Production

Double $c\bar{c}$ Production at the B Factories

Two outstanding issues in quarkonium production are the discrepancies between theory and experiment in exclusive and inclusive double $c\bar{c}$ production.

In the case of exclusive production of $J/\psi + \eta_c$ the leading-order theoretical prediction of about 3.78 fb lies about a factor of 4.7–6.6 below the experimental measurements. However, there has been recent theoretical progress. A calculation of the corrections at next-to-leading order (NLO) in α_s indicates that those corrections increase the cross section by a factor of about $1.96^{+1.47}_{-.57}$. Relativistic corrections also increase the cross section by a factor $2^{+10.9}_{-1.1}$. However, this latter result has enormous uncertainties that make it of limited utility. Furthermore, it is not clear whether one should multiply the K factor that arises from the corrections at (NLO) in α_s and the K factor that arises from the relativistic corrections or merely add the corresponding increases in the cross section. The Belle result of $25.6 \pm 2.8 \pm 3.4$ fb is about 45% higher than the BaBar result of $17.6 \pm 2.8 \pm 2.1$ fb.

Action Items:

- It is important to reduce the theoretical uncertainties in the corrections of higher order in α_s and v, especially those of higher order in v.
- It is important to calculate for $\sigma(e^+e^- \to J/\psi + \eta_c)$ the cross term that gives the relativistic correction to the order α_s correction. This is anticipated to be large and positive.
- The Belle and BaBar results are compatible within uncertainties. However, those uncertainties are quite large, and it would be useful to reduce them, if possible.

In the case of inclusive production of $J/\psi + X_{c\bar{c}}$, the Belle result of $\sigma(e^+e^- \to J/\psi + X_{c\bar{c}})/\sigma(e^+e^- \to J/\psi + X) = 0.82 \pm 0.15 \pm 0.14$ is far removed from the theoretical prediction of 0.1.

Action Items:

- A check of the Belle result by BaBar is very important.
- The corrections at NLO in α_s and NLO in v^2 to this process should be computed in the NRQCD factorization framework.

Quarkonium Production at the Tevatron

Quarkonium production rates at the Tevatron are interesting in their own right. They also have been used to extract NRQCD color-octet matrix elements that can be used to make predictions for other production processes and, hence, to test the NRQCD factorization prediction of the universality of the matrix elements. To date, the production rates have been calculated through order α_s^3. Some subprocesses proceed at order α_s^2. For these subprocesses, the existing order-α_s^3 calculations are at next-to-leading order. However, for other important subprocesses, the existing order-α_s^3 calculations are at the leading order, and are subject to large uncertainties from contributions of higher order in α_s.

Action Items:

- A complete calculation in the NRQCD factorization framework of all of the relevant subprocesses for quarkonium production at the Tevatron at NLO in α_s should be completed. These calculations should be used to obtain new extractions of the NRQCD color-octet matrix elements from fits to the Tevatron data. This is essential in order to carry out high-precision tests of the universality of the matrix elements and to make reliable predictions of quarkonium production rates at the LHC.

J/ψ and $J/\psi(2S)$ Polarization at the Tevatron

The prediction of NRQCD factorization of substantial transverse polarization of J/ψ and $J/\psi(2S)$ mesons produced at large transverse momentum at the Tevatron is the "smoking-gun" signature for the color-octet mechanism. The CDF Run I results for J/ψ polarization differ with theoretical predictions at large transverse momentum. The CDF Run II results for the J/ψ polarization differ with the prediction over the entire transverse-momentum range and seem to be incompatible with the Run I results for the J/ψ polarization. The Run I and Run II results for the $J/\psi(2S)$ polarization are compatible, but the error bars are considerably larger than in the results for the J/ψ polarization.

Action Items:

- A check of the CDF polarization results by DO is very important.
- An effort should be made to understand the origins of the differences between the CDF Run I and Run II results for J/ψ polarization.
- It would be useful for CDF to obtain higher statistics for the $\psi(2S)$ polarization.

