

Inelastic photo- and electroproduction of charmonium



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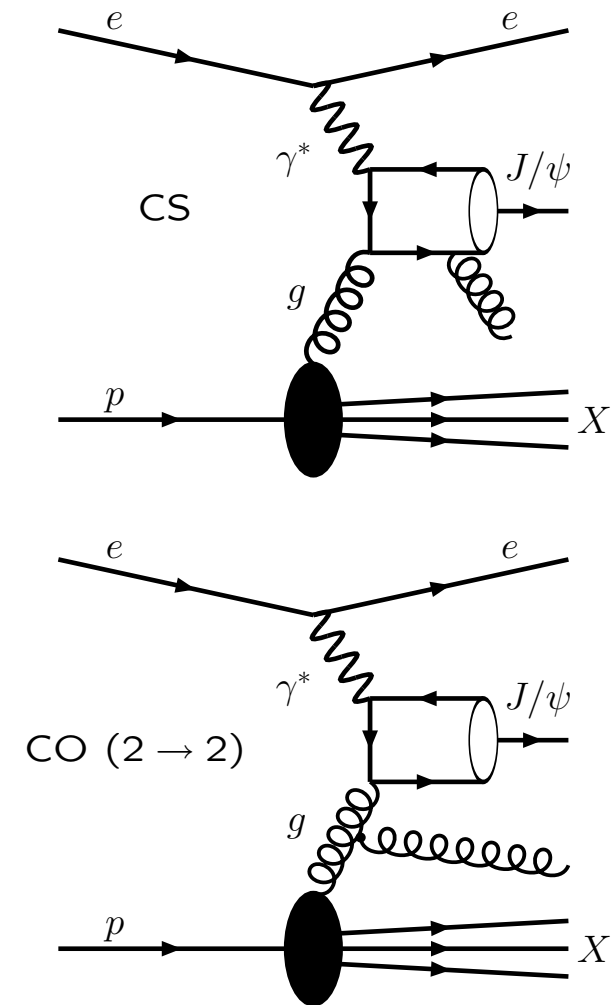


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- Introduction
- Inelastic Photoproduction of Charmonium
- Inelastic J/ψ Electroproduction
- Summary

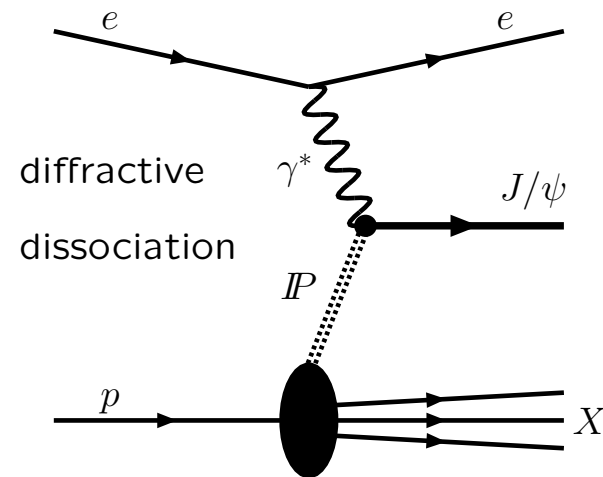
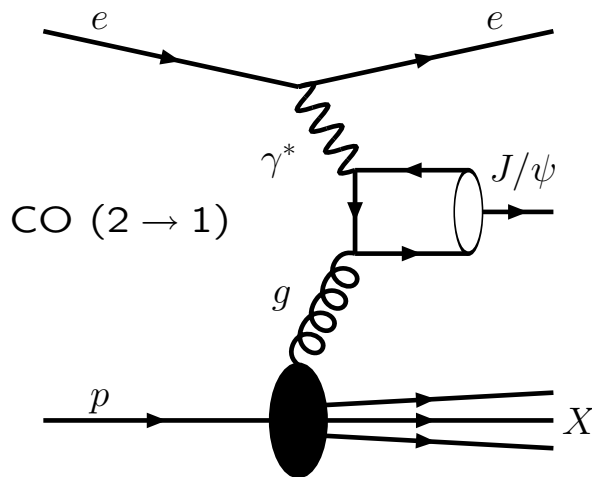
Introduction

- Process $e + p \rightarrow e + J/\psi + X$:
 - z – fraction of virtual photon (γ^*) energy transferred to J/ψ in proton rest frame (inelasticity)
 - dominant $c\bar{c}$ production mechanism: BGF \Rightarrow information on gluon density in proton
 - different approaches to describe formation of $c\bar{c}$ bound state
- Colour Singlet Model:
 - $c\bar{c}$ has quantum numbers of J/ψ
 - $\Gamma_{\psi \rightarrow l+l^-}$ – the only phenomenological parameter
 - failed to describe high p_T production of J/ψ at Tevatron \Rightarrow NRQCD
- NRQCD factorization approach:
 - $c\bar{c}$ in colour octet (CO) states contribute to J/ψ production (at higher z for direct and lower z for resolved)
 - more parameters: LDMEs; LDMEs are believed to be process independent
- k_t -factorization approach:
 - non-collinear parton dynamics (BFKL evolution equations)
 - unintegrated (k_t -dependent) gluon densities

