Gluons in the Proton and Charm and Charmonium Production in DIS

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- Introduction
- Elastic J/ψ and Diffractive $\psi(2S)$ Production in DIS
- Inelastic and Inclusive Production of J/ψ in DIS
- Gluon Density $\boldsymbol{x\,g(x,\mu)}$ from Open Charm
- Conclusions

J/ψ Production at HERA

$$z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} = \frac{E_\psi}{E_\gamma}$$

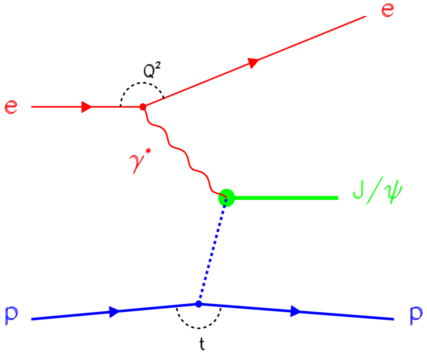
in p rest frame

Diffractive

- Elastic

$z \simeq 1$

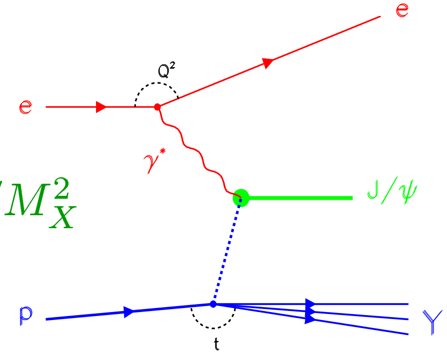
$M_X = m_p$



- p diffractive dissociation

$z \simeq 1$

small M_X, $\sim 1/M_X^2$



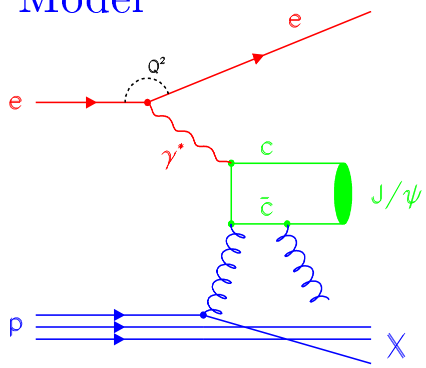
"Inelastic"

- Mainly Photon Gluon Fusion
- Colour Singlet Model

medium z

CSM in NLO

describes γp



- NRQCD Factorization approach

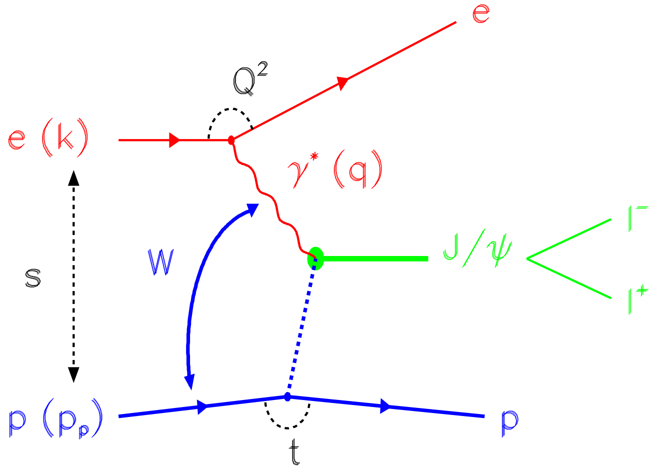
$\rightarrow$ Colour Octet states (large z ?)

$\rightarrow$ additional parameters (CO ME; universal ?)

. . . + resolved (small z, negligible in DIS)
. . . + B decays (small z, negligible)

Elastic J/ψ Production in ep Scattering

Vectormeson production analyzed in terms of



Q^2	$:=$	$-q^2$	e four-momentum transfer^2
W^2	$:=$	$(p_p + q)^2 \simeq Q^2/x$	Mass^2 of had. final state
t	$\simeq$	$-p_{t,p}^2$	p four-momentum transfer^2

. . . and decay angles

HERA constraint: $\sqrt{s} \simeq 300$ GeV $\boxed{Q^2 \simeq x\, y\, s}$

$\Longrightarrow$

m_c large

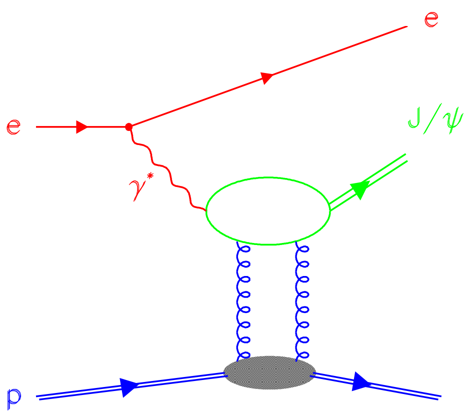
$\Longrightarrow$

Q^2 large

$\Longrightarrow$

$|t|$ large

$\Longrightarrow$



Quantitative description within perturbative QCD

The phenomenological (soft) Pomeron:

$$\frac{d\sigma}{dt} \sim e^{-b|t|} \left(\frac{W}{W_0}\right)^{2(\alpha_P(t)-1)} , \quad \alpha_P \simeq 1.08 + 0.25t$$

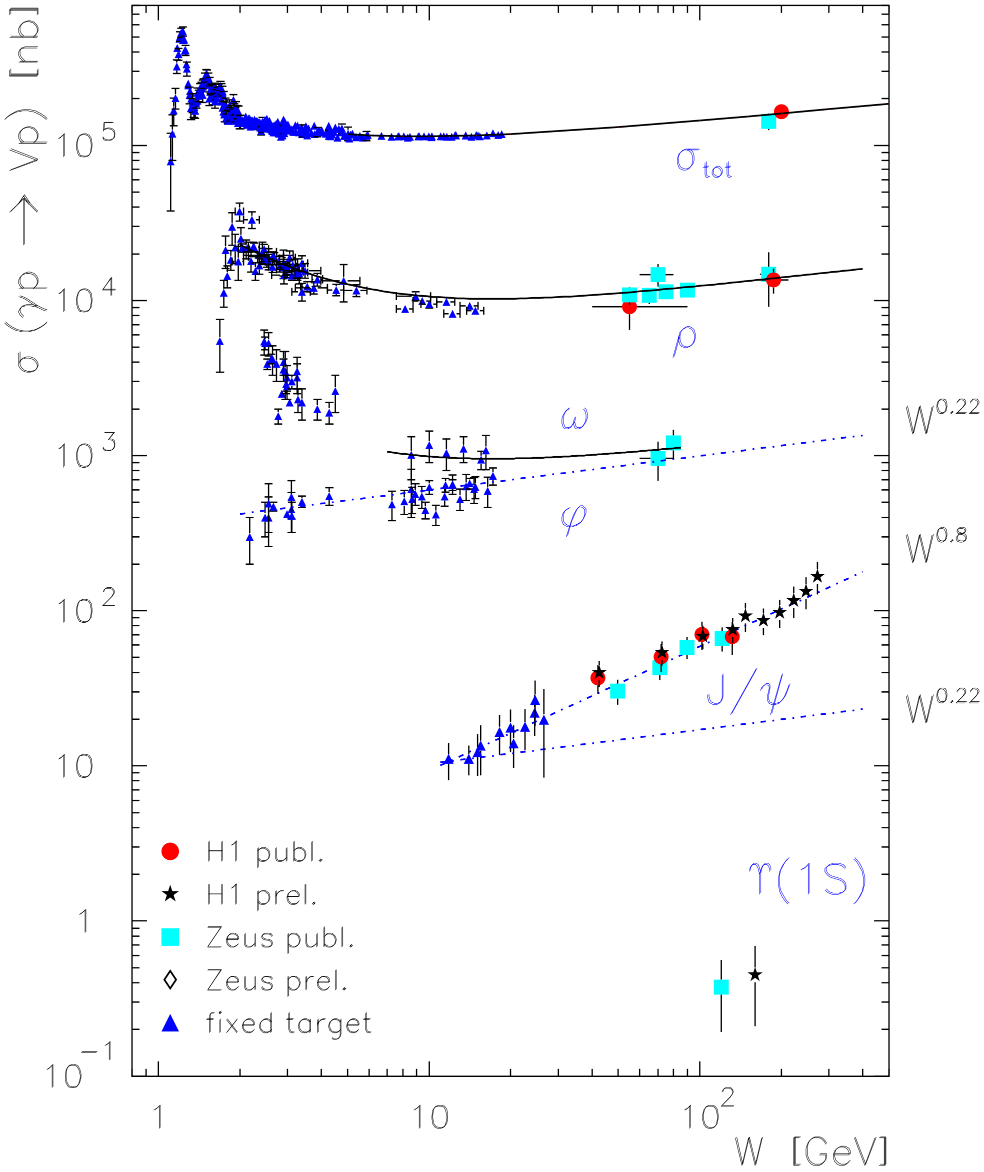
$$\left.\frac{d\sigma}{dt}\right|_{t=0} \sim W^{0.22} , \quad b = b(W_0) + 2\alpha' \ln\left(\frac{W^2}{W_0^2}\right)$$

p1. Steeper rise of $\sigma_{\gamma p}(W)$, driven by $x\,g(x)$

p2. Absence of shrinkage ($\alpha' \simeq 0$)

p3. Universal t dep., $b \simeq 4 - 5\,\text{GeV}^{-2}$

Elastic Vectormeson Photoproduction



HERA data: $W^{0.80\pm0.10}$ (H1 Prel.)

