PRODUCTION OF QUARKONIA IN $p\overline{p}$, e^+e^- AND ep COLLISIONS

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The detailed measurement of quarkonia in $\overline{p}p$ collisions at TEVATRON energies has led to some surprises as regards the origin and theoretical description of such processes. Charmonium production in ep collsions is starting to be investigated and first results seem to be in agreement with theoretical ideas. Searches for prompt production of quarkonia in e^+e^-collisions lead to first indications of signals.

1 Introduction

Quarkonia production in $p\overline{p}$, e^+e^- and ep interactions is an interesting testing ground for different production mechanisms of heavy quarks, which are calculable in perturbative QCD. Recent data from the TEVATRON, LEP, and HERA are reviewed.

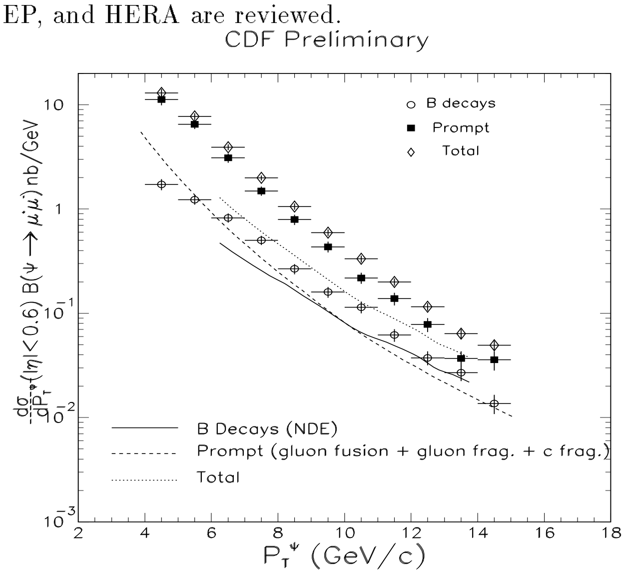

Figure 1: J/ψ differential cross section from CDF. The lowest set of data points(open circles) is the J/ψ component from B decays which agrees roughly with the NLO calculation(full curve).The prompt component (full squares) on the other hand is above the prediction (dashed curve).

2 $p\overline{p}$ Collisions (TEVATRON)

Data come from the CDF and D0 collaborations at $\sqrt{s}$ = 1800 GeV. J/ψ, ψ', χ_c and Υ states have been analysed. The total data sample available for CDF e.g. is 75 pb^{-1}, but the data presented mostly use only partial data samples.

2.1 J/ψ and χ_c Production

Production mechanisms in $p\overline{p}$ collisions for J/ψ include

a) B-decay, recognised experimentally by the long lifetime of the parent particles which leads to long distances between the J/ψ decay point and the beam interaction point;

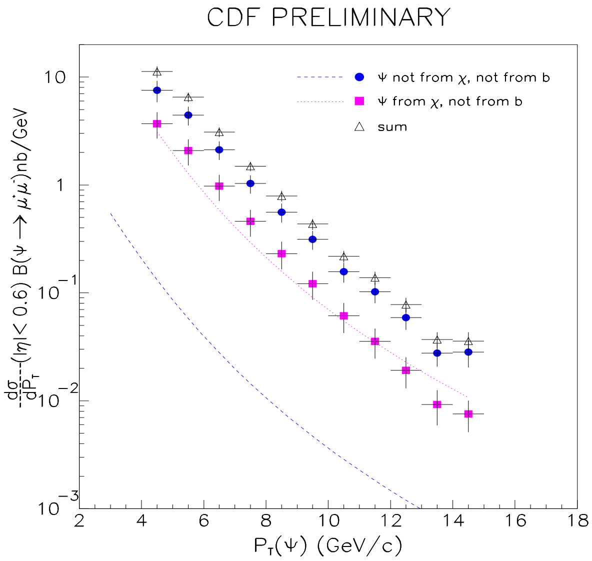

Figure 2: J/ψ differential cross sections as a function of the p_t of the J/ψ with the contribution from B decays removed; the circles show the direct component, the squares correspond to J/ψ from χ_c and the triangle is the sum. The curves are the NLO QCD calculations.

b) direct α_s^3 processes calculable in QCD [1]; e.g. gluon–gluon fusion in the colour singlet model;

c) so–called fragmentation processes which are of order α_s^4 but dominate over process b) at high p_t of the J/ψ[2].

