Calculations of the high energy atmospheric neutrinos

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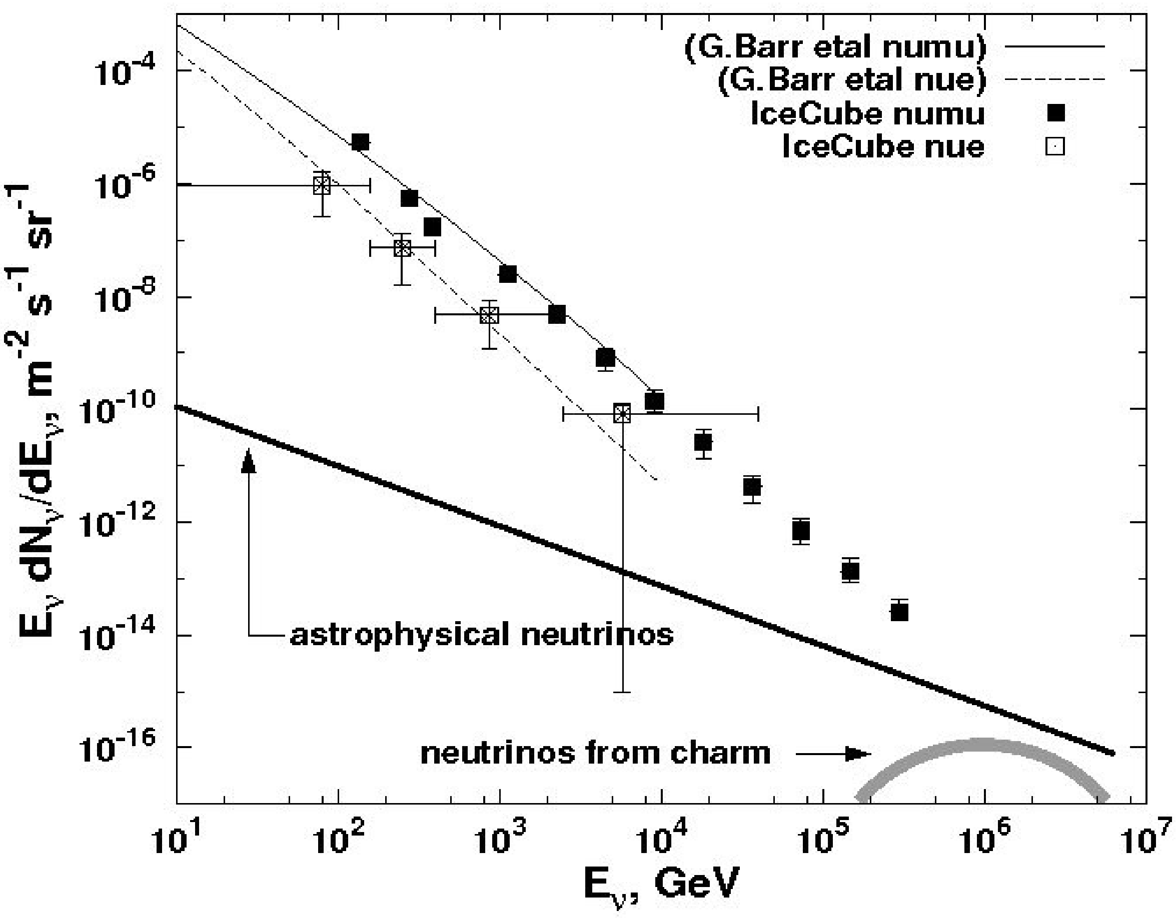
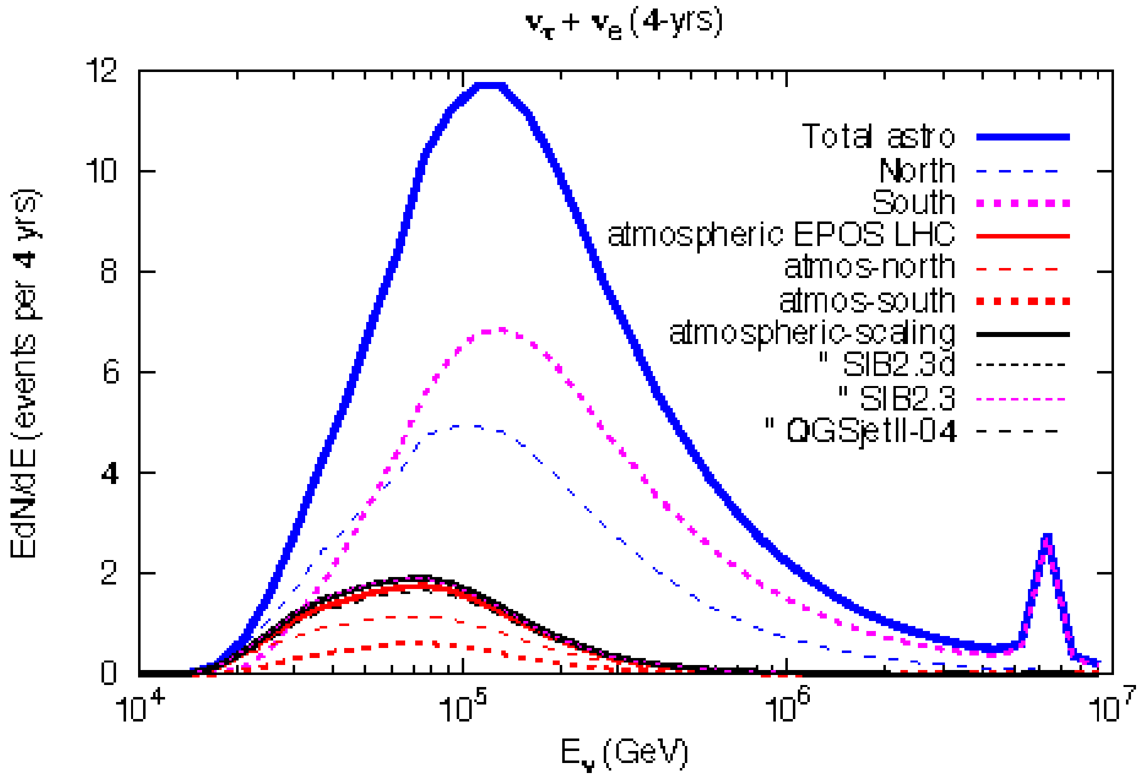
We will discuss the performance of the new version of the hadronic interaction model Sibyll 2.3 that also generates charm hadrons which decay and generate very high energy atmospheric neutrinos.

This talk is based on work done with Tom Gaisser, Ralph Engel, and especially by Felix Riehn and Anatoli Fedynitch. Some of these results were presented by Ralph Engel at the ICRC2015.



The current high interest in the `prompt' neutrinos from charm is due to the detection by IceCube of a number of neutrinos of energy above 30 TeV, a fraction of which must be of astrophysical origin.

If we can reliably estimate the contrubution of charm to the atmospheric neutrino flux we can estimate better the flux of astrophysical neutrinos.



The figure shows the estimate of the total neutrino energy (not the one deposited in the detector) of the atmospheric and astrophysical neutrinos detected by the IceCube experiment.

