

Inelastic quarkonium production at HERA

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**Heavy quark Physics at the upgraded HERA collider
Rehovot, 19–22 October 2003**



- Introduction
- Inelastic Photoproduction of Charmonium
- Inelastic J/ψ Electroproduction
- HERA II prospects (J/ψ , χ_c , Υ)
- 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:
 - $Q\bar{Q}$ must have quantum numbers of Quarkonium
 - one phenomenological parameter fixed from l^+l^- decay width
 - failed to describe high- p_T quarkonia production
at Tevatron by orders of magnitude \Rightarrow what about HERA?

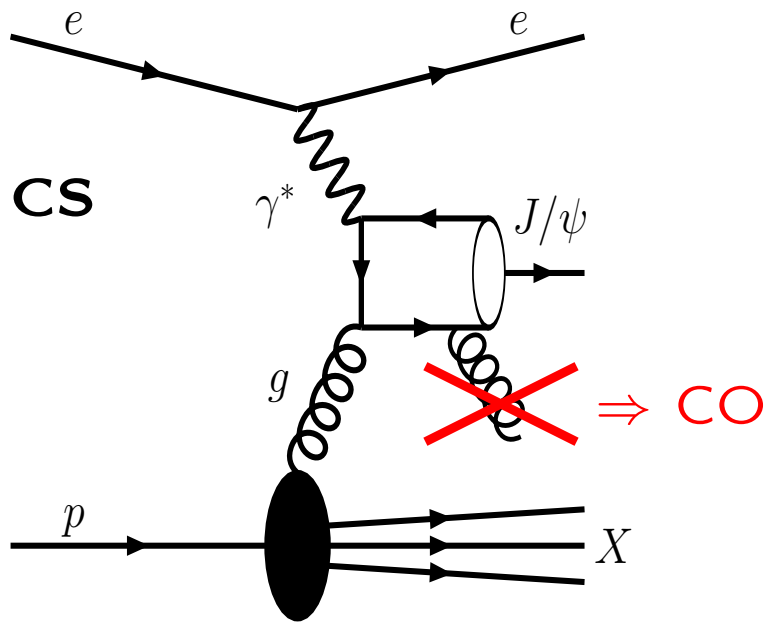
Introduction (cont'd)

- 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 \Rightarrow
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)

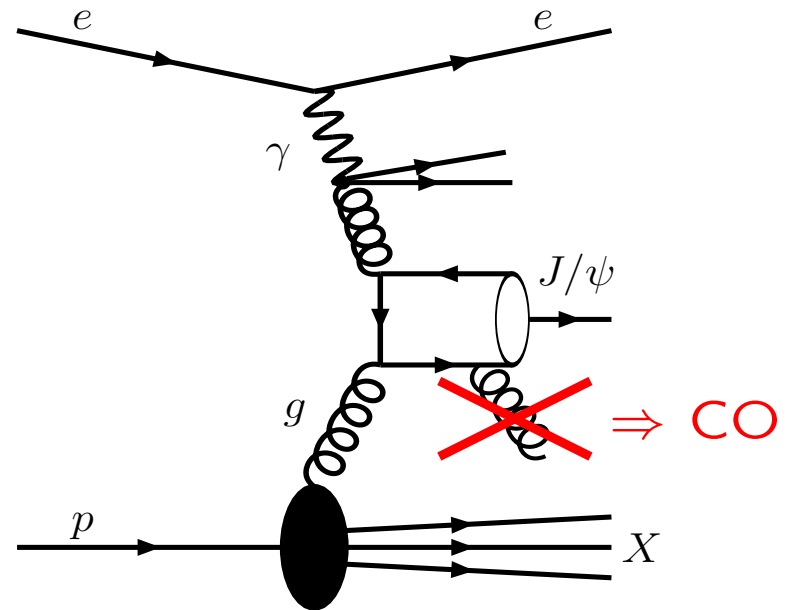
z : fraction of virtual photon energy transferred to J/ψ (in proton rest frame)

direct photon processes ($z \gtrsim 0.2$)



CO: contributes significantly at high z ;
delicate phase space region;
resummation technique needed

