addressing the phenomenology from the perspective in which somehow a quark-antiquark "dipole" defines the hadronic interaction, as Figure 2b tries to show. Many call this the new paradigm of low-x deep scattering, both elastic and inelastic, and build "dipole models" to which they try then to apply QCD [9]. The dipole picture is not, however, critical to the way the data are – and hopefully will be further – analysed. For, as special relativity says, the basic electroweak gauge boson-quark coupling indeed "looks like" an incident dipole in the Lorentz frame in which the target proton is at rest and the dipole has a large Ioffe length [10]. But also as special relativity says, in the Lorentz frame in which the target proton has high momentum, we still retain the "classic" Feynman picture of the photon interacting with a frozen quark constituent of the proton, and with a similar, Lorentz invariant, lateral dimension. It is gratifying therefore to an experimentalist that these measurements are so manifestly insensitive to such paradigms, and that therefore they remain critical for fundamental QCD calculations of diffraction.

As in all important research, progress depends on the unexpected and the unanticipated. Recent, unexpected theoretical progress in QCD theory, in particular with reference to the validity of factorisation between structure and dynamics, has made it feasible to contemplate using exclusive, vector meson, electroproduction (electroweak, the photon, and chromodynamic, $\rho(770)$, $\varphi(1010)$, $\omega(770)$, J/Ψ and Y) as the means to understand the "tomography" of the proton. In essence measurements of the differential cross sections for such processes, and in particular the exclusive electroproduction of photons $ep \rightarrow e\gamma p$ (deeply virtual Compton scattering DVCS), are sensitive to the dependence of the partonic structure of the proton on transverse proton dimension, so called "generalised parton densities" (GPDs). Measurements over a wide kinematic range are needed, which now motivates a new round of measurements to combine with the HERA results, and, after initial results from HERMES [11] at HERA, they are now also being planned for the COMPASS [12] experiment at CERN. What is truly exciting is to consider how these measurements, analysed in terms of GPDs, will tighten the understanding of diffractive elastic scattering at the energy frontier in terms of proton structure mentioned above [6].

This exemplifies the way that measurements hitherto considered too difficult, and until recently not fully appreciated for their theoretical significance, can influence the on-going challenge of understanding in QCD the original (aristocratic!) diffraction of hadrons.

I have dwelt long on the important developments in exclusive diffraction which continue to take forward the challenge of achieving a rigorous, gauge theoretic, approach to diffractive hadron scattering.

For me the highlight at EDS09 which points to where exclusive diffraction may be taking us has come with the conclusions of new measurements at the TeVatron. They are motivated by addressing experimentally whether exclusive, diffractive, Higgs-boson, (H) production $pp \to pHp$, that is as the afficianados say "Higgs production with no mess", is experimentally feasible at the terascale of the LHC [13]. In short, the issue has been the magnitude of the production cross section and, for experiment, the acceptance possible and the feasibility. The former involves Standard Model (SM) couplings in diagrams of the form of Fig. 4(a).

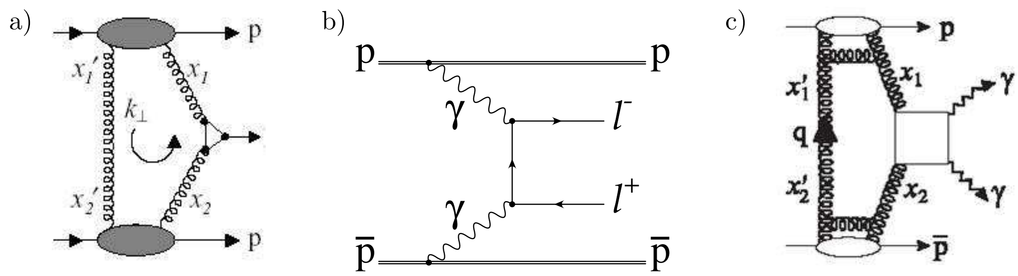


Figure 4: (a) leading order QCD diagram for the production of the Higgs in doubly-diffractive production $pp \to pHp$; and leading order QED diagrams for the production of (b) lepton pairs, and also quark pairs and thus exclusive dijets, and (c) photon pairs, all in the same "diffractive" configurations.

To this end, there has been much theoretical debate leading now to something of a consensus concerning the magnitude of the "diffractive Higgs" production cross section. There has also been much experimental R & D, based on experience with forward "pots" at TeVatron and HERA and the possibility of similar operation very close to the LHC beam with the necessary kinematic coverage.

