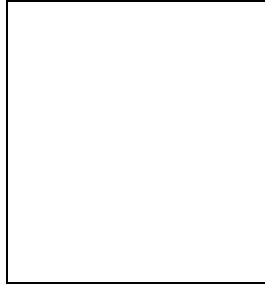


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QCD AND HARD DIFFRACTION AT THE LHC

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As an introduction to QCD at the LHC I give an overview of QCD at the Tevatron, emphasizing the high Q^2 frontier which will be taken over by the LHC. After describing briefly the LHC detectors I discuss high mass diffraction, in particular central exclusive production of Higgs and vector boson pairs. I introduce the FP420 project to measure the scattered protons 420m downstream of ATLAS and CMS.

1 Recent QCD Studies at the Tevatron (CDF and DØ)

1.1 Jets

Every pp and $p\bar{p}$ interaction is QCD! (Even two photon processes $p + p \rightarrow p \oplus e^+e^- \oplus p$ and $p + p \rightarrow p \oplus W^+W^- \oplus p$, where \oplus means a large rapidity gap with *no particles* have small QCD corrections!) From May 2003 to May 2005 CDF (DØ) published 43 (10) “QCD” papers on many topics^{1,2}. All of these will be studied at the LHC, most in the early low-luminosity period.

Most obviously QCD is the high p_T jet (J) production cross section, its E_T, η and \sqrt{s} dependence. The Tevatron took data at $\sqrt{s} = 630, 1800$ and 1960 GeV. Hopefully the LHC will take some data below 14 TeV ... 1960 GeV would be useful to compare pp and $p\bar{p}$, albeit with different detectors. Hadron jets are not uniquely defined objects; we need some *algorithm*. Good algorithms give a good approximation to a scattered parton’s 4-momentum (itself not well-defined quantum mechanically) and allow reasonable comparisons between experimental data and a theoretically-based simulation. Most commonly used are *cone* (circle in η, ϕ) and k_T (transverse momentum w.r.t. a jet axis) algorithms. Internal jet structure (charged multiplicity distributions, quark/gluon differences, c - and b -quark content), di-jet azimuthal separation, and

3-jet events have all been studied, and values of $\alpha(s)$ extracted. At the Tevatron central jets with E_T below 50 GeV are mostly gluon jets; above 400 GeV (the spectra now extend to ≈ 600 GeV mostly from $q\bar{q}$ scattering). This E_T dependence enables us to study q/g fragmentation differences. At the LHC the jets with $E_T \lesssim 100$ GeV will be nearly pure gluon jets. Events at the highest E_T are mostly spectacularly clean (on event displays) 2-jet (or sometimes 3-jet) final states. Projected cross sections at the LHC extend, in 100 fb^{-1} , to $E_T \approx 4 \text{ TeV}$ ($M_{JJ} = 8 \text{ TeV}$) with still a few events per 100 GeV bin. Let us hope these projections are quite wrong! Let us hope for peaks or excesses or even a cut-off (due to black hole production) - the end of high- p_T physics!

The LHC will extend our coverage in the (x, Q^2) plane ($x = \text{Bjorken-}x$) by more than an order of magnitude to smaller x and higher Q^2 ... up to $\approx 10^8 \text{ GeV}^2$ corresponding to a transverse distance $\approx 2 \times 10^{-18} \text{ cm}$. To reach the smallest x -values, $\lesssim 10^{-5}$, requires very forward detectors like LUCID (ATLAS) and TOTEM (CMS). Very forward jet measurements allow important studies of BFKL and Mueller-Navelet jets. A BFKL pomeron is a color-singlet exchange between quarks, constructed from a pair of reggeized gluons in a ladder. It enhances the cross section for qq -scattering especially at large $\frac{x}{t}$, i.e. for jets with large rapidity separation. It is interesting to study both the “elastic” case (with a large rapidity gap Δy between them) and the inelastic case (with n minijets in between). This is a fundamental probe of a new regime: non-perturbative QCD at short distances; it requires very forward hadron calorimeters in both forward directions.

