Rigorous predictions for prompt neutrino fluxes in view of VLVνT upgrades.

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

PROSA
proton structure analyses in hadronic collisions

mainly on the basis of [arXiv: 1911.13164 [hep-ph]] + work in progress

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Neutrino Astronomy

- 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 galactic and/or extragalactic sources (AGNs, etc....).
- This is possible thanks to
  - ν weak interactions only ($\neq$ Cosmic Rays)
  - ν propagation not bended by galactic and extra-galactic magnetic fields ($\neq$ Cosmic Rays)

Very Large Volume Neutrino Telescopes

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

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

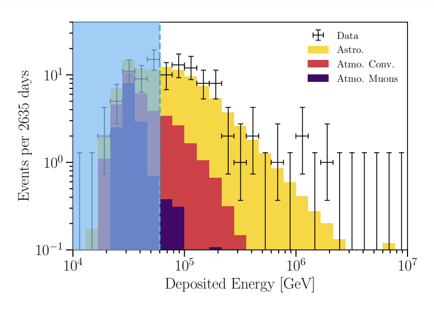
- time, position and amplitude of the photon signal allow to reconstuct $\ell^{\pm}$ trajectory;
- total amount of light allows to reconstruct the energy of the event.

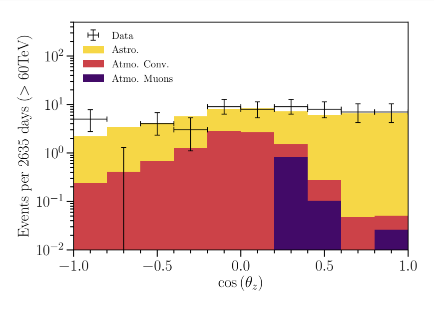
$*$ under-water neutrino telescopes: Baikal, upgraded to Baikal-GVD and ANTARES/ NEMO/NESTOR, now working in a joint effort towards a full KM3NeT Mediterranean Neutrino Observatory, with an instrumented volume similar to that of Ice-Cube.

$*$ 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 at this Conference).

Last update of the IceCube HESE analysis

* **2020**: 2635-day analysis, with a total of **102** events (42 with $E < 60$ TeV and 60 with $E > 60$ TeV).
  The last ones are compatible with a single power spectrum with spectral index $\Gamma = -2.87^{+0.20}_{-0.19}$.
  No new events with deposited energy above 450 TeV with respect to the previous analyses !





2020 best fit of the (astrophysical + atmospheric) components vs. experimental data

from IceCube collaboration, [arXiv:2011.03545 [astro-ph]]

* high-energy diffuse flux further tested by ANTARES and testable by KM3Net/ARCA

Why the HESE analysis has not found prompt neutrinos ?

Some possible explanations:

- Low statistics at the relevant energies.
- Analysis not designed specifically at this aim.
- Big uncertainties on the prompt neutrino predictions may play a role.

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:

$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow \pi^{\pm}, K^{\pm} + X' \rightarrow \nu_{\ell}(\bar{\nu}_{\ell}) + \ell^{\pm} + X',$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow K_S^0,\ K_L^0 + X \rightarrow \pi^{\pm} + \ell^{\mp} + \overset{(-)}{\nu}_{\ell} + X$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow \textit{light hadron} + X' \rightarrow \nu(\bar{\nu}) + X''$$

$*$ prompt neutrino flux:

$$NN \rightarrow c, b, \bar{c}, \bar{b} + X \rightarrow \textit{heavy-hadron} + X' \rightarrow \nu(\bar{\nu}) + X'' + X'$$

where the decay to neutrino occurs through semileptonic and leptonic decays:

$D^+ \rightarrow e^+\nu_e X, \quad D^+ \rightarrow \mu^+\nu_\mu X,$

$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm},$ with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + X$

proper decay lenghts: $c\tau_{0,\,\pi^{\pm}} = 780$ cm, $c\tau_{0,\,K^{\pm}} = 371$ cm, $c\tau_{0,\,D^{\pm}} = 0.031$ cm

Critical energy $\epsilon_h = m_h c^2 h_0\ /\ (c\ \tau_{0,h} \cos(\theta))$, 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, due to finite atmosphere height h_0.

Conventional $\rightarrow$ prompt transition

Prompt fluxes expected to dominate above $E_{lab,\nu} > 10^5$ - 10^6 GeV, depending of the flavour and zenith angle.

Investigating the transition requires accurate computation of both fluxes:

– predictions for conventional fluxes at high energies are more uncertain than at lower ones.

– same applies to prompt fluxes.

– characterizing the transition point is important for an explicit detection of prompt fluxes.

– Possible computation of both fluxes in a consistent framework. But the physics of the interactions at the core of the two fluxes differs.

Light flavour vs. heavy flavour

$*$ Light-flavoured hadrons include only light quarks as valence quarks in their composition.

$* \; m_u, \;\; m_d, \;\; m_s << \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_u), \;\; \alpha_S(m_d), \;\; \alpha_S(m_s) \;\; > 1$

$\Rightarrow$ Light hadron production at low p_T is dominated by non-perturbative QCD effects.

$*$ Heavy-flavoured hadrons include at least one heavy-quark as valence quark in their composition.

$* \; m_c, \;\; m_b >> \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_c), \;\; \alpha_S(m_b), \;\; << 1$

$\Rightarrow$ At a scale $\sim m_Q$, QCD is still perturbative. Charm is produced perturbatively (if one neglects possible intrinsic charm contributions from PDFs) even at low p_T, but non-perturbative effects at such low scales may also play important roles.

$* \; m_c, \;\; m_b <<$ present collider energies

$\Rightarrow$ Multiscale issues, appearence of large logs.

Heavy-quark production in hadronic collisions

* Heavy quarks are mostly produced in pairs in the Standard Model.
* This process is dominated by QCD effects.

* Collinear factorization theorem is assumed:

$$d\sigma(N_1 N_2 \to Q\bar{Q} + X) = \sum_{ab} PDF_a^{N_1}(x_a, \mu_F) PDF_b^{N_2}(x_b, \mu_F) \otimes$$
$$\otimes \; d\hat{\sigma}_{ab \to Q\bar{Q}X'}(x_a, x_b, \mu_F, \mu_R, m_Q)$$

$d\hat{\sigma}$: differential perturbative partonic hard-scattering cross-section,

μ_F, μ_R reabsorb IR and UV divergences (truncation of P.T. series),

PDFs: perturbative evolution with factorization scale μ_F,
non-perturbative dependence on $x = p^+/P_N^+$.

<u>QCD uncertainties</u>

* μ_F and μ_R choice: no univocal recipe.
* Approximate knowledge of heavy-quark mass values m_Q (SM input parameters).
* Choice of the Flavour Number Scheme (several possibilities).
* PDF (+ $\alpha_S(M_Z)$) fits to experimental data.

From parton production to heavy-flavour hadrons

Different descriptions of the transition are possible:

1) Convolution of cross-sections with Fragmentation Functions

2) Fixed-order QCD + Parton Shower + hadronization:
match the fixed-order calculation with a parton-shower algorithm (resummation of part of the logarithms related to soft and collinear emissions on top of the hard-scattering process), followed by hadronization (phenomenological model).

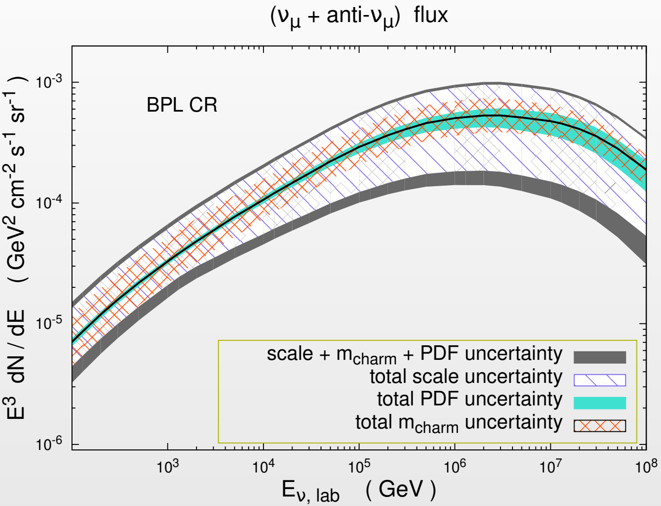
Advantage: fully exclusive event generation, correlations between final state particles/hadrons are kept.

Problem: accuracy not exactly known.

Both methods 1) and 2) used here.

It is possible to consider additional non-perturbative contributions (e.g. those due to intrinsic $\langle k_T \rangle$, related to the confinement of the initial state partons into hadrons).

PROSA 2019 atmospheric prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux: QCD scale, mass and PDF uncertainties



PDF uncertainty subdominant, assuming extrapolation at $x < 10^{-6}$ works.

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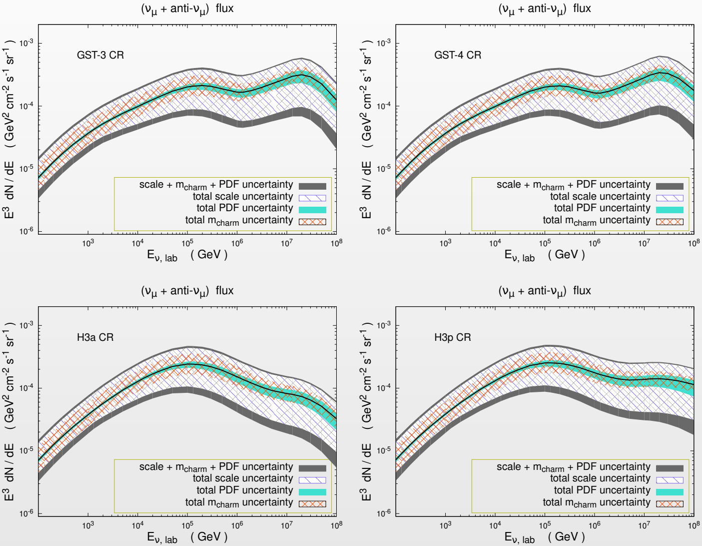
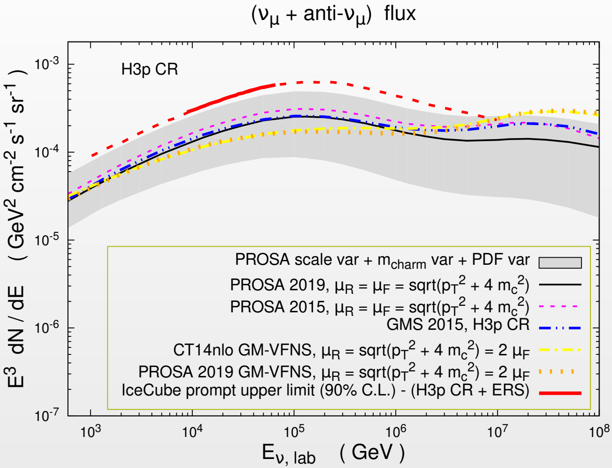
Prompt neutrino flux uncertainties: summary of main QCD + astroparticle uncertainties



∗ Panels differ for different assumptions in CR composition.

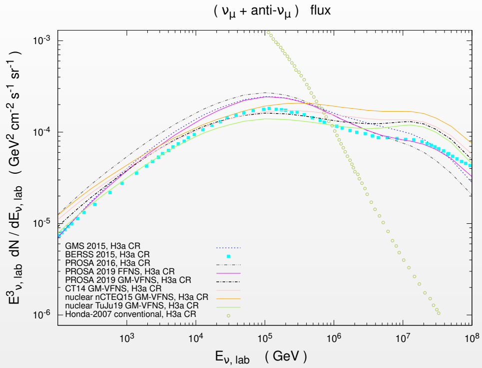
Prompt neutrino fluxes:

theoretical predictions vs. IceCube upper limits



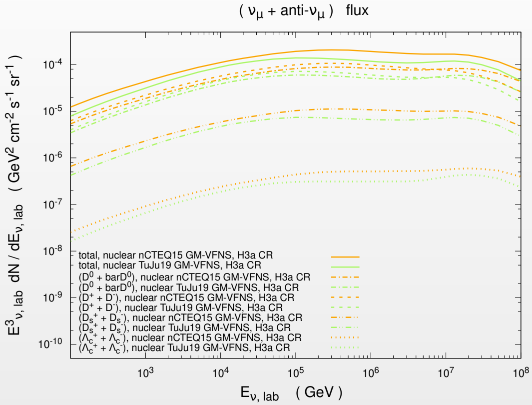
IceCube upper limit on prompt fluxes from the 6-year analysis of thoroughgoing μ tracks from the Northest Hemisphere [arXiv:1607.08006] assumed the ERS flux as a basis for modelling prompt neutrinos (reweighted to the H3p CR flux).

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: transition region



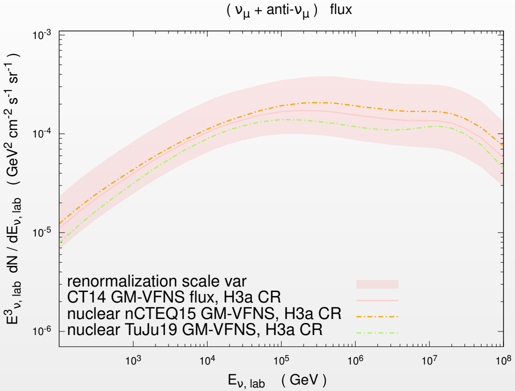
- $*$ Honda-2007 conventional flux reweighted with respect to a more modern CR primary spectrum (H3a).
- $*$ Our predictions point to a transition energy in the interval $E_\nu = 10^5$ - 10^6 GeV: are the bins where IceCube has seen only very few events $E_{DEP} = (6 \cdot 10^5$ - 10^6 GeV) filled just by prompt ν ?
- $*$ central GM-VFNS, PROSA, BERSS and GMS flux predictions all yield to a very similar transition point $E_\nu \sim (6-9) \cdot 10^5$ GeV.

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: components



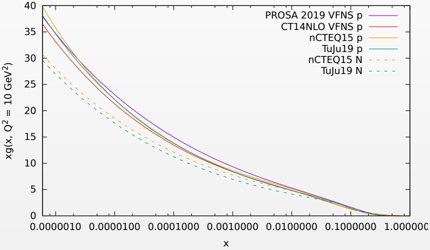
* The largest contributions to total prompt $(\nu_\mu + \bar{\nu}_\mu)$ fluxes are from $(D^0 + \bar{D}^0)$ and $(D^+ + D^-)$ production and decay.

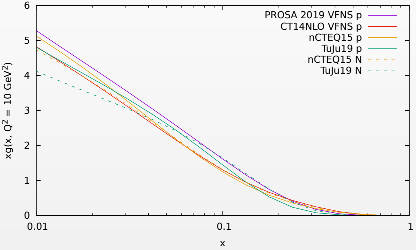
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: cold nuclear matter effects



* Predictions using nuclear PDFs within scale uncertainty bands of those with proton PDFs and superposition model.
* Suppression of prompt fluxes due to CNM effects ?
  Large shadowing effects do not emerge for all nuclear PDF fits, especially for low-mass nuclei

gluon PDFs in Proton and Nitrogen





* N gluon PDFs at low x slightly suppressed w.r.t. p ones, but still in the uncertainty bands of the latter.
* N gluon PDFs at large x resemble the p ones: no antishadowing effects.

Conclusions

* New dedicated measurements for exploring prompt neutrinos are needed, especially looking to the $(\nu_e + \bar{\nu}_e)$ and $(\nu_\tau + \bar{\nu}_\tau)$ components.
Increasing statistics (IceCube-Gen2, new observatories....) would help.

* Big uncertainties on theory predictions for prompt neutrino fluxes are related to the small value of the charm mass:
  - multiscale issues in pQCD computations at large $\sqrt{s}$.
  - slowness in the convergence of the pQCD expansion of the partonic cross-sections
  - interplay of perturbative and non-perturbative effects
  - intrinsic uncertainty in the m_c^{pole} value

* Cold nuclear matter effects need to be better constrained and understood.
At present predictions with N PDFs are compatible with those from p PDF and superposition model.
  - Shadowing/antishadown effects do not seem to produce big modifications in the spectra of prompt neutrino fluxes.
  - More data capable of constraining nuclear PDFs are wanted.
  - Possible relevance of Runs with O beams at the LHC + new experiments (FPF, LHeC....).
  - Are other CNM effect capable of suppressing these fluxes more intensively ?

Thank you for your attention!