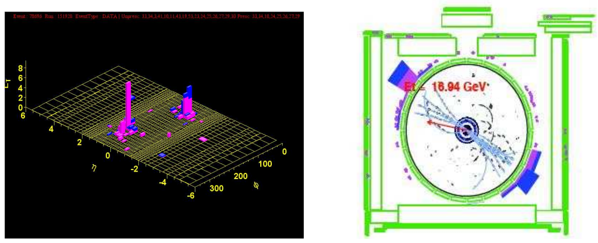


Figure 5: Event observed in CDF with the topology of only two jets in a configuration consistent with the exclusive process $pp \to p(jet + jet)p$, further illustrating the experimental feasibility of exclusive diffraction at a collider such as the LHC.

At the TeVatron, CDF has now demonstrated such exclusive diffraction in the electromagnetic sector of the SM in the processes (Fig. 4b, c) $pp \to pe^+e^-p$ and $pp \to p\gamma\gamma p$. Many of the doubts concerning the QCD predictions for Higgs production are addressed by these measurements, albeit at the TeVatron, and not the Tera, energy scale. CDF have reported signals (handfuls of events) consistent with expectation, checking QED+QCD and thereby underpinning the present estimates of the diffractive, Higgs production, cross section using electroweak+QCD at the LHC. CDF also reported here at EDS09 exclusive dijet production $pp \to p(jet+jet)p$ (Fig. 4c and Fig. 5) [13], which now piles on the pressure for more theoretical precision in diffractive QCD!

Exclusive diffraction has come along way since the days of the first high energy elastic scattering measurements. Our progress to an understanding at the level at which we can say can be applied with confidence to all strong interaction systems continues to be substantial, but far from complete. And the possibilities and horizons which are now before us at the LHC to probe further are huge.

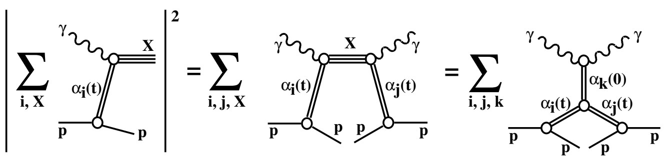
3 Inclusive Diffraction

Relativistic hadron physics is remarkable for its scope. Most notably, and using the language of optical diffraction, the ability to observe and measure inelastic final states in diffractive interactions, such as $pp \to pp$ + hadrons, opens the way to understand the "diffractive shadow" as well as diffraction itself $pp \to pp$ [1]. Measurements over decades have exposed the universality of production characteristics – the pomeron at work between dissociating protons, and rules relating to quantum number flow including spin, parity, flavour isospin, and multiplicity.

At the highest energies, and pioneered at the CERN ISR, inelastic diffraction has demonstrated with the help of "Müller sub-unitarity" that the Regge approach can be extended to the concept of "triple Regge" diagrams (examples in Fig. 6a). In this context, straightforward Regge phenomenology, despite being only a leading approximation at high energy, still shows remarkable consistency and universality in the Reggeon parameters extracted from the data, including those of the (soft) pomeron. This success, for that is what it unquestionably is, forms therefore the soft physics template in analyses which pursue short distance aspects of inelastic diffraction. The best, relatively more recent, example has come with the analysis of inelastic photoproduction data from HERA. Figure 6b summarises the outcome of an exhaustive analysis [15] which also includes lower energy measurements at Fermilab [16] so as to gain the all-important "lever arm" in interaction energy alongside the substantial range which the HERA kinematics gives to the inclusive, diffractive, mass range. The fits are extremely good with a minimum number of trajectories, there is no requirement for any non-Regge "background", and the Reggeon couplings, including the pomeron, and trajectory parameters are remarkably well determined. The soft physics template is thus established for photon induced inelastic diffraction.

So it is in the face of all of the above success in recent decades that we must look at where now we are in understanding inelastic diffraction. Following in the noble footsteps of the CERN ISR and the CERN UA experiments, the CDF experiment at the TeVatron continues to pioneer what is called "single" diffraction $pp \to p +$ hadrons (Fig. 7a) and "double" diffraction $pp \to pp +$ hadrons. In all the CERN experiments and in CDF, the detector configurations have involved one of the most demanding of experimental challenges, namely the operation as close as possible to the stored beams of forward proton detectors. The results have been spectacular.

a) $$\frac{\mathrm{d}\sigma}{\mathrm{d}t\,\mathrm{d}M_X^2} = \frac{s_0}{W^4}\sum_{i,j,k} G_{ijk}(t)\,\left(\frac{W^2}{M_X^2}\right)^{\alpha_i(t)+\alpha_j(t)}\left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}\cos\left[\phi_i(t)-\phi_j(t)\right]$$



b)

