# Charm hadroproduction in the atmosphere, QCD and Neutrino Astronomy

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mainly on the basis of work in collaboration with S. Moch, G. Sigl

[arXiv:1507.01570]

DESY-TH Seminar, Hamburg, November 23 th, 2015

#### From low-energy Neutrino Astrophysics to high-energy Neutrino Astronomy

\* Neutrinos from the Sun were intercepted by detectors on the Earth already long time ago  $\Rightarrow$  solar  $\nu$  oscillation experiments.

\* A bunch of SuperNova neutrinos (< 30) were also seen, due to SN1987A explosion in the LMC  $\Rightarrow$  study of nuclear processes in stellar core collapse.

\* First idea to use lake or sea water as an extended target for  $\nu$  interactions was suggested by Markov in  $\sim$  1960  $\Rightarrow$  Neutrino Telescopes.

\*  $\nu_l / \bar{\nu}_l + N \rightarrow \ell^{\pm} + X$ , with  $\ell^{\pm}$  emitting Cherenkov light detected by PMTs in the transparent medium:

- time, position and amplitude of the photon signal allow to reconstuct ℓ<sup>±</sup> trajectory;
- total amount of light allows to reconstruct the energy of the event.

\*  $\mu$  path lenght large and  $\mu$  emitted almost collinearly to the original  $\nu_{\mu}$  at high-energy  $\rightarrow \nu$  direction reconstruction.

## Neutrino Astronomy and VLV $\nu$ T

- Observation of high-energy ν's by large volume neutrino telescopes, as a window to better understand the high-energy Universe, in particular the relation between these ν and high-energy Cosmic Rays, and particle acceleration in possible sources like AGNs, GRBs, Starburst galaxies, SNRs.
- This is possible thanks to
  - $\nu$  weak interactions ( $\neq$  Cosmic Rays)
  - $\nu$  propagation not bended by galactic and extra-galactic magnetic fields ( $\neq$  Cosmic Rays)
- under-water neutrino telescopes: Baikal, now under upgrade to GVD/Baikal and ANTARES/NEMO/NESTOR, now working in a joint effort towards the KM3NeT Mediterranean Neutrino Observatory, with an instrumented volume similar to that of IceCube.
- in-ice neutrino telescopes: IceCube 1 km<sup>3</sup> instrumented volume already allowed for the actual detection of a high-energy  $\nu$  flux (last updates, including results from the Northern Sky: 2015).

### **Event topologies @ IceCube**

Events @ IceCube are classified according to the following topologies in the DOMs:

- shower events: produced by  $u_e$
- track events: produced by  $\nu_{\mu}$
- double-bang events: two showers, one from  $\nu_{\tau}$  interaction products (except  $\tau$ ) and the second, displaced, from  $\tau$  decay.
- sizable background due to atmospheric μ: only from the North Emisphere, smaller for horizontal events than for vertical ones.



#### 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  $\sigma$  excess over the expected atmospheric background).
- \* **2014**: 988-day analysis, with a total of **37** events with energy [30 TeV 2 PeV] (5.7  $\sigma$  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  $\sigma$  excess), spectral  $\Gamma = -2.58 \pm 0.25$ .



#### 2014

2015

#### figures from the presentation of C. Kopper, ICRC2015

\* high-energy diffuse flux further testable by KM3Net/ARCA

# Candidate sources for HESE considered so far in literature

1) Astrophysical Sources:

extragalactic: AGNs, GRBs, Starburst galaxies, galaxy clusters... galactic: SNRs, pulsars, microquasars, Fermi bubbles, Galactic halo

- 2) Heavy DM decay, DM-DM annihilation
- 3) Atmospheric leptons

May be a combination of some of the previous ones ?

For sure, precise predictions/measurements of the atmospheric  $\nu$  fluxes have to be taken into account in the analyses, because they represent a "background" for any astrophysical or BSM hypothesis.

#### Atmospheric $\nu$ flux: conventional and prompt components



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

- \* Two contributing mechanisms, following two different power-law regimes:
  - conventional  $\nu$  flux from the decay of  $\pi^\pm$  and  $\textit{K}^\pm$
  - prompt  $\nu$  flux from charmed and heavier hadrons (D's,  $\Lambda_c^{\pm}$ 's....)

# Standard procedure to get 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):

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

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

- Particle Production:

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

- Particle Decay:

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

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

#### Z-moments for 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:

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

- $\ast$  These hadrons are then decayed semileptonically, producing leptons (+ X)
- \* Integration variable:  $x'_E = E_I/E_h$
- \* Z-moments for intermediate hadron decay:

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

# The QCD core of the Z-moments for prompt fluxes: $d\sigma(pp \rightarrow c\bar{c})/dx_E$

 $\ast$  We used QCD in the standard collinear factorization formalism.

$$\sigma_{H_1H_2 \to X} = \sum_{i,j} \int dx_1 dx_2 f_{i/H_1}(x_i, \mu_F^2) f_{j/H_2}(x_j, \mu_F^2) \hat{\sigma}_{ij \to X}(x_i \rho_1, x_j \rho_2; \alpha_5, \mu_R^2, \mu_F^2)$$

where

 $x_i = p_{z,i}/p_{z,H_1} = B$ jorken variable

 $f_{i/H_1}(x_i, \mu_F^2) = PDFs$  (long-distance physics) reabsorb infrared collinear singularities uncancelled within the hard-scattering and are universal (process independent). At a given scale, they are non-perturbative objects, but their evolution with  $\mu_F$  is governed by perturbation theory (DGLAP equation).

 $\hat{\sigma}_{ij \to X}$  = partonic hard-scattering cross-section (short-distance physics), computable by pQCD.

 $\mu_F$  = factorization scale: separates long-distance physics (non-perturbative QCD) from short-distance physics (perturbative QCD).

 $\mu_R$  = renormalization scale: renormalization eliminates UV divergences, by reabsorbing the divergences in renormalized quantities.

# The QCD core of the *Z*-moments for prompt fluxes: $d\sigma(pp \rightarrow charmed \ hadrons)/dx_E$

\* We used QCD in the standard collinear factorization formalism.

\* So far this has been succesfully employed not only to explain ATLAS and CMS results (central pseudorapidities), but even many observables at LHCb (mid-forward pseudorapidities  $2 < \eta < 5$ ).

\* LHCf is able to investigate in very-forward rapidity regions (8.4 <  $\eta$  <  $\infty$ ) the production of  $\gamma$ 's,  $\pi^{0}$ 's, neutrons and light neutral hadrons, no charmed charged particles :-(

\* 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).



Monday, December 9, 13

 $\sigma(pp 
ightarrow c ar{c})$  at LO, NLO, NNLO QCD



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

\* 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  $m_c(m_c) = 1.275 \pm 0.025$  GeV
- \* Conversion to the pole mass scheme suffers from poor convergence:  $m_c(m_c) = 1.27 \text{ GeV} \rightarrow m_c^{pole} = 1.48 \text{ GeV}$  at 1-loop  $m_c(m_c) = 1.27 \text{ GeV} \rightarrow m_c^{pole} = 1.67 \text{ GeV}$  at 2-loop
- \* Furthermore, accuracy of the pole mass limited to be of the order of  $O(\Lambda_{QCD})$  by the renormalon ambiguity.
  - $\Rightarrow$  We fix  $m_c^{pole} = 1.4 \pm 0.15$  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  $\mu_R \sim \mu_F \sim 2 m_{charm} \; .$ 

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

# $\sigma(pp ightarrow car{c})$ : <code>PDFs</code> and their behaviour at low Bjorken <code>x</code>



\* Probing higher astrophysical energies allows to probe smaller x region, down to values where no data constrain PDFs yet (at least at present).

\*  $f(x, \mu_F^2)$ :  $\mu_F^2$  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 in LHAPDF 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  $\rightarrow$  good candidates for ultra-high-energy applications.
- \* CT10 PDFs in marginal agreement with PROSA fit.
- \* **NNPDF** PDFs: at present still the largest uncertainties, at least when looking to the public release available in LHAPDF, they recenly work at incorporating PROSA idea in their fit as well (Gauld et al. [arXiv:1506.08025]).

 $d\sigma(pp \rightarrow c\bar{c} \rightarrow D^0 + X)/dx_E$ : scale and mass uncertainties



\* Here plots for *pp* collisions at  $E_{p, lab} = 10^7$  GeV, shape remains similar at different energies.

#### All-particle Cosmic Ray flux [Todero et al., arXiv:1502.00305]



Experimental data cover lab energies up to  $E_{lab} \sim 10^{20} \text{ eV}$ (although with a suppressed flux, cut-off at  $E_{cm} = 300 - 400 \text{ TeV}$ )

## The all-nucleon CR spectra: considered hypotheses



Cosmic Ray primary all-nucleon flux

- \* 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



 $v_{\mu}$  + anti- $v_{\mu}$  flux

Elab,v (GeV)

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# $( u_{\mu} + ar{ u}_{\mu})$ fluxes: scale and mass variation - power law CR



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

 $(
u_{\mu} + ar{
u}_{\mu})$  fluxes: PDF variation - power law CR



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









summary

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



vu + anti-vu flux



# 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 2015...
  - ullet Garzelli, Moch, Sigl, JHEP 1510 (2015) 115 ightarrow this talk
  - Gauld, Roho, Rottoli, et al. [arXiv:1511.06346]

## $( u_{\mu} + ar{ u}_{\mu})$ fluxes: comparison with other predictions

 $v_{\mu}$  + anti- $v_{\mu}$  flux



Our uncertainty band is an envelope of theoretical uncertainties, not only normalization but even shape of  $\nu$  fluxes can change within the envelope.

### Recent news from other groups



Gauld, Roho, Rottoli et al. [arXiv:1511.06346]:

- methodology very similar to that described in our paper;
- same astrophysical input;
- some QCD input is changed, in particular the PDFs.

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



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

# Expected events at IceCube: prompt $(\nu + \overline{\nu})$ component



\* Gaisser CR fluxes give rise to event distribution steeper with respect to power-law.

\* For 988-day exposure, expected number of prompt events  $N_{prompt}(E > 10^5 \text{ GeV}) = 1.6$  for power-law CR and = 0.8 - 0.9 for Gaisser spectra.

# Expected events at IceCube: , prompt ( $\nu + \bar{\nu}$ ) component



\* Gaisser 2014 - var 1 CR spectrum is considered.

\* Our central prediction is within the BERSS 2015 uncertainty band.

# Expected events at IceCube: prompt, conventional and total ( $\nu + \bar{\nu}$ ) components



\* Gaisser 2014 - var 1 CR spectrum is considered.

\* Prompt flux overcomes conventional flux around  $E_{rec} = 5 \cdot 10^5$  GeV.

# Expected events at IceCube: prompt, conventional and total ( $\nu + \bar{\nu}$ ) components



\* Only uncertainties related to (scale +  $m_{charm}$  + PDF) variation are included; for 988 days,  $N_{prompt}(E > 10^5 \text{ GeV}) = 0.87 + 0.68 - 0.63$ .

### Conclusions

\* Prompt lepton fluxes are background for astrophysical high-energy  $\nu$  seen by in-ice or under-water large volume neutrino telescopes.

\* We provide a new estimate of the prompt  $\nu$  component, on the basis of up-to-date QCD theoretical results + recent knowledge in astrophysical CR fluxes.

 $\ast$  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 most recent predictions is available: http://promptfluxes.desy.de

# What Next ? (from the point of view of people providing theoretical predictions for high-energy lepton fluxes)

\* Further scenarios, on the basis of alternative QCD factorization frameworks, are worth of being explored as well.

\* Comparisons of predictions from different scenarios are valuable.

\* Uncertainties on hadronization and on soft and hard multiple particle interactions deserve probably a dedicated study.

 $\ast$  Role of nuclear media in modifying properties of the microscopic collisions to be better explored.

\* Run-I at LHC provided a boost for QCD theory (e.g. NLO QCD revolution, Standard Model confirmed with high precision) and developments will probably continue (e.g. NNLO predictions for hard-scatterings and PDFs, EW effects, new  $\alpha_S$  determination, decay properties of heavy-hadrons....).

\* Data from Run-I and Run-II at LHC very useful in constraining: PDFs (LHCb, CMS, ATLAS), *pp* inelastic and elastic cross-sections (TOTEM), role of nuclear media in modifying *pp* collisions (ALICE), QCD factorization (CMS, ATLAS, LHCb, LHCf).

\* New *hh* collider at higher energy (e.g. FCC-hh at  $\sqrt{s} = 100 \text{ TeV}$ ) can be necessary as well to test high-energy QCD factorization, low Bjorken-x PDFs, precise determination of heavy-quark masses, New Physics (?). What Next ? (for CR and  $\nu$  Telescope experimentalists)

\* Provide measurements of cosmic-ray composition, as much as possible independent of the theory, in the energy region above  $10^{15}$  -  $10^{16}$  eV.

\* Provide precise measurements of atmospheric lepton fluxes, including the prompt component, independent of the theory.

\* In case the uncertainties on these measurements will be smaller than those from theoretical predictions, use astroparticle measurements to constrain QCD and, more generally, the SM: complementarity with respect to collider experiments (LHC and future colliders....).