There are several previous estimates of the contribution of charm to the atmospheric neutrino flux:

Thunman, Ingelman, Gondolo, Astropart Phys 5 (1996)
Bugaev et al. , PRD 58 (1998)
Maartin, Ryskin, Stasto, Acta Phys Polonica B34 (2003)
Endberg, Reno, Sarcevich, PRD78 (2008)
Fedynich, Becker Tjus, Desiati, PRD86 (2012)

ERS is the model used by IceCube to estimate the flux of astrophysical neutrinos. It is a very good estimate, except that it uses the cosmic ray flux used by TIG.

We are attempting to do a new calculation that agrees with all accelerator measurements of the charm production starting at low energies and including all LHC data. A special attention will be payed also to the cosmic ray flux energy spectrum.

Analytic and semi-analytic calculations of the atmospheric neutrino flux use the modified Elbert formula: see Tom Gaissers book and recent talks:

$$\phi(E_\nu) = \phi(E_N) \times \{ \frac{A_{\pi\nu}}{1+B_{\pi\nu}cos(\theta)E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1+B_{K\nu}cos(\theta)E_\nu/\epsilon_K} + \frac{A_{C\nu}}{1+B_{C\nu}cos(\theta)E_\nu/\epsilon_C} \}$$

Where the critical energy *epsilon* is
115 GeV for pions,
850 GeV for Kaons,
10 PeV for charm mesons

The decay length for charged D mesons is 0.34 mm and 0.15 mm for neutral D mesons. Another significant difference is that pions and Kaons generate electron neutrinos through muon decays and Ke3 decays, D mesons lepton decay channels produce equal numbers of muon and electron neutrinos.

Sibyll 2.3 corrects several problems of Sibyll 2.1 that is widely used for air shower calculations, such as

- Very high interaction *pp* cross section not consistent with the LHC cross section measurements
- implements parton shadowing to generate similar correct shower depth of maximum as Sibyll 2.1
- The excessive K+ production in p-Nucleus interactions that affects the atmospheric neutrino production
- Generates more baryon-antibaryon pairs to agree with the accelerator measurements

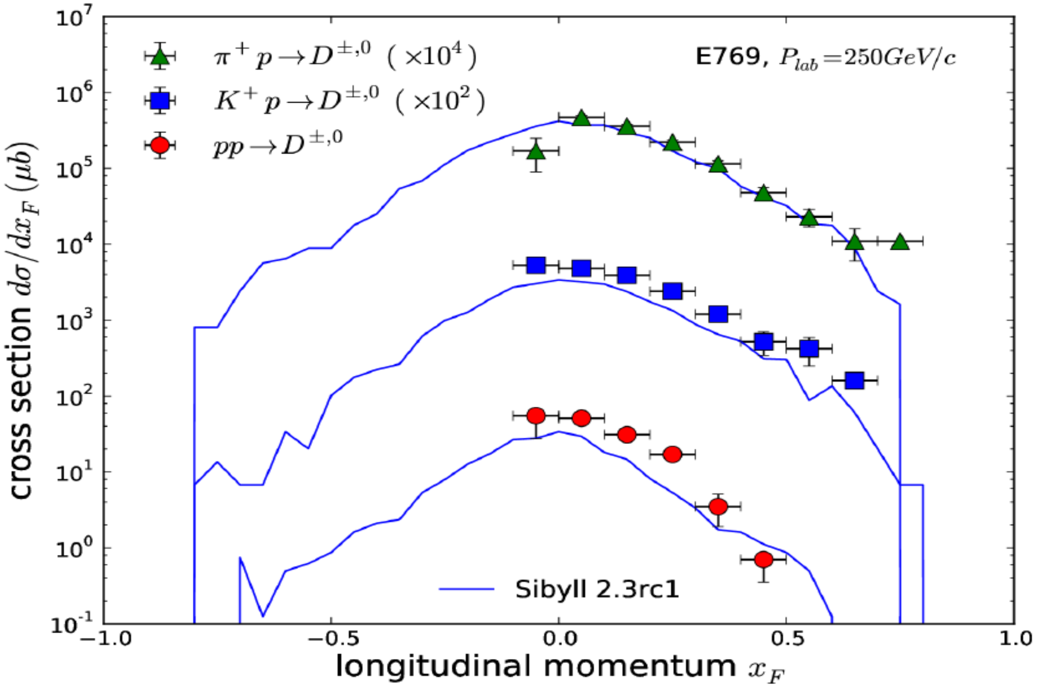
It also generates charm mesons and baryons

Sibyll2.3 includes

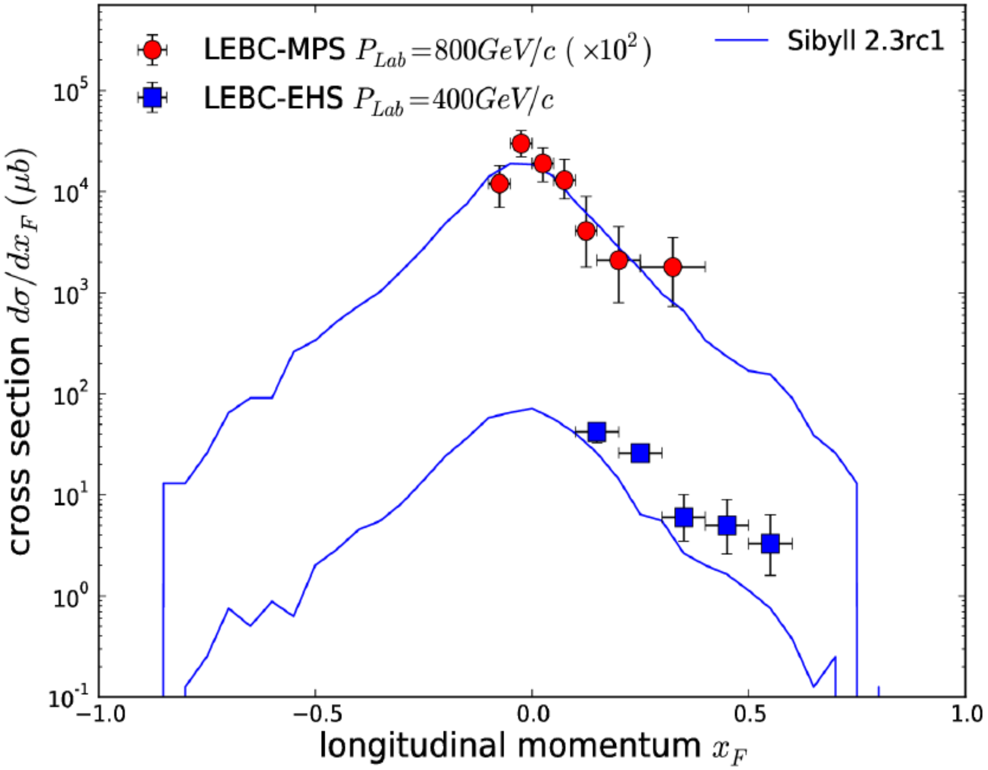
- multiple parton interactions
- hard and soft scattering
- diffraction dissociation
- Lund fragmentation of strings

