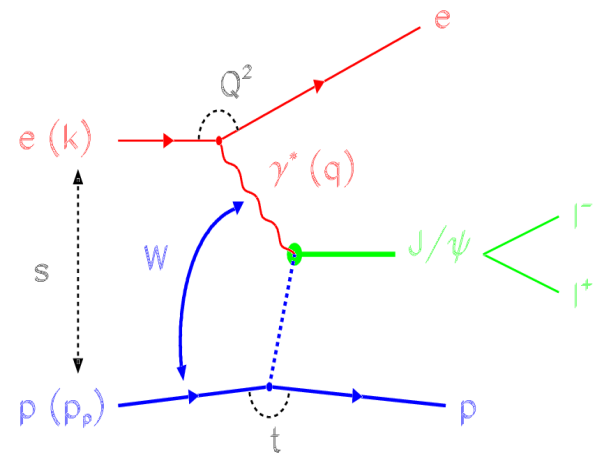
Quarkonium Production

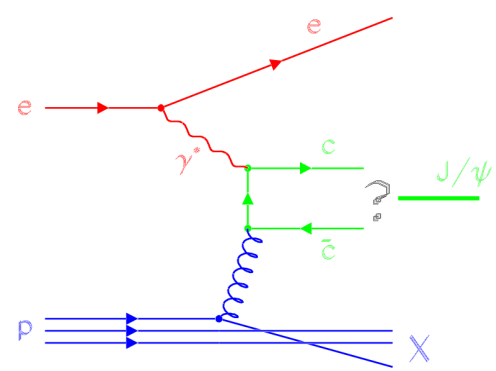
Arnd Meyer, Fermilab
HQ2k
Rio de Janeiro
Oct 11, 2000

- Introduction
- Tevatron – past, present, and future
  - Run I: cross section and polarization measurements (J/Ψ, Ψ', Υ(1S,2S,3S))
  - Prospects for Run II
- HERA – past, present, and future
  - Inclusive and inelastic production measurements (J/Ψ)
  - Exclusive production: total and differential cross sections (J/Ψ, Ψ', Υ)
  - Prospects for 2001+
- Conclusions

Introduction

- History
  - Inelastic J/Ψ production at HERA: a golden way to extract gluon density
  - Elastic/diffractive J/Ψ production to measure luminosity
  - ...
- Tevatron (Run 1 1992−96, 20 pb^{-1} (1A) + 90 pb^{-1} (1B)):
  - $p \rightarrow\leftarrow \bar{p}$ at $\sqrt{s}=1.8\,\mathrm{TeV}$
  - η, p_T, polarization
- HERA:
  - $e^{\pm}(27.5\,\mathrm{GeV}) \rightarrow\leftarrow p(820/920\,\mathrm{GeV})$ with $\sqrt{s}=300/320\,\mathrm{GeV}$
  - Q^2, W, z, p_T, t, ..., polarization
  - overconstrained kinematics
- Variety of presumed production mechanisms:
  - Diffractive/elastic
  - Gluon−gluon−fusion, photon−gluon−fusion
  - Gluon fragmentation
  - "Resolved photon"−gluon/quark−fusion
  - + decays

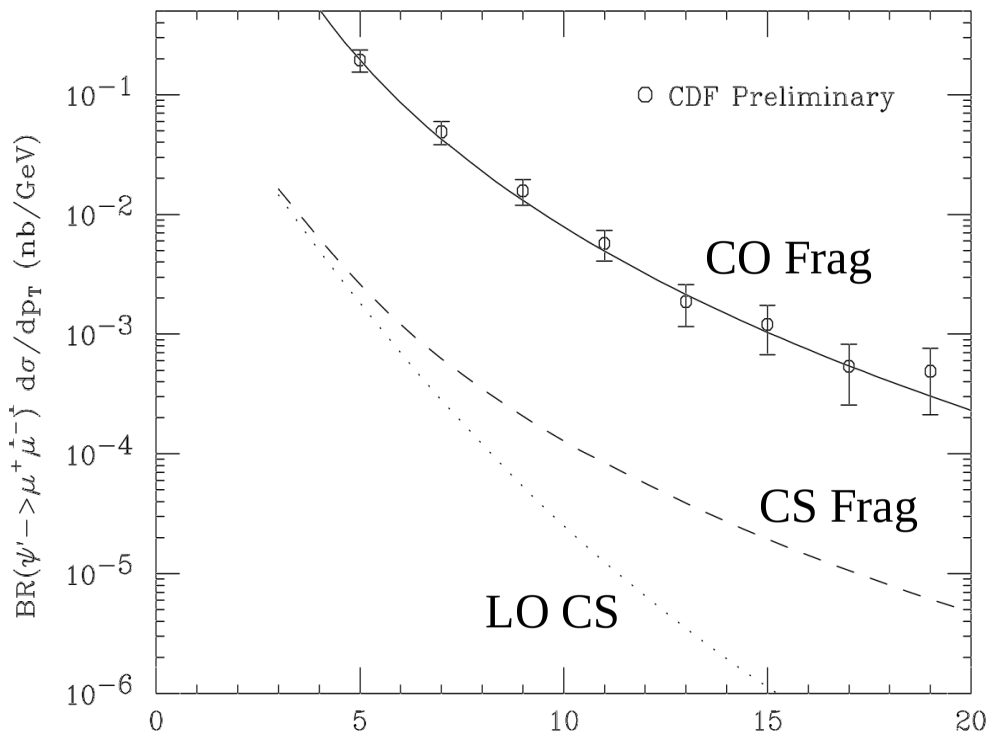




Direct Ψ(2S) Cross Section

- Run 1A data, 18 pb^{-1}
- $|\eta| < 0.6$
- Lifetime information from SVX used to extract prompt component
- Prompt = direct for Ψ(2S)
- Colour singlet fusion: α_S^3/p_T^8
- CS fragmentation (Braaten, Yuan, PRL 71(1993) 1673): α_S^5/p_T^4

  $g* \rightarrow 2g + c\bar{c}(^3S_1^{(1)}) \rightarrow \Psi'$
- NRQCD expansion
  - $d\sigma(H) = \sum_n d\sigma[c\bar{c}(n)] \langle O^H(n) \rangle$
  - n includes colour singlet and octet states
  - Expansion in α_s and v (relative velocity of quark and anti−quark)

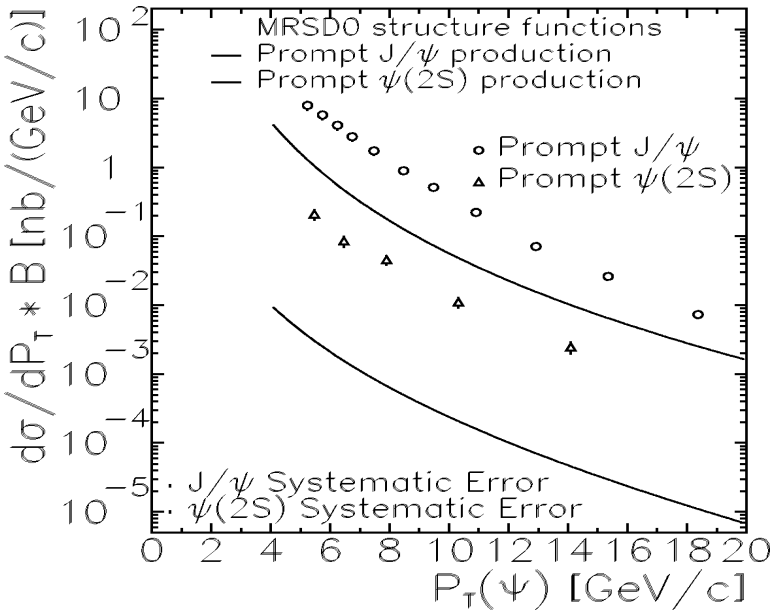


Braaten, Fleming PRL 74(1995) 3327
CDF Data: PRL 79(1997) 572

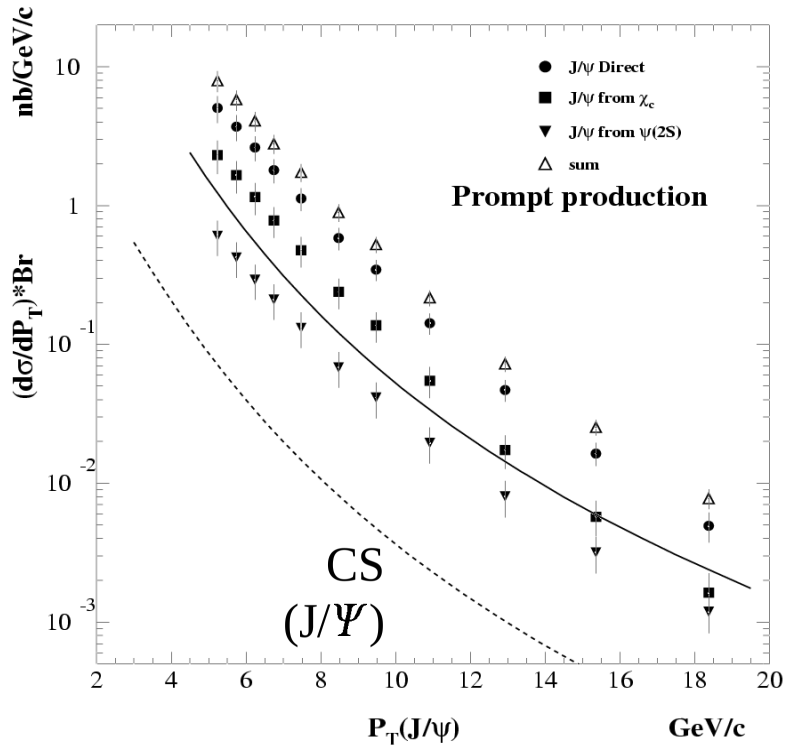
- Colour octet fragmentation (Braaten, Fleming, PRL 74(1995) 3327): $\alpha_S^3 v^4/p_T^4$

  $g* \rightarrow c\bar{c}(^3S_1^{(8)}) \rightarrow \Psi'$
- Fragmentation dominates at high p_T

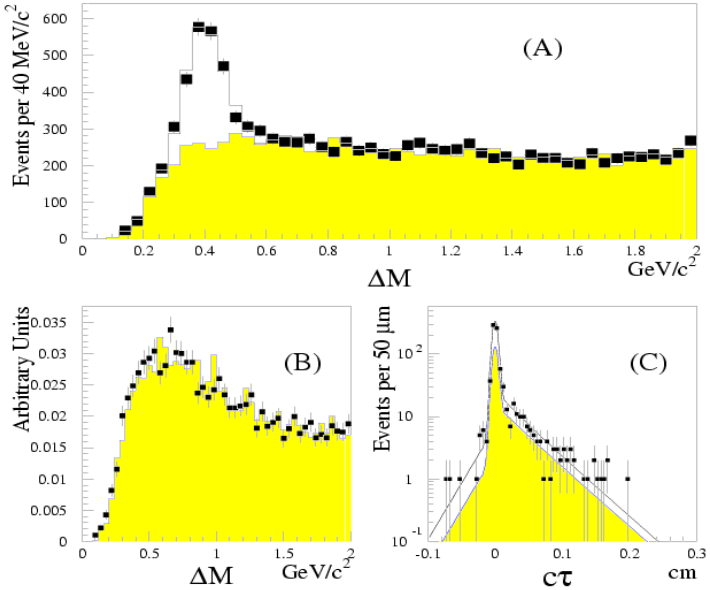
Prompt / Direct J/Ψ Cross Section



- Prompt J/Ψ cross section includes
  - χ_c decays ($\chi_c \rightarrow J/\Psi\gamma$ measured)
  - Ψ(2S) feed−down (measured)
  - Direct J/Ψ (64±6%)



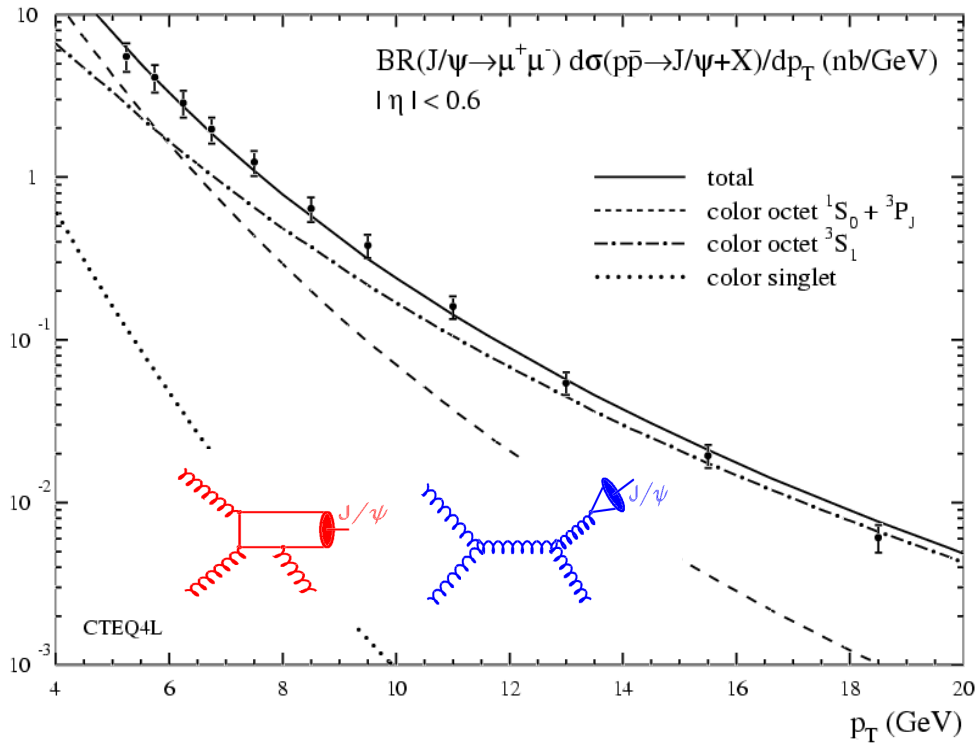
CS+CO
(χ_c)



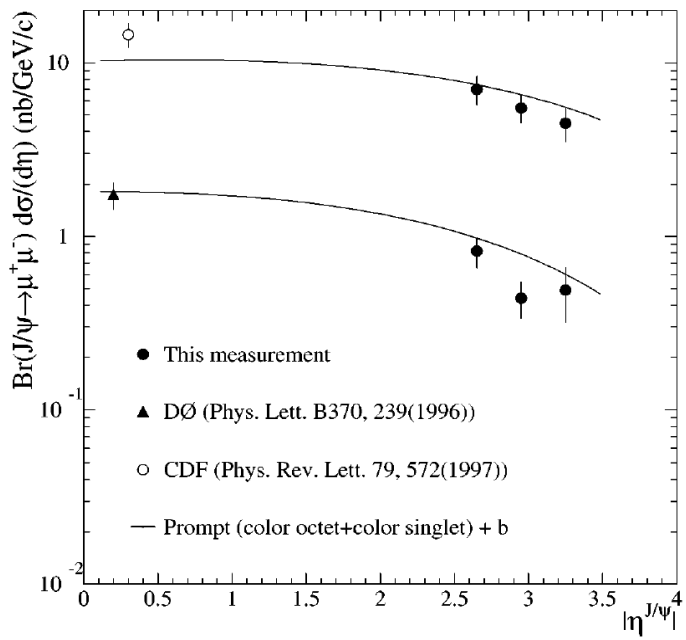
CDF, PRL 79(1997) 572, 578

Direct J/Ψ Cross Section

- Large uncertainties in the extracted matrix elements
  - low p_T: effects of gluon k_t
  - parton density functions