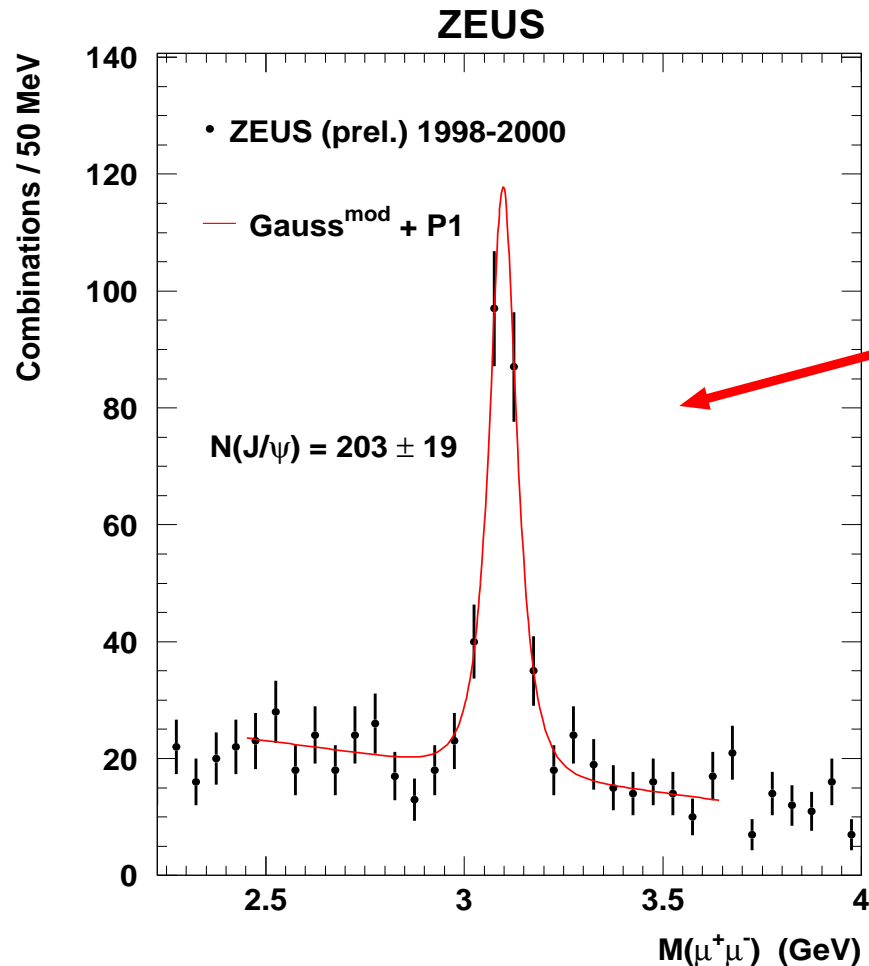


J/ψ at HERA

- Search for signatures of CO, test possible alternatives \Rightarrow e.g. k_t -factorization
- Backgrounds for inelastic J/ψ production measurement:
 - \rightarrow diffractive production (subtracted)
 - \rightarrow decays of beauty (small, not subtracted)
 - \rightarrow decays of $\psi(2S)$ ($\sim 15\%$ in photoproduction, to be discussed)



Kinematic ranges and signals



- Signal measured in photoproduction data ($Q^2 \sim 0 \text{ GeV}^2$):
 - Integrated lumi $\mathcal{L} = 38 \text{ pb}^{-1}$
 - $0.1 < z < 0.9$
 - $50 < W < 180 \text{ GeV}$
- Signal measured in electroproduction data:
 - Integrated lumi $\mathcal{L} = 73.3 \text{ pb}^{-1}$
 - $2 < Q^2 < 80 \text{ GeV}^2$
 - $50 < W < 250 \text{ GeV}$
 - $0.2 < z < 0.9$
 - $-1.6 < Y_{\text{lab}} < 1.3$
- Advantages of electroproduction:
 - diffractive processes suppressed
 - resolved-photon processes suppressed
 - reduced uncertainties of perturbative calculations

Photoproduction: theoretical models

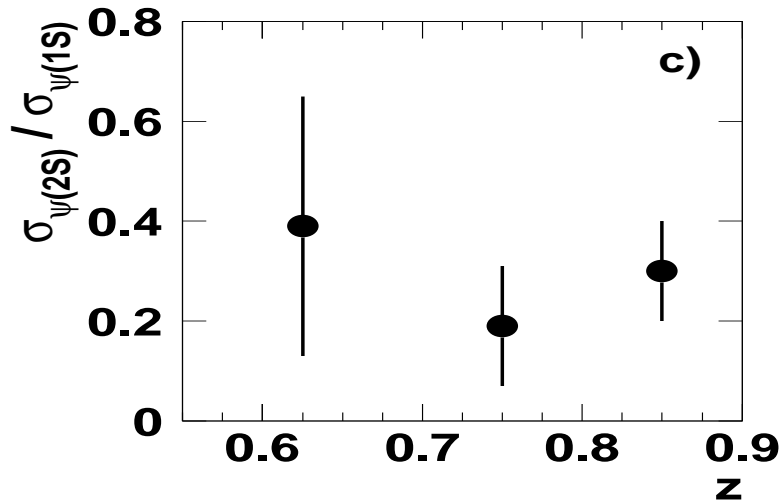
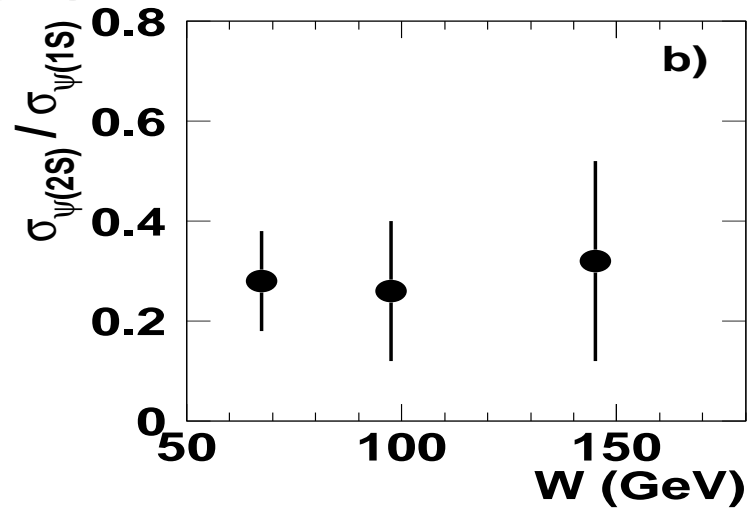
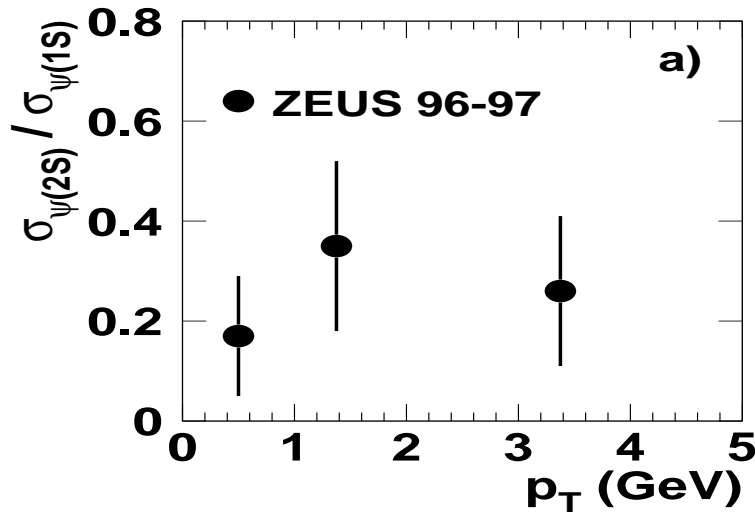
- Three types of calculations: NLO CS, LO CS, LO NRQCD
- NLO CS calculation by Krämer et al. (KZSZ (NLO, CS)):
 - the only NLO available for J/ψ production!
 - only direct processes, no resolved
 - MRST01, $1.3 < m_c < 1.6$ GeV,
 $\mu = m_c/\sqrt{2}$ ($\max(m_c/\sqrt{2}, \sqrt{m_c^2 + p_T^2}/2)$) for p_T^2 distribution)
- LO CS calculation by Krämer et al. (KZSZ (LO, CS)):
 - both direct and resolved processes included
 - GRV94 LO (proton), GRV LO (photon),
 $\Lambda_{\text{QCD}} = 200$ MeV, $\mu = 2m_c$, $m_c = 1.5$ GeV
- BKV (LO, CS): extension of the previous calculation to helicity distributions
- Calculations of helicity distributions within CSM and k_t -factorization by Baranov with two different choices of unintegrated gluon density