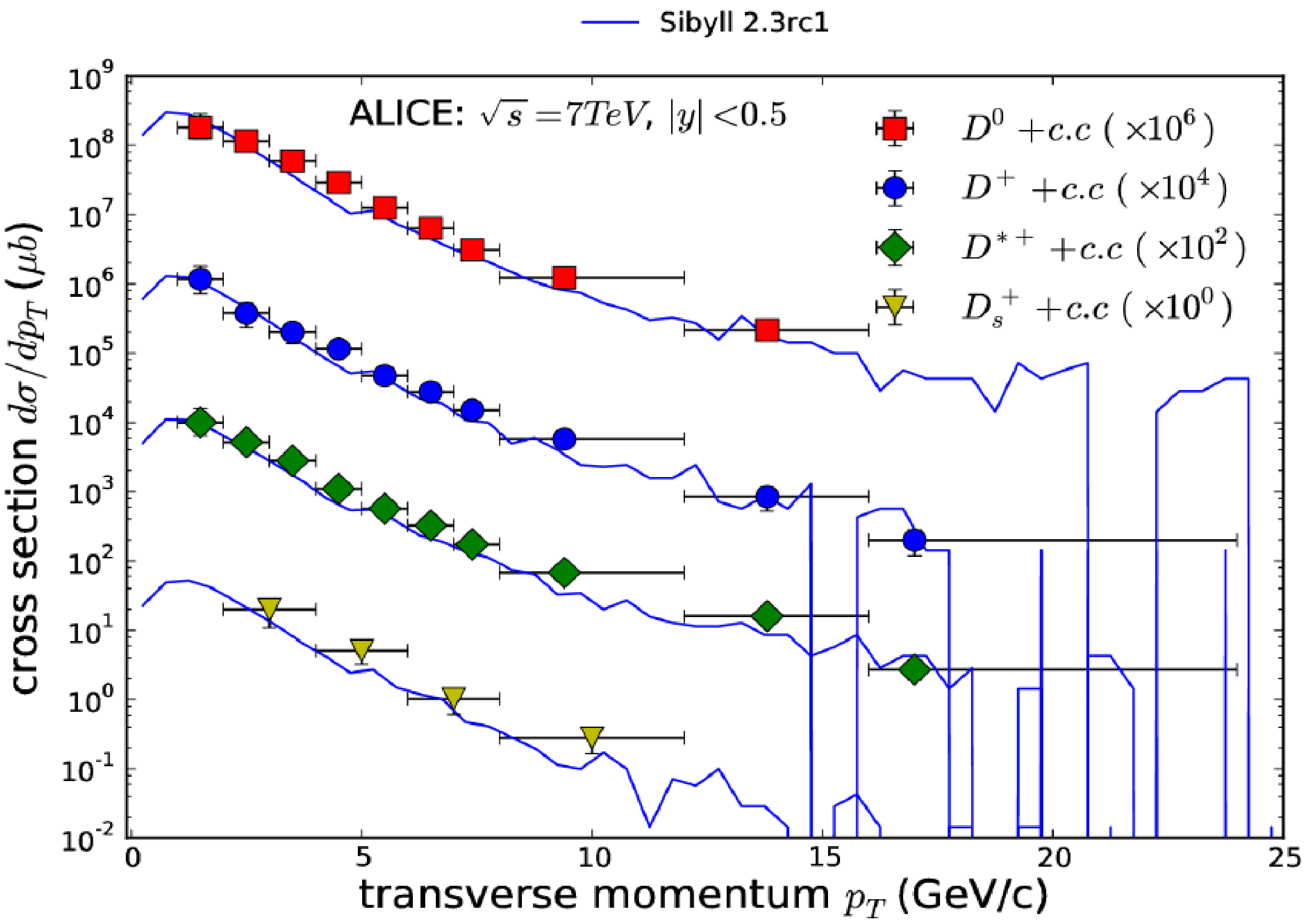
We have added charm production to the hard scattering (perturbative QCD component). Since there is evidence in data also for non-perturbative component (leading charm particles and assymetry) we have also added charm to the valence scattering part of the code.

The charm production measurements from 250 GeV/c in the Lab to *sqrt(s)* of 8 TeV were compared to the charm production of Sibyll.



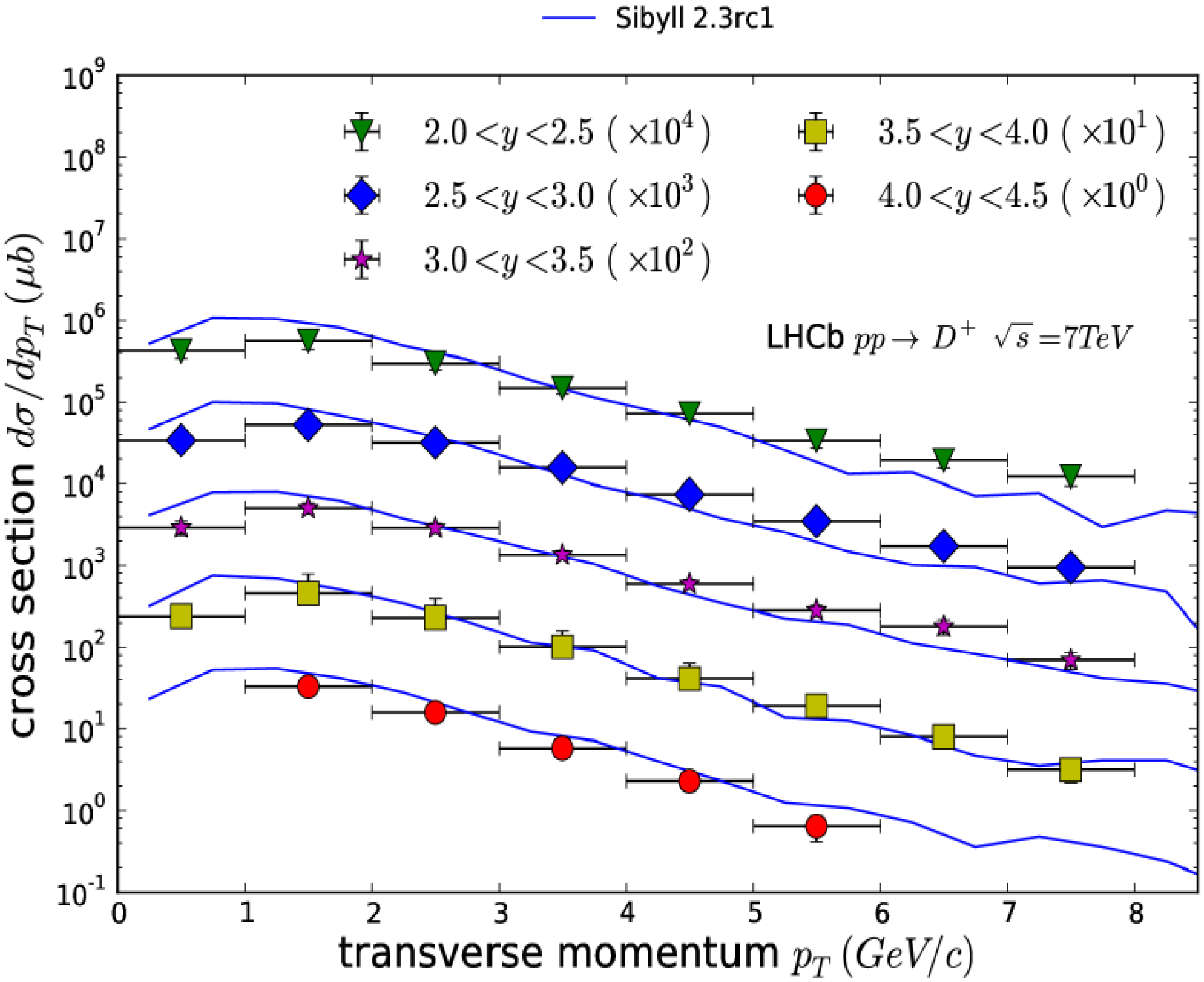
Almost full phase space coverage exists in these experiments.