resolved photon processes ($z \lesssim 0.2$)
suppressed at high Q^2

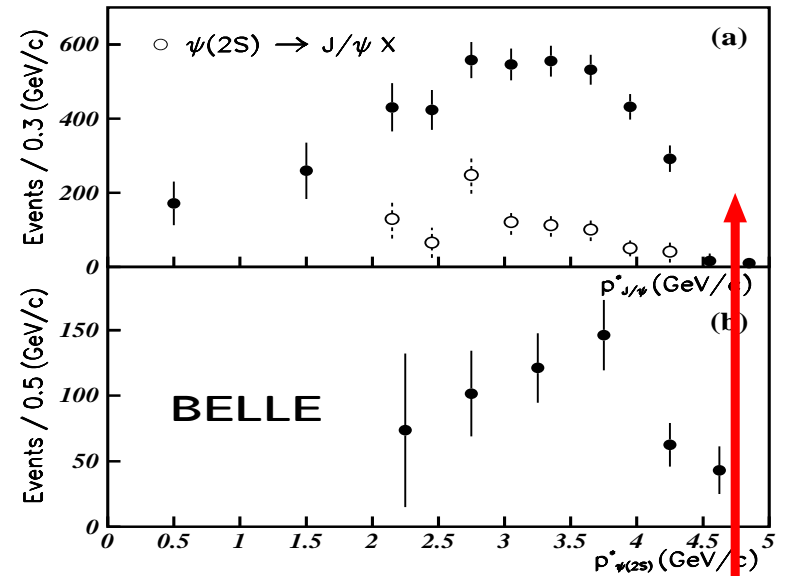
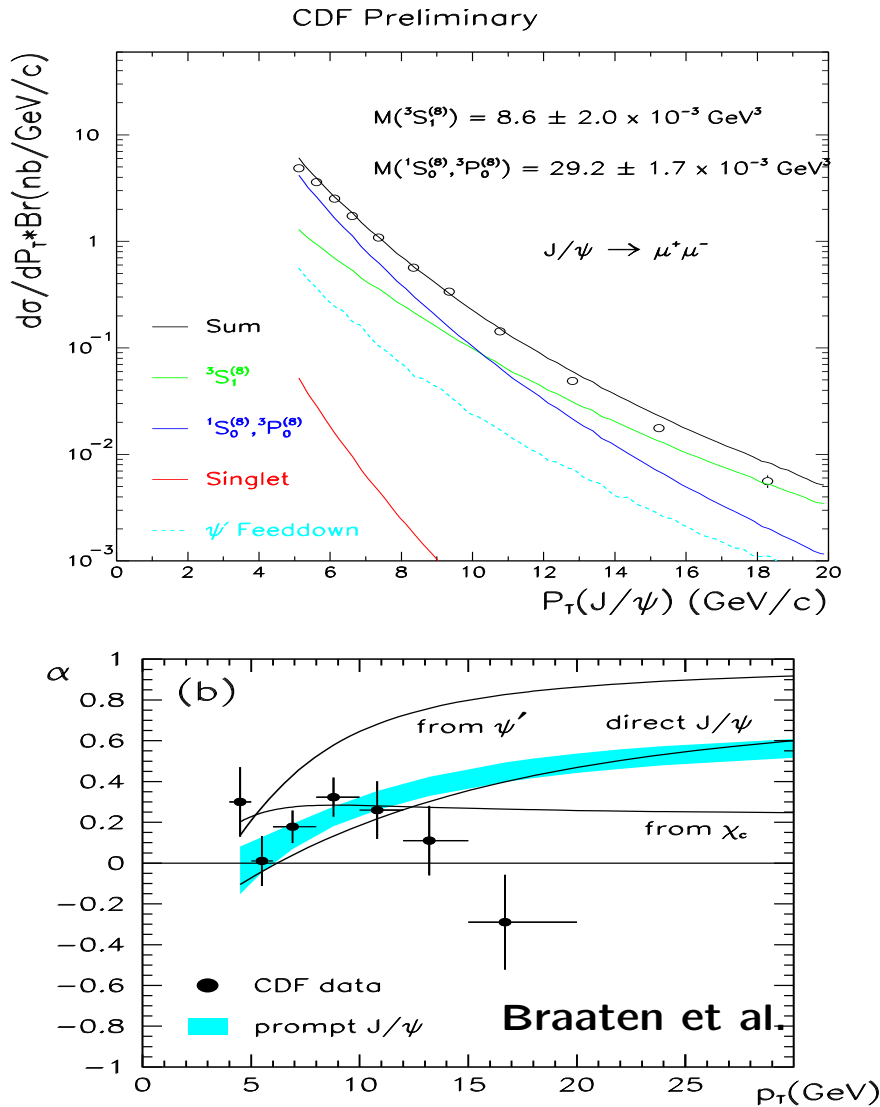


CO: significant contributions;
analogy to hadroproduction

Elastic/diffractive phenomena must be eliminated (not accounted for in theory)

