Inclusive $D^*$ Production in Photon-Photon Collisions with Massive Quarks in NLO
Photon 2003, Frascati

Three approaches $\gamma + \gamma \rightarrow D^{*\pm} + X$

NLO: $\gamma + \gamma \rightarrow c + \bar{c} + g$

direct contribution

$\alpha$) massless approach $m_c = 0, N_f = 4$

$$d\sigma(\gamma\gamma \rightarrow cX) = \frac{\alpha}{2\pi} P_{c\gamma} d\sigma(\gamma c \rightarrow cg) \ln \frac{s}{M^2}$$

$M$ factorization scale $O(\sqrt{s})$

originates from collinear divergent piece

$$d\sigma(\gamma\gamma \rightarrow cX) = \frac{\alpha}{2\pi} \left(-\frac{1}{e}\right) \left(\frac{4\pi\mu^2}{s}\right)^e P_{c\gamma} d\sigma(\gamma c \rightarrow cg)$$

$\rightarrow \left(\frac{4\pi\mu^2}{M^2}\right)^e \left(\frac{M^2}{s}\right)^e$

$\rightarrow$ into NLO corr

$\rightarrow$ absorbed in $f_c^\gamma$
(iii) massive approach $m_c \neq 0$, $N_f = 3$

$$d\sigma (g g \to c X) = \frac{\alpha}{2\pi} P_{c g} d\sigma (g c \to cg) \ln \frac{s}{M^2_c}$$

factorization scale $M = m_c \to \text{large}$

charm only in final state: $f_c = 0$

(iv) massive approach $m_c \neq 0$, $N_f = 4$

$$\ln \frac{s}{m^2_c} = \ln \frac{s}{M^2_f} + \ln \frac{M^2}{m^2_c}$$

$\uparrow$

as in massless

$\uparrow$ absorbed in $f_c^y$

charm also in initial state:

single and double resolved with charm

same procedure for second and third diagram

factorization scale $M_f$

need fragmentation for $c \to D^* : D_c^{D^*}(x)$
• (i) \( m_c = 0 \) from start \( \ (ZM - VFN) \)
  \( m_c^2 / p_T^2 \) terms neglected
  good only for large \( p_T \)
  \( \ln \frac{M^2}{m_c^2} \) terms summed in evolved \( f_c^r \) and \( D_c^{D^*} \)

• (ii) \( m_c \neq 0 \) \( \ (FFN) \ n_f = 3 \)
  no \( c \) quarks in initial state
  \( f_c^r = 0 \), \( D_c^{D^*} \) not evolved, fragmentation pert.
  good for \( p_T^2 \approx m_c^2 \), \( m_c^2 / p_T^2 \) terms included

• (iii) \( m_c \neq 0 \) \( \ (Massive\ VFN) \ n_f = 4 \)
  \( c \) quarks in initial state
  \( f_c^r \neq 0 \), \( f_c^r \) and \( D_c^{D^*} \) evolved
  \( \ln \frac{M^2}{m_c^2} \) terms summed
  \( m_c^2 / p_T^2 \) terms included
  good for \( p_T^2 \gg m_c^2 \), where \( f_c^r \neq 0 \), \( D_c^{D^*} \neq 0 \)
  \( p_T^2 \ll m_c^2 \) transition to FFN
massless limit of (iii) neglects $m_c^2/p_t$ terms

- (i) and $m_c \to 0$ limit of (iii) identical?
  answer: no!

- (i) and (iii) differ by finite terms
do not vanish for $m_c \to 0$

- finite terms subtracted to match (i)
calculated for
direct process
  G.K. + H. Spiesberger
  EPJC 22, 289 (2001)
  hep-ph/0302081

- direct process
  finite terms = LO pert. fragmentation functions

- finite terms in (iii) subtracted to match (i)
(i) is for $\overline{\text{MS}}$ factorization scheme
  scheme for PDF and FF $c \to D^*$ is $\overline{\text{MS}}$
\[ e^+ e^- \rightarrow D^* + X \]

two components: \[ e^+ e^- \rightarrow c + X \quad \rightarrow D^* \]

\[ e^+ e^- \rightarrow b + X \quad \rightarrow D^* \]


\[ \text{NLO} \quad \text{MS factorization} \]
direct process

\[ \frac{d\sigma}{dy dp_T} \quad [\text{pb/GeV}] \]

(a) \[ p_T [\text{GeV}] \]

(b) \[ p_T [\text{GeV}] \]

LO

\[ \frac{d\sigma(m)}{dy dp_T} / \frac{d\sigma(m=0)}{dy dp_T} \]

(a) \[ p_T [\text{GeV}] \]

(b) \[ p_T [\text{GeV}] \]

NLO-4

\[ \frac{d\sigma(m)}{dy dp_T} / \frac{d\sigma(m=0)}{dy dp_T} \]

(a) \[ p_T [\text{GeV}] \]

(b) \[ p_T [\text{GeV}] \]

NLO-4(BKK)
single-resolved process

(a) DR: $\frac{d\sigma}{dp_T}$ [pb/GeV]

(b) DR: $\frac{d\sigma}{dp_T}$ [pb/GeV]

(c)  

- massless
- massive

- no charm
*double-resolved contribution*

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**RR:** \( \frac{d\sigma}{dp_T} \) \([\text{pb/GeV}]\)

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no charm

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(a) \( \frac{d\sigma}{dp_T} \) \([\text{pb/GeV}]\)

(b) \( \frac{d\sigma}{dp_T} \) \([\text{pb/GeV}]\)

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direct + single resolved

+ double resolved

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off shell: \( m^2 \) to be a small
ALEPH, L3, OPAL

different constraints on $\sqrt{s_{av}}$, tagging, $\gamma$ range
Conclusions

Resummed NLO calculation with $m_c \neq 0$ exists

Good agreement with ALEPH, L3 and OPA data for $p_T > 2$ GeV

Matching to NLO FFN, $n_f = 3$

at small $p_T$ needs further study