Heavy Quark and Quarkonium Production in Hadron and Photon Collisions

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Contents

For top-quark production, see talk by T. Teubner.

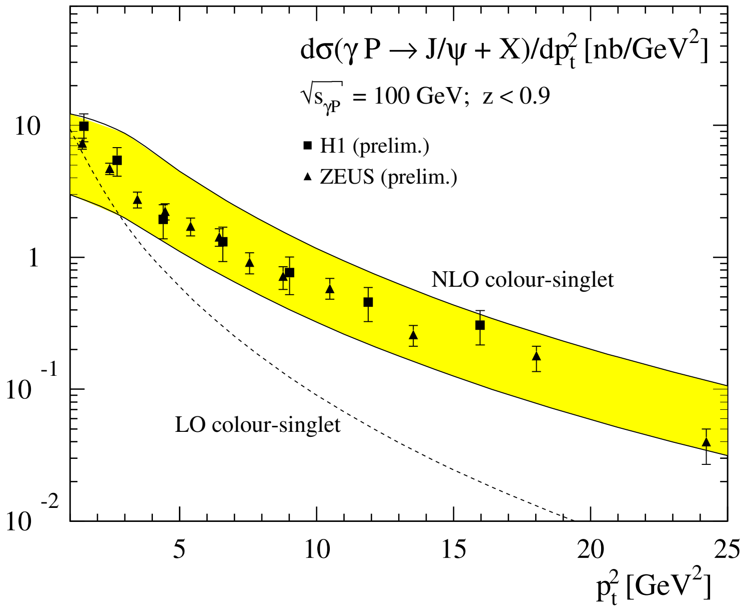
1. Quarkonium production
(a) Theoretical aspects

Heavy quarkonium H
- useful testing ground for QCD;
- simplest laboratory to study the binding of quarks to hadrons.

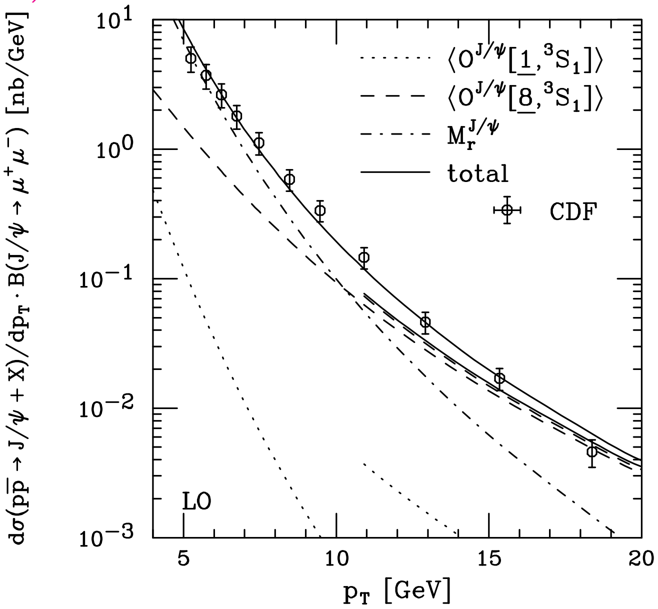
Color Singlet Model:[1]
- Factorization in perturbative short-distance part $[\alpha_s(m_Q), m_Q]$ and nonperturbative long-distance part $[R_S(0), R'_P(0)]$.
- $Q\overline{Q}$ pair must be in CS state and have same ${}^{2S+1}L_J$ quantum numbers as H.

$\oplus$ Explains direct J/ψ photoproduction at HERA in NLO.
$\ominus$ No general argument for validity in higher orders.
$\ominus$ Logarithmic IR divergences in P-wave decays to light hadrons and relativistic corrections to S-wave annihilation.
$\ominus$ Falls far short of Tevatron $p\overline{p}$, LEP2 $\gamma\gamma$, and HERA ep DIS data.

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



M. Krämer, J. Zunft, J. Steegborn, P.M. Zerwas, Phys. Lett. **B348** (1995) 657; M. Krämer, Nucl. Phys. **B459** (1996) 3.



E. Braaten, S. Fleming, Phys. Rev. Lett. **74** (1995) 3327; P. Cho, A.K. Leibovich, Phys. Rev. **D53** (1996) 150; 6203.

Color Evaporation Model:[2]

- Local parton-hadron duality

$$\sigma(H) \approx \frac{1}{9}\rho_H \int_{(2m_Q)^2}^{(2m_{Q\,\mathrm{meson}})^2} ds_{Q\overline{Q}} \frac{d\sigma(Q\overline{Q})}{ds_{Q\overline{Q}}},$$

where $1/9$ statistical probability that $3 \times \overline{3}$ $Q\overline{Q}$ pair is asymptotically in a CS state and ρ_H fraction of onia that materialize as H.

- $Q\overline{Q}$ can be in CS or color-octet state.
- Soft-gluon exchange with underlying event.

⊕ Useful qualitative picture, often used for diffractive processes.

⊕ Explains observed excess of Tevatron data over CSM prediction up to K factor.

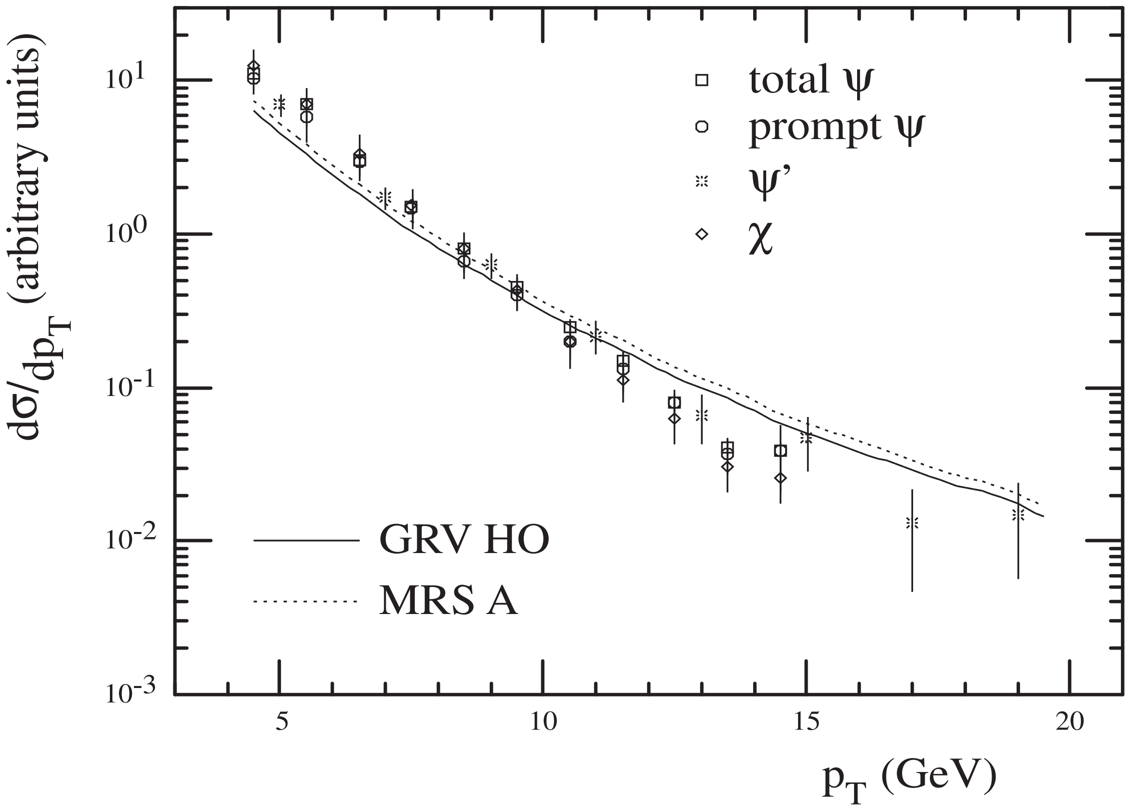
⊖ Prescription, rather than rigorous theory.

⊖ ${}^{2S+1}L_J$ quantum numbers of H do not enter.

⊖ No clear prediction for relative weights ρ_H.

⊖ Prediction for $\sigma(\chi_{cJ})/\sigma(J/\psi)$ disagrees with data.

[2] H. Fritzsch, Phys. Lett. **B67** (1977) 217; F. Halzen, Phys. Lett. **B69** (1977) 105; M. Glück, J.F. Owens, E. Reya, Phys. Rev. **D17** (1978) 2324.



G.A. Schuler, R. Vogt, Phys. Lett. **B387** (1996) 181; J.F. Amundson, O.J.P. Eboli, E.M. Gregores, F. Halzen Phys. Lett. **B390** (1997) 323; M.B. Gay Ducati, V.P. Goncalves, C.B. Mariotto, Phys. Rev. **D65** (2002) 037503.

Hard comover scattering:[3]

• Perturbative rescattering of $Q\overline{Q}$ pair with remnant comoving color field created by bremsstrahlung from initial state of $gg \to Q\overline{Q}$.

• $Q\overline{Q}$ can be in CS or CO state.

• Only in hadroproduction, but not in direct photoproduction, $\gamma\gamma$ collisions, e^+e^- annihilation, etc.

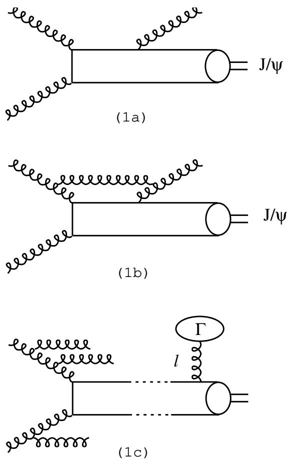
⊕ Qualitatively explains observed excess of Tevatron data over CSM prediction, while no effect on photoproduction at HERA.

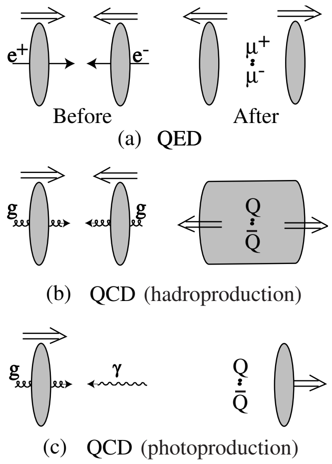
⊕ Direct S-wave hadroproduction is unpolarized.

