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QCD: how we can help each other

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Abstract. A brief summary is given of the outstanding issues in experimental work on the strong interaction at collider experiments. I focus particularly on those areas where more than one collider can address the same issue.

(Some figures in this article are in colour only in the electronic version; see `www.iop.org`)

1. Introduction

The theory of strong interactions, quantum chromodynamics, has been around for quite a while and has been confronted with a wide range of data. Whilst there has been a great deal of success, certainly enough to confirm QCD as the leading candidate theory, the situation is by no means as clear cut as that in the electroweak sector. High-precision data on hadronic physics exist in abundance, but few calculations with reliability of better than a few per cent exist. Not only do the perturbative series converge slower than those for QED because α_s is larger than α, but more seriously the non-perturbative, long-distance phase of QCD always intervenes between a parton (perturbative) calculation and measurable hadrons.

So there is much interest in studying QCD further, both in terms of making measurements which can be more reliably predicted, and in improving calculational techniques. QCD is *the* theory of how hadrons and nuclei stick together. It is unique in the standard model in exhibiting both strong interactions and asymptotic freedom in experimentally accessible regimes. It is also ubiquitous. Around half of high-energy physics is done with incoming parton beams, and more than half of all interesting decays are to quarks or gluons.

There is clearly no chance of covering all this here. I will focus on current areas of common interest, and will leave the fertile fields of diffraction and heavy flavours to others [1, 2]. Furthermore, since measuring the coupling constant α_s is the most obvious area of overlap between experiments, it is frequently covered in reviews such as this and is worth a whole talk in itself. I will not attempt to cover this topic here.

2. Hadronic structure

The classic measurement of hadronic structure is the measurement of the parton distributions as a function of momentum fraction in the proton, by which an integration over transverse momentum of the quarks and gluons is implied so that they are treated as being collinear with the proton. The quarks are directly measured by F_2 (HERA and fixed target data are shown in figure 1). The gluons are also constrained via scaling violations and more direct measurments such as jets or charm. However, they are less well known, particularly at high x, which means high $\hat{s}$ in a hadron collider.

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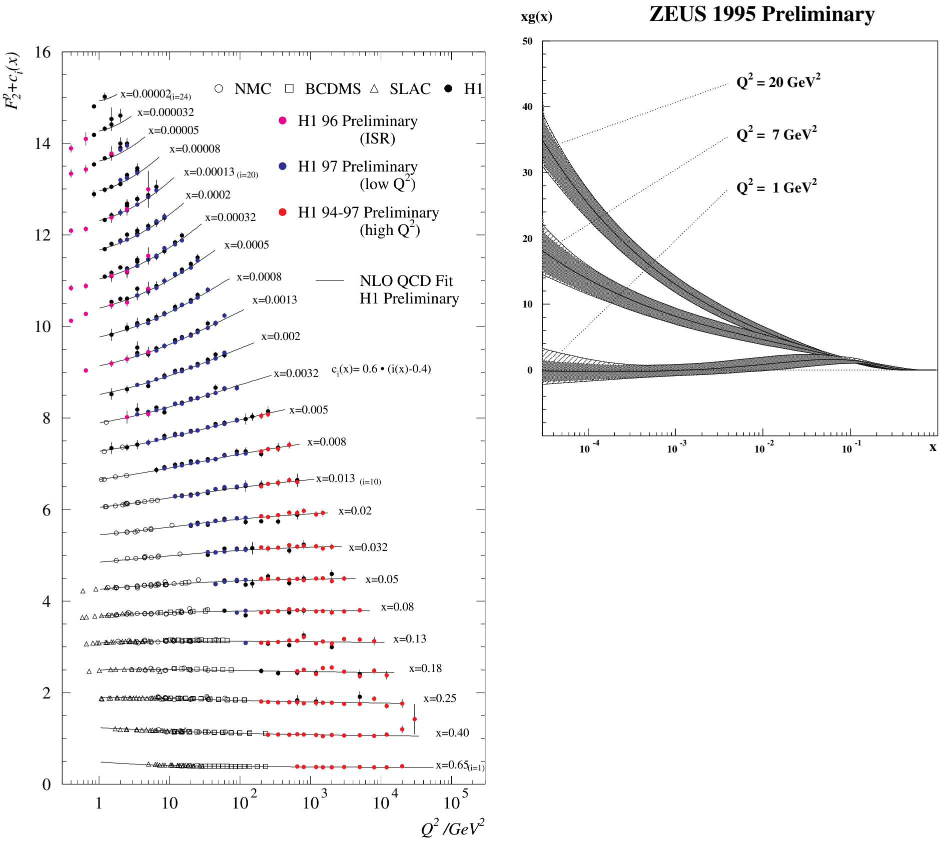

Figure 1. F_2^{proton} and the gluon distribution [3].

