Is production of charmed hadrons fully perturbative ?

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Antoni Szczurek [1,2] Rafał Maciuła [1] Victor Goncalves [3]

[1]Institute of Nuclear Physics PAN Kraków
[2]University of Rzeszów
[3]University of Pelotas

Our works on charm production

- D meson production in k_t-factorization, correlation between $D^0\bar{D}^0$ mesons. Relatively good description of the LHC data.
  R. Maciuła and A. Szczurek,
  “Open charm production at the LHC: k_t-factorization approach”,
  Phys. Rev. **D87** (2013) 094022.
- Large contribution of double parton scattering to $cc\bar{c}\bar{c}$ at large energies.
  M. Łuszczak, R. Maciuła and A. Szczurek,
  “Production of two $c\bar{c}$ pairs in double-parton scattering”, Phys. Rev. **D85** (2012) 094034.
- Small contribution of single parton scattering to $cc\bar{c}\bar{c}$ at large energies.
  W. Schäfer and A. Szczurek,
  “Production of two $c\bar{c}$ pairs in gluon-gluon scattering in high energy proton-proton scattering”,
  Phys. Rev. **D85** (2012) 094029.
  A. van Hameren, R. Maciula and A. Szczurek,
  "Single-parton scattering versus double-parton scattering in the production of two $c\bar{c}$ pairs and charmed meson correlations at the LHC"

Our works on charm production

- $D^0 D^0$ corrrelations.
  R. Maciuła and A. Szczurek,
  "Production of $c\bar{c}c\bar{c}$ in double-parton scattering within k_t-factorization approach: meson-meson correlations",
  Phys. Rev. **D87** (2013) 074039.
- $pp \to c\bar{c}j$. SPS cross sections.
  R. Maciula and A. Szczurek,
  "Charm quark and meson production in association with single-jet at the LHC",
  Phys. Rev. **D94** (2016) 114037.
- $pp \to c\bar{c}jj$. SPS vs DPS
  R. Maciuła and A. Szczurek,
  "Double-parton scattering effects in associated production of charm mesons and dijets at the LHC",
  Phys. Rev. **D 96**, 074013 (2017).

Our works on charm production

- Simultaneous production of charm and bottom ($pp \to DBX$).
  R. Maciula and A. Szczurek,
  “Double-parton scattering effects in D^0B^+ and B^+B^+ meson-meson pair production in proton-proton collisions at the LHC”,
  Phys. Rev. **D97** (2018) 094010.
- Triple parton scattering. $D^0D^0D^0$ cross section
  R. Maciuła and A. Szczurek,
  “Can the triple-parton scattering be observed in open charm meson production at the LHC?”,
  Phys. Lett. **B772** (2017) 849.
- Diffractive production of charm,
  M. Łuszczak, R. Maciuła, A. Szczurek and M. Trzebiński,
  “Single-diffractive production of charmed mesons at the LHC within the k_t-factorization approach”, JHEP **02** (2017) 089.

Our works on charm production

- Enhanced production of Λ_c.
  R. Maciuła and A. Szczurek
  , “Production of Λ_c baryons at the LHC within k_t-factorization approach and independent parton fragmentation”,
  Phys. Rev. **D98** (2018) 014016.
- D^+D^- asymmetry. Consequences for fixed target experiments and atmospheric neutrinos
  R. Maciuła and A. Szczurek,
  “D meson production asymmetry, unfavored fragmentation, and consequences for prompt atmospheric neutrino production”,
  Phys. Rev. **D 97** (2018) 074001.
- The role of semileptonic decays in production of ν_μ in the Earth’s atmosphere.
  V. Goncalves, R. Maciuła, R. Pasechnik and A. Szczurek,
  “Mapping the dominant regions of the phase space associated with $c\bar{c}$ production relevant for the prompt atmospheric neutrino flux”,
  Phys. Rev. **D96** (2017) 094026.
- $D_s^+D_s^-$ asymmetry and production of ν_τ neutrinos.
  V. Goncalves, R. Maciuła and A.S., arXiv:1809.05424.

Our works on hidden charm production

- Single J/ψ production in k_t-factorization
  A. Cisek and A. Szczurek,
  "Prompt inclusive production of J/ψ , ψ' and χc mesons at the LHC in forward directions within the NRQCD k_t-factorization approach: Search for the onset of gluon saturation",
  Phys. Rev. **D97** (2018) 034035.
- Double J/ψ and double χ_c production in k_t-factorization.
  A. Cisek, W. Schäfer and A. Szczurek,
  "Production of χ_c pairs with large rapidity separation in k_T factorization",
  Phys. Rev. **D97** (2018) 114018.

Introduction

- It is believed that high-energy neutrinos observed by IceCube are of extraterrestial, even extragalactic, origin.
- Another important component comes from semileptonic decays of D mesons produced in the atmosphere by the collision of cosmic rays (mostly protons) with the atmosphere (mostly ^{14}N)
- The flux of cosmic rays is relatively well known (Auger experiment).
- It is known that the dominant mechanism of charm production is $gg \to c\bar{c}$ partonic subprocesses.
- Recently we have performed a critical analysis of uncertainties in the high-energy production of charm (D mesons). Goncalves, Maciula, Pasechnik, Szczurek, Phys. Rev. **D96** (2017) 094026.

Introduction

- The high-energy neutrinos are produced mostly in very high-energy proton-proton collisions, (larger than at the LHC).
- The region of $x_F > 0.3$ is crucial
  (not accessible at the LHC !)
- Both very small and very large x (longitudinal momentum fractions) of gluons are important. These regions are not well known !
- LHCb observed D^+ and D^- asymmetry at forward directions (R. Aij et al., Phys. Lett. **B718** (2013) 902).
- Routinely one assumes that D mesons are produced from c or $\bar{c}$ fragmentation (no asymmetry at leading order).
- We have included recently subleading fragmentation
  Maciuła-Szczurek, arXiv:1711.08616
  adjusted to the LHCb asymmetries.

Introduction

- The subleading fragmentation leads to asymmetry in K^+ and K^- production (SPS, RHIC/BRAHMS).
  Also $\pi^+\pi^-$ asymmetry was observed.
- Standard calculations predict too small cross sections at low energies
  (not well known !)
- We adjust fragmentation parameters to describe LHCb asymmetry and make predictions for lower and higher energies and large Feynman-x.
- Particularly interesting are predictions for the regions important for production of high-energy neutrinos observed by IceCube.

Atmospheric neutrinos

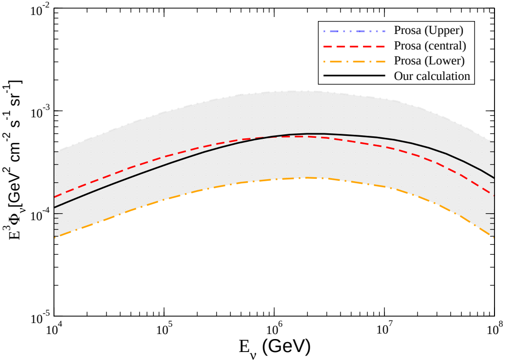


Figure: Comparison of our predictions for the prompt neutrino flux and the Prosa results.

Z-moment method, $\frac{d\sigma}{dx_F}(x_F, \sqrt{s})$ is an input.

