Note to Fermilab Long-range Planning Committee
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GTeV: Gluon Physics at the Tevatron

Abstract

If BTeV is approved, the Tevatron Collider will run for several years beyond 2009. We are considering increasing the coverage of one of the existing detectors to 4-pi, with magnetic tracking in the few degree region and with forward and very forward Roman pots, to study QCD.

Of the elementary particles that are known to exist, the gluon is probably the least well studied. There is a wealth of experimental data on neutrinos, charged leptons, quarks, the photon and weak bosons. Certainly there is no shortage of physics still to be done with these particles, especially neutrinos and the third generation, and we need to understand how they relate to fundamental symmetries, such as CP. Experiments in these fields are popular and manifold (e.g. BELLE, BaBar, CDF, D0, LHCB and BTeV all address B physics, and there are many neutrino mixing experiments with more being proposed). The detailed study of the gluon and of many aspects of the strong interaction has been seriously neglected, not just relatively but absolutely. Yet the strong interaction is just as fundamental and, we think, as fascinating as the electroweak and gravitational interactions. The experiment we plan to propose will remedy this situation.

We assume that BTeV will be approved, and the detector will start taking data in 2009. We assume that by 2009 the high mass, high pT frontier (Higgs, SUSY, top, extra dimensions and other high mass exotics) now dominating the Tevatron program will pass to the LHC and will no longer provide any reason for continuing with that program here. Indeed the Director has stated that it is planned to terminate CDF and D0 in 2009. We expect BTeV to operate for at least 5 years. During that period another experiment could run simultaneously with no negative effects on BTeV, and no incremental cost to Tevatron operations.

The gluon is at the center of QCD. We have already a long list of measurements which need to be done, which will not have been done at the Tevatron or elsewhere by 2009, largely because of the intense focus on the new massive particle searches, and which will not be done at LHC for the same reason. At the beginning of LHC running with low luminosity a small fraction of the physics on our program will be studied there. This is highly desirable as it gives independent measurements as well as s-dependence. Both ATLAS and CMS may have very forward Roman Pots, partly because of the interest in diffractive Higgs production. We will not attempt to compete with the LHC in two frontiers of QCD, namely measurements of the highest ET jets (smallest distances) and studies of nuclear matter at extreme temperatures and densities (AA collisions now studied at RHIC, later in ALICE). This leaves a vast terrain of the strong interaction to explore.

A key feature of QCD, which has not yet been proven theoretically, is confinement. We have become used to picturing high energy processes in terms of quarks and gluons because they provide a high-Q^2 description and one can do perturbative calculations.

The confinement of the outgoing partons into color singlet hadrons does not have a complete theoretical (only a phenomenological) description. In approximately 1/3 of the interactions there are large rapidity gaps (no hadrons over at least 4 units) between hadrons or clusters of hadrons. This is also known as diffraction. It corresponds to the exchange of 4-momentum in a color singlet configuration, predominantly gluonic. The relationship between confinement and large rapidity gaps is still unclear.This diffractive exchange can leave the energy of the incident protons (read proton and antiproton) unchanged, as in elastic scattering, or one or both can be reduced by up to about 5% as in inelastic diffraction. If only one proton is “leading” the other can be excited to a high mass state (up to 450 GeV at the Tevatron) in which we have observed high ET jets, W, Z and heavy flavor. These provide tools for understanding the exchange. If both protons are leading, the lost energy goes into a central hadron system between two rapidity gaps. This can be thought of as “diffractive excitation of the vacuum” at least for small masses. For the high mass (up to about 200 GeV) dijets, which we have observed, a description in terms of normal parton scattering with color rearrangement is reasonably successful (but it is a phenomenological not a theoretical description). Does this color rearrangement have something to say about how confinement operates?

