Open charm production at low energies

Short review and some ideas worth trying at SPD conditions

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The review on charm production in handronic interaction at low and middle energies

By now, we have a draft of the review in preparation to be published in the Bulletin of Moscow University. This draft contain dozens of pages and more than 100 references. In this study we itemize the experiments on hadronic charm production, as well as the theoretical approaches to the description of the charm production. In this report the content of the review will not be described in details, but the main theoretical approaches to the problem will be briefly highlighted and also some proposals for studying open charm at SPD will be put forward.

Open charm production at high energies

- Gluon fusion

  $gg \to c\bar{c}$

- Quark-antiquark annihilation

  $q\bar{q} \to c\bar{c}$

- Charm excitation

  $gc \to gc$

Main approaches:

GM-VFNS **General-mass variable-flavor-number scheme**
(B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger)
The heavy quark is treated as any other massless parton, the mass is taken into account as large logarithms $\ln(p_T/m)$ in parton distribution and fragmentation functions, where they are resummed by imposing the DGLAP evolution [1].

FONLL **Fixed-order Next-to-Leading-Logarithm**
(M. Cacciari, M. Greco and P. Nason)
NLO (massive quark) + resummation of large logarithms.
At $p_T < 5m_c$ NLO works without logarithm resummation (see eq. 6.1 in [2]).

k_T fact. LO (massive quark) + virtual initial gluons
(It seems that sea c quark is not needed) [3]
Widely applied by S. P. Baranov, A. V. Lipatov, N. P. Zotov and V. A. Saleev [3, 4, 5].

Interactive cross section estimation within FONLL:
http://www.lpthe.jussieu.fr/∼cacciari/fonll/fonllform.html

Fragmentation mechanism

The isolated quark cannot be observed and therefore must be hadronized:

$$c(\mathbf{p}) \xrightarrow{D(z)dz} H_c(z\mathbf{p})$$

$$\frac{d\sigma_{H_c}}{dz} = D(z) \cdot \sigma_{c\bar{c}}$$

$D(z)dz$ — the process-independent probability for the charm quark to transform into the open charm hadron H_c.

$$\frac{d\sigma_{H_c}}{dp_T} = \int_{2p_T/\sqrt{s}}^{1} \frac{d\sigma_{c\bar{c}}}{dk_T}\left(\frac{p_T}{z}\right)\frac{D(z)}{z}dz$$

$$0 < z < 1$$

Works fairly well at $|\vec{p}| \to \infty$. Difficulties at $|\vec{p}| \sim m_c$:

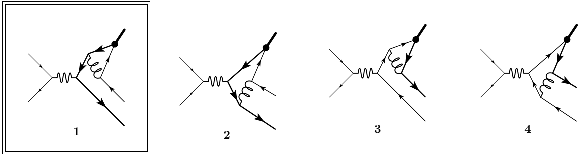
- $m_Q \neq m_H$ (The invariant mass can not be conserved).
- The predictions depend essentially on the fragmentation variable choose ($|\vec{p}|$, E, p_+).
- The predictions depend on the coordinate system.

pQCD motivated FF

FF for B_c can be calculated.

$$\frac{M_{B_c}^2}{s_{e^+e^-}} \to 0$$

$$\frac{d\sigma_{B_c}}{dz} = D_{\bar{b}\to B_c}(z) \cdot \sigma_{b\bar{b}}$$



Feynman diagrams for $e^+e^- \to B_c + X$.

$$D_{\bar{b}\to B_c^*}(z) = \frac{2\alpha^2|R_S(0)|^2}{81\pi m_c^3}\frac{rz(1-z)^2}{(1-(1-r)z)^6}\times$$
$$\times\,(6-18(1-2r)z+(21-74r+68r^2)z^2-2(1-r)(6-19r+18r^2)z^3+3(1-r)^2(1-2r+2r^2)z^4)$$

$$D_{\bar{b}\to B_c}(z) = \frac{2\alpha^2|R_S(0)|^2}{27\pi m_c^3}\frac{rz(1-z)^2}{(1-(1-r)z)^6}\times$$
$$\times\,(2-2(3-2r)z+3(3-2r+4r^2)z^2-2(1-r)(4-r+2r^2)z^3+(1-r)^2(3-2r+2r^2)z^4)$$

$$r = \frac{m_c}{m_c+m_b}$$

The pQCD motivated FFs are used within FONLL to describe $c \to D$ (r — free parameter).