2.1. *Uncertainities in parton distributions*

These distributions are a necessary input to all perturbative processes at Tevatron and HERA, such as high-E_T^{Jet} cross sections, and W, Z, t, γ production. In accurate measurements of such processes, and in searches for new physics, estimates of the true uncertainty (rather than the degree of theoretical consensus) in parton distributions can be critical [4]. A fairly well-worn example of this is the kerfuffle about the Tevatron inclusive jet measurements. One of a number of good reasons for doubting that the apparent rise in the CDF cross section above the theory at high E_T^{Jet} is a signal for new physics is the fact that the discrepancy can be removed by adjusting the gluon distribution at high x [5]. It is true that the gluon distribution thus obtained is peculiar in the extreme, but it serves to illustrate the need for firm data on parton distributions across the widest possible kinematic regime. It should also be noted that other systematic uncertainties in these cross sections are also significant [6].

2.2. k_T *of the incoming partons*

In the strict parton model, the transverse momentum of quarks and gluons inside the hadron is neglected. This approximation is still made even when QCD corrections are introduced in the DGLAP [15] formalism. However, it is increasingly clear that this approach is inadequate

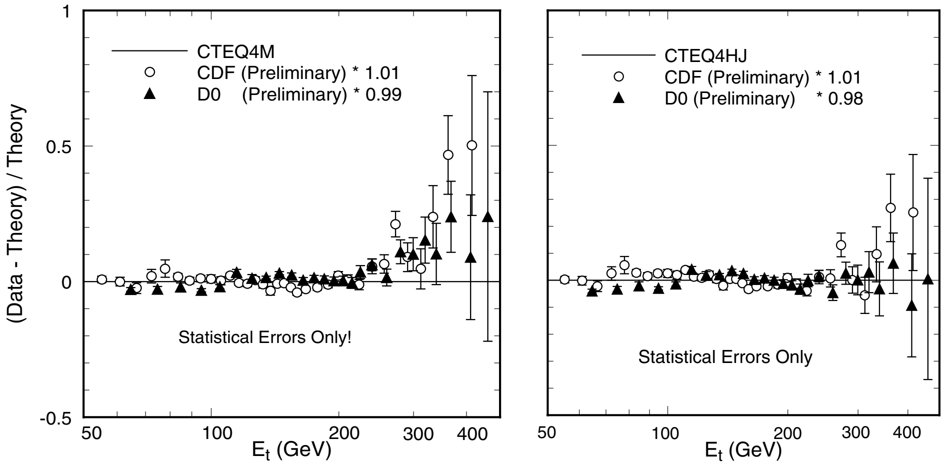

Figure 2. Tevatron high-$E_T^{\rm Jet}$ cross sections.

in several cases. The low-x kinematic reach of HERA and the desire to make precise measurements at the Tevatron demand an understanding of the transverse momentum of the quark and gluon fluxes which are the starting point for the calculation of the hard processes.

For example, one way of constraining the gluon distribution at high x is prompt photon production, ($\mathrm{qg} \to \mathrm{q}\gamma$). A large amount of data exist from fixed-target, $\mathrm{p\bar{p}}$ and $\gamma\mathrm{p}$ experiments, as well as from LEP. However, there are several problems associated with the interpretation of these data; in particular, it is difficult to fit all the data with NLO QCD calculations. The presence of incoming partonic k_T has been appealed to as a mechanism for resolving this discrepancy. If the amount of k_T is tuned for each measurement, agreement can certainly be obtained—see, for example, figure 3(*a*)—but at a heavy price in terms of the loss of predictive power. Large intrinsic k_T effects should, in principle, be amenable to perturbative calculation.