⊖ Contradicts observed excess of $\gamma\gamma$ and ep DIS data over CSM prediction.

⊖ $\sigma_{\mathrm{dir}}(\chi_{c2})/\sigma_{\mathrm{dir}}(\chi_{c1}) = 5/3$ exceeds Tevatron measurement 0.96 ± 0.29 by 2.4 σ.

⊖ Can only estimate cross section ratios and polarizations.





[3] P. Hoyer, S. Peigné, Phys. Rev. **D59** (1999) 034011; N. Marchal, S. Peigné, P. Hoyer, Phys. Rev. **D62** (2000) 114001.

NRQCD factorization formalism:[4]

- 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 $\langle\mathcal{O}^H[n]\rangle$ governed by velocity scaling rules. $\rightsquigarrow$ Double expansion in $\alpha_s(m_H)$ and $v\approx\alpha_s(m_H)$. $v^2\approx 0.3$ (0.1) for J/ψ (Υ).
- CSM recovered for $v\to 0$.
- Predicts CO processes, to be identified in other kinds of experiments.

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

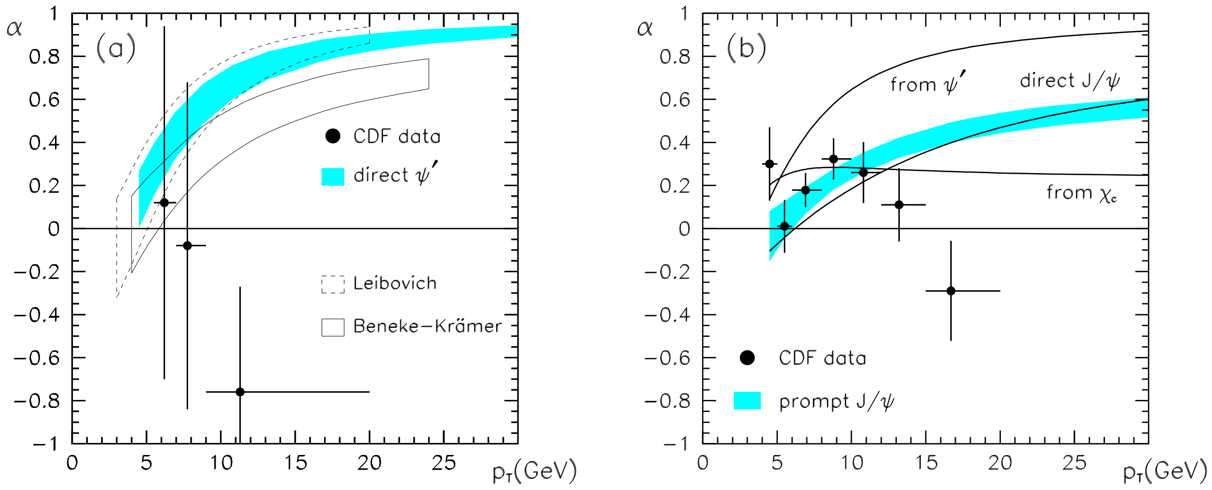
k	η_c	$\psi(nS)$	h_c	χ_{cJ}
3	${}^1S_0^{(1)}$	${}^3S_1^{(1)}$	—	—
5	—	—	${}^1P_1^{(1)}$, ${}^1S_0^{(8)}$	${}^3P_J^{(1)}$, ${}^3S_1^{(8)}$
7	${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^1P_1^{(8)}$	${}^1S_0^{(8)}$, ${}^3S_1^{(8)}$, ${}^3P_J^{(8)}$	—	—

[4] W. E. Caswell, G. P. Lepage, Phys. Lett. **B167** (1986) 437; G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. **D51** (1995) 1125; D55 (1997) 5853 (E).

(b) Charmonium

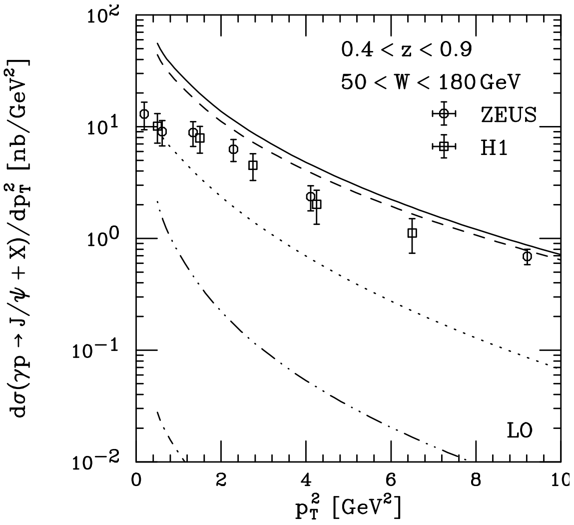
$v_c \approx \alpha_s(m_{J/\psi}) \approx 0.3 \rightsquigarrow$ PT likely to be applicable to Wilson coefficients.

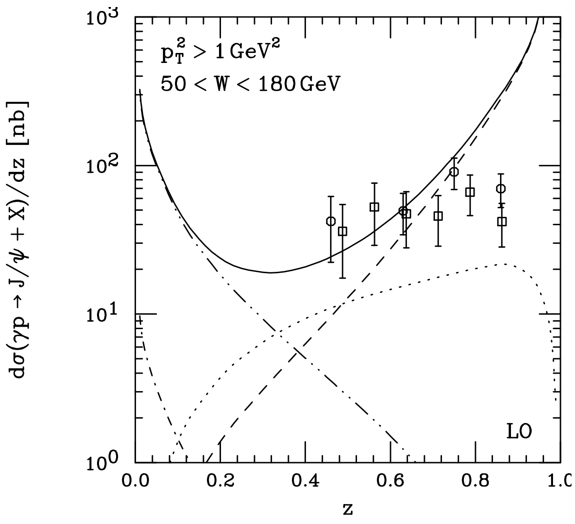
(i) Polarization in $p\overline{p} \longrightarrow J/\psi + X$ at the Tevatron:



M. Beneke, M. Krämer, Phys. Rev. **D55** (1997) 5269; A. Leibovich, Phys. Rev. **D56** (1997) 4412; E. Braaten, B.A. Kniehl, J. Lee, Phys. Rev. **D62** (2000) 094005.

(ii) $\gamma p \longrightarrow J/\psi + X$ at HERA:

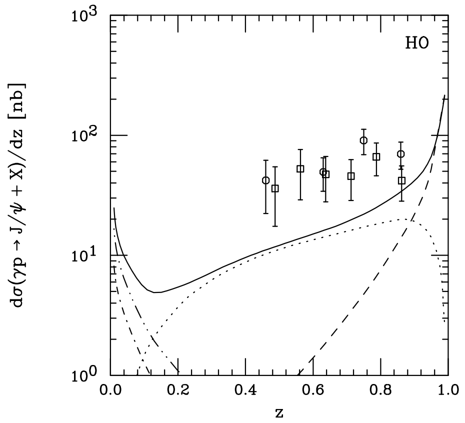




M. Cacciari, M. Krämer, Phys. Rev. Lett. **76** (1996) 4128; P. Ko, J. Lee, H.S. Song, Phys. Rev. **D54** (1996) 4312; **D60** (1999) 119902 (E).

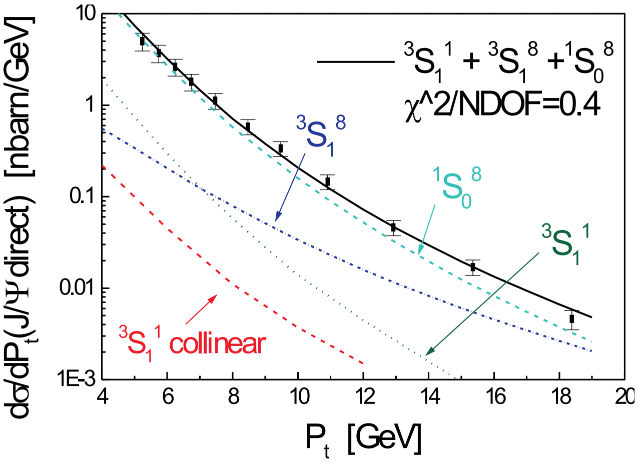
Proposals to overcome Tevatron-HERA CO charmonium anomaly:

- HO improvement:[5] Include gluon ISR and AP evolution of $g \longrightarrow c\bar{c}$ to extract MEs from Tevatron data.

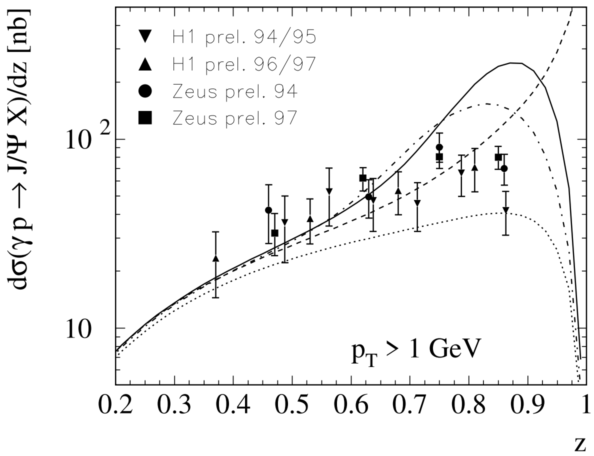


[5] B. Cano-Coloma, M.A. Sanchis-Lozano, Phys. Lett. **B406** (1997) 232; Nucl. Phys. **B508** (1997) 753; B.A. Kniehl, G. Kramer, Eur. Phys. J. **C6** (1999) 493.

• Intrinsic-k_T effects:[6]



• Shape functions:[7] Resum HO effects related to kinematics of soft-gluon radiation and difference between partonic and hadronic phase spaces.



$\Lambda = (0/300/500)$ MeV (dash/solid/dash-dot) typical energy of radiated soft-gluon system; CSM (dot).

