Production asymmetry of open charm mesons within unfavored fragmentation scenario

Rafał Maciuła
Institute of Nuclear Physics PAN, Kraków, Poland

in collaboration with Antoni Szczurek

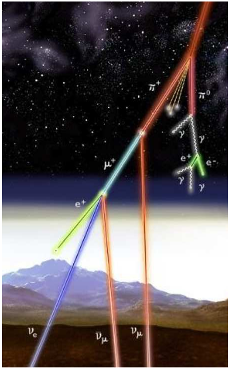
15th International Workshop on Meson Physics - MESON 2018
7th - 12th June 2018, Kraków, Poland

Motivation from the atmosphere...

High-Energy Neutrinos: it is believed that the extremely high-energetic neutrinos observed by IceCube Experiment are of extraterrestial origin.

Atmospheric background: neutrinos produced by the collision of cosmic rays (mostly protons) with the atmosphere (mostly ^{14}N)

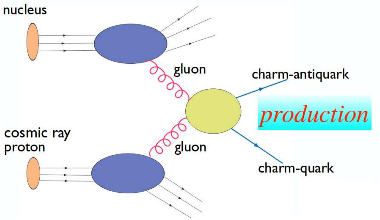
- **low-energy component:** conventional flux from decays of π, K
- **high-energy component:** prompt flux from semileptonic decays of D mesons
- **Charm production at very high energies**: crucial for reliable identification of the origin - cosmic or atmospheric - of high-energy neutrinos detected by IceCube
- **Commonly accepted statement**: the only dominant partonic mechanism for open charm meson production at high-energies is $gg \to c\bar{c}$ driven by gluon-gluon fusion.



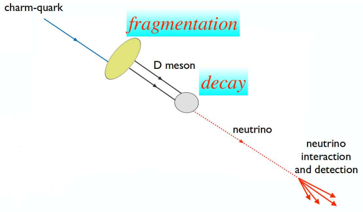
Recently we have performed a critical analysis of uncertainties in the high-energy production of charm (D mesons) in the context of high-energy neutrinos
Goncalves, Maciuła, Pasechnik, Szczurek, Phys. Rev. D96 (2017) 094026.

Neutrinos from charm at very forward directions

The high-energy atmospheric neutrinos are produced mostly in very high-energy proton-Air collisions - $\sqrt{s}$ larger than at the LHC



- **Very forward production**: the region of $x_F > 0.3$ is crucial (not accessible at the LHC !)
- **Unknown kinematical regime**: configuration with one very small and one very large x's (longitudinal momentum fractions) of gluons.

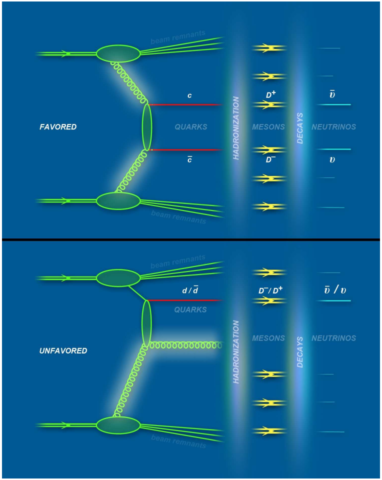


- **Leading (favored) scenario**: routinely one assumes that D mesons are produced from c or $\bar{c}$ fragmentation
- no meson/antimeson production asymmetry at leading-order.
- LHCb observed D^+/D^- asymmetry at forward directions (Phys. Lett. B718 (2013) 902)

Reason: electroweak effects? NLO effects?
light quark/antiquark asymmetry in proton?

Subleading (unfavored) fragmentation scenario

We concentrate on the effect of initial quark/antiquark asymmetry in proton and formally on subleading light quark/antiquark fragmentation.



- The subleading fragmentation leads to asymmetry in K^+ and K^- production (SPS, RHIC/BRAHMS). Also $\pi^+\pi^-$ asymmetry was observed.
- We adjust **light-quark $\to$ D fragmentation** parameters to describe LHCb D^+/D^- production asymmetry and make predictions for charm production at lower and higher energies and large Feynman-x.

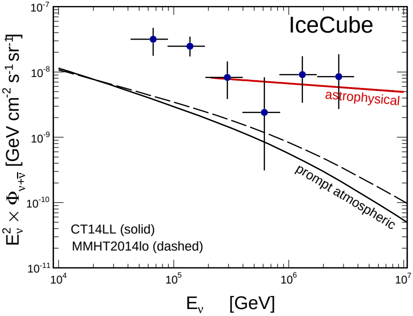
It may be...