D0 actually measure the k_T of diphotons, as shown in figure 3(*b*). Again, significant k_T is required to fit the data. The measurement of prompt photons at HERA (in $\gamma\mathrm{p}$ events) is shown in figure 3(*c*). In this case the calculation agrees with the data without the need for any k_T. Several approaches are tried to resolve such a dilemma. Aurenche *et al* describe all fixed-target data without k_T, except for E706. However, in doing this they rule out lowest E_T ($<$4.2 GeV) data because their studies show that there is no scale at which the calculations are stable. By performing a QCD resummation of soft gluons, Catani *et al* obtain a reduced scale dependence. It may be that a combination of these approaches would allow a fit along the lines of the Aurenche group which also ‘recovers’ the low E_T data—although simultaneous description of the E706 data and the rest of the data set appears unlikely.

A related point to note in the case of prompt photons is that an absolute isolation criterion is not infra-red safe, since an arbitrarily soft gluon radiated into the isolation cone flips the photon between pass and fail. With careful definition of the isolation criteria, calculations can be compared with LEP prompt photon data to extract the photon fragmentation functions, which can then be used at the Tevatron or HERA [8].

There are also several resummed calculations and data on Z transverse momentum. In general it is clear that resumming significantly affects the result, and seems to improve agreement. However, there are some discrepancies between the results of the different theory groups [9] which remain to be understood. These processes are of critical importance since

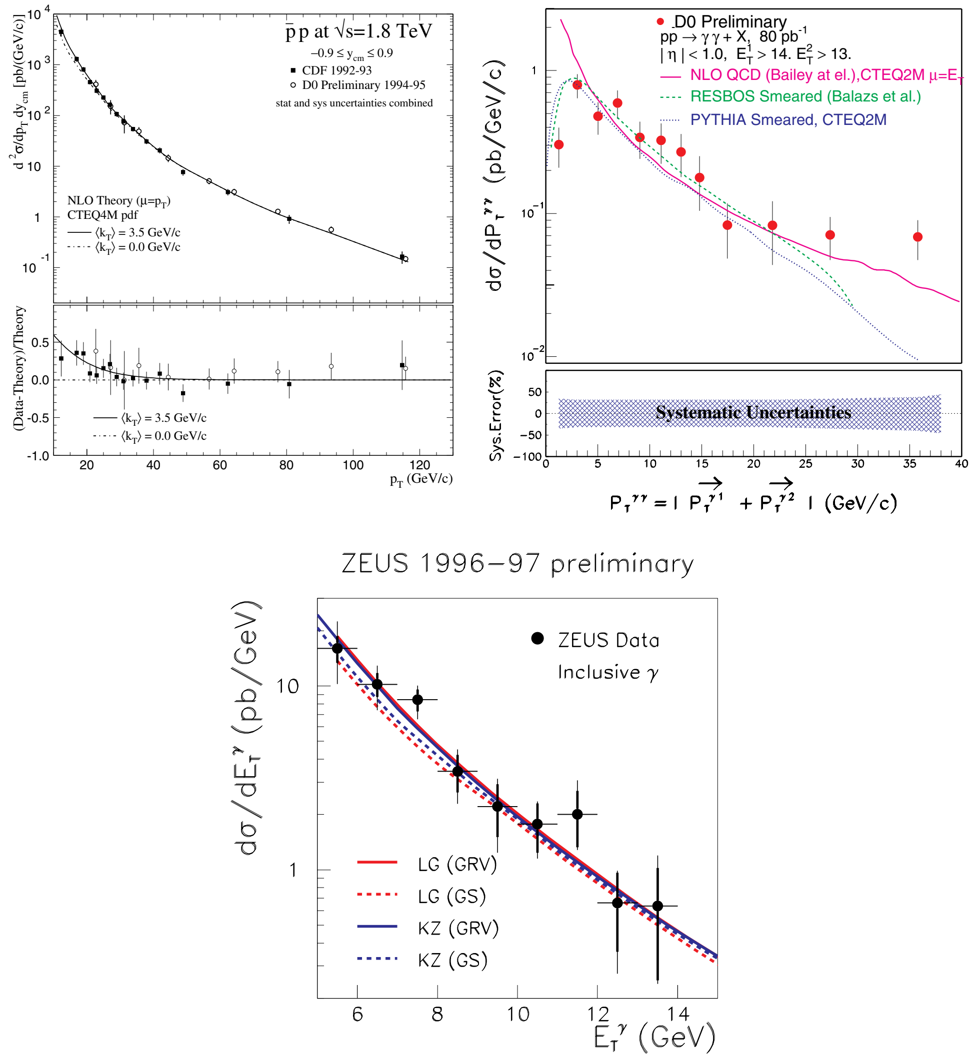

Figure 3. Prompt photons [7].

the measurement of the Z k_T is used to predict the W k_T at the Tevatron, which forms one of the limiting systematic uncertainties on the mass measurement [10].

