GTeV: GLUON PHYSICS AT THE TEVATRON

Michael G. Albrow
Fermi National Accelerator Laboratory, Batavia, IL

Abstract

I discuss the future of QCD physics at the Tevatron, and present a case for upgrading the CDF or D0 detectors for an experiment studying QCD into the LHC era.

1 Introduction

In 2009 CDF and D0 are scheduled to complete data taking because the LHC will have taken over the high mass/high p_T frontier. However it is expected that the Tevatron will continue to run for another four years or so for BTeV, an experiment on charm and beauty physics. There is much physics, primarily perturbative and non-perturbative QCD, which will not have been studied in CDF or D0 and that is the primary goal of the GTeV (Gluon physics at the TeVatron) proposal. The idea is to use either the CDF or the D0 detector as the "core", supplemented with new precision forward and very forward detectors for high x_F and high rapidity particles.

2 Goals

The physics agenda of GTeV is broad, but at present we focus on six general topics.
(1) The gluon density in the proton at low Bjorken x, $g(x, Q^2)$, down to $x \approx 10^{-5}$. This addresses questions of gluon saturation, unitarity, the non-perturbative frontier and gluodynamics in general.
(2) The study of pure gluon jets, their profiles, content and color connections. Compare pure gg dijets with the pure $q\bar{q}$ dijets studied at LEP.
(3) Study the glueball spectrum, and relate it to pomeron trajectories, string models, lattice QCD calculations, etc.
(4) Measure exclusive χ_c and χ_b, meaning $p\bar{p} \to p + \chi + \bar{p}$ with no other particles in the final state (+ signifies a rapidity gap). This relates to the study of the Standard Model Higgs boson through exclusive production at the LHC (the cross section is too small at the Tevatron).
(5) Discover new exotic hadrons. Examples are hybrids ($q\bar{q}g$), 4-quark states such as X(3872) and pentaquarks such as $\theta_{c,b}$.
(6) Search for exotic fundamentals. This is highly speculative, but some beyond-the-Standard Model windows exist for which this proposal might be relevant, such as a CP-odd Higgs, radions, gluinoballs, QCD_S and the white pomeron.

3 Glue-glue Collider

If the incoming p and $\bar{p}$ both emerge with less than about 5% fractional momentum loss ξ ($\xi = 1 - p_L/p_{beam}$) and are well measured, the momentum loss is carried predominantly by gluons and we can use the Tevatron as a tagged glue-glue collider (not gluon-gluon, as it is color singlet exchange) with $\sqrt{s_{gg}} \approx 1 - 100$ GeV and resolution approaching $\sigma(\sqrt{s_{gg}}) \approx 100$ MeV (stretch goal).
Some of the program could be done now, but we do not have 2-arm forward

taggers (behind dipole magnets), the small angle region ($\theta < 3^\circ$) has no tracking and limited calorimetry, there is a limit on the number of triggers and the bandwidth that could be allocated for this physics is small. In addition to the new forward detectors we would aim to increase the data taking rate from 60 Hz to about 1 KHz (an intermediate step to about 250 Hz is underway). This would give 10^{10} events/year, enabling searches for rare objects or processes even in zero-bias events. Clearly QCD would dominate this program; indeed it is not clear if there is *any* non-QCD physics that would qualify.

4 Physics Topics

At high Q^2 the strong coupling α_s becomes small (0.117 at M_Z), calculations are perturbative and converge and quarks and gluons look progressively more point-like. As Q^2 decreases past 1 GeV^2 α_s rises through 0.5, the strong interaction becomes *really* strong, calculations become non-perturbative and diverge and quarks and gluons look extended. There are many theoretical approaches to this region but none is complete. Lattice Gauge Theory makes the approximation of discrete space-time, and can only handle limited volumes (hadron size). Thus reactions such as elastic scattering cannot be computed. Regge Theory [1] is based on sound and fundamental principles such as analyticity, unitarity and crossing symmetry, augmented by complex angular momenta. It is the best theory we have for some reactions (e.g. $\pi^- p \to \pi^0 n$) and gives rise to the concept of the pomeron for high energy elastic scattering and other diffractive processes. There are string models and potential models describing hadrons, and so on. Our ultimate goal is a complete understanding of the strong interaction from $Q^2 = 0$ (where the proton is point-like!) to $Q^2 = \infty$. On the way we pass the non-perturbative $\Longleftrightarrow$ perturbative transition region.