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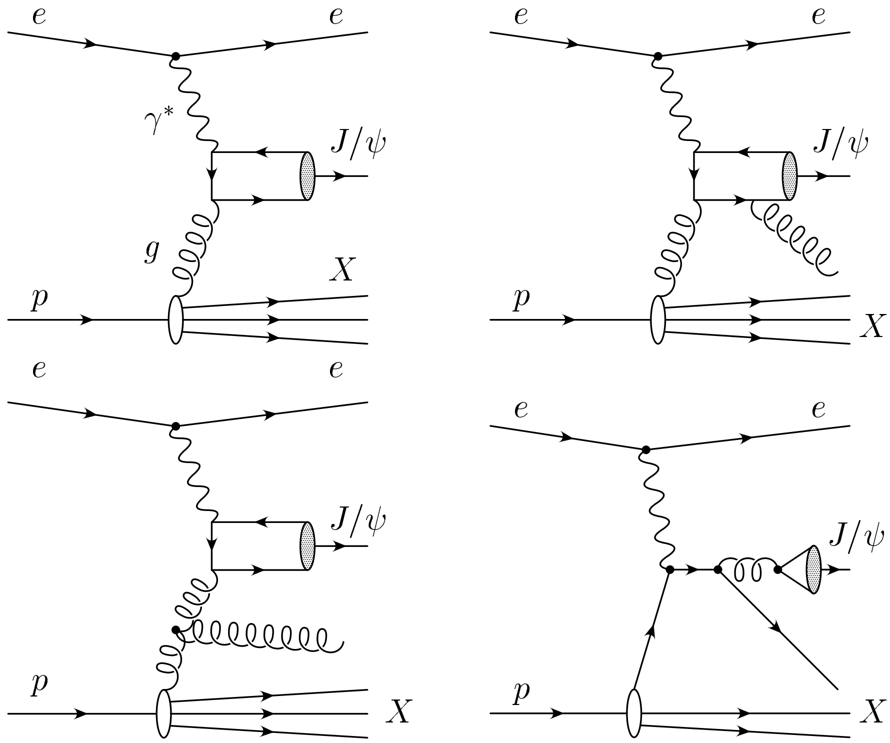
[6] K. Sridhar, A.D. Martin, W.J. Stirling, Phys. Lett. **B438** (1998) 211; Ph. Hägler, R. Kirschner, A. Schäfer, L. Szymanowski, O.V. Teryaev, Phys. Rev. Lett. **86** (2001) 1446; Phys. Rev. **D63** (2001) 077501; F. Yuan and K.-T. Chao, Phys. Rev. **D63** (2001) 034006; Phys. Rev. Lett. **87** (2001) 022002; V.A. Saleev, Phys. Rev. **D65** (2002) 054041.

[7] M. Beneke, G.A. Schuler, S. Wolf, Phys. Rev. **D62** (2000) 034004.

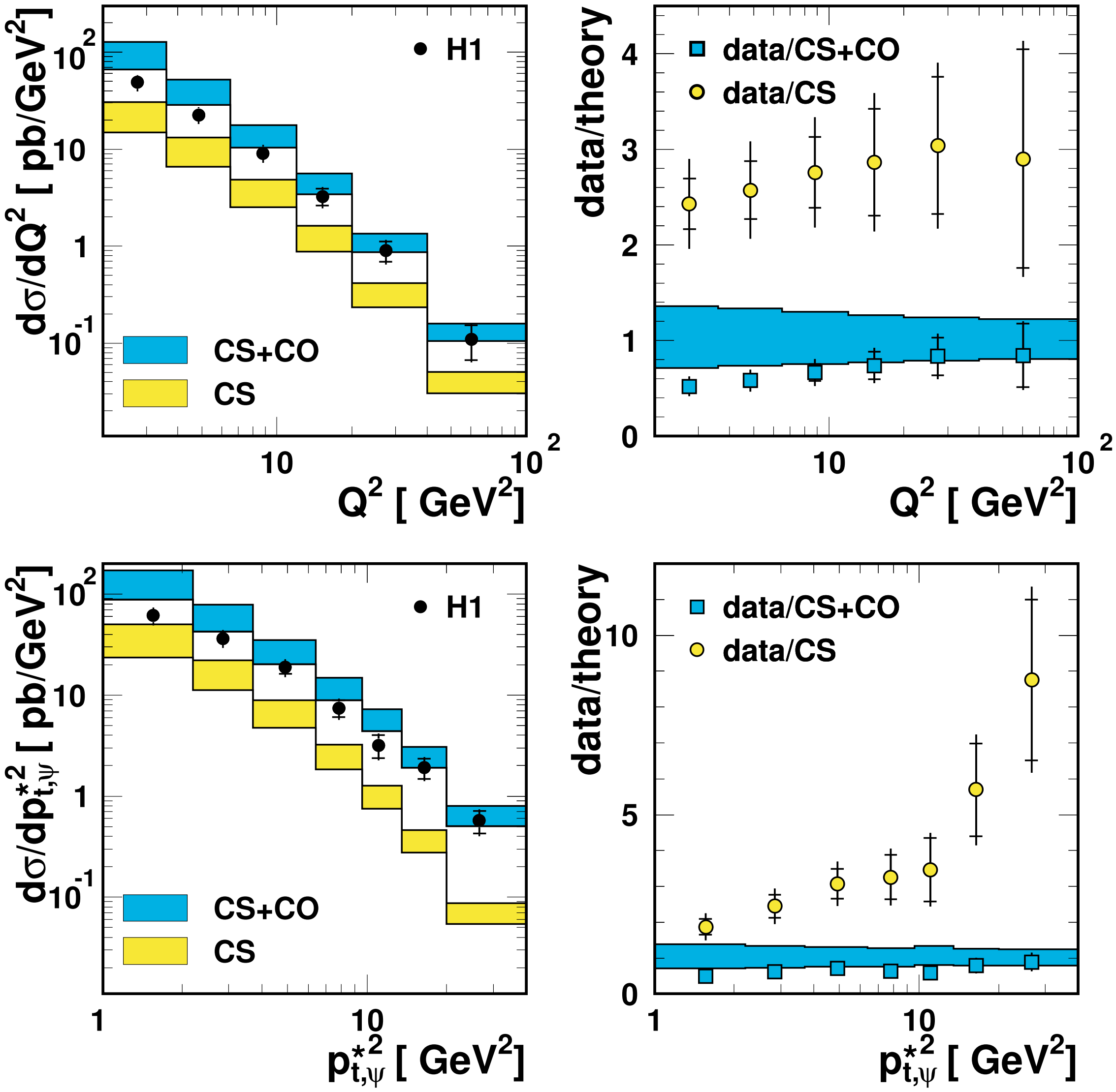
(iii) $ep \to J/\psi + X$ in DIS at HERA:[8]

- 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?
- Feed down from χ_{cJ} and ψ' subtracted.
- Exclude diffractive processes by z_{max}, $(p_T^\star)_{\mathrm{min}}$, or $(M_X)_{\mathrm{min}}$ cuts.
- This also avoids collinear singularities in $e+g \to e+c\bar{c}[n]+g$ with $n = {}^1S_0^{(8)}, {}^3P_J^{(8)}$.
- Disagreement with S. Fleming, T. Mehen, Phys. Rev. **D57** (1998) 1846; F. Yuan, K.-T. Chao, Phys. Rev. **D63** (2001) 034017.



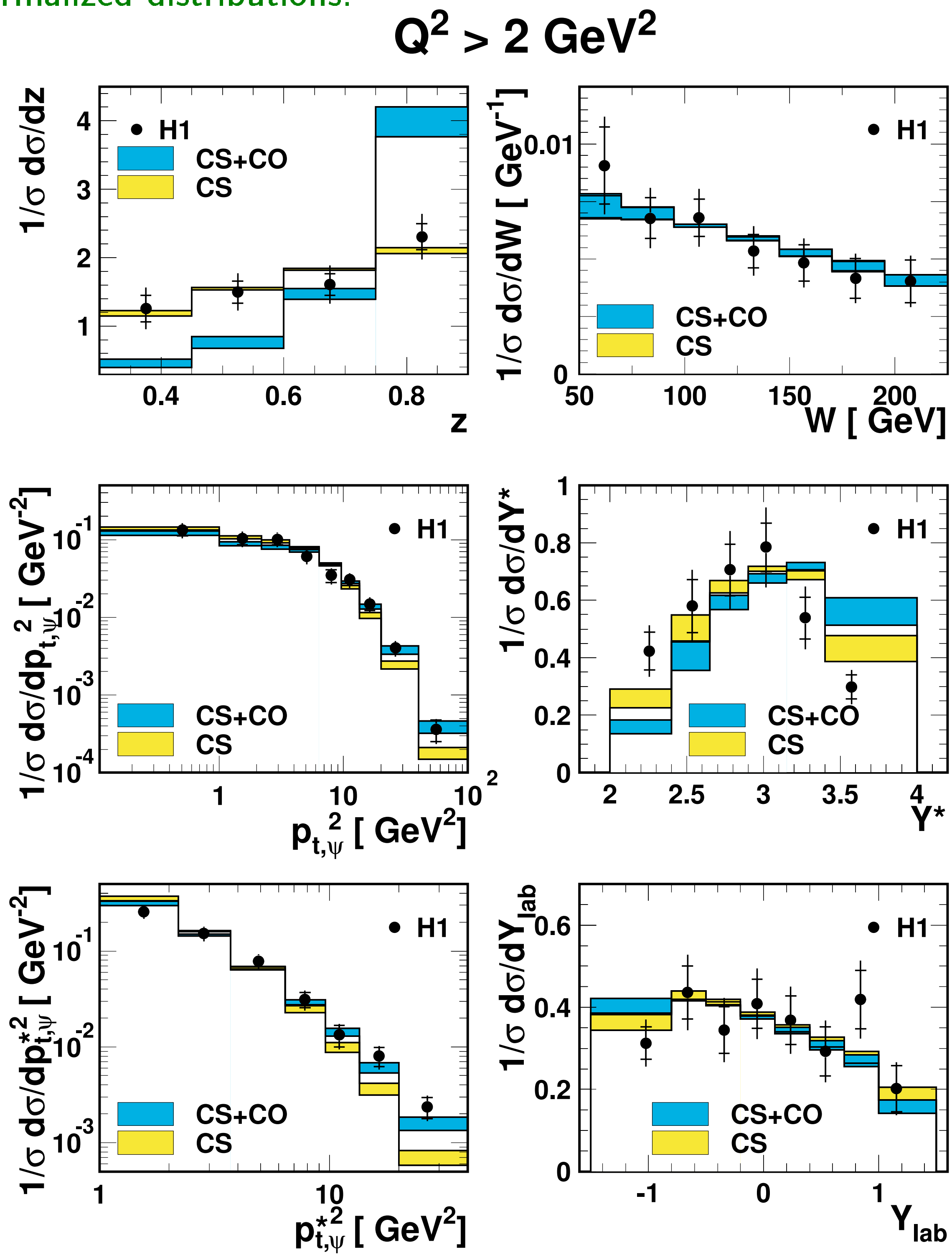
[8] B.A. Kniehl, L. Zwirner, Nucl. Phys. **B621** (2002) 337.