D0, PRL 82(1999)35



p_T>5GeV

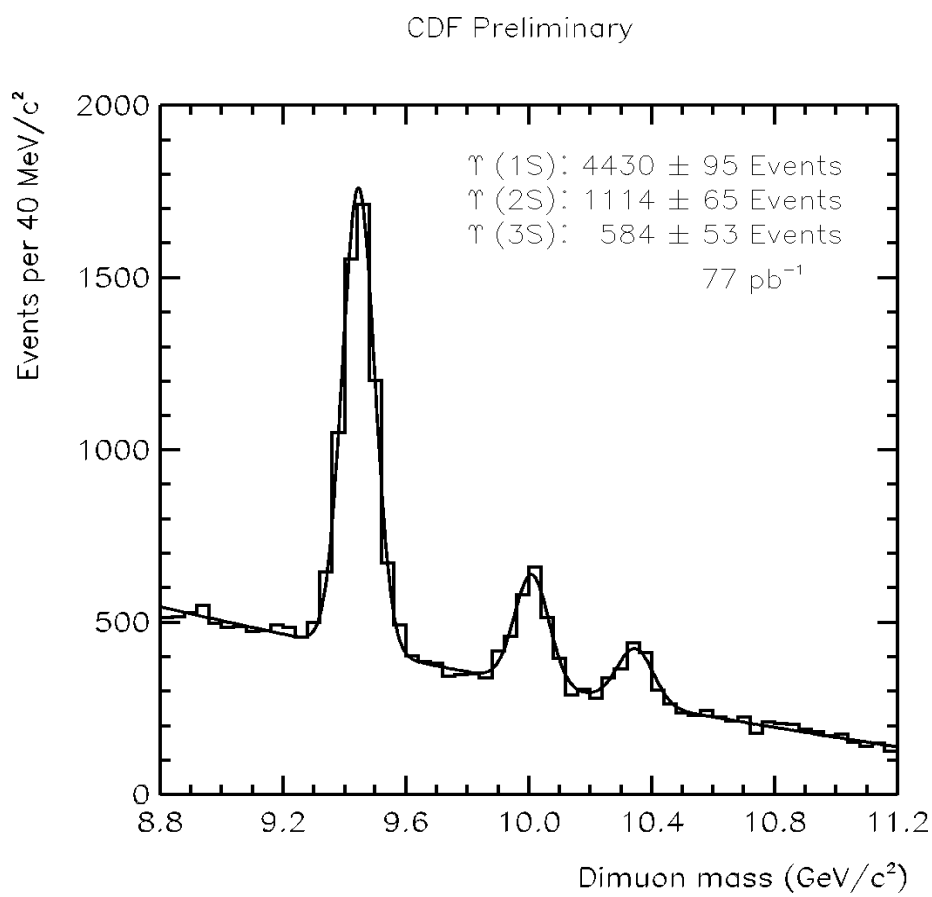
p_T>8GeV

- Reasonable agreement with D0 measurement at large $|\eta|$

Beneke, Krämer, PRD 55(1997) 5269

Υ Cross Sections

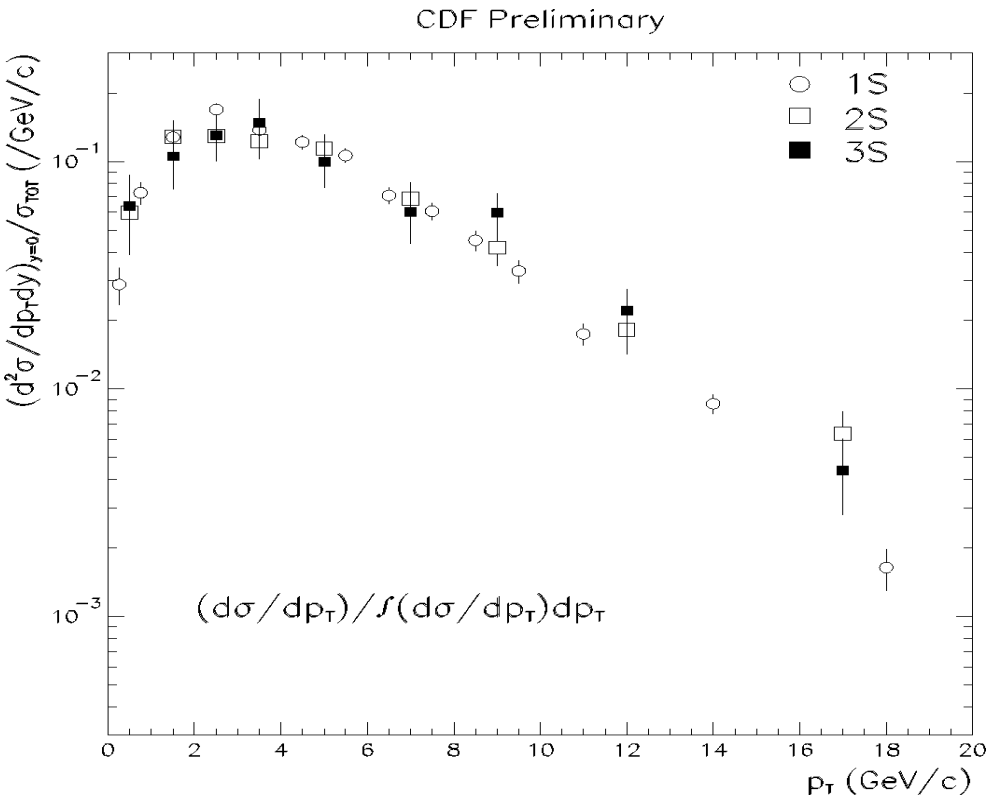
- Run 1B data, 77 pb^{-1}
- $|y(\Upsilon)| < 0.4$
- Awaiting publication
- Decomposition of Υ cross section:
  - $27.1 \pm 6.9(stat) \pm 4.4(syst)\%$ from $\chi_b(1P)$
  - $10.5 \pm 4.4(stat) \pm 1.4(syst)\%$ from $\chi_b(2P)$
  - $<6\%$ from $\chi_b(3P)$
  - $10.7^{+7.7}_{-4.8}\%$ from $\Upsilon(2S)$
  - $0.8^{+0.6}_{-0.4}\%$ from $\Upsilon(3S)$
  - $50.9 \pm 8.2(stat) \pm 9.0(syst)\%$ direct

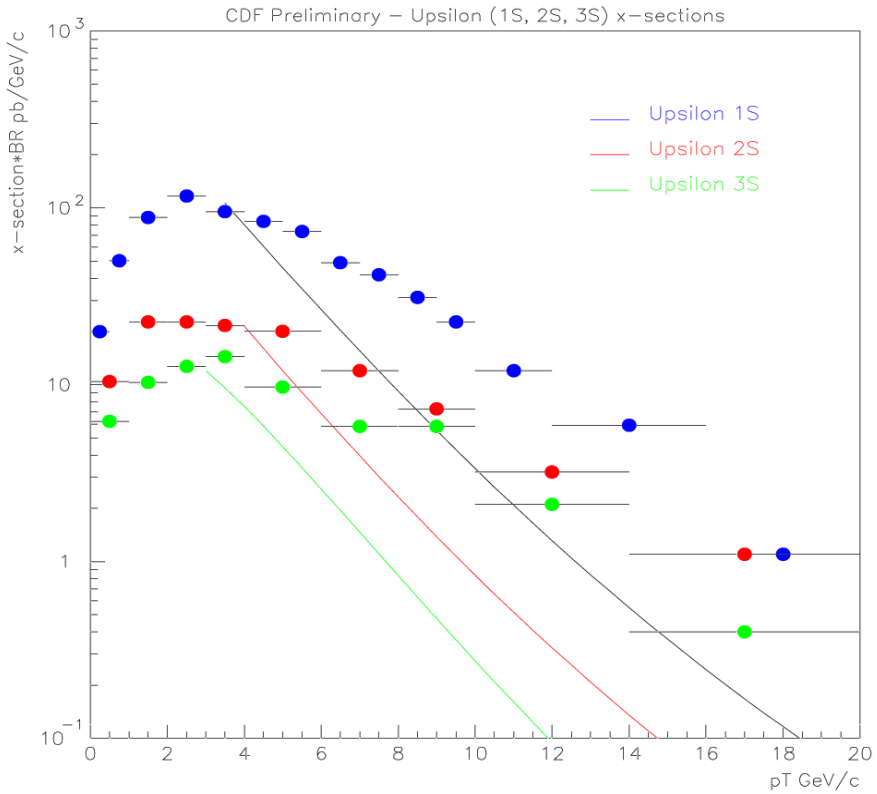


www−cdf.fnal.gov/physics/new/bottom/cdf5027/cdf5027.html

Υ Cross Sections

- Comparable shape of Υ(1S), Υ(2S), Υ(3S)
- Colour singlet shape and magnitude disagreement

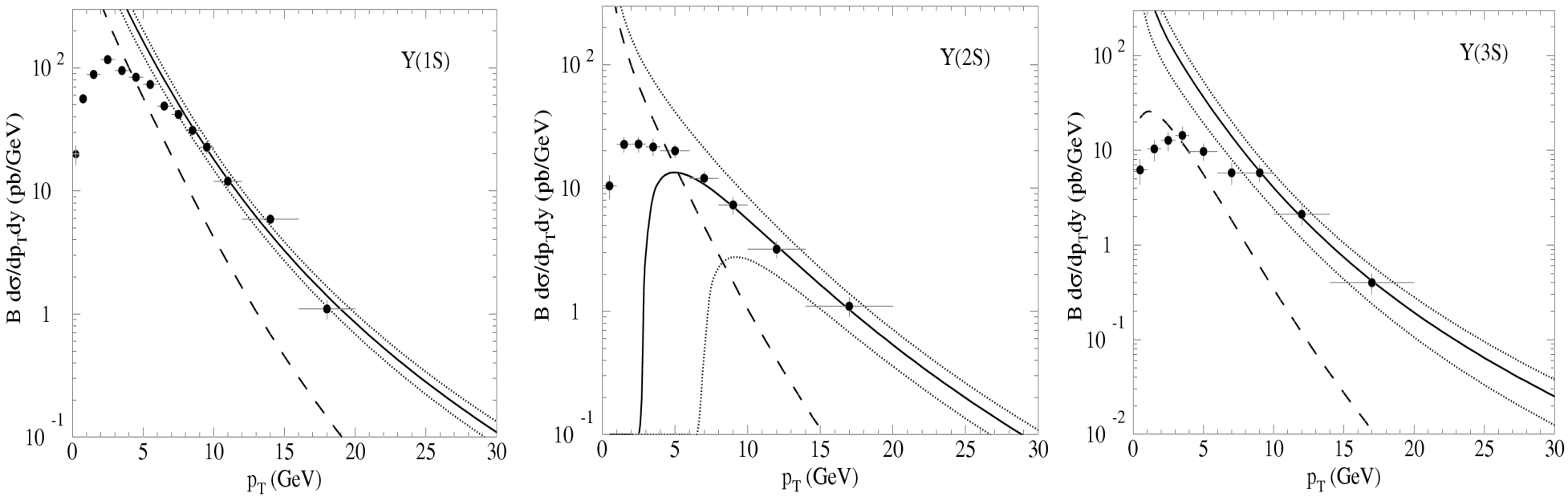




Υ Cross Sections

- Υ cross sections revisited with new CDF data
- Take feed−down between Bottomonium states into account
- Avoid low p_T < 8 GeV (soft gluon resummation)
- Most matrix elements come out reasonable, but large errors

Braaten, Fleming, Leibovich: hep−ph/0008091



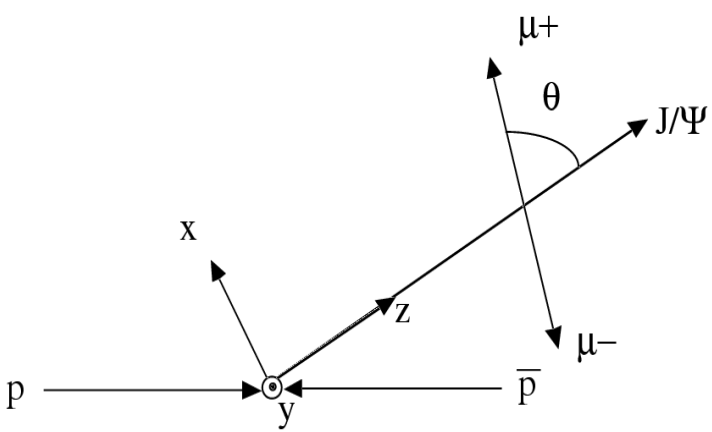
J/Ψ Polarization

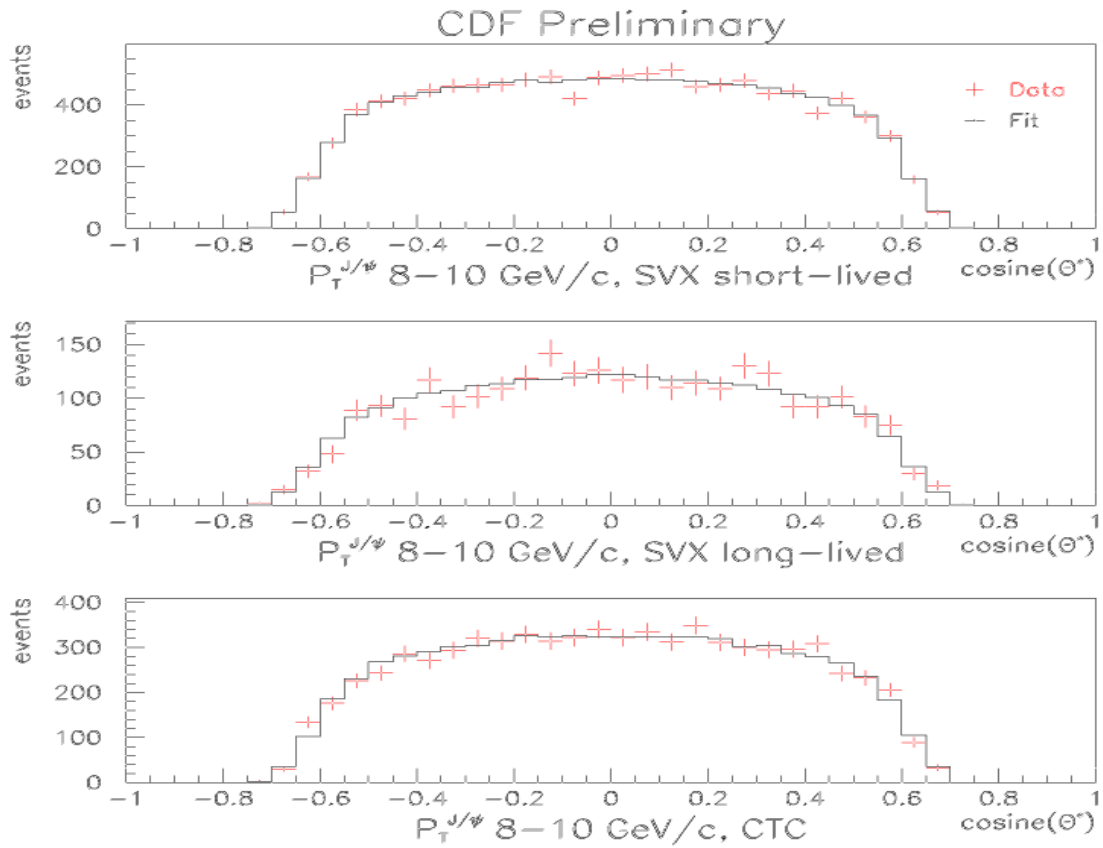
- Run 1, 110 pb^{-1}
- $p_T > 4$ GeV, $|y| < 0.6$
- Small acceptance at large $|\cos \Theta|$
- χ^2 fit using templates for longitudinal and transverse polarization