Peterson FF

To describe heavy quark hadronization into heavy-light meson the Peterson FF is usually used:

$$D_{Q\to(Q\bar{q})}(z) \sim \frac{1}{z\left(1-\frac{1}{z}-\frac{\epsilon}{1-z}\right)^2}.$$

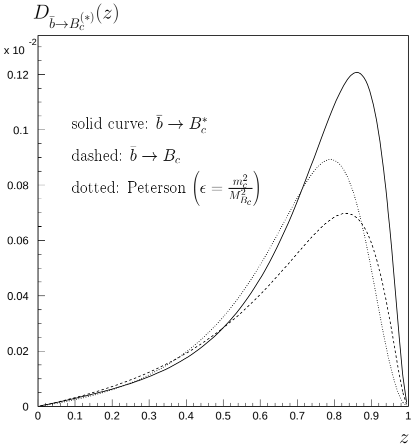
The dependence of "nonperturbative" Peterson FF is partially determined by denominator of perturbative propagator for $Q^* \to (Q\bar{q}) + jet$ process:

$$m_Q^2 - (P_{(Q\bar{q})} + P_{\rm jet})^2.$$

$$m_Q^2 - (P_{(Q\bar{q})} + P_{\rm jet})^2 \approx m_Q^2 - \frac{m_{(Q\bar{q})}^2}{z} - \frac{m_{\rm jet}^2}{1-z}.$$

For $m_Q \approx m_{(Q\bar{q})}$:

$$m_Q^2 - (P_{(Q\bar{q})} + P_{\rm jet})^2 \sim 1 - \frac{1}{z} - \frac{m_{\rm jet}^2}{m_Q^2}\frac{1}{1-z}.$$



FF for $b \to B_c^{(*)}$ obtained within pQCD vs. Peterson parametrization.

Kartvelishvili-Likhoded-Petrov FF [6]

$$D_{KLP}(z) = (\alpha + 1)(\alpha + 2)z^{\alpha}(1 - z)$$

- Shape is close to shapes of other FFs.
- Formula looks like the formula for the hadronic structure function.
- Based on Gribov-Lipatov reciprocity.

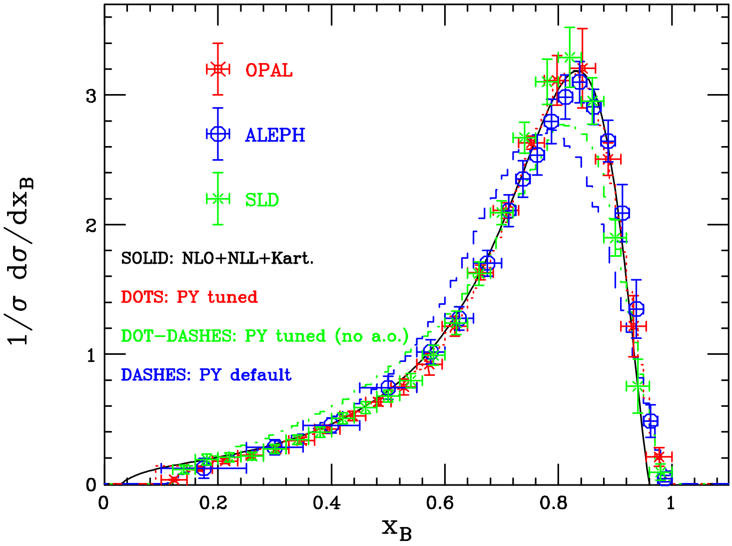
$$|\textbf{hadron}\rangle = \sum_i |\text{parton}\rangle_i \quad \Longleftrightarrow$$

$$|\textbf{parton}\rangle = \sum_j |\text{hadron}\rangle_j$$

FF	the main z dependence
pQCD motivated	propagator (+WF)
Peterson	propagator
KLP	WF

