

Prompt neutrino fluxes from atmospheric charm revisited

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[arXiv:1507.01570](https://arxiv.org/abs/1507.01570)

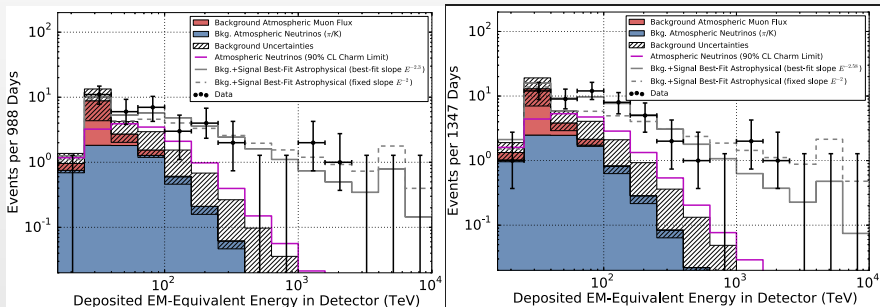
14th International Conference on Topics in Astroparticle and
Underground Physics, Torino, September 7 - 11 th, 2015



The astrophysical issue:

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

- * 2013: 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].
- * 2015: 4-year analysis, with a total of 54 events, gap partially filled.



figures from the presentation of C. Kopper, ICRC2015

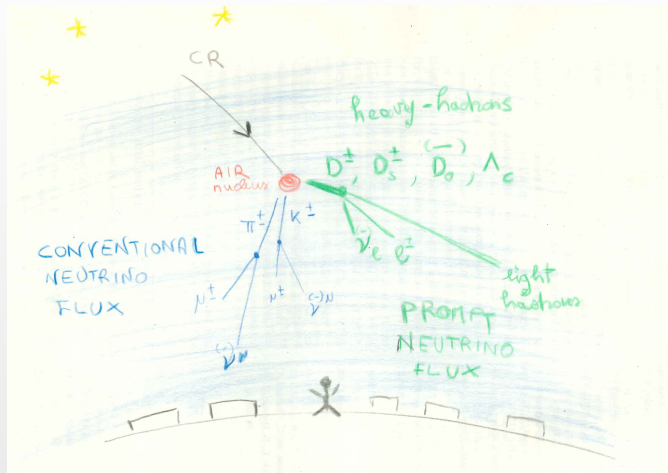
Candidate sources for high-energy ν events considered in literature

- * Astrophysical sources:
AGNs, GRBs, SNRs, Starburst galaxies...
- * Heavy DM decay, DM-DM annihilation
- * Atmospheric leptons

May be a combination of all of them ?

Precise predictions/measurements of **atmospheric ν 's** have to be considered and represent a **"background"** for any astrophysical or BSM hypothesis.

Conventional and Prompt atmospheric ν flux



Cosmic Rays + Atmospheric Nuclei \rightarrow hadrons \rightarrow neutrinos + X

- * Two contributing mechanisms, following two different power-law regimes:
 - conventional ν flux from the decay of π^\pm and K^\pm
 - prompt ν flux from charmed and heavier hadrons (D 's, Λ 's.....)
- * Transition point: still subject of investigation.....

Standard procedure: from cascade equations to Z-moments

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

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

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

– Particle Production:

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

– Particle Decay:

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

Solutions available for $E_j \gg E_{crit,j}$ and for $E_j \ll E_{crit,j}$, respectively, are interpolated geometrically.

Z-moments for heavy hadron production and decay

- * CR + Air interactions producing heavy hadrons (in particular including charm) parameterized in terms of p - p collisions
- * Integration variable: $x_E = E_h/E_p$
- * Z-moments for intermediate **hadron production**:

$$Z_{ph}(E_h) = \int_0^1 \frac{dx_E}{x_E} \frac{\phi_p(E_h/x_E)}{\phi_p(E_h)} \frac{A_{air}}{\sigma_{p-Air}^{tot,inel}(E_h)} \frac{d\sigma_{pp \rightarrow c\bar{c} \rightarrow h+X}(E_h/x_E)}{dx_E}$$

- * These hadrons are then decayed semileptonically, producing $\nu_l + l + X$
- * Integration variable: $x'_E = E_l/E_h$
- * Z-moments for intermediate **hadron decay**:

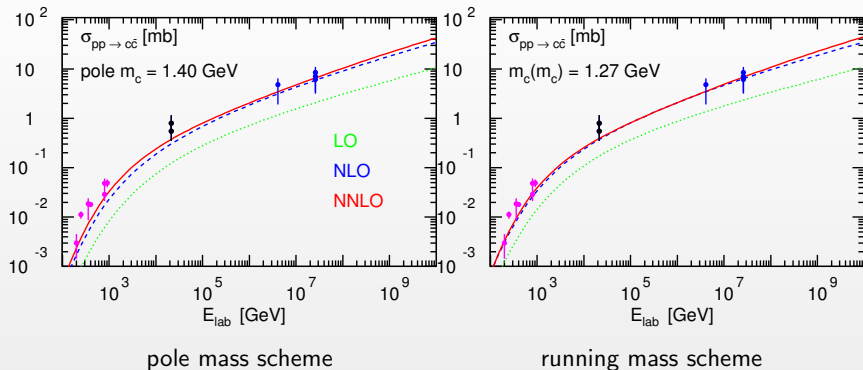
$$Z_{hl}(E_l) = \int_0^{1 - \frac{s_{X,h}^{eff}}{m_h^2}} \frac{dx'_E}{x'_E} \frac{\phi_h(E_l/x'_E)}{\phi_h(E_l)} F_{h \rightarrow l}(x'_E)$$

The QCD core of the Z -moments for prompt fluxes:

$$d\sigma(pp \rightarrow \text{charmed hadrons})/dx_E$$

- * We used QCD in the standard collinear factorization formalism.
- * So far this has been successfully employed not only to explain ATLAS and CMS results (central rapidities), but even many observables at LHCb (mid-forward rapidity).
- * total cross-section for $c\bar{c}$ pair hadroproduction using NNLO QCD radiative corrections in pQCD.
- * differential cross-section for $c\bar{c}$ pair hadroproduction not yet available at NNLO; use of a NLO QCD + Parton Shower + hadronization + decay approach.
- * QCD parameters of computation and uncertainties due to the missing higher orders fixed by looking at the convergence of the perturbative series (LO/NLO/NNLO comparison).

$\sigma(pp \rightarrow c\bar{c})$ at LO, NLO, NNLO QCD



exp data from fixed target exp + colliders (STAR, PHENIX, ALICE, ATLAS, LHCb).

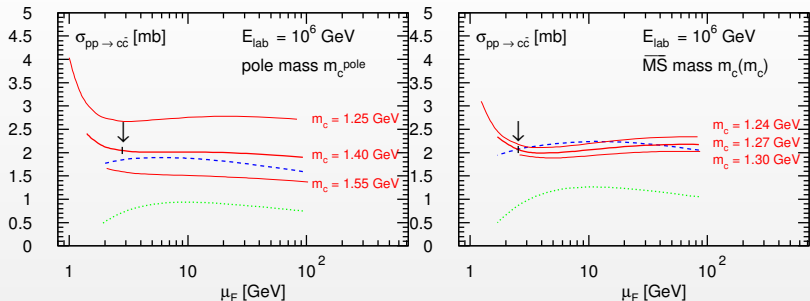
$$(E_{lab} = 10^6 \text{ eV} \sim E_{cm} = 1.37 \text{ TeV})$$

$$(E_{lab} = 10^8 \text{ eV} \sim E_{cm} = 13.7 \text{ TeV})$$

$$(E_{lab} = 10^{10} \text{ eV} \sim E_{cm} = 137 \text{ TeV})$$

* Assumption: pQCD in DGLAP formalism valid on the whole energy range.

$\sigma(pp \rightarrow c\bar{c})$: scale and mass dependence



- * PDG running mass in the \overline{MS} scheme

$$m_c(m_c) = 1.275 \pm 0.025 \text{ GeV}$$

- * Conversion to the pole mass scheme suffers from poor convergence:

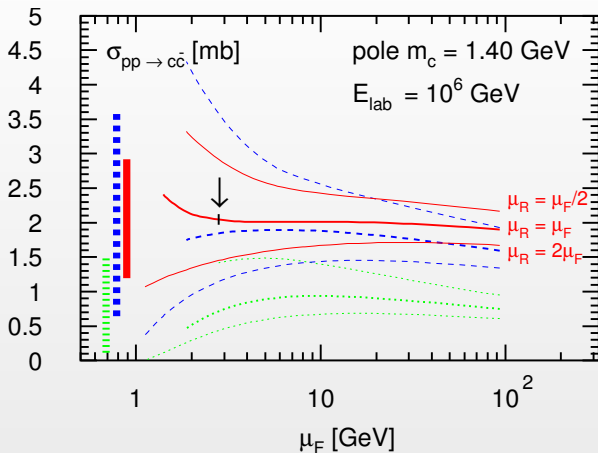
$$m_c(m_c) = 1.27 \rightarrow m_c^{pole} = 1.48 \text{ at 1-loop}$$

$$m_c(m_c) = 1.27 \rightarrow m_c^{pole} = 1.67 \text{ at 2-loop}$$

- * Furthermore, accuracy of the pole mass limited to be of the order of $\mathcal{O}(\Lambda_{QCD})$ by the renormalon ambiguity.

\Rightarrow We fix $m_c^{pole} = 1.4 \pm 0.15 \text{ GeV}$. With this choice the cross-section in the pole mass scheme approximately reproduces that in the running mass scheme.

$\sigma(pp \rightarrow c\bar{c})$: scale dependence

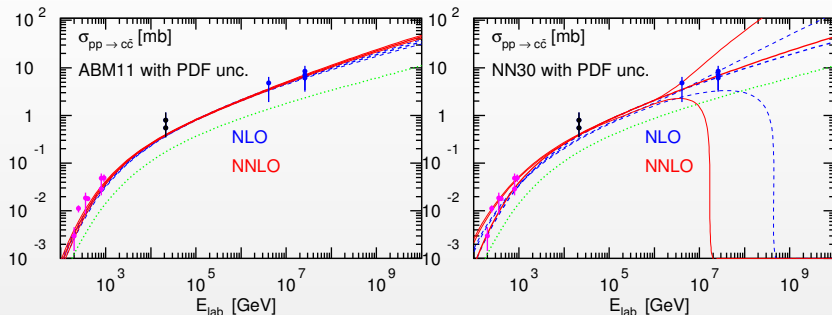


* Minimal sensitivity to radiative corrections is reached at a scale

$$\mu_R \sim \mu_F \sim 2m_{\text{charm}}.$$

* This translates into a dynamical scale $\sqrt{p_{T,\text{charm}}^2 + 4m_{\text{charm}}^2}$ to better catch dynamics in differential distributions.

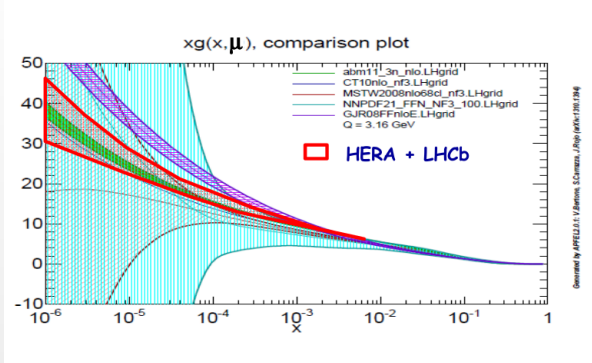
$\sigma(pp \rightarrow c\bar{c})$: PDFs and their behaviour at low Bjorken x



- * Probing higher astrophysical energies allows to probe smaller x region, down to values where no data constrain PDFs yet (at least at present).
- * $f(x, Q^2)$: Q^2 evolution fixed by DGLAP equations, x dependence non-perturbative: ansatz + extraction from experimental data.
- * Different behaviour of different PDF parameterizations:
 - ABM parameterization constrains PDFs at low x ;
 - NNPDF parameterization reflects the absence of constraints from experimental data at low x .

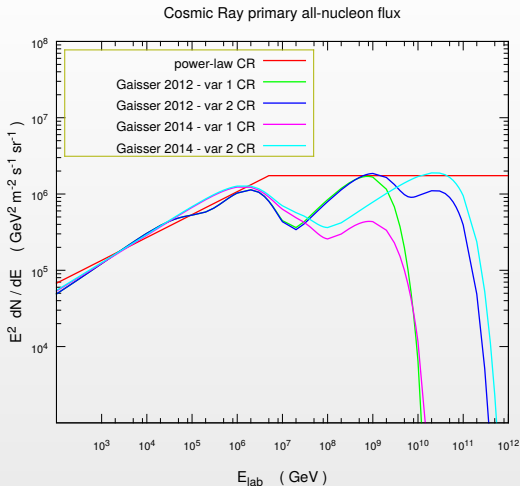
PROSA PDF fit [O. Zenaiev, A. Geiser et al. [arXiv:1503.04585]]

First fit already including some LHCb data (charm and bottom) appeared in arXiv.



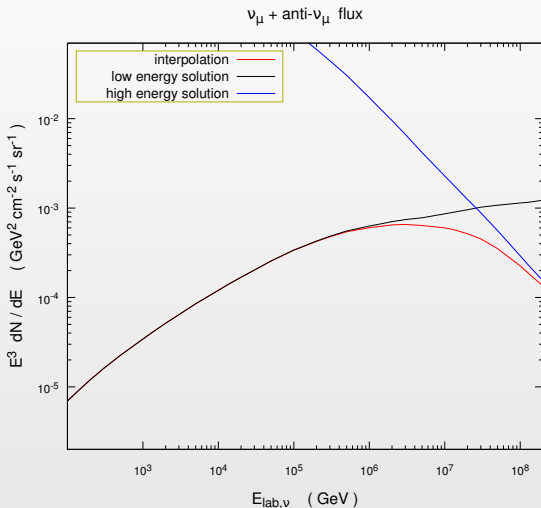
- * ABM PDFs, although non including any info from LHCb, in agreement with PROSA fit → good candidates for ultra-high-energy applications.
- * CT10 PDFs in marginal agreement with PROSA fit.
- * NNPDF PDFs: the largest uncertainties, they are working to try to incorporate PROSA idea in their fit as well (Gauld et al. [arXiv:1506.08025], not yet available in the 3 flavour scheme).

The all nucleon CR spectra: considered hypotheses

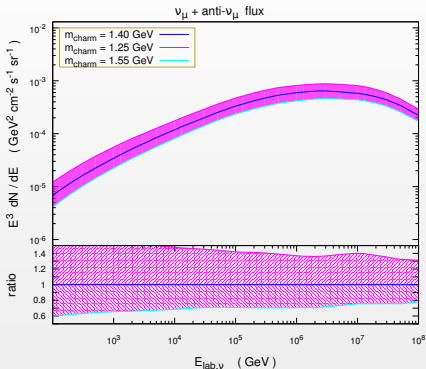
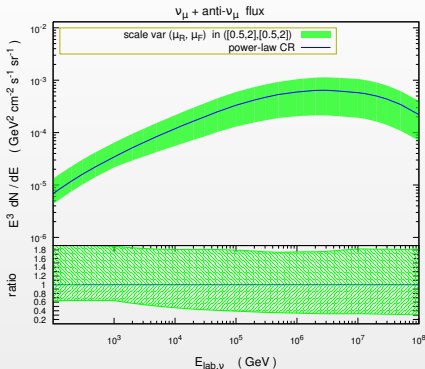


- * All nucleon spectra obtained from all particles ones under different assumptions as for the CR composition at the highest energies.
- * Models with 3 (2 gal + 1 extra-gal) or 4 (2 gal + 2 extra-gal) populations are available.

$\nu_\mu + \bar{\nu}_\mu$ fluxes: interpolation between high energy and low energy solutions - power law CR

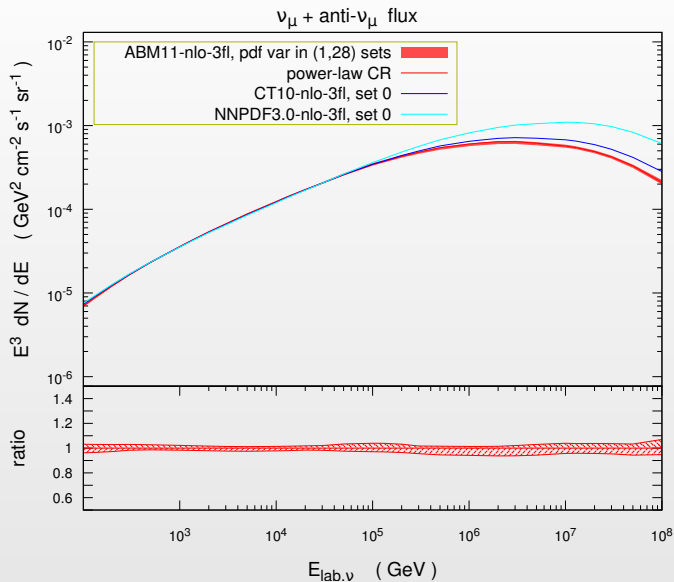


$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: scale and mass variation - power law CR



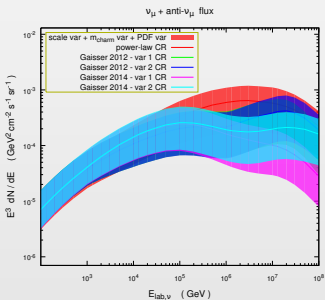
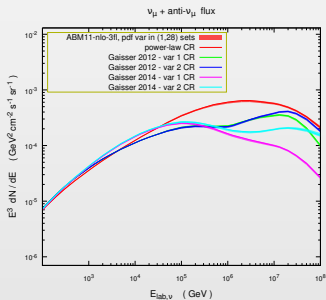
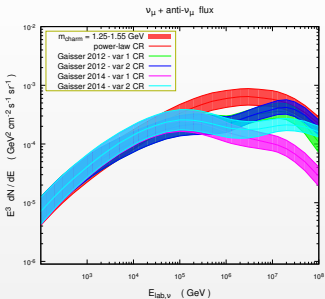
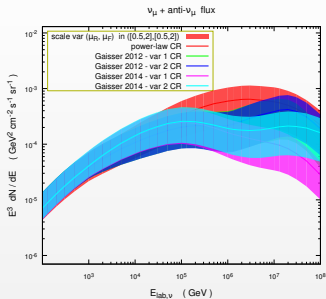
- * scale uncertainty slowly changes with $E_{\text{lab},\nu}$, it accounts for missing higher orders (pQCD).
- * m_{charm} mass uncertainty decreases with increasing $E_{\text{lab},\nu}$, because configurations with smaller $x_E = E_{\text{had}}/E_p$ become possible.

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: PDF variation - power law CR

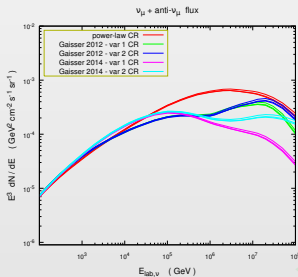
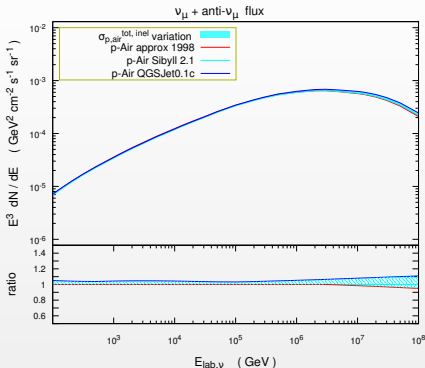
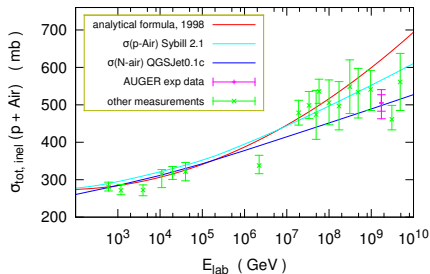


$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: (scale + mass + PDF) variation

summary



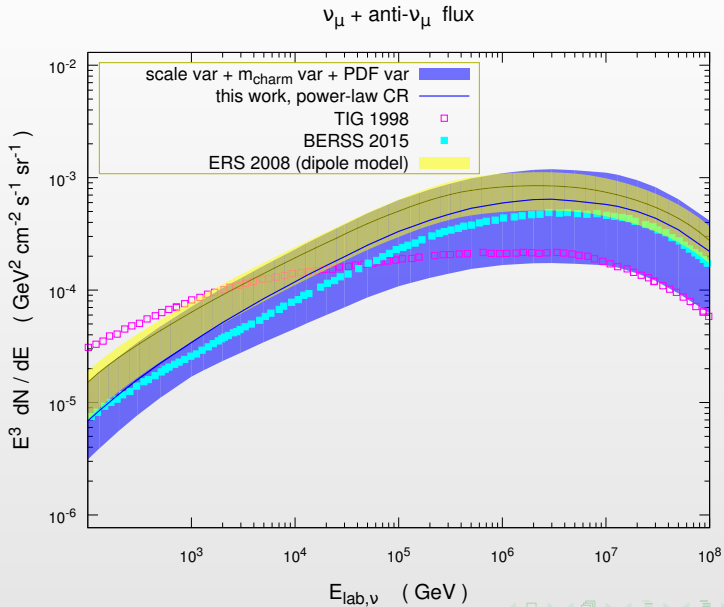
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: variation in the total inelastic σ_{p-Air}



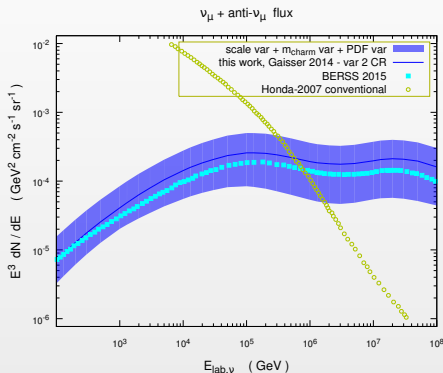
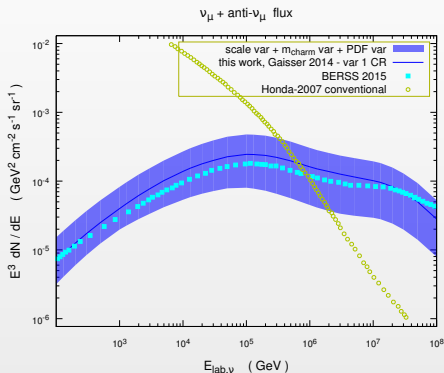
Prompt neutrino flux hadroproduction in the atmosphere: theoretical predictions in literature

- * [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
 - Fedynitch, Gaisser et al. ICRC 2015, TAUP (see talk of T. Gaisser).
 - Garzelli, Moch, Sigl, [arXiv:1507.01570] → **this talk**
 - + other works in preparation.....

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison with other predictions



$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparisons with other predictions and transition region



- * Our predictions point to a transition energy $E_{\text{trans}} = 6_{-3}^{+12} \cdot 10^5$ GeV: is the last E bin where IceCube did not see events just filled by prompt ν ?

Conclusions

- * Prompt lepton fluxes are **background** for astrophysical high-energy ν seen by in-ice or under-water large volume neutrino telescopes.
- * We provide a **new estimate of the prompt ν component**, on the basis of up-to-date QCD theoretical results + recent knowledge in astrophysical CR fluxes.
- * Our **central predictions** are **in between** those recently obtained by pQCD by another group (**BERSS 2015**) and those previously obtained by the same group (**ERS 2008**) with a phenomenological dipole model.
- * We got a **sizable uncertainty band**, larger than those previously (under)estimated, dominated by **QCD renormalization and factorization scale** uncertainties very slowly varying with $E_{lab,\nu}$ energy.
- * At increasing energies above the transition region, the uncertainties on **primary cosmic ray origin (galactic/extragalactic)** and **composition (p /heavy ions)** become increasingly more important (and comparable to QCD uncertainty): more investigation is needed from EAS experiments.
- * A **web page** with our predictions is **under construction**. Alternatively, they can be requested to the authors (**just e-mail us!**)