Theoretical Aspects of Heavy-Meson Production

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Contents

1. 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:[1] $ab \to Q\overline{Q} + X$

- $n_l = n_f - 1$ 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.

[1] 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 $\overline{\rm MS}$ scheme:[2] $ab \to c + X$ with $c \to Q$ meson

• n_f massless flavors a, b, c treated in $\overline{\rm MS}$ 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. $\leadsto$ Valid for $p_T \gtrsim \mathrm{few} \times m_Q$.

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

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

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

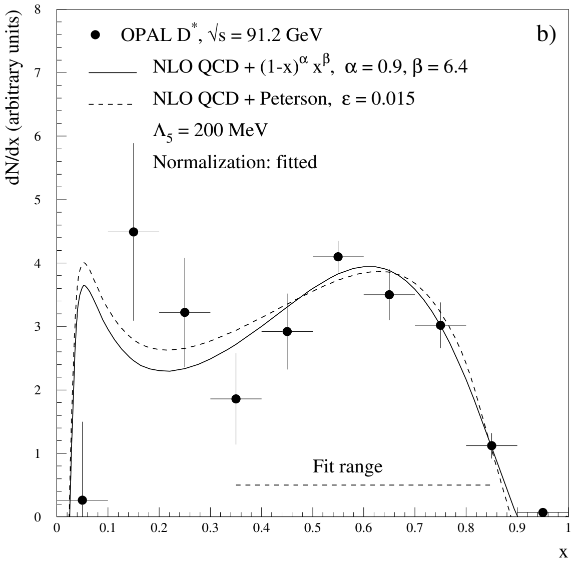
Perturbative FFs:[3] $ab \to c + X$ with $c \to Q$

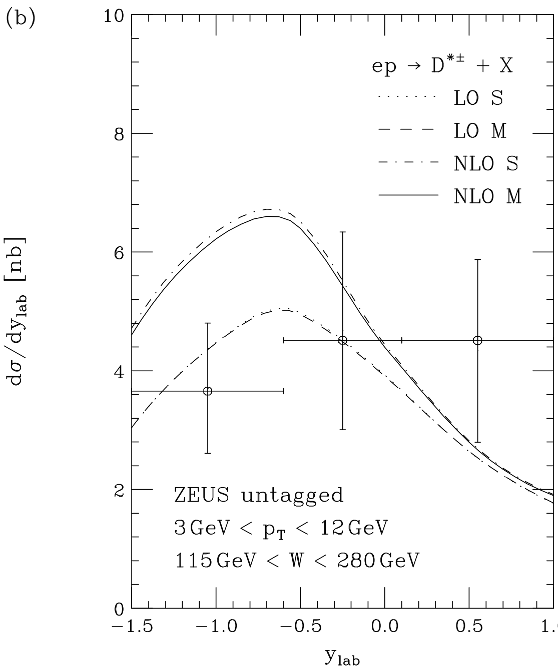
- Match

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

- Can incorporate PFFs by change of scheme.[4]
- Still need nonperturbative FFs to match data.

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





[3] 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.

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

"FONLL":[5]

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

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

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

$\ominus$ $(\mathrm{RS} - \mathrm{FOM0})$ abnormally large.
$\ominus$ For $p_T \lesssim \mathrm{few} \times m_Q$ problems of massive-Q scheme (non-universality of FFs).
$\ominus$ For $p_T \gtrsim \mathrm{few} \times m_Q$ problems of PPFs (low-quality fit, unsatisfactory perturbative stability).

[5] 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":[6]

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

$$\lim_{m\to 0} \frac{d\sigma}{dp_T dy}(m) = \left.\frac{d\sigma}{dp_T dy}\right|_{\overline{\mathrm{MS}},m=0} + \frac{\Delta d\sigma}{dp_T dy}$$

• 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^-, direct and resolved $\gamma\gamma$ 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[7] in operation also for $p_T \lesssim \mathrm{few} \times m_Q$.

$\rightsquigarrow$ Universality of FFs.