$$d\Gamma / d\cos\Theta \propto 1 + \alpha \cos^2 \Theta$$

$\alpha = 1$ transverse

$\alpha = -1$ longitudinal

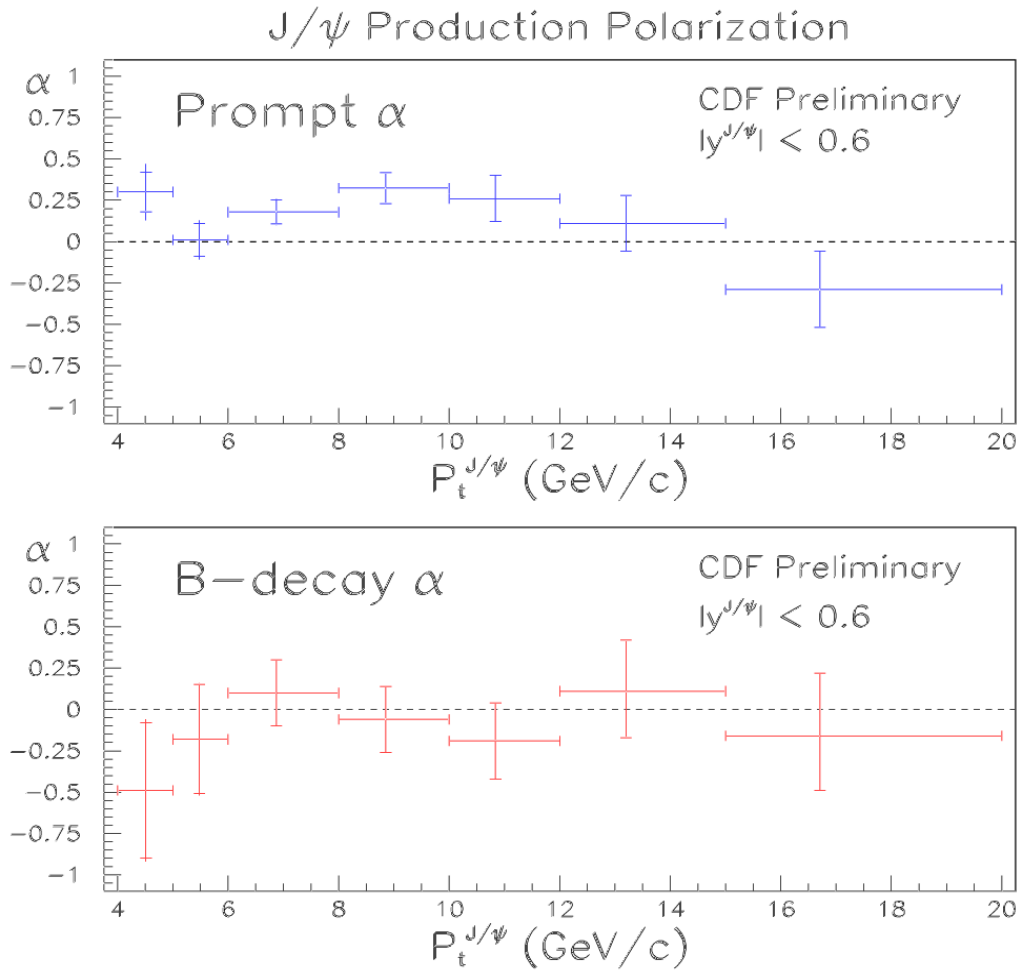




CDF, hep−ex/0004027

J/Ψ Polarization

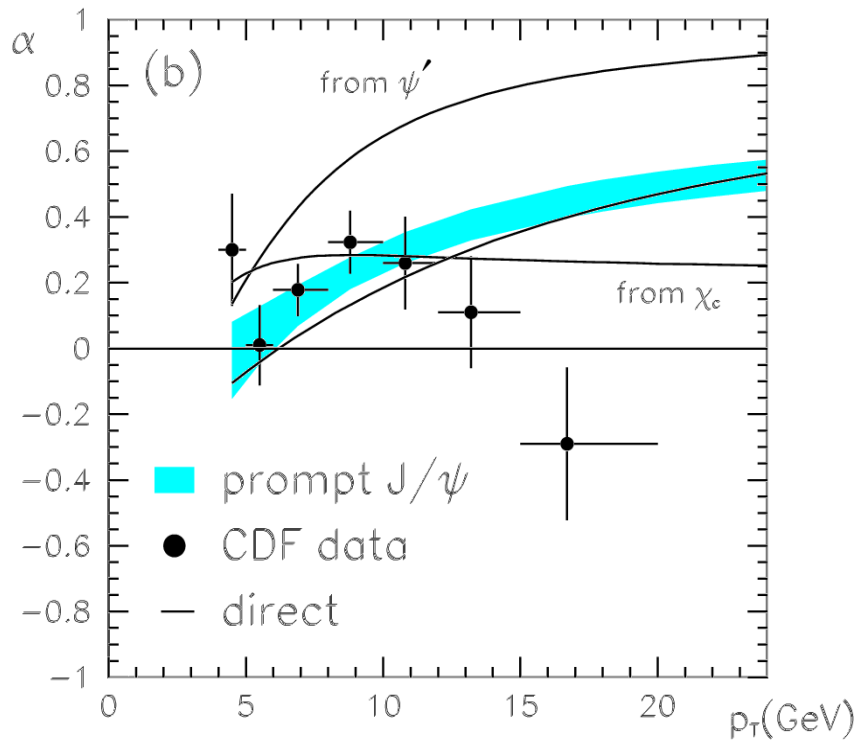
- J/Ψ from B decays essentially unpolarized



CDF, hep−ex/0004027

Prompt J/Ψ Polarization

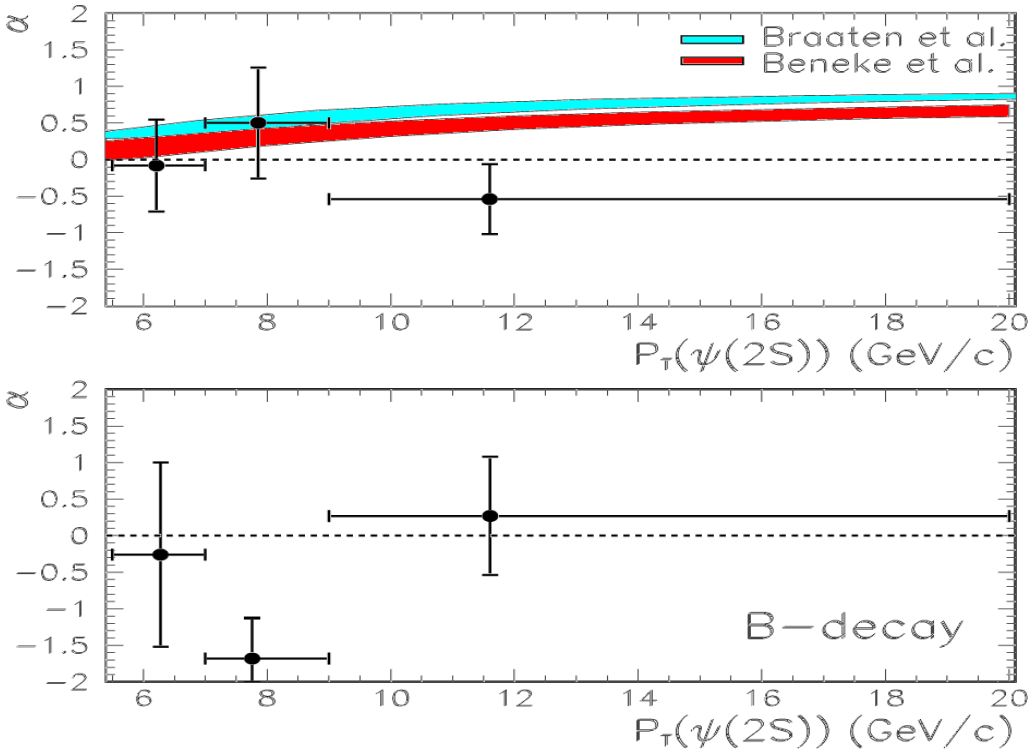
- Need to take into account Ψ(2S) and χ_c contributions
- Data do not show a trend towards transverse polarization at large p_T
- Phenomenological models give better description
  - E.g. colour evaporation model: mostly unpolarized J/Ψ at large p_T



Braaten, Kniehl, Lee
hep−ph/9911436

Ψ(2S) Polarization

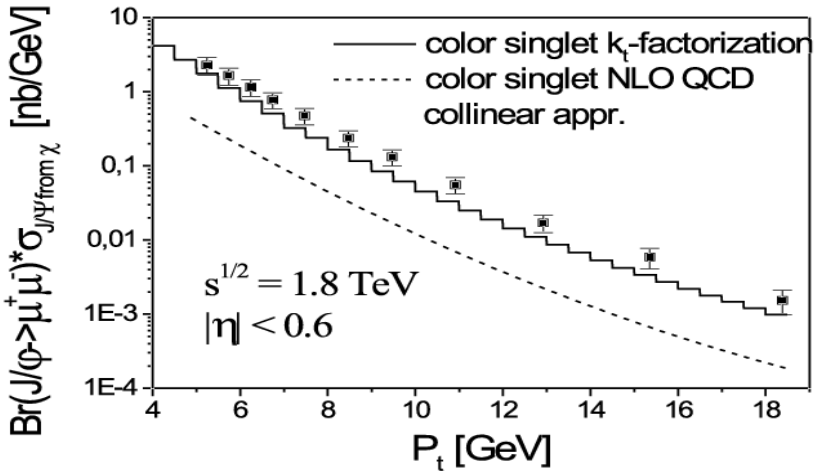
- Same procedure, but limited statistics
- Preferable to J/Ψ since no contamination from indirect production
- Inconclusive



CDF, hep−ex/0004027

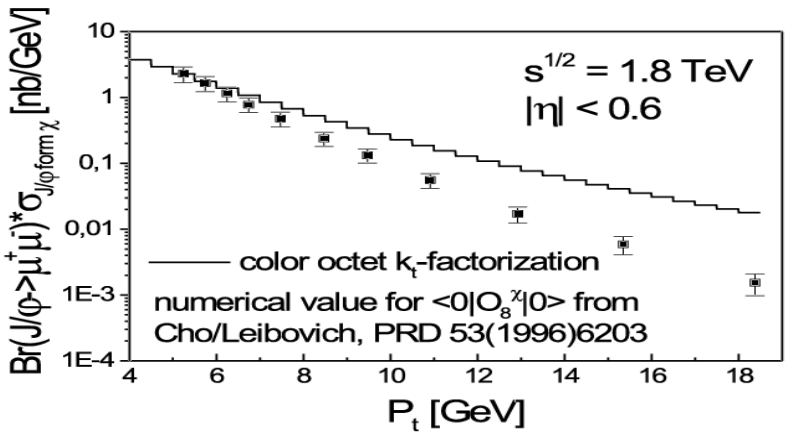
k_t Factorization

- Unintegrated gluon distribution + BFKL next−to−leading−log−approximation
- Little room for colour octet in χ_c production
- Changes values of extracted octet ME for $^3S_1^{(8)}$ by 1/30, but $^1S_0^{(8)}$ and $^3P_0^{(8)}$ not by much (see Hera−Tevatron anomaly)

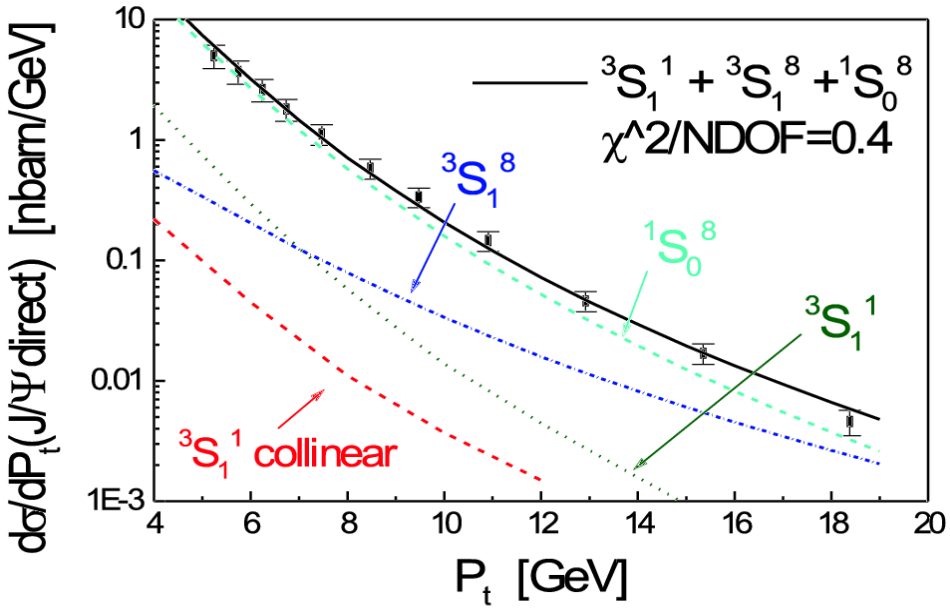


Hägler et al., hep−ph/0004263

(also Yuan, Chao)

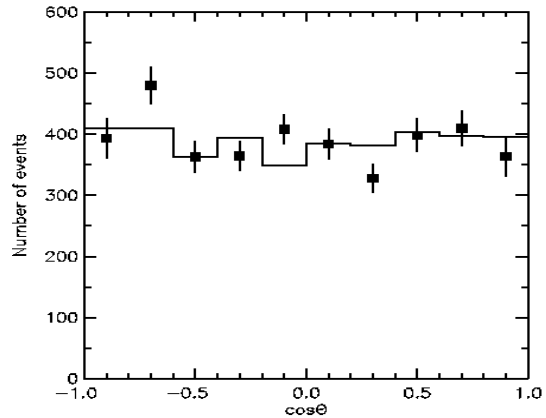


Hägler et al., hep−ph/0008316



Υ Polarization

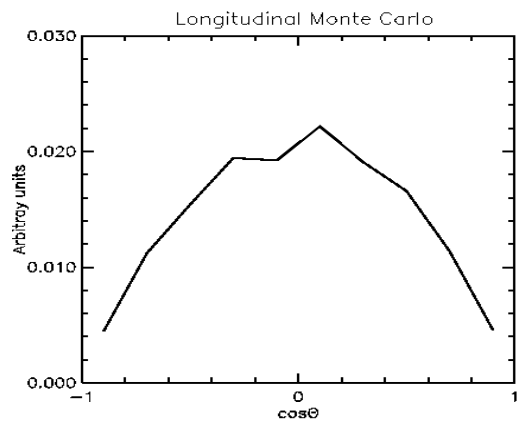
- $\alpha = -0.08 \pm 0.09$ for $2 < p_T < 20$ GeV
  - Unpolarized
- NRQCD predicts transverse polarization only for $p_T \gg m_\Upsilon$

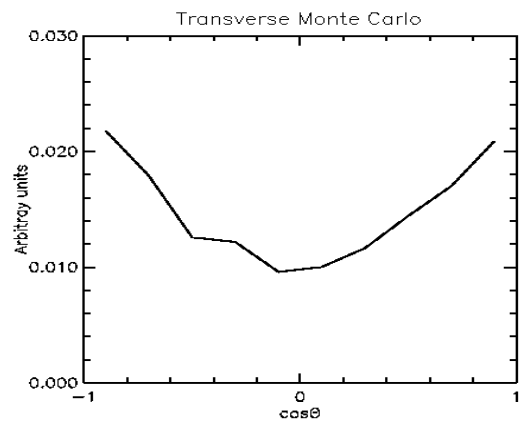


CDF Preliminary
Υ(1S) Polarization

$|y(\Upsilon)| < 0.4$
$2\ \mathrm{Gev}/c < p_T(\Upsilon) < 20\ \mathrm{Gev}/c$

$\Gamma_L/\Gamma = 0.37 \pm 0.04$

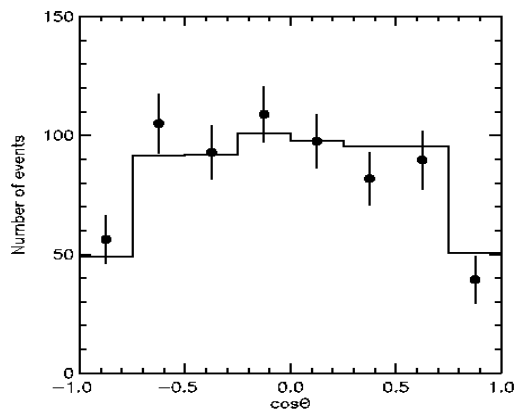




www−cdf.fnal.gov/physics/new/bottom/cdf5027/cdf5027.html

Υ Polarization (high p_T)

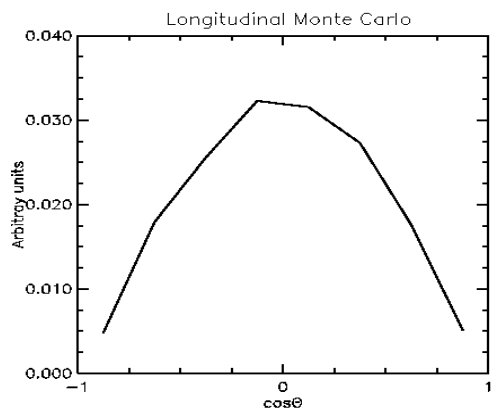
- $\alpha = 0.03 \pm 0.25$ for $8 < p_T < 20$ GeV