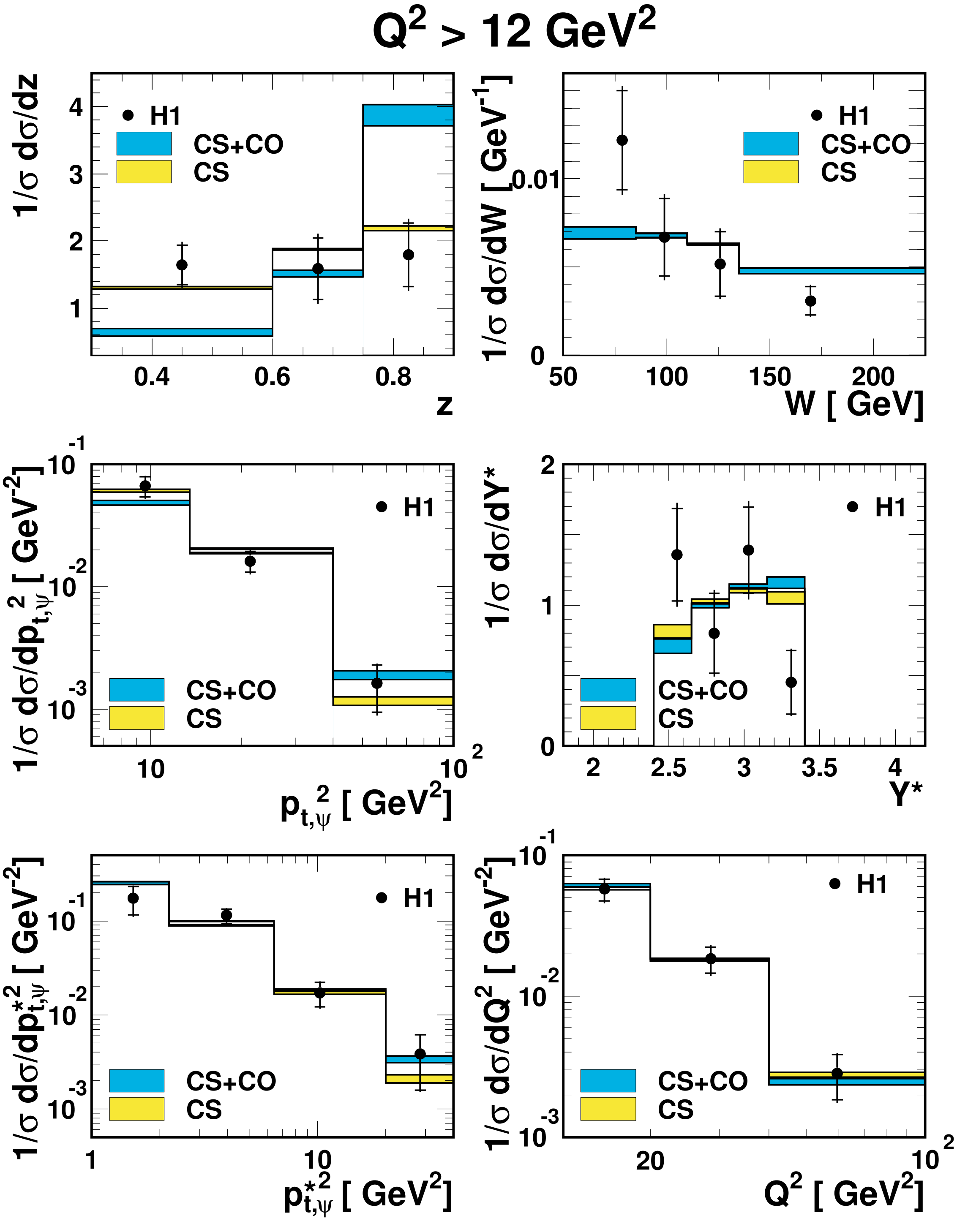
Comparison with H1 data (1997–2000; 77.0 pb^{-1}):[9]



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

Normalized distributions:




Q^2 > 12 GeV^2
1/σ dσ/dz
z
H1
CS+CO
CS
1/σ dσ/dW [GeV^-1]
W [GeV]
1/σ dσ/dp_{t,ψ}^2 [GeV^-2]
p_{t,ψ}^2 [GeV^2]
1/σ dσ/dY*
Y*
1/σ dσ/dp*_{t,ψ}^2 [GeV^-2]
p*_{t,ψ}^2 [GeV^2]
1/σ dσ/dQ^2 [GeV^-2]
Q^2 [GeV^2]

(iv) $\nu + N \to \nu + J/\psi + X$ in NC DIS:[10]

- CDHS and CHORUS measurements agree.[11] No evidence seen by NuTeV.[12]
- As for CO $2 \to 2$ subprocesses (Zg fusion), agreement with A.A. Petrov, T. Torma, Phys. Rev. **D60** (1999) 093009.
- $2 \to 3$ subprocesses new (axial-vector coupling).
- Diffractive processes estimated using VDM with new input.
- Prompt J/ψ.
- Contribution from B negligible.
- Nuclear corrections:[13] $\sigma_A = A^\alpha \sigma_1$ with $\alpha_{\text{coh}} = 1.19 \pm 0.02$ and $\alpha_{\text{in}} = 1.05 \pm 0.03$. $\rightsquigarrow$ Enhancement factors $2.75^{+0.32}_{-0.27}$ and $1.31^{+0.22}_{-0.20}$.
- Energy spectrum of neutrino beam:

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

$20 < E_\nu < 200$ GeV; $\langle E_\nu \rangle = 27$ GeV;
$\nu_\mu : \overline{\nu}_\mu : \nu_e : \overline{\nu}_e = 93\% : 6\% : 1\% : < 1\%$.

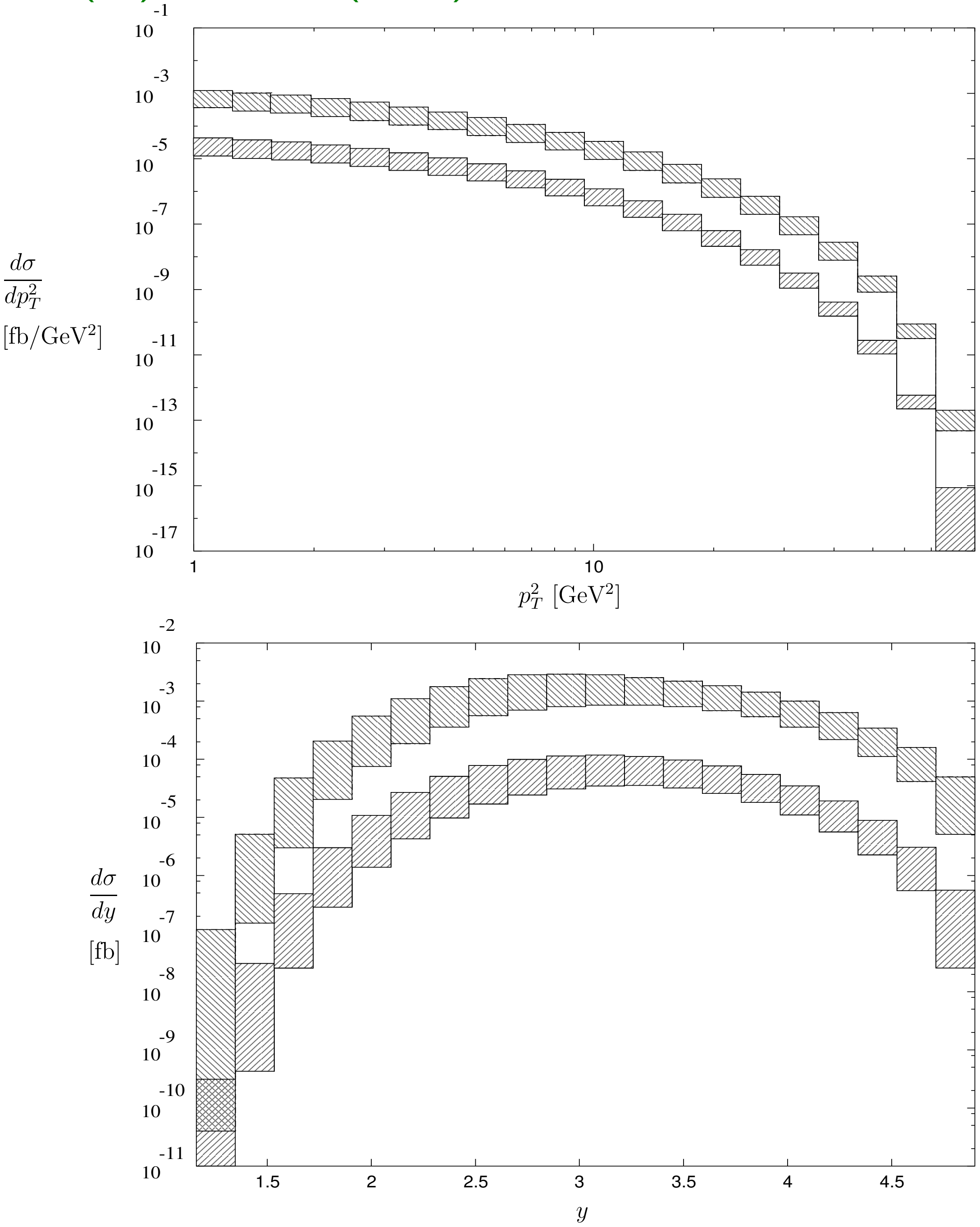
[10] B.A. Kniehl, L. Zwirner, Nucl. Phys. **B637** (2002) 311.