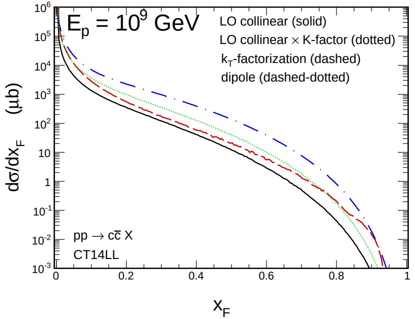
- **helpful** to understand charm production cross section at low energies (favored scenario underestimates experimental data)
- **particularly interesting** for predictions for the kinematical regions important for production of high-energy neutrinos observed by IceCube.

Maciuła, Szczurek, Phys.Rev. D97, 074001 (2018)

Prompt neutrino flux from charm

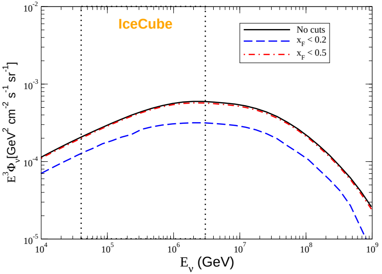
Six-year experimental data collected by the IceCube Observatory

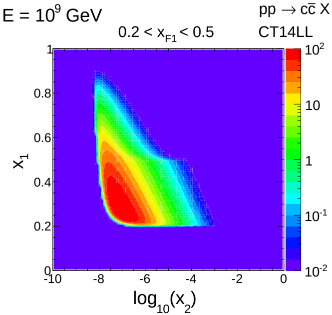




- our predictions for **prompt atmospheric neutrino flux** together with a fit for the **astrophysical contribution** from Aartsen et al., Astrophys. J. 833, 3 (2016)
- large experimental uncertainties
- very uncertain theoretical input of charm production cross section in the very forward direction
- different pQCD approaches lead to quite different results

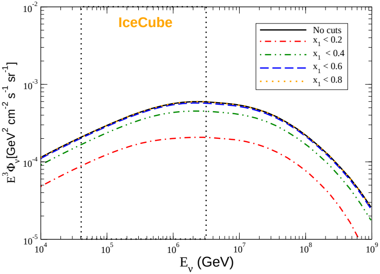
Unknown kinematical regime @ IceCube Observatory

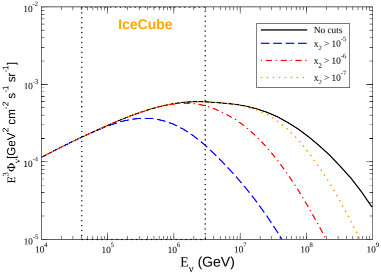




- the dominant contribution to the neutrino flux comes typically from x_F in the region $0.2 < x_F < 0.5$
- within this x_F window, the dominant contribution comes from the region of $x_1 \in (0.2 - 0.6)$ and $x_2 \in (10^{-8} - 10^{-5})$
- in both these regions of longitudinal momentum fractions gluon distribution is poorly constrained
- behavior of the x_F distribution at intermediate x_F is directly associated with the charm production at large rapidities, beyond those probed currently by the LHC detectors

Unknown kinematical regime @ IceCube Observatory





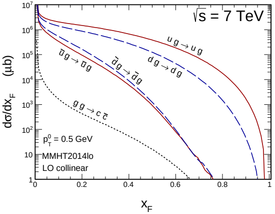
- the dominant contribution to the neutrino flux comes typically from x_F in the region $0.2 < x_F < 0.5$
- within this x_F window, the dominant contribution comes from the region of $x_1 \in (0.2 - 0.6)$ and $x_2 \in (10^{-8} - 10^{-5})$
- in both these regions of longitudinal momentum fractions gluon distribution is poorly constrained
- behavior of the x_F distribution at intermediate x_F is directly associated with the charm production at large rapidities, beyond those probed currently by the LHC detectors

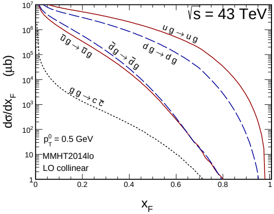
Parton-level calculations within subleading scenario

Light quark/antiquark production:

- we calculate the dominant at large x_F high-energy processes:
  $ug \to ug$, $dg \to dg$, $\bar{u}g \to \bar{u}g$ and $\bar{d}g \to \bar{d}g$
- the calculations are done in the leading-order collinear factorization approach with a special treatment of minijets at low transverse momenta, as adopted in PYTHIA, by multiplying standard cross section by a somewhat arbitrary suppression factor

$$F_{sup}(p_T) = \frac{p_T^4}{((p_T^0)^2 + p_T^2)^2}\theta(p_T - p_{T,cut}), \quad \text{where} \;\; p_T^0 = 0.5, 1.0, 1.5 GeV$$





- x_F-distributions of light minijet – $u, d, \bar{u}, \bar{d}$ – used as an input in unfavored fragmenation
- in the forward (projectile) region, cross sections much larger than for standard $gg \to c\bar{c}$ mechanism

Unfavored $u, \bar{u}, d, \bar{d} \to D^i$ parton fragmentation

The subleading FFs fulfill the following flavour symmetry conditions:

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

Similar relations hold for fragmentation of u and $\bar{u}$ to D^0 and $\bar{D}^0$ mesons. However $D_{q\to D^0}(z) \neq D_{q\to D^+}(z)$ because of the contributions from decays of vector D^* mesons.

- we assume for doubly suppressed fragmentations: $D_{\bar{u}\to D^\pm}(z) = D_{u\to D^\pm}(z) = 0$
- we are particularly interested in low transverse momentum D mesons so we ignore possible DGLAP evolution effects important at somewhat larger scales

We can parametrize the unfavoured fragmentation functions in this phase space region as:

$$D_{q\to D}(z) = A_\alpha(1-z)^\alpha \quad \text{(called } triangle\text{)}.$$

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

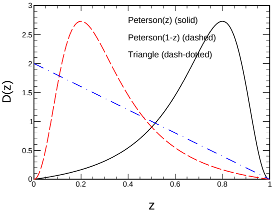
$$P_{q\to D} = \int dz\, A_\alpha\, (1-z)^\alpha\ .$$

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:

$$D_{q\to D}(z) = P_{q\to D} \cdot D_{\text{Peterson}}(1-z)\ ,$$

here $P_{q_f\to D}$ is the only free parameter.

Unfavored $u, \bar{u}, d, \bar{d} \to D^i$ parton fragmentation



- for heavy quark fragmentation ($c \to D$) the Peterson FF is peaked at large z
- FF for light quark is expected to be dominant at small z
- this is the case of Peterson fragmentation function reflected with respect to $z = 1/2$
- we use such a functions purely phenomenologically to test uncertainties related to the shape of the a priori unknown FF

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:

$$\bar{u} \to D^{*,0} \to D^+ \ \text{(forbidden)}, \quad u \to \bar{D}^{*,0} \to D^- \ \text{(forbidden)},$$
$$\bar{d} \to D^{*,+} \to D^+ \ \text{(allowed)}, \quad d \to D^{*,-} \to D^- \ \text{(allowed)}.$$

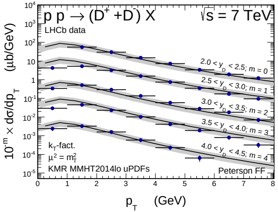
In reality the first two chains are not possible as the decays of corresponding vector mesons ($D^{*,0}$ and $\bar{D}^{*,0}$) are forbidden by lack of phase space.

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

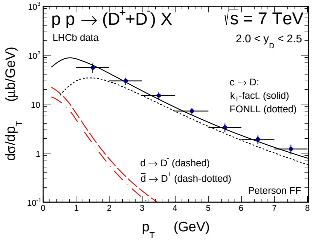
$$D^{\text{eff}}_{d/\bar{d} \to D^{\mp}}(z) = D^{0}_{d/\bar{d} \to D^{\mp}}(z) + P_{\mp \to \mp} \cdot D^{1}_{d/\bar{d} \to D^{*,\mp}}(z) \ .$$

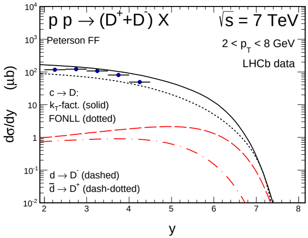
The decay branching ratios can be found in PDG and is $P_{\pm \to \pm} = 0.323$.

