Charmonium Production in Deep-Inelastic Scattering

Bernd Kniehl
II. Institut für Theoretische Physik
Universität Hamburg
Luruper Chaussee 149, 22761 Hamburg
Germany
kniehl@desy.de

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[1] B.A. Kniehl, L. Zwirner, Nucl. Phys. **B621** (2002) 337.
[2] B.A. Kniehl, L. Zwirner, Nucl. Phys. **B637** (2002) 311.
[3] B.A. Kniehl, L. Zwirner, DESY 02-134.

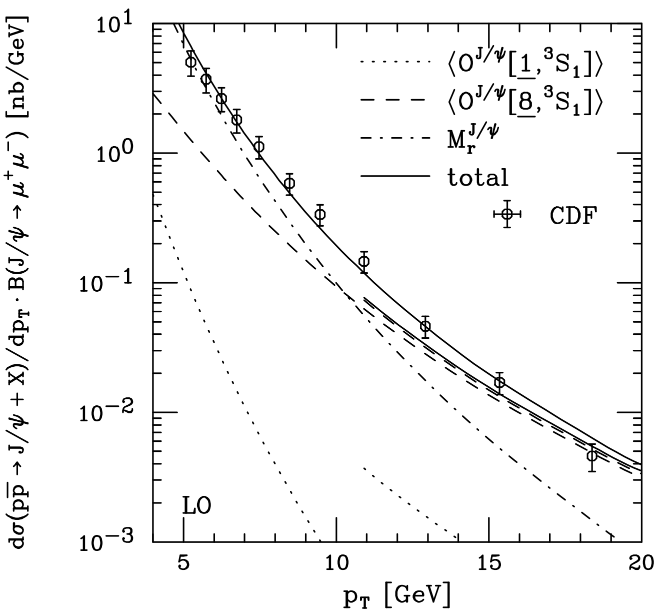
1 Introduction

Heavy quarkonium H provides useful laboratory for QCD tests.

Color Singlet Model:[4] Factorization in perturbative short-distance part $(\alpha_s(m_Q),\ m_Q)$ and nonperturbative long-distance part $(R_S(0),\ R'_P(0))$; $Q\overline{Q}$ pair must have same quantum numbers as heavy quarkonium.

Failure of CSM:

- No general argument for validity in higher orders.
- Logarithmic IR divergences in P-wave decays to light hadrons and relativistic corrections to S-wave annihilation.
- Falls far short of Tevatron data.



M. Cacciari, M. Krämer, Phys. Rev. Lett. **76** (1996) 4128; B.A. Kniehl, G. Kramer, Eur. Phys. J. **C6** (1999) 493.

[4] E.L. Berger, D. Jones, Phys. Rev. **D23** (1981) 1521; R. Baier, R. Rückl, Phys. Lett. **102B** (1981) 364.

NRQCD factorization formalism:[5]

- Rigorous theoretical framework, renormalizable, predictive.
- Factorization in perturbative short-distance coefficients and long-distance matrix elements:

$$d\sigma(a+b \to H+d) = \sum_n \left\langle \mathcal{O}^H[n] \right\rangle d\sigma(a+b \to Q\overline{Q}[n]+d),$$

where $n = {}^{2S+1}L_J^{(c)}$.

- Relative importance of $\left\langle \mathcal{O}^H[n] \right\rangle$ governed by velocity scaling rules. $\rightsquigarrow$ Double expansion in $\alpha_s(m_H)$ and v.

$v \approx 0.3$ (0.1) for J/ψ (Υ).

- Recover CSM for $v \to 0$.
- Predicts color-octet processes.

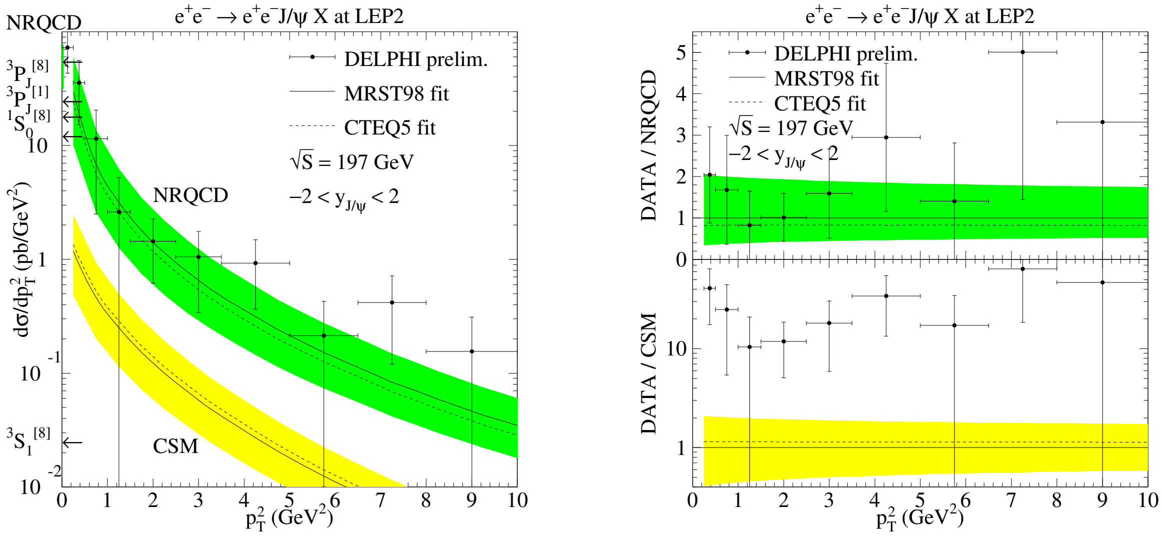
Table 1: $\left\langle \mathcal{O}^H[n] \right\rangle \propto v^k$

k	η_c	$\psi(nS)$	h_c	χ_{cJ}
3	${}^1S_0^{(1)}$	${}^3S_1^{(1)}$	—	—
5	—	—	${}^1P_1^{(1)}$, ${}^1S_0^{(8)}$	${}^3P_J^{(1)}$, ${}^3S_1^{(8)}$
7	${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^1P_1^{(8)}$	${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^3P_J^{(8)}$	—	—

[5] G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. **D51** (1995) 1125; D55 (1997) 5853 (E).

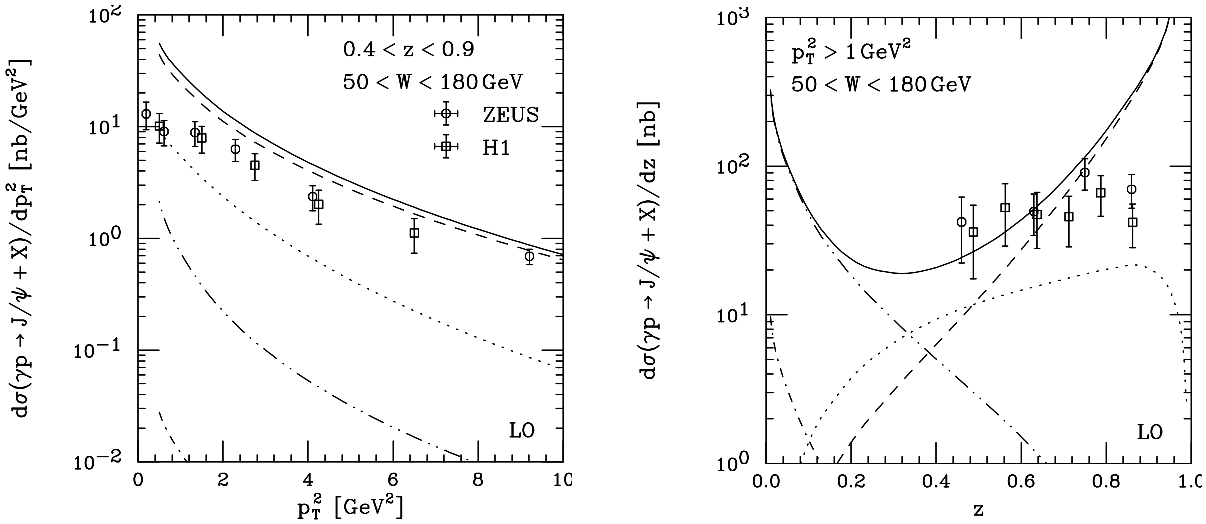
Identify CO processes in other kinds of experiments.

- $\gamma\gamma \to J/\psi + X$ at LEP2 (see M. Klasen):



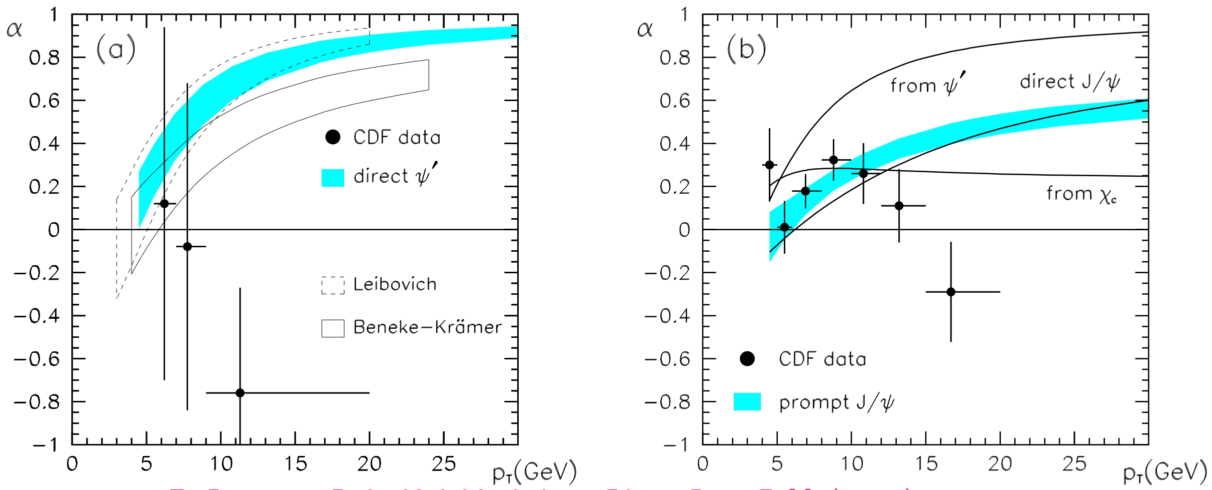
M. Klasen, B.A. Kniehl, L.N. Mihaila, M. Steinhauser, Phys. Rev. Lett. **89** (2002) 032001.