1.2 Particle Production

Generic particle production has been much studied at the Tevatron, and is important information for our understanding of non-perturbative QCD. Results on total production cross sections and/or their p_T, η and \sqrt{s} dependence have been published for strongly interacting particles ($K_S^0, \Lambda, c(D), J/\psi, \psi', B, B\bar{B}, \Upsilon, t\bar{t}$) and not-strongly interacting ($\gamma, e^+e^-, W, Z, VV(V = \gamma, W, Z)$). In all cases the differential production cross sections are compared with Monte Carlo simulations (which have some QCD-inspired hadronization code) and generally agree within claimed uncertainties. B-hadrons and Υ are measured from $p_T = 0$ to 25 (20) GeV/c respectively, the former thanks to a fast secondary-vertex trigger in CDF.

1.3 Hadron Decays

Hadron decays are also of course QCD, albeit non-perturbative, and thanks to the special triggers and large production rate of B -hadrons, especially B_s and B_c which are inaccessible at B -factories, new and important physics is done. At the LHC this program will continue, with LHCb but also with ATLAS and CMS. Results from the Tevatron on the following decays have been published (lifetimes and branching fractions): $B_s^0 \rightarrow \phi\phi, J/\psi\phi; B^0 \rightarrow \text{hadrons}, \gamma X, J/\psi X, J/\psi K^* \pi^+ \pi^-$ and $\tau(\Lambda_b \rightarrow J/\psi\Lambda)$. CDF made the first observation of the decay $B_s \rightarrow \phi\phi$ with 12 events on a background of 2, and $\text{BR}(B_s \rightarrow \phi\phi) = [1.4 \pm 0.6(\text{stat}) \pm 0.2(\text{syst}) \pm 0.5(\text{BRs})] \times 10^{-5}$. The rare decay $B_d \rightarrow \pi^+ \pi^-$ has also been observed with a BR 5×10^{-6} . At least a factor $\times 25$ in sensitivity is expected from the Tevatron.

1.4 Hadron Spectroscopy

Hadron spectroscopy with c - and b -quarks provides important tests especially of Lattice QCD. The hidden charm state $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ was clearly seen in CDF within a week of its discovery by BELLE. More attention should be paid by Tevatron physicists to its potential in this regard. Pentaquark searches (e.g. $\Xi^- \pi^-$) proved negative, despite very high sensitivity. A competitive measurement of $\Delta m(D_s^+ - D^+)$ was published. CDF observed $B_c \rightarrow J/\psi \pi^+$ as a

narrow peak at $6.287 \pm 0.005 \text{ GeV}/c^2$ (much higher precision than the Run 1 observation in the semileptonic decay). This state is the most perturbative hadron that does not decay strongly. Its spectroscopy will be very valuable ($B_c^* \rightarrow B_c \gamma, B_c \pi \pi$). A possibility is that hadrons with two heavy quarks can be made relatively cleanly in double pomeron interactions ($IP(gg)IP(gg) \rightarrow B_c BDX?$)

1.5 Probing Very Small- x Gluons

At very small $x \approx 10^{-5}$, gluon densities become very high and new saturation phenomena can occur. At HERA $q(x)$ has been measured and $g(x)$ inferred by evolution and by charm production. At the LHC very low- x gluons can be measured more directly. In a 2-parton scattering process resulting in n jets with p_T^i and η_i , the incident parton x 's are given by:

$$x_{1(2)} = \frac{1}{\sqrt{s}} \sum_{i=1}^n p_T^i e^{+(-)\eta_i}$$

so e.g. for $\sqrt{s} = 14 \text{ TeV}$, with two jets with $p_T = 5 \text{ GeV}$, $\eta_1 = \eta_2 = 4$ (2.1°) we have $x_1 = 0.08$ and $x_2 = 1.4 \times 10^{-5}$. To reach this physics we need to instrument the few degree region with tracking and calorimetry (electromagnetic and hadronic) measuring muons, J/ψ , jets and photons. CASTOR (in CMS) and TOTEM do this only partially.