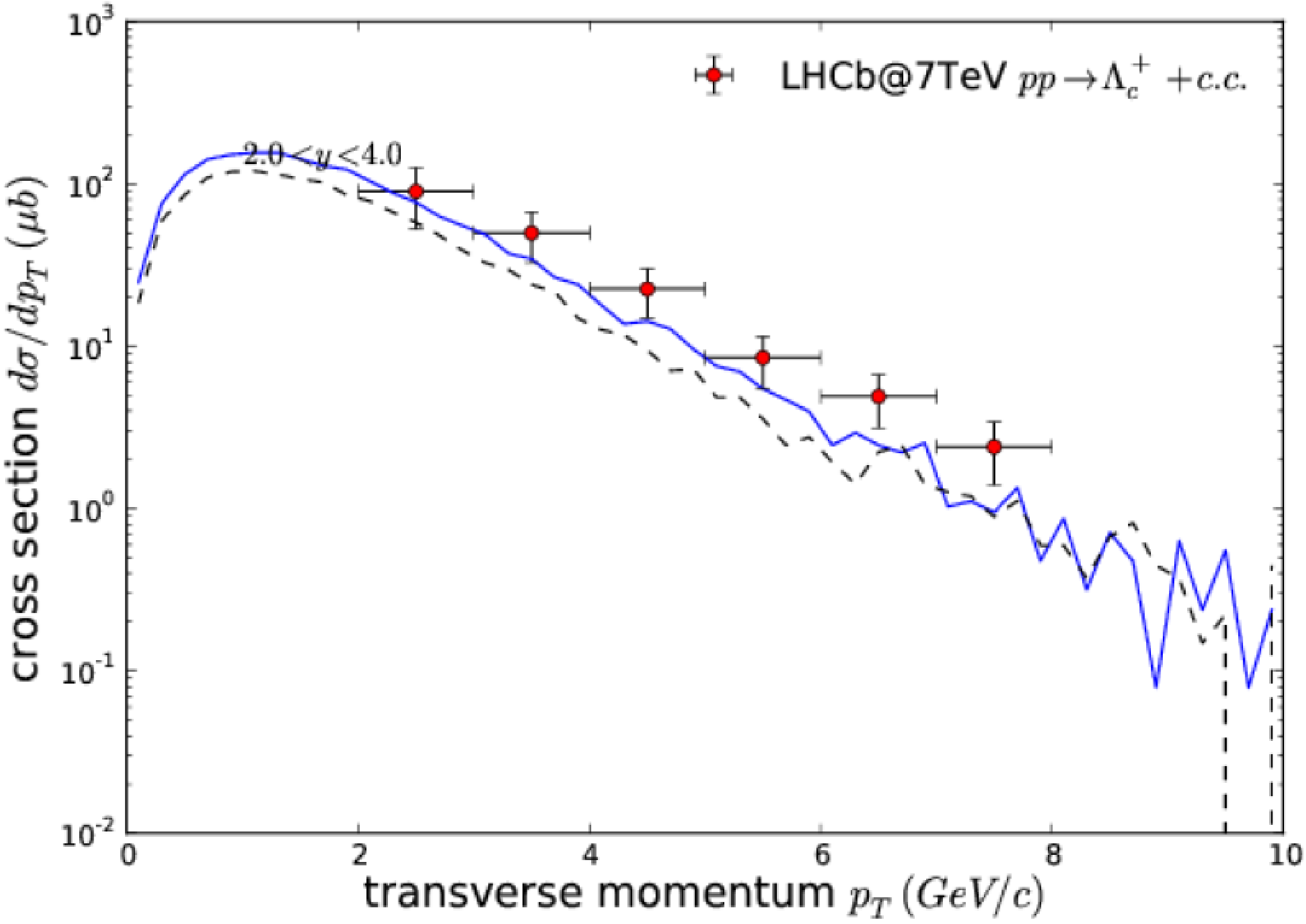


It is different in collider experiments. Different detectors cover different parts of the phase space.

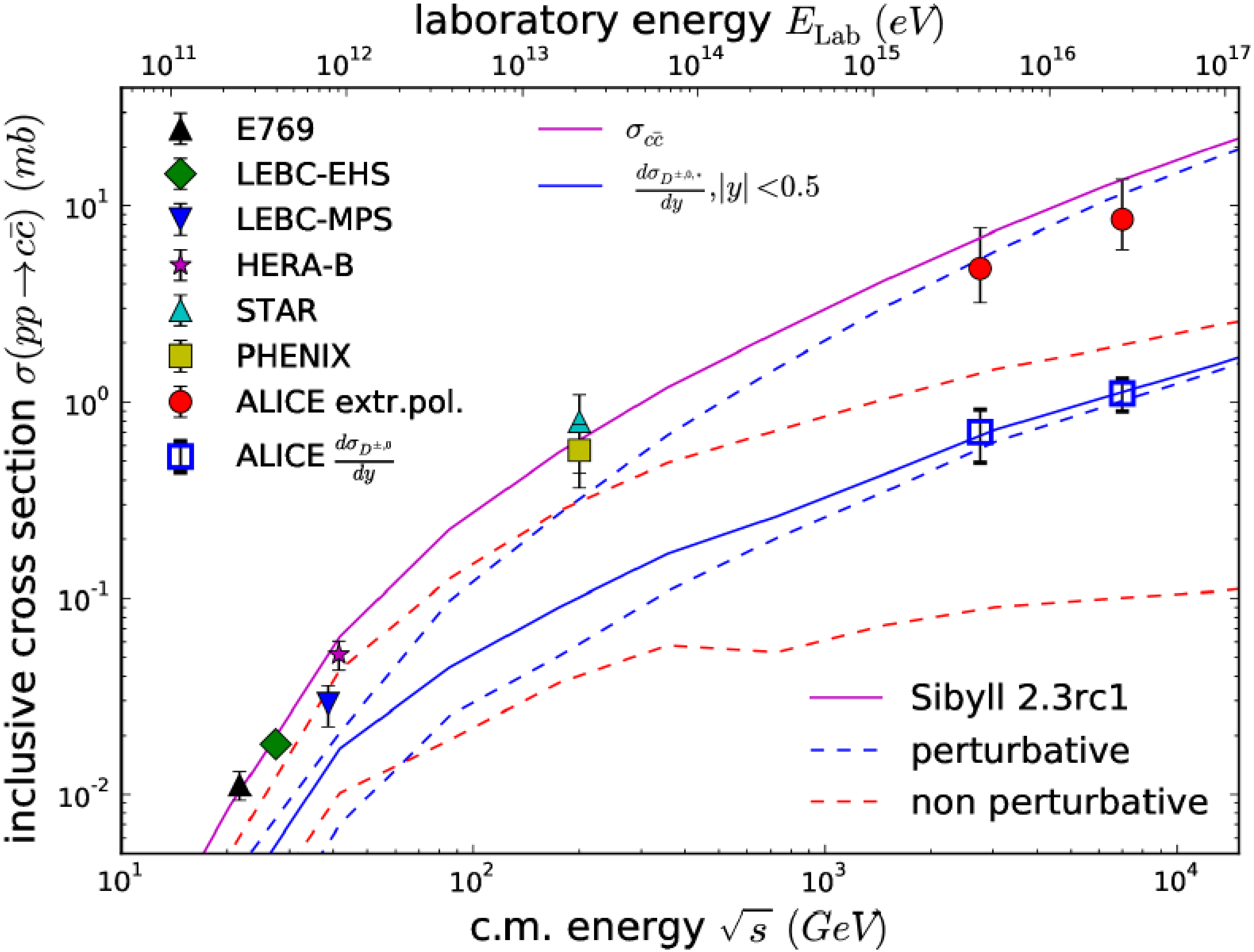
For |y| < 0.5 in ALICE the central charm meson production is enirely due to pertubative processes.