Atmospheric neutrinos

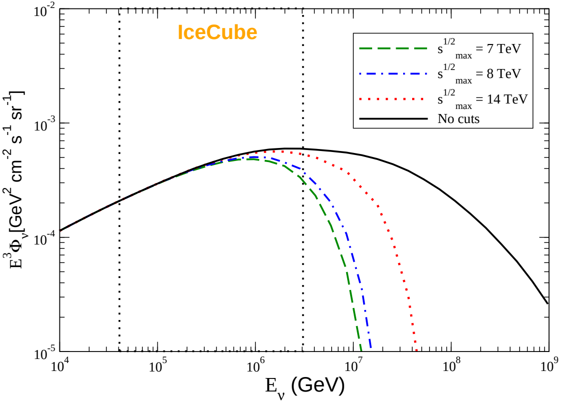


Figure: Impact of different cuts on the maximal center-of-mass *pp* collision energy for the prompt neutrino flux.

Atmospheric neutrinos

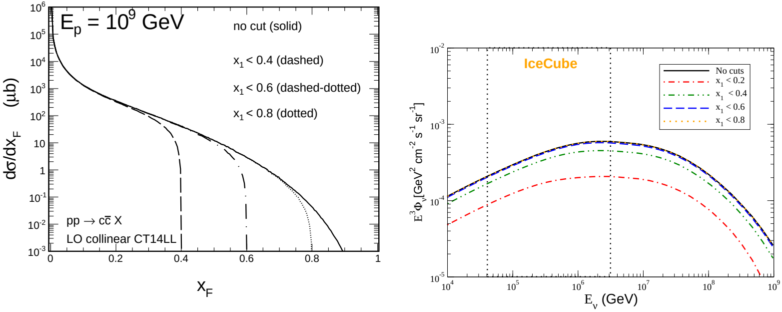


Figure: The effect of x_1 cuts on the charm production cross section $d\sigma/dx_F$ (left) and on the prompt neutrino flux (right).

Atmospheric neutrinos

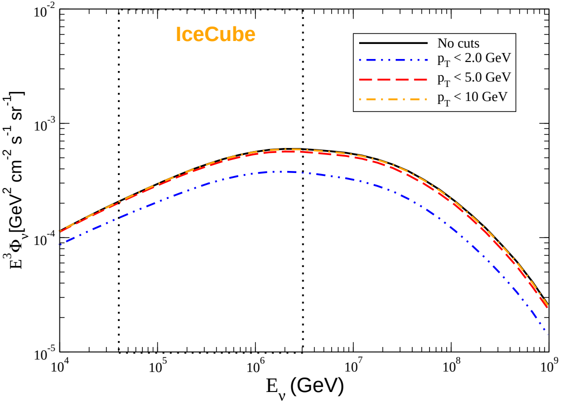


Figure: The effect of cuts on the quark transverse momentum p_T on the prompt neutrino flux.

Atmospheric neutrinos

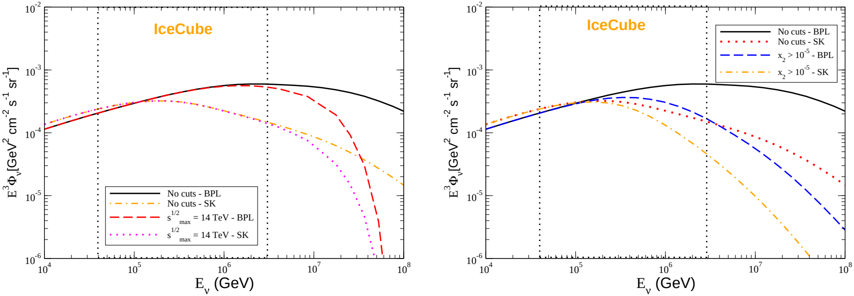


Figure: Comparison between the predictions for the neutrino flux obtained using the Broken Power Low (BPL) and Sharp Knee (SK) models for the primary nucleon flux considering cuts on the maximal center – of – mass *pp* collision energy (left) and on the value of x_2 (right).

Atmospheric neutrinos

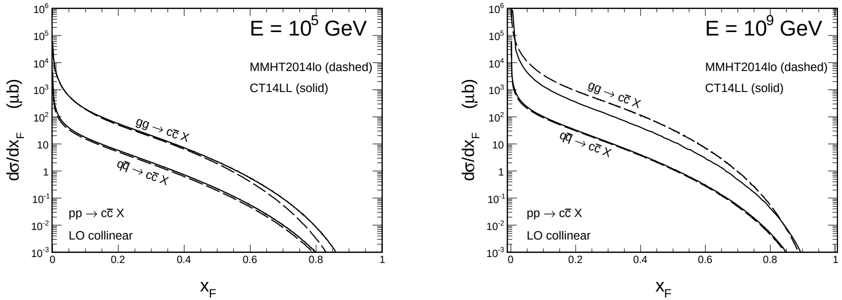


Figure: The charm production cross section $d\sigma/dx_F$ obtained with the leading-order collinear factorization for two different energies (left and right panel) and for two different PDF sets. Here, the $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$ components are shown separately.

Atmospheric neutrinos

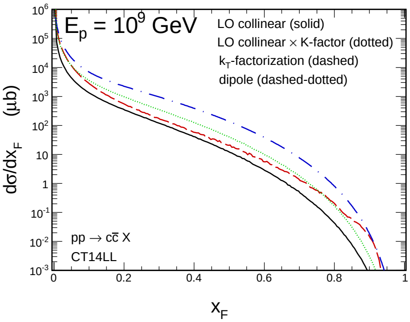


Figure: The charm production cross section $d\sigma/dx_F$ obtained with three different QCD approaches: collinear factorization (solid and dotted lines), k_T-factorization with the KMR UGDF (dashed line) and the dipole model (dash-dotted line).

Atmospheric neutrinos

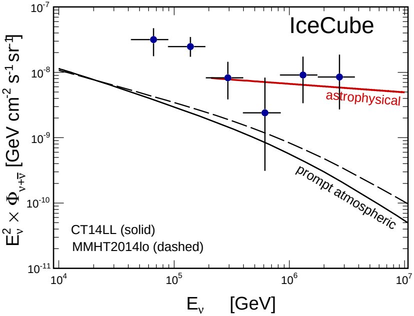


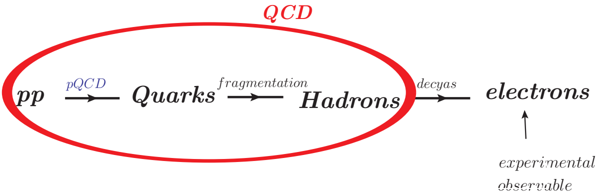
Figure: Comparison of predictions obtained with the CT14 and MMHT PDFs for the prompt neutrino flux. The data points are taken from IceCube. For comparison, a fit for the astrophysical contribution, proposed in Aartsen et al., 2016, is presented as well.

There seem to be room for astrophysical contribution

$D\bar{D}$ asymmetry and subleading fragmentation

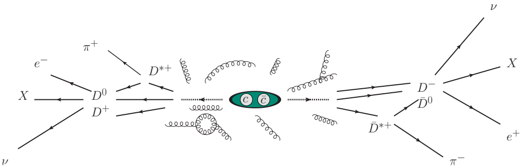
- LHCb observed asymmetry in production of D^+ and D^- mesons.
- What is reason for the asymmetry ?
  - electroweak effects ?
  - higher-order pQCD effects ?
  - light quark/antiquark asymmetry in proton ?
  - asymmetric intrinsic charm ?
- Here we concentrate on the effect of initial quark/antiquark asymmetry and formally subleading light quark/antiquark fragmentation.