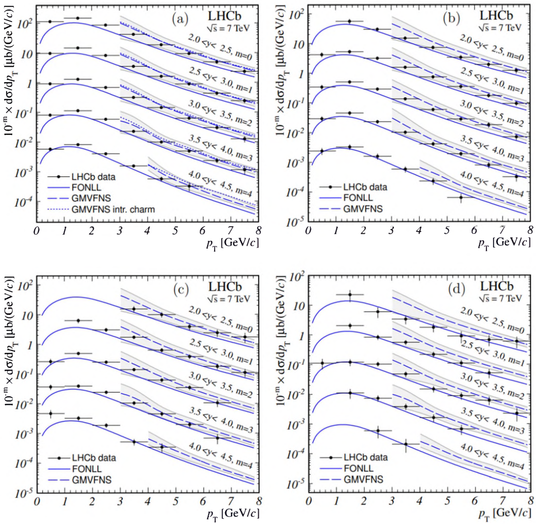
- Any approach for heavy quark production can be used with any FF parameterizations.
- But the FF parameter values essentially depend on the choice of heavy quark production model.
- Only the cross section of heavy hadrons can be measured experimentally.

Open beauty production in e^+e^- collisions

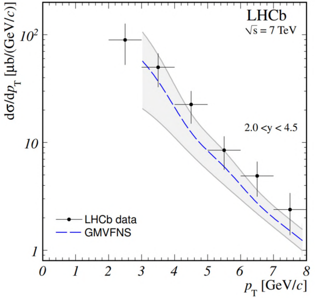


OPAL [7], ALEPH [8], SLD [9]

Open charm production at LHCb

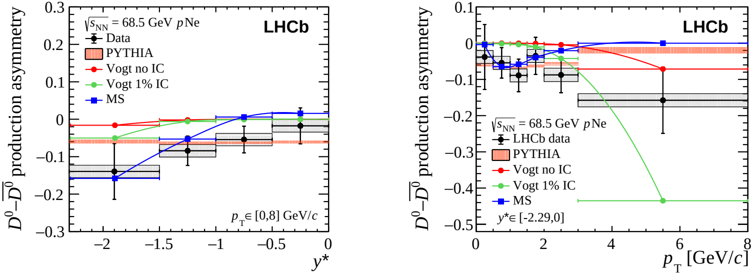


Differential cross-sections for (a) D^0, (b) D^+, (c) D^{+*}, and (d) D_s^+ meson production compared to theoretical predictions.



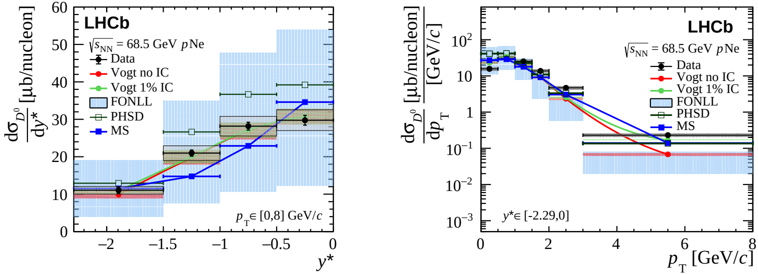
Differential cross-sections for Λ_c^+ baryon production compared to the theoretical prediction from the GMVFNS scheme.

Hadronization effects in LHCb data [12] (I)



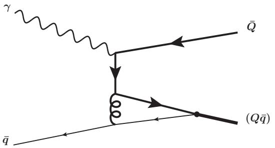
The considered models do not account precisely for all the features observed in the LHCb data, but theoretical predictions including 1% intrinsic charm and 10% recombination contributions (MS [10]) better describe the data than the other models considered (Pythia, Vogt [11]).

Hadronization effects in LHCb data [12] (II)



Good news: the cross section values can be fairly described within the mentioned approaches.