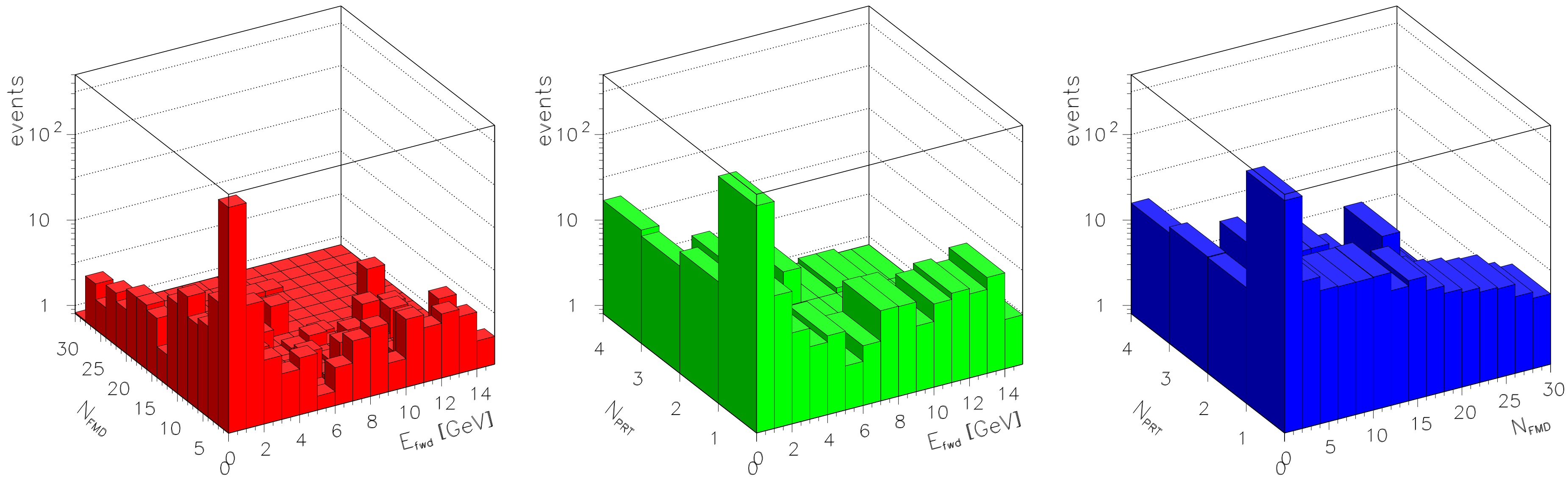
J/ψ photoproduction incompatible

with "soft" Pomeron

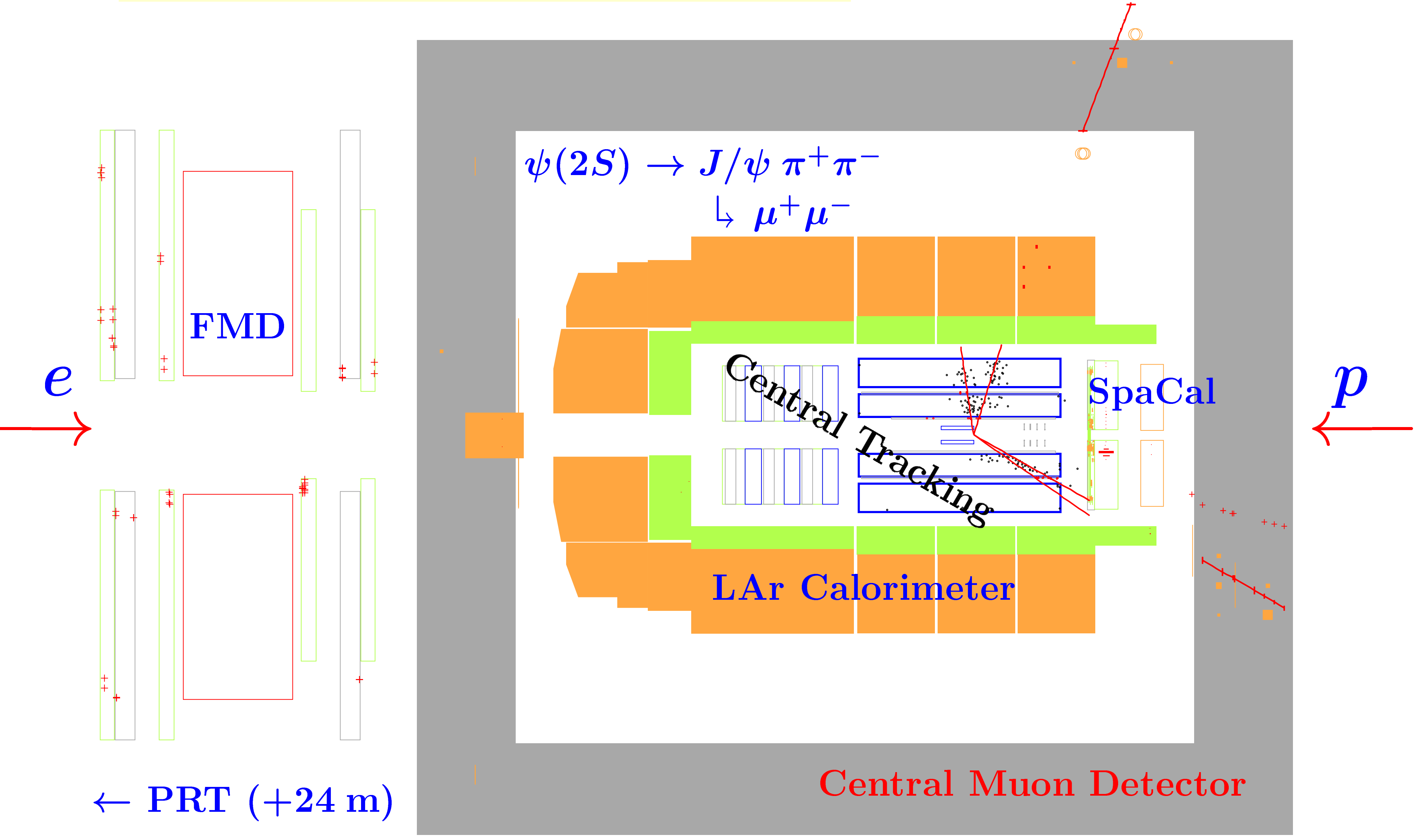
$\Longrightarrow$ Two Pomerons ???

J/ψ Production in H1

- Use leptonic decay modes: $J/\psi \to \mu\mu$, $J/\psi \to ee$, $\psi(2S) \to J/\psi\,\pi^+\pi^-$
- Diffractive: Require "empty" events: no significant activity except VM (and possibly scattered e^+)
- Two distinct regimes: Untagged/tagged photoproduction, $Q^2 \lesssim 1\,\mathrm{GeV}^2$, and DIS, $Q^2 \gtrsim 2\,\mathrm{GeV}^2$
- Forward detectors allow to separate $ep \to eVp$ from $ep \to eVY$ — "tagging" down to $M_X \simeq 1.6\,\mathrm{GeV}$



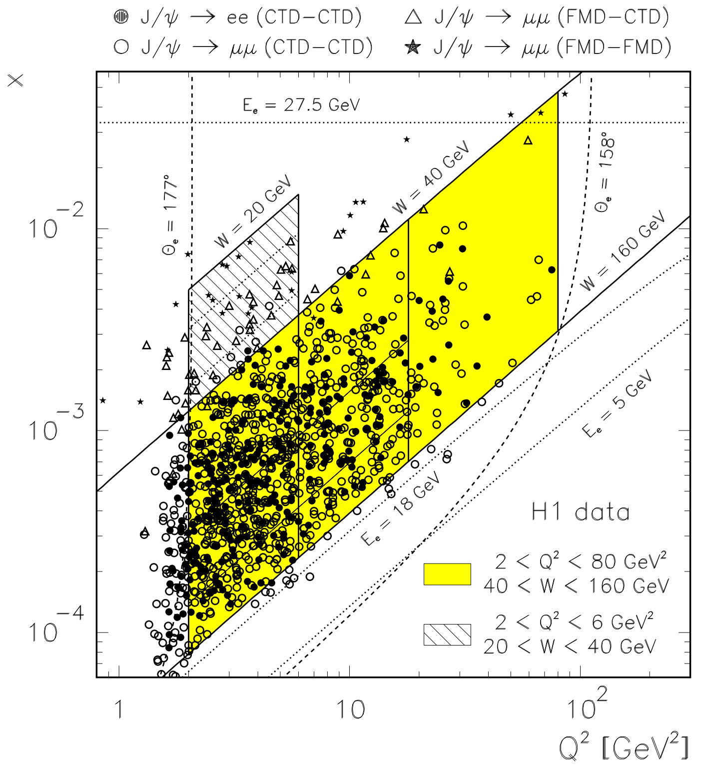
Candidate Event for $\psi(2S)$ Production

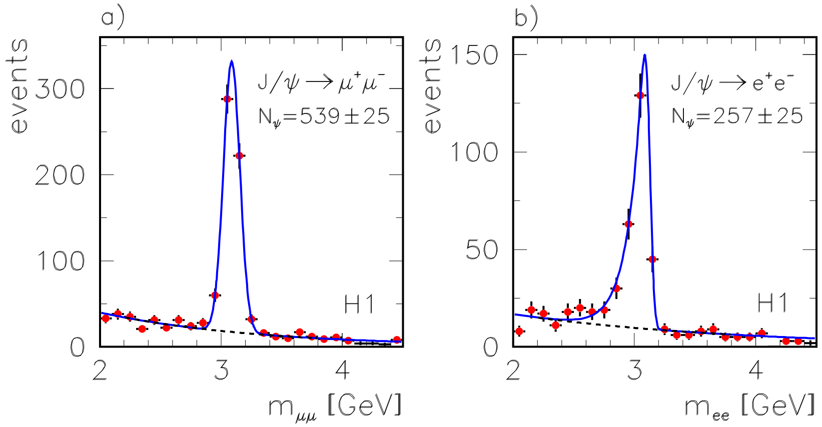


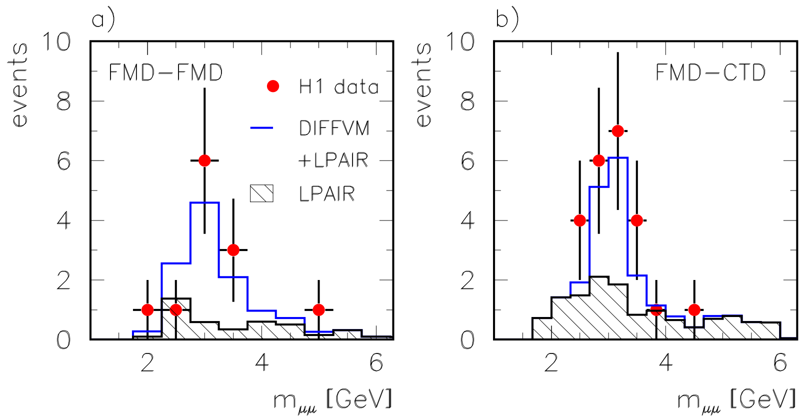
Elastic J/ψ Production in DIS, $J/\psi \to \mu^+\mu^-$ and e^+e^-