$Q\bar{Q}$, 3-step process



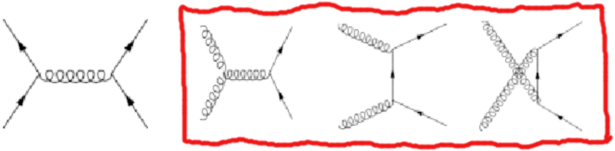
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

$$\frac{d\sigma^e}{dyd^2p} = \frac{d\sigma^Q}{dyd^2p} \otimes D_{Q\rightarrow H} \otimes f_{H\rightarrow e}$$

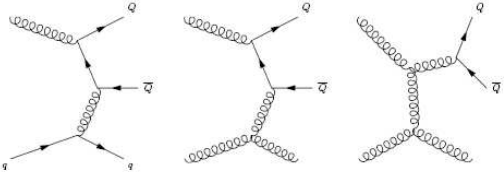


Dominant mechanisms of $Q\bar{Q}$ production

- Leading order processes contributing to $Q\bar{Q}$ production:

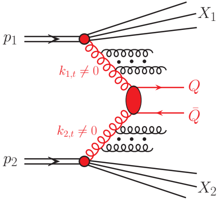


- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
- some of next-to-leading order diagrams:



NLO contributions → K-factor

k_t-factorization (semihard) approach



- charm and bottom quarks production at high energies $\longrightarrow$ gluon-gluon fusion
- QCD collinear approach → only inclusive one particle distributions, total cross sections

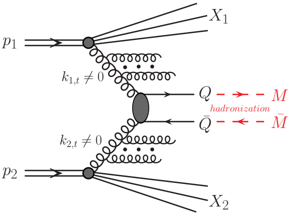
LO k_t-factorization approach $\longrightarrow \kappa_{1,t}, \kappa_{2,t} \neq 0$
$\Rightarrow Q\bar{Q}$ correlations

- multi-differential cross section

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{ij\to Q\bar{Q}}|^2}$$
$$\times \quad \delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathcal{F}_i(x_1, \kappa_{1,t}^2)\, \mathcal{F}_j(x_2, \kappa_{2,t}^2)$$

- off-shell $\overline{|\mathcal{M}_{gg\to Q\bar{Q}}|^2} \longrightarrow$ Catani, Ciafaloni, Hautmann (rather long formula)
- major part of NLO corrections automatically included
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated parton distributions
- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$,
  $x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2)$, where $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$.

Fragmentation functions technique



- fragmentation functions extracted from e^+e^- data
- often used: Braaten et al., Kartvelishvili et al., Peterson et al.
- rescalling transverse momentum
  at a constant rapidity (angle)

- from heavy quarks to heavy mesons:

$$\frac{d\sigma(y,p_t^M)}{dyd^2p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y,p_t^Q)}{dyd^2p_t^Q} dz$$

where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0,1)$

- **approximation:**
  rapidity unchanged in the fragmentation process → $y_Q \approx y_M$

Production of *D* mesons in this framework:
Maciula, Szczurek, Phys. Rev. **D87** (2013) 094022.

Parton distributions

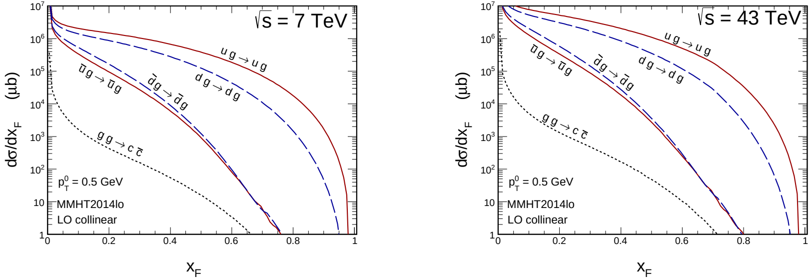


Figure: Quark and antiquark distributions in Feynman x_F for $\sqrt{s} = 7$ TeV (left panel) and $\sqrt{s} = 43$ TeV (right panel) corresponding to $E_{\rm lab}(p)$ = 10^9 GeV. This calculation was performed within collinear-factorization approach with $p_T^0 = 0.5$ GeV.

$$F_{sup}(p_T) = \frac{p_T^4}{((p_T^0)^2 + p_T^2)^2}\theta(p_T - p_{T,cut}) \; . \tag{1}$$

Parton distributions

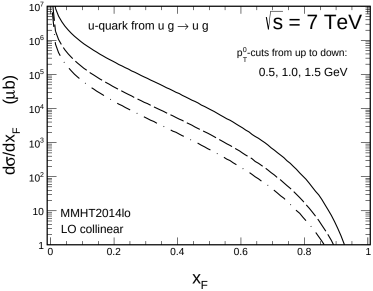


Figure: Light u-quark distribution in Feynman x_F for $\sqrt{s} = 7$ TeV for different values of p_T^0 = 0.5, 1.0, and 1.5 GeV.

Parton distributions

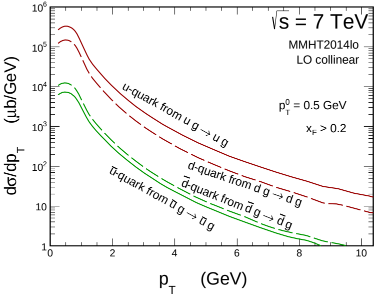


Figure: Transverse momentum distribution of light quarks/antiquarks for $x_F > 0.2$.

$D^+(c\bar{d})$, $D^-(\bar{c}d)$
consider $\bar{d} \to D^+$ and $d \to D^-$ (unfavoured, subleading)

Unfavoured fragmentation functions

We include $u, \bar{u}, d, \bar{d} \rightarrow D^i$ parton fragmentation.

$$D_{d\rightarrow D^-}(z) = D_{\bar{d}\rightarrow D^+}(z) = D^{(0)}(z)\ . \tag{2}$$

Similar symmetry relations hold for fragmentation of u and $\bar{u}$ to D^0 and $\bar{D}^0$ mesons.
However, $D_{q\rightarrow D^0}(z) \neq D_{q\rightarrow D^+}(z)$ which is caused by the contributions from decays of vector D^* mesons. Furthermore we assume for doubly suppressed fragmentations:

$$D_{\bar{u}\rightarrow D^\pm}(z) = D_{u\rightarrow D^\pm}(z) = 0\ . \tag{3}$$

V. Bertone talk: quark/antiquark to charged hadrons, i.e. no flavour and kind of particle separation, no charmed mesons.

Unfavoured fragmentation functions

The fragmentation functions at sufficiently large scales undergo DGLAP evolution equations

$$\frac{d}{d\ln\mu^2} D_a(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \sum_b \int_x^1 \frac{dy}{y} P^T_{a\to b}\left(y, \alpha_s(\mu)\right) D_b\left(\frac{x}{y}, \mu\right) \;, \quad (4)$$

where $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}$. In the case of e^+e^- collisions the scale is usually taken as $\mu^2 = s$. When fitting fragmentation functions to $e^+e^- \to D$ data one usually assumes

$$D_{q/\bar{q}\to D}(z, \mu_0^2) = 0 \quad (5)$$

at some initial scale usually taken as $\mu_0 = m_c, 2m_c$, where m_c is charm quark mass.

Here we are particularly interested in low transverse momentum D mesons. Then our typical factorization scales $\mu^2 = p_T^2 + m_q^2$ are very small. Therefore we limit in the following to a phenomenological approach and ignore possible DGLAP evolution effects important at somewhat larger transverse momenta.