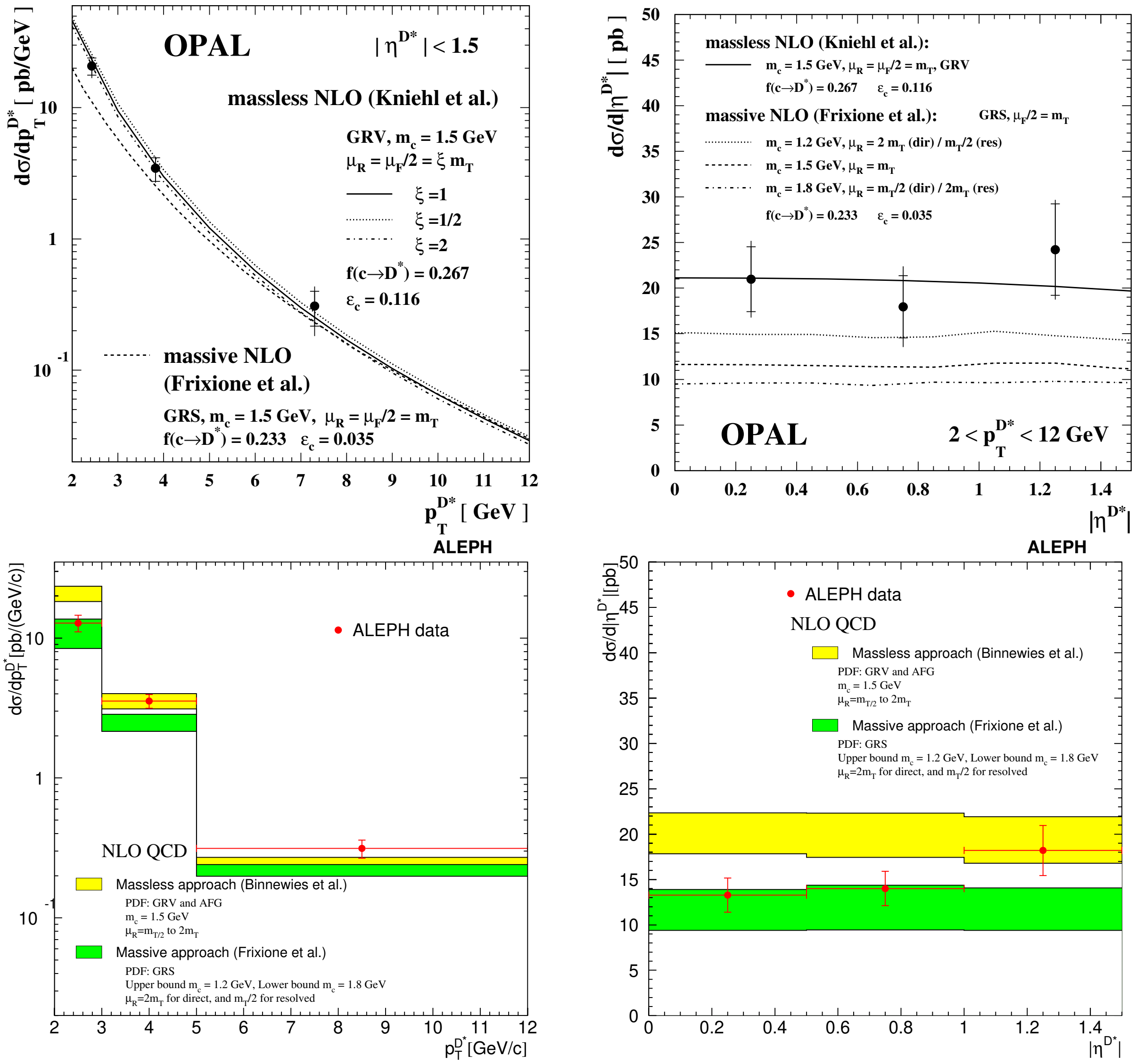
[6] G. Kramer, H. Spiesberger, Eur. Phys. J. **C22** (2001) 289; **C28** (2003) 495.

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

2. $D^{*\pm}$ mesons

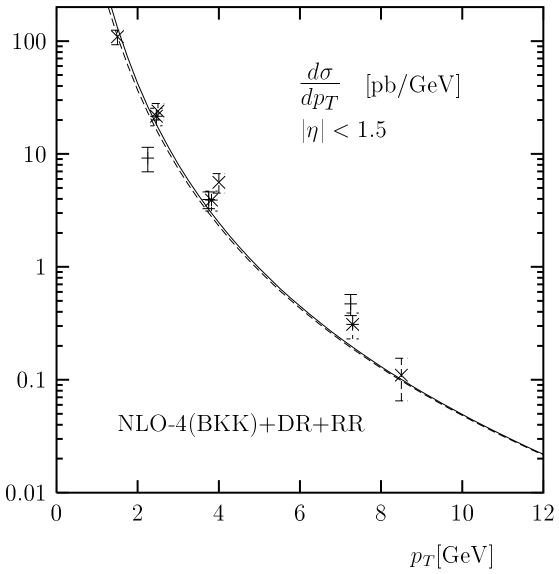
$\gamma\gamma \to D^{*\pm} + X$ at LEP2:[8]

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

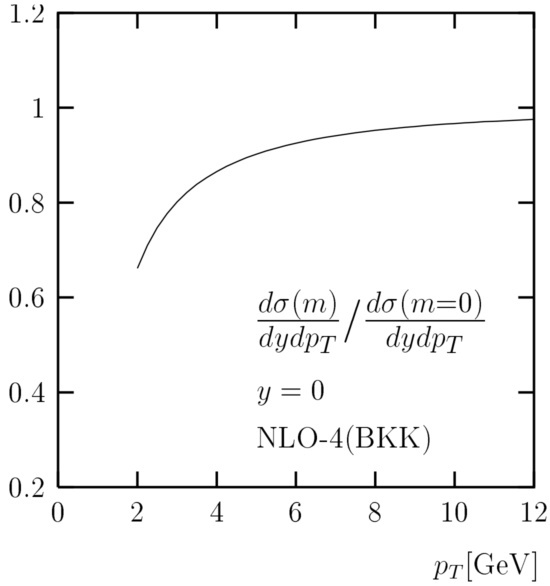


[8] OPAL Collaboration, G. Abbiendi et al., Eur. Phys. J. **C16** (2000) 579; ALEPH Collaboration, A.B. Ngac, private communication.