The χ_{c1}–χ_{c2} Ratio at the Tevatron

A recent CDF measurement of production rates of χ_{c1} and $\chi_c 2$ at the Tevatron gives a ratio of about 1.4 and is essentially constant as a function of transverse momentum. This result is not compatible with any existing theoretical model. The color-evaporation model predicts a ratio of 3/5 at all transverse momenta. Detailed calculations do not exist for the NRQCD factorization approach or the color-singlet model. However, NRQCD factorization predicts a ratio of 3/5 at transverse momenta substantially above the charmonium mass and a smaller ratio at smaller transverse momenta. The color-singlet model predicts a ratio that is less than one.

Action Items:

- It is very important for D0 to check this result, if possible.
- A prediction for this ratio as a function of transverse momenta should be computed within the NRQCD factorization framework.

Double $c\bar{c}$ Production at the Tevatron

See the discussion above on Double $c\bar{c}$ Production at the B Factories.

Action Items:

- A measurement at the Tevatron of the ratio of the production rates of $J/\psi + X_{c\bar{c}}$ and $J/\psi + X$ might shed some light on the production mechanism, especially if the result is anomalously large.
- A theoretical calculation should be carried out in the NRQCD factorization framework of the ratio of the production rates of $J/\psi + X_{c\bar{c}}$ and $J/\psi + X$ at the Tevatron.

Quarkonium Production at the LHC

Measurement of quarkonium production rates and polarizations at the LHC should allow one to test theoretical models at higher values of transverse momenta than have been available previously. While measurements over the entire range of available transverse momentum are valuable, measurements at the

highest available transverse momentum are particularly interesting theoretically because factorization is on the soundest theoretical footing there.

Planning for observations of quarkonium production at the LHC requires the existence of a flexible, fully differential quarkonium-production Monte Carlo whose output can be run through detector-simulation programs.

Action Items:

- The LHC experiments should be encouraged to measure charmonium and bottomonium production rates and polarizations over the available range of transverse momenta and especially at the highest available transverse momentum.
- It is important to construct parton-shower Monte Carlos codes, based on NRQCD factorization, that can be used to predict differential rates for quarkonium production at the LHC.

Quarkonium Production Near Kinematic Endpoints

Near kinematic endpoints of quarkonium production processes, NRQCD breaks down. In these regions, it is essential to marry NRQCD with Soft-Collinear Effective Theory (SCET). This technique allows one to resum large logarithms that occur near the endpoint and to extract nonperturbative shape functions that govern the soft and collinear physics near the endpoint. This approach could allow one to resolve discrepancies between theory and experiment for individual production processes and to extract universal shape distributions that apply to all processes.

Action Items:

- The NRQCD-SCET program for treating kinematic endpoints should be completed for quarkonium production in e^+e^- collisions at the B factories and for inelastic quarkonium photoproduction at HERA. The success of this program may rely on resolving the discrepancies between theory and experiment in quarkonium production in e^+e^- collisions at the B factories that are described above.

Quarkonium Production at HERA

The two experiments H1 and ZEUS at the HERA ep collider have presented measurements of J/ψ and $\psi(2S)$ production cross sections in photoproduction (γp) and electroproduction (ep) based on HERA-I data (1996-2000). J/ψ decay angular distributions, giving access to the J/ψ polarization states, have also been measured. The HERA-II data (2003-2007) will comprise a factor of four more integrated luminosity, giving access to more detailed measurements with improved statistical precision and an increased reach in transverse momentum.

In connection with improved theoretical calculations, the HERA measurements provide a fundamental test of the NRQCD factorization ansatz and the universality of the matrix elements.

Action Items:

- H1 and ZEUS will perform improved measurements based on HERA-II data of J/ψ and $\psi(2S)$ production cross sections in photoproduction and electroproduction.
- The J/ψ decay angular distributions will be measured in photoproduction and electroproduction (new preliminary results were presented by the ZEUS collaboration at ICHEP06, Moscow).
- An attempt will be made to measure the production fraction of χ_c w.r.t. J/ψ photoproduction.
- Measurements of Υ production are being performed for the diffractive production channel. It is unlikely that the data will allow to identify Υ signals in the inelastic production channel.