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

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

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

NRQCD (up) and CSM (down) predictions:



Comparison with CHORUS:

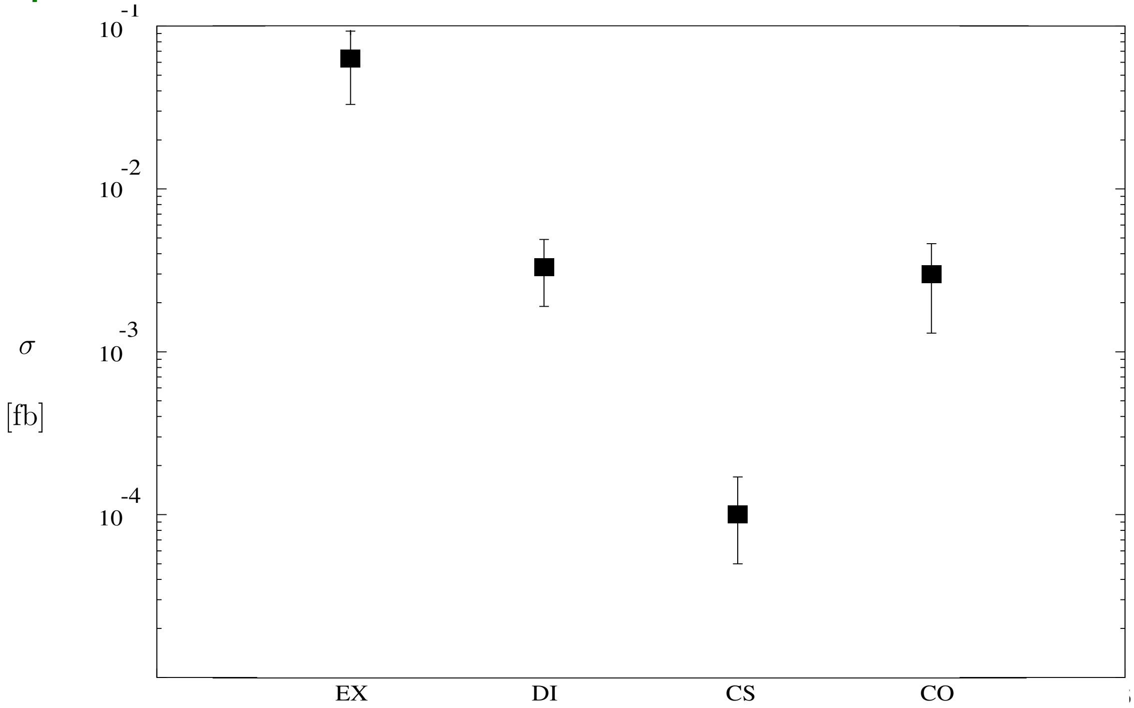
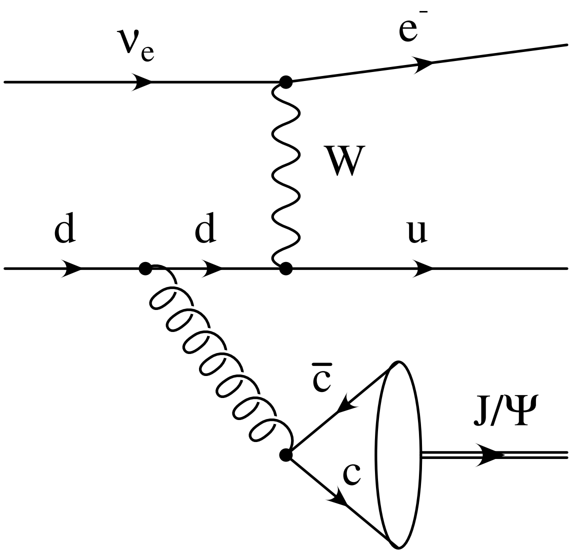


Table 2: $\sigma(\nu + \mathrm{Pb} \to J/\psi + X)$ in 10^{-3} fb.

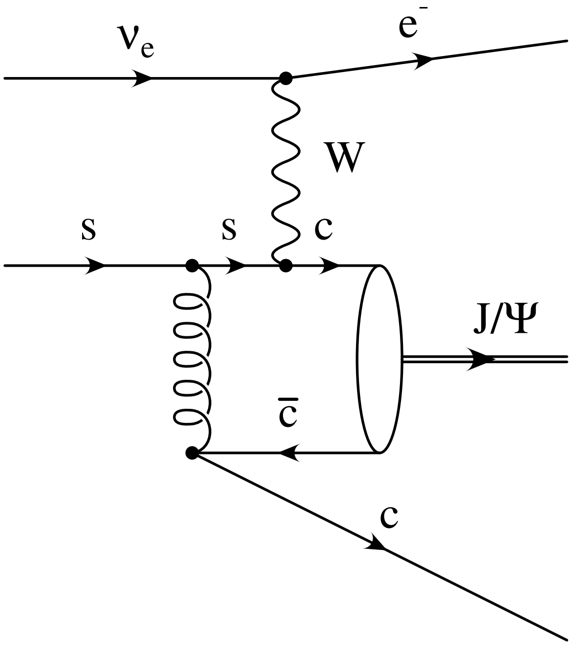
	EX	DI	CS	CO
σ	63 ± 30	$3.3^{+1.6}_{-1.4}$	$0.10^{+0.07}_{-0.05}$	$3.0^{+1.6}_{-1.7}$
direct		64%	78%	72%
χ_{cJ}		19%	—	14%
ψ'		17%	22%	14%

(v) $\nu + N \to e + J/\psi + X$ in CC DIS:[14]

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



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



charmed jet
both CS and CO

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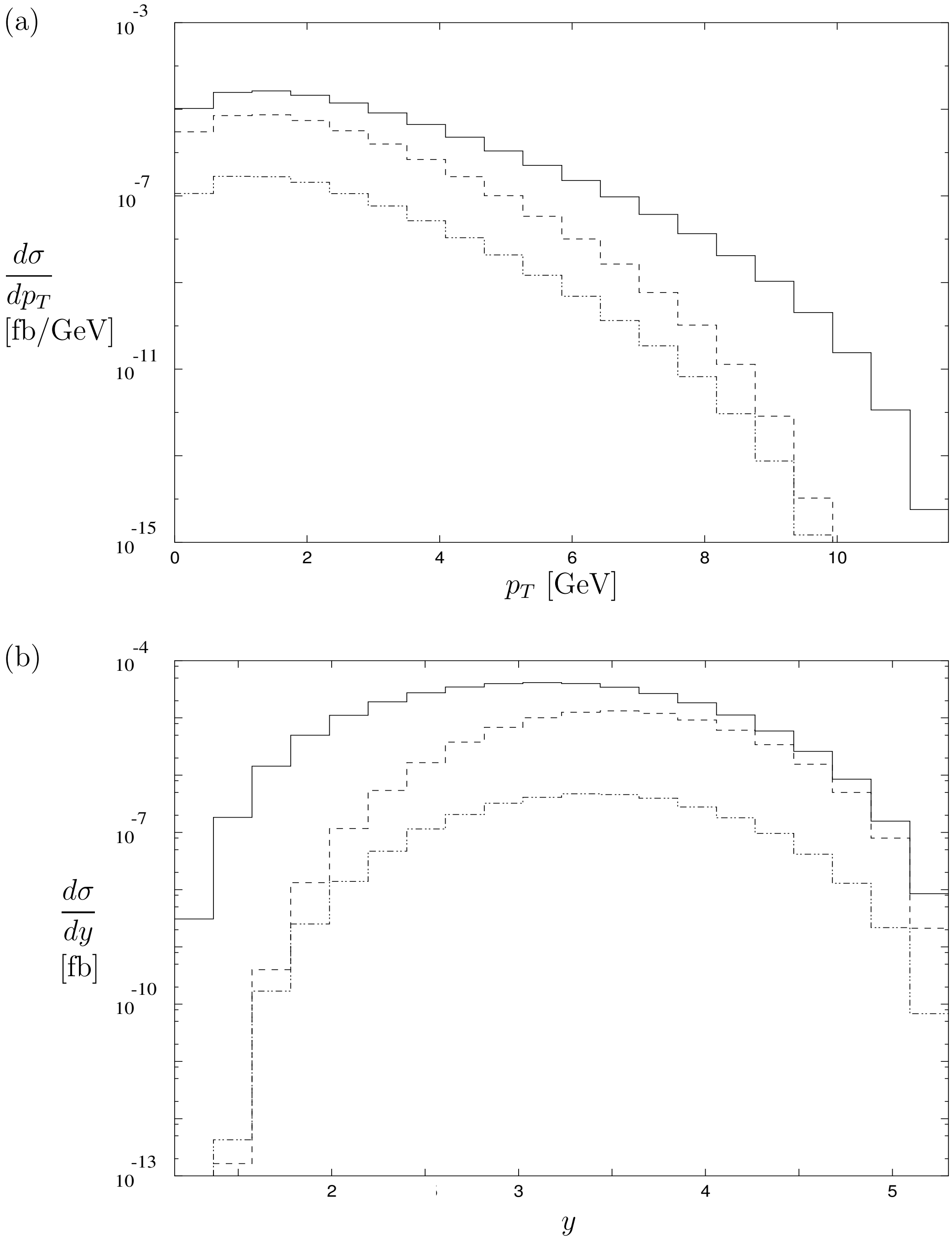
[14] B.A. Kniehl, L. Zwirner, DESY 02-134.

NRQCD (solid) and CSM (dash) predictions for NOMAD:

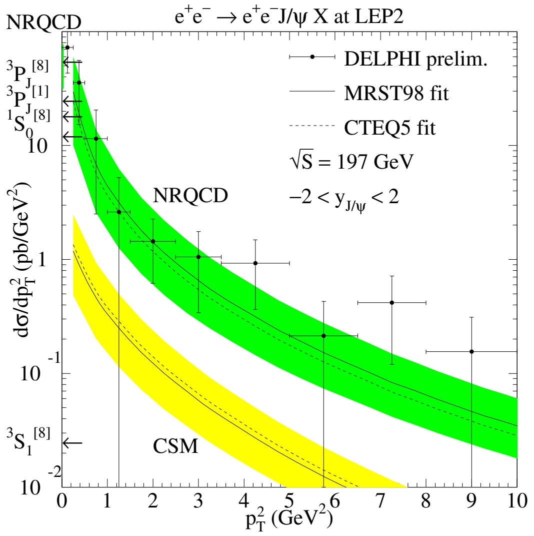


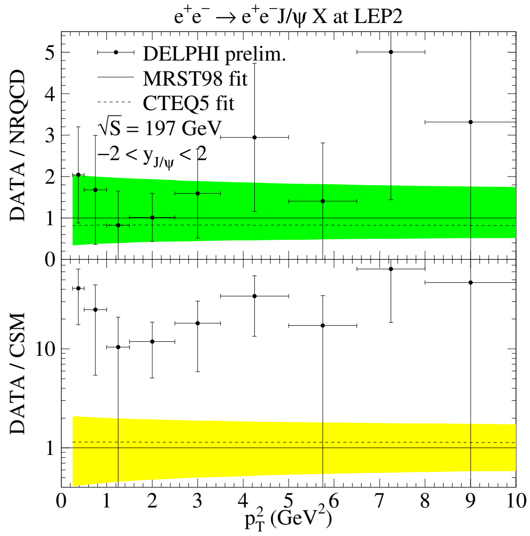
$\sigma(ud) = 4.9^{+3.4}_{-2.3} \times 10^{-5}$ fb, $\quad \sigma(c) = 1.8^{+1.5}_{-0.9} \times 10^{-5}$ fb.