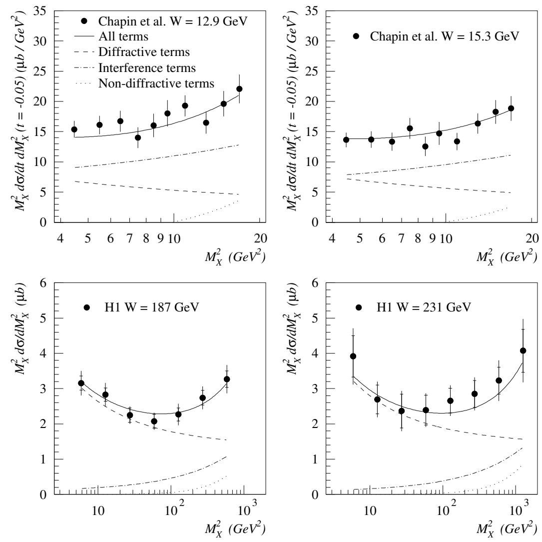


Figure 6: (a) Müller triple Regge diagrams indicating how the cross section for inclusive diffractive mass production can be replaced through sub-unitarity in this mass by the amplitude for diffractive scattering; (b) measurements of the differential cross section (multiplied by M_X) for the production of a diffractive mass M_X at different photoproduction energies compared with a fit to a triple Regge based set of amplitudes.

For the first time jets were seen in single diffraction $pp \to p + jet + \ldots$, and, with di-jet events, even information on the fractional momentum dependence of the jet-initiating partons from the protons was obtained by UA8 [17]. The surprise was that the jets are produced with partons from the diffracting protons with surprisingly large momentum, thereby being very suggestive of "hard" pomeron dynamics. These measurements amount to the discovery of the first evidence for partonic degrees of freedom in high energy diffraction.

The status these days concerning high energy inelastic diffraction has moved on hugely thanks to the exploitation of the large diffractive component in low-x deep-inelastic electron-proton scattering at HERA and the availability of good statistics for measurements of the process $ep \to eXp$ (Fig. 7b) [18]. As a result, it has been possible to probe in the classic

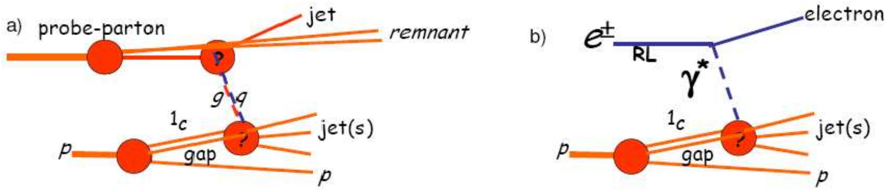


Figure 7: Diagrams illustrating (a) "single diffraction" measurements at a pp collider in which a parton from one proton is used to probe the short distance structure of the other diffractively interacting proton; (b) deep-inelastic lepton-nucleon diffraction in which a lepton probes the structure of a diffractively interacting proton. In each case the rapidity "gap" is marked in which no hadrons are observed thereby defining a leading proton as a particle carrying very nearly all of its incident momentum in undergoing the inelastic diffractive interaction.

"deeply inelastic" manner the short distance structure of the diffractive interaction of a proton, rather than the proton itself. Just as for the latter where totally inclusive measurements of $ep \to eX$ are made in the form of structure functions, results have now been produced with amazing precision in the form of "diffractive structure functions" (shown because of the precision possible as "reduced cross sections"). They reveal for the first time the QCD dynamics of the diffractive t-channel, the pomeron.

There is no space or time here to discuss completely the wealth of detail in these measurements and how they build a picture of the QCD nature of diffractive exchange which must constrain future theoretical approaches. In Fig. 8a, $x_{I\!P}$ dependences (cf. Table 1) for different fractional momentum of the struck quark β and different Q^2 are shown, revealing dominant contributions at low $x_{I\!P} \leq 0.05$ consistent with hadronic diffraction in the form of appropriate pomeron "splitting", together with sub-leading Regge splitting at larger $x_{I\!P}$ consistent with f^0 exchange (cf. Table 1 and discussion in text with it). In Fig. 8b the classic "scaling violation" figure shows the Q^2 evolution of the diffractive structure function, with rising dependence with increasing Q^2 for all but the highest ($\beta > 0.6$) fractional momentum β of the quark coupling to the gauge boson (photon), the struck quark. Rising scaling violations at intermediate and larger β are exactly what is expected if the structure is attributable to quantum fluctuation of both quarks and gluons, and not attributable to spatial extent due to a constituent bound state (cf. the scaling violations of the structure function F_2 of the proton for values of the appropriate variable Bjoerken-x[4] similar to the diffractive variable β). In Fig. 8c the β dependence (note the logarithmic abscissa scale) of the reduced diffractive cross section (in essence the diffractive structure function) for different Q^2 reveals a dependence which is strikingly different from that of a hadron, and which is consistent with a large contribution at large fractional momentum β from gluon, and not quark, splitting to produce the struck quarks [cf. Table 2 and the well known interpretation of the structure functions in terms of parton density functions $F_2 = \sum_q xq(x)$].

