Inelastic quarkOnium production at HERA

Igor Katkov
Skobeltsyn Institute of Nuclear Physics
Moscow State University

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• Introduction
• Inelastic Photoproduction of Charmonium
• Inelastic $J/\psi$ Electroproduction
• HERA II prospects ($J/\psi$, $\chi_c$, $\Upsilon$)
• Conclusions
Introduction

- Quarkonium production =
  \( Q\bar{Q} \) creation (short-distance scales) \( \otimes \)
  bound state formation (long-distance scales)
- Boson-Gluon Fusion (DIS) \( \otimes \)
  different approaches to parton dynamics and
  \( Q\bar{Q} \) bound state formation
- Colour Singlet Model:
  \( \rightarrow Q\bar{Q} \) must have quantum numbers of Quarkonium
  \( \rightarrow \) one phenomenological parameter fixed from \( l^+l^- \) decay width
  \( \rightarrow \) failed to describe high-\( p_T \) quarkonia production
  at Tevatron by orders of magnitude \( \Rightarrow \) what about HERA?
Introduction (cont’d)

- NRQCD factorisation formalism:
  - $Q\bar{Q}$ in Colour Octet states must contribute to Quarkonium production (evolution into physical Quarkonium via soft gluon emission at long-distance scales)
  - “$Q\bar{Q} \rightarrow$ Quarkonium” 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?

- $k_T$-factorisation approach:
  - non-collinear parton dynamics (BFKL evolution equations)
  - $\sigma =$ unintegrated (transverse momentum dependent) gluon densities $\otimes$ off-shell matrix elements
  - less significant CO contributions than in NRQCD
**Introduction (cont’d)**

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

- Direct photon processes \((z \gtrsim 0.2)\)
- Resolved photon processes \((z \lesssim 0.2)\) suppressed at high \(Q^2\)

\(\text{CS}\): contributes significantly at high \(z\); delicate phase space region; resummation technique needed

\(\text{CO}\): significant contributions; analogy to hadroproduction

Elastic/diffractive phenomena must be eliminated (not accounted for in theory)
**World DATA vs NRQCD**

- Significance of CO contributions (applicability of NRQCD) not yet established
- How HERA data complement this picture?
Photoproduction: DATA vs NLO CSM

H1 DATA:
$60 < W < 240 \text{ GeV}$,
$0.3 < z < 0.9$,
$p_T^2 > 1 \text{ GeV}^2$

NLO CSM by Krämer et al.

NLO CSM: describes data within large normalisation uncertainties, LO is softer
Photoproduction: DATA vs LO NRQCD

- H1 DATA: $120 < W < 260$ GeV, $p_T^2 > 1$ GeV$^2$;
  ZEUS DATA: $50 < W < 180$ GeV, $p_T > 2$ GeV
- Calculations by Krämer (CS+CO LO), Kniehl and Kramer (CS+CO HO improved), Beneke, Schuler and Wolf (solid lines)
- Resolved contributions improve description at low $z$
- Resummation improves at high $z$, but large uncertainties
Photoproduction: polarisation

Polarisation: independent of normalisation uncertainties
calculation by Beneke, Krämer and Vanttinen
Photoproduction: $\frac{\sigma_{\psi(2S)}}{\sigma_{\psi(1S)}}$

- $\sigma(\psi')/\sigma(J/\psi) = 0.33 \pm 0.10^{+0.01}_{-0.02}$
- flat, consistent with 0.24 from LO CS prediction, the same production mechanism for $\psi'$
- estimate of $J/\psi$ fraction coming from $\psi'$ cascade decays consistent with expectations (15%); NLO theoretical predictions scaled by 1.15
Photoproduction: DATA vs CASCADE

- H1 DATA:
  - $60 < W < 240 \text{ GeV}$,
  - $0.3 < z < 0.9$,
  - $p_{T,\psi}^2 > 1 \text{ GeV}^2$

- CASCADE + JS unintegrated gluon distributions

- high $z$: missing CO? old version of CASCADE (:-)?

- no CASCADE prediction in DIS?
Electroproduction: DATA vs LO NRQCD

- H1 DATA:
  \[ 50 < W < 225 \text{ GeV}, \]
  \[ Q^2 > 2 \text{ GeV}^2, \]
  \[ p_T^* > 1 \text{ GeV}^2, \]
  \[ 0.3 < z < 0.9 \]

- LO NRQCD by Kniehl and Zwirner

- CS factor 2.7 too low, too soft \( p_T \) (higher orders?)

- CS + CO: factor 2 above at low \( Q^2, p_T \); improves at high \( Q^2, p_T \)
Electroproduction: NRQCD & $k_T$

- ZEUS DATA:
  $50 < W < 250$ GeV,
  $2 < Q^2 < 80$ GeV$^2$,
  $0.2 < z < 0.9$,
  $-1.6 < Y_{lab} < 1.3$

- LO NRQCD by Kniehl and Zwirner, $\mu^2 = Q^2 + M_\psi^2$

- $k_T$-factorisation within CSM by Lipatov and Zotov, $\mu^2 = q_T^2$ ($q_T$: virtuality of initial gluon)

- $k_T$-factorisation: higher order corrections are effectively included, but still $p_T$ spectrum too soft
NRQCD: missing higher order corrections or resummation procedure at high $z$?

$k_T$-factorisation within CSM describes data reasonably well
HERA II prospects

- Upgraded detector:
  - improved reconstruction efficiencies
  - improved background rejection (beauty)

- Larger statistics ⇒ smaller uncertainties ⇒ more decisive tests:
  - especially helpful for polarisation studies
  - polarisation at lower $z$ (resolved photon, CO sensitive)

- Higher $Q^2$ and $p_T^2$ reachable:
  - smaller theoretical uncertainties, total x-section asymptotic behaviour directly probes CO matrix elements
  - overlap with $p_T$ range available at Tevatron
  - polarisation properties more pronounced
HERA II prospects (cont’d)

- $\chi_c \,(\rightarrow J/\psi \gamma)$ production: leading CS process suppressed, only CO contributes

- Associated $J/\psi + \gamma$: region of intermediate and large values of $z$ dominated by CO

- $\gamma$: suppressed by some two orders of magnitude w.r.t. $J/\psi \Rightarrow$ given $0.5 – 1 \, \text{fb}^{-1}$ of collected lumi (now too optimistic?), statistics $\lesssim 100$ events
Conclusions

- Photoproduction:
  - NLO corrections are essential to describe medium- and high-\(z\), high-\(p_T\) data within CSM
  - At low \(z\) resolved photon contributions improve description, but contributions from \(B\)-decays and higher mass charmonium states are not accounted for in data
  - Improvement in statistics is needed to make polarisation measurements conclusive
Conclusions (cont’d)

- Electroproduction:
  → LO CS contributions are below data; LO CS transverse momenta spectra are too soft (NLO?)
  → LO NRQCD calculations above data at high $z$, describe data well at high $Q^2$ and transverse momenta
  → $k_T$-factorisation within CSM calculation describes data well, except softer $p_T^*$

- Theoretical uncertainties (higher order corrections, soft gluon emission treatment) as well as experimental errors too large to constrain CO contributions

- Good prospects of HERA II: many things to do and improve!