- Extend previous analyses: more data, larger kinematic reach
- $\int \mathcal{L}dt \simeq 27\,\mathrm{pb}^{-1}$ from 1995-97
- Kinematic range:

$$2 < Q^2 < 80\ \mathrm{GeV}^2$$
$$25 < W < 160\ \mathrm{GeV}$$

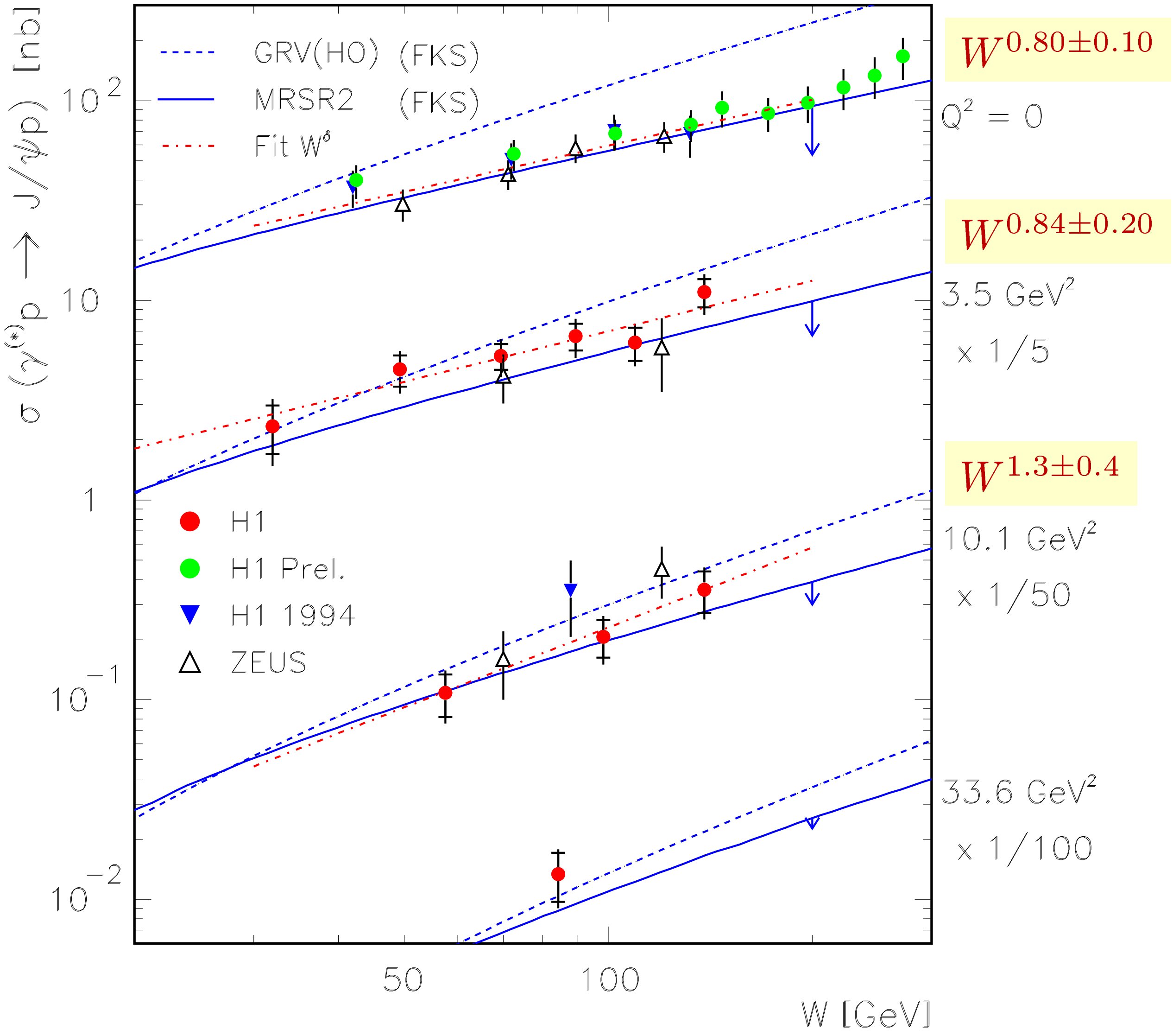






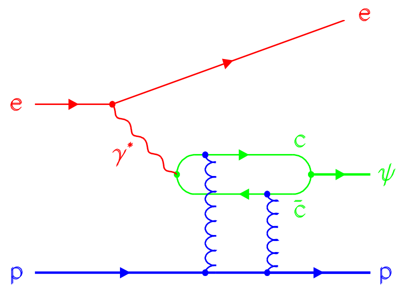
- Extend to smaller W using FMD (muon id. up to $\eta \simeq 3.5$)

Cross Section as Function of W



- Similar W dependence in photoproduction and DIS
- Systematic uncertainties dominated by:
  - unfolding of elastic/p-dissociation
  - lepton identification
- Model of Frankfurt, Koepf and Strikman describes data

$$\sigma_{\gamma^* p} \sim \left|\alpha_s(Q^2_{eff})\, xg(x, Q^2_{eff})\right|^2 \cdot \left(1 + \epsilon \frac{Q^2}{m^2_\psi}\right) \cdot \mathcal{C}(Q^2)$$



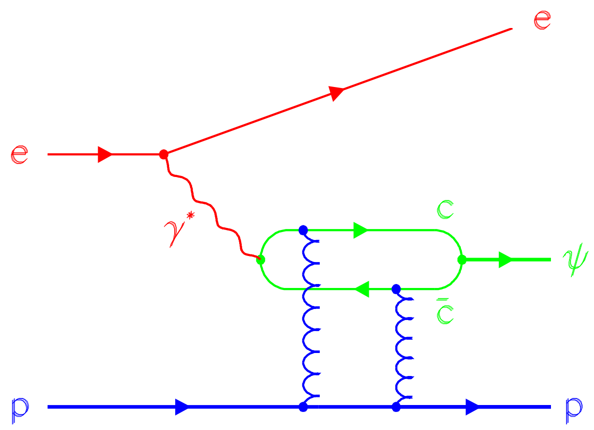
Perturbative QCD Approach: the Model of Frankfurt et al.

- For large W: Factorization

  a) Photon fluctuates into $c\bar{c}$

  b) $c\bar{c}$ scatters off proton

  c) $c\bar{c}$ bound state formation



- leading $\alpha_s \ln(Q^2_{eff}/\Lambda^2_{QCD})$ approximation:

$$\boxed{\left.\frac{d\sigma_{\gamma^* p}}{dt}\right|_{t=0} \sim \frac{\Gamma_{ee}}{(Q^2+4m_c^2)^4} \cdot \left|\alpha_s(Q^2_{eff})\, xg(x, Q^2_{eff})\right|^2 \cdot \left(1+\epsilon\frac{Q^2}{m_\psi^2}\right) \cdot \mathcal{C}(Q^2)}$$

$\left(1+\epsilon\frac{Q^2}{m_\psi^2}\right)$: Contributions of transversely and longitudinally polarized photons

$\mathcal{C}(Q^2)$: "Finite Q^2 correction" $\longrightarrow$ wave function, Fermi-motion of quarks

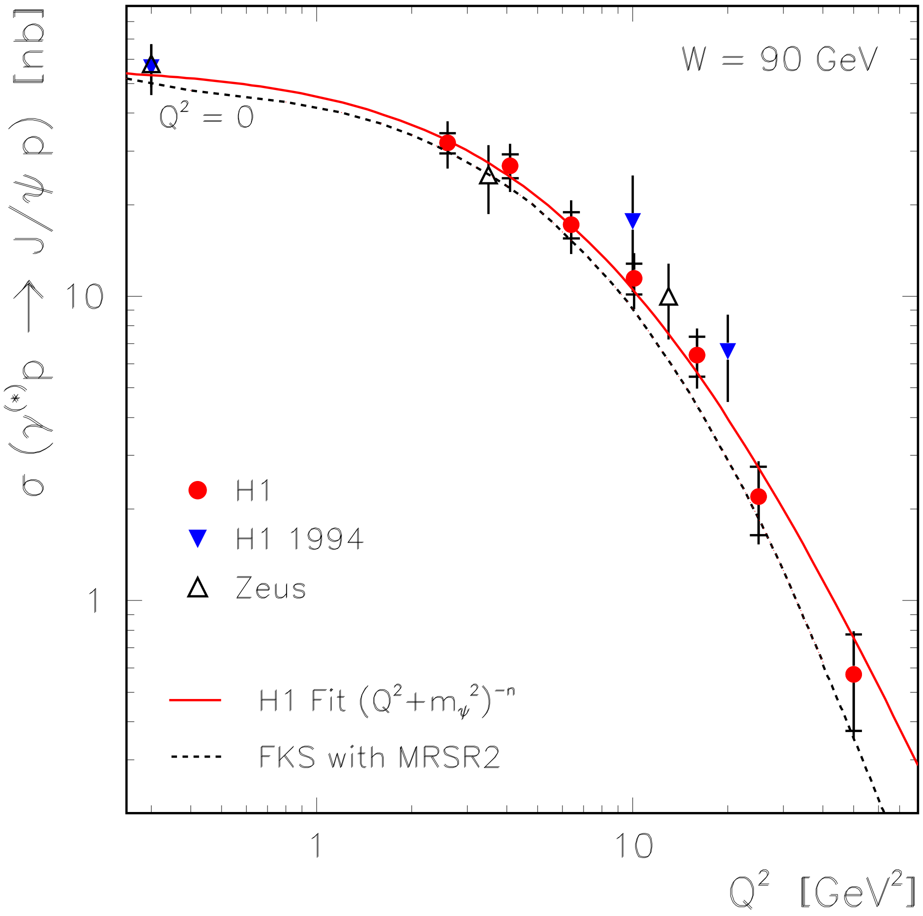
Q^2_{eff} : is of the order $\gtrsim (Q^2+m_\psi^2)/4$, $x = 4Q^2_{eff}/W^2$