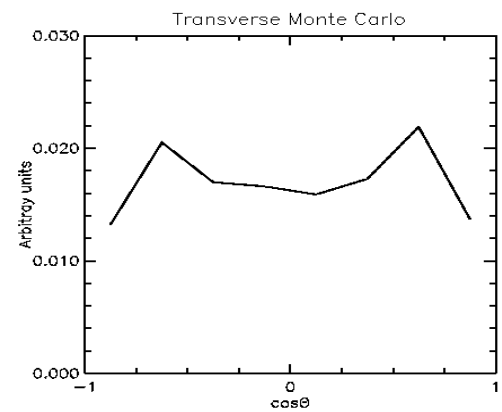


CDF Preliminary
Υ(1S) Polarization

$|y(\Upsilon)| < 0.4$
$8\ \mathrm{Gev}/c < p_T(\Upsilon) < 20\ \mathrm{Gev}/c$

$\Gamma_L/\Gamma = 0.32 \pm 0.11$



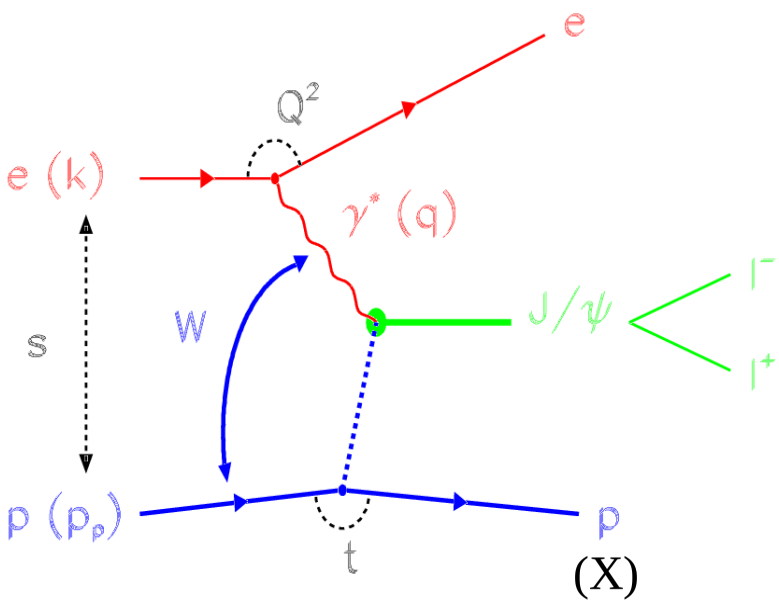


www−cdf.fnal.gov/physics/new/bottom/cdf5027/cdf5027.html

Prospects for Run II

- 2 fb^{-1} in about 2 years, beginning March 2001
- Will get many J/Ψ's for free, probably also Upsilon, but
  - Is the charm system massive enough?
  - For J/Ψ, will always have feed−down to J/Ψ final states
  - Especially for Υ, can we reach high enough p_T? Can probably get the precision of the $8<p_T<20$ GeV bin (700 candidates) in the $16<p_T<20$ GeV bin − probably $p_T \gg m_\Upsilon$ needed for theory to be reliable
- $\Psi(2S)$ not so clear
- For many measurements, there are now 2 experiments
- Also better muon coverage, improved trigger capabilities, use decays into e^+e^-, ...
- There will be other possible measurements that can shed light on the colour octet issue
  - h_c, η_c, ... production cross sections
  - Associated jets in direct production
- CDF II is in the commissioning phase

Quarkonia at HERA

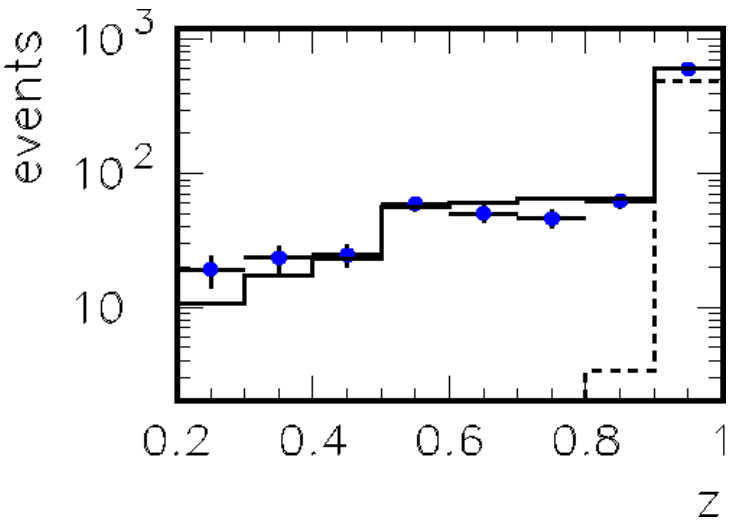


$$Q^2 := -q^2$$
$$W^2 := (p_p + q)^2 \simeq Q^2/x$$
$$Q^2 \simeq x\,y\,s$$

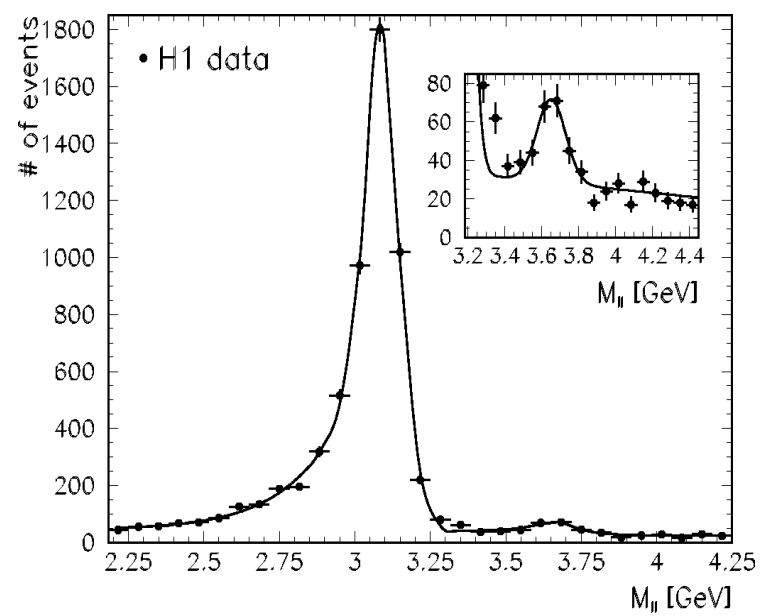
- DIS
  - $Q^2 > 1\ \mathrm{GeV}^2$
- Tagged/untagged photoproduction
  - Median $Q^2 \simeq 10^{-4}\ \mathrm{GeV}^2$
- Decays into e^+e^- and $\mu^+\mu^-$
- Central tracking ($|\eta|<1.8$)
  - $30 < W < 180$ GeV
  - In addition, dedicated analyses with specific statistical and systematic limitations (forward muon spectrometer, backward calorimetry, ...)

HERA

$$z = \frac{P_p \cdot P_\Psi}{P_p \cdot P_\gamma} = \frac{E_\Psi}{E_\gamma} \qquad \text{in p rest frame}$$

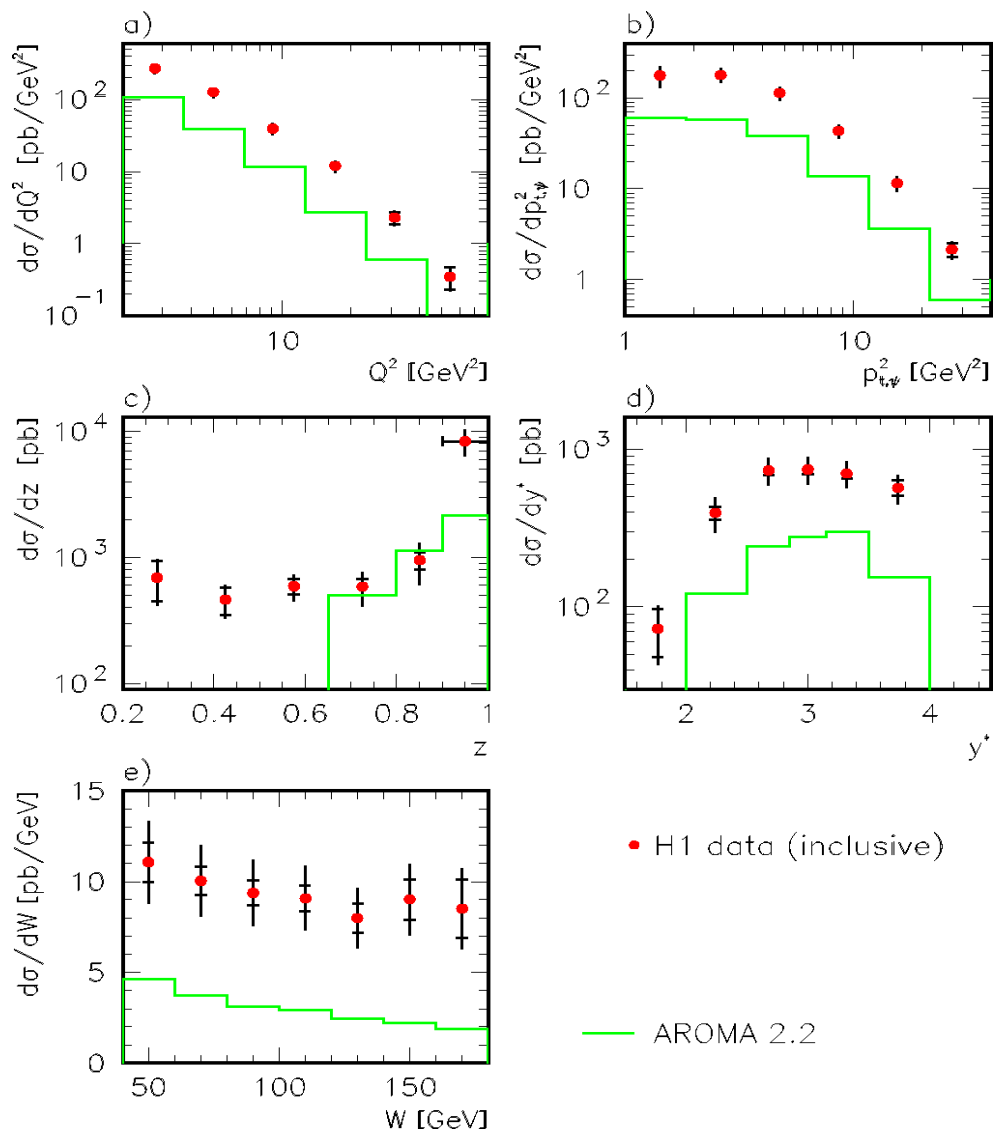


- Order of magnitude comparable
  - "Elastic" $z \simeq 1$ ($M_X = m_p$)
  - p diffractive dissociation $z \simeq 1$ ($\sigma \propto 1/M_X^2$)
  - "Inelastic" $z < 1$
- Small contributions (small z) from
  - Resolved photon
  - B production
- Background increases with decreasing z
- Typically 3−50/pb integrated luminosity
  - > 100/pb on disk per experiment



Inclusive J/Ψ Production in DIS

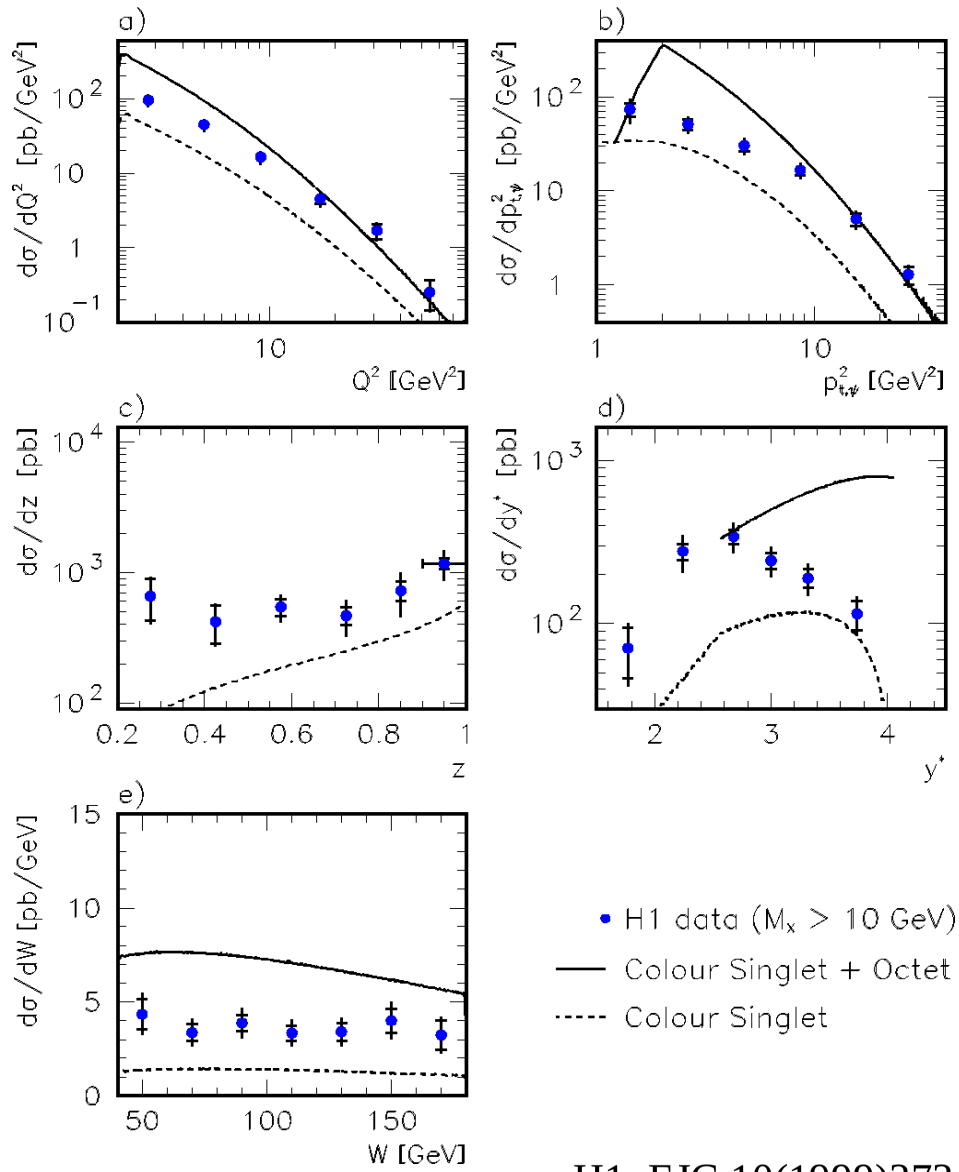
- $2 < Q^2 < 80\ \mathrm{GeV}^2$
- $40 < W < 180$ GeV
- 27 pb^{-1} collected in 1995–97
- Phenomenological model of Soft Colour Interactions (Aroma) give reasonable description of data
  - $d\sigma/dz$ not described: Aroma includes only the LO BGF matrix element; colour singlet contribution missing
  - SCI prediction undershoots data



H1, EJC 10(1999)373

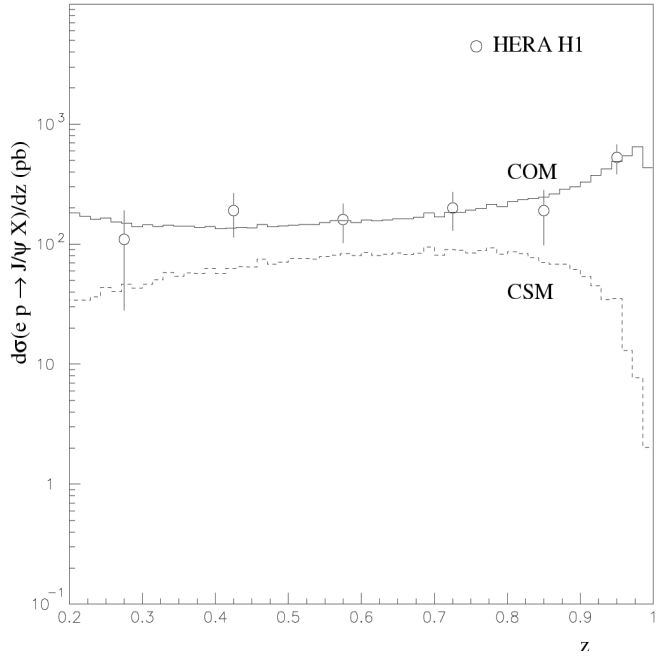
Inelastic J/Ψ Production in DIS

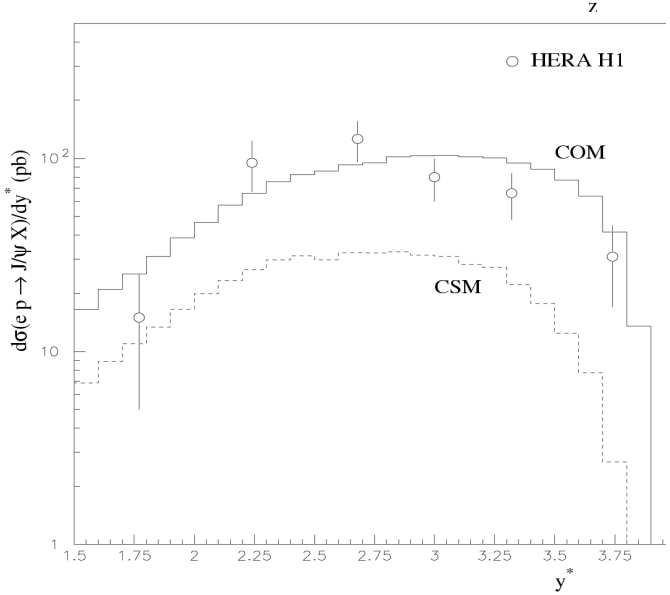
- Avoid cutting in z, which is theoretically unsafe
  - instead, remove contribution with a low mass proton remnant, by using forward calorimetry
  - M_X>10 GeV should keep colour octet contributions (Fleming/Mehen)
- LO colour singlet describes some aspects, but is too low
- LO colour octet + singlet using ME extracted from CDF data don't fit
- Need for
  - NLO?
  - hadronization effects?
  - adjusting CO ME?