LHCb measures D production in the central and forward regions. Sibyll reproduces the measurements well, although there is a little problem with very high transverse momenta.

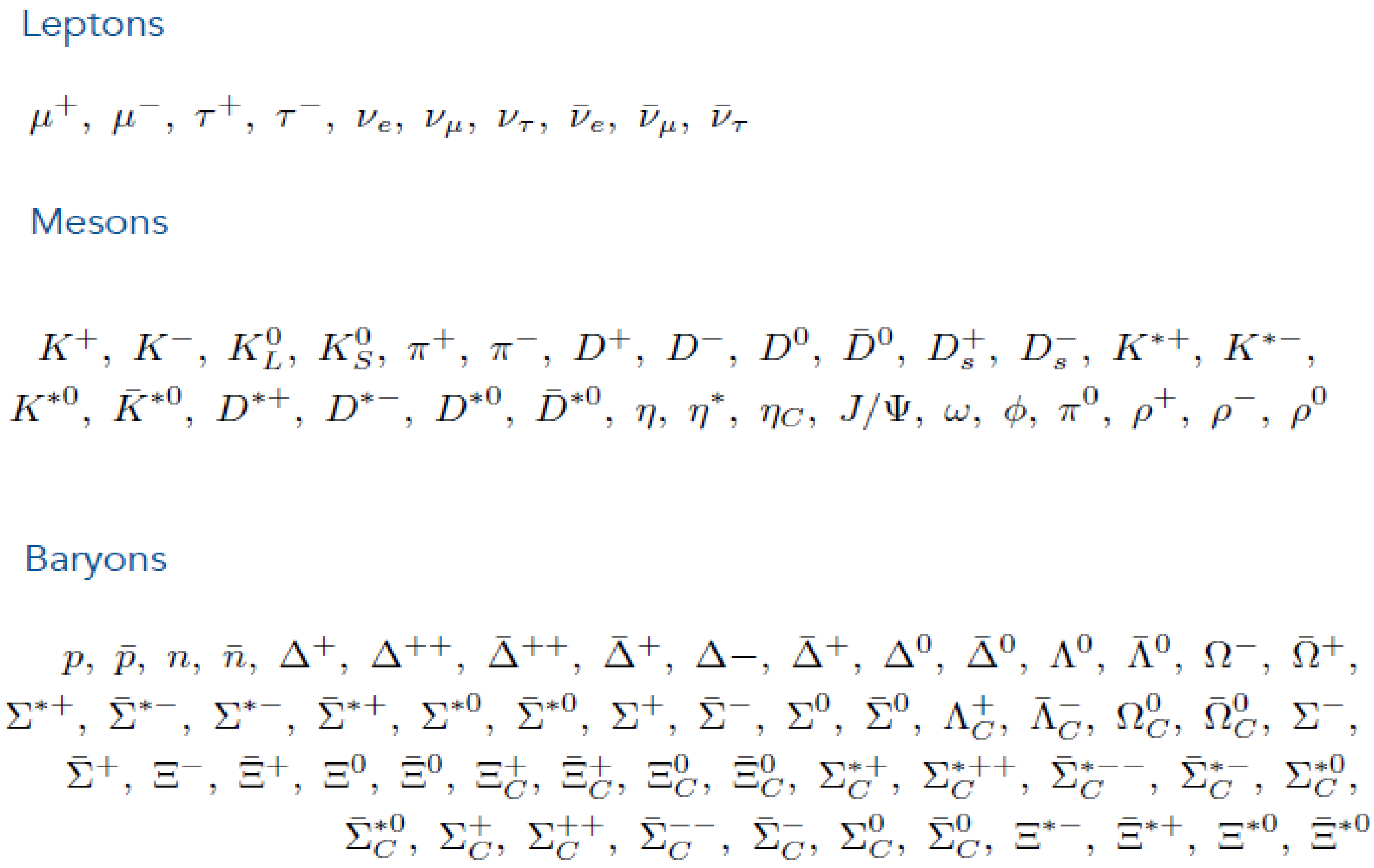


Similar problem exists also with the measured charmed Lambda production. It is important because the *x* distribution of Lambdas is very flat, which means after decay it generates high energy neutrinos.



Sibyll 2.3 performance in the whole energy range. There is still not a full agreement between the total inclusive cross section and the central charm production measured by ALICE.

For calculations of the atmospheric muon and neutrino fluxes a matrix method developed by A. Fedinitch is used. It involves the following particles that Sibyll generates:



Leptons

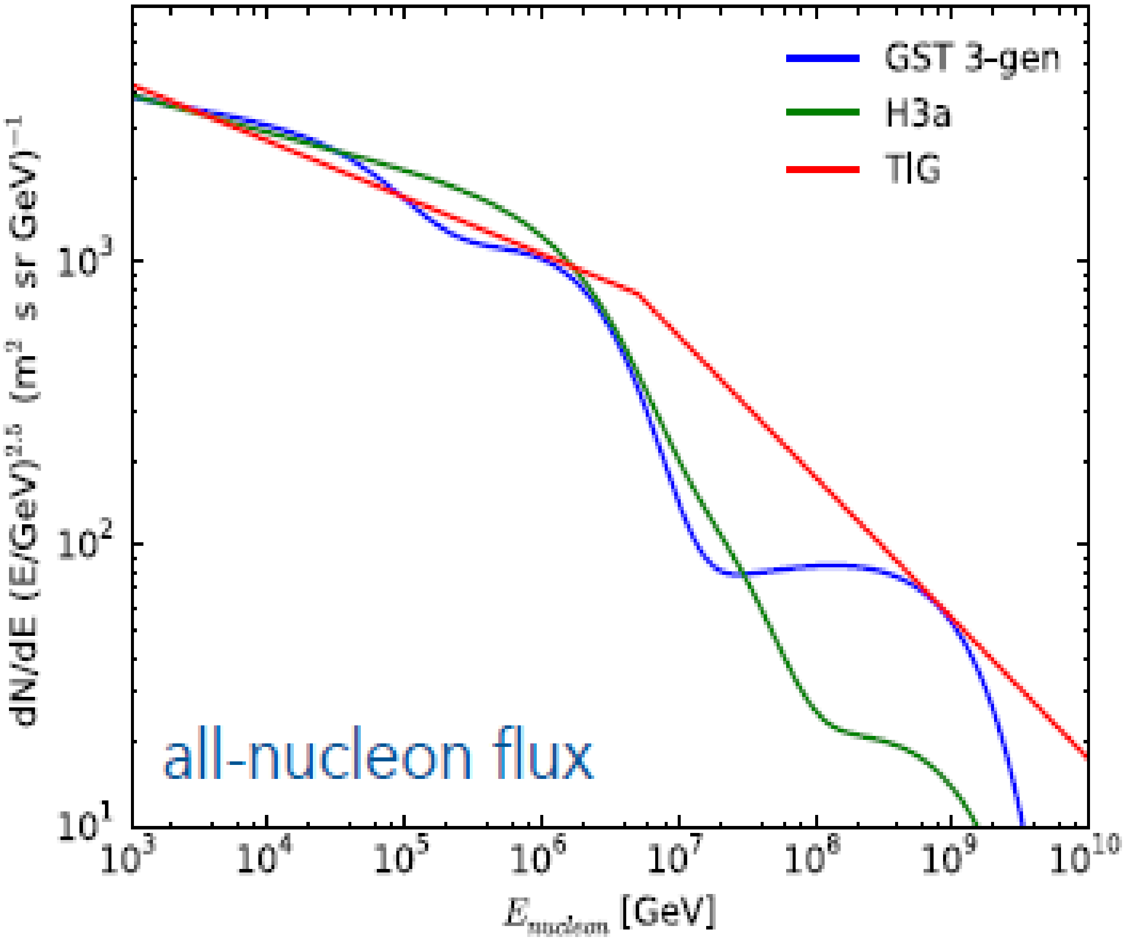
$\mu^+,\ \mu^-,\ \tau^+,\ \tau^-,\ \nu_e,\ \nu_\mu,\ \nu_\tau,\ \bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau$

Mesons

$$K^+,\ K^-,\ K_L^0,\ K_S^0,\ \pi^+,\ \pi^-,\ D^+,\ D^-,\ D^0,\ \bar{D}^0,\ D_s^+,\ D_s^-,\ K^{*+},\ K^{*-},\\ K^{*0},\ \bar{K}^{*0},\ D^{*+},\ D^{*-},\ D^{*0},\ \bar{D}^{*0},\ \eta,\ \eta^*,\ \eta_C,\ J/\Psi,\ \omega,\ \phi,\ \pi^0,\ \rho^+,\ \rho^-,\ \rho^0$$

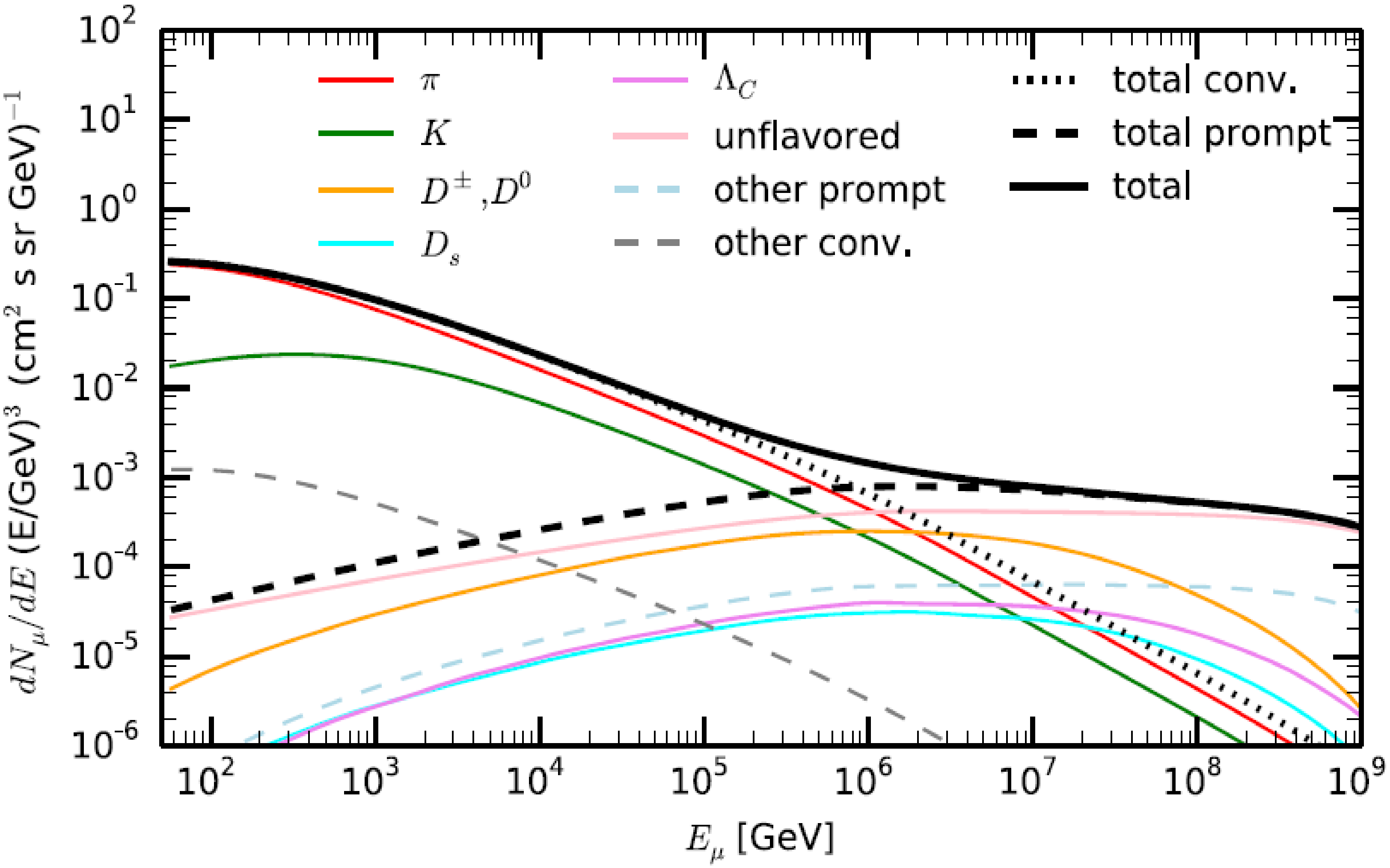
Baryons

$$p,\ \bar{p},\ n,\ \bar{n},\ \Delta^+,\ \Delta^{++},\ \bar{\Delta}^{++},\ \bar{\Delta}^+,\ \Delta-,\ \bar{\Delta}^+,\ \Delta^0,\ \bar{\Delta}^0,\ \Lambda^0,\ \bar{\Lambda}^0,\ \Omega^-,\ \bar{\Omega}^+,\\ \Sigma^{*+},\ \bar{\Sigma}^{*-},\ \Sigma^{*-},\ \bar{\Sigma}^{*+},\ \Sigma^{*0},\ \bar{\Sigma}^{*0},\ \Sigma^+,\ \bar{\Sigma}^-,\ \Sigma^0,\ \bar{\Sigma}^0,\ \Lambda_C^+,\ \bar{\Lambda}_C^-,\ \Omega_C^0,\ \bar{\Omega}_C^0,\ \Sigma^-,\\ \bar{\Sigma}^+,\ \Xi^-,\ \bar{\Xi}^+,\ \Xi^0,\ \bar{\Xi}^0,\ \Xi_C^+,\ \bar{\Xi}_C^+,\ \Xi_C^0,\ \bar{\Xi}_C^0,\ \Sigma_C^{*+},\ \Sigma_C^{*++},\ \bar{\Sigma}_C^{*--},\ \bar{\Sigma}_C^{*-},\ \Sigma_C^{*0},\\ \bar{\Sigma}_C^{*0},\ \Sigma_C^+,\ \Sigma_C^{++},\ \bar{\Sigma}_C^{--},\ \bar{\Sigma}_C^-,\ \Sigma_C^0,\ \bar{\Sigma}_C^0,\ \Xi^{*-},\ \bar{\Xi}^{*+},\ \Xi^{*0},\ \bar{\Xi}^{*0}$$