- Large sensitivity on gluon density in the proton (…and mass of the c-quark)

- Total cross section:

$$\sigma_{\gamma^* p} = \frac{1}{b} \cdot \left.\frac{d\sigma_{\gamma^* p}}{dt}\right|_{t=0}$$

Cross Section as Function of Q^2

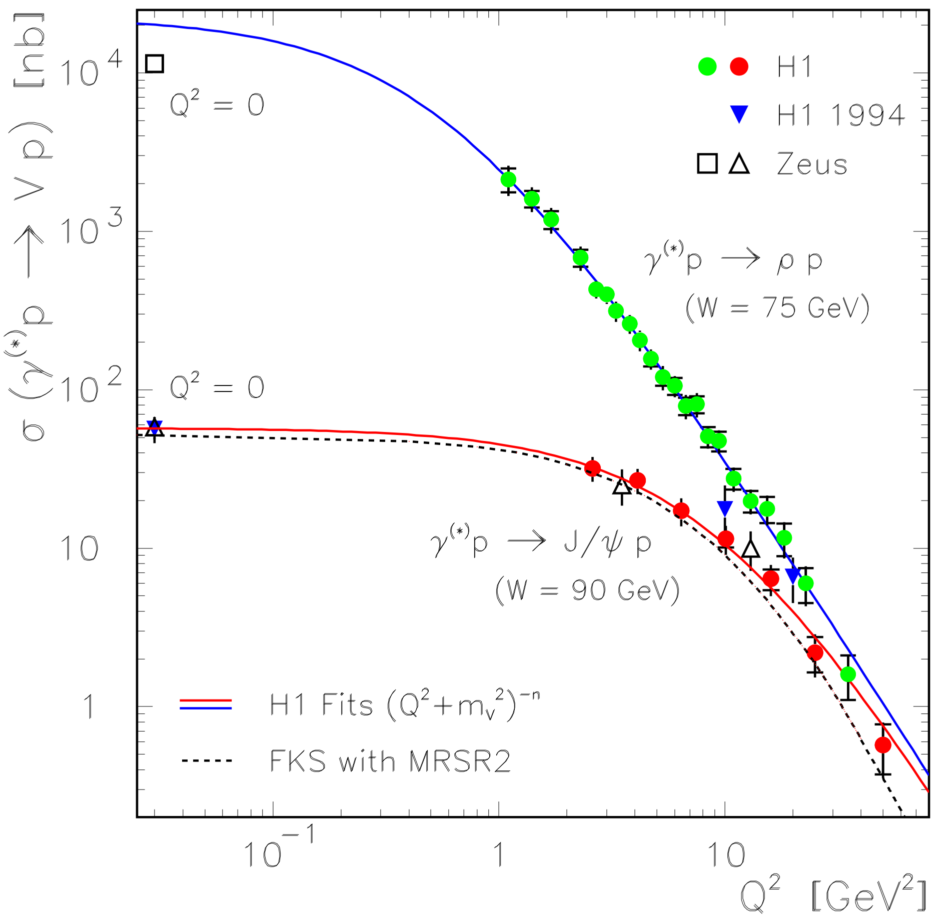


- Fit H1 data with $\sigma_{\gamma^* p} \sim 1/(Q^2 + m_\psi^2)^n \implies \boxed{n = 2.38 \pm 0.11}$
- Similar to other VM (ρ, ϕ)
- Hint for steepening at large Q^2:

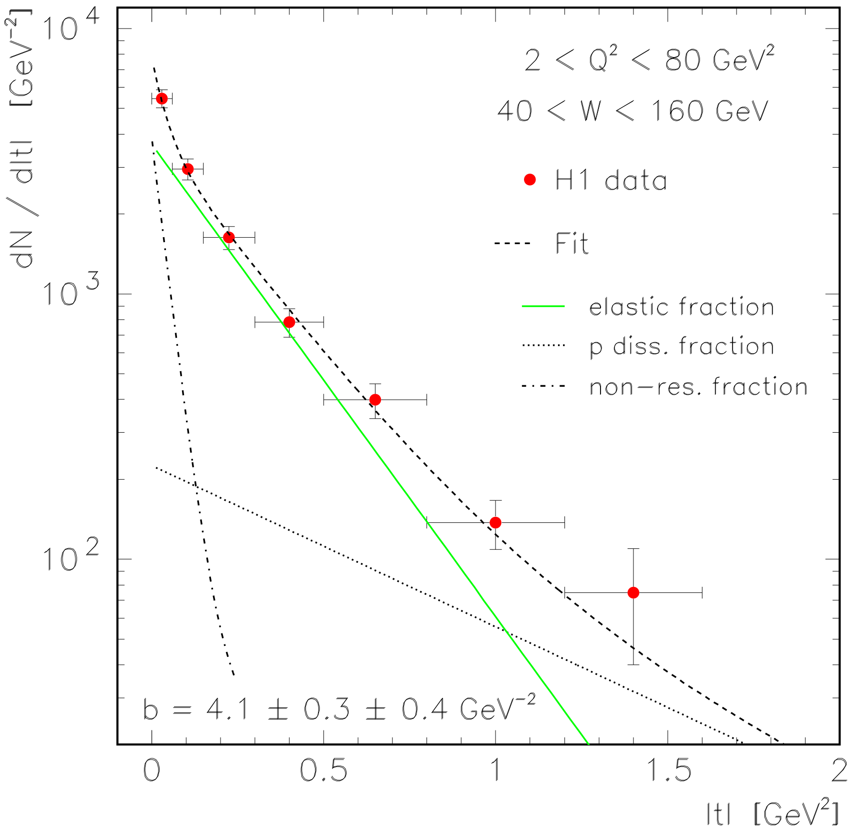
  $n = 2.12 \pm 0.20$ for $Q^2 < 12$ GeV^2

  $n = 2.97 \pm 0.51$ for $Q^2 > 12$ GeV^2

Cross Section as Function of Q^2



t Distribution — Slope Parameter



- Fit assuming exponential e^{bt} for elastic production yields

  $b = 4.1 \pm 0.3 \pm 0.4\ \mathrm{GeV}^{-2}$

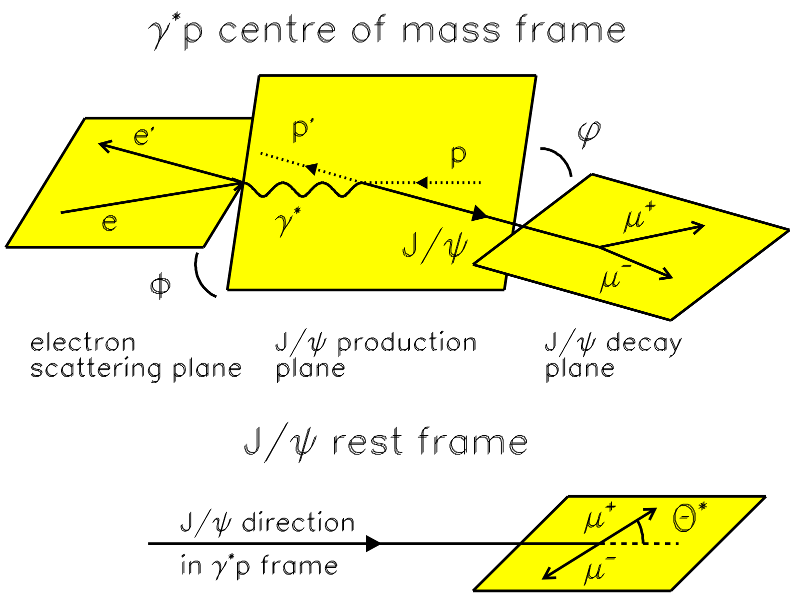
- Results compatible with J/ψ photoproduction
  (H1: $4.4 \pm 0.3\ \mathrm{GeV}^{-2}$,
  ZEUS: $4.6 \pm 0.6\ \mathrm{GeV}^{-2}$)

- Compare ρ photoproduction: $\mathcal{O}(10\ \mathrm{GeV}^{-2})$

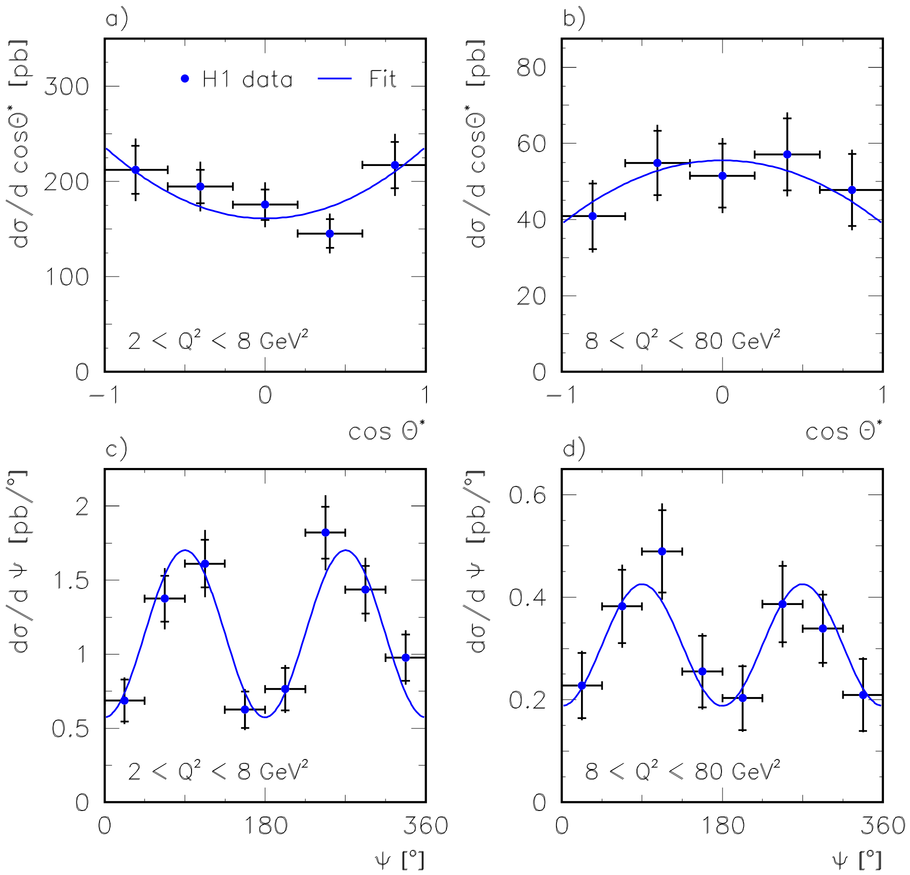
- Small-size $q\bar{q}$ configurations:

  $b \sim R_p^2 + R_{VM}^2$

Helicity Analysis — Measurement of $R := \sigma_L/\sigma_T$



$\Psi := \varphi - \phi$



- Measure $\cos\theta^*$ and Ψ distributions

  $\longrightarrow$ test SCHC and measure R

- $\cos\theta^*$ and Ψ distributions yield r^1_{1-1} values compatible with each other

  $\longrightarrow$ supporting SCHC approximation

$R = 0.18^{+0.18}_{-0.18}$ $(Q^2 = 4\,\mathrm{GeV}^2)$

$R = 0.94^{+0.97}_{-0.43}$ $(Q^2 = 16\,\mathrm{GeV}^2)$

(from $\cos\theta^*$)

Comparable to ρ production at same Q^2/M_V^2

Diffractive $\psi(2S)$ Production

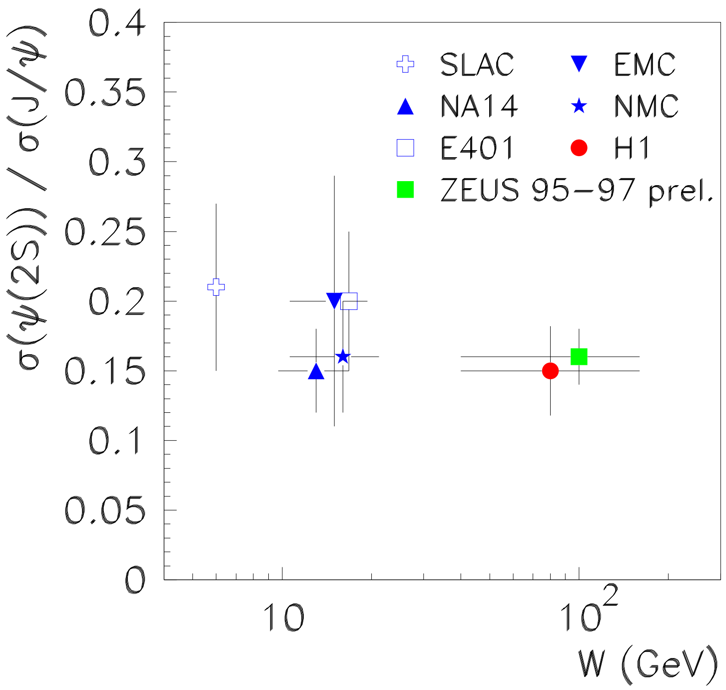
- The ratio

$$R := \frac{\sigma_{\gamma^* p}(\psi(2S))}{\sigma_{\gamma^* p}(J/\psi)}$$

  is sensitive to the radial wave function of the Charmonium

- QCD prediction for Photoproduction: $R = 0.17$

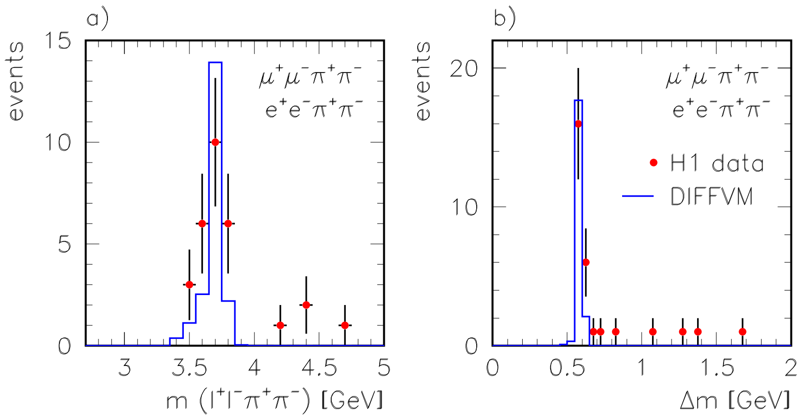
- No significant dependence on W

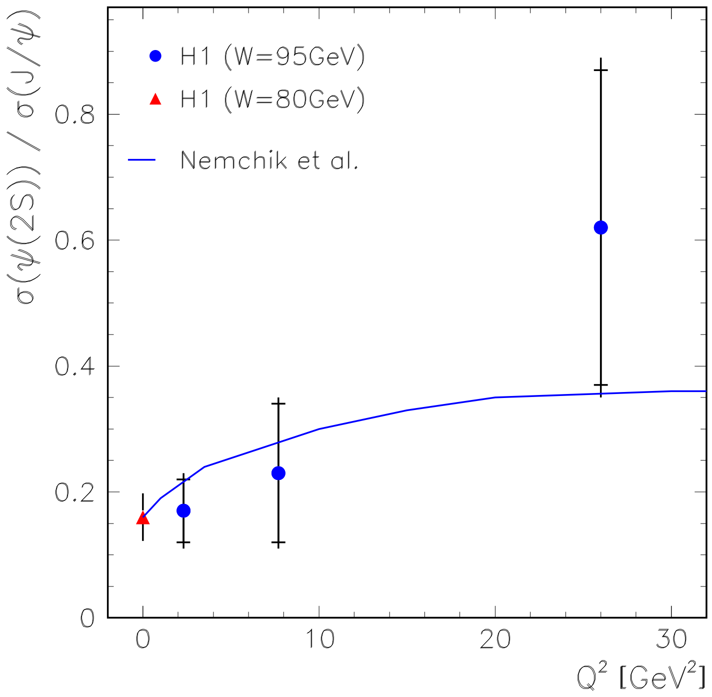


- . . . What about Q^2 ?

Diffractive $\psi(2S)$ Production in DIS

$\psi(2S) \longrightarrow J/\psi\,\pi^+\pi^-$ $\quad BR = (30.2 \pm 1.9)\,\%$





- H1 data 1995-97: $\int \mathcal{L}dt \simeq 25\ \mathrm{pb}^{-1}$
- Kinematic range:

$$1 < Q^2 < 80\ \mathrm{GeV}^2$$
$$40 < W < 180\ \mathrm{GeV}$$

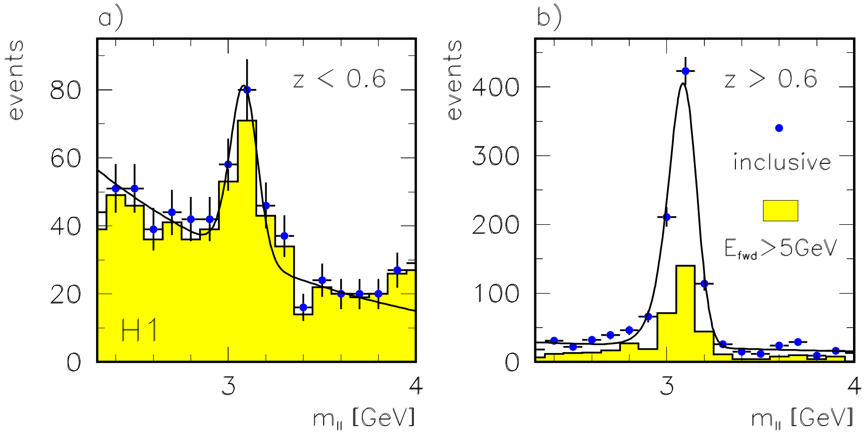
- Good agreement between photoproduction (H1 and ZEUS prel.) and result at low Q^2
- Indication ($\simeq 2\sigma$) for a rise with Q^2, compatible with QCD predictions