Processes b) and c) lead to “prompt” $c\overline{c}$ bound states produced at the beam interaction vertex. Until recently it was believed that J/ψ production is dominated by formation of χ_c which subsequently decays to J/ψ[1,3].

Investigating ψ' production, CDF has found a strong direct component which does not come from B decay (χ states cannot contribute to ψ'), which is a factor $\approx$ 50 above predictions[4,5].

The measured cross section $d\sigma/dp_t \cdot BR(J/\psi \to \mu^+\mu^-)$ for J/ψ in a range of pseudo-rapidity $|\eta| < 0.6$ from CDF[5] is shown in fig. 1. The fraction coming from B decays is indicated: $f_B = 0.196 \pm 0.015$ for $p_t > 4$ GeV.

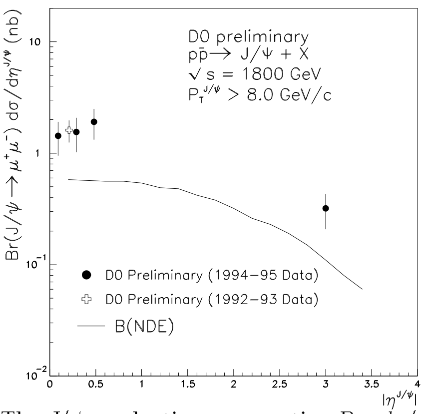

Figure 3: The J/ψ production cross section $Br \cdot d\sigma/d\eta$ as a function of $|\eta_{J/\psi}|$ for $p_t^{J/\psi} > 8$ GeV/c. The error bars include statistical and systematic errors added in quadrature, a scale error is not included.

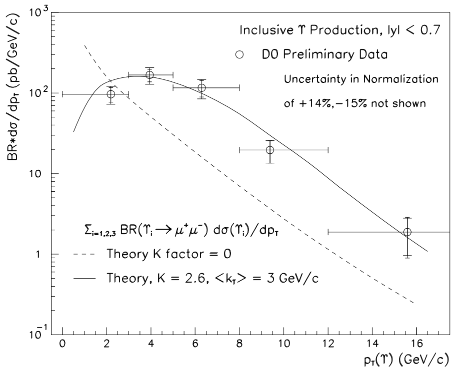

Figure 4: $Br \cdot d\sigma/dp_t$ for Υ (sum of 1s,2s,3s) production from D0 for $|y_\Upsilon| < 0.7$. A scale error of 15% is not included in the error bars. The dashed curve is the theoretical NLO prediction. The full curve has been adjusted to the data by including a primordial parton k_T and an ad hoc k–factor.

D0[6] has also measured the p_t spectrum above 8 GeV. Their results agree with CDF. They find a B fraction of $f_B = 0.35 \pm 0.09 \pm 0.10$ for $p_t > 8$ GeV in the central region.

Next, the origin of the J/ψs which do not come from B decays was investigated. χ_c states are reconstructed through their $J/\psi\ \gamma$ decay.After efficiency correction the fraction of J/ψ from χ_c decays is found to be $f_\chi = 0.323 \pm 0.02 \pm 0.015$ by CDF[7] and $f_\chi = 0.30 \pm 0.07 \pm 0.07$ by D0[6]. Thus the majority of prompt J/ψ do **not** come from χ_c decays. While the J/ψ component from χ_c decays is well described by QCD the direct component (see fig. 2) is approximately a factor ~ 50 above the theoretical predictions.

D0 extends[8] the measurements of J/ψ to large rapidities (see fig. 3). They also perform an analysis of the topology of the final state. They find a fraction of the non-B J/ψs with isolated decay leptons as expected for χ_c decays. But in addition a large non–isolated component is present.