Unfavoured fragmentation functions

We have to parametrize the unfavoured fragmentation functions as:

$$D_{q\to D}(z) = A_\alpha (1-z)^\alpha \ . \tag{6}$$

Instead of fixing the uknown A_α we will operate rather with the fragmentation probability:

$$P_{q\to D} = \int dz\, A_\alpha \,(1-z)^\alpha \ . \tag{7}$$

and calculate corresponding A_α for a fixed $P_{q\to D}$ and α. Therefore in our effective approach we have only two free parameters.
Another simple option one could consider is:

$$D_{q_f\to D}(z) = P_{q_f\to D} \cdot D_{\mathrm{Peterson}}(1-z) \ . \tag{8}$$

Then $P_{q_f\to D}$ would be the only free parameter.

Unfavoured fragmentation functions

In addition to the direct fragmentation (given by $D^{(0)}(z)$) there are also contributions with intermediate vector D^* mesons. Then the chain of production of charged D mesons is naively as follows:

$$\begin{aligned} \bar{u} &\to D^{*,0} \to D^+ \ (\text{forbidden}), \\ u &\to \bar{D}^{*,0} \to D^- \ (\text{forbidden}), \\ \bar{d} &\to D^{*,+} \to D^+ \ (\text{allowed}), \\ d &\to D^{*,-} \to D^- \ (\text{allowed}). \end{aligned} \tag{9}$$

In reality the first two chains are not possible as the decays of corresponding vector mesons ($D^{*,0}$ and $\bar{D}^{*,0}$) are forbidden by lack of phase space.

Including both direct and resonant contributions the combined fragmentation function of light quarks/antiquarks to charged D mesons can be written as:

$$D^{\text{eff}}_{d/\bar{d}\to D^\mp}(z) = D^0_{d/\bar{d}\to D^\mp}(z) + P_{\mp\to\mp} \cdot D^1_{d/\bar{d}\to D^{*,\mp}}(z) \ . \tag{10}$$

The decay branching ratios can be found in PDG and is $P_{\pm\to\pm} = 0.323$. The indirect vector meson contributions have the same

Unfavoured fragmentation functions

Finally we shall take an approximation:

$$D^{(0)}(z) \approx D^{(1)}(z) \tag{11}$$

which can be easily relaxed if needed. We think that such an approximation is, however, sufficient for the present exploratory calculations.

Flavour asymmetry

The flavour asymmetry in production is defined as:

$$A_{D^+/D^-}(\xi) = \frac{\frac{d\sigma_{D^-}}{d\xi}(\xi) - \frac{d\sigma_{D^+}}{d\xi}(\xi)}{\frac{d\sigma_{D^-}}{d\xi}(\xi) + \frac{d\sigma_{D^+}}{d\xi}(\xi)} \, , \tag{12}$$

where $\xi = x_F, y, p_T, (y, p_T)$. In the following we shall consider several examples of selecting ξ.

To calculate asymmetry we have to include also dominant contribution corresponding to conventional $c/\bar{c} \to D/\bar{D}$ fragmentation. The leading-order pQCD calculation is not reliable in this context. In the following the conventional contribution is calculated within the k_t-factorization approach with the Kimber-Martin-Ryskin unintegrated parton distributions which has proven to well describe the LHC data (Maciuła-Szczurek). Such an approach seems consistent with collinear next-to-leading order approach (Maciuła-Szczurek).

Flavour asymmetry

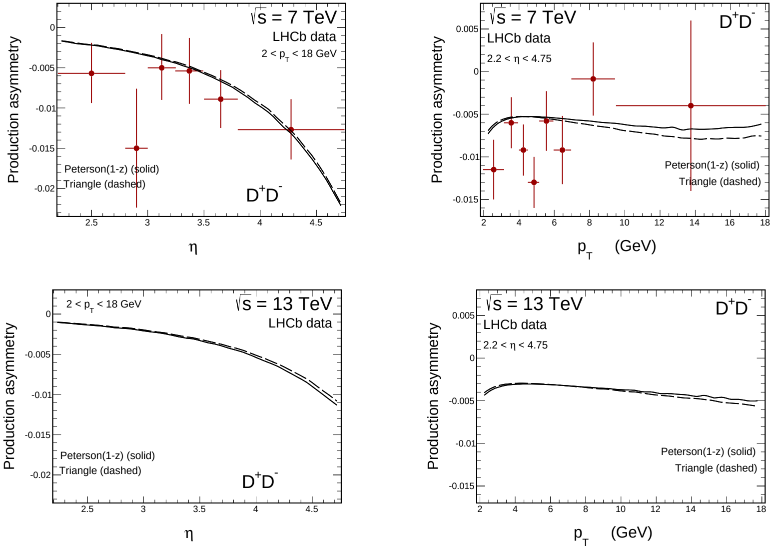


Figure: A_{D^+/D^-} production asymmetry measured by the LHCb collaboration at $\sqrt{s} = 7$ TeV as a function of D meson pseudorapidity

$D\bar{D}$ asymmetry at lower energies

Table: Different contributions to the cross sections (in microbarns) for $D^+ + D^-$ production at low energies. The results presented here have been obtained with $p_T^0 = 1.5$ GeV.

process	$\sqrt{s}$ = 27 GeV	$\sqrt{s}$ = 39 GeV
$g^*g^* \to c\bar{c} \quad (c/\bar{c} \to D^\pm)$	1.52	4.58
$q^*\bar{q}^* \to c\bar{c} \quad (c/\bar{c} \to D^\pm)$	0.08	0.19
$g\bar{d} \to g\bar{d} \quad (\bar{d} \to D^+)$	9.53	13.89
$g\bar{d} \to g\bar{d} \quad (\bar{d} \to D^+)$	3.03	4.78
theory predictions	22.93	35.94
experiment	NA27: 11.9 ± 1.5	E743: 26 ± 4 ± 25%

Large contribution of subleading fragmentation at low energies

$D\bar{D}$ asymmetry at lower energies

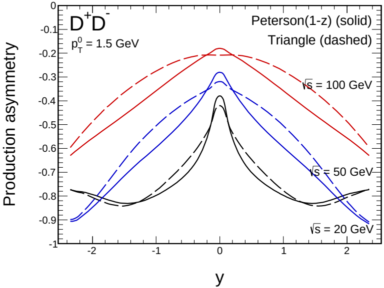


Figure: $A_{D^+D^-}(y)$ production asymmetry in proton-proton collisions for different $\sqrt{s}$.

Large asymmetries at low energies

Fixed-target experiment with LHCb

The LHCb collaboration has an experience in measuring the asymmetry in D^+ and D^- production. It would be valueable to repeat such an analysis for fixed target experiment $p +^4\mathrm{He}$ with gaseous target. The data have been already collected. The nuclear effects for ^{4}He should not be too large. Then the collision may be treated as a superposition of *pp* and *pn* collsions. Neglecting the nuclear effects the differential cross section (in the collinear factorization approach) for production of $q/\bar{q}$ (particle 1) and associated parton (particle 2) can be written approximately as:

$$\frac{d\sigma_{p\,^4\mathrm{He}}}{dy_1 dy_2 dp_T} = 2\frac{d\sigma_{pp}}{dy_1 dy_2 dp_T} + 2\frac{d\sigma_{pn}}{dy_1 dy_2 dp_T}\ . \qquad (13)$$

Fixed-target experiment with LHCb

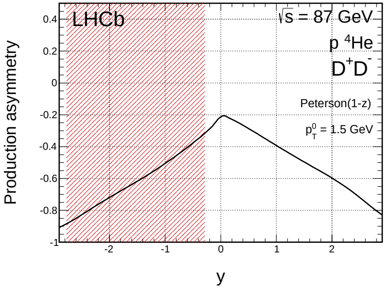


Figure: $A_{D^+D^-}(y)$ production asymmetry for the fixed target $p+{}^4He$ reaction for $\sqrt{s} = 87$ GeV.