These comprehensive and beautiful measurements point unquestionably to the observation of struck quarks from gluon splitting, that is of much gluon exchange in diffractive exchange.

[4]For non-afficianados, Bjoerken-x amounts to the fractional momentum of the struck quark in the infinite-momentum frame of the target proton first invoked by Feynman.

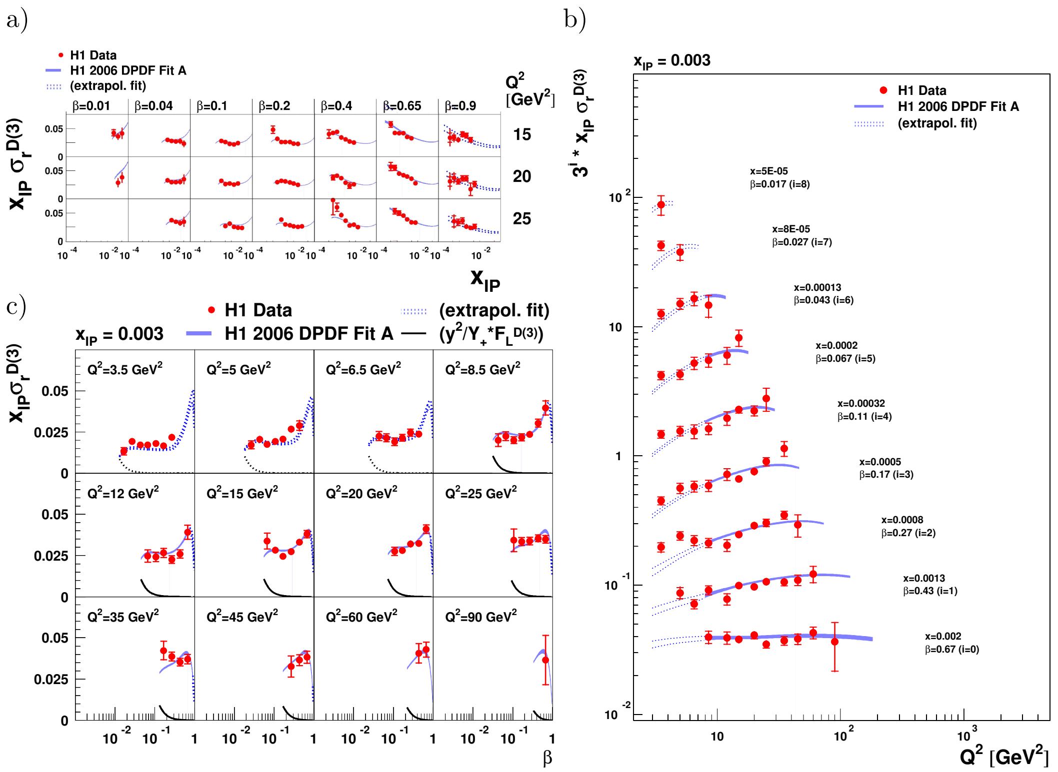


Figure 8: The reduced diffractive cross section, very nearly the diffractive structure function) multiplied by the "Regge" fractional momentum variable $x_{\mathbb{P}}$ for the diffractive t-channel averaged over all t: (a) samples of the $x_{\mathbb{P}}$ dependence for different fractional momentum of the struck quark β and Q^2, revealing dominant contributions at low $x_{\mathbb{P}}$ consistent with hadronic diffraction with appropriate pomeron "splitting" together with sub-leading Regge exchange at larger $x_{\mathbb{P}}$ (Table 1); (b) The Q^2 evolution for $x_{\mathbb{P}} = 0.003$ showing the persistence of violations of scale invariance (no dependence on Q^2) of a nature which rise with increasing Q^2 for a wide range of values of $\beta \leq 0.6$; (c) the β dependence (note the log abscissa scale) of the reduced diffractive cross section for different Q^2, revealing a dependence which is strikingly different from that of a hadron, which is consistent with a large contribution from gluon splitting (Table 2), and which amounts to the structure of the pomeron. In all figures the curves shown correspond to the results of a full QCD fit to obtain parton densities in diffractive exchange.