Photoproduction: theoretical models

- KZSZ (LO, CS+CO) and BKV (LO, CS+CO):
 - both direct and resolved contributions for CS and CO
 - LDMEs extracted from $p\bar{p}$ data \Rightarrow main uncertainty
- NRQCD calculation by Kniehl and Kramer: (KK (LO, CS+CO)):
 - both direct and resolved contributions for CS and CO
 - improved procedure (higher-order effects) to extract LDMEs from $p\bar{p}$ data
 - CTEQ4LO (proton), GRV LO (photon), $\Lambda_{\text{QCD}}^{(4)} = 296 \text{ MeV}$, $\mu = \sqrt{4m_c^2 + p_T^2}$
- LO calculation by M. Beneke, G.A. Schuler and S. Wolf within NRQCD (BSW (LO, CS+CO)):
 - no resolved contributions
 - soft gluon emission resummed at high z ($\Lambda : 300\text{--}500 \text{ MeV}$)
 - LDMEs extracted from B decays

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

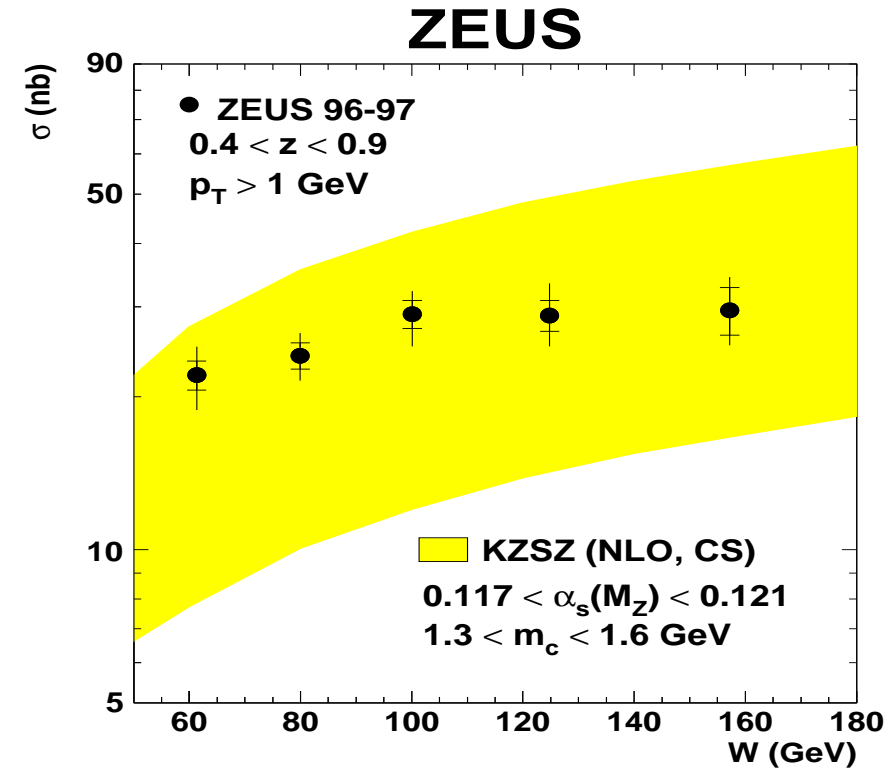
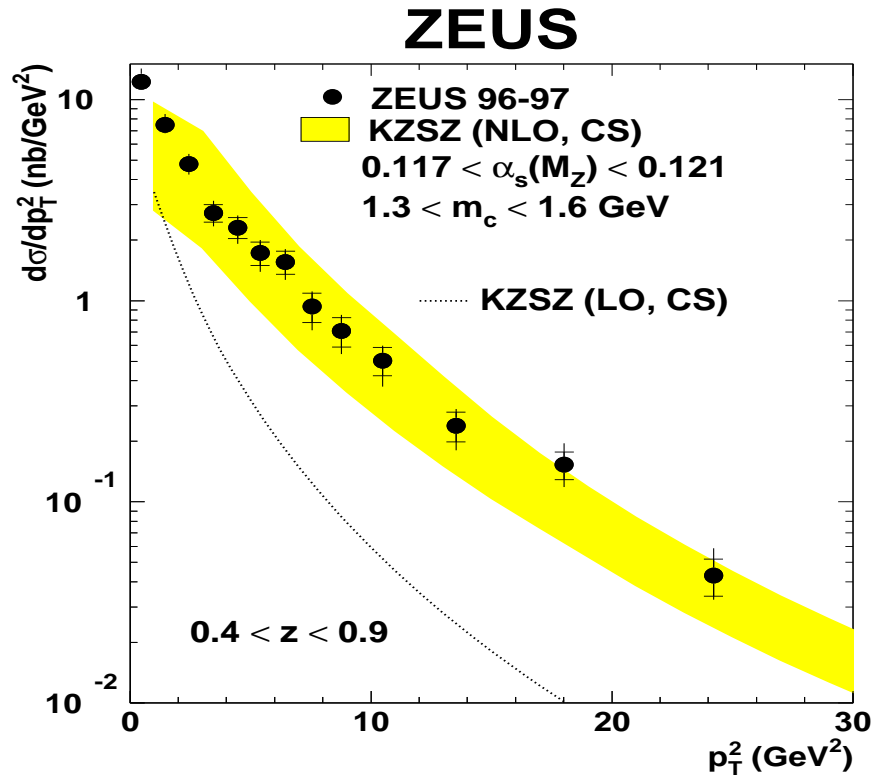
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- $\sigma(\psi')/\sigma(J/\psi) = 0.33 \pm 0.10^{+0.01}_{-0.02}$
- flat, consistent with 0.24 from KZSZ (LO, CS), the same production mechanism for ψ 's
- estimate of J/ψ fraction coming from ψ' cascade decays consistent with expectations (15%) \Rightarrow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

