Atmospheric Charm, QCD and Neutrino Astronomy

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

Excellence Cluster Universe

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

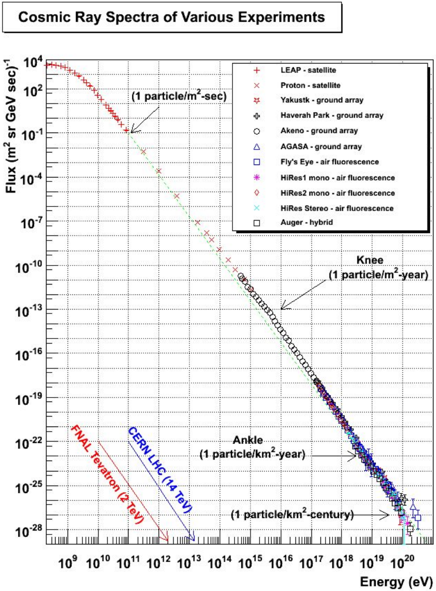
Outline

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)



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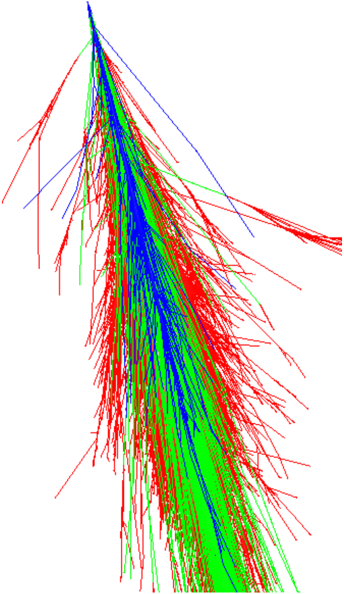
Extended Air Showers



- 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 $X_{\max}$
- Number of muons at ground level R_μ
- ... but the air showers also generate a background for UHE neutrinos

Goal

Describe particle fluxes in the atmosphere

Measured or Predicted Neutrino Fluxes

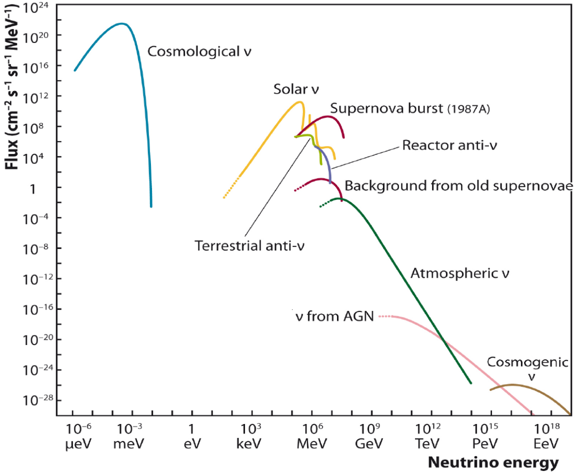


figure from U. Katz and C. Spiering Prog. Part. Nucl. Phys. 67 (2012) 651-704

* 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

Neutrino Astronomy and VLVνT

- 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
  - ν weak interactions ($\neq$ Cosmic Rays)
  - ν propagation not bended by galactic and extra-galactic magnetic fields ($\neq$ Cosmic Rays)

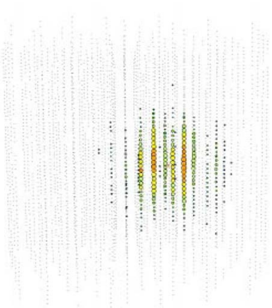
- under-water neutrino telescopes: Baikal, now under upgrade to GVD/Baikal and ANTARES/NEMO/NESTOR, now working in a joint effort towards the KM3NeT Mediterranean Neutrino Observatory, with an instrumented volume similar to that of IceCube.

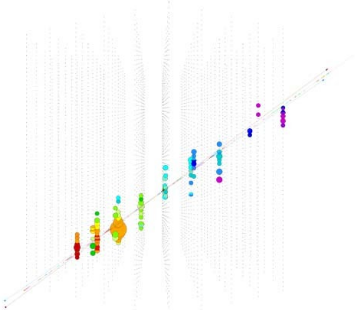
- in-ice neutrino telescopes: IceCube 1 km^3 instrumented volume already allowed for the actual detection of a high-energy ν flux (last updates, including results at lower energies: 2017-2018).

Event topologies @ VLVνTs

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

- shower events: produced by ν_e
- track events: produced by ν_μ
- double-bang events: two showers, one from ν_τ interaction products (except τ) and the second, displaced, from τ decay.
- sizable background due to atmospheric μ: 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 ?

∗ <u>conventional</u> neutrino flux:

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

∗ <u>prompt</u> 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.

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):

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

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 $\sigma_{p-Air}^{tot,inel}$,
  - nuclear treatment of pA interactions: relation between pA and pp,
  - theory and input parameters in $\sigma(pp \to c + X)$.

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 in 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

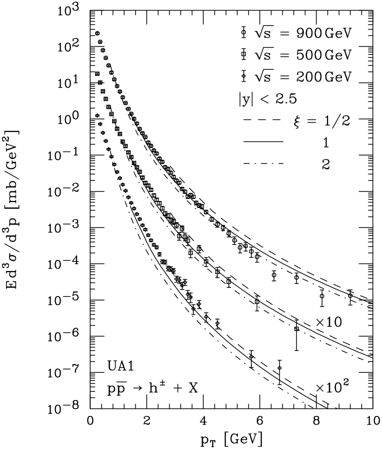
- For massless partons i, j, k there exists a well known **factorization theorem**

$$d\sigma_{A+B\to H+X} = \sum_{i,j,k} \int dx_1\, dx_2\, \frac{dz}{z}\, f_{i/A}(x_1,\mu_F)\, f_{j/B}(x_2,\mu_F) \cdot d\hat{\sigma}_{i+j\to k+X}(p_T, y, x_1, x_2, z, \mu_F, \mu_R)\, D_{H/k}(z,\mu_F)$$

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!

ZM-VFNS



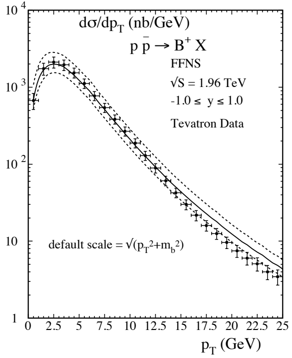
BK, Kramer, Pötter '01

- 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

FFN

- 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 $\ln(p_T/m)$ 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

GM-VFNS

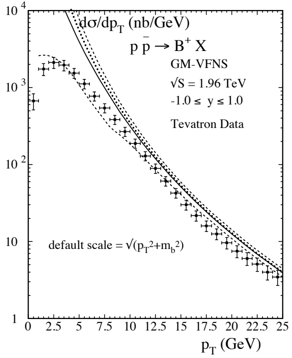
- For the application in the cascade equations the complete p_T spectrum is needed
- Combining the ZM-VFN (high p_T) and FFN (small p_T) schemes yields the GM-VFN scheme BK, Kramer, Schienbein, Spiesberger '05
- Combine massive and massless results and subtract terms to avoid double counting
- Radiative 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 $\log(\mu_{I/F}^2/s)$ 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)

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

$\to$ Subtract these terms in the combination

$$\frac{d\sigma}{dp_T\,dy} = \frac{d\sigma_{\mathrm{FFN}}}{dp_T\,dy} - \lim_{m\to 0}\frac{d\sigma_{\mathrm{FFN}}}{dp_T\,dy} + \frac{d\sigma_{\mathrm{ZM}}}{dp_T\,dy}$$

GM-VFNS



- $d\sigma/dp_T$ 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)

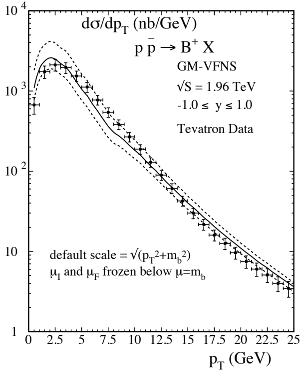
BK, Kramer, Schienbein, Spiesberger '15

Scale Choices

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

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

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

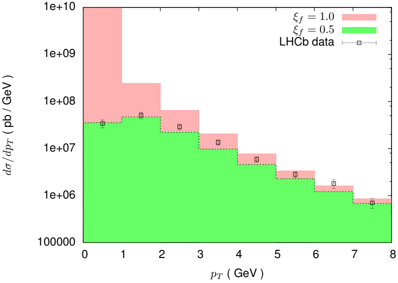


- Choose ξ_I appropriately
- Similar reasoning applies to ξ_F in the FFs
- Finally it works!

BK, Kramer, Schienbein, Spiesberger '15

Implementation

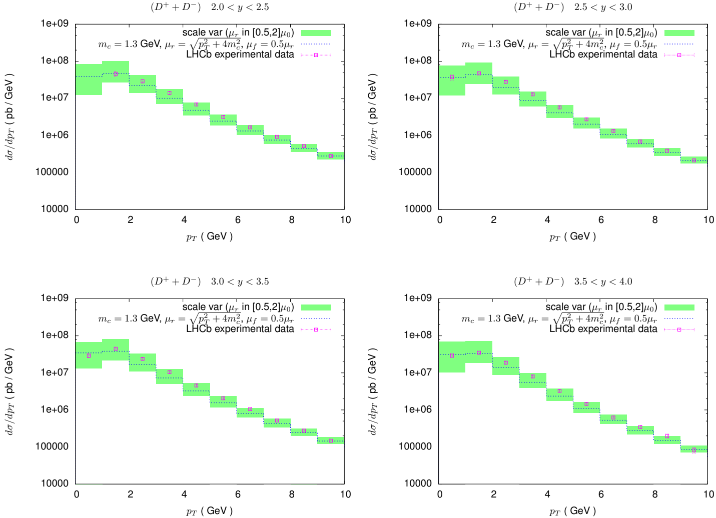
- There are FORTRAN codes available implementing the procedure
- Single differential in p_T (or y)



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

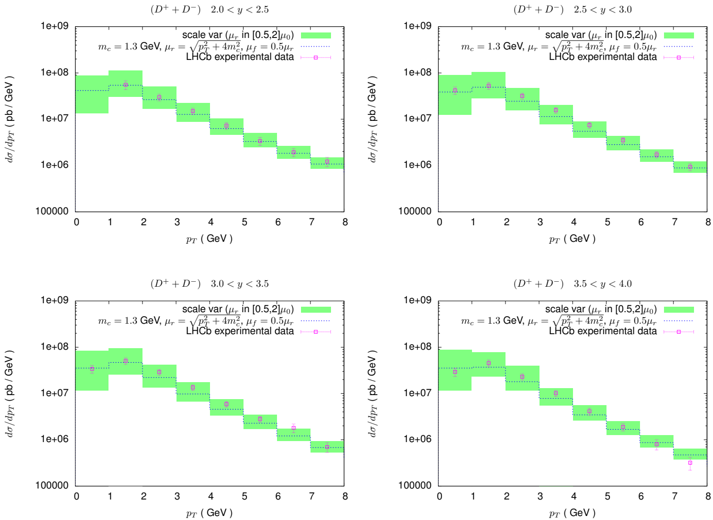
Results

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



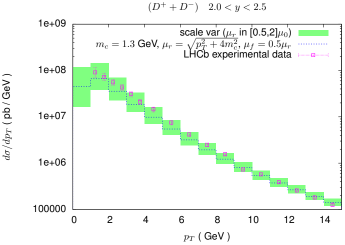
Results

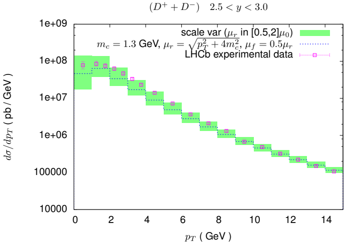
- Inclusive production of $D^+ + D^-$ at 7 TeV LHCb '13

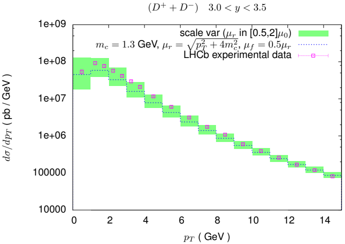


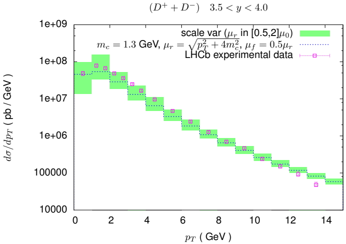
Results

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

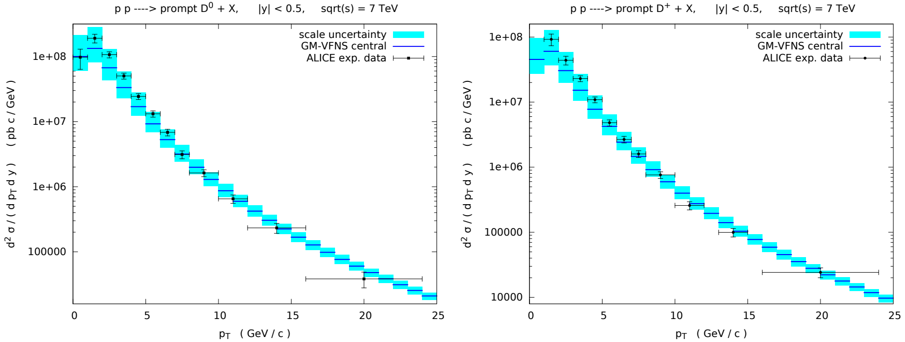








Comparison of GM-VFNS predictions on prompt open D-mesons with ALICE experimental data



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

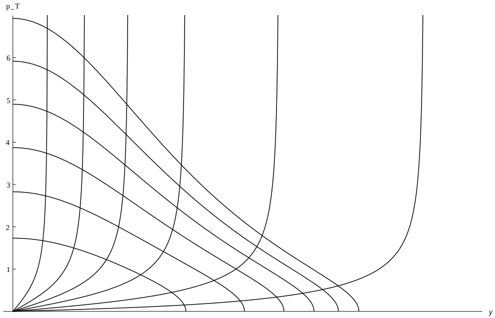
∗ Same GM-VFNS settings as used for the comparison with LHCb data.

∗ 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] GeV: GM-VFNS in good agreement with the experiment for $p_T \to 0$.

Implementation

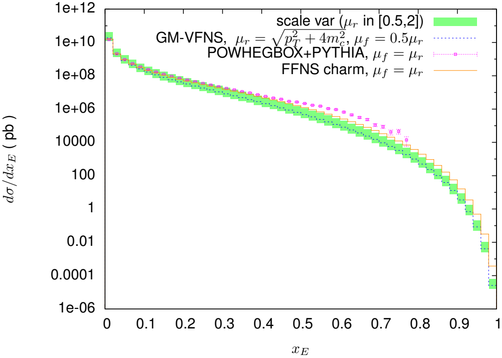
- Single differential in p_T (or y)
  $\rightarrow$ for astroparticle applications we need to subsitute p_T and y with E (or $x_E = E/E_p$) and θ in the laboratory frame
- Phase space properties $m \neq 0$:



- Furthermore, boost into lab frame

Results useful for prompt neutrino fluxes

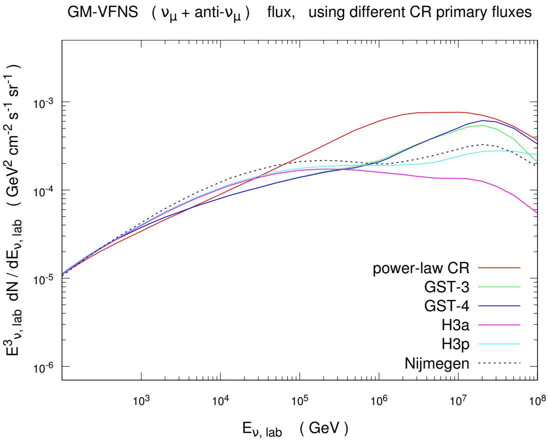
- Nice agreement with LHC Monte Carlo (PYTHIA) at low CM energies



- 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

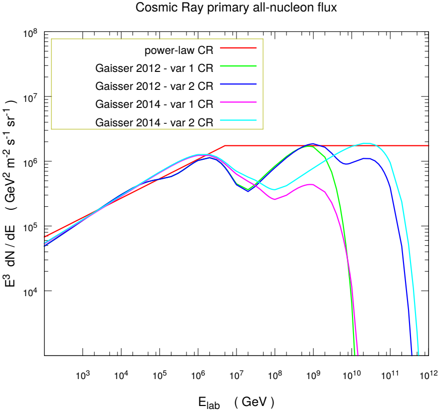
Prompt Neutrino Fluxes

- Insert in cascade equations (use different primary fluxes)



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

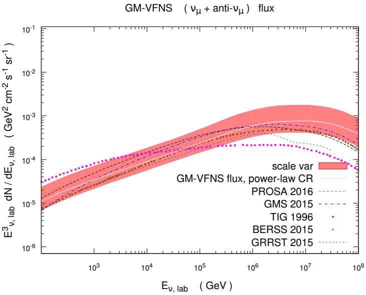
The all-nucleon CR spectra: considered hypotheses

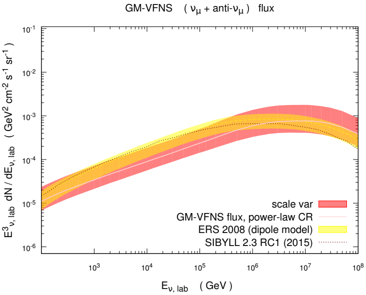


* All-nucleon spectra obtained from all-particles ones under different assumptions as for the CR composition at the highest energies.
* Models with 3 (2 gal + 1 extra-gal) or 4 (2 gal + 2 extra-gal) populations are available.

Prompt Neutrino Fluxes

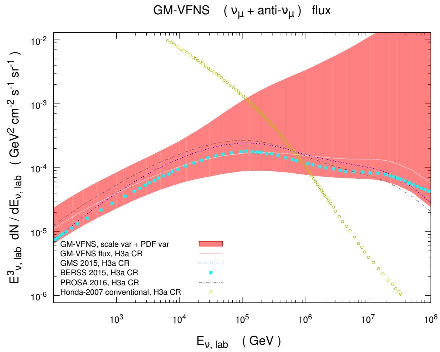
- Comparison to other calculations





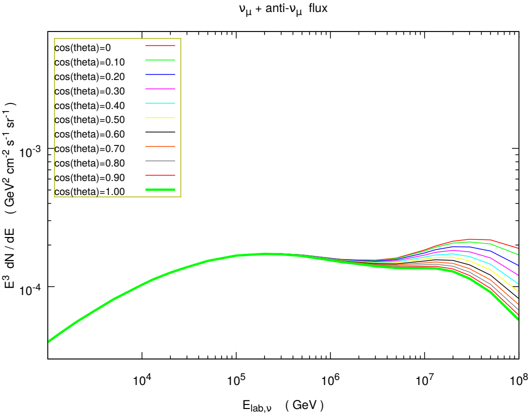
- Left: comparison with other predictions based on perturbative QCD, Right: other phenomenological models
- Even though the predictions by different authors look similar, it might be accidental, due to the use of different astrophysical input

$(\nu_\mu + \bar{\nu}_\mu)$ 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 ν ?
* 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

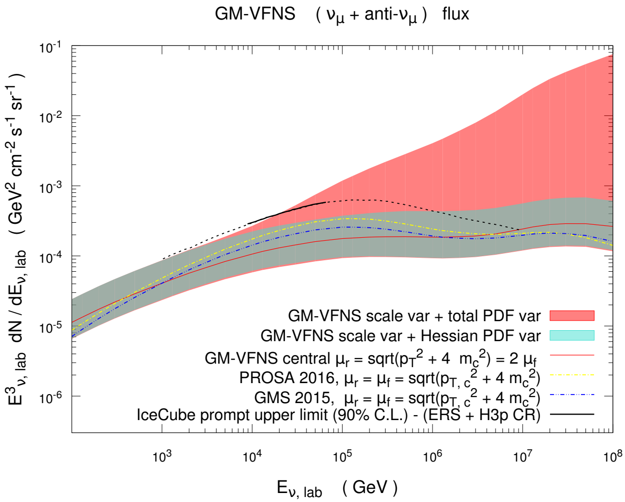


Flux computed with H3a primary CR spectrum

* prompt fluxes are not isotropic (although this approximation is good at low energies).
* At high energies, they increase towards the horizon.

Prompt neutrino fluxes:

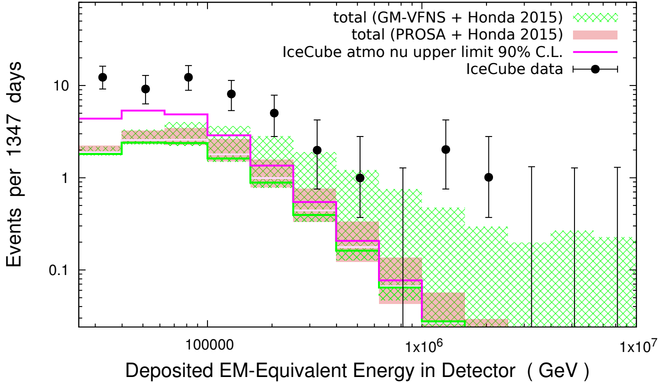
Theoretical predictions from [arXiv:1705.10386] vs. IceCube upper limits



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

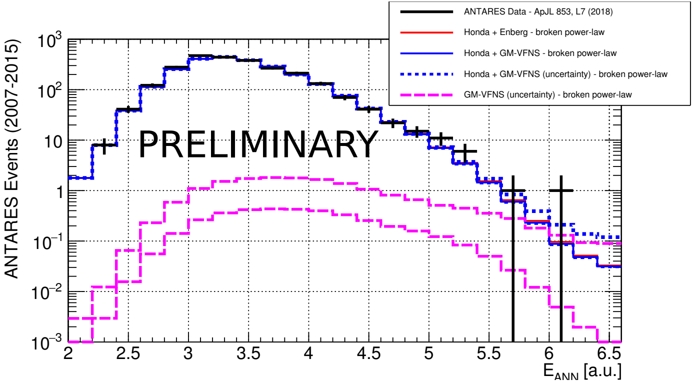
HESE analysis:

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.
* μ-background contribution (relevant in the first four bins) is missing in the theory predictions but present in the experimental data.

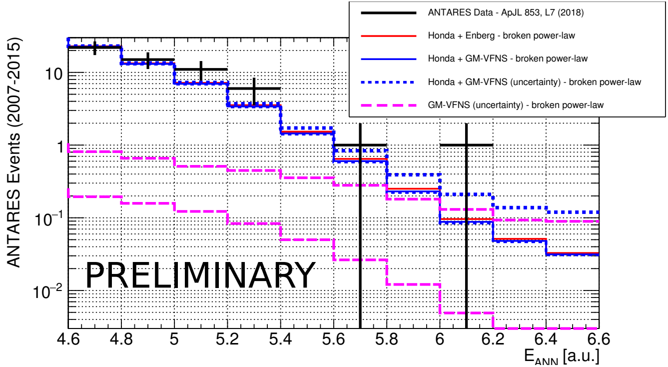
Effects of the GM-VFNS prompt flux in the analysis of ANTARES High-Energy Track Events



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.

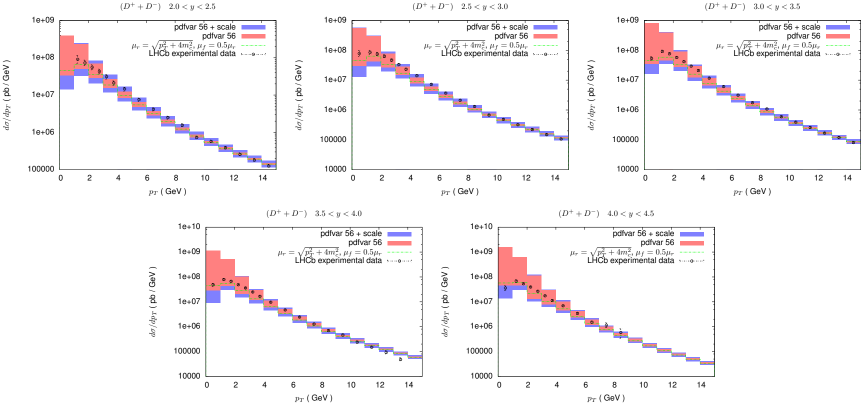
Effects of the GM-VFNS prompt flux in the analysis of ANTARES High-Energy Track Events



courtesy of the 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).

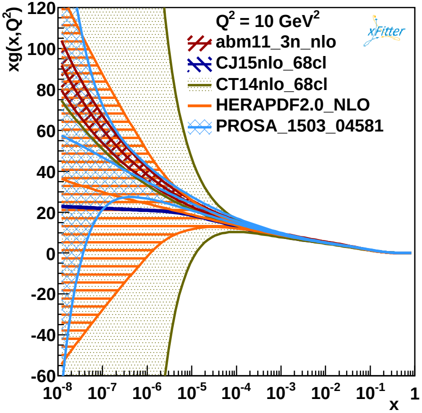
How do global PDF fits (CT14nlo), not including LHCb data, behave ? $pp \to D^{\pm} + X$ at LHCb at 13 TeV



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

∗ Large PDF uncertainties, increasing at low p_T / large y.

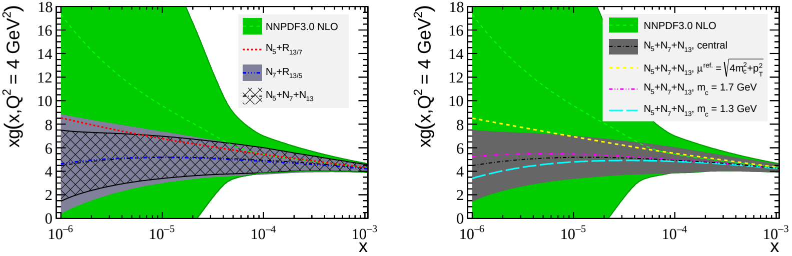
gluon PDF: comparison between different PDF fits



* 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.)



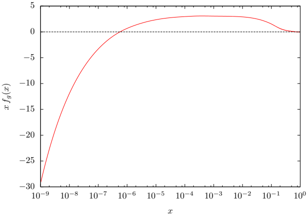
∗ their first fit includes 7 TeV open charm data [arXiv:1511.06346]

∗ most recent fit includes 5, 7, 13 TeV open charm data, as well as 13/7, 13/5 ratios [arXiv:1610.09373 v2]

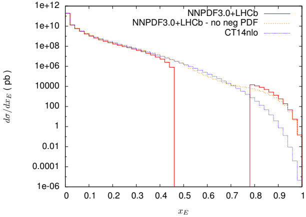
⇒ new version after last LHCb data correction!

∗ still space for improvement.....

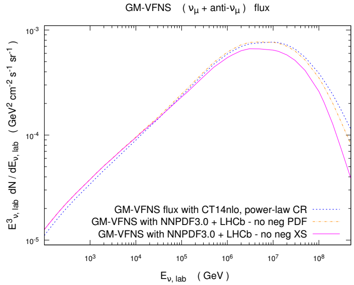
The NNPDF3.0 + LHCb PDF fit and GM-VFNS prompt neutrino fluxes



gluon PDF for $Q = 1.7$ GeV



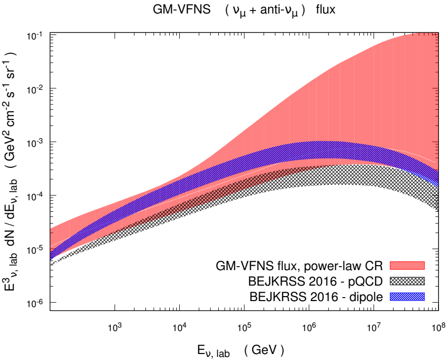
$d\sigma/dx_E$ for $pp \to D^0 + X$ for p with $E_{lab} = 10^5$ GeV



from [arXiv:1705.10386]

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

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).

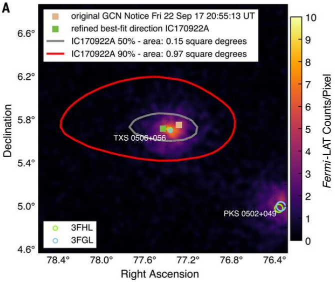
Summary

- 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 ($m_H > \Lambda_{\mathrm{QCD}}$) 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

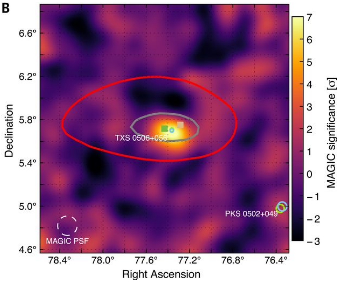
First evidence of a HE ν and γ source:

the TXS 0506+056 blazar and Multimessenger Astronomy

∗ On 22 september 2017 IceCube detected a $\sim$ 290 TeV ν_μ track event (IceCube-170922A alert) from a direction consistent with the flaring γ-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 σ. MAGIC follow-up observations on 28 september reported a significant VHE (up to 400 GeV) γ-ray excess signal.



IceCube + Fermi-LAT



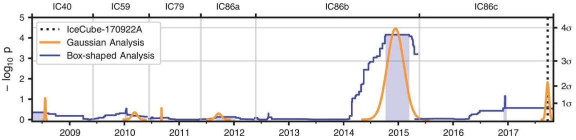
IceCube + MAGIC

from Science 361 (2018) 146

∗ 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].

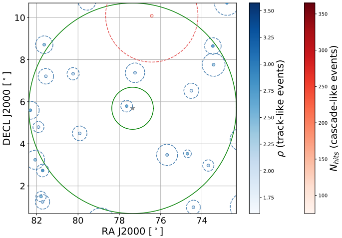
Further studies of ν emission from TXS 0506+056

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



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.



from ANTARES Collaboration, [arXiv:1807.04309]

Thank you for your attention!