- $\gamma p \to J/\psi + X$ at HERA:



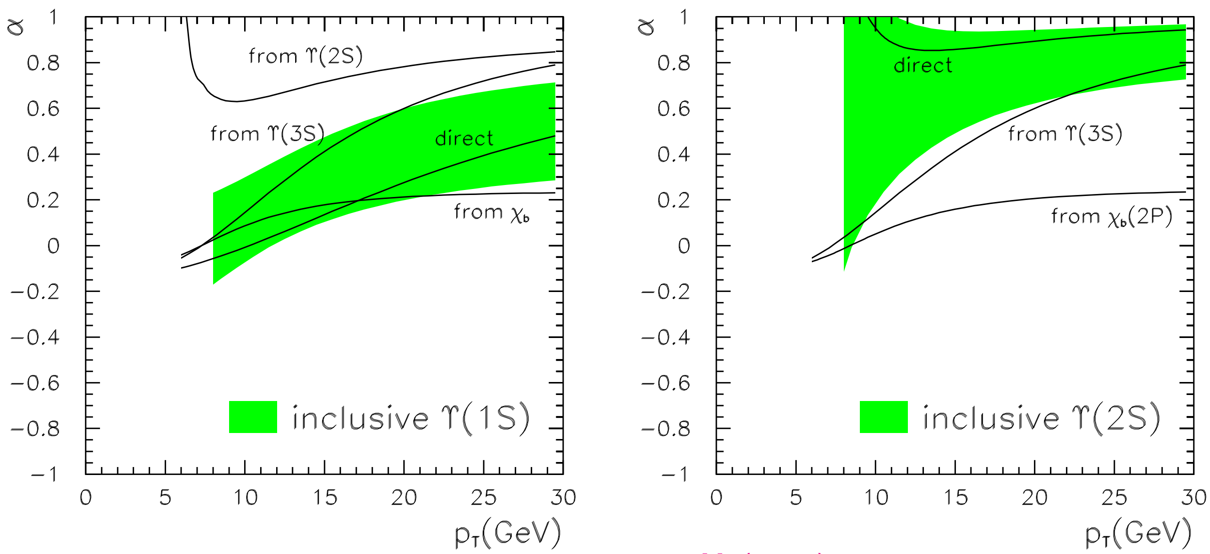
B.A. Kniehl, G. Kramer, Eur. Phys. J. **C6** (1999) 493.

- J/ψ polarization in $p\overline{p} \rightarrow J/\psi + X$ at the Tevatron:



E. Braaten, B.A. Kniehl, J. Lee, Phys. Rev. **D62** (2000) 094005.

- Υ polarization in $p\overline{p} \rightarrow \Upsilon + X$ at the Tevatron:



E. Braaten, J. Lee, Phys. Rev. **D63** (2001) 071501.

2 Electromagnetic current: $e+p\to e+J/\psi+X$

Motivation:

- Experimental data available.[6]
- Large scale Q^2. $\rightsquigarrow$ pQCD valid; resolved-photon contribution negligible.
- Handle on gluon PDF in the proton.
- Does Tevatron-HERA CO charmonium anomaly for $z\to 1$ persist for large Q^2?
- Subprocesses $e+a\to e+c\overline{c}[n]+a$ with $a=q,\overline{q},g$ contribute to $e+p\to J/\psi+X$ at NLO.
- Inconsistencies in literature:

[1] S. Fleming, T. Mehen, Phys. Rev. **D57** (1998) 1846.

[2] J.G. Körner, J. Cleymans, M. Kuroda, G.J. Gounaris, Phys. Lett. **114B** (1982) 195.

[3] J.-Ph. Guillet, Z. Phys. **C39** (1988) 75.

[4] H. Merabet, J.F. Mathiot, R. Mendez-Galain, Z. Phys. **C62** (1994) 639.

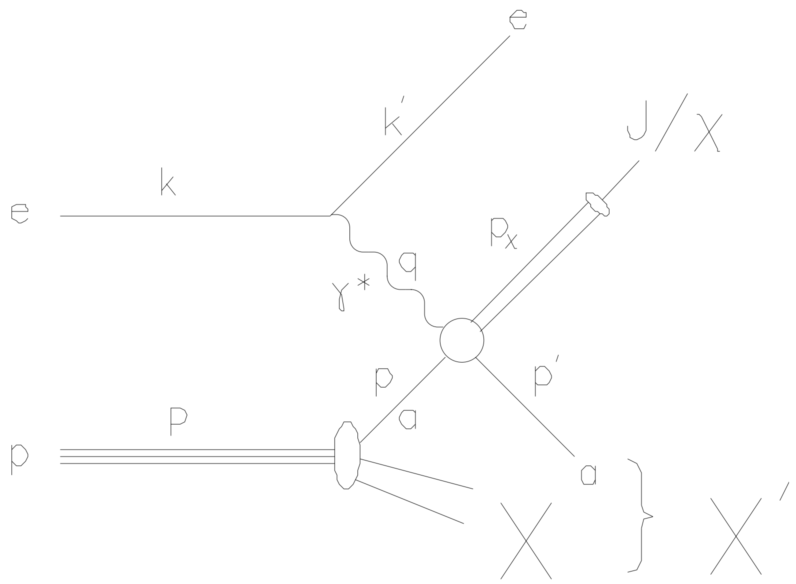
[5] D. Krücker, PhD Thesis, RWTH Aachen, 1995.

[6] F. Yuan, K.-T. Chao, Phys. Rev. **D63** (2001) 034017.

Disagreement, except for $e+g\to e+c\overline{c}\left[{}^1S_0^{(8)}\right]+g$ in [6].

[6] H1 Collaboration, C. Adloff et al., Eur. Phys. J. **C10** (1999) 373; DESY 02-060.

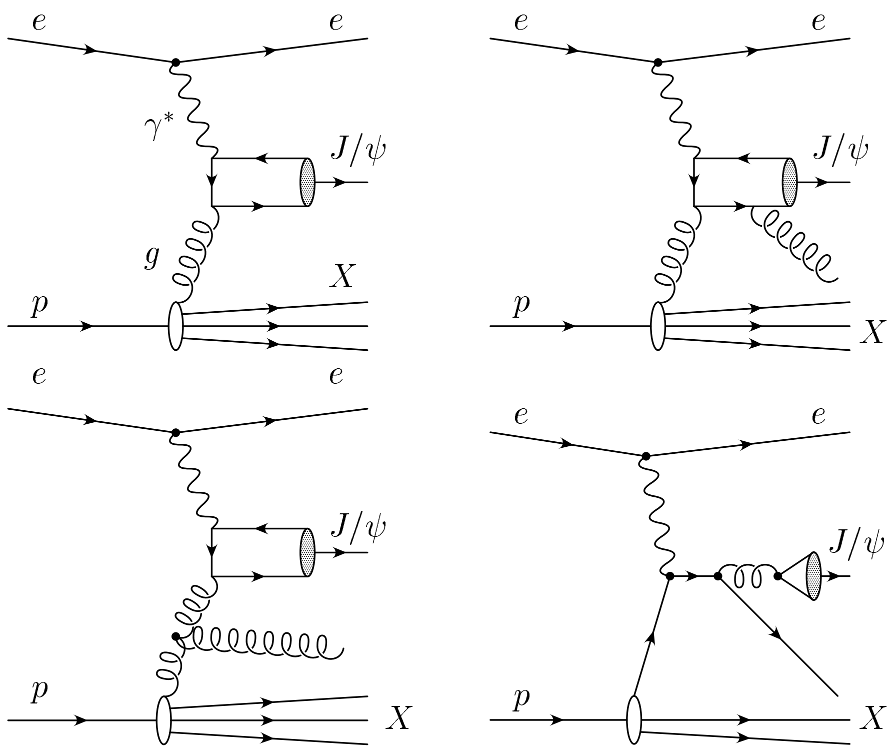
Kinematics:



$$
\begin{aligned}
S &= (k+P)^2, \\
Q^2 &= -q^2 > 0, \\
p &= xP, \\
y &= q\cdot P/k\cdot P, \\
z &= p_\psi \cdot P/q\cdot P, \\
M_{X'}^2 &= (q+P-p_\psi)^2 = (1-x)y(1-z)S, \\
W^2 &= (q+P)^2 = yS - Q^2, \\
\hat{s} &= (q+p)^2 = xyS - Q^2, \\
\hat{t} &= (q-p_\psi)^2 = -xy(1-z)S, \\
\hat{u} &= (p-p_\psi)^2 = M_\psi^2 - xyzS.
\end{aligned}
$$

Eliminate diffractive processes by $z_{\max}$, $(p_T^\star)_{\max}$, or $(M_{X'})_{\min}$ cuts.