1.6 Underlying Event

In a hard collision producing jets color fields are everywhere and it is not possible to separate an “underlying event” from jet fragmentation products. However we can define a region of solid angle perpendicular in azimuth to a jet axis and measure charged particle multiplicities and p_T -spectra there, to make comparisons between soft collisions (no high p_T jets), hard collisions and event generators. This is interesting in itself, as well as affecting the comparisons of jet spectra with perturbative QCD calculations. A special case is the study of the associated hadrons in events with one or two $W \rightarrow l\nu$ or $Z \rightarrow l^+l^-$, when the underlying event is unambiguously defined. CDF has made many studies: e.g. the p_T spectrum at 90° to the leading jet axis is harder than in minimum bias interactions; the number of charged particles there is also higher but hardly changes as the leading (charged) jet increases from $p_T = 20 \text{ GeV}/c$ to $150 \text{ GeV}/c$. Such observations allow tuning of Monte Carlo generators (e.g. PYTHIA Tune A) for the Tevatron, giving us our best estimates of events at LHC.

Part of the underlying event can be double or multiple parton scattering (DPS/MPS). ISR data hinted at the existence of DPS observing 4 “jets” that seemed to be more pair-wise back-to-back than expected from double bremsstrahlung ($2 \rightarrow 4$). It has been more clearly seen in UA2 and in CDF (with $\gamma + JJJ$). One can study specific parton correlations, e.g. if quarks are accompanied by a correlated gluon cloud we should have a positive correlation between a Drell-Yan lepton pair and a $c\bar{c}/b\bar{b}$ pair. If di-quarks have some significance in the proton wave function then double Drell-Yan could be enhanced in $p\bar{p}$ collisions.

1.7 Diffraction and Rapidity Gaps

Since May 2003 results from the Tevatron included diffractive production of di-jets and J/ψ , inclusive double pomeron exchange *DIPE*, and double-gap events [$XGXG\bar{p}$] where X is “hadrons” and G is a rapidity gap. The latter process is like *DIPE* with one proton dissociating. We showed that if the price paid for a rapidity gap is about 0.01, the extra price for a second gap is only about 0.1. Prior to 2003 a wealth of diffractive data has been published from the Tevatron ($J = \text{jet}$): $\sigma_T, \frac{d\sigma}{dt}, \frac{d\sigma}{dM^2 dt}(SDE), SDE \rightarrow JJ, J/\psi, b, W, Z, DIPE \rightarrow JJ$ and $J - G - J$.

At the LHC we have a larger rapidity range than at the Tevatron, $\Delta y = 2 \ln \frac{\sqrt{s}}{m_p} = 19.2$ (cf. 15.2 at the Tevatron). Noting that as a rule-of-thumb a hadronic cluster takes up about $\Delta y = 2 \ln M(\text{GeV})$ in rapidity, we can have the following situations: (a) Single Diffractive Excitation up to $M = 2$ TeV with a $\Delta y = 4$ gap (dominated by \mathbb{P}) (b) Opposite side very forward jets separated by a $\Delta y = 6$ gap (c) $D\mathbb{P}E$ with a 700 GeV central state and two $\Delta y \gtrsim 3$ gaps (d) $p - G3 - X - G3 - X - G3 - p$ multi-pomeron exchange with $M(X) \approx 6$ GeV and 3-unit gaps.

2 At the LHC

2.1 Detectors

Ways in which the Tevatron program and the LHC program can mutually enhance each other have been studied in the series of TeV4LHC Workshops (google tev4lhc). The QCD group had several subgroups on pdf's, jet algorithms, matrix element/Monte Carlos, hadronization and underlying events, and diffraction.

