Atmospheric Charm, QCD and Neutrino Astronomy

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XIIIth Quark Confinement and the Hadron Spectrum
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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 ($\sim 10^{18} \text{ eV}$)
- 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
  \[ X = \int d\vec{r} \rho(\vec{r}) \text{ (top to bottom)} \]
- Separate **hadronic interactions** from propagation through atmosphere
- Primary interaction creates pions, kaons, nucleons, \( \Lambda \ldots \) which then propagate and interact with other nuclei of the atmosphere or decay
- Heavier hadrons (\( D \ldots \)) 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 $C\nu B$, cosmogenic $(UHECR + CMB \gamma$’s and $UHECR + EBL \gamma$’s)
* Created in the laboratory: reactors, accelerators

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:

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

* prompt neutrino flux:

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

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

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:
  - Battistoni, Bloise, Forti et al., Astropart. Phys. 4 (1996) 351

* 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, VLVT 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 \[\text{[review in Gaisser, 1990; Lipari, 1993]}\]

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 $E_j \gg E_{\text{crit},j}$ and for $E_j \ll E_{\text{crit},j}$, 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 $\log\left(\frac{\mu_F}{p_T}\right)$

- 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).

$\rightarrow$ **ZM-VFN scheme**

- But partonic cross section diverges for $p_T \rightarrow 0$.

- In astroparticle applications also the **forward region** is relevant.
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 $\rightarrow$ discrepancy with data at high $p_T$
- Predictions can be improved by convoluting with phenomenological FF

BK, Kramer, Schienbein, Spiesberger '15
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 $\log(\mu_I/F/s)$ of the massless calculation

Also, taking the limit $m \to 0$ of the massive result does not reduce to the massless one (dimreg and finite mass regulators yield different finite terms)

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

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

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

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

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 $y$)

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

- $\mu_F = 1.0 \sqrt{p_T^2 + 4m_c^2}$ vs $\mu_F = 0.5 \sqrt{p_T^2 + 4m_c^2}$
- 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
Results

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

![Graphs showing the inclusive production of $D^+ + D^-$ at 7 TeV LHCb '13 with different scale factors and momentum ranges.](image-url)
Results

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

![Graphs showing the inclusive production of $D^+ + D^-$ at 13 TeV LHCb '13 for different ranges of $y$.](image-url)
Comparison of GM-VFNS predictions on prompt open D-mesons with ALICE experimental data

\[
\frac{d^2 \sigma}{d p_T dy} \ (\text{pb c}/\text{GeV}) \\
\text{p p ----> prompt } D^0 + X, \ |y| < 0.5, \ \text{sqrt}(s) = 7 \text{ TeV}
\]

\[
\text{scale uncertainty} \quad \text{GM-VFNS central} \quad \text{ALICE exp. data}
\]

\[
\frac{d^2 \sigma}{d p_T dy} \ (\text{pb c}/\text{GeV}) \\
\text{p p ----> prompt } D^+ + X, \ |y| < 0.5, \ \text{sqrt}(s) = 7 \text{ TeV}
\]

\[
\text{scale uncertainty} \quad \text{GM-VFNS central} \quad \text{ALICE exp. data}
\]

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 \([0,1]\) GeV: GM-VFNS in good agreement with the experiment for \(p_T \rightarrow 0\).
Implementation

- Single differential in $p_T$ (or $y$)
  $\rightarrow$ 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 $m \neq 0$:

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)

![GM-VFNS (ν_µ + anti-ν_µ) flux, using different CR primary fluxes](image)

- 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**

![Graph showing comparison of neutrino flux predictions](image)

- **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
\((\nu_\mu + \bar{\nu}_\mu)\) 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 $\left(\nu_\mu + \bar{\nu}_\mu\right)$ 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

![Graph showing the analysis of ANTARES Events (2007-2015)](image)

* 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 $y$. 
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.)

* 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

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

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

* 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 as 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].
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 for different years and regions.](image)

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 hits in cascade-like and track-like events.](image)

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