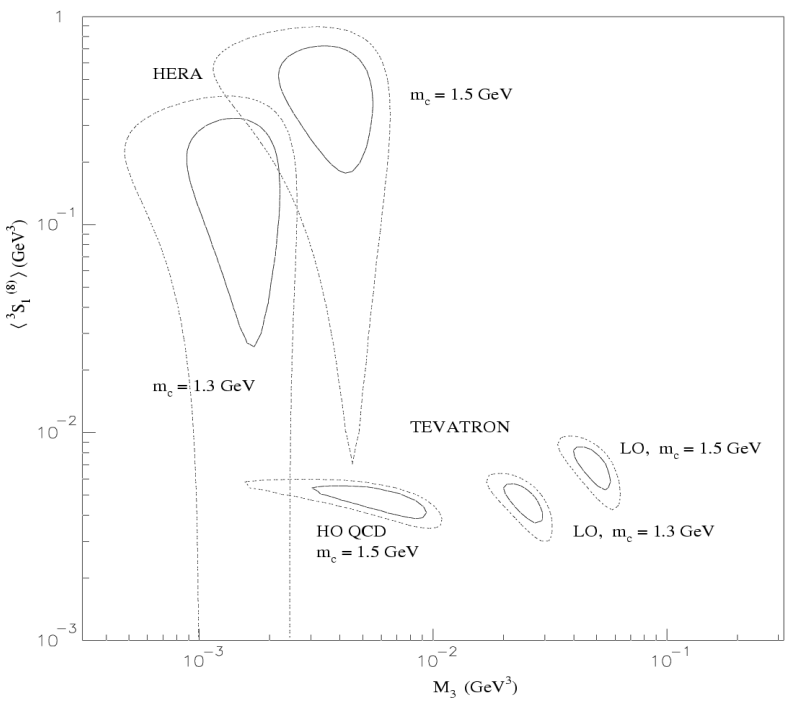
H1, EJC 10(1999)373

HERA vs. Tevatron ME





- Only use theoretically safe regime: p_T^2, $Q^2 > 4\ \mathrm{GeV}^2$, $M_X > 10$ GeV
  - Statistics limited
- Consistent description seems difficult



J.K.Mizukoshi, hep−ph/9911384

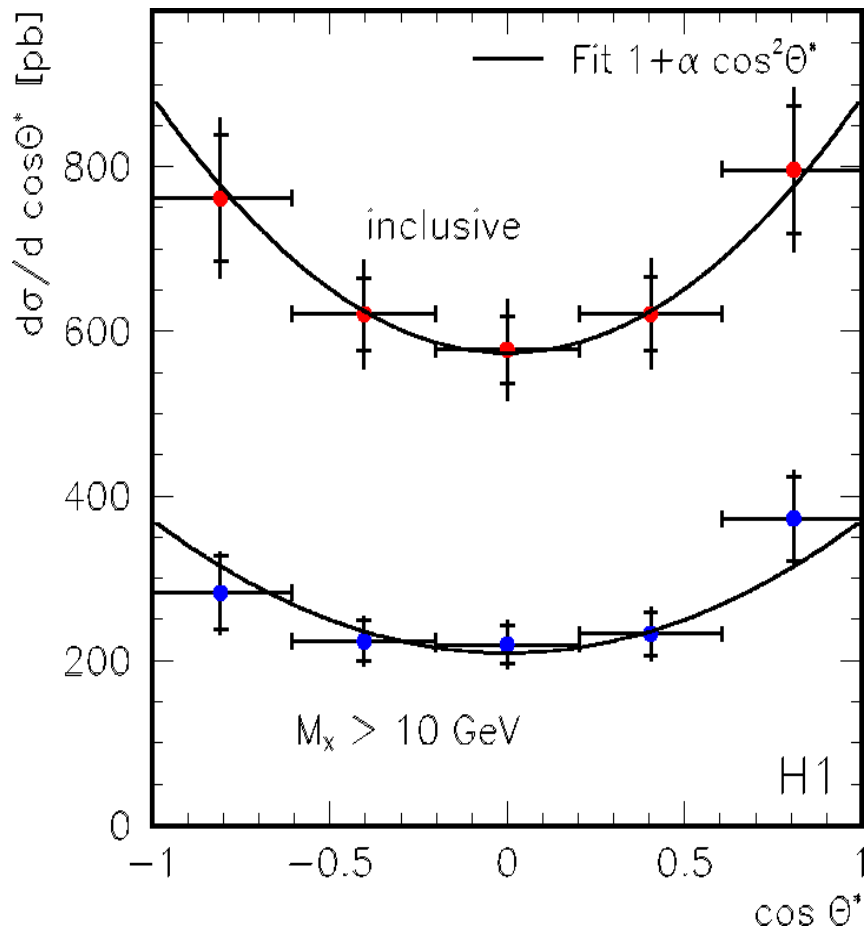
J/Ψ in DIS: Polarization

- Again, polarization of J/Ψ is one way to distinguish production mechanisms
- Expect $\alpha \simeq 0.5$ for colour singlet, $|\alpha|<0.5$ for colour octet, with sign depending on which intermediate state dominates
- Measure

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

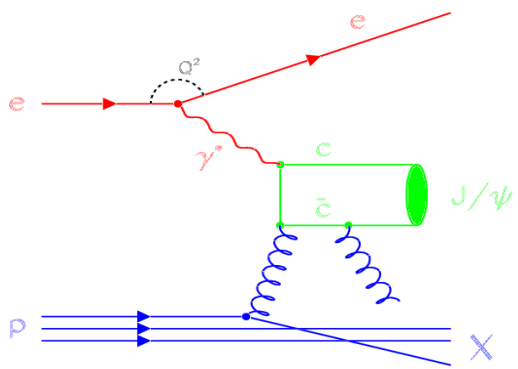
$$\alpha = 0.77^{+0.44}_{-0.38} \quad (M_X > 10\ \text{GeV})$$

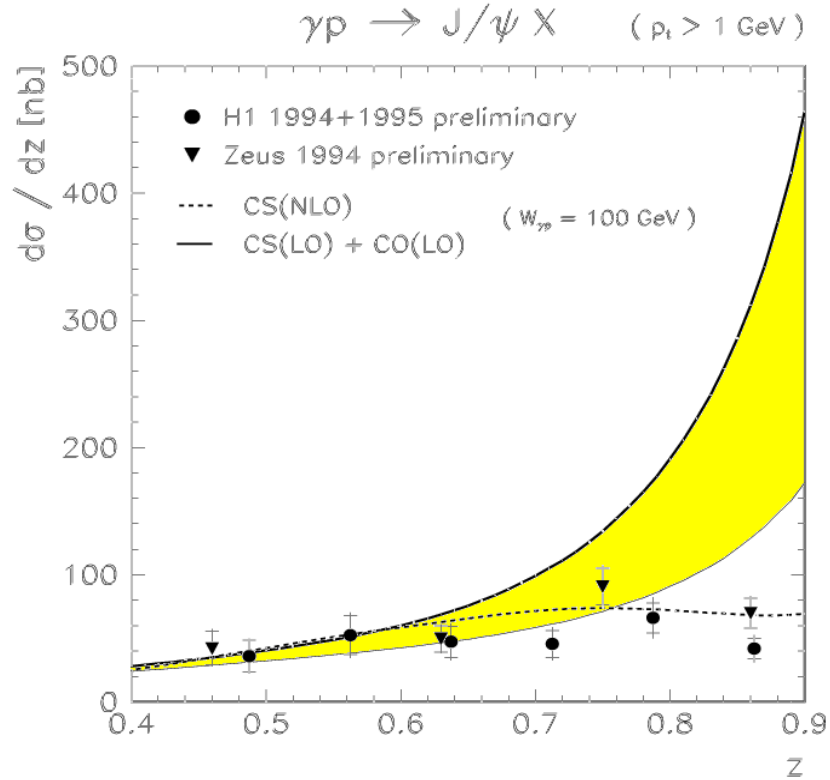
- Could become interesting with more data



H1, EJC 10(1999)373

J/Ψ Photoproduction – historic



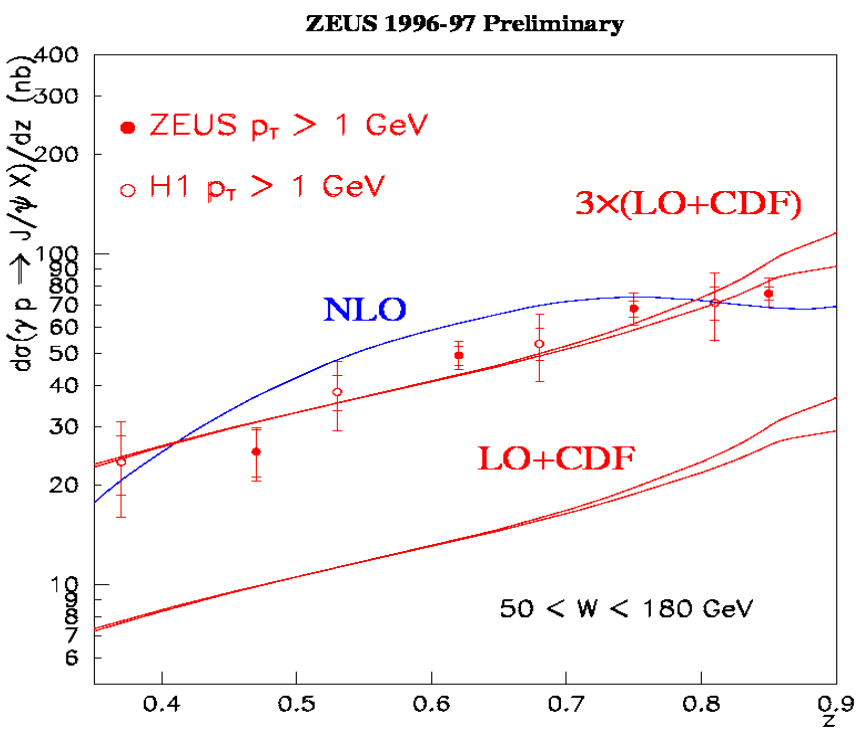


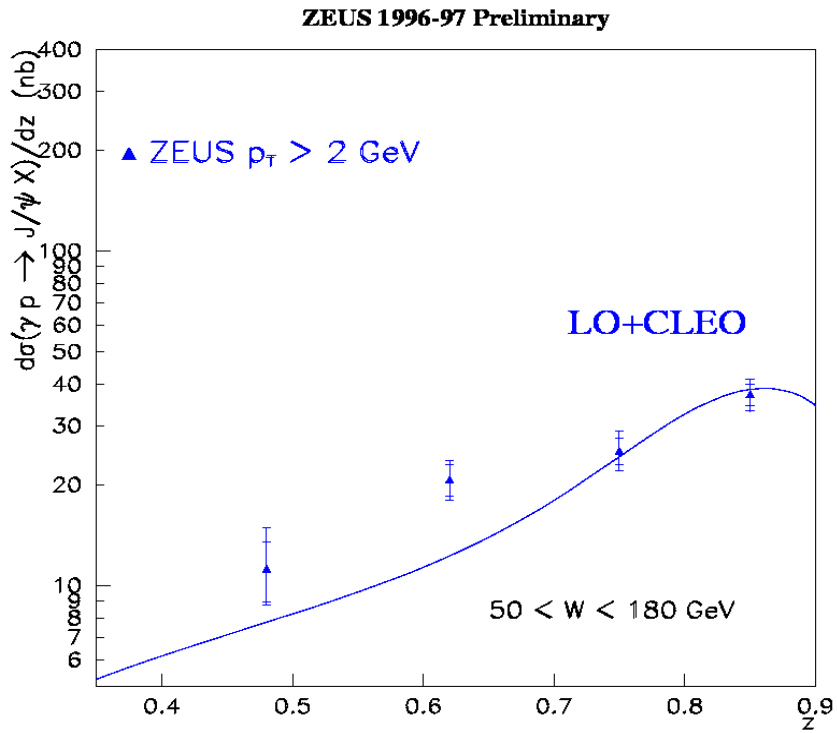
- Extract gluon density from

$$\sigma(\gamma\, p \to c\,\bar{c}\,X) = \int dx_g\, G(x_g, \mu^2)\ \sigma(\gamma\, p \to c\,\bar{c})$$

- Use colour octet ME from CDF data to predict HERA cross section, dσ/dz (Cacciari, Krämer, Phys.Lett. 76 (1996) 4128)
  - the other HERA anomaly

J/Ψ Photoproduction



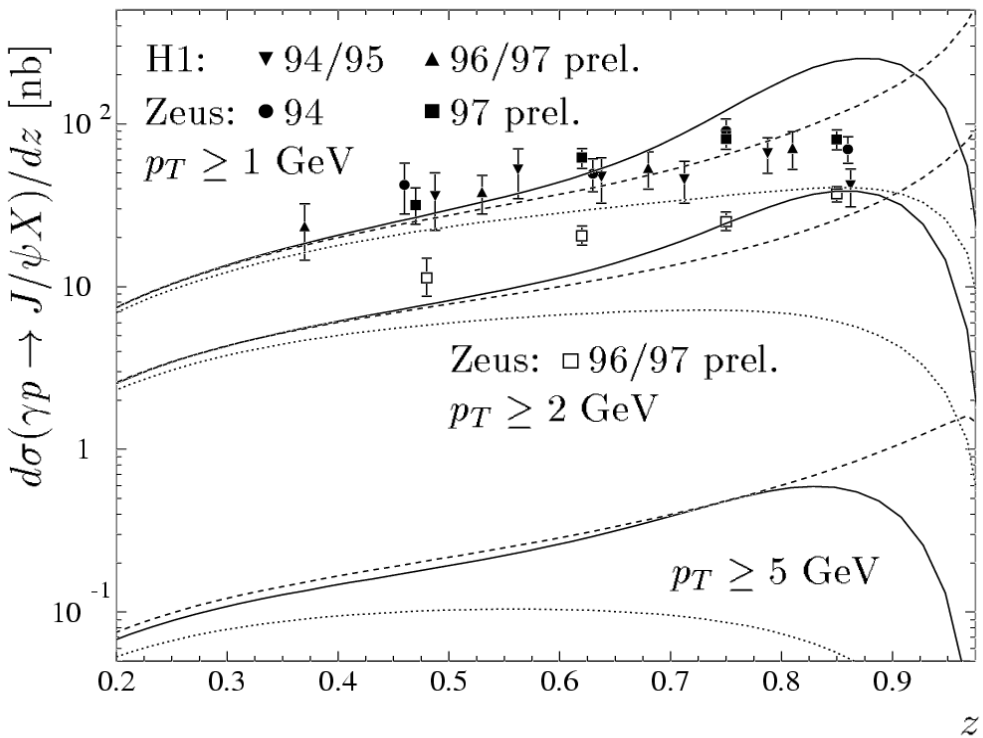


ZEUS, ICHEP 2000 (#446)

- Colour singlet + octet with CDF ME: shape OK, but undershoots data
- NLO direct colour singlet: fine!
- Sensitive to direct colour singlet
- For p_T>2GeV, colour singlet + octet with CLEO ME looks quite good, without k−factor

J/Ψ Photoproduction: Shape Functions

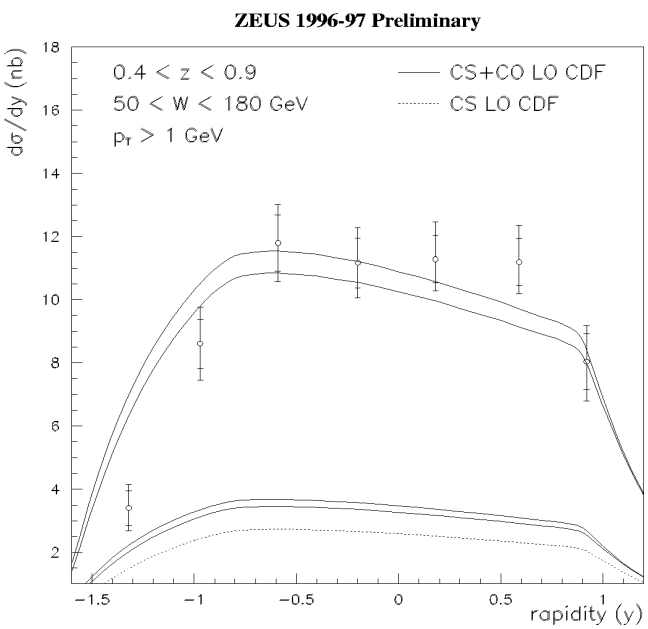
- Breakdown of the NRQCD velocity expansion near the kinematic endpoint, when the J/Ψ carries close to its maximal energy
  - $z > 1 - v^2 \simeq 0.7$
- Introduce shape functions for each production channel
- Improved description of the data
- Less predictive power of theory
  - Need higher p_T

