Inelastic photo- and electroproduction of charmonium

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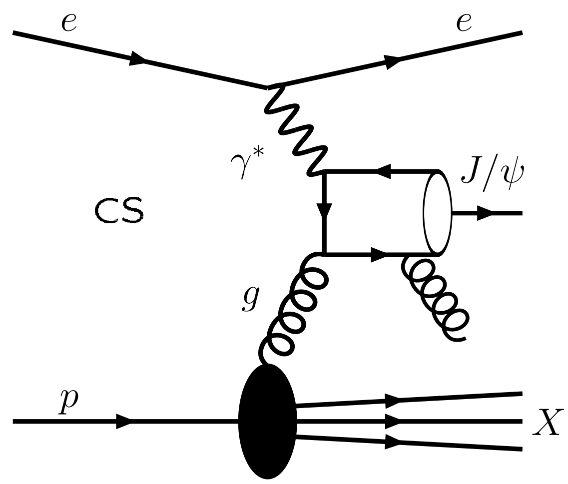
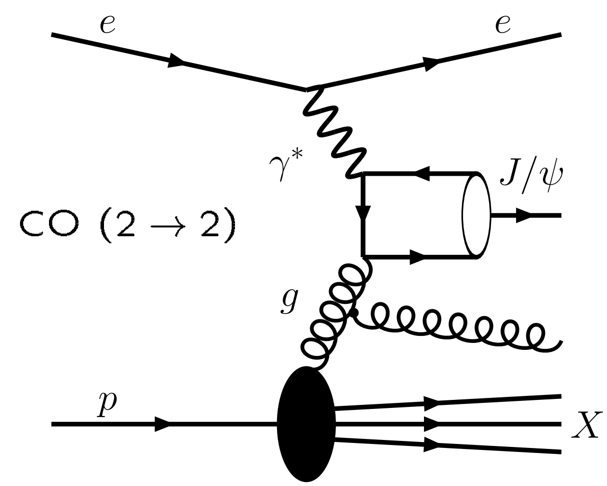
Introduction

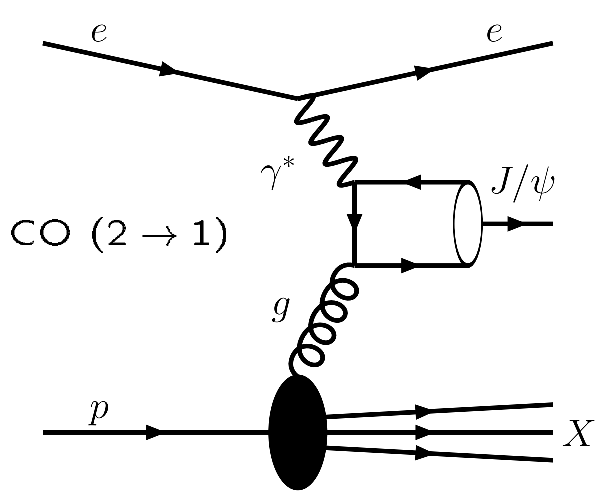
- Process $e + p \to e + J/\psi + X$:
  $\to z$ – fraction of virtual photon (γ^*) energy transfered to J/ψ in proton rest frame (inelasticity)
  $\to$ dominant $c\bar{c}$ production mechanism: BGF $\Rightarrow$ information on gluon density in proton
  $\to$ different approaches to describe formation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

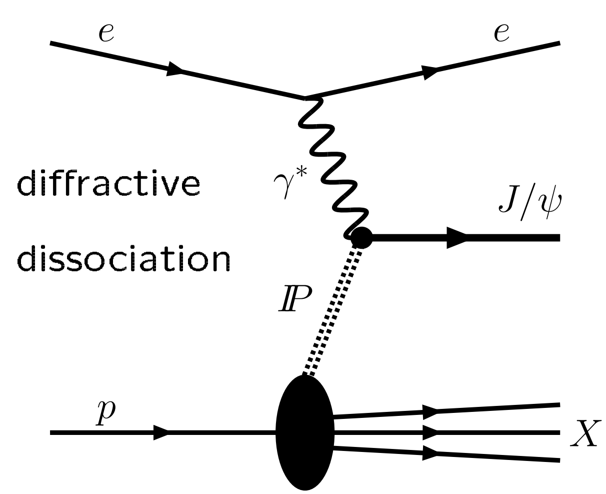




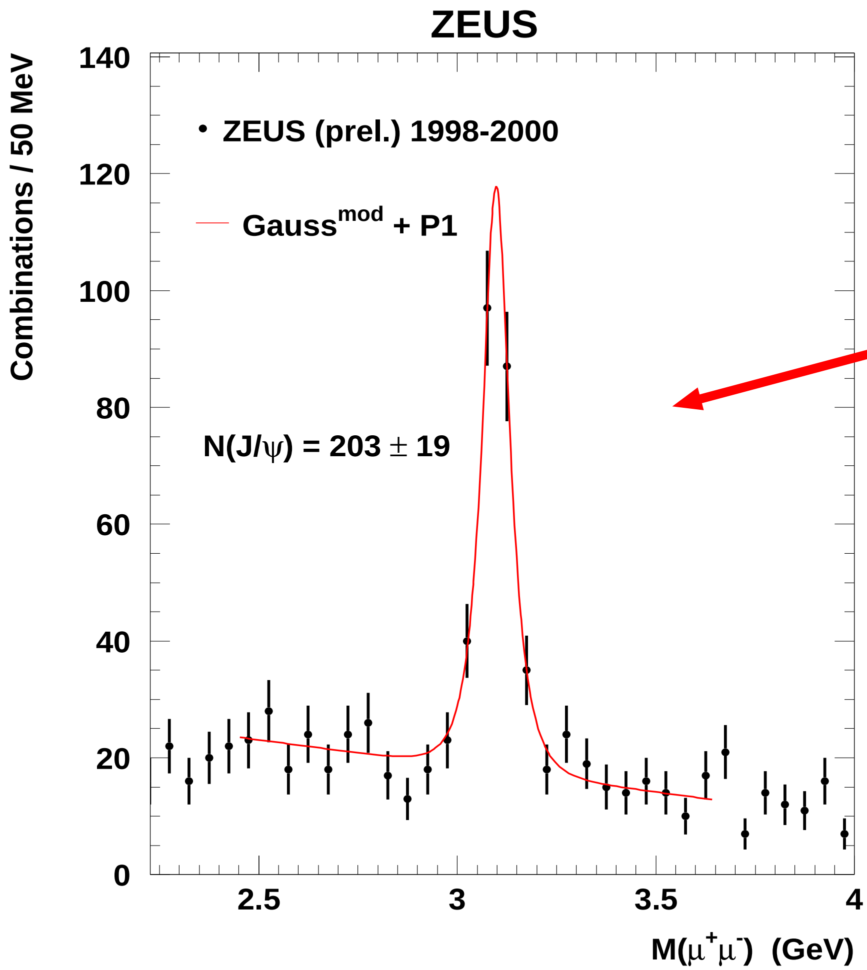
J/ψ at HERA

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

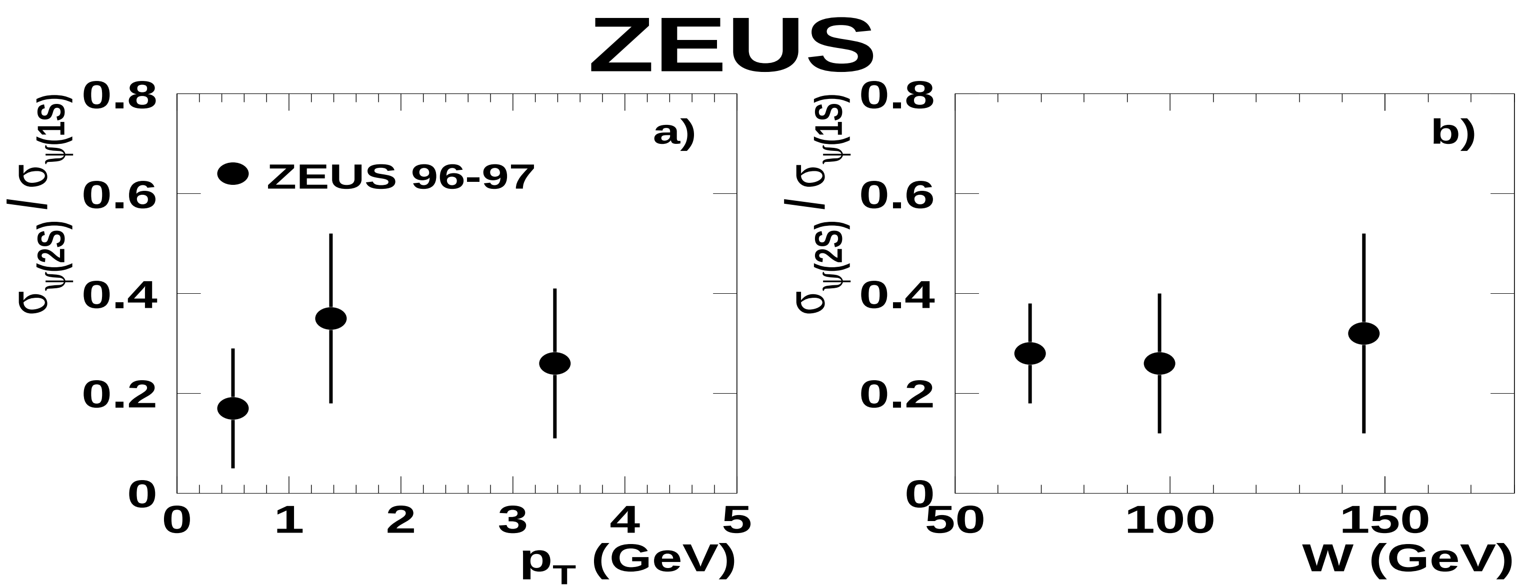
Photoproduction: theoretical models

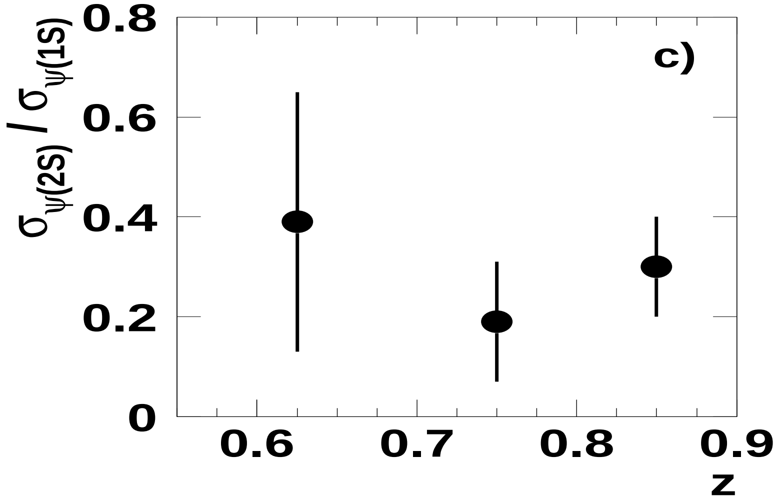
- Three types of calculations: NLO CS, LO CS, LO NRQCD
- NLO CS calculation by Krämer et al. (KZSZ (NLO, CS)):
  → the only NLO available for J/ψ production!
  → only direct processes, no resolved
  → MRST01, $1.3 < m_c < 1.6$ GeV,
  $\mu = m_c/\sqrt{2}$ (max$(m_c/\sqrt{2}, \sqrt{m_c^2 + p_T^2}/2)$ for 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 distibutions 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 ⇒ 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), $\Lambda^{(4)}_{\mathrm{QCD}} = 296\,\mathrm{MeV}$, $\mu = \sqrt{4m_c^2 + p_T^2}$
- 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 (Λ : 300–500 MeV)
  - → LDMEs extracted from B decays

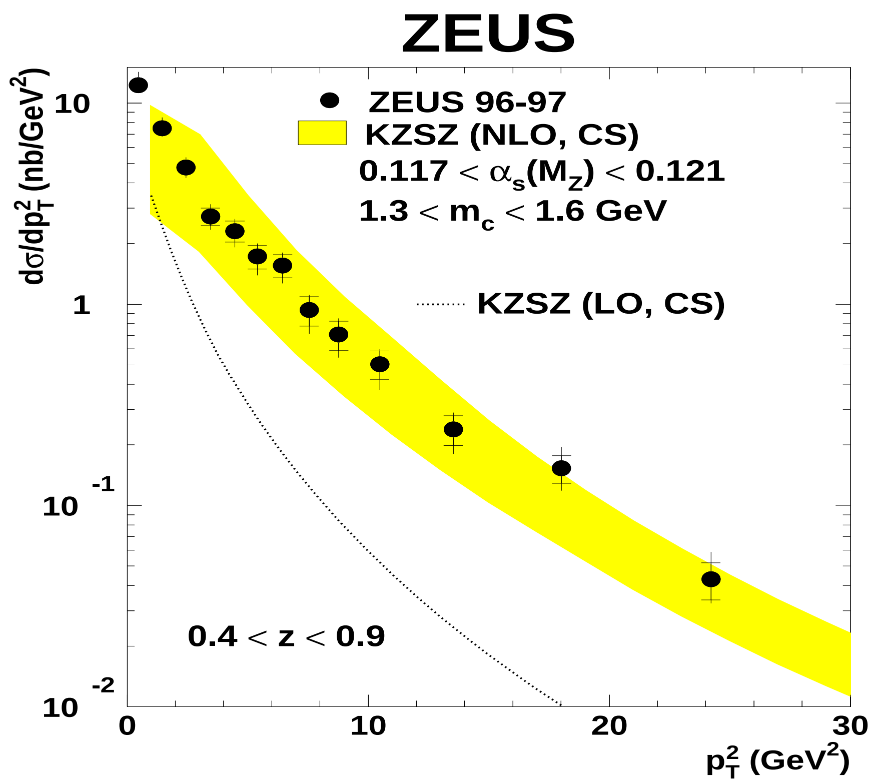
Photoproduction: $\sigma_{\psi(2S)}/\sigma_{\psi(1S)}$

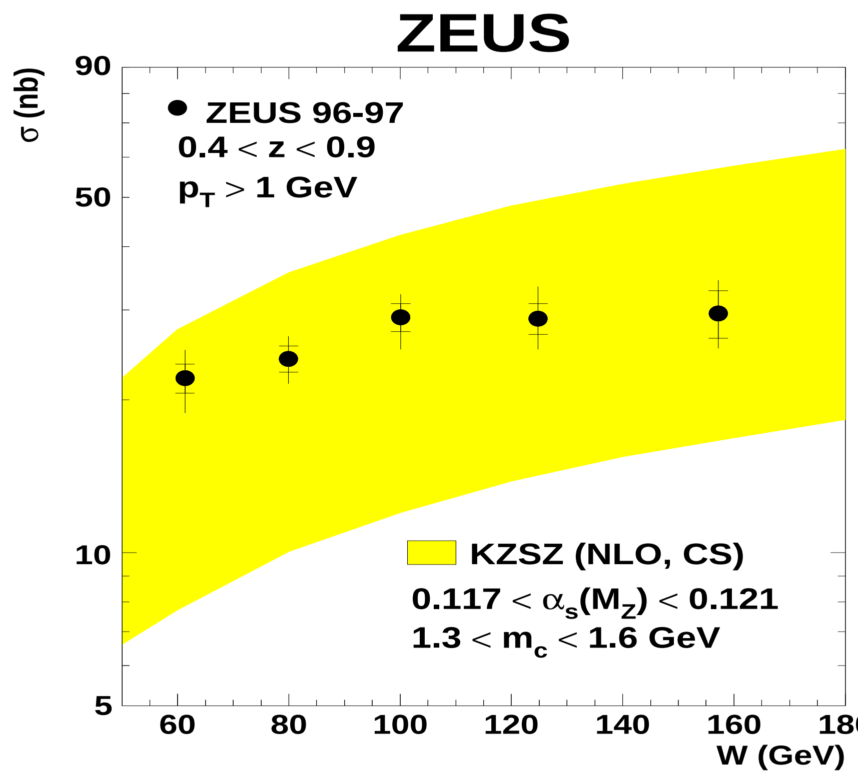




- $\sigma(\psi')/\sigma(J/\psi) = 0.33 \pm 0.10^{+0.01}_{-0.02}$
- flat, consistent with 0.24 from KZSZ (LO, CS), the same production mechanism for ψ's
- estimate of J/ψ fraction coming from ψ' cascade decays consistent with expectations (15%) $\Rightarrow$ theoretical predictions scaled by 1.15

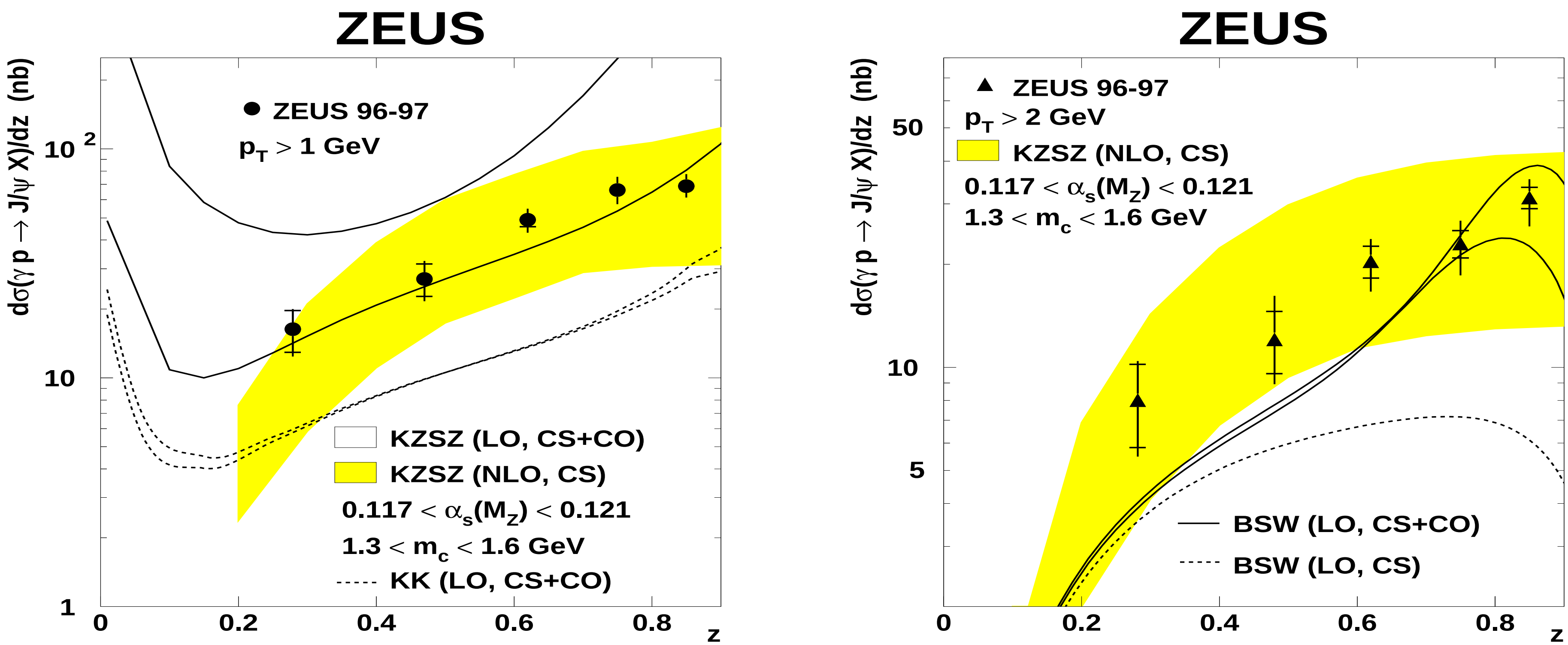
Photoproduction: p_T^2 and W





- 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

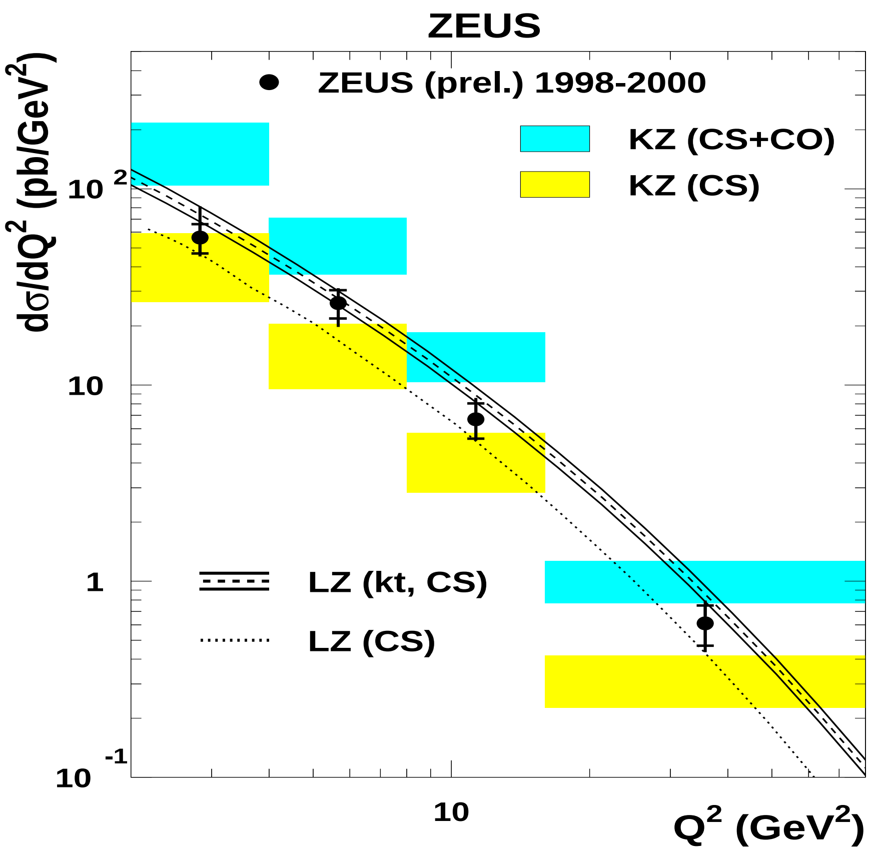


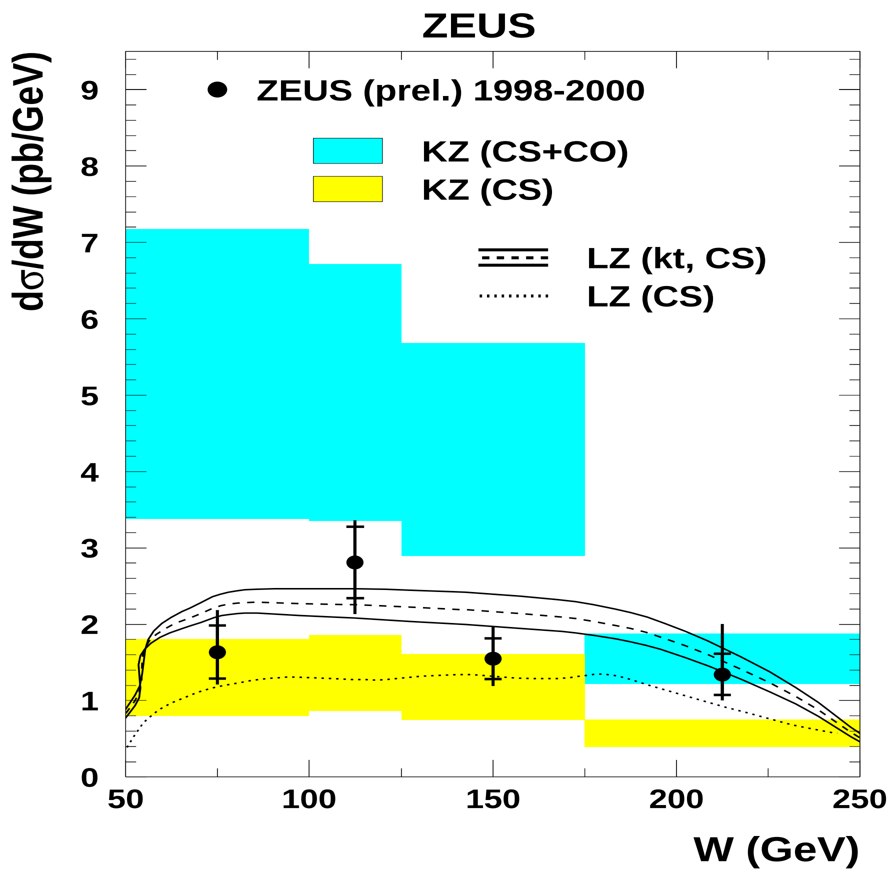
- NLO CSM agrees with data
- Left plot: NRQCD describes shapes (large LDMEs uncertainties), KK (LO, CS+CO) needs k-factor
- Right plot: damping at high z for BSW (LO, CS+CO) $\Rightarrow$ better agreement

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: $0.20 < \bar{\Delta} < 0.53$), $\Lambda_{\text{QCD}} = 250\,\text{MeV}$, $\mu^2 = \boldsymbol{q}_T^2$ ($\boldsymbol{q}_T^2$ – 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), $\Lambda_{\text{QCD}} = 250\,\text{MeV}$, $\mu^2 = p_T^2 + M_\psi^2$

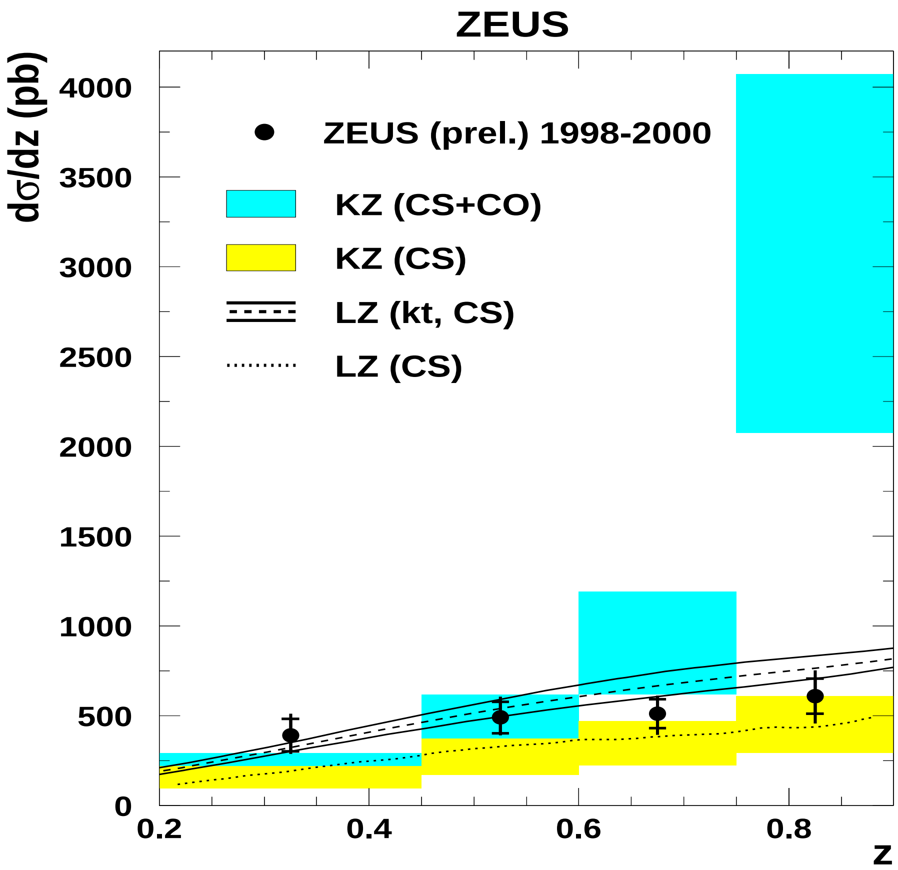
Electroproduction: Q^2 and W





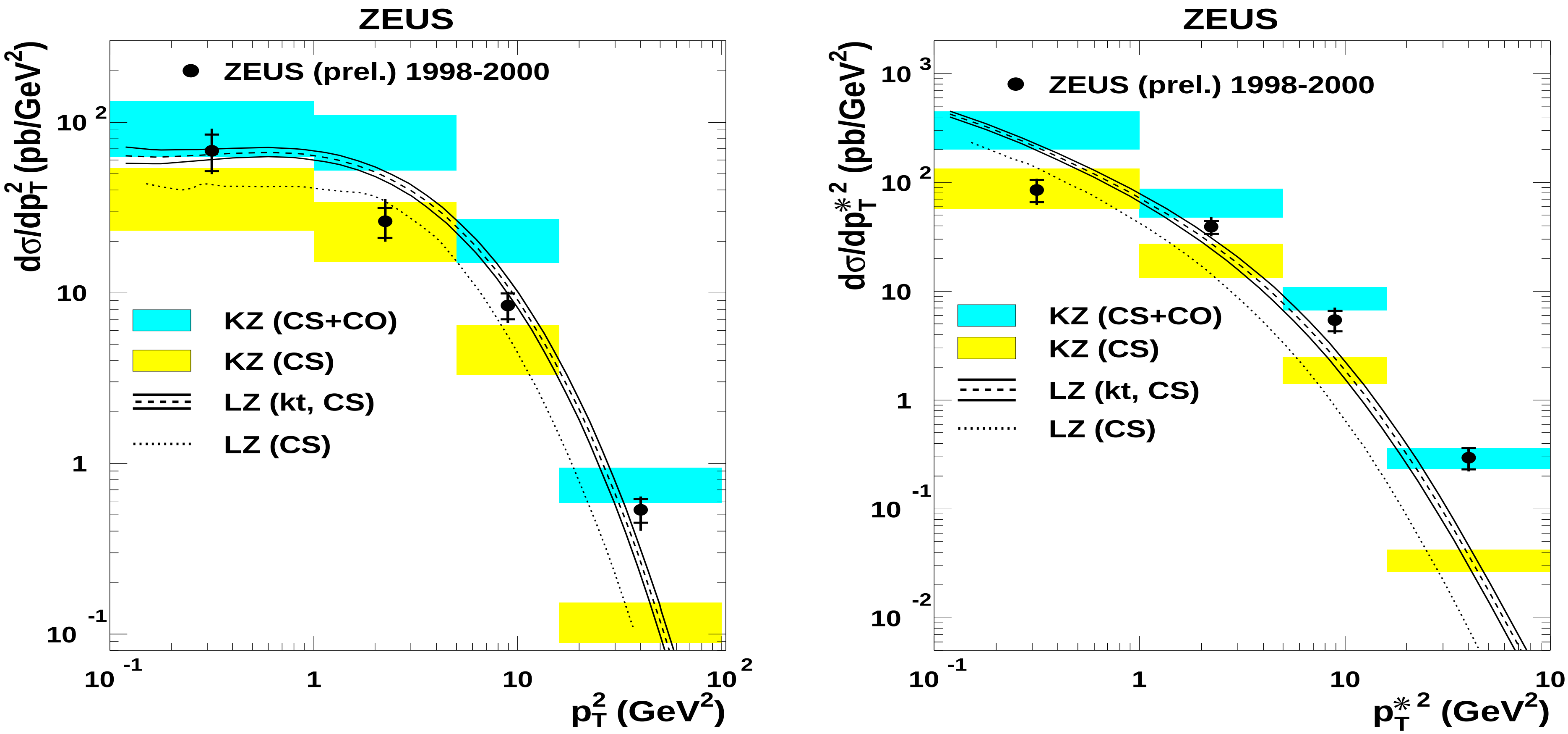
- KZ(CS) and LZ(CS): lower but consistent with data
- KZ(CS+CO): mostly overshoots data
- LZ(kt, CS): agrees with data

Electroproduction: inelasticity



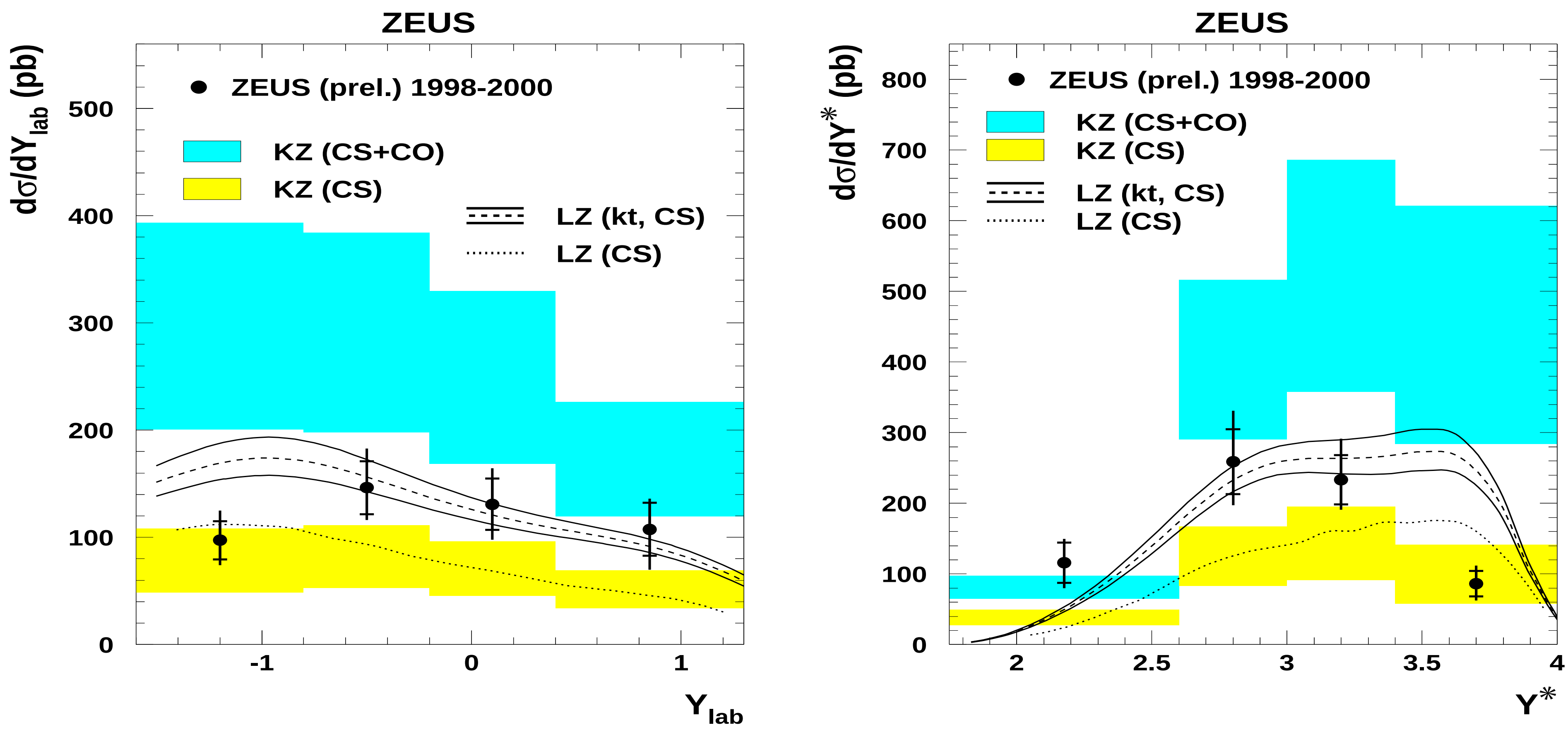
- KZ(CS+CO): too high at large z values (high-z resummation needed?)
- CS predictions are consistent with data

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



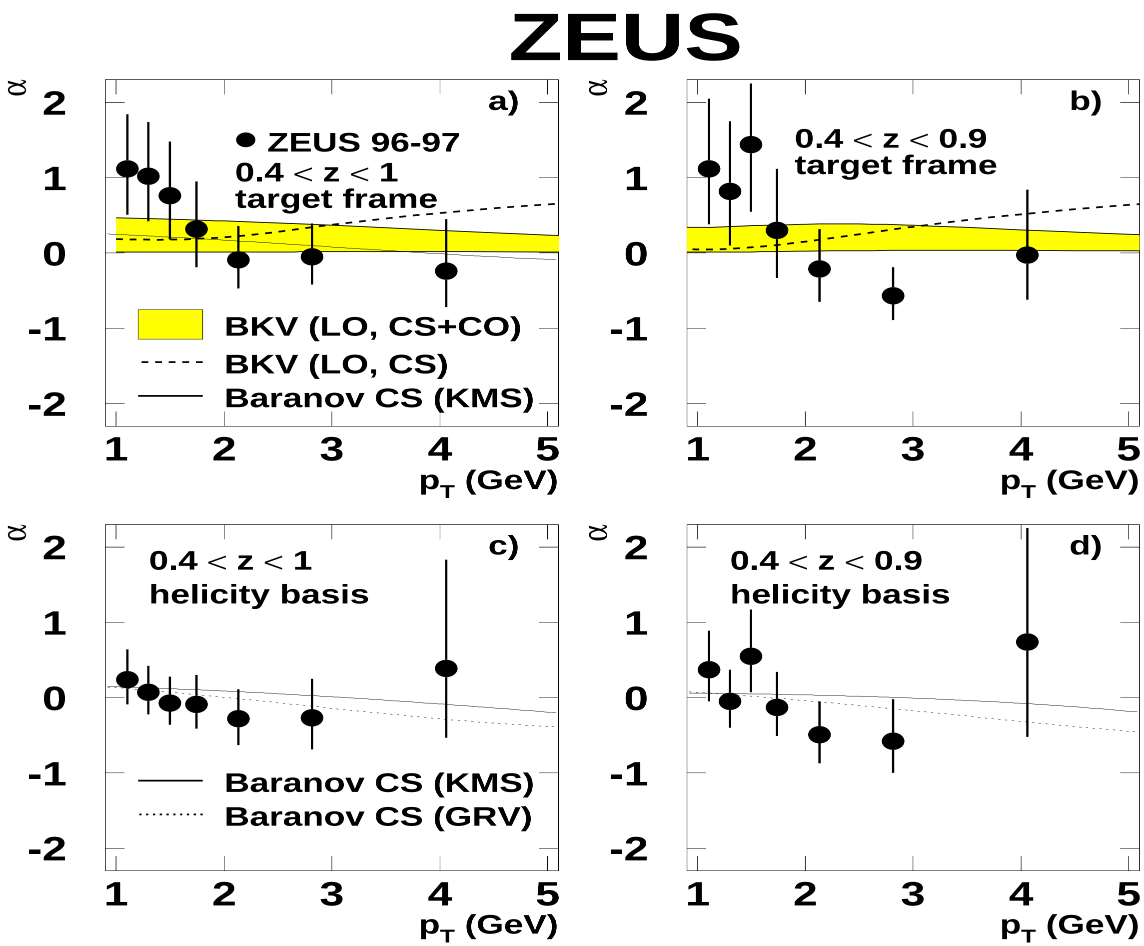
- KZ(CS) and LZ(CS): too soft in comparison to data
- KZ(CS+CO): overshoots data at low p_T^* values
- LZ(kt, CS): also too soft (NLO corrections?)

Electroproduction: rapidity



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

Photoproduction: helicity



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

Summary

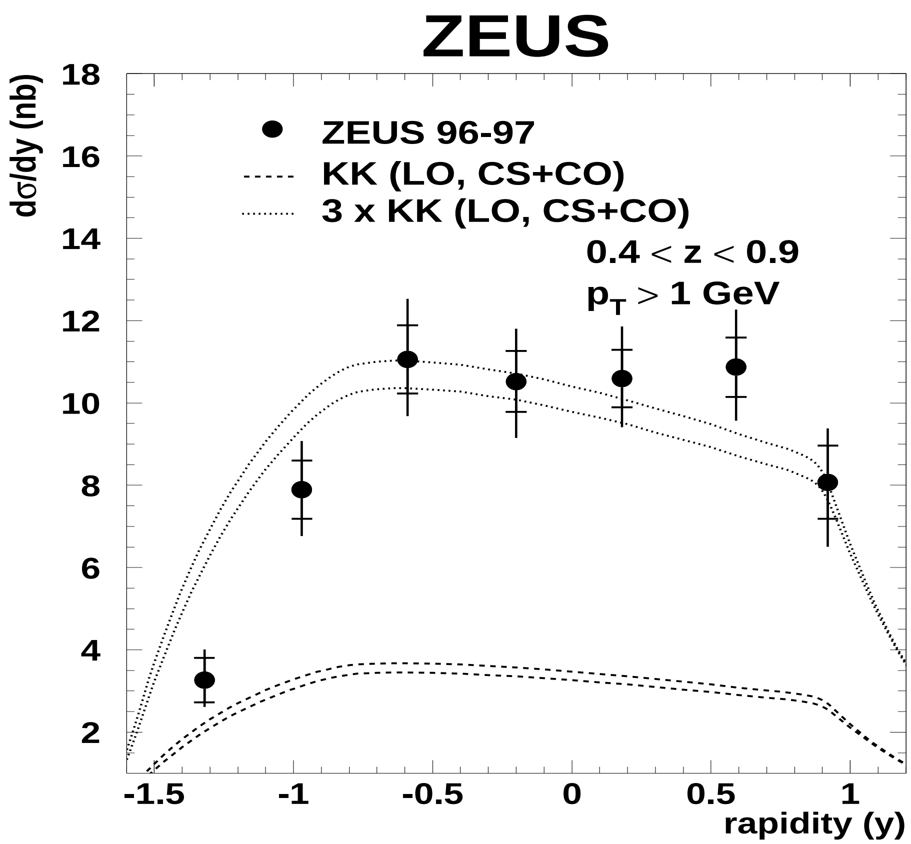
Photoproduction:

- 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



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