Recombination mechanism



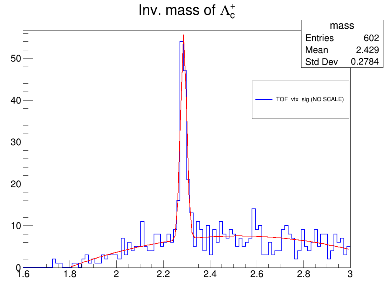
$$\left.\frac{d\hat{\sigma}[\bar{q}g \to (Q\bar{q}) + \bar{Q}]}{d\hat{\sigma}[gg \to Q\bar{Q}]}\right|_{\theta=\pi/2} \approx \frac{256\pi}{189}\alpha_s \frac{m_Q^2}{m_Q^2 + p_T^2}$$

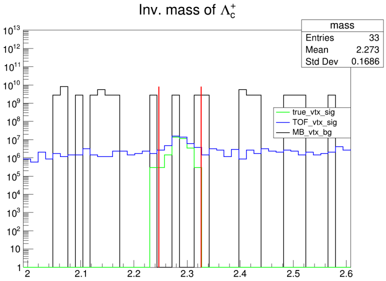
$$\frac{d\hat{\sigma}[\bar{q}g \to (Q\bar{q}) + \bar{Q}]}{dp_T} \sim \frac{1}{p_T^6}$$

$$\left.\frac{d\hat{\sigma}[\bar{q}g \to (Q\bar{q}) + \bar{Q}]}{d\hat{\sigma}[gg \to Q\bar{Q}]}\right|_{\theta=0} \approx \frac{256\pi}{81}\alpha_s \sim 1$$

The result above can be obtained within HQET [13] or within NRQCD motivated model [14]. The recombination is not suppressed in the forward (backward) region!

$\Lambda_c \to pK\pi$ at SPD





Seems like Λ_c can be investigated at SPD conditions using the simplest mode $\Lambda_c \to pK\pi$. The signal significance after 1 year data taking was preliminary estimated as

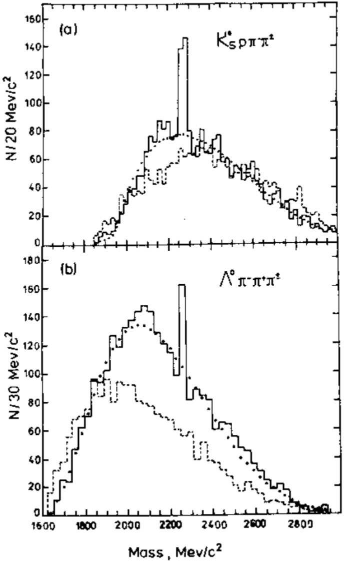
$$\frac{N_{sig}}{\sqrt{N_{bg}}} \sim 36$$

Many thanks to Atrem Smirnov and Leonid Seregin for their study!

$\Lambda_c \to K_s p\pi^-\pi^+$ and $\Lambda_c \to \Lambda^0\pi^-\pi^+\pi^+$

Experiment: BIS-2 [15]
Serpukhov accelerator
Beam: neutrons;
$\sqrt{s} \approx 10$ GeV;
Target: C.

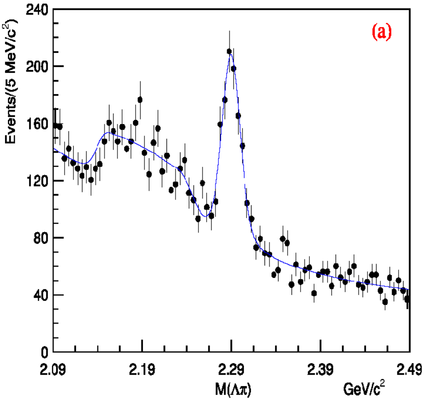
The mode was chosen due to a reliable detection of the decays of subsequent long-living states:
$K_s \to \pi^+\pi^-$ and $\Lambda^0 \to p\pi^-$.
Kinematic region: $(X_F > 0.5)$



$\Lambda_c \to K_s p$ and $\Lambda_c \to \Lambda^0 \pi^+$

Experiment: FOCUS [16] [15]
FermiLab
Beam: bremsstrahlung photons from electrons;
$\sqrt{s_e} \approx 300$ GeV;
Target: Be.