2.3. Photon ‘structure’

Another fruitful area for the investigation of QCD, where this time LEP and HERA both contribute, is in the measurement of photon structure—that is, the measurement of the splitting of the photon into $q\bar{q}$ and the subsequently developed hadronic system. Comparisons between the proton and photon bring out several features. Because of the presence of the $\gamma \to q\bar{q}$ splitting, the scaling violations in the photon are positive at all x (as shown in figure 4(*a*), whereas for the proton they turn over at $x \approx 0.2$. The low-x behaviour of the photon structure is also an issue of great interest. The rise in F_2 at low x seen at HERA [3] can, in general, be

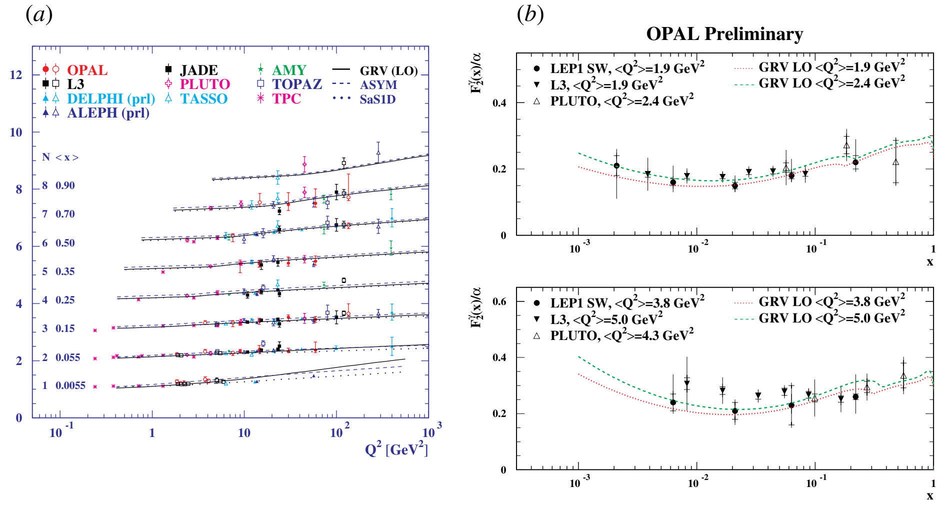

Figure 4. Photon structure: (*a*) scaling violations and (*b*) x distribution.

well modelled by DGLAP evolution [15]. If this mechanism is responsible for the rise, it is hard to avoid the conclusion that a similar rise should occur in the photon structure function. This expectation is explictly contained in the GRV [11] suite of parton distributions. Some of the more recent data are shown in figure 4(*b*). They are not yet accurate enough to see the rise (or its absence) but with improved statistics and systematics from the full LEP2 data set, this may be achieved.

Since at HERA the photon is probed by a parton from the proton, HERA does not measure F_2^γ. The HERA equivalent of F_2^γ is a jet cross section. This has the major disadvantage that hadronization, as well as choice of jet definition, plays a role. An advantage, however, is that the gluon distribution in the photon enters directly in the cross section at leading order. The measured cross sections may be compared with NLO pQCD calculations, which take a photon parton distribution function (PDF) as input. If the jets have high enough transverse energy (E_T^{Jet}) the hadronization corrections are expected to be at the level of a few per cent. The probing scale is something of the order of E_T^{Jet}.

The latest ZEUS preliminary data are shown in figure 5 for differential cross sections defined as in [12] but now measured above a variety of E_T^{Jet} thresholds, increasing the hard scale. The data are compared with a calculation [13] using the AFG-HO Photon PDF [14]. The high-x_γ^{OBS} data are in excellent agreement with the theory. However, in the region including both high- and low-x_γ^{OBS} data there is a discrepancy, particularly in the forward region, where the lowest values of x_γ^{OBS} are probed.

There is a wide variety of jet measurements available from HERA, as well as the prompt photon measurements discussed above, and charged particle multiplicities. All of these measurements have sensitivity to the photon structure, and a full QCD fit to these data is very desirable.

Two other areas of interest in photon structure are the charm structure, and the structure of the virtual photon (see [2,16]). Measurements exist from both LEP and HERA. Both processes offer the possiblity of a fully calculable parton structure—an excellent test of QCD.

