Heavy Vector Meson Production at HERA

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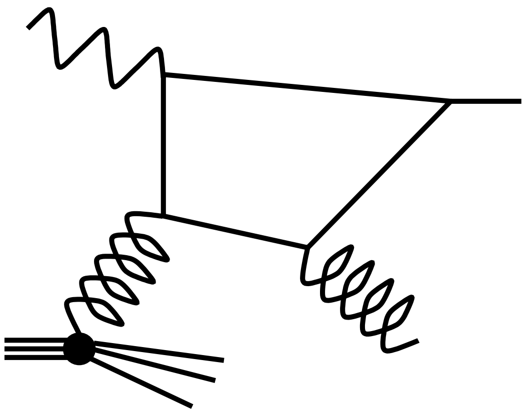
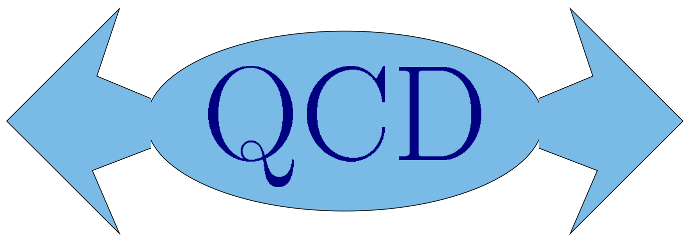
on behalf of the

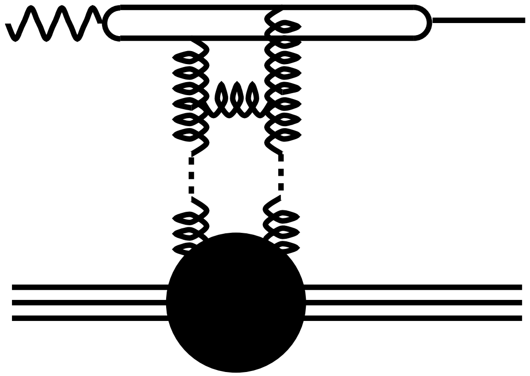
H1 and ZEUS Collaborations

inelastic J/ψ production

exclusive J/ψ, Υ production







NRQCD factorisation approach

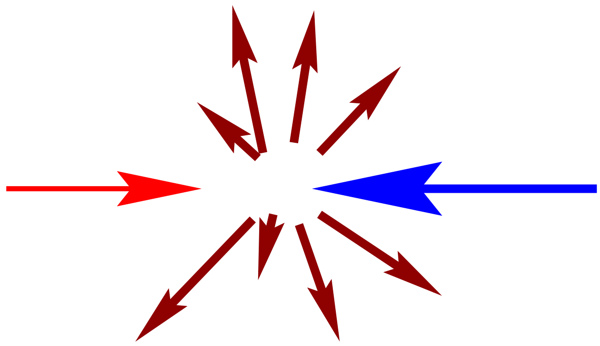
pQCD hard pomeron

The Next Half Hour

- The HERA Collider
- What Heavy Vector Meson Production Looks Like
- Inclusive J/ψ Production
- Exclusive J/ψ and Υ Production
- BFKL Signature in J/ψ Production ?
- Conclusions