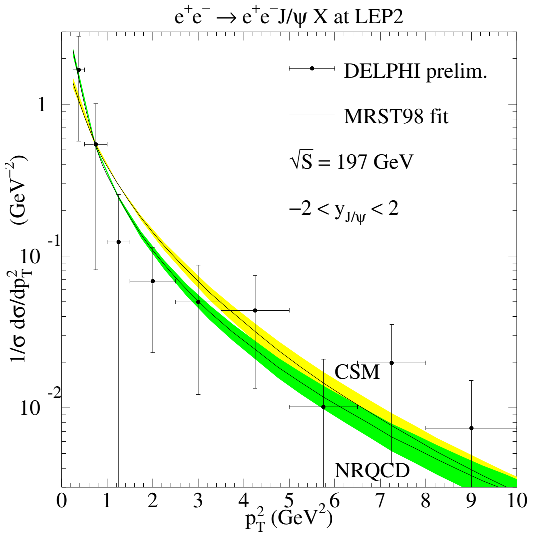
$e + p \to \nu + J/\psi + X$ challenge for HERA and THERA.

(vi) $\gamma\gamma \to J/\psi + X$ at LEP2:

- No prompt photons in remnant X.
- 1% direct, 98% singly resolved, 1% doubly resolved.
- 91% direct J/ψ, 9% from χ_{cJ} and ψ'.
- Contribution from B negligible.
- $\chi^2/N = 0.49$ (1.79) for NRQCD (CSM).





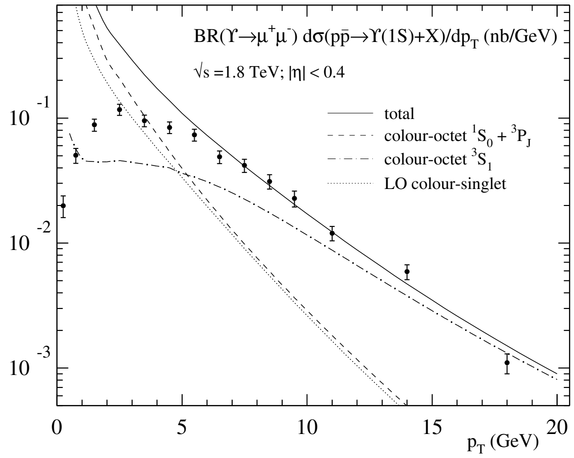


M. Klasen, B.A. Kniehl, L.N. Mihaila, M. Steinhauser, Phys. Rev. Lett. **89** (2002) 032001.

(c) Bottomonium

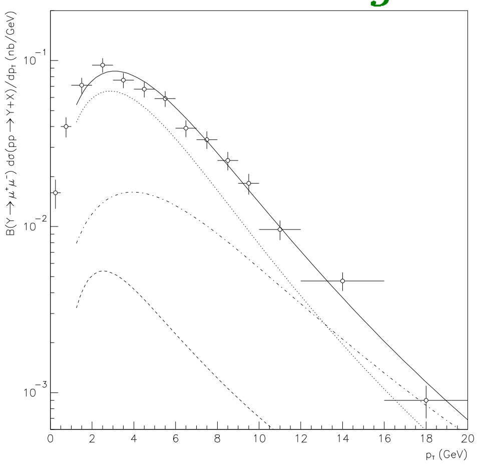
$v_b^2 \approx \alpha_s(m_\Upsilon) \approx 0.1 \rightsquigarrow$ PT safe.

(i) $p\overline{p} \to \Upsilon + X$ at the Tevatron:



M. Krämer, Prog. Part. Nucl. Phys. 47 (2001) 141.

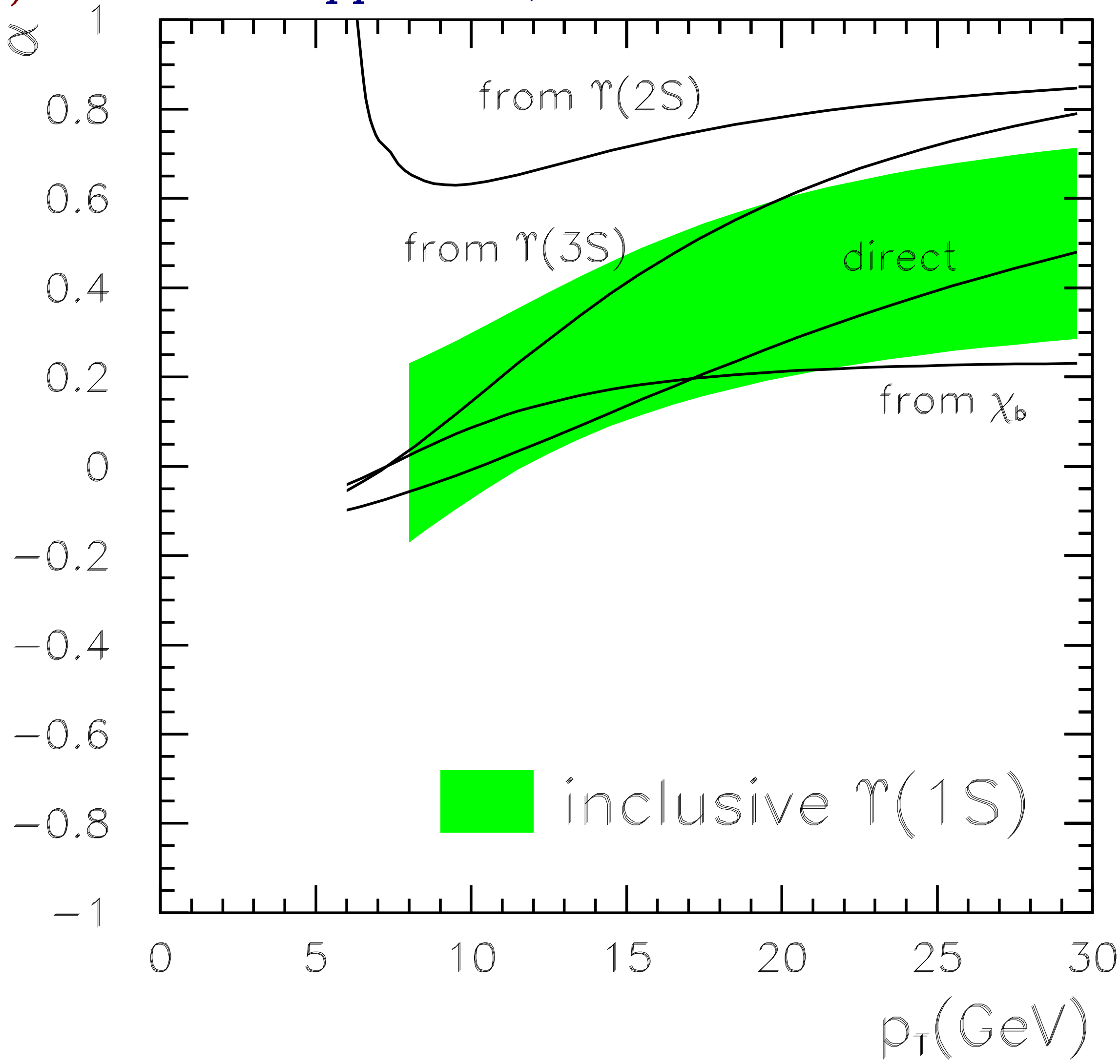
Include gluon ISR and AP evolution of $g \to b\overline{b}$:



J.L. Domenech-Garret, M.A. Sanchis-Lozano, Phys. Lett. **B476** (2000) 65; Nucl. Phys. **B601** (2001) 395.

- CO processes generally less important.
- Feed down from χ_{bJ} dominantly CS process.

(ii) Polarization in $p\overline{p} \to \Upsilon + X$ at the Tevatron:



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

- Consistent with longitudinal fractions measured by CDF: $\Gamma_L/\Gamma = 0.37 \pm 0.04$ (0.32 ± 0.11) for $2 < p_T < 20$ GeV $(8 < p_T < 20$ GeV).

2. Open heavy-quark production
(a) Theoretical aspects

- Focus on inclusive heavy-meson production.
- Cross section much larger than for quarkonium.
- Appropriate scheme depending on p_T/m_Q?
- Heavy-quark fragmentation?

Massive-Q scheme:[15] $ab \to Q\overline{Q} + X$

- $n_l = n_f - 1$ massless flavors a, b treated in $\overline{\mathrm{MS}}$ renormalization and factorization scheme, appear in PDFs.
- Q treated in OS scheme (OS mass and WFR CTs, decoupling in $\alpha_s(\mu)$ for $\mu \ll m_Q$), not *intrinsic*.
- No collinear divergences related to outgoing Q line. $\rightsquigarrow$ No factorization. $\rightsquigarrow$ No conceptual necessity for FFs.

$\oplus$ Valid for $0 \leq p_T \lesssim \text{few} \times m_Q$. $\rightsquigarrow$ σ_{tot} well defined.

$\oplus$ Appropriate for t (no fragmentation).

$\ominus$ Breaks down for $p_T \gg m_Q$ due to would-be collinear divergences $\propto \alpha_s \ln(p_T^2/m_Q^2)$.

$\ominus$ FFs introduced ad hoc to match D and B data. No AP evolution, no universality. $\rightsquigarrow$ Different $\epsilon_{\text{Peterson}}$ for different scales, types of experiment. $\rightsquigarrow$ Global data analysis unfeasible.

