ZEUS Measurement of Inelastic $J/\psi \rightarrow \mu^+\mu^-$
Production in DIS

Alexei Antonov
Moscow Engineering and Physics Institute @ DESY
on behalf of the ZEUS Collaboration

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- Introduction
- Inelastic $J/\psi$ Electroproduction
- Conclusions
Introduction

- Inelastic charmonium production =
  - $c\bar{c}$ creation (short-distance scales) $\otimes$
  - bound state formation (long-distance scales)
- Photon-Gluon Fusion (DIS)
  - different approaches to parton dynamics and
    $c\bar{c}$ bound state formation

Advantages of electroproduction:
- diffractive processes suppressed
- resolved-photon processes suppressed
- reduced uncertainties of perturbative calculations
Introduction (cont’d)

- Colour Singlet Model:
  - $c\bar{c}$ must have quantum numbers of Charmonium
  - one phenomenological parameter fixed from $l^+l^-$ decay width
  - failed to describe high-$p_T$ charmonia production at Tevatron by orders of magnitude ⇒ what about HERA?

- NRQCD factorisation formalism:
  - $c\bar{c}$ in Colour Octet states must contribute to charmonium production (evolution into physical charmonium via soft gluon emission at long-distance scales)
  - “$c\bar{c} \rightarrow$ charmonium” transition parametrised using a (universal) set of Long Distance Matrix Elements; currently fixed from hadroproduction or $B$-decays data ⇒ can HERA data be included in this global analysis?
Motivation: World DATA vs NRQCD

CDF Run I

NRQCD $e^+e^- \rightarrow e^+e^- J/\psi X$ at LEP2

DELPHI

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- Mainstream - NRQCD $\Rightarrow$ CO contributions: essential to describe high-$p_T$ $\psi$ production @ Tevatron, BUT...
- Polarisation properties?
- NRQCD factorisation holds for $\psi$? ME universality? ME uncertainties? Soft gluon emission under control (resummation)?
**Motivation:** $k_T$-factorisation - BFKL/CCFM

- $k_T$-factorisation approach:
  - non-collinear parton dynamics (BFKL/CCFM evolution equations)
  - $\sigma = \text{unintegrated (transverse momentum dependent) gluon densities} \otimes \text{off-shell matrix elements}$
  - less significant CO contributions than in NRQCD
  - broader $p_T$ spectra, specific polarisation properties

- Succeeded in describing the $p_T$ spectra and quarkonium polarization properties measured at Fermilab and HERA.
• $e p \rightarrow e J/\psi X$ was believed to be a good gauge for gluon density.

• check H1 main conclusion on the same analysis: inclusion of CO contributions provides better description of shapes except for bad description of inelasticity distribution

• Search for signatures of CO, test possible alternatives $\Rightarrow$ e.g. $k_t$-factorization
Analysis

- Analysis of 96-00 data
  → Integrated lumi $L = 109$ pb$^{-1}$
- The reaction $e p \rightarrow e J/\psi X$
  with $J/\psi \rightarrow \mu^+\mu^-$ is studied for:
  
  $2 < Q^2 < 80$ GeV$^2$
  $50 < W < 250$ GeV
  $0.2 < z < 0.9$
  $-1.6 < Y_{lab} < 1.3$

$z$: fraction of virtual photon energy transfered to $J/\psi$ (in proton rest frame)

- The diffractive proton-dissociative background where estimated($\sim 6\%$) and subtracted from data.
- Data sample include contributions from $\psi'$ and $B$–meson decays into $J/\psi$. This contributions were estimated and added to theoretical predictions.
- The contribution of $\chi_c$ radiative decays into $J/\psi$ was neglected.

The cross section for the process is $302 \pm 23$ (stat.) $^{+28}_{-20}$ (syst.) pb.
Theoretical models

- NRQCD calculations by Kniehl and Zwirner. Marked as NRQCD(CS+CO) and NRQCD(CS).
  
  Uncertainties (added in quadrature):
  - $m_c = 1.5 \pm 0.1$ GeV
  - $\mu = (0.5 \div 2)\sqrt{Q^2 + M_{\psi}^2}$
  - PDF set MRST98LO (CTEQ5L)
  - non-perturbative ME from hadroproduction

- $k_t$-factorization calculations by Lipatov and Zotov. Marked as $k_t$-fact.(LZ)
  
  BFKL evolution of parton cascade.
  - KMS unintegrated gluon density, low $k_T$ cut-off 1 GeV;
  - $m_c = 1.4$ GeV (KMS)
  - $\mu = k_T$ for $k_T > 1$ GeV, for $k_T \leq 1$ GeV the scales were fixed at 1 GeV.

- CASCADE: (MC implementation of CCFM evolution)
  - $m_c = 1.5$ GeV
  - $\alpha_s = \alpha_s(m_T)$
  - J2003 set 2 unintegrated gluon density
Measurements of $d\sigma/dz$ and $1/\sigma d\sigma/dz$

- NRQCD CS generally agree.
- CS + CO: resummation needed? higher order corrections?
- $k_T$-factorisation gives good description;
- CASCADE (J2003 set 2): absolute prediction overshoots data; shape reasonable.
Measurements of $d\sigma/dQ^2$ and $d\sigma/dW$
Measurements of $\frac{d\sigma}{dp_T^2}$ and $\frac{d\sigma}{dY^*}$ in $\gamma p$
Measurements of $d\sigma/d\log(M_X^2/\text{GeV}^2)$ and $d\sigma/dY_X$

where $M_X$ is the invariant mass of the hadronic final state.
Comparison to H1 results $d\sigma/dz$ and $1/\sigma d\sigma/dz$

The ZEUS data are in agreement with the H1 results.

H1 kinematic range:
- $2 < Q^2 < 100 \text{ GeV}^2$
- $50 < W < 225 \text{ GeV}$
- $0.3 < z < 0.9$
- $p_T^* > 1 \text{ GeV}^2$
Comparison to H1 results $d\sigma/dp_T^2$ and $d\sigma/dY^*$ in $\gamma p$

![Graph showing comparisons between different experimental results and theoretical models for $d\sigma/dp_T^2$ and $d\sigma/dY^*$ in $\gamma p$. The graph includes data from ZEUS and H1 experiments, as well as predictions from NRQCD and NRQCD (CS) models.](image-url)
Summary and conclusions

- New ZEUS measurement of inelastic $J/\psi$ in DIS using complete data sample available at HERA I
- The data are in agreement with the H1 results.
- The data are compared with LO NRQCD predictions, including both CS and CO contributions, and $k_T$–factorisation calculations (BFKL and CCFM).
- Calculations of the CS process only generally agree with the data whereas inclusion of CO terms spoils this agreement. Also the $k_T$–factorisation calculations generally agree with the data. CASCADE (J2003 set 2) is above data, shapes of distributions are reasonably described except for $W$.
- Calculations with higher order corrections and soft gluon emission treatment needed.