UHE atmospheric neutrinos and FCC-hh

Maria Vittoria Garzelli
in collaboration with
W. Bai, M. Diwan, Y.S. Jeong, M.H. Reno

CERN, Department of Theoretical Physics,
Universität Hamburg, II Institut für Theoretische Physik

mainly on the basis of [arXiv:2212.07865[hep-ph]]

FCC-hh ESPP studies, meeting 5
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December 17, 2024

Measured or Predicted Neutrino fluxes

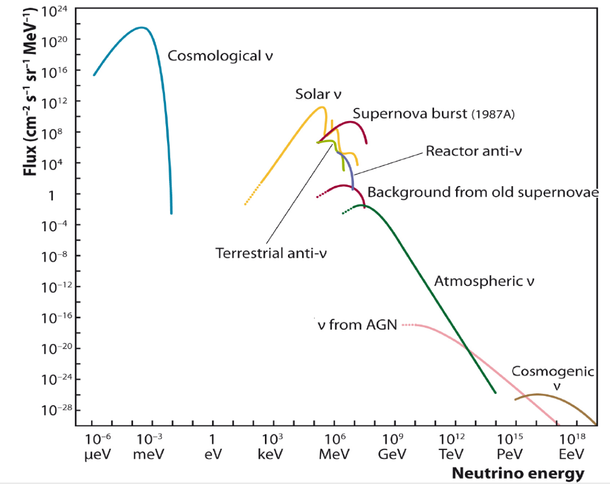
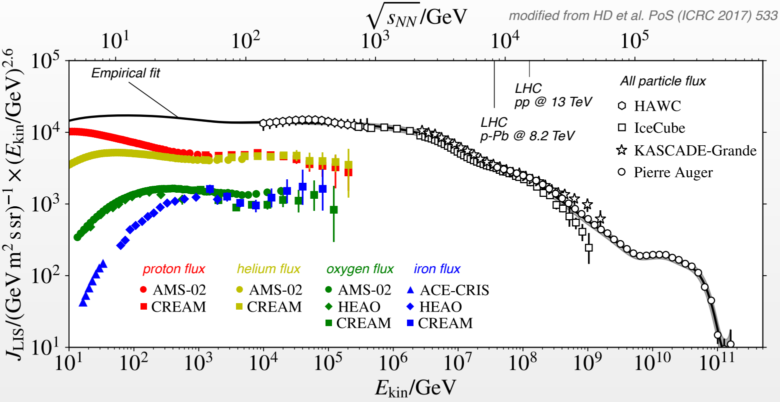


figure from U. Katz and C. Spiering Prog. Part. Nucl. Phys. 67 (2012) 651-704

- Detected: solar, Supernovae, atmospheric, geoneutrinos, astrophysical
- Not yet detected directly: cosmological CνB (see e.g. [arXiv:2207.12413]), cosmogenic (UHECR + CMB γ's and UHECR + EBL γ's)
- Created in the laboratory: reactors, accelerators

The all particle CR flux as a function of primary energy



* we are interested in E, arrival direction, mass A, event-by-event to understand CR origin (multimessenger approach: γ, ν, GW signals can help)
* direct detection for $E < 100$ TeV
* indirect detection for $E > 100$ TeV (E, A reconstructed from EAS products: E from size of e, γ component, A from X_{max}, N_μ; direction from particle arrival times)
* tail with energies much larger than LHC

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 / $\bar{\nu}_l + N \to \ell^{\pm} + X$, 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.

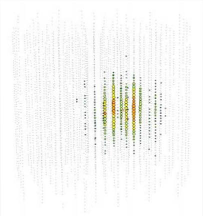
* under-water neutrino telescopes: Baikal, upgraded to Baikal-GVD and ANTARES/NEMO/NESTOR, now working in a joint effort towards a full KM3NeT Mediterranean Neutrino Observatory, with an instrumented volume similar to that of IceCube.

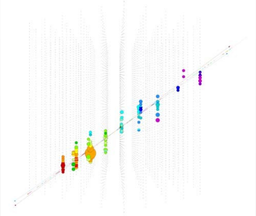
* in-ice neutrino telescopes: IceCube 1 km^3 instrumented volume already allowed for the actual detection of a high-energy ν flux

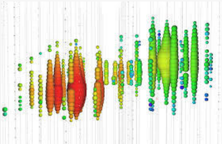
The future: IceCube-Gen2 (10-fold increase of sensitivity), see also recommendations from the P5 panel after the Snowmass 2021 process, completion of KM3NeT, further proposals for future experiments in the Northern Hemisphere.

Experiments sensitive to high-energy astrophysical/atmospheric neutrinos

∗ Atmospheric neutrinos at ANTARES, IceCube, KM3NeT, Baikal-GVD...
track / shower events from CC and NC $\nu + \bar{\nu}$ induced DIS in ice/water.



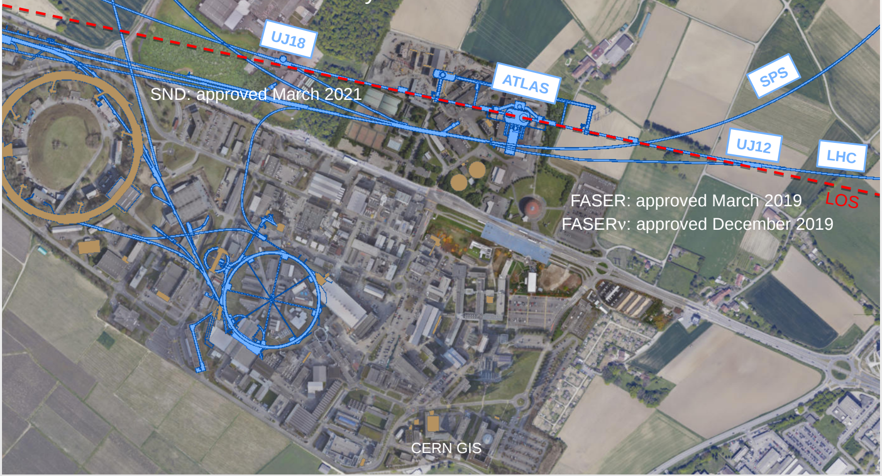




- lighter targets for DIS than in far-forward LHC/FCC experiments
- these experiments distinguish different flavour (like the LHC/FCC ones)
- these experiments do not distinguish ν and $\bar{\nu}$ (differently from LHC/FCC ones).
- these experiments do not have a ν and $\bar{\nu}$ pseudorapidity cut (differently from LHC/FCC ones).

FAR FORWARD LHC EXPERIMENTS

The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.



Atmospheric neutrino fluxes

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

∗ conventional neutrino flux:

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

∗ prompt neutrino flux:

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

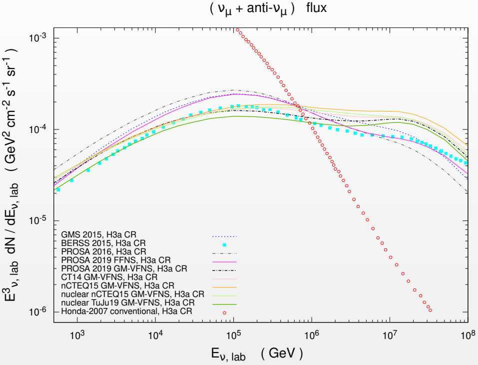
where the decay to neutrino occurs through semileptonic and leptonic decays:
$D^+ \rightarrow e^+ \nu_e X$, $D^+ \rightarrow \mu^+ \nu_\mu X$,
$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm}$, with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + X$

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

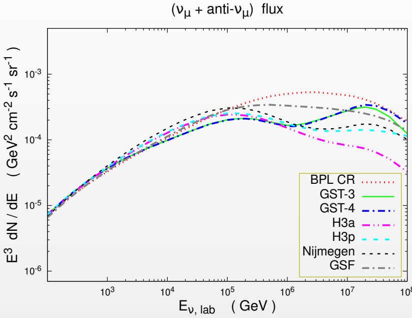
$\epsilon_\pi^{\pm} < \epsilon_K^{\pm} << \epsilon_D \Rightarrow$ conventional flux is suppressed with respect to prompt one,
for energies high enough, due to finite atmosphere height h_0.

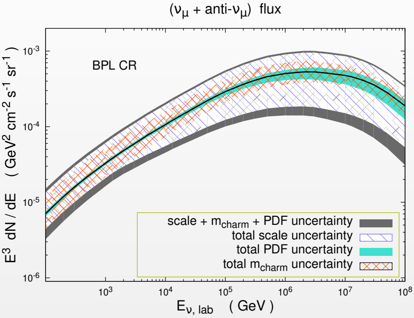
$(\nu_\mu + \bar{\nu}_\mu)$ atmospheric fluxes: conventional $\rightarrow$ prompt transition



* Atmospheric ν from solving a system of coupled differential eqs. for the variation of fluxes of different particles as a function of the atmospheric depth.
* Honda-2007 conventional flux reweighted with respect to a more modern CR primary spectrum (H3a).
* central GM-VFNS, PROSA, BERSS and GMS flux predictions all yield to a very similar transition point for $\nu_\mu + \bar{\nu}_\mu$: $E_\nu \sim (6-9) \cdot 10^5$ GeV.
* Transition prompt conventional absent at colliders

Uncertainties on prompt neutrino fluxes

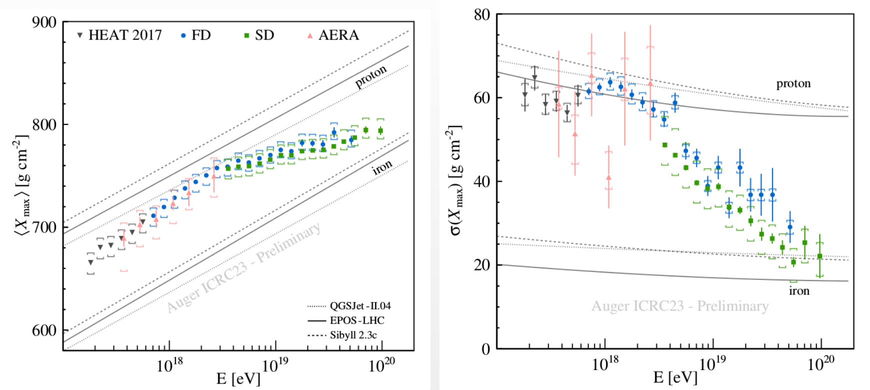




∗ Uncertainties in CR composition turn out to be smaller than QCD uncertainties. but still sizable ⇒ EAS CR experiments shall reduce them

∗ QCD uncertainties include here:
- renormalization and factorization scale variation
- charm mass
- parton distribution functions

$< X_{max} >$ and $\sigma(X_{max})$ from Phase I at the PAO

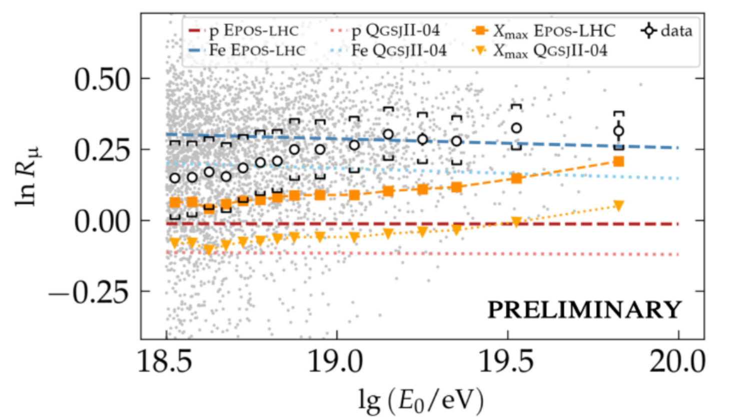


from PAO collaboration, PoS(ICRC 2023) 016

∗ SD allows to extend energy coverage (w.r.t. FD).

∗ Some systematics in the difference SD/FD still to be understood but measurements conducted with different techniques point to similar overall features concerning CR composition.

The μ puzzle at the PAO: phase I results

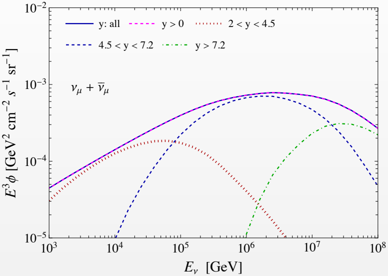


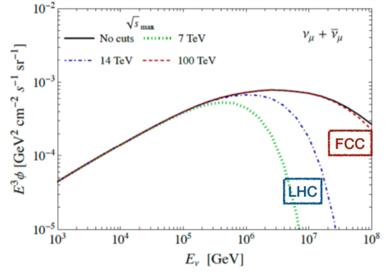
from PAO collaboration, PoS(ICRC 2023) 016

N_μ predictions from composition inferred from $\langle X_{max} \rangle$ are inconsistent with N_μ combined (FD+SD) data.

N_μ is related to the hadronic energy fraction. Measurements of π^0, ρ^0, $\pi^\pm$, $K^\pm$, K/π production are essential.

Prompt atmospheric ν fluxes and LHC phase-space coverage





∗ To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4.5 < y_c < 7.2$.

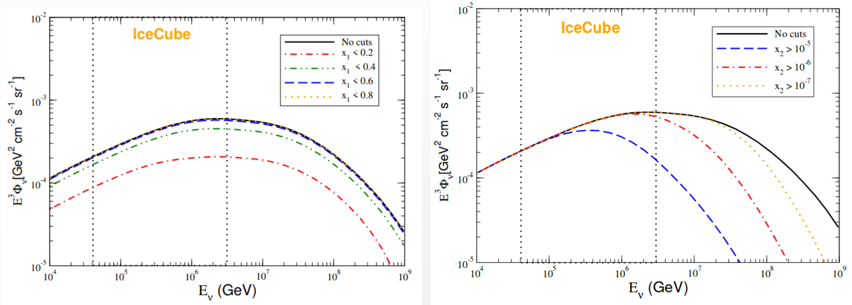
∗ The $\sqrt{s} = 14$ TeV at LHC is in any case a limitation, FCC would be better.

∗ There is kinematic overlap between the heavy-flavour production region explorable at FCC-hh (provided that detectors covering the relevant rapidity region $y_c > 4.5$ will be built) and in the atmosphere.

Important ingredient of these calculations: PDF fits

* x-dependence of PDFs is fitted to experimental data.
* HERA data (core of all PDF fits) offer good coverage in the range $10^{-4} < x < 10^{-1}$.
* Prompt ν fluxes sensitive to a wider range of x values, due to the fact that
  - The $\sqrt{s}$ for the relevant collisions involve a wide range of energies (from $\sqrt{s} \sim 100$ GeV to $\sqrt{s} \sim 150$ TeV).
  - The relevant rapidities extend to values much larger than those accessible in traditional experiments at human-made colliders.

Prompt atmospheric ν fluxes, small-x and large-x PDFs



, *from V. Goncalves et al. [arXiv:1708.03775]*

∗ A robust estimate of large x effects is important for determining the normalization of prompt atmospheric neutrino fluxes

∗ Region particularly relevant: $0.2 < x < 0.6$, partly testable through experiments at the LHC (including far-forward ν ones).

∗ On the other hand, for ν above the PeV scale, knowledge of PDF around and below $x < 10^{-6}$ is mandatory: this requires future colliders (LHeC, FCC-hh, FCC-eh).

Conclusions - prompt atmospheric neutrinos

* Prompt neutrino fluxes in the atmosphere are a background to neutrinos from far astrophysical sources.

* Theory uncertainties still large and constraints from VLVνT still loose.
  More accurate measurements expected from the future
  (high-statistics IceCube, IceCube-Gen2, KM3NeT).
  $\Rightarrow$ Computing higher-order corrections to charm hadroproduction is an indispensable ingredient for reducing these uncertainties.
  $\Rightarrow$ Better constraining PDF fits at small and large x is also relevant,
  * Synergy (LHC/FCC-hh)-(HERA/EIC/FCC-eh)-astroparticle physics

* There is kinematical overlap between the charm hadron production region explorable at FCC-hh and the one explorable in VLVνT's.

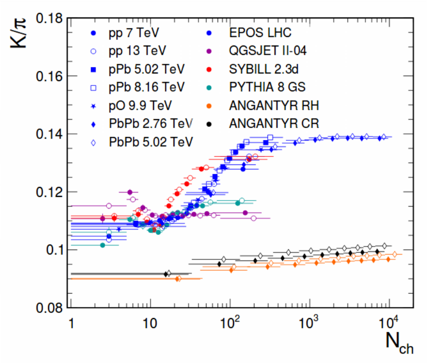
* Further measurements of kaon and pion production and their ratio are important to solve the "composition problem", affecting both UHECR physics and the computation of UHE atmospheric fluxes.

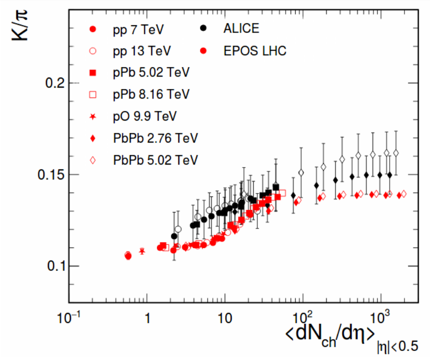
Thank you for your attention!

Back-up slides

Measurements helpful to discriminate

between different MC





from R. Scaria et al. [arXiv:2304.00294]

- ∗ K/π ratios and correlation with charged particle multiplicity N_{ch}
- ∗ $R(\eta) = \langle dE_{em}/d\eta \rangle / \langle dE_{had}/d\eta \rangle$
- ∗ $(R,\ N_{ch})$, $(K/\pi,\ R)$ correlations