The LHC is a *QCD Machine* and *all* the experiments are *QCD Detectors*. I will not say more on ALICE, very QCD oriented in its study of heavy ion collisions and possible QCD phase transitions, and LHCb which will teach us not only about CP-violation but much about hadron spectroscopy and decays. The QCD potential of both the major detectors, ATLAS and CMS, will be greatly enhanced by detectors in the forward and very forward regions. At the same intersection (P5) as CMS the TOTEM experiment is designed to measure σ_T , elastic scattering and single diffraction, with some special medium/high- β LHC operation and hopefully different \sqrt{s} values. Apart from a series of roman pots out to 215m, the TOTEM T1 and T2 detectors provide some tracking and calorimetry in the forward regions, and T2 is followed on at least one side by the CASTOR(CMS) calorimeter. Together TOTEM and CMS attempt to cover 4π with detectors and this enables a rich diffractive program. ATLAS does not have similar coverage; there is to be a forward multi-cell gas Cerenkov counter, LUCID, and some roman pots, motivated by luminosity measurements but with some diffractive physics capability. Groups in both CMS (with TOTEM) and ATLAS would like to add very forward proton detectors, 420m downstream on both sides, a project in the R&D phase called "FP420"³.

2.2 Central Exclusive Production

Central Exclusive Production, $pp \rightarrow p \oplus X \oplus p$, where X is a specific state, becomes very interesting at the LHC; according to the above rule-of-thumb $M_X(\text{max}) \approx 100$ GeV at the Tevatron becomes ≈ 700 GeV at the LHC. We therefore reach into the domain of Higgs H , W^+W^- , ZZ , $t\bar{t}$ production and maybe the unknown X . The possibility of seeing $pp \rightarrow p \oplus H \oplus p$ is exciting. The main channel for H production at hadron colliders is gg fusion through a top loop. Another gluon exchange can cancel the color and even leave the protons in their ground states, to be measured way downstream (after 116m of 8T dipoles in a vacuum!). The cross section has been estimated⁴ to be about 3 fb for a SM H of about 130 GeV, giving some 100 events (\times acceptance) in a 30 fb⁻¹ year. There are theoretical uncertainties involving skewed gluon distributions, gluon k_T , gluon radiation (Sudakov form factors) etc, estimated to be a factor ≈ 2.5 . The theory can be tested at the Tevatron by the same process with the top loop replaced with a $b(c)$ -loop $\rightarrow \chi_{b(c)}$ or a u -loop $\rightarrow \gamma\gamma$. We are looking for these processes and have good candidates in CDF for exclusive $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$. Unfortunately we do not have forward proton detection and the background is not as low as it might have been. If even a dozen or so $pp \rightarrow p \oplus H \oplus p$ events are measured it will be important; the mass can be measured by the missing mass technique⁵ with $\sigma_M \lesssim 2$ GeV per event, and it can be established that the state is a scalar⁶ (hard to do another way before the ILC). Exclusive $D\mathbb{P}E \rightarrow q\bar{q}$ di-jets are

strongly suppressed by the $J_Z = 0$ rule⁴, so the signal:background ratio is high (≈ 1). In the case of a non-SM Higgs sector life can be even more interesting! The production cross section can be much higher⁷ and one can have a close triplet h, A, H where A is mostly CP-odd. It can be difficult to resolve these states if they are within a few GeV. In central exclusive production the middle state A is absent (CP-odd) and the h and H may be resolved.

The TOTEM roman pots at 215m have no acceptance, in the standard low- β high luminosity running, for $M_X \lesssim 300$ GeV. We need to measure protons that have lost $\lesssim 1\%$ of their energy. This requires going further forward; there is an ideal location 420m downstream. Here there is a 15m straight section where a cryogenic by-pass will allow us to put very small (6mm \times 24mm) tracking detectors (probably 3D silicon) within 3mm of the proton beam. We plan to also have high precision (≈ 10 ps) time of flight counters, which measure the interaction point in z from the time difference. Measuring protons here, on both sides or with one proton in a 220m detector, gives acceptance for $M_X \gtrsim 50$ GeV. A consortium of ATLAS and CMS people submitted a LOI to the LHCC in June 2005, to support R&D towards common technical solutions (FP420)³.