World DATA vs NRQCD

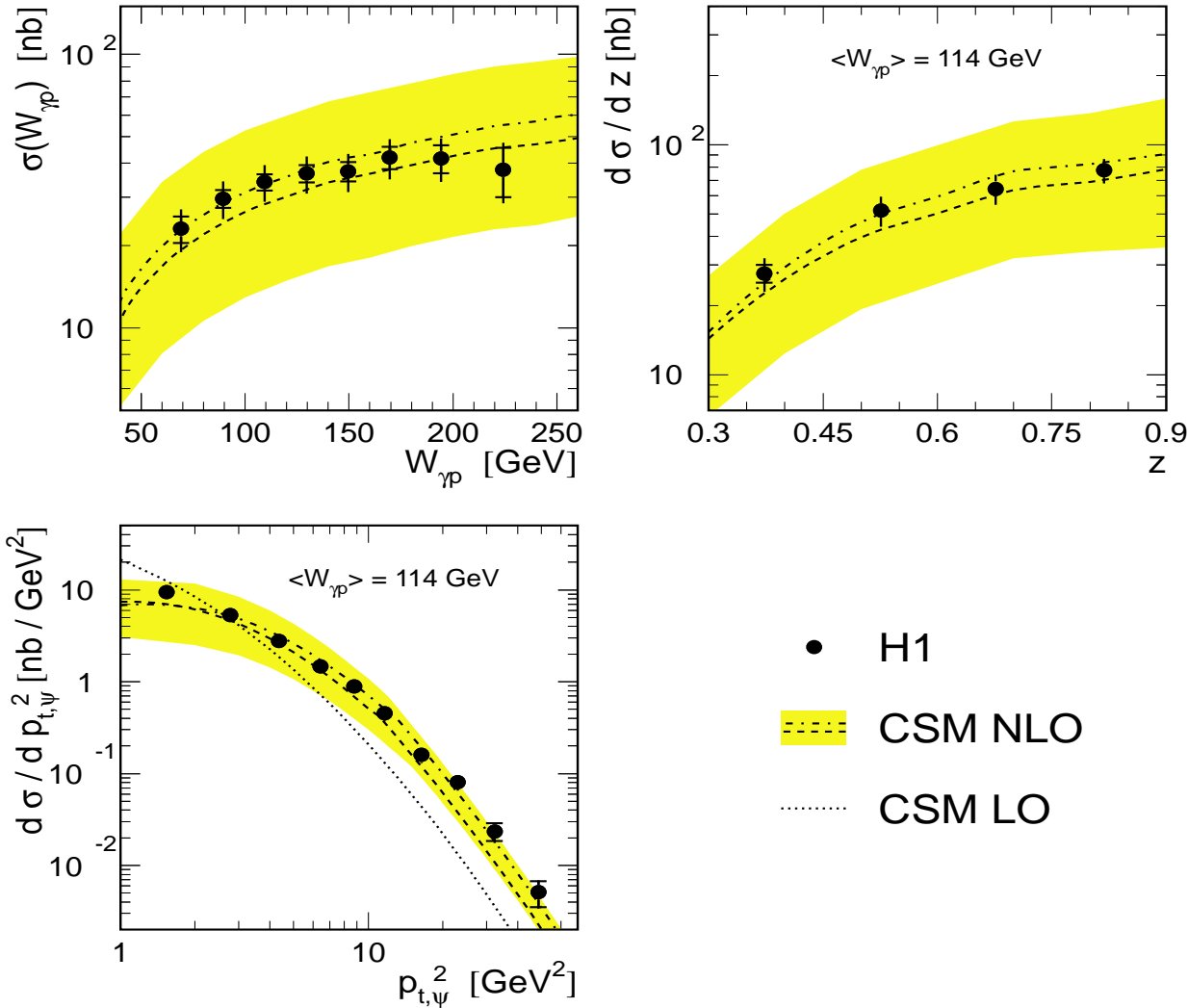
HQHERA.2, REHOVOT, 19-22 OCTOBER 2003



leading CO process expected here

- Significance of CO contributions (applicability of NRQCD) not yet established
- How HERA data complement this picture?

Photoproduction: DATA vs NLO CSM



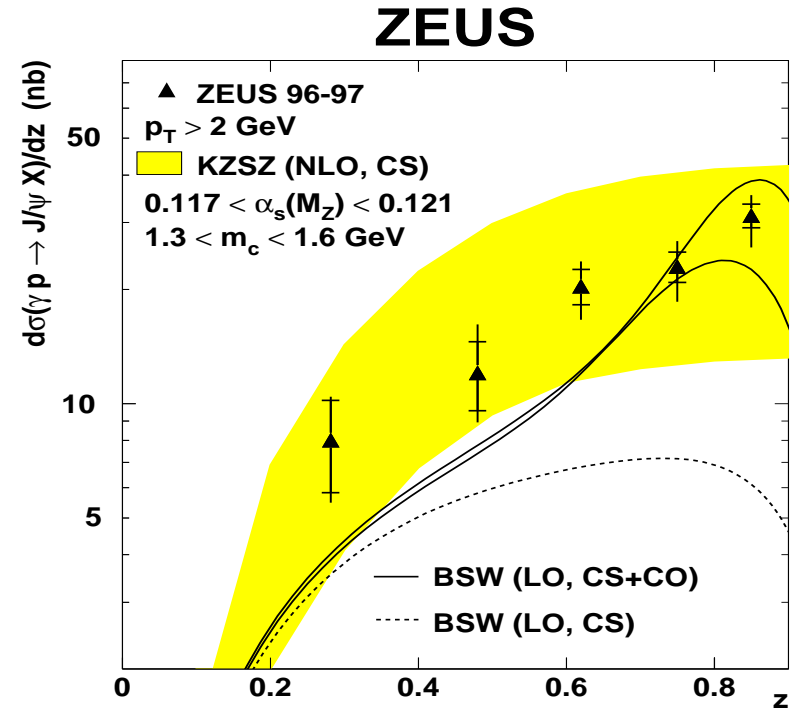
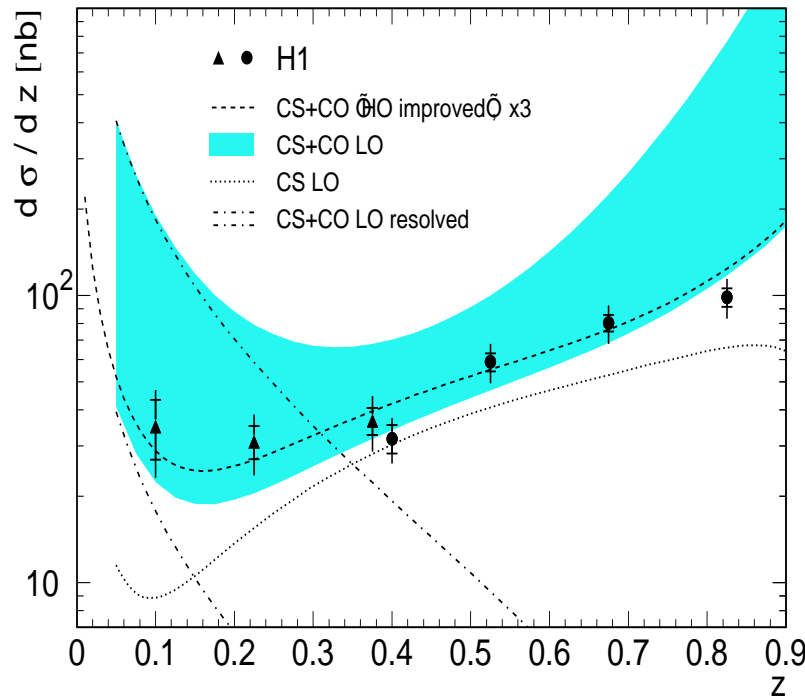
H1 DATA:
 $60 < W < 240$ GeV,
 $0.3 < z < 0.9$,
 $p_T^2 > 1$ GeV²

NLO CSM by Krämer et al.