Quantitative fits of the data to extract factorisable diffractive parton density functions (dpdf), using QCD formalism from proton structure (DGLAP [19, 20]), quantify gluon content as being responsible for $\sim 70\%$ of diffractive exchange momentum [15]. The latest measurements of diffractive deep-inelastic scattering now include the longitudinal structure function F_L^D which, like its totally inclusive partner F_L, has a leading contribution dependent on gluon content, so it is expected to be large. At EDS09 we have seen that there is complete consistency of this first measurement of F_L^D with the above overall picture of large gluon exchanges in diffractive structure.

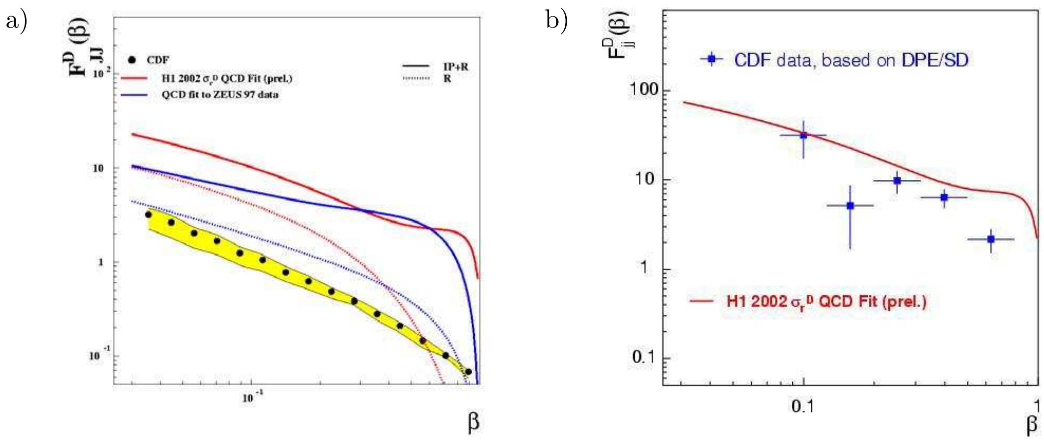


Figure 9: (a) Factorisation breakdown showing the measured cross section for inclusive jet production in single diffraction by CDF at the TeVatron, compared with the expectation using dpdfs from HERA - "gap suppression"; (b) confirmation of the universality of factorisable dpdfs from HERA comparing the measured cross section for inclusive jet production in double diffraction by CDF at the TeVatron.

The establishment theoretically of dpdfs as factorisable, and therefore portable [20], was accompanied by first comparisons of them with measurements of inclusive jet production in single diffraction (Fig. 7a) by CDF at the TeVatron. A massive discrepancy was discovered between what is taken to be a measurement of cross section, and expectation, amounting to a massive (sometimes $\times 10$) breakdown of the expectations of factorisation with the supposedly universally applicable dpdfs [14]. There then followed the invention of the paradigm of rapidity "gap suppression" to explain it (Fig. 9a) in which it is supposed that re-scattering of open colour at low momentum transfer is hypothesised to create hadrons which fill the rapidity gap (Fig. 10). Here at EDS09, CDF have followed this puzzling result with a beautiful sequel using doubly diffractive, inclusive, jet production (Fig. 7b) [14]. A similar analysis of this sample shows, in stark contrast, consistency with the universality of dpdfs, namely "gap restoration" (Fig. 9b).

In Fig. 10 are shown simple diagrammatic approaches to illustrate how the suppression of a gap with additional hadronisation due to open colour interactions is likely to be suppressed when in double *pp* diffraction the probe parton originates from a pomeron, rather than a proton. There are manifestly fewer opportunities in double diffraction for rescattering arising from open colour at small momentum transfer. Furthermore, and perhaps this is the most significant outcome of this new result from CDF, the replacement in double diffraction of a parton by a pomeron as a hard probe means exactly that, namely a remnant-free, "direct", pomeron-parton vertex. These measurements thereby expose a completely new aspect of diffractive physics and "pomeron-pomeron" interactions in which the pomeron takes on the role of a quantum phenomenon which can probe itself!