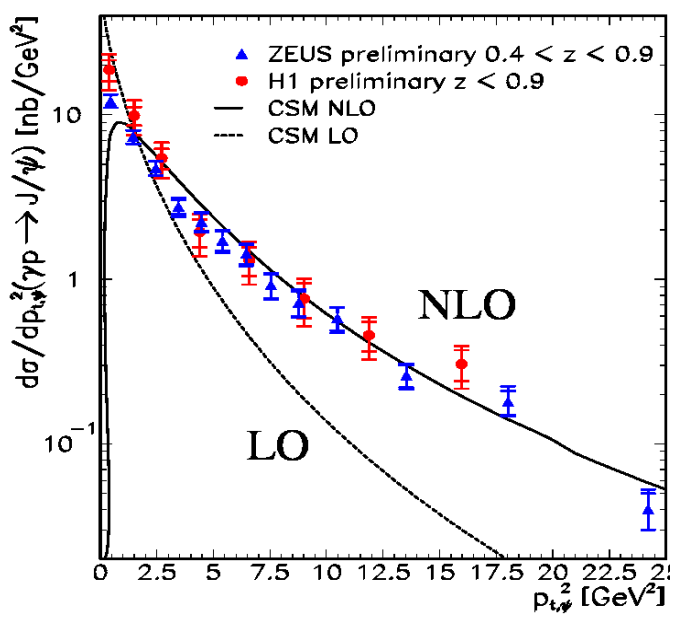


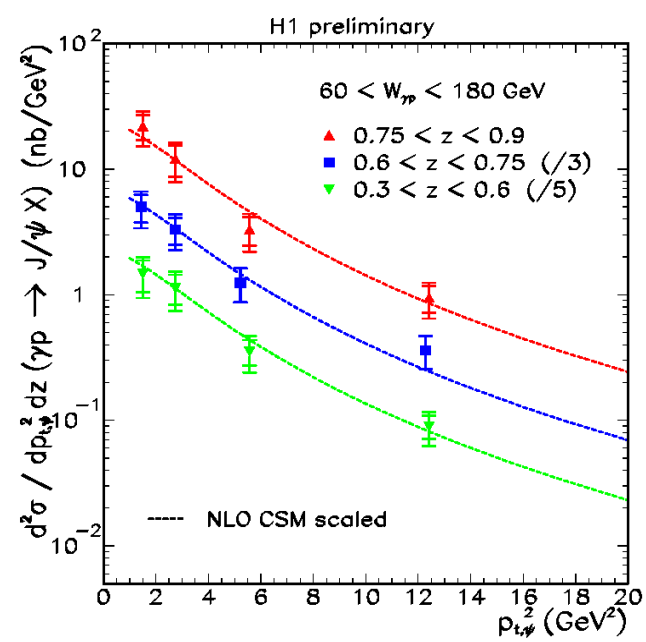
Beneke, Schuler, Wolf, PRD 62(2000)034004
Wolf, hep−ph/0008180

J/Ψ Photoproduction

- Rapidity distribution: colour singlet + octet (CDF ME) too low, some shape discrepancy
- p_T distribution: colour singlet NLO direct describes shape and normalization







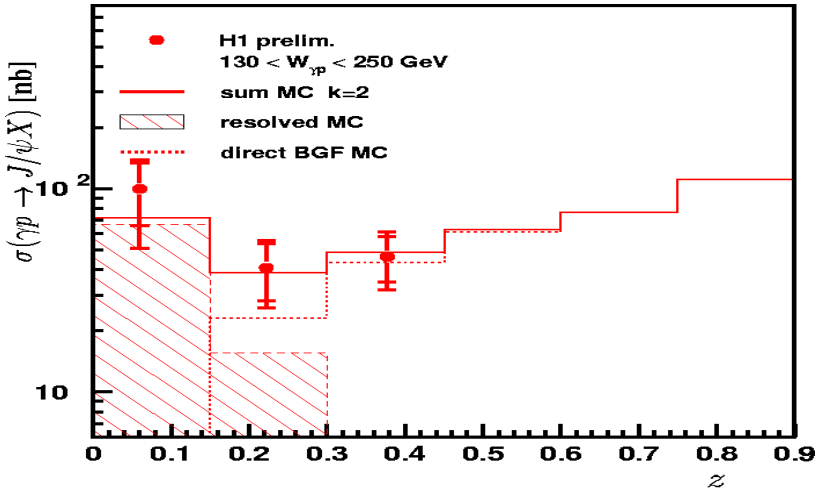
ZEUS, ICHEP 2000 (#446); H1, EPS 1999 (#157aj)

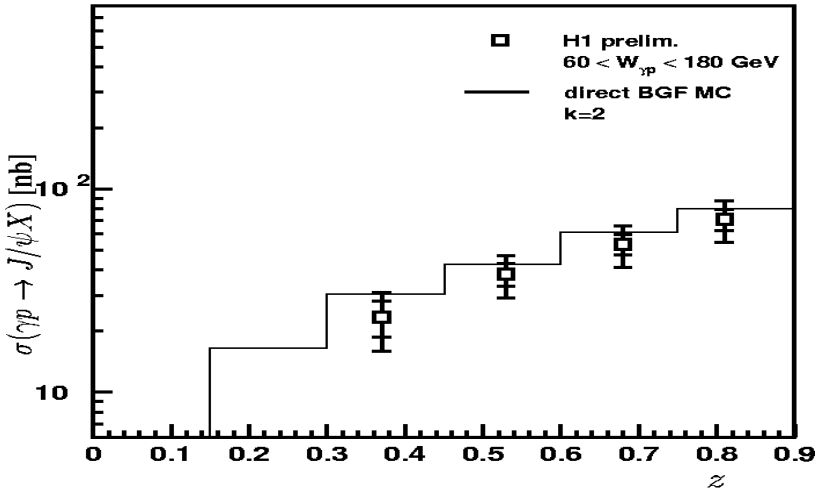
Arnd Meyer
Oct 11, 2000

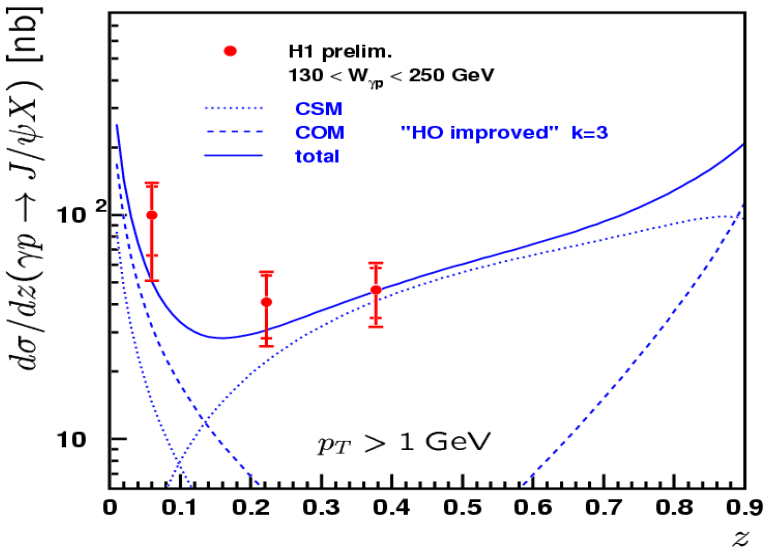
J/Ψ Photoproduction: low z

- First look at low z region
  - Resolved photon component
  - B production (small)
- Detector accepance: low z ⇔ high W
  - No direct comparison
- Monte Carlo simulation:
  - LO photon−gluon and gluon−gluon fusion
  - k−factor 2
- Need resolved contribution to describe data

$p_T > 1$GeV



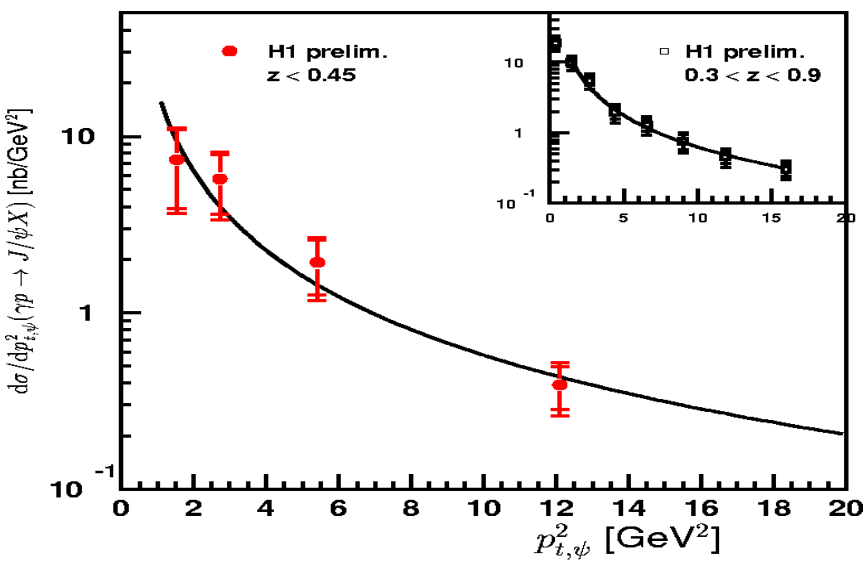


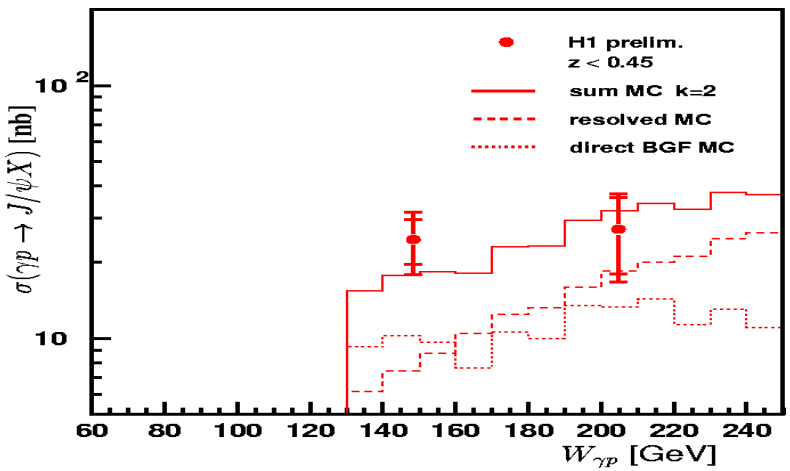


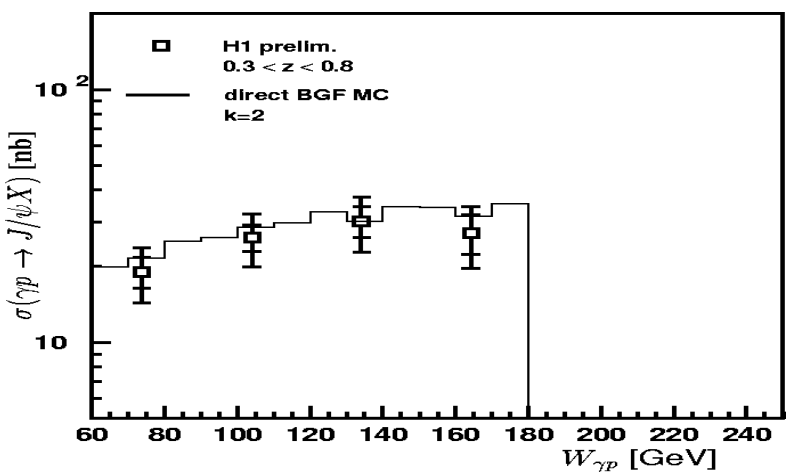
H1, DIS 2000

J/Ψ Photoproduction: low z

- p_T^2 shape does not depend significantly on z
- Resolved component increases with W

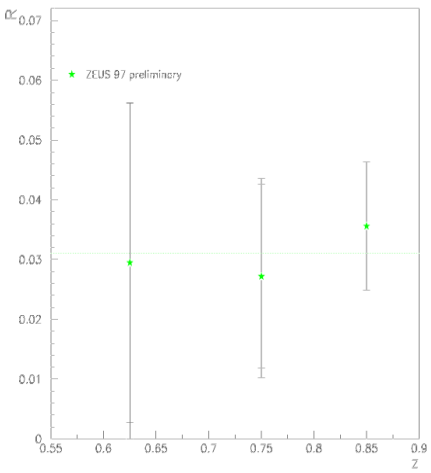


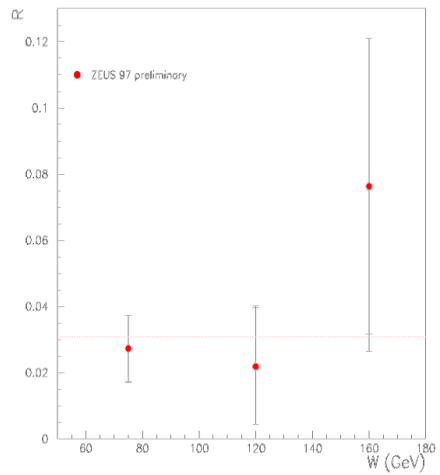


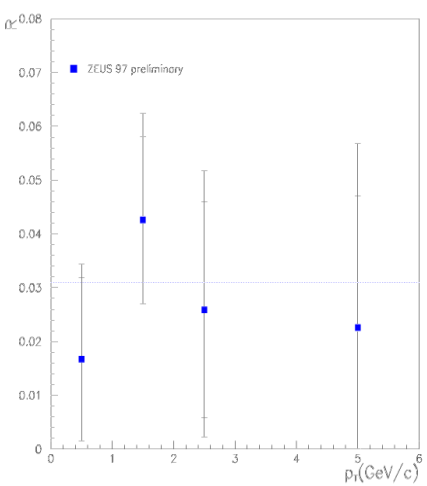


H1, DIS 2000

Ψ(2S)/J/Ψ Ratio







ZEUS, EPS 1999
H1, EPS 1999

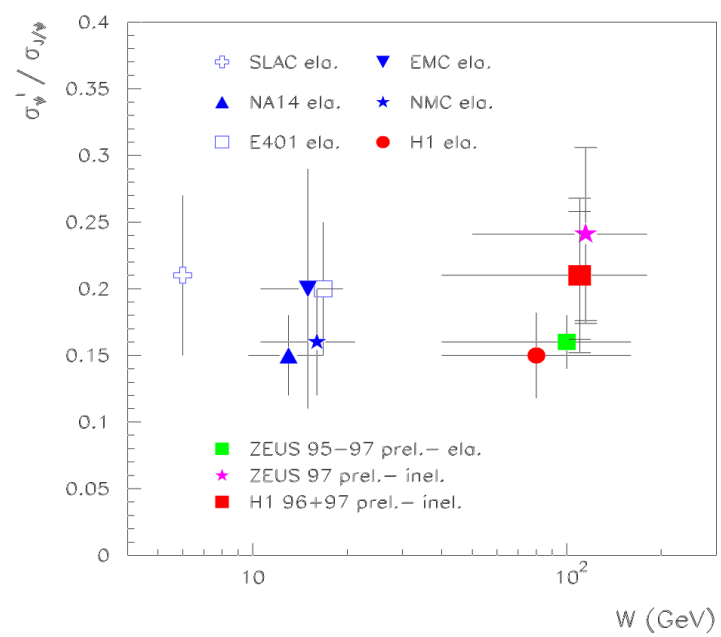
- Ψ(2S) is the only significant feed−down to J/Ψ at HERA
- Ψ(2S) / J/Ψ flat in z, W, p_T
- naïve expectation:

$$R = \frac{B_{\Psi'}}{B_{\Psi}} \cdot \left(\frac{m_{\Psi}}{m_{\Psi'}} \right)^3 \cdot \frac{\Gamma_{\Psi' \to ll}}{\Gamma_{\Psi \to ll}} = 0.031$$