NLO CSM: describes data within large normalisation uncertainties, LO is softer

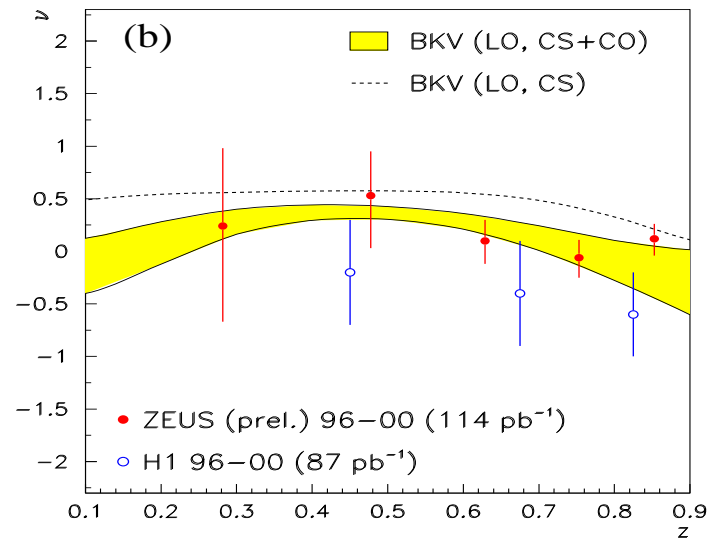
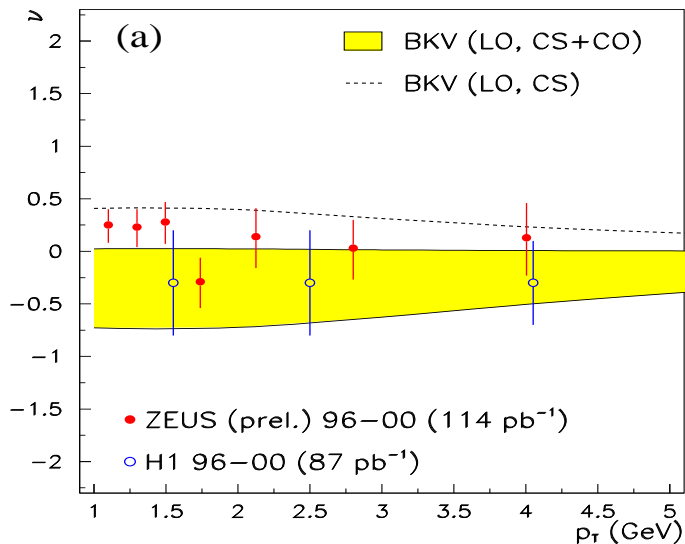
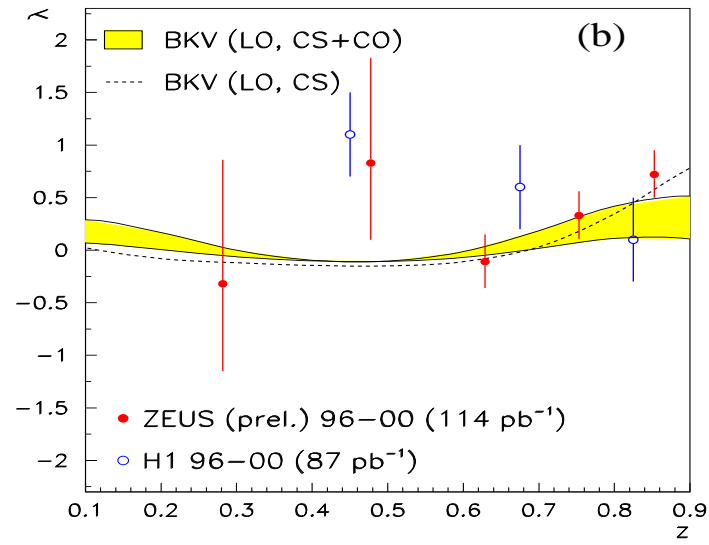
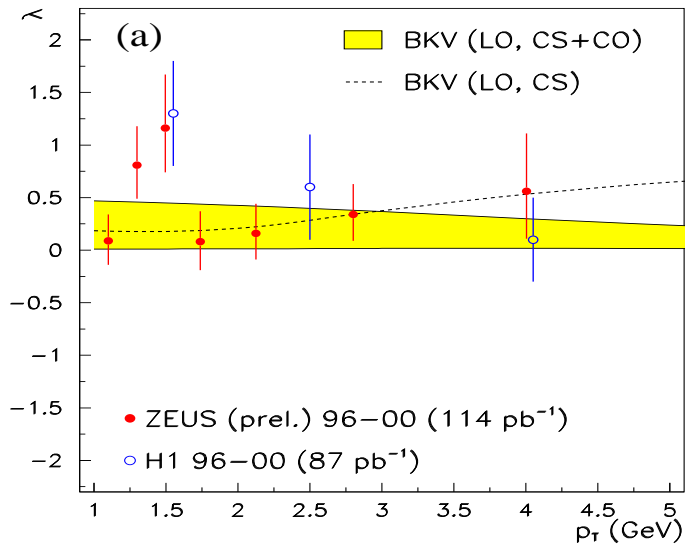
- H1
- CSM NLO
- CSM LO

Photoproduction: DATA vs LO NRQCD



- H1 DATA: $120 < W < 260 \text{ GeV}$, $p_T^2 > 1 \text{ GeV}^2$;
ZEUS DATA: $50 < W < 180 \text{ GeV}$, $p_T > 2 \text{ GeV}$
- 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