4.1 Small-x gluons

HERA experiments measure [2] the quarks $q(x, Q^2)$ down to $x \approx 10^{-5}$ at low Q^2, and determine gluons $g(x, Q^2)$ indirectly from the evolution equations down to $x \approx 10^{-4}$ (factor 2 uncertainty at low Q^2). At very low x gluon densities become very high and new phenomena, such as gluon saturation, may appear. These regions can be probed directly at the Tevatron by measuring two very forward (e.g. $y_1 = y_2 = 4(2.1^\circ)$) jets or heavy flavors. Suppose the objects have the same $p_T = 5$ GeV, and $\sqrt{s} = 1960$ GeV. For a 2-to-2 process the x_i of the initial partons are:

$$x_{1(2)} = \frac{p_T}{\sqrt{s}}(e^{(-)y_1} + e^{(-)y_2}) \tag{1}$$

so $x_1 = 0.56$ and $x_2 = 10^{-4}$. Therefore we should instrument the region $0.5^\circ < \theta < 3^\circ$ with tracking, good calorimetry (em + hadronic) and muons.

4.2 Gluon jets

Experiments at LEP-I, on the Z, made detailed studies of some 10^7 q-jets. They obtained limited samples of fairly pure g-jets (439 in the case of OPAL), using 3-jet events with two b-tagged jets [3]. In $p\bar{p} \to p + JJ + \bar{p}$ calculate the *Missing Mass* defined as

$$MM_{cen}^2 = (p_1 + p_2 - p_3 - p_4)^2 \tag{2}$$

where p_i are the 4-vectors of the incoming and outgoing protons. When $M_{JJ} \approx MM_{cen}$, so the central event is two jets and nothing else, they are $> 99\%$ pure gg dijets, as light quark jets are suppressed by the $J_z = 0$ rule [4]. CDF have measured the cross section for such events, not seeing the proton but selecting a rapidity gap of 4 units on the p-side, with two central jets above $E_T = 10$ GeV and $R_{jj} = M_{jj}/M_{cen} > 0.8$, to be about 40 pb. We are currently studying these jets to see if they look g-like. GTeV would collect over 10^4 such events per year with the p and $\bar{p}$ both tagged, and the unique gg dijet configuration.

4.3 Central exclusive production

This refers to collisions where the p and $\bar{p}$ are both scattered intact with small momentum loss and a low mass hadronic system in the central region is fully measured. We can call this "diffractive excitation of the vacuum" as any virtual states in the vacuum can be promoted to real states by the glancing passage of two hadrons. At the high energy of the Tevatron the dominant process is "double pomeron exchange" DPE, with vacuum quantum number exchange, and the quantum numbers of the central system are restricted to be $I^G = 0^+$ and at $0°$ $J^{PC} = 0^{++}, 2^{++}$, the latter being supressed for a $q\bar{q}$ state, thus favoring glueballs (G) and hybrids. Away from $0°$ some other J^{PC} are allowed: $0^{-+}, 1^{-+}, 1^{++}$. Correlations between the forward protons ($t_1, t_2, \Delta\phi$) can determine the quantum numbers of the central state, and in addition if they are well enough measured one can trigger on the missing mass and constrain it to equal the central mass.

4.3.1 Invisible missing mass

We can look for invisible objects (e.g. $Z \to \nu\bar{\nu}$, or something new) using:

$$MM_{invis}^2 = (p_1 + p_2 - p_3 - p_4 - \sum_{rest} p_i)^2 \tag{3}$$

A threshold bump in MM_{invis} could signify the pair production of LSPs. For this one probably needs to measure forward particles as completely as possible ("cone spectrometers" in CDF, see later) and to minimize random coincidences of beam halo particles in the pots with precision timing.

4.4 Central exclusive production (continued)

This is an ideal laboratory for glueball spectroscopy, a subject still confused after 25 years. Glueballs G are hadrons without valence quarks, and are allowed in QCD (so if they do not exist that will be a challenge to QCD). Some can mix with normal $q\bar{q}$ mesons, others have exotic quantum numbers e.g. $J^{PC} = 0^{--}, even^{+-}$ and cannot. A glue-glue collider is ideal for producing these, singly if allowed and others in association: GG' or G+mesons.Apart from central states of particular interest for glueball physics ($\phi\phi, \pi\pi KK$, etc.) exclusive strangeness and charm production ($\Lambda\bar{\Lambda}, D\bar{D}, X(3872), \chi^0$ etc.) is also important. Note that hyperon ($\Lambda, \Sigma, \Xi, \Omega$) pairs provide information on the spin structure of the reaction.