We predict large asymmetries

Charge-to-neutral *D* meson ratio

$$R_{c/n} \equiv \frac{D^+ + D^-}{D^0 + \bar{D}^0} \quad (14)$$

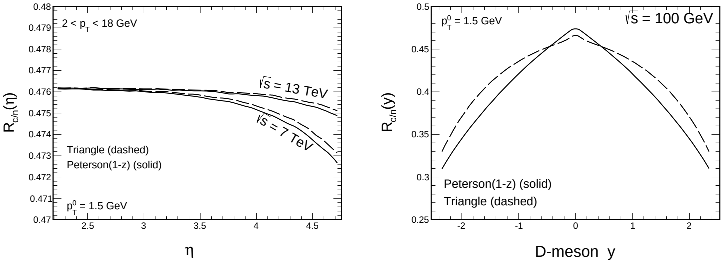


Figure: The $R_{c/n}$ ratio as a function of meson pseudorapidity for $\sqrt{s} = 7$ and 13 TeV for the LHCb kinematics (left panel) and as a function of meson rapidity for $\sqrt{s}$ = 100 GeV in the full phase-space (right panel). Only quark-gluon subleading components are included here.

Energy and rapidity dependence of $R_{c/n}$.

No such dependence when only $c \to D$ fragmentation.

Very high energies

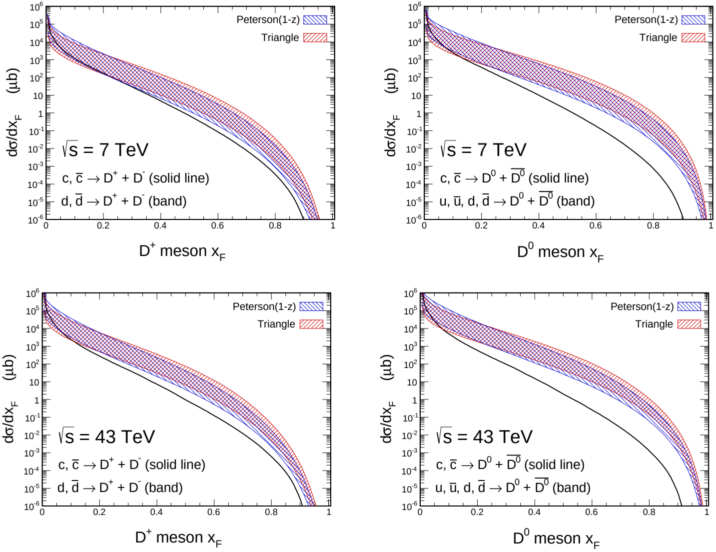


Figure: Distribution in x_F for charged D^++D^- (left panel) and neutral D^0+$\bar{D}^0$ (right panel) D mesons from conventional (solid lines) and

Very high energies

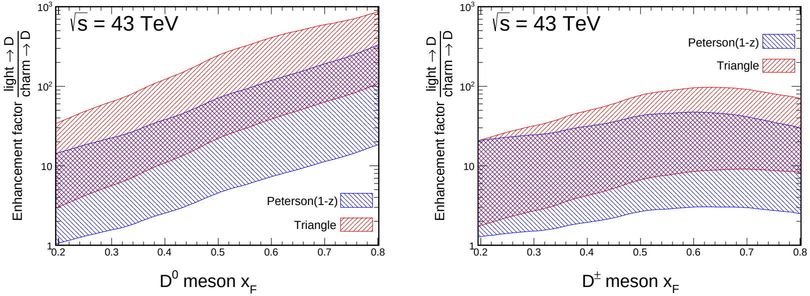


Figure: Enhancement factor for neutral (left panel) and charged (right panel) charm meson for $\sqrt{s}$ = 43 TeV.

As a consequence an enhancement of the atmosperic neutrino flux at high neutrino energies

less room for cosmic neutrinos ?

Under evaluation in collaboration with V. Goncalves

Very high energies

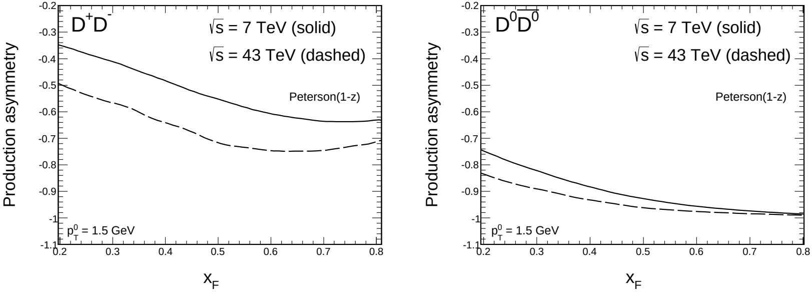


Figure: Production asymmetry as a function of x_F for D^+/D^- (left panel) and for $D^0/\bar{D}^0$ (right panel). The solid lines correspond to $\sqrt{s} = 7$ TeV and the dashed lines correspond to $\sqrt{s} = 43$ TeV. The results are obtained with $p_T^0 = 1.5$ GeV.

Flavour $D^0 - \bar{D}^0$ asymmetry for LHC

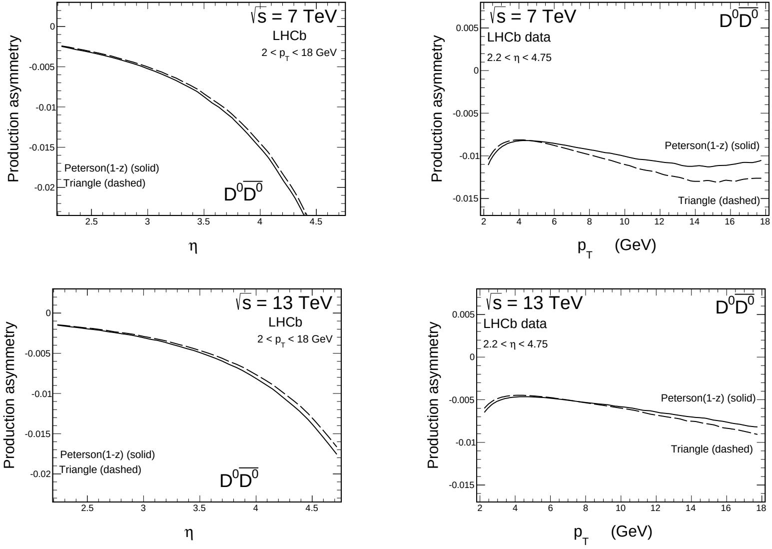


Figure: $A_{D^0/\bar{D}^0}$ production asymmetry relevant for a possible LHCb collaboration measurement as a function of D meson pseudorapidity (left

D_s meson production

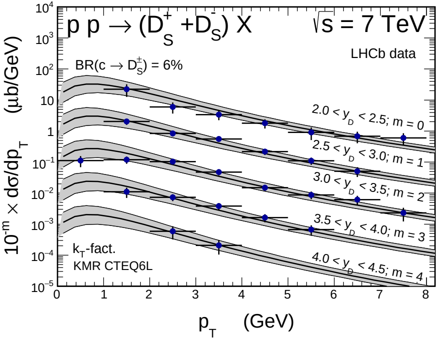


Figure: Transverse momentum distributions of $D_S^+ + D_S^-$ for different ranges of rapidity. The LHCb data are shown for comparison.