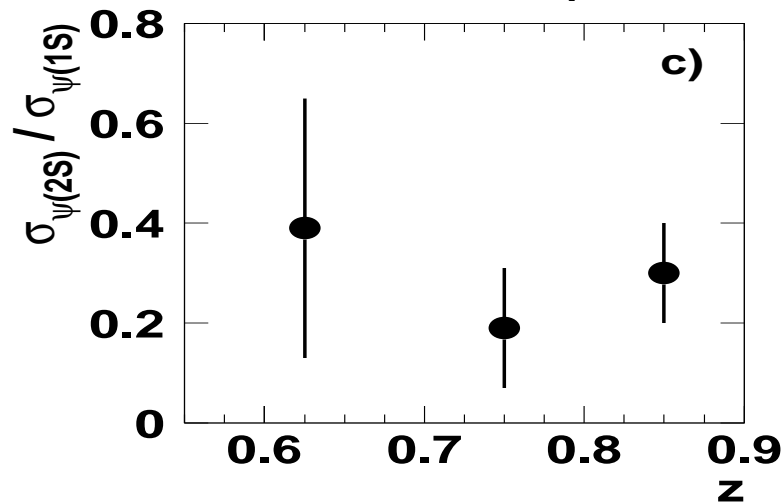
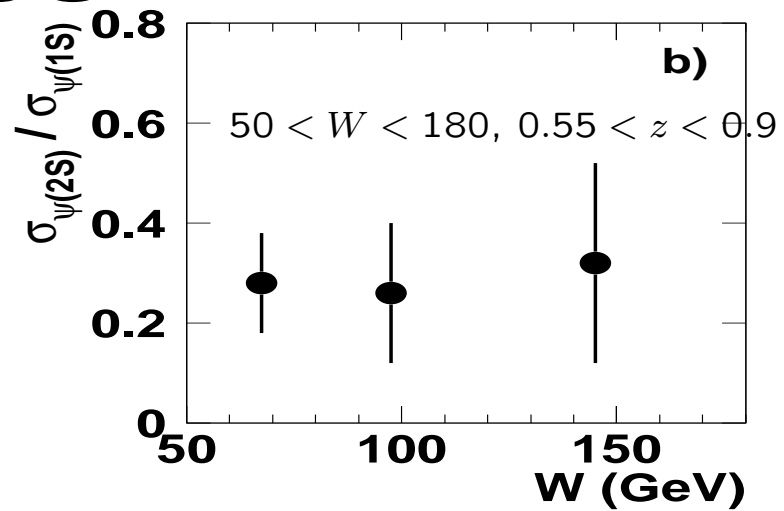
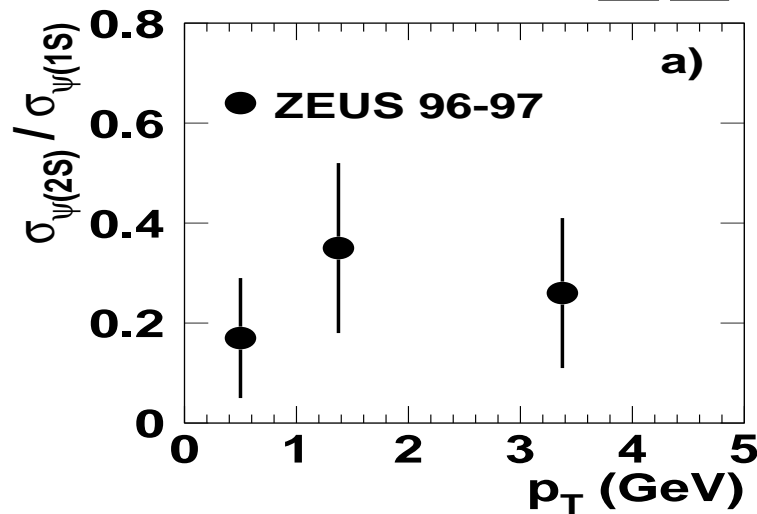