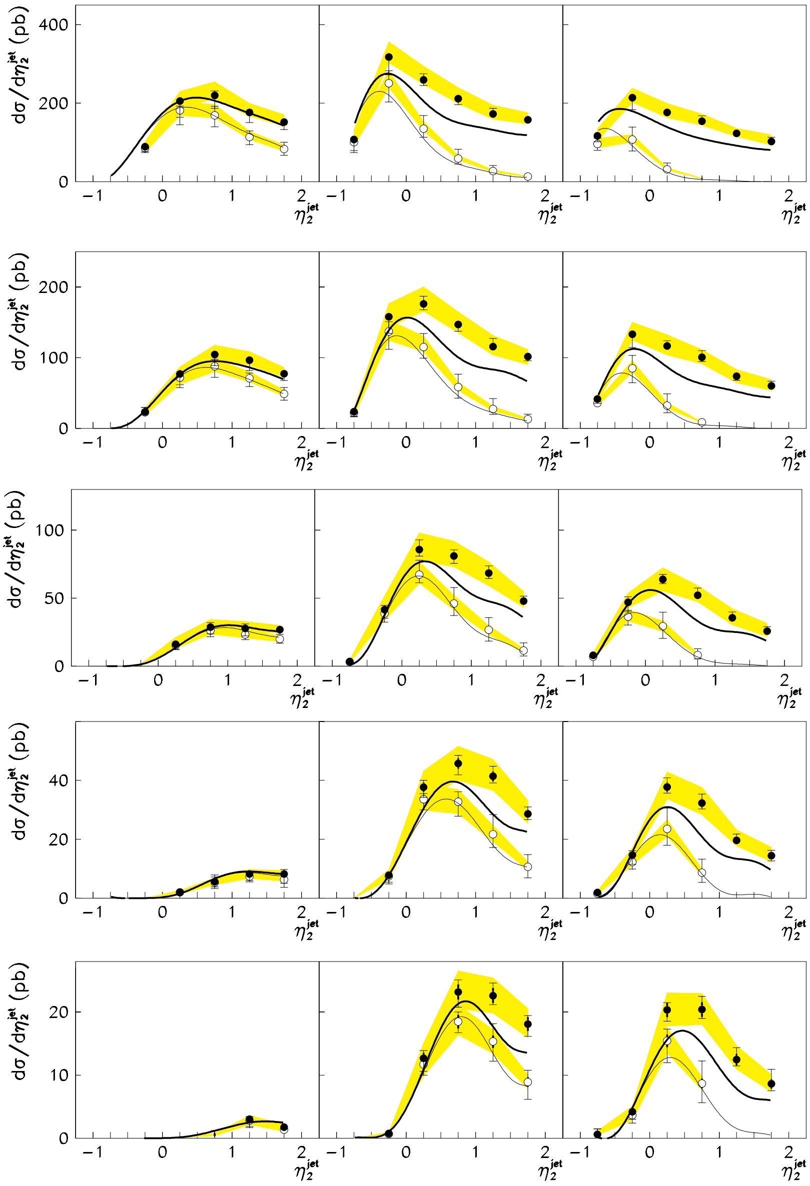

Figure 5. Dijet cross sections at HERA.

3. Jets and fragmentation

3.1. Underlying events

Many of the issues faced in photon structure studies at HERA are in fact more general jet physics issues. Features such as the QCD radiation within and around jets and non- or semi-perturbative remnant interactions play an important role and can be studied at LEP, HERA and the Tevatron. One clear message from recent history and from the discussions at this workshop is that there is a need for great transparency in the treatment of such effects by the experiments.