Less abundant D mesons, $P_{c \to D_S}$ is 6 - 8 %

V. Goncalves, R. Maciuła and A. Szczurek, arXiv:1809.05424.

Production of strange quarks/antiquarks

D_s have no $u, d, \bar{u}, \bar{d}$ constituents.

Do we have subleading fragmentation ?

Yes, consider e.g. $s + g \to s + g$ and $\bar{s} + g \to \bar{s} + g$ partonic processes with $s \to D_s$ fragmentation.

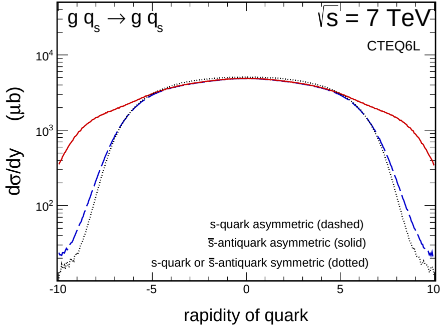


Figure: Rapidity distribution of s quarks and $\bar{s}$ antiquarks.

We have taken CTEQ6.5 parton distributions for which $s \neq \bar{s}$.

Production of $D_s^{\pm}$ mesons

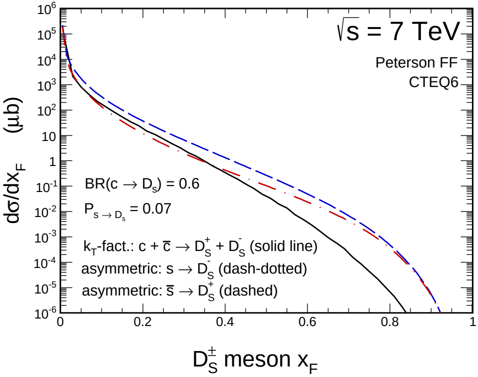


Figure: x_F distribution of D_s^+ and D_s^- mesons.

$s \neq \bar{s}$ leads to $D_s^+ \neq D_s^-$

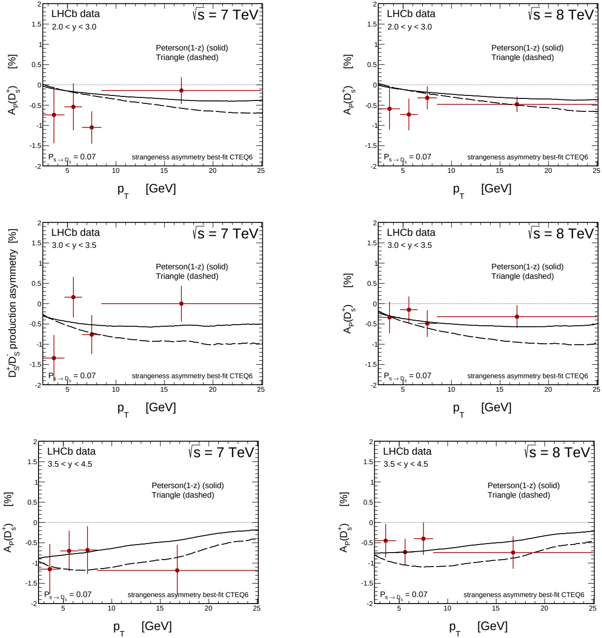
$A_{D_s^+/D_s^-}$ asymmetry vs LHCb data

We define the mesonic asymmetry:

$$A = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)} \tag{15}$$

There are new results for the asymmetry from LHCb:
R. Aaij *et al.* [LHCb Collaboration],
"Measurement of $D_s^\pm$ production asymmetry in *pp* collisions at
$\sqrt{s} = 7$ and 8 TeV,",
J. High Energy Phys. **08**, 008 (2018).
We include a new mechanism:
$s \to D_s^-$, $\bar{s} \to D_s^+$
And take into account: $s(x) \neq \bar{s}(x)$
(meson cloud effects)

$A_{D_s^+/D_s^-}$ asymmetry vs LHCb data



τ neutrinos from collisions and cosmos

D_s mesons are the main source of τ-neutrinos:

$D_s^+ \rightarrow \tau^+ + \nu_\tau$

$D_s^- \rightarrow \tau^- + \overline{\nu}_\tau$

and

$\tau^+ \rightarrow \bar{\nu}_\tau + X$

$\tau^- \rightarrow \nu_\tau + X$

Both emissions should be included.

Naively from cosmic sources (assumed to be pions) due to neutrino oscillations one predicts (in the Standard Model):

$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1.

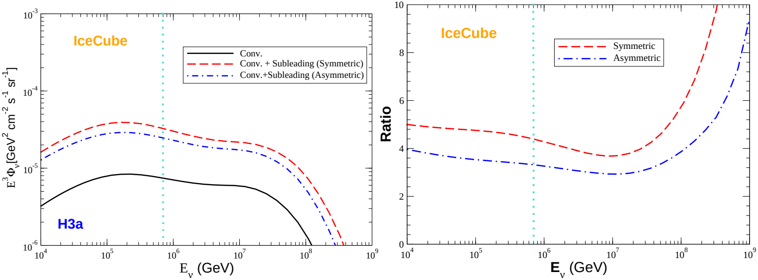
In the atmosphere this ratio is:

$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:0.1.

The subleading fragmentation discussed here modifies the flavour composition of the atmospheric neutrinos.

Officially no high-energy τ neutrinos were identified so far in IceCube.

Enhanced production of τ-neutrino in the atmosphere



Sizeable enhancement of the ν_τ flux due to subleading fragmentation

Fixed target experiment SHiP

DONUT and OPERA have sbeen seen only ν_τ
antineutrinos were never observed (!)
SHiP (Search for Hidden Particles)
p_{lab} = 400 GeV, $p + Mo \to \nu_\tau/\bar{\nu}_\tau$
τ neutrino factory

Experiment estimated production rate of ν_τ and $\bar{\nu}_\tau$
10^{20} protons → 10^{15} (anti)neutrinos → tousands of interactions

W. Bai and M. Reno, arXiv:1807.02746
Calculated dN/dE for ν_τ and $\bar{\nu}_\tau$.

Our calculations are in progress
We include leading and subleading fragmentation
We predict production asymmetry of ν_τ and $\bar{\nu}_\tau$.

Light-to-heavy fragmentation

How to do light-to-heavy fragmentation is not completely clear.
Light-to-heavy:
$q \to D$, $s \to D_s$, but also $g \to D$.

$g \to D$ fragmentation was previously considered.
It appears as a consequence of DGLAP evolution.
The following observations can be done for charm production via $g \to D$ fragmentation:

- Good for large p_t of D meson production (Saleev et al.)
- Its presence breaks universality of σ_{eff} = 15 mb for $pp \to DD$ production in the so-called pocket formula for DPS (increase it considerably !)
  Maciula, Saleev, Shipilova and Szczurek, Phys. Lett. **B758** (2016) 458.

Remarks on $s/\bar{s}$ fragmentation

$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2}[x_1 g(x_1,\mu^2)\, x_2 s(x_2,\mu^2)\, \overline{|\mathcal{M}_{gs\to gs}|^2} + x_1 s(x_1,\mu^2)\, x_2 g(x_2,\mu^2)\, \overline{|\mathcal{M}_{sg\to sg}|^2}] \times F_{sup}(p_t)\,, \tag{16}$$

Similar for $\bar{s}$

Cut-off (regulator) at small transverse momenta:

$$F_{sup}(p_t) = \frac{p_t^4}{((p_t^0)^2 + p_t^2)^2}\,. \tag{17}$$

Similar as in Pythia (MPI, underlying event)

Remarks on $s/\bar{s}$ fragmentation

For $c \to D$ meson fragmentation one assumes $y_D = y_c$.
For light-quarks/antiquarks to heavy mesons it may be naive.
Different simple possibilities exist:

- $p_H = z p_q$ (momentum scaling),
- $E_H = z E_q$ (energy scaling),
- $p_H^+ = z p_q^+$ (light-cone scaling) where $p^+ = E + p$.