Feynman diagrams:



- Master formula:

$$\frac{d^3\sigma}{dy\,dQ^2\,d\hat{t}}(e+a\to e+c\overline{c}[n]+a)$$
$$=\frac{\alpha}{2\pi}F_a[n]\left[\frac{1+(1-y)^2}{yQ^2}T_a[n]-\frac{4(1-y)}{y}L_a[n]\right]$$

- Photoproduction limit:

$$\frac{d\sigma}{d\hat{t}}(\gamma+a\to c\overline{c}[n]+a)=F_a[n]T_a[n]|_{Q^2=0}$$

- Use covariant-projector method.[7]
- $e+q(\overline{q})\to e+c\overline{c}\left[{}^3S_1^{(1)}\right]+q(\overline{q})$ forbidden by color conservation.
- $e+g\to e+c\overline{c}[n]+g$ with $n={}^1S_0^{(8)},{}^3P_J^{(8)}$ produce collinear singularires for $\hat{t}\to 0$, which are to be factorized into gluon PDF for $e+g\to e+c\overline{c}[n]$.

[7] J.H. Kühn, J. Kaplan, E.G.O. Safiani, Nucl. Phys. **B157** (1979) 125; A. Petrelli et. al., Nucl. Phys. **B514** (1998) 245.

Kinematic conditions:

$$\begin{aligned}
&\sqrt{S} = 300\ \text{GeV},\\
&2 < Q^2 < 80\ \text{GeV}^2,\\
&40 < W < 180\ \text{GeV},\\
&0.2 < z < 0.9.
\end{aligned}$$

Default input:

- LO $\alpha_s^{(n_f)}(\mu)$ with $n_f = 3$ and $\Lambda^{(3)} = 204$ MeV.
- MRST98 LO proton PDFs.
- Set $\mu_i = \xi_i \sqrt{Q^2 + M^2}$ with $\xi_i = 1$ $(i = r, f)$.
- BKL MEs.
- Set

$$\begin{aligned}
\left\langle \mathcal{O}^{\psi}\left[{}^1S_0^{(8)}\right]\right\rangle &= \kappa M_r,\\
\left\langle \mathcal{O}^{\psi}\left[{}^3P_0^{(8)}\right]\right\rangle &= (1-\kappa)\frac{m_c^2}{r} M_r,
\end{aligned}$$

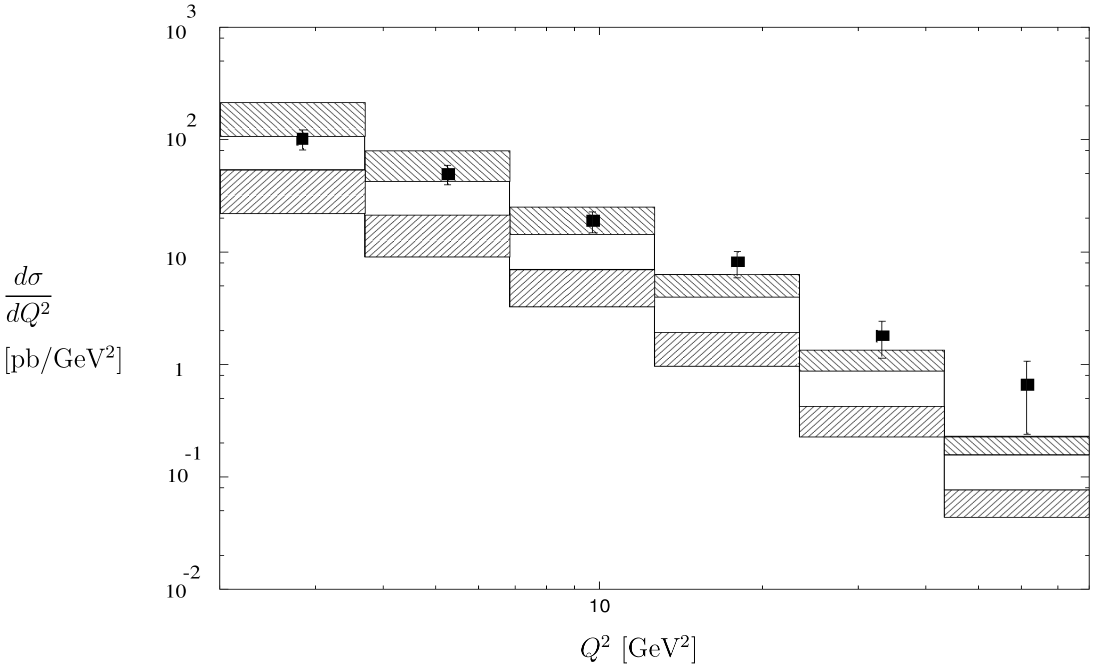
with $\kappa = 1$, where

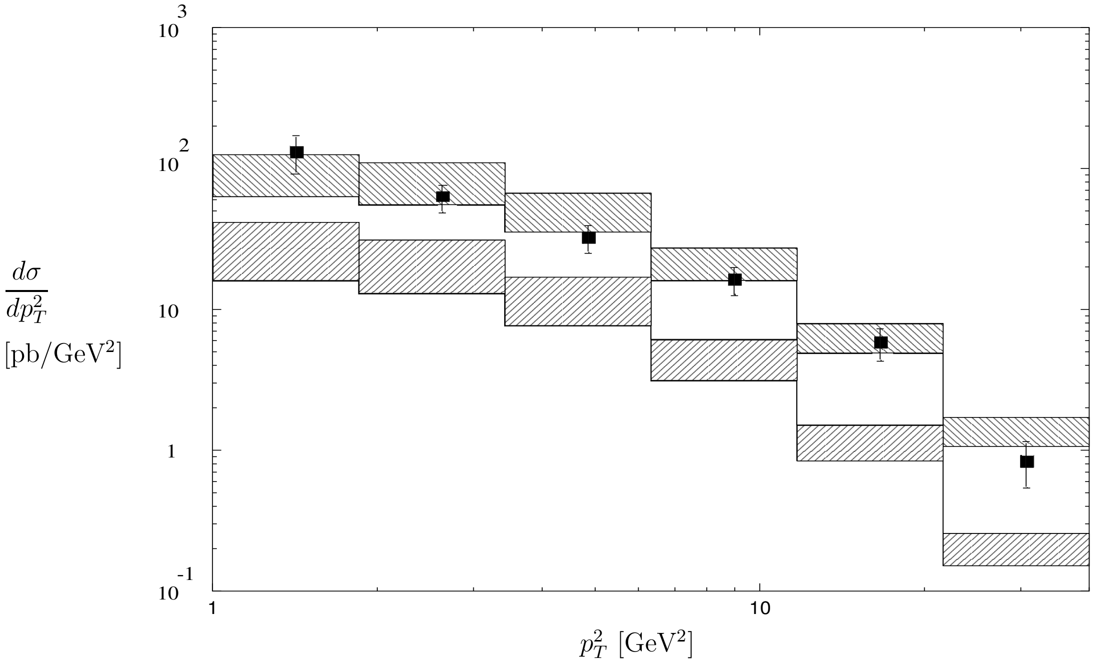
$$M_r = \left\langle \mathcal{O}^{\psi}\left[{}^1S_0^{(8)}\right]\right\rangle + \frac{r}{m_c^2}\left\langle \mathcal{O}^{\psi}\left[{}^3P_0^{(8)}\right]\right\rangle.$$

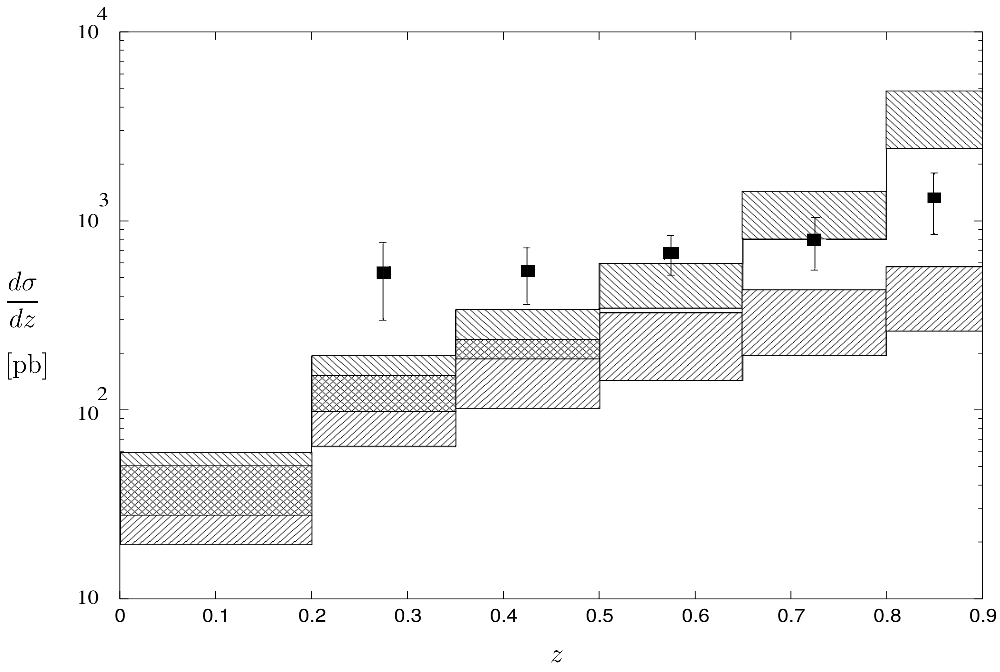
Theoretical errors:

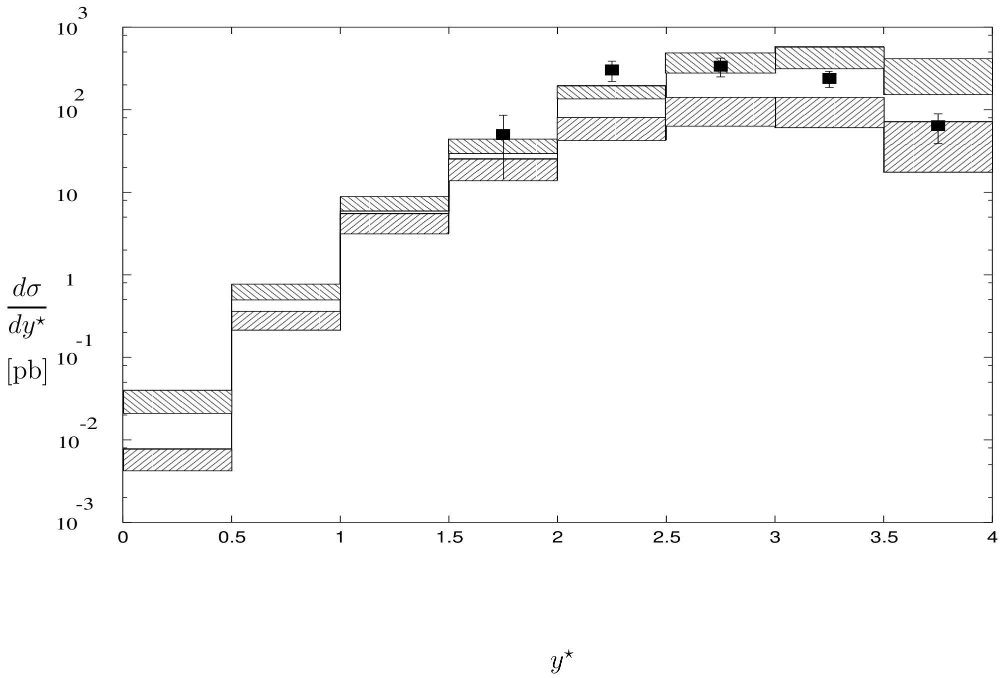
- Vary $0.5 < \xi_r, \xi_f, \kappa < 2$.
- $m_c = (1.5 \pm 0.1)$ GeV, experimental errors on default MEs.
- Switch to CTEQ5L proton PDFs adjusting $\Lambda^{(3)}$ and MEs.

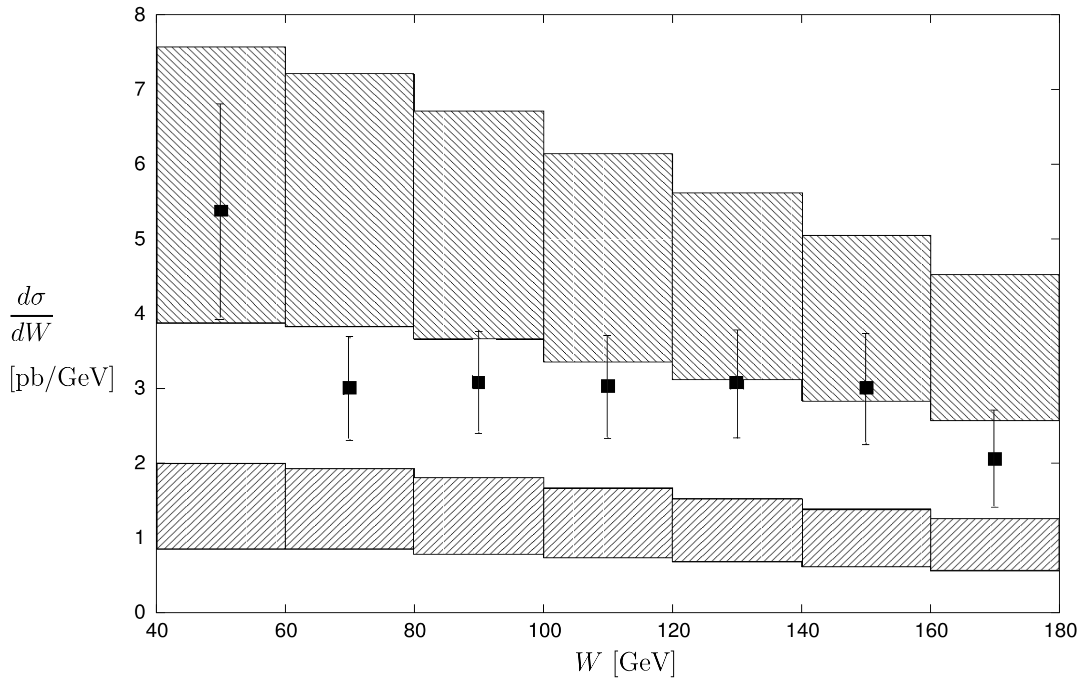
Comparison with H1 95–97 (27.3 pb^{-1}):





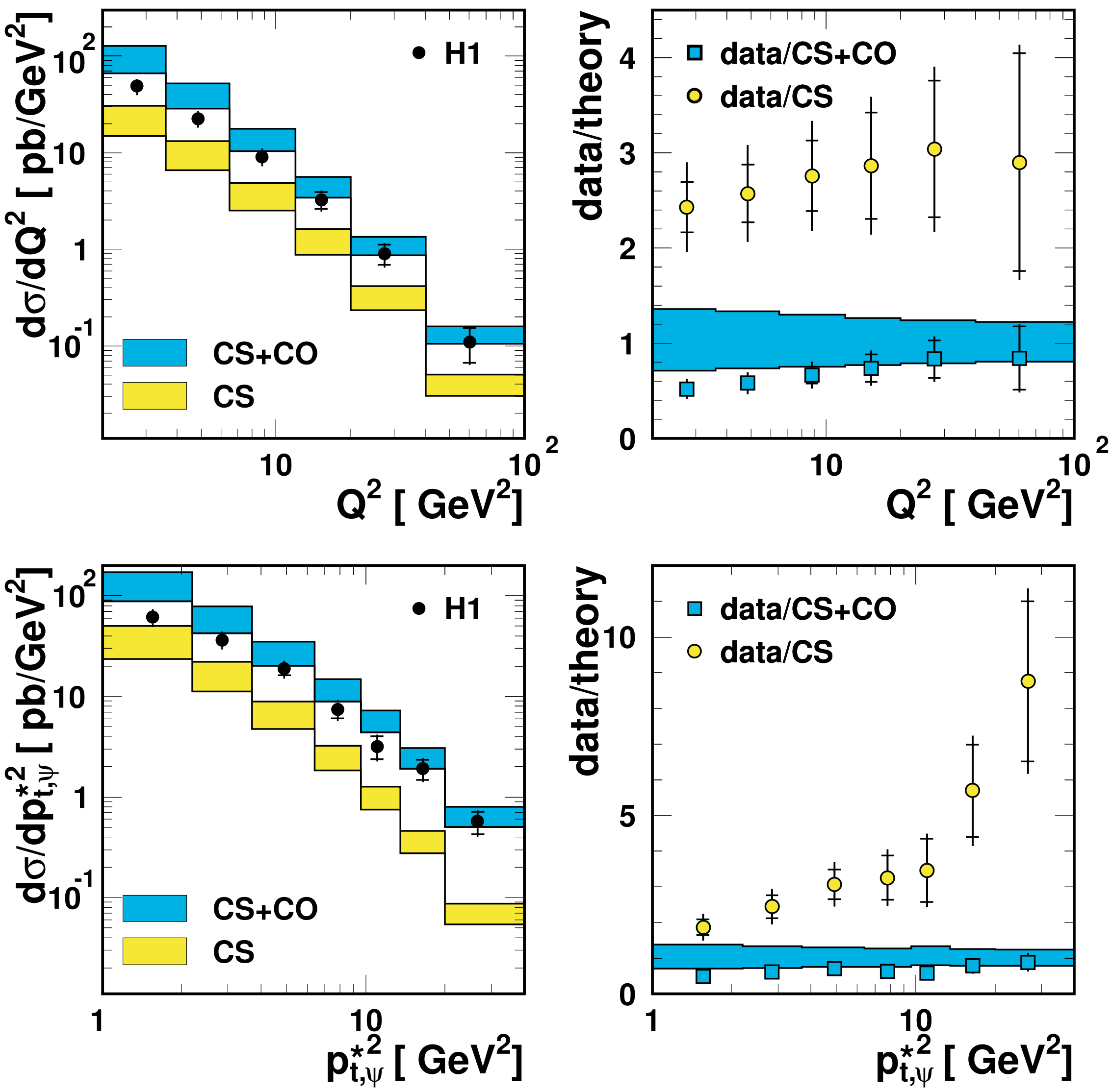

10^4
10^3
10^2
10
$\frac{d\sigma}{dz}$
[pb]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
z


10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
$\frac{d\sigma}{dy^\star}$
[pb]
0
0.5
1
1.5
2
2.5
3
3.5
4
$y^\star$