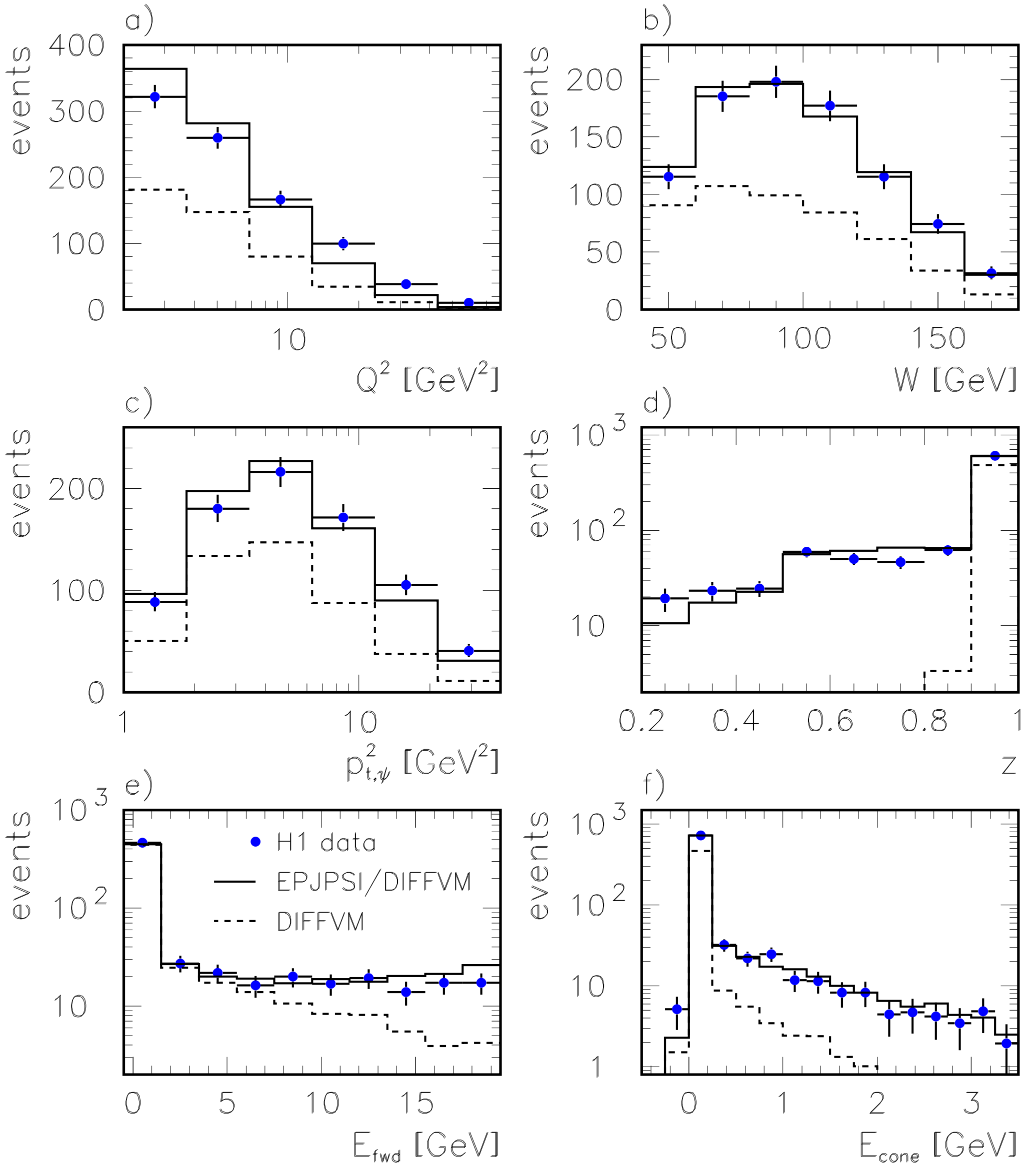
Inclusive J/ψ Production

- Inclusive cross sections may help in understanding production mechanisms
- Use a tuned mix of diffractive and LO Colour Singlet simulations to correct for acceptance and efficiencies
- Kinematic region:

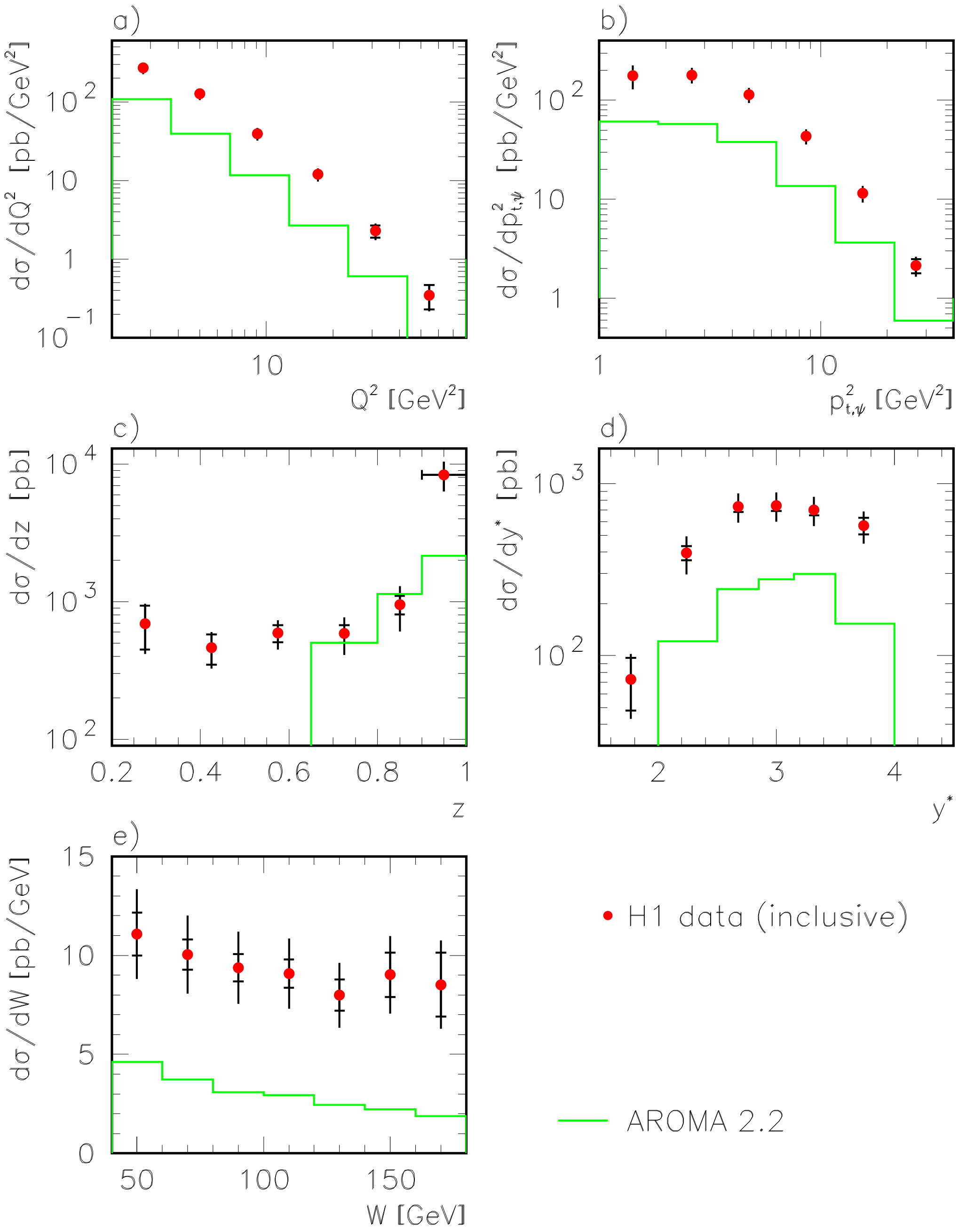
$$z > 0.2$$

$$2 < Q^2 < 80\ \mathrm{GeV}^2$$
$$40 < W < 180\ \mathrm{GeV}$$





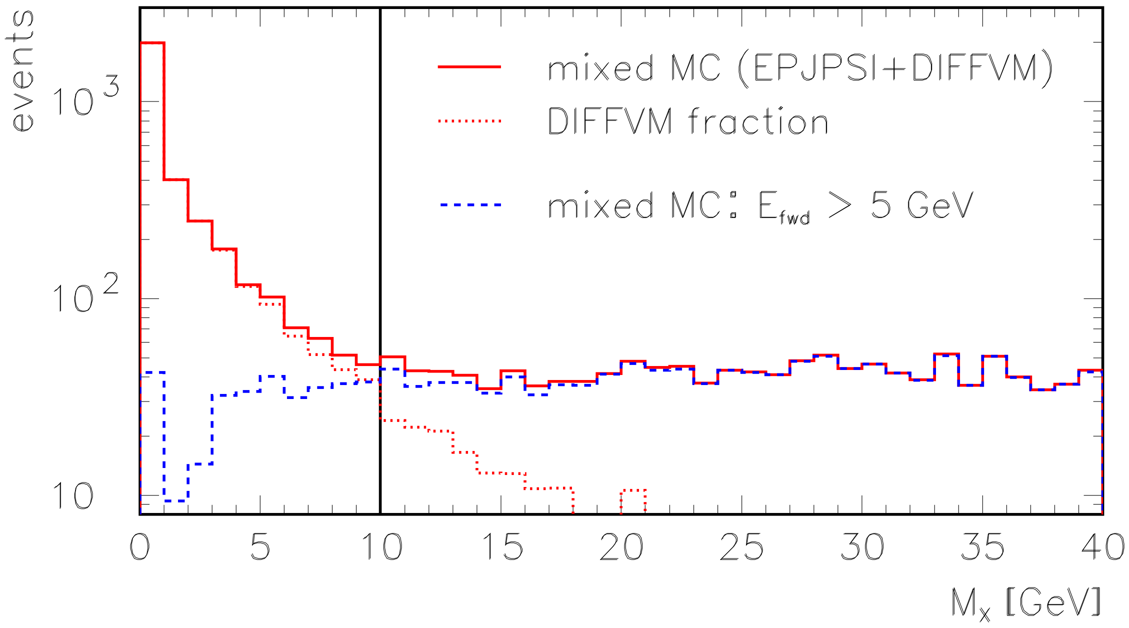
Inclusive J/ψ Production $ep \longrightarrow eJ/\psi X$