In addition fragmentation functions are completely unknown We tried different forms:

- $D(z) = P \cdot \mathrm{Peterson}(1 - z)$ (called reversed Peterson),
- $D(z) = P \cdot 2(1 - z)$ (called triangle),
- $D(z) = P \cdot 6z(1 - z)$ (called hiperbolic).

The transition probability $P = P_{s \to D_s}$ can be treated as a free parameter.

Remarks on $s/\bar{s}$ fragmentation

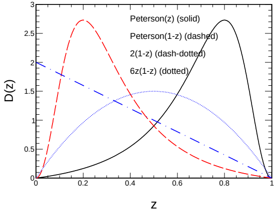
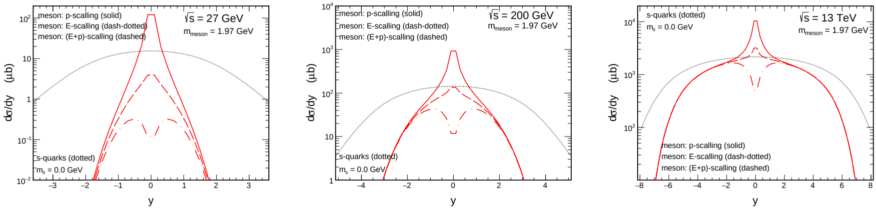


Figure: Fragmentation functions used in the present analysis. Here $\int D(z)\,dz = 1$.

Different forms used, let us see consequaences

Remarks on $s/\bar{s}$ fragmentation

$s \rightarrow D_s$ fragmentation

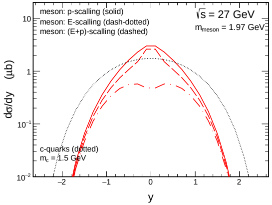


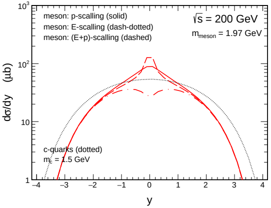
Not yet multipled by fragmentation fraction

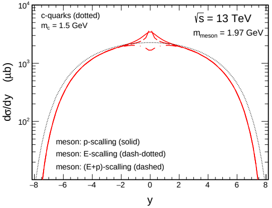
May be FF with transverse momentum kick are necessary

Remarks on $c/\bar{c}$ fragmentation

$c/\bar{c} \to D_s^{\pm}$ fragmentation







Not yet multiplied by fragmentation fraction

Remarks on $s/\bar{s}$ fragmentation

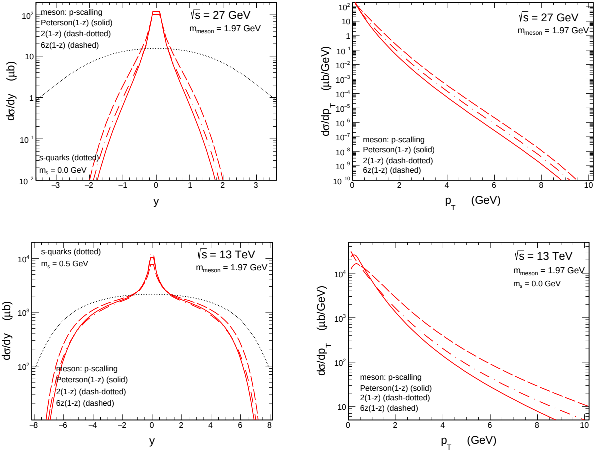
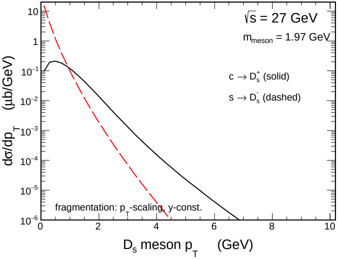
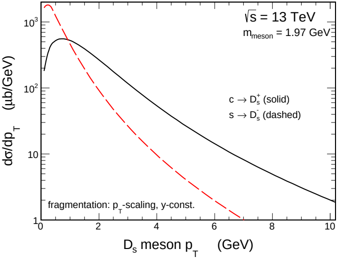


Figure: Rapidity (left) and transverse momentum (right) distributions of $D_s^{\pm}$ mesons from $s/\bar{s} \to D_s^{\pm}$ fragmentation for $\sqrt{s} = 27$ GeV (top) and $\sqrt{s} = 13$ TeV (bottom) for different parametrizations of fragmentation functions.

Two components together





Here fragmentation branching fractions are taken.

Are they realistic? Probably too large for $s \rightarrow D_s$.

Λ_c production

Does the independent parton fragmentation works ?

$$\frac{d\sigma(pp \to hX)}{dy_h d^2p_{t,h}} \approx \int_0^1 \frac{dz}{z^2} D_{c\to h}(z) \frac{d\sigma(pp \to cX)}{dy_c d^2p_{t,c}}\Bigg|_{\substack{y_c=y_h \\ p_{t,c}=p_{t,h}/z}} , \qquad (18)$$

where $p_{t,c} = \frac{p_{t,h}}{z}$ and z is the fraction of longitudinal momentum of charm quark c carried by a hadron $h = D, \Lambda_c$. A typical approximation in this formalism assumes $y_h = y_c$.

D mesons for reference

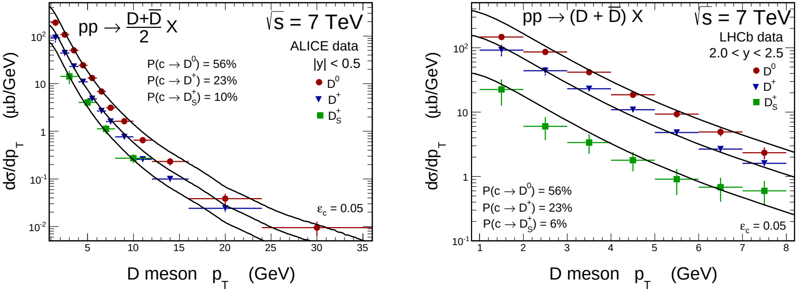


Figure: Transverse momentum distribution of *D* mesons for $\sqrt{s} = 7$ TeV for ALICE (left panel) and LHCb (right panel).

Standard approach for Λ_c

$y_{\Lambda_c} = y_c$

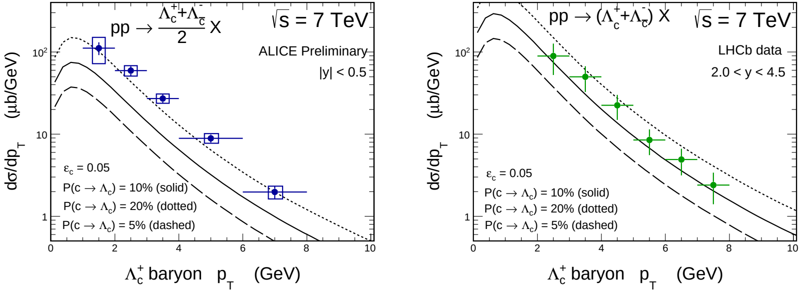


Figure: Transverse momentum distribution of Λ_c baryon for $\sqrt{s}$ = 7 TeV for ALICE (left panel) and LHCb (right panel).