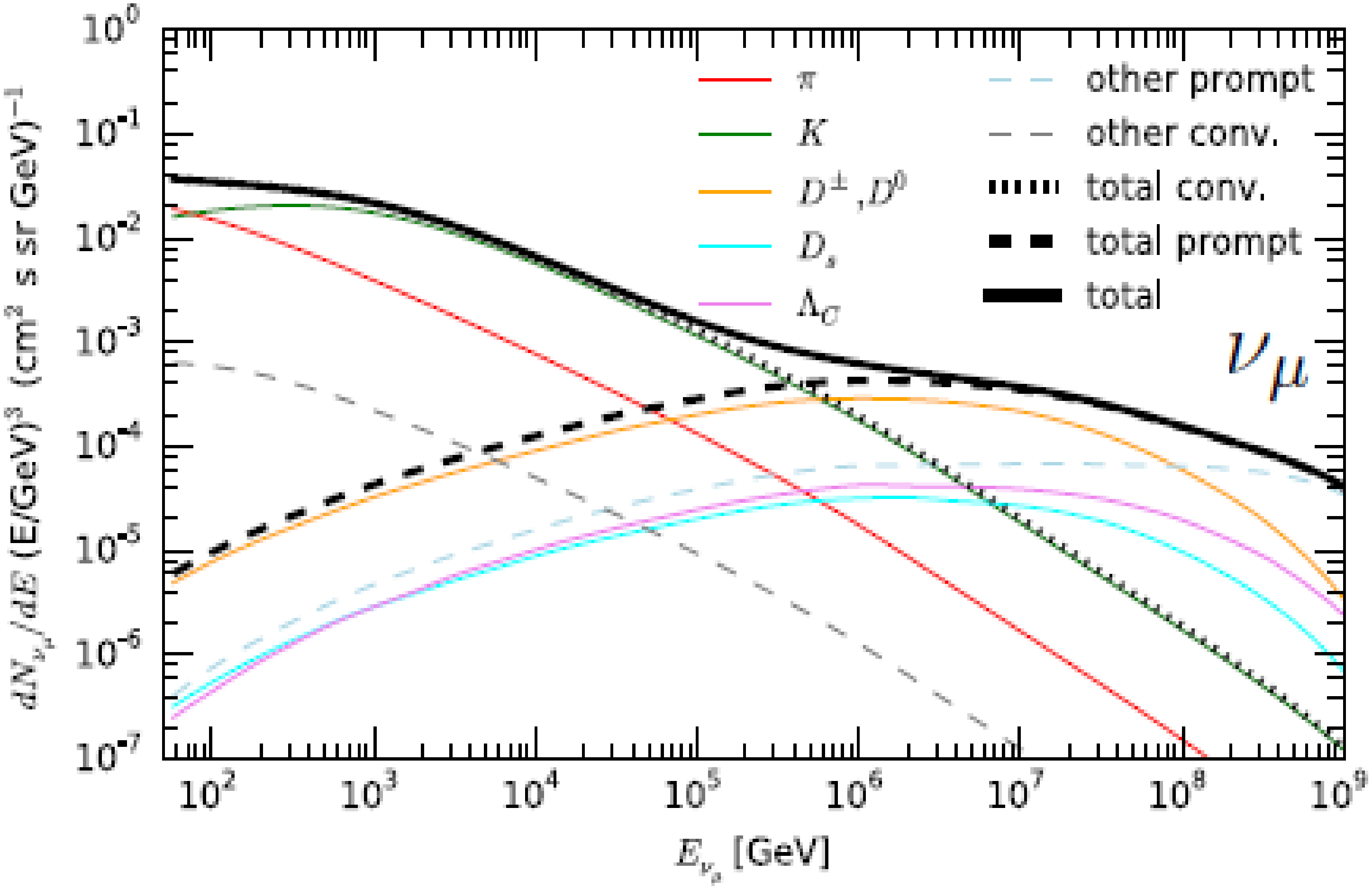


The MonteCarlo calculations we have done are folded with the fluxes of protons and neutrons in the primary cosmic rays that hit the atmosphere. This should generate the right ratio of neutrinos to antineutrinos in the atmospheric neutrino fluxes.

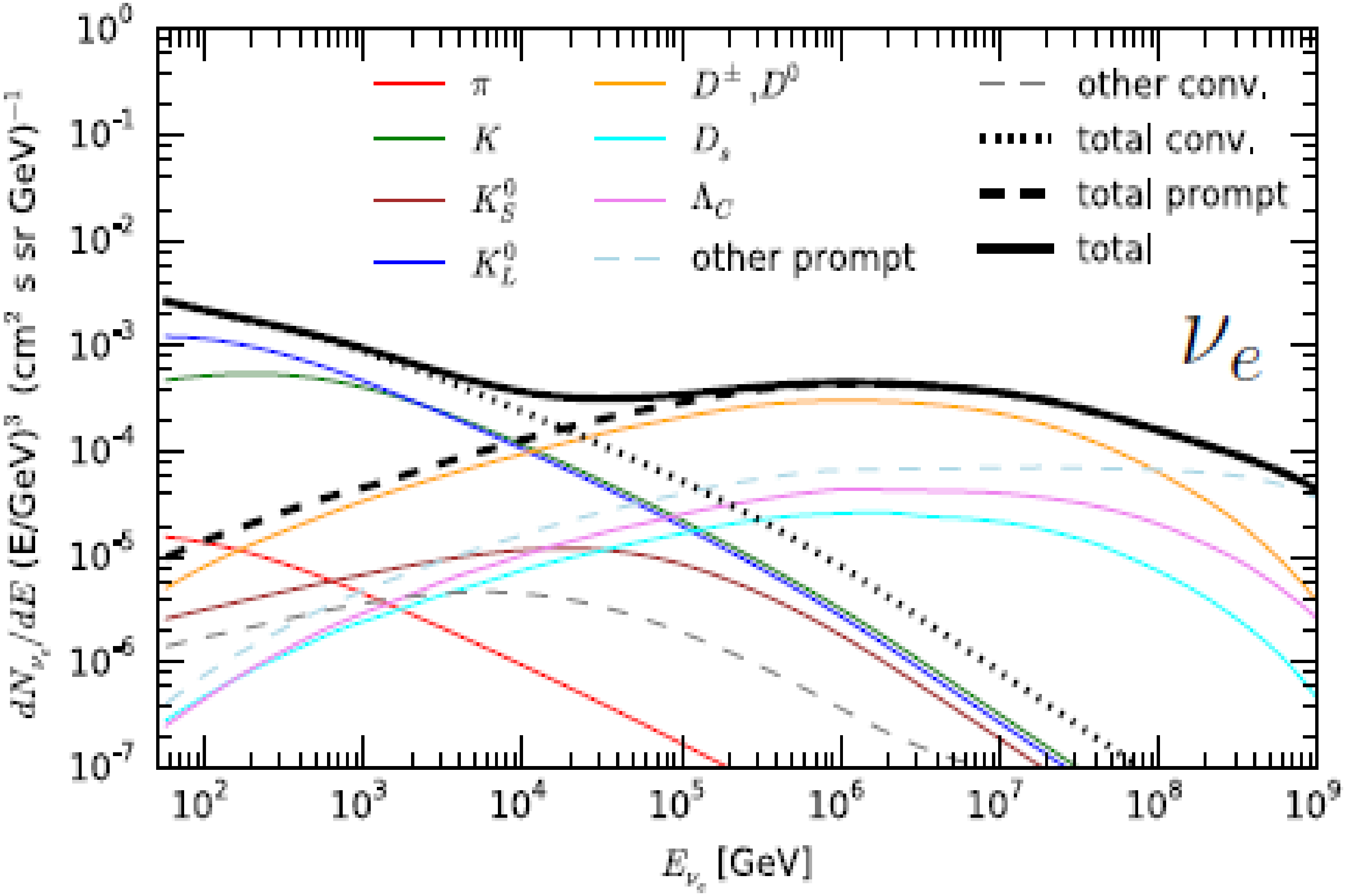
Comparison of the all nucleon fluxes in Gaissers model h3a and the fit GST to the TIG cosmic ray flux used in all previous calculations of atmospheric neutrinos including charm. The cosmic ray flux used in the calculation changes the shape of the atmospheric neutrino flux at high energy.



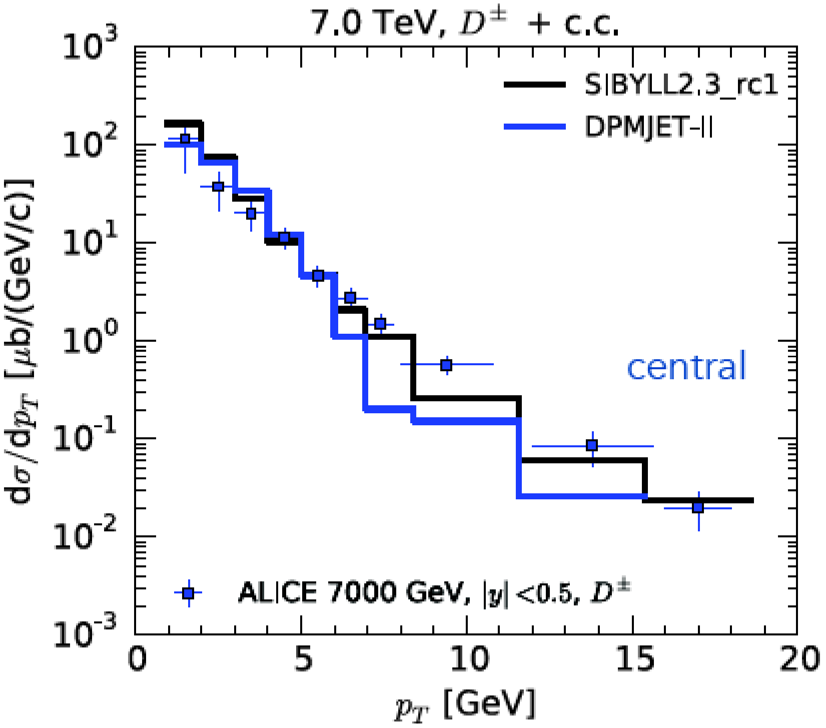
Contribution of different particle decays to the atmospheric muon flux. Note that the prompt muons start dominating over the conventional muon fluxes above 1 PeV, Note that the muon fluxes are multiplied by the muon energy cubed.

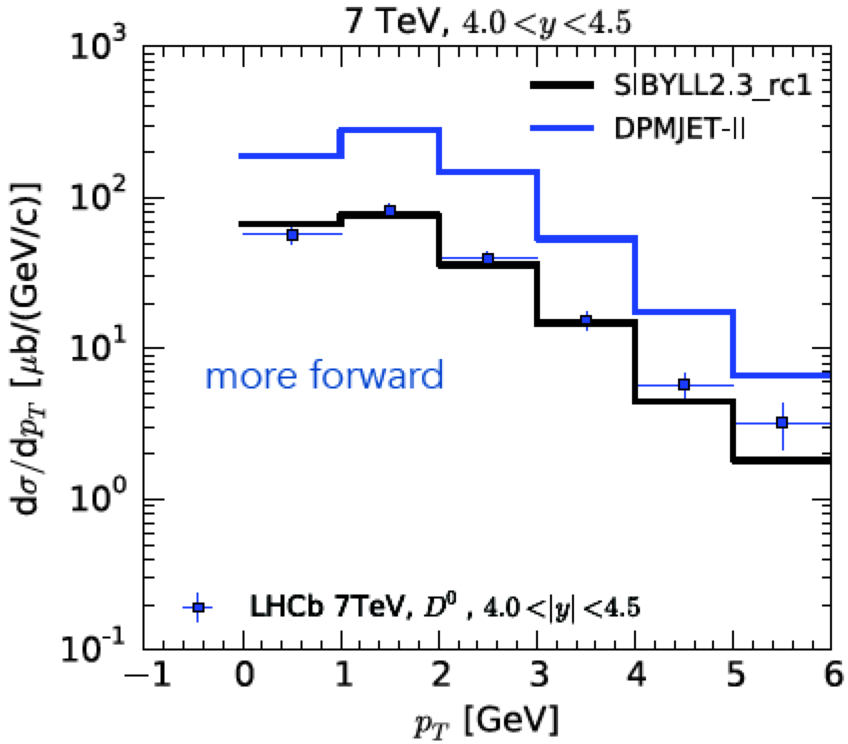


In the case of muon neutrinos (and antineutrinos) the cross over is at slightly lower energy of about 500 TeV.



For electron neutrinos the crossover is at about 20 TeV, which means that prompt electron neutrinos contribute to all IceCube high energy neutrino events.





We compared our predictions for charm production at LHC to those of DPMJET II. While in the central region the two predictions are similar, in the central and forward regions DPMJET generates many more charm particles, while Sibyll is consistent with the experimental data in the whole phase space.

Conclusions:

We are currently happy with the Sibyll 2.3 descriptions of *pp* interactions and the charm mesons and baryon production in them. We feel that more checking should be performed on p-Nucleus collisions. Luckily there is data on such collisions and we are concentrating on them now.

It will not be difficult to describe the charm baryons and mesons interactions, in cases they do not decay.

The new Sibyll 2.3 model is now public, it can be used within CORSICA for calculations of all kinds of atmospheric cascades including the generation of very high energy atmospheric neutrinos.

Thanks