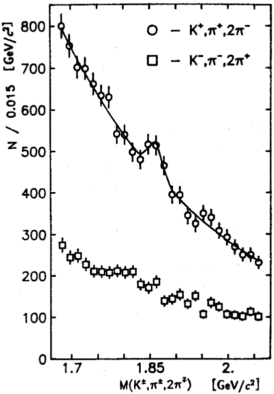
A broad structure at around 2.2 GeV/c coming from the decay mode $\Lambda_c \to \Sigma^0(\Lambda\gamma)\pi^+$ where the photon from the Σ^0 decay is not reconstructed.
(See also [17, 18])

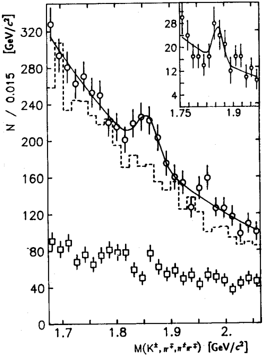


$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$

Experiment: BIS-2 [19]
Serpukhov accelerator
Beam: neutrons;
$\sqrt{s} \approx 10$ GeV;
Target: H, C and Al.

At least four charged particles with a common vertex in the target region were selected. Cerenkov threshold hodoscopes were used for kaon and pion identification.
Kinematic region:
$30 < P_L < 60$ GeV/c $(X_F \gtrsim 0.5)$
and $p_T < 1$ GeV/c.
As $\sim 78\%$ of the decay goes through the intermediate ρ^0 state, the signal quality can be improved with cut on $\pi^+\pi^-$ invariant mass.





At least one of the $\pi^+\pi^-$ pairs is in the ρ^0 mass region:
$660 \leq M_{\pi^+\pi^-} \leq 860GeV/c^2$

$D^{+*} \to D^0\pi^+$

Experiment: BEATRICE [20]

CERN

Beam: π^-;

$\sqrt{s} \approx 350$ GeV;

Target: Si, W and Cu.

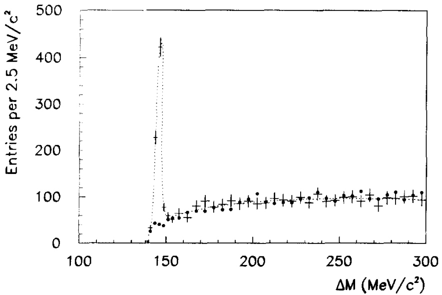
It is possible to observe a narrow peak in the mass difference distribution:

$$m_{D^{*+}}(K^-\pi^+\pi^+) - m_{D^0}(K^-\pi^+)$$

The momentum of soft pion from $D^{+*} \to D^0\pi^+$ can be estimated as

$$P_{\pi^+_{soft}} \sim \frac{m_\pi}{m_D} P_D \sim 0.1 P_D.$$

Thus an essential amount of D^0 with $P_{D^0} \gtrsim 1.5$ GeV is needed to observe $m_{D^{*+}}$ at SPD.



Plans, suggestions and conclusions

Λ_c-baryon:

- Try to improve selection quality for $\Lambda_c \to pK\pi$ decay;
- Try modes $\Lambda_c \to \Lambda^0\pi^-\pi^+\pi^+$ and $\Lambda_c \to K_s p\pi^-\pi^+$;
- $\Lambda_c \to \Lambda^0\pi^+$ and $\Lambda_c \to K_s p$;

D-meson:

- Search for D^* meson in mass difference $m(K\pi\pi) - m(K\pi)$ to obtain narrower peak;
- $D^0 \to K^-\pi^+\pi^+\pi^-$;

This study was carried out within the project "Production of open charm and tau leptons at the NICA SPD: phenomenology and simulation" supported by JINR.

Thank you for your attention!

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