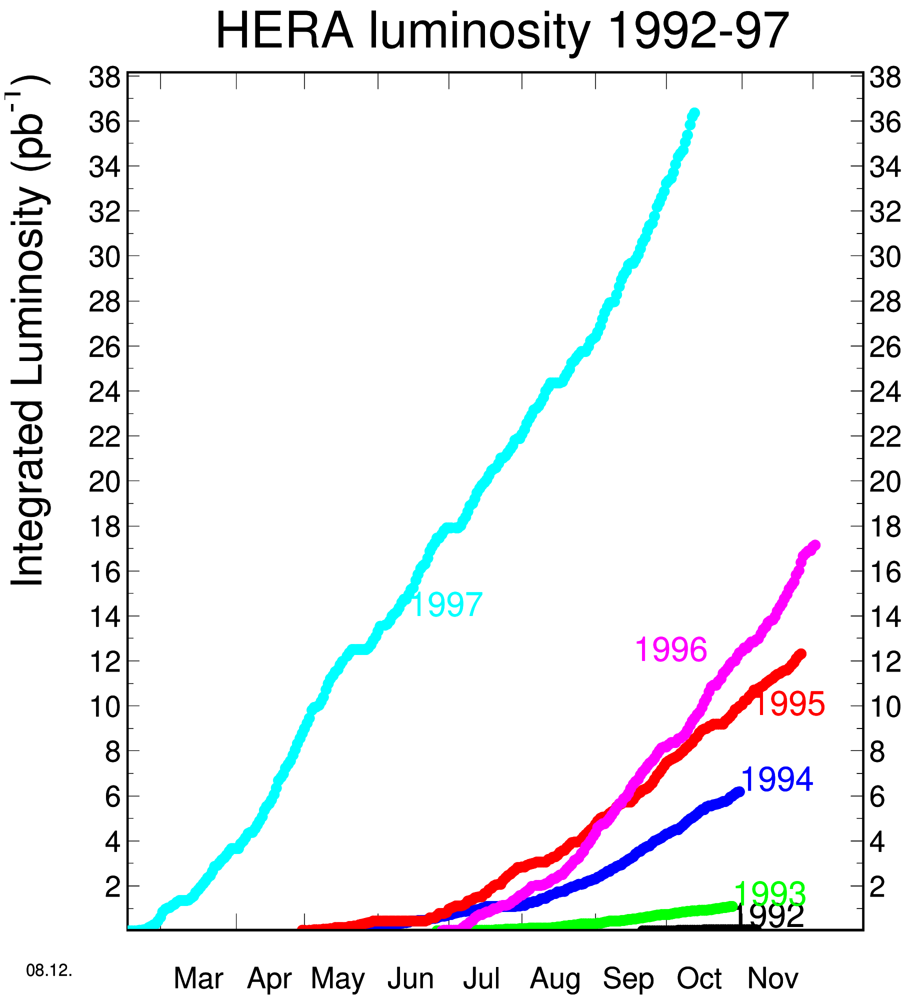
The HERA Collider

$E_{e+} = 27.5$ GeV



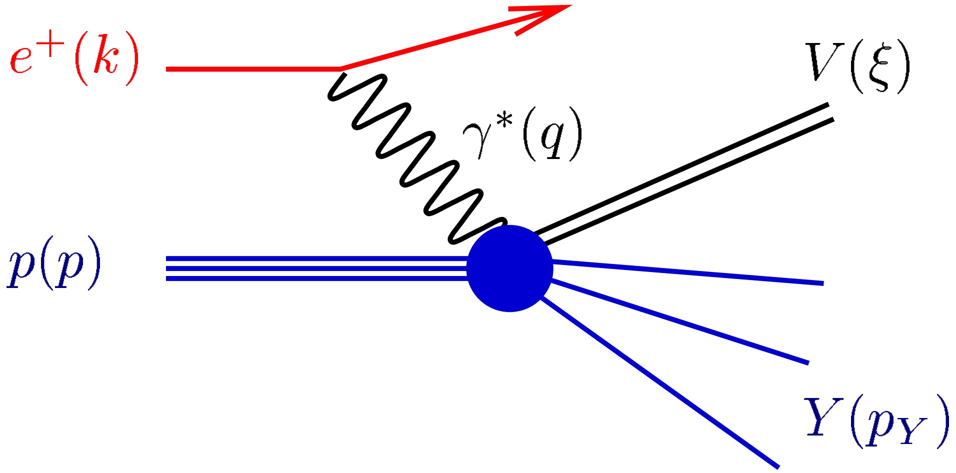
$E_p = 820$ GeV

$\sqrt{s} = 300$ GeV



- 1996-7 data results partially extant

Kinematics of Vector Meson Production



$Q^2 \equiv -q.q$ photon virtuality

$W^2 \equiv (p+q)^2$ $\gamma^* p$ collision energy

$z \equiv p.\xi / p.q$ elasticity

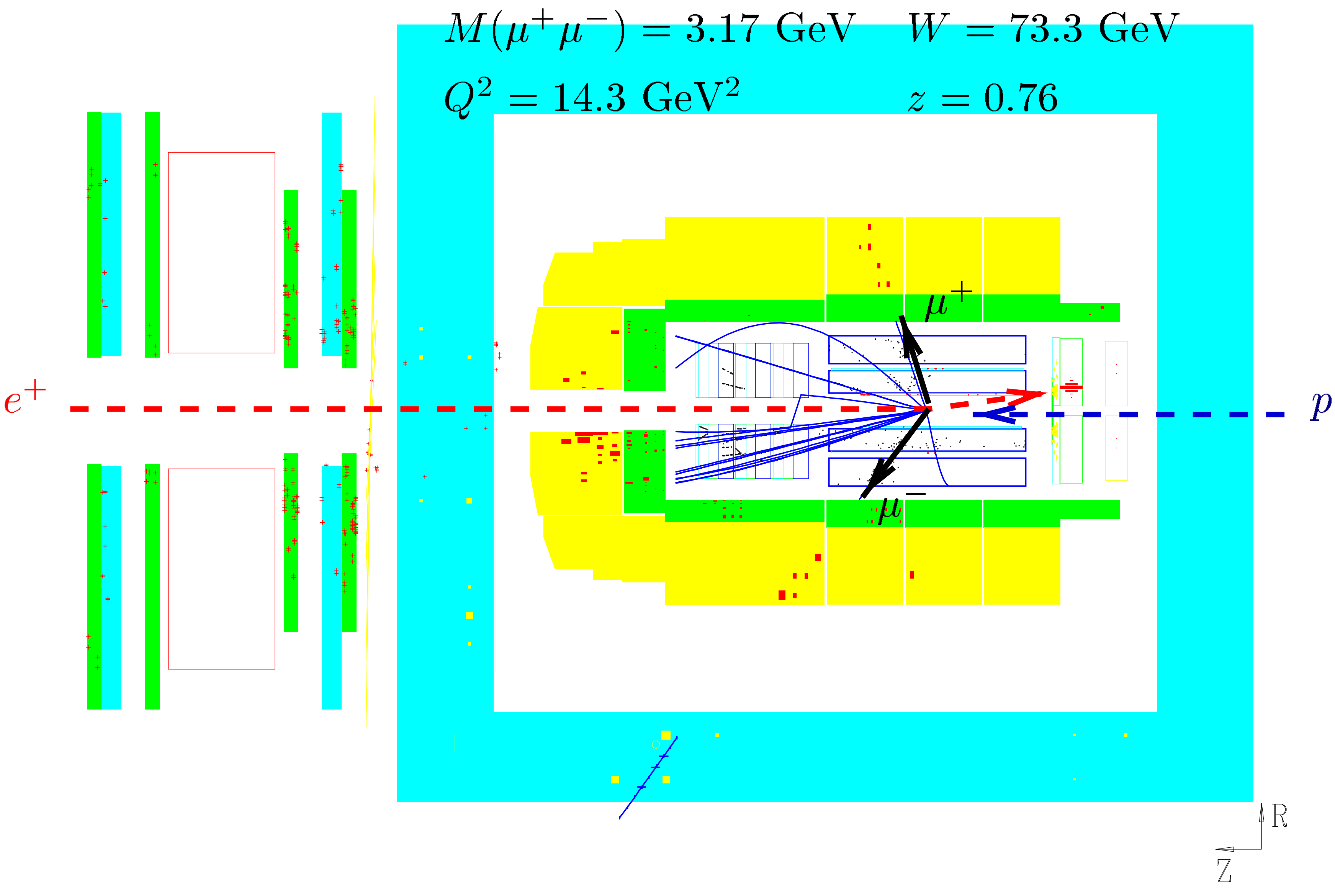
$t \equiv (\xi - q)^2$ momentum transfer

HERA as $\gamma^* p$ collider

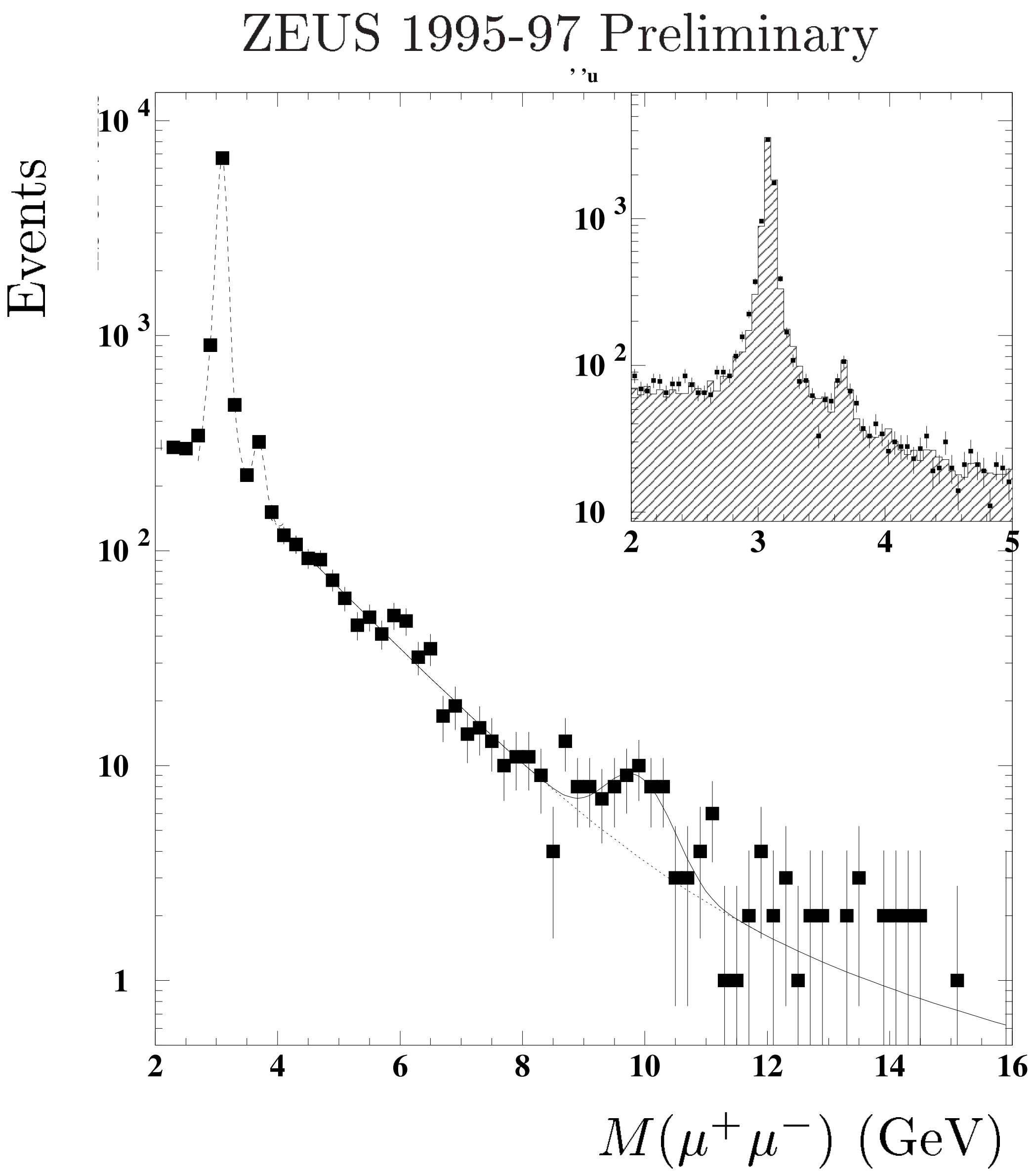
$$\sigma_{ep}(W_a < W < W_b, Q_a^2 < Q^2 < Q_b^2) = \int_{W_b}^{W_b} dW \int_{Q_a^2}^{Q_b^2} dQ^2 f_{\gamma/e}(W, Q^2) \sigma_{\gamma^* p}(W, Q^2)$$

$$Q^2 \to 0 \text{ GeV}^2 \longleftrightarrow \text{“photo-production”}$$

$ep \to eJ/\psi Y$ Event in the H1 Detector



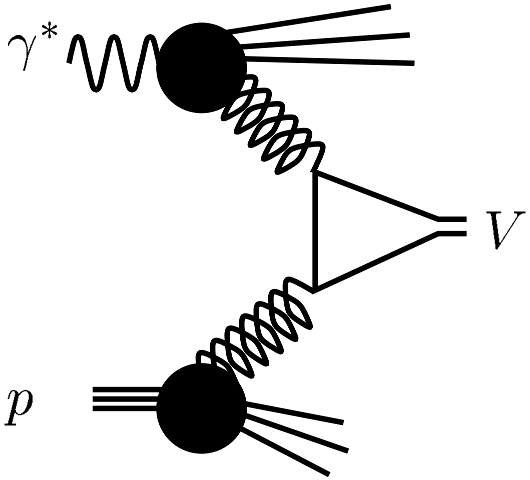
Di-muon Invariant Mass Distribution



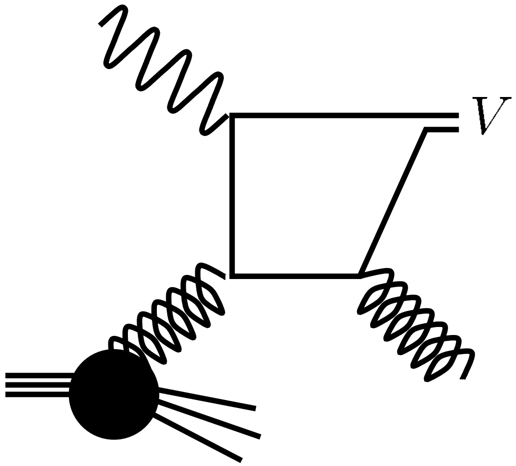
- J/ψ, $\psi(2S)$, Υ visible
- decays to e^+e^- also used