A particular case of central exclusive production which has attracted much interest is $pp \to p + H + p$. The main channel for Higgs production at hadron colliders is gg-fusion; in this particular case another soft gluon exchange has canceled the color and left the p's intact. There are theoretical uncertainties in the cross section involving skewed gluon distributions, gluon k_T, Sudakov form factors/gluon radiation. One expects [5] a cross section for the Standard Model Higgs $\sigma_{SMH} \approx 0.2$ fb at the Tevatron which is invisible, but at the LHC the cross section is probably a factor ≈ 15 larger, and the luminosity will also be much higher, so it may be possible. If seen it will usefully complement other channels, as it may give the best mass resolution ($\approx 2\%$) and can show that the state is a scalar. It is important to calibrate the theoretical estimates, and in the process learn about the physics of exclusive production.

Exclusive χ_c, χ_b and $\gamma\gamma$ production by DPE [4, 6] are important channels for understanding exclusive Higgs production, as the diagram is the same but with the virtual top loop replaced with charm, bottom or (mainly) up quarks. CDF has carried out a search for exclusive $\chi_c \to J/\psi\gamma$, finding 10 candidate events. Unfortunately one cannot be sure there were no missed particles, and the mass resolution of $M(J/\psi\gamma)$ is not good enough to separate $\chi_{c0}(3415), \chi_{c1}(3510)$ and $\chi_{c2}(3555)$. If one could detect the outgoing p and $\bar{p}$ with good resolution these limitations could be overcome. The statistics in this study are very low, despite the relatively large cross section, predicted to be 600 nb [4] or 735 nb [6]. The BR ($\chi_{c0} \to J/\psi\gamma) \approx 10^{-2}$, BR$(J/\psi \to \mu^+\mu^-) \approx 6 \times 10^{-2}$, the acceptance of the two-muon trigger for low p_T $J/\psi \approx 1\%$ and requiring no other interaction in the same beam crossing is another factor 0.25. A higher acceptance single muon trigger with forward gaps is being tested. It may be possible to use other decay modes (e.g. $2(\pi^+\pi^-)$ $= 3.7\%$). Exclusive χ_b production has a predicted cross section ≈ 5000 times smaller, but the trigger acceptance is nearly 100 times larger and we could expect about 100 events per fb^{-1}. Measuring the forward $p, \bar{p}$ also allows measurement of the quantum numbers of the central state, which should be dominated by $J^P = 0^+$, as 2^{++} is suppressed at $t = 0$ for a $q\bar{q}$ state.

5 Beyond the Standard Model

While the motivation for GTeV is Standard Model QCD physics it cannot be excluded that there is sensitivity to beyond Standard Model physics. I give four examples of possibilities that have been considered, each of which may seem unlikely but which are not yet excluded; other scenarios may well be invented.

5.1 CP-odd Higgs

In some SUSY models with CP-violation one can have [7] a light (20 GeV $< M(h) <$60 GeV) Higgs h that is predominantly CP-odd, does not couple strongly to W, Z and would have escaped detection at LEP. It will also not be seen by the standard modes of associated production with W at the Tevatron or LHC. It can however be produced by $gg \to h$ exclusively, and might be seen in DPE [8] with excellent missing mass resolution.

5.2 Radions

Radions [9, 10] are scalar or tensor quantum fluctuations in an extra 5th dimension between two 3-branes (known particles reside on one such brane). The allowed regions of parameter space include masses down to 20 GeV if the couplings are just right. Radions couple more strongly to gg than the SM higgs, they are expected to be narrow (KeV) and decay to $b\bar{b}$.

5.3 Light gluinos and gluinoballs

Although not a favored scenario, the gluino $\tilde{g}$ could be [11] the lightest SUSY particle, and if R-parity is conserved it will not decay. It can form heavy hadrons, and/or $\tilde{g}\tilde{g}$ bound states - "gluinoballs" $\tilde{G}$. For a 60 GeV gluinoball the cross section for exclusive production by DPE has been estimated to be $\approx$ 20fb at the Tevatron.