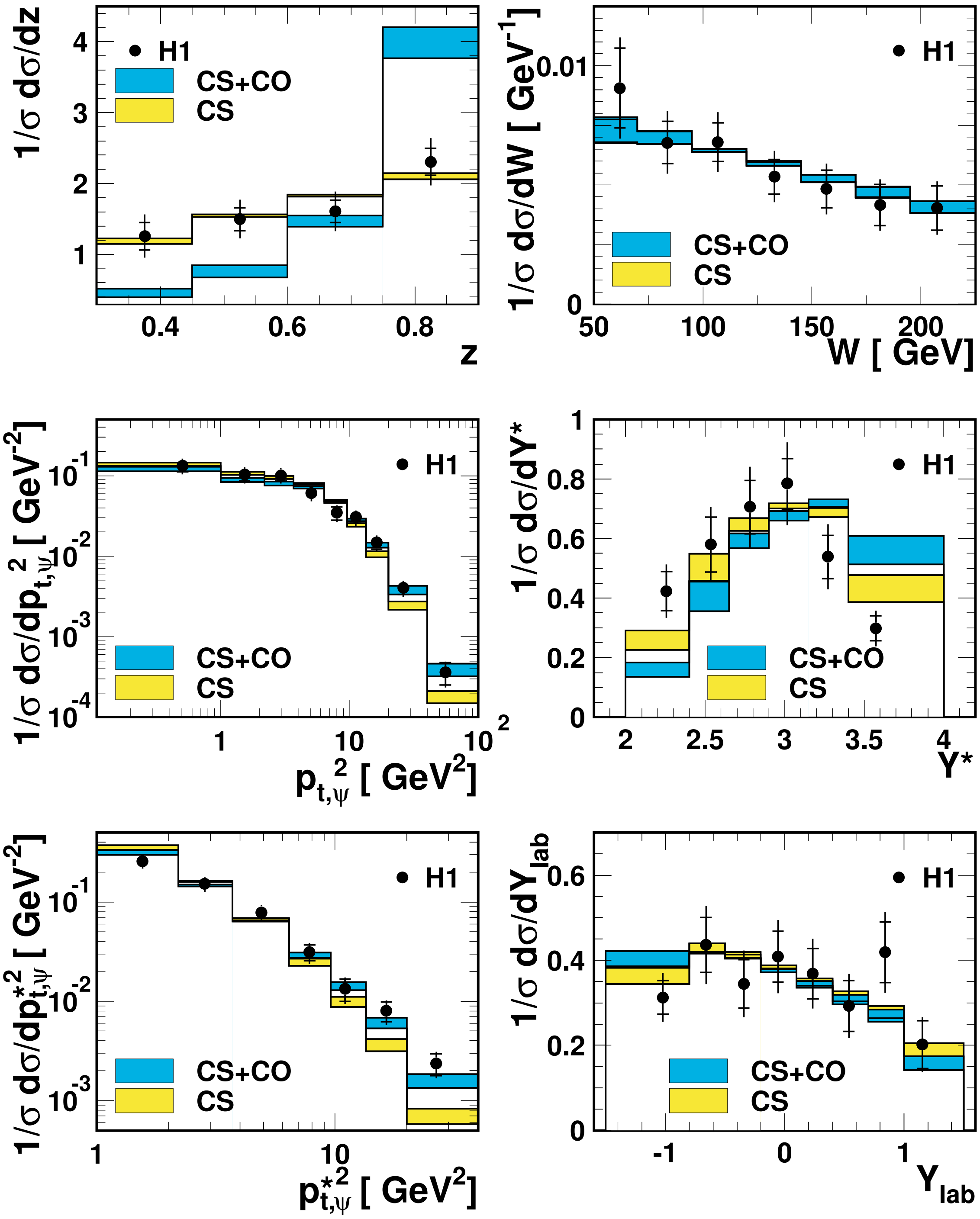
$\frac{d\sigma}{dW}$
[pb/GeV]
8
7
6
5
4
3
2
1
0
40
60
80
100
120
140
160
180
W [GeV]

Comparison with H1 97–00 (77.0 pb^{-1}):

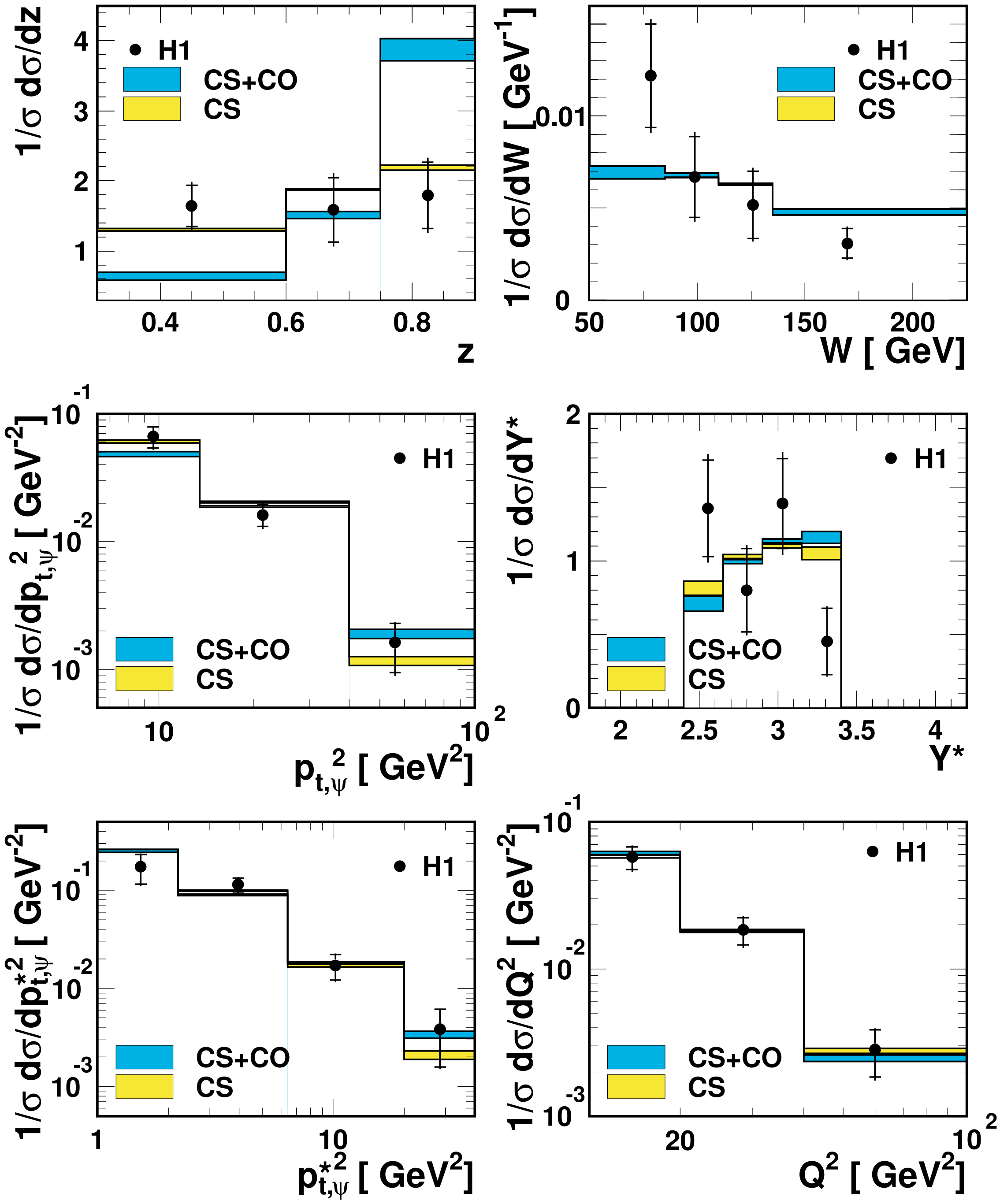


Normalized distributions

$Q^2 > 2\ \mathrm{GeV}^2$



$Q^2 > 12\ \mathrm{GeV}^2$



3 Weak neutral current: $\nu + N \to \nu + J/\psi + X$

Motivation:

- Experimental data available from CDHS and CHORUS.[8]
- No evidence seen by NuTeV.[9]
- Interplay of diffractive and non-diffractive scattering mechanisms.
- Literature on VDM; Zg fusion in CEM and CSM; and NRQCD:

[1] M.K. Gaillard, S.A. Jackson, D.V. Nanopoulos, Nucl. Phys. **B102** (1976) 326; **B112** (1976) 545 (E).

[2] J.H. Kühn, R. Rückl, Phys. Lett. **B95** (1980) 431.

[3] V. Barger, W.Y. Keung, R.J.N. Phillips, Phys. Lett. **B92** (1980) 179.

[4] R. Baier, R. Rückl, Nucl. Phys. **B201** (1982) 1.

- $\nu + a \longrightarrow \nu + c\overline{c}[n] + a$ with $a = q, \overline{q}, g$ in NRQCD not yet studied.

[8] CDHS Collaboration, H. Abramowicz et al., Phys. Lett. **B109** (1982) 115; CHORUS Collaboration, E. Eskut et al., Phys. Lett. **B503** (2001) 1.

[9] NuTeV Collaboration, T. Adams et al., Phys. Rev. **D61** (2000) 092001.