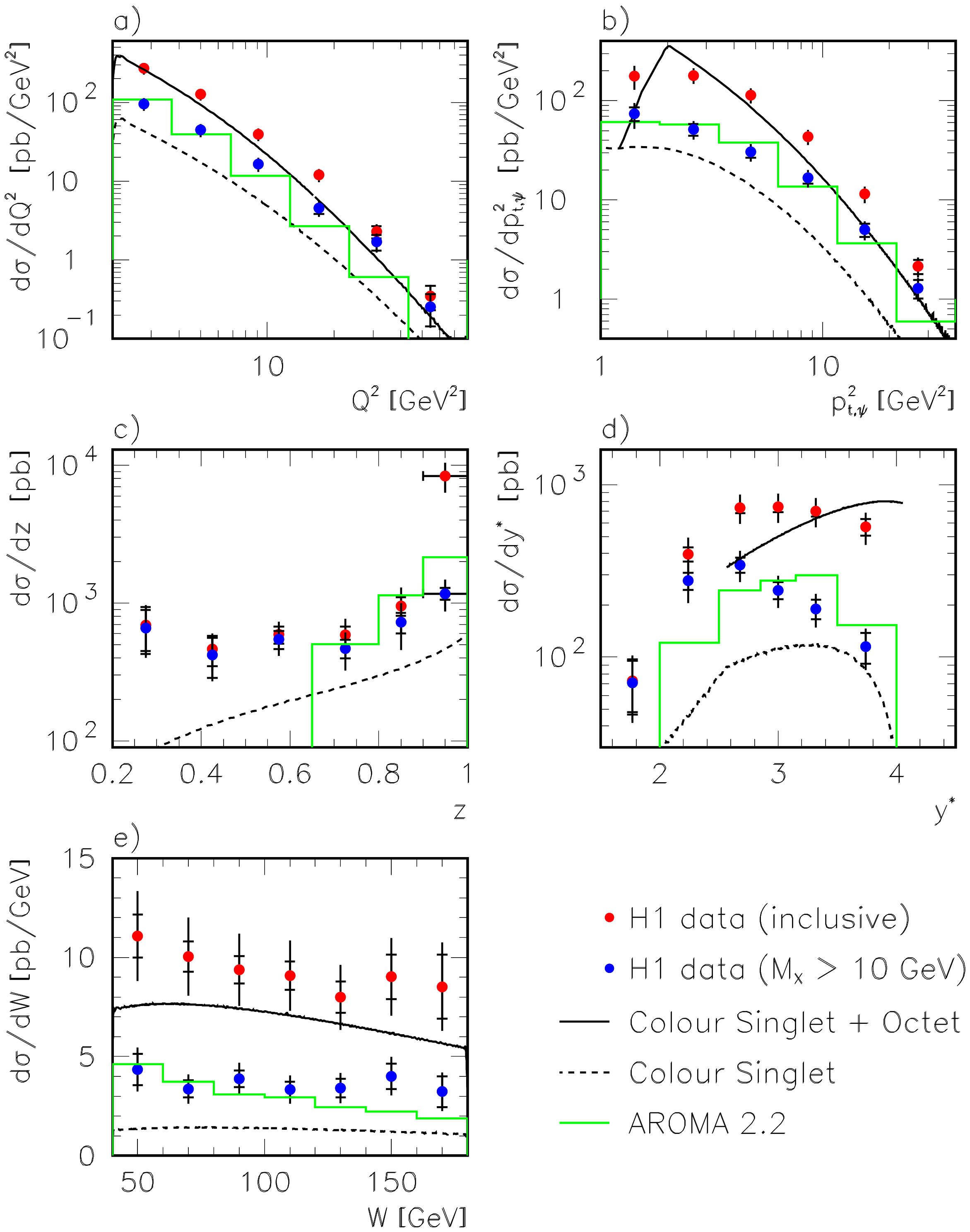
- Compare Soft Colour Interaction Model (Aroma 2.2) with the data:
- Good description, except:
  - Normalization of Aroma too low
  - $d\sigma/dz$ not described
- Aroma includes so far only the LO BGF matrix element
  $\rightarrow$ Colour Singlet contribution missing

Inelastic J/ψ Production

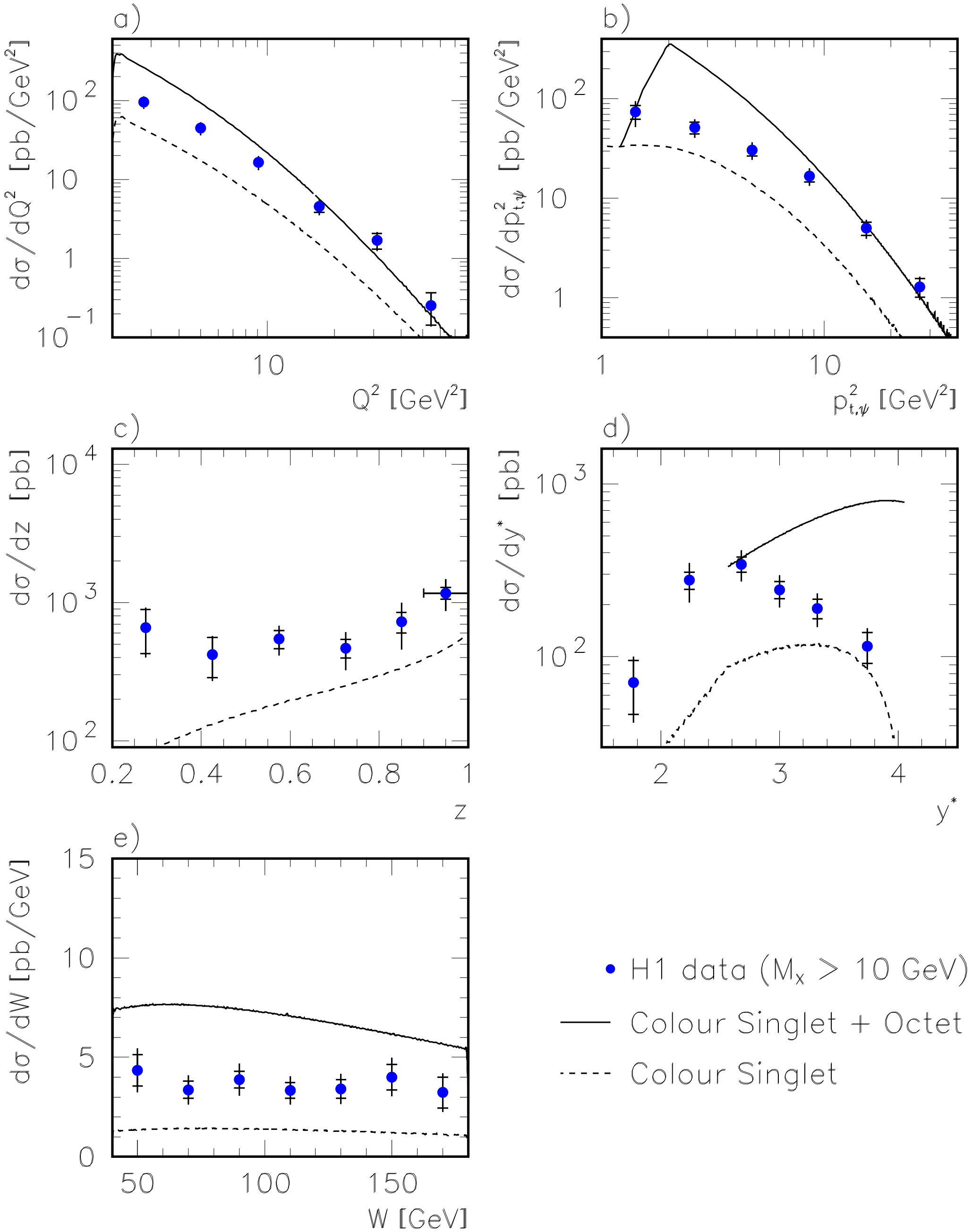
- An explicit cut in z (e.g. $z < 0.9$) as conventionally applied reduces colour octet contributions by an unknown amount
- Alternatively quote cross sections for a minimal M_X
- $M_X > 10$ GeV safe for Colour Octet according to Fleming/Mehen
- Experimentally require substantial energy deposits in forward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



Inclusive and Inelastic J/ψ Production



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



- 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 ?
  - hadonisation effects ?
  - adjusting CO ME ?

J/ψ Polarization

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

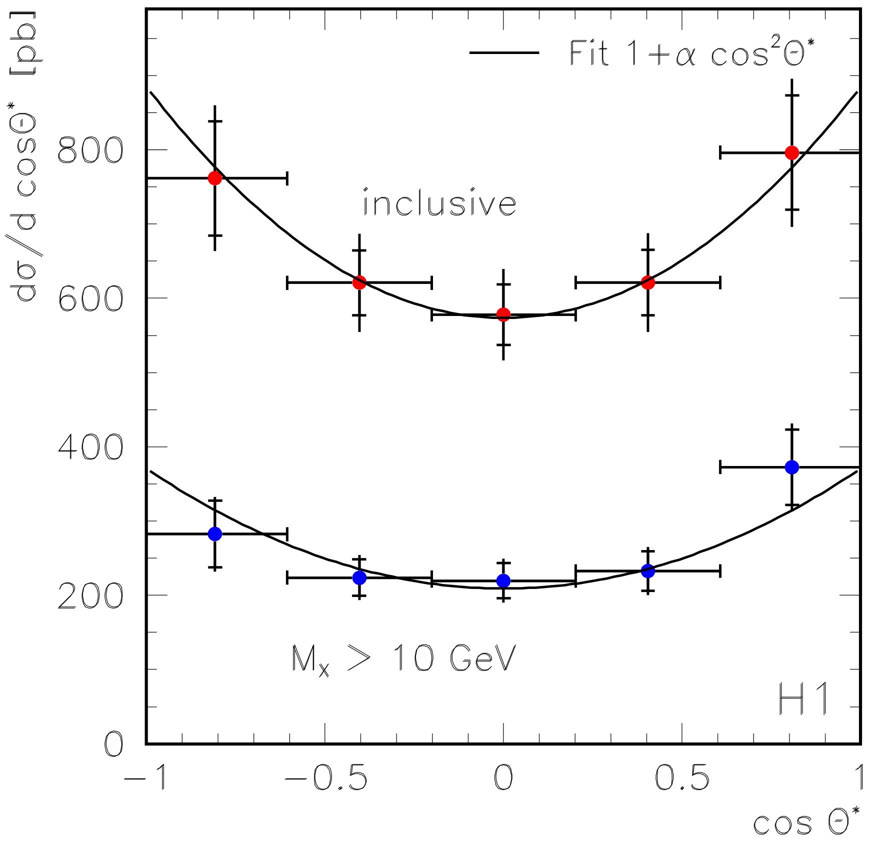
$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \alpha\cos^2\theta^*$$