Production Model According to Elasticity

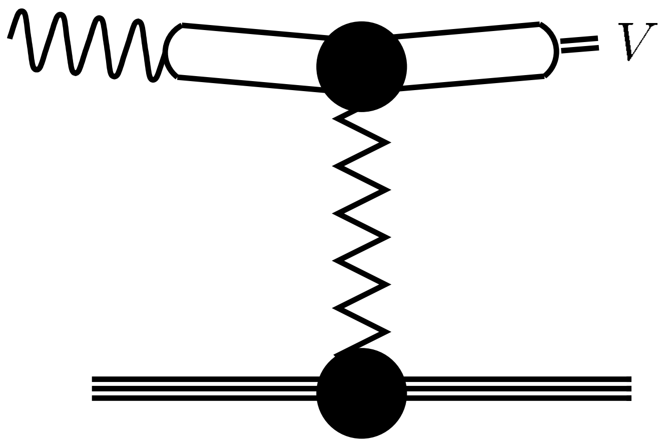
$z = 0.0$ $z = 1.0$



resolved γ



direct inelastic



exclusive

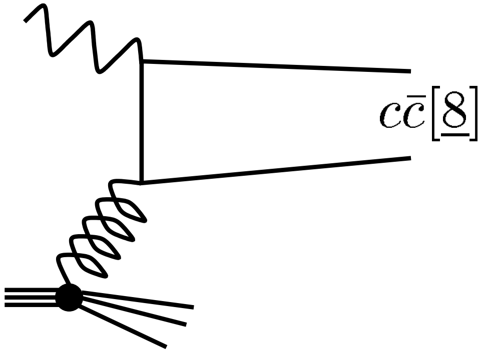
Model of Direct Inelastic J/ψ Production

NRQCD Factorisation Approach [Bodwin, Braaten, Lepage] :

$$d\sigma(\gamma^* p \to J/\psi Y) = \sum_n \quad d\hat{\sigma}(\gamma^* p \to c\bar{c}[n] Y') \quad \langle\, \mathcal{O}^{J/\psi}([n]) \rangle$$

pQCD

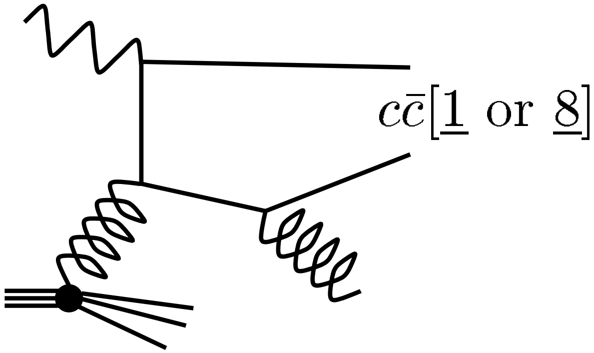
non-perturbative transition
$c\bar{c}[n] \to J/\psi +$



‘velocity scaling rules’
suppress $c\bar{c}[\underline{8}] \to J/\psi$

extracted from data fits

universal



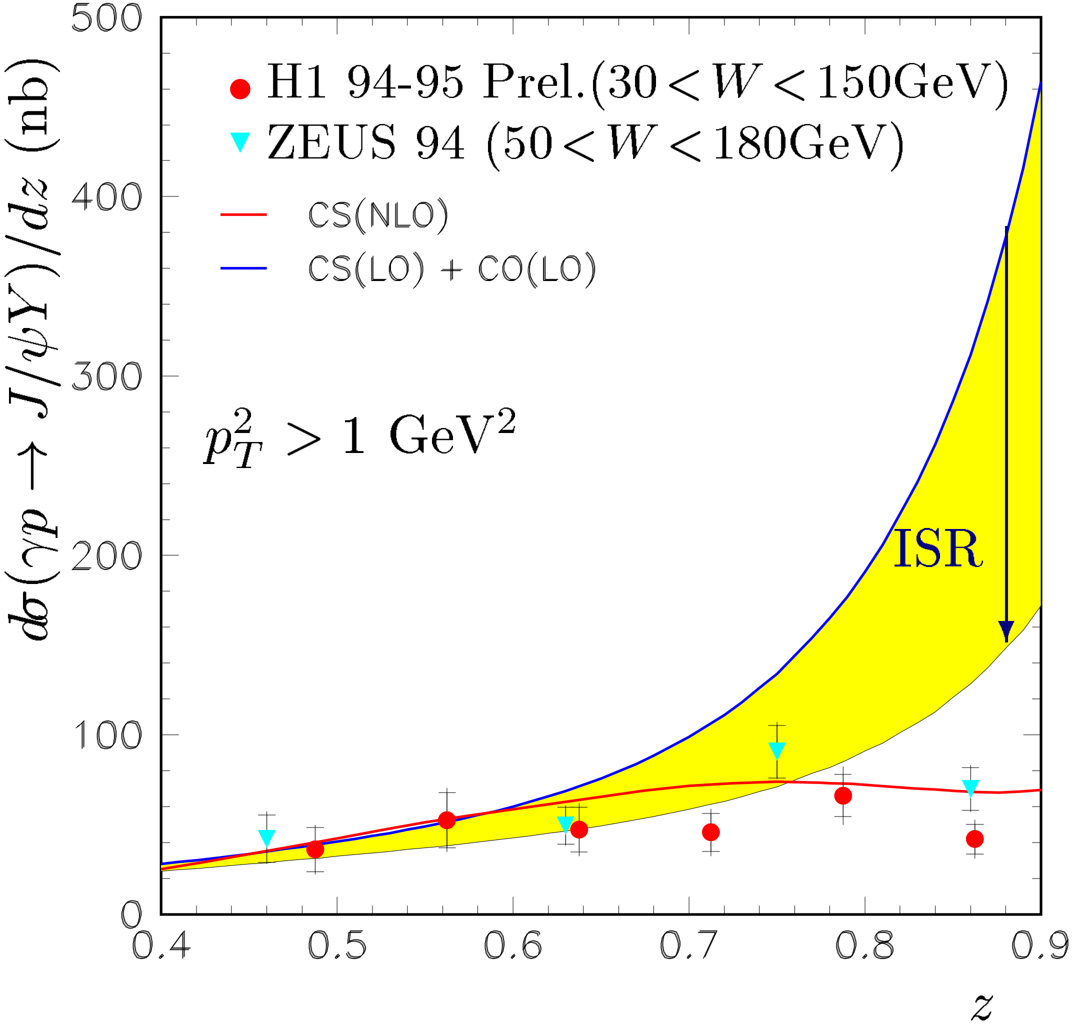
Issues of NRQCD Factorisation Approach

- Simultaneous description of HERA and TEVATRON data possible ?

- validity of factorisation
- size of colour octet ([$\underline{8}$]) contributions
- effects of initial state radiation and higher orders in α_S

- g(x) extraction possible ?

J/ψ Photoproduction: Elasticity Dependence of $\boldsymbol{\sigma}$



[calculation of Krämer]

- Colour Singlet ([1]):

$$\mathcal{O}\ (\alpha\alpha_S^3)$$
$$m_c = 1.4 \text{ GeV}$$
$$\Lambda_{\text{QCD}} = 300 \text{ MeV}$$

$\to$ reproduces data

- Colour Octet ([8]):