New features compared to EM DIS at HERA:

- Axial-vector contribution.
- $2 \longrightarrow 2$ and $2 \longrightarrow 3$ subprocesses.
- Diffractive processes.
- Prompt production, i.e. direct production plus χ_{cJ} and ψ' decays with

$$\begin{aligned}
B(\chi_{c0} \longrightarrow J/\psi + \gamma) &= (0.66 \pm 0.18)\%,\\
B(\chi_{c1} \longrightarrow J/\psi + \gamma) &= (27.3 \pm 1.6)\%,\\
B(\chi_{c2} \longrightarrow J/\psi + \gamma) &= (13.5 \pm 1.1)\%,\\
B(\psi' \longrightarrow J/\psi + X) &= (55 \pm 5)\%.
\end{aligned}$$

- Nuclear corrections:[10] $\sigma_A = A^\alpha \sigma_1$ with $\alpha_{\mathrm{coh}} = 1.19 \pm 0.02$ and $\alpha_{\mathrm{in}} = 1.05 \pm 0.03$. $\rightsquigarrow$ Enhancement factors $2.75^{+0.32}_{-0.27}$ and $1.31^{+0.22}_{-0.20}$.
- Energy spectrum of neutrino beam:

$$\sigma = \frac{\sum_\nu \int dE_\nu \, \phi_\nu(E_\nu)\sigma_\nu(E_\nu)}{\sum_\nu \int dE_\nu \, \phi_\nu(E_\nu)}.$$

[10] New Muon Collaboration, P. Amaudruz et al., Nucl. Phys. **B371** (1992) 553.

Subprocesses:

- $2 \to 2$: $\nu + g \to \nu + c\bar{c}[n]$ with $n = {}^1S_0^{(8)}, {}^3S_1^{(8)}, {}^3P_J^{(8)}$.
- $2 \to 3$: $\nu + a \to \nu + c\bar{c}[n] + a$ with $a = q, \bar{q}, g$ and $n = {}^3S_1^{(1)}, {}^3P_J^{(1)}, {}^1S_0^{(8)}, {}^3S_1^{(8)}, {}^3P_J^{(8)}$.

Table 2: Relative importance. Direct $2 \to 3$ CS contribution is of $\mathcal{O}\left(\alpha^2\alpha_s^2 v^3\right)$.

	J/ψ, ψ'	χ_{cJ}
$2 \to 2$ CO	$v^4/\alpha_s \approx \alpha_s$	$v^2/\alpha_s \approx 1$
$2 \to 3$ CS	1	$v^2 \approx \alpha_s$
$2 \to 3$ CO	$v^4 \approx \alpha_s^2$	$v^2 \approx \alpha_s$

Divergences:

- $2 \to 3$ CS χ_{cJ} production channel IR divergent if final-state gluon soft. $\rightsquigarrow$ Absorb into $\left\langle \mathcal{O}^{\chi_{cJ}}\left[{}^3S_1^{(8)}\right]\right\rangle$ of $\nu + g \to \nu + c\bar{c}\left[{}^3S_1^{(8)}\right]$.
- $2 \to 3$ CO channels collinearly divergent for $p_T^\star \to 0$. $\rightsquigarrow$ Absorb into proton PDFs of $2 \to 2$ CO channels.
- Divergent channels do not contribute in LO.

Diffractive production:

- $Z^\star \to \gamma^\star$

$$\frac{d^2\sigma}{dy\,dQ^2}(\nu + N \to \nu + H + N')$$
$$= \left[\frac{g^2 v_c Q^2}{e^2 e_c\left(Q^2+M_Z^2\right)}\right]^2 \frac{d^2\sigma}{dy\,dQ^2}(\mu + N \to \mu + H + N')$$

- $\gamma^\star \to \gamma$

$$\frac{d^2\sigma}{dy\,dQ^2}(\mu + N \to \mu + H + N')$$
$$= \frac{\alpha}{2\pi}\frac{y - Q^2/(2Em)}{Q^2(y^2+Q^2/E^2)}\left\{\left[1+(1-y)^2+\frac{Q^2}{2E^2}\right]\sigma_T(\nu,Q^2) + \left[2(1-y)-\frac{Q^2}{2E^2}\right]\sigma_L(\nu,Q^2)\right\},$$

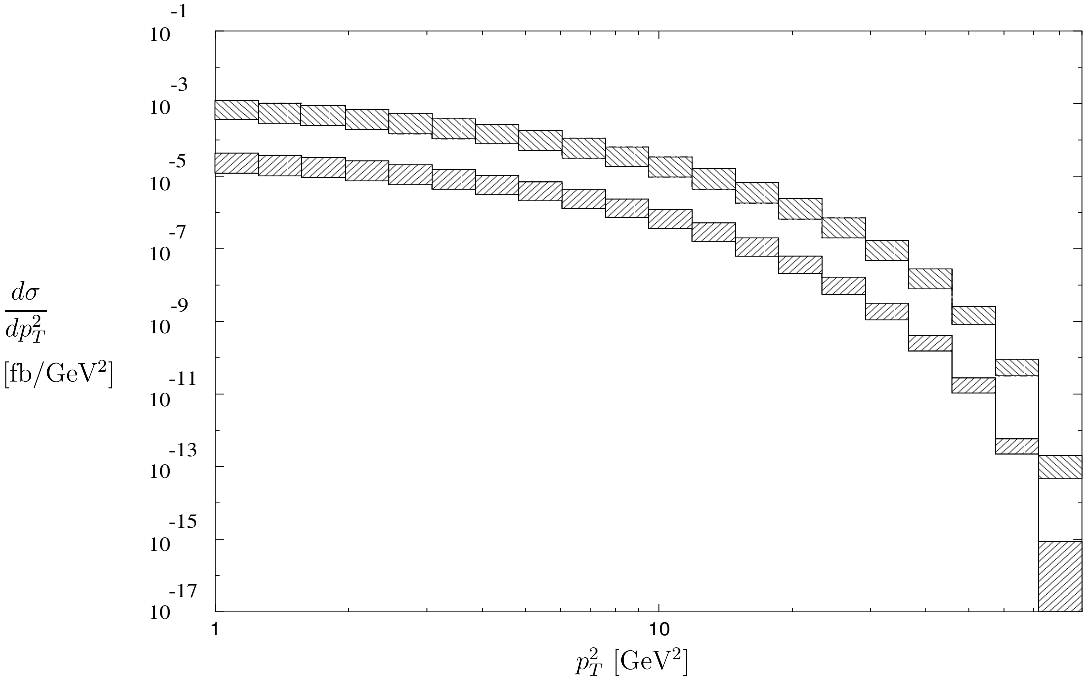
where E and $\nu = yE$ incoming-ν and $\gamma^\star$ energies.

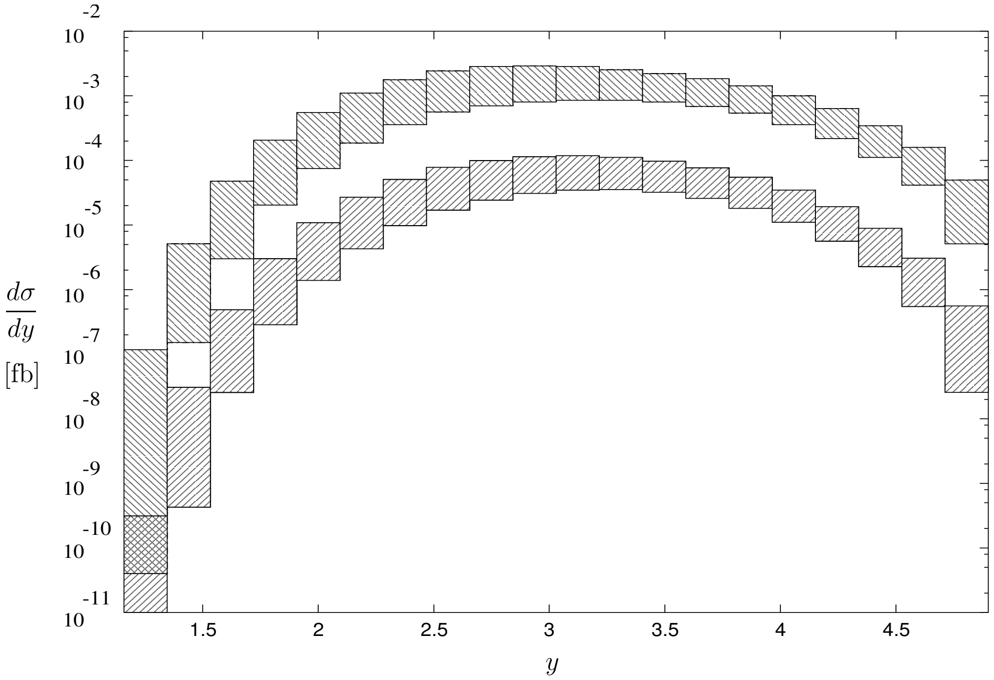
- $\gamma \to \gamma_T$, VDM

$$\sigma_T(\nu,Q^2) = \frac{\sigma(\nu)}{(1+Q^2/M_V^2)^2},$$
$$\sigma_L(\nu,Q^2) \approx 0,$$

where $M_V = (3.2 \pm 0.6)$ GeV and
$\sigma(\nu) = 20$ nb $\times \exp[-45/(\nu/\text{GeV} - 6)]$.