Photoproduction: p_T^2 and W

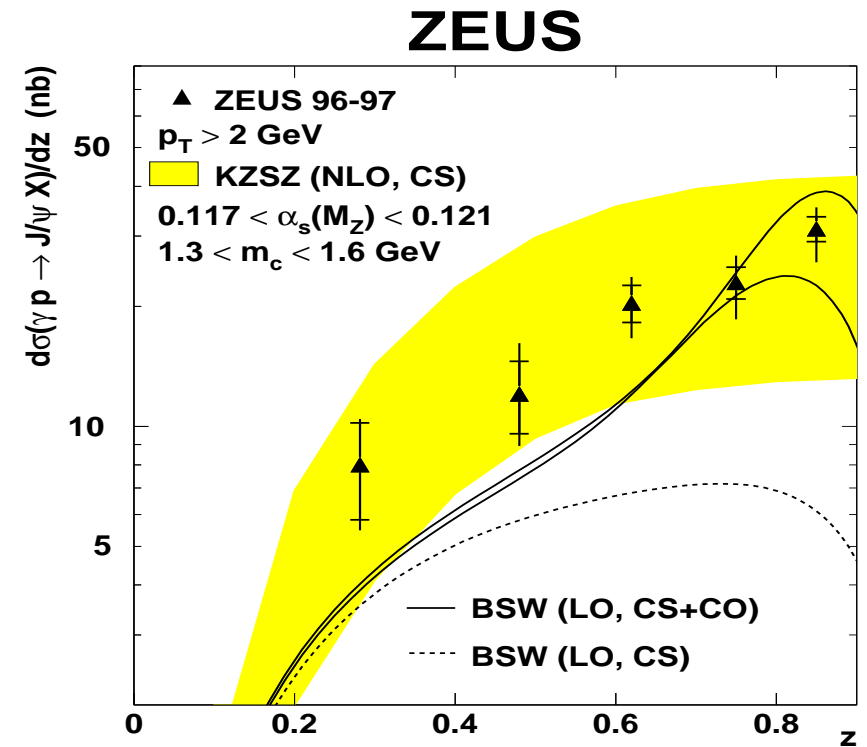
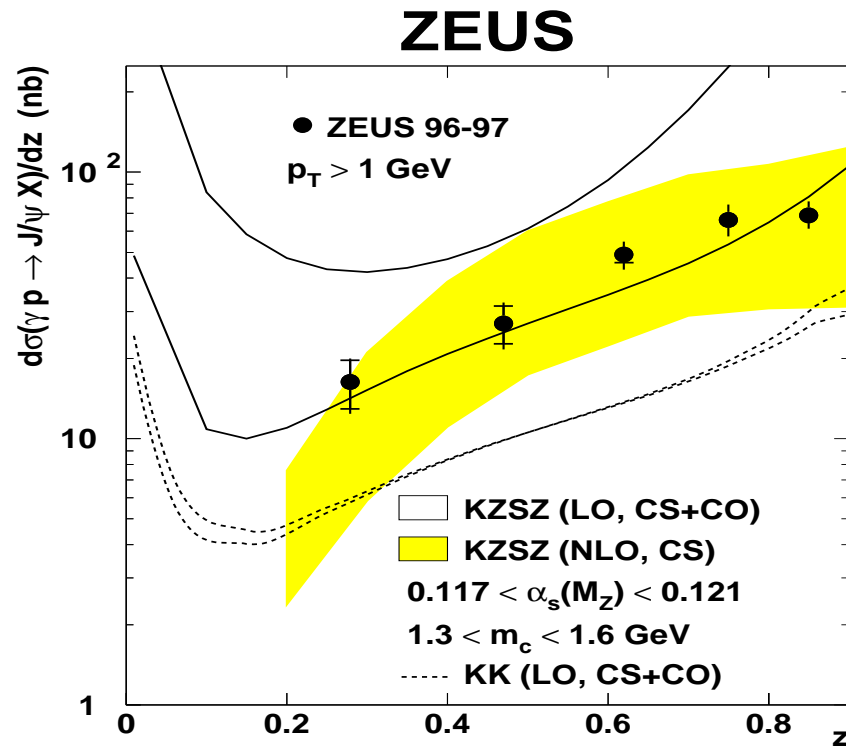
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- LO CSM prediction fails to describe high p_T production
- NLO corrections are needed to describe high p_T production of J/ψ (large theoretical uncertainties)

Photoproduction: inelasticity

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- NLO CSM agrees with data
- Left plot: NRQCD describes shapes (large LDMEs uncertainties), KK (LO, CS+CO) needs k-factor
- Right plot: damping at high z for BSW (LO, CS+CO) \Rightarrow better agreement