[15] P. Nason, S. Dawson, R.K. Ellis, Nucl. Phys. **B327** (1989) 49; **B335** (1990) 260 (E); W. Beenakker, H. Kuijf, W.L. van Neerven, J. Smith, Phys. Rev. **D40** (1989) 54; M. Drees, M. Krämer, J. Zunft, P.M. Zerwas, Phys. Lett. **B306** (1993) 371; B.A. Kniehl, M. Krämer, G. Kramer, M. Spira, Phys. Lett. **B356** (1995) 539; M. Cacciari, M. Greco, B.A. Kniehl, M. Krämer, G. Kramer, M. Spira, Nucl. Phys. **B466** (1996) 173.

n_f-flavor $\overline{\mathrm{MS}}$ scheme:[16] $ab \to c + X$ with $c \to Q$ meson

• n_f massless flavors a, b, c treated in $\overline{\mathrm{MS}}$ renormalization and factorization scheme, appear in PDFs.

• Collinear divergences related to outgoing c line factorized into nonperturbative FFs.

$\oplus$ $\alpha_s^{n+1,n} \ln^n(p_T^2/m_Q^2)$ terms resummed by AP evolution. $\rightsquigarrow$ Valid for $p_T \gtrsim \mathrm{few} \times m_Q$.

$\oplus$ Scaling violation and universality of FFs guaranteed by factorization theorem. $\rightsquigarrow$ Unique $\epsilon_{\mathrm{Peterson}}$. $\rightsquigarrow$ Global data analysis possible.

$\ominus$ $(m_Q/p_T)^n$ terms not included. $\rightsquigarrow$ Breaks down for $p_T \lesssim m_Q$. $\rightsquigarrow$ No σ_{tot}.

[16] J. Binnewies, B.A. Kniehl, G. Kramer, Phys. Rev. **D58** (1998) 014014; 034016.

Perturbative FFs:[17] $ab \to c + X$ with $c \to Q$

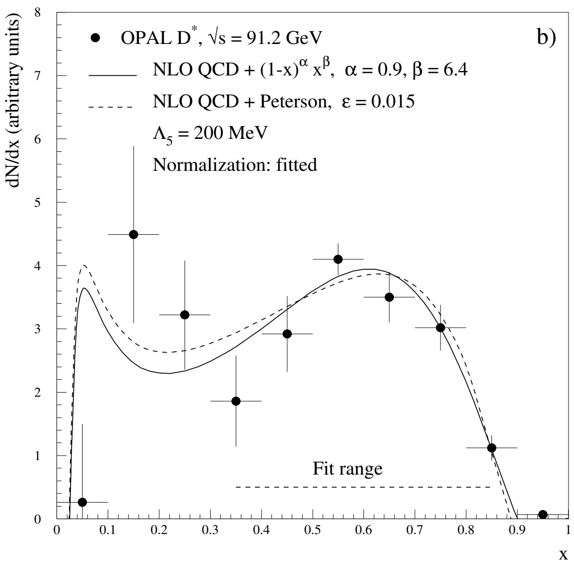
- Match

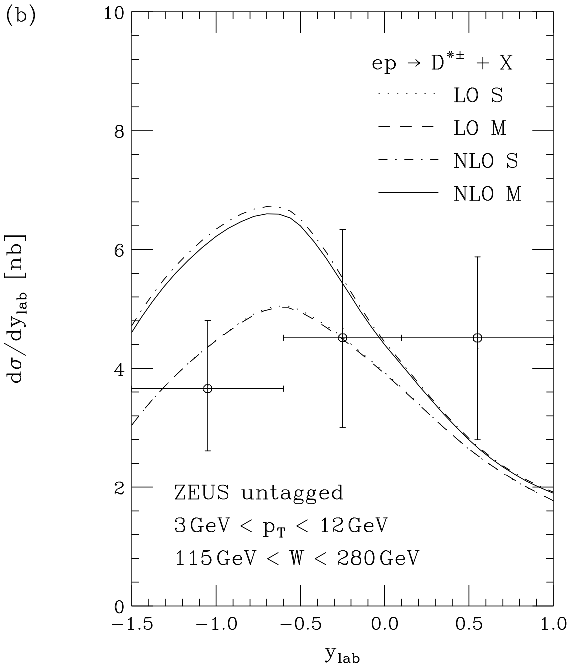
$$\frac{d\sigma_{e^+e^- \to Q\overline{Q}+X}}{dx}(x, s, m_Q^2) = \sum_c \int_x^1 \frac{dz}{z} D_c^Q\left(\frac{x}{z}, \mu^2, m_Q^2\right) \times \frac{d\sigma_{e^+e^- \to c+X}}{dz}(z, s, \mu^2).$$

- Can incorporate PFFs by change of scheme.[18]
- Still need nonperturbative FFs to match data.

⊖ $d\sigma_{e^+e^- \to Q\overline{Q}+X}/dx < 0$ for $x \gtrsim 0.9$! $\rightsquigarrow$ Low-quality fit.

⊖ Unsatisfactory perturbative stability.





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[17] B. Mele, P. Nason, Nucl. Phys. **B361** (1991) 626; J.P. Ma, Nucl. Phys. **B506** (1997) 329; J. Binnewies, B.A. Kniehl, G. Kramer, Z. Phys. **C76** (1997) 677; M. Cacciari, M. Greco, Phys. Rev. **D55** (1997) 7134.

[18] B.A. Kniehl, G. Kramer, M. Spira, Z. Phys. **C76** (1997) 689.

"FONLL":[19]

• $\mathbf{FONLL = FO} + G(m_Q, p_T) \times \mathbf{(RS - FOM0)}$

FO: massive-Q scheme; α_s and evolution of gluon PDF in n_f-flavor $\overline{\mathrm{MS}}$ scheme; no intrinsic Q.

RS: n_f-flavor $\overline{\mathrm{MS}}$ scheme with PFFs.

FOM0: $m_Q \to 0$ limit of FO.

$G(m_Q, p_T)$: arbitrary function with $G(m_Q, p_T) \to 1$ for $m_Q/p_T \to 0$, e.g. $G(m_Q, p_T) = p_T^2/(p_T^2 + 25m_Q^2)$.

• RS and FOM0 evaluated at $p_T \to m_T = \sqrt{p_T^2 + m_Q^2}$.

⊖ $\mathbf{(RS - FOM0)}$ abnormally large.

⊖ For $p_T \lesssim \mathrm{few} \times m_Q$ problems of massive-Q scheme (non-universality of FFs).

⊖ For $p_T \gtrsim \mathrm{few} \times m_Q$ problems of PPFs (low-quality fit, unsatisfactory perturbative stability).

[19] M. Cacciari, M. Greco, P. Nason, JHEP 05 (1998) 007; M. Cacciari, P. Nason, Phys. Rev. Lett. **89** (2002) 122003.

"NLO n_f-flavor scheme":[20]

• Massive-Q scheme with would-be collinear singularities of form $\alpha_s \ln(p_T^2/m_Q^2)$ $\overline{\mathrm{MS}}$-subtracted.

• Residual $\alpha_s \ln(p_T^2/\mu_F^2)$ terms small for $\mu_F \approx p_T$.

• $\alpha_s \ln(\mu_F^2/m_Q^2)$ terms absorbed into PDFs and FFs, and resummed by AP evolution.

• In e^+e^- and direct $\gamma\gamma$ collisions, subtraction terms coincide with those generated by PPFs. Other processes?

$\oplus$ Naturally interpolates between massive-Q and n_f-flavor $\overline{\mathrm{MS}}$ schemes.

$\oplus$ Factorization theorem[21] in operation also for $p_T \lesssim \mathrm{few} \times m_Q$.

$\rightsquigarrow$ Universality of FFs.

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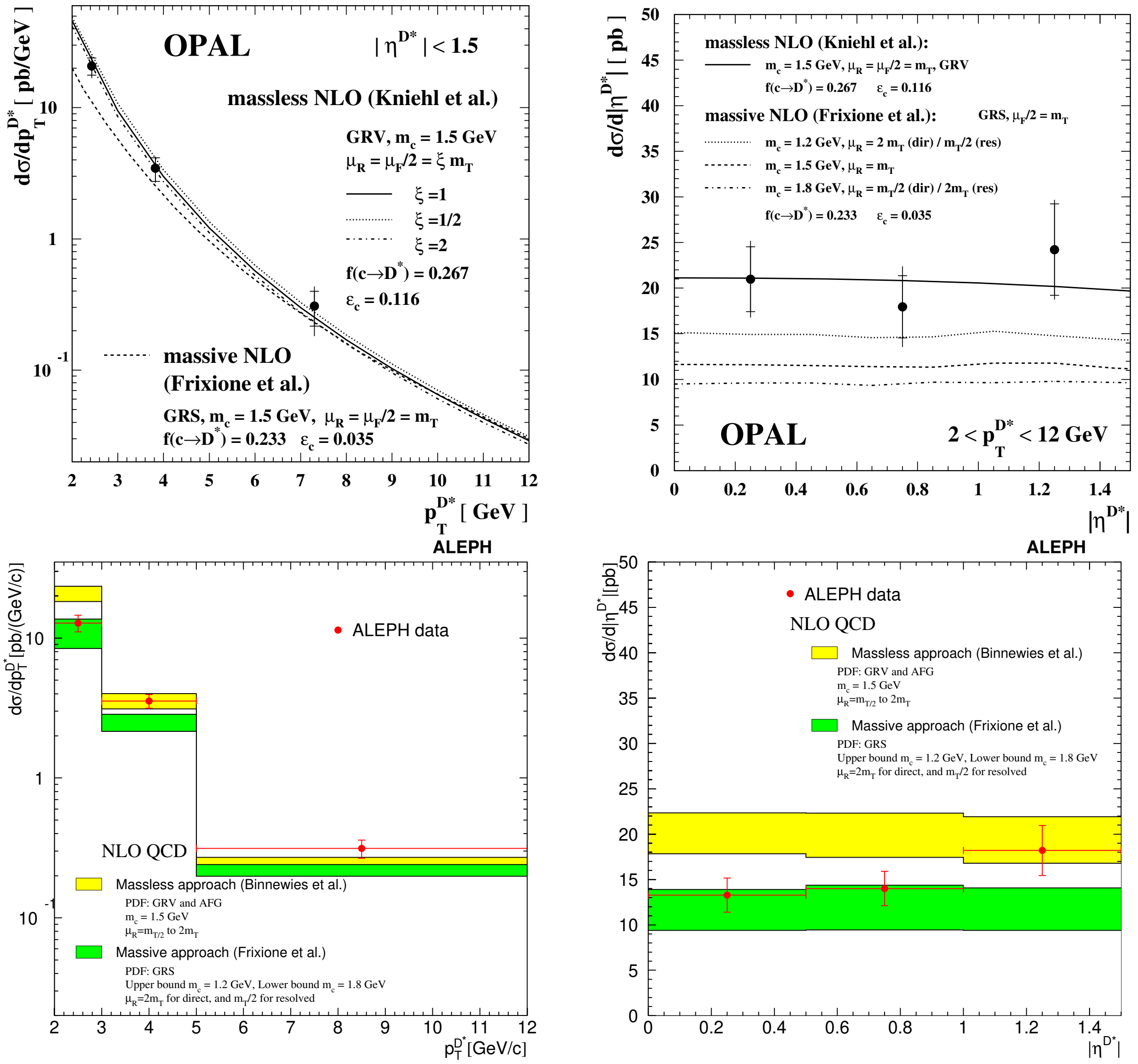
[20] G. Kramer, H. Spiesberger, Eur. Phys. J. **C22** (2001) 289.