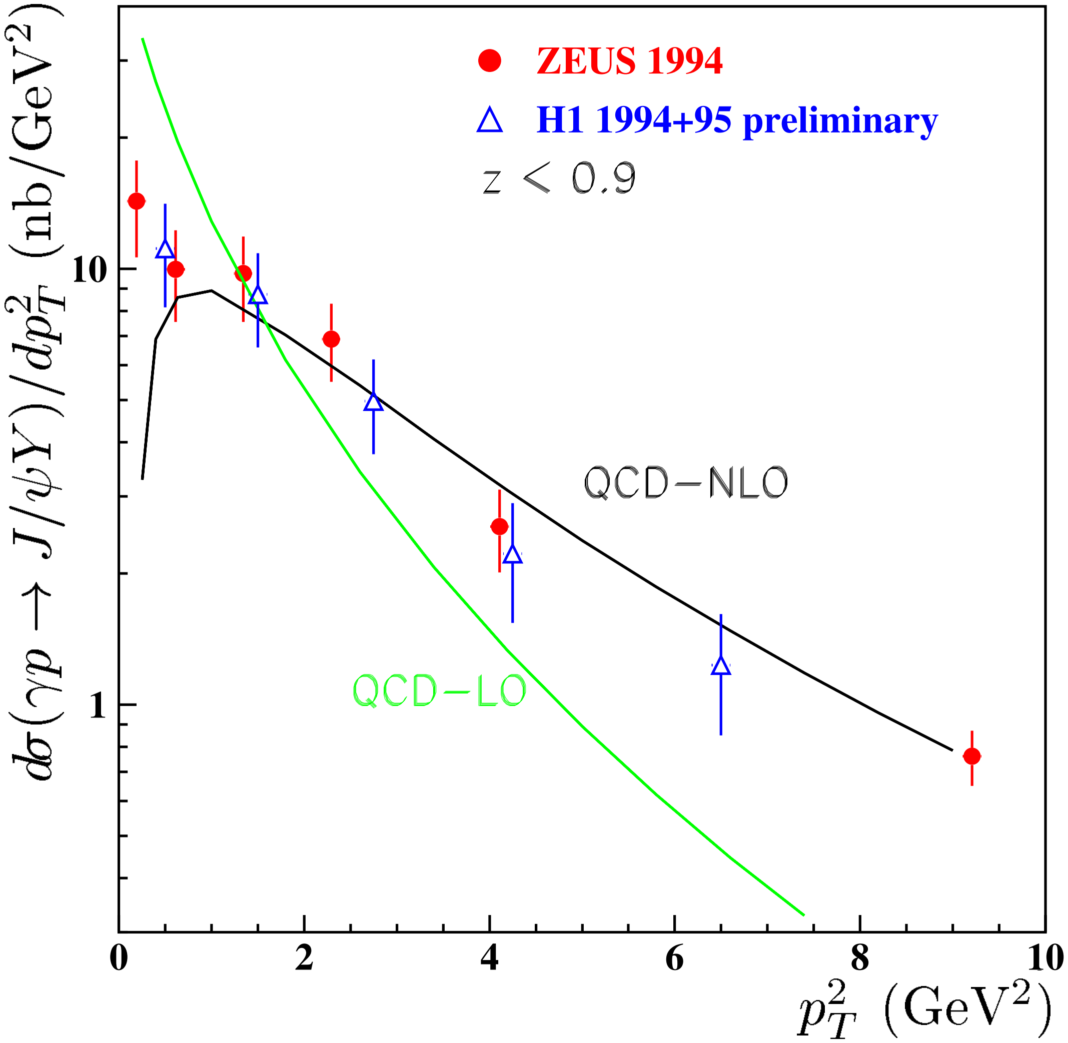
$$\mathcal{O}\ (\alpha\alpha_S^2)$$

$\to$ no sign

- Initial State g Radiation:

$\to$ simultaneous HERA and TEVATRON description possible

Photoproduction: p_T Dependence of σ



- Colour Singlet NLO:

  $\mathcal{O}\ (\alpha\alpha_S^3)$

  $m_c = 1.4$ GeV

  $\Lambda_{\rm QCD} = 300$ MeV

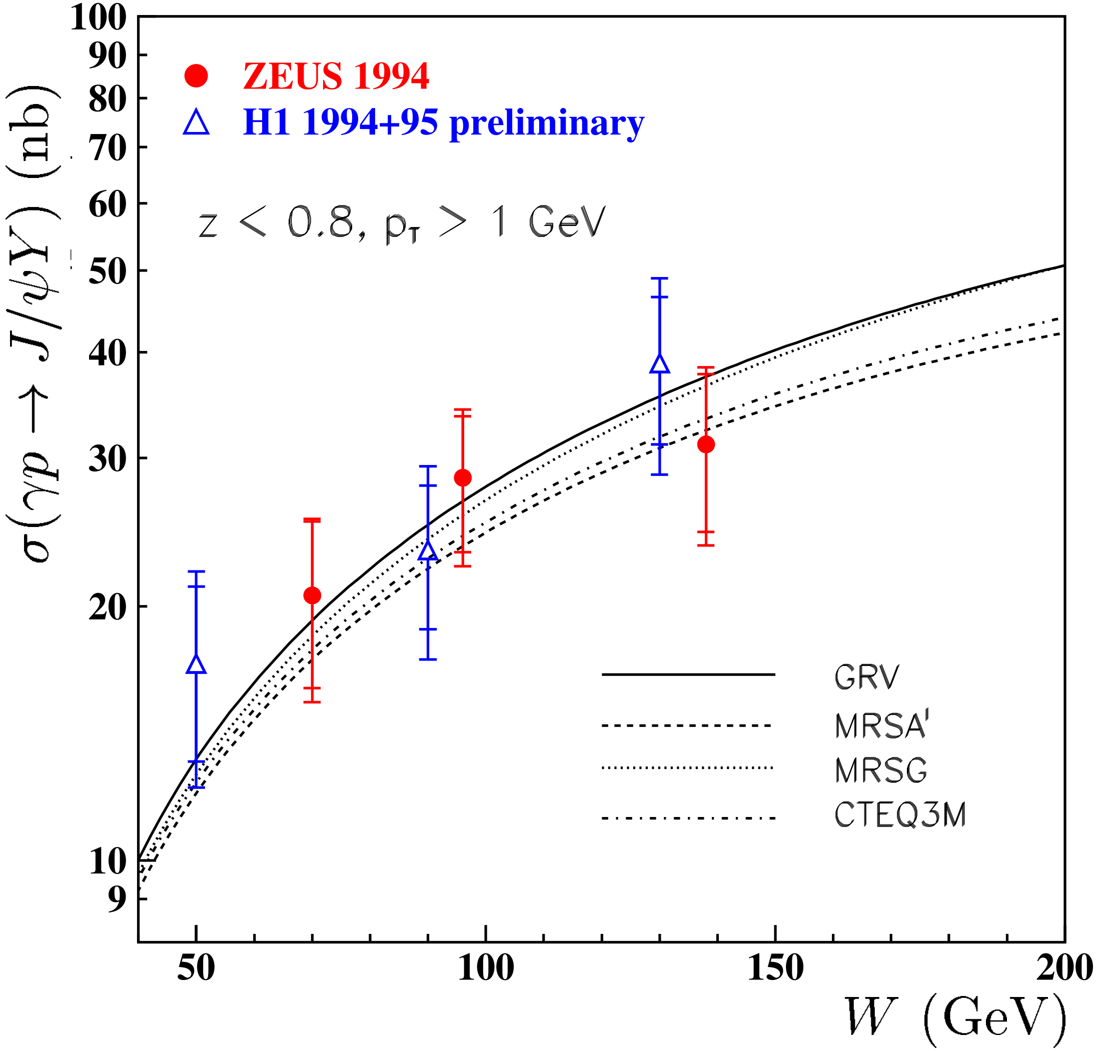
$\rightarrow$ reproduces data

- Colour Singlet LO:

  $\mathcal{O}\ (\alpha\alpha_S^2)$

$\rightarrow$ inadequate

Photoproduction: Energy Dependence of $\boldsymbol{\sigma}$



- Colour Singlet NLO:

  $\mathcal{O}\ (\alpha\alpha_S^3)$

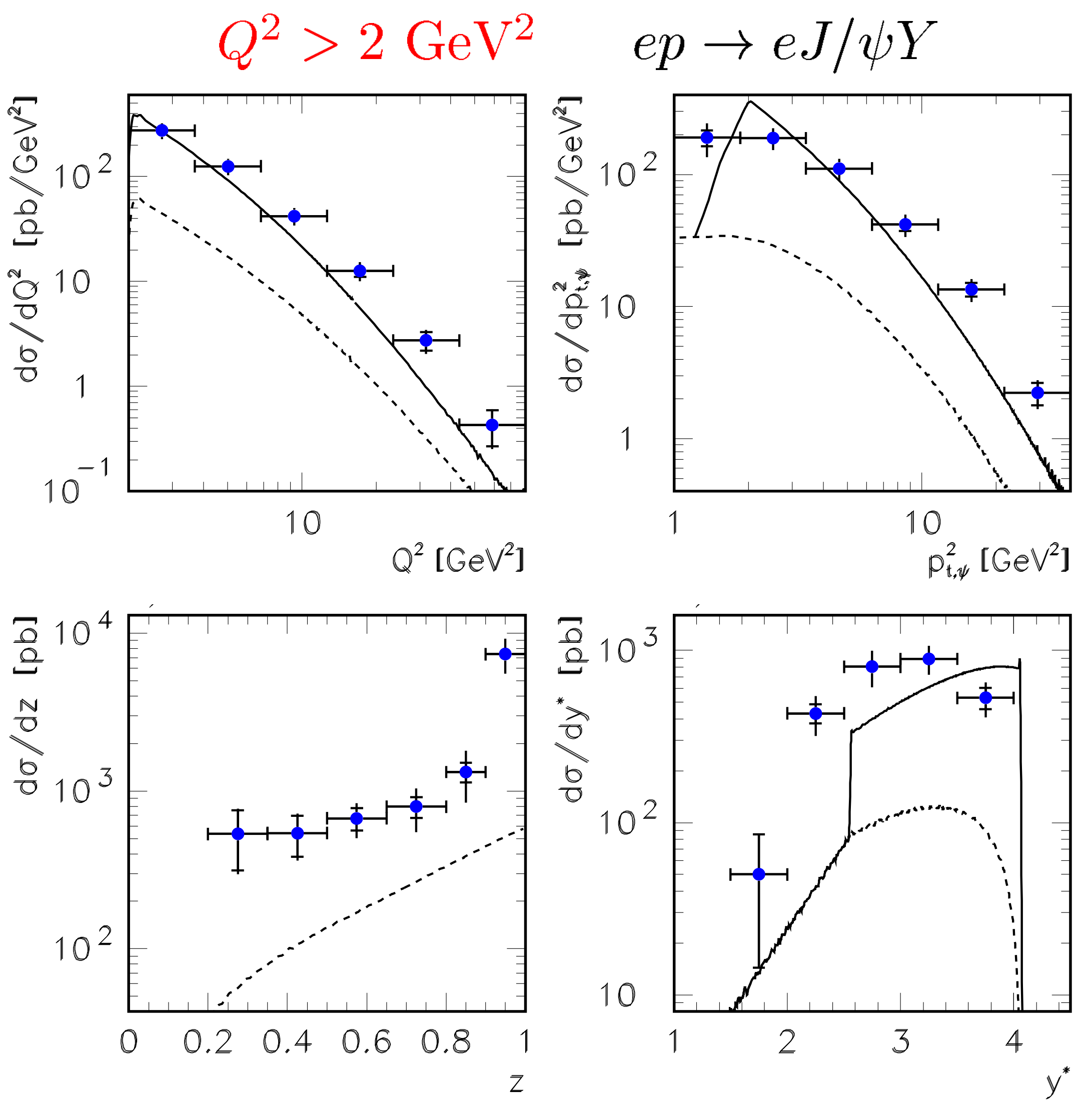
  $m_c = 1.4$ GeV

  $\Lambda_{\rm QCD} = 300$ MeV

$\rightarrow$ reproduces data

$\rightarrow$ little $g(x)$ dependence

$Q^2 > 2$ GeV^2: Differential Distributions



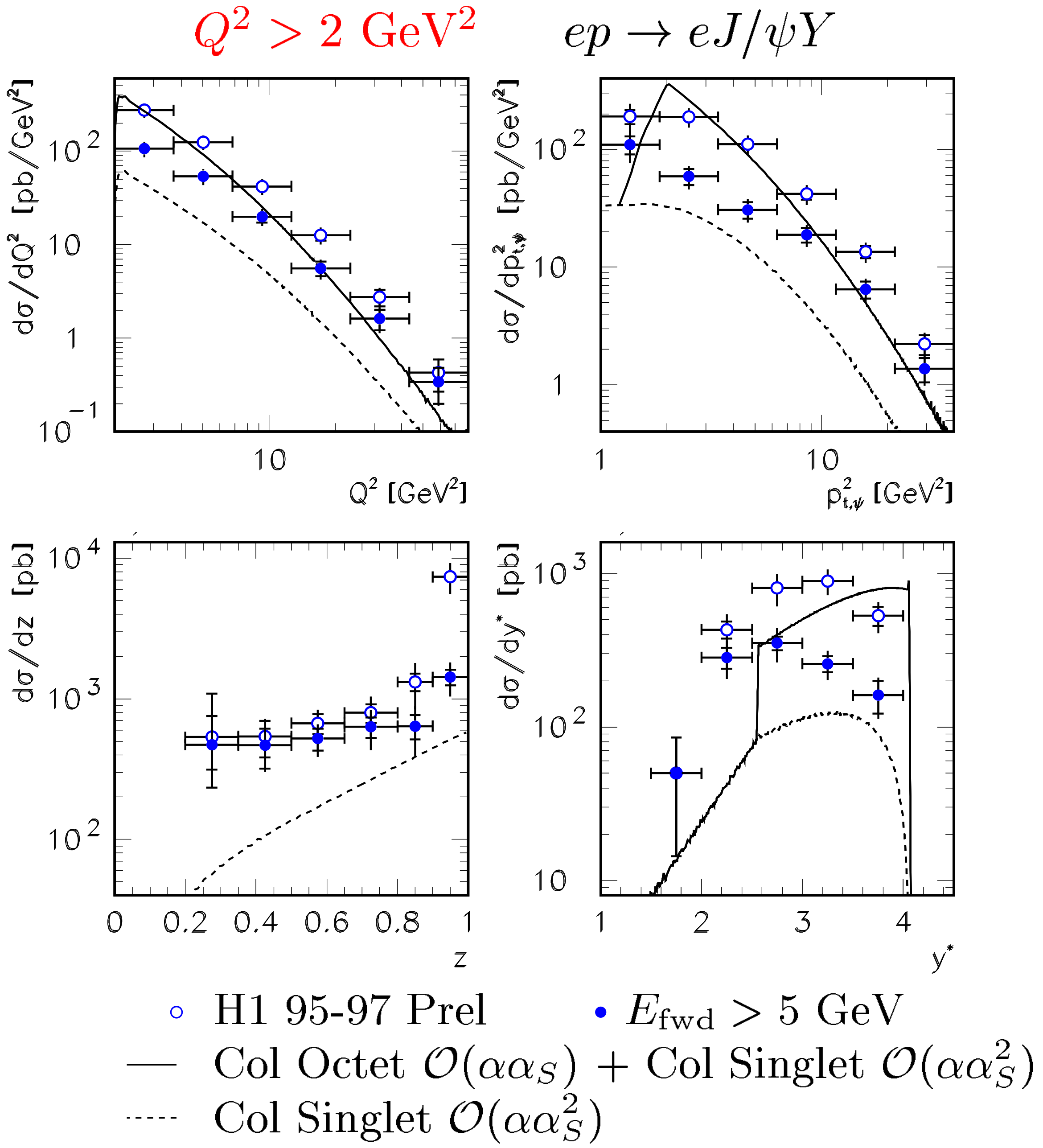
- H1 95-97 Preliminary
- — Col Octet $\mathcal{O}(\alpha\alpha_S)$ + Col Singlet $\mathcal{O}(\alpha\alpha_S^2)$
- ---- Col Singlet $\mathcal{O}(\alpha\alpha_S^2)$

[Calculation of Fleming and Mehen]

- CS $\mathcal{O}(\alpha\alpha_S^2)$ wrong in magnitude
- CO $\mathcal{O}(\alpha\alpha_S)$ recovers magnitude, but shapes wrong

- diffractive contribution present in data

$Q^2 > 2$ GeV^2: Differential Distributions



- suppress diffractive contribution in data with cut on energy in forward part of H1, $E_{\text{fwd}} > 5$ GeV
- model still describes data poorly

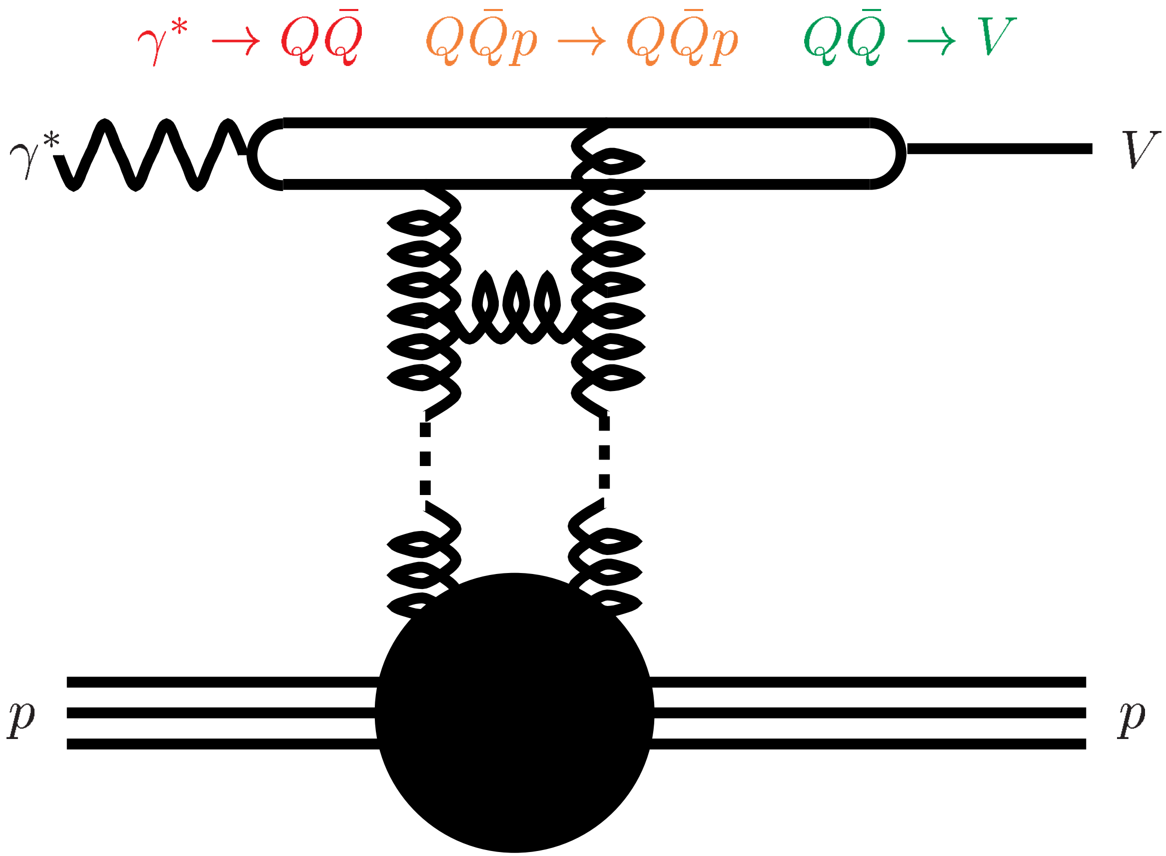
Conclusions of Inclusive J/ψ Production Studies