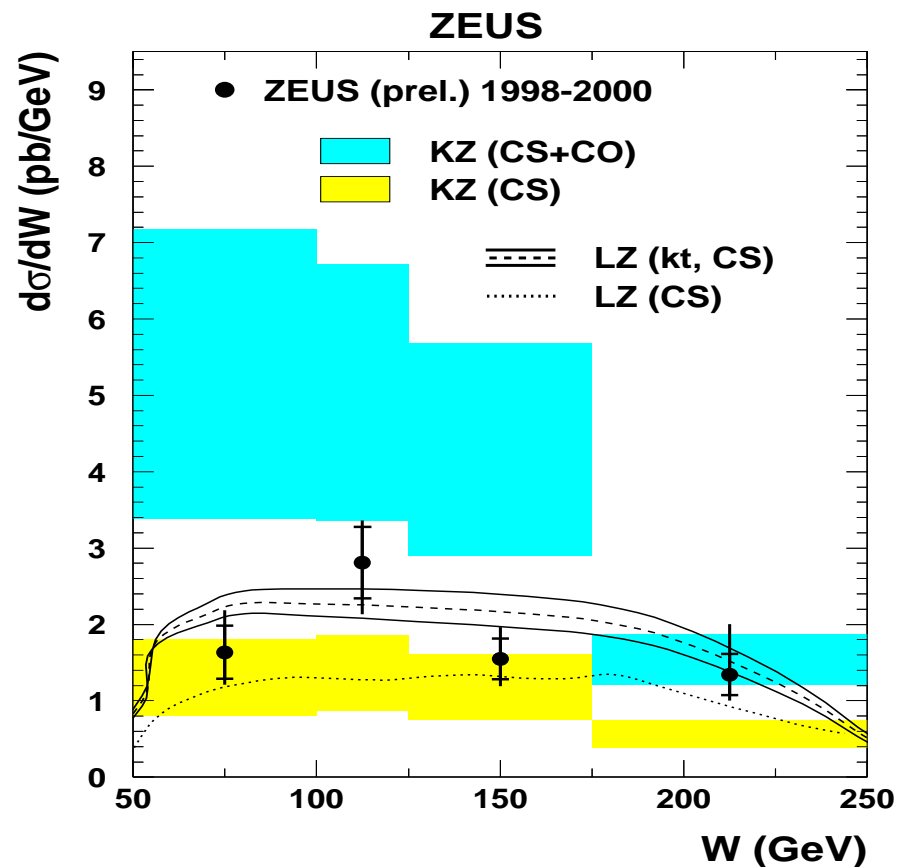
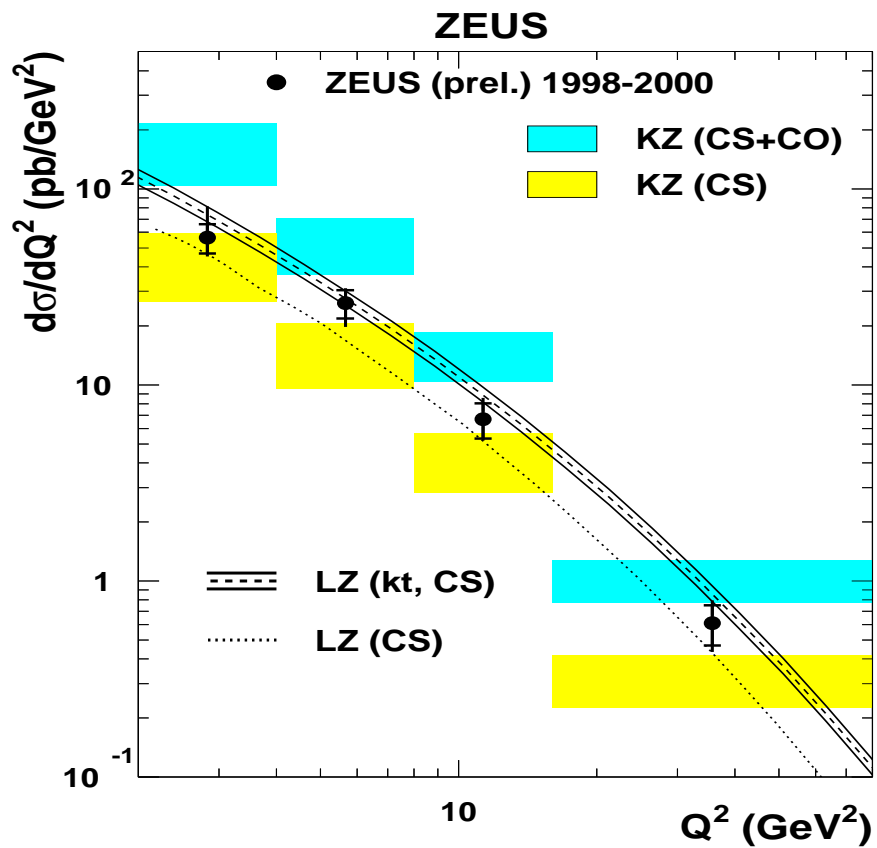
Electroproduction: theoretical models

- NRQCD calculations by Kniehl and Zwirner (KZ (CS+CO), KZ(CS)):
 - default parameters: $m_c = 1.5 \text{ GeV}$, MRST98LO ($\Lambda^{(4)} = 174 \text{ MeV}$),

$$\mu = \sqrt{Q^2 + M_\psi^2}$$
 - uncertainties (added in quadrature): $1.4 < m_c < 1.6 \text{ GeV}$, CTEQ5L, factorization scale variation, LDMEs
- CSM calculations by Lipatov and Zotov:
 - LZ (kt, CS) (k_t -factorization): $m_c = 1.55 \text{ GeV}$, JB unintegrated gluon density (at pomeron intercept value $\bar{\Delta} = 0.35$, uncertainty: $0.20 < \bar{\Delta} < 0.53$), $\Lambda_{\text{QCD}} = 250 \text{ MeV}$, $\mu^2 = \mathbf{q}_T^2$ (\mathbf{q}_T^2 – virtuality of initial BFKL gluon), gluon transverse momentum cut-off $Q_0^2 = 1 \text{ GeV}^2$
 - LZ (CS) (collinear calculations): $m_c = 1.55 \text{ GeV}$, GRV(LO), $\Lambda_{\text{QCD}} = 250 \text{ MeV}$, $\mu^2 = p_T^2 + M_\psi^2$

Electroproduction: Q^2 and W

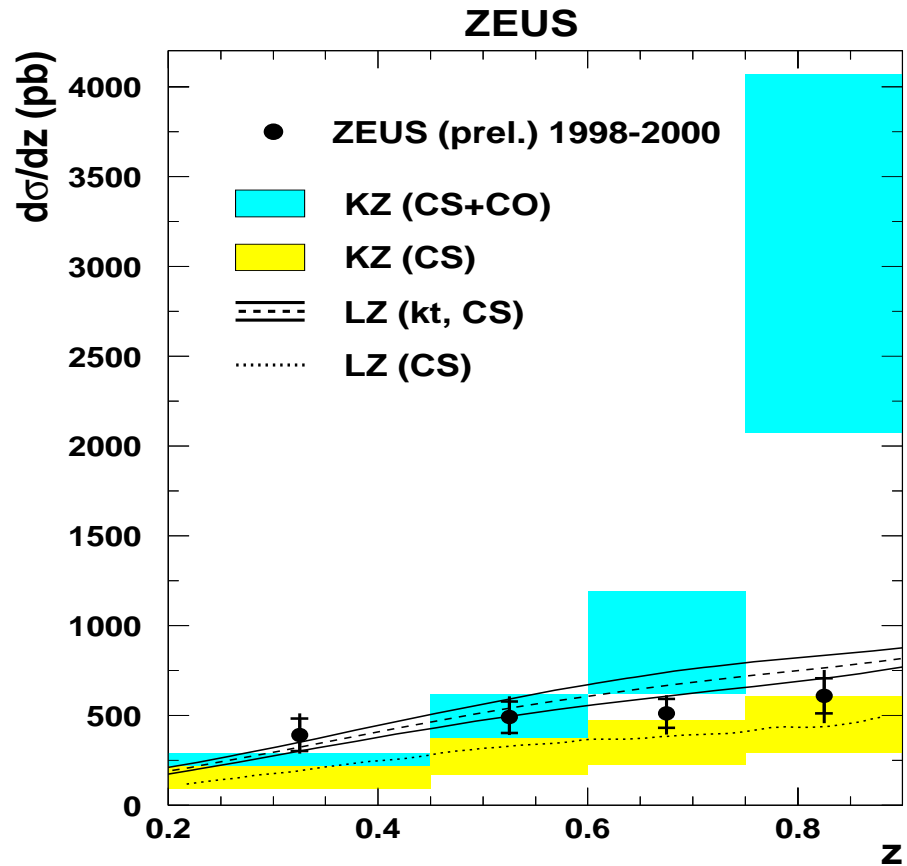
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- KZ(CS) and LZ(CS): lower but consistent with data
- KZ(CS+CO): mostly overshoots data
- LZ(kt, CS): agrees with data

Electroproduction: inelasticity

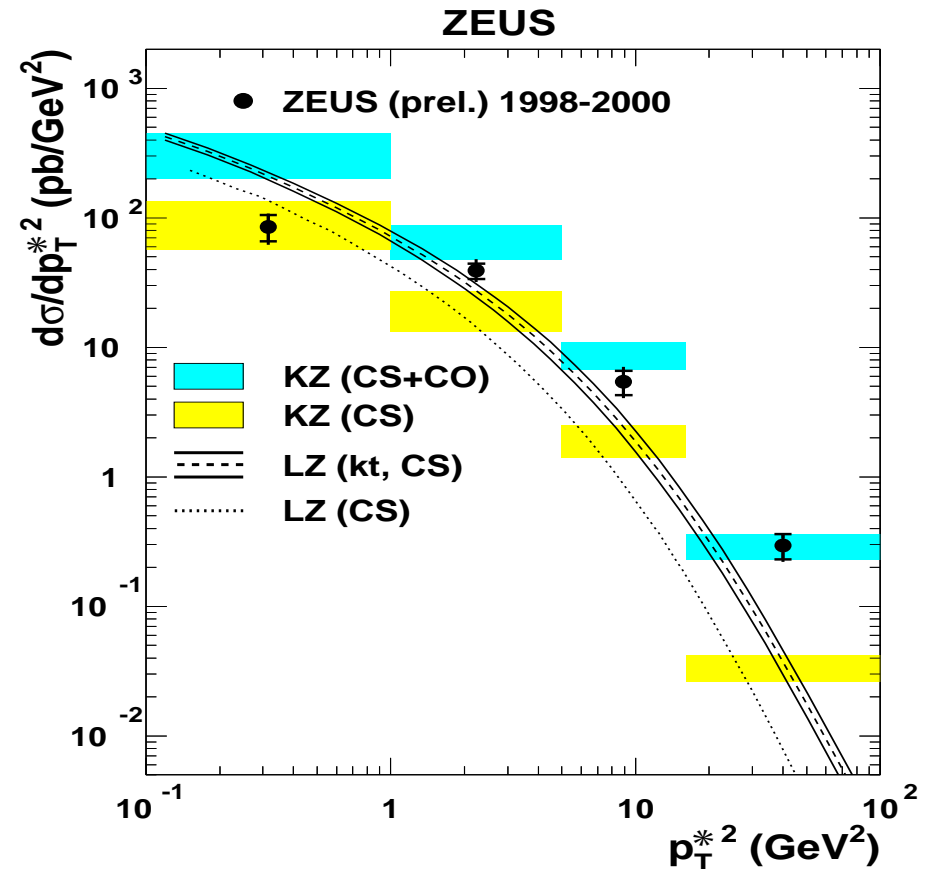
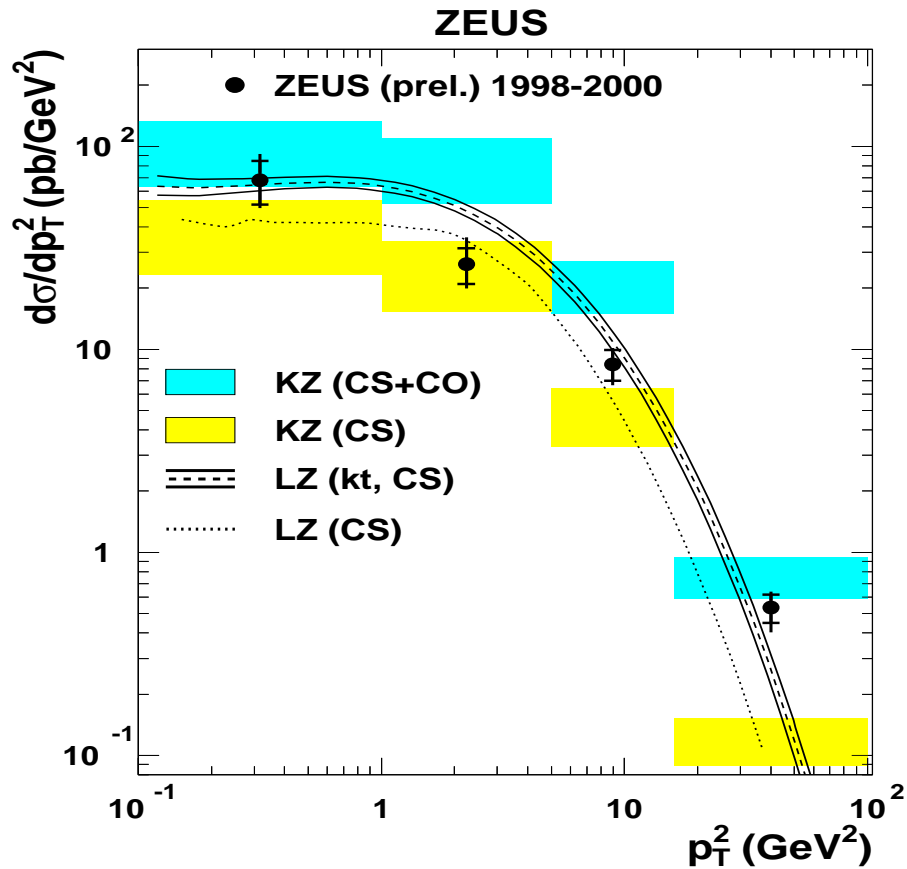
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- KZ(CS+CO): too high at large z values (high- z resummation needed?)
- CS predictions are consistent with data

Electroproduction: p_T^2 and p_T^{*2}

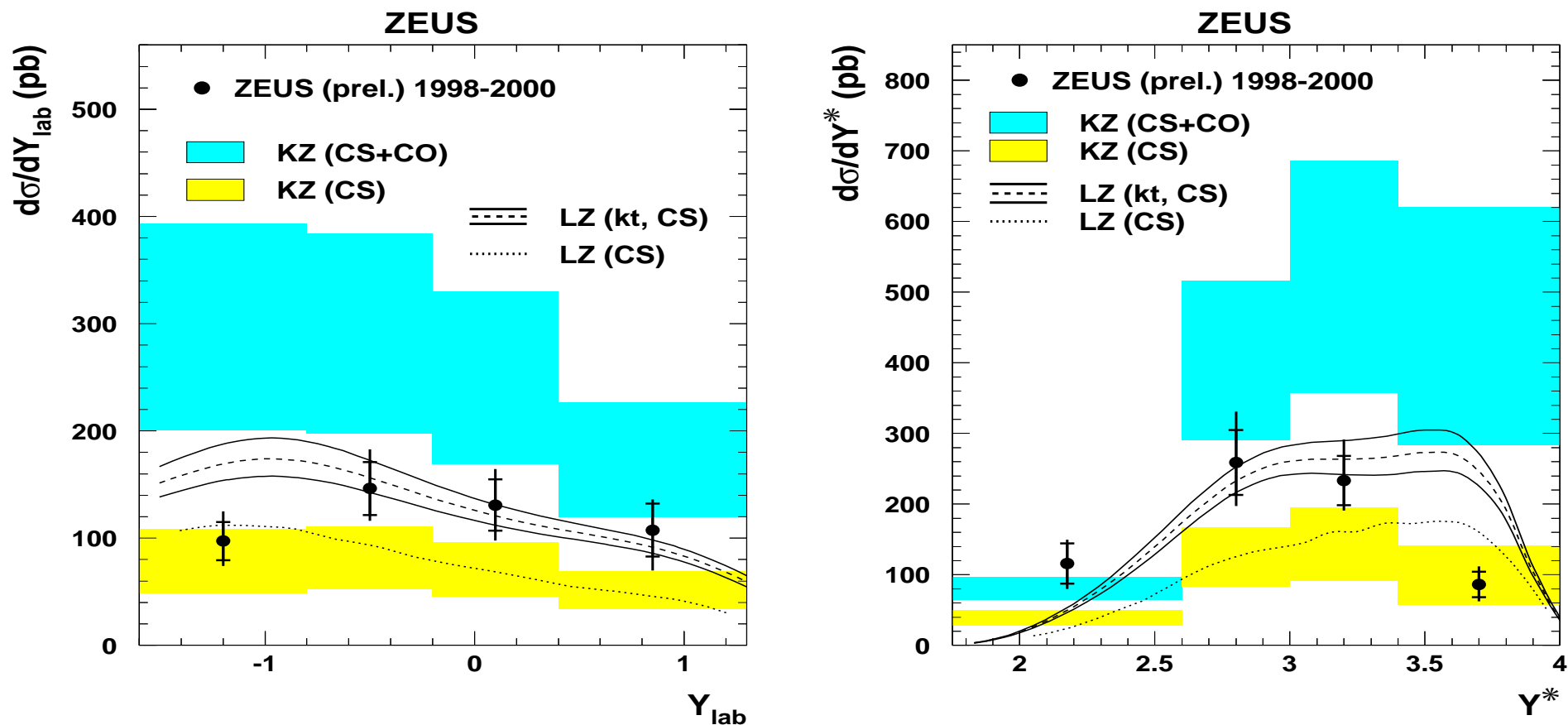
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- KZ(CS) and LZ(CS): too soft in comparison to data
- KZ(CS+CO): overshoots data at low p_T^* values
- LZ(kt, CS): also too soft (NLO corrections?)

Electroproduction: rapidity

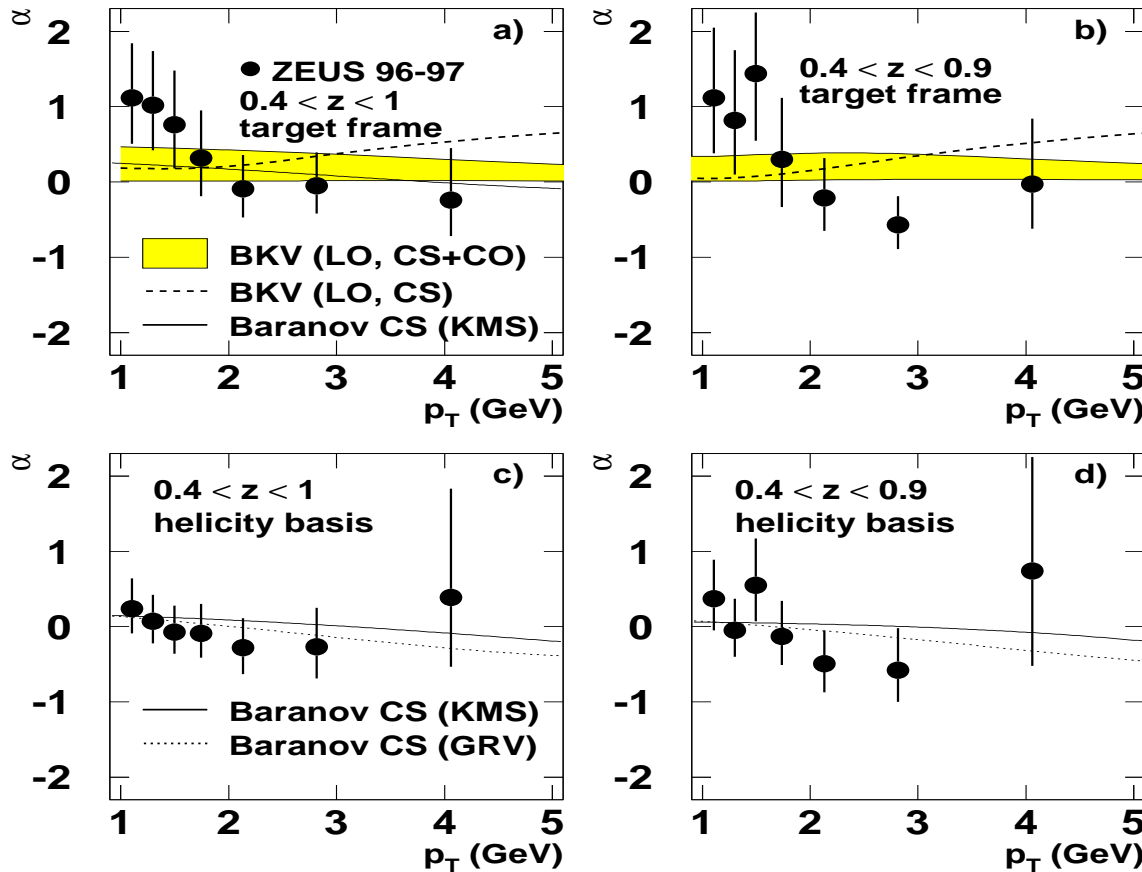
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- LZ(kt, CS) tends to be above data in photon direction

Photoproduction: helicity

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- $dN/d\cos\theta^* \propto 1 + \alpha \cos^2\theta^*$
- BKV – collinear calculations
- Baranov – k_t -factorization
- Statistics is yet not enough to discriminate between models

Summary

Photoproduction:

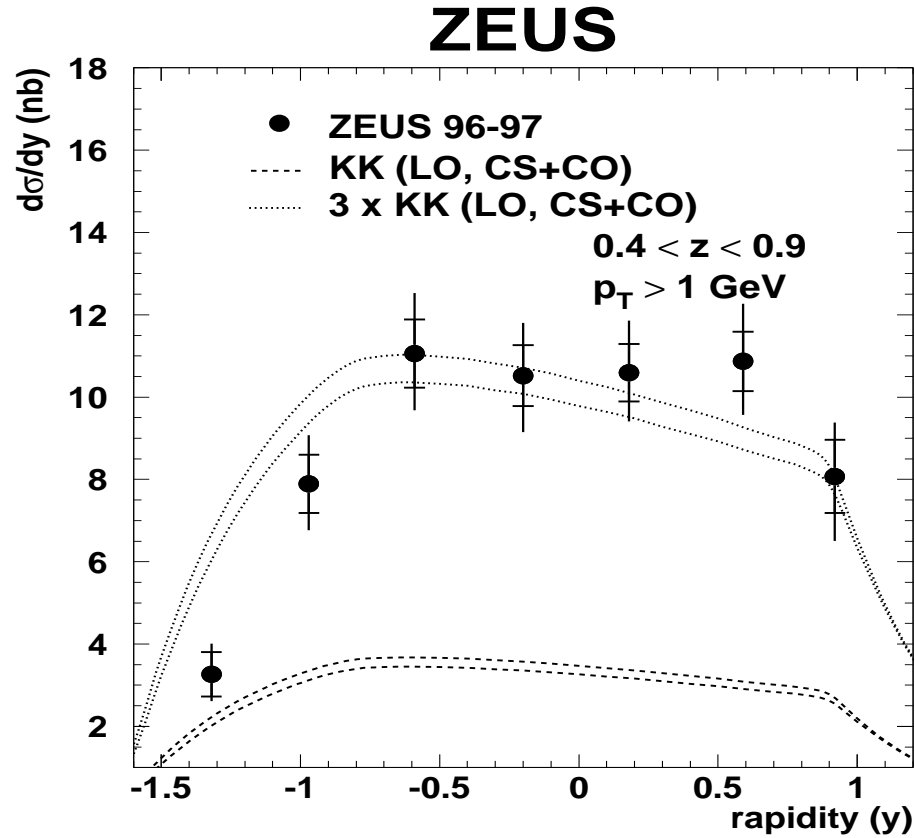
- NLO corrections enable one to describe high p_T production of J/ψ within CSM
- theoretical uncertainties are large: CO contributions cannot be excluded

Electroproduction:

- LO CS: below but consistent with data except high p_T range (NLO corrections?)
- NRQCD (CS+CO): too high at large z and small p_T^* values
- k_t -factorization (CS): agrees with data except at high p_T^* (too low) and in photon direction (too high)

Photoproduction: rapidity

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- As in case of z k-factor is needed
- Shape is reasonably reproduced