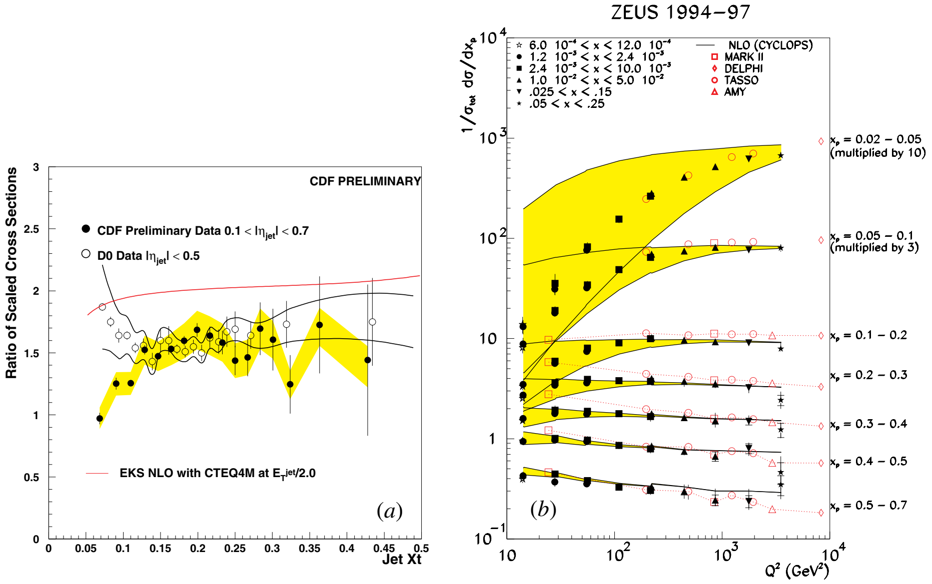

Figure 6. (*a*) Ratio of jet cross sections at the Tevatron at 630 and 1800 GeV [20]. (*b*) Fragmentation functions in the current region at HERA compared with LEP and with the QCD prediction [21].

Details of the jet definition and of the corrections applied can have large and unexpected effects and need to be reproducible in calculations before clear physics conclusions can be drawn. An example of this is seen in figure 6(*a*), which shows the ratio of the inclusive jet cross section at the Tevatron at two different beam energies (630 GeV and 1.8 TeV) as a function of the scaled E_T^{Jet}. There is clearly no satisfactory agreement between the data and QCD, and although the data sets are consistent at high E_T^{Jet} they diverge at lower E_T^{Jet}. A possible explanation for this is that both experiments apply corrections for an 'underlying event' which behave differently as the centre-of-mass energy changes. Certainly, underlying events are a significant (or even dominant) systematic error in the interpretation of jet production in hadronic collisions. If underlying event corrections are made at the same time as genuine experimental corrections for pile-up or calorimeter noise, for instance, they become very difficult to untangle and thus introduce significant and unwelome model dependence into the measurement. One promising model for underlying events is multiple partonic interactions in the same hadronic collision. Fits have been made to LEP and HERA data constraining multiparton interaction models [17], and there is evidence for multiparton interactions in p$\bar{\mathrm{p}}$ events [18]. The amount of underlying event (even apart from QCD radiation) explicitly depends upon the hard subprocess in these models. It is not clear whether is is possible to fit $\gamma\gamma$, γp and p$\bar{\mathrm{p}}$ with the same model, and even less clear what might be expected at the LHC.

3.2. *Fragmentation and event shapes*

Jet variables are a special case of an event shape. There is an increasing array of data and calculations of event shapes at LEP and HERA [19]. The calculations make use of 'power corrections' to fit a low-energy effective coupling $\bar{\alpha}_0$. This provides a powerful way of investigating universality of the hadronization process and subsequently extraction of both α_s and $\bar{\alpha}_0$. It is clearly of great benefit to confront such calculations with a wide array of data from all three machines.

Another way in which comparisons can be made across experiments is to compare the current region fragmentation (in the Breit frame) at HERA with half a hemisphere of $e^+e^- \to$ hadrons. An example of such a comparison is shown in figure 6(*b*). There is good agreement at high scales between all the data sets and the theory. At lower scales the data diverge, and the theory becomes unreliable—there is evidence for strong higher-order corrections in this region. The theory also becomes unreliable at low x, where non-perturbative effects become significant. An *ad hoc* estimate of a power-suppressed correction is indicated by the shaded band in the figure.

4. A personal list of priorities for this workshop

There two major areas where progress is needed and can be expected to be stimulated by more contact between Tevatron, HERA and LEP experiments. One is better PDFs for the proton and photon, including error estimates and (at least in the case of the proton) k_T, and possibly off-diagonal terms, something I have had no space to discuss here. A related topic is the treatment of charm and beauty hadro- and photo-production. A second area is the relationship between partons and hadrons in the final state. Better treatment of the 'underlying event' and hadronization effects across all experiments, and a better understanding of isolation criteria for prompt photons and definitions for jets. The reward would be a qualitatively better understanding of the strong interaction, with knock-on benefits for many other measurements.

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