5.4 Color sextet quarks and the white pomeron

Alan White has developed [12] a theory, QCD_S, in which the pomeron consists of one reggeized gluon and a cloud of "wee" gluons, and in which there is necessarily a doublet of heavy color sextet quarks U, D. These sextet quarks Q_S form bound states like $\Pi^{\pm}, \Pi^{\circ}, \eta_6$. The W and Z get their masses by "eating" the Π, and the η_6 is responsible for the Higgs mechanism. The "white pomeron" couples strongly to the sextet quarks, and the cross section for DPE

$\rightarrow W^+W^-/ZZ$ is much larger than in the S.M. once one is above threshold. This would seem to be beyond the reach of the Tevatron, but within the reach of the LHC, however it should clearly be looked for.

6 Single Diffractive Excitation

Many single diffractive excitation studies have been done at the Tevatron, and we have studied hard diffractive processes where high E_T jets, W and Z are produced with one or both of the protons remaining intact, and with one or two large rapidity gaps. One can measure a diffractive structure function (essentially the standard non-diffractive structure function with the condition of a large gap and/or leading proton). This differs in normalization from the diffractive structure function measured in ep-collisions at HERA (non-factorization).Diffractive studies have formed a major part of the experimental program at HERA. They find a difference between the pomeron trajectory $\alpha(t)$ in soft processes (e.g. $ep \rightarrow e'\rho p$ photoproduction) and harder processes ($ep \rightarrow e'J/\psi p$). At the Tevatron we should map out the pomeron trajectory for soft and hard (jets, W, Z) diffraction. In leading order we have:

$$\sigma_{inv} = \frac{d\sigma}{dtdM^2} = \frac{m_0^2}{16\pi^2 s} \sum_{iij} G_{iij}(t) \left(\frac{s}{M^2}\right)^{2\alpha_i(t)} \left(\frac{M^2}{m_0^2}\right)^{\alpha_j(0)} + ... \qquad (4)$$

so that by measuring the s-dependence at fixed M^2 and several values of t one can extract the trajectory $\alpha_i(t)$. This should be done separately for different classes of diffractive events, e.g. all soft particles, or hard jets, W, Z. This is an argument for running the Tevatron for short periods (2-3 weeks?) at different $\sqrt{s}$ values, say 630, 920, 1340 and 1960 GeV (equi-spaced in ln(s)).

7 BFKL and Mueller-Navalet Jets

The leading order diagram for qq scattering with a single gluon being exchanged is not gauge invariant, so other diagrams must be added. Techniques for summing all these diagrams result in a gauge-invariant exchange called a "reggeized gluon" [1]. This is still colored and therefore not a pomeron, but two reggeized gluons, exchanging gluons in a ladder, can be a color singlet: the BFKL pomeron. This color singlet exchange between quarks (or gluons) enhances the cross section for high-E_T jets at very large rapidity separations (large s_{qq} and small t_{qq}). One can have a large rapidity gap between these jets (with jets in the "cone" region this could be as large as $\Delta\eta = 7$) or mini-jets in between ("cut" BFKL pomeron). This is a fundamental empirical probe of a new regime, namely non-perturbative QCD at short distances. We should systematically measure both the gap events and the mini-jet events as a function of η_1, η_2, p_T, and $\sqrt{s}$.

8 Hadron Spectroscopy

In 2003 much interest in hadron spectroscopy was generated by the discovery by BELLE [13] of the X(3872) decaying to $J/\psi\pi^+\pi^-$. It is surprisingly narrow: $M_{X(3872)} - M_{J/\psi} - 2M_\pi = 495$ MeV while $\Gamma < 3.5$ MeV. Within about a week the X(3872) was seen in CDF data [14] as a 10σ effect, and it could have been discovered at the Tevatron if there had been focus on this field. The jury is still out on its structure and why it is narrow. With very forward roman pots one could look for it in DPE, and if seen exclusively not only measure its quantum numbers but say something about its "size" from the magnitude of the cross section. The $\theta^+(1540)$, a pentaquark state, was also observed by many experiments, and if it exists the Tevatron should be able to study it, along with its charm and beauty analogs (for which the Tevatron may be the only source). There could be many pentaquark states to be discovered and studied. There are also many not-yet-seen baryons, containing c- and b-quarks (ccc, bbc?) that will be produced with a low cross section but can perhaps be seen with enough data using secondary vertex triggers and zero-bias triggers with a very high rate (1 KHz to tape, 10^{10} events per year).