2.3 Vector Boson Pair Production by DPE

Vector boson pairs are especially interesting whether produced non-diffractively or diffractively. Consider prompt pairs, i.e. not from $t\bar{t}$ and not from H . At the Tevatron 90% of W^+W^- and $W^\pm Z$ come from $q\bar{q}$ annihilation with t -channel quark exchange. Also $q\bar{q}$ annihilation with an s -channel W^*/Z^* contributes $\approx 10\%$ to W^+W^- and $W^\pm Z$ (not ZZ). Any pair (even W^+W^+) can be produced by two incident quarks radiating virtual W/Z which scatter and become real; in this case the quarks give forward high- p_T (“tagging”) jets. This is an important process for the quartic boson coupling (and direct channel resonances such as the Higgs!). At the Tevatron cross sections (limits for WZ and ZZ) agree with the CTEQ NLO predictions $\sigma(WW/WZ/ZZ) = 12.4/3.65/1.39$ pb. At the LHC they are a factor ≈ 10 higher. If the same rules-of-thumb apply, about 1% will be single diffractive and 10^{-3} will be in *DPE*. So our “guesstimate” for $DPE \rightarrow WW(ZZ) + \text{anything}$ is ≈ 1 pb (100fb).

Exclusive V -pairs are another matter. The process $pp \rightarrow p \oplus W^+W^- \oplus p$ by two photon exchange is guaranteed and ≈ 100 fb; the protons will have very small (Coulombic) momentum transfer t which helps distinguish this from the more interesting two pomeron exchange. Exclusive $DPE \rightarrow W^+W^-$ should be completely negligible, unless Alan White is right⁸. The signature is spectacular. In the (only) 4.5% of cases where both W decay to e or μ the two leptons are on a vertex with *no hadrons*. If the two protons are measured there are several missing mass variables of interest, which enable all exclusive VV -pairs to be used except (probably) the fully hadronic ($VV \rightarrow JJJJ$) case. For example if $WW \rightarrow JJ\mu\nu$ then not only $M_{JJ} = M_W$ but

$$M_{invisible}^2 = (p_1 + p_2 - p_3 - p_4 - p_{J1} - p_{J2} - p_\mu)^2 = M_\nu^2 = 0$$

and

$$MM_2^2 = (p_1 + p_2 - p_3 - p_4 - p_{J1} - p_{J2})^2 = M_W^2.$$

In the case $ZZ \rightarrow e^+e^-\nu\bar{\nu}$ then

$$MM_{invisible}^2 = (p_1 + p_2 - p_3 - p_4 - p_{e-} - p_{e+})^2 = M_Z^2$$

which is an interesting case of seeing $Z \rightarrow \nu\bar{\nu}$ as a narrow peak (only using precision tracking, no calorimetry). Unfortunately it may be only a handful (or even no) events, but this makes it an almost background free channel for new (BSM) physics.

The only new physics of which I am aware that should give a *large peak* in the aforementioned $Z \rightarrow \nu\bar{\nu}$ mass plot is Alan White’s theory of color sextet quarks and what I call the “white pomeron”. This would be a spectacular discovery. The white pomeron is a reggeized gluon

color-neutralized by an infinite cloud of wee gluons. A pair of heavy color sextet (analogous to double color, like RR) quarks U and D , are required to saturate asymptotic freedom. Double pomeron exchange will produce exclusive W^+W^- and ZZ prolifically, once above threshold (at the LHC not the Tevatron) through U, D loops. We can also have Z photoproduction ($\gamma P \rightarrow Z$) at the LHC which would also be dramatic as it is tiny in the Standard Model. FP420³ has the potential for dramatic discoveries!

3 Summary

The Tevatron is, and the LHC will be, a cornucopia of QCD physics. At the LHC we will have the Q^2 -range $\approx 0.01 \rightarrow 50,000,000 \text{ GeV}^2$. We will measure jets, W, Z, b, c production, spectroscopy and decays, rapidity gaps, exclusive production of jets, H, WW, ZZ and BSM physics. Adding very forward proton detection can open up a new window on strong and electroweak interactions.

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