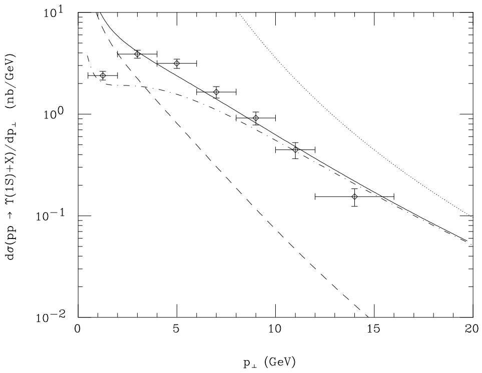

Figure 5: The differential cross section for $\Upsilon(1S)$ production from CDF is shown as function of transverse momentum in the rapidity interval $|y| \le 0.4$ compared with theoretical predictions. The dashed curve depicts the colour–singlet contribution which includes direct $\Upsilon(1S)$ production as well as radiative feeddown from $\chi_{bj}(1P)$ and $\chi_{bj}(2P)$ states. The dot–dashed curve illustrates the colour–octet contribution to $\Upsilon(1S)$ production. The solid curve equals the sum of the colour–singlet and colour–octet contributions and represents the total theoretical differential cross section.

There have been many proposals to explain the origin of the excess of J/ψ and ψ', among them the production of resonances above $D\overline{D}$ threshold and production of colour octet states [9,10].

2.2 Υ States

Υ production has been analysed by CDF[11] in a data sample of 16.6 pb^{-1} for Υ rapidities of $|y_\Upsilon| < 0.4$. D0[12] has analysed 6.6 pb^{-1} with $|y_\Upsilon| < 0.7$. The Υ is reconstructed through $\mu^+\mu^-$ decays.

D0 cannot separate the radial excitations but rather measures a sum of them. The p_t spectrum measured by D0 is shown in fig. 4. NLO calculations are a factor 5 below the measurement.

CDF's $\Upsilon(1s)$ spectrum is shown in fig. 5 together with recent calculations from Cho and Leibovich[9], who in addition to colour singlet contributions also take into account colour–octet states at the price of new free parameters.

3 e^+e^- Collisions (LEP)

The main source for J/ψ and ψ' in Z^0 decays at LEP are believed to be decays of B states. A prompt component is predicted via so–called fragmentation processes [13] which lead to $J/\psi\ c\bar{c}$ states at the 10^{-4} level. The same fragmentation mechanism also predicts $\Upsilon b\bar{b}$ states – and thus prompt Υs– in Z^0 decays at the 10^{-5} level.

DELPHI[14] has searched in more than $3 \cdot 10^6$ hadronic Z^0 decays for direct production of oppositely charged lepton pairs with the help of their silicon vertex detector and applying an isolation cut for the lepton pair. The num-

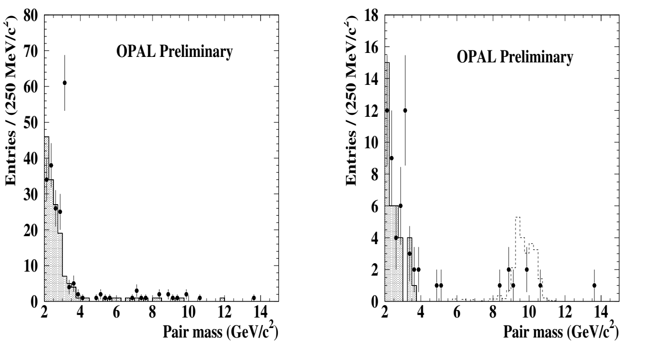

Figure 6: Invariant mass distribution for unlike sign lepton pairs (dots) after having applied all cuts. In the left figure the isolation cut is not applied. Superimposed (shaded) is the expected background estimated with $e^{\pm}\mu^{\mp}$ pairs. The dashed line in the right figure corresponds to the MC expected shape from inclusive Υ states, assuming $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ produced with the same rate and taking into account their different leptonic widths. Radiative decays $\Upsilon \rightarrow \ell^+\ell^-\gamma$ were not included in the simulation.