9 The Low-p_T Frontier

Bjorken has argued that low p_T is the true frontier of QCD. What happens when p_T is decreased from 200 MeV/c to 50 MeV/c, corresponding to distance scales rising from 1 fm to 4 fm? How do the gluon fields in the proton "cut off"? We should study the multiplicity of such low-p_T particles and correlations (including Bose-Einstein) between them. Are there very soft photons (of course there should be, but they have never been studied). Do certain events have an unusual low p_T "cloud"? How can we select very large impact parameter collisions? Very small $|t|$ DPE would be one method. We could do some running with reduced solenoidal field, focusing on the Si-only tracking in the case of CDF. The D0 tracker is not sensitive to the field. Such a short run could be done already in the CDF/D0 era.

10 Detectors

The CDF detector is an excellent all-purpose detector with silicon and drift chamber tracking, $\frac{dE}{dx}$ and TOF particle identification, a solenoid, Pb-scintillator e.m. and Fe-scintillator hadronic calorimetry and muon chambers. There are some concerns about the state of the tracking detectors five years from now, but assuming they are still usable for our intended physics we would probably keep all these detectors. The set of triggers would be different but should be accommodated with the present hardware.

For polar angles below $3°(|\eta| > 3.6)$ there are conical holes in the Plug Calorimeters which could be instrumented with "Cone Spectrometers". By removing a redundant magnet the low-β quadrupoles can be withdrawn 2m for extra space, and we could install tracking before and after a deep (em + hadronic) calorimeter. We need to study how well this would measure jets, $e, \gamma, \mu, J/\psi$. The cone spectrometers are important for studying far-separated jets (BFKL) with minijets in between, or a large ($\Delta\eta > 6$) gap, or a low-mass system X between two $\Delta\eta > 3$ gaps (is this different from X in $p\bar{p} \to p+X+\bar{p}$?)

The D0 detector has silicon and scintillating fiber tracking, a solenoid and liquid argon em and hadron calorimetry, followed by muon chambers. The D0 detector could be used for this program, although the central tracking and particle identification is weaker, and as the cryostat goes very close to the beam pipe there is no possibility of the "cone spectrometers".

We would install roman pot detectors for diffractively scattered protons 55m and 165m downstream on both beam pipes. Both CDF and D0 have roman pots beyond dipoles but only on one side, and D0 also has pots behind quadrupole magnets. For GTeV we would require precision tracking in the pots, replacing the scintillating fiber trackers with silicon strips. We also desire high precision timing ($\approx$ 30 ps) which will enable us to (a) check that the p and $\bar{p}$ came from the same interaction (b) measure the z of the interaction (c) give a start time for TOF identification of central particles (otherwise $\pi\pi$ and KK could not be separated) (d) tell where in the bunches (in z) the p and $\bar{p}$ were, which can help with the MM resolution.

11 Tevatron Issues

In order to install new roman pots, spaces have to be made in the Tevatron lattice, which can be achieved by replacing 3 normal dipoles with two high field dipoles separated by a gap. 6 Tesla dipoles that operate at the same temperature and current can be made, but the lead time is about 4 years. The preferred luminosity for GTeV is $2 - 4 \times 10^{31} cm^{-2} s^{-1}$ to get the most single interactions. BTeV will run about 5$\times$ higher, and we should run together. This can be achieved by a crossing angle (medium beta would be preferable but looks difficult). There are many other issues (beam-beam and long-range tune shifts, luminosity lifetime, precision beam position monitors, etc.) but none appears to be insurmountable.

12 Other Physics

There are many subjects I have not covered. Very forward particle production data are needed to calibrate cosmic ray event generators. Very soft photons (< 100 MeV/c) can be studied via conversions, perhaps in a low field run. Can one see the proton fragmenting into three very forward jets (with or without rapidity gaps)? Directional Bose-Einstein correlations using different particle types, in different types of events, and with very high statistics would be very instructive (3D shape of the interaction volume). Many more studies would be done.

13 Summary

There will probably be a great deal of QCD physics still to be done when CDF and D0 complete data taking in 2009. As the low-p_T frontier is largely unknown territory, discoveries are likely. The CDF and D0 detectors are excellent central detectors for this program, suitably upgraded at modest cost, and the Tevatron will be running anyway for BTeV.

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