($\alpha = +1$ 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

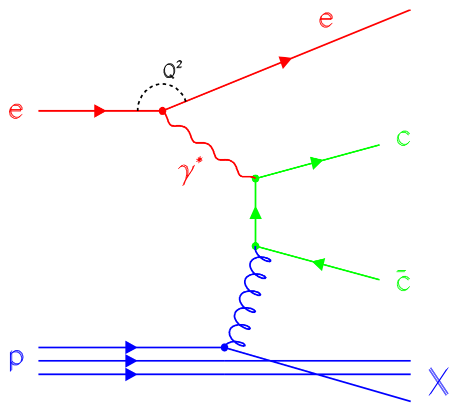
$\alpha = 0.54^{+0.29}_{-0.26}$ (inclusive)

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



Gluon Density from D^* Production

$D^* \longrightarrow D^0\pi_{slow} \longrightarrow (K^-\pi^+)\pi_{slow}$



- Photoproduction and DIS:

γp	$0.02 < y < 0.32$	$Q^2 \simeq 0$
	$0.29 < y < 0.62$	
DIS	$0.05 < y < 0.7$	$2 < Q^2 < 100$ GeV^2

- $\int \mathcal{L} dt \simeq 10$ pb^{-1}

- Momentum fraction of gluon:

$$x_g = \frac{\hat{s} + Q^2}{ys}$$

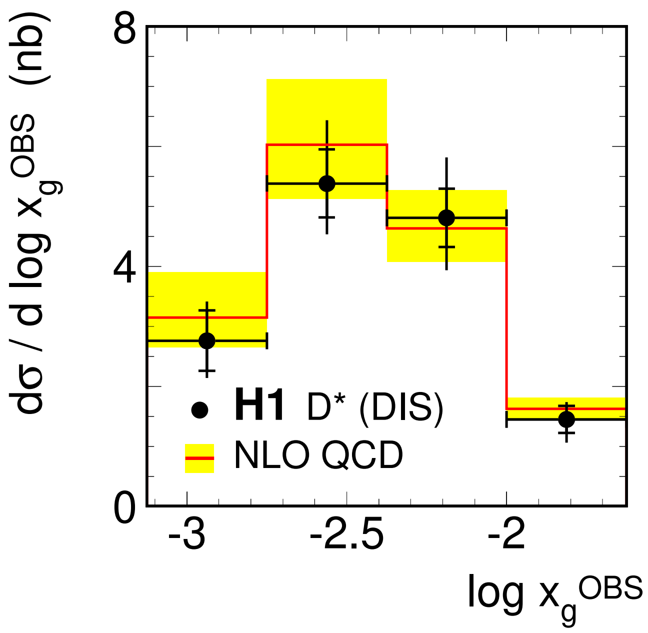
$$\hat{s} = \frac{p_{\perp c}^{*2} + m_c^2}{z(1-z)}, \quad z = \frac{P_p \cdot P_c}{P_p \cdot P_\gamma} = \frac{(E-p_z)_c}{2yE_e}$$

- Approximate

$$(E-p_z)_c \longrightarrow (E-p_z)_{D^*}, \quad p_{\perp c}^* \longrightarrow 1.2 p_{\perp D^*}^*$$

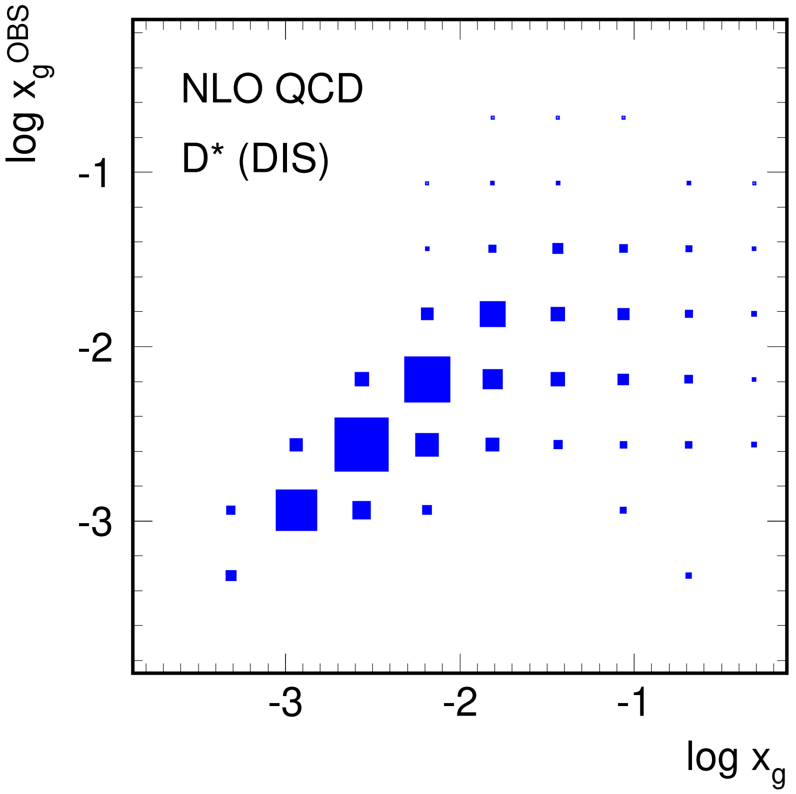
$$x_g \longrightarrow x_g^{obs}$$

- Determine cross section $d\sigma/dx_g^{obs}$ e.g. DIS:



Gluon Density from D^* Production

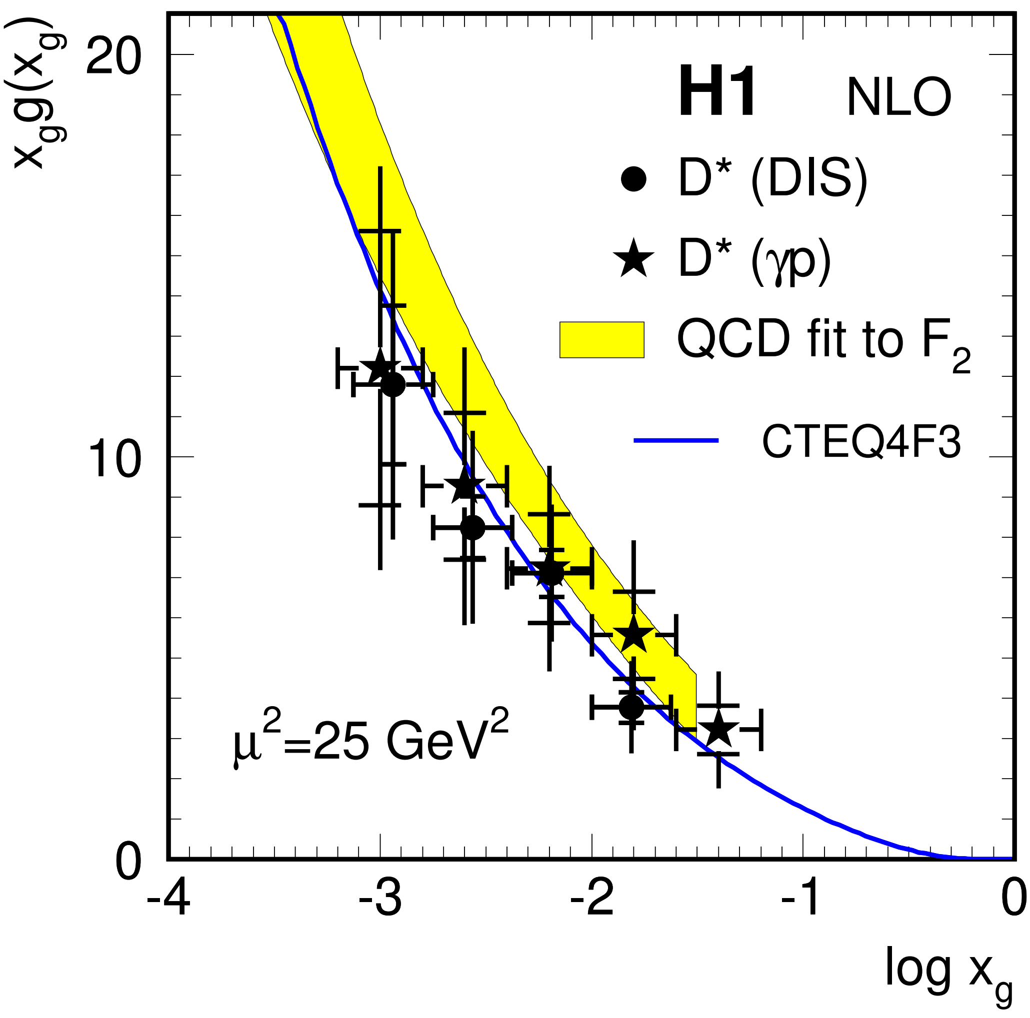
- Subtract quark-induced
- Unfold to *true* x_g using NLO QCD programs + Peterson fragmentation
  (Massive scheme. Harris/Smith in DIS,
  Frixione/Mangano/Nason/Ridolfi in γp).
  Iterative unfolding procedure (d'Agostini).
- Assume only direct photon contribution (additional cuts in photoproduction)



Gluon Density from D^* Production

- The gluon density is obtained from the cross section measurement by

$$g(x_{g,i},\mu^2)^{exp} = g(x_{g,i},\mu^2)^{th} \cdot \frac{\sigma(x_{g,i})^{exp}}{\sigma(x_{g,i})^{th}} \qquad \mu^2 = \text{QCD scale}$$



- Uncertainty dominated by statistics and fragmentation

Summary and Conclusions

- More precise data on elastic J/ψ electroproduction

  — pQCD models can reasonably describe cross sections
  — SCHC is a good approximation $\rightarrow$ R measurement

- First observation of $\psi(2S)$ in DIS at HERA

  — Rise of $\sigma(\psi(2S))/\sigma(J/\psi)$ with Q^2 (?)

- Inclusive J/ψ electroproduction

  — Many (not all) aspects described by model of SCI

- Inelastic J/ψ electroproduction

  — Improvements to theory needed

- Gluon distribution from D^* production

  — More direct than via scaling violations
  — Universality of gluon structure function