INELASTIC CHARMONIUM PRODUCTION AT HERA

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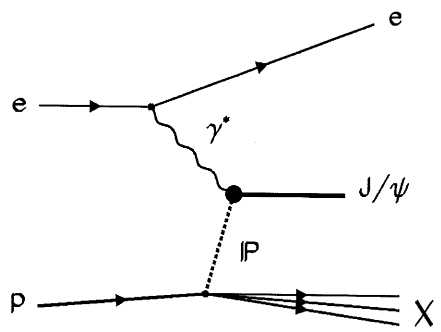
- PRODUCTION MECHANISMS
- INELASTIC PHOTOPRODUCTION: ZEUS
- INCLUSIVE AND INELASTIC ELECTROPRODUCTION: H1
- CONCLUSIONS

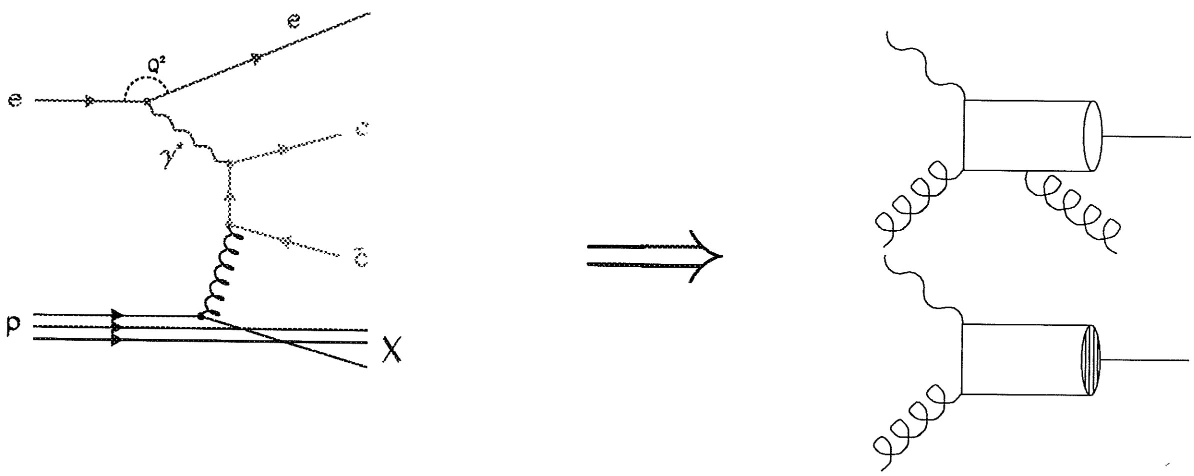
J/ψ Production Mechanisms at HERA

DIFFRACTIVE - elastic, proton dissociative

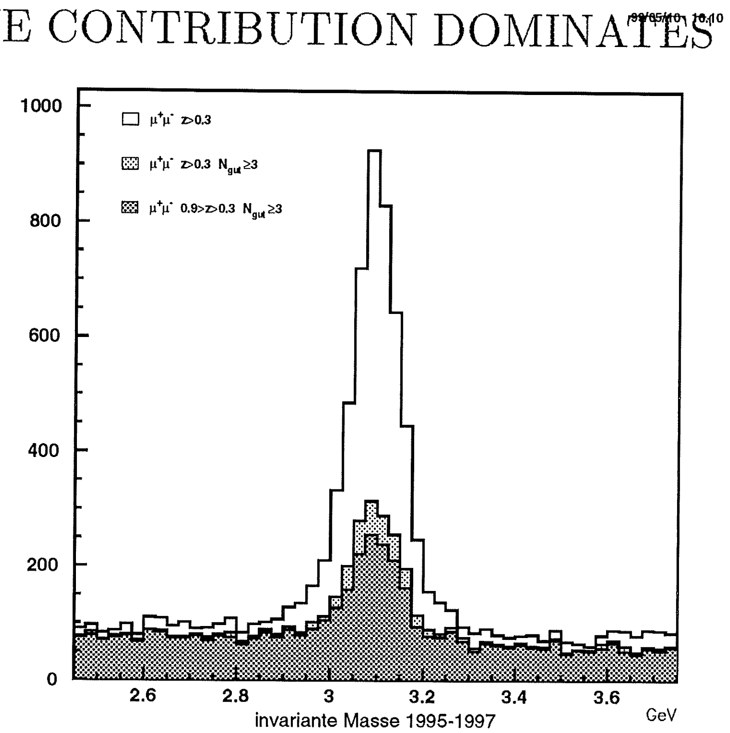


rapidity gap between
J/ψ and X
characteristic t, W, M_X and θ
dependence,
$z \simeq 1$

INELASTIC photon gluon fusion



DIFFRACTIVE CONTRIBUTION DOMINATES (at low Q^2)



J/ψ Production Mechanisms at HERA

Transition to J/ψ meson: Two classes of models

- ✦ ACCOUNT FOR COLOUR AND ANGULAR MOMENTUM IN HARD INTERACTION

  — NON RELATIVISTIC QCD/FACTORISATION APPROACH "COLOUR OCTET MODEL" (BODWIN, BRAATEN, LEPAGE) EFFECTIVE FIELD THEORY, MANY FREE PARAMETERS
  — COLOUR SINGLET MODEL (CSM) (HISTORICALLY COMES BEFORE COM)
  — ETC.

- ✦ DISREGARD COLOUR AND ANGULAR MOMENTUM IN HARD INTERACTION

  — COLOUR EVAPORATION MODEL (HALZEN, EBOLI, ET AL)
  — SOFT COLOUR INTERACTIONS (INGELMAN, RATHSMAN ET AL.)
  — ETC.

Sensitive Parameters in all approaches:

Quark mass m_c, strong coupling α_s, gluon density, factorisation (renormalisation) scale, ...

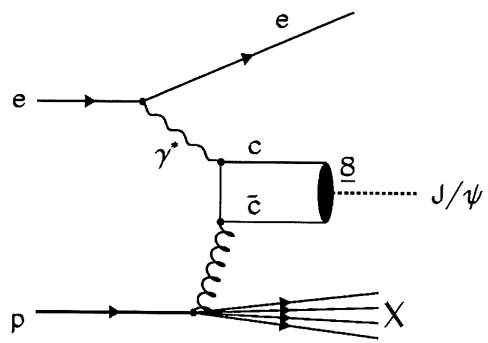
Theoretical uncertainties are expected to decrease at higher Q^2 .

NRQCD/factorisation approach at HERA

$$\sigma(e+p \to e+J/\psi+X) = \sum_n c_n(e+p \to e+c\bar{c}[n]+X) \quad \langle \mathcal{O}_n^{J/\psi} \rangle$$

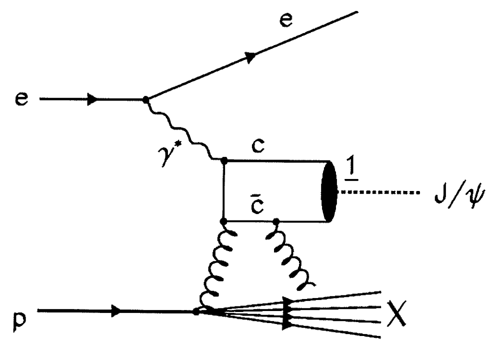
calculable in pQCD   not calculable

Coulour Octet



- colour singlet and octet terms $\langle \mathcal{O}_{(1)}^{J/\psi}(^3S_1)\rangle$, $\langle \mathcal{O}_{(8)}^{J/\psi}(^1S_0)\rangle$, $\langle \mathcal{O}_{(8)}^{J/\psi}(^3P_0)\rangle/m_c^2$
- long range matrix elements $\langle \mathcal{O}_n^{J/\psi}\rangle$ unknown
- magnitude estimated from $p\bar{p}$ data $\to$ additional parameters (universal ?)

Colour Singlet Model

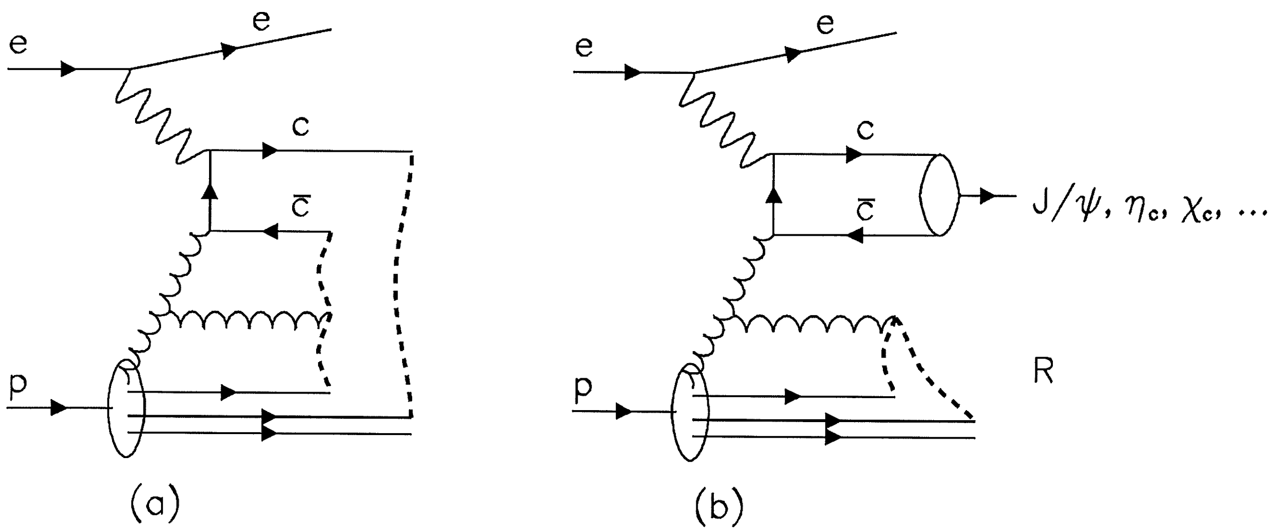


- $c\bar{c}$ in colour singlet $^3S_1$ state
- emission of hard (perturbative) gluon
- no free parameters: $\langle \mathcal{O}_{(1)}^{J/\psi}(^3S_1)\rangle \propto \Gamma_{ee}^{J/\psi}$
- undershoots $p\bar{p}$ data by factor ≈ 50

Soft Colour Interactions - SCI

Edin, Ingelman, Rathsman

- ✦ PRODUCTION OF $c\bar{c}$ VIA FIXED ORDER MATRIX ELEMENT
- ✦ PARTON SHOWERS DOWN TO A CUTOFF Q_0
- ✦ BELOW CUTOFF: COLOUR EXCHANGE BETWEEN PARTONS, NON-PERTURBATIVE
- ✦ MAY LEAD TO FORMATION OF COLOUR SINGLET $c\bar{c}$ STATE



Installed in Monte Carlo generator AROMA

- ✦ MASS OF $c\bar{c}$ PAIR IN PRINCIPLE GIVEN BY HARD INTERACTION. SMEARED OUT, SO:

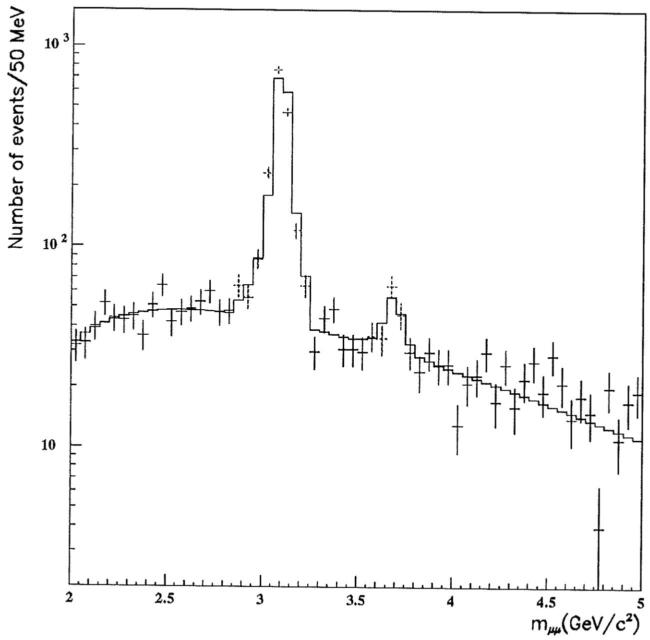
$$\sigma_{onium} = \int_{2m_c}^{2m_D} \frac{d\sigma}{d\,m_{c\bar{c}}} \otimes SCI\,d\,m_{c\bar{c}}$$

ONIUM: J/ψ, χ, ψ',...

DISTRIBUTION ACCORDING TO: $(2\,J+1)/n$, N=RADIAL QUANTUM NUMBER

DATA

✦ ZEUS: PHOTOPRODUCTION $Q^2 \simeq 0$

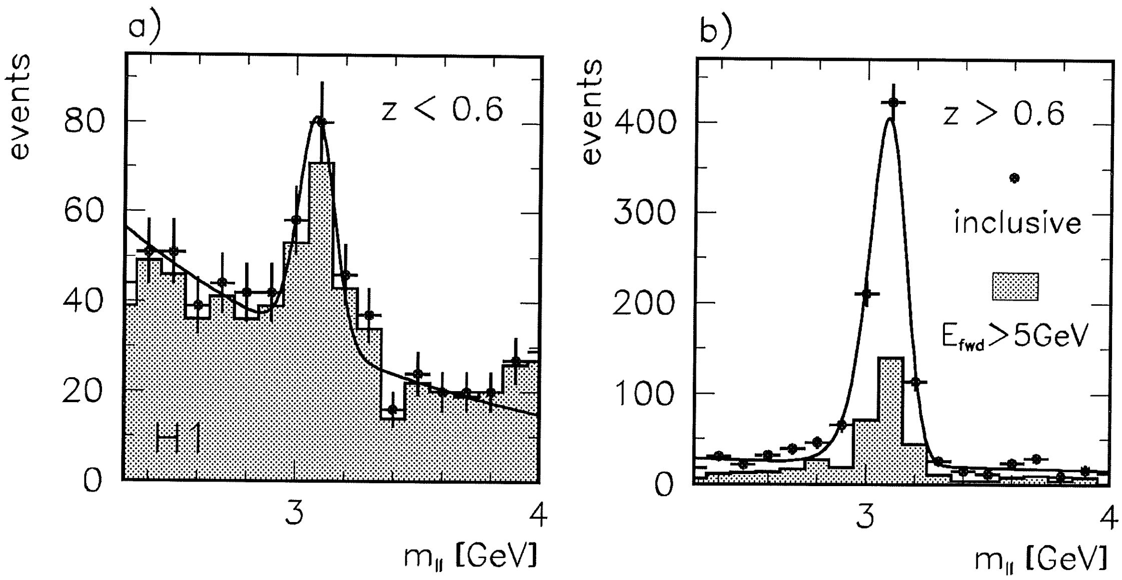


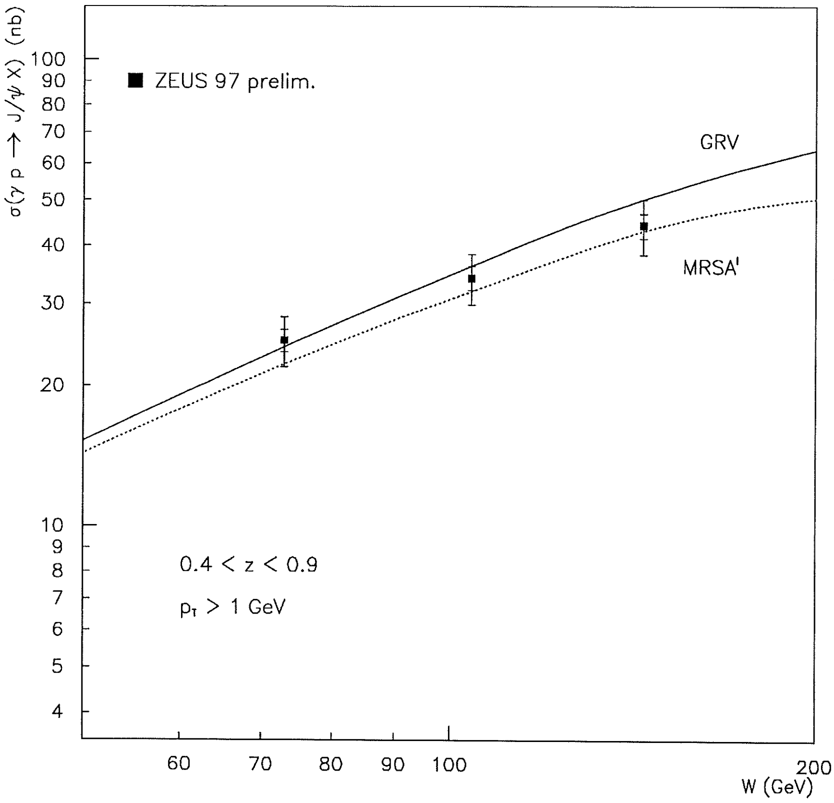
$26\,\text{pb}^{-1}$
$Q^2 < 1$ GeV
$50 < W_{\gamma p} < 180$ GeV
$p_t^{\psi} > 1$ GeV

Inelastic Selection:
Energy in forward region of detector: $E_{fwd} > 1$ GeV corresponds roughly to $M_X > 4$ GeV
$0.4 < z < 0.9$

✦ H1: $Q^2 \geq 2$ GeV^2

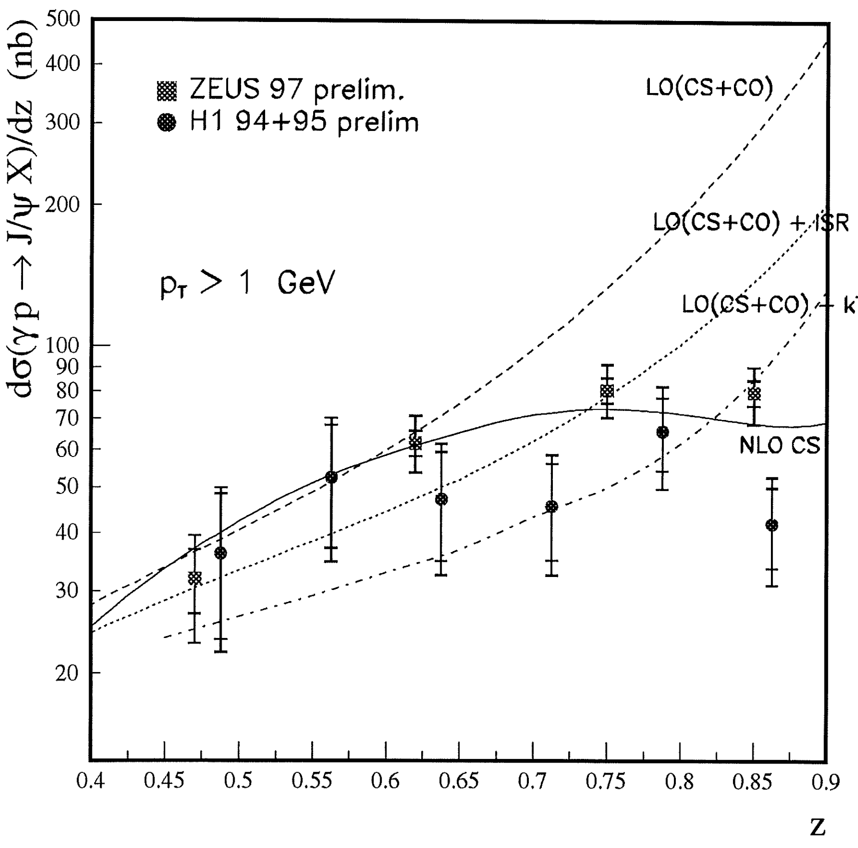
$27\,\text{pb}^{-1}$; $2 < Q^2 < 80$ GeV^2; $40 < W_{\gamma p} < 180$ GeV; $z > 0.2$
Inclusive and Inelastic Analysis





ZEUS: $Q^2 < 1$ GeV, $50 < W_{\gamma p} < 180$ GeV
$p_t^\psi > 1$ GeV, $0.4 < z < 0.9$

theory: Colour Singlet Model, NLO (M. Krämer et al.)
parameters: $\Lambda_{QCD} = 300\,\mathrm{MeV}$, scale $\mu^2 = 2\,m_c^2$, $m_c = 1.4$ GeV



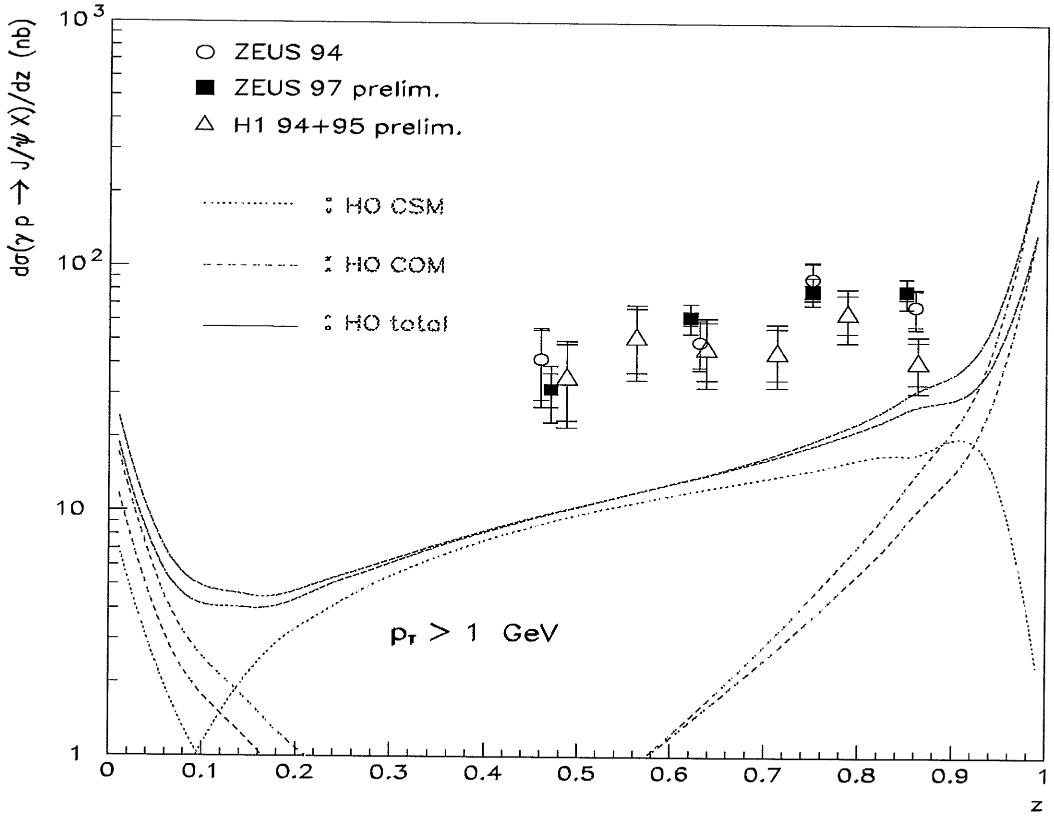
A bit of history: After the large discrepancy of data and colour singlet prediction observed at CDF, long range matrix elements were extracted and used to predict photoproduction of J/ψ. Prediction ~ factor 10 above data. Discussion of possible effects to diminish prediction: radiation, k_t of gluon in $p\overline{p}$ and γp.

$$z = \frac{p_\psi \cdot q}{p_\psi \cdot P} = \frac{E^*_\psi}{E^*_\gamma}$$

Inelastic Photoproduction

Comparison to modified "Colour Octet" prediction:

Take higher orders approximately into account for extraction of long range matrix elements (Kniehl et al.):



Conclusion from photoproduction:

No large effect seen from Colour Octet Contributions

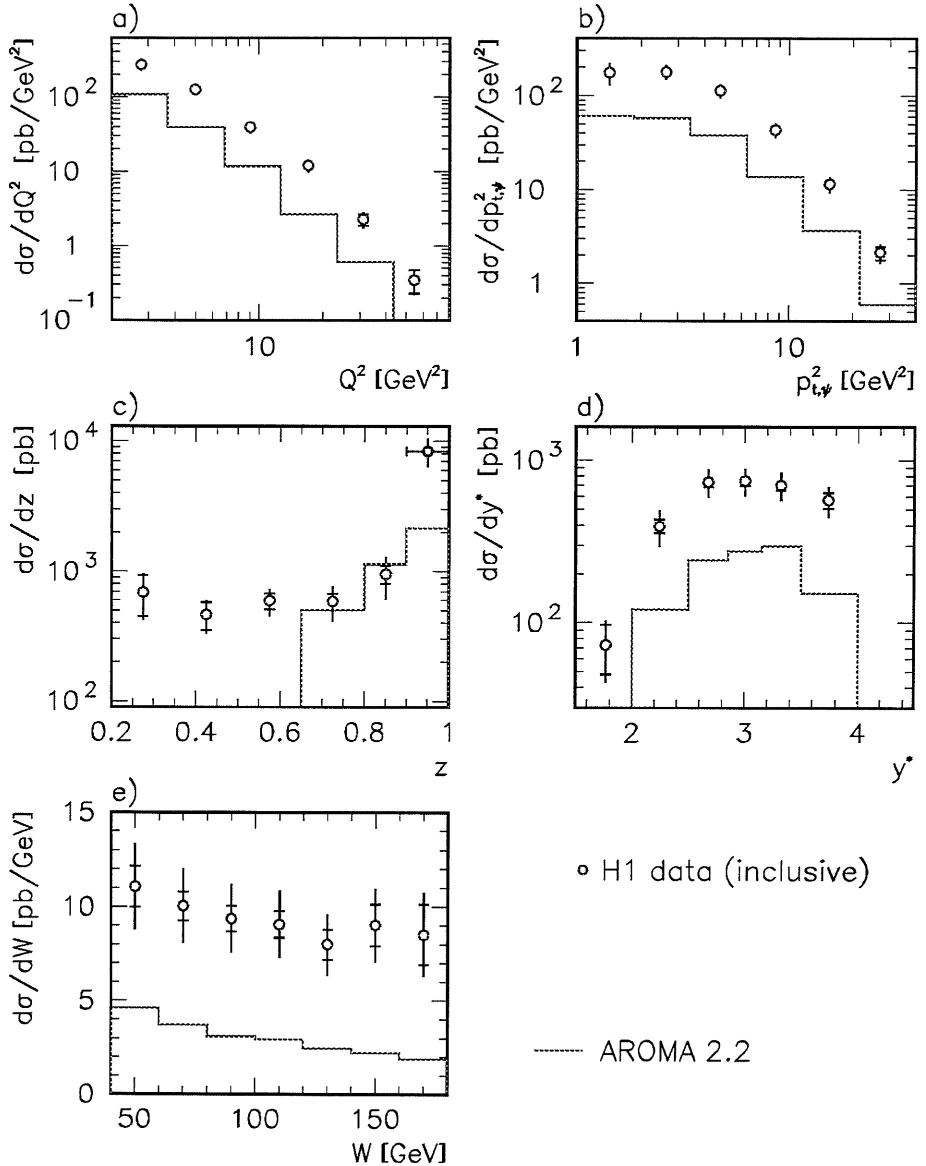
Large k-factor necessary to describe data (LO!)

dsdz-kniehl.eps Change analysis procedure:

Inclusive cross sections may help in understanding production mechanisms

In inelastic analysis avoid z-cut which seems to get rid of colour octet contributions

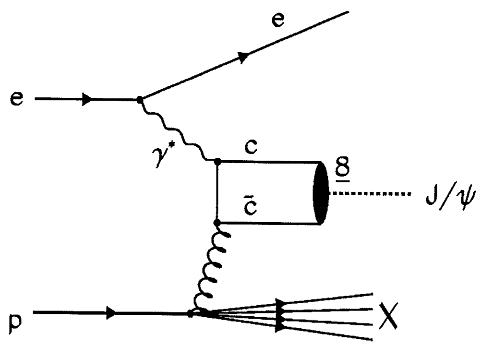
Inclusive J/ψ Production $ep \longrightarrow eJ/\psi X$

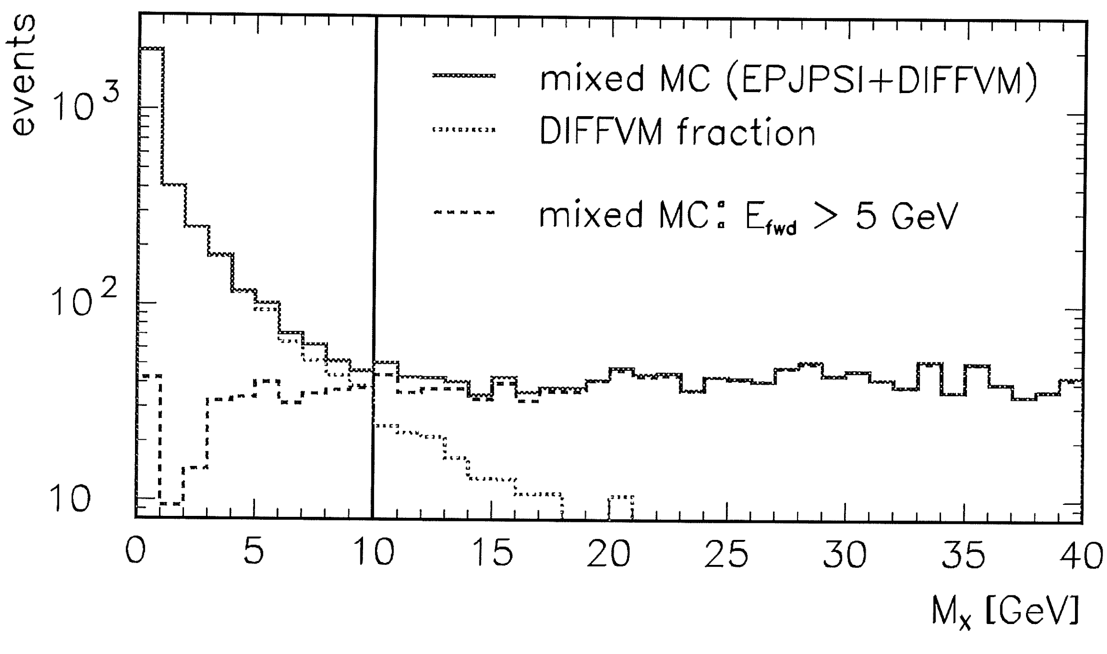


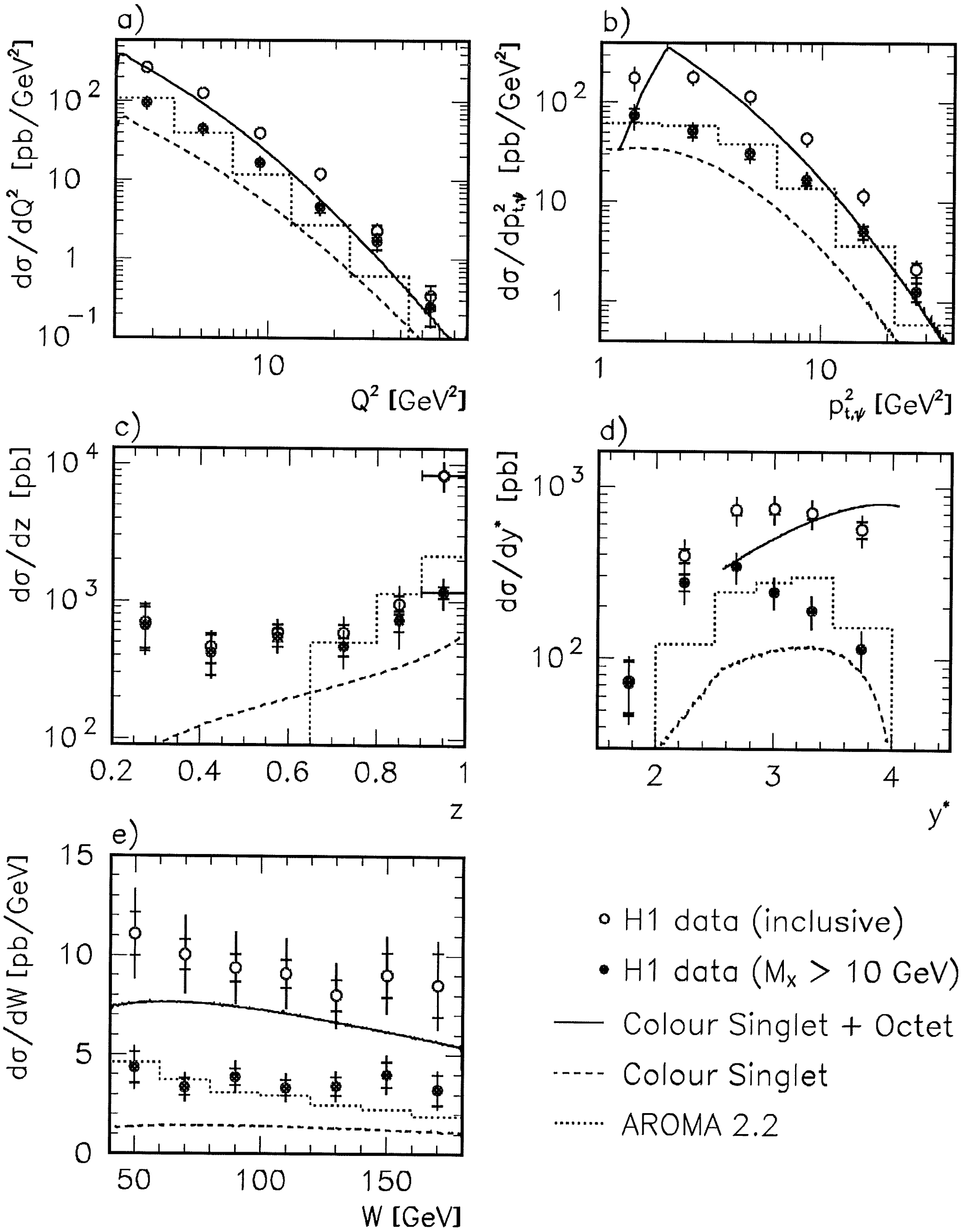
- ✦ Compare Soft Colour Interaction Model (Aroma 2.2) with the data:
- ✦ Good description, except:
  - Normalization of Aroma too low
  - $d\sigma/dz$ not described
- ✦ Aroma includes so far only the LO BGF matrix element
  $\rightarrow$ Colour Singlet contribution missing

Inelastic J/ψ Production

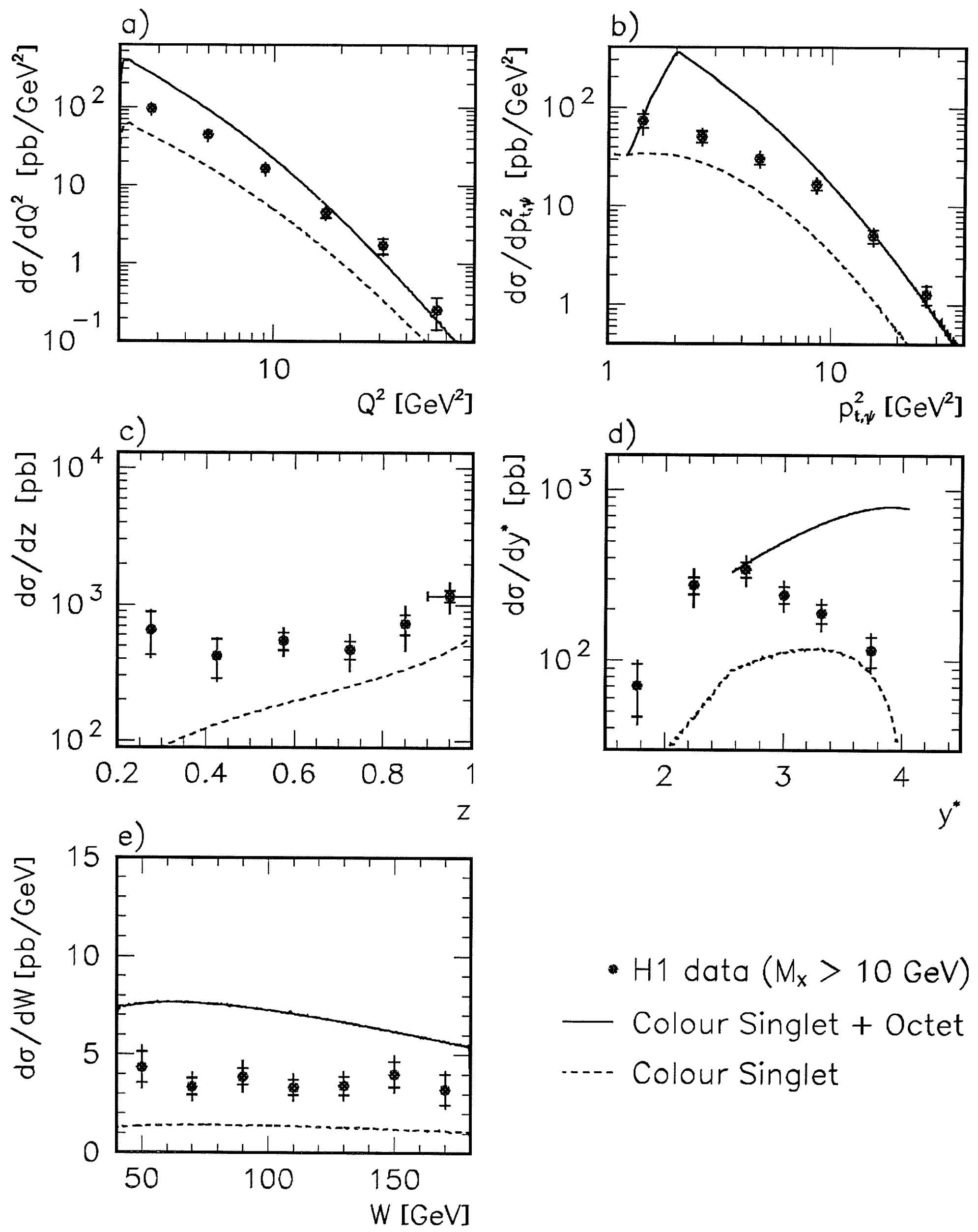
- An explicit cut in z (e.g. $z < 0.9$) as conventionally applied reduces colour octet contributions by an unknown amount
- Alternatively quote cross sections for a minimal M_X
- $M_X > 10$ GeV safe for Colour Octet according to Fleming/Mehen
- Experimentally require substantial energy deposits in forward calorimeter and correct for remaining low M_X contribution






a)
dσ/dQ² [pb/GeV²]
Q² [GeV²]
b)
dσ/dp²t,ψ [pb/GeV²]
p²t,ψ [GeV²]
c)
dσ/dz [pb]
z
d)
dσ/dy* [pb]
y*
e)
dσ/dW [pb/GeV]
W [GeV]
H1 data (inclusive)
H1 data (Mx > 10 GeV)
Colour Singlet + Octet
Colour Singlet
AROMA 2.2

Inelastic J/ψ Production $ep \longrightarrow eJ/\psi X$



- Calculations within NRQCD/ factorisation: Fleming, Mehen; long range matrix elemnts from $p\bar{p}$ data
- Colour Singlet (LO) is below the data, shapes not too bad
- Colour Singlet + Octet (LO) using CO ME from CDF data is above the data, shapes disagree
- Need for
  - NLO ?
  - hadronisation effects ?
  - adjusting CO ME ?

J/ψ Polarization

- Polarization of J/ψ is one possibility to distinguish production mechanisms
- Parameterize as

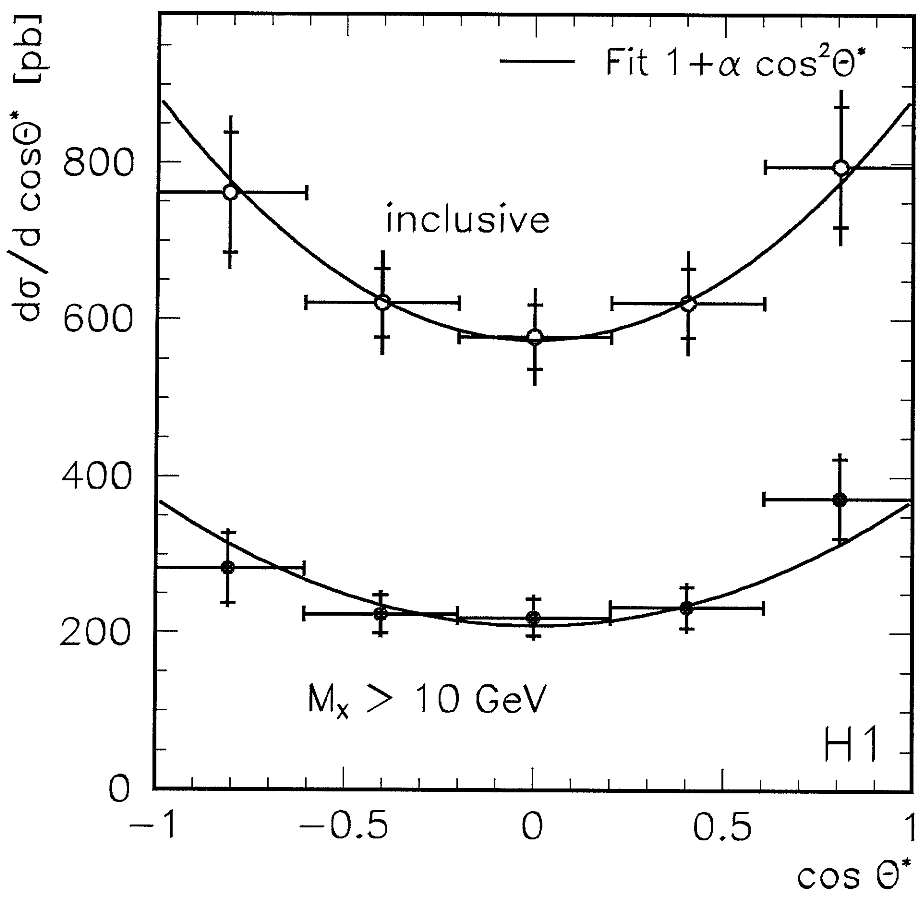
$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \alpha \cos^2\theta^*$$

($\alpha = +1$ transverse, $\alpha = -1$ longitudinal)

- Expect $\alpha \simeq 0.5$ for Colour Singlet, $|\alpha| \lesssim 0.5$ for Colour Octet, sign depending on which intermediate $c\bar{c}$ state dominates
- Measure

$\alpha = 0.54^{+0.29}_{-0.26}$ (inclusive)

$\alpha = 0.77^{+0.44}_{-0.38}$ ($M_X > 10$ GeV)



Summary and Conclusions

- Precision of data on inelastic J/ψ production substantially improved due to higher statistics corresponding to $\gtrsim 26\,\mathrm{pb}^{-1}$

- Photoproduction New Data From ZEUS
  - Data well described by colour singlet model in NLO
  - No large effect due to colour octet mechanism seen within kinematics studied (z–cut??)

- Electroproduction $Q^2 > 2$ GeV^2 New Data from H1
  - Inclusive J/ψ electroproduction
    - Many (not all) aspects described by model of SCI
  - Inelastic J/ψ electroproduction
    - Improvements to theory needed

- Future

  soon: Inelastic $\psi(2s)$

  low z, resolved??

  Polarisation: Future, Luminosity Upgrade?