Recent progress concerning atmospheric charm

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TeV Particle Astrophysics 2018
Berlin, Germany, 27–31 August 2018

In collaboration with M. Benzke, T. Gaisser, B. Kniehl, G. Kramer, S. O. Moch, F. Riehn, G. Sigl

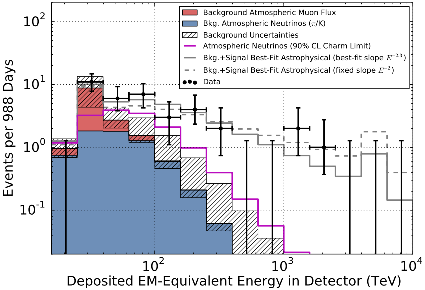
See:
MVG et al. (PROSA collaboration) JHEP 1705 (2017) 004;
M. Benzke, MVG, B. Kniehl, G. Kramer, S. O. Moch, G. Sigl, JHEP 1712 (2017) 021;
A. Fedynitch, F. Riehn, R. Engel, T. Gaisser, T. Stanev, [arXiv:1806.04140];

+ work in progress

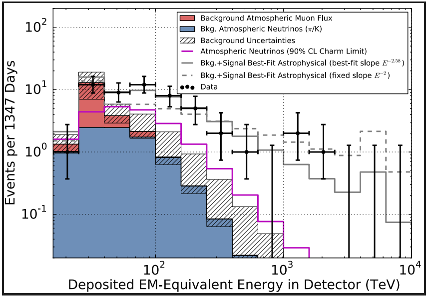
The astrophysical case:

IceCube high-energy events ([arXiv:1405.5303] + ICRC 2015)

- **2013**: 662-day analysis, with **28** candidates in the energy range [50 TeV - 2 PeV]. (4.1 σ excess over the expected atmospheric background).
- **2014**: 988-day analysis, with a total of **37** events with energy [30 TeV - 2 PeV] (5.7 σ excess), no events in the energy range [400 TeV - 1 PeV], spectral $\Gamma = -2.3 \pm 0.3$.
- **2015**: 1347-day analysis, with a total of **53 + 1** events, previous energy gap partially filled, (7 σ excess), spectral $\Gamma = -2.58 \pm 0.25$.



2014



2015

figures from the presentation of C. Kopper, ICRC2015

Last updates of the IceCube HESE analysis

∗ **2017**: 2078-day analysis, with a total of **82** events, spectral $\Gamma = -2.92^{+0.33}_{-0.29}$, no new events with deposited energy above 300 TeV with respect to the previous analyses !

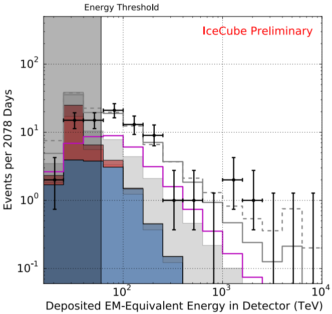


figure from the presentation of C. Kopper, ICRC2017, PoS (ICRC 2017) 981

∗ **2018**: 2635-day analysis with a total of **103** events, spectral $\Gamma = -2.91^{+0.33}_{-0.22}$ (for events with $E > 60$ TeV), new events and new binning, new atmospheric passing fractions (self-veto).

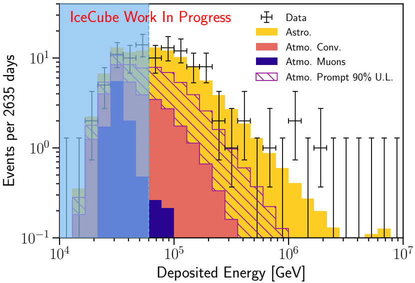


figure from the presentation of C. Schnaider, TeVPA 2018

* high-energy diffuse flux further tested by ANTARES and testable by KM3Net/ARCA

Atmospheric neutrino fluxes

CR + Air interactions:
- $A - A'$ interaction approximated as $A * (N - A')$ interactions (superposition);
- $N - A'$ approximated as $A' * (N - N)$ interactions: up to which extent is this valid ?

$*$ conventional neutrino flux:

$$NN \rightarrow \pi^{\pm}, K^{\pm} + \mathrm{X} \rightarrow \nu_\mu(\bar{\nu}_\mu) + \mu^{\pm} + \mathrm{X},$$
$$NN \rightarrow K^0_S, K^0_L + \mathrm{X} \rightarrow \pi^{\pm} + e^{\mp} + \bar{\nu}_e(\nu_e) + \mathrm{X}, \quad \pi^{\pm} + \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu) + \mathrm{X}$$

$*$ prompt neutrino flux:

$$NN \rightarrow c, b, \bar{c}, \bar{b} + \mathrm{X} \rightarrow \textit{heavy-hadron} + \mathrm{X} \rightarrow \nu(\bar{\nu}) + \mathrm{X}' + \mathrm{X}$$

$c\tau_{0,\,\pi^\pm} = 780$ cm, $c\tau_{0,\,K^\pm} = 371$ cm, $c\tau_{0,\,D^\pm} = 0.031$ cm

Critical energy $\epsilon_h = m_h c^2 h_0 \,/\, (\mathrm{c}\ \tau_{0,h} \cos(\theta))$, above which hadron decay probability is suppressed with respect to its interaction probability:

$\epsilon_\pi^{\pm} < \epsilon_K^{\pm} << \epsilon_D \Rightarrow$ conventional flux is suppressed with respect to prompt one, for energies high enough.

How to get atmospheric fluxes? From cascade equations to Z-moments [*review in Gaisser, 1990; Lipari, 1993*]

Solve a system of coupled differential equations regulating particle evolution in the atmosphere (interaction/decay/(re)generation):

$$\frac{d\phi_j(E_j,X)}{dX} = -\frac{\phi_j(E_j,X)}{\lambda_{j,int}(E_j)} - \frac{\phi_j(E_j,X)}{\lambda_{j,dec}(E_j)} + \sum_{k\neq j} S_{prod}^{k\to j}(E_j,X) + \sum_{k\neq j} S_{decay}^{k\to j}(E_j,X) + S_{reg}^{j\to j}(E_j,X)$$

Under assumption that X dependence of fluxes factorizes from E dependence, analytical approximated solutions in terms of Z-moments:

– Particle Production:

$$S_{prod}^{k\to j}(E_j,X) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k,X)}{\lambda_k(E_k)} \frac{1}{\sigma_k} \frac{d\sigma_{k\to j}(E_k,E_j)}{dE_j} \sim \frac{\phi_k(E_j,X)}{\lambda_k(E_j)} Z_{kj}(E_j)$$

– Particle Decay:

$$S_{decay}^{j\to l}(E_l,X) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j,X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\to l}(E_j,E_l)}{dE_l} \sim \frac{\phi_j(E_l,X)}{\lambda_j(E_l)} Z_{jl}(E_l)$$

Solutions available for $E_j >> E_{crit,j}$ and for $E_j << E_{crit,j}$, respectively, are interpolated geometrically.

Z-moments for prompt fluxes: Z_{ph} definition

$$Z_{ph}(E_h) = \int_{E_h}^{+\infty} dE'_p \frac{\phi_p(E'_p, 0)}{\phi_p(E_h, 0)} \frac{\lambda_{p,int}(E_h)}{\lambda_{p,int}(E'_p)} \frac{1}{\sigma_{p-Air}^{tot,inel}(E'_p)} \frac{d\sigma_{p-Air \to c+X \to h+X'}}{dE_h}(E'_p, E_h)$$

$*$ Z_{ph} (as well as the other Z-moments) are energy dependent.

$*$ Z_{ph} at a fixed E_h, depends on charm production cross-section $\sigma(pA \to c + X)$ over a range of proton energies $E_h < E'_p < +\infty$.

$*$ Crucial inputs: all.
Differences among predictions of different authors can come from:
- differences in the calculation of $\sigma_{p-Air}^{tot,inel}$,
- treatment of pA interactions: relation between pA and pp,
- theory and input parameters in $\sigma(pp \to c + X \to h + X)$.

Prompt neutrino flux hadroproduction in the atmosphere: theoretical predictions in literature

∗ Long non-exhaustive list of papers, including, among the others:

- Lipari, Astropart. Phys. 1 (1993) 195
- Battistoni, Bloise, Forti et al., Astropart. Phys. 4 (1996) 351
- Gondolo, Ingelman, Thunman, Astropart. Phys. 5 (1996) 309
- Bugaev, Misaki, Naumov et al., Phys. Rev. D 58 (1998) 054001
- Pasquali, Reno, Sarcevic, Phys. Rev. D 59 (1999) 034020
- Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

∗ Updates and recently renewed interest:

- Bhattacharya, Enberg, Reno, et al., JHEP 1506 (2015) 110, JHEP 1611 (2016) 167
- Fedynitch, Riehn, Engel, Gaisser and Stanev, [arXiv:1806.04140] → **this talk**
- Garzelli, Moch, Sigl, JHEP 1510 (2015) 115
- Gauld, Rojo, Rottoli, Sarkar, Talbert, JHEP 1602 (2016) 130
- Halzen, Wille, arXiv:1601.03044, PRD 94 (2016) 014014
- Laha, Brodsky, PRD 96 (2017) 123002
- PROSA Collaboration, JHEP 1705 (2017) 004 → **this talk**
- Benzke, Garzelli, Kniehl, Kramer, Moch, Sigl, JHEP 1712 (2017) 021 → **this talk**
- ......

motivated by new results from VLVνT's and updated theory and new results from LHC

Focus on three independent computations of atmospheric charm

∗ PROSA 2017:

- QCD computation of differential cross-sections for $pp \to c\bar{c}$, including NLO pQCD corrections to the hard-scattering, matched with Parton Shower and non-perturbative hadronization.
- PROSA NLO PDFs, including LHCb constraints on gluon PDFs at low-x/high-energy, used as input.
- *p-Air* from superposition of *pp* (A=14).

∗ GM-VFNS 2017:

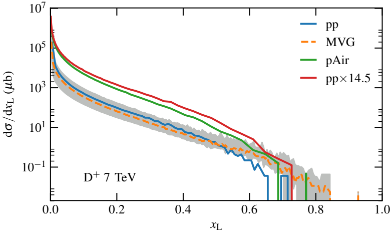
- QCD computation of differential cross-sections for $pp \to D$-meson $+ X$, including NLO pQCD corrections to the hard-scattering, and resummation of NLL logs of (p_T/m). Fragmentation functions describe the transition $g, q, c \to D$-meson.
- CT14NLO PDFs used as input.
- *p-Air* from superposition of *pp* (A=14).

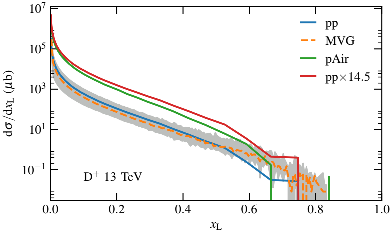
∗ SIBYLL 2.3c 2018:

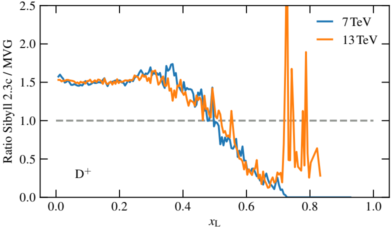
- differential cross-sections for $pp \to D$-meson $+ X$, including a) LO pQCD hard-scattering (minijet), b) global rescaling by a K-factor to mimic higher-order contributions, c) hadronization, d) beam-remnant effects, e) valence-quark effects, f) diffractive contribution.
- *p-Air* according to the Glauber model ($\sigma < \sigma_{superposition}$).

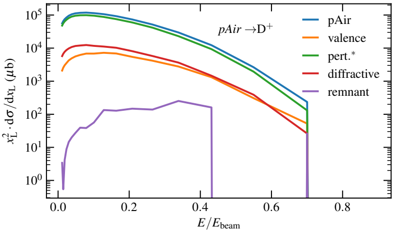
D^{+} hadroproduction: SIBYLL vs PROSA

PRELIMINARY - Low Statistics at large x_L





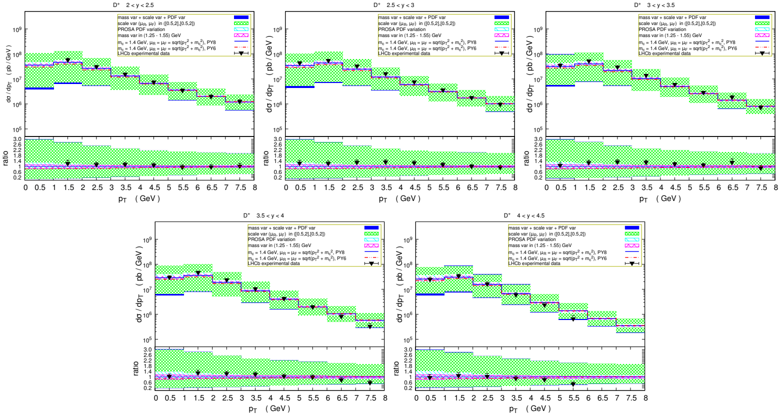




* SIBYLL predictions dominated by pQCD part (especially at small $x_L = E_{D^+}/E_{beam}$)
* PROSA central predictions are smaller than SIBYLL ones for x_L up to 0.5.
* superposition approximation overestimates the SIBYLL $p - Air$ cross-section.

Theory predictions (PROSA) vs. LHCb experimental data

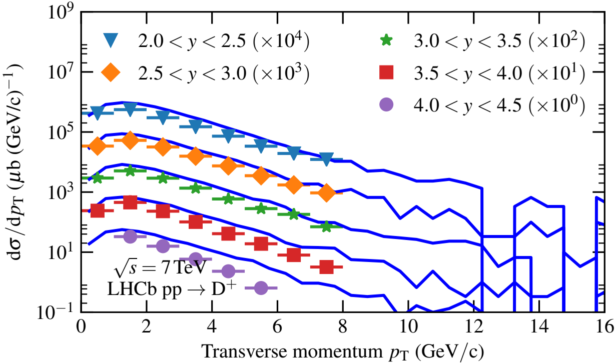
$pp \to D^{\pm} + X$ at $\sqrt{S} = 7$ TeV



* Here we compare theoretical absolute cross-sections to experimental data.
  Ratios of these data at different rapidities have been included in the PROSA PDF fit.
* Big uncertainties on the theoretical predictions, dominated by μ_R and μ_F scale variations.
* LHCb coverage: $2 < |y| < 4.5$, <u>but</u> astrophysical data cover larger $|y|$ as well.....

SIBYLL predictions vs. LHCb experimental data

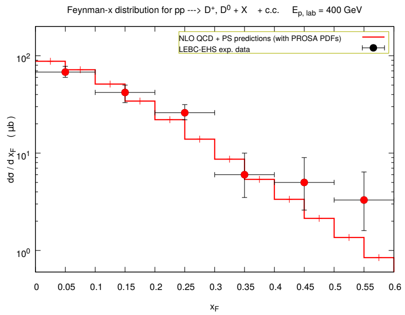
$pp \to D^{\pm} + X$ at $\sqrt{S} = 7$ TeV



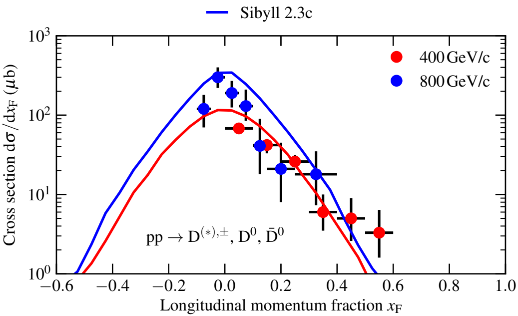
by F. Riehn et al.

* For rapidities $y > 3.5$, D^+ hadroproduction (slightly) overestimated by SIBYLL.
* Is the global K-factor $= \sigma_{NLO}/\sigma_{LO} = 2$ used in the program a too naive approximation and/or the Fragmentation Function/Fraction in $D^{\pm}$ needs better modeling ?

Performances of the PROSA QCD computation of D-meson production w.r.t. LEBC-EHS exp. data



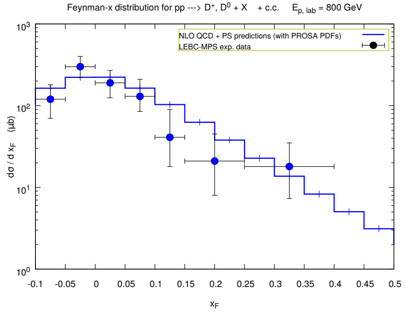
PROSA



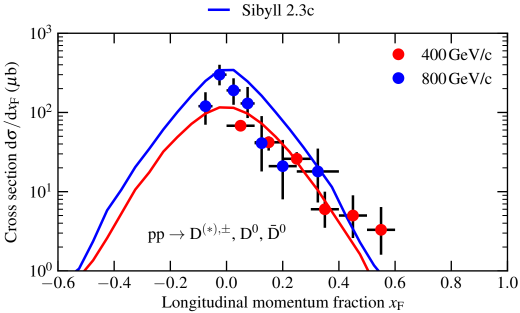
SIBYLL

- ∗ Fixed target experiment with $E_{p,\, lab} = 400$ GeV.
- ∗ Measure relatively large $x_F = p_{z,D}/p_{z,D}^{max}$ (up to $x_F \sim 0.6$).
- ∗ Sizable QCD uncertainty band not included in the plot.

Performances of the PROSA and SIBYLL computation of D-meson production w.r.t. LEBC-MPS exp. data



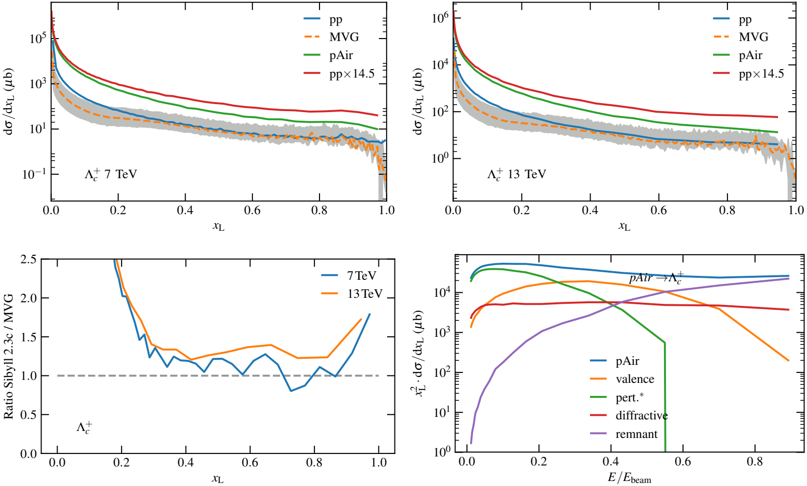
PROSA



SIBYLL

- $*$ Fixed target experiment with $E_{lab} = 800$ GeV.
- $*$ Measure relatively large x_F (up to $x_F \sim 0.4$).
- $*$ Sizable theory QCD uncertainty band not included in the plot.

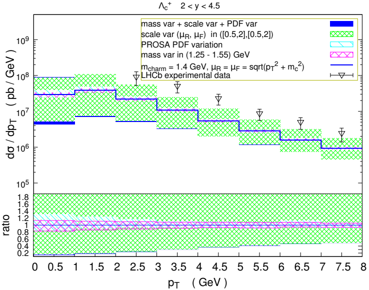
Λ_c^+ hadroproduction: SIBYLL vs PROSA

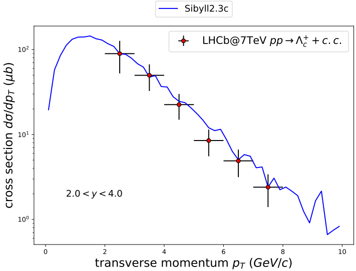


∗ PROSA predictions are smaller than SIBYLL ones, especially at low x_L .

∗ SIBYLL predictions still dominated by pQCD part at $x_L \sim 0.1$.

Λ_c^+ hadroproduction at LHCb: PROSA vs. SIBYLL





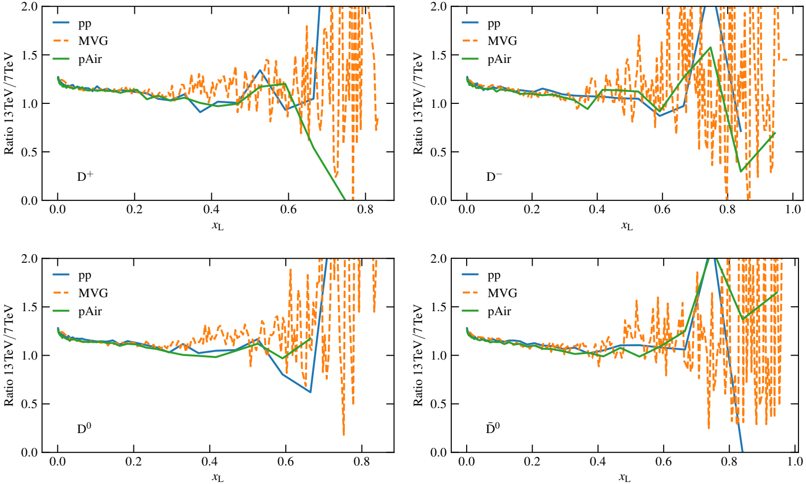
* LHCb experimental data at $\sqrt{s} = 7$ TeV above the PROSA theory bands (differences within 2σ). Better compatibility with SIBYLL.
* Update of branching ratios and fragmentation fractions needed: large uncertainties on these elements ($\sim 25\%$ and 8%).
* What does it happen at $\sqrt{s} = 13$ and 5 TeV ?
* LHCb is measuring Λ_c/D^0 ratios in $p - Pb$ collisions.

⇒ Extension to pp would be important for assessing fragmentation/hadronization mechanisms and for testing the intrinsic charm hypothesis.

A rapidity dependence is to be expected/checked.

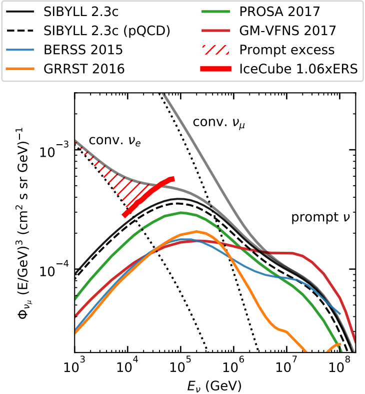
D^+, D^-, D^0, $\bar{D}^0$ hadroproduction: SIBYLL vs PROSA

scaling with energy PRELIMINARY - Low Statistics



All predictions scale the same way with energy
(at least, in the range 7 TeV $< \sqrt{s} <$ 13 TeV) .

Neutrino fluxes: comparison between different predictions



plot by A. Fedynitch

$*$ Theory predictions refer to zenith angle calculation.

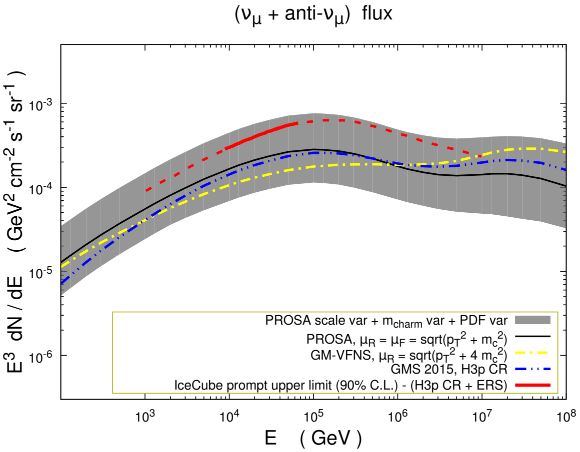
$*$ Assumption: prompt ν_e spectrum similar to prompt ν_μ

$*$ Shapes of PROSA and SIBYLL prompt flux spectra in remarkable agreement: accident ?

$*$ Normalization difference come from the use of different input in the prompt flux evolution equations: Z_{pp}, Z_{hh}, Z_{hl}, σ_{p-Air}

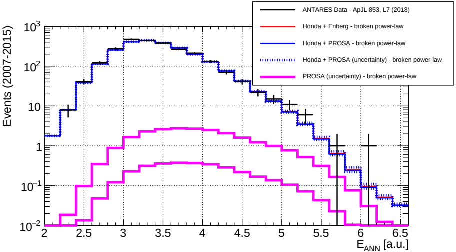
$*$ Shape of the GM-VFNS prompt flux spectrum at high-energy enhanced by the choice of different scales and resummation of the big $log(p_T/m)$

Prompt neutrino QCD uncertainty band

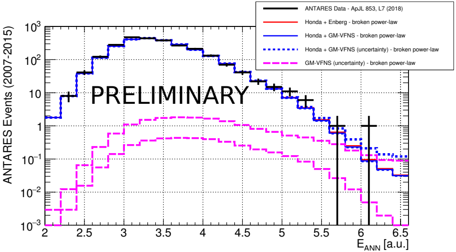


* Different calculations still in agreement within PROSA QCD uncertainty band.
* SIBYLL (not shown) within the PROSA uncertainty band for all E_ν.

Effects of the PROSA and GM-VFNS prompt flux in the analysis of ANTARES High-Energy Track Events



PROSA



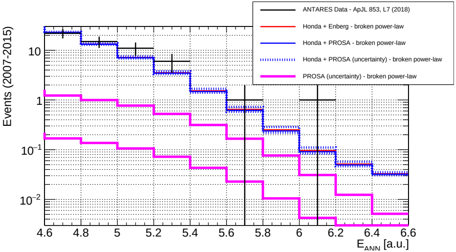
GM-VFNS

courtesy of L. Fusco, ANTARES collaboration

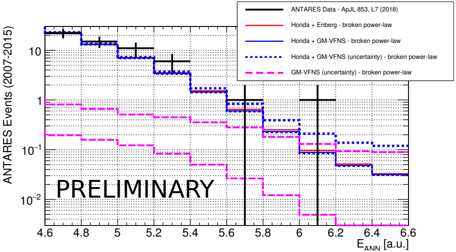
∗ Broken power-law CR primary spectrum assumption.

∗ Only $\sim 1\ \sigma$ excess above the atmospheric only hypothesis:
no striking need of astrophysical neutrinos to explain these data.

Effects of the PROSA and GM-VFNS prompt flux in the analysis of ANTARES High-Energy Track Events



PROSA



GM-VFNS

courtesy of L. Fusco, ANTARES collaboration

∗ Effects of different prompt predictions hardly distinguishable.

∗ Accurate estimate of the uncertainties on conventional flux needed before reaching any firm conclusion on astrophysical neutrinos.

∗ Waiting for more statistics (KM3NeT).

Conclusions

* Different recent **independent** prompt flux computations available: we present some comparison among SIBYLL, PROSA and GM-VFNS.
* Main difference: differential cross-sections for charm hadroproduction, but even other input may differ.
* SIBYLL Monte Carlo (initially designed for EAS) does not reproduce charm data at large x_F / large rapidities, where soft physics effects might play a role, better than PROSA, driven by LHC developments.
* **Compatibility** within the huge QCD uncertainty bands.
* Open question: how to include nuclear effects in QCD computations ?
* Open question: how to assign uncertainties to the computations made by the EAS MC event generators ?
* VLVνT results published so far are not enough to rule out, confirm or prefer any of the most recent predictions
(but they can rule out very extreme cases).
* PROSA and GM-VFNS predictions available at

`http://www.desy.de/~lepflux`