Numerical results:





Comparison with CHORUS:

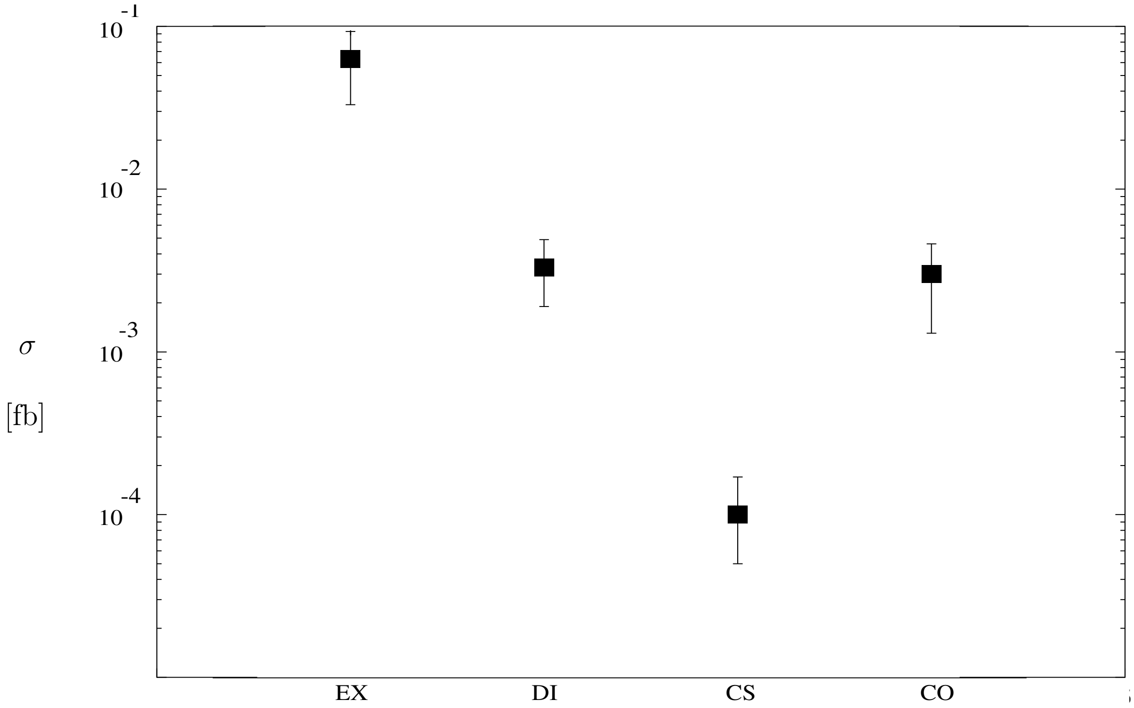


Table 3: $\sigma(\nu + \text{Pb} \to J/\psi + X)$ in 10^{-3} fb.

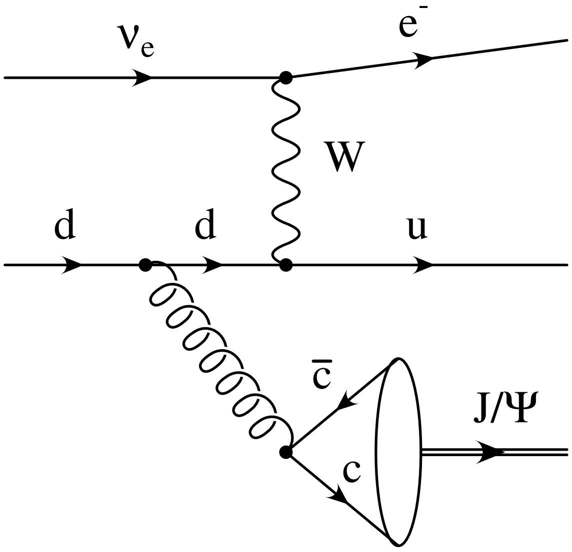
	EX	DI	CS	CO
σ	63 ± 30	$3.3^{+1.6}_{-1.4}$	$0.10^{+0.07}_{-0.05}$	$3.0^{+1.6}_{-1.7}$
direct		64%	78%	72%
χ_{cJ}		19%	—	14%
ψ'		17%	22%	14%

4 Charged current: $e + p \to \nu + J/\psi + X$, $\nu + N \to e + J/\psi + X$

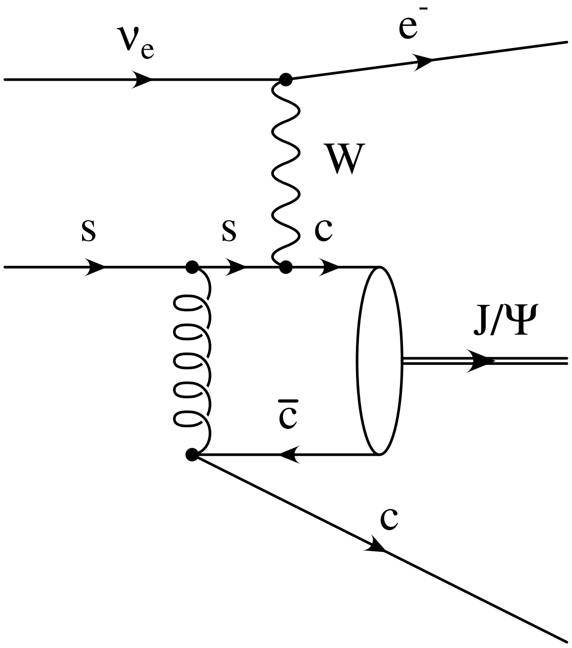
Motivation:

- Clear experimental signature.
- Not studied yet.
- No singularities.
- No diffractive processes.
- Good probe of CO processes.

Feynman diagrams:

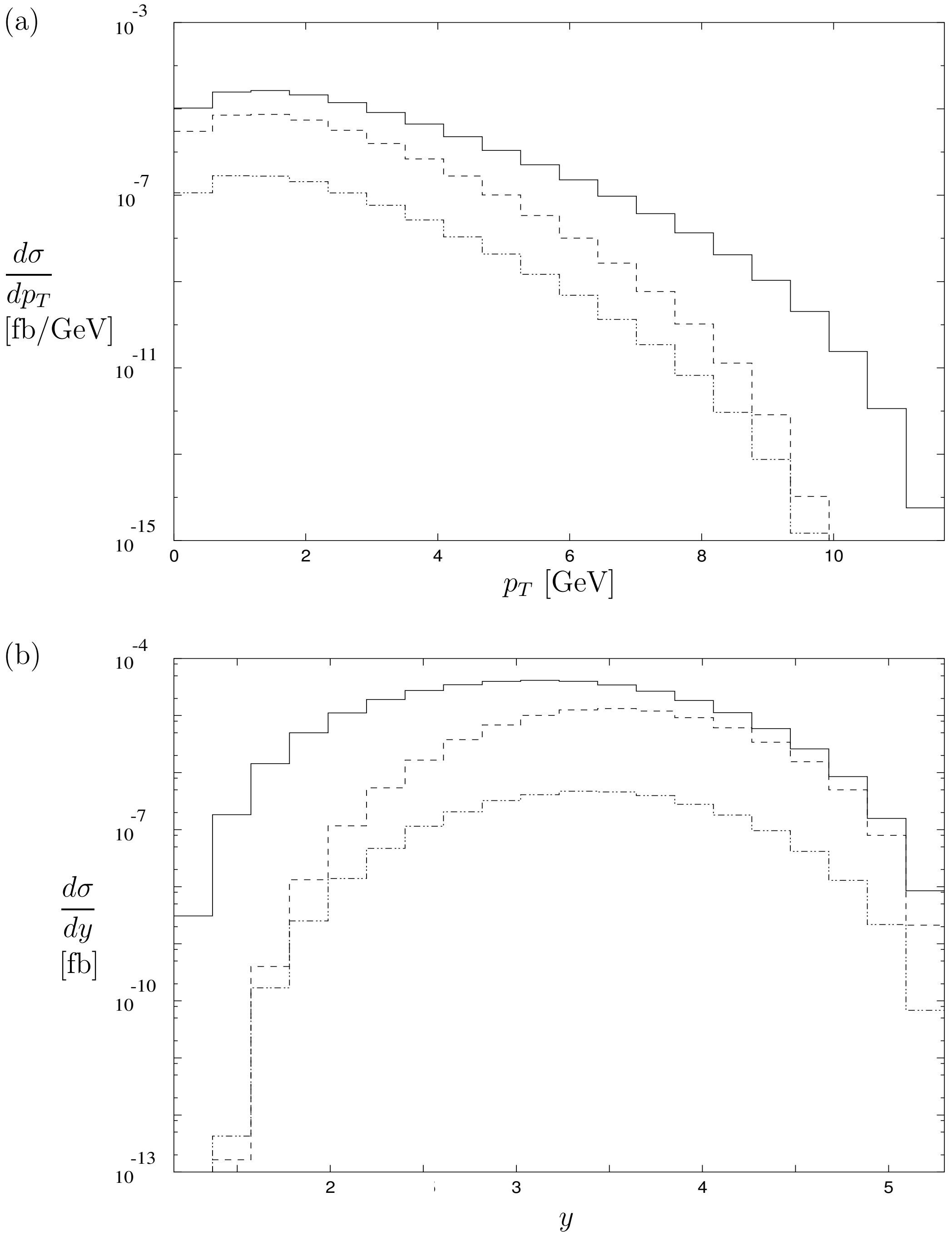


uncharmed jet
$^3S_1^{(8)}$ only



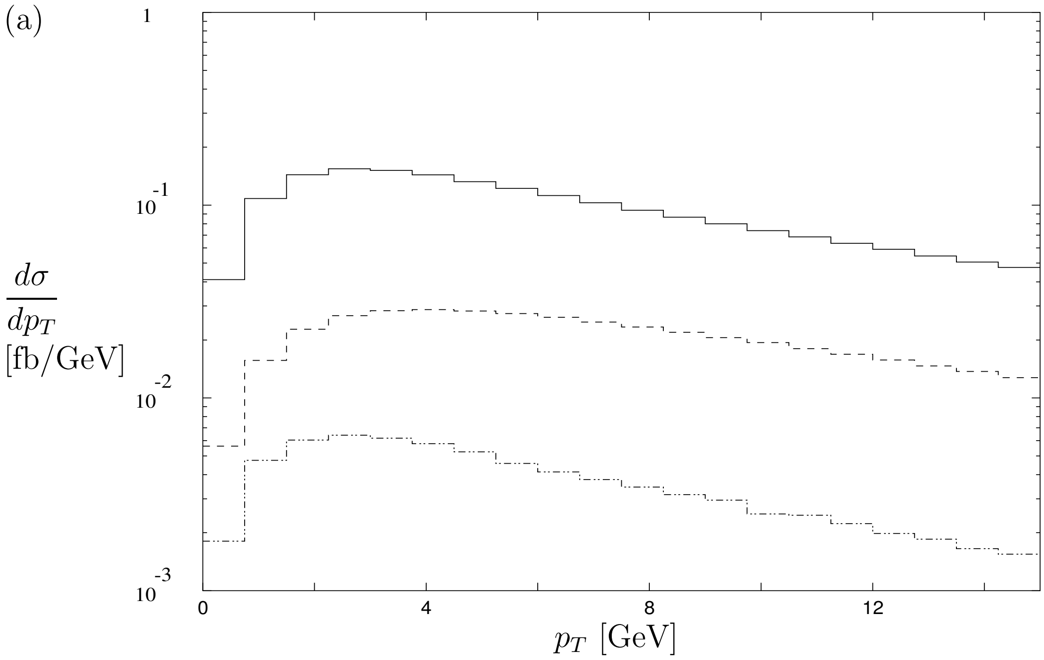
charmed jet
both CS and CO

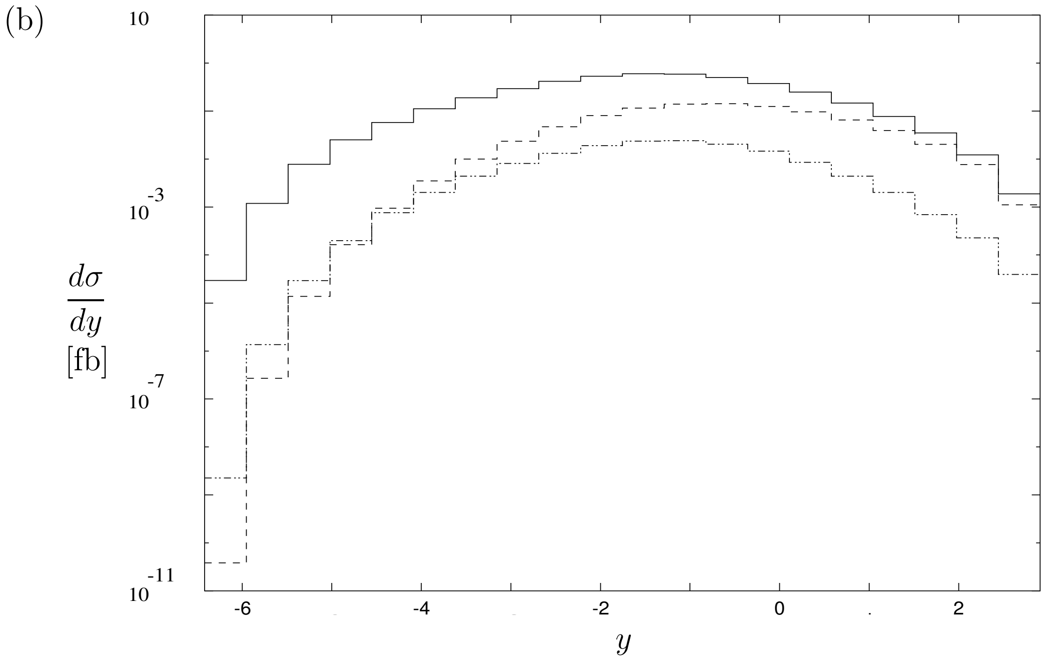
Numerical results for CHORUS:



$$\sigma(ud) = 4.9^{+3.4}_{-2.3} \times 10^{-5}\ \text{fb}, \quad \sigma(c) = 1.8^{+1.5}_{-0.9} \times 10^{-5}\ \text{fb}.$$

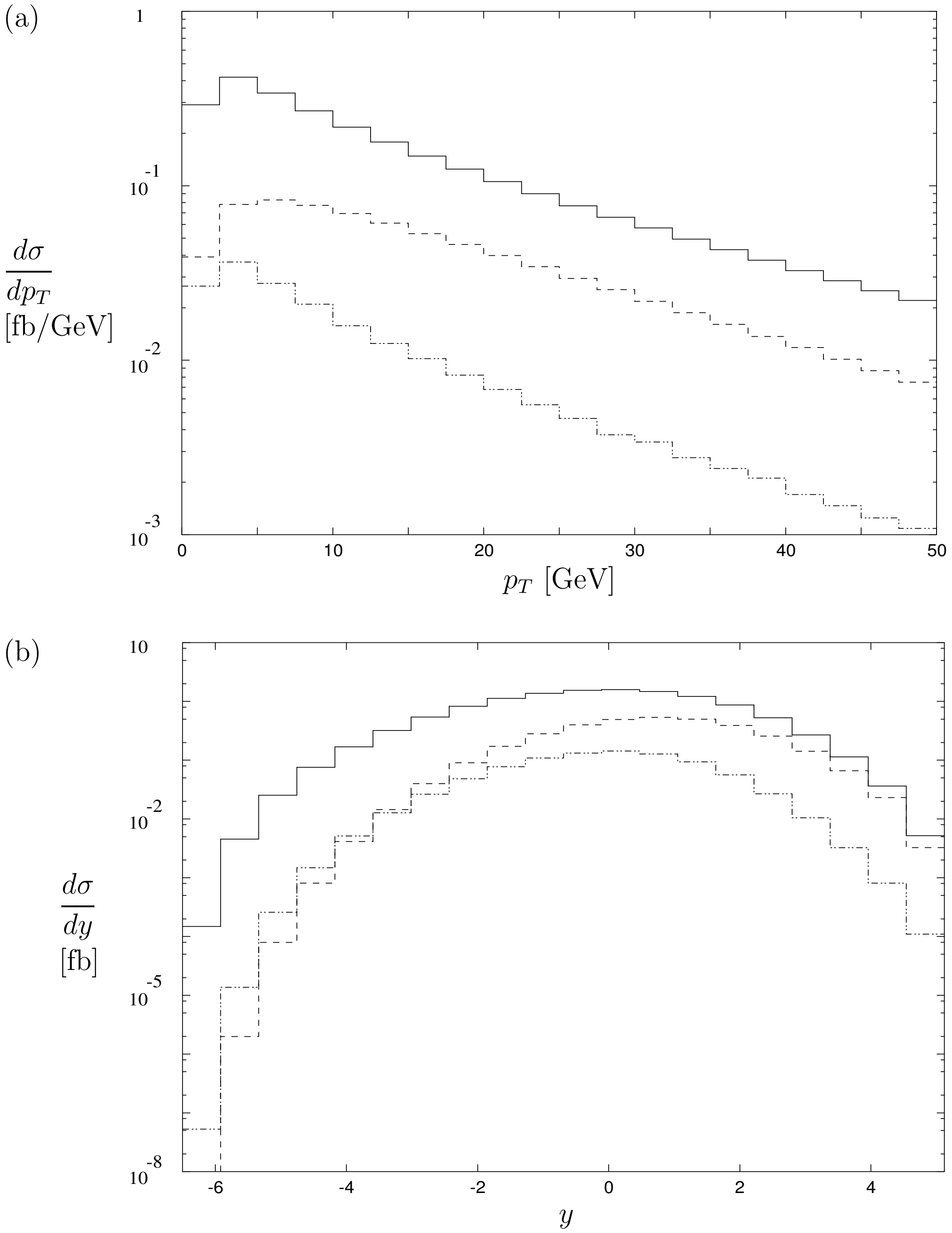
Numerical results for HERA:





$\sigma(ud) = 1.5^{+0.5}_{-0.4}$ fb, $\sigma(c) = 0.50^{+0.16}_{-0.13}$ fb.

Numerical results for THERA:



$$\sigma(ud) = 4.5^{+1.5}_{-1.2}\ \text{fb}, \quad \sigma(c) = 2.5^{+0.8}_{-0.6}\ \text{fb}.$$

5 Conclusions

- J/ψ production in DIS good probe of CO processes.
- H1 data generally confirms NRQCD and disfavors CSM.
- Distinct rise for $z \longrightarrow 1$ predicted by NRQCD at LO is not seen in the data. $\rightsquigarrow$ HO effects, k_T effects, shape functions, . . . ?
- CHORUS measurement significantly exceeds LO prediction (diffractive + nondiffractive). $\rightsquigarrow$ Need more statistics, independent measurements, separation of diffractive processes, NLO corrections, . . .
- J/ψ production in CC DIS free of diffraction, interesting for νN scattering experiments, challenge for HERA and THERA.
- LO predictions suffer from large theoretical uncertainties. $\rightsquigarrow$ Include NLO in α_s and v, at least for inclusive cross sections. Redo fits to Tevatron data to extract MEs.
- Study Υ production in DIS.