- NLO 4-flavor scheme:



Massive (dash), massless (solid).

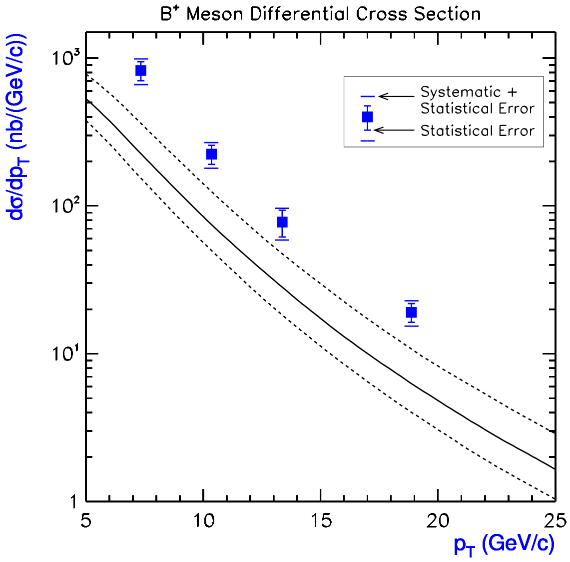


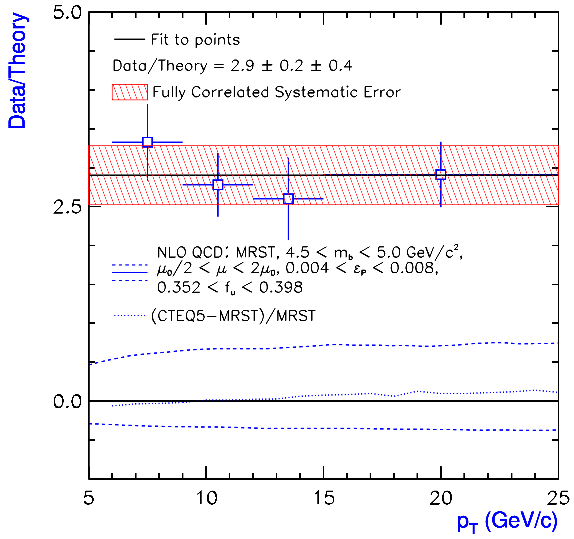
Ratio for direct channel.

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

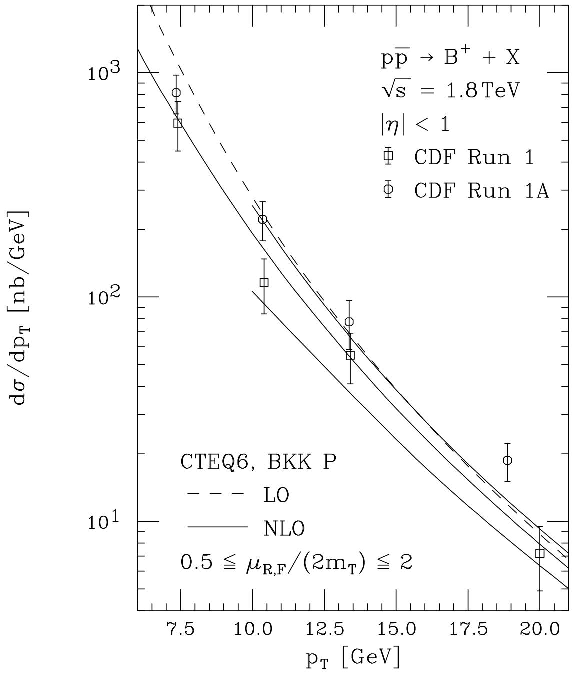
3. B mesons

$p\overline{p} \to B^+ + X$ at the Tevatron:[9]

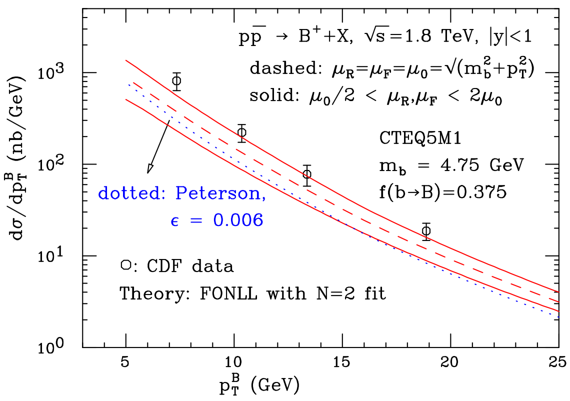




Massive-Q scheme



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



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

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

4. Summary and outlook

- Massive-Q scheme (with conventional $\epsilon_{\mathrm{Peterson}}$) 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 $p_T \lesssim \mathrm{few} \times m_Q$ 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),[10]. . .

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

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