- $\simeq$10% contribution to J/Ψ cross section

measured:

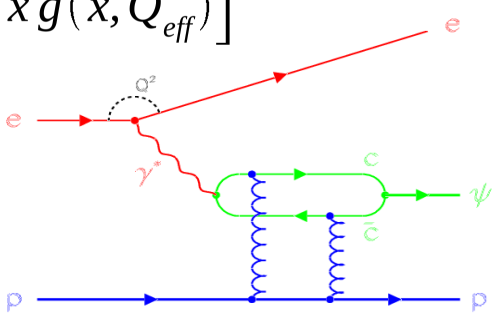
$$R = \frac{B_{\psi'} \sigma_{\psi'}}{B_{J/\psi} \sigma_{J/\psi}}$$

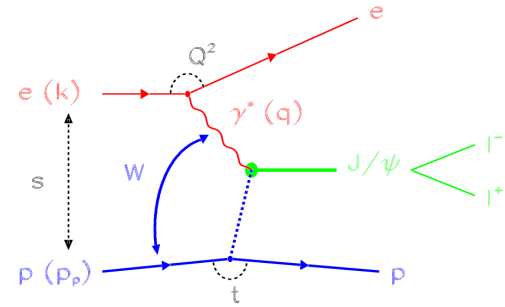


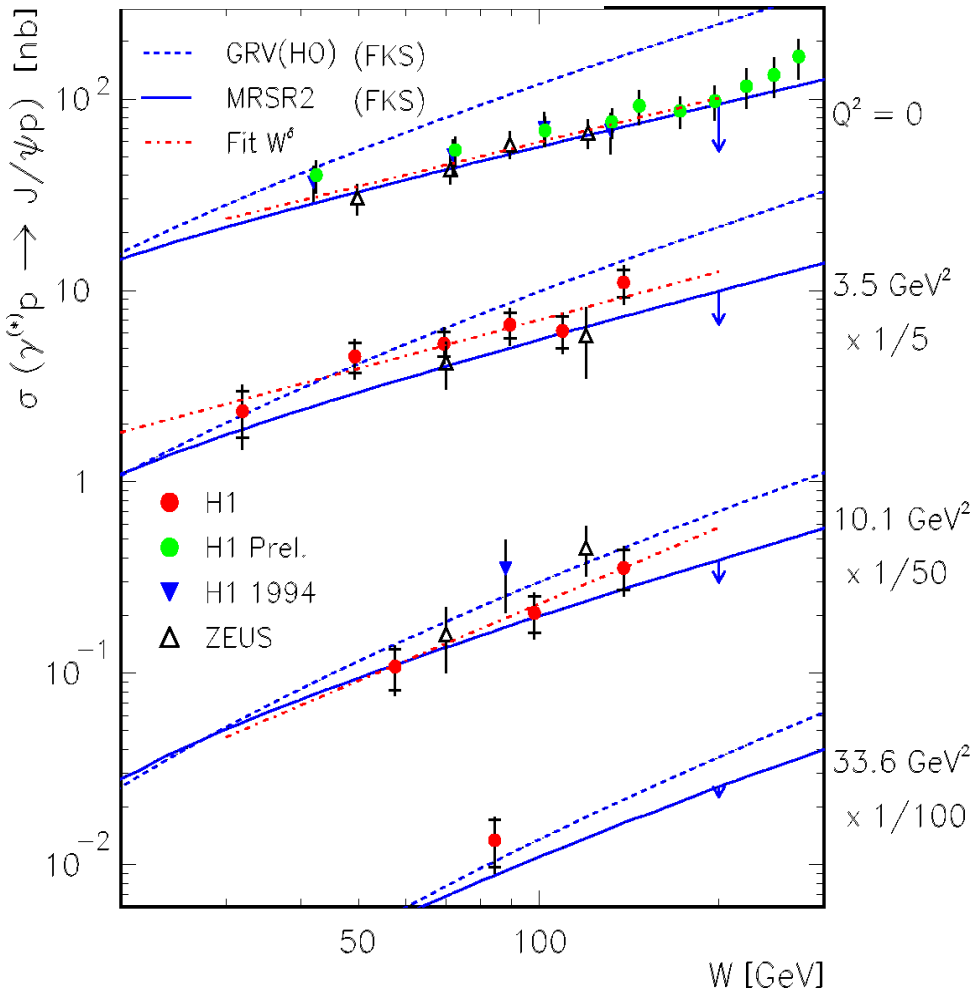
Elastic J/Ψ Production: W

- Strong rise of the cross section with W
  - Signature for "hard" process
  - $\sigma_{\gamma p} \propto W^{0.8}$
- "Soft" Pomeron exchange: slow rise of cross section $\propto W^{0.22}$
- "Hard" process (pQCD applicable):
  - Colourless exchange as gluon ladder
  - Factorization
    - Photon fluctuates into $c\bar{c}$
    - $c\bar{c}$ scatters off proton
    - Bound state formation
  - Steep rise of cross section driven by gluon density:

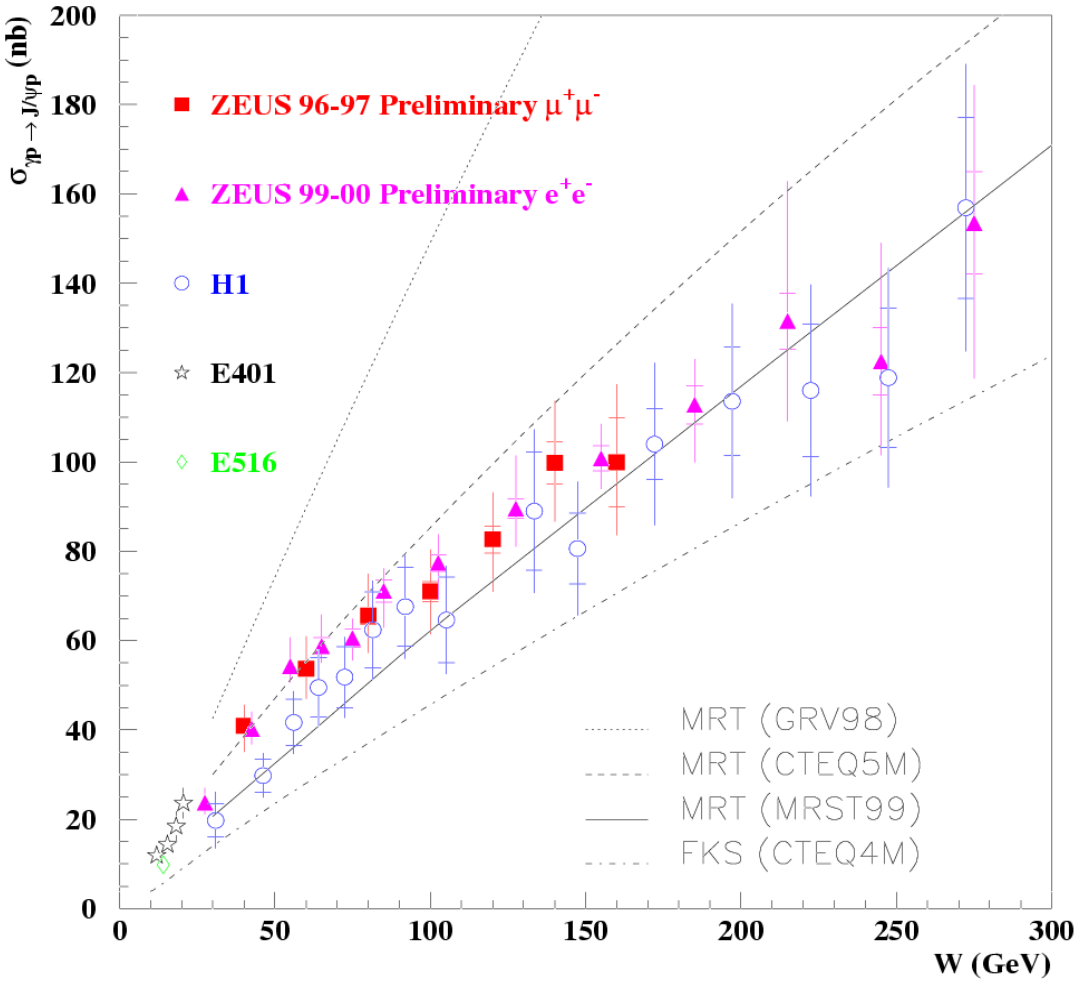
$$\sigma_{\gamma p} \propto \left[\alpha_s(Q^2_{eff})\, x\, g(x, Q^2_{eff})\right]^2$$







Elastic J/Ψ Production: W



- Large spread in model predictions
  - Choice of wave function
  - Parton density functions
  - Charm quark mass
  - Fermi motion
  - ...

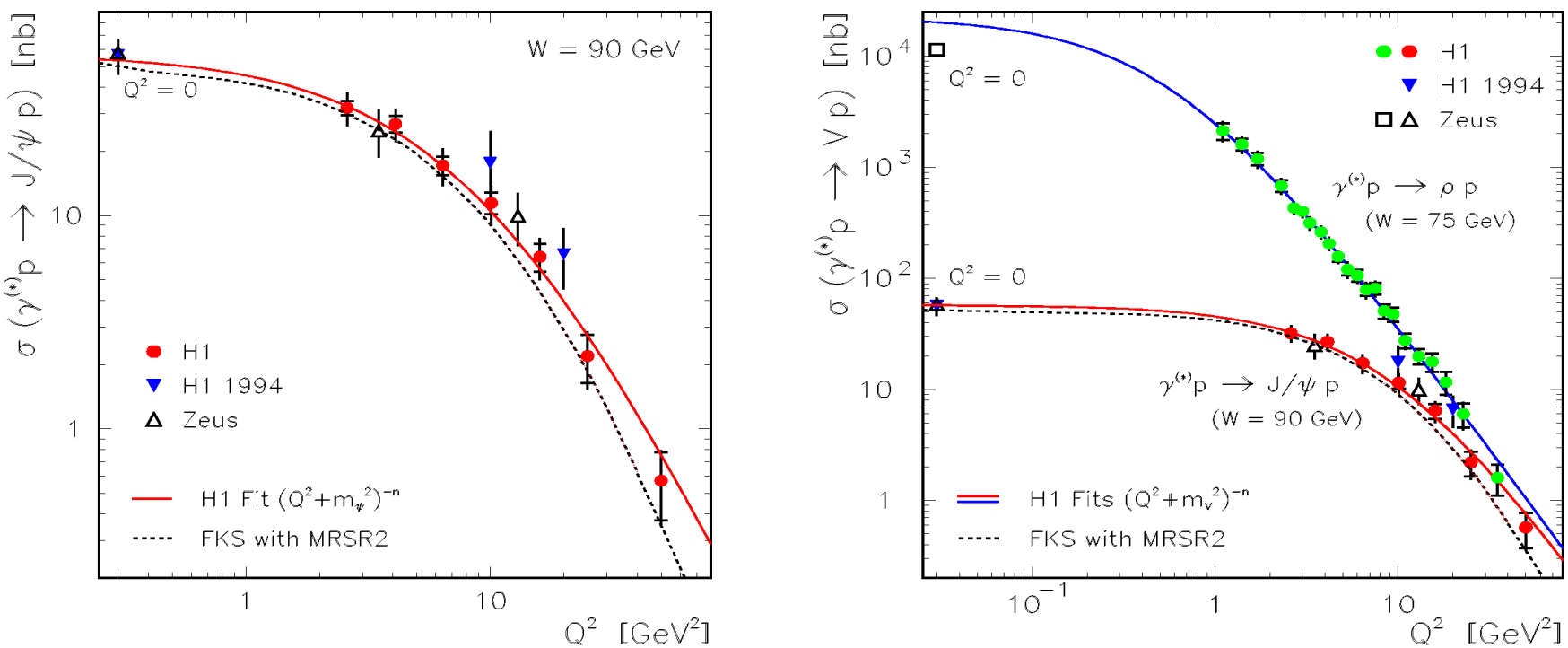
ZEUS, ICHEP 2000 (#437)

Elastic J/Ψ Production: Q^2

- Data are well described by the functional form

$$\sigma_{\gamma p \to J/\Psi\, p} \propto \left(\frac{1}{Q^2 + m_\Psi^2} \right)^n \quad \text{with} \quad n \simeq 2.4$$

- ρ and J/Ψ cross sections comparable at large Q^2

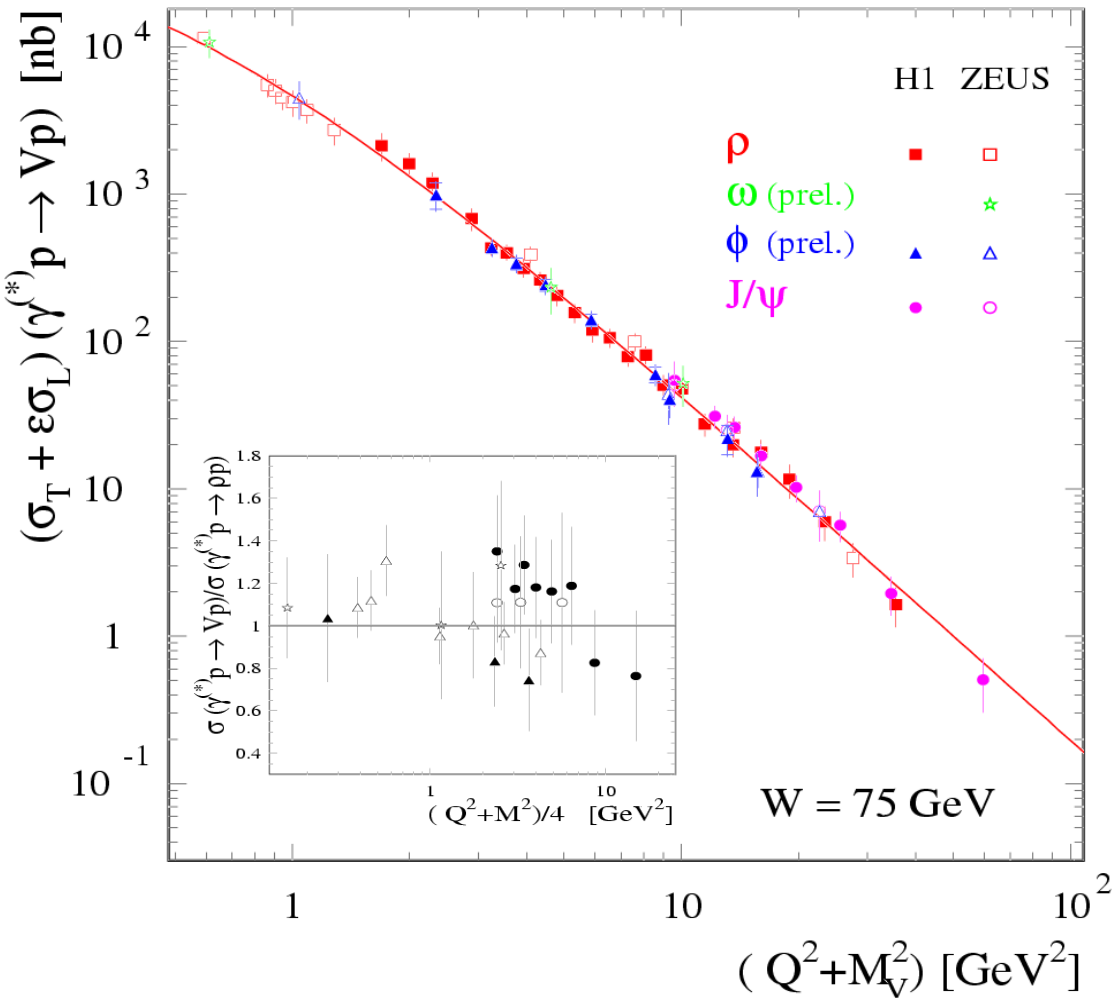


Scale of the Interaction

- In search of the relevant scale
  - Q^2, m_V^2, t
- $(Q^2 + m_V^2) / 4$ looks universal
- Photon couples to quarks, and VM − proton interaction is universal
- Fit to $(Q^2 + m_V^2 + a)^b$ (ρ data)
  - $a = 0.42 \pm 0.09$ GeV^2
  - $b = -2.37 \pm 0.10$
- Measurements at large t
  - VM cross section ratios rise faster with t than with Q^2
  - t plays a different role