Polarisation:
independent
of normalisation
uncertainties

calculation by
Beneke, Krämer and
Vanttinen

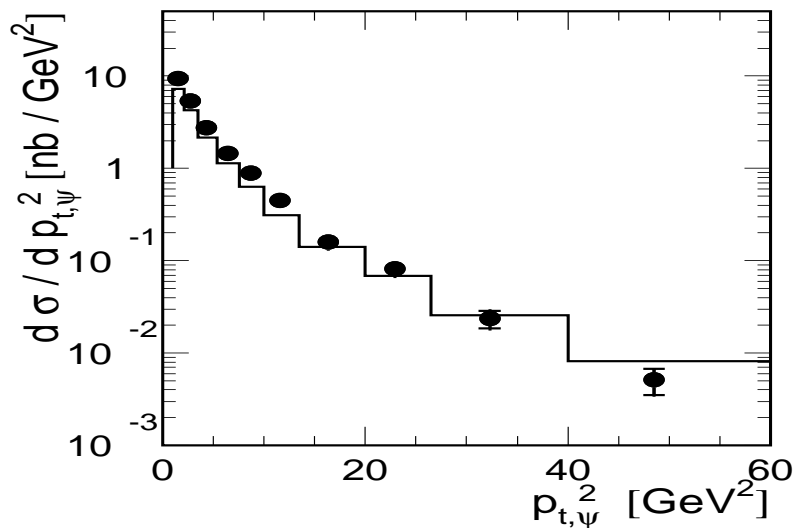
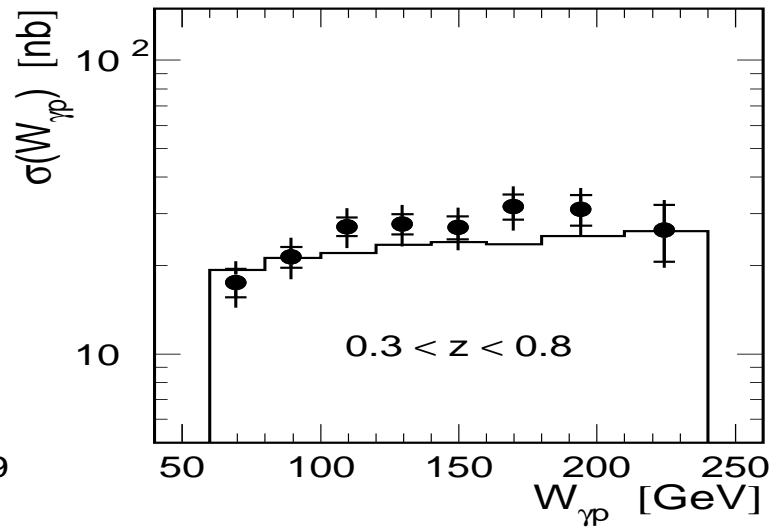
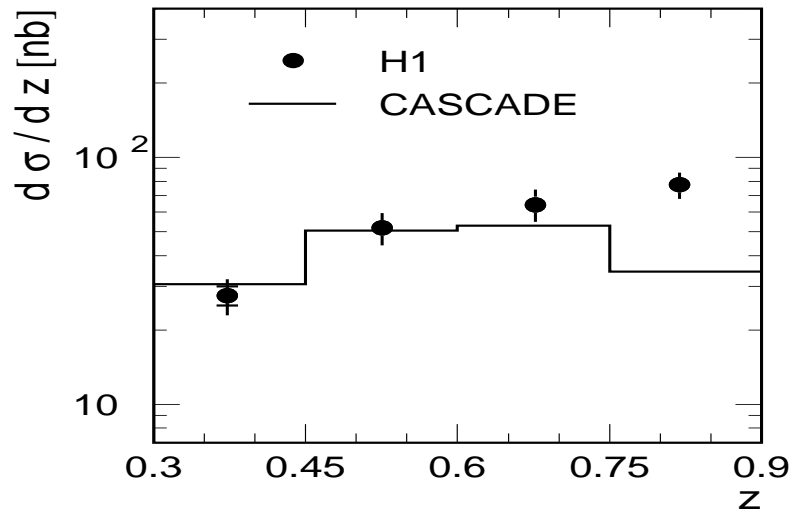
Photoproduction: $\sigma_{\psi(2S)}/\sigma_{\psi(1S)}$

ZEUS



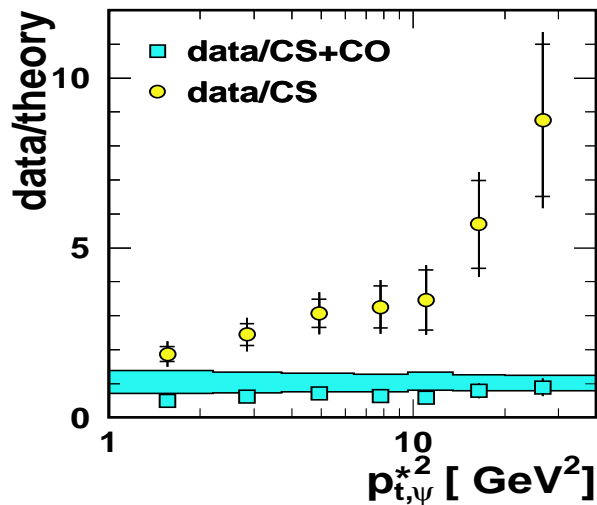
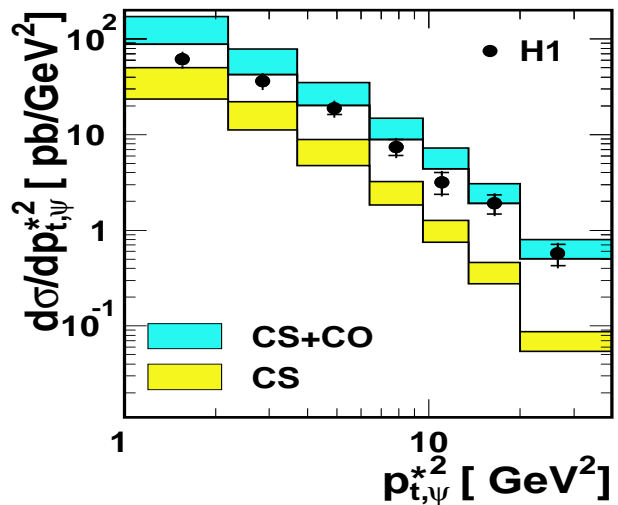
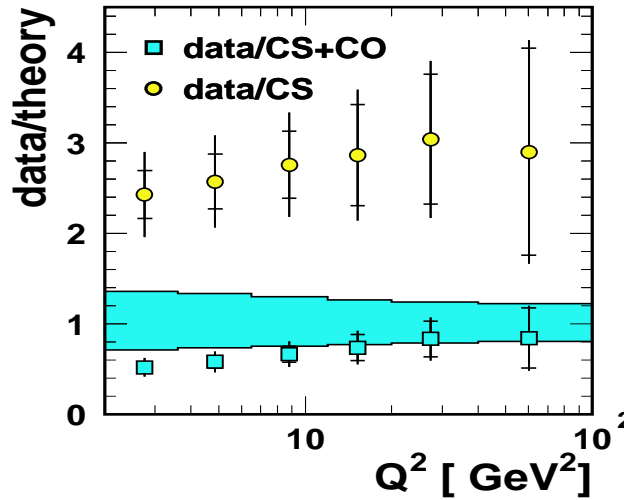
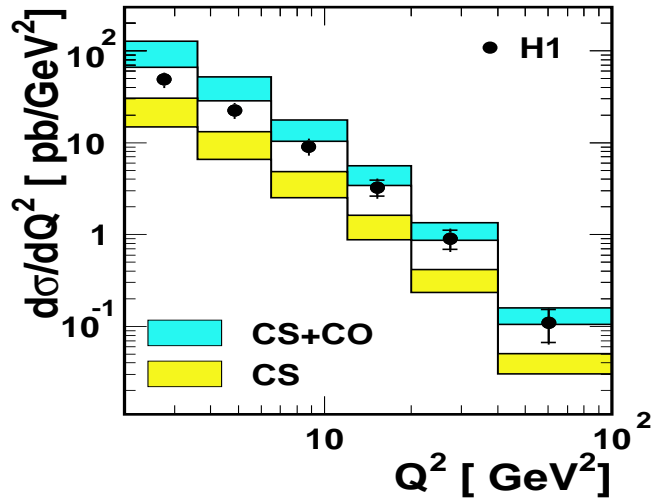
- $\sigma(\psi')/\sigma(J/\psi) = 0.33 \pm 0.10^{+0.01}_{-0.02}$
- flat, consistent with 0.24 from LO CS prediction, the same production mechanism for ψ 's
- estimate of J/ψ fraction coming from ψ' cascade decays consistent with expectations (15%); NLO theoretical predictions scaled by 1.15

