Inelastic J/ψ Photo- and Electroproduction

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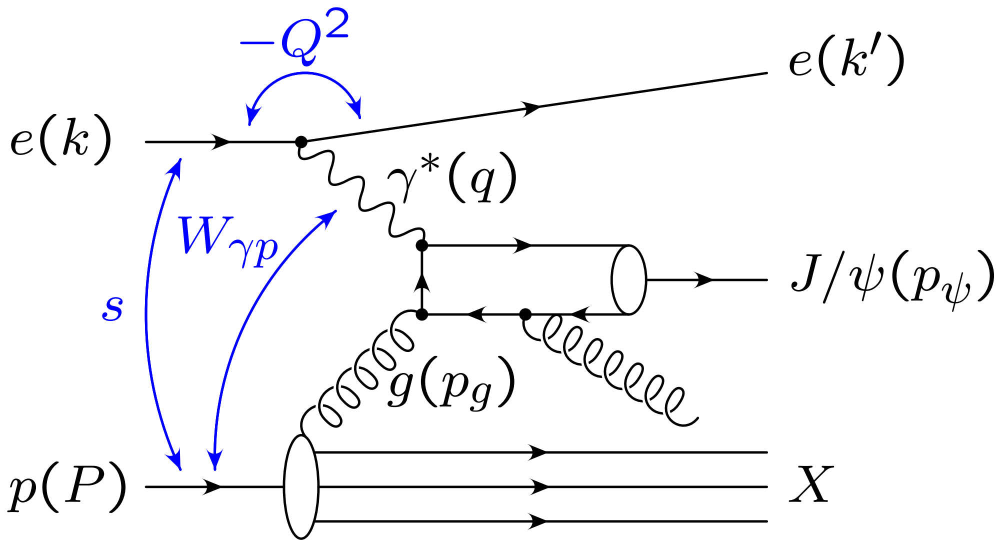
Introduction



kinematic variables:

$$Q^2 = -q^2$$
$$s = (P+k)^2$$
$$W_{\gamma p} = \sqrt{(P+q)^2}$$
$$z = \frac{p_\psi \cdot P}{q \cdot P} = \frac{E^*_\psi}{E^*_\gamma} \text{ in proton rest frame}$$

photoproduction ($Q^2 < 1$ GeV^2):

scattered e not seen in main detector

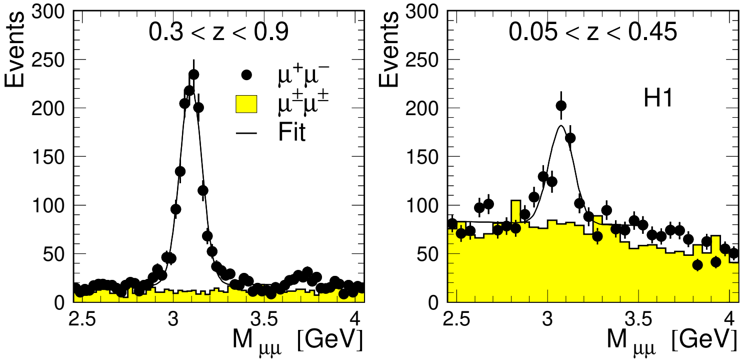
electroproduction ($2 < Q^2 < 100$ GeV^2):

scattered e detected in backward calorimeter

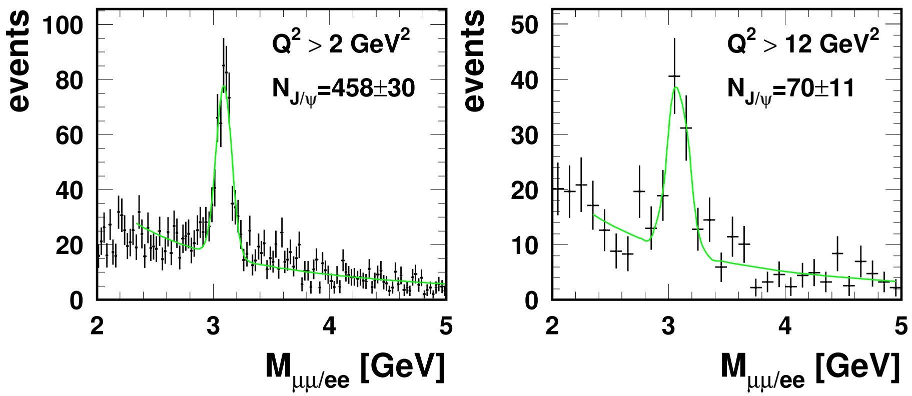
Introduction

- information about gluon density in the proton: $\sigma \propto x_g\, g(x_g, Q^2_{eff})$
- HERA I data completely analysed (1996-2000): $\sim 80\,\mathrm{pb}^{-1}$

photoproduction: $Q^2 < 1$ GeV^2



electroproduction: $2 < Q^2 < 100$ GeV^2



medium z low z $\langle Q^2 \rangle = 10.6$ GeV^2 $\langle Q^2 \rangle = 30.9$ GeV^2

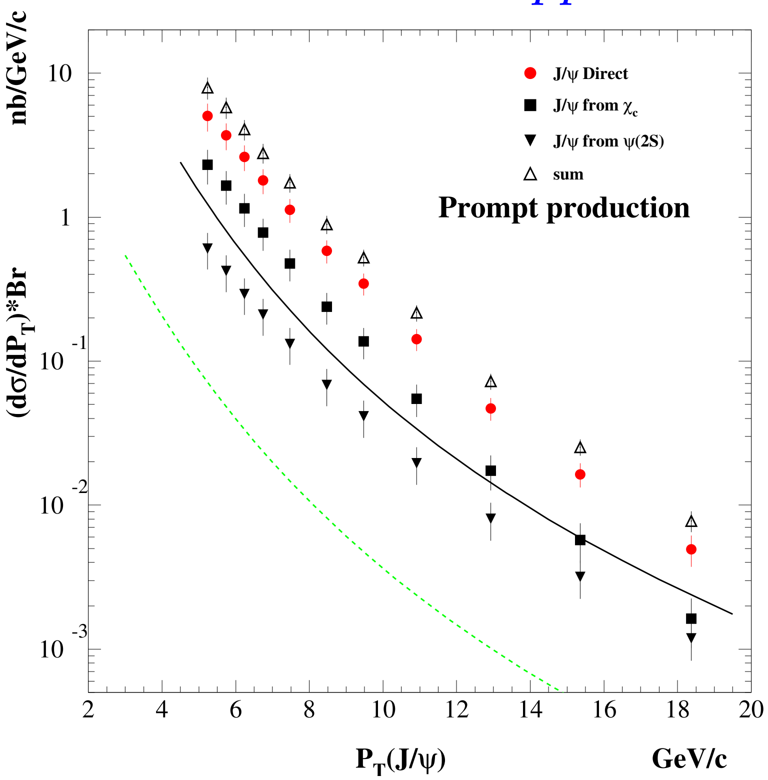
Photoproduction	Electroproduction
$0.05 < z < 0.9$	$0.3 < z < 0.9$
$60 < W_{\gamma p} < 260$ GeV	$50 < W_{\gamma p} < 225$ GeV
$1 < p^2_{t,\psi} < 60$ GeV^2	$1 < p^{*2}_{t,\psi} < 40$ GeV^2

- photoproduction: larger statistics
  electroproduction: less theoretical uncertainties

Introduction

two models for $c\bar{c} \to J/\psi$ are discussed:

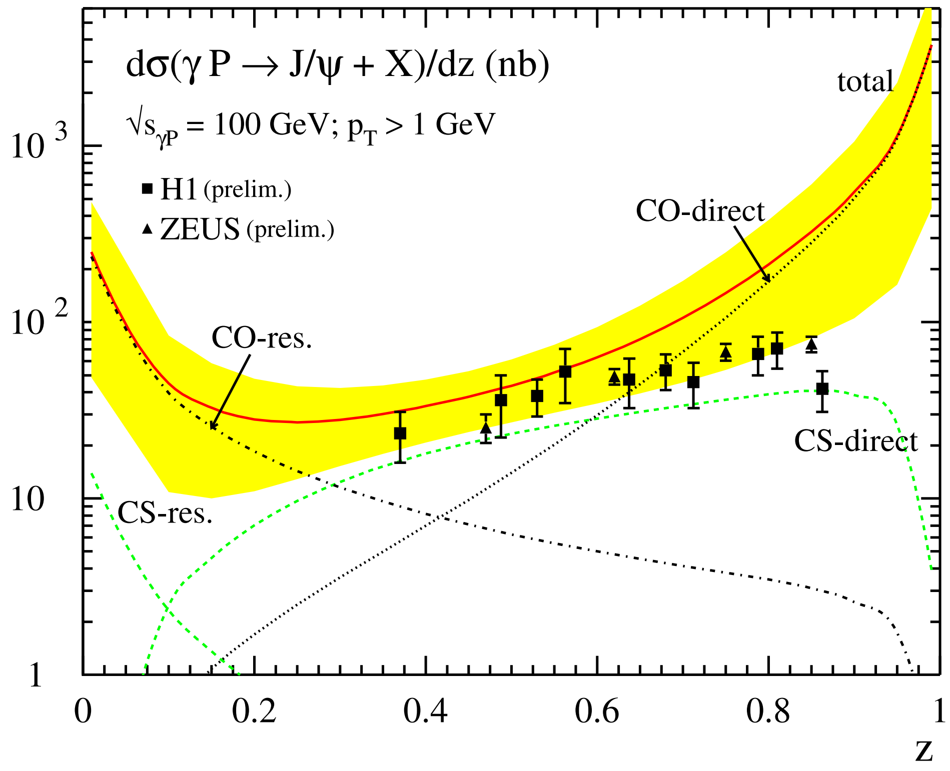
Tevatron: $p\bar{p}$



Colour Singlet Model (CSM)
orders of magnitude too low

→ non-relativistic QCD (NRQCD)

HERA



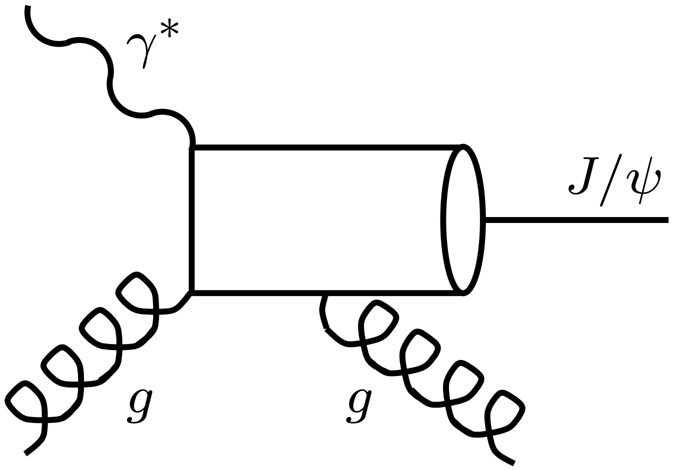
CSM factor ~ 2 too low
explainable in model

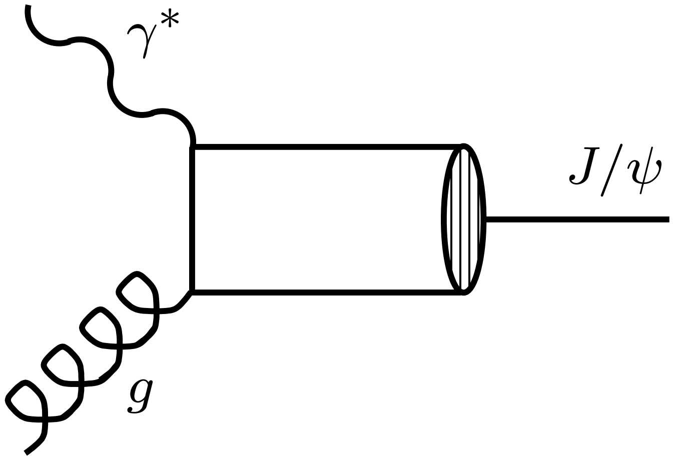
NRQCD too high at large z?

Production Mechanisms

inelastic J/ψ production processes

- direct photon gluon fusion: $z \gtrsim 0.3$





Colour Singlet Model

$c\bar{c}$ must have J/ψ quantum numbers
one parameter
fixed from $\Gamma_{\psi \to l^+ l^-}$

CSM

non-relativistic QCD

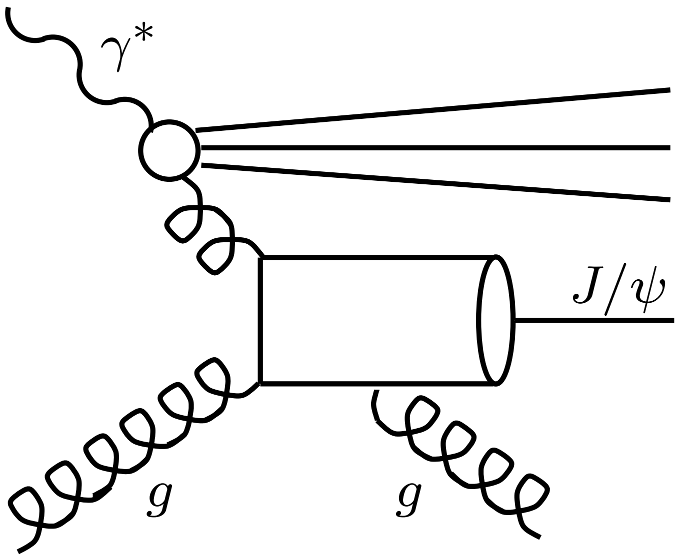
$c\bar{c}$ also in colour octet state
additional free parameters
long distance matrix elements 'LDMEs'
LDMEs not calculable $\longrightarrow$ from experiment

CS+CO

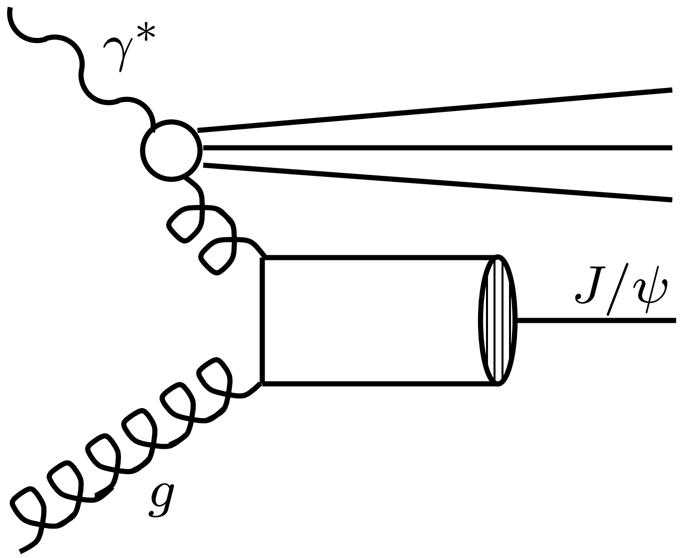
Production Mechanisms

inelastic J/ψ production processes (cont.)

- resolved photon processes (gluon gluon fusion): $z \lesssim 0.3$, suppressed with increasing Q^2



Colour Singlet Model

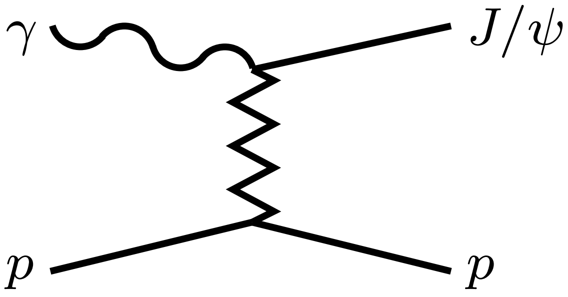


non-relativistic QCD

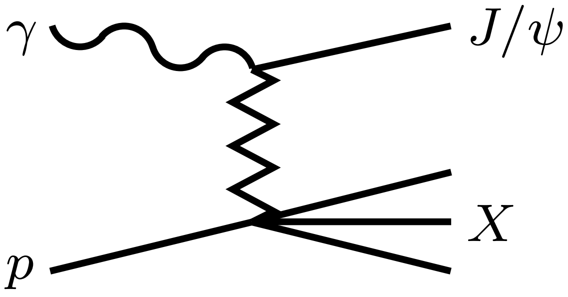
Production Mechanisms

other J/ψ production processes (background)

- diffraction



elastic diffraction
$z = 1$



proton dissociation
$z \approx 1$

  can be suppressed by cuts on:

  – z ($z < 0.9$)

  – $p^*_{t,\psi}$ ($\approx p_{t,\psi}$ in photoproduction): transverse J/ψ momentum in γp cms

  – additional activity in the detector

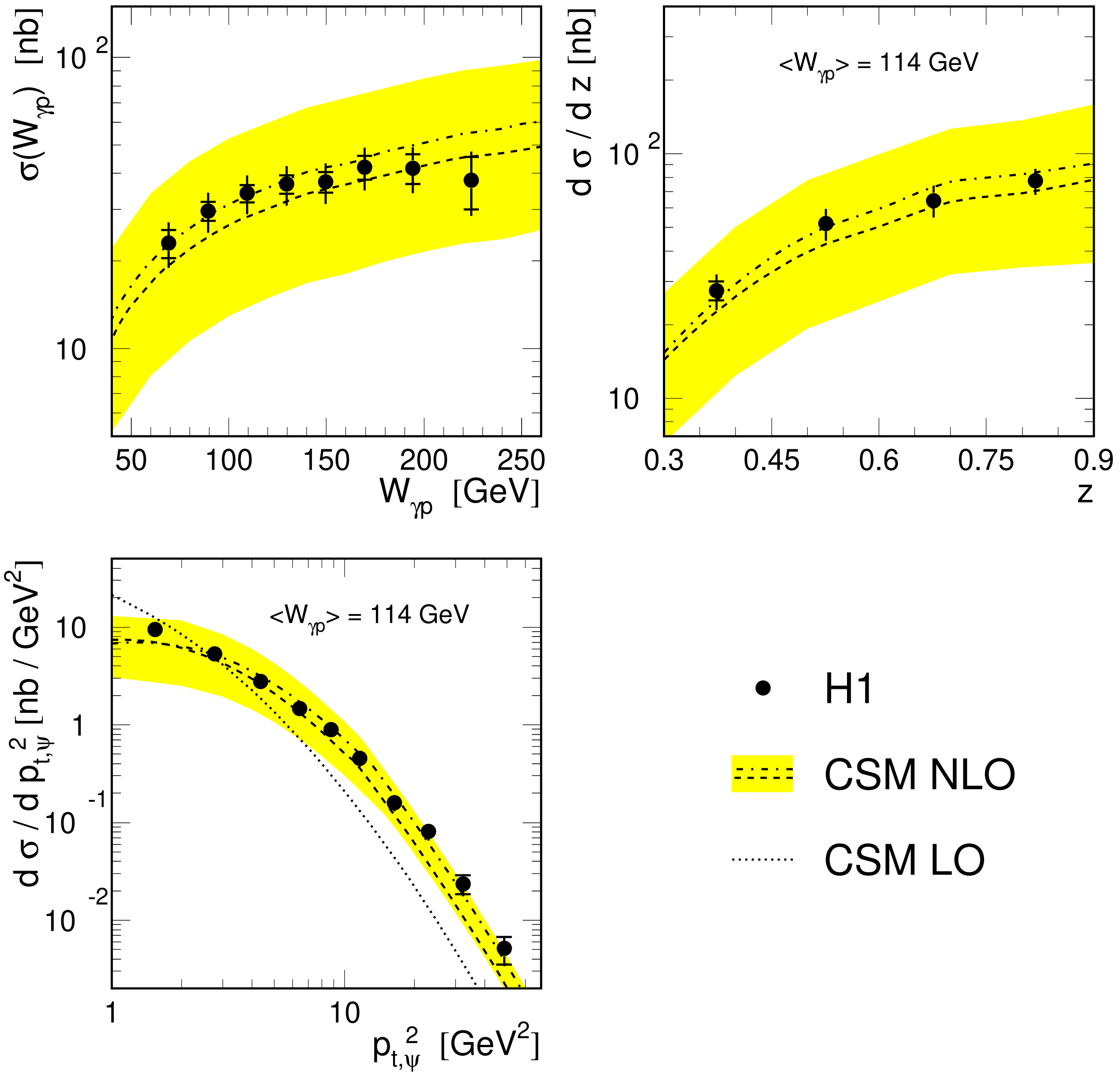
- decay of diffractively or inelastically produced ψ' mesons: $\psi' \rightarrow J/\psi\,\pi\,\pi$

- decay of χ_c mesons: $\chi_c \rightarrow J/\psi\,\gamma$ (low z)

- decay of B mesons: $B \rightarrow J/\psi\,X$ (low z, high $p_{t,\psi}$)

  not subtracted in data!

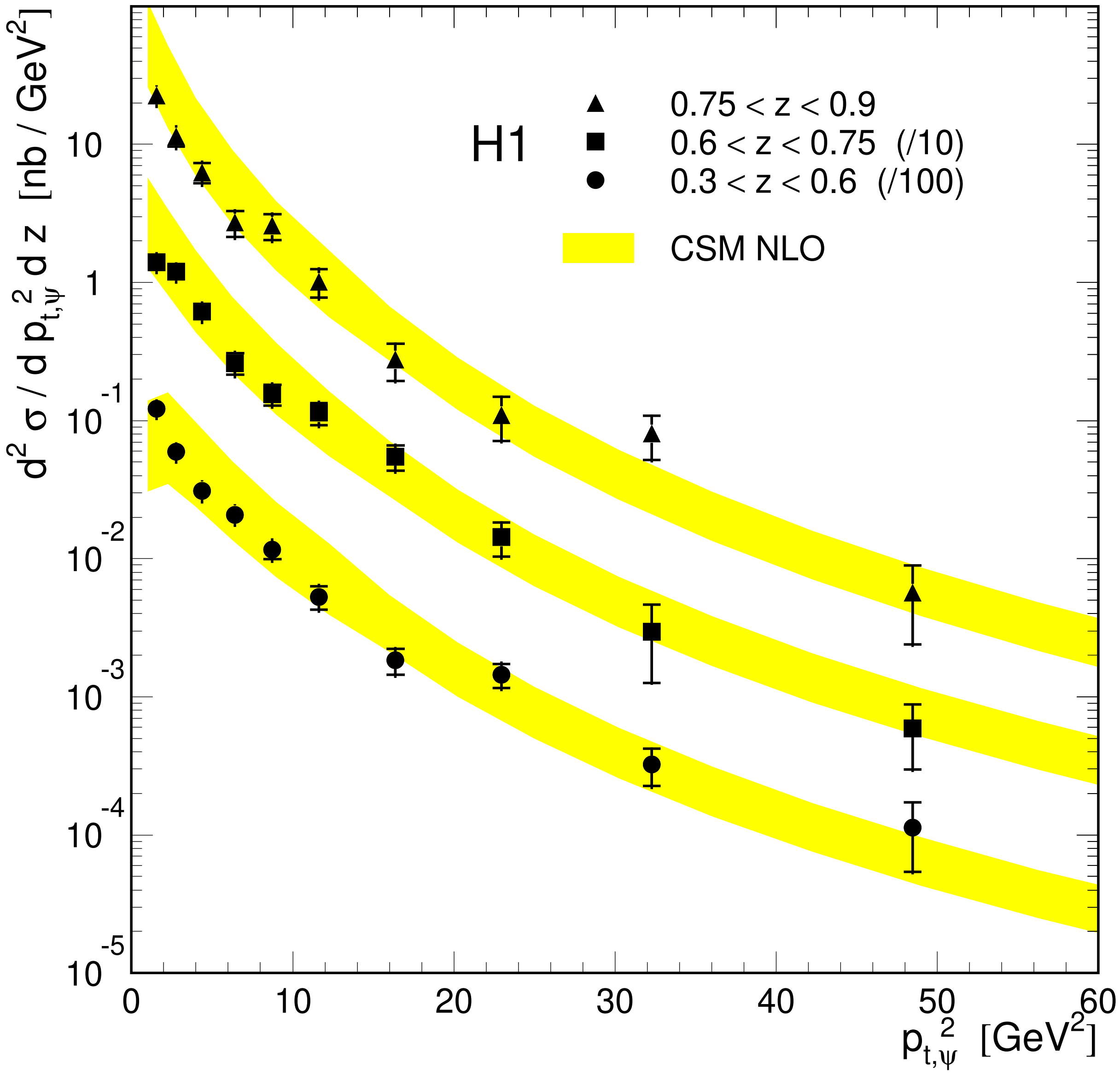
Photoproduction: Comparison with CSM NLO



- full NLO calculation of the direct photon gluon fusion in the CSM (M. Krämer)
- MRST, $1.3 \leq m_c \leq 1.5\,\text{GeV}$, $0.1175 \leq \alpha_s(M_Z) \leq 0.1225$
  $m_c = 1.3\,\text{GeV}$, $\alpha_s(M_Z) = 0.1175$ and $m_c = 1.4\,\text{GeV}$, $\alpha_s(M_Z) = 0.1225$ describe normalisation

$\Rightarrow$ shape is well described in NLO, LO too steep in $p_{t,\psi}^2$

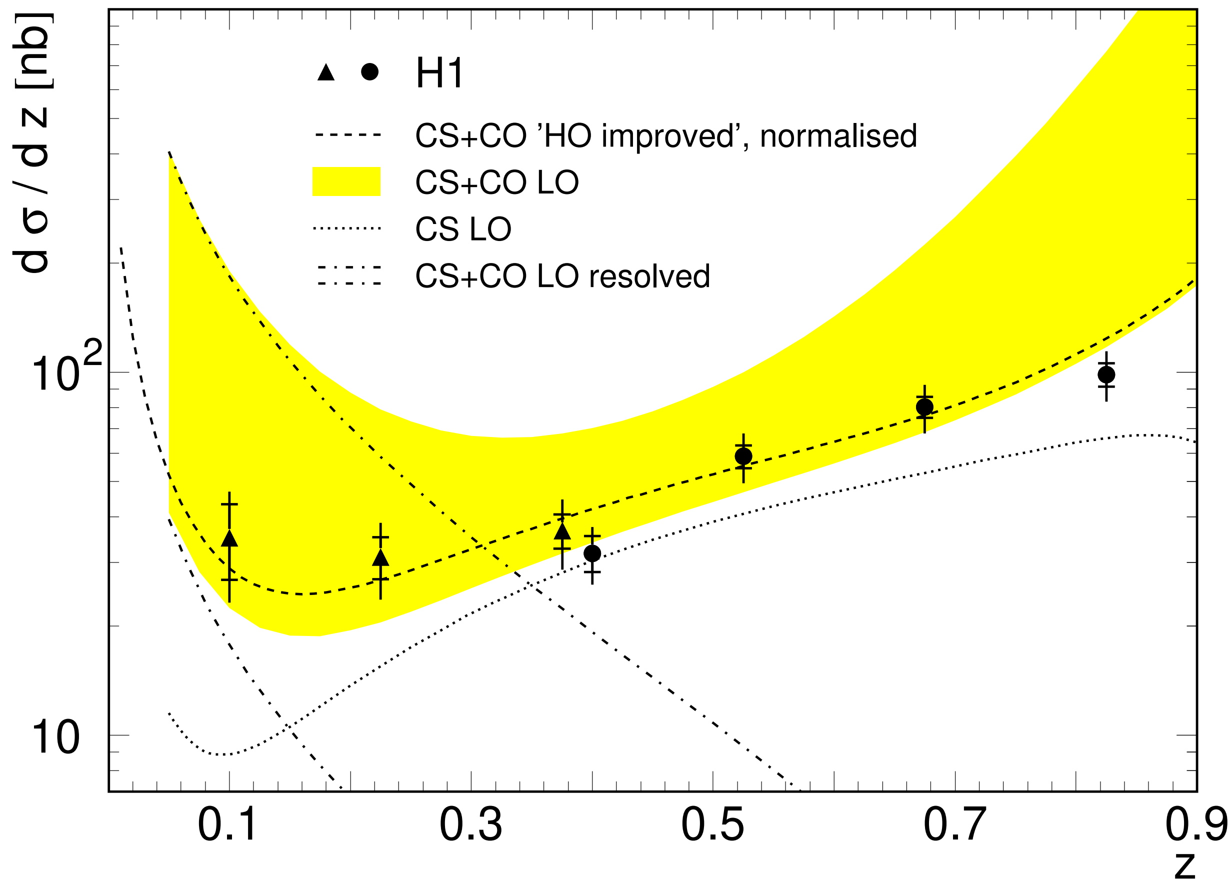
Photoproduction: Comparison with CSM NLO



- CSM NLO gives reasonable description in all z regions

$\Rightarrow$ important, since NRQCD contributions expected to depend on z

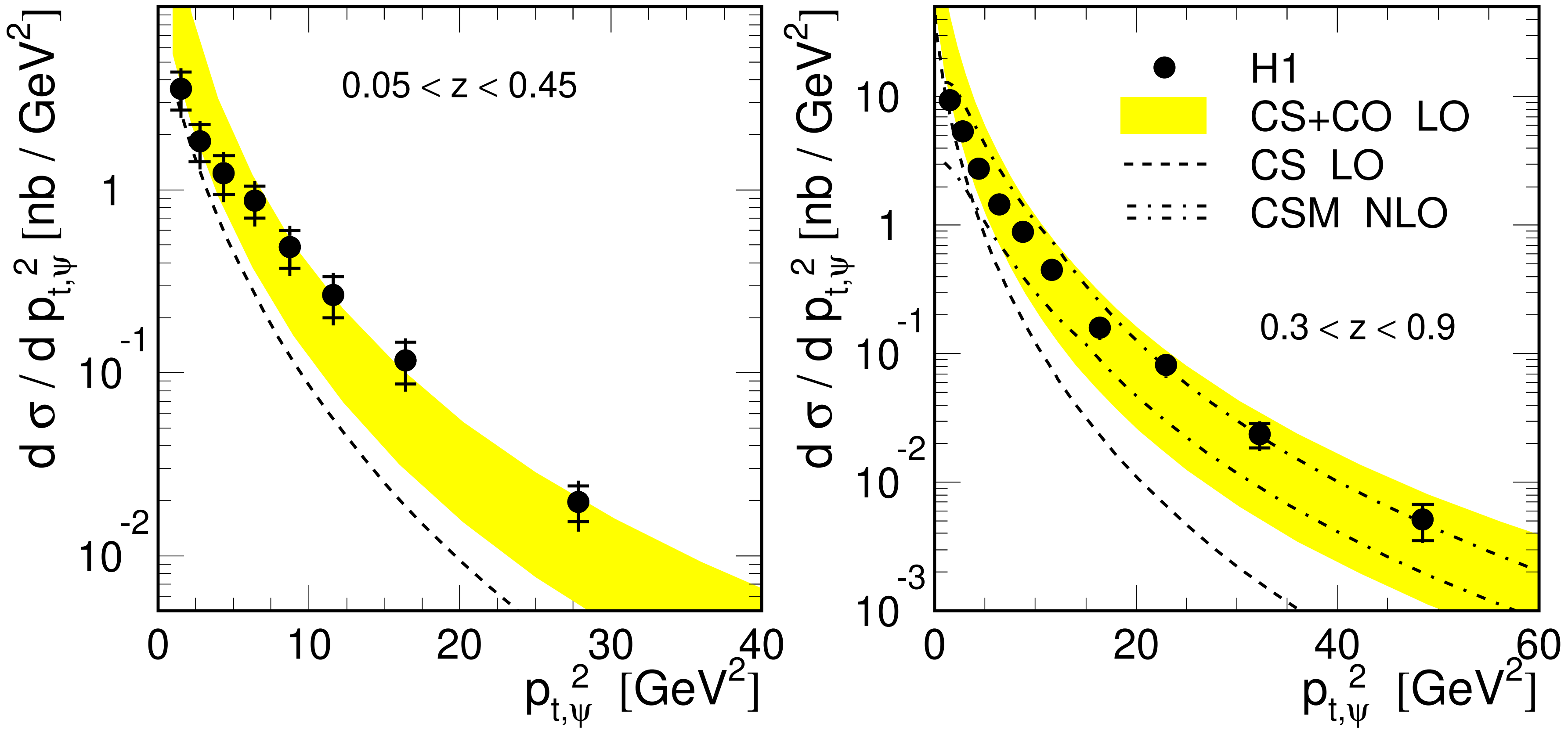
Photoproduction: Comparison with NRQCD (LO)



- first measurement of low z region
- LO NRQCD calculation including direct and resolved photon processes (M. Krämer)
- large uncertainties in calculation due to LDMEs
- large LDMEs excluded here
- resolved contributions improve description
- 'HO improved' (B.A. Kniehl and G. Kramer): hard subprocess at LO, NLO pdf's, LDMEs extracted with HO corrections from p_t spectrum of prompt J/ψ production in $p\bar{p}$ collisions (up to factor 10 lower than LO) $\rightarrow$ substantial k factor (~ 3) needed

$\Rightarrow$ fair description of whole z range with small LDMEs

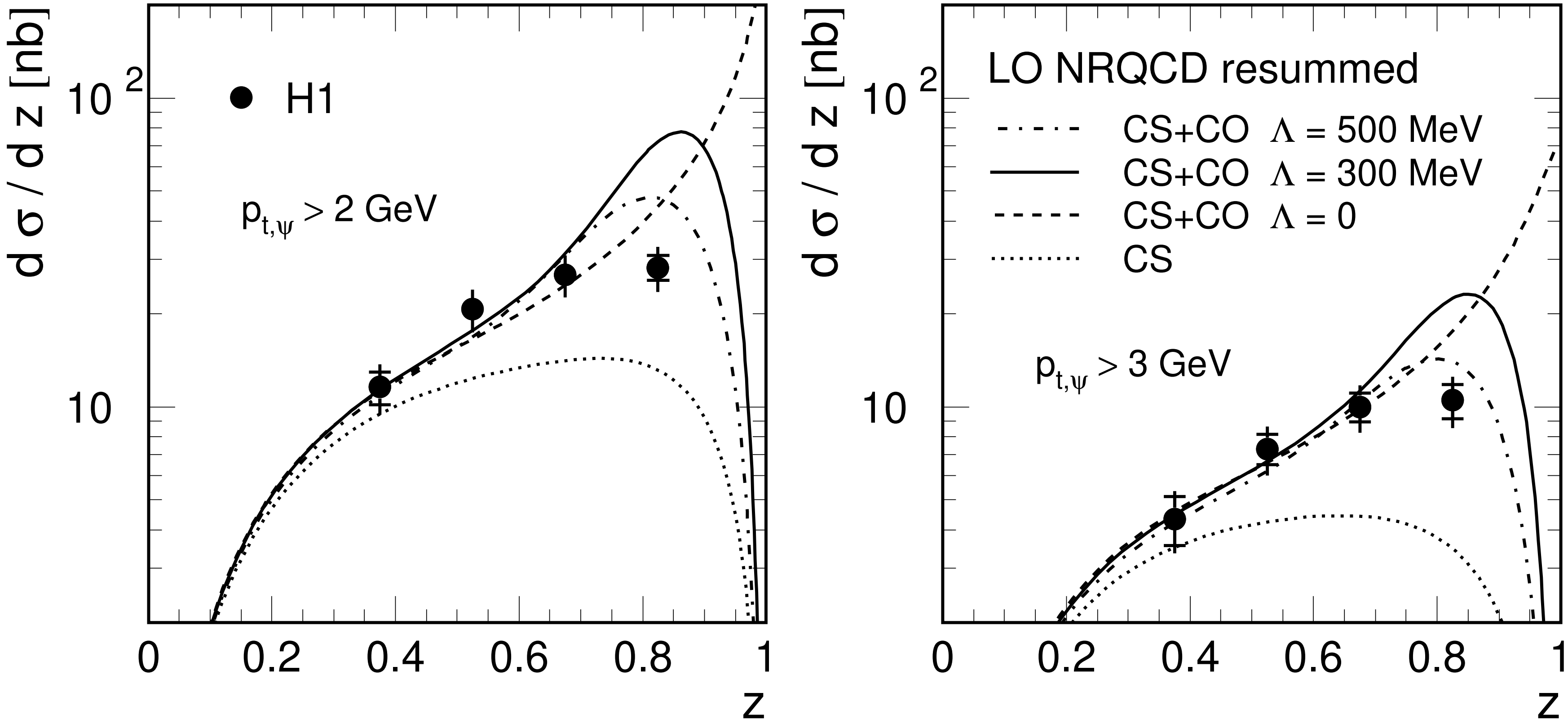
Photoproduction: Comparison with NRQCD (LO)



- $p_{t,\psi}^2$ dependence similar at low z and medium z
- CS (LO) contribution alone too steep
- NRQCD (CS+CO) shows a tendency to fall too steeply

$\Rightarrow$ B decay contribution in data?

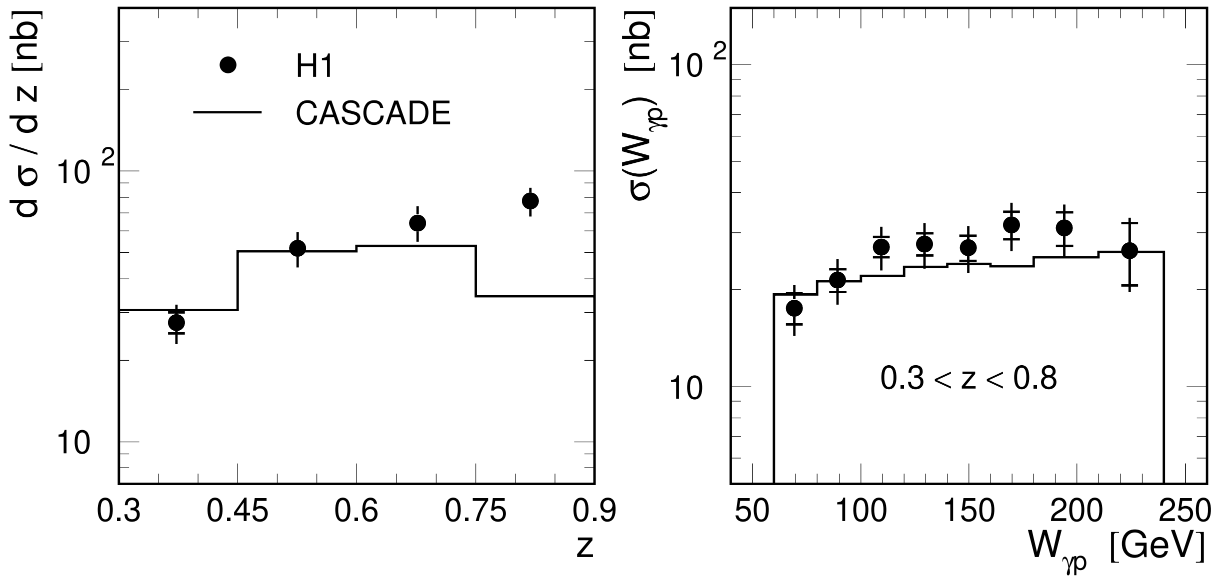
Photoproduction: Comparison with NRQCD (LO)

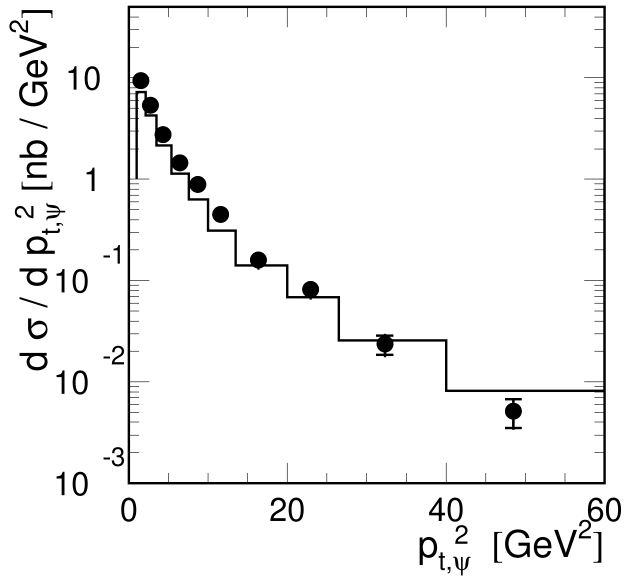


- LO NRQCD calculation resumming soft contributions at high z (M. Beneke, G.A. Schuler and S. Wolf)
- Λ: Energy loss of J/ψ due to soft gluon radiation
- k factors of 2 ($p_{t,\psi} > 2\,\mathrm{GeV}$) and 3 ($p_{t,\psi} > 3\,\mathrm{GeV}$)

$\Rightarrow$ resummation reduces discrepancy at high z

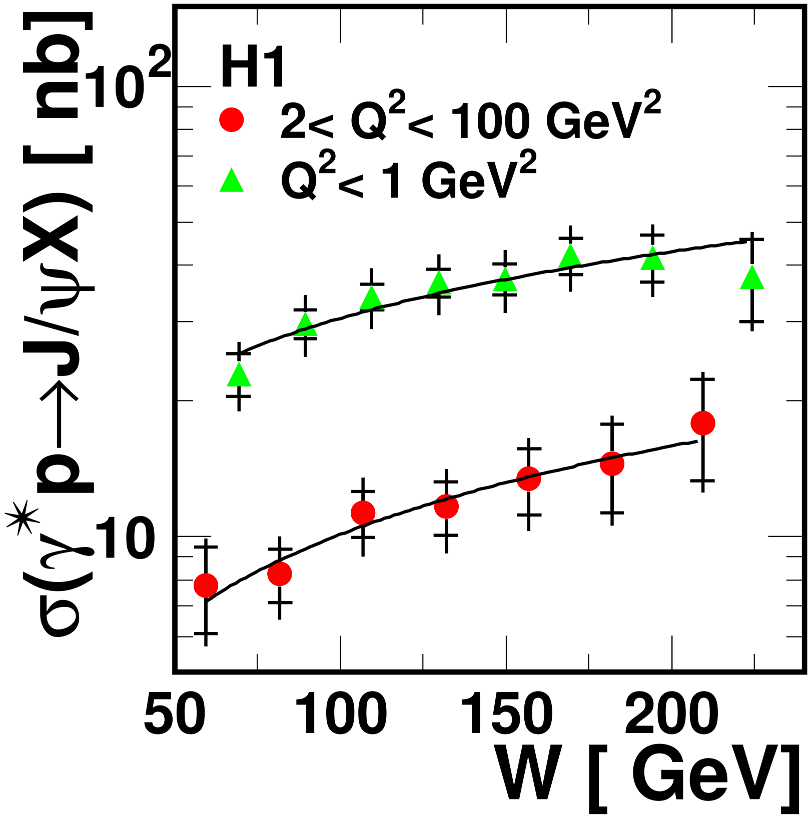
Photoproduction: Comparison with CASCADE





- CASCADE: CSM Monte Carlo generator based on k_t factorisation approach
- unintegrated gluon density: gluon inside proton can have transverse momentum k_t
- high z: missing relativistic corrections
- other distributions: reasonably well described

Comparison of $W_{\gamma p}$ Dependence in Photo- and Electroproduction



parameterisation: $\sigma \propto W_{\gamma p}^{\delta}$

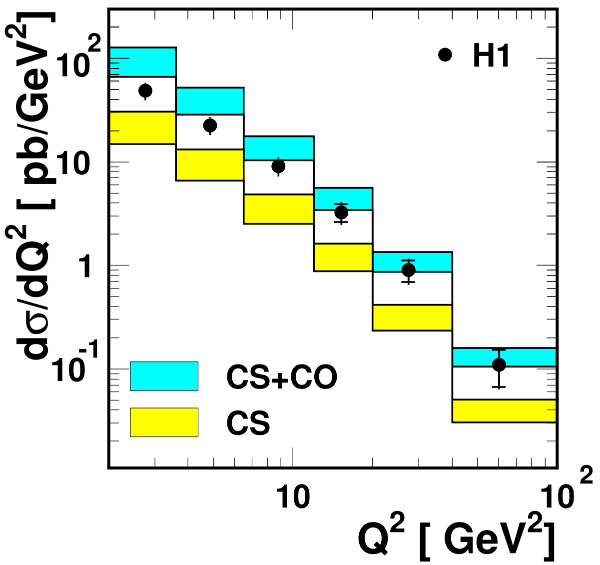
$\langle Q^2 \rangle \approx 0.05\,\mathrm{GeV}^2$: $\delta = 0.49 \pm 0.16$

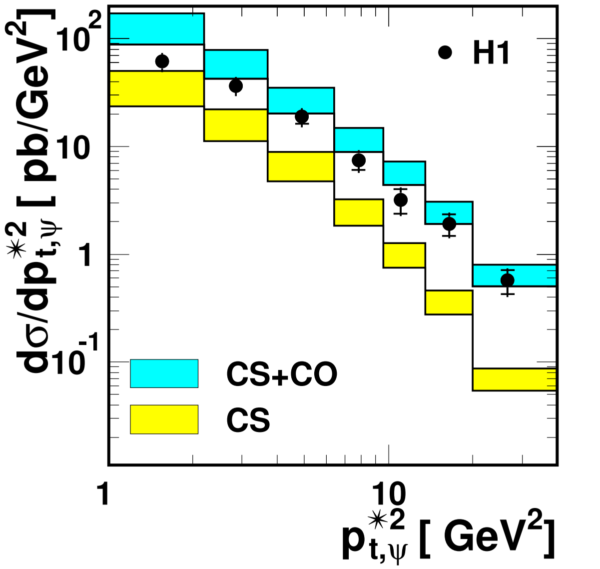
$\langle Q^2 \rangle = 10.6\,\mathrm{GeV}^2$: $\delta = 0.65 \pm 0.25$

- γp cross section shows similar $W_{\gamma p}$ dependence in photo- and electroproduction

$\Rightarrow$ reflects $g(x_g, \sim Q^2 + m_{J/\psi}^2)$

Electroproduction: Q^2 and $p_{t,\psi}^{*\,2}$ Dependence





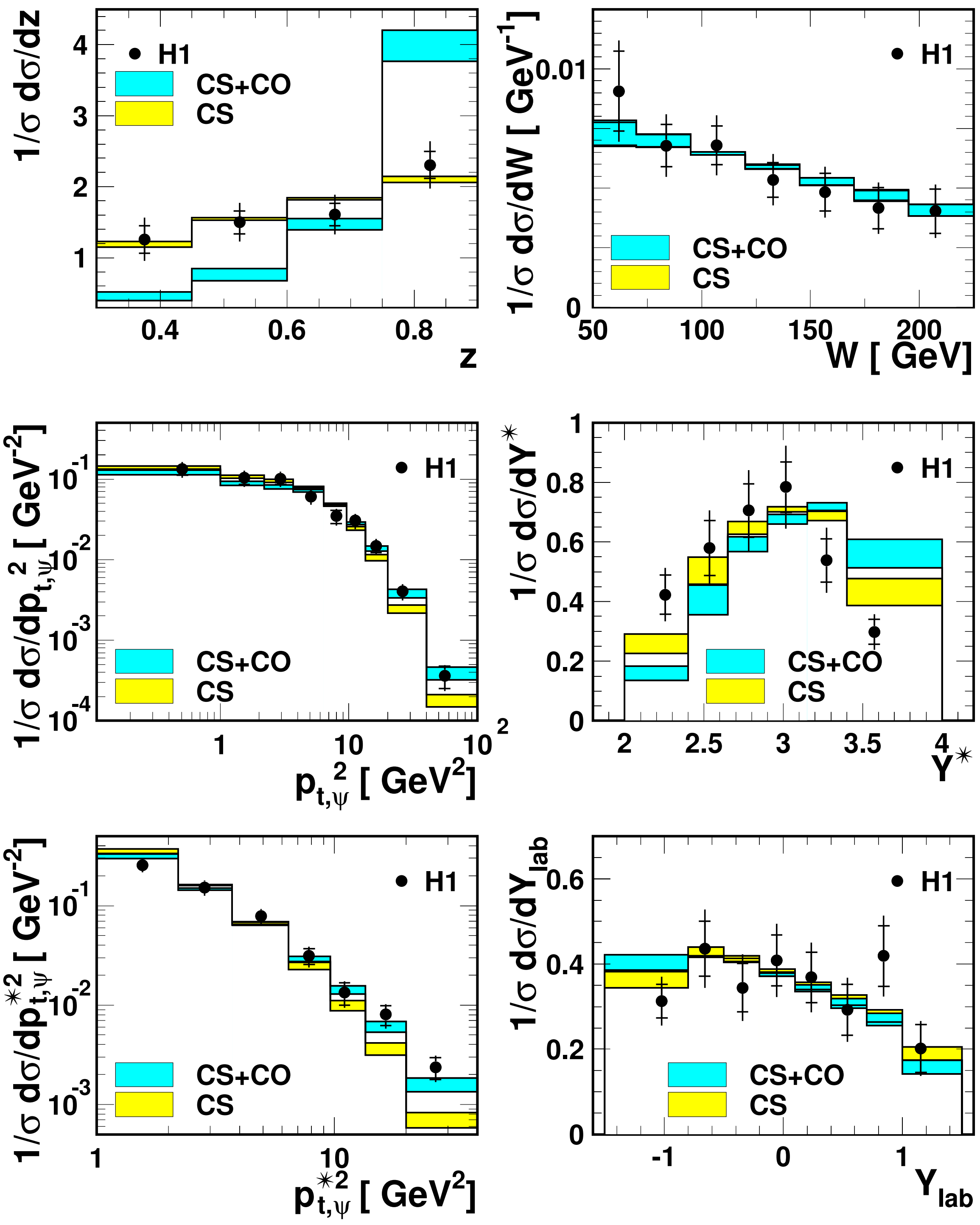
- comparison with LO NRQCD calculation and CS contribution (B.A. Kniehl and L. Zwirner)

- CS contribution alone too low (factor ~ 2.7)
- CS too steep in $p_{t,\psi}^{*\,2}$

$\rightarrow$ missing higher orders?

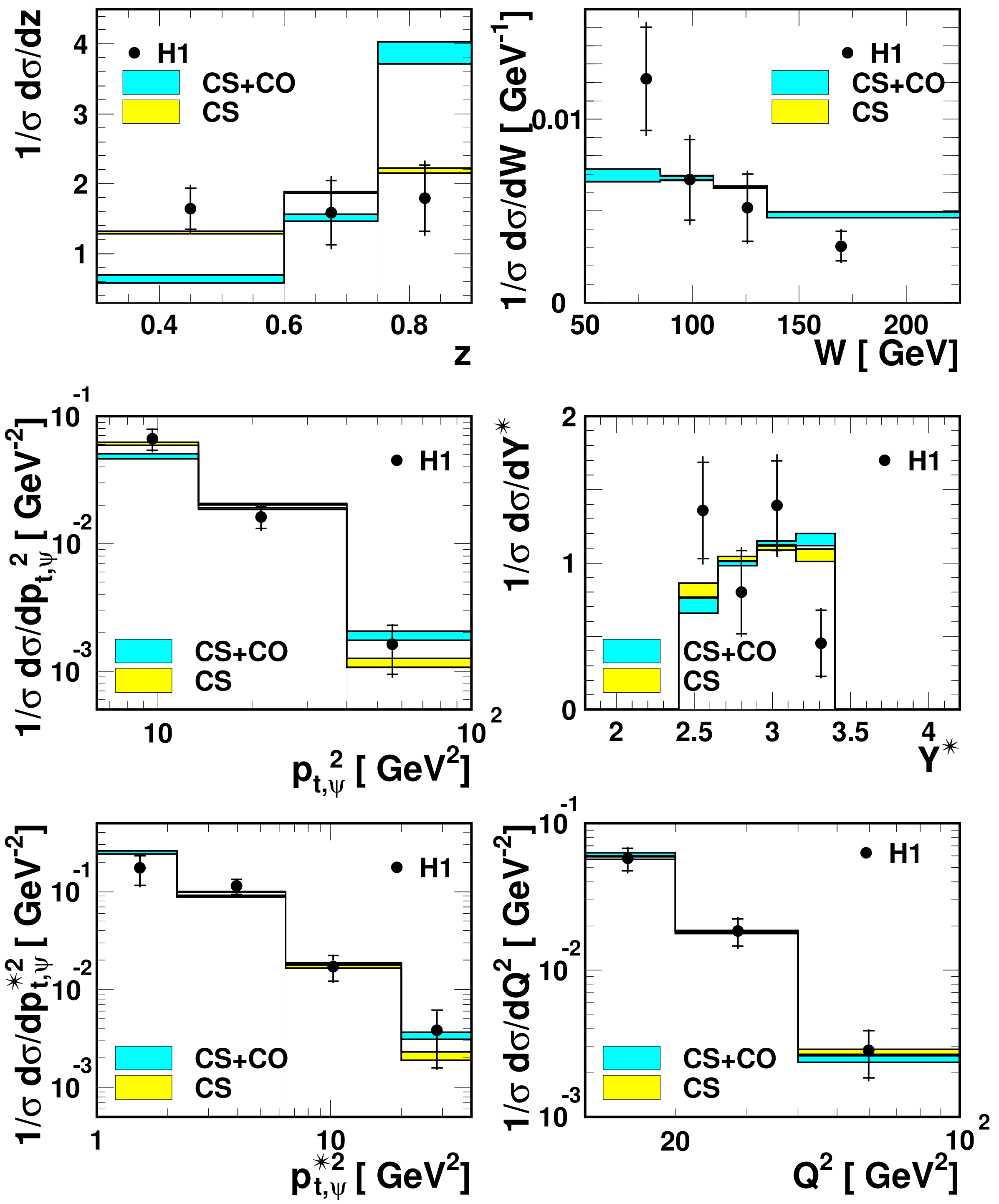
- CS+CO too high at low Q^2, $p_{t,\psi}^{*\,2}$ (factor ~ 2)
- CS+CO description improves at high Q^2, $p_{t,\psi}^{*\,2}$ (smaller theoretical errors)

Electroproduction: Normalised Cross Sections $Q^2 > 2\,\mathrm{GeV}^2$



- normalised x-sections to facilitate shape comparison
- Y^* (Y_{lab}): J/ψ rapidity in γp cms (lab system)
- z: missing resummation of soft terms for CS+CO?
- $p_{t,\psi}^2$, $p_{t,\psi}^{*\,2}$: missing higher orders for CS?

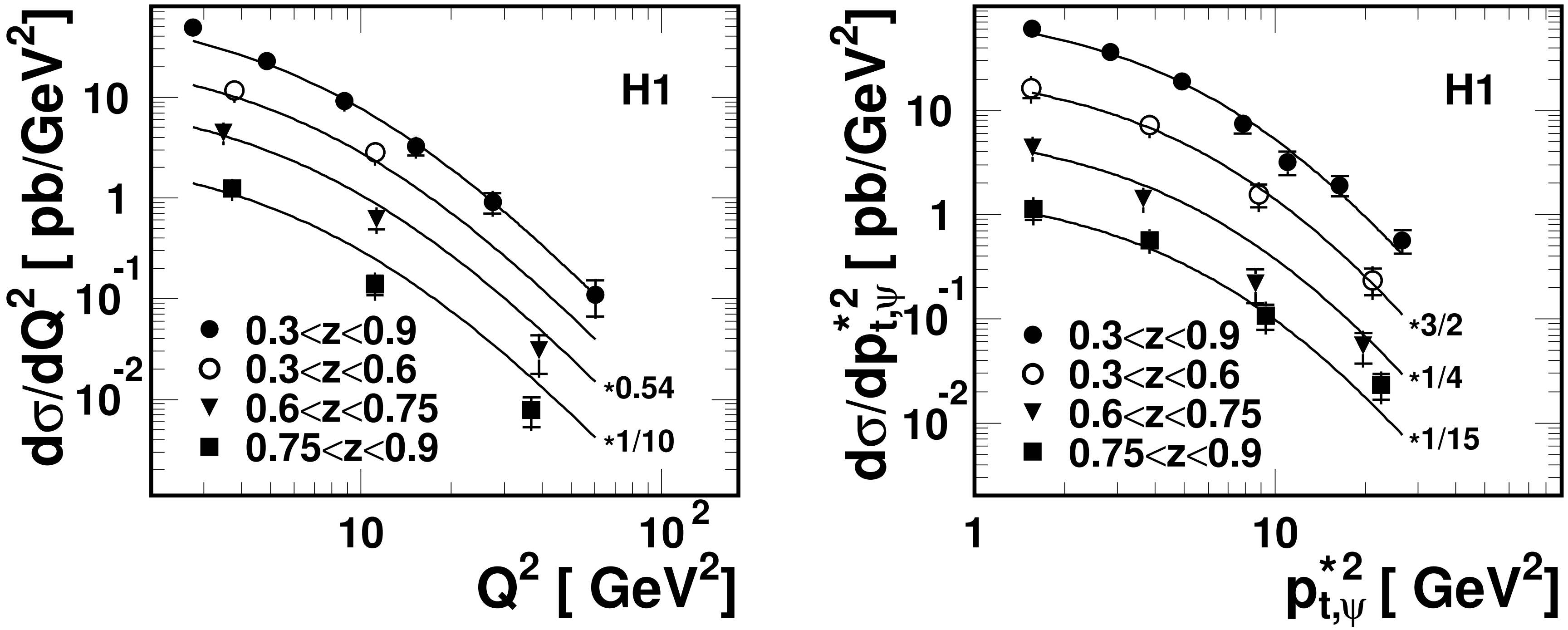
Electroproduction: Normalised Cross Sections $Q^2 > 12\,\mathrm{GeV}^2$



- theoretical uncertainties smaller at higher Q^2
- data statistics reduced

$\Rightarrow$ no substantial change in comparison

Electroproduction: Cross Sections in z Regions



- parameterisations in whole z range:

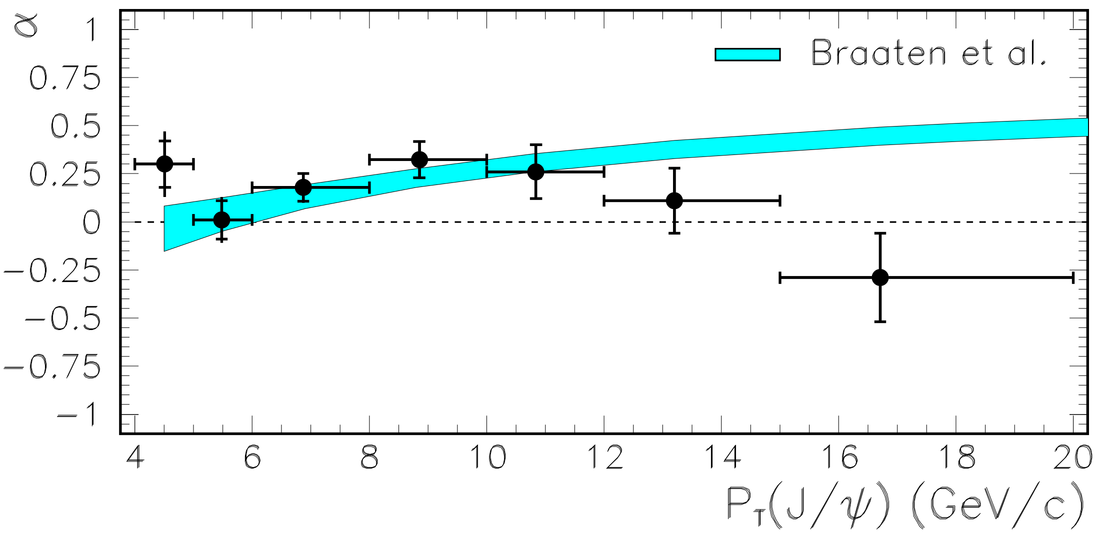
$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \propto (Q^2 + m_\psi^2)^{-m} \qquad\qquad \frac{\mathrm{d}\sigma}{\mathrm{d}p_{t,\psi}^{*\,2}} \propto (p_{t,\psi}^{*\,2} + m_\psi^2)^{-n}$$

- tendency for steeper fall with Q^2 at high z
- similar $p_{t,\psi}^{*\,2}$ dependence in all z regions (as in photoproduction)

Polarisation Measurements

- polarisation of J/ψ provides information on production process independent of normalisation uncertainties

  CDF measurement compared to NRQCD calculation



- polarisation is measured in decay angular distributions in J/ψ rest system

- θ^*: angle μ^+ to z' axis
  ϕ^*: angle μ^+ to plane determined by incoming photon and proton

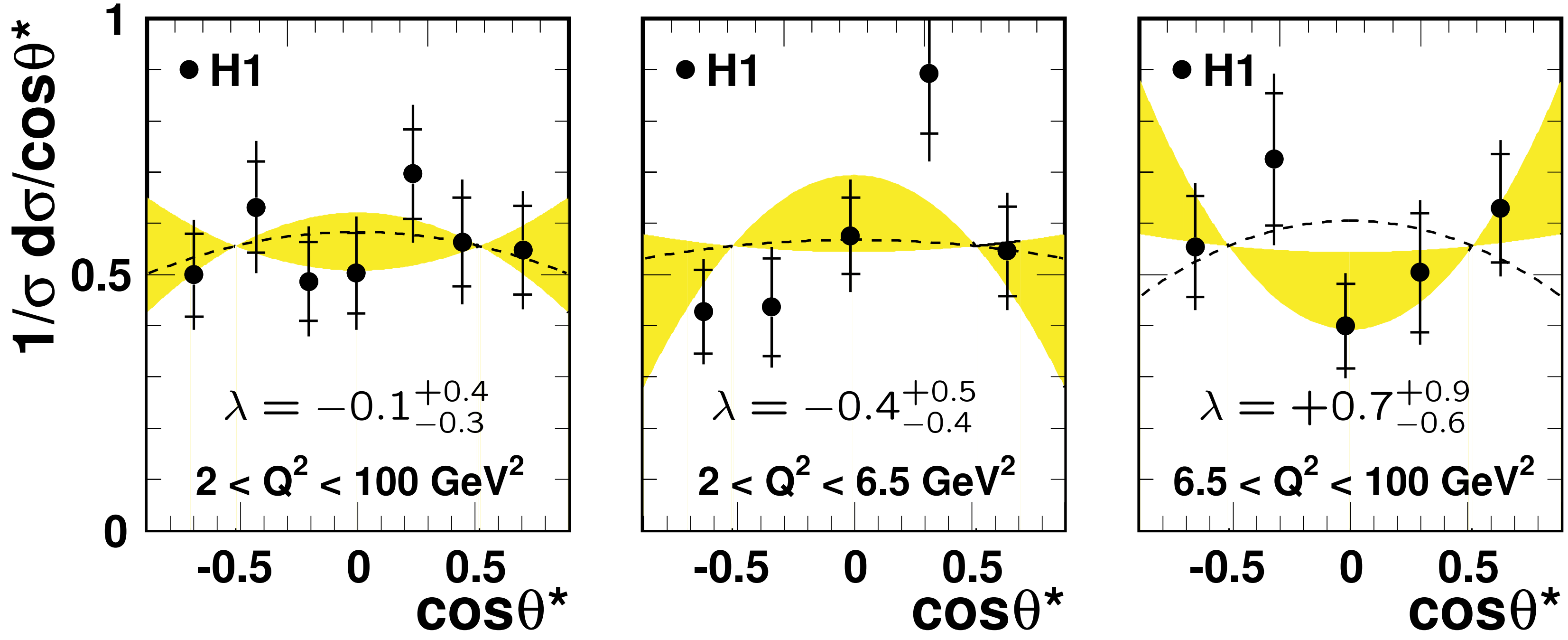
- parameterisations:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} \propto 1 + \lambda\cos^2\theta^*$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi^*} \propto 1 + \frac{\lambda}{3} + \frac{\nu}{3}\cos 2\phi^*$$

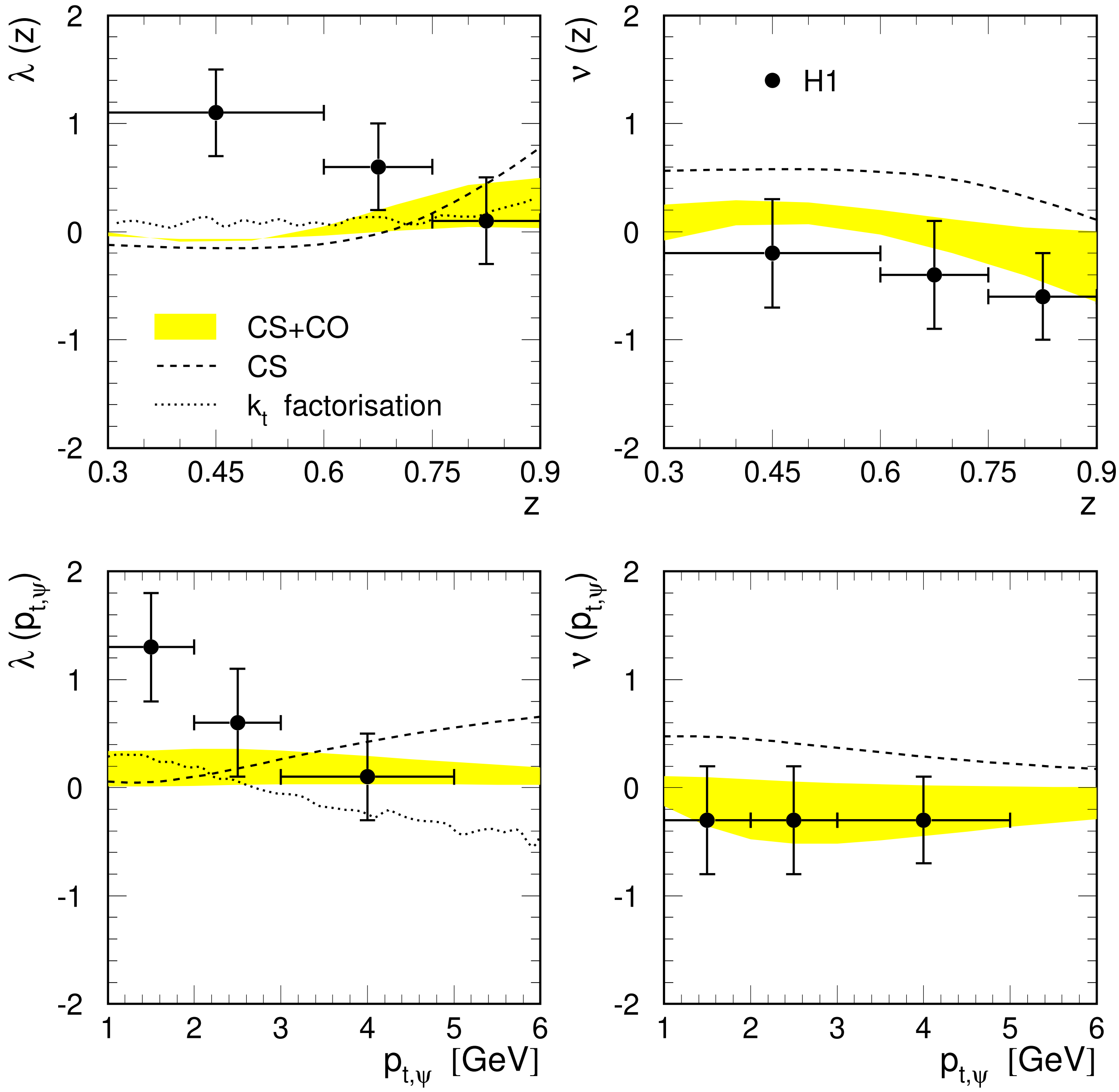
- $\lambda(=\alpha) = +1$: transverse polarisation
  $\lambda(=\alpha) = -1$: longitudinal polarisation

Polarisation Measurements: Electroproduction



- yellow band: $\pm 1\sigma$ region of fit
- dashed line: CSM calculation based on k_t factorisation (S.P. Baranov) (gluon inside proton can have transverse momentum)
- maybe increase of λ with Q^2? $\rightarrow$ more data needed!

Polarisation Measurements: Photoproduction



- tendency for decrease of λ with z and $p_{t,\psi}$
- ν independent of z and $p_{t,\psi}$?

$\longrightarrow$ more data needed for decision on production mechanism

Conclusions and Outlook

new results on inelastic J/ψ production
compared to CSM and NRQCD

- photoproduction:
  - medium z: good agreement with CSM NLO calculations
  - low z: resolved photon contributions improve agreement
  - NRQCD with small LDMEs gives reasonable description

- electroproduction:
  - similar $W_{\gamma p}$ dependence as in photoproduction
  - CS (LO) alone too low, wrong $p_{t,\psi}^{*\,2}$ dependence
  - NRQCD OK at high Q^2 and $p_{t,\psi}^{*\,2}$, but problems in z

- major improvement in data statistics needed for conclusions from polarisation measurements $\rightarrow$ only possible with HERA II data

$\Rightarrow$ NLO calculations for electroproduction and in NRQCD needed!