Λ_c/D^0 ratio, standard approach

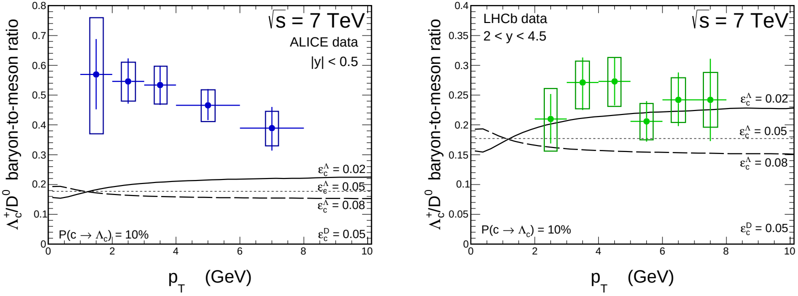


Figure: Transverse momentum dependence of the Λ_c/D^0 baryon-to-meson ratio for ALICE (left) and LHCb (right) for different choices of the ε_c^Λ parameter for $c \to \Lambda_c$ transition in the Peterson fragmentation function.

$\eta_h = \eta_c$ approximation

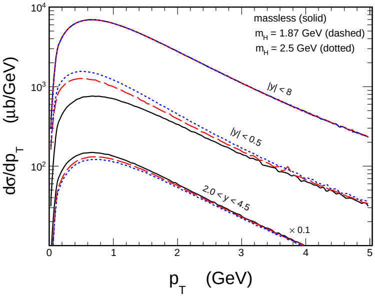


Figure: Transverse momentum dependence of the cross section for different intervals of rapidities and for different approaches to fragmentation procedure. The dotted and dashed lines correspond to the $\eta_h = \eta_c$ prescription for fragmentation. The solid lines are calculated with the standard $y_h = y_c$ approximation.

Λ_c/D^0 ratio

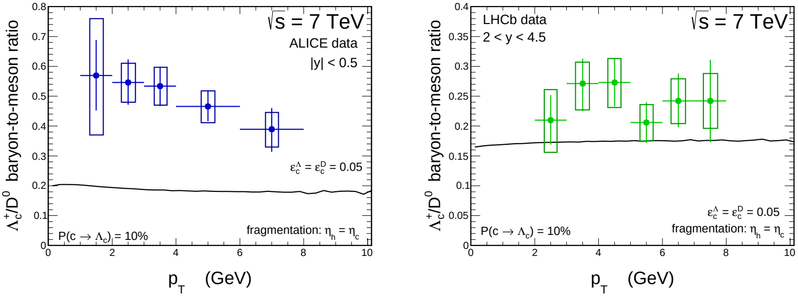


Figure: Transverse momentum dependence of the Λ_c/D^0 baryon-to-meson ratio for ALICE (left) and LHCb (right) for the $\eta_h = \eta_c$ approximation. Here only one (default) set of ε_c parameters for the Peterson fragmentation functions was used.

Feed down scenario

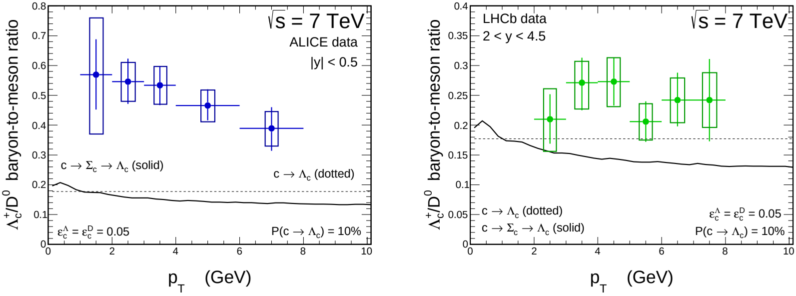


Figure: Transverse momentum dependence of the Λ_c/D^0 baryon-to-meson ratio for ALICE (left) and LHCb (right) for the feed-down mechanism (solid lines). Here the standard $y_h = y_c$ fragmentation procedure with only one (default) set of ε_c parameter for the Peterson fragmentation function was used. The dashed lines are from direct production $c \to \Lambda_c$.

6 states Σ_c with spin 1/2
6 states Σ_c with spin 3/2
$\Sigma_c \to \Lambda_c + \pi$ (a Monte Carlo code)

Conclusions

- We have made critical analysis of charm / D meson production in the Earth's atmosphere.
- The high-energy neutrinos produced by:
  - high-energy collisions, larger than at the LHC
  - large x_F
  - small x_1 and large x_2, where gluon PDFs are not well known
- Present standard, rather unsure, approach leaves room for extraterrestial neutrinos.
- By analogy to K^+, K^- production we have considered a possibility of unfavoured fragmentation (fragmentation induced by light quarks/antiquarks)
- The intial parton asymmetry leads then to $D\bar{D}$ asymmetry.
- We have adjusted parameters of the subleading fragmentation to describe the LHCb D^+D^- asymmetry.
- We have predicted similar asymmetry for D^0 and $\bar{D}^0$ production. May it be important for CP studies (?)

Conclusions

- Huge asymmetries have been predicted for small energies and/or large Feynman-x.
  fixed-target LHCb experiment and NA61 experiment at SPS could look at this !
- The subleading fragmentation dominates over $c \to D$ or $\bar{c} \to \bar{D}$ fragmentation at low energies.
  And explains missing strength !
- We find large contribution of the subleading fragmentation to large-x_F region also at very high collision energies, relevant for high-energy neutrinos measured by IceCube.
- We predict dominance of electron/muon neutrinos over corresponding antineutrinos but this is difficult to measure.
- Can the new mechanism explain the IceCube high-energy data requires further critical analysis?
  (We are working on inclusion of such processes into atmospheric neutrino simulations)
- NLO, electroweak and meson cloud corrections must be included in a future in a consistent manner !

Conclusions on D_s^+ and D_s^- production

- We have calculated cross section for D_s meson production
  Reasonable agreement with the LHCb data
- W have included subleading $s \to D_s^-$ and $\bar{s} \to D_s^+$ fragmentation.
- Taking $s \neq \bar{s}$ we get asymmetry for D_s^+ and D_s^-.
  A reasonable description of the LHCb asymmetry has been achieved by adjusting $P_{s \to D_s}$ (correct sign)!!!
  PYTHIA gives incorrect sign.
- $D_s^+ \to \nu_\tau + \tau^+$ and $D_s^- \to \overline{\nu}_\tau + \tau^-$.
  Two mechanisms included
  Enhanced production of τ-neutrinos at IceCube is predicted (calculation underway).

Conclusions on Λ_c

- Production of Λ_c was discussed in the framework of k_t-factorization approach and independent fragmentation model.
- In the standard approach for fragmentation ($y_{\Lambda_c} = y_c$) we almost get the LHCb data but underpredict the mid-rapidity ALICE data
- The $\eta_{\Lambda_c} = \eta_c$ approximation improves the situation a bit but definitly not in sufficient way.
- A feed down from higher excited baryons was considered. The effect is not sufficient.
- There is an evidence for a new mechanism for the high-energy, large multiplicity *pp* collisions (coalescence ?).
- A study of Λ_c^+/Λ_c^- asymmetry would be very useful to pin down the underlying mechanism.
- A study of Λ_c as a function of event multiplicity would be valueable too.

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Thank You