Photoproduction: DATA vs CASCADE



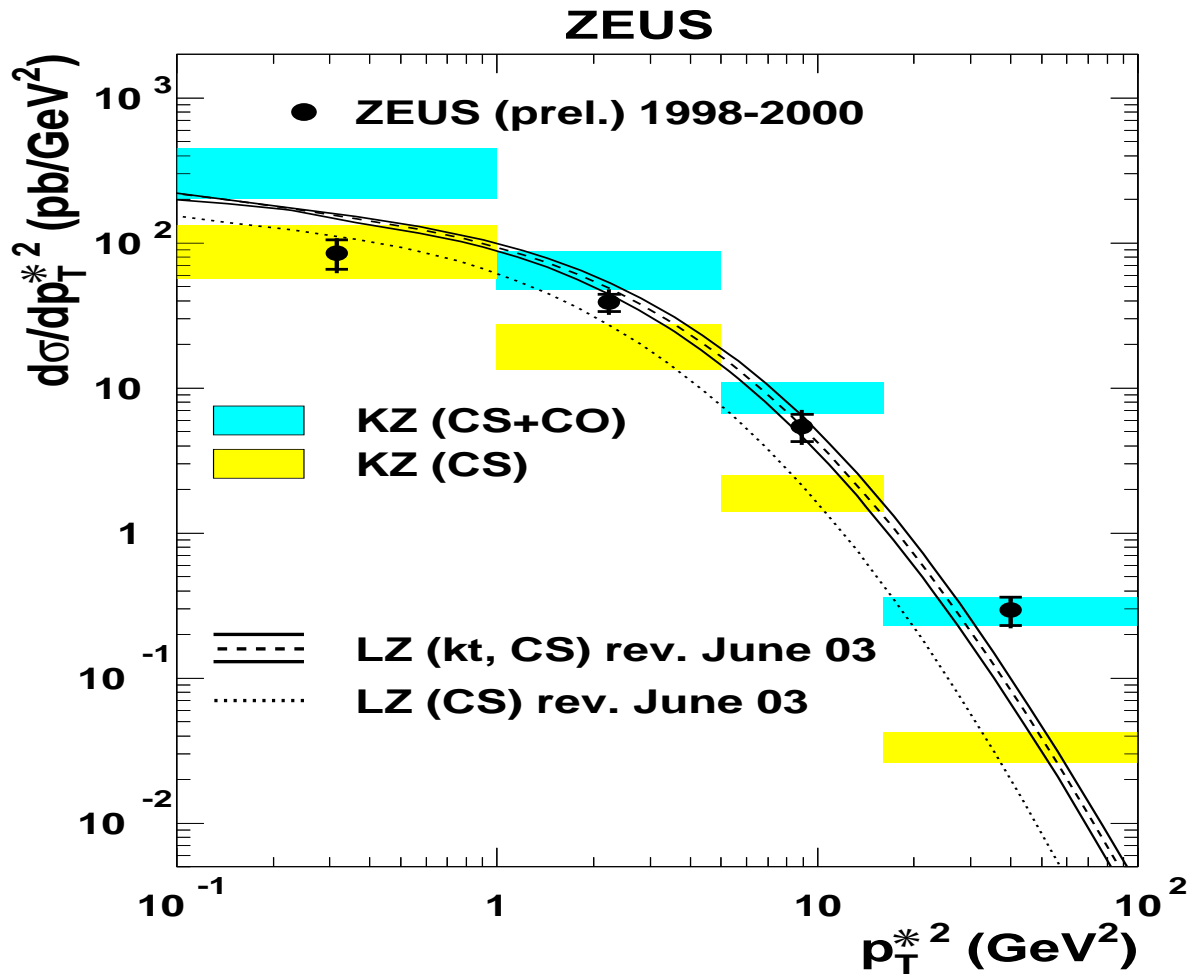
- H1 DATA:
 $60 < W < 240 \text{ GeV}$,
 $0.3 < z < 0.9$,
 $p_T^2 > 1 \text{ GeV}^2$
- CASCADE + JS unintegrated gluon distributions
- high z : missing CO? old version of CASCADE (:-)?
- no CASCADE prediction in DIS?