- photo-production described by $\mathcal{O}(\alpha\alpha_S^3)$ colour singlet alone
- no sign of significant colour octet contributions
- no decent description of $Q^2 > 2$ GeV^2 data in model, *but*
- non-leading orders in α_S important

further experimental enlightenment to come:

- J/ψ helicity studies
- resolved photon contribution
- associate $J/\psi\gamma$ production
- h_c production

QCD Picture of Exclusive Heavy VM Production



leading log Q^2 approximation:

$$d\sigma/dt(t=0) \sim x_g^2 g(x_g, \mu^2)^2$$

$$x_g = (M_V^2 + Q^2)/W^2 \approx 10^{-3}$$

$$\mu^2 = (M_V^2 + Q^2)/4$$

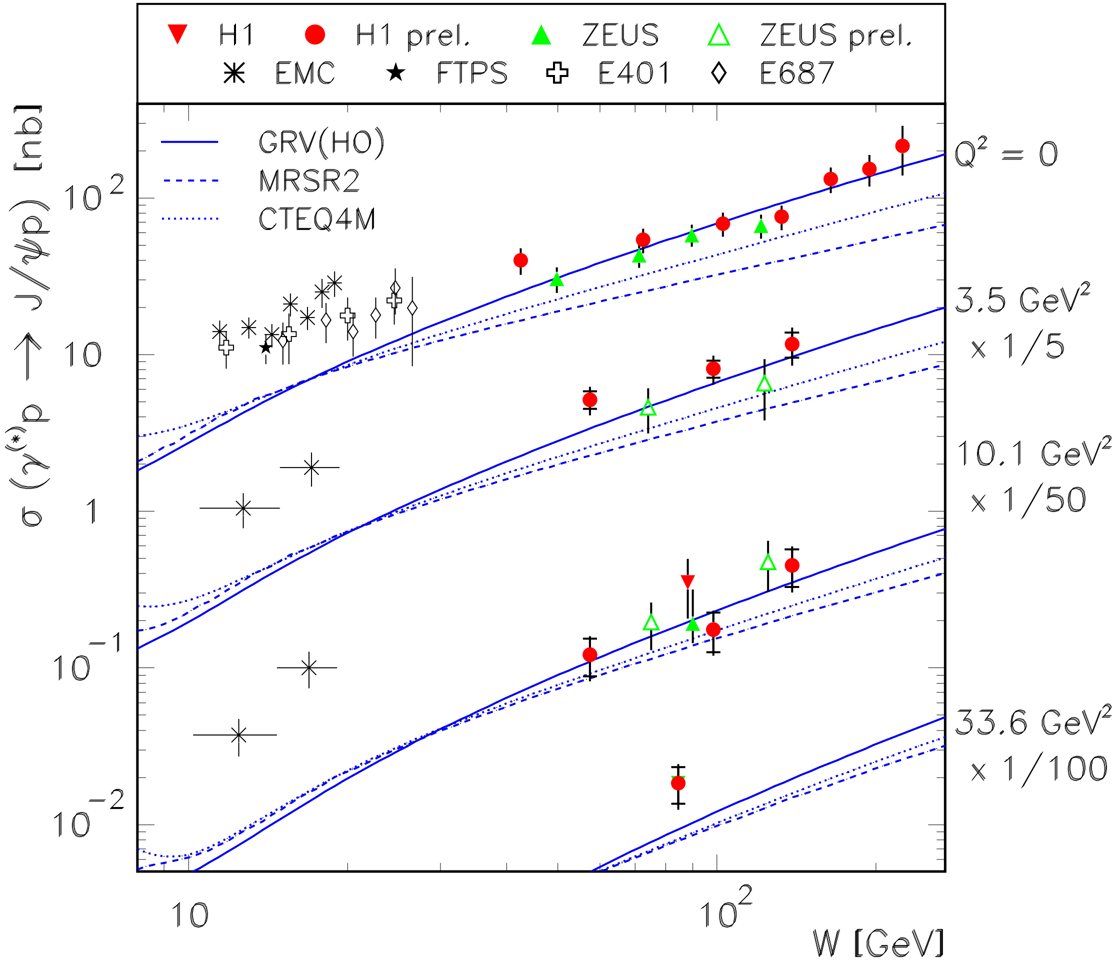
Issues in Exclusive Heavy VM Production

- Does the pQCD calculation work ?
- Can we extract the gluon density in the proton ?

- Connection to phenomenology of soft hadronic physics:

hard QCD $I\!\!P$omeron		soft $I\!\!P$omeron phenomenology
heavy VM production light VM's at $Q^2 >$ few GeV^2	$\longleftrightarrow$	total hadronic x-sections light VM photo-production

Energy and Q^2 Dependence of σ



- Data:

fast rise of σ with W

- pQCD:

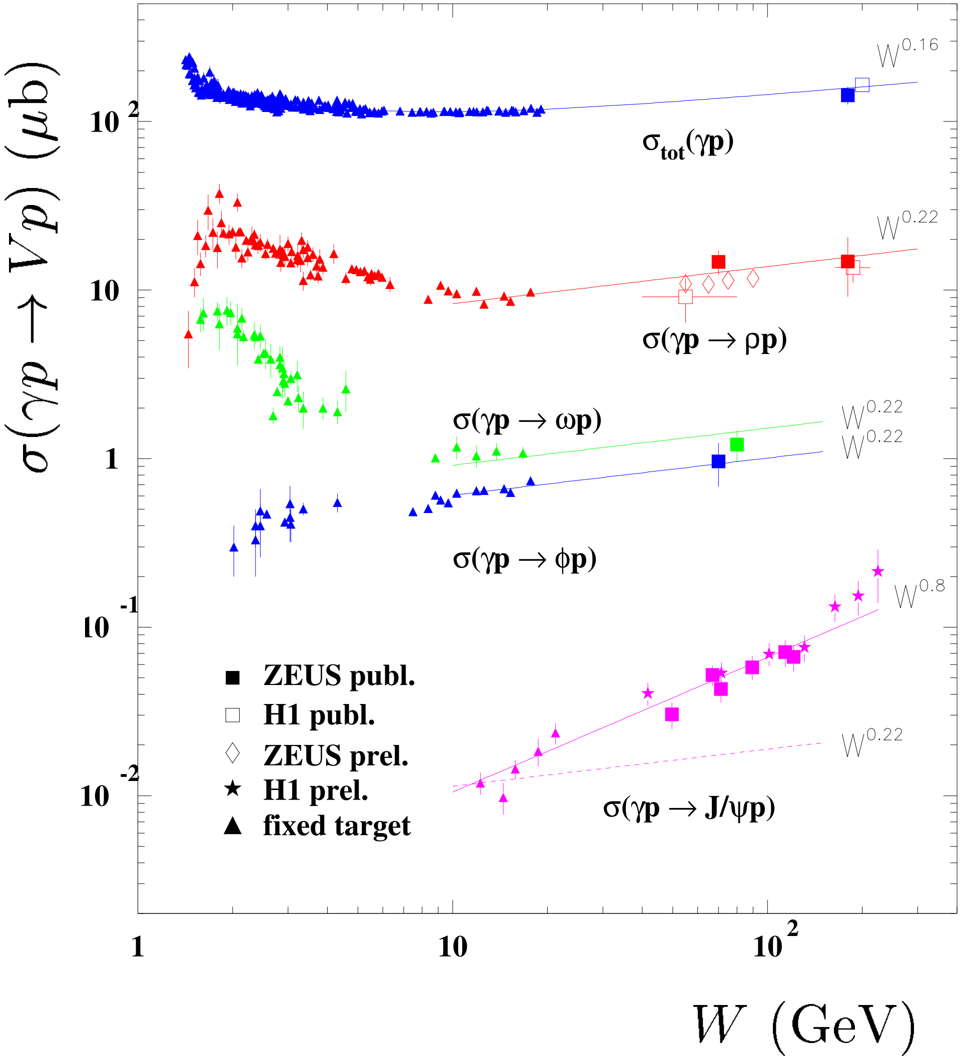
qualitatively OK for HERA energies

rise of σ reflects gluons with small x_g

recall $x_g = (M_{J/\psi}^2 + Q^2)/W^2$

[pQCD calculations of Frankfurt, Koepf, Strikman]