ber of remaining events in the J/ψ, ψ' and Υ regions is slightly more than background from known sources. In the Υ region for example they find 2 events and expect a background of $0.47 \pm 0.06 \pm 0.14$ which is calculated to have a 1% statistical probability only. The 90% confidence level upper limit for $Z^0 \rightarrow J/\psi\ c\bar{c}$ is $6.2 \cdot 10^{-4}$ (expectation $0.7 \cdot 10^{-4}$) and for $Z^0 \rightarrow \Upsilon b\bar{b}$ it is $8.7 \cdot 10^{-4}$ (expectation $0.7 \cdot 10^{-5}$). All fractions are with respect to $Z^0 \rightarrow$ hadrons.

OPAL[15] has concentrated the search on the Υ region where no background from B–decays is present. The two lepton mass spectra before and after applying an isolation cut on the lepton pairs is shown in fig. 6. A signal of 6 isolated events is observed. the calculated background is 0.8± 0.4 mainly from 4 lepton events. The calculated branching ratio is BR $(Z^0 \rightarrow \Upsilon + X) = \left(1.2^{+0.9}_{-0.6} \pm 0.2^{+1.7}_{-0.4}\right) \cdot 10^{-4}$, where the first error is statistical, the second experimental systematic and the third error is due to model uncertainties in the acceptance calculation. The expectation is 10^{-5}.

4 *ep* Interactions (HERA)

J/ψ production at HERA is a continuation at higher center of mass energy of previous fixed target experiments with incident charged leptons and photons. *ep* scattering can be viewed as a two step process: emission of an almost real ($Q^2 \approx 0$) or virtual photon followed by a photon proton scattering process. Two production mechanisms of quarkonia have been discussed: diffractive production is described in the Generalized Vector Dominance (GVDM) model[16] which can proceed *elastically* or with *proton dissociation*. Boson gluon fusion in the colour singlet model[17] which has been calculated in perturbative QCD in NLO[18] leads to *inelastic* events.

Up to now the experiments H1[19,20] and ZEUS[21,22] have analysed elastic and inelastic J/ψ production at $Q^2 \approx 0$ and H1 has presented first data[23] on J/ψ production at $Q^2 > 0$. The J/ψ meson is reconstructed via its leptonic decay, examples of mass spectra are shown in fig. 7. Elastic photoproduction cross sections of H1 and ZEUS corrected for contributions of proton dissociation as a function of the γp cm energy $W_{\gamma p}$ are shown in fig. 8. Compared to previous fixed target data the cross section is on average a factor 2.5 higher and shows a rise even within the HERA range, which is not described by the GVDM prediction (for details see figure caption). This rise may be described by QCD inspired models where the cross section is proportional to the square of the gluon density in the proton[24].

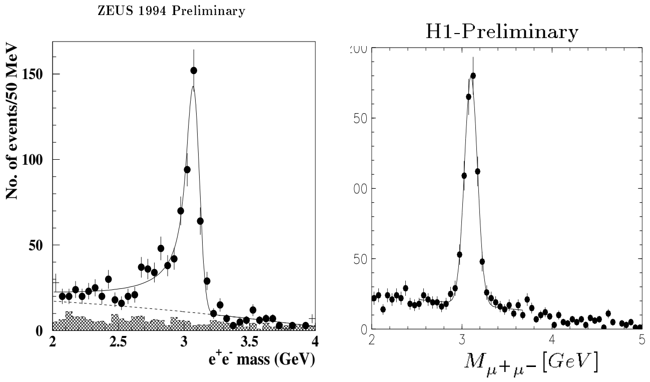

Figure 7: **Left:** Mass distribution of selected e^+e^- pairs for the elastic J/ψ sample from ZEUS. The solid line indicates a fit to the data with the convolution of a Gaussian and a bremsstrahlung function to describe the energy loss of the e^+e^- in the material. The dashed line represents a quadratic polynomial parametrising the background from misidentified pions and from the two–photon process. The shaded area is the expected contribution from the two–photon process only. **Right:** Mass distribution from H1 of $\mu^+\mu^-$ pairs selected for elastic and inelastic J/ψ production . The data points are fitted by a Gaussian plus a linear background.