Electroproduction: DATA vs LO NRQCD



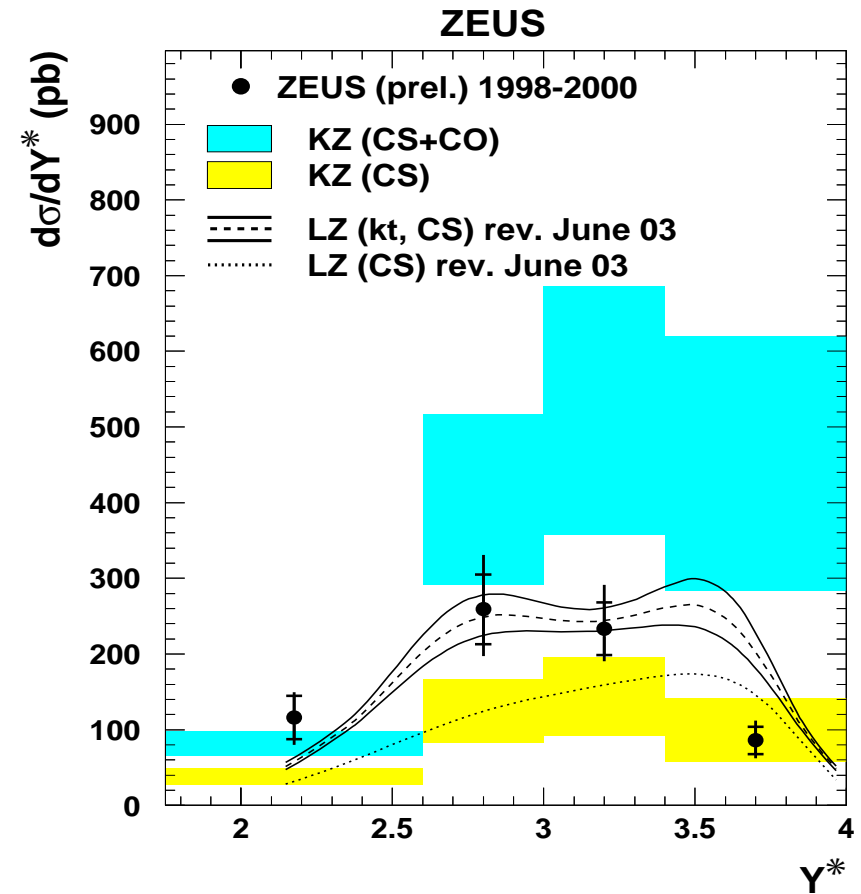
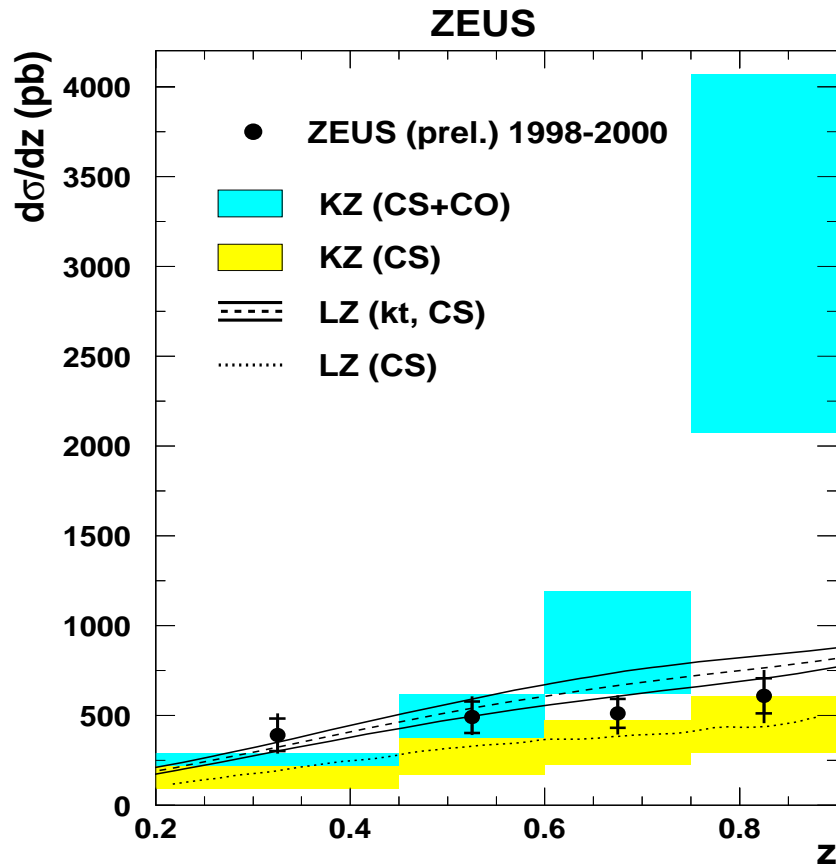
- H1 DATA:
 $50 < W < 225 \text{ GeV}$,
 $Q^2 > 2 \text{ GeV}^2$,
 $p_T^{*2} > 1 \text{ GeV}^2$,
 $0.3 < z < 0.9$
- LO NRQCD by Kniehl and Zwirner
- CS factor 2.7 too low, too soft p_T (higher orders?)
- CS + CO: factor 2 above at low Q^2, p_T ; improves at high Q^2, p_T

Electroproduction: NRQCD & k_T



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

Electroproduction: NRQCD & k_T



- 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 \Rightarrow smaller uncertainties \Rightarrow 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
- Υ : 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!