It is clear from the above that breakthroughs of major significance continue in inelastic diffractive physics. We are now at a stage where we have measurements of a sophistication and

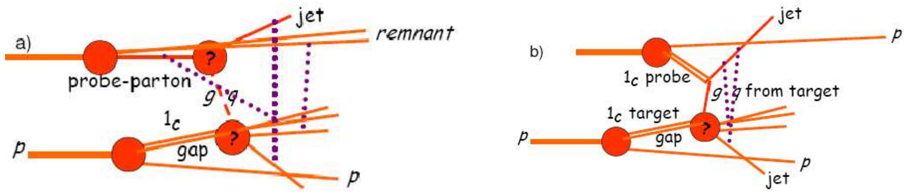


Figure 10: Diagrams illustrating (a) "single diffraction" measurements at a pp collider in which a parton from one proton probes the diffractive exchange of the other; the dotted lines indicate some possible open-colour soft interactions which can occur and which would fill the rapidity gap defining the leading final proton; (b) "double diffraction" measurements in which two rapidity gaps are required with two high p_T jets thereby removing the possibility of substantial open-colour soft interactions which can occur and which would mean that gap suppression was reduced.

precision which must surely tie down the next steps in the direct application of QCD to high energy hadron physics. We have achieved a new level of precision in quantifying experimentally diffractive dynamics as a function of hard scale, while at the same time revealing the make-up of the partonic structure of this dynamics, conveniently, but not necessarily, referred to as the partonic structure of the pomeron. There is now a need to consider this asymptotically free, partonic, structure to see how it could further enable and liberate the theoretical QCD approaches to diffractive dynamics, whose difficulty is so manifestly illustrated in the pioneering, hugely labour intensive, Lipatov-style [4], calculations.

And finally as they say, here at EDS09 we have perhaps seen a glimpse of the next steps in the detailed work which continues to be required. New results with now valuable precision are being obtained at HERA in which forward neutron and forward proton counters have operated enabling measurements of what remains at high energy of non-diffractive, colour singlet, dynamics [21]. By demanding and reconstructing a leading neutron (LN) in an interaction with a lepton $ep \to eXn$, in the language of the Regge asymptotic limit one aims to probe the structure of a colour singlet, flavour exchange, as well as leading proton (LP) production, in regions of $x_L = 1 - x_{I\!P}$ beyond just pomeron exchange (Fig. 11a).

Data have been available since the start-up of HERA, but the results have been difficult to obtain not least because the leading Reggeon is a meson with trajectory intercept $\alpha(t=0) = 0.5$, or more likely less (for π-exchange $\alpha(t=0) \sim 0$), and therefore with a falling dependence on interaction energy (a constant or rising dependence on $x_{I\!P}$, now written as $x_L = 1 - x_{I\!P}$ in the effective splitting function: cf. Table 1). This dependence on x_L, together with the small cross section, also makes the distinction between dynamics which are genuine, colour singlet, exchange (Fig. 11a), and dynamics which arise from that part of inclusive proton fragmentation with a baryon tending to lead, hazardous (Fig. 11b).

Nevertheless, the x_L spectra (Fig. 11c) show a comparison of LP and LN cross sections in a kinematic region for LP in which we know diffraction is dead ($x_L < 0.95$ see Fig. 8a). The difference between the cross sections, together with the subtleties of the different dependencies, already suggest a π-exchange contribution ($\alpha(t=0) \sim 0$) in LN at larger x_L, and higher trajectory meson exchanges in both LP and LN ($\alpha(t=0) \sim 0.5$) at lower x_L.

The job is now to use these data samples to measure the deep-inelastic structure of the