LHCb charm data and theory predictions



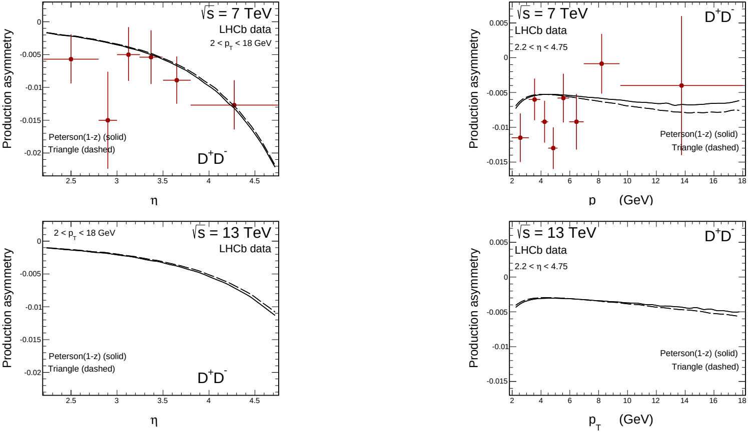
- to calculate asymmetry we have to include dominant contribution from conventional $c/\bar{c} \to D/\bar{D}$ fragmentation
- the LO pQCD calculation is not reliable in this context
- in the following the conventional contribution is calculated within the k_T-factorization approach
- such an approach seems consistent with collinear next-to-leading order approach – FONLL
- at high energies the subleading contribution seems to be negligible, except of very small p_T's and very large rapidities





D^+/D^- production asymmetry at the LHCb

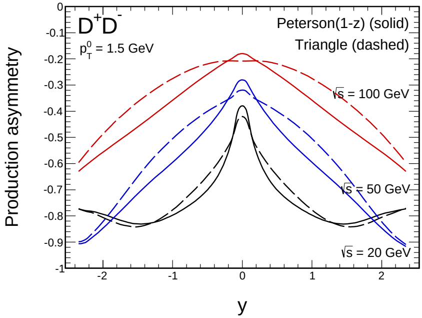
$$A_{D^+/D^-}(\xi) = \frac{\frac{d\sigma_{D^-}}{d\xi}(\xi) - \frac{d\sigma_{D^+}}{d\xi}(\xi)}{\frac{d\sigma_{D^-}}{d\xi}(\xi) + \frac{d\sigma_{D^-}}{d\xi}(\xi)}, \text{ where } \xi = x_F, y, p_T, (y, p_T)$$

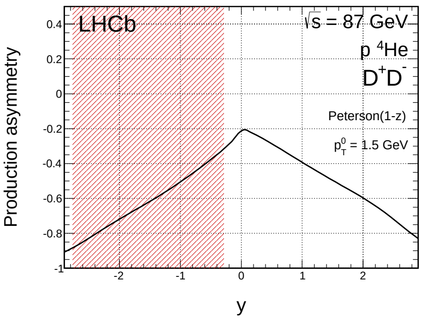


- $P_{q\to D} = 0.005 \pm 0.001$ for *triangle* FF and $P_{q\to D} = 0.007 \pm 0.001$ for Peterson$(1-z)$
- larger collision energy $\Rightarrow$ smaller asymmetry

Large asymmetries at low-energies

Here we include all partonic processes with light quark/antiquark in the final state.



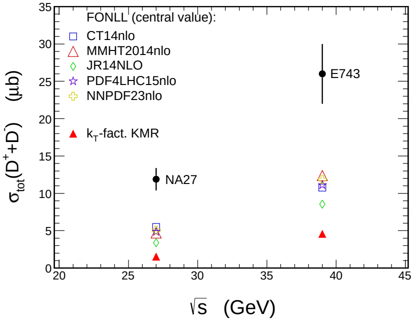


- asymmetry at the lower energies is much larger than that for the LHC energies
- even at midrapidity $y \approx 0$ we predict sizeable asymmetries
- our rough predictions could be checked at SPS , RHIC or at fixed target LHCb.
- it would allow to better pin down the rather weakly constrained so far $D_{q \to D}(z)$