Inelastic events are selected by demanding $z < 0.90$, where $z = E_{J/\psi}/E_\gamma$ (calculated in the γp cms system). Low z values are excluded in the event selection to suppress contributions from resolved photons and a correction is applied. The results are shown in fig. 9 as a function of $W_{\gamma p}$. The rise of the cross section is described by the NLO QCD model [18] using a gluon distribution rising towards low x values. The absolute agreement can be improved by cutting out low p_t values of the J/ψ.

Conclusion

Analysis of $p\bar{p}$ collisions at a cms energy of 1.8 TeV has revealed an unexpected large cross section for *prompt* J/ψ and ψ' — neither from B decays nor from decays of P–wave states χ_c — which is not described in current NLO QCD calculations. Analysis of the Υ region is not as far

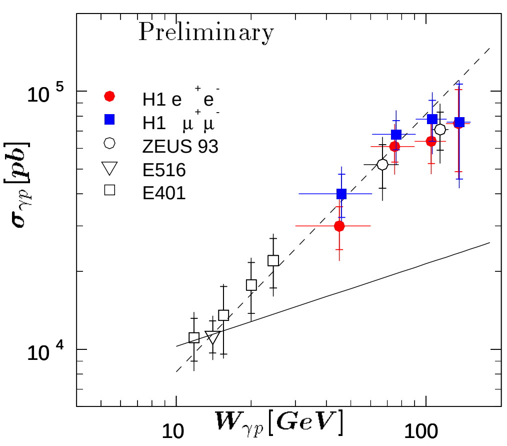

Figure 8: γp cross section for elastic J/ψ production in the HERA energy range compared to previous fixed target data. The full line shows $\sigma_{\gamma p} \sim W_{\gamma p}^{4\epsilon}$ with $\epsilon = 0.081$ as predicted for soft pomeron exchange, the dashed line shows the same function with $\epsilon = 0.25$. Both curves are normalized to the E516 data point. The outer (inner) error bars are the total (statistical) errors.

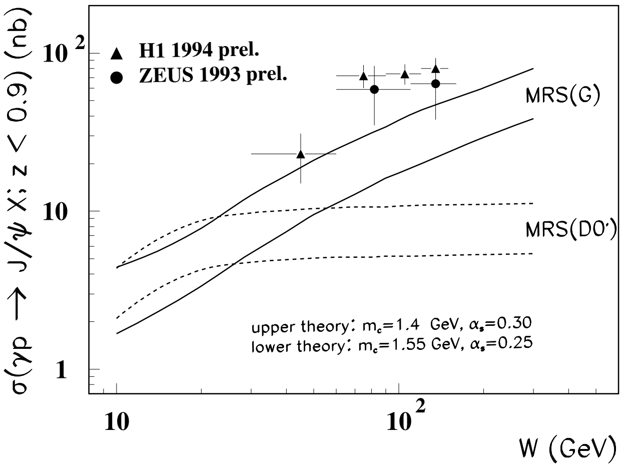

Figure 9: γp cross section for inelastic J/ψ production. The theoretical curves are NLO calculations for different structure functions. MRS(G) includes a gluon distribution rising toward low x, while MRS(DO') has a flat gluon distribution. The errors contain statistical and systematic ($\approx 20\%$) errors added in quadrature.

advanced, but measured cross sections also indicate an excess compared with QCD.

Searches for directly produced quarkonia in e^+e^- annihilations at LEP energy seem to be on the verge of delivering signals. Sensitivities are approximately an order of magnitude above expectations.

Elastic J/ψ production in ep collisions at $Q^2 \approx 0$ (photoproduction) shows an increase of the cross section with γp cms energy not compatible with GVDM ideas. QCD inspired models may describe this rising cross section.

Inelastic J/ψ production was measured and is within errors in agreement with predictions by the γg fusion model if NLO calculations are used.

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