Atmospheric Charm, QCD and Neutrino Astronomy

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XIIIth Quark Confinement and the Hadron Spectrum
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In collaboration with M. Benzke, M. V. Garzelli, G. Kramer, S. O. Moch, G. Sigl
See: JHEP 1510 (2015) 115; 1705 (2017) 004; 1712 (2017) 021; work in progress
Outline

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Introduction

- Cosmic ray spectrum
- Features: knee, ankle, cutoff intra-/extra-galactic sources
- Composition: primarily protons at lower energy open question for ultra high energies ($\sim 10^{18}$ eV)
- One type of relevant experiment: measurement of extended air showers (EAS)
Extended Air Showers

- Interaction of primary particle (proton, helium, iron ion... ) with atmosphere
- Ordering parameter: atmospheric depth $X = \int d\vec{r} \rho(\vec{r})$ (top to bottom)
- Separate **hadronic interactions** from propagation through atmosphere
- Primary interaction creates pions, kaons, nucleons, Λ... which then propagate and interact with other nuclei of the atmosphere or decay
- Heavier hadrons ($D...$) are also created, but do not propagate significantly decaying immediately instead
Observables

- Some interesting observables:
- Shower maximum $X_{\text{max}}$
- Number of muons at ground level $R_\mu$
- ...but the air showers also generate a background for UHE neutrinos

Goal

Describe particle fluxes in the atmosphere
Measured or Predicted Neutrino Fluxes

* Detected: solar, Supernovae, atmospheric, geoneutrinos, astrophysical
* Not yet detected with certainty or directly: cosmological CνB, cosmogenic (UHECR + CMB γ’s and UHECR + EBL γ’s)
* Created in the laboratory: reactors, accelerators

figure from U. Katz and C. Spiering Prog. Part. Nucl. Phys. 67 (2012) 651-704
Neutrino Astronomy and VLVνT

- Observation of high-energy $\nu$'s by large volume neutrino telescopes, as a window to better understand the high-energy Universe, in particular the relation between these $\nu$ 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$^3$ instrumented volume already allowed for the actual detection of a high-energy $\nu$ flux (last updates, including results at lower energies: 2017-2018).
Event topologies @ VLVνTs

Events @ VLVνTs are classified according to the following topologies in the Optical Modules:

- **shower** events: produced by $\nu_e$
- **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 $\mu$: only from the Northern Hemisphere, smaller for horizontal events than for vertical ones.
Atmospheric neutrino fluxes

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

* **conventional** neutrino flux:

\[
\begin{align*}
NN & \rightarrow \pi^\pm, K^\pm + X \rightarrow \nu_\mu (\bar{\nu}_\mu) + \mu^\pm + X, \\
NN & \rightarrow K_0^0, K_L^0 + X \rightarrow \pi^\pm + e^{\mp} + \nu_e + X, \quad \pi^\pm + \mu^{\mp} + \nu_\mu + X
\end{align*}
\]

* **prompt** neutrino flux:

\[
\begin{align*}
NN & \rightarrow c, b, \bar{c}, \bar{b} + X \rightarrow \text{heavy-hadron} + X \rightarrow \nu (\bar{\nu}) + X' + X
\end{align*}
\]

\[c\tau_0, \pi^\pm = 780 \text{ cm}, \ c\tau_0, K^\pm = 371 \text{ cm}, \ c\tau_0, D^\pm = 0.031 \text{ cm}\]

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

\[\epsilon^{\pm}_{\pi} < \epsilon^{\pm}_{K} << \epsilon_D \Rightarrow \text{conventional flux is suppressed with respect to prompt one, for energies high enough.}\]
Modeling of air showers

- Several different methods are employed:
- The Heitler-Matthews is purely phenomenological and assumes binary splittings for each particle with a fixed step length
  Matthews ’05
- There are Monte Carlo generators available, which simulate events in detail
  CORSIKA handles the propagation and decay of particles and has integrated different hadronic interaction models
    - SIBYLL
    - QGSJet
    - EPOS
    - and more
- They are mostly based on Regge Field theory (pomeron exchange models the QCD interactions)
- Alternative: Cascade Equations for inclusive fluxes
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; 1611 (2016) 167 [FONLL, CT10 PDFs w/o error band]
  - Fedynitch, Gaisser et al., ICRC 2015, TAUP 2015, VLVνT 2015 [SYBILL 2.3]
  - Garzelli, Moch, Sigl, JHEP 1510 (2015) 115 [NLO FFNS + PYTHIA, ABM11 PFDs]
  - Gauld, Rojo, Rottoli et al., JHEP 1602 (2016) 130 [POWHEG, NNPDF3.0+LHCb PDFs]
  - Halzen, Wille, Phys. Rev. D 94 (2016) 014014 [forward $\bar{D}^0\Lambda_c$]
  - Laha, Brodsky, PRD 96 (2017) 123002 [intrinsic charm]
  - PROSA Collaboration (Garzelli et al.), JHEP 1705 (2017) 004 [NLO FFNS + PYTHIA, PROSA PDFs]
  - Benzke, Garzelli, BK, Kramer, Moch, Sigl, JHEP 1712 (2017) 021 → this talk
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):

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

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

- **Particle Production**:

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

- **Particle Decay**:

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

Solutions available for $E_j >> E_{\text{crit}, j}$ and for $E_j << E_{\text{crit}, j}$, respectively, are interpolated geometrically.
**Z-moments for prompt fluxes: \( Z_{ph} \) definition**

\[
Z_{ph}(E_h) = \int_{E_h}^{+\infty} dE_p' \frac{\phi_p(E_p', 0)}{\phi_p(E_h, 0)} \frac{\lambda_{p,\text{int}}(E_h)}{\lambda_{p,\text{int}}(E_p')} \frac{1}{\sigma_{p-Air}^{\text{tot,inel}}(E_p')} \frac{d\sigma_{p-Air\rightarrow c+X\rightarrow h+X'}(E_p', E_h)}{dE_h}
\]

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

* \( Z_{ph} \) at a fixed \( E_h \), depends on charm production cross-section \( \sigma(pA \rightarrow c + X) \) 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 \( \sigma_{p-Air}^{\text{tot,inel}} \),
  - nuclear treatment of \( pA \) interactions: relation between \( pA \) and \( pp \),
  - theory and input parameters in \( \sigma(pp \rightarrow c + X) \).
Cascade Equations and Differential X-sections

- Use cascade equations to determine flux of particle species of interest at each depth, i.e. the flux of charmed hadrons to determine the neutrino background
- The important theoretical QCD input is encoded in $\frac{d\sigma}{dE}$
- The differential (in final particle energy) cross sections to produce a certain meson or baryon (color neutral) plus X
- In collider physics the usual kinematic variables are **transverse momentum** $p_T$ and **rapidity** $y$
The Cross Section in QCD

- For massless partons $i, j, k$ there exists a well known factorization theorem

$$d\sigma_{A+B \rightarrow H+X} = \sum_{i,j,k} \int dx_1 \, dx_2 \, \frac{dz}{z} \, f_{i/A}(x_1, \mu_F) \, f_{j/B}(x_2, \mu_F)$$

$$\cdot \, d\hat{\sigma}_{i+j \rightarrow k+X}(p_T, y, x_1, x_2, z, \mu_F, \mu_R) \, D_{H/k}(z, \mu_F)$$

Collins, Soper, Sterman ’80s

- with the PDFs $f_{i/A}$, the partonic $x$-section $\hat{\sigma}$ and the fragmentation function (FF) $D_{H/k}$

- IR divergences absorbed into non perturbative PDFs and FF (shape at a certain scale determined by fits to experimental data)

- Allows resummation of large logs $\log(\frac{\mu_F}{p_T})$

- Only valid for large $p_T$!
This picture is applicable when \( p_T \) is much larger than the mass of the produced hadron.

- All partons in the hard part are considered massless (and can appear in the initial hadrons).

\[ \rightarrow \text{ZM-VFN scheme} \]

- But partonic cross section \textbf{diverges} for \( p_T \to 0 \).

- In astroparticle applications also the \textbf{forward region} is relevant.

BK, Kramer, Pötter ’01
This divergence is regularized by the **finite mass** of the final state partons.

The **FFN scheme** uses massive final state quarks (which do not appear in the initial state hadron).

However, no factorization into FF.

Large logs \( \ln \left( \frac{p_T}{m} \right) \) are not resummed → discrepancy with data at high \( p_T \).

Predictions can be improved by convoluting with phenomenological FF.

BK, Kramer, Schienbein, Spiesberger '15
GM-VFNS

- For the application in the cascade equations the complete $p_T$ spectrum is needed.
- Combining the ZM-VFN (high $p_T$) and FFN (small $p_T$) schemes yields the GM-VFN scheme BK, Kramer, Schienbein, Spiesberger ’05.
- Combine massive and massless results and subtract terms to avoid double counting.
- Radiative corrections give rise to IR divergences which cancel in the sum of virtual and real diagrams.
- In the massive calculation there remain finite terms including some containing $\log(m^2/s)$.
- These logs correspond to the $\log(\mu^2/F/s)$ of the massless calculation.
- Also, taking the limit $m \to 0$ of the massive result does not reduce to the massless one.

\[
\lim_{m \to 0} d\sigma_{FFN} = d\sigma_{ZM}(\mu_I = \mu_F = m) + d\sigma_{sub}
\]

→ Subtract these terms in the combination

\[
\frac{d\sigma}{dp_T dy} = \frac{d\sigma_{FFN}}{dp_T dy} - \lim_{m \to 0} \frac{d\sigma_{FFN}}{dp_T dy} + \frac{d\sigma_{ZM}}{dp_T dy}
\]
\[ d\sigma/dp_T \] still diverging for \( p_T \to 0 \), since contributions with heavy quarks in initial state dominate

- Need a prescription to **suppress these ZM contributions** for low \( p_T \)

- Some ad hoc matching functions are suggested in the literature (FONLL)

BK, Kramer, Schienbein, Spiesberger '15
Scale Choices

- Alternatively use the fact, that heavy quark PDFs **vanish** below a certain value of the scale (usually $m_Q$)

$$f_{Q/p}(\mu_I) = 0 \text{ for } \mu_I = \xi_I \sqrt{p_T^2 + m_Q^2} < m_Q$$

$$\Leftrightarrow p_T < m_Q \sqrt{1/\xi_I^2 - 1}$$

- Choose $\xi_I$ appropriately
- Similar reasoning applies to $\xi_F$ in the FFs
- Finally it works!

BK, Kramer, Schienbein, Spiesberger ’15
Implementation

- There are FORTRAN codes available implementing the procedure
- Single differential in $p_T$ (or $y$)

\[ \frac{d\sigma}{dp_T} \text{ (pb / GeV)} \]

\[ p_T \text{ (GeV)} \]

\[ \xi_f = 1.0 \]
\[ \xi_f = 0.5 \]

LHCb data

\[ \mu_F = 1.0 \sqrt{p_T^2 + 4m_c^2} \quad \text{vs} \quad \mu_F = 0.5 \sqrt{p_T^2 + 4m_c^2} \]

- Choose scale parameters for best fit
- Scale uncertainty determined by variation of renormalization scale
- GM-VFNS NLO FFs for charmed hadrons fitted to Belle, CLEO, ALEPH & OPAL data Kneesch, BK, Kramer, Schienbein, ’08
Results

- Inclusive production of $D^+ + D^-$ at 5 TeV LHCb ’13

\[
(D^+ + D^-) \quad 2.0 < y < 2.5
\]

\[
(D^+ + D^-) \quad 2.5 < y < 3.0
\]

\[
(D^+ + D^-) \quad 3.0 < y < 3.5
\]

\[
(D^+ + D^-) \quad 3.5 < y < 4.0
\]
Results

- Inclusive production of $D^+ + D^-$ at 7 TeV LHCb ’13
Results

- Inclusive production of $D^+ + D^-$ at 13 TeV LHCb '13

![Graphs showing the production of $D^+ + D^-$ at different $y$ ranges and scale variables.](image)
Comparison of GM-VFNS predictions on prompt open D-mesons with ALICE experimental data

exp. data from ALICE collab., EPJC 77 (2017) 550

* Same GM-VFNS settings as used for the comparison with LHCb data.
* ALICE probes more central rapidity \(|y| < 0.5\) w.r.t. LHCb \(2 < y < 4.5\).
* ALICE capable for the first time to measure \(p_T\) in the bin \([0,1] \text{ GeV}\): GM-VFNS in good agreement with the experiment for \(p_T \rightarrow 0\).
Implementation

- Single differential in $p_T$ (or $y$)
  - for astroparticle applications we need to substitute $p_T$ and $y$ with $E$ (or $x_E = E/E_p$) and $\theta$ in the laboratory frame

- Phase space properties $m \neq 0$:

  ![Phase space diagram](image)

- Furthermore, boost into lab frame
Results useful for prompt neutrino fluxes

- Nice agreement with LHC Monte Carlo (PYTHIA) at low CM energies

Some discrepancies at high hadron energies, due to fragmentation

The comparison between the GM-VFNS and the FFNS demonstrates the effect of the log resummation and of the FF
Prompt Neutrino Fluxes

- Insert in cascade equations (use different primary fluxes)

- Extended energy range
- Effect of different CR primary flux composition (biggest uncertainties at largest energies)
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.
Prompt Neutrino Fluxes

- Comparison to other calculations

![Comparison to other calculations](image1)

- Left: comparison with other predictions based on perturbative QCD,
  Right: other phenomenological models

- Even though the predictions by different authors look similar, it might be accidental, due to the use of different astrophysical input
(ν_μ + ¯ν_μ) fluxes: transition region

∗ Honda-2007 conventional flux reweighted with respect to a more modern CR primary spectrum (H3a).

∗ Our predictions point to a transition energy in the interval

\( E_\nu = 10^5 - 10^6 \) GeV: is the bin where IceCube has not seen any event

\( E_{DEP} = (6 \cdot 10^5 - 10^6 \) GeV) filled just by prompt \( \nu \) ?

∗ central GM-VFNS, PROSA and GMS flux predictions all yield to a very similar transition point

\( E_\nu \sim (6 - 7) \cdot 10^5 \) GeV.
Zenith angle dependence of the GM-VFNS prompt ($\nu_\mu + \bar{\nu}_\mu$) flux

Flux computed with H3a primary CR spectrum

* prompt fluxes are not isotropic (although this approximation is good at low energies).
* At high energies, they increase towards the horizon.
Prompt neutrino fluxes:
Theoretical predictions from [arXiv:1705.10386] vs. IceCube upper limits

* IceCube results give clear indication that the CT14nlo gluon PDF uncertainties at low $x$'s (see PDF error sets 53-56) are too large!
HESE analysis:

Theoretical predictions on neutrino events vs. IceCube experimental data

* GM-VFNS 2017 predictions vs PROSA 2016 predictions vs IceCube exp. data
* GM-VFNS 2017 predictions dominated by CT14nlo PDF uncertainties.
* \(\mu\)-background contribution (relevant in the first four bins) is missing in the theory predictions but present in the experimental data.
Effects of the GM-VFNS prompt flux in the analysis of ANTARES High-Energy Track Events

courtesy of the 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 GM-VFNS prompt flux in the analysis of ANTARES High-Energy Track Events

* 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).

courtesy of the ANTARES collaboration
How do global PDF fits (CT14nlo), not including LHCb data, behave?  \( pp \rightarrow D^\pm + X \) at LHCb at 13 TeV

* GM-VFNS predictions using CT14nlo PDFs, constrained only down to \( x \sim 10^{-4} \)

* Large PDF uncertainties, increasing at low \( p_T \) / large \( y \)
gluon PDF: comparison between different PDF fits

* PDF non-perturbative dependence on $x$: fit to experimental data

* The higher are $E_{CM}$ and the most forward is the scattering ($y_H$ large), the lower are the $x$ values probed.
The NNPDF3.0 + LHCb PDF fit
(via Bayesian reweighting of the NNPDF3.0 fit.)

\[ xg(x, Q^2 = 4 \text{ GeV}^2) = 4 \text{ GeV}^2 x, Q \]

* their first fit includes 7 TeV open charm data [arXiv:1511.06346]

* most recent fit includes 5, 7, 13 TeV open charm data, as well as 13/7, 13/5 ratios [arXiv:1610.09373 v2]
  ⇒ new version after last LHCb data correction!

* still space for improvement.....
The NNPDF3.0 + LHCb PDF fit and GM-VFNS prompt neutrino fluxes

The gluon PDF for $Q = 1.7$ GeV.

differential cross-section $d\sigma/dx_E$ for $pp \rightarrow D^0 + X$ for $p$ with $E_{lab} = 10^5$ GeV

GM-VFNS $(\nu\mu + \antineutral\nu\mu)$ flux

Too negative PDFs produce negative (i.e. unphysical) differential cross-sections!

from [arXiv:1705.10386]
**Prompt neutrino fluxes and nuclear PDFs**

![Graph showing GM-VFNS flux, power-law CR, BEJKRSS 2016 - pQCD, BEJKRSS 2016 - dipole]

* Bhattacharya et al. [JHEP 1611 (2016) 167] produced pQCD predictions by using nuclear PDFs, instead of nucleon PDFs + superposition model → their prompt fluxes look suppressed with respect to their older ones, which adopted nucleon PDFs.

* However, still compatible with our GM-VFNS predictions on the basis of nucleon PDFs + superposition model, if one takes into account that present uncertainties on nuclear PDF fits are underestimated.

* Our predictions are also compatible with those of 3 different dipole models (Soyez, AAMQS, Block).
Summary

- Information about cosmic rays can be obtained by observing the evolution of extended air showers.
- Theoretical modeling can be done by employing cascade equations.
- This requires the calculation of the differential cross section in $E$.
- For massless partons the cross section diverges for small $p_T$.
- The GM-VNF scheme with an appropriate scale choice allows calculation of massive particles fluxes ($m_H > \Lambda_{QCD}$) in the whole $p_T$ range.
- Open questions concerning the non-perturbative part and behavior for very small $p_T$, as well a high CM energies in the lab frame.
First evidence of a HE $\nu$ and $\gamma$ source: the TXS 0506+056 blazar and Multimessenger Astronomy

* On 22 September 2017 IceCube detected a $\sim 290$ TeV $\nu_\mu$ track event (IceCube-170922A alert) from a direction consistent with the flaring $\gamma$-ray BL-LAC blazar TXS 0506+056, observed by Fermi-LAT under IceCube alert. The significance of the spatial and temporal coincidence of the two observations was estimated at $3 \sigma$. MAGIC follow-up observations on 28 September reported a significant VHE (up to 400 GeV) $\gamma$-ray excess signal.

* On the other hand, the online follow-up and the time-dependent analysis by the ANTARES collaboration yield no event related to that source [arXiv:1807.04309].

IceCube + Fermi-LAT

IceCube + MAGIC

* From Science 361 (2018) 146
Further studies of $\nu$ emission from TXS 0506+056

Further IceCube analyses show an enhanced $\nu$ emission from the same spatial region w.r.t. to the atmospheric background, especially in a previous period in 2015:

![Graph showing log_10 p vs Time](image1)

from IceCube collaboration, Science 361 (2018) 147-151

On the other hand, the time-integrated analysis by the ANTARES collaboration observed 13 track and 1 shower candidate events within an angular distance of 5 degrees from the considered source, of which 1 track event (on 12/12/2013) lies within 1 degree. No candidates were observed in 2015.

![Map showing Nhits and declination](image2)

from ANTARES Collaboration, [arXiv:1807.04309]
Thank you for your attention!