Low-energy disagreement

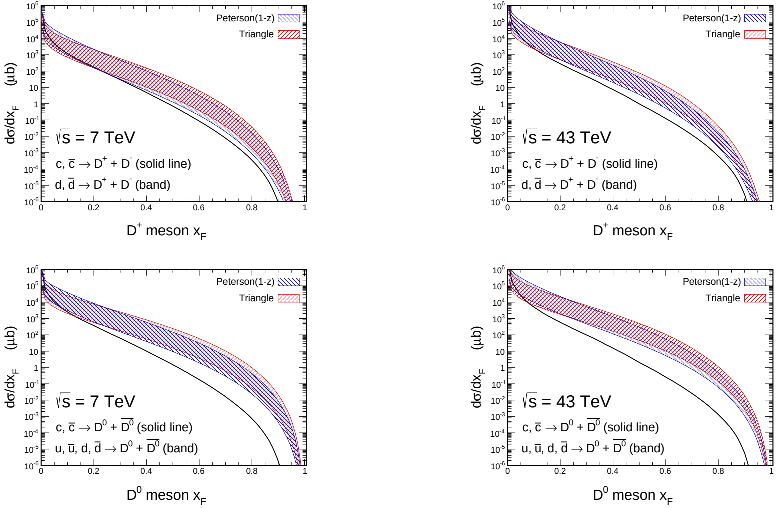
- dominant at high-energy $gg \to c\bar{c}$ mechanism gives only 13% and 18% for $\sqrt{s} = 27$ and 39 GeV, respectively and strongly underestimates the NA27 and E743 data

Process:	$\sqrt{s} = 27$ GeV	$\sqrt{s} = 39$ GeV
$g^*g^* \to c\bar{c}$ $(c/\bar{c} \to D^\pm)$	1.52	4.58
$q^*\bar{q}^* \to c\bar{c}$ $(c/\bar{c} \to D^\pm)$	0.08	0.19
$gd \to gd$ $(d \to D^-)$	9.53	13.89
$g\bar{d} \to g\bar{d}$ $(\bar{d} \to D^+)$	3.03	4.78
$dd \to dd$ $(d \to D^-) \times 2$	3.07	4.29
$\bar{d}\bar{d} \to \bar{d}\bar{d}$ $(\bar{d} \to D^+) \times 2$	0.29	0.49
$\bar{d}d \to \bar{d}d$ $(d \to D^-)$	0.58	0.88
$d\bar{d} \to d\bar{d}$ $(\bar{d} \to D^+)$	0.58	0.88
$ud \to ud$ $(d \to D^-)$	2.76	3.72
$\bar{u}\bar{d} \to \bar{u}\bar{d}$ $(\bar{d} \to D^+)$	0.12	0.19
$\bar{u}d \to \bar{u}d$ $(d \to D^-)$	0.40	0.63
$u\bar{d} \to u\bar{d}$ $(\bar{d} \to D^+)$	0.97	1.42
Theory predictions	22.93	35.94
Experiment	NA27: 11.9 ± 1.5	E743: $26 \pm 4 \pm 25\%$



- the discussed by us mechanism of subleading fragmentation leads to enhanced production of D mesons at lower energies.

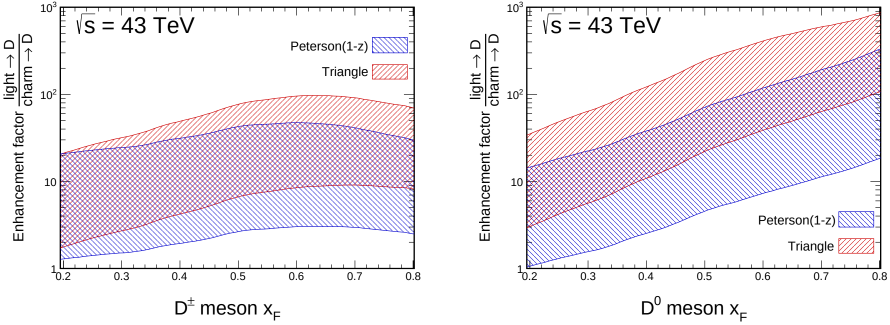
Very-high energies



Unfavored fragmentation mechanism may be very important for high-energy neutrinos!

Consequences for prompt neutrino flux

Large enhancement of the cross section at large x_F



- at $\sqrt{s} = 43$ TeV for $x_F \sim 0.5$ the cross section for charged mesons ($D^+ + D^-$) is $3 - 15$ times bigger than for conventional approach while the cross section for neutral mesons ($D^0 + \bar{D}^0$) is $20 - 200$ times bigger.

Conclusions

- We have made critical analysis of charm production in the Earth's atmosphere.
- 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.
- 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 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.
- Can the new mechanism explain the IceCube high-energy data requires further critical analysis?
- NLO, electroweak and meson cloud corrections must be included in a future in a consistent manner !

Thank You!