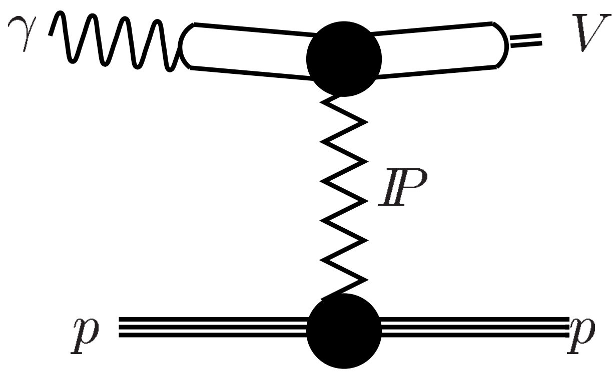
Photoproduction: Comparison with Light VM's



- light VM's:

universal shallow W dependence

→ soft $I\!P$omeron exchange



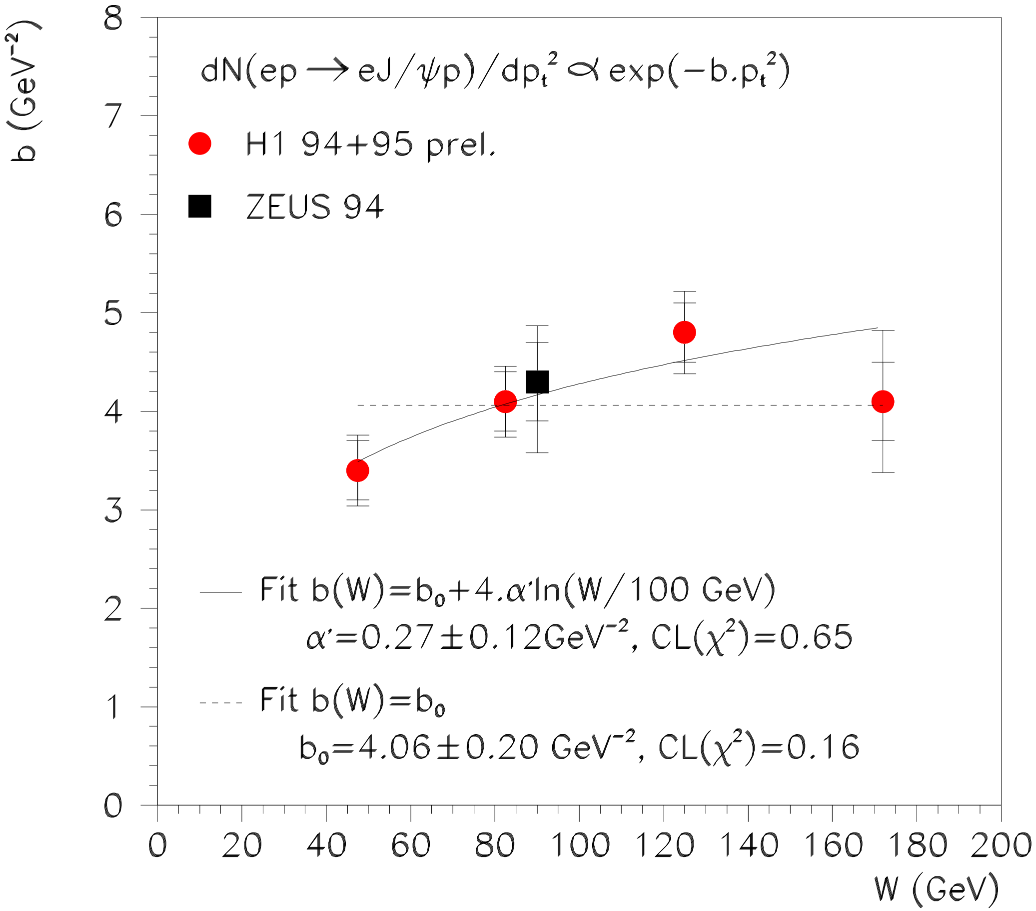
- J/ψ:

steep W dependence

→ hard $I\!P$omeron exchange

conseqence of hard scale

J/ψ Photoproduction: 'Shrinkage' ?



- $dN/dp_t^2 \sim \exp(-b(W).p_t^2)$
- $I\!P$ exchange models:

$\rightarrow b(W) = b_0 + 4.\alpha' \log W/W_0$

- soft $I\!P$: $\alpha' \approx 0.25$ GeV^{-2}

$\rightarrow$ 'shrinkage'

Q. does the hard $I\!P$omeron shrink ?

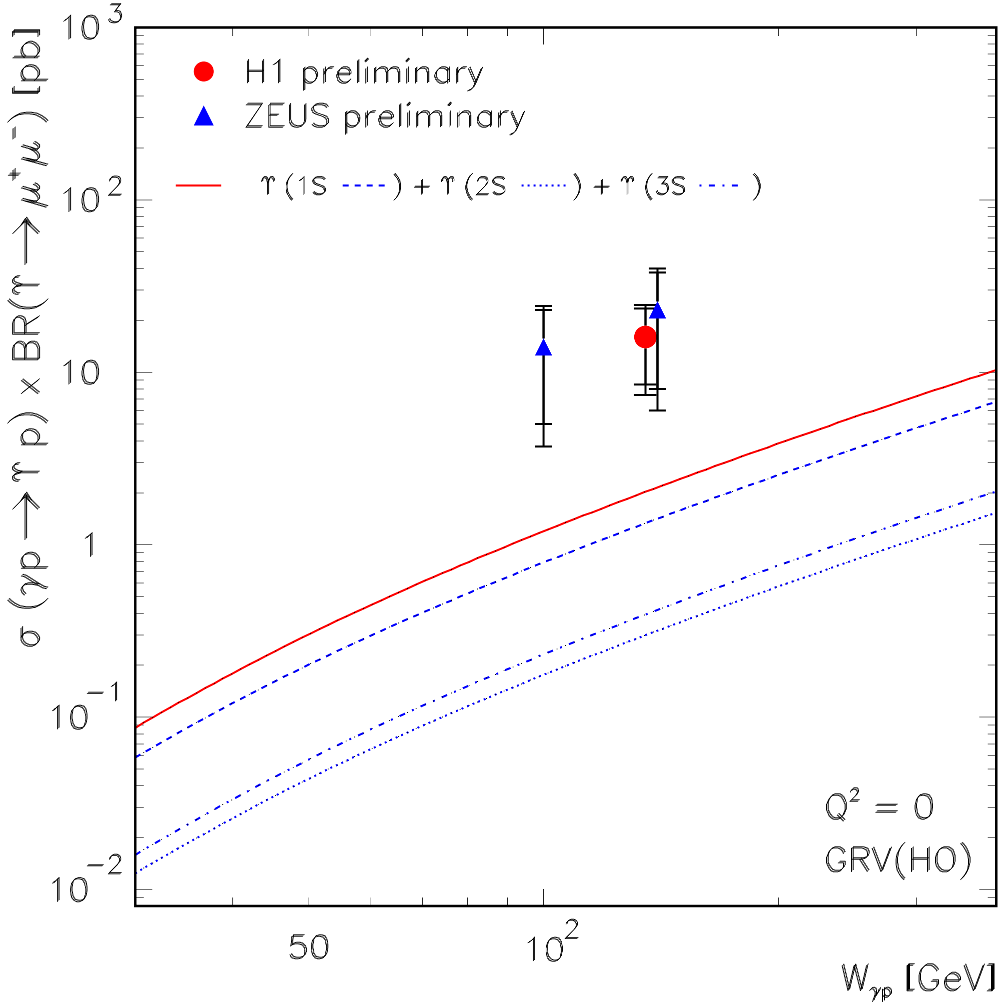
- fit to HERA data:

$\rightarrow \alpha' = 0.27 \pm 0.12$ GeV^{-2}

- $\alpha' = 0$ also compatible

A. don't know yet

Photoproduction of Υ Mesons



Υ(1S),(2S),(3S) indistinguishable

- ZEUS: 1995-7 data, 43.3 pb^{-1}

$Q^2 < 1\ \mathrm{GeV}^2$

$\mathrm{N}(\Upsilon \to \mu^+\mu^-) = 32 \pm 10$

- H1: 1994-7 data, 34.5 pb^{-1}

$Q^2 < 2\ \mathrm{GeV}^2$, $70 < W < 270$ GeV

$\mathrm{N}(\Upsilon \to \mu^+\mu^-) = 25 \pm 8$

- $\sigma(\Upsilon) \sim \sigma(J/\psi)/150$
- pQCD prediction too low

[pQCD calculations of Frankfurt, Koepf, Strikman]

Conclusions on Exclusive Heavy VM Production

- hard scale, M_V, (significant Q^2 for light VM's) $\Rightarrow$ hard $I\!\!P$omeron:

$\rightarrow$ steep energy dependence of σ

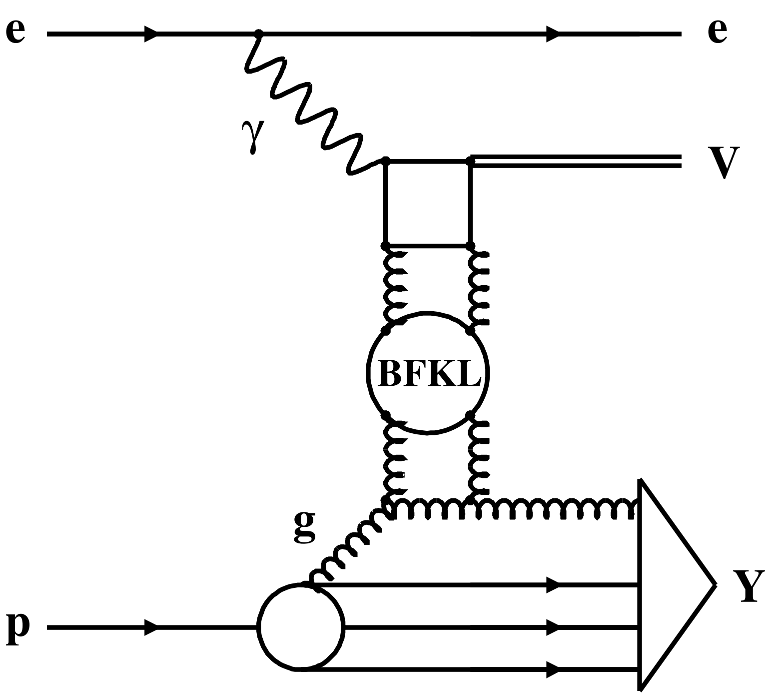
$\rightarrow$ do we see shrinkage of the forward peak ?

- pQCD looks promising for J/ψ
- but what about Υ ?

Still to come:

- results on J/ψ photoproduction from 1996-7 data
- many more Υ in the new millenium

J/ψ Photoproduction at High $|t|$: a BFKL Calculation



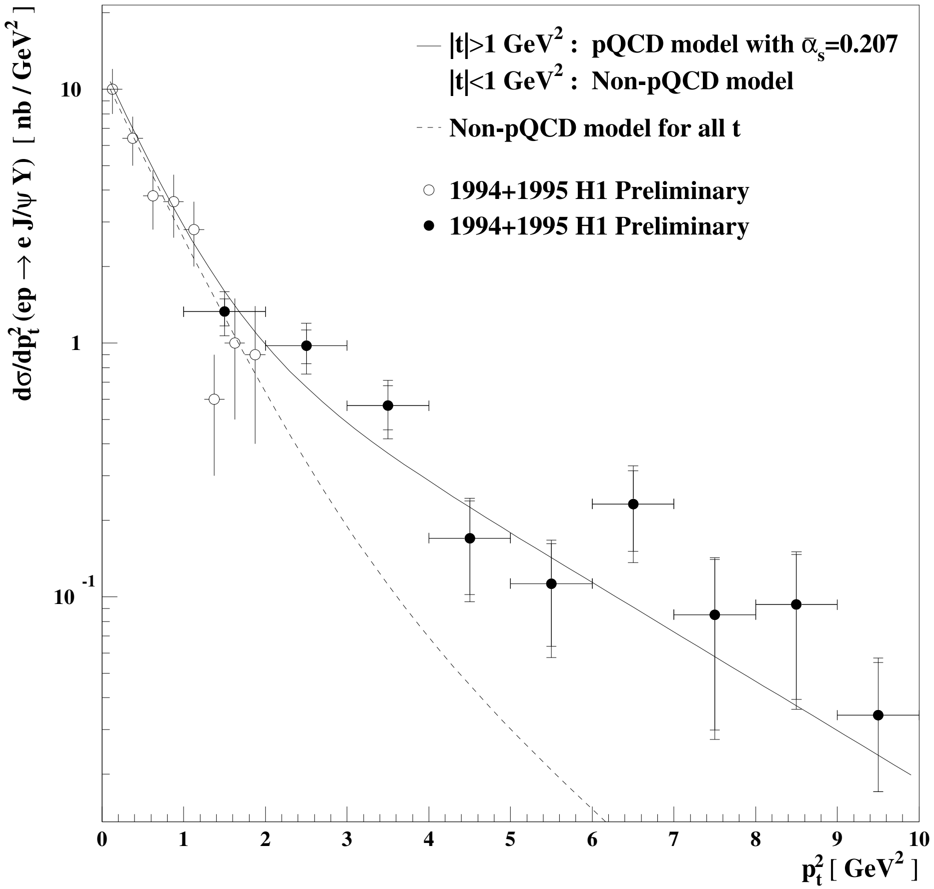
pQCD calculation for $\gamma p \to VY$ for:

$z > 0.95$ 'proton dissociation'
$|t| > 1$ GeV^2 large momentum transfer

exchange calculated in BFKL formalism

predicts σ, $d\sigma/dt$, $d\sigma/dW$
one free parameter $\bar{\alpha_S}$

J/ψ Production with p Dissociation at Large $|t|$: $d\sigma/dp_t^2$



$30 < W < 150$ GeV, $Q^2 < 4$ GeV^2

$p_t^2 \approx |t|$

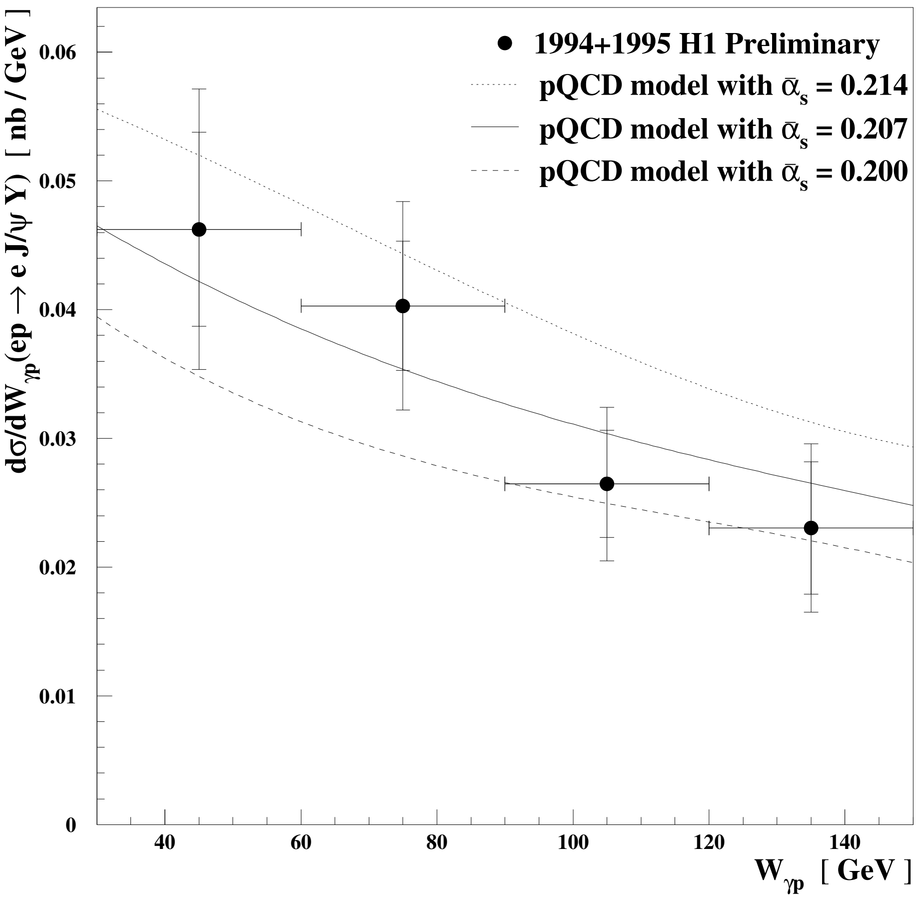
- observe:

$\rightarrow$ p_t^2 tail above simple exponential

$\rightarrow$ described by pQCD calculation for $p_t^2 > 1$ GeV^2

[calculation by Forshaw]

J/ψ Production with p Dissociation at Large $|t|$: $d\sigma/dW$



$|t| > 1.0\ \mathrm{GeV}^2$, $Q^2 < 4\ \mathrm{GeV}^2$

- observe:

$\rightarrow$ good description by pQCD calculation

- conclude:

$\rightarrow$ significant yield of J/ψ with proton dissociation at $|t| > 1\ \mathrm{GeV}^2$

$\rightarrow$ impressive description of data by LO pQCD calculation a la BFKL

Summary

Measurements:

- J/ψ: inelastic and exclusive — increasing ranges in energy, photon viruality, momentum transfer
- Υ: first observation and cross-section determination
- future: many more results to come

Understanding QCD:

- J/ψ inelastic: progress understanding HERA and TEVATRON data simultaneously
- J/ψ, Υ exclusive: pQCD calculations promising

the experimental observations show the way forward