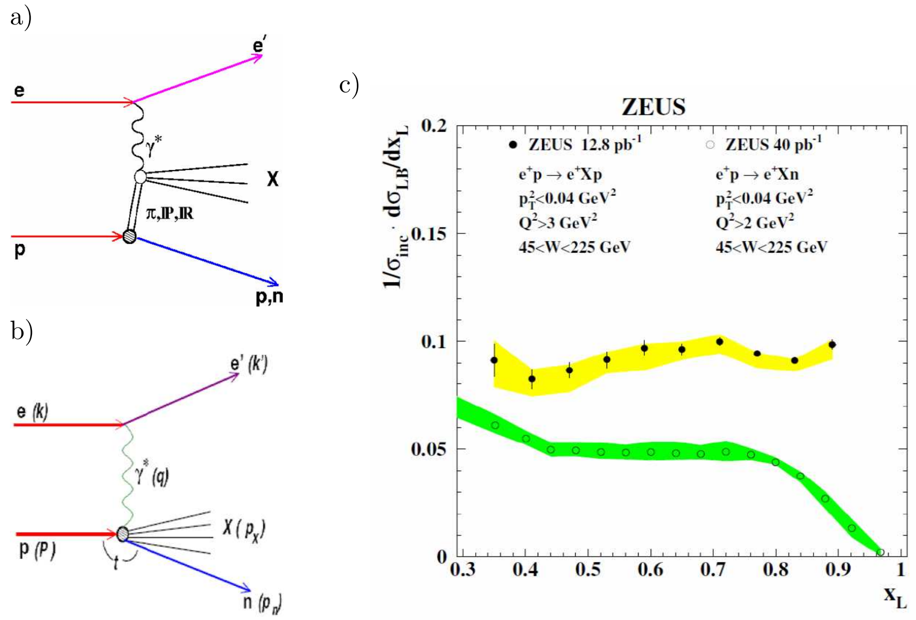


Figure 11: (a) Electron-proton, deep-inelastic, hadron production involving either a leading proton or a leading neutron; (b) electron-proton, deep-inelastic, inclusive hadron production indicating the fact that a "leading" proton or neutron is possible from the incident proton fragmentation; (c) ratio of the leading neutron and the leading proton differential cross sections to the total inclusive hadron cross sections as a function of fractional momenta of the two leading baryons. x_L revealing evidence for a substantial contribution from meson exchanges with Regge intercepts $\alpha(t = 0) = 0.5$ in both leading proton and leading neutron, and a component at largest with Regge intercept $\alpha(t = 0) = 0$ consistent with π-exchange.

interactions with a view to revealing any effects of "hard meson" structure and dynamics, just as has been discussed above for the diffractive component and the "hard pomeron", here in Fig 11c invisible at $x_L \geq 0.95$. The salivating experimentalist is driven by the notion of discovering Q^2-evolving, and therefore non-universal, meson exchanges, together with structure functions of the form of a bound hadron, exhibiting scaling violations consistent with major components from $q \to q$ and $q \to g$ splitting (cf. Table 2), also constrained by appropriate QCD sum rules. For some time now initial analyses have produced results of limited precision for the structure function of the pion, which, in the light of these new data, bodes well for the future [22], and level-headed theorists continue to say that hard mesons will not be significant. So the stage is set!

4 New Experiments

In terms of new experiments we are of course at the dawn of a new diffractive era. Already in the above we have touched on issues and challenges at the LHC Terascale.

It is now the case that substantial forward instrumentation is installed and ready to go round the CMS experiment, prosaically called TOTEM (Fig. 12a). Both experiments will run simultaneously and synchronously, so elastic and inelastic diffraction are anticipated just as soon as some luminosity is available at the LHC. Similar measurements are now possible with forward detectors at ATLAS. But also for ATLAS, a major initiative is underway to take advantage, as first pioneered in H1 at HERA, of possible modifications to the LHC cryogenic system for proton detectors 420 m either side downstream. The intention is to greatly enhance the kinematic acceptance for inelastic diffraction (with of course "Higgs production with no mess" very much in mind) [23].

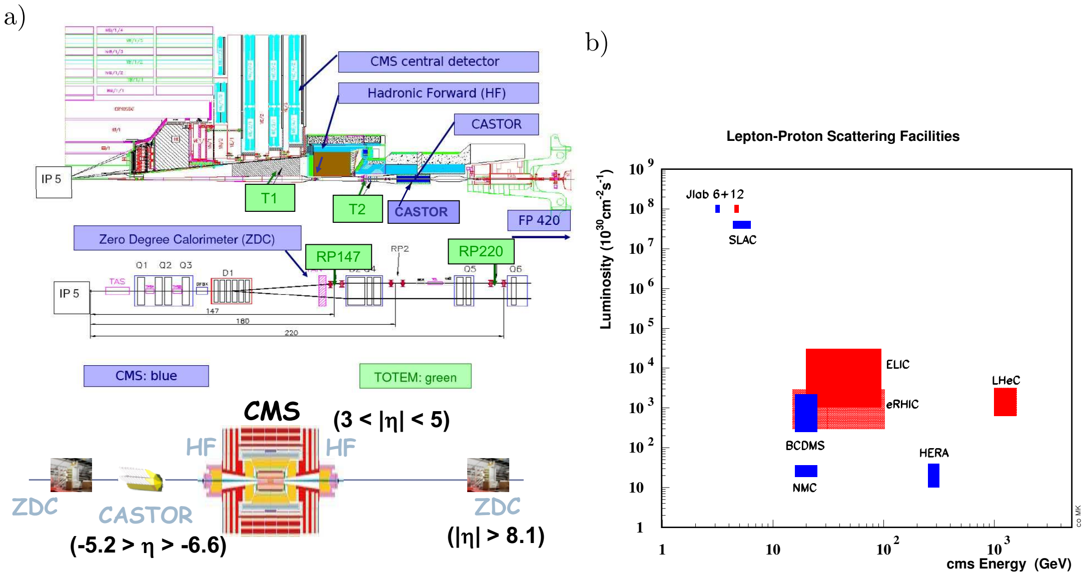


Figure 12: (a) The situation of the TOTEM experiment with respect to the CMS experiment at LHC Point 5. (b) Lepton-proton luminosity at all lepton deep-inelastic hadron experiments hitherto and all proposals now in evaluation, demonstrating the supremacy in both energy reach and luminosity of the proposed LHeC collider.

Another possible upgrade of the LHC, which has been kicked around in the long grass for years, indeed for as long as the LHC was proposed in the LEP tunnel, is for an intense electron (and positron) beam of 50 to 150 GeV momentum in collision with one of the LHC hadron beams, either protons or heavy ions, a Large Hadron-Electron collider LHeC.

First evaluations have been published [24]. It is demonstrated a) that ep and e-ion physics is possible alongside an on-going LHC programme, and b) that huge luminosity, in fact luminosity which exceeds any previous, deep-inelastic, lepton-nucleon experiment by factors except for that at the pioneering SLAC end-station in the late 1960s (Fig. 12b), is possible (power permitting) with a kinematic reach in ep energy of at least 1.4 TeV.

An initiative is now underway, requested by ECFA, endorsed strongly by NuPECC, the host laboratory CERN and the CERN Council Strategy group, and "blessed" by ICFA[5], to

[5] The acronyms need defining: European Committee on Future Accelerators ECFA, Nuclear Physics European

prepare and then submit a Conceptual Design Report some time in late 2010 [25]. LHeC will then be "on the table" alongside other future possibilities at the LHC at CERN, and hopefully will be given even more impetus to prepare a Technical Design Report. Needless to say, the opportunities for new measurements of diffraction encompassing a huge kinematic range, and with also ion targets, are "mind boggling"!

Given the venue of EDS09, perhaps the most appropriate session has been that concerned with new experiments [26]. Taking advantage of the unique breadth of expertise present, the session was enlivened by a discussion of how to decide a running strategy for data taking during the first period of LHC collisions imminent later this year (2009). As a result, there cannot ever before have been such a wide representation of theoretical and experimental expertise in the immediate decision making affecting the first physics from a brand new machine at a brand new energy scale!

5 Conclusion

Diffraction is at the heart of hadron physics, and hadron physics remains one of the unresolved conundrums of the Standard Model, and possibly also beyond.

Despite its decades-long standing as the major feature of high energy hadron interactions, and the substantial phenomenology which grew up with it based on the analyticity of the hadronic scattering matrix, developments in only the last 15 years have revolutionised our approach and understanding of diffraction in terms of QCD. This recent progress has resulted from innovative new measurements at the *pp* and *ep* colliders at the Fermi scale, the TeVatron and HERA, together with intense synergy between experimentalists and theorists. With this progress comes the recognition and definition of new opportunities in the future. The programme at EDS09 reflects this state of affairs perfectly.

These opportunities span a wide energy range.

The energy frontier in the immediate future will soon pass from the TeVatron to the LHC, where we can expect diffractive physics results, elastic and inelastic, with the first *pp* collisions.

But as has always been the case in hadronic diffraction, new understanding brings new opportunities at lower energies, where already one can see a huge program developing concerned with exclusive production leading to more precise measurements to pin down the soft-hard interface. Exclusive electroproduction will produce precision proton tomography which will take us forward in achieving better understanding of the diffractive coupling of the proton. Continuing synergy of these initiatives with the extension of the energy frontier to the Terascale cannot but influence radically our quantitative picture of diffractive scattering and dissociation.

Regrettably the HERA collider terminated before it could fully exploit the opportunities that new investment would have brought in electron-ion physics and the opportunities this brings for much progress in low-x, and therefore diffractive, physics. This loss may yet be recouped using the RHIC beam at Brookhaven (eRHIC) or with ELIC at JLab, but with nothing like the HERA kinematic reach (Fig. 12b).

So until an electron beam can be constructed at CERN, and an LHeC realised, elastic and diffractive scattering, and thus EDS meetings, will be concerned with classic hadron-hadron experimentation at the LHC *pp* energy frontier, alongside what will inevitably be the on-going development of new QCD-driven phenomenology based on data we have and will still be able

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Collaboration Committee NuPECC, International Committee on Future Accelerators ICFA.

to take at lower energies. This is already an important, and a wonderful, horizon. I commend it to you all.

Acknowledgements

Accounts of all the results which I have presented here can be found in talks written up in these proceedings. They depend on the work of many, most of whom have not been present at EDS09. To all I give thanks. I have unashamedly plagiarized and copied from these EDS09 presentations in formulating this summary. I thank everyone concerned for letting me do so, and I hope that I haven't misrepresented anything.

The task of the last speaker must include calling for a vote of thanks to the organizers of EDS09, especially the conference staff here at CERN, who have worked like Trojans to ensure that EDS09 has been such a gripping, productive, and memorable meeting. On behalf of you all, thank you to all who set up and who ran this conference.

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