The class of interactions in which both protons emerge with small scattering angle (|t| ~ pT^2 <~ 2 GeV^2) and Feynman x >~ 0.95 is particularly important. These particles stay in the beam until they pass through quadrupoles or, especially, dipoles which deflect them. They can be detected in small (a few cm^2) tracking detectors in special vacuum chambers often called “Roman pots” (having been first used by the CERN-Rome group at the ISR). As the interaction point is known from the central particles, the momentum of the scattered beam particles is measured. Both CDF and D0 currently have such “dipole spectrometers” on one side of the interaction. Putting a dipole spectrometer on the other side can be done, but requires some rearrangement of some of the Tevatron magnets. By measuring both outgoing protons (in silicon detectors with higher precision than the scintillating fiber trackers currently deployed), one can calculate the missing mass which is equal to the mass of the central system, with a resolution ~ 250 MeV (it might be possible to improve this under certain conditions).

This technique has been proposed with a view to seeing the SM (or even better MSSM) Higgs, centrally and exclusively produced (pp --> pHp). While there are sizeable uncertainties in the cross section for this process, which can be much reduced by measuring accessible related processes, it is probably too small to be seen at the Tevatron (~ 1 event expected in 5 fb^-1). In a CP-violating Higgs scenario, a mainly CP-odd Higgs can be as light as 50 GeV and still have escaped detection at LEP and the Tevatron because of a small coupling to W and Z. Central exclusive production may be the only way to see a mostly CP-odd Higgs before a Linear e+e- Collider, although the background at the Tevatron may be prohibitive. The process has a much higher cross section at the LHC, and with the higher luminosity dozens (or even hundreds) of events will be produced in a favorable background environment. (Whether they can be actually extracted and measured is another question we do not address here, but there are several groups working on it). Even a few events would be very significant, not only for the Higgs mass measurement (which would have comparable resolution to the gamma-gamma channel) but, most importantly, it can determine that the observed particle is indeed JP = 0+, which is difficult if not impossible anywhere else before the Linear e+e-

Collider. For near 0-deg proton scattering the quantum numbers are constrained on general principles to be IGJPC = 0+0++ or 0+2++, and furthermore any 0+2++ state cannot be q-qbar. Seeing a state such as the Higgs boson exclusively produced with small angle protons thus proves that it is a +ve parity scalar, which is clearly extremely important, even if it discovered previously through a more conventional channel. See A.B.Kaidalov et al., hep-ph/0307064
http://arxiv.org/PS_cache/hep-ph/pdf/0307/0307064.pdf

In order to reduce the theoretical uncertainties on such a process we need to measure related processes that provide benchmark tests. See:
http://arxiv.org/PS_cache/hep-ph/pdf/0207/0207313.pdf
The Higgs production diagram is gg --> top loop --> H. Replacing the top loop with a c-loop or b-loop produces a chi_c(0++) or chi_b(0++) (these have the same quantum numbers as a scalar Higgs ... and the vacuum!). We are now searching in CDF and D0 for exclusive chi_c production, in the form of events with a central J/psi and photon in the right mass region and apparently no other hadrons, either central or forward (except the protons which stay in the beam pipe undetected). CDF has a few candidate events. The theoretical approaches can be very well tested with thousands of events. The cross section is expected to be ~ 600 nb, or ~ 20 Hz! Due to branching fractions and acceptance the signal is lower by a factor ~10^5, but we could eventually get tens of thousands of events. Because this physics has low priority at present we will not get such high statistics before 2009, and also the forward protons are not being detected. Exclusive chi_b is also very important; the statistics will be lower but still very interesting as a probe of the frontier between non-perturbative and perturbative QCD.