Cross sections scaled according to quark content

$$\rho : \omega : \phi : J/\Psi : Y = 9:1:2:8:2$$



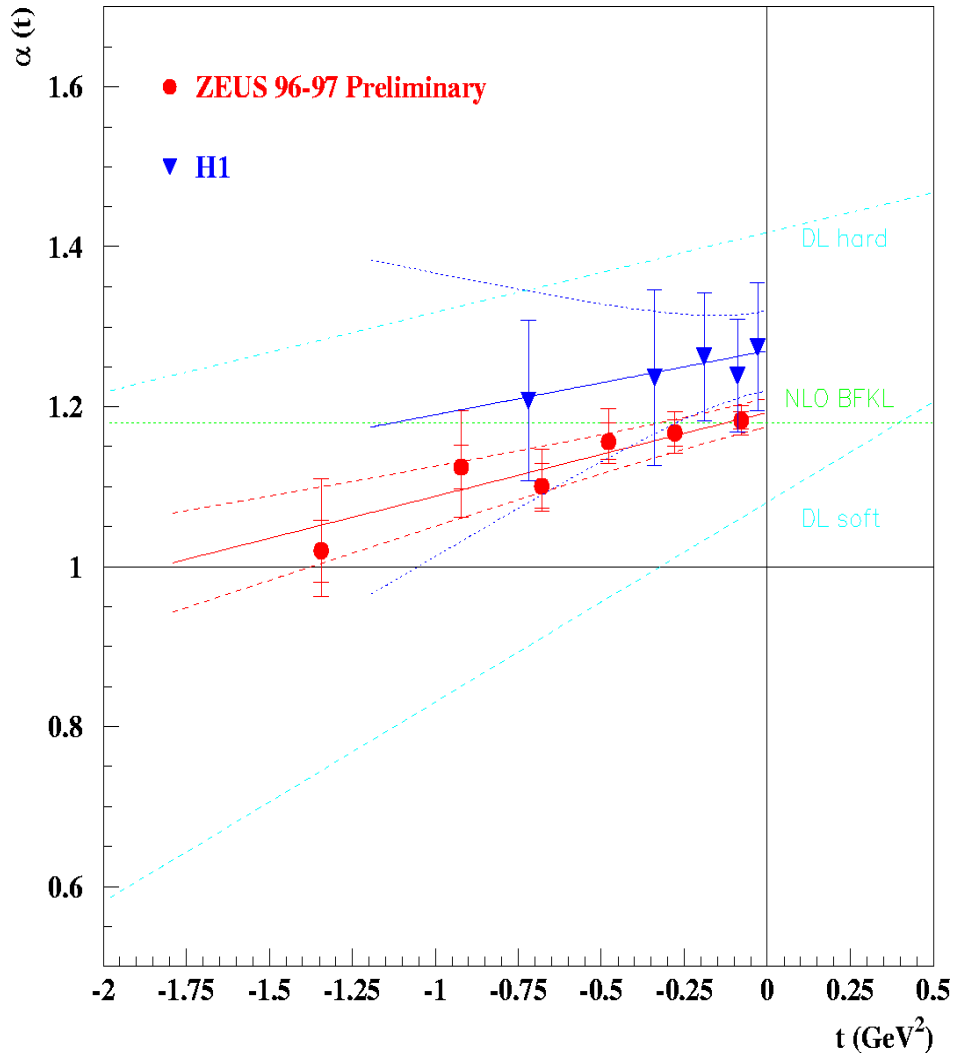
H1, Moriond 2000

Elastic J/Ψ Production: "Shrinkage"

$$\frac{d\sigma}{dt} = F(t) \cdot (W^2)^{2\alpha_P(t)-2}$$

- Usually assume $\alpha_P(t) = \alpha_P(0) + \alpha' t$
- $\alpha_P(0)$ is much larger for J/Ψ than for the "soft" Pomeron trajectory
- Expect $\alpha' \simeq 0.25\ \mathrm{GeV}^{-2}$ for "soft" Pomeron, but small for "hard" process
- Most direct determination: measure $d\sigma/dt$ as a function of W for fixed t
- Shrinkage small in J/Ψ photoproduction

$$\alpha_P(t) = (1.19 \pm 0.02) + (0.11 \pm 0.03\,\mathrm{GeV}^{-2}) \cdot t$$



ZEUS, ICHEP 2000 (#437)

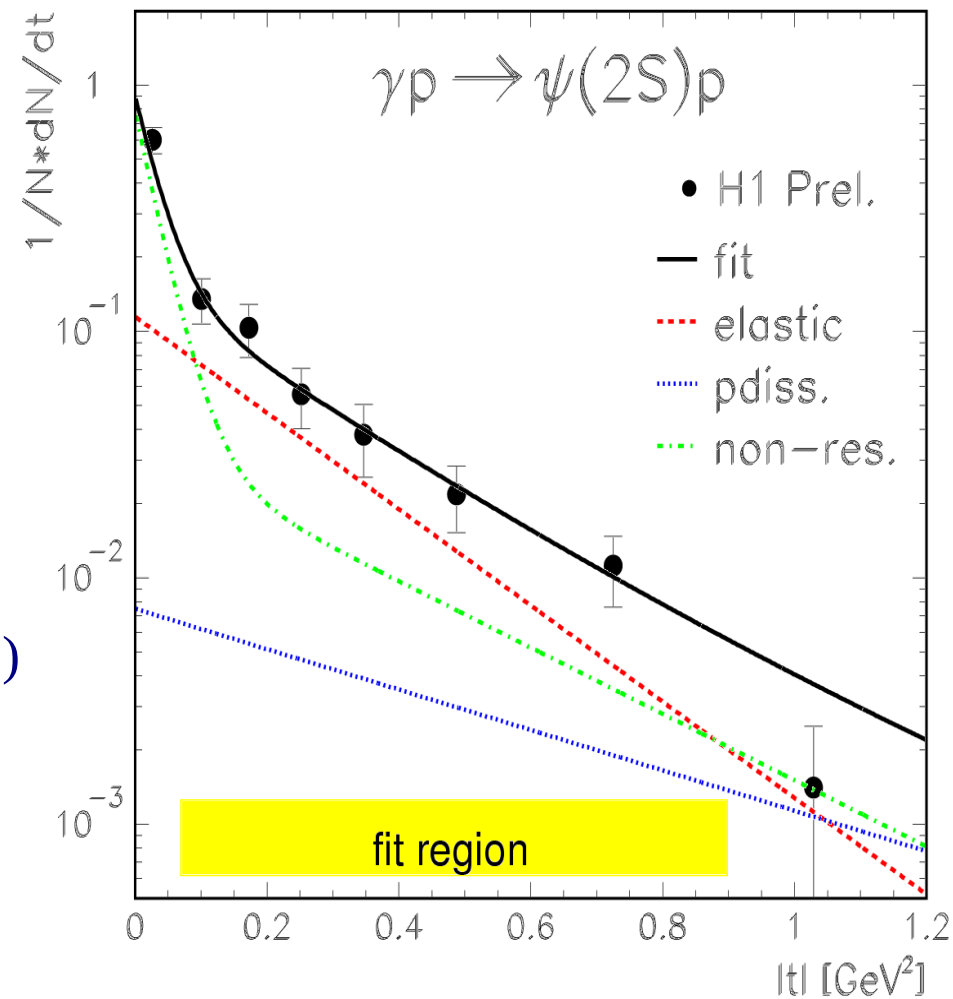
Elastic Ψ(2S) Photoproduction

- Important background to elastic J/Ψ production
  - reduce systematic uncertainties
- Interesting in itself due to node effect (wave function)
- Result assuming $d\sigma/dt \propto e^{-bt}$:

$$b = 4.5 \pm 1.2(stat)\ ^{+1.4}_{-0.7}(syst)\,\mathrm{GeV}^{-2}$$

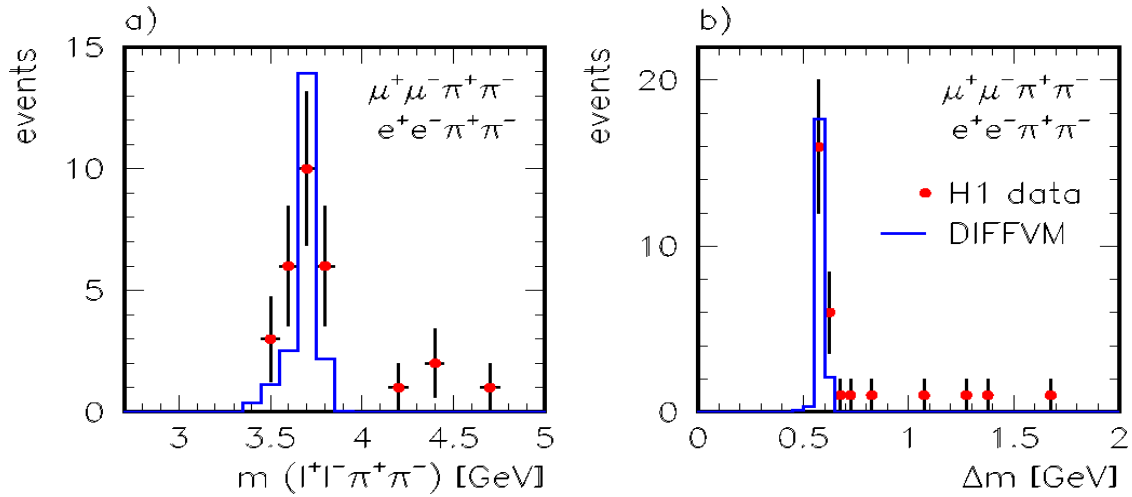
- Similar to J/Ψ (compare ~ 10 GeV^{-2} for ρ)
  - Small size $q\bar{q}$ configurations,

$$b \propto R_p^2 + R_V^2$$

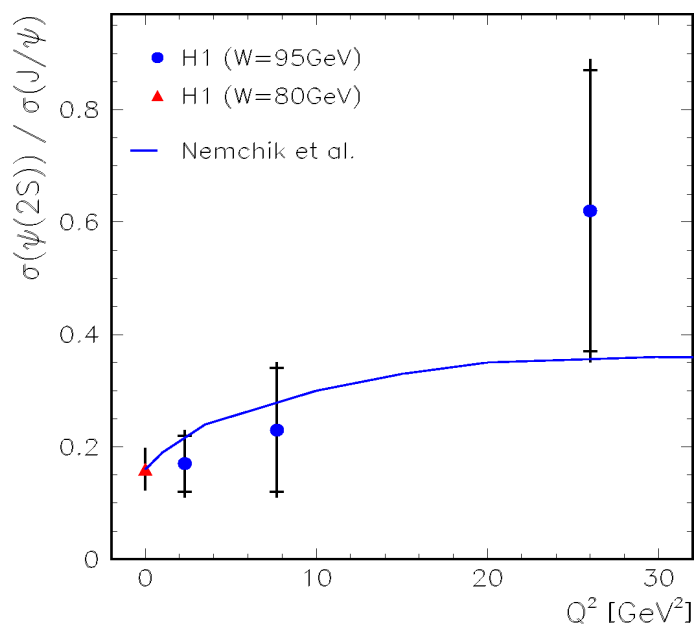


H1, ICHEP 2000 (#300)

Elastic Ψ(2S) Production in DIS



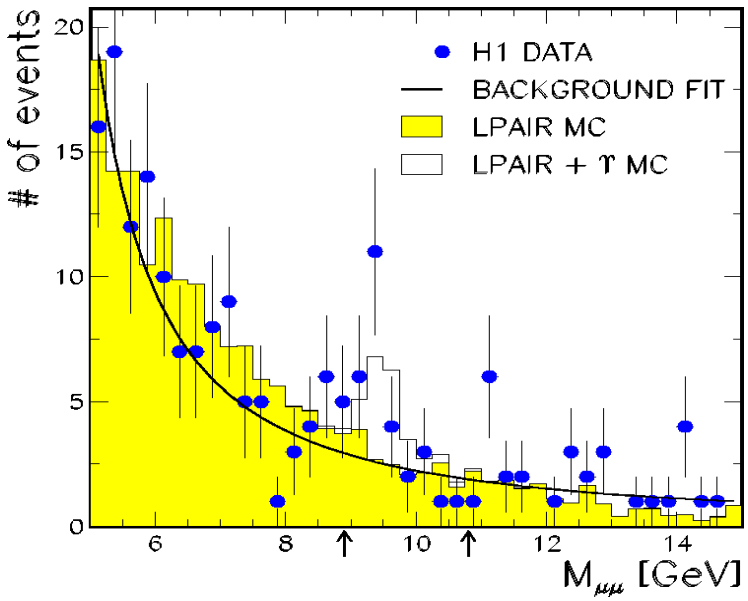
- Indication for a rise with Q^2, compatible with QCD expectations

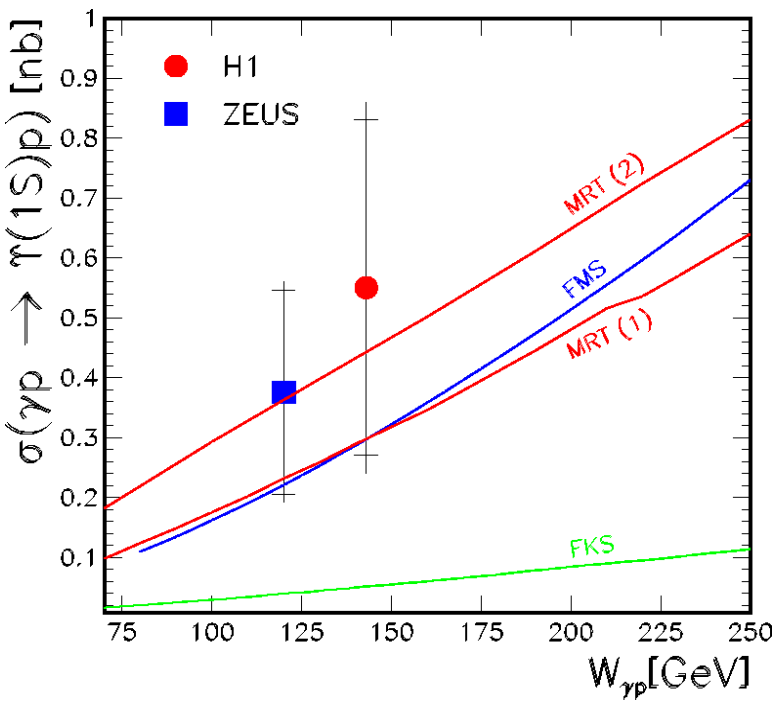


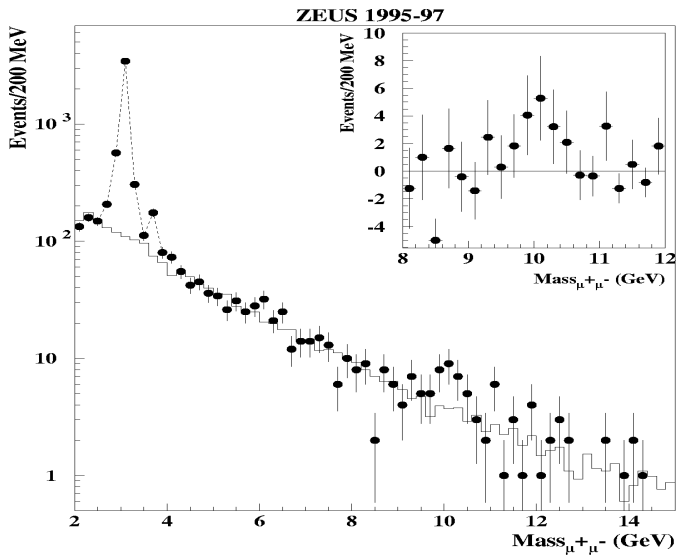
H1, EJC 10(1999)373

Elastic Υ Production

- Interesting input to phenomenology (skewed parton distributions)
- Needs lots of additional data
- Υ(1S), Υ(2S), Υ(3S) not resolved (yet)







H1, PL B483(2000) 23
ZEUS, PL B437(1998) 432

HERA Prospects

- Very successful 2000 running period ended in September
  - Another > 50 pb^{-1} per experiment, giving a total of > 100 pb^{-1}
- Most analyses do not yet make use of the full data sets
- After the HERA upgrade:
  - ~1 fb^{-1} per experiment until ~2005
  - Polarized $e^{\pm}$ beams
- Various detector upgrades
  - ZEUS Silicon
  - New fast track trigger for H1
  - ...

Conclusions

- Quarkonium production at HERA and the Tevatron revealed quite a few surprises
  - Large J/Ψ and Ψ(2S) cross sections at the Tevatron
  - J/Ψ and Ψ(2S) polarization from CDF
  - Steep rise of the elastic J/Ψ cross section at HERA
- Theorists invented quite a few explanations
  - Colour octet
  - Two Pomerons
  - ...
- ... and still new surprises came up
  - HERA / Tevatron anomaly
- I hope there is still more to come