[21] J.C. Collins, Phys. Rev. **D58** (1998) 094002.

(b) $D^{*\pm}$ mesons

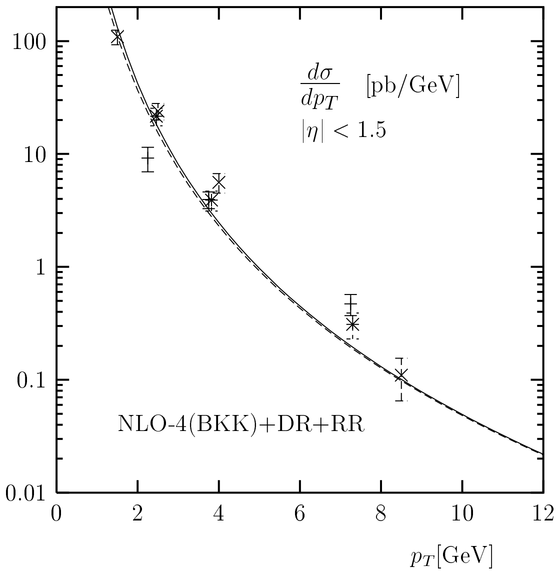
$\gamma\gamma \to D^{*\pm} + X$ at LEP2:[22]

- Massive-Q and n_f-flavor $\overline{\mathrm{MS}}$ schemes:

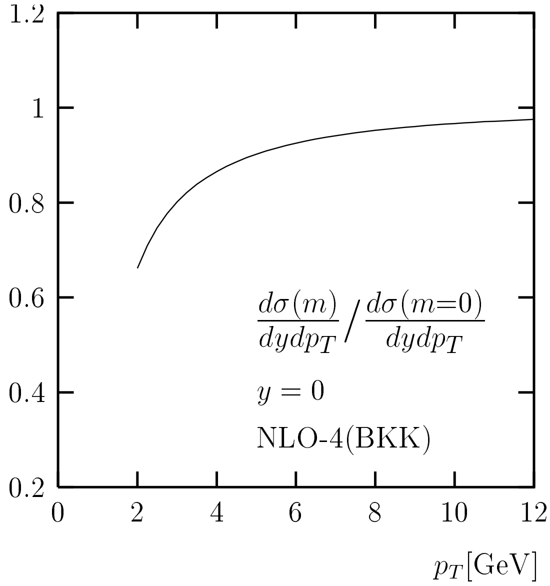


[22] OPAL Collaboration, G. Abbiendi et al., Eur. Phys. J. **C16** (2000) 579; ALEPH Collaboration, A.B. Ngac, private communication.

- NLO 4-flavor scheme:



Massive (dash), massless (solid).

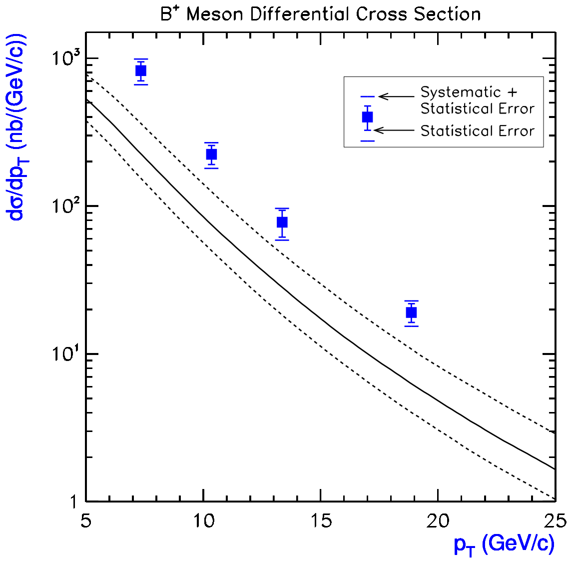


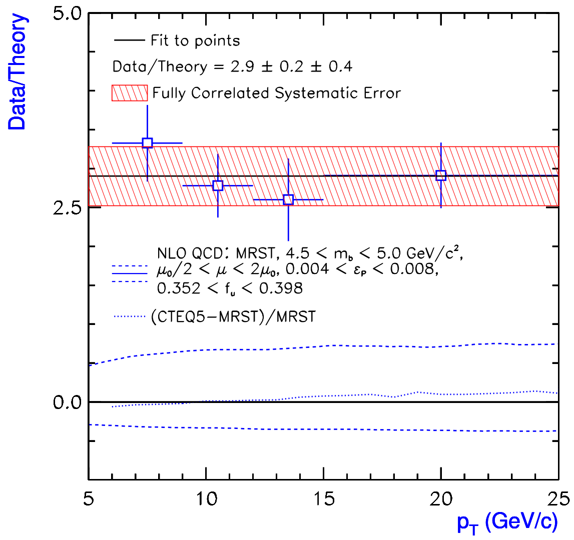
Ratio for direct channel.

G. Kramer, H. Spiesberger, Eur. Phys. J. **C22** (2001) 289.

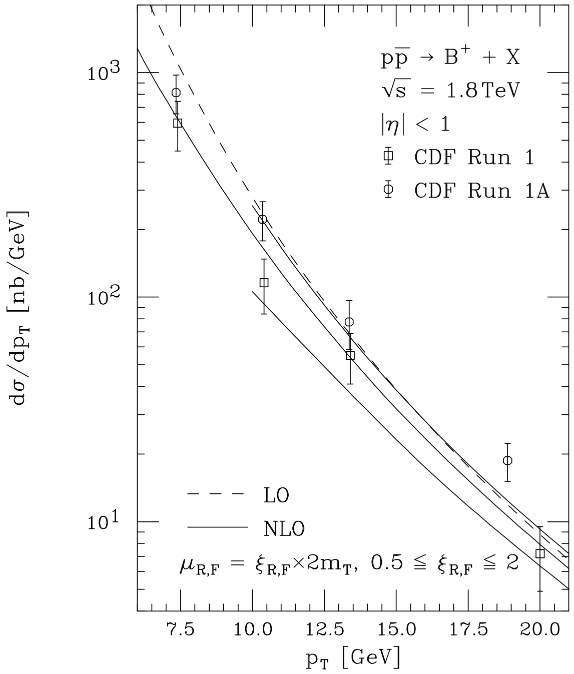
(c) B mesons

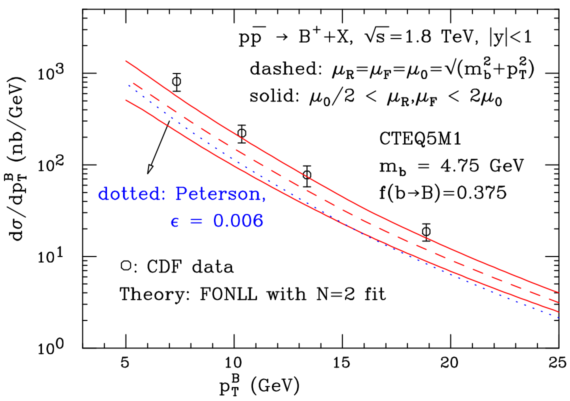
$p\bar{p} \longrightarrow B^+ + X$ at the Tevatron:[23]





Massive-Q scheme





5-flavor $\overline{\mathrm{MS}}$ scheme

FONLL, only $\langle x \rangle_{\mathrm{LEP1}}$ used

[23] CDF Collaboration, D. Acosta et al., Phys. Rev. **D65** (2002) 052005.

3. Summary and outlook

Quarkonium production:

- NRQCD factorization hypothesis generally supported by (unpolarized) J/ψ hadro-, lepto-, and photoproduction at Tevatron, HERA, and LEP2.
- Measurements of J/ψ polarization at large p_T and νN NC DIS not yet precise enough.
- Large theoretical uncertainties in LO. $\rightsquigarrow$ Include NLO in α_s and v. Redo fits to Tevatron data to extract MEs.
- First NLO results available.[24] Work in progress.
- Some room for nonperturbative ingredients (intrinsic k_T, shape functions, etc.)
- NRQCD seems to work for Υ.

[24] A. Petrelli, M. Cacciari, M. Greco, F. Maltoni, M.L. Mangano, Nucl. Phys. **B514** (1998) 245; F. Maltoni, M.L. Mangano, A. Petrelli, Nucl. Phys. **B519** (1998) 361; M. Klasen, B.A. Kniehl, L. Mihaila, M. Steinhauser, Nucl. Phys. **B609** (2001) 518.

Open heavy-quark production:

- Massive-Q scheme (with conventional $\epsilon_{\rm Peterson}$) dramatically undershoots data of B hadro-, lepto-, and photoproduction.
- Nonperturbative FFs crucial to describe $D^{*\pm}$ and B data.
- AP evolution and universality of FFs requisite for global data analysis. Both lacking in massive-Q scheme and for $p_T \lesssim \text{few} \times m_Q$ in FONLL!
- NLO n_f-flavor scheme introduces collinear factorization in massive-Q framework.
- Implementation of m_Q effects near threshold, kinematic constraints on threshold behaviour, ACOT(χ),[25]. . .

Expect exciting new data from HERA-II, Tevatron Run II, B factories, LHC, TESLA, . . . !

[25] W.-K. Tung, S. Kretzer, C. Schmidt, J. Phys. **G28** (2002) 983.