There will be a rich field of lower mass hadron spectroscopy, unique for two reasons: (1) at very low Q^2 (~ 1 GeV^2) the exchange is known to be predominantly two gluons in a color singlet. Both glueball and hybrid states couple very strongly to the exchange, and we can expect the central system to be a beautiful laboratory for this still badly understood (rather, not understood) spectroscopy. (2) equally important, by the same general principles that provided a filter on the Higgs quantum numbers, we have here a filter on the quantum numbers of the glueball, hybrid, 4-quark meson or q-qbar meson etc states. (e.g. It would be interesting to see the presence or absence of the newly observed J/psi pi pi (3871) in this reaction.) Glueballs are at the heart of non-relativistic QCD. Lattice QCD calculations are extensive, but after more than 20 years of searching in many channels the experimental situation is still messy. We think this central production channel is probably the best way to study the 0+0++ and 0+2++ states, and it has only been done up to sqrt(s) = 63 GeV (at lower energies it is not clean, as one cannot have long enough rapidity gaps). Hadron spectroscopy in general inelastic (non-diffractive) collisions may also still be a rich field on this timescale. The recent observation of the J/psi pi pi (3871) in CDF data is an example of an interesting hadron that was waiting to be discovered. Perhaps there are others in the upsilon sector or elsewhere that will become visible with very high statistics and, especially, looking in the right place. This would be part of our program.

When one has a balancing pair of jets and little else in the central region, and rapidity gaps out to the two forward protons, more than 99.9% of the jets are gluon jets. See V.A.Khoze, A.D.Martin and M.G.Ryskin:
Eur.Phys.J.C19:477-483,2001, Erratum-ibid.C20:599,2001

http://arxiv.org/PS_cache/hep-ph/pdf/0011/0011393.pdf
Quark jets are highly suppressed by the J_z = 0 rule. The main background comes from 3-jet events. This is a gluon factory! At LEP on the Z, millions of quark jets were produced and studied in exquisite detail. The only high purity gluon jet sample was obtained at LEP/OPAL (only 439 b-bbar-g events with both b jets tagged). We should study ~ 10^5 g-jets with the same thoroughness that the quark jets (of similar ET) were studied at LEP (internal kinematics, particle composition, etc).

In the poorly explored regions of QCD we have a long “shopping list” of topics that will surely provide a large number of opportunities for students and result in many publications. But here we have focused on just three, which stand out (from today’s viewpoint ... most probably others will seem more important in 5 years). These are, to summarize:

(1) The measurement of exclusive chi_c and chi_b states.
(2) A nearly pure tagged gluon jet factory.
(3) A fertile hunting ground for glueballs, hybrids and other exotic hadrons.

How do we envisage this program coming about? We assume CDF and D0 will be complete in 2009, but the detectors should still be in good condition, modulo questions about the silicon detectors at that time. One of these two detectors could then be taken over as the core of the new QCD experiment. Although many of the CDF and D0 team members will move on to LHC or other projects, we imagine that a substantial number would prefer to stay at the Tevatron doing a first class physics program. We should also attract physicists of like mind from the Fixed Target, RHIC, HERA and other programs. The core detector would be supplemented by modest upgrades, such as very forward proton taggers (e.g. dipole spectrometers on both sides at two distances for low mass states and high mass states). Other upgrades are being considered: forward and very forward silicon tracking, with dipole magnets, possibly with identification etc. It would be premature to say more at this stage. An important feature must be a high throughput trigger system designed to optimize this physics program.

The community of cosmic ray physicists has for decades been crying out for measurements of particle spectra as far forward as possible at as high an energy as possible. This has never been done since the CERN ISR, sqrt(s) = 63 GeV (fixed target equivalent ~ 2 TeV); the Tevatron has a fixed target equivalent energy of 2000 TeV. Models of high energy interaction can be much better tested thanks to this lever arm.

We are planning to pursue these ideas in working groups and with a workshop in Spring 2004, with a view to a report later in the year. We believe that if BTeV is approved the experiment we propose will be an exciting and very active addition to the Fermilab program, maximizing the pay-off of the Tevatron in that time. It will also be an excellent training ground at Fermilab in techniques for collider experiments for a new generation of experimental physicists. If BTeV is not approved, we still intend to develop the case with a view to a more modest extension of the Tevatron for CDF and/or D0.

These ideas were developed during the Vth Workshop on Small-x and Diffractive Physics, Sept 2